# Heavy Quark Physics

## Cracking the Standard Model?

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# Lecture 1

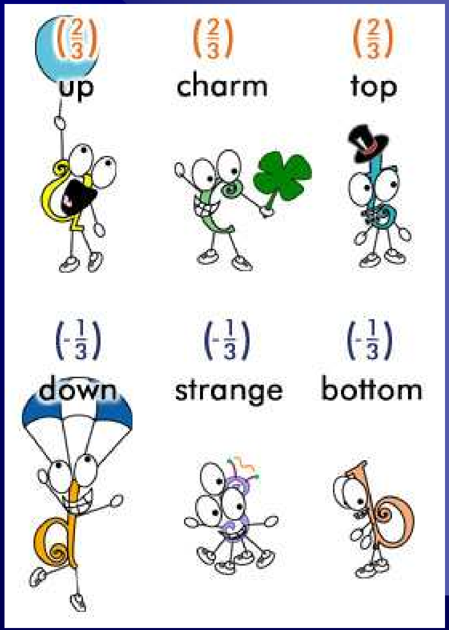
- Flavor questions
- Beyond the Standard Model
- Precision measurements in the quark sector
- A bit of QCD …

# 1. Flavor Questions

Generations, Hierarchies,
CP Violation, Baryogenesis

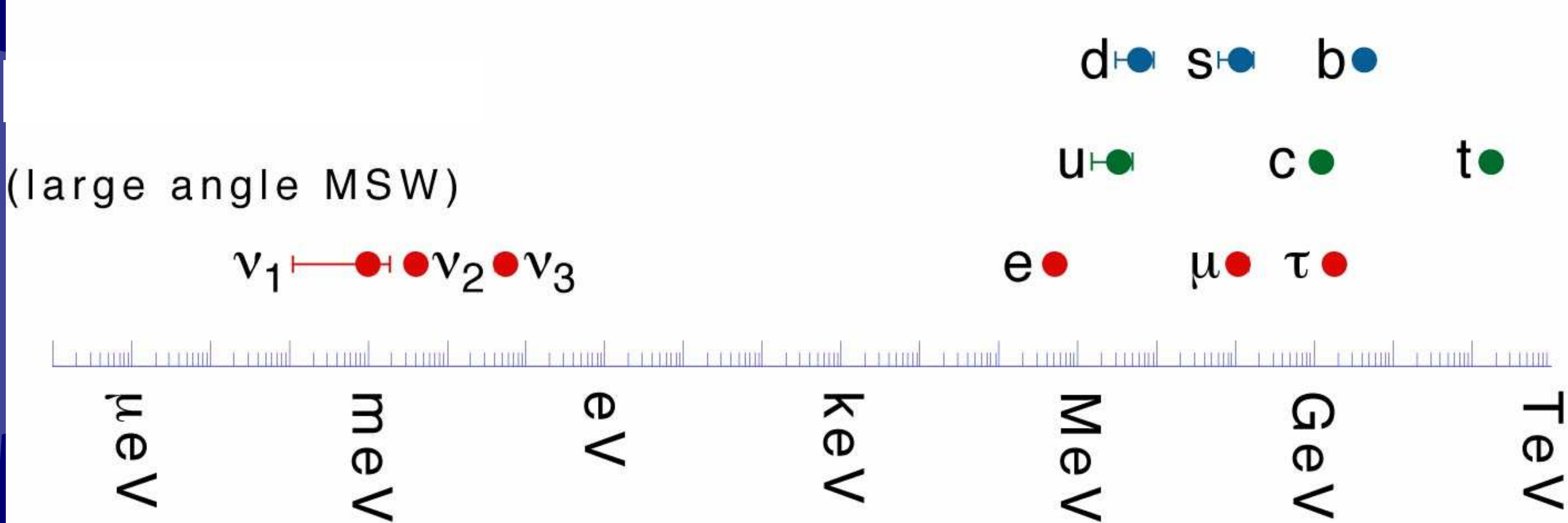
# Problem of generations

- 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 ?



# Hierarchies

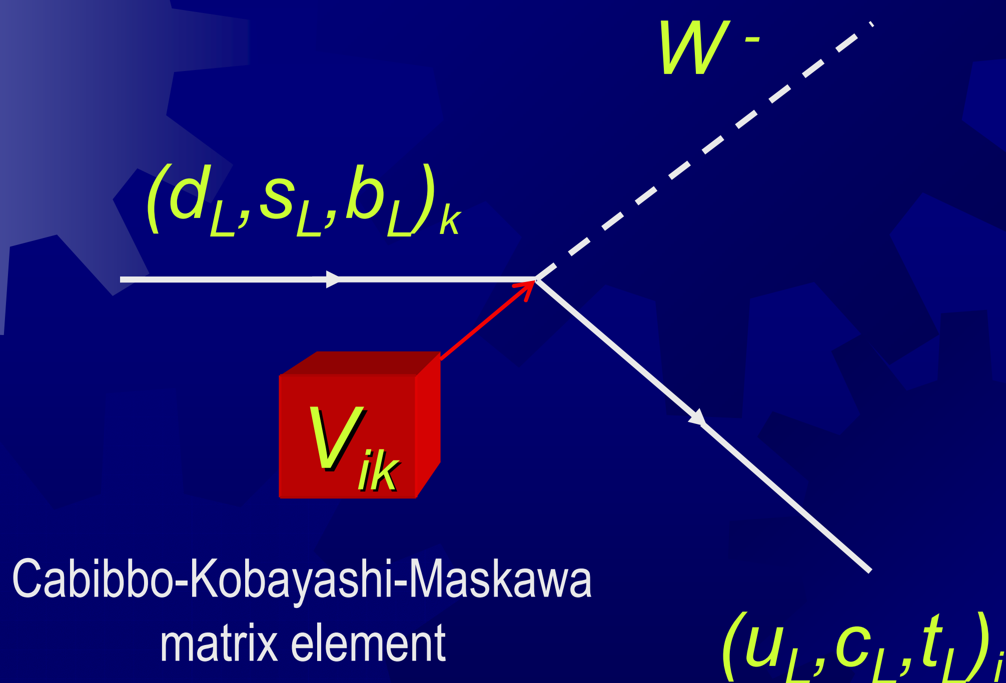
Masses of quarks and leptons

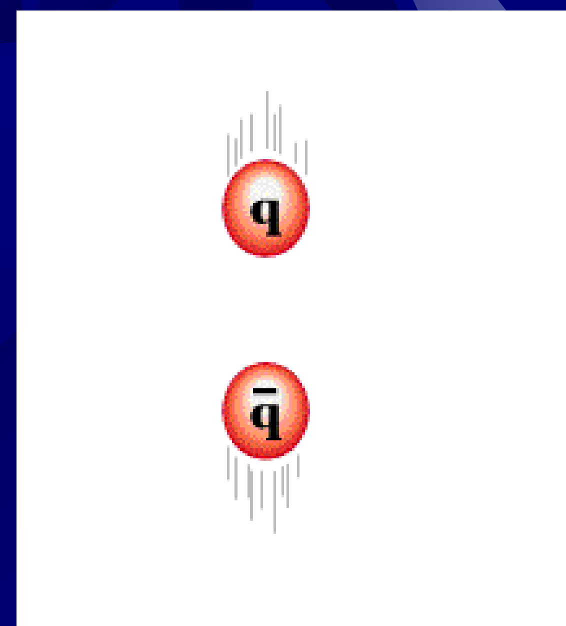



Fermion masses and mixings constitute many of the parameters of the SM

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

- Fermions of different generations can communicate via flavor-changing weak interactions
- New parameters (mixing angles, phases)



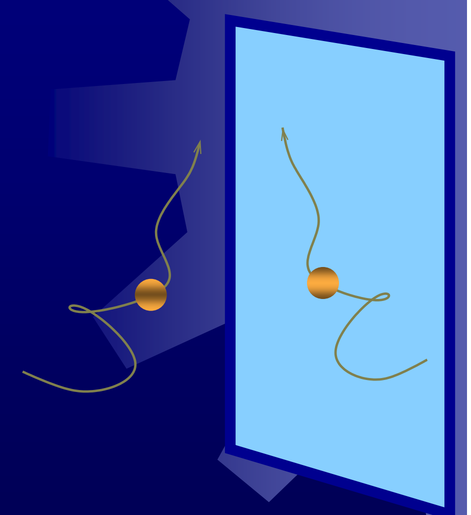
- New hierarchies:

small

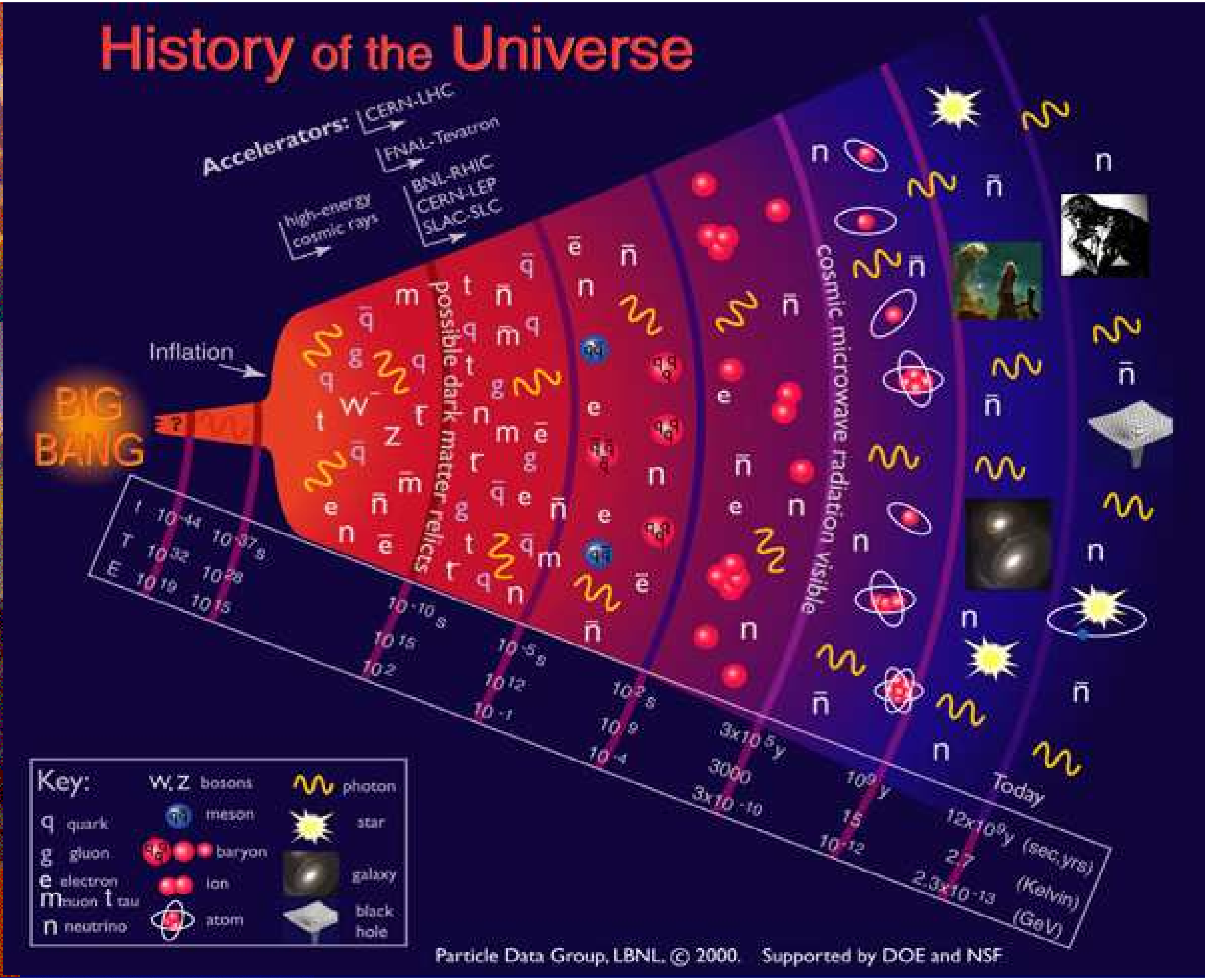
$$V_{CKM} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad U_{MNS} \approx \begin{pmatrix} 1 & 1 & \varepsilon \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

- Possible explanation of CP violation!

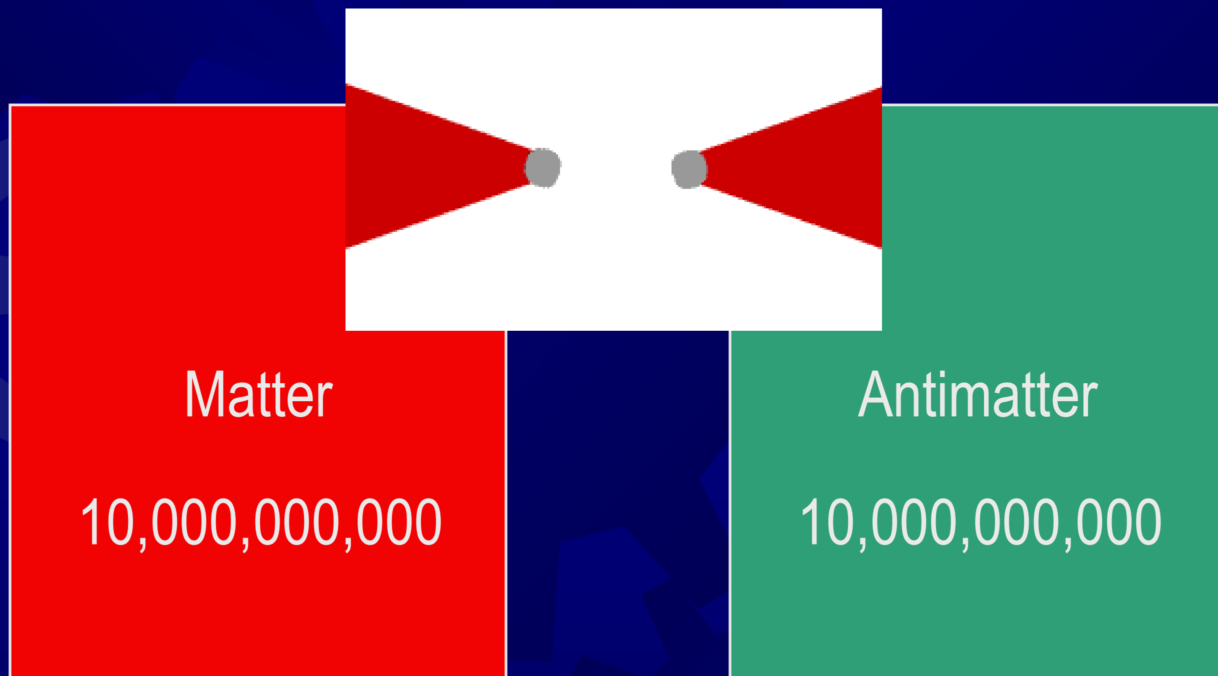
Properties of matter $\xleftrightarrow{\cancel{CP}}$ Properties of antimatter



  - 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 relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
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 cosmic connection: Baryon asymmetry




Early Universe

# The big annihilation

Today:

us

1

➢ Sakharov criteria:

- Baryon-number violation
- CP violation
- Non-equilibrium

- 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!***

# 2. Beyond the Standard Model

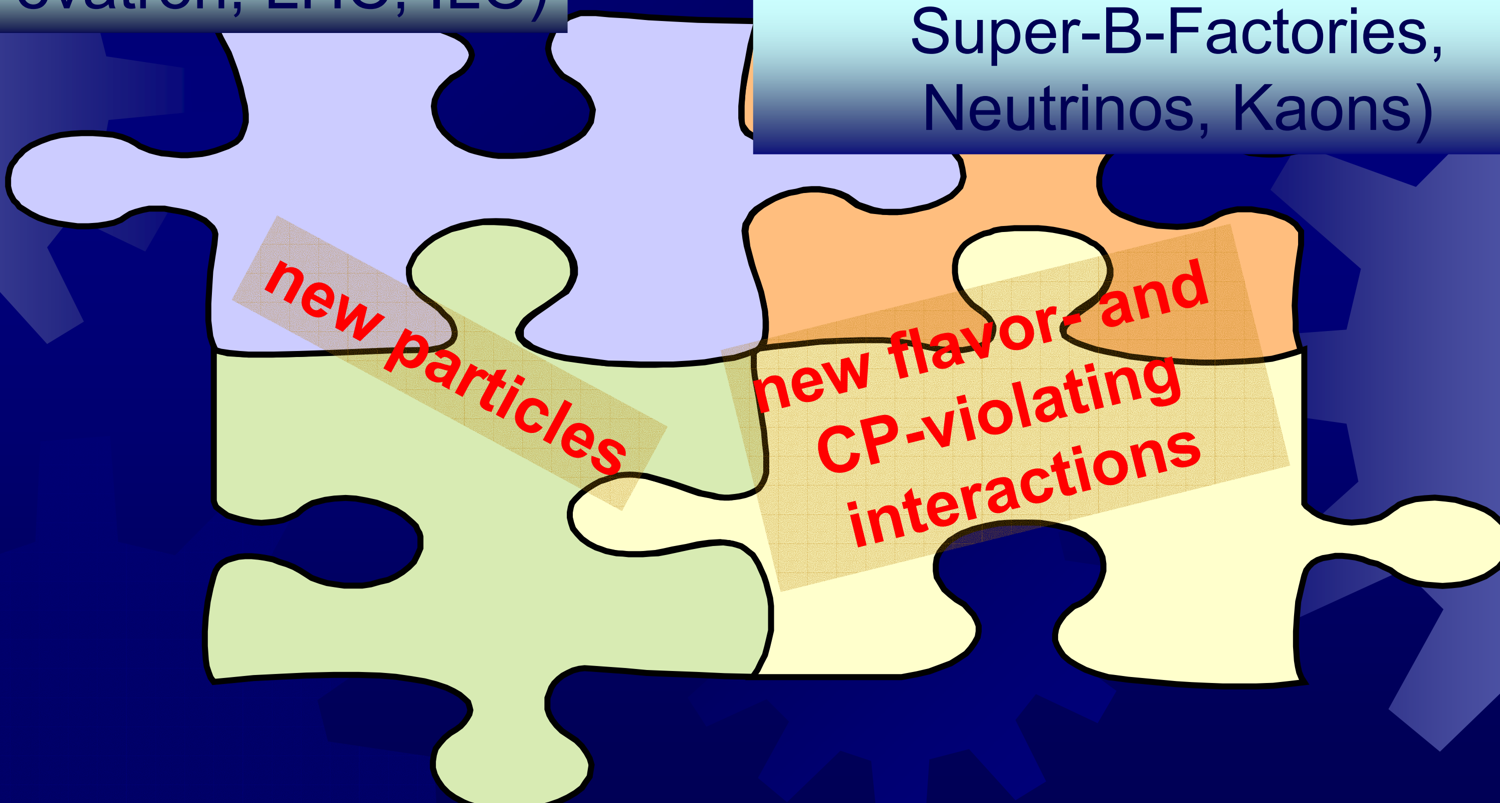
Complementarity of High Energy and High Luminosity

# Exploring Nature

Colliders
(Tevatron, LHC, ILC)

+

Factories
(BaBar, Belle, BTeV, LHC-b,
Super-B-Factories,
Neutrinos, Kaons)



# Future role of flavor physics

- Flavor physics can probe effects of New Physics at scales of 1-1000 TeV, far extending beyond the range of LHC and ILC
- Many flavor- and CP-violating couplings can only be measured at highest luminosity

# Examples: top & neutrinos

## Top-Quark:

- Direct production proves existence und gives mass and spin


- Mass predicted using electroweak precision measurements
- Couplings $|V_{ts}|$~0.04 and $|V_{td}|$~0.01 and CP-violating phase can only be measured in *B*- and *K*-physics

## Neutrinos:

- Existence known since long, but only discovery of flavor-changing interactions (neutrino oscillations) brought far-reaching discoveries
- Possibility of CP violation in the lepton sector; lepto-genesis
- Completely different hierarchy as in the quark

# Empirical fact

- Data show no compelling evidence for Physics beyond the Standard Model:
  - Electroweak precision tests
  - Precision measurements in flavor physics
- *Either:*
  New Physics decouples very effectively:
  - SUSY, split SUSY
- *Or:*
  New Physics lives at scales of several TeV (apart from a few possibly lighter particles)
  - Extra dimensions, “little Higgs”, technicolor

# Flavor/CP-violating couplings

- Generic properties:
  - Many new particles (SUSY partners, Kaluza-Klein partners, new gauge bosons, new fermions, etc.) at the TeV scale
  - Generation-changing couplings of new particles are not diagonal after field redefinitions of SM fields
- There *must* be effects in the flavor sector at some level of precision!

# 3. Precision Measurements in the Quark Sector

Cabibbo-Kobayashi-Maskawa Matrix, Unitarity Triangle, “Standard Analysis”, Future Potential

# 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

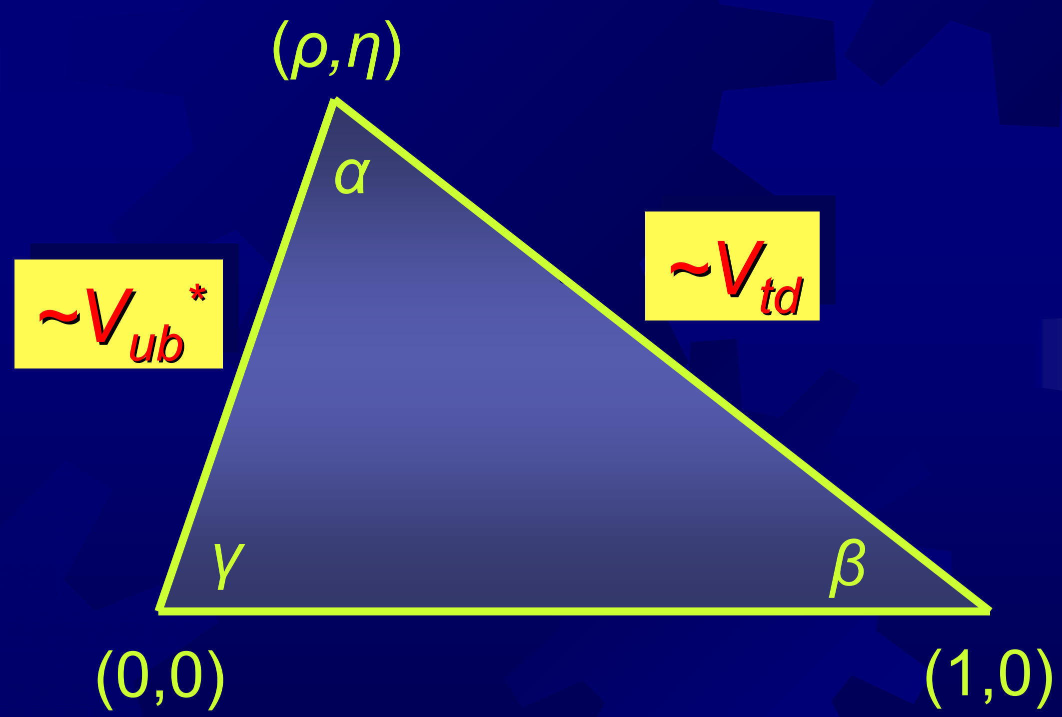
- Complex couplings ⟹ CP violation!

$\lambda$=0.22, $A$=0.84 well determined

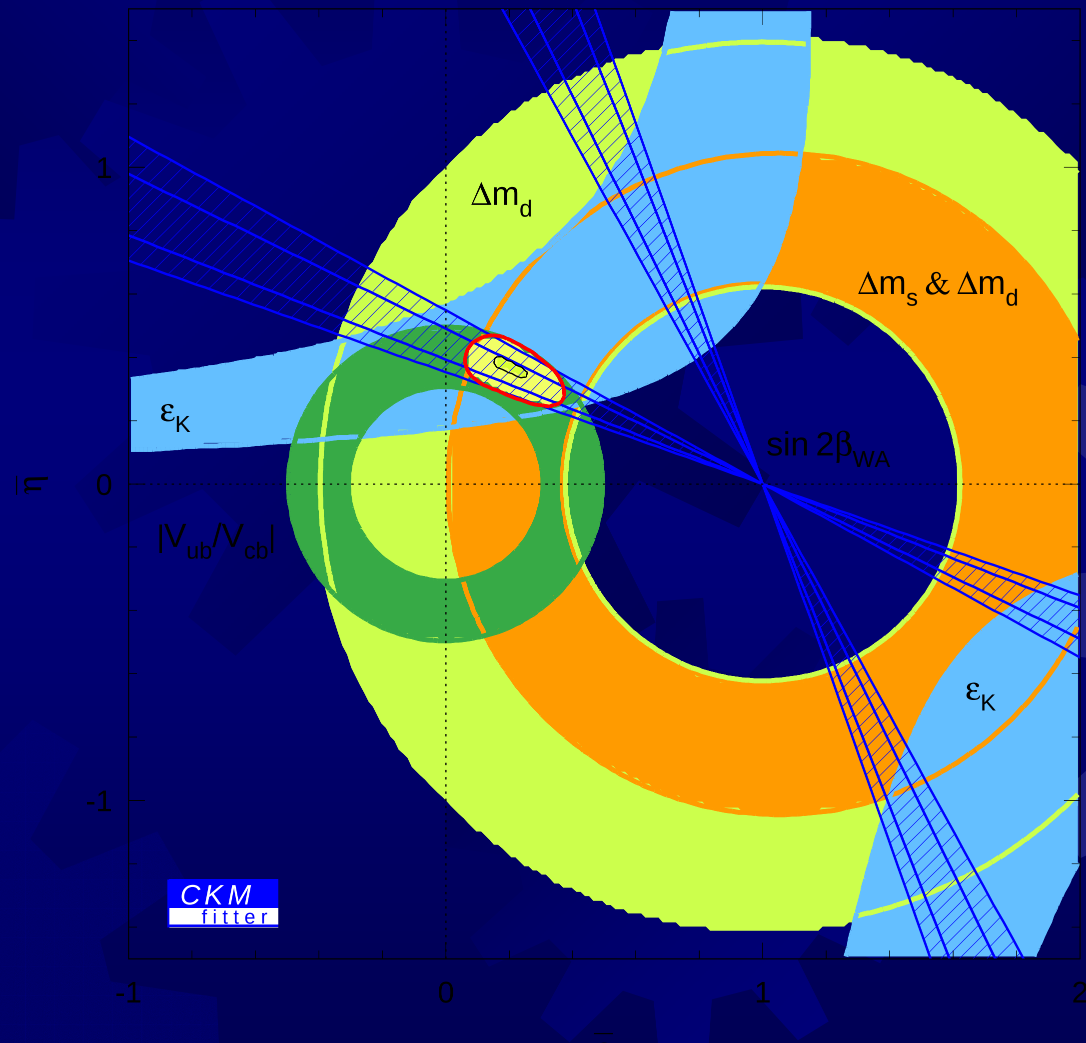
($\rho$,$\eta$) are being determined at the *B*-factories

- Experimental information on $(\rho,\eta)$ can be presented as a "unitarity triangle":

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



# The "standard analysis"



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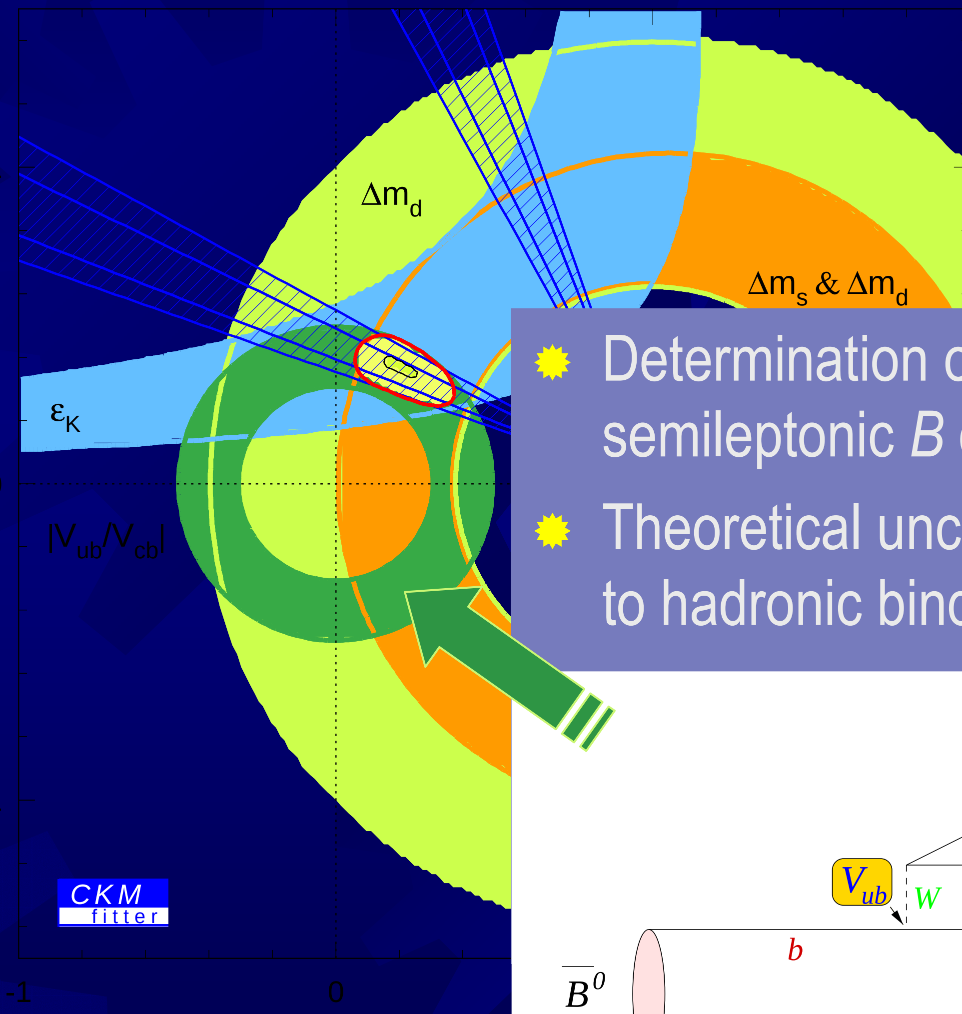
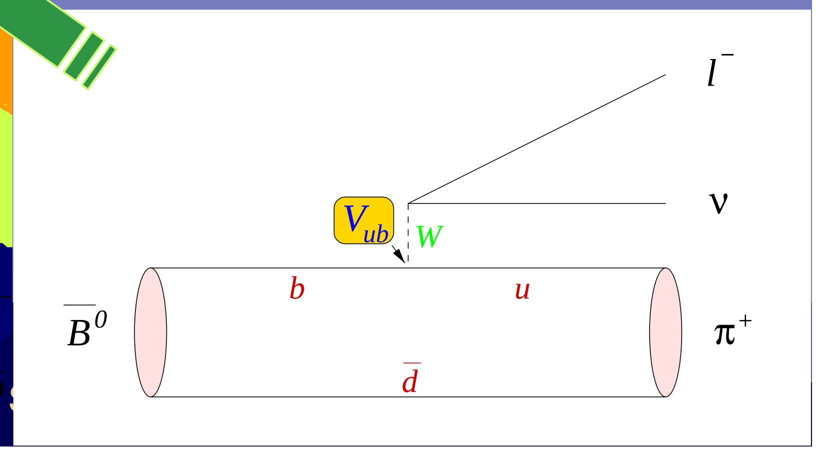
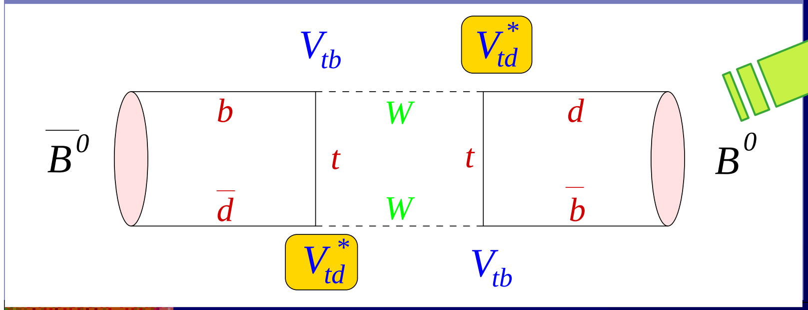


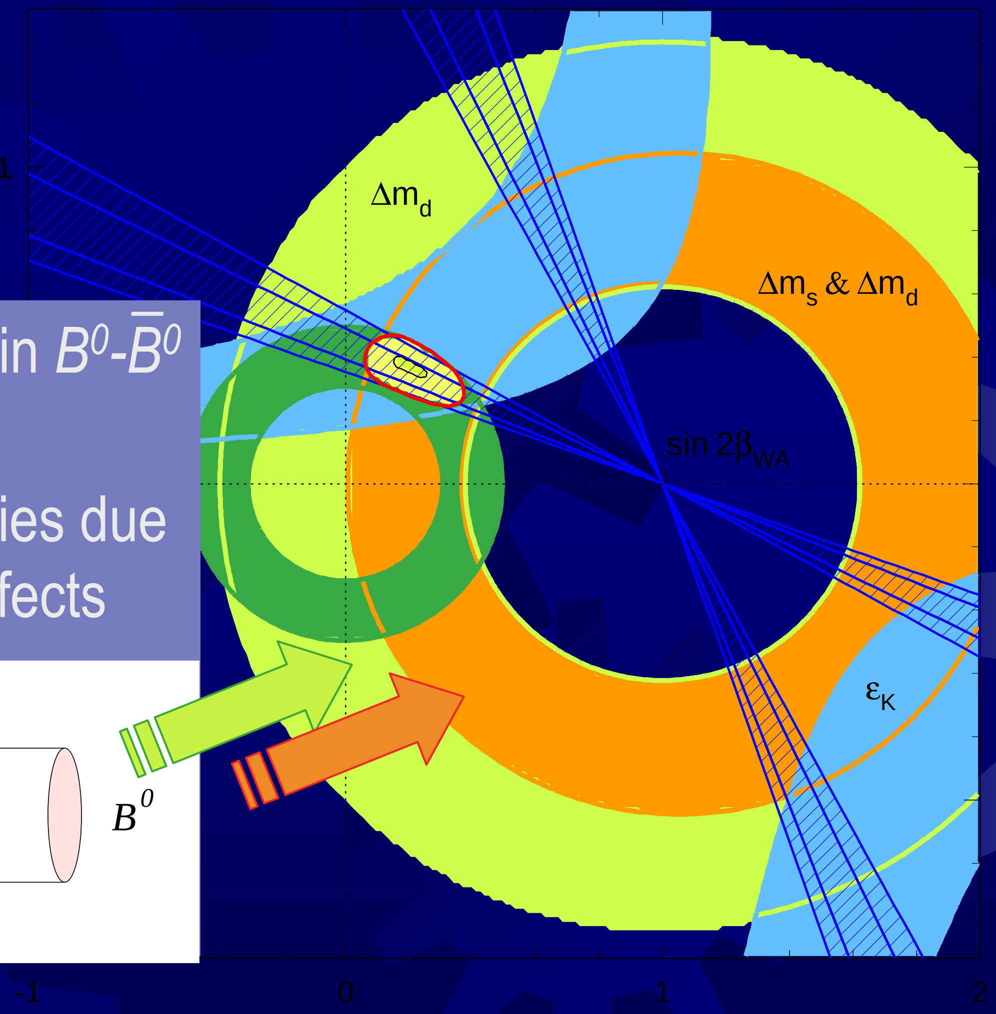

- Determination of $|V_{ub}|$ in semileptonic $B$ decays
- Theoretical uncertainties due to hadronic binding effects



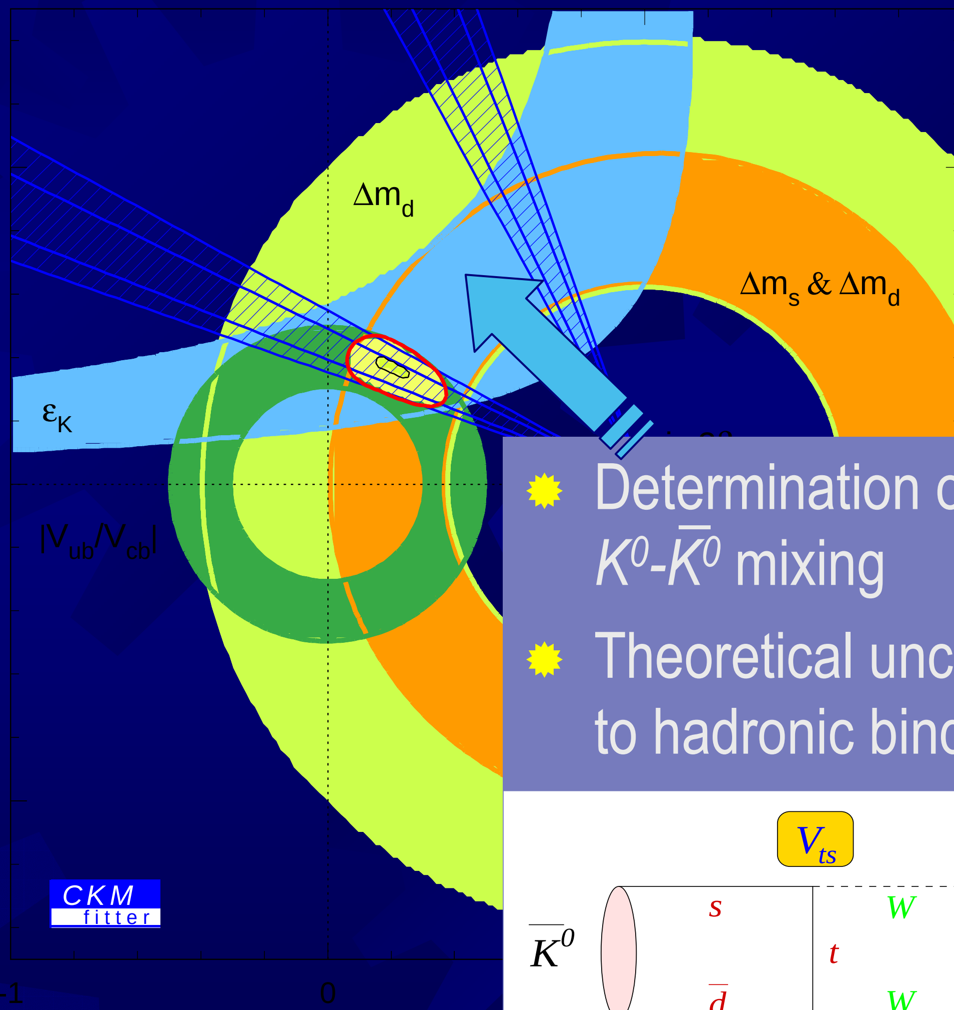
# The "standard analysis"

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

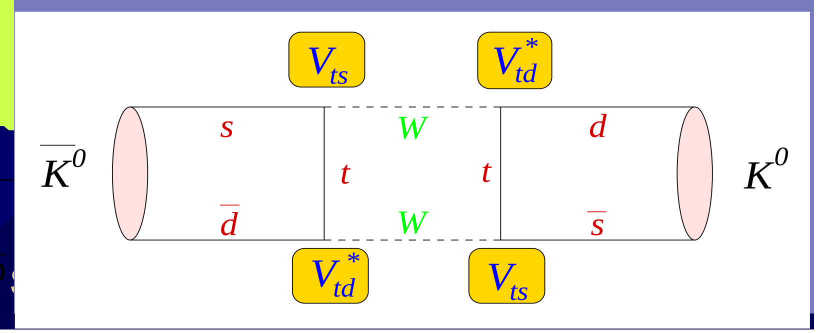


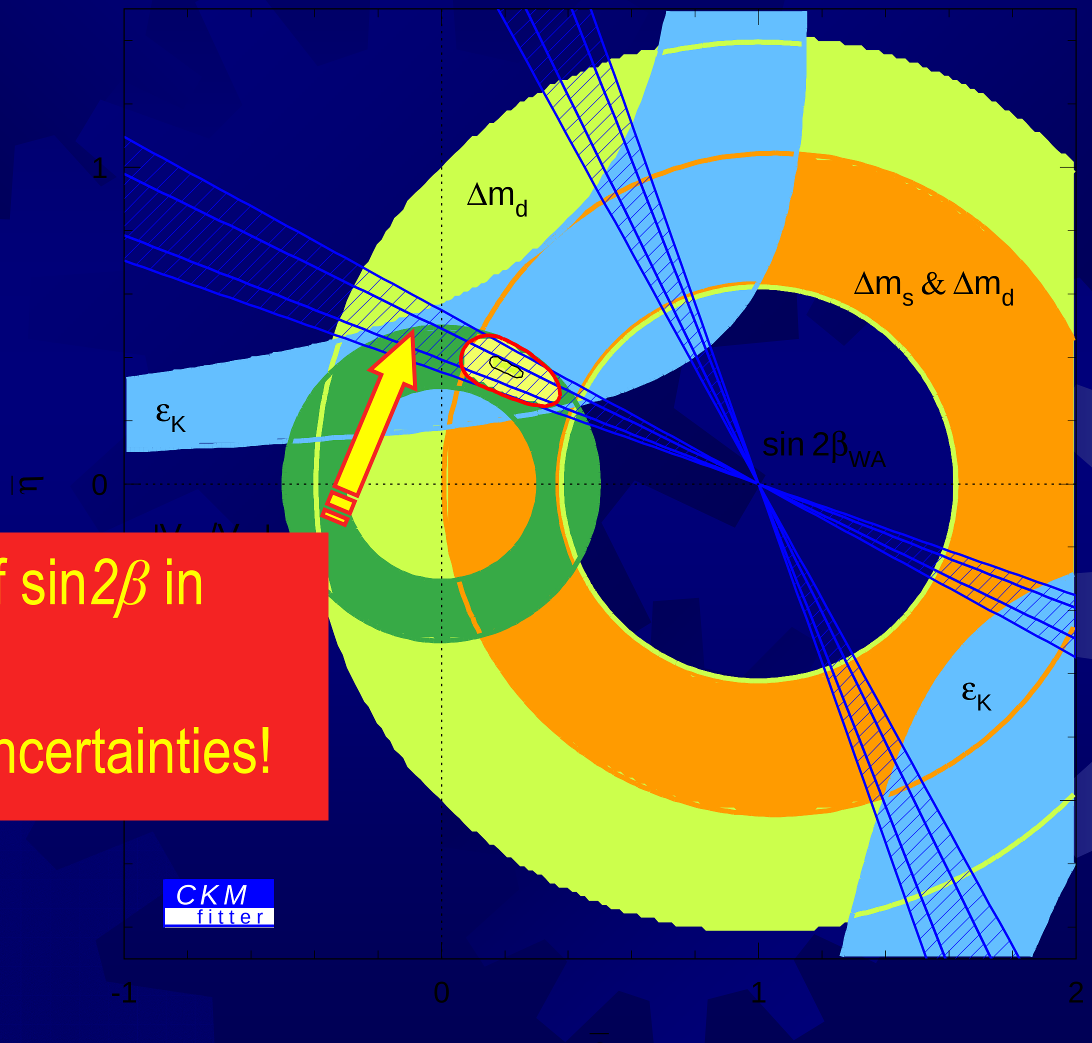
# The “standard analysis”




- Determination of Im($V_{td}^2$) in $K^0$-$\bar{K}^0$ mixing
- Theoretical uncertainties due to hadronic binding effects



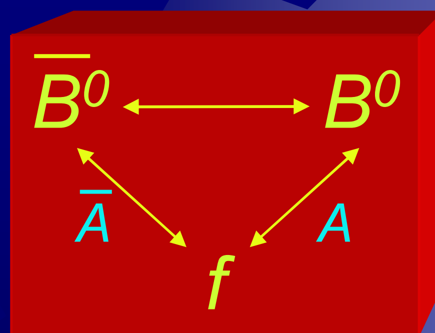
# The "standard analysis"




- Determination of sin2$\beta$ in $B^0$-$\bar{B}^0$ mixing
- No theoretical uncertainties!

# Measurement of sin2$\beta$

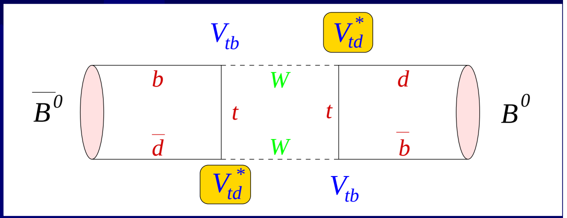
- CP-violating phases can only be probed via quantum-mechanical interference
- Simplest case: Interference of *B* decay and $B^0$-$\bar{B}^0$ mixing for transitions into a CP eigenstate *f*
- If decay amplitude *A* has a single CP-violating phase $\varphi_A$, then:




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

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

# How does this work?




- Schrödinger equation for $B^0$, $\bar{B}^0$:

$$i\frac{d}{dt}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \begin{pmatrix} M & \frac{1}{2}e^{-2i\beta}\Delta m \\ \frac{1}{2}e^{2i\beta}\Delta m & M \end{pmatrix}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}, \qquad M_\pm = M \pm \frac{\Delta m}{2}$$

- Time evolution of a state $B^0$ at time t=0:

$$|\psi(t)\rangle = e^{-iMt}\left[\cos(\tfrac{1}{2}\Delta mt)\,|B^0\rangle + ie^{2i\beta}\sin(\tfrac{1}{2}\Delta mt)\,|\bar{B}^0\rangle\right]$$

- 2 decay modes: $B^0 \rightarrow f$ (A) and $\bar{B}^0 \rightarrow f$ ($\bar{A}$)

# How does this work?

- Amplitude for decay of this state into final state f after some time t>0:

$$\mathcal{A}_{B^0}(t) = e^{-iMt}\left[A\cos(\tfrac{1}{2}\Delta m t) + i\bar{A}\, e^{2i\beta}\sin(\tfrac{1}{2}\Delta m t)\right]$$

- Corresponding decay rate (assume $A \sim e^{i\varphi_A}$, $\bar{A} \sim e^{-i\varphi_A}$ single weak phase):

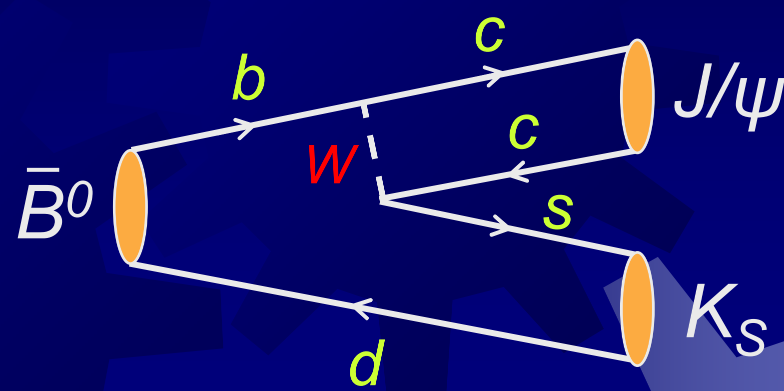
$$\begin{aligned}\Gamma_{B^0}(t) &= |A|^2\cos^2(\tfrac{1}{2}\Delta m t) + |\bar{A}|^2\sin^2(\tfrac{1}{2}\Delta m t) + \mathrm{Re}(iA^*\bar{A}\, e^{2i\beta})\sin(\Delta m t)\\ &\stackrel{|A|=|A^*|}{=} |A|^2\left[1 - \sin 2(\beta - \varphi_A)\sin(\Delta m t)\right]\end{aligned}$$

- Time-dependent CP asymmetry:

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

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

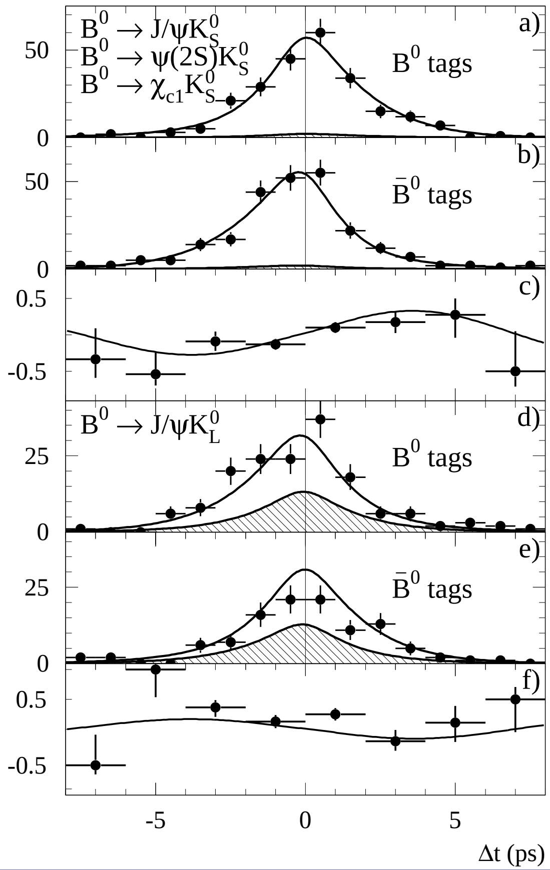
- "Golden" decay mode: $B \to J/\psi\, K_S$



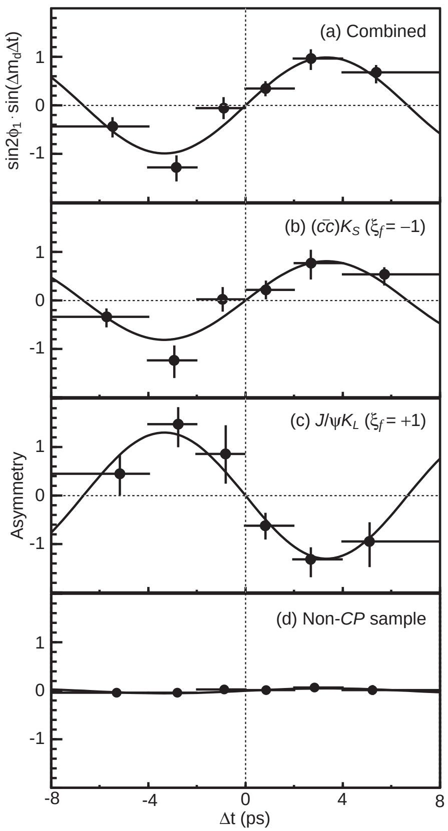

- Amplitude is real to an excellent approximation, i.e. $\varphi_A$=0

**Direct determination on sin$2\beta$, practically without theoretical uncertainties (~1%)**

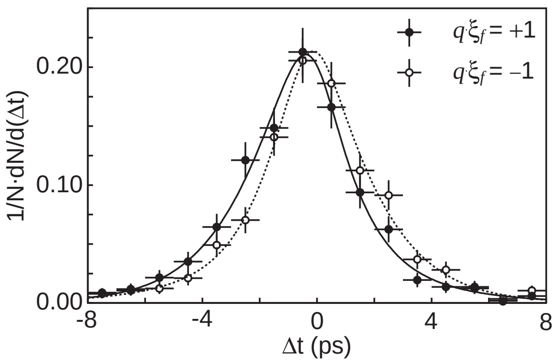
# CP violation visible with the naked eye!




*BaBar (2001)*



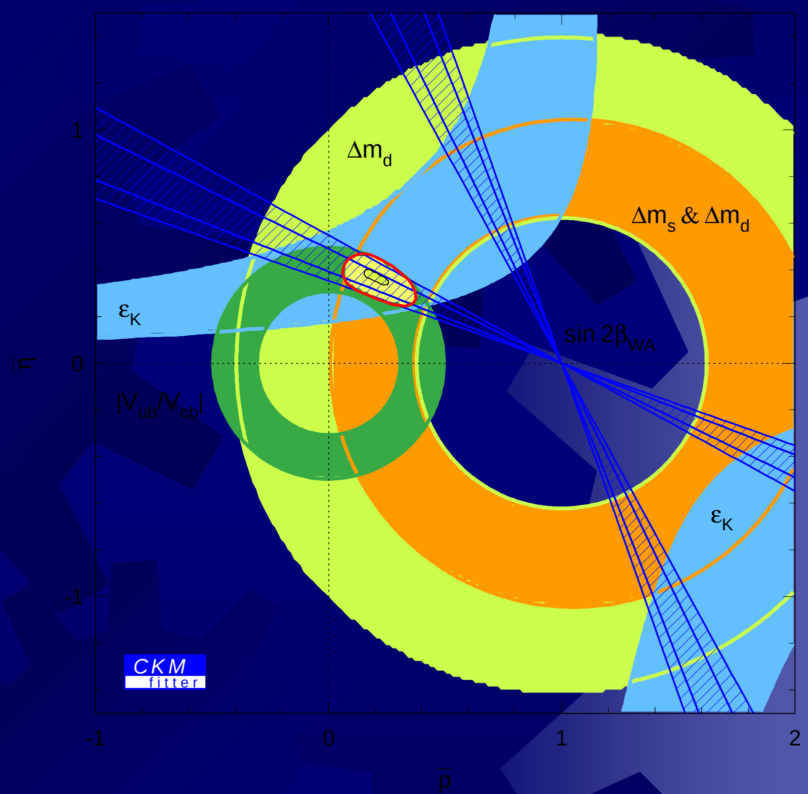

*Belle (2001)*




Combined: $\sin 2\beta = 0.73 \pm 0.04$

# Combination

- So far, 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., $\mathrm{Im}(V_{td}) \neq 0$



# Future potential

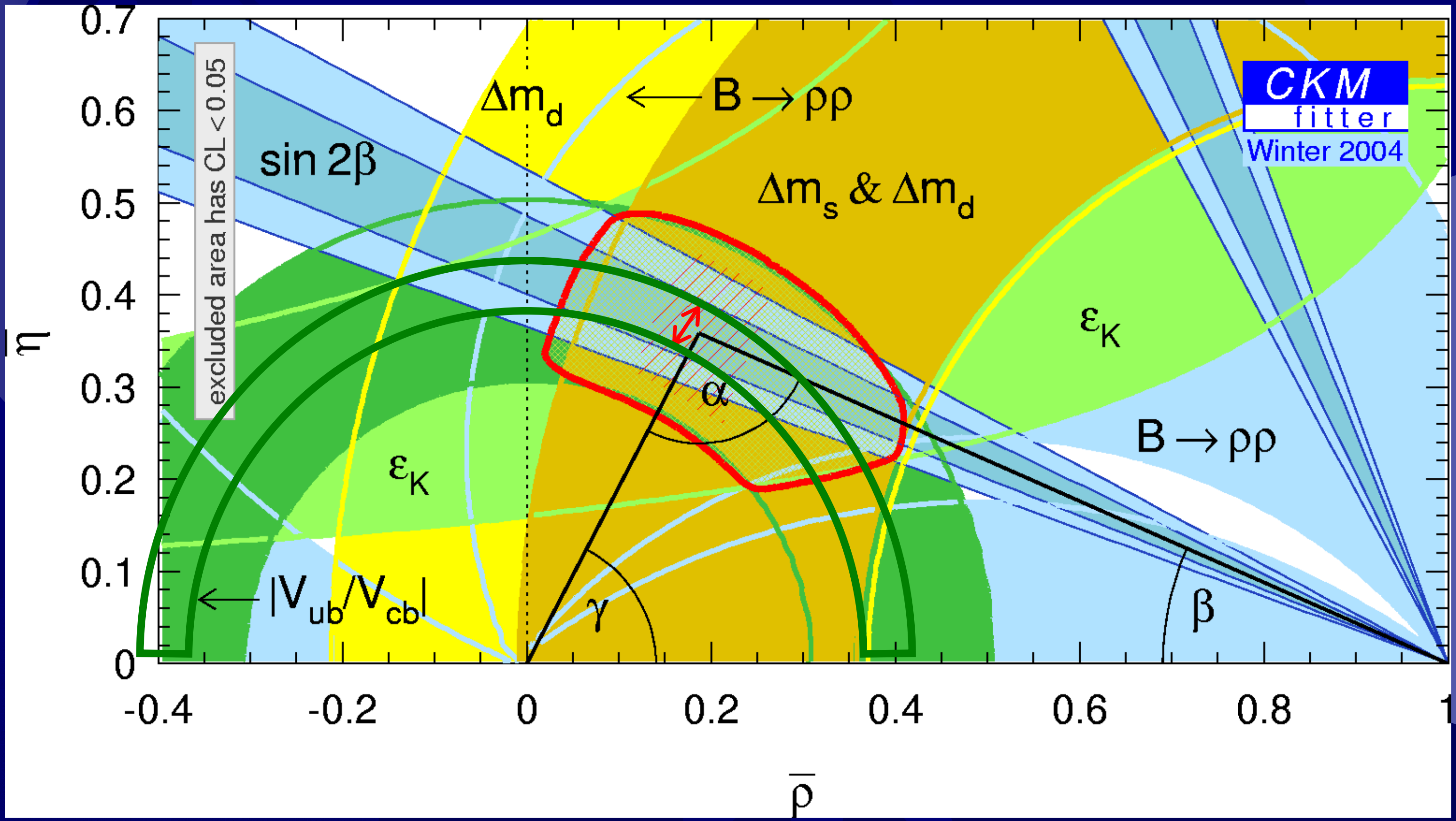
- Probe of new Physics in $B_s$-$\overline{B}_s$ mixing at Tevatron (hopefully…) and/or LHC
  - Expect larger New Physics effects in $b\to s$ FCNC transitions as compared with $b\to d$
  - True for $\Delta B=2$ and $\Delta B=1$ *(2nd lecture)*
  - May become the most important measurement at the Tevatron!

# Future potential

- Greater precision on $|V_{ub}|$:
  - Recent theoretical work using soft-collinear effective theory allows precision determination from *inclusive* $B \to X_u l \nu$ decay with theory errors at the 5% level [Bosch, Lange, MN, Paz]
  - First measurements using this technology have just appeared (April-May 2005), with combined errors of about 10%
  - Comparison with β will test SM with unprecedented precision

# Impact of precise $|V_{ub}|$

- Realistic: $\delta|V_{ub}|$: $\pm 7\%$



# 4. A bit of QCD …

## Soft-Collinear Factorization in Inclusive B Decays

# Basics

- Separation of scales ("factorization") is crucial to many applications of QCD

$$Q^2 \gg \Lambda_{QCD}{}^2$$

- Wilsonian OPE: integrate out heavy particles or large virtualities (Fermi theory, HQET, correlators at large $Q^2$…)
- Expansion in $(\Lambda_{QCD}{}^2/Q^2)^n$ and $\alpha_s(Q^2)$

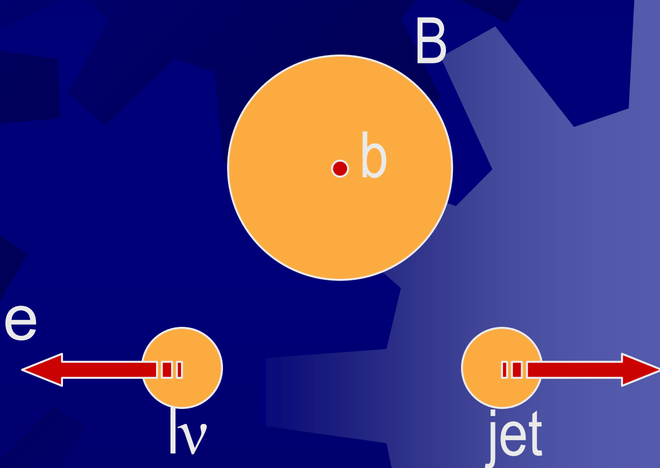
# Basics

- Complication for jet-light physics: large energies and momenta, but small virtualities
  - $e^+e^- \to$ jets, $B \to$ light particles, …
- Light-cone kinematics

How to integrate out short-distance physics in a situation where $p^\mu$ is large, but $p^2$ small?

# Challenge

- Construct short-distance expansions for processes involving both soft and energetic light partons
  - Soft: $p_{soft} \sim \Lambda_{QCD}$
  - Collinear: $p_{col}^2 \ll E_{col}^2$
  - $p_{soft} \cdot p_{col} \sim E_{col}\Lambda$: semi-hard scale




- Technology: effective field theory, OPE, RG

# Soft-collinear effective theory

[Bauer, Pirjol,Stewart]

- Effective Lagrangian for this kinematics
- Systematic power counting in $\lambda=\Lambda_{QCD}/2E_{jet}$
  - Operators classified in terms of their scaling with $\lambda$
- More complicated than previous heavy-quark expansions
  - Expansion in non-local string operators integrated over light-like field separation
  - Many degrees of freedom

# Soft-collinear factorization

- Separation of short- and long-distance physics order by order in $1/m_b$:

$$\Gamma = H\,J \otimes S$$

$$+\,\frac{1}{m_b}\,H_i'\,J_i' \otimes S_i'$$

[Korchemsky, Sterman]

[Lee, Stewart]

[Bosch, MN, Paz]

Hard functions ($\sim m_b$)

Jet functions ($\sim\sqrt{m_b\Delta}$)

Soft functions ($\sim\Delta$)

# Scale separation

- Master formula for inclusive decay B-decay rates:

$$\Gamma \sim H(\mu_h) \;*\; U(\mu_h,\mu_i) \;*\; J(\mu_i) \;*\; U(\mu_i,\mu_0) \;*\; S(\mu_0)$$

QCD ⟶ SCET ⟶ (RG evolution) ⟶ HQET ⟶ (RG evolution) ⟶ Shape Function

Perturbation theory

Non-perturbative physics

# Example: B→X$_s$γ decay

- Photon spectrum:

$$\frac{d\Gamma_s}{dE_\gamma} = \frac{G_F^2 \alpha}{2\pi^4} E_\gamma^3 \, |V_{tb} V_{ts}^*|^2 \, \overline{m}_b^2(\mu_h) \, |C_{7\gamma}^{\rm eff}(\mu_h)|^2 \, U(\mu_h, \mu_i) \, \mathcal{F}_\gamma(P_+)$$

$$\mathcal{F}_\gamma^{(0)}(P_+) = |H_s(\mu_h)|^2 \int_0^{P_+} d\hat\omega \, m_b \, J(m_b(P_+ - \hat\omega), \mu_i) \, \hat S(\hat\omega, \mu_i)$$

- Jet function:

$$J(p^2, \mu) = \delta(p^2) \left[ 1 + \frac{C_F \alpha_s(\mu)}{4\pi} (7 - \pi^2) \right] + \frac{C_F \alpha_s(\mu)}{4\pi} \left[ \frac{1}{p^2} \left( 4 \ln \frac{p^2}{\mu^2} - 3 \right) \right]_*^{[\mu^2]}$$

# Example: B→$X_s\gamma$ decay

- Hard function:

$$H_s(\mu_h) = 1 + \frac{C_F\alpha_s(\mu_h)}{4\pi}\left(-2\ln^2\frac{m_b}{\mu_h} + 7\ln\frac{m_b}{\mu_h} - 6 - \frac{\pi^2}{12}\right) + \varepsilon_{\rm ew}$$
$$+ \frac{C_{8g}^{\rm eff}(\mu_h)}{C_{7\gamma}^{\rm eff}(\mu_h)}\frac{C_F\alpha_s(\mu_h)}{4\pi}\left(-\frac{8}{3}\ln\frac{m_b}{\mu_h} + \frac{11}{3} - \frac{2\pi^2}{9} + \frac{2\pi i}{3}\right)$$
$$+ \frac{C_1(\mu_h)}{C_{7\gamma}^{\rm eff}(\mu_h)}\frac{C_F\alpha_s(\mu_h)}{4\pi}\left(\frac{104}{27}\ln\frac{m_b}{\mu_h} + g(z) - \frac{V_{ub}V_{us}^*}{V_{tb}V_{ts}^*}\left[g(0) - g(z)\right]\right)$$

# Nonperturbative input

- Shape function of B meson (usual parton distribution function) can be measured with good precision in $B \to X_s \gamma$ decay
- Use result to predict $B \to X_u l \nu$ decay spectra
  - Extraction of $|V_{ub}|$
- Other applications:
  very precise determination of $m_b$ from moments of $B \to X_s \gamma$ photon spectrum:

$$m_b^{SF} = (4.68 \pm 0.03_{th} \pm 0.07_{exp})\ \mathrm{GeV}$$

# Lecture 2

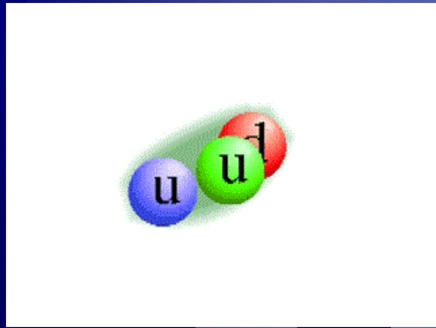
- Rare hadronic B decays
- Departures from the Standard Model ?
- Conclusions

# 1. Rare Hadronic B Decays

Determination of γ, Topological Amplitudes, Penguin Zoology

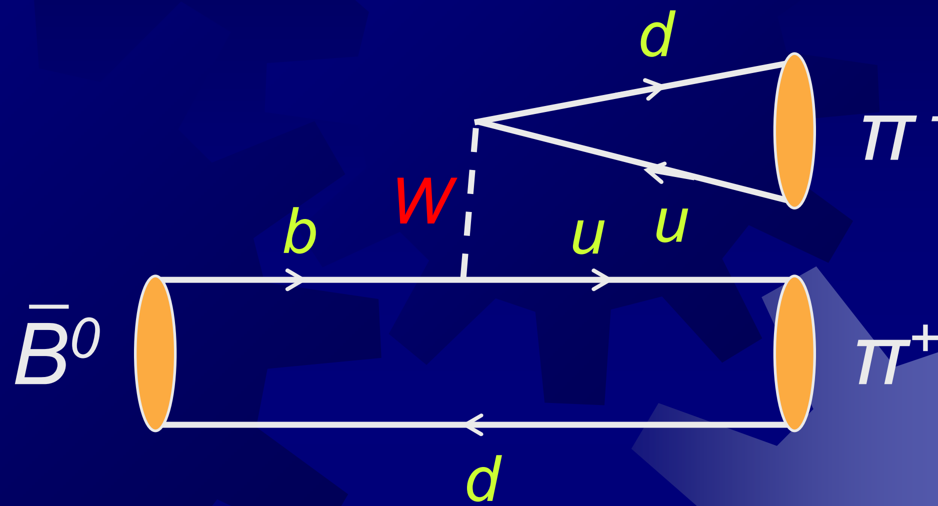
# Rare exclusive B decays

- Precise determination of the phase $V_{ub} \sim e^{-i\gamma}$ is difficult (→LHC-b, Super-B-factories)
  - clean measurement à la sin$2\beta$ possible at LHC (?)
- Independently, important information can be gained from rare hadronic $B \to M_1 M_2$ decays
- Theoretically challenging, since hadronic binding effects must be controlled
  - Much recent progress!



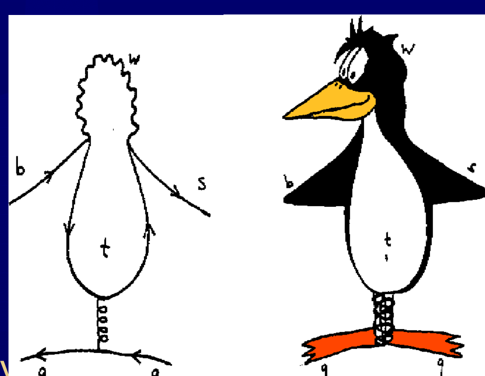
# Flavor topologies

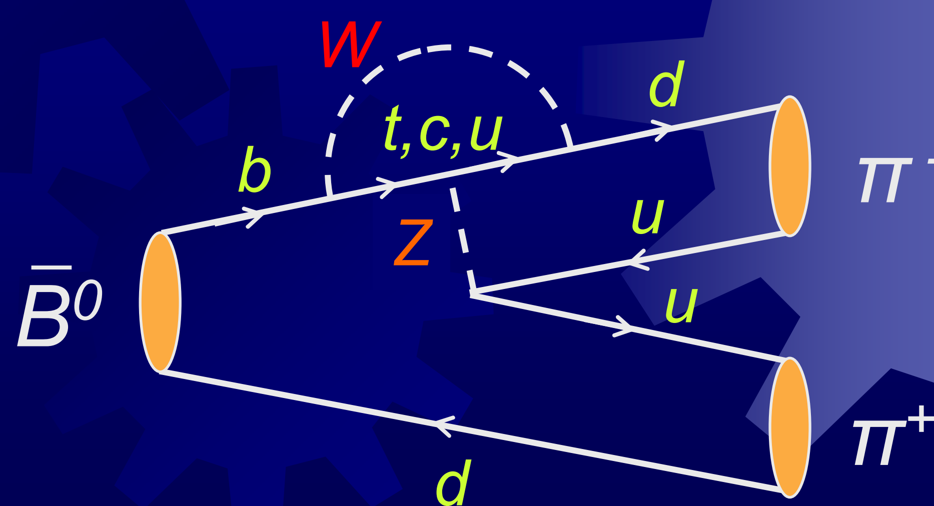
Tree:




Penguin:

Electroweak!





# Beware of penguins …

# Amplitude interference

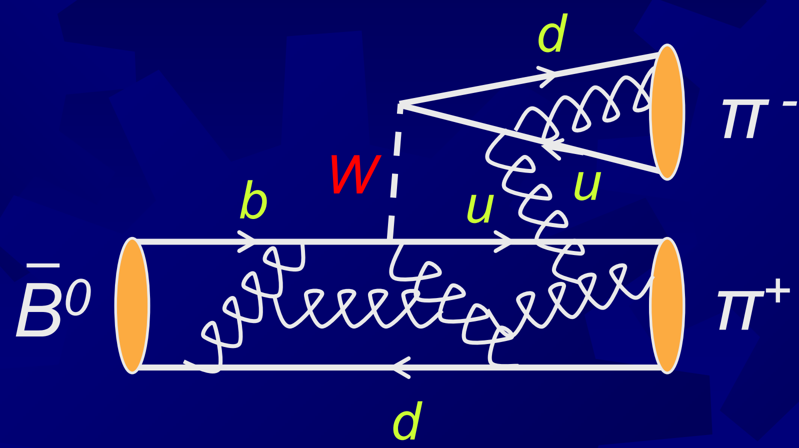
Rates for many charmless *B* decays are characterized by significant interference of tree and penguin topologies:

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

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

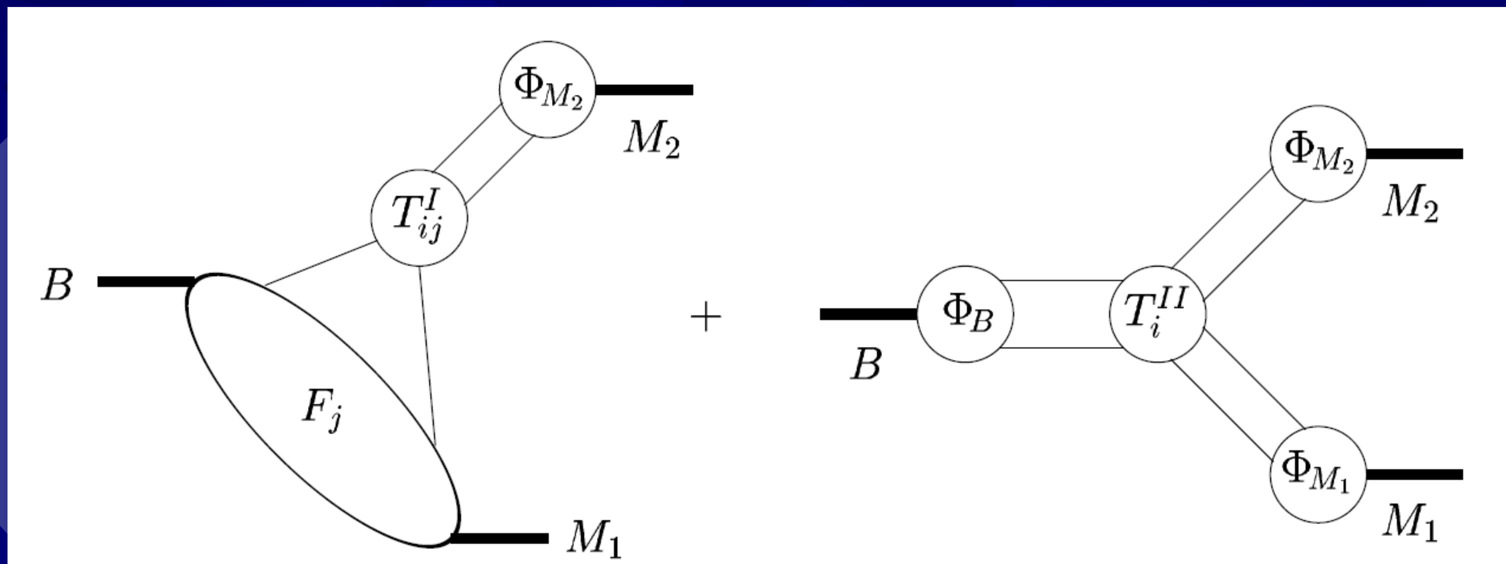
Asymmetry: $$\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f}) \sim \sin\gamma\sin(\delta_i - \delta_j)$$

# Reality is far more complicated:




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

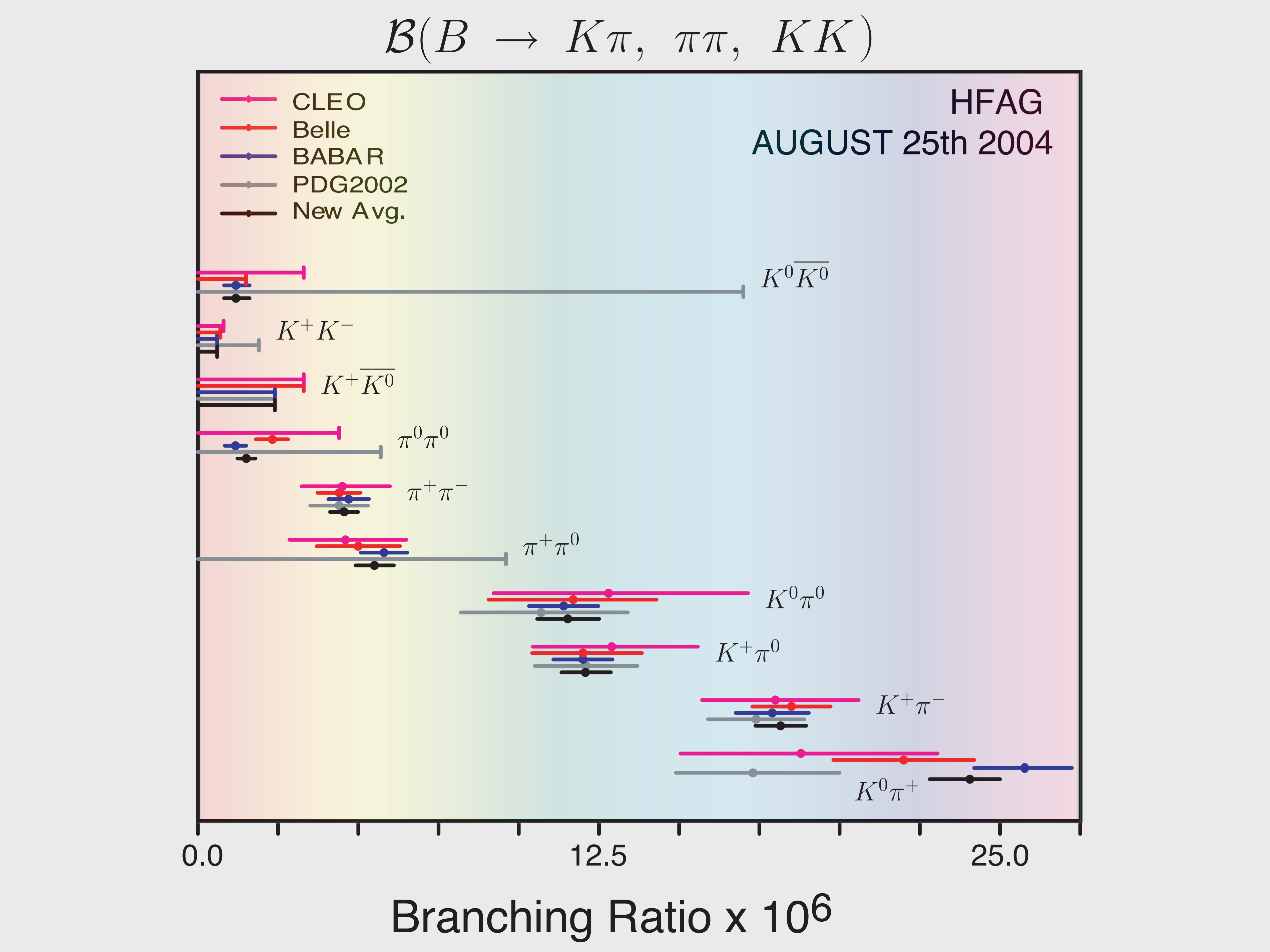
# QCD factorization formula



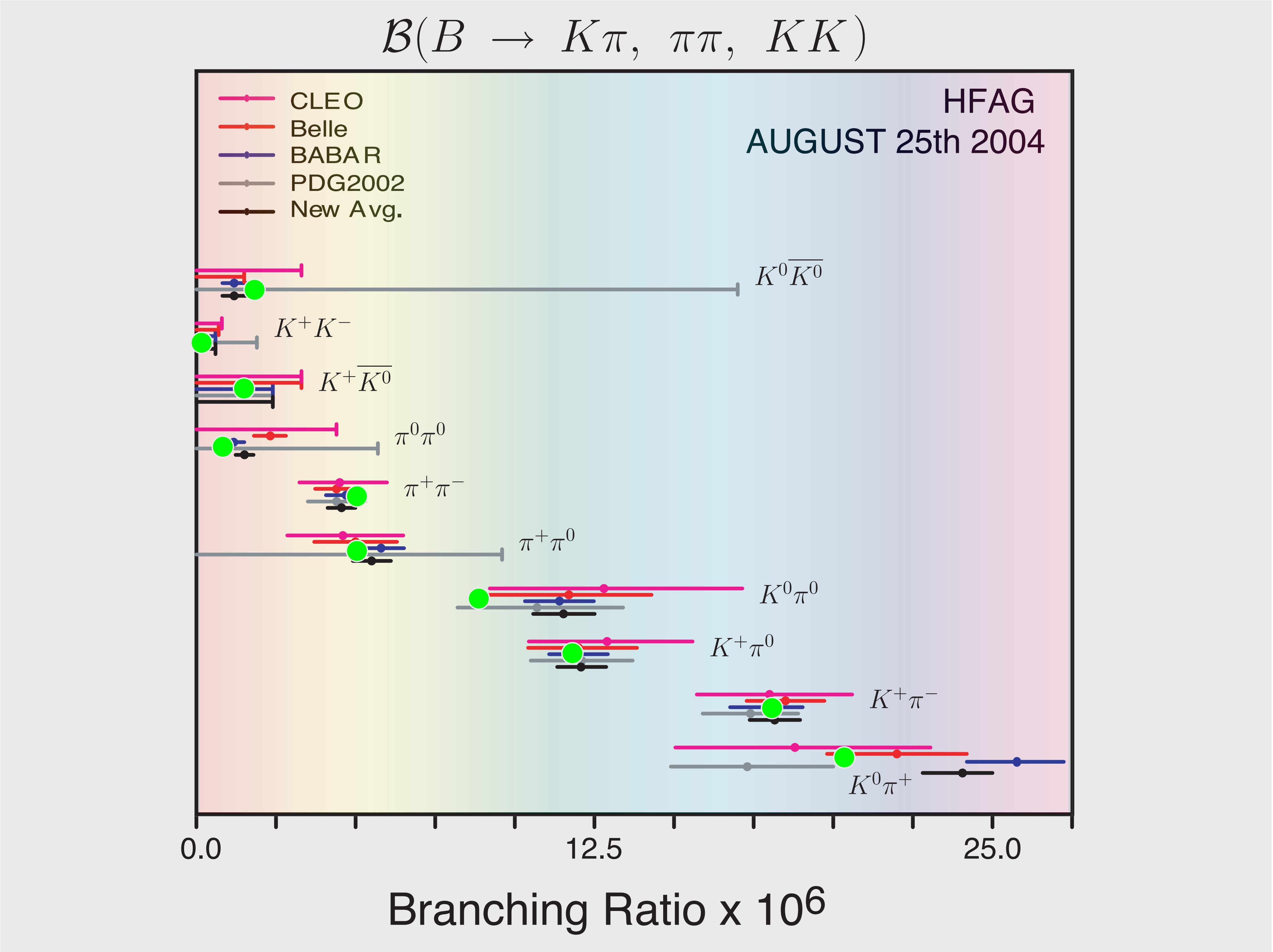

- First-principles calculation of decay amplitudes and their rescattering phases in heavy-quark limit

# How well does it work?

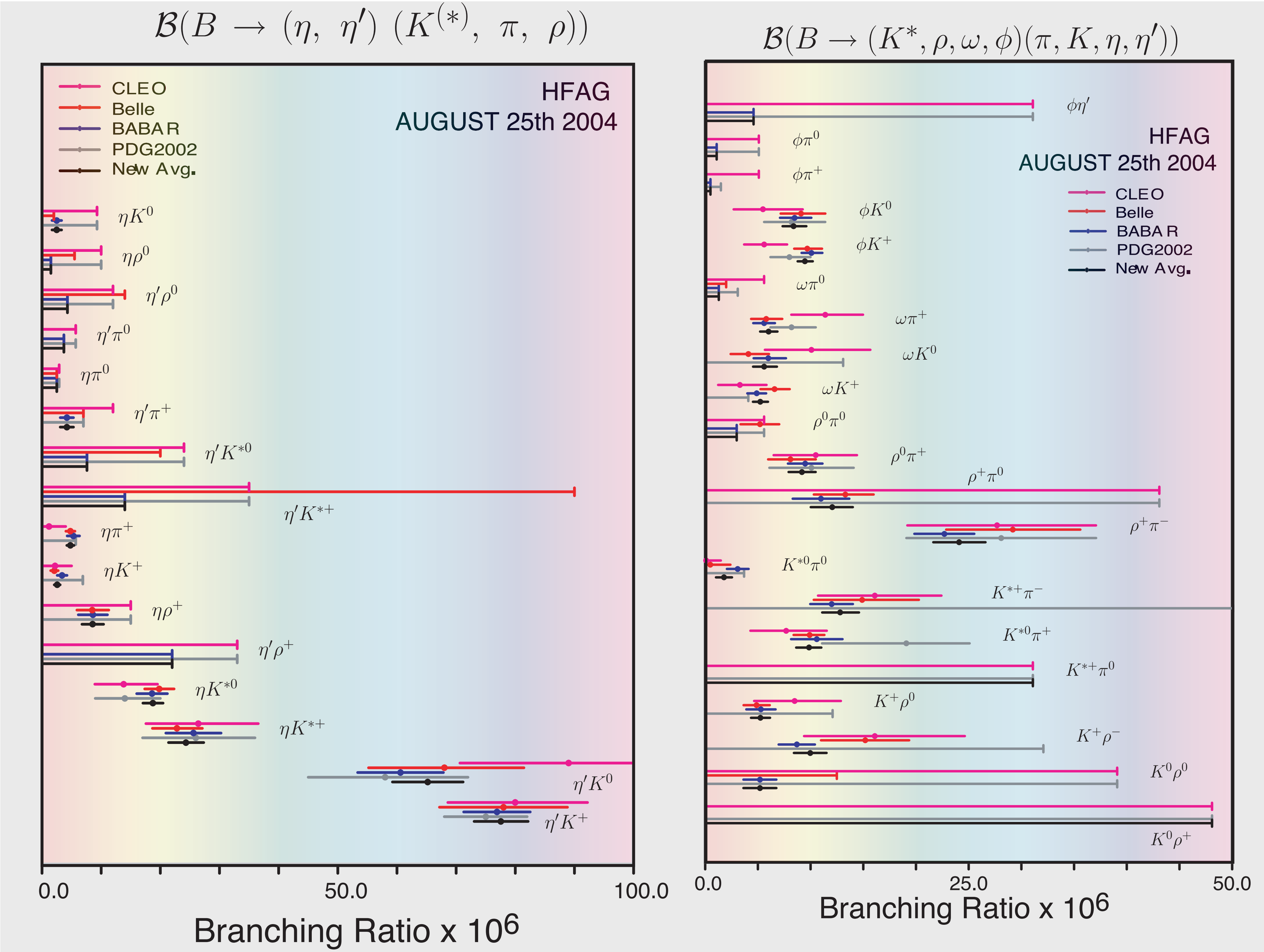
- Compare theory predictions from 2003 (for fixed set of input parameters) with all available present experimental data
- Find good global agreement
- Heavy-quark limit appears to be a good first approximation to the intricate dynamics of these decays



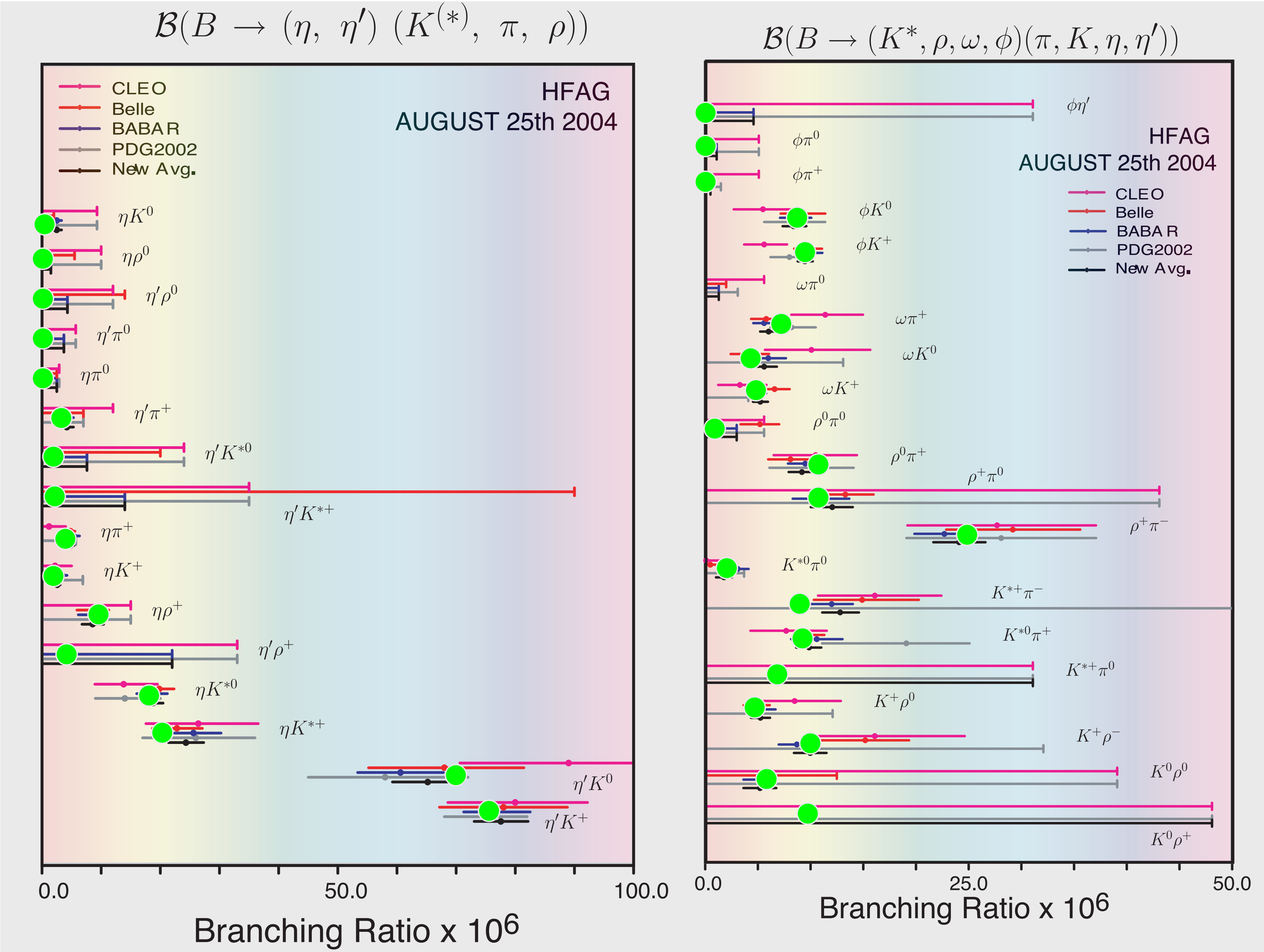
$\mathcal{B}(B \rightarrow K\pi,\ \pi\pi,\ KK)$
CLEO
Belle
BABAR
PDG2002
New Avg.
HFAG
AUGUST 25th 2004
$K^0\overline{K^0}$
$K^+K^-$
$K^+\overline{K^0}$
$\pi^0\pi^0$
$\pi^+\pi^-$
$\pi^+\pi^0$
$K^0\pi^0$
$K^+\pi^0$
$K^+\pi^-$
$K^0\pi^+$
0.0
12.5
25.0
Branching Ratio x $10^6$

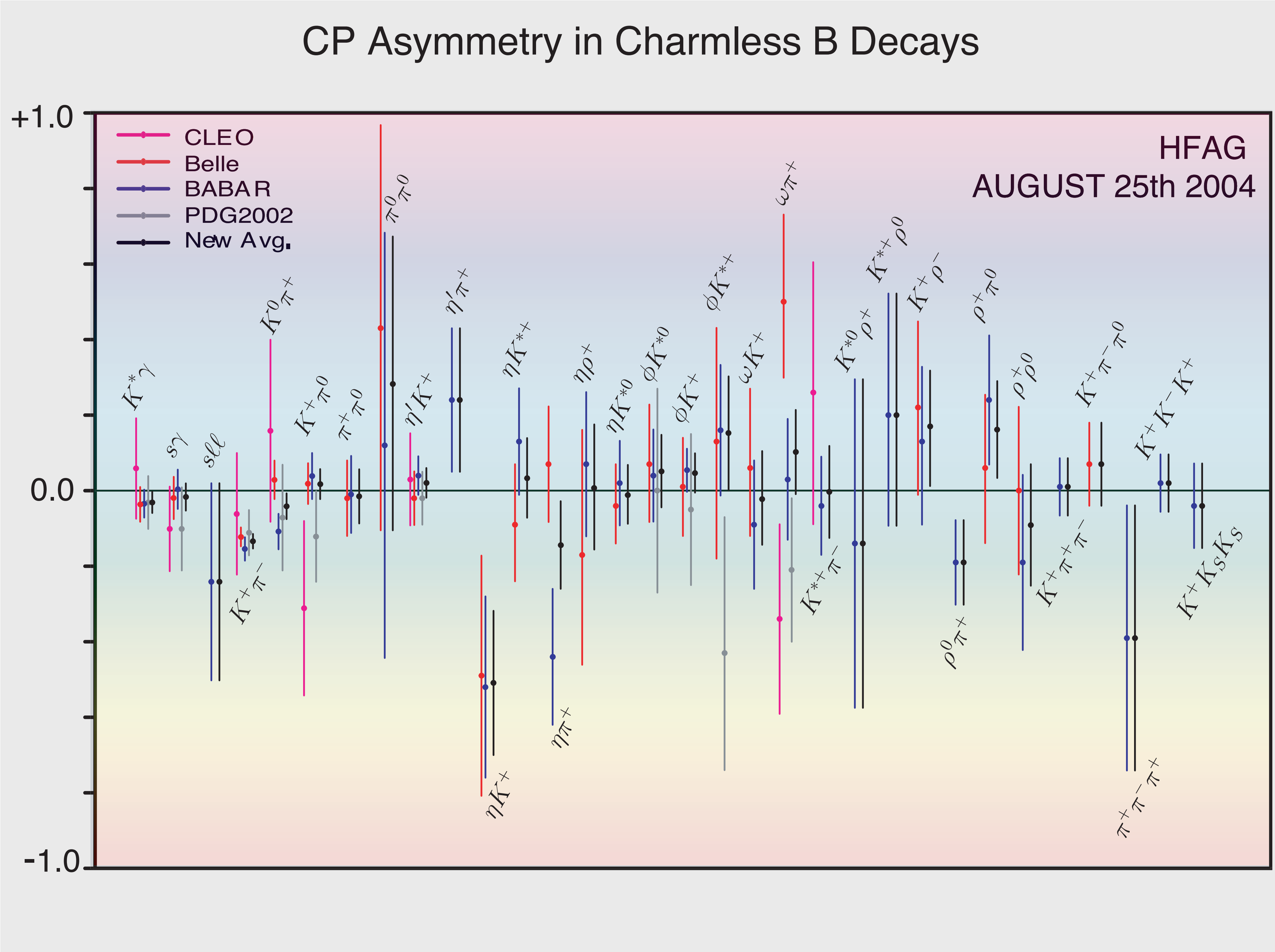


$\mathcal{B}(B \to K\pi,\ \pi\pi,\ KK)$
CLEO
Belle
BABAR
PDG2002
New Avg.
HFAG
AUGUST 25th 2004
$K^0\overline{K^0}$
$K^+K^-$
$K^+\overline{K^0}$
$\pi^0\pi^0$
$\pi^+\pi^-$
$\pi^+\pi^0$
$K^0\pi^0$
$K^+\pi^0$
$K^+\pi^-$
$K^0\pi^+$
0.0
12.5
25.0
Branching Ratio x $10^6$

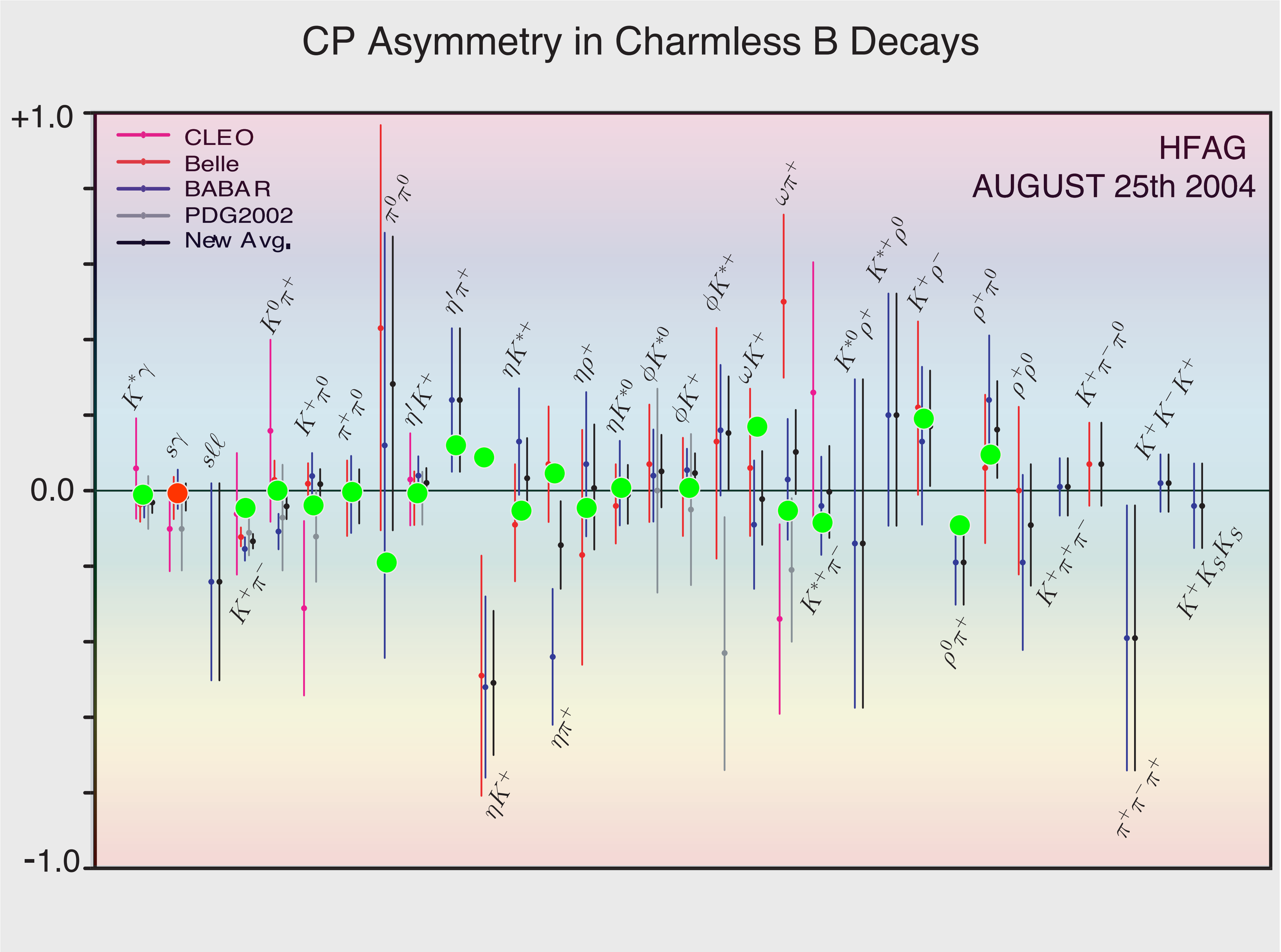


$\mathcal{B}(B \to (\eta,\ \eta')\ (K^{(*)},\ \pi,\ \rho))$
CLEO
Belle
BABAR
PDG2002
New Avg.
HFAG
AUGUST 25th 2004
$\eta K^0$
$\eta\rho^0$
$\eta'\rho^0$
$\eta'\pi^0$
$\eta\pi^0$
$\eta'\pi^+$
$\eta' K^{*0}$
$\eta' K^{*+}$
$\eta\pi^+$
$\eta K^+$
$\eta\rho^+$
$\eta'\rho^+$
$\eta K^{*0}$
$\eta K^{*+}$
$\eta' K^0$
$\eta' K^+$
0.0
50.0
100.0
Branching Ratio x $10^6$
$\mathcal{B}(B \to (K^*,\rho,\omega,\phi)(\pi,K,\eta,\eta'))$
$\phi\eta'$
$\phi\pi^0$
$\phi\pi^+$
$\phi K^0$
$\phi K^+$
$\omega\pi^0$
$\omega\pi^+$
$\omega K^0$
$\omega K^+$
$\rho^0\pi^0$
$\rho^0\pi^+$
$\rho^+\pi^0$
$\rho^+\pi^-$
$K^{*0}\pi^0$
$K^{*+}\pi^-$
$K^{*0}\pi^+$
$K^{*+}\pi^0$
$K^+\rho^0$
$K^+\rho^-$
$K^0\rho^0$
$K^0\rho^+$
0.0
25.0
50.0
Branching Ratio x $10^6$


$\mathcal{B}(B \to (\eta,\ \eta')\ (K^{(*)},\ \pi,\ \rho))$
CLEO
Belle
BABAR
PDG2002
New Avg.
HFAG
AUGUST 25th 2004
$\eta K^0$
$\eta\rho^0$
$\eta'\rho^0$
$\eta'\pi^0$
$\eta\pi^0$
$\eta'\pi^+$
$\eta' K^{*0}$
$\eta' K^{*+}$
$\eta\pi^+$
$\eta K^+$
$\eta\rho^+$
$\eta'\rho^+$
$\eta K^{*0}$
$\eta K^{*+}$
$\eta' K^0$
$\eta' K^+$
0.0
50.0
100.0
Branching Ratio x $10^6$
$\mathcal{B}(B \to (K^*,\rho,\omega,\phi)(\pi,K,\eta,\eta'))$
$\phi\eta'$
$\phi\pi^0$
$\phi\pi^+$
HFAG
AUGUST 25th 2004
CLEO
Belle
BABAR
PDG2002
New Avg.
$\phi K^0$
$\phi K^+$
$\omega\pi^0$
$\omega\pi^+$
$\omega K^0$
$\omega K^+$
$\rho^0\pi^0$
$\rho^0\pi^+$
$\rho^+\pi^0$
$\rho^+\pi^-$
$K^{*0}\pi^0$
$K^{*+}\pi^-$
$K^{*0}\pi^+$
$K^{*+}\pi^0$
$K^+\rho^0$
$K^+\rho^-$
$K^0\rho^0$
$K^0\rho^+$
0.0
25.0
50.0
Branching Ratio x $10^6$



CP Asymmetry in Charmless B Decays
+1.0
0.0
-1.0
CLEO
Belle
BABAR
PDG2002
New Avg.
HFAG
AUGUST 25th 2004


CP Asymmetry in Charmless B Decays
+1.0
0.0
-1.0
CLEO
Belle
BABAR
PDG2002
New Avg.
HFAG
AUGUST 25th 2004
$K^*\gamma$
$s\gamma$
$s\ell\ell$
$K^+\pi^-$
$K^0\pi^+$
$K^+\pi^0$
$\pi^+\pi^0$
$\pi^0\pi^0$
$\eta' K^+$
$\eta'\pi^+$
$\eta K^+$
$\eta K^{*+}$
$\eta\pi^+$
$\eta\rho^+$
$\eta K^{*0}$
$\phi K^{*0}$
$\phi K^+$
$\phi K^{*+}$
$\omega K^+$
$\omega\pi^+$
$K^{*+}\pi^-$
$K^{*0}\rho^+$
$K^{*+}\rho^0$
$K^+\rho^-$
$\rho^0\pi^+$
$\rho^+\pi^0$
$\rho^+\rho^0$
$K^+\pi^+\pi^-$
$K^+\pi^-\pi^0$
$\pi^+\pi^-\pi^+$
$K^+K^-K^+$
$K^+K_SK_S$

# Extraction of $\gamma = \arg(V_{ub}^*)$

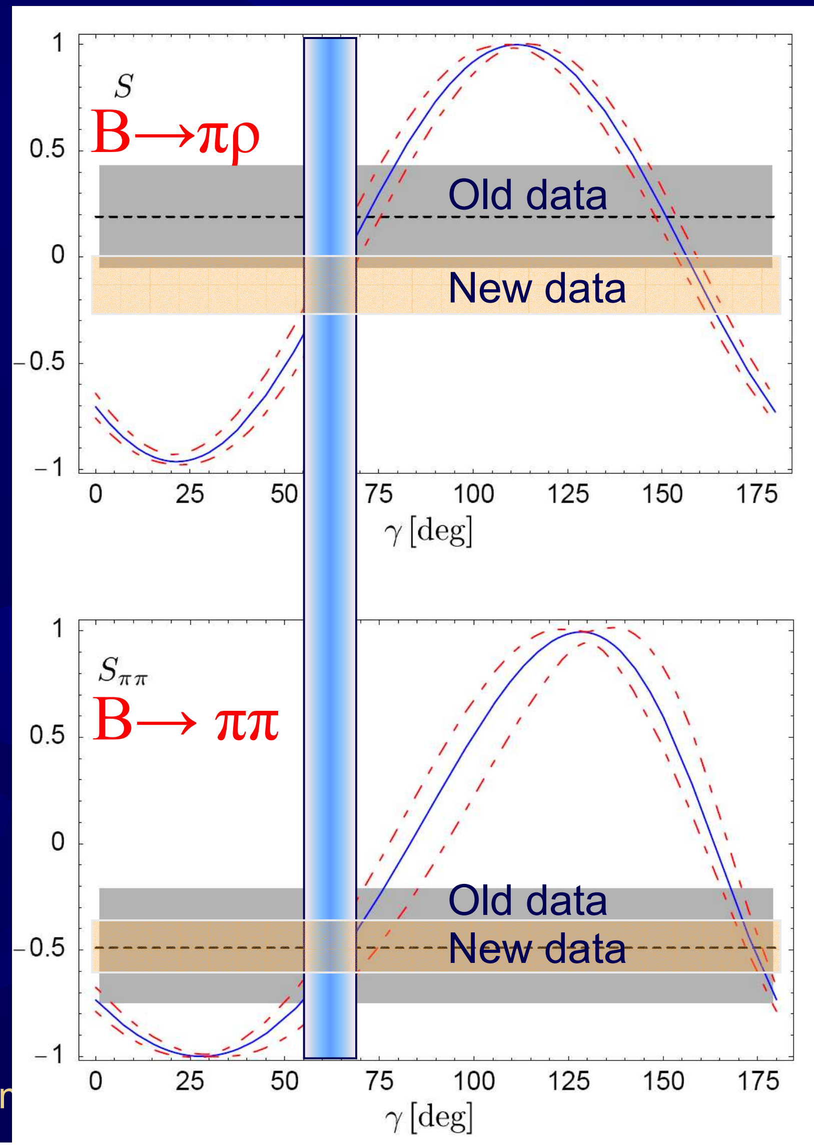
- Decays $B \to \pi\pi$, $\pi\rho$ are dominated by tree topologies
- In limit where penguin amplitudes are neglected, decay amplitudes have phase $\varphi_A = -\gamma$, and hence time-dependent CP asymmetries measure $\sin 2(\beta+\gamma)$
- Use QCD factorization to estimate "penguin pollution"

# Extraction of γ in B→πρ decay

[Beneke, MN]

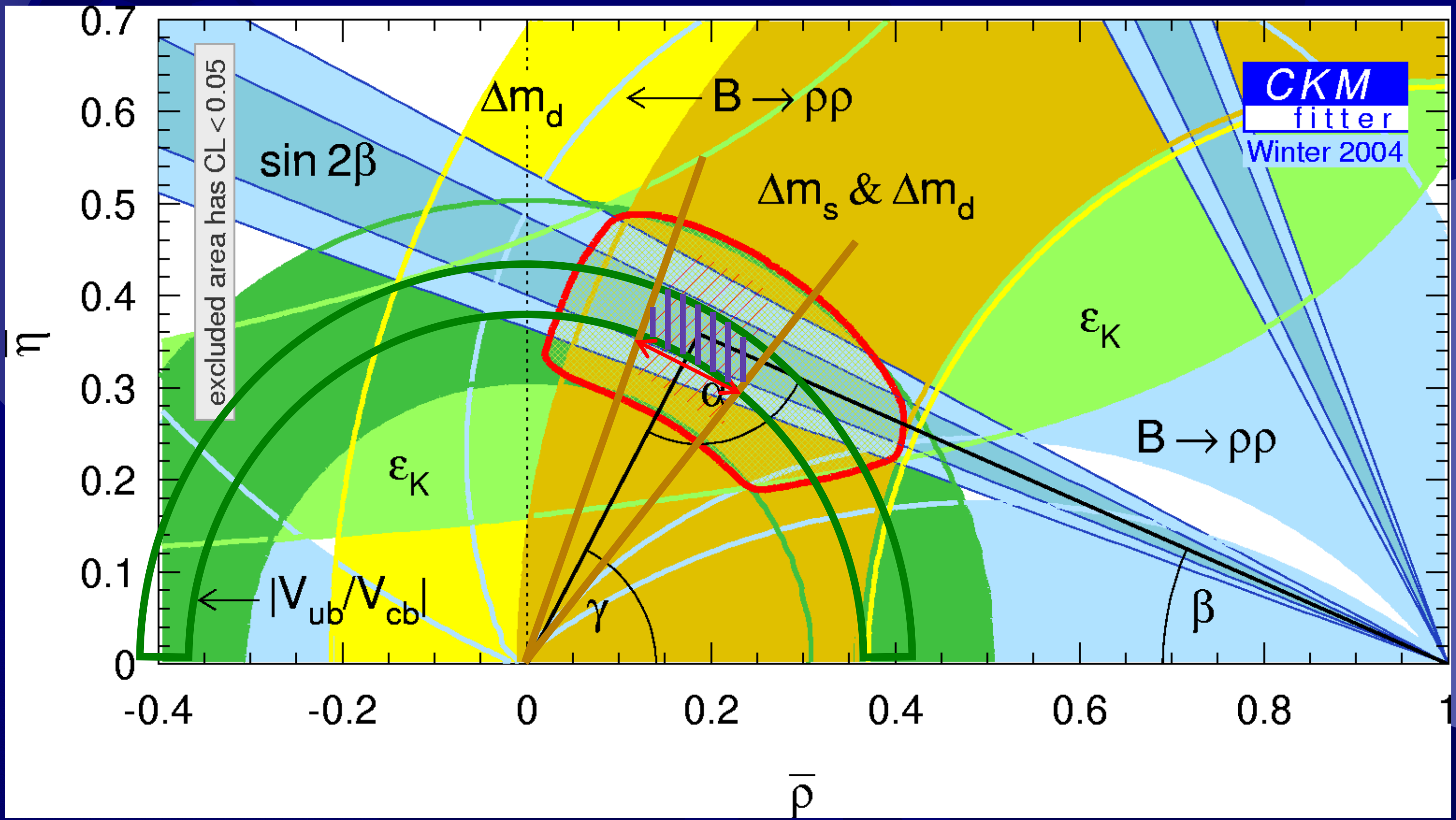
- B→PV modes have smaller penguin contributions than B→PP modes
- Smaller theory uncertain-ties when γ is extracted from time-dependent rates in B→πρ decays
- Result:

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



# Impact of precise γ

- Realistic: δγ: ±8° (better at LHC-b?)



# 2. Departures from the Standard Model ?

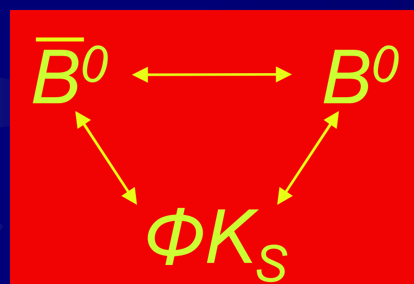
Quest for New Physics

# Searching for the unknown

- So far, all measurements in the flavor sector are in agreement with the SM
- However, there are tantalizing hints of New Physics effects in some rare, penguin-dominated decays
- Not in contradiction with anything we know from other processes (e.g., $B \rightarrow X_s \gamma$)
- Experimental situation stabilizes, and theory is under good control

# CP asymmetry in $B \to \Phi K_S$

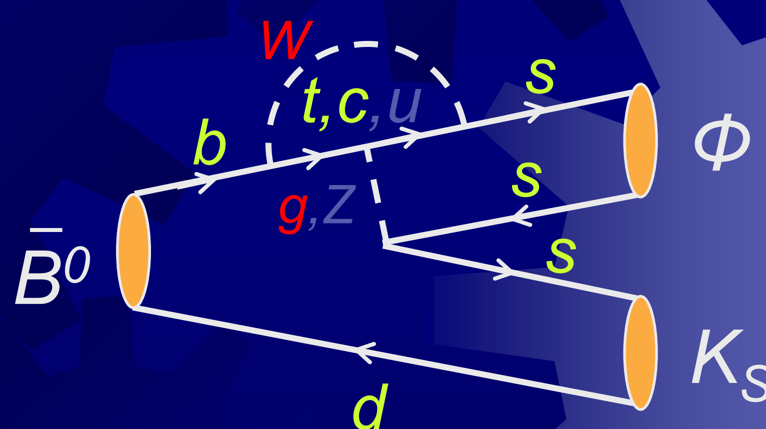
- Interference of mixing and decay:




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

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

- Penguin graph is real to very good approximation!




[Beneke, MN]

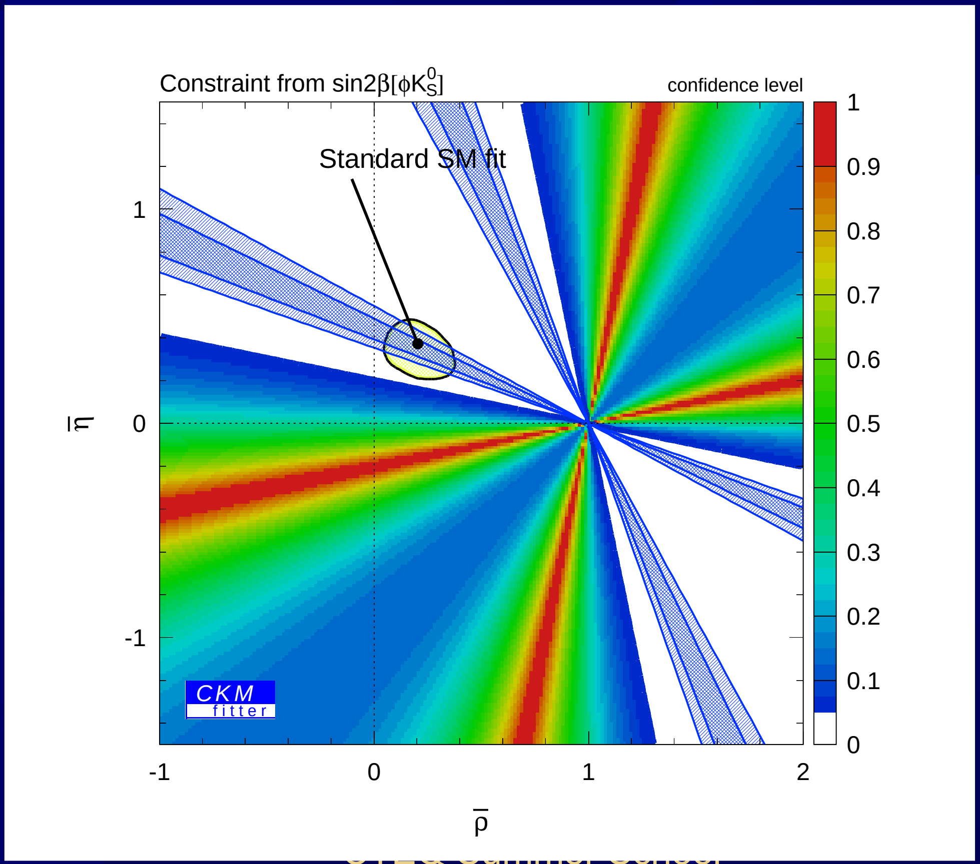
# It’s been a rollercoaster!

## Experimental situation: (prior to LP 03)

- $S(\Phi K_S)$ = -0.18±0.51±0.07 BaBar
- $S(\Phi K_S)$ = -0.73±0.64±0.22 Belle

-0.38±0.41

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

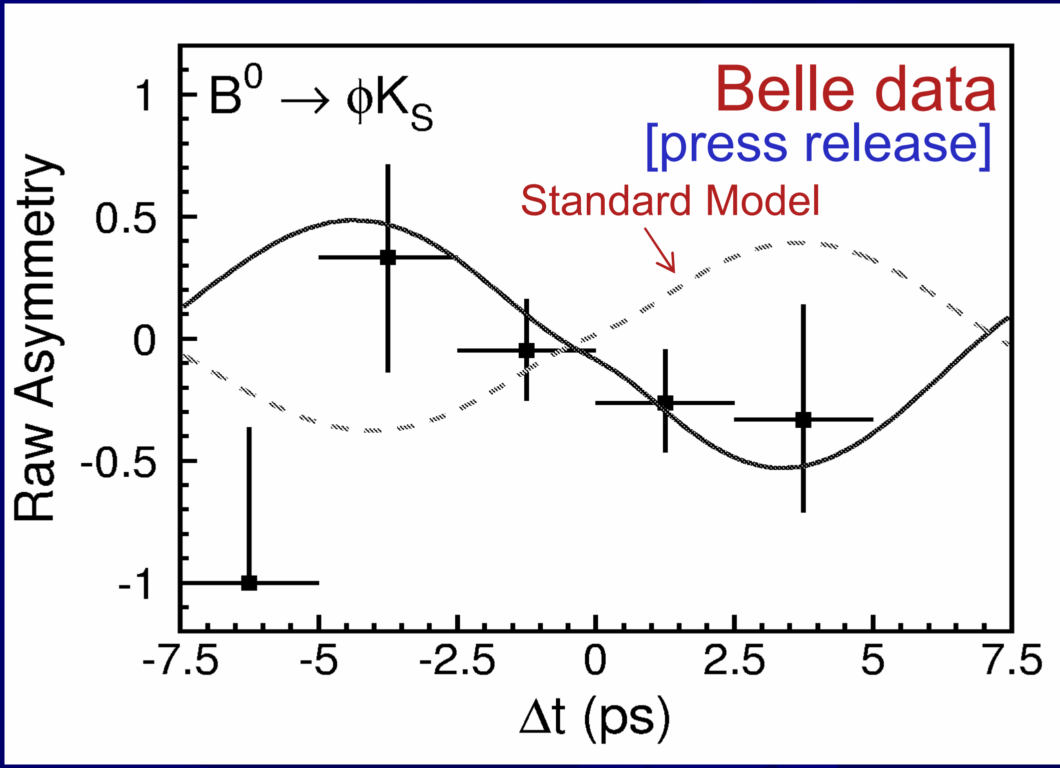


## Experimental situation: (after LP 03)

- $S(\Phi K_S)$ =+0.45±0.43±0.07 BaBar
- $S(\Phi K_S)$ = -0.96±0.50±0.10 Belle

$\}$ -0.15±0.33

**$S(\Phi K_S)$ - $S(J/\psi\ K_S)$ = -0.88±0.33 (2.7σ)**



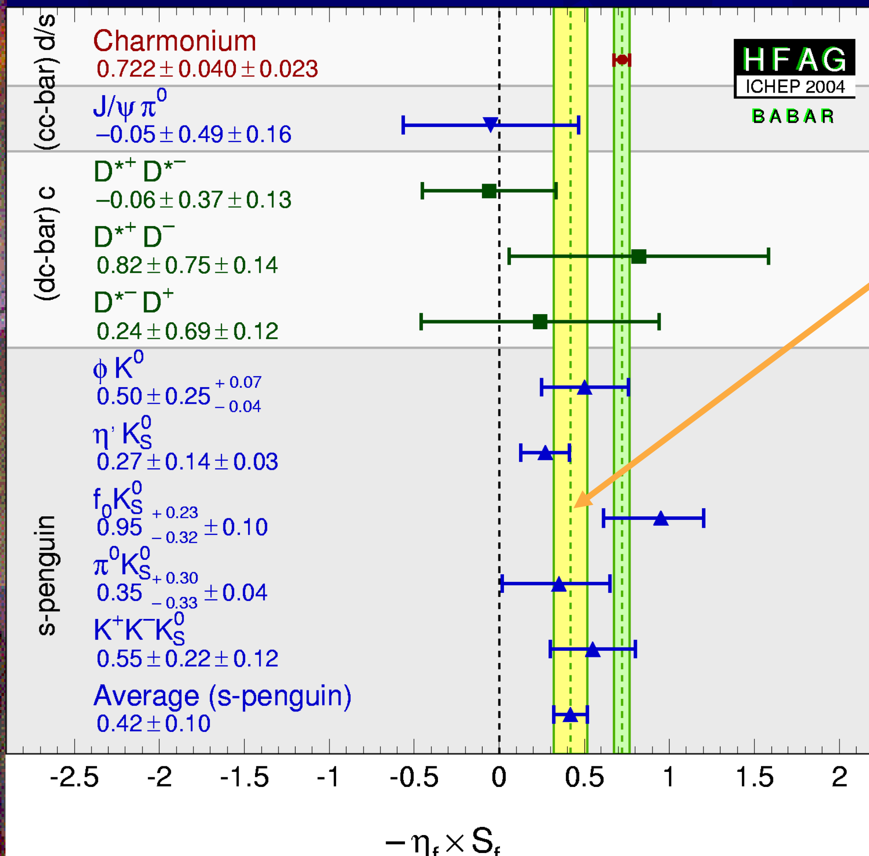
- Experimental situation: (after ICHEP 04)
  - $S(\Phi K_S)$ =+0.50±0.25±0.06 BaBar
  - $S(\Phi K_S)$ =+0.06±0.33±0.09 Belle

$\left.\begin{array}{l} \\ \\ \end{array}\right\}$ 0.27±0.25

$S(\Phi K_S) - S(J/\psi\ K_S) = -0.46\pm0.25\ (1.8\sigma)$

- But, trends for deviations are also seen in other $b\rightarrow s$ penguin modes, e.g. a $3\sigma$ effect for $\eta' K_S$ from BaBar!

# New Physics ?

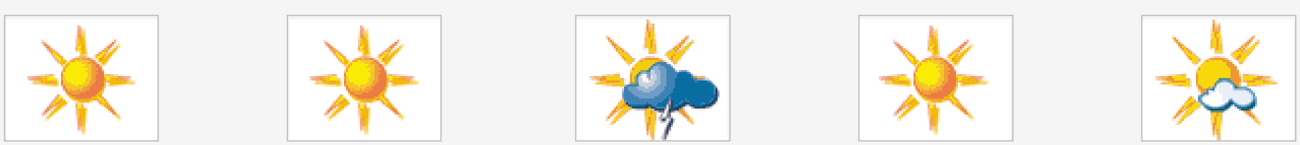



*s*-penguin average at 2.7σ different from sin2β[cc] (BABAR)

Similar difference at 2.4 σ seen by Belle

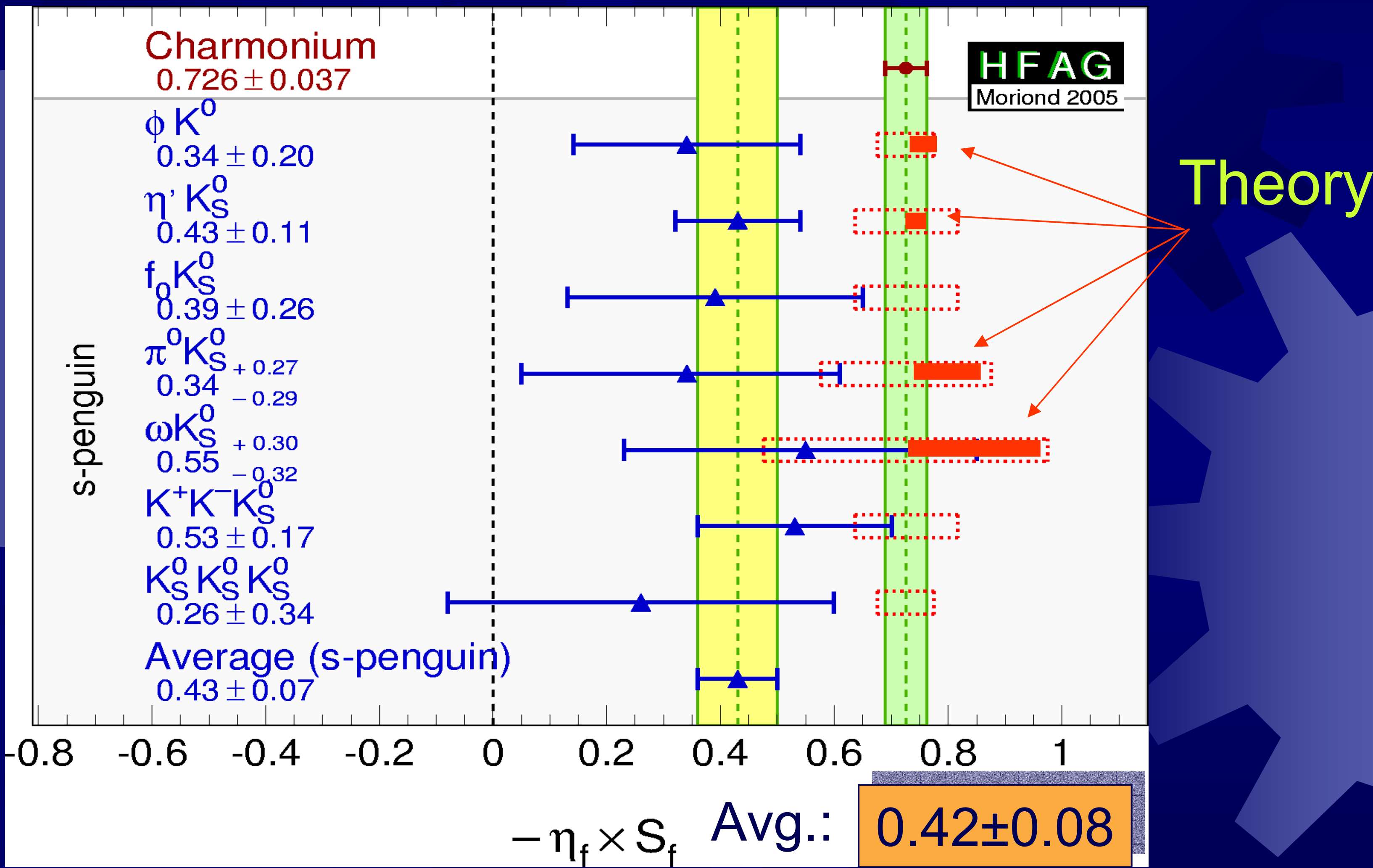
*[A. Hoecker, ICHEP 2004]*

$B^0 \to \phi K^0$ $\quad$ $B^0 \to K^+K^-K^0$ $\quad$ $B^0 \to \eta' K^0$ $\quad$ $B^0 \to f_0 K^0$ $\quad$ $B^0 \to \pi^0 K^0$



# A year later …

# 7 reasons for excitement!



# Measurements now consistent!

| Mode | $\Delta S_f$ (Theory) | $\Delta S_f$ [Range] | Experiment [3] (BaBar/Belle) |
|---|---|---|---|
| $\pi^0 K_S$ | $0.07^{+0.05}_{-0.04}$ | $[+0.02, 0.15]$ | $-0.39^{+0.27}_{-0.29}$ $(-0.38^{+0.30}_{-0.33}/-0.43^{+0.60}_{-0.60})$ |
| $\rho^0 K_S$ | $-0.08^{+0.08}_{-0.12}$ | $[-0.29, 0.02]$ | — |
| $\eta' K_S$ | $0.01^{+0.01}_{-0.01}$ | $[+0.00, 0.03]$ | $-0.30^{+0.11}_{-0.11}$ $(-0.43^{+0.14}_{-0.14}/-0.07^{+0.18}_{-0.18})$ |
| $\eta K_S$ | $0.10^{+0.11}_{-0.07}$ | $[-1.67, 0.27]$ | — |
| $\phi K_S$ | $0.02^{+0.01}_{-0.01}$ | $[+0.01, 0.05]$ | $-0.39^{+0.20}_{-0.20}$ $(-0.23^{+0.26}_{-0.25}/-0.67^{+0.34}_{-0.34})$ |
| $\omega K_S$ | $0.13^{+0.08}_{-0.08}$ | $[+0.01, 0.21]$ | $-0.18^{+0.30}_{-0.32}$ $(-0.23^{+0.34}_{-0.38}/+0.02^{+0.65}_{-0.66})$ |

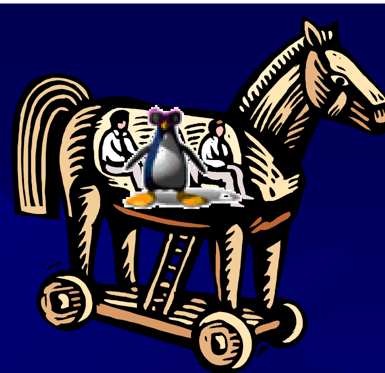
***Deviation is 3.8σ !!!***

# In all cases …

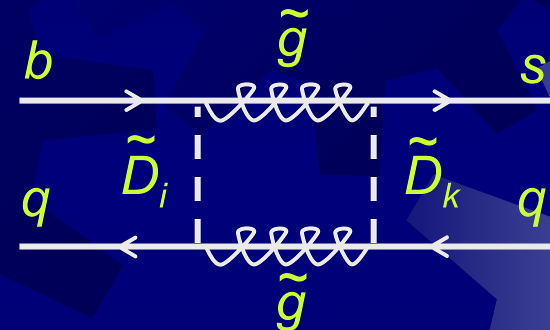
- Possible explanation in terms of new, CP-violating flavor-changing neutral currents (FCNC) of the type $b \to s\bar{q}q$, preferrably with $(\bar{q}q)$ in flavor non-singlet configuration ("trojan penguins")
- Predicted in a variety of theories, e.g. SUSY (quark-squark-gluino couplings) and extra dimensions (Kaluza-Klein Z')

[Grossman, Kagan, MN 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 $\alpha_{EM}$ suppression
- e.g., gluino-squark box graphs in SUSY:




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

## Sensitivity to large scales:

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

# 3. Conclusions

## Summary and Outlook

# 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 $b \rightarrow s\bar{q}q$
  - 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!