Flavour Physics: Theoretical Status and Prospects

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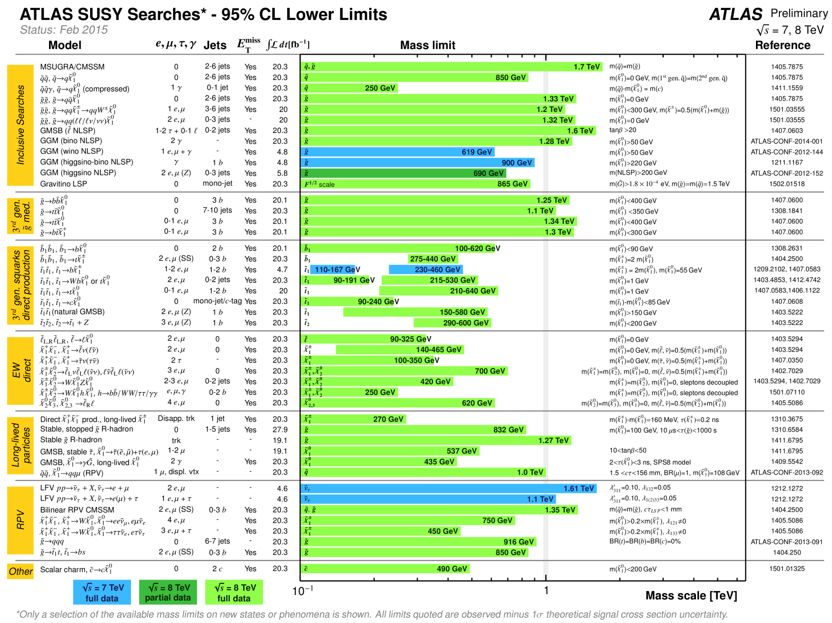
- Setting the Stage
- Theoretical Framework
- Studies of CP Violation
- Studies of Rare Decays
- Concluding Remarks

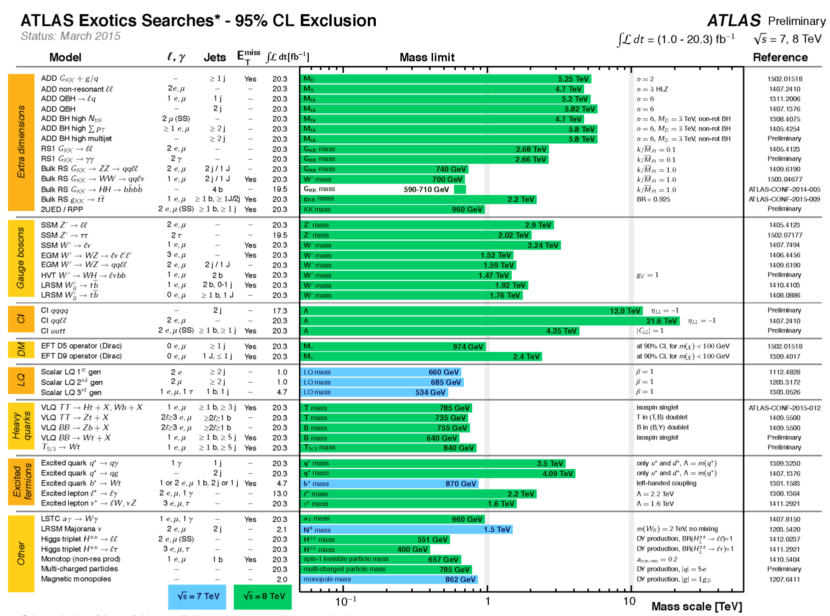
Setting the Stage

Status @ LHC High-Energy Frontier

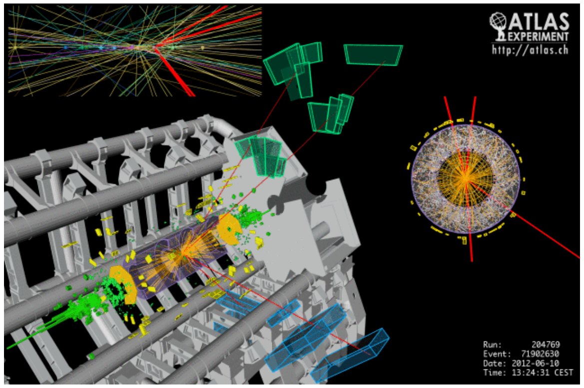
- Examples of New Physics searches @ ATLAS: $\rightarrow$ *no signals* (CMS similar)
  - SUSY:

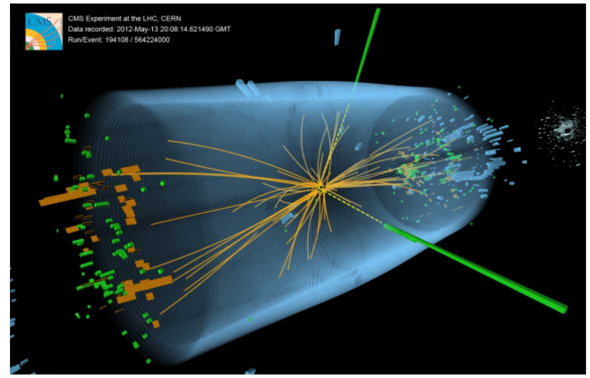


  - Exotics:

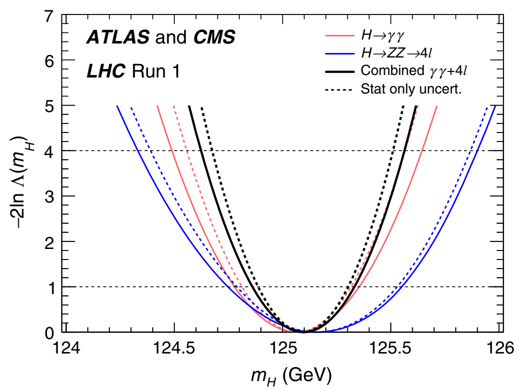


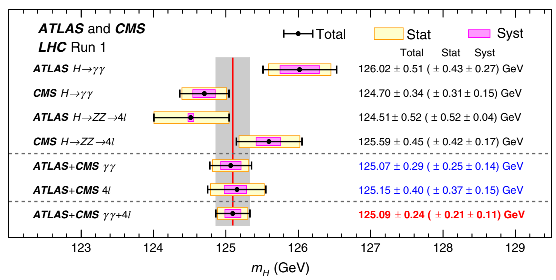
… but "Higgs-like" particle @ ATLAS and CMS

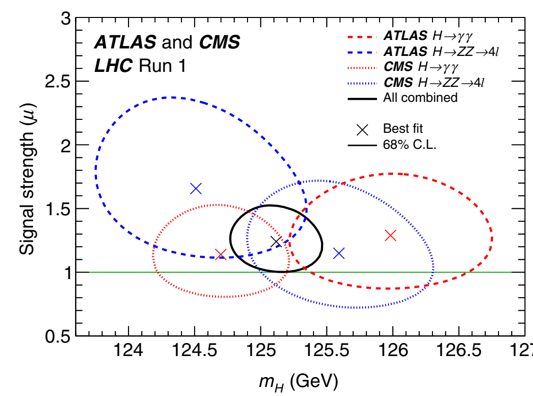




- Combined ATLAS and CMS measurement of the Higgs mass:







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

[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 consistent with the Standard Model.
  - Some "tensions" with respect to the SM have recently emerged:

    $\rightarrow$ not (yet?) conclusive, but 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: $\rightarrow$ LHC run II, Belle II, LHCb upgrade

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

The Quark-Flavour Code

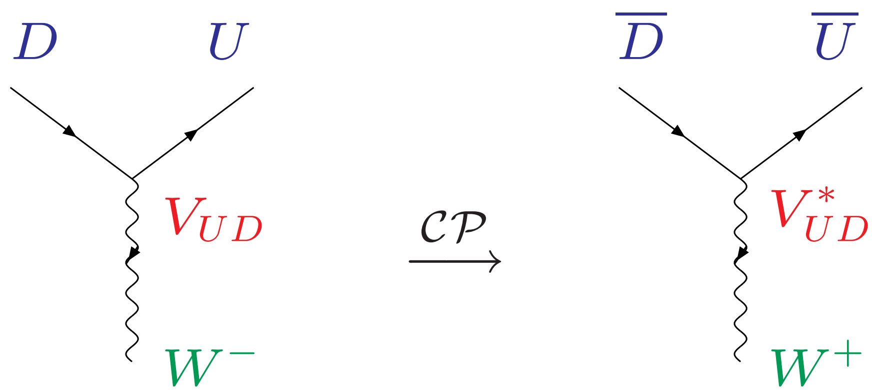
- Quark flavour physics and CP violation in the Standard Model (SM):

$$\left.\begin{array}{c}\text{flavour}\\\text{eigen-}\\\text{states}\end{array}\right\}\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}\left\{\begin{array}{c}\text{mass}\\\text{eigen-}\\\text{states}\end{array}\right.$$

quark-mixing matrix, also known as the

Cabibbo–Kobayashi–Maskawa (CKM) matrix

$\rightarrow$ *unitary* matrix; *complex* phase $\rightarrow$ CP violation



- New Physics (NP): $\rightarrow$ typically new sources for flavour and CP violation.

$\Rightarrow$ *encoded in weak decays of K, D and B mesons ...*

$\rightarrow$ *before searching for NP, understand the SM picture ...*

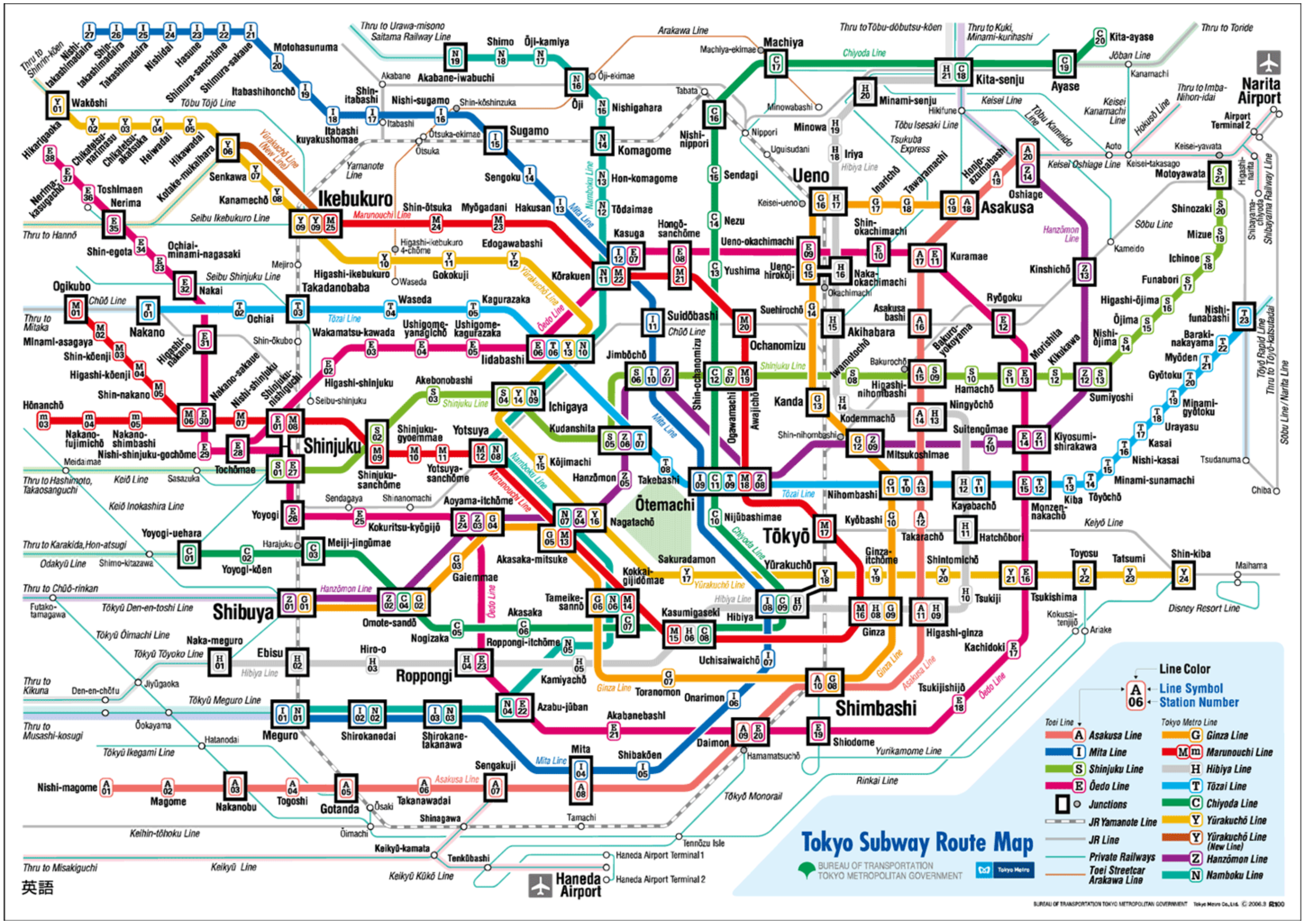
- The key problem:
  - The theory is formulated in terms of quarks, while flavour-physics experiments use their QCD bound states, i.e. B, D and K mesons.
  - *Impact of strong interactions (QCD)* $\rightarrow$ "hadronic" uncertainties

- The B-meson system is a *particularly promising* flavour probe:
  - Simplifications through the large b-quark mass $m_b \sim 5\,\text{GeV} \gg \Lambda_{\text{QCD}}$.
  - Offers various strategies to eliminate the hadronic uncertainties and to determine the hadronic parameters from the data.
  - Tests of clean SM relations that could be spoiled by NP ...

- This feature led to the "rise of the B mesons": $\rightarrow$ focus of this talk

... after K decays had dominated for 35 years!

→ very rich phenomenology, as complex as the *Tokyo Subway Map:*



⇒ have to make a selection: **[challenges, progress & hot topics]**

Theoretical Framework

. . . in a nutshell

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, ...

Low-Energy Effective Hamiltonians

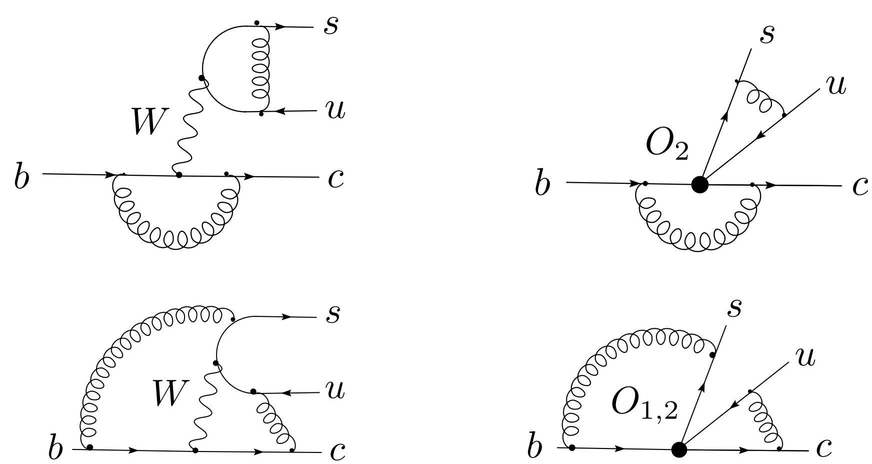
- Separation of short-distance from long-distance contributions (OPE):

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

[$G_{\rm F}$: 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:

$\Rightarrow B_K$ 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):

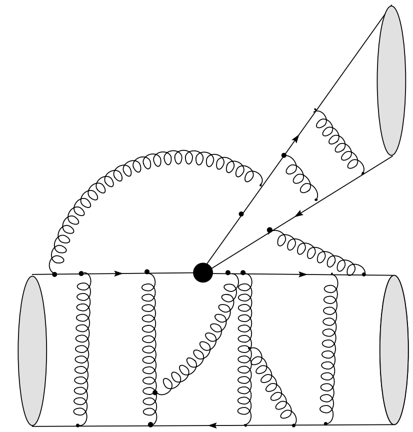
http://itpwiki.unibe.ch/flag/

- 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 & Huber (14)

- 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...

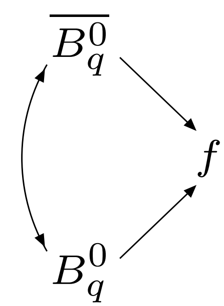
Studies of CP Violation

Circumvent $\langle \overline{f} | Q_k^j(\mu) | \overline{B} \rangle$ in CP-B Studies:

- Amplitude relations allow us in fortunate cases to eliminate the hadronic matrix elements ($\rightarrow$ typically strategies to determine the UT angle γ):
  - *Exact* relations: class of pure "tree" decays (e.g. $B \to DK$).
  - *Approximate* relations, which follow from the *flavour symmetries* of strong interactions, i.e. $SU(2)$ isospin or $SU(3)_{\rm F}$:

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

- Decays of neutral B_d or B_s mesons:



Interference effects through B^0_q–$\overline{B^0_q}$ mixing:

  - Lead to "mixing-induced" CP violation $S(f)$, in addition to "direct" CP violation $C(f)$ (caused by interference between decay amplitudes).
  - If one CKM amplitude dominates:

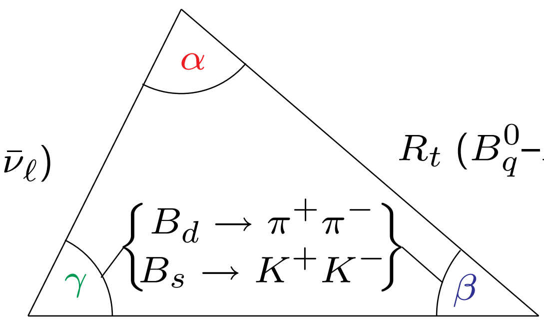
$$\Rightarrow \ \textit{hadronic matrix elements cancel in } S(f), \textit{ while } C(f) = 0.$$

A Brief Roadmap of Quark-Flavour Physics

- CP-B studies through various processes and strategies:

$B \to \pi\pi$ (isospin), $B \to \rho\pi$, $B \to \rho\rho$

R_b ($b \to u, c\ell\bar{\nu}_\ell$)



R_t (B_q^0–$\bar{B}_q^0$ mixing)

$B \to \pi K$ (penguins)

$\left.\begin{array}{l} B_u^\pm \to K^\pm D \\ B_d \to K^{*0} D \\ B_c^\pm \to D_s^\pm D \end{array}\right\}$ only trees

$B_d \to \psi K_S$ ($B_s \to \psi\phi$: $\phi_s \approx 0$)

$B_d \to \phi K_S$ (pure penguin)

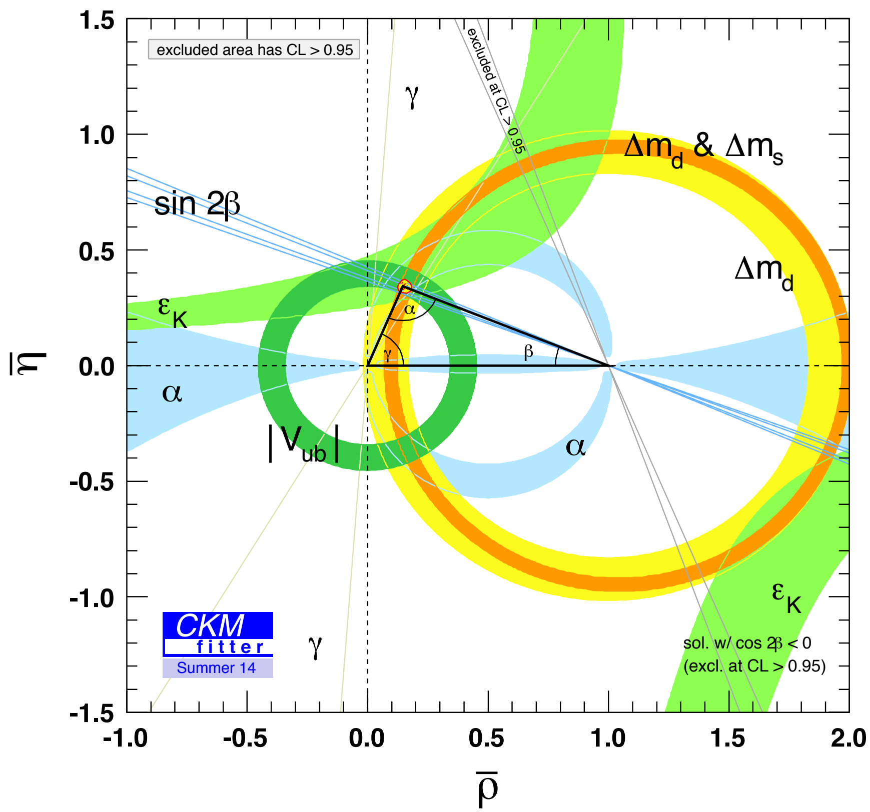
$\left.\begin{array}{l} B_d \to D^{(*)\pm}\pi^\mp : \ \gamma + 2\beta \\ B_s \to D_s^\pm K^\mp : \ \gamma + \phi_s \end{array}\right\}$ only trees

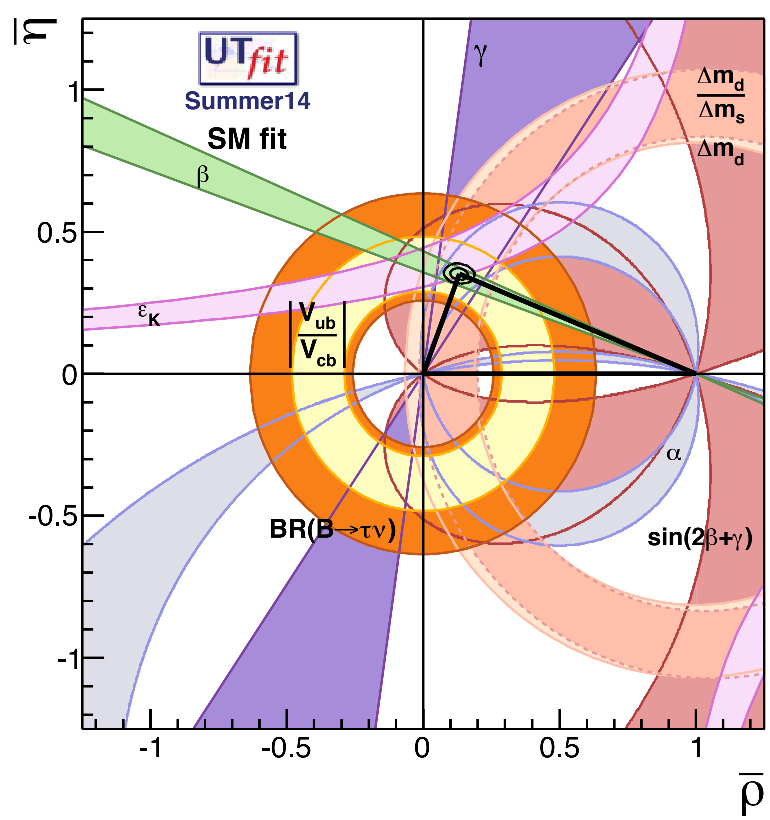
- Moreover "rare" decays: $B \to X_s\gamma$, $B_{d,s} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$, ...
  - Originate from loop processes in the SM.
  - Interesting correlations with CP-B studies.

New Physics (NP) $\Rightarrow$ Discrepancies (!?)

Unitarity Triangle

- Status of global fits:
  - *CKMfitter* Collaboration [http://ckmfitter.in2p3.fr/];
  - *UTfit* Collaboration [http://www.utfit.org/UTfit/WebHome]:

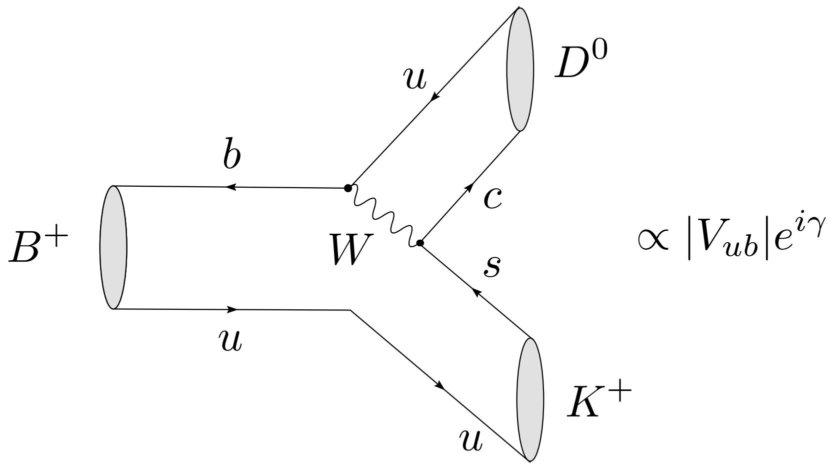


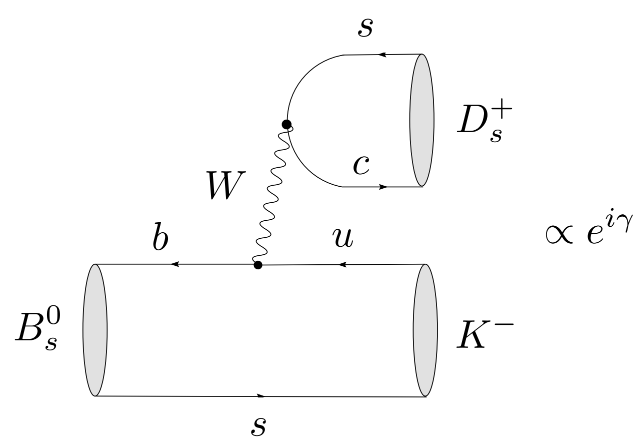


$\Rightarrow$ γ has currently still sizeable errors ...

Prospects for Extracting γ

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





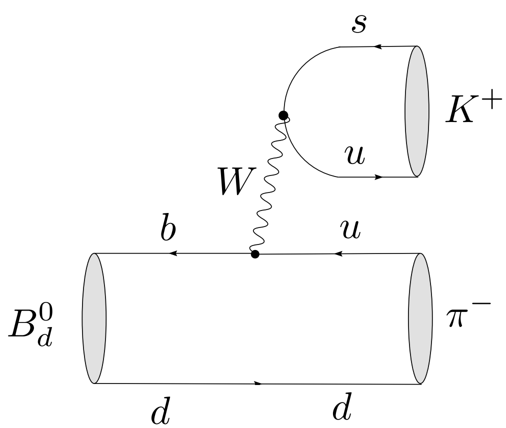
  - The corresponding determinations of γ are *theoretically clean*, i.e. the hadronic matrix elements cancel out (simply speaking).
  - Decays are very robust with respect to New-Physics contributions:

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

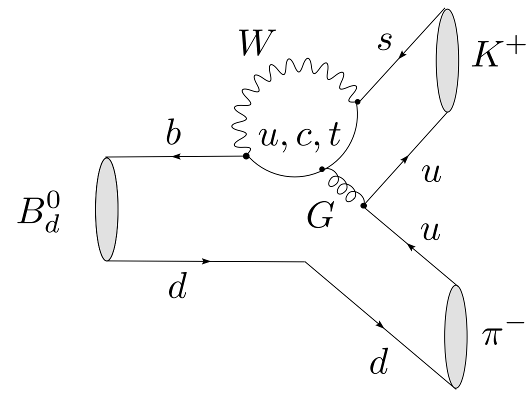
  - Excellent prospects for the era of Belle II and the LHCb upgrade:

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

- Decays with loops, i.e. penguin contributions: $B_{(s)} \to \pi\pi, \pi K, KK$



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



$\propto A\lambda^2$

  - 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* $(\gamma)_{\rm loops}$ *and comparison with* $(\gamma)_{\rm tree}$

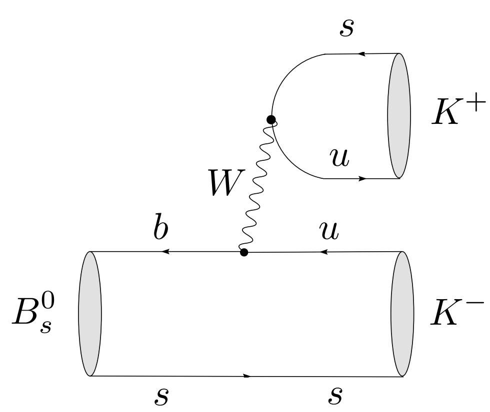
$\Rightarrow$ will discrepancies show up?

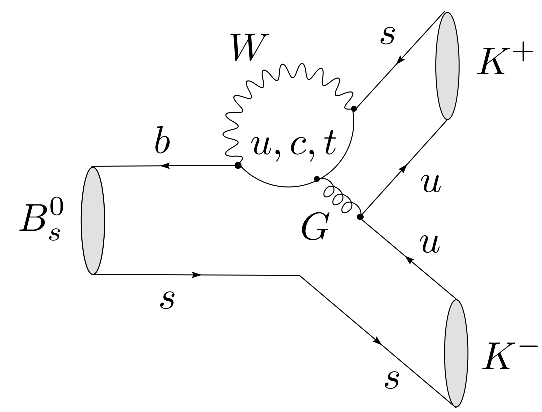
$\to$ particularly (most) promising method ...

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

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

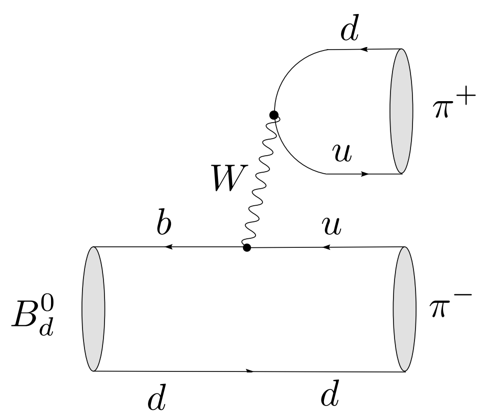
$$A(B_s^0 \to K^+K^-) \propto \mathcal{C}' \left[e^{i\gamma} + \left(\frac{1-\lambda^2}{\lambda^2}\right) d' e^{i\theta'}\right]$$

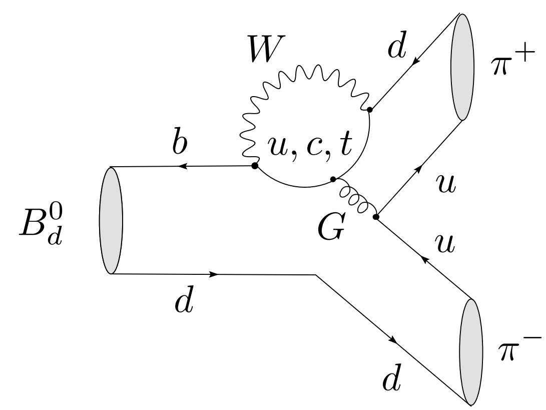




- $B_d^0 \to \pi^+\pi^-$:

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





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

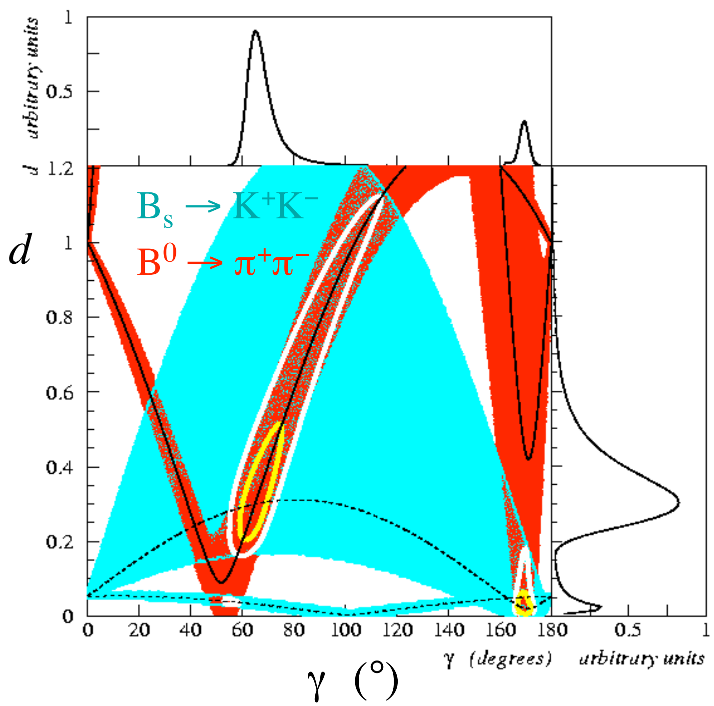
- The decays $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ are related to each other through the interchange of all down and strange quarks:

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

  - 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:

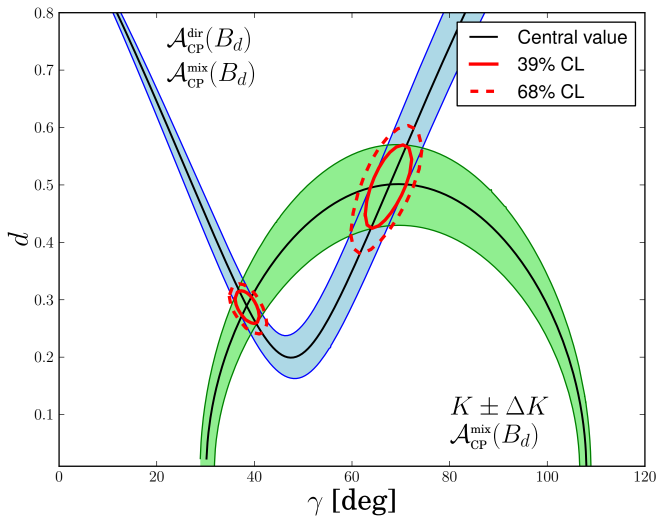


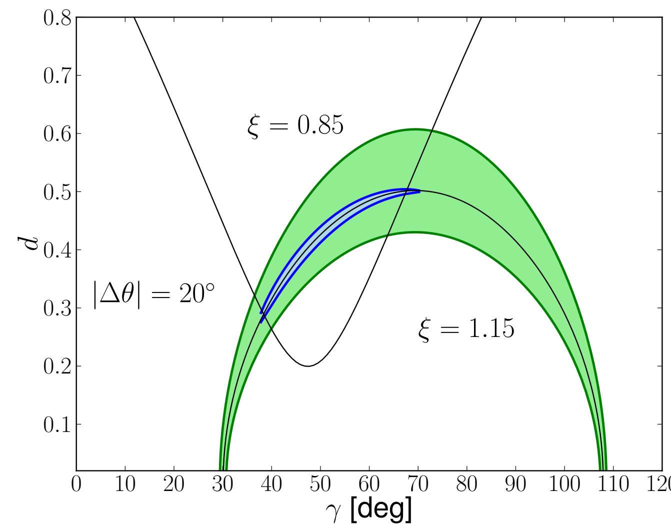
→ experimental accuracy for γ of a few degrees!

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

Extraction of γ

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





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

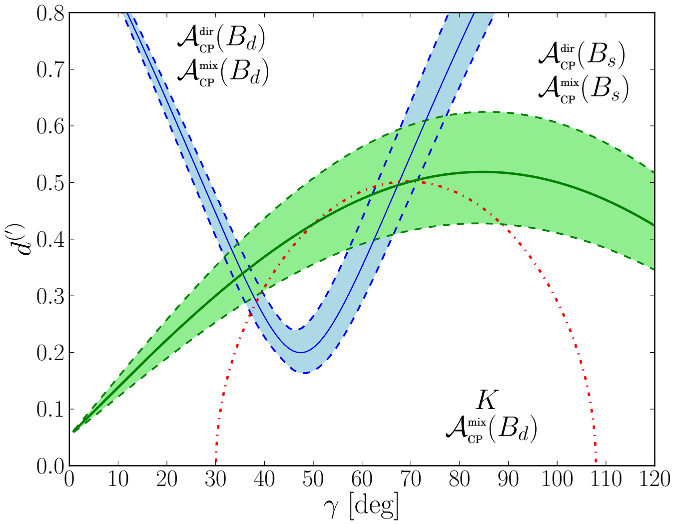
(2-fold ambiguity can be resolved [R.F. ('07)])

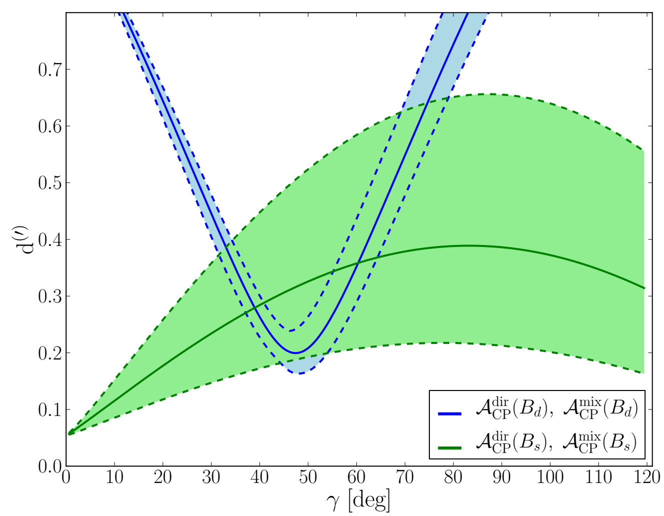
- "Tree-level" results: $\gamma = (73.2^{+6.3}_{-7.0})^\circ$ [CKMfitter], $(68.3 \pm 7.5)^\circ$ [UTfit].

[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 valuable 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]

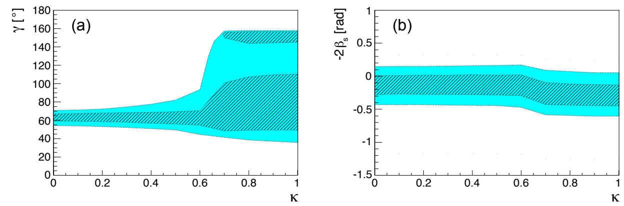


Figure 1: Dependences of the 68% (hatched areas) and 95% (filled areas) probability intervals on the allowed amount of non-factorizable U-spin breaking, for (a) γ from analysis A and (b) $-2\beta_s$ from analysis B.

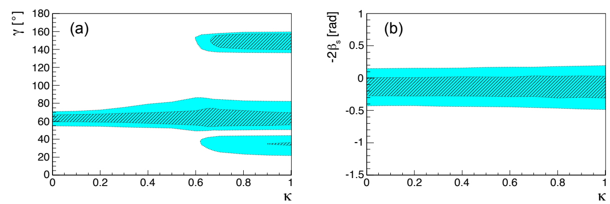


Figure 3: Dependences of the 68% (hatched areas) and 95% (filled areas) probability intervals on the allowed amount of non-factorizable U-spin breaking, for (a) γ from analysis C and (b) $-2\beta_s$ from analysis D.

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

[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.

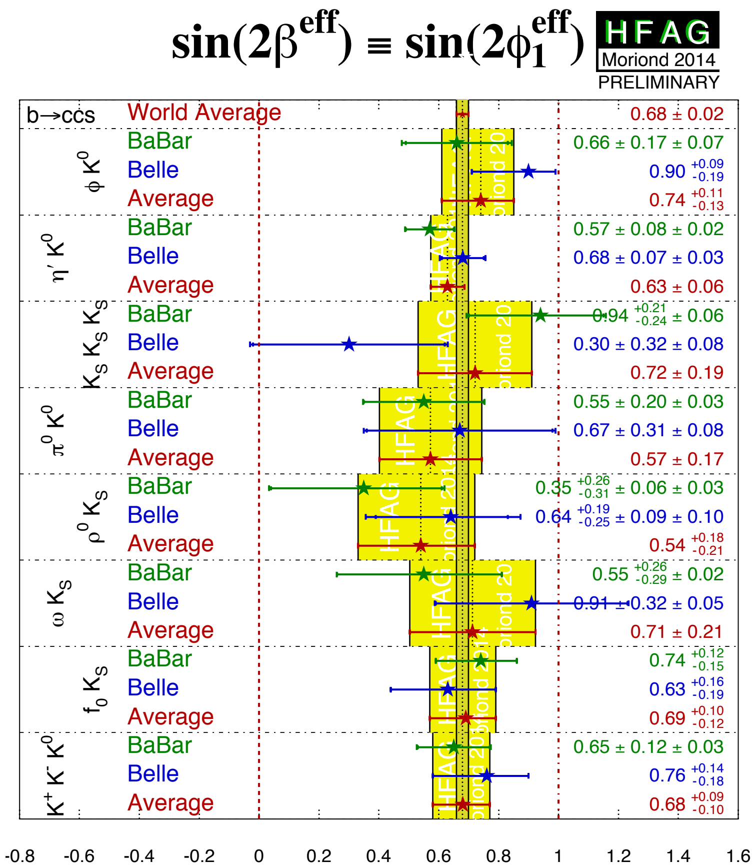
- The U-spin method – analogous to the $B^0_s \rightarrow K^+K^-$, $B^0_d \rightarrow \pi^+\pi^-$ system – to extract γ can be applied to each point of the Dalitz plot.

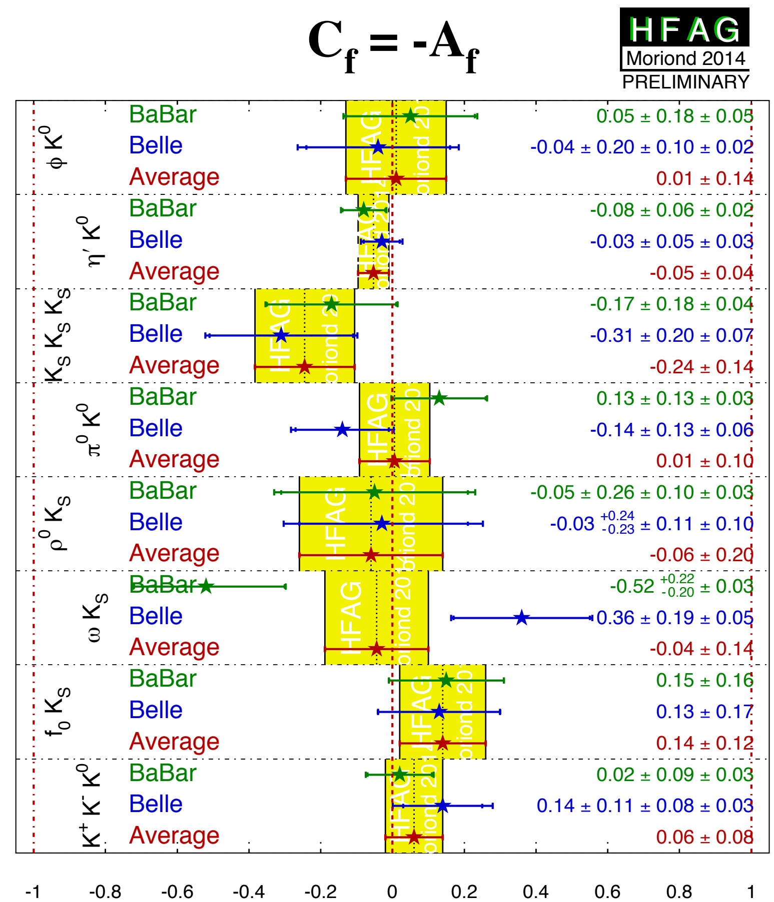
- A potential advantage of using three-body decays is that the effects of U-spin breaking may be reduced by averaging over the Dalitz plot.

[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 ...

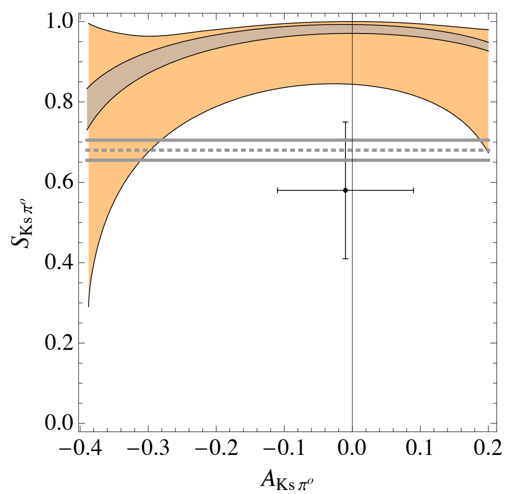
Particularly Interesting Decay: $B^0 \to \pi^0 K^0$

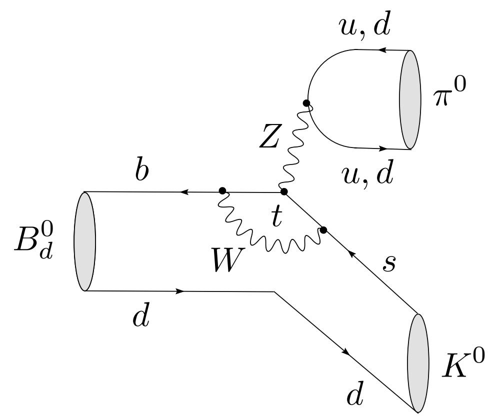
- Isospin relation between neutral $B \to \pi K$ amplitudes:

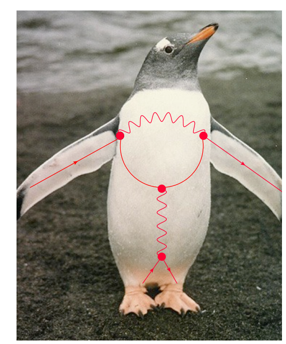
$$\sqrt{2}\,A(B^0 \to \pi^0 K^0) + A(B^0 \to \pi^- K^+) = -\underbrace{\left[(\hat{T}+\hat{C})e^{i\gamma} + \hat{P}_{\rm ew}\right]}_{(\hat{T}+\hat{C})(e^{i\gamma} - q e^{i\omega})} \equiv 3A_{3/2}$$

- Implies a correlation between the CP asymmetries:

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



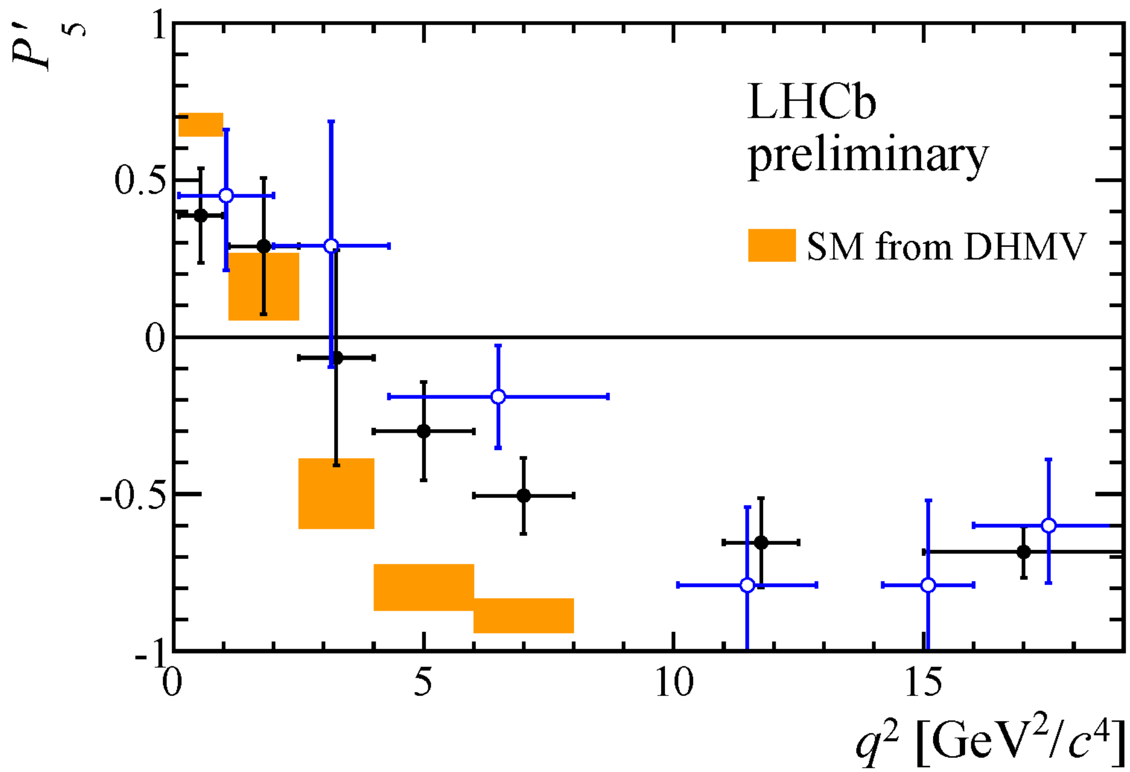




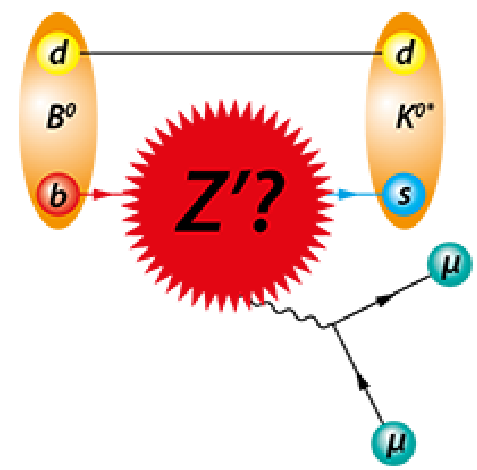
Electroweak "penguin" contribution $\to$ NP?

[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:



[$\to$ see below]

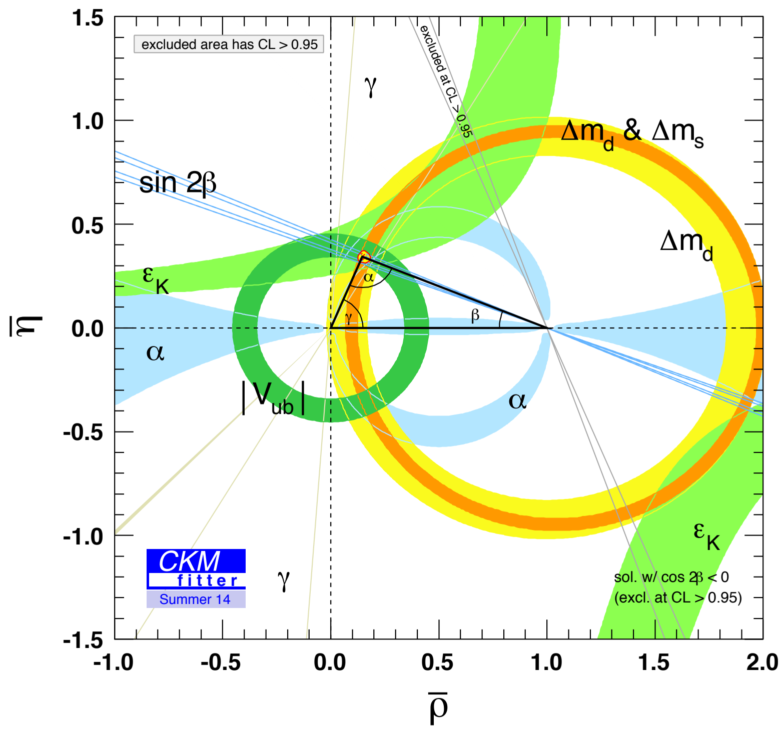


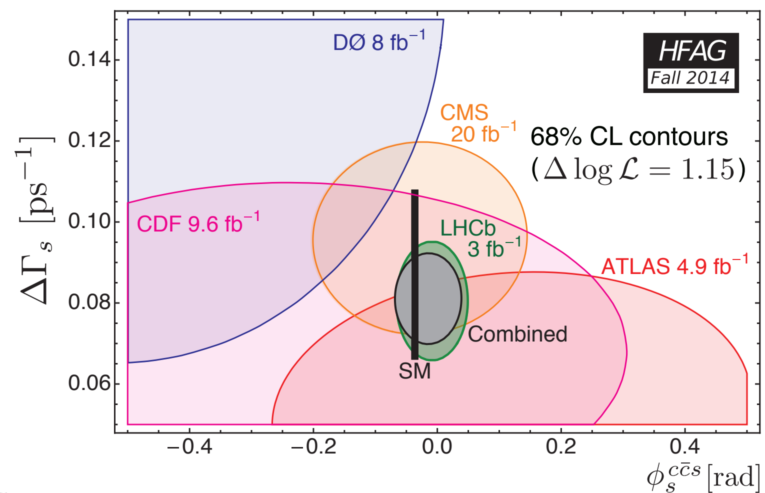
- Puts also other non-leptonic B-meson decays with sensitivity to Electroweak Penguins (again...) into the spotlight:

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

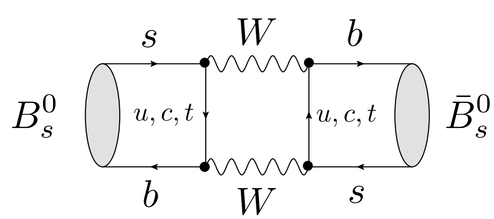
Precision Measurements of the B_q^0–$\bar{B}_q^0$ Mixing Phases

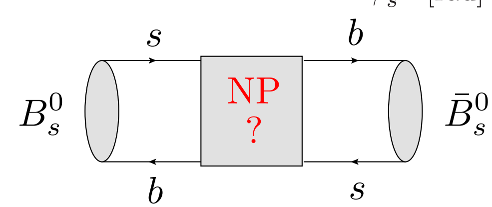
Current Experimental Situation





- B_s^0–$\bar{B}_s^0$ mixing phase:



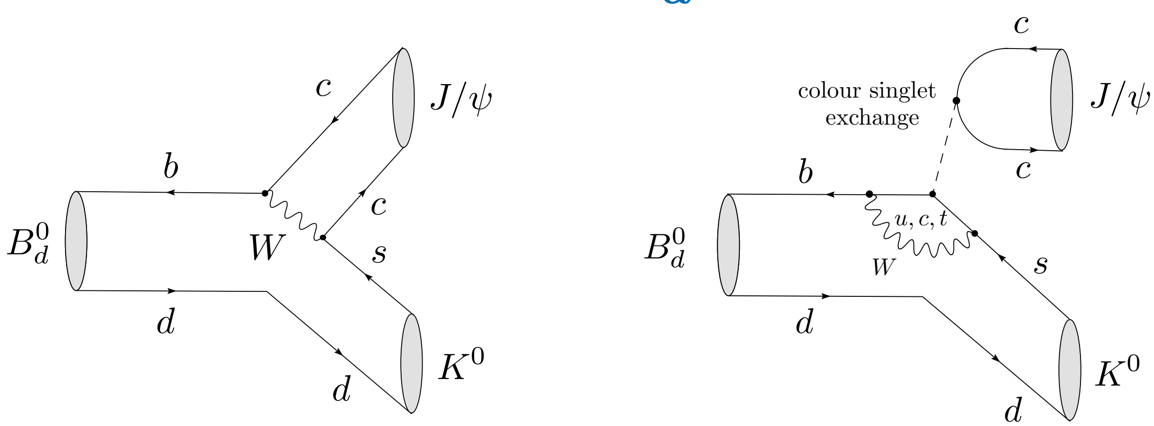


$$\boxed{\phi_s^{c\bar{c}s} \equiv \phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP} = -2\lambda^2\eta + \phi_s^{\rm NP}}$$

- HFAG average of the current experimental data:

$$\phi_s = -(0.86 \pm 2.01)^\circ \quad \text{vs.} \quad \phi_s^{\rm SM} = -\left(2.086^{+0.080}_{-0.069}\right)^\circ$$

CP Violation in $B_d^0 \to J/\psi K_S$



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

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

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

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

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

[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:

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

  - Key feature: $\to$ *"magnified" penguin parameters (no ϵ suppression)*

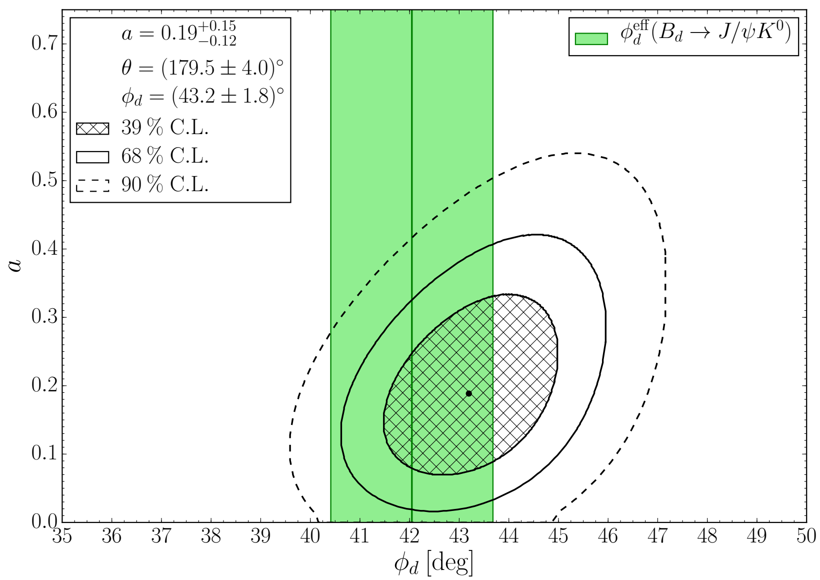
$$\boxed{A(B^0_s \to J/\psi K_{\mathrm{S}}) \propto \left[1 - a e^{i\theta} e^{i\gamma}\right]}$$

  - 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:*

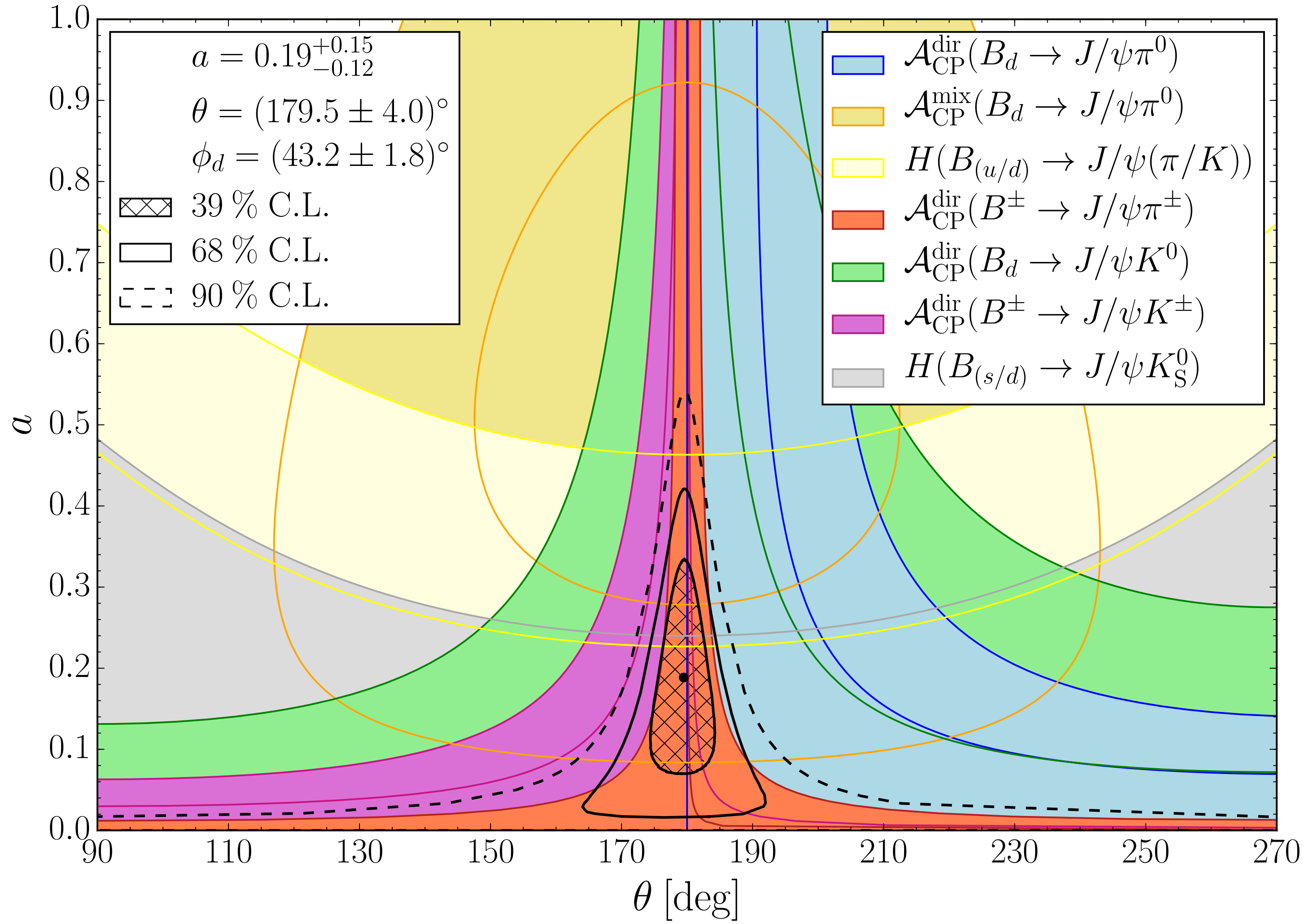
- Internal consistency checks look fine, i.e. not any "anomalous" feature.
- The global fit yields $\chi^2_{\rm min} = 2.6$ for four degrees of freedom $(a, \theta, \phi_d, \gamma)$, indicating good agreement between the different input quantities:



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

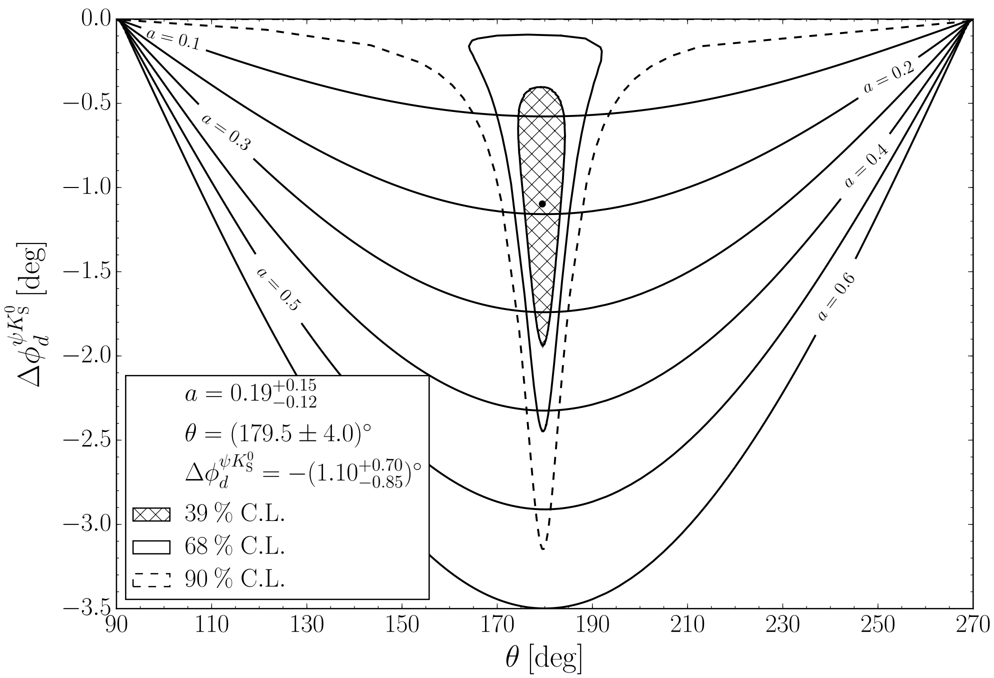
[K. De Bruyn and R.F., JHEP **1503** (2015) 145 [arXiv:1412.6834 [hep-ph]]]

- 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 $\Delta\phi_d^{\psi K^0_S}$

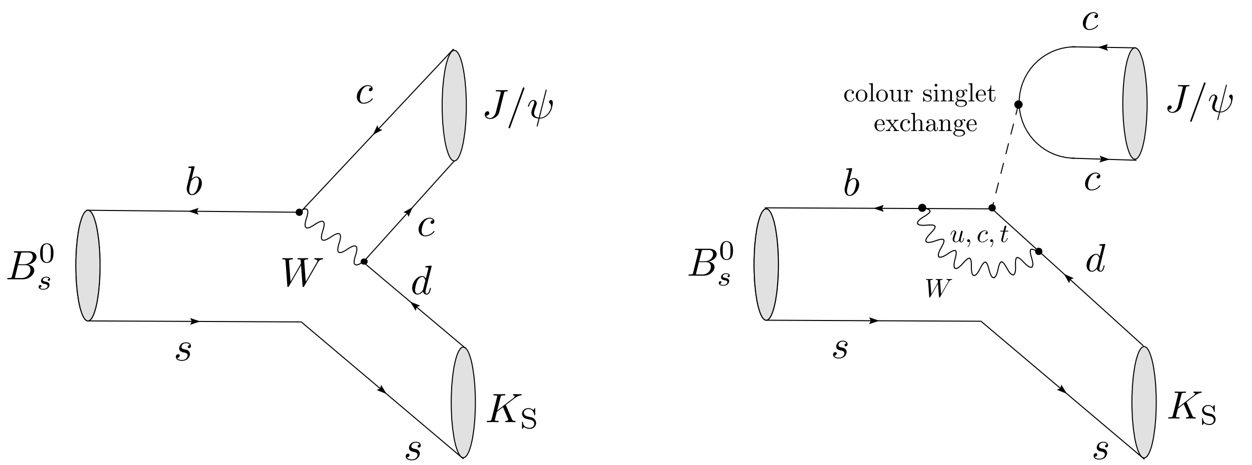


$$\Delta\phi_d^{\psi K^0_S} = -\left(1.10^{+0.70}_{-0.85}\right)^\circ$$

$\rightarrow \chi^2$ 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:

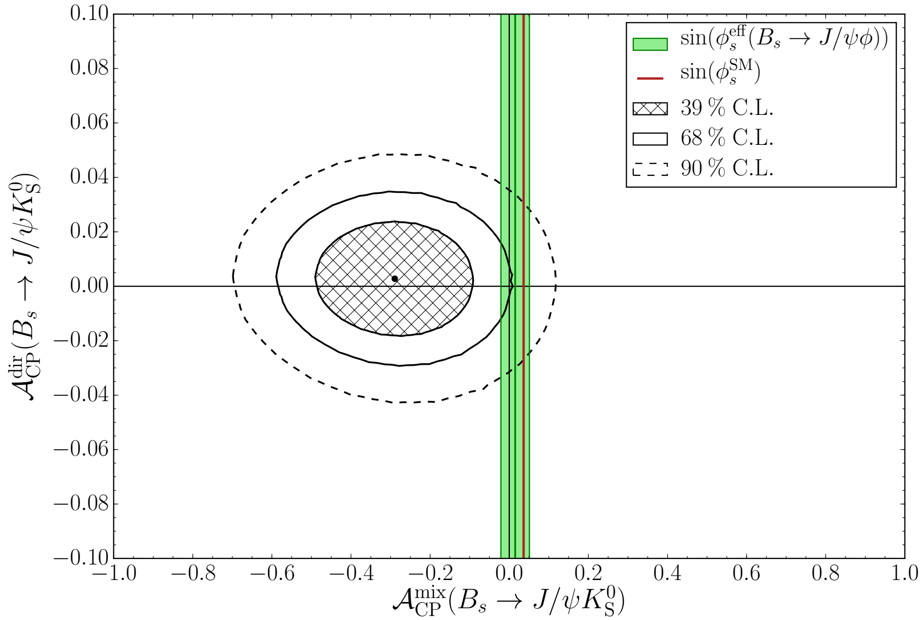
$$a e^{i\theta} \stackrel{U\,\text{spin}}{=} a' e^{i\theta'}$$

[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 $B \rightarrow D^{(*)}K^{(*)}$: $\gamma = (70 \pm 1)^\circ$
  - ϕ_s measured from $B^0_s \rightarrow J/\psi\phi$ and penguin strategies (see below):

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

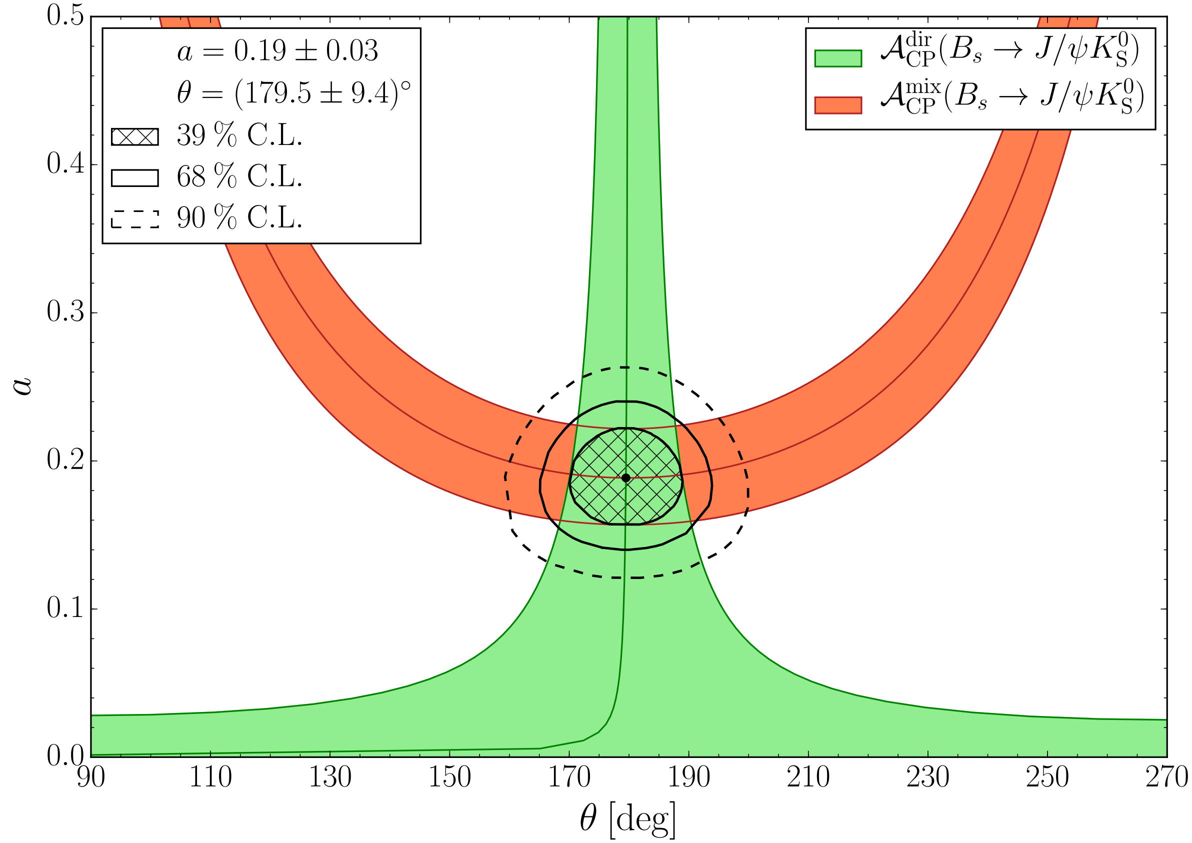
  - CP violation in the $B_s \rightarrow J/\psi K^0_{\rm S}$ decay:[1]

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

[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 $B^0_s \rightarrow D^\mp_s K^\pm$ decays, corrected for the $B^0_s \rightarrow J/\psi K^0_{\rm S}$ event yield (no *official* LHCb study).

Determination of Penguin Parameters



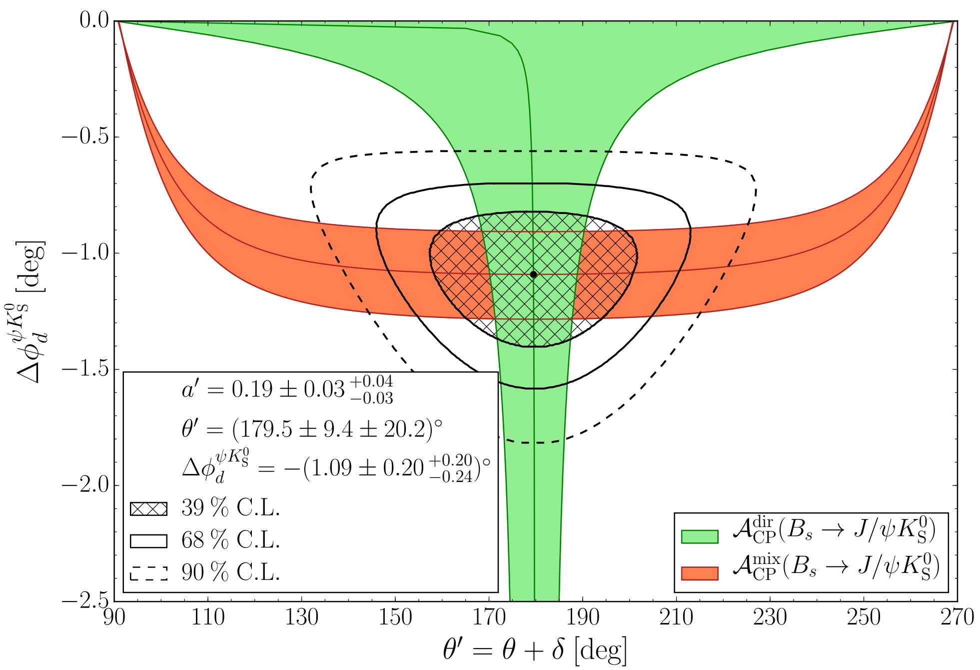
- <u>Comments:</u>
  - This determination of a and θ is *theoretically clean*.
  - Relation to a', θ' (enter $B_d \to J/\psi K_{\rm S}$) through U-spin symmetry.

... conversion into $\Delta\phi_d$

- U-spin relation between $B^0_s \to J/\psi K^0_{\rm S}$ and $B^0_d \to J/\psi K^0_{\rm S}$:

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

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



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

Using Branching Ratio Information

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

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

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

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

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

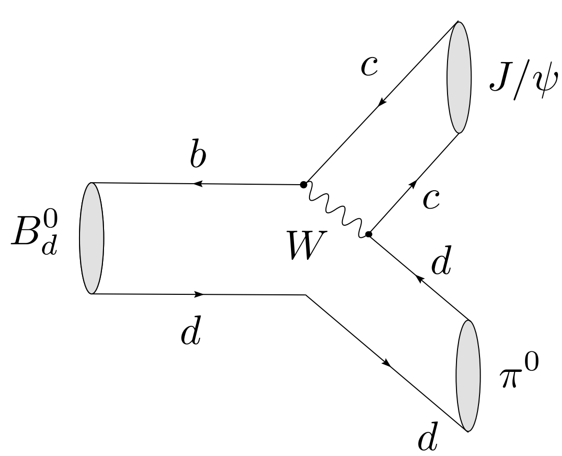
$$\left|\frac{\mathcal{A}'}{\mathcal{A}}\right| = \sqrt{\epsilon\, H_{(a,\theta)} \frac{\mathrm{PhSp}\,(B_s \rightarrow J/\psi K^0_{\rm S})}{\mathrm{PhSp}\,(B_d \rightarrow J/\psi K^0_{\rm S})} \frac{\tau_{B_s}}{\tau_{B_d}} \frac{\mathcal{B}\,(B_d \rightarrow J/\psi K^0_{\rm S})_{\rm theo}}{\mathcal{B}\,(B_s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

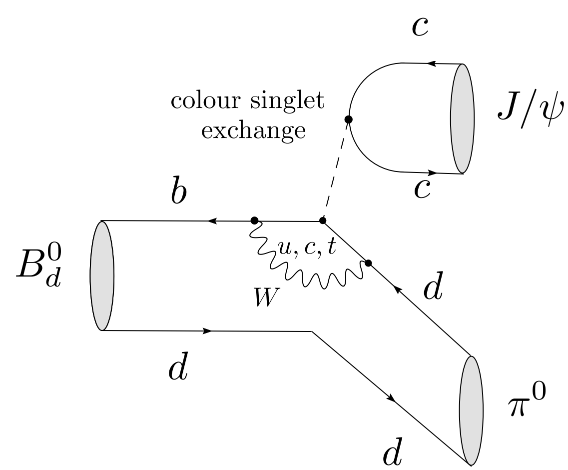
- $\mathcal{B}(B_s \rightarrow f)$ measurements @ LHCb limited by $f_s/f_d = 0.259 \pm 0.015$:

  $\rightarrow$ 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 $\Rightarrow$ $B_d^0 \to J/\psi\pi^0$

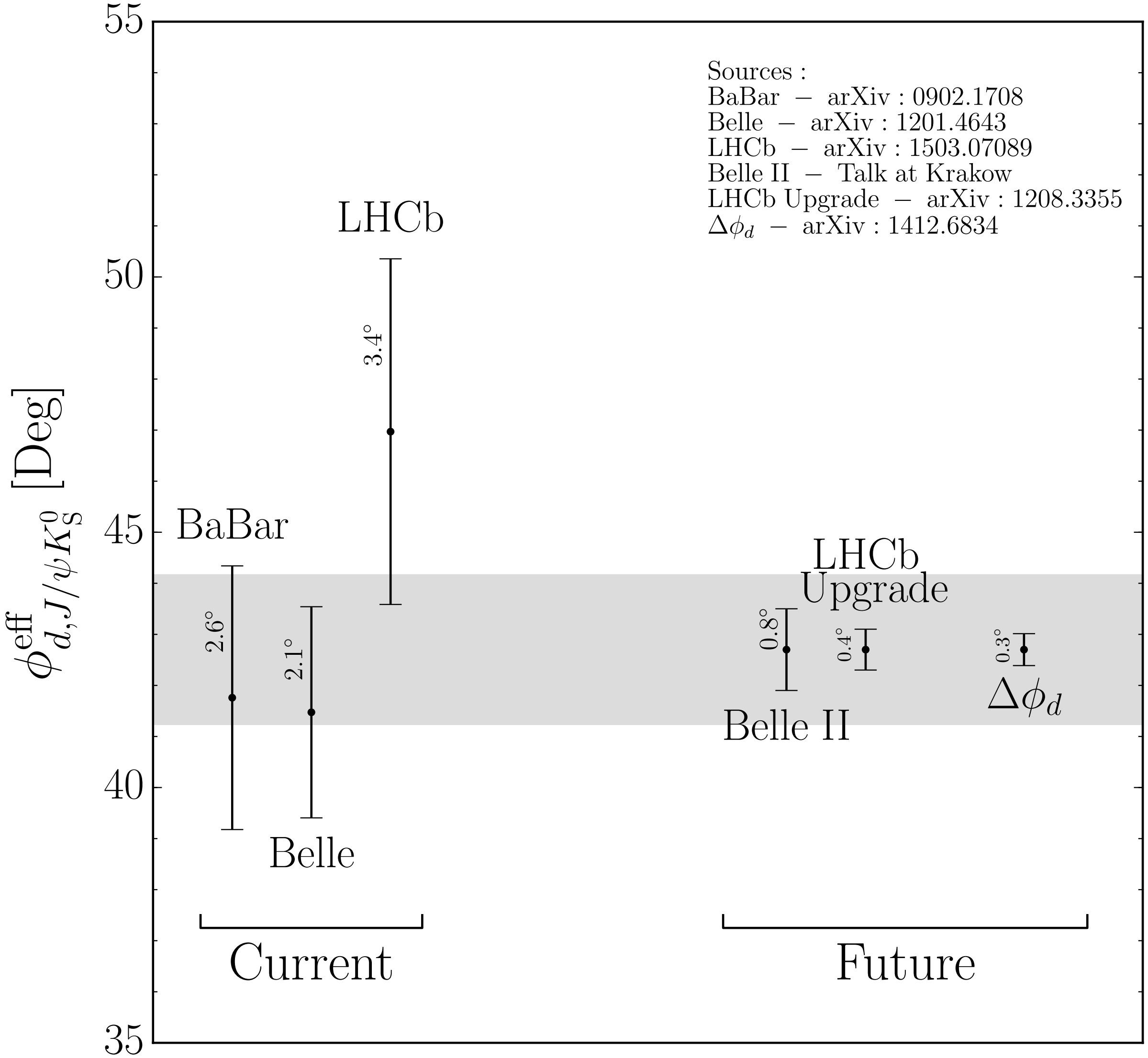
- CKM amplitude structure of $B_d^0 \to J/\psi\pi^0$ is analogous to $B_s^0 \to J/\psi K_{\rm S}$:

$\Rightarrow$ 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

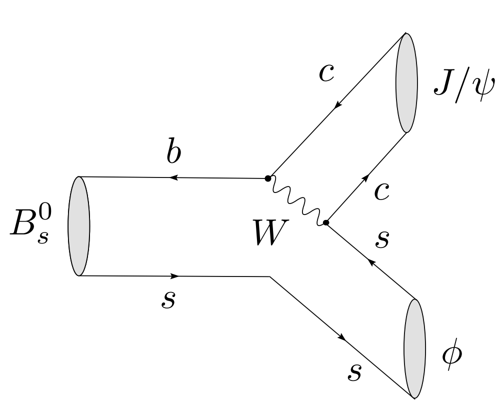


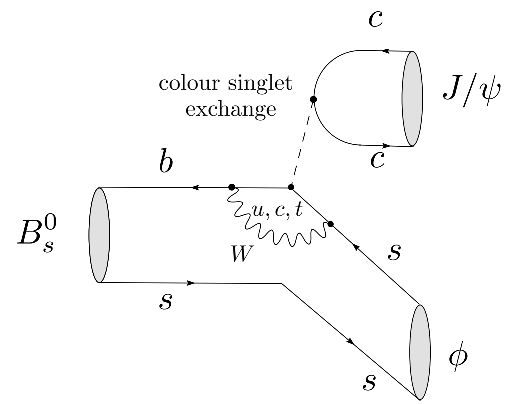
[Compilation: Kristof De Bruyn]

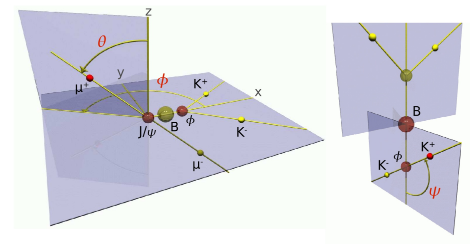
$B^0_{s,d} \to J/\psi V$ Decays:

- $B^0_s \to J/\psi\phi$: 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 $\phi_{s,f}^{\rm eff}$: $\to$ *pioneering character:*

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

  - Assuming a universal value of $\phi_s^{\rm eff}$:

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

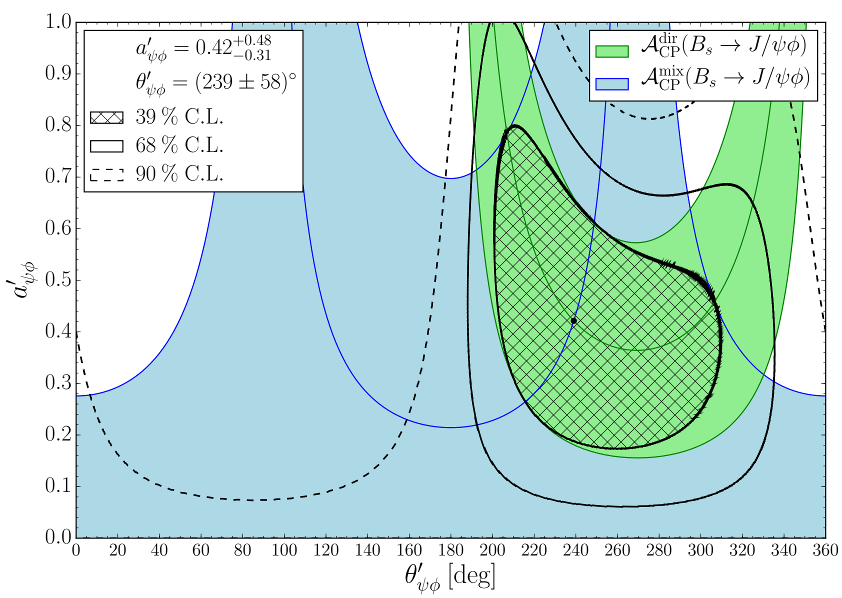
- Further polarisation-dependent LHCb results for $B_s^0 \to J/\psi\phi$:

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

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

⋆ 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:



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

- Use the $SU(3)$ flavour symmetry.

- Neglect certain E and PA topologies:

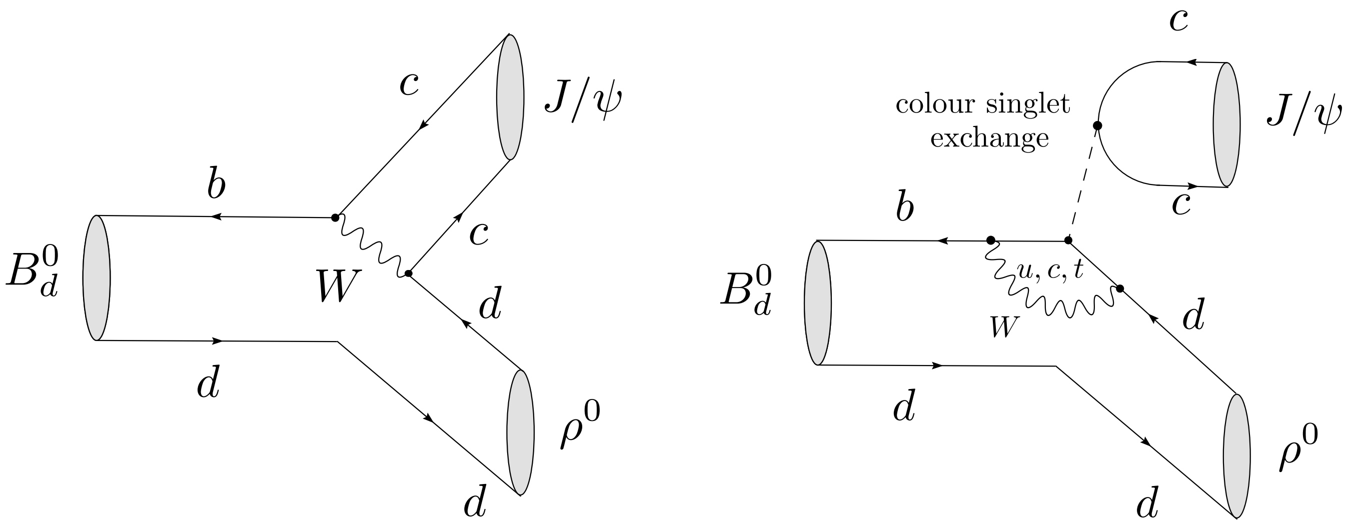
  – Probed through $B_d^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\rho^0$.

  – 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: $\to \phi_{d,f}^{\text{eff}} \equiv 2\beta_f^{\text{eff}}$ (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: $\Rightarrow$

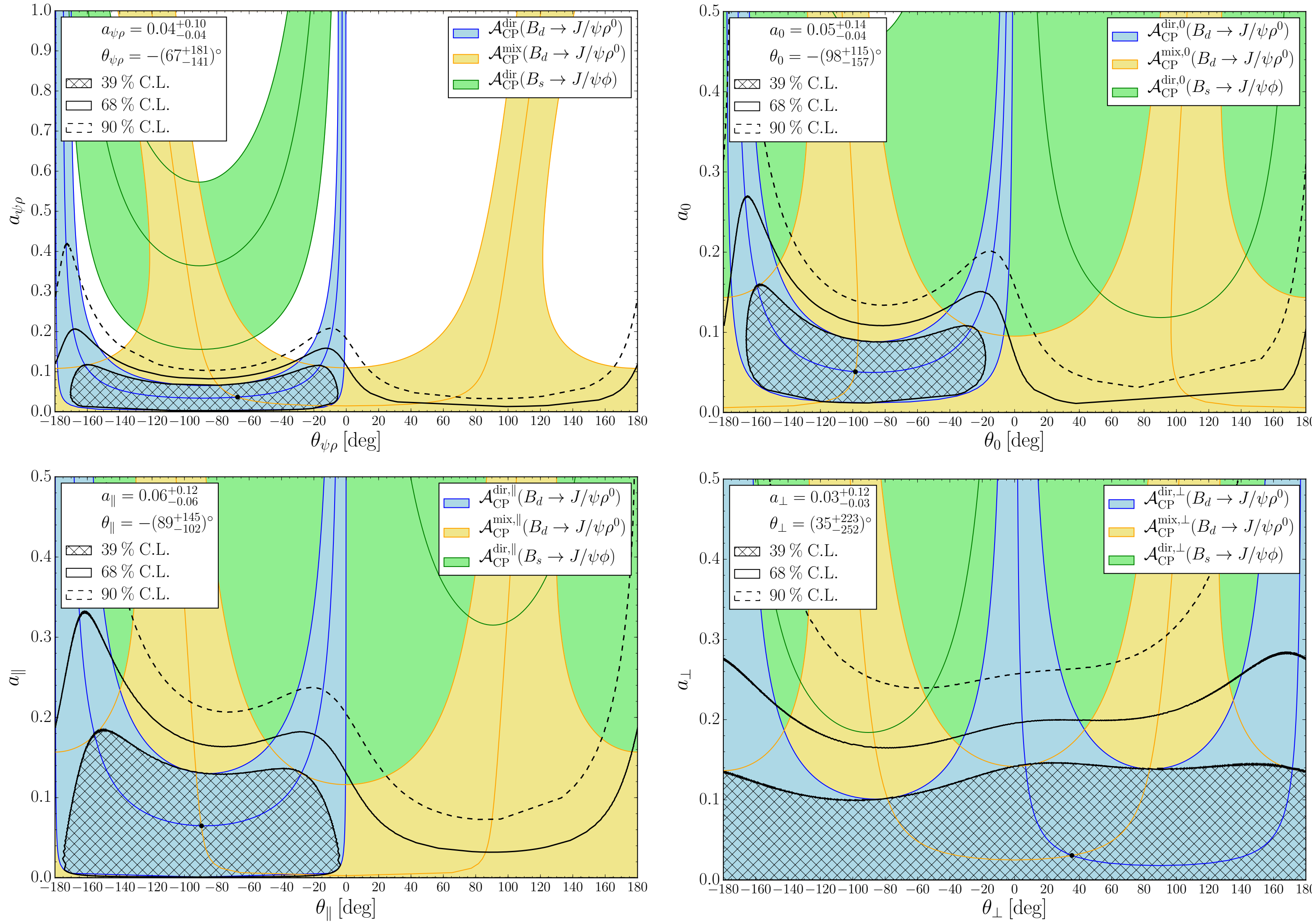
$$\phi_d^{\rm eff} = \left(41.7 \pm 9.6^{+2.8}_{-6.3}\right)^\circ$$

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

- 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:

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

- 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: [$\to B_{s,d}^0 \to J/\psi K_\text{S}$ discussion]

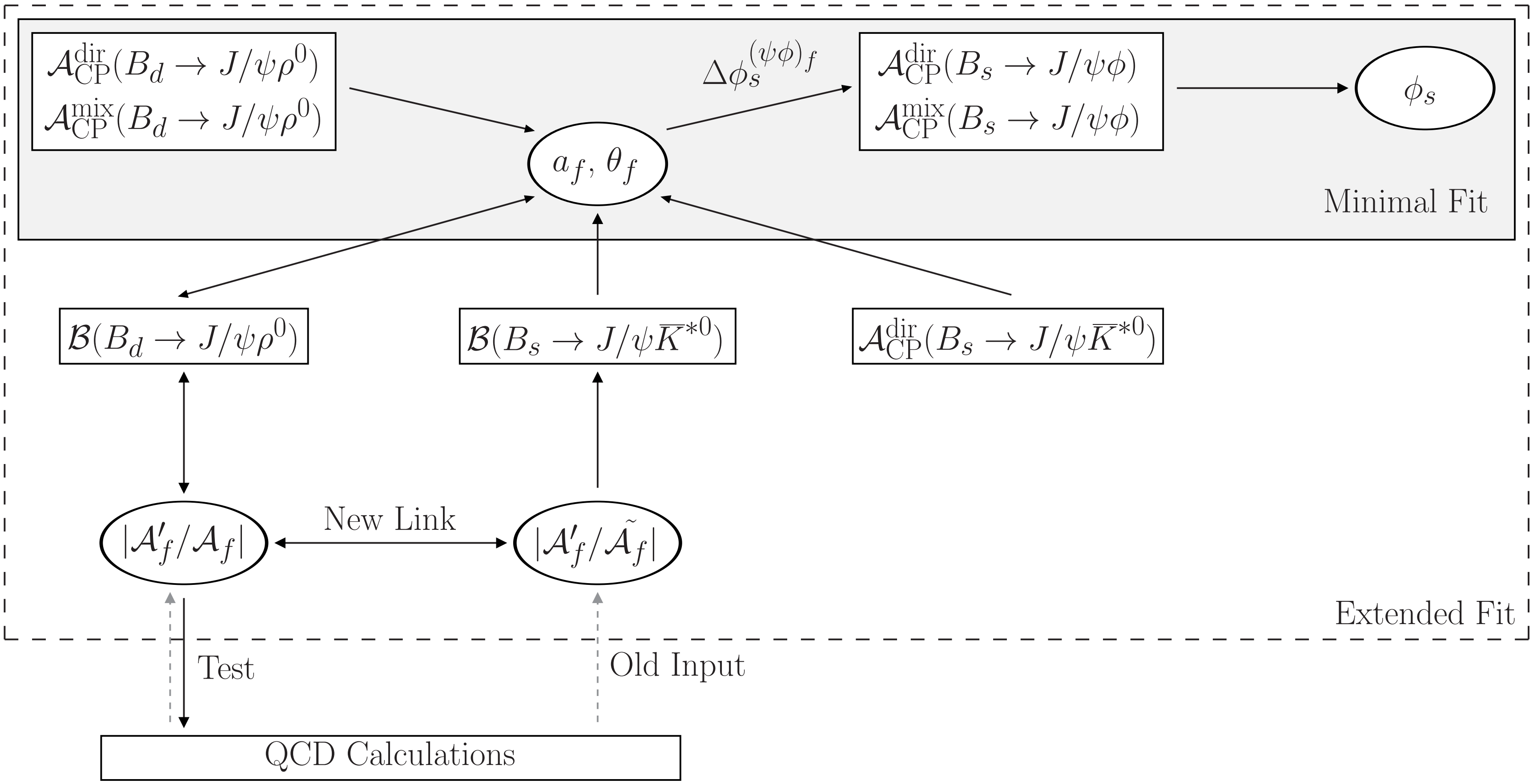
$$\left|\frac{\mathcal{A}'_0(B_s\to J/\psi\phi)}{\mathcal{A}_0(B_d\to J/\psi\rho^0)}\right| = 1.06 \pm 0.07\,(\text{stat}) \pm 0.04\,(\text{a}_0, \theta_0) \stackrel{\text{fact}}{=} 1.43 \pm 0.42$$

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

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

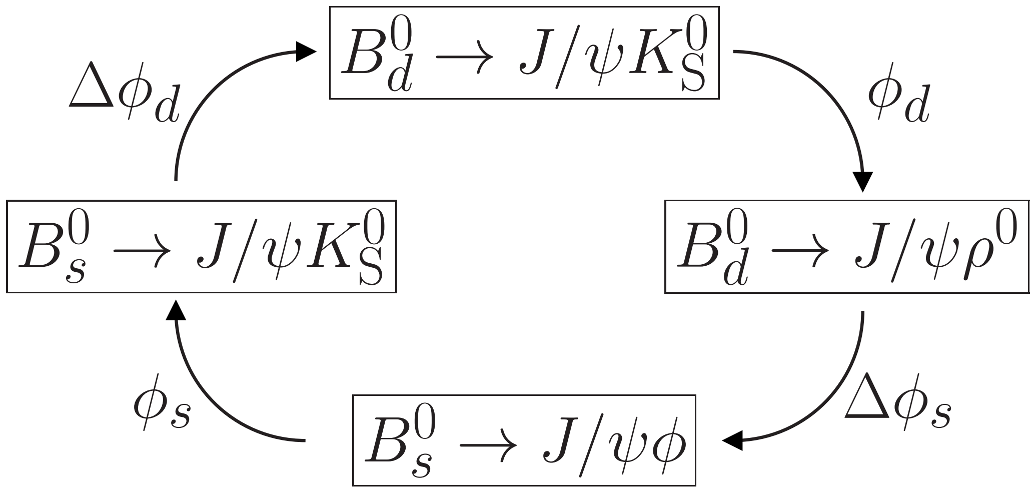
[Naive "fact" refers to LCSR form factors [Ball & Zwicky ('05)];
recent PQCD calculation: X. Liu, W. Wang and Y. Xie (2014)]

A Penguin Roadmap



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

Interplay Between the ϕ_d and ϕ_s Analyses



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

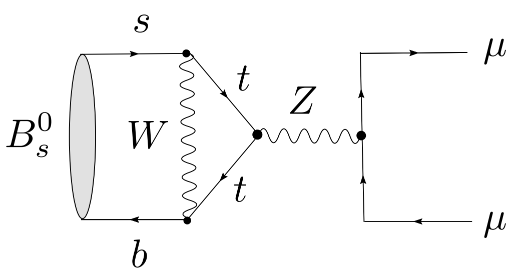
Studies of Rare Decays

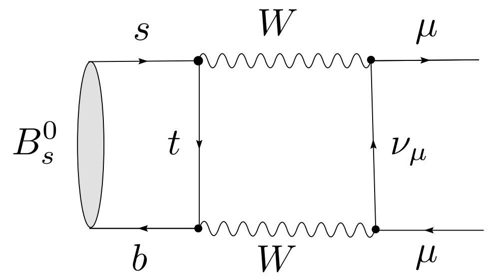
New Observables

$\rightarrow$ 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**

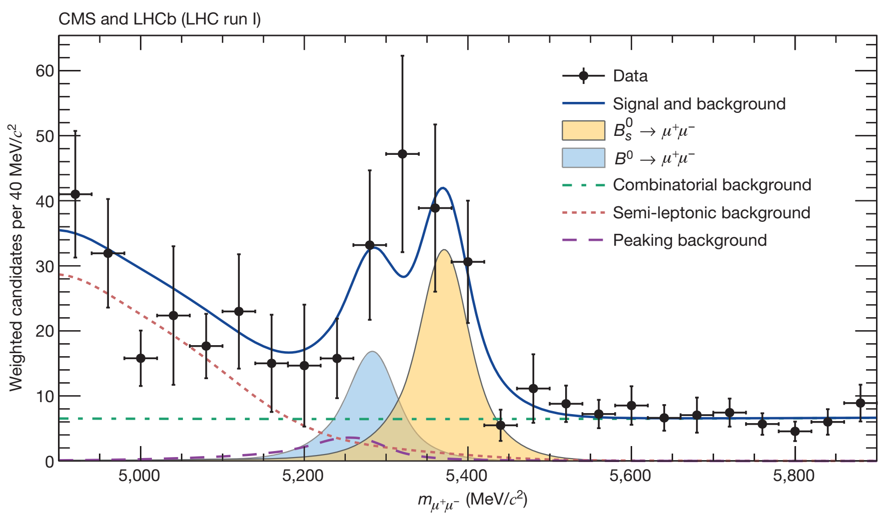
- Hadronic sector: $\to$ very simple, only the B_s decay constant F_{B_s} enters:

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

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

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

- Combined analysis of CMS and LHCb:



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

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

- Most recent theoretical Standard Model analysis:

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

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

- Interesting situation to monitor:

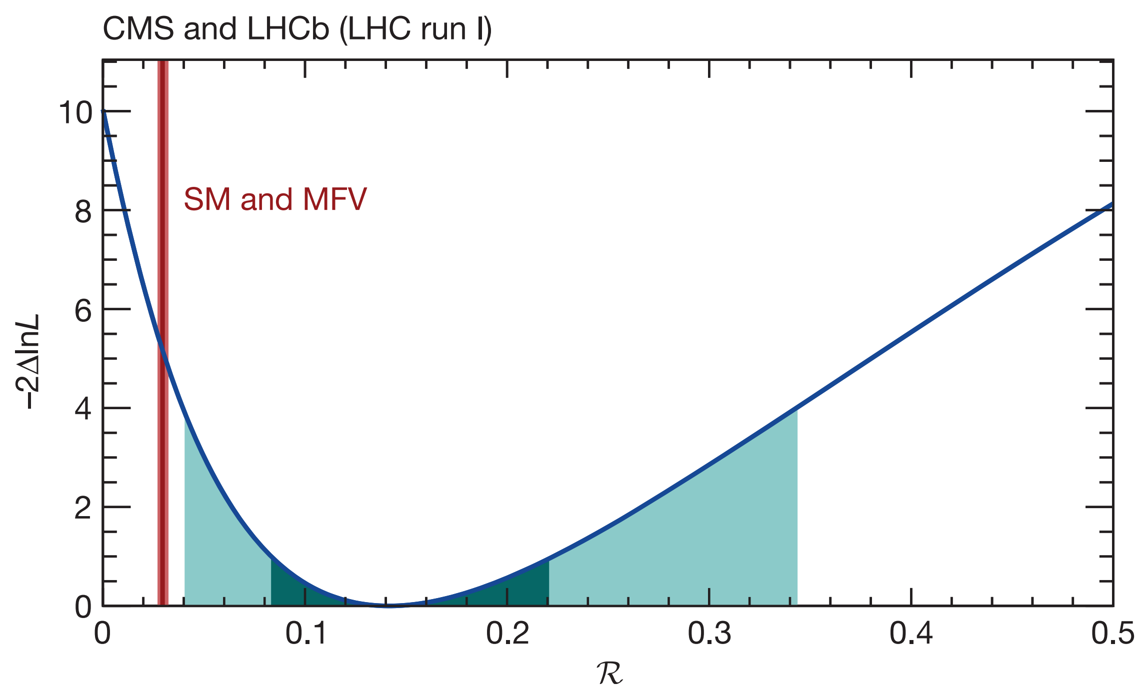


Figure 4 | Variation of the test statistic $-2\Delta\ln L$ as a function of the ratio of branching fractions $\mathcal{R} \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$. The dark and light (cyan) areas define the $\pm 1\sigma$ and $\pm 2\sigma$ confidence intervals for $\mathcal{R}$, 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:

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

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

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

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

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

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

  - Currently only time-integrated analyses $\to$ 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:

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

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

  – Current situation: $R = 0.82 \pm 0.21$

  – R *does not* allow a separation of the P and S contributions:

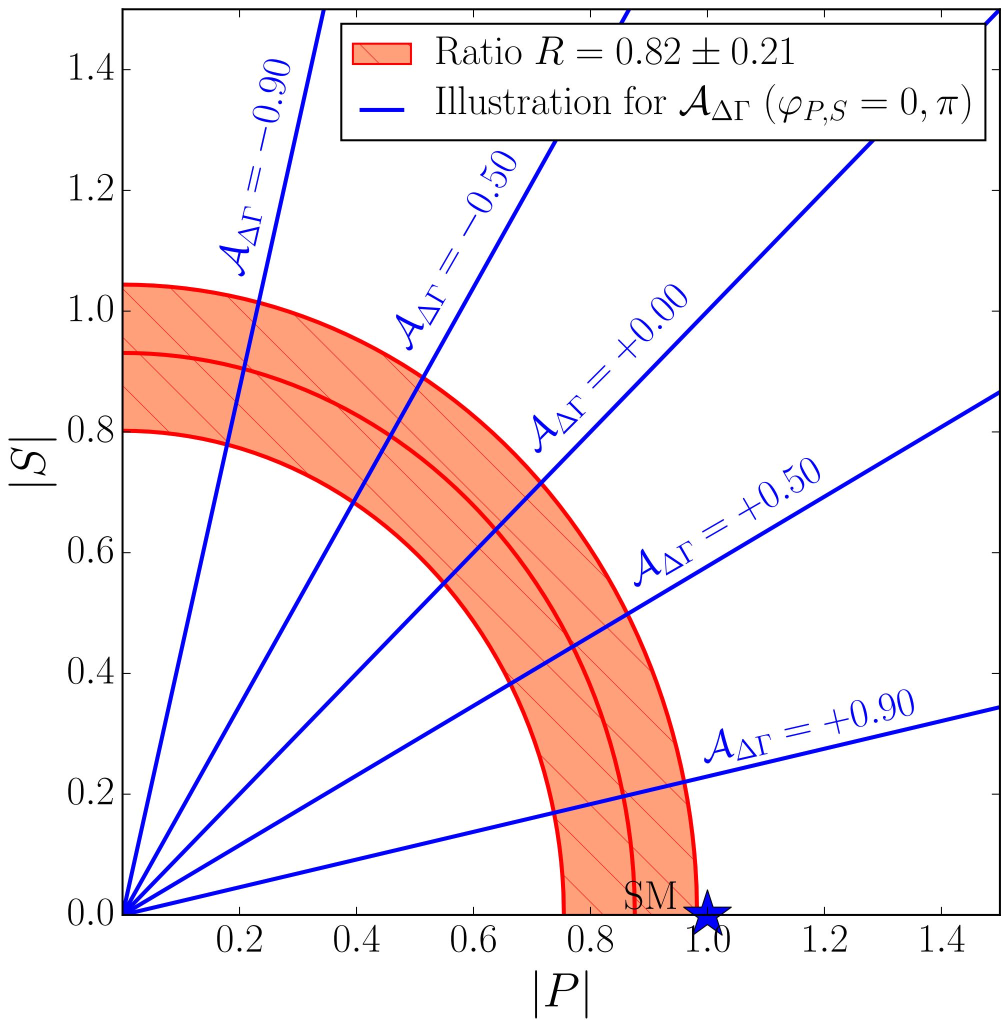
$\Rightarrow$ sizeable NP could be present ...

- 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 $B_s \to \mu^+\mu^-$

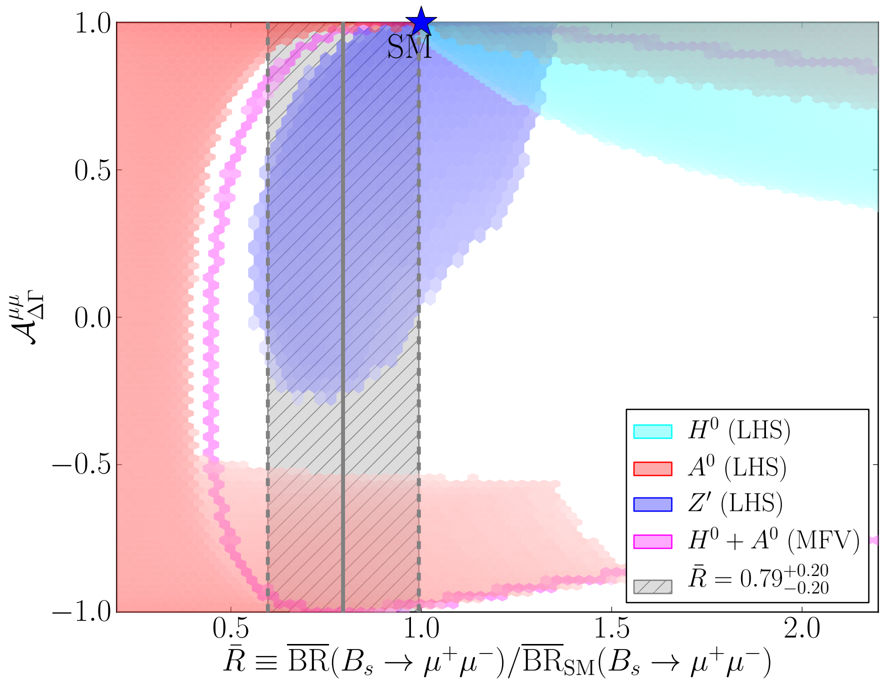
- Current constraints in the $|P|$–$|S|$ plane and illustration of those following from a future measurement of the $B_s \to \mu^+\mu^-$ obsevable $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$:



- 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.

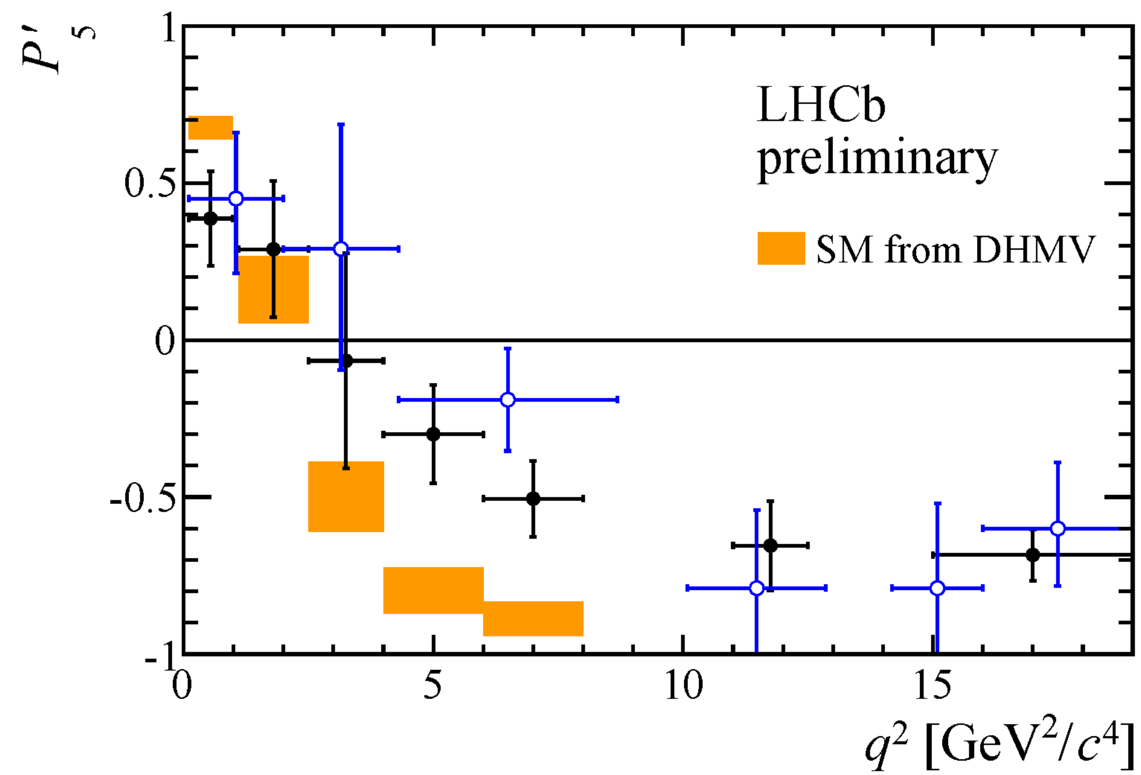
$\to$ { interesting to fully exploit the physics potential of semileptonic rare $B_{(s)}$ decays in the era of Belle II and the LHCb upgrade.

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

“Puzzles” in
Semileptonic
Rare B Decays

Results from LHCb: $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$

- "Optimised" observables of the angular distribution: $\to$ focus on P_5'



[Descotes-Genon, Matias & Virto ('13); Buras & Girrbach ('13); Jäger & Martin Camalich ('13); Hurth & Mahmoudi ('14); Lyon & Zwicky ('14); Hiller & Zwicky ('14); Descotes-Genon, Hofer, Matias & Virto, ...]

- Detailed recent analysis: Altmannshofer & Straub, arXiv:1503.06199

$\to$ *guideline for the following discussion + results*

- Many more observables provided by $b \to s$ semileptonic rare decays:

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

Table 1: Observables where a single measurement deviates from the SM by 1.9σ or more (cf. [15] for the $B \to K^*\mu^+\mu^-$ predictions at low q^2).

- Complemented by yet another puzzling LHCb measurement: [$\to$ see below]

$$R_K \equiv \frac{\mathcal{B}(B \to K\mu^+\mu^-)_{[1,6]}}{\mathcal{B}(B \to Ke^+e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$\Rightarrow$ *indication for lepton flavour non-universality (!?)*

- Global fit to the $b \to s\mu^+\mu^-$ and $b \to s e^+ e^-$ data:

Coeff.	best fit	1σ	2σ	$\sqrt{\chi^2_{\text{b.f.}} - \chi^2_{\text{SM}}}$	p [%]
C_7^{NP}	-0.04	$[-0.07, -0.02]$	$[-0.10, 0.01]$	1.52	1.1
C_7'	0.00	$[-0.05, 0.06]$	$[-0.11, 0.11]$	0.05	0.8
C_9^{NP}	-1.12	$[-1.34, -0.88]$	$[-1.55, -0.63]$	4.33	10.6
C_9'	-0.04	$[-0.26, 0.18]$	$[-0.49, 0.40]$	0.18	0.8
C_{10}^{NP}	0.65	$[0.40, 0.91]$	$[0.17, 1.19]$	2.75	2.5
C_{10}'	-0.01	$[-0.19, 0.16]$	$[-0.36, 0.33]$	0.09	0.8
$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.20	$[-0.41, 0.05]$	$[-0.60, 0.33]$	0.82	0.8
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.57	$[-0.73, -0.41]$	$[-0.90, -0.27]$	3.88	6.8
$C_9' = C_{10}'$	-0.08	$[-0.33, 0.17]$	$[-0.58, 0.41]$	0.32	0.8
$C_9' = -C_{10}'$	-0.00	$[-0.11, 0.10]$	$[-0.22, 0.20]$	0.03	0.8

$$\chi^2_{\text{SM}} = 125.8 \text{ for 91 measurements } (p = 0.92\%)$$

[W. Altmannshofer @ Portorož 2015]

- Constraints on Wilson coefficient functions:

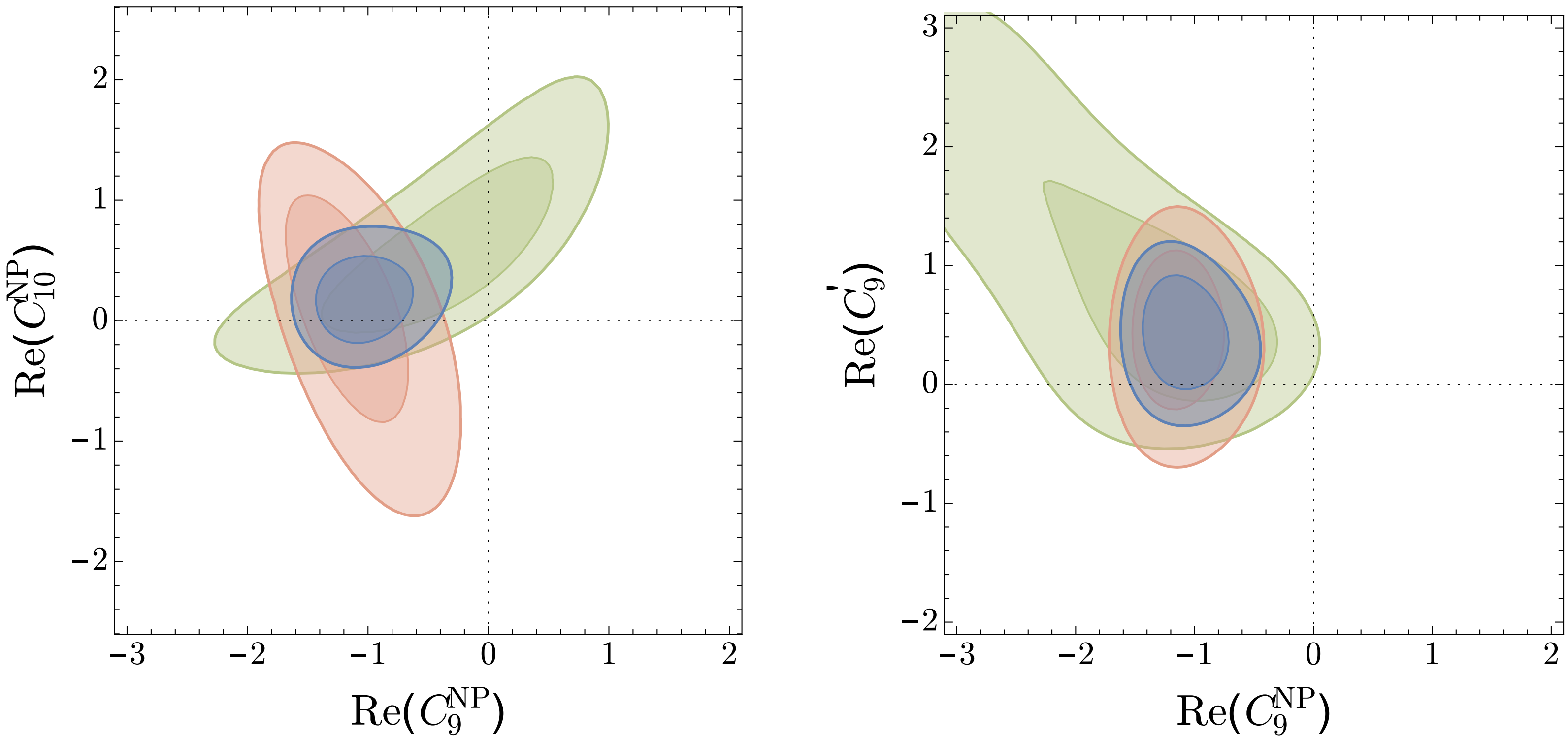


Figure 1 – Allowed regions in the $\mathrm{Re}(C_9^{\mathrm{NP}})$-$\mathrm{Re}(C_{10}^{\mathrm{NP}})$ plane (left) and the $\mathrm{Re}(C_9^{\mathrm{NP}})$-$\mathrm{Re}(C_9')$ plane (right). The blue contours correspond to the 1 and 2σ best fit regions from the global fit. The green and red contours correspond to the 1 and 2σ regions if only branching ratio data or only data on $B \to K^* \mu^+ \mu^-$ angular observables is taken into account.

$\to Z'$ boson could do the job ...

[Altmannshofer & Straub, arXiv:1503.06199 [hep-ph]]

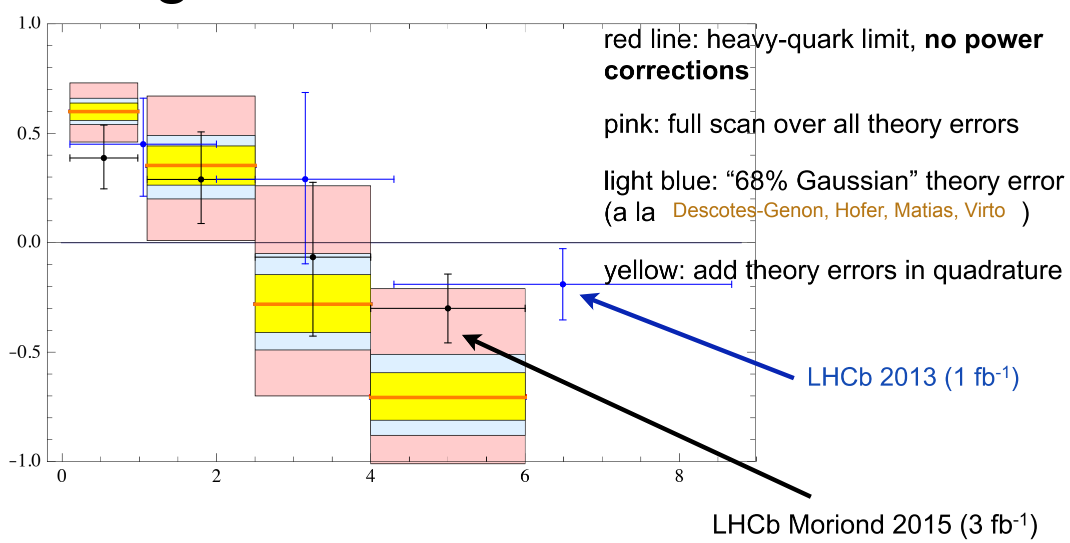
Key question: $\rightarrow$ *Standard Model or New Physics?*

- Sources of hadronic uncertainties:
  - Power corrections $\Lambda_{\rm QCD}/m_b$ affecting form-factor relations.
  - Influences of hadronic resonances ...
  - Complicated hadronic setting ...

- Important to have *critical* analyses: $\rightarrow$ *example ...* [S. Jäger @ Portorož 2015]

Angular observable P5'

SJ, Martin Camalich, preliminary



Pure heavy-quark limit (!) describes data surprisingly well.

Within errors there appears to be no significant discrepancy

Cannot support LHCb claim of 2.9 sigma effect in the 4..6 GeV^2 bin

- Interesting experimental probe: $\rightarrow q^2$ dependence of $C_9^{\rm NP}$

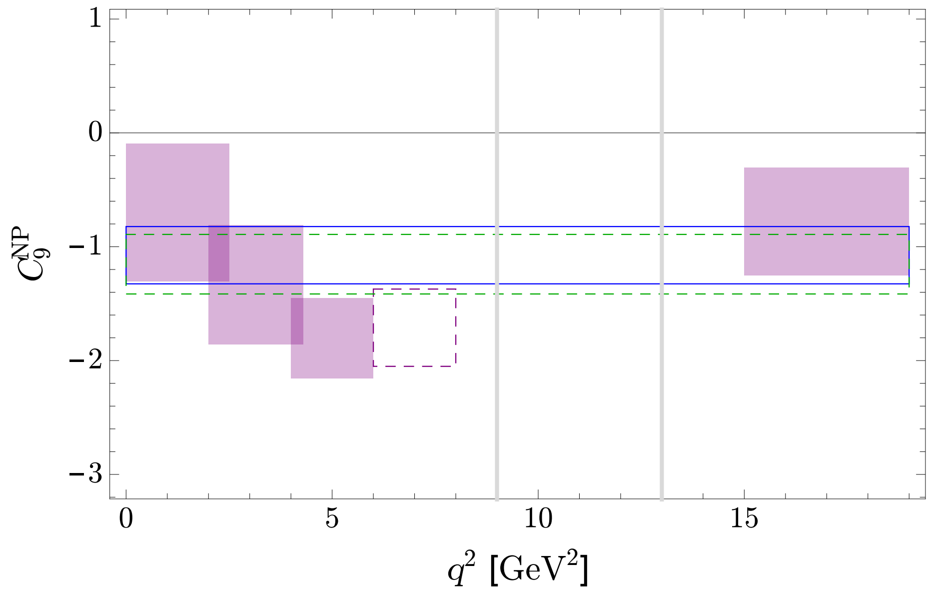


Figure 2 – Purple: ranges preferred at 1σ for a new physics contribution to C_9 from fits to all $B \to K^* \mu^+ \mu^-$ observables in different bins of q^2. Blue: 1σ range for $C_9^{\rm NP}$ from the global fit (cf. tab. 2). Green: 1σ range for $C_9^{\rm NP}$ from a fit to $B \to K^* \mu^+ \mu^-$ observables only. The vertical gray lines indicate the location of the J/ψ and ψ' resonances, respectively.

– Should $C_9^{\rm NP}$ be found to be q^2 independent: $\Rightarrow$ support for NP

– Should $C_9^{\rm NP}$ show q^2 dependence: $\Rightarrow$ support for hadronic effects...

$\Rightarrow$ stay tuned ...

[Altmannshofer & Straub, arXiv:1503.06199 [hep-ph]]

Closer Look @ Testing Lepton Flavour Universality

- Observable in the current spot light:

$$R_K \equiv \frac{\mathcal{B}(B \to K\mu^+\mu^-)_{[1,6]}}{\mathcal{B}(B \to K e^+ e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

[Hiller & Krüger [hep-ph/0310219]; Data: LHCb [hep-ph/0310219]]

- Standard Model prediction: $\boxed{R_K = 1}$ $\to$ excellent approximation

$\Rightarrow$ $2.6\,\sigma$ deviation from LHCb (!?)

[Bobeth, Hiller and Piranishvili [arXiv:0709.4174 [hep-ph]]]

- Differences with respect to the $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$ observables:
  - Hadronic effects cannot explain the LHCb central value...
  - Is it an experimental fluctuation?
  - Is it New Physics? $\to$ Various studies in the literature:

leptoquarks, Z' models, composite Higgs models, ...

[Hiller & Schmaltz (2014); Gripaios & Nardecchia (2014); Niehoff, Stangl & Straub (2015); Becirevic, Fajfer & Kosnik (2015); De Medeiros Varzielas & Hiller (2015); Crivellin (2015); Celis *et al.* (2015); Alonso, Grinstein & Martin Camalich ('15); ...]

Concluding Remarks

Great Opportunities for Flavour Physics

$\rightarrow$ *many more interesting topics than covered in this talk: ...*

- Leptonic and semileptonic B decays with τ leptons:

  $\Rightarrow$ intriguing data for $B \to \tau\bar{\nu}_\tau, D^{(*)}\tau\bar{\nu}_\tau$: extended Higgs sector (?)

  – First LHCb $\bar{B} \to D^*\tau\bar{\nu}$ result and Belle update @ FPCP 2015:

  $\Rightarrow$ (still) inconclusive situation ...

- Charm physics: $\rightarrow$ complementay to the B-meson system:

  $\Rightarrow$ *down-type quarks in FCNC loop processes*

  – Pattern of tiny CP violation in the SM model.
  – Difference $\Delta\mathcal{A}_{\rm CP}$ of CP violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ has received a lot of attention some time ago: looks now SM-like ...
  – Hadronic uncertainties are challenging, $SU(3)$ is a useful tool...

- Search for lepton-flavour-violating processes:

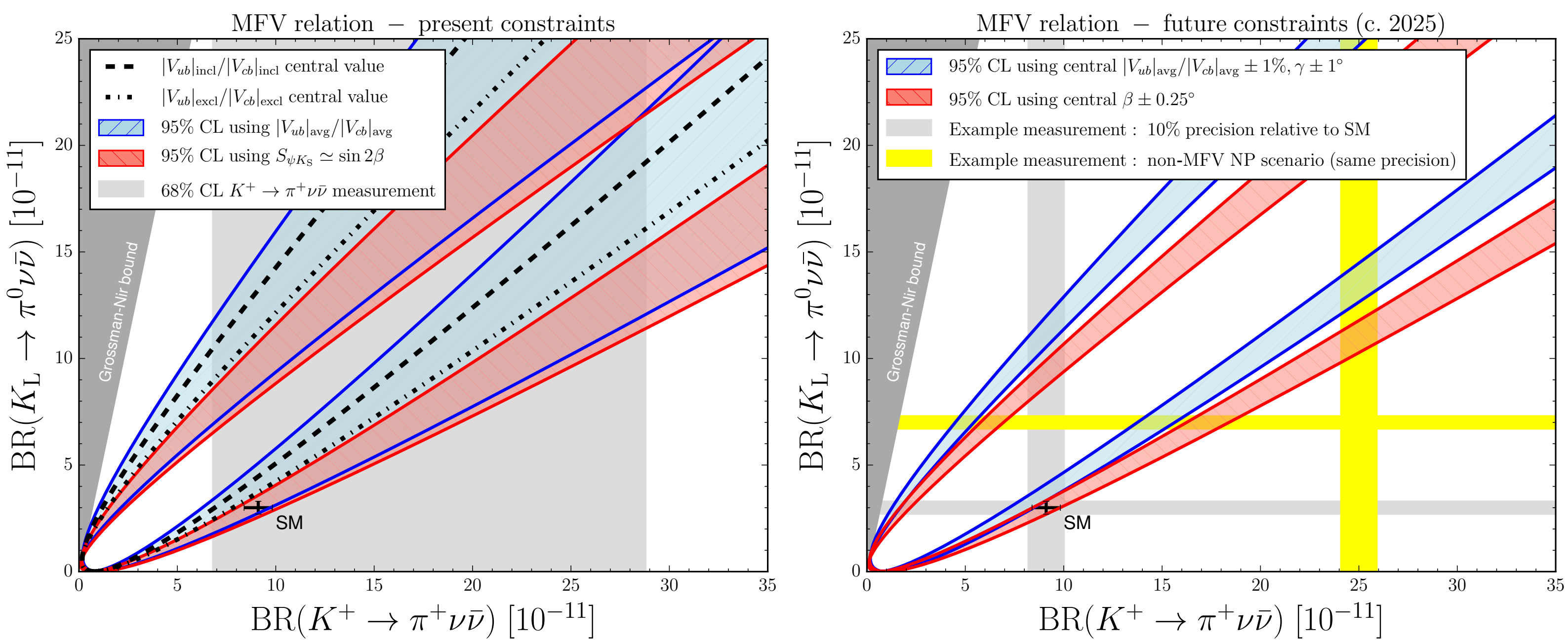
$$B \to K\mu e,\ B \to K\mu\tau,\ B_s \to \mu e,\ B_s \to \mu\tau, \ldots$$

  – Would be unambiguous signals of New Physics.
  – Links to violation of lepton flavour universality?

- Kaon physics: → *focus on rare kaon decays:*

$$K^+ \to \pi^+\nu\bar{\nu} \text{ and } K_{\rm L} \to \pi^0\nu\bar{\nu}$$

  - NA62 (CERN) and KOTO (J-PARC) aim to measure the BRs.
  - Theoretically very clean and interesting probes for New Physics:



[Recent update: Buras, Buttazzo, Girrbach-Noe & Knegjens [arXiv:1503.02693]]

Towards New Frontiers in Precision Flavour Physics

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

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

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

- Exciting times for (quark) flavour physics:

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

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

$\Rightarrow$ *hot topics for discussions @ WIN 2015*