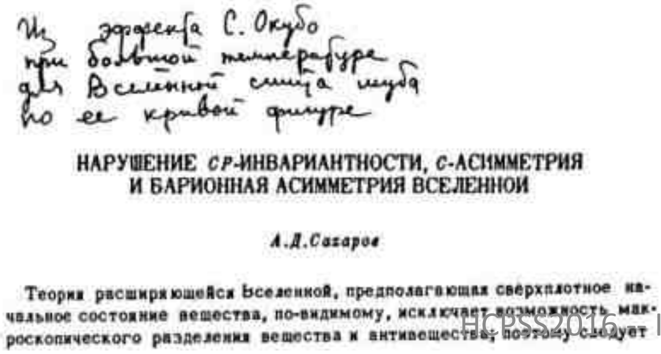
Are we done ? (Didn’t the B factories accomplish their mission, recognized by the 2008 Nobel Prize in Physics ?)



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

BAU: KM (Kobayashi-Maskawa) mechanism still short by 10 orders of magnitude !!!

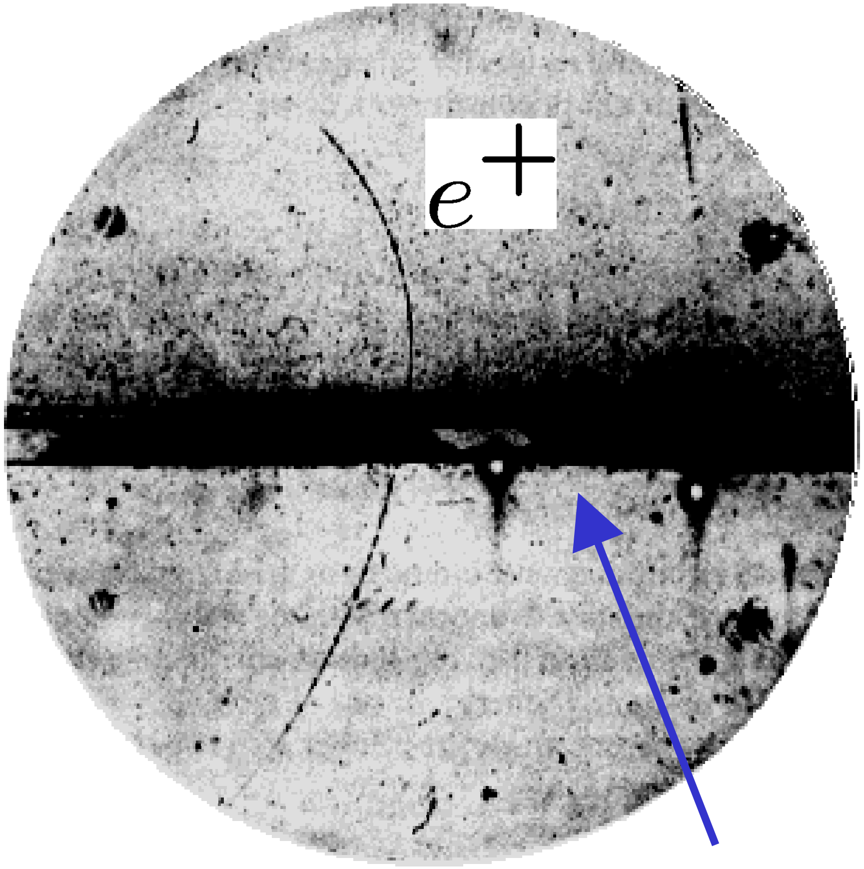
Discovery of antimatter

- **Dirac relativistic wave equation (1928): extra, "negative-energy" solutions. Positron interpretation confirmed by Anderson.**
- **A radical idea: doubling the number of kinds of particles!**

$$\begin{aligned} e^- &\rightarrow e^+ \\ p(udu) &\rightarrow \bar{p}(\bar{u}\bar{d}\bar{u}) \\ \gamma &\rightarrow \gamma \\ \nu &\rightarrow \bar{\nu}\ (= \nu?) \end{aligned}$$

- **Supersymmetry: doubles the number of particles again!**

$$e^- \longrightarrow \tilde{e}^-$$



$\otimes \vec{B}$

Pb: 6 mm thick

P.A.M. Dirac, Proc. Roy. Soc. (London), **A117**, 610 (1928); ibid., **A118**, 351 (1928).
C.D. Anderson, Phys. Rev. **43**, 491 (1933).

Parity Violation

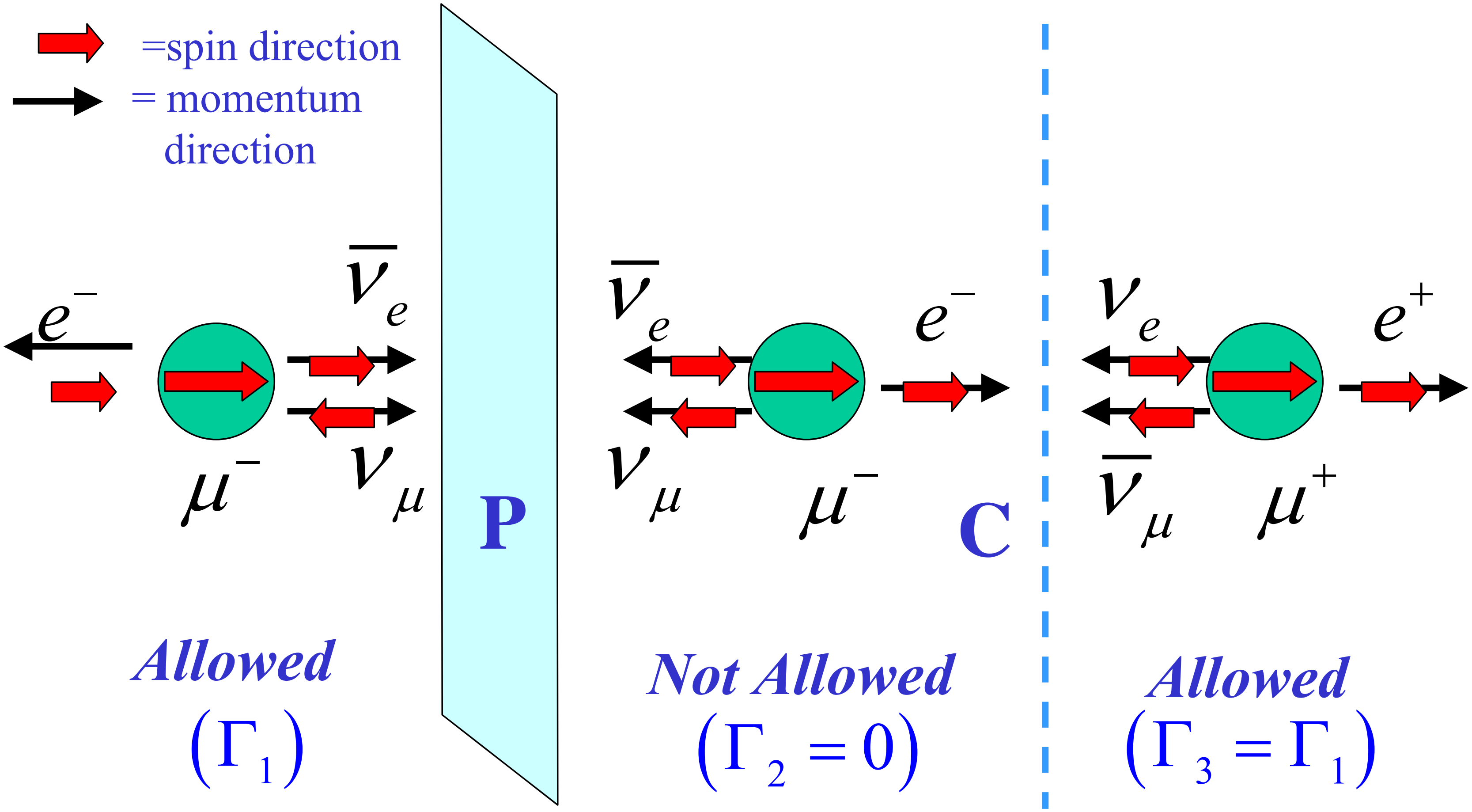
The $\theta - \tau$ puzzle:

- two strange charged particles discovered
  - the "θ" decaying to $\pi^+\pi^0$
  - the "τ" decaying to $\pi^+\pi^-\pi^+$
- parities of 2π and 3π are opposite, but masses and lifetimes of θ & τ found to be the same

Parity violation discovered 1957 (C.N.Wu et al, then many others, all following T.D.Lee and C.N.Yang)

θ & τ are the same particle: " K^+ "

P and *C* violation in polarized muon decay



🟥 =spin direction

→ = momentum direction

e^- $\overline{\nu}_e$ μ^- ν_μ

P

$\overline{\nu}_e$ e^- ν_μ μ^-

C

ν_e e^+ $\overline{\nu}_\mu$ μ^+

Allowed

(Γ_1)

Not Allowed

$(\Gamma_2 = 0)$

Allowed

$(\Gamma_3 = \Gamma_1)$

P and C are individually violated <u>maximally</u> in the weak interactions, but combined CP is a good symmetry [redacted] for most weak processes!

Discovery of CP violation

- CP violation at a tiny level (10^{-3}) was first discovered in 1964 in the decays of neutral kaons (mesons with strange quarks).

$$B(K_L^0 \to \pi^+\pi^-) = (2.0 \pm 0.4)\times 10^{-3} \qquad \eta_{CP}(\pi^+\pi^-, L=0) = +1$$

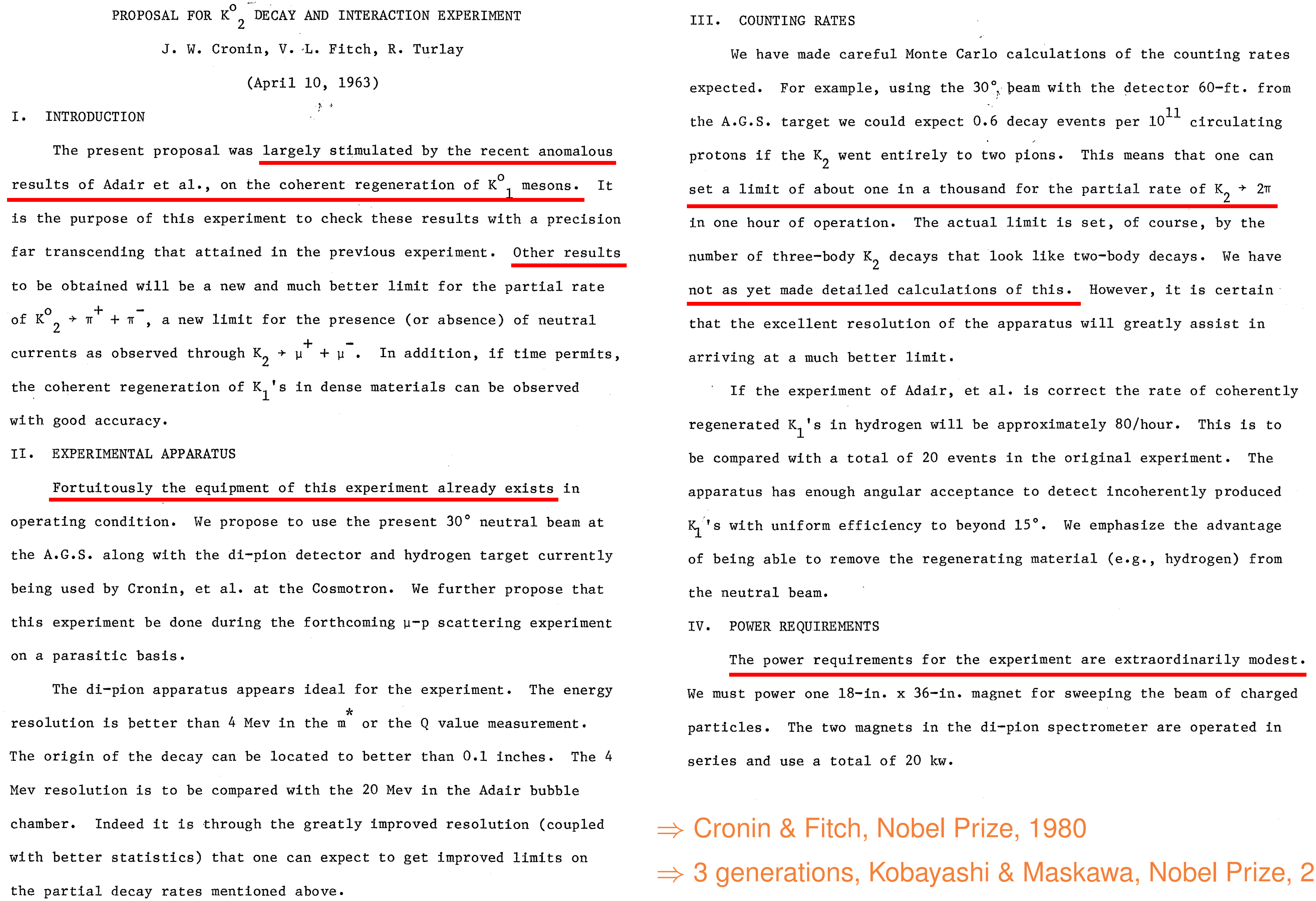
- Demonstrated that K_L^0 is not an eigenstate of CP: $[H, CP] \neq 0$

Jim Cronin's Nobel Prize lecture:

> "...the effect is telling us that at some tiny level there is a fundamental asymmetry between matter and antimatter, and it is telling us that at some tiny level interactions will show an asymmetry under the reversal of time. We know that improvements in detector technology and quality of accelerators will permit even more sensitive experiments in coming decades. We are hopeful then, that at some epoch, perhaps distant, this cryptic message from nature will be deciphered."

For a fascinating historical perspective on the discovery of CP violation, see J. Cronin @ 50 years of CP violation
https://indico.ph.qmul.ac.uk/indico/conferenceDisplay.py?confId=15

Experimental Proposal (1963)



PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXPERIMENT

J. W. Cronin, V. L. Fitch, R. Turlay

(April 10, 1963)

I. INTRODUCTION

The present proposal was largely stimulated by the recent anomalous results of Adair et al., on the coherent regeneration of K^o_1 mesons. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K^o_2 \to \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \to \mu^+ + \mu^-$. In addition, if time permits, the coherent regeneration of K_1's in dense materials can be observed with good accuracy.

II. EXPERIMENTAL APPARATUS

Fortuitously the equipment of this experiment already exists in operating condition. We propose to use the present 30° neutral beam at the A.G.S. along with the di-pion detector and hydrogen target currently being used by Cronin, et al. at the Cosmotron. We further propose that this experiment be done during the forthcoming μ-p scattering experiment on a parasitic basis.

The di-pion apparatus appears ideal for the experiment. The energy resolution is better than 4 Mev in the m^* or the Q value measurement. The origin of the decay can be located to better than 0.1 inches. The 4 Mev resolution is to be compared with the 20 Mev in the Adair bubble chamber. Indeed it is through the greatly improved resolution (coupled with better statistics) that one can expect to get improved limits on the partial decay rates mentioned above.

III. COUNTING RATES

We have made careful Monte Carlo calculations of the counting rates expected. For example, using the 30° beam with the detector 60-ft. from the A.G.S. target we could expect 0.6 decay events per 10^{11} circulating protons if the K_2 went entirely to two pions. This means that one can set a limit of about one in a thousand for the partial rate of $K_2 \to 2\pi$ in one hour of operation. The actual limit is set, of course, by the number of three-body K_2 decays that look like two-body decays. We have not as yet made detailed calculations of this. However, it is certain that the excellent resolution of the apparatus will greatly assist in arriving at a much better limit.

If the experiment of Adair, et al. is correct the rate of coherently regenerated K_1's in hydrogen will be approximately 80/hour. This is to be compared with a total of 20 events in the original experiment. The apparatus has enough angular acceptance to detect incoherently produced K_1's with uniform efficiency to beyond 15°. We emphasize the advantage of being able to remove the regenerating material (e.g., hydrogen) from the neutral beam.

IV. POWER REQUIREMENTS

The power requirements for the experiment are extraordinarily modest. We must power one 18-in. x 36-in. magnet for sweeping the beam of charged particles. The two magnets in the di-pion spectrometer are operated in series and use a total of 20 kw.

⇒ Cronin & Fitch, Nobel Prize, 1980

⇒ 3 generations, Kobayashi & Maskawa, Nobel Prize, 2008

Cosmology: Sakharov's three conditions

A. Sakharov (1967): How to generate an asymmetry between *N*(baryons) and *N*(anti-baryons) in the universe (assuming equal numbers initially)?

1. Baryon-number-violating process
2. Both C and CP violation [redacted]
3. Departure from thermal equilibrium

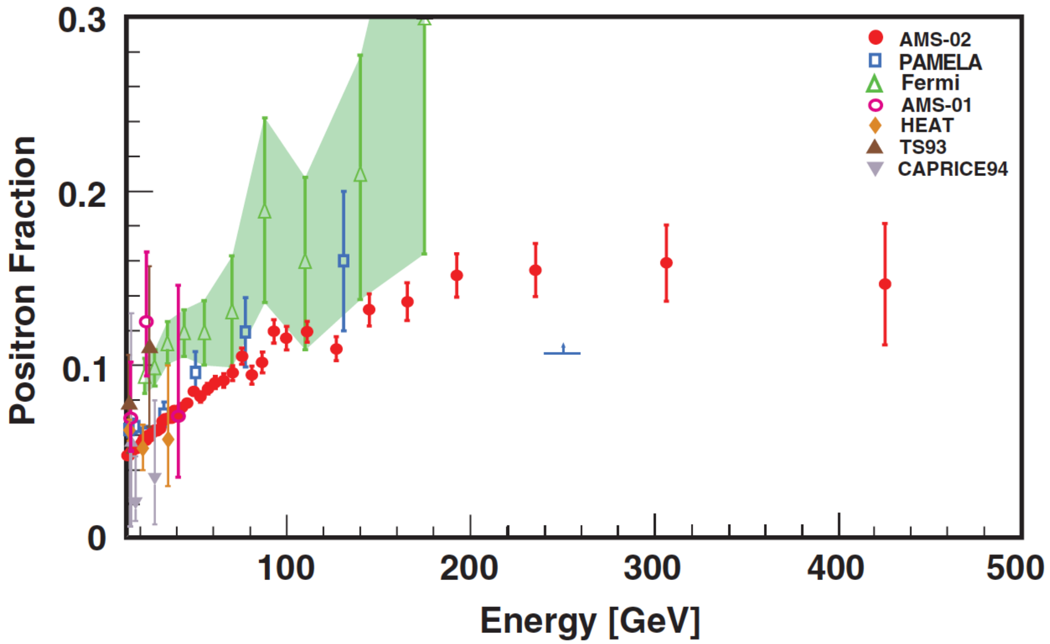
$$\left(N_{\text{bar}} - N_{\text{anti-bar}}\right) \propto \sum_i \left[\Gamma(X \to Y_i) - \Gamma(\bar{X} \to \bar{Y}_i)\right] \cdot \Delta B_i$$

$$\Delta N_B / N_\gamma = (N(\text{baryon}) - N(\text{antibaryon}))/N_\gamma \sim 10^{-10}$$

We appear to owe our existence to some form of CP violation at work in the early universe

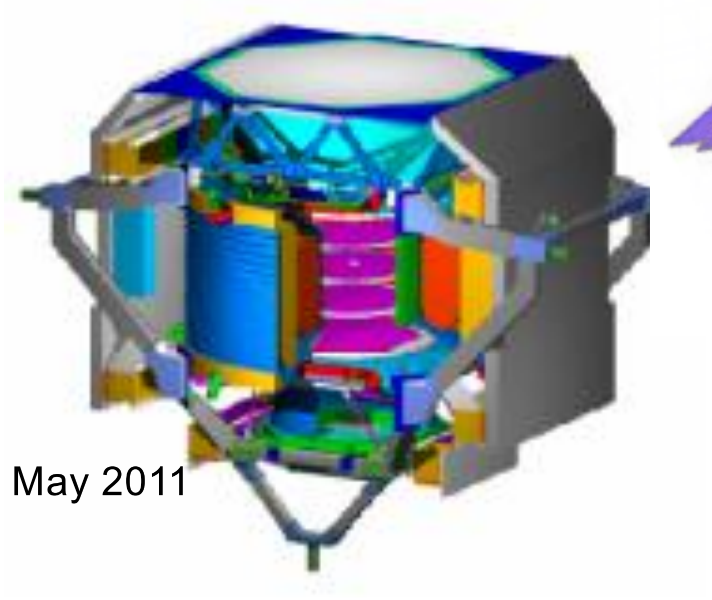
Digression: Are there antimatter dominated regions of the Universe?

- Possible signals:
  - Photons produced by matter-antimatter annihilation at domain boundaries – not seen
    - Nearby anti-galaxies ruled out
  - Cosmic rays from anti-stars
    - Best prospect: Anti-^{4}He nuclei
    - Searches ongoing ...



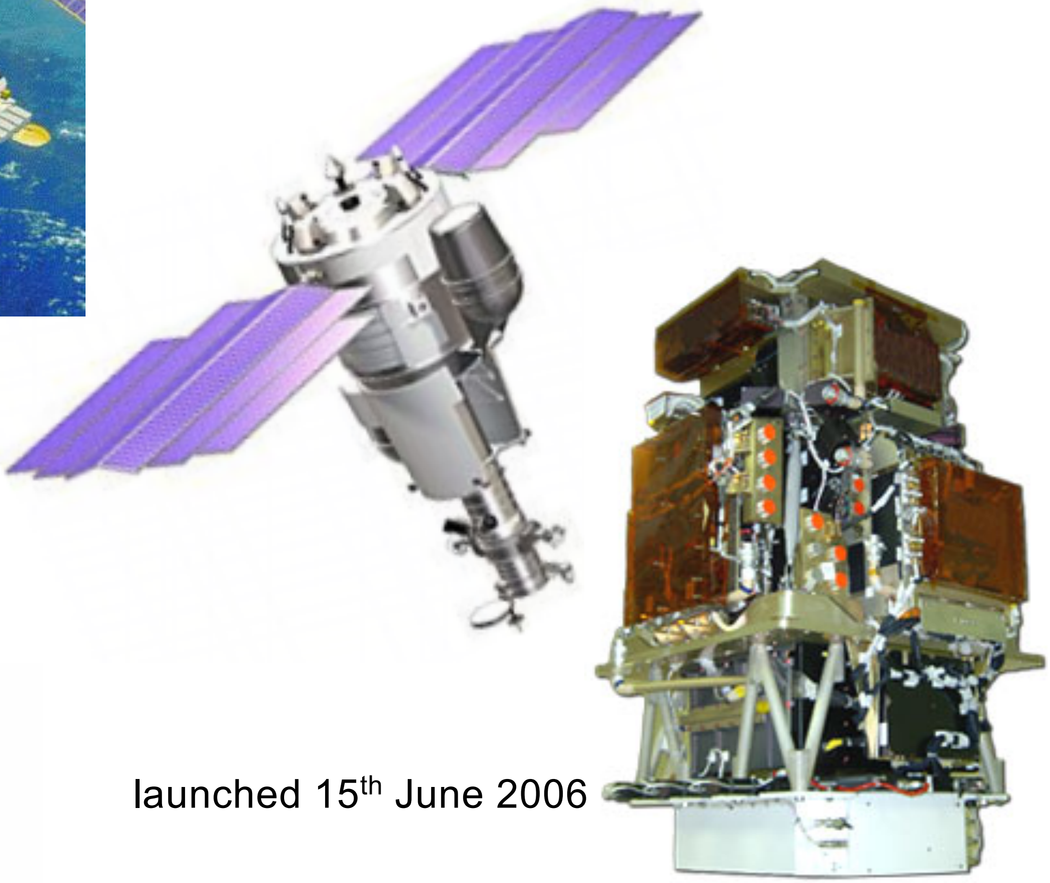
Searches for astrophysical antimatter

Alpha Magnetic Spectrometer Experiment on board the International Space Station



launched 16th May 2011

Payload for AntiMatter Exploration and Light-nuclei Astrophysics Experiment on board the Resurs-DK1 satellite



launched 15th June 2006

CKM CP Violation & the BAU

- We can estimate the magnitude of the baryon asymmetry of the Universe caused by KM CP violation

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx \frac{n_B}{n_\gamma} \sim \frac{J \times P_u \times P_d}{M^{12}}$$

◄ N.B. Vanishes for degenerate masses

$$J = \cos(\theta_{12})\cos(\theta_{23})\cos^2(\theta_{13})\sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\sin(\delta)$$

$$P_u = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)$$

$$P_d = (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)$$

PRL 55 (1985) 1039

- The Jarlskog parameter J is a parametrization invariant measure of CP violation in the quark sector: J ~ $O(10^{-5})$
- The mass scale M can be taken to be the electroweak scale O(100 GeV)
- This gives an asymmetry $O(10^{-17})$
  - much much below the observed value of $O(10^{-10})$

More CP Violation needed

- Widely accepted that SM CPV insufficient to explain observed baryon asymmetry of the Universe
- To create a larger asymmetry, require
  - new sources of CP violation
  - that occur at high energy scales
- Where might we find it?
  - quark sector: discrepancies with KM predictions
  - lepton sector: CP violation in neutrino oscillations
  - gauge sector, extra dimensions, other new physics: precision measurements of flavour observables are generically sensitive to additions to the Standard Model

CP violation and aliens from outer space

We can use our knowledge of CP violation to determine whether alien civilizations are made of matter or antimatter without having to touch them.

$$A_{CP}=\frac{\Gamma(\overline{B}^0\to K^-\pi^+)-\Gamma(B^0\to K^+\pi^-)}{\Gamma(\overline{B}^0\to K^-\pi^+)+\Gamma(B^0\to K^+\pi^-)}\ ;\quad -8\%$$

$b\overline{d}$

$\overline{b}d$

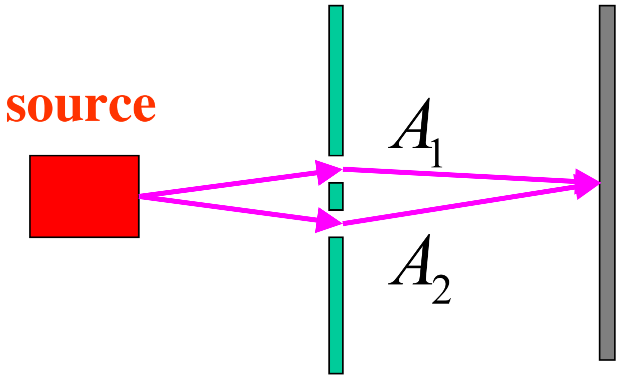
We have these inside of us.

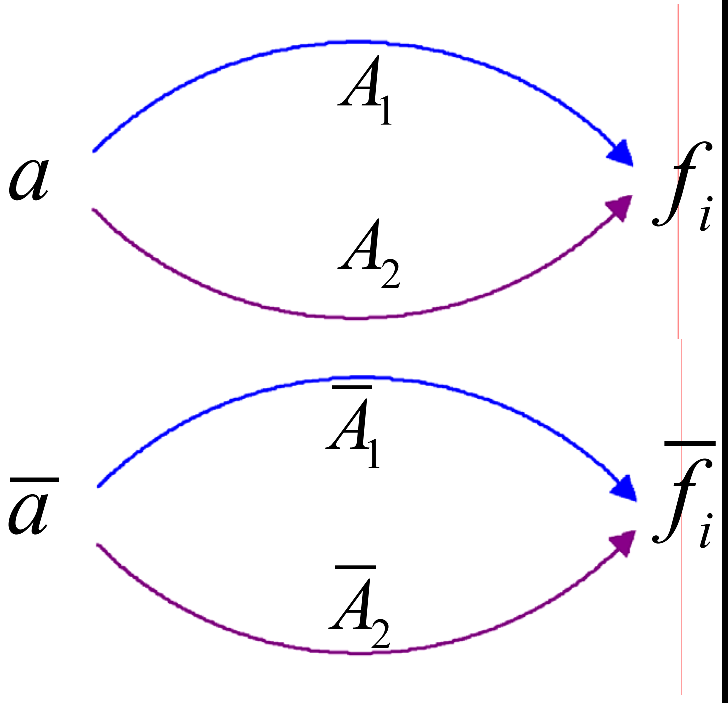
$$K^-=\overline{u}s$$

$$\pi^-=\overline{u}d$$

How are CP violating asymmetries produced?

The Standard Model predicts that, if CP violation occurs, it must occur through specific kinds of quantum interference effects..





Double-slit experiment: if the final state does not distinguish between the paths, then the amplitudes A_1 and A_2 interfere!

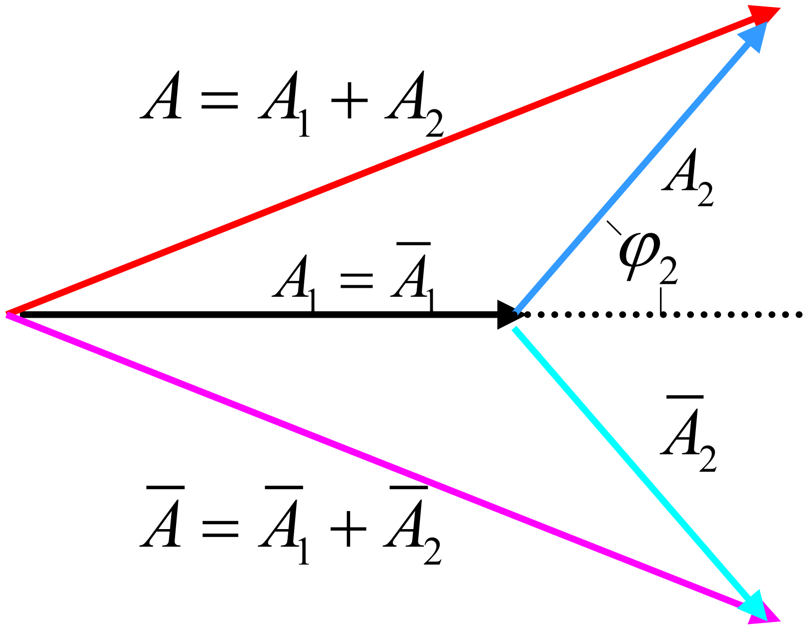
Two amplitudes with a CP-violating relative phase

- Suppose a decay can occur through two processes, with amplitudes A_1 and A_2. Let A_2 have a CP-violating phase ϕ_2.

$$A = A_1 + A_2 e^{i\varphi_2}$$

$$\overline{A} = \overline{A}_1 + \overline{A}_2 e^{-i\varphi_2}$$

No CP asymmetry!



Two amplitudes with CP-conserving & CP-violating phases

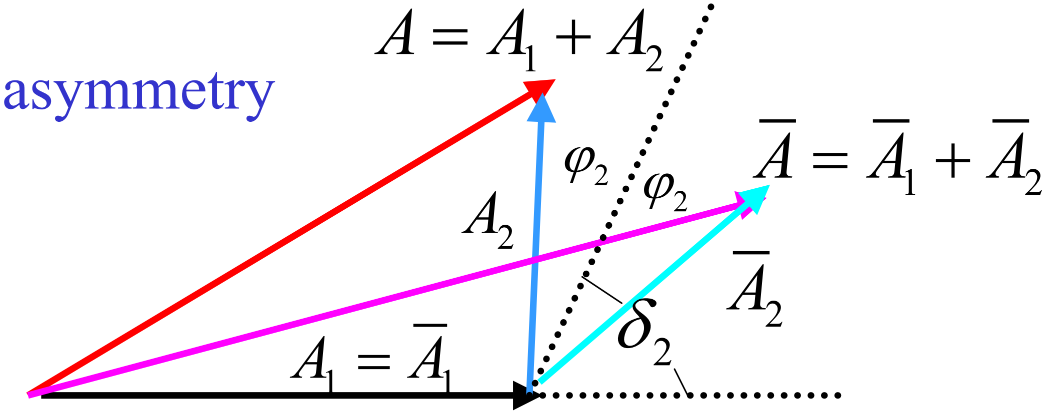
- Next, introduce a *CP-conserving* phase in addition to the *CP-violating* phase.

$$A = A_1 + A_2 e^{i(\varphi_2+\delta_2)}$$

$$\overline{A} = \overline{A_1} + \overline{A_2} e^{i(-\varphi_2+\delta_2)}$$

- Now have a CP asymmetry

$$|A| \neq |\overline{A}|$$



Three Kinds of *CP* Violation

We have seen that CP violation arises as an interference effect.

- Need at least two interfering amplitudes
- Need relative CP-violating phase
- Need relative CP-conserving phase

A single CP-violating amplitude will not produce observable CP violation!

What breaks the flavor symmetry ?

- In the Standard Model, the vacuum expectation value of the Higgs field breaks the electroweak symmetry
- Fermion masses arise from the Yukawa couplings of the quarks and charged leptons to the Higgs field (taking $m_\nu=0$)
- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks
- Consequently, the only flavour-changing interactions are the charged current weak interactions
  - no flavour-changing neutral currents (GIM mechanism)
  - not generically true in most extensions of the SM
  - flavour-changing processes provide sensitive tests

What causes the difference between matter and anti-matter?

- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks

$$V_{CKM} = U_u U_d^+$$

U matrices from diagonalisation of mass matrices

Quark mixing formalism

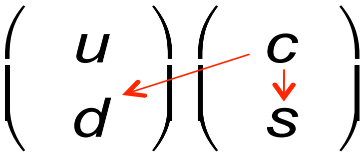
- Lagrangian for charged current interactions is

$$L_{cc} = -\frac{g}{\sqrt{2}} J^{\mu}_{cc} W^{\dagger}_{\mu} + h.c.,$$

- where

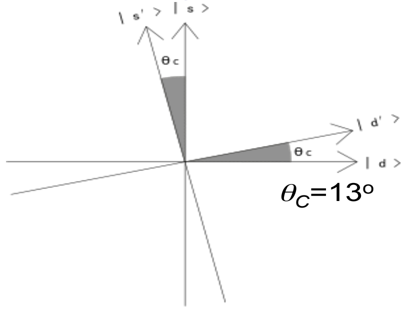
$$J^{\mu}_{cc} = (\bar{\nu}_e,\ \bar{\nu}_{\mu},\ \bar{\nu}_{\tau})\,\gamma^{\mu} V_{MNS} \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} + (\bar{u}_L,\ \bar{c}_L,\ \bar{t}_L)\,\gamma^{\mu} V_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

- Consider the charm quark. It forms a 2nd generation doublet with the strange quark (c,s). Yet it also decays into the d quark which is in the first generation with the u quark (u,d).



- We say this happens because the s & d quarks are "mixed" i.e. their wave functions really are described by a rotation matrix

$$\begin{bmatrix} d' \\ s' \end{bmatrix} = \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix}$$



where the s´ couples to c

What causes the difference between matter and anti-matter?

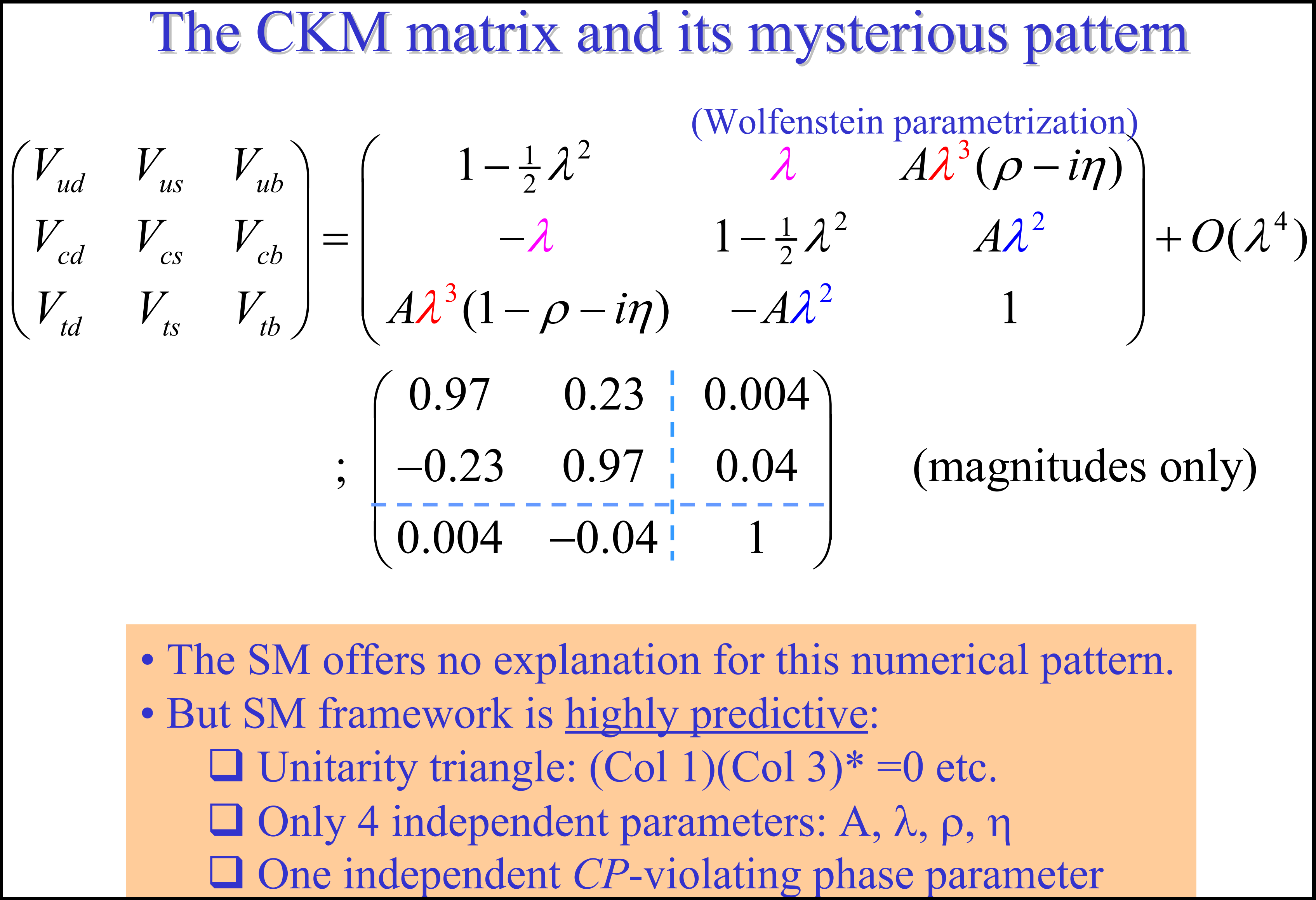
- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks

$$V_{CKM} = U_u U_d^+$$

U matrices from diagonalisation of mass matrices

- It is a 3x3 complex unitary matrix
  - described by 9 (real) parameters
  - 5 can be absorbed as phase differences between the quark fields
  - 3 can be expressed as (Euler) mixing angles
  - the fourth makes the CKM matrix complex (i.e. gives it a phase)
    - weak interaction couplings differ for quarks and antiquarks
    - CP violation

CKM Matrix



The CKM matrix and its mysterious pattern

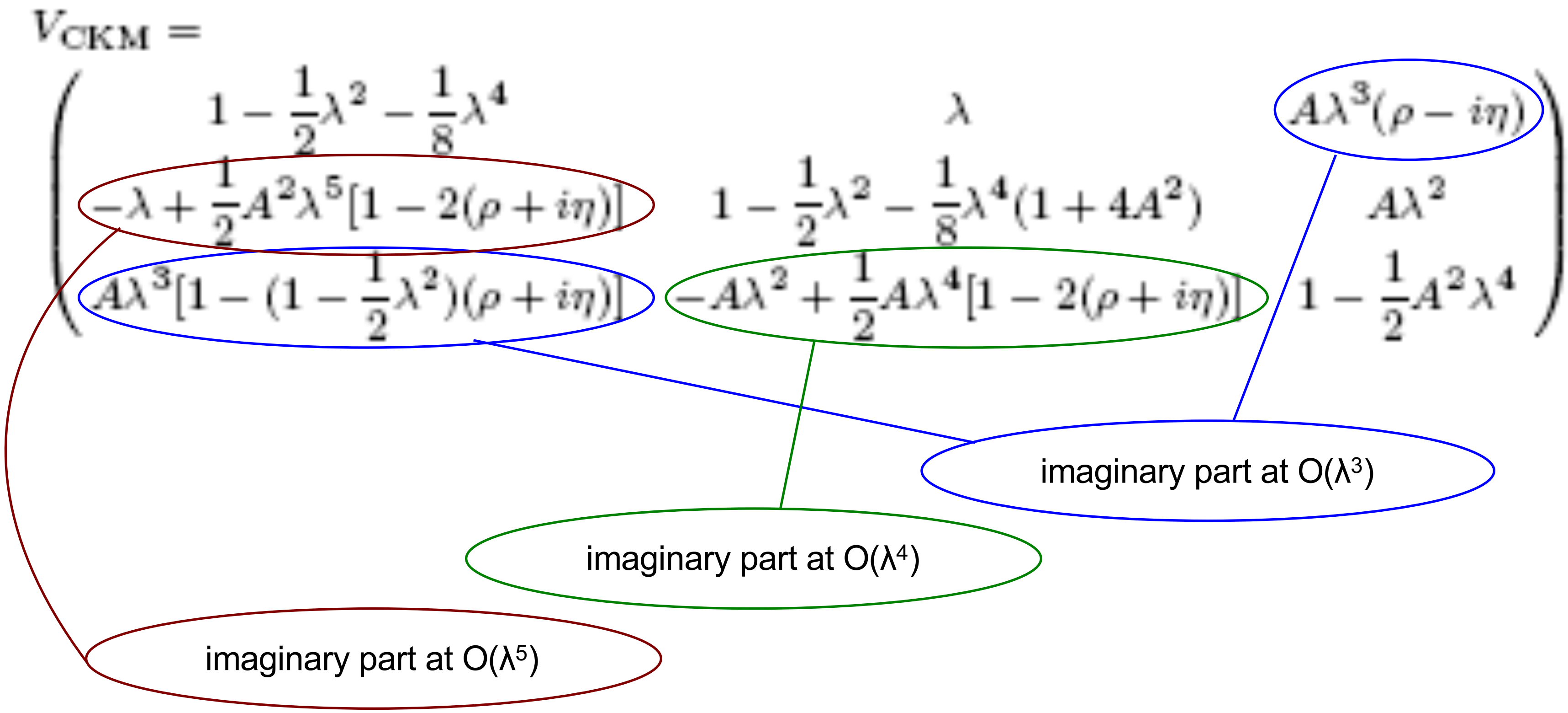
(Wolfenstein parametrization)

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$$; \left(\begin{array}{cc|c} 0.97 & 0.23 & 0.004 \\ -0.23 & 0.97 & 0.04 \\ \hline 0.004 & -0.04 & 1 \end{array}\right) \quad \text{(magnitudes only)}$$

- The SM offers no explanation for this numerical pattern.
- But SM framework is highly predictive:
  - ☐ Unitarity triangle: (Col 1)(Col 3)* =0 etc.
  - ☐ Only 4 independent parameters: A, λ, ρ, η
  - ☐ One independent *CP*-violating phase parameter

CKM matrix to O(λ^5)



$$V_{\mathrm{CKM}} =$$

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

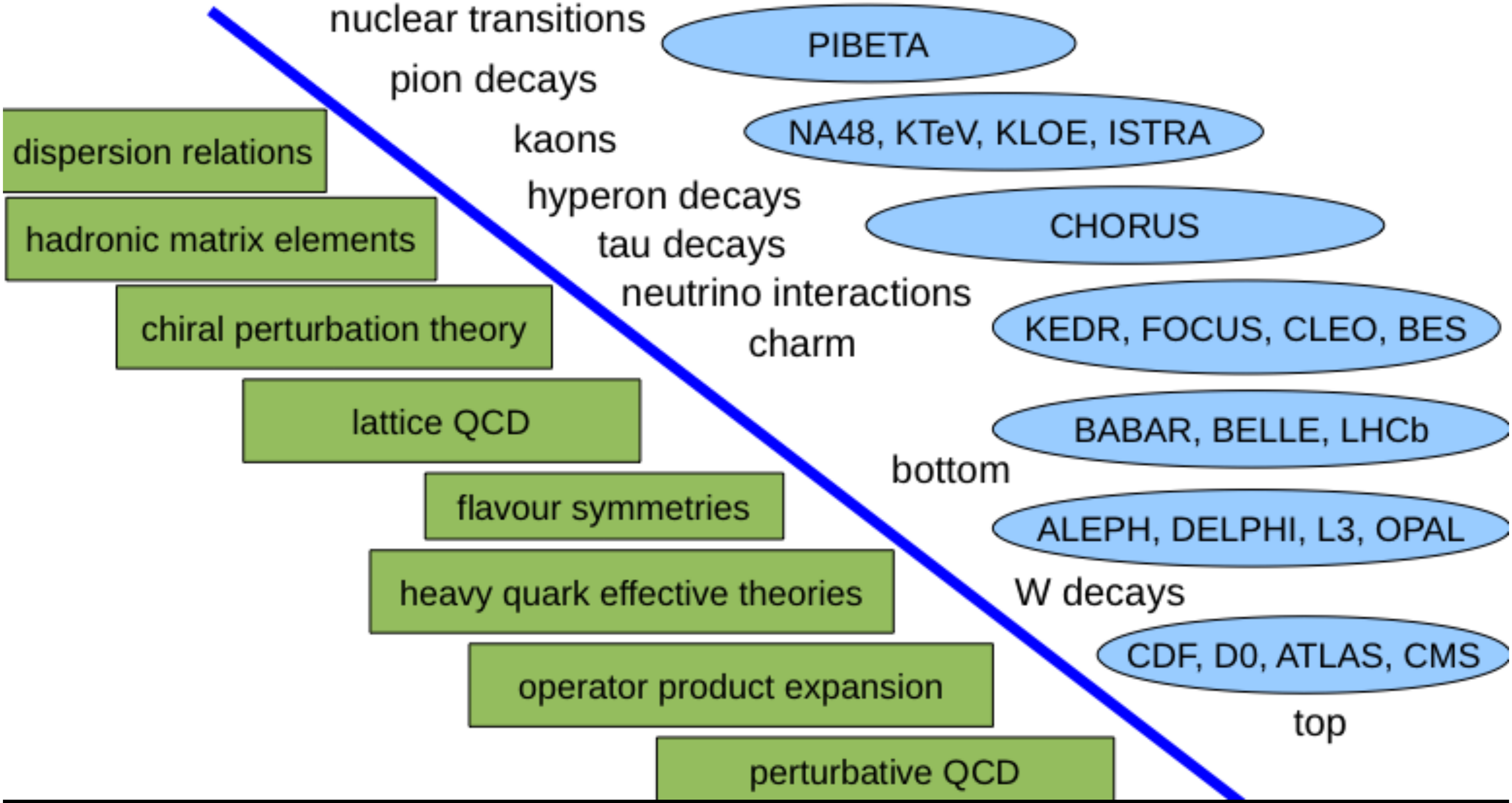
imaginary part at O(λ^3)

imaginary part at O(λ^4)

imaginary part at O(λ^5)

Remember – only *relative* phases are observable

Range of CKM Phenomena



nuclear transitions

pion decays

kaons

hyperon decays

tau decays

neutrino interactions

charm

bottom

W decays

top

PIBETA

NA48, KTeV, KLOE, ISTRA

CHORUS

KEDR, FOCUS, CLEO, BES

BABAR, BELLE, LHCb

ALEPH, DELPHI, L3, OPAL

CDF, D0, ATLAS, CMS

dispersion relations

hadronic matrix elements

chiral perturbation theory

lattice QCD

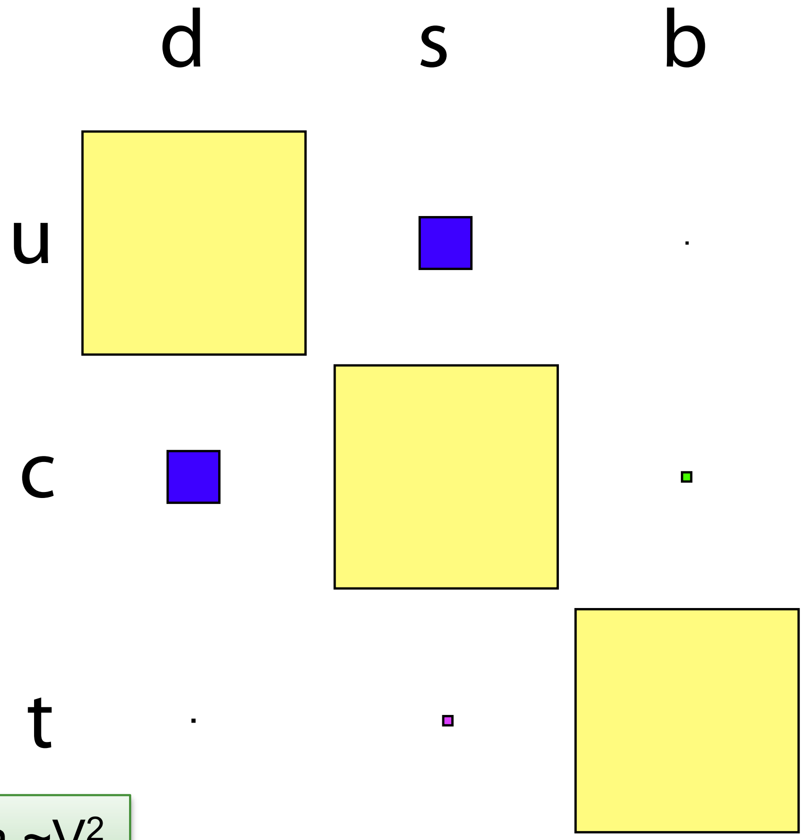
flavour symmetries

heavy quark effective theories

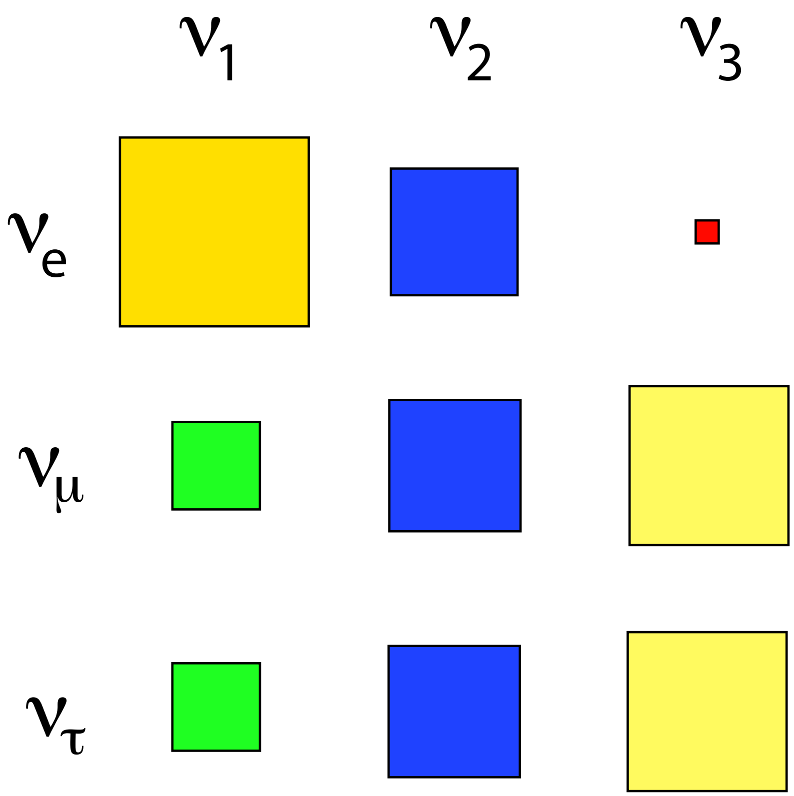
operator product expansion

perturbative QCD

CKM



PMNS

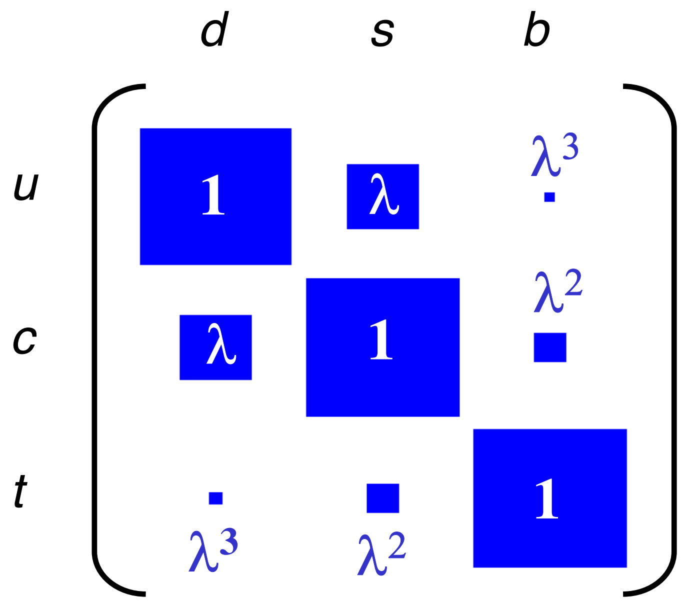


Area ~V^2

Why these values? Are the two related? Are they related to masses?

CKM Matrix: Simplified picture

Magnitudes of CKM elements



Largest phases in the Wolfenstein parametrization

$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$

Note: all terms in the inner product between columns 1 and 3 are of order λ^3. This produces a unitarity triangle of roughly equal sides.

Unitarity Triangles

Unitarity

[Column i][Column j]*=0

[Row i][Row j]*=0

$$V_{ud}V_{us}^{*}+V_{cd}V_{cs}^{*}+V_{td}V_{ts}^{*}=0$$

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

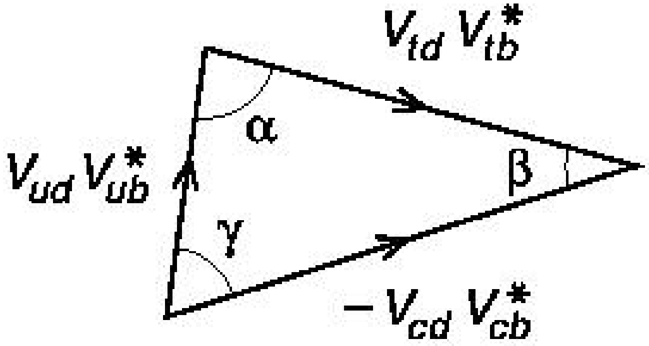
$$V_{us}V_{ub}^{*}+V_{cs}V_{cb}^{*}+V_{ts}V_{tb}^{*}=0$$

$$O(\lambda)+O(\lambda)+O(\lambda^{5})=0$$

$$O(\lambda^{3})+O(\lambda^{3})+O(\lambda^{3})=0$$

$$O(\lambda^{4})+O(\lambda^{2})+O(\lambda^{2})=0$$

(Col 1)(Col 3)* =0



Overall orientation of the triangle has no physical significance.

Fat unitarity triangle
➔large angles
➔large CP asymmetry
But only certain decays have interfering amps!

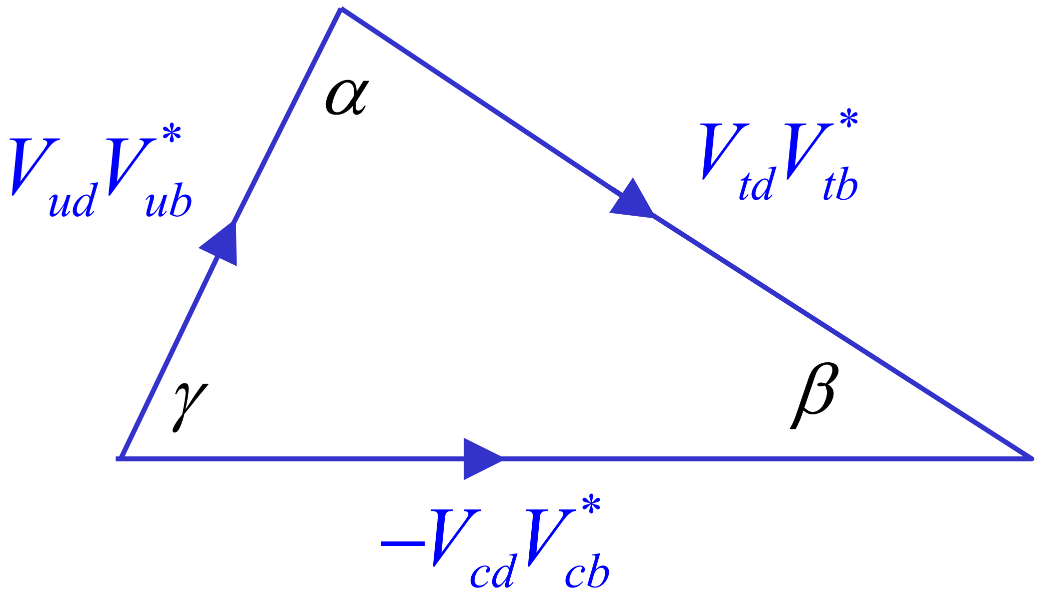
Consider two complex numbers z_1 and z_2.

$$z_1 = |z_1| e^{i\theta_1} \qquad z_2 = |z_2| e^{i\theta_2} \quad \Rightarrow \quad \frac{z_2/|z_2|}{z_1/|z_1|} = e^{i(\theta_2-\theta_1)} \qquad \arg\left(\frac{z_2}{z_1}\right) = \theta_2 - \theta_1$$

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

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

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



The Unitarity Triangle

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

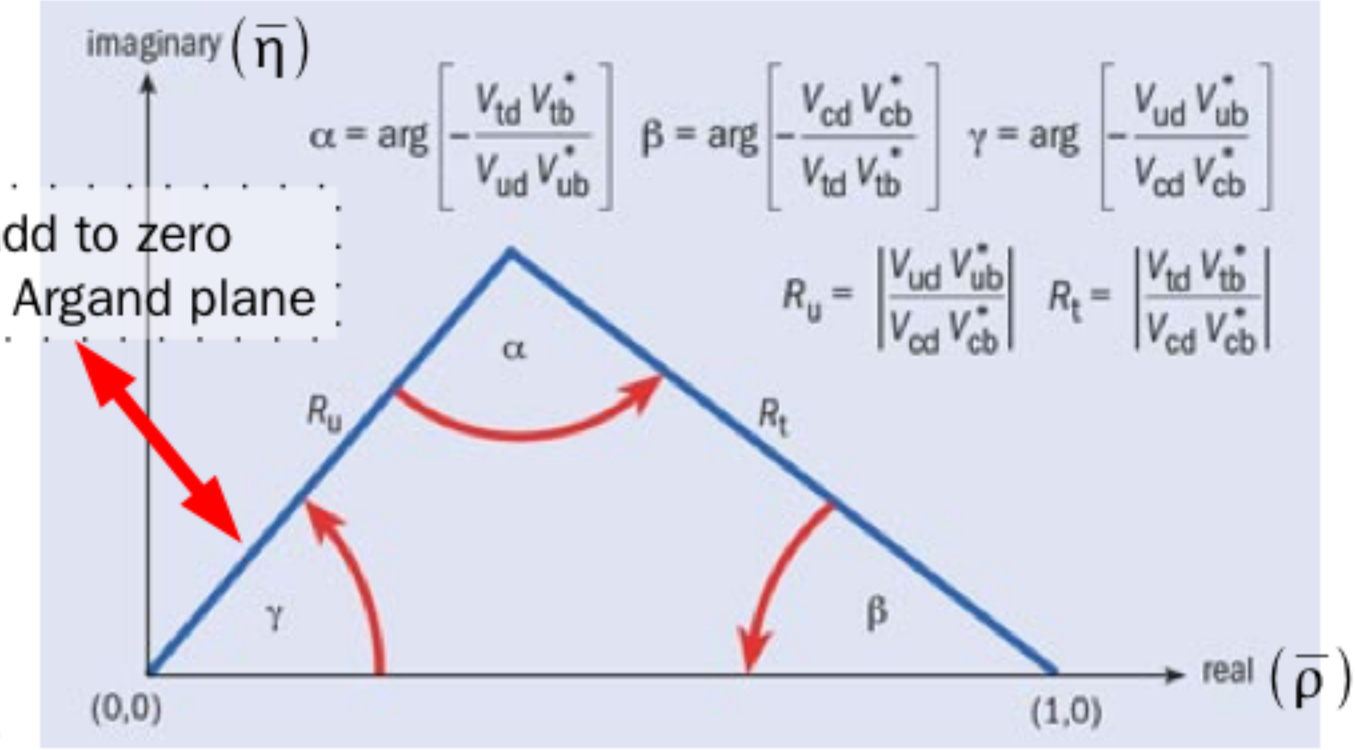
Three complex numbers add to zero

⇒ triangle in Argand plane

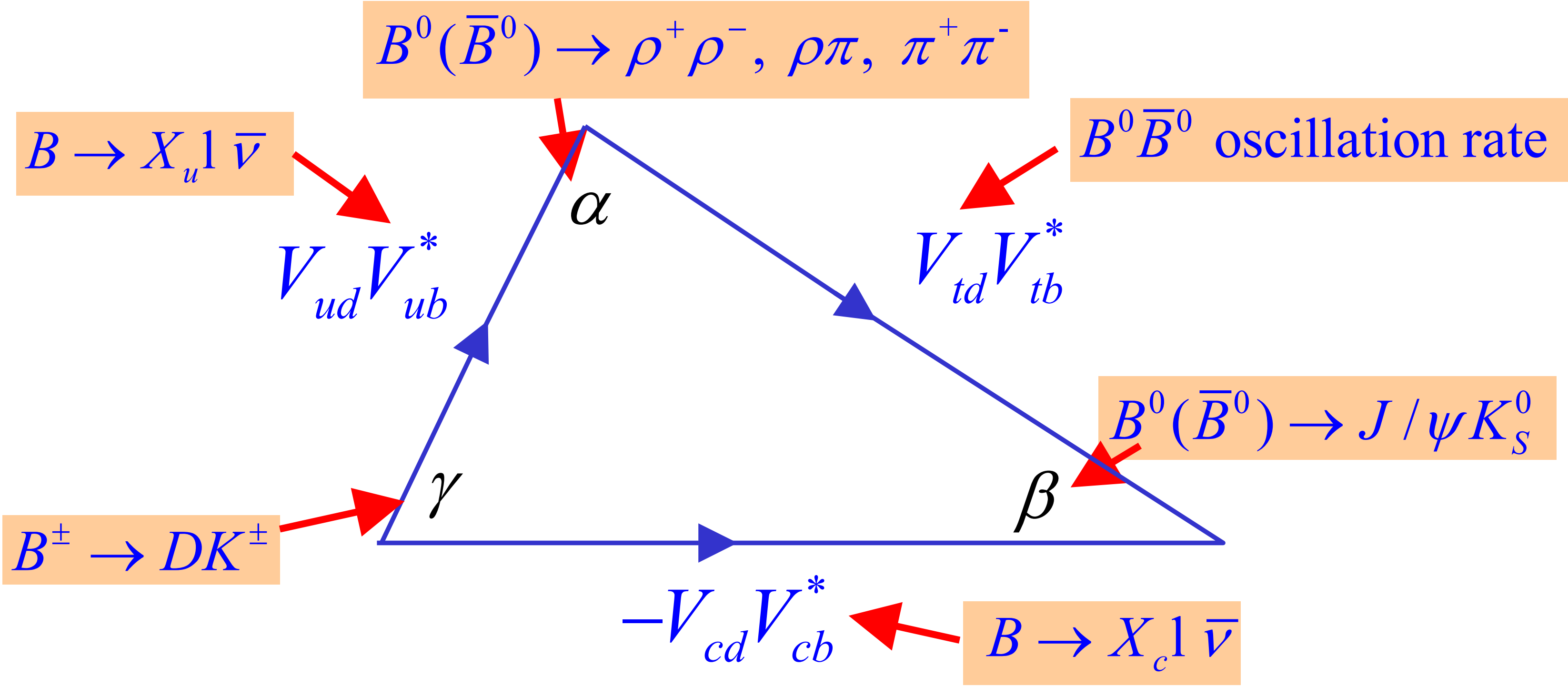
Axes are $\bar\rho$ and $\bar\eta$ where

$$\bar\rho + i\bar\eta \equiv -\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}$$

$$\rho + i\eta = \frac{\sqrt{1-A^2\lambda^4}(\bar\rho + i\bar\eta)}{\sqrt{1-\lambda^2}\left[1-A^2\lambda^4(\bar\rho + i\bar\eta)\right]}$$



Standard Model predicts that ALL measurements of *W*-mediated quark processes must be consistent with the CKM framework.



$B^0(\overline{B}^0) \to \rho^+\rho^-,\ \rho\pi,\ \pi^+\pi^-$

$B \to X_u l\,\bar{\nu}$

$B^0\overline{B}^0$ oscillation rate

α

$V_{ud}V_{ub}^*$

$V_{td}V_{tb}^*$

$B^0(\overline{B}^0) \to J/\psi K_S^0$

γ

β

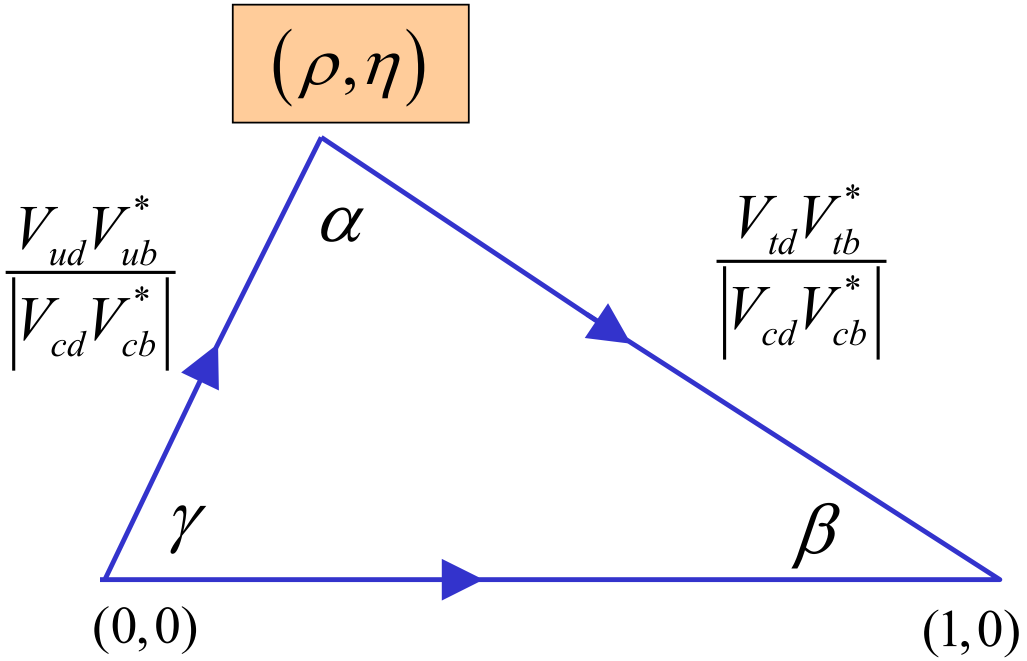
$B^\pm \to DK^\pm$

$-V_{cd}V_{cb}^*$

$B \to X_c l\,\bar{\nu}$

- **Angles** of triangle: measure from CP **asymmetries** in *B* decay
- **Sides** of triangle: measure **rates** for b→ulν, $B^0\overline{B}^0$ mixing
- **Other constraints** in ρ,η plane from CP violation in *K* decay

Big Questions: *Are determinations of angles consistent with determinations of the sides of the triangle ? Are angle determinations from loop and tree decays consistent ?*



$$V_{ub} = A\lambda^{3}(\rho - i\eta)$$

$$V_{cb} = A\lambda^{2}$$

$$V_{td} = A\lambda^{3}(1-\rho - i\eta)$$

$$\left|\frac{V_{cb}}{V_{us}}\right|^{2} = A$$

$$\left|V_{ub}^{*}/V_{cd}V_{cb}\right| = \sqrt{\rho^{2}+\eta^{2}}$$

$$\left|V_{td}\right|^{2} = A^{2}\lambda^{6}\left[(1-\rho)^{2}+\eta^{2}\right]$$

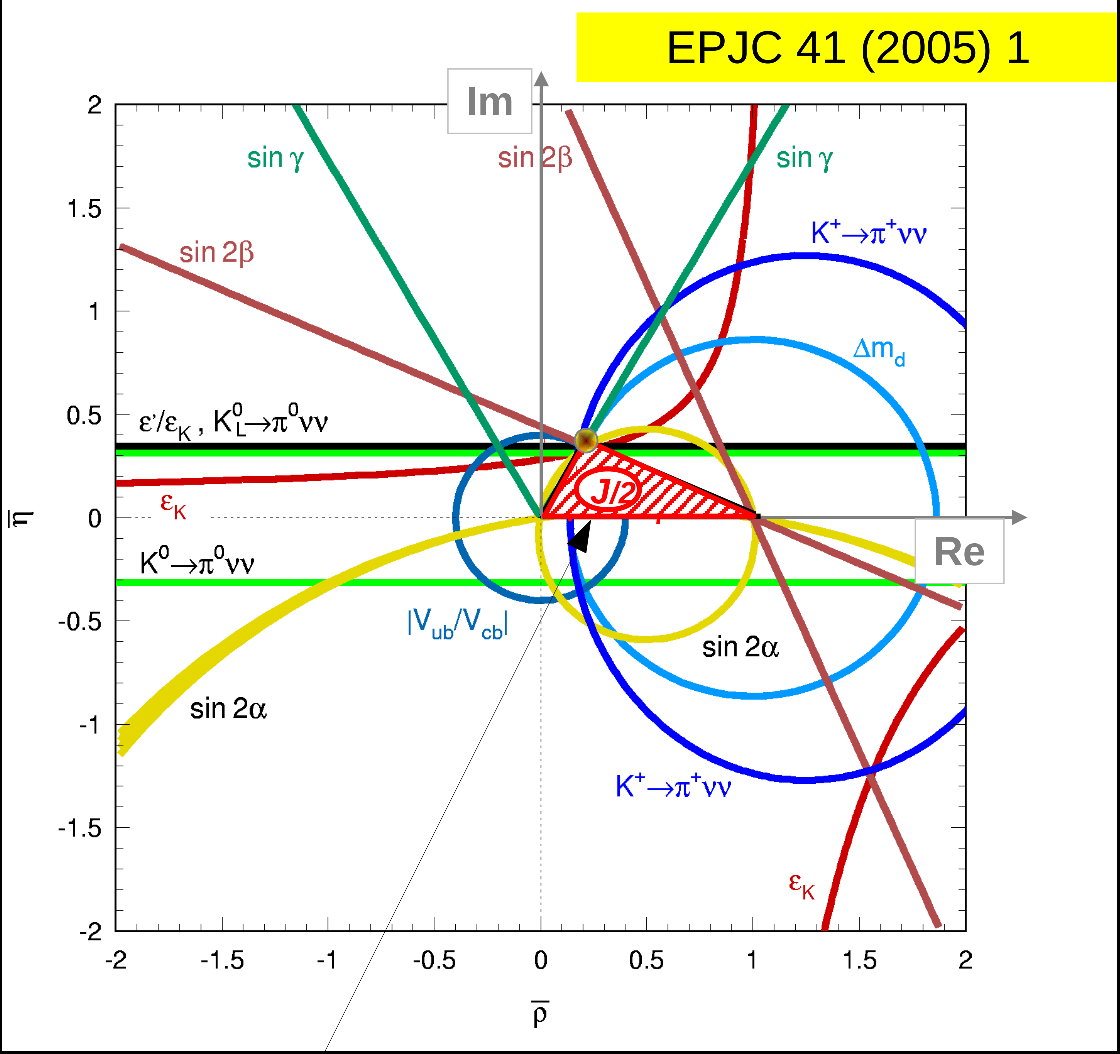
CKM constraints on unitarity plane

In the Standard Model the KM phase is the sole origin of CP violation

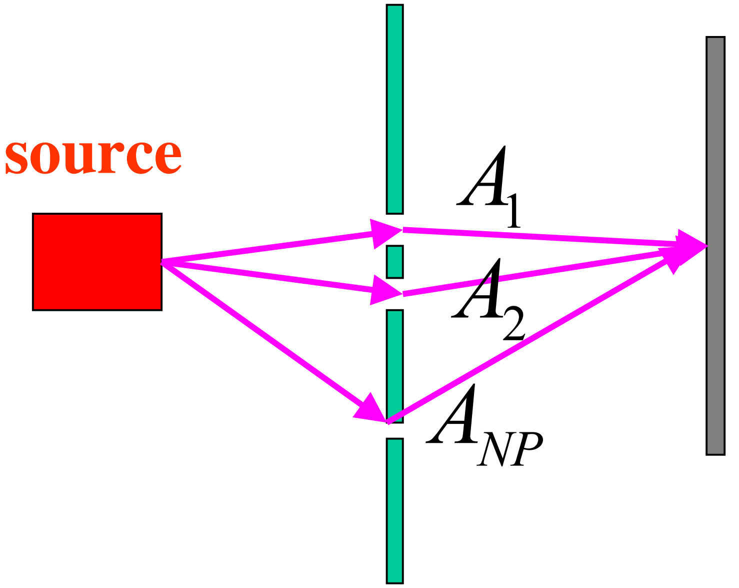
Hence:

all measurements must agree on the position of the apex of the Unitarity Triangle

(Illustration shown assumes no experimental or theoretical uncertainties)


EPJC 41 (2005) 1

Area of (all of) the Unitarity Triangle(s) is given by the Jarlskog invariant



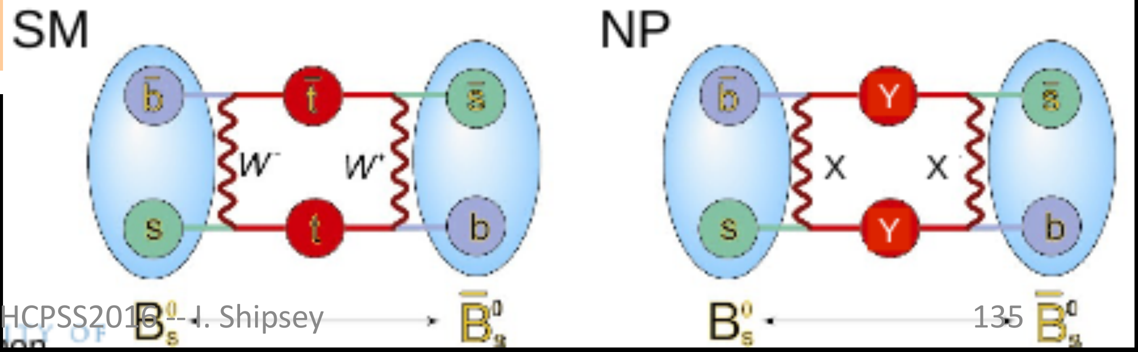
Study processes in which there can be extra amplitudes arising from new physics (NP).

Must be sure that all SM amplitudes are fully understood.

A_{NP} from physics at high mass scales is small

$\Rightarrow$ want to use processes in which $A_{1,2}$ are small

Hope to find a departure from the expected (SM) pattern of CP-violating asymmetries!



If history is our guide

New physics can show up at the intensity/precision frontier before the energy frontier

The power of quantum loops:

Beta-decay @ MeV energies informs us of a virtual mediator at 80 GeV (W)

GIM mechanism before the discovery of charm

CP violation/ CKM before the discovery of beauty and top

Neutral currents before the discovery of Z

The GIM Mechanism

$K^+ \rightarrow \mu^+ \nu_\mu$ & $\pi^0 \mu^+ \nu_\mu$ so why not $K^0 \rightarrow \mu^+ \mu^-$ & $\pi^0 \mu^+ \mu^-$?

- GIM (Glashow, Iliopoulos, Maiani) mechanism (1970)

  no tree level flavour changing neutral currents

  suppression of FCNC via loops

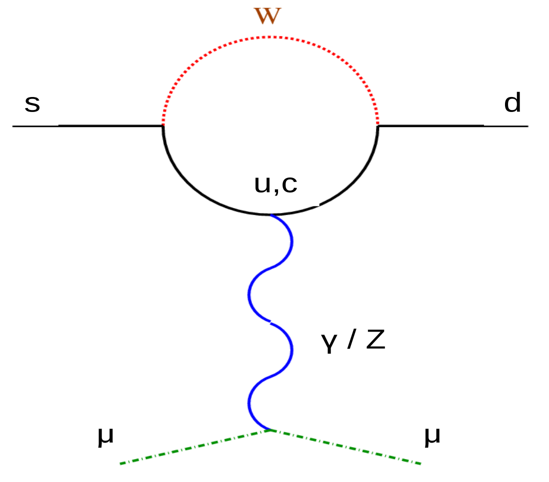
- Requires that quarks come in pairs (predicting charm)

$$A = V_{us} V_{ud}^* f(m_u/m_W) + V_{cs} V_{cd}^* f(m_c/m_W)$$

2x2 unitarity: $V_{us} V_{ud}^* + V_{cs} V_{cd}^* = 0$

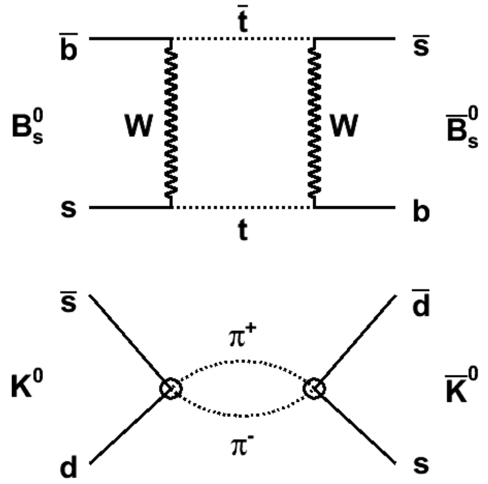
$m_u, m_c < m_W \therefore f(m_u/m_W) \sim f(m_c/m_W) \therefore A \sim 0$

kaon mixing $\Rightarrow$ predict m_c



Neutral meson oscillations

- We have flavour eigenstates M^0 and $\bar{M}^0$
  - M^0 can be K^0 ($\bar{s}d$), D^0 ($c\bar{u}$), B_d^0 ($\bar{b}d$) or B_s^0 ($\bar{b}s$)
- These can mix into each other
  - via short-distance or long-distance processes



- Time-dependent Schrödinger eqn.

$$i\frac{\partial}{\partial t}\begin{pmatrix}M^0\\ \bar{M}^0\end{pmatrix}=H\begin{pmatrix}M^0\\ \bar{M}^0\end{pmatrix}=\left(M-\frac{i}{2}\Gamma\right)\begin{pmatrix}M^0\\ \bar{M}^0\end{pmatrix}$$

  - H is Hamiltonian; M and Γ are 2x2 Hermitian matrices
- CPT theorem: $M_{11} = M_{22}$ & $\Gamma_{11} = \Gamma_{22}$

particle and antiparticle have equal masses and lifetimes

Solving the Schrödinger equation

- Physical states: eigenstates of effective Hamiltonian

$$M_{S,L} = p\, M^0 \pm q\, \bar{M}^0$$

p & q complex coefficients that satisfy $|p|^2 + |q|^2 = 1$

label as either S,L (short-, long-lived) or L,H (light, heavy) depending on values of Δm & ΔΓ (labels 1,2 usually reserved for CP eigenstates)

  - CP conserved if physical states = CP eigenstates ($|q/p| = 1$)

- Eigenvalues

$$\lambda_{S,L} = m_{S,L} - \tfrac{1}{2}i\Gamma_{S,L} = (M_{11} - \tfrac{1}{2}i\Gamma_{11}) \pm (q/p)(M_{12} - \tfrac{1}{2}i\Gamma_{12})$$

$$\Delta m = m_L - m_S \qquad \Delta\Gamma = \Gamma_S - \Gamma_L$$

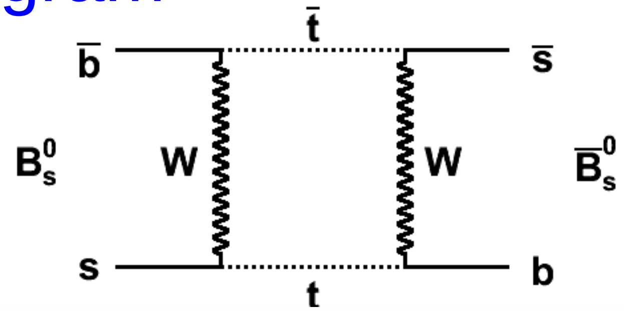
$$(\Delta m)^2 - \tfrac{1}{4}(\Delta\Gamma)^2 = 4(|M_{12}|^2 + \tfrac{1}{4}|\Gamma_{12}|^2)$$

$$\Delta m \Delta\Gamma = 4\mathrm{Re}(M_{12}\Gamma_{12}^*)$$

$$(q/p)^2 = (M_{12}^* - \tfrac{1}{2}i\Gamma_{12}^*)/(M_{12} - \tfrac{1}{2}i\Gamma_{12})$$

Simple picture of mixing parameters

- Δm: value depends on rate of mixing diagram
  - together with various other constants ...



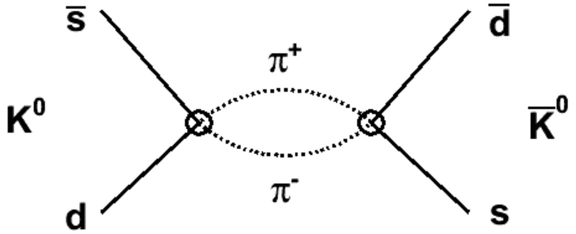
$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{tb}|^2 |V_{td}|^2$$

  - that can be made to cancel in ratios

remaining factors can be obtained from lattice QCD calculations

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

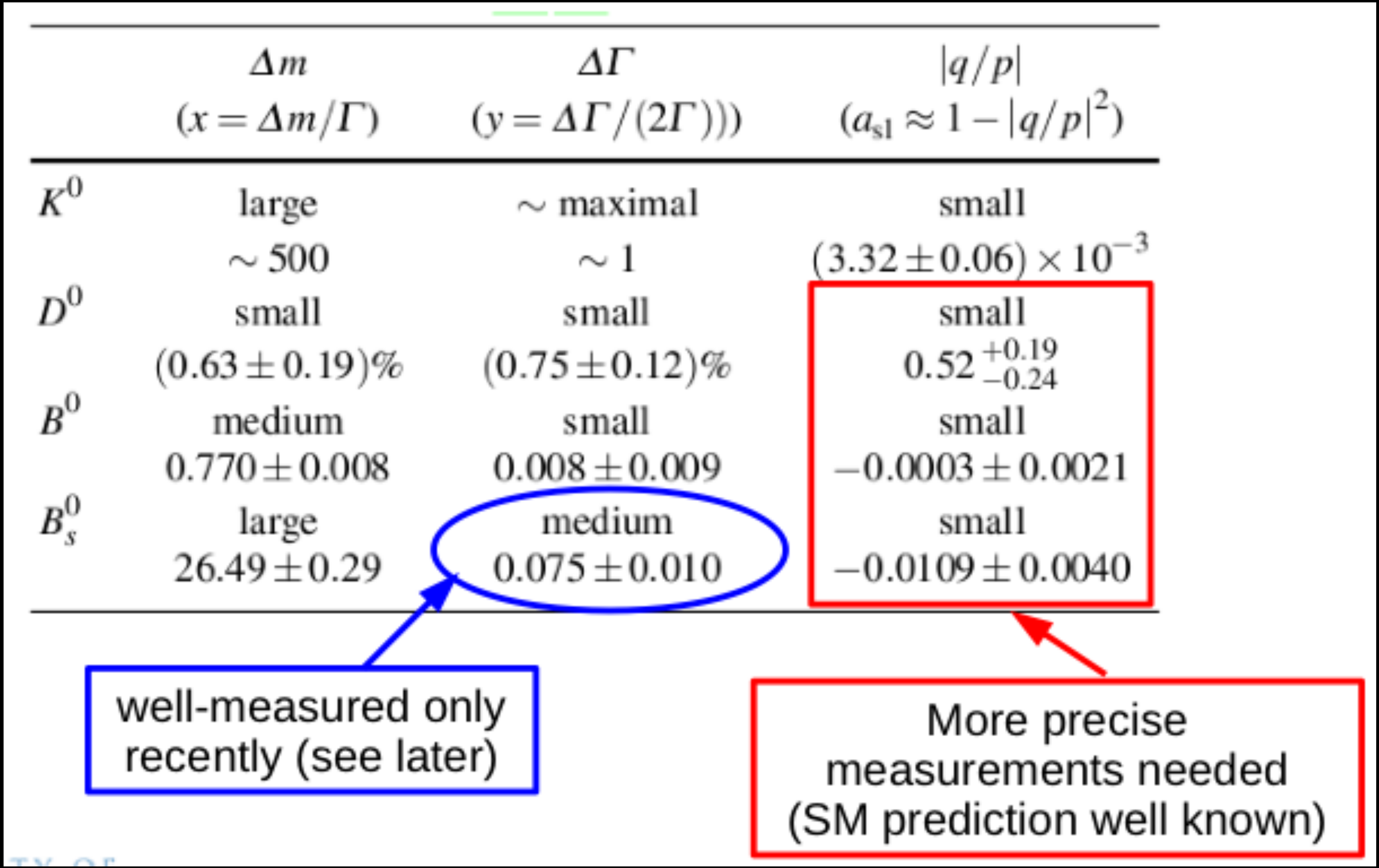
- ΔΓ: value depends on widths of decays into common final states (CP-eigenstates)
  - large for K^0, small for D^0 & B_d^0



- $q/p \approx 1$ if $\arg(\Gamma_{12}/M_{12}) \approx 0$ ($|q/p| \approx 1$ if $M_{12} \ll \Gamma_{12}$ or $M_{12} \gg \Gamma_{12}$)
  - CP violation in mixing when $|q/p| \neq 1$

$$\left(\epsilon = \frac{p-q}{p+q} \neq 0\right)$$

Simple picture of mixing parameters



	Δm $(x = \Delta m/\Gamma)$	$\Delta\Gamma$ $(y = \Delta\Gamma/(2\Gamma)))$	$\lvert q/p \rvert$ $(a_{sl} \approx 1 - \lvert q/p \rvert^2)$
K^0	large ~ 500	$\sim$ maximal ~ 1	small $(3.32 \pm 0.06) \times 10^{-3}$
D^0	small $(0.63 \pm 0.19)\%$	small $(0.75 \pm 0.12)\%$	small $0.52^{+0.19}_{-0.24}$
B^0	medium 0.770 ± 0.008	small 0.008 ± 0.009	small -0.0003 ± 0.0021
B_s^0	large 26.49 ± 0.29	medium 0.075 ± 0.010	small -0.0109 ± 0.0040

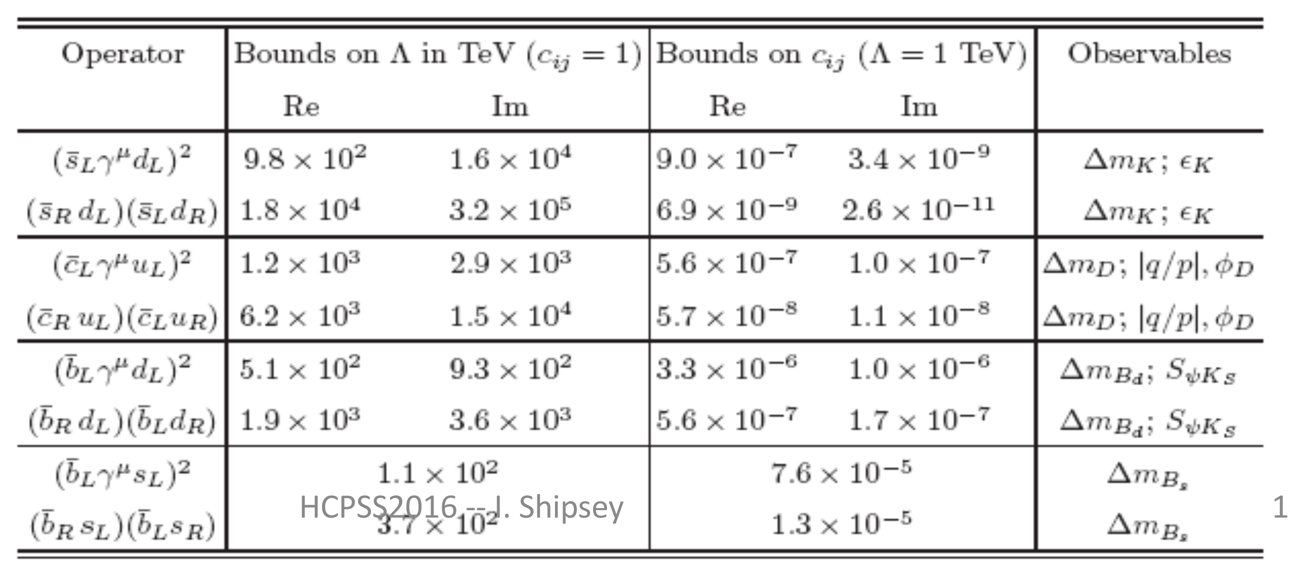
well-measured only recently (see later)

More precise measurements needed (SM prediction well known)

Constraints on NP from mixing

- All measurements of Δm & $\Delta\Gamma$ consistent with SM
  - K^0, D^0, $B_d^{\,0}$ and $B_s^{\,0}$
- This means $|A_{NP}| < |A_{SM}|$ where $\mathcal{A}_{\rm SM}^{\Delta F=2} \approx \frac{G_F^2 m_t^2}{16\pi^2}(V_{ti}^* V_{tj})^2 \times \langle \overline{M}|(\overline{Q}_{Li}\gamma^\mu Q_{Lj})^2|M\rangle \times F\left(\frac{M_W^2}{m_t^2}\right)$
- Express NP as perturbation to the SM Lagrangian
  - couplings c_i and scale $\Lambda > m_W$ $\qquad \mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields})$
- For example, SM like (left-handed) operators $\Delta\mathcal{L}^{\Delta F=2} = \sum_{i\neq j} \frac{c_{ij}}{\Lambda^2}(\overline{Q}_{Li}\gamma^\mu Q_{Lj})^2$

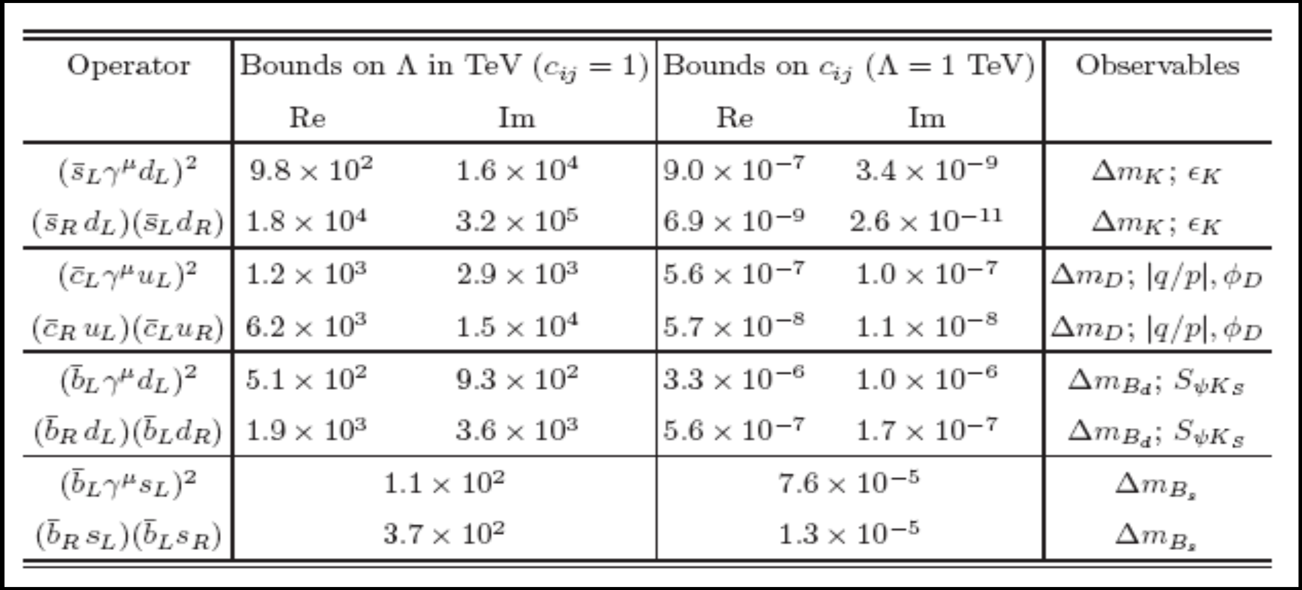
Ann.Rev.Nucl.Part.Sci.
60 (2010) 355
arXiv:1002.0900



Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

Constraints on NP from mixing

Ann.Rev.Nucl.Part.Sci.
60 (2010) 355
arXiv:1002.0900



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$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
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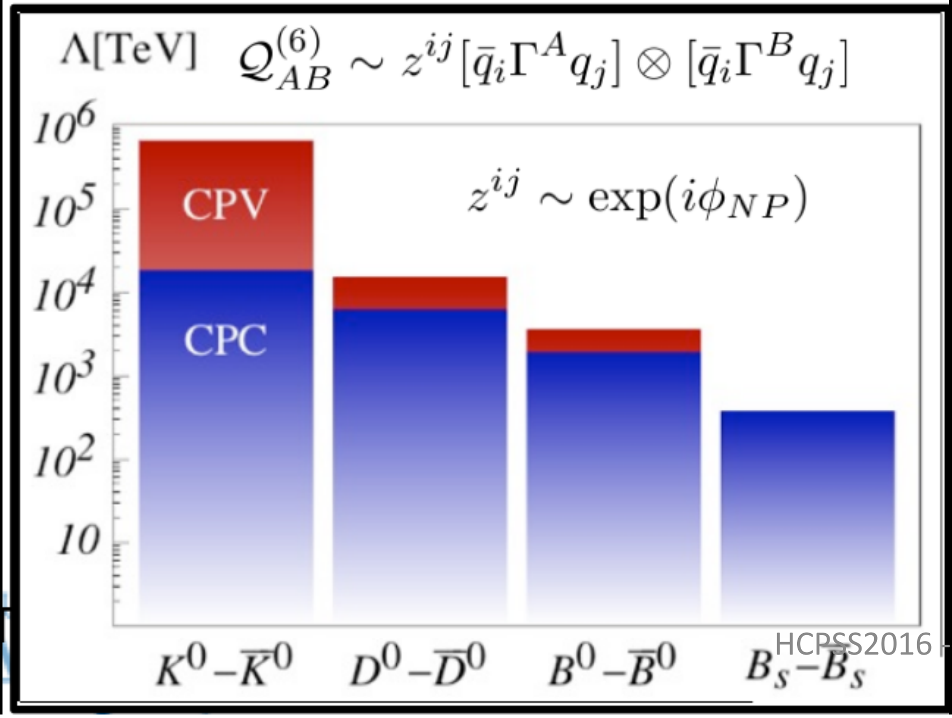
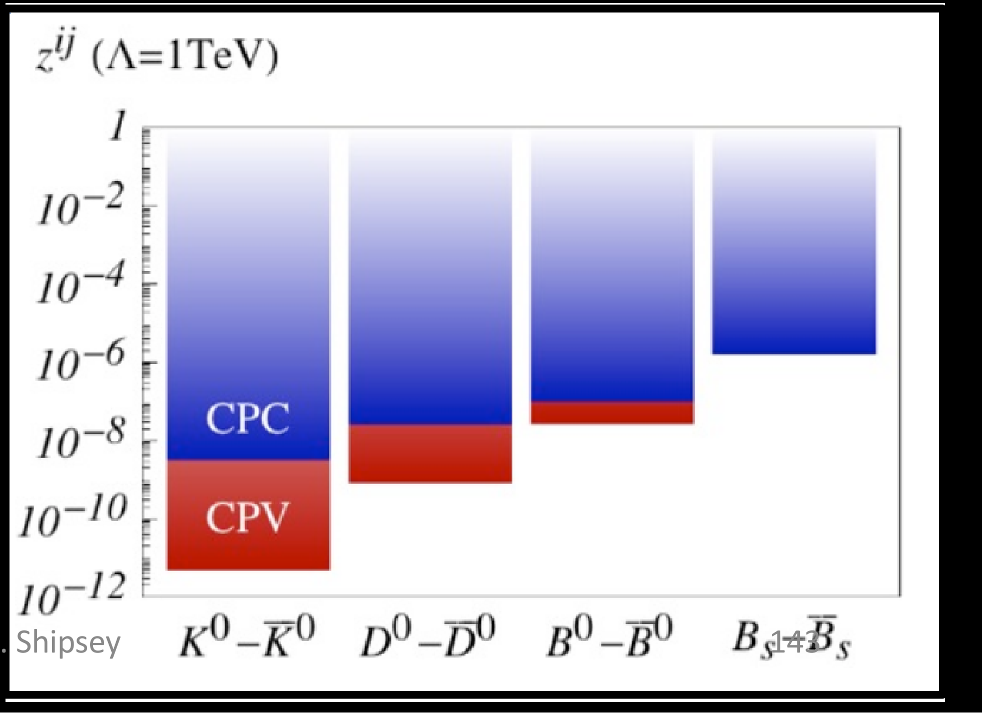
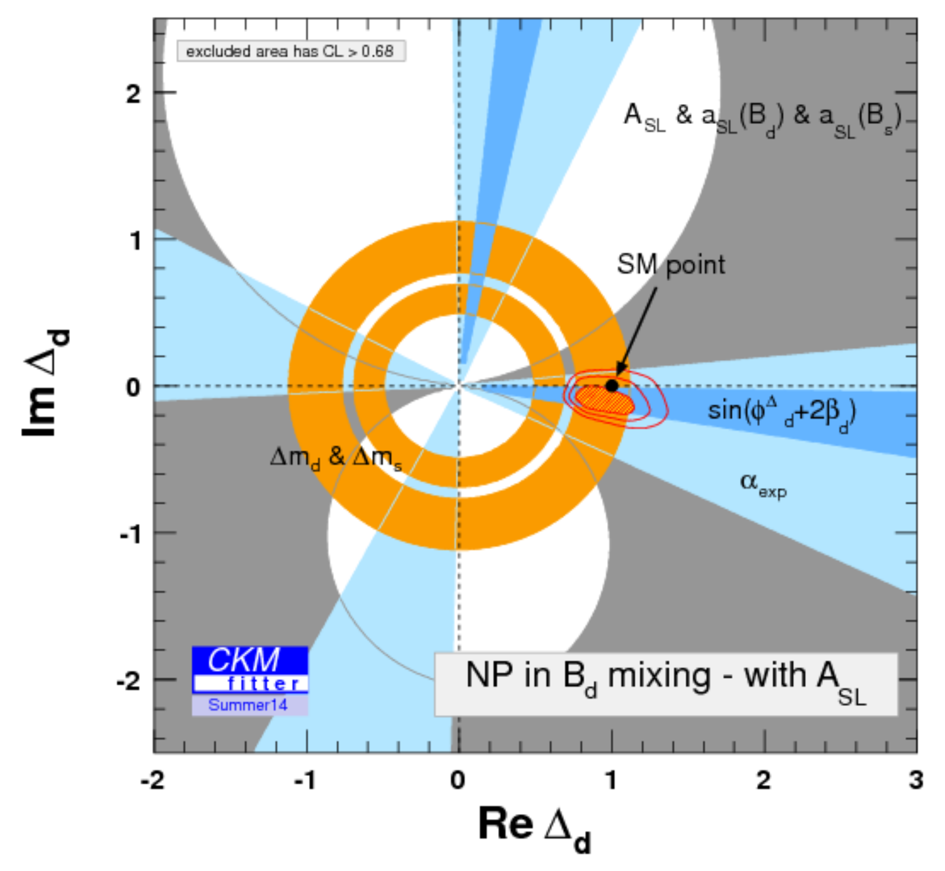
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

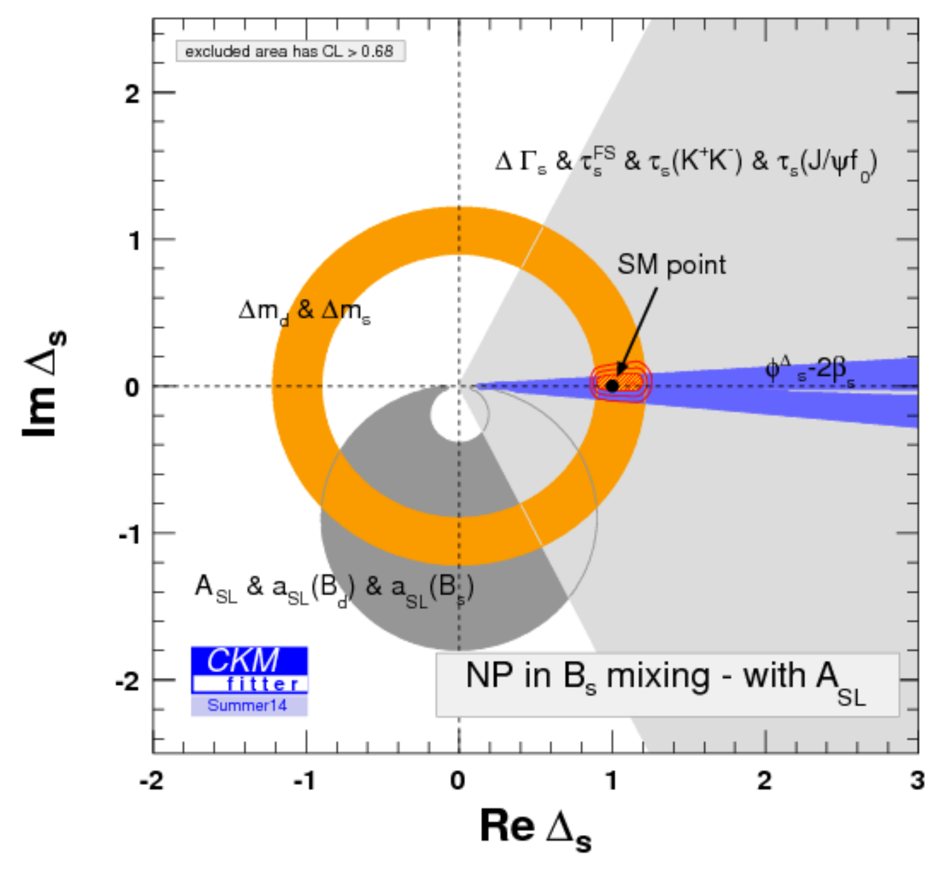




Similar story in pictures

including more inputs (& more up-to-date)





arXiv:1501.05013

Phys.Rev. D91 (2015) 073007

New Physics Flavour Problem

- Limits on NP scale at least 100 TeV for generic couplings
  - model-independent argument, also for rare decays
- But we need NP at the TeV scale to solve the hierarchy problem (and to provide DM candidate, etc.)
- So we need NP flavour-changing couplings to be small
- Why?
  - minimal flavour violation?
    - perfect alignment of flavour violation in NP and SM
  - some other approximate symmetry?
  - flavour structure tells us about physics at very high scales
- There are still important observables that are not yet well-tested

NPB 645 (2002) 155

Like-sign dimuon asymmetry

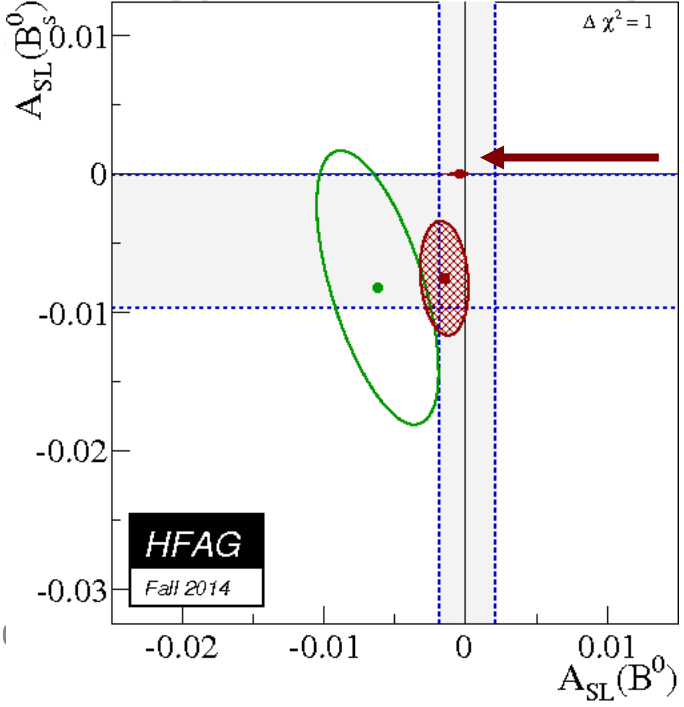
- Semileptonic decays are flavour-specific
- B mesons are produced in $B\bar{B}$ pairs
- Like-sign leptons arise if one of $B\bar{B}$ pair mixes before decaying
- If no CP violation in mixing N(++) = N(– –)

- Inclusive measurement ↔ contributions from both B_d^0 and B_s^0
  - relative contributions from production rates, mixing probabilities & SL decay rates

PRD 89 (2014) 012002

$$A_{SL} = (1 - |q/p|^4)/(1+|q/p|^4)$$

UNIVERSITY OF

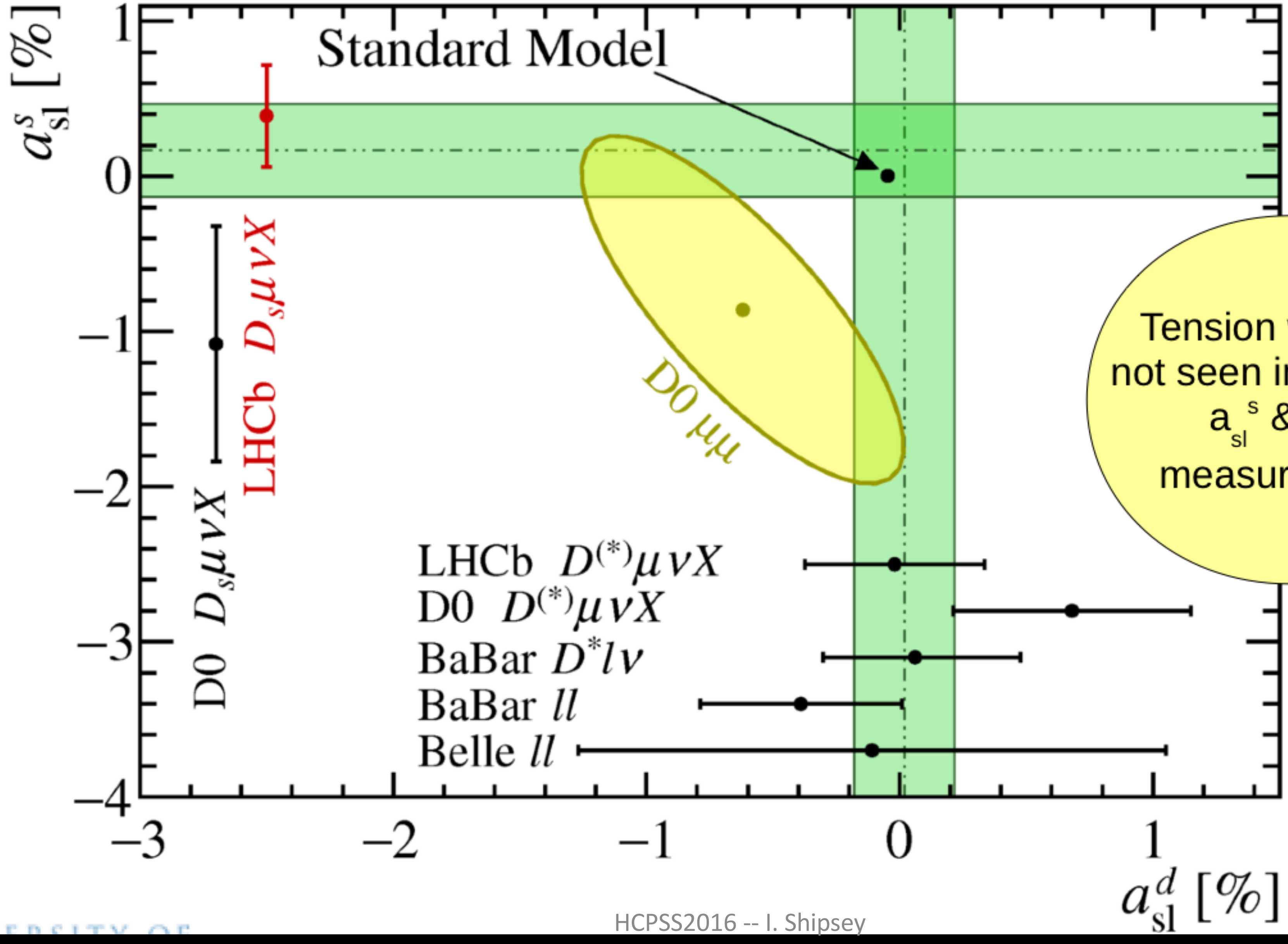


SM predictions

48

Global $a_{sl}^{s} - a_{sl}^{d}$ plot

arXiv:1605.09768

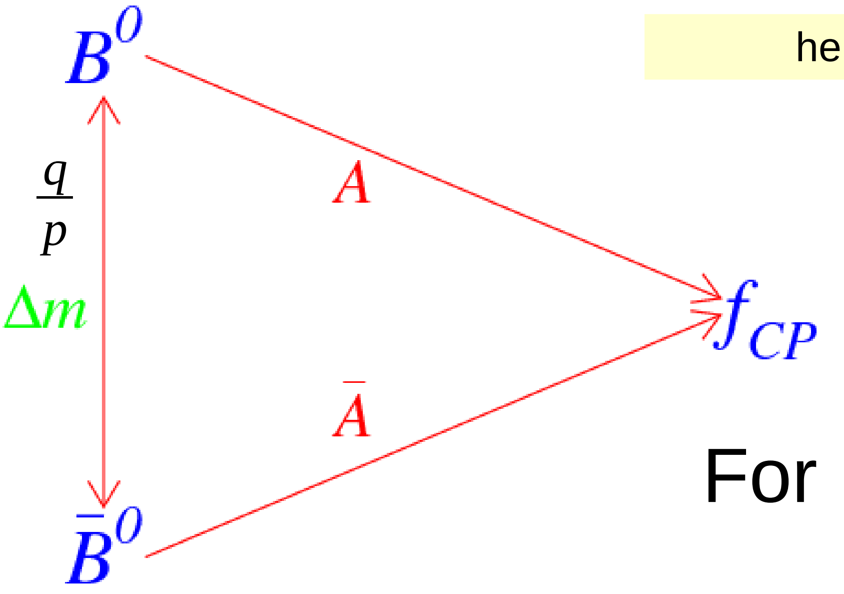


Tension with SM not seen in separate a_{sl}^{s} & a_{sl}^{d} measurements

Time-Dependent CP Violation in the B^0–$\bar{B}^0$ System

- For a B meson known to be 1) B^0 or 2) $\bar{B}^0$ at time t=0, then at later time t:

$$\Gamma\left(B^0_{phys}\rightarrow f_{CP}(t)\right)\propto e^{-\Gamma t}\left(1-\left(S\sin(\Delta m t)-C\cos(\Delta m t)\right)\right)$$
$$\Gamma\left(\bar{B}^0_{phys}\rightarrow f_{CP}(t)\right)\propto e^{-\Gamma t}\left(1+\left(S\sin(\Delta m t)-C\cos(\Delta m t)\right)\right)$$



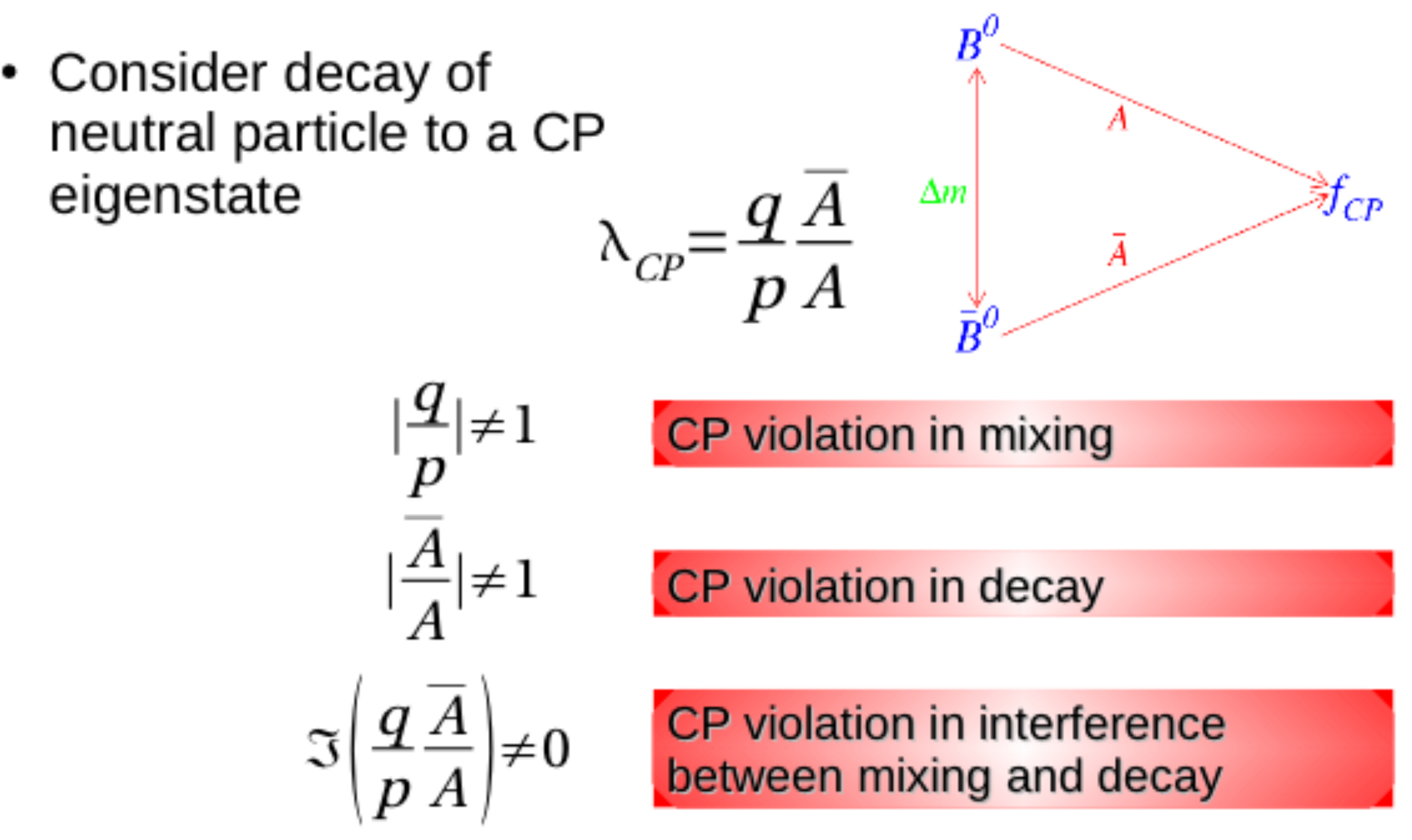
here assume ΔΓ negligible – will see full expressions later

$$S=\frac{2\Im(\lambda_{CP})}{1+|\lambda_{CP}|^2}\qquad C=\frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2}\qquad \lambda_{CP}=\frac{q}{p}\frac{\bar{A}}{A}$$

For B^0 → J/ψ K_s, S = sin(2β), C=0

NPB 193 (1981) 85

Types of CP violation



- Consider decay of neutral particle to a CP eigenstate

$$\lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A}$$

$$\left|\frac{q}{p}\right| \neq 1$$

CP violation in mixing

$$\left|\frac{\bar{A}}{A}\right| \neq 1$$

CP violation in decay

$$\Im\left(\frac{q}{p}\frac{\bar{A}}{A}\right) \neq 0$$

CP violation in interference between mixing and decay

Principle of measurement at Asymmetric B Factory

To measure t require B meson to be moving

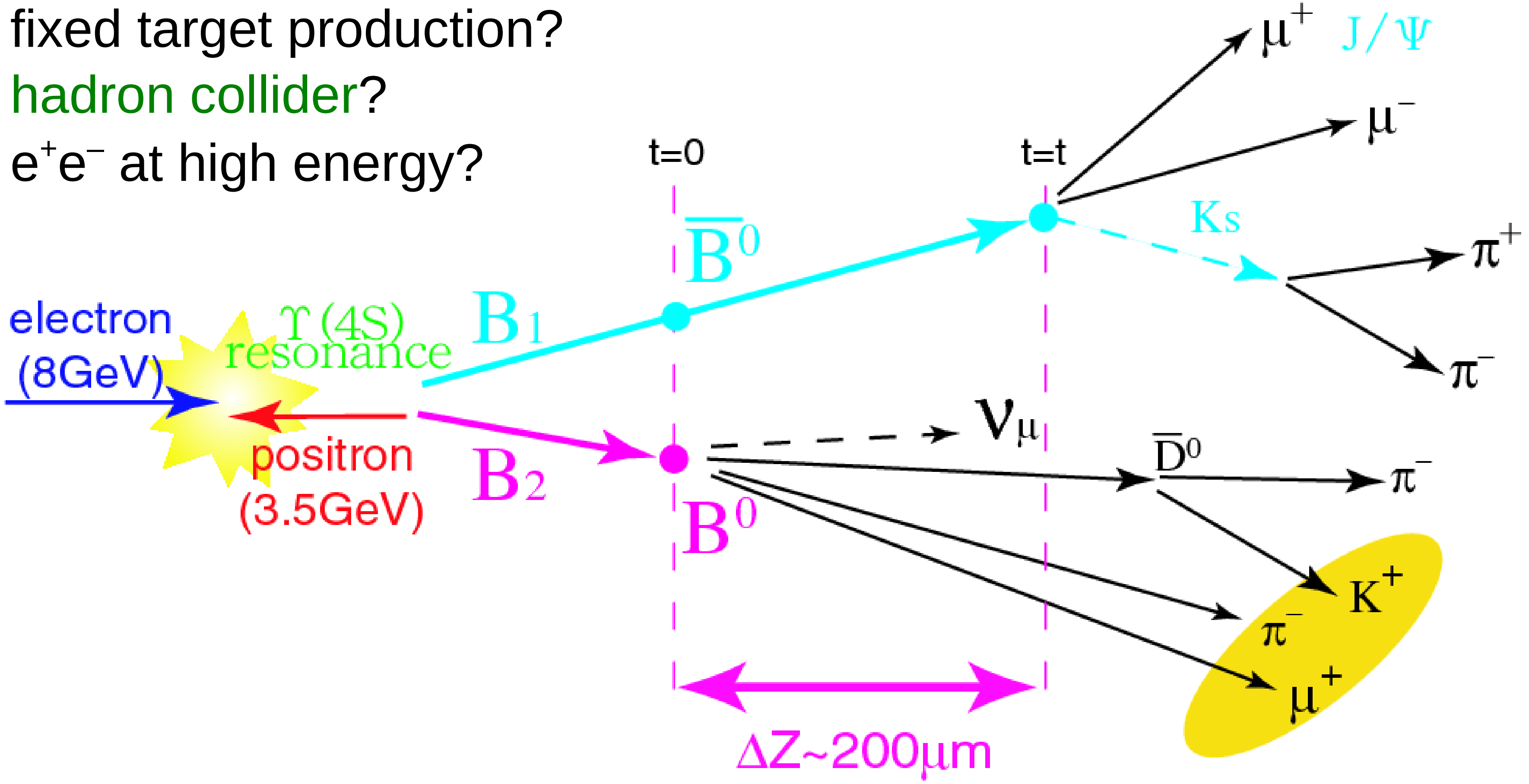
→ e^+e^- at threshold with asymmetric collisions (Oddone)

Other possibilities considered

→ fixed target production?

→ hadron collider?

→ e^+e^- at high energy?

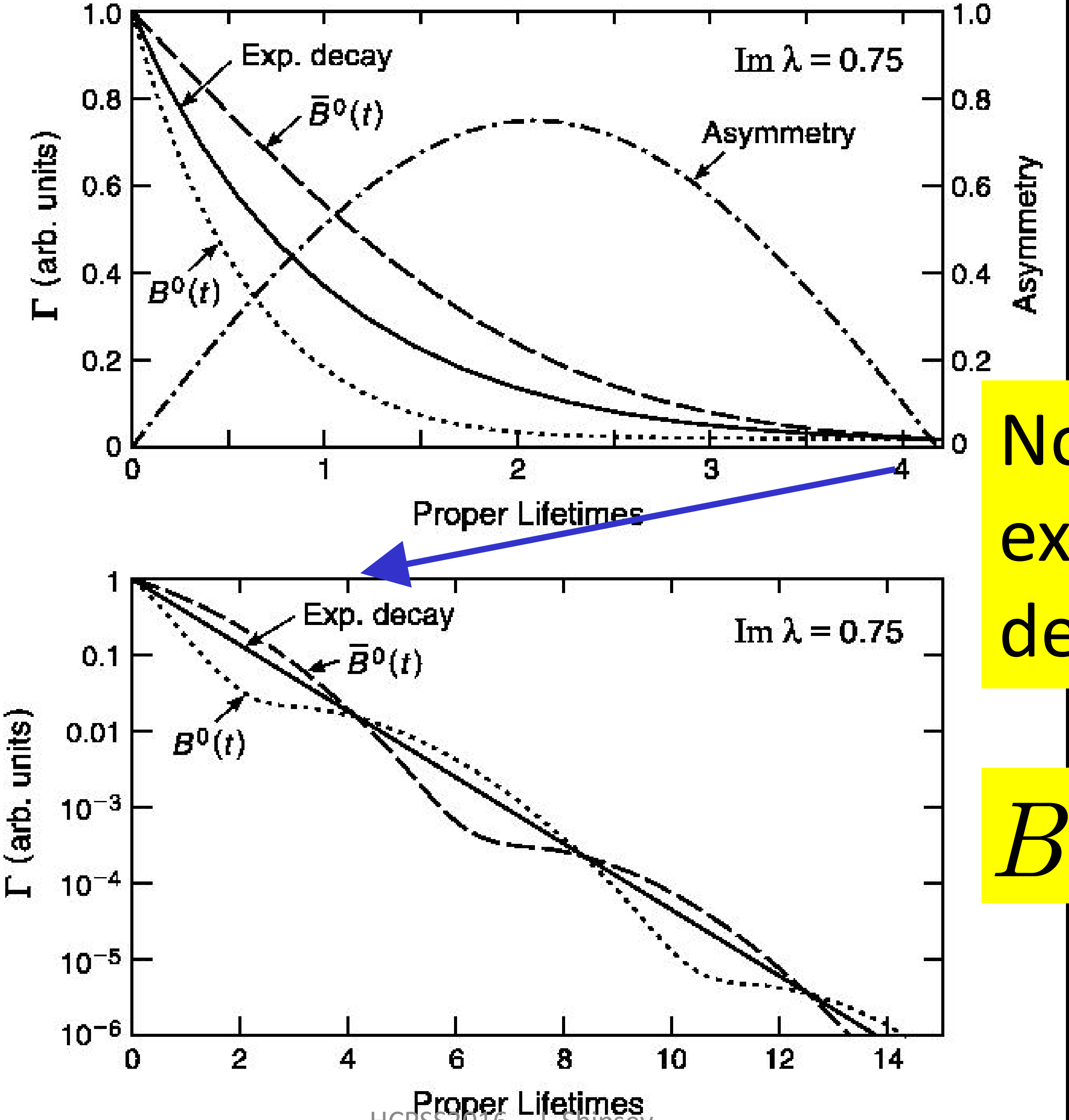


What we expect to see:

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

Linear scale

Log scale



Non-exponential decay

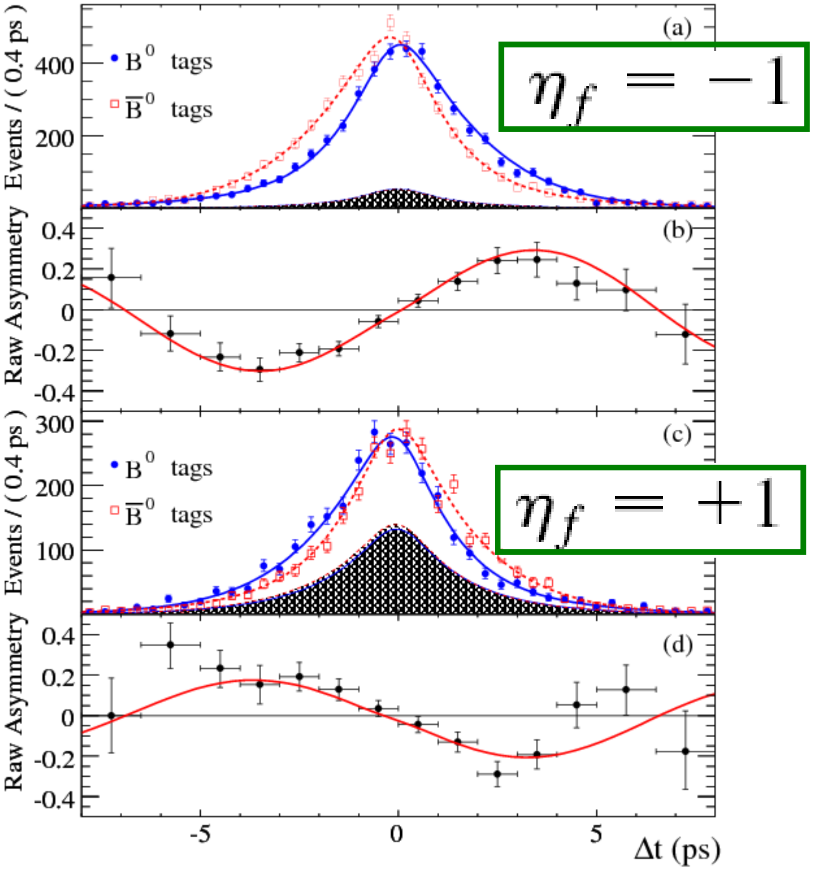
$B^0 \neq \overline{B^0}$

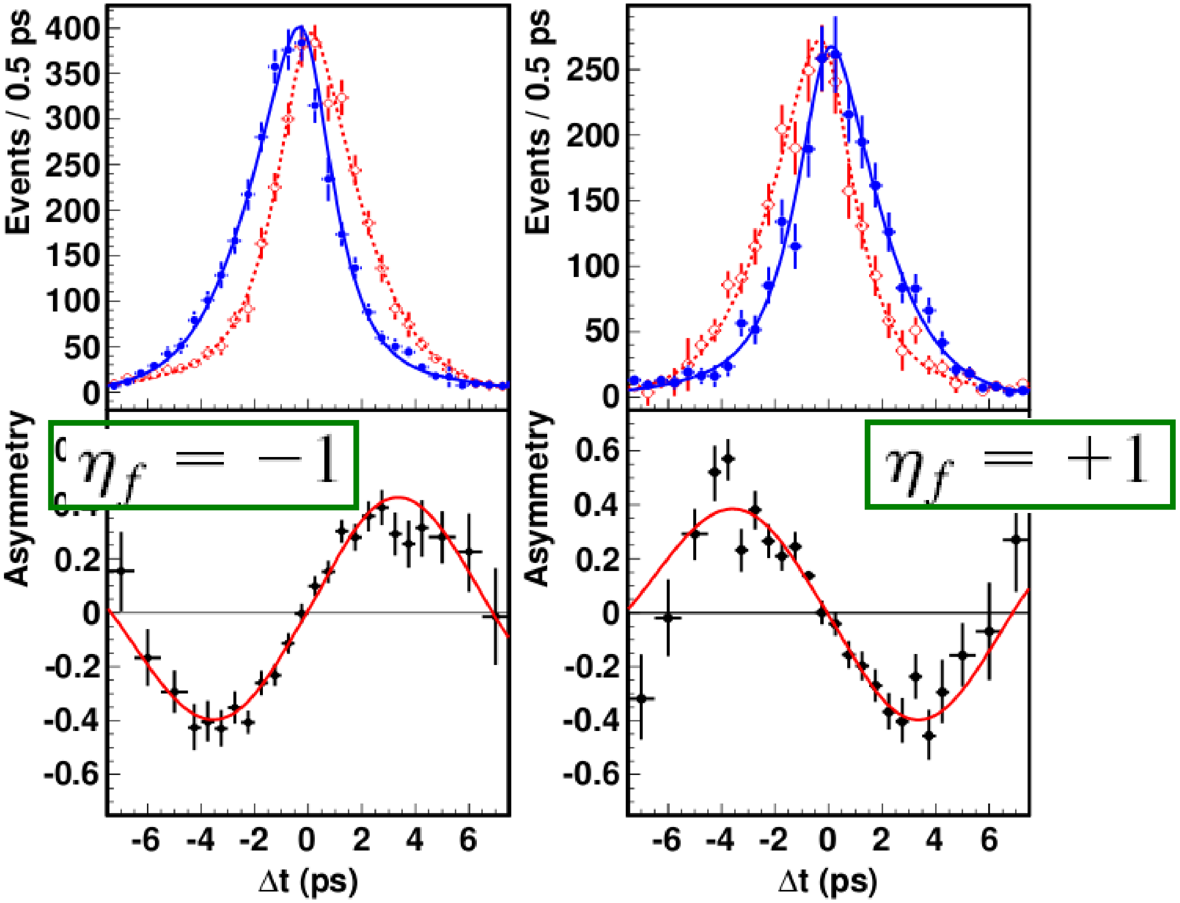
Results for the golden mode

$$B^0 \rightarrow J/\psi K^0$$

BABAR

BELLE





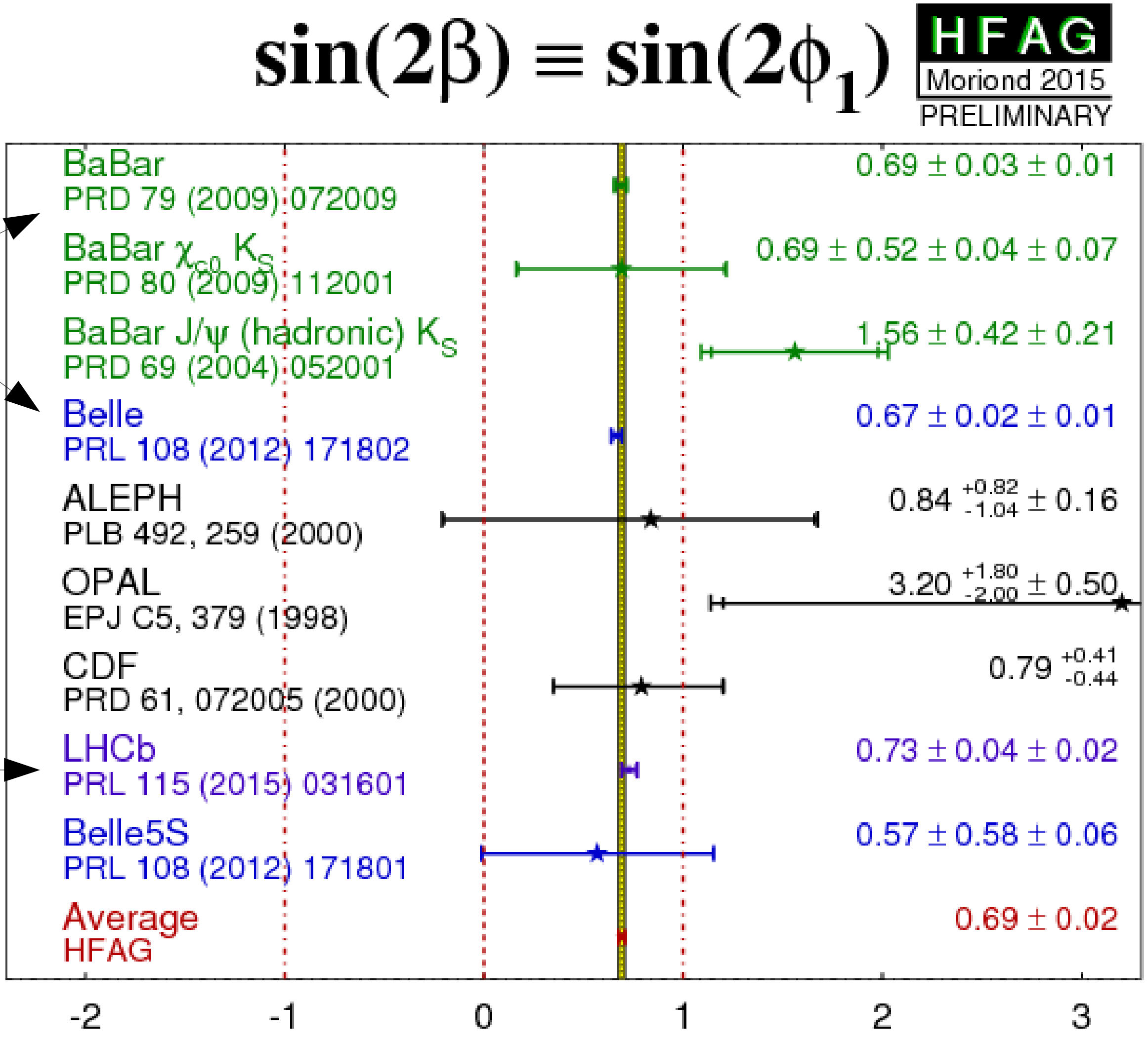
PRD 79 (2009) 072009

PRL 108 (2012) 171802

Compilation

Results on previous slide

Note LHCb also highly competitive

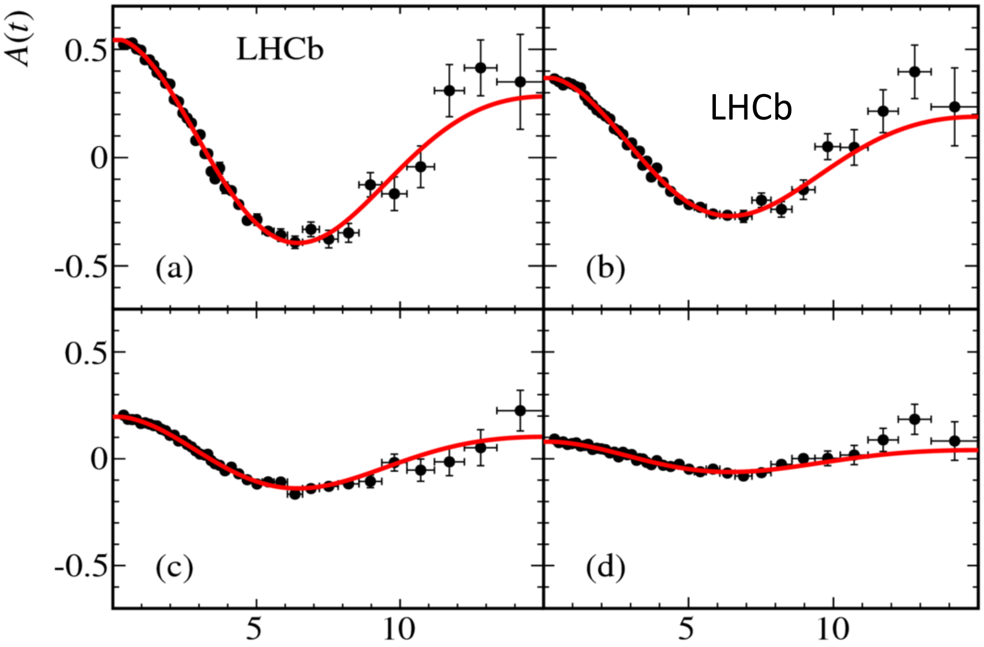


R_t side from BB mixing

World average based on many measurements

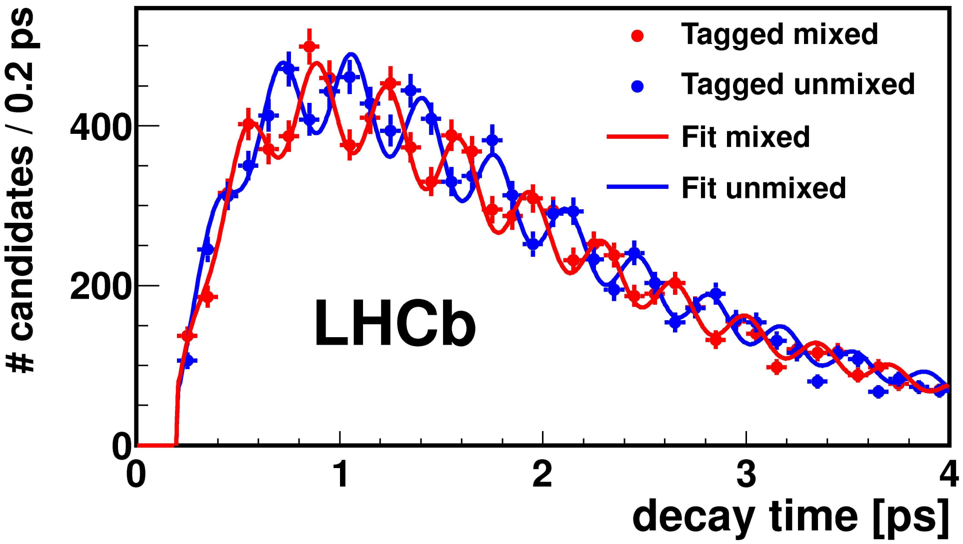
$$R_t = \left|\frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}}\right| \quad \& \quad \frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

$P(\Delta t) = (1 \pm \cos(\Delta m t))e^{t}/2\tau$



$\Delta m_d = (0.5050 \pm 0.0021 \pm 0.0010)\ \mathrm{ps}^{-1}$

arXiv:1604.03475



$\Delta m_s = (17.768 \pm 0.023 \pm 0.006)\ \mathrm{ps}^{-1}$

NJP 15 (2013) 053021

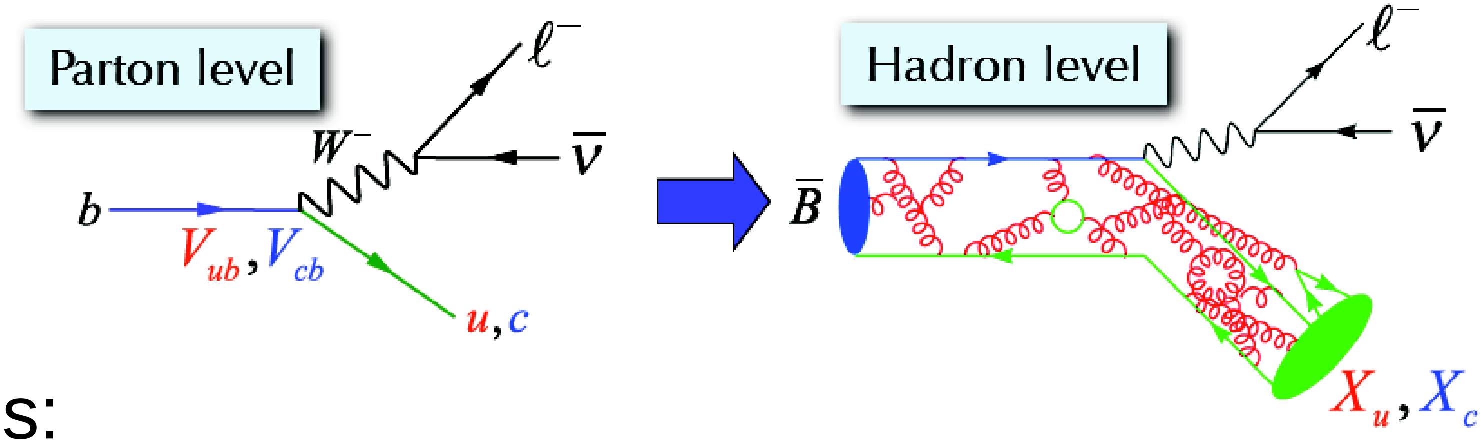
$$|V_{td}/V_{ts}| = 0.216 \pm \overset{\uparrow}{0.001} \pm \overset{\uparrow}{0.011}$$

experimental uncertainty

theoretical uncertainty

R_u side from semileptonic decay

$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right|$$



- Approaches:
  - exclusive semileptonic B decays, eg. $B^0 \rightarrow \pi^- e^+ \nu$
    - require knowledge of form factors
      - can be calculated in lattice QCD at kinematical limit
  - inclusive semileptonic B decays, eg. $B \rightarrow X_u e^+ \nu$
    - clean theory, based on Operator Product Expansion
    - experimentally challenging:
      - need to reject b → c background
      - cuts re-introduce theoretical uncertainties

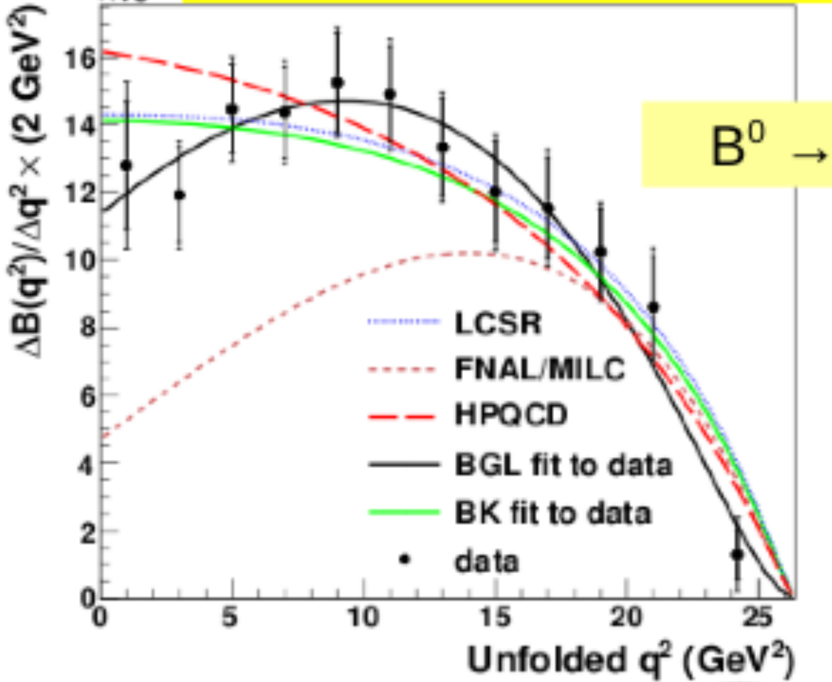
$|V_{ub}|$ from exclusive semileptonic decays

Current best measurements use $B^0 \rightarrow \pi^- l^+ \nu$

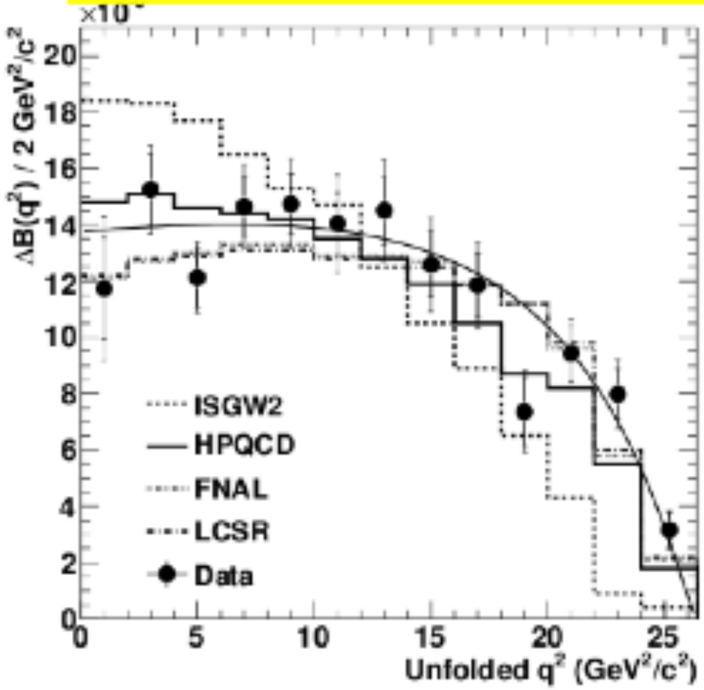
(recent competitive measurement from LHCb with $\Lambda_b \rightarrow p\mu\nu$)

BaBar experiment
PRD 83 (2011) 052011
PRD 83 (2011) 032007

Belle experiment
PRD 83 (2011) 071101(R)



$B^0 \rightarrow \pi^- l \nu$



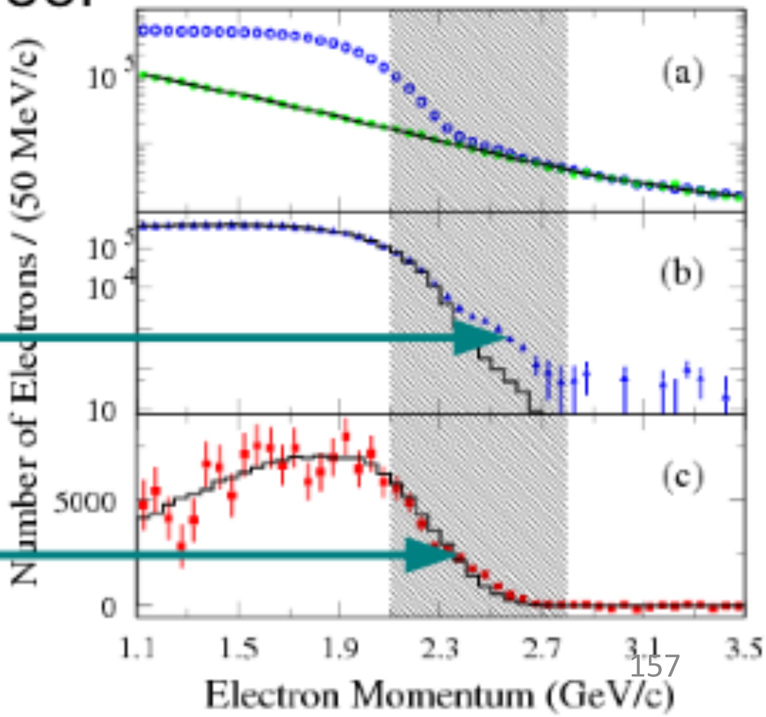
$$|V_{ub}| = (3.09 \pm 0.08 \pm 0.12 \, \boxed{{}^{+0.35}_{-0.29}}) \times 10^{-3}$$

$$|V_{ub}| = (3.43 \pm 0.33) \times 10^{-3}$$

$\uparrow$ lattice uncertainty

$|V_{ub}|$ from inclusive semileptonic decays

- Main difficulty to measure inclusive $B \rightarrow X_u\, l^+ \nu$
  - background from $B \rightarrow X_c\, l^+ \nu$
- Approaches
  - cut on E_l (lepton endpoint), q^2 ($l\nu$ invariant mass squared), $M(X_u)$, or some combination thereof
- Example: endpoint analysis

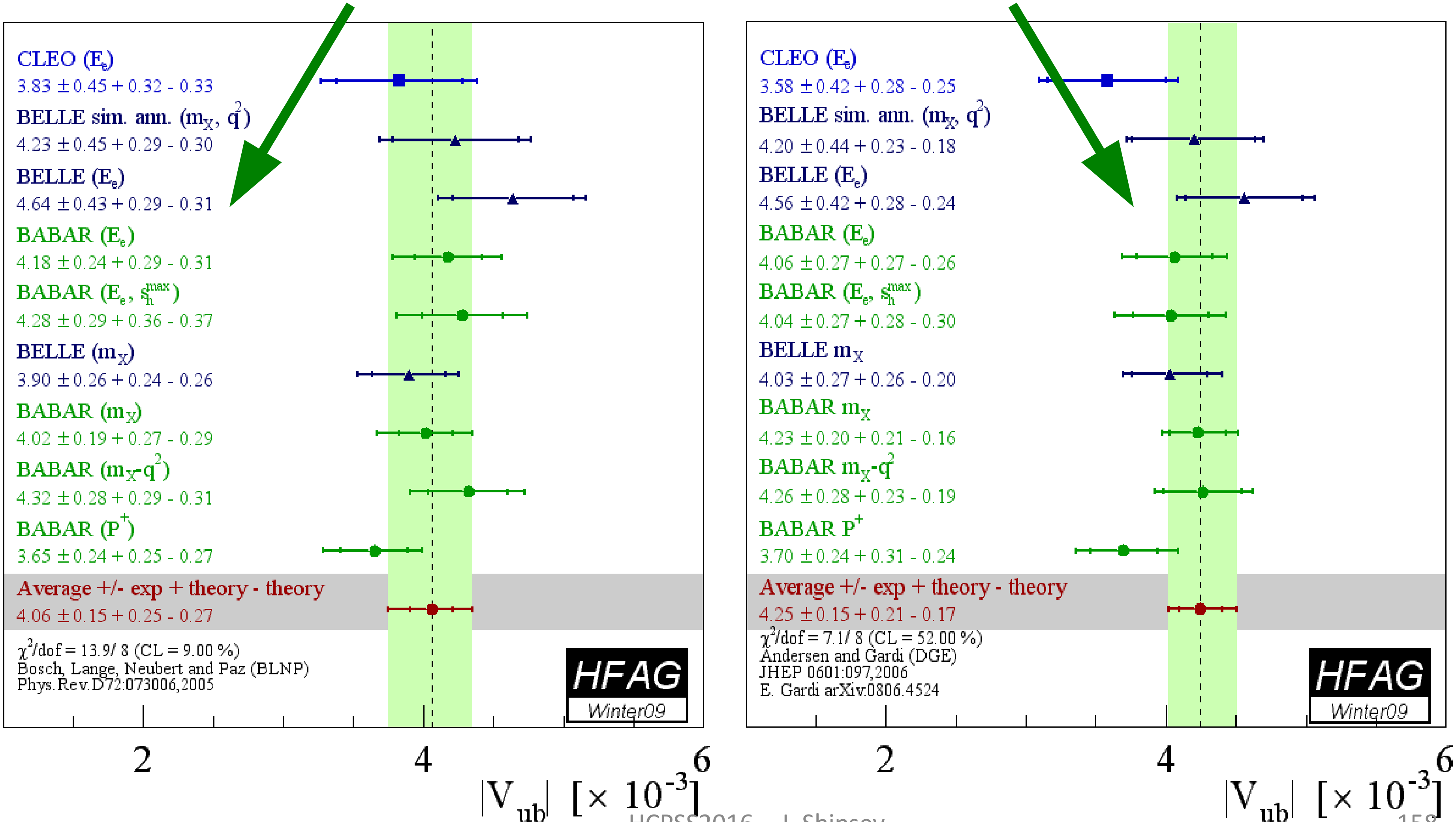


non $B\bar{B}$ background subtracted

$X_c\, l^+ \nu$ background subtracted

$|V_{ub}|$ from inclusives compilation

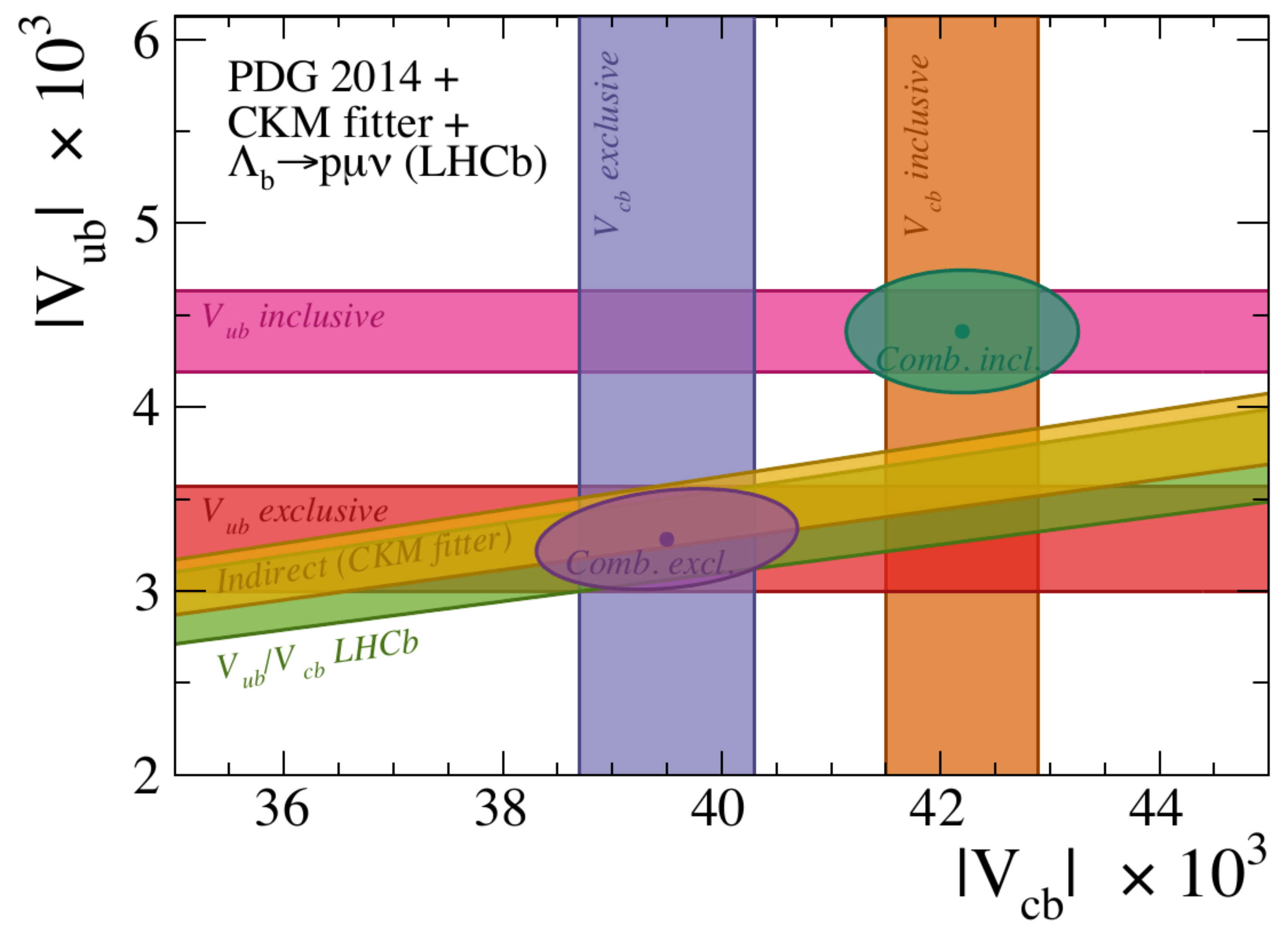
Different theoretical approaches (2 of 4 used by HFAG)



$|V_{ub}|$ average

- Averages on $|V_{ub}|$ from both exclusive and inclusive approaches
  - exclusive: $|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$
  - inclusive: $|V_{ub}| = (4.41 \pm 0.22) \times 10^{-3}$
  - notable “tension” between these results
  - in both cases theoretical errors are dominant
    - but some “theory” errors can be improved with more data
  - PDG2014 does naïve average rescaling due to inconsistency to obtain $|V_{ub}| = (4.13 \pm 0.49) \times 10^{-3}$

$|V_{ub}|$ summary



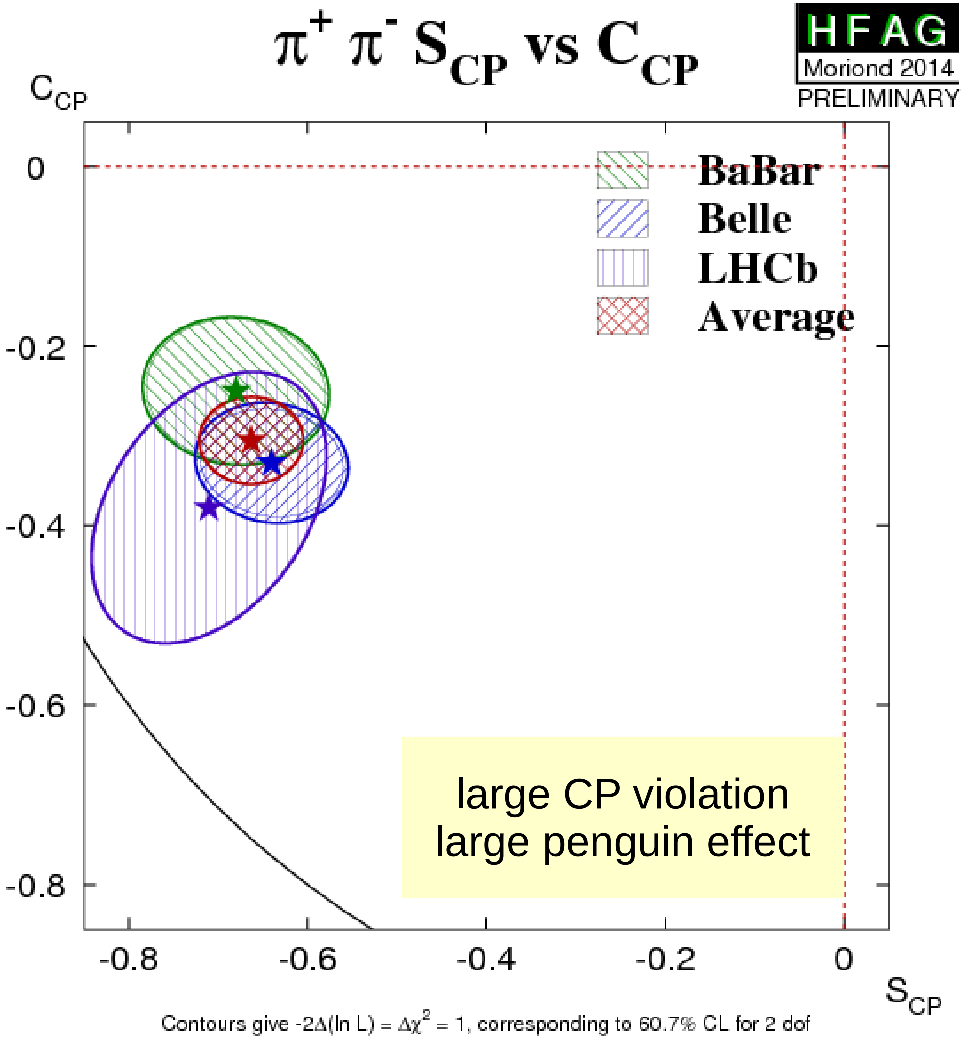
Longstanding discrepancy needs resolution

Measurement of α

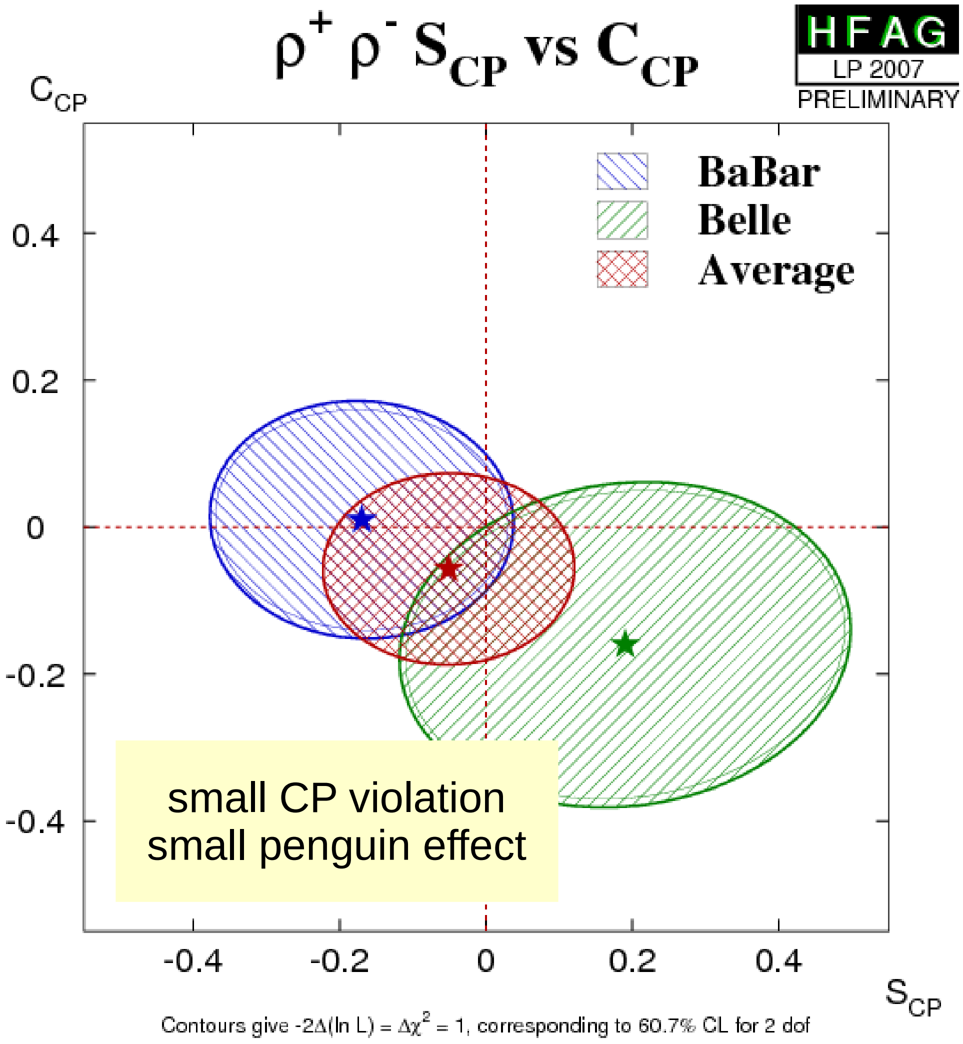
- Similar analysis using b → u$\bar{u}$d decays (e.g. $B_d^0 \to \pi^+\pi^-$) probes π–(β+γ) = α
  - but b → du$\bar{u}$ penguin transitions contribute to same final states ⇒ “penguin pollution”
  - C ≠ 0 ⇔ direct CP violation can occur
  - $S \neq +\eta_{CP} \sin(2\alpha)$
- Two approaches (optimal approach combines both)
  - try to use modes with small penguin contribution
  - correct for penguin effect (isospin analysis)

PRL 65 (1990) 3381

Measurement of α

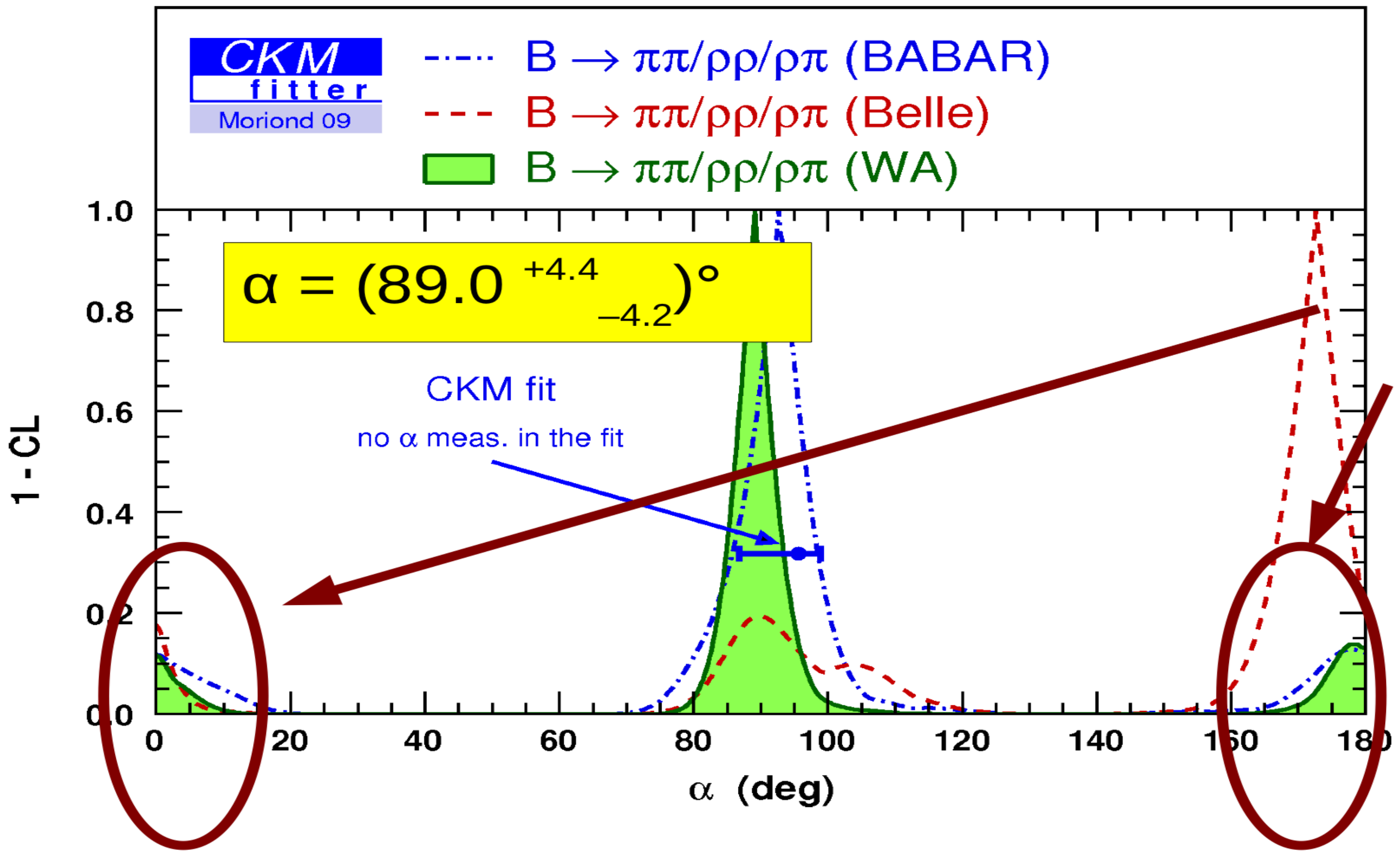


large CP violation
large penguin effect



small CP violation
small penguin effect

Measurement of α

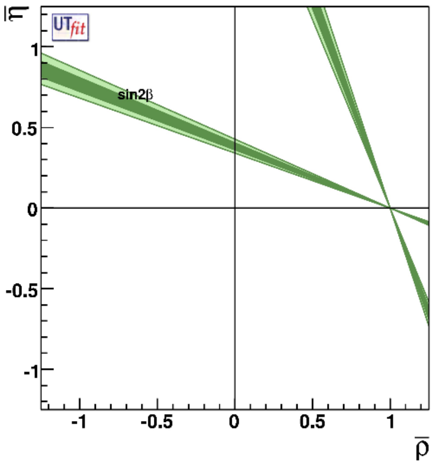


THESE SOLUTIONS RULED OUT BY OBSERVATION OF DIRECT CP VIOLATION IN $B^0 \to \pi^+\pi^-$

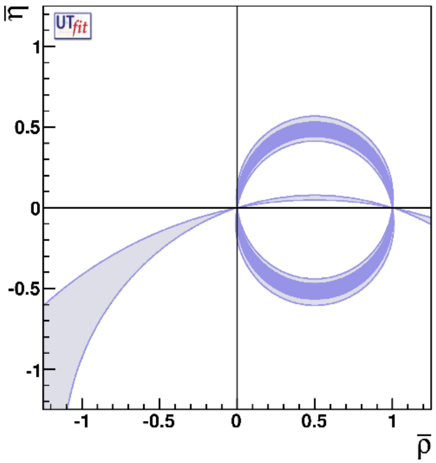
Is there any physical significance in the fact that α ≈ 90°?

Summary so far

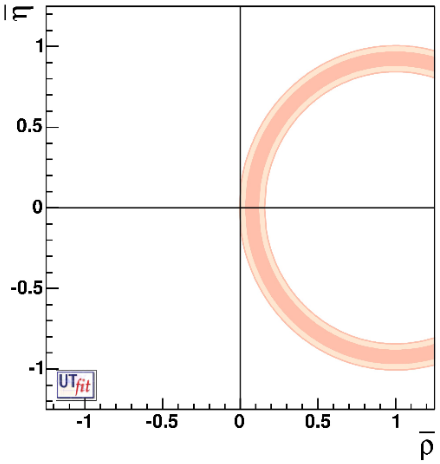
$\sin(2\beta)$



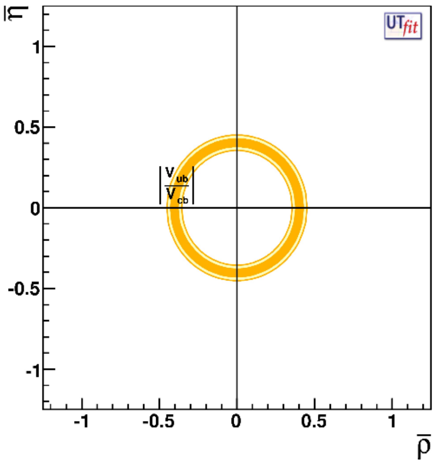
α



$\left|\Delta m_d/\Delta m_s\right|$

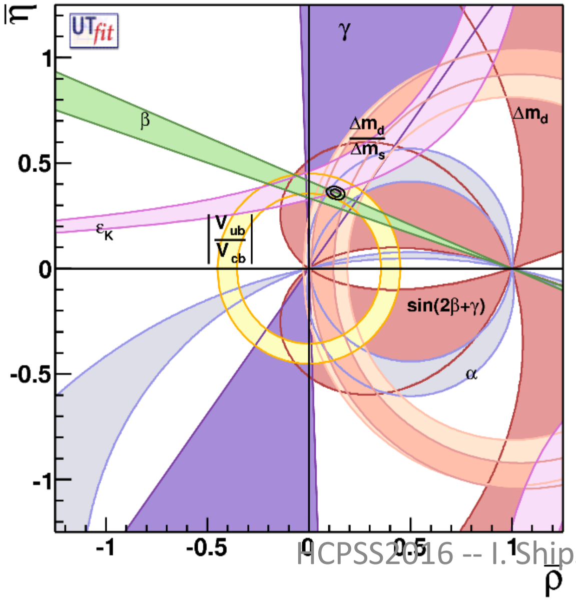


$\left|V_{ub}/V_{cb}\right|$



Adding a few other constraints we find

$$\bar{\rho} = 0.132 \pm 0.020$$
$$\bar{\eta} = 0.358 \pm 0.012$$

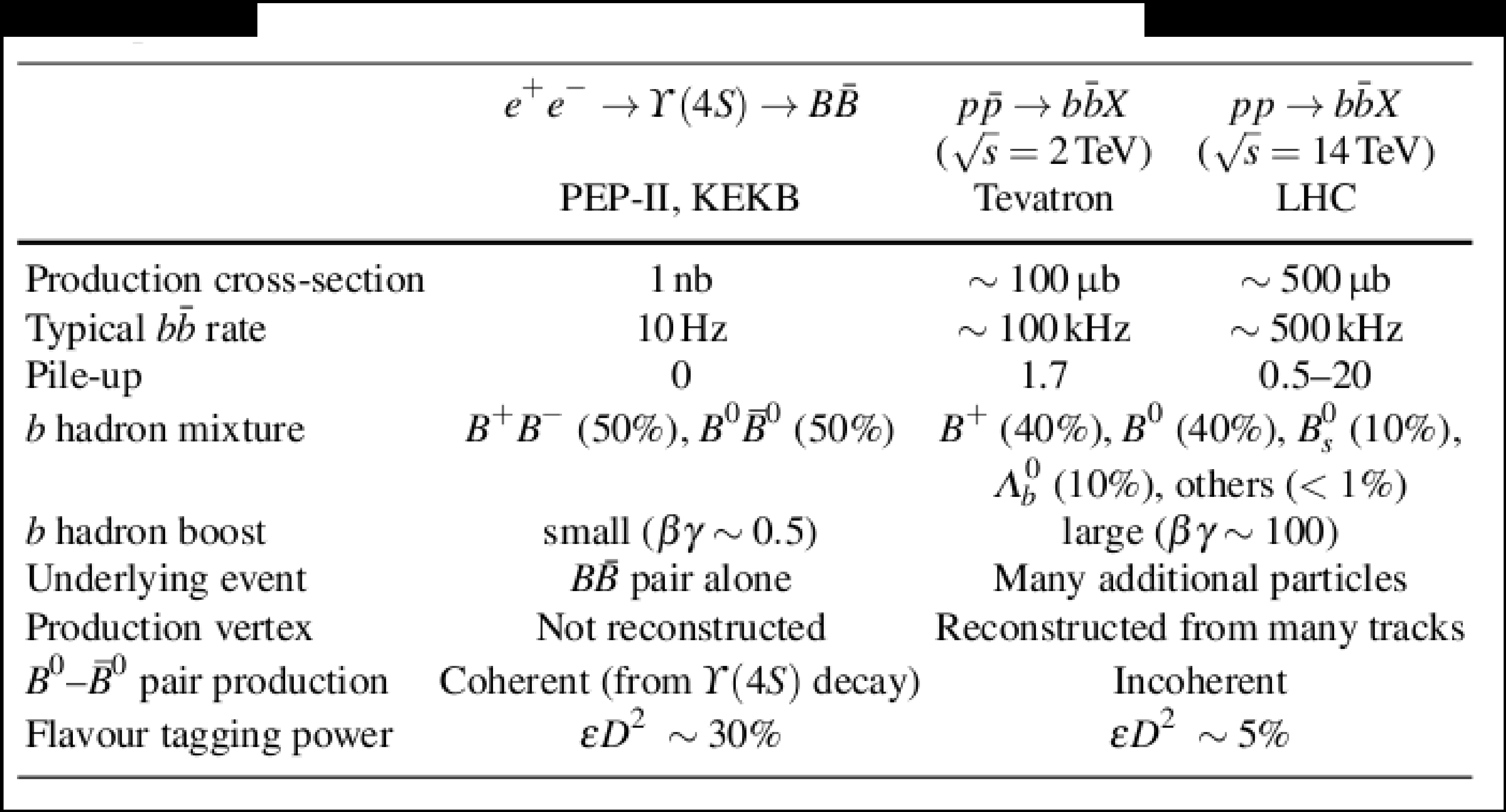


Consistent with Standard Model fit

- some “tensions”

Still plenty of room for new physics

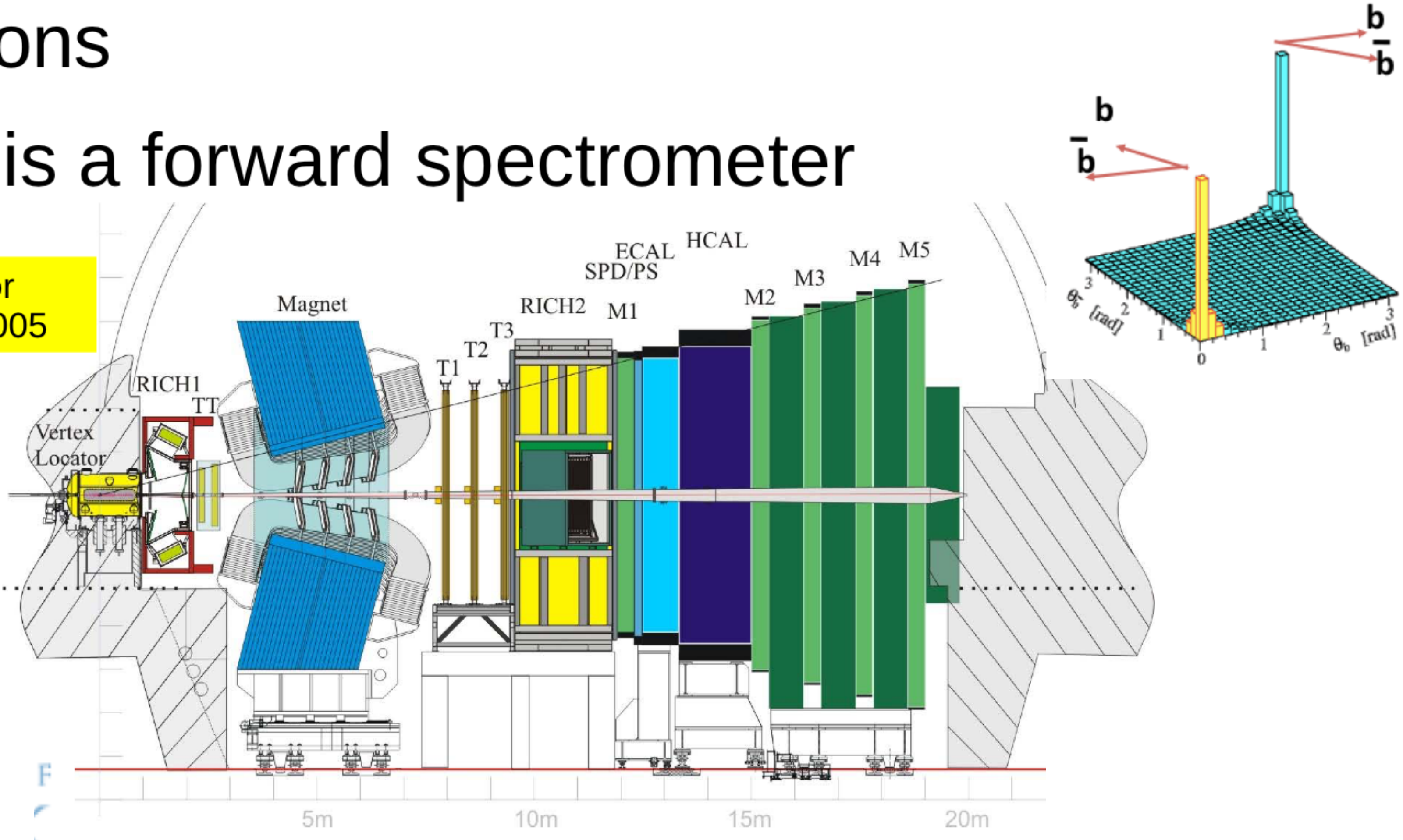
Flavor physics at hadron colliders



	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ PEP-II, KEKB	$p\bar{p} \to b\bar{b}X$ ($\sqrt{s} = 2\,\mathrm{TeV}$) Tevatron	$pp \to b\bar{b}X$ ($\sqrt{s} = 14\,\mathrm{TeV}$) LHC
Production cross-section	$1\,\mathrm{nb}$	$\sim 100\,\mu\mathrm{b}$	$\sim 500\,\mu\mathrm{b}$
Typical $b\bar{b}$ rate	$10\,\mathrm{Hz}$	$\sim 100\,\mathrm{kHz}$	$\sim 500\,\mathrm{kHz}$
Pile-up	0	1.7	0.5–20
b hadron mixture	B^+B^- (50%), $B^0\bar{B}^0$ (50%)	B^+ (40%), B^0 (40%), B^0_s (10%), Λ^0_b (10%), others (< 1%)	
b hadron boost	small ($\beta\gamma \sim 0.5$)	large ($\beta\gamma \sim 100$)	
Underlying event	$B\bar{B}$ pair alone	Many additional particles	
Production vertex	Not reconstructed	Reconstructed from many tracks	
B^0–$\bar{B}^0$ pair production	Coherent (from $\Upsilon(4S)$ decay)	Incoherent	
Flavour tagging power	$\varepsilon D^2 \sim 30\%$	$\varepsilon D^2 \sim 5\%$	

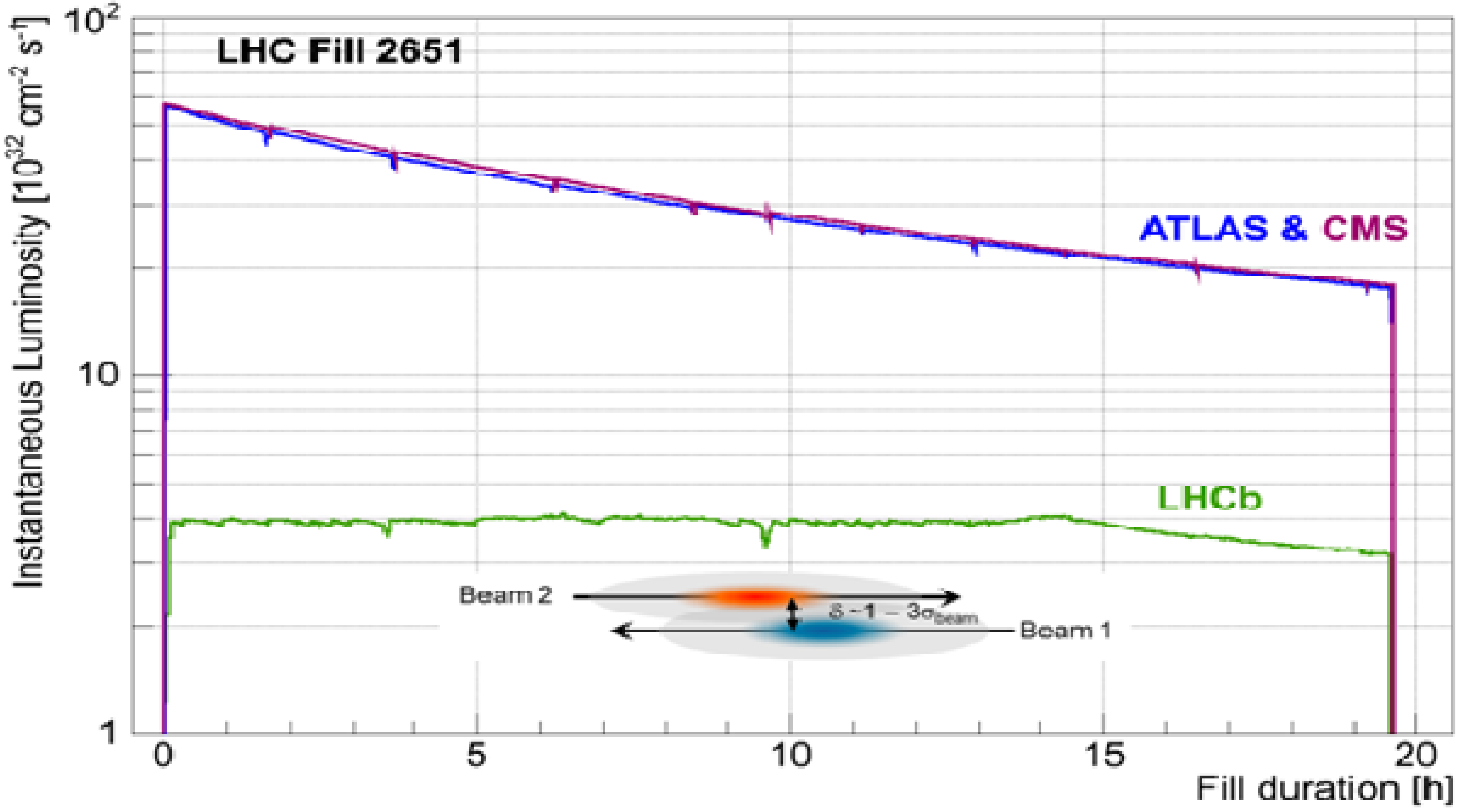
Flavor physics at hadron colliders

- In high energy collisions, $b\bar{b}$ pairs produced predominantly in forward or backward directions
- LHCb is a forward spectrometer



The LHCb Detector
JINST 3 (2008) S08005

Flavor physics at hadron colliders



luminosity
levelling at
around
$4x10^{32}$ cm^{-2}s^{-1}
via
transverse
separation
(with tilted
crossing angle)

from C. Gaspar, via. F. Zimmerman

Flavor physics at hadron colliders

- Measured cross-section, in LHCb acceptance, 7 TeV

$$\sigma(pp \rightarrow b\bar{b}X) = (75.3 \pm 5.4 \pm 13.0)\ \mu b$$

PLB 694 (2010) 209

- So, number of $b\bar{b}$ pairs produced in 1/fb (2011 sample)

$$10^{15} \times 75.3\ 10^{-6} \sim 10^{11}$$

- Compare to combined data sample of e^+e^- “B factories” BaBar and Belle of ~ 10^9 $B\bar{B}$ pairs

for any channel where the (trigger, reconstruction, stripping, offline) efficiency is not too small, LHCb has world's largest data sample

- p.s.: for charm, $\sigma(pp \rightarrow c\bar{c}X) = (6.10 \pm 0.93)$ mb

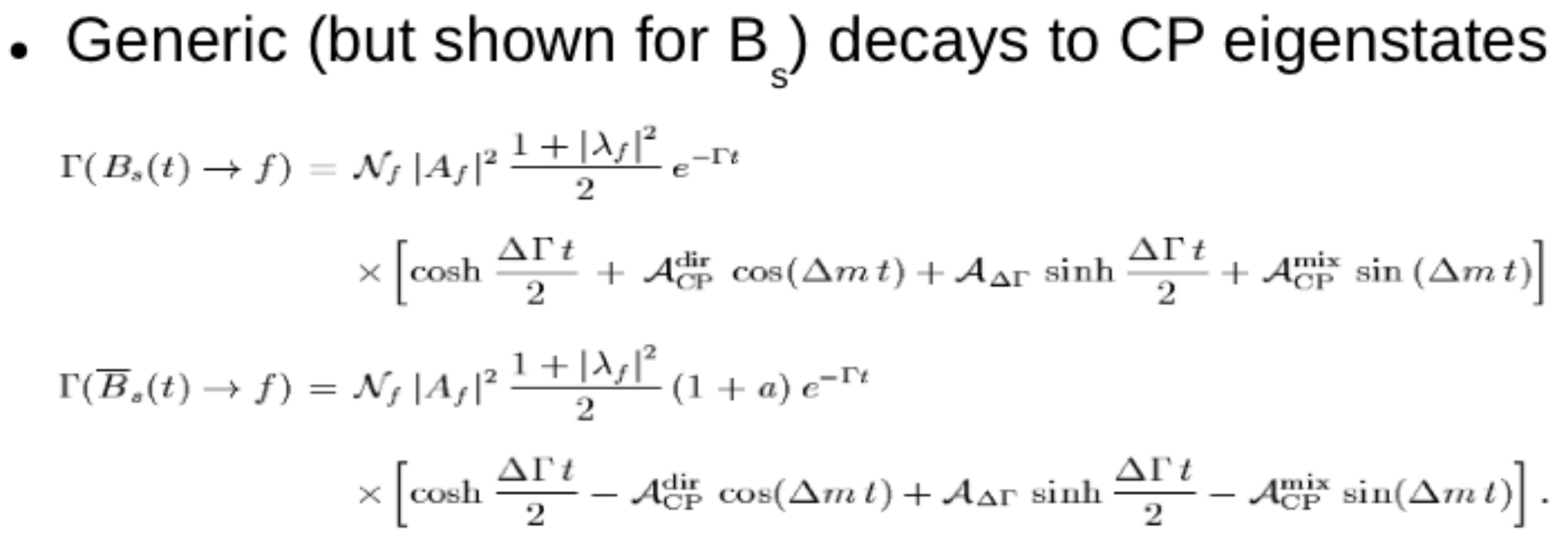
LHCb-CONF-2010-013

Other unitarity triangles

- High statistics available at LHCb will allow sensitivity to smaller CP violating effects
  - CP violating phase in B_s oscillations ($O(\lambda^4)$)
    - B_s oscillations (Δm_s) measured 2006 (CDF)
  - CP violating phase in D^0 oscillations ($O(\lambda^5)$)
    - D^0 oscillations ($x_D = \Delta m_D/\Gamma_D$ & $y_D = \Delta\Gamma_D/2\Gamma_D$) measured 2007 (BaBar, Belle, later CDF)
    - First definitive (5σ) observation 2011 (LHCb)

- Observations of CP violation in both K^0 and B^0 systems won Nobel prizes!

Time-dependent CP violation formalism



- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, e^{-\Gamma t}$$

$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}\, \cos(\Delta m\, t) + \mathcal{A}_{\Delta\Gamma}\, \sinh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}\, \sin(\Delta m\, t)\right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, (1+a)\, e^{-\Gamma t}$$

$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}\, \cos(\Delta m\, t) + \mathcal{A}_{\Delta\Gamma}\, \sinh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}\, \sin(\Delta m\, t)\right].$$

Time-dependent CP violation formalism

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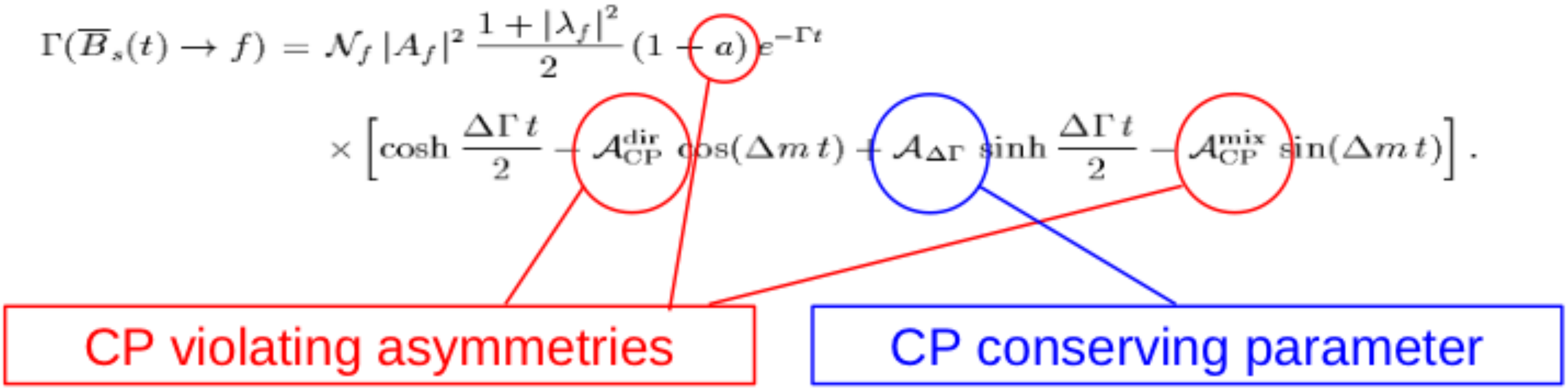


$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f\,|A_f|^2\,\frac{1+|\lambda_f|^2}{2}\,(1+a)\,e^{-\Gamma t}$$

$$\times\left[\cosh\frac{\Delta\Gamma\,t}{2} - \mathcal{A}_{\rm CP}^{\rm dir}\,\cos(\Delta m\,t) + \mathcal{A}_{\Delta\Gamma}\,\sinh\frac{\Delta\Gamma\,t}{2} - \mathcal{A}_{\rm CP}^{\rm mix}\,\sin(\Delta m\,t)\right].$$

CP violating asymmetries

CP conserving parameter

$$A_{CP}^{dir} = C_{CP} = \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2} \qquad A_{\Delta\Gamma} = \frac{2\,\Re(\lambda_{CP})}{1+|\lambda_{CP}|^2} \qquad A_{CP}^{mix} = S_{CP} = \frac{2\,\Im(\lambda_{CP})}{1+|\lambda_{CP}|^2}$$

$$(A_{CP}^{dir})^2 + (A_{\Delta\Gamma})^2 + (A_{CP}^{mix})^2 = 1$$

Time-dependent CP violation formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t}$$
$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} \qquad + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma \, t}{2} \qquad \right]$$
$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t}$$
$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} \qquad + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma \, t}{2} \qquad \right] .$$

- Untagged analyses still sensitive to some interesting physics

Time-dependent CP violation formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, e^{-\Gamma t}$$

$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} + \boxed{0} + \mathcal{A}_{\Delta\Gamma}\, \sinh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix}\, \sin\left(\Delta m\, t\right)\right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, (1 + \boxed{0}\; e^{-\Gamma t}$$

$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} - \boxed{0} + \mathcal{A}_{\Delta\Gamma}\, \sinh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix}\, \sin(\Delta m\, t)\right].$$

- In some channels, expect no direct CP violation
- and/or no CP violation in mixing

Time-dependent CP violation formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, e^{-\Gamma t}$$
$$\times \Big[\boxed{1} + \mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}} \cos(\Delta m\, t) + \boxed{0} + \mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}} \sin(\Delta m\, t) \Big]$$
$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, (1+a)\, e^{-\Gamma t}$$
$$\times \Big[\boxed{1} - \mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}} \cos(\Delta m\, t) + \boxed{0} - \mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}} \sin(\Delta m\, t) \Big] .$$

- In some channels, expect no direct CP violation
- B_d case: ΔΓ negligible

Time-dependent CP violation formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t)\to f) = \mathcal{N}_f\,|A_f|^2\,\frac{1+|\lambda_f|^2}{2}\,e^{-\Gamma t}$$

$$\times\left[\boxed{1} + \mathcal{A}_{\rm CP}^{\rm dir}\,\boxed{1} + \mathcal{A}_{\Delta\Gamma}\,\boxed{y\Gamma t} + \mathcal{A}_{\rm CP}^{\rm mix}\,\boxed{x\Gamma t}\right]$$

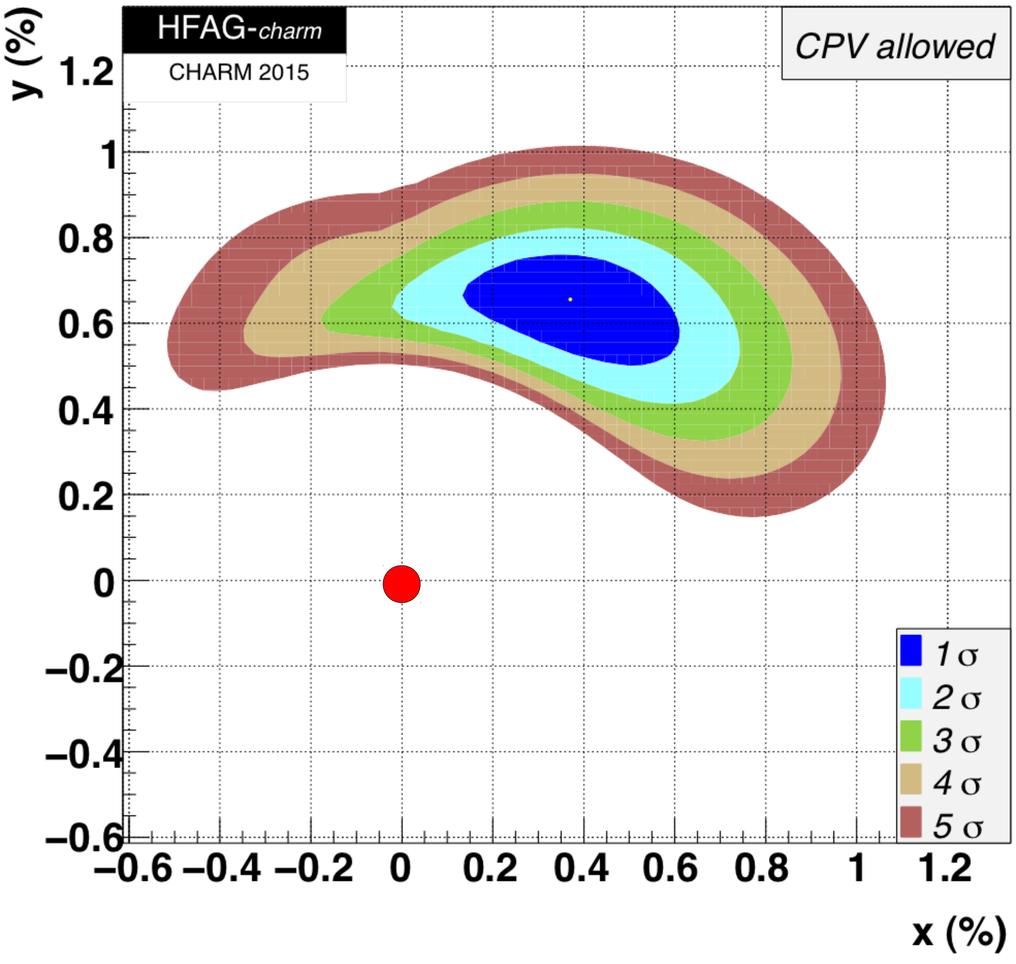
$$\Gamma(\overline{B}_s(t)\to f) = \mathcal{N}_f\,|A_f|^2\,\frac{1+|\lambda_f|^2}{2}\,(1+a)\,e^{-\Gamma t}$$

$$\times\left[\boxed{1} - \mathcal{A}_{\rm CP}^{\rm dir}\,\boxed{1} + \mathcal{A}_{\Delta\Gamma}\,\boxed{y\Gamma t} - \mathcal{A}_{\rm CP}^{\rm mix}\,\boxed{x\Gamma t}\right].$$

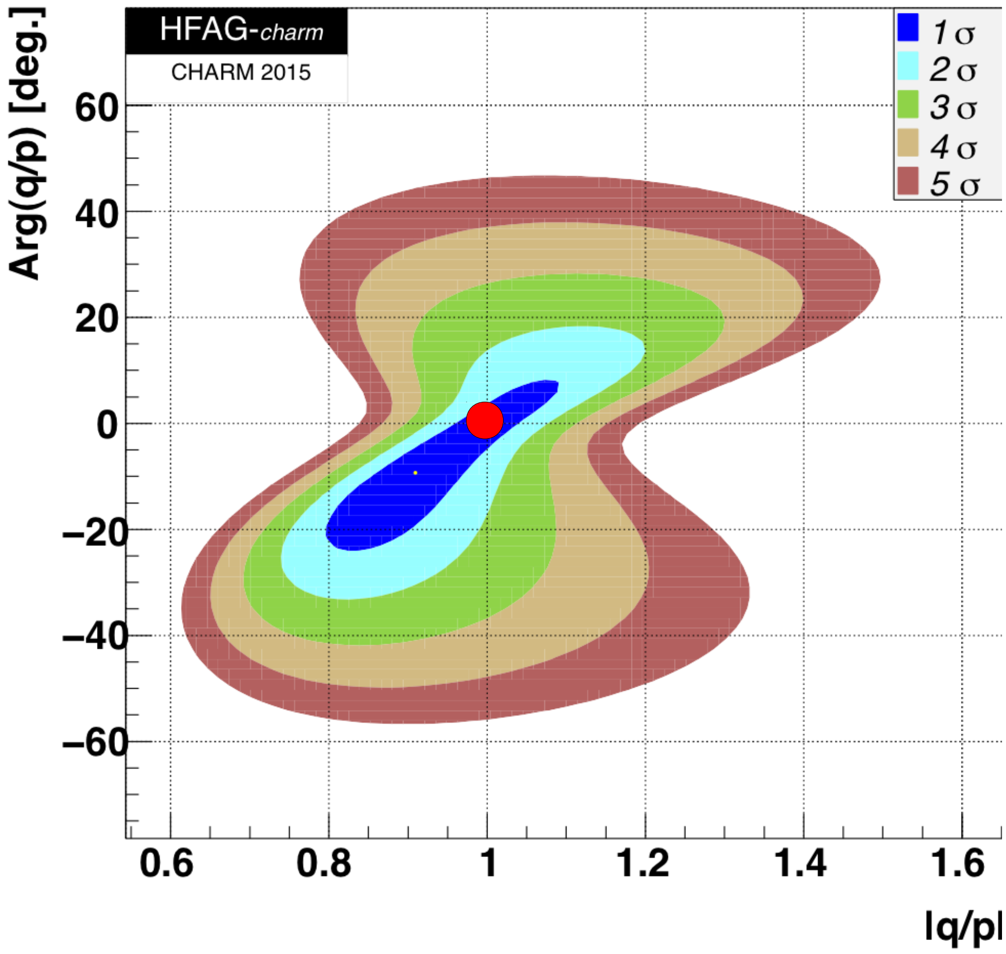
- In some channels, expect no direct CP violation
- B_d case: ΔΓ negligible
- D^0 case: both $x = \Delta m/\Gamma$ and $y=\Delta\Gamma/2\Gamma$ small

Charm mixing and CP violation

HFAG world average Including results from BABAR, Belle, CDF, CLEO(c), FOCUS, LHCb



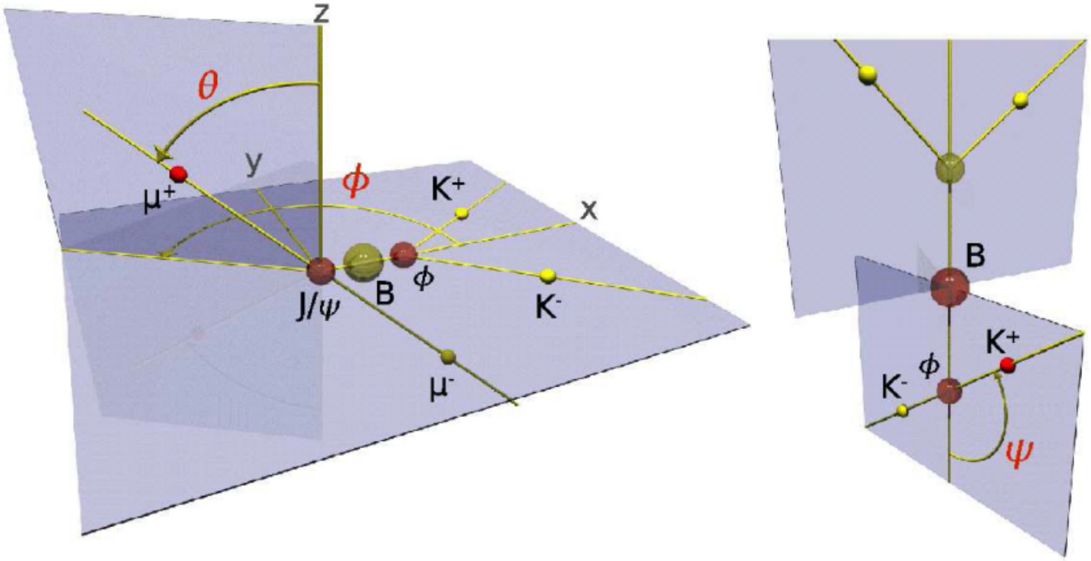
Inconsistent with no mixing point (0,0)



Consistent with no CP violation point (1,0)

Charm provides unique neutral meson “laboratory” to study CP violation effects in up-type quarks

$\Phi_s = -2\beta_s$



- Most attractive channel $B_s^0 \to J/\psi\varphi$
- VV final state

  three helicity amplitudes

  → mixture of CP-even and CP-odd

  disentangled using angular & time-dependent distributions

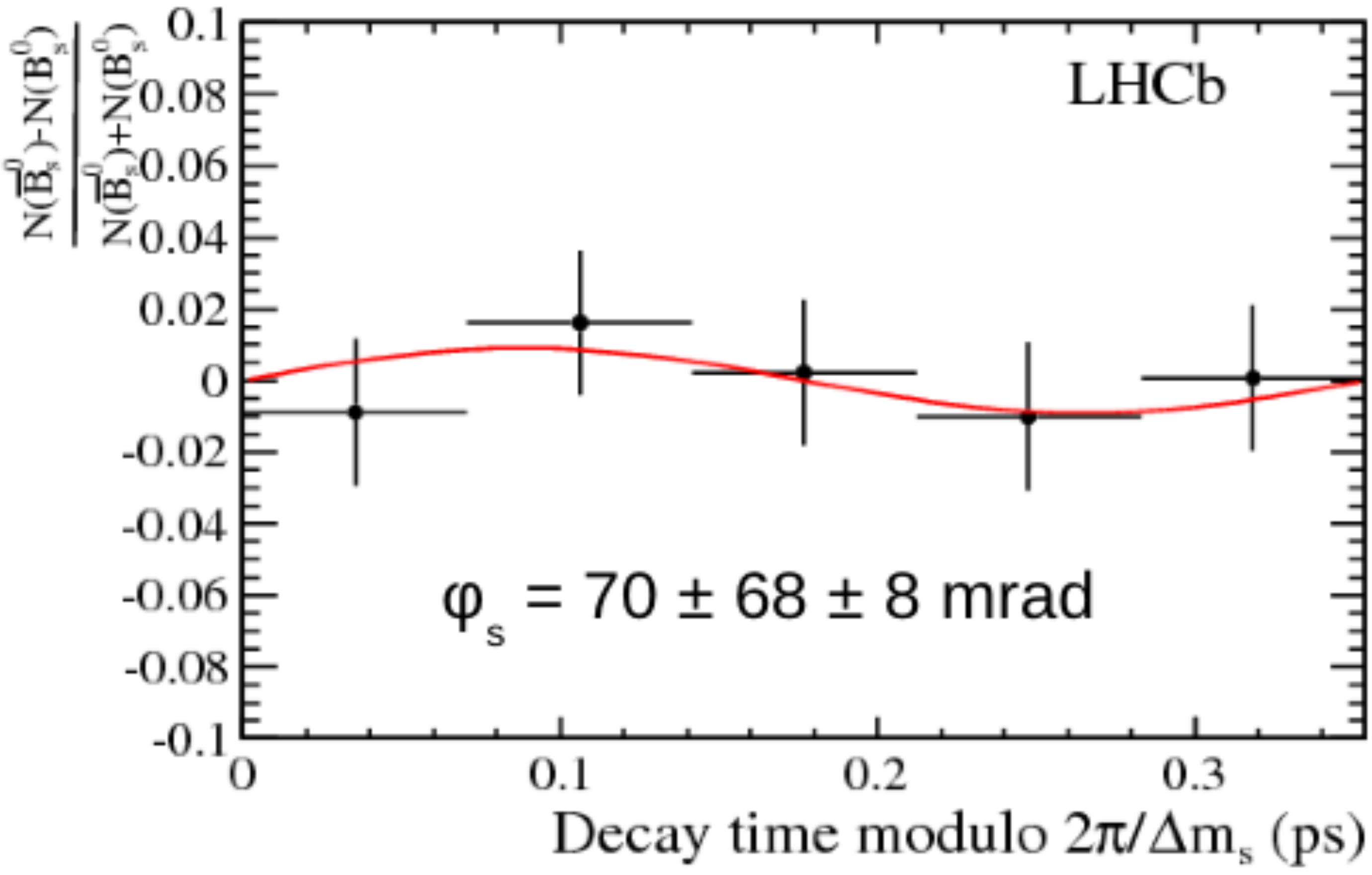
  → additional sensitivity

  many correlated variables

  → complicated analysis
- LHCb also uses $B_s \to J/\psi f_0$ $(f_0 \to \pi^+\pi^-)$
  - CP eigenstate; simpler analysis
  - fewer events; requires input from J/ψφ analysis (Γ_s, $\Delta\Gamma_s$)

CP violation in $B_s^0 \rightarrow J/\psi\pi^+\pi^-$

PLB 736 (2014) 186

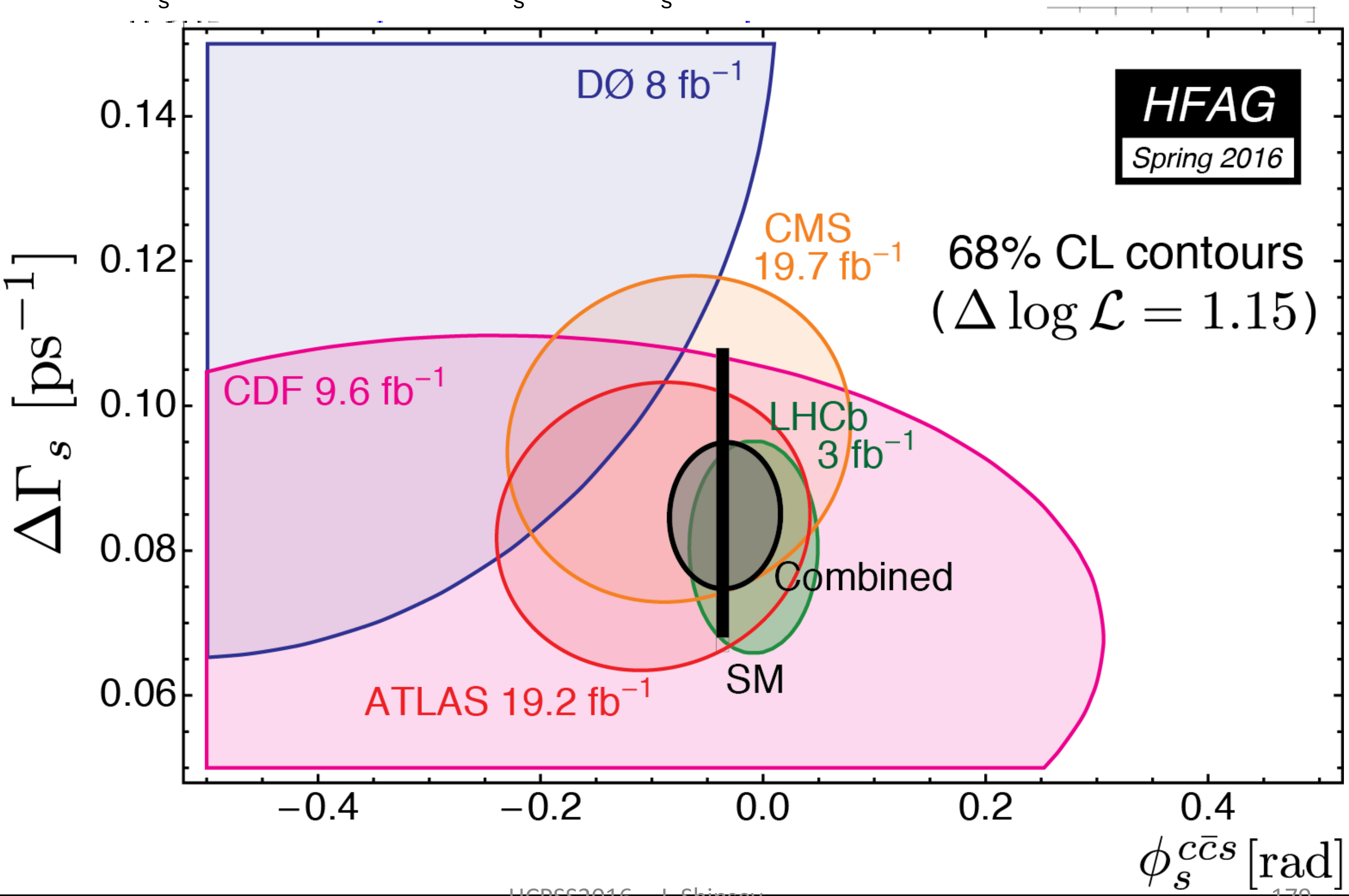


$\varphi_s = 70 \pm 68 \pm 8$ mrad

Asymmetry expected to be very small in the SM

CP violation in $B_s^0 \rightarrow J/\psi\phi$ & $J/\psi\pi\pi$

Analyses of $B_s^0 \rightarrow J/\psi\phi$ measure ϕ_s and $\Delta\Gamma_s$ simultaneously



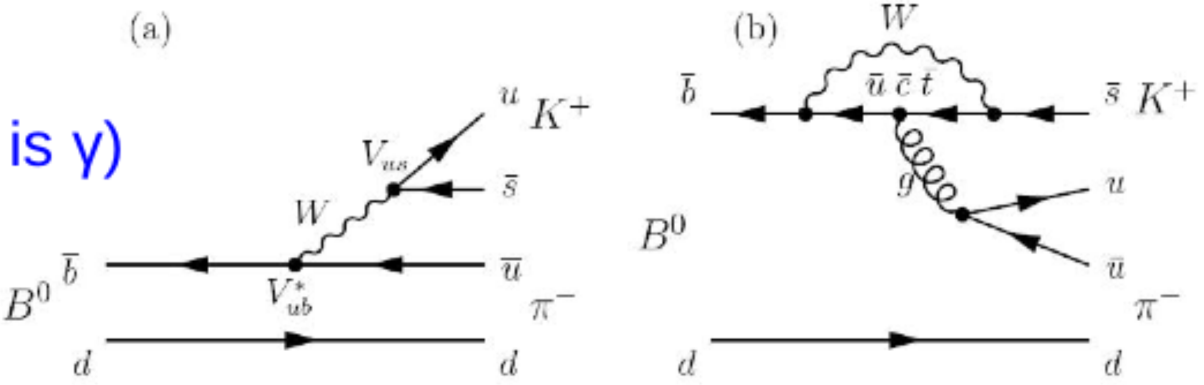
CP Violation in Decay

- Condition for CPV in decay: $|\bar{A}/A| \neq 1$
- Need $\bar{A}$ and A to consist of (at least) two parts
  - with different weak (φ) and strong (δ) phases
- Often realised by “tree” and “penguin” diagrams

$$A = |T| e^{i(\delta_T - \phi_T)} + |P| e^{i(\delta_P - \phi_P)} \qquad \bar{A} = |T| e^{i(\delta_T + \phi_T)} + |P| e^{i(\delta_P + \phi_P)}$$

$$A_{CP} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2\,|T||P| \sin(\delta_T - \delta_P) \sin(\phi_T - \phi_P)}{|T|^2 + |P|^2 + 2\,|T||P| \cos(\delta_T - \delta_P) \cos(\phi_T - \phi_P)}$$

Example: B → Kπ
(weak phase difference is γ)



Feynman tree (a) and penguin (b) diagrams for the $B_d^0 \to K^+\pi^-$ decay

Tim Gershon
Flavour & CPV

Fact or fable?

Penguin diagram

From Wikipedia, the free encyclopedia

In quantum field theory, **penguin diagrams** are a class of Feynman diagrams which are important for understanding CP violating processes in the standard model. They were first isolated and studied by Mikhail Shifman, Arkady Vainshtein, and Valentin Zakharov.[1] The processes which they describe were first directly observed in 1991 and 1994 by the CLEO collaboration.

Origin of the name

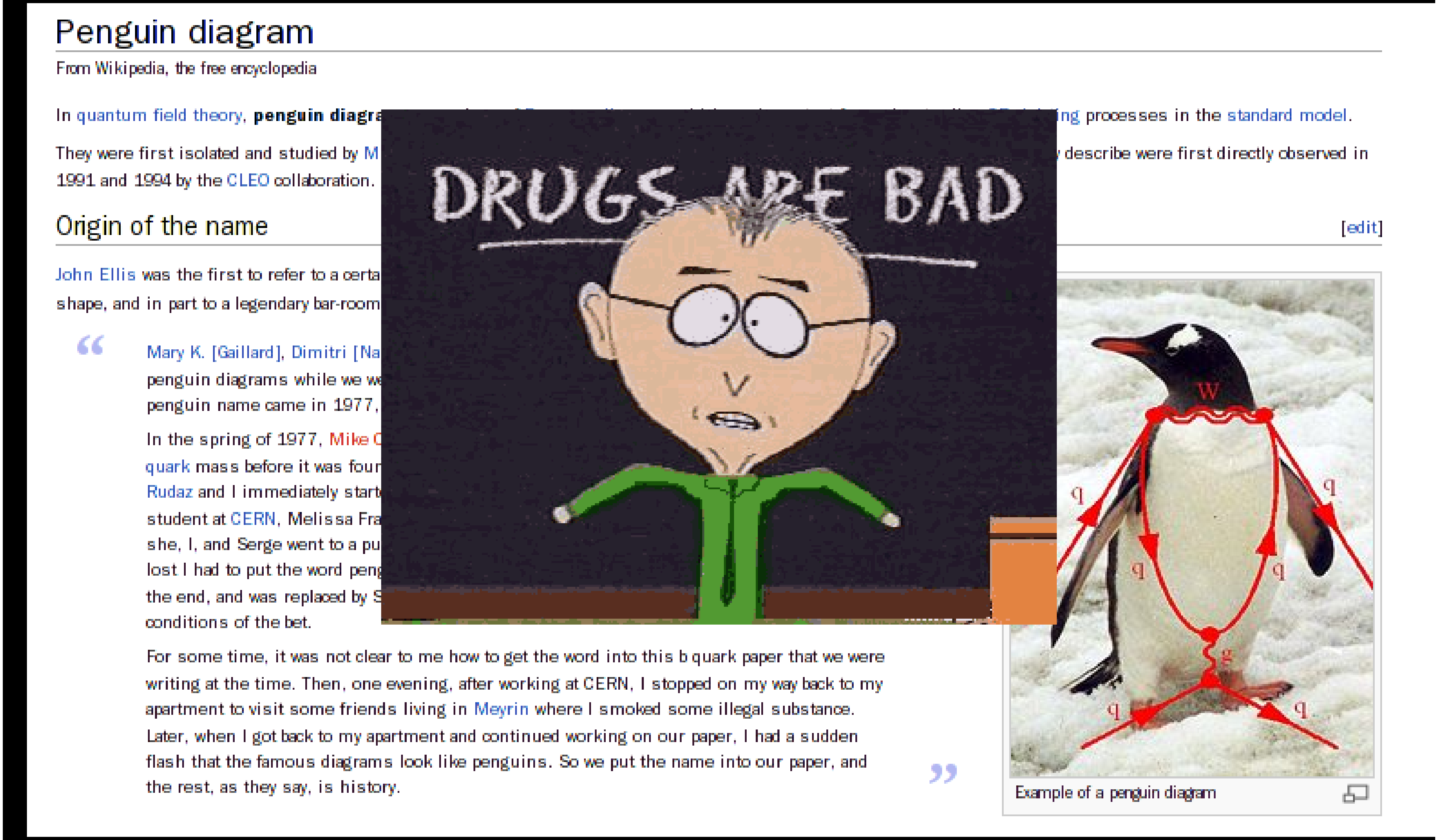
[edit]

John Ellis was the first to refer to a certain class of Feynman diagrams as **penguin diagrams**, due in part to their shape, and in part to a legendary bar-room bet with Melissa Franklin. According to John Ellis:[2]

> Mary K. [Gaillard], Dimitri [Nanopoulos] and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976... The penguin name came in 1977, as follows.
>
> In the spring of 1977, Mike Chanowitz, Mary K and I wrote a paper on GUTs predicting the b quark mass before it was found. When it was found a few weeks later, Mary K, Dimitri, Serge Rudaz and I immediately started working on its phenomenology. That summer, there was a student at CERN, Melissa Franklin who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.
>
> For some time, it was not clear to me how to get the word into this b quark paper that we were writing at the time. Then, one evening, after working at CERN, I stopped on my way back to my apartment to visit some friends living in Meyrin where I smoked some illegal substance. Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history.

Example of a penguin diagram

Fact or fable?



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Example of a penguin diagram

Direct CP violation in B → Kπ

- Direct CP violation in B → Kπ sensitive to γ

too many hadronic parameters ⇒ need theory input

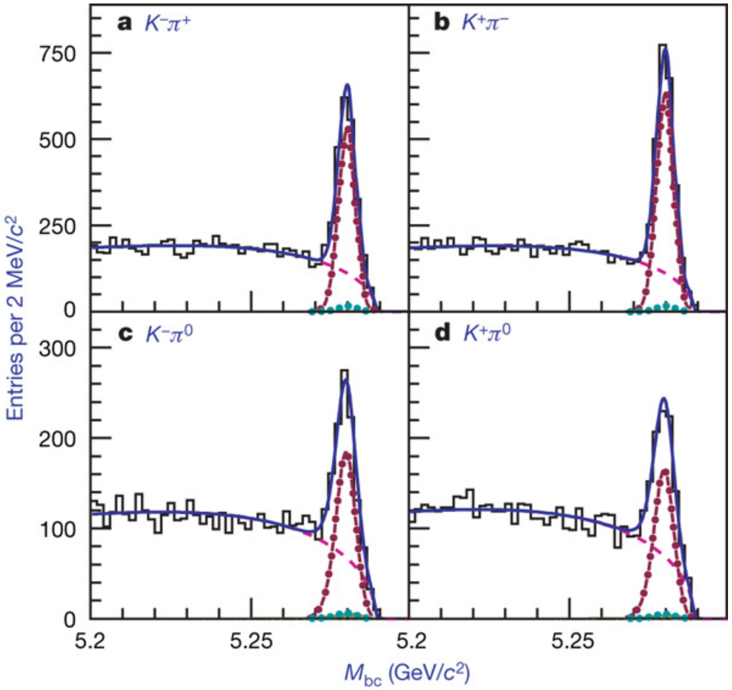
NB. interesting deviation from naïve expectation

Belle Nature 452 (2008) 332

"Kπ puzzle"

$$A_{CP}(K^-\pi^+) = -0.082 \pm 0.006$$
$$A_{CP}(K^-\pi^0) = +0.040 \pm 0.021$$

HFAG averages



Could be a sign of new physics …
… but first need to rule out possibility of
larger than expected QCD corrections

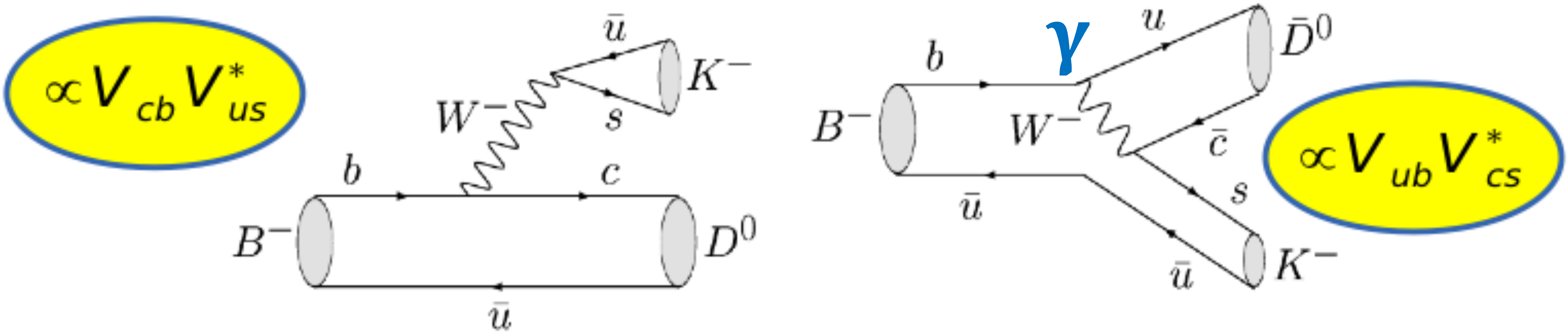
B →DK & determination of γ

- γ plays a unique role in flavour physics

the only CP violating parameter that can be measured through tree decays (*)

(*) more-or-less

- A benchmark Standard Model reference point
    - doubly important after New Physics is observed

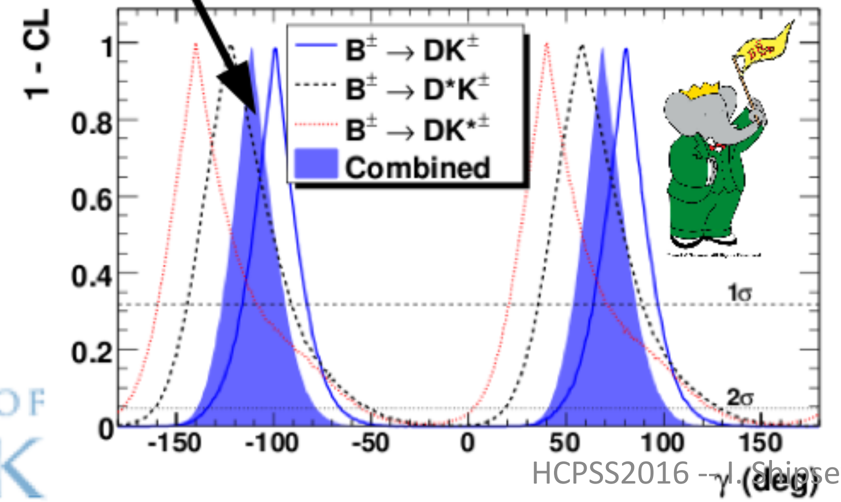


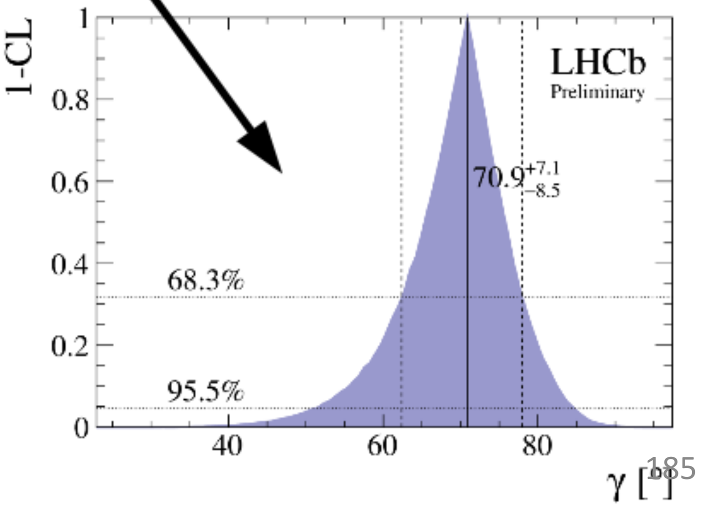
Variants use different B or D decays
require a final state common to both D^0 and $\bar{D}^0$

B →DK & determination of γ

BaBar PRD 87 (2013) 052015
Belle CKM2012 preliminary
LHCb PLB 726 (2013) 151
& LHCb-CONF-2016-001

- All direct CP violation effects caused by γ in the Standard Model
- Only those in B→DK type processes involve only tree-level diagrams
  - enable determination of γ with negligible theoretical uncertainty
- Several different B and D decays can be used
- Combination includes results from GLW/ADS (D→hh) & GGSZ (D→$K_S$hh)
- Sensitivity: BaBar & Belle each ~16°; latest LHCb ~7°

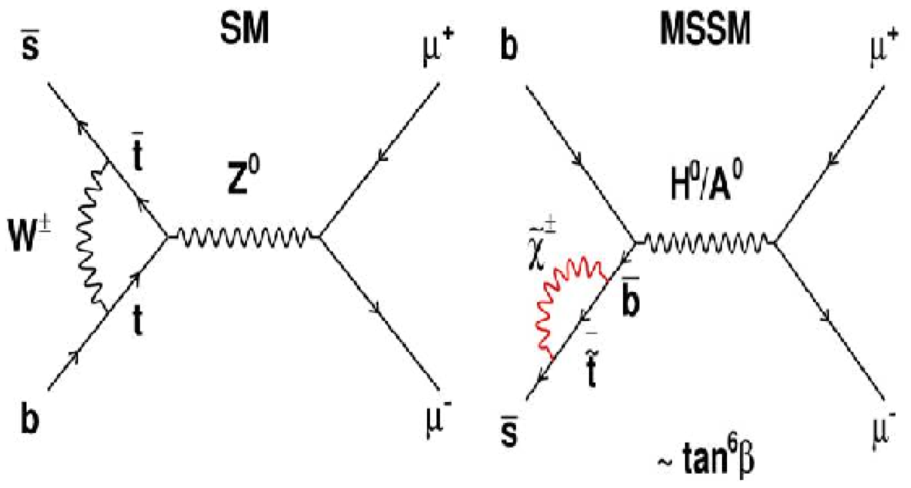




The 30 year search for $B^0_{s,d} \to \mu^+\mu^-$

Killer app. for new physics discovery

- Very small in the SM
  - no tree-level FCNC
  - CKM suppression
  - helicity suppression

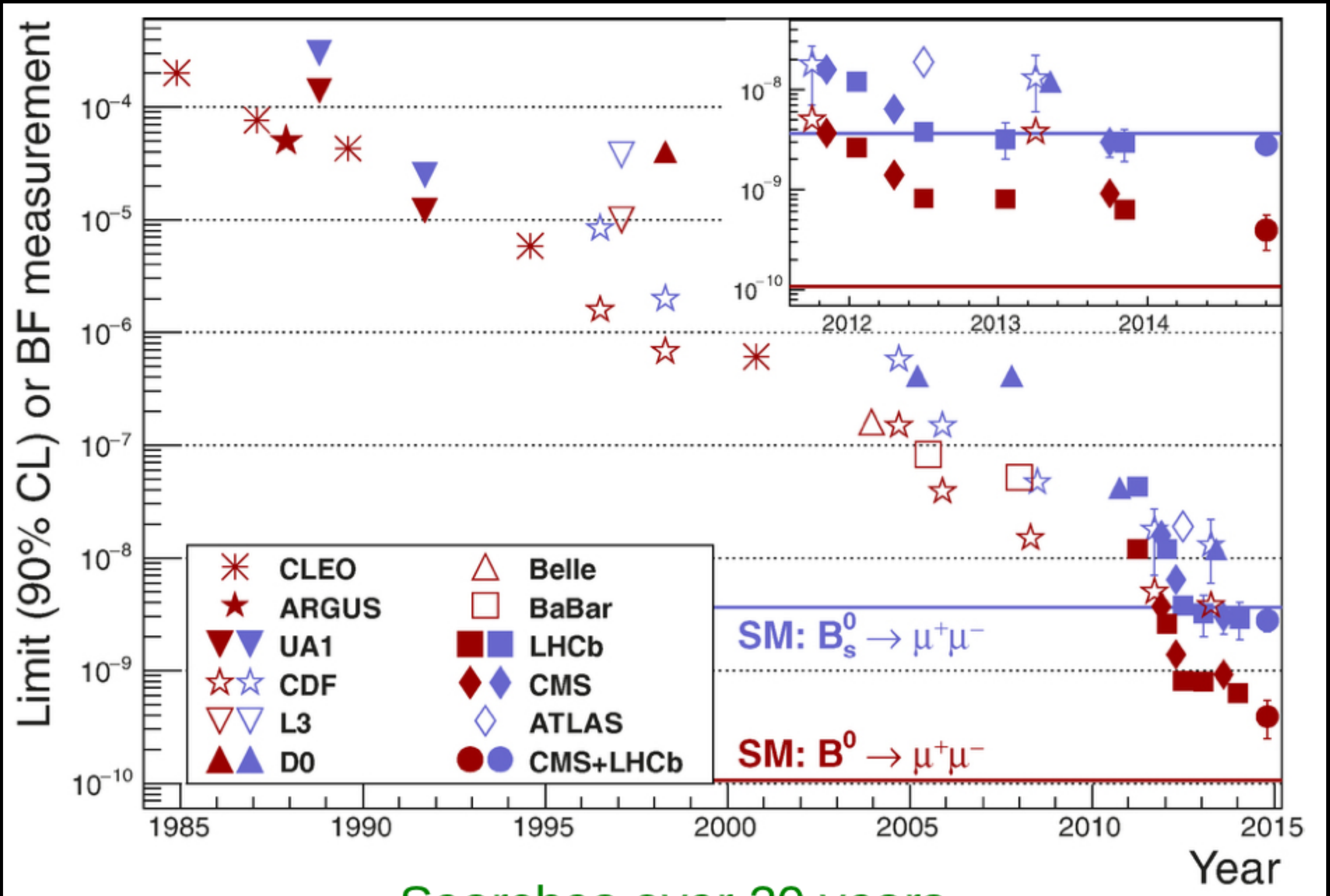


- Huge NP enhancement possible (tan β = ratio of Higgs vevs)

$$BR(B_s \to \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-9} \qquad BR(B_s \to \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M^4_{A0}$$

- Clean experimental signature

The 30 year search for $B^0_{s,d} \to \mu^+\mu^-$



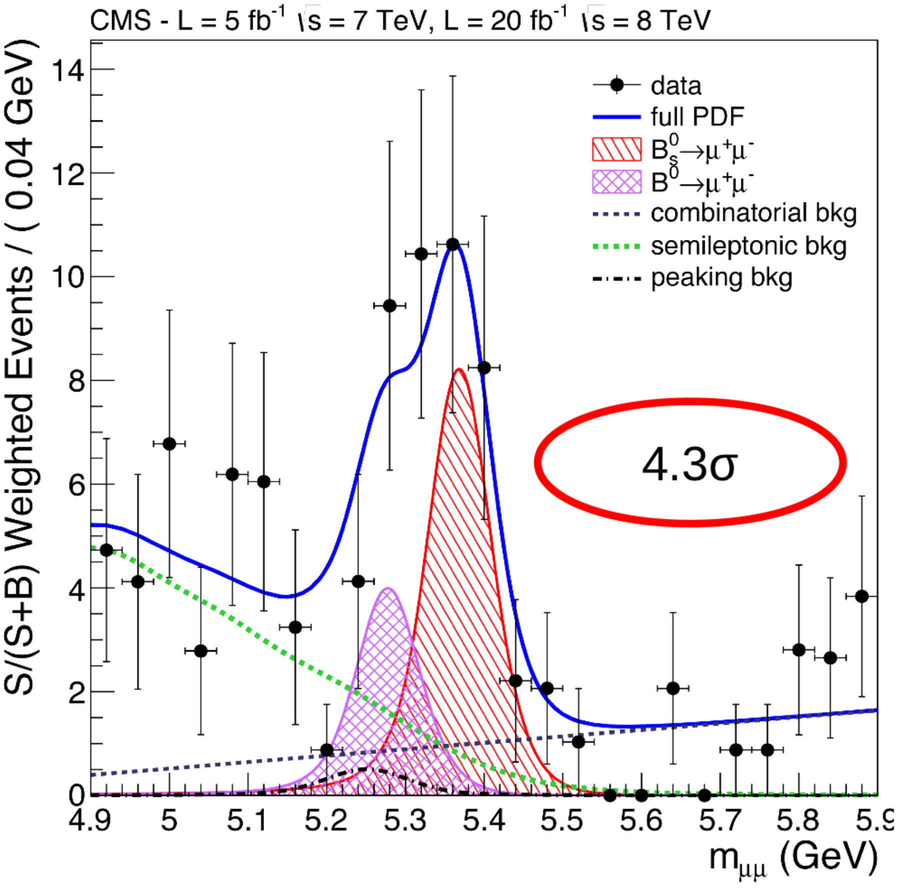
Searches over 30 years

Observation of $B^0_{s,d} \to \mu^+\mu^-$

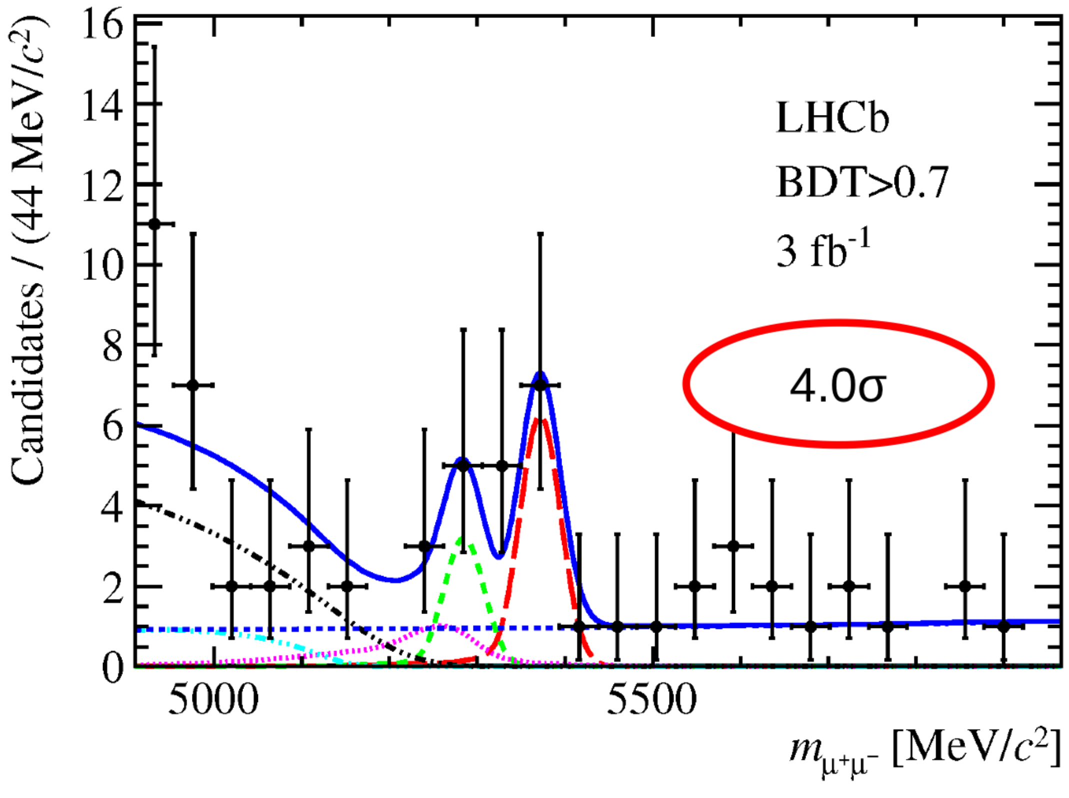
latest results from CMS & LHCb

CMS PRL 111 (2013) 101804

LHCb PRL 111 (2013) 101805

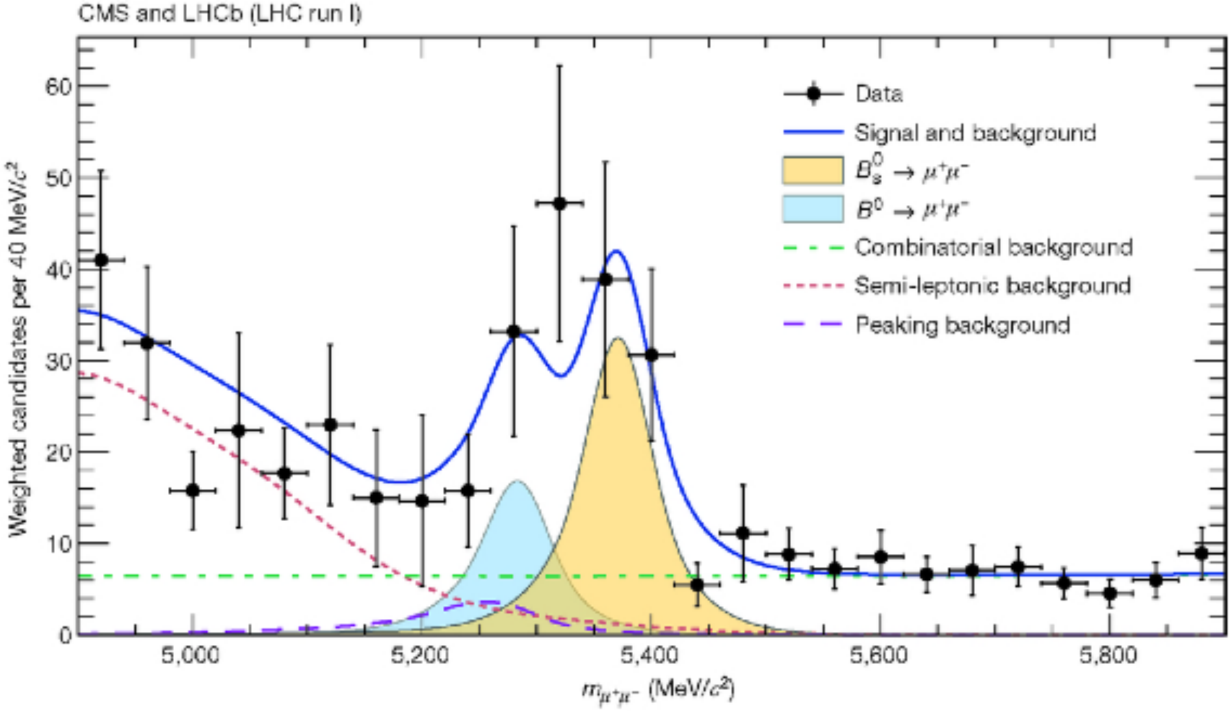


Events weighted by S/(S+B)



Only events with BDT > 0.7

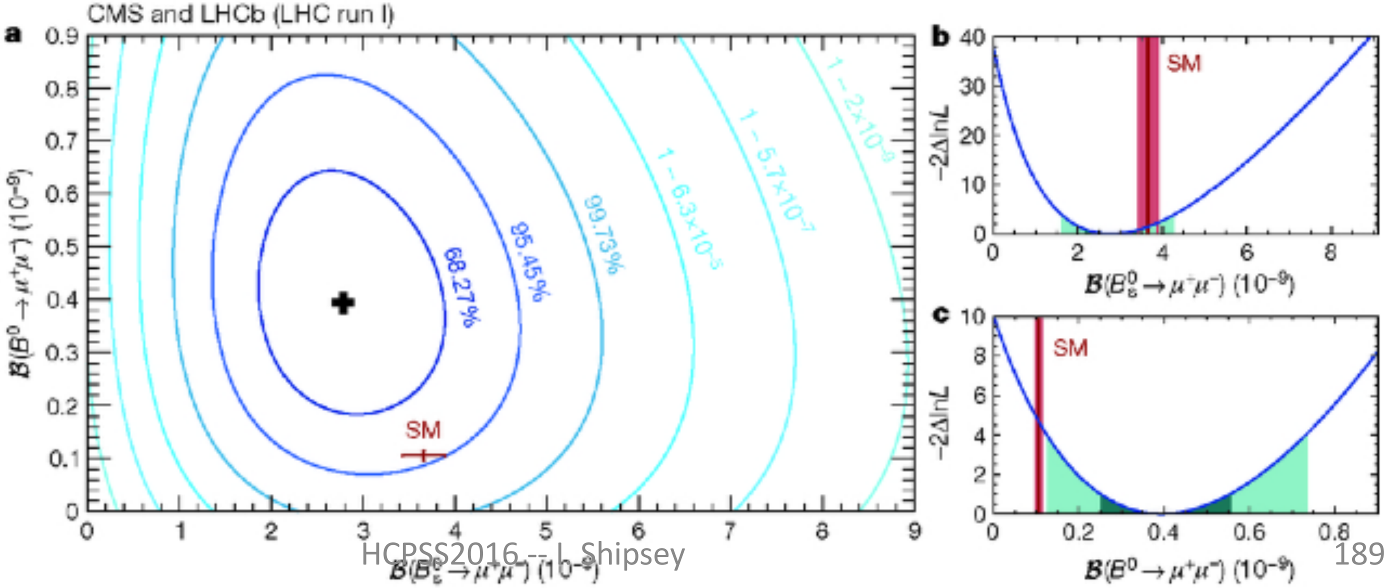
Observation of $B^0_{s,d} \rightarrow \mu^+ \mu^-$



Combination of CMS and LHCb data results in first observation of $B_s \rightarrow \mu^+\mu^-$ and first evidence for $B^0 \rightarrow \mu^+\mu^-$

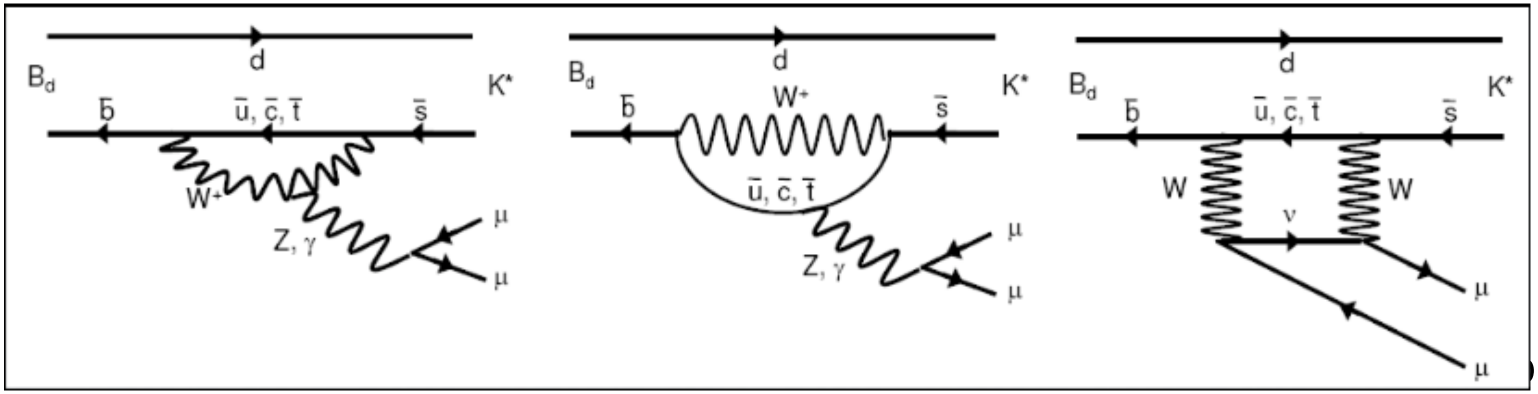
Results consistent with SM at 2σ level

Recent results from ATLAS not included (arXiv:1604.04263)



$B \to K^* \mu^+ \mu^-$

- $b \to s l^+ l^-$ processes also governed by FCNCs
  - rates and asymmetries of many exclusive processes sensitive to NP
- Especially $B_d \to K^{*0} \mu^+ \mu^-$
  - superb laboratory for NP tests
  - experimentally clean signature
  - many kinematic variables …
  - … with clean theoretical predictions (at least at low q^2)



Operator Product Expansion

- Build an effective theory for b physics
  - take the weak part of the SM
  - integrate out the heavy fields (W,Z,t)
  - (like a modern version of Fermi theory for weak interactions)

$$\mathcal{L}_{\text{(full EW}\times\text{QCD)}} \longrightarrow \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED}\times\text{QCD}}\left(\begin{smallmatrix}\text{quarks} \neq t\\ \text{\& leptons}\end{smallmatrix}\right) + \sum_n C_n(\mu)\, Q_n$$

Q_n – local interaction terms (operators), C_n – coupling constants (Wilson coefficients)

Wilson coefficients

- encode information on the weak scale
- are calculable and known in the SM (at least to leading order)
- are affected by new physics

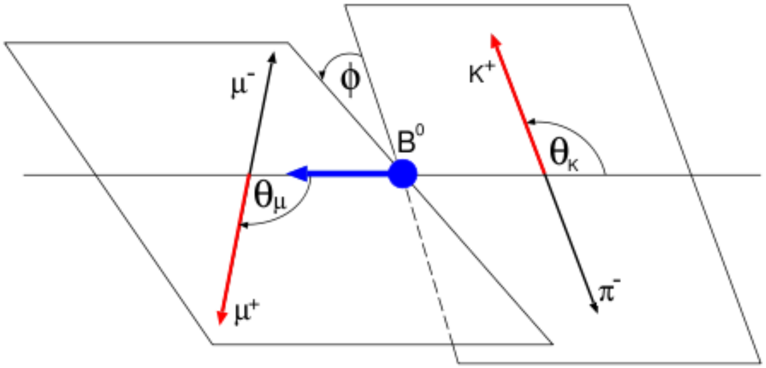
For K*μμ we care about C_7 (also affects b→sγ), C_9 and C_{10}

Angular analysis of B→K*μ⁺μ⁻

LHCb-CONF-2015-002

- Differential decay distribution

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big].$$

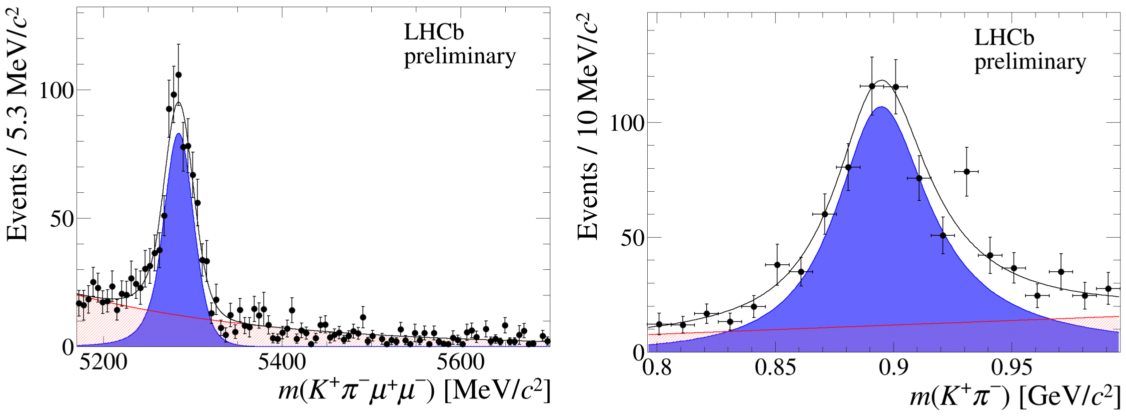


S_i terms related to Wilson coefficients and form factors

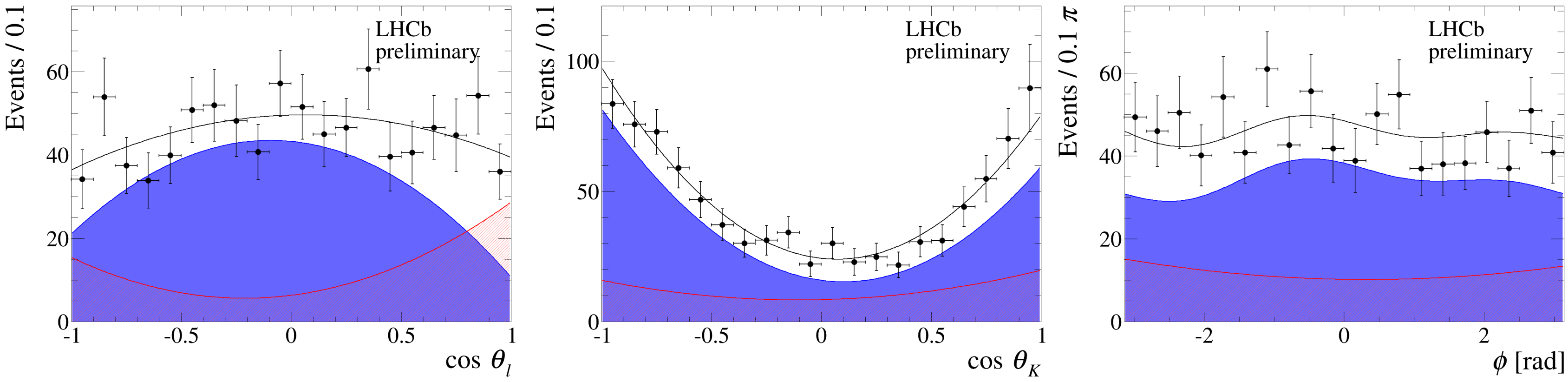
Full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

LHCb-CONF-2015-002

- Example of fits, in $1.1 < q^2 < 6.0$ GeV^2 bin

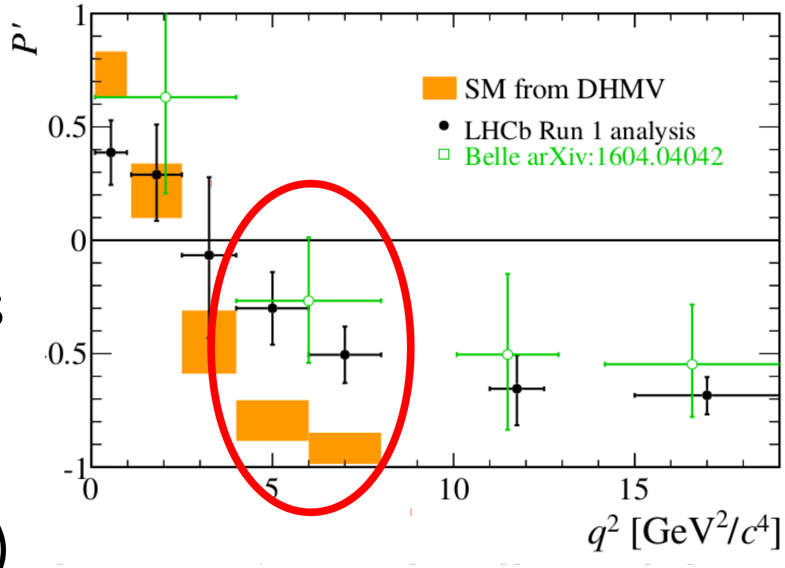


Angle and m(Kπ) projections in ± 50 MeV around B peak



Tension in P_5'

JHEP 02 (2016) 104

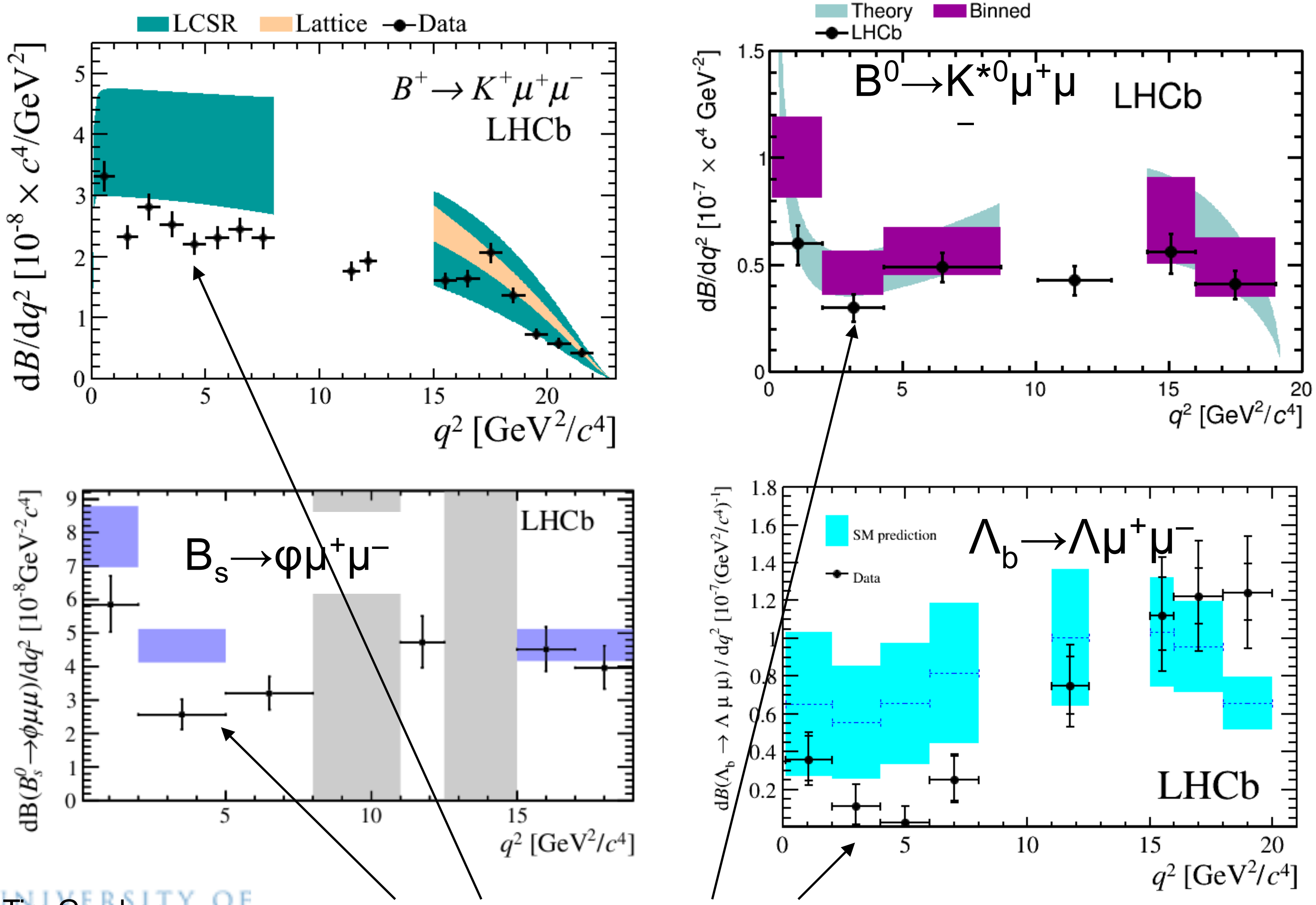


- Dimuon pair is predominantly spin-1
  - either vector (V) or axial-vector (A)
- There are 6 non-negligible amplitudes
  - 3 for VV and 3 for VA
  - expressed as $A^{L,R}_{0,\perp,\parallel}$ (transversity basis)
- P_5' related to difference between relative phase of longitudinal (0) and perpendicularly ($\perp$) polarised amplitudes for VV and VA
  - constructed so as to minimise form-factor uncertainties

$$P_5' = \sqrt{2}\frac{\mathrm{Re}\left(A_0^{\mathrm{L}} A_\perp^{\mathrm{L}*} - A_0^{\mathrm{R}} A_\perp^{\mathrm{R}*}\right)}{\sqrt{\left(|A_0^{\mathrm{L}}|^2 + |A_0^{\mathrm{R}}|^2\right)\left(|A_\parallel^{\mathrm{L}}|^2 + |A_\parallel^{\mathrm{R}}|^2 + |A_\perp^{\mathrm{L}}|^2 + |A_\perp^{\mathrm{R}}|^2\right)}}$$

Sensitive to NP in V or A couplings (Wilson coefficients $C_9^{(')}$ & $C_{10}^{(')}$)

$b \rightarrow s\mu^+\mu^-$ branching fractions

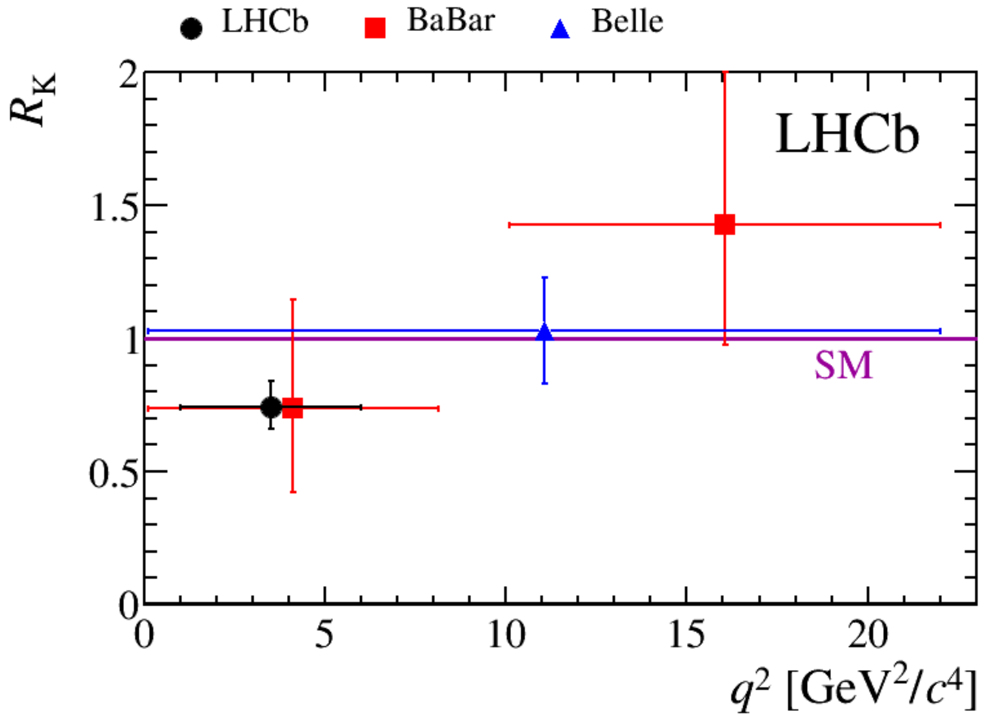


Trend to be below SM prediction at low q^2?

Lepton universality – R_K

PRL 113 (2014) 151601

Deficit of B → $K\mu^+\mu^-$ compared to expectation
also seen in $K\mu^+\mu^-/Ke^+e^-$ ratio (R_K) – negligible theoretical uncertainty

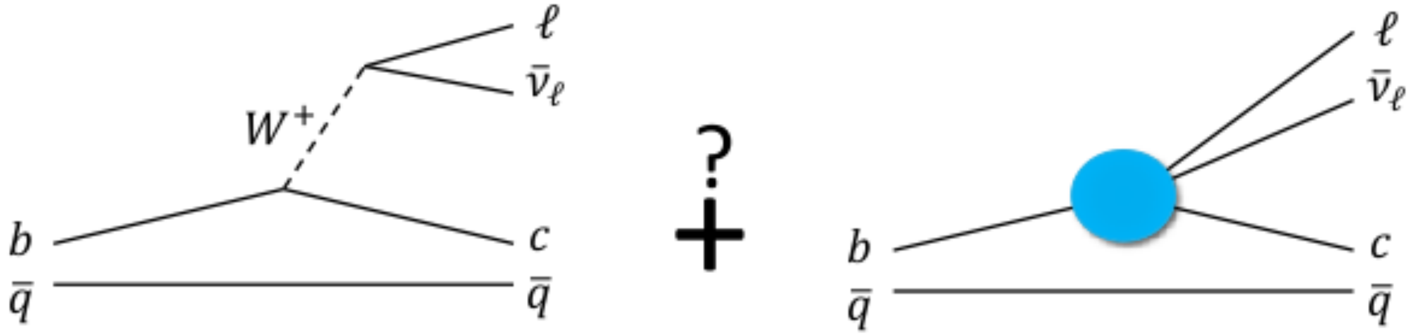


$$R_K(1 < q^2 < 6\ \text{GeV}^2) = 0.745\ ^{+0.090}_{-0.074} \pm 0.036$$

<3σ from SM but suggestive

$B \to D^{(*)}\tau\nu$

- Powerful channel to test lepton universality
  - ratios $R(D^{(*)}) = \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\mu\nu)$ could deviate from SM values, e.g. in models with charged Higgs
- Heightened interest in this area
  - anomalous results from BaBar
  - other hints of lepton universality violation, e.g. R_K



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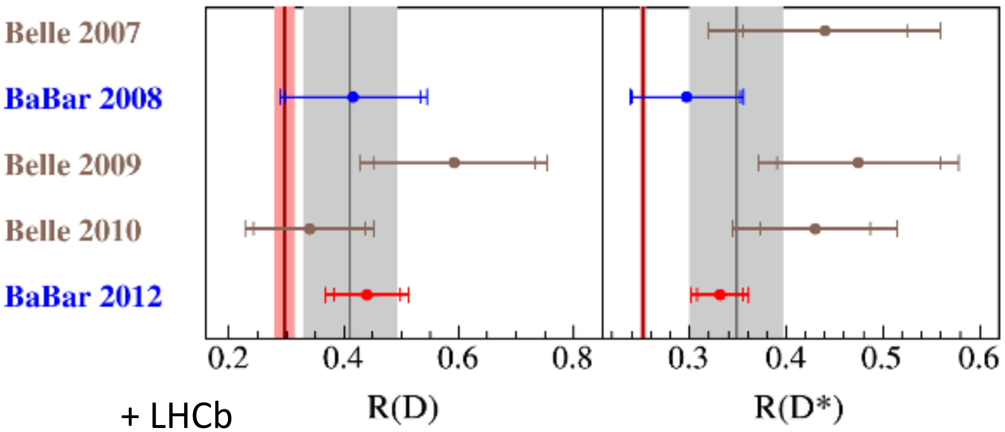
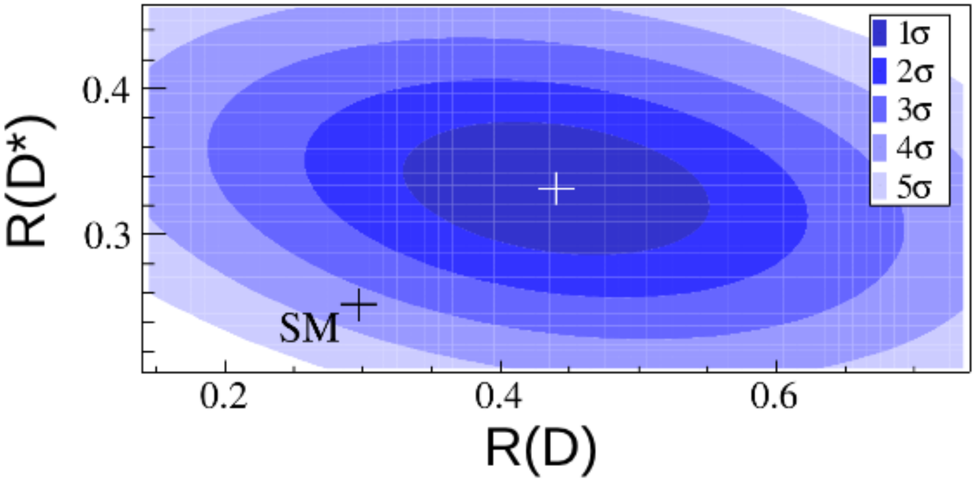
PRL 109 (2012) 101802
& PRD 88 (2013) 072012



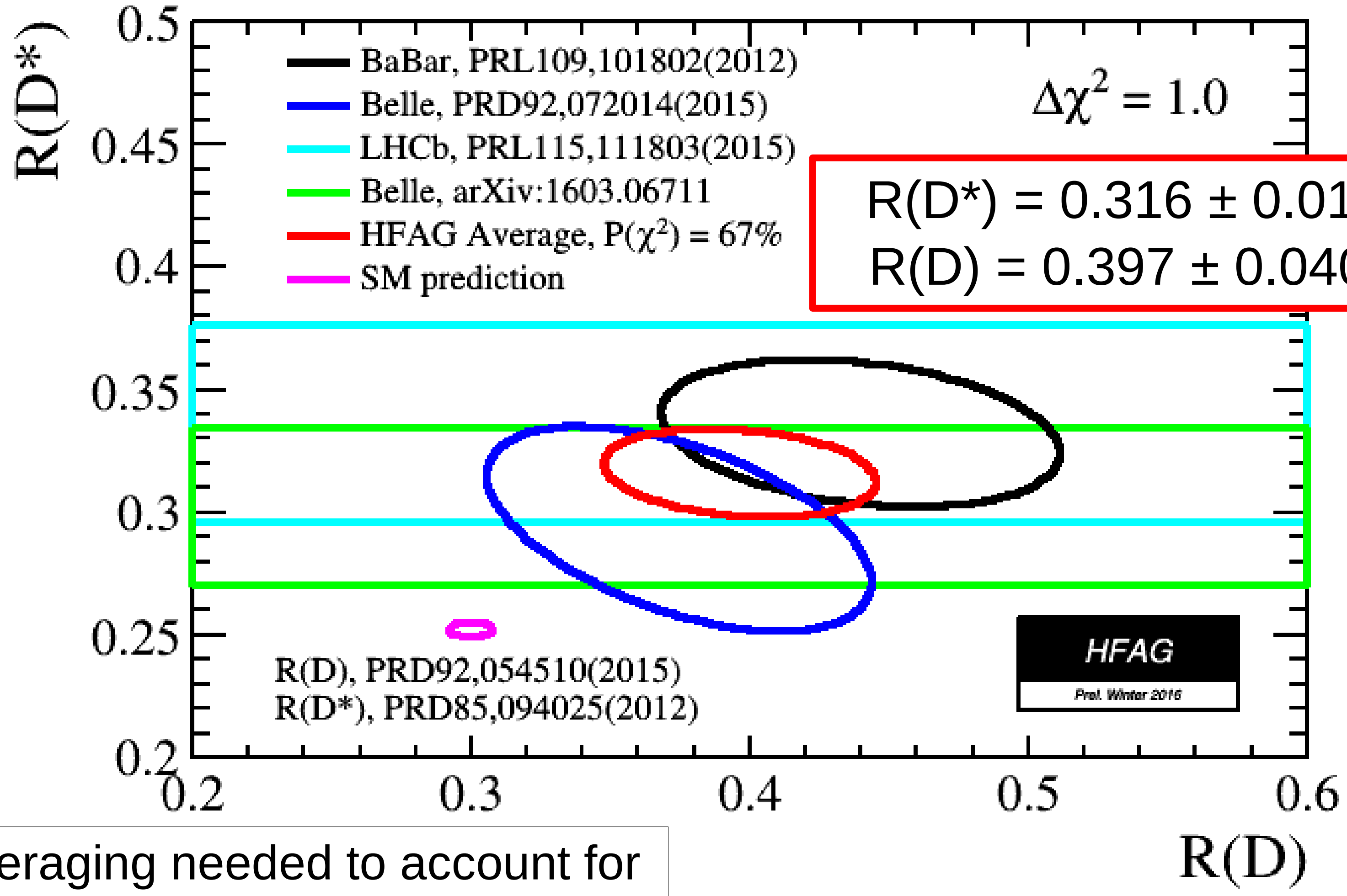
+ LHCb



R(D*) = 0.336 ± 0.027 ± 0.030

$B \rightarrow D^{(*)}\tau\nu$

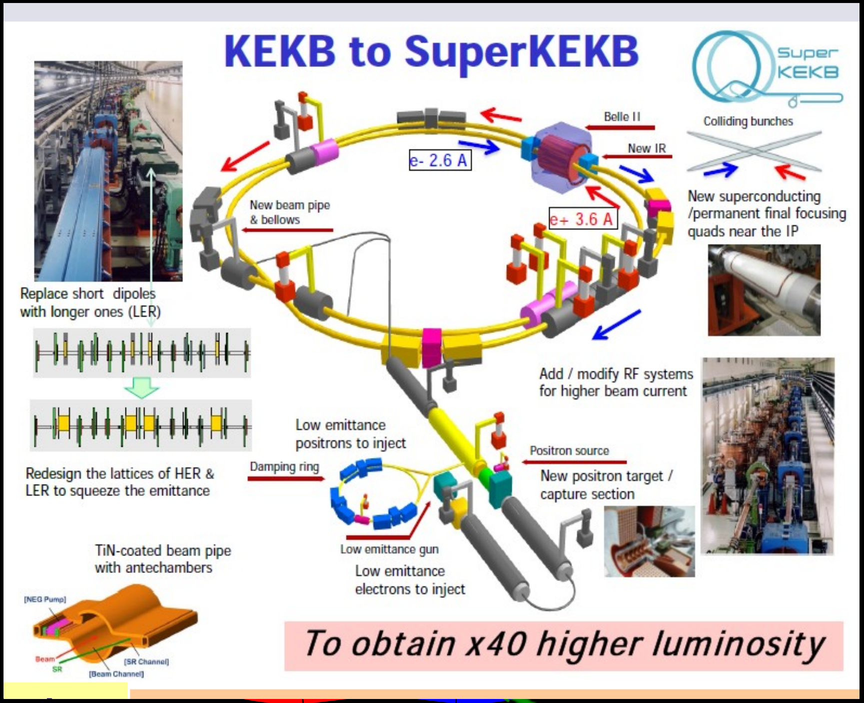
Tension with SM at 4.0σ



$R(D^*) = 0.316 \pm 0.016 \pm 0.010$
$R(D) = 0.397 \pm 0.040 \pm 0.028$

Careful averaging needed to account for statistical and systematic correlations

Future: Physics Reach Belle II & LHCb upgrade



KEKB to SuperKEKB

Belle II

New IR

Colliding bunches

e- 2.6 A

e+ 3.6 A

New beam pipe & bellows

New superconducting /permanent final focusing quads near the IP

Replace short dipoles with longer ones (LER)

Add / modify RF systems for higher beam current

Low emittance positrons to inject

Positron source

Damping ring

New positron target / capture section

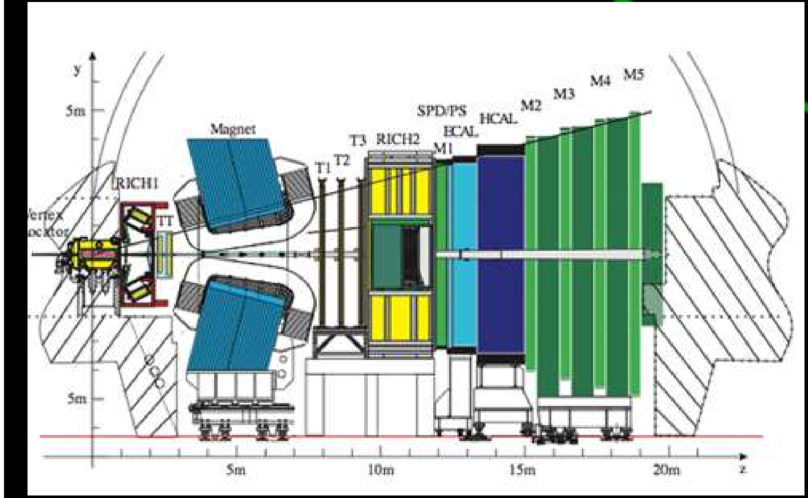
Redesign the lattices of HER & LER to squeeze the emittance

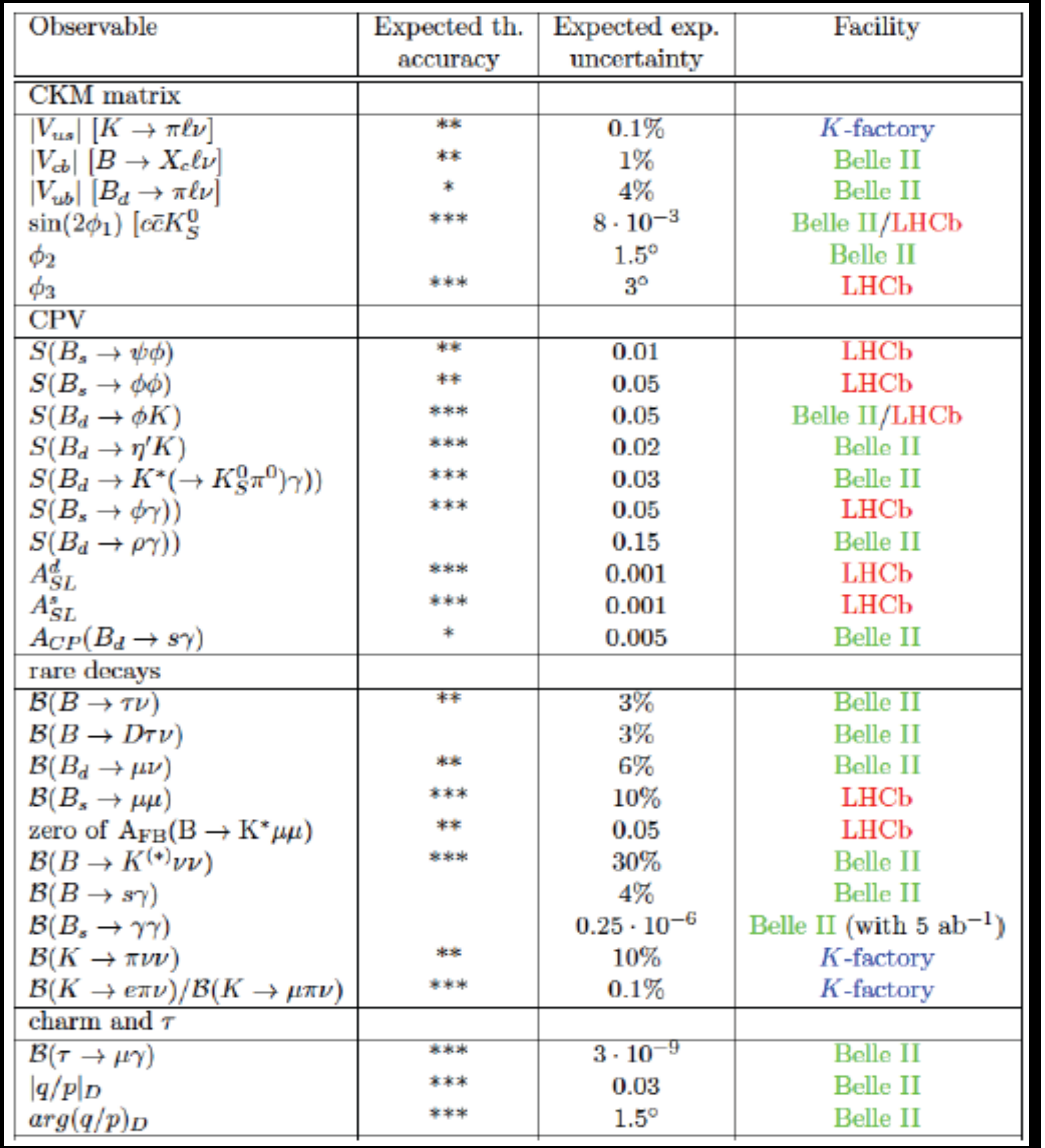
Low emittance gun

Low emittance electrons to inject

TiN-coated beam pipe with antechambers

To obtain x40 higher luminosity





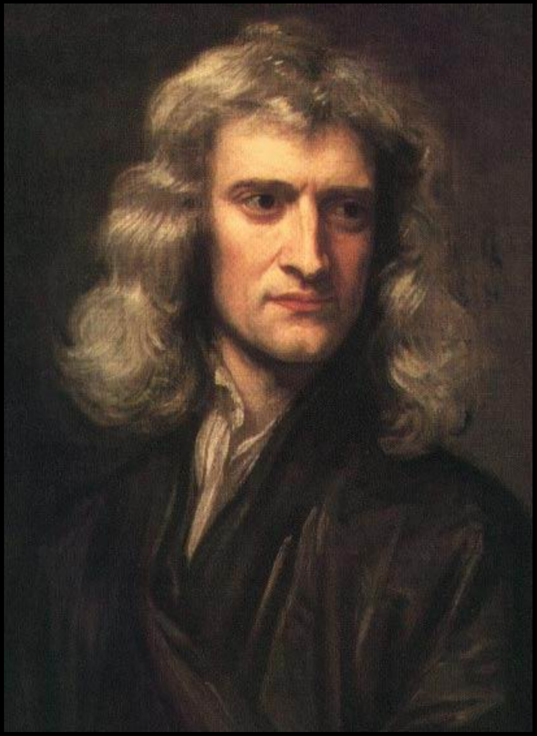
Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\lvert V_{us}\rvert$ $[K \to \pi \ell \nu]$	**	0.1%	K-factory
$\lvert V_{cb}\rvert$ $[B \to X_c \ell \nu]$	**	1%	Belle II
$\lvert V_{ub}\rvert$ $[B_d \to \pi \ell \nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K^0_S]$	***	$8 \cdot 10^{-3}$	Belle II/LHCb
ϕ_2		1.5°	Belle II
ϕ_3	***	3°	LHCb
CPV			
$S(B_s \to \psi\phi)$	**	0.01	LHCb
$S(B_s \to \phi\phi)$	**	0.05	LHCb
$S(B_d \to \phi K)$	***	0.05	Belle II/LHCb
$S(B_d \to \eta' K)$	***	0.02	Belle II
$S(B_d \to K^*(\to K^0_S\pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A^d_{SL}	***	0.001	LHCb
A^s_{SL}	***	0.001	LHCb
$A_{CP}(B_d \to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B \to \tau\nu)$	**	3%	Belle II
$\mathcal{B}(B \to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d \to \mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb
zero of $A_{FB}(B \to K^*\mu\mu)$	**	0.05	LHCb
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B \to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K \to \pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K \to e\pi\nu)/\mathcal{B}(K \to \mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\lvert q/p\rvert_D$	***	0.03	Belle II
$arg(q/p)_D$	***	1.5°	Belle II

Other future flavor experiments

- Rare kaon decays
  - $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ (NA62, CERN); $K^0 \rightarrow \pi^0 \nu\bar{\nu}$ (K0T0, J-PARC)
- Muon to electron conversion (charged lepton flavour violation)
  - COMET/PRIME (J-PARC); mu2e (FNAL)
  - also MEG upgrade & μ3e (PSI)
- Various electric & magnetic dipole experiments
  - $(g-2)_\mu$ in FNAL & J-PARC

Summary

- We still don't know:
  - why there are so many fermions in the SM
  - what causes the baryon asymmetry of the Universe
  - where exactly the new physics is …
  - … and what it's flavour structure is
- Understanding flavor is essential.
- Prospects are good for progress in the next few years
- Will have continuing programme of flavor physics into the 2020s and I hope beyond
  - complementary to the high-p_T programme of the LHC
  - Complementary to searches and studies of neutrinos, dark matter, dark energy and inflation



“What we know is a droplet, what we don’t know is an Ocean”

Sir Isaac Newton (1643-1727)

The ocean is for *your* generation to explore.
You will make great discoveries.

References and further reading

- Reviews by the Particle Data Group
  - http://pdg.lbl.gov/
- Heavy Flavour Averaging Group (HFAG)
  - http://www.slac.stanford.edu/xorg/hfag/
- CKMfitter & UTfit
  - http://ckmfitter.in2p3.fr/ & http://www.utfit.org/
- Review journals (e.g. Ann. Rev. Nucl. Part. Phys.)
  - http://nucl.annualreviews.org
- Proceedings of CKM workshops
  - Phys.Rept. 494 (2010) 197, eConf C100906
- Books
  - CP violation, I.I.Bigi and A.I.Sanda (CUP)
  - CP violation, G.C.Branco, L.Lavoura & J.P.Silva (OUP)

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