Theory of hadronic B decays: penguin amplitudes

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Part of this is based on chapter 9.1 in the CKM 2008 proceedings,
Phys.Rept.494 (2010) 197-414, arXiv:0907.5386v2

Physical amplitudes

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

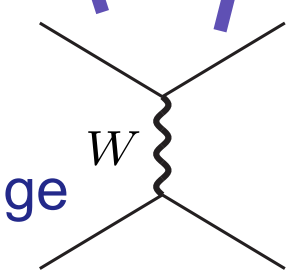
$$\mathcal{A}(\bar{B} \to M_1 M_2) = e^{-i\gamma} T_{M_1 M_2} + P_{M_1 M_2}$$

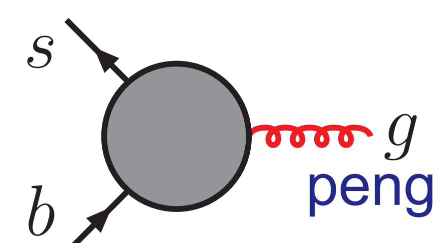
$$T_{M_1 M_2} = V_{uD}|V_{ub}|\Big[C_1\langle Q_1^u\rangle + C_2\langle Q_2^u\rangle + \sum_{i=3}^{12} C_i\langle Q_i\rangle\Big]$$ "tree"

$$P_{M_1 M_2} = V_{cD}|V_{cb}|\Big[C_1\langle Q_1^c\rangle + C_2\langle Q_2^c\rangle + \sum_{i=3}^{12} C_i\langle Q_i\rangle\Big]$$ "penguin"

CKM factor (D=d or s)

tree W exchange





penguins (QCD, magnetic, EW)

Q_i: operators in weak hamiltonian

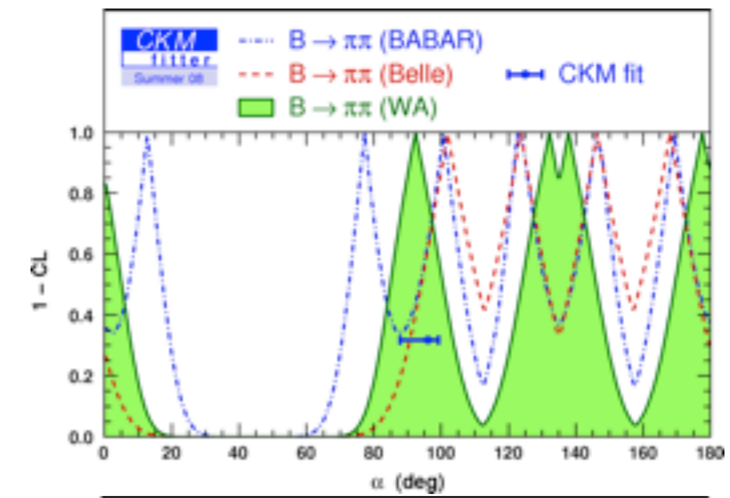
C_i: QCD corrections from short distances (< hc/m_b) & new physics

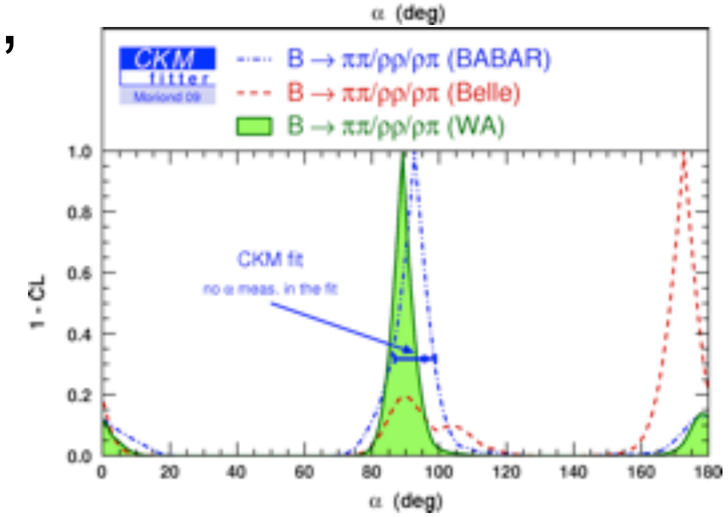
$\langle Q_i\rangle = \langle M_1 M_2 | Q_i | B\rangle$: QCD at distances > hc/$m_b$, strong phases

Relevance of penguins

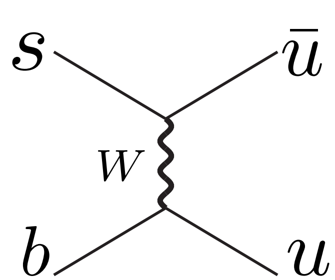
- angle measurements in tree-dominated modes (ππ, πρ, ρρ):
  $S_{+-} = \sin(2\alpha)$ in no-penguin limit

  knowledge of P/T "pollution" determines α (γ), without need for isospin constructions, SU(3), etc.

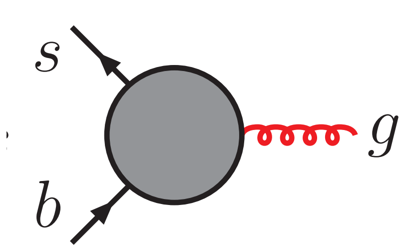




- b➔s decays penguin-dominated in SM



$\sim \lambda^4$



$\sim \lambda^2$

sensitive to loops & new physics

πK puzzle, etc

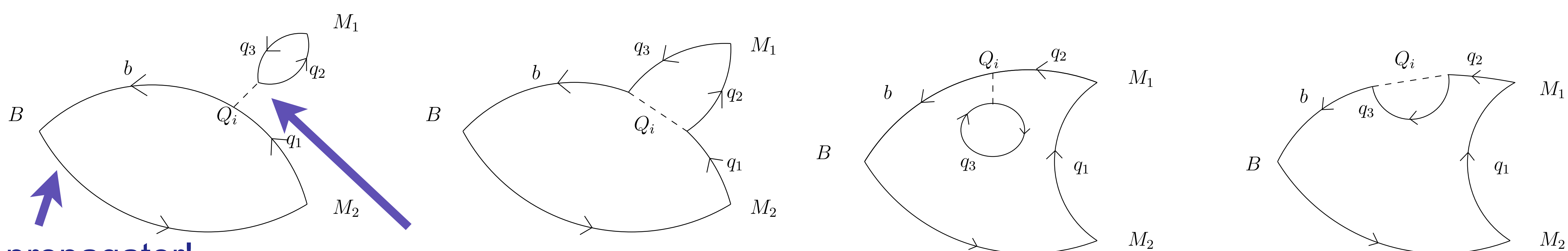
Topological amplitudes

- matrix elements are contained in correlation functions (LSZ)

$$\langle M_1 M_2 | Q_i | B \rangle \sim \int dA \int d\bar{\psi}\, d\psi\, j_B^{\mu}(x) j_{M_1}^{\nu}(y) j_{M_2}^{\rho}(z) Q_i(w) e^{i(S_{QCD+QED})}$$

which can be represented as "Wick contractions"

[Buras&Silvestrini hep-ph/9812392]

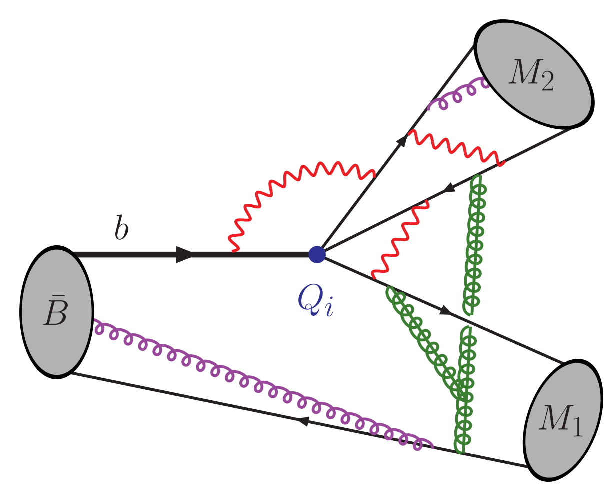


full propagator!   operators Q_i

- RG invariant combinations of these define "topological" amplitudes - nonperturbatively!

- represent the contribution to the matrix element of Q_i as

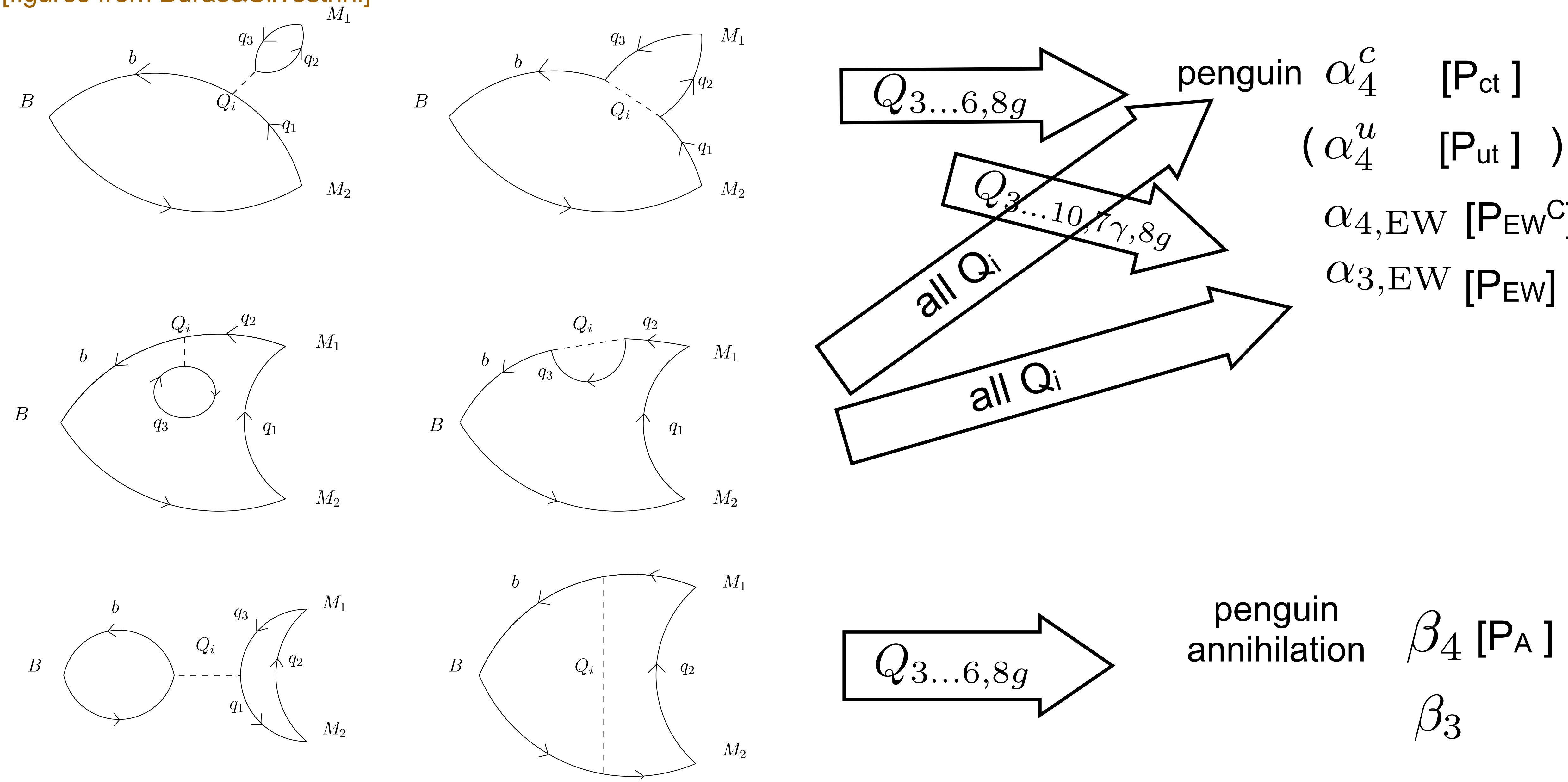
  (still no perturbation expansion)



etc

Penguin anatomy I

[figures from Buras&Silvestrini]



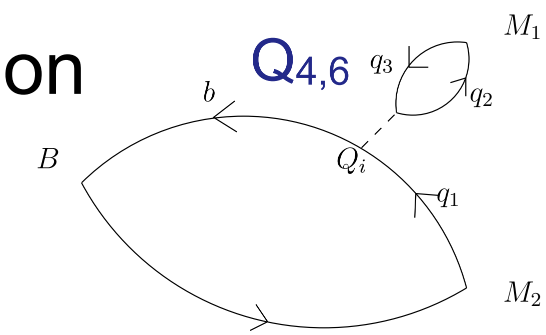
β_3 "mixes" with α_4^c under RG (above m_b) but useful to keep separate for heavy-quark limit
it has traditionally been considered a part of the (topological) penguin amplitude

Example: $P_{\bar{B}^0\to\pi^+K^-} = |V_{cs}V_{cb}|A_{\pi K}\left(\alpha_4^c + \beta_3^c + \alpha_{4,\mathrm{EW}}^c - \frac{1}{2}\beta_{3,\mathrm{EW}}^c\right)$

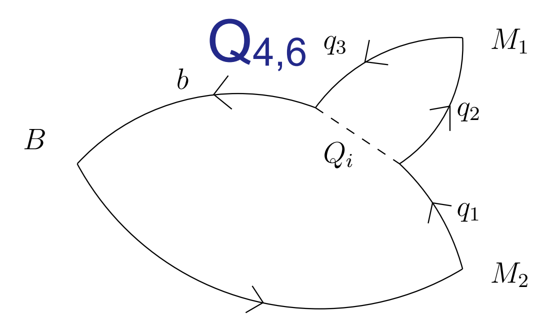
hadronic normalization
(form factor & decay constants) - a convention

Theory approaches I

- $1/N_c$ expansion
  e.g.



O(1)

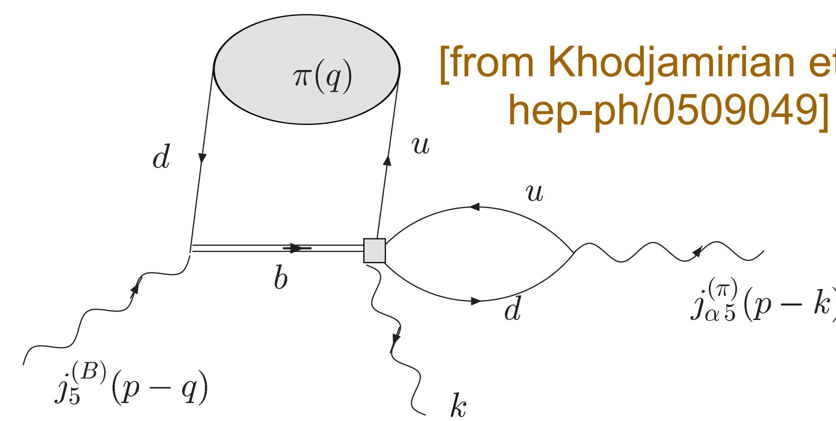


$O(1/N^2)$

[Buras et al 86, Bauer et al 87]

  - "naive factorization" for N_c -> infinity
  - strong phase of penguin is $O(1/N^2)$
  - main drawback: can't compute

- QCD light-cone sum rules
  evaluate correlation function off shell;
  OPE & lightcone expansion
  - express hadronic matrix elements
    in terms of simpler objects (form factors etc.) and
    a perturbatively evaluated dispersion integral.
  - works also for form factors themselves (and other objects)
  - main drawback: uncertainty due to "continuum threshold"
    is difficult to quantify



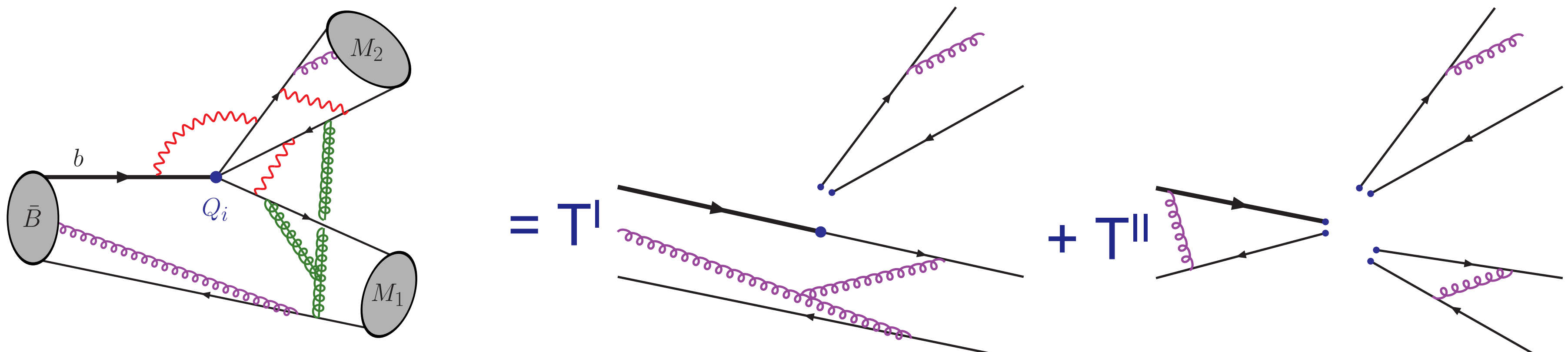
[from Khodjamirian et al, hep-ph/0509049]

Theory approaches II

[Beneke, Buchalla, Neubert, Sachrajda (BBNS); Bauer et al]

- heavy-quark expansion in Λ_{QCD}/m_B (talk G Bell) [QCDF / SCET; pQCD approach]

[Keum, Li, Sanda, ...]



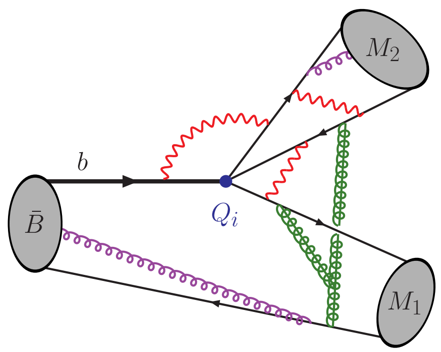
T^I, T^{II} computable in perturbation theory in strong coupling

- "naive factorization" for m_B -> infinity
- strong phases are $O(\alpha_s)$ or $O(\Lambda_{QCD}/m_b)$
- annihilation power suppressed altogether
- hierarchies of penguin amplitudes between final states containing pseudoscalars and vectors
- main drawback: $O(\Lambda_{QCD}/m_B)$ power corrections don't factorize, in general, and hard to estimate

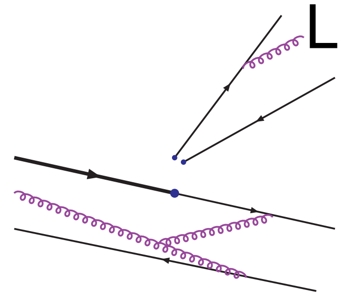
- flavour SU(3) - relate b➔s and b➔d; eliminate amplitudes from data. Good if redundant observables (γ in SM), less powerful for NP search; SU(3) breaking not controlled

[Zeppenfeld 81; Gronau et al 94; Fleischer, ...]

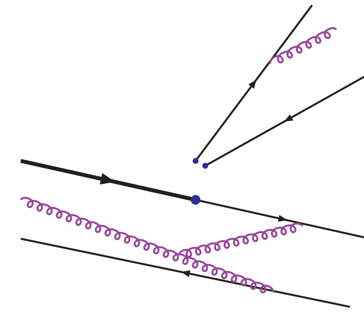
Penguin anatomy II: $1/m_b$



like quark chiralities



opposite quark chiralities



("scalar penguin")

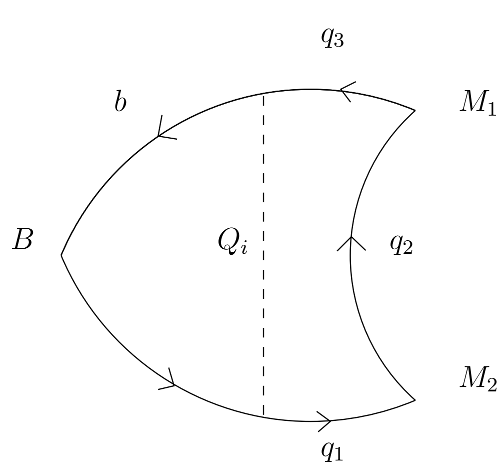
$$\alpha_4^c \quad = \quad a_4 \quad + \quad r_\chi^{M_2} a_6$$

$O(1/m_b)$ but factorizes !

However: $$r_\chi^\pi(\mu) = \frac{2m_\pi^2}{m_b(\mu)\,(m_u + m_d)(\mu)} \sim \frac{\Lambda_{\rm QCD}}{m_b}$$

but ~ 1 numerically
"chiral enhancement"

no chiral enhancement present for vector M_2 -> much smaller penguin amplitudes



β_3

$O(1/m_b)$, does *not* factorize

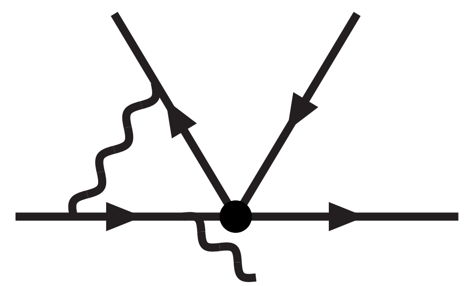
modeled by naively factorized expression with IR cutoff by BBNS

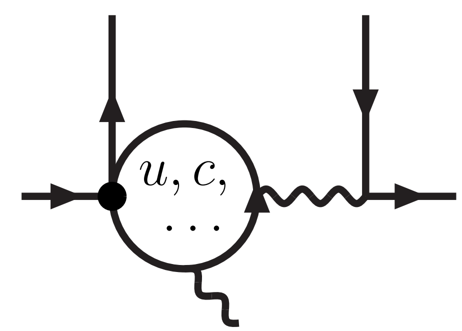
large and complex in pQCD approach [Keum, Li, Sanda 2000]
very small in light-cone sum rules [Khodjamirian et al 2005]

Status of perturbative kernels

- a_4 computed to $O(\alpha_s)$ (vertex kernel T^I) Beneke et al 1999-2001
  $O(\alpha_s^2)$ (spectator scattering kernel T^{II}) Beneke, SJ 2006
  Jain, Rothstein, Stewart 2007

For the latter one needs to compute (besides simpler terms)





penguin loop could be large because C_1~1 first appears at this order
however, due to a (not understood) cancellation it gives almost no contribution

proves factorization & perturbative stability but leaves NLO results intact. Hence instead of quoting numbers I refer to the comprehensive phenomenology in [Beneke&Neubert 03]

- a_6 computed to $O(\alpha_s)$ (vertex kernel T^I) Beneke et al 1999-2001
  spectator scattering vanishes at this order
  At $O(\alpha_s^2)$ one needs to compute the same diagrams as above
  could potentially be large contribution for PP and VP final states

Comparison to data I

$$P_{M_1M_2}/(C_{\pi\pi}+T_{\pi\pi}) \sim \hat{\alpha}_4^c(M_1M_2)/(\alpha_1(\pi\pi)+\alpha_2(\pi\pi))$$

can be fit to BR, A_{CP} (π^+K^-) and BR($\pi^+\pi^-$) using one SU(3) relation

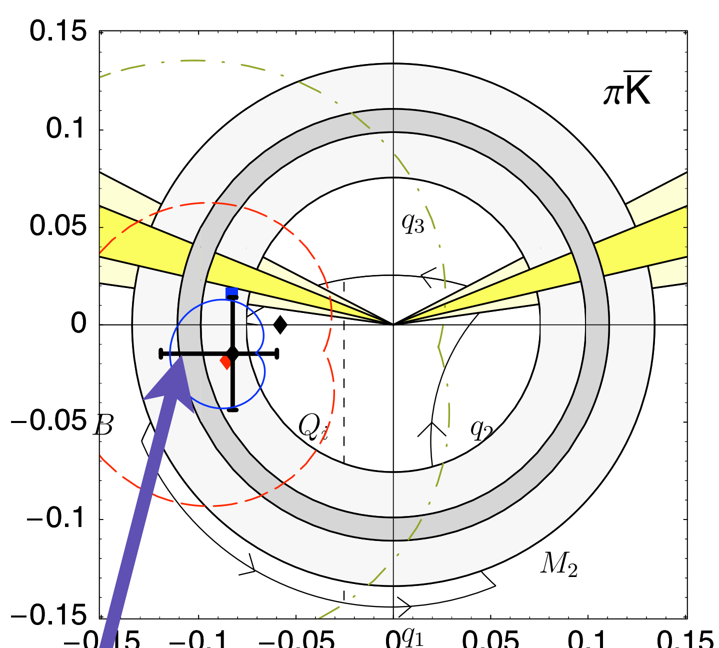
$$P_{M_1M_2} \sim \hat{\alpha}_4^c(M_1M_2) = a_4(M_1M_2) \pm r_\chi^{M_2} a_6(M_1M_2) + \beta_3^p(M_1M_2)$$

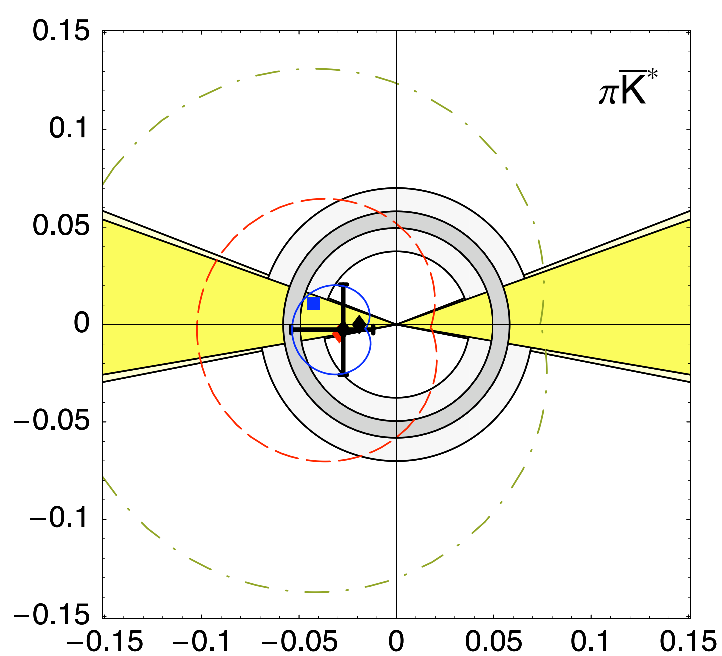
factorizable power correction

annihilation (modeled a la BBNS)

chirally enhanced for M_2 pseudoscalar

small for M_2 vector





BBNS model of annihilation

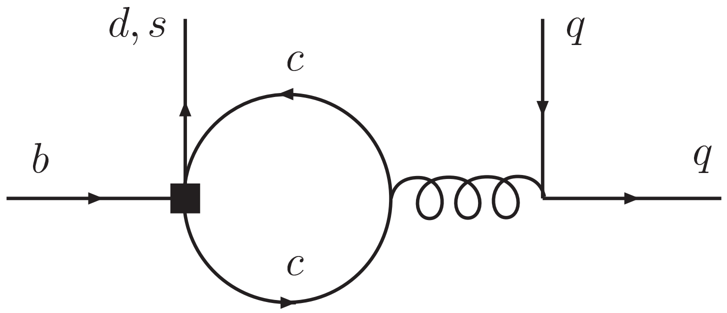
[Beneke, Neubert 2003; Beneke, SJ 2007]

pattern agrees quite well with theory (also for ρK, ρK*)

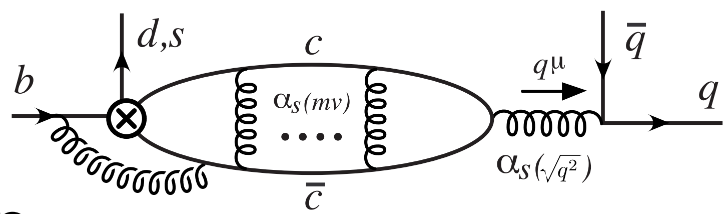
wrong imaginary part for πK unless annihilation is fairly large (well known problem)

Charming penguin

- Charm penguin loops appear as part of the penguin amplitude. Could a priori be large [Ciuchini et al 97]

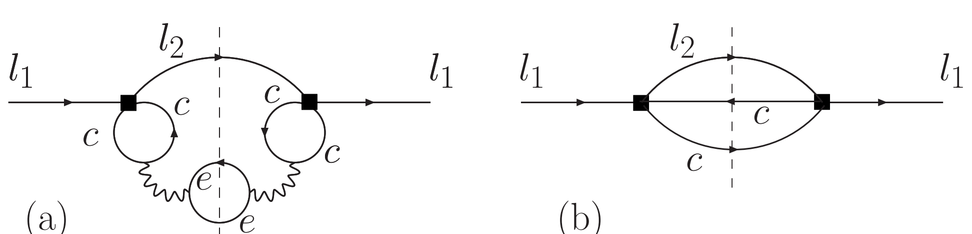


- In the HQE, they enter both a_4 and a_6 ; were argued to factorize at leading power ("hard" regions)
- Bauer et al (BPRS) 2004: One should add a nonperturbative contribution $A_{c\bar{c}}^{M_1 M_2}$ for the nonrelativistic charm "threshold" region



- disagreement over power suppression of this region. It also evidently overlaps with the "hard" region.
- BBNS 2009: power counting in BPRS 2004 was wrong (error in matching onto nonrelativistic effective theory).

This paper also explains how in $B \to X_s\, l^+ l^-$ the nonrelativistic charm region can account for 99% or the rate: It is not inclusive enough



part of rate

not part of rate

I consider this issue fully resolved.

Comparison to data II

- The direct CP asymmetries come out wrong for several modes, particularly for the πK final states (see talk by S Mishima)

  $A_{CP}(\pi^+K^-)$ has opposite sign [cf above]

  $A_{CP}(\pi^0K^-) \neq A_{CP}(\pi^0K^-)$ at around 5σ [eg Belle, Nature 2008]

- It has been argued that this implies new physics, see eg

  [Buras, Fleischer, Recksiegel, Schwab 03; Baek et al 04; Lunghi, Soni 08; Arnowitt et al; Khalil, Kou; Hou; Soni et al 08; Barger et al 09; Khalil, Masiero, Murayama 09; many more ...]

  for instance through modified electroweak penguin contributions (which factorize similarly to tree amplitudes)

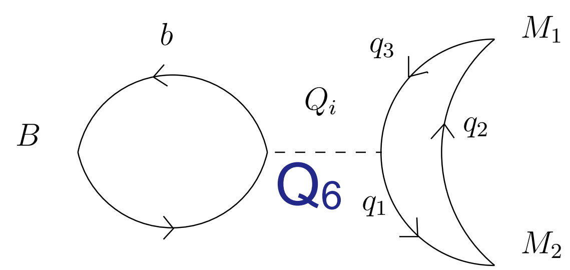
- and/or that the colour-suppressed tree amplitude is large and complex and/or the penguin imaginary parts are wrong in factorization (or receive large power corrections), see eg

  Gronau et al; Buras, Fleischer, Recksiegel, Schwab 03; Baek et al 04, 09; Yoshikawa 03; Ciuchini et al 08, Gronau,Pirjol,Zupan 10

  Some support for the latter from $A_{CP}(\pi^+\pi^-)$ via SU(3)

Annihilation β_3

- The colour-leading piece to the annihilation contribution β_3 to the QCD penguin amplitude has a naively factorizing structure



(where Q_6 has been "Fierzed" to colour singlet x singlet form)

This is proportional to the "scalar form factor". A sum rule calculation gives a small and approximately real result, so it cannot resolve the penguin puzzles [Khodjamirian Mannel, Melcher, Melic, hep-ph/0509049]

Note that this is a relatively "simple" sum rule for a form factor, for which sum rules have a good track record (when compared with lattice or data driven determinations)

- In contrast, the pQCD approach finds a large and complex value albeit with large uncertainties. [Keum, Li, Sanda 2000]

Summary

- Dynamical description of penguin amplitudes

  - well-defined $1/m_b$ expansion, leading terms factorize with a stable perturbation expansion

  - one potentially large missing piece (in a_6)

  - leading-power long-distance charm penguin dead

- Data

  - clearly respects the hierarchies predicted by the HQ expansion (PP, VP versus PV, VV)

  - on direct CP asymmetries doesn't fit well with theory: either higher orders in a_6 are important, or annihilation terms are large, or there is new physics in some amplitudes, or a combination of these