THEORY OF HADRONIC B DECAYS

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CAVEAT

IN 20-25 MINUTES I WILL NOT BE ABLE TO COVER ALL OF THE LATEST DEVELOPMENTS IN THIS WIDESPREAD FIELD.

AS I AM GOING TO DISCUSS CONCEPTUAL AS WELL AS PHENOMENOLOGICAL ASPECTS, THE PHENOMENOLOGICAL PART OF MY TALK WILL NECESSARILY BE SELECTIVE AND SHORT.

I APOLOGIZE FOR NOT COVERING YOUR FAVOURITE TOPIC(S)!

OUTLINE

THEORY

- REVIEW OF QCDF / PQCD / SCET
- RECENT DEVELOPMENTS: CHARMING PENGUINS
  - GLAUBER GLUONS IN PQCD
  - PERTURBATIVE CORRECTIONS IN QCDF

PHENOMENOLOGY

- TREE-DOMINATED DECAYS: $B \to \pi\pi \,/\, \pi\rho \,/\, \rho\rho$
- PENGUIN-DOMINATED DECAYS: $B \to \pi K$

THEORY

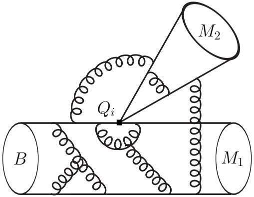
Charmless hadronic B decays

Particularly rich laboratory to probe the nature of flavour-changing

$$b \to u\bar{u}d \;/\; u\bar{u}s \qquad\qquad b \to d\bar{q}q \;/\; s\bar{q}q$$

quark transitions and to test the CKM mechanism of CP violation

The challenge: quantitative control over $\langle M_1 M_2 | Q_i | B \rangle$



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Two complementary strategies:

- flavour symmetries (isospin, SU(3), ...) [Gronau et al; Fleischer et al; ... 90+]
  extract hadronic matrix elements from data
  use approximate symmetries of QCD $\Rightarrow$ relate strong decay amplitudes
- dynamical approaches
  calculate hadronic matrix elements in QCD
  exploit factorization in heavy quark limit $m_b \gg \Lambda_{QCD}$ [Beneke et al; Li et al; Bauer et al; ... 99+]
  some additional insights from light-cone sum rules [Khodjamirian et al 00+]

Factorization

Exploit $m_b \gg \Lambda_{QCD}$ to disentangle

- short-distance effects $\sim m_b$ $\Rightarrow$ perturbatively calculable
- long-distance effects $\sim \Lambda_{QCD}$ $\Rightarrow$ universal hadronic parameters

This is not a model, but describes QCD in the well-defined limit $m_b \to \infty$

Why are there three different incarnations of factorization?

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Why are there three different incarnations of factorization?

Factorization of hard exclusive processes pioneered more than 30 years ago for $\pi\gamma^* \to \pi$

$$\langle \pi | J | \pi \rangle \simeq \int du\, dv\; T(u,v)\; \phi_\pi(u)\; \phi_\pi(v)$$

[Brodsky, Lepage 79]

For charmless hadronic B decays expect

$$\langle M_1 M_2 | Q_i | B \rangle \simeq \int d\omega\, du\, dv\; T_i(\omega,u,v)\; \phi_B(\omega)\; \phi_{M_1}(v)\; \phi_{M_2}(u) \quad ?$$

Problem: convolutions over ω and v diverge $\Rightarrow$ not dominated by hard gluon exchange!?

but still: convolution over u finite $\Rightarrow$ ”colour transparency” [Bjorken 89]

QCDF / pQCD / SCET

- QCD factorization [Beneke, Buchalla, Neubert, Sachrajda 99]

$$\langle M_1 M_2 | Q_i | B \rangle \simeq F^{BM_1}(0) \int du \, T_i^I(u) \, \phi_{M_2}(u) + \int d\omega \, du \, dv \, T_i^{II}(\omega, u, v) \, \phi_B(\omega) \, \phi_{M_1}(v) \, \phi_{M_2}(u)$$

convolutions are finite, endpoint divergence hidden in F^{BM_1} which is not factorized

QCDF / pCQD / SCET

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- perturbative QCD [Keum, Li, Sanda 00]

$$\langle M_1 M_2|Q_i|B\rangle \simeq \int d\omega\, du\, dv\, dk_{i\perp}\, T_i(\omega,u,v,k_{i\perp})\, \phi_B(\omega,k_{1\perp})\, \phi_{M_1}(v,k_{2\perp})\, \phi_{M_2}(u,k_{3\perp})$$

  + Sudakov resummation $\Rightarrow$ endpoint divergence smeared out by transverse momenta

QCDF / pQCD / SCET

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$+$ Sudakov resummation $\Rightarrow$ endpoint divergence smeared out by transverse momenta

- Soft-collinear effective theory [Bauer, Pirjol, Rothstein, Stewart 04]

SCET $=$ QCDF: simply EFT vs diagrammatical formulation

BPRS $\neq$ BBNS: phenomenological implementation for $B \to M_1 M_2$ quite different

issues: F^{BM_1} traded for ξ^{BM_1}, $\alpha_s(\sqrt{\Lambda m_b})$ non-perturbative, ... (minor)

long-distance charm loops, zero-bin subtractions (major)

Long-distance charm loops

Old charming penguin story – two different questions:

- power-suspressed but numerically important [Colangelo et al. 89; Ciuchini et al. 97+]

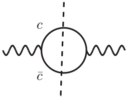
  ⇒ not supported by light-cone sum rule estimate [Khodjamirian, Mannel, Melic 03]

- leading power spoiling factorization [BPRS vs BBNS 04,05]

  does the threshold region with a non-relativistic $c\bar{c}$ pair require a special treatment?

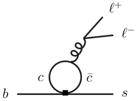
Recent work addresses second question [BBNS 09]

(a) $e^+e^- \to$ hadrons



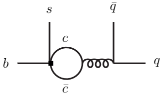
$$\int dq^2 \ldots \text{Im}\,\Pi(q^2)$$

(b) $B \to X_s \ell^+ \ell^-$



$$\int dq^2 \ldots \left|\Pi(q^2)\right|^2$$

(c) charming penguins



$$\int dq^2 \ldots \Pi(q^2)$$

⇒ global quark-hadron duality holds in (a) and (c), but breaks down in (b)

⇒ no special treatment required in (c), long-distance charm loops are power-suppressed

Glauber gluons in pQCD

It has been realized recently that k_T-factorization breaks down in $pp \to h_1 h_2 X$ at high p_T

[Collins, Qiu 07]

- problem related to a peculiar mode: Glauber gluons
- effect is a non-universal long-distance contribution $\Rightarrow$ ruins k_T-factorization
- problem not present in collinear factorization

Important for pQCD approach to non-leptonic B decays

- confirmed that problem exists $\Rightarrow$ modification of pQCD approach [Li, Mishima 09]
- claimed that it leads to an universal soft factor e^{iS} $\Rightarrow$ k_T-factorization still holds
- e^{iS} from fit to Br$(\pi^0\pi^0)$ $\Rightarrow$ large complex C $\Rightarrow$ "solves" $\pi\pi/\pi K$ puzzles

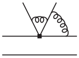
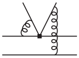
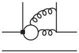
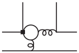
Issues:
- operator definition of soft factor?
- if universal why associated to π but not to ρ? $\Rightarrow$ would worsen Br$(\rho^0\rho^0)$
- at present I consider this rather as a fit than as a dynamical explanation

Perturbative corrections in QCDF

Ongoing effort to compute NNLO corrections in QCDF

$$\langle M_1 M_2 | Q_i | B \rangle \simeq F^{BM_1}\, T_i^I \otimes \phi_{M_2} + T_i^{II} \otimes \phi_B \otimes \phi_{M_1} \otimes \phi_{M_2}$$

strong phases $\sim \mathcal{O}(\alpha_s)$ $\Rightarrow$ NNLO is first correction for direct CP asymmetries!

Status	2-loop vertex corrections (T_i^I)	1-loop spectator scattering (T_i^{II})
Trees	 [GB 07, 09] [Beneke, Huber, Li 09]	 [Beneke, Jäger 05] [Kivel 06] [Pilipp 07]
Penguins	 in progress	 [Beneke, Jäger 06] [Jain, Rothstein, Stewart 07]

- factorization found to hold (as expected) at highly non-trivial order
- direct CP asymmetries not yet available at NNLO
- first NNLO results for CP-averaged branching ratios of tree-dominated decays

[GB, Pilipp 09; Beneke, Huber, Li 09]

Summary of theory part

	BBNS (QCDF)	pQCD	BPRS (SCET)
$\alpha_s(\sqrt{\Lambda m_b})$	perturbative	perturbative	non-perturbative
charm loops	perturbative (small phase)	perturbative (small phase)	non-perturbative (large phase from fit to data)
weak annihilation (power correction)	non-perturbative (crude model, arbitrary phase)	perturbative (large phase)	perturbative (with zero bins, small phase)
strong phases	generically small ($\sim \alpha_s, 1/m_b$)	can be sizeable (annihilation, Glaubers)	can be sizeable (charm loops)
perturbative calculation	partially NNLO	partially NLO	NLO
hadronic input	from lattice + QCD sum rules	from QCD sum rules + data, model $\phi_B(x, b)$	from QCD sum rules + data, model $\xi_J^{BM}(z)$

- theory predictions for direct CP asymmetries can unfortunately differ a lot!
- measurements (even bounds) of pure annihilation decays highly appreciated: $B_d \to K^- K^+, B_s \to \pi\pi/\pi\rho/\rho\rho$

PHENOMENOLOGY

$B \to \pi\pi/\pi\rho/\rho\rho$

Large $\text{Br}(\pi^0\pi^0) = (1.55 \pm 0.19) \cdot 10^{-6}$ challenging for dynamical approaches

- seems to indicate large C/T $\Rightarrow$ interesting in view of πK puzzle
- Babar: $(1.83 \pm 0.21 \pm 0.13) \cdot 10^{-6}$ Belle: $(1.1 \pm 0.3 \pm 0.1) \cdot 10^{-6}$

$\Rightarrow$ reconsider in the light of NNLO calculation in QCDF and $\pi\rho/\rho\rho$ data

Tree amplitudes now completely determined to NNLO

$$\begin{aligned} T \sim \alpha_1(\pi\pi) &= [\,1.008\,]_{V_0} + [\,0.022 + 0.009\,i\,]_{V_1} + [\,0.024 + 0.026\,i\,]_{V_2} \\ &\quad - [\,0.014\,]_{S_1} - [\,0.016 + 0.012\,i\,]_{S_2} - [\,0.008\,]_{1/m_b} \\ &= 1.015^{+0.020}_{-0.029} + (0.023^{+0.015}_{-0.015})\,i \\ C \sim \alpha_2(\pi\pi) &= [\,0.224\,]_{V_0} - [\,0.174 + 0.075\,i\,]_{V_1} - [\,0.029 + 0.046\,i\,]_{V_2} \\ &\quad + [\,0.084\,]_{S_1} + [\,0.037 + 0.022\,i\,]_{S_2} + [\,0.052\,]_{1/m_b} \\ &= 0.194^{+0.130}_{-0.095} - (0.099^{+0.057}_{-0.056})\,i \end{aligned}$$

- individual NNLO corrections quite significant, but substantial cancellations
- $\text{Re}(\alpha_2)$ still uncertain, mainly due to poor knowledge of $\lambda_B^{-1} = \int \frac{d\omega}{\omega}\phi_B(\omega)$

CP-averaged branching ratios

[GB, Pilipp 09]

Mode	QCDF	B	Experiment
$\pi^- \pi^0$	$6.22^{+2.37}_{-2.01}$	5.46	$5.59^{+0.41}_{-0.40}$
$\rho_L^- \rho_L^0$	$21.0^{+8.5}_{-7.3}$	21.3	$22.5^{+1.9}_{-1.9}$
$\pi^- \rho^0$	$9.34^{+4.00}_{-3.23}$	10.4	$8.3^{+1.2}_{-1.3}$
$\pi^0 \rho^-$	$15.1^{+5.7}_{-5.0}$	11.9	$10.9^{+1.4}_{-1.5}$
$\pi^+ \pi^-$	$8.96^{+3.78}_{-3.32}$	5.21	$5.16^{+0.22}_{-0.22}$
$\pi^0 \pi^0$	$0.35^{+0.37}_{-0.21}$	0.63	$1.55^{+0.19}_{-0.19}$
$\pi^+ \rho^-$	$22.8^{+9.1}_{-8.0}$	13.2	$15.7^{+1.8}_{-1.8}$
$\pi^- \rho^+$	$11.5^{+5.1}_{-4.3}$	8.41	$7.3^{+1.2}_{-1.2}$
$\pi^\pm \rho^\mp$	$34.3^{+11.5}_{-10.0}$	21.6	$23.0^{+2.3}_{-2.3}$
$\pi^0 \rho^0$	$0.52^{+0.76}_{-0.42}$	1.64	$2.0^{+0.5}_{-0.5}$
$\rho_L^+ \rho_L^-$	$30.3^{+12.9}_{-11.2}$	22.3	$23.6^{+3.2}_{-3.2}$
$\rho_L^0 \rho_L^0$	$0.44^{+0.66}_{-0.37}$	1.33	$0.69^{+0.30}_{-0.30}$

B: enhanced colour-suppressed amplitude with
$\lambda_B = 0.2$, $F_+^{B\pi} = 0.21$ and $A_0^{B\rho} = 0.27$

- theo. uncertainties highly correlated (F^{BM_1}, $|V_{ub}|$)
- colour-suppressed modes $\pi^0\pi^0/\pi^0\rho^0/\rho^0\rho^0$ rather uncertain (λ_B and $1/m_b$)
- $\rho^0\rho^0$ and $\pi^0\rho^0$ (with smaller penguins) fit better than $\pi^0\pi^0$
- preference for enhanced colour-suppressed amplitude

[for a similar analysis cf. Beneke, Huber, Li 09]

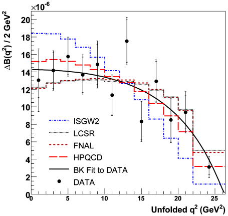
Testing factorization

Eliminate dependence on F^{BM_1} and $|V_{ub}|$ via

$$\mathcal{R}_{M_3}(M_1 M_2) = \frac{\Gamma(B \to M_1 M_2)}{d\Gamma(B \to M_3 \ell\nu)/dq^2|_{q^2=0}}$$

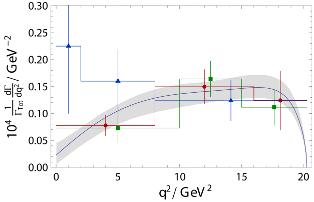
$\Rightarrow$ requires measurement of semileptonic decay spectrum and extrapolation to $q^2 = 0$

$B \to \pi\ell\nu$



[Babar 07]

$B \to \rho\ell\nu$



[Babar 05; Belle 07; CLEO 07; figure from Flynn et al 08]

$\Rightarrow \quad |V_{ub}| F_+^{B\pi}(0) = (9.1 \pm 0.7) \cdot 10^{-4}$

currently insufficient to extract $|V_{ub}| A_0^{B\rho}(0)$

Testing factorization

Eliminate dependence on F^{BM_1} and $|V_{ub}|$ via

$$\mathcal{R}_{M_3}(M_1 M_2) = \frac{\Gamma(B \to M_1 M_2)}{d\Gamma(B \to M_3 \ell\nu)/dq^2|_{q^2=0}}$$

[GB, Pilipp 09]

Mode	QCDF	B	Experiment
$\mathcal{R}_\pi(\pi^-\pi^0)$	$0.70^{+0.12}_{-0.08}$	0.95	$0.81^{+0.14}_{-0.14}$
$\mathcal{R}_\rho(\rho_L^-\rho_L^0)$	$1.91^{+0.32}_{-0.23}$	2.38	n.a.
$\mathcal{R}_\rho(\pi^-\rho^0)$	$0.85^{+0.22}_{-0.14}$	1.16	n.a.
$\mathcal{R}_\pi(\pi^0\rho^-)$	$1.71^{+0.27}_{-0.24}$	2.07	$1.57^{+0.32}_{-0.32}$
$\mathcal{R}_\pi(\pi^+\pi^-)$	$1.09^{+0.22}_{-0.20}$	0.97	$0.80^{+0.13}_{-0.13}$
$\mathcal{R}_\pi(\pi^+\rho^-)$	$2.77^{+0.32}_{-0.31}$	2.46	$2.43^{+0.47}_{-0.47}$
$\mathcal{R}_\rho(\pi^-\rho^+)$	$1.12^{+0.20}_{-0.14}$	1.01	n.a.
$\mathcal{R}_\rho(\rho_L^+\rho_L^-)$	$2.95^{+0.37}_{-0.35}$	2.68	n.a.
$R(\rho_L^-\rho_L^0/\rho_L^+\rho_L^-)$	$0.65^{+0.16}_{-0.11}$	0.89	$0.89^{+0.14}_{-0.14}$
$R(\pi^-\pi^0/\pi^+\pi^-)$	$0.65^{+0.19}_{-0.14}$	0.98	$1.01^{+0.09}_{-0.09}$

- $\pi^-\pi^0/\rho^-\rho^0$ provide clean access to $|T+C|$
- good overall description (in particular for small λ_B)
- only exception Br$(\pi^0\pi^0)$ which has a substantial penguin contribution and large theo. uncertainties

B: enhanced colour-suppressed amplitude with
$\lambda_B = 0.2$, $F_+^{B\pi} = 0.21$ and $A_0^{B\rho} = 0.27$

[for a similar analysis cf. Beneke, Huber, Li 09]

The $B \to \pi K$ puzzle

Since 2006 branching ratios do no longer look puzzling

	QCDF	Experiment
R_c	$1.15^{+0.21}_{-0.18}$	1.12 ± 0.07
R_n	$1.16^{+0.24}_{-0.20}$	1.02 ± 0.07

$$R_c = 2\,\frac{\Gamma(B^- \to \pi^0 K^-)}{\Gamma(B^- \to \pi^- \bar{K}^0)} \qquad R_n = \frac{1}{2}\,\frac{\Gamma(\bar{B}_d^0 \to \pi^+ K^-)}{\Gamma(\bar{B}_d^0 \to \pi^0 \bar{K}^0)}$$

But direct CP asymmetries look somewhat odd

A_{CP} [%]	QCDF	Experiment
$\pi^0 K^-$	$9.4^{+12.1}_{-14.6}$	$5.0^{+2.5}_{-2.5}$
$\pi^+ K^-$	$5.6^{+12.2}_{-15.1}$	$-9.8^{+1.2}_{-1.1}$
ΔA_{CP}	$3.8^{+2.9}_{-2.7}$	$14.8^{+2.7}_{-2.8}$

ΔA_{CP} can be predicted quite precisely

$\Rightarrow$ could be NP but also large + complex C/T beyond factorization

More robust SM test given by isospin sum rule [Gronau 05]

A_{CP} [%]	Sum rule	Experiment
$\pi^0 \bar{K}^0$	-0.15 ± 0.04	-0.01 ± 0.10

$$A_{CP}(\pi^+ K^-) + A_{CP}(\pi^- \bar{K}^0) \simeq A_{CP}(\pi^0 K^-) + A_{CP}(\pi^0 \bar{K}^0)$$

$\Rightarrow$ predicts large $A_{CP}(\pi^0 \bar{K}^0)$, but discrimination of NP requires much more data

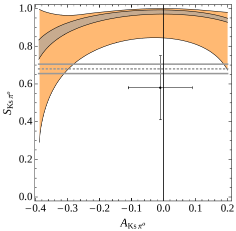
Mixing-induced CP asymmetry

Naive expectation neglecting doubly Cabibbo-suppressed terms

$$S_{\pi^0 K_S} \simeq \sin(2\beta)_{J/\psi K_S} = 0.681 \pm 0.025 \qquad S_{\pi^0 K_S} \stackrel{\text{exp}}{=} 0.57 \pm 0.17$$

"tree pollution" estimated to increase $S_{\pi^0 K_S}$ by 0.04–0.12 [Beneke 05; Williamson, Zupan 06]

Isospin relations reveal some tension with πK data [Fleischer, Jäger, Pirjol, Zupan 08]



uses two SU(3) relations $\Rightarrow$ R_{T+C} and R_q

SU(3) breaking estimated with QCDF

$$\Rightarrow \quad S_{\pi^0 K_S} = 0.99^{+0.01}_{-0.08}\Big|_{\text{exp}}{}^{+0.000}_{-0.001}\Big|_{R_{T+C}}{}^{+0.00}_{-0.11}\Big|_{R_q}{}^{+0.00}_{-0.07}\Big|_{\gamma}$$

uncertainty reducible by lattice determination of $F^{BK}/F^{B\pi}$

Additional information on πK puzzle can be obtained from $\pi K^*/\rho K$ sector

$\Rightarrow$ at present data still insufficient, but expect sizeable direct CP asymmetries

[Chiang, London 09; Gronau, Pirjol, Zupan 10]

Conclusion

Factorization is based on a twofold expansion in $\alpha_s(m_b)$ and $1/m_b$

- perturbative calculations are reaching NNLO precision
- unfortunately no similar progress (yet) on power corrections

Satisfactory overall description of $\pi\pi/\pi\rho/\rho\rho$ branching ratios

- large Br($\pi^0\pi^0$) still puzzling, but not necessarily a failure of factorization
- $A_{CP}(\pi^+\pi^-)$ from Belle also somewhat large, but $\sim 2\sigma$ above Babar value

The $B \to \pi K$ puzzle continues to be exciting

- depends crucially on experimental progress on $\pi^0 \bar{K}^0$ observables

There are many interesting topics which I could not discuss

- B_s decays, $B \to VV$ polarization puzzle, B decays with scalars, baryons, 3-body, ...