Theoretical Interest in B-Physics at LHC

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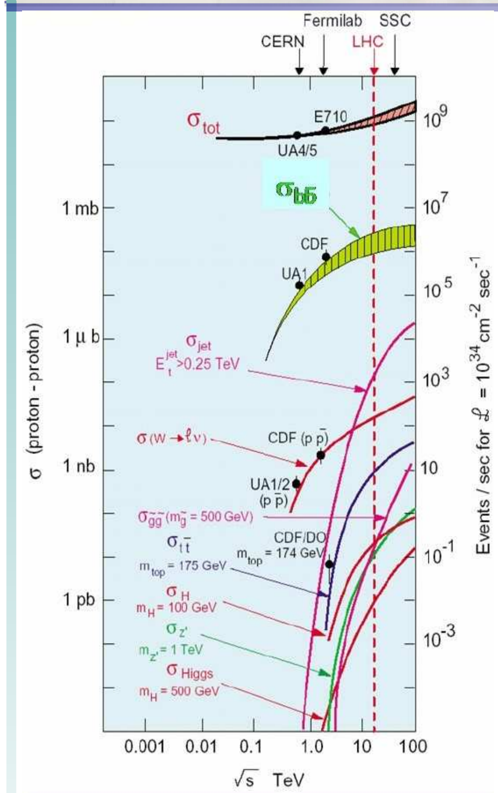
Plan of Talk

- Profile of B-Physics at the LHC
- Current Knowledge of $|V_{\rm CKM}|$
- B-Factory measurements of α, β, γ and improvements at the LHC
- Some selected Radiative Rare B-Decays
  - $b \to s\gamma$: SM vs. Experiment
  - $b \to d\gamma$: Example: $B \to (\rho, \omega)\gamma$: Current Status
- Dilepton Mass Spectrum and Leptonic Forward-Backward Asymmetry in $B \to K^* \ell^+ \ell^-$: Current Status and Benchmark Measurements
- The Decay $B_s \to \mu^+ \mu^-$ in the SM and SUSY
- Summary

B-Physics at LHC



B-production at LHC:

σ_{total} = 100 mb

$\sigma_{inelastic}$ = 80 mb

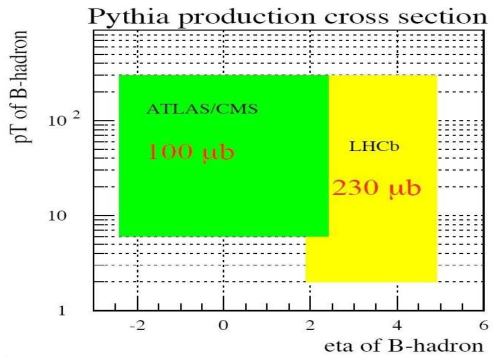
$\sigma_{b\bar{b}}$ = 500 μb

ATLAS/CMS general purpose	LHCb B-Physics dedicated
$\|\eta\| < 2.5$, $p_T > 10$ GeV, $\sigma = 100$ μb	$1.9 < \eta < 4.9$, $p_T > 2$ GeV, $\sigma = 230$ μb
$L_{low} = 1 \div 2 \cdot 10^{33}$ cm^{-2}s^{-1} $L_{high} = 10^{34}$ cm^{-2}s^{-1} $B^0_{s,d} \to \mu^+\mu^-$ triggerable at L_{high}	$L = 2 \cdot 10^{32}$ cm^{-2}s^{-1} ($L_{max} = 5 \cdot 10^{32}$ cm^{-2}s^{-1}) from 1st physics run
$n_{low} \sim 3$ $n_{high} \sim 23$ f = 32 MHz	n ~ 0.5 => clean environment f = 30 MHz
$L_{int} = 10$ fb^{-1}/year at L_{low} (3 years)	$L_{int} = 2$ fb^{-1}/year (10 fb^{-1} after 5 years)
ATLAS: $\sigma_{Bs\to\mu\mu}$ = 80 MeV CMS: $\sigma_{Bs\to\mu\mu}$ = 46 MeV	$\sigma_{Bs\to\mu\mu}$ = 18 MeV
Distance from beam: ATLAS ~ 5 cm CMS ~ 4 cm	LHCb ~ 8 mm

L – instantaneous luminosity

f – non-empty bunch crossing rate

n – mean number of inelastic pp-interactions in bunch crossing = $L \cdot \sigma_{inelastic}/f$



B-factories vs. b-factory

	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ PEPII, KEKB	$pp \to b\bar{b}X$ ($\sqrt{s}$ = 14 TeV, Δt_{bunch}=25 ns) LHC (LHCb–ATLAS/CMS)
Production σ_{bb}	1 nb	~500 μb
Typical $b\bar{b}$ rate	10 Hz	100–1000 kHz
$b\bar{b}$ purity	~1/4	$\sigma_{bb}/\sigma_{inel}$ = 0.6% Trigger is a major issue !
Pileup	0	0.5–5
b-hadron types	B^+B^- (50%) $B^0\bar{B}^0$ (50%)	B^+ (40%), B^0 (40%), B_s (10%) B_c (< 0.1%), b-baryons (10%)
b-hadron boost	Small	Large (decay vertexes well separated)
Production vertex	Not reconstructed	Reconstructed (many tracks)
Neutral B mixing	Coherent $B^0\bar{B}^0$ pair mixing	Incoherent B^0 and B_s mixing (extra flavour-tagging dilution)
Event structure	$B\bar{B}$ pair alone	Many particles not associated with the two b hadrons

Completing the program on B Physics…

- Precise measurement of B^0_s-$\overline{B}^0_s$ mixing: Δm_s, $\Delta\Gamma_s$ and phase ϕ_s.

  $B_s \to D_s\pi$, …
  $B_s \to J/\psi\phi$, $B_s \to J/\psi\eta^{(')}$

- Search for effects of NP appearing in suppressed and rare exclusive and inclusive B decays

  $B_{(s)}{}^0 \to X\gamma$, $B^0 \to K^{*0} l^+ l^-$,
  $b \to s l^+ l^-$, $B_s \to \mu^+\mu^-$...

- Precise γ determinations including processes only at tree-level, in order to disentangle possible NP contributions

  $B_s \to D_s K$,
  $B^0 \to D^0 K^{*0}$, $B^\pm \to D K^\pm$,
  $B^0 \to \pi\pi$ & $B_s \to KK$, …

- Other measurements of CP phases in different channels to over-constrain the Unitarity Triangles

  $B^0 \to \phi K_s$, $B_s \to \phi\phi$, ...
  $B^0 \to \rho\pi$, $B^0 \to \rho\rho$, …

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Expected Physics Performance

B-mixing:

- "control channel" $B^0 \to J/\psi\, K_S$
- Δm_s with $B_s^0 \to D_s\pi$
- ϕ_s and $\Delta\Gamma_s$ with $B^0_s \to J/\psi\phi\ (\eta)$

Suppressed and rare decays:

- Exclusive $b \to s\, \mu^+\mu^-$
- $B_s^0 \to \mu^+\mu^-$

Measurement of γ:

- from $B_s \to D_s K$
- from $B^0 \to D^0 K^{*0}$
- from $B^\pm \to DK^\pm$
- from $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$

The Cabibbo-Kobayashi-Maskawa Matrix

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

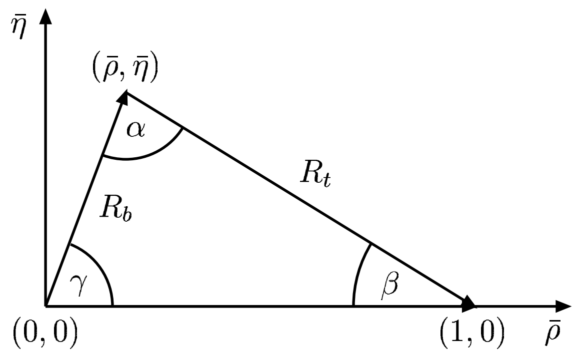
- Customary to use the handy Wolfenstein parametrization

$$V_{\text{CKM}} \simeq \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda(1+iA^2\lambda^4\eta) & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2(1+i\lambda^2\eta) & 1 \end{pmatrix}$$

- Four parameters: A, λ, ρ, η
- Perturbatively improved version of this parametrization

$$\bar{\rho} = \rho(1-\lambda^2/2), \quad \bar{\eta} = \eta(1-\lambda^2/2)$$

- The CKM-Unitarity triangle $[\phi_1 = \beta; \ \phi_2 = \alpha; \ \phi_3 = \gamma]$



Summary of the First 2 Rows of $V_{\rm CKM}$

- $|V_{ud}| = 0.97377(27)$ [PDG 2006]
- $|V_{us}| = 0.2257(21)$ [PDG 2006]
- $|V_{ub}| = (4.40 \pm 0.20 \pm 0.27) \times 10^{-3}$ [PDG 2006; inclusive]
  $|V_{ub}| = (3.84^{+0.67}_{-0.49}) \times 10^{-3}$ [PDG 2006; exclusive; Lattice-QCD & LC-QCD SR]

Unitarity of the Ist Row of $V_{\rm CKM}$

$$1 - (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2) = 0.0004 \pm 0.0011 \quad [\text{Schune, EPS, 2005}]$$

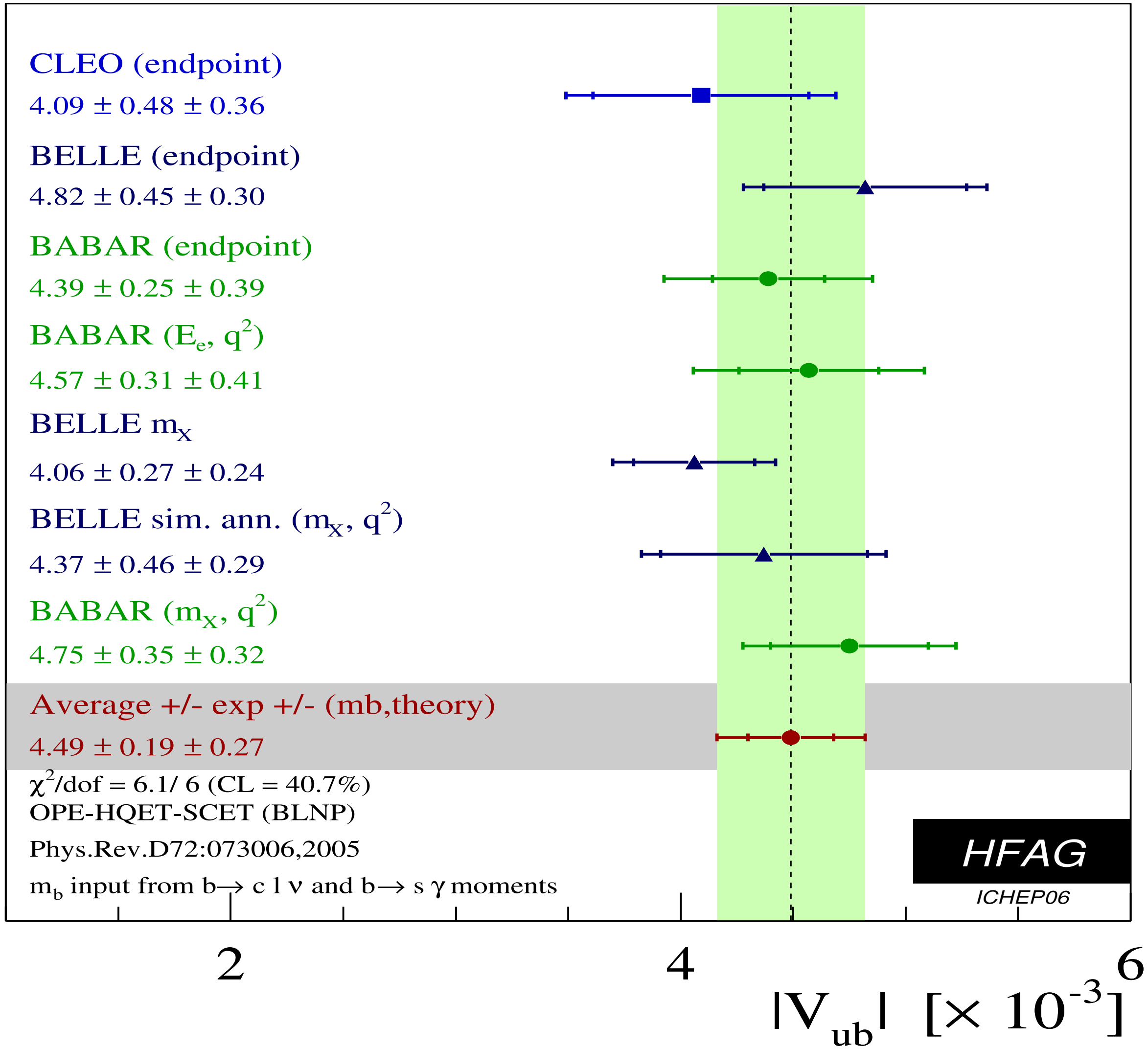
- $|V_{cd}| = 0.230(11)$ [PDG 2006]
- $|V_{cs}| = 0.957 \pm 0.017 \pm 0.093$ [CLEO-c; Lattice QCD; PDG 2006]
- $|V_{cb}| = (41.70 \pm 0.70) \times 10^{-3}$ [PDG 2006; inclusive]
  $|V_{cb}| = (40.9 \pm 1.8) \times 10^{-3}$ [PDG 2006; exclusive]

Unitarity of the first two Rows of $V_{\rm CKM}$

$$\Sigma_{u,c,d,s,b}|V_{ij}|^2 = 2.002 \pm 0.027 \quad [\text{LEP} \quad \text{Average}]$$

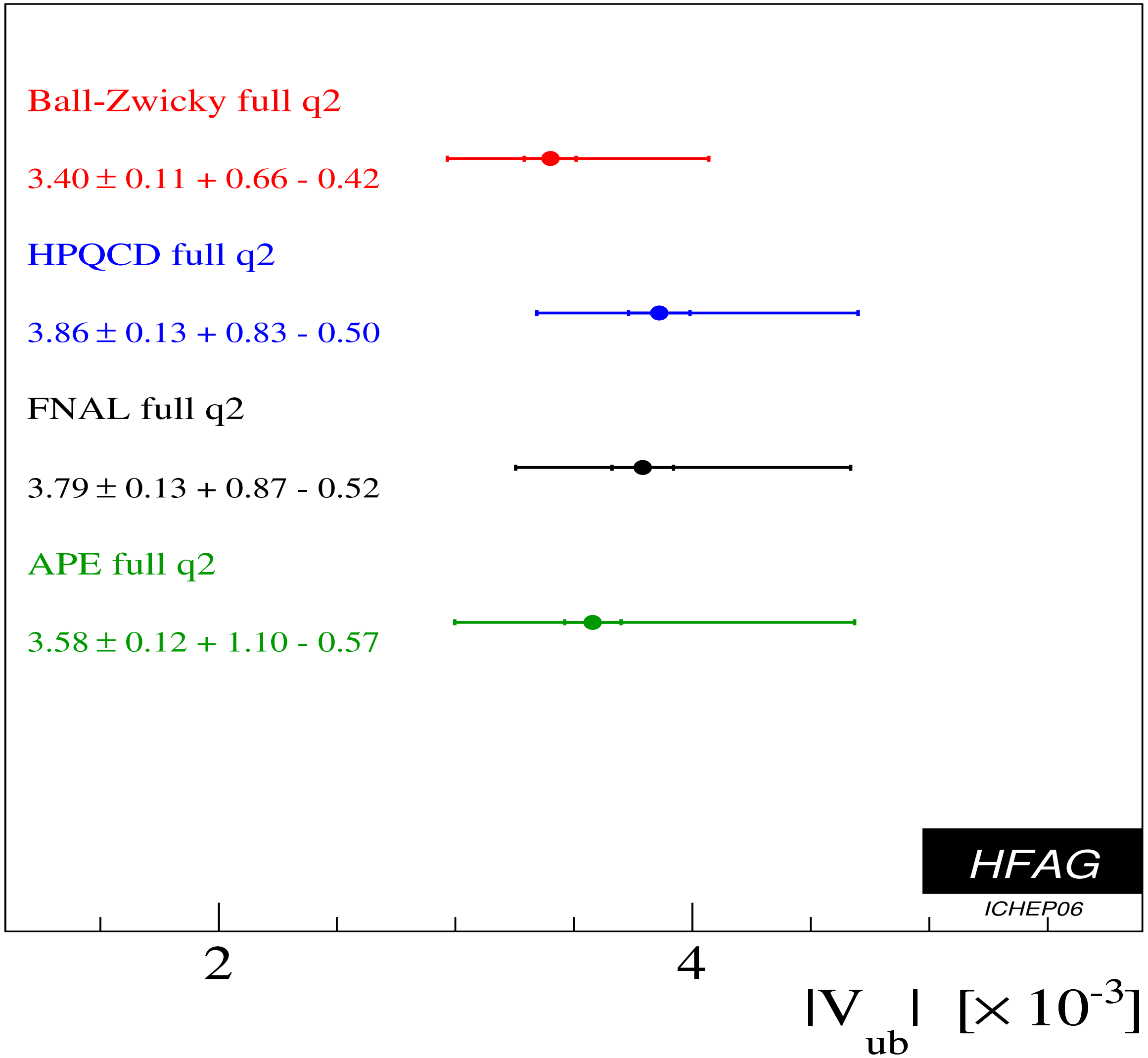
- Conclusion: No BSM Physics in the first two rows of $V_{\rm CKM}$

$|V_{ub}|$ from inclusive $B \to X_u \ell \nu_\ell$ decays (HFAG: ICHEP 2006 Update)



$|V_{ub}|$ from Exclusive decay $B \to \pi \ell \nu_\ell$

(HFAG: ICHEP 2006 Update)



Status of the Third Row of $V_{\rm CKM}$

$|V_{tb}|$

- From direct production and decays of the top quark (hep-ex/0505091)

$$R \equiv \frac{\mathcal{B}(t \to W + b)}{\mathcal{B}(t \to W + \sum_q q)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

$$R = 1.12^{+0.21}_{-0.19}\ (\text{stat})^{+0.17}_{-0.13}(\text{syst.})$$

- Assuming CKM unitarity & CDF Data $\Longrightarrow |V_{tb}| > 0.78$ (95% C.L.)

$|V_{td}|$

- From B_d^0 - $\overline{B_d^0}$ Mixing; $\Delta M_d = (0.508 \pm 0.004)$ ps^{-1} [HFAG 2006]
- SM (Box contribution with NLO QCD corrections) ($x_t = m_t^2/m_W^2$)

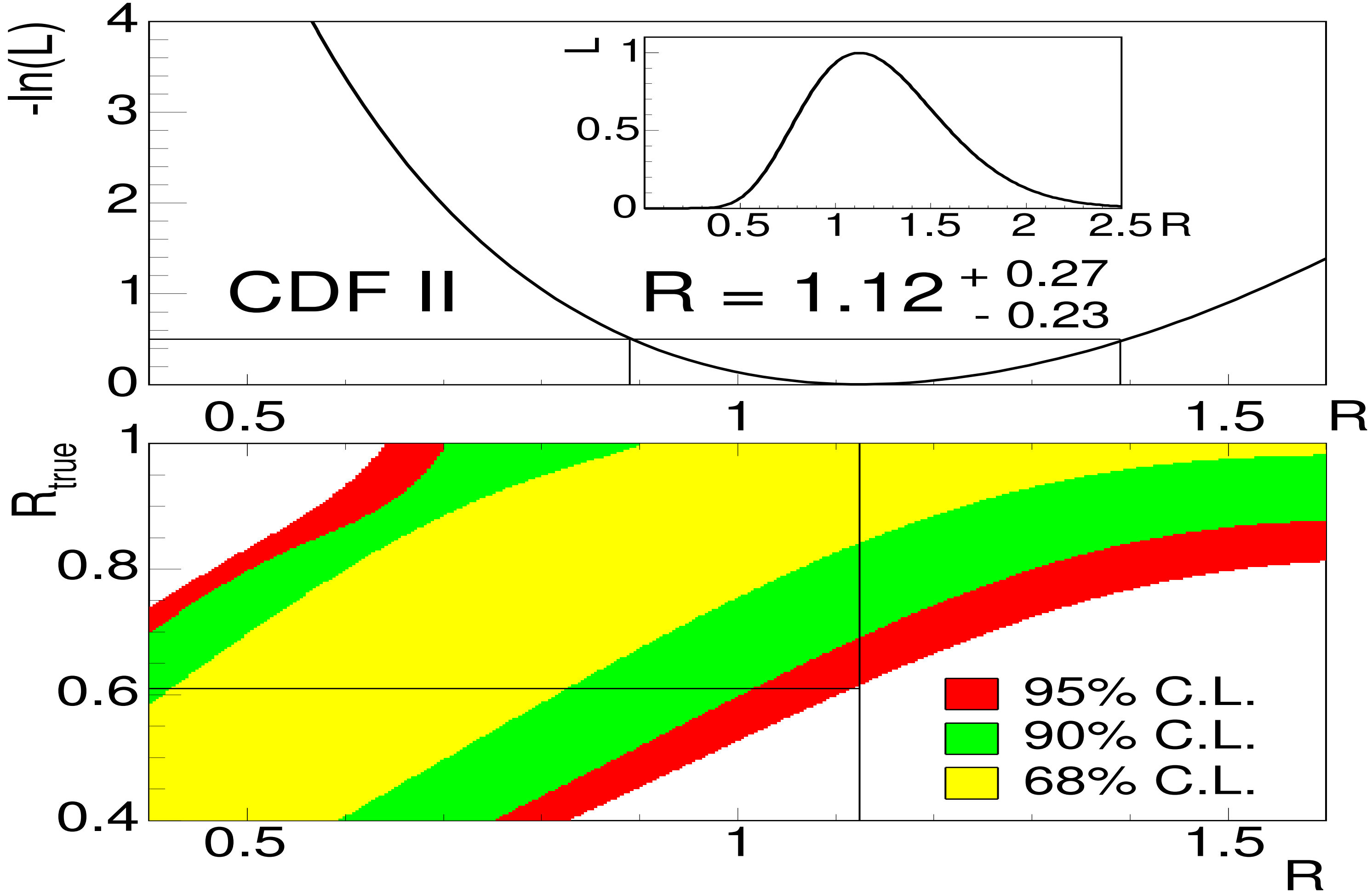
$$\Delta M_d = \frac{G_F^2}{6\pi^2} \hat{\eta}_B |V_{td}V_{tb}^*|^2 M_{B_d}(f_{B_d}^2 \hat{B}_{B_d}) M_W^2 S_0(x_t)$$

$$S_0(x) = x \cdot \left[\frac{1}{4} + \frac{9}{4}\frac{1}{(1-x)} - \frac{3}{2}\frac{1}{(1-x)^2} - \frac{3}{2}\frac{x^2 \ln x}{(1-x)^3}\right]$$

$$\langle \bar{B}_q^0 | (\bar{b}\gamma_\mu(1-\gamma_5)q)^2 | B_q^0 \rangle \equiv \frac{8}{3} f_{B_q}^2 B_{B_q} M_{B_q}^2$$

$-ln(L)$ vs. R from t-quark decays

[D. Acosta et al. (CDF Collaboration); hep-ex/0505091]



$|V_{td}|$ and $|V_{ts}|$ with Lattice-QCD

$|V_{td}|$

- Unquenched Lattice-QCD [Gray et al. (HPQCD); Aoki et al. (JLQCD)]:
  $\sqrt{\hat{B}_{B_d}} f_{B_d} = 244 \pm 26$ MeV; $\bar{m}_t(m_t) = 162.3(2.2)$ GeV; $S_0(x_t) = 2.29(5)$

$$|V_{td}^* V_{tb}| = 7.4 \times 10^{-3} \left[\frac{244 \text{ MeV}}{\sqrt{\hat{B}_{B_d}} f_{B_d}}\right] \sqrt{\frac{2.29}{S_0(x_t)}}$$

  - Lattice-QCD & SM $\Longrightarrow$ $|V_{td}^* V_{tb}| = (7.4 \pm 0.8) \times 10^{-3}$ [PDG 2006]

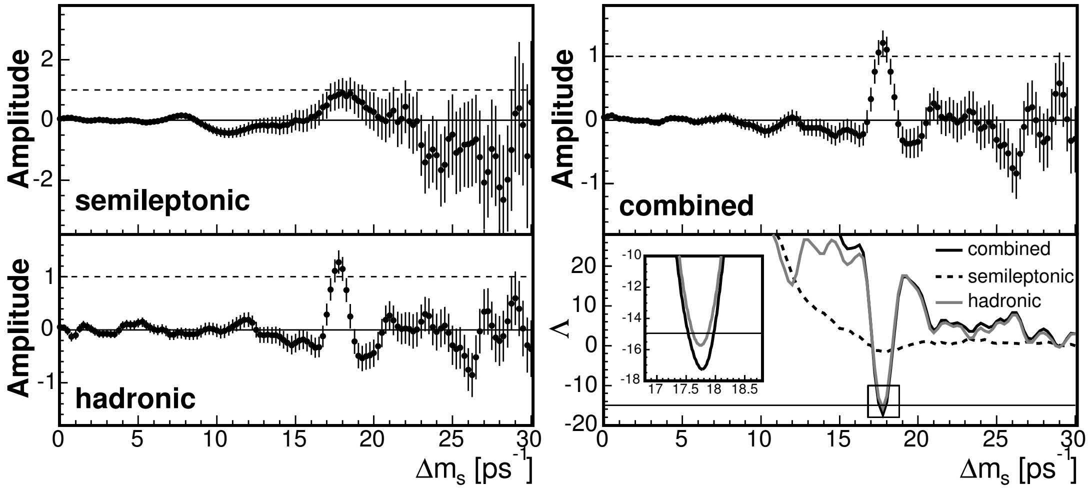
$|V_{ts}|$

- B_s^0 - $\overline{B_s^0}$ Mixing: $\Delta M_s = (17.77 \pm 0.10 \text{ (stat)} \pm 0.07 \text{ (syst)})$ ps^{-1} [CDF 2006]
- SM: $\Delta M_s = \frac{G_F^2}{6\pi^2} \hat{\eta}_B |V_{ts}^* V_{tb}|^2 M_{B_s} (f_{B_s}^2 \hat{B}_{B_s}) M_W^2 S_0(x_t)$
- Lattice-QCD: $\sqrt{\hat{B}_{B_s}} f_{B_s} = 281 \pm 21$ MeV [HPQCD 2006] &
  $|V_{ts}^* V_{tb}| = 4.1(1) \times 10^{-2} \Longrightarrow \Delta M_s = (20.3 \pm 3.0 \pm 0.8)(\text{ps})^{-1}$
- Using the ratio $\Delta M_s / \Delta M_d$ and Lattice-QCD (Okamoto et al.) : $\xi = 1.21^{+0.047}_{-0.035}$

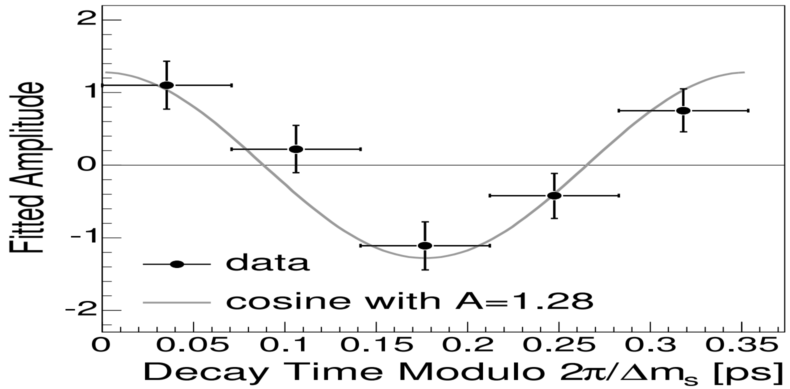
$$\frac{\Delta M_s}{\Delta M_d} = \xi \frac{M_{B_s}}{M_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2}; \quad \xi = \sqrt{\frac{f_{B_s}^2 \hat{B}_{B_s}}{f_{B_d}^2 \hat{B}_{B_d}}}$$

$$\Longrightarrow |V_{td}/V_{ts}| = 0.2060 \pm 0.0007(\text{exp}) \,^{+0.008}_{-0.006}(\text{th})$$

CDF Measurement of ΔM_s [hep-ex/0609040]



- Using the Amplitude Analysis Method by Moser and Roussarie
- Λ is the Logarithm of the ratio of likelihoods $\Lambda = \log[\mathcal{L}^{A=0}/\mathcal{L}^{A=1}(\Delta m_s)]$



ΔM_s (expt) vs. SM Estimates

- **Indirect UT-based fits**

  $\Delta M_s = (20.9 \pm 2.6)\ (\mathrm{ps})^{-1}$ [UTfit 2006]

  $\Delta M_s = (21.7^{+5.9}_{-4.2})\ (\mathrm{ps})^{-1}$ [CKMfitter 2006]

- **Lattice QCD Calculation [HPQCD; hep-lat/0610104]**

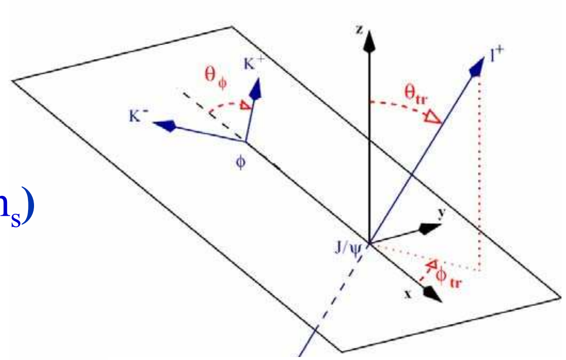
  $f_{B_s}\sqrt{\hat{B}_{B_s}} = 0.281(21)$ **GeV &** $|V_{ts}^* V_{tb}| = 4.1(1) \times 10^{-2}$
  $\Longrightarrow\ \Delta M_s = (20.3 \pm 3.0 \pm 0.8)\ (\mathrm{ps})^{-1}$

- **CDF Measurement:**
  $\Delta M_s = (17.77 \pm 0.10 \pm 0.07)\ (\mathrm{ps})^{-1}$ **[CDF 2006]**

- $\frac{\Delta M_s^{\mathrm{expt}}}{\Delta M_s^{\mathrm{SM}}} =$
  0.85 ± 0.10 [UTfit]; 0.82 ± 0.20 [CKMfitter]; 0.88 ± 0.13 [HPQCD]
- SM estimates for ΔM_s larger compared to CDF by circa 1σ
- Error dominated by theory

ϕ_s and $\Delta\Gamma_s$ from $B_s \to J/\psi\phi$ (η,η'...)

- SU(3) analogue of $B \to J/\psi K_s$, measuring the B_s- $\bar{B}_s$ mixing phase
- in SM $\phi_s = -\arg(V_{ts}^2) = -2\lambda\eta^2 \sim -0.04$ → increased sensitivity to New Physics
- large CP asymmetry would signal Physics Beyond SM
- also needed for extracting γ from $B_s \to D_s K$ or from $B \to \pi\pi$ and $B_s \to K K$

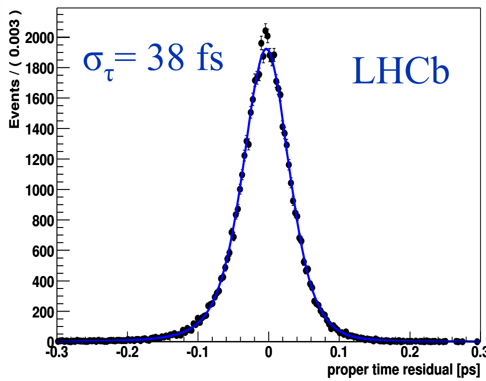


J/ψφ is not a pure CP eigenstate:

- ✓ 2 CP even, 1 CP odd amplitudes contributing
- ✓ need to fit angular distributions of decay final states as function of proper time (needs external Δm_s)
- ✓ requires very good proper time resolution

Expected sensitivity: (at $\Delta m_s = 20\ \mathrm{ps}^{-1}$)

- ✓ LHCb: 125k $Bs \to J/\psi\phi$ signal events/year
  - → $\sigma_{stat}(\sin\phi_s) \sim 0.031$, $\sigma_{stat}(\Delta\Gamma_s/\Gamma_s) \sim 0.011$ /(1year, $2\mathrm{fb}^{-1}$)
  - → $\sigma_{stat}(\sin\phi_s) \sim 0.013$ after first 5 years, adding pure CP modes like $J/\psi\eta$, $J/\psi\eta'$ (small improvement)
- ✓ ATLAS: similar event rate as LHCb but less sensitive
  - → $\sigma_{stat}(\sin\phi_s) \sim 0.08$ (1year, $10\mathrm{fb}^{-1}$)
- ✓ CMS: > 50k events/year, sensitivity study ongoing



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Interplay of Mixing & Decays of B^0 and $\overline{B^0}$ to CP Eigenstate

- Involving tree-dominated B-decays ($b \to c\bar{c}s$), such as $B^0/\overline{B^0} \to J/\psi K_s;\ J/\psi K_L$

$$\mathcal{A}_f(t) = \frac{\Gamma(\overline{B^0}(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\overline{B^0}(t) \to f) + \Gamma(B^0(t) \to f)}$$

$$= C_f \cos(\Delta M_B t) + S_f \sin(\Delta M_B t)$$

$$C_f = \frac{(|\lambda_f|^2) - 1}{(|\lambda_f|^2 + 1)}; \qquad S_f = \frac{2\ \mathrm{Im}\lambda_f}{(|\lambda_f|^2 + 1)}$$

- Definitions:

$$\lambda_f \equiv (q/p)\ \rho(f); \qquad \rho(f) = \frac{\bar{A}(f)}{A(f)}$$

$$A(f) = \langle f|H|B^0\rangle; \quad \bar{A}(f) = \langle f|H|\overline{B^0}\rangle$$

$$q/p = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} = \mathrm{e}^{-2i\phi_{\mathrm{mixing}}} = \mathrm{e}^{-2i\beta}$$

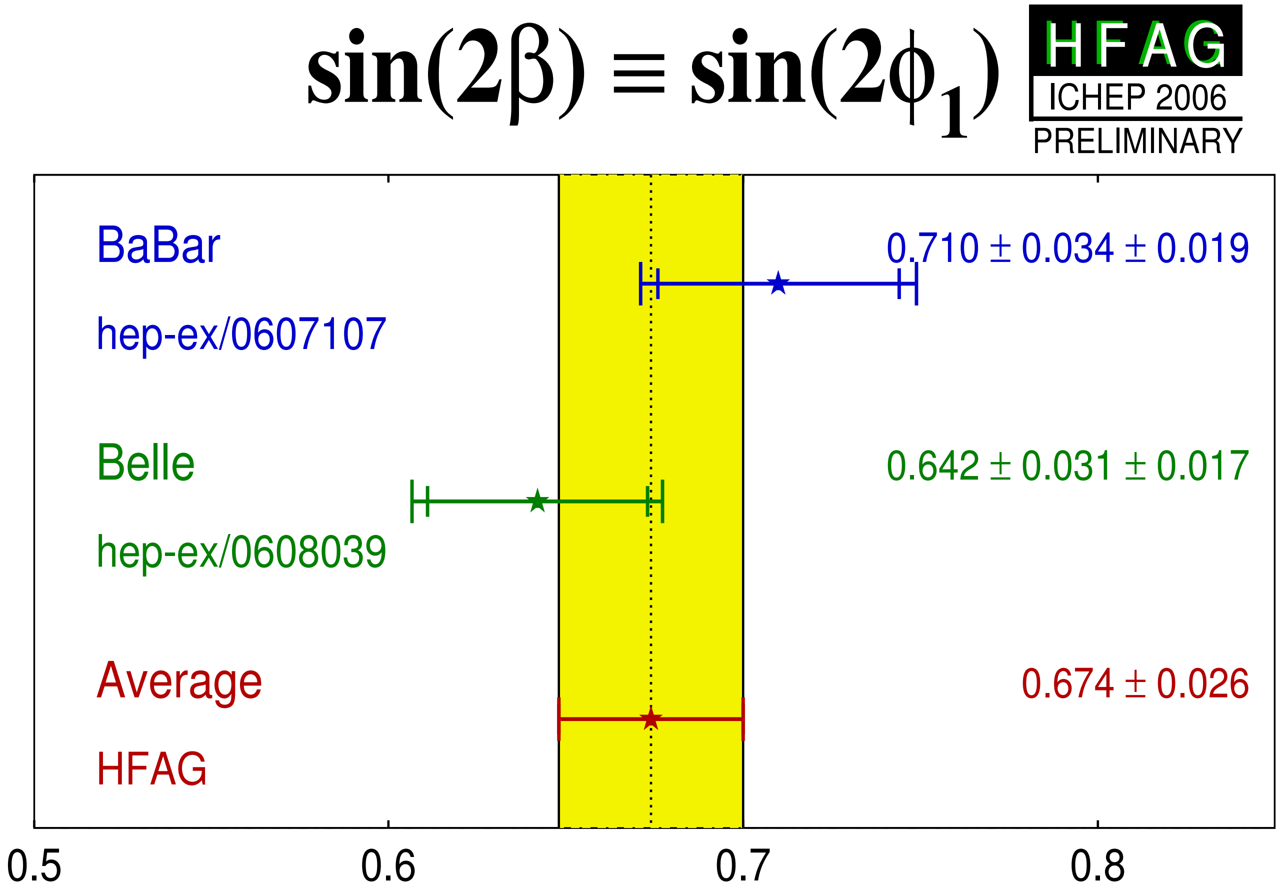
- If only a Single Amplitude dominant, then one can write:

$$\rho(f) = \eta_f \mathrm{e}^{-2i\phi_{\mathrm{decay}}}$$

where $\eta_f = \pm 1$ is the intrinsic CP-Parity of the state $f \Rightarrow |\rho(f)| = 1$

$$\mathcal{A}_f(t) = S_f \sin(\Delta M_B t);\ S_f = -\eta_f \sin 2(\phi_{\mathrm{mixing}} + \phi_{\mathrm{decay}});\ C_f = 0$$

Current World Average [ICHEP 2006]



sin(2β) from $B^0 \to J/\psi\, K_S$

- "gold-plated" decay channel at B-factories for measuring the B_d- $\bar{B}_d$ mixing phase
- needed for extracting γ from $B \to \pi\pi$ and $B_s \to K\,K$, or from $B \to D^*\pi$
- in SM A_{CP}^{dir}~0, non-vanishing value $\mathcal{O}(0.01)$ could be a signal of Physics Beyond SM

$$A_{CP}^{th}(t) = A_{CP}^{dir} \cdot \cos(\Delta m_d \cdot t) + A_{CP}^{mix} \cdot \sin(\Delta m_d \cdot t)$$

One of the first CP measurements at LHC:

✓ demonstrate CP analysis performance

✓ study tagging systematics

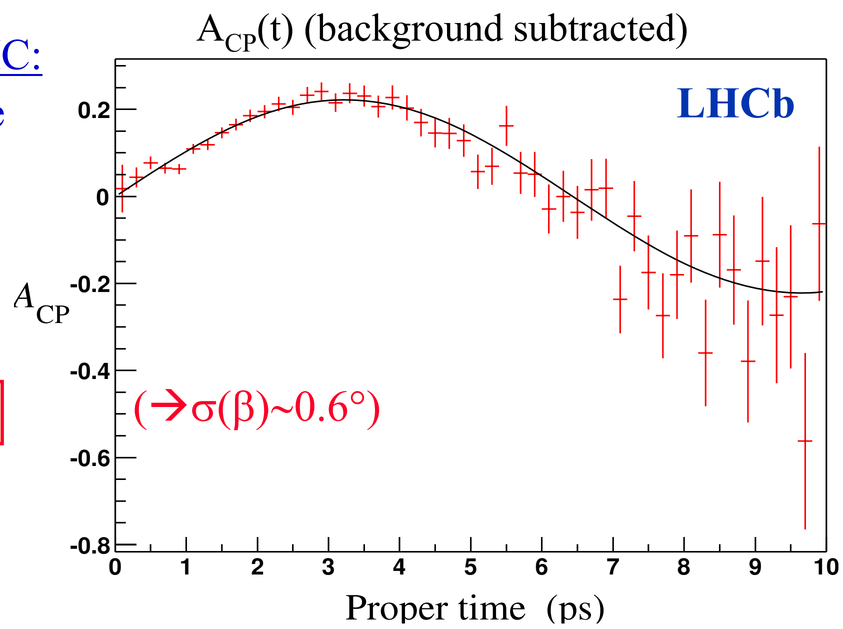
Expected sensitivity:

✓ LHCb: 240k signal events/year

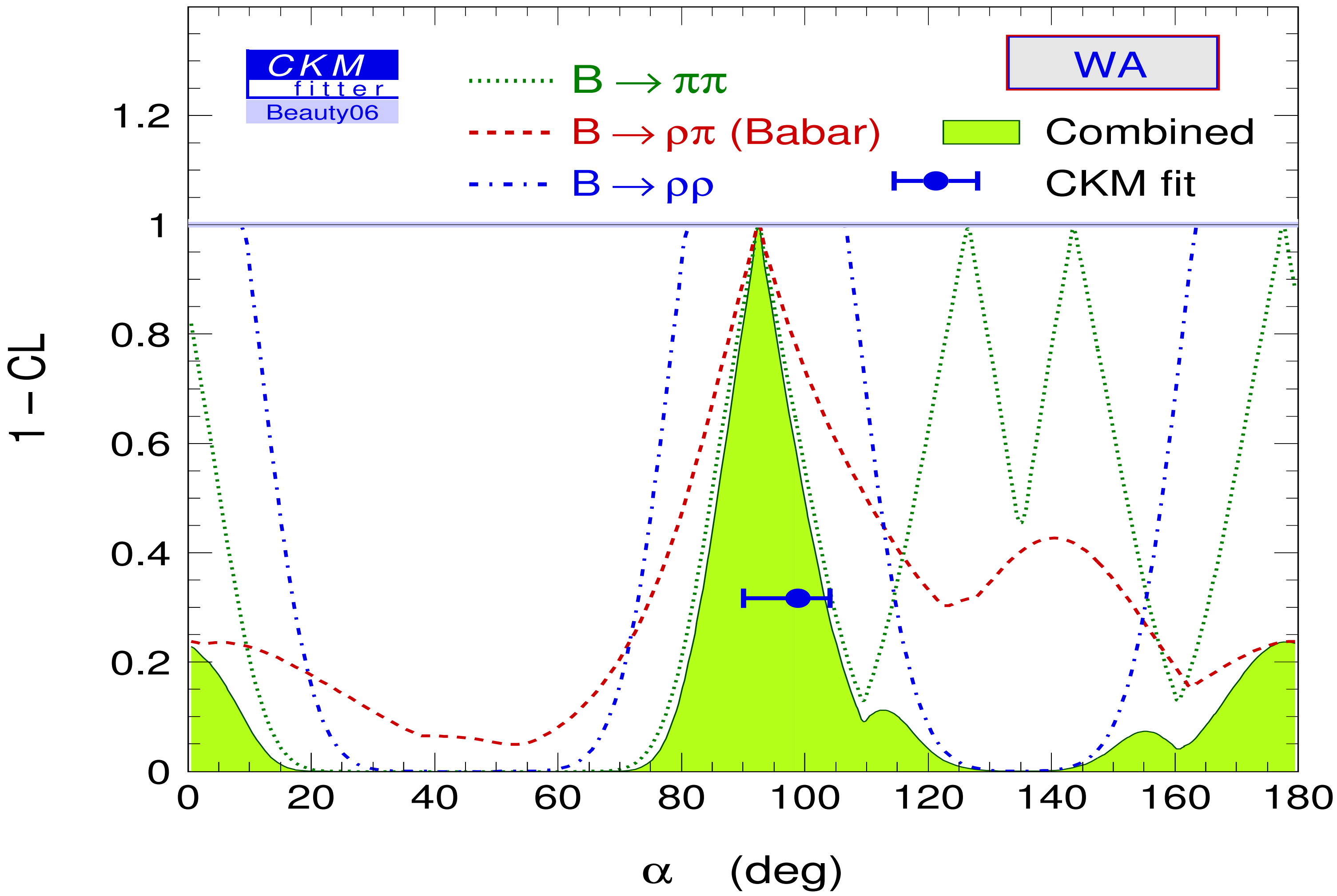
→ $\sigma_{stat}(\sin(2\beta)) \sim 0.02$ (1year, 2fb^{-1})

✓ ATLAS: similar sensitivity for (first 3years, 30fb^{-1})

Search for direct CP violating term…

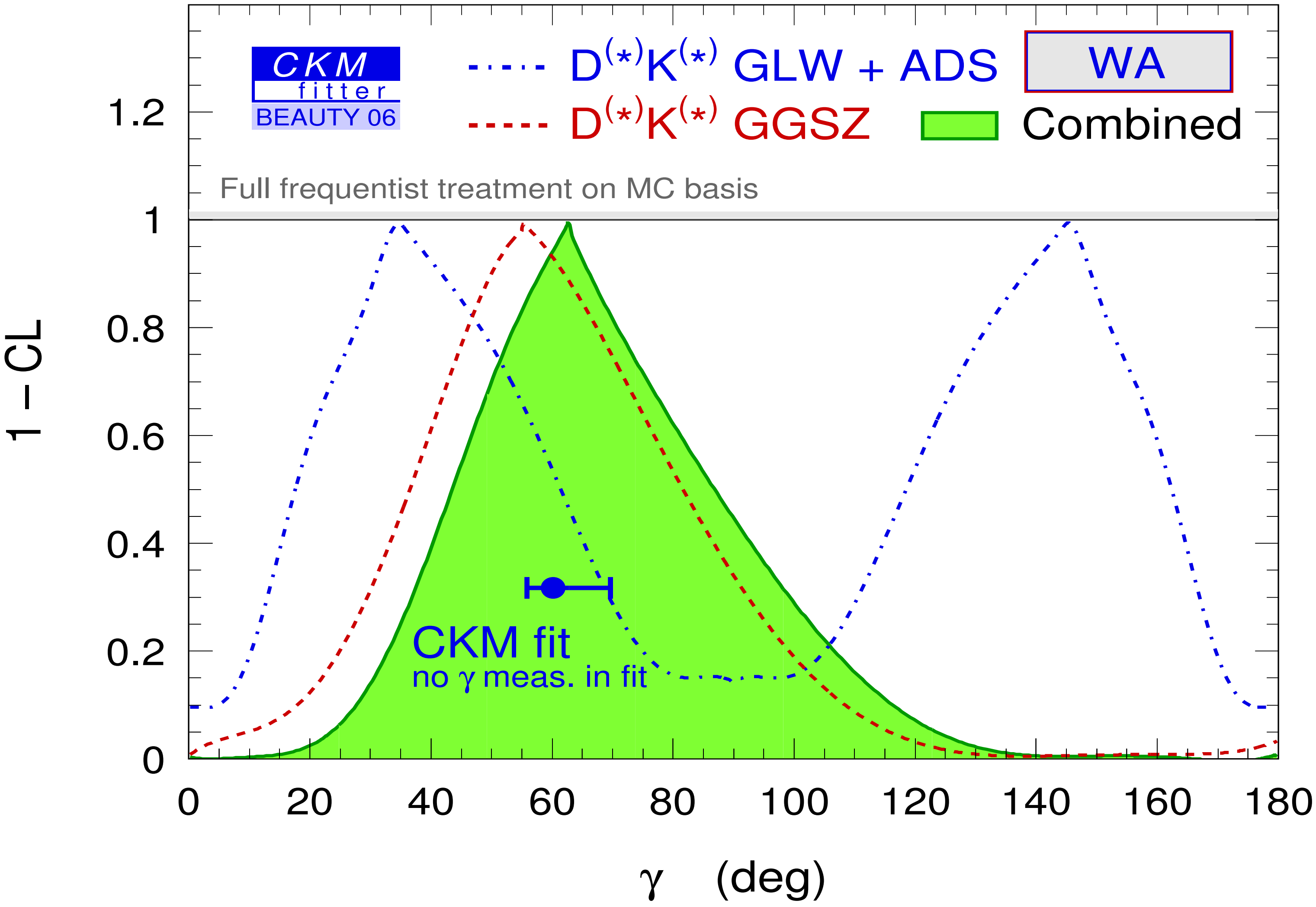


Current World Average of α [CKMfitter 2006]



ICHEP 2006 Update: $\boldsymbol{\alpha} = [\mathbf{92.6}^{+10.7}_{-9.3}]^{\circ}$ [Direct Measurements]

Current World Average of γ [CKMfitter 2006]



ICHEP 2006 Update: $\gamma = [60^{+38}_{-24}]^\circ$ [Direct Measurements]

Projected Precision on γ at LHC

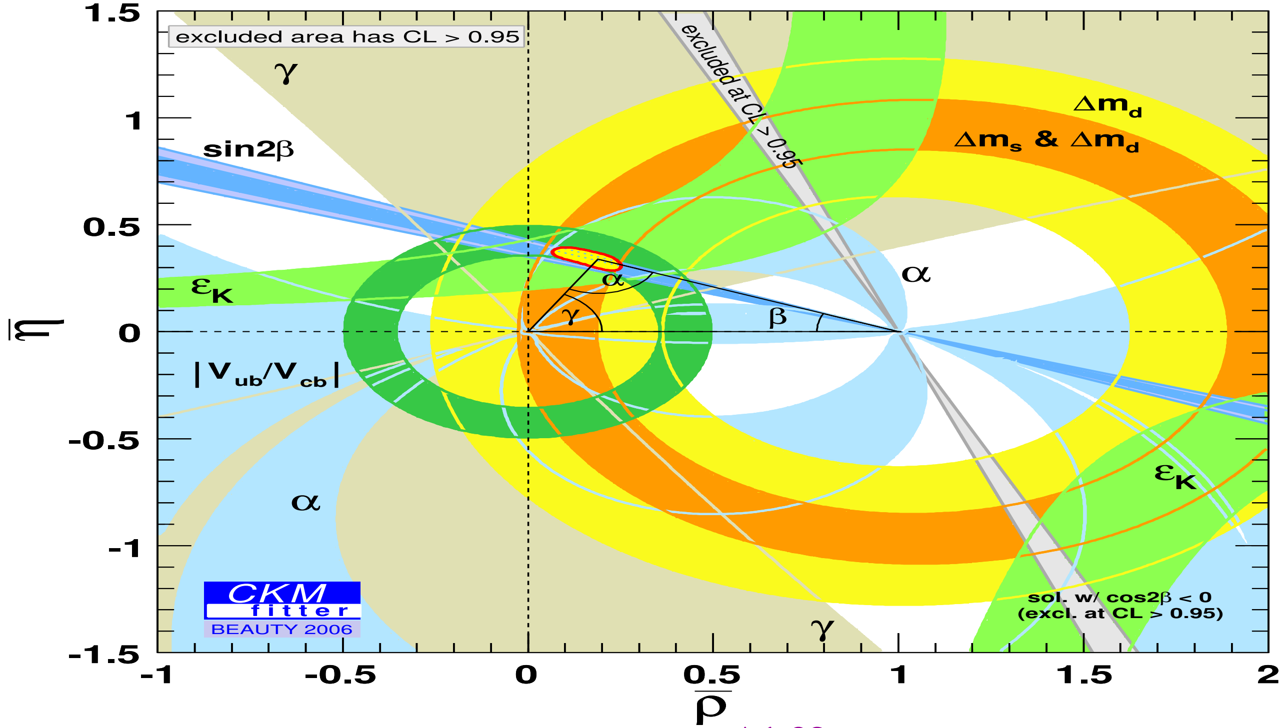
- γ from $B_s \to D_s K$ $\Longrightarrow$ $\sigma(\gamma) \sim 14^\circ$ in 1 year at 2 fb^{-1}
  - 2 time-dependent asymmetries from 4 decays: $B_s(\bar{B}_s) \to D_s^- K^+, D_s^+ K^-$
  - 2 tree decays ($b \to c$ and $b \to u$) of same magnitude ($\sim \lambda^3$) interfere via B_s mixing

- γ from $B^0 \to D^0 K^{*0}$ $\Longrightarrow$ $\sigma(\gamma) \sim 8^\circ$ in 1 year at 2 fb^{-1}
  - Dunietz variant of Gronau-Wyler method [Phys. Lett. B270, 75 (1991)]
  - Two color-suppressed diagrams interfering via D^0-meson mixing
  - 6 decay rates, self-tagged and time-integrated

- γ from $B^\pm \to D^0 K^\pm$ $\Longrightarrow$ $\sigma(\gamma) \sim 5^\circ$ in 1 year at 2 fb^{-1}
  - based on Atwood-Dunietz-Soni method [Phys. Rev. Lett. 78, 3257 (1997)]
  - measure relative rates of $B^- \to D^0(K\pi)K^-$ and $B^+ \to D^0(K\pi)K^+$

- γ from $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$ $\Longrightarrow$ $\sigma(\gamma) \sim 5^\circ$ in 1 year at 2 fb^{-1}
  - large penguin contributions in both decays $\longrightarrow$ sensitive to New Physics
  - measure time-dependent CP asymmetry for $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$
  - C and S depend on γ, mixing phases, and penguin-to-tree amplitude ratio $d\,\mathrm{e}^{i\theta}$
  - exploit "U-spin" symmetry ($d \leftrightarrow s$) [R. Fleischer, Phys. Lett. B459, 306 (1999)]

SM confronts current measurements in the quark flavour sector



- $\sin 2\beta = 0.675 \pm 0.026 (\beta = [21.23^{+1.03}_{-0.99}]^\circ)$ [Direct Measurement]
  $\beta = [22.03^{+0.72}_{-0.62}]^\circ)$ [Fit-value]
- $\alpha = [92.6^{+10.7}_{-9.3}]^\circ$ [Direct Measurement]
  $\alpha = [99.0^{+4.0}_{-9.4}]^\circ$ [Fit-value]
- $\gamma = [60^{+38}_{-24}]^\circ$[Direct Measurement]
  $\gamma = [59.0^{+9.2}_{-3.7}]^\circ$ [Fit-value]
- Direct and indirect measurements of angles agree well

Inclusive Rare B decays

Two inclusive rare B-decays of experimental interest

$$\bar{B} \to X_s\gamma \quad \text{and} \quad \bar{B} \to X_s l^+ l^-$$

$X_s =$ any hadronic state with $S = -1$, containing no charmed particles

Theoretical Interest:

- Both measured; accurate measurements anticipated at B-factories and LHC
- Non-perturbative effects under control
- Sensitivity to new physics

Status of the NNLO perturbative calculations:

- $\bar{B} \to X_s l^+ l^-$: completed several years ago
  [Bobeth et al.; Gambino et al.; Asatrian et al.; Ghinculov et al.; Huber et al.]
- $\bar{B} \to X_s\gamma$: Just completed
  - The first estimate of $\mathcal{B}(\bar{B} \to X_s\gamma)$, Misiak et al. (17 authors), hep-ph/0609232
  - Analysis of $\mathcal{B}(\bar{B} \to X_s\gamma)$ at NNLO with a cut on Photon energy,
    T. Becher and M. Neubert, hep-ph/0610067

The effective Lagrangian:

$$\mathcal{L} = \mathcal{L}_{QCD\times QED}(q,l) + \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) O_i$$

$(q = u, d, s, c, b, \; l = e, \mu)$

$$O_i = \begin{cases} (\bar{s}\Gamma_i c)(\bar{c}\Gamma_i' b), & i = 1,2, & |C_i(m_b)| \sim 1 \\ (\bar{s}\Gamma_i b)\mathbf{\Sigma}_q(\bar{q}\Gamma_i' q), & i = 3,4,5,6, & |C_i(m_b)| < 0.07 \\ \frac{em_b}{16\pi^2}\bar{s}_L\sigma^{\mu\nu}b_R F_{\mu\nu}, & i = 7, & C_7(m_b) \sim -0.3 \\ \frac{gm_b}{16\pi^2}\bar{s}_L\sigma^{\mu\nu}T^a b_R G^a_{\mu\nu}, & i = 8, & C_8(m_b) \sim -0.15 \\ \frac{e^2}{16\pi^2}(\bar{s}_L\gamma_\mu b_L)(\bar{l}\gamma^\mu\gamma_5 l), & i = 9, \mathbf{10} & |C_i(m_b)| \sim 4 \end{cases}$$

Three steps of the calculation:

Matching: Evaluating $C_i(\mu_0)$ at $\mu_0 \sim M_W$ by requiring equality of the SM and the effective theory Green functions

Mixing: Deriving the effective theory RGE and evolving $C_i(\mu)$ from μ_0 to $\mu_b \sim m_b$

Matrix elements: Evaluating the on-shell amplitudes at $\mu_b \sim m_b$

Structure of the SM calculations for $\bar{B} \to X_s \gamma$

$$\mathcal{H}_{\text{eff}} \sim \sum_{i=1}^{10} C_i(\mu) O_i$$

• $\mathcal{H}_{\text{eff}}$ independent of the scale μ, while $C_i(\mu)$ and $O_i(\mu)$ depend on μ
$\Longrightarrow$ Renormalization Group Equation (RGE) for $C_i(\mu)$:

$$\mu \frac{d}{d\mu} C_i(\mu) = \gamma_{ij}^{\mathrm{T}} C_j(\mu)$$

• γ_{ij}: anomalous dimension matrix

• Matching usually done at high scale $(\mu_0 \sim M_W, m_t)$

• Full theory and the matrix elements of the effective operators have the same large logarithms

$\mu_0 \sim O(M_W)$
$\downarrow$ RGE
$\mu_b \sim O(m_b)$: matrix elements of the operators at this scale don't have large logs; they are contained in the $C_i(\mu_b)$

• Evaluation of the on-shell amplitudes at $\mu_b \sim m_b$

Experimental data

Experimental Data on $B \to V\gamma$ Decays

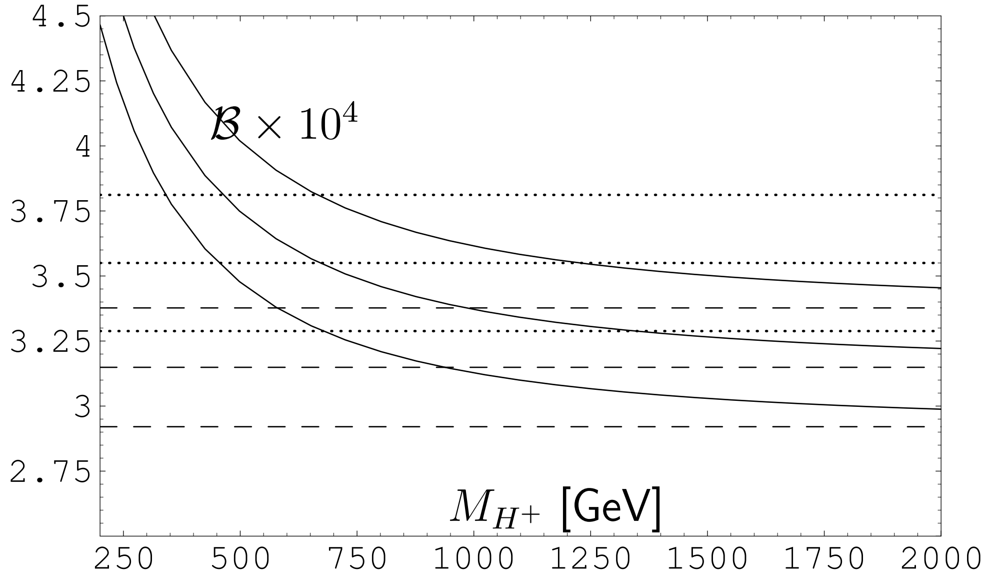
Branching ratios (in units of 10^{-6}) [August 2006]

Mode	BABAR	BELLE	CLEO	Average [HFAG]
$B \to X_s\gamma$	$327 \pm 18^{+55}_{-41}$	$355 \pm 32^{+30+11}_{-31-7}$	$321 \pm 43^{+32}_{-29}$	$355 \pm 24^{+9}_{-10} \pm 3$ ‡
$B^+ \to K^*(892)^+\gamma$	$38.7 \pm 2.8 \pm 2.6$	$42.5 \pm 3.1 \pm 2.4$	$37.6^{+8.9}_{-8.3} \pm 2.8$	40.3 ± 2.6
$B^0 \to K^*(892)^0\gamma$	$39.2 \pm 2.0 \pm 2.4$	$40.1 \pm 2.1 \pm 1.7$	$45.5^{+7.2}_{-6.8} \pm 3.4$	40.1 ± 2.0
$B^+ \to K_1(1270)^+\gamma$		$43 \pm 9 \pm 9$		43 ± 12
$B^+ \to K_2^*(1430)^+\gamma$	$14.5 \pm 4.0 \pm 1.5$			14.5 ± 4.3
$B^0 \to K_2^*(1430)^0\gamma$	$12.2 \pm 2.5 \pm 1.0$	$13.0 \pm 5.0 \pm 1.0$		12.4 ± 2.4
$B^+ \to \rho^+\gamma$	$1.06^{+0.35}_{-0.31} \pm 0.09$	$0.55^{+0.42+0.09}_{-0.36-0.08}$	< 13.0	$0.87^{+0.27}_{-0.25}$
$B^0 \to \rho^0\gamma$	$0.77^{+0.21}_{-0.19} \pm 0.07$	$1.25^{+0.37+0.07}_{-0.33-0.06}$	< 17.0	$0.91^{+0.19}_{-0.18}$
$B^0 \to \omega\gamma$	$0.39^{+0.24}_{-0.20} \pm 0.03$	$0.56^{+0.34+0.05}_{-0.27-0.10}$	< 9.2	$0.45^{+0.20}_{-0.17}$
$B \to (\rho,\omega)\gamma$	$1.01 \pm 0.21 \pm 0.08$	$1.32^{+0.34+0.10}_{-0.31-0.09}$	< 14.0	
$B^0 \to \phi\gamma$	< 0.85		< 3.3	< 0.85
$B^0 \to J/\psi\,\gamma$	< 1.6			< 1.6

‡ Calculated for the photon energy range $E_\gamma > 1.6$ GeV

$\mathcal{B}(\bar{B} \to X_s \gamma)$: Experiment vs. SM & 2HDM

[Misiak et al., hep-ph/0609232]

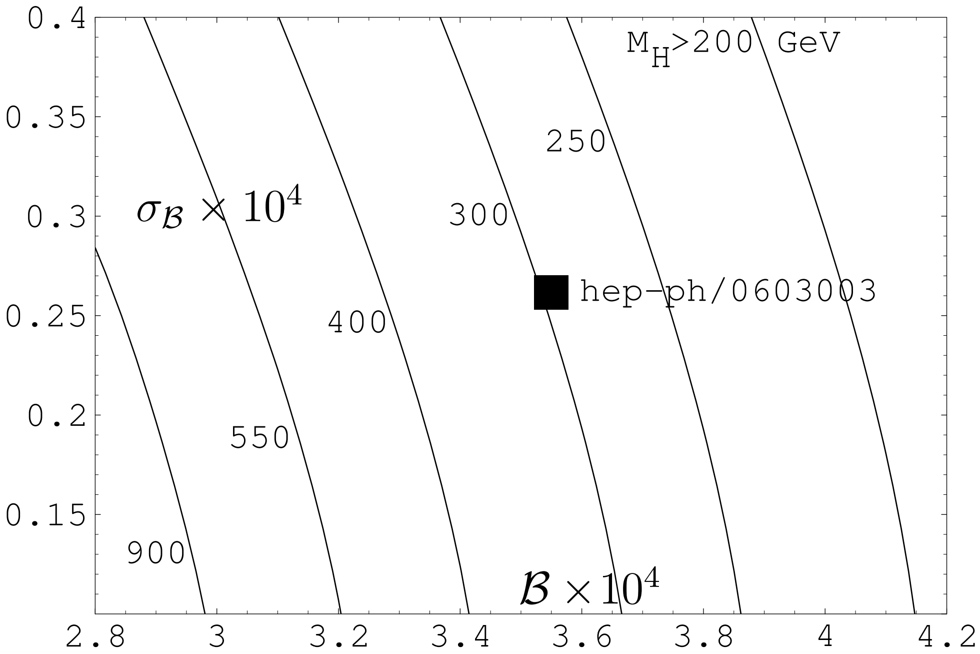


[$\cdots$ (exp); — — —— (SM); solid (2HDM)]

- Experiment ($E_\gamma > 1.6$ GeV); [HFAG: hep-ex/0603003]
  $\mathcal{B}(\bar{B} \to X_s \gamma) = (3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}$
- NNLO SM: $\mathcal{B}(\bar{B} \to X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4}$
- SM is below the experiments by about 1 σ
- In 2HDM, preferred value is $M_{H^+} \simeq 650$ GeV
- 95% C.L. lower bound is around 295 GeV

95% C.L. Lower Bound on M_{H^+} in 2HDM from $\mathcal{B}(\bar{B} \to X_s \gamma)$

[Misiak et al., hep-ph/0609232]



Fraction $F(E_0)$ of BR $(B \to X_s\gamma)$ above the cut $E_\gamma > E_0$

- Theory and experiment compared for $E_\gamma > E_0$; need to evaluate the fraction $F(E_0)$ of the events surviving this cut to get full BR
- $F(E_0)$ usually calculated using (model-dependent) shape functions [Kagan, Neubert; Benson, Bigi, Uraltsev,...]
- Recently, it has been pointed out [Neubert, hep-ph/0408179] that $R(E_0)$ can be calculated without reference to shape functions using a multi-scale OPE
- Theoretical framework for this calculation is the so-called Soft Collinear Effective Theory (SCET) involving several scales: m_b, $m_b\Delta$, and Δ, with $\Delta = m_b - 2E_0$
- Large logarithms associated with these scales are summed at NLL order; sensitivity to the scale $\Delta \simeq 1.4$ GeV (for $E_0 = 1.6$ GeV) introduces additional uncertainties [Becher & Neubert hep-ph/0610067]:

$$T \equiv F(1.6 \text{ GeV})/F(1.0 \text{ GeV}) = (93^{+3}_{-5}(\text{pert}) \pm 2(\text{hadr}) \pm 2(\text{param}))\%$$

$$\Longrightarrow \mathcal{B}(B \to X_s\gamma) = (2.98 \pm 0.26) \times 10^{-4}$$

- $\mathcal{B}(B \to X_s\gamma)$ in the multi-scale SM is about 1.4σ below Experiment

$$\frac{\mathcal{B}(B \to X_s\gamma)(\text{exp})}{\mathcal{B}(B \to X_s\gamma)(\text{SM})} = 1.19 \pm 0.09(\text{exp}) \pm 0.10(\text{th})$$

$B \to \rho\gamma$ Branching Fraction

[AA, Parkhomenko; Bosch, Buchalla; Ball, Zwicky; for an update see hep-ph/0610149]

- In the leading order penguin and annihilation amplitudes, the ratio of the branching ratios for the charged and neutral B-meson decays can be written as

$$\frac{\mathcal{B}(B^- \to \rho^- \gamma)}{2\mathcal{B}(B^0 \to \rho^0 \gamma)} \simeq \left| 1 + \epsilon_A e^{i\phi_A} \frac{V_{ub} V_{ud}^*}{V_{tb} V_{td}^*} \right|^2$$

- $\epsilon_A e^{i\phi_A}$ includes dominant W-annihilation and possible sub-dominant long-distance contributions
- Isospin-violating corrections depend on the unitarity triangle angle α

$$\frac{V_{ub} V_{ud}^*}{V_{tb} V_{td}^*} = - \left| \frac{V_{ub} V_{ud}^*}{V_{tb} V_{td}^*} \right| e^{i\alpha} = F_1 + i F_2$$

$B \to \rho\gamma$ Branching Fraction in NLO

- Including the annihilation contribution, the charged-conjugate averaged branching ratio in the NLO is

$$\begin{aligned}\bar{\mathcal{B}}_{\rm th}(B^\pm \to \rho^\pm\gamma) &= \tau_{B^+}\, \frac{G_F^2 \alpha |V_{tb}V_{td}^*|^2}{32\pi^4}\, m_{b,\rm pole}^2\, M^3 \left[\xi_\perp^{(\rho)}(0)\right]^2 \\ &\times \Big\{ (C_7^{(0)\rm eff} + A_R^{(1)t})^2 + (F_1^2 + F_2^2)\,(A_R^u + L_R^u)^2 \\ &+ 2F_1\, [C_7^{(0)\rm eff}(A_R^u + L_R^u) + A_R^{(1)t} L_R^u] \Big\}\end{aligned}$$

- The amplitude $A^{(1)t}(\mu)$ can be decomposed in three contributing parts

$$A^{(1)t}(\mu) = A_{C_7}^{(1)}(\mu) + A_{\rm ver}^{(1)}(\mu) + A_{\rm sp}^{(1)\rho}(\mu_{\rm sp})$$

- In addition to $A^{(1)t}(\mu)$, the u-quark contribution $A^u(\mu)$ from penguin diagrams can no longer be ignored
- $A^u(\mu)$ also contains vertex and hard-spectator contributions

$B \to (\rho, \omega)\gamma$ Branching Fractions

- Taking into account the ratio of the CKM matrix elements

$$|V_{td}/V_{ts}| = 0.201 \pm 0.008 \qquad [\Delta M_s;\ \text{CDF Collab. (2006)}]$$

the branching ratios can be estimated as

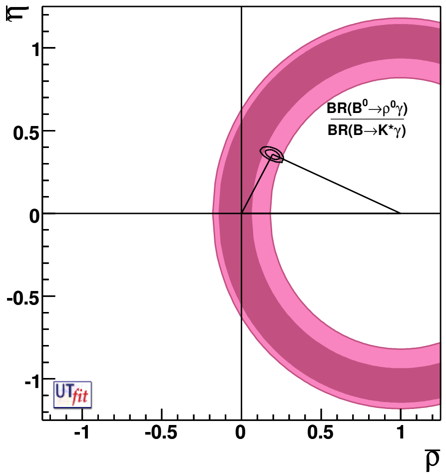
$$\bar{\mathcal{B}}_{\rm th}(B^\pm \to \rho^\pm\gamma) = (1.37 \pm 0.26[\rm th] \pm 0.09[\rm exp]) \times 10^{-6}$$
$$\bar{\mathcal{B}}_{\rm th}(B^0 \to \rho^0\gamma) = (0.65 \pm 0.12[\rm th] \pm 0.03[\rm exp]) \times 10^{-6}$$
$$\bar{\mathcal{B}}_{\rm th}(B^0 \to \omega\gamma) = (0.53 \pm 0.12[\rm th] \pm 0.02[\rm exp]) \times 10^{-6}$$

- In the above estimates, the first error is defined by uncertainties of the theory and the second one is from the direct experimental data on the $B \to K^*\gamma$ branching fractions

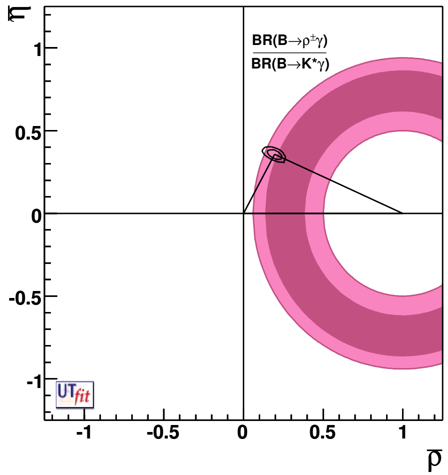
Branching ratios (in units of 10^{-6}) [August 2006]

Mode	BABAR	BELLE	CLEO	Average [HFAG]
$B^+ \to \rho^+\gamma$	$1.06^{+0.35}_{-0.31} \pm 0.09$	$0.55^{+0.42+0.09}_{-0.36-0.08}$	< 13.0	$0.87^{+0.27}_{-0.25}$
$B^0 \to \rho^0\gamma$	$0.77^{+0.21}_{-0.19} \pm 0.07$	$1.25^{+0.37+0.07}_{-0.33-0.06}$	< 17.0	$0.91^{+0.19}_{-0.18}$
$B^0 \to \omega\gamma$	$0.39^{+0.24}_{-0.20} \pm 0.03$	$0.56^{+0.34+0.05}_{-0.27-0.10}$	< 9.2	$0.45^{+0.20}_{-0.17}$

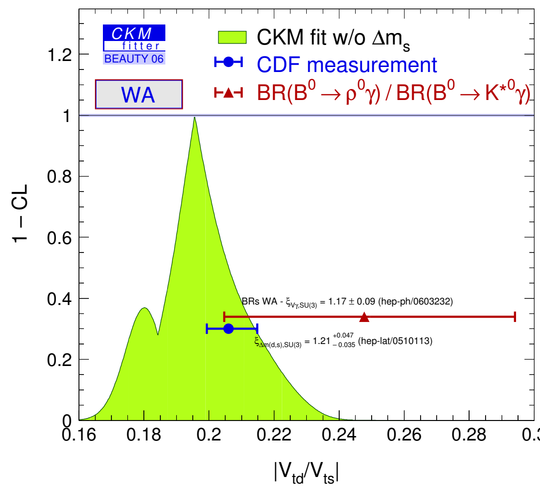
Impact on CKM Unitarity Triangle



Neutral modes



Charged modes



$\bar{B} \to X_s l^+ l^-$

- The NNLO calculation of $\bar{B} \to X_s l^+ l^-$ corresponds to the NLO calculation of $\bar{B} \to X_s \gamma$, as far as the number of loops in the diagrams is concerned.

- Coefficients of the two additional operators

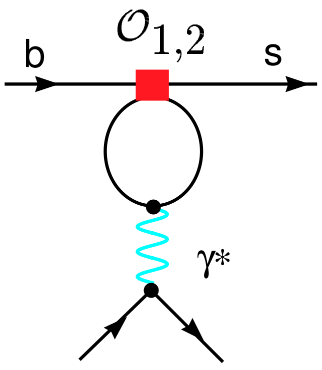
$$O_i = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L)(\bar{l} \gamma^\mu \gamma_5 l), \qquad i = 9, 10$$

have the following perturbative expansion:

$$\begin{aligned} C_9(\mu) &= \frac{4\pi}{\alpha_s(\mu)} C_9^{(-1)}(\mu) + C_9^{(0)}(\mu) + \frac{\alpha_s(\mu)}{4\pi} C_9^{(1)}(\mu) + \ldots \\ C_{10} &= C_{10}^{(0)} + \frac{\alpha_s(M_W)}{4\pi} C_{10}^{(1)} + \ldots \end{aligned}$$

- After an expansion in α_s, the term $C_9^{(-1)}(\mu)$ reproduces (the dominant part of) the electro-weak logarithm that originates from photonic penguins with charm quark loops:

$$\frac{4\pi}{\alpha_s(m_b)} C_9^{(-1)}(m_b) = \frac{4}{9} \ln \frac{M_W^2}{m_b^2} + \mathcal{O}(\alpha_s)$$



$C_9^{(-1)}(m_b) \simeq 0.033 \ll 1 \quad \Longrightarrow \quad \frac{4\pi}{\alpha_s(m_b)} C_9^{(-1)}(m_b) \simeq 2$

On the other hand: $\quad C_9^{(0)}(m_b) \simeq 2.2$

Electroweak Penguins $b \to s\ell^+\ell^-$

- $B \to X_s\ell^+\ell^-$ decay rate

$$\mathcal{B}(B \to X_s\ell^+\ell^-) = (4.46^{+0.98}_{-0.96}) \times 10^{-6} \quad [\mathrm{HFAG'05}]$$

$$SM: (4.2 \pm 0.7) \times 10^{-6} \quad [\mathrm{AGHL'01}]; \quad (4.6 \pm 0.8) \times 10^{-6} \quad [\mathrm{GHIY'04}]$$

- Differential distributions in $B \to X_s\ell^+\ell^-$

  • $M(X_s)$-distribution: tests $s \to X_s$ fragmentation model; current FMs provide reasonable fit to data

  • $q^2 = M^2_{\ell^+\ell^-}$-distribution away from the $J/\psi, \psi', \ldots$ resonances is sensitive to short-distance physics; current data in agreement with the SM estimates but the precision is not better than 25%

  • Forward-Backward Asymmetry (FBA) is likewise sensitive to the SM and BSM effects, in particular encoded in the Wilson coefficients C_7, C_9 and C_{10}

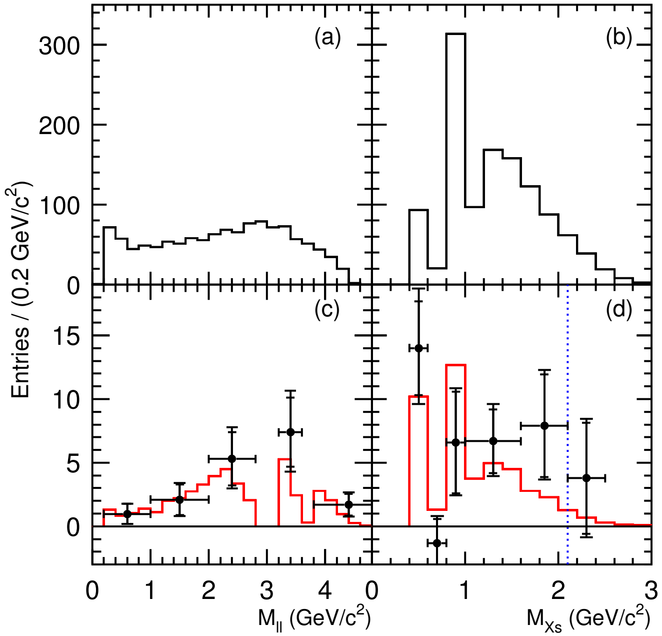
$$A_{\mathrm{FB}}(\hat{s} \sim C_{10}(2C_7 + C_9(\hat{s})\hat{s}); \quad \hat{s} = q^2/M_B^2$$

- $A_{\mathrm{FB}}(\hat{s})$ not yet measured; possible only in experiments at B factories

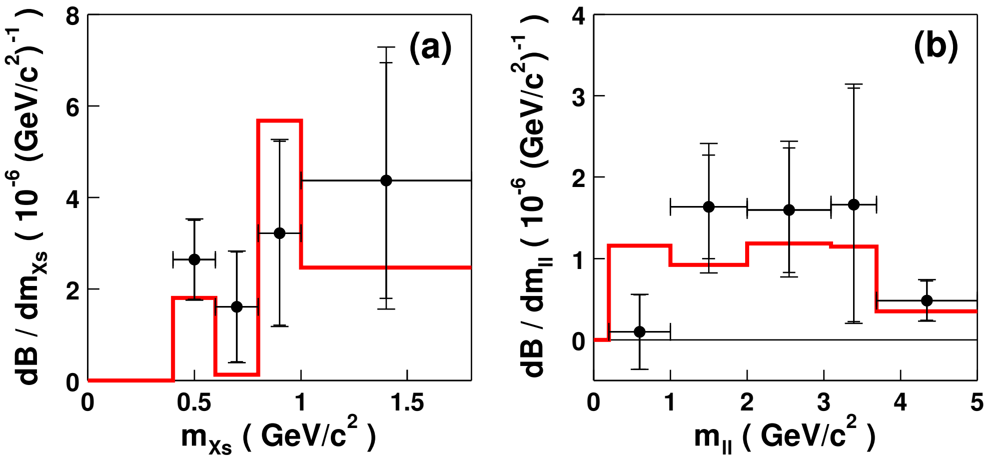
Decay distributions in $\bar{B} \to X_s \ell^+ \ell^-$

$M_{\ell\ell}$ and M_{X_s} Spectra

[BELLE]



[BABAR]



- In agreement with the NNLO SM calculations

$B \to K^* \ell^+ \ell^-$ decay in SCET

[AA, Gustav Kramer, Guohuai Zhu; hep-ph/0601034 (EPJC (2006))]

- Soft Collinear Effective Theory (SCET): Applicable to any QCD processes which contain collinear meson or jet, i.e. $P^2 \ll Q^2$, in the final states

- The idea is borrowed from HQET and NRQCD, but technically SCET is more involved than HQET because of the collinear degrees of freedom

- For $B \to K^* \ell^+ \ell^-$ decay, in the region 1 GeV$^2 \leq q^2 \leq 8$ GeV^2

$$P^\mu_{K^*} = (2.34, 0, 0, 2.16) \text{ GeV} \qquad [q^2 = 4 \text{ GeV}^2]$$

- Light-cone vectors $n^\mu = (1, 0, 0, 1)$, $\bar{n}^\mu = (1, 0, 0, -1)$,
satisfying $n^2 = \bar{n}^2 = 0$ and $n \cdot \bar{n} = 2$

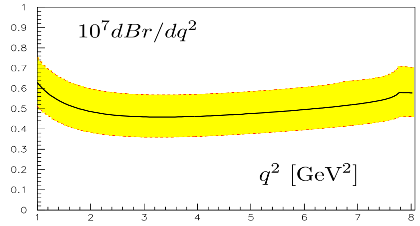
$$P^\mu = n \cdot P \frac{\bar{n}^\mu}{2} + \bar{n} \cdot P \frac{n^\mu}{2} + P^\mu_\perp = (P_+, P_-, P_\perp) \sim E(\lambda^2, 1, \lambda)$$

$[P_+ = 0.18$ GeV, $P_- = 4.5$ GeV, $\lambda \sim 0.2]$

- Power counting and expansion in λ, $\lambda \sim \frac{\Lambda_{QCD}}{E}$

Comparison with Data

Numerical results

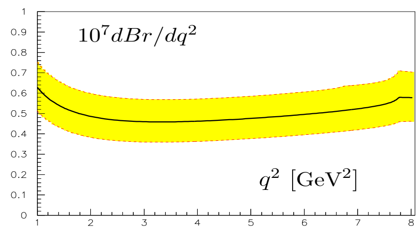


Theor. vs. Belle

$$Br|_{q^2 \in [4,8]\ \mathrm{GeV}^2} = (1.94^{+0.44}_{-0.40}) \times 10^{-7}$$
$$= (4.8^{+1.4}_{-1.2}|_{\mathrm{stat}} \pm 0.3|_{\mathrm{syst}} \pm 0.3|_{\mathrm{model}}) \times 10^{-7}$$

Comparison with experiments

Numerical results



Form factor determination

LCSRs $\zeta_{\|}(0) = 0.40 \pm 0.05$, $\zeta_{\perp}(0) = 0.40 \pm 0.04$, their q^2 dependencies

LCSRs + $B \to K^* \gamma$ $\zeta_{\perp}(0) = 0.32 \pm 0.02$

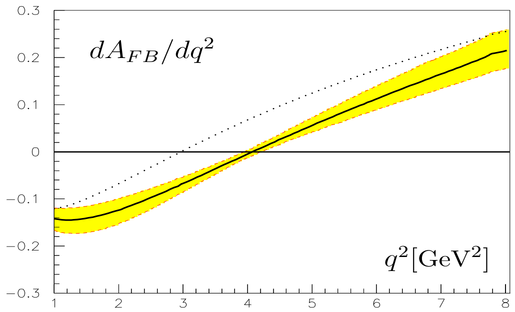
Theor. vs. BaBar

$$Br|_{q^2 \in [1,7]\ \mathrm{GeV}^2} = (2.92^{+0.57}_{-0.50}|_{\zeta_{\|}}\ {}^{+0.30}_{-0.28}|_{\mathrm{CKM}}\ {}^{+0.18}_{-0.20}) \times 10^{-7}$$

$$Br|_{q^2 \in [0.1,8.4]\ \mathrm{GeV}^2} = (2.7^{+1.2}_{-1.0}|_{\mathrm{stat}} \pm 0.5|_{\mathrm{syst}}) \times 10^{-7}$$

Reduction of Scale Uncertainty in SCET

Forward-backward asymmetry



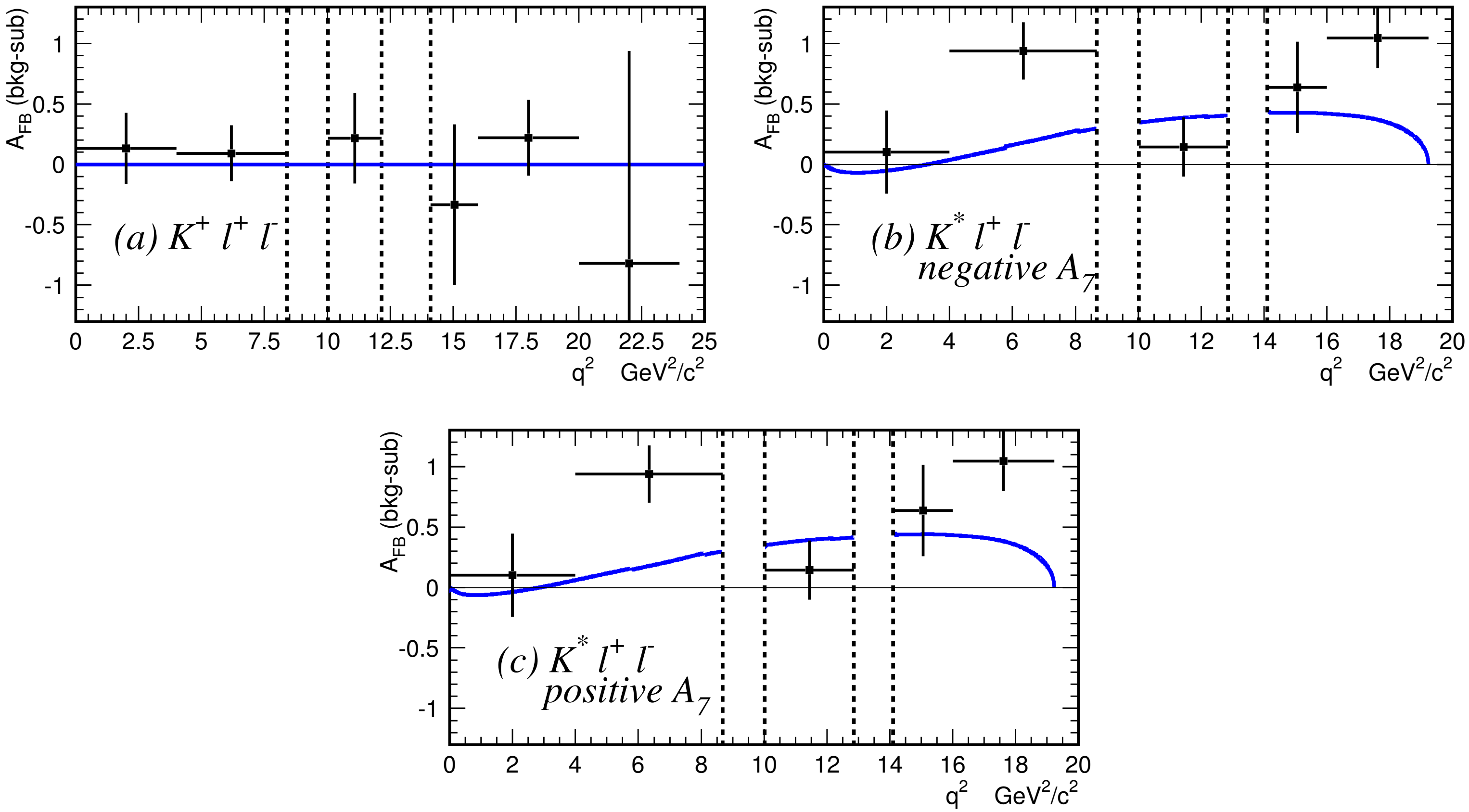
$A_{FB}(q_0^2) = 0$ free of hadronic uncertainties [Burdman1998, Ali et al., 2000]

$q_0^2 = (4.07^{+0.16}_{-0.13})$ GeV^2 with $\Delta(q_0^2)_{\mathrm{scale}} = {}^{+0.08}_{-0.05}$ GeV^2

QCD-F [Beneke/Feldmann/Seidel 2001]

$q_0^2 = (4.39^{+0.38}_{-0.35})$ GeV^2 with $\Delta(q_0^2)_{\mathrm{scale}} = \pm 0.25$ GeV^2

Belle FB Asymmetry Distributions (EPS 2005)



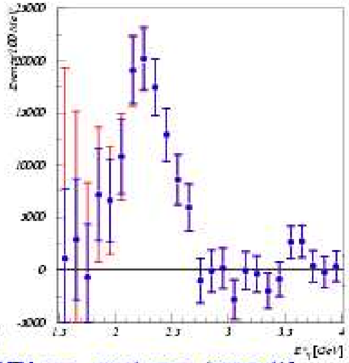
Best Fits

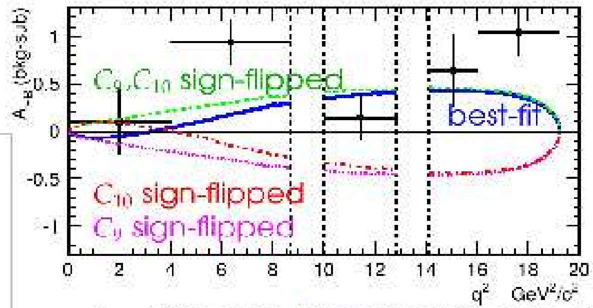
- $A_7 = -0.33$: $A_9/A_7 = -15.3^{+3.4}_{-4.8}$; $A_{10}/A_7 = 10.3^{+5.2}_{-3.5}$
- $A_7 = +0.33$: $A_9/A_7 = -16.3^{+3.7}_{-5.7}$; $A_{10}/A_7 = 11.1^{+6.0}_{-3.9}$
- SM: $A_7 = -0.33$; $A_9/A_7 = -12.3$; $A_{10}/A_7 = 12.8$

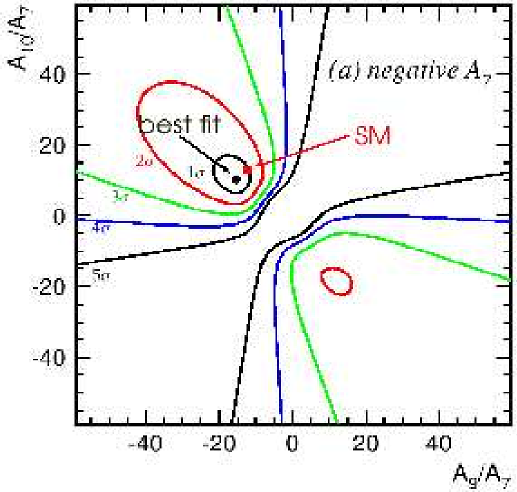
LHC-B MC Studies

Messages from the B factories

- $\mathbf{b} \to \ell\ell\mathbf{s} \Rightarrow C_9$ and C_{10}
  [Ishikawa et al., hep-ex/0603018]







- $\mathbf{b} \to \mathbf{s}\gamma \Rightarrow C_{7\gamma}$
  [Koppenburg et al., PRL93, 061803 (2004)]
  [Aubert et al., hep-ex/0507001] [...]

$\longrightarrow$ It's unlikely that the A_{FB} is very different from the SM value.

- Need precision to find differences

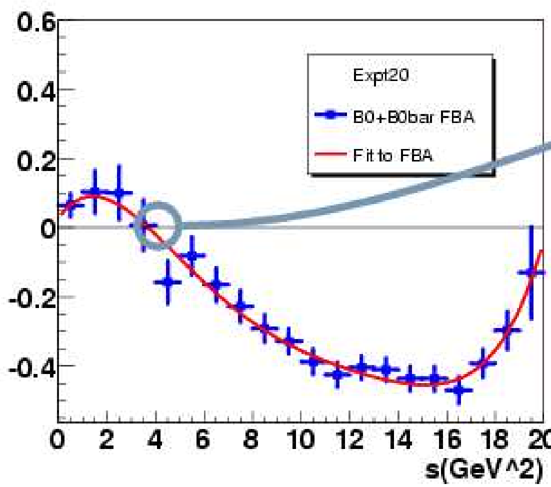
P. Koppenburg LHC — rare semileptonic and radiative $\mathbf{B}$ decays— Beach 2006 – p.14/21

LHC-B MC Studies

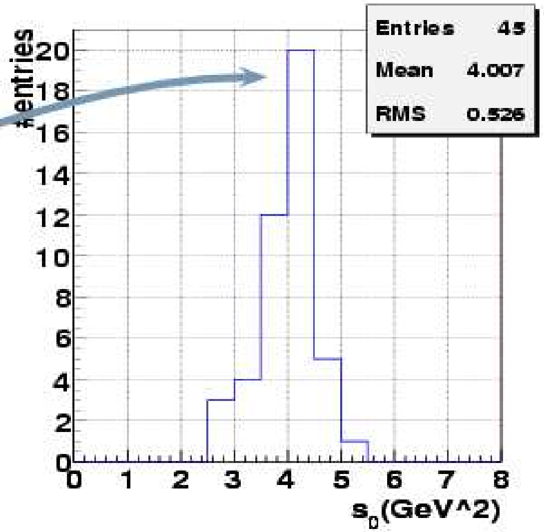
Zero of $B \to \mu\mu K^*$ A_{FB}

From Toy MC

- $2\ \text{fb}^{-1}$: $(4.0 \pm 1.2)\ \text{GeV}^2$
- $10\ \text{fb}^{-1}$: $(4.0 \pm 0.5)\ \text{GeV}^2$ $\Rightarrow$ 13% error on C_7/C_9



Typical $A_{FB}(s)$ measurement



Spread of s_0

P. Koppenburg

LHC — rare semileptonic and radiative B decays— Beach 2006 – p.16/21

$B_s \to \mu^+\mu^-$ in SM

- Effective Hamiltonian

$$\mathcal{H}_{eff} = -\frac{G_F\alpha}{\sqrt{2}\pi} V_{ts}{}^* V_{tb} \sum_i \left[C_i(\mu)\mathcal{O}_i(\mu) + C'_i(\mu)\mathcal{O}'_i(\mu) \right]$$

$$\mathcal{O}_{10} = (\bar{s}_\alpha \gamma^\mu P_L b_\alpha)\,(\bar{l}\gamma_\mu\gamma_5 l)\,, \qquad \mathcal{O}'_{10} = (\bar{s}_\alpha \gamma^\mu P_R b_\alpha)\,(\bar{l}\gamma_\mu\gamma_5 l)$$

$$\mathcal{O}_S = m_b\,(\bar{s}_\alpha P_R b_\alpha)\,(\bar{l}l)\,, \qquad \mathcal{O}'_S = m_s\,(\bar{s}_\alpha P_L b_\alpha)\,(\bar{l}l)$$

$$\mathcal{O}_P = m_b\,(\bar{s}_\alpha P_R b_\alpha)\,(\bar{l}\gamma_5 l)\,, \qquad \mathcal{O}'_P = m_s\,(\bar{s}_\alpha P_L b_\alpha)\,(\bar{l}\gamma_5 l)$$

$$\mathrm{BR}\left(\bar{B}_s \to \mu^+\mu^-\right) = \frac{G_F^2\alpha^2 m_{B_s}^2 f_{B_s}^2 \tau_{B_s}}{64\pi^3} |V_{ts}{}^* V_{tb}|^2 \sqrt{1-4\hat{m}_\mu^2} \times \left[\left(1-4\hat{m}_\mu^2\right) |F_S|^2 + |F_P + 2\hat{m}_\mu^2 F_{10}|^2 \right]$$

where $\hat{m}_\mu = m_\mu/m_{B_s}$ and

$$F_{S,P} = m_{B_s}\left[\frac{C_{S,P}m_b - C'_{S,P}m_s}{m_b+m_s}\right], \qquad F_{10} = C_{10} - C'_{10}$$

$$\mathrm{BR}\left(\bar{B}_s \to \mu^+\mu^-\right)_{\mathrm{SM}} = (3.46 \pm 1.5) \times 10^{-9} \quad \text{[Buchalla, Buras]}$$

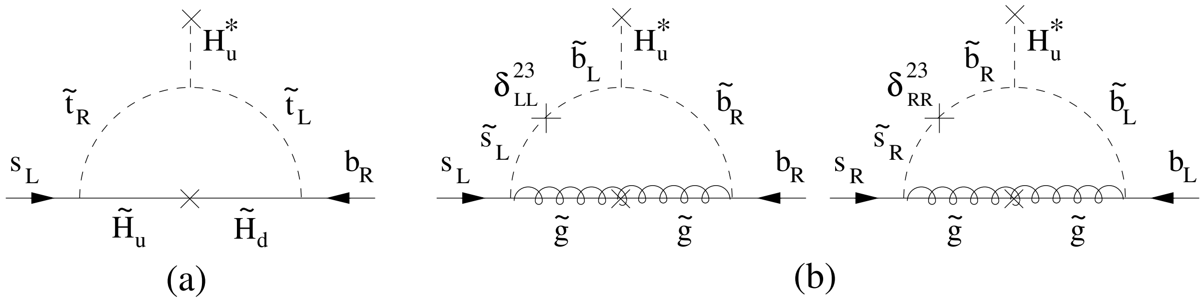
$$f_{B_s} = (230 \pm 30)\ \text{MeV}$$

$B_s \to \mu^+\mu^-$ in Supersymmetric Models

- The decay $B_s \to \mu^+\mu^-$ probes essentially the Higgs sector of Supersymmetry, a type-II two-Higgs doublet model

$$\mathcal{L} = \overline{Q} Y_U U_R H_u + \overline{Q}_L Y_D D_R H_d$$

- Higgs-induced FCNC interactions are generated through loops



- As H_u gets a VEV (v_u), it contributes an off-diagonal piece to the down-type fermion mass matrix, mixing s_L and b_L by an angle θ

$$\sin\theta = y_b \epsilon v_u / m_b; \quad \text{as } m_b = y_b v_d, \ \sin\theta = \epsilon \tan\beta$$

- $\mathcal{A}(b\bar{s} \to \mu^+\mu^-) \simeq \sin\theta \mathcal{A}(b\bar{b} \to \mu^+\mu^-) \ \propto \tan\beta / \cos^2\beta \Longrightarrow \tan^3\beta$ for large-$\tan\beta$

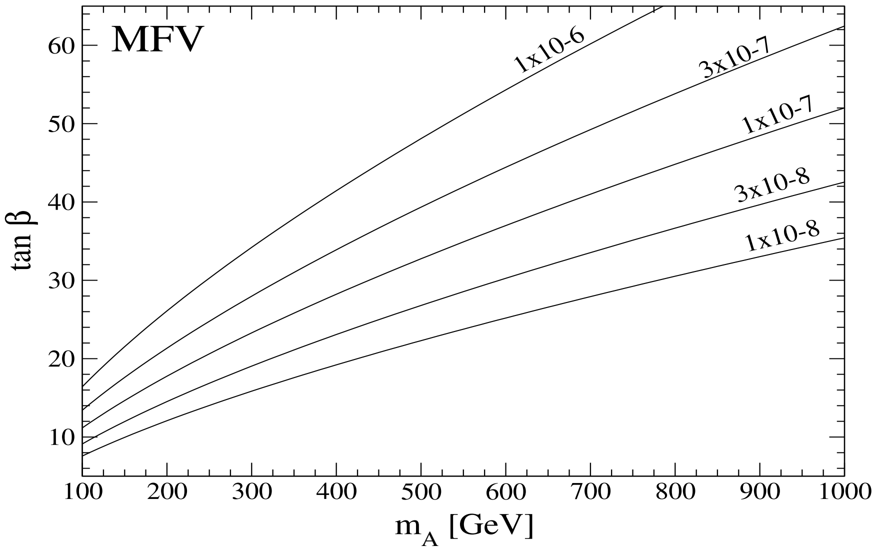
$B_s \to \mu^+\mu^-$ in Minimal Flavor Violation SUSY Models

- Higgsino contribution to $\mathcal{B}(B_s \to \mu^+\mu^-)$ [Babu, Kolda;...]

$$\mathcal{B}(B_s \to \mu\mu) \simeq \frac{G_F^2}{8\pi}\, \eta_{\rm QCD}^2 m_{B_s}^3 f_{B_s}^2 \tau_{B_s} m_b^2\, m_\mu^2 \left(\frac{\tan^2\beta}{\cos^4\beta}\right)\left(\frac{\kappa_{\widetilde{H}}^2}{m_A^4}\right).$$

- $\eta_{\rm QCD} \simeq 1.5$ is the QCD correction due to the RG between the SUSY and B_s scales

$$\kappa_{\widetilde{H}} = -\frac{G_F\, m_t^2\, V_{ts}V_{tb}}{4\sqrt{2}\pi^2 \sin^2\beta}\, \mu A_t\, f(\mu^2, m_{\tilde{t}_L}^2, m_{\tilde{t}_R}^2)$$



$B_s \to \mu^+\mu^-$

- Very rare decay, sensitive to new physics
- BR ~ 3.5 × 10^{-9} in SM, can be strongly enhanced in SUSY
- Current limit from Tevatron:
  - ✓ D0: 2.3×10^{-7} at 95% CL
  - ✓ CDF: 1.0×10^{-7} at 95% CL

LHC has prospect for significant measurement

but difficult to get reliable estimate of expected background:

- ✓LHCb: Full simulation: 10M incl. bb events + 10M $b\to\mu$, $b\to\mu$ events (all rejected)
- ✓ATLAS: 80k $bb\to\mu\mu$ events with generator cuts, efficiency assuming cut factorization
- ✓CMS: 10k $b\to\mu$, $b\to\mu$ events with generator cuts, trigger simulated at generator level, efficiency assuming cut factorization

	1 year	$B_s \to \mu^+\mu^-$ signal (SM)	$b\to\mu$, $b\to\mu$ background	Inclusive bb background	Other backgrounds
LHCb	2 fb^{-1}	30	< 100	< 7500	
ATLAS	10 fb^{-1}	7	< 20		
CMS (1999)	10 fb^{-1}	7	< 1		

- New assessment of ATLAS/CMS reach at 10^{34} $cm^{-2}s^{-1}$ in progress

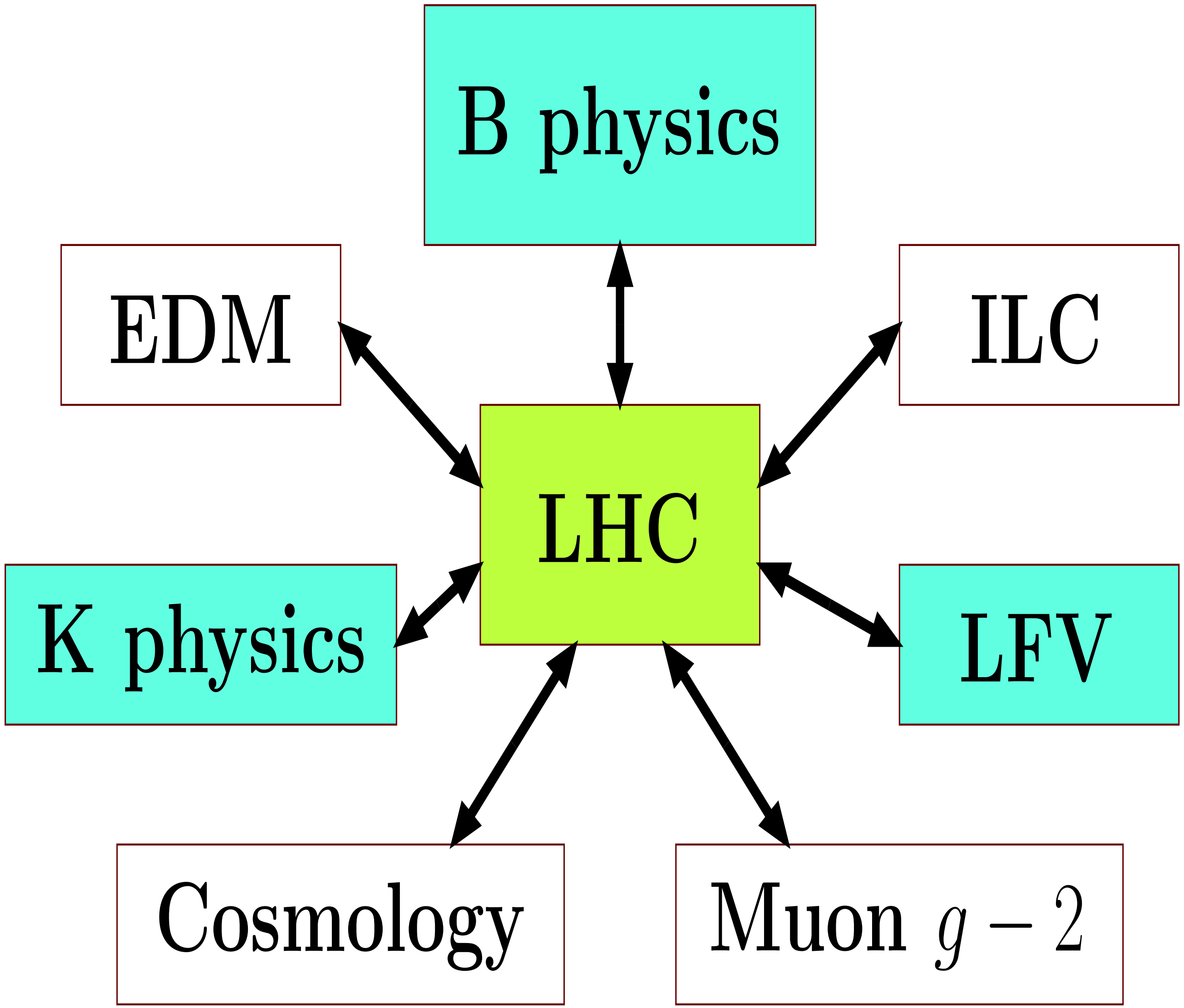
LHC B-Meson Physics Program

- Experiments at LHC will pursue an extensive program on B-physics
  - with high statistics
  - access to B_s-meson decays
- **LHCb** can fully exploit large B-meson yields at LHC from the start-up
- **ATLAS** and **CMS** will also contribute significantly
  - competitive for modes with muons and small BR
- **After 5 years:**

Quantity	σ	SM expectation	
$\phi_s(B_s \to \bar{c}c\bar{s}s)$	~ 0.013	~ 0.035	
$\text{Br}(B_s \to \mu^+\mu^-)$	$\sim 0.7 \times 10^{-9}$	$\sim 3.5 \times 10^{-9}$	
$\gamma(D_s K,\, DK)$	$\sim 1^\circ$	$\sim 60^\circ$	(tree only)
$\gamma(KK + \pi\pi)$	$\sim 2^\circ$	$\sim 60^\circ$	(tree + penguin)

Flavor Physics at LHC will contribute significantly to search for New Physics via precise and complementary measurements of CKM angles and study of loop decays

Synergy of Various Approaches in Search of BSM Physics

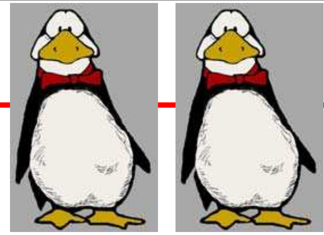


Backup Slides

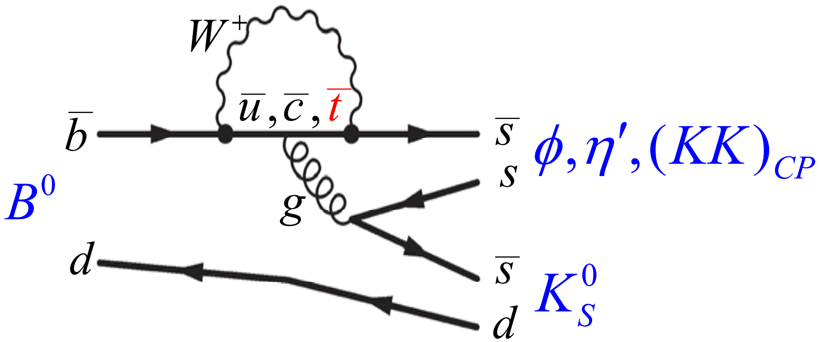
Feynman Diagrams for $\sin 2\beta$ from Penguins

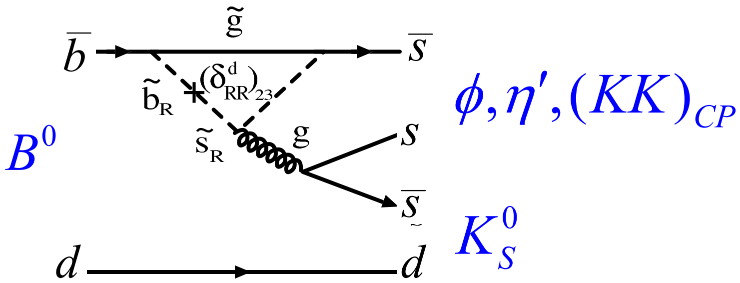
$\sin 2\beta$ and...

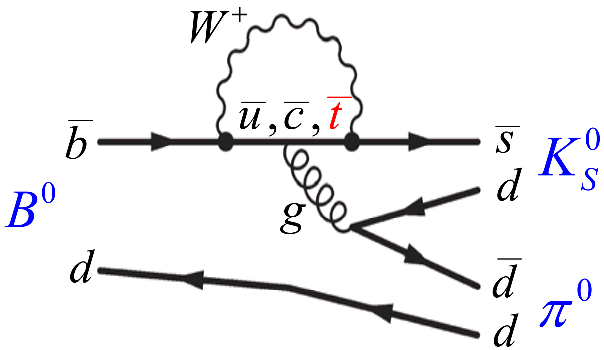
and....



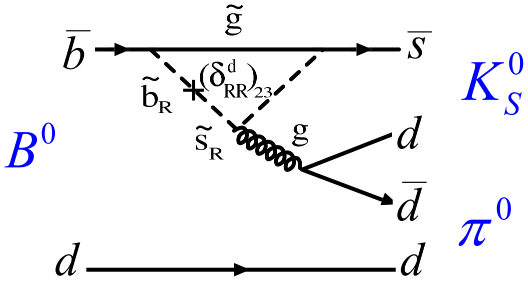
In SM interference between B mixing, K mixing and Penguin $b \to s\bar{s}s$ or $b \to s\bar{d}d$ gives the same $e^{-2i\beta}$ as in tree process $b \to c\bar{c}s$. However loops can also be sensitive to New Physics!



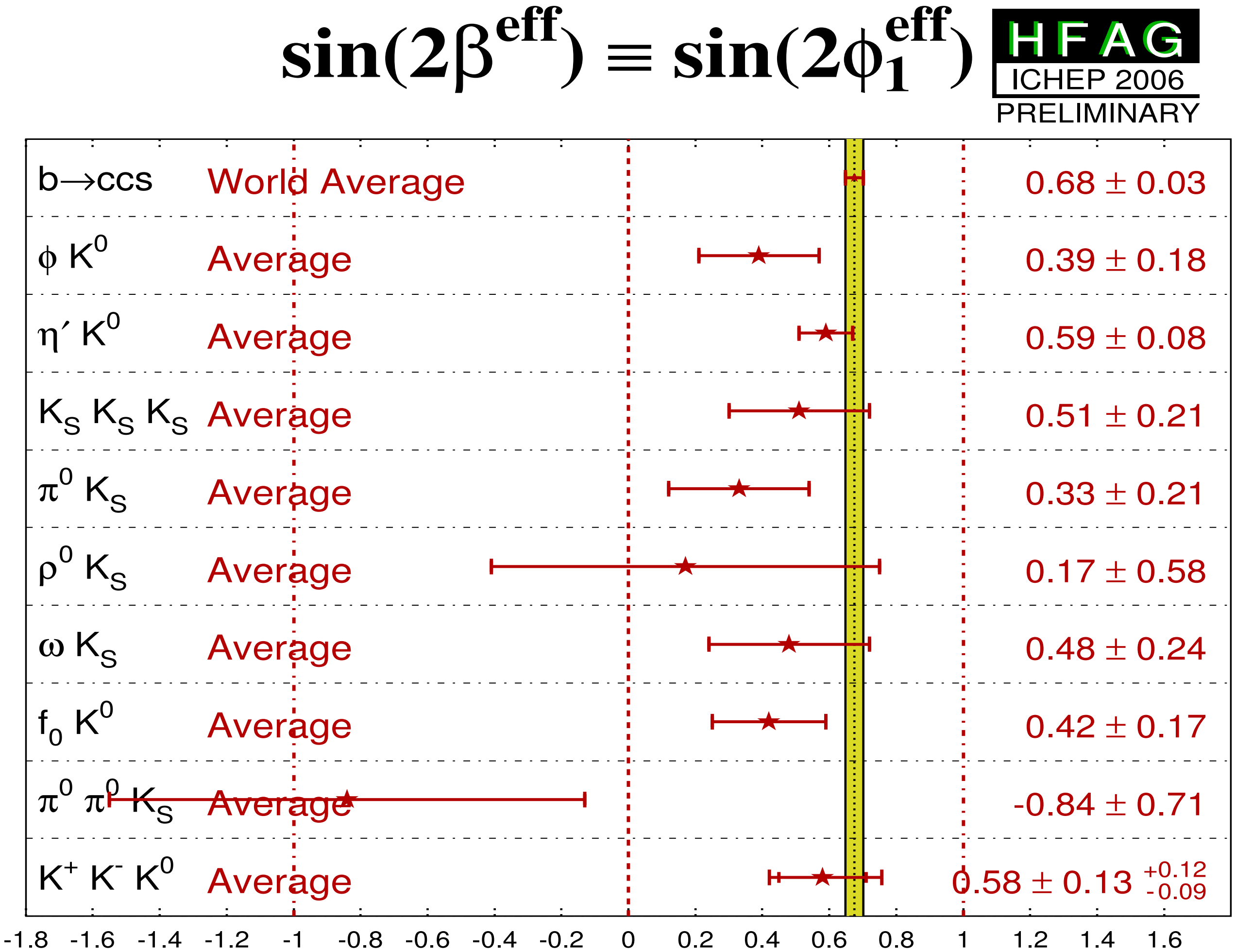




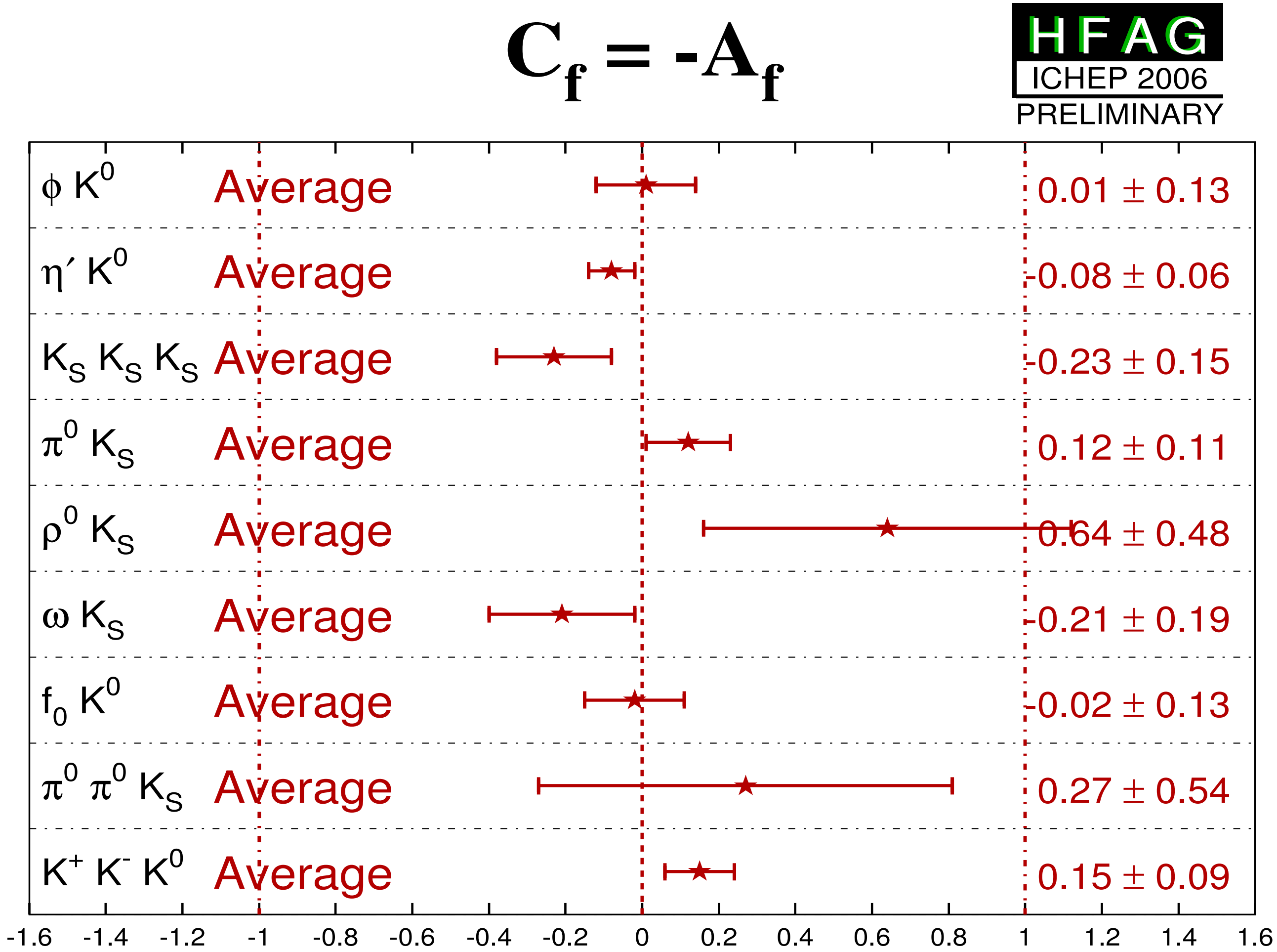
New phases from SUSY?



$S_{b\to q\bar{q}s}$ [HFAG 2006; ICHEP 2006 Update]



$C_{b\to q\bar{q}s}$ [HFAG 2006; ICHEP 2006 Update]



$SU(3)_{\rm F}$-averaged $B \to (\rho,\omega)\gamma$ Branching Ratio

- This averaging procedure is defined as

$$\bar{\mathcal{B}}[B \to (\rho,\omega)\,\gamma] \equiv \frac{1}{2}\left\{\mathcal{B}(B^+ \to \rho^+\gamma) + \frac{\tau_{B^+}}{\tau_{B^0}}\left[\mathcal{B}(B_d^0 \to \rho^0\gamma) + \mathcal{B}(B_d^0 \to \omega\gamma)\right]\right\}$$

- Combining all the branching fractions together, such an estimate gives

$$\bar{\mathcal{B}}_{\rm th}[B \to (\rho,\omega)\gamma] = (1.32 \pm 0.26) \times 10^{-6}$$

- Good agreement with experimental measurements within current errors

Branching ratios (in units of 10^{-6}) [August 2006]

Mode	BABAR	BELLE	CLEO	Average [HFAG]
$B \to (\rho,\omega)\gamma$	$1.01 \pm 0.21 \pm 0.08$	$1.32^{+0.34+0.10}_{-0.31-0.09}$	< 14.0	$1.11^{+0.19}_{-0.18}$

Determination of $|V_{td}/V_{ts}|$ from $\bar{R}_{\rm exp}[(\rho,\omega)\,\gamma/K^*\gamma]$

- To extract the value of $|V_{td}/V_{ts}|$ from the $B \to (K^*, \rho, \omega)\,\gamma$ decays, one can use the ratio

$$\bar{R}_{\rm exp}[(\rho,\omega)\gamma/K^*\gamma] = \frac{\bar{\mathcal{B}}_{\rm exp}[B \to (\rho,\omega)\,\gamma]}{\bar{\mathcal{B}}_{\rm exp}(B \to K^*\gamma)} = r_{\rm th}^{(\rho/\omega)} \left|\frac{V_{td}}{V_{ts}}\right|^2 \zeta^2$$

- ζ and $|V_{td}/V_{ts}|$ are treated as free variables
- All other parametric uncertainties are combined in $r_{\rm th}^{(\rho/\omega)}$ error

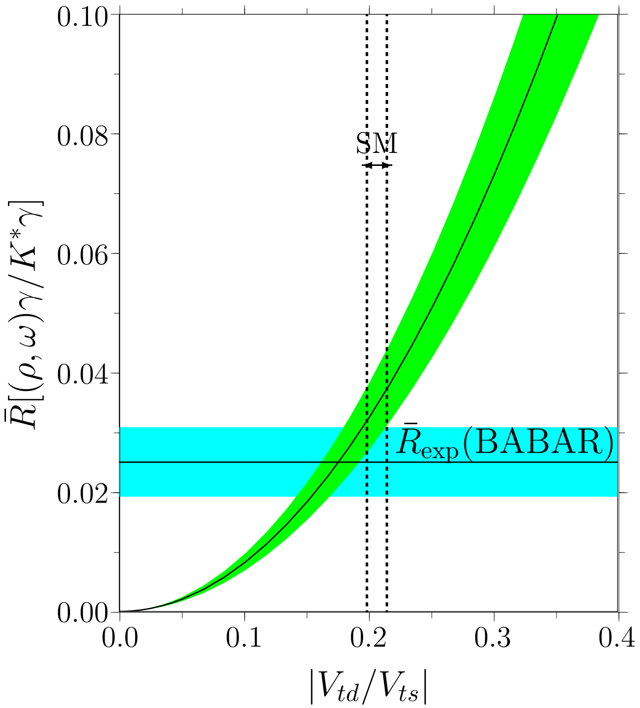
$$r_{\rm th}^{(\rho/\omega)} = 1.09 \pm 0.06$$

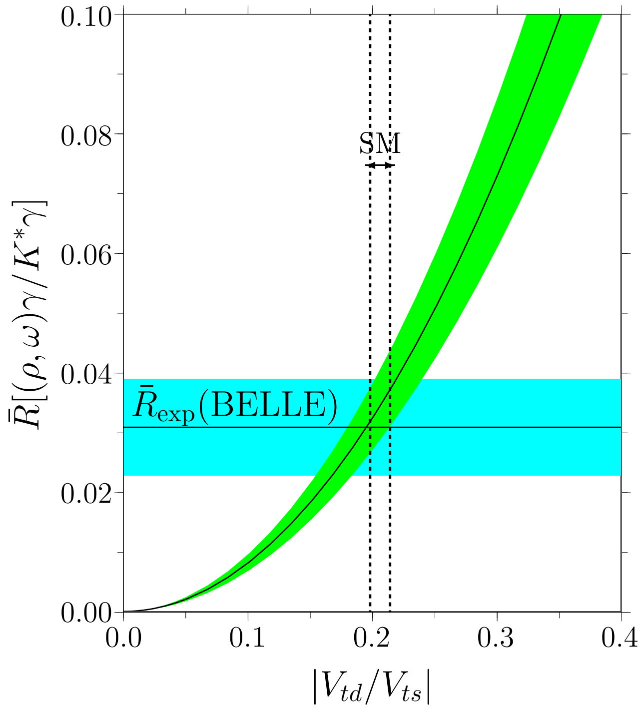
- Recent result $\zeta = 0.86 \pm 0.07$ by Ball and Zwicky can be used

Quantity	BABAR	BELLE	Average [HFAG]
$\bar{R}_{\rm exp}[(\rho,\omega)\gamma/K^*\gamma]$	0.025 ± 0.006	$0.032 \pm 0.008 \pm 0.002$	0.027 ± 0.005
$\|V_{td}/V_{ts}\|\,\zeta$	$0.151^{+0.017}_{-0.019}$	$0.171^{+0.021}_{-0.024}$	0.156 ± 0.014
$\|V_{td}/V_{ts}\|$	0.176 ± 0.026	0.199 ± 0.031	0.181 ± 0.022

- From global CKM fits: $|V_{td}/V_{ts}| = 0.2003^{+0.0146}_{-0.0059}$ [CKMfitter]
  $|V_{td}/V_{ts}| = 0.208 \pm 0.007$ [UTfit]

Determination of $|V_{td}/V_{ts}|$ from $\bar{R}_{\rm exp}[(\rho,\omega)\,\gamma/K^*\gamma]$





$$|V_{td}/V_{ts}| = 0.171^{+0.018}_{-0.021}(\text{exp})^{+0.017}_{-0.014}(\text{th})$$

$$|V_{td}/V_{ts}| = 0.199^{+0.026}_{-0.025}(\text{exp})^{+0.018}_{-0.015}(\text{th})$$

$$|V_{td}/V_{ts}|_{\rm SM} = 0.2003^{+0.0146}_{-0.0059}$$