B properties and CP violation

LHCP 2015, St. Petersburg

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CERN

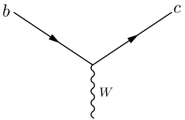
On behalf of the LHCb Collaboration

September 4, 2015

1. Introduction

Introduction

- Quark mixing in the Standard Model (SM) described by the CKM matrix

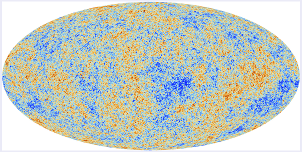


- Gives rise to CP violating phases
- Importance of CP violation
  - Explain matter dominated universe
  - CPV in SM not enough to account for baryon-photon asymmetry, $N_\gamma/N_\Lambda \approx 10^{10}$
  - CPV from new physics?
- B mesons and baryons are a fantastic laboratory to study CPV and the CKM matrix
- Study of the CKM matrix
  - Overconstrain SM
  - Find CP violation from New Physics (NP)
  - Reduce theoretical uncertainties for NP searches in rare decays
    - 6.9% of 8.5% theory uncertainty on $\mathcal{B}(B_s^0 \to \mu\mu)$ from CKM elements
    - Wilson coefficient extraction for $b \to s\ell\ell$ affected by CKM elements
- Today:
  - Discuss latest results constraining CKM elements

CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CMB - [ESA/Plank]



Important ingredient for a good heavy flavour analysis

1. Decay time resolution
   - Good vertex finding
   - Good tracking system
2. Flavour tagging the B meson
   - Good particle ID / particle flow
3. Decay time and angular efficiencies
4. Lots of events
   - High luminosity
   - Good trigger

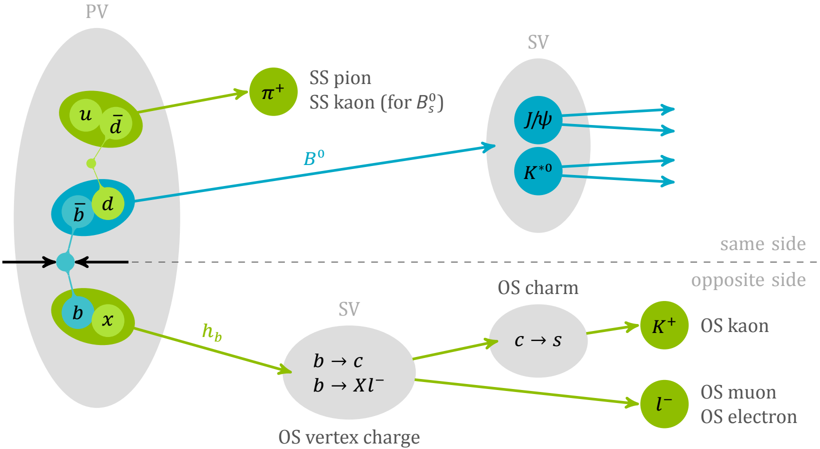
- There are many ways to skin a cat:

At the institute of particle physics

(a) BaBar (b) Belle(2) (c) LHCb (d) ATLAS (e) CMS (f) CDF (g) D0

Flavour tagging

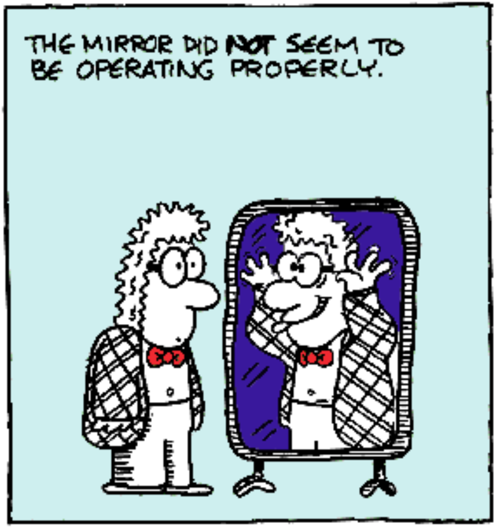
- An example from LHCb $B^0 \to J/\psi K^{*0}$ analysis



- Tagging output is usually:
  - A tag decision
  - A tag (or mistag) probability

2. CKM matrix

CP violation



Quark mixing in the SM

- Quark mixing in the SM described by the CKM matrix

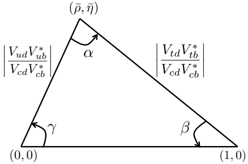
CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \underbrace{\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}}_{\text{Wolfenstein parametrisation}} + \mathcal{O}(\lambda^4)$$

- $\sim \mathcal{O}(10^0)$, $\sim \mathcal{O}(10^{-1})$, $\sim \mathcal{O}(10^{-2})$, $\sim \mathcal{O}(10^{-3})$
- Further from diagonal, the weaker the couplings (hierachy)
- **In the SM**, unitarity requires that $VV^\dagger = \mathbb{I}$
- Imposes 6 conditions (off diagonals of $VV^\dagger = 0$) - **unitarity triangles**

"B^0 unitarity triangle"

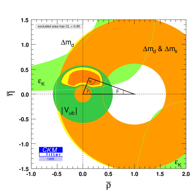
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



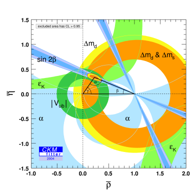
The B^0 unitarity triangle

- CKM picture now well verified - any discrepancies could be of great importance

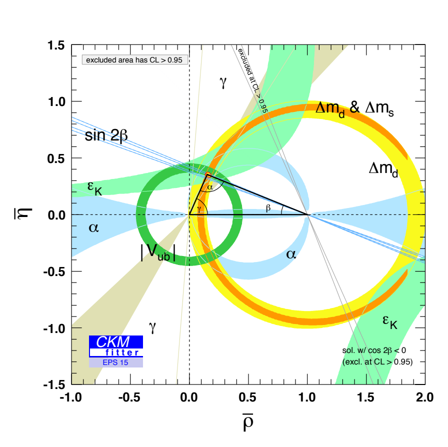
1995



2004



2015



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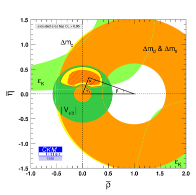
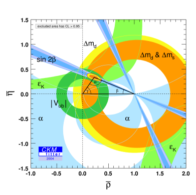
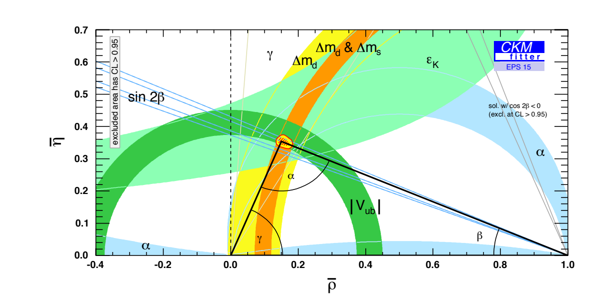


2004



2015 - zoom



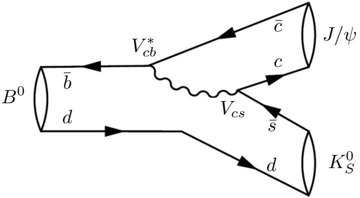
3. sin(2β)

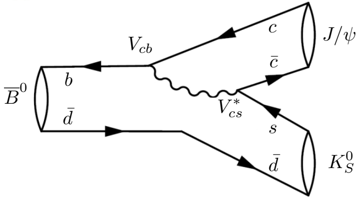
Measuring sin(2β) with $B^0 \to J/\psi K^0_S$

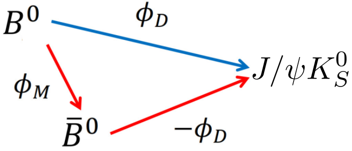
- *Interference* between mixing (via B-$\overline{B}$ oscillation) and decay (to J/ψ K^0_S) gives a CP violating phase:

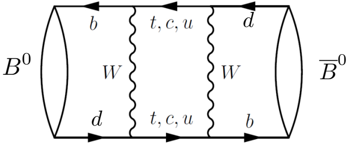
$$\beta = \arg\left(-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right)$$

$$2\beta = \phi = \phi_M - 2\phi_D$$





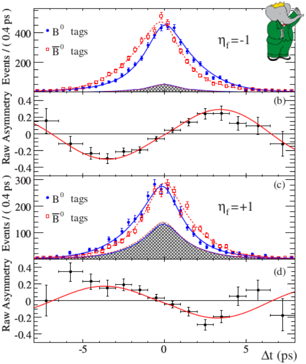


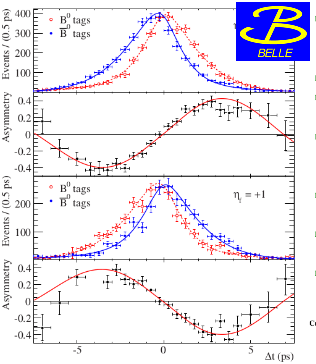


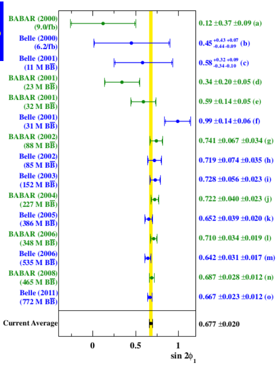
$\sin(2\beta)$ at the B factories

- Measure $B\overline{B}$ decay asymmetry to get $\sin(2\beta)$

$$\mathcal{A}(t) = \frac{\Gamma(\overline{B}^0(t) \to J/\psi\, K^0_{\mathrm{S}}) - \Gamma(B^0(t) \to J/\psi\, K^0_{\mathrm{S}})}{\Gamma(\overline{B}^0(t) \to J/\psi\, K^0_{\mathrm{S}}) + \Gamma(B^0(t) \to J/\psi\, K^0_{\mathrm{S}})}$$







- *"The Physics of the B factories"* - [Eur. Phys. J. C74 (2014) 3026]

  BaBar: $0.687 \pm 0.028 \pm 0.012$ [PRD 79, 072009 (2009)]

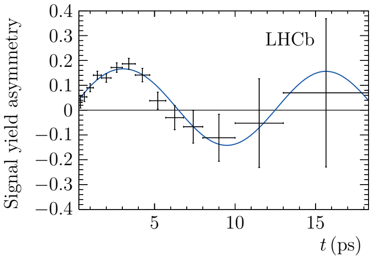
  Belle: $0.667 \pm 0.023 \pm 0.012$ [PRL 108, 171802 (2012)]

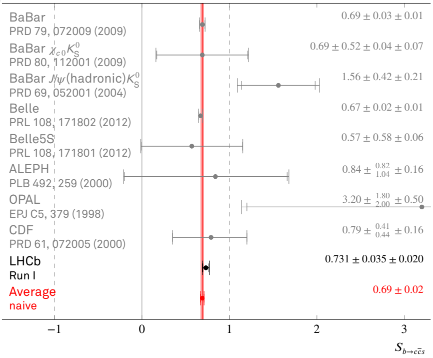
Measuring sin(2β) with $B^0 \to J/\psi K^0_S$

- LHCb has new result with $3\,\text{fb}^{-1}$- [Phys. Rev. Lett. 115 (2015) 031601]
  - Result: $\sin(2\beta) = 0.731 \pm 0.035 \pm 0.020$
  - precision comparable with B factories

World average (HFAG Winter 2015)

$\sin(2\beta) = 0.691 \pm 0.017$

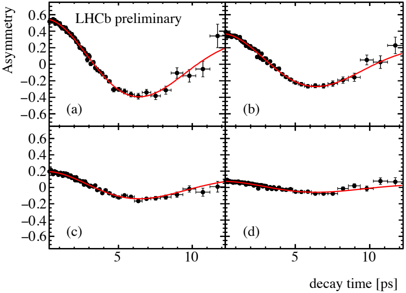


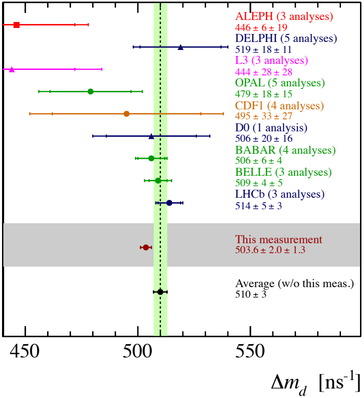


4. Δm_d

Δm_d with semileptonic decays

- Use $B^0 \to D^{(*)-}\mu^+\nu_\mu X$ decays with 3 fb^{-1}:
  - $\sim$ 2M events $D^- \to K^+\pi^+\pi^-$
  - $\sim$ 1M events $D^{*-} \to \bar{D}^0(K^+\pi^-)\pi^-$
- Tag B flavour and calculate time dependent asymmetry to extract Δm_d:
  $\Delta m_d = (503.5 \pm 2.0 \pm 1.3)$ ns^{-1}
  - [LHCb-CONF-2015-003] (preliminary)





World Average

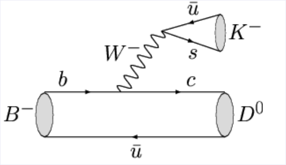
Before	(510 ± 3) ns^{-1}
After	(506 ± 2) ns^{-1}

5. γ

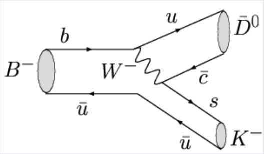
Measuring angle γ from trees

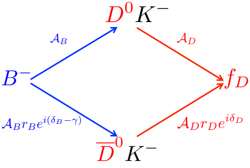
- Use tree decays of $B^{\pm} \to DK^{\pm}$ $(D\pi^{\pm})$ which lead to the same final state

Favoured



Suppressed





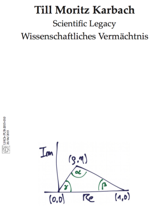
- Inteference between D^0 $-\bar{D}^0$ decays to the same final state
- Combine results of many modes with different methodologies:

Method	Decay	Reference
GGSZ	$D \to K^0_S \pi^{\pm}\pi^{\mp}$, $D \to K^0_S K^{\pm} K^{\mp}$	[JHEP 10 (2014) 097]
GLW	$D \to K^{\pm}K^{\mp}(\pi^0)$, $D \to \pi^{\pm}\pi^{\mp}(\pi^0)$,	[PLB 712 (2012)203-212]
ADS	$D \to \pi^{\pm}K^{\mp}(\pi^0)$, $D \to h3\pi$	[PLB 712 (2012)203-212]
GLS	$D \to K^0_S K^{\pm}\pi^{\mp}$	[PLB 718 (2012) 43-55]

- Complicated by D^0-$\overline{D}^0$ mixing (especially in $B \to D\pi$ modes)

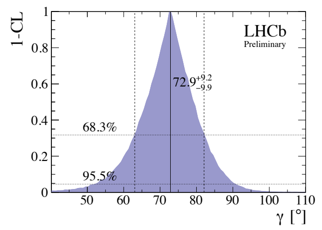
LHCb combination of angle γ from trees

- Nominal result: $\gamma = (72.9^{+9.2}_{-9.9})^{\circ}$ - [arXiv:1411.4600]
- Uncertainty $< 10^{\circ}$ is better than combined B factories
- Run 1 modes soon to be included with $3\,\text{fb}^{-1}$
  - GLW/ADS $B^{+} \to DK^{+}$, $D \to hh$ and $D \to h\pi\pi\pi$
  - GLW/ADS $B^{+} \to DK^{+}$, $D \to hh\pi^{0}$
  - GLW/ADS $B^{+} \to DK^{+}\pi\pi$, $D \to hh$
  - GGSZ $B \to DK^{*0}$
  - $B^{0} \to D^{0}K\pi$
- New LHCb combination expected later this year

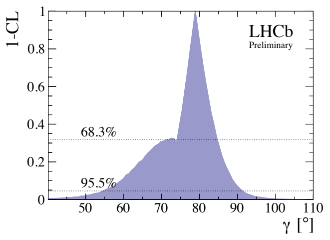


[LHCb-PUB-2015-010]

Result combining $B \to DK$ decays



Result combining all $B \to Dh$ decays

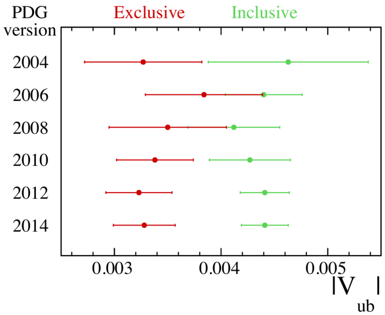


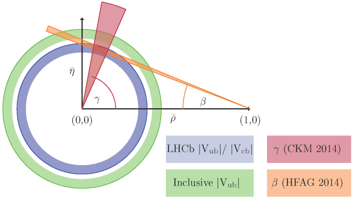
6. V_{ub}

V_{ub} history

- Long standing discrepancy between exclusive $B \to \pi\ell\nu$ and inclusive $b \to \mu\ell\nu$ decays
- Previously a B factory measurement with semileptonic decays
- As of PDG 2014:

Inclusive	$(4.41 \pm 0.15^{+0.15}_{-0.10}) \times 10^{-3}$
Exclusive	$(3.28 \pm 0.29) \times 10^{-3}$
Average	$(4.13 \pm 0.49) \times 10^{-3}$

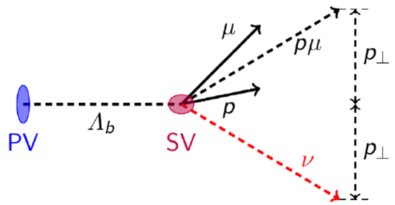


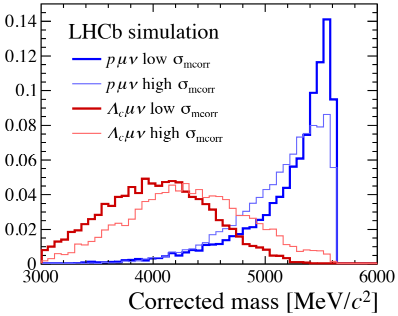


$|V_{ub}|/|V_{cb}|$ using $\Lambda_b \to p\mu^-\overline{\nu}$

- LHCb is a B meson and baryon factory: $B^0 : B_s^0 : \Lambda_b \approx 4 : 1 : 2$
  - Measure: $\frac{\mathcal{B}(\Lambda_b^0 \to p\mu\nu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu\nu)}$ to extract $|V_{ub}|/|V_{cb}|$ [Nature Physics 3415 (2015)]
  - Very few background protons because $\mathcal{B}(B \to pX)$ is small
  - Use corrected mass:

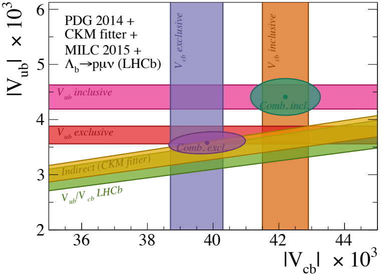
$$m_{\text{corr}} = \sqrt{m^2 + p_\perp^2} + p_\perp \quad (1)$$

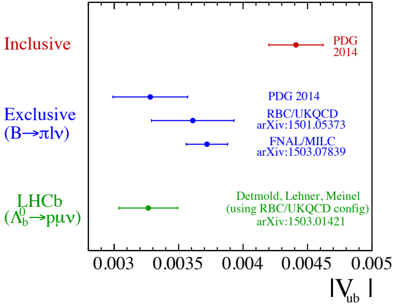


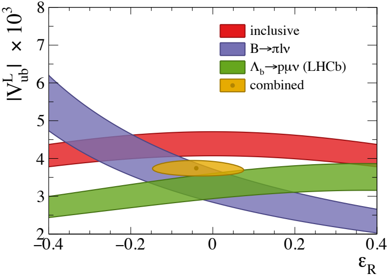


$|V_{ub}|/|V_{cb}|$ using $\Lambda_b \to p\mu^-\overline{\nu}$

- Find:
  $|V_{ub}| = (3.27 \pm 0.15 \pm 0.17 \pm 0.06) \times 10^{-3}$
  [Nature Physics 3415 (2015)]
- Puzzle remains
  - LHCb measures $|V_{ub}|/|V_{cb}|$ while B factories measure individual
- Right handed currents no longer seem to explain $|V_{ub}|$ discrepancy







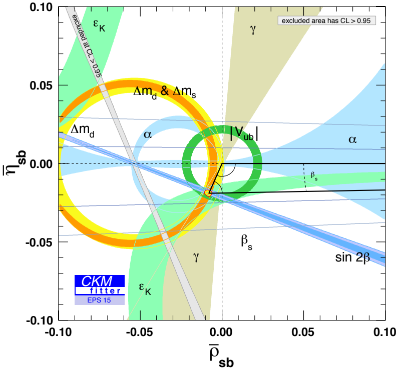
7. ϕ_s

B_s^0 unitarity triangle

- There is also a B_s^0 unitarity triangle (more "squeezed") from the constraint:

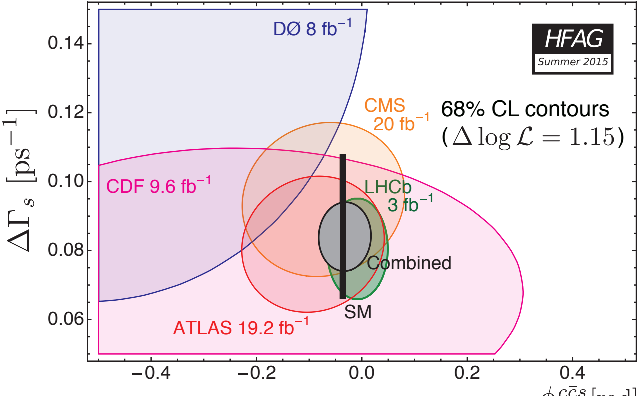
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \quad (2)$$

- Phase of B_s^0 mixing, $\phi_s = -2\beta_s$ in the SM ($\phi_s = 2\phi_D - \phi_M$)
- Very small and precisely predicted in the SM ~ 1 deg ($0.017\,\mathrm{rad}$)
- Great potential for NP searches



ϕ_s in $B_s^0 \to J/\psi K^+K^-$, $B_s^0 \to J/\psi \pi\pi$, $B_s^0 \to D_s^+ D_s^-$

- Golden mode is $B_s^0 \to J/\psi\, \phi(KK)$
  - angular analysis to disentangle polarization states
  - time dependent and flavour tagged
- Early results from Tevatron were tantalising
- LHC experiments have clarified this picture
  - ATLAS, CMS, LHCb
  - Future LHC precision can probe theoretical prediction



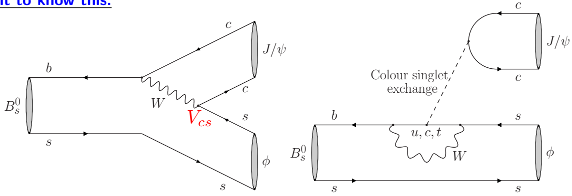
Penguins

- New physics potential can be harmed by unknown penguin contributions

Penguin contribution

$$\phi_s^{\text{measured}} = \phi_s + \delta_{\text{penguin}} + \delta_{\text{newphysics}}$$

Want to know this:



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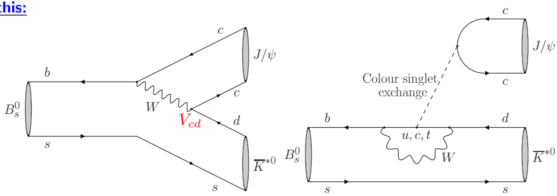
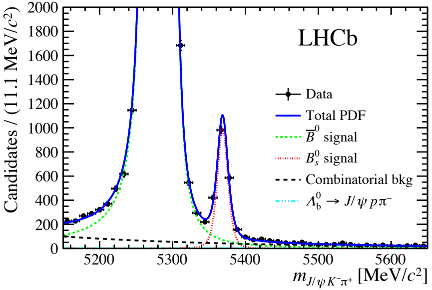


Penguin pollution from $B_s^0 \to J/\psi K^{*0}$

- Measure the size of penguin contributions in decays where penguin / tree ratio is not suppressed e.g. $B_s^0 \to J/\psi K^{*0}$ - [LHCb-PAPER-2015-034]
- Use angular analysis measure δ_{ϕ_s} for each polarization state in $B_s^0 \to J/\psi \phi$
- Combine with SU(3) related $B_s^0 \to J/\psi \rho^0$ - [PLB 742 (2015) 38]
- **Penguin contributions are small!!**



$$\Delta\phi_{s,0}^{J/\psi\phi} = 0.000^{+0.009}_{-0.011}\,(\text{stat})^{+0.004}_{-0.009}\,(\text{syst})\ \text{rad}$$

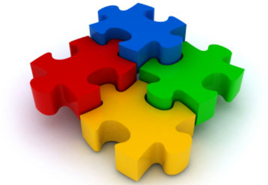
$$\Delta\phi_{s,\parallel}^{J/\psi\phi} = 0.001^{+0.010}_{-0.014}\,(\text{stat})^{+0.007}_{-0.008}\,(\text{syst})\ \text{rad}$$

$$\Delta\phi_{s,\perp}^{J/\psi\phi} = 0.003^{+0.010}_{-0.014}\,(\text{stat})^{+0.007}_{-0.008}\,(\text{syst})\ \text{rad}$$

Summary

- CKM matrix is incredibly successful description of the quark sector in the SM
- Measurements of CKM elements are becoming increasingly precise
- Finding new sources of CP violation can lead us to New Physics
- Great prospects for more precision in the future
  - Measuring penguin contributions in the SM
  - Resolution of $|V_{ub}|$ puzzle?
  - Should get close to indirect precision on γ ($\sim 3\,\text{deg}$) over the next decade
  - More data at the LHC
  - Future experiments like Belle2

Thank You



Back Up

BACK UP

CP violation in B mixing from $B_s^0 \to J/\psi\,\phi$