LHCb results on CP violation in B decays

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on behalf of the LHCb Collaboration

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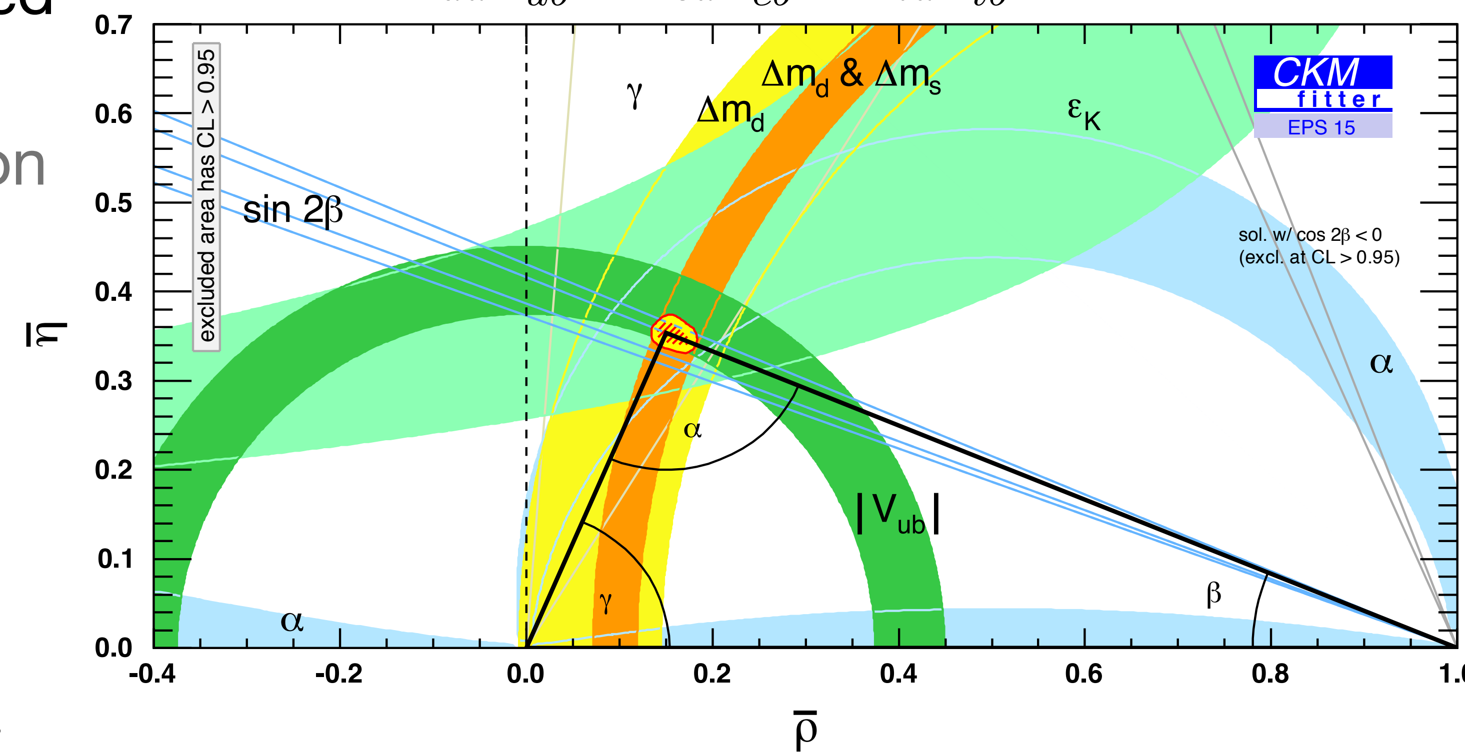
CP violation

- The Standard Model predicted CP asymmetry is not sufficient to explain the baryon asymmetry of the Universe
  ⇒New Physics $\not{C}\not{P}$ effects are expected

- Precise measurements of heavy hadron decays ⇒ redundant determination of the CKM parameters

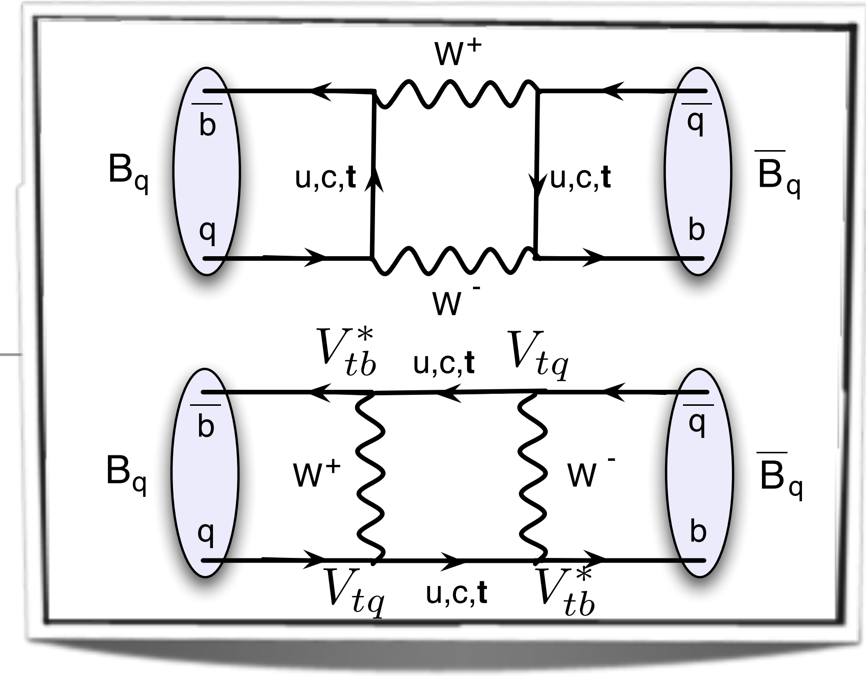
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



In this talk LHCb Run-I results

- ✔ Measurement of the B^0 mixing frequency
- ✔ Measurement of $\not{C}\not{P}$ in $B^0 \to J/\psi K^0_S$ decays
- ✔ Measurement of $\not{C}\not{P}$ and polarization fractions in $B^0_s \to J/\psi \overline{K}^{*0}$ decays
- ✔ Study of $B^- \to \overset{(-)}{D}{}^0 K^-\pi^+\pi^-$ and $B^- \to \overset{(-)}{D}{}^0\pi^-\pi^+\pi^-$ decays and determination of the CKM angle γ
- ✔ Determination of the CKM parameter $|V_{ub}|$

Precision measurement of Δm_d



$\Delta m \propto (V_{tb}^* V_{tq})^2$

- In neutral meson systems, the flavour oscillation frequency is $\Delta m = m_H - m_L$

- Mixing asymmetry measured in: $B^0 \to D^{(*)-}\mu^+\nu_\mu X$ decays

$$A(t) = \frac{N^{not\ osc}(t) - N^{osc}(t)}{N^{not\ osc}(t) + N^{osc}(t)} = \cos(\Delta m_d t)$$

Precision measurement of Δm_d

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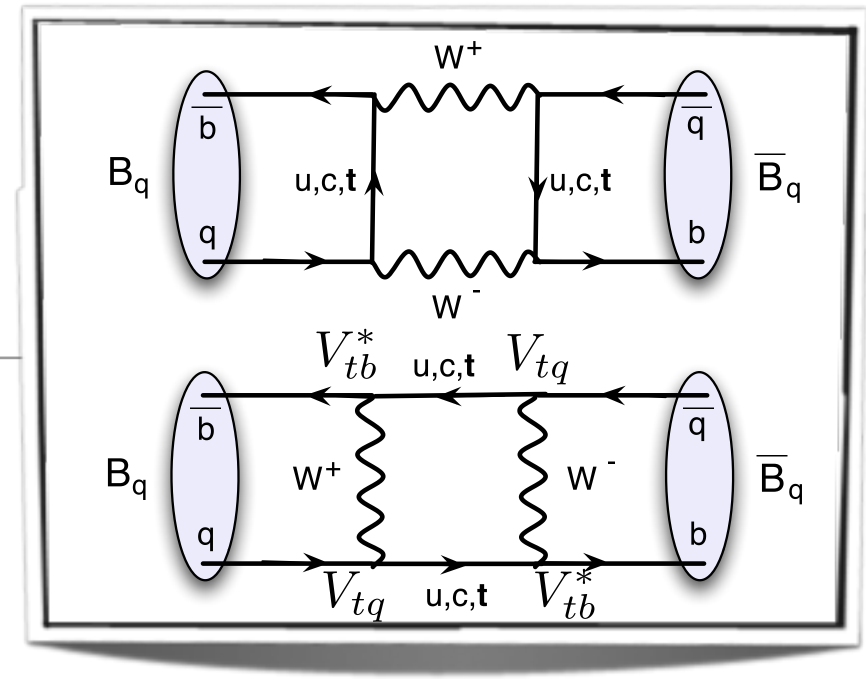

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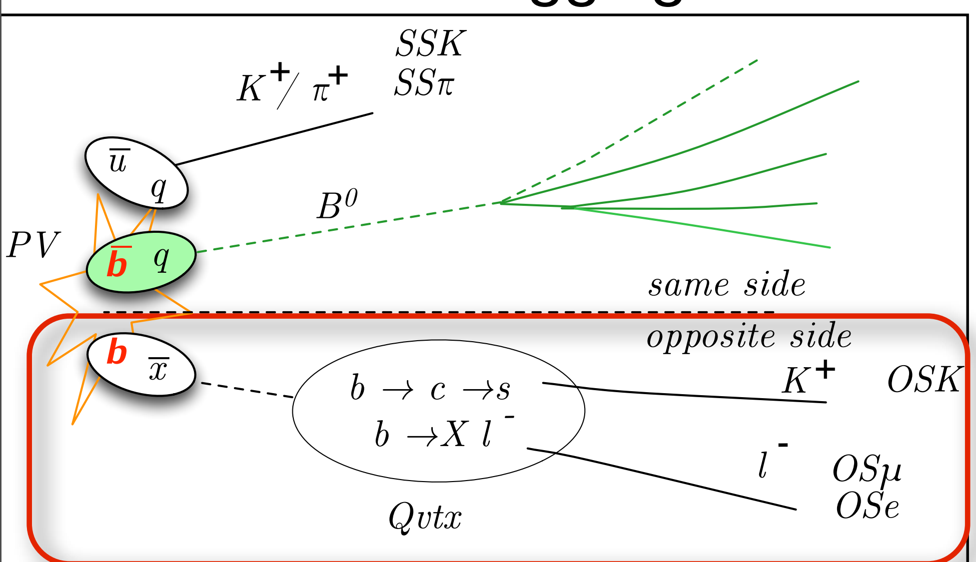
Flavor tagging



$\mathcal{P} = \epsilon_{tag}(1 - 2\omega)^2 \sim 2.4\%$

Decay time reconstruction

- $k = p_{reco}/p_{true}$ factor determined with simulation
- correct the reconstructed decay time and account for the momentum resolution

Background rejection

- $B^+ \to D^{(*)-}\mu^+\nu_\mu X^+$ background rejection with a Multivariate Classifier

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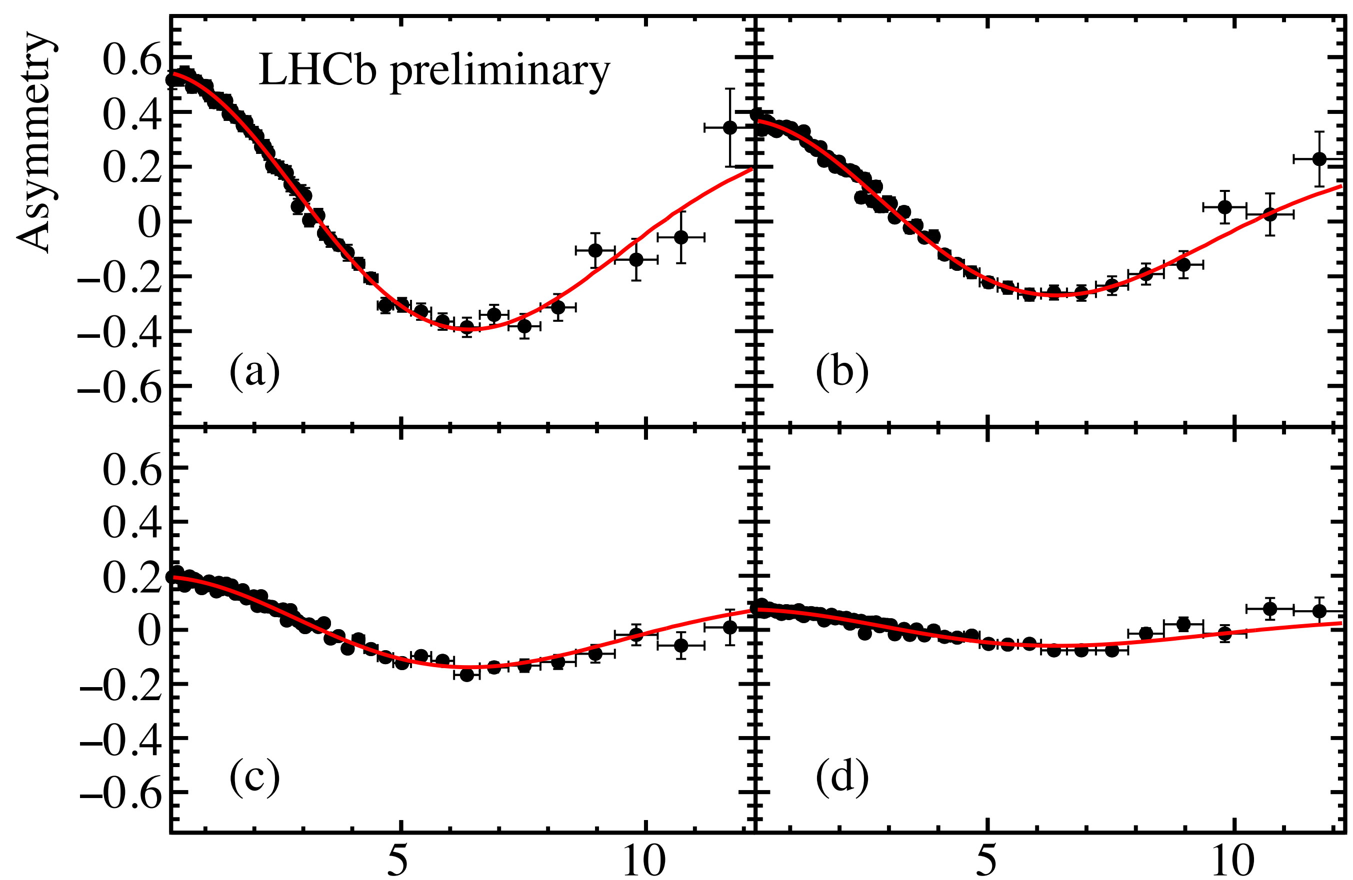
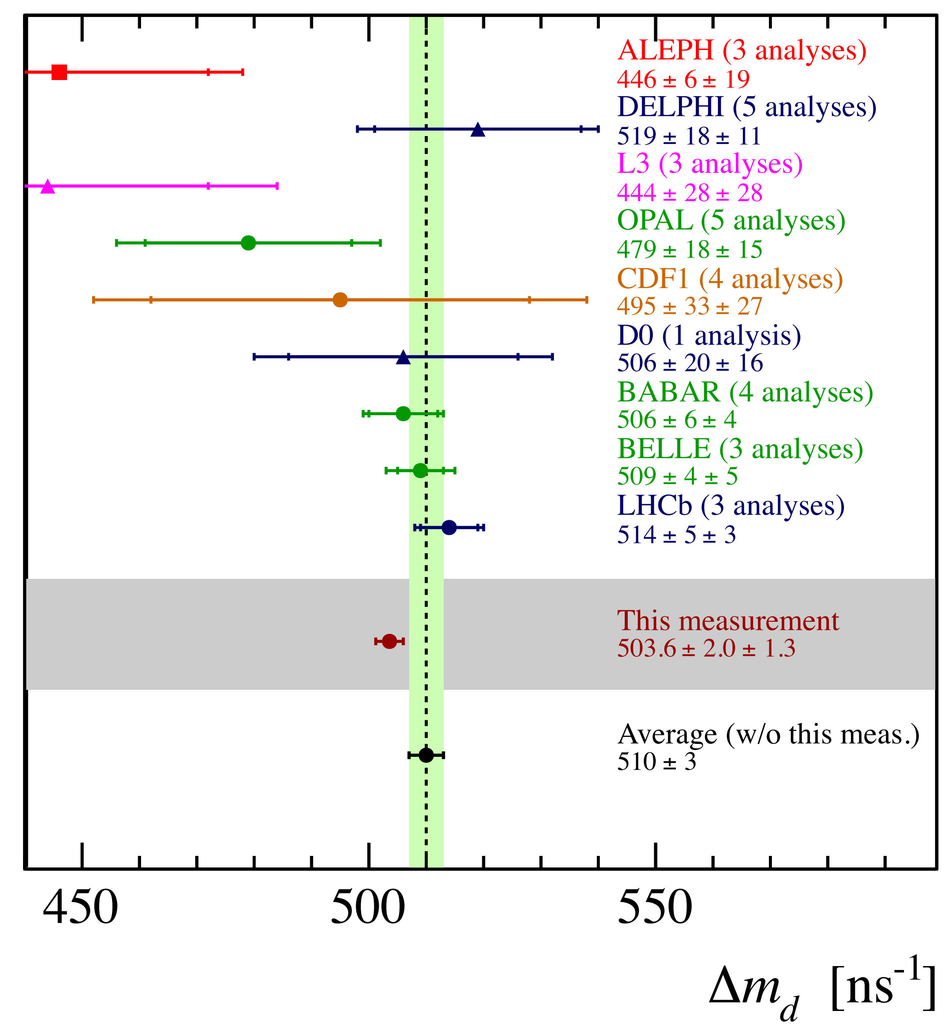
Precision measurement of Δm_d

- Fit to the decay time distribution for unmixed and mixed events
- Mixing asymmetry projections in four flavour tagging categories



$B^0 \to D^- \mu^+ \nu_\mu X$

$$\Delta m_d = 503.6 \pm 2.0(\mathrm{stat}) \pm 1.3(\mathrm{syst})\mathrm{ns}$$



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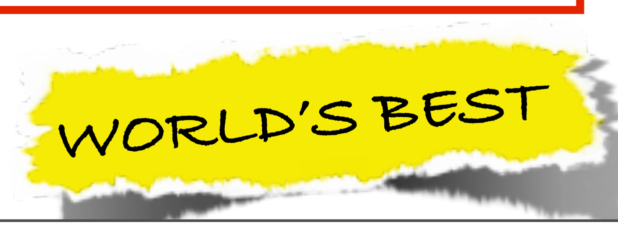
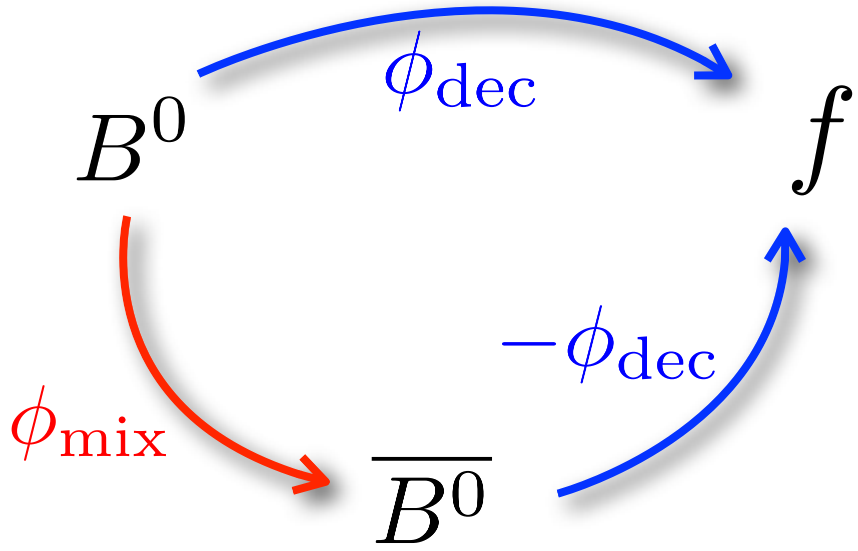
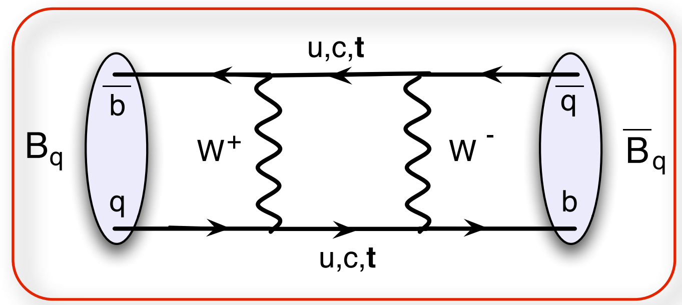
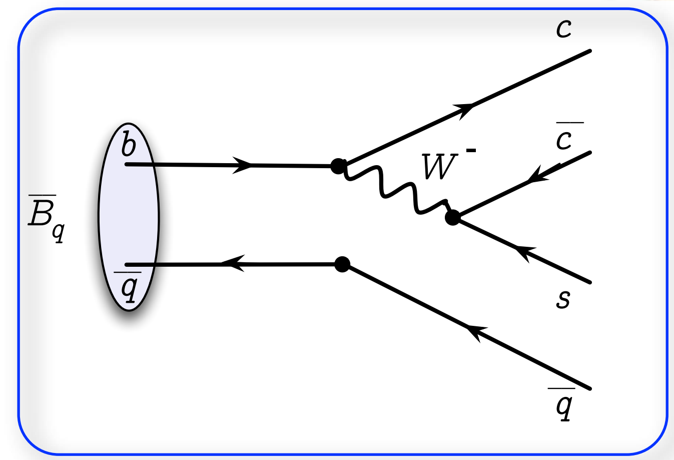


The Evergreens: $\sin(2\beta)$ using $B^0 \to J/\psi K^0_S$ decays

- Mixing induced $\not{CP}$: in the interference of direct decay and decay after mixing







$$\phi_q = \phi_{\rm mix} - 2\phi_{\rm dec}$$

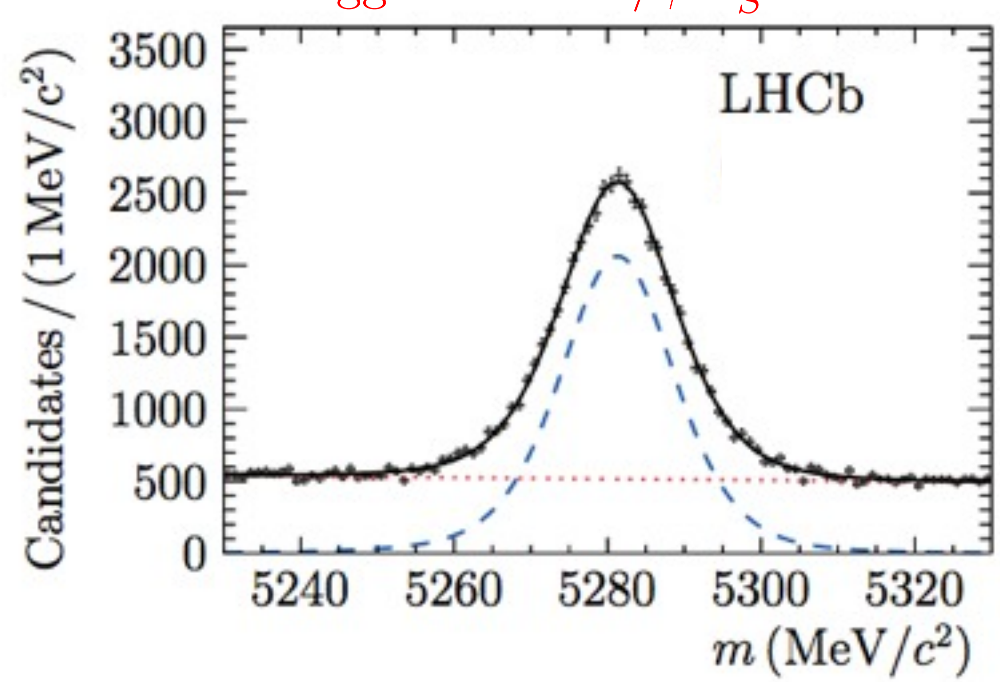
$$\phi_q = -2\left(-\frac{V_{cb}V^*_{cq}}{V_{tb}V^*_{tq}}\right) = 2\beta_{(s)}$$ neglecting penguin contributions

$$A_{CP}(t) = \frac{\Gamma_{B^0\to f}(t) - \Gamma_{\overline{B^0}\to f}(t)}{\Gamma_{B^0\to f}(t) + \Gamma_{\overline{B^0}\to f}(t)}$$

$$= S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$$

with $\Delta\Gamma = 0$ $\quad S_{J/\psi K^0_S} \approx \sin(2\beta)$

41560 tagged $B^0 \to J/\psi K^0_S$ candidates

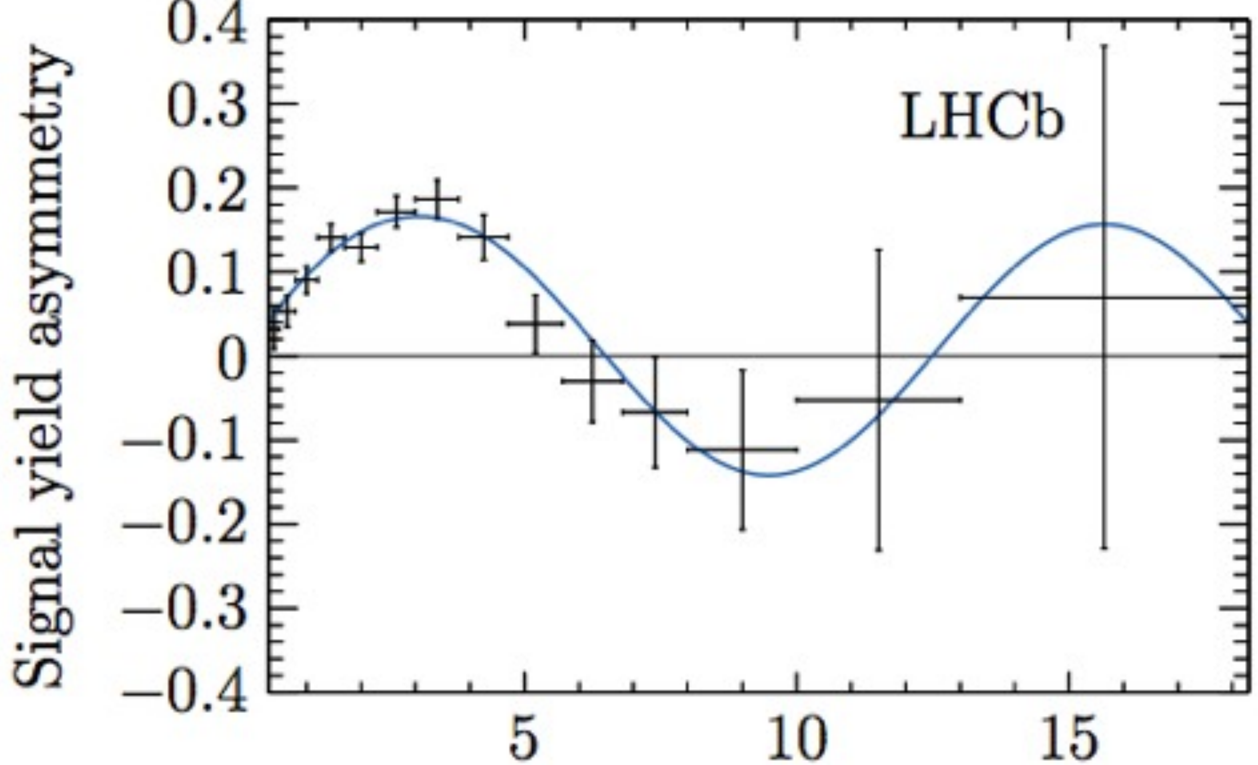


- Multidimensional unbinned maximum likelihood fit to extract CP observables
- Accounted for flavour tagging and B meson production asymmetries

PRL 115, 031601 (2015)

The Evergreens: $\sin(2\beta)$, ϕ_s

$A_{CP}(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$



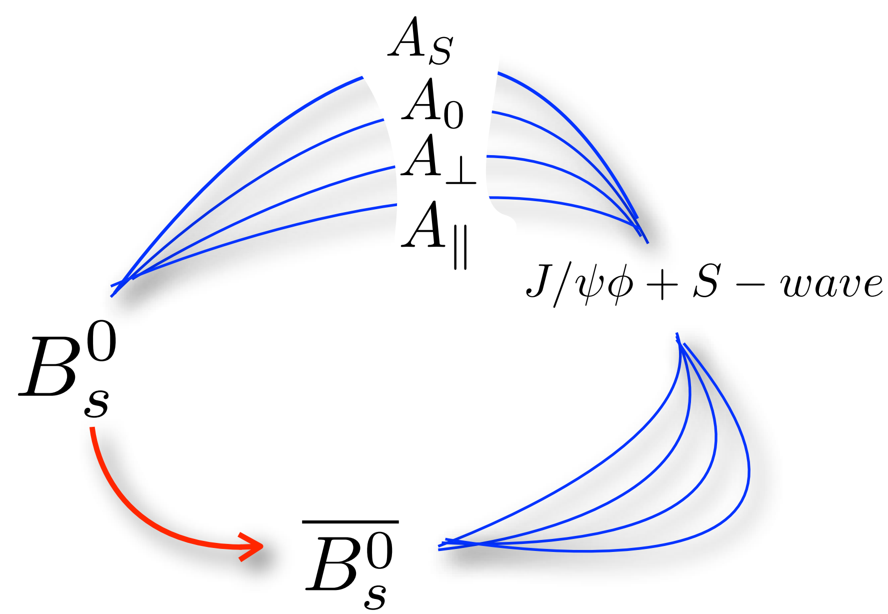
$S_{J/\psi K^0_S} \approx \sin(2\beta)$

$$S_{J/\psi K^0_S} = +0.731 \pm 0.035 \pm 0.020$$
$$C_{J/\psi K^0_S} = -0.038 \pm 0.032 \pm 0.005$$

PRL 115, 031601 (2015)

- Consistent with world average and similar precision to B factories

- 95690 $B^0_s \to J/\psi[\to \mu^+\mu^-]\phi[\to K^+K^-]$ candidates
- time dependent angular analysis to disentangle CP even and CP odd



$$\phi_s = -0.058 \pm 0.049 \pm 0.006\text{rad}$$

PRL 114, 041801 (2015)

- combined with $B^0_s \to J/\psi\pi^+\pi^-$
  $$\phi_s = -0.010 \pm 0.039\text{rad}$$

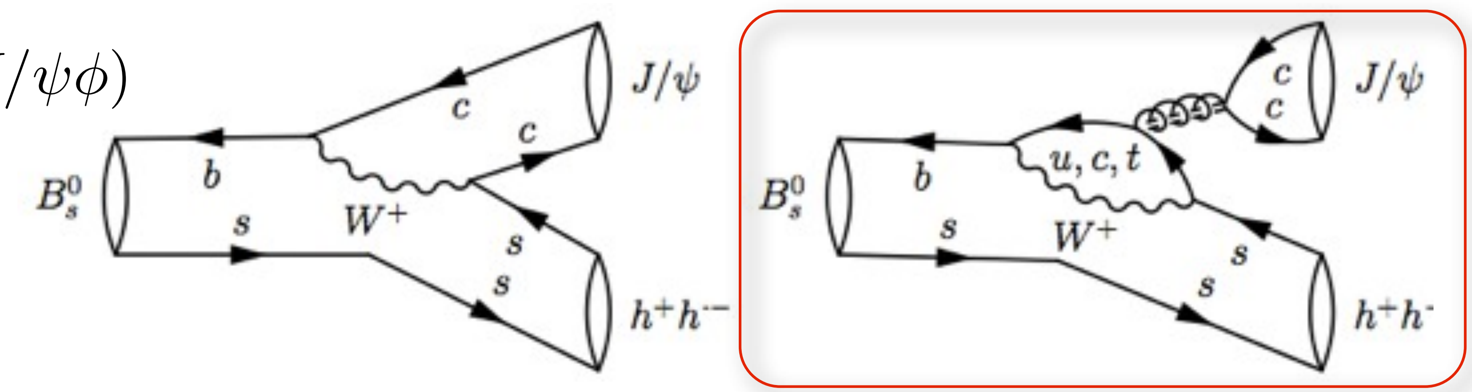
PENGUIN POLLUTION???

CP violation and polarization fractions in $B_s^0 \to J/\psi \overline{K}^{*0}$ decays

$$\phi_q^{\text{measured}} = \phi_q^{SM} + \Delta\phi_{\text{Penguin}} + \Delta\phi_{\text{NewPhysics}}$$

Nierste et al. arXiv:1503.00859,
Liu et al. PRD 89, 094010 (2014)

$B_s^0 \to (J/\psi\phi)$



- $\Delta\phi_{\text{Penguin}}$ and/or $\not{CP}$ could be different for each polarization state

- Measurement of $\Delta\phi_{\text{Penguin}}$ with decays where the penguin/tree ratio is not suppressed

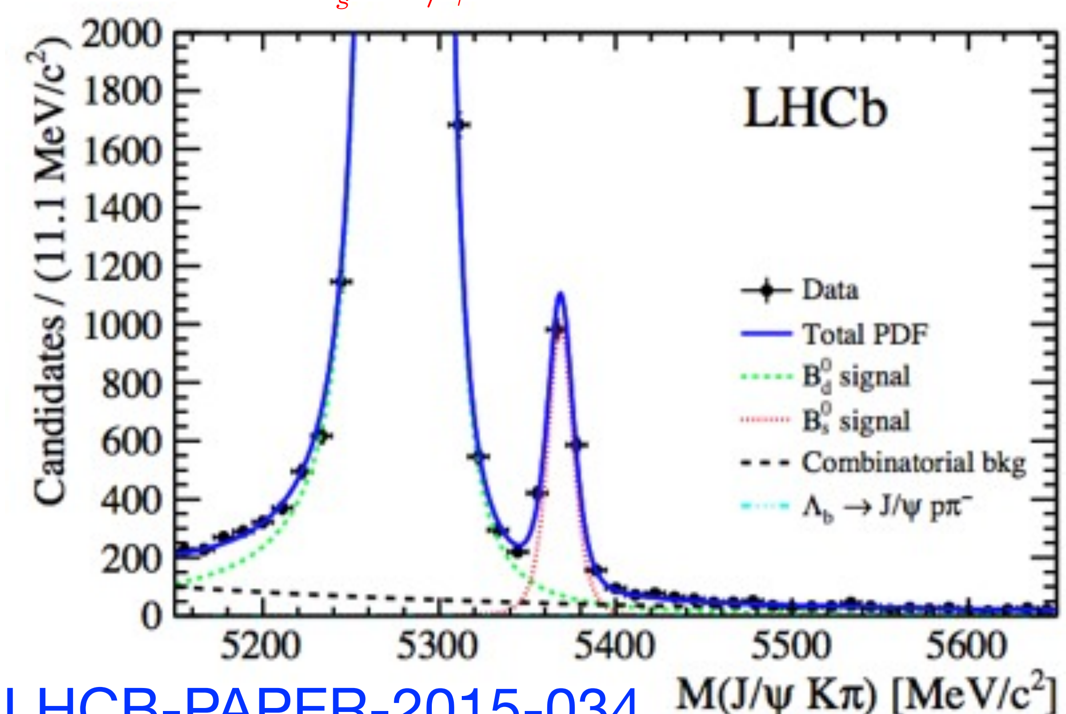
$$A(B_s^0 \to (J/\psi\overline{K}^{*0})_i) = -\lambda\mathcal{A}_i(1 - a_i e^{i\theta_i} e^{i\gamma})$$

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

$i \in (0, \perp, \|, S)$

$SU(3)$ flavor : $a_i = a'_i, \theta_i = \theta'_i$

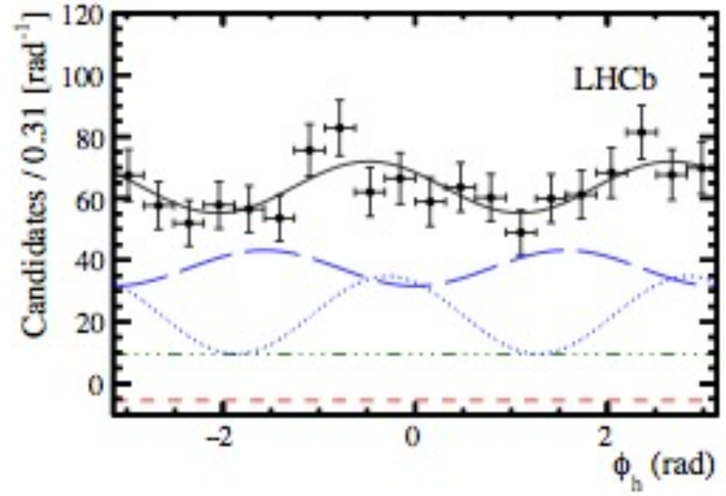
$N_{B^0 \to J/\psi K^{*0}} = 208700 \pm 500$
$N_{B_s^0 \to J/\psi \overline{K}^{*0}} = 1800 \pm 60$

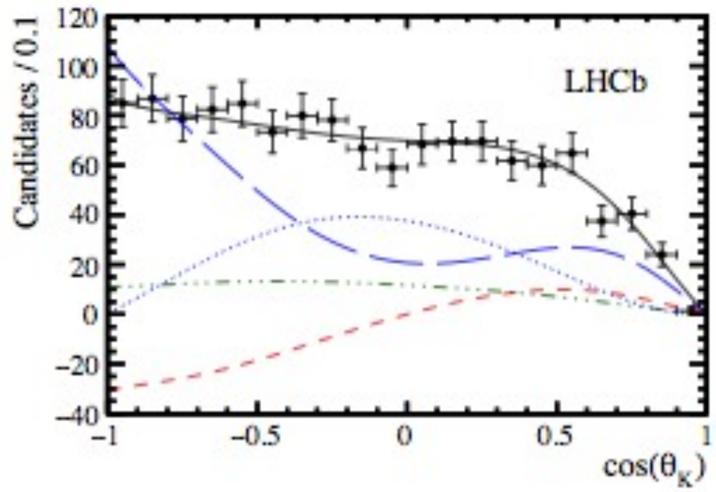


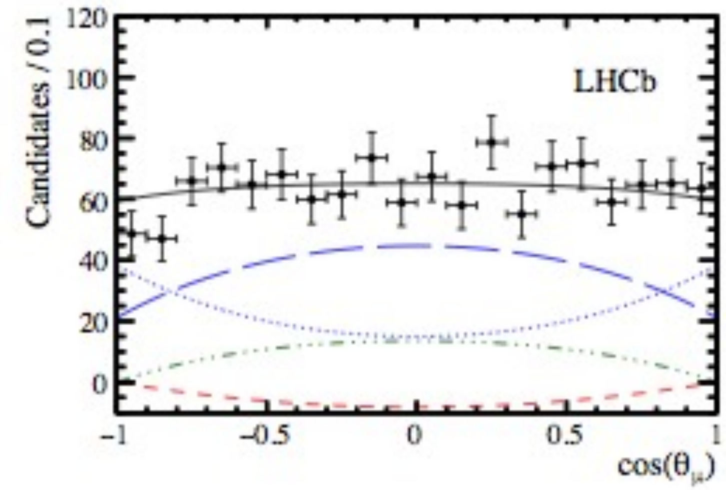
LHCB-PAPER-2015-034

CP violation and polarization fractions in $B_s^0 \to J/\psi \overline{K}^{*0}$ decays

- measurement of direct $\not{C}\not{P}$
  ($J/\psi K^+\pi^-$ vs $J/\psi K^-\pi^+$) decays are flavour specific
    - time integrated
    - polarization dependent
- Account for production and detection asymmetries







- Results

$$f_0 = 0.497 \pm 0.025(\mathrm{stat}) \pm 0.025(\mathrm{syst})$$
$$f_\parallel = 0.179 \pm 0.027(\mathrm{stat}) \pm 0.013(\mathrm{syst})$$
$$A_0^{CP}(B_s^0 \to J/\psi \overline{K}^{*0}) = -0.048 \pm 0.057(\mathrm{stat}) \pm 0.020(\mathrm{syst})$$
$$A_\parallel^{CP}(B_s^0 \to J/\psi \overline{K}^{*0}) = 0.171 \pm 0.152(\mathrm{stat}) \pm 0.028(\mathrm{syst})$$
$$A_\perp^{CP}(B_s^0 \to J/\psi \overline{K}^{*0}) = -0.049 \pm 0.096(\mathrm{stat}) \pm 0.025(\mathrm{syst})$$

$$\mathcal{B}(B_s^0 \to J/\psi \overline{K}^{*0}) = \left(4.13 \pm 0.16(\mathrm{stat}) \pm 0.25(\mathrm{syst}) \pm 0.24(\mathrm{f_d/f_s})\right) \times 10^{-5}$$

LHCB-PAPER-2015-034

- Combined with $B^0 \to J/\psi \rho^0$:

$$\Delta\phi_{s,0}^{J/\psi\phi} = 0.000^{+0.009}_{-0.011}(\mathrm{stat})^{+0.004}_{-0.009}(\mathrm{syst})\mathrm{rad}$$
$$\Delta\phi_{s,\parallel}^{J/\psi\phi} = 0.001^{+0.010}_{-0.014}(\mathrm{stat})^{+0.007}_{-0.008}(\mathrm{syst})\mathrm{rad}$$
$$\Delta\phi_{s,\perp}^{J/\psi\phi} = 0.003^{+0.010}_{-0.014}(\mathrm{stat})^{+0.007}_{-0.008}(\mathrm{syst})\mathrm{rad}$$

absolute shift smaller than 19 mrad
current experimental precision:

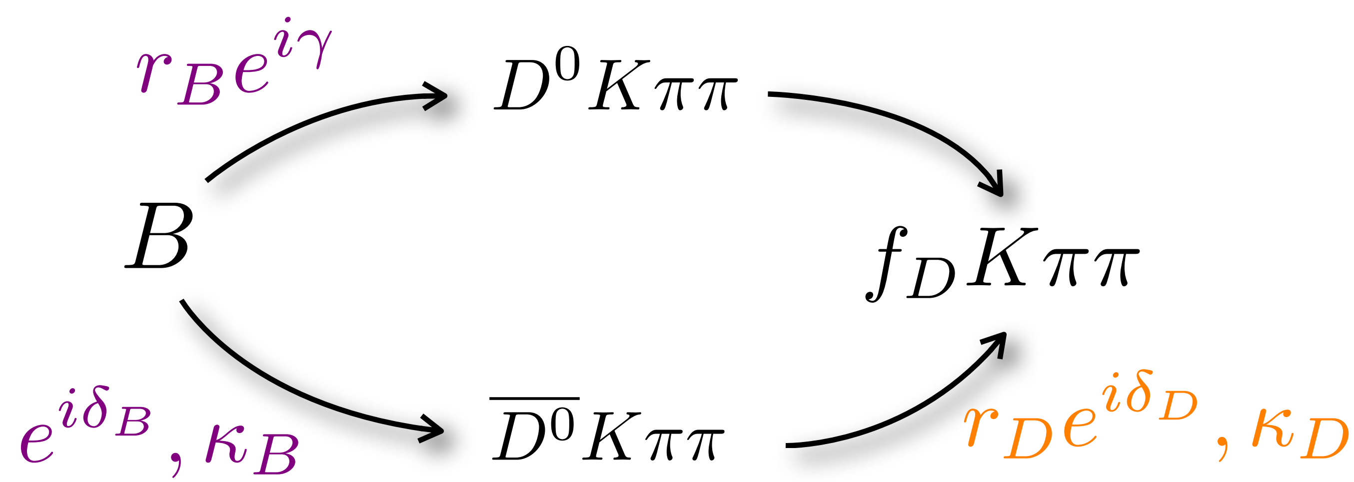
$$\sigma(\phi_s) = \pm 0.035\ \mathrm{rad}$$

NO NEED TO WORRY YET

Study of $B^- \to \overset{(-)}{D}{}^0 K^- \pi^+ \pi^-$ and $B^- \to \overset{(-)}{D}{}^0 \pi^- \pi^+ \pi^-$ decays and determination of the CKM angle γ

- CKM angle $\gamma \equiv [-(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)]$
- Study the interference between $B^- \to D^0 X_{s,d}^-$ and $B^- \to \overline{D^0} X_{s,d}^-$ decays, selecting final states accessible to both D^0 and $\overline{D^0}$ (all tree level)

Example



$f_D = K^\pm \pi^\mp$

r_B and δ_B are the amplitude ratio and strong phase difference between $B \to D^0 X$ and $B \to \overline{D^0} X$

$r_D e^{\delta_D}$ is the ratio between the Cabibbo Favoured and the Doubly Cabibbo Suppressed amplitudes

Coherence factors κ appear with multibody states

CP observable:

$$R^{X^\pm} = \frac{\Gamma(B^\pm \to [K^\mp \pi^\pm]_D X^\pm)}{\Gamma(B^\pm \to [K^\pm \pi^\mp]_D X^\pm)} = \frac{r_B^2 + r_D^2 + 2\kappa r_B r_D \cos(\delta_B + \delta_D \pm \gamma)}{1 + r_B^2 r_D^2 + 2\kappa r_B r_D \cos(\delta_B - \delta_D \pm \gamma)}$$

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Study of $B^- \to \overset{(-)}{D^0} K^-\pi^+\pi^-$ and $B^- \to \overset{(-)}{D^0} \pi^-\pi^+\pi^-$ decays and determination of the CKM angle γ

- CKM angle $\gamma \equiv [-(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)]$
- Study the interference between $B^- \to D^0 X_{s,d}^-$ and $B^- \to \overline{D^0} X_{s,d}^-$ decays, selecting final states accessible to both D^0 and $\overline{D^0}$ (all tree level)
- Different "methods":

ADS selection of quasi-flavor specific final states, Cabibbo favoured (CF) and doubly Cabibbo suppressed (DCS) $D \to K^\pm\pi^\mp$

CP observable of interest: relative widths of DCS to CF, separated by charge

GLW selection of CP eigenstates $D \to K^+K^-$, $D \to \pi^+\pi^-$

CP observables of interest: charge-averaged yields ratios, charge asymmetries

- Counting analyses
- Ratios or double ratios reduce the systematic uncertainties

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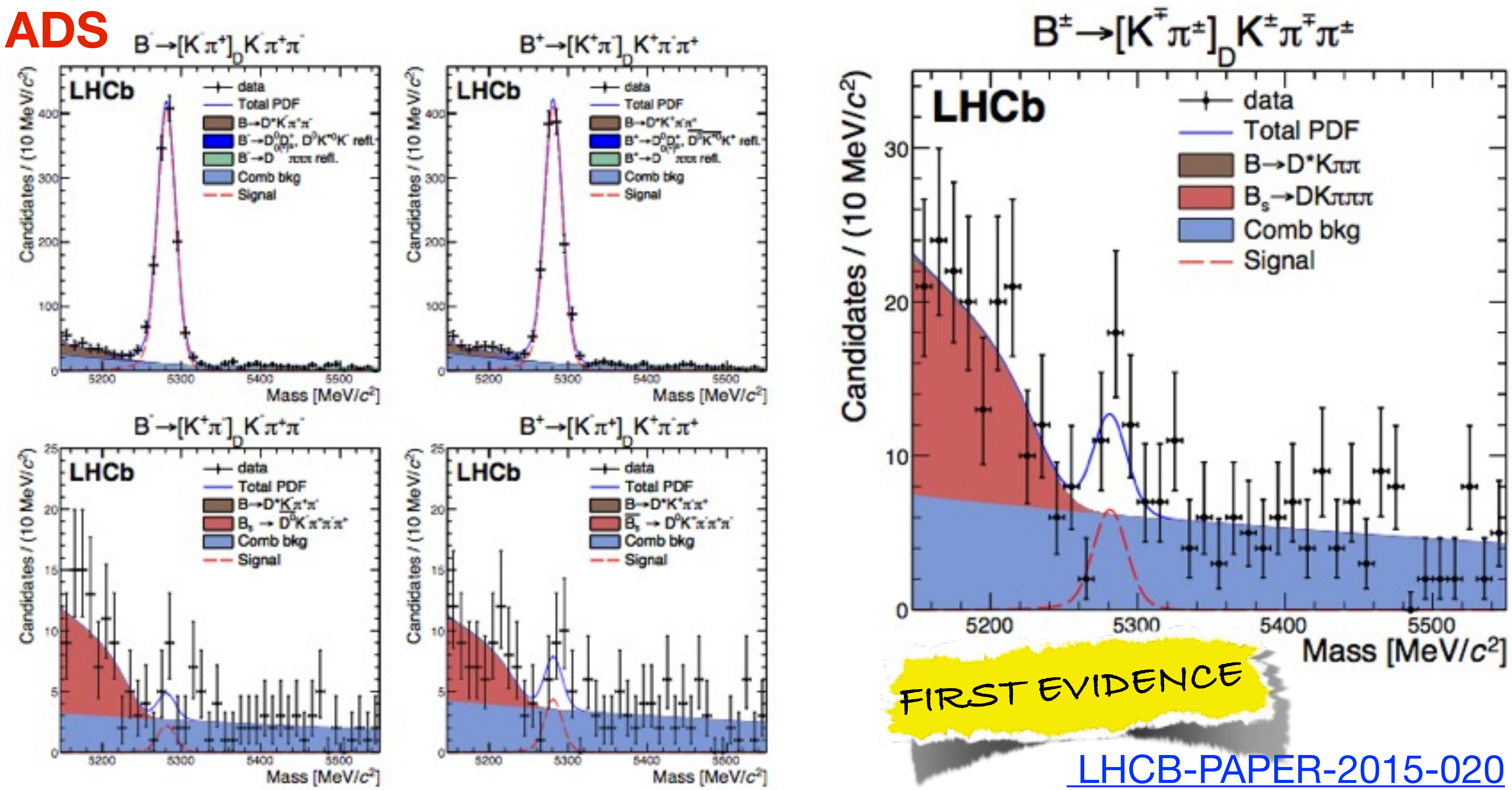
Study of $B^- \to \overset{(-)}{D^0} K^- \pi^+ \pi^-$ and $B^- \to \overset{(-)}{D^0} \pi^- \pi^+ \pi^-$ decays and determination of the CKM angle γ

- Signal yields are obtained with a simultaneous unbinned extended maximum likelihood fit to the B candidate invariant mass spectra



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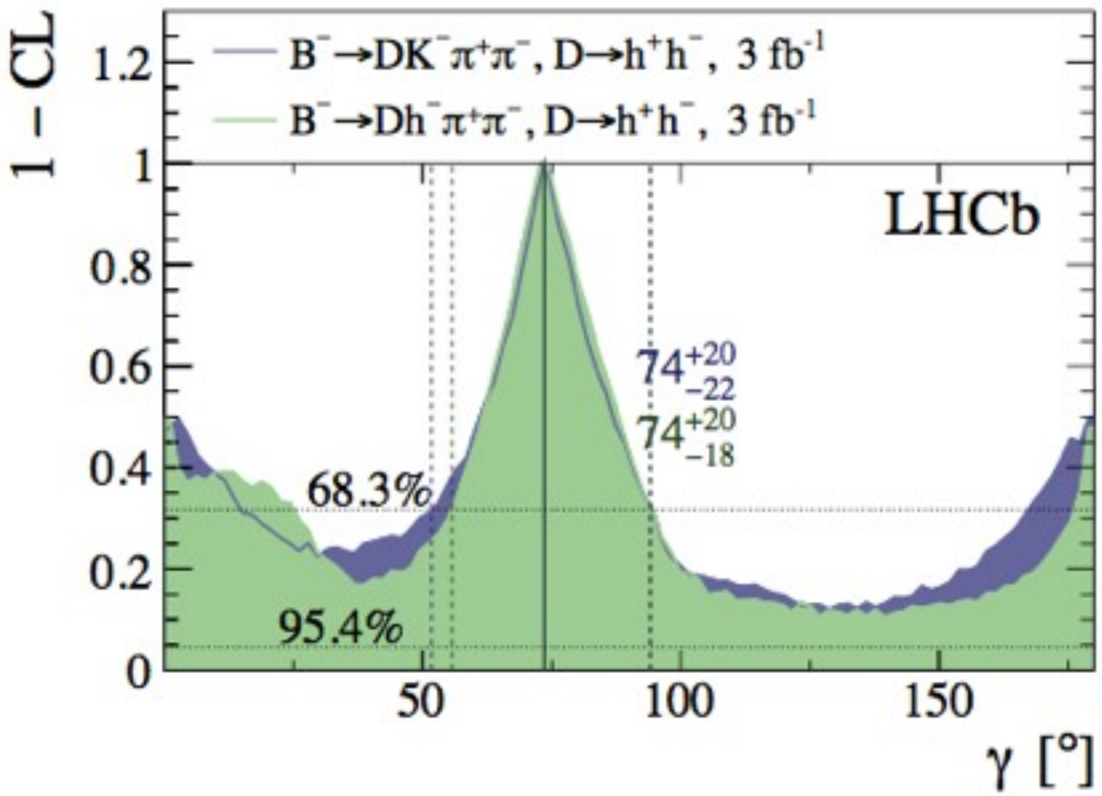
- Fitted signal yields are corrected (for the events removed by the vetoes, charmless background, B production asymmetry, kaon and pion detection asymmetries)

Constraints on γ



$\gamma = (74^{+20}_{-22})^\circ$ using $B \to DX_s$ only

$\gamma = (74^{+20}_{-18})^\circ$ using $B \to DX_s$ and $B \to DX_d$

- The precision is comparable or better than most previous measurements

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LHCb combination & previous measurements

- Measurements included:
  - $B^+ \to Dh^+, D \to hh$ GLW/ADS, 1 fb^{-1} Phys. Lett. B712 (2012)203
  - $B^+ \to Dh^+, D \to K\pi\pi\pi$, ADS, 1 fb^{-1} Phys. Lett. B723 (2013) 44
  - $B^+ \to DK^+, D \to K^0_S hh$, model independent, GGSZ, 3 fb^{-1} JHEP 10 (2014) 097
  - $B^+ \to DK^+, D \to K^0_S K\pi$, GLS, 3 fb^{-1} Phys. Lett. B733 (2014) 36
  - $B^0 \to DK^{*0}$, $D \to hh$, GLW/ADS, 3 fb^{-1} Phys. Rev. D90 (2014) 112002
  - $B^0_s \to D^\mp_s K^\pm$, time-dependent, 1 fb^{-1} JHEP 11 (2014) 060
- Combination accounts for $D^0 - \overline{D^0}$ mixing effect and supplementary informations from other experiments
- Taking the best fit value and 68% CL interval

$$\gamma = (73^{+9}_{-10})^\circ$$

LHCB-CONF-2014-004

Determination of $|V_{ub}|$

Nature Physics 10 (2015)

- |Vub| is complementary to γ and β in constraining the Unitarity Triangle
- Tension between the exclusive and inclusive measurements of |Vub|
- **LHCb strategy:** measure the ratio of branching fractions of the Λ_b^0 baryon into $p\mu^-\overline{\nu_\mu}$ and $\Lambda_c^+\mu^-\overline{\nu_\mu}$

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu_\mu})} R_{FF}$$

$R_{FF} = 1.470 \pm 0.115(\text{stat}) \pm 0.104(\text{syst})$
W. Detmold, C. Lehner and S. Meinel
arXiv:1503.01421

Belle measurement arXiv:1312.7826

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu})_{q^2>15GeV^2/c^4}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu_\mu})_{q^2>7GeV^2/c^4}} = \frac{N(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu})}{N(\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\overline{\nu_\mu})} \times \frac{\epsilon(\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\overline{\nu_\mu})}{\epsilon(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu})} \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$$

world average

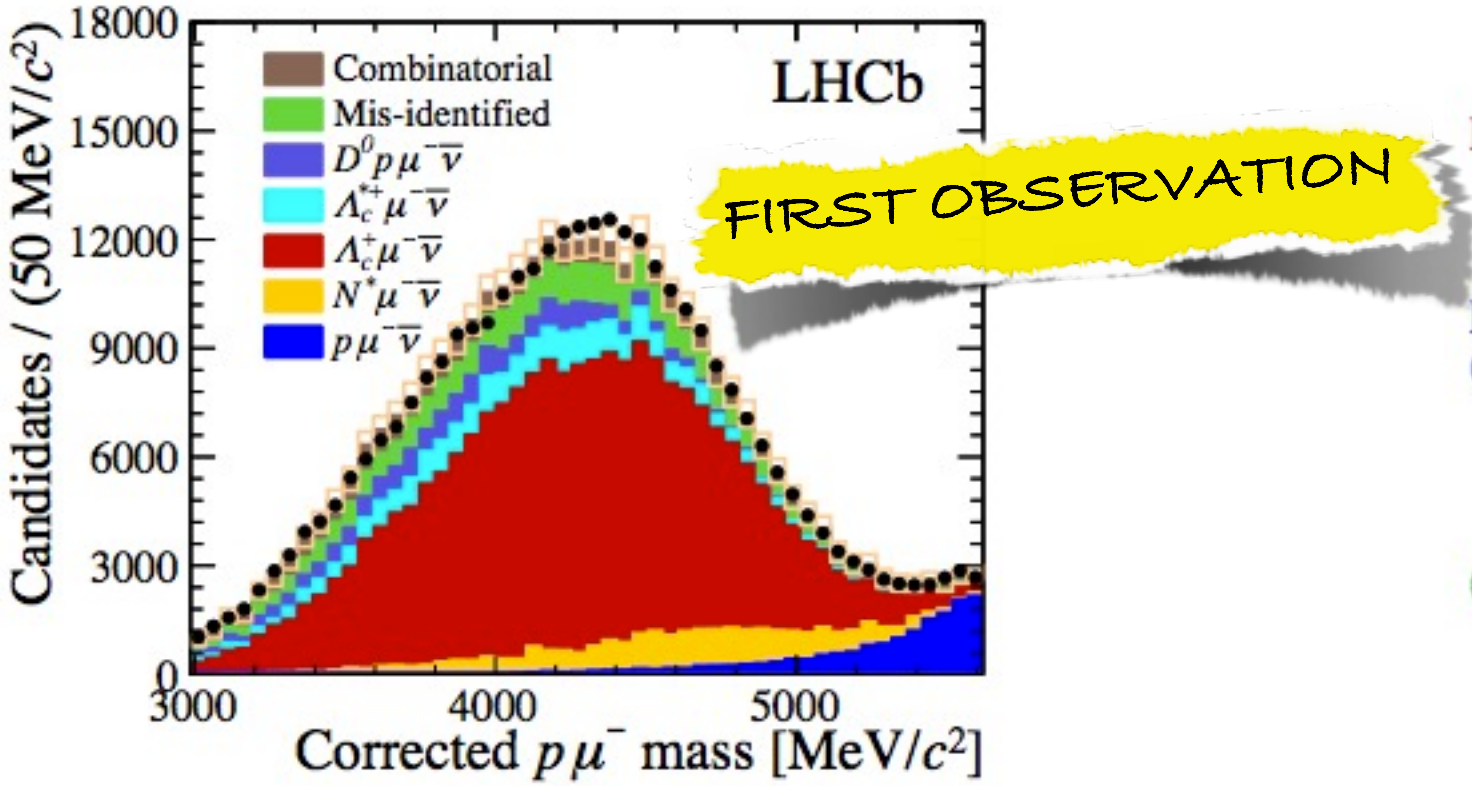
$|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3}$

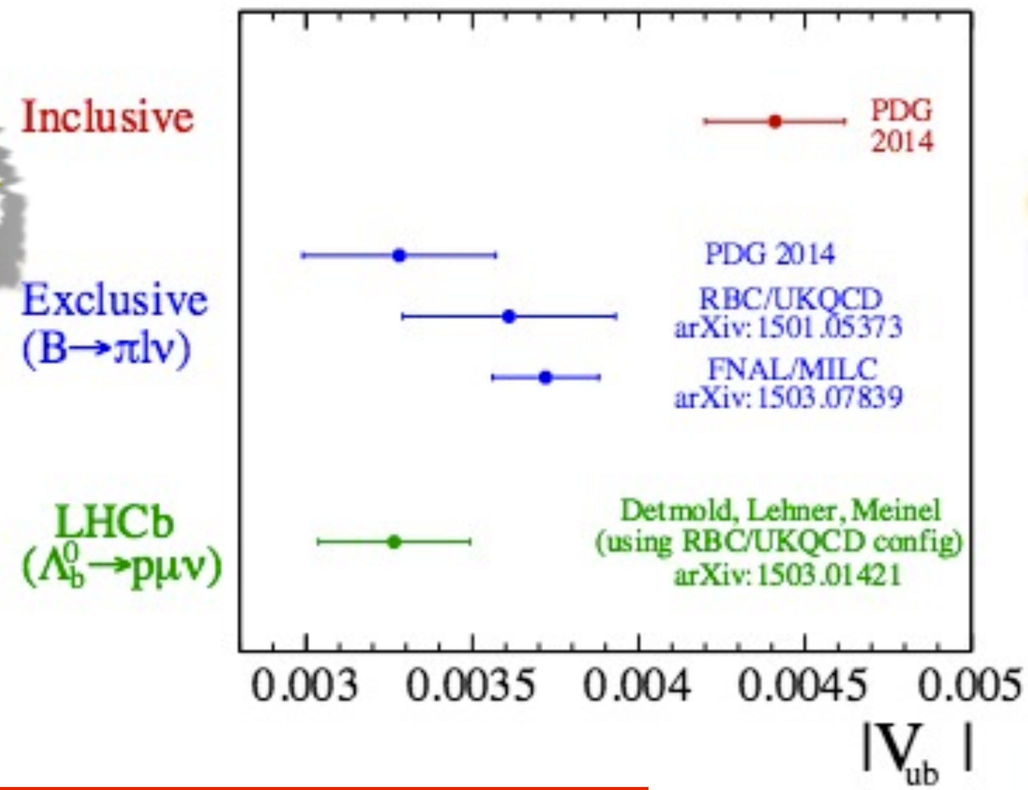
- Boosted decision tree removes backgrounds with additional charged tracks that could vertex with a pμ candidate.
- Efficiency from simulation, with many data-driven corrections

Determination of $|V_{ub}|$

- Corrected mass, $m_{\rm corr} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp$ fits are used to extract signal and control sample yields, accounting for the per-event uncertainty

$$N(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu}) = 17687 \pm 733 \ (\mathcal{L} = 2\ {\rm fb}^{-1})$$





$$|V_{ub}| = (3.27 \pm 0.15({\rm exp}) \pm 0.16({\rm theo}) \pm 0.06(|{\rm V_{cb}}|)) \times 10^{-3}$$

FIRST @Hadron Colliders

- In agreement with the exclusively measured world average, 3.5σ deviation from the inclusive measurement
- can check the consistency of $|V_{ub}|/|V_{cb}|$ with β
- does not support a right-handed coupling of significant magnitude

Nature Physics 10 (2015)

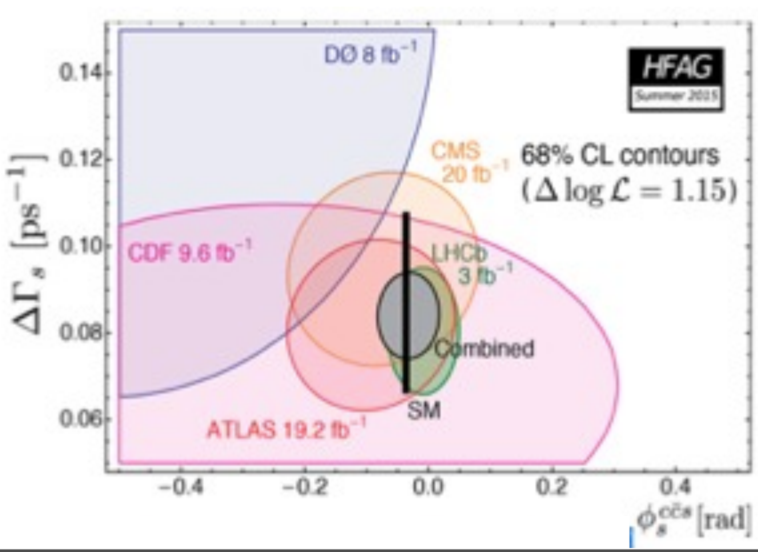
Summary and Conclusions

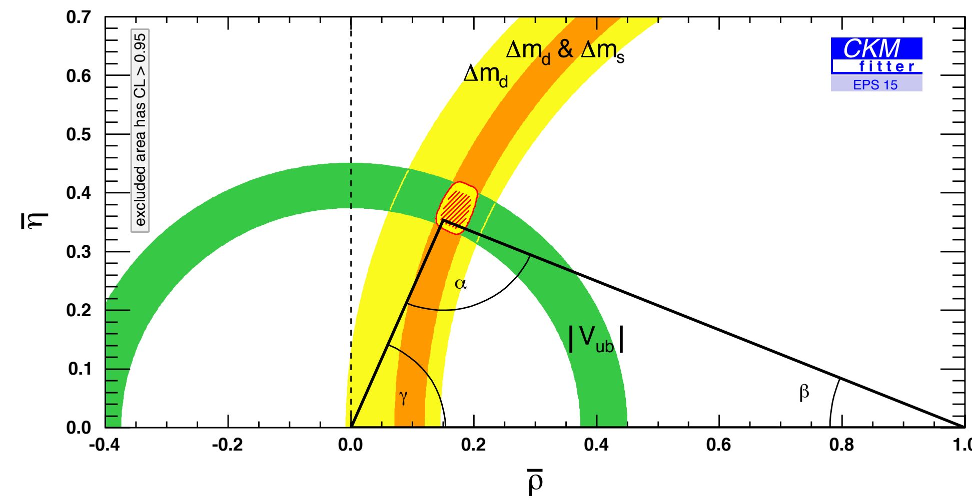
- Precise measurements using b-hadron decays multiply the complementary constraints to the CKM picture

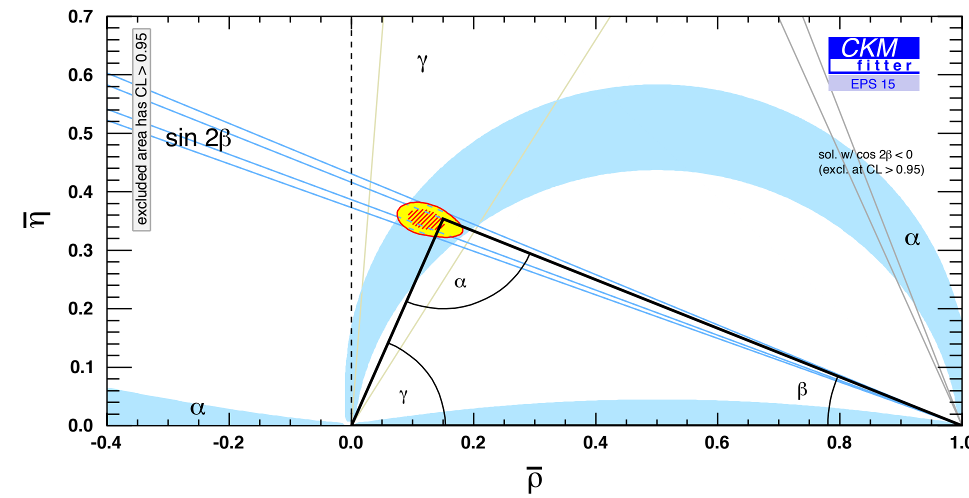
- ***CP-conserving quantities***:
  - world's best measurement of Δm_d
  - first measurement at Hadron Colliders of $|V_{ub}|/|V_{cb}|$

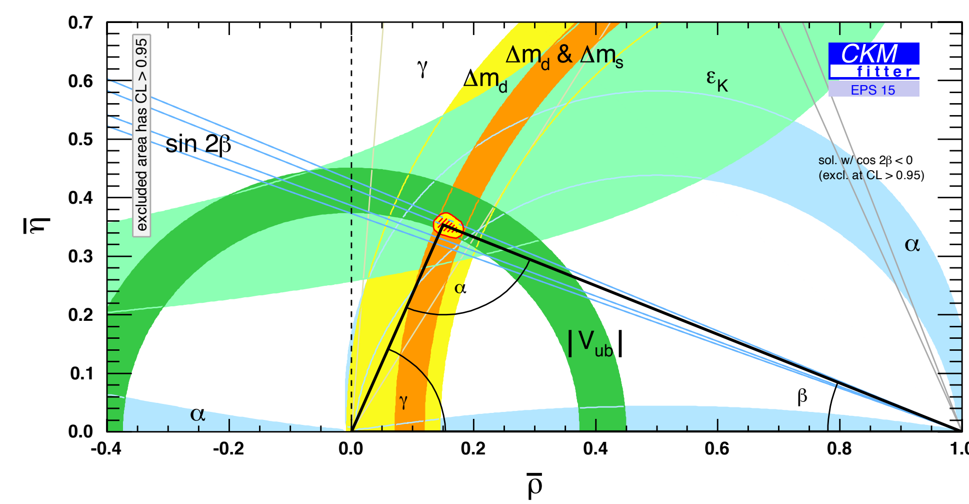
- ***CP-violating quantities***:
  - γ determination with B→DKππ and B→Dπππ decays and γ combination
  - Run-I measurements of sin(2β) and ϕs
  - Contributions from "Penguin pollution" are shown to be small!

- Stay tuned for Run-II!









Backup slides

Δm_d : *B* decay time and Resolutions

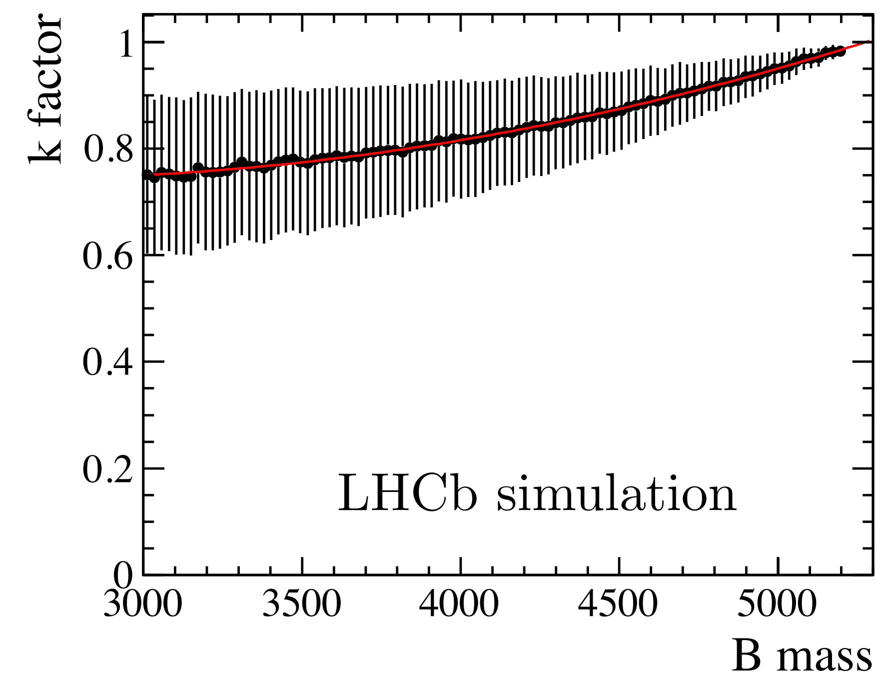
- The momentum of the B meson cannot be measured precisely due to the partial reconstruction of the decay.

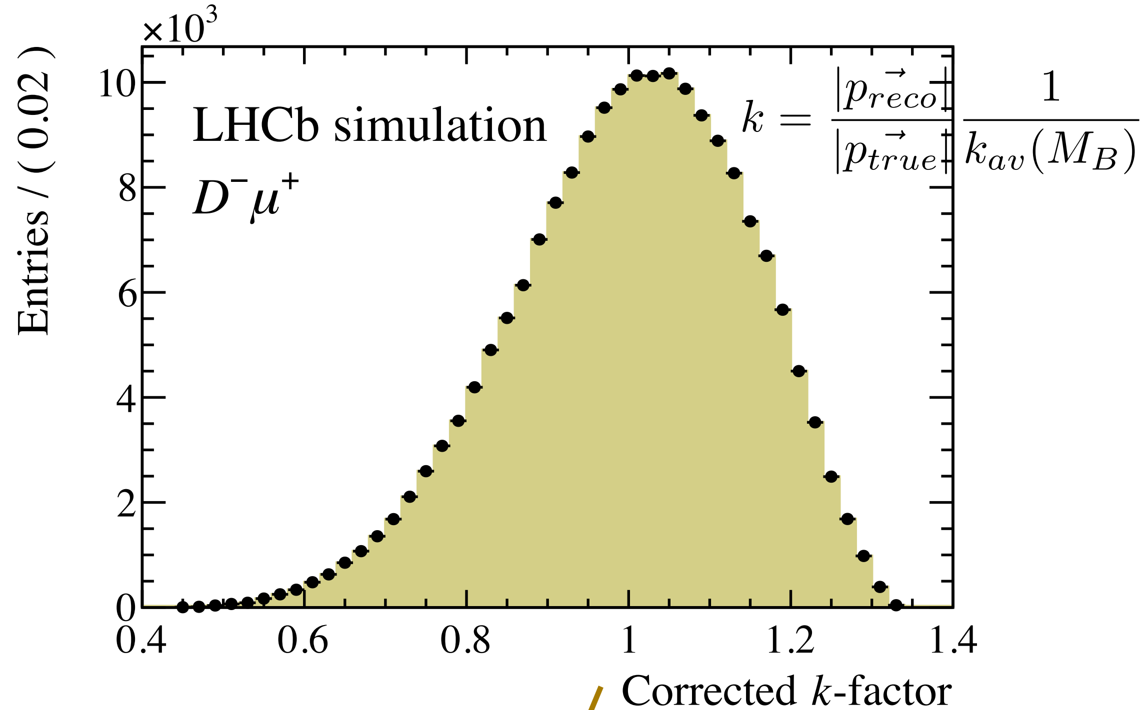
$$t = \frac{L \cdot M_{PDG}}{|\vec{p}|} \cdot k_{av}(M)$$

- The B decay time is corrected using the factor:

$$k = p_{reco}/p_{true}$$

- The k-factors are also used to model the decay time resolution:



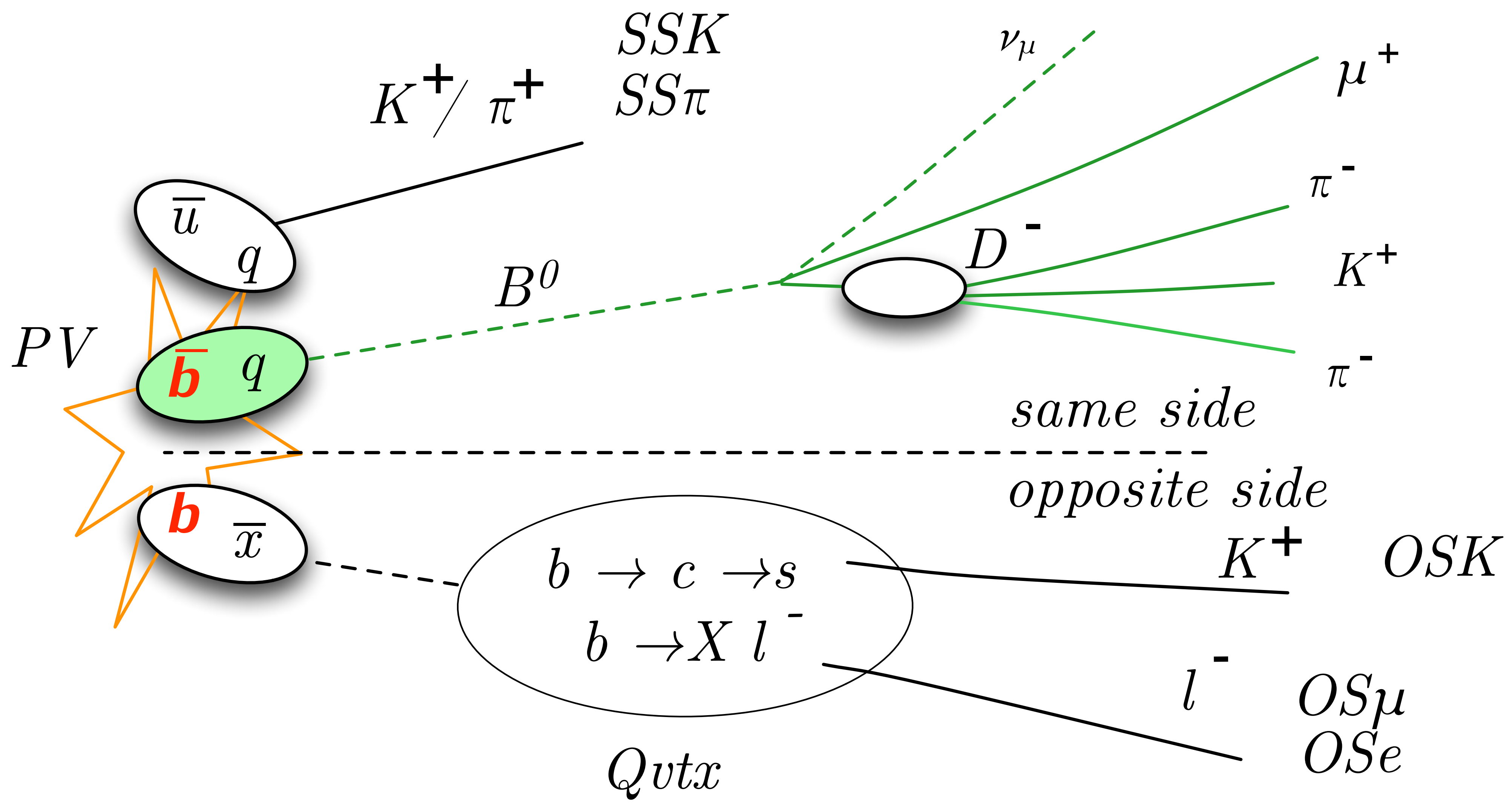


"L resolution"

$$\mathcal{P}_{sig} = (T(t) \otimes_t R(t) \otimes_k F(k)) \cdot A(t)$$

LHCB-CONF-2015-003

Flavour tagging



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ADS selection of flavor specific final states, Cabibbo favoured (CF) and doubly Cabibbo suppressed (DCS) $D \to K^{\pm}\pi^{\mp}$

CP observable of interest:

$$R^{X^\pm} = \frac{\Gamma(B^\pm \to [K^\mp\pi^\pm]_D X^\pm)}{\Gamma(B^\pm \to [K^\pm\pi^\mp]_D X^\pm)} = \frac{r_B^2 + r_D^2 + 2\kappa r_B r_D \cos(\delta_B + \delta_D \pm \gamma)}{1 + r_B^2 r_D^2 + 2\kappa r_B r_D \cos(\delta_B - \delta_D \pm \gamma)}$$

GLW selection of CP eigenstates $D \to K^+K^-$, $D \to \pi^+\pi^-$

CP observables of interest:

$$R_{CP+}^{h^+h^-} = 2\frac{\Gamma(B^- \to [h^+h^-]_D X_s^-) + \Gamma(B^+ \to [h^+h^-]_D X_s^+)}{\Gamma(B^- \to [K^-\pi^+]_D X_s^-) + \Gamma(B^+ \to [K^+\pi^-]_D X_s^+)} \qquad R_{CP+} = \frac{R_{s/d}^{h^+h^-}}{R_{s/d}^{K\pi}}$$

$$= 1 + r_B^2 + 2kr_B\cos\delta_B\cos\gamma$$

$$\mathcal{A}_{X^\pm}^f \equiv \frac{\Gamma(B^- \to f_D X^-) - \Gamma(B^+ \to \bar{f}_D X^+)}{\Gamma(B^- \to f_D X^-) + \Gamma(B^+ \to \bar{f}_D X^+)} = 2kr_B\sin\delta_B\sin\gamma/R_{CP+}$$

- Ratios or double ratios reduce the systematic uncertainties LHCB-PAPER-2015-020

$|V_{ub}|$: significant right-handed coupling

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{ub}^L (\bar{u}\gamma_\mu P_L b + \epsilon_R \bar{u}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu P_L l) + h.c.$$

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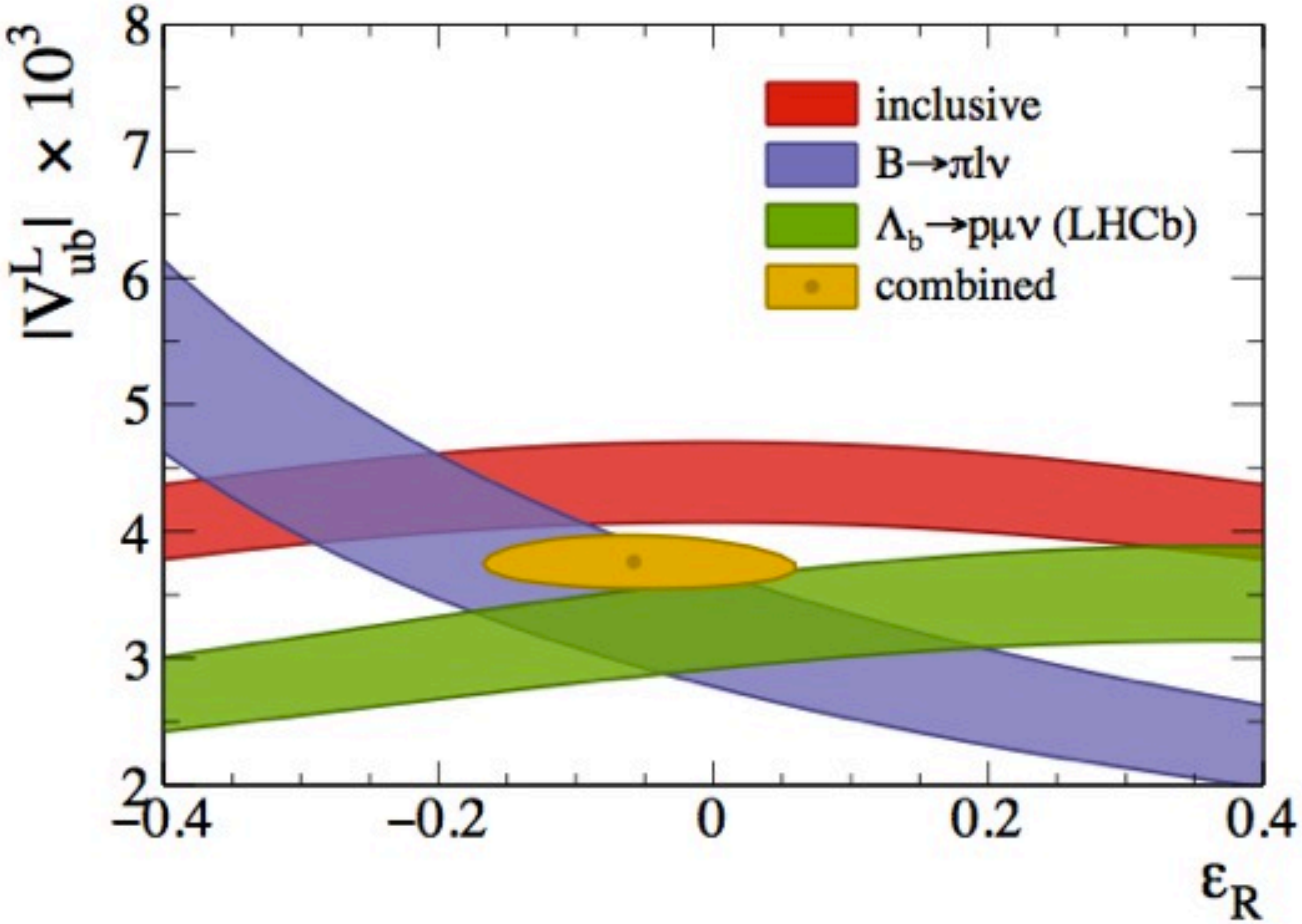

- Hypothesis of a right-handed coupling (Bernlochner et al., arXiv:1408.2516 , Crivellin, arXiv.0907.2461) is not supported by the combination after inclusion of the LHCb measurement