Flavor Physics in the LHC Era

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Outline

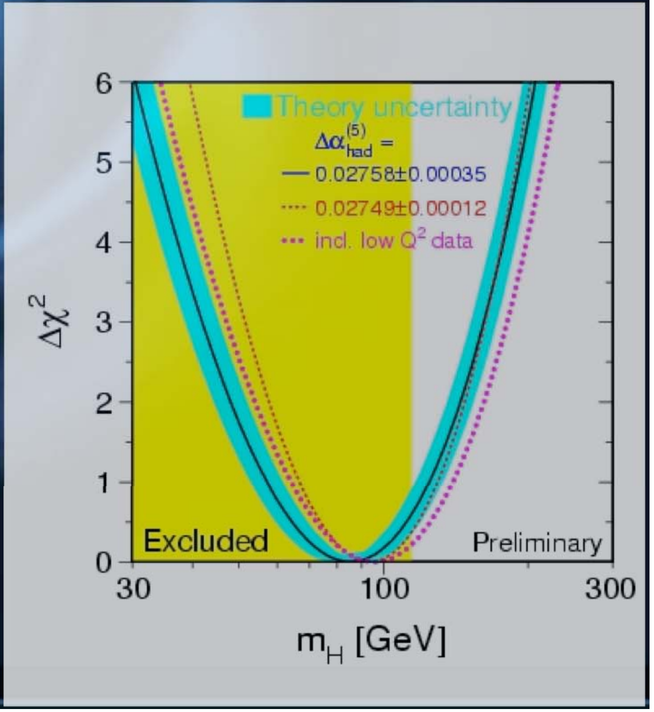
- Snapshot of particle physics
- Precision studies of the CKM matrix
- Particle physics at a crossroad
- Beyond the Standard Model
- Potential impact of Super B-factory
- Summary

Snapshot of particle physics

Too good to be true …

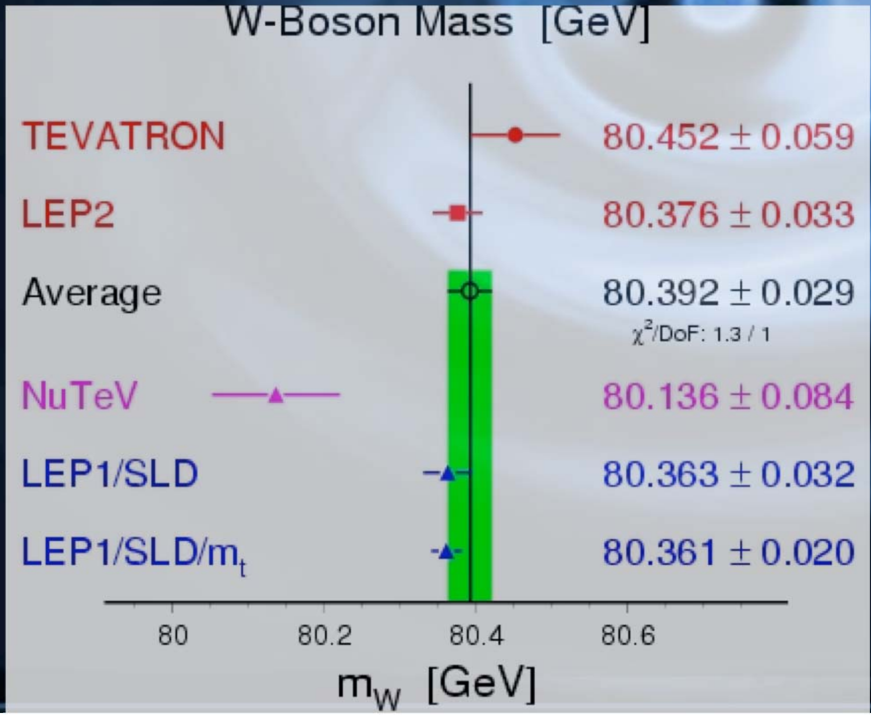
Hints from experiment

- Standard Model (SM) of elementary particle interactions works marvelously
- A triumph of 20th century science!
- No compelling evidence for New Physics from electro-weak precision measurements (Z pole and beyond)
- Preference for a light Higgs



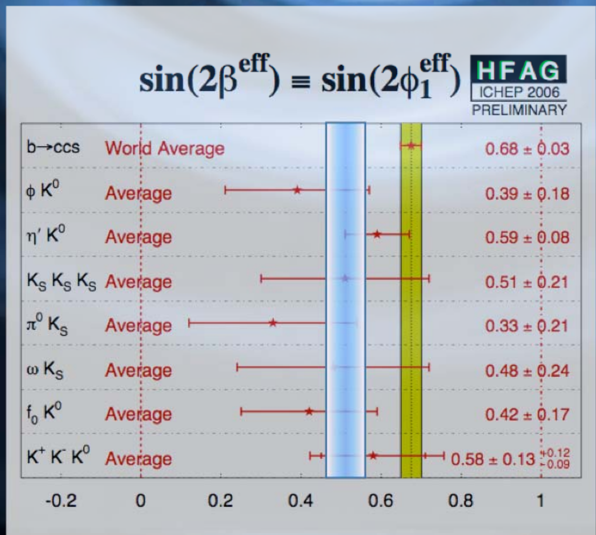
Hints from experiment

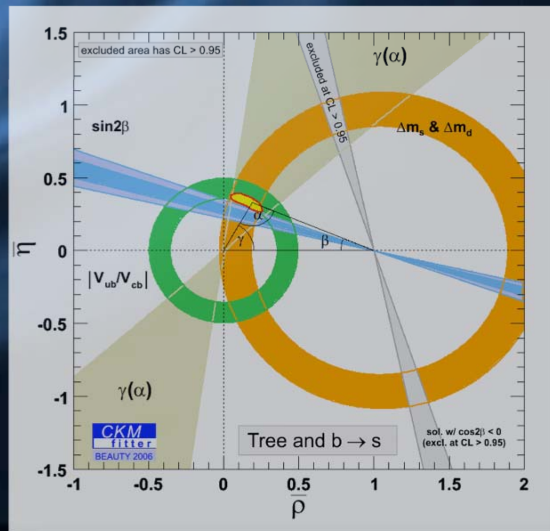
- $A_{FB}{}^{b}$ and NuTeV off by 3σ, but not readily explained by New Physics (stat. fluct.?)



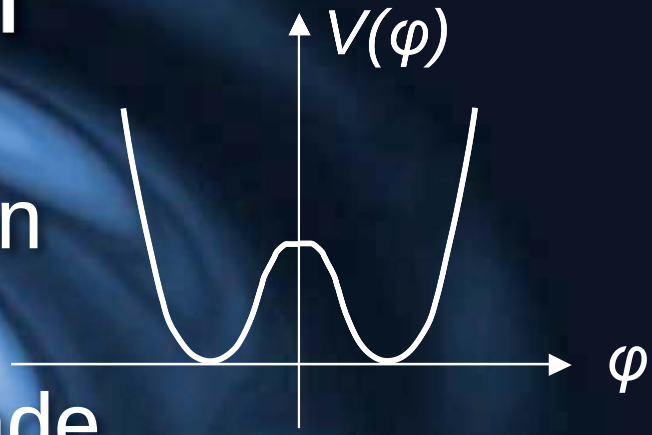
Hints from experiment

- Other 2-3σ effects present in low-energy precision measurements
  - Muon anomalous magnetic moment, $(g-2)_\mu$
  - B physics (several small, but intriguing effects)





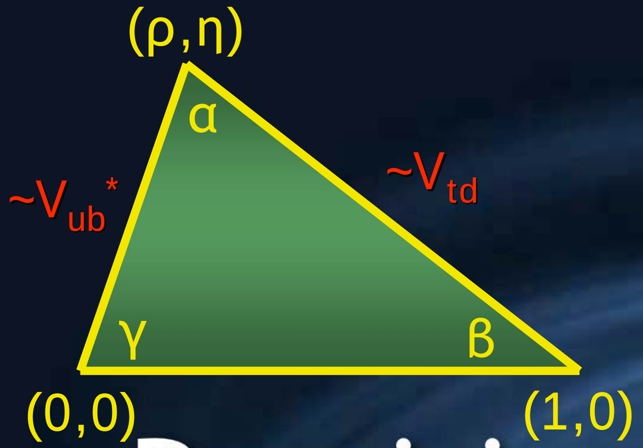
Higgs sector

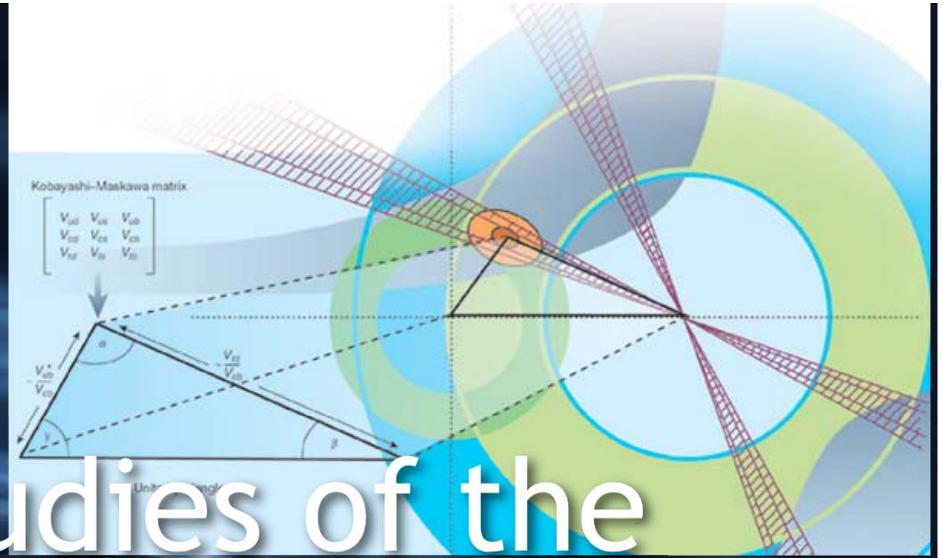


- ✧ Comprehensive exploration of scalar sector main challenge for coming decade
- ✧ In SM, flavor physics intimately connected with Higgs sector via Yukawa matrices ($V_{CKM}=U_u^\dagger U_d$), hence indispensible part of this program

Higgs sector

- LHC is a discovery machine, but not a precision tool
- Many properties of new particles (if discovered) will not be measured at LHC
- Requires facilities offering high precision: high-luminosity facilities at low energies (B, K, neutrinos, g-2, EDMs, $0\nu\beta\beta$ decay, etc.)



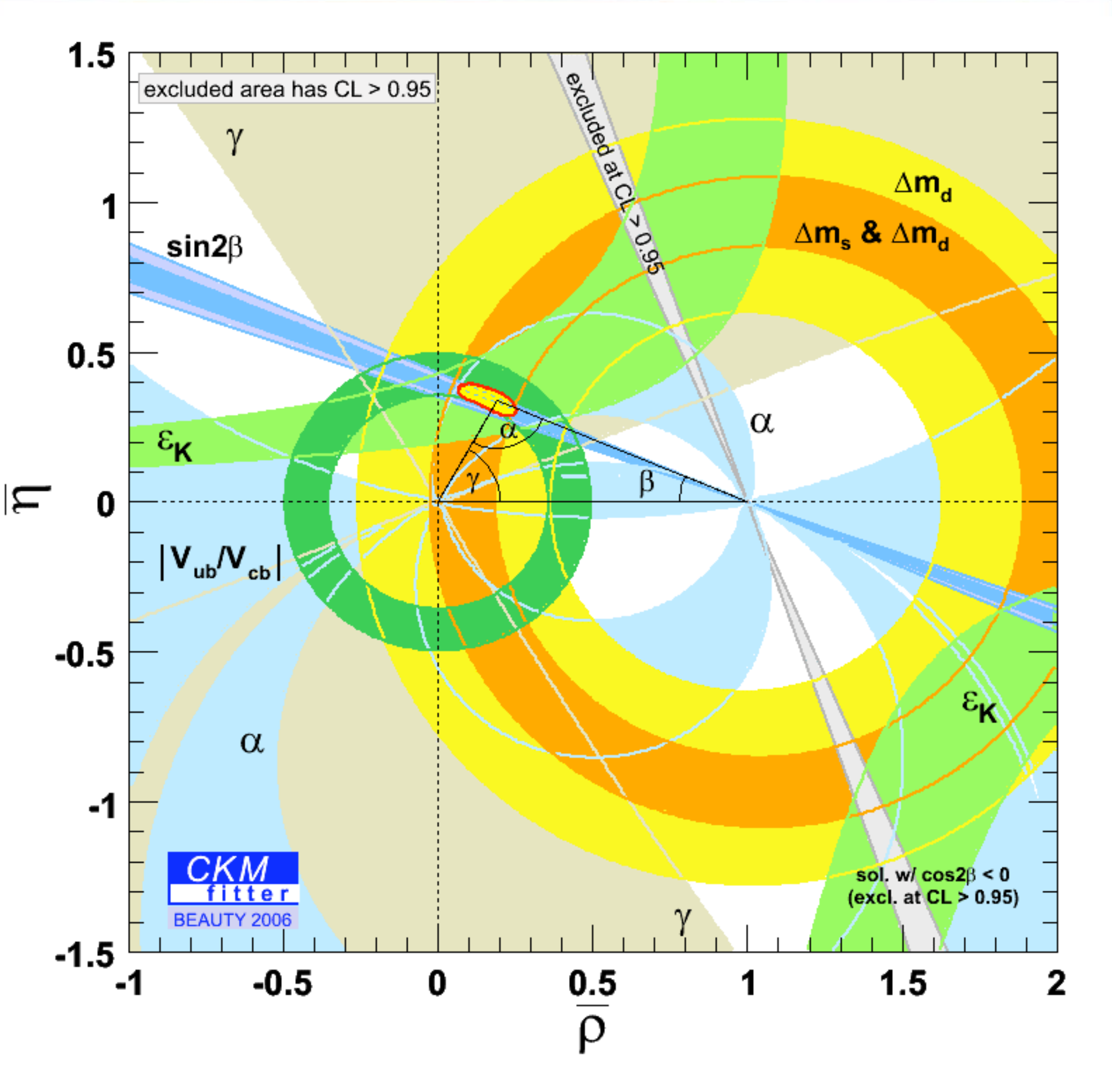


Precision studies of the CKM matrix

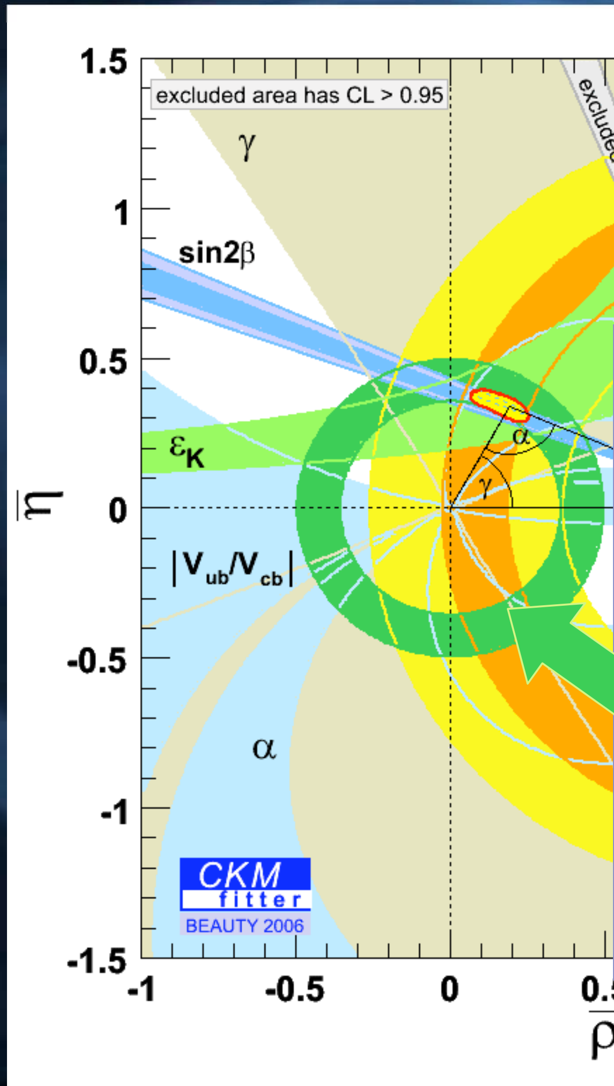
Overdetermining the unitarity triangle

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

Determinations of the UT

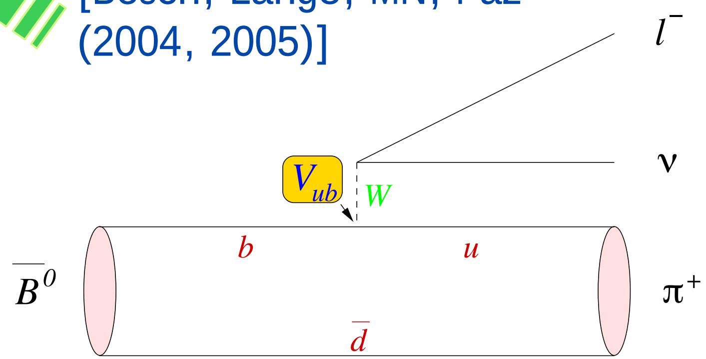


Determinations of the UT



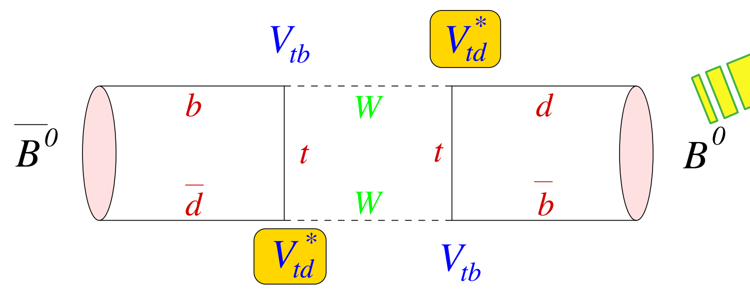
- Determination of $|V_{ub}|$ in semilept. B decays
- Theoretical uncertainty recently reduced to 5%

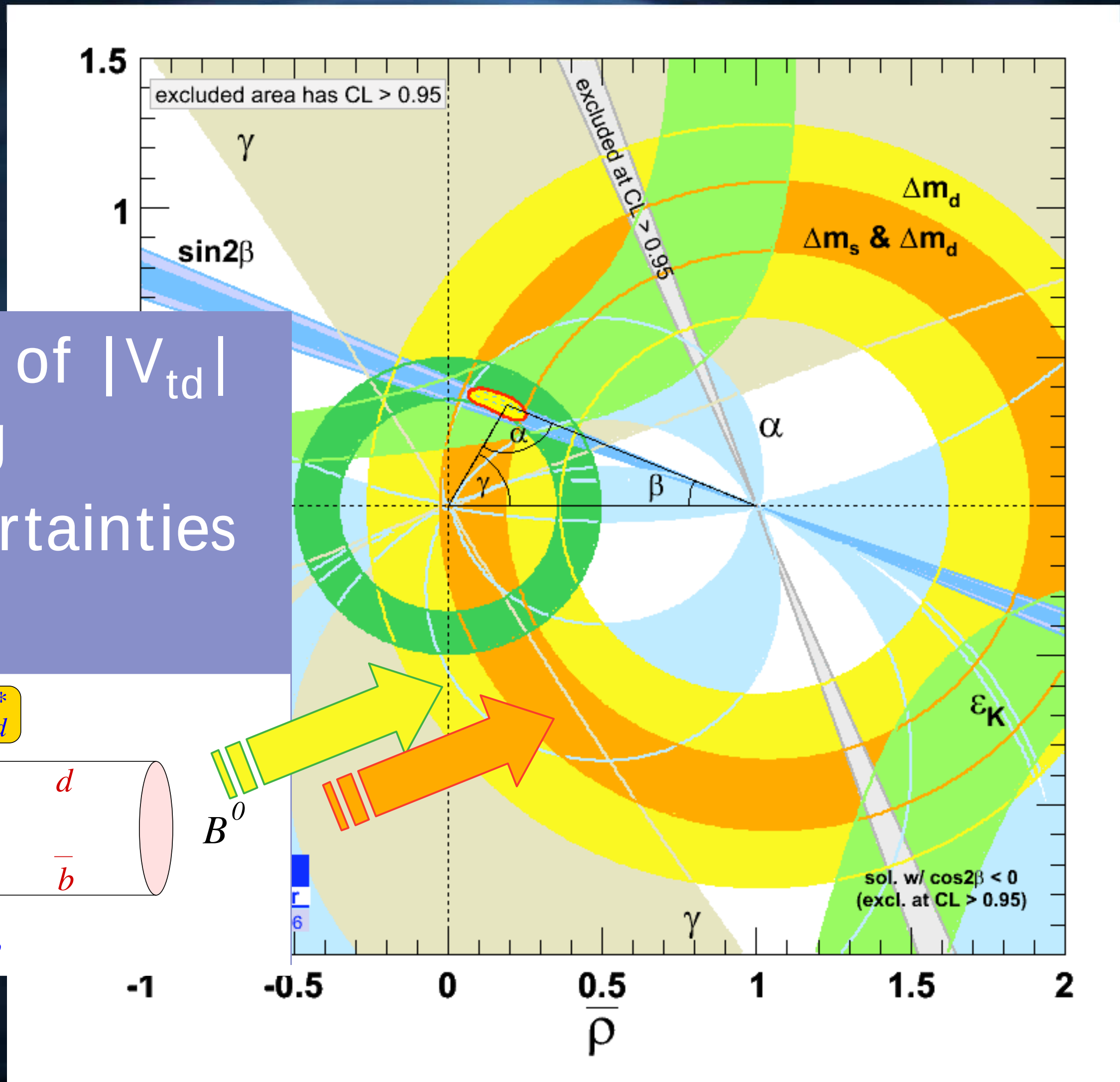
[Bosch, Lange, MN, Paz (2004, 2005)]



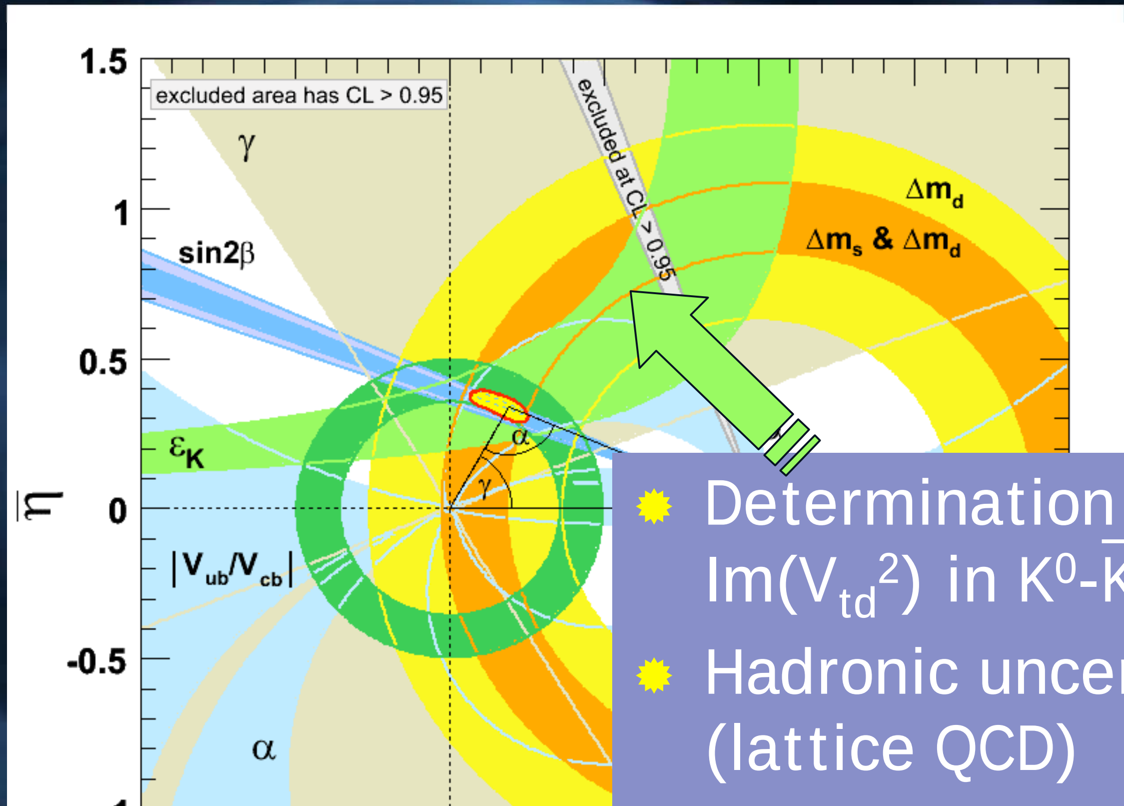
Determinations of the UT

- Determination of $|V_{td}|$ in B^0-$\bar{B}^0$ mixing
- Hadronic uncertainties (lattice QCD)

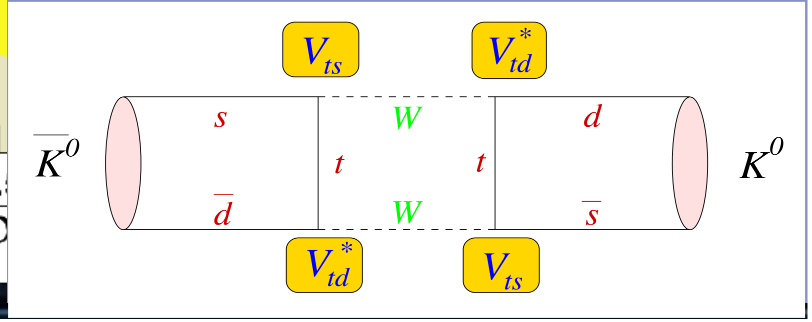




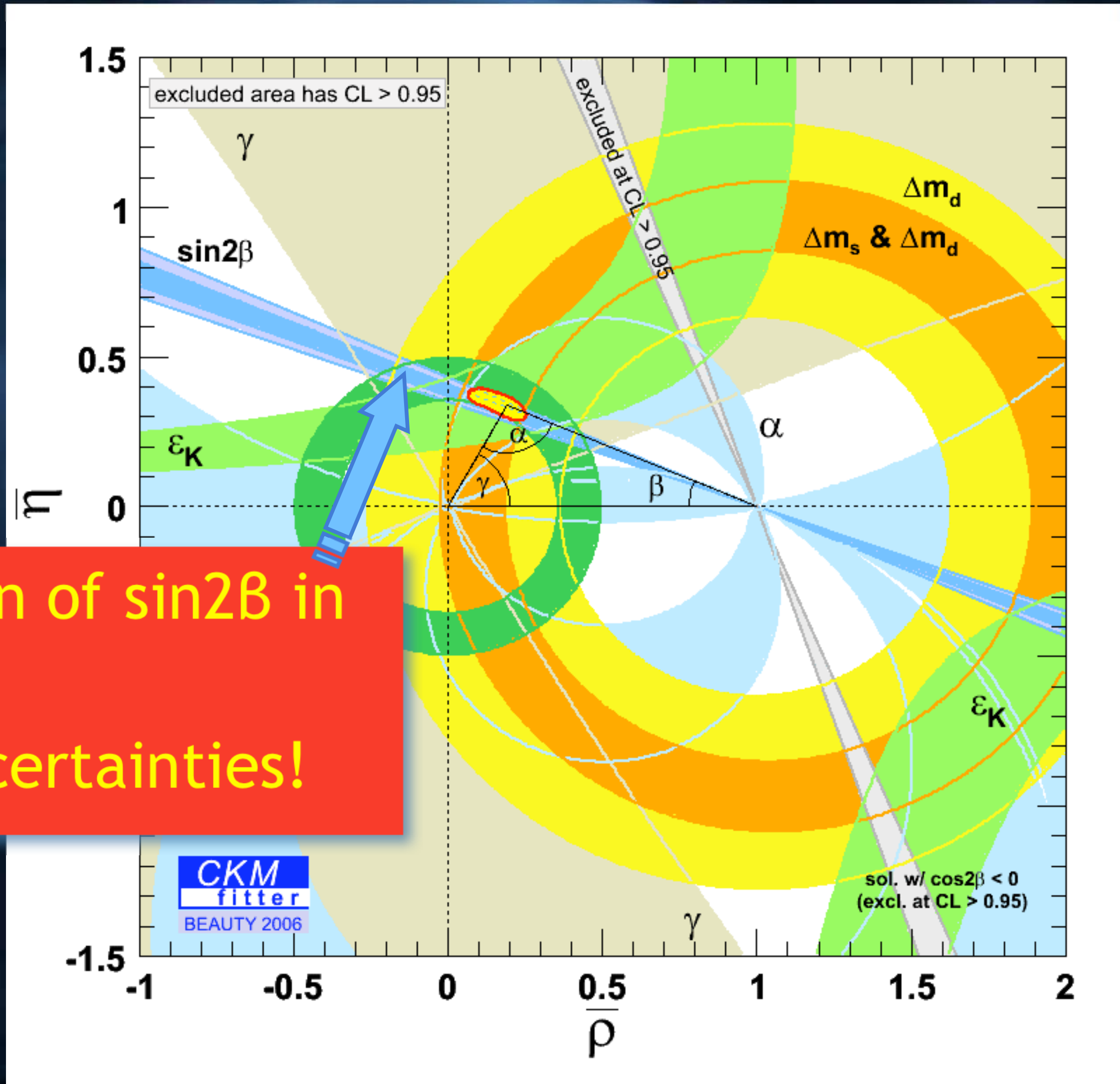
Determinations of the UT



- Determination of $Im(V_{td}^2)$ in K^0-$\bar{K}^0$ mixing
- Hadronic uncertainties (lattice QCD)



Determinations of the UT



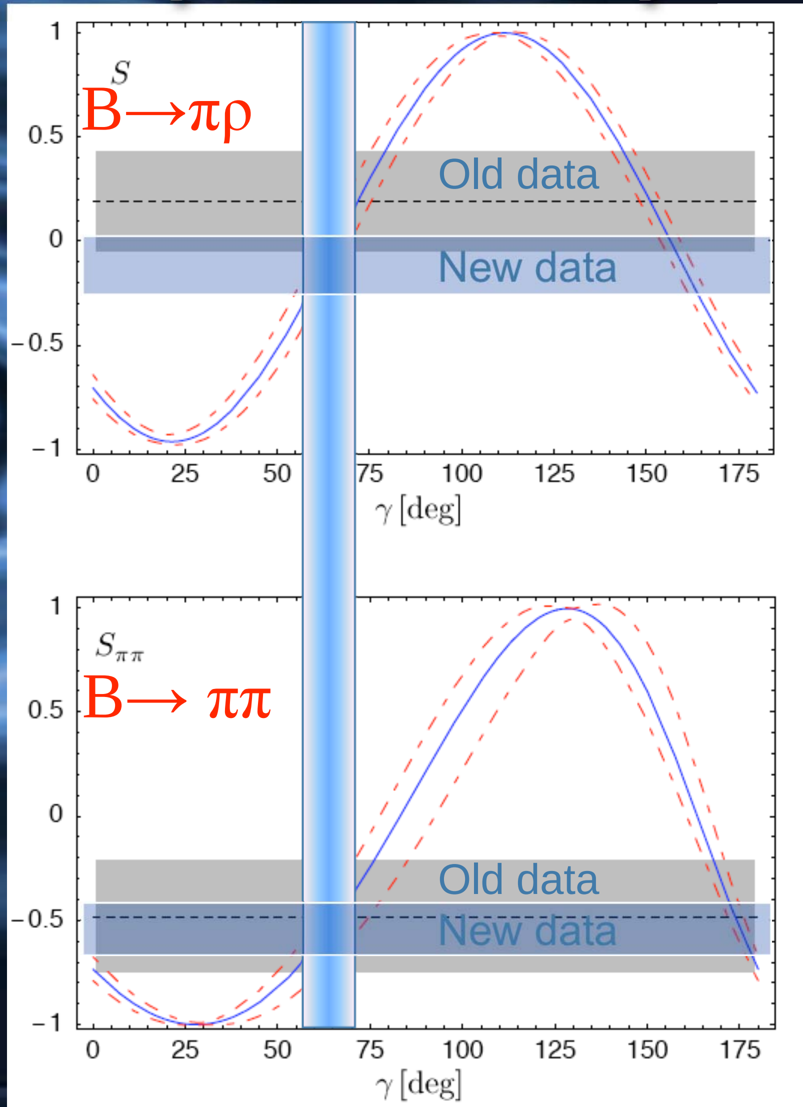
- Determination of sin2β in B^0-$\bar{B}^0$ mixing
- No theor. uncertainties!

Determination of γ in B→πρ

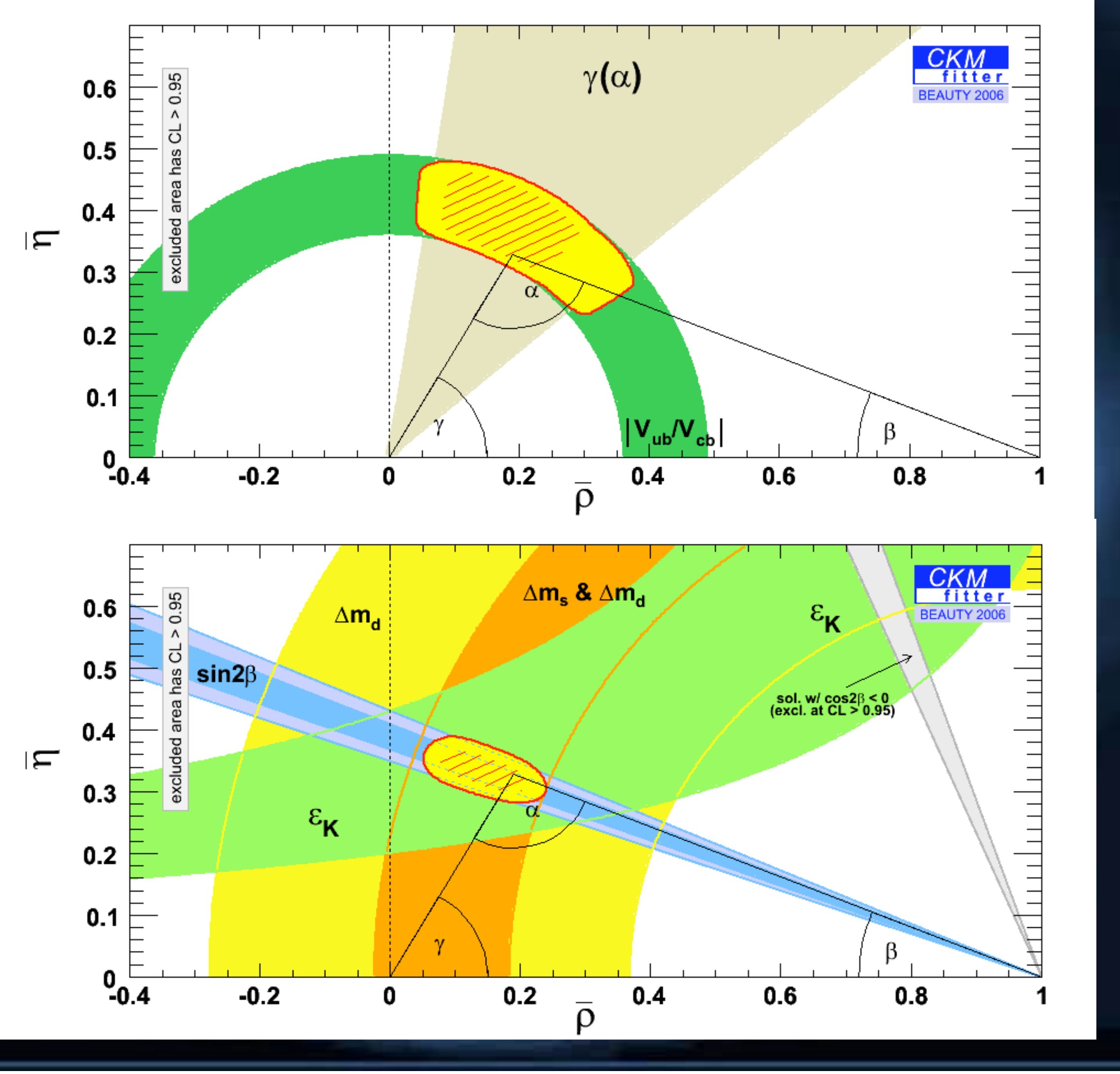
- B→PV modes receive smaller penguin contributions than B→PP modes
- Allows extraction of γ with small theoretical errors from time-dependent B→πρ rates
- Result:

γ = (62±8)°

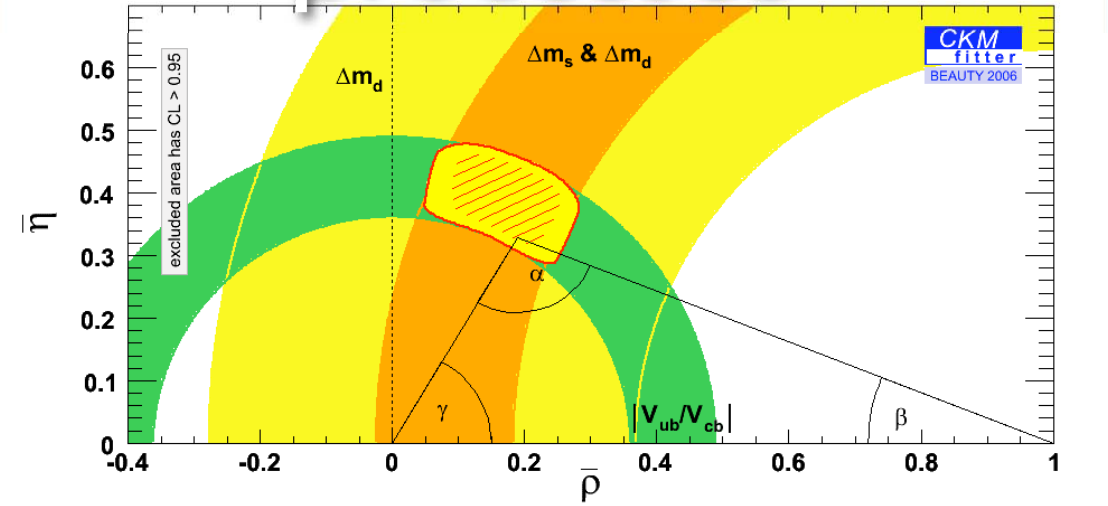
[Beneke, MN (2003)]

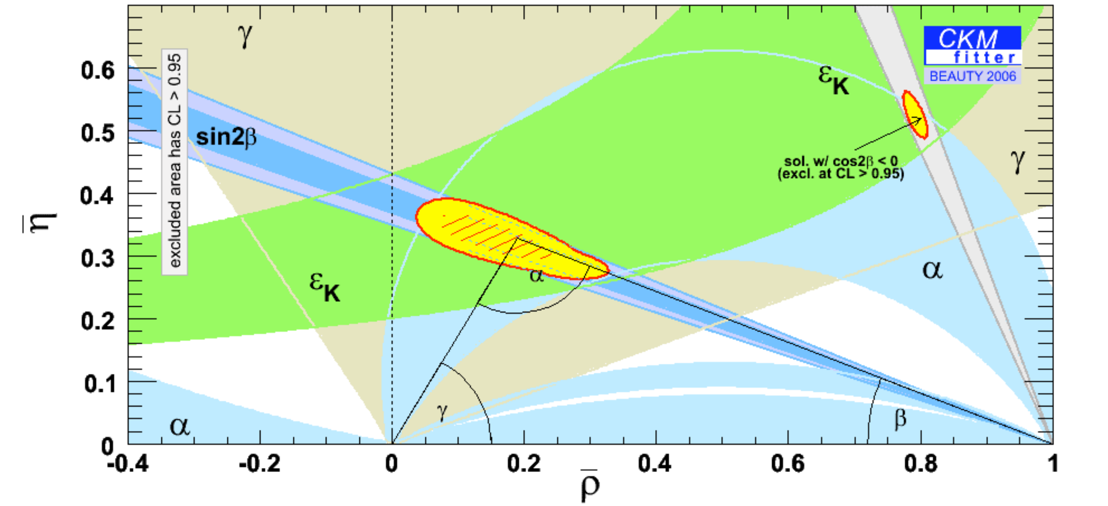


Tree vs. penguin processes

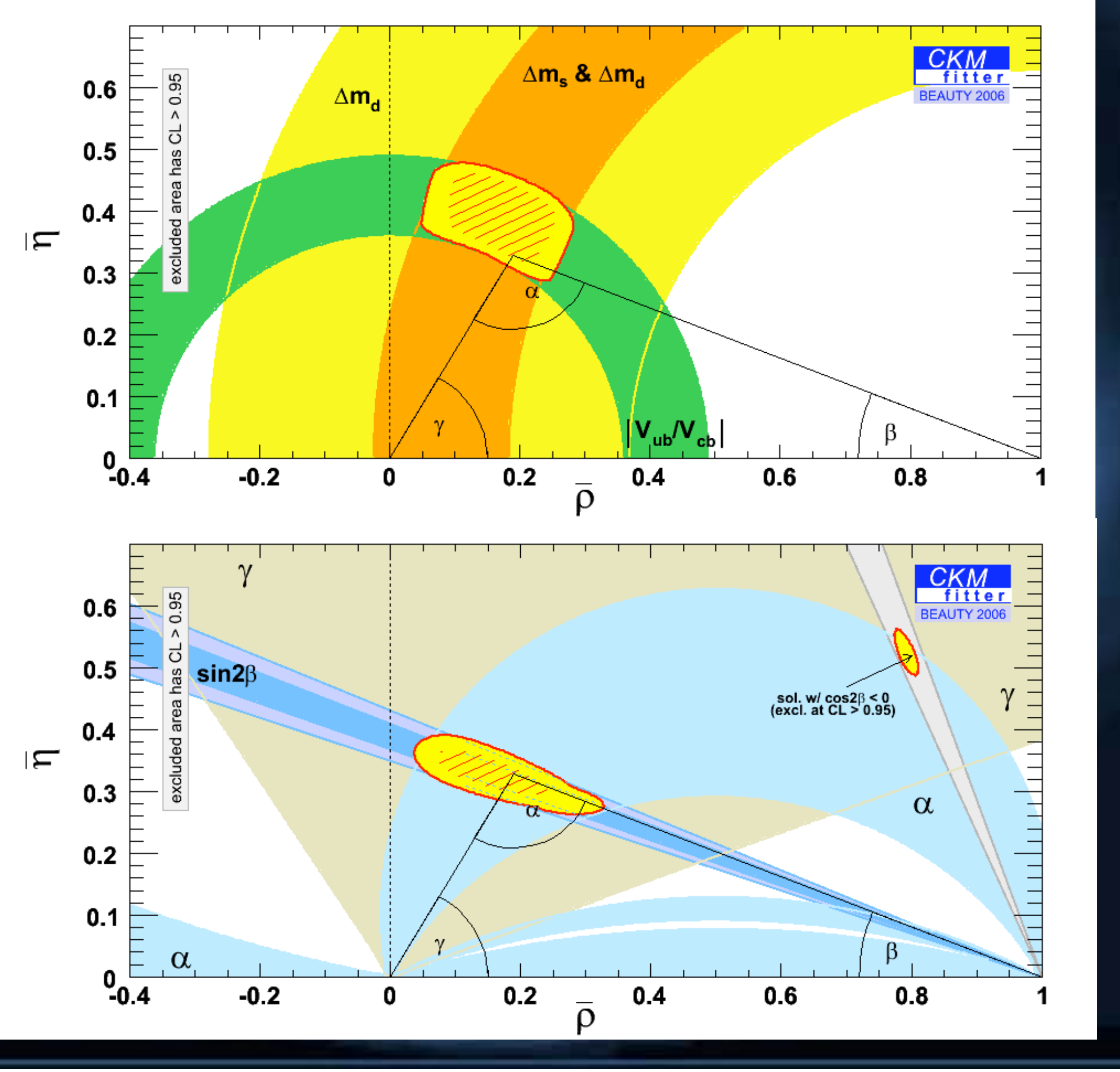


CP-conserving vs. CP-violating processes





Sides vs. angles

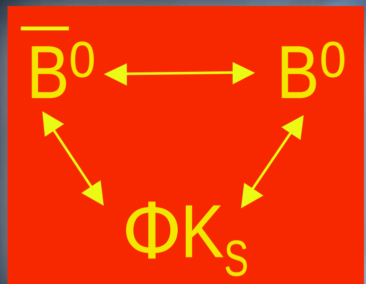


Summary

- CKM model of flavor and CP violation works spectacularly!
- Definitely the main source of these effects
- New Physics can only give corrections to the CKM picture
- Still, there is a possibility for finding some significant New Physics effects in the flavor sector

CP asymmetries in $B \to \Phi K_S, \eta' K_S$

✧ Interference of mixing and decay:



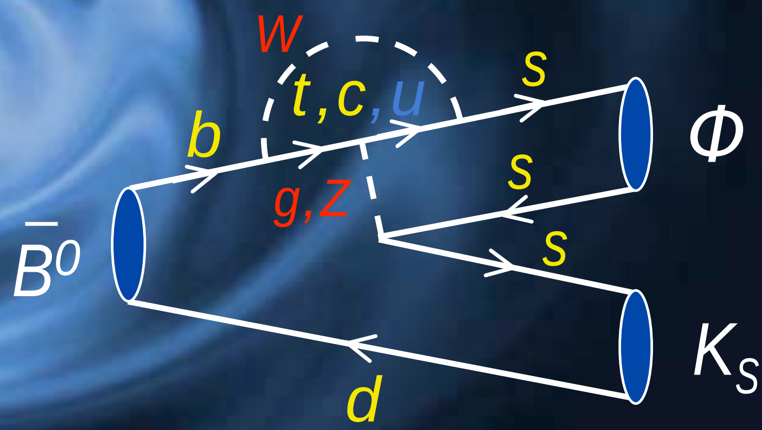
✧ Phase structure identical to golden decay $B \to J/\psi\ K_S$

✧ Theor. prediction:

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

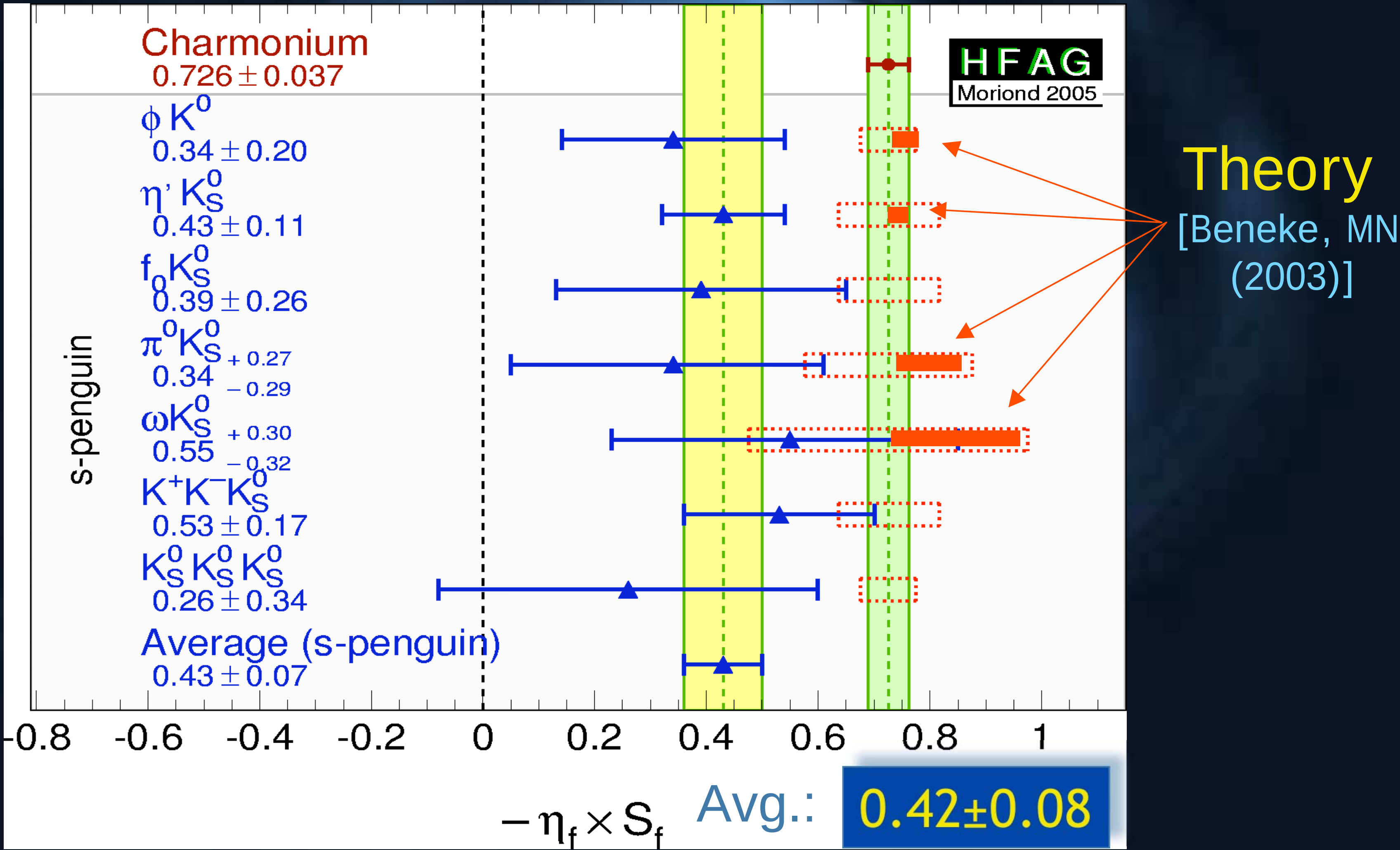
[Beneke, MN (2003)]

✧ Penguin graph real to excellent approx.



[Grossman, Worah (1996)]

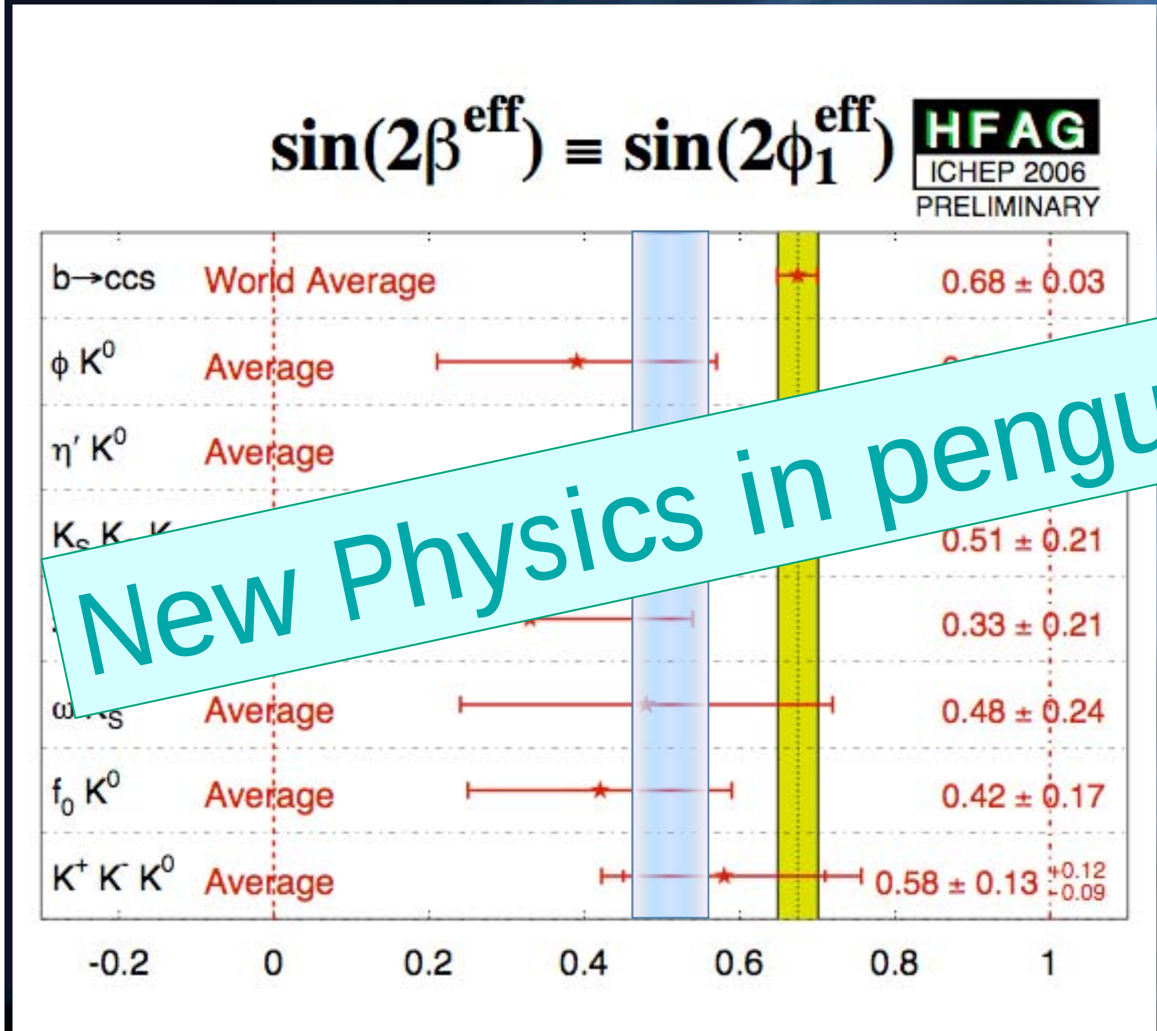
2005: 7 reasons for excitement



Avg.: 0.42±0.08

Deviation of 3.8σ!

Current situation



New Physics in penguin processes?

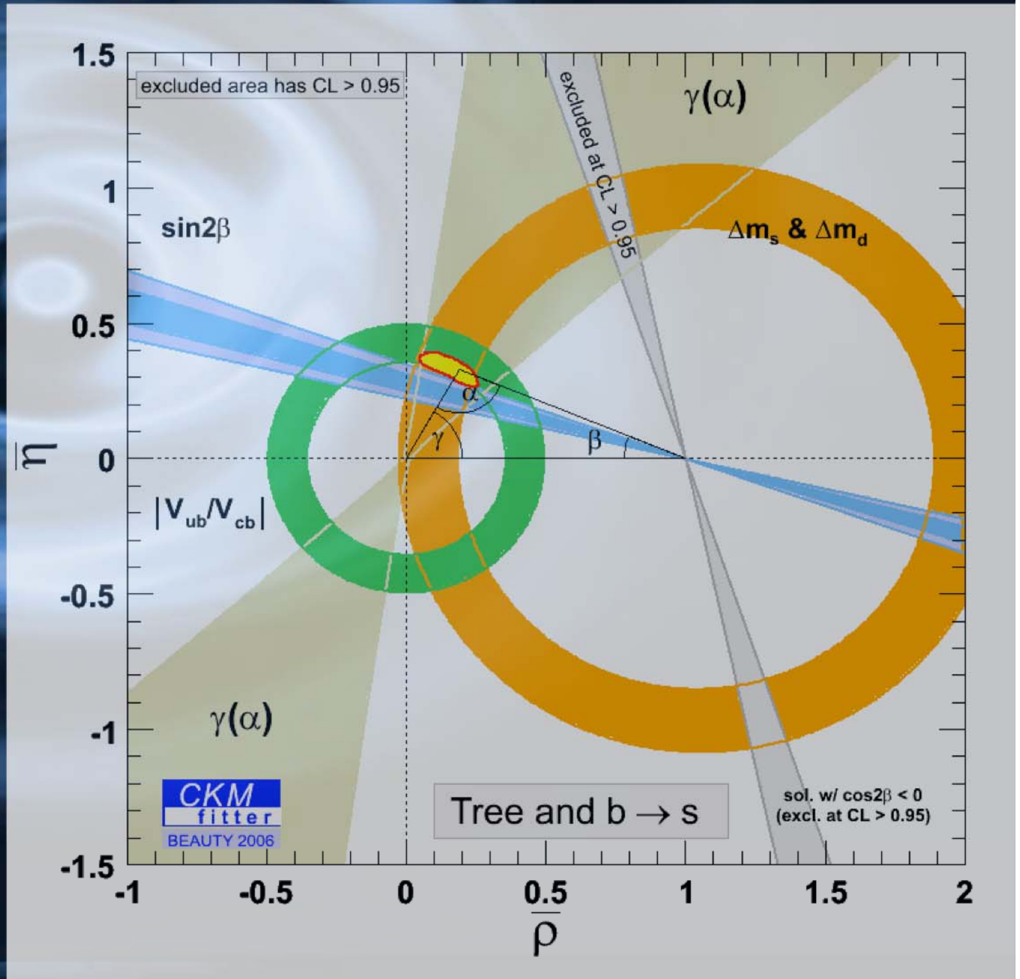
- Reference value reduced to …
- … increased to

0.52±0.05

- Deviation reduced to 2.8σ ☹

Current situation

- Combined average sin2β=0.638±0.026 lies below the "tree" value sin2β=0.794±0.045 deduced from $|V_{ub}|$ and $|V_{td}|$
- Important:
  - Increased precision in determination of $|V_{ub}|$
  - Measurement of B_s-$\bar{B}_s$ mixing (D0, CDF)



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

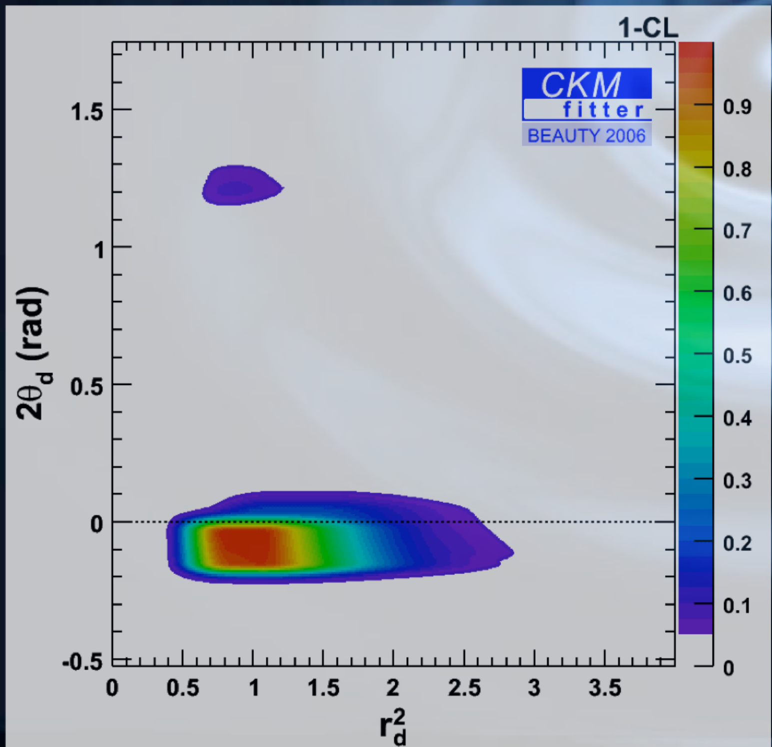
- Plausible explanation of these effects
- Possible and even natural in extensions of SM with new particles near TeV scale (e.g. SUSY, new Z' bosons, extra dimensions ...)

  → ~~*see talk by L. Silvestrini*~~

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

✧ General parametrization:

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



- ✧ New Physics contributions up to 50% of SM allowed
- ✧ Best fit prefers new, CP-violating phase $\theta_d \neq 0$
- ✧ After discovery of new particles at LHC → allowed parameter space for new flavor parameters

Other small deviations

- B_s-$\bar{B}_s$ mixing phase 2σ off SM value

[Lenz, Nierste, hep-ph/0612167]

- NNLO prediction for $B \rightarrow X_s\gamma$ is 1.4σ lower than world-average experimental result

[Misiak et al., hep-ph/0609232; Becher, MN, hep-ph/0610067]

$$\mathrm{Br}(\bar{B} \to X_s \gamma) = (2.98\,^{+0.13}_{-0.17}{}_{\mathrm{pert}} \pm 0.16_{\mathrm{hadr}} \pm 0.11_{\mathrm{pars}} \pm 0.09_{m_c}) \cdot 10^{-4}$$

Combined theory error: ±9%

$B_{exp}(E_\gamma > 1.6\ \mathrm{GeV}) = (3.55 \pm 0.24 \pm 0.09 \pm 0.03) \cdot 10^{-4}$

- Re-opens possibility for sizable New Physics contributions!

Crucial question

Are any of these effects real?

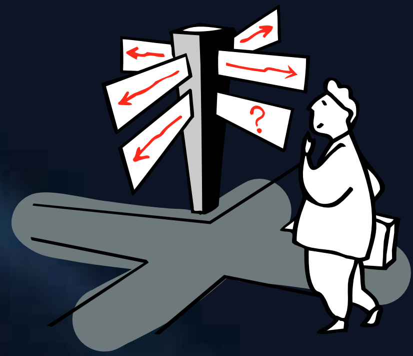
What one would need to explain them are O(0.1-0.2)
New Physics contributions to the decay amplitudes!

Crucial question

- We probably won't establish New Physics in any of these channels prior to LHC data
- After LHC (or Tevatron) discovery, we would reinterpret the effects in terms of measurements of new flavor parameters
- Yet, it's fundamentally important that some of the effects are real, because only then will we be able to distinguish New Physics effects from SM backgrounds!

Flavor physics is hard

- Interpretation of New Physics signals in weak decays is difficult due to SM background
- In presence of New Physics, methods that are clean in the SM often become sensitive to hadronic uncertainties
- Consider how difficult is has been to determine the 4 parameters of the CKM matrix, for which there is no background



Particle physics at a crossroad

On the verge of discovery?

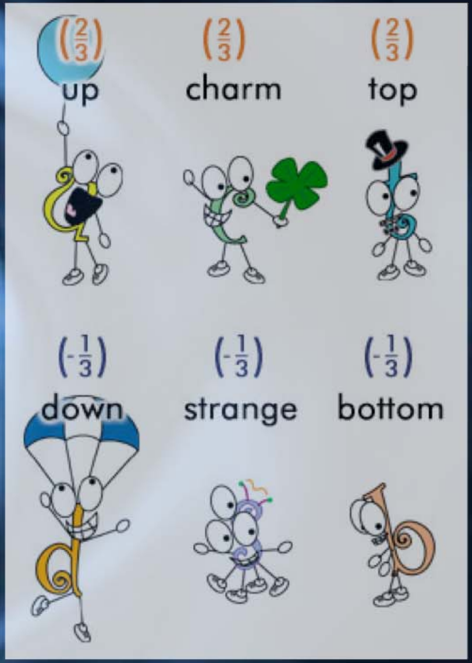
The big questions

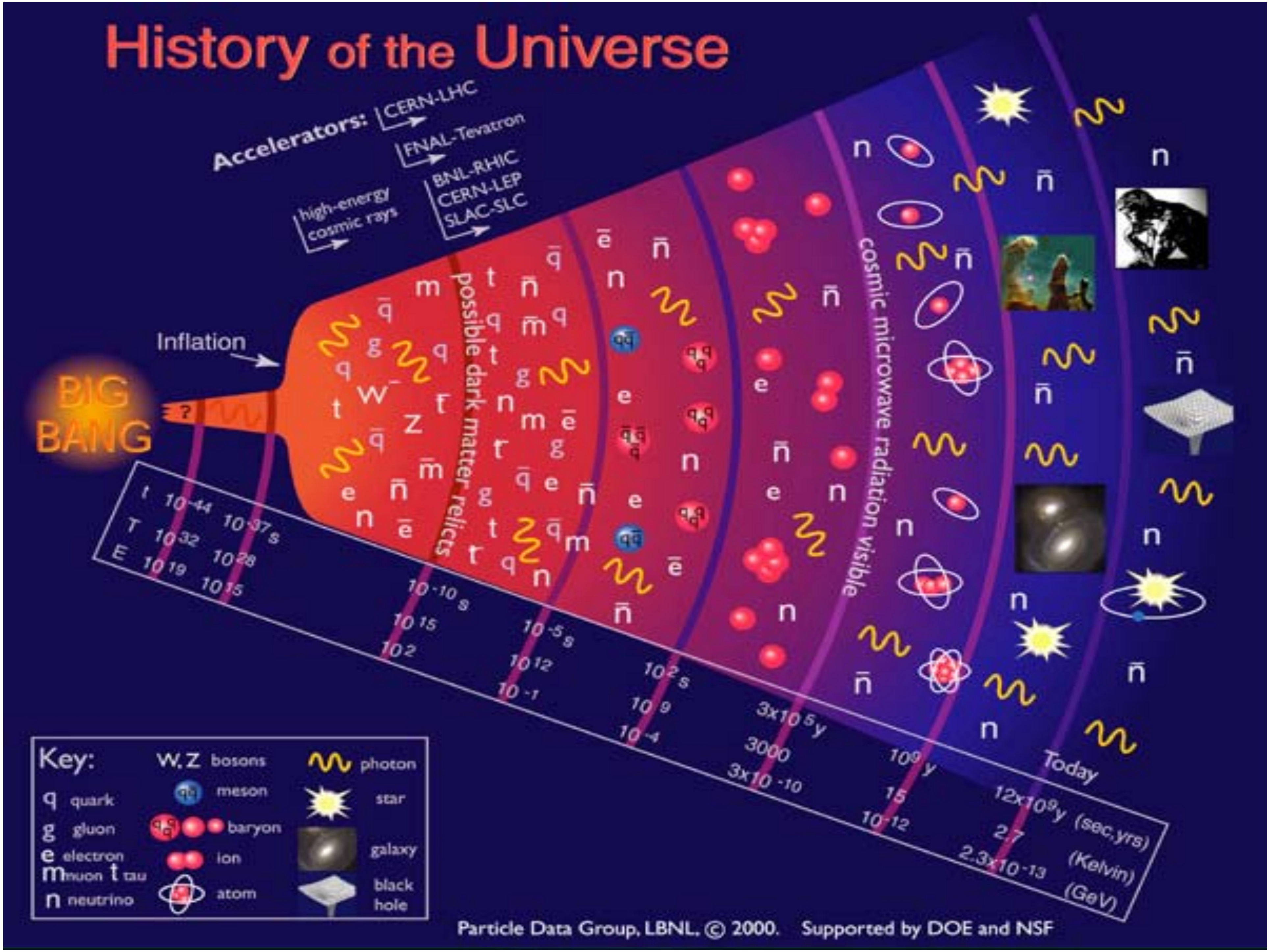
Despite great efforts in >30 years, have made little progress on really hard questions:

- Mechanism of electroweak symmetry breaking, responsible for masses of elementary particles?
  - Nature of scalar sector?
  - How stabilized?
- Curiously: most of mass in Universe from chiral symmetry breaking (QCD effect, well understood)!

The big questions

- Why $SU(3)_C xSU(2)_L xU(1)_Y$?
  - Do other forces exist?
  - Right-handed currents?
- Why 3 generations?
  - Dynamics of flavor?
  - New quantum number?
- Curiously: required for CP violation, but not responsible for matter-antimatter asymmetry!

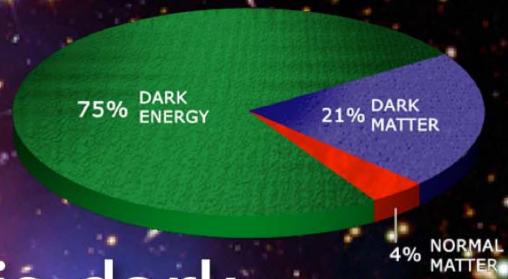



History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s 10-10 s 10-5 s 10 2 s 3x10 5 y 10 9 y Today 12x10 9 y (sec,yrs)
T 10 32 10 28 10 15 10 12 10 9 3000 15 2.7 (Kelvin)
E 10 19 10 15 10 2 10 -1 10 -4 3x10 -10 10-12 2.3x10-13 (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

The big questions

- What explains hierarchy of Yukawa matrices?
  - Fermion masses and mixings
  - Why different for quarks and leptons?
- What creates neutrino masses?
  - Do right-handed neutrinos exist?
  - Majorana or Dirac masses?
  - Sterile neutrinos?
  - See-saw mechanism?

The big questions

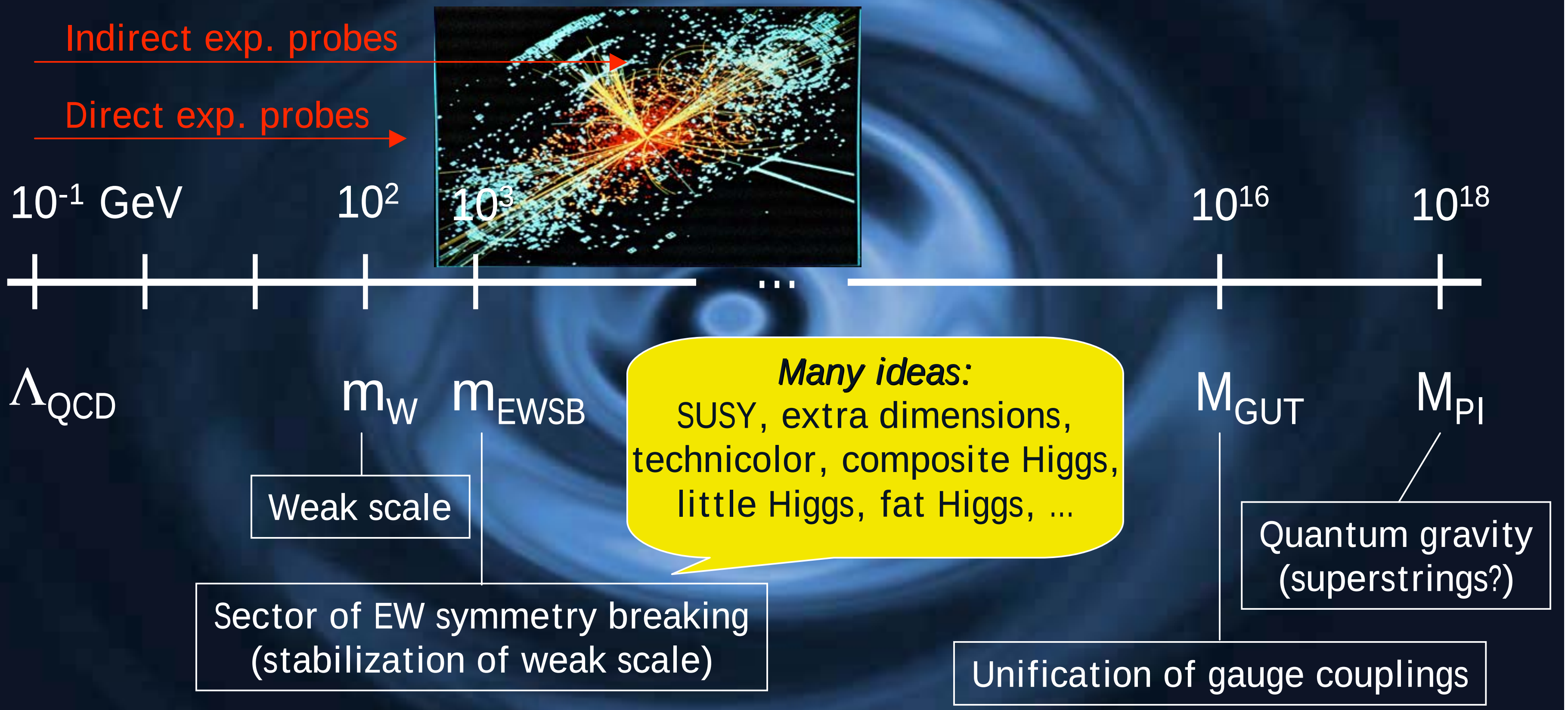


New questions:

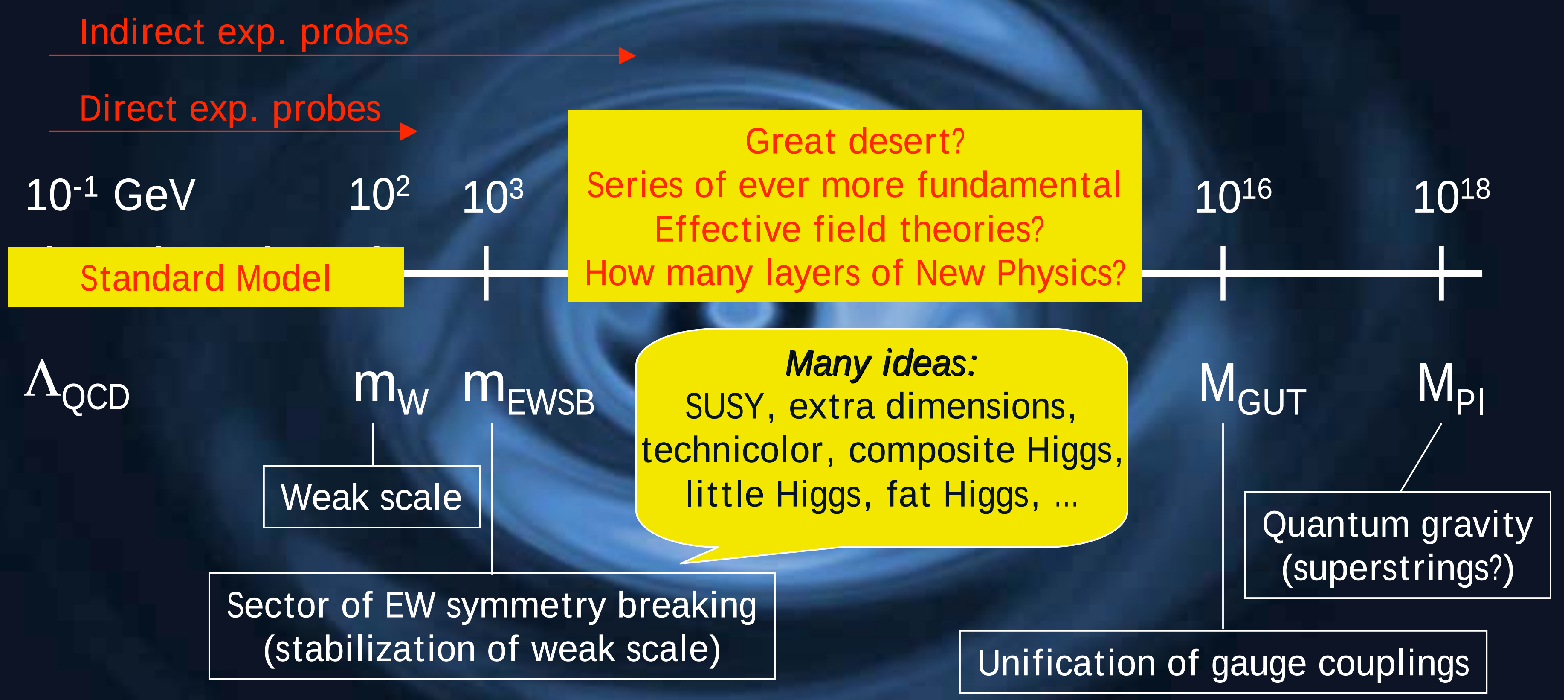
✧ What is dark matter? What is dark energy?

✧ Theory of inflation?

Conventional picture



Conventional picture

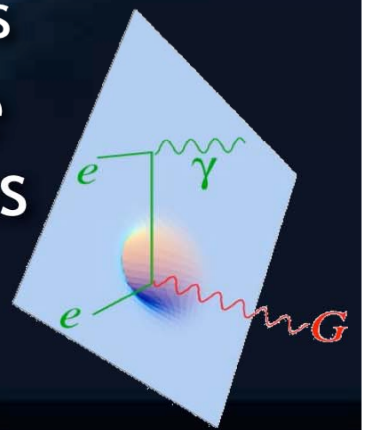


A note of caution

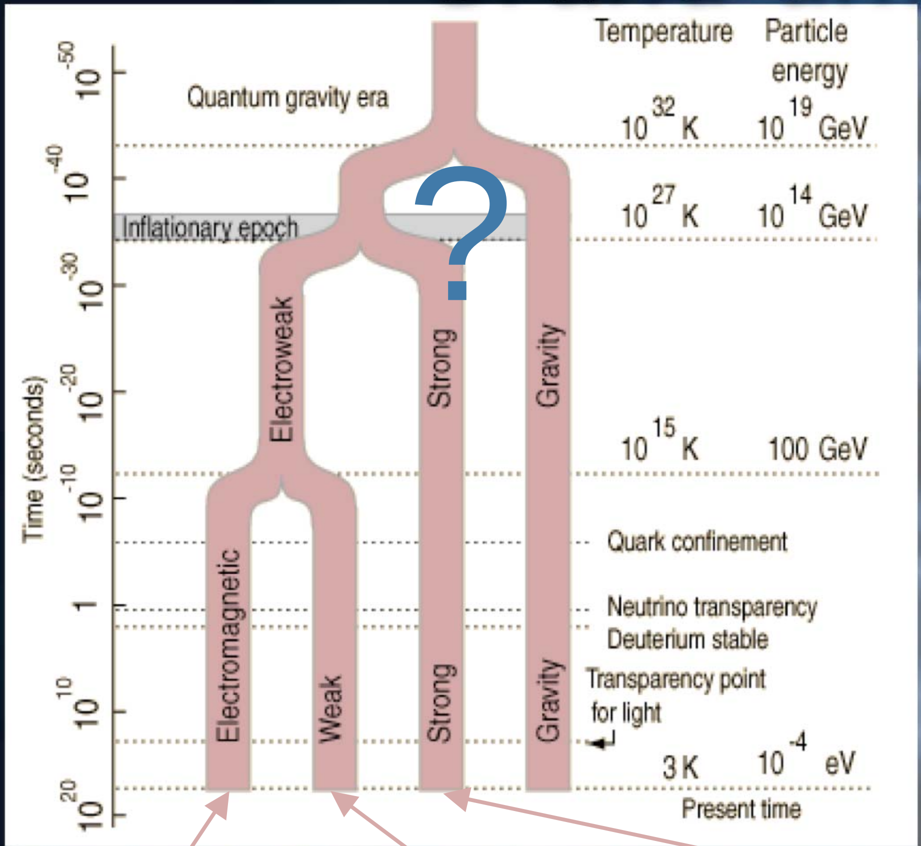
- All hope for New Physics at TeV scale rests on fine-tuning problem
- Experiment tells us the contrary!
- Either we've been unlucky and New Physics is really just around the corner, or something may be wrong with this reasoning
- Worth questioning some of the salient assumptions

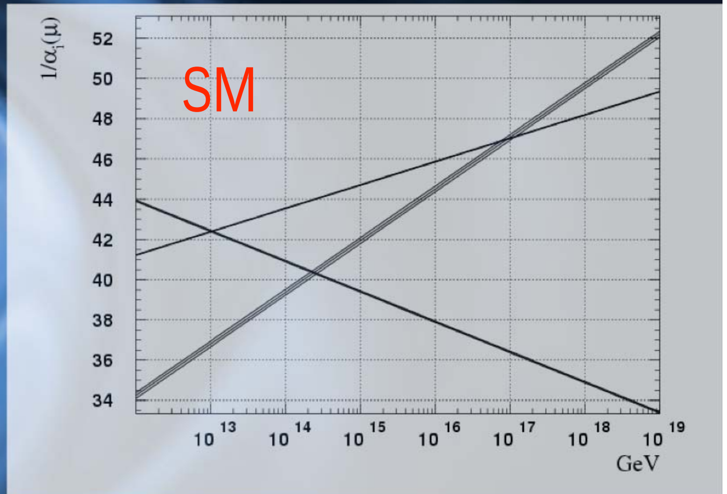
Radical questions

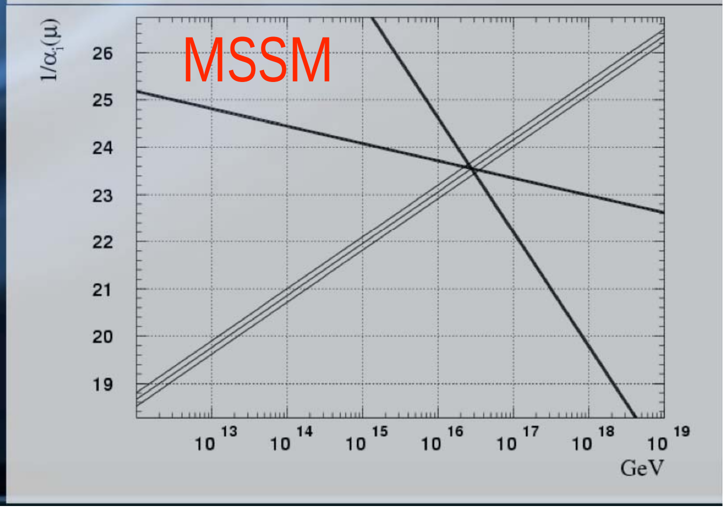
- How sure are we that M_{Pl} and M_{GUT} are fundamental scales?
  - ✓ Unification of gauge couplings and neutrino masses hint at New Physics near M_{GUT}
  - × But gravity only tested down to 0.1mm, corresponding to scale ~10^{-11} GeV
  - × Assumption that Newton's law holds over another 30 orders of magnitude seems preposterous
- Models with extra dimensions eliminate Planck scale (ADD) or explain it in terms of warped geometry (RS)



Grand unification







Radical questions

- How sure are we about existence of New Physics at the TeV scale?

✓ Hierarchy problem (stabilization of weak scale), based on naturalness assumption

× World is full of "unnaturally" small ratios; fine-tuning problematic only if heavy particles exist that couple to scalar sector

✓ Unification of gauge couplings with TeV-scale SUSY

× Unification possible in alternative ways

✓ Need for dark matter (WIMP with m_{DM}~TeV would fit well)

× Alternative explanations for dark matter exist (e.g. axions, warm sterile neutrinos, ...) [Kusenko et al. (2003)]

- Split-SUSY models ignore fine-tuning problem and postulate New Physics only at very high scales [Arkani-Hamed, Dimopoulos (2004)]

Beyond the Standard Model

Some scenarios

Starting point

- SM is an effective field theory, tested to energies ~ 100 GeV, and believed to break down and some higher scale Λ

$$H_{eff} = H_{SM} + 1/\Lambda \sum_i b_i O_i^{(5)} + 1/\Lambda^2 \sum_i c_i O_i^{(6)} + \ldots$$

- Flavor-conserving ops.: Λ_{EWSB}>1-10 TeV ("little hierarchy problem")
- Flavor-violating ops.: Λ_{FV}>$10^{2\text{-}3}$ TeV provided c_i=O(1) ("flavor problem")

Complication

$$H_{eff} = H_{SM} + 1/\Lambda \sum_i b_i O_i^{(5)} + 1/\Lambda^2 \sum_i c_i O_i^{(6)} + \ldots$$

- Already know examples where cutoff is much higher, $\Lambda \sim 10^{14\text{-}16}$ GeV
  - Neutrino masses (d=5 operators)
  - Proton and lepton-number violating processes
- In first case there is a well-motivated mechanism explaining this (heavy right-handed neutrino, see-saw); in second case some symmetry needs to be invoked (e.g. R-parity in SUSY)

Complication

- Below, will assume that there exists some New Physics at scales not too far from TeV scale (otherwise particle physics is dead ...)

Possible interpretations

A. Flavor violation related to EWSB ($\Lambda_{FV} \sim \Lambda_{EWSB}$), then:
   - ✧ Need a symmetry to keep many c_i small, e.g. minimal flavor violation (MFV) hypothesis
   - ✧ There should be measurable effects in present data (i.e., some puzzles should be true)
   - ✧ Is indeed “natural” to get O(0.1) effects with New Physics at TeV scale

✧ Best possible scenario! Super B-factories would do for New Physics what B-factories did for SM!

Possible interpretations

B. Flavor violation not related to EWSB ($\Lambda_{FV} \gg \Lambda_{EWSB}$), then:

- Sad …
- Strange, since virtually any extension of SM that can solve the hierarchy problem contains a zoo of new flavor parameters
- E.g., extra dimension models offer a new approach to understand "generations" in terms of fermion localization

  [Arkani-Hamed, Schmaltz (1999); Grossman, MN (1999)]

Possible interpretations

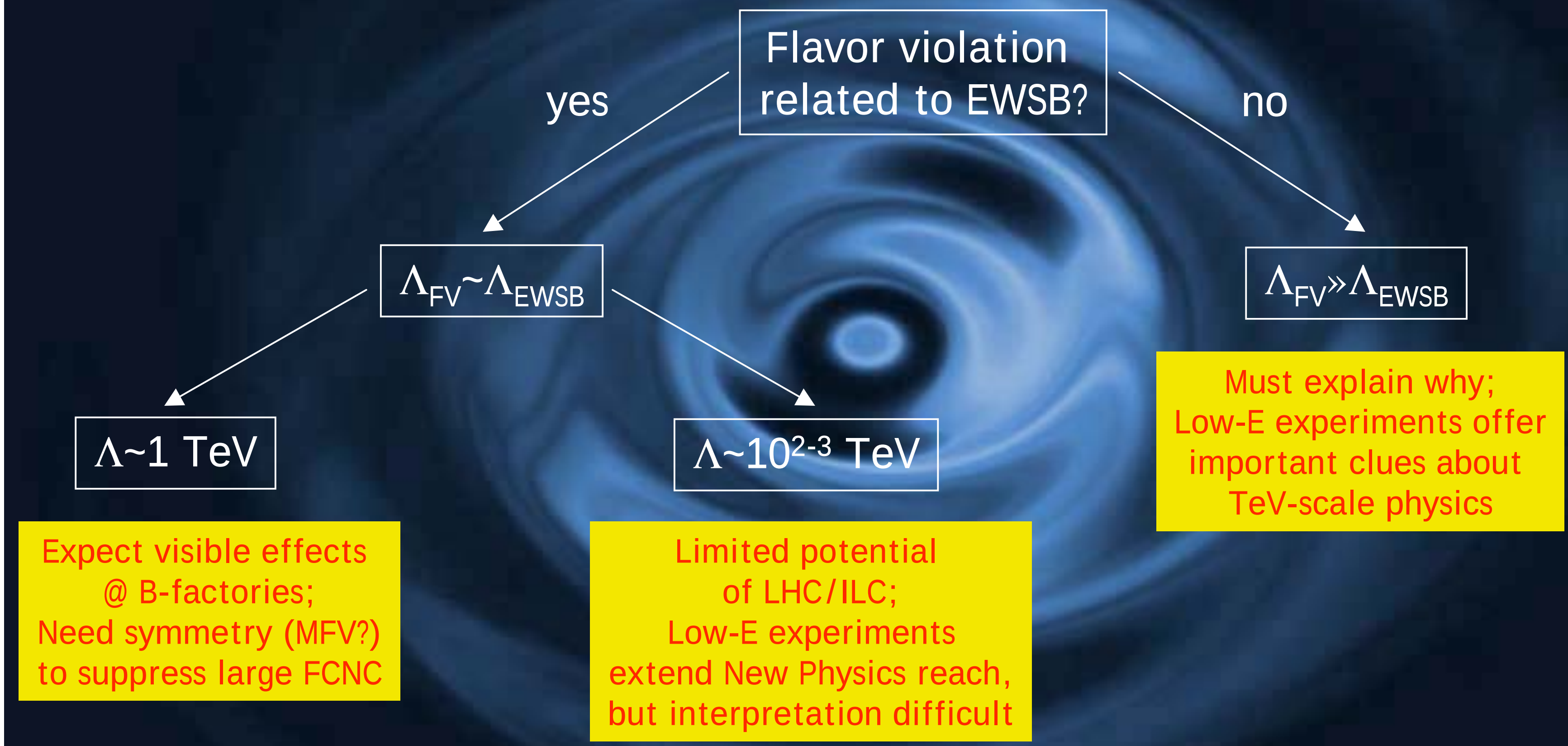
C. Flavor violation related to EWSB (Λ_{FV}~Λ_{EWSB}), but Λ_{EWSB}»1 TeV much higher than anticipated, then:
- Pessimistic, but not excluded
- Examples of such models exist ("finely tuned SM") e.g.:
  - Split-SUSY [Arkani-Hamed, Cohen, Katz, Nelson (2002)]
  - Little Higgs models (or a tower of such models) with UV completion at a high scale (involve some New Physics, but effects can be kept small using MFV)

- LHC will test this scenario. If true, we'll only explore Higgs sector, not much more

Possible interpretations

- In this scenario, flavor physics (and other low-energy measurements) can probe mass scales far extending beyond LHC/ILC range
- However, there won't be a tool for a direct confirmation of a potential indirect discovery

Overview scenarios



Potential impact of a Super B-factory

Never stop exploring!

Role of Super B-factory

- In best case scenario (A): help to determine or place constraints on flavor parameters of some new particles (e.g., quark-squark-gluino couplings in SUSY, KK fermions, ...)
- Much like B-factories did for b- and t-quarks (V_{cb}, V_{ub}, V_{ts}, V_{td}, β, γ)

Role of Super B-factory

- In more pessimistic scenario (B): absence of new sources of flavor-violation at TeV scale would teach us important lessons about nature of EWSB, and perhaps even SUSY breaking, fermion localization in extra dimensions, etc.
- In some very rare or forbidden processes ($\mu \to e\gamma$, or $B \to X_s \nu\bar{\nu}$) one can probe scales into the $10^{2\text{-}3}$ TeV range or even higher

Role of Super B-factory

- Like in electroweak precision measurements, New Physics effects must show up at some level of precision in flavor physics
- In the worst case that we would not see any large signals in B physics, a Super B-factory would play a similar role as LEP played for the understanding of EWSB
- It would then impose most severe constraints on model building for the post LHC era

Role of Super B-factory

- In worst case scenario (C): flavor physics our only hope to learn anything beyond the SM, but would this be sufficient to keep the field alive?

Summary

Conclusions

- Flavor physics a vital component in the exploration of the TeV scale
- Complementarity with LHC/ILC
- Impact will depend on whether there is some flavor structure near TeV scale
- Compelling physics case for a Super B-factory; would be a "no-brainer" if any of the present hints turn out to be true ...