Theoretical Interest in B-Meson Physics at the B Factories, Tevatron and the LHC

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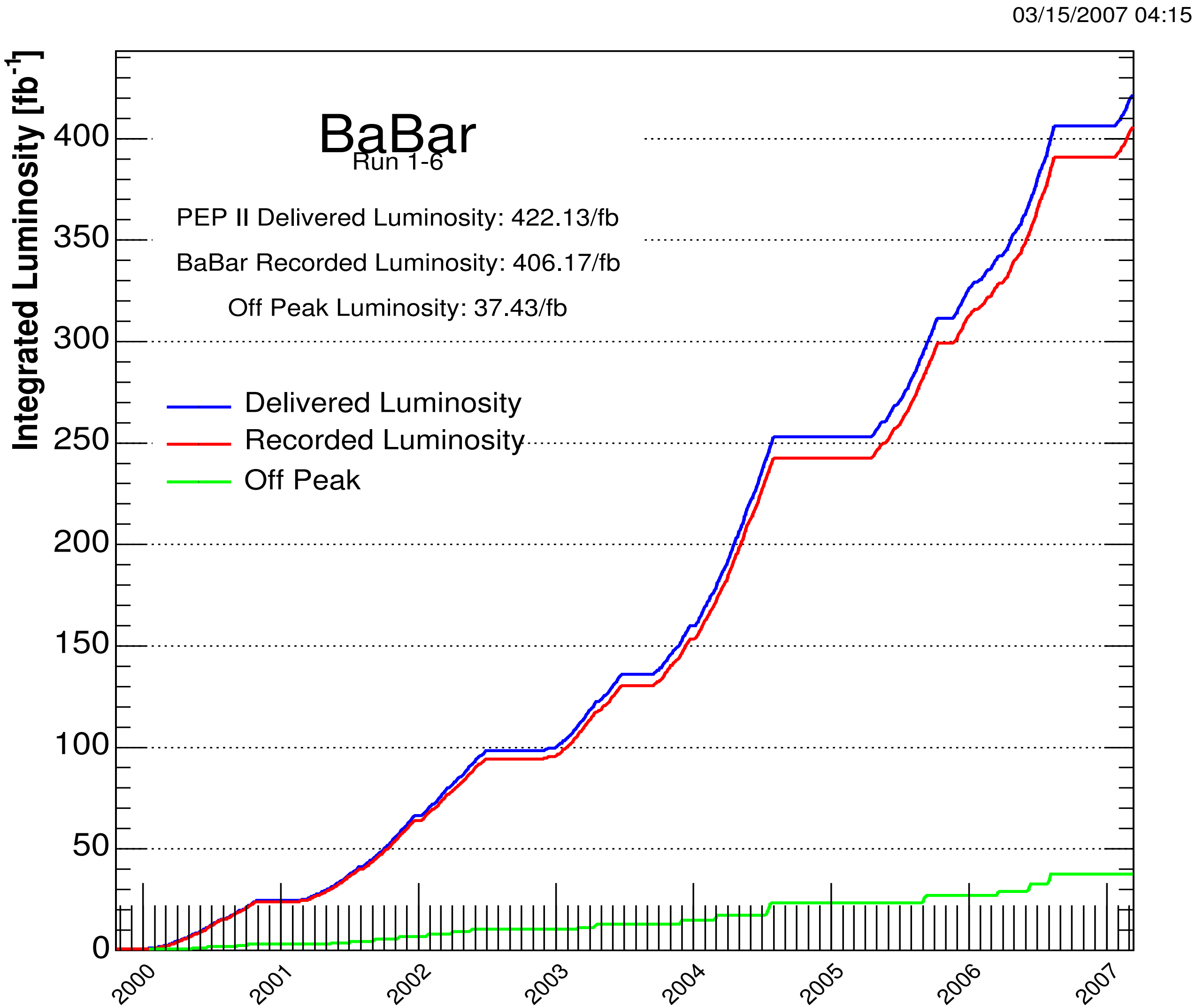
Plan of Talk

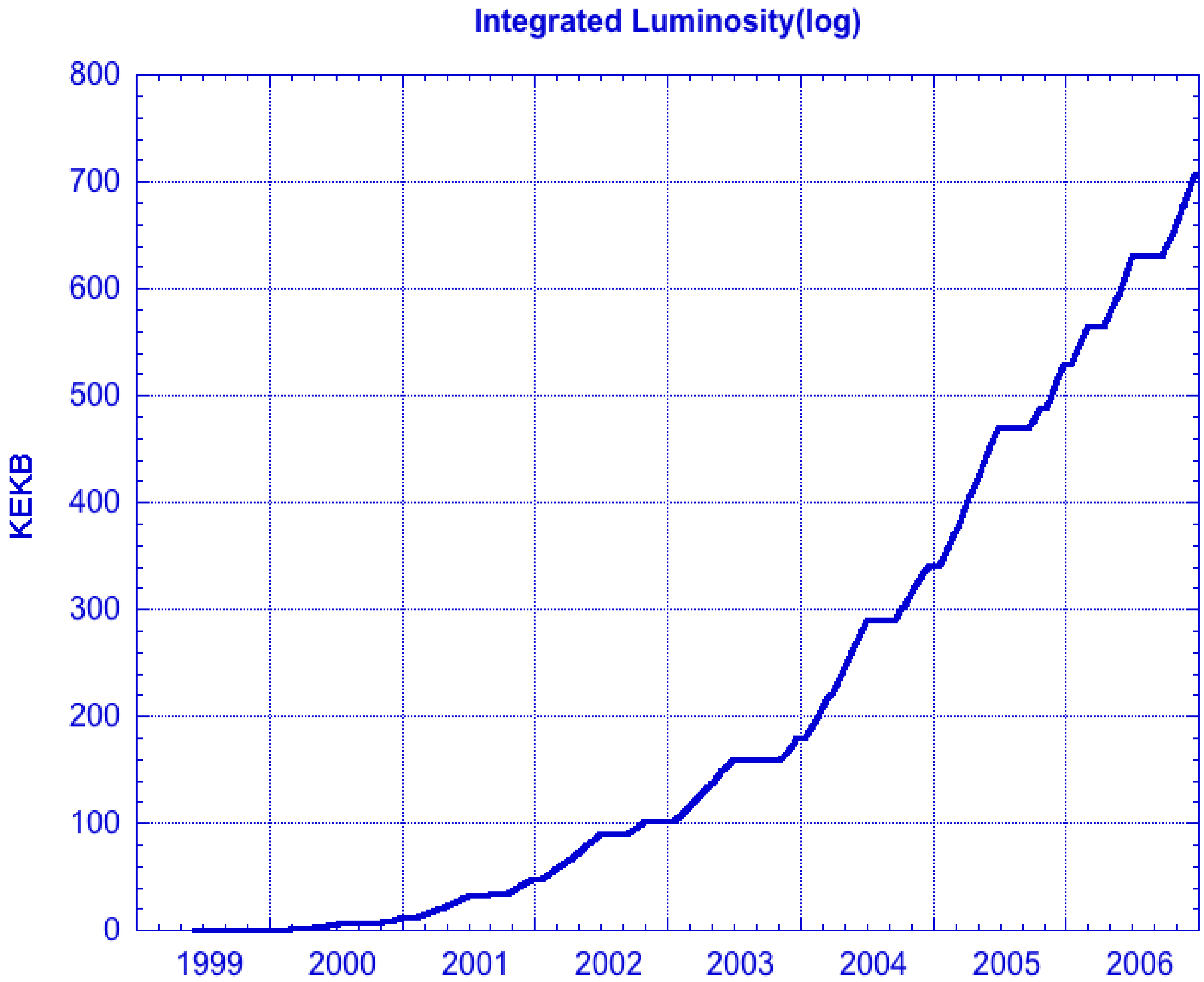
- Current B-physics facilities
- The CKM-Matrix and the impact of B-physics on $V_{\rm CKM}$
- CP Violation in the B-meson sector & the current knowledge of the CP Violating phases α, β, γ
- Theoretical interest in Rare B-decays
  - $b \to s\gamma$: SM vs. Experiment
  - $B \to (X_s, K, K^*)\ell^+\ell^-$: Current Status
- Profile of B-physics at the LHC
- Benchmark for the LHC:
  - Mixings, Nonleptonics & CP Asymmetries
  - $B_s \to \mu^+\mu^-$ in the SM and SUSY
- Summary

SLAC B Factory



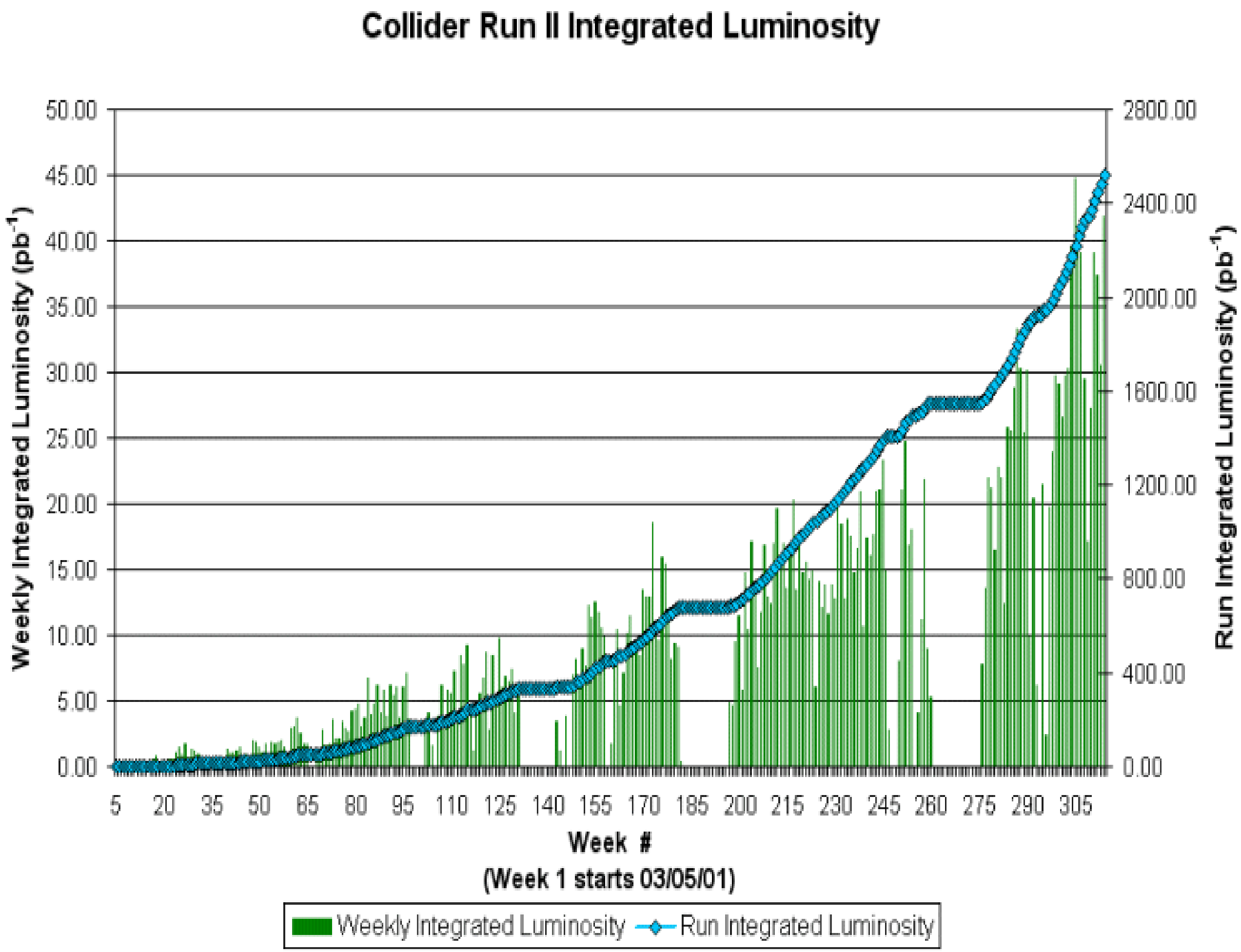
KEK B Factory

Luminosity recorded by BELLE (15/3/2007)



Tevatron Collider at Fermilab

Integrated Luminosity (15/03/2007)



The Cabibbo-Kobayashi-Maskawa Matrix

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

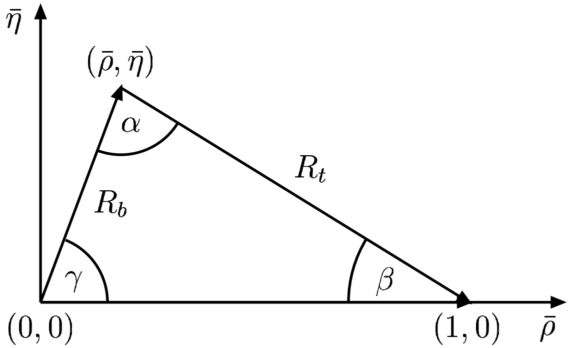
- Customary to use the handy Wolfenstein parametrization

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

- Four parameters: $A, \ \lambda, \ \rho, \ \eta$
- Perturbatively improved version of this parametrization

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

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



Phases and sides of the UT

$$\alpha \equiv \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right), \qquad \beta \equiv \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right), \qquad \gamma \equiv \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

- β and γ have simple interpretation

$$V_{td} = |V_{td}| e^{-i\beta}, \qquad V_{ub} = |V_{ub}| e^{-i\gamma}$$

- α defined by the relation: $\alpha = \pi - \beta - \gamma$

- The Unitarity Triangle (UT) is defined by:

$$R_b \mathrm{e}^{i\gamma} + R_t \mathrm{e}^{-i\beta} = 1$$

$$R_b \equiv \frac{|V_{ub}^* V_{ud}|}{|V_{cb}^* V_{cd}|} = \sqrt{\bar{\rho}^2 + \bar{\eta}^2} = \left(1 - \frac{\lambda^2}{2}\right) \frac{1}{\lambda} \left|\frac{V_{ub}}{V_{cb}}\right|$$

$$R_t \equiv \frac{|V_{tb}^* V_{td}|}{|V_{cb}^* V_{cd}|} = \sqrt{(1-\bar{\rho})^2 + \bar{\eta}^2} = \frac{1}{\lambda} \left|\frac{V_{td}}{V_{cb}}\right|$$

$|V_{cb}|$ from Inclusive decays $B \to X_c \ell \nu_\ell$

- Theoretical Method

  Heavy Quark Mass Expansion and Operator Product Expansion (OPE)

  [Chay, Georgi, Grinstein; Voloshin, Shifman; Bigi et al.; Manohar, Wise; Blok et al.]

- Perform an OPE: m_b is much larger than any scale appearing in the matrix element
- Decay rate for $B \to X_c \ell \bar{\nu}_\ell$

$$\Gamma = \Gamma_0 + \frac{1}{m_b}\Gamma_1 + \frac{1}{m_b^2}\Gamma_2 + \frac{1}{m_b^3}\Gamma_3 + \cdots$$

- Γ_i are power series in $\alpha_s(m_b)$ $\to$ Perturbaton theory
- Γ_0 is the decay of a free quark ("Parton Model")
- Γ_1 vanishes due to Luke's theorem
- Γ_2 is expressed in terms of two non-perturbative parameters

  $2M_B\lambda_1 = \langle B(v)|\bar{Q}_v(iD)^2 Q_v|B(v)\rangle$

  $6M_B\lambda_2 = \langle B(v)|\bar{Q}_v\sigma_{\mu\nu}[iD^\mu, iD^\nu]Q_v|B(v)\rangle$

  λ_1: Kinetic energy, λ_2: Chromomagnetic moment (also called as μ_π^2 and μ_G^2)

- Γ_3 is currently under investigation; involves several new Non-perturbative parameters

Moment analysis of $B \to X_c \ell \nu_\ell$ with lepton energy cut

Lepton-energy and hadron mass moments

[Gambino, Uraltsev; Benson et al.]

$$M_\ell^{(n)}(E_{\rm cut}) = \frac{\int_{E_{\rm cut}} E_\ell^n \frac{{\rm d}\Gamma}{{\rm d}E_\ell}\,{\rm d}E_\ell}{\int_{E_{\rm cut}} \frac{{\rm d}\Gamma}{{\rm d}E_\ell}\,{\rm d}E_\ell}, \quad \langle M_X^\nu \rangle = \left(\langle M_X^2\rangle\right)^{\frac{\nu}{2}} \left[1 + \sum_{k=2}^{\infty} C_{\frac{\nu}{2}}^{k} \frac{\langle (M_X^2 - \langle M_X^2\rangle)^k\rangle}{\langle M_X^2\rangle^k}\right]$$

- Combined with the decay $B \to X_s \gamma$

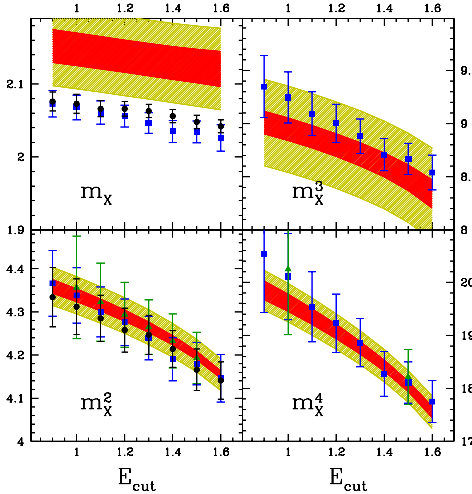
$$\langle m_X^{2n}\rangle_{E_{\rm cut}} = \frac{\int_{E_{\rm cut}} (m_X^2)^n \frac{{\rm d}\Gamma}{{\rm d}m_X^2}\,{\rm d}m_X^2}{\int_{E_{\rm cut}} \frac{{\rm d}\Gamma}{{\rm d}m_X^2}\,{\rm d}m_X^2}, \qquad \langle E_\gamma^n\rangle_{E_{\rm cut}} = \frac{\int_{E_{\rm cut}} E_\gamma^n \frac{{\rm d}\Gamma}{{\rm d}E_\gamma}\,{\rm d}E_\gamma}{\int_{E_{\rm cut}} \frac{{\rm d}\Gamma}{{\rm d}E_\gamma}\,{\rm d}E_\gamma}$$

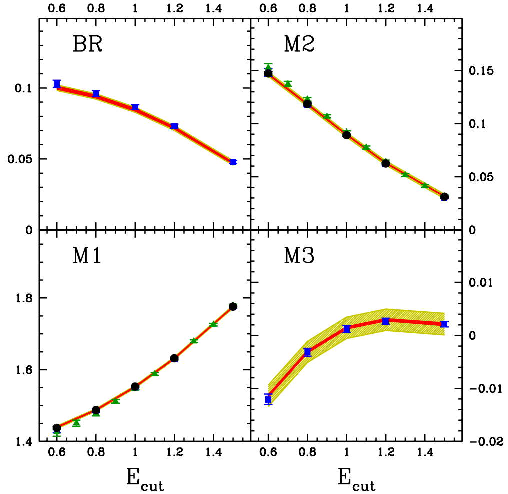
- Kinematic-mass scheme, $\mu \simeq 1$ GeV
- No Expansion in $1/m_c$
- Theory depends on $m_c(\mu), m_b(\mu), \quad \underbrace{\mu_\pi^2(\mu), \mu_G^2,}_{\mathcal{O}(\Lambda_{\rm QCD}^2/m_b^2)} \quad \underbrace{\rho_{\rm LS}^3(\mu), \rho_{\rm D}^3(\mu)}_{\mathcal{O}(\Lambda_{\rm QCD}^3/m_b^3)}$

Analysis of the moments by Bauer et al.

[Bauer, Ligeti, Luke, Manohar, Trott, hep/ph/0408002]

- Global fit of data from BABAR, BELLE, CDF, CLEO, DELPHI
- Theory precision: up to $\mathcal{O}(\alpha_s^2\beta_0)$, $\alpha_s\Lambda_{\rm QCD}/m_b$, $\Lambda_{\rm QCD}^3/m_b^3$
- Parameters: $m_b(\mu)$, $\underbrace{\lambda_1}_{\mathcal{O}(\Lambda_{\rm QCD}^2/m_b^2)}$, $\underbrace{\rho_1, \tau_1 - 3\tau_4, \tau_2 + \tau_4, \tau_3 + 3\tau_4}_{\mathcal{O}(\Lambda_{\rm QCD}^3/m_b^3)}$
- Analyse: $m_X^n \equiv \langle m_X^n \rangle$, $\langle E_\ell^n \rangle$, ($n = 1,\ldots 4$) $(B \to X_c \ell \nu_\ell)$; $\langle E_\gamma^n \rangle$ $(B \to X_s \gamma)$





$$|V_{cb}| = (41.4 \pm 0.6 \pm 0.1_{\tau_B}) \times 10^{-3},$$

$$m_b^{1S} = (4.68 \pm 0.03)\ \text{GeV},$$

- $|V_{cb}|_{\rm inclusive} = (41.7 \pm 0.7) \times 10^{-3}$ [PDG 2006 Update]

$|V_{cb}|$ from $B \to (D, D^*)\, \ell \nu_\ell$ decays

$B \to D^* \ell \nu_\ell$ decays

$$\frac{d\Gamma}{d\omega} = \frac{G_F^2}{4\pi^3} \left(\omega^2 - 1\right)^{1/2} m_{D^*}^3 \left(m_B - m_{D^*}\right)^2 \mathcal{G}(\omega) \left|V_{cb}\right|^2 \left|\mathcal{F}(\omega)\right|^2$$

- $\mathcal{G}(\omega)$ phase space factor: $\mathcal{G}(1) = 1$, $\mathcal{F}(\omega) =$ Isgur–Wise function: $\mathcal{F}(1) = 1$;
- Leading $\Lambda_{\rm QCD}/m_b$ corrections absent Luke's theorem
- Theoretical issues: precise determination of the second order correction to $\mathcal{F}(\omega = 1)$, slope ρ^2 and curvature c

$$\mathcal{F}(\omega) = \mathcal{F}(1) \left[1 + \rho^2 (\omega - 1) + c\,(\omega - 1)^2 + ...\right] .$$

HFAG (Summer 2006 Update)

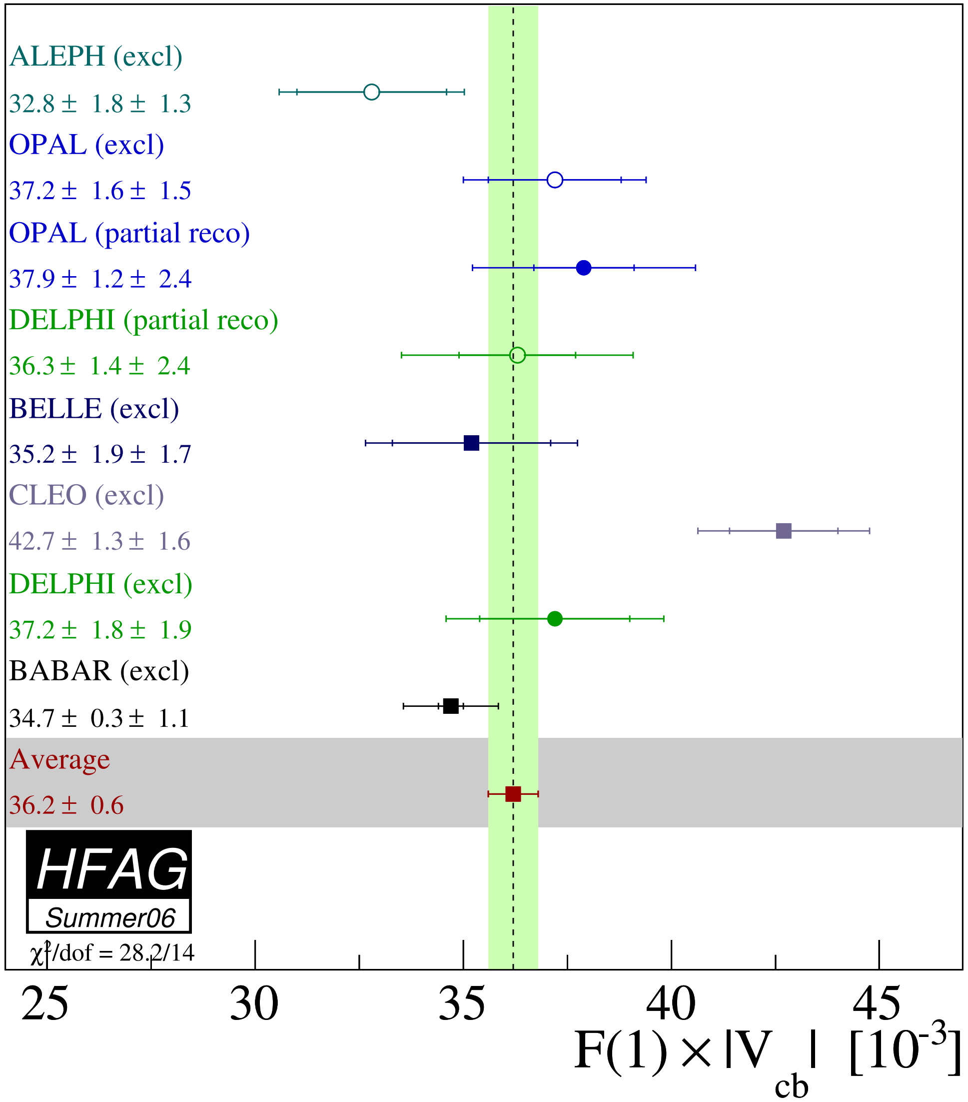
$$\mathcal{F}(1)|V_{cb}| = (36.2 \pm 0.6) \times 10^{-3}\,, \qquad \rho^2 = 1.19 \pm 0.05 \quad (\chi^2 = 28.2/14)$$

Current values of $\mathcal{F}(1)$

$$\begin{aligned} \mathcal{F}(1) &= 0.91 \pm 0.04 \quad \text{[BABAR book]} \\ & 0.919^{+0.030}_{-0.035} \quad \text{[Lattice QCD (Hashimoto et al.)]} \end{aligned}$$

- With $\mathcal{F}(1) = 0.91 \pm 0.04$: $|V_{cb}|_{B \to D^* \ell \nu_\ell} = (40.9 \pm 1.8) \times 10^{-3}$

$\mathcal{F}(1)|V_{cb}|$ (Summer 2006)



$|V_{ub}|$

From End-point spectra in $B \to X_u \ell \nu_\ell$ and $B \to X_s \gamma$

- To remove the background from $B \to X_c \ell \nu_\ell$, need to impose a large E_ℓ-cut
- Decay rate in the cut-region depends on the shape function $f(\omega)$
  - $2M_B f(\omega) = \langle B|\bar{Q}_v \delta(\omega + n \cdot (iD)) Q_v |B\rangle; \quad (n.v = 1,\ n^2 = 0)$
- Use of OPE to calculate inclusive spectra:

  Example: Photon Spectrum in $B \to X_s \gamma$ [Neubert; Bigi et al.]

- Leading Shape Function ($x = \frac{2E_\gamma}{m_b}$):

$$\frac{d\Gamma}{dx} = \frac{G_F^2 \alpha m_b^5}{32\pi^4} |V_{ts} V_{tb^*}|^2 |C_7|^2 f(1-x)$$

  - E_ℓ - and M_{X_u} -spectra in $B \to X_u \ell \nu_\ell$ governed also by $f(x)$
  - $f(x)$ can be measured in $B \to X_s \gamma$

Model independent determination of $|V_{ub}/(V_{ts}^* V_{tb})|$

$\longrightarrow$ Define Observables (E_c – energy cut)

$$\Gamma_u(E_c) = \int_{E_c}^{m_B/2} dE_\ell \frac{d\Gamma_u}{dE_\ell}, \qquad \Gamma_s(E_c) = \frac{2}{m_b}\int_{E_c}^{m_B/2} dE_\gamma (E_\gamma - E_c)\frac{d\Gamma_s}{dE_\gamma}$$

Including subleading Shape functions [Bauer, Luke, Mannel]

- $b \longrightarrow s\gamma$:

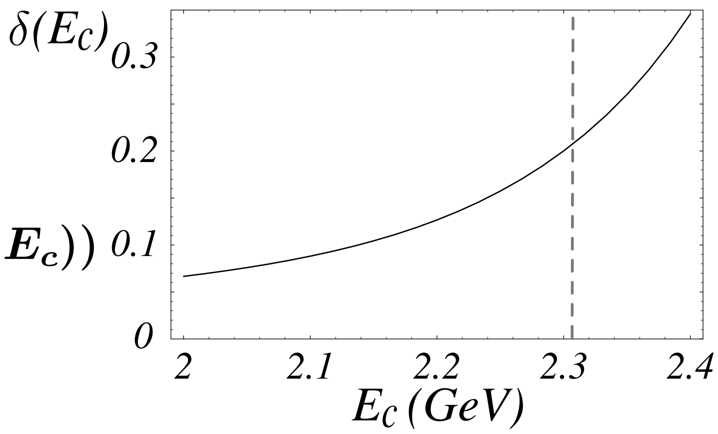
$$\frac{d\Gamma}{dE_\gamma} = \frac{\Gamma_0^s}{m_b}\left[(4E_\gamma - m_b) f(m_b - 2E_\gamma) + \frac{1}{m_b}\left[h_1(m_b - 2E_\gamma) + H_2(m_b - 2E_\gamma)\right]\right]$$

- $b \longrightarrow u\ell\bar{\nu}_\ell$

$$\frac{d\Gamma}{dE_\ell} = \frac{2\,\Gamma_0}{m_b}\int d\omega\, \theta(m_b - 2E_\ell - \omega)\left[f(\omega)\left(1 - \frac{\omega}{m_b}\right) - \frac{1}{m_b}h_1(\omega) + \frac{3}{m_b}H_2(\omega)\right]$$

- Ratio receives $1/m_b$ corrections

$$\left|\frac{V_{ub}}{V_{tb}V_{ts}^*}\right| = \left(\frac{3\alpha}{\pi}|C_7^{\rm eff}|^2 \frac{\Gamma_u(E_c)}{\Gamma_s(E_c)}\right)^{\frac{1}{2}} (1 + \delta(E_c))$$

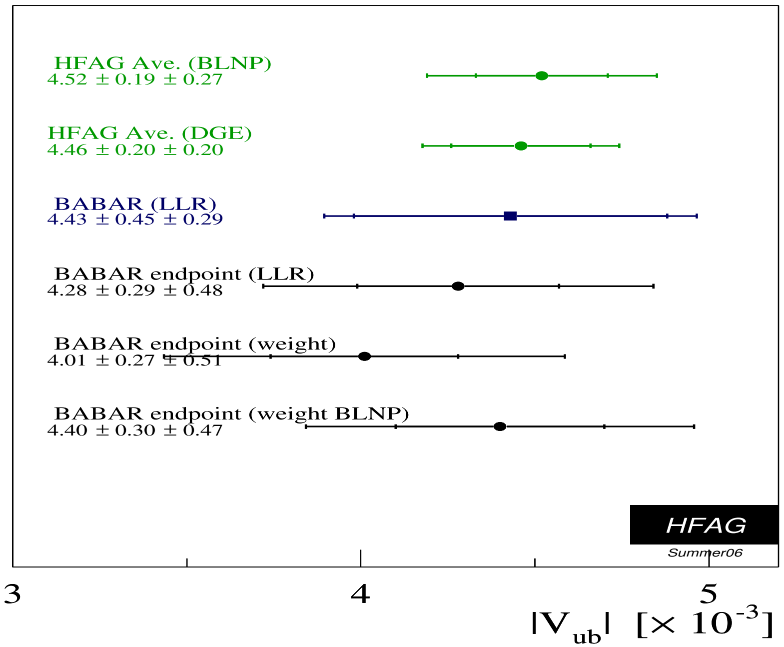


- $\delta(E_c)$ causes a shift of $\mathcal{O}(15\%)$ in $|V_{ub}|$

$|V_{ub}|$ in Inclusive Semileptonic Decays (HFAG 2006)

Based on several theoretical proposals

BLNP: Lange, Neubert, Paz (2005)
DGE: Andersen, Gardi (2006)
BLL: Bauer, Ligeti, Luke (2001)
LLR: Leibovitch, Low, Rothstein (2000; 2005)



PDG (2006): $|V_{ub}| = (4.40 \pm 0.20 \pm 0.27) \times 10^{-3}$

$|V_{ub}|$ from exclusive decays $B \to \pi \ell \nu_\ell$

$$\langle \pi(p_\pi)|\bar{b}\gamma_\mu q|B(p_B)\rangle = \left((p_B + p_\pi)_\mu - \frac{m_B^2 - m_\pi^2}{q^2} q_\mu \right) F_+(q^2) \; + \; \frac{m_B^2 - m_\pi^2}{q^2} F_0(q^2)\, q_\mu \, ,$$

Techniques used to determine $F_+(q^2)$, $F_0(q^2)$

- Light-cone QCD sum rules [Colangelo, Khodjamirian; Ball, Zwicky]
- Lattice-QCD (Quenched) [APE, UKQCD, FNAL, JLQCD]
- Lattice-QCD (Unquenched) [HPQCD, FNAL]
- Lattice-QCD and phenomenological models [Becirevic, Kaidalov]

BELLE & BABAR Analysis (in units of 10^{-3})

$$|V_{ub}|_{\text{Ball\&Zwicky}} = (3.40 \pm 0.11 + 0.66 - 0.42)$$

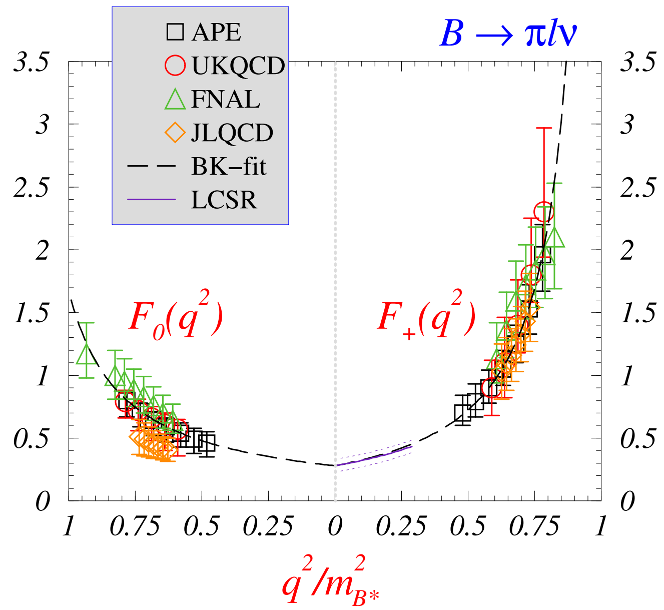
$$|V_{ub}|_{\text{APE}} = (3.58 \pm 0.12 + 1.10 - 0.57)$$

$$|V_{ub}|_{\text{FNALQCD}} = (3.79 \pm 0.13 + 0.87 - 0.52)$$

$$|V_{ub}|_{\text{HPQCD}} = (3.86 \pm 0.13 + 0.83 - 0.50)$$

- $|V_{ub}|_{\text{exclusive}} = (3.84^{+0.67}_{-0.49}) \times 10^{-3}$ [PDG 2006 Average]

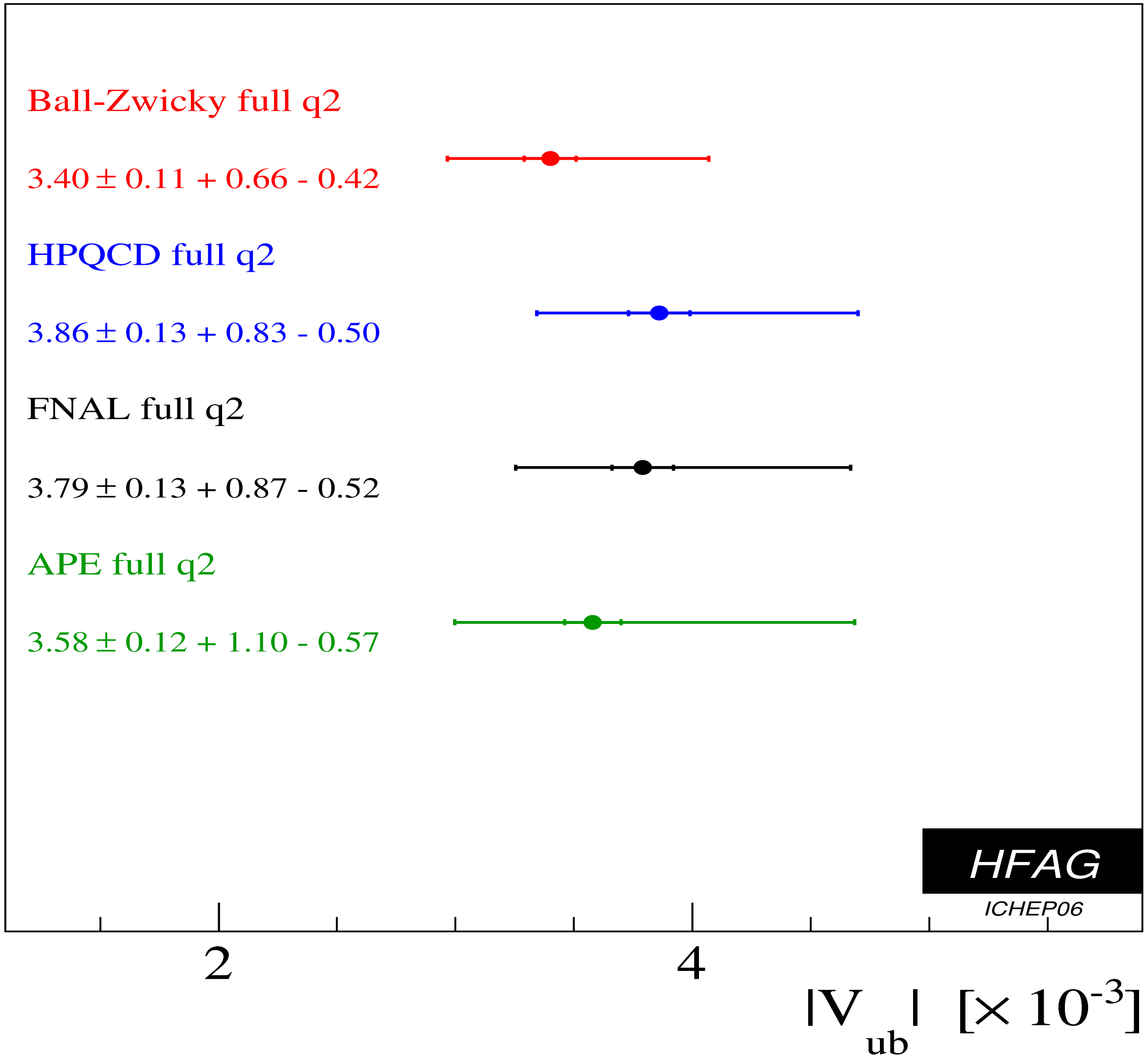
[Becirevic]



- $|V_{ub}|_{\text{excl}}$ smaller than $|V_{ub}|_{\text{incl}}$

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

(HFAG: ICHEP 2006 Update)



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]
  $\Longrightarrow |V_{ub}| = (4.31 \pm 0.30) \times 10^{-3}$ [PDG 2006; Average]

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

$$1 - (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2) = (1 \pm 1) \times 10^{-3} \text{ [Blucher et al., CKM 2005]}$$

- $|V_{cd}| = 0.230(11)$ [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]
  $\Longrightarrow |V_{cb}| = (41.6 \pm 0.60) \times 10^{-3}$ [PDG 2006; Average]

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

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

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

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) ($x_t = m_t^2/m_W^2$)

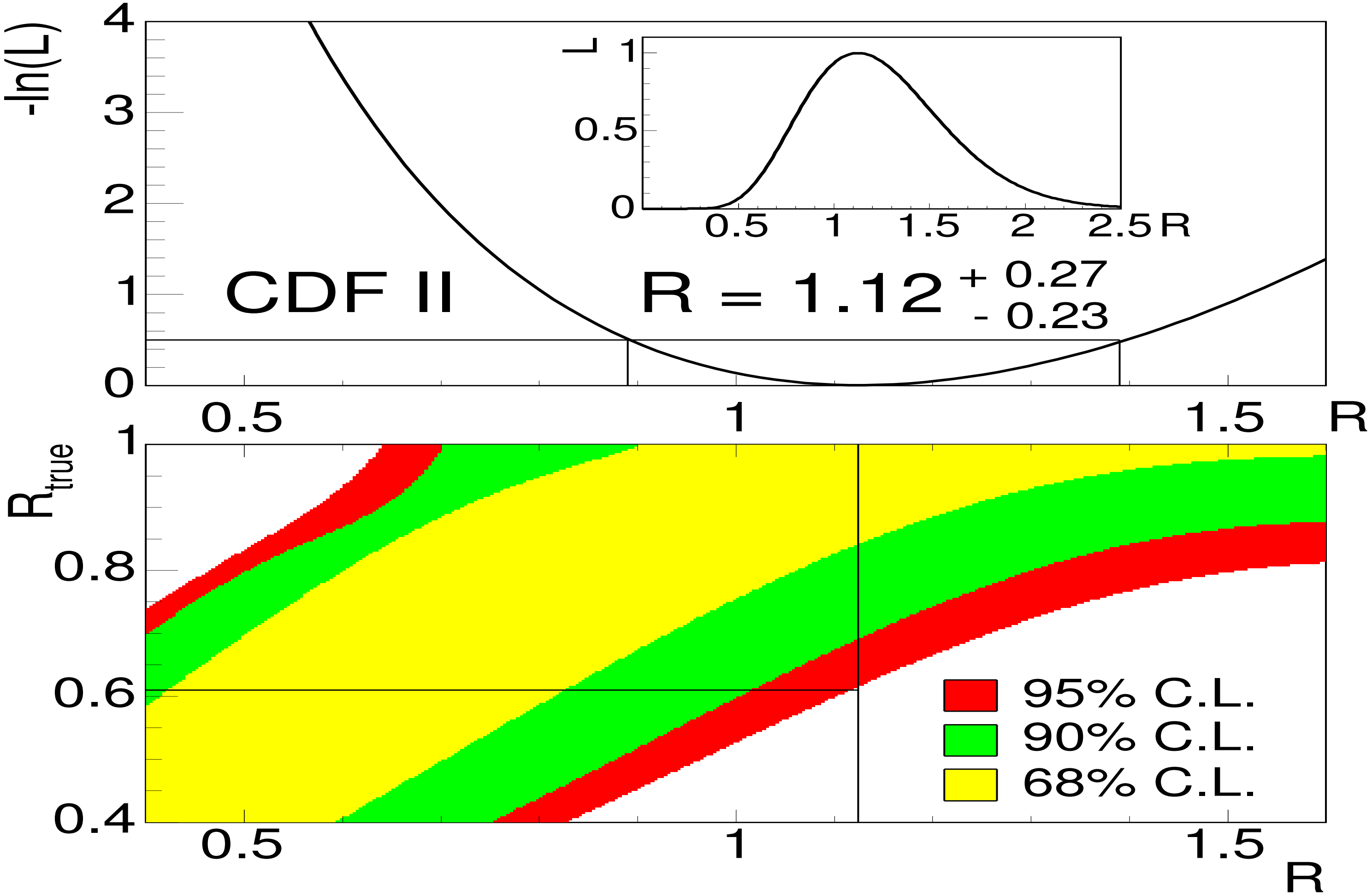
$$\Delta M_d = \frac{G_F^2}{6\pi^2} \hat{\eta}_B |V_{td} V_{tb}^*|^2 M_{B_d} (f_{B_d}^2 \hat{B}_{B_d}) M_W^2 S_0(x_t)$$

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

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

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

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



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

- 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; $S_0(x_t) = 2.29(5)$

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

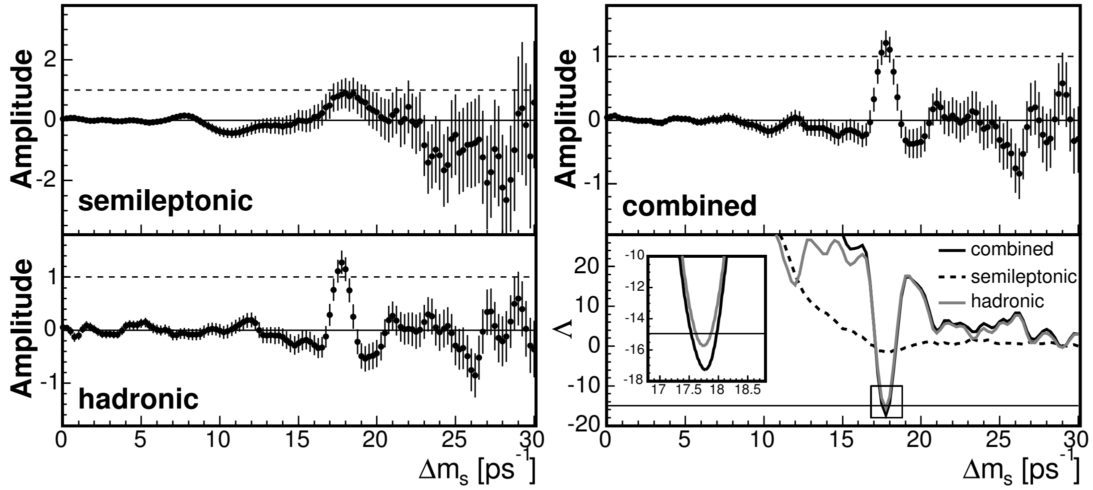
  - Lattice-QCD & SM $\Longrightarrow$ $|V_{td}{}^* V_{tb}| = (7.4 \pm 0.8) \times 10^{-3}$ [PDG 2006]

- 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 $\xi = 1.21^{+0.047}_{-0.035}$ [Lattice-QCD (Okamoto et al.)]

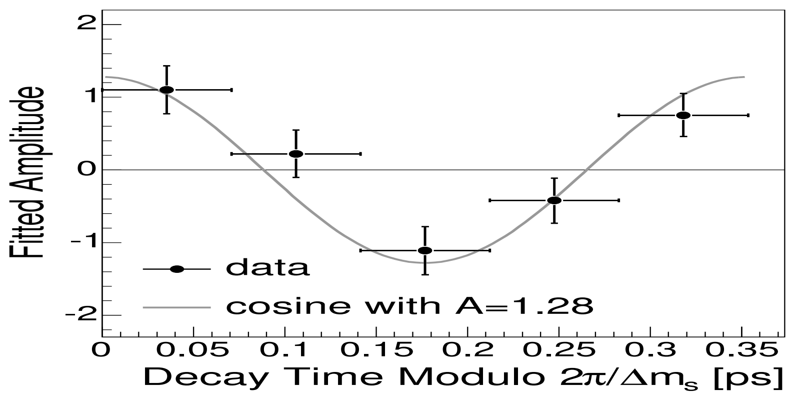
$$\frac{\Delta M_s}{\Delta M_d} = \xi \frac{M_{B_s}}{M_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2}; \quad \xi = \sqrt{\frac{f_{B_s}^2 \hat{B}_{B_s}}{f_{B_d}^2 \hat{B}_{B_d}}}$$

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

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]

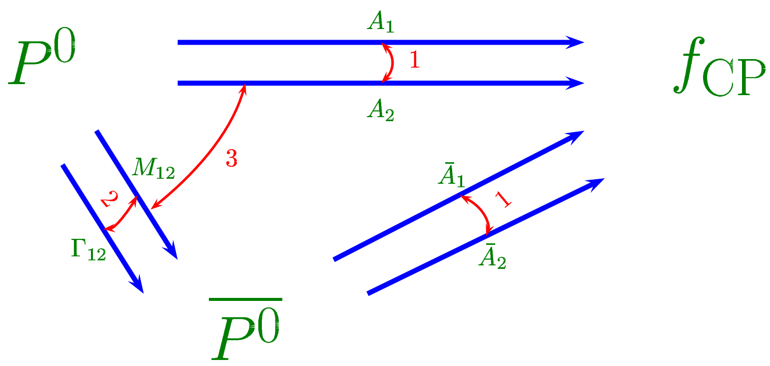
- Lattice QCD Calculation [HPQCD; hep-lat/0610104]

  $f_{B_s}\sqrt{\hat{B}_{B_s}} = 0.281(21)$ 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

CP violation in neutral meson decay into a CP eigenstate



1. In decay: $\bar{A}/A \neq 1$ $\left(\frac{\bar{A}}{A} = \frac{\bar{A}_1+\bar{A}_2}{A_1+A_2}\right)$
   (For example, A_1 is a Tree amplitude & A_2 is Penguin)
2. In mixing: $|q/p| \neq 1$ $\left(\frac{q}{p} = \frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta m - (i/2)\Delta\Gamma}\right)$
3. In interference: $\mathcal{I}m\lambda \neq 1$ $\left(\lambda = \frac{q}{p}\frac{\bar{A}}{A}\right)$

- The case theorists love!
  - Decay dominated by a single CPV phase: $|\frac{\bar{A}}{A}| = 1$;
  - CPV in mixing negligible $|\frac{q}{p}| = 1$;
  - The remaining eefect is: $S_f \sim \sin[\arg(M_{12}) - 2\arg(A)] = 1$

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

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

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

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

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

- Definitions:

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

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

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

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

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

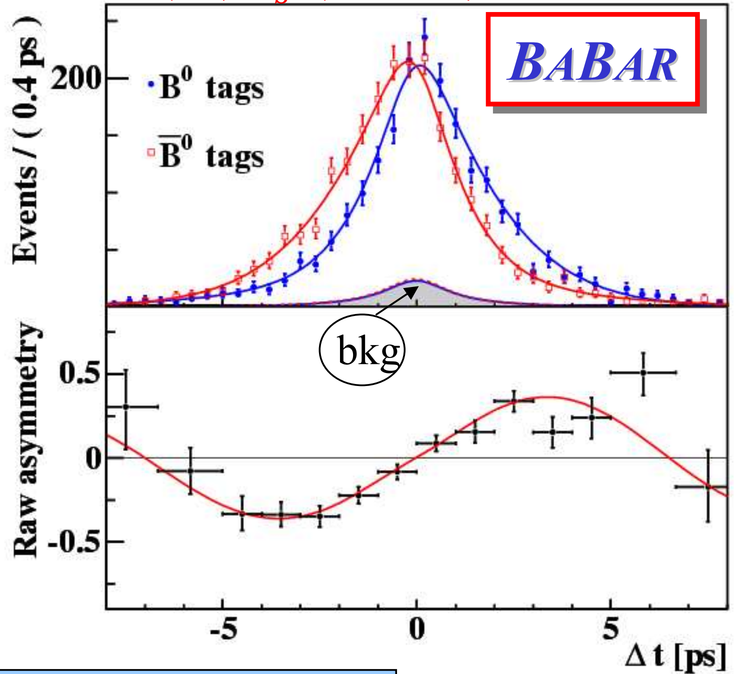
where $\eta_f = \pm 1$ is the intrinsic CP-Parity of the state $f \Rightarrow |\rho(f)| = 1$

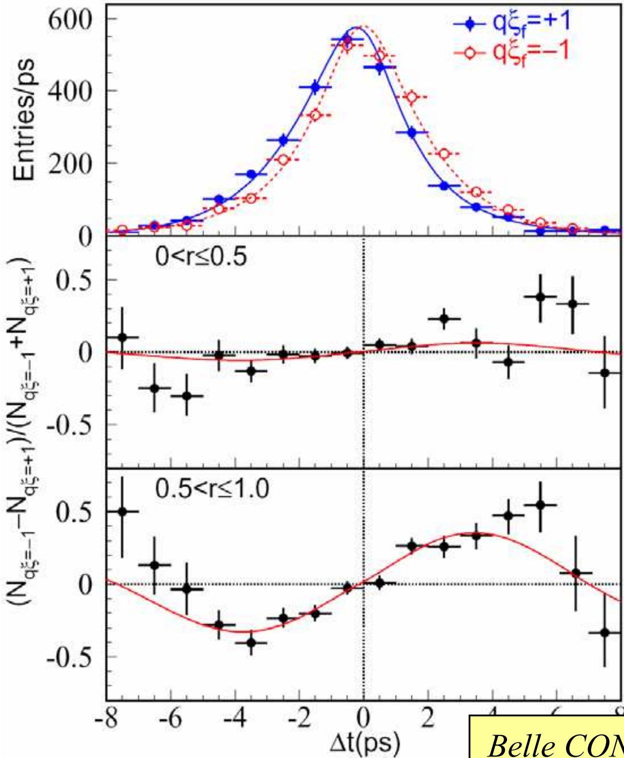
$$\mathcal{A}_f(t) = S_f \sin(\Delta M_B t); \quad S_f = -\eta_f \sin 2(\phi_{\mathrm{mixing}} + \phi_{\mathrm{decay}}); \quad C_f = 0$$

CPV in B-Decays-1

$\sin 2\beta$ results from charmonium modes

$(c\bar{c})K_S^0$ (CP odd) modes





Belle 2003

Update for ICHEP04 *BABAR PUB-04/038* *Belle CONF-0436*

BABAR		Belle
$\sin 2\beta = +0.722 \pm 0.040 \pm 0.023$	$(c\bar{c})K_S^0 +$	$\sin 2\beta = +0.728 \pm 0.056 \pm 0.023$
$\lvert\lambda\rvert = \lvert\bar{A}/A\rvert = 0.950 \pm 0.031 \pm 0.013$	$(c\bar{c})K_L^0$	$\lvert\lambda\rvert = \lvert\bar{A}/A\rvert = 1.007 \pm 0.041 \pm 0.033$

Limit on direct CPV

$205\ fb^{-1}$ on peak or $227M\ B\bar{B}$ pairs — 7730 CP events (tagged signal)

$140\ fb^{-1}$ on peak or $152M\ B\bar{B}$ pairs — 4347 CP events (tagged signal)

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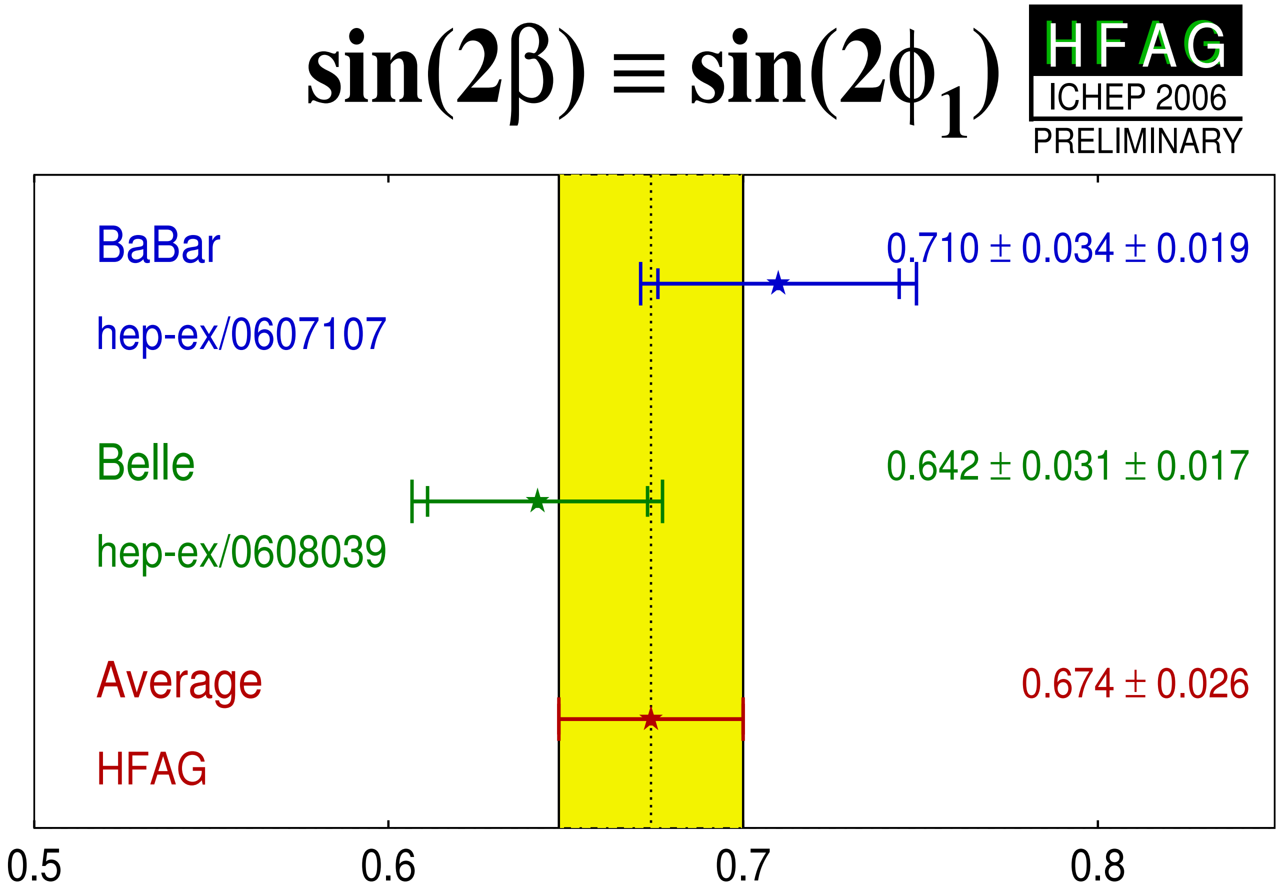
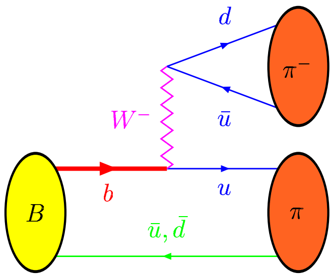
Current World Average [ICHEP 2006]



$B \to \pi\pi$ *Topologies*

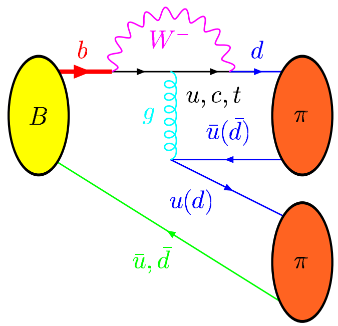
Dominant topologies contributed within the Standard Model

Tree ($\mathcal{T}$)



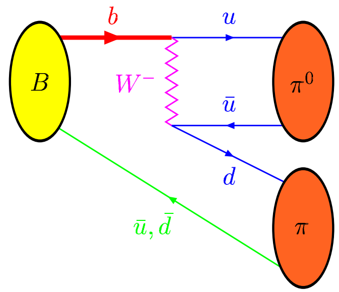
$B^- \to \pi^- \pi^0$
$\bar{B}^0 \to \pi^+ \pi^-$

Penguin ($\mathcal{P}$)



$\bar{B}^0 \to \pi^+ \pi^-$
$\bar{B}^0 \to \pi^0 \pi^0$

Color-suppressed ($\mathcal{C}$)



$B^- \to \pi^- \pi^0$
$\bar{B}^0 \to \pi^0 \pi^0$

Subdominant topologies:

- exchange ($\mathcal{E}$) $\Longrightarrow$ $\bar{B}^0 \to \pi^+\pi^-,\ \pi^0\pi^0$
- annihilation ($\mathcal{A}$) $\Longrightarrow$ $B^- \to \pi^-\pi^0$
- penguin-annihilation ($\mathcal{PA}$) $\Longrightarrow$ $\bar{B}^0 \to \pi^+\pi^-,\ \pi^0\pi^0$
- electroweak-penguin ($\mathcal{P}_{\rm EW}$) $\Longrightarrow$ $B^- \to \pi^-\pi^0,\ \bar{B}^0 \to \pi^0\pi^0$
- color-suppressed electroweak-penguin ($\mathcal{P}^C_{\rm EW}$) $\Longrightarrow$ $\bar{B}^0 \to \pi^+\pi^-,\ \pi^0\pi^0$

Parameterization of Tree and Penguin Amplitudes

[Gronau, Rosner; Fleischer, Buras; Gronau, Pirjol, Yan;...]

- $B \to \pi\pi$ amplitudes
- In the (Gronau-Rosner c-) convention, amplitudes are

$$
\begin{aligned}
\sqrt{2}\,A^{+0} &= -\,(T+C) = -|T|\,\mathrm{e}^{i\delta_T}\,\mathrm{e}^{i\gamma}\left[1+|C/T|\,\mathrm{e}^{i\Delta}\right] \\
A^{+-} &= -\,(T+P) = -|T|\,\mathrm{e}^{i\delta_T}\left[\mathrm{e}^{i\gamma}+|P/T|\,\mathrm{e}^{i\delta}\right] \\
\sqrt{2}\,A^{00} &= -\,(C-P) = -|T|\,\mathrm{e}^{i\delta_T}\left[|C/T|\,\mathrm{e}^{i\Delta}\,\mathrm{e}^{i\gamma}-|P/T|\,\mathrm{e}^{i\delta}\right]
\end{aligned}
$$

- Charged-conjugate amplitudes $\bar{A}^{ij}$ differ by the replacement $\gamma \to -\gamma$
- 5 dynamical parameters: $|T|$, $r \equiv |P/T|$, δ, $|C/T|$, Δ
  ($\delta_T = 0$ for the overall phase assumed)
- Weak phase γ can be extracted if the complete set of experimental data on $B \to \pi\pi$ decays available. This is not the case at present

Isospin Relations

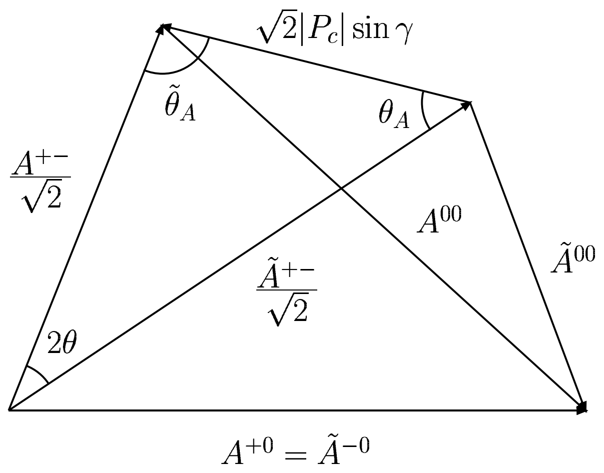
[Gronau, London]

- Effective Hamiltonian for $b \to d$ transitions ($\lambda_p^{(d)} = V_{pb} V_{pd}^*$)

$$\mathcal{H}_W^{b\to d} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p^{(d)} \left(C_1\, \mathcal{O}_1^{(p)} + C_2\, \mathcal{O}_2^{(p)} + \sum_{i=3}^{10} C_i\, \mathcal{O}_i + C_{7\gamma}\, \mathcal{O}_{7\gamma} + C_{8g}\, \mathcal{O}_{8g} \right)$$

- $B \to \pi\pi$ decay amplitudes (subdominant topologies are neglected):

$$\begin{aligned} A^{+0} &= A(B^+ \to \pi^+\pi^0) = -\frac{1}{\sqrt{2}}\,(\mathcal{T} + \mathcal{C}) \\ A^{+-} &= A(B^0 \to \pi^+\pi^-) = -\,(\mathcal{T} + \mathcal{P}) \\ A^{00} &= A(B^0 \to \pi^0\pi^0) = \frac{1}{\sqrt{2}}\,(\mathcal{P} - \mathcal{C}) \end{aligned}$$



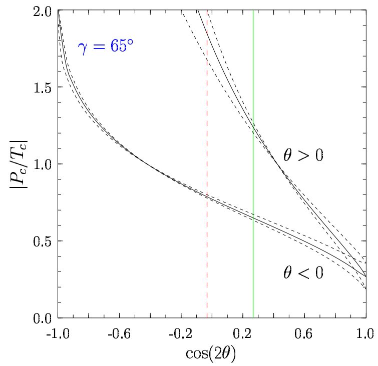
- The amplitudes A^{ij} and their charged-conjugates $\bar{A}^{ij}$ obey the isospin relations

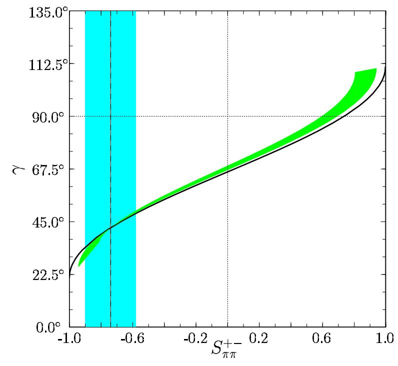
$$A^{+0} = \frac{1}{\sqrt{2}}\, A^{+-} + A^{00}, \qquad \bar{A}^{-0} = \frac{1}{\sqrt{2}}\, \bar{A}^{+-} + \bar{A}^{00}$$

Bounds on $B \to \pi\pi$ Decays in the SM

Based on the Quantities

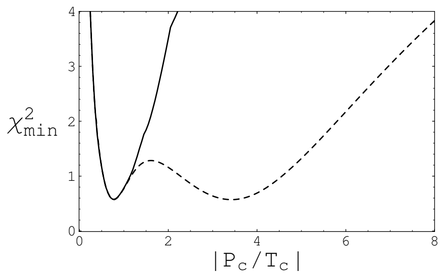
- $B^{ij} \equiv \left(|A^{ij}|^2 + |\bar{A}^{ij}|^2\right)/2$
- $C \equiv \left(|A^{+-}|^2 - |\bar{A}^{+-}|^2\right) / \left(|A^{+-}|^2 + |\bar{A}^{+-}|^2\right)$
- $Y \equiv 2|A^{+-}||\bar{A}^{+-}| / \left(|A^{+-}|^2 + |\bar{A}^{+-}|^2\right)$
- $S \equiv Y \sin(2\alpha_{\rm eff}) \equiv Y \sin(2\alpha + 2\theta)$
- $C^2 + S^2 = 1 - Y^2 \cos^2(2\alpha_{\rm eff}) \leq 1$





Bounds on Penguin Pollution

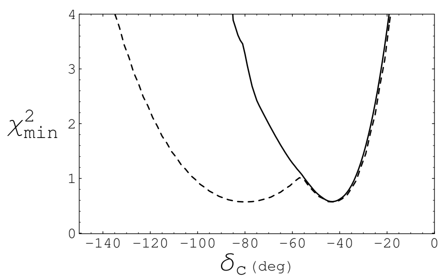
- Grossman and Quinn $\cos(2\theta) \geq 1 - 2B^{00}/B^{+0}$
- Charles $\cos(2\theta) \geq \left[1 - 2B^{00}/B^{+0}\right]/Y$
  $\cos(2\theta) \geq \left[1 - 4B^{00}/B^{+-}\right]/Y$



- Gronau, London, Sinha, Sinha (GLSS)

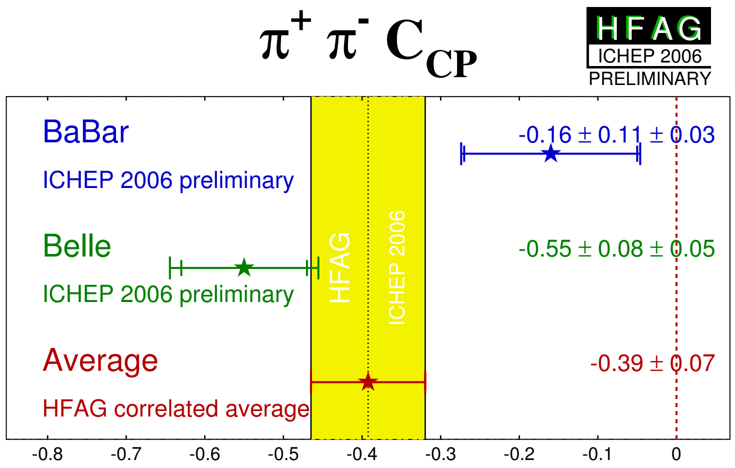
$$\cos(2\theta) \geq \left[(B^{+-}/2 + B^{+0} - B^{00})^2/(B^{+-}B^{+0}) - 1\right]/Y$$

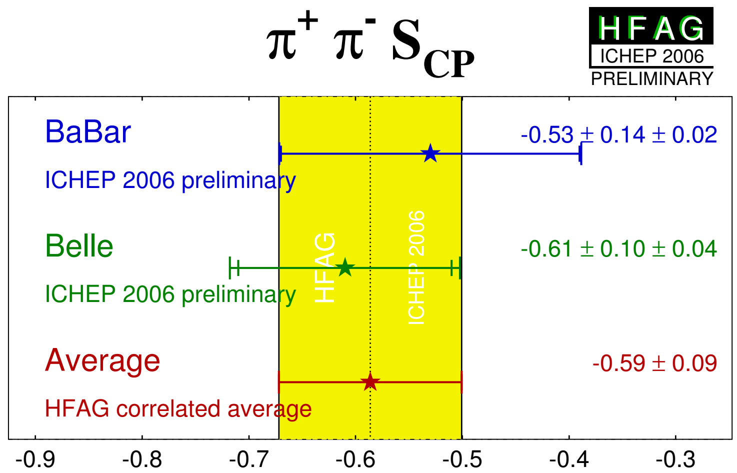
Bounds on the angle γ



- Buchalla and Safir $\tan\gamma \geq \frac{\cos(2\beta) + \sqrt{1-S^2}}{\sin(2\beta) - S}$
- Botella and Silva $\tan\gamma \geq \frac{1 + \sqrt{Y^2 - S^2}\cos(2\beta) + S\sin(2\beta)}{\sqrt{Y^2 - S^2}\sin(2\beta) - S\cos(2\beta)}$

Current Data on $B \to \pi\pi$ Decays





- $BR(B^0 \to \pi^+\pi^-) = (5.2 \pm 0.2) \times 10^{-6}$
- $BR(B^+ \to \pi^+\pi^0) = (5.7 \pm 0.4) \times 10^{-6}$
- $BR(B^0 \to \pi^0\pi^0) = (1.3 \pm 0.2) \times 10^{-6}$
- $A_{\rm CP}(B^+ \to \pi^+\pi^0) = 0.04 \pm 0.05$
- $A_{\rm CP}(B^0 \to \pi^0\pi^0) = 0.36^{+0.33}_{-0.31}$

- **These measurements are combined with isospin analysis to determine α**

Time-dependent decays of $B^0 \to \pi^+\pi^-\pi^0$

$$|A(\Delta t; s_+, s_-)|^2 = e^{-\Gamma|\Delta t|}\left\{(|A_{3\pi}|^2 + |\overline{A}_{3\pi}|^2)\right.$$
$$\left. - Q_{\rm tag}(|A_{3\pi}|^2 - |\overline{A}_{3\pi}|^2)\cos(\Delta m_d \Delta t) + Q_{\rm tag}\, 2\,{\rm Im}\,[\frac{q}{p}A^*_{3\pi}\overline{A}_{3\pi}]\sin(\Delta m_d\Delta t)\right\}$$

$Q_{\rm tag} = +1(-1)$ for the tagged meson being B^0 ($\overline{B^0}$)

- $B^0 \to \pi^+\pi^-\pi^0$ dominated by $(\rho\pi)^0$
- 3 Decay Modes: $B^0 \to \rho^+\pi^-$; $B^0 \to \rho^-\pi^+$; $B^0 \to \rho^0\pi^0$

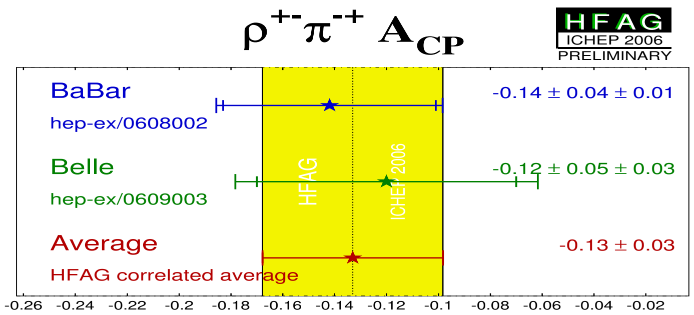
$$\begin{aligned} A_{3\pi}(s_+, s_-) &= f_+(s_+, s_-)A^+ + f_-(s_+, s_-)A^- + f_0(s_+, s_-)A^0 \\ \frac{q}{p}\overline{A}_{3\pi}(s_+, s_-) &= \overline{f}_+(s_+, s_-)\overline{A}^+ + \overline{f}_-(s_+, s_-)\overline{A}^- + \overline{f}_0(s_+, s_-)\overline{A}^0 \end{aligned}$$

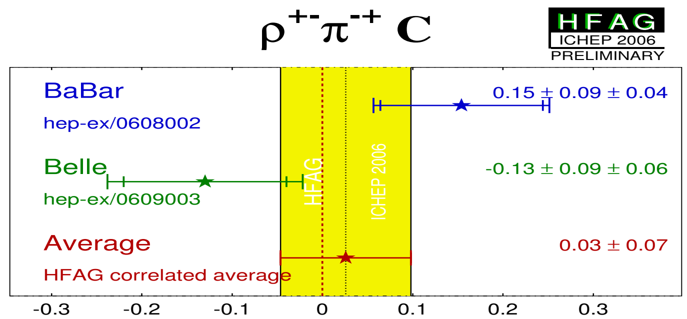
- Time-dependent amplitude analysis involves 27 coefficients involving the products of the complex amplitudes A^k and $\overline{A}^k$; determined by the fit to the data
- Time-dependent decay width:

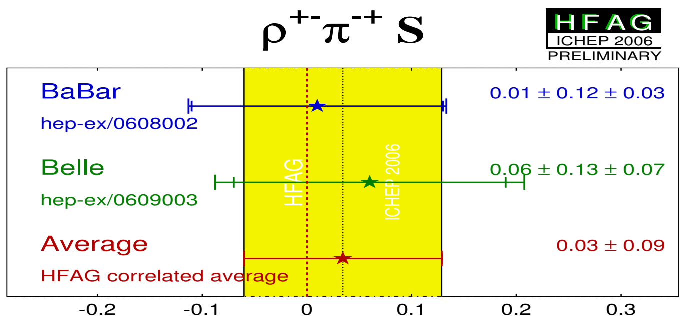
$$\Gamma(B^0 \to \rho^\pm\pi^\mp(\Delta t)) = (1 \pm A_{\rm CP}(\rho\pi))e^{-|\Delta t|/\tau}/8\tau$$
$$\times[1 + Q_{\rm tag}(S_{\rho\pi} \pm \Delta S_{\rho\pi})\sin(\Delta m\Delta t) - Q_{\rm tag}(C_{\rho\pi} \pm \Delta C_{\rho\pi})\cos(\Delta m\Delta t)]$$

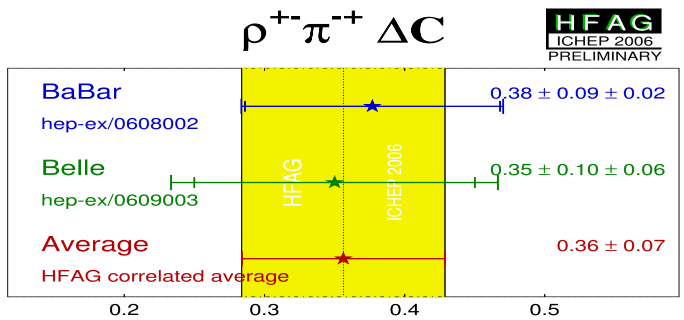
- CP is violated if either of the following holds: $A_{\rm CP} \neq 0$, $C_{\rho\pi} \neq 0$, $S_{\rho\pi} \neq 0$

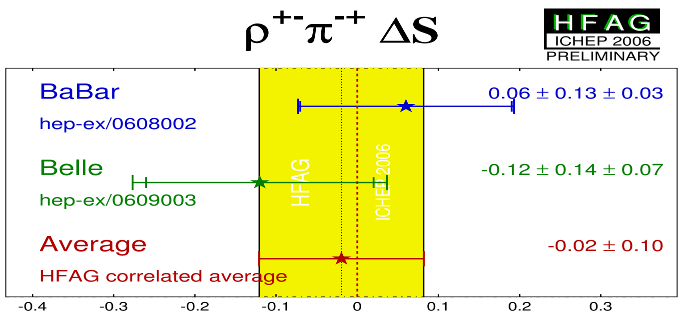
$B^0 \to \pi^+\pi^-\pi^0$ time-dependent Dalitz Analysis





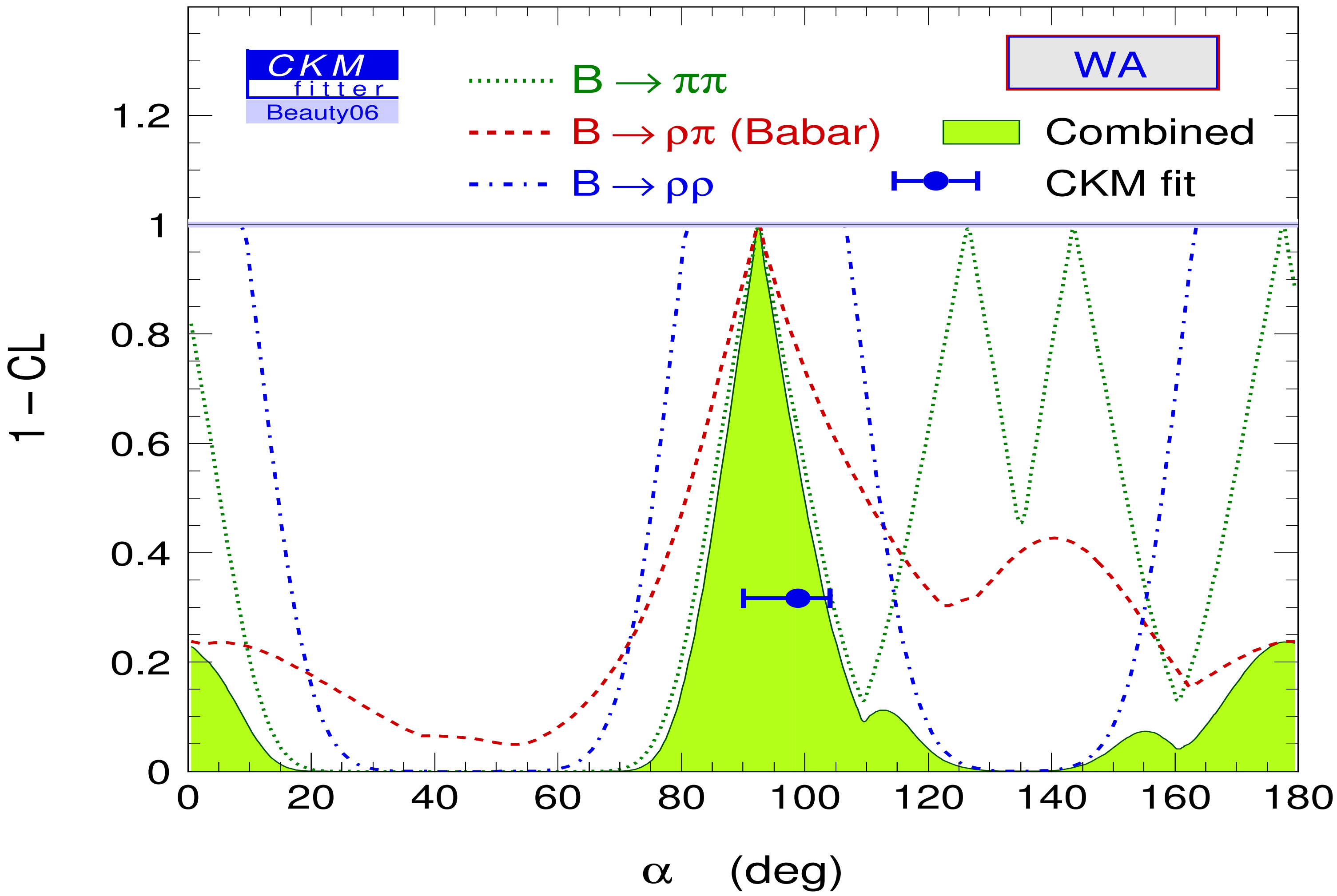






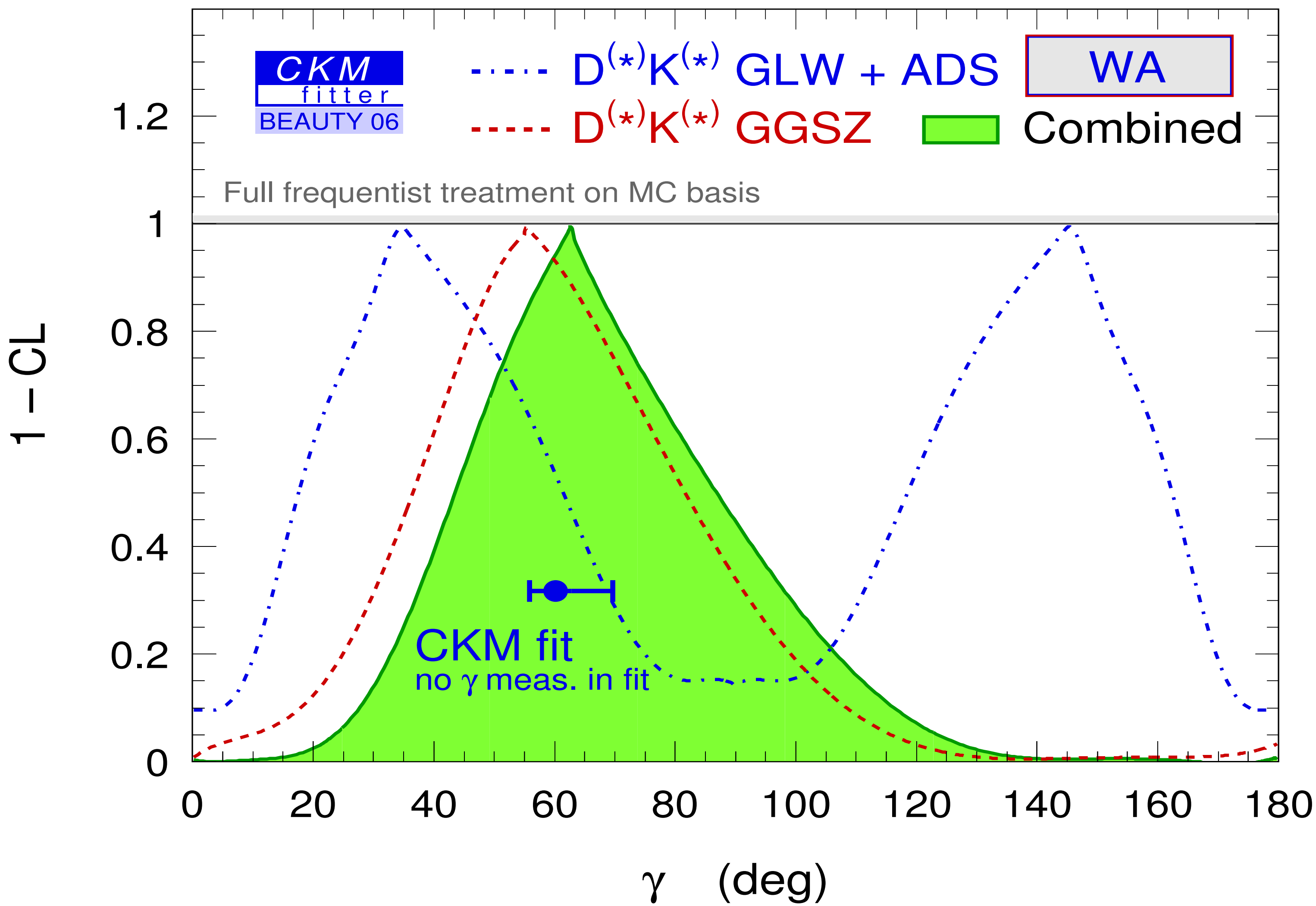
BABAR: $75^\circ < \alpha < 152^\circ$; **BELLE:** $\alpha = (83^{+12}_{-23})^\circ$

Current World Average of α [CKMfitter 2006]



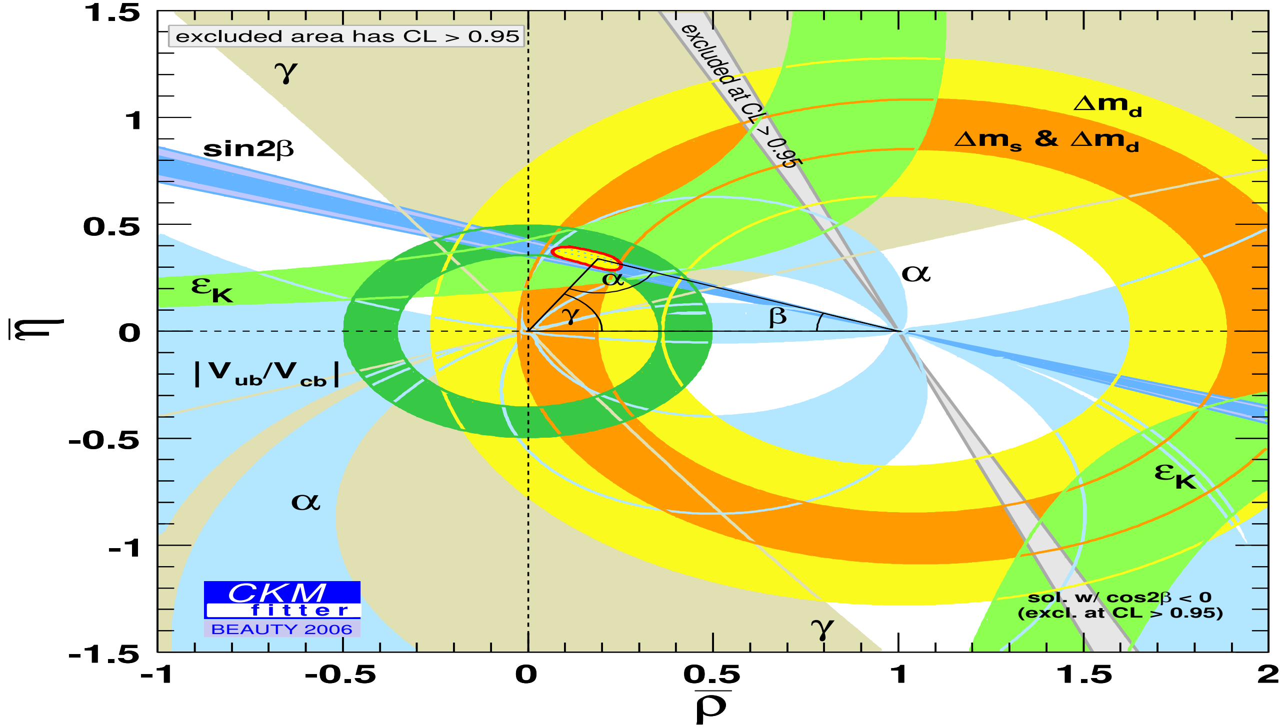
ICHEP 2006 Update: $\alpha = [92.6^{+10.7}_{-9.3}]^\circ$ [Direct Measurements]

Current World Average of γ [CKMfitter 2006]



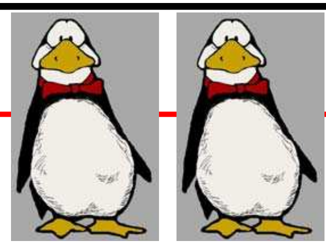
ICHEP 2006 Update: $\gamma = [60^{+38}_{-24}]^\circ$ [Direct Measurements]

Current Status of the CKM-Unitarity Triangle

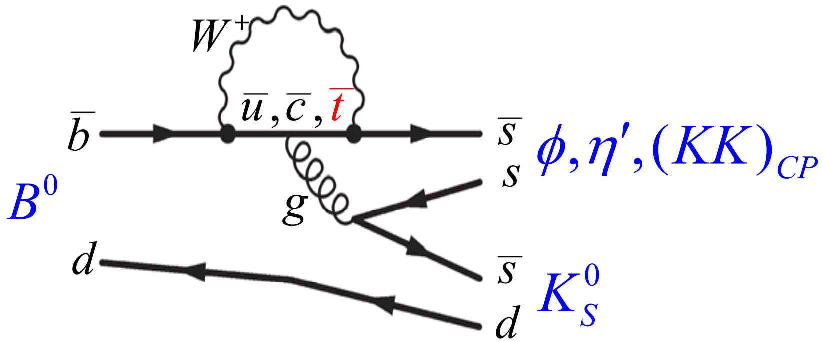


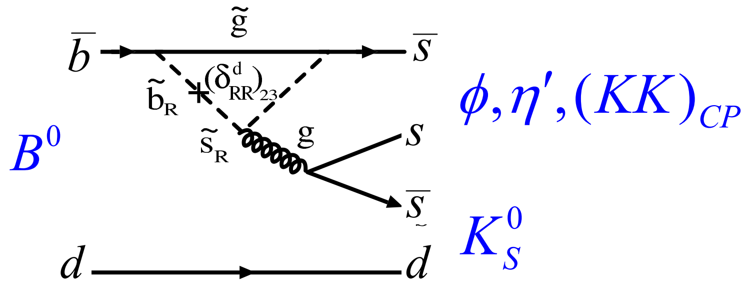
- $\sin 2\beta = 0.675 \pm 0.026 (\beta = [21.23^{+1.03}_{-0.99}]^\circ)$ [Direct Measurement]
  $\beta = [22.03^{+0.72}_{-0.62}]^\circ)$ [Fit-value]
- $\alpha = [92.6^{+10.7}_{-9.3}]^\circ$ [Direct Measurement]
  $\alpha = [99.0^{+4.0}_{-9.4}]^\circ$ [Fit-value]
- $\gamma = [60^{+38}_{-24}]^\circ$[Direct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

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

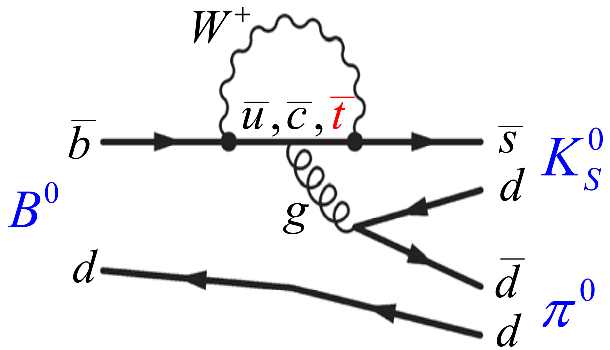
$\sin 2\beta$ and...  and.... 

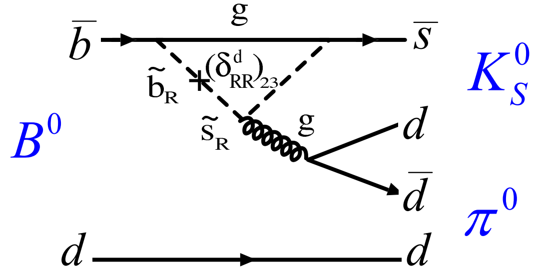
In SM interference between B mixing, K mixing and Penguin $b \to s\bar{s}s$ or $b \to s\bar{d}d$ gives the same $e^{-2i\beta}$ as in tree process $b \to c\bar{c}s$. However loops can also be sensitive to New Physics!





New phases from SUSY?





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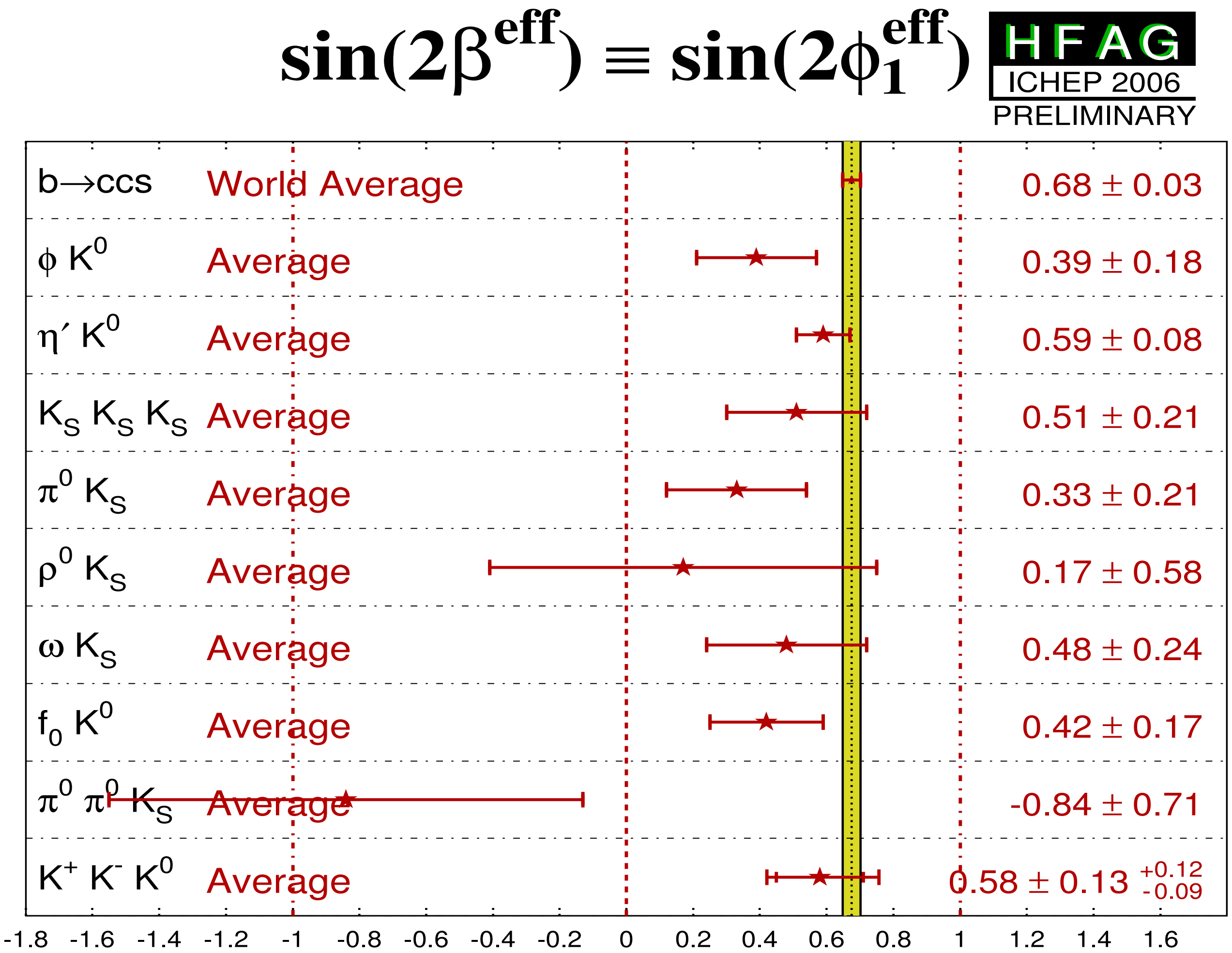
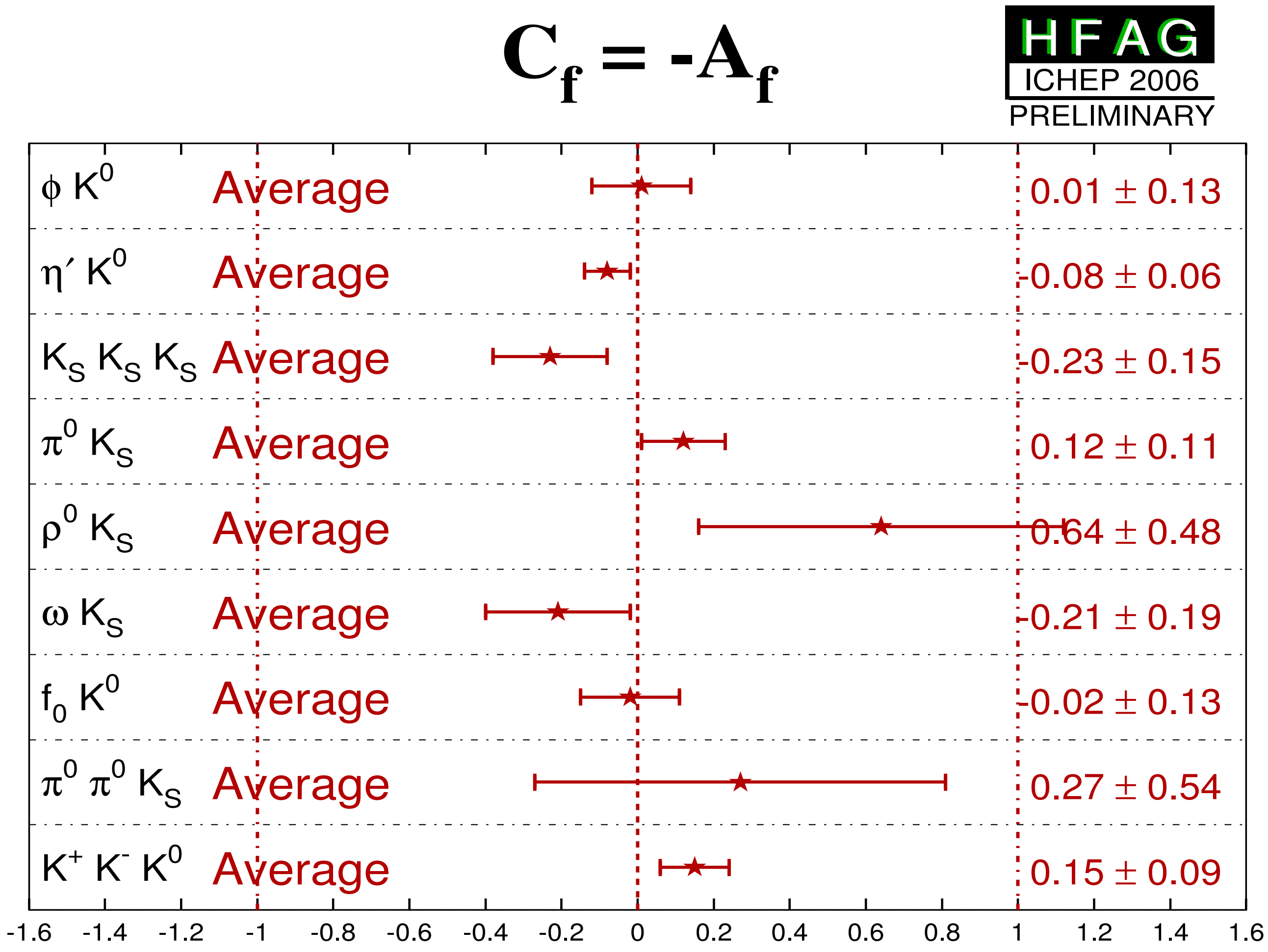
$S_{b\to q\bar{q}s}$ [HFAG 2006; ICHEP 2006 Update]



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



Interest in Rare B Decays

- Rare B Decays $(b \to s\gamma, b \to s\ell^+\ell^-, ...)$ are Flavour-Changing-Neutral-Current (FCNC) processes $(|\Delta B| = 1, |\Delta Q| = 0)$; not allowed at the Tree level in the SM
- FCNC processes are governed by the GIM mechanism, which imparts them sensitivity to higher scales (m_t, m_W) and the CKM matrix elements, in particular, $V_{ti}; i = d, s, b$
- FCNC processes are sensitive to physics beyond the SM, such as supersymmetry, and the BSM amplitudes can be comparable to the (tW)-part of the GIM amplitudes
- Last, but not least, Rare B-decays enjoy great interest in the ongoing and planned experimental programme in heavy quark physics (CLEO, BABAR, BELLE, CDF, D0, LHC, Super-B factory)

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- and SuperB-factories
- 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:

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

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

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

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 $\mu_b \sim m_b$

Wilson Coefficients

Wilson Coefficients of Four-Quark Operators

	$C_1(\mu_b)$	$C_2(\mu_b)$	$C_3(\mu_b)$	$C_4(\mu_b)$	$C_5(\mu_b)$	$C_6(\mu_b)$
LL	-0.257	1.112	0.012	-0.026	0.008	-0.033
NLL	-0.151	1.059	0.012	-0.034	0.010	-0.040

Wilson Coefficients of Other Operators

	$C_7^{\text{eff}}(\mu_b)$	$C_8^{\text{eff}}(\mu_b)$	$C_9(\mu_b)$	$C_{10}(\mu_b)$
LL	-0.314	-0.149	2.007	0
NLL	-0.308	-0.169	4.154	-4.261
NNLL			4.214	-4.312

- Obtained for the following input:

$$\mu_b = 4.6 \text{ GeV} \qquad \bar{m}_t(\bar{m}_t) = 167 \text{ GeV}$$

$$M_W = 80.4 \text{ GeV} \qquad \sin^2\theta_W = 0.23$$

- Three-loop running is used for α_s coupling with $\Lambda_{\overline{\text{MS}}}^{(5)} = 220$ GeV

Experimental data

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

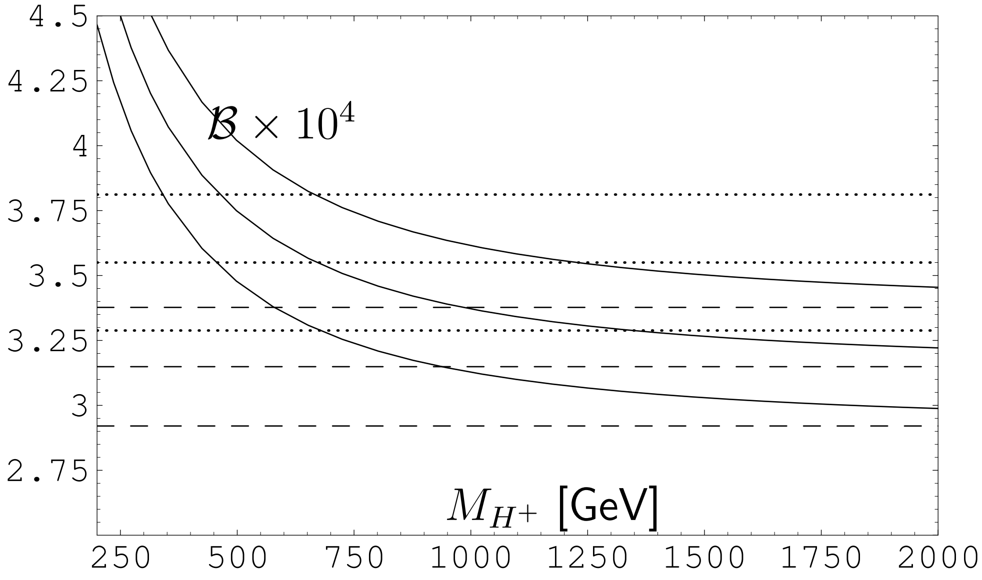
Branching ratios (in units of 10^{-6}) [August 2006]

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]

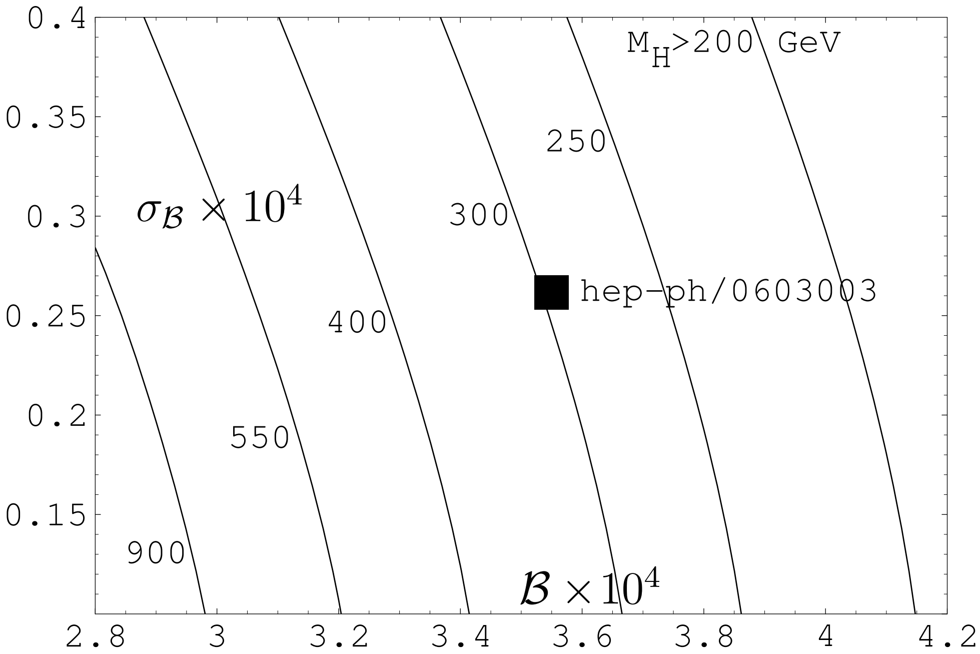


[$\cdots$ (exp); — — —— (SM); solid (2HDM)]

- 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]



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

- 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.

- Wilson Coefficients of the two additional operators

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

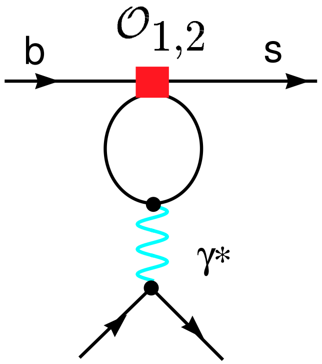
have the following perturbative expansion:

$$C_9(\mu) = \frac{4\pi}{\alpha_s(\mu)} C_9^{(-1)}(\mu) + C_9^{(0)}(\mu) + \frac{\alpha_s(\mu)}{4\pi} C_9^{(1)}(\mu) + \ldots$$

$$C_{10} = C_{10}^{(0)} + \frac{\alpha_s(M_W)}{4\pi} C_{10}^{(1)} + \ldots$$

- 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: $C_9^{(0)}(m_b) \simeq 2.2$; need to calculate NNLO

Inclusive $B \to X_s \ell^+ \ell^-$ in NNLO in SM

Dilepton Invariant Mass

$$\frac{d\Gamma(b \to X_s \ell^+ \ell^-)}{d\hat{s}} = \left(\frac{\alpha_{em}}{4\pi}\right)^2 \frac{G_F^2 m_{b,pole}^5 \left|V_{ts}^* V_{tb}\right|^2}{48\pi^3} (1-\hat{s})^2$$
$$\times \left((1+2\hat{s}) \left(\left|\tilde{C}_9^{\text{eff}}\right|^2 + \left|\tilde{C}_{10}^{\text{eff}}\right|^2 \right) + 4\,(1+2/\hat{s}) \left|\tilde{C}_7^{\text{eff}}\right|^2 + 12\text{Re}\left(\tilde{C}_7^{\text{eff}} \tilde{C}_9^{\text{eff}*} \right) \right)$$

$$\begin{aligned}
\tilde{C}_7^{\text{eff}} &= \left(1 + \frac{\alpha_s(\mu)}{\pi}\omega_7(\hat{s})\right) A_7 \\
&\quad - \frac{\alpha_s(\mu)}{4\pi}\left(C_1^{(0)} F_1^{(7)}(\hat{s}) + C_2^{(0)} F_2^{(7)}(\hat{s}) + A_8^{(0)} F_8^{(7)}(\hat{s})\right) \\
\tilde{C}_9^{\text{eff}} &= \left(1 + \frac{\alpha_s(\mu)}{\pi}\omega_9(\hat{s})\right) \left(A_9 + T_9\, h(\hat{m}_c^2, \hat{s}) + U_9\, h(1, \hat{s}) + W_9\, h(0, \hat{s})\right) \\
&\quad - \frac{\alpha_s(\mu)}{4\pi}\left(C_1^{(0)} F_1^{(9)}(\hat{s}) + C_2^{(0)} F_2^{(9)}(\hat{s}) + A_8^{(0)} F_8^{(9)}(\hat{s})\right) \\
\tilde{C}_{10}^{\text{eff}} &= \left(1 + \frac{\alpha_s(\mu)}{\pi}\omega_9(\hat{s})\right) A_{10}
\end{aligned}$$

- A_7, A_8, A_9, A_{10}, T_9, U_9, W_9 are linear combinations of the Wilson coefficients

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

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

$$\mathcal{B}(B \to X_s\ell^+\ell^-) = (4.46^{+0.98}_{-0.96}) \times 10^{-6} \quad \text{[HFAG'06]}$$

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

- 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%

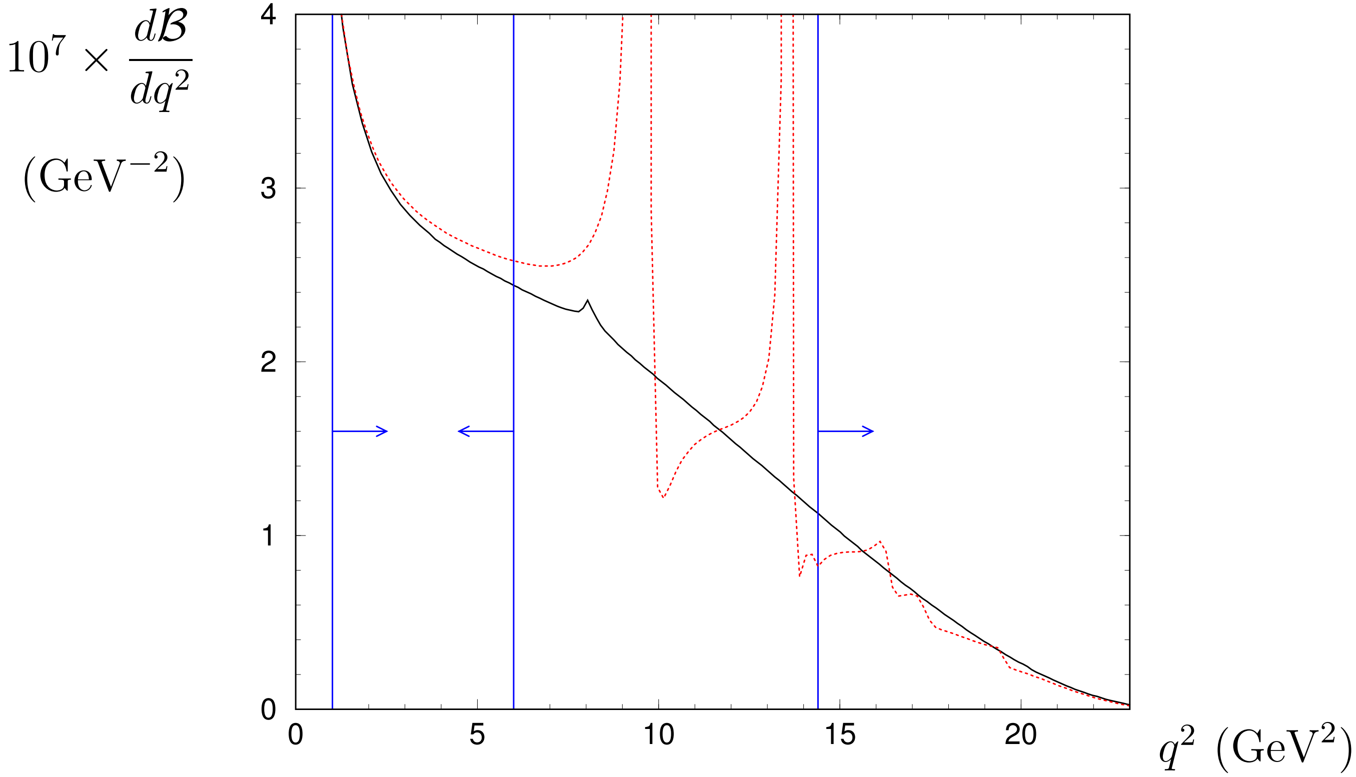
• Forward-Backward Asymmetry (FBA) is likewise sensitive to the SM and BSM effects, in particular encoded in the Wilson coefficients C_7, C_9 and C_{10}

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

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

Dilepton invariant mass distribution in $\bar{B} \to X_s \ell^+ \ell^-$:

[Ghinculov, Hurth, Isidori, Yao 2004]

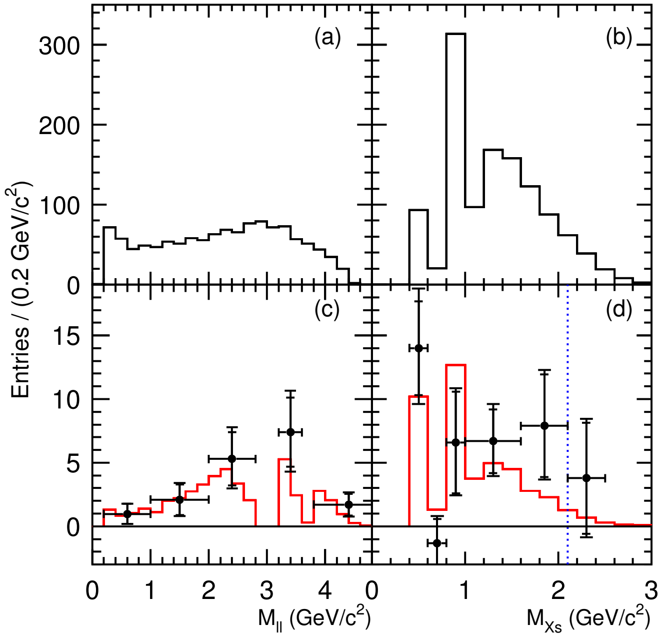


- $\mathbf{BR}(\bar{B} \to X_s \ell^+ \ell^-)$; $\quad q^2 \in [1,6]\ \mathrm{GeV}^2 = (1.63 \pm 0.20) \times 10^{-6}$
- $\mathbf{BR}(\bar{B} \to X_s \ell^+ \ell^-)$; $\quad q^2 > 14\ \mathrm{GeV}^2 = (4.04 \pm 0.78) \times 10^{-7}$
- $\mathbf{BR}(\bar{B} \to X_s \mu^+ \mu^-)$; $\quad q^2 > 4m_\mu^2 = (4.6 \pm 0.8) \times 10^{-6}$,
  in agreement with the earlier NNLO analysis
  [AA, Greub, Hiller, Lunghi 2001; Bobeth, Gambino, Gorbahn, Haisch, 2003]

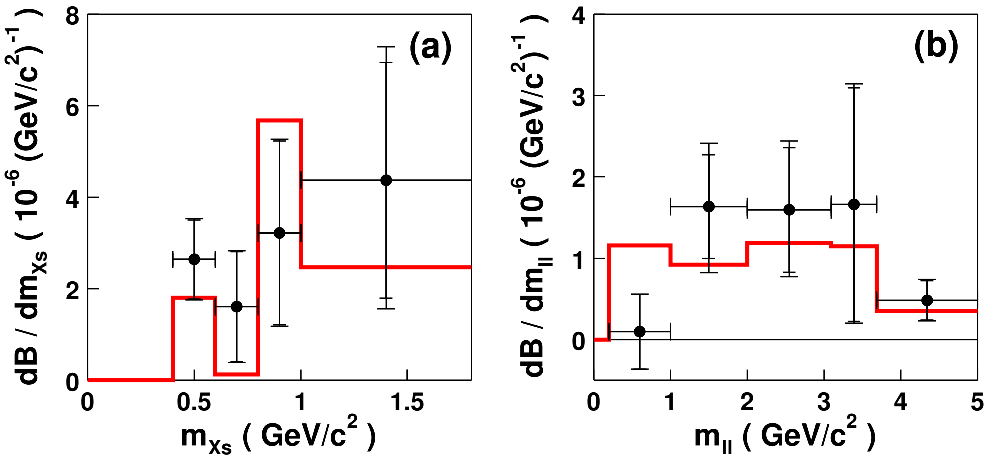
Decay distributions in $\bar{B} \to X_s \ell^+ \ell^-$

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

[BELLE]



[BABAR]



- In agreement with the NNLO SM calculations

NNLL-Forward-Backward Asymmetry in $B \to X_s \ell^+\ell^-$

[Asatrian, Bieri, Greub, Hovhannisyan; Ghinculov, Hurth, Isidori, Yao]

Normalized FB Asymmetry

$$\overline{A}_{\rm FB}(\hat{s}) = \frac{\int_{-1}^{1} \frac{d^2\Gamma(b\to X_s\,\ell^+\ell^-)}{d\hat{s}\,dz}\,\mathrm{sgn}(z)\,dz}{\int_{-1}^{1} \frac{d^2\Gamma(b\to X_s\,\ell^+\ell^-)}{d\hat{s}\,dz}\,dz}$$

Unnormalized FB Asymmetry

$$A_{\rm FB}(\hat{s}) = \frac{\int_{-1}^{1} \frac{d^2\Gamma(b\to X_s\,\ell^+\ell^-)}{d\hat{s}\,dz}\,\mathrm{sgn}(z)\,dz}{\Gamma(B \to X_c e \bar{\nu}_e)}\,\mathrm{BR}_{\rm sl}$$

$$\int_{-1}^{1} \frac{d^2\Gamma(b \to X_s\,\ell^+\ell^-)}{d\hat{s}\,dz}\,\mathrm{sgn}(z)\,dz = \left(\frac{\alpha_{\rm em}}{4\,\pi}\right)^2 \frac{G_F^2\, m_{b,\rm pole}^5\,\left|V_{ts}^* V_{tb}\right|^2}{48\,\pi^3}(1-\hat{s})^2$$
$$\times \left[-3\,\hat{s}\,\mathrm{Re}(\widetilde{C}_9^{\rm eff}\widetilde{C}_{10}^{\rm eff*})\left(1+\frac{2\alpha_s}{\pi}\,f_{910}(\hat{s})\right) - 6\,\mathrm{Re}(\widetilde{C}_7^{\rm eff}\widetilde{C}_{10}^{\rm eff*})\left(1+\frac{2\alpha_s}{\pi}\,f_{710}(\hat{s})\right)\right]$$

- NNLL Contributions stabilize the scale ($=\mu$) dependence of the FB Asymmetry

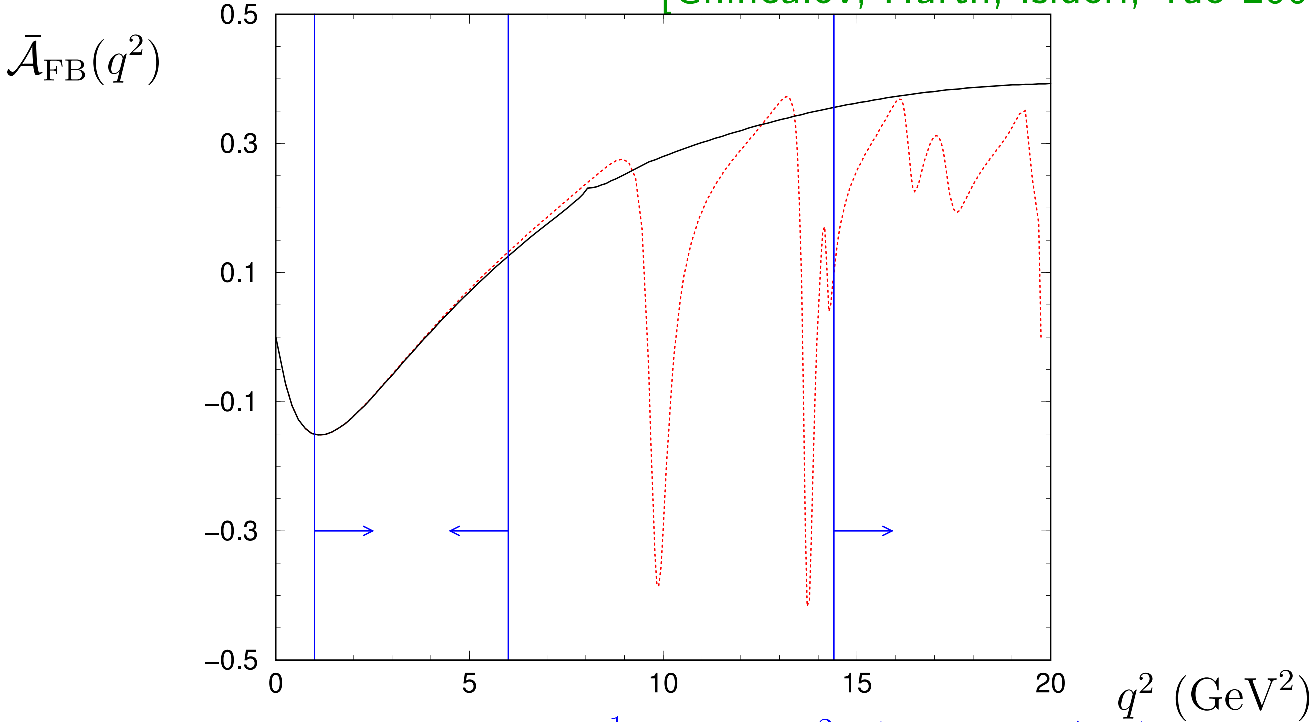
$$A_{\rm FB}^{\rm NLL}(0) = -(2.51 \pm 0.28) \times 10^{-6}; \quad A_{\rm FB}^{\rm NNLL}(0) = -(2.30 \pm 0.10) \times 10^{-6}$$

- Zero of the FB Asymmetry is a precise test of the SM, correlating $\widetilde{C}_7^{\rm eff}$ and $\widetilde{C}_9^{\rm eff}$

$$\hat{s}_0^{\rm NLL} = 0.144 \pm 0.020; \quad \hat{s}_0^{\rm NNLL} = 0.162 \pm 0.008$$

Normalized FB-Asymmetry in $\bar{B} \to X_s \ell^+ \ell^-$:

[Ghinculov, Hurth, Isidori, Yao 2004]



$$\bar{\mathcal{A}}_{\rm FB}(q^2) = \frac{1}{d\mathcal{B}(B \to X_s \ell^+ \ell^-)/dq^2} \int_{-1}^{1} d\cos\theta_\ell \, \frac{d^2\mathcal{B}(B \to X_s \ell^+ \ell^-)}{dq^2 \, d\cos\theta_\ell} \mathsf{sgn}(\cos\theta_\ell)$$

- Zero of the FB-Asymmetry is a precision test of the SM

$q_0^2 = (3.90 \pm 0.25)$ GeV^2 [Ghinculov, Hurth, Isidori, Yao 2004]

$q_0^2 = (3.76 \pm 0.22_{\rm theory} \pm 0.24_{m_b})$ GeV^2 [Bobeth, Gambino, Gorbahn, Haisch 2003]

Exclusive Decays $B \to (K, K^*)\ell^+\ell^-$

- $B \to K$ (pseudoscalar P); $B \to K^*$ (Vector V) Transitions involve the currents:

$$\Gamma_\mu^1 = \bar{s}\gamma_\mu(1-\gamma_5)b, \quad \Gamma_\mu^2 = \bar{s}\sigma_{\mu\nu}q^\nu(1+\gamma_5)b$$

$$\langle P|\Gamma_\mu^1|B\rangle \supset f_+(q^2), f_-(q^2)$$

$$\langle P|\Gamma_\mu^2|B\rangle \supset f_T(q^2)$$

$$\langle V|\Gamma_\mu^1|B\rangle \supset V(q^2), A_1(q^2), A_2(q^2), A_3(q^2)$$

$$\langle V|\Gamma_\mu^2|B\rangle \supset T_1(q^2), T_2(q^2), T_3(q^2)$$

- 10 non-perturbative q^2-dependent functions (Form factors) $\Longrightarrow$ model-dependence
- Data on $B \to K^*\gamma$ provides normalization of $T_1(0) = T_2(0) \simeq 0.28$
- HQET/SCET-Approach allows to reduce the number of independent form factors from 10 to 3; perturbative symmetry-breaking corrections [Beneke, Feldmann, Seidel; Beneke, feldmann]
- HQET & SU(3) relate $B \to (\pi, \rho)\ell\nu_\ell$ and $B \to (K, K^*)\ell^+\ell^-$ to determine the remaining FF's

Experimental data vs. SM in $B \to (X_s, K, K^*)\ell^+\ell^-$ Decays

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

SM: [A.A., Lunghi, Greub, Hiller, hep-ph/0112300]

Decay Mode	Expt. (BELLE & BABAR)	Theory (SM)
$B \to K\ell^+\ell^-$	0.45 ± 0.05	0.55 ± 0.08
$B \to K^* e^+ e^-$	$1.26^{+0.28}_{-0.27}$	1.25 ± 0.39
$B \to K^* \mu^+\mu^-$	1.45 ± 0.23	1.19 ± 0.31
$B \to X_s \mu^+\mu^-$	$4.26^{+1.18}_{-1.16}$	7.0 ± 2.1
$B \to X_s e^+ e^-$	$4.70^{+1.24}_{-1.23}$	5.8 ± 1.8
$B \to X_s \ell^+\ell^-$	$4.46^{+0.98}_{-0.96}$	6.2 ± 1.5

- Inclusive measurements and the SM rates include a cut $M_{\ell^+\ell^-} > 0.2$ GeV
- SM & Data agree within $\boldsymbol{O(20-30)\%}$

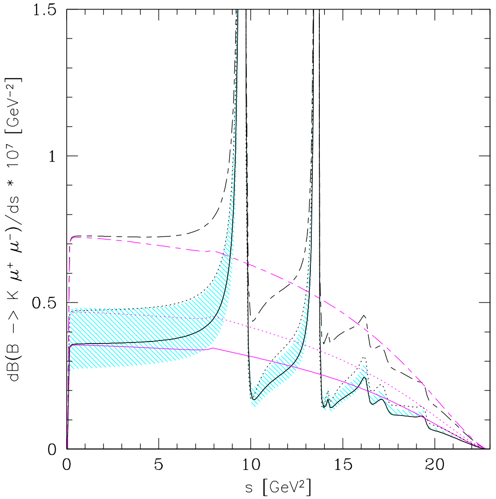
Dilepton mass-Spectrum in $\bar{B} \to (K, K^*)\ell^+\ell^-$ in SM and SUSY

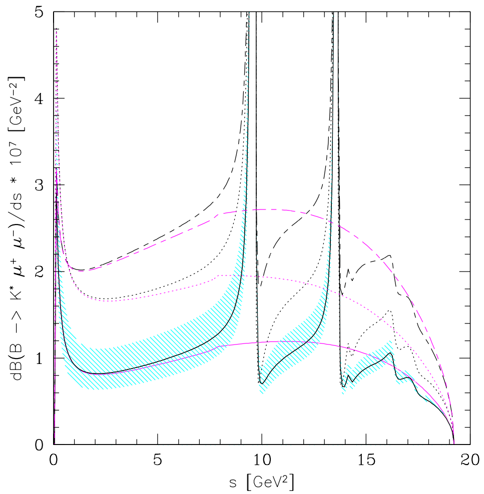
AA, Ball, Handoko, Hiller; hep-ph/9910221

- **NP contributions coded in** $R_i(\mu); \; i = 7, \; 9, \; 10$

$$R_i(\mu) \equiv \frac{C_i^{\mathrm{NP}} + C_i^{\mathrm{SM}}}{C_i^{\mathrm{SM}}}$$

  - **SM (solid); SUGRA** $[R_7 = -1.2]$ **(dots);**
  - **MIA** $[R_7 = -0.83, \; R_9 = 0.92, \; R_{10} = 1.6]$ **(dashed)**





$B \to K^*\ell^+\ell^-$ 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, $\lambda \sim \frac{\Lambda_{QCD}}{E}$

Leading order in $1/m_b$ and all orders in α_s

The factorization formula in SCET

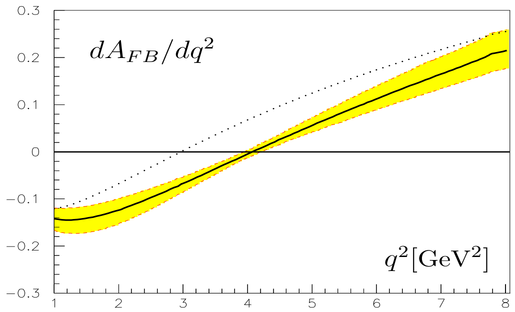
$$\langle K_a^* \ell^+ \ell^- | H_{eff} | B \rangle = T_a^I(q^2) \zeta_a(q^2) + \sum_{\pm} \int_0^\infty \frac{d\omega}{\omega} \phi_\pm^B(\omega) \int_0^1 du \, \phi_{K^*}^a(u) T_{a,\pm}^{II}(\omega, u, q^2)$$

where $a = \|, \perp$ denotes the polarization of the K^* meson

- formally coincides with the formula in QCD Factorization [Beneke/Feldmann/Seidel 2001], but valid to all orders of α_s
- for T^{II}, the logarithms are summed from $\mu = m_b$ to $\sqrt{m_b \Lambda_h}$
- Compared with BFS, the definition of $\zeta_{\perp,\|}$ is also different here

Reduction of Scale Uncertainty in SCET

Forward-backward asymmetry



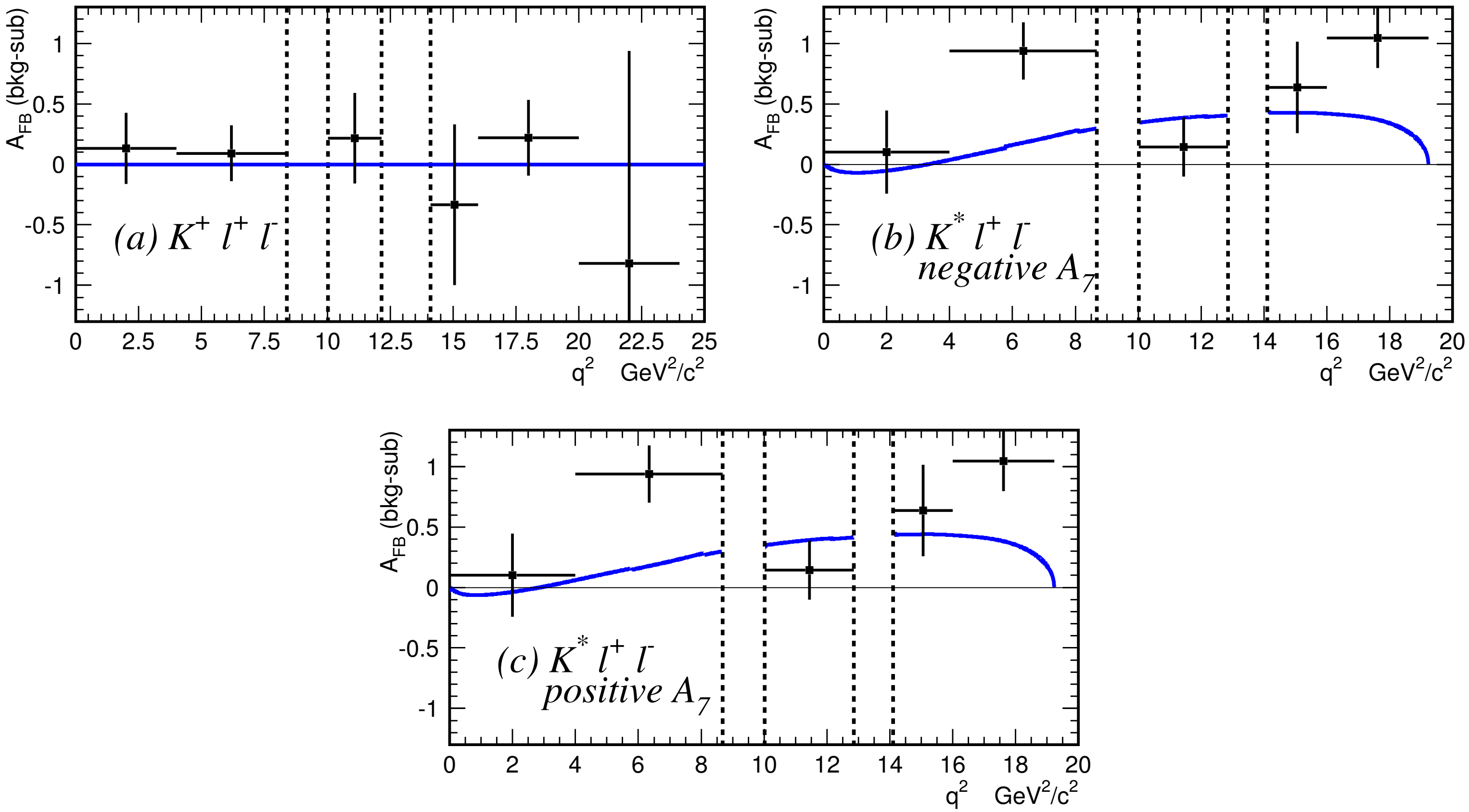
$A_{FB}(q_0^2) = 0$ free of hadronic uncertainties [Burdman1998, Ali et al., 2000]

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

QCD-F [Beneke/Feldmann/Seidel 2001]

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

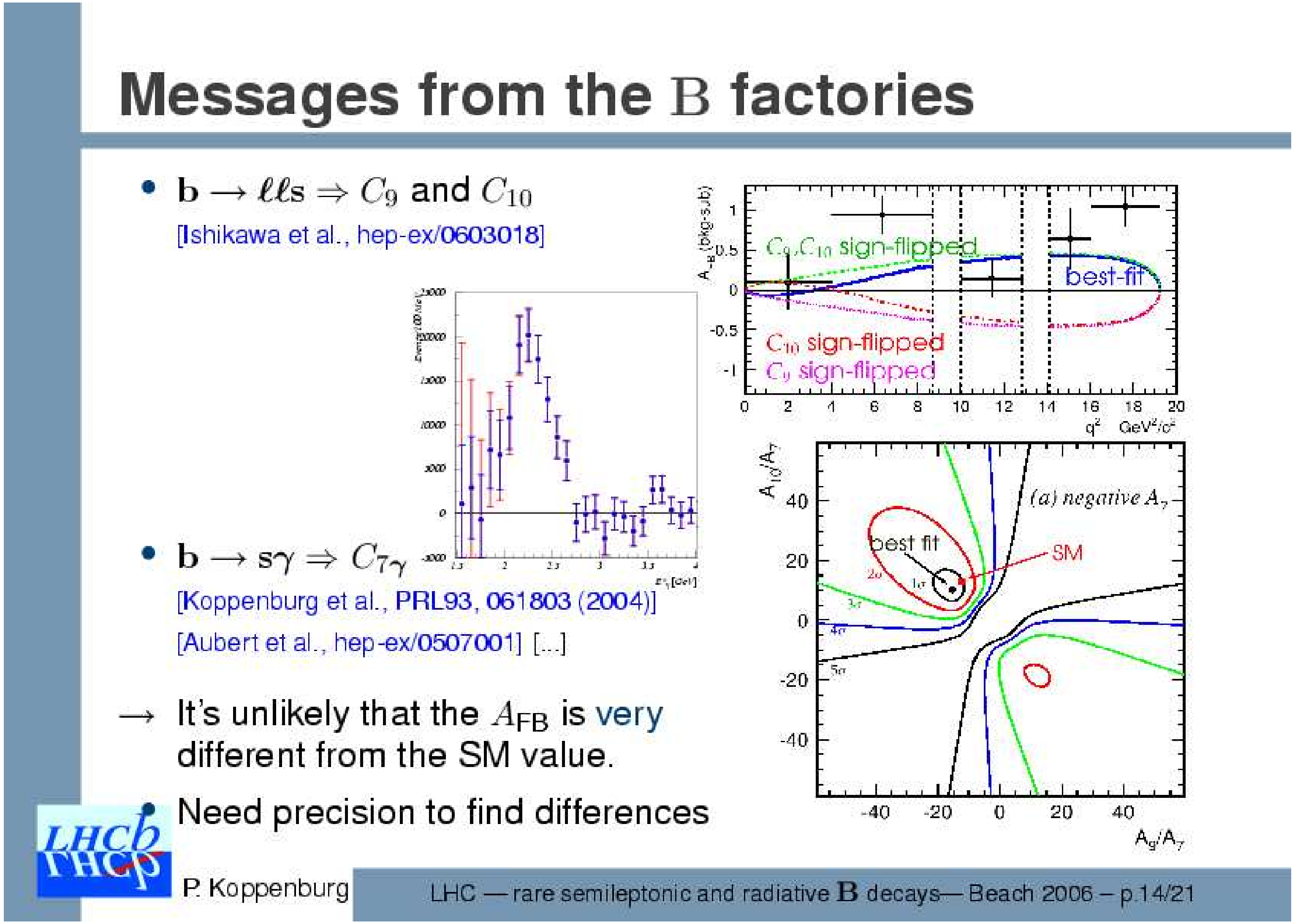
Belle FB Asymmetry Distributions (EPS 2005)



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: $A_7 = -0.33$; $A_9/A_7 = -12.3$; $A_{10}/A_7 = 12.8$

Present Constraints

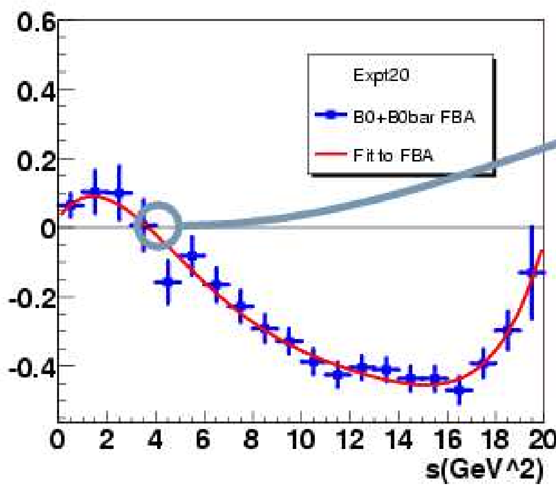


LHC-B MC Studies

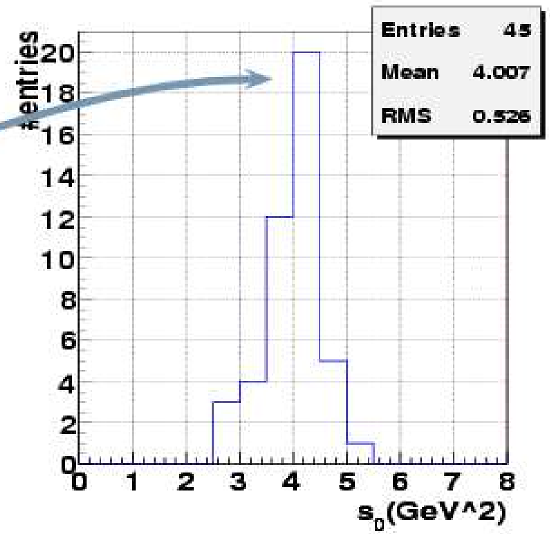
Zero of $B \to \mu\mu K^*$ A_{FB}

From Toy MC

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



Typical $A_{FB}(s)$ measurement



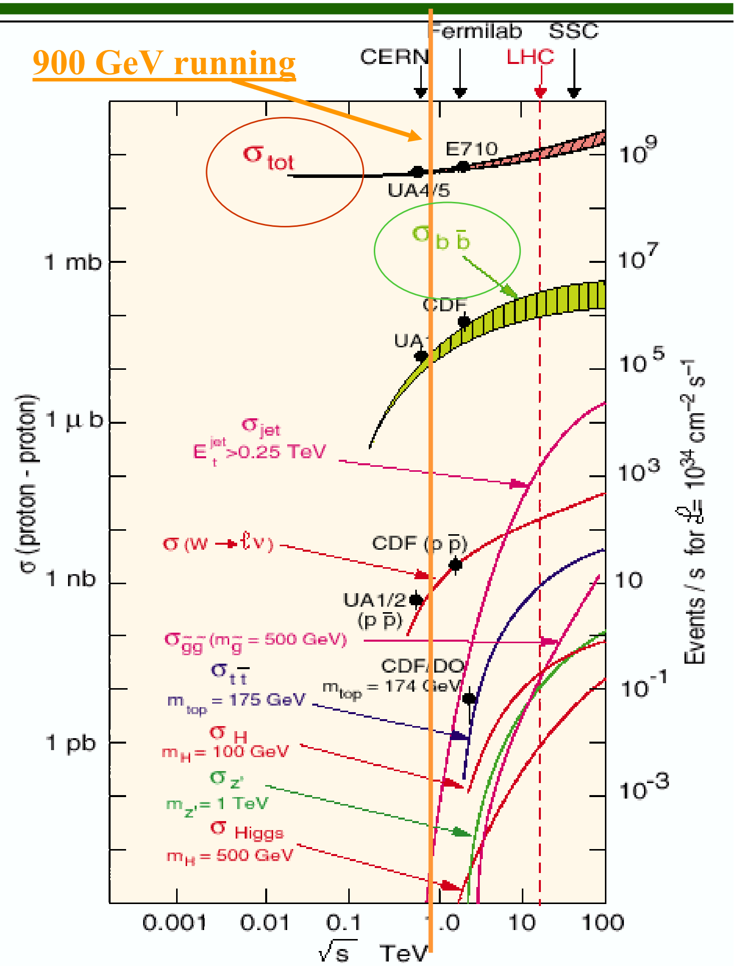
Spread of s_0

P. Koppenburg   LHC — rare semileptonic and radiative $\mathbf{B}$ decays— Beach 2006 – p.16/21

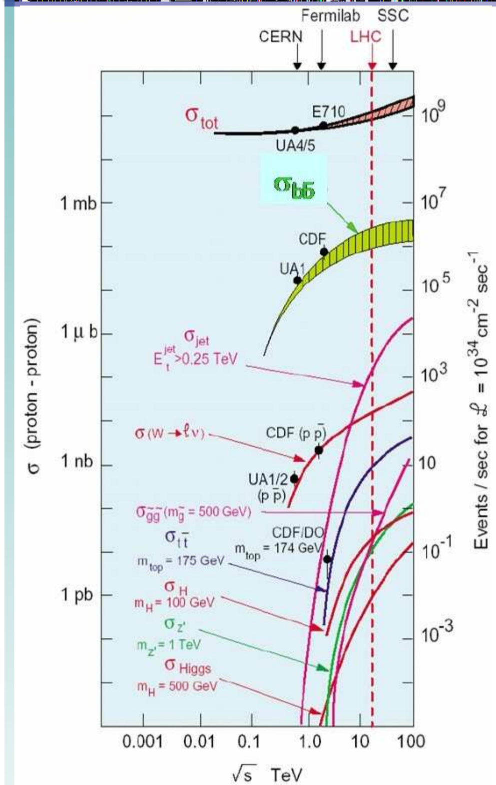
B Physics at LHC

- **LHC: proton-proton collisions at $\sqrt{s}$ = 14 TeV, bunch crossing rate 40kHz**
- **High $b\bar{b}$ production cross section: ~ 500 μb (~ 1 in 100 p-p collisions → $b\bar{b}$ pair). Those of interest must be select by B-trigger.**
- **Current luminosity plans:**
  - **Pilot-run in 2007, 900 GeV, ~10^{29} $cm^{-2}s^{-1}$**
  - **low-luminosity: up to 2×10^{33} $cm^{-2}s^{-1}$ (~10 fb^{-1} per year)**
  - **high-luminosity: 10^{34} $cm^{-2}s^{-1}$ (~100 fb^{-1} per year)**

  Beauty cross section dominates at 900 GeV and 14 TeV
- **ATLAS B-physics programme:**
  - **CP violation (e.g. $B \to J/\psi(X)$, $B \to \mu\mu$)**
  - **B_s oscillations (e.g. $B_s \to D_s\pi$, $B_s \to D_s a_1$)**
  - **Rare decays (e.g. $B \to \mu\mu(X)$, $B \to K^*\gamma$)**
  - **Inclusive cross section measurement**



B-Physics at LHC



B-production at LHC:

σ_{total} = 100 mb

$\sigma_{inelastic}$ = 80 mb

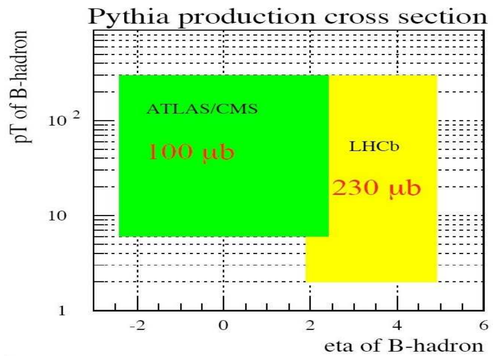
$\sigma_{b\bar{b}}$ = 500 μb

ATLAS/CMS general purpose	LHCb B-Physics dedicated
$\|\eta\| < 2.5$, $p_T > 10$ GeV, $\sigma = 100\ \mu b$	$1.9 < \eta < 4.9$, $p_T > 2$ GeV, $\sigma = 230\ \mu b$
$L_{low} = 1 \div 2 \cdot 10^{33}\ cm^{-2}s^{-1}$ $L_{high} = 10^{34}\ cm^{-2}s^{-1}$ $B^0_{s,d} \to \mu^+\mu^-$ 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.

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

- 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

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

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

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

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:

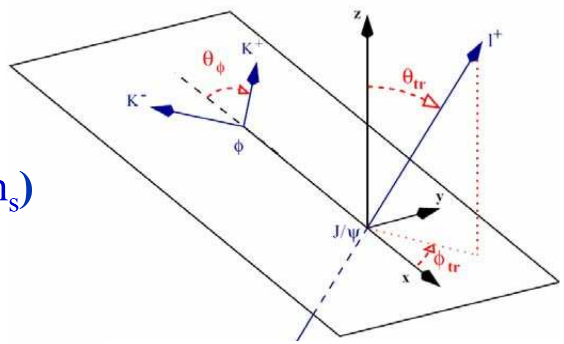
- from $B_s \to D_s K$
- from $B^0 \to D^0 K^{*0}$
- from $B^\pm \to DK^\pm$
- from $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$

Mixings, Nonleptonics & CP Violation

- Measurements of ϕ_s and $\Delta\Gamma_s$ in the B_s^0 - $\overline{B_s^0}$ system
- Measurements of BRs in $B_s^0 \to h_1 h_2$ decays, with $h_1, h_2 = \pi, K, \eta, \eta', \rho, K^*, \phi, ...$, enabling the measurements of a number of ratios of BRs involving $B_s^0 \to h_1 h_2$ and $B_d^0 \to h_1 h_2$; yielding precision tests of SM
- Time-dependent and integrated CP asymmetries in partial decay modes yielding more precise determinations of α, β, γ
- Searches of BSM physics in the Penguin-dominated decays of the B_s^0 meson

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

- 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

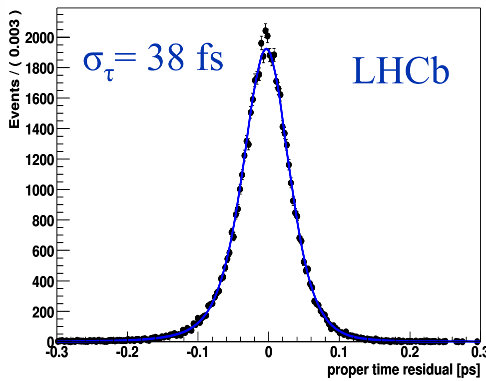
→ $\sigma_{stat}(\sin\phi_s) \sim 0.031$, $\sigma_{stat}(\Delta\Gamma_s/\Gamma_s) \sim 0.011$ /(1year, $2\mathrm{fb}^{-1}$)

→ $\sigma_{stat}(\sin\phi_s) \sim 0.013$ 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



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

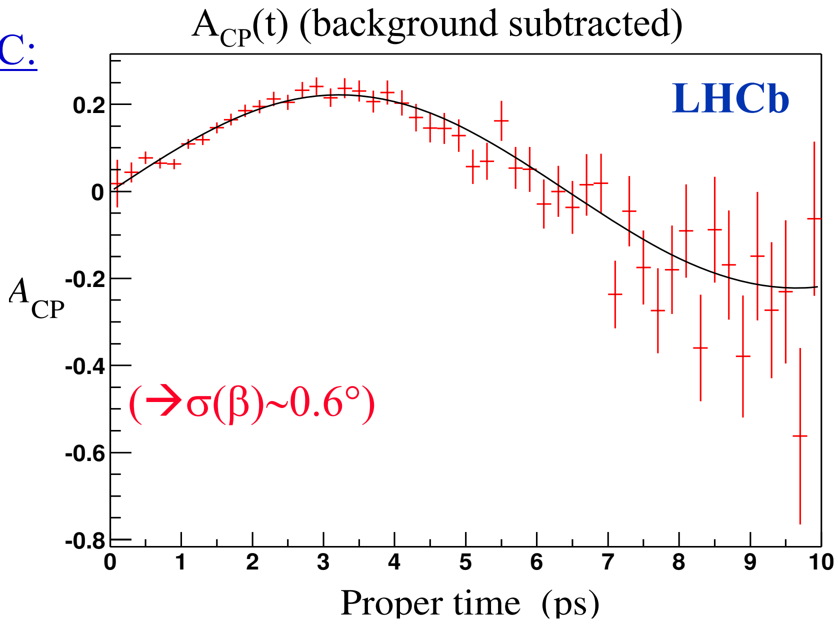
Expected sensitivity:

✓ 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…



(→σ(β)~0.6°)

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Projected Precision on γ at LHC

- γ from $\boldsymbol{B_s \to D_s K}$ $\quad\Longrightarrow\quad$ $\boldsymbol{\sigma(\gamma) \sim 14^\circ}$ 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 $\boldsymbol{B^0 \to D^0 K^{*0}}$ $\quad\Longrightarrow\quad$ $\boldsymbol{\sigma(\gamma) \sim 8^\circ}$ 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 $\boldsymbol{B^\pm \to D^0 K^\pm}$ $\quad\Longrightarrow\quad$ $\boldsymbol{\sigma(\gamma) \sim 5^\circ}$ 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 $\boldsymbol{B^0 \to \pi^+\pi^-}$ and $\boldsymbol{B_s \to K^+K^-}$ $\quad\Longrightarrow\quad$ $\boldsymbol{\sigma(\gamma) \sim 5^\circ}$ 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 $d\,e^{i\theta}$
  - exploit "U-spin" symmetry ($d \leftrightarrow s$) [R. Fleischer, Phys. Lett. B459, 306 (1999)]

Some interesting $\overline{B_s^0} \to h_1 h_2$ Decays

- Measurements of BRs in $\overline{B_s^0} \to h_1 h_2$ decays, with $h_1, h_2 = \pi, K, \eta, \eta', \rho, K^*, \omega, \phi, ...$ is an integral part of the LHC B_s-physics programme

- Decay rates and CP asymmetries calculated in specific theories [QCDF, SCET, pQCD, SU(3) and U-spin symmetry arguments and Data]
[Beneke, Neubert; Williamson, Zupan; AA, Kramer,Lü et al., Fleischer, Matias; London et al.; Gronau, Rosner; Buras et al.,...]

- Examples of $\overline{B_s^0} \to PP$ decays having large ($\geq 10^{-6}$) BRs:

Decays	BRs Theory (10^{-6})	BRs Experiment (10^{-6})
• $\overline{B_s^0} \to K^+\pi^-$	$5 - 15$	$5.0 \pm 0.75 \pm 1.0$
• $\overline{B_s^0} \to K^+K^-$	$12 - 25$	$24.4 \pm 1.4 \pm 4.6$
• $\overline{B_s^0} \to K^0\bar{K}^0$	$12 - 25$	$--$
• $\overline{B_s^0} \to K^0\eta'$	$1 - 5$	$--$

- And many more involving η, η'-mesons, as well as vector mesons

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

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

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

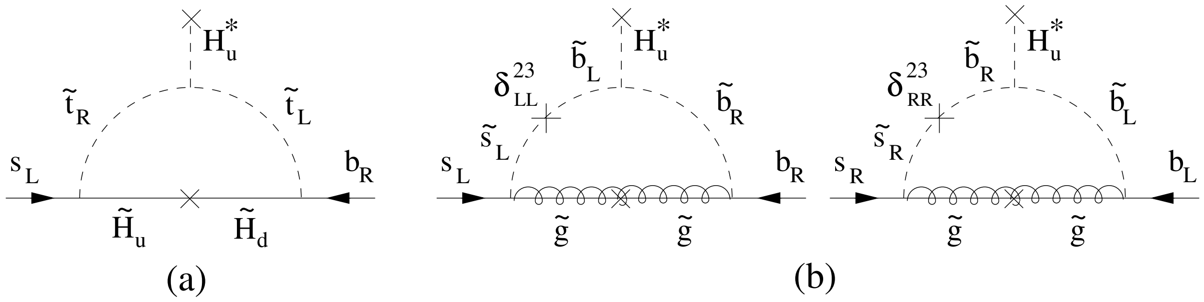
$$f_{B_s} = (230 \pm 30)\ \text{MeV}$$

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

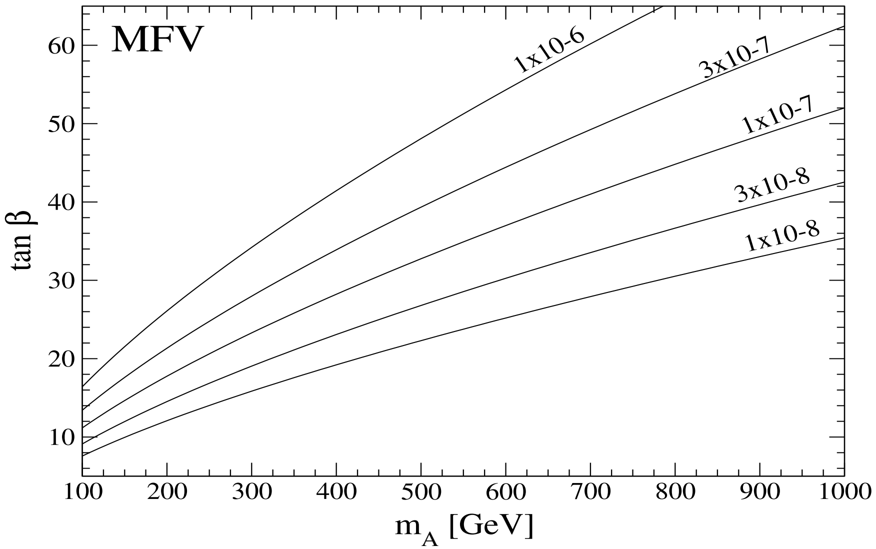
$B_s \to \mu^+\mu^-$ in Minimal Flavor Violation SUSY Models

- 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→μ, b→μ events (all rejected)
- ✓ATLAS: 80k bb→μμ events with generator cuts, efficiency assuming cut factorization
- ✓CMS: 10k b→μ, b→μ events with generator cuts, trigger simulated at generator level, efficiency assuming cut factorization

	1 year	$B_s \to \mu^+\mu^-$ signal (SM)	b→μ, b→μ 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	
$\mathrm{Br}(B_s \to \mu^+\mu^-)$	$\sim 0.7 \times 10^{-9}$	$\sim 3.5 \times 10^{-9}$	
$\gamma(D_sK,\, DK)$	$\sim 1^\circ$	$\sim 60^\circ$	(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

Summary

- All current measurements involving CC and FCNC processes (decay rates and distributions, Mixings, CP Violation) of the $B^{\pm}$ and B_d^0 mesons are in agreement with the SM

- Tevatron has provided first measurements for the B_s^0; Experiments at the LHC will extend this frontier enormously: $\Delta M_s,\ \phi_s,\ \gamma,\ \mathcal{B}(B_s \to \mu^+\mu^-)$; QCD and Electroweak penguins

- A lot of theoretical interest remains in precision studies of Rare B-decays: $\mathcal{B}(B \to X_s\gamma)$; $\mathcal{B}(B \to (X_s, K^*)\ell^+\ell^-)$, in particular the Forward-Backward Asymmetries of the leptons

- CP Asymmetries & Rare B-Decays have the potential to discover Physics Beyond-the-SM in the flavour sector; In all likelihood this would require the statistical power of a Super-B factory and LHC

- Hope that the synergy of high energy frontier and low energy precision physics, which worked so well in piecing together the SM yielding precise knowledge of the CKM matrix, will continue to hold sway in the LHC-era, providing valuable information on the flavour aspects of the next Paradigm!