Theoretical Prospects for B Physics

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Flavor Physics & CP violation 2015 – FPCP 2015
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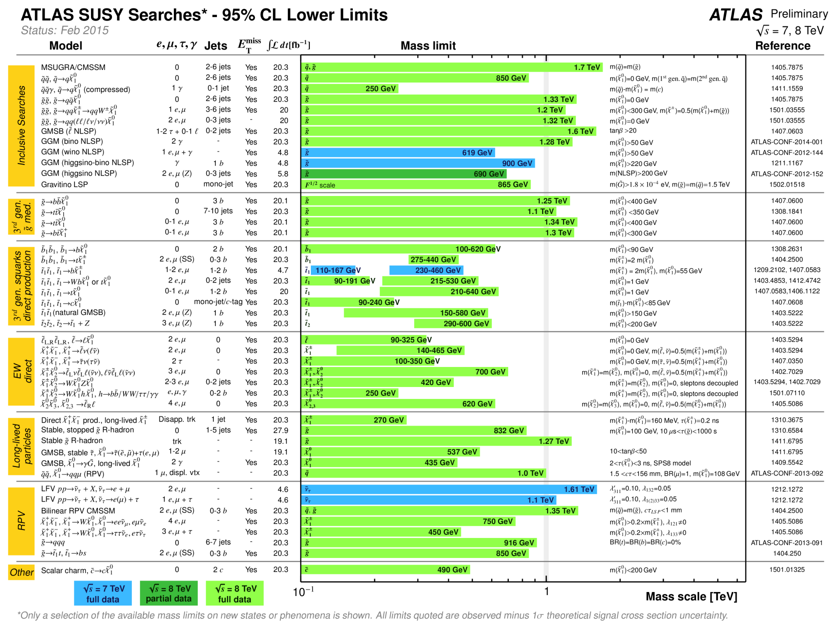
- Setting the Stage
- Theoretical Framework
- Studies of CP Violation
- Prespectives for Rare B_s Decays
- Conclusions

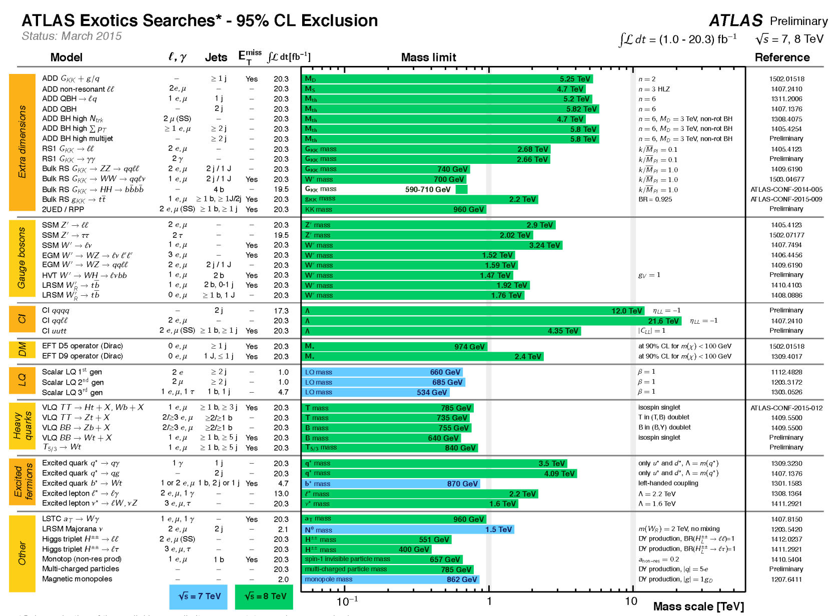
Setting the Stage

Status @ LHC High-Energy Frontier

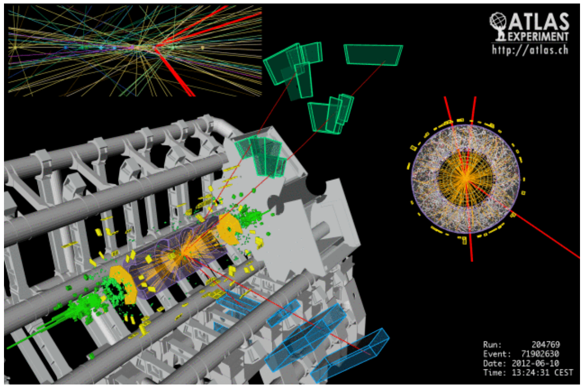
- Examples of NP searches @ ATLAS: $\rightarrow$ *no signals* (CMS similar)
  - SUSY:

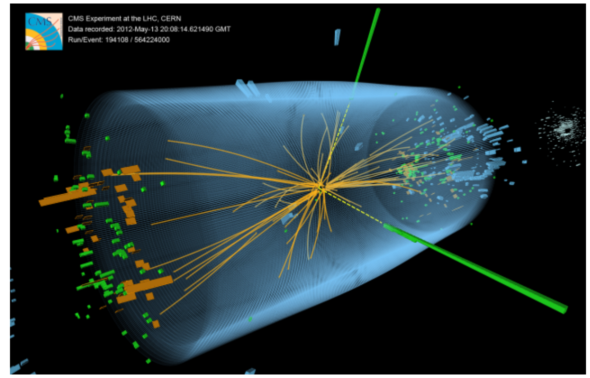


  - Exotics:

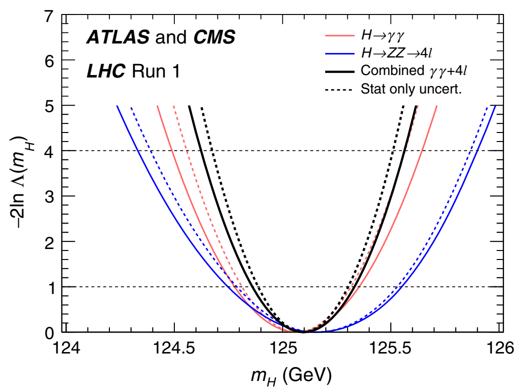


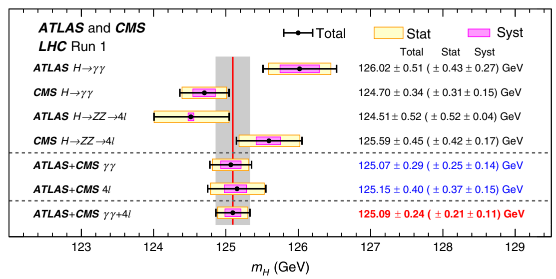
... but “Higgs-like” particle @ ATLAS and CMS

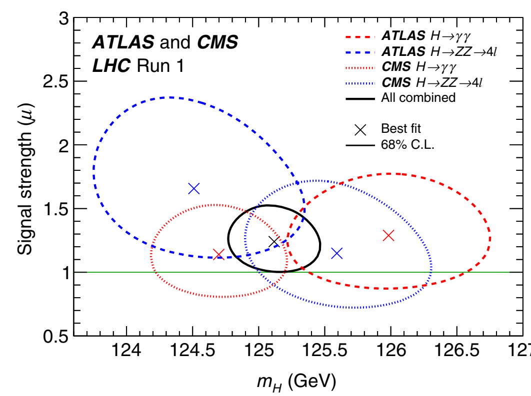




- Combined ATLAS and CMS measurement of the Higgs mass:







$$m_H = [(125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})] \text{ GeV}$$

[ATLAS & CMS Collaborations, PRL **114** (2015) 191803]

- Key question: *is the new particle really the SM Higgs particle?*

Status @ LHC High-Precision Frontier

- Flavour Physics:
  - Observables are globally very consistent with the SM picture.
  - A few "tensions" with respect to the SM have recently emerged:

    → not yet conclusive, hot topics for this conference!

- Implications for the general structure of NP:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm NP}(\varphi_{\rm NP}, g_{\rm NP}, m_{\rm NP}, ...)$$

  - Large characteristic NP scale $\Lambda_{\rm NP}$, i.e. not just $\sim$ TeV, which would be bad news for the direct searches at ATLAS and CMS, or (and?) ...
  - Symmetries prevent large NP effects in FCNCs and the flavour sector; most prominent example: *Minimal Flavour Violation (MFV)*.

- Much more is yet to come: → LHC run II, Belle II, LHCb upgrade

... but prepare to deal with "smallish/challenging" NP effects!

Theoretical Framework

Hierarchy of Scales

$$\underbrace{\Lambda_{\rm NP} \sim 10^{(0\ldots?)}\,\text{TeV} \gg \Lambda_{\rm EW} \sim 10^{-1}\,\text{TeV}}_{\text{(very) short distances}} \ggg \underbrace{\Lambda_{\rm QCD} \sim 10^{-4}\,\text{TeV}}_{\text{long distances}}$$

- Powerful theoretical concepts/techniques:

  → "Effective Field Theories"

  - Heavy degrees of freedom (NP particles, top, Z, W) are "integrated out" from appearing explicitly: → *short-distance loop functions.*
  - Calculation of *perturbative QCD corrections*.
  - *Renormalization group* allows the summation of large $\log(\mu_{\rm SD}/\mu_{\rm LD})$.

- Applied to the SM and various NP scenarios, such as the following:

  - MSSM, UED, WED, LH, LHT, Z' models, ...

[→ talks by Wolfgang Altmannshofer and Jorge Martin Camalich]

Low-Energy Effective Hamiltonians

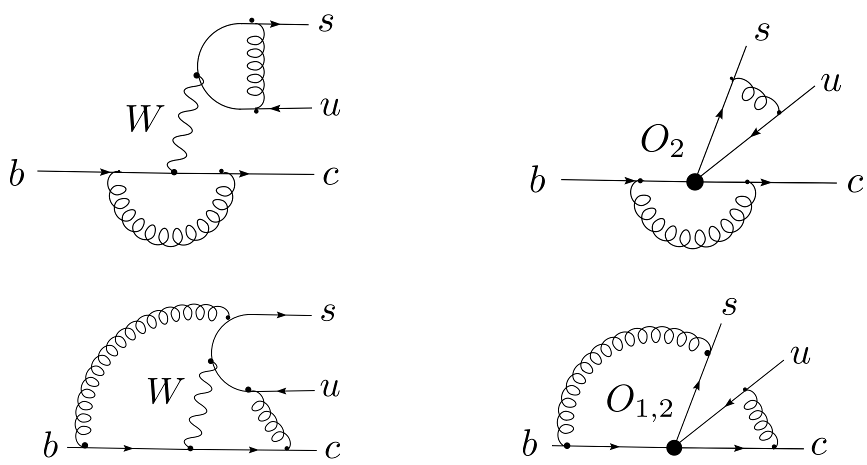
- Separation of short-distance from long-distance contributions (OPE):

$$\langle \overline{f} | \mathcal{H}_{\text{eff}} | \overline{B} \rangle = \frac{G_{\rm F}}{\sqrt{2}} \sum_j \lambda^j_{\rm CKM} \sum_k C_k(\mu) \, \langle \overline{f} | Q^j_k(\mu) | \overline{B} \rangle$$

[$G_{\rm F}$: Fermi's constant, $\lambda^j_{\rm CKM}$: CKM factors, μ: renormalization scale]

- Short-distance physics: [Buras *et al.*; Martinelli *et al.* ('90s); ...]

  $\rightarrow$ Wilson coefficients $C_k(\mu)$ $\rightarrow$ *perturbative* quantities $\rightarrow$ known!



- Long-distance physics:

  $\rightarrow$ matrix elements $\langle \overline{f} | Q^j_k(\mu) | \overline{B} \rangle$ $\rightarrow$ *non-perturbative* $\rightarrow$ "unknown" !?

Theoretical Challenges ...

- Theoretical precision is generally limited by *strong interactions*:

$$\rightarrow \boxed{\text{hadronic matrix elements}}$$

  – Non-perturbative methods of QCD needed: QCD rum rules, lattice ...

- Impressive recent progress in Lattice QCD: [→ talk by Norman Christ]

  $\Rightarrow B_K$ parameter (kaon physics), decay constants, form factors, ...:

$$\rightarrow \textit{rare } B^0_{s,d} \rightarrow \mu^+\mu^- \textit{ decays, semileptonic } B \textit{ decays.}$$

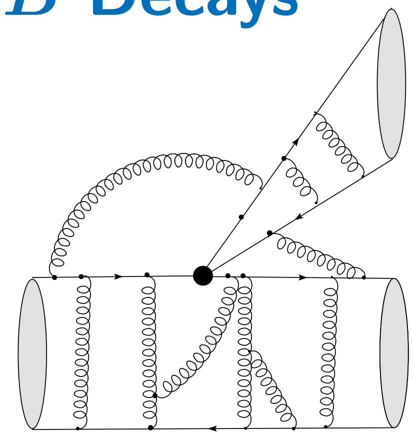
  – Flavour Lattice Averaging Group (FLAG): [→ talk by Anastassios Vladikas]

  `http://itpwiki.unibe.ch/flag/`

- However, still a big challenge for Lattice QCD:

$$\rightarrow \textit{non-leptonic } B \textit{ decays}$$

Theoretical Framework for Non-Leptonic B Decays



$$|A_j|e^{i\delta_j} \propto \sum_k \underbrace{C_k(\mu)}_{\text{pert. QCD}} \times \boxed{\langle \overline{f}|Q_k^j(\mu)|\overline{B}\rangle}$$

- QCD factorization (QCDF):

  Beneke, Buchalla, Neubert & Sachrajda (99–01); Beneke & Jäger (05); ... Bell, Bobeth, ...

- Perturbative Hard-Scattering (PQCD) Approach:

  Li & Yu ('95); Cheng, Li & Yang ('99); Keum, Li & Sanda ('00); ...

- Soft Collinear Effective Theory (SCET):

  Bauer, Pirjol & Stewart (2001); Bauer, Grinstein, Pirjol & Stewart (2003); ...

- QCD sum rules:

  Khodjamirian (2001); Khodjamirian, Mannel & Melic (2003); ...

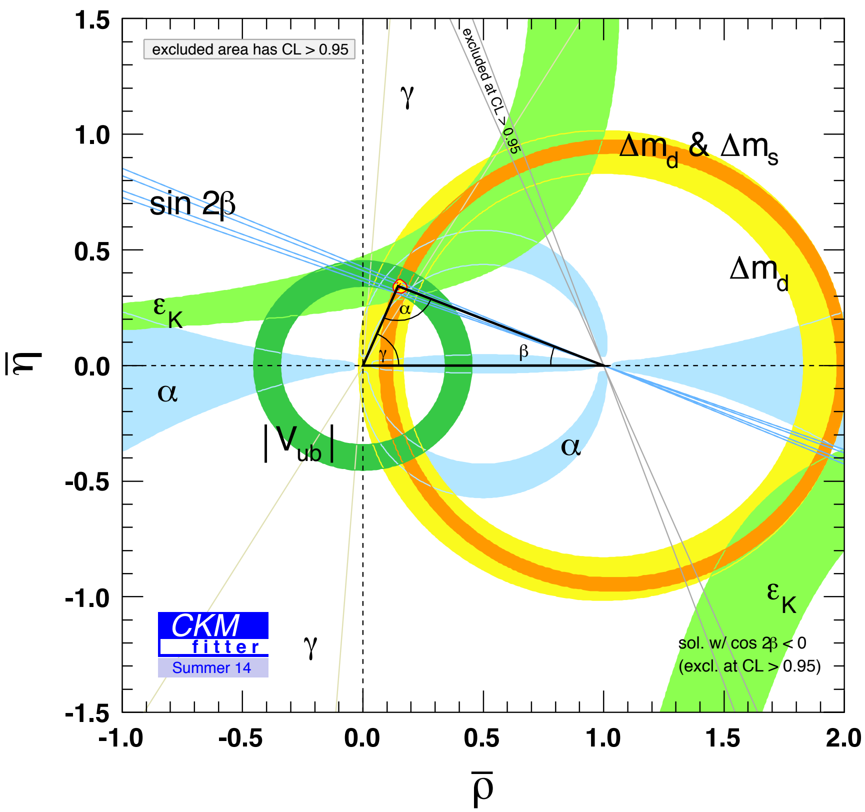
$\Rightarrow$ **Lots of (technical) progress, still a theoretical challenge**

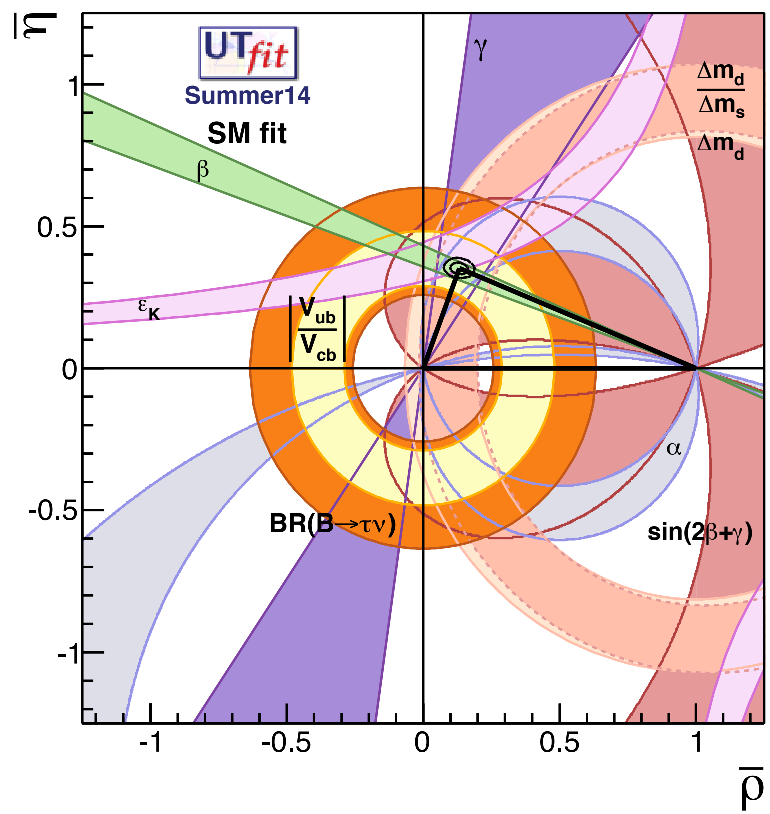
[$\longrightarrow$ talk by Rahul Sinha]

Studies of CP Violation

Unitarity Triangle

- Status of global fits: → *dictionary* $\boxed{\beta \equiv \phi_1, \quad \alpha \equiv \phi_2, \quad \gamma \equiv \phi_3}$
  - *CKMfitter* Collaboration [http://ckmfitter.in2p3.fr/];
  - *UTfit* Collaboration [http://www.utfit.org/UTfit/WebHome]:

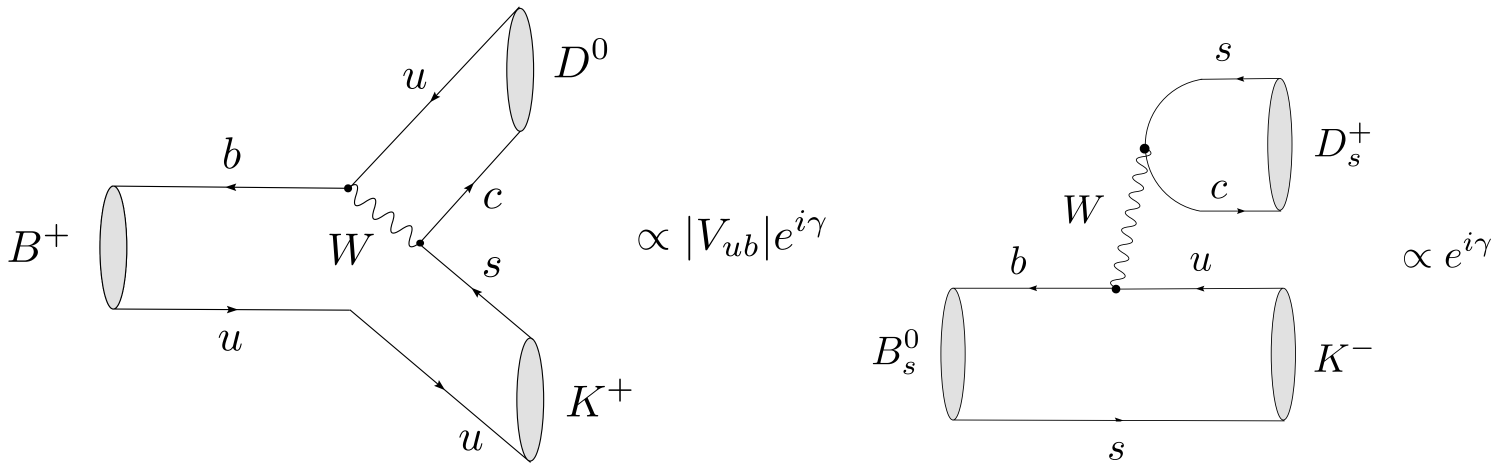




⇒ $\boxed{\gamma \text{ has currently still sizeable errors ...}}$

Prospects for Extracting γ

- Pure tree decays: $B \to D^{(*)}K^{(*)}$ and $B_s \to D_s^{\mp}K^{\pm}$



– The corresponding determinations of γ are *theoretically clean*, i.e. the hadronic matrix elements cancel out (simply speaking).

– Decays are very robust with respect to New-Physics contributions:

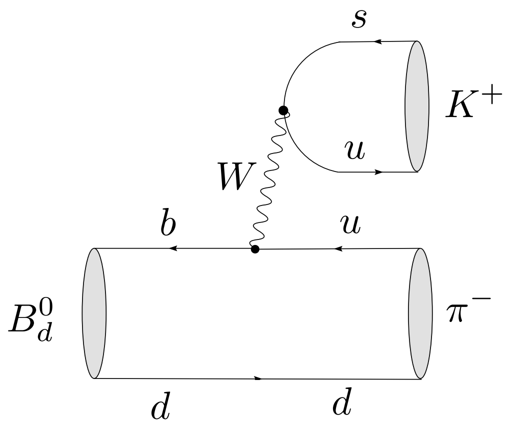
$\Rightarrow$ *reference for the "true" Standard Model value of* γ*.*

– Excellent precision for the era of Belle II and the LHCb upgrade:

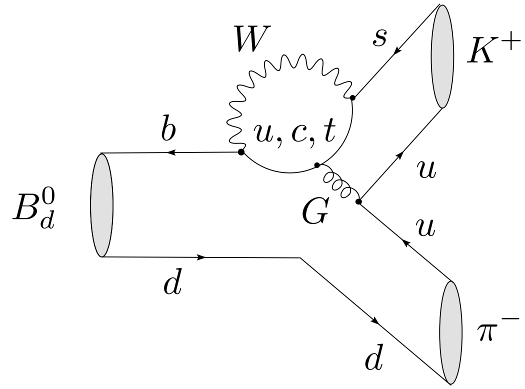
$\Rightarrow$ uncertainty of $\Delta\gamma_{\rm exp} \sim 1^\circ$ (!)

- Decays with loops, i.e. penguin contributions:

$$\boxed{B_{(s)} \to \pi\pi, \pi K, KK}$$



$\propto A\lambda^4 R_b\, e^{i\gamma}$



$\propto A\lambda^2$

  – Decay amplitude relations following from $SU(3)$ flavour symmetry.
    [Hernandez, London, Gronau & Rosner (1994–...); R.F. (1995–...); R.F. and Mannel (1997); Neubert and Rosner (1998); Buras & R.F. (1998); ...]

  – Complemented through QCD factorization/SCET/PQCD, calculations of $SU(3)$-breaking corrections, etc., [Beneke and Neubert (2003); ...]

- Goal: *extraction of* $(\gamma)_{\text{loops}}$ *and comparison with* $(\gamma)_{\text{tree}}$

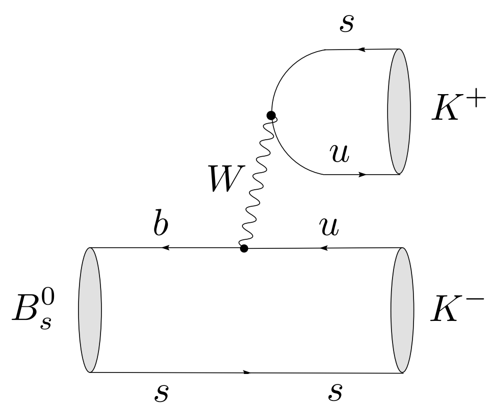
$\Rightarrow$ will discrepancies show up?

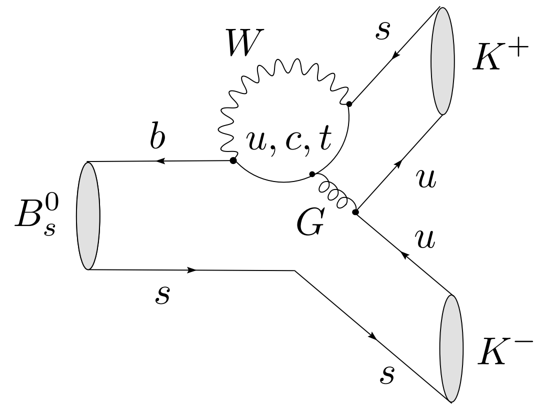
$\to$ particularly (most) promising method ...

The $B_s^0 \to K^+K^-$, $B_d^0 \to \pi^+\pi^-$ System

- $B_s^0 \to K^+K^-$:

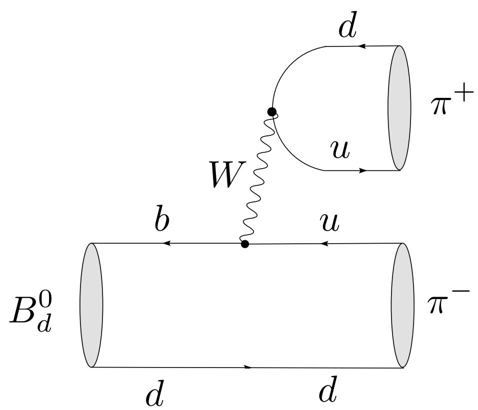
$$A(B_s^0 \to K^+K^-) \propto \mathcal{C}' \left[e^{i\gamma} + \left(\frac{1-\lambda^2}{\lambda^2} \right) d' e^{i\theta'} \right]$$

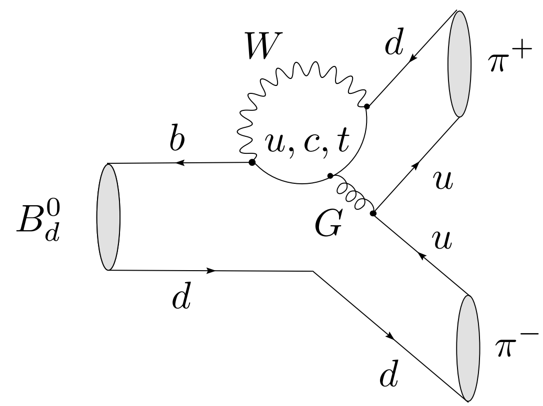




- $B_d^0 \to \pi^+\pi^-$:

$$A(B_d^0 \to \pi^+\pi^-) \propto \mathcal{C} \left[e^{i\gamma} - d\, e^{i\theta} \right]$$





$$\Rightarrow \quad \boxed{s \leftrightarrow d}$$

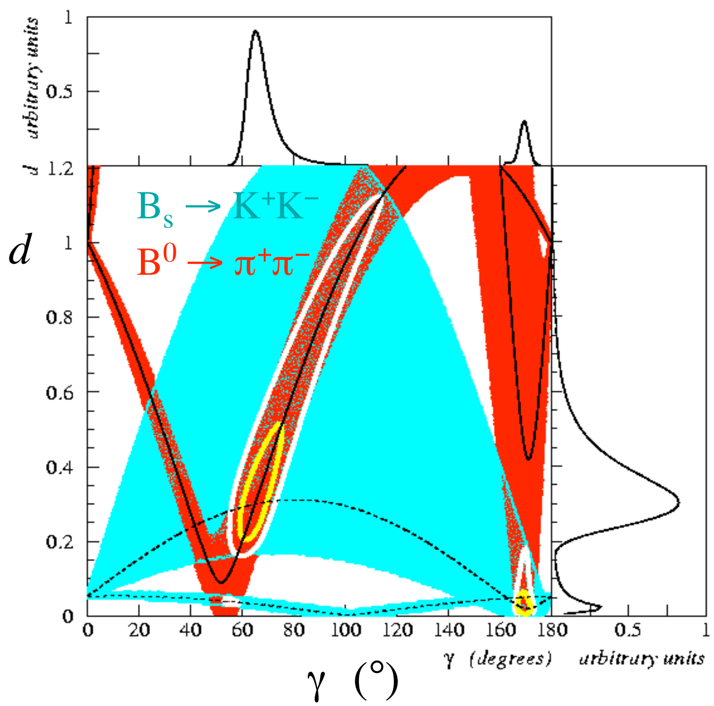
- The decays $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ are related to each other through the interchange of all down and strange quarks:

$$\boxed{U\text{-spin symmetry}} \quad \Rightarrow \quad d' = d,\ \theta' = \theta$$

  - Determination of γ and hadronic parameters $d(= d')$, θ and θ'.
  - Internal consistency check of the U-spin symmetry: $\theta \stackrel{?}{=} \theta'$.

[R.F. (1999, 2007)]

- Detailed studies show that this strategy is very promising for LHCb:

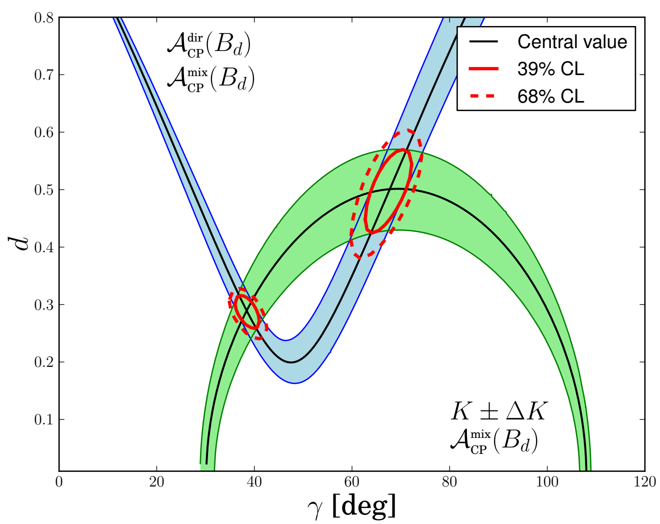


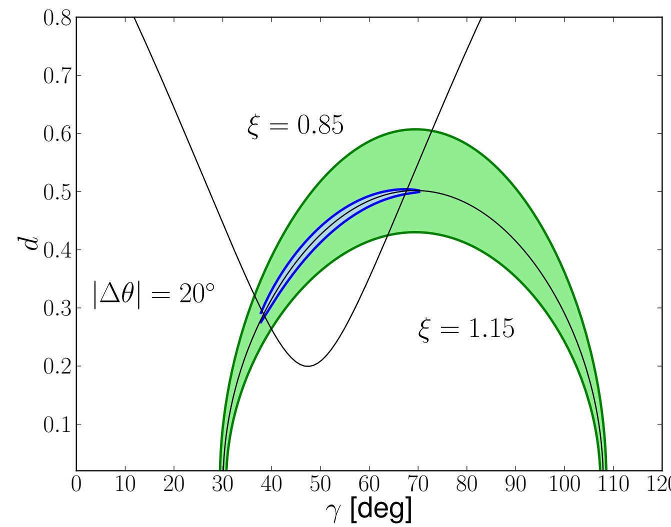
→ experimental accuracy for γ of a few degrees!

[LHCb Collaboration (B. Adeva *et al.*) LHCb-PUB-2009-029, arXiv:0912.4179v2]

Extraction of γ

- Input data:
  - Information on $K \propto \text{BR}(B_s \to K^+K^-)/\text{BR}(B_d \to \pi^+\pi^-)$;
  - CP violation in $B_d^0 \to \pi^+\pi^-$ and $B_d^0 \to \pi^\mp K^\pm$;
  - U-spin-breaking corrections: $\xi \equiv d'/d = 1 \pm 0.15$, $\Delta\theta \equiv \theta' - \theta = \pm 20^\circ$:





$$\Rightarrow \boxed{\gamma = \left(67.7^{+4.5}_{-5.0}\big|_{\rm input}{}^{+5.0}_{-3.7}\big|_{\xi}{}^{+0.1}_{-0.2}\big|_{\Delta\theta}\right)^\circ}$$

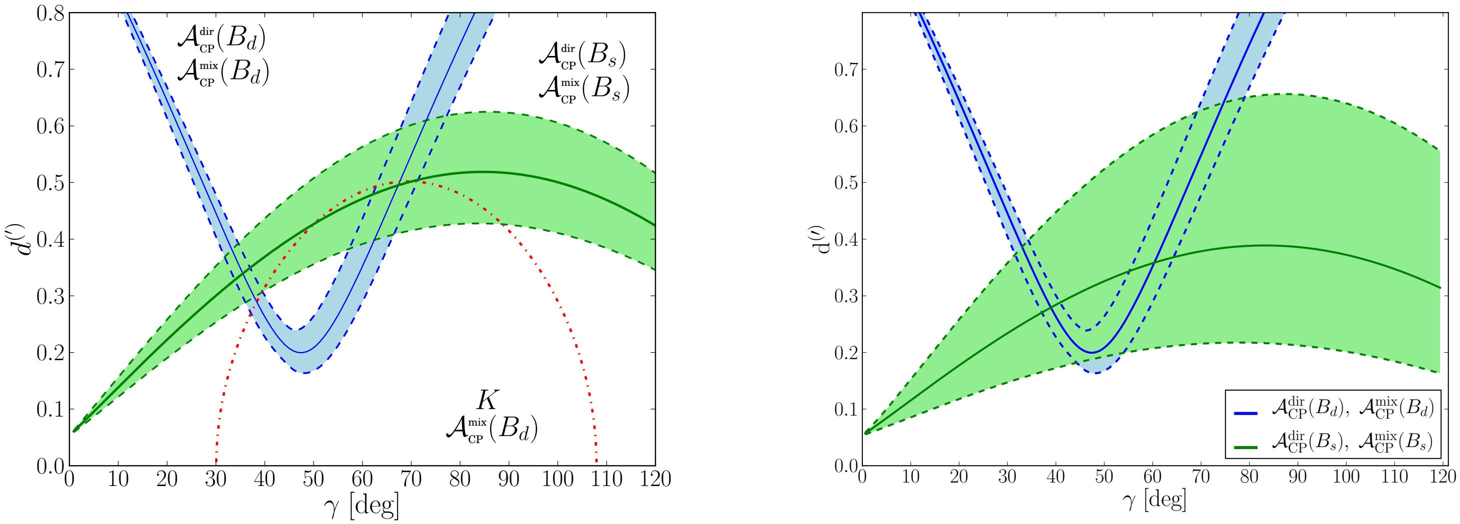
(2-fold ambiguity can be resolved [R.F. ('07)])

- "Tree-level" results: $\gamma = (73.2^{+6.3}_{-7.0})^\circ$ [CKMfitter], $(68.3 \pm 7.5)^\circ$ [UTfit].

[R.F. (2007); R.F. & R. Knegjens (2010); numerics: R. Knegjens, PhD thesis (2014)]

Prospects: "Optimal" Determination of γ

- Measurement of the CP asymmetries of $B_s^0 \to K^+K^-$:



Green bands: current SM projection | current LHCb result

- γ and the hadronic parameters $d = d'$ and θ, θ' [$\to$ U-spin test] can be determined through the intersection of two *theoretically clean* contours.

- Information on the branching ratios (form factors, etc.) is not needed, but rather provides further insights into U-spin-breaking effects.

$\Rightarrow$ **look forward to high-precision CPV measurements in $B_s^0 \to K^+K^-$**

Interesting Variant of the Method

- Combines the $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$ U-spin method (see above) with the Gronau–London isospin $B \to \pi\pi$ analysis:
  - Reduces the sensitivity to U-spin-breaking effects.
  - Provides a competitive determination of $\phi_s = -2\beta_s$.

[Ciuchini, Franco, Mishima & Silvestrini (2012)]

- Pioneering LHCb analysis: [κ parametrises U-spin-breaking effects]

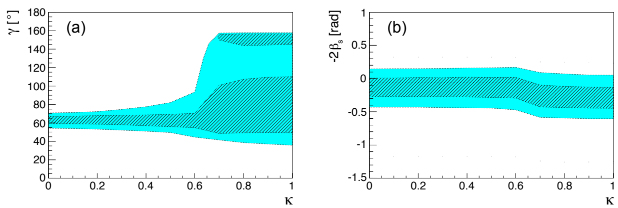


Figure 1: Dependences of the 68% (hatched areas) and 95% (filled areas) probability intervals on the allowed amount of non-factorizable U-spin breaking, for (a) γ from analysis A and (b) $-2\beta_s$ from analysis B.

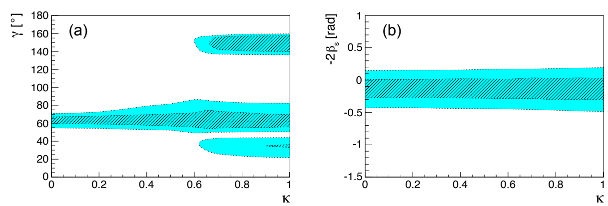


Figure 3: Dependences of the 68% (hatched areas) and 95% (filled areas) probability intervals on the allowed amount of non-factorizable U-spin breaking, for (a) γ from analysis C and (b) $-2\beta_s$ from analysis D.

$$\gamma = \left(63.5^{+7.2}_{-6.7}\right)^\circ, \quad \phi_s \equiv -2\beta_s = -\left(6.9^{+9.2}_{-8.0}\right)^\circ$$

[LHCb Collaboration, V. Vagnoni et al., arXiv:1408.4368 [hep-ex]]

Yet Another Variant ...

$\rightarrow$ *Application of the U-spin method to $B \rightarrow PPP$ decays:*

- Utilises the following decays:

$$\boxed{B^0_{d,s} \rightarrow K_{\rm S} h^+ h^- \quad (h = K, \pi)}$$

- Time-dependent Dalitz plot analyses allow the measurement of the corresponding branching ratios and CP asymmetries.

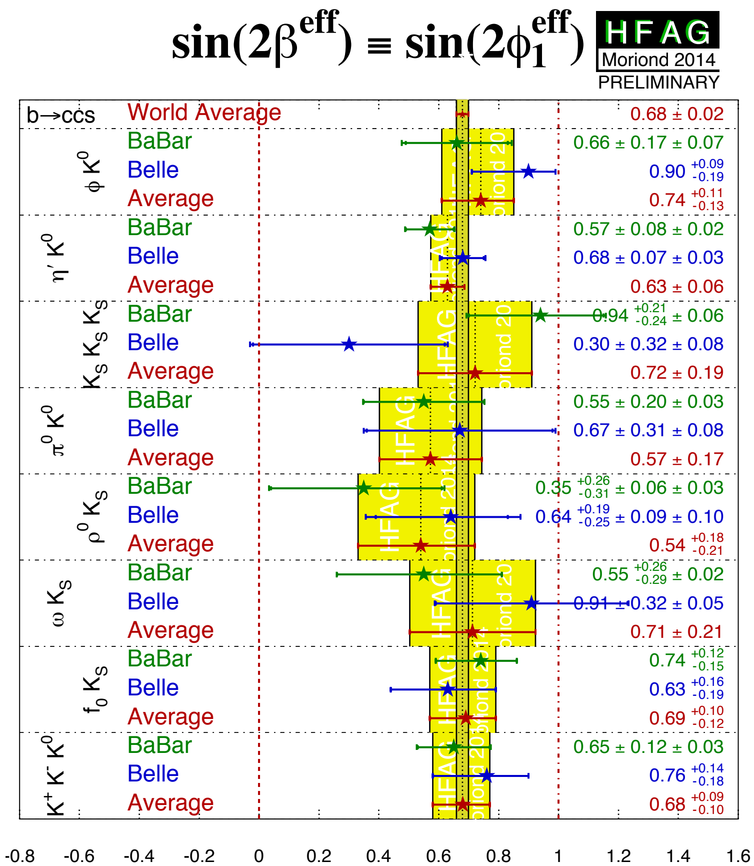
- The U-spin method – analogous to the $B^0_s \rightarrow K^+K^-$, $B^0_d \rightarrow \pi^+\pi^-$ system – to extract γ can be applied to each point of the Dalitz plot.

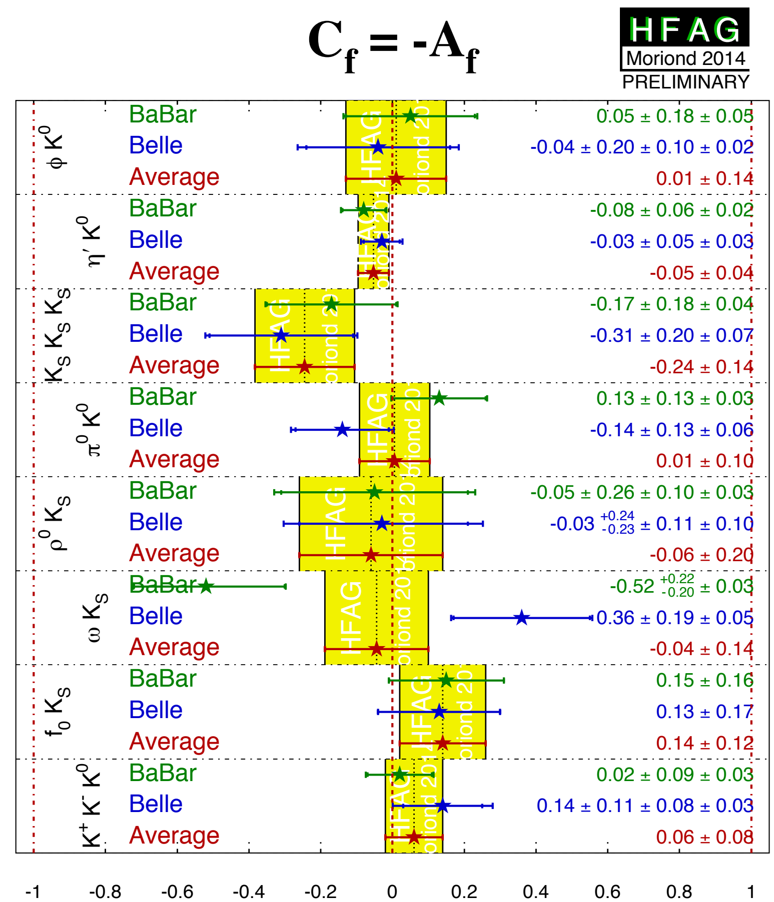
- A potential advantage of using three-body decays is that the effects of U-spin breaking may be reduced by averaging over the Dalitz plot.

[Bhattacharya & London, arXiv:1503.00737 [hep-ph]]

CP Violation in $b \to s$ Penguin-Dominated Modes

- Plenty of experimental data:





$\Rightarrow$ NP could be present, but still cannot be resolved!?

- Key problem: control hadronic uncertainties ...

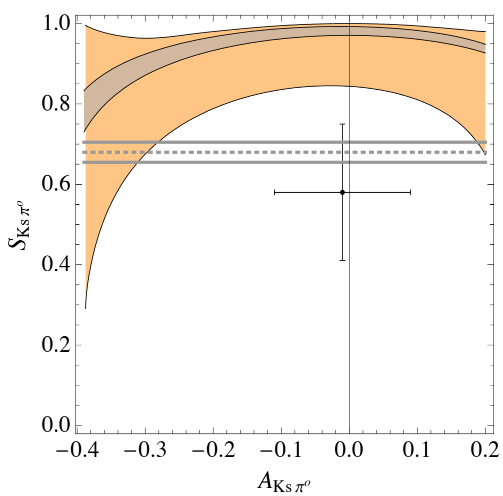
Particularly Interesting Decay: $B^0 \to \pi^0 K^0$

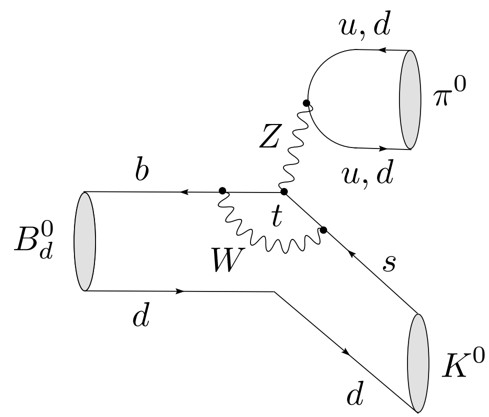
- Isospin relation between neutral $B \to \pi K$ amplitudes:

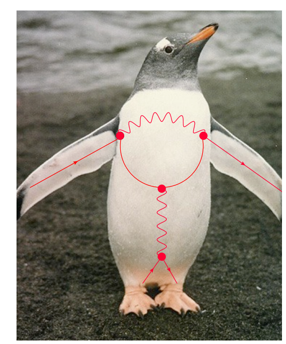
$$\sqrt{2}\,A(B^0 \to \pi^0 K^0) + A(B^0 \to \pi^- K^+) = -\underbrace{\left[(\hat{T}+\hat{C})e^{i\gamma} + \hat{P}_{\rm ew}\right]}_{(\hat{T}+\hat{C})(e^{i\gamma} - q e^{i\omega})} \equiv 3A_{3/2}$$

- Implies a correlation between the CP asymmetries:

$$\frac{\Gamma(\bar{B}^0(t) \to \pi^0 K_{\rm S}) - \Gamma(B^0(t) \to \pi^0 K_{\rm S})}{\Gamma(\bar{B}^0(t) \to \pi^0 K_{\rm S}) + \Gamma(B^0(t) \to \pi^0 K_{\rm S})}$$
$$= A_{\pi^0 K_{\rm S}} \cos(\Delta M_d\, t) + S_{\pi^0 K_{\rm S}} \sin(\Delta M_d\, t)$$



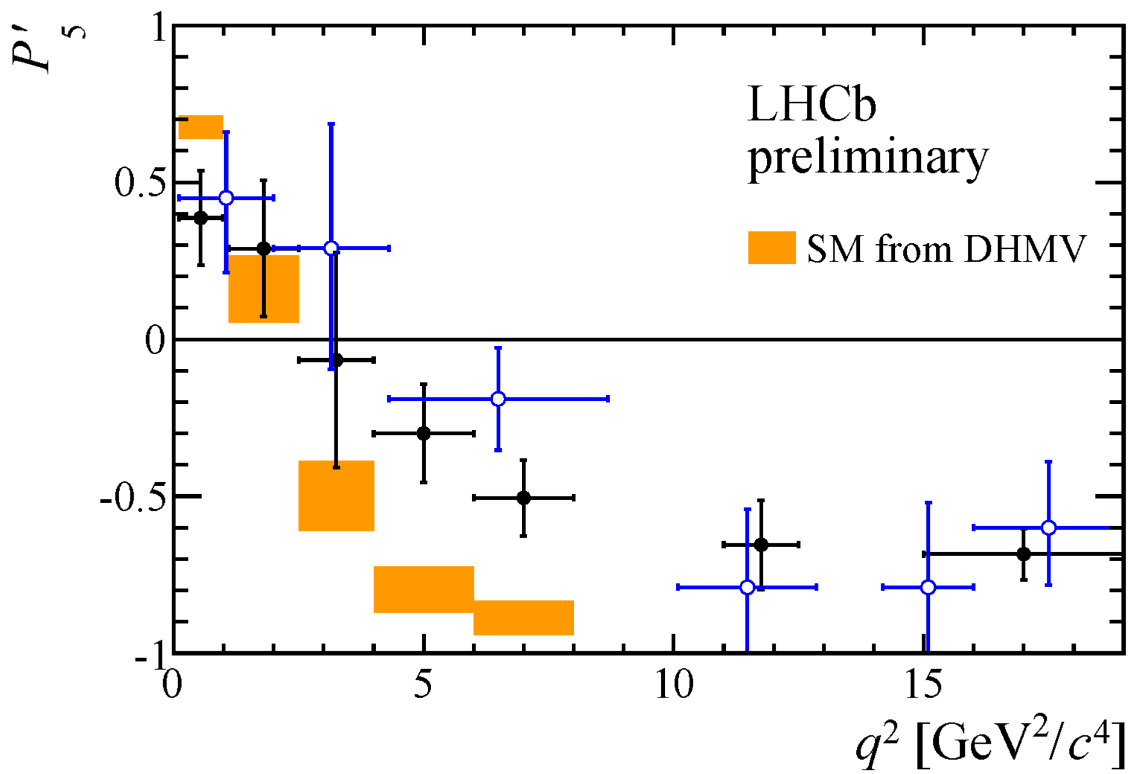


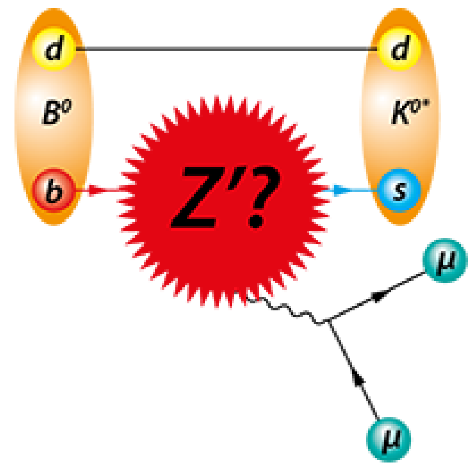


Electroweak "penguin" contribution → NP?

[R.F., S. Jäger, D. Pirjol and J. Zupan ('08); confirmed by Gronau & Rosner ('08)]

◇ Hot Topic in view of $B_d^0 \to K^{*0}\mu^+\mu^-$ @ LHCb:





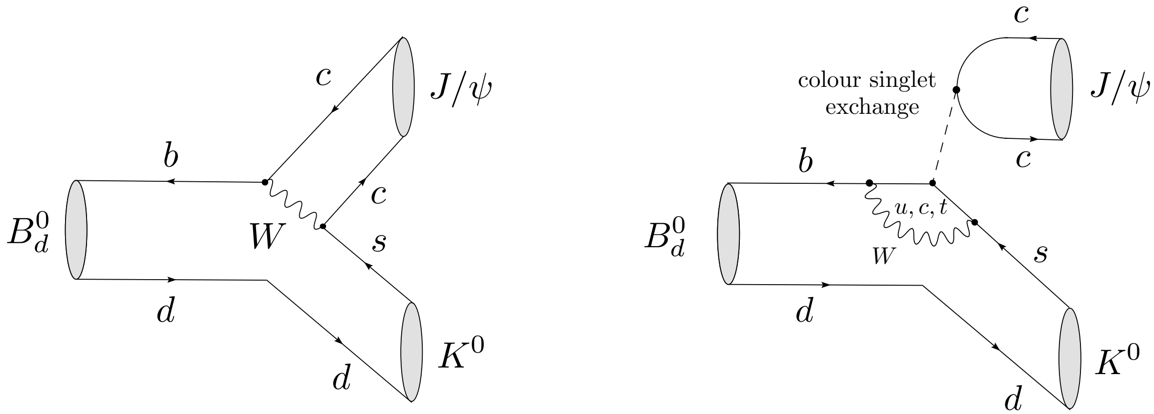
[→ talks by Wolfgang Altmannshofer & Christoph Bobeth]

- Puts also other non-leptonic B-meson decays with sensitivity to Electroweak Penguins (again...) into the spotlight:

$$B^+ \to \pi^0 K^+,\ B_s^0 \to \phi\phi,\ B_s^0 \to \pi^0\phi,\ B_s^0 \to \rho^0\phi,\ \ldots$$

Precision Measurements of the B_q^0–$\bar{B}_q^0$ Mixing Phases

CP Violation in $B_d^0 \to J/\psi K_\mathrm{S}$



- SM corrections: $\to$ *doubly Cabibbo-suppressed penguins*

$$\boxed{A(B_d^0 \to J/\psi\, K_\mathrm{S}) = \left(1-\lambda^2/2\right)\mathcal{A}'\left[1+\epsilon a' e^{i\theta'} e^{i\gamma}\right]}\quad [\epsilon \equiv \lambda^2/(1-\lambda^2) \sim 0.05]$$

- Generalized expression for mixing-induced CP violation: $[\phi_d = 2\beta + \phi_d^{\mathrm{NP}}]$

$$\frac{S(B_d \to J/\psi K_\mathrm{S})}{\sqrt{1-C(B_d \to J/\psi K_\mathrm{S})^2}} = \sin(\phi_d + \Delta\phi_d)$$

$$\begin{aligned} \sin\Delta\phi_d &\propto 2\epsilon a' \cos\theta' \sin\gamma + \epsilon^2 a'^2 \sin 2\gamma \\ \cos\Delta\phi_d &\propto 1 + 2\epsilon a' \cos\theta' \cos\gamma + \epsilon^2 a'^2 \cos 2\gamma \end{aligned}$$

[S. Faller, R.F., M. Jung & T. Mannel (2008)]

Towards High-Precision Analyses

- Era of Belle II and the LHCb upgrade

  – Experimental precision requires the control of the penguin corrections to reveal possible CP-violating NP contributions to B^0_d–$\bar{B}^0_d$ mixing.

  – The topic receives increasing interest in the theory community:

    R.F., (99); Ciuchini, Pierini & Silvestrini (05, 11); Faller, R.F., Jung & Mannel (08); Gronau & Rosner(08); De Bruyn, R.F. & Koppenburg; Jung (2012); De Bruyn & R.F. (15); Frings, Nierste & Wiebusch (15); ...

- The hadronic phase shift $\Delta\phi_d$ *cannot* be calculated in a reliable way:

$$\Rightarrow \textit{use data for } B^0_s \to J/\psi K_{\rm S}\textit{:}$$

  – Key feature: $\rightarrow$ *"magnified" penguin parameters (no ϵ suppression)*

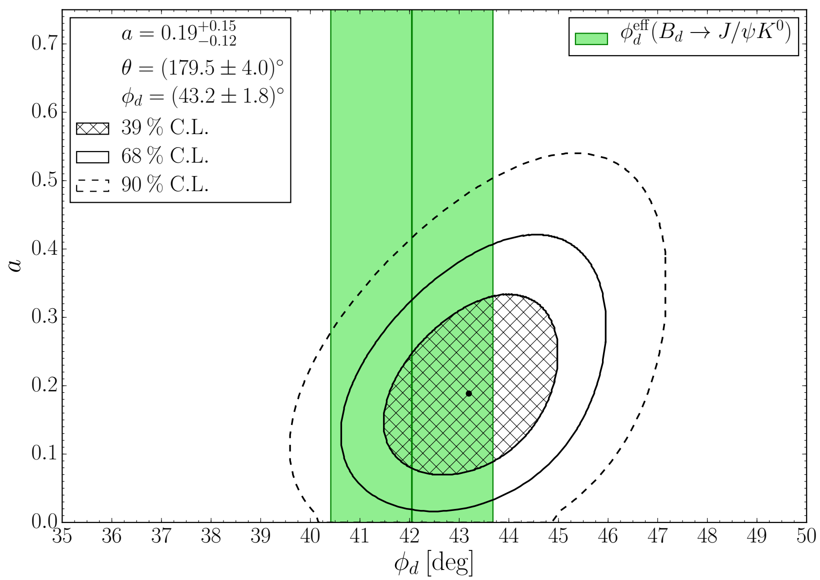
$$\boxed{A(B^0_s \to J/\psi K_{\rm S}) \propto \left[1 - a e^{i\theta} e^{i\gamma}\right]}$$

  – U-spin flavour symmetry: $\boxed{a e^{i\theta} = a' e^{i\theta'}}$

Constraints on the Penguin Parameters: χ^2 Fit

$\rightarrow$ *uses* $SU(3)$ *and currently available data on* $B \rightarrow J/\psi X$ *decays:*

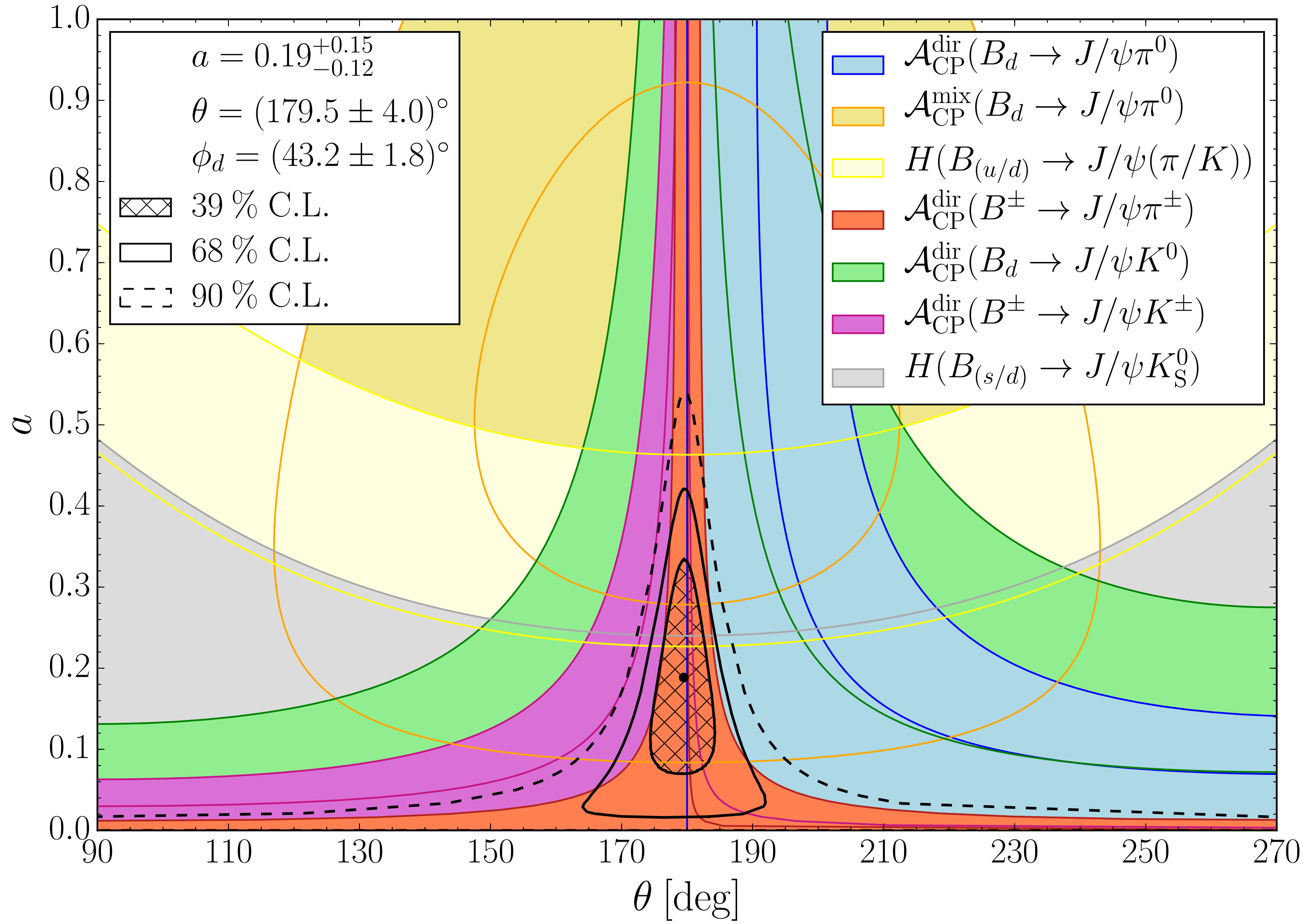
- Internal consistency checks look fine, i.e. not any "anomalous" feature.
- The global fit yields $\chi^2_{\rm min} = 2.6$ for four degrees of freedom $(a, \theta, \phi_d, \gamma)$, indicating good agreement between the different input quantities:



$$a = 0.19^{+0.15}_{-0.12}\,, \qquad \theta = (179.5 \pm 4.0)^\circ\,, \qquad \phi_d = \left(43.2^{+1.8}_{-1.7}\right)^\circ$$

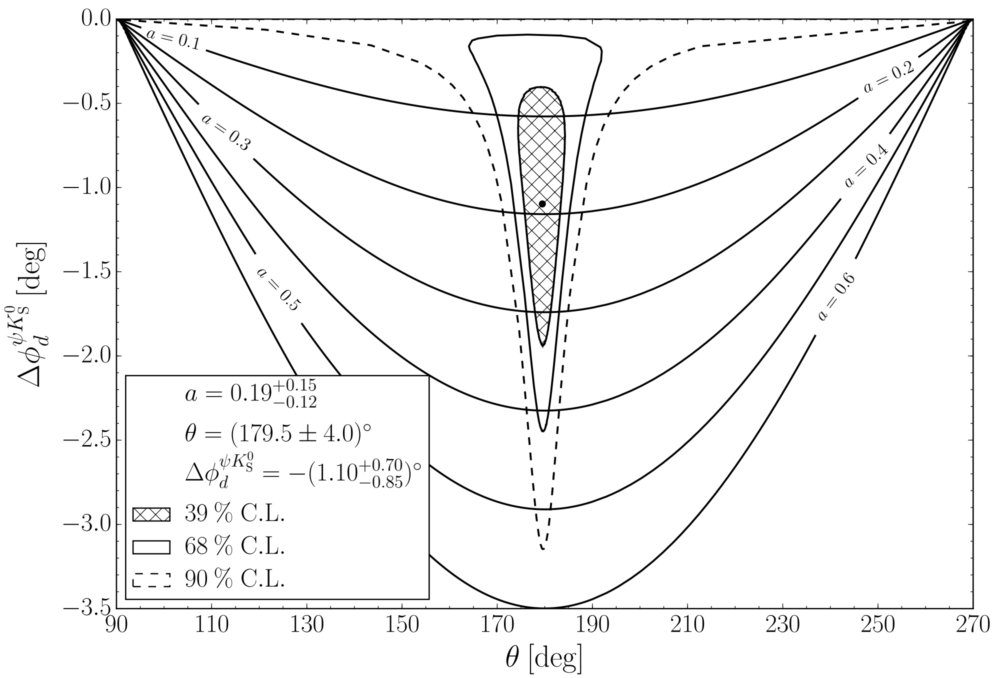
[K. De Bruyn and R.F., JHEP **1503** (2015) 145 [arXiv:1412.6834 [hep-ph]]]

- Illustration through intersecting contours for the different observables:



[K. De Bruyn and R.F., JHEP **1503** (2015) 145 [arXiv:1412.6834 [hep-ph]]]

Constraints on $\Delta\phi_d^{\psi K_S^0}$

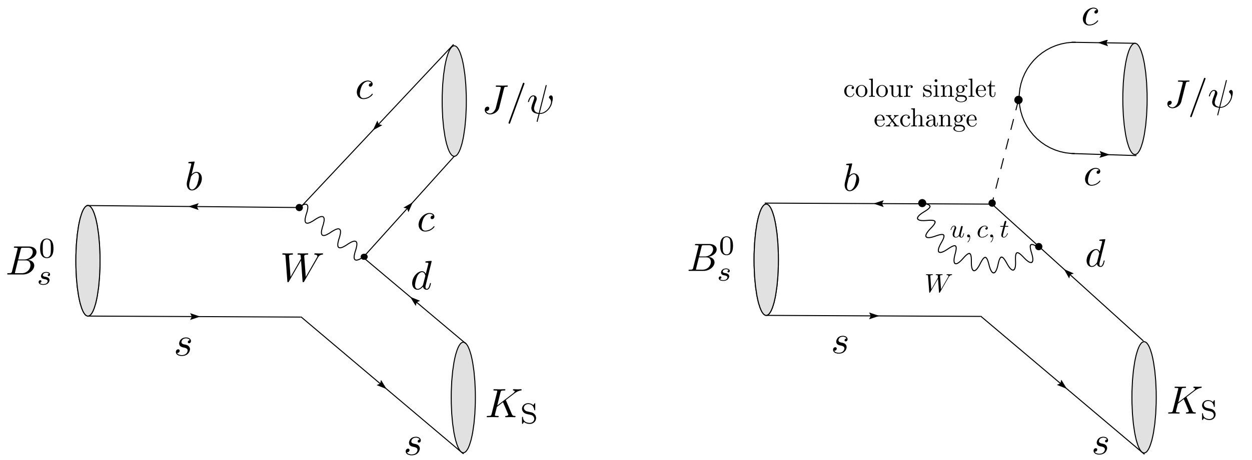


$$\Delta\phi_d^{\psi K_S^0} = -\left(1.10^{+0.70}_{-0.85}\right)^\circ$$

$\rightarrow \chi^2$ fit gives "guidance" for the importance of penguin effects.

[K. De Bruyn and R.F., JHEP **1503** (2015) 145 [arXiv:1412.6834 [hep-ph]]]

Prospects: CP Violation in $B_s^0 \to J/\psi K_S$



$$A(B_s^0 \to J/\psi\, K_S) = -\lambda\, \mathcal{A}\left[1 - a e^{i\theta} e^{i\gamma}\right]$$

- CP asymmetries allow *clean* determination of a and θ.

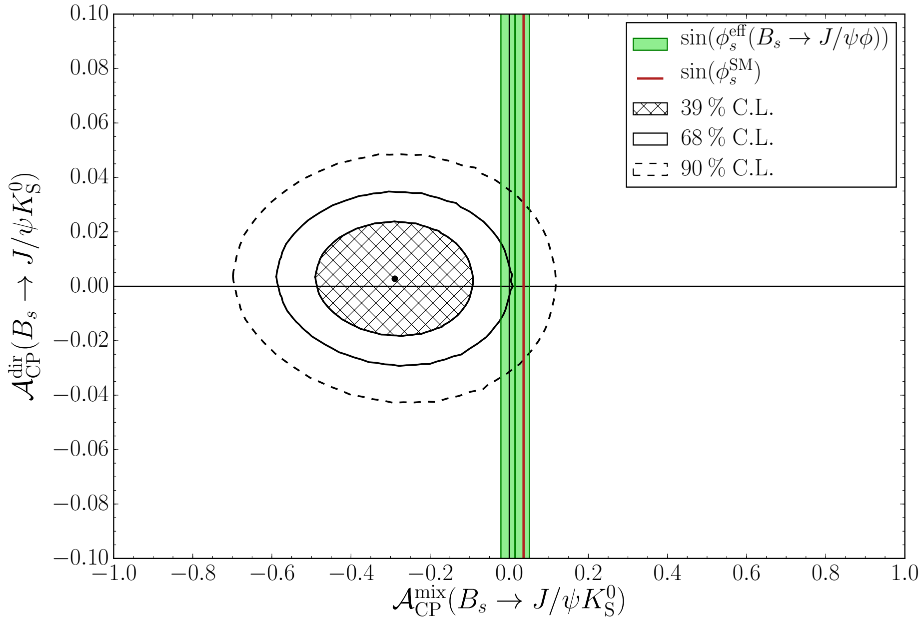
- U-spin partner of the $B_d^0 \to J/\psi K_S$ decay:

$$a e^{i\theta} \stackrel{U\,\text{spin}}{=} a' e^{i\theta'}$$ [no further dynamical assumptions (E and PA)]

- *Cleanest penguin control* for determination of ϕ_d from $B_d^0 \to J/\psi K_S$.

[R.F. (1999); De Bruyn, R.F. & Koppenburg (2010); De Bruyn & R.F. (2015)]

- Confidence contours for the CP asymmetries of $B_s^0 \to J/\psi K_S^0$ in the Standard Model following from the global χ^2 fit:



$$\begin{aligned} \mathcal{A}_{\rm CP}^{\rm dir}|_{\rm SM} &= 0.003 \pm 0.021 \\ \mathcal{A}_{\rm CP}^{\rm mix}|_{\rm SM} &= -0.29 \pm 0.20 \\ \mathcal{A}_{\Delta\Gamma}|_{\rm SM} &= 0.957 \pm 0.061 \end{aligned}$$

- Pioneering LHCb analysis: [LHCb, K. De Bruyn et al., arXiv:1503.07055 [hep-ex]]

$\to$ *first measurement of the CP asymmetries:*

$$\begin{aligned} \mathcal{A}_{\rm CP}^{\rm dir}(B_s \to J/\psi K_S^0) &= -0.28 \pm 0.41({\rm stat}) \pm 0.08({\rm syst}) \\ \mathcal{A}_{\rm CP}^{\rm mix}(B_s \to J/\psi K_S^0) &= 0.08 \pm 0.40({\rm stat}) \pm 0.08({\rm syst}) \\ \mathcal{A}_{\Delta\Gamma}(B_s \to J/\psi K_S^0) &= 0.49^{+0.77}_{-0.65}({\rm stat}) \pm 0.06({\rm syst}) \end{aligned}$$

$\star$ LHCb Upgrade Era:

$\rightarrow$ benchmark scenario for the $B^0_{d,s} \rightarrow J/\psi K^0_{\rm S}$ analysis:

- Assumes the following future measurements: [see also arXiv:1208.3355]
  - Clean γ determination from tree decays $B \to D^{(*)}K^{(*)}$: $\gamma = (70 \pm 1)^\circ$
  - ϕ_s measured from $B^0_s \to J/\psi\phi$ and penguin strategies (see below):

$$\phi_s = -\left(2.1 \pm 0.5|_{\rm exp} \pm 0.3|_{\rm theo}\right)^\circ = -(2.1 \pm 0.6)^\circ\,.$$

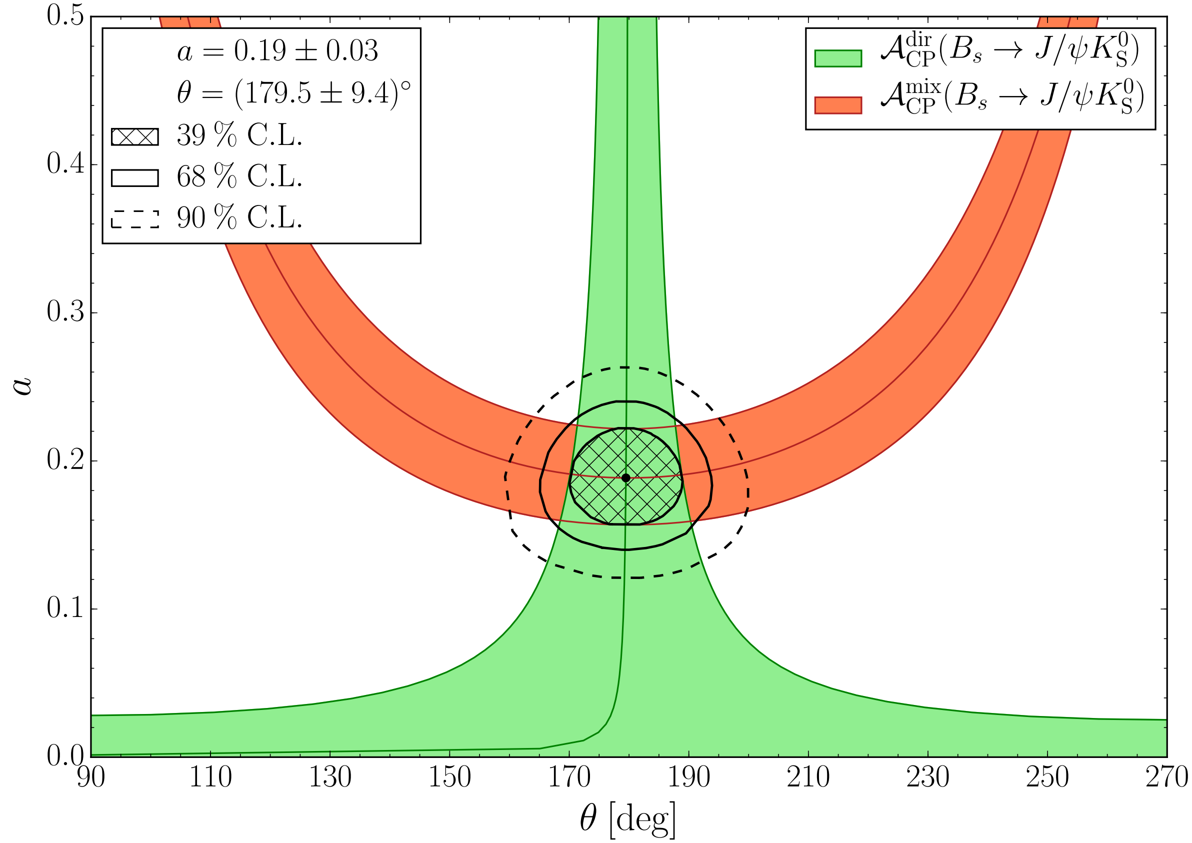
  - CP violation in the $B_s \to J/\psi K^0_{\rm S}$ decay:[1]

$$\begin{aligned} \mathcal{A}_{\rm CP}^{\rm dir}(B_s \to J/\psi K^0_{\rm S}) &= 0.00 \pm 0.05 \\ \mathcal{A}_{\rm CP}^{\rm mix}(B_s \to J/\psi K^0_{\rm S}) &= -0.28 \pm 0.05 \end{aligned}$$

[K. De Bruyn and R.F., JHEP **1503** (2015) 145 [arXiv:1412.6834 [hep-ph]]]

[1] These uncertainties were extrapolated from the current LHCb measurements of the CP violation in $B^0_s \to D^{\mp}_s K^{\pm}$ decays, corrected for the $B^0_s \to J/\psi K^0_{\rm S}$ event yield (no *official* LHCb study).

Determination of Penguin Parameters



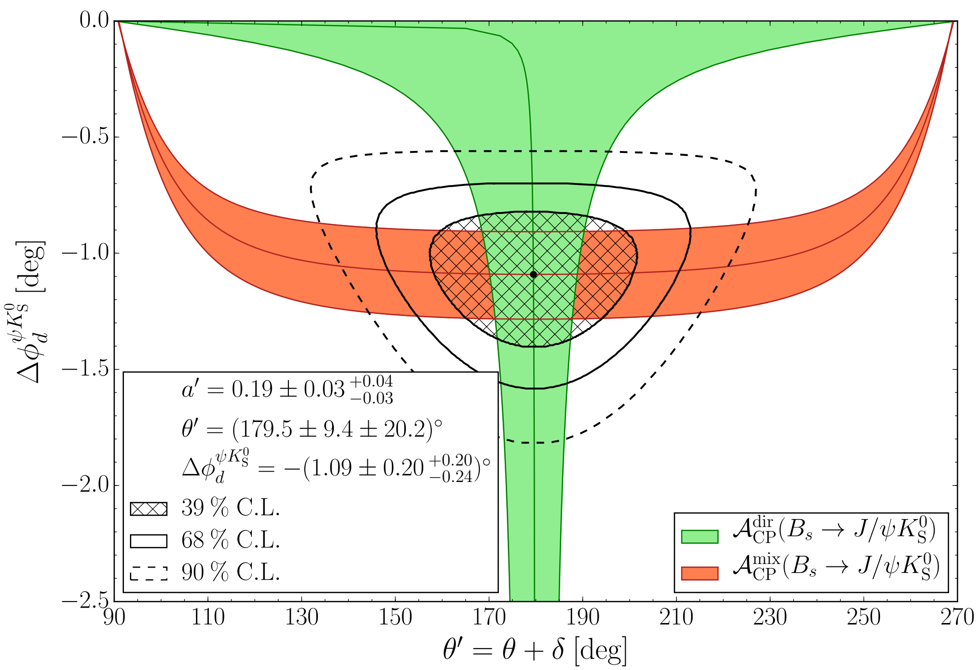
- <u>Comments:</u>
  - This determination of a and θ is *theoretically clean*.
  - Relation to a', θ' (enter $B_d \to J/\psi K_{\rm S}$) through U-spin symmetry.

... conversion into $\Delta\phi_d$

- <u>U-spin relation between $B_s^0 \to J/\psi K_S^0$ and $B_d^0 \to J/\psi K_S^0$:</u>

$$a' = \xi a\,, \qquad \theta' = \theta + \delta$$

$\to$ allow for U-spin breaking (non-fact.): $\xi = 1.00 \pm 0.20$, $\delta = (0 \pm 20)^\circ$:



$$\Delta\phi_d^{\psi K_S^0} = -\left[1.09 \pm 0.20\,(\text{stat})^{+0.20}_{-0.24}\,(\text{U spin})\right]^\circ = -\left[1.09 \pm 0.30\right]^\circ$$

Using Branching Ratio Information

It is important to emphasise that BRs are not required in this analysis:

- Knowing (a, θ) ($\to$ clean!), the following quantitiy can be determined:

$$H = \frac{1 - 2\,a\cos\theta\cos\gamma + a^2}{1 + 2\epsilon a'\cos\theta'\cos\gamma + \epsilon^2 a'^2} \propto \frac{\mathcal{B}\,(B_s \to J/\psi K_{\rm S})}{\mathcal{B}(B_d \to J/\psi K_{\rm S})}$$

$$\Rightarrow \quad H_{(a,\theta)} = 1.172 \pm 0.037\,(a,\theta) \pm 0.0016\,(\xi,\delta)$$

- We may then extract the following amplitude ratio from the BRs:

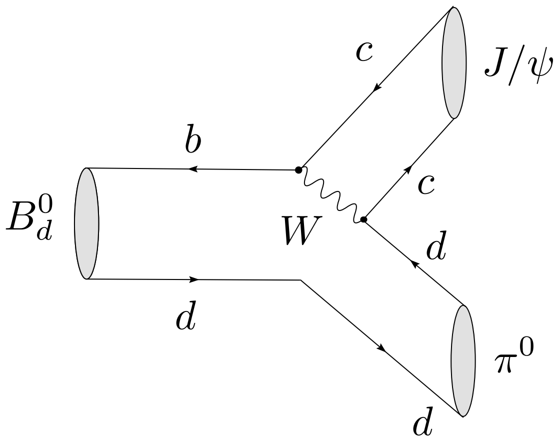
$$\left|\frac{\mathcal{A}'}{\mathcal{A}}\right| = \sqrt{\epsilon\, H_{(a,\theta)} \frac{\mathrm{PhSp}\,(B_s \to J/\psi K^0_{\rm S})}{\mathrm{PhSp}\,(B_d \to J/\psi K^0_{\rm S})} \frac{\tau_{B_s}}{\tau_{B_d}} \frac{\mathcal{B}\,(B_d \to J/\psi K^0_{\rm S})_{\rm theo}}{\mathcal{B}\,(B_s \to J/\psi K^0_{\rm S})_{\rm theo}}}$$

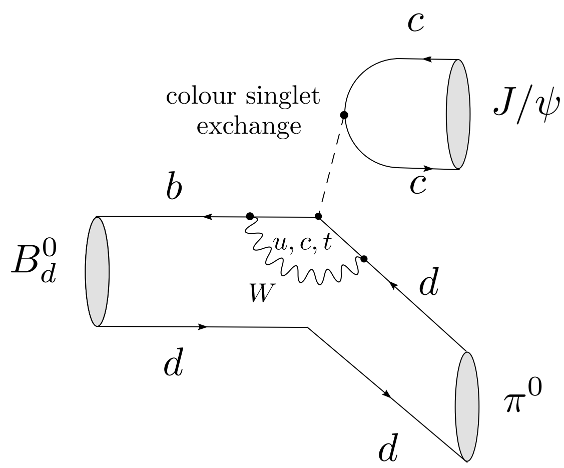
- $\mathcal{B}(B_s \to f)$ measurements @ LHCb limited by $f_s/f_d = 0.259 \pm 0.015$:

  $\to$ assuming no improvement of f_s/f_d, which is conservative $\Rightarrow$

$$\left|\frac{\mathcal{A}'}{\mathcal{A}}\right|_{\rm exp} = 1.160 \pm 0.035 \quad \text{vs} \quad \left|\frac{\mathcal{A}'}{\mathcal{A}}\right|^{\rm LCSR}_{\rm fact} = 1.16 \pm 0.18 \quad (!)$$

Control Channel for Belle II: $B_d^0 \to J/\psi\pi^0$





⋆ Replace s spectator of $B_s^0 \to J/\psi K_{\rm S}$ by d quark $\Rightarrow$ $B_d^0 \to J/\psi\pi^0$

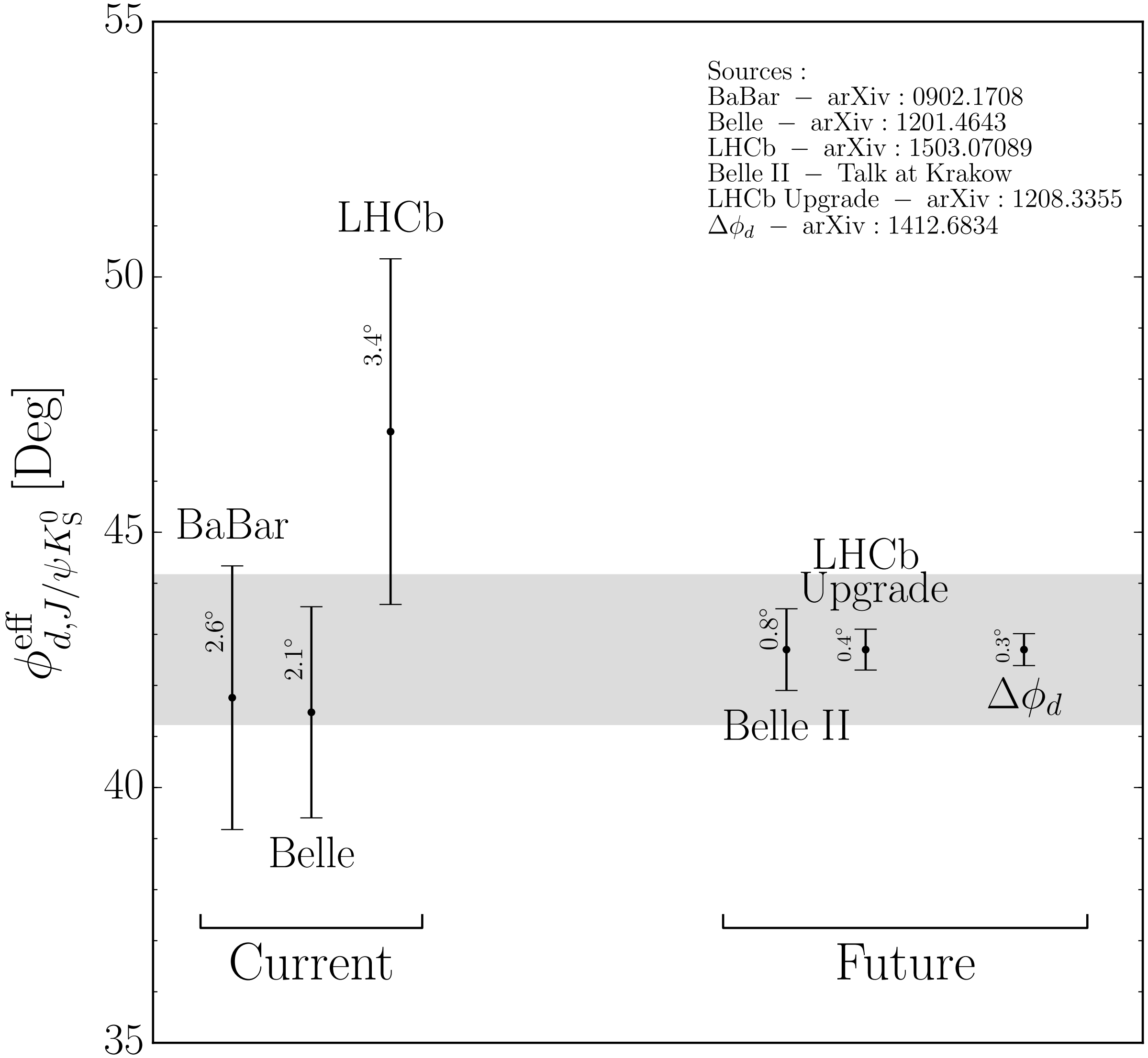
- CKM amplitude structure of $B_d^0 \to J/\psi\pi^0$ is analogous to $B_s^0 \to J/\psi K_{\rm S}$:

$\Rightarrow$ shows also "magnified penguins"!

- Exchange and penguin annihilation amplitudes have to be neglected in $B_d^0 \to J/\psi\pi^0$ as they have no counterpart in $B_d^0 \to J/\psi K_{\rm S}$:
  - Expected to be tiny, but can be probed through $B_s^0 \to J/\psi\pi^0$ and $B_s^0 \to J/\psi\rho^0$ [no evidence in the current LHCb data].

[R.F. (1999): $B_d^0 \to J/\psi\rho^0$; Ciuchini, Pierini & Silvestrini (2005, 2011)]

Prospects for Measuring ϕ_d

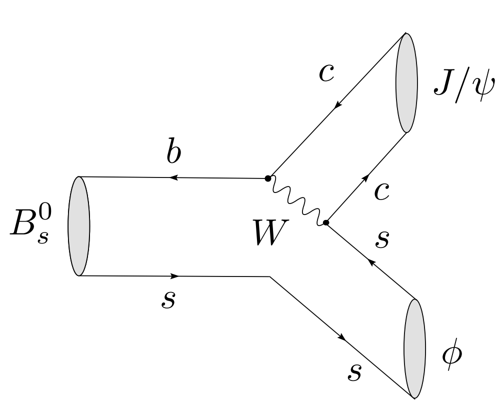


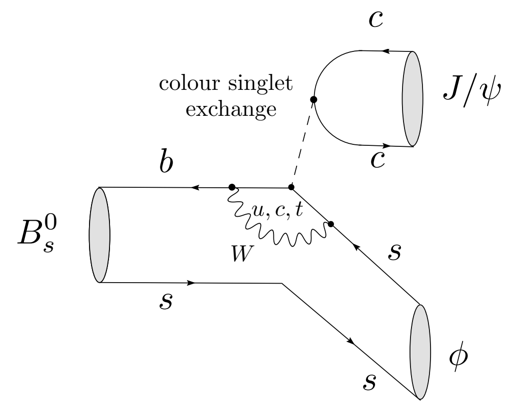
[Compilation: Kristof De Bruyn]

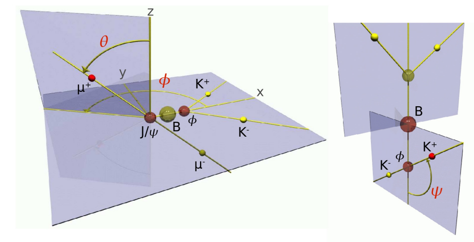
$B^0_{s,d} \to J/\psi V$ Decays:

- $B^0_s \to J/\psi\phi$: benchmark decay to extract ϕ_s
- $B^0_d \to J/\psi\rho^0$: penguin probe $\to$ CPV @ LHCb
- $B^0_s \to J/\psi\bar{K}^{*0}$: yet another penguin probe

The $B_s^0 \to J/\psi\phi$ Decay







- Final state is mixture of CP-odd and CP-even states:

$\to$ disentangle through $J/\psi[\to \mu^+\mu^-]\phi[\to K^+K^-]$ angular distribution

- Impact of SM penguin contributions: $f \in \{0, \parallel, \perp\}$

$$A\left(B_s^0 \to (J/\psi\phi)_f\right) = \left(1 - \frac{\lambda^2}{2}\right)\mathcal{A}'_f\left[1 + \epsilon a'_f e^{i\theta'_f} e^{i\gamma}\right]$$

$\star$ CP-violating observables $\Rightarrow$ $\phi^{\text{eff}}_{s,(\psi\phi)_f} = \phi_s + \Delta\phi_s^{(\psi\phi)_f}$

- Smallish B_s^0–$\bar{B}_s^0$ mixing phase ϕ_s (indicated by data ...):

$\Rightarrow$ $\Delta\phi_s^f$ at the 1° level would have a significant impact ...

[Faller, R.F. & Mannel (2008)]

News on $B_s^0 \to J/\psi\phi$

- Penguin parameters:
  - (a'_f, θ'_f) are expected to differ for different final-state configurations f.
  - Simplified arguments along the lines of factorisation:

$$\Rightarrow\ a'_f \equiv a'_{\psi\phi}\,, \qquad \theta'_f \equiv \theta'_{\psi\phi} \qquad \forall f \in \{0, \|, \perp\}$$

$\to$ **interesting to test through data!** [R.F. (1999)]

- New LHCb results for $B_s \to J/\psi\phi$: [LHCb, arXiv:1411.3104]
  - First polarisation-dependent results for $\phi_{s,f}^{\mathrm{eff}}$: $\to$ *pioneering character:*

$$\begin{aligned}
\phi_{s,0}^{\mathrm{eff}} &= -0.045 \pm 0.053 \pm 0.007 &&= -(2.58 \pm 3.04 \pm 0.40)^\circ \\
\phi_{s,\|}^{\mathrm{eff}} - \phi_{s,0}^{\mathrm{eff}} &= -0.018 \pm 0.043 \pm 0.009 &&= -(1.03 \pm 2.46 \pm 0.52)^\circ \\
\phi_{s,\perp}^{\mathrm{eff}} - \phi_{s,0}^{\mathrm{eff}} &= -0.014 \pm 0.035 \pm 0.006 &&= -(0.80 \pm 2.01 \pm 0.34)^\circ
\end{aligned}$$

  - Assuming a universal value of ϕ_s^{eff}:

$$\phi_s^{\mathrm{eff}} = \phi_s + \Delta\phi_s = -0.058 \pm 0.049 \pm 0.006 = -(3.32 \pm 2.81 \pm 0.34)^\circ$$

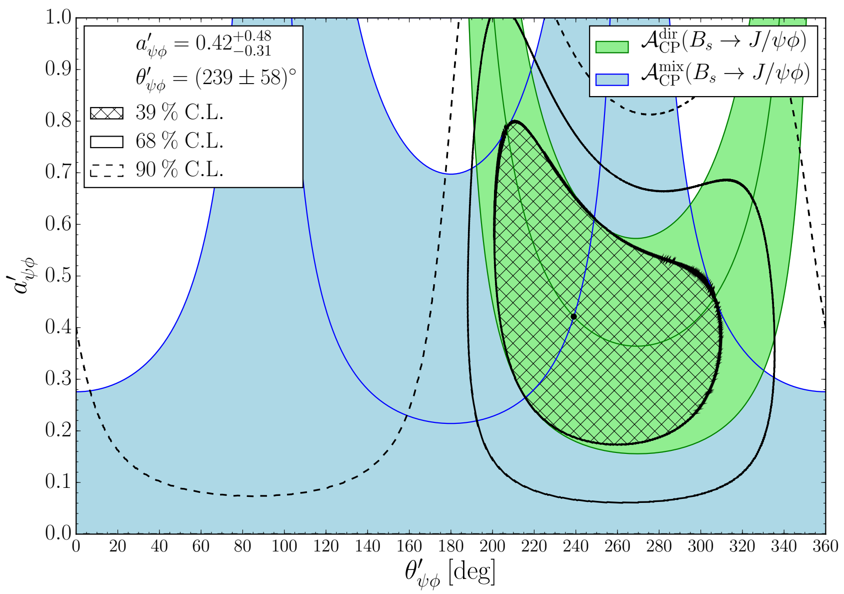
- Further polarisation-dependent LHCb results for $B_s^0 \to J/\psi\phi$:

$$|\lambda_f| \equiv \left|\frac{A(\bar{B}_s^0 \to (J/\psi\phi)_f}{A(B_s^0 \to (J/\psi\phi)_f}\right| = \left|\frac{1+\epsilon a'_f e^{i\theta'_f} e^{-i\gamma}}{1+\epsilon a'_f e^{i\theta'_f} e^{+i\gamma}}\right|$$

$$\begin{aligned} |\lambda^0| &= 1.012 \pm 0.058 \pm 0.013 \\ |\lambda^\perp/\lambda^0| &= 1.02 \pm 0.12 \pm 0.05 \\ |\lambda^\parallel/\lambda^0| &= 0.97 \pm 0.16 \pm 0.01 \end{aligned}$$

  - ⋆ Assuming a universal $|\lambda^f| \equiv |\lambda_{\psi\phi}|$: $\Rightarrow$ $|\lambda_{\psi\phi}| = 0.964 \pm 0.019 \pm 0.007$

- Constraints in the $\theta'_{\psi\phi}$–$a'_{\psi\phi}$ plane following from the "universal" LHCb values of $\phi_s^{\rm eff}$ and $|\lambda_{\psi\phi}|$, assuming the SM value of ϕ_s:



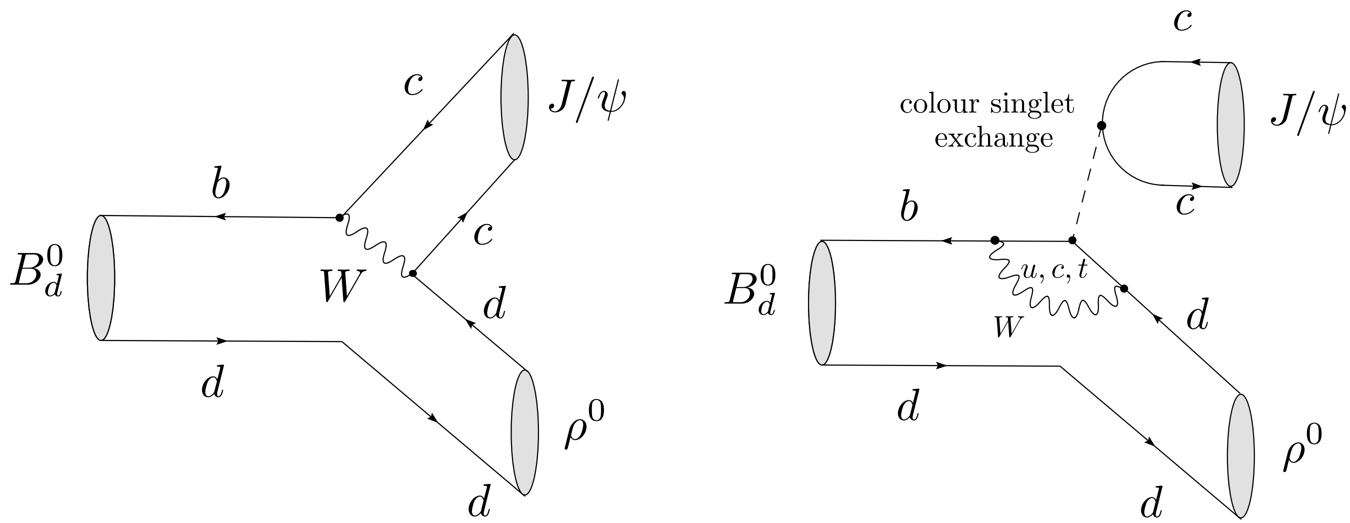
⋆ Controlling the Penguin Effects in $B_s^0 \to J/\psi\phi$:

- Use the $SU(3)$ flavour symmetry.
- Neglect certain E and PA topologies:
  - Probed through $B_d^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\rho^0$.
  - No evidence for enhancement in LHCb data:

$\to$ stronger bounds in the future ...

[R.F. (1999), Faller, R.F. & Mannel (2008), De Bruyn & R.F. (2015)]

The $B_d^0 \to J/\psi\rho^0$ Decay



- Decay amplitude:

$$\sqrt{2}\, A\left(B_d^0 \to (J/\psi\rho^0)_f\right) = -\lambda \mathcal{A}_f \left[1 - a_f e^{i\theta_f} e^{i\gamma}\right]$$

- CKM structure similar to $B_s^0 \to J/\psi K_S$ and $B_d^0 \to J/\psi\pi^0$:

$\to$ "magnified penguin contributions"

  – Hardonic parameters in $B_{s,d}^0 \to J/\psi K_S^0$ and $B_d^0 \to J/\psi\rho^0$ are generally expected to differ from one another.

- CP violation: $\to \phi_{d,f}^{\mathrm{eff}} \equiv 2\beta_f^{\mathrm{eff}}$ (in general polarisation dependent)

PHYSICAL REVIEW D, VOLUME 60, 073008

Extracting CKM phases from angular distributions of $B_{d,s}$ decays into admixtures of CP eigenstates

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(Received 27 April 1999; published 8 September 1999)

The time-dependent angular distributions of certain $B_{d,s}$ decays into final states that are admixtures of CP-even and CP-odd configurations provide valuable information about CKM phases and hadronic parameters. We present the general formalism to accomplish this task, taking also into account penguin contributions, and illustrate it by considering a few specific decay modes. We give particular emphasis to the decay $B_d \to J/\psi \rho^0$, which can be combined with $B_s \to J/\psi \phi$ to extract the B_d^0-$\bar{B}_d^0$ mixing phase and—if penguin effects in the former mode should be sizeable—also the angle γ of the unitarity triangle. As an interesting by-product, this strategy allows us to take into account also the penguin effects in the extraction of the B_s^0-$\bar{B}_s^0$ mixing phase from $B_s \to J/\psi \phi$. Moreover, a discrete ambiguity in the extraction of the CKM angle β can be resolved, and valuable insights into $SU(3)$-breaking effects can be obtained. Other interesting applications of the general formalism presented in this paper, involving $B_d \to \rho\rho$ and $B_{s,d} \to K^* \bar{K}^*$ decays, are also briefly noted. [S0556-2821(99)03619-X]

PACS number(s): 12.15.Hh, 13.25.Hw

- First experimental results for CP violation in the $B_d^0 \to J/\psi\rho^0$ channel:

$\to$ *pioneering polarisation-dependent analysis:*

$$\begin{aligned} \phi_{d,0}^{\rm eff} &= + \left(44.1 \pm 10.2^{+3.0}_{-6.9}\right)^\circ \\ \phi_{d,\parallel}^{\rm eff} - \phi_{d,0}^{\rm eff} &= - \left(0.8 \pm 6.5^{+1.9}_{-1.3}\right)^\circ \\ \phi_{d,\perp}^{\rm eff} - \phi_{d,0}^{\rm eff} &= - \left(3.6 \pm 7.2^{+2.0}_{-1.4}\right)^\circ \end{aligned}$$

[L. Zhang and S. Stone, arXiv:1212.6434; LHCb Collaboration, arXiv:1411.1634]

- Assuming *polarisation-independent* penguin parameters: $\Rightarrow$

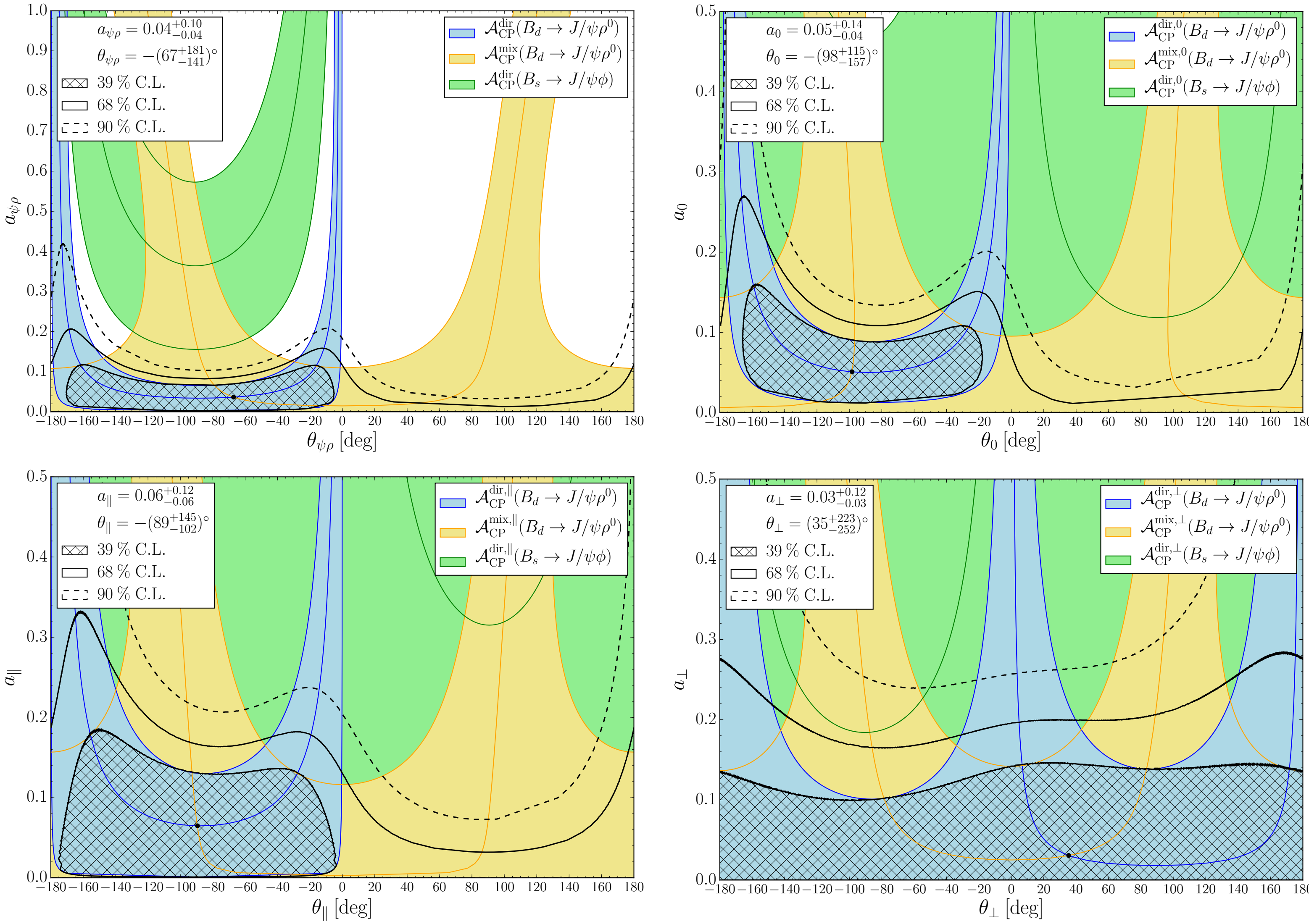
$$\phi_d^{\rm eff} = \left(41.7 \pm 9.6^{+2.8}_{-6.3}\right)^\circ$$

$$\begin{aligned} \mathcal{A}_{\rm CP}^{\rm dir}(B_d \to J/\psi\rho) \equiv C_{J/\psi\rho} &= -0.063 \pm 0.056^{+0.019}_{-0.014} \\ -\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to J/\psi\rho) \equiv S_{J/\psi\rho} &= -0.66^{+0.13+0.09}_{-0.12-0.03} \end{aligned}$$

- Using $\gamma = (70.0^{+7.7}_{-9.0})^\circ$ [CKMfitter] and $\phi_d = \left(43.2^{+1.8}_{-1.7}\right)^\circ$ determined from our $B \to J/\psi P$ analysis (see above), a χ^2 fit to the data yields:

$$\boxed{a_{\psi\rho} = 0.037^{+0.097}_{-0.037}\,, \quad \theta_{\psi\rho} = -\left(67^{+181}_{-141}\right)^\circ\,, \quad \Delta\phi_d^{J/\psi\rho^0} = -\left(1.5^{+12}_{-10}\right)^\circ}$$

- Illustration of the determination of a_f and θ_f from the χ^2 fit through intersecting contours derived from the CP observables in $B_d^0 \to J/\psi\rho^0$:



[K. De Bruyn & R.F. (2015)]

$\star$ *Further Implications of the $B_d^0 \to J/\psi\rho^0$ Analysis:*

- Conversion into the $B_s^0 \to J/\psi\phi$ penguin parameters:

$$a'_{\psi\phi} = \xi a_{\psi\rho} \quad \theta'_{\psi\phi} = \theta_{\psi\rho} + \delta \quad [\xi = 1.00 \pm 0.20,\ \delta = (0 \pm 20)^\circ]$$

$$\Rightarrow \quad \boxed{\Delta\phi_s^{\psi\phi} = \left[0.08^{+0.56}_{-0.72}\,(\text{stat})^{+0.15}_{-0.13}\,(\text{SU(3)})\right]^\circ} \quad (!)$$

... to be compared with $\phi_s^{\text{eff}} = \phi_s + \Delta\phi_s^{\psi\phi} = -(3.32 \pm 2.81 \pm 0.34)^\circ$.

[In agreement with LHCb Collaboration, S. Stone et al., arXiv:1411.1634]

- Extraction of hadronic amplitude ratios: [$\to B_{s,d}^0 \to J/\psi K_S$ discussion]

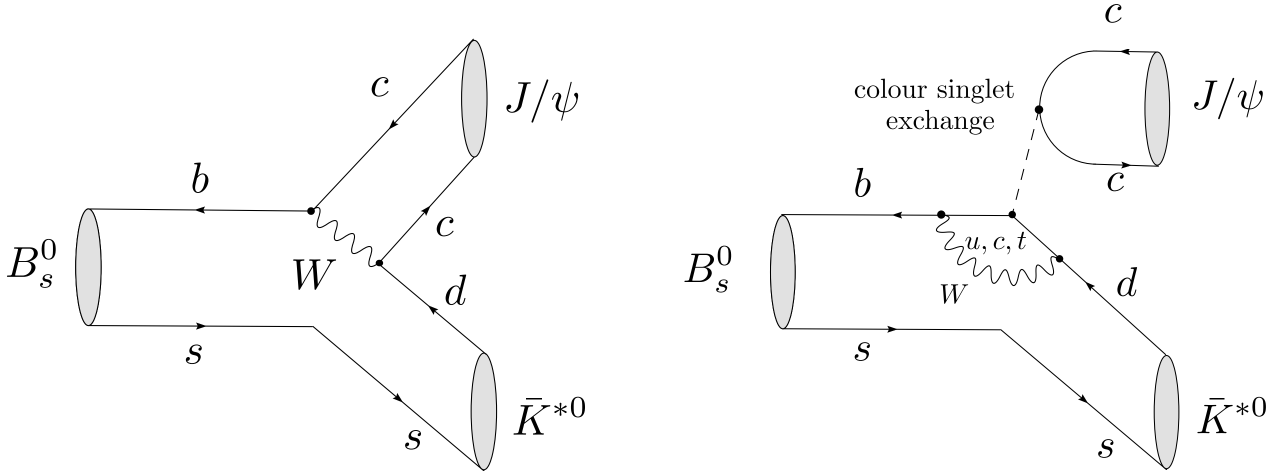
$$\left|\frac{\mathcal{A}'_0(B_s\to J/\psi\phi)}{\mathcal{A}_0(B_d\to J/\psi\rho^0)}\right| = 1.06 \pm 0.07\,(\text{stat}) \pm 0.04\,(\text{a}_0, \theta_0) \stackrel{\text{fact}}{=} 1.43 \pm 0.42$$

$$\left|\frac{\mathcal{A}'_{||}(B_s\to J/\psi\phi)}{\mathcal{A}_{||}(B_d\to J/\psi\rho^0)}\right| = 1.08 \pm 0.08\,(\text{stat}) \pm 0.05\,(\text{a}_{||}, \theta_{||}) \stackrel{\text{fact}}{=} 1.37 \pm 0.20$$

$$\left|\frac{\mathcal{A}'_{\perp}(B_s\to J/\psi\phi)}{\mathcal{A}_{\perp}(B_d\to J/\psi\rho^0)}\right| = 1.24 \pm 0.15\,(\text{stat}) \pm 0.06\,(\text{a}_{\perp}, \theta_{\perp}) \stackrel{\text{fact}}{=} 1.25 \pm 0.15$$

[Naive "fact" refers to LCSR form factors [Ball & Zwicky ('05)];
recent PQCD calculation: X. Liu, W. Wang and Y. Xie (2014)]

The $B_s^0 \to J/\psi \overline{K}^{*0}$ Decay



- Decay amplitude: $A(B_d^0 \to (J/\psi \overline{K}^{*0})_f) = -\lambda \tilde{\mathcal{A}}_f \left[1 - \tilde{a}_f e^{i\tilde{\theta}_f} e^{i\gamma}\right]$

- $SU(3)$ and neglect of PA and E topologies:

$$\tilde{a}_f e^{i\tilde{\theta}_f} = a_f e^{i\theta_f} \,, \qquad \tilde{\mathcal{A}}_f = \mathcal{A}_f \,.$$

- Important *difference/disadvantage* with respect to $B_d^0 \to J/\psi \rho^0$:

$$\to \textit{no mixing-induced CP violation} \Rightarrow$$

  - Untagged rate measurement $\oplus$ direct CP violation.
  - Angular analysis is required to disentangle final states $f \in \{0, \parallel, \perp\}$

[S. Faller, R.F. & T. Mannel (2008)]

- In more detail: *untagged rate measurement* $\rightarrow$

$$\tilde{H}_f \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}'_f}{\tilde{\mathcal{A}}_f}\right|^2 \frac{\mathrm{PhSp}\,(B_s\to J/\psi\phi)}{\mathrm{PhSp}(B_s\to J/\psi \overline{K}^{*0})}\frac{\mathcal{B}(B_s\to J/\psi\overline{K}^{*0})_{\mathrm{theo}}}{\mathcal{B}(B_s\to J/\psi\phi)_{\mathrm{theo}}}\frac{\tilde{f}^{\mathrm{exp}}_{\mathrm{VV},f}}{f^{\mathrm{exp}}_{\mathrm{VV},f}}$$

$$f^{\mathrm{exp}}_{\mathrm{VV},f} \equiv \frac{\mathcal{B}(B_s\to (f)_f)_{\mathrm{exp}}}{\sum_f \mathcal{B}(B_s\to (f)_f)_{\mathrm{exp}}}$$

$\tilde{H}_f$ requires $|\mathcal{A}'_f/\tilde{\mathcal{A}}_f|$ $\rightarrow$ hadronic uncertainties...

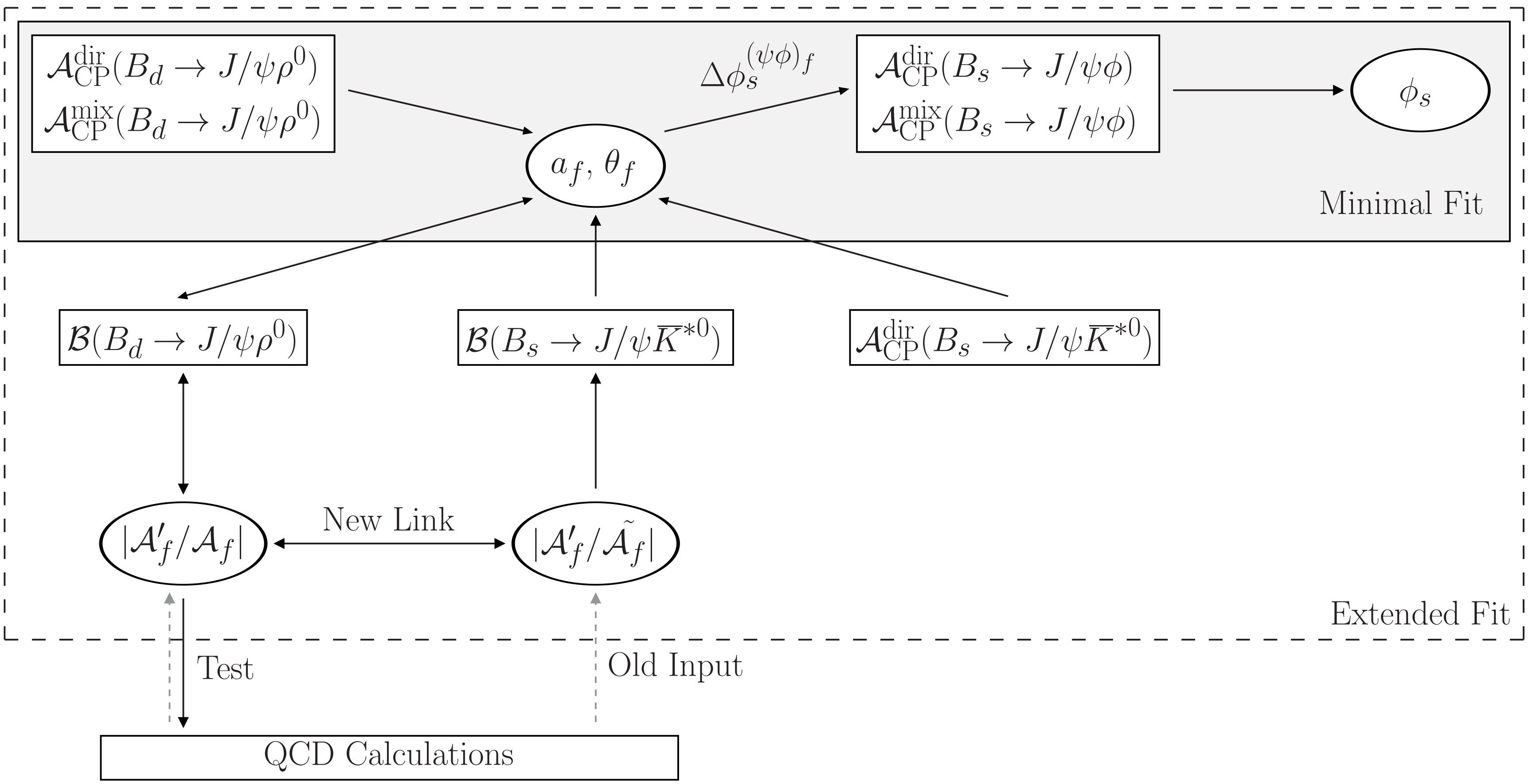
[Experimental analysis: CDF (2011); LHCb, arXiv:1208.0738]

- Important next step: *CP violation measurements* $\rightarrow$
  - We expect them to approximately equal those of $B^0_d\to J/\psi\rho^0$:

$$\begin{aligned}
\mathcal{A}^{\mathrm{dir}}_{\mathrm{CP}}(B_s\to J/\psi\overline{K}^{*0})_0 &= -0.094\pm 0.071\\
\mathcal{A}^{\mathrm{dir}}_{\mathrm{CP}}(B_s\to J/\psi\overline{K}^{*0})_{\parallel} &= -0.12\pm 0.12\\
\mathcal{A}^{\mathrm{dir}}_{\mathrm{CP}}(B_s\to J/\psi\overline{K}^{*0})_{\perp} &= 0.03\pm 0.22
\end{aligned}$$

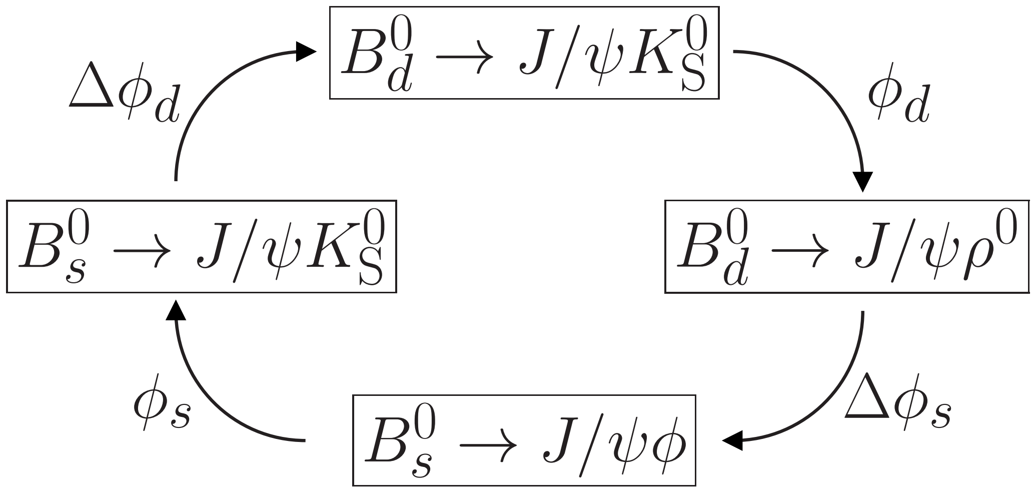
  - Look forward to compare with future LHCb measurements ...

A Penguin Roadmap



[K. De Bruyn & R.F. (2015)]

Interplay Between the ϕ_d and ϕ_s Analyses



[K. De Bruyn & R.F. (2015)]

Correlation Between ϕ_d and ϕ_s for New Physics

$\rightarrow$ *Illustration for non-$\overline{MFV}$ models:*

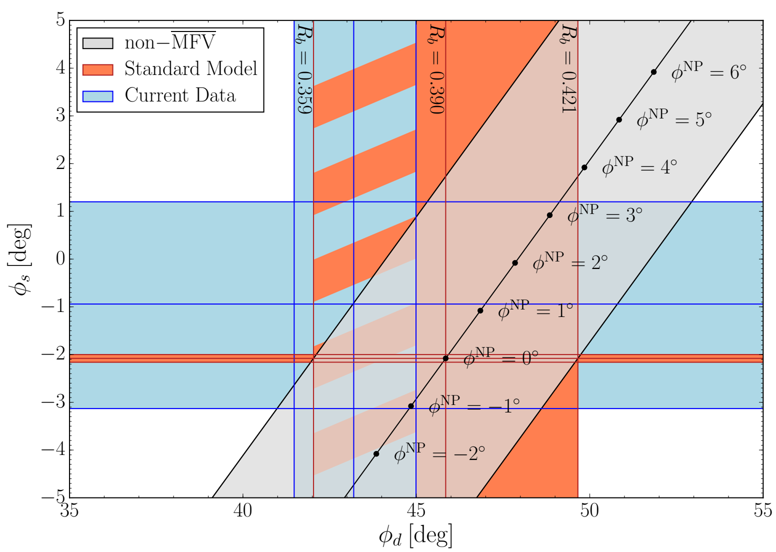
- Non-MFV models with flavour-universal CP-violating NP phases:

$$\phi_s^{\rm NP} = \phi_d^{\rm NP} \equiv \phi^{\rm NP} \quad \Rightarrow \quad \phi_s = \phi_d + \left(\phi_s^{\rm SM} - \phi_d^{\rm SM}\right)$$

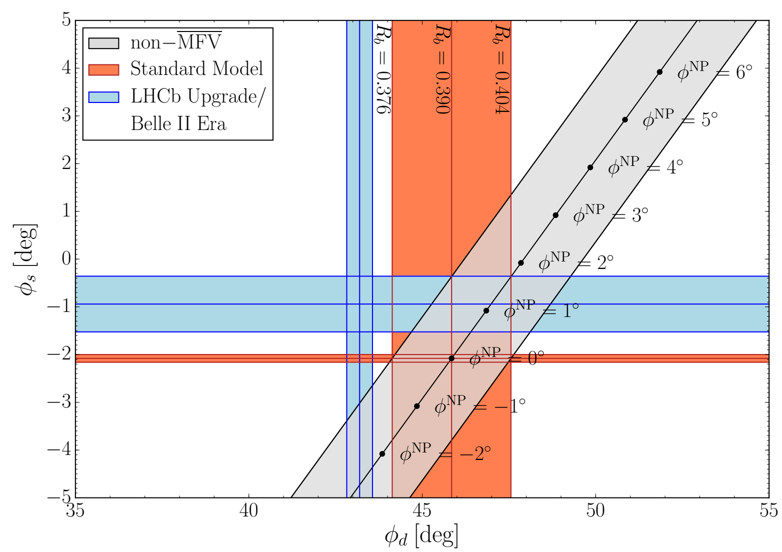
[Ball & R.F. (2006); Buras & Guadagnoli (2008); Buras & Girrbach (2014)]

- Current situation and extrapolation to the LHCb upgrade era:

$$\sin 2\beta = \frac{2R_b \sin\gamma(1 - R_b\cos\gamma)}{(R_b\sin\gamma)^2 + (1 - R_b\cos\gamma)^2} \Rightarrow \boxed{R_b \text{ key limitation for } \phi_d^{\rm SM} = 2\beta\text{:}}$$

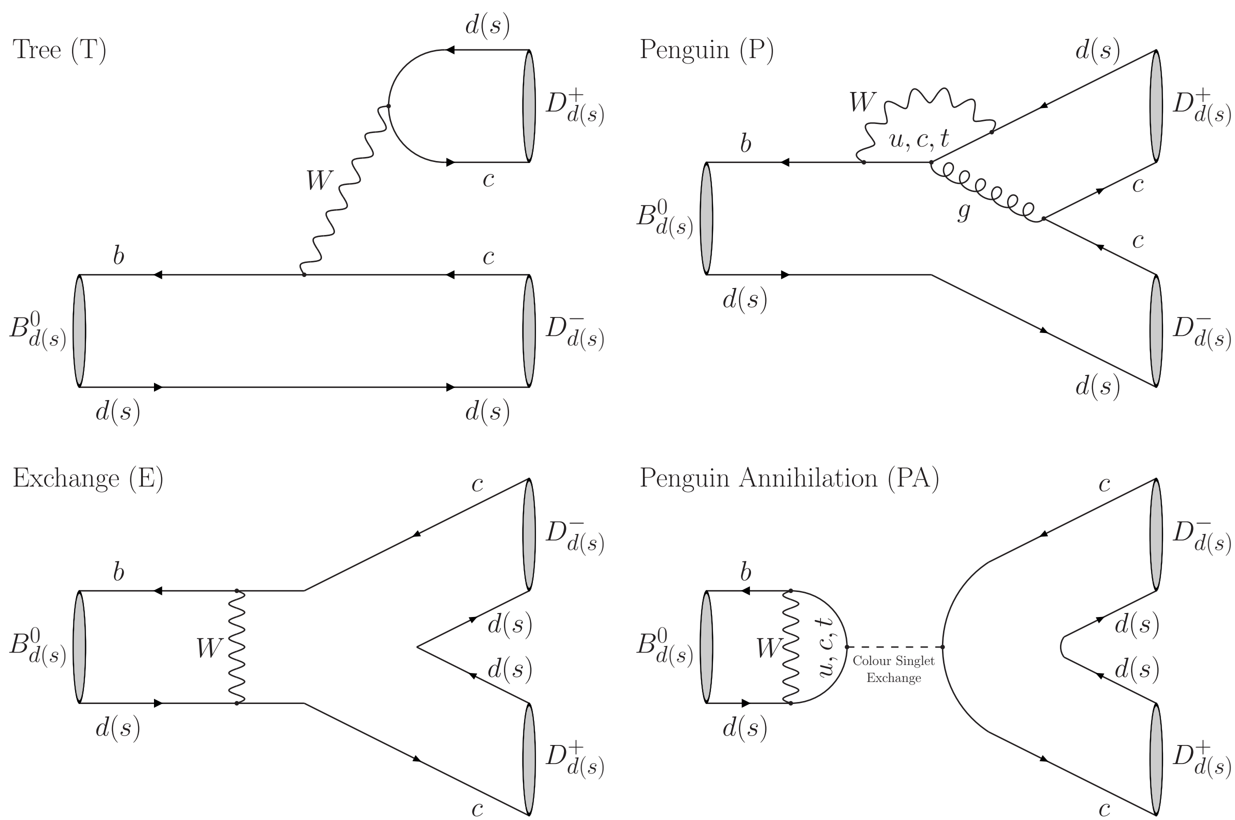


[current situation]



[Belle II/LHCb upgrade era]

Another Penguin Playground: $B \to D\overline{D}$ Decays



- Various interesting features:
  - Extraction of the B_q^0–$\bar{B}_q^0$ mixing phases from the CP asymmetries.
  - Probes of exchange and penguin annihilation topologies.
  - Tests of factorization, ...

[R.F. (1999, 2007); Gronau, Rosner & Pirjol (2008); Jung & Schacht (2015); ...]

Anatomy of $B \to D\overline{D}$ Decays

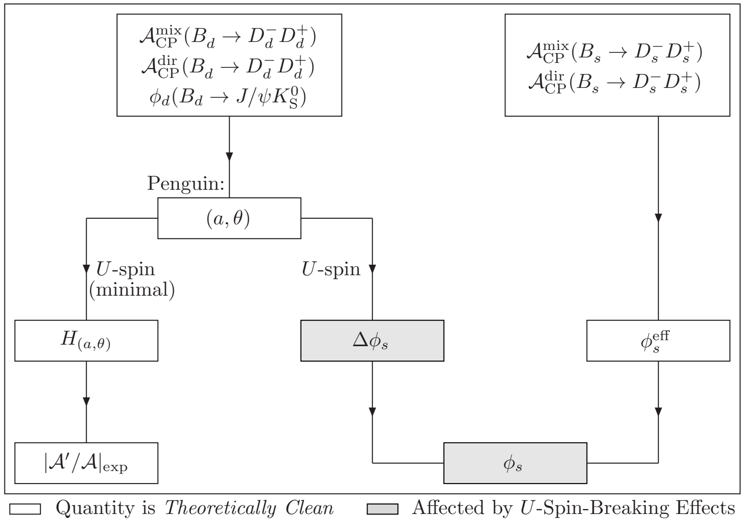
$\to$ comprehensive recent analysis: $\to$ key results:

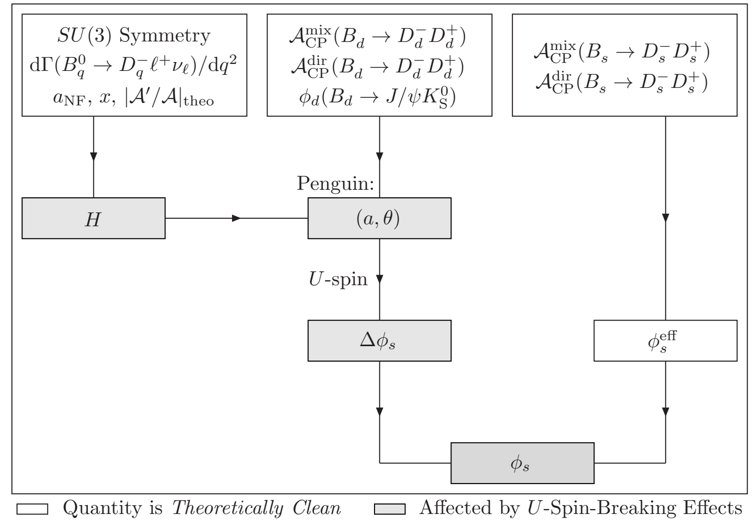
- Significantly enhanced exchange and penguin annihilation topologies.
- Indications for potentially enhanced penguin contributions.
- Factorization tests utilizing semileptonic $B_d^0 \to D_d^- \ell^+ \nu_\ell$ modes.
- Tests of $SU(3)$-breaking effects.
- Detailed exploration of prospects for the LHCb upgrade and Belle II era:

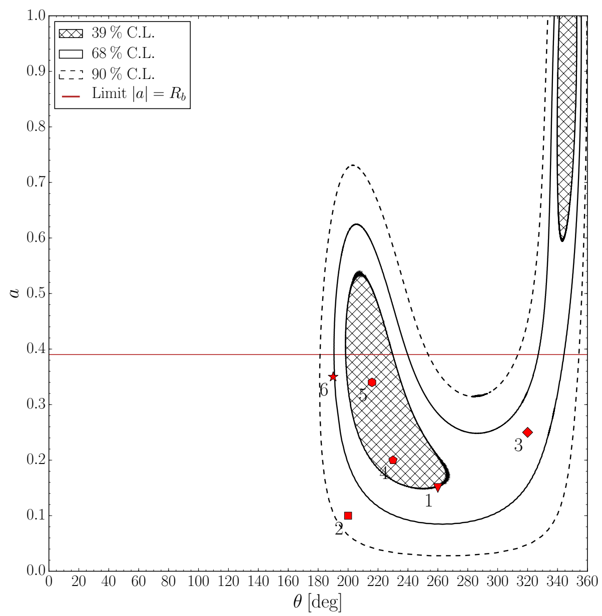
$\Rightarrow$ penguin strategies depend on future measured observables:

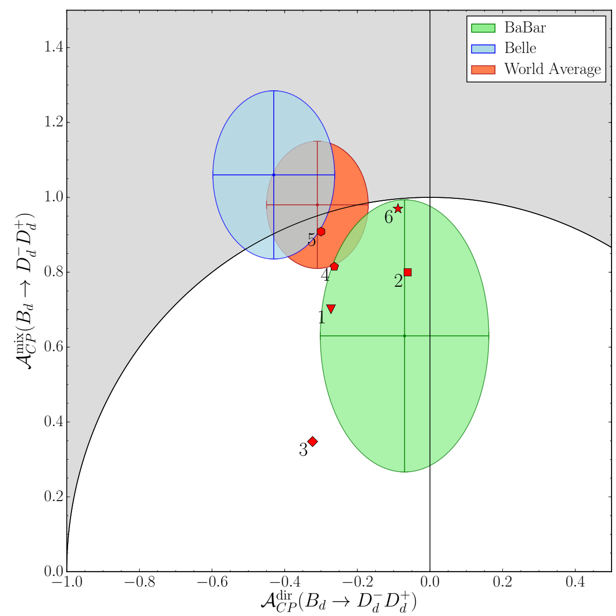
$\to$ allow us to control penguins in ϕ_s from $B_s^0 \to D_s^+ D_s^+$

[L. Bel, K. De Bruyn, R.F., M. Mulder & N. Tuning, arXiv:1505.01361 [hep-ph]]









→ <u>Details:</u> L. Bel, K. De Bruyn, R.F., M. Mulder & N. Tuning, arXiv:1505.01361 [hep-ph]

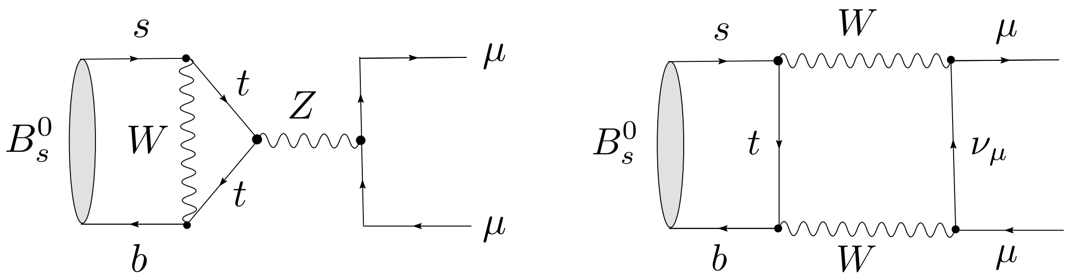
Prespectives for Rare B_s Decays:

New Observables

$\rightarrow$ LHCb Upgrade Era

General Features of $B_s^0 \to \mu^+\mu^-$

- Situation in the Standard Model (SM): $\to$ only loop contributions:



  – Moreover: helicity suppression $\to$ BR $\propto m_\mu^2$

$\Rightarrow$ **strongly suppressed decay**

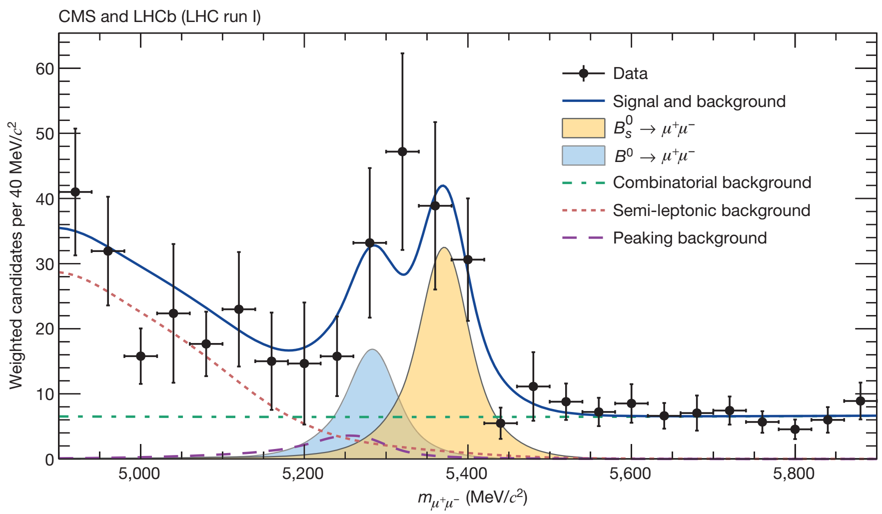
- Hadronic sector: $\to$ very simple, only the B_s decay constant F_{B_s} enters:

$$\langle 0|\bar{b}\gamma_5\gamma_\mu s|B_s^0(p)\rangle = iF_{B_s}p_\mu$$

$\Rightarrow$ **$B_s^0 \to \mu^+\mu^-$ belongs to the cleanest rare B decays**

Highlight of LHC Run I: Observation of $B_s^0 \to \mu^+\mu^-$

- Combined analysis of the CMS and LHCb collaborations:



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}, \quad \mathcal{B}(B_d^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

[CMS and LHCb Collaborations, Nature, 13 May 2015]

- Most recent theoretical Standard Model analysis: [$\to$ talk by C. Bobeth]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9},$$
$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

[Bobeth, Gorbahn, Hermann, Misiak, Stamou & Steinhauser, Phys. Rev. Lett. **112** (14) 101801]

- <u>Interesting situation to monitor:</u>

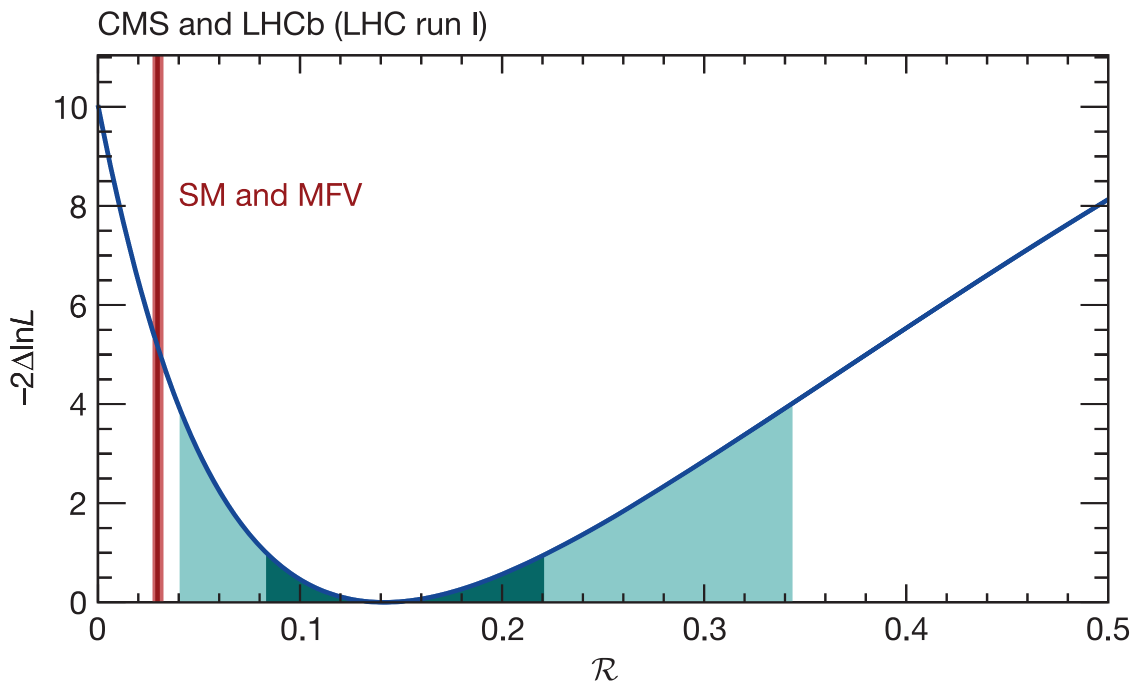


Figure 4 | Variation of the test statistic $-2\Delta\ln L$ as a function of the ratio of branching fractions $\mathcal{R} \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$. The dark and light (cyan) areas define the $\pm 1\sigma$ and $\pm 2\sigma$ confidence intervals for $\mathcal{R}$, respectively. The value and uncertainty for $\mathcal{R}$ predicted in the SM, which is the same in BSM theories with the minimal flavour violation (MFV) property, is denoted with the vertical (red) band.

[CMS and LHCb Collaborations, Nature, 13 May 2015]

LHCb Upgrade Era: $B_s^0 \to \mu^+\mu^-$

- Branching ratio measurement requires normalization:

$$\mathrm{BR}(B_s^0 \to \mu^+\mu^-) = \mathrm{BR}(B_q \to X)\frac{\epsilon_X}{\epsilon_{\mu\mu}}\frac{N_{\mu\mu}}{N_X}\frac{f_q}{f_s}$$

→ ratio of fragmentations functions f_s/f_d is the major limiting factor...

[R.F., Nicola Serra & Niels Tuning (2010)]

- Is there an observable beyond the branching ratio?: *yes ...*
  - Exploit the sizeable B_s decay width difference $\Delta\Gamma_s$:

$$y_s \equiv \frac{\Delta\Gamma_s}{2\,\Gamma_s} \equiv \frac{\Gamma_{\mathrm{L}}^{(s)} - \Gamma_{\mathrm{H}}^{(s)}}{2\,\Gamma_s} = 0.075 \pm 0.012$$

  - Provides access to another observable:

$$\mathcal{A}_{\Delta\Gamma}^{\mu\mu} = \frac{|P|^2\cos(2\varphi_P - \phi_s^{\mathrm{NP}}) - |S|^2\cos(2\varphi_S - \phi_s^{\mathrm{NP}})}{|P|^2 + |S|^2} \xrightarrow{\mathrm{SM}} 1$$

[De Bruyn, R.F., Knegjens, Koppenburg, Merk, Pellegrino & Tuning (2012)]

Comments on $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$: *theoretically clean*

- $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ involves the following New Physics parameters:

$$\mathcal{H}_{\rm eff} = -\frac{G_{\rm F}}{\sqrt{2}\pi} V_{ts}^* V_{tb} \alpha \big[C_{10} O_{10} + C_S O_S + C_P O_P + C'_{10} O'_{10} + C'_S O'_S + C'_P O'_P\big]$$

$$P \equiv |P| e^{i\varphi_P} \equiv \frac{C_{10} - C'_{10}}{C_{10}^{\rm SM}} + \frac{M_{B_s}^2}{2\, m_\mu}\left(\frac{m_b}{m_b + m_s}\right)\left(\frac{C_P - C'_P}{C_{10}^{\rm SM}}\right) \xrightarrow{\rm SM} 1$$

$$S \equiv |S| e^{i\varphi_S} \equiv \sqrt{1 - 4\frac{m_\mu^2}{M_{B_s}^2}} \frac{M_{B_s}^2}{2\, m_\mu}\left(\frac{m_b}{m_b + m_s}\right)\left(\frac{C_S - C'_S}{C_{10}^{\rm SM}}\right) \xrightarrow{\rm SM} 0$$

- $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ can be extracted from a *time-dependent* untagged analysis:

$$\langle \Gamma(B_s(t) \to \mu^+\mu^-)\rangle \equiv \Gamma(B_s^0(t) \to \mu^+\mu^-) + \Gamma(\bar{B}_s^0(t) \to \mu^+\mu^-)$$

$$\propto e^{-t/\tau_{B_s}}\big[\cosh(y_s t/\tau_{B_s}) + \mathcal{A}_{\Delta\Gamma}^{\mu\mu} \sinh(y_s t/\tau_{B_s})\big]$$

  - Currently only time-integrated analyses $\rightarrow$ BR measurement.
  - Need to correct for $\Delta\Gamma_s$ when comparing with theory BR calculation.

New Degree of Freedom to Probe New Physics

- Useful to introduce the following ratio:

$$R \equiv \frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm exp}}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM}} = \left[\frac{1+\mathcal{A}_{\Delta\Gamma}^{\mu\mu}\, y_s}{1-y_s^2}\right] \left(|P|^2 + |S|^2\right)$$

$$= \left[\frac{1+y_s\cos(2\varphi_P - \phi_s^{\rm NP})}{1-y_s^2}\right] |P|^2 + \left[\frac{1-y_s\cos(2\varphi_S - \phi_s^{\rm NP})}{1-y_s^2}\right] |S|^2$$

  - Current situation: $R = 0.82 \pm 0.21$
  - R *does not* allow a separation of the P and S contributions:

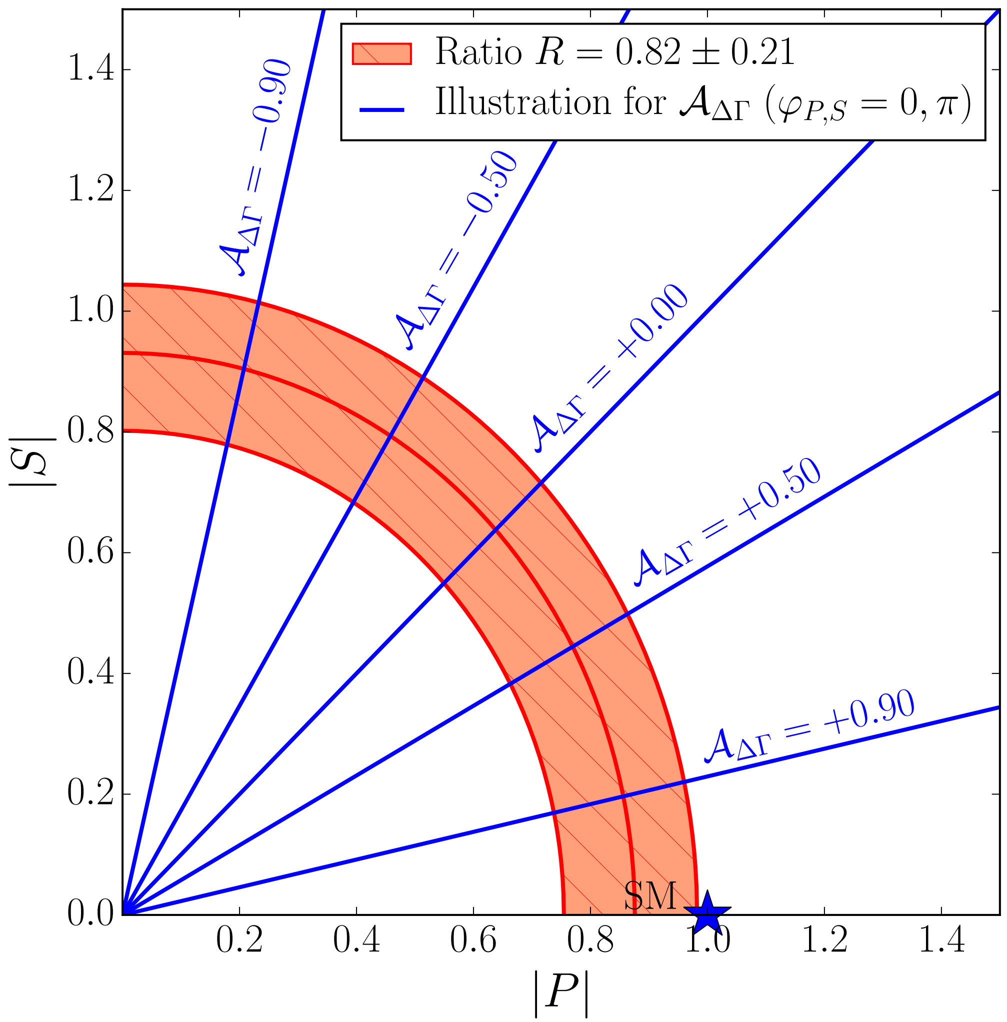
$\Rightarrow$ sizeable NP could be present ...

- Further information from the measurement of $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$:

$$|S| = |P| \sqrt{\frac{\cos(2\varphi_P - \phi_s^{\rm NP}) - \mathcal{A}_{\Delta\Gamma}^{\mu\mu}}{\cos(2\varphi_S - \phi_s^{\rm NP}) + \mathcal{A}_{\Delta\Gamma}^{\mu\mu}}}$$

$\Rightarrow$ offers a new window for NP in $B_s \to \mu^+\mu^-$

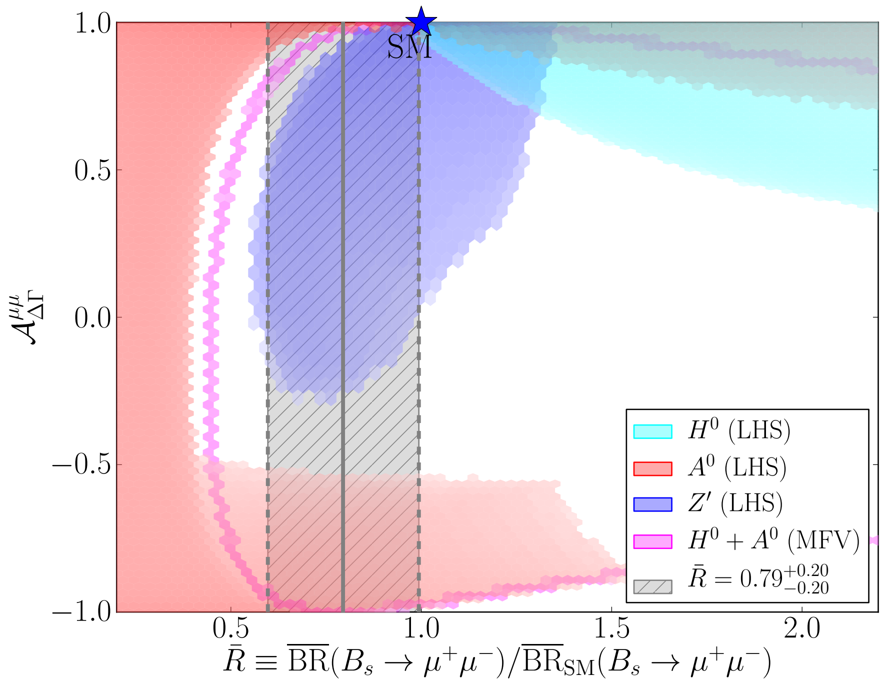
- Current constraints in the $|P|$–$|S|$ plane and illustration of those following from a future measurement of the $B_s \to \mu^+\mu^-$ obsevable $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$:



- Assumes no NP phases for the $\mathcal{A}_{\Delta\Gamma}$ curves (e.g. MFV without flavour-blind phases).

[De Bruyn, R.F., Knegjens, Koppenburg, Merk, Pellegrino & Tuning (2012)]

- Detailed analysis within specific NP scenarios:



[Buras, R.F., Girrbach & Knegjens (2013)]

- $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ is encoded in the effective $B_s^0 \to \mu^+\mu^-$ lifetime:

$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\,\langle\Gamma(B_s(t)\to\mu^+\mu^-)\rangle\,dt}{\int_0^\infty \langle\Gamma(B_s(t)\to\mu^+\mu^-)\rangle\,dt} = \frac{\tau_{B_s}}{1-y_s^2}\left[\frac{1+2\,\mathcal{A}_{\Delta\Gamma}^{\mu\mu}y_s+y_s^2}{1+\mathcal{A}_{\Delta\Gamma}^{\mu\mu}y_s}\right]$$

$\rightarrow$ promising observable for the LHCb upgrade era!

New Observables in $B_s^0 \to \phi\ell^+\ell^-$

- In analogy to the $B_s^0 \to \mu^+\mu^-$, the decay width difference $\Delta\Gamma_s$ can also be utilized in the rare decay $B_s^0 \to \phi\ell^+\ell^-$:
  - Angular analysis is required.
  - Much more involved than $B_s^0 \to \mu^+\mu^-$: form factors, resonances, etc.,
  - Interesting to complement the search for NP with $B_d^0 \to K^{*0}\mu^+\mu^-$.

- Discuss also the observables of the time-dependent analysis of the angular distribution of the $B_d^0 \to K^{*0}(\to \pi^0 K_S)$ decay.

$\to$ { interesting to fully exploit the physics potential of semileptonic rare $B_{(s)}$ decays in the era of Belle II and the LHCb upgrade.

[S. Descotes-Genon and J. Virto, arXiv:1502.05509 [hep-ph]]

Conclusions

Exciting Opportunities for B Physics

$\rightarrow$ *selection out of many interesting topics:*

- Excellent prospects for measuring γ:
  - $B \to D^{(*)}K^{(*)}$ and $B_s \to D_s^{\mp}K^{\pm}$ (clean): pure *tree* decays
  - $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$ (U spin): *loops* involved; new variants.
  - $B \to \pi K$ decays: $SU(3)$ methods to extract γ $\rightarrow$ change of focus:

    $\rightarrow$ *probe electroweak penguins:* $B_d^0 \to \pi^0 K_{\rm S}$ particularly interesting, complemented by $B^+ \to \pi^0 K^+$, $B_s^0 \to \phi\phi$, $B_s^0 \to \pi^0\phi$, ...

- High-precision measurements of the $B^0_{d,s}$–$\bar{B}^0_{d,s}$ mixing phases:

  $\rightarrow$ *penguin corrections have to be controlled:*

  - $B_s^0 \to J/\psi K_{\rm S}$: cleanest control of penguins in ϕ_d from $B_d^0 \to J/\psi K_{\rm S}$.
  - $B_d^0 \to J/\psi \rho^0$, $B_s^0 \to J/\psi \bar{K}^{*0}$: $\Rightarrow$ ϕ_s from $B_s^0 \to J/\psi\phi$ ... already impressive contraints and insights, also for $SU(3)$-breaking effects.
  - $B \to D\bar{D}$ decays: interesting complementary setting for penguins.

- Rare B_s decays: $\rightarrow$ *new observables for the LHCb upgrade era:*
  - $B_s^0 \to \mu^+\mu^-$: effective lifetime probes NP complementary to the BR.
  - $B_s^0 \to \phi\ell^+\ell^-$: observables utilising $\Delta\Gamma_s$

- Crucial for the full exploitation of B physics in the next ~ 10 years:

  ◇ (continued) strong interaction theory $\leftrightarrow$ experiment:

  – Hadronic physics: factorization, $SU(3)$-breaking corrections, data...
  – Think about new observables to probe the SM/NP.
  – Explore correlations/patterns between processes in specific NP models.

- Important to finally resolve a long-standing problem:

  $\rightarrow$ discrepancies inclusive/exclusive $|V_{ub}|$, $|V_{cb}|$ determinations.

- Exciting times for B physics: $\rightarrow$ *hot topics @ FPCP 2015*

  $(2–3)\sigma$ deviations seem to accumulate: $\rightarrow$ first footprints of NP (?):

  – First signals for $B_d^0 \rightarrow \mu^+\mu^-$ (?)
  – Anomalies in $B_d^0 \rightarrow K^{*0}\mu^+\mu^-$ (?)
  – $R_K = \mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)/\mathcal{B}(B^+ \rightarrow K^+e^+e^-)$ (?).
  – Data for $B \rightarrow \tau\nu$ decays, $B \rightarrow D^{(*)}\tau\nu$ decays (?).