B Physics: Theoretical Overview

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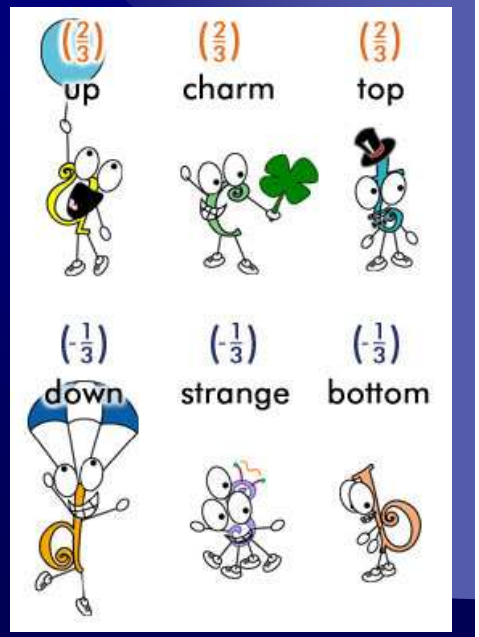
- Flavor physics
- *B* physics in the LHC Era
- Precision measurements in the quark sector
- Search for New Physics
- Outlook

1. Flavor Physics

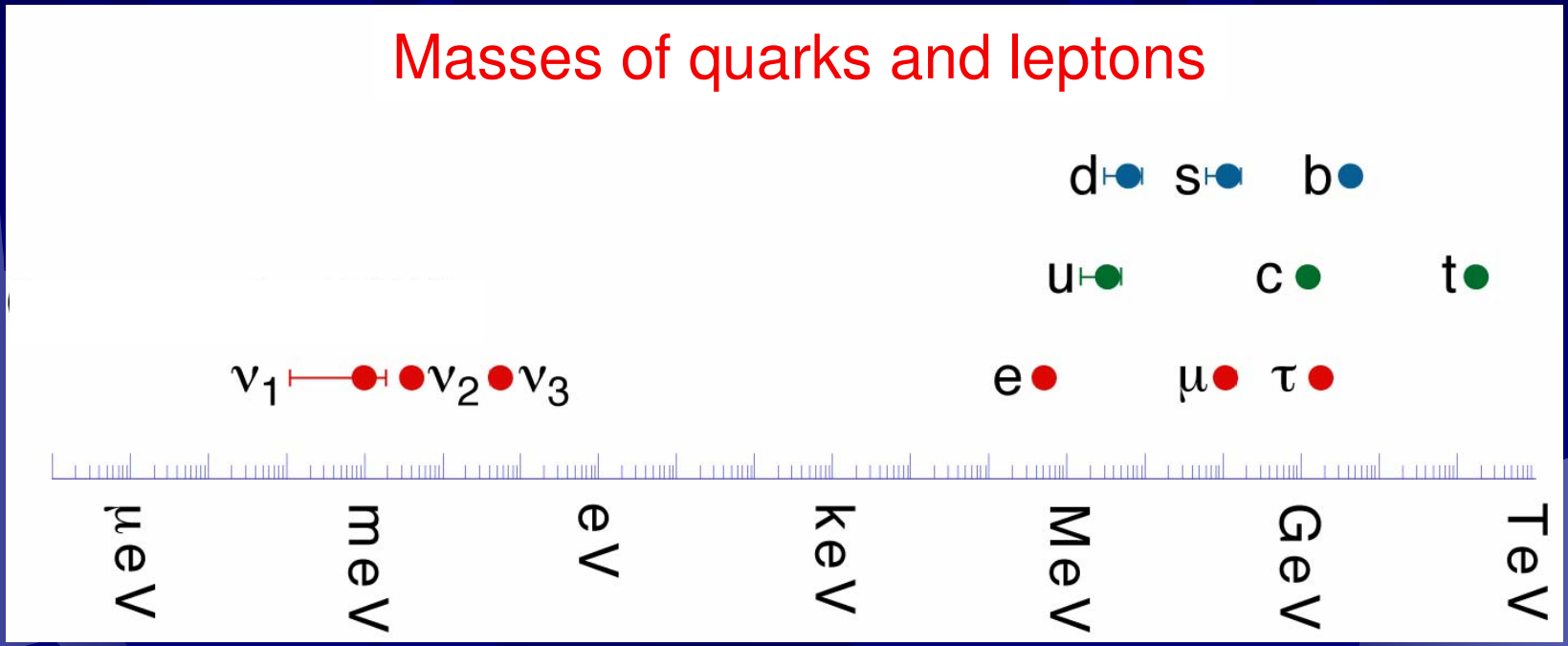
Generations, CP violation,
Particle physics and cosmology

Problem of Generations

- Gauge forces in SM do not distinguish betw. fermions of different generations:
  - e,μ have same electrical charge
  - Quarks have same color charge
  - All equal, but not quite equal …
- Why generations ?
- Why 3 ?
- A new quantum number ?



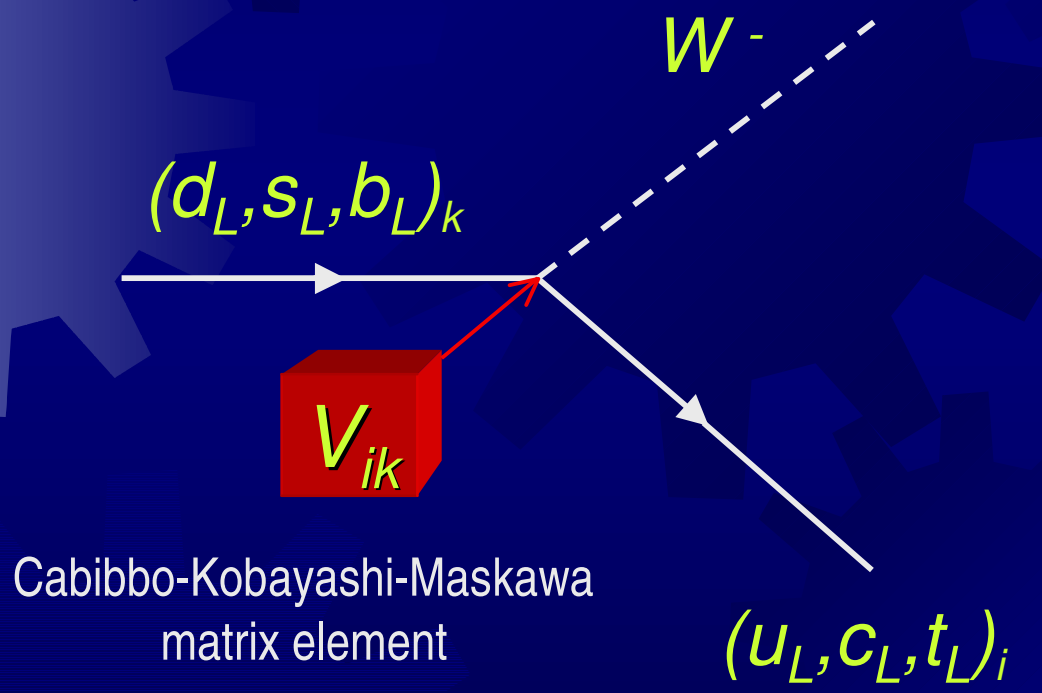
Why such different masses ?

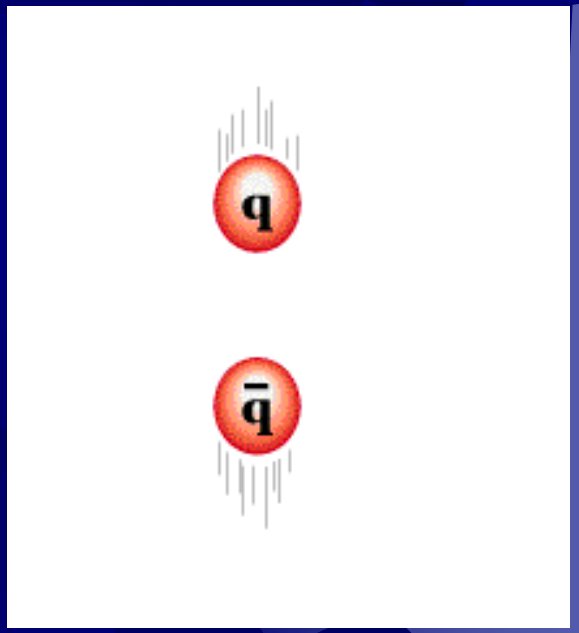


Fermion masses and mixings constitute many of the parameters of the SM!

Neutrino masses may indicate the relevance of a very large (GUT?) mass scale (see-saw mechanism), or the existence of extra dimensions!

- Fermions of different generations can communicate via flavor-changing weak interactions:



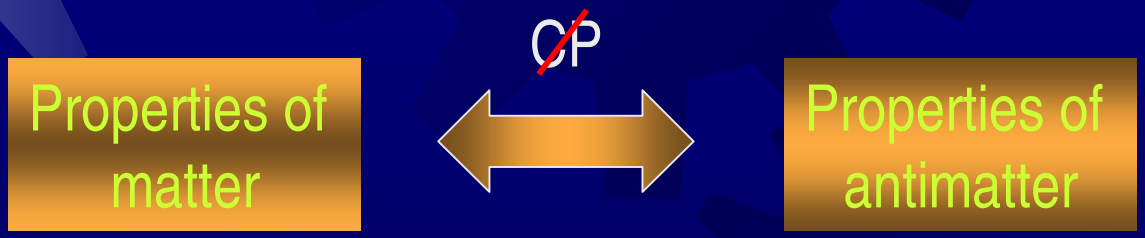


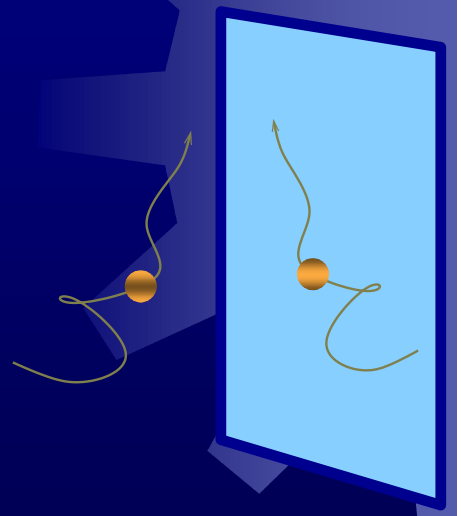
- New parameters (mixing elements)
- New hierarchies:

small

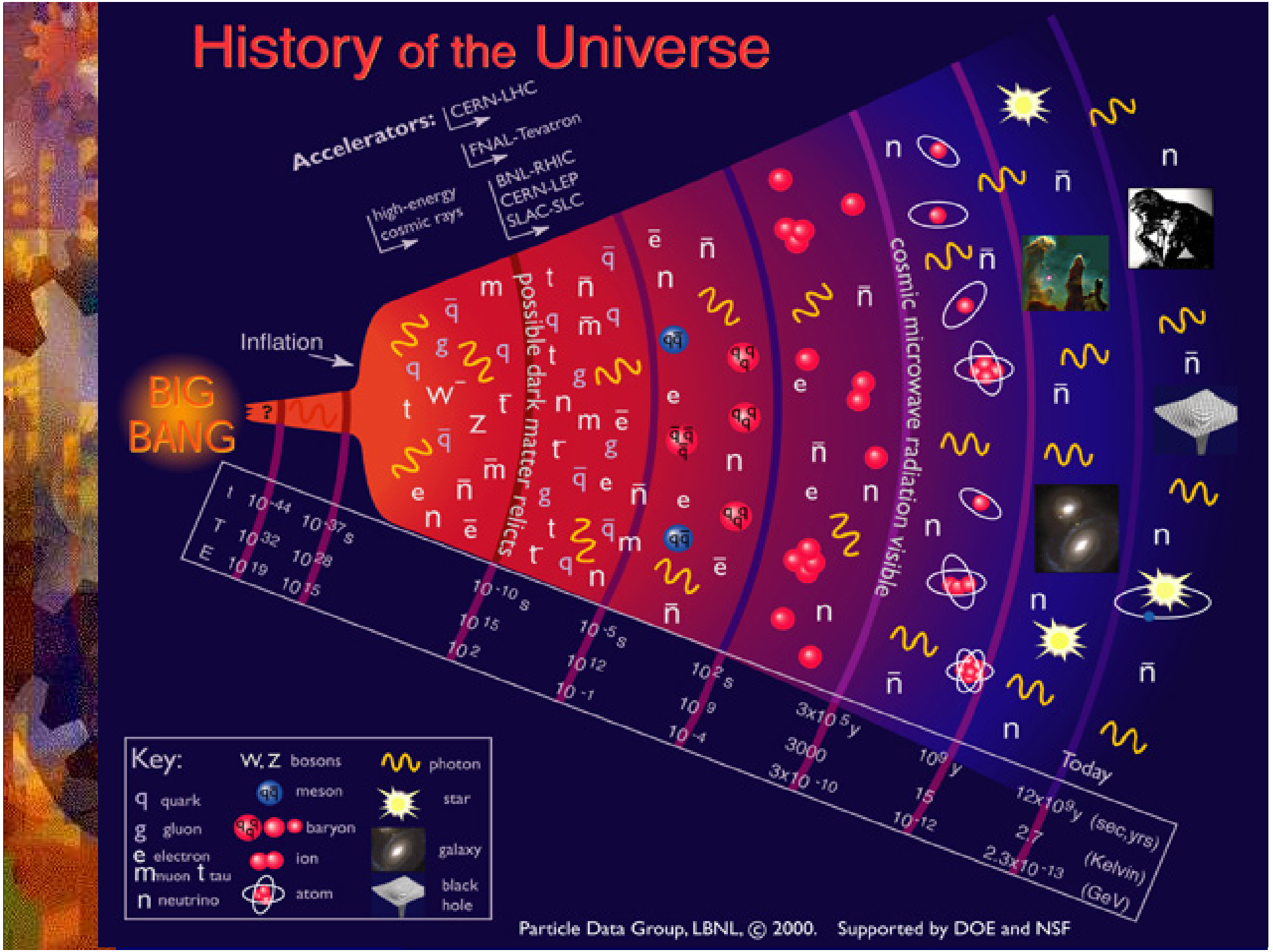
$$V_{CKM} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad U_{MNS} \approx \begin{pmatrix} 1 & 1 & \varepsilon \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

- Possible explanation of CP violation!

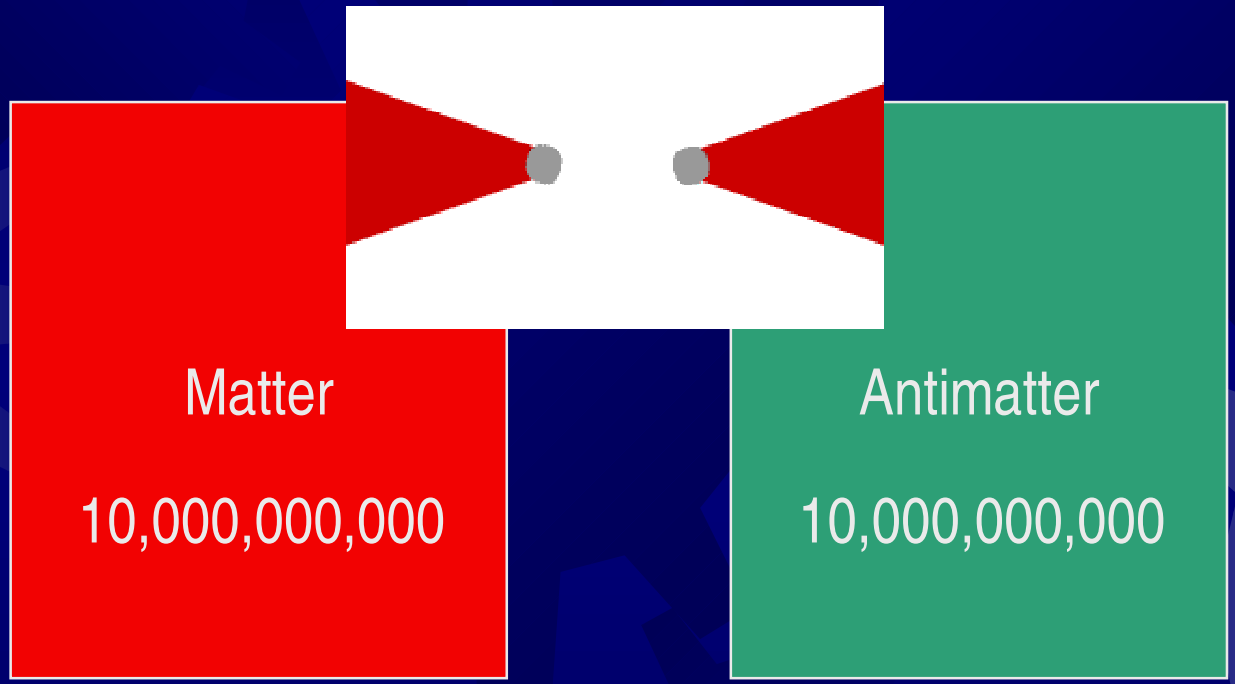




  - Needs ≥3 generations!


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 10-37 s
T 1032 1028
E 1019 1015
10-10 s
10 15
10 2
10-5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
12x10 9 y
2.7
2.3x10 -13
Today
(sec,yrs)
(Kelvin)
(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

The Cosmic Connection: Baryon Asymmetry



Early Universe

The Big Annihilation

Today:

us

1

- Sakharov criteria:
  - Baryon-number violation
  - CP violation
  - Non-equilibrium

Fundamental connection between particle physics and cosmology!

- SM satisfies prerequisites for baryogenesis:
  - Baryon-number violation at high temperatures ($\Delta B = \Delta L$)
  - Non-equilibrium during phase transitions (symmetry breaking)
  - CP violation in the quark and lepton sectors
- *However:* CKM phase in the quark sector is not sufficient to account for the baryon asymmetry in the Universe

Need for additional CP-violating couplings!

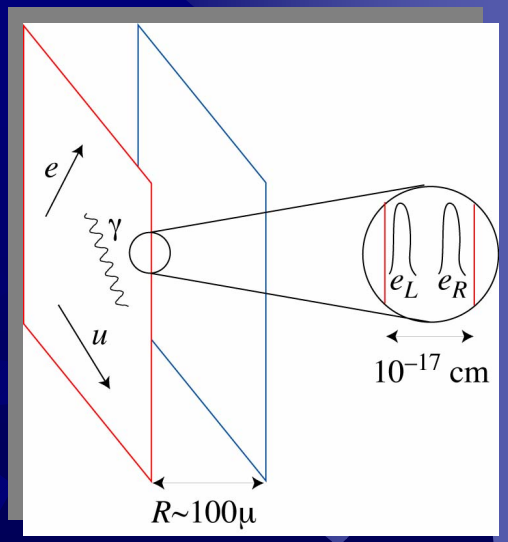
Theory of Generations ?

- One of the big unsolved problems in particle physics is to obtain a fundamental understanding of the origin of fermion generations:
  - Generation symmetry ?
  - Generation dynamics ?
- Deep, difficult questions, whose answers will lead to fundamental discoveries
- Any progress would be most significant!

Dynamics of a Generation Symmetry ?

New symmetries, forces, dimensions ?

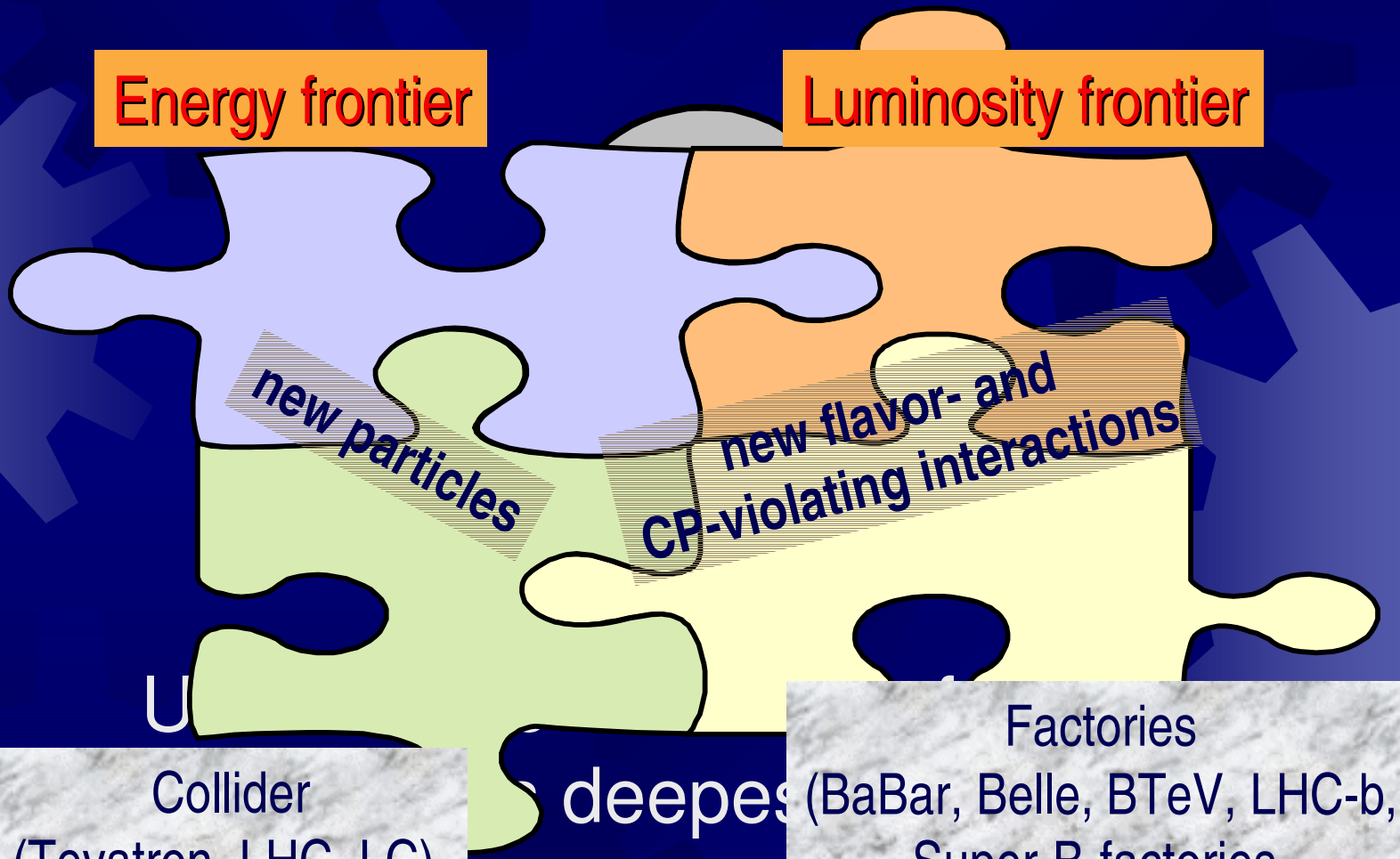
- Supersymmetry:
  Anomalous U(1) gauge symmetry with Green-Schwarz breaking
- Extra Dimensions:
  Fat branes with spatially separated fermions
- Technicolor:
  New (broken) gauge symmetry at the 100 TeV scale



2. *B* Physics in the LHC Era

Complementarity between experiments at the energy and luminosity frontiers

Energy & Luminosity



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Collider
(Tevatron, LHC, LC)

Factories
(BaBar, Belle, BTeV, LHC-b,
Super-B-factories,
Neutrino exp., Kaon exp.)

- Study of flavor physics complements the discovery of new particles at high energy
- Any extension of the SM that can solve the hierarchy problem contains many new flavor parameters

  (e.g. SUSY: 43 new CP-violating phases!)
- If *New Physics* exists at or below a TeV, its effects should show up in flavor physics!
- Flavor and CP-violating couplings can only be studied using precision measurements at highest luminosity

Examples: Top & Neutrinos

Top quark:

- Direct production proves existence und determines mass and spin
- Mass prediction based on electroweak precision measurements
- Couplings $|V_{ts}|$~0.04 and $|V_{td}|$~0.003 as well as their CP-violating phase can only be measured in *B* and *K* physics

e long, lavor-

(neutrino oscillations) has led to revolutionary discoveries

- Possibility of CP violation in the lepton sector; leptogenesis
- Hierarchy of mixing matrix completely different from that in the quark sector!

In Summary

- Study of flavor physics is an indispensable part of the *road map* for the exploration of the TeV scale
- This role exists now and even more so in the future, when new particles will be discovered at LHC
- Many of their properties can only be studied using precision measurements at highest luminosity

3. Precision Measurements in the Quark Sector

Cabibbo-Kobayashi-Maskawa matrix, Unitarity triangle,
CP violation in the *b* and *t* sectors

Goals

- Precise determinations of the elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix
- Tests of the CKM mechanism of flavor and CP violation
- Search for deviations from the SM

Wolfenstein Parameterization and Unitarity Triangle

- CKM matrix can be parameterized in terms of 4 real quantities:

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

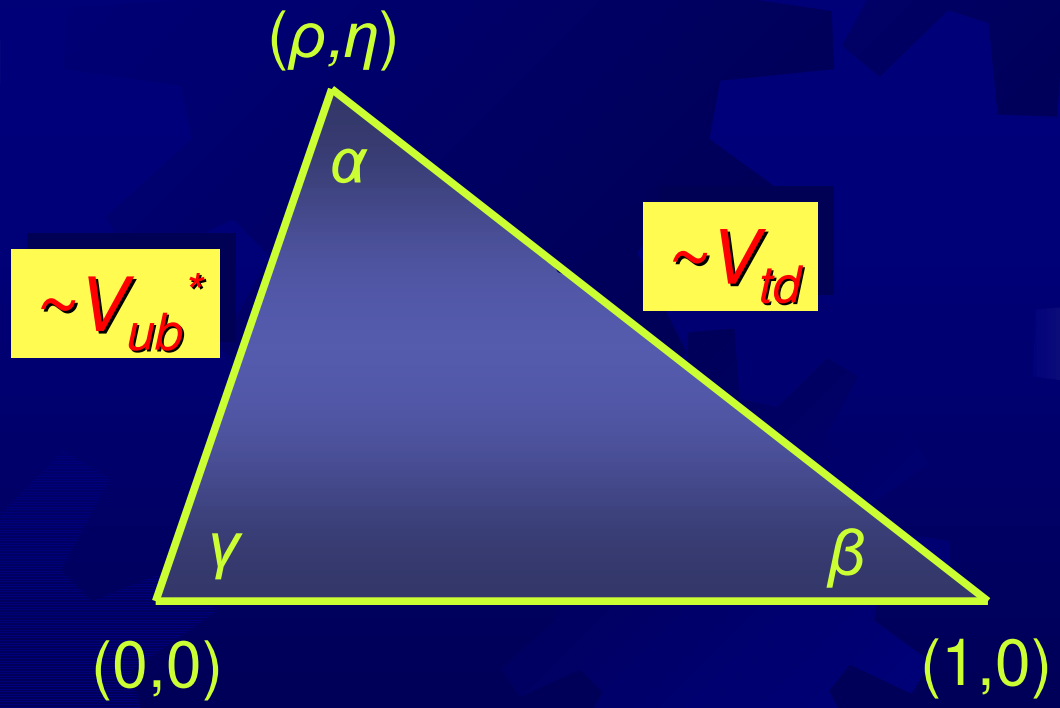
- Complex couplings ⇨ CP violation!

λ=0.22, A=0.84 well determined

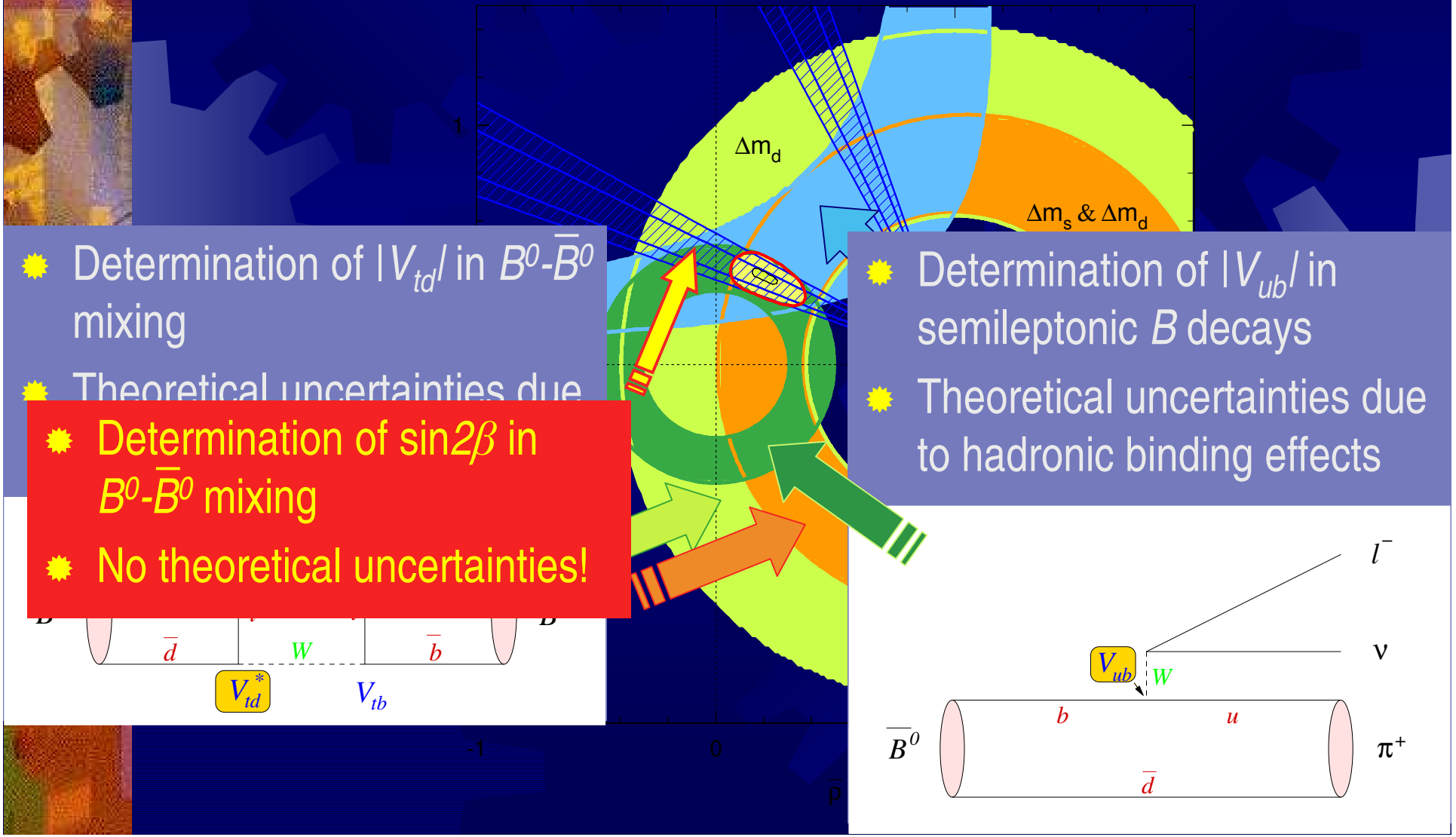
(ρ,η) are being determined at the *B*-factories

- Experimental information on (ρ,η) can be presented as a "unitarity triangle":

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



“Standard analysis”: CP Violation in the *t* Sector



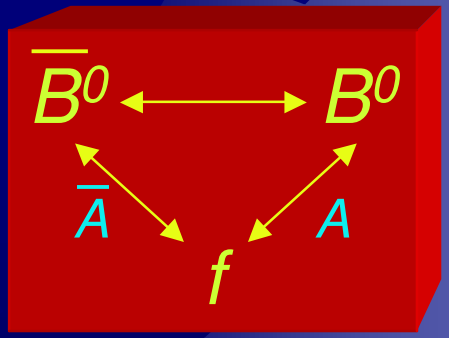
- Determination of $|V_{td}|$ in B^0-$\bar{B}^0$ mixing
- Theoretical uncertainties due

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

- Determination of $|V_{ub}|$ in semileptonic *B* decays
- Theoretical uncertainties due to hadronic binding effects

Determination of sin2β

- CP-violating phases can only be measured via interference
- Simplest case: Interference of B decay and B^0-$\overline{B}^0$ mixing for transitions into a CP eigenstate f
- If the decay amplitude A has a common CP phase φ_A, then:



$$\Gamma(\overline{B}^0(t) \to f) \propto e^{-t/\tau_B}\left[1 \mp S(f)\sin(\Delta m_B t)\right]$$

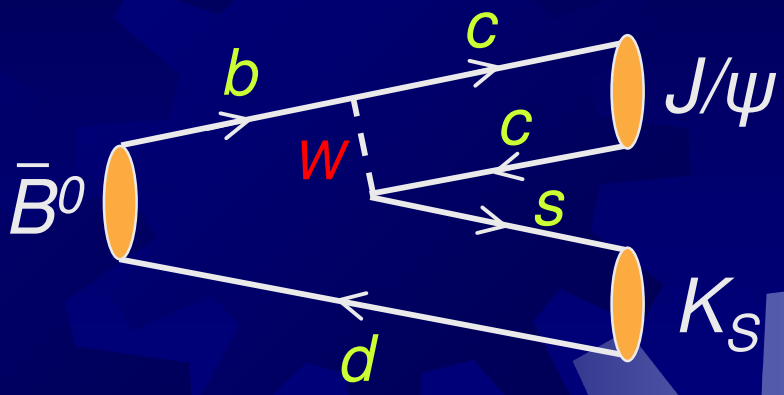
with: $S(f) = \pm \sin 2(\beta - \varphi_A)$

- Time-dependent CP asymmetry:

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

- Direct determination of CP phases, even without knowledge of the decay amplitudes!

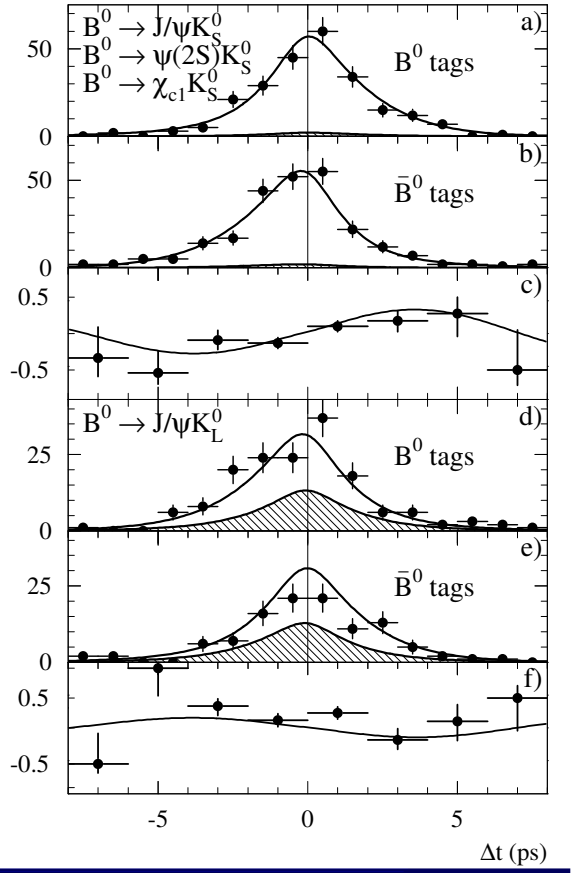
- Golden mode: $B \to J/\psi\, K_S$



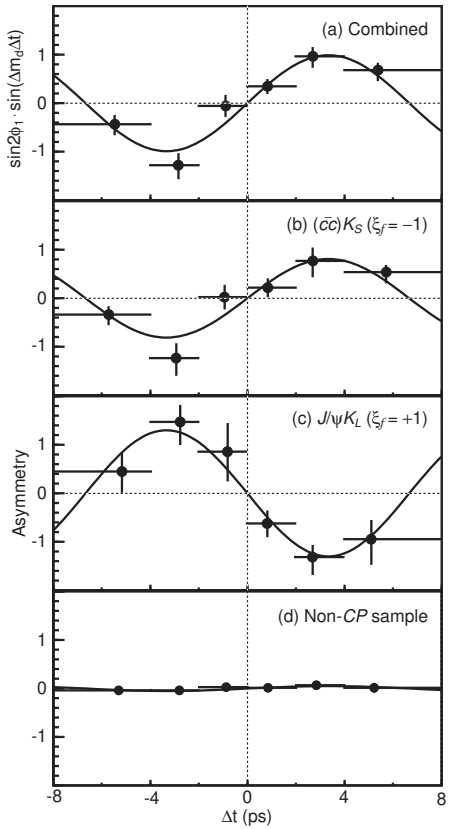
- Decay amplitude real to excellent approximation, i.e., $\varphi_A = 0$

Direct determination of sin2β, essentially without any theoretical uncertainties (~1%)

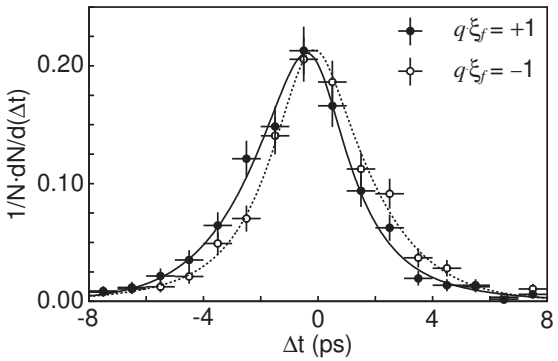
CP Violation visible to the Naked Eye!



BaBar (2001)



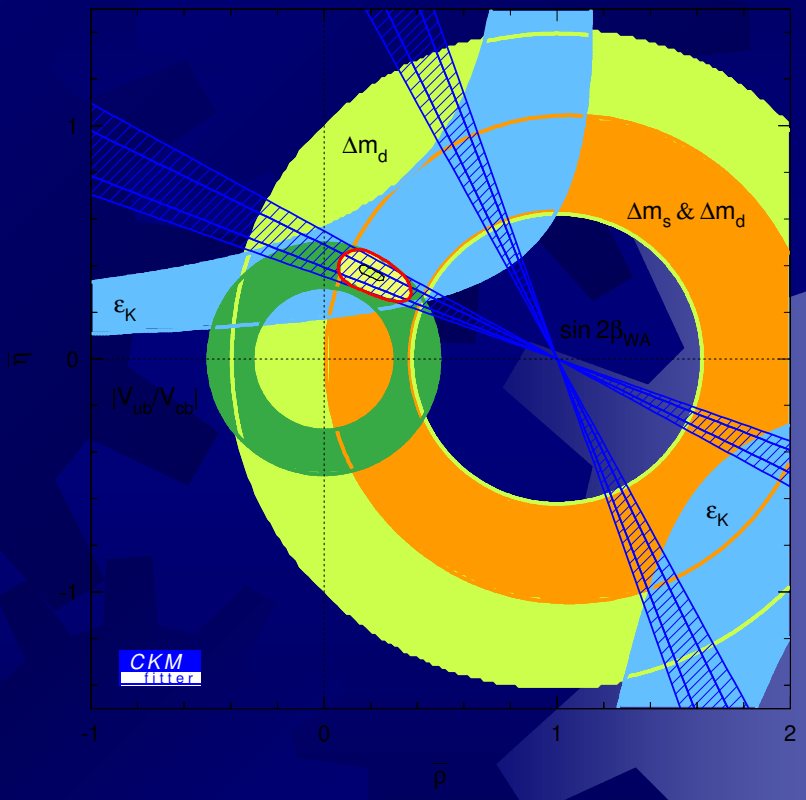
Belle (2001)



Combined: $\sin 2\beta = 0.73 \pm 0.05$

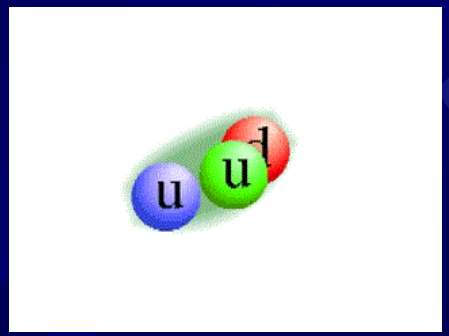
Combination

- All measurements are consistent with each other
- CKM mechanism established as the dominant contribution to flavor-changing interactions
- Confirmation of CP violation in the *t* sector of the CKM matrix, i.e., $\mathrm{Im}(V_{td}) \neq 0$



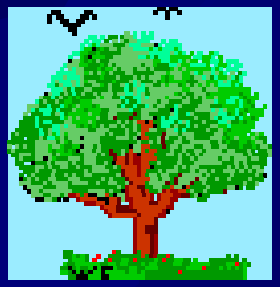
CP Violation in the *b* Sector

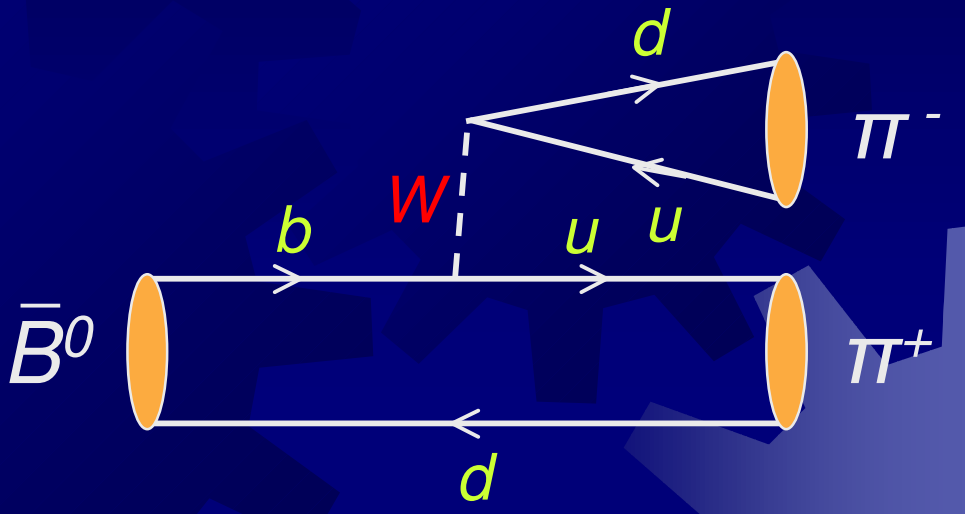
- Precise determination of the phase $V_{ub} \sim e^{-i\gamma}$ is difficult ($\longrightarrow$ BTeV, LHC-b, Super-B-factories)
  - clean measurement à la $\sin 2\beta$ possible at LHC
- Independently, important information can be gained from *rare, hadronic B decays*
- Theoretically challenging, since hadronic binding effects must be controlled
  - Much recent progress!



Flavor Topologies

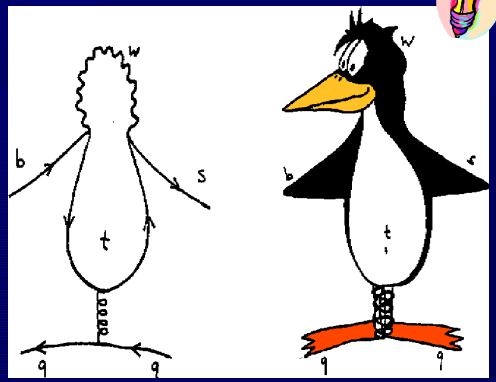
Tree:

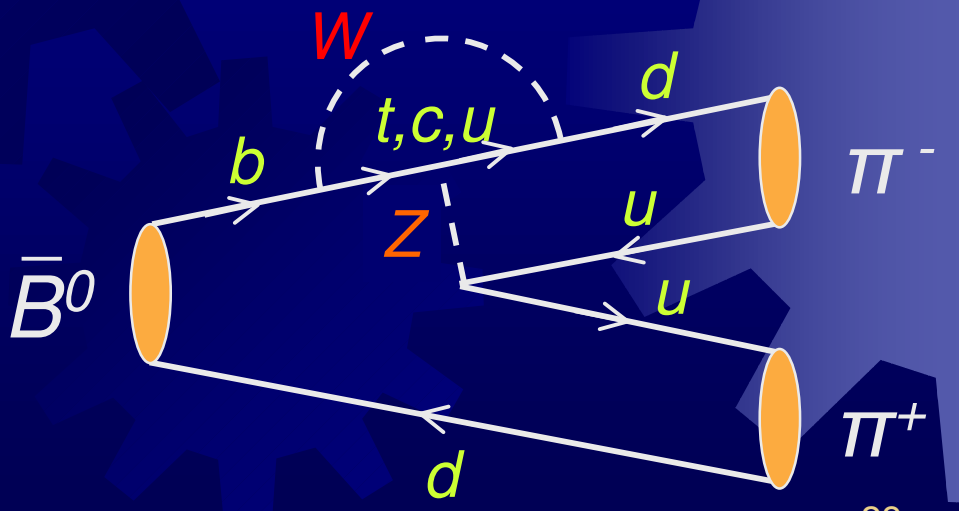




Penguin:

Electroweak!





Amplitude Interference

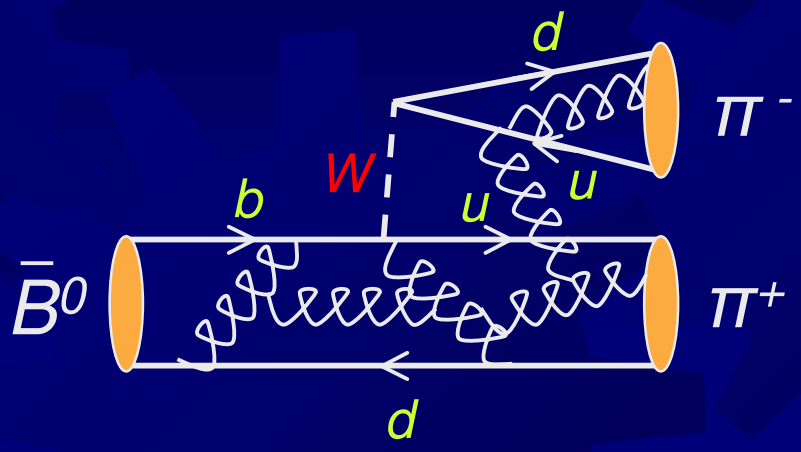
Rates for many charmless *B* decays are characterized by significant interference of tree and penguin topologies:

Amplitude: $$\mathrm{A} = Te^{i\delta_1}e^{-i\gamma} + Pe^{i\delta_2} + P_{EW}e^{i\delta_3}$$

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

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

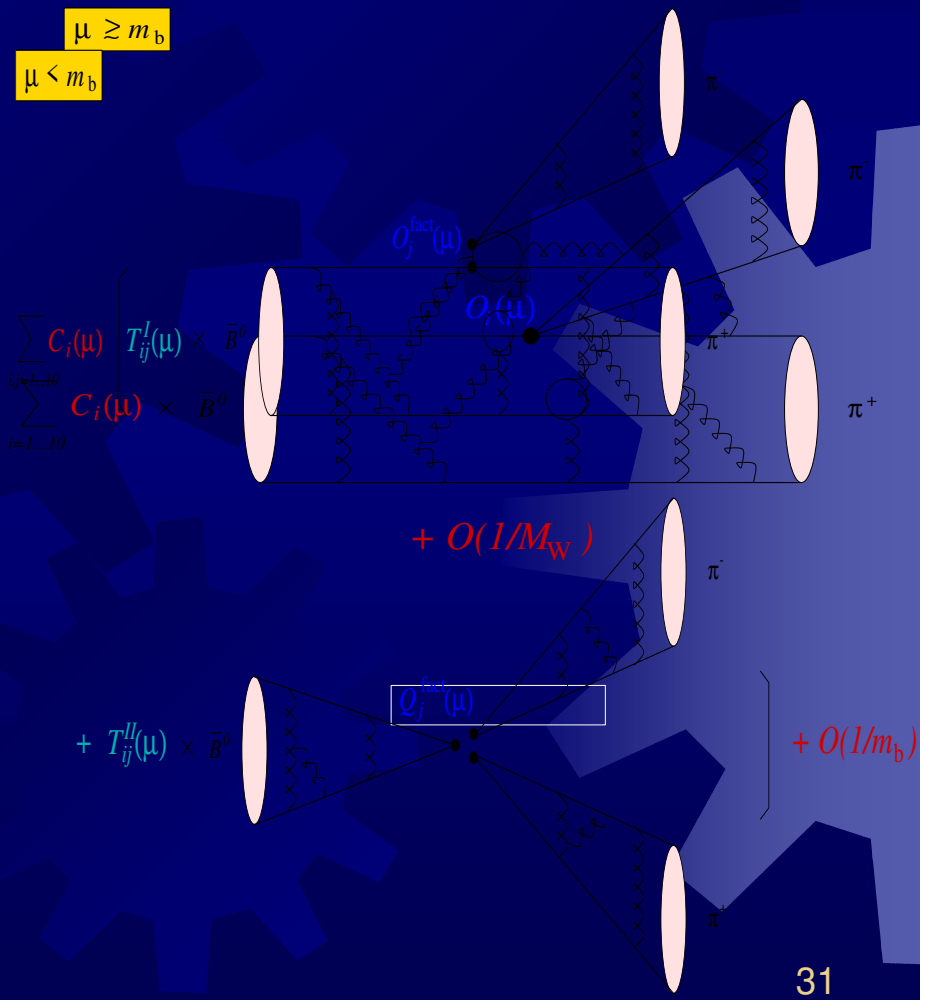
Reality is far more complicated:



- Until few years ago such nonleptonic decays were believed to be theoretically intractable
- Recent developments:
  - QCD factorization *[Beneke, Buchalla, Neubert, Sachrajda 1999]*
  - Soft-Collinear Effective Theory
    [Bauer, Fleming, Luke, Pirjol, Stewart 2000; Beneke et al. 2002; Hill, Neubert 2002]
- Systematic treatment (Λ_{QCD}/m_b expansion)

Main Idea: Color Transparency

- $\gamma_\pi = E_\pi / m_\pi \sim 19$, $v_\pi/c \sim 0.999$ pions are highly relativistic
- Only "hard" gluons can interact with fast, color-neutral hadrons
  - perturbation theory, OPE
- "soft" nonfactorizable gluons decouple!
- Hadronic effects can be reduced to decay constants, form factors, and light-cone distribution amplitudes
  - experimentally accessible!
- Theoretical uncertainties quantifiable!



Tests of Factorization

- Many tests of QCD factorization can already be performed using current data
- Confirmed:
  - ✓ Magnitudes of tree amplitudes
  - ✓ Magnitudes of penguin amplitudes
  - ✓ Small relative strong phases between tree and penguin amplitudes (small direct CP asymmetries)
- Theory is in good shape!

Global Description: Branching Ratios [10^{-6}]

Beneke, Neubert [2003]:

- Theoretical central values for fixed set of input parameters
- Simultaneous description of all existing data (γ=70°)!

ΔD=1 decays

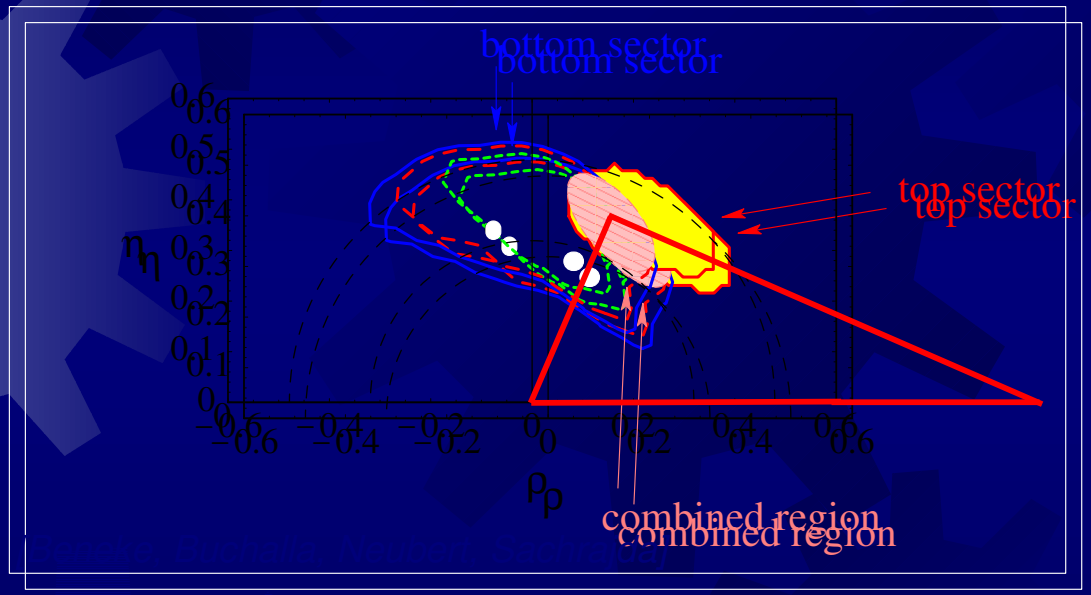
Mode	Theory	Experiment
$B^- \to \pi^-\pi^0$	5.1	5.3 ± 0.8
$\bar{B}^0 \to \pi^+\pi^-$	5.2	4.6 ± 0.4
$\bar{B}^0 \to \pi^0\pi^0$	0.7	1.6 ± 0.7
		(< 3.6)
$B^- \to \pi^-\eta$	3.8	3.9 ± 0.9
$B^- \to \pi^-\rho^0$	12.3	9.4 ± 2.5
$\bar{B}^0 \to \pi^+\rho^-$	11.8	13.9 ± 2.7
$\bar{B}^0 \to \pi^-\rho^+$	11.8	8.9 ± 2.5
$\bar{B}^0 \to \pi^\pm\rho^\mp$	23.6	22.8 ± 2.5
$B^- \to \pi^-\omega$	8.4	5.9 ± 0.9

ΔS=1 decays

Mode	Theory	Experiment
$B^- \to \pi^-\bar{K}^0$	20.3	20.6 ± 1.3
$B^- \to \pi^0 K^-$	11.7	12.8 ± 1.1
$\bar{B}^0 \to \pi^+ K^-$	18.4	18.2 ± 0.8
$\bar{B}^0 \to \pi^0\bar{K}^0$	8.0	11.2 ± 1.4
$B^- \to \eta K^-$	1.6	3.1 ± 0.7
$B^- \to \eta' K^-$	76.1	77.6 ± 4.6
$\bar{B}^0 \to \eta'\bar{K}^0$	70.3	60.6 ± 7.0
$B^- \to \pi^-\bar{K}^{*0}$	8.4	13.0 ± 3.0
$\bar{B}^0 \to \pi^+ K^{*-}$	8.1	16.0 ± 6.0
$\bar{B}^0 \to K^-\rho^+$	10.1	8.5 ± 2.1
$B^- \to K^-\omega$	5.9	5.3 ± 0.8
$\bar{B}^0 \to \bar{K}^0\omega$	4.9	5.6 ± 1.3
$B^- \to K^-\phi$	12.5	9.2 ± 0.7
$\bar{B}^0 \to \bar{K}^0\phi$	11.2	7.7 ± 1.1
$B^- \to \eta K^{*-}$	19.9	25.4 ± 5.3
$\bar{B}^0 \to \eta\bar{K}^{*0}$	18.6	16.4 ± 3.0

Fit of $B \to \pi K$ and $B \to \pi\pi$

Highest precision (theor.+exp.):



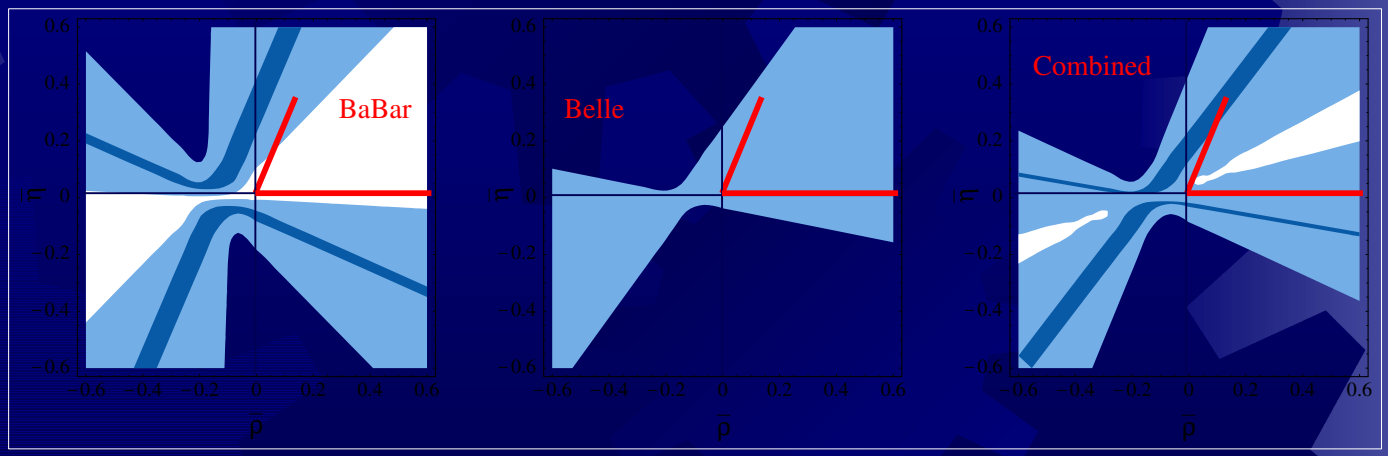
CKM parameters:

$\beta=(24\pm2)^\circ$
$\gamma=(67\pm15)^\circ$
$\rho=0.15\pm0.08$
$\eta=0.36\pm0.09$

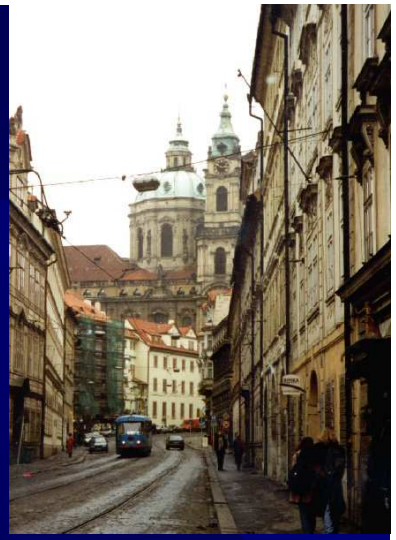
- Establishes CP violation in the *b* sector ($\mathrm{Im}\, V_{ub} \neq 0$)
- Agreement with data from the *t* sector constitutes a great success for the CKM model!

Controversy: $B \to \pi^+\pi^-$

- Measurement of the time-dependent CP asymmetry could yield interesting information about (ρ,η)
- Unfortunately, BaBar and Belle are inconsistent:
  - $S(\pi^+\pi^-) = 0.02 \pm 0.34 \pm 0.05$ *[BaBar]*
  - $S(\pi^+\pi^-) = -1.23 \pm 0.41 \pm 0.07$ *[Belle]*
- Implications:



Next year we'll know better …

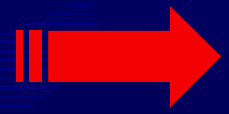


4. Departures from the Standard Model ?

2-3σ effects and the search for physics beyond the Standard Model

Searching for the Unknown

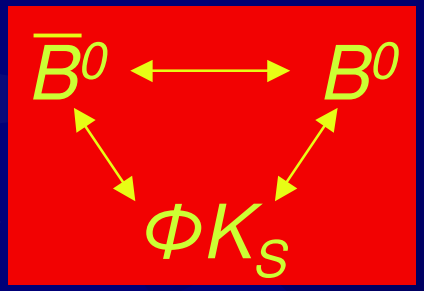
- So far, all measurements in the flavor sector are in agreement with the SM
- However, like in the electroweak sector, some observables show discrepancies at the level of ~ 2-3σ
- Interesting, if theoretical uncertainties can be controlled



3 examples …

CP Asymmetry in $B \to \Phi K_S$

- Interference of mixing and decay:

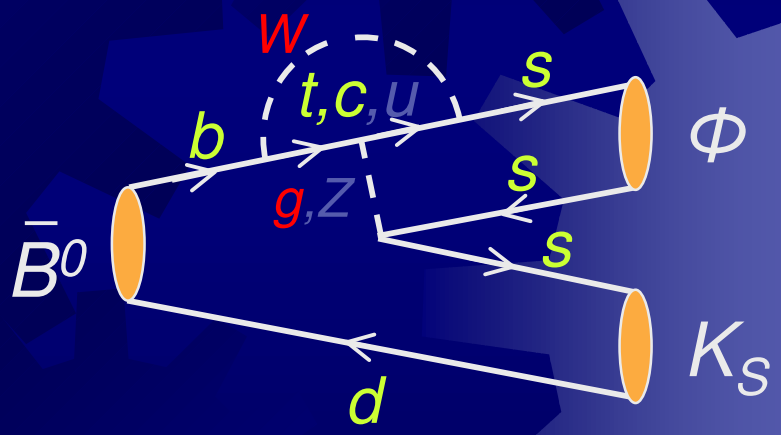


- Phase structure identical to the decay $B \to J/\psi\, K_S$
- Model-independent result:

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

[Beneke, Neubert 2003]

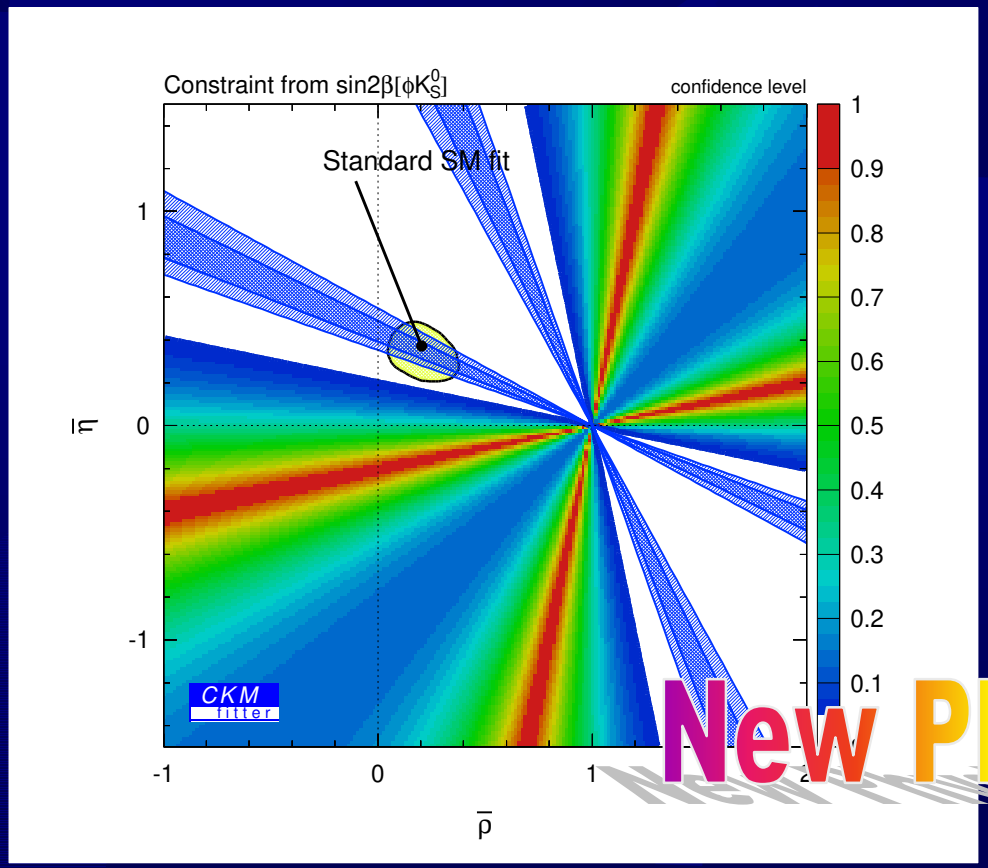
- Penguin graph is real to very good approximation!



- Experimental situation:
  - $S(\Phi K_S) = -0.18 \pm 0.51 \pm 0.07$ BaBar
  - $S(\Phi K_S) = -0.73 \pm 0.64 \pm 0.22$ Belle

  } -0.38 ± 0.41

$S(\Phi K_S) - S(J/\psi\, K_S) = -1.11 \pm 0.41$ (2.8σ)



New Physics ?

Large $B \to \pi^0 K_S$ Rate

Theoretical value of the ratio

= +0.1 in SM

$$R_{00} = \frac{\Gamma(B \to \pi^0 K_S)}{\Gamma(B \to \pi^- K_S)} \cong \left|1 - \frac{P_{EW}}{P}\right|^2 = 0.79 \pm 0.07$$

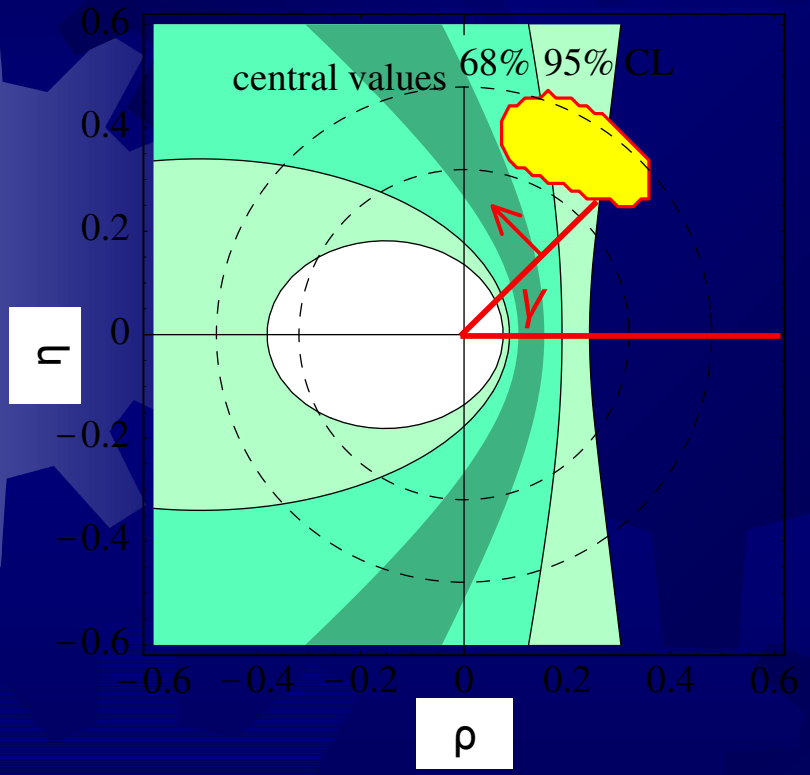
is significantly smaller than in the data:

$R_{00}^{exp} = 1.18 \pm 0.17$ (2.1σ)

[Beneke, Neubert 2003]

Central values:
BaBar 1.13, Belle 1.24, CLEO 1.48
(3x stat. fluctuation ?)

NR Bound on γ



$$R_* = \frac{\Gamma(B^\pm \to \pi^\pm K_S)}{2\Gamma(B^\pm \to \pi^0 K^\pm)} = 0.80 \pm 0.09$$

- A model-independent bound on γ can be obtained from the ratio of the CP-averaged rates for the decays $B \to \pi^\pm K_S$ and $B \to \pi^0 K^\pm$
- Result $\gamma > 45^o$ (95% CL) is compatible with the SM, but central value $\gamma \sim 90^o$ ist significantly higher

[Neubert, Rosner 1998]

In all Cases …

- Possible explanation in terms of new, CP-violating flavor-changing neutral currents (FCNC) of the type $b \to s\bar{q}q$ *(sg)*

- $S(\Phi K_S)$:
  Requires a large, new CP-violating phase;
  $(\bar{q}q)$ in flavor singlet possible (octet preferred)
- R_{00} and NR bound:
  Requires $(\bar{q}q)$ in flavor octet (modification of the electroweak penguin necessary!)

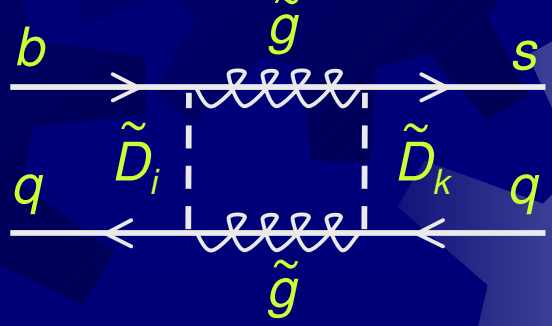
Trojan Penguins!

[Grossman, Kagan, Neubert 1999]

Trojan Penguins

- In the SM, $b \to s\bar{q}q$ transitions with $q=d,s\neq u$ are mediated exclusively by electroweak penguins
- Extensions of the SM can contain such processes without α_{EM} suppression

- e.g., gluino-squark box graphs in SUSY:



- *New Physics* can easily compete with the SM!

Sensitivity to large scales:

$$M_{NP}^2 = (\alpha_s/\alpha_{EM})\, M_W^2$$

Some Examples

Model	$S(\Phi K_S)$	ΔR_{00}	$\Delta\gamma_{\pi K}$
Z', FCNC Z, SUSY without R_p	O(1)	O(1)	180^0
SUSY	0.5	0.15-0.50	25^o-180^o
2HDM	0.1	0.05	10^o
Anomalous gauge boson couplings	0.2	0.10	20^o

- It is not difficult to obtain large effects
- It would be difficult to suppress them!

5. Outlook

Conclusions

Summary

- Precision measurements in the flavor sector (quarks and leptons) complement the search for *New Physics* at high energy and are an indispensable part of the exploration of the TeV scale
- The determination of the CKM matrix and tests of the CKM mechanism have reached a new quality:
  - Discovery of CP violation in both the *t* and *b* sectors of the CKM matrix
  - Precise determination of the unitarity triangle

Summary

- CKM physics is only one of many ways to search for and explore *New Physics* effects
- Interesting hints exist for new, CP-violating FCNC interactions of the type $b \to s\bar{q}q$
  - Evidence for *New Physics* at the TeV scale (?)
  - Possible relevance for cosmology (baryogenesis)
- When will the SM collapse, and what lies beyond it ?
  - The coming years will tell!