theory of
tree amplitudes
in hadronic B decays

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Outline

- motivation
- theoretical calculations and uncertainties
    - color-allowed tree
    - color-suppressed tree
    - up-penguin
    - annihilation
- comparison with data
- open issues

Physical amplitudes

- Any SM 2-light-hadron amplitude can be written

$$\mathcal{A}(\bar{B} \to M_1 M_2) = e^{-i\gamma} T_{M_1 M_2} + P_{M_1 M_2}$$

$$T_{M_1 M_2} = V_{uD} |V_{ub}| \left[C_1 \langle Q_1^u \rangle + C_2 \langle Q_2^u \rangle + \sum_{i=3}^{12} C_i \langle Q_i \rangle \right] \qquad \text{“tree”}$$

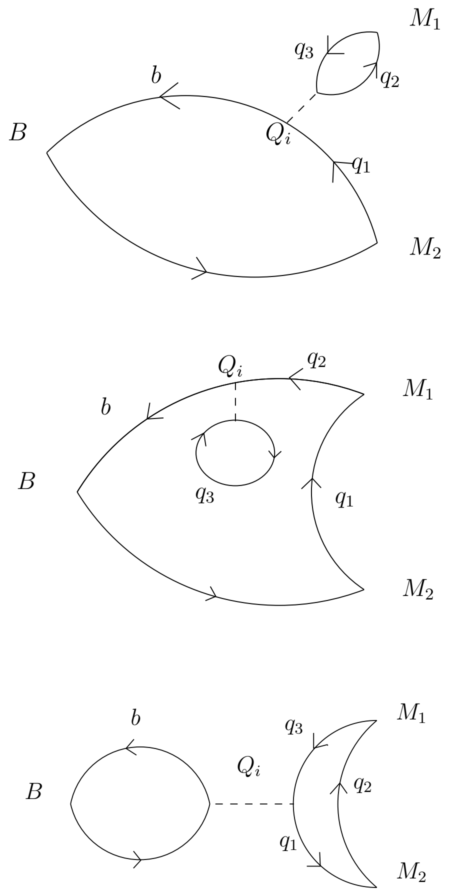
$$P_{M_1 M_2} = V_{cD} |V_{cb}| \left[C_1 \langle Q_1^c \rangle + C_2 \langle Q_2^c \rangle + \sum_{i=3}^{12} C_i \langle Q_i \rangle \right] \qquad \text{“penguin”}$$

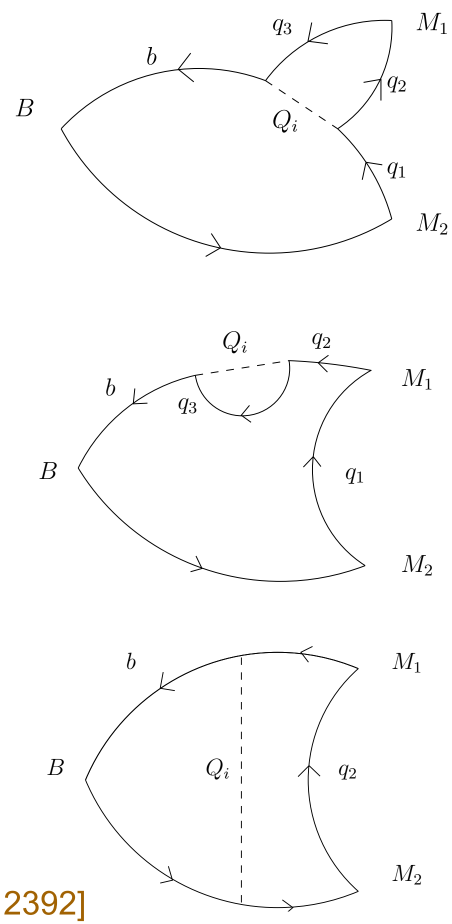
- If penguins somewhat suppressed, ΔD=1 are tree and ΔS=1 penguin dominated (generically)
- Theory (factorization, 1/N) provides suitable penguin suppression (C.W. Bauer, C.D. Lü talks)
- for CKM angles, either eliminate P (or T) using data (yesterday’s talks), or attempt to compute the ratios

Why calculate?

- tree-dominated modes ($\pi\pi$, $\pi\rho$, $\rho\rho$):
  $S_{+-} = \sin(2\alpha)$ in no-penguin limit
  - knowledge of P/T “pollution” determines α (γ), without need for isospin constructions, SU(3), etc.
- penguin-dominated modes:
  S(ΦK, η’K, πK, ωK, ...) <-> $\sin(2\beta)$ in no-tree limit.
  - T/P determines SM shifts; comparison of $\sin(2\beta)_{J/\psi\ K}$ and $\sin(2\beta)_{peng}$ beyond average
- beyond CKM: more theory => more independent observables (e.g. direct CP asymmetries in πK) => more probes of new physics

Topological amplitudes





[from Buras&Silvestrini hep-ph/9812392]

$Q_i = Q_{1,2}^u$ ⇒ $a_{1,2}$ $[T, C][E_{1,2}]$

color-allowed/
-suppressed tree

$Q_i = Q_{3\ldots12}$ ⇒

$Q_i = Q_{1,2}^u, Q_{3\ldots12}$ ⇒ α_4^u $[P_{ut}][P_1 - P_1^{\mathrm{GIM}}]$

up-penguin
(incl. also
penguin ann.,
excl. EWP)

$Q_i = Q_{1,2}^u$ ⇒ $b_{1,2}$ $[E, A][A_{2,1}]$

tree annihilation

ex.: $-\mathcal{A}(\bar{B}^0 \to \pi^0\pi^0) = V_{ud}^* V_{ub} \left[A_{\pi\pi} \left(a_2(\pi\pi) - \alpha_4^u(\pi\pi)\right) + B_{\pi\pi} b_1(\pi\pi)\right]$

$+V_{cd}^* V_{cb}$ terms $+$ EWP terms

Theory approaches

- 1/N expansion (only counting rules)
- Λ_{QCD}/m_B expansion (QCDF/SCET; pQCD): computation of important pieces possible

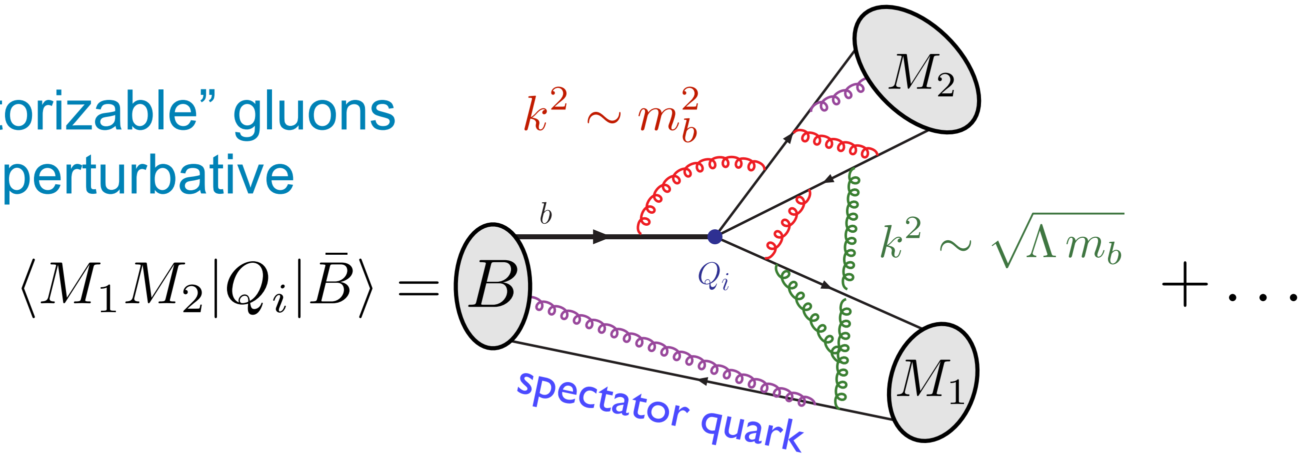
	a_1/T/E_1	a_2/C/E_2	α_4^u	b_1/E/A_2	b_2/A/A_1
1/N	1	1/N	1/N	1/N	1 [?]
Λ/m_B	1	1	1	Λ/m_B	Λ/m_B

- QCD light-cone sum rules: partly complementary set of calculable amplitudes; constrain “inputs” to Λ/m_B
- SU(3) [U-spin] relates ΔD=1 and ΔS=1: e.g. trees in πK from ππ; penguins in ρρ from ρK^*, etc. (m_s/Λ_{QCD} corrections; annihilation contamination)

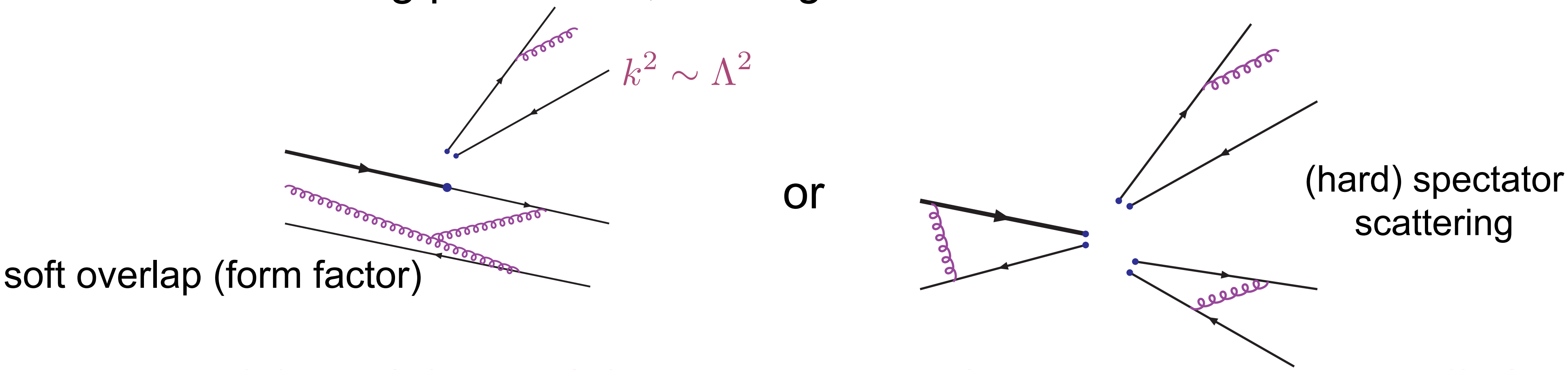
QCDF/SCET/pQCD

Beneke, Buchalla, Neubert, Sachrajda;
Keum, Li, Sanda; Chay, Kim;
Bauer, Pirjol, Rothstein, Stewart

"nonfactorizable" gluons
are perturbative



To leading power in Λ/m_b *long-distance* interactions look like



- SCET, QCDF, pQCD agree on this (but implementations differ)
- a limit of QCD, not a model
- model dependence enters at subleading power

Color-allowed tree [QCDF]

- computation of O(α_s) BBNS 99-01 and O(α_s^2) pieces
  Hill, Becher, Lee, Neubert 2004; Beneke, Yang 2005; Kirilin 2005; Beneke, SJ 2005, 2006; Kivel 2006; Pilipp 2007; Bell 2007

$$
\begin{aligned}
a_1(\pi\pi) &= 1.015 + [0.025 + 0.012i]_V + [? + 0.027i]_{VV} \\
&\quad - \left[\frac{r_{\rm sp}}{0.485}\right] \left\{[0.020]_{\rm LO} + [0.034 + 0.029i]_{HV} + [0.012]_{\rm tw3}\right\} \\
&= 0.975^{+0.034}_{-0.072} + (0.010^{+0.025}_{-0.051})i,
\end{aligned}
$$

form-factor term

spectator scattering

[arXiv:0801.1833v1]

- translation to SCET approach (BPRS) straightforward (change of operator basis)

- very similar for other PP, PV, VP, $V_L V_L$ modes

- naive factorization provides an excellent approximation; corrections up to NNLO tiny; theory uncertainties small (few percent)

Color-suppressed tree

- computation identical to a_1, but different color factors, Wilson coefficients

form-factor term:cancellation

$$
\begin{aligned}
a_2(\pi\pi) &= 0.184 - [0.153 + 0.077i]_V + [? - 0.049i]_{VV} \\
&\quad + \left[\frac{r_{\rm sp}}{0.485}\right] \left\{ [0.122]_{\rm LO} + [0.050 + 0.053i]_{HV} + [0.071]_{\rm tw3} \right\} \\
&= 0.275^{+0.228}_{-0.135} + (-0.073^{+0.115}_{-0.082})i.
\end{aligned}
$$

spectator scattering dominates

- naive factorization fails badly
  Size of a_2 depends on a hadronic normalization r_{sp} (mainly the B wave function inverse moment $1/\lambda_B$)

- pQCD predictions generically agree with QCDF, within errors. $O(\alpha_s^2)$ result for c.s.t. Li, Mishima, Sanda 2005 finds factor 3 enhancement & large imaginary part - employs NLO BBNS kernel, renormalized at very low scales (< 1GeV). Justified?

Can one constrain λ_B?

- LC sum rules, shape models give λ_B=(350-600) MeV

  Braun; Khodjamirian et al; Lee, Neubert, ...

  - how reliable are the quoted uncertainties

- Babar [0704.1478] reports $\lambda_B \gtrsim$ 600 MeV from

  non-observation of $B \to \gamma\, l\, \nu$
  - uses LO factorization result [NLO known],
  - in part of the signal region, γ rather soft
  Q: How would bound change for tighter cut, NLO ?
  If confirmed, it implies an upper bound on the QCDF (or SCET) prediction for a_2 (C)

- Alternatively, can fit λ_B (and form factors) to $\pi\pi$ data. Implicit in SCET fits; scenario “S4” (BBNS) or “G” (Beneke, SJ), one needs λ_B ~ 200 MeV

up-penguin

- contributions from both penguin contractions of $Q_1(u)$ and from QCD-penguin operators
- found small in all approaches (1/N counting, pQCD, QCDF/SCET); partial NNLO known in QCDF/SCET; partial NNLO in pQCD SJ; Jain, Rothstein, Stewart; Li, Mishima, Sanda
- unlike the charming penguin, no special treatment of u loop in SCET approach

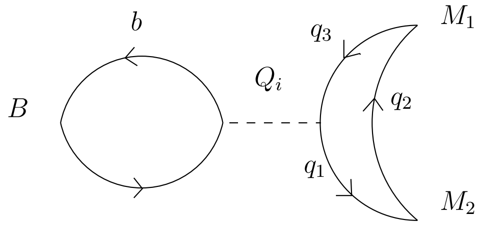
annihilation

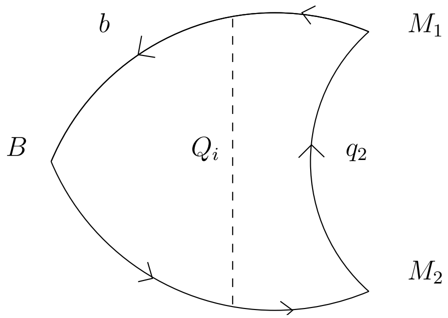
- $b_{1,2}$ power-suppressed in heavy-quark limit -- but come with large Wilson coefficients
  - incalculable in QCDF/SCET (endpoint divergence: not short-distance-dominated)
  - pQCD: Sudakov suppression of LD contributions

- b_1(enters ππ amplitudes) 1/N suppressed

- b_2 (in πK (also πρ) amplitudes) not 1/N suppressed. However, leading (in 1/N) piece "factorizable" and suppressed by current conservation (explicit in BBNS annihilation model, in pQCD, in LCSR calculation)

[Khodjamirian, Mannel, Melcher, Melic hep-ph/0509049]





Summary predictions

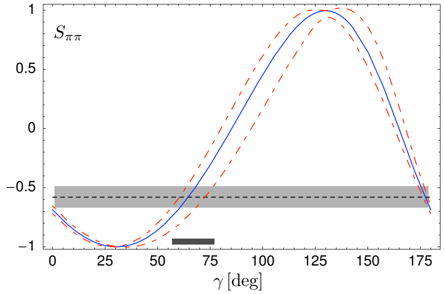
- Of the amplitudes relevant to the (physical) "trees",
  - a_1/T/E_1 and α_4^u / P_{ut} are predictable, hence so are the physical color-allowed trees

  - a_2/C/E_2 has O(1) uncertainty, knowledge (or bound) on normalization factor may constrain it

  - b_2/A/A_1 (relevant to $B^+ \to \pi K$ decays) not computable but power-suppressed. Should be numerically suppressed relative to T

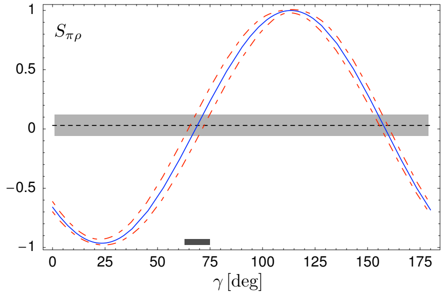
- C/T, and in particular (T+C)/T, has small strong phase (for any isospin-set of PP, VP, PV, $V_L V_L$ modes) - constrained to 0 in the fits in the SCET approach Bauer,Pirjol,Rothstein,Stewart; Williamson,Zupan, ...

γ determination from time-dependent CP asymmetry



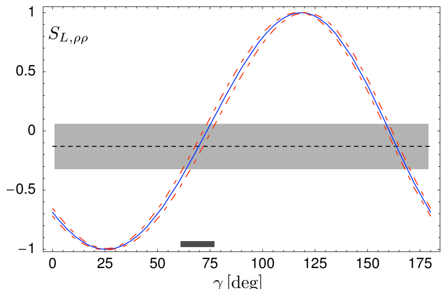
$$S_{\pi\pi} = -0.58 \pm 0.09$$

$$\Rightarrow \qquad \gamma = (65\,^{+12}_{-8})^\circ$$



$$S_{\pi\rho} = 0.03 \pm 0.09$$

$$\Rightarrow \qquad \gamma = (69\,^{+6}_{-6})^\circ$$



$$S_{\rho\rho} = -0.13 \pm 0.19$$

$$\Rightarrow \qquad \gamma = (69\,^{+8}_{-8})^\circ$$

Mutually consistent

$$\gamma = (68 \pm 4)^\circ$$

and consistent with the standard mixing-based fit (UTfit, 2007):

$$\gamma = (61 \pm 5)^\circ$$

[M. Beneke, talk at CERN theory institute]

- requires computation of Re(P/T)
- similar for sin(2β) from b→s peng (Cai-Dian's talk)

Comparison with data

- πK puzzle (QCDF/SCET version)
  (T+C)/T real implies $A(K^+\pi^0) \approx A(K^+\pi^-)$, expt. 5σ
  could be NP, for example BSM electroweak penguin

- C small (λ_B large) implies small BR($\pi^0\pi^0$). Recent Babar measurement $(1.83\pm0.21\pm0.13)10^{-6}$ far out small-λ_B scenario G: $\left(0.73^{+0.27}_{-0.24}(\mathrm{CKM})^{+0.52}_{-0.21}(\mathrm{hadr.})^{+0.35}_{-0.25}(\mathrm{pow.})\right)10^{-6}$
  could be NP in principle

- fits of some amplitudes to data possible, many recent works; also talk by Pierini.
  Gronau et al; Buras et al; Baek et al; Yoshikawa; Gronau, Rosner; Agashe et al; Grossman et al; Feldmann et al;...

- fits (unsurprisingly) lead to large C, often complex
  - maybe a_2 receives very large power correction.
  - annihilation b_2 contributes to physical C, but also generates $A(\pi^+K^0)$ generically -- not observed

Outlook

- theory calculations in the heavy-quark limit at the NNLO / $O(\alpha_s^2)$ stage. Perturbation theory stable, most data described within errors
- competitive determination of γ from $b \to d$ transitions
- some puzzles exist, which may be new physics or unexpectedly large power-suppressed amplitudes
- experimental input on radiative leptonic decays can help with hadronic decays!
- theory uncertainties will (after NNLO completed) be dominated by uncertain power corrections, need conceptual breakthrough (endpoint divergences)