Theoretical Interest in B-Physics at the LHC

Ahmed Ali
DESY, Hamburg

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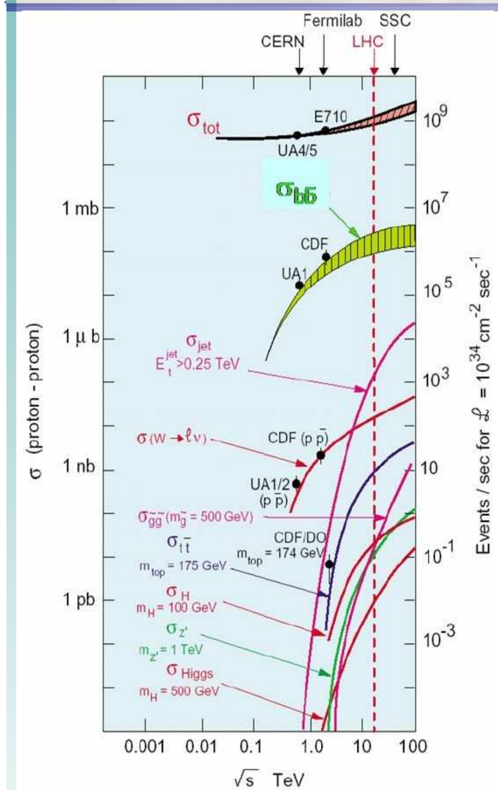
Plan of Talk

- Profile of B-Physics at the LHC
- The CKM-Matrix: Current Knowledge of $V_{\rm CKM}$ & the Phases α, β, γ
- Benchmark for the LHC: Mixings, Nonleptonics & CP Asymmetries
- Theoretical Interest in Rare B-Decays
  - $b \to s\gamma$: SM vs. Experiment
  - $B \to (X_s, K, K^*)\ell^+\ell^-$: Current Status & Precision Measurements at the LHC
  - $B_s \to \mu^+\mu^-$ in the SM and SUSY: Prospects at the LHC
- Summary

B-Physics at LHC



ATLAS/CMS general purpose	LHCb B-Physics dedicated
$\lvert\eta\rvert < 2.5$, $p_T > 10$ 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

B-production at LHC:

σ_{total} = 100 mb

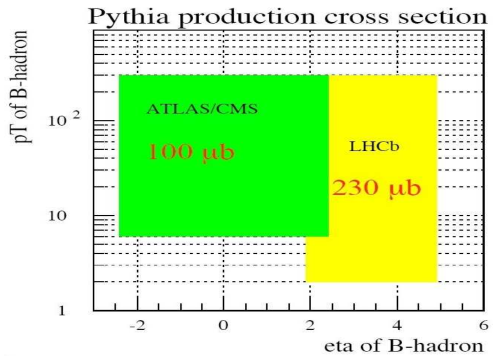
$\sigma_{inelastic}$ = 80 mb

$\sigma_{b\bar{b}}$ = 500 μb

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

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

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

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

Vancouver, 9-12 April 2006 Flavor Physics and CP Violation Andreas Schopper 3

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 $B_s \to K^+K^-$

ATLAS B-physics goals: precision measurements and new physics

- **CP-violation parameters**
- **B-hadron parameters**: masses, lifetimes, widths, oscillation parameters, couplings, b-production, etc.
- **Search for New Physics effects**: very rare decay modes, forbidden decays/couplings, etc.

CP violation	$B_d \to J/\psi K^0_s(\pi\pi)$ $J/\psi \to \mu\mu/ee$	$\sin(2\beta) + \Phi_{NP}$
Measurement of B_s properties	$B_s \to D_s\pi; B_{s,d} \to D_s a_1$ $B_s \to J/\psi(\mu\mu)\phi(KK)$ $B_{s,d} \to J/\psi(\mu\mu)\eta(\gamma\gamma)$	Δm_s, $\Delta\Gamma_s$, Γ_s, the weak phase ϕ_s
B_c mesons	$B_c \to J/\psi\pi; B_c \to J/\psi\mu\nu$	B_c mass, τ, QCD/EW interplay
Λ_b polarization measurements	$\Lambda_b \to J/\psi(\mu\mu)\Lambda(p\pi)$	Asymmetry parameter α_b, P_b, life-time measurements
Rare decays	$B_{s,d} \to \mu^+\mu^-; B^0_d \to K^{*0}\mu\mu$ $\Lambda_b \to \Lambda\mu\mu; B^0_s \to \phi^0\mu\mu$	Precise measurements of the branching ratios and asymmetries

Beauty 2006, Oxford, 25-29 September 2006

The Cabibbo-Kobayashi-Maskawa Matrix

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

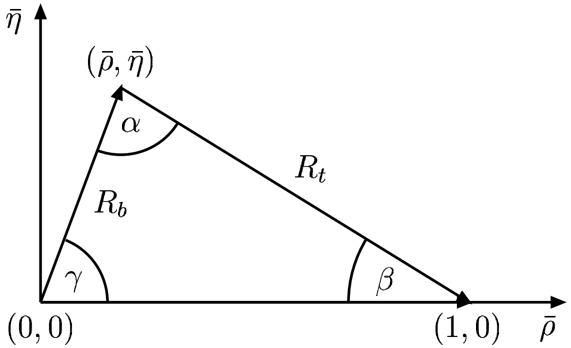
- Customary to use the handy Wolfenstein parametrization

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

- Four parameters: A, 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]
  $\Longrightarrow |V_{ub}| = (4.31 \pm 0.30) \times 10^{-3}$ [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) ($x_t = m_t^2/m_W^2$)

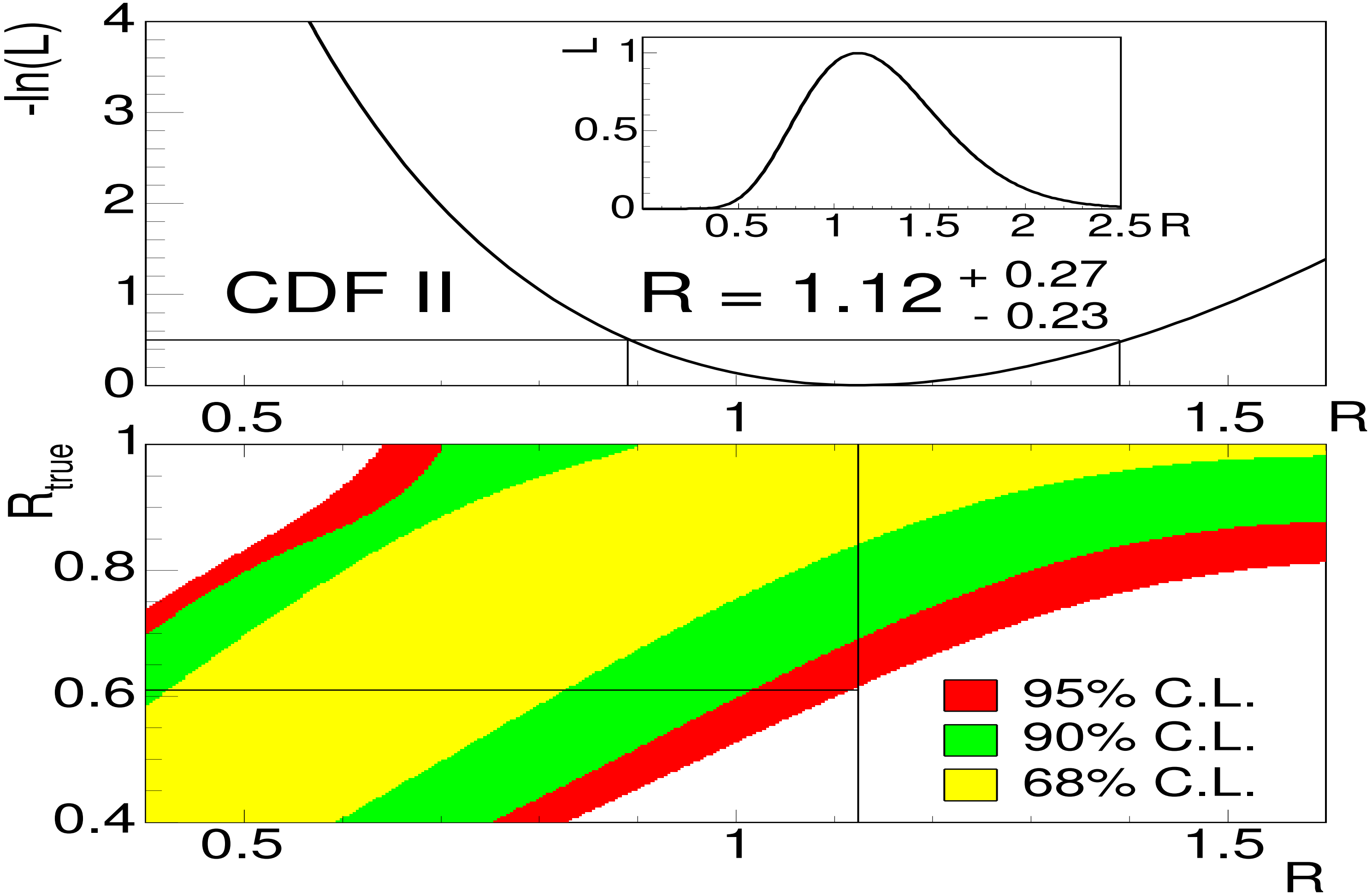
$$\Delta M_d = \frac{G_F^2}{6\pi^2} \hat{\eta}_B |V_{td}V_{tb}^*|^2 M_{B_d} (f_{B_d}^2 \hat{B}_{B_d}) M_W^2 S_0(x_t)$$

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

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

$-ln(L)$ 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; $\quad S_0(x_t) = 2.29(5)$

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

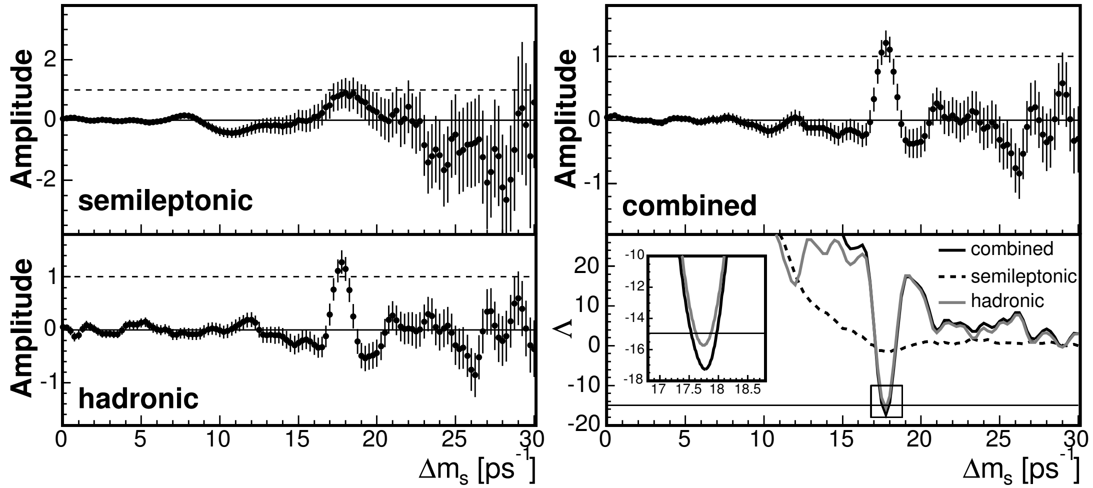
  - Lattice-QCD & SM $\Longrightarrow$ $|V_{td}{}^* V_{tb}| = (7.4 \pm 0.8) \times 10^{-3}$ [PDG 2006]

- 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.)]

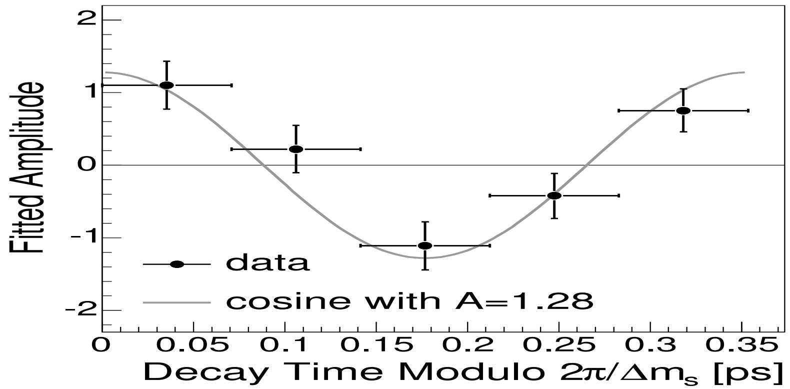
$$\frac{\Delta M_s}{\Delta M_d} = \xi \frac{M_{B_s}}{M_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2}; \quad \xi = \sqrt{\frac{f_{B_s}^2 \hat{B}_{B_s}}{f_{B_d}^2 \hat{B}_{B_d}}}$$

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

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

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 $B^0/\overline{B^0} \longrightarrow J/\psi K_s;\ J/\psi K_L$

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

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

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

- Definitions:

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

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

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

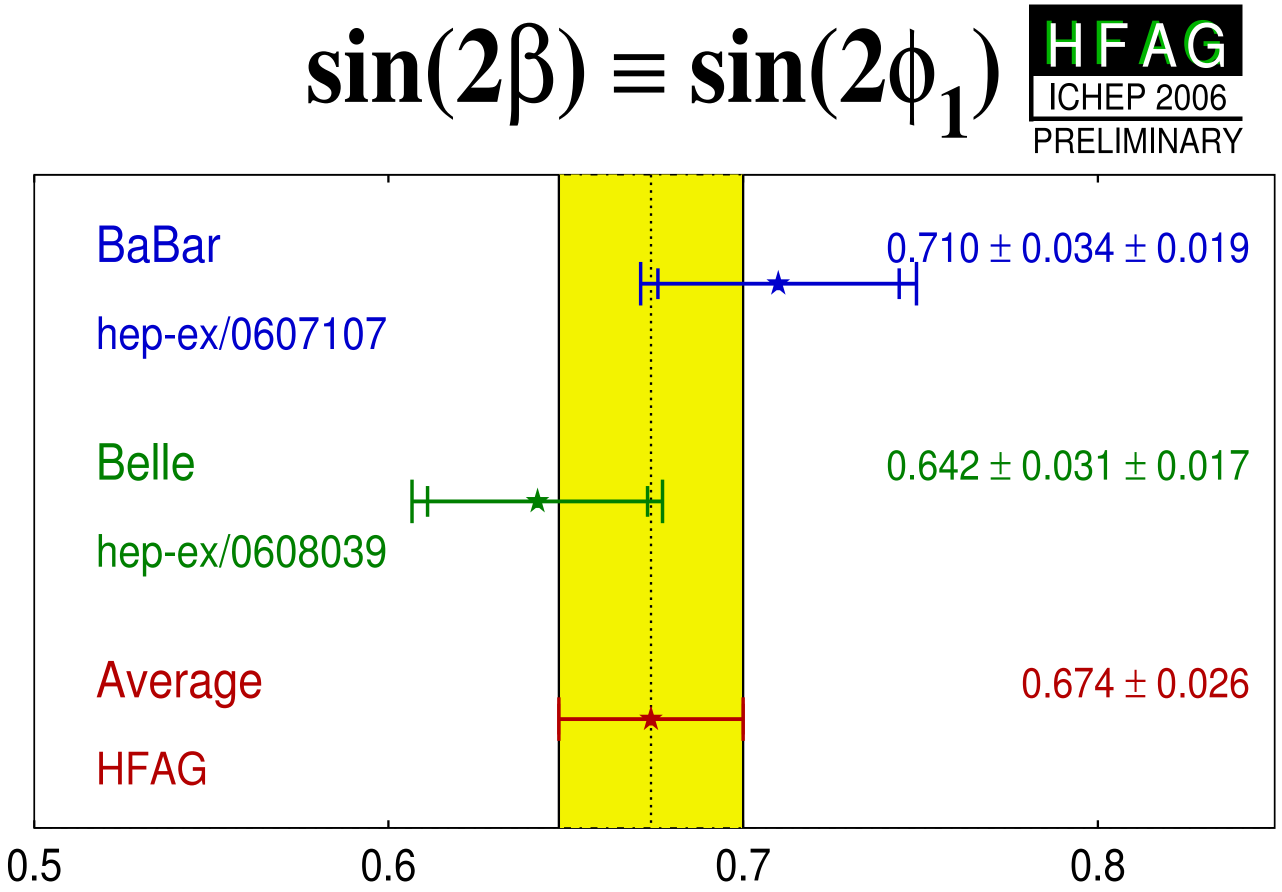
- If only a Single Amplitude dominant, then one can write:

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

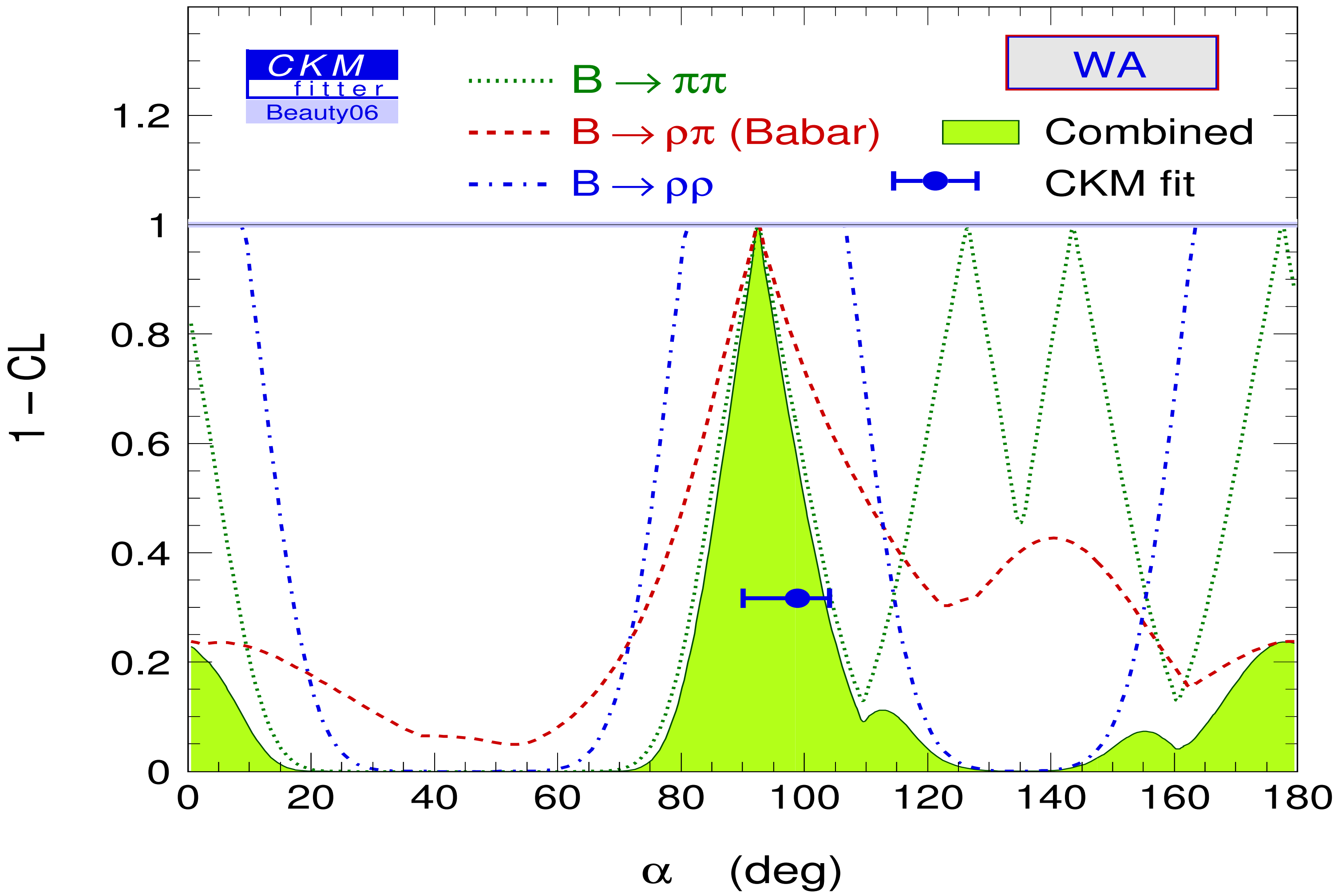
where $\eta_f = \pm 1$ is the intrinsic CP-Parity of the state $f \Rightarrow |\rho(f)| = 1$

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

Current World Average [ICHEP 2006]

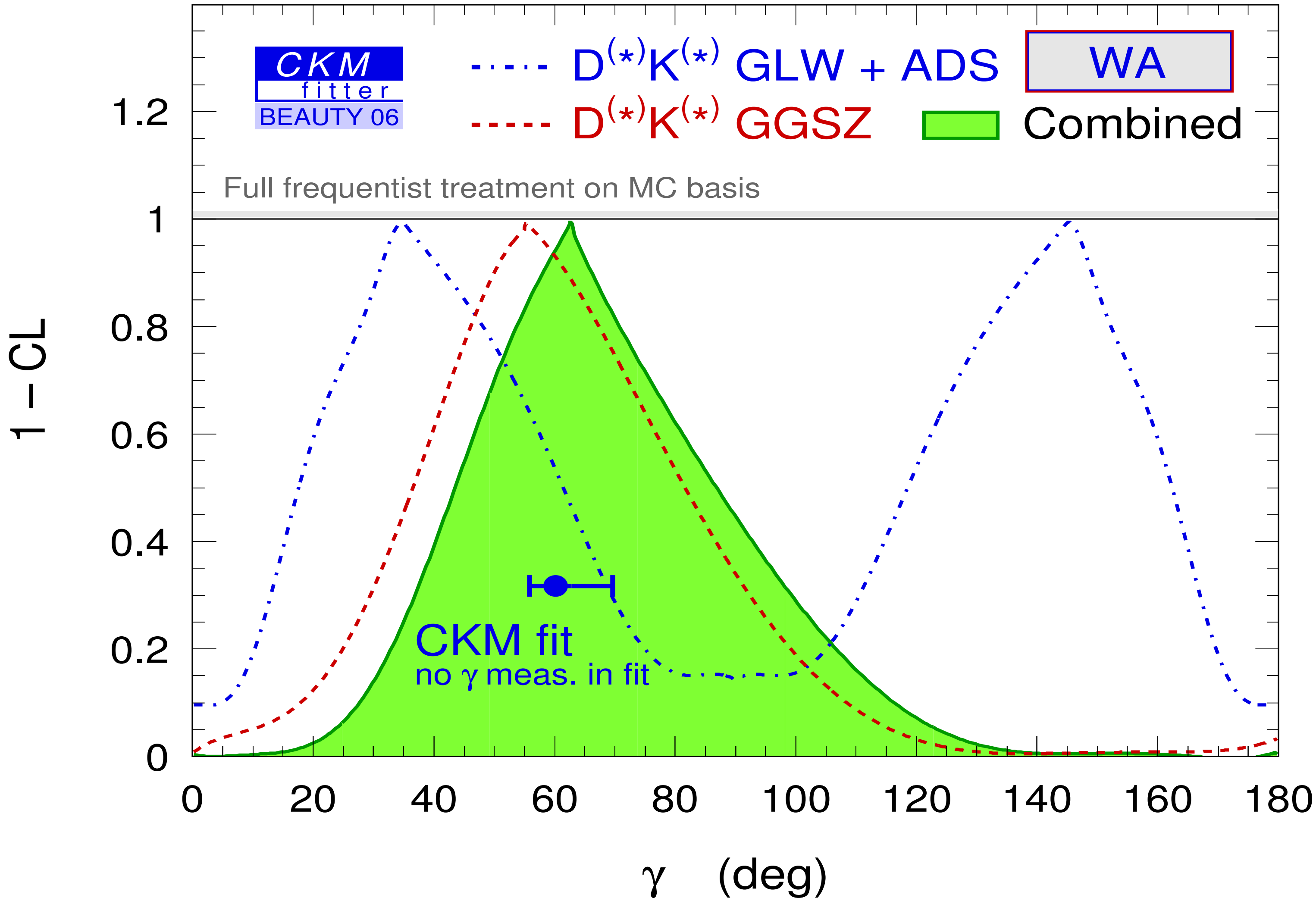


Current World Average of α [CKMfitter 2006]



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]

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 $B_s \to J/\psi\phi$ $(\eta, \eta' \ldots)$

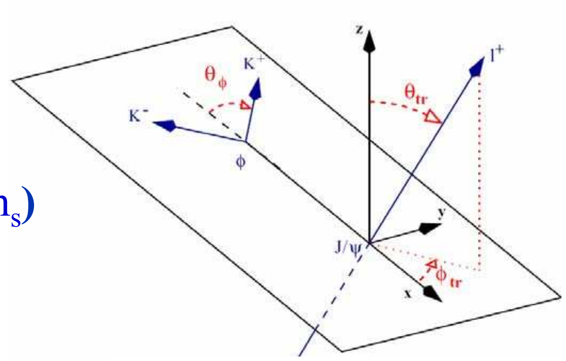
- SU(3) analogue of $B \to J/\psi K_s$, measuring the B_s- $\overline{B}_s$ mixing phase
- in SM $\phi_s = -\arg(V_{ts}^2) = -2\lambda\eta^2 \sim -0.04$ → increased sensitivity to New Physics
- large CP asymmetry would signal Physics Beyond SM
- also needed for extracting γ from $B_s \to D_s K$ or from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

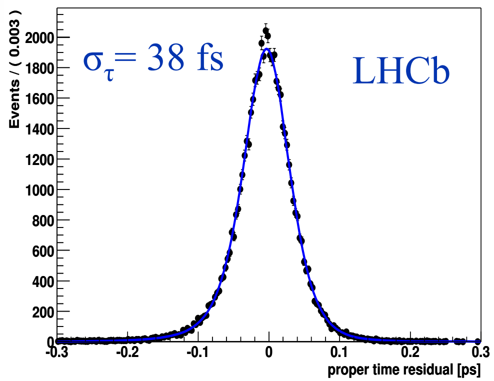
→ $\sigma_{stat}(\sin\phi_s) \sim 0.031$, $\sigma_{stat}(\Delta\Gamma_s/\Gamma_s) \sim 0.011$ /(1year, $2\mathrm{fb}^{-1}$)

→ $\boxed{\sigma_{stat}(\sin\phi_s) \sim 0.013 \text{ after first 5 years,}}$ 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



$\sin(2\beta)$ 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

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

One of the first CP measurements at LHC:

✓ demonstrate CP analysis performance

✓ study tagging systematics

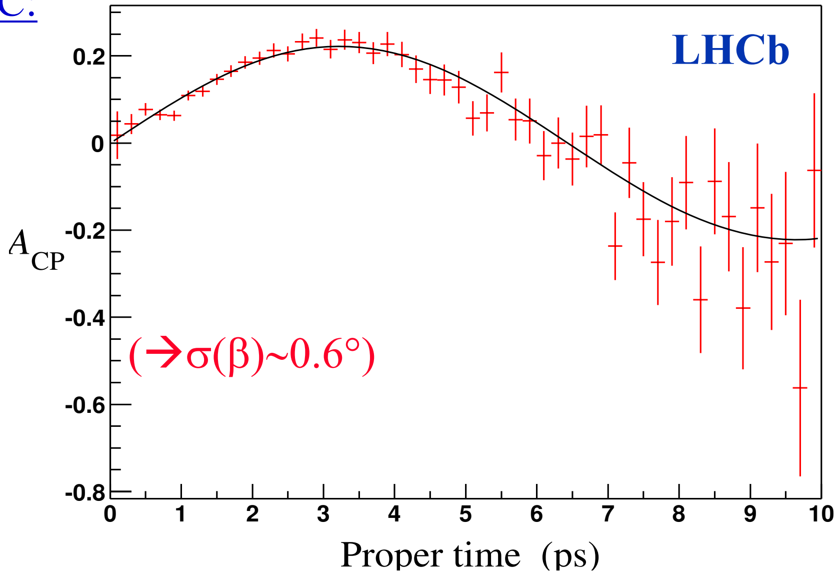
Expected sensitivity:

✓ LHCb: 240k signal events/year

→ $\boxed{\sigma_{stat}(\sin(2\beta)) \sim 0.02 \;\; (1\text{year}, 2\text{fb}^{-1})}$ ($\to \sigma(\beta)$~0.6°)

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

Search for direct CP violating term…



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 $d\,\mathrm{e}^{i\theta}$
  - exploit "U-spin" symmetry ($d \leftrightarrow s$) [R. Fleischer, Phys. Lett. B459, 306 (1999)]

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

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

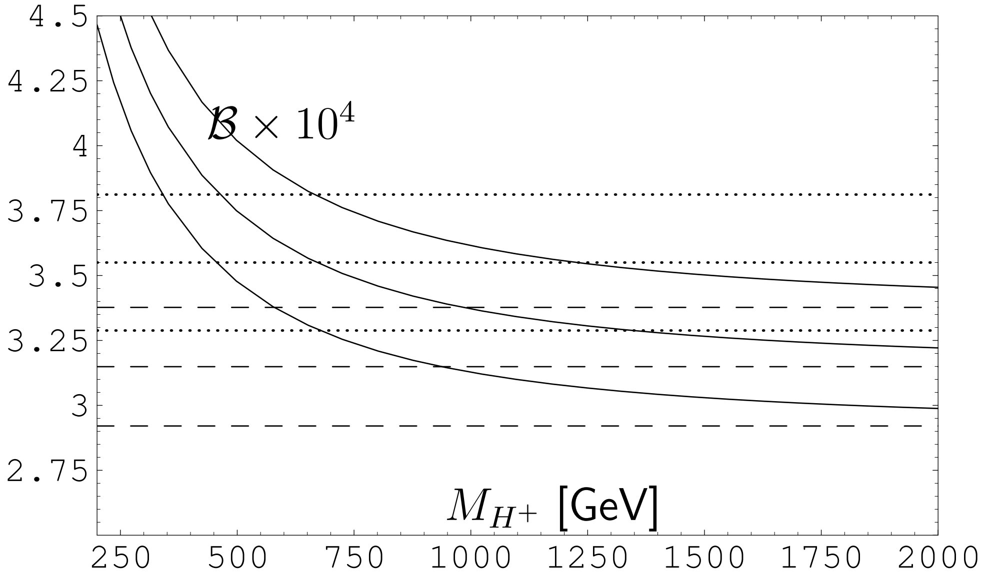
Branching ratios (in units of 10^{-6}) [August 2006]

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]

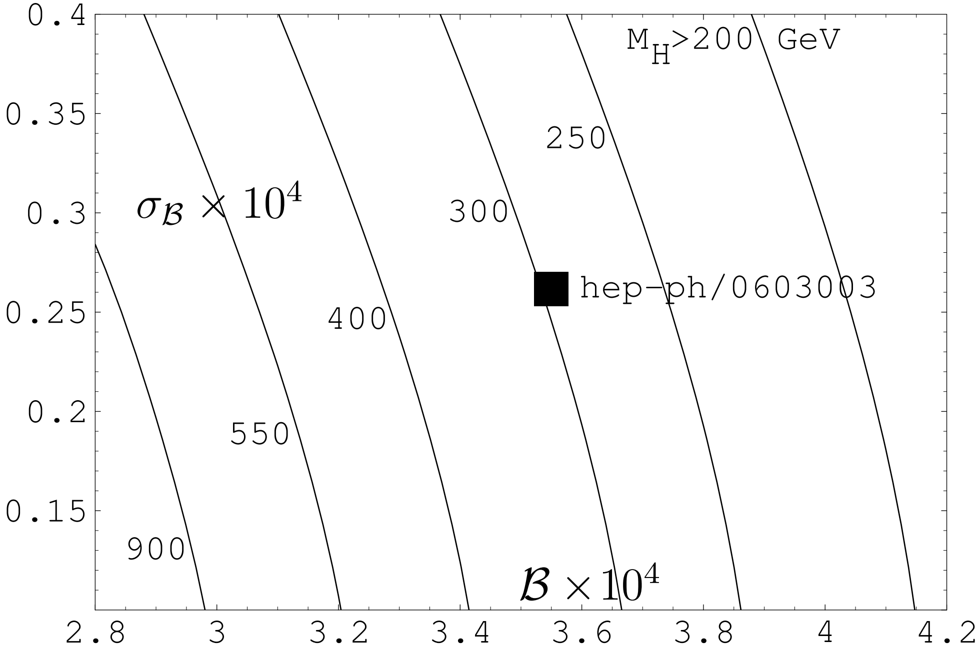


[$\cdots$ (exp); $- - - -$ (SM); solid (2HDM)]

- 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

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

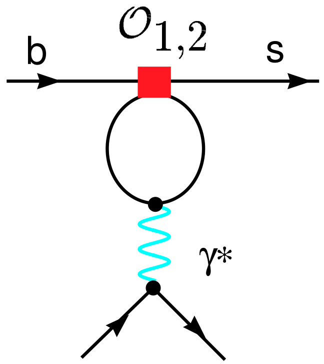
have the following perturbative expansion:

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

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

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

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

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

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

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

- 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}

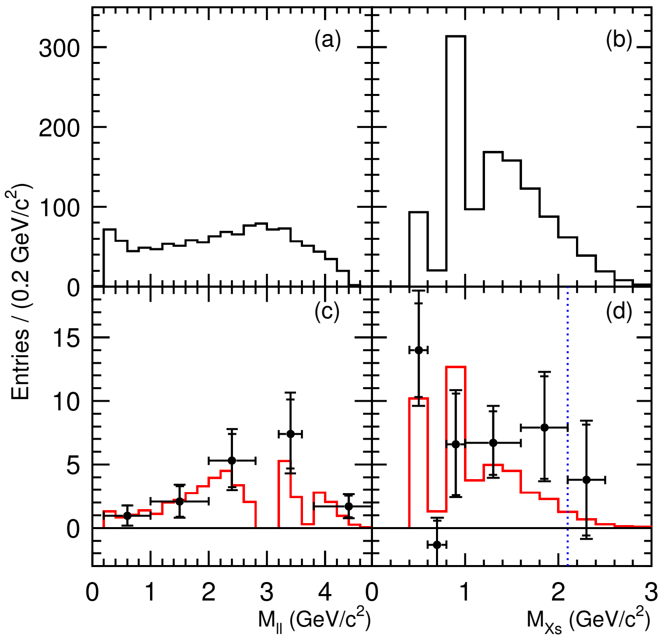
$$A_{\mathrm{FB}}(\hat{s} \sim C_{10}(2C_7 + C_9(\hat{s})\hat{s}); \quad \hat{s} = q^2/M_B^2$$

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

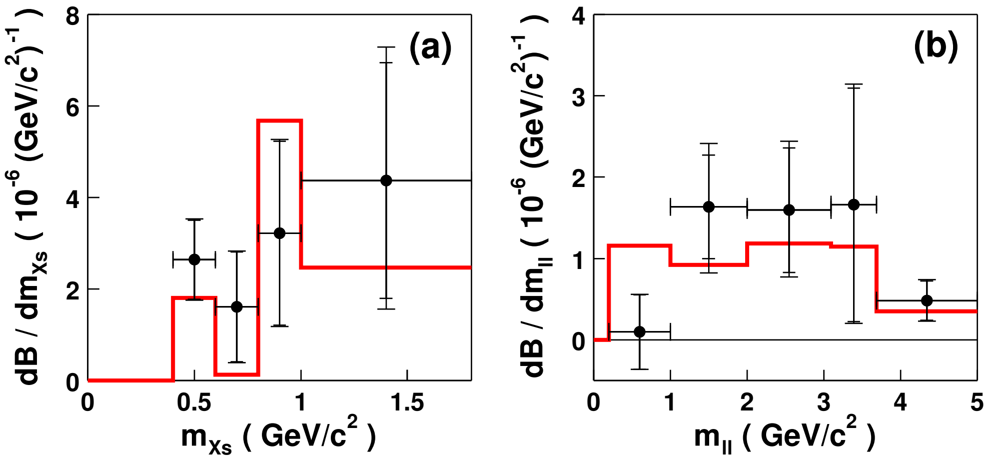
Decay distributions in $\bar{B} \to X_s \ell^+ \ell^-$

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

[BELLE]



[BABAR]



- In agreement with the NNLO SM calculations

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

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

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

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

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

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

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

- 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 $\boldsymbol{O(20-30)\%}$

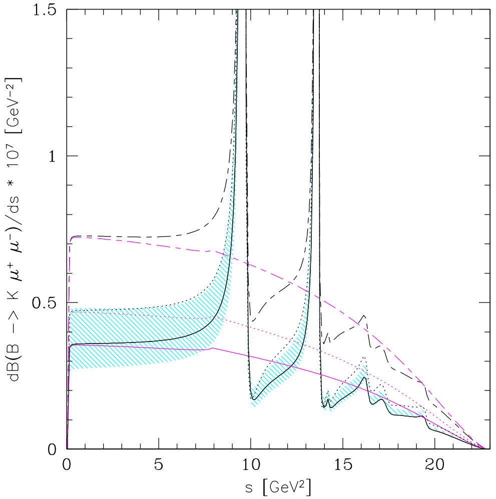
Dilepton mass-Spectrum in $\bar{B} \to (K, K^*)\ell^+\ell^-$ in SM and SUSY

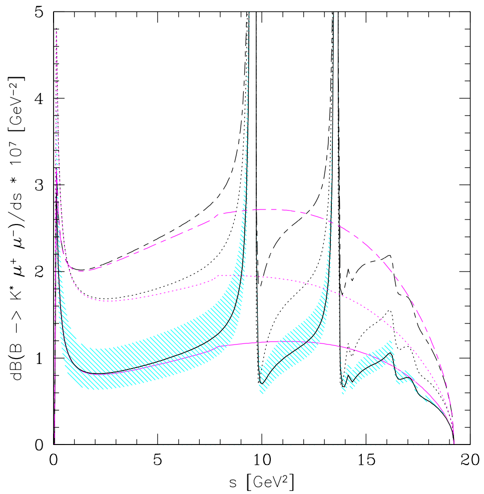
AA, Ball, Handoko, Hiller; hep-ph/9910221

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

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

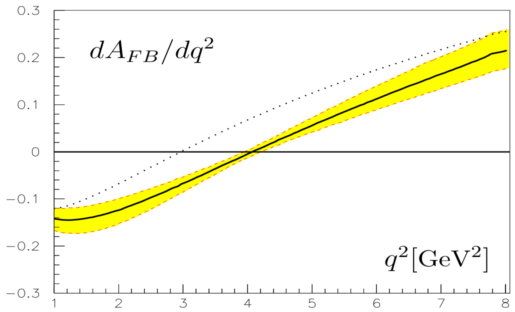
  - SM (solid); SUGRA $[R_7 = -1.2]$ (dots);
  - MIA $[R_7 = -0.83,\ R_9 = 0.92,\ R_{10} = 1.6]$ (dashed)





Reduction of Scale Uncertainty in SCET

Forward-backward asymmetry



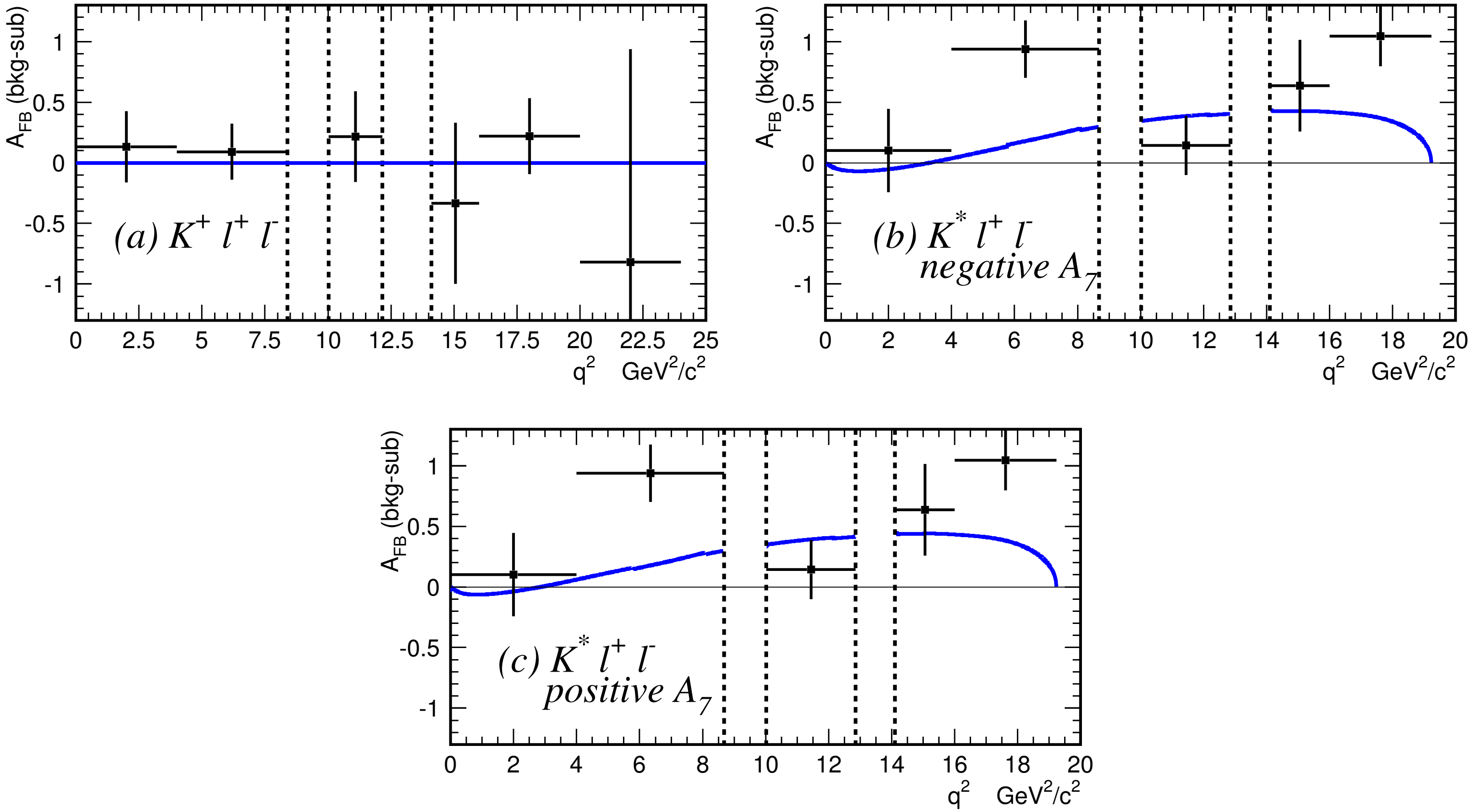
$A_{FB}(q_0^2) = 0$ free of hadronic uncertainties [Burdman1998, Ali et al., 2000]

$q_0^2 = (4.07^{+0.16}_{-0.13})\ \mathrm{GeV}^2$ 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 $\Delta(q_0^2)_{\mathrm{scale}} = \pm 0.25\ \mathrm{GeV}^2$

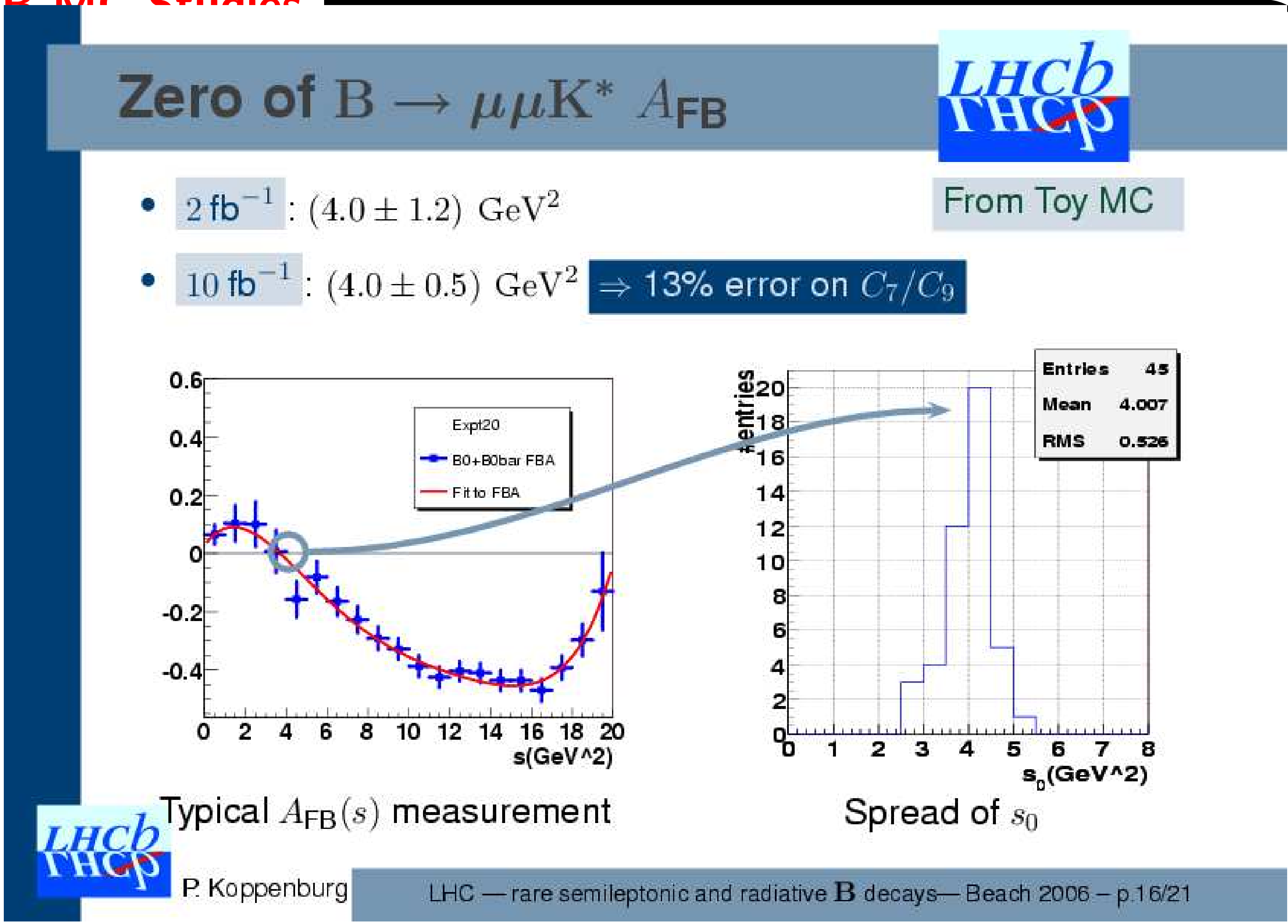
Belle FB Asymmetry Distributions (EPS 2005)



<u>Best Fits</u>

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

LHC-B MC Studies



B physics with 100 pb^{-1}: sensitivity to rare exclusive B decays

Decay	Statistics or limit with 100 pb^{-1}	Measurement today
$B^+ \rightarrow \mu\mu K^+$	23	Belle today 80?
$B^0 \rightarrow \mu\mu K^{0*}$	12	
$B_s \rightarrow \mu\mu \phi$	9	
$\Lambda_b \rightarrow \mu\mu\Lambda$	3	
$B_s \rightarrow \mu\mu$	6.4×10^{-8} at 90% C.L.	CDF currently 8.0×10^{-8} at 90% C.L.

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Beauty 2006, Oxford, 25-29 September 2006

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

- Effective Hamiltonian

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

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

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

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

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

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

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

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

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

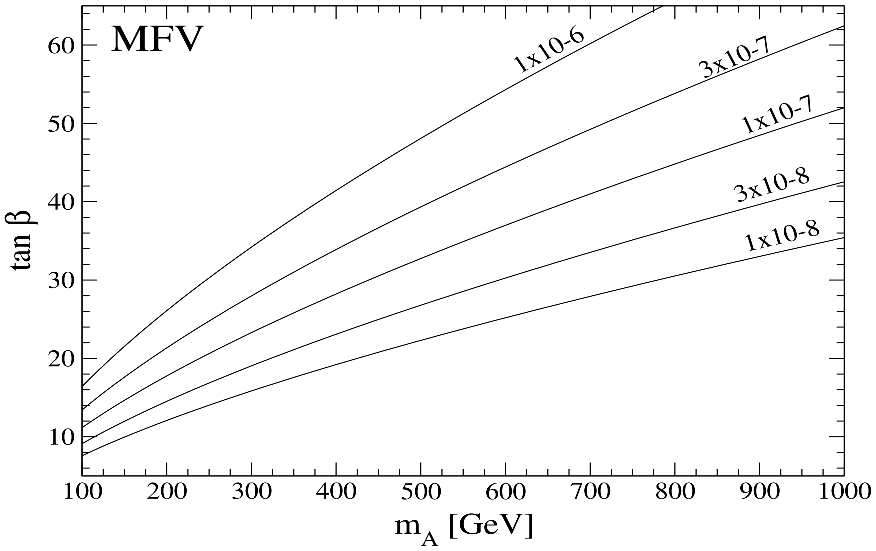
$B_s \to \mu^+\mu^-$ in Minimal Flavor Violation SUSY Models

- 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

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



$B^0_s \to \mu^+\mu^-$ with 100 pb^{-1}, 10 fb^{-1} and 30 fb^{-1}

Discovery channel $B^0_s \to \mu^+\mu^-$

Integrated LHC luminosity	N(signal) after all cuts	N(backgr.) after all cuts	ATLAS upper limit for $Br(B^0_s \to \mu^+\mu^-)$ at 90% C.L.	CDF upper limit for $Br(B^0_s \to \mu^+\mu^-)$ at 90% C.L.
100 pb^{-1}	~ 0	~ 0.2	6×10^{-8}	8.0×10^{-8}
10 fb^{-1}	~ 7	~ 20	1.2×10^{-8}	
30 fb^{-1}	~ 21	~ 60	7×10^{-9}	

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

- 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

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!