Theory of hadronic B decays

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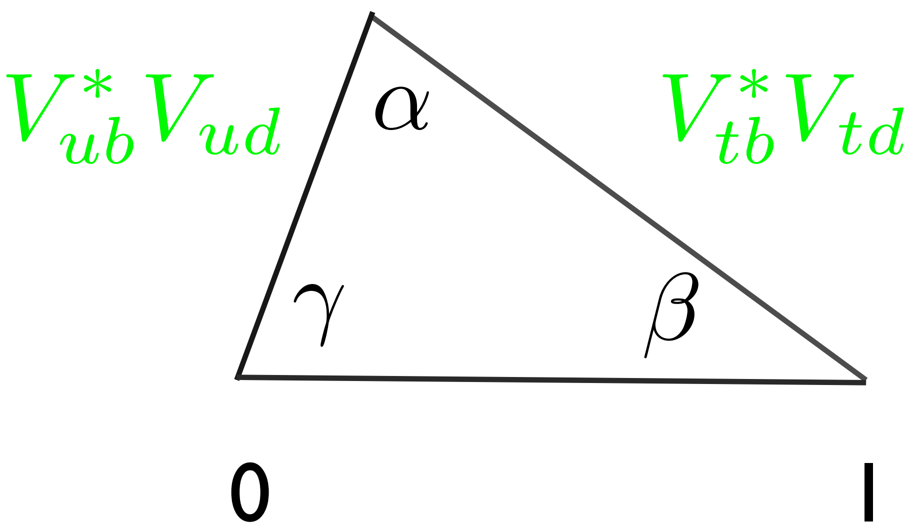
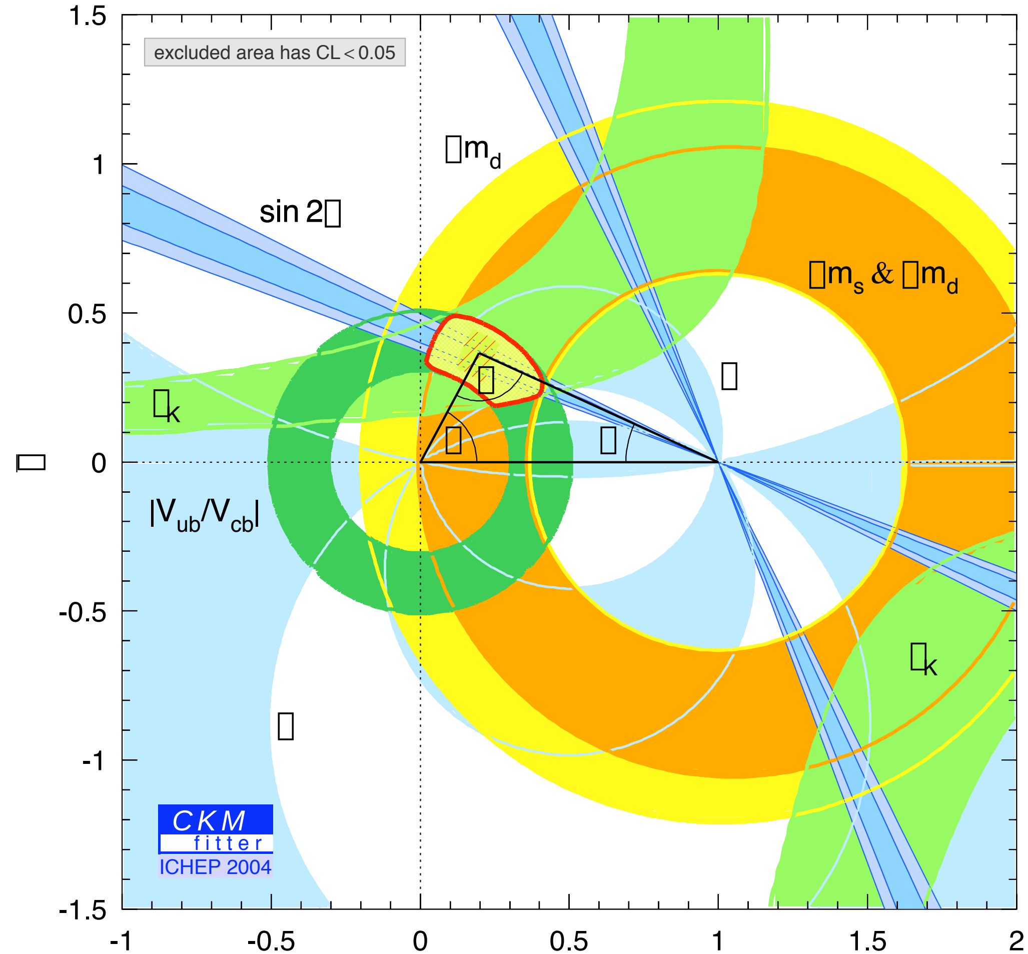
Outline

- Hadronic B decays - probes of the flavor structure of the Standard model
- The challenge of the strong interactions
  - Factorization methods (QCDF, pQCD)
  - Progress from the Soft-Collinear Effective Theory (SCET)
- Factorization in B decays into two light mesons
  - Phenomenological study of corrections to factorization $B \to \pi\pi$
- Factorization in $B \to D^{(*)}\pi$ - implications for $2\beta + \gamma$
- Conclusions

The goal



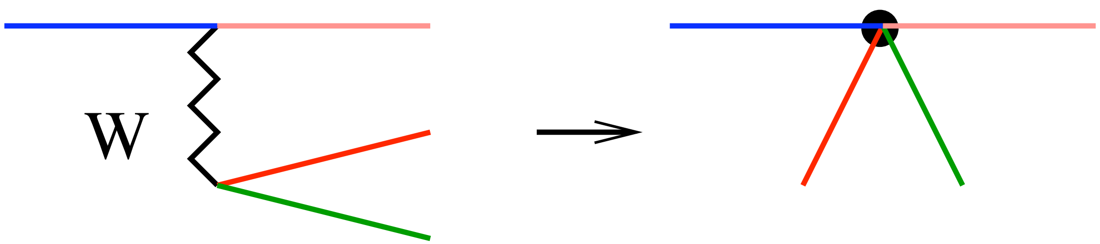


- Independent measurements of the sides and angles of the UT should overconstrain the CKM matrix
- Test consistency with the SM picture, or find signals for new physics

Electroweak Hamiltonian

$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}} \sum_i \lambda_{CKM}^{(i)} C_i(\mu) O_i$$

Integrate out the top and W

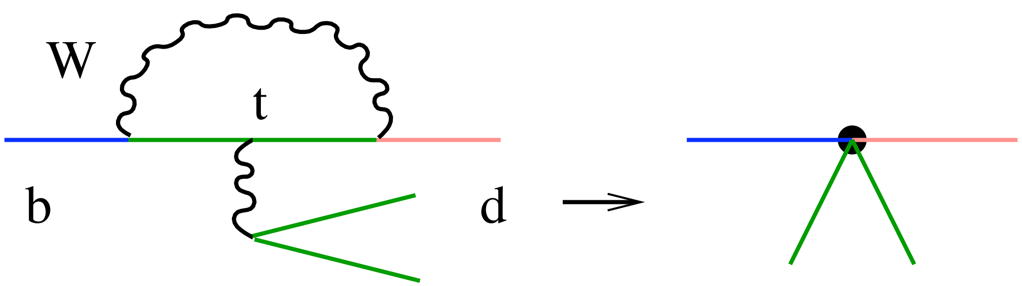


Tree operators

$$O_1^u = (\bar{u}b)_{V-A}(\bar{d}u)_{V-A}$$

$$O_2^u = (\bar{u}_i b_j)_{V-A}(\bar{d}_j u_i)_{V-A}$$

Penguin operators



$$O_{3-6} = (\bar{d}b)_{V-A} \sum_q (\bar{q}q)_{V\pm A}$$

$$O_{7-10} = (\bar{d}b)_{V-A} \sum_q e_q (\bar{q}q)_{V\pm A}$$

+ new physics contributions...

Now known at NNLO

Gorbahn, Haisch - hep-ph/0411071

Gorbahn, Haisch, Misiak - hep-ph/0504194

Strong-interaction effects

Weak interactions of quarks take place inside hadrons -> need to account for strong interaction nonperturbative effects

$$\langle M_1 M_2 | \mathcal{H}_{EW} | \bar{B} \rangle = ?$$

Controlling these effects is a central part of SM physics

- Lattice QCD
- Exploit symmetries of QCD:
  - flavor SU(3)
  - chiral symmetry
  - heavy quark symmetry
- Factorization theorems of hard QCD

Effective field theories

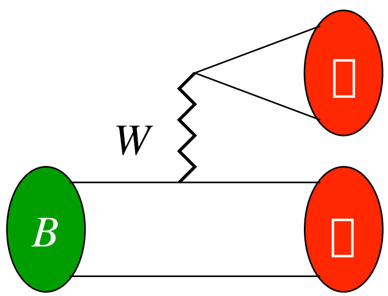
Recent progress from Soft-Collinear Effective Theory

Flavor symmetry - SU(3)

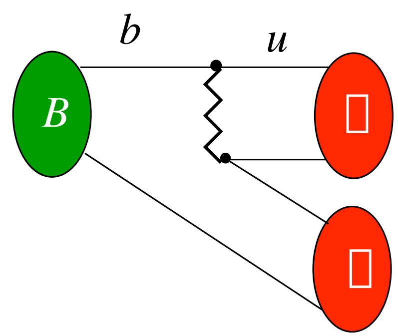
Gronau, Hernandez, London, Rosner

The B decay amplitude can be given as a sum over graphical amplitudes (equivalent to SU(3) Wigner-Eckart)

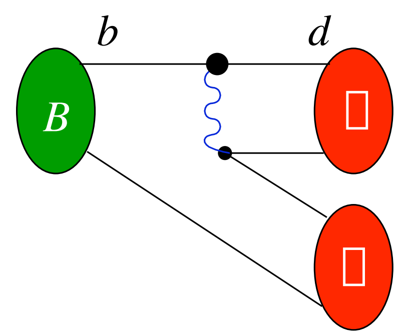
6 ‘graphical’ amplitudes = 5 reduced matrix elements



Tree (T)

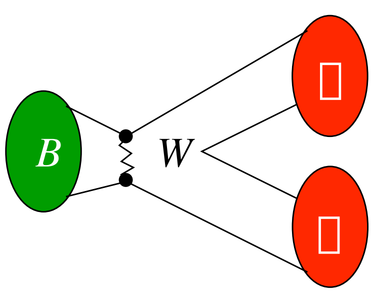


Color-suppressed (C)

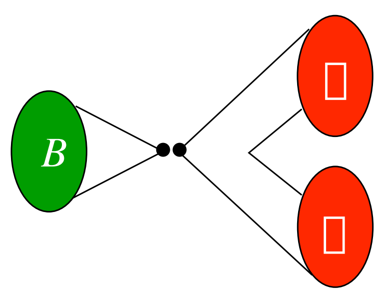


Penguin (P)

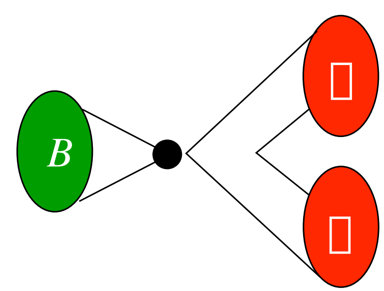
+ EWPs



W-exchange (E)



Weak annihilation (A)



Penguin annihilation (PA)

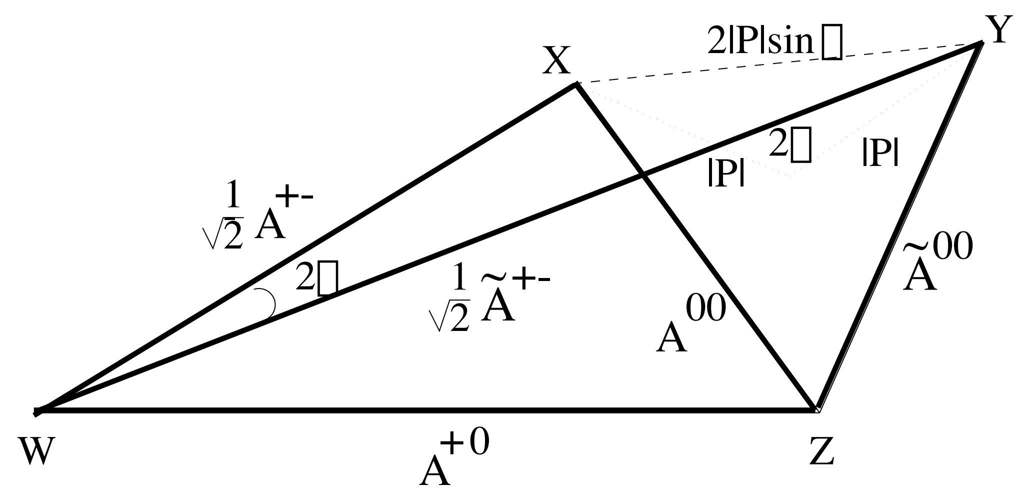
Counting amplitudes and strong phases

$B \to P_8 P_8$	5 amps	4 phases
$B \to P_8 V_8$	10 amps	4 phases
$B \to V_8 V_8$	5 amps	4 phases
$B \to M \eta_1$	4 amps	

In certain lucky cases the strong amplitudes can be completely eliminated using experimental input

- Isospin analysis in $B \to \pi\pi$

Gronau, London



More often than not, additional dynamical information is required - usually assuming negligible rescattering or weak annihilation $A \sim E \sim PA \sim 0$

Powerful approach, if used carefully

see talk of M. Gronau

A dynamical approach needed, providing a guide to the hierarchy of amps

Theoretical approaches - factorization

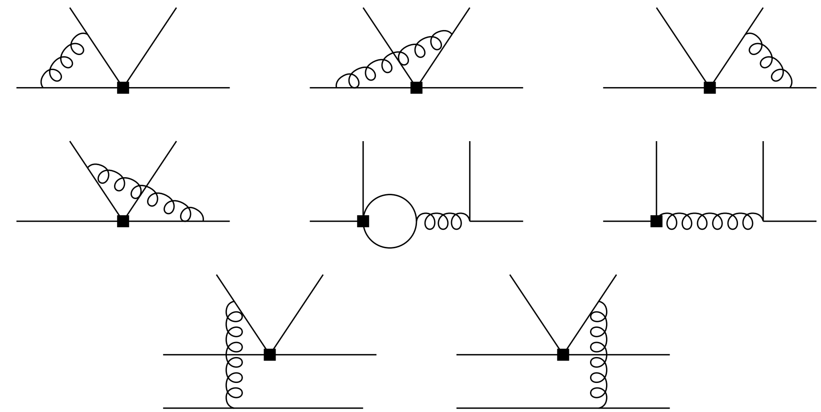
- Large Nc QCD — Schwinger; Bauer,Stech,Wirbel; Bardeen, Buras, Gerard; Blok, Shifman; Neubert,Stech
- Naive/`improved' factorization — Buras,Silvestrini; Ali, Lu
- QCD factorization — Beneke,Buchalla,Neubert,Sachrajda; Du, Lu, Sun, Yang, Zhu; Ciuchini et al.
- pQCD - kT factorization — Keum, Li, Sanda
- SCET — Bauer, Fleming, DP, Rothstein,Stewart; Chay, Kim; Beneke,Chapovsky, Diehl,Feldmann; Hill, Becher,Neubert,Lee

QCD factorization

Beneke,Buchalla,Neubert,Sachrajda

Example: $B \to M_1 M_2$

$M_{1,2} = \pi, K, \eta, \cdots$



At leading order in Λ/m_b and $O(\alpha_s)$ the hadronic matrix elements of $\mathcal{H}_W$ simplify

$$A(B \to M_1 M_2) = C \times \{F^{BM_1} \times T_I \star \Phi_{M_2} + \Phi_B \star T_{\rm II} \star \Phi_{M_1} \star \Phi_{M_2}\}$$

``form-factor term''  ``hard-scattering term''

T_I and $T_{\rm II}$ are calculable kernels.

Strong phases introduced through the Bander,Silverman,Soni mechanism and hard loop corrections -> generically small

$$\Delta\phi \sim O(\alpha_s, \frac{\Lambda}{m_b})$$

Theoretical issues

- All-order (in α_s) proof ?
- Factorization $\Leftrightarrow$ scale separation

  Identify all relevant scales

- How well do we know the hadronic input parameters?

  Form-factors, wave functions, decay constants
  - nonperturbative QCD

- Factorization for power correction terms?

Can be addressed in the Soft-Collinear Effective Theory

Soft-Collinear Effective Theory

- Systematic power counting in Λ/m_b for B processes involving energetic hadrons

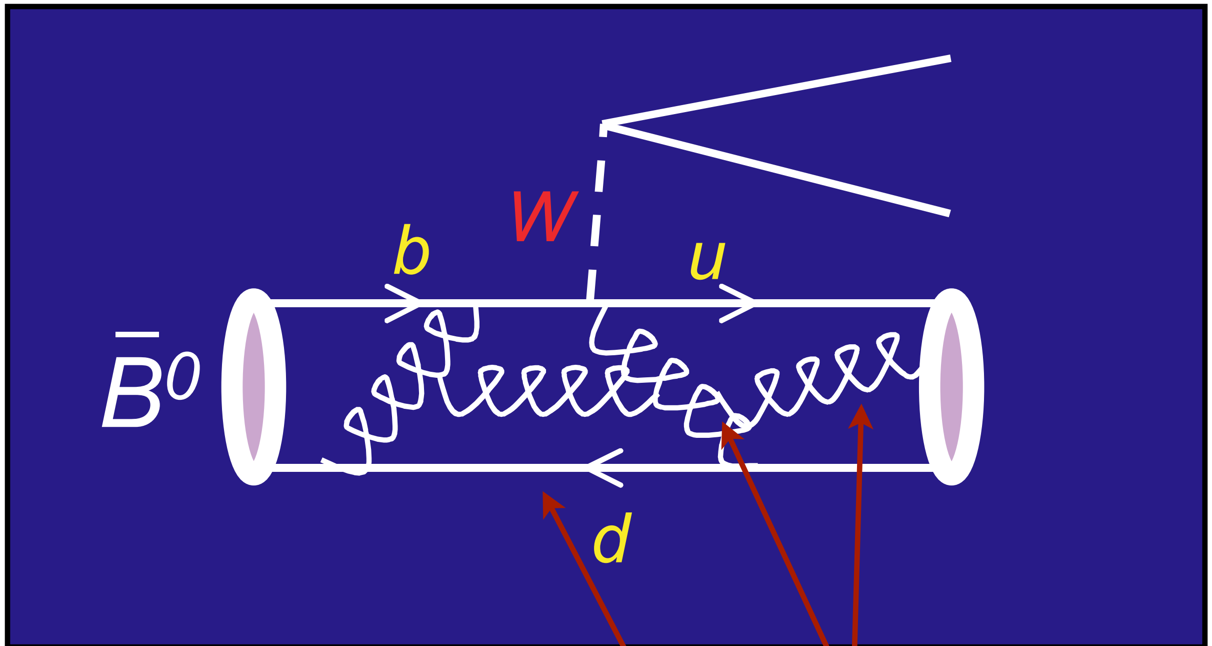
- Introduce distinct fields for the relevant degrees of freedom: soft, collinear, hard-collinear, etc.

- Construct effective Lagrangians for strong and weak interactions describing the dynamics of the relevant degrees of freedom

- Guiding principles - new symmetries: collinear/soft gauge invariance, reparameterization invariance

Example: Semileptonic $B \to \pi \ell \nu$ decay at large recoil

$E_\pi \sim m_B/2$



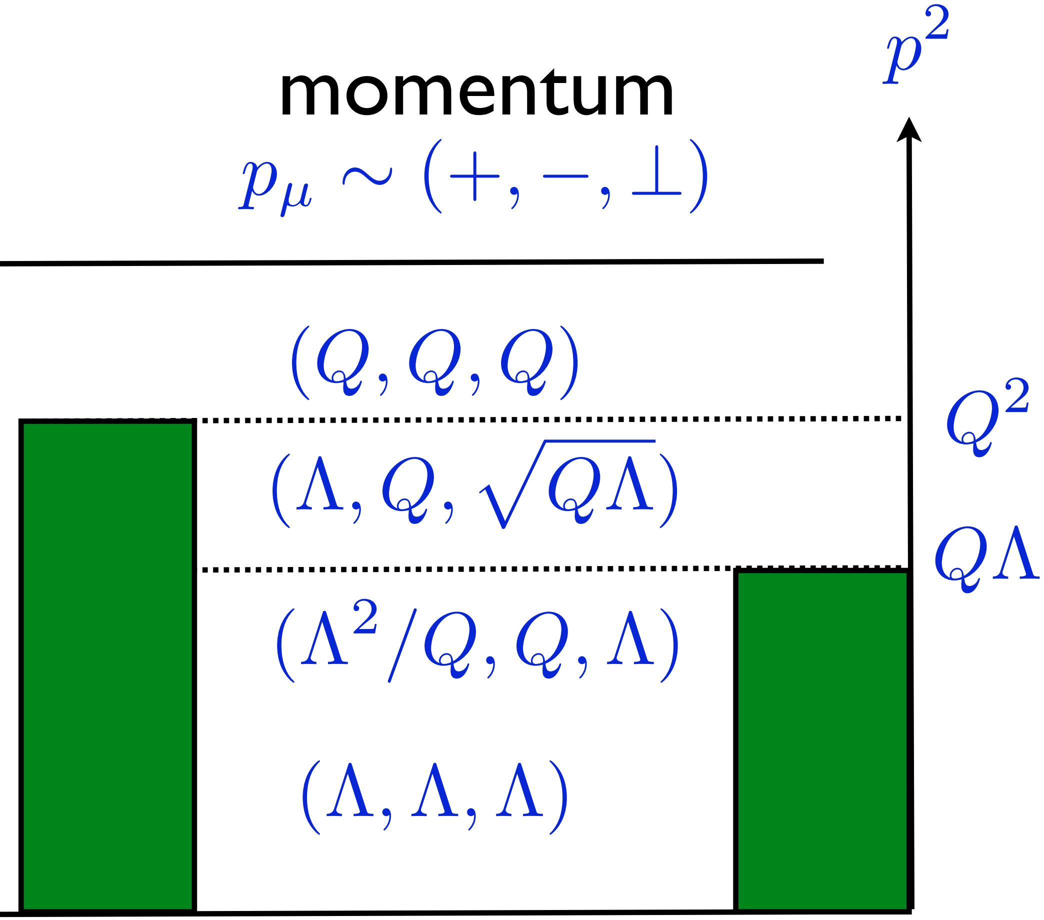
Relevant modes:

Mode		
- Soft	$p_s^2 \sim \Lambda^2$	$p_s^\mu \sim \Lambda$
- Collinear	$p_c^2 \sim \Lambda^2$	$n \cdot p_c \sim Q$
- Hard-collinear	$p_{hc}^2 \sim Q\Lambda$	$n \cdot p_{hc} \sim Q$

SCET - degrees of freedom

Introduce fields for each degree of freedom, with well-defined momentum scaling and power counting

mode	field	momentum $p_\mu \sim (+, -, \perp)$
hard	—	(Q, Q, Q)
hard-collinear	$A_{n,q}, \xi_{n,p}$	$(\Lambda, Q, \sqrt{Q\Lambda})$
collinear	$A_{n,q}, \xi_{n,p}$	$(\Lambda^2/Q, Q, \Lambda)$
soft/usoft	A_s, q, b_v	$(\Lambda, \Lambda, \Lambda)$



2-step matching: QCD → ($\mu^2 \sim Q^2$) → SCET_I → ($\mu^2 \sim Q\Lambda$) → SCET_II

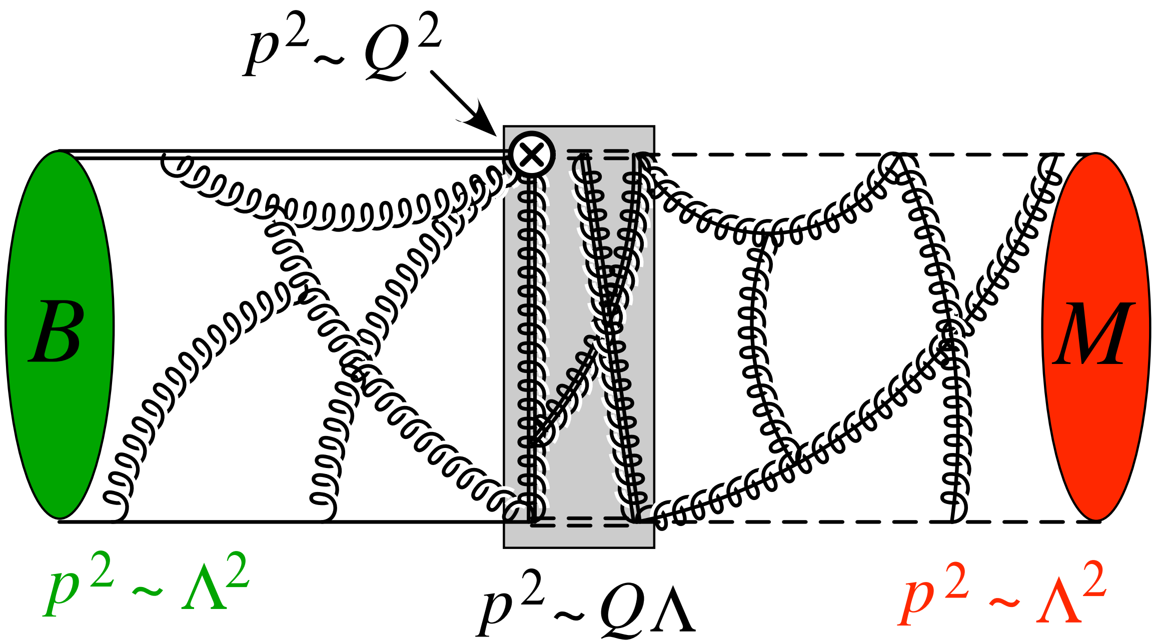
Factorization

In the large recoil region, the heavy-to-light form factors satisfy a factorization theorem

Beneke, Feldman; Bauer, DP, Stewart

$$f_i(E) = C_i(E,\mu)\zeta(E,\mu) + \int_0^1 dx dk_+ B_i(E,\mu,z) J(x,z,k_+)\phi_B^+(k_+)\phi_\pi(x)$$

"nonfactorizable" "factorizable"



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"nonfactorizable" "factorizable"

Ingredients

Wilson coefficients - hard momenta $C_1(\omega) = 1 + O(\alpha_s(Q))$

Jet function - hard-collinear momenta $J = \frac{\pi\alpha_s(\sqrt{Q\Lambda})C_F}{N_c}\frac{1}{\bar{x}k_+} + O(\alpha_s^2)$

term also known (Becher, Hill, Lee, Neubert)

Soft form factor - matrix element in SCET-II $\zeta(E,\mu)$

Collinear matrix elements - light-cone wave functions

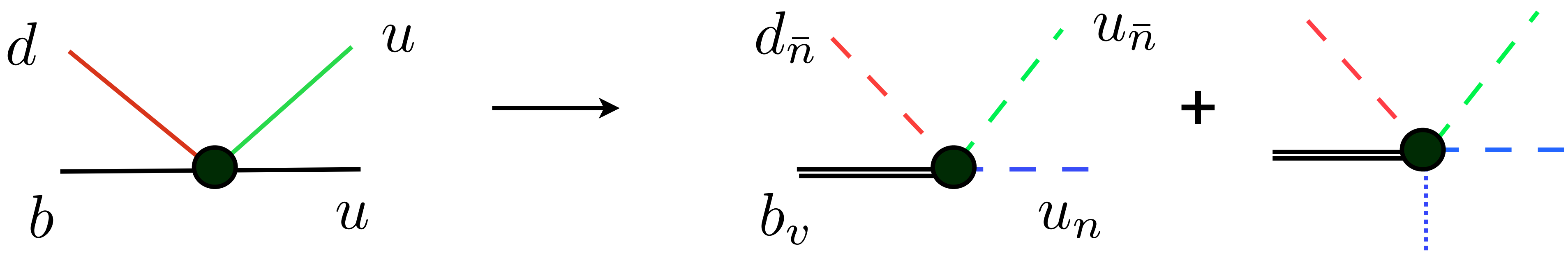
Nonleptonic B decays

1. Recent theory progress from SCET
   - SCET operator analysis and factorization in 2-body nonleptonic B decays
     Chay, Kim
   - Universality of the jet function in form factors and nonleptonic B decays
     Bauer, DP, Rothstein, Stewart
   - Comparison with QCDF, pQCD
2. Phenomenology of power corrections
   Grossman, Hoecker, Ligeti, DP

SCET proof of factorization in $B \to M_1 M_2$

Bauer, Rothstein, DP, Stewart

QCD $\longrightarrow$ SCET$_{\mathrm{I}}$ matching



$[W^\dagger i \not{D}_\perp W]_n$

$$(\bar{u}b)(\bar{d}u) \to c_i(\omega_i, \mu) Q_i^{(0)} + b_i(\omega_i, \mu) Q_i^{(1)} + \cdots$$

$O(\lambda^0)$ $\quad$ $O(\lambda)$ $\quad$ $\lambda^2 = \dfrac{\Lambda}{m_b}$

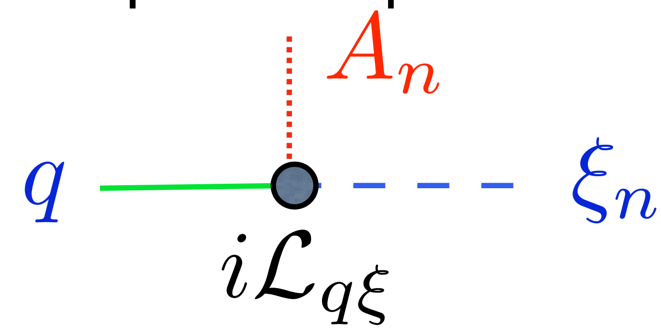
The LO Wilson coefficients $c_i(\omega_i, \mu)$ known to 1-loop order

BBNS

$b_i(\omega_i, \mu)$ known only at tree level

SCET$_\mathrm{I}$ $\longrightarrow$ SCET$_\mathrm{II}$ matching

Add the interaction with the spectator quark



Beneke, Chapovsky, Diehl, Feldmann

- <u>Nonfactorizable terms</u>

$$\langle T\{Q_i^{(0)}, i\mathcal{L}_{q\xi}^{(1,2)}\}\rangle \longrightarrow \zeta(E,\mu)$$

(soft form factor)

- <u>Factorizable terms</u>

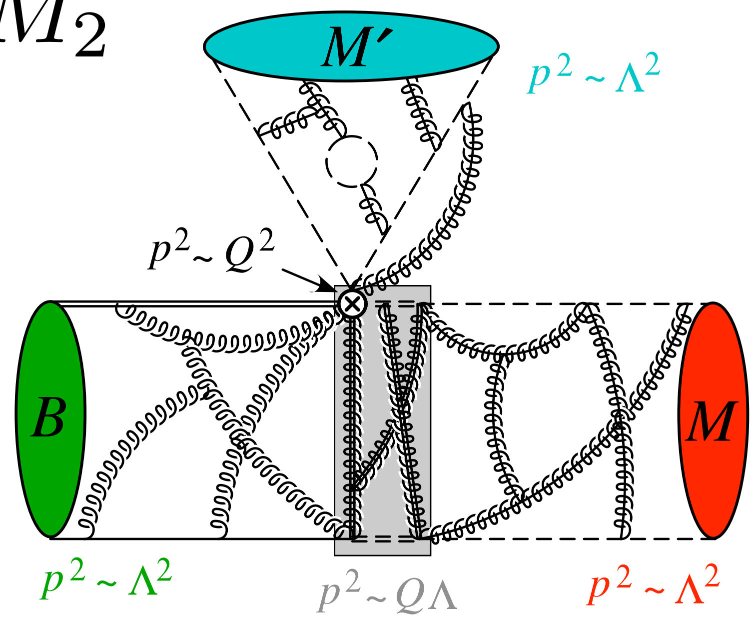
$$T\{Q_i^{(1)}, i\mathcal{L}_{q\xi}^{(1)}\} \longrightarrow J \otimes (q_n b_v) \otimes (\bar{q}_n q_n) \otimes (\bar{q}_{\bar{n}} q_{\bar{n}})$$

(convolutions of light-cone B and light mesons w.f.'s)

Factorization in $B \to M_1 M_2$

After matching onto SCET-II, scale separation is achieved

hard	$p^2 \sim Q^2$
hard-collinear	$p^2 \sim Q\Lambda$
collinear }	$p^2 \sim \Lambda^2$
soft }	



LO Factorization relation

$$A(\bar{B} \to M_1 M_2) = \langle Q_{cc} \rangle + f_{M_2} \zeta^{BM_1} \int_0^1 du T_2(u) \phi_{M_2}(u) + (1 \leftrightarrow 2)$$

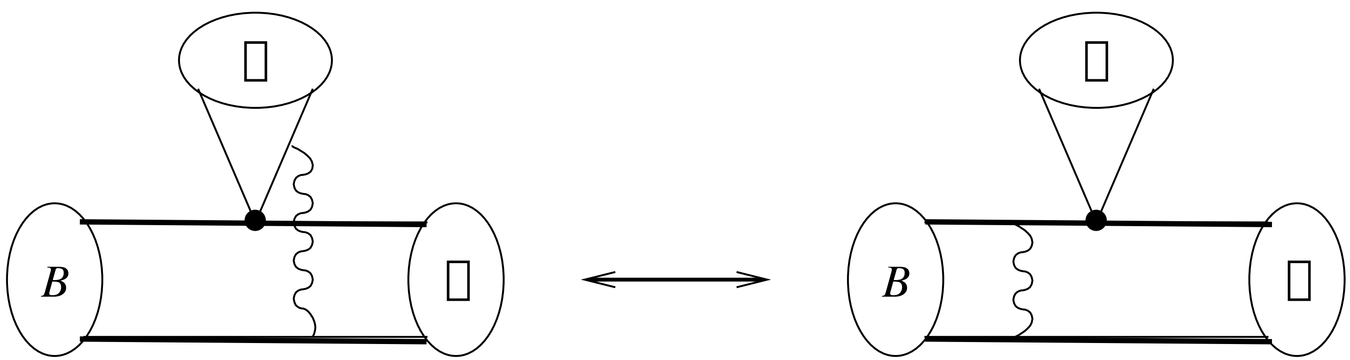
$$+ \int_0^1 dx dz du dk_+ J(x, z, k_+) [T_{2J}(u, z) \phi_{M_1}(x) \phi_{M_2}(u) + T_{1J}(u, z) \phi_{M_1}(u) \phi_{M_2}(x)] \phi_B^+(k_+)$$

Matrix element of $Q_{cc} = (\bar{s}c)(\bar{c}b)$ left in unfactorized form

Jet universality

1. The hard-collinear contribution is contained into a unique jet function (same for all mesons)

2. The jet function is identical to that appearing in the form factors - great computational simplification



$$J(x, k_+) = \frac{\pi \alpha_s(\sqrt{Q\Lambda}) C_F}{N_C} \frac{1}{x k_+} + O(\alpha_s^2)$$

The $O(\alpha_s^2)$ terms also known

Hill, Becher, Lee, Neubert

The expansion in $\alpha_s(\sqrt{\Lambda Q})$ might not be perturbative: $\sqrt{\Lambda Q} \sim 1.4\mathrm{GeV}$

Introduce the nonperturbative function

$$\zeta_J^{B\pi}(z) = \frac{f_B f_\pi}{m_B^2} \int dx dk_+ J(x, z, k_+) \phi_\pi(x) \phi_B^+(k_+)$$

and allow as a logical possibility $\zeta_J^{B\pi}(z) \sim \zeta^{B\pi}$ (SCET power counting)

Decay amplitudes

All B -> MM' amplitudes (and B -> M form factors) can be written in terms of $\zeta^{BM}, \zeta_J^{BM}(z)$

The result has a simple form in terms of graphical amplitudes:

$A(\pi^+\pi^-)$	$-T-P$	$A(K^-\pi^+)$	$-T-P+P_{EW}^C-P_{EW}^P$
$\sqrt{2}A(\pi^+\pi^0)$	$-T-C$	$\sqrt{2}A(K^-\pi^0)$	$-T-C-P+P_{EW}^T+P_{EW}^C-P_{EW}^P$
$A(\pi^0\pi^0)$	$-C+P$	$A(\bar{K}^0\pi^-)$	$P+\frac{1}{2}P_{EW}^C-P_{EW}^P$
		$\sqrt{2}A(\bar{K}^0\pi^0)$	$-C+P+P_{EW}^T+\frac{1}{2}P_{EW}^C+P_{EW}^P$

Relation to SCET parameters:

$$T_{K\pi} = -N_0 f_K [\langle c_{1u}\rangle_K \zeta^{B\pi} + \langle b_{1u}\zeta_J^{B\pi}\rangle_K]$$

$$C_{K\pi} = -N_0 f_K [\langle c_{2u}\rangle_\pi \zeta^{BK} + \langle b_{2u}\zeta^{BK}\rangle_\pi]$$

etc.

Implications:
- Small strong phases of T,C amplitudes $\delta_{TC} \sim O(\alpha_s(m_b), \frac{\Lambda}{m_b})$
- Weak annihilation amplitudes A, E, PA power suppressed

$$A \sim E \sim PA \sim O(\Lambda/m_b)$$

Comparison with QCDF and pQCD factorization approaches

1. At lowest order in perturbation theory, the QCDF results are reproduced

2. SCET allows a more general hierarchy of the nonfactorizable vs. factorizable contributions

QCDF:	pQCD:	SCET:
$\zeta_J \ll \zeta$	$\zeta \sim 0$	$\zeta \sim \zeta_J \sim (\Lambda/m_b)^{3/2}$

3. The SCET result is a strict implementation of the power counting; QCDF and pQCD include subsets of power suppressed terms

$$A(\bar{B} \to M_1 M_2) = A_0 + \frac{\Lambda}{m_b} A_1 + \cdots$$

Phenomenology

- Determining α from an isospin analysis in $B \to \pi\pi$
- Introducing dynamical input
- The $B \to \pi\pi$ puzzle - possible explanations
- Study of penguins and power corrections in $B \to \pi\pi$

Grossman, Hoecker, Ligeti, DP

$B \to \pi^+\pi^-$ and $\beta + \gamma$

Standard method for determining $\sin 2\alpha$

In the absence of penguin contamination ⇨

$$S_{\pi\pi} = \sin 2\alpha$$
$$C_{\pi\pi} = 0$$

	BABAR (227m)	Belle (275m)	Average
$S_{\pi\pi}$	–0.30 ± 0.17 ± 0.03	–0.67 ± 0.16 ± 0.06	–0.50 ± 0.12
$C_{\pi\pi}$	–0.09 ± 0.15 ± 0.04	–0.56 ± 0.12 ± 0.06	–0.37 ± 0.10

BABAR, hep-ex/0501071
Belle, hep-ex/0502035

The penguins are significant: isospin analysis required — Gronau-London

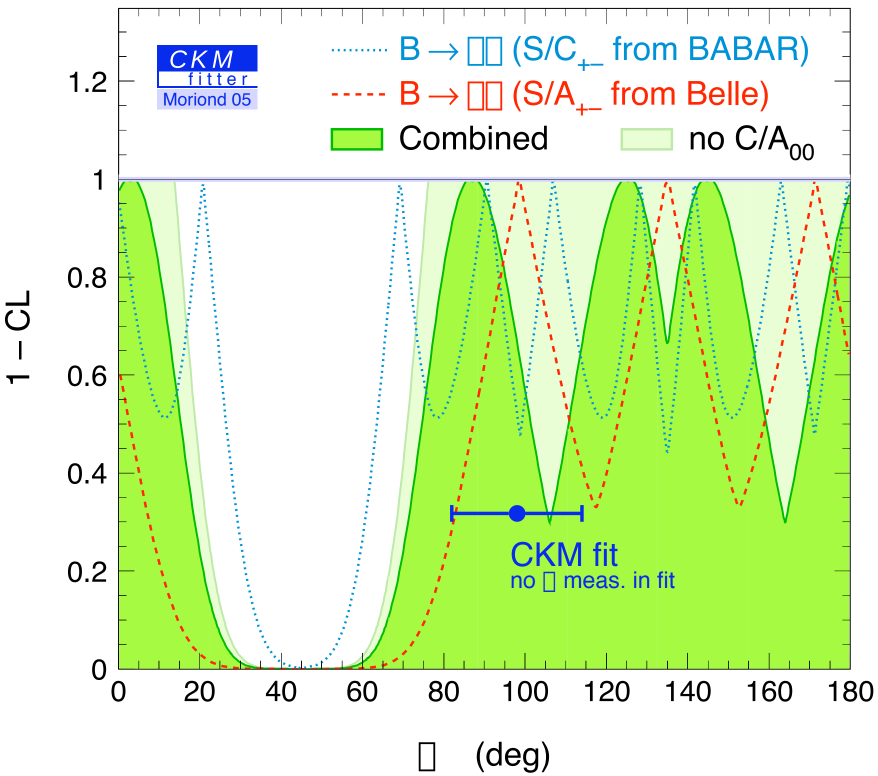
	$\mathrm{Br}(10^{-6})$
$B^+ \to \pi^+\pi^0$	5.5 ± 0.6
$B^0 \to \pi^+\pi^-$	4.6 ± 0.4
$B^0 \to \pi^0\pi^0$	1.51 ± 0.28
$S_{\pi^+\pi^-}$	-0.50 ± 0.12
$C_{\pi^+\pi^-}$	-0.37 ± 0.10
$C_{\pi^0\pi^0}$	-0.28 ± 0.40

$$A_{+-} = \lambda_u^{(d)} T_c (1 + r_c e^{i\delta_c} e^{i\gamma})$$
$$\sqrt{2} A_{00} = \lambda_u^{(d)} T_n (1 + r_n e^{i\delta_n} e^{i\gamma})$$
$$\sqrt{2} A_{-0} = \lambda_u^{(d)} (T_n + T_c)$$

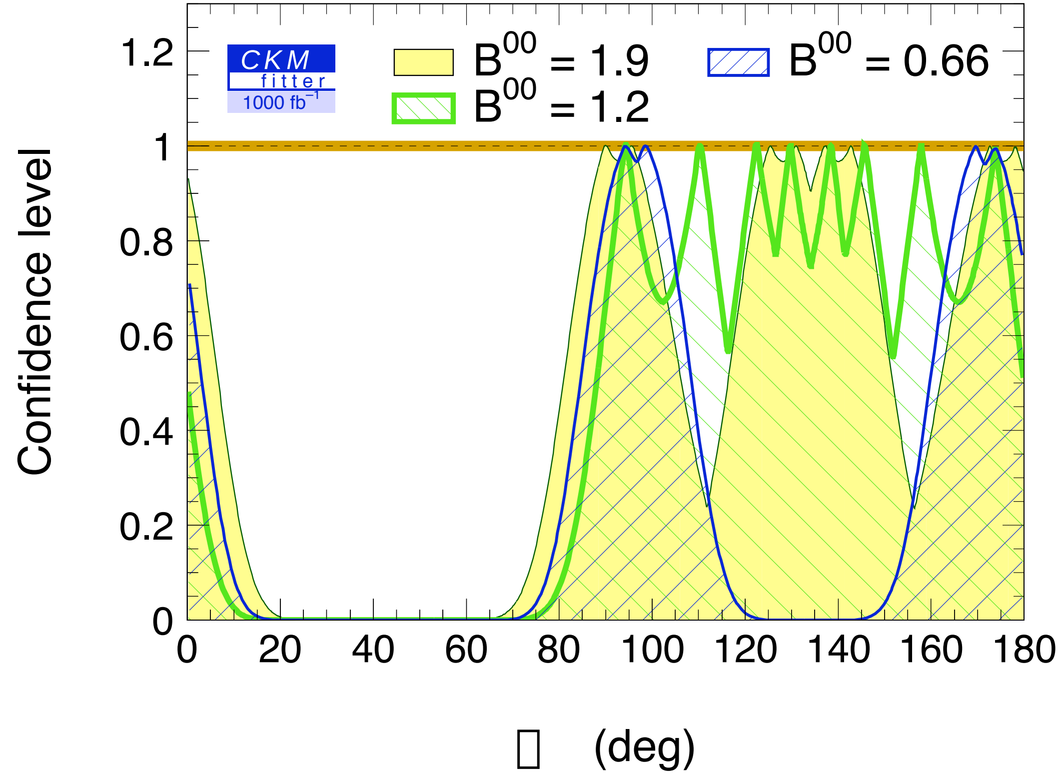
5 hadronic parameters + α

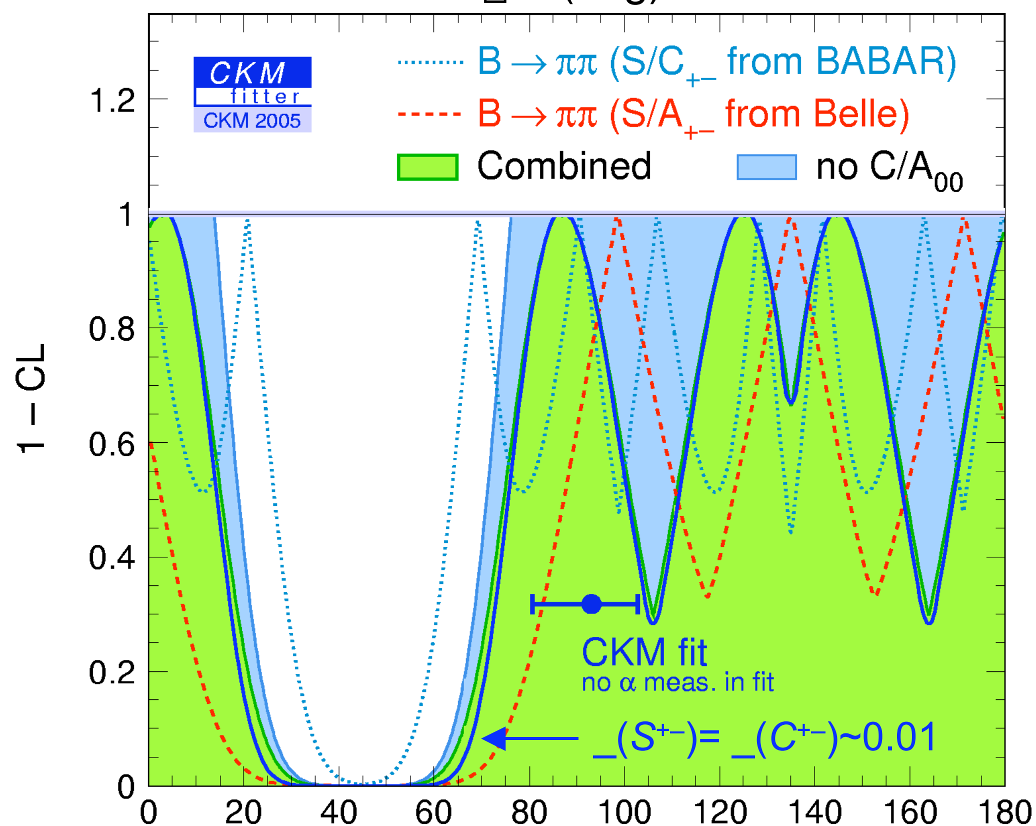
-> can be determined using 6 data points

Isospin analysis



Additional dynamical input required





SCET determination of α

Bauer, Rothstein, Stewart

At leading order in $\alpha_s(m_b)$ and Λ/m_b ,the strong phases among tree amplitudes vanish

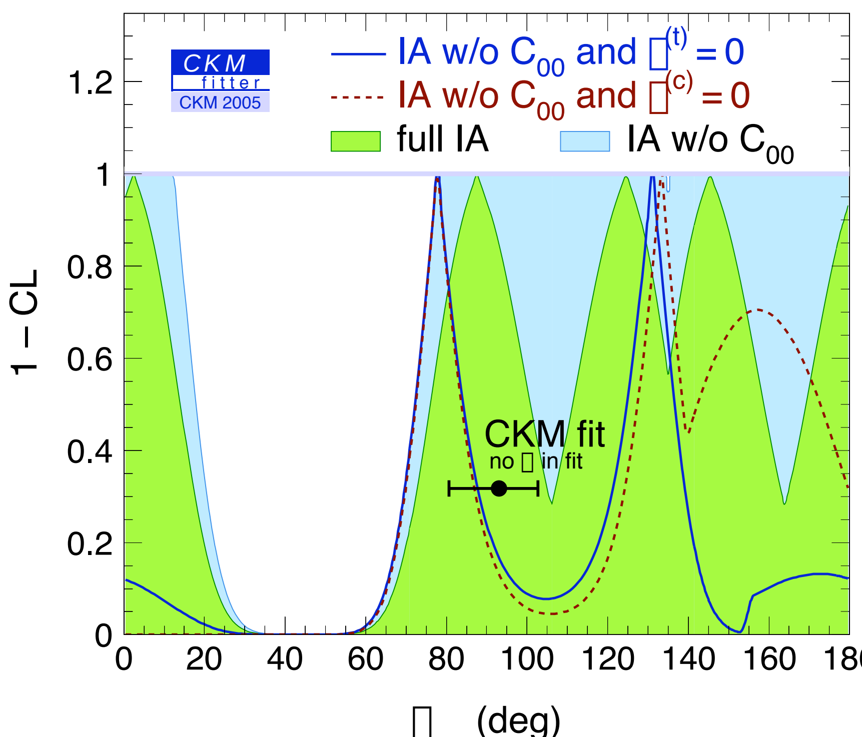
$$\mathrm{Arg}(T_n/T_c) \sim O(\alpha_s(m_b), \frac{\Lambda}{m_b})$$

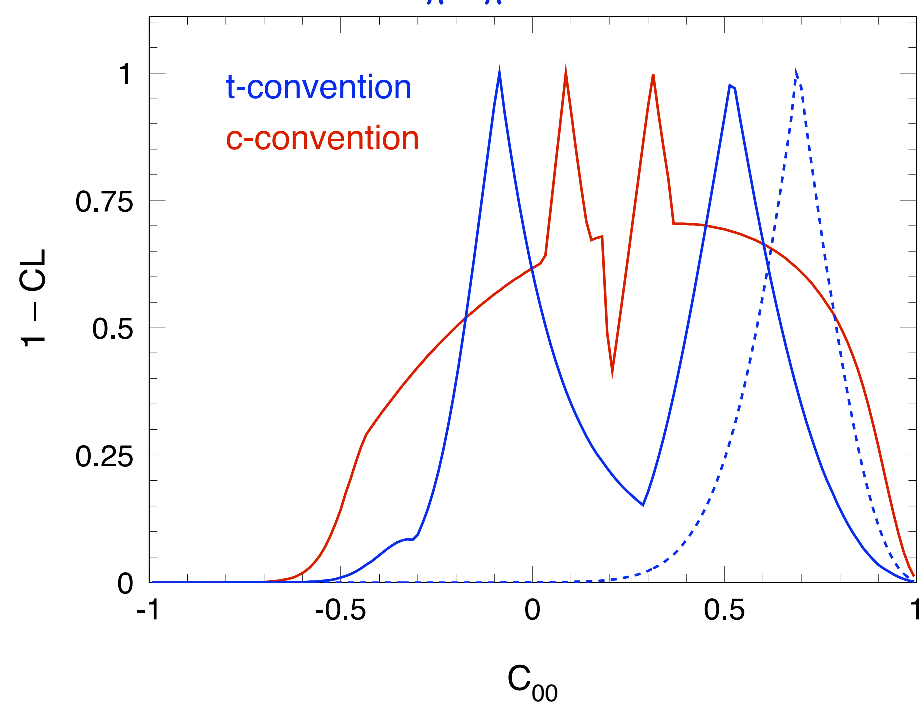
$$A_{+-} = \lambda_u^{(d)} T_c (1 + r_c e^{i\delta_c} e^{i\gamma})$$
$$\sqrt{2} A_{00} = \lambda_u^{(d)} T_n (1 + r_n e^{i\delta_n} e^{i\gamma})$$
$$\sqrt{2} A_{-0} = \lambda_u^{(d)} (T_n + T_c)$$

Eliminates one hadronic parameter

Can be used to make predictions for α , $C_{\pi^0\pi^0}$

$$C_{\pi^0\pi^0}^{\mathrm{exp}} = -0.28 \pm 0.40$$





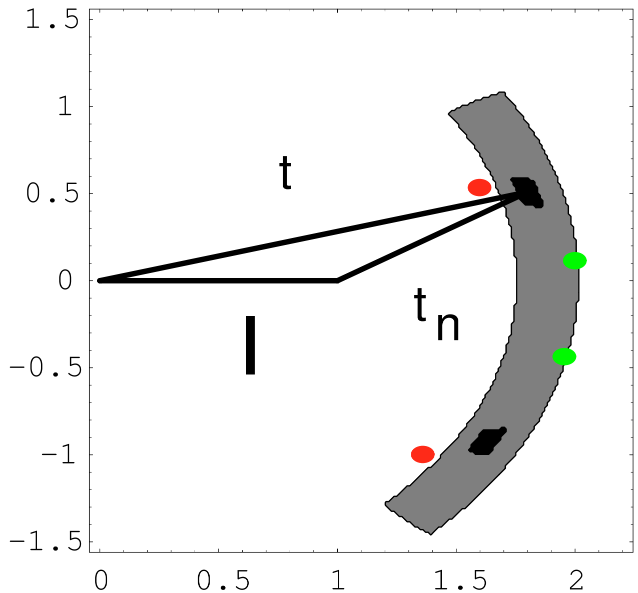
The $B \to \pi\pi$ `puzzle'

$$T_c + T_n = T_{-0}$$

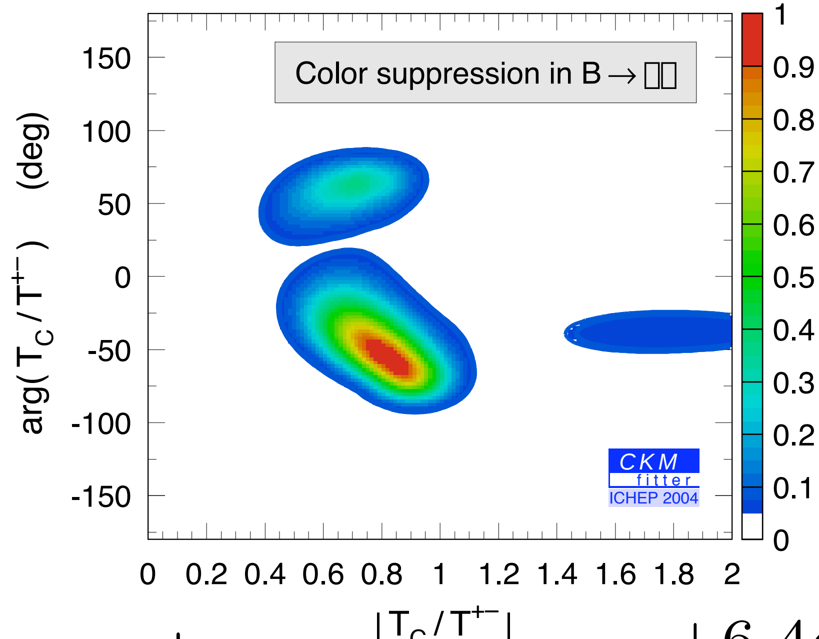
Determine the tree amplitudes T_c, T_n, T_{-0}

Graphical representation of the isospin relation $1 + t_n = t$

$$t = \frac{T_{-0}}{T_c} \qquad t_n = \frac{T_n}{T_c}$$



$\gamma = 54^\circ, 64^\circ, 74^\circ$



$\gamma|_{CKMfit} = 59^{+6.4\circ}_{-4.9}$

Large strong phases $\mathrm{Arg}(T_n/T_c) \sim 40^\circ - 50^\circ$

Significant color-suppressed amplitudes $t_n \sim O(1)$

Ali, Lunghi, Parkhomenko

Buras, Fleischer,...

Bauer, Rothstein, DP, Stewart

Possible explanations

- Factorizable contributions larger than previous estimates (w/ input from QCD sum rules)

  Bauer, Rothstein, DP, Stewart

LO SCET analysis
large factorizable contributions can overcome color suppression

- Large penguin/power correction terms

The 'tree' amplitudes contain penguins!

Grossman,Hoecker, Ligeti, DP
see also Feldmann, Hurth

$$A(B \to \pi^+\pi^-) = \lambda_u^{(d)}(T + P_u) + \lambda_c^{(d)} P_c + \lambda_t^{(d)} P_t$$

$$= \lambda_u(T + P_u - P_t) + \lambda_c(P_c - P_t) \quad \text{c-convention}$$

$$= \lambda_u(T + P_u - P_c) + \lambda_t(P_t - P_c) \quad \text{t-convention}$$

- New physics

$B \to \pi\pi$ in SCET @ LO

Bauer, Rothstein, DP, Stewart

- Working to leading order in matching at $\mu = m_b$

$$\sqrt{2}A(B^- \to \pi^-\pi^0) = N_\pi \frac{1}{3}\lambda_u^{(d)}(C_1 + C_2)(4\zeta^{B\pi} + 7\zeta_J^{B\pi}) + O(\frac{\Lambda}{m_b})$$

$$A(\bar{B}^0 \to \pi^+\pi^-) = N_\pi \lambda_u^{(d)}\{(C_1 + \frac{C_2}{3})\zeta^{B\pi} + [C_1 + (1 + \langle \bar{u}^{-1}\rangle_\pi)\frac{C_2}{3}]\zeta_J^{B\pi}\}$$
$$+\lambda_c^{(d)}\langle Q_{c\bar{c}}\rangle + \lambda_t^{(d)}\{-(C_4 + \frac{C_3}{3})\zeta^{B\pi} - [C_4 + (1 + \langle \bar{u}^{-1}\rangle_\pi)\frac{C_3}{3}]\zeta_J^{B\pi}\} + O(\frac{\Lambda}{m_b})$$

- Use the data to extract the SCET parameters $\zeta^{B\pi}, \zeta_J^{B\pi}$

$$\zeta^{B\pi}|_{\gamma=64^\circ} = (0.08 \pm 0.03)\left(\frac{0.0039}{|V_{ub}|}\right)$$

$$\zeta_J^{B\pi}|_{\gamma=64^\circ} = (0.10 \pm 0.02)\left(\frac{0.0039}{|V_{ub}|}\right)$$

Comparable factorizable vs. nonfactorizable parameters!

Predictions

Predict the semileptonic $B \to \pi \ell \nu$ and rare $B \to \pi \ell^+ \ell^-$ form factors

(only exp. errors shown)

$$f_+(q^2 = 0) = \zeta^{B\pi} + \zeta_J^{B\pi} = (0.18 \pm 0.02)\left(\frac{0.0039}{|V_{ub}|}\right)$$

$$f_T(q^2 = 0) = \zeta^{B\pi} - \zeta_J^{B\pi} = -(0.02 \pm 0.05)\left(\frac{0.0039}{|V_{ub}|}\right)$$

Different from the usual factorization prediction (e.g. Luo, Rosner), because of large hard scattering amplitude $\zeta_J^{B\pi}$

$$\sqrt{2} A(B^- \to \pi^- \pi^0) = \lambda_u^{(d)} N_0 \{ \frac{4}{3}(C_1 + C_2) f_+^{B\pi}(q^2 = 0) + (C_1 + C_2)\zeta_J^{B\pi})\}$$

Smaller results than in QCD sum rule calculations

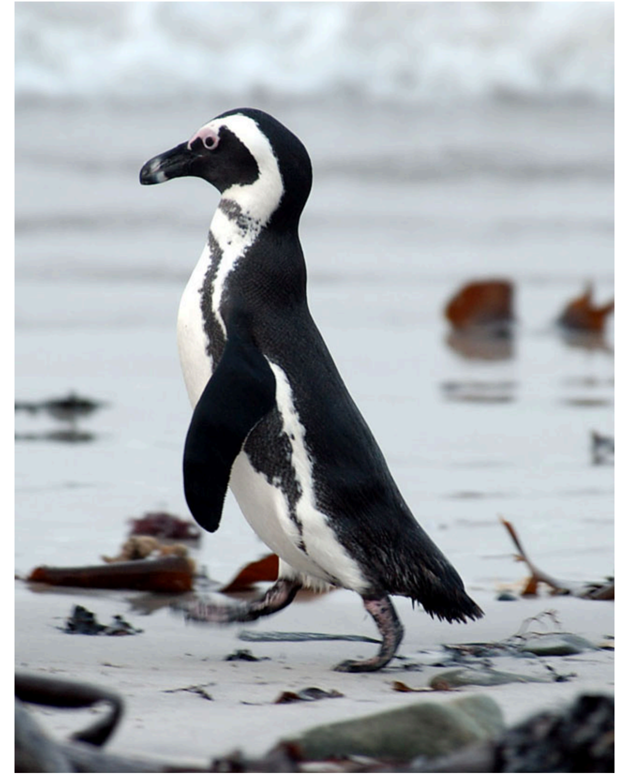
Ball, Zwicky - hep-ph/0406232

$$f_+^{B\pi}(0) = 0.26 \pm 0.03 \qquad f_T^{B\pi}(0) = 0.25 \pm 0.03$$

Testing penguins/power suppressed terms in $B \to \pi\pi$

Grossman, Hoecker, Ligeti, DP

The penguin hierarchy problem



The penguin hierarchy problem

$$A(B \to \pi^+\pi^-) = \lambda_u^{(d)}(T + P_u) + \lambda_c^{(d)} P_c + \lambda_t^{(d)} P_t$$

Theory issues:

- Pt could contain large chirally enhanced terms
  = subleading but large corrections - included in QCDF
- Pc could contain nonperturbative contributions - charming penguins
- Pu could be enhanced by rescattering

Ciuchini et al., Bauer et al.

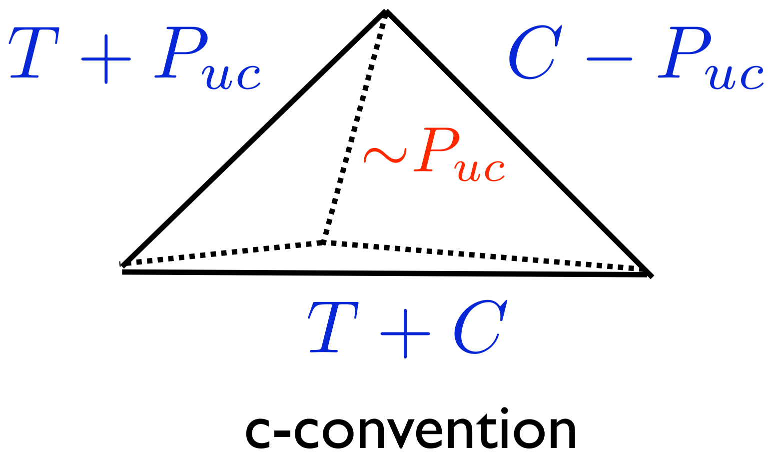
What can we say about their relative magnitude using data? ‘PHP’

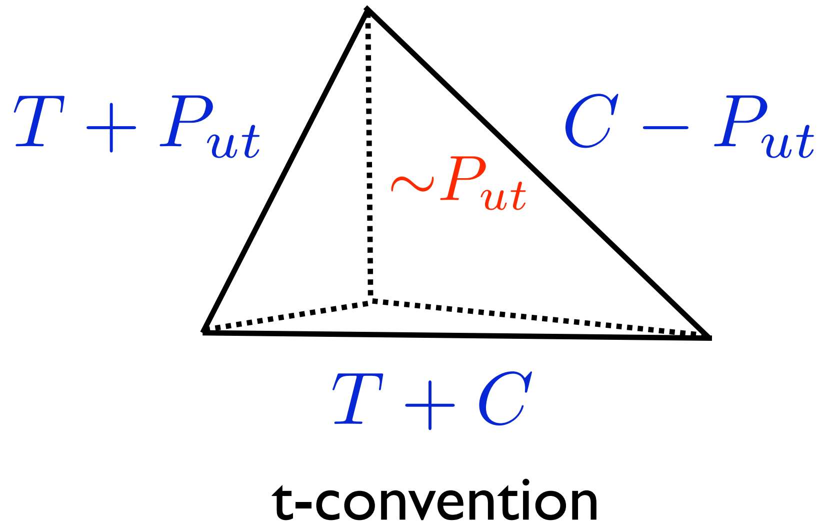
Use unitarity of the CKM matrix

$$= \lambda_u(T + P_u - P_t) + \lambda_c(P_c - P_t) \qquad \text{c-convention}$$

$$= \lambda_u(T + P_u - P_c) + \lambda_t(P_t - P_c) \qquad \text{t-convention}$$

Compare the shapes of the tree triangles in different conventions





Pc enters ‘tree’ amplitudes only in the c-convention

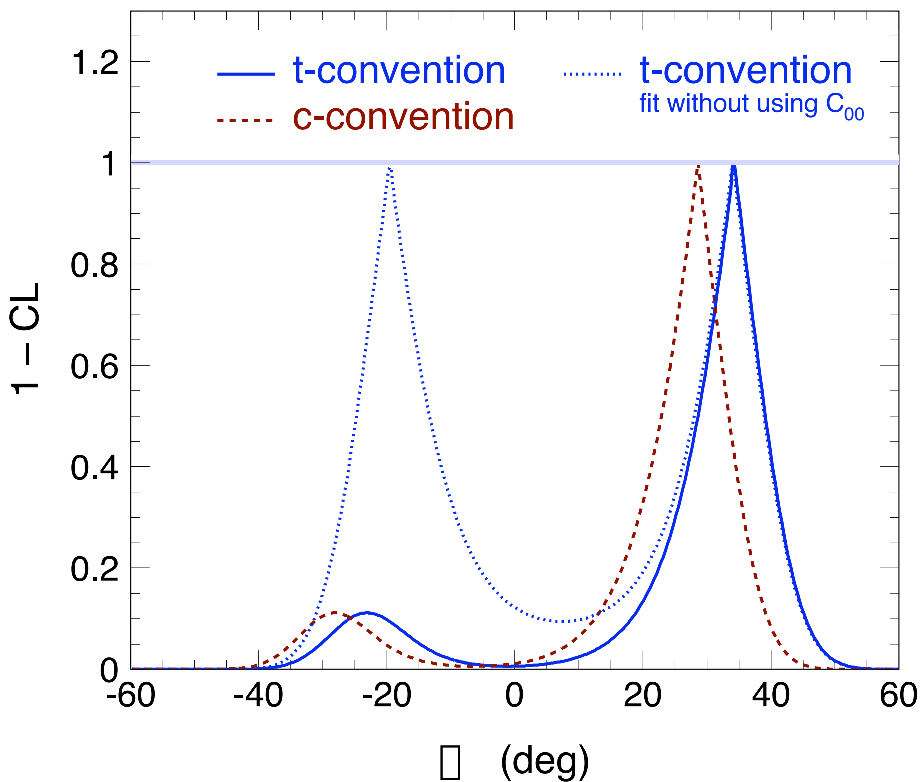
Pt enters ‘tree’ amplitudes only in the t-convention

Pu enters ‘tree’ amplitudes in both conventions

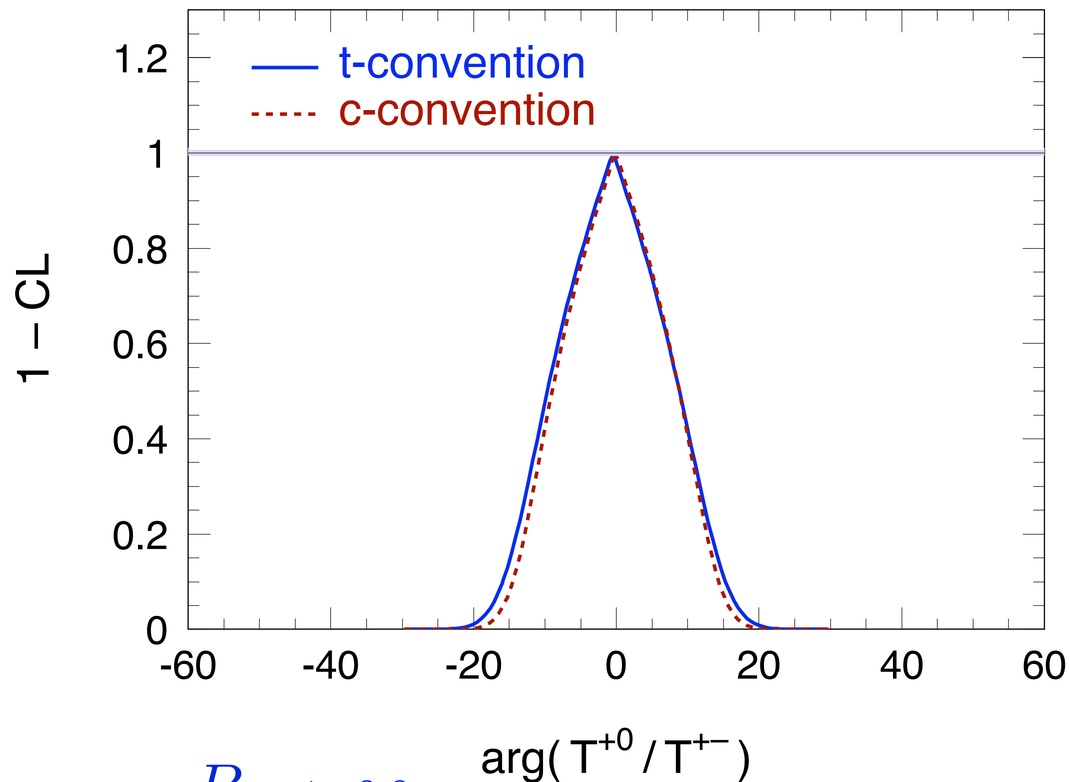
Compare the strong phases

$\tau^{(c)} \equiv Arg[(T + P_{uc})/(T + C)]$ vs. $\tau^{(t)} \equiv Arg[(T + P_{ut})/(T + C)]$

Results



$B \to \pi\pi$



$B \to \rho\rho$

$B \to \pi\pi$

Large Pu amplitude, smaller Pc, Pt $\longrightarrow$ significant weak annihilation?

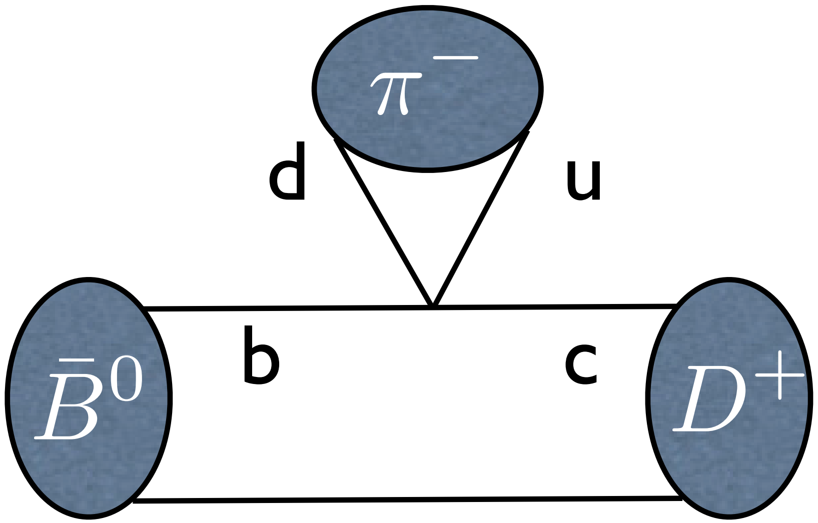
$B \to \rho\rho$

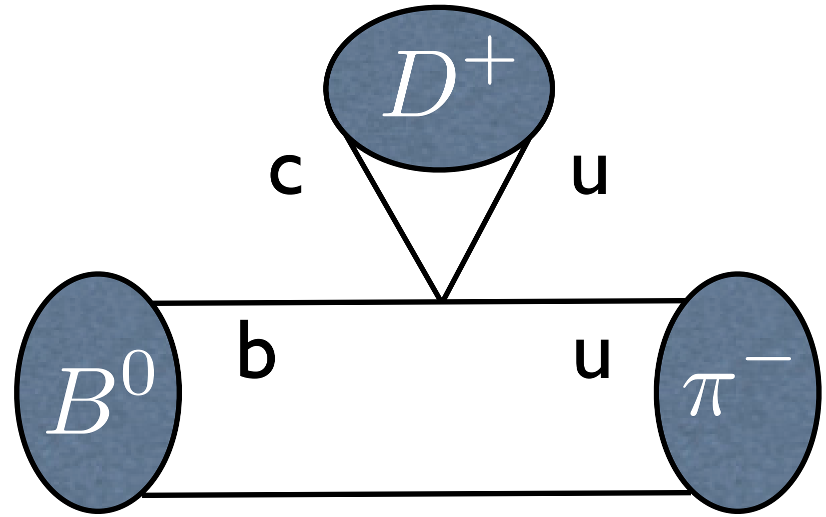
Small penguins $\longrightarrow$ SCET constraint on α may help

Factorization in $B \to D^{(*)}\pi$ and implications for $2\beta + \gamma$

Interference of tree-mediated decays

Aleksan et al., Dunietz, Rosner





$$\bar{B}^0 \to D^{(*)+}\pi^- \sim V_{cb}V_{ud}^* \qquad B^0 \to D^{(*)+}\pi^- \sim V_{ub}^* V_{cd}$$

$B^0 - \bar{B}^0$ mixing induces a time-dependent CP asymmetry

Final state = non-CP eigenstate → The asymmetry depends on hadronic parameters

Time-dependent decay rates

$$\Gamma(B(t) \to f) \sim \frac{e^{-|t|/\tau}}{2\tau}(1 \mp S_\zeta \sin(\Delta M t) \mp \eta C_\zeta \cos(\Delta M t))$$

$$(\eta, \zeta) = +(-) \leftrightarrow D^-\pi^+(D^+\pi^-)$$

Tagging meson $\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$

The asymmetry parameters depend on hadronic physics

$$\frac{A(B^0 \to D^+\pi^-)}{A(\bar{B}^0 \to D^+\pi^-)} = re^{i\delta+\gamma}$$

$$r \sim \lambda \frac{V_{ub}}{V_{cb}} O(1) \sim 0.02$$

color-allowed

as

$$S_\pm = \frac{2r}{1+r^2}\sin(2\beta + \gamma \pm \delta)$$

$$C = \frac{1-r^2}{1+r^2}$$

BABAR and BELLE measured fully and partially reconstructed $D^{(*)\pm}\pi^{\mp}$

BABAR includes also $D^{\pm}\rho^{\mp}$

Measurements expressed in terms of 2 parameters

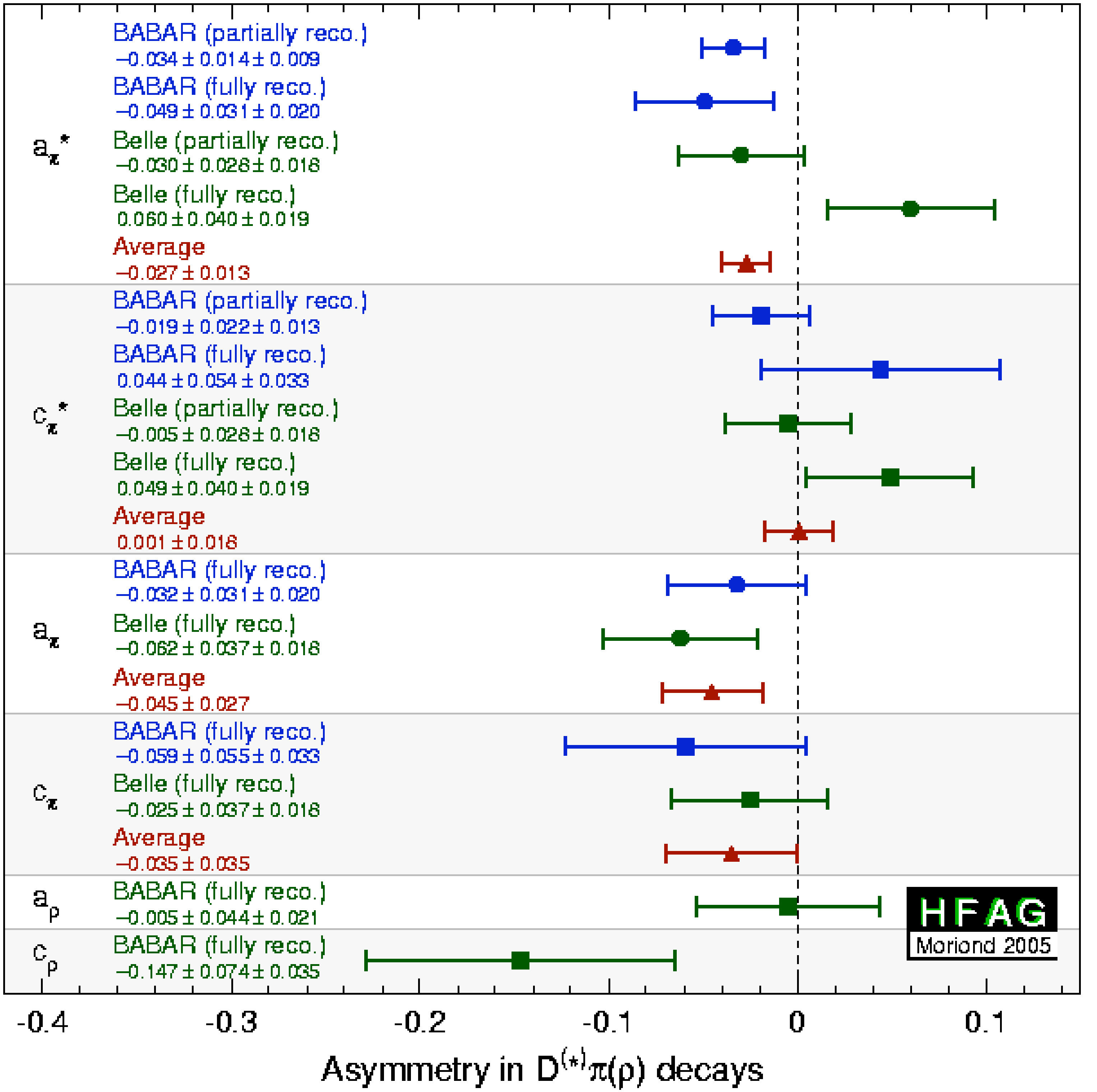
$$a_{D^{(*)}\pi} = \mp 2 r_{D^{(*)}\pi} \sin(2\beta+\gamma)\cos\delta_{D^{(*)}\pi}$$

$$c_{D^{(*)}\pi} = \mp 2 r_{D^{(*)}\pi} \cos(2\beta+\gamma)\sin\delta_{D^{(*)}\pi}$$

HFAG

WA	$D\pi$	$D^*\pi$
a	-0.045 ± 0.027	-0.027 ± 0.013
c	-0.035 ± 0.035	0.001 ± 0.018

- Extract r from $r^2 = \frac{Br(B^0 \to D^+\pi^-)}{Br(B^0 \to D^-\pi^+)} \sim 3 \times 10^{-4}$
- Combine a and c to determine $2\beta+\gamma$ (up to a 4-fold ambiguity)



a_π^*
BABAR (partially reco.)
−0.034 ± 0.014 ± 0.009
BABAR (fully reco.)
−0.049 ± 0.031 ± 0.020
Belle (partially reco.)
−0.030 ± 0.028 ± 0.018
Belle (fully reco.)
0.060 ± 0.040 ± 0.019
Average
−0.027 ± 0.013
c_π^*
BABAR (partially reco.)
−0.019 ± 0.022 ± 0.013
BABAR (fully reco.)
0.044 ± 0.054 ± 0.033
Belle (partially reco.)
−0.005 ± 0.028 ± 0.018
Belle (fully reco.)
0.049 ± 0.040 ± 0.019
Average
0.001 ± 0.018
a_π
BABAR (fully reco.)
−0.032 ± 0.031 ± 0.020
Belle (fully reco.)
−0.062 ± 0.037 ± 0.018
Average
−0.045 ± 0.027
c_π
BABAR (fully reco.)
−0.059 ± 0.055 ± 0.033
Belle (fully reco.)
−0.025 ± 0.037 ± 0.018
Average
−0.035 ± 0.035
a_ρ
BABAR (fully reco.)
−0.005 ± 0.044 ± 0.021
c_ρ
BABAR (fully reco.)
−0.147 ± 0.074 ± 0.035
HFAG
Moriond 2005
-0.4
-0.3
-0.2
-0.1
0
0.1
Asymmetry in $D^{(*)}\pi(\rho)$ decays

Issues

- The Cabibbo suppressed mode $B^0 \to D^+\pi^-$ is very hard to measure

- Additional theory input is required for extracting r

  - Factorization
  - SU(3) based methods (+ dynamical assumptions)

- Tagging using nonleptonic modes introduces dependence on the hadronic parameters of the tag mode

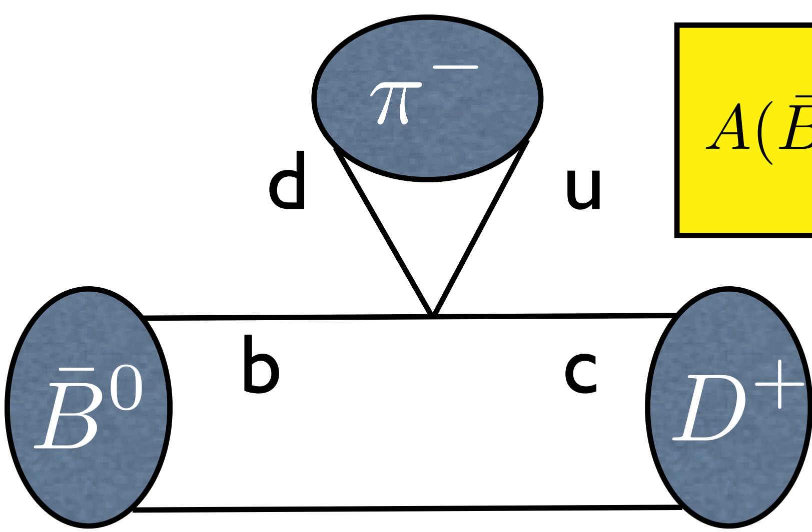
Factorization

What does factorization tell us about r and δ ?

$$\frac{A(B^0 \to D^+\pi^-)}{A(\bar{B}^0 \to D^+\pi^-)} = re^{i\delta+\gamma}$$

The CKM allowed mode $b \longrightarrow cd\bar{u}$ is calculable in factorization at leading order in $1/m_b$

BBNS; Bauer, DP, Stewart



$$A(\bar{B}^0 \to D^+\pi^-) \sim a_1 F_{B\to D} f_\pi + O(\alpha_s(m_b), \frac{\Lambda}{m_b})$$

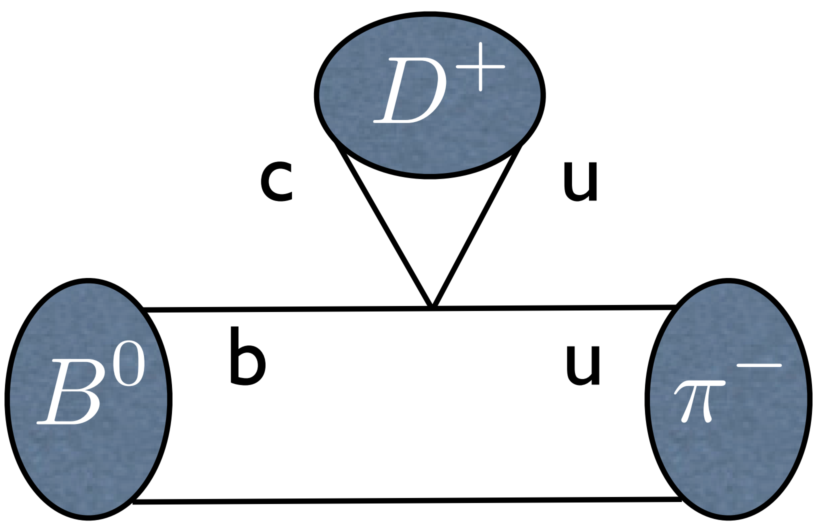
small strong phases

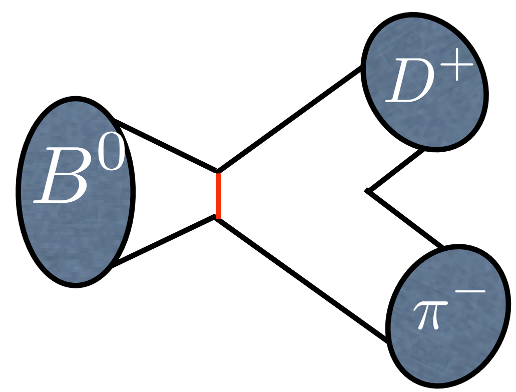
No proof of factorization exists so far for the CKM suppressed ('wrong-charm decay) $b \to ud\bar{c}$ modes

Computations in pQCD C.D.Lu

The only known limit of QCD where factorization holds for DCS modes is the large Nc limit

Only valid for color-allowed modes!





$$\sim O(\frac{1}{N_c})$$

$$\sim (C_1 + \frac{C_2}{3}) F_{B\to\pi} f_D + O(\frac{1}{N_c})$$

Large Nc factorization

$$r_{D\pi} = \lambda \left| \frac{V_{ub}}{V_{cb}} \right| R_{D\pi} \simeq 0.01$$

R = ratio of hadronic matrix elements

$$R_{D\pi} = \frac{(m_B^2 - m_\pi^2) F_0^{B\to\pi}(m_D^2) f_D}{(m_B^2 - m_D^2) F_0^{B\to D}(m_\pi^2) f_\pi} \simeq 0.4$$

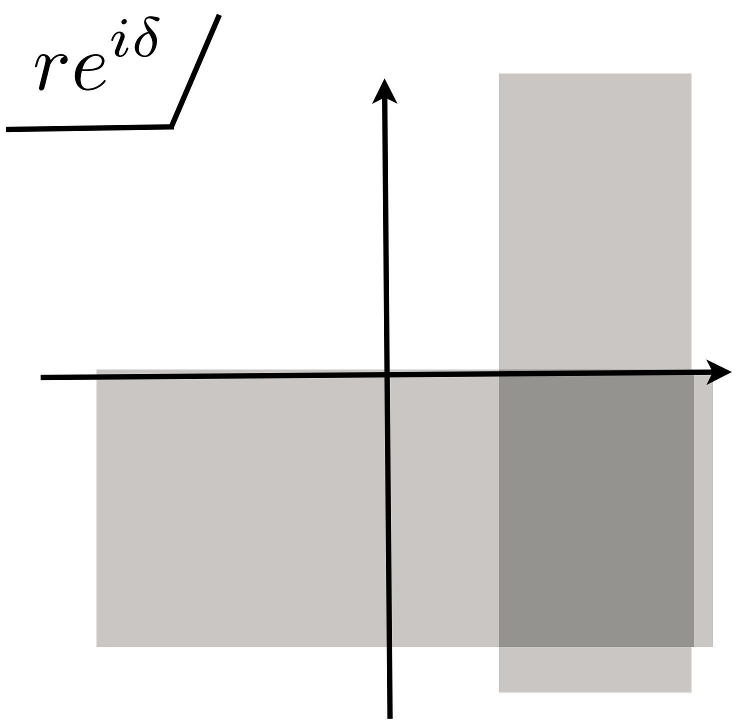
Corrections ~ 30-50%

Small strong phase δ predicted

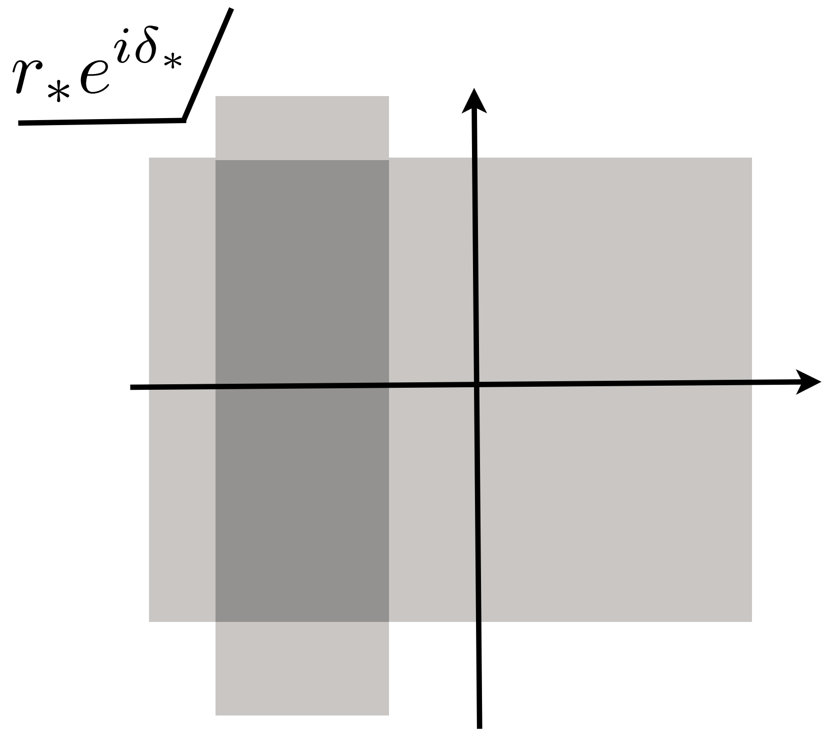
Consistency check for the large Nc estimate for r

What does data tell us about the strong phases?

Assume $\beta = 23^\circ, \gamma = 60^\circ$



$$B \to D\pi$$



$$B \to D^*\pi$$

Significant strong phases allowed !

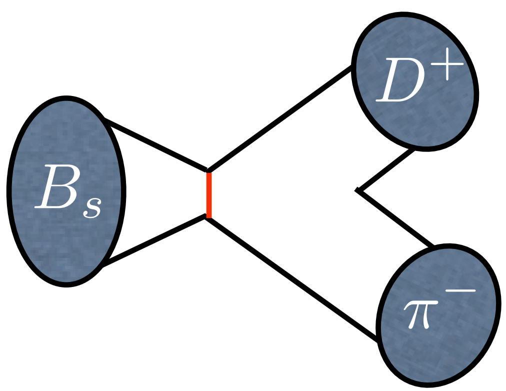
The large Nc estimate can be trusted if future data rule out large strong phases

SU(3) flavor

Exact SU(3) relations

$$A(B^0 \to D^{(*)+}\pi^-) = \lambda[A(B^0 \to D_s^{(*)+}\pi^-) + A(B_s \to D^{(*)+}\pi^-)]$$

$$= \lambda A(B_s \to D_s^{(*)+}K^-)$$



$B_s \to D^{(*)+}\pi^-$

is pure W exchange

Assuming that it can be neglected, data on $B^0 \to D_s^+\pi^-$ can determine r

$$r_* = \lambda\sqrt{\frac{B(B^0 \to D_s^{*+}\pi^-)}{B(B^0 \to D^{*-}\pi^+)}}\frac{f_{D^*}}{f_{D_s^*}} = 0.015^{+0.006}_{-0.004}$$

BABAR hep-ex/0504035

Error estimate

Sources of theory error in this r determination

- SU(3) breaking ~ 30%
- Neglect of the W-exchange amplitude E

The W-exchange amplitude can be measured in:

- $\Delta S = 1 \quad B_s \text{ decays} : B_s \to D^+ \pi^- \, , \quad B_s \to D^0 \pi^0$
- $\Delta S = 0 \quad B_d \text{ decays} : \quad B^0 \to D_s^+ K^- \text{ (but not } \bar{B}^0 \to D_s^+ K^- \text{ !)}$

In the absence of such data, the error on r could be as large as 100%

Conclusions

- A model-independent theory of nonleptonic B decays is now available, based on an effective field theory with a well-defined power counting in Λ/m_b
- SCET separates the contributions of the physics on different scales: factorization
- SCET yields a surprising connection between semileptonic, rare and nonleptonic B decays: at LO they are parameterized in terms of a small set of common parameters
- A combined fit to all these (measured) modes can extract these parameters and allows predictions for new modes
- Much work remains to be done to explore power corrections to these results. Phenomenological studies reveal an intriguing pattern of corrections in $B \to \pi\pi$