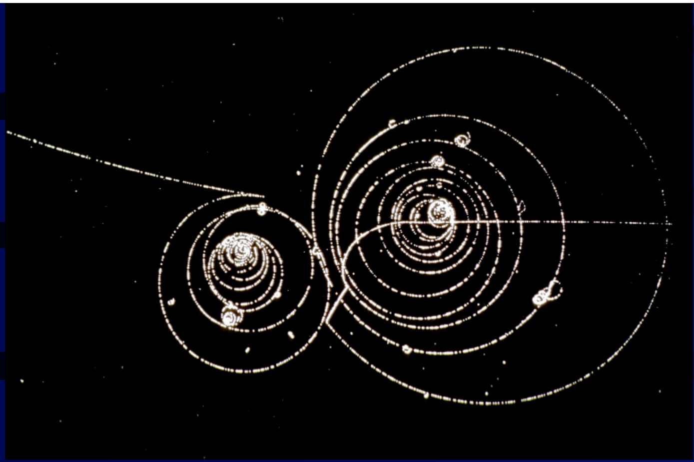 

# Precision Studies in the Quark Sector and the Search for “New Physics”


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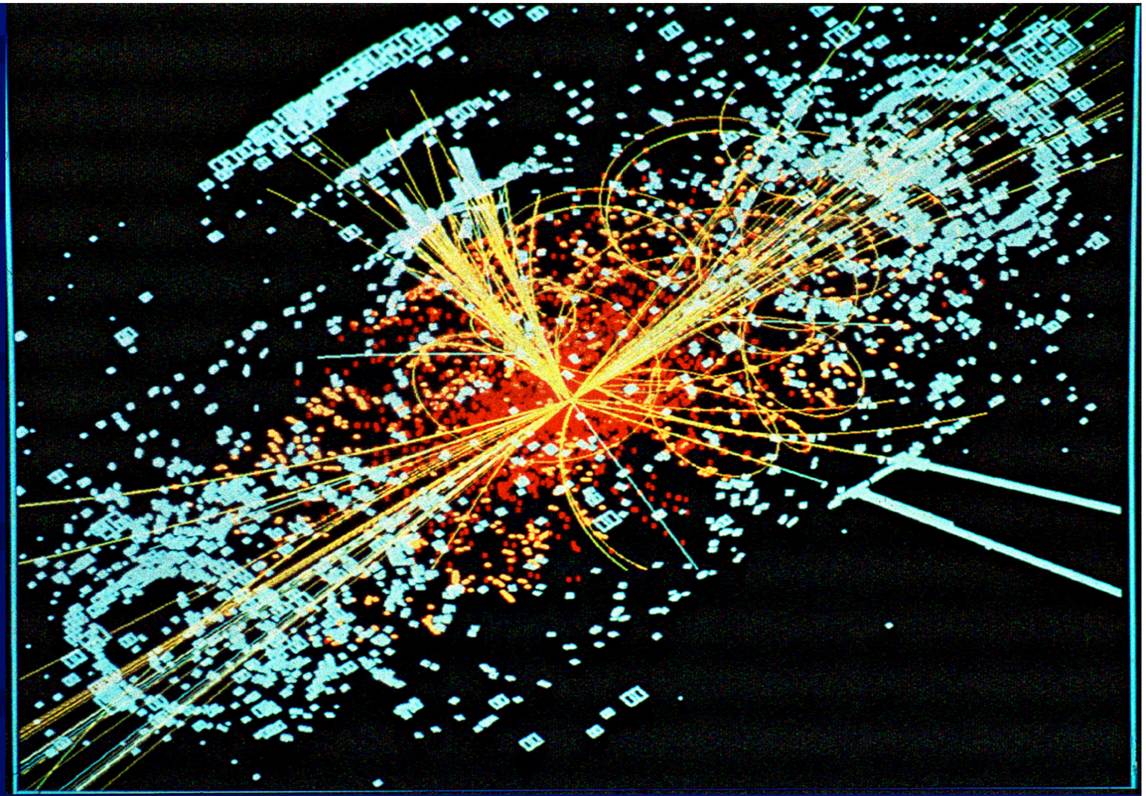
# Overview

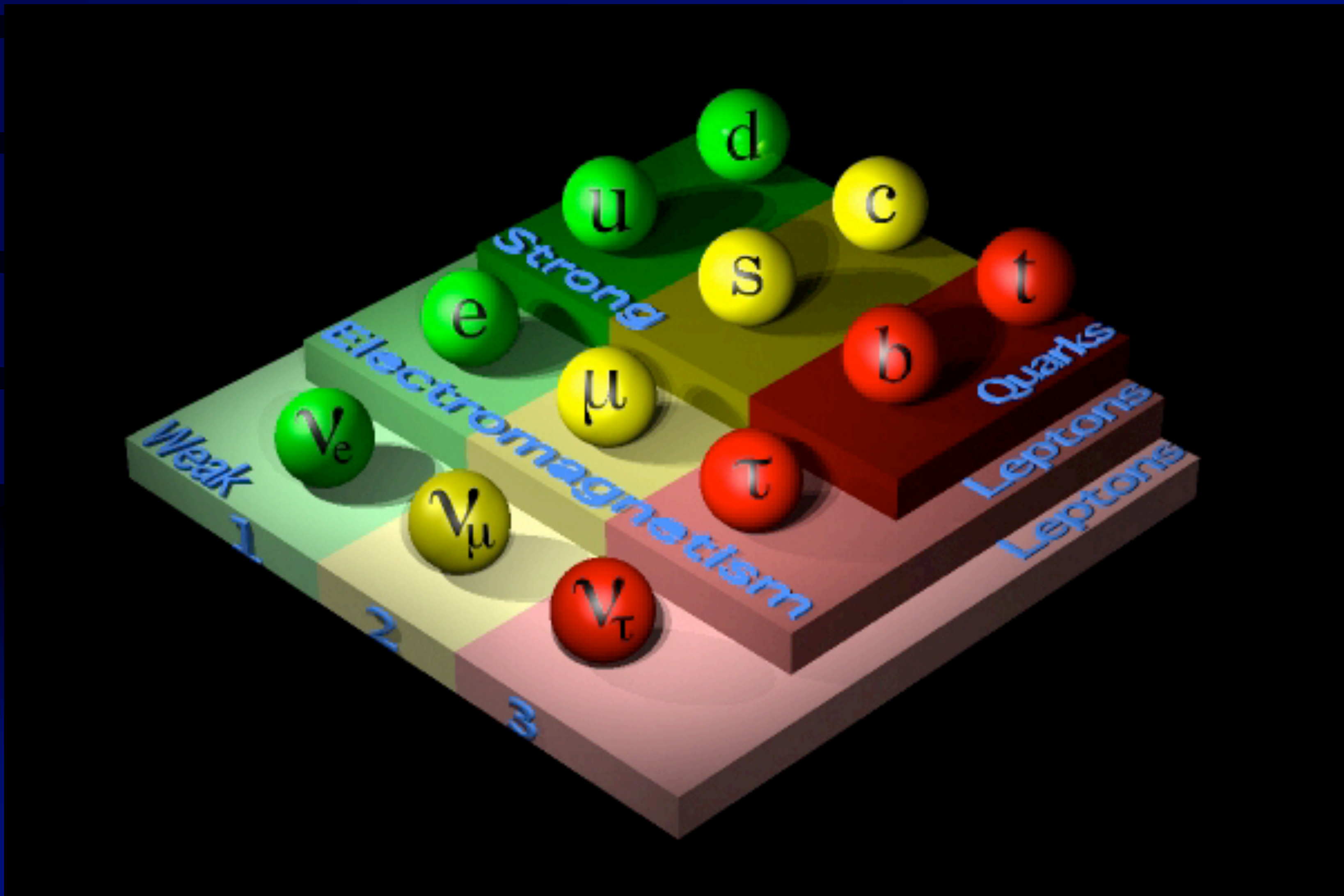
- Introduction
- Open questions in flavor physics
- Mixing of neutral mesons & CP violation
- Precision studies of the CKM matrix
- Hints of "New Physics"?
- Conclusions

# Introduction



Concepts and open questions in high-energy physics

# The Standard Model

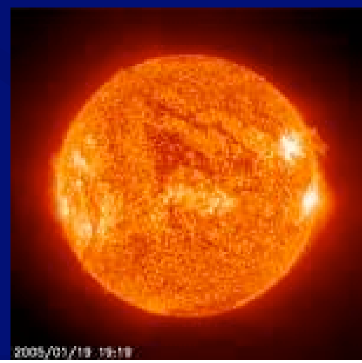


# Forces of Nature …

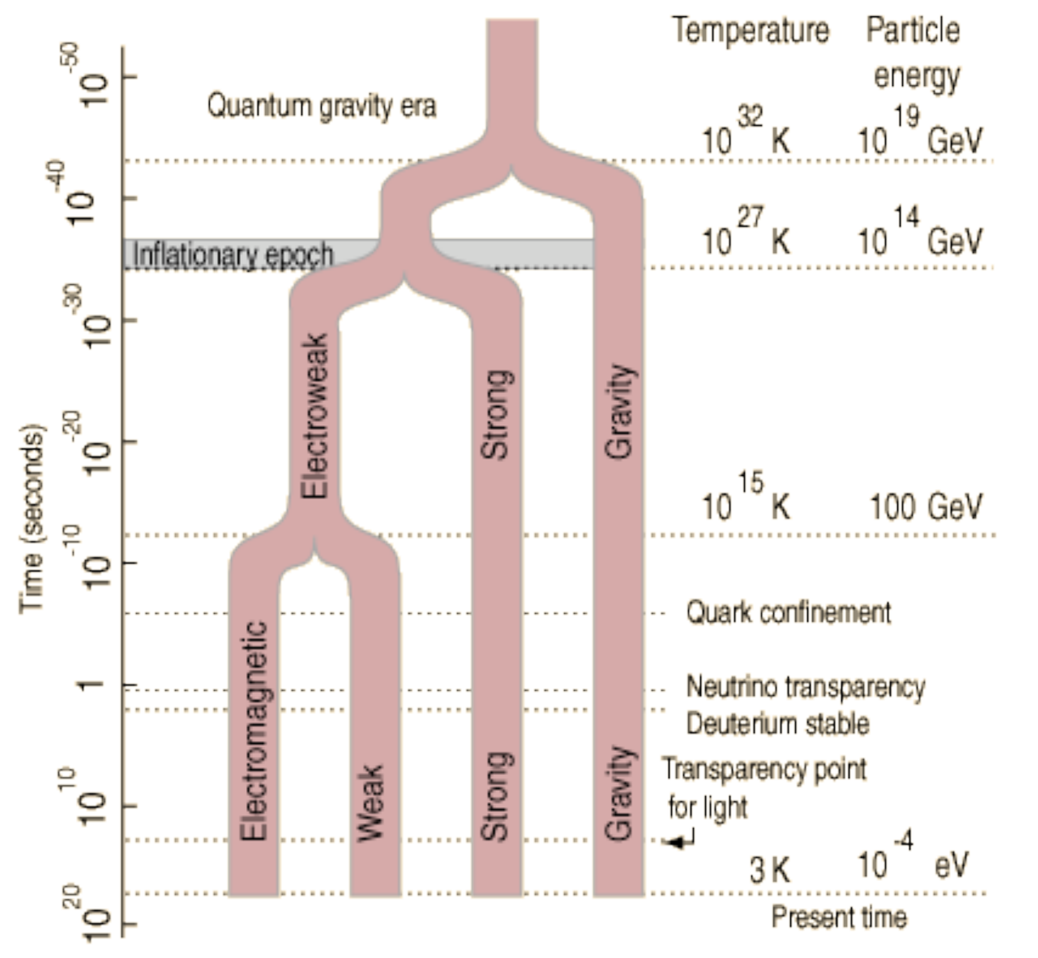



# Fundamental forces

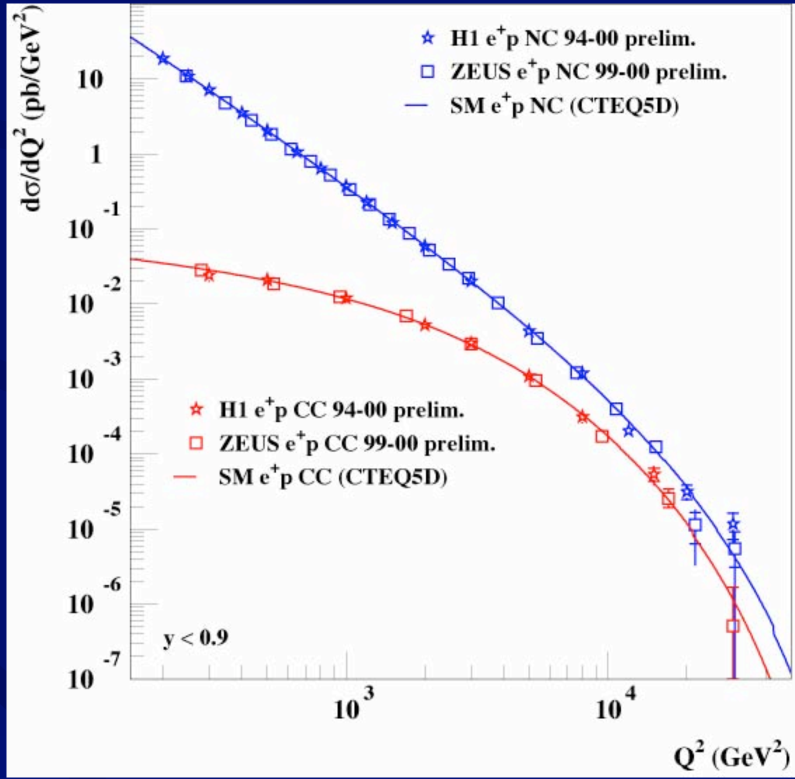
- Gravity:
  - classical description: general relativity
  - quantum gravity: string theory, alternatives?
- Electromagnetism:
  - quantum electrodynamics (QED), abelian gauge theory
- Strong interaction:
  - quantum chromodynamics (QCD), nonabelian gauge theory
- Weak interaction:
  - quantum flavordynamics, spontaneously broken nonabelian gauge theory
  - unification with electromagnetism for energies above 100 GeV



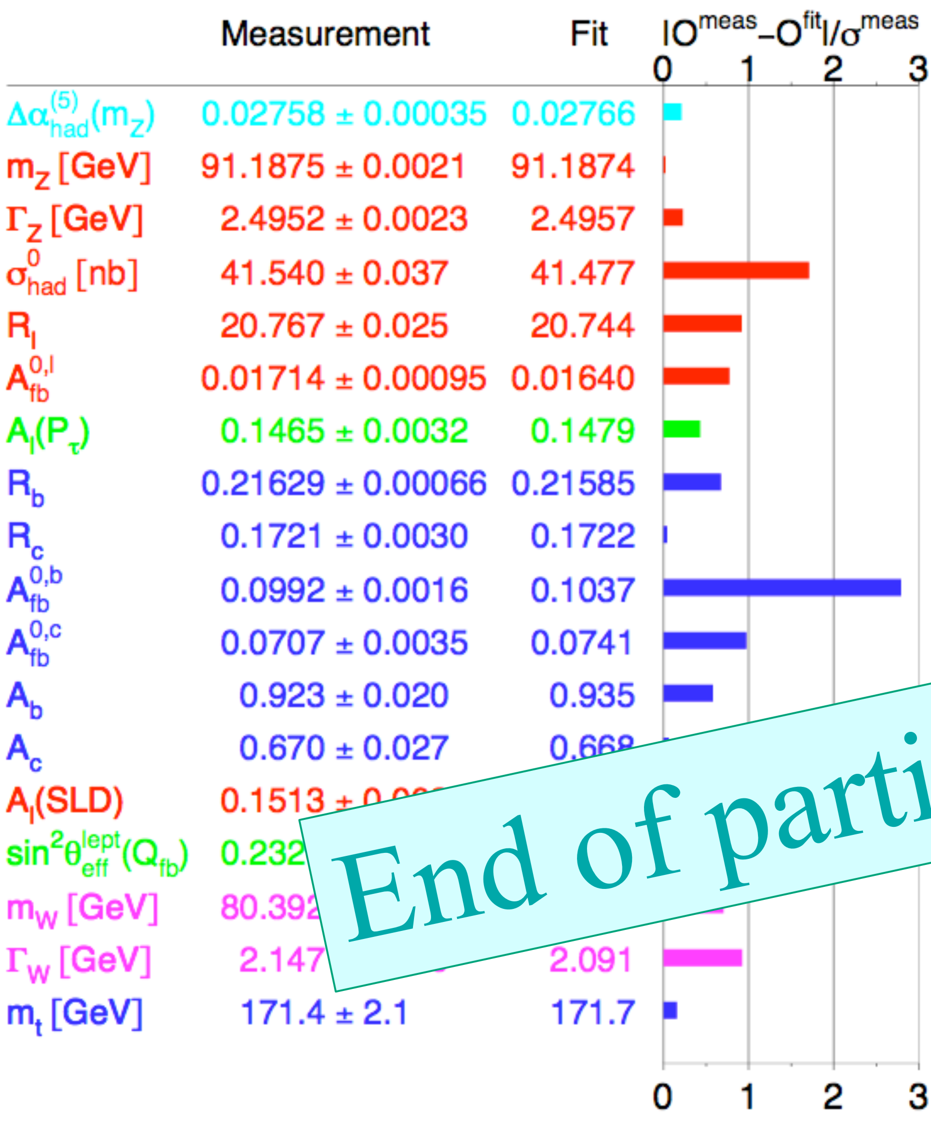
# Grand unification?

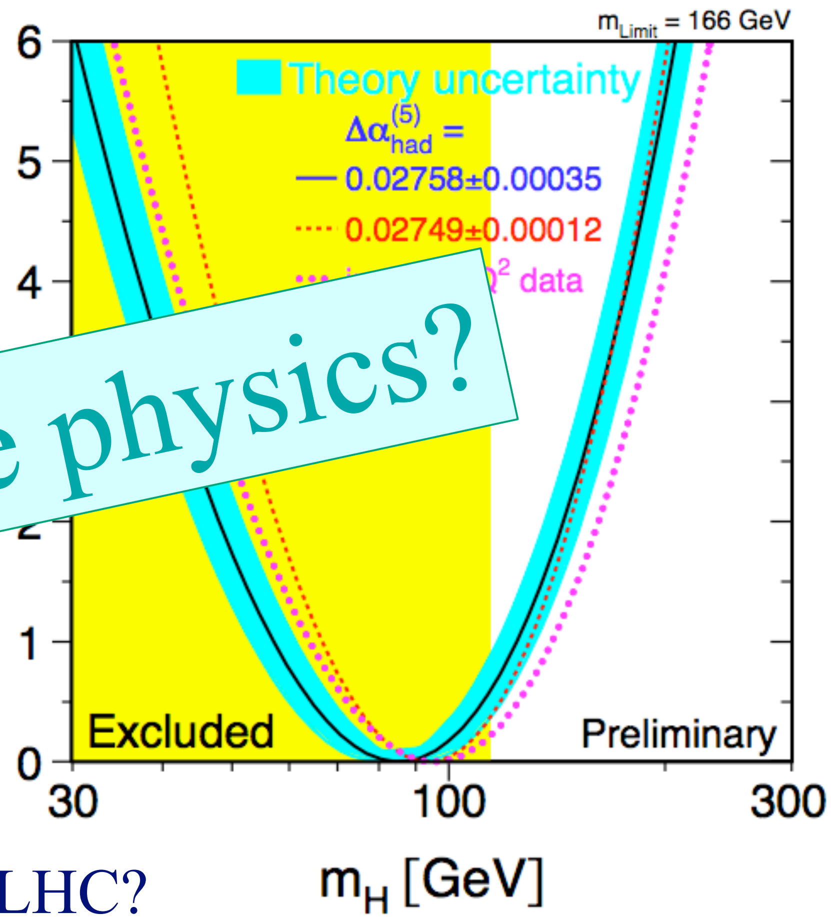



- First step:
  electroweak unification
  (HERA data, DESY)



- Indirect determination of the Higgs mass:



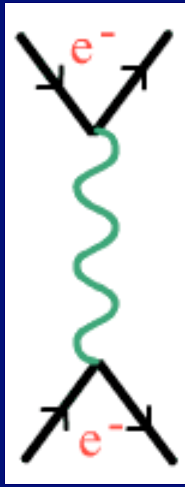

End of particle physics?

Imminent Higgs discovery at Tevatron/LHC?

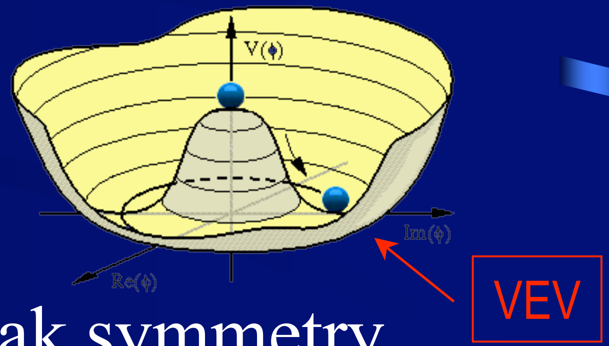
# Special role of weak interaction

- Complete understanding of weak force still a challenge:
  - breaking of electroweak symmetry?
  - mass generation for weak gauge bosons ($W^{\pm}$,$Z^0$)?
  - explanation of Yukawa couplings?
    (mass generation for fermions)

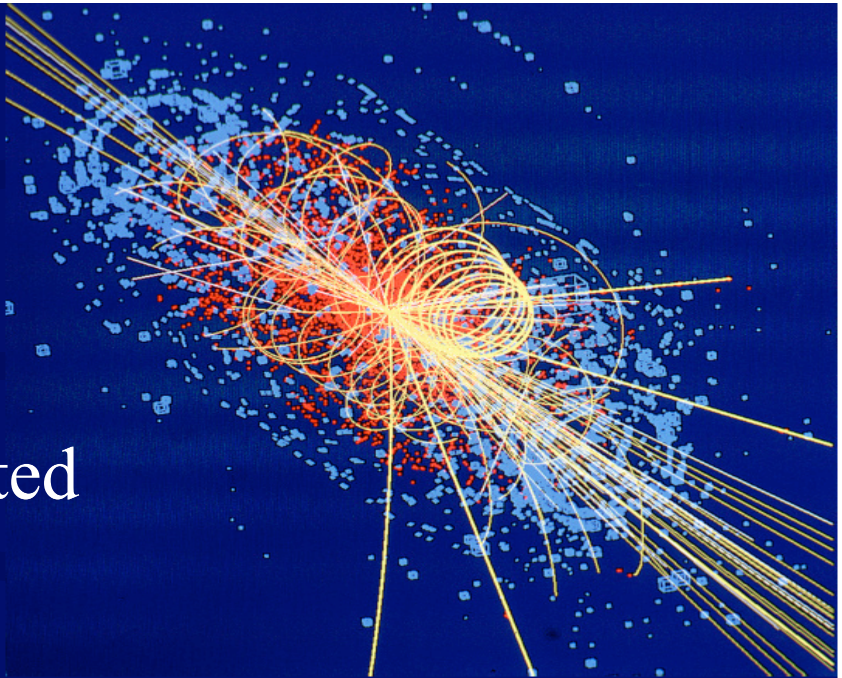
# Hierarchy problem




- Quantum fluctuations produce enormous masses for all particles not protected by a symmetry
- Importance of gauge invariance:
  - massless gauge bosons (γ,g,W,Z)
  - massless chiral fermions (q,l)
- Spontaneous breaking of electroweak symmetry generates "small" masses ~ <H> for W, Z and for quarks and leptons



# Hierarchy problem



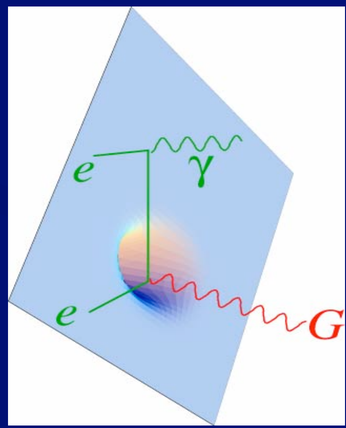
- Higgs mass itself not protected by a symmetry:

$m_H \ll M_{GUT} \sim 10^{16}$ GeV unnatural!

Higgs discovery = birth of the hierarchy problem
(not completion of Standard Model)

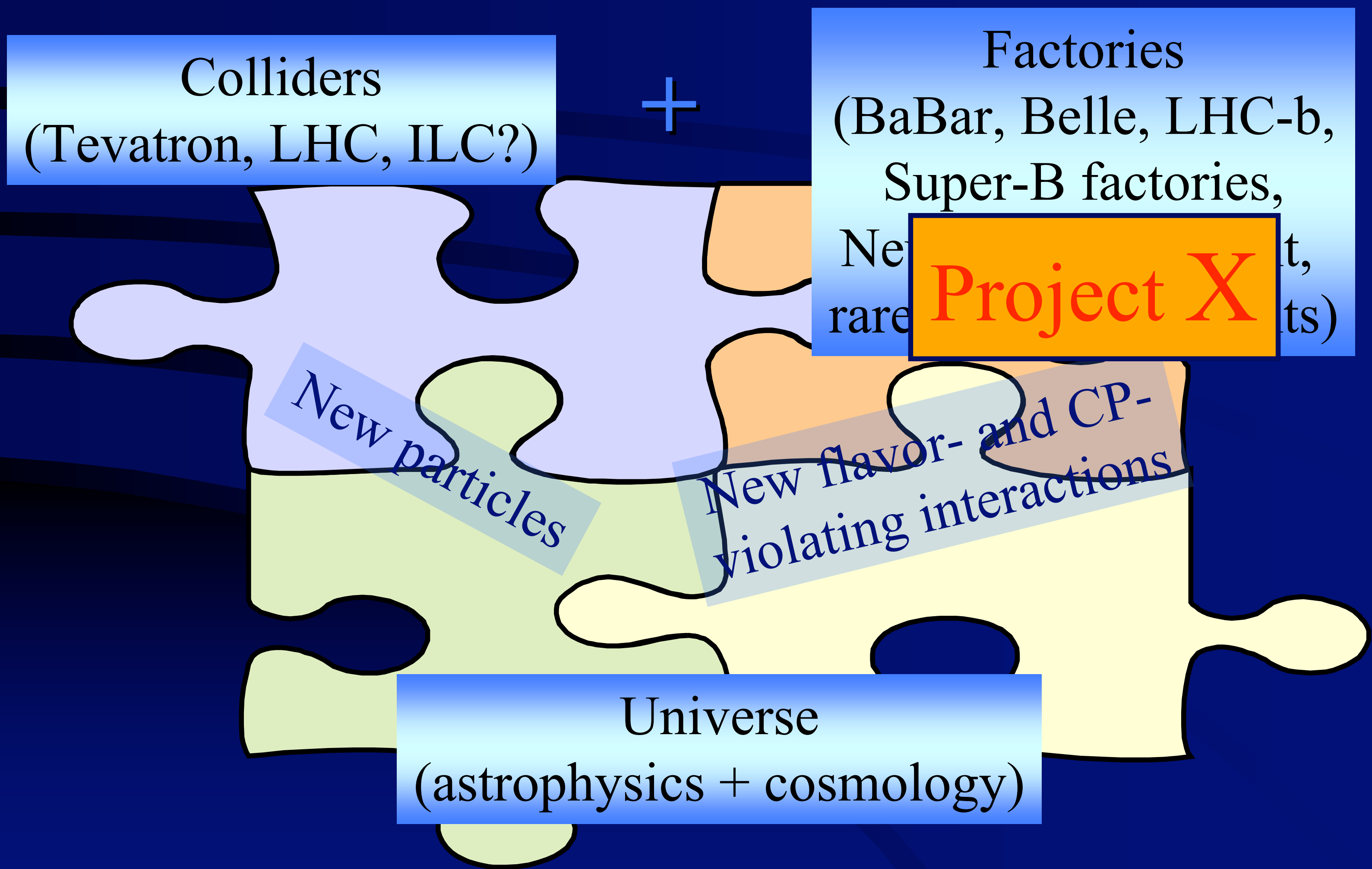
# Proposed solutions ("New Physics")

- Supersymmetry:
  - new symmetry at TeV scale protecting the Higgs mass
- Extra dimensions:
  - Elimination of the Planck scale
- Technicolor:
  - Higgs as a bound state of a new strong force operating at the TeV scale
- "Little Higgs" models:
  - Higgs as a pseudo-Goldstone boson



# Search for “New Physics” …

# Complementarity



# Flavor physics in the LHC era

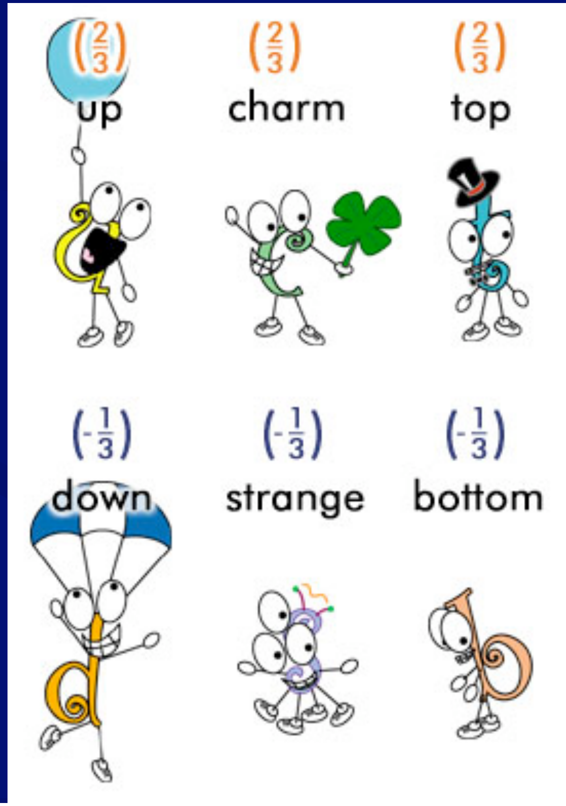
- Flavor physics can be sensitive to “New Physics” at scales of 1-1000 TeV, far exceeding those accessible at LHC and ILC
- Many flavor- and CP-violating couplings can only be probed at highest luminosity
- Indirect searches for “New Physics” will profit from LHC discoveries!

# Open Questions in Flavor Physics

Generation problem,
hierarchies, CP violation

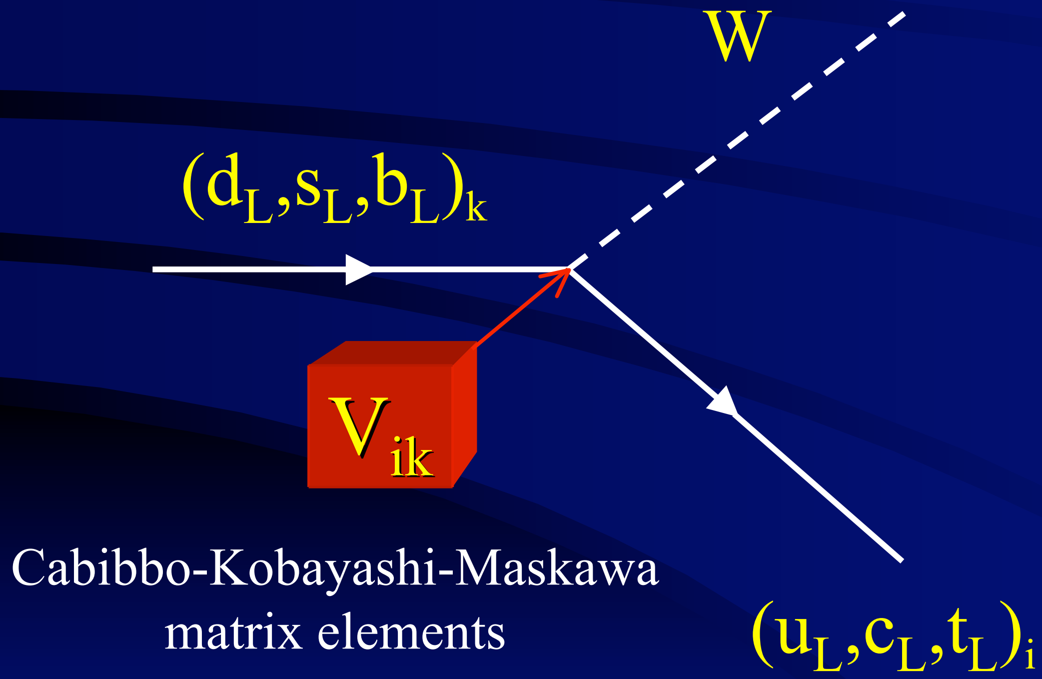
# Generation problem

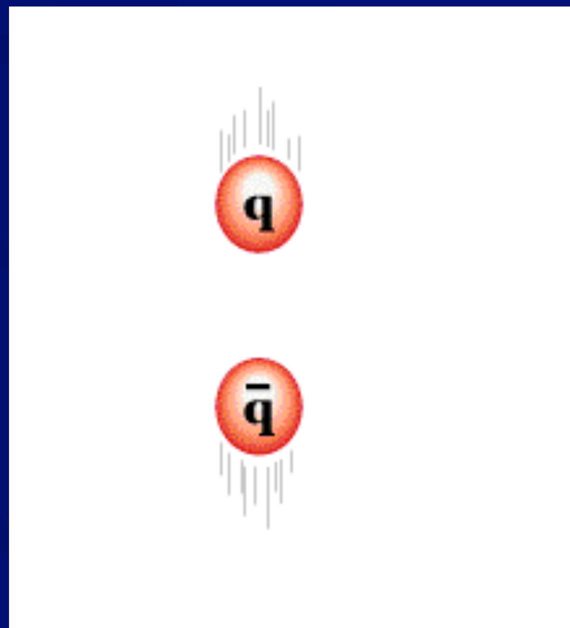
- Gauge forces do not distinguish between fermions of different generations
  - e, μ have same charges
  - quarks have same color
- Why 3 generations?
- New quantum number?
- Many parameters, hierarchies (masses and mixing angles)



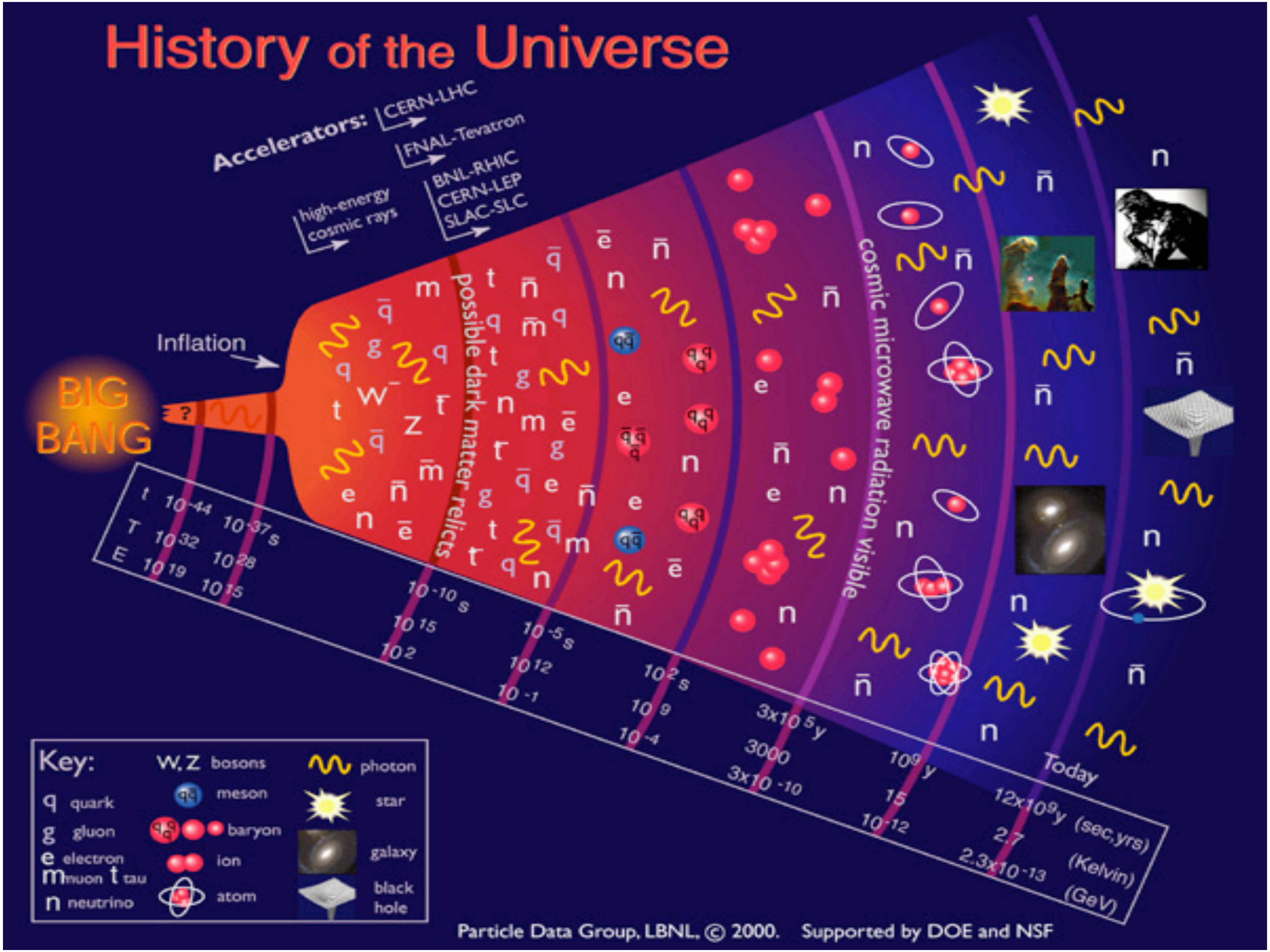
# Communication between generations

- Flavor-changing weak interactions:




- Complex entries: CP violation!


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t $10^{-44}$
T $10^{32}$
E $10^{19}$
$10^{-37}$ s
$10^{28}$
$10^{15}$
$10^{-10}$ s
$10^{15}$
$10^{2}$
$10^{-5}$ s
$10^{12}$
$10^{-1}$
$10^{2}$ s
$10^{9}$
$10^{-4}$
$3 \times 10^{5}$ y
3000
$3 \times 10^{-10}$
$10^{9}$ y
15
$10^{-12}$
Today
$12 \times 10^{9}$ y (sec,yrs)
2.7 (Kelvin)
$2.3 \times 10^{-13}$ (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

# Strategies in flavor physics

- Two paths to discovery:
  - precision measurements of CKM parameters
  - studies of rare decays with small Standard Model "background" (e.g., $B \to X_s\gamma$, $B \to X_s l^+ l^-$, $B \to \tau\nu$, $B_s \to \mu\mu$)
  - various 2-3σ effects exist, which could be interpreted as hints of "New Physics" in $B$-$\bar{B}$ mixing or in rare decay processes (FCNC)
  - among more compelling hints, with $(g-2)_\mu$, for physics beyond the Standard Model

# CKM mixing matrix

- Wolfenstein parameterization exhibits hierarchy of matrix elements:

b-sector CPV

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

t-sector CPV

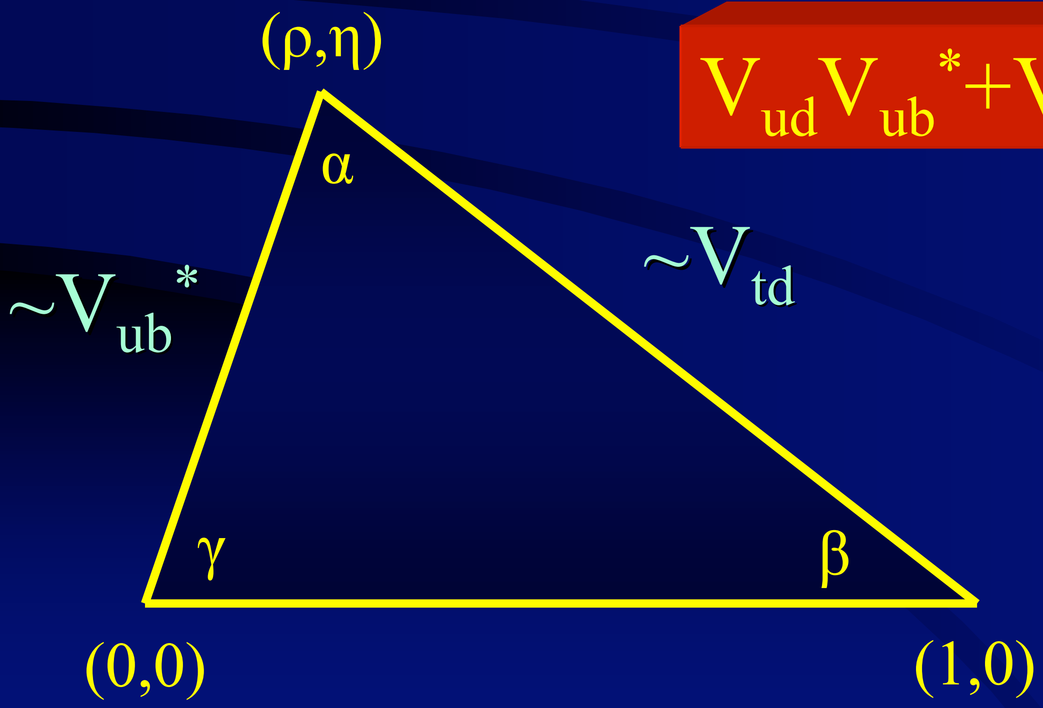
$\lambda$=0.227, A=0.82
well measured

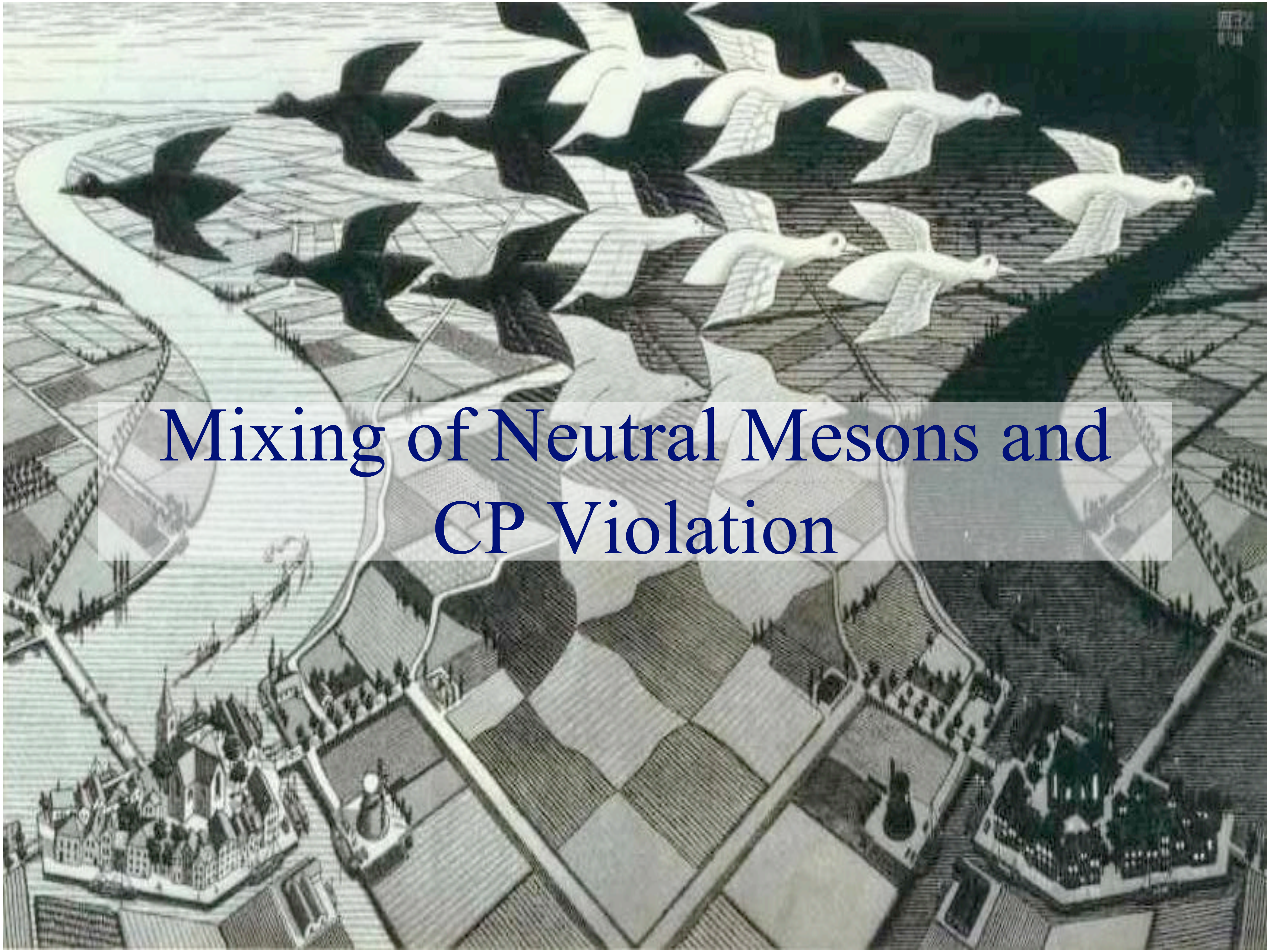
($\rho$,$\eta$) determined at
B factories

# Focus on smallest matrix elements: Unitarity triangle

- $V_{ub}$ and $V_{td}$ contain CP-violating imaginary parts (standard parameterization)

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

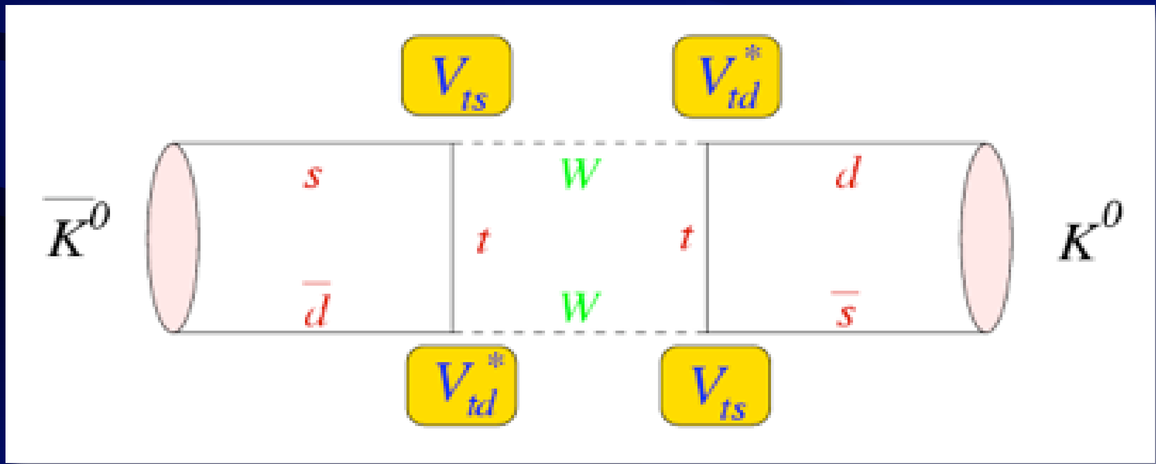




# Mixing of Neutral Mesons and CP Violation

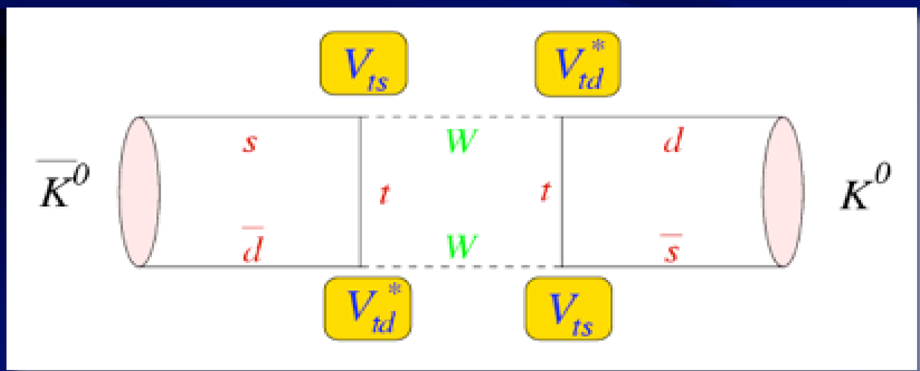
# Flavor oscillations

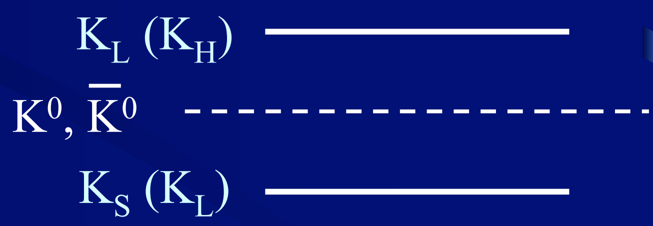
- Second-order weak-interaction processes can transform long-lived neutral mesons into their antiparticles ($K^0$, $B_d^0$, $B_s^0$, $D^0$):



# Flavor oscillations

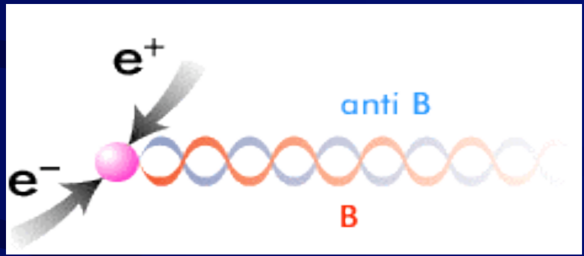
- Analogy with quantum-mechanical system of coupled pendula: state $K^0$ at t=0 develops into a superpositions of states $K^0$ and $\bar{K}^0$ with time-dependent amplitudes



# Flavor oscillations

- B factories produce pairs of $B^0$ and $\bar{B}^0$ mesons in coherent quantum states

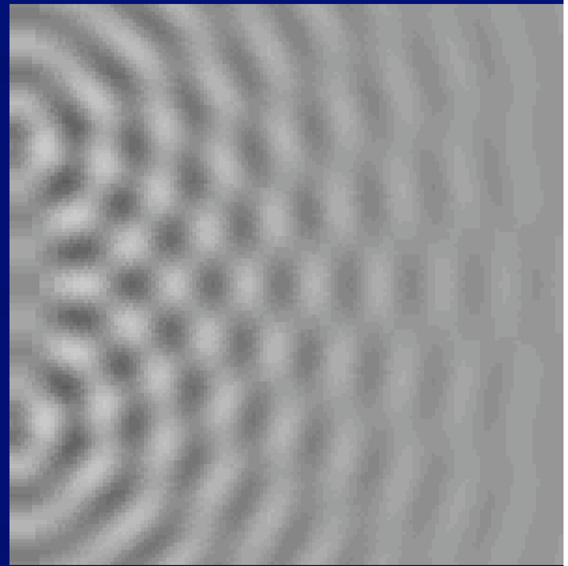



- Decay of one meson (reconstruction of its flavor) initiates time measurement for the other meson

# CP violation

- Complex entries in CKM matrix can lead to CP asymmetries
- Three types of CP violation:
  - in meson-antimeson mixing
    ("indirect CP violation")
  - in weak decay
    ("direct CP violation")
  - in interference of mixing and decay
    ("time-dependent CP violation")

# CP violation



- Measuring effects of a complex coupling requires:
  - interference of at least two amplitudes with different CP-violating phases:

$$\varphi_{weak} \xrightarrow{CP} -\varphi_{weak}$$

  - presence of another, CP-conserving ("strong") phase difference:

$$\delta_{strong} \xrightarrow{CP} \delta_{strong}$$

# CP violation in decay

- Arises whenever $\Gamma(i \rightarrow f) \neq \Gamma(\bar{i} \rightarrow \bar{f})$ due to interference of at least two partial amplitudes with different weak and strong phases
- First observed in $K \rightarrow \pi\pi$ decay (tiny effect, parameter $\varepsilon' \sim 10^{-6}$)
- Recently observed in many B-meson decays, e.g.: $B \rightarrow \pi K$, $B \rightarrow \pi\rho$, $B \rightarrow \eta' K$
- sometimes large effects, O(0.1-0.3)

# Amplitude interference

- Rates for rare, charmless B decays are characterized by significant interference of tree and penguin amplitudes:

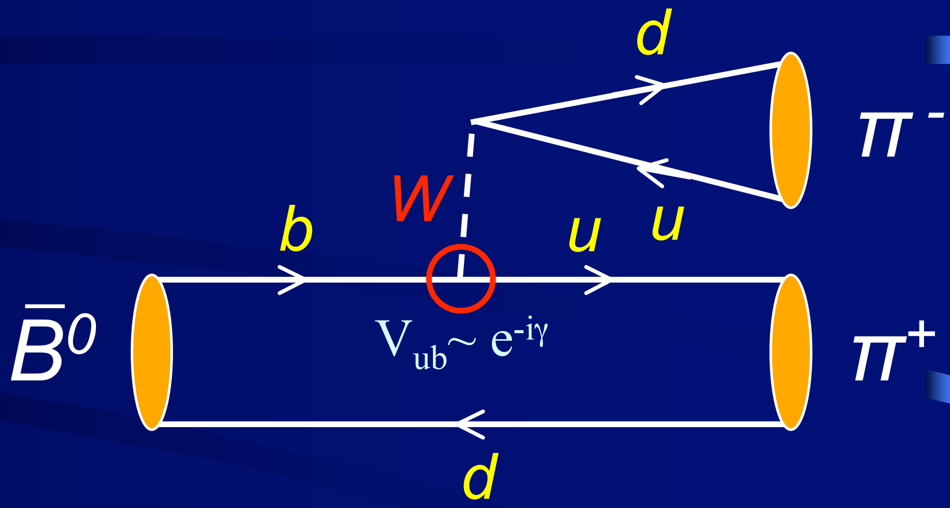
**Amplitudes:** $$\mathrm{A} = Te^{i\delta_1} e^{-i\gamma} + Pe^{i\delta_2}$$

**Rates:** $$\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f}) \sim \cos\gamma \cos(\delta_i - \delta_j)$$

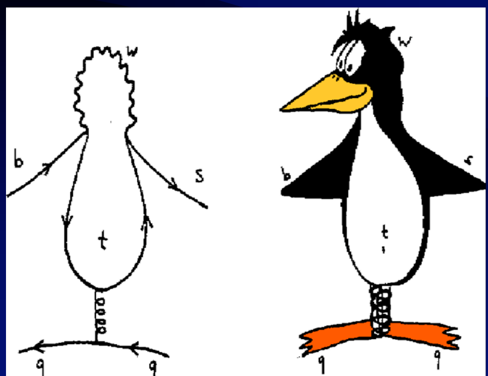
**Asymmetries:** $$\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f}) \sim \sin\gamma \sin(\delta_i - \delta_j)$$

# Amplitude interference

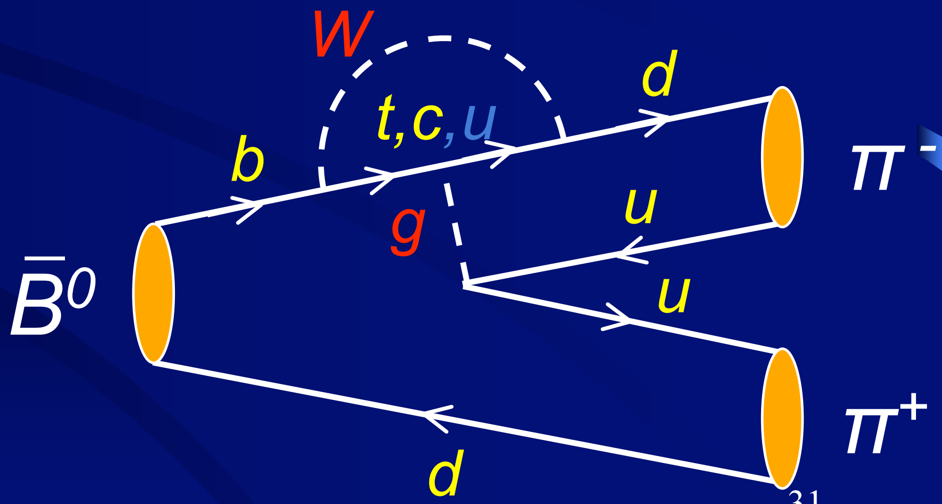
Trees:




Penguins:

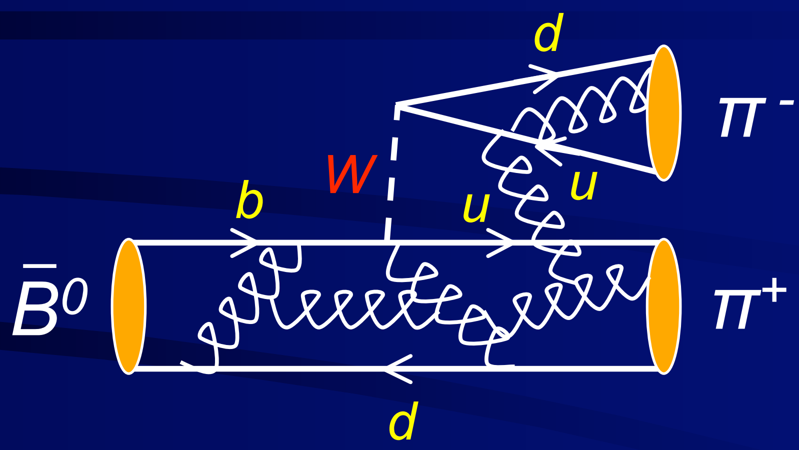



(Hurth)



# Interfering penguins …

# Reality is far more complicated



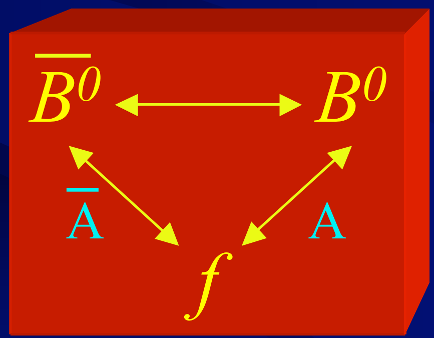

- Nonleptonic weak decays were long thought to be intractable to theory
- First rigorous theoretical description:
  - QCD factorization
  - "Soft-collinear effective theory"

Beneke, Buchalla, MN, Sachrajda (1999-2003)

Bauer, Pirjol, Stewart (2000-2005)

# CP violation in the interference of mixing and decay

- Arises in decays of neutral mesons into CP eigenstates
- CP-conserving ("strong") phase develops due to quantum-mechanical time evolution of states



# CP violation in the interference of mixing and decay

- If decay amplitude contains a single weak phase $\varphi_A$, the resulting time-dependent CP asymmetry can be calculated without hadronic uncertainties:

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\overline{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = S(f)\sin(\Delta m_B t)$$

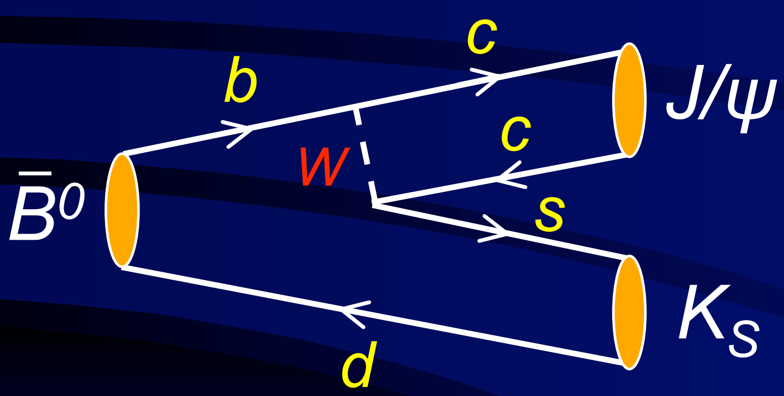
with:

$$S(f) = \pm \sin 2(\beta - \varphi_A)$$

- Most useful class of CP asymmetries for B factories

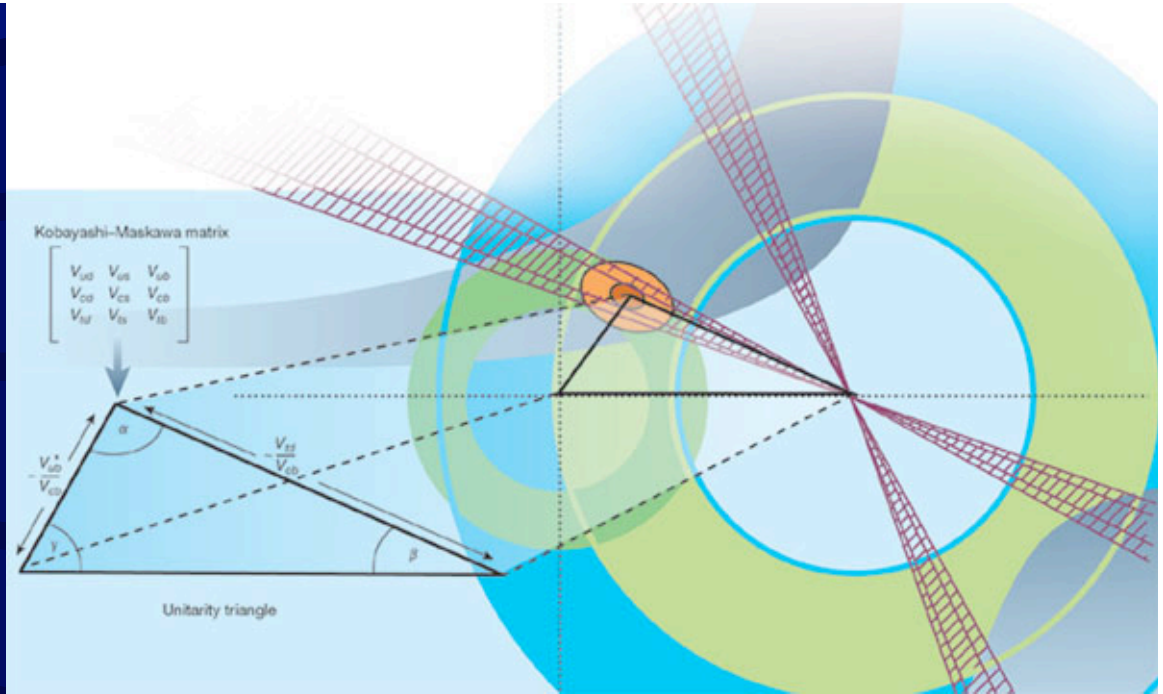
# CP violation in the interference of mixing and decay

- "Golden" mode: $B \to J/\psi\ K_S$




- Amplitude real to good approximation, $\varphi_A = 0$

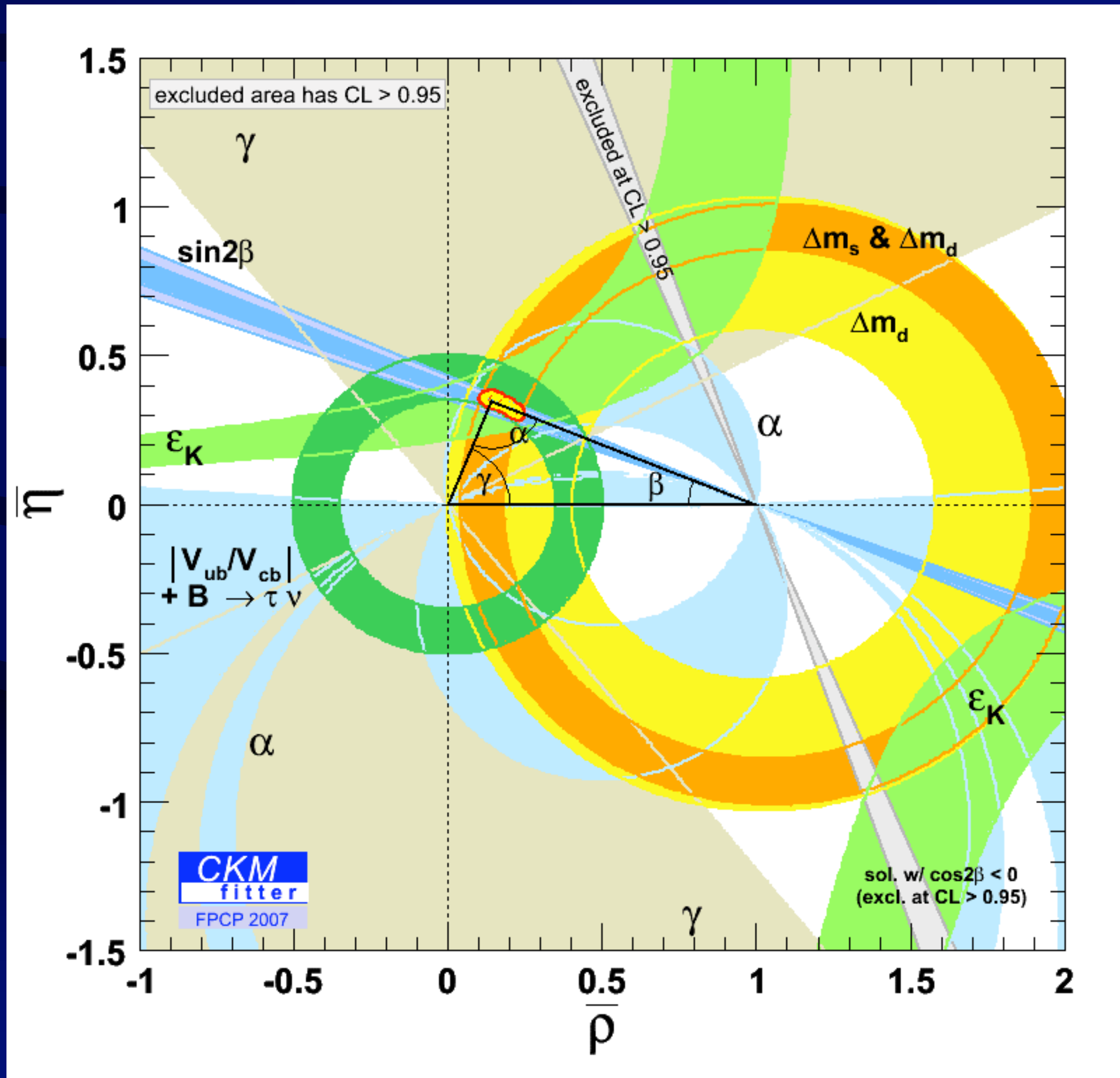
- CP asymmetry $S(f)=\sin 2\beta$ yields CP-violating phase even without any knowledge about decay amplitudes
- Theoretical uncertainty very small (~1%)



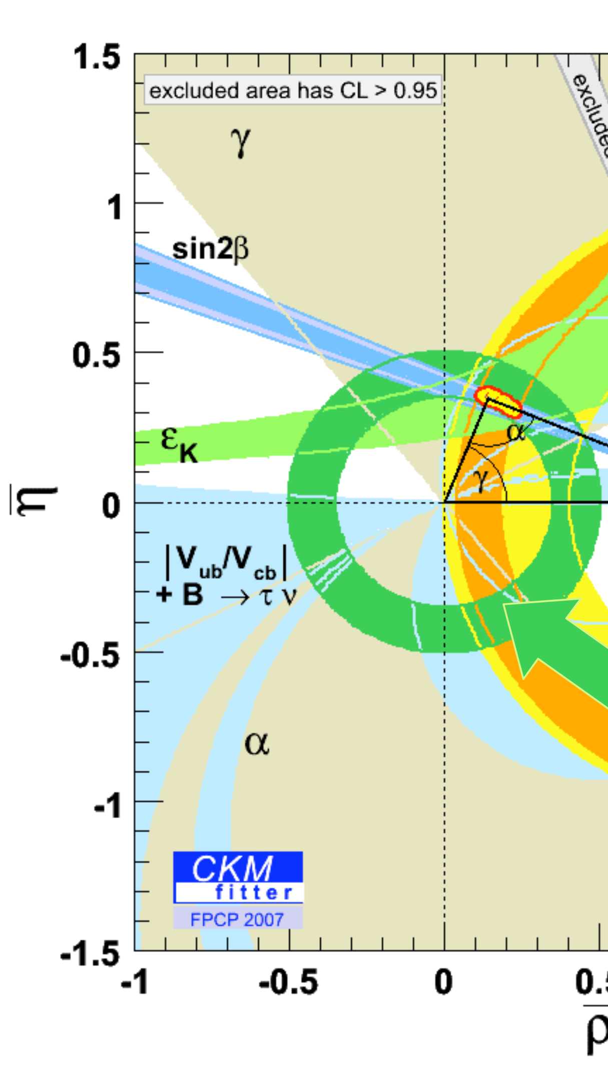

# Precision Studies of the CKM Matrix

## Overdetermination of the unitarity triangle

# Unitary triangle determinations

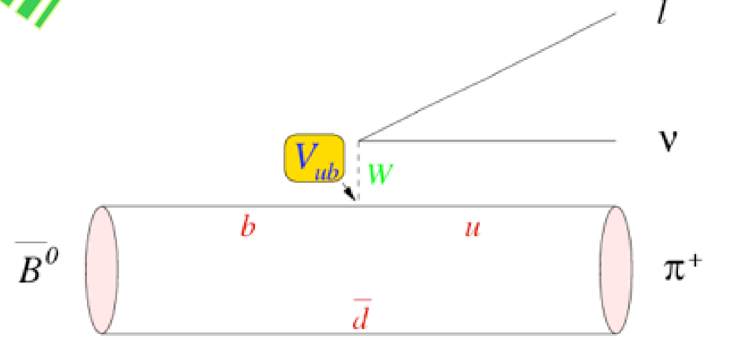


# Unitary triangle determinations



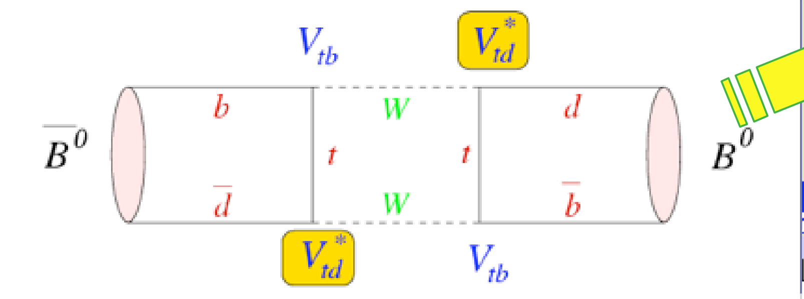

- Extraction of $|V_{ub}|$ in semileptonic B decays
- Theoretical uncertainty recently reduced to 7%

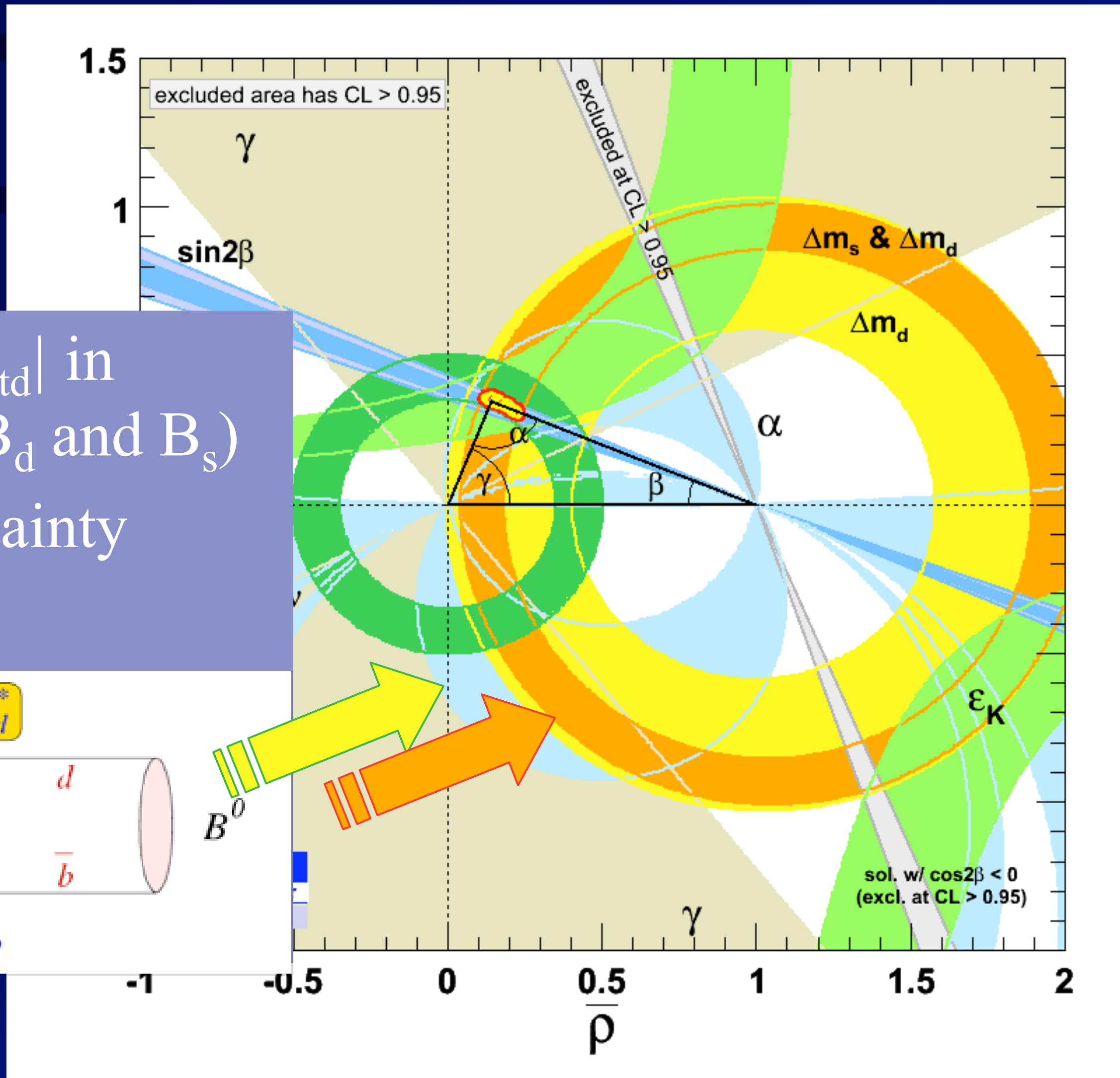
Bosch, Lange, MN, Paz (2004, 2005)



# Unitary triangle determinations

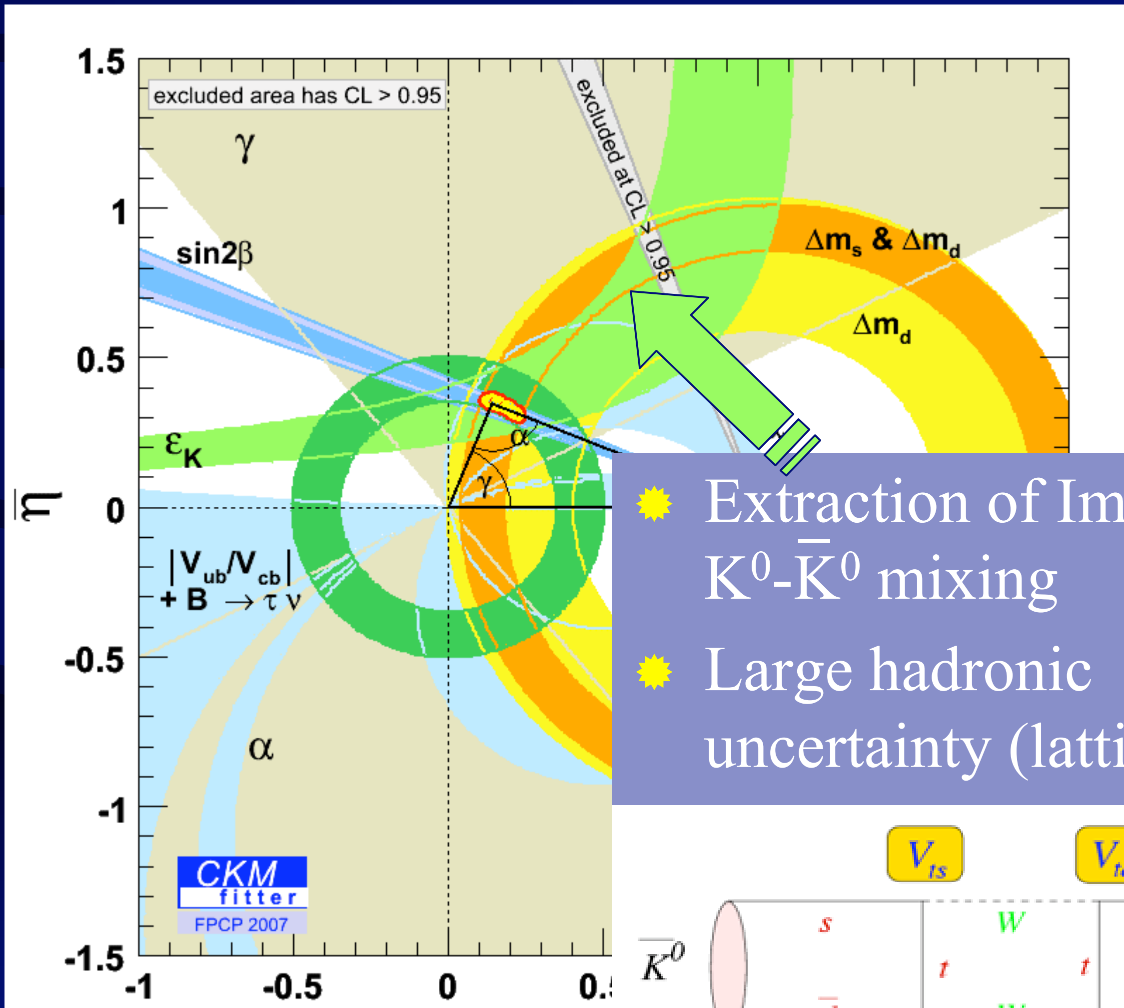
- Extraction of $|V_{td}|$ in $B^0$-$\bar{B}^0$ mixing ($B_d$ and $B_s$)
- Hadronic uncertainty (lattice QCD)



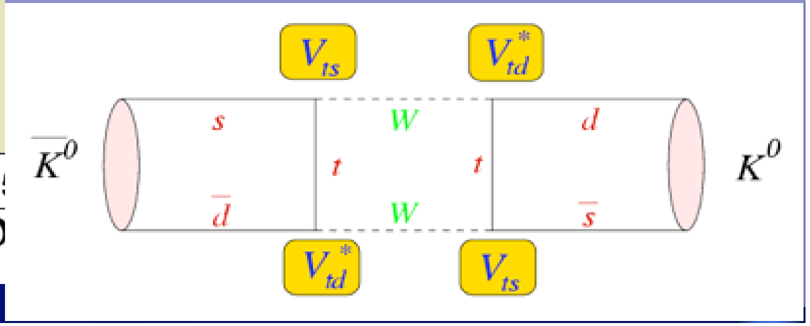




Tevatron very important!

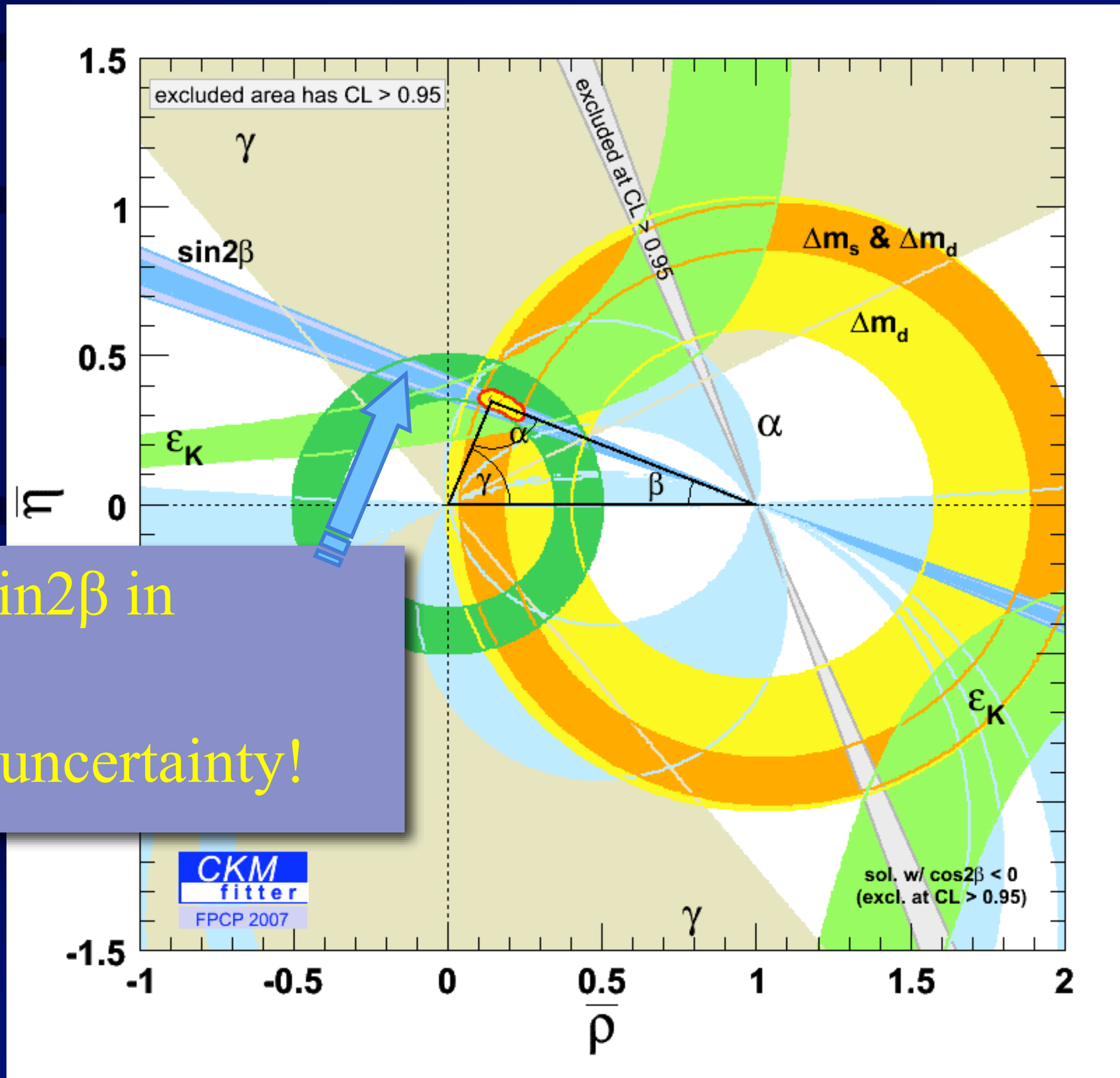
# Unitary triangle determinations




- Extraction of $\mathrm{Im}(V_{td}^2)$ in $K^0$-$\bar{K}^0$ mixing
- Large hadronic uncertainty (lattice QCD)



# Unitary triangle determinations




- Extraction of sin2β in $B^0$-$\bar{B}^0$ mixing
- No theoretical uncertainty!

# Determination of $\gamma$ in $B \rightarrow \pi\rho$, $\pi\pi$

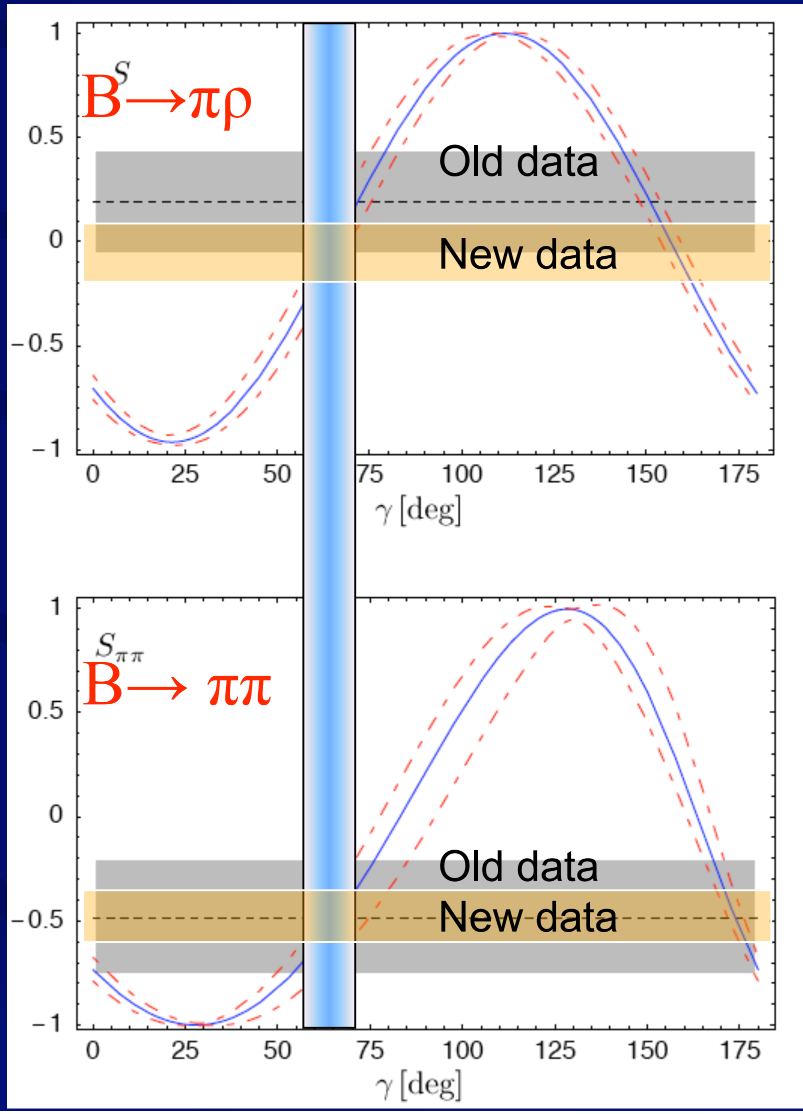
- Rare decays $B \rightarrow \pi\pi$, $B \rightarrow \rho\pi$ are dominated by tree topologies, but also receive penguin contributions
- In limit of negligible penguins, decay amplitudes carry the weak phase $\varphi_A = -\gamma$, in which case the time-dependent CP asymmetries would measure $\sin 2(\beta+\gamma)=\sin 2\alpha$
- Can use QCD factorization to estimate and correct for "penguin pollution"

# Determination of γ in B→πρ, ππ

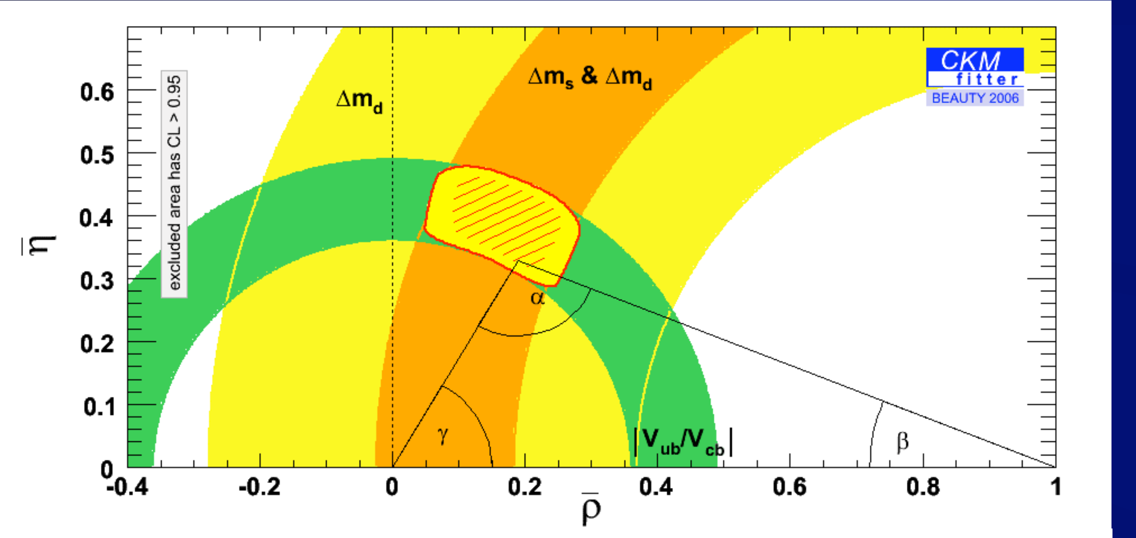
- B→PV modes receive smaller penguins than B→PP modes
- Possibility to extract γ with small theoretical uncertainties from time-dependent rates in B→πρ, with B→ππ as cross check
- Result:

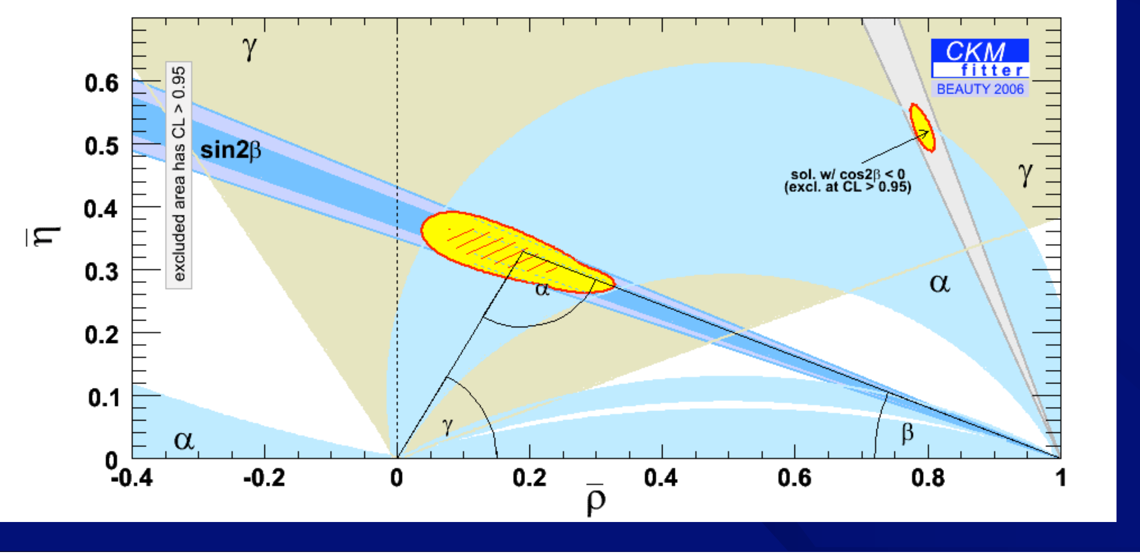
$\gamma = (62 \pm 8)^{o}$

Beneke, MN (2003)

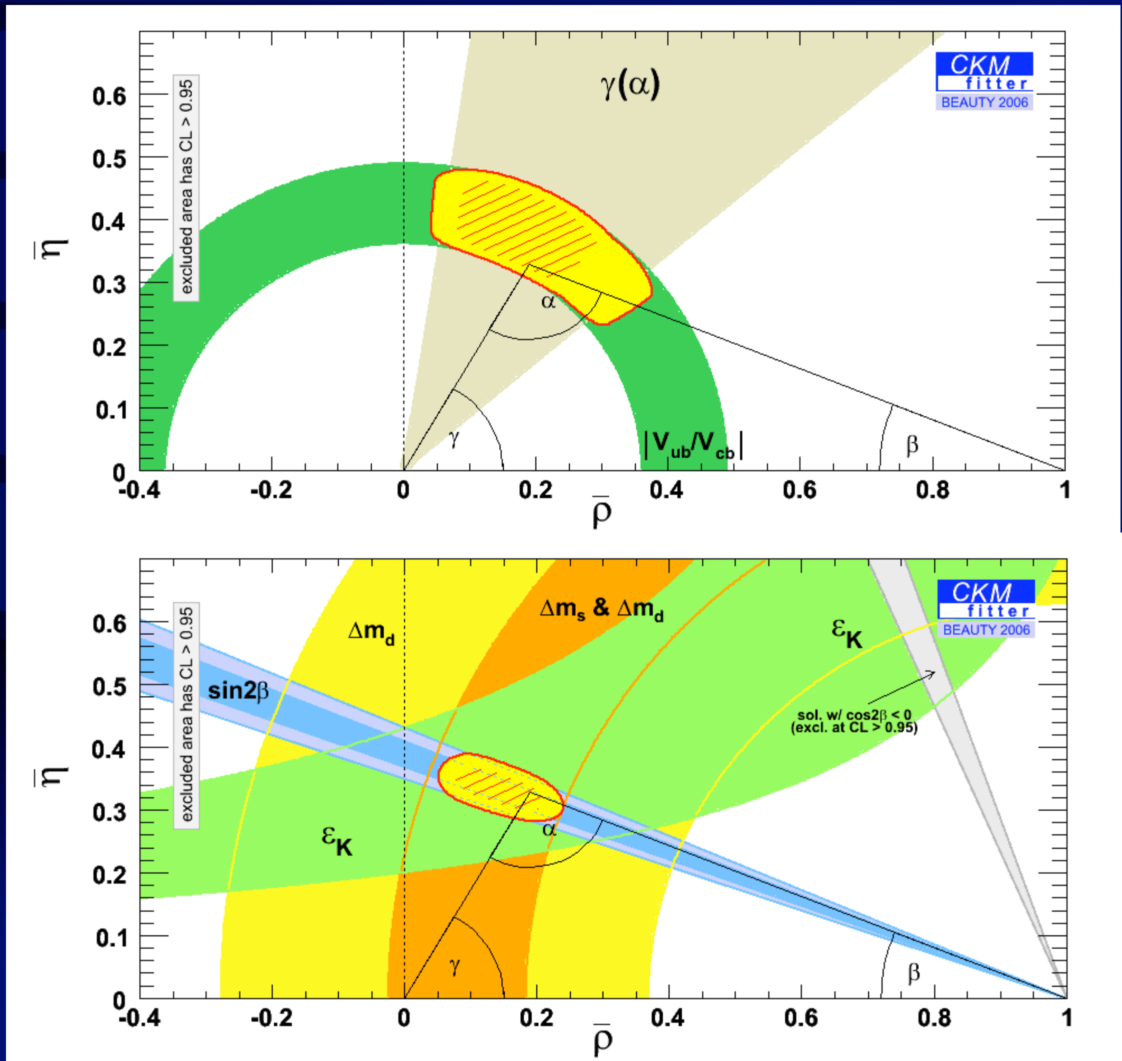


# Sides vs. angles



# Tree vs. penguin processes



# Facit

- CKM model of flavor- and CP violation works beautifully
- Definitely the main source of these effects
- "New Physics" can only give corrections to the CKM picture
- Yet, there is hope and possibility for finding and studying significant "New Physics" contributions in some weak decays!


# Hints of "New Flavor Physics"?

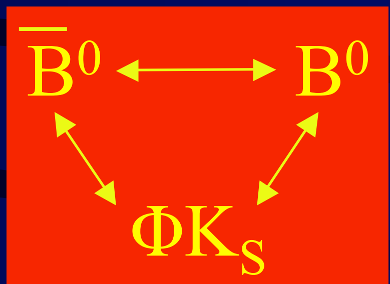
"New Physics" in loop processes?

"New Physics" in B-$\bar{B}$ mixing?

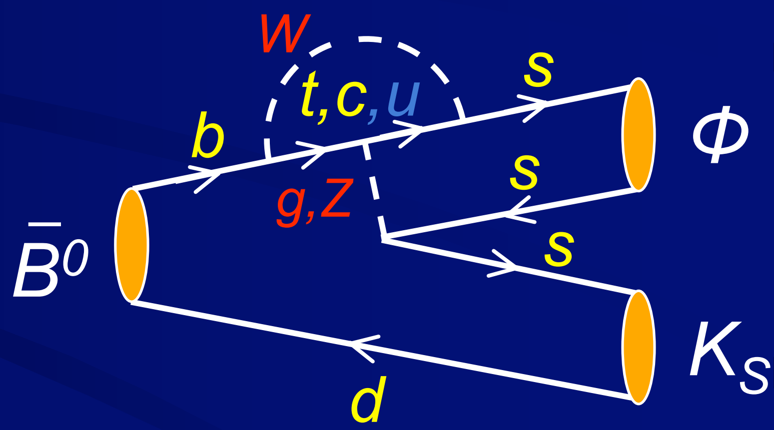
Facts or fiction?

# CP asymmetries for $B \to \Phi K_S, \eta' K_S$

- Interference of mixing and decay:




- Phase structure identical to $B \to J/\psi K_S$
- Theoretical prediction:
- Penguin graph real in excellent approximation

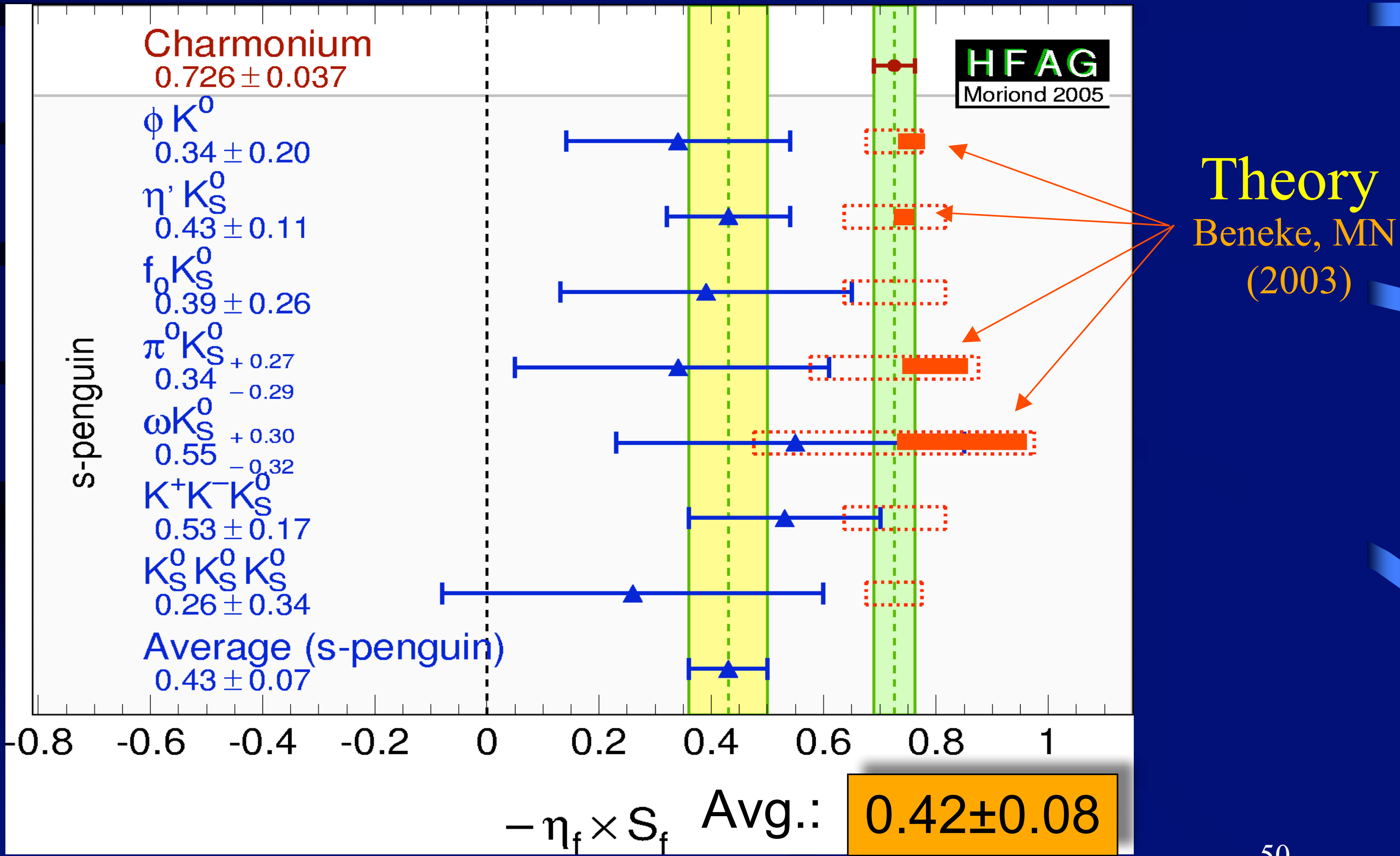



Grossman, Worah (1996)

$$S(\Phi K_S) - S(J/\psi K_S) = 0.02 \pm 0.01$$

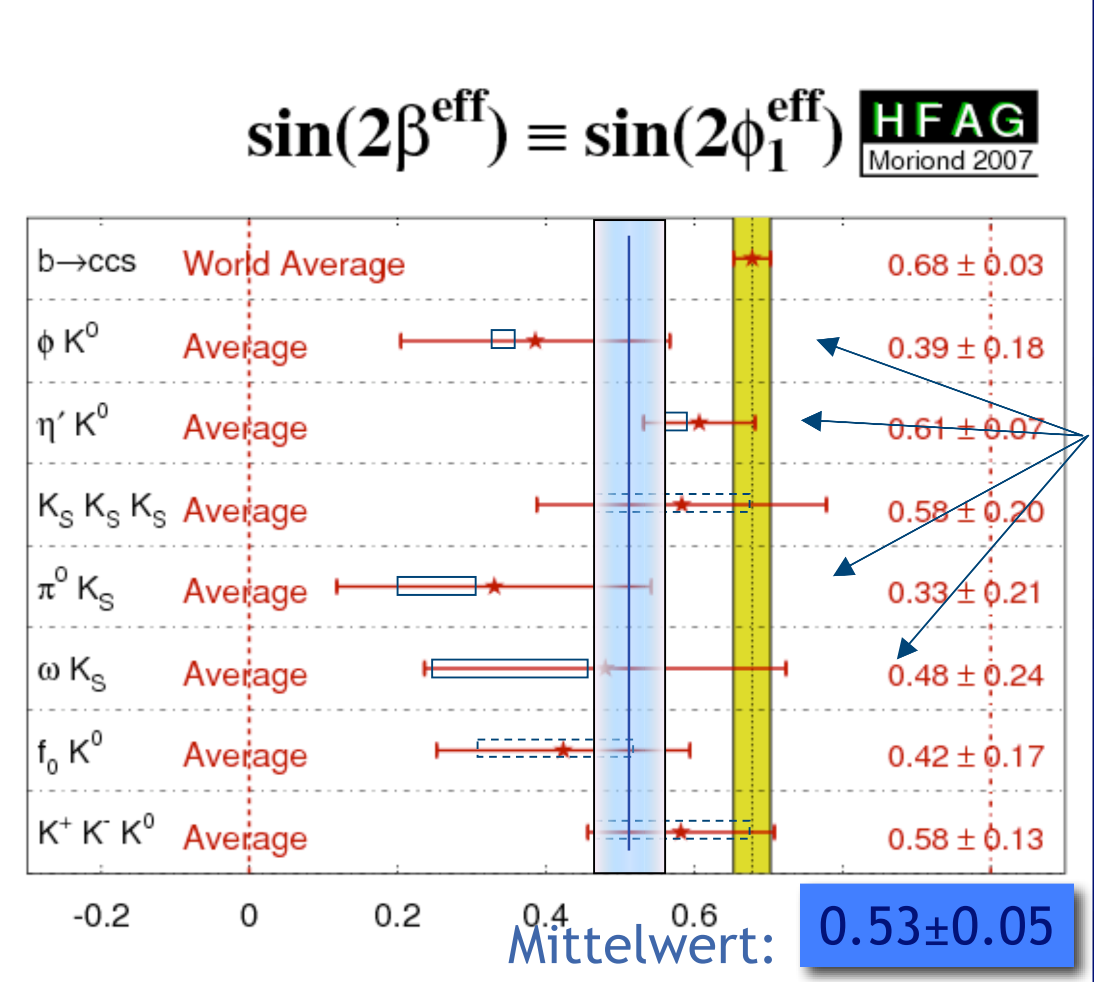
Beneke, MN (2003)

# 2005: seven reasons for excitement!




Deviation of 3.8σ !

# Present situation



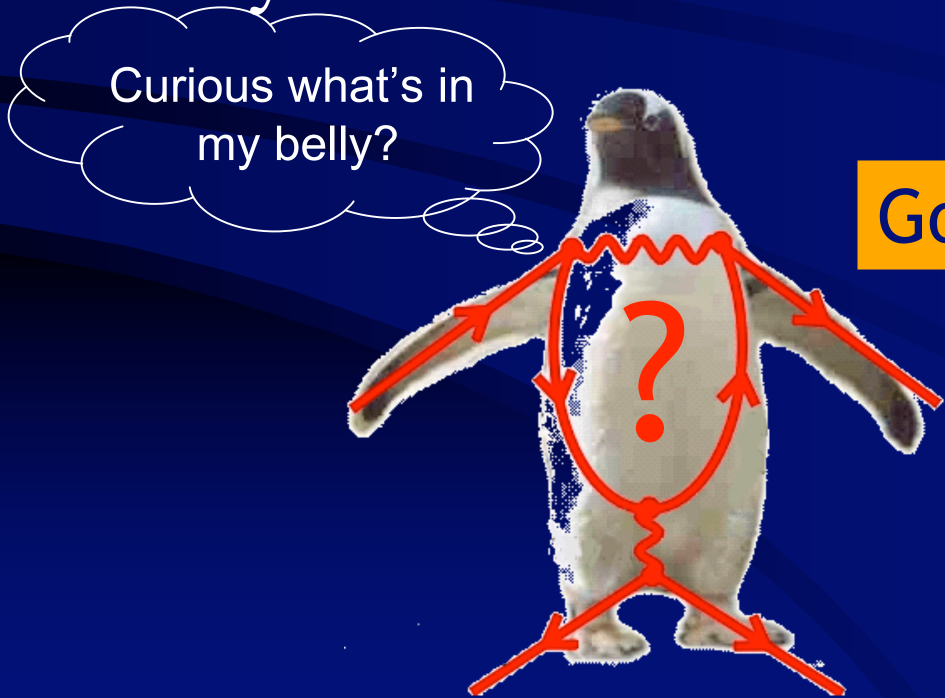

Deviation 2.4σ

- Standard ruler (golden mode) reduced to 0.68±0.03
- Average value from penguin modes raised

Theory corrections

# $(\sin 2\beta)_{tree}$ vs. $(\sin 2\beta)_{penguin}$

- Explanation of the effect in terms of new penguin contributions (e.g. SUSY), preferably in electroweak sector

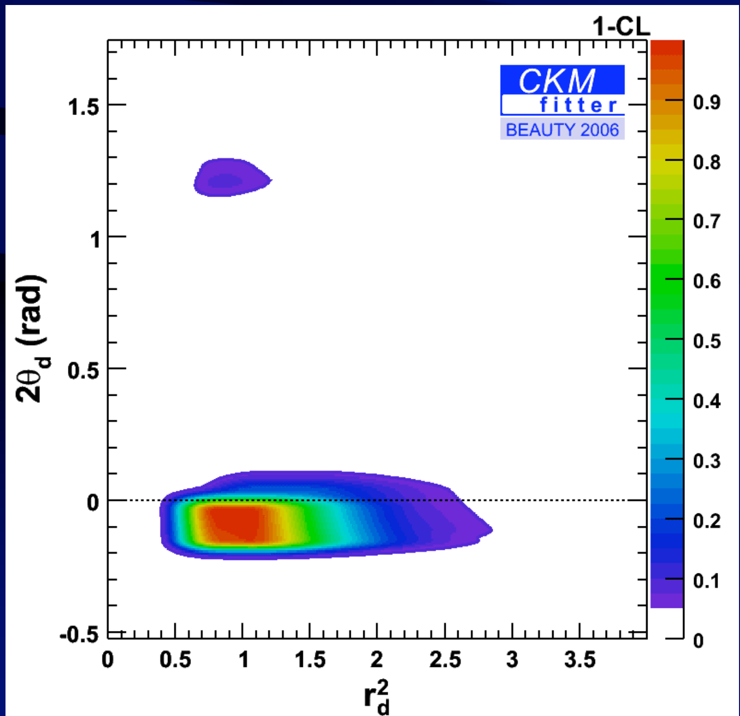



Go check at LHC!

# Another example: "New Physics" in $B_{d,s}$ mixing?

- General parameterization:

$$\Delta m_d = \Delta m_d^{SM} * r_d^2 \, e^{i2\theta_d}$$




- "New Physics" contributions up to ~50% of SM still allowed
- Even more room in $B_s$ mixing
- After discovery of new particles at LHC → allowed parameter space for new flavor parameters (e.g., quark-squark-gluino couplings in SUSY)

# Conclusions

- Flavor physics has enjoyed more than two decades of active experiments and spectacular progress
- It remains an important component of the particle-physics program in the LHC era (complementarity)
- Indirect searches for “New Physics” will greatly profit from LHC discoveries
- Deviations from Standard Model predictions will then be interpreted as measurements of new flavor parameters!