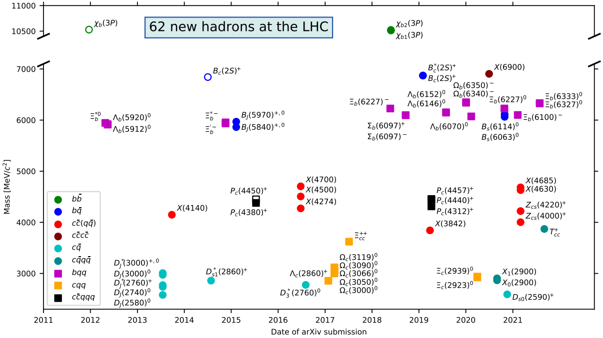
Amplitude analyses for CPV and γ measurements

PWA12/ATHOS7 2021

Philippe d'Argent (CERN) on behalf of the LHCb collaboration

07.09.2021

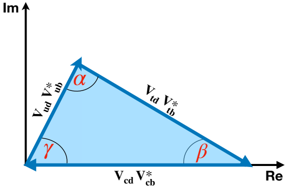
Amplitude analyses



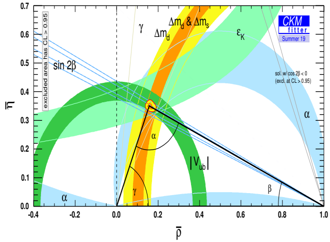
[https://www.nikhef.nl/ pkoppenb/particles.html]

- LHCb is a hadron discovery factory
- Especially discoveries of tetra/penta-quarks candidates triggered excitement in the theory community
- Amplitude analyses are a powerful tools for spectroscopy: determine mass, width, spin, parity of resonances
- Intrinsic sensitivity to phases ⇒ **CPV measurements**

Unitarity Triangle measurements



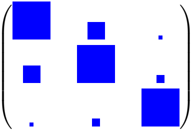
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



- Complex CKM matrix elements are the only source of CPV in SM
- **Key test of the SM:** Verify unitarity of CKM matrix
  - **Magnitudes:** Measure branching fractions or mixing frequencies
  - **Phases:** Measure CPV

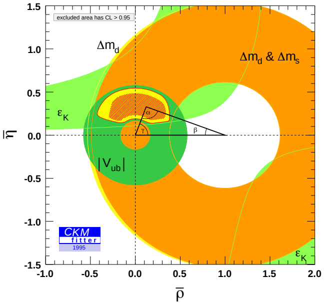
$\Rightarrow$ Sensitivity to NP effects from global consistency of various measurements

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} =$$

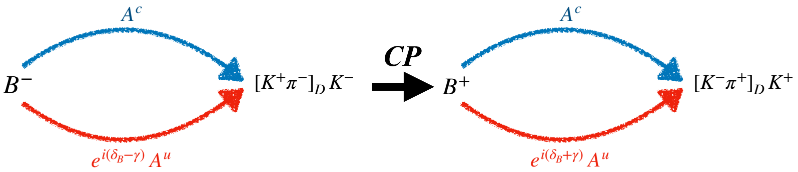


CKM angle γ

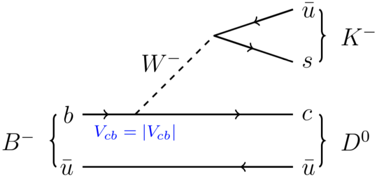
- γ is the phase between $b \to c$ and $b \to u$ decays
- Can be determined entirely from tree decays $\Rightarrow$ **SM benchmark**
- Significant experimental progress over past 25 years
- Close sensitivity gap:
  - **Direct measurement**: $\gamma = (71.1^{+4.1}_{-4.5})^\circ$ [HFLAV20]
  - **Indirect measurement**: $\gamma = (65.7^{+1.0}_{-2.5})^\circ$ [CKMfitter19]

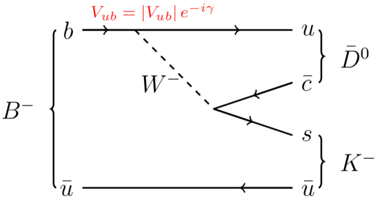


Direct CPV in $B^\pm \to DK^\pm$

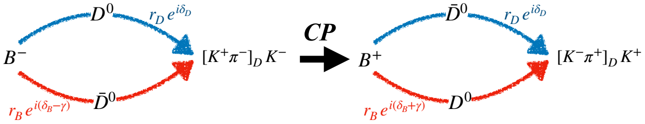


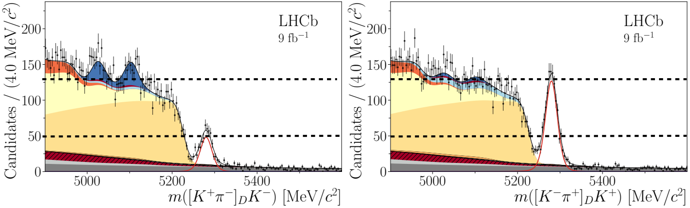
- Amplitude ratio: $r_B = A^u / A^c \approx 0.1$
- Weak phase: **CP** $\gamma = -\gamma$
- Strong phase: **CP** $\delta_B = +\delta_B$



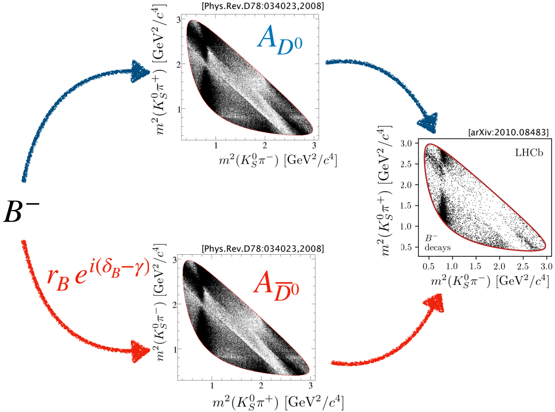


Direct CPV in $B^{\mp} \to DK^{\mp}, D \to K^{\pm}\pi^{\mp}$





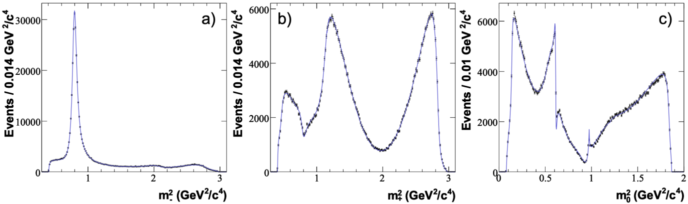
- **Decay rates:** $\Gamma \propto |r_D e^{i\delta_D} + r_B\, e^{i(\delta_B-\gamma)}|^2$, $\bar{\Gamma} \propto |r_D e^{i\delta_D} + r_B\, e^{i(\delta_B+\gamma)}|^2$
- **CP Asymmetry:** $A_{CP} = \frac{2 r_B r_D \sin(\delta_B+\delta_D)\sin(\gamma)}{r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B+\delta_D)\cos(\gamma)} = (45.1 \pm 2.6)\%$
- Only two observables but 3 unknowns
  $\Rightarrow$ no standalone measurement of γ possible
- Additional information from $D \to KK, \pi\pi, K^{\mp}\pi^{\pm}$ (and part. reco. $B^{\pm} \to D^* K^{\pm}$) allows deriving tight constraints



- Main idea: Perform a $D \to hh$ like analysis in regions of the Dalitz plot
- Total amplitude for $B^\mp \to DK^\mp$:
  $A_{B^\mp}(m^2_{K_s\pi^+}, m^2_{K_s\pi^-}) = A_{D^0}(m^2_{K_s\pi^+}, m^2_{K_s\pi^-}) + r_B\, e^{i(\delta_B \mp \gamma)}\, A_{D^0}(m^2_{K_s\pi^-}, m^2_{K_s\pi^+})$
- Requires knowledge of the strong phase variation over Dalitz plot

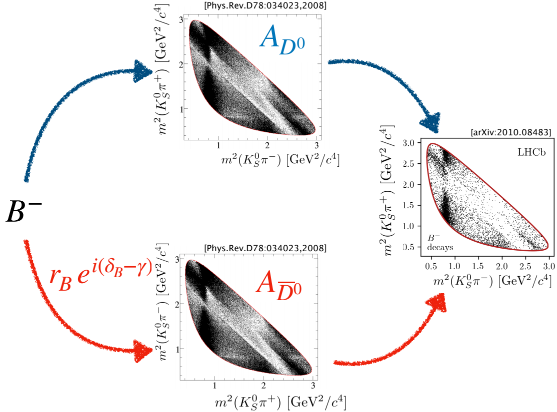
$D \to K_S^0 hh$ Amplitude model

[Phys.Rev.D78(2008)034023]



- Amplitude model has been developed by BaBar using flavor-tagged D^0 decays from $D^{*+} \to D^0\pi^+$
- Using this as input for a model-dependent γ measurement makes optimal use of the available statistics
- **But** systematic of the amplitude description is hard to quantify

CKM γ from $B^\pm \to Dh^\pm$, $D \to K^0_S hh$



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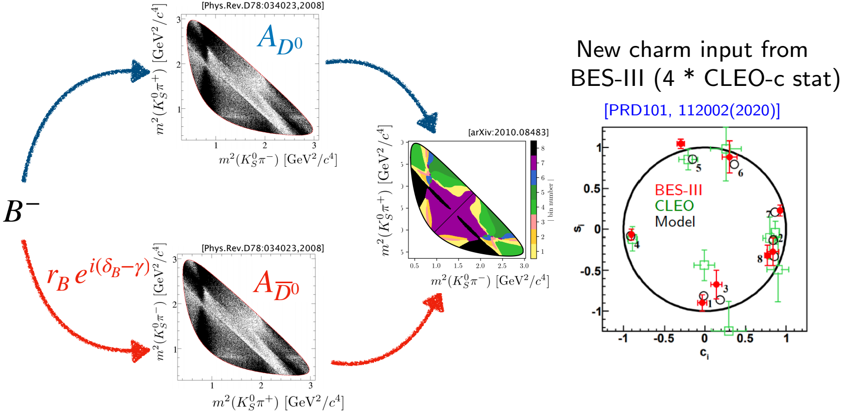
- Strong phase difference $\delta_D = \arg(A_{D^0}) - \arg(A_{\bar{D}^0})$ measured by CLEO-c/BES-III in Dalitz-plot bins $\Rightarrow$ **Allows model-independent measurement of γ!**
  [BPGGSZ, arXiv:2006.12404]
- Amplitude model still crucial to choose a binning with optimal sensitivity



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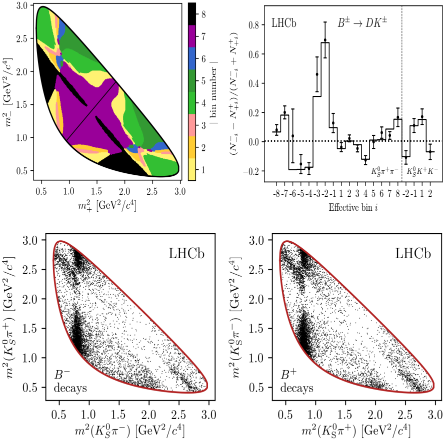
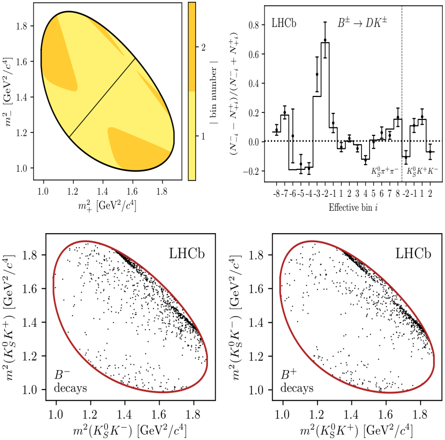


- Updated measurement with full Run 1+2 (9fb^{-1}) data [JHEP02(2021)169]
- Compare yields in bins between B^- and B^+ decays
- Includes $B^\pm \to D(\mathbf{K}/\pi)^\pm$ with $\boldsymbol{D \to K_S^0\pi\pi}$ and $D \to K_S^0 KK$
- $r_B^{DK} = 0.0904^{+0.0077}_{-0.0075}, \delta_B^{DK} = (118.3^{+5.5}_{-5.6})^\circ, \gamma = (68.7^{+5.2}_{-5.1})^\circ$
  $\Rightarrow$ **Most precise single measurement!**

CKM γ from $B^\pm \to Dh^\pm$, $D \to K^0_S hh$



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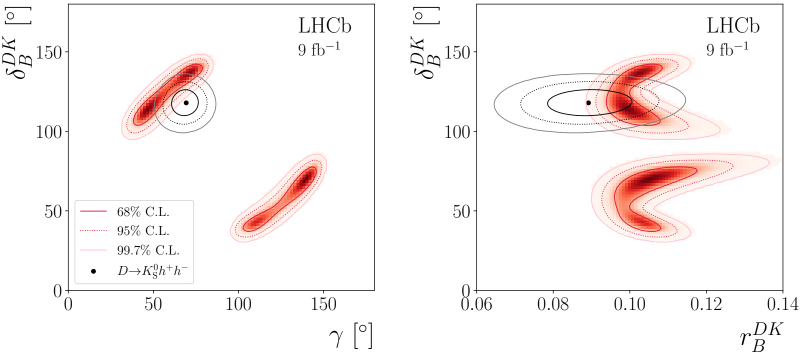
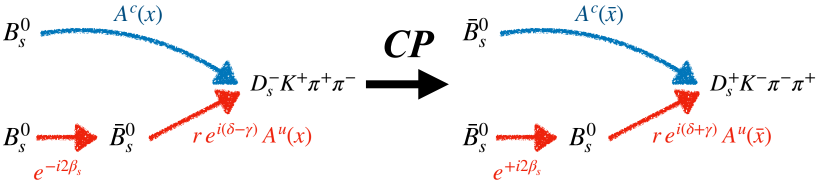
Direct CPV in $B^{\pm} \to D^{(*)}h^{\pm}$

[JHEP04(2021)081, JHEP02(2021)169]



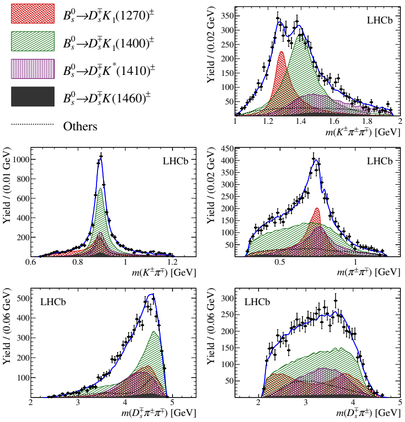
- $D \to hh$: In total 30 observables (asymmetries, ratios) are measured
  $\Rightarrow$ Combined information allows deriving tight constraints on r_B, δ_B, γ
- Combination with $D \to K_S^0 hh$ resolves ambiguities
- Excellent agreement between $D \to hh$ and $D \to K_S^0 hh$

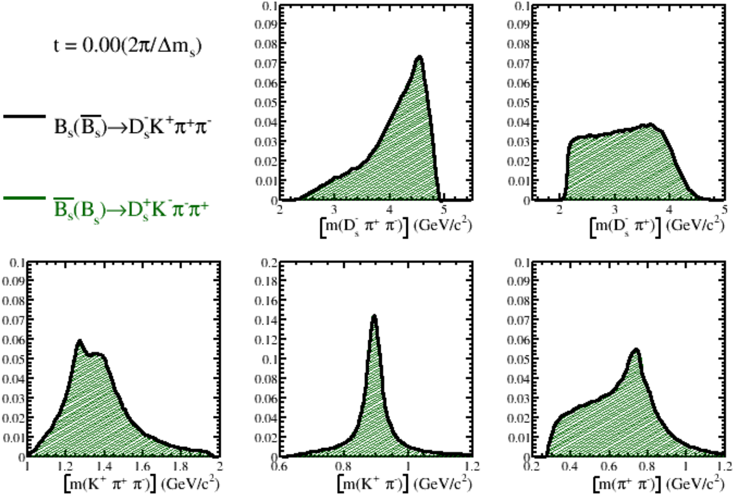
Mixing-induced CPV in $B_s \to D_s K\pi\pi$



- Interference between $b \to c$ and $b \to u$ achieved through $B_s^0 - \bar{B}_s^0$ mixing
- Strong phases in $A^c(x)$ and $A^u(x)$ depend on 5D phase-space
- Two approaches:
  - **Model-dependent:** Describe resonance contributions with amplitude model
  - **Model-independent:** Integrate over phase-space space $\Rightarrow$ Coherence factor κ dilutes sensitivity
  - Use full Run 1+2 (9fb^{-1}) data

[JHEP03(2021)137]





(Toy simulation, Animation only playable with Adobe Reader)

Calibration channel $B_s \to D_s\pi\pi\pi$

Flavor-specific $B_s \to D_s\pi\pi\pi$ used for:

- **Calibration of flavor tagging algorithms:**
  - Have we produced a B_s^0 or a $\bar{B}_s^0$?
  - Mixing asymmetry:

$$A_{mix} = \frac{\text{Unmixed - Mixed}}{\text{Unmixed + Mixed}} = (1-2\omega)\cos(\Delta m_s t)$$

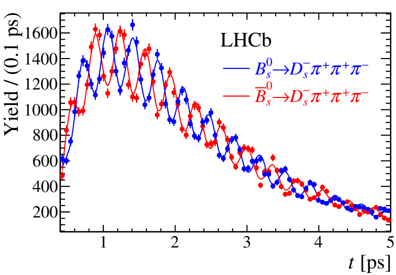
$\Rightarrow$ Mistag $\omega \approx 40\%$

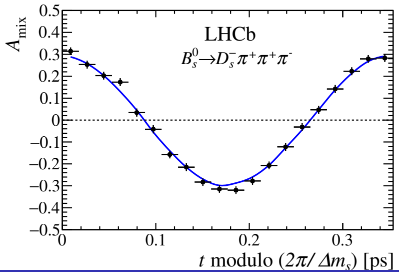
  - Tagging power $\epsilon_{\text{eff}} = \epsilon_{\text{tag}}\,(1-2\,\omega)^2 \approx 6\%$

- **Mixing frequency:**
  - Excellent decay-time resolution: $\langle\sigma_t\rangle \approx 37\text{fs} \ll 2\pi/\Delta m_s \approx 350$ fs
  - $\Delta m_s = (17.757 \pm 0.007 \pm 0.008)\text{ps}^{-1}$
  - **More precise than world average!**

(PDG20: $\Delta m_s = (17.756 \pm 0.021)\text{ps}^{-1}$)

[JHEP03(2021)137]





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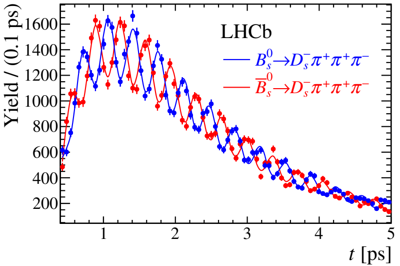
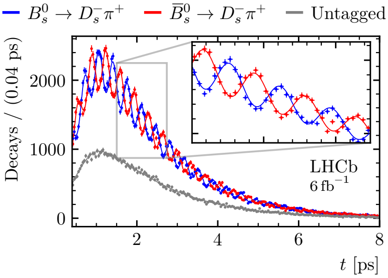
  - **More precise than world average!**
    (PDG20: $\Delta m_s = (17.756 \pm 0.021)\text{ps}^{-1}$)
  - **New measurement from $B_s \to D_s\pi$:** $\Delta m_s = (17.7683 \pm 0.0051 \pm 0.0032)\text{ps}^{-1}$

[JHEP03(2021)137]



[arXiv:2104.04421]



Amplitude model selection

Plenty of possible decay channels ! How to select them ?

Decay channel
$B_s \to D_s^- \, [K_1(1270)^+[S,D] \to \pi^+ \, K^*(892)^0]$
$B_s \to D_s^- \, [K_1(1270)^+ \to \pi^+ \, K^*(1430)^0]$
$B_s \to D_s^- \, [K_1(1270)^+[S,D] \to K^+ \, \rho(770)^0]$
$B_s \to D_s^- \, [K_1(1400)^+[S,D] \to \pi^+ \, K^*(892)^0]$
$B_s \to D_s^- \, [K_1(1400)^+[S,D] \to K^+ \, \rho(770)^0]$
$B_s \to D_s^- \, [K(1460)^+ \to K^+ \, \sigma]$
$B_s \to D_s^- \, [K(1460)^+ \to \pi^+ \, K^*(892)^0]$
$B_s \to D_s^- \, [K(1460)^+ \to K^+ \, \rho(770)^0]$
$B_s \to D_s^- \, [K^*(1410)^+ \to \pi^+ \, K^*(892)^0]$
$B_s \to D_s^- \, [K^*(1410)^+ \to K^+ \, \rho(770)^0]$
$B_s \to D_s^- \, [K_2^*(1430)^+ \to \pi^+ \, K^*(892)^0]$
$B_s \to D_s^- \, [K_2^*(1430)^+ \to K^+ \, \rho(770)^0]$
$B_s \to D_s^- \, [K^*(1680)^+ \to \pi^+ \, K^*(892)^0]$
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$B_s \to D_s^- \, [K_2(1770)^+ \to K^+ \, \rho(770)^0]$
$B_s \to \sigma^0 (D_s^- K^+)_S$
$B_s[S,P,D] \to \rho(770)^0 \, (D_s^- K^+)_V$
$B_s \to K^*(892)^0 \, (D_s^- \pi^+)_S$
$B_s[S,P,D] \to K^*(892)^0 \, (D_s^- \pi^+)_V$
$B_s \to (D_s^- K^+)_S \, (\pi^+\pi^-)_S$
...

$\approx$ 100 in total !

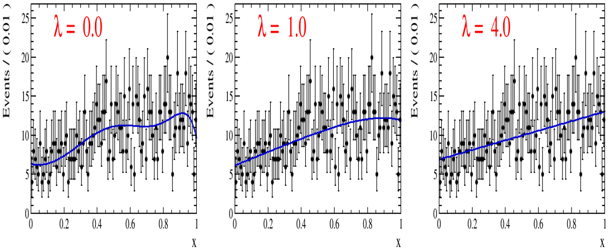
Amplitude model selection

- Overwhelmingly high number of possible amplitudes
- Adding more fit parameters will describe **this** data better
  $\Rightarrow$ **Overfitting**

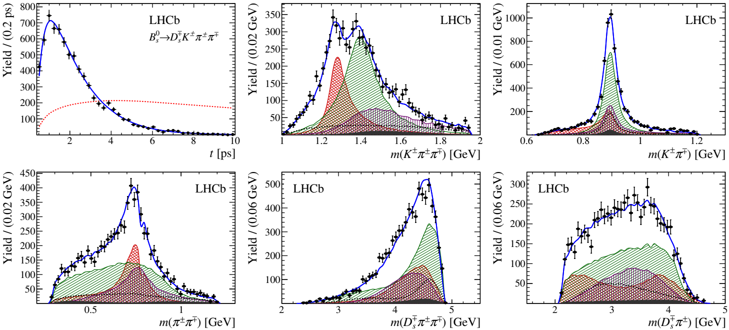
LASSO

- Data-driven method for model selection
  [M. Williams, arXiv:1505.05133]
- Include "all" amplitudes, but penalize complexity in the likelihood:
  $-2{\cdot}\log(L) \rightarrow -2{\cdot}\log(L) + \lambda \cdot \sum_i |r_i|$

(Toys generated with pdf $= 1 + x$, fitted with 10-order polynomial)



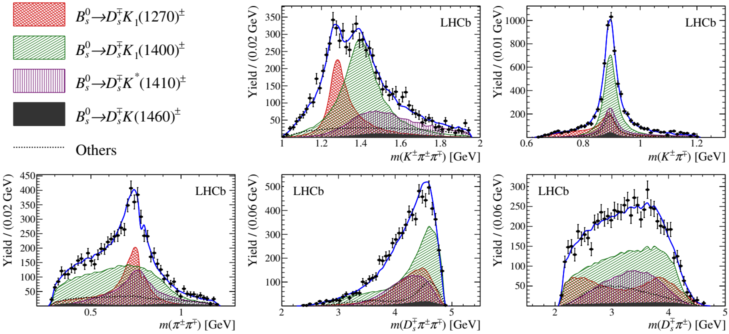
Full time-dependent amplitude fit with LASSO model



[JHEP03(2021)137]

- 6D time-dependent amplitude fit
- Selected 8 $b \to c$ and 8 $b \to u$ amplitudes

Full time-dependent amplitude fit with LASSO model



[JHEP03(2021)137]

- 6D time-dependent amplitude fit
- Selected 8 $b \to c$ and 8 $b \to u$ amplitudes

Selected LASSO amplitudes

- 2 amplitude models fitted simultaneously
- Total amplitudes: $A^c(x) = \sum_i a_i^c A_i(x)$, $A^u(x) = \sum_i a_i^u A_i(x)$
- Fit fractions: $F_i^{c(u)} = \int |a_i^{c(u)} A_i(x)|^2 d\Phi_4 / \int |A^{c(u)}(x)|^2 d\Phi_4$

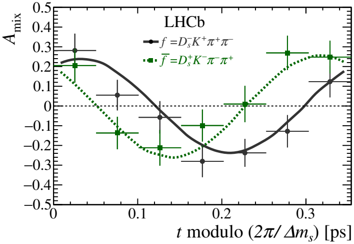
[JHEP03(2021)137]

Decay Channel	F^c[%]	F^u[%]
$B_s \to D_s\,(K_1(1270) \to K^*(892)\,\pi)$	$13.0 \pm 2.4 \pm 2.7 \pm 3.4$	$4.1 \pm 2.2 \pm 2.9 \pm 2.6$
$B_s \to D_s\,(K_1(1270) \to K\,\rho(770))$	$16.0 \pm 1.4 \pm 1.8 \pm 2.1$	$5.1 \pm 2.2 \pm 3.5 \pm 2.0$
$B_s \to D_s\,(K_1(1270) \to K_0^*(1430)\,\pi)$	$3.4 \pm 0.5 \pm 1.0 \pm 0.4$	$1.1 \pm 0.5 \pm 0.6 \pm 0.5$
$B_s \to D_s\,(K_1(1400) \to K^*(892)\,\pi)$	$63.9 \pm 5.1 \pm 7.4 \pm 13.5$	$19.3 \pm 5.2 \pm 8.3 \pm 7.8$
$B_s \to D_s\,(K^*(1410) \to K^*(892)\,\pi)$	$12.8 \pm 0.8 \pm 1.5 \pm 3.2$	$12.6 \pm 2.0 \pm 2.6 \pm 4.1$
$B_s \to D_s\,(K^*(1410) \to K\,\rho(770))$	$5.6 \pm 0.4 \pm 0.6 \pm 0.7$	$5.6 \pm 1.0 \pm 1.2 \pm 1.8$
$B_s \to D_s\,(K(1460) \to K^*(892)\,\pi)$		$11.9 \pm 2.5 \pm 2.9 \pm 3.1$
$B_s \to (D_s\,\pi)_P\;K^*(892)$	$10.2 \pm 1.6 \pm 1.8 \pm 4.5$	$28.4 \pm 5.6 \pm 6.4 \pm 15.3$
$B_s \to (D_s\,K)_P\;\rho(770)$	$0.9 \pm 0.4 \pm 0.5 \pm 1.0$	
Sum	$125.7 \pm 6.4 \pm 6.9 \pm 19.9$	$88.1 \pm 7.0 \pm 10.0 \pm 20.9$

Coherence factor can be derived from amplitude models:

$$\kappa \equiv \frac{|\int \mathcal{A}^c(x)^* \mathcal{A}^u(x) d\Phi_4|}{\sqrt{\int |\mathcal{A}^c(x)|^2 d\Phi_4}\sqrt{\int |\mathcal{A}^u(x)|^2 d\Phi_4}} = 0.72 \pm 0.04 \pm 0.06 \pm 0.04$$

Model-independent fit



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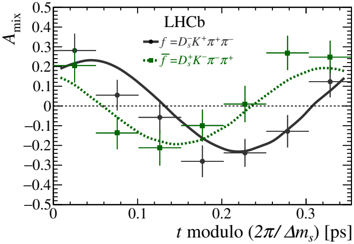
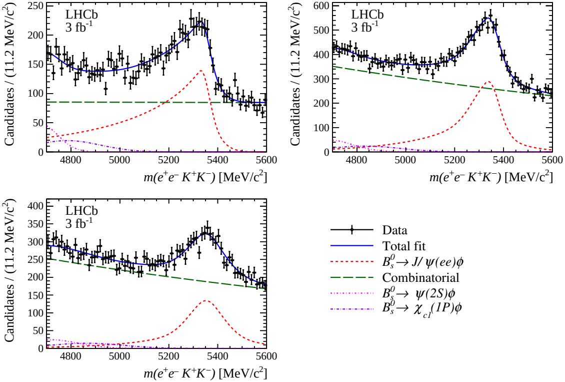


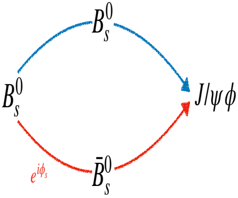
[JHEP03(2021)137]

Parameter	Model-independent	Model-dependent
r	$0.47^{+0.08}_{-0.08}{}^{+0.02}_{-0.03}$	$0.56 \pm 0.05 \pm 0.04 \pm 0.07$
κ	$0.88^{+0.12}_{-0.19}{}^{+0.04}_{-0.07}$	$0.72 \pm 0.04 \pm 0.06 \pm 0.04$
δ [°]	$-6^{+10}_{-12}{}^{+2}_{-4}$	$-14 \pm 10 \pm 4 \pm 5$
$\gamma - 2\beta_s$ [°]	$42^{+19}_{-13}{}^{+6}_{-2}$ (stat, sys)	$42 \pm 10 \pm 4 \pm 5$ (stat, sys, model)

- Good agreement between methods!
- What about β_s?

[arXiv:2105.14738]

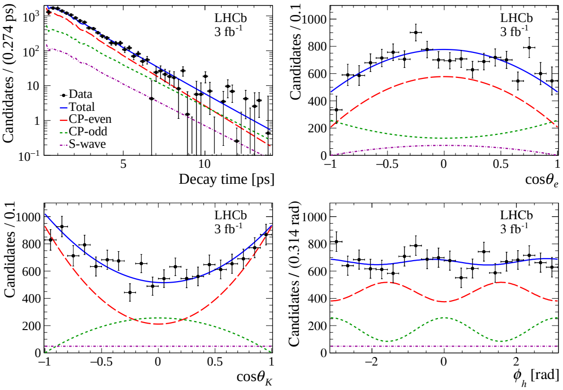


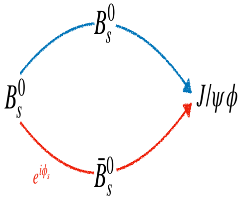


- First time-dependent angular analysis with electron final state (Run1 data (3fb^{-1}))
- Follows similar strategy as $J/\psi \to \mu^+\mu^-$ analysis
- Important cross-check with different systematics
- $-2\beta_s \approx \phi_s = (0.00 \pm 0.27 \pm 0.10)$rad (PDG20: $\phi_s = (-0.051 \pm 0.023)$rad)

Measurement of ϕ_s from $B_s \to J/\psi(e^+e^-)\phi$

[arXiv:2105.14738]





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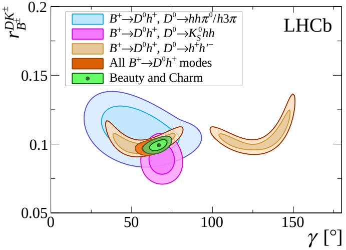
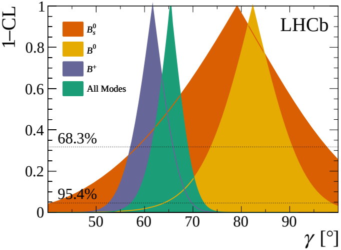
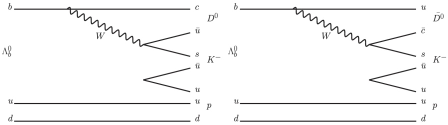
- Last LHCb average: $\gamma = (74^{+5}_{-6})^\circ$ [LHCb-CONF-2018-002]
- **New** average $\boldsymbol{\gamma = (65.4^{+3.8}_{-4.2})^\circ}$ includes:
  - $B^\pm \to D^{(*)}h^\pm$ with $D \to hh, K^0_S hh$ updated with Run2 data [JHEP04(2021)081, JHEP02(2021)169]
  - TD $B_s \to D_s^\mp K^\pm \pi^\pm \pi^\mp$ for the first time [JHEP03(2021)137]
  - and more (including charm input for the first time) [LHCB-CONF-2021-001]
  - Amplitude analyses crucial to optimize sensitivity of multi-body modes
- Getting closer to challenge precision of global fits: $\gamma = (65.7^{+1.0}_{-2.5})^\circ$ [CKMfitter]
- **New** precise measurements of Δm_s and β_s vital input for global CKM fits





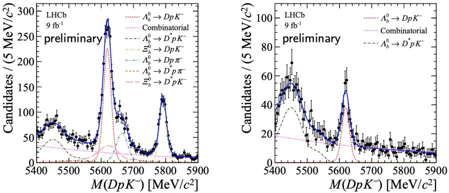
Search for CP violation in $\Lambda_b \to [K^+\pi^-]_D pK^-$ decays

- No measurement of γ from baryon decays yet
- $\Lambda_b \to DpK^-$ sensitive to γ as $b \to c$ and $b \to u$ amplitudes are of similar magnitude for suppressed mode
- Amplitude model could be useful to find regions of enhanced sensitivity
- For more details see Anton's talk!



- Favored decay: $\Lambda_b \to [K^-\pi^+]_D pK^-$
- Suppressed decay: $\Lambda_b \to [K^+\pi^-]_D pK^-$

(discovered for the first time!)



[LHCB-PAPER-2021-027 (in preparation)]

- $R = \frac{N_{FAV}}{N_{SUP}} = 7.14 \pm 0.79(stat)^{+0.43}_{-0.33}(sys)$
- $A = \frac{N_{SUP}(\Lambda_b^0) - N_{SUP}(\bar{\Lambda}_b^0)}{N_{SUP}(\Lambda_b^0) + N_{SUP}(\bar{\Lambda}_b^0)} =$

$0.119 \pm 0.088(stat)^{+0.024}_{-0.026}(sys)$

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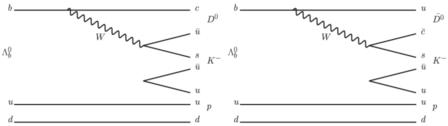

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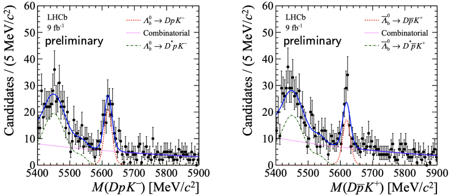


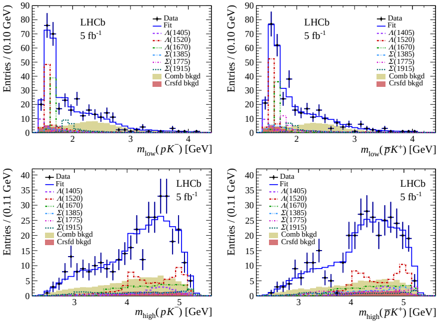
[LHCB-PAPER-2021-027 (in preparation)]

- No CPV in the baryon sector observed yet!
- Search in $\Xi_b \to pK^-K^-$ decays motivated by large local CPV observed in $B^+ \to hhh$
  [Phys.Rev.Lett.124(2020)031801]
- First amplitude analysis of b-baryon decay allowing for CPV!
- For more details see Anton's talk!

Component	A^{CP} (10^{-2})
$\Sigma(1385)$	-26.6 ± 33.9 (stat) ± 72.7 (syst)
$\Lambda(1405)$	-0.8 ± 24.5 (stat) ± 31.9 (syst)
$\Lambda(1520)$	-4.7 ± 8.7 (stat) ± 7.6 (syst)
$\Lambda(1670)$	3.1 ± 14.0 (stat) ± 10.1 (syst)
$\Sigma(1775)$	-47.4 ± 25.5 (stat) ± 13.8 (syst)
$\Sigma(1915)$	11.3 ± 26.1 (stat) ± 21.8 (syst)

$$\mathcal{B}\left(\Xi_b^- \to \Sigma(1385)K^-\right) = (0.26 \pm 0.11 \pm 0.17 \pm 0.10) \times 10^{-6},$$
$$\mathcal{B}\left(\Xi_b^- \to \Lambda(1405)K^-\right) = (0.19 \pm 0.06 \pm 0.07 \pm 0.07) \times 10^{-6},$$
$$\mathcal{B}\left(\Xi_b^- \to \Lambda(1520)K^-\right) = (0.76 \pm 0.09 \pm 0.08 \pm 0.30) \times 10^{-6},$$
$$\mathcal{B}\left(\Xi_b^- \to \Lambda(1670)K^-\right) = (0.45 \pm 0.07 \pm 0.13 \pm 0.18) \times 10^{-6},$$
$$\mathcal{B}\left(\Xi_b^- \to \Sigma(1775)K^-\right) = (0.22 \pm 0.08 \pm 0.09 \pm 0.09) \times 10^{-6},$$
$$\mathcal{B}\left(\Xi_b^- \to \Sigma(1915)K^-\right) = (0.26 \pm 0.09 \pm 0.21 \pm 0.10) \times 10^{-6},$$

[arXiv:2104.15074]

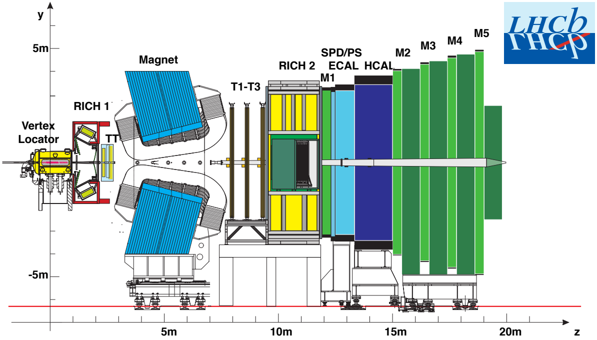


Amplitude analyses are a powerful tool for CPV measurements!

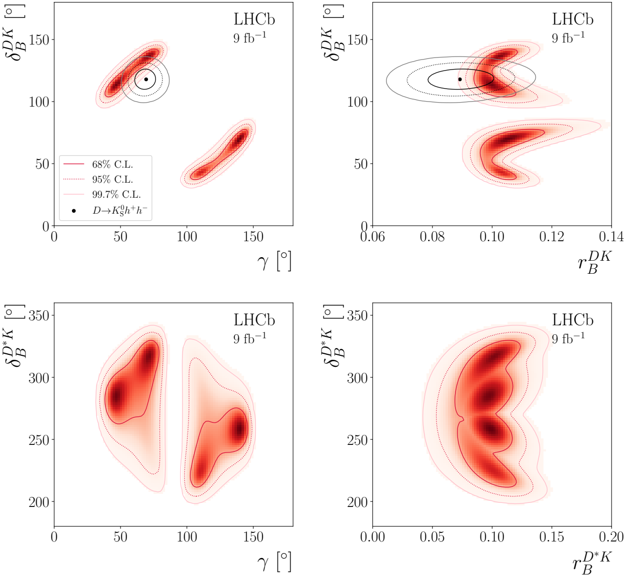
- Model-dependent CPV searches:
  - $\Xi_b \to pK^- K^-$ [arXiv:2104.15074]
  - $B^+ \to hhh$ [Phys.Rev.Lett.124(2020)031801]
  - $D \to KK\pi\pi$ [Phys.Lett.B769(2017)345-356], $D \to \pi\pi\pi\pi$ [JHEP05(2017)143]
- Improved statistical precision for γ measurement in time-dependent $B_s \to D_s K\pi\pi$ [JHEP03(2021)137]
- Optimization of model-independent measurements:
  - Direct CPV in $B \to DK$ [JHEP02(2021)169] or $\Lambda_b \to DpK^-$ [LHCB-PAPER-2021-027 (in preparation)]
  - Charm mixing [Phys.Rev.Lett.122(2019)23,231802]
  - Search for CPV in $D \to \pi\pi\pi\pi$ with energy test [Phys.Lett.B769(2017)345-356]

Backup: LHCb detector

- One-arm spectrometer optimised for studies of beauty and charm decays at LHC
- Excellent time resolution (≈ 45fs), momentum resolution ($dp/p \approx 0.4 - 0.6\%$) and PID performance (RICH)
- Calorimetry: reconstruct neutrals (π^0, γ) in the final state

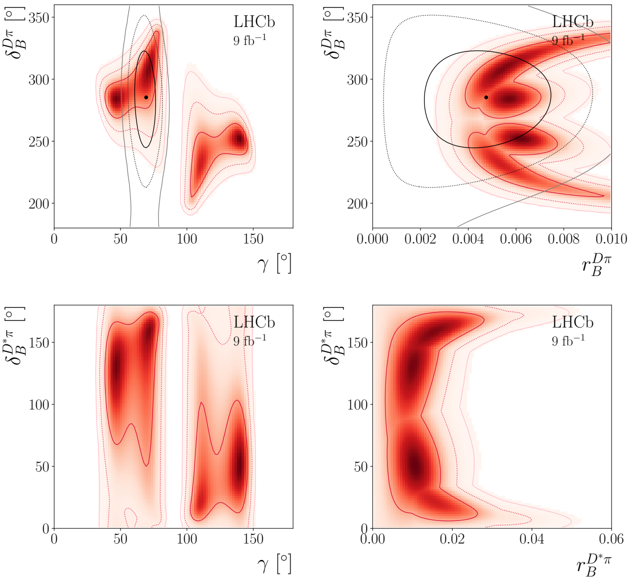


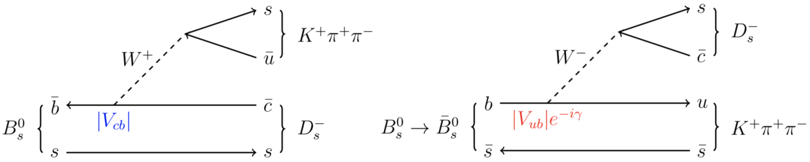
[arXiv:2012.09903, JHEP02(2021)169]



Backup: $B^\mp \to D^{(*)}\pi^\mp$ results

[arXiv:2012.09903, JHEP02(2021)169]



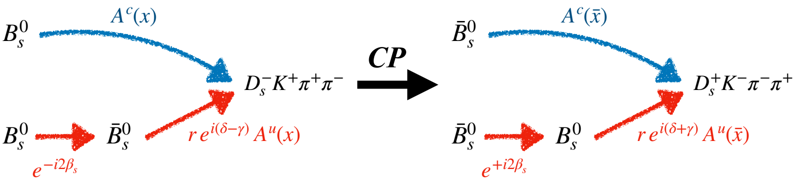


Full time-dependent amplitude PDF

$$\frac{d\Gamma(x,t)}{e^{-\Gamma_s t}\,dt\,d\Phi_4} \propto \left(|\mathcal{A}^c(x)|^2 + r^2\,|\mathcal{A}^u(x)|^2\right)\cosh\left(\frac{\Delta\Gamma_s\,t}{2}\right)$$
$$+\,q\,f\left(|\mathcal{A}^c(x)|^2 - r^2\,|\mathcal{A}^u(x)|^2\right)\cos\left(\Delta m_s\,t\right)$$
$$-\,2\mathrm{Re}\left(\mathcal{A}^c(x)^*\,r\,\mathcal{A}^u(x)\,e^{i\delta - if(\gamma-2\beta_s)}\right)\sinh\left(\frac{\Delta\Gamma_s\,t}{2}\right)$$
$$-\,2\,q\,f\,\mathrm{Im}\left(\mathcal{A}^c(x)^*\,r\,\mathcal{A}^u(x)\,e^{i\delta - if(\gamma-2\beta_s)}\right)\sin\left(\Delta m_s\,t\right)$$

$q = +1(-1)$ for B_s^0 ($\bar{B}_s^0$) initial state
$f = +1(-1)$ for $D_s^- K^+$ ($D_s^+ K^-$) final state
Convention with $\Delta\Gamma_s > 0$

Backup: $B_s \to D_s^{\mp} K^{\pm} \pi^{\pm} \pi^{\mp}$ model-independent PDF

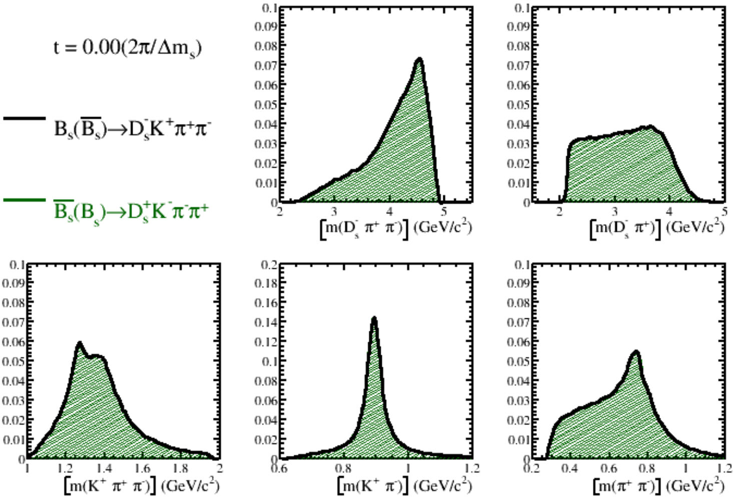


Phasespace integrated PDF

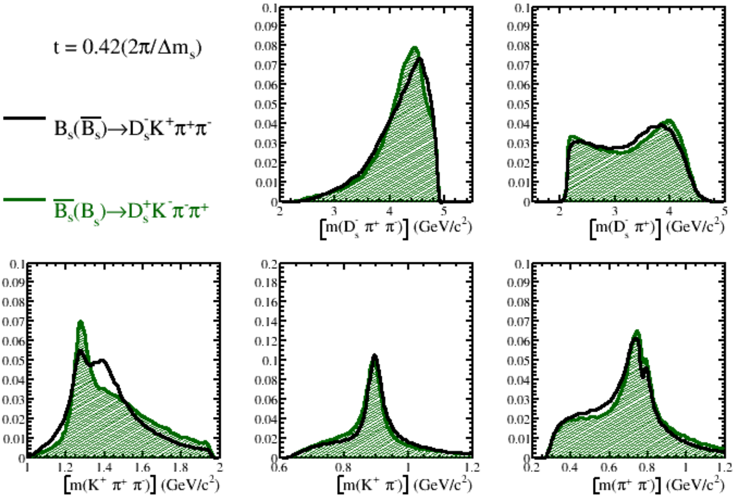
$$\frac{d\Gamma(t)}{e^{-\Gamma_s t}\, dt} \propto \cosh\left(\frac{\Delta\Gamma_s\, t}{2}\right) + q\, f\, C \cos\left(\Delta m_s\, t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_s\, t}{2}\right) - q\, S_f \sin\left(\Delta m_s\, t\right)$$

$$C = \frac{1-r^2}{1+r^2},\quad A_f^{\Delta\Gamma} = -\frac{2\, r\, \kappa \cos\left(\delta - f\left(\gamma - 2\beta_s\right)\right)}{1+r^2},\quad S_f = f\, \frac{2\, r\, \kappa \sin\left(\delta - f\left(\gamma - 2\beta_s\right)\right)}{1+r^2}$$

Coherence factor dilutes sensitivity: $\kappa \equiv \frac{|\int \mathcal{A}^c(x)^* \mathcal{A}^u(x) d\Phi_4|}{\sqrt{\int |\mathcal{A}^c(x)|^2 d\Phi_4} \sqrt{\int |\mathcal{A}^u(x)|^2 d\Phi_4}} \in [0, 1]$



(Toy simulation)



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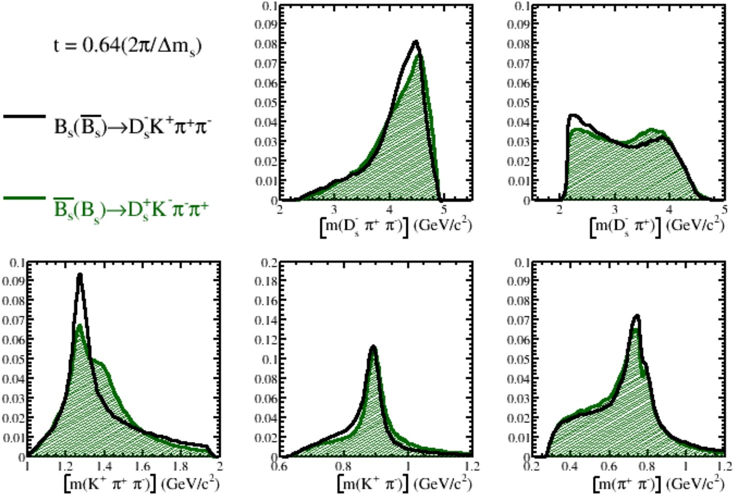

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