Flavour Physics: in the Standard Model and beyond

Ecole de Gif 2012

Physics at LHC

17 September - 21 September 2012, LAL Orsay, France

Tatsuya NAKADA
Laboratory for High Energy Physics (LPHE)
Swiss Federal Institute of Technology Lausanne (EPFL)
Lausanne, Switzerland

Plan of Lectures

- Direct-search versus Indirect-search
- Early History
- Standard Model Flavour Framework
- More of Weak Decay
- Current Status of V_{CKM}
- Any Sign of New Physics
- Closer Look
- Epilogue

What is on the moon?

What is on the moon?

Of course going there...

What is on the moon?

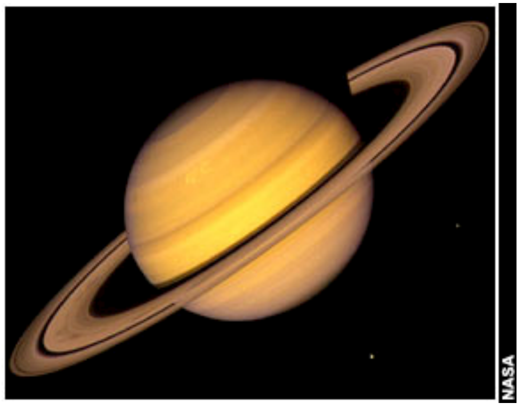
Of course going there...

But you can study a lot from here before

What is on the moon?

Of course going there…

But you can study a lot from here before



And may be finding something new?

What is on the moon?

Of course going there...

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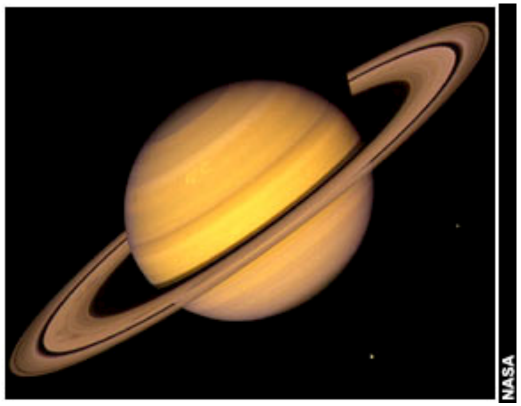


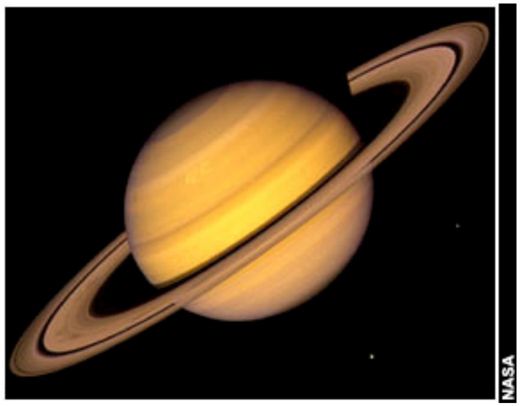
And may be finding something new?

Instruments can be improved and

What is on the moon?

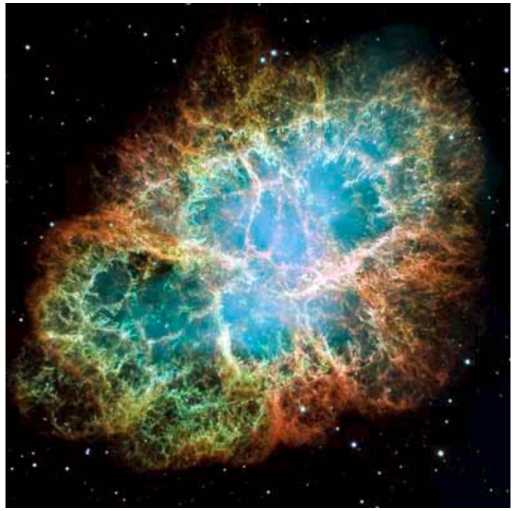
Of course going there...

But you can study a lot from here before



And may be finding something new?

Instruments can be improved and



We see far beyond the direct reach...

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Early History

Start with Isospin (Heisenberg)...

$\rightarrow$ p and n are the doublets under SU(2)

similarly π^+, π^0 and π^- are the triplets under O(3)

$\Downarrow$

p and n (or π^+, π^0 and π^-) are identical when switching off alectromagnetic interactions, i.e. nuclear forces

Early History

Start with Isospin (Heisenberg)...

$\rightarrow$ p and n are the doublets under SU(2)

similarly π^+, π^0 and π^- are the triplets under O(3)

"Strangeness" played a role in establishing the concept of flavour quantum numbers (Gell-Mann 56, Nishijima 55)

$\Downarrow$

Response to the discovery of long living particles (1947)
selection rule based on a quantum number which is
conserved in strong and electromagnetic interactions
but not conserved in weak interactions

Early History

Start with Isospin (Heisenberg)...

→ p and n are the doublets under SU(2)

similarly π^+, π^0 and π^- are the triplets under O(3)

"Strangeness" played a role in establishing the concept of flavour quantum numbers

(Gell-Mann 56, Nishijima 55)

"quark" in early 1960's

(Gell-Mann, Ne'eman, Han-Nambu, Nishijima, Sakata, Zweig, etc.)

SU(3) flavour symmetry: (u, d, s)

⇓

Responding to the particle zoo, in particular the hyperons

Early History

Start

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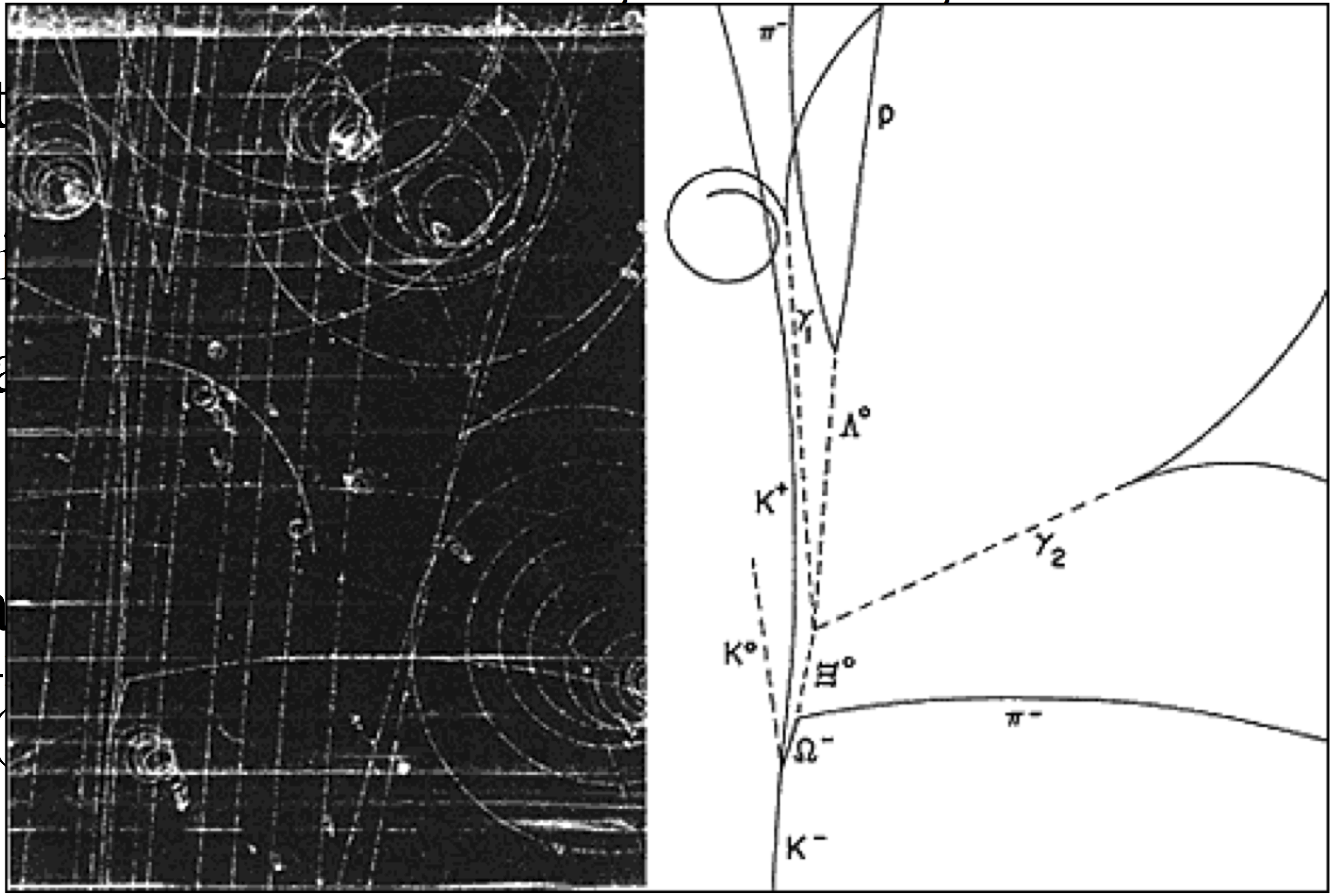

→Ω^- (sss) prediction,

discovered in 1964, Barmes et al.

Early History

Start with Isospin (Heisenberg)...

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the concept of flavour quantum numbers

(Gell-Mann 56, Nishijima 55)

"quark" in early 1960's

(Gell-Mann, Ne'eman, Han-Nambu, Nishijima, Sakata, Zweig, etc.)

SU(3) flavour symmetry: (u, d, s)

My private reflection

Colour was needed for the constituent quark model:

Δ^{++}(Q=+2, Spin 3/2 baron) = (u↑, u↑, u↑).

We know now: the spin of baryon is given little by the valence quark…?

Early History

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing:

PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

Behavior of Neutral Particles under Charge Conjugation

M. GELL-MANN,* *Department of Physics, Columbia University, New York, New York*

AND

A. PAIS, *Institute for Advanced Study, Princeton, New Jersey*

(Received November 1, 1954)

Some properties are discussed of the θ^0, a heavy boson that is known to decay by the process $\theta^0 \to \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and K particles, the θ^0 possesses an antiparticle $\bar{\theta}^0$ distinct from itself. Some theoretical implications of this situation are discussed with special reference to charge conjugation invariance. The application of such invariance in familiar instances is surveyed in Sec. I. It is then shown in Sec. II that, within the framework of the tentative schemes under consideration, the θ^0 must be considered as a "particle mixture" exhibiting two distinct lifetimes, that each lifetime is associated with a different set of decay modes, and that no more than half of all θ^0's undergo the familiar decay into two pions. Some experimental consequences of this picture are mentioned.

$$K^0 \leftrightarrow \pi^+\pi^- \leftrightarrow \overline{K}^0 \Longrightarrow \quad K_1 = \frac{K^0 + \overline{K}^0}{\sqrt{2}}, \quad K_2 = \frac{K^0 - \overline{K}^0}{\sqrt{2}}$$

under C symmetry, K_1 and K_2 two very different lifetimes

Why?

(later $\not{C}$ discovered → change to CP conservation)

Early History

Observation of Long-Lived Neutral *V* Particles*

Phys Rev Lett. 1956

K. LANDE, E. T. BOOTH, J. IMPEDUGLIA, AND L. M. LEDERMAN,
Columbia University, New York, New York

AND

W. CHINOWSKY, *Brookhaven National Laboratory, Upton, New York*

(Received July 30, 1956)

cloud chamber exposure at BNL

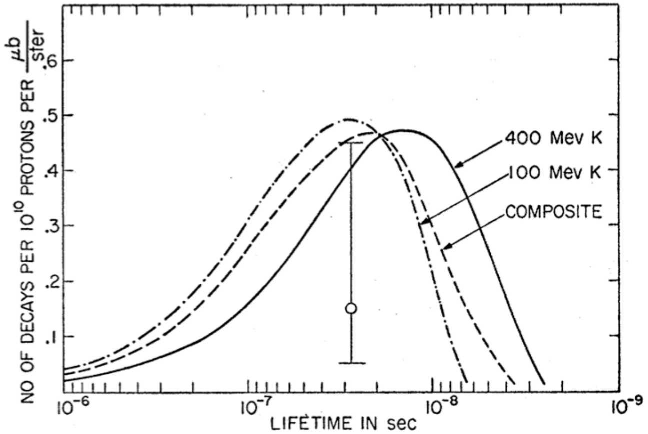

FIG. 2. Detection sensitivity for *K* mesons as function of lifetime. The composite curve is obtained with the spectra of reference 5. The point indicates the observed yield with a production cross section of $\sim 20\ \mu$b/sterad.

lifetime for $\pi^+\pi^-$ decay already known to be $\sim 10^{-10}$ sec

lifetime measurement for 3-body decays ($\pi\mu\nu$, $\pi e\nu$, $\pi^+\pi^-\pi^0$) $>10^{-9}$ sec

Establish two particle states: short-living, K_S, decays into 2π and long-living, K_L, decays into 3π, $\pi l\nu$: $K^0 - \overline{K}^0$ mixing

Early History

Phys Rev Lett. 1956

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K. Lande, E. T. Booth, J. Impeduglia, and L. M. Lederman,
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This seemed to have triggered the idea of ν-$\bar{\nu}$ mixing (not the ν flavour mixing) by Pontecorvo in 1957

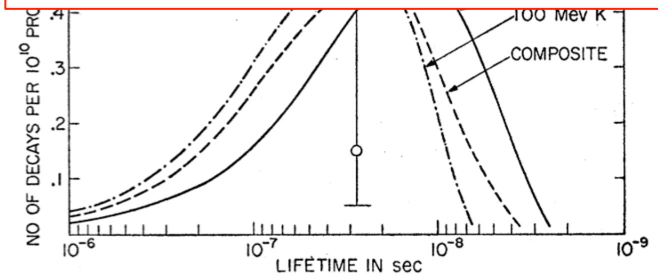

Fig. 2. Detection sensitivity for *K* mesons as function of lifetime. The composite curve is obtained with the spectra of reference 5. The point indicates the observed yield with a production cross section of ~20 μb/sterad.

lifetime measurement for 3-body decays ($\pi\mu\nu$, $\pi e\nu$, $\pi^+\pi^-\pi^0$) $>10^{-9}$ sec

Establish two particle states: short-living, K_S, decays into 2π and long-living, K_L, decays into 3π, $\pi l\nu$: K^0–$\overline{K}^0$ mixing

Early History

Cabibbo theory (Phys. Rev. Let. 1963)

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

Why ΔS=1 decay process is suppressed?
e.g. $\Gamma(K \rightarrow \mu\nu) << \Gamma(\pi \rightarrow \mu\nu)$ after correcting the phase space

$\Downarrow$

Weak interaction charged current (ΔQ=1)

$J\mu = \cos\theta \times j_\mu(\Delta S=0) + \sin\theta \times j_\mu(\Delta S=1)$

θ: Cabibbo angle

(unitary through $\cos^2\theta + \sin^2\theta = 1$)

Early History

Cabibbo theory (Phys. Rev. Let. 1963)

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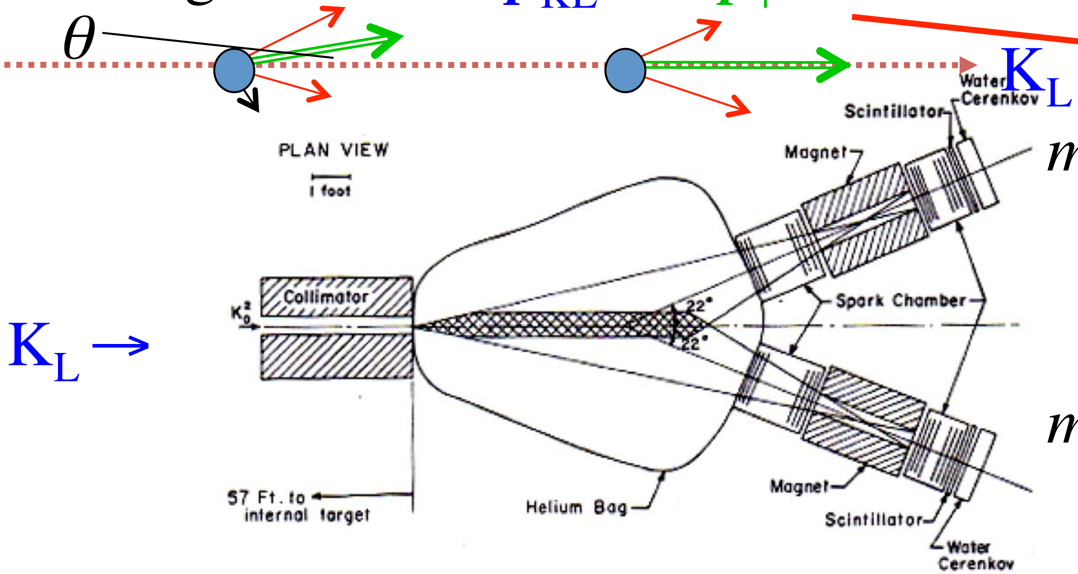
CP violating $K^0_L \to \pi^+\pi^-$ decays: 1964, J.H. Christenson et al.

$\boldsymbol{p}_{+-} = \boldsymbol{p}_{\pi+} + \boldsymbol{p}_{\pi-}$

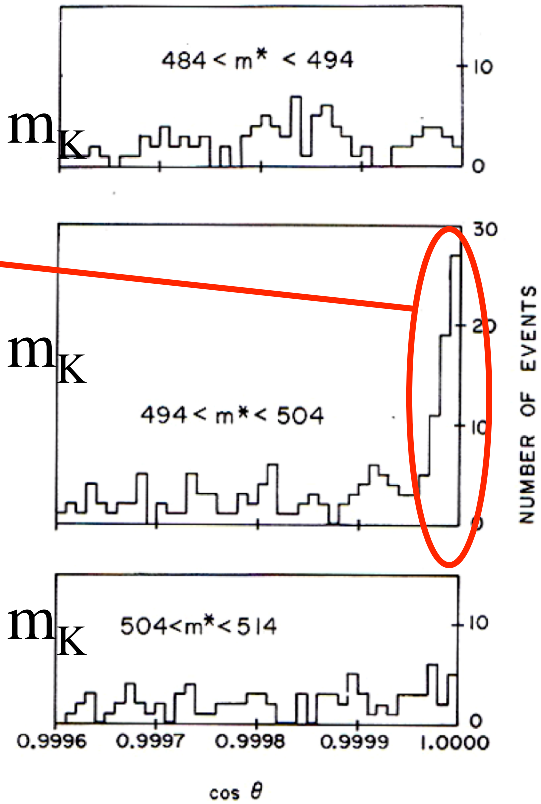
θ = angle between $\boldsymbol{p}_{KL}$ and $\boldsymbol{p}_{+-}$



$m(\pi^+\pi^-) < m_K$

$m(\pi^+\pi^-) = m_K$

$m(\pi^+\pi^-) > m_K$



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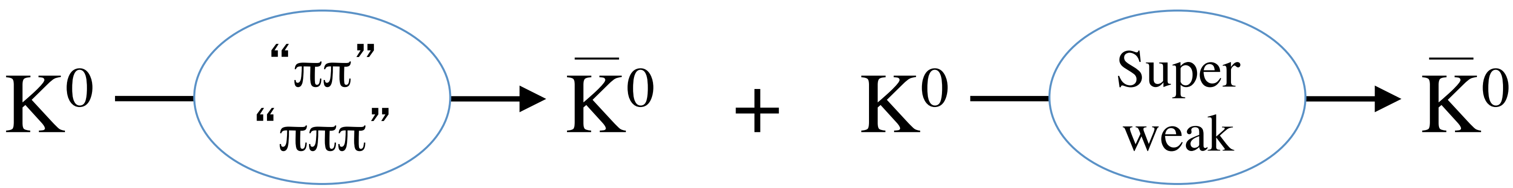
CP violating $K^0_L \rightarrow \pi^+\pi^-$ decays: 1964, J.H. Christenson et al.

This was beyond the comprehension of that time and no relation between the flavour considered:

e.g. Superweak model (Phys. Rev. Let. 1964)

VIOLATION OF *CP* INVARIANCE AND THE POSSIBILITY OF VERY WEAK INTERACTIONS*

L. Wolfenstein
Carnegie Institute of Technology, Pittsburgh, Pennsylvania
(Received 31 August 1964)



Early History

Glashow–Iliopoulos–Maiani mechanism (Phys Rev D 1970)

Why Δm_K is so small and $K_L \rightarrow \mu^+\mu^-$ very suppressed?

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

Early History

Glashow–Iliopoulos–Maiani mechanism (Phys Rev D 1970)

Why Δm_K is so small and $K_L \to \mu^+\mu^-$ very suppressed?

Having 4th quark already considered in ~1964 (even with the name "charm")
(Gell-Mann, Tarjanne and Teplitz, Hara, Bjørken and Glashow,)
ν_μ discovered in 1962, Lederman, Schwartz and Steinberger,

$$\begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} c \\ s' \end{pmatrix} \begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

$$d' = d\cos\theta + s\sin\theta$$

$$s' = -d\sin\theta + s\cos\theta$$

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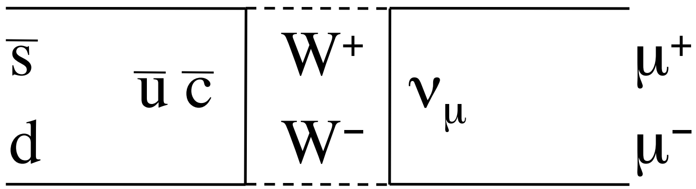
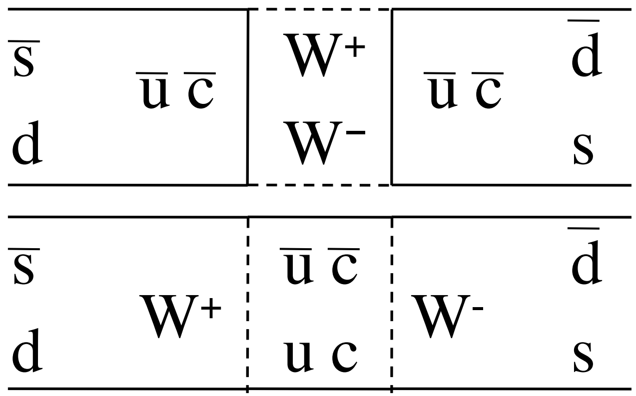




$$Br(K^0 \to \mu^+\mu^-) = F(m_c, \ldots) \qquad \Delta m_K = G(m_c, \ldots)$$

$$\text{if } m_c = m_u, \propto \sin\theta\cos\theta - \sin\theta\cos\theta = 0$$

Early History

Glashow–Iliopoulos–Maiani mechanism (Phys Rev D 1970)

Why Δm_K is so small and $K_L \to \mu^+\mu^-$ very suppressed?

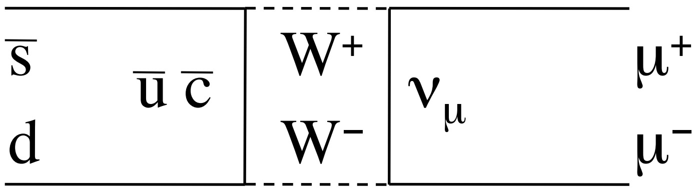
Estimation of $m_c \sim 1.5$ GeV (Gaillard and Lee, Phys Rev D 1974)

$K_L \to \mu^+\mu^-$ suppressed

$K_L \to \gamma\gamma$ not suppressed

$\Delta m_K = m_L - m_S$ experimentally measured

$$d' = d\cos\theta + s\sin\theta$$
$$s' = -d\sin\theta + s\cos\theta$$



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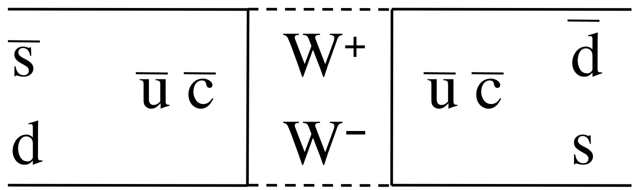

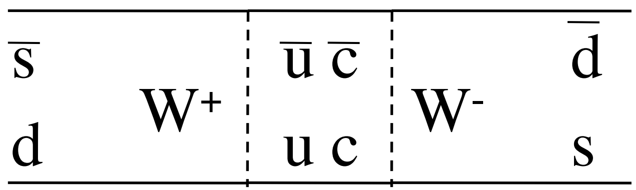

$$\Delta m_K = G(m_c, \ldots)$$

Early History

echanism (Phys Rev D 1970)

μ^- very suppressed?

l and Lee, Phys Rev D 1974)

Experimental Observation of a Heavy Particle J†

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

and

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

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

Charm discovery with hadron and e^+e^- machines

Aubert et al. and Augustin et al., 1974

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

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

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

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

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Aubert et al. and Augustin et al., 1974

Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

Institute for Nuclear Study University of Tokyo

**Yokohama National University*

August 9, 1971

Emulsion exposed in a JAL Jet cargo plane

One event of $X \rightarrow \pi^0$ + one charged hadron

hypo.	$\pi^0\pi^{charged}$	$\pi^0 p$
τ(s)	2.2×10^{-14}	3.6×10^{-14}
m(GeV)	1.78	2.95

Observation of $D\rightarrow K\pi^0$ decay in 1971?

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Third quark family (Kobayashi and Maskawa, Prog. Theor. Phys. 1973)

naturally introduces
CP violation
in weak interactions

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

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Flavour framework of the Standard Model established

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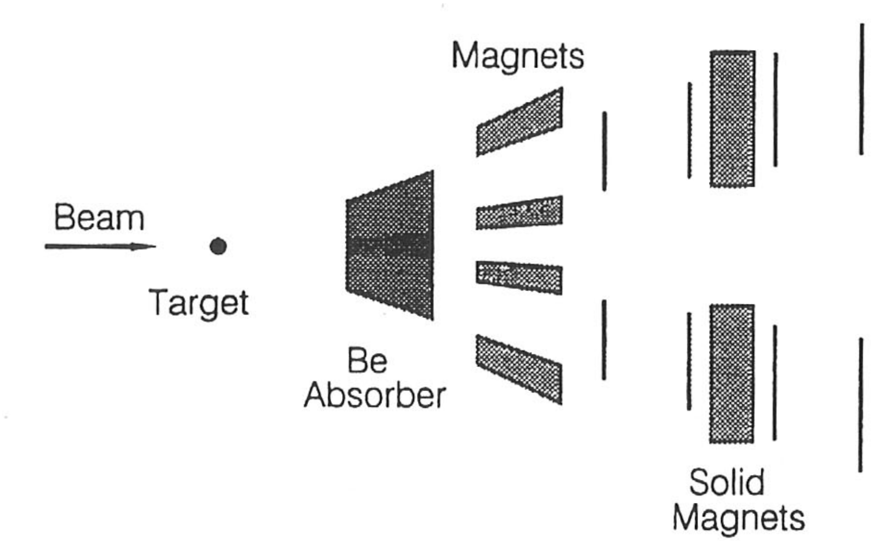
Flavour framework of the Standard Model established

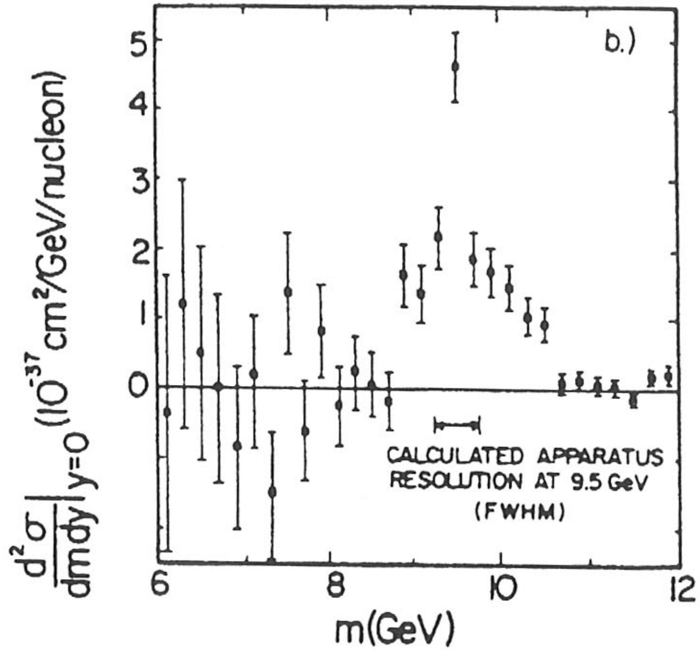
And b quark discovered in 1977

Early History

E288 experiment @ FNAL, S. Herb et al. in 1977

p(400 GeV) + Cu or Pt → $\Upsilon(\rightarrow \mu^+ \mu^-)$ + X





$(b\bar{b})$ bound states; $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

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Standard Model Flavour Framework

flavour eigenstatetates	⇒	masseigenstates
-non-diagonal mass matrix		-diagonal mass matrix
-strong and EM interactions		-weak interactions
-flavour conservation		-flavour changing

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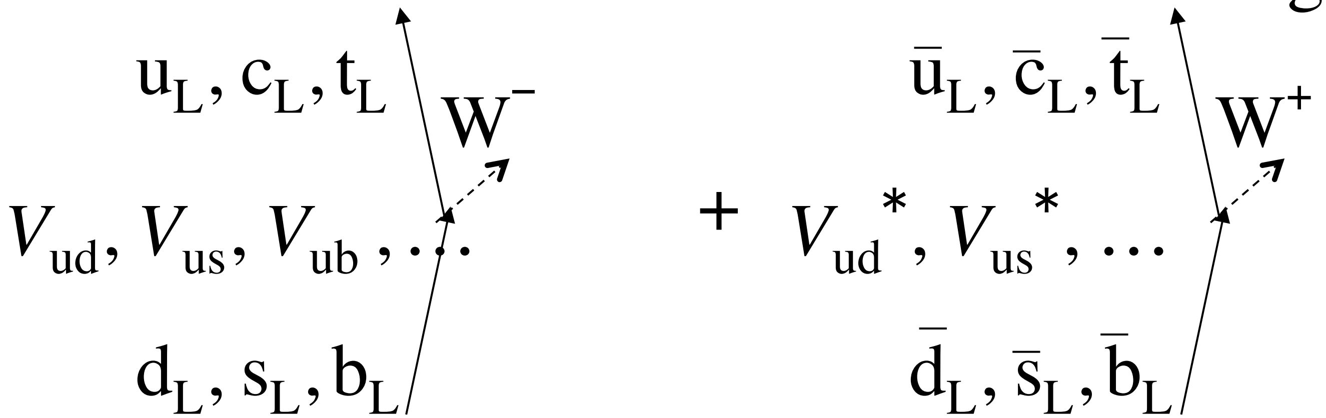

$$L \propto V_{ij}\, \overline{U}_i\, \gamma^\mu(1-\gamma_5)\, D_j\, W_\mu^\dagger + V_{ij}^*\, \overline{D}_i\, \gamma^\mu(1-\gamma_5)\, U_j\, W_\mu$$

Standard Model Flavour Framework

flavour eigenstatetates	$\Rightarrow$	masseigenstates
-non-diagonal mass matrix		-diagonal mass matrix
-strong and EM interactions		-weak interactions
-flavour conservation		-flavour changing

u_L, c_L, t_L W^- $V_{ud}, V_{us}, V_{ub}, \ldots$ d_L, s_L, b_L $+$ $\bar{u}_L, \bar{c}_L, \bar{t}_L$ W^+ $V_{ud}^*, V_{us}^*, \ldots$ $\bar{d}_L, \bar{s}_L, \bar{b}_L$

$$L \propto V_{ij}\, \bar{U}_i\, \gamma^\mu(1-\gamma_5)\, D_j\, W_\mu^\dagger + V_{ij}^*\, \bar{D}_i\, \gamma^\mu(1-\gamma_5)\, U_j\, W_\mu$$

$\Updownarrow$ CP conjugation

$$L_{CP} \propto V_{ij}\, \bar{D}_i\, \gamma^\mu(1-\gamma_5)\, U_j\, W_\mu + V_{ij}^*\, \bar{U}_i\, \gamma^\mu(1-\gamma_5)\, D_j\, W_\mu^\dagger$$

Standard Model Flavour Framework

flavour eigenstatetates	⇒	masseigenstates
-non-diagonal mass matrix		-diagonal mass matrix
-strong and EM interactions		-weak interactions
-flavour conservation		-flavour changing

u_L, c_L, t_L — W^- — $V_{ud}, V_{us}, V_{ub}, \ldots$ — d_L, s_L, b_L

$+$ $\bar{u}_L, \bar{c}_L, \bar{t}_L$ — W^+ — $V_{ud}^*, V_{us}^*, \ldots$ — $\bar{d}_L, \bar{s}_L, \bar{b}_L$

$$L \propto V_{ij}\, \bar{U}_i\, \gamma^\mu (1-\gamma_5)\, D_j\, W_\mu^\dagger + V_{ij}^*\, \bar{D}_i\, \gamma^\mu (1-\gamma_5)\, U_j\, W_\mu$$

⇕ CP conjugation

$$L_{CP} \propto V_{ij}\, \bar{D}_i\, \gamma^\mu (1-\gamma_5)\, U_j\, W_\mu + V_{ij}^*\, \bar{U}_i\, \gamma^\mu (1-\gamma_5)\, D_j\, W_\mu^\dagger$$

If $V_{ij}^* = V_{ij} \rightarrow L = L_{CP}$: i.e. CP conservation

Standard Model Flavour Framework

flavour eigenstatetates ⇒ masseigenstates

flavour eigenstatetates	⇒	masseigenstates
-non-diagonal mass matrix		-diagonal mass matrix
-strong and EM interactions		-weak interactions
-flavour conservation		-flavour changing

V_{CKM}: generally called CKM (mass mixing) matrix

$$V_{\mathrm{CKM}}^{\dagger} \times V_{\mathrm{CKM}} = 1$$

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

Standard Model Flavour Framework

flavour eigenstatetates	$\Rightarrow$	masseigenstates
-non-diagonal mass matrix		-diagonal mass matrix
-strong and EM interactions		-weak interactions
-flavour conservation		-flavour changing

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \sim\lambda & ? \\ \sim -\lambda & 1-\frac{\lambda^2}{2} & ? \\ ? & ? & ? \end{pmatrix}$$

$$\lambda = \sin\,\theta_{Cabibbo} \approx 0.22$$

V_{CKM}: generally called CKM (mass mixing) matrix

$$V^{\dagger}_{CKM} \times V_{CKM} = 1$$

Can you show this explicitly by using the arbitrary quark phases and unitarity?

Pre KM, V_{CKM} was 2×2

With 2×2 unitary matrix, one angle (1-2 rotation)

Standard Model Flavour Framework

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$$V^{\dagger}_{\mathrm{CKM}} \times V_{\mathrm{CKM}} = 1$$

Pre KM, V_{CKM} was 2×2

With 2×2 unitary matrix, one angle (1-2 rotation)

With 3×3 matrix, three angles (1-2, 2-3, 1-3 rotations) and one phase

⇒ with three families, some of V_{ij}'s are intrinsically complex

Standard Model Flavour Framework

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$$\hat{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right),\ \hat{\eta} = \rho\left(1-\frac{\eta^2}{2}\right)$$

λ, A, ρ, η: Wolfenstein's parameterization

Approximation with expansions in λ

NB $A \neq 0$, $\rho \neq 0$, $\eta \neq 0$ for CP violation

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$$\hat{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right),\ \hat{\eta} = \rho\left(1-\frac{\eta^2}{2}\right)$$

JADE Physics Letters B 1983

$\tau < 1.4\times10^{-12}$ s (95% CL)

Theoretical predictions e.g. V. Barger et al.

$0.8\times10^{-14} < \tau < 1.4\times10^{-13}$ sec, J. Phys. G 5, L147 (1979)

i.e. general prejudice was $|V_{cb}| \approx |V_{us}|$

Standard Model Flavour Framework

MAC

Phys. Rev. Lett. 51, (1983) 1022

Lifetime of Particles Containing *b* Quarks

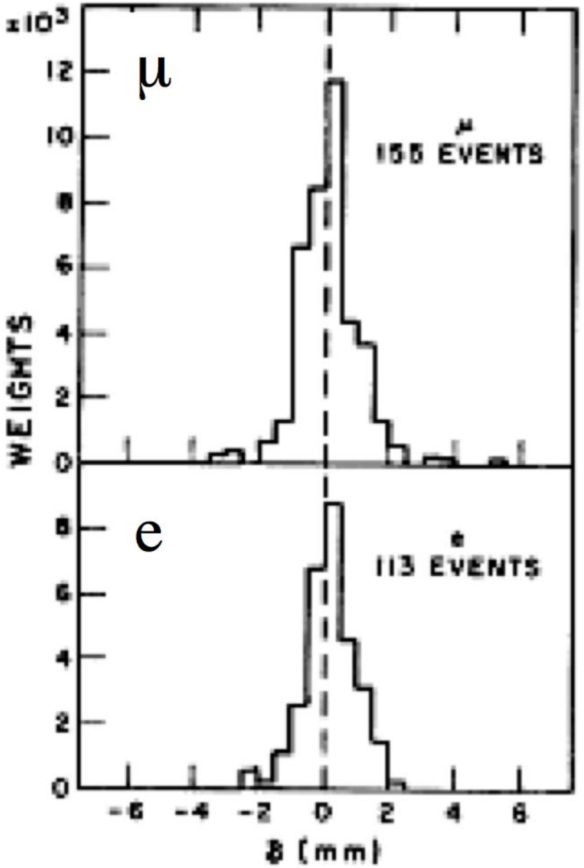
$[1.8\pm0.6(\text{stat.})\pm0.4(\text{syst.})]\times10^{-12}$ sec.

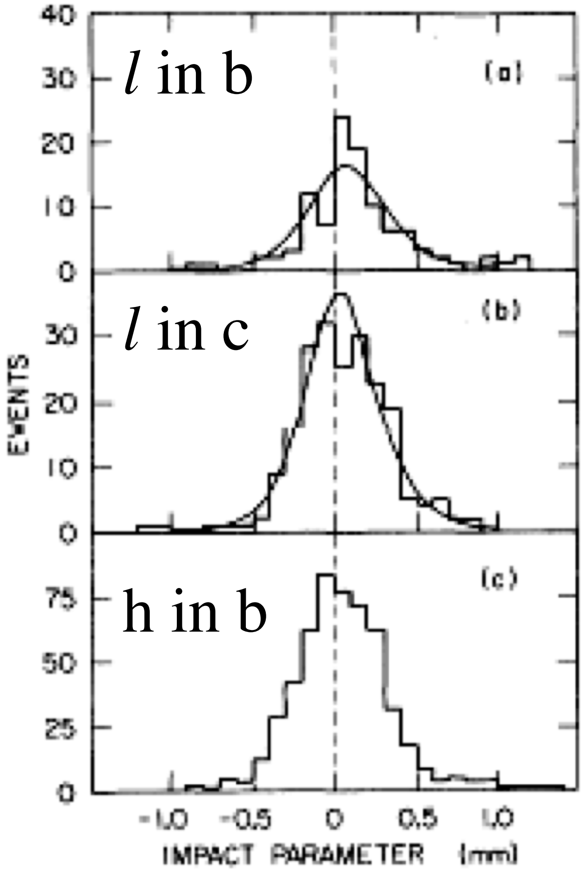
Mark II

Phys. Rev. Lett. 51, (1983) 1316

Measurement of the Lifetime of Bottom Hadrons

$\tau_b=(12.0^{+4.5}_{-3.6}\pm3.0)\times10^{-13}$ sec





Standard Model Flavour Framework

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$$\hat{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right),\ \hat{\eta} = \eta\left(1-\frac{\lambda^2}{2}\right)$$

discovery of large b lifetime, i.e. small $|V_{\mathrm{cb}}|$

MAC: Phys. Rev. Lett. 51, (1983) 1022
Mark II: Phys. Rev. Lett. 51, (1983) 1316

$\tau_B \sim 10^{-12}$ sec, $|V_{\mathrm{cb}}| \sim 0.05$,
i.e. << $\sin\theta_{\mathrm{Cabibbo}} \sim 0.2$

Standard Model Flavour Framework

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$$\lambda = \sin\,\theta_{\mathrm{Cabibbo}} \approx 0.22$$

$$A \approx 0.8$$

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Standard Model Flavour Framework

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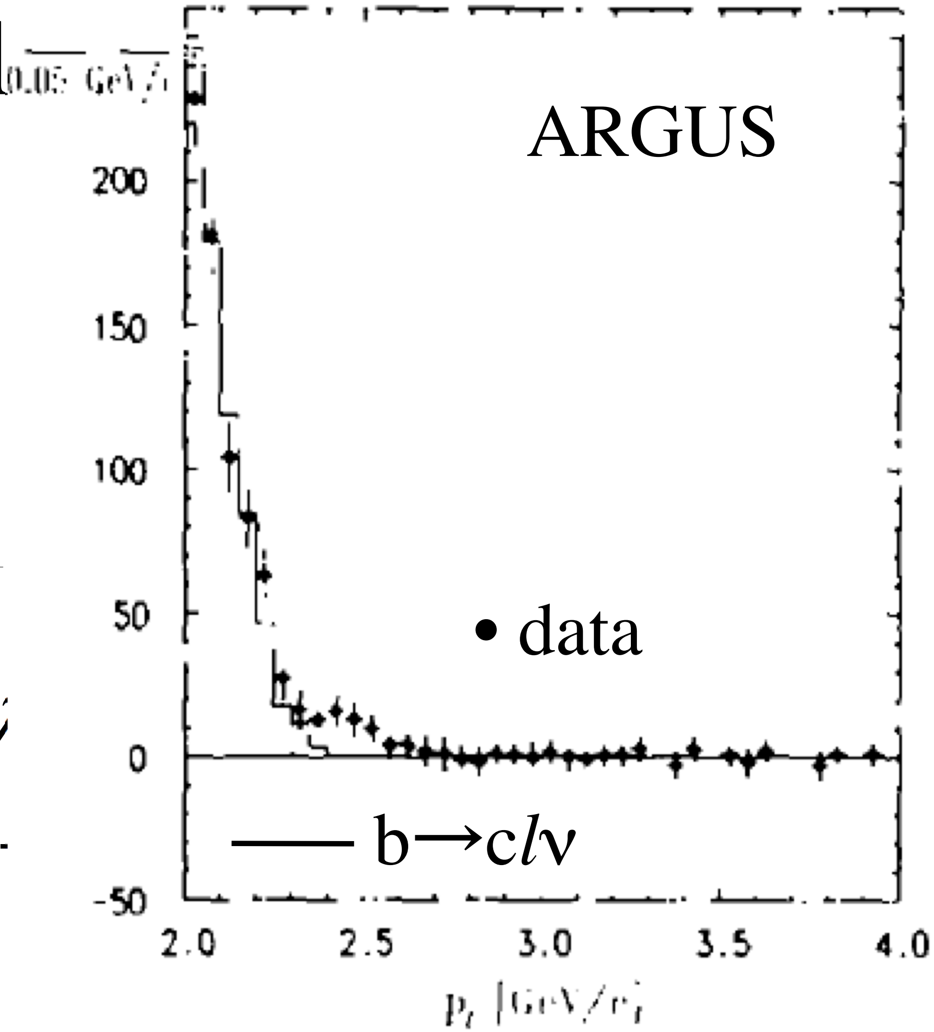
Observation of b $\rightarrow$ u$l\nu$ decays: $|V_{\mathrm{ub}}| \neq 0$

(cf. like θ_{13} in ν now)

Standard Model Fl

flavour eigenstatetates
-non-diagonal mass matrix
-strong and EM interactions
-flavour conservation



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$\lambda = \sin\,\theta_{\mathrm{Cabibbo}} \approx 0.22$

$A \approx 0.8$

Observation of b → ulν decays: $|V_{ub}| \neq 0$

$|\boldsymbol{p}_l| = 2.4 - 2.6$ GeV/c in the B rest frame

$|V_{ub}|$ is very small ≈ 0.005

$= 76 \pm 18 \pm 8$ in 2.4-2.6 GeV/c CLEO 1990

$= 49 - (18.2 \pm 3.3)_{\mathrm{background}}$ ARGUS 1990

Standard Model Flavour Framework

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$$\lambda = \sin\,\theta_{\mathrm{Cabibbo}} \approx 0.22$$

$$A \approx 0.8$$

$$\rho^2 + \eta^2 \approx 0.3$$

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$A \approx 0.8$

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Observation of B^0-$\overline{B}^0$ oscillations: $|V_{\mathrm{td}}| \neq 0$

Standard Model Flavour Framework

Phys. Lett. B 192 (1987) 245

ARGUS, 1987

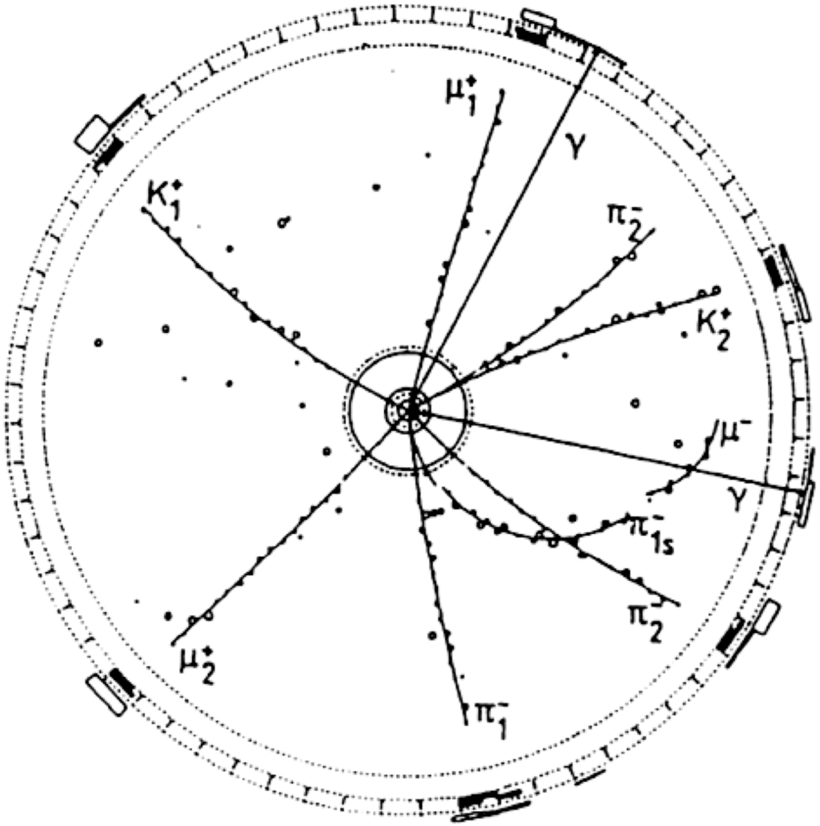
$\Upsilon(4S) \rightarrow B_d^0 \overline{B}_d^0$

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

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

24.8±7.6±3.8

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



Volume 192, number 1,2 PHYSICS LETTERS B

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

Using the ARGUS detector at the DORIS II storage ring we have searched in three different ways for B^0–$\bar{B}^0$ mixing in Υ(4S) decays. One explicitly mixed event, a decay Υ(4S)$\rightarrow B^0B^0$, has been completely reconstructed. Furthermore, we observe a 4.0 standard deviation signal of 24.8 events with like-sign lepton pairs and a 3.0 standard deviation signal of 4.1 events containing one reconstructed $B^0(\bar{B}^0)$ and an additional fast $\ell^+(\ell^-)$. This leads to the conclusion that B^0–$\bar{B}^0$ mixing is substantial. For the mixing parameter we obtain $r = 0.21 \pm 0.08$.

Standard Model Flavour Framework

Phys. Lett. B 192 (1987) 245

ARGUS, 1987

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

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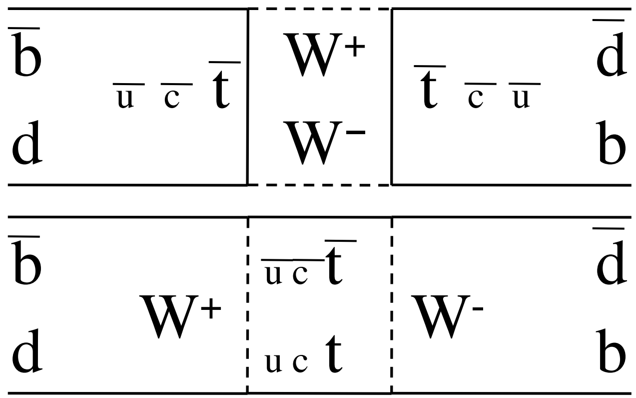

$$\Delta m_B = G(|V_{td}V_{tb}|, m_t, \ldots)$$

Volume 192, number 1,2 PHYSICS LETTERS B 25 June 1987

$m_t > 50$ GeV/c^2

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Phys. Lett. B 192 (1987) 245

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Volume 192, number 1,2 PHYSICS LETTERS B 25 June 1987

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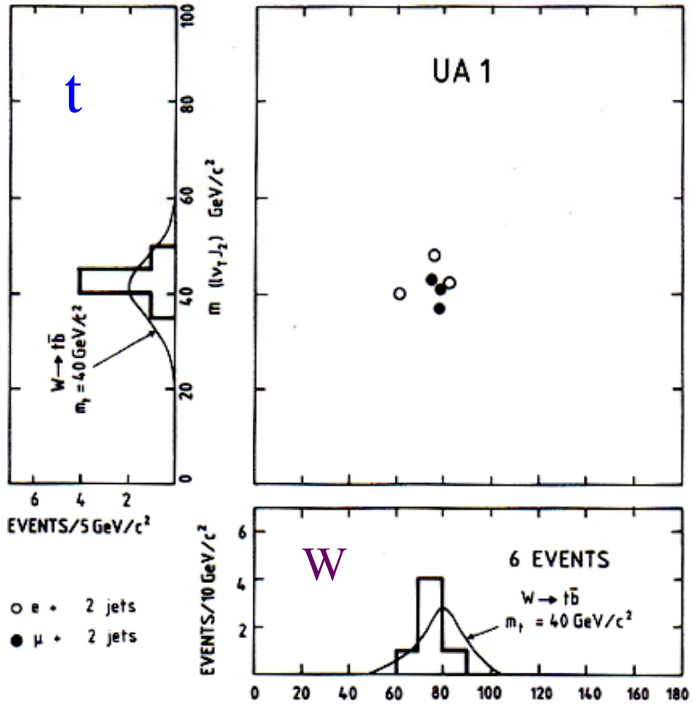
UA1, 1984

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

$\quad \llcorner\!\rightarrow W^+ \rightarrow t\,\bar{b}$ ($\bar{b} \rightarrow$ jet)

$\qquad \llcorner\!\rightarrow b\ell\nu$ ($b \rightarrow$ jet)

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



Phys. Lett. 147B (1984) 493

Standard Model Flavour Framework

Phys. Lett. B 192 (1987) 245

ARGUS, 1987

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LEP
electroweak fit
150~210 GeV/c^2

1995
CDF
175±8±10 GeV/c^2
D0
199^{+19}_{-21}±22 GeV/c^2

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My private reflection:
With Δm_{d} and ε_{K} (CPV in K-$\overline{\mathrm{K}}$ oscillation), CPV in $\mathrm{B_d} \rightarrow \mathrm{J}/\psi \mathrm{K_S}$ could be predicted without m_{t} mass, which was still unknown at that time.
Uncertainty was due to hadronic parameters: $\mathrm{B_d f_d^2 / B_K}$.
This provided a benchmark *L* for B-factories under consideration.

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$(1 - \hat{\rho})^2 + \hat{\eta}^2 \approx 0.9$

It shows clearly $\eta \neq 0$, i.e. CPV!

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$b \rightarrow s\gamma$ decays and B_s^0-$\overline{B}_s^0$ oscillations for $|V_{ts}|$

Plan of Lectures

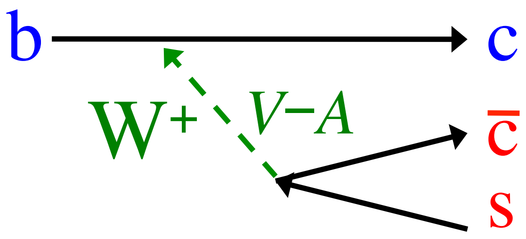
- Direct-search versus Indirect-search
- Early History
- Standard Model Flavour Framework
- More of Weak Decay
- Current Status of V_{CKM}
- Any Sign of New Physics
- Closer Look
- Epilogue

More on Weak Decays

decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

quark decay

$b \rightarrow c + W^-(\rightarrow \bar{c}s)$



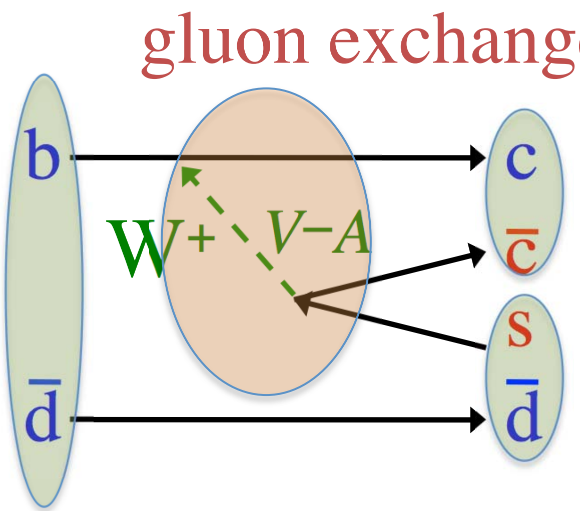
More on Weak Decays

decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

quark decay to hadron decay

$B \rightarrow J/\psi K_S$

starts from a b-$\bar{d}$ bound state



quarks have to form hadrons

More on Weak Decays

decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

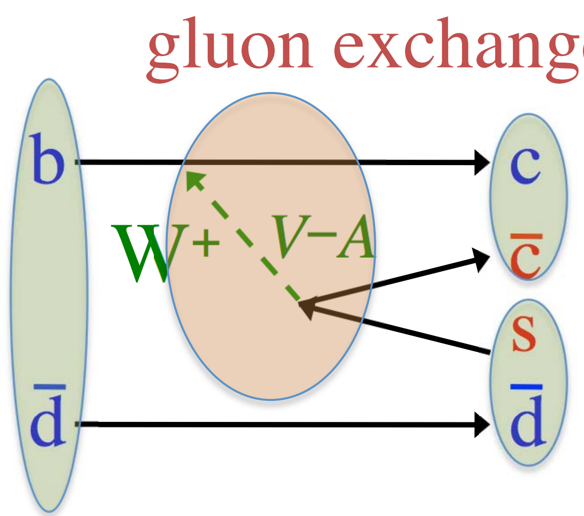
Theoretical tool to describe the decay amplitude for M→F

$$A(M \to F) = \left\langle F \middle| H^{\text{weak decay}}_{\text{effective}} \middle| M \right\rangle = \frac{G_F}{\sqrt{2}} \sum_i \xi^i_{\text{CKM}} C_i(\mu) \langle F | Q_i(\mu) | M \rangle$$

Q_i: quark operators

$B \to J/\psi K_S$

starts from a b-$\bar{d}$ bound state

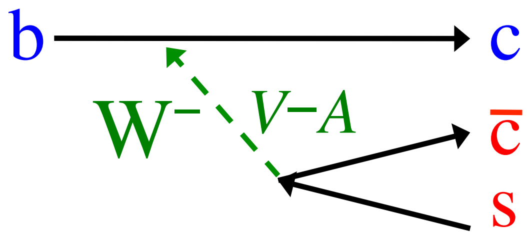


quarks have to form hadrons

More on Weak Decays

decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

lowest order weak interactions ($\Delta F = 1$)



No QCD

More on Weak Decays

decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

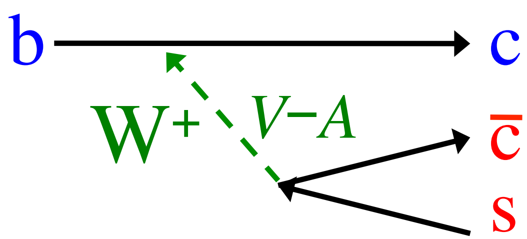
lowest order weak interactions ($\Delta F = 1$)

$$(\bar{c}_i b_i)_{V-A} (\bar{s}_j c_j)_{V-A}$$

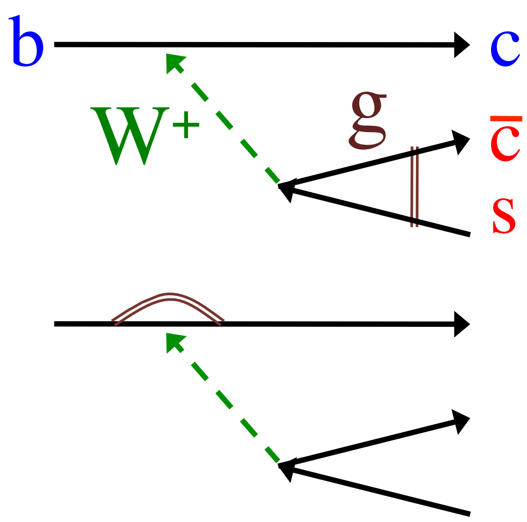
More on Weak Decays

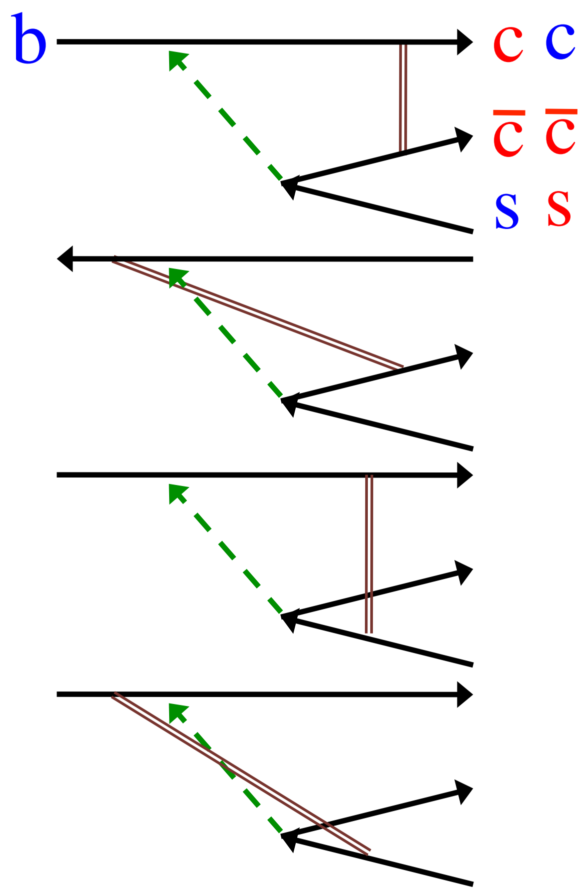
decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

lowest order weak interactions ($\Delta F = 1$)



Switching on QCD





More on Weak Decays

decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

lowest order weak interactions ($\Delta F = 1$)

$(\bar{c}_i b_i)_{V-A} (\bar{s}_j c_j)_{V-A}$

No-QCD tree diagram

+ one gluon =
tree diagrams with two different colour structures

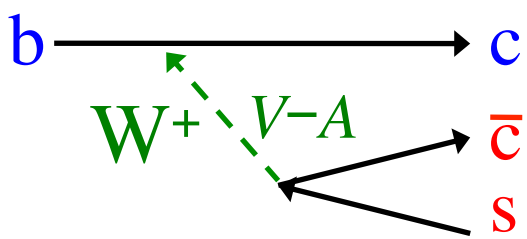
$(\bar{c}_i b_i)_{V-A} (\bar{s}_j c_j)_{V-A}$

$(\bar{c}_j b_i)_{V-A} (\bar{s}_i c_j)_{V-A}$

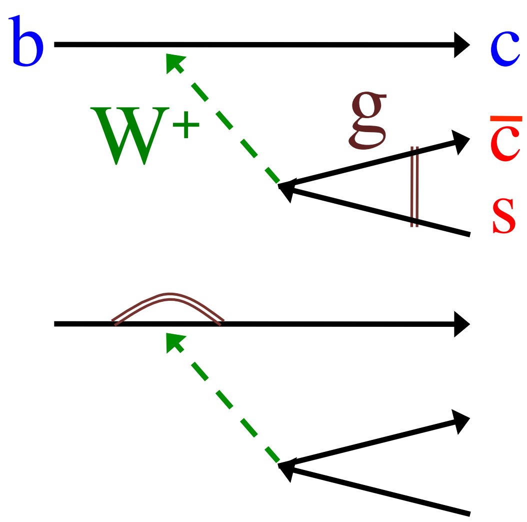
More on Weak Decays

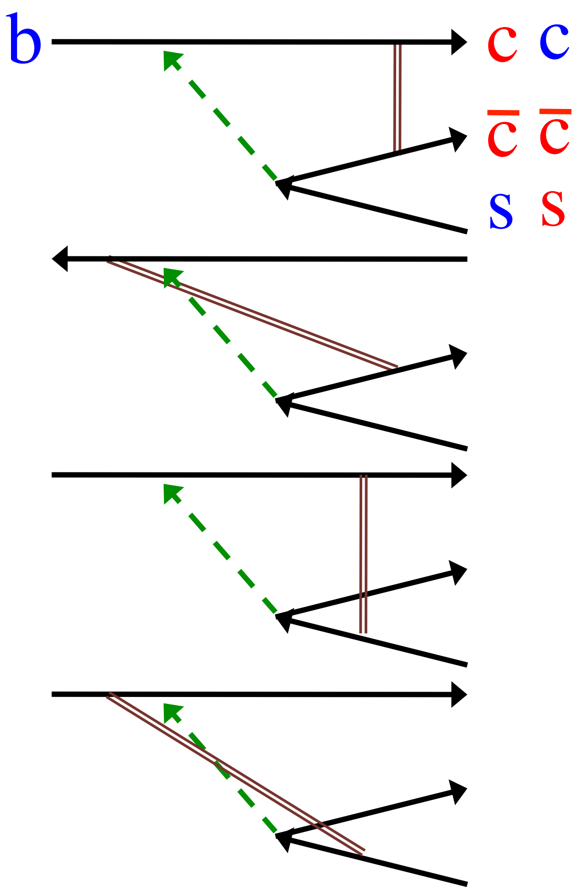
decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

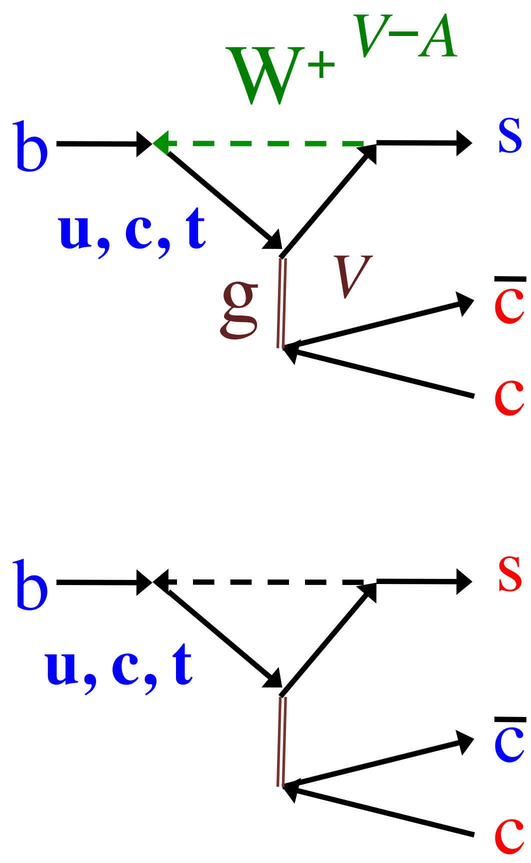
lowest order weak interactions ($\Delta F = 1$)



Switching on QCD







gluon penguins

More on Weak Decays

decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

lowest order weak interactions ($\Delta F = 1$)

$(\bar{c}_i b_i)_{V-A} (\bar{s}_j c_j)_{V-A}$

No QCD tree diagram

+ one gluon =
tree diagrams with two
different colour structures

$(\bar{c}_i b_i)_{V-A} (\bar{s}_j c_j)_{V-A}$

$(\bar{c}_j b_i)_{V-A} (\bar{s}_i c_j)_{V-A}$

+ gluon penguins with two
different colour structure
(gluon = V)

$(\bar{s}_i b_i)_{V-A} (\bar{c}_j c_j)_V$

$(\bar{s}_j b_i)_{V-A} (\bar{c}_i c_j)_V$

More on Weak Decays

decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

lowest order weak interactions ($\Delta F = 1$)

$(\bar{c}_i b_i)_{V-A} (\bar{s}_j c_j)_{V-A}$

No QCD tree diagram

$(\bar{c}_i b_i)_{V-A} (\bar{s}_j c_j)_{V-A}$

$(\bar{c}_j b_i)_{V-A} (\bar{s}_i c_j)_{V-A}$

+ one gluon
tree diagrams with two different colour structures

$(\bar{s}_i b_i)_{V-A} (\bar{c}_j c_j)_{V-A}$

+ gluon penguins with two different colour structure (gluon = V)
→ split to ($V-A$) + ($V+A$)
(needed for the Q^2 evolution)

$(\bar{s}_i b_i)_{V-A} (\bar{c}_j c_j)_{V+A}$

$(\bar{s}_j b_i)_{V-A} (\bar{c}_i c_j)_{V-A}$

$(\bar{s}_j b_i)_{V-A} (\bar{c}_i c_j)_{V+A}$

More on Weak Decays

decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

lowest order weak interactions ($\Delta F = 1$)

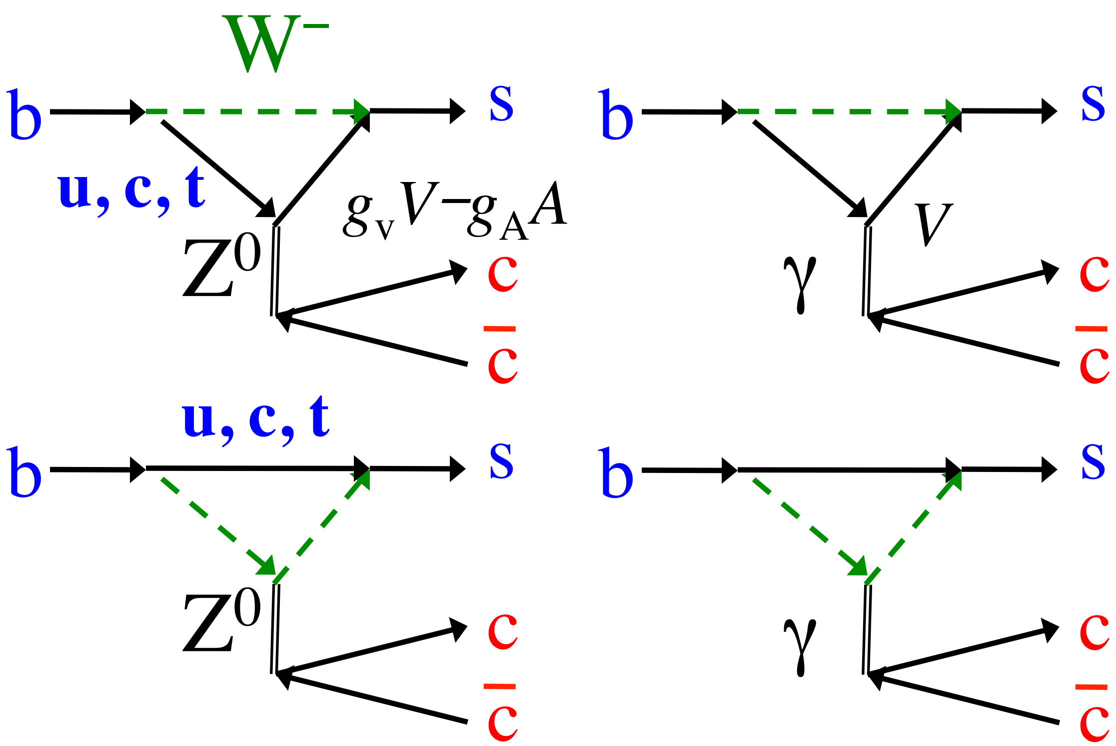
		operators
$(\bar{c}_i b_i)_{V-A}(\bar{s}_j c_j)_{V-A}$ No QCD tree diagram	$(\bar{c}_i b_i)_{V-A}(\bar{s}_j c_j)_{V-A}$	Q_2
+ one gluon tree diagrams with two different colour structures	$(\bar{c}_j b_i)_{V-A}(\bar{s}_i c_j)_{V-A}$	Q_1
	$(\bar{s}_i b_i)_{V-A}(\bar{c}_j c_j)_{V-A}$	Q_3
+ gluon penguins with two different colour structure (gluon = V)	$(\bar{s}_i b_i)_{V-A}(\bar{c}_j c_j)_{V+A}$	Q_5
→ split to $(V-A) + (V+A)$	$(\bar{s}_j b_i)_{V-A}(\bar{c}_i c_j)_{V-A}$	Q_4
(needed for the Q^2 evolution)	$(\bar{s}_j b_i)_{V-A}(\bar{c}_i c_j)_{V+A}$	Q_6

More on Weak Decays

decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

the second order electroweak interactions ($\Delta F = 1$)

electroweak penguins



$$q_j(\bar{s}_i b_i)_{V-A}\,(\bar{c}_j c_j)_{V-A} \quad Q_7$$

$$q_j'(\bar{s}_i b_i)_{V-A}\,(\bar{c}_j c_j)_{V+A} \quad Q_9$$

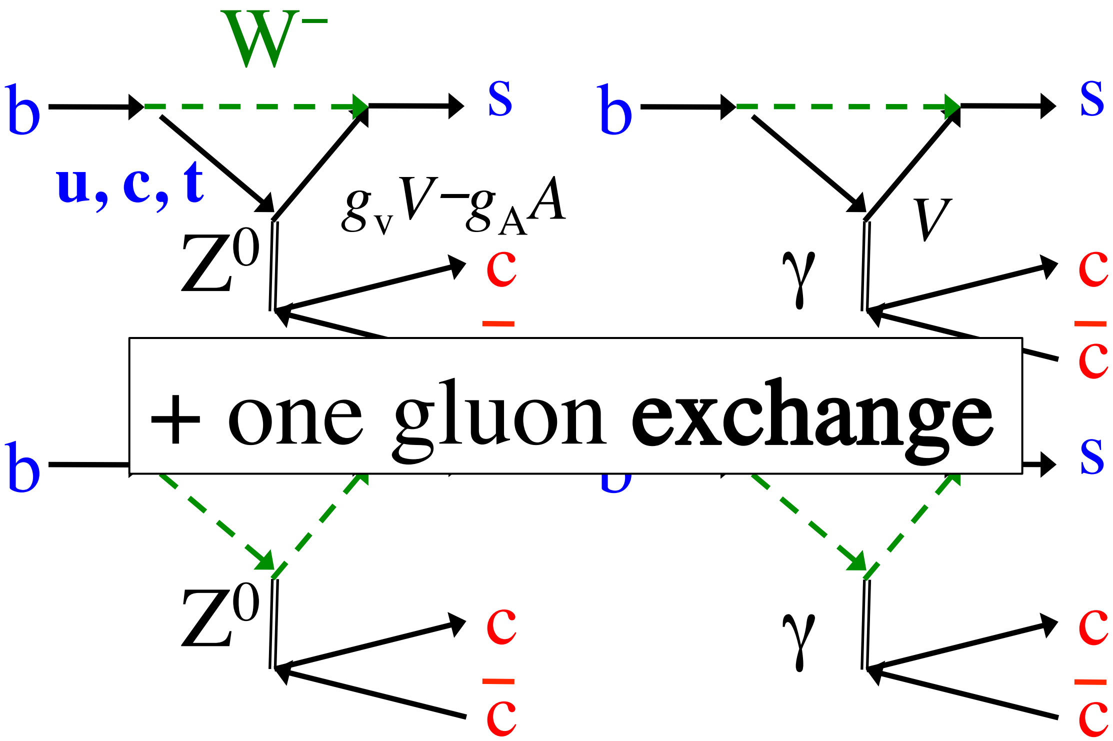
q_j and q_j' are appropriate electroweak coupling constants

More on Weak Decays

decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

the second order electroweak interactions ($\Delta F = 1$)

electroweak penguins + QCD



$q_j(\bar{s}_i b_i)_{V-A}\,(\bar{c}_j c_j)_{V-A}$ $\quad Q_7$

$q_j'(\bar{s}_i b_i)_{V-A}\,(\bar{c}_j c_j)_{V+A}$ $\quad Q_9$

$q_j(\bar{s}_i b_i)_{V-A}\,(\bar{c}_j c_j)_{V-A}$ $\quad Q_8$

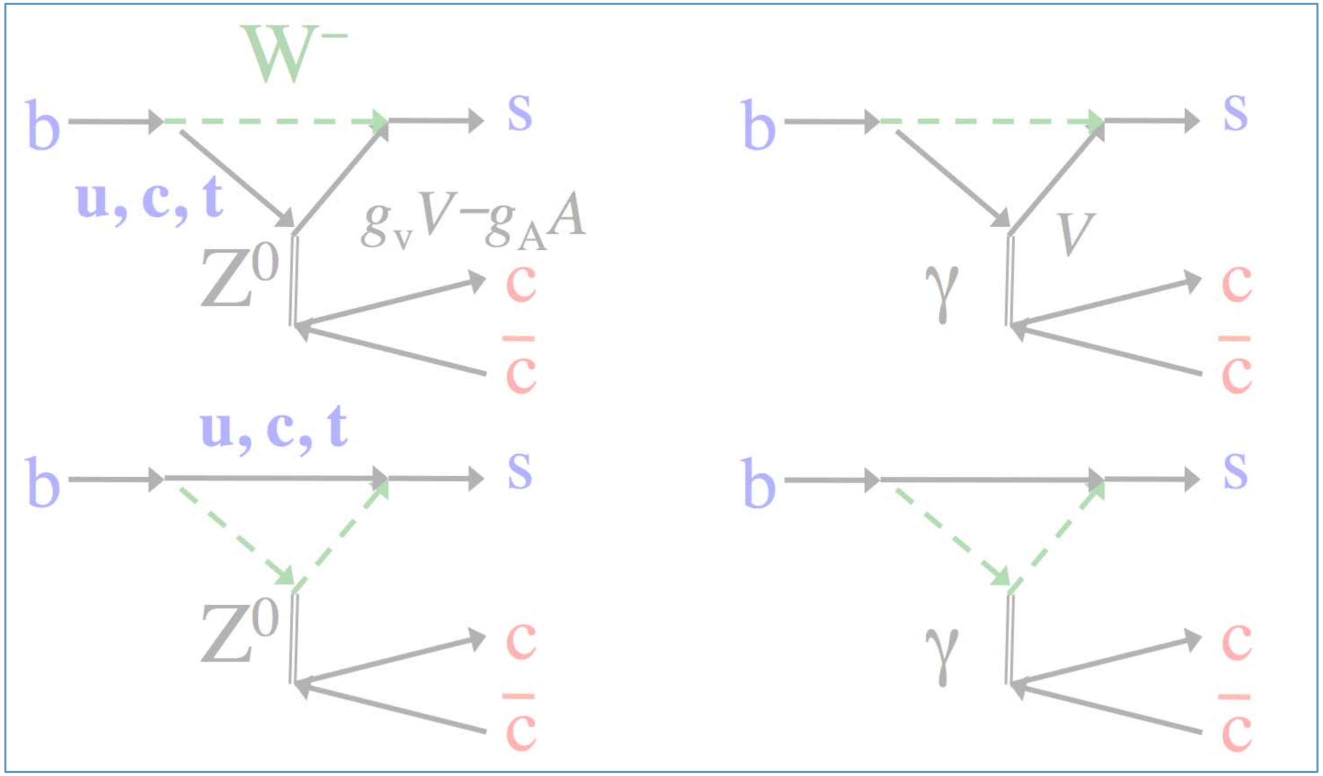
$q_j'(\bar{s}_i b_i)_{V-A}\,(\bar{c}_j c_j)_{V+A}$ $\quad Q_{10}$

q_j and q_j' are appropriate electroweak coupling constants

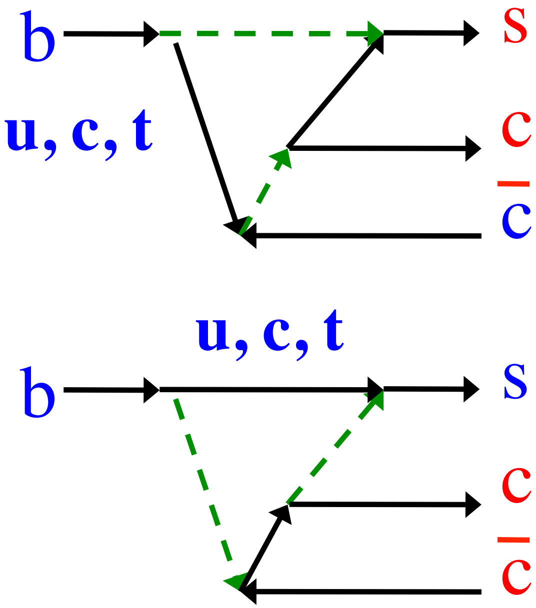
More on Weak Decays

decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

also the second order electroweak interactions, $\Delta F = 2$



Box diagrams



More on Weak Decays

decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

Theoretical tool to describe the decay amplitude for M→F

$$A(M \to F) = \left\langle F \middle| H^{\text{weak decay}}_{\text{effective}} \middle| M \right\rangle = \frac{G_{\mathrm{F}}}{\sqrt{2}} \sum_i \xi^i_{\mathrm{CKM}} C_i(\mu) \langle F | Q_i(\mu) | M \rangle$$

G_{F}: Fermi constant,

$Q_i(\mu)$: Local four-fermion operators evaluated at energy scale μ
calculable in perturbation

$C_i(\mu)$: Coupling constants for $Q_i(\mu)$ at energy scale μ
i.e. Wilson coefficient, calculable in perturbation

$\langle F|Q_i(\mu)|M\rangle$: Hadronic matrix element
long distance effect

ξ_i^{CKM}: Combination of the CKM elements
the ultimate interest for Flavour Physics
extraction of the CKM matrix, search for new physics

More on Weak Decays

decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

Theoretical tool to describe the decay amplitude for M→F

$$A(M \to F) = \left\langle F \middle| H^{\text{weak decay}}_{\text{effective}} \middle| M \right\rangle = \frac{G_F}{\sqrt{2}} \sum_i \xi^i_{\text{CKM}} C_i(\mu) \langle F | Q_i(\mu) | M \rangle$$

- Comparing the full and effective theory at $\mu = m_W$
  → $C_i(\mu = m_W)$

- Scale C_i down to $\mu \approx 1$ GeV (K), m_c (D), m_b (B)

$$C_i(\mu) = U_{ij}(\mu,\ \mu = m_W) C_j(\mu = m_W)$$

U_{ij} not diagonal ⇒ mixing of the operators in the evolution

- Evaluate $\langle F|Q_i(\mu)|M\rangle$ (hadronic matrix element)
  with non perturbative methods at μ
  lattice, HQET, QCD sum rule, etc.
  major source of uncertainties

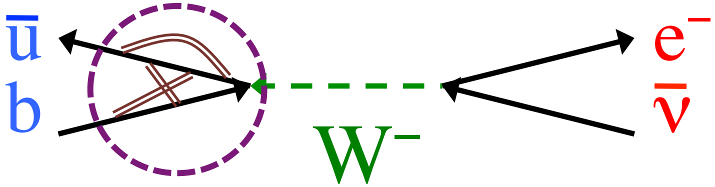
More on Weak Decays

decay ($\Delta F = 1$) and oscillation amplitudes ($\Delta F = 2$)

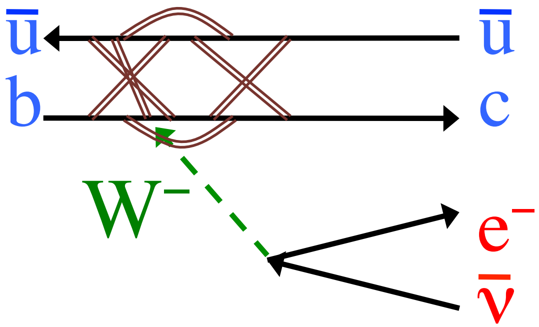
Theoretical tool to describe the decay amplitude for M→F

$$A(M \to F) = \left\langle F \middle| H^{\text{weak decay}}_{\text{effective}} \middle| M \right\rangle = \frac{G_F}{\sqrt{2}} \sum_i \xi^i_{\text{CKM}} C_i(\mu) \langle F | Q_i(\mu) | M \rangle$$

- Evaluate $\langle F|Q_i(\mu)|M\rangle$ (hadronic matrix element)



One decay constant f_B



Form factors $f(q^2)$:
functions of momentum transfer
B→hadrons
depend on the hadrons

Many theoretical models: ultimately the lattice QCD

Plan of Lectures

- Direct-search versus Indirect-search
- Early History
- Standard Model Flavour Framework
- More of Weak Decay
- Current Status of V_{CKM}
- Any Sign of New Physics
- Closer Look
- Epilogue

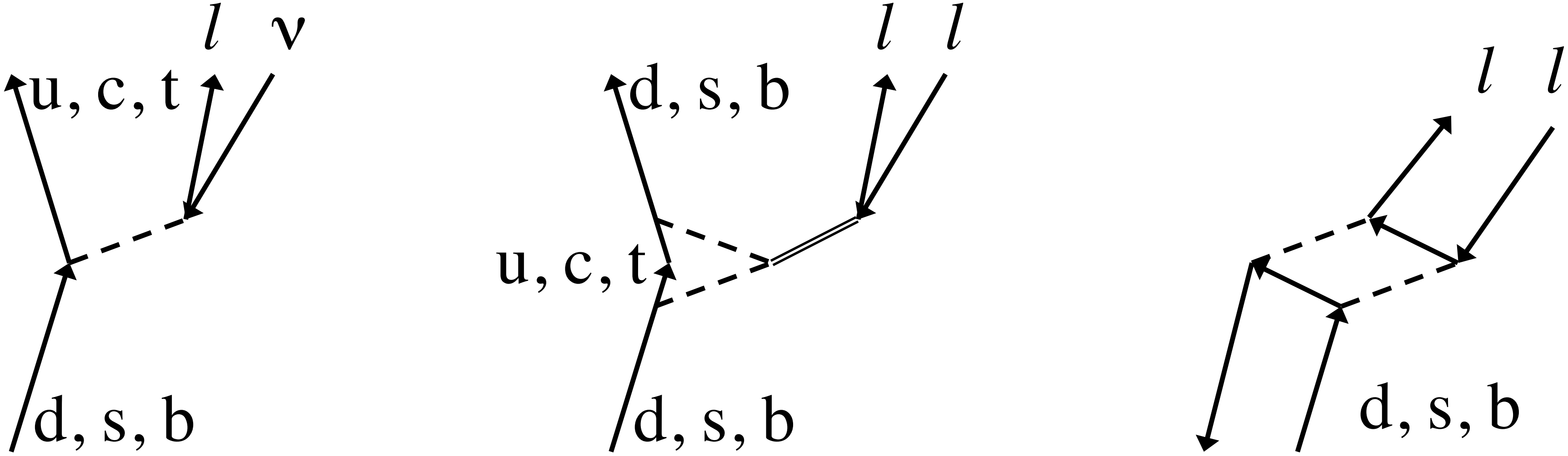
Current Status of V_{CKM}

Can be extract from decay widths generated by the tree, penguin, and box processes

examples of semileptonic and leptonic decays

$$V_{\mathrm{UD}} \begin{cases} \mathrm{U} = \mathrm{u},\ \mathrm{c},\ \mathrm{t} \\ \mathrm{D} = \mathrm{d},\ \mathrm{s},\ \mathrm{b} \end{cases}$$

$\Gamma \propto |V_{\mathrm{UD}}|$ $\qquad\qquad \propto |\sum_{\mathrm{U}} V_{\mathrm{UD}} V_{\mathrm{UD'}}^{*} f(m_{\mathrm{U}})|$



Current Status of V_{CKM}

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

First 2×2 sub-matrix: four $|V_{ij}|$ are measured by nucleus, pion, kaon and charm hadron decays

It is “almost” unitary with one single parameter

$\lambda\ (\equiv \sin\theta_{\mathrm{Cabibbo}}) = |V_{\mathrm{us}}| = 0.2246 \pm 0.0012$ (PDG 2012)

$$V_{\mathrm{CKM}} \approx \begin{pmatrix} 1 & \lambda & V_{\mathrm{ub}} \\ -\lambda & 1 & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$

Current Status of V_{CKM}

$$V_{CKM} \approx \begin{pmatrix} 1 & \lambda & V_{ub} \\ -\lambda & 1 & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$|V_{cb}|$ and $|V_{ub}|$ measured by semileptonic B_u and B_d decays

$$|V_{cb}| = \begin{cases} (41.9 \pm 0.7)\times 10^{-3} \text{ inclusive decays} \\ (39.6 \pm 0.9)\times 10^{-3} \text{ exclusive decays} \end{cases}$$

-errors limited theoretically-

2.0σ discrepancy (PDG 2012)

$$|V_{ub}| = \begin{cases} (4.41 \pm 0.22)\times 10^{-3} \text{ inclusive decays} \\ (3.23 \pm 0.31)\times 10^{-3} \text{ exclusive decays} \end{cases}$$

-errors very limited theoretically-

3.1σ discrepancy (PDG 2012)

exclusives systematically smaller than exclusives…?

Current Status of V_{CKM}

$$V_{\mathrm{CKM}} \approx \begin{pmatrix} 1 & \lambda & V_{ub} \\ -\lambda & 1 & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$|V_{cb}|$ and $|V_{ub}|$ measured by semileptonic B_u and B_d decays

arg $V_{cb} = 0$ by a phase convention

Current Status of V_{CKM}

$$V_{CKM} \approx \begin{pmatrix} 1 & \lambda & V_{ub} \\ -\lambda & 1 & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$|V_{cb}|$ and $|V_{ub}|$ measured by semileptonic B_u and B_d decays

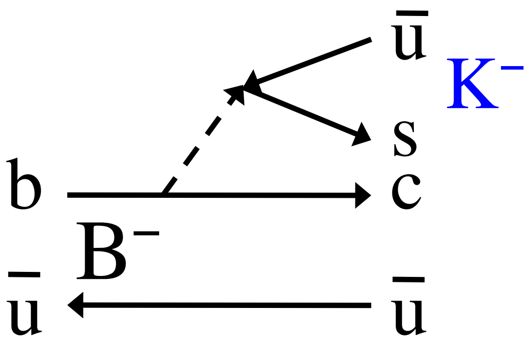
arg $V_{cb} = 0$ by a phase convention

arg V_{ub} by CP violation in $B \rightarrow DK$

Current Status of V_{CKM}

arg V_{ub} so called angle "γ"

two decay diagrams producing identical final states

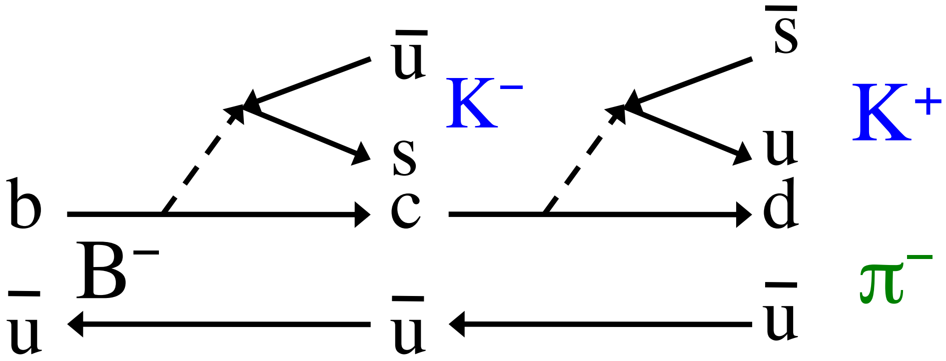


$V_{cb}V_{us}^*$

Current Status of V_{CKM}

arg V_{ub} so called angle "γ"

two decay diagrams producing identical final states

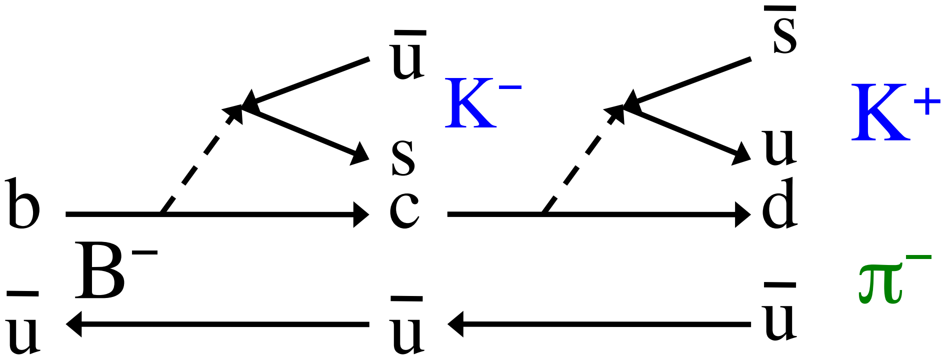


$V_{cb}V_{us}^*V_{cd}^*V_{us}$

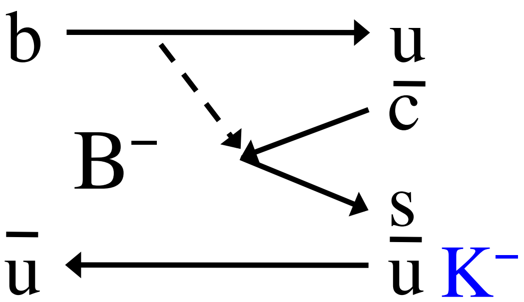
Current Status of V_{CKM}

arg V_{ub} so called angle "γ"

two decay diagrams producing identical final states



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

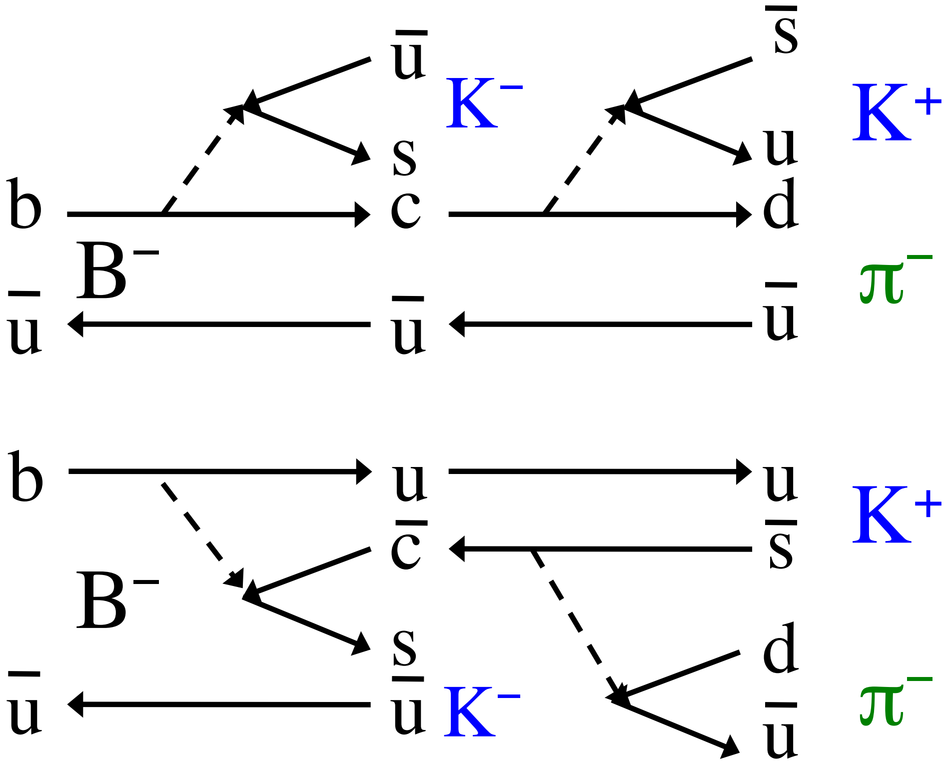


$V_{ub}V_{cs}{}^{*}$

Current Status of V_{CKM}

arg V_{ub} so called angle "γ"

two decay diagrams producing identical final states



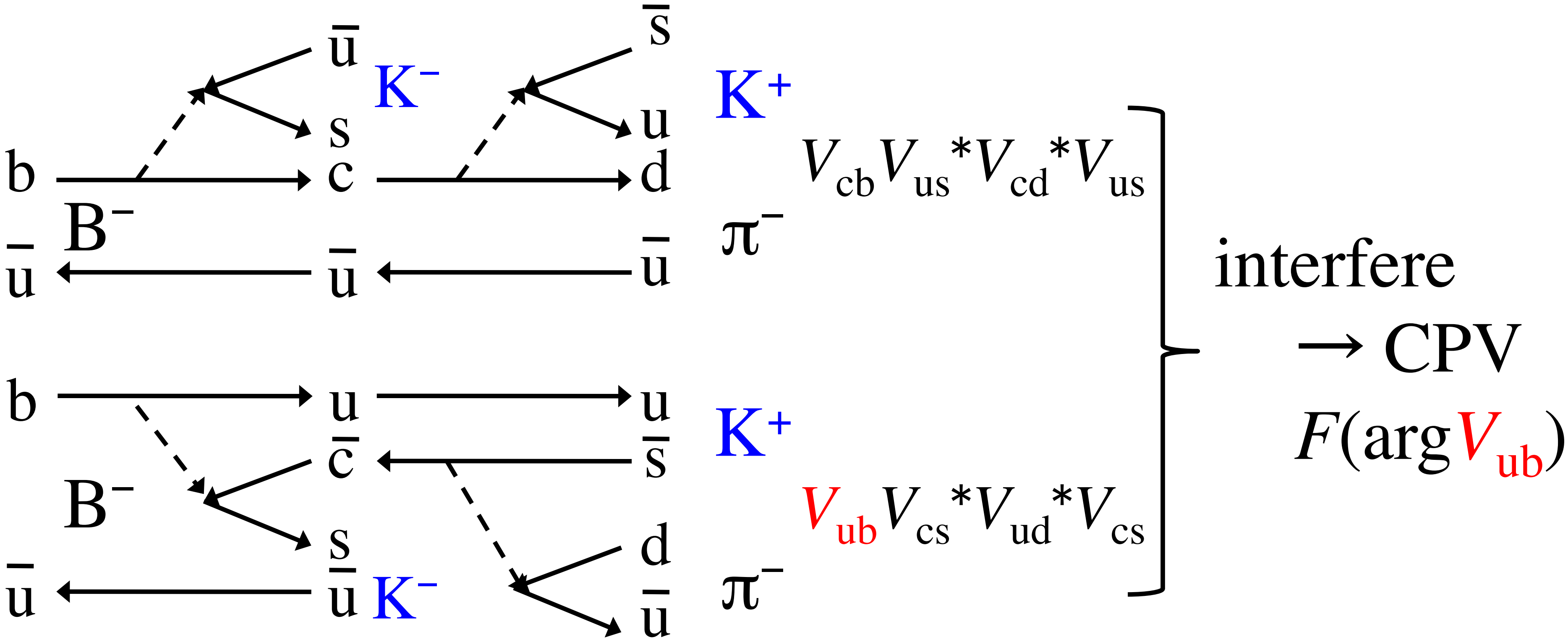
$V_{cb}V_{us}^{*}V_{cd}^{*}V_{us}$

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

Current Status of V_{CKM}

arg V_{ub} so called angle "γ"

two decay diagrams producing identical final states

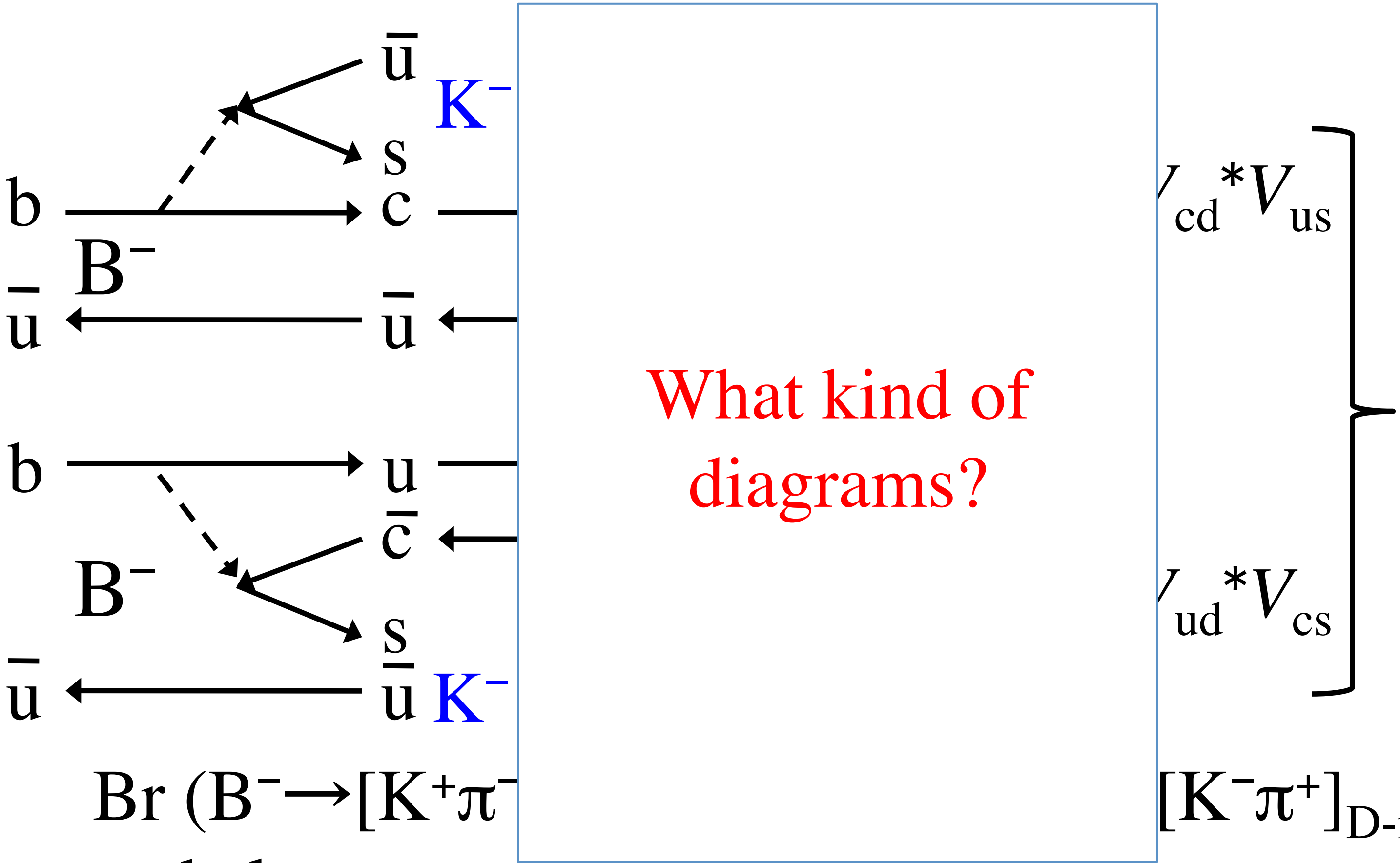


$$\mathrm{Br}\,(B^- \to [K^+\pi^-]_{D\text{-mass}}\, K^-) \neq \mathrm{Br}\,(B^+ \to [K^-\pi^+]_{D\text{-mass}}\, K^+)$$

Current Status of V_{CKM}

arg V_{ub} so called angle "γ"

two decay diagrams producing identical final states



interfere

→ CPV

$F(\arg V_{ub})$

Br ($B^-\rightarrow[K^+\pi^-$ … $[K^-\pi^+]_{D\text{-mass}}\ K^+$)

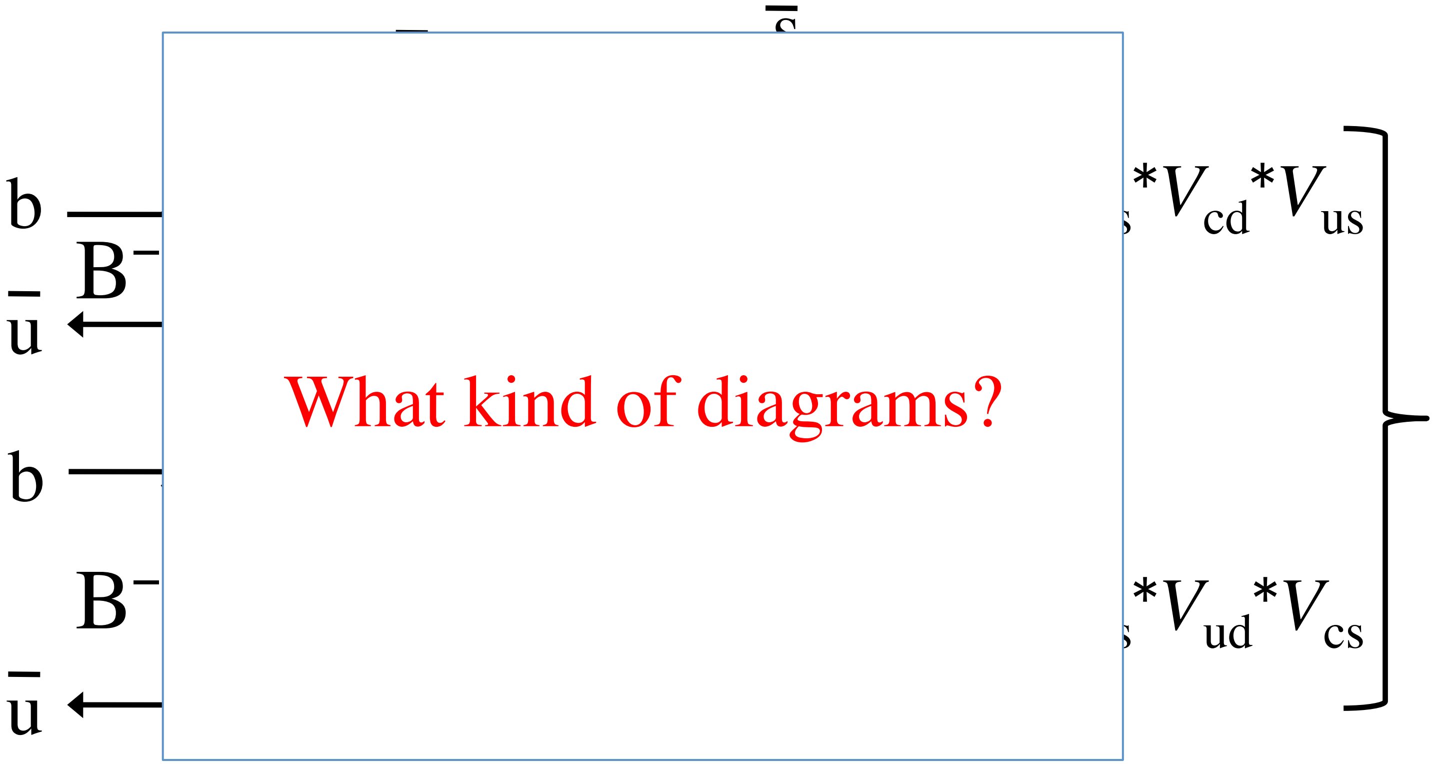
and also

Br ($B^-\rightarrow[K^-\pi^+]_{D\text{-mass}}\ K^-$) ≠ Br ($B^+\rightarrow[K^+\pi^-]_{D\text{-mass}}\ K^+$)

Current Status of V_{CKM}

arg V_{ub} so called angle "γ"

two decay diagrams producing identical final states



interfere

→ CPV

$F(\arg V_{ub})$

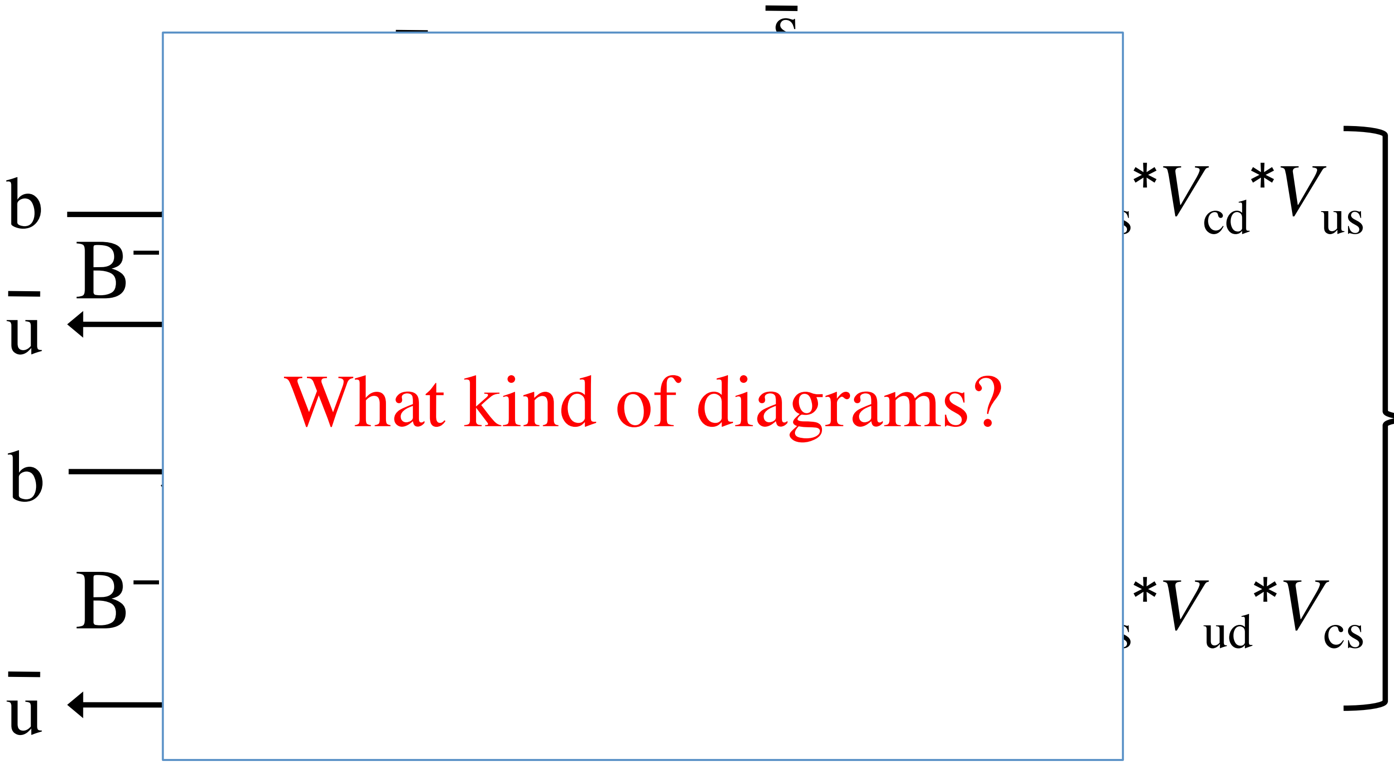
$\text{Br}\,(B^-\to[K^+K^-]_{\text{D-mass}}\,K^-) \neq \text{Br}\,(B^+\to[K^+K^-]_{\text{D-mass}}\,K^+)$

$\text{Br}\,(B^-\to[\pi^+\pi^-]_{\text{D-mass}}\,K^-) \neq \text{Br}\,(B^+\to[\pi^+\pi^-]_{\text{D-mass}}\,K^+)$

Current Status of V_{CKM}

arg V_{ub} so called angle "γ"

two decay diagrams producing identical final states



interfere

→ CPV

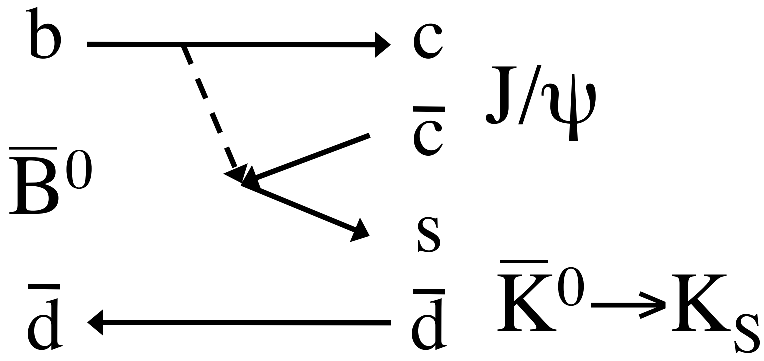
$F(\arg V_{ub})$

$$\mathrm{Br}\,(B^-\to[K_S\pi^+\pi^-]_{D\text{-mass}}\,K^-) \neq \mathrm{Br}\,(B^+\to[K_S\pi^+\pi^-]_{D\text{-mass}}\,K^+)$$

Current Status of V_{CKM}

$\overline{\mathrm{B}}^0 \longrightarrow \overline{\mathrm{B}}^0$ $\quad \mathrm{b} \rightarrow \mathrm{c}+\bar{\mathrm{c}}\mathrm{s}$: $V_{\mathrm{cb}}V_{\mathrm{cs}}{}^* \propto e^{\iota 0}$

$\searrow$ $\mathrm{J}/\psi\ \mathrm{K_S}$

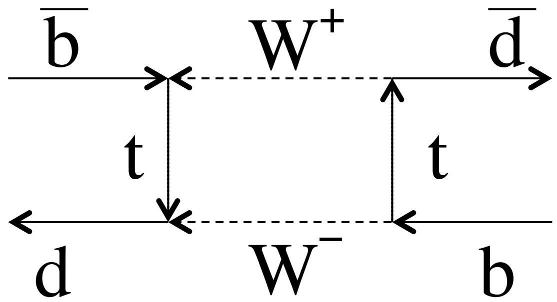


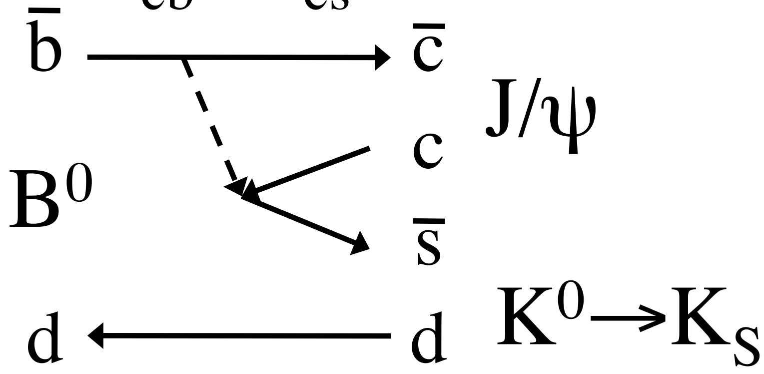
Current Status of V_{CKM}

$\bar{B}^0$ → B^0 → $J/\psi\, K_S$

$M_{12} \propto -e^{2i\arg V_{td}}$

$\bar{b} \to \bar{c}+c\bar{s}$: $V_{cb}{}^* V_{cs} \propto e^{\iota 0}$





Current Status of V_{CKM}

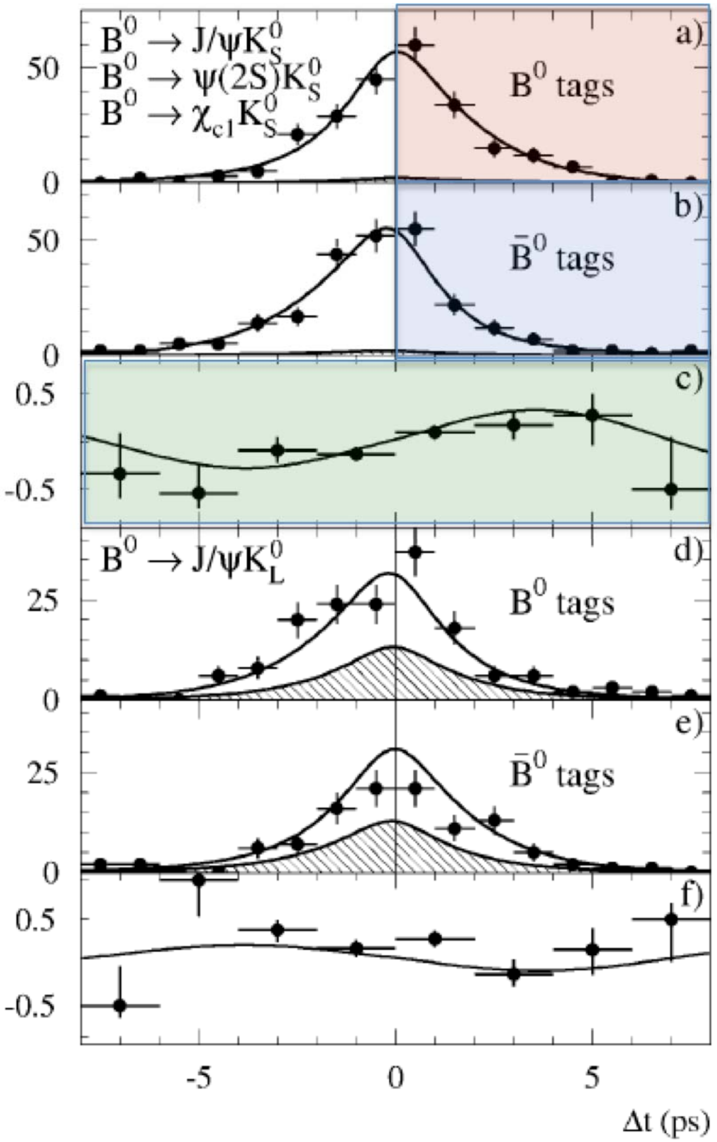
$\overline{\mathrm{B}}^0 \longrightarrow \overline{\mathrm{B}}^0$ $\mathrm{b} \to \mathrm{c}+\bar{\mathrm{c}}\mathrm{s}$: $V_{\mathrm{cb}} V_{\mathrm{cs}}{}^* \propto e^{\iota 0}$

$\overline{\mathrm{B}}^0 \to \mathrm{J}/\psi\, \mathrm{K_S}$, $\mathrm{B}^0 \to \mathrm{J}/\psi\, \mathrm{K_S}$

$M_{12} \propto -e^{2i\arg \mathrm{V_{td}}}$ $\overline{\mathrm{B}}^0 \to \mathrm{B}^0$ $\bar{\mathrm{b}} \to \bar{\mathrm{c}}+\mathrm{c}\bar{\mathrm{s}}$: $V_{\mathrm{cb}}{}^* V_{\mathrm{cs}} \propto e^{\iota 0}$

two processes interfere → CPV ∝ sin $2\arg V_{\mathrm{td}}$

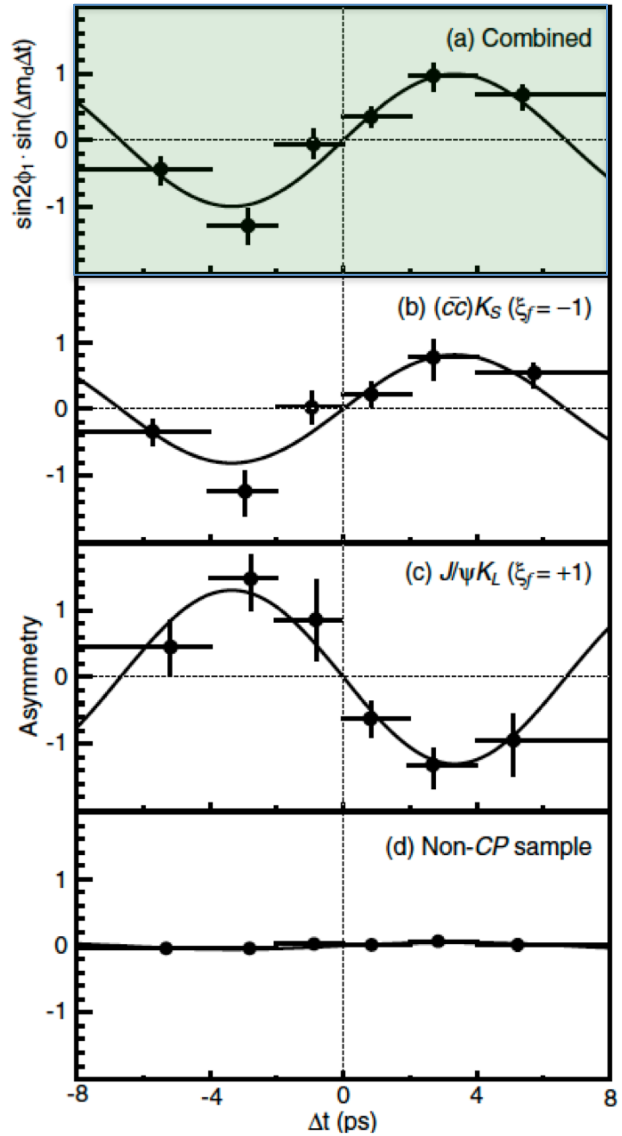
Current Status of V_{CKM}



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

$B^0{}_{t=0} \to J/\psi K_S(t)$

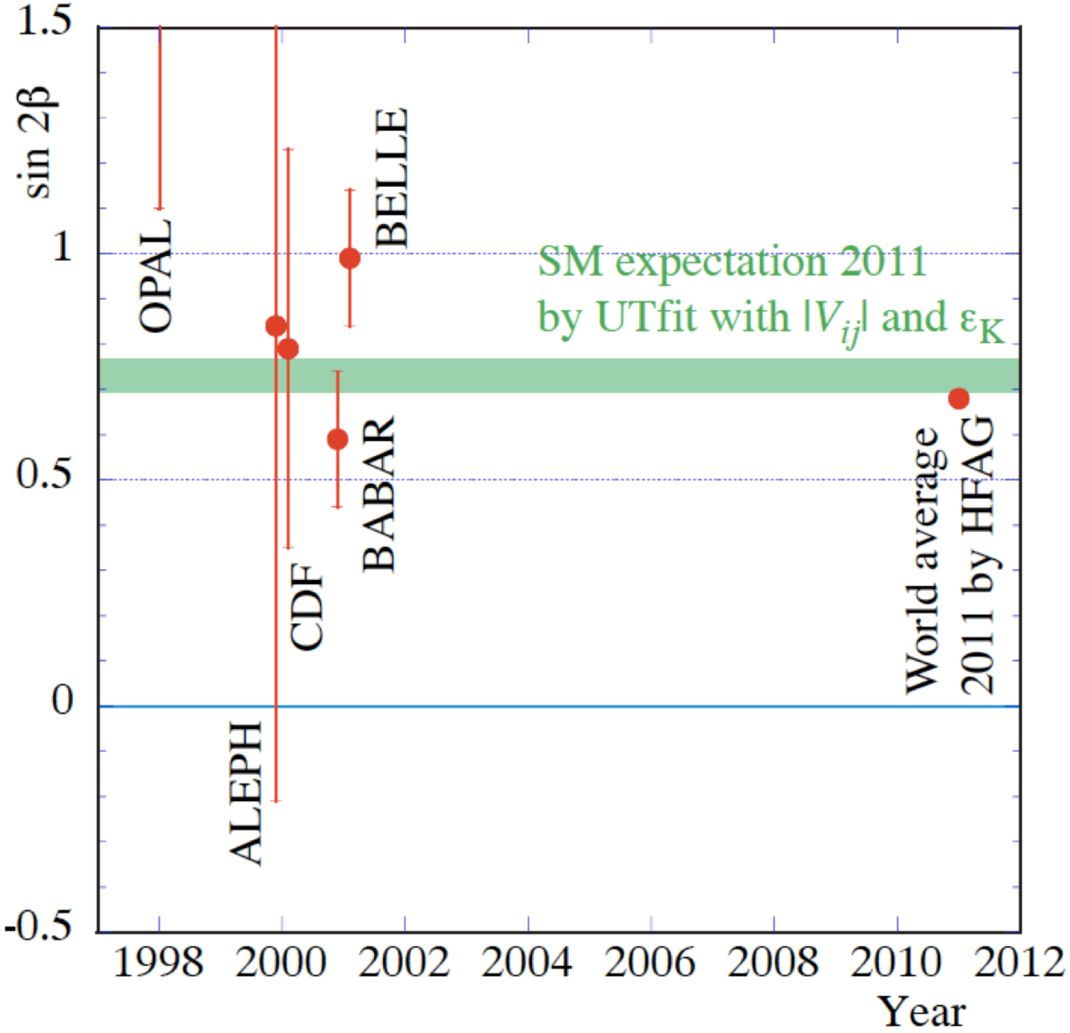
Time dependent CP asymmetries



BABAR: Phys. Rev. Lett. 87, 091801 (2001)

BELLE: Phys. Rev. Lett. 87, 091802 (2001)

Current Status of V_{CKM}



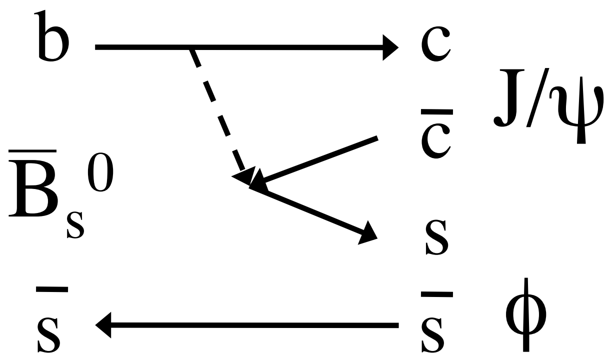
two processes interfere → CPV ∝ sin $2\arg V_{td}$

0.679 ± 0.020 (HFAG 2012)

Current Status of V_{CKM}

$\overline{B}_s^0 \longrightarrow \overline{B}_s^0 \searrow$ $b \rightarrow c + \bar{c}s$: $V_{cb}V_{cs}^* \propto e^{\iota 0}$

$J/\psi\phi$

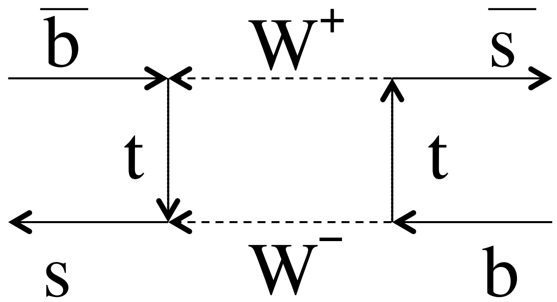


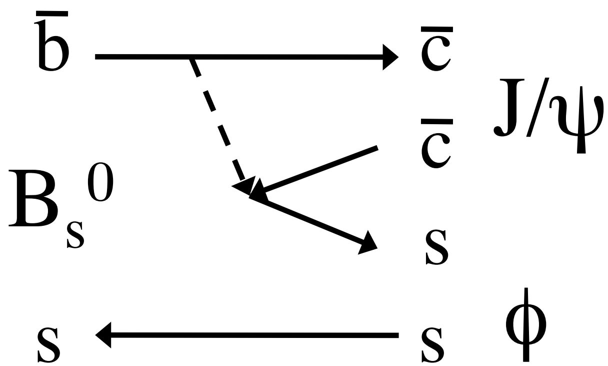
Current Status of V_{CKM}

$\overline{\mathrm{B}}_s^0 \to \mathrm{B}_s^0 \to \mathrm{J}/\psi\, \mathrm{K_S}$ or $\mathrm{J}/\psi\phi$

$$M_{12} \propto -e^{2i\arg V_{td}} \text{ or } -e^{2i\arg V_{ts}}$$

$$\bar{\mathrm{b}} \rightarrow \bar{\mathrm{c}}+\mathrm{c}\bar{\mathrm{s}}:\ V_{cb}{}^* V_{cs} \propto e^{\iota 0}$$





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$\bar{B}_s^0 \longrightarrow \bar{B}_s^0 \qquad b \to c+\bar{c}s$: $V_{cb}V_{cs}^* \propto e^{\iota 0}$

$\bar{B}_s^0 \longrightarrow J/\psi\phi$

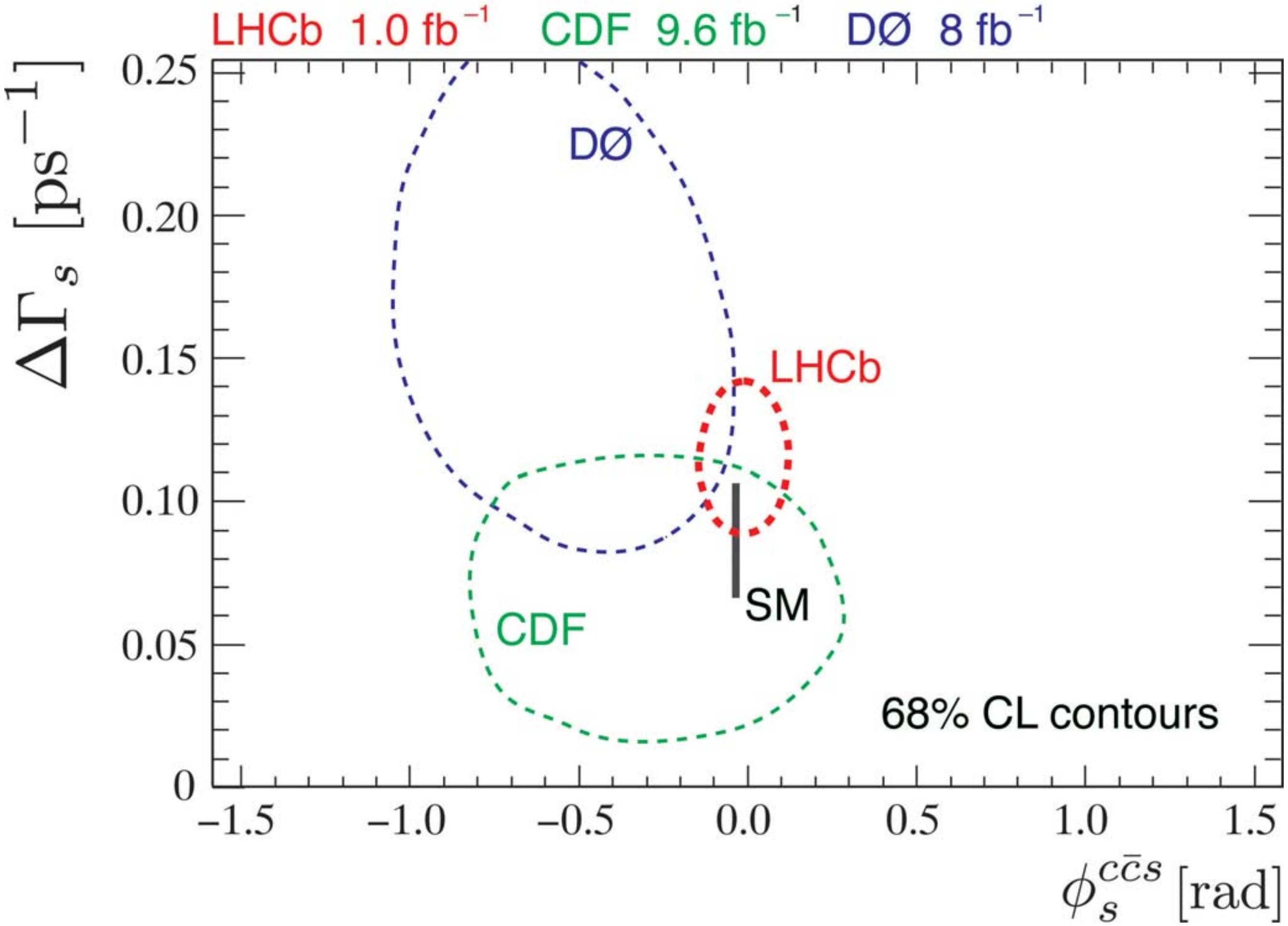
$B_s^0 \longrightarrow J/\psi\phi$

$M_{12} \propto -e^{2i\arg V_{ts}} \qquad \bar{B}_s^0 \longrightarrow B_s^0 \qquad \bar{b} \to \bar{c}+c\bar{s}$: $V_{cb}^*V_{cs} \propto e^{\iota 0}$

two processes interfere → CPV ∝ sin $2\arg V_{ts}$

not yet well measured

Current Status of V_{CKM}



two processes interfere → CPV ∝ sin 2argV_{ts}

$$-0.044^{+0.090}_{-0.085}$$ (HFAG 2012)

Current Status of V_{CKM}

$$\approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

$$\hat{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right)$$

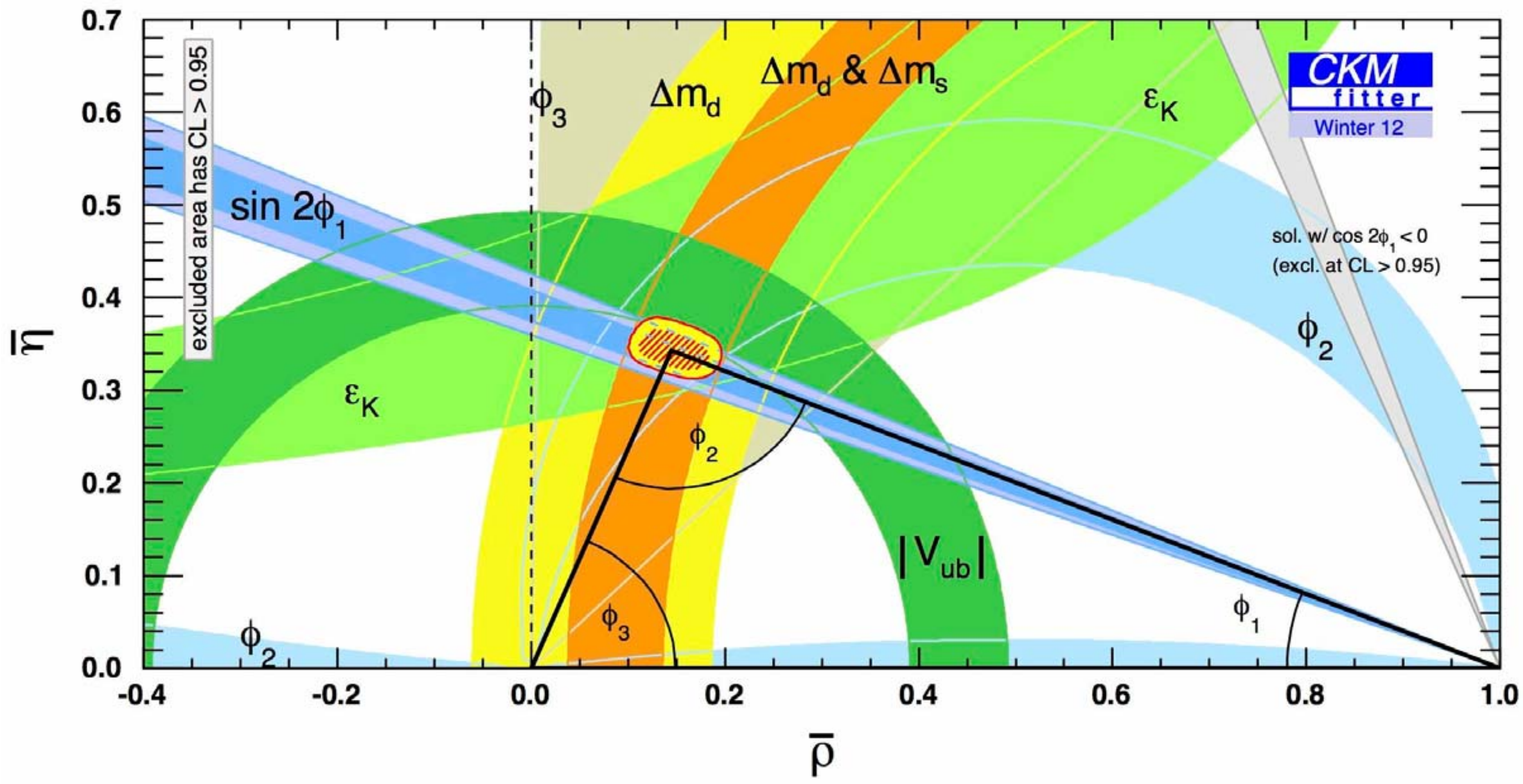
$$\hat{\eta} = \eta\left(1-\frac{\lambda^2}{2}\right)$$

A from $|V_{cb}|$, ρ and η from

- $|V_{ub}|$ and arg V_{ub}
- $|V_{tb}|$ and arg V_{tb}
- $|V_{ub}|$ and $|V_{tb}|$
- $|V_{td}|$ and arg V_{ub}

many solutions i.e. consistency can be checked

Current Status of V_{CKM}



- BABAR completed in 2008 and Belle completed in 2010 $\sim 1.2\ \mathrm{ab}^{-1}$ data, i.e. $\sim 1.3\times 10^9\ B\overline{B}$
- CDF and D0 completed in 2011, $\sim 20\ \mathrm{fb}^{-1}$ data
- LHCb running, 7 TeV in 1010+2011 ($1\ \mathrm{fb}^{-1}$), 8 TeV in 2012

Current Status of V_{CKM}

- To look for New Physics, extraction of (λ, A, ρ, η) with the processes totally dominated by the SM
  $\rightarrow$ tree decays
  - λ and A are already from the tree decay modes
  - (ρ, η) from the tree decays:
    $|V_{ub}/V_{cb}|$ from the semileptonic decays
    arg V_{ub} from $B\rightarrow DK^*$ (interference between $b\rightarrow c$ and $b\rightarrow u$)

$B^\pm \rightarrow$ "D" $K^\pm$, with "D" $\rightarrow K^+\pi^-$ and $K^-\pi^+$
with "D" $\rightarrow K^+K^-$ or $\pi^+\pi^-$
with "D" $\rightarrow K_S\pi^+\pi^-$ Dalitz plot

$B^0 \rightarrow$ "D" K^{*0} and "D" K^{*0} with "D" decays

} BABAR, Belle, LHCb

Time dependent CP asymmetries
of $B_s(t{=}0)\rightarrow D_s^\pm K^\mp$ vs CP conjugated state — LHCb

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$B^{\pm} \rightarrow$ "D" $K^{\pm}$, with "D" $\rightarrow K^{+}\pi^{-}$ and $K^{-}\pi^{+}$

Can you demonstrate these?

$B^{0} \rightarrow$ "D" K^{*0} and "D" K^{*0} with "D" decays

Time dependent CP asymmetries
of $B_s(t=0) \rightarrow D_s^{\pm}K^{\mp}$ vs CP conjugated state — LHCb

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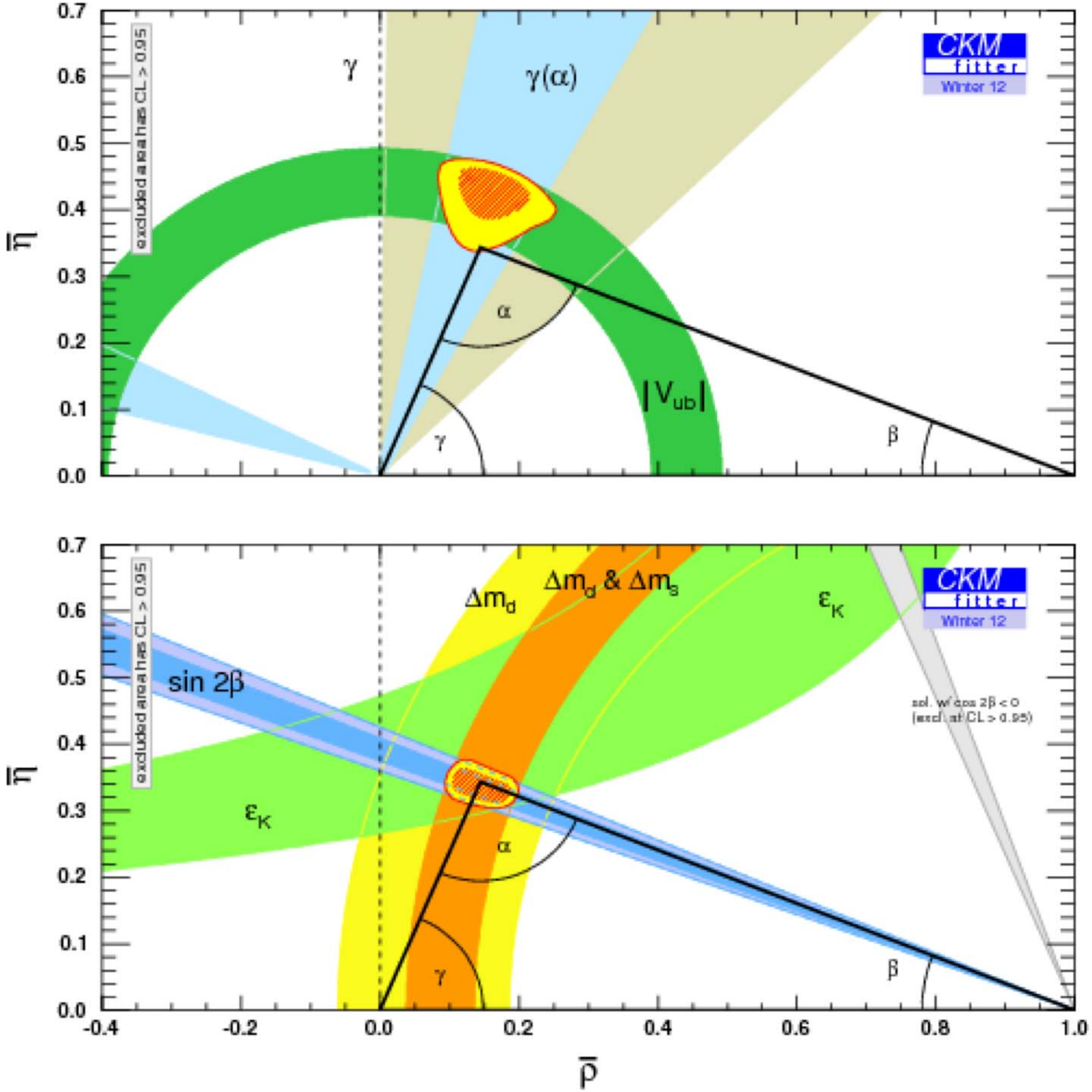
  - Combination of ε_K with $|V_{td}|$ or CPV in $B_d \rightarrow J/\psi K_S$

- To ... ρ, η)
  wit ... SM
  - 2
  - (



- Sh ... p
  pro
  - l
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Current Status of V_{CKM}

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  - Combination of ε_K with $|V_{td}|$ or CPV in $B_d \to J/\psi K_S$
- Further improvement with the LHCb data expected

Current Status of V_{CKM}

- No sign of new physics in $B \to \mu^+\mu^-$
  Now results dominated by the LHC experiments

95% CL upper limit

Mode	Limit	ATLAS	CMS	LHCb 2010	LHCb 2011	Combined
$B_s^0 \to \mu^+\mu^-$ (10^{-9})	Bkg Only	23	(3.6)	65	3.4	2.3
	Bkg+SM		8.4		7.2	6.1
	Obs	22	7.7 (7.2)	56	4.5	4.2
$B^0 \to \mu^+\mu^-$ (10^{-10})	Bkg Only	–	(13)	180	11	7.3
	Bkg+SM	–	16			
	Obs	–	14 (16)	150	10	8.1

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\text{SM}} = (3.2 \pm 0.2) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{\text{SM}} = (1.0 \pm 0.1) \times 10^{-10}$$

Plan of Lectures

- Direct-search versus Indirect-search
- Early History
- Standard Model Flavour Framework
- More of Weak Decay
- Current Status of V_{CKM}
- Any Sign of New Physics
- Closer Look
- Epilogue

Any Sign of New Physics?

- There exist solid observations for physics beyond the Standard Model

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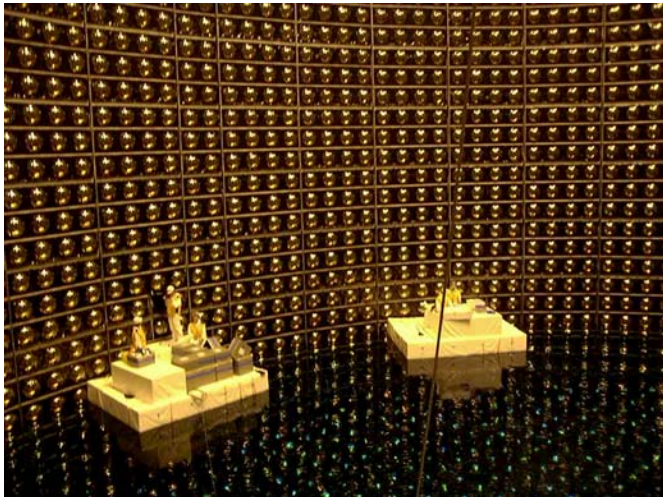
  Neutrino oscillations → in the SM, $m_\nu = 0$ by definition

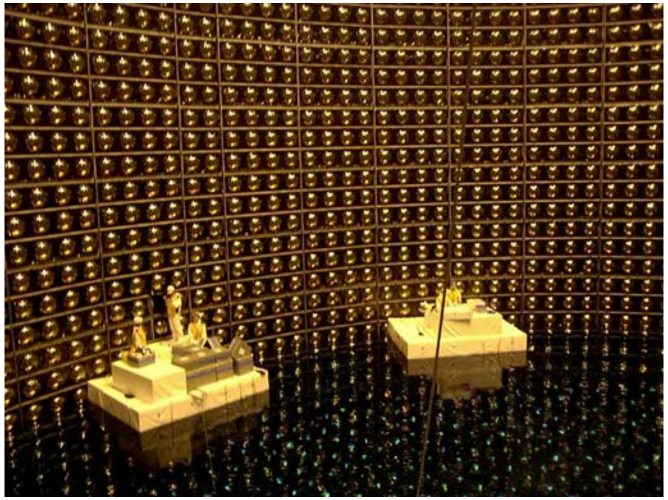
S-KAMIOKANDE



Any Sign of New Physics?

- There exist solid observations for physics beyond the Standard Model
  - Neutrino oscillations
  - Dark matter → no candidate particle in the SM

S-KAMIOKANDE

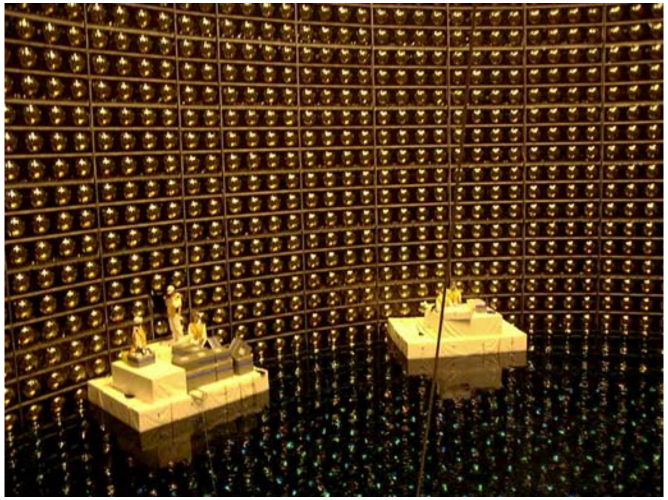


Bullet Galaxy Clusters

Any Sign of New Physics?

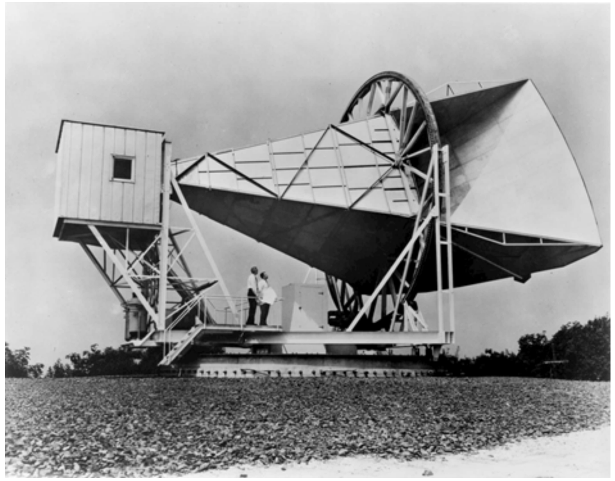
- There exist solid observations for physics beyond the Standard Model
  - Neutrino oscillations
  - Dark matter
  - $N_B / N_\gamma = 10^{-10}$ → the SM CPV not sufficient

S-KAMIOKANDE



Bullet Galaxy Clusters

The Horn Antenna
Bell Telephone Laboratory



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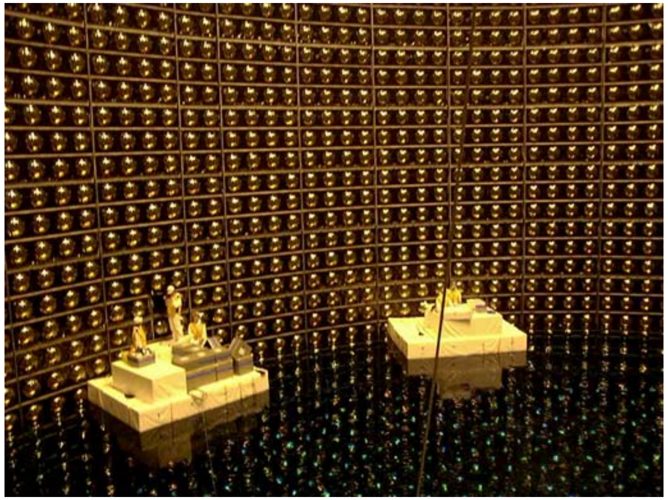

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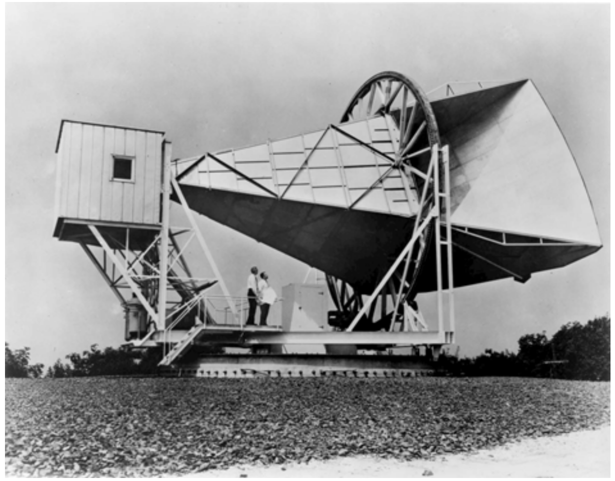

- And the SM includes no gravity, has too many parameters, requires some fine tunings, etc.

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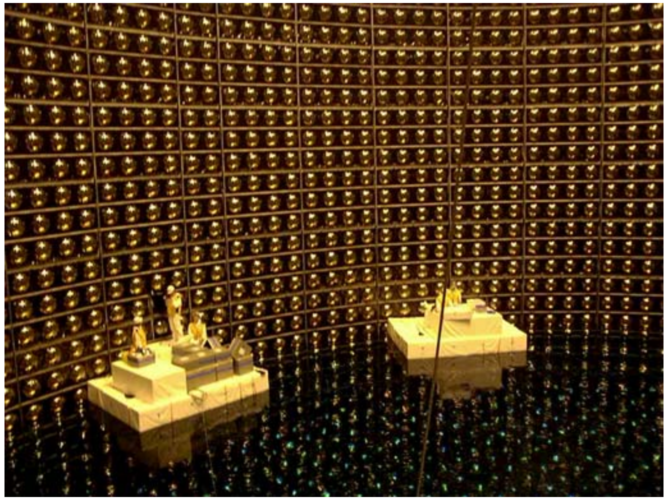

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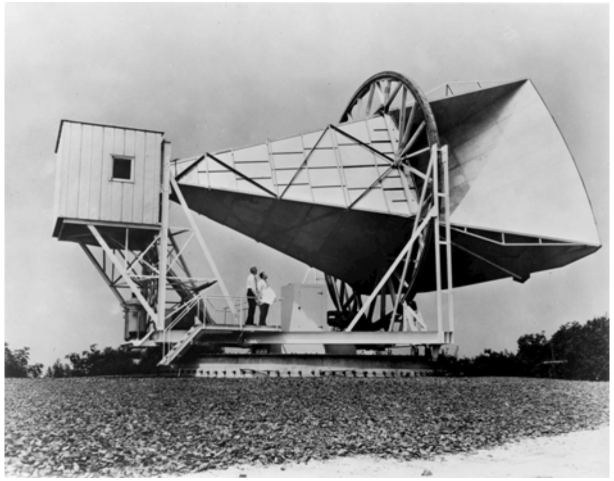
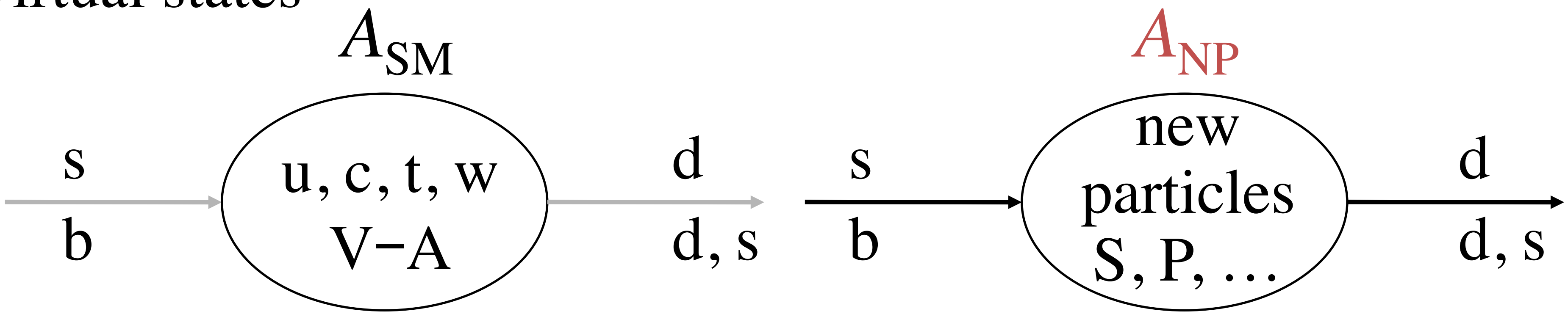


- And the SM includes no gravity, has too many parameters, requires some fine tunings, etc. However, we do not know whether the energy scale for new physics accessible to us…

Closer Look

In general, new physics can enter in the loop diagrams as virtual states



amplitude: $A = A_{SM} + A_{NP}$

Plan of Lectures

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Closer Look

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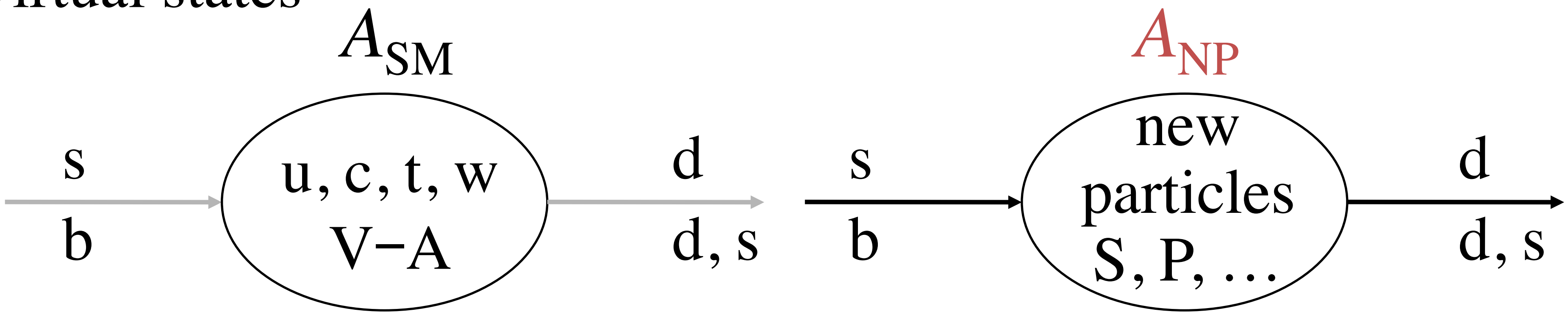

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|*A*|: rare decays (ΔF=1), Δm (ΔF=2)

arg *A*: CP violation

Closer Look

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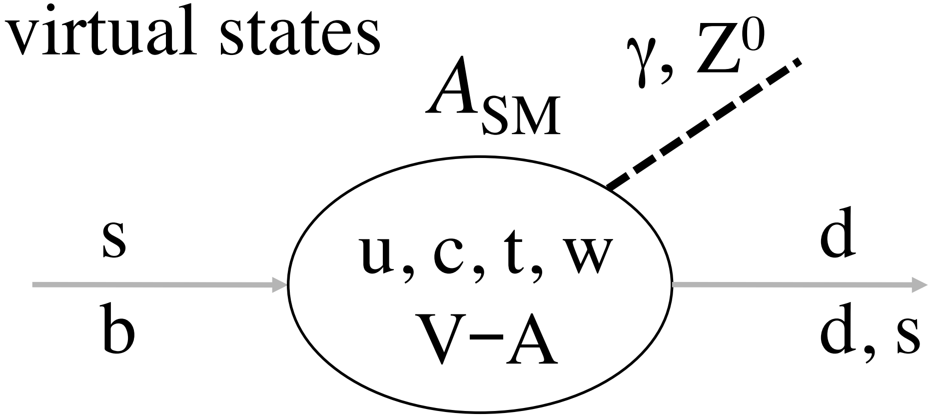

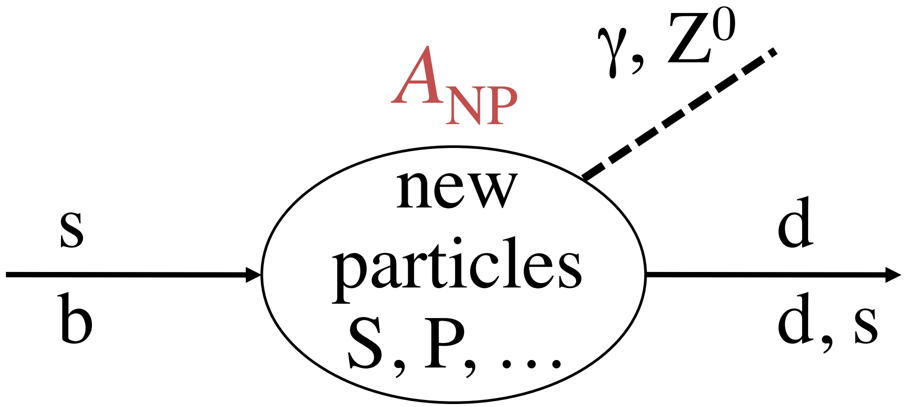

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Lorentz structure of A: "photon" polarization via
final state angular distribution or mixing-decay CP violation

Closer Look

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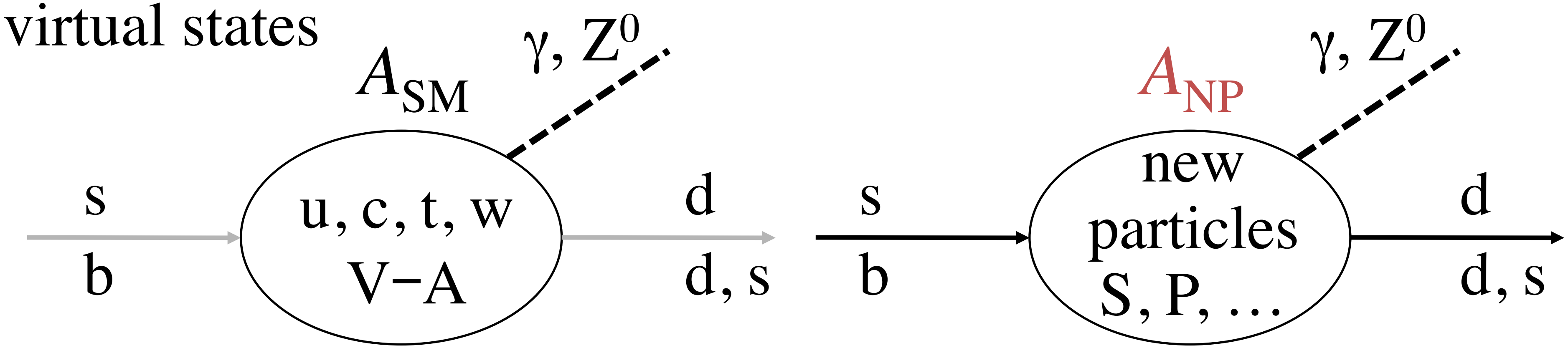

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Lorentz structure of A: "photon" polarization via

final state angular distribution or mixing-decay CP violation

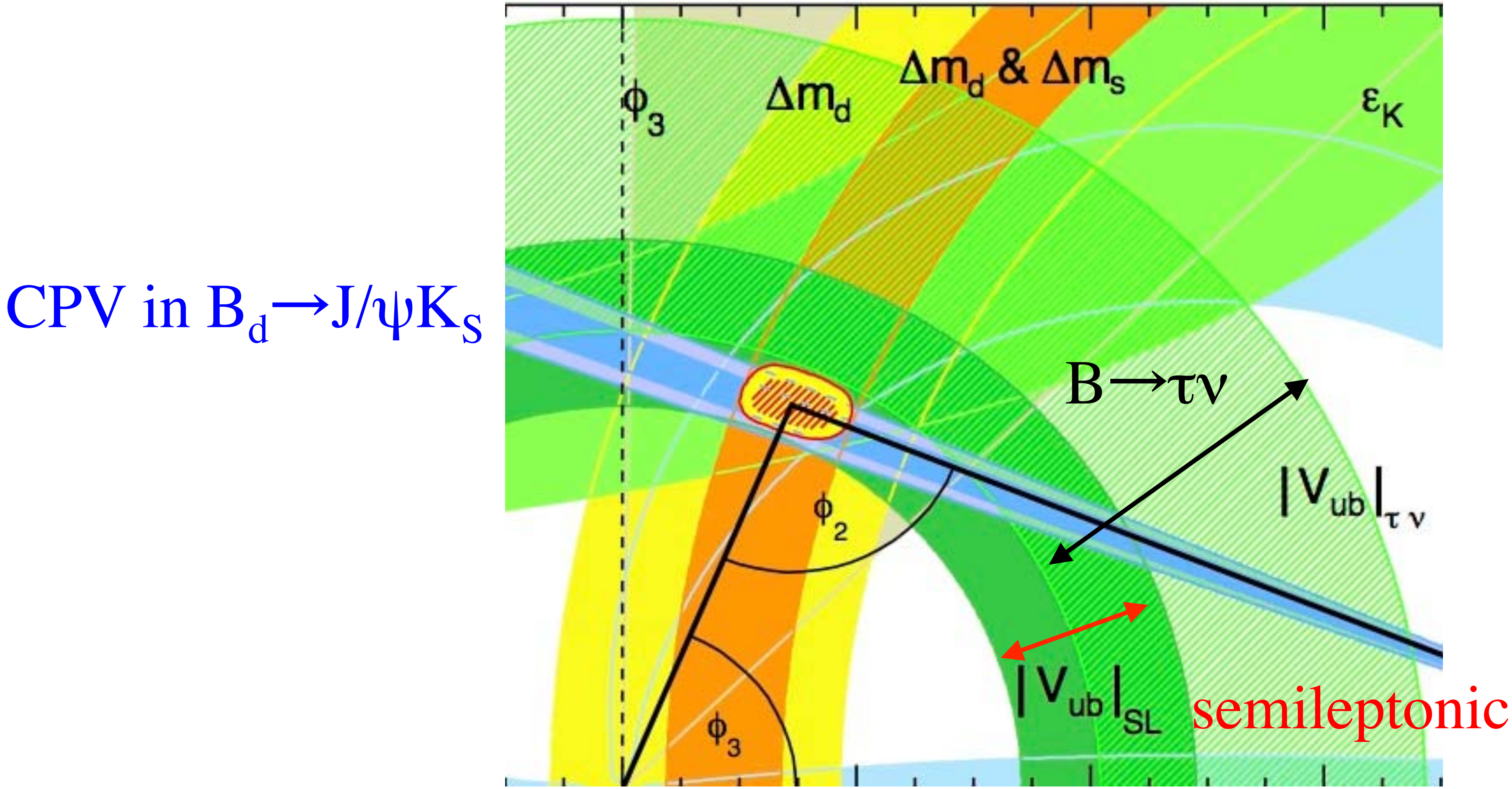
If coupling ≈ O(weak), already m(NP) > O(100TeV)

→ Minimal Flavour Violation (same origin for all FSB)?

Should be still visible in the Br. and Lorentz structure

Closer Look

- If one looks closer, any hint of discrepancies?
  - "sin 2β" extracted from CPV in $B_d \to J/\psi K_S$ somewhat small
  - $|V_{ub}|$ extracted from $B \to \tau\nu$ decays larger than $|V_{ub}|$ extracted from the semileptonic decays.



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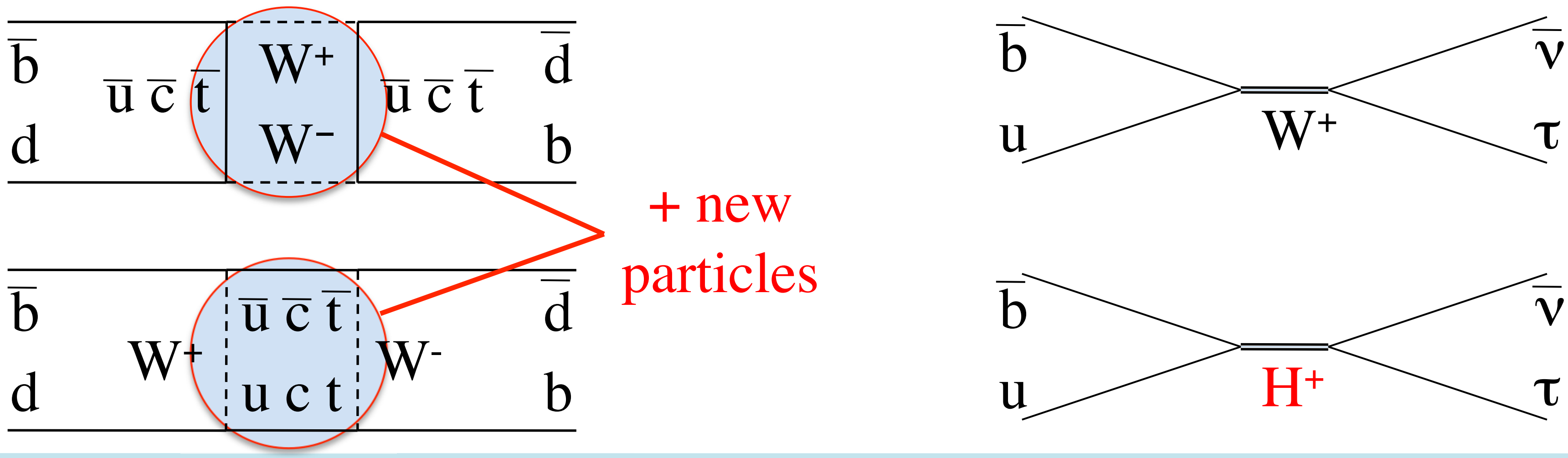
- This could be due to
  1. Problem with extracting $|V_{ub}/V_{cb}|$ due to the hadronic uncertainties
     OR
  2. New Physics in B^0-B^0 oscillations and charged Higgs in $B \rightarrow \tau\nu$



Closer Look

$|V_{cb}|$ and $|V_{ub}|$

Errors are dominated by the theoretical uncertainties in the strong interaction for the semleptonic decays.

⇒can be reduced by studying the decay kinematics,

e.g. lepton momentum, hadronic-mass distribution, etc.

with higher statistics in a clean environment

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Case for Super B Factories:

Closer Look

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Case for Super B Factories:

$|V_{ub}|$ from $B^{\pm}\rightarrow\tau^{\pm}\nu$ error still statistics limited.

Recent Belle: $(1.14\pm0.23)\times10^{-4}$, only 1.3σ away from SM

Another case Super B Factories

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Another case Super B Factories

$Br(B \to D^{(*)}\tau\nu)$ by BABAR: larger than SM by $\sim 3.4\sigma$,

also due to charged Higgs? (but only complicated ones)

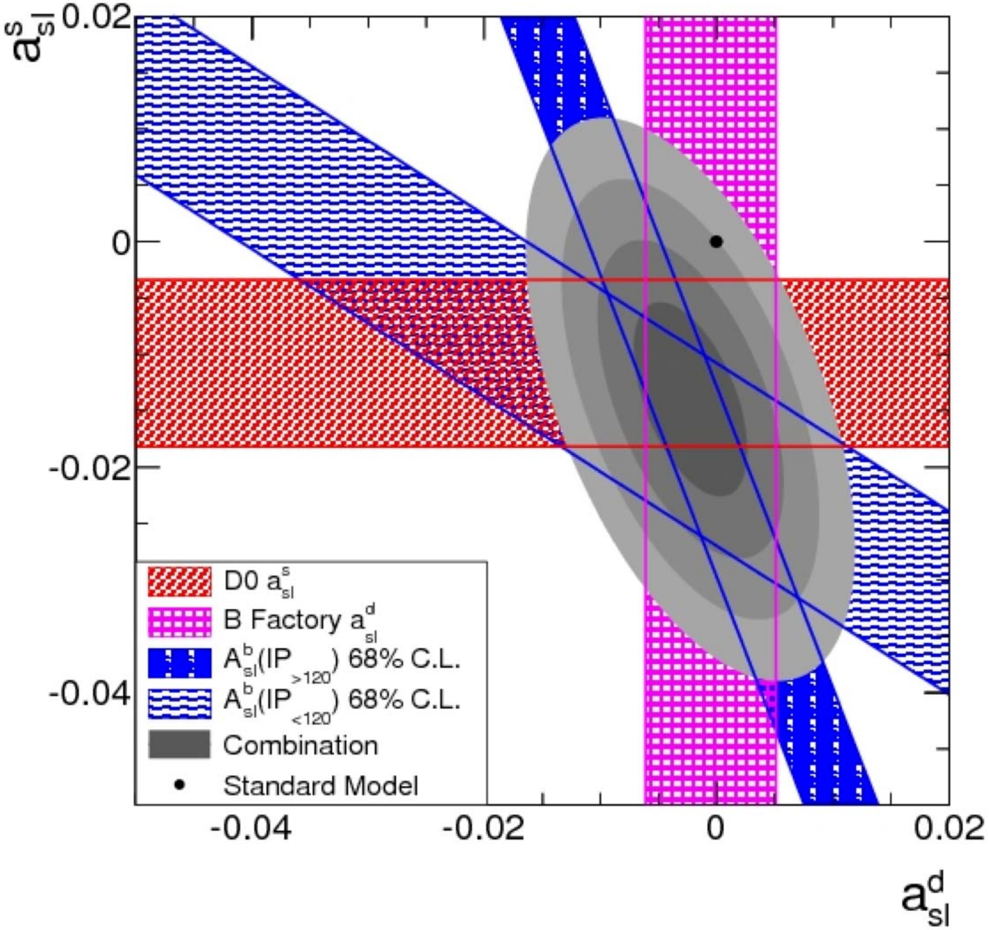
Looking forward to the Belle analysis

Closer Look

- CPV in the B_s system: used to be “almost” untouched territory:
  Started with CDF and D0

Closer Look

- CPV in the B_d-$\overline{B}_d$ and B_s-$\overline{B}_s$ oscillations: SM small
  D0 measures possibly large CPV for B_s



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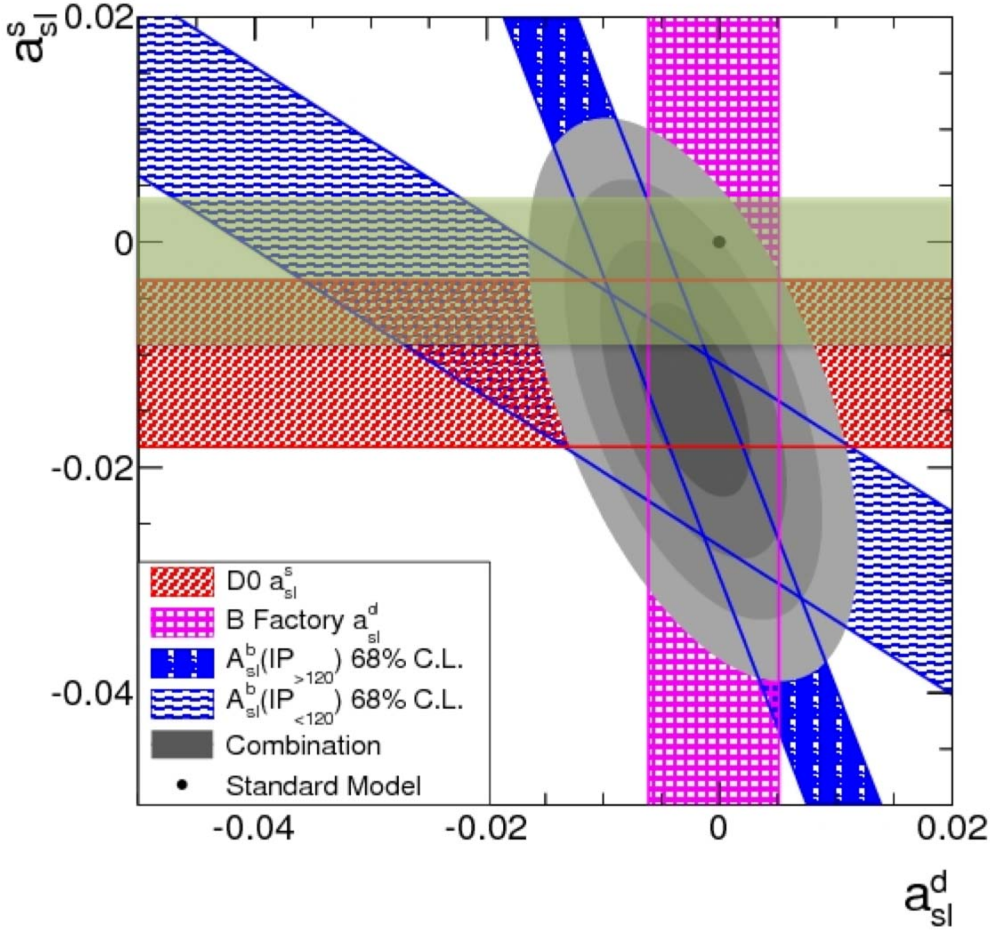
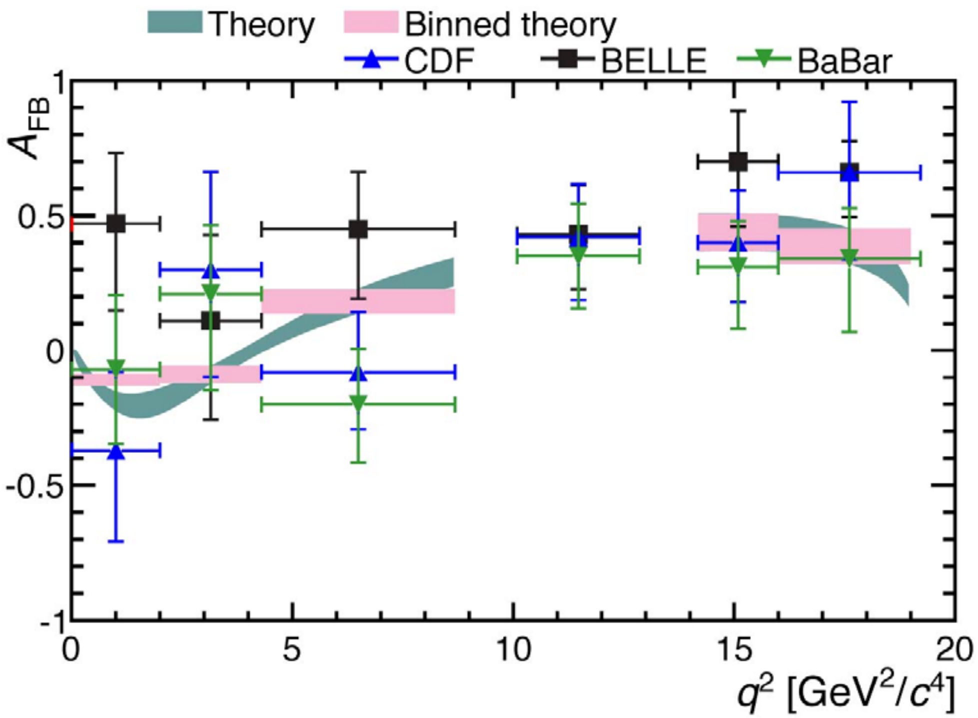


Not confirmed by
by LHCb 1 fb^{-1} data
Much more data
in future

Closer Look

- Lorentz structure of electroweak penguin current with $B \rightarrow K^{*0}\mu^+\mu^-$ decays:
  example: A_{FS} of the muon pairs v.s. $m^2(\mu^+\mu^-)$
  BABAR+BELLE+CDF: inconclusive



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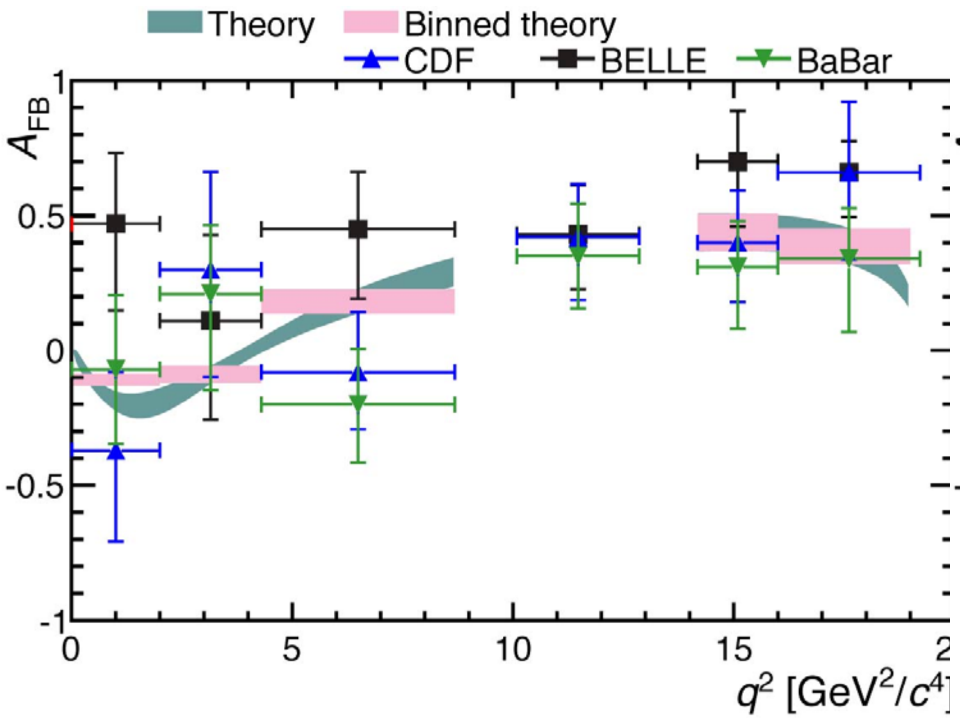
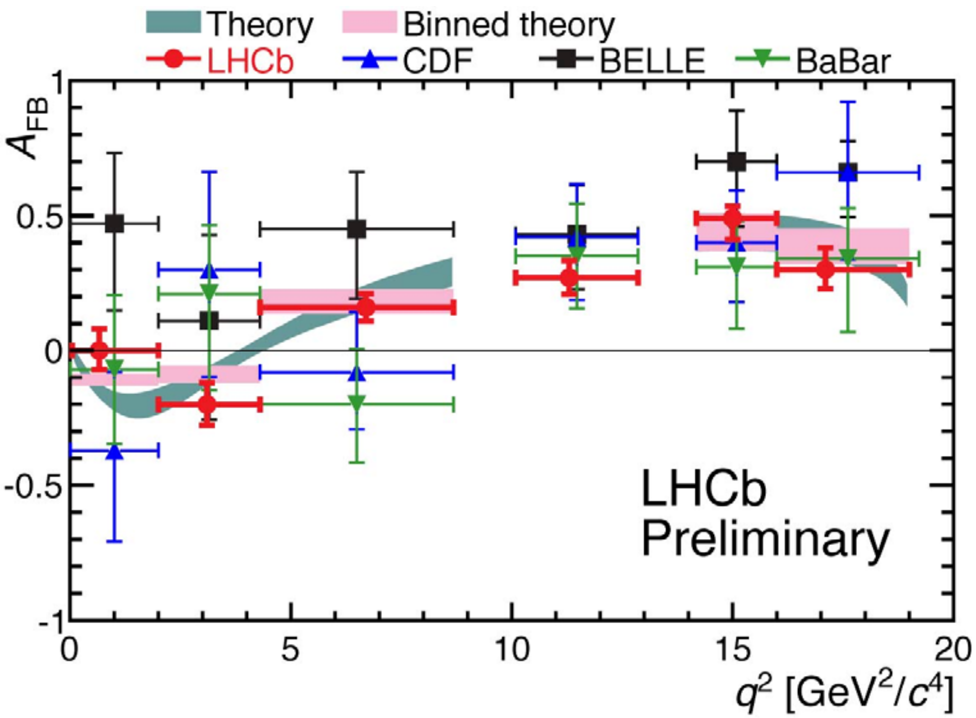
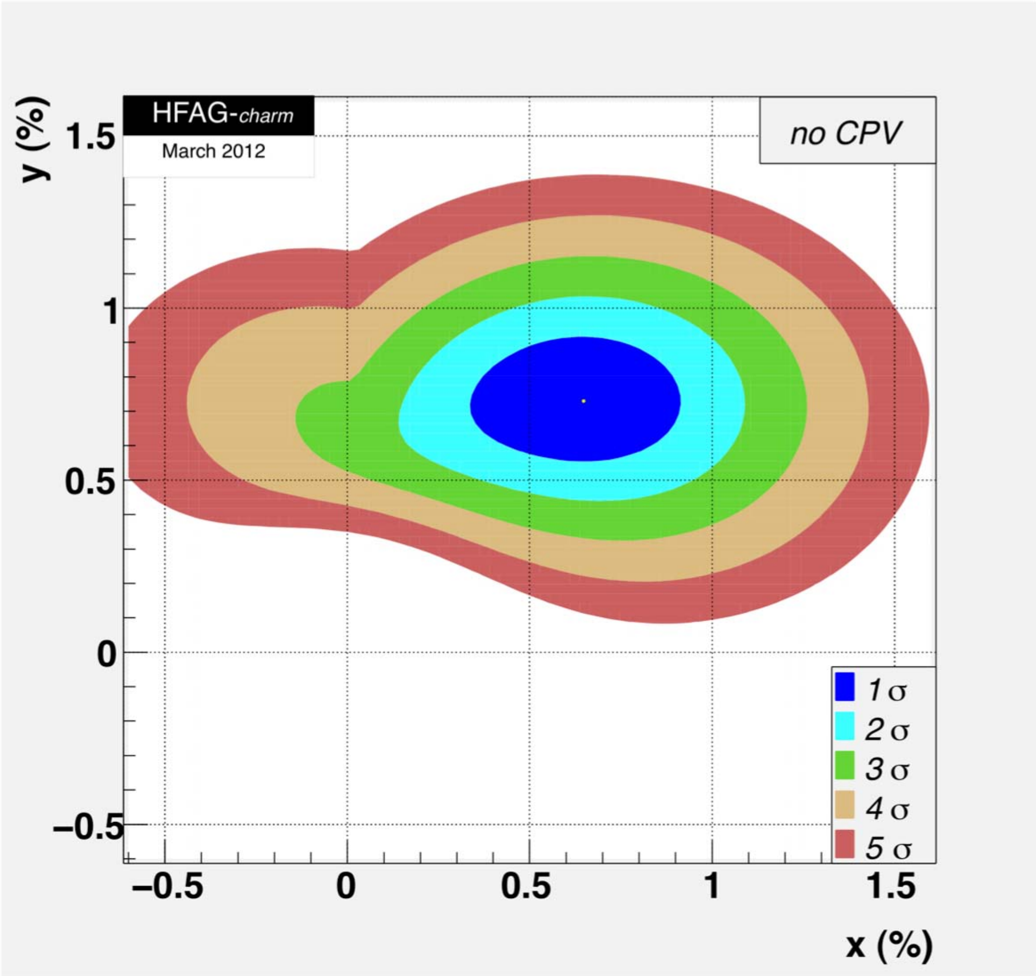
  LHCb (1 fb^{-1}) good agreement with SM





Closer Look

- Up-type quarks: D-meson system:
  $\bar{D}$-D mixing observed, SM prediction difficult



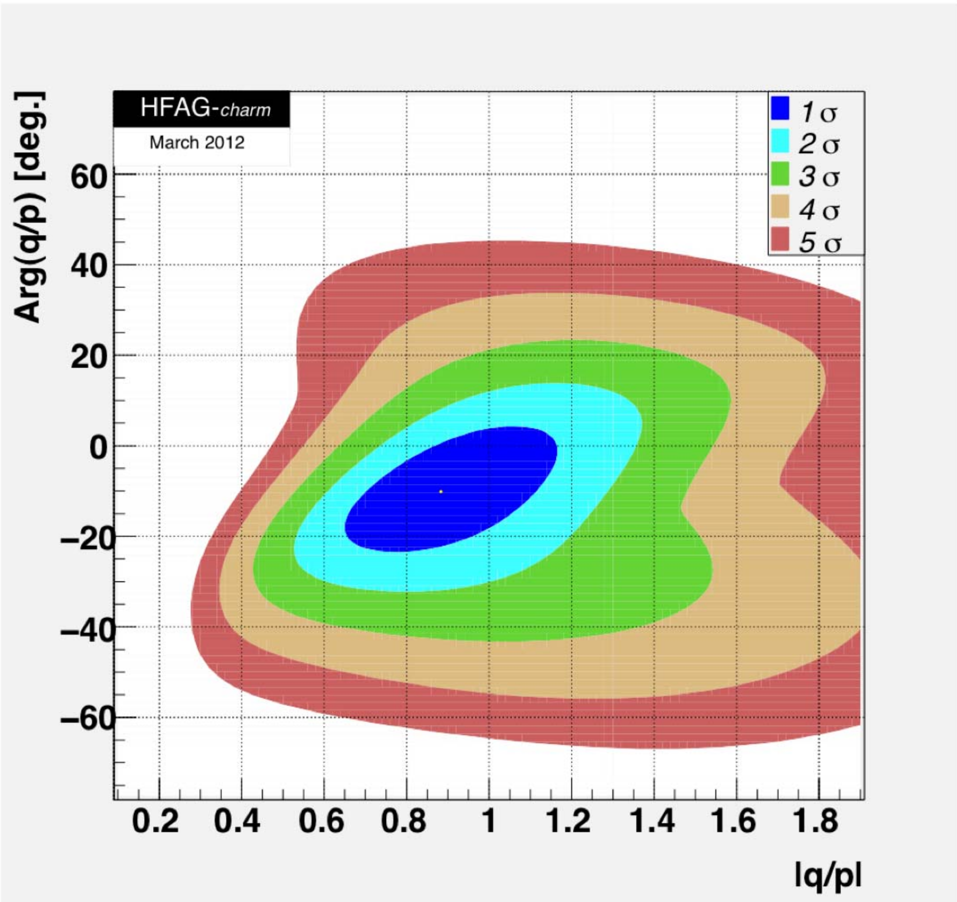
$x = \Delta m / \bar{\Gamma}$

$y = \Delta\Gamma / \bar{\Gamma}$

No mixing: $x = y = 0$

Closer Look

- Up-type quarks: D-meson system:
  $\bar{D}$-D mixing observed, SM prediction difficult
  CPV in $\bar{D}$-D oscillations not seen, small in SM



No CPV in oscillations

$|p/q|=1$

$\arg(p/q) = 0$

Closer Look

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  $\bar{D}$-D mixing observed, SM prediction difficult
  CPV in $\bar{D}$-D oscillations not seen, small in SM
  CPV in the decay amplitudes: ???

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  CPV in the decay amplitudes: ???

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

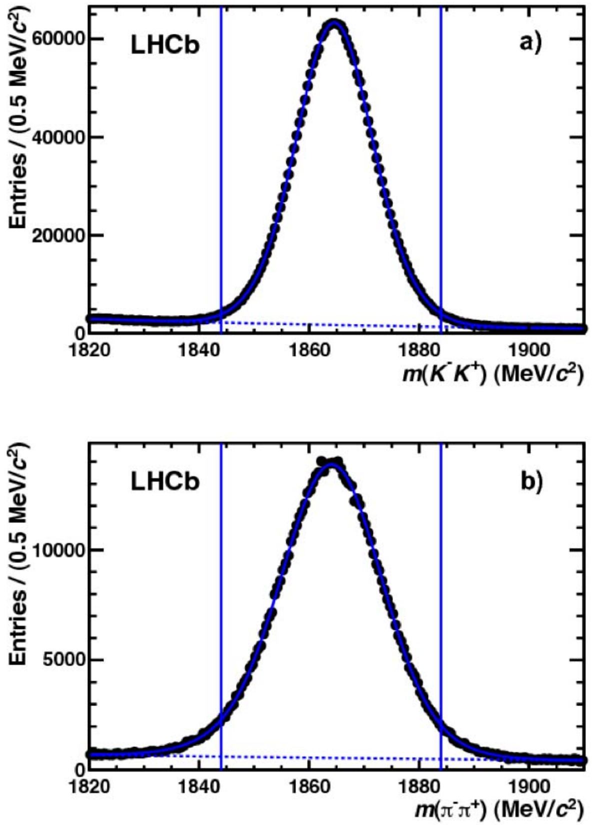
LHCb	-0.82 ± 0.24	$(0.62\ \mathrm{fb}^{-1})$
CDF	-0.62 ± 0.23	
Belle	-0.87 ± 0.41	

SM expectation was $O(10^{-3})$
could be stretched to $\sim 5\times10^{-3}$?

Closer Look

- Up-type quarks: D-meson system:
  $\bar{D}$-D mixing observed, SM prediction difficult
  CPV in $\bar{D}$-D oscillations not seen, small in SM
  CPV in the decay amplitudes: ???

More data with LHCb will be interesting
c.f. very clean tagged D signal



And Bigger Picture

- Kaon physics $K^+ \rightarrow \pi^+ \nu\nu$, $K^0_L \rightarrow \pi^0 \nu\nu$
  testing of MFV

- Charged lepton flavour violation search
  SUSY?

- And even more fundamental…
  Quark-lepton flavour unification?
  Origin of flavour structure?

Plan of Lectures

- Direct-search versus Indirect-search
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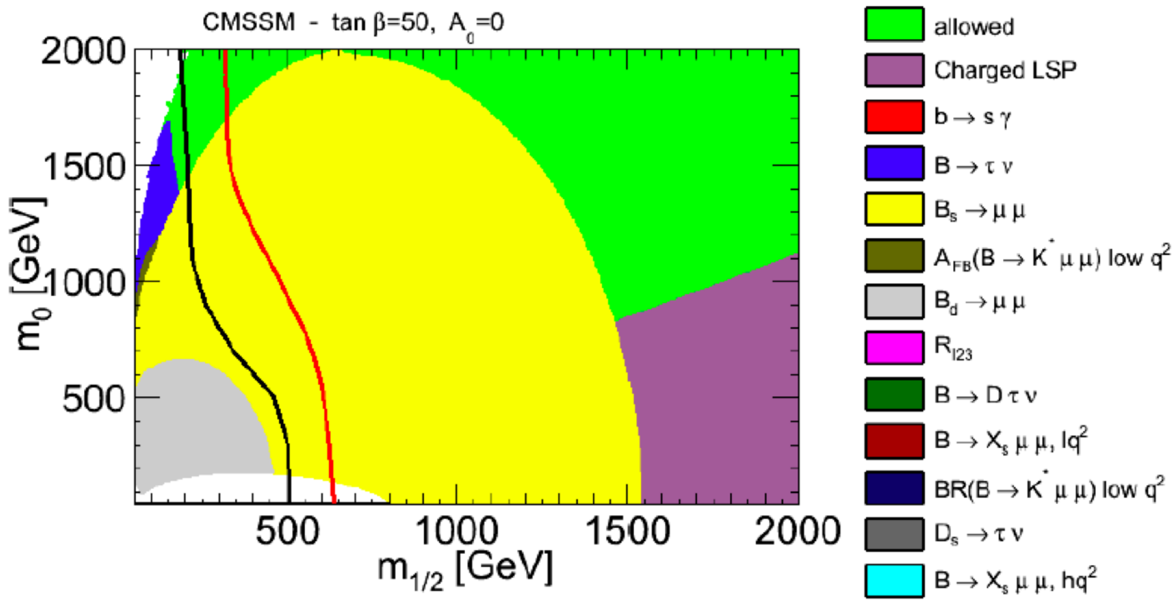
Epilogue

Synergy between the direct and indirect search

Implications



Black line: CMS exclusion limit with 1.1 fb^{-1} data

Red line: CMS exclusion limit with 4.4 fb^{-1} data

New LHCb limits for $\text{BR}(B_s \to \mu^+\mu^-)$ and $\text{BR}(B_d \to \mu^+\mu^-)$

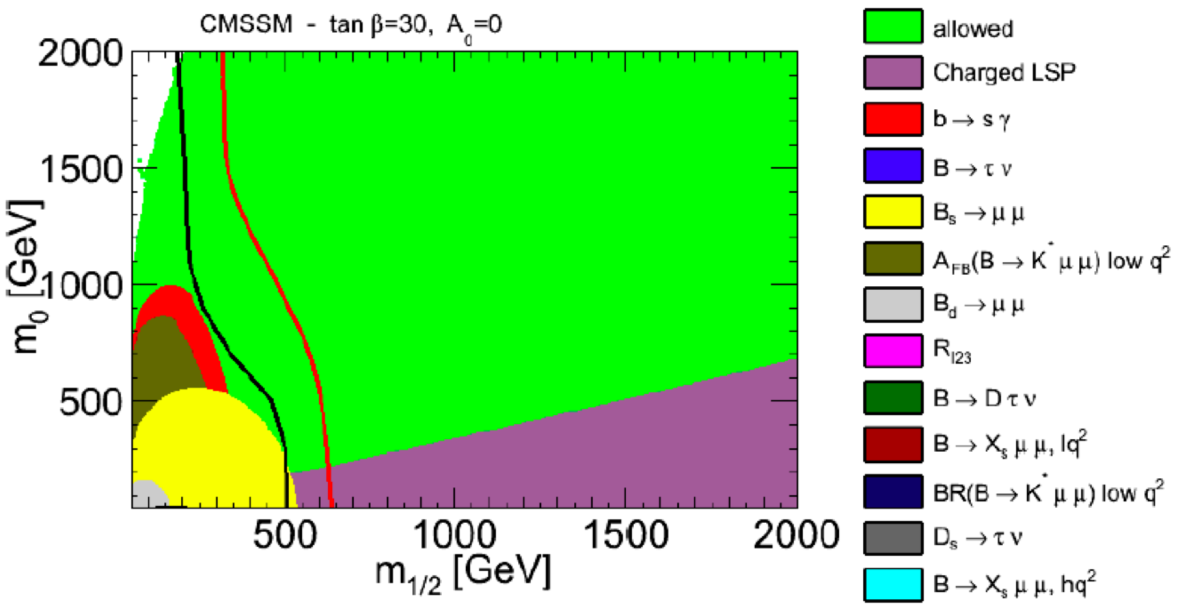
SuperIso v3.2+

Nazila Mahmoudi CERN, March 30, 2012

Epilogue

Synergy between the direct and indirect search

Implications



Black line: CMS exclusion limit with 1.1 fb^{-1} data
Red line: CMS exclusion limit with 4.4 fb^{-1} data
New LHCb limits for BR($B_s \to \mu^+\mu^-$) and BR($B_d \to \mu^+\mu^-$)

SuperIso v3.2+

Nazila Mahmoudi CERN, March 30, 2012

Epilogue

By the ~~middle of 2012…~~ end of 2017

ATLAS CMS high p_T physics	BSM
LHCb flavour physics	Only SM
Particle Physics	☺

Epilogue

By the ~~middle of 2012…~~ end of 2017

ATLAS CMS high p_T physics	BSM	Only SM
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Epilogue

By the ~~middle of 2012…~~ end of 2017

ATLAS CMS high p_T physics	BSM	Only SM	BSM
LHCb flavour physics	Only SM	BSM	BSM
Particle Physics	☺	☺	☺

Epilogue

By the ~~middle of 2012…~~ end of 2017

ATLAS CMS high p_T physics	BSM	Only SM	BSM	
LHCb flavour physics	Only SM	BSM	BSM	
Particle Physics	☺	☺	☺	

Oh, no more space left…

Epilogue

In any case,

Exciting time is ahead of us all.