Beautiful mixing and *CP* violation at LHCb

Particle Physics Seminar, University of Manchester

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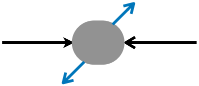
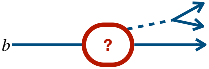
- SM remarkably succesful!
- **But leaves many open questions:**
  - Where has all the antimatter gone?
  - What is dark matter and dark energy?
  - What about gravity?
  - $\cdots$
- How to uncover new phenomena?



- Direct detection probes masses $m < \sqrt{s}/2$
- Simpler to interpret



- Precision measurement of decay rates and CPV
- Probes much higher energy scales

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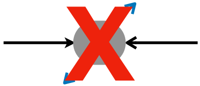

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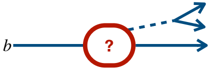

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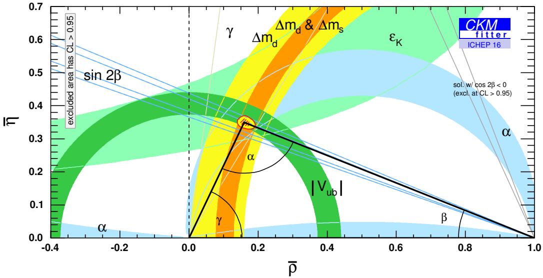
Outline



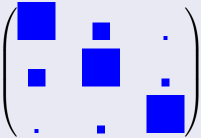
- CP Violation in the SM
- Direct CPV in $B^+ \to DK^+$ decays
- Mixing-induced CPV in $B_s^0 \to D_s^- K^+ \pi^+ \pi^-$ decays

Part 1:
CP Violation in the SM

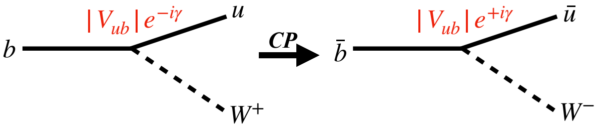
CKM Matrix

- In the SM quarks can change flavor by emission of a $W^{\pm}$ boson
- CKM matrix describes flavor transitions across generations

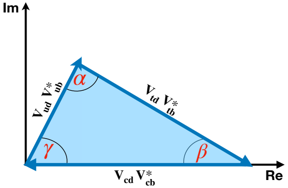
$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} =$$



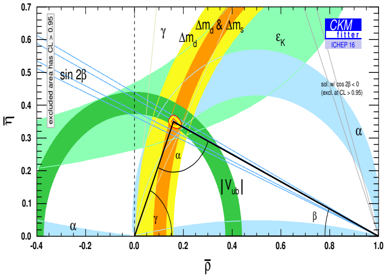
- Matrix elements determine the transition probability
- Complex elements are **only** source of CPV in SM



Unitarity of CKM Matrix

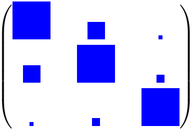


$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$



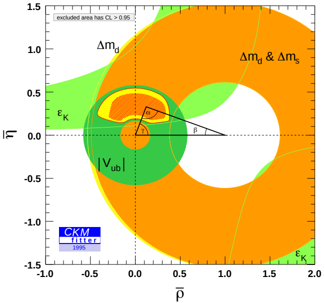
- CKM elements not predicted by SM → determine experimentally:
  - **Magnitudes:** Measure decay rates (*eg* $|V_{ub}|$ from $\Gamma(\Lambda_b \to p\mu^- \bar{\nu}_\mu)$)
  - **Phases:** Measure CPV
- **Unitarity:** Only 3 real parameters and 1 phase are independent
  ⇒ **Key test** of the SM: Verify unitarity with global CKM fit

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

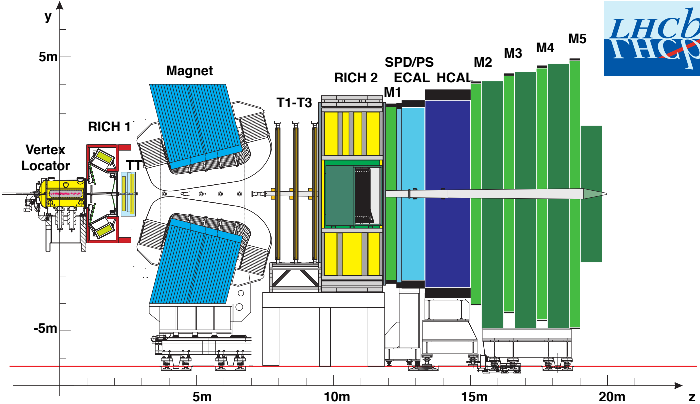


CKM angle γ

- 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]



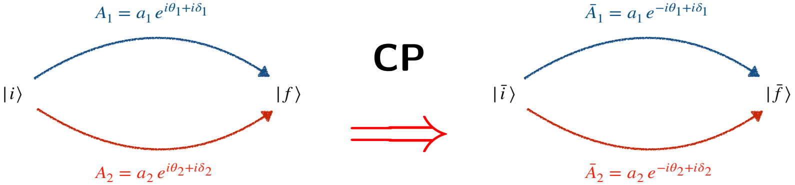
Why LHCb?



- High *b* production cross-section
- Excellent time resolution ($\approx$ 45fs)
- Excellent momentum and mass resolution ($dp/p \approx 0.4 - 0.6\%$)
- Excellent PID

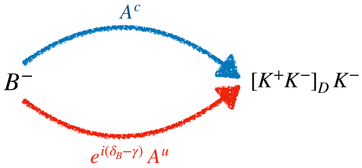
Part 2:
Direct CP Violation

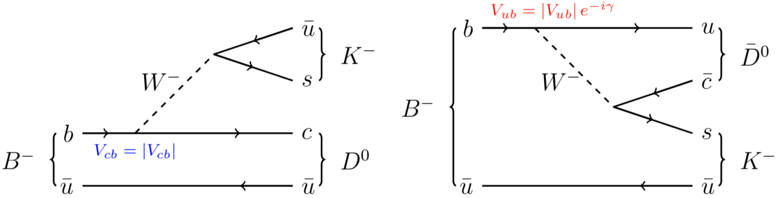
How to measure CP Violation ?



- Global phase is not observable:
  $A \to Ae^{i\theta}$, $|A|^2 \to |A|^2$
- Need at least two interfering processes with different:
  Weak phase : $CP\theta = -\theta$
  Strong phase: $CP\delta = +\delta$
- Asymmetry: $A_{CP} = \frac{\Gamma(i\to f) - \Gamma(\bar{i}\to\bar{f})}{\Gamma(i\to f) + \Gamma(\bar{i}\to\bar{f})} \propto \frac{a_2}{a_1} sin(\Delta\theta) sin(\Delta\delta)$

Example: Direct CPV in $B^{\pm} \to DK^{\pm}$





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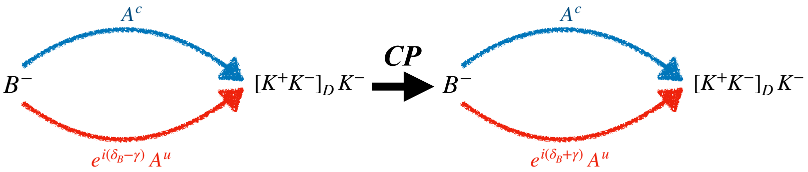
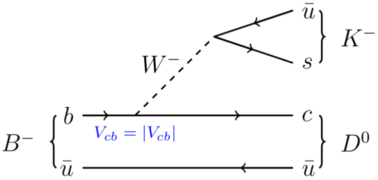
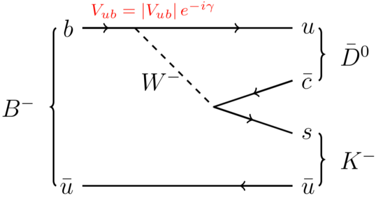
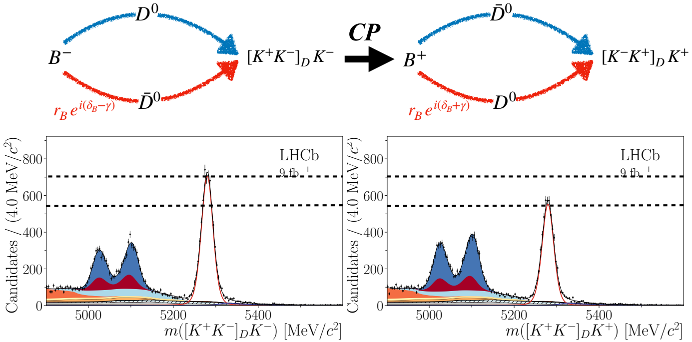


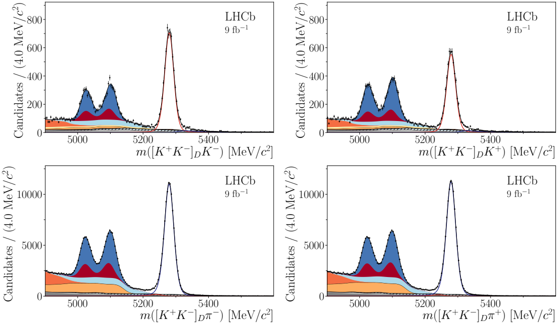


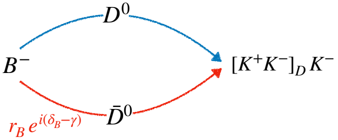




- Measurement with full Run 1+2 (9fb^{-1}) LHCb data [JHEP04(2021)081]
- **Decay rates:** $\Gamma \propto |A^c + e^{i(\delta_B-\gamma)} A^u|^2$, $\bar{\Gamma} \propto |A^c + e^{i(\delta_B+\gamma)} A^u|^2$
- **CP Asymmetry:** $A_{CP} \propto r_B \sin(\delta_B) \sin(\gamma) \approx 10\%$
- Only two observables but 3 unknowns
  $\Rightarrow$ no standalone measurement of γ possible with $D \to KK$ only

[JHEP04(2021)081]





$$A_{CP} = \frac{2r_B \sin(\delta_B)\sin(\gamma)}{1+r_B^2+2r_B\cos(\delta_B)\cos(\gamma)}$$

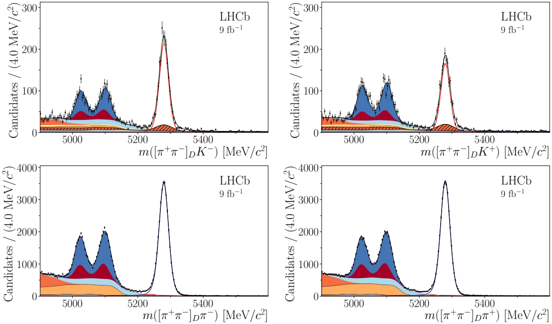
[GLW, Phys. Lett. B253(1991)483]
[GLW, Phys. Lett. B265(1991)172]

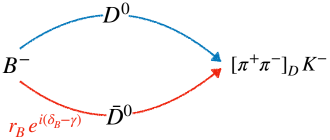
Analysis also uses information from:

- $B^\mp \to D\pi^\mp$ with $r_B^{D\pi} \approx 0.005$
- Partially reconstructed $B^\pm \to D^*(\to D\gamma, D\pi^0)h^\pm$
- **Additional channels:** $D \to \pi^+\pi^-$, $D \to K^-\pi^+$, $D \to K^+\pi^-$

Direct CPV in $B^{\mp} \to DK^{\mp}$, $D \to \pi^+\pi^-$

[JHEP04(2021)081]





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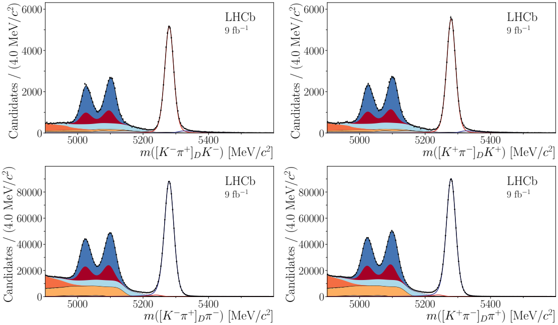

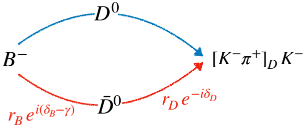

$$A_{CP} = \frac{2 r_B r_D \sin(\delta_B - \delta_D)\sin(\gamma)}{1 + r_B^2 r_D^2 + 2 r_B r_D \cos(\delta_B - \delta_D)\cos(\gamma)}$$

$r_D = 0.0587 \pm 0.0002$ [HFLAV]

[ADS, Phys. Rev. Lett. 78 (1997) 3257]

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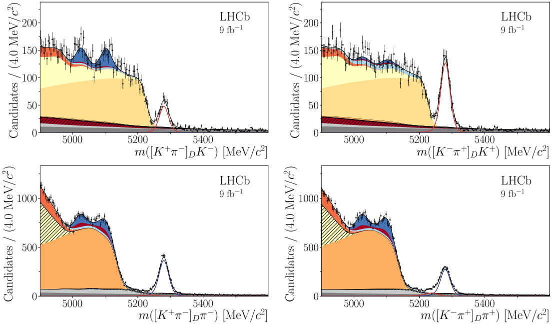

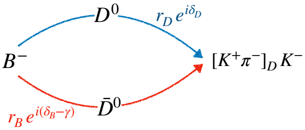

$$A_{CP} = \frac{2 r_B r_D \sin(\delta_B + \delta_D)\sin(\gamma)}{r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma)}$$

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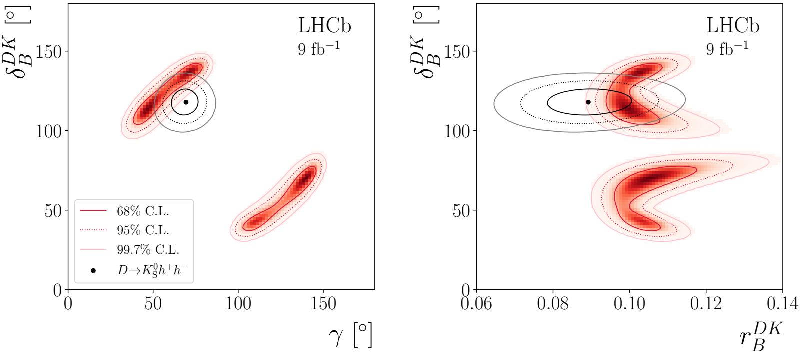
[JHEP04(2021)081]

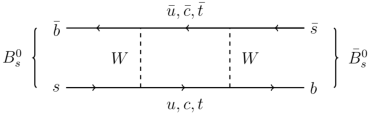


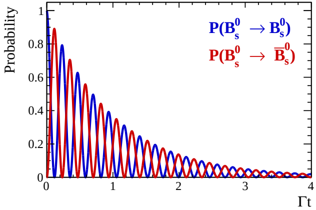
- In total 30 observables (asymmetries, ratios) are measured
  $\Rightarrow$ Combined information allows deriving tight constraints on r_B, δ_B, γ
- Combination with other measurements resolves ambiguities

Part 3:

Mixing-induced CP vioaltion

Neutral Meson Mixing





- Neutral mesons can change their flavor via box-diagram transition
- Effective SE for time-development:

$$-i\frac{\partial}{\partial t}\begin{pmatrix}|B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle\end{pmatrix} = (\mathbf{M} - \frac{i}{2}\mathbf{\Gamma})\begin{pmatrix}|B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle\end{pmatrix}$$

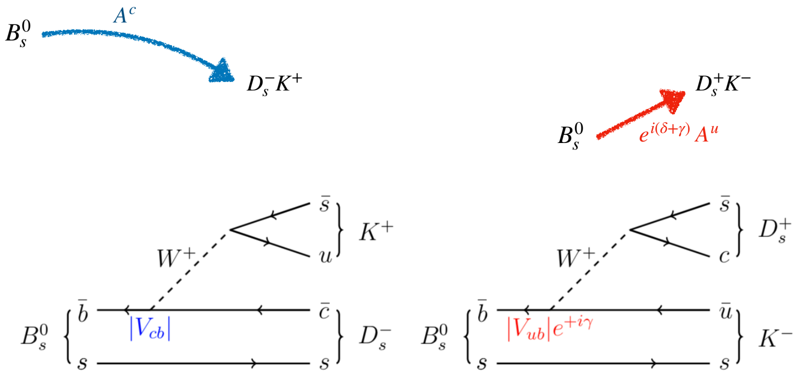
- Flavor eigenstates $(B_s^0, \bar{B}_s^0) \neq$ Mass eigenstates (B_L, B_H):
- Mixing probabilities:

  $P(B_s^0 \rightarrow B_s^0) = e^{-\Gamma_s t}\,[\cosh(\Delta\Gamma_s/2\,t) + \cos(\Delta m_s\,t)]$

  $P(B_s^0 \rightarrow \bar{B}_s^0) = e^{-\Gamma_s t}\,[\cosh(\Delta\Gamma_s/2\,t) - \cos(\Delta m_s\,t)]$

  with oscillation frequency $\Delta m_s \propto |V_{ts}V_{tb}|^2$, mean lifetime $\tau = 1/\Gamma_s$ and lifetime difference $\Delta\Gamma_s$

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



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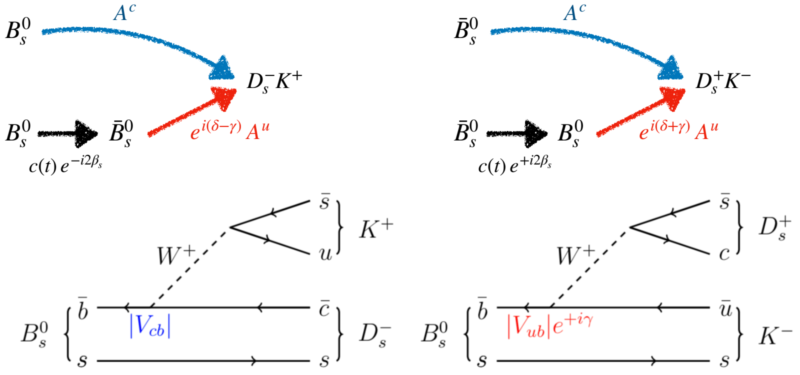

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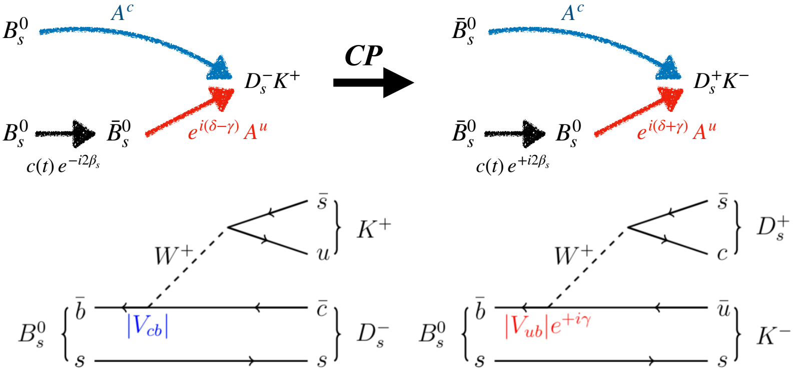
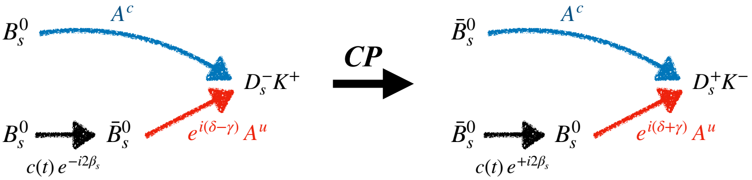


Decay rates:

$$\Gamma \propto |A^c + c(t)\, e^{i(\delta-\gamma-2\beta_s)} A^u|^2$$
$$\bar{\Gamma} \propto |A^c + c(t)\, e^{i(\delta+\gamma+2\beta_s)} A^u|^2$$

Asymmetry:

$$\Gamma - \bar{\Gamma} \propto \underbrace{\frac{A^u}{A^c}}_{r \approx 0.4}\; c(t) \sin(\delta)\, \sin(\gamma + 2\beta_s) \neq 0 \Rightarrow CPV$$



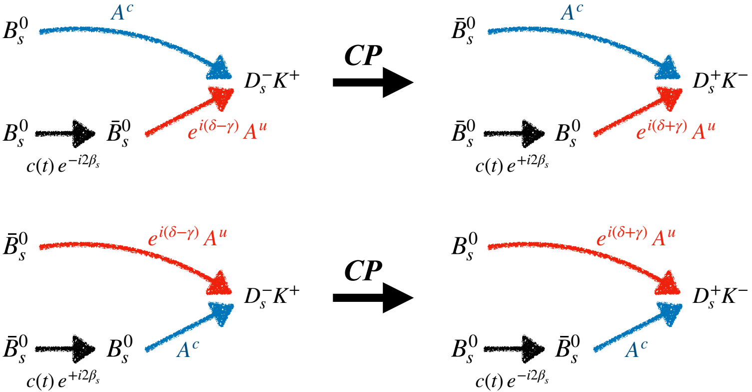
The actual decay rates are more complicated and follow from the SE:

$$\frac{\Gamma(t|q,f)}{e^{-\Gamma_s t}} \propto \left(1+r^2\right) \cosh\left(\frac{\Delta\Gamma_s\, t}{2}\right) + q\, f\, \left(1-r^2\right) \cos\left(\Delta m_s\, t\right)$$
$$- 2r\, \cos(\delta - f(\gamma - 2\beta_s)) \sinh\left(\frac{\Delta\Gamma_s\, t}{2}\right) - 2\, q\, f\, r\, \sin(\delta - f(\gamma - 2\beta_s)) \sin\left(\Delta m_s\, t\right)$$

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

- 4 observables: $\Gamma(B_s^0 \to f), \Gamma(\bar{B}_s^0 \to f), \Gamma(B_s^0 \to \bar{f}), \Gamma(\bar{B}_s^0 \to \bar{f})$
- 3 unknown physical parameters: r, δ, γ

$\Rightarrow$ Standalone measurement of CKM angle γ!



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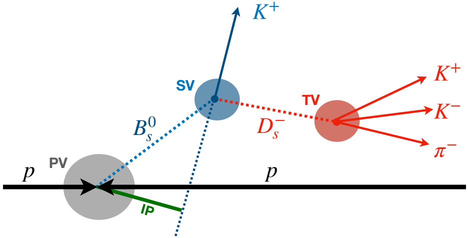
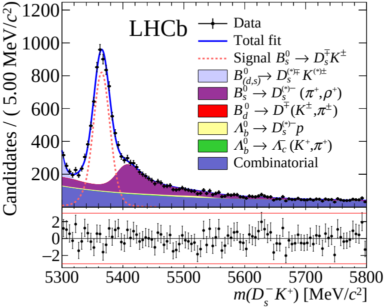
How to select $B_s \to D_s K$ candidates?



- Reconstruct three D_s final-states: $KK\pi$, $\pi\pi\pi$ and $K\pi\pi$
- Both B_s and D_s fly $\mathcal{O}(1cm)$ before they decay
  $\Rightarrow$ require vertex separation
- Final state particles are expected to have large IP and p_T
- Use PID info from RICH detectors to discriminate π and K
- Main suppression of comb. bkg with MVA using kinematic, topological variables and track/vertex fit quality

$B_s \to D_s K$ data sample



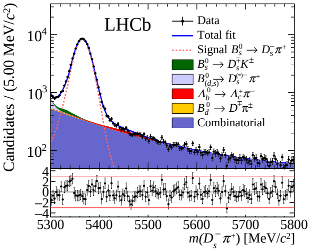
- Analysis using Run-I LHCb data set (3fb^{-1}) [JHEP03(2018)059]
- Signal yield of 6k
- Leakage of misidentified partially reconstructed bkg into signal region: $B_s \to (D_s^* \to D_s \underbrace{\gamma}_{\text{not rec.}}) \underbrace{\pi}_{\text{rec. as K}}$
- Bkg statistically subtracted by applying event weights

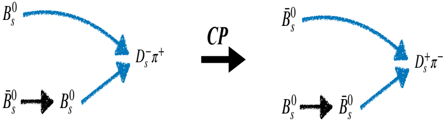
Experimental challenges

$$\mathcal{P}(t|q,f) \propto \left(\frac{d\Gamma(t'|q,f)}{dt'} \otimes R(t-t')\right) \epsilon(t)$$

- **Time-resolution:**
  How well can we measure the decay time?
- **Time-acceptance:**
  Does the selection bias our measurement?
- **Tagging:**
  Have we produced a B_s^0 or a $\bar{B}_s^0$?

Calibration channel $B_s \to D_s\pi$

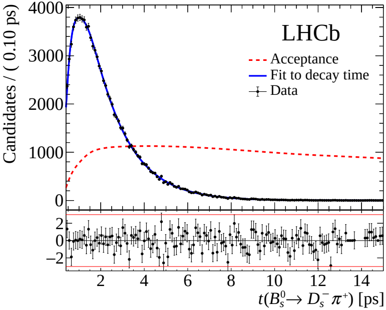




- Identical topology, similar kinematics
- Apply same selection (except PID cut on bachelor track)
  $\Rightarrow$ Signal yield of 100k
- Flavor specific decay: $B_s^0 \to D_s^-\pi^+$ but $B_s^0 \not\to D_s^+\pi^-$
  $\Rightarrow$ Simplified PDF:

$$\Gamma(t|q,f) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s\, t}{2}\right) + q\, f \cos\left(\Delta m_s\, t\right)\right]$$

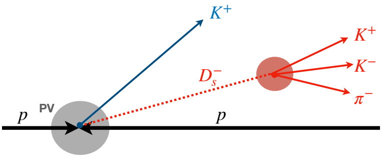
Time-Acceptance

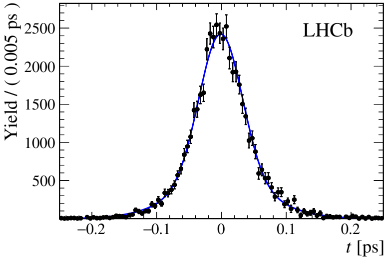


- Fit initial+final state averaged $B_s \to D_s \pi$ decay time distribution:

  $\langle \Gamma(t) \rangle \propto \epsilon(t)\, e^{-\Gamma_s t} \cosh\left(\frac{\Delta\Gamma_s\, t}{2}\right)$ (Γ_s, $\Delta\Gamma_s$ fixed to PDG value)

- Acceptance $\epsilon(t)$ parameterized with cubic spline

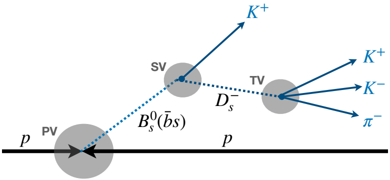




- Use prompt K and D_s to create 'fake' B_s candidates with known decay time $t = 0$
- Spread of reconstructed decay times = Resolution
- $\langle \sigma_t \rangle \approx 45\text{fs} \ll 2\pi/\Delta m_s \approx 350$ fs

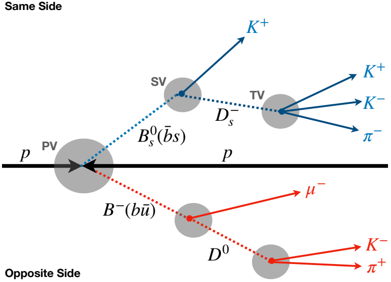
How to determine the production flavor?

Same Side



Opposite Side

How to determine the production flavor?



- *b*-quarks are produced in a $q\bar{q}$ pair
- **OS:** Use other B in the event to infer flavor of signal B_s
  $\Rightarrow$ Search for flavor specific decays

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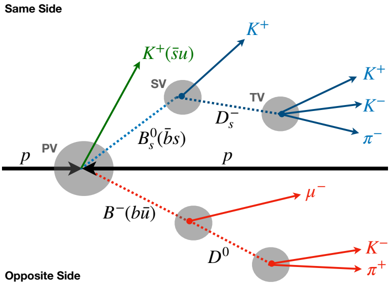

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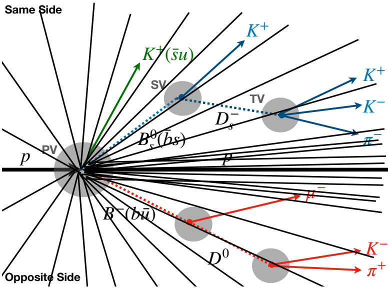
  $\Rightarrow$ Search for high momentum K in vicinity of B_s



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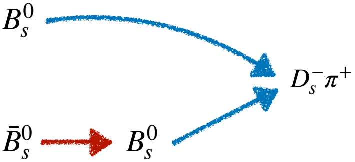
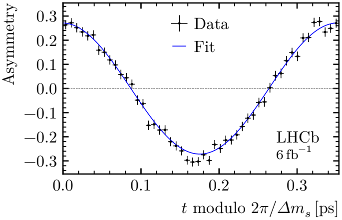
  $\Rightarrow$ Search for high momentum K in vicinity of B_s
- Tagging algorithms use MVA techniques to increase performance

Tagging calibration on $B_s \to D_s\pi$ data





- Taggers provide a decision for $\epsilon_{\text{tag}} \approx 80\%$ of the events
- How often are they wrong?
- Mixing asymmetry of $B_s \to D_s\pi$:

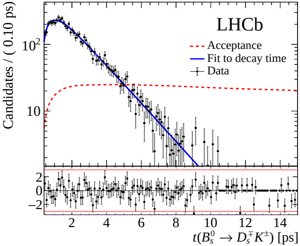
$$A_{mix} = \frac{N(B_s^0 \to f) - N(\bar{B}_s^0 \to f)}{N(B_s^0 \to f) + N(\bar{B}_s^0 \to f)} = \frac{\text{Unmixed - Mixed}}{\text{Unmixed + Mixed}} = (1 - 2\omega)\cos(\Delta m_s t)$$

$\Rightarrow$ Mistag $\omega \approx 35\%$

- Effective fraction of events with correct tag: $\epsilon_{\text{eff}} = \epsilon_{\text{tag}}\,(1 - 2\,\omega)^2$
- Poor tagging performance $\epsilon_{\text{eff}} \approx 6\%$ is compensated by high B production cross-section

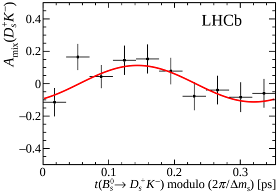
- Decay-time fit to $B_s \to D_s K$:

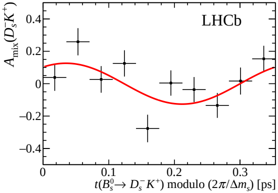
$$r = 0.37^{+0.10}_{-0.09}$$
$$\delta = (358^{+13}_{-14})^\circ$$
$$\gamma = (128^{+17}_{-22})^\circ$$



- Systematics well under control
  (acceptance, resolution, tagging, bkg subtraction, fit bias, nuisance asymmetries, ...)

- Measurement statistically limited



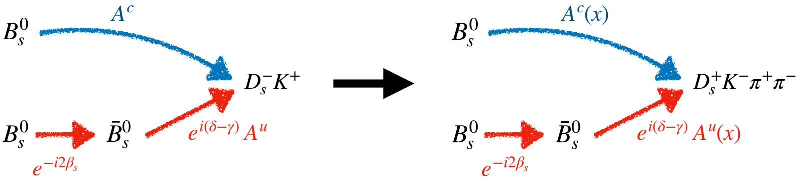


Part 4:

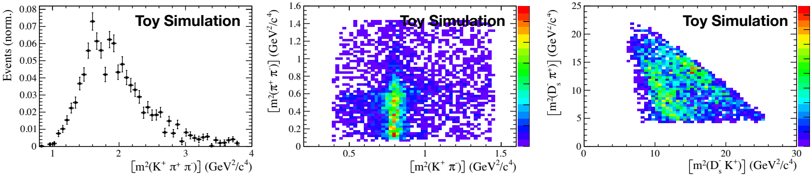
Measurement of the CKM angle γ from

$B_s \to D_s K \pi\pi$

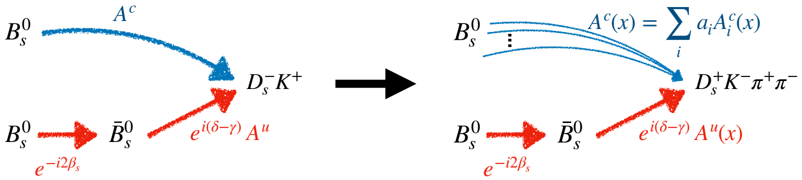
Measurement of CKM γ from $B_s \to D_s K\pi\pi$



- Method can be extended to multi-body decays
  - **Advantage:**
    Strong phase not constant but depends on kinematic configuration (5D phase space)
  - **Disadvantage:**
    Complicated hadronic structure



Measurement of CKM γ from $B_s \to D_s K\pi\pi$



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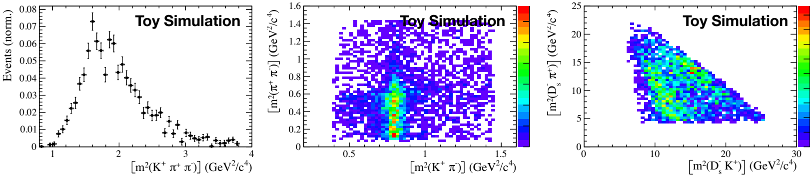
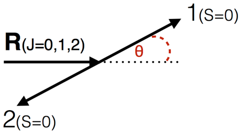
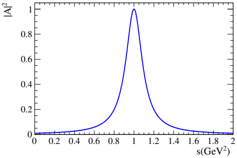
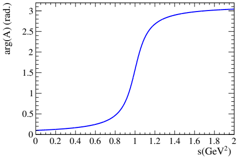


Resonances

- Decay via intermediate hadron state
- Short lived resonance:
  $\tau \approx \mathcal{O}(10^{-23}s) \Rightarrow \Gamma_0 = \frac{1}{\tau} \approx \mathcal{O}(100 MeV)$
- Peak in scattering amplitude:
  $BW(s) = \frac{1}{m_0^2 - s - im_0\Gamma_0}$

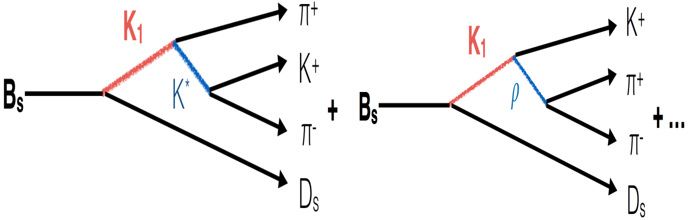




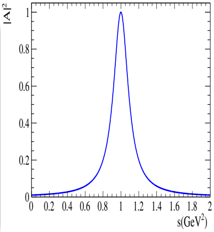


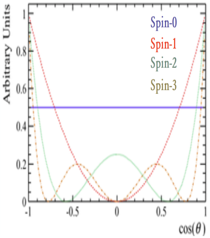
- Non-isotropic distribution of decay products if **R** has **spin**
- Angular distribution given by spherical harmonics:
  $J = 0 : A \propto 1$
  $J = 1 : A \propto cos\theta$
  $J = 2 : A \propto (cos\theta^2 - \frac{1}{3})$
  $J \quad : A \propto P_J(\theta)$

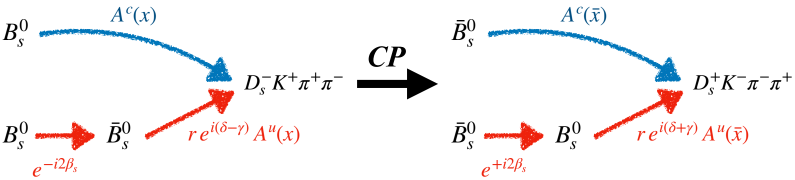
Parameterization of intermediate-state amplitudes



- Single channel amplitudes:
  $A_1(x) \approx BW_{K_1} \cdot BW_{K^*} \cdot S_f$
  $A_2(x) \approx BW_{K_1} \cdot BW_{\rho} \cdot S_f$
- Total amplitudes:
  $A^c(x) = \sum_i a_i^c \, A_i(x)$
  $A^u(x) = \sum_i a_i^u \, A_i(x)$



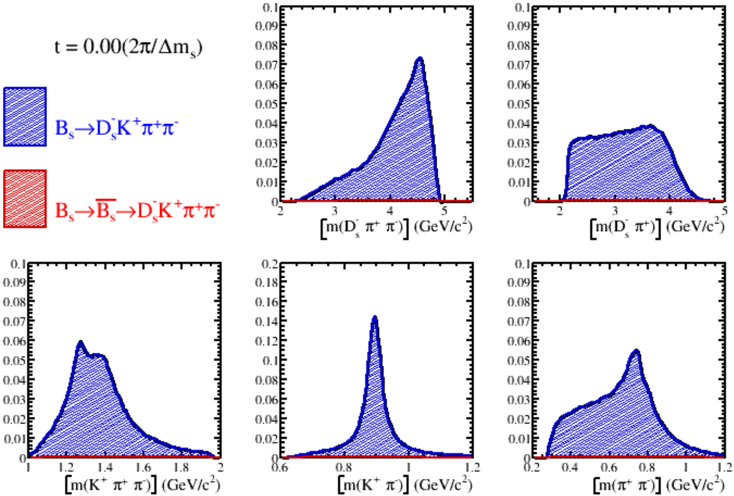




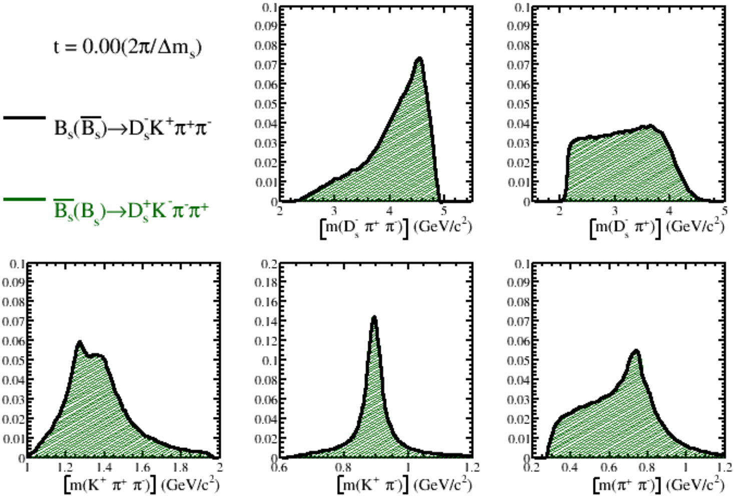
Full time-dependent amplitude PDF

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

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

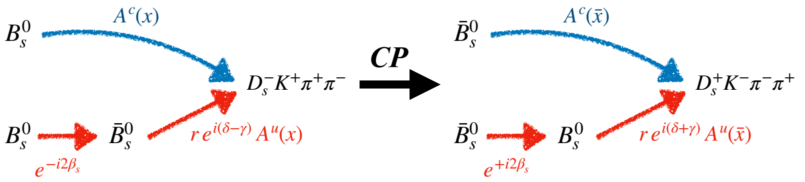


(Toy simulation)



(Toy simulation)

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



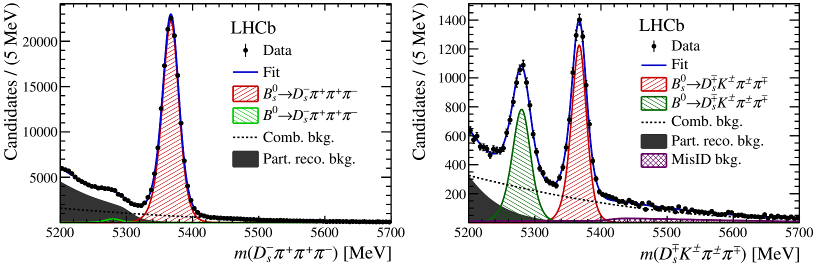
Phasespace integrated PDF

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

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

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

Data set



- Measurement with full Run 1+2 (9fb^{-1}) LHCb data
  [JHEP03(2021)137]
- Selection similar to $B_s \to D_s K$ analysis
- Have selected 7.5k signal events (150k calibration events)

Experimental challenges

$$\mathcal{P}(x, t, q_t) = [P(x, t', q_t) \otimes R(t, t')] \cdot \epsilon(t)$$

Time-Acceptance

Determined on $B_s \to D_s\pi\pi\pi$ data

Time-Resolution

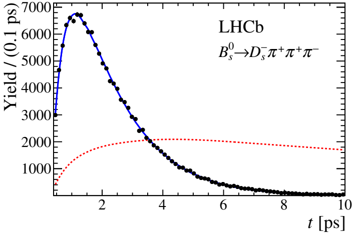
$\sigma_t \approx 40$ fs

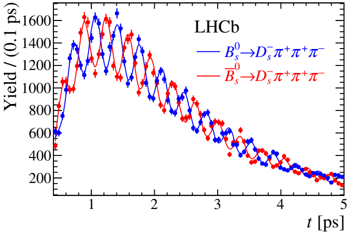
Better than for $B_s \to D_s K$ as 2 additional tracks improve SV reconstruction

Tagging

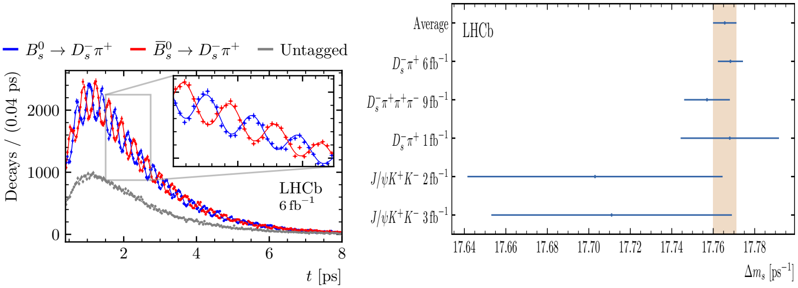
- Calibrated on $B_s \to D_s\pi\pi\pi$ ($\epsilon_{eff} \approx 5.5\%$)
- $\Delta m_s = (17.757 \pm 0.007 \pm 0.008)\text{ps}^{-1}$

  More presice than PDG average: $\Delta m_s = (17.757 \pm 0.021)\text{ps}^{-1}$





[JHEP03(2021)137]



- New high precision (0.3 ‰) measurement with $B_s \to D_s \pi$:

  $\Delta m_s = (17.7683 \pm 0.0051 \pm 0.0032)\text{ps}^{-1}$ [arxiv:2104.04421]
- LHCb average: $\Delta m_s = (17.7666 \pm 0.0057)\text{ps}^{-1}$
- Legacy measurement as crucial input for future time-dependent CP measurements

Amplitude model selection

Plenty of possible decay channels ! How to select them ?

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

$\approx$ 100 in total !

Amplitude model selection

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

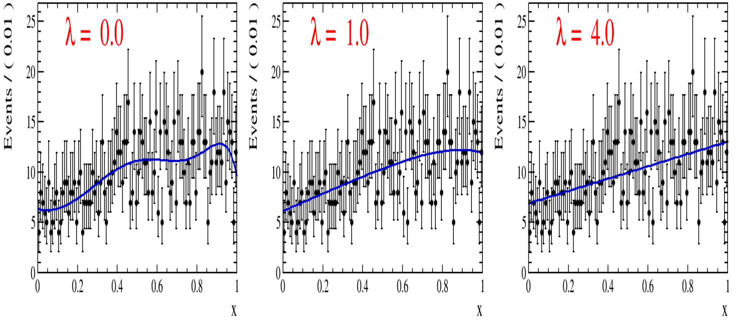
LASSO

- Data-driven method for model selection
  [M. Williams, arXiv:1505.05133]
- Include "all" amplitudes, but penalize complexity in the likelihood:

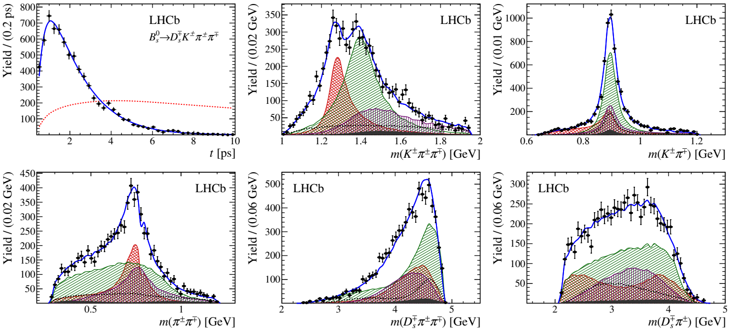
  $-2 \cdot \log(L) \rightarrow -2 \cdot \log(L) + \lambda \cdot \sum_i |r_i|$
- Larger λ value produces simpler model

LASSO: Toy experiment

- Generated: pdf $= 1 + x$
- Fitted pdf $= 1 + \sum_{i=1}^{10} c_i\, x^i$
- $-2\cdot\log(L) \rightarrow -2\cdot\log(L) + \lambda \cdot \sum_i |c_i|$



Full time-dependent amplitude fit with LASSO model

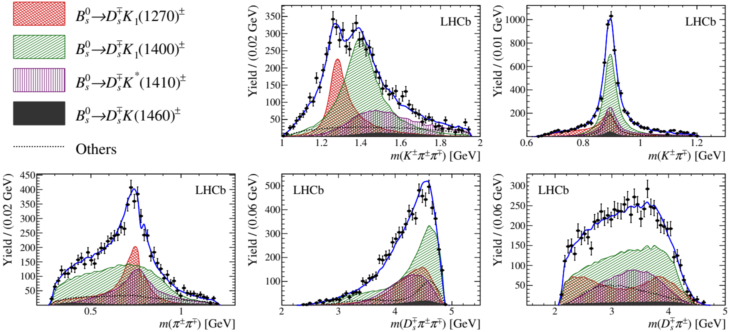


[JHEP03(2021)137]

Selected 8 $b \to c$ and 8 $b \to u$ amplitudes

Time-dependent Amplitude Fit

Full time-dependent amplitude fit with LASSO model



[JHEP03(2021)137]

Selected 8 $b \to c$ and 8 $b \to u$ amplitudes

Selected LASSO amplitudes

Total amplitudes: $A^c(x) = \sum_i a_i^c A_i(x)$, $A^u(x) = \sum_i a_i^u A_i(x)$

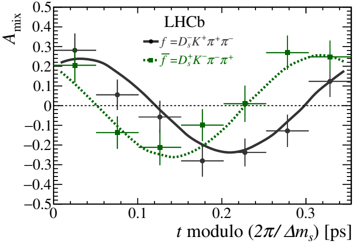
with fit fractions: $F_i^{c(u)} = \int |a_i^{c(u)} A_i(x)|^2 \mathrm{d}\Phi_4 / \int |A^{c(u)}(x)|^2 \mathrm{d}\Phi_4$

[JHEP03(2021)137]

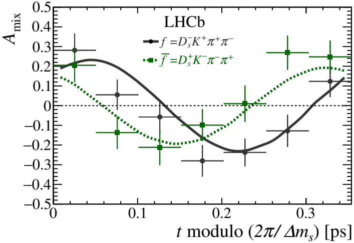
Decay Channel	F^c[%]	F^u[%]
$B_s \to D_s\,(K_1(1270) \to K^*(892)\,\pi)$	13.0 ± 2.4 ± 2.7 ± 3.4	4.1 ± 2.2 ± 2.9 ± 2.6
$B_s \to D_s\,(K_1(1270) \to K\,\rho(770))$	16.0 ± 1.4 ± 1.8 ± 2.1	5.1 ± 2.2 ± 3.5 ± 2.0
$B_s \to D_s\,(K_1(1270) \to K_0^*(1430)\,\pi)$	3.4 ± 0.5 ± 1.0 ± 0.4	1.1 ± 0.5 ± 0.6 ± 0.5
$B_s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

CKM γ from $B_s \to D_s K\pi\pi$

Model-independent fit



Model-dependent fit



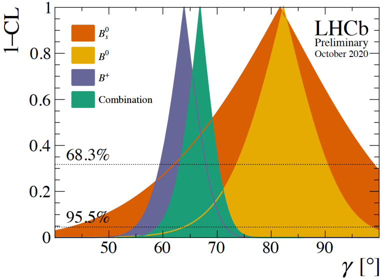
[JHEP03(2021)137]

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 [°]	$-6\ {}^{+10}_{-12}\ {}^{+2}_{-4}$	$-14 \pm 10 \pm 4 \pm 5$
$\gamma - 2\beta_s$ [°]	$42\ \underbrace{{}^{+19}_{-13}}_{\text{stat}}\ \underbrace{{}^{+6}_{-2}}_{\text{sys}}$	$42 \pm \underbrace{10}_{\text{stat}} \pm \underbrace{4}_{\text{sys}} \pm \underbrace{5}_{\text{model}}$

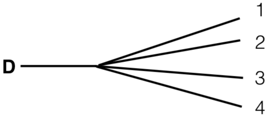
Good agreement between methods!

Conclusion: LHCb γ combination

- **LHCb continues to produce world-leading results on CPV and mixing in B decays**
- Last LHCb average: $\gamma = (74^{+5}_{-6})^\circ$ [LHCb-CONF-2018-002]
- **New** average $\boldsymbol{\gamma = (67 \pm 4)^\circ}$ includes:
  - $B^\pm \to D^{(*)}K^\pm$ with $D \to hh$ updated with Run2 data [JHEP04(2021)081]
  - TD $B_s \to D_s^\mp K^\pm \pi^\pm \pi^\mp$ for the first time [JHEP03(2021)137]
  - and more, see LHCb-CONF-2020-003
- Getting closer to challenge precision of global fits: $\gamma = (65.7^{+1.0}_{-2.5})^\circ$ [CKMfitter]
- **New** high precision measurement of Δm_s vital input for global CKM fits



Questions?



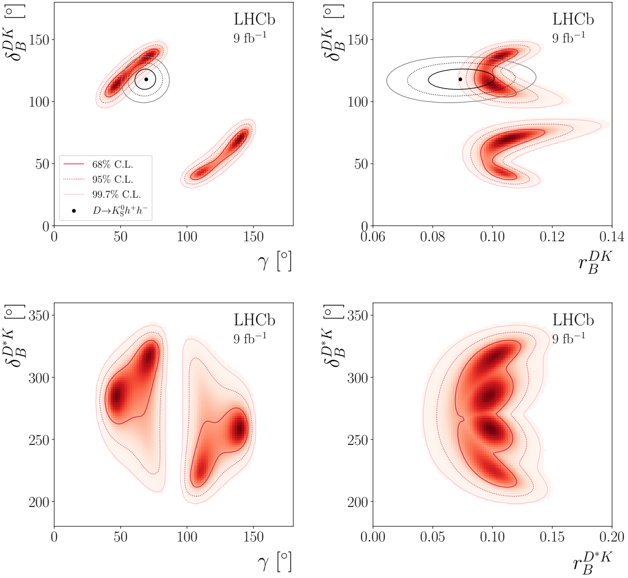
Four-momenta	**16**
Meson masses ($p_i^2 = m_i^2$)	**-4**
E, p conservation	**-4**
Arbitrary orientation	**-3**
Independent variables	**5**

Decay rate

- $d\Gamma \approx |M_{fi}|^2 \, \Phi_4 \, dm_{12}^2 \, dm_{23}^2 \, dm_{34}^2 \, dm_{123}^2 \, dm_{234}^2$
- Phase space density function is not flat ($\Phi_4 \neq 1$)
- 5D phasespace $\Rightarrow$ cannot easily be visualized

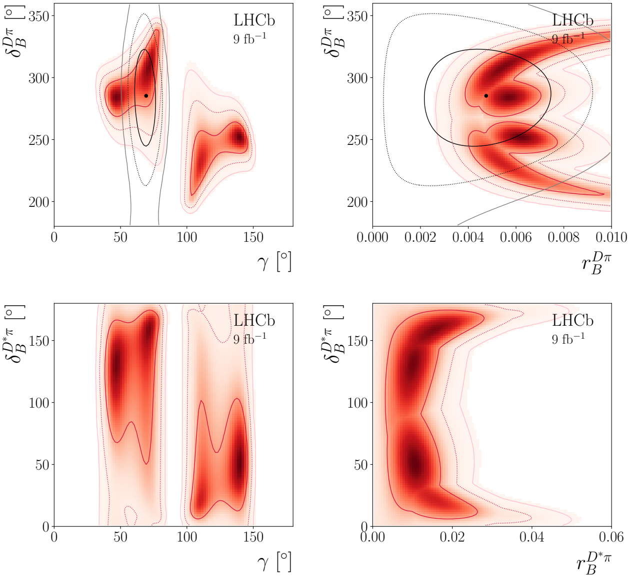
Backup: $B^{\mp} \to D^{(*)}K^{\mp}$ results

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

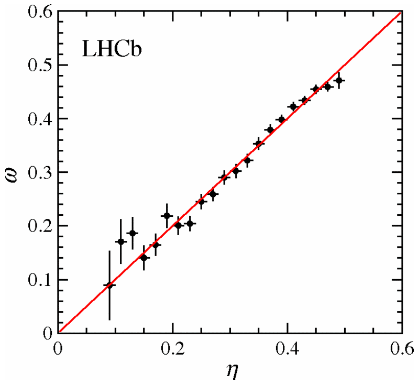


Backup: $B^{\mp} \to D^{(*)}\pi^{\mp}$ results

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

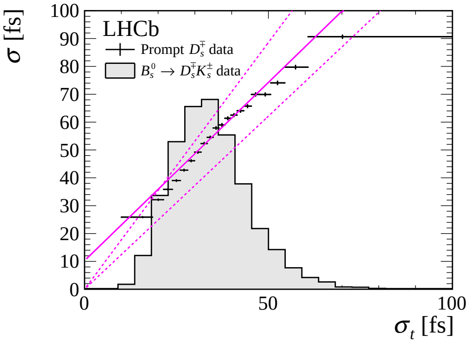


Backup: Tagging



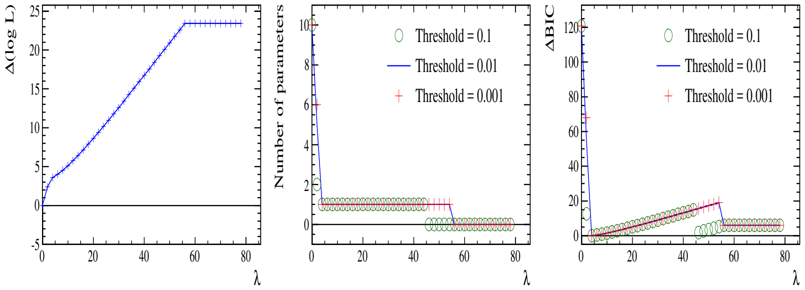
$B_s^0 \to D_s^- \pi^+$	ε_{tag} [%]	ε_{eff} [%]
OS only	12.94 ± 0.11	1.41 ± 0.11
SS only	39.70 ± 0.16	1.29 ± 0.13
Both OS and SS	24.21 ± 0.14	3.10 ± 0.18
Total	76.85 ± 0.24	5.80 ± 0.25

Backup: Time-Resolution



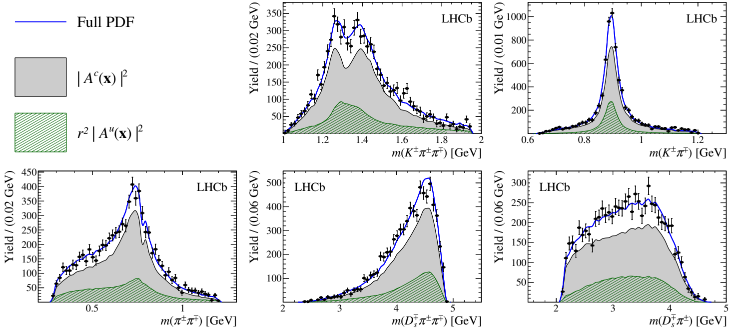
How to choose λ ?

- $\text{BIC}(\lambda) = -2 \cdot \log(L) + r \cdot \log(N_{events})$
  r = Number of parameters with: $|c_i| >$ threshold
- Balances **gain in fit quality vs. complexity**
- Optimal value $\lambda \approx 4$



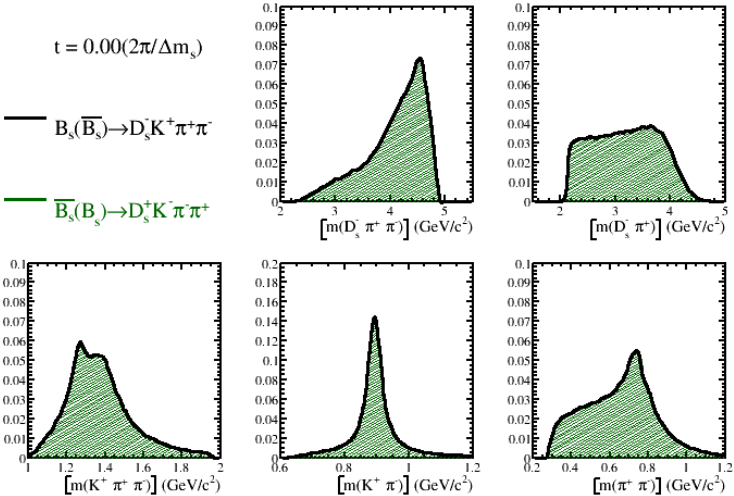
Backup: Time-dependent Amplitude Fit

Full time-dependent amplitude fit with LASSO model

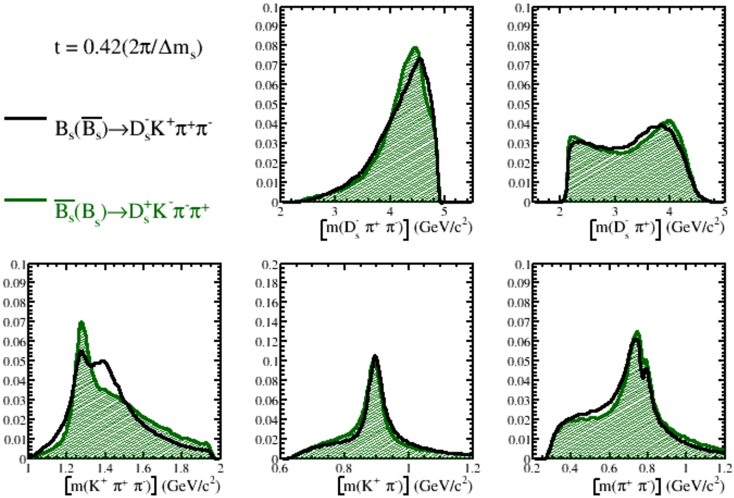


[JHEP03(2021)137]

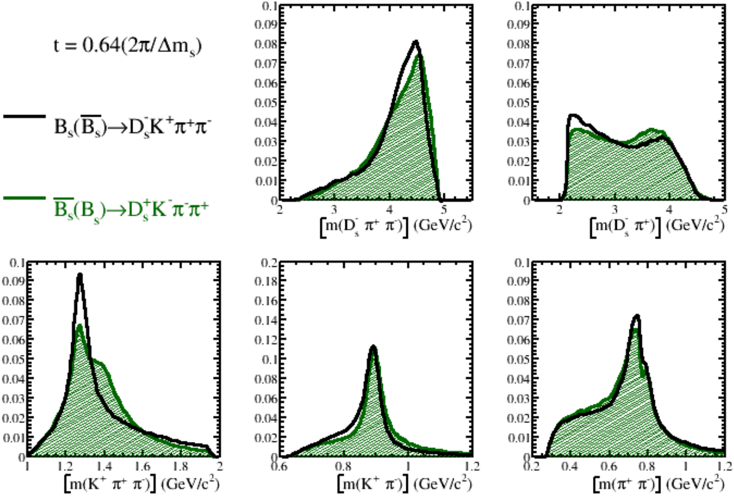
Selected 8 $b \to c$ and 8 $b \to u$ amplitudes



(Toy simulation)



(Toy simulation)



(Toy simulation)