# CP Violation in Heavy Meson Systems

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DFG Deutsche Forschungsgemeinschaft

LIO International Conference on Flavour, Composite Higgs and Dark Matter

24th of November 2015, IPNL, Lyon, France

# Interpretation of CPV

Interpreting CPV inherently difficult:

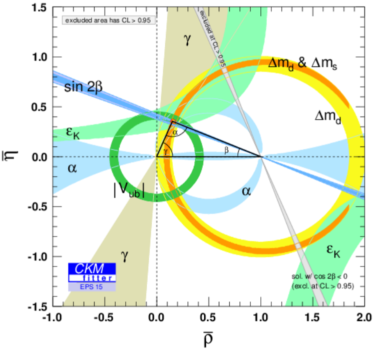
- Different phenomenological sources [see Yasmine's talk]
  - ➥ CPV in mixing, decay and interference.
- Each can receive contributions in the SM and from NP

Methods:

- Identify SM null tests
- Find "simple" SM prediction ($e.g.$ $S = \sin 2\beta$)
  - ➥ perform consistency checks ($e.g.$ global UT fit)

➥ SM flavour sector established:

➥ "Small" NP influence

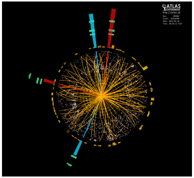



**Subleading SM contributions important**

# Consequences of the Flavour Problem

Higher precision necessary

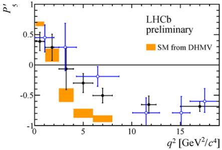
- Experimental challenge:
  Control systematics at high luminosities
- Theoretical challenge:
  Reduce hadronic uncertainties



More complex analyses, e.g.

- Inclusion of neglected contributions
- Differential distributions even for rare decays

➥ Possible due to experimental advances!




Combination of many observables

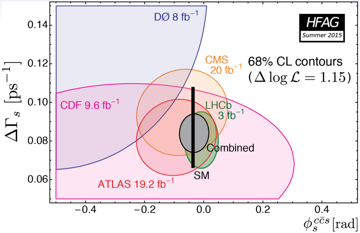
- Use more available information
- Tests of more realistic models
  ➥ Danger of higher model-dependence
- Model-independent analyses e.g. in HEFT
  ➥ Rather weak statements regarding flavour

# CPV & NP in mixing

Three parameters in $B_q$ mixing:

$$\Delta M_q \simeq 2|M_{12}^q|\,,\ \Delta\Gamma_q \simeq 2|\Gamma_{12}^q|\cos\phi_q^{12}$$

$$a_{\rm SL}^q = \frac{|\Gamma_{12}^q|}{|M_{12}^q|}\sin\phi_q^{12}$$




NP in $\Gamma_{12}$ severely constrained [Dighe et al.'10,Bauer/Dunn, Oh/Tandean, Dorsner et al., Bobeth/Haisch '11]

➥ Not considered here

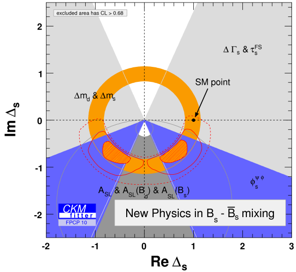
Parametrization for NP *only* in $M_{12}$: $M_{12}^q = \Delta_q M_{12}^{\rm SM}$ .

Development for $B_s$-mixing:

[Lenz et al. '10,'12, CKMfitter]

2010:

- Apparent large effects, $|\phi_s| \gg \phi_s^{\rm SM}$
- Driven by $\phi_s$ from CDF,D0 and $a_{\rm SL}$ from D0
- Both could be fitted by $\Delta_{d,s}$



# CPV & NP in mixing

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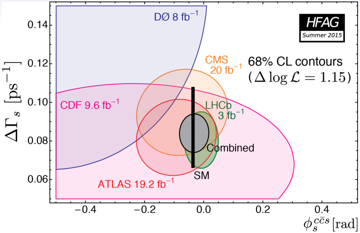


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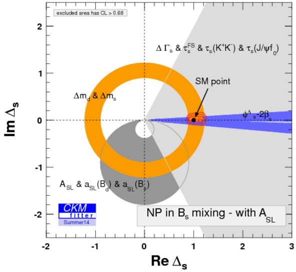
Development for $B_s$-mixing:

[Lenz et al. '10,'12, CKMfitter]

2014:

- LHC (and CDF) results fix $\phi_s$, $\Delta\Gamma$
- Best fit basically SM, large effects excluded
- $\phi_s$ and $A_{\rm SL}$ not compatible



# 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 in
$B \to J/\psi M$, $B \to DD$ & $D \to PP$

# 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 ($\lambda$, 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
- Applied here for $B \to J/\psi M$ and $B \to DD$

# $B \to J/\psi M$ 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 [but see Frings+'15]
- 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: $\sim 20\%$

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 (but to all orders for $P = \pi, K$!)
- EWPs with $\Delta I = 1, 3/2$ neglected (tiny!)
- $A(B_s \to J/\psi\pi^0) = 0$: testable (challenging)

# Digression: BR measurements and isospin violation

Again: detail due to high precision and small NP

➥ Not specific to $B \to J/\psi K^{(*)}$!

Branching ratio measurements require normalization...

- $B$ factories: depends on $\Upsilon \to B^+B^-$ vs. $B^0\bar{B}^0$
- LHCb: normalization mode, usually obtained from $B$ factories

Assumptions entering this normalization:

- PDG: assumes $r_{+0} \equiv \Gamma(\Upsilon \to B^+B^-)/\Gamma(\Upsilon \to B^0\bar{B}^0) \equiv 1$
- LHCb: assumes $f_u \equiv f_d$, uses $r_{+0}^{\mathrm{HFAG}} = 1.058 \pm 0.024$

Both approaches problematic: [MJ 1510.03423]

- Potential large isospin violation in $\Upsilon \to BB$ [Atwood/Marciano'90]
- Measurements in $r_{+0}^{\mathrm{HFAG}}$ assume isospin in exclusive decays
  - ➥ This is one thing we want to test!

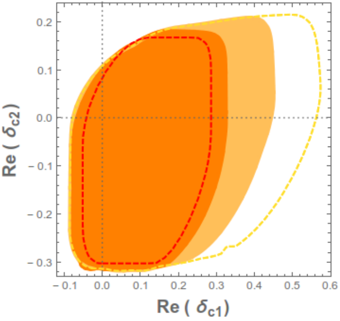
➥ Avoiding this assumption yields $r_{+0} = 1.027 \pm 0.037$

➥ Isospin asymmetry $B \to J/\psi K$: $A_I = -0.009 \pm 0.024$

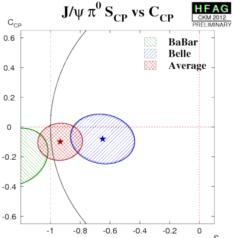
# Preliminary results for $B \to J/\psi P$ [MJ'12,Beaujean/MJ/Knegjens('15)]

**Fit to $\mathbf{B_{d,u,s} \to J/\psi(K,\pi)}$ data (including correlations)**

- PDG uncertainties applied
- Annihilation included
- SU(3) breaking $\leq 55\%$ allowed
- $P/T, A_u/T \leq (100, 55, 16, 0)\%$
- Excellent fit $(\chi^2/\mathrm{dof} \leq 1)$
- SU(3) breaking $\lesssim 30\%$
- Pen. + Ann. consistent with 0
- Issues: $R_{\pi K}$, $S_{\rm CP}(B \to J/\psi\pi^0)$




| $\lvert P, A/T\rvert$ | $\phi/^\circ$ | $\Delta\phi/^\circ(95\%)$ |
|---|---|---|
| 100% | $22.2 \pm 0.9$ | $[-0.5, 1.0]$ |
| 55% | $22.1 \pm 0.8$ | $[-0.5, 0.6]$ |
| 16% | $22.0 \pm 0.8$ | $[-0.2, 0.2]$ |




N.B.: $|\Delta\phi| \leq 0.7^\circ$ for [Frings+'15]

# Application to $B \to J/\psi V$

Differences for $B \to J/\psi V$ ($V = \phi, \omega, \rho, K^*$):

- Polarization! $\Rightarrow 3\times$ #parameters
  - ➥ but *larger* increase in measurements
- Final states with from octet *and* singlet
  - ➥ Slightly complicates $SU(3)$ analysis
  - ➥ Control modes with $K^*, \rho$ not sufficient!

Annihilation in $A_c$ is important!

- Suppression unclear for heavy final states
  - ➥ $\sim 20\%$ in $A_c(B \to DD)$ [MJ/Schacht'15]
- Determines singlet contributions in $B_s \to J/\psi\phi$
  - ➥ Penguin pollution in $B_s \to J/\psi\phi$ potentially underestimated
  - ➥ Affects $\eta - \eta'$ mixing angle from $B_{d,s} \to J/\psi\eta^{(\prime)}$

➥ Analysis in progress. . . [Beaujean/MJ/Knegjens('16)]

# $B \to DD$ decays [MJ/Schacht '14]

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

Furthermore:

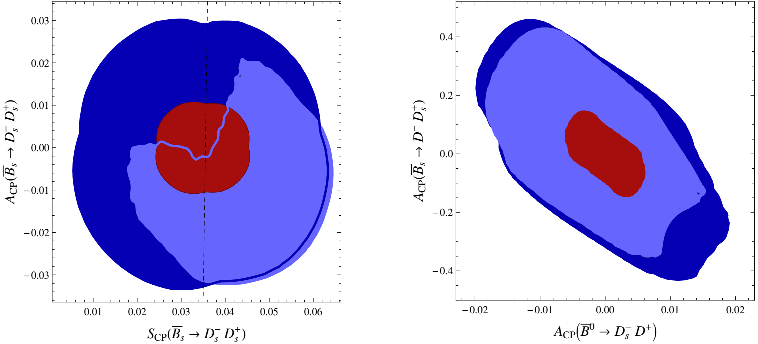
- Other correlations in $B \to DD \to$ NP searches
- Quasi-isospin rules for rates, test $\Delta I = 1, 3/2$ NP
- Learn about annihilation

Aspects of the analysis:

- Inclusion of singlets unproblematic
- Larger rates, but experimentally more difficult
  ➥ Ideas for increasing selection efficiency?
- Extraction of $\gamma$ not feasible because of RI
- Exp. issue: $A_{\mathrm{CP}}(t)(B^0 \to D^+ D^-)$ Belle vs. BaBar
- Assumptions: SU(3) breaking only in $A_c$, other terms included (theoretically restricted)

# $B \to DD$ decays: Results [MJ/Schacht '14]

Predictions for unmeasured CP asymmetries from data!

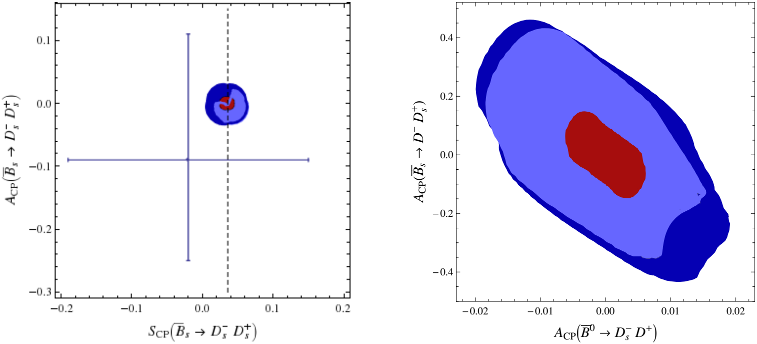



Red: expected PC. Blue: enhanced penguins (dark BaBar, light WA)

- 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

# $B \to DD$ decays: Results [MJ/Schacht '14]

Predictions for ~~unmeasured~~ CP asymmetries from data!

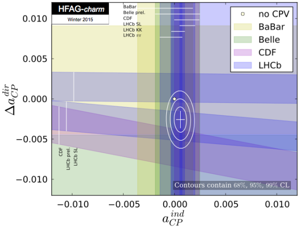



Red: expected PC. Blue: enhanced penguins (dark BaBar, light WA)

- Outside red: large penguins or NP. Outside blue: NP.
- Any sizable CPV in $b \to s$ transitions: NP
- Fit with present data! "2022": $\Delta\phi_s^{\text{pen}} \lesssim 0.6^\circ$

# CPV in $D \to PP$

Expected to be tiny ($\sim \lambda^4 \times P/T$)
$\Delta A_{CP} = A_{CP}(D \to KK) - A_{CP}(D \to \pi\pi)$
"back to normal" (both tagging methods)
Long discussion whether $\Delta A_{CP}$ is NP or not...
➥ We need more information!




What are we aiming at?

- NP or enhanced penguins - other modes should be affected
- Independent of enhancement: SM implies pattern in CPV
- Find a description of the full $D \to PP$ data, not just $\Delta A_{CP}$
  - ➥ Branching ratios and CP asymmetries, $\delta_{K\pi}$
- Find (more) discriminants between NP and SM

How are we doing this?

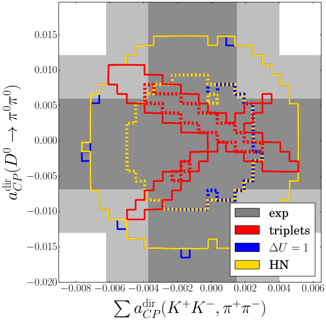
- Exact limits do not work well
  - ➥ Include corrections!

# Direct CPV in D decays

Results of the full $D \to PP$ fit:

- SU(3) breaking $(30 - 40\%)$ for whole multiplet - not trivial!
- New data: more correlations visible [Hiller/MJ/Schacht'15, in prep.]
- Red: SM. Blue/Yellow: NP models
  ➥ Differentiable!

➥ Both, BRs and CPAs are important!




A few "non-fit" possibilities:

- $A_{\rm CP}^{\rm SM}(D^- \to \pi^-\pi^0) \equiv 0$ [also Bucella et al.'93, Grossman et al.'12]
- Isospin sum rules [Grossman et al.'12]
- Enhancements for hadronic decays with suppressed rates, e.g. $D^0 \to K_S K_S$: [Atwood/Soni'13,Hiller/MJ/Schacht'13,Nierste+'15]

$$A_{CP}(D^0 \to K_S K_S) \sim \frac{1}{\epsilon} A_{CP}(D^0 \to K^+K^-)$$

# 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

- High precision $\to$ Control penguins and annihilation
  ➥ Possible for $\phi_d$ by $B \to J/\psi P$, $|\Delta\phi| \leq 0.6^\circ$ (95% CL)
- Careful interpretation of BR data necessary
- Results will improve with coming data, penguins tamed

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

- $\Delta A_{CP}$ gone, but charm remains interesting
- SM correlations can be tested in global fit, also e.g. isospin predictions

Exciting times ahead!

# Input Values for $B \to J/\psi P$ Decays: BRs

| Observable | Value | Ref./Comments |
|---|---|---|
| $\frac{1}{c_-}\mathrm{BR}(B^- \to J/\psi K^-)$ | $(10.27 \pm 0.31) \times 10^{-4}$ | |
| $\frac{1}{c_-}\mathrm{BR}(B^- \to J/\psi \pi^-)$ | $(0.38 \pm 0.07) \times 10^{-4}$ | |
| $\frac{\mathrm{BR}(B^- \to J/\psi \pi^-)}{\mathrm{BR}(B^- \to J/\psi K^-)}$ | $0.040 \pm 0.004$ | scaling factor 3.2 |
| | $0.0386 \pm 0.0013$ | Excluding BaBar |
| | $0.052 \pm 0.004$ | Excluding LHCb |
| $\frac{1}{c_0}\mathrm{BR}(\bar{B}^0 \to J/\psi \bar{K}^0)$ | $(8.73 \pm 0.32) \times 10^{-4}$ | |
| $r\,\frac{\mathrm{BR}(B^- \to J/\psi K^-)}{\mathrm{BR}(\bar{B}^0 \to J/\psi \bar{K}^0)}$ | $1.090 \pm 0.045$ | correlations neglected |
| $\frac{1}{c_0}\mathrm{BR}(\bar{B}^0 \to J/\psi \pi^0)$ | $(0.176 \pm 0.016) \times 10^{-4}$ | scaling factor 1.1 |
| $\frac{f_s}{f_d}\frac{\mathrm{BR}(\bar{B}_s \to J/\psi K_S)}{\mathrm{BR}(\bar{B}^0 \to J/\psi K_S)}$ | $0.0112 \pm 0.0006$ | $f_s/f_d = f_s/f_d\|_{\mathrm{LHCb}}$ |
| $\frac{\mathrm{BR}(\bar{B}_s \to J/\psi K_S)}{\mathrm{BR}(\bar{B}^0 \to J/\psi K_S)}$ | $0.038 \pm 0.009$ | uses $f_s/f_d = f_s/f_d\|_{\mathrm{Tev}}$ |
| $\frac{1}{c_0}\mathrm{BR}(\bar{B}^0 \to J/\psi \eta)$ | $0.123 \pm 0.019 \times 10^{-4}$ | |
| $\mathrm{BR}(\bar{B}_s \to J/\psi \eta)$ | $(5.1 \pm 1.1) \times 10^{-4}$ | |
| $R_s = \frac{\mathrm{BR}(\bar{B}_s \to J/\psi \eta')}{\mathrm{BR}(\bar{B}_s \to J/\psi \eta)}$ | $0.73 \pm 0.14$ | $\rho(BR, R_s) = -23\%$ |
| $R_s$ | $0.902 \pm 0.084$ | $\rho(R_s, R) = 1\%$ |
| $R = \frac{\mathrm{BR}(\bar{B}^0 \to J/\psi \eta')}{\mathrm{BR}(\bar{B}^0 \to J/\psi \eta)}$ | $1.11 \pm 0.48$ | $\rho(R, R_\eta) = -73\%$ |
| $\frac{f_d}{f_s} R_\eta = \frac{f_d}{f_s}\frac{\mathrm{BR}(\bar{B}^0 \to J/\psi \eta)}{\mathrm{BR}(\bar{B}_s \to J/\psi \eta)}$ | $0.072 \pm 0.024$ | $\rho(R_\eta, R_s) = 9\%$ |

# Input Values for $B \to J/\psi P$ Decays: CP Asymmetries

| Observable | Value | Ref./Comments |
|---|---|---|
| $\mathcal{A}_{\rm CP}(B^- \to J/\psi K^-)$ | $0.003 \pm 0.006$ | |
| $\mathcal{A}_{\rm CP}(B^- \to J/\psi \pi^-)$ | $0.001 \pm 0.028$ | |
| $-\eta_{\rm CP}\mathcal{S}_{\rm CP}(\bar{B}^0 \to J/\psi K_{S,L})$ | $0.687 \pm 0.019$ | |
| $\mathcal{A}_{\rm CP}(\bar{B}^0 \to J/\psi K_{S,L})$ | $0.016 \pm 0.017$ | $\rho(\mathcal{S}_{\rm CP}, \mathcal{A}_{\rm CP}) = -15\%$ |
| $\mathcal{S}_{\rm CP}(\bar{B}^0 \to J/\psi \pi^0)$ | $-0.94 \pm 0.29$ | |
| | $-0.65 \pm 0.22$ | Belle only |
| $\mathcal{A}_{\rm CP}(\bar{B}^0 \to J/\psi \pi^0)$ | $0.13 \pm 0.13$ | |
| | $0.08 \pm 0.17$ | Belle only |
| $\mathcal{S}_{\rm CP}(\bar{B}_s \to J/\psi K_S)$ | $-0.08 \pm 0.41$ | |
| $\mathcal{A}_{\rm CP}(\bar{B}_s \to J/\psi K_S)$ | $0.28 \pm 0.42$ | |
| $\mathcal{A}_{\Delta\Gamma}(\bar{B}_s \to J/\psi K_S)$ | $0.49^{+0.77}_{-0.65} \pm 0.06$ | |
| $f_s/f_d\|_{\rm LHCb}$ | $0.259 \pm 0.015$ | |
| $y_s$ | $0.0611 \pm 0.0037$ | |
| $r = f_{+-}/f_{00}$ | $1.027 \pm 0.037$ | |

Data in both tables: PDG, HFAG, LHCb, Belle, BaBar

# A word on meson mixing

Neutral singlets and octets can mix under QCD
➥ Complicates SU(3) analysis

$B \to J/\psi P$: $\eta, \eta'$ not necessary to determine $\phi_d$
$B \to J/\psi V$: $\phi$ central mode
➥ Meson mixing has to be dealt with

$N_C \to \infty$ and in the SU(3) limit: degenerate $P_{1,8}$ and $V_{1,8}$
➥ Relative size of corrections determines mixing angle
➥ Large mixing does not mean breakdown of SU(3)!

$\eta, \eta'$: large correction to $1/N_C$ from anomaly (singlet)
➥ $\eta, \eta'$ remain approximate SU(3) eigenstates
$\phi, \omega$: $1/N_C$ effects small (OZI) $\to$ SU(3) breaking dominant
➥ eigenstates according to strange content, large mixing

Only the octet part can be controlled by $K^*$ and $\rho$!
➥ Data for $\omega$ necessary to control singlet in SU(3)

# Annihilation contributions in $B \to J/\psi M$

Annihilation is important!

- Suppression unclear for heavy final states
  - ➥ $\sim 20\%$ in $A_c(B \to DD)$ [MJ/Schacht'15]
- Determines singlet contributions in $B_s \to J/\psi\phi$
- Affects extraction of $\eta - \eta'$ mixing angle from $B_{d,s} \to J/\psi\eta^{(\prime)}$
- Its neglect correlates e.g. $A_u$ in $B^- \to J/\psi\pi^-$ and $B^0 \to J/\psi K^0$' directly
  - ➥ Overly "precise" predictions for CP asymmetries

In $B \to J/\psi M$ three annihilation contributions:

- Annihilation in $A_c$, taken into account where appropriate
- Two annihilation contributions in $A_u$, $a_2 \sim a_1/N_C$
  - ➥ $a_2 \ll 1 \to BR(B_s \to J/\psi\pi^0, \rho^0) \approx 0$, $A_I(B \to J/\psi K) \approx 0$ $BR(B_s \to J/\psi\rho) \leq 3.6 \times 10^{-6}\,(90\%\mathrm{CL})$
  - ➥ No improvement from inclusion (unlike [Ligeti/Robinson'15] )
  - ➥ Only leading contribution included later

# Factorization in $B \to J/\psi M$

$B \to J/\psi M$ *formally* factorizes for $m_{c,b} \to \infty$... [BBNS'00]

➥ ...but corrections are large: $\Lambda_{\rm QCD}/(\alpha_s m_{c,b})$

$B \to J/\psi M$ *formally* factorizes for $N_C \to \infty$... [Buras+'86]

➥ ...but corrections are large: $A_c \sim C_0 v_0 + C_8(v_8 - a_8)$ [Frings+'15]
Non-factorizable $a_8, v_8 \sim v_0/N_C$, but $C_8 \sim 17 C_0$!

$BR(B \to J/\psi M)$ remains uncalculable
N.B.: No reason to assume $F_{B\to K}/F_{B\to\pi}$ for $SU(3)$ breaking

Factorization for $P/T$: [Frings+'15]

- $\mathcal{A}(B \to J/\psi M) = \lambda_{cs} A_c + \lambda_{us} A_u$, $A_u$ "penguin pollution"

➥ $A_u \sim p + a$, includes penguin and annihilation contributions
No annihilation in $B_d \to J/\psi K$, but in $B_s \to J/\psi \phi$

- $p = \sum_j \langle J/\psi M | \mathcal{O}_j^u | B \rangle = \sum_k \langle J/\psi M | \mathcal{O}_k^c | B \rangle + \mathcal{O}(\Lambda/m_{J/\psi})$
- Estimating $\langle J/\psi M | \mathcal{O}_k^c | B \rangle$ in $1/N_C$ yields $\Delta\phi_{d,s}|_p \lesssim 1^\circ$

# 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]

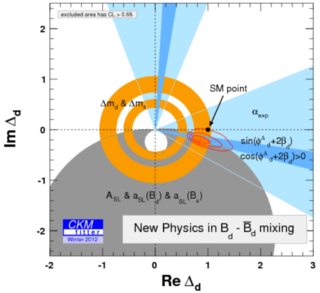
Transformation changes weak phase, but not form of amplitude

- ➜ Sensitivity to (subleading) weak phase lost (presence visible)
  - $\phi_w = \gamma$ in given analyses
  - Usually broken by including symmetry partners
    - ➜ Proposals to extract $\gamma$ in $B \to J/\psi P$ or $B \to DD$
  - However: partially restored when including SU(3) breaking! [MJ/Schacht'14]
    - ➜ Reason for large range for $\gamma$ 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
- ➜ Addition of new terms, e.g. $A_c^{\Delta I=1}$ additional option

# NP in mixing II

Less change in $B_d$ mixing, 2012 results: [Lenz et al. '12]

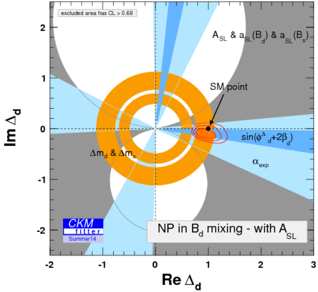
- $a_{\mathrm{SL}}$ marginally compatible
- p-value $\Delta_d = 1$ (SM): $3\sigma$
- However: Largely due to $B \to \tau\nu$
  - ➥ Not a mixing observable



# NP in mixing II

2014 results (incl. $B \to \tau\nu_{\mathrm{Belle}}$): [CKMfitter]

- $a_{\mathrm{SL}}^d$ compatible (new measurements agree with SM)
- p-value $\Delta_d = 1$ (SM): $1.2\sigma$



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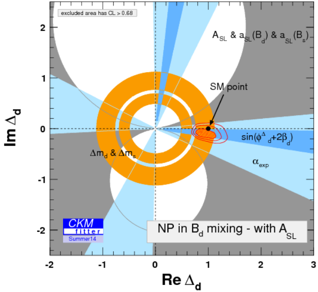


Alltogether:

- Worse fit than 2010 with only NP in $M_{12}$
- Semileptonic asymmetry in conflict with $\phi_{d,s}$
  - ➥ Independent check important!
- Additional NP in $\Gamma_{12}^q$ possible, but difficult
- Interpretation of $\Delta \sin 2\beta$ as NP in mixing challenged

# Quasi-isospin relations in $B \to D^{(*)}D$

Observation: $\mathcal{H}_c$ is basically an SU(3) triplet [Lipkin/Sanda'88]

- Quasi-isospin relations for $\mathcal{A}_c$ in $b \to d$ and $b \to s$ decays [Sanda/Xing'97,Gronau et al.'05,'08]
- Can be extended to include penguins! [MJ/Schacht'14]

$$
\begin{aligned}
\mathcal{A}_{\bar{B}^0 \to D_s^- D^+} &= \mathcal{A}_{B^- \to D_s^- D^0} + \mathcal{O}(\delta^5)\,,\\
\mathcal{A}_{\bar{B}_s \to D^- D^+} &= -\mathcal{A}_{\bar{B}_s \to \bar{D}^0 D^0} + \mathcal{O}(\delta^6)\,, \quad \text{and}\\
\mathcal{A}_{B^- \to D^- D^0} &= \mathcal{A}_{\bar{B}^0 \to D^- D^+} + \mathcal{A}_{\bar{B}^0 \to \bar{D}^0 D^0} + \mathcal{O}(\delta^3)\,.
\end{aligned}
$$

- Unaffected by SU(3) breaking!
- $b \to s$ rules yield penguin-independent precision predictions!
- $b \to d$ rule tests annihilation and yields correlations

$$
\begin{aligned}
\mathrm{BR}_{B^- \to D_s^- D^0} &= r_{\tau,\mathrm{PS}}\, \mathrm{BR}_{\bar{B}^0 \to D_s^- D^+} \left(1 + \mathcal{O}(\delta^5)\right)\,,\\
\mathrm{BR}_{\bar{B}_s \to \bar{D}^0 D^0} &= \mathrm{BR}_{\bar{B}_s \to D^- D^+} \left(1 + \mathcal{O}(\delta^4)\right)\,,\\
\mathrm{BR}_{\bar{B}^0 \to D^- D^+} &= \tilde{r}_{\tau,\mathrm{PS}}\, \mathrm{BR}_{B^- \to D^- D^0} \left(1 + \mathcal{O}(\delta^2)\right)\,.
\end{aligned}
$$

# Confronting quasi-isospin relations with data

$$\frac{\mathrm{BR}_{B^-\to D_s^- D^0}}{\mathrm{BR}_{\bar{B}^0\to D_s^- D^+}} - r_{\tau,\mathrm{PS}} \overset{LHCb}{=} 0.14 \pm 0.07 \overset{SM}{=} \mathcal{O}(\delta^5) \lesssim 0.004$$

- $\sim 2\sigma$ tension
- Confirmation of CV would imply NP with $\Delta I = 1$!

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\mathrm{BR}_{\bar{B}_s \to D^- D^+} &\overset{LHCb}{=} (0.27 \pm 0.05) \times 10^{-3}\,.
\end{aligned}$$

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$$\frac{\mathrm{BR}_{B^- \to D_s^{*-} D^0}}{\mathrm{BR}_{\bar{B}^0 \to D_s^{*-} D^+}} \Bigg/ \frac{\mathrm{BR}_{B^- \to D_s^- D^{*0}}}{\mathrm{BR}_{\bar{B}^0 \to D_s^- D^{*+}}} - \tilde{r}_{\tau,\mathrm{PS}} \overset{SM}{=} \mathcal{O}(\delta^5)\,.$$

- Double-ratio independent of *e.g.* $f_u/f_d$!