CP violation and all that

Stefan Leupold

Department of Physics and Astronomy
Uppsala University

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1. baryon number violation

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2. C violation (C massively broken in weak theory ✓) **and CP violation** (too small in weak theory) $\rightarrow$ new physics
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CP violation — where to look for?

need a larger amount of CP violation

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  (good to have upper and lower limits)

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↪ baryon decays

↪ **can we reach accuracies comparable to meson sector?**

Classification of flavor changing baryon decays

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[B: initial baryon (not B meson); b: final baryon]

- semi-leptonic decays

$$B \to b\,\ell\nu_\ell$$

- non-leptonic decays, e.g.

$$B \to b\,\pi$$

- radiative flavor-changing decays

$$B \to b\,\gamma \qquad \text{or e.g.} \qquad B \to b\,\mu^+\mu^-$$

Operators and scales in semi-leptonic decays

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- one quark changes flavor

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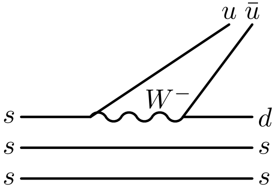
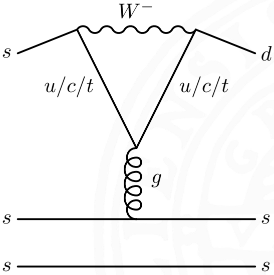
  - rearrangement of bound-state wave function
  - medium-distance effect $\sim 1/m_{\rm hadron}$

Some illustration

two quarks changing flavor:



one quark changing flavor — penguin:



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e.g. $B \to b\,\pi$

- two quarks change flavor
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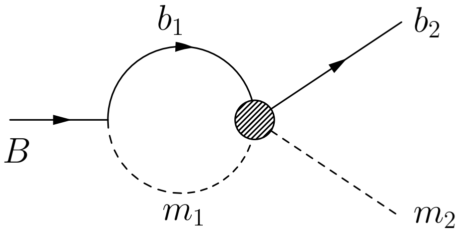
- strong final-state interaction (FSI)
  - elastic or inelastic
  - medium- to long-distance effect $\sim 1/m_\pi$

Strong final-state interaction (FSI)



(of course even more complicated for many-body decays)

Operators and scales in radiative decays

$$B \to b\,\gamma \qquad \text{or e.g.} \qquad B \to b\,\mu^+\mu^-$$

- two quarks change flavor (or penguin ...)
  and
  quark or W emits photon
  - probes four- and six-quark operators

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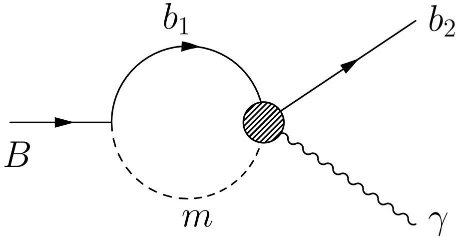
- **alternative:** non-leptonic decay
  plus inelastic final-state interaction (FSI)
  - medium- to long-distance effect $\sim 1/m_\pi$

Radiation as a final-state effect



Which observables can be measured?

basics:

- CP violation relates to relative phases

$\hookrightarrow$ we are looking for interference patterns
(except if we deal with CP eigenstates — baryons are not)

[a] mesons with spin can decay electromagnetically, do not live long

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↪ need to measure sequence of decays, not just one decay

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- interference pattern in hyperon decays driven by relative phase between partial waves

$\hookrightarrow$ no extra suppression for some observables ("T-odd")

Partial waves, relative phases, and FSI

- interested in CP violation = T violation (CPT theorem)

Partial waves, relative phases, and FSI

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$\hookrightarrow$ but we cannot easily reverse decay processes
(resonance formation in weak scattering processes)

$\hookrightarrow$ look for P violating decays and compare baryons and antibaryons

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example: non-leptonic decay $B \to b\,\pi$

1. discuss initial process
(at hadron level where short-distance process is not resolved)
2. switch on final-state interactions (assume elastic for simplicity)

Partial waves, relative phases, ~~and FSI~~

effective Lagrangian for initial processes $B \to b\,\pi$ and $\bar{B} \to \bar{b}\,\pi^\dagger$

$$\mathcal{L} = |s| e^{i\xi_{\rm CPV}}\, i\bar{b}B\pi^\dagger - |s| e^{-i\xi_{\rm CPV}}\, i\bar{B}b\,\pi - p\,\bar{b}i\gamma_5 B\pi^\dagger - p\,\bar{B}i\gamma_5 b\,\pi$$

- needs to be hermitian

$\hookrightarrow$ only phases, no size difference
between particles and antiparticles for couplings s or p

- one overall phase is for free

$\hookrightarrow$ choose $p \in \mathbb{R}^+$

$\hookrightarrow$ have pushed relative phase into parity violating s-wave

(N. Salone et al., Phys.Rev.D 105 (2022) 11, 116022)

Partial waves, relative phases, ~~and FSI~~

effective Lagrangian for initial process $B \to b\,\pi$

$$\begin{aligned}\mathcal{L} &= |s|e^{i\xi_{\rm CPV}}\, i\bar{b}B\pi^\dagger - |s|e^{-i\xi_{\rm CPV}}\, i\bar{B}b\,\pi - p\,\bar{b}i\gamma_5 B\pi^\dagger - p\,\bar{B}i\gamma_5 b\,\pi \\ &= s_{\rm part}\, i\bar{b}B\pi^\dagger + s_{\rm anti}\, i\bar{B}b\,\pi - p\,\bar{b}i\gamma_5 B\pi^\dagger - p\,\bar{B}i\gamma_5 b\,\pi\end{aligned}$$

- p-waves are parity conserving, s-waves are parity violating
- CP conservation means: $s_{\rm part} = -s_{\rm anti} \in \mathbb{R}$

↪ CP violating phase $\xi_{\rm CPV}$:

$$s_{\rm part} = |s|\, e^{i\xi_{\rm CPV}}\,, \qquad s_{\rm anti} = -|s|\, e^{-i\xi_{\rm CPV}}$$

↪ look for interferences between s- and p-wave,
i.e. angular distributions, and compare particles to antiparticles

- but first include (strong) final-state interaction

Partial waves, relative phases, and FSI

inclusion of (C, P conserving) final-state interaction:

$$\begin{aligned} s_{\rm part} &= |s|\, e^{i\xi_{\rm CPV}}\, e^{i\delta^s_{\rm FSI}}\,, \\ s_{\rm anti} &= -|s|\, e^{-i\xi_{\rm CPV}}\, e^{i\delta^s_{\rm FSI}}\,, \\ p &= |p|\, e^{i\delta^p_{\rm FSI}} \end{aligned}$$

look for interferences between s- and p-wave:

- in principle measureable from angular distribution of decay products (relative to polarization):

$$\begin{aligned} \alpha_{\rm part/anti} &\sim {\rm Re}(p\, s^*_{\rm part/anti})\,, \\ \beta_{\rm part/anti} &\sim {\rm Im}(p\, s^*_{\rm part/anti}) \end{aligned}$$

- will contain $\xi_{\rm CPV}$ and $\Delta\delta_{\rm FSI} := \delta^p_{\rm FSI} - \delta^s_{\rm FSI}$
- typically: $\xi_{\rm CPV} \ll \Delta\delta_{\rm FSI} \ll 1$

Partial waves, relative phases, and FSI

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- what signals CP violation? (use $\xi_{\rm CPV} \ll \Delta\delta_{\rm FSI} \ll 1$)

$$
\begin{aligned}
\alpha_{\rm part} + \alpha_{\rm anti} &\sim \tan \xi_{\rm CPV}\, \tan \Delta\delta_{\rm FSI} \\
\beta_{\rm part} + \beta_{\rm anti} &\sim \tan \xi_{\rm CPV}
\end{aligned}
$$

- what has highest sensitivity?

Partial waves, relative phases, and FSI

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- what has highest sensitivity?

↪ the former is only activated by the (small!) FSI

↪ can we get β's?

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$$\alpha_{\rm part} + \alpha_{\rm anti} \sim \tan\xi_{\rm CPV}\, \tan\Delta\delta_{\rm FSI} \qquad \text{T-even}$$
$$\beta_{\rm part} + \beta_{\rm anti} \sim \tan\xi_{\rm CPV} \qquad \text{T-odd}$$

- what has highest sensitivity?

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↪ can we get β's?

P-odd, T-even, and T-odd

- we do not look at formation instead of decay

$\hookrightarrow$ what is meaning of "T-even" and "T-odd" in the context of decays?

- P flip:
  (energy,momentum) $\rightarrow$ (energy,$-$momentum);
  polarization $\rightarrow$ $+$polarization
- formal T operation:
  (energy,momentum) $\rightarrow$ (energy,$-$momentum);
  polarization $\rightarrow$ $-$polarization

$\hookrightarrow$ without proof: both α and β are P-odd (parity violating), α is T-even, β is T-odd

(G. Valencia, AIP Conf.Proc. 531 (2000) 1, 45-68)

P-odd, T-even, and T-odd — continued

- consider decay $B \to b\,\pi$
  with four-momenta q_B and q_b and polarizations P_B and P_b
- Feynman amplitudes can only depend on Lorentz invariant quantities

$\hookrightarrow$ only non-trivial combinations are

$$q_b \cdot P_B \,, \qquad q_B \cdot P_b \,, \qquad \epsilon_{\mu\nu\alpha\beta}\, q_B^\mu\, q_b^\nu\, P_B^\alpha\, P_b^\beta$$

- all are odd under P
- but only the last combination is odd under T

$\hookrightarrow$ all quantities qualify for P tests
(and CP if one compares particles and antiparticles)

$\hookrightarrow$ but only last combination appears together with
T-odd CP-test variables

$\hookrightarrow$ requires determination of both polarizations P_B, P_b,
i.e. of the initial **and** of the final state

P-odd and T-odd

need an $\epsilon_{\mu\nu\alpha\beta}$ for T-odd CP test (e.g. for $\beta_{\rm part} + \beta_{\rm anti}$)

[b] necessary but not sufficient requirement

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$\hookrightarrow$ use instead angular distributions, i.e. one has only four-vectors

$\hookrightarrow$ requires at least[b] 5 external states, e.g. a four-body decay

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need an $\epsilon_{\mu\nu\alpha\beta}$ for T-odd CP test (e.g. for $\beta_{\rm part} + \beta_{\rm anti}$)

$\hookrightarrow$ suppose initial polarization not achieved by magnetic field, final polarization not measured by Stern-Gerlach apparatus

$\hookrightarrow$ use instead angular distributions, i.e. one has only four-vectors

$\hookrightarrow$ requires at least[b] 5 external states, e.g. a four-body decay (or sequence of two-body decays)

examples:

- BESIII: $J/\psi \to \Xi\,\bar{\Xi}$ with subsequent $\Xi \to \Lambda\pi$ and $\Lambda \to p\pi$

$\hookrightarrow$ five external states: J/ψ, $\bar{\Xi}$, p, and two π

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- LHCb type: $B_b \to B_c\pi$ with subsequent $B_c \to B_s\pi$ and $B_s \to b\pi$

$\hookrightarrow$ five external states: B_b, b and three pions

(P.Adlarson, A.Kupść, Phys.Rev.D 100 (2019) 11, 114005)

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Which observables can be calculated?

available techniques:

- scale separation between flavor-changing process (S), quark rearrangement (M), final-state interactions (L)
- short-distance process (S): operator product expansion

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- advantages, disadvantages?
- qualitative understanding, semi-quantitative guiding, quantitative model-independent calculations

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- purpose of concrete predictions for CP violation:
  guidance for experiments which observables are most promising

Key questions

- Which data can help to improve theory calculations?
- Which theory calculations can help in guiding experimental searches for CP violation in baryon decays?

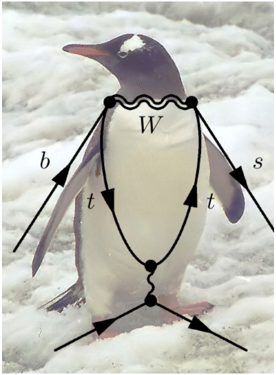
questions towards lattice calculations as the first-principle method:

- what is feasible for baryons? (now?, in near future?)
    - form factors?
    - four-quark operators?
    - six-quark operators?
- for which flavors?

Spare slides

SPARE SLIDES

A penguin and its diagram



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