Interpreting CP Violation in Hadronic Heavy Meson Decays

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Interpretation of CPV

Interpreting CPV inherently difficult:

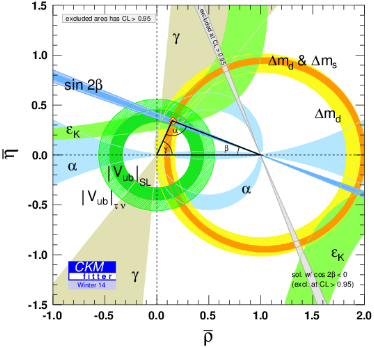
- Different phenomenological sources [Talks by Tagir + Marco]
  - ➥ CPV in mixing, decay and interference
- Each can receive contributions in the SM and from NP

Methods:

- SM null tests
  ($e.g.$ $A^{\rm dir}_{J/\Psi K_S} = 0$)
- "Simple" SM predictions
  ($e.g.$ $S_{J/\Psi K_S} = -\sin 2\beta$)
  - ➥ consistency checks $\Longrightarrow$

➥ SM flavour sector established

➥ "Small" NP influence



Subleading SM contributions important

Extracting weak phases in hadronic decays

UT angles extracted from non-leptonic decays

➥ Hadronic matrix elements (MEs) main theoretical difficulty!

Options:

- Lattice: not yet feasible for (most) three-meson MEs
- Other non-perturbative methods: idem, precision
- QCDF/SCET: applicability, power corrections
- Symmetry methods: limited applicability or precision

➥ New/improved methods necessary!

UT angles extracted by avoiding direct calculation of MEs

➥ Revisit approximations for precision analyses

Here: Improve SU(3) analysis
Applications: $B \to J/\Psi P$, $B \to DD$, $D \to PP$

Flavour SU(3) and its breaking

SU(3) flavour symmetry ($m_u = m_d = m_s$)...

- does not allow to calculate MEs, but relates them (WE theorem)
- provides a model-independent approach
- allows to determine MEs from data
  ➥ improves "automatically"!
- includes final state interactions

flavour octet

SU(3) breaking...

- is sizable, $\mathcal{O}(20 - 30\%)$
- can systematically be included: tensor (octet) $\sim m_s$
  [Savage'91,Gronau et al.'95,Grinstein/Lebed'96,Hinchliffe/Kaeding'96]
  ➥ even to arbitrary orders [Grinstein/Lebed'96]

Main questions:

- How large is the SU(3)-expansion parameter?
- Is the number of reduced MEs tractable?

Power counting

SU(3) breaking typically $\mathcal{O}(30\%)$

Several other suppression mechanisms involved:

- CKM structure (λ, but also $R_u \sim 1/3$)
- Topologial suppression: penguins and annihilation
- $1/N_C$ counting

All these effects should be considered!

➥ Combined power counting in $\delta \sim 30\%$ for all effects

➥ Neglect/Constrain only multiply suppressed contributions

Yields predictive frameworks with weaker assumptions!

- Uses full set of observables for related decays
- Assumptions can be checked within the analysis

$B \to J/\psi M$ decays - basics

$B_d \to J/\psi K$, $B_s \to J/\psi\phi$:

- Amplitude $A = \lambda_{cs} A_c + \lambda_{us} A_u$
- Clearly dominated by A_c [Bigi/Sanda '81]
- Very clear experimental signature
- Subleading terms:
  - Doubly Cabibbo suppressed
  - Penguin suppressed
  - ➥ Estimates $|\lambda_{us} A_u|/|\lambda_{cs} A_c| \lesssim 10^{-3}$ [Boos et al.'03, Li/Mishima '04, Gronau/Rosner '09]

The golden modes of B physics: $|S| = \sin\phi$

However:

- Quantitative calculation still unfeasible
- Fantastic precision expected at LHC and Belle II

➥ Subleading contributions should be controlled:
Apparent phase $\tilde{\phi} = \phi_{\rm SM}^{\rm mix} + \Delta\phi_{\rm NP}^{\rm mix} + \Delta\phi_{\rm pen}$

Including $|A_u| \neq 0$ – Penguin Pollution

$$A_u \neq 0 \;\Rightarrow\; S \neq \sin\phi,\;\; A_{\rm CP}^{\rm dir} \neq 0$$

Idea: U-spin-related modes constrain A_u [Fleischer'99, Ciuchini et al.'05,'11, Faller/Fleischer/MJ/Mannel'09, ...]

- Increased relative penguin influence in $b \to d$
- Extract $\phi = \phi_{\rm SM}^{\rm mix} + \Delta\phi_{\rm NP}^{\rm mix}$ and $\Delta\phi_{\rm pen}$
- Issue: Dependence of $\Delta\phi_{\rm pen}$ on SU(3) breaking

Using full SU(3) analysis: [MJ'12]

➥ Determines model-independently SU(3) breaking: $\lesssim 20\%$

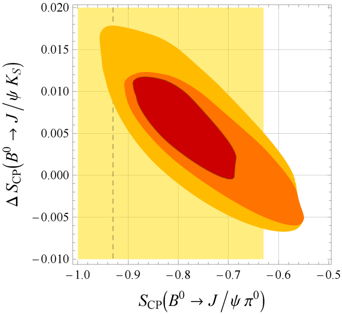
Improved extraction of $\phi_d (\to \Delta\phi_{\rm NP}^{\rm mix})$ and $\Delta\phi_{\rm pen}$!

Remaining weaker approximations:

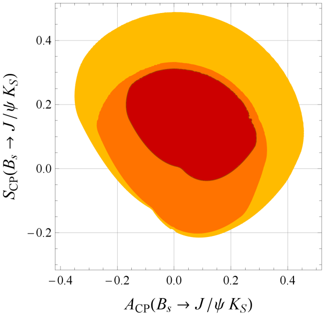
- SU(3) breaking for A_c, only
- EWPs with $\Delta I = 1, 3/2$ neglected (tiny!)
- $A(B_s \to J/\Psi\pi^0) = 0$: testable (extremely challenging)

Results for $B \to J/\Psi P$

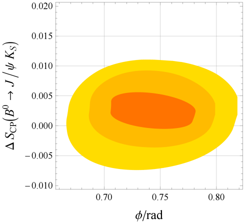
Indirect CP asymmetries



Predictions for $B_s \to J/\Psi K$



- Fit prediction for $S(B \to J/\Psi\pi)$ shifted
- $\Delta S \lesssim 0.01$, further reducible →
- γ not accessible (RI, later)
- $BR(B^- \to J/\Psi\pi^-)/BR(B^- \to J/\Psi K^-)$: LHCb



Red/Orange: 68/95% CL, $r_{SU(3)} \leq 40\%$, $r_{\rm pen} \leq 50\%$.
Yellow: 95% CL, $r_{SU(3)} \leq 60\%$, $r_{\rm pen} \leq 75\%$

$B \to DD$ decays [MJ/Schacht '14, in prep.]

$B_s \to D_s^+ D_s^-$ theoretically golden mode
➥ Clean extraction of ϕ_s w/o angular analysis!

Furthermore:

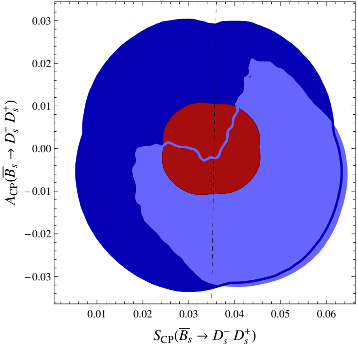
- Quasi-isospin rules for rates, test $\Delta I = 1, 3/2$ NP
- Access to ϕ_d as well ($B^0 \to D^+ D^-$, less clean)
- Sensitivity to annihilation

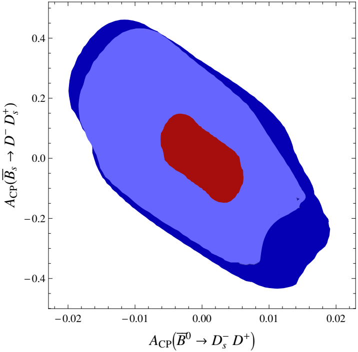
Aspects of the analysis:

- Similar to $B \to J/\Psi K$, A_u highly suppressed
- Larger rates, but experimentally more difficult
  ➥ Recent LHCb results render analysis possible
- Singlet final states have to be included $\to$ more MEs
- Extraction of γ not feasible because of RI
- Exp. issue: $A_{\rm CP}(t)(B^0 \to D^+ D^-)$ Belle/BaBar
- Assumptions: SU(3) breaking only in A_c, other terms included (theoretically restricted)

Preliminary results [MJ/Schacht '14, in prep.]

Predictions for unmeasured CP asymmetries from other data!





Red: expected PC. Blue: enhanced penguins (dark BaBar, light WA)

- Outside red: large penguins or NP. Outside blue: NP.
- Any sizable CPV in $b \to s$ transitions: NP
- Measurements like $A_{CP}(\bar{B}_s \to D^- D_s^+)$ influential
- Not discussed: rates provide access to isospin-breaking NP

Reparametrization invariance and NP sensitivity

$$\mathcal{A} = \mathcal{N}(1 + r\, e^{i\phi_s} e^{i\,\phi_w}) \to \tilde{\mathcal{N}}(1 + \tilde{r}\, e^{i\tilde{\phi}_s} e^{i\tilde{\phi}_w})$$

Reparametrization invariance:

[London et al.'99,Botella et al.'05,Feldmann/MJ/Mannel'08]

Transformation changes weak phase, but not form of amplitude

- ➥ Sensitivity to (subleading) weak phase lost (presence visible)
  - $\phi_w = \gamma$ in given analyses
  - Usually broken by including symmetry partners
    - ➥ Proposals to extract γ in $B \to J/\Psi P$ or $B \to DD$
  - However: partially restored when including SU(3) breaking!

    [MJ/Schacht'14 in prep.]
    - ➥ Reason for large range for γ observed in [Gronau et al.'08]
    - ➥ Extracted phase fully dependent on SU(3) treatment
- ➥ NP phases in $\mathcal{A}$ not directly visible
- ➥ NP tests remain possible (as shown)
- ➥ Addition of new terms, e.g. $A_c^{\Delta I=1}$ additional option

Direct CPV in D decays

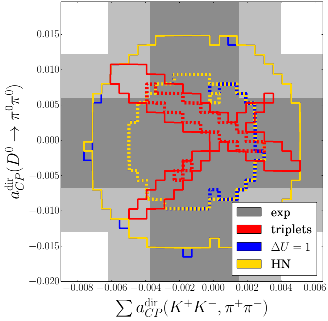
CPV in charm and beauty decays very different [Talk by Marko Staric]

- Extremely small $\sim |V_{cb} V_{ub}^*|/|V_{cs} V_{us}^*| \sim 2 \times 10^{-3}$
- Additionally: penguin suppression
  - ➡ again unknown, discussion after first LHCb announcement
- Idea: test specific SM SU(3) structure [Hiller/MJ/Schacht'13]

➡ SU(3) breaking $(30 - 40\%)$ for whole multiplet - not trivial!

➡ New data: more correlations visible [Hiller/MJ/Schacht'14, in prep.]

- With new data from LHCb and Belle [Marco's talk this morning]
- Red: SM. Blue/Yellow: NP models
  - ➡ Differentiable!
- Dynamical input $\to$ stronger constraints [Hiller/MJ/Schacht'14, in prep.]



Conclusions

- Smallness of NP poses new challenges to CPV interpretation
- SU(3) with breaking enables model-independent analyses
- Combined power counting of small effects necessary

- Controlling penguins is necessary for very high precision
- Possible for ϕ_d by $B \to J/\psi P$ $|\Delta S| \lesssim 0.01$ (95% CL)
  correct treatment of $SU(3)$ breaking essential
  ➥ BR measurements important!
- Results will improve with coming data, penguins tamed

- $B_s \to D_s^+ D_s^-$ theoretically golden mode
  ➥ Extraction of ϕ_s w/o angular analysis
- Predictions for CPV observables from global $B \to DD$ analysis
- Various NP tests from CPV and quasi-isospin rules

- Direct CP violation in charm remains exciting
- First unbiased, comprehensive analysis of $D \to PP$
- Description possible with reasonable $SU(3)$ breaking

➥ More data will help to distinguish different scenarios


Thank You!

Experimental data for $B \to J/\Psi P$

Decay	$BR/10^{-4}$	$A_{\rm CP}/\%$	$S_{\rm CP}$
$\bar{B}^0 \to J/\psi \bar{K}^0$	8.71 ± 0.32	1.0 ± 1.2	0.673 ± 0.016
$\bar{B}^0 \to J/\psi \pi^0$	0.176 ± 0.016	10 ± 13	-0.93 ± 0.29
$B^- \to J/\psi K^-$	10.13 ± 0.34	0.1 ± 0.7	—
$B^- \to J/\psi \pi^-$	0.50 ± 0.04	1 ± 7	—
set 2 (LHCb)	0.39 ± 0.02	0.5 ± 2.9	—
$\bar{B}^s \to J/\psi K^0$	0.34 ± 0.05		