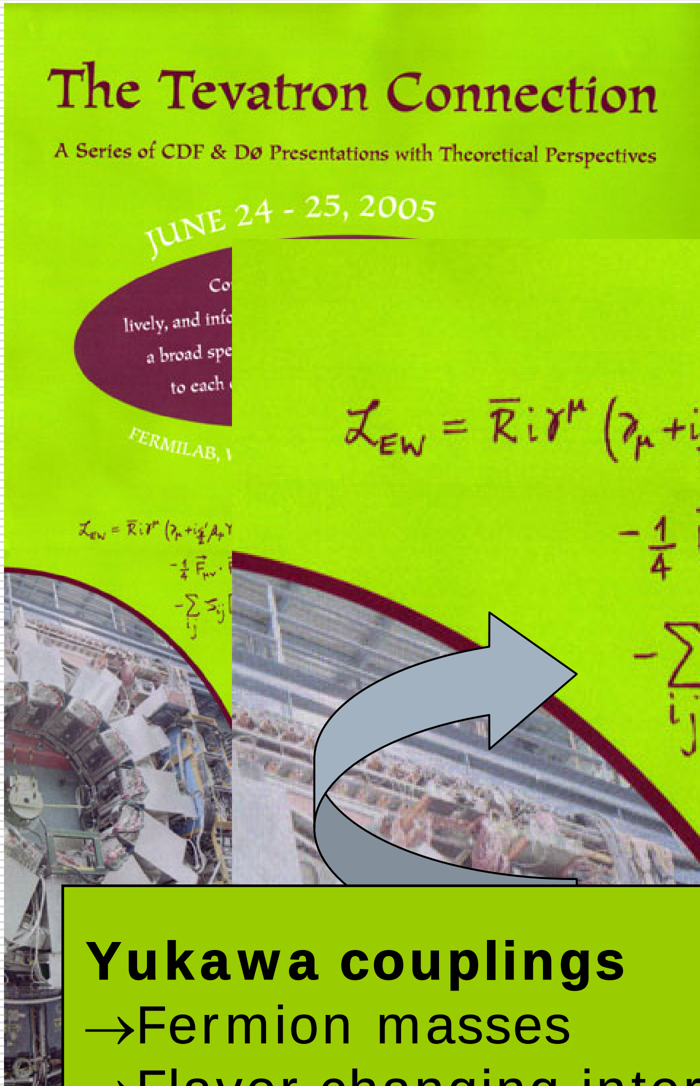
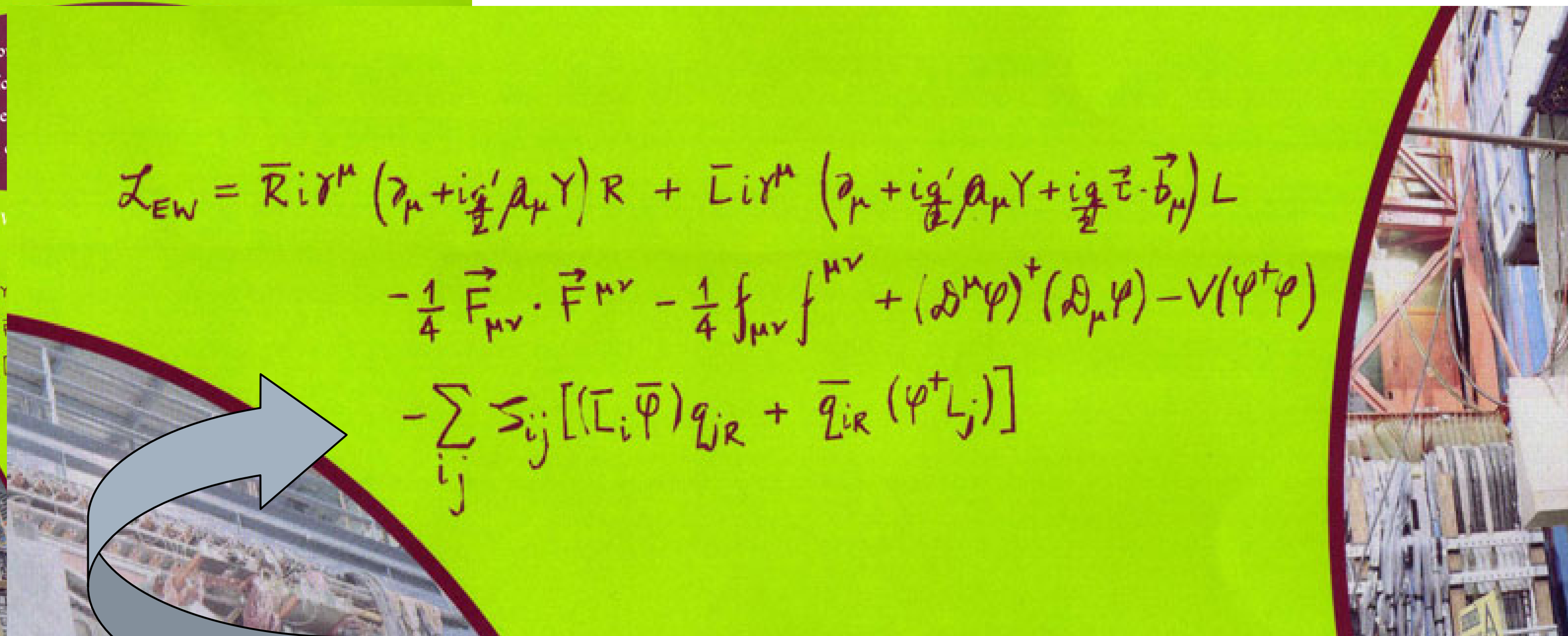
B-physics theory

Thomas Becher, Fermilab

The Tevatron Connection,
June 24, 2005





Yukawa couplings

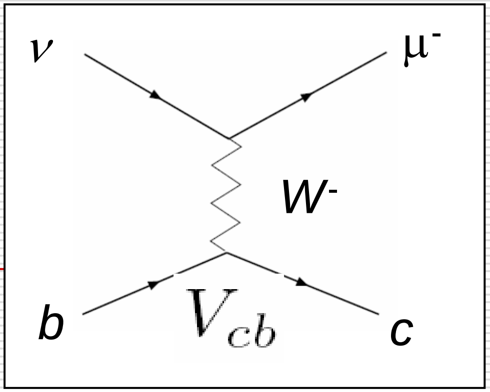
$\rightarrow$Fermion masses

$\left.\begin{array}{l}\rightarrow\text{Flavor changing interactions}\\ \rightarrow\text{CP violation}\end{array}\right\}$ CKM matrix

Overview

- CKM status and news
  - Exclusive V_{ub} from the lattice
  - sin(2β): trees vs. penguins
- B-physics with “collider physics methods”
  - Heavy-to-light decays: Factorization, Soft-Collinear Effective Theory, ...
  - Scope, limitations and relevance for B-physics program at the Tevatron

The CKM matrix



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

- Flavor changing quark interactions
- Unitary. 4 parameters including 1 complex CP violating phase

Wolfenstein parameterization

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\,\lambda^3\,(\rho - i\,\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\,\lambda^2 \\ A\,\lambda^3\,(1-\rho-i\eta) & -A\,\lambda^2 & 1 \end{pmatrix}$$

- $\lambda = |V_{us}| \approx 0.22$. ($A \approx 0.8$, $\rho \approx 0.2$, $\eta \approx 0.3$)
- Almost diagonal. Hierarchical.

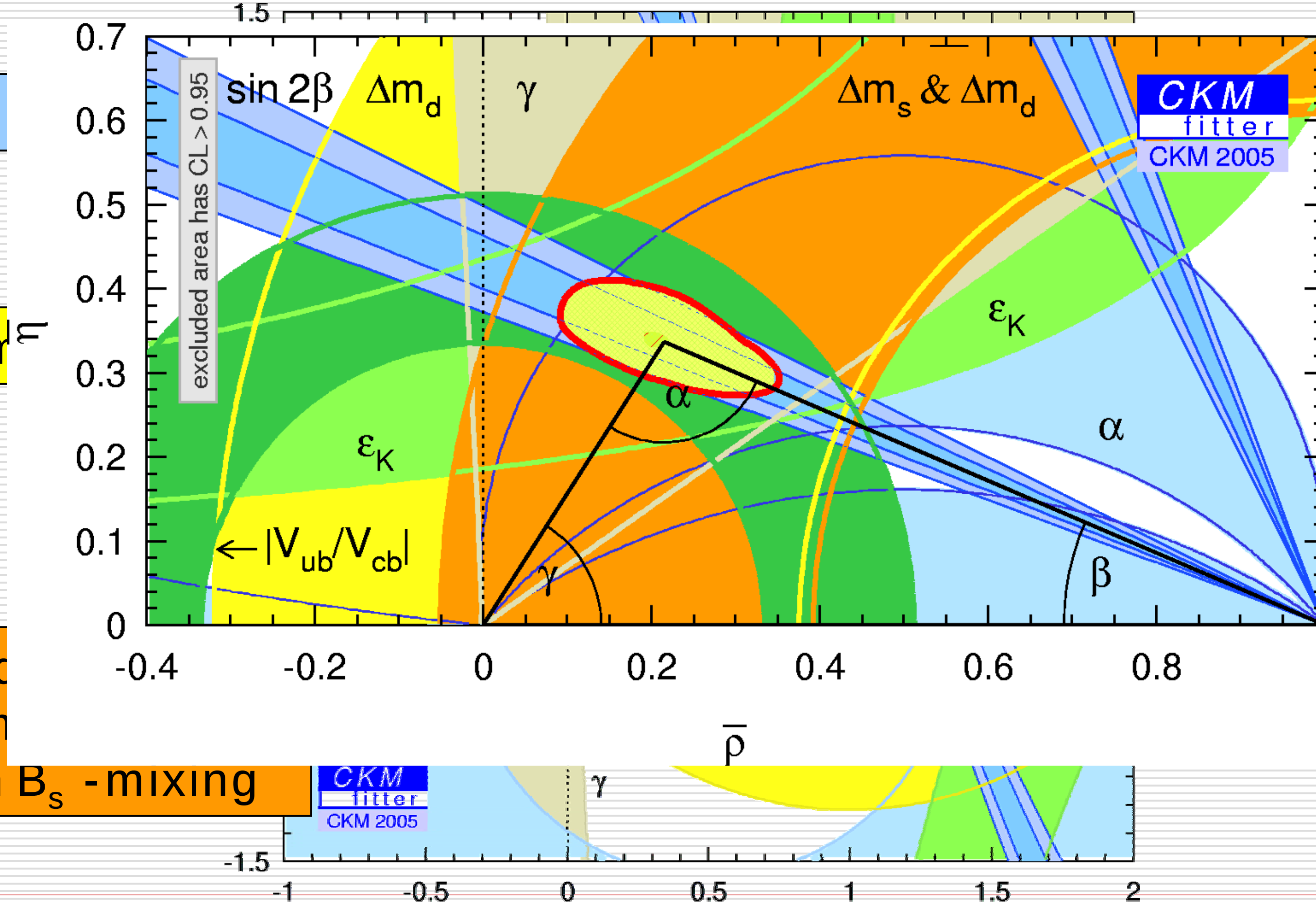
Constraints on ρ,η: the unitarity triangle

$A_{CP}(t)$

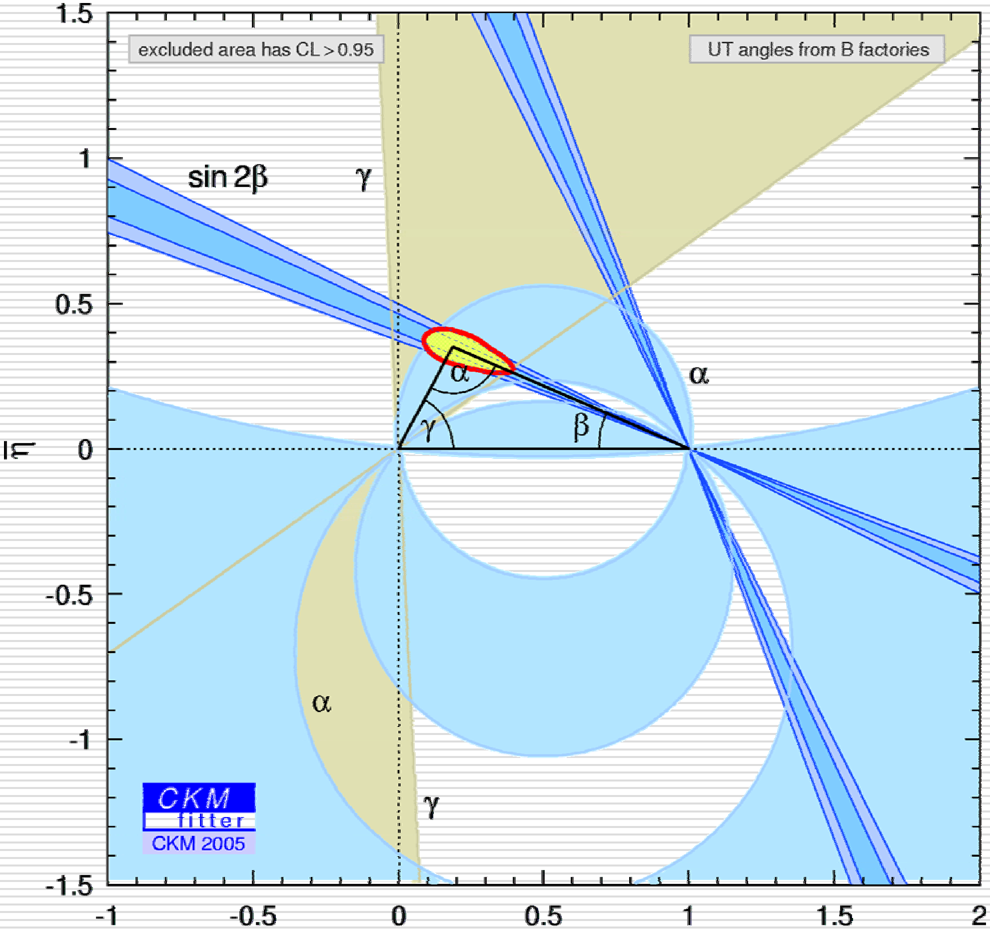
$B_d \overline{B}_d$ -m

nic

Combined
from B_d-m
bound on B_s -mixing



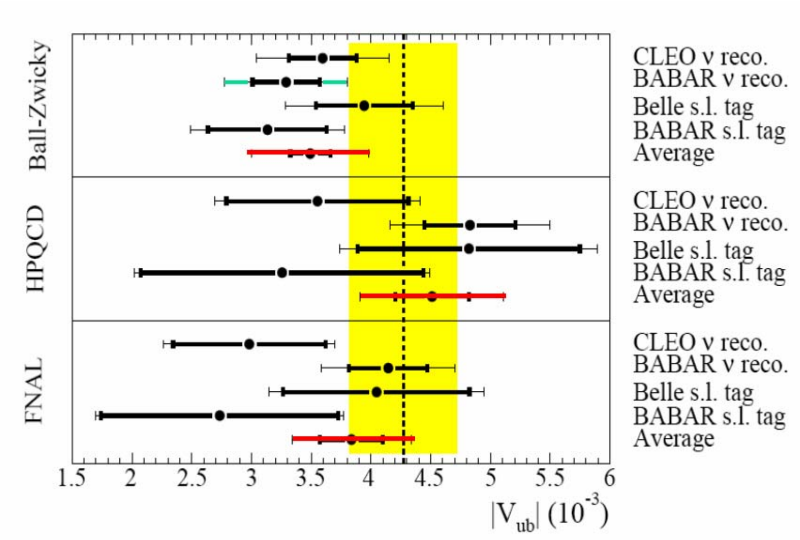
New constraints: α and γ

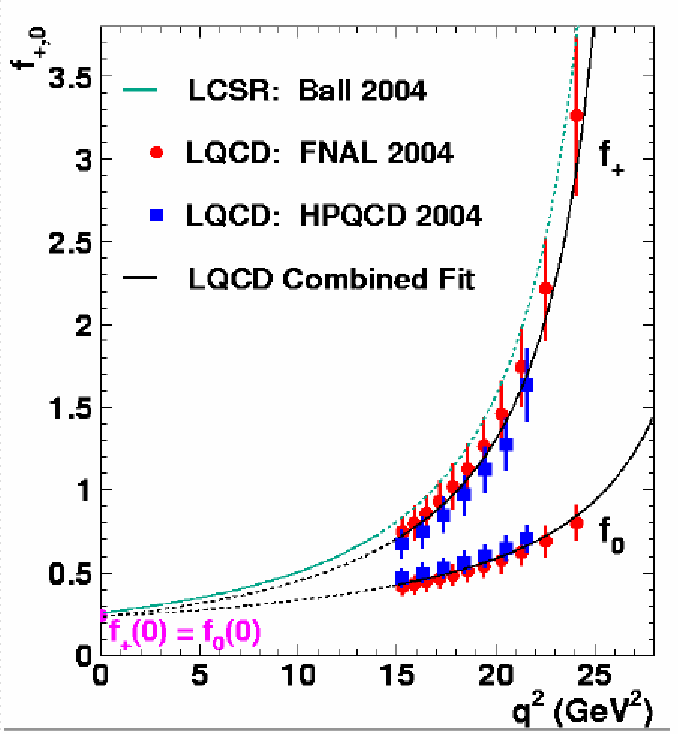


- α from $A_{CP}(t)$ in $B \to \pi\pi$, $B \to \rho\rho$, $B \to \rho\pi$ "isospin analysis"
- γ from $B^{\pm} \to \{D^0, \overline{D}^0\} K^{\pm} \to f\, K^{\pm}$

Exclusive $|V_{ub}|$ from $B \to \pi l \nu$

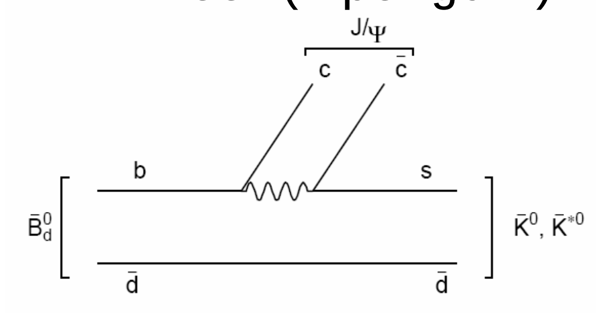
- New: *Dynamical* ($n_f=3$) lattice calculations of semileptonic form factors.



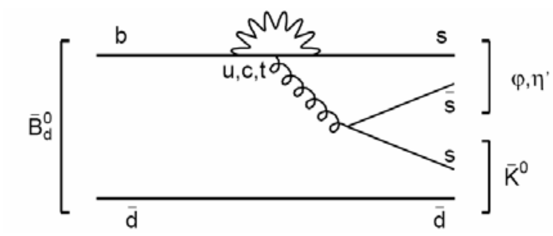


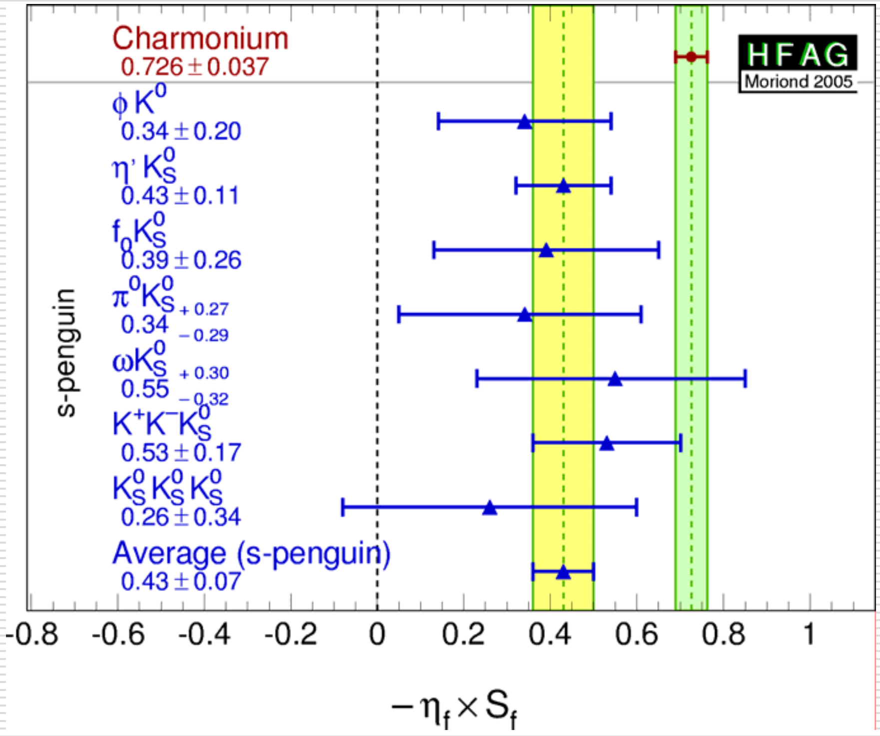
sin(2β) from loop dominated processes

Tree (+penguin)



Penguin



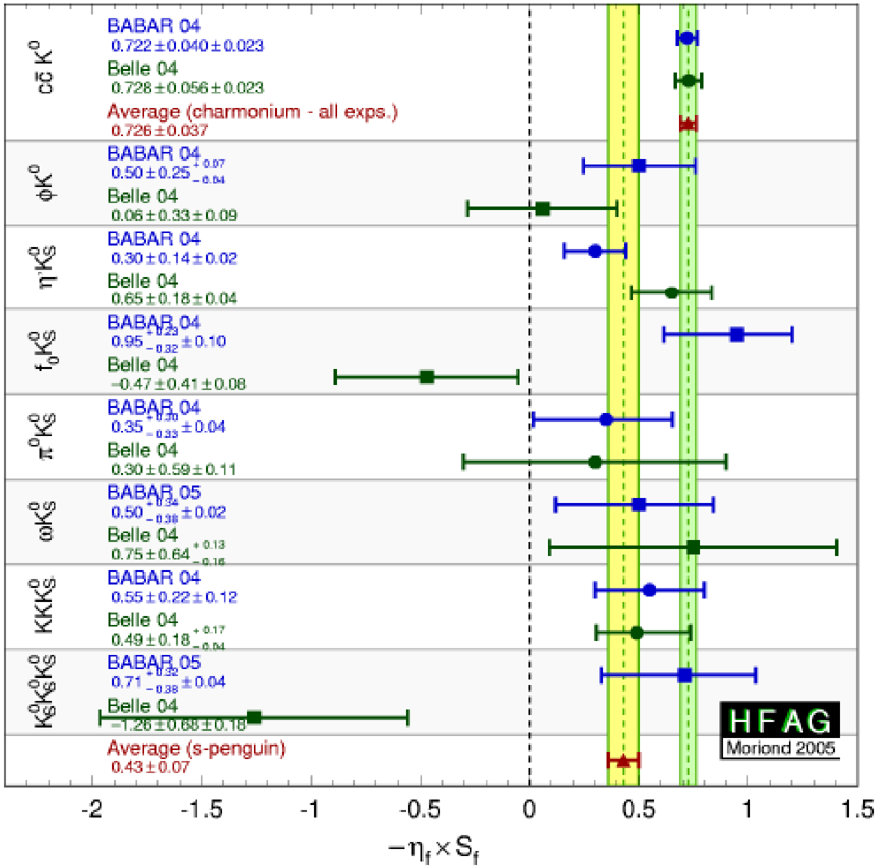


Questions

- **Babar vs. Belle?**
- **Theoretical uncertainties?**
  Contribution from small amplitudes?
  - Suppressed by

$$\left|\frac{V_{ub}V_{us}^*}{V_{cb}V_{cs}^*}\right| \approx \frac{1}{50}$$

  - Calculable in QCDF/SCET



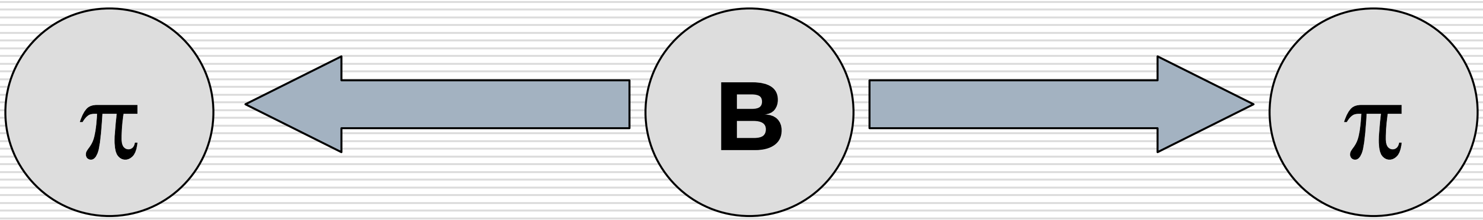
Collider physics methods in B-physics?

Factorization, Soft and Collinear particles, Jet-functions, Distribution Amplitudes...

WHAT IS WRONG WITH THE B-THEORISTS?

Hard scattering for $m_b \to \infty$

- In heavy-to-light decays, the decay products are typically energetic, e.g.

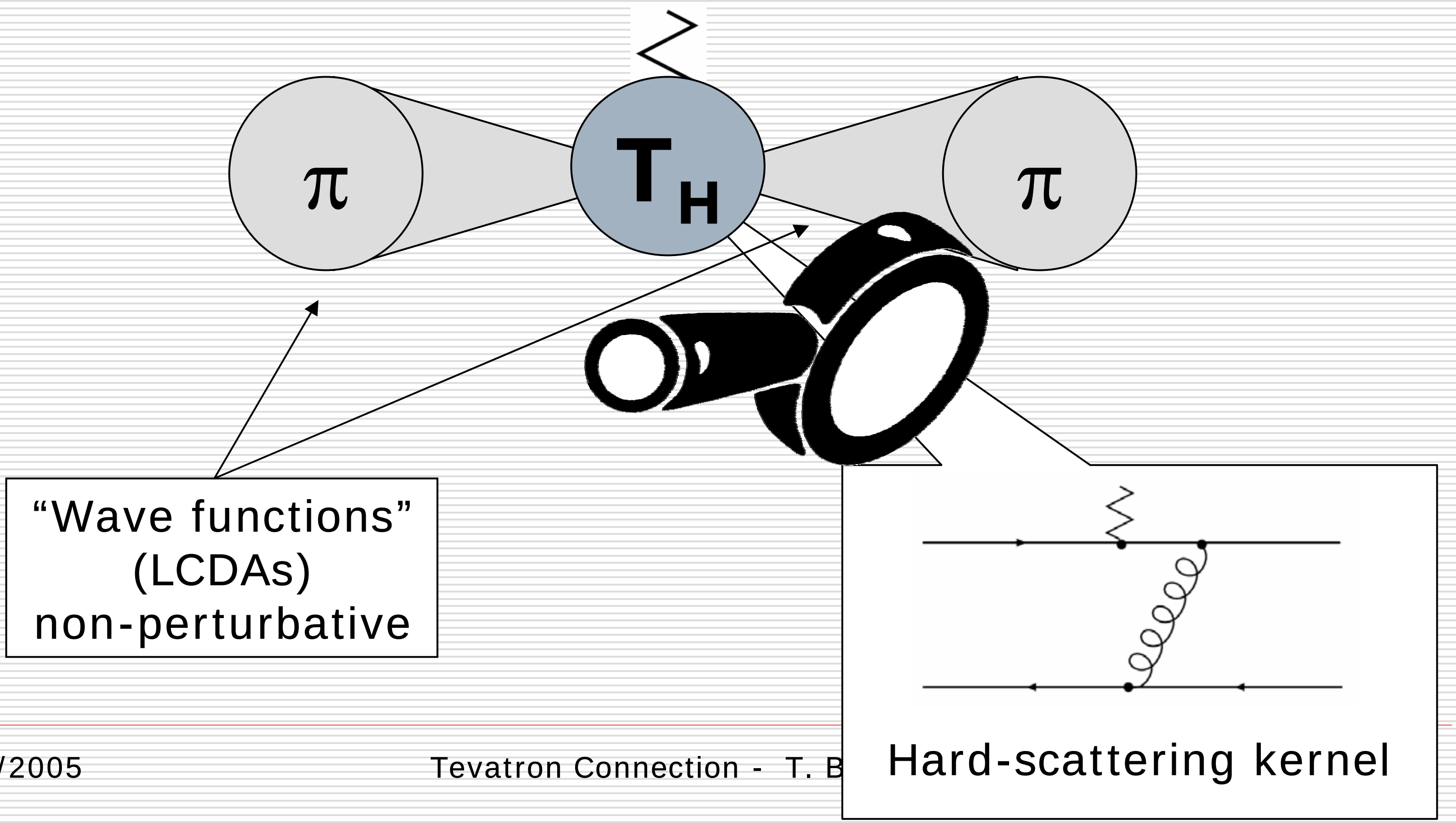


$$E_\pi = \frac{m_B}{2} \qquad\qquad E_\pi = \frac{m_B}{2}$$

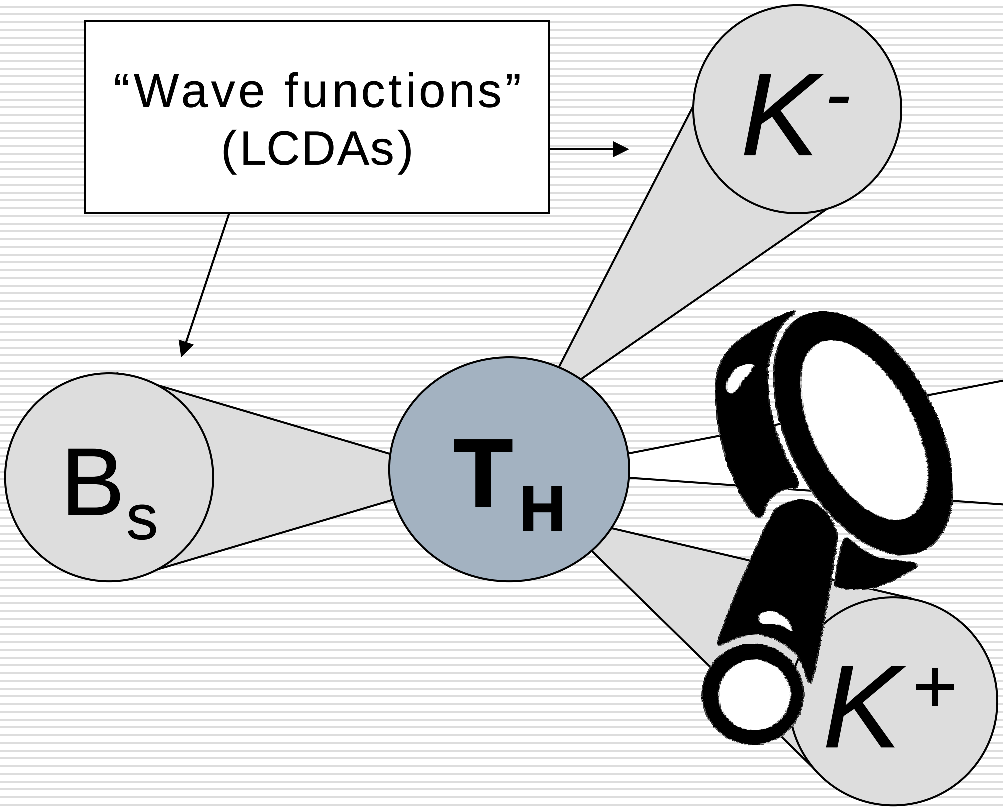
- Large momentum transfer $\to$ factorization?

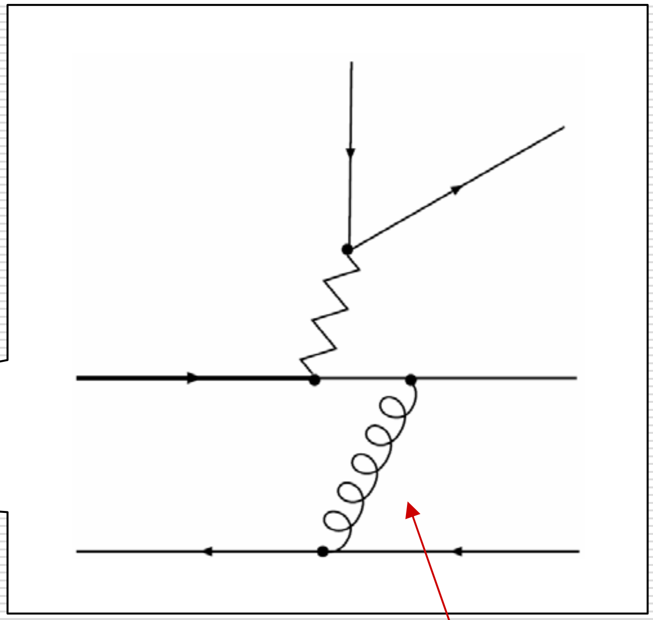
Remember? (1980)

- $\pi\pi$ form factor at large Q^2



Factorization for $m_b \to \infty$?



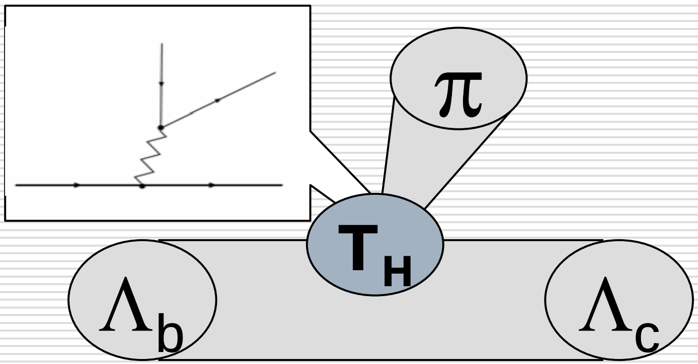


Factorization FAILS!

Ways out?

- Ignore the problem: Naïve factorization.
- Assume that non-factorizable effects are small after Sudakov resummation: “pQCD”.
- Give up on complete factorization. Allow for non-factorizable form factor piece: “QCD factorization”.

Example: $\Lambda_b \to \Lambda_c \pi$



Form factor (from semileptonic decay)

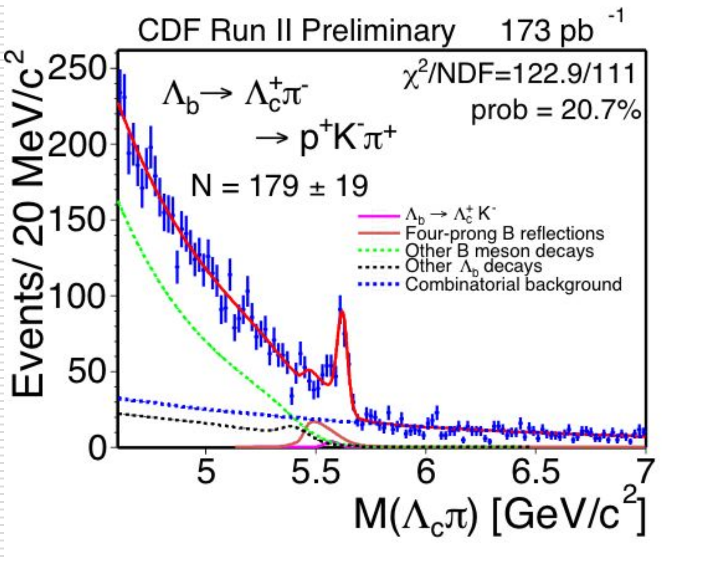
$$\mathcal{A} \propto V_{cb} V_{ud}^{*} \mathcal{F}_{\Lambda_b \to \Lambda_c}(q^2 \approx 0) f_\pi \overbrace{\int_0^1 dx\, T_H(x) \phi_\pi(x)}^{=1+O(\alpha_s)} + \mathcal{O}(\Lambda/E_\pi)$$

- Note: Obtain naïve factorization result to lowest order in α_s.
- Decays to two light hadrons also contain a completely factorizable piece.

CDF: $\frac{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-)} = 20.0 \pm 3.0\,(stat) \pm 1.2\,(syst) \begin{matrix} +0.7 \\ -2.1 \end{matrix}\,(BR) \pm 0.5\,(UBR)$

$$\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-) = \left(0.41 \pm 0.19\,(stat \oplus syst) \begin{matrix} +0.06 \\ -0.08 \end{matrix}\,(P_T \text{ spectrum})\right)\%,$$

$$\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \overline{\nu}_\mu) = \left(8.1 \pm 1.2\,(stat) \begin{matrix} +1.1 \\ -1.6 \end{matrix}\,(syst) \pm 4.3\,(\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-))\right)\%.$$



- Theory prediction?

  Leibovich et al. hep-ph/0312319

  - Needs $F(q^2\approx 0)$ as an input!

    $$\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-) \approx 0.46\%$$

  same $F(q^2)$ gives

  $$\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \bar{\nu}) \approx 6\%$$

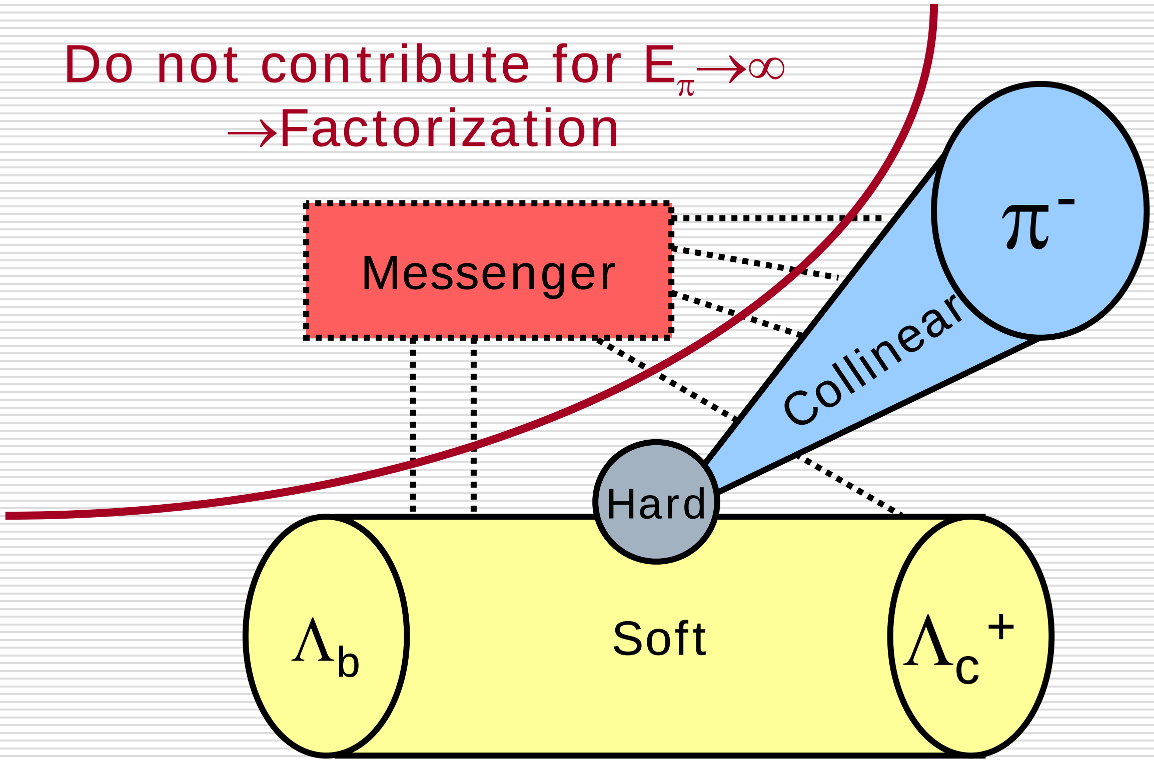
Soft-Collinear Effective Theory

- Effective Lagrangian instead of diagrammatic language: systematic and transparent analysis of factorization properties.
- The "HQET" for heavy-to-light processes.
- Complicated field content
  - Soft-fields: partons of b- (and c-) hadrons
  - Collinear fields: partons of energetic light particles
  - Messenger fields: low energy interactions between soft and collinear partons. Absent for factorizable quantities.
- Hard scattering kernels $T_H \leftrightarrow$ Wilson coefficients of operators in SCET
- Based on "Strategy of Regions". Fields in SCET $\leftrightarrow$ Relevant momentum regions for expansion of diagrams.

$\Lambda_b \to \Lambda_c \pi$ analysis in SCET

Do not contribute for $E_\pi \to \infty$

$\to$Factorization



Applications

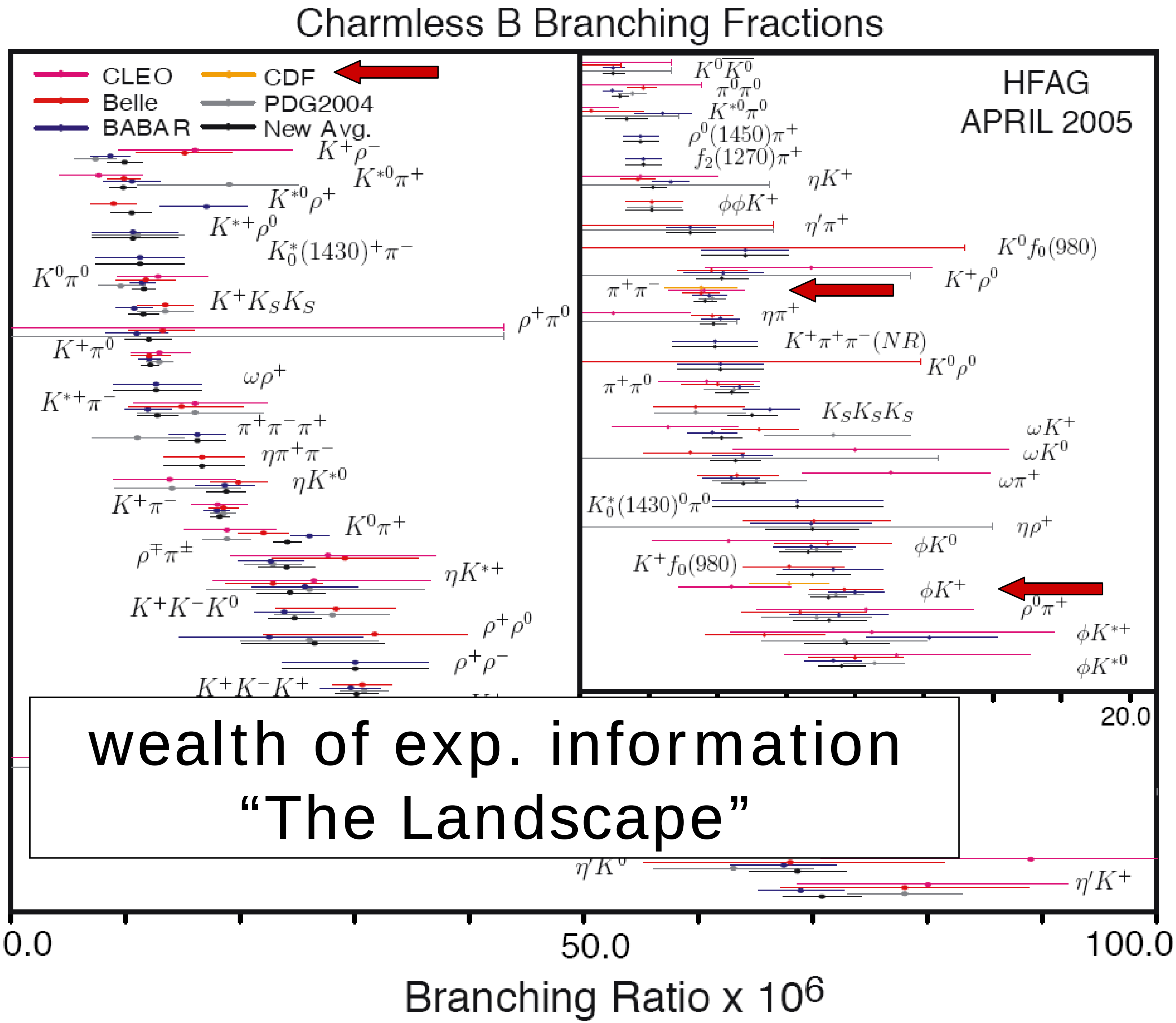
- Factorization analysis (M: light meson)
  - $B_{s,d} \to D_{s,d} M$, $\Lambda_b \to \Lambda_c M$
  - $B_{s,d} \to M_1 M_2$, $B \to M l\nu$
  - $B_{s,d} \to M \gamma$, $B_{s,d} \to M \mu^+ \mu^-$, $B \to \gamma l\nu$
  - $B \to X_u l\nu$, $B \to X_s \gamma$ (end-point region)
- Sudakov resummation
  - $B \to M l\nu$, $B \to K^* \gamma$, $B \to \gamma l\nu$
  - $B \to X_u l\nu$, $B \to X_s \gamma$
- Λ/m_b power corrections
  - $B \to X_u l\nu$, $B \to X_s \gamma$ ("subleading shape functions")
  - $B^0 \to D^{(*)0}\pi^0$
  - partial results for $B_{s,d} \to M_1 M_2$

Hadronic input for two-body decays

- Need form-factors at $q^2=0$ as well as meson wave functions as input.
  - Have $B\to D$ form factor
  - Some knowledge on $B\to\pi$ form factors (exp., lattice)
  - Little lattice info on wave functions. B-meson wave function is especially difficult.
  - Can use SU(2) and SU(3) to relate hadronic parameters.
- Many factorization predictions rely on (light-cone) sum rule determinations for form factors and wave functions.

Strategies for charmless decays

- Beneke et al. "QCDF" ($B \to PP$, $B \to VP$)
  - Use sum rule input for leading power
  - Estimate enhanced power corrections
    - chiral enhancement, annihilation
- Bauer et al. "SCET" ($B \to \pi\pi$)
  - Use $B \to \pi\pi$ data to determine hadronic parameters.
  - Do not attempt to factorize "charming penguins"
  - To retain predictability: drop power and $\alpha_s(m_b)$ corrections.
- CKM fitter group: fit to charmless decays in QCDF.



wealth of exp. information

“The Landscape”

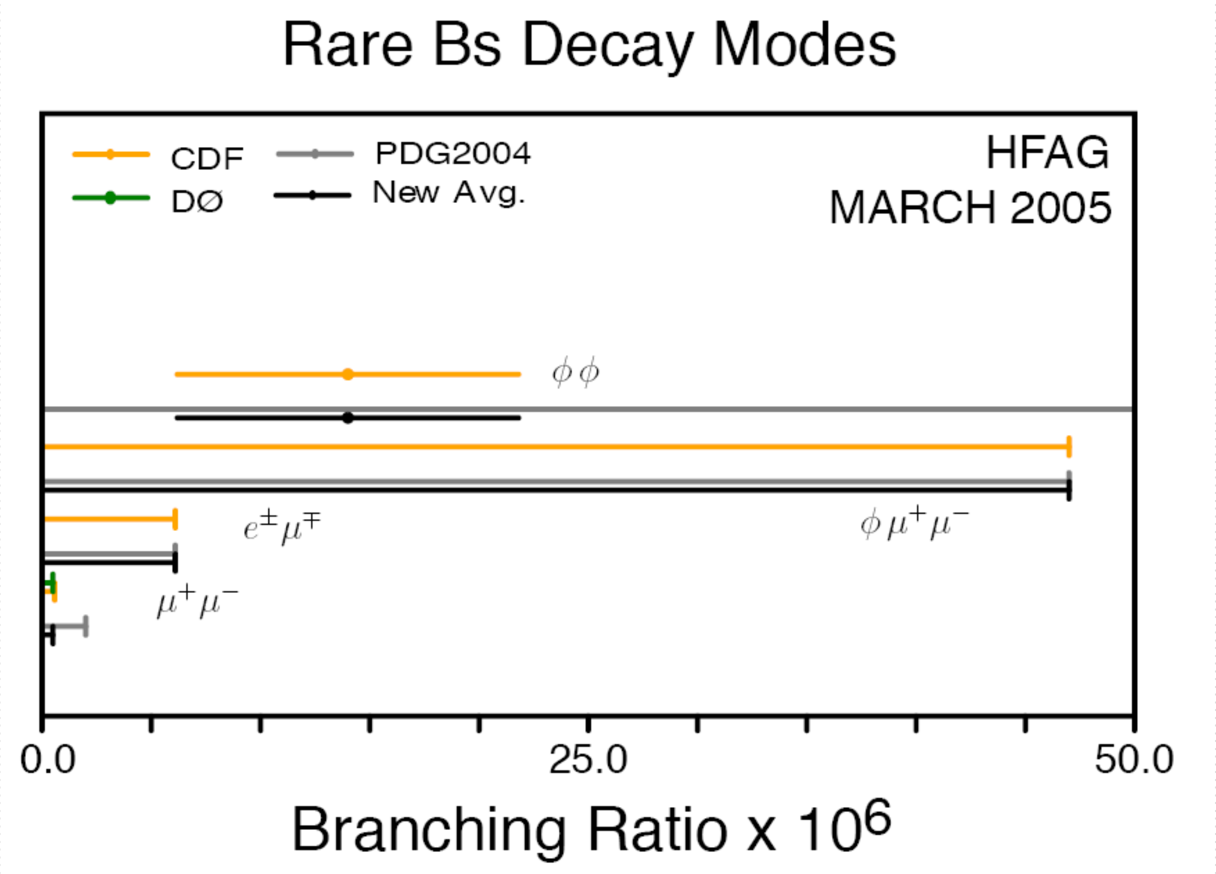
CDF results for $B_{s,d} \to hh$

- CDF sample of $B_d \to hh$ is as large as BaBar sample (and growing faster).
- Only a few decay channels measured up to now, but with *competitive accuracy*

Mode	BaBar	Belle	CDF
$10^6\,\mathrm{Br}(B \to \pi^+\pi^-)$	$4.7 \pm 0.6 \pm 0.2$	$4.4 \pm 0.6 \pm 0.3$	$4.5^{+1.4}_{-1.2}{}^{+0.5}_{-0.4}$
$10^6\,\mathrm{Br}(B \to K^+K^-)$	< 0.6	< 0.7	< 3.1
$10^6\,\mathrm{Br}(B \to \phi K^+)$	$10^{+0.9}_{-0.8} \pm 0.5$	$9.60 \pm 0.92^{+1.05}_{-0.84}$	$7.6 \pm +1.3 \pm 0.6$
$\mathrm{A}_{CP}(B \to \phi K^+)$	$0.054 \pm 0.056 \pm 0.012$	$0.01 \pm 0.12 \pm 0.05$	$-0.07 \pm 0.17^{+0.03}_{-0.02}$

- In future: $B_s \to KK, K\pi, \pi\pi$, ...

The first B_s charmless two-body decay!



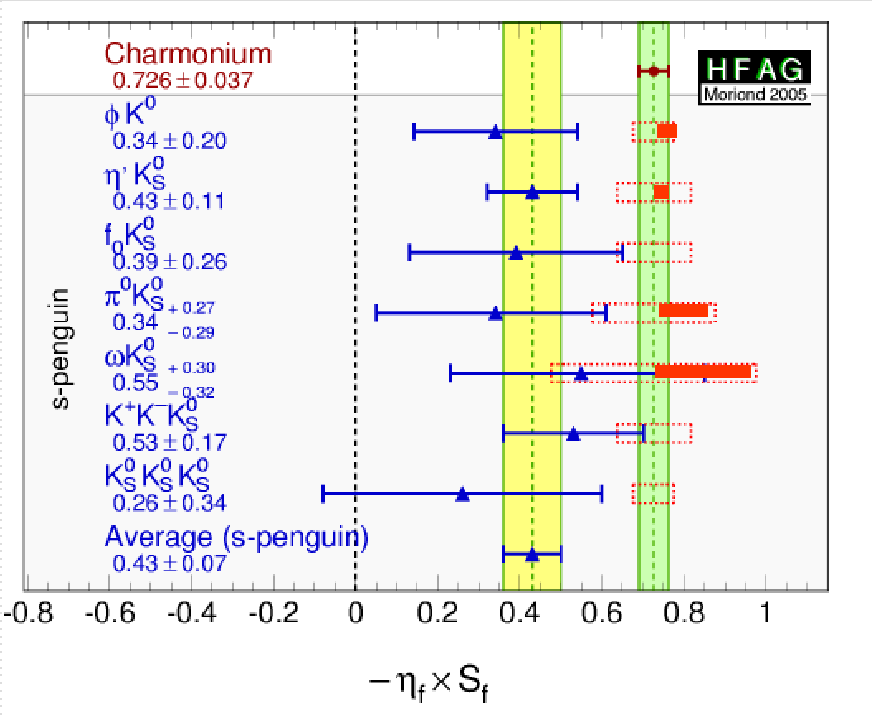
Outlook

(see talks of U. Nierste and R. Harr at INT workshop)

- $B_{d,s} \to h^+h^-$, $B_s \to \phi\phi$, ...
  - Updated Br() results
  - more theoretical work on VV decays
  - $B_s \to \phi\phi$, $B_s \to K^+K^-$ lifetime measurements?
    - Sensitive to *CP phase in* $b \to \bar{q}qs$
  - Isospin violating decay $B_s \to \rho^0\phi$?
  - Time-dep. CP asymmetries?
- Baryonic decays $\Lambda_b \to p(\pi,K)$
  - Direct CP asymmetry
  - Factorization analysis (hadronic parameters?)
- Rare decay $B_s \to \phi\mu^+\mu^-$
- γ from $B \to D^0K$

sin(2β) from penguin dominated modes

- Beneke (hep-ph/0505075) evaluates the corrections to sin(2β) from the small amplitudes.
- Scans over all input parameters, (require BR's to 3σ). Gives resulting range.
- Positive contribution to ΔS. Strengthens the discrepancy!



Summary

- With the exception of sin(2β) from penguin dominated modes all measurements are consistent with the CKM picture of the flavor sector.
  - theoretical uncertainty on sin(2β) extraction is small.
- $B_d \to M^+ M^-$ decays
  - Theoretically challenging: understand the limit $m_b \to \infty$
    - Power corrections, hadronic input.
  - Tevatron measurents of $B_d \to M^+ M^-$ are competitive with B-factories.
  - I look forward to $B_s \to M^+ M^-$, ...
- Apologies. Much more B-physics at the Tevatron than in my talk...just keep listening!

Extra slides

B→D M

Decay	Br(10^{-3})	$\lvert A\rvert$ (10^{-7} GeV)	Decay	Br(10^{-3})	$\lvert A\rvert$ (10^{-7} GeV)
$\bar{B}^0 \to D^+\pi^-$	2.76 ± 0.25	5.99 ± 0.27	$\bar{B}^0 \to D^{*+}\pi^-$	2.76 ± 0.21	6.06 ± 0.23
$B^- \to D^0\pi^-$	4.98 ± 0.29	7.72 ± 0.22	$B^- \to D^{*0}\pi^-$	4.6 ± 0.4	7.50 ± 0.33
$\bar{B}^0 \to D^0\pi^0$	0.25 ± 0.02	1.81 ± 0.08	$\bar{B}^0 \to D^{*0}\pi^0$	0.28 ± 0.05	1.95 ± 0.18
$\bar{B}^0 \to D^+\rho^-$	7.7 ± 1.3	10.2 ± 0.9	$\bar{B}^0 \to D^{*+}\rho^-$	6.8 ± 0.9	9.10 ± 0.61
$B^- \to D^0\rho^-$	13.4 ± 1.8	12.9 ± 0.9	$B^- \to D^{*0}\rho^-$	9.8 ± 1.7	10.5 ± 0.92
$\bar{B}^0 \to D^0\rho^0$	0.29 ± 0.11	1.97 ± 0.37	$\bar{B}^0 \to D^{*0}\rho^0$	< 0.51	< 2.78

The Experimental Program for sin $2\beta_{eff}$

Mode	*CP*	Tot. error Belle $\mathcal{L} \sim 253\ fb^{-1}$	Tot. error BABAR $\mathcal{L} \sim 195\text{-}212\ fb^{-1}$	$\langle\Delta(SM)\rangle$ [in σ]	Error estimate at 2 ab^{-1}	Syste-matics	Max. central value for 5σ deviation at 2 ab^{-1}	Quality [naïve theoretical cleanliness]
ϕK^0	–1	0.34	0.26	– 1.9	0.10	small	0.22	☻ ☻ ☻
$\eta' K^0$	–1	0.18	0.14	– 2.6	< 0.05	small	0.45	☻ ☻ (☻)
$f_0(980)K^0$	+1	0.42	0.29	– 1.3	< 0.12	Q2B	0.12	☻ ☻
$K_S K_S K^0$	±1	0.71	0.36	– 1.4	< 0.16	vertex	– 0.08	☻ ☻ ☻
$K^+K^-K^0$	~+1	0.25	0.25	– 1.1	< 0.08	*CP*	0.31	☻ (☻)
$\pi^0 K_S$	–1	0.60	0.32	– 1.4	0.13	vertex	0.07	☻
ωK^0	–1	0.66	0.36	– 0.6	< 0.15	small	– 0.03	(☻)
$\rho^0 K^0$	–1	-	-	?	?	Q2B	?	(☻)
ηK_S	+1	-	-	?	?	vertex	?	-
Average	-	0.39 ± 0.11	0.45 ± 0.09	– 3.7	< 0.034	ok	0.53	☻ ☻

3. Lifetime measurements in $b \to s\bar{s}s$ decays

A combined fit to CP asymmetries in rare hadronic $b \to s\bar{q}q$ decays measured at BaBar and BELLE indicates a deviation from the Standard Model by 3.8σ (O. Tajima, Aspen 2005).

Consider a new CP phase σ in the $b \to s\bar{s}s$ decay. Let now $\overset{(-)}{B}_s \to f_{CP+}$ denote a $b \to s\bar{s}s$ decay into a CP-even final state, e.g. $f_{CP+} = (\phi\phi)_{L=0}$. With

$$\langle f_{CP+} | B_s \rangle \propto e^{i\sigma} \qquad \text{and} \qquad \langle f_{CP+} | \overline{B}_s \rangle \propto -e^{-i\sigma}$$

the coefficients in

$$\Gamma[f,t] \propto |\langle f | B_L \rangle|^2 e^{-\Gamma_L t} + |\langle f | B_H \rangle|^2 e^{-\Gamma_H t}$$

read:

$$|\langle f_{CP+} | B_L \rangle|^2 \propto \frac{1+\cos(\phi+2\sigma)}{2}, \qquad |\langle f_{CP+} | B_H \rangle|^2 \propto \frac{1-\cos(\phi+2\sigma)}{2}$$

$$\Gamma[f_{CP+},t] \propto \frac{1+\cos(\phi+2\sigma)}{2} e^{-\Gamma_L t} + \frac{1-\cos(\phi+2\sigma)}{2} e^{-\Gamma_H t}$$

For the Standard Model case $\phi = \sigma = 0$ only B_L can decay into f_{CP+} and the lifetime measured in e.g. $\overset{(-)}{B}_s \to (\phi\phi)_{L=0}$ determines Γ_L.

If the lifetime measured in $\overset{(-)}{B}_s \to (\phi\phi)_{L=0}$ is longer than the one measured in $\overset{(-)}{B}_s \to (J/\psi\phi)_{L=0}$, new physics in the $b \to s\bar{s}s$ decay amplitude is established through $\sigma \neq 0$, with the possibility of $\phi = 0$ or $\phi \neq 0$.
If the lifetime measured in $\overset{(-)}{B}_s \to (\phi\phi)_{L=0}$ is shorter than the one measured in $\overset{(-)}{B}_s \to (J/\psi\phi)_{L=0}$, new physics in both the $b \to s\bar{s}s$ decay amplitude and $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing is established through $\sigma \neq 0$ and $\phi \neq 0$.

The same argument applies to the $b \to s\bar{u}u$ amplitude triggering $\overset{(-)}{B}_s \to K^+K^-$ except that here a small tree amplitude is present, so that $\sigma \neq 0$ already in the Standard Model.