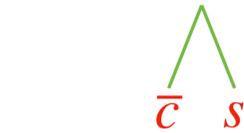# LHCb measurements of non-leptonic colour-allowed tree-level decays

Quentin Führing

On behalf of the LHCb collaboration
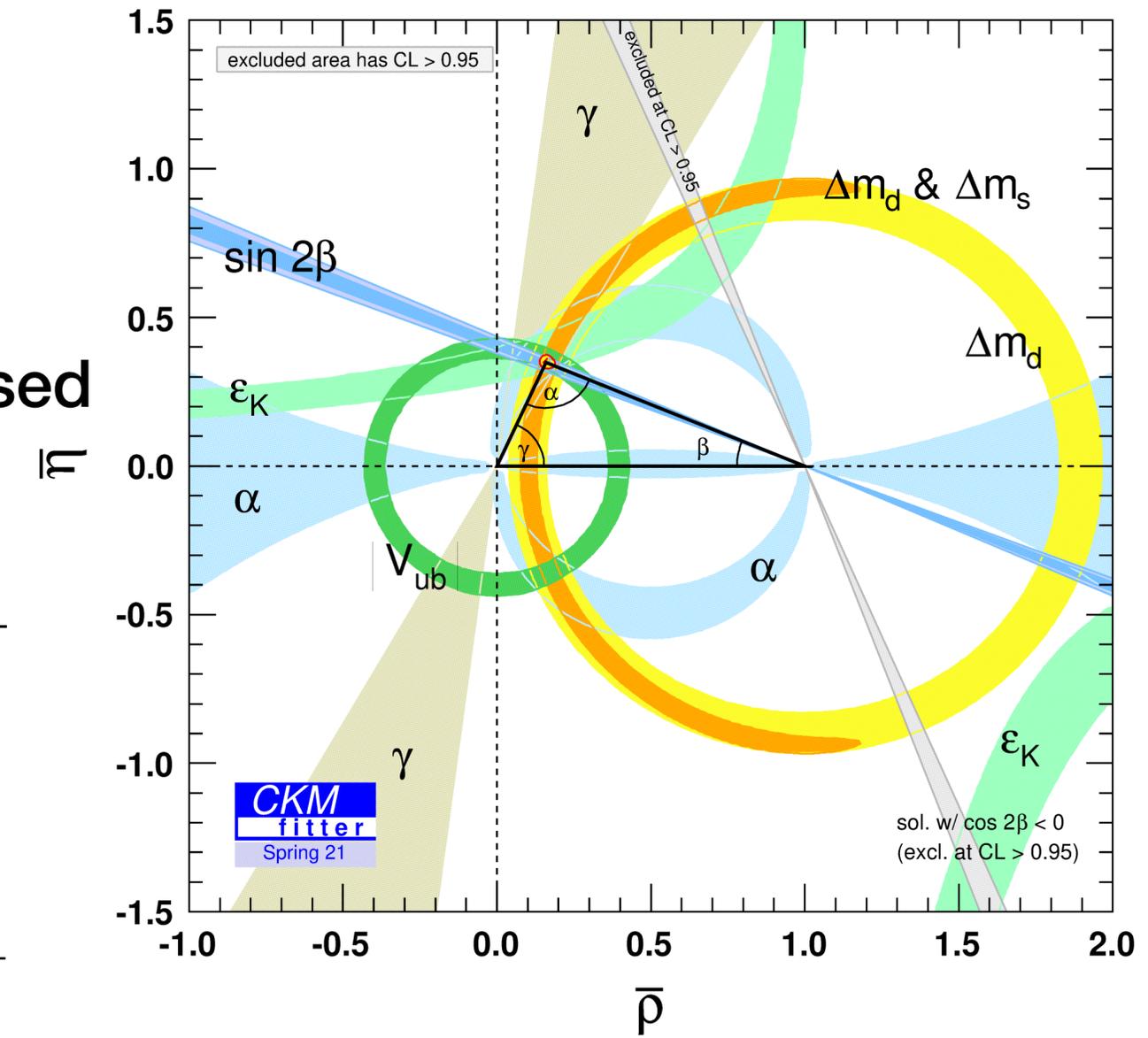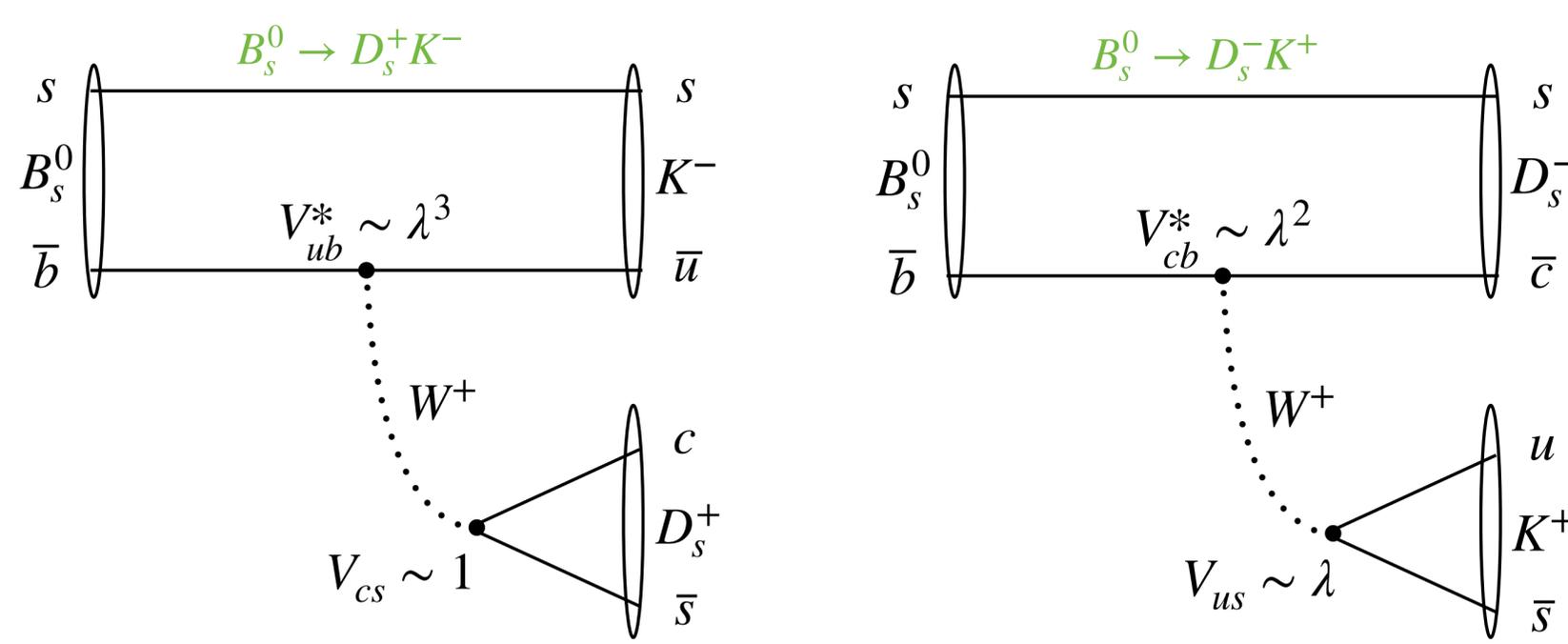
Status and prospects of non-leptonic *B* meson decays

Experimental session

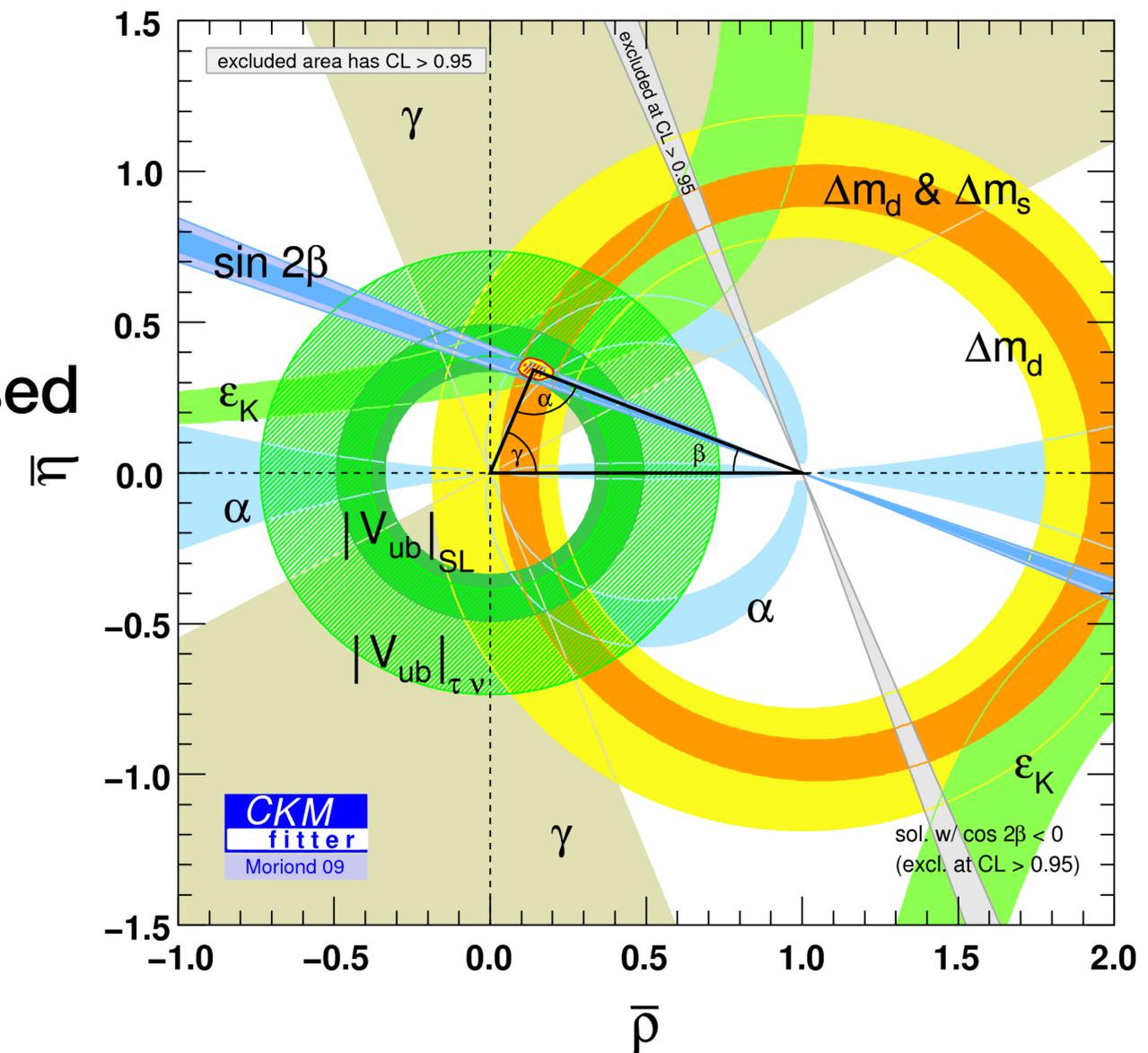Siegen - 2022-05-31
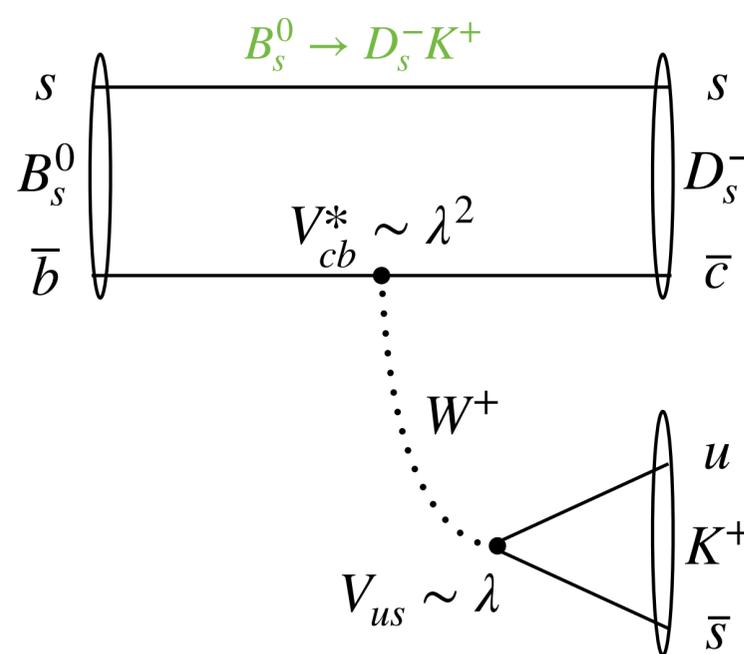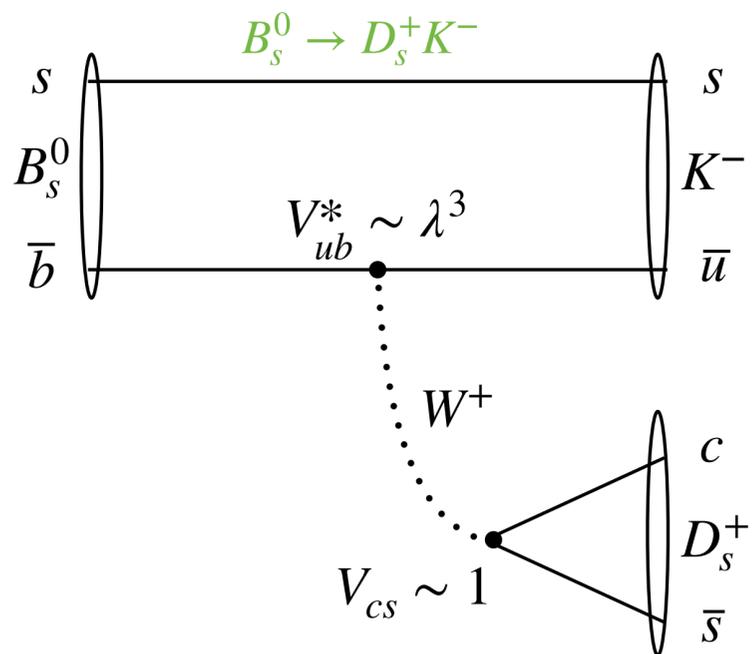
The beauty of colour-allowed tree-level decays

- **Weak decays in presence of a spectator**
  - ▸ $b \to u\bar{c}s\,[\bar{b} \to \bar{u}c\bar{s}]$ sensitive to $|V_{ub}|$
  - ▸ γ from interference with $b \to c\bar{u}s\,[\bar{b} \to \bar{c}u\bar{s}]$

- **Simpler QCD cf. exchange or colour-suppressed**

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

$$s \quad\quad\quad\quad\quad s$$
$$B_s^0 \quad\quad\quad\quad\quad K^-$$
$$\bar{b} \quad\quad\quad\quad\quad \bar{u}$$
$$V_{ub}^* \sim \lambda^3$$
$$W^+$$
$$c$$
$$D_s^+$$
$$V_{cs} \sim 1 \quad\quad \bar{s}$$

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

$$s \quad\quad\quad\quad\quad s$$
$$B_s^0 \quad\quad\quad\quad\quad D_s^-$$
$$\bar{b} \quad\quad\quad\quad\quad \bar{c}$$
$$V_{cb}^* \sim \lambda^2$$
$$W^+$$
$$u$$
$$K^+$$
$$V_{us} \sim \lambda \quad\quad \bar{s}$$

excluded area has CL > 0.95

excluded at CL > 0.95

γ

$\sin 2\beta$

Δm_d & Δm_s

ε_K

Δm_d

α

α

α

β

γ

V_{ub}

γ

ε_K

$\bar{\eta}$

$\bar{\rho}$

CKM
fitter
Spring 21

sol. w/ cos 2β < 0
(excl. at CL > 0.95)

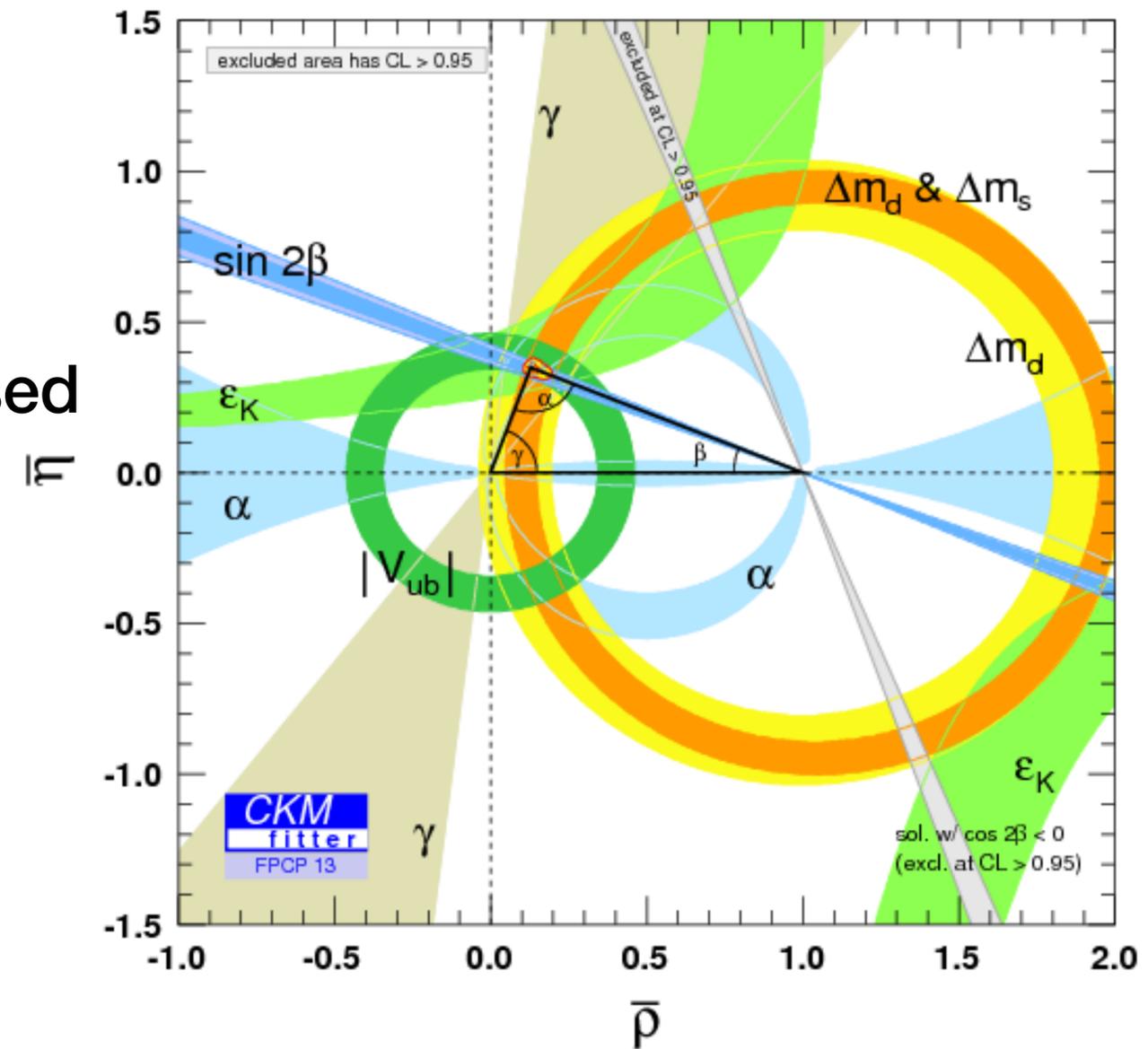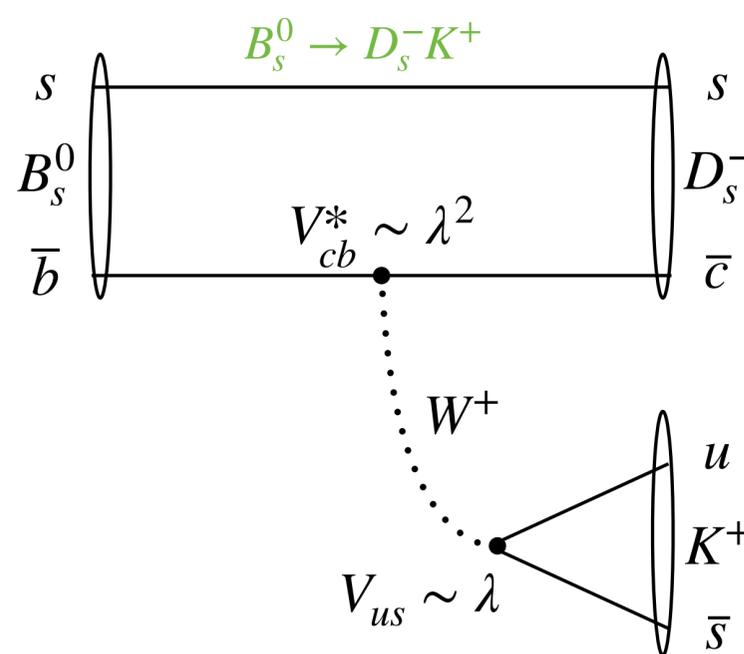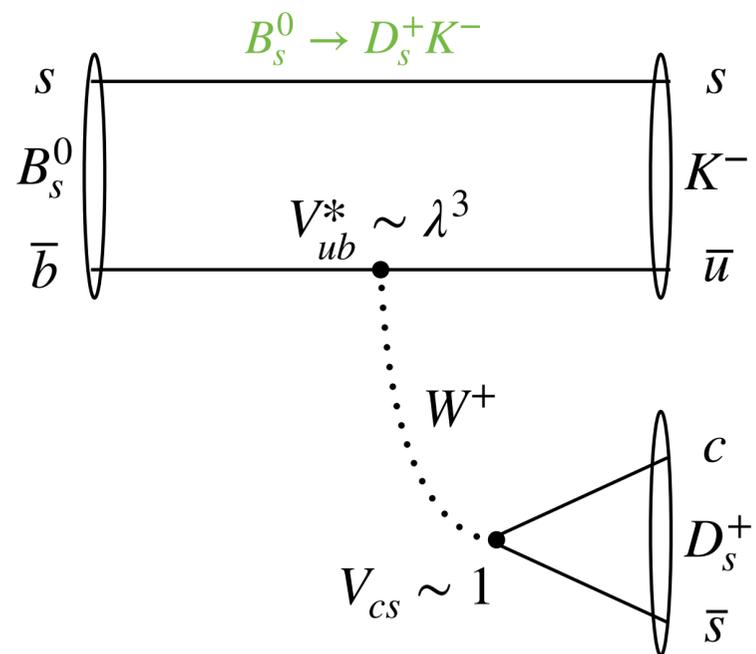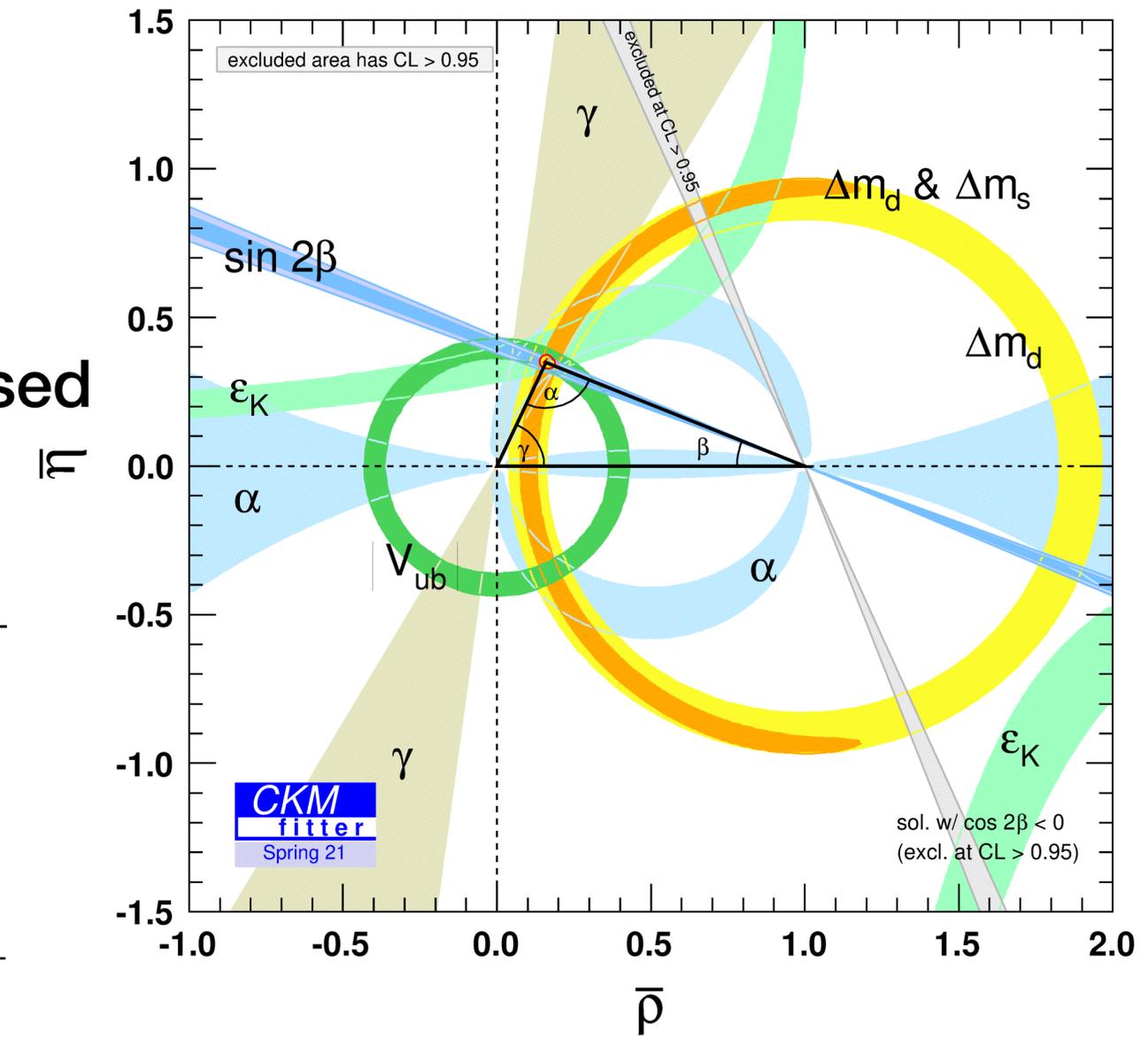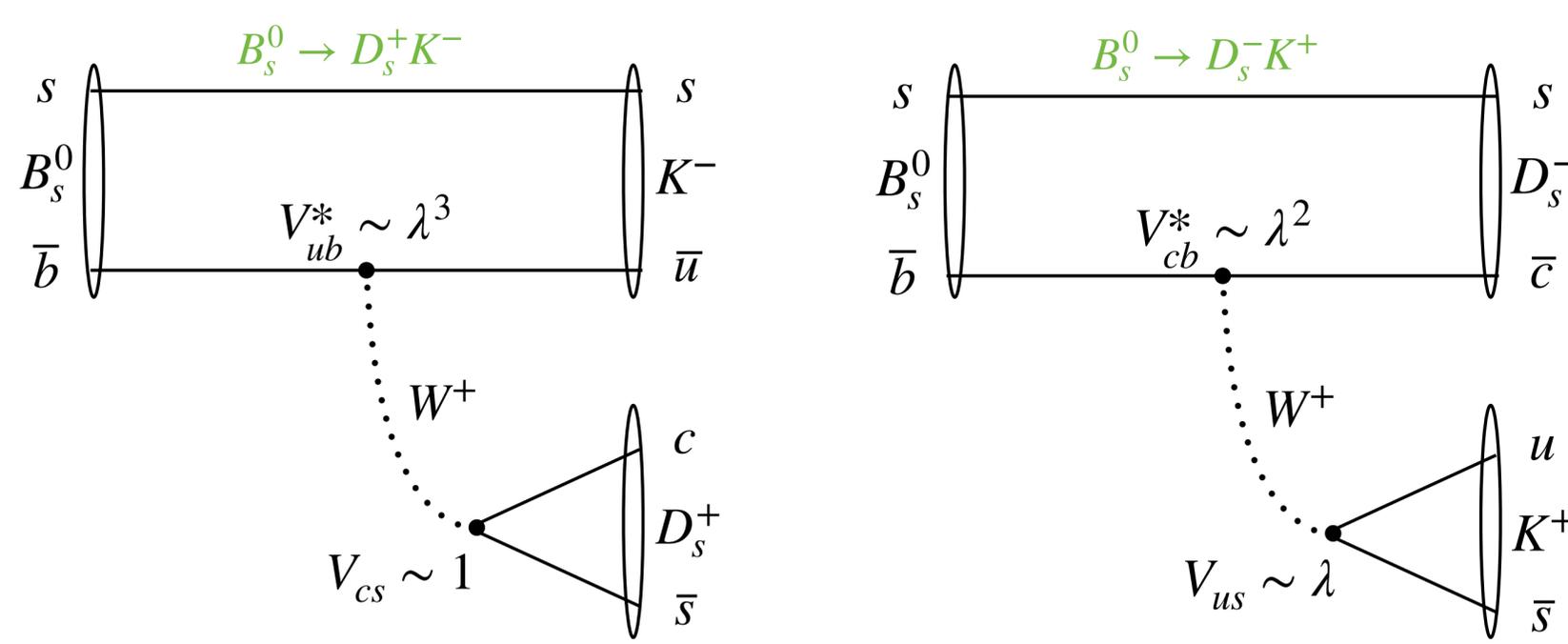# The beauty of colour-allowed tree-level decays

- **Weak decays in presence of a spectator**

  - $b \rightarrow u\bar{c}s\,[\bar{b} \rightarrow \bar{u}c\bar{s}]$ sensitive to $|V_{ub}|$

  - γ from interference with $b \rightarrow c\bar{u}s\,[\bar{b} \rightarrow \bar{c}u\bar{s}]$

- **Simpler QCD cf. exchange or colour-suppressed**

technische universität
dortmund

FSP LHCb
Erforschung von
Universum und Materie

LHCb

The beauty of colour-allowed tree-level decays

- **Weak decays in presence of a spectator**

  ‣ $b \to u\bar{c}s\,[\bar{b} \to \bar{u}c\bar{s}]$ sensitive to $|V_{ub}|$

  ‣ γ from interference with $b \to c\bar{u}s\,[\bar{b} \to \bar{c}u\bar{s}]$

- **Simpler QCD cf. exchange or colour-suppressed**

technische universität
dortmund

FSP LHCb
Erforschung von
Universum und Materie

LHCb

The beauty of colour-allowed tree-level decays
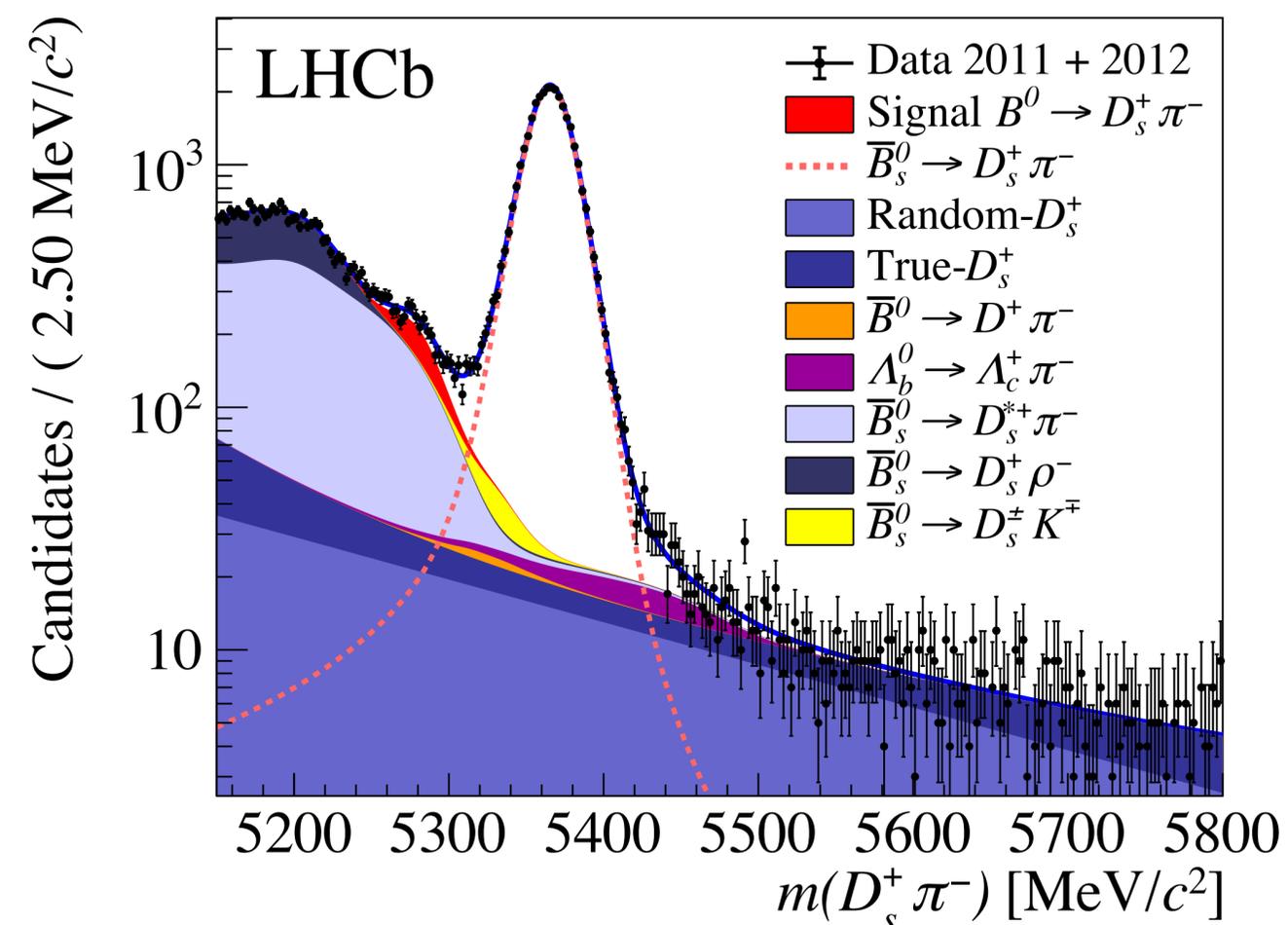
- **Weak decays in presence of a spectator**
  - $b \to u\bar{c}s$ $[\bar{b} \to \bar{u}c\bar{s}]$ sensitive to $|V_{ub}|$
  - γ from interference with $b \to c\bar{u}s$ $[\bar{b} \to \bar{c}u\bar{s}]$

- **Simpler QCD cf. exchange or colour-suppressed**
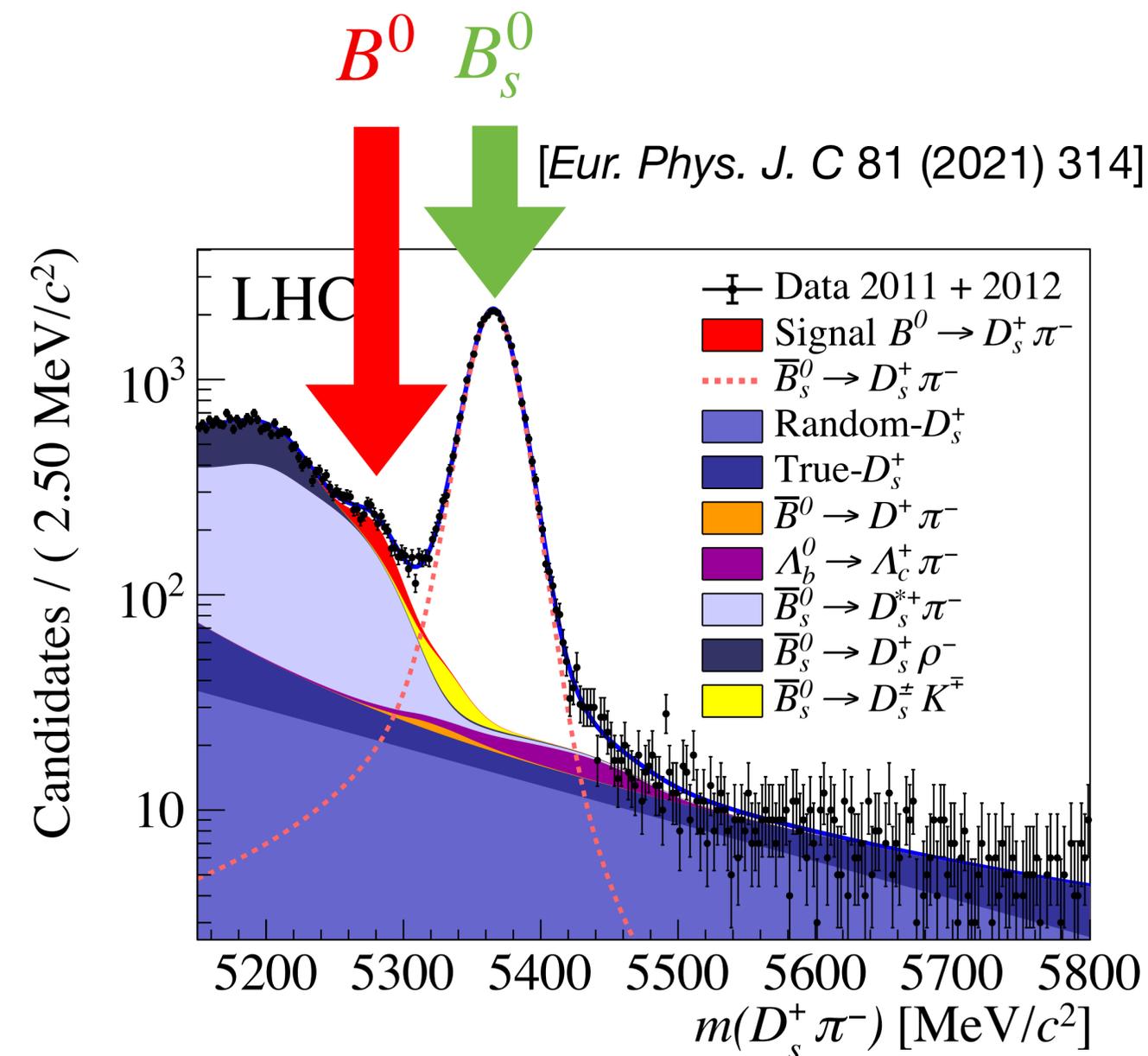
The experiment of choice - LHCb

- **Enormous data set** [*Phys.Rev.Lett.* 118, 052002 (2017)]

  ‣ $\sigma(pp \to b\bar{b}X) = 144 \pm 1 \pm 21\,\mu\mathrm{b}$
     at 13TeV within LHCb acceptance

  ‣ So far >1 trillion $b\bar{b}$-pairs produced

- **Excellent decay-vertex resolution**

  ‣ Separation of detached b-hadron decays

  ‣ Decay-time resolution < 50 fs

- **Good hadron separation**

  ‣ B^0 / B_s^0 by ~20 MeV mass resolution

  ‣ Final-state identification from RICH

[*Eur. Phys. J. C* 81 (2021) 314]

![tu technische universität dortmund]
![FSP LHCb Erforschung von Universum und Materie]
![LHCb]

The experiment of choice - LHCb

- **Enormous data set** [*Phys.Rev.Lett*. 118, 052002 (2017)]

  ‣ $\sigma(pp \to b\bar{b}X) = 144 \pm 1 \pm 21\,\mu$b at 13TeV within LHCb acceptance

  ‣ So far >1 trillion $b\bar{b}$-pairs produced

- **Excellent decay-vertex resolution**

  ‣ Separation of detached b-hadron decays

  ‣ Decay-time resolution < 50 fs

- **Good hadron separation**

  ‣ B^0 / B_s^0 by ~20 MeV mass resolution

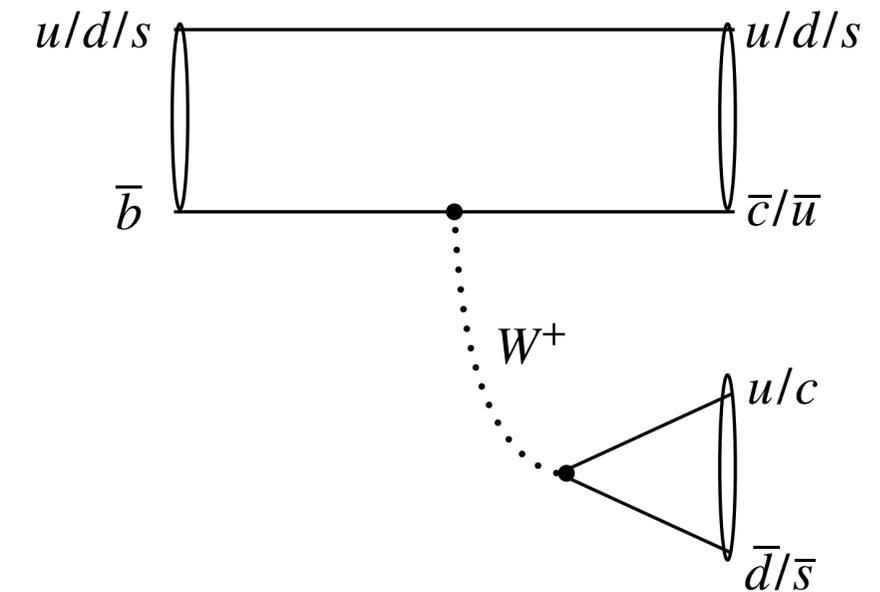 ‣ Final-state identification from RICH
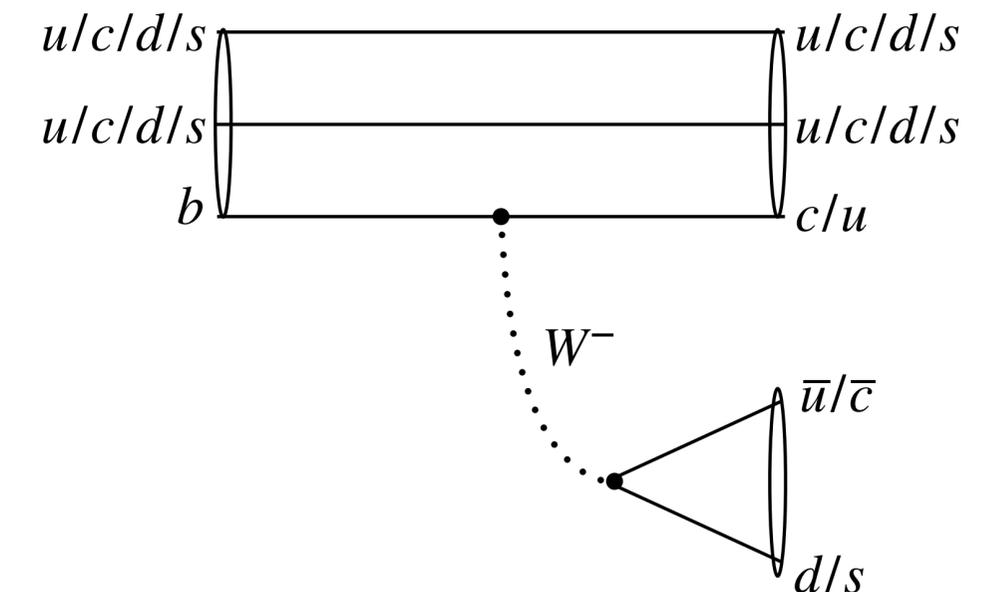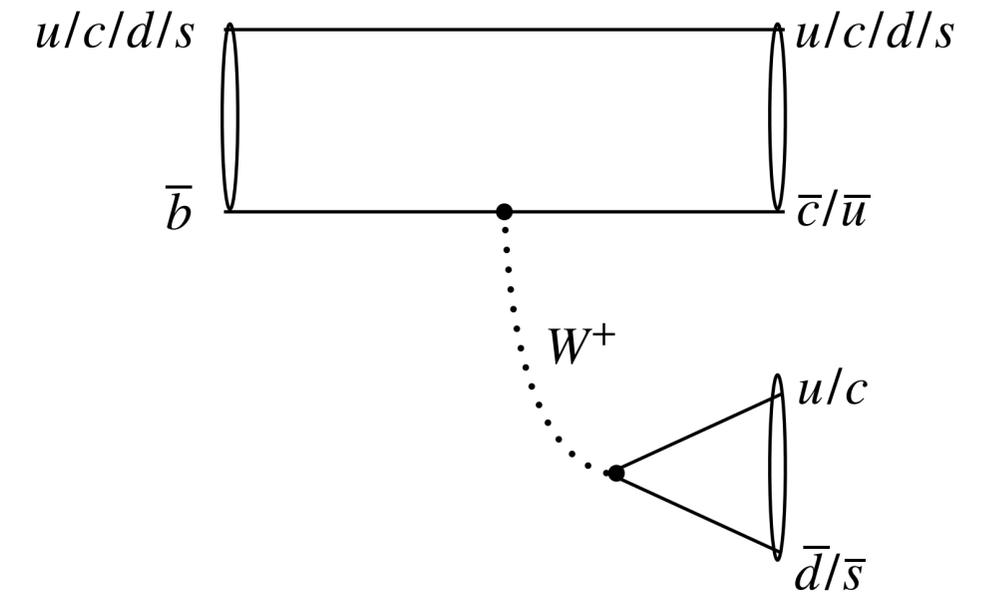

[*Eur. Phys. J. C* 81 (2021) 314]

Colour-allowed tree-level decays at LHCb

- **Diverse decay channels studied**
  - ▸ $B^0, B^\pm, B_s^0, B_c^\pm$ mesons

- **Many observables of interest**
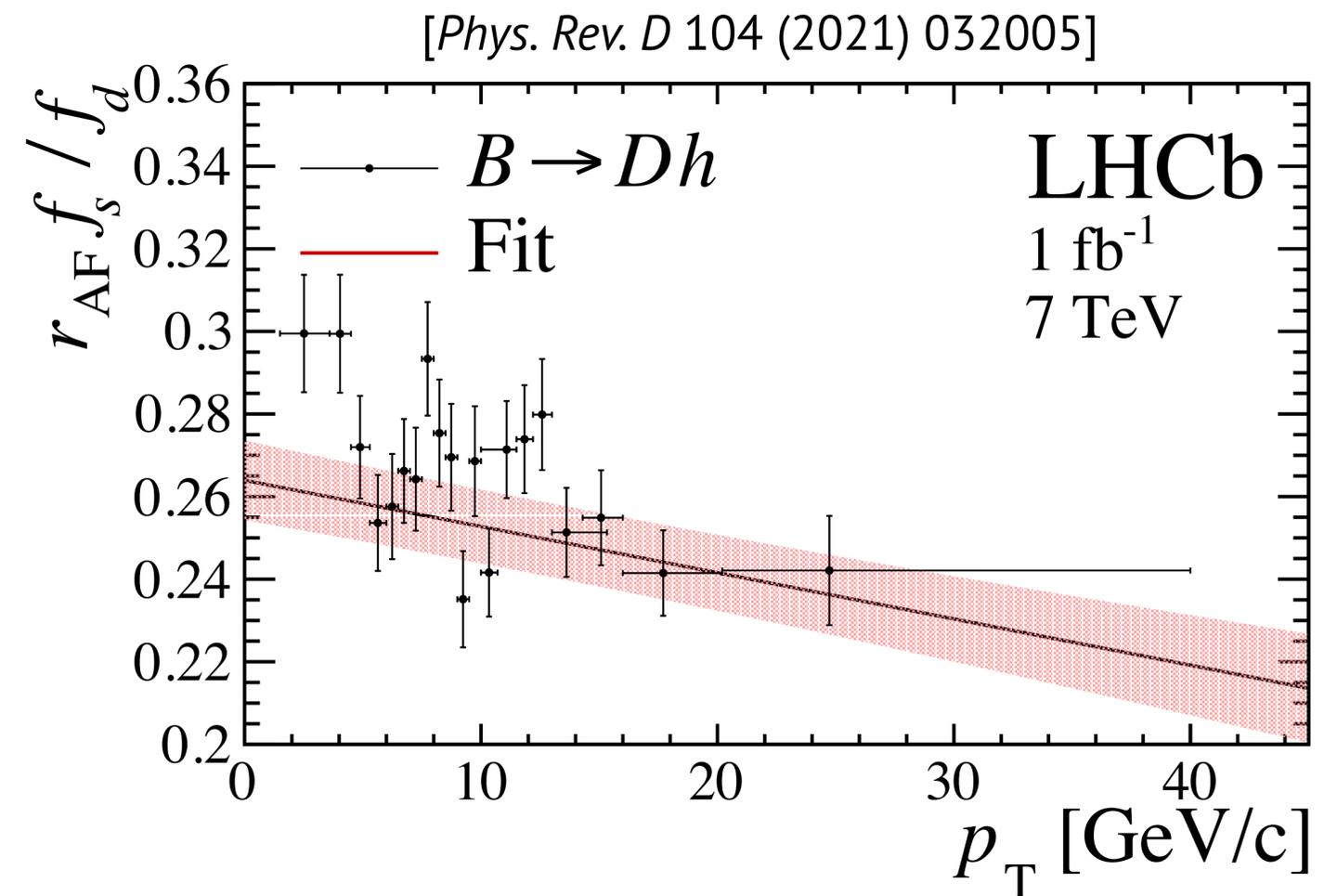

- **Both theoretical & experimental implications**

Colour-allowed tree-level decays at LHCb

- **Diverse decay channels studied**
  - ▸ $B^0, B^\pm, B^0_s, B^\pm_c$ mesons
  - ▸ $\Lambda^0_b, \Xi^{0/\pm}_b, \Omega^\pm_b$ baryons (and more)

- **Many observables of interest**

- **Both theoretical & experimental implications**

technische universität
dortmund

FSP LHCb
Erforschung von
Universum und Materie

LHCb

Colour-allowed tree-level decays at LHCb

- **Diverse decay channels studied**

  ▸ $B^0, B^\pm, B^0_s, B^\pm_c$ mesons

  ▸ $\Lambda^0_b, \Xi^{0/\pm}_b, \Omega^\pm_b$ baryons (and more)

- **Many observables of interest**

  ▸ Branching & fragmentation fractions

  ▸ Mass & lifetime

  ▸ Oscillation frequency & gamma, …

- **Both theoretical & experimental implications**

[*Phys. Rev. D* 104 (2021) 032005]

technische universität
dortmund

FSP LHCb
Erforschung von
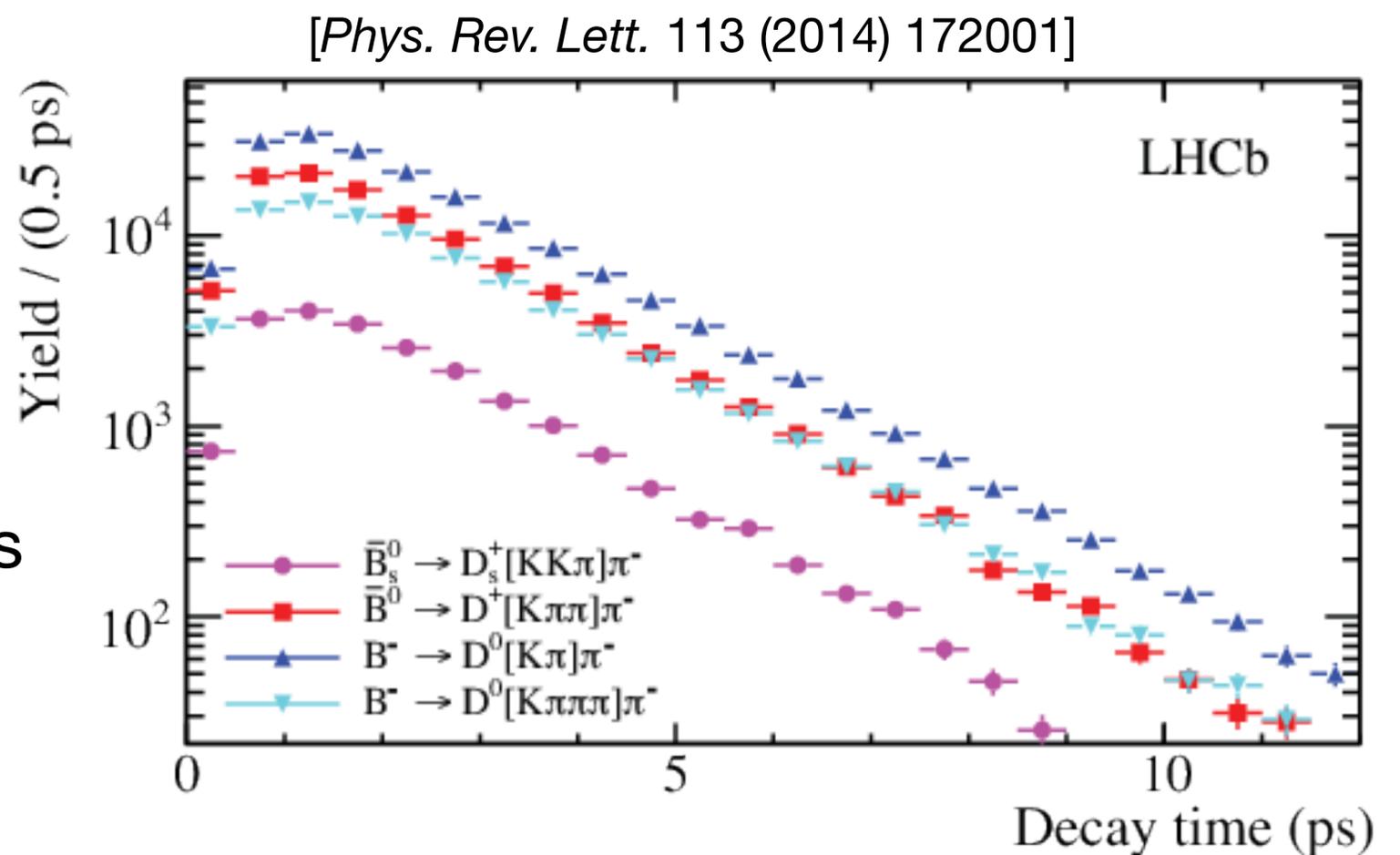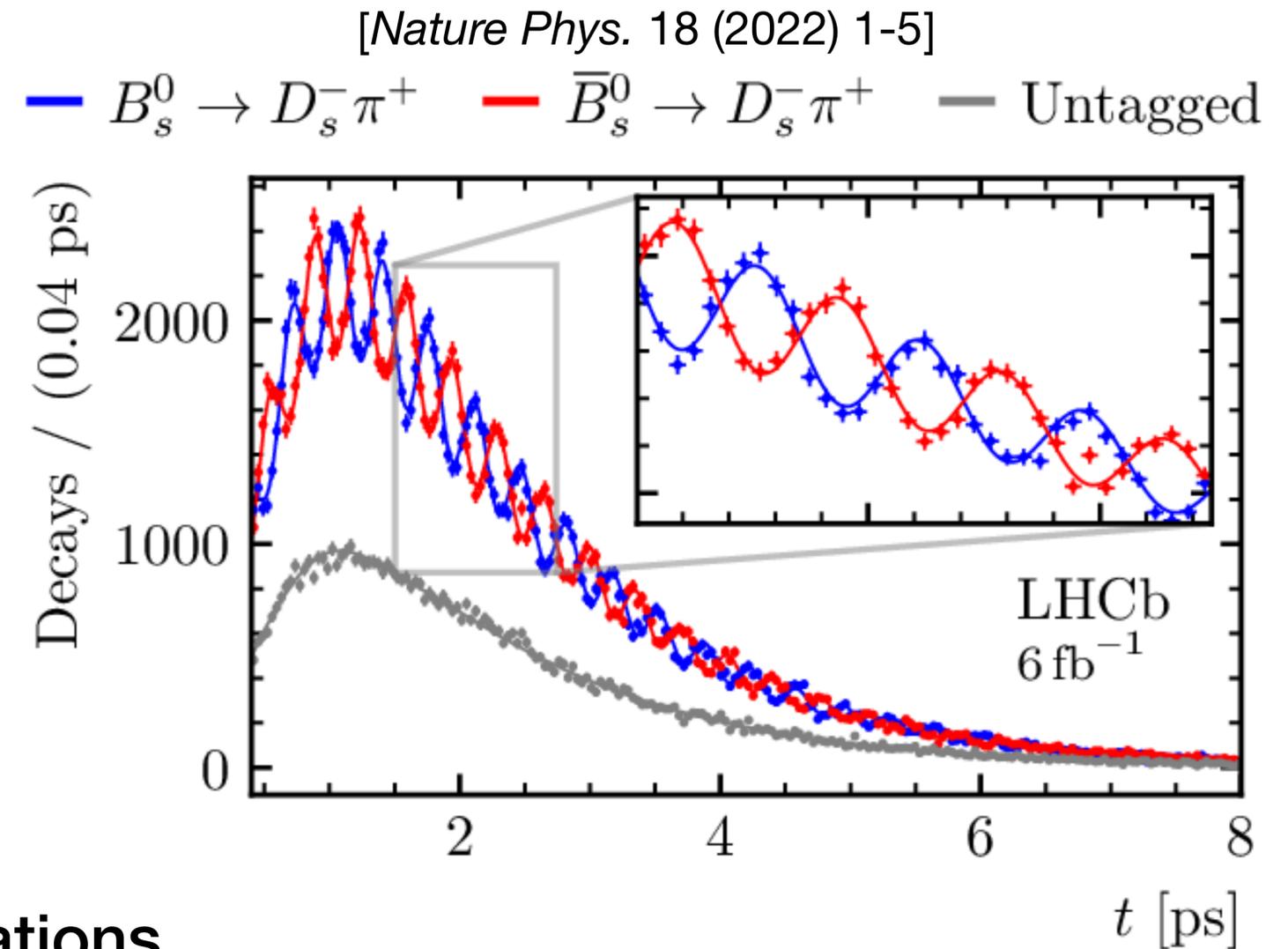Universum und Materie

LHCb

Colour-allowed tree-level decays at LHCb

- **Diverse decay channels studied**

  ▸ $B^0, B^\pm, B_s^0, B_c^\pm$ mesons

  ▸ $\Lambda_b^0, \Xi_b^{0/\pm}, \Omega_b^\pm$ baryons (and more)

- **Many observables of interest**

  ▸ Branching & fragmentation fractions

  ▸ Mass & lifetime

  ▸ Oscillation frequency & gamma, …

- Both theoretical & experimental implications

[*Phys. Rev. Lett.* 113 (2014) 172001]

technische universität
dortmund

FSP LHCb
Erforschung von
Universum und Materie

LHCb

Colour-allowed tree-level decays at LHCb

- **Diverse decay channels studied**

  ▸ $B^0, B^{\pm}, B_s^0, B_c^{\pm}$ mesons

  ▸ $\Lambda_b^0, \Xi_b^{0/\pm}, \Omega_b^{\pm}$ baryons (and more)

- **Many observables of interest**

  ▸ Branching & fragmentation fractions

  ▸ Mass & lifetime

  ▸ Oscillation frequency & gamma, …

- **Both theoretical & experimental implications**

[*Nature Phys.* 18 (2022) 1-5]

$B \to Dh^{\pm}$ decays at LHCb

- **Usually very abundant decays**

- **Charm resonance for background suppression**

- **Less penguin and exchange contributions cf. $B \to DD$ for** [*JHEP* 1507 (2015) 108]

  ‣ $h^{\pm} := \pi^{\pm}$

  ‣ $h^{\pm} := K^{\pm}$

- **Use charged final-state particles only**

$$D^{*+} \to D^0\pi^+ \qquad\qquad D^0 \to K^+\pi^-$$
$$D^+ \to \pi^+K^+\pi^- \qquad\qquad D_s^+ \to K^+K^-\pi^+$$

Branching fraction

$$\mathscr{B}(B^0 \rightarrow D_s^+ \pi^-)$$

[*Eur. Phys. J. C* 81 (2021) 314]

Relative branching fraction ratios

- **Limited knowledge of $\overline{b}$-hadron cross section**
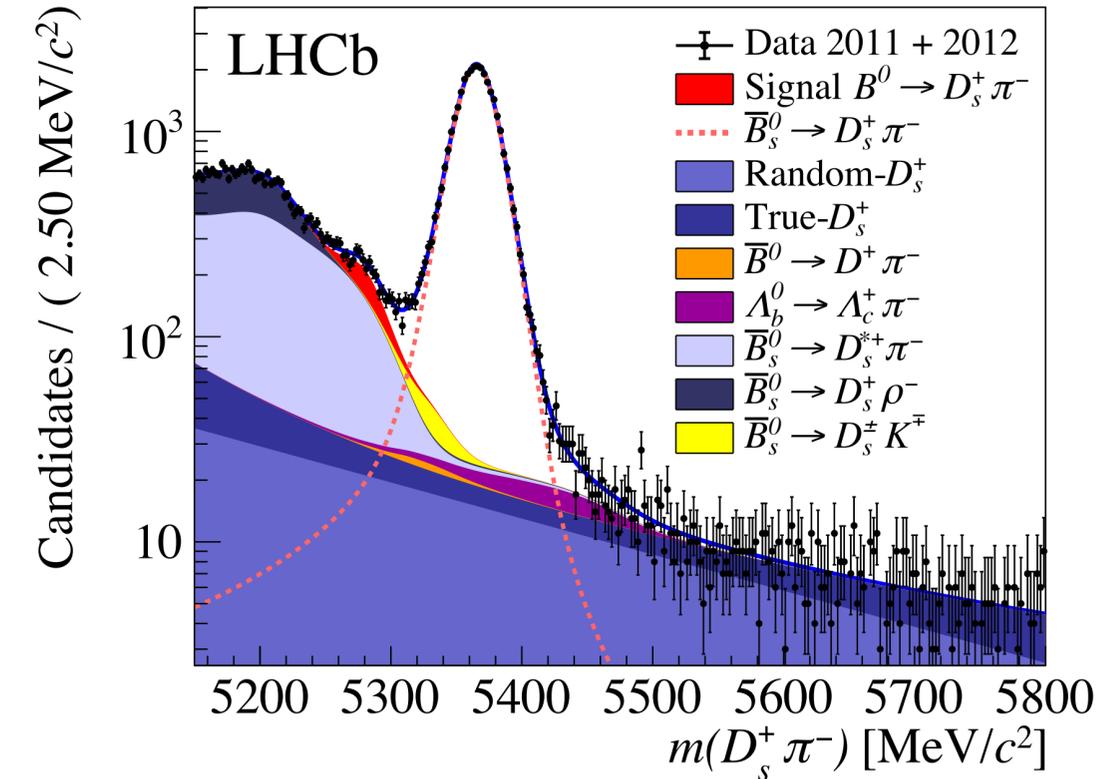
  ▸ Reduce systematics by building ratios

$$\frac{\mathscr{B}(B^{0/\pm}_{(s)} \to X)}{\mathscr{B}(B^0 \to Y)} = \frac{N(B^{0/\pm}_{(s)} \to X)}{N(B^0 \to Y)} \frac{\varepsilon(B^0 \to Y)}{\varepsilon(B^{0/\pm}_{(s)} \to X)} \frac{f_{d/s/u}}{f_d}$$

- **Precise inputs necessary**

  ▸ Yields of signal and normalization

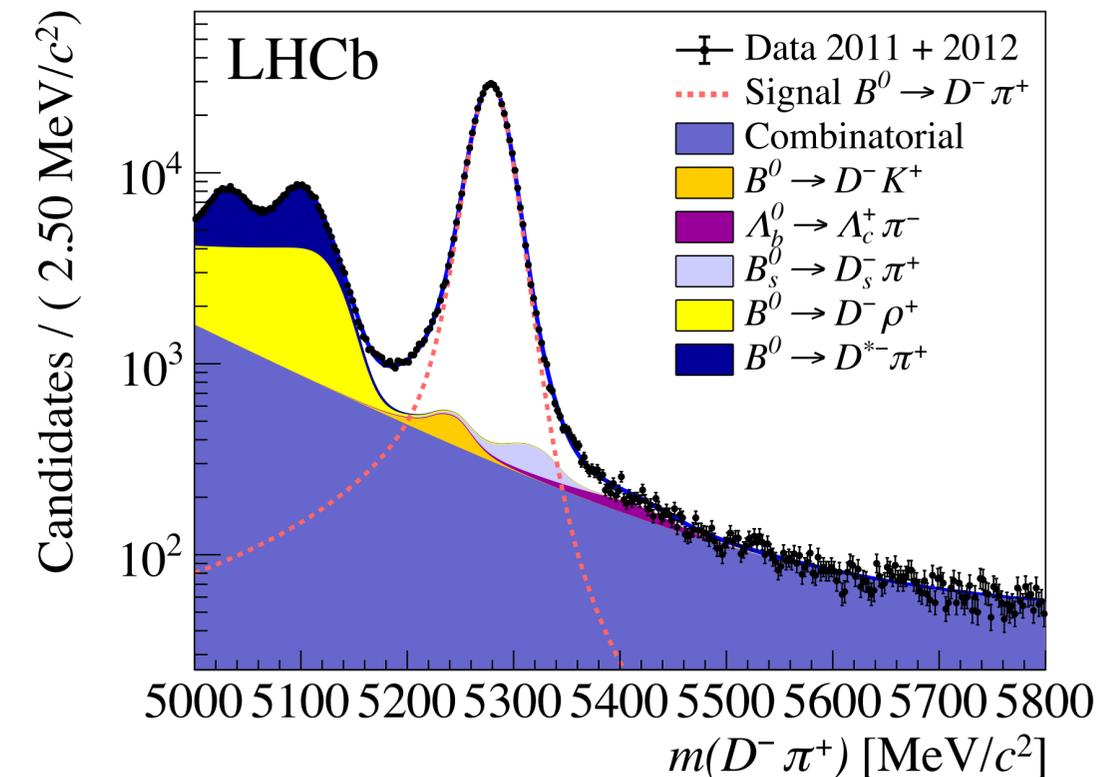 ▸ Relative efficiencies

  ▸ Often limited by hadronization fractions

Measurement of $\mathscr{B}(B^0 \to D_s^+ \pi^-)$

- **Precise counting measurement**

  ‣ Signal yield from fit to invariant mass

  ‣ Normalization from $B^0 \to D^- \pi^+$

  ‣ Carefully determined efficiencies

[*Eur. Phys. J. C* 81 (2021) 314]

- **Wide span of results / implications**

  ‣ $B^0 \to D_s^+ \pi^-$ branching fraction

  ‣ Constraining $|V_{ub}| \cdot |a_{NF}|$
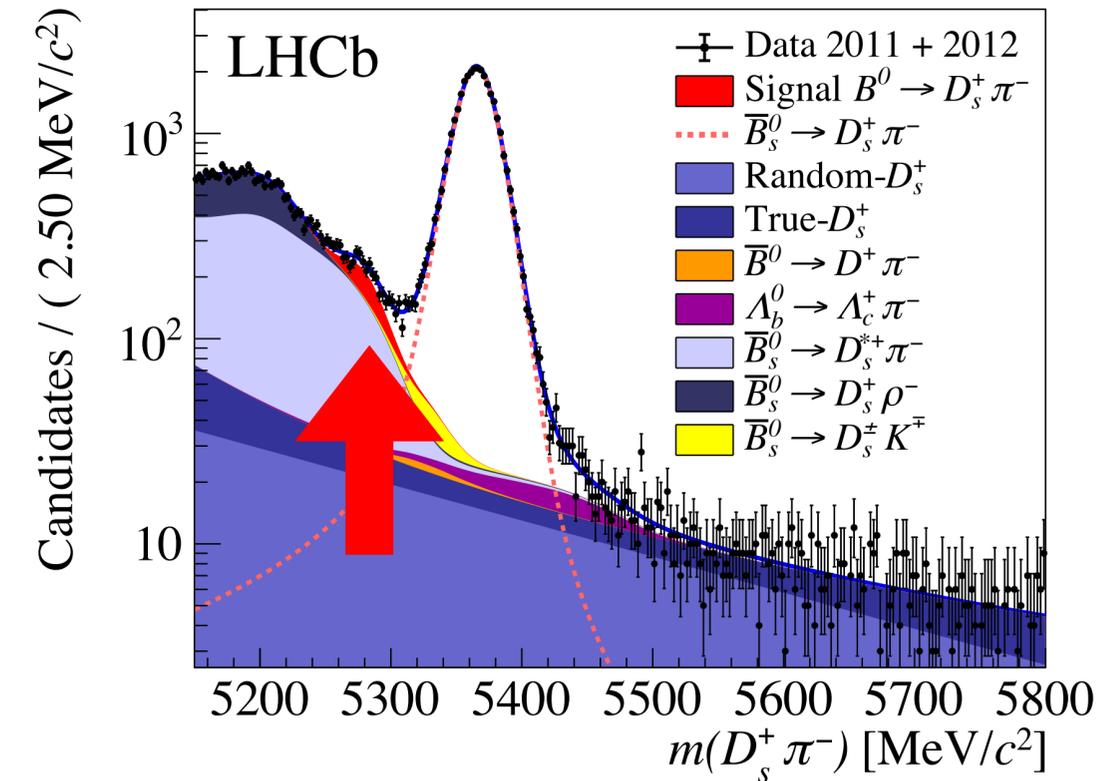
  ‣ Amplitude ratio $r_{D\pi}$

  ‣ Probing f_s/f_d

Measurement of $\mathscr{B}(B^0 \to D_s^+ \pi^-)$

- **Precise counting measurement**

  ‣ Signal yield from fit to invariant mass

  ‣ Normalization from $B^0 \to D^- \pi^+$

  ‣ Carefully determined efficiencies

- **Wide span of results / implications**

  ‣ $B^0 \to D_s^+ \pi^-$ branching fraction

  ‣ Constraining $|V_{ub}| \cdot |a_{NF}|$

  ‣ Amplitude ratio $r_{D\pi}$
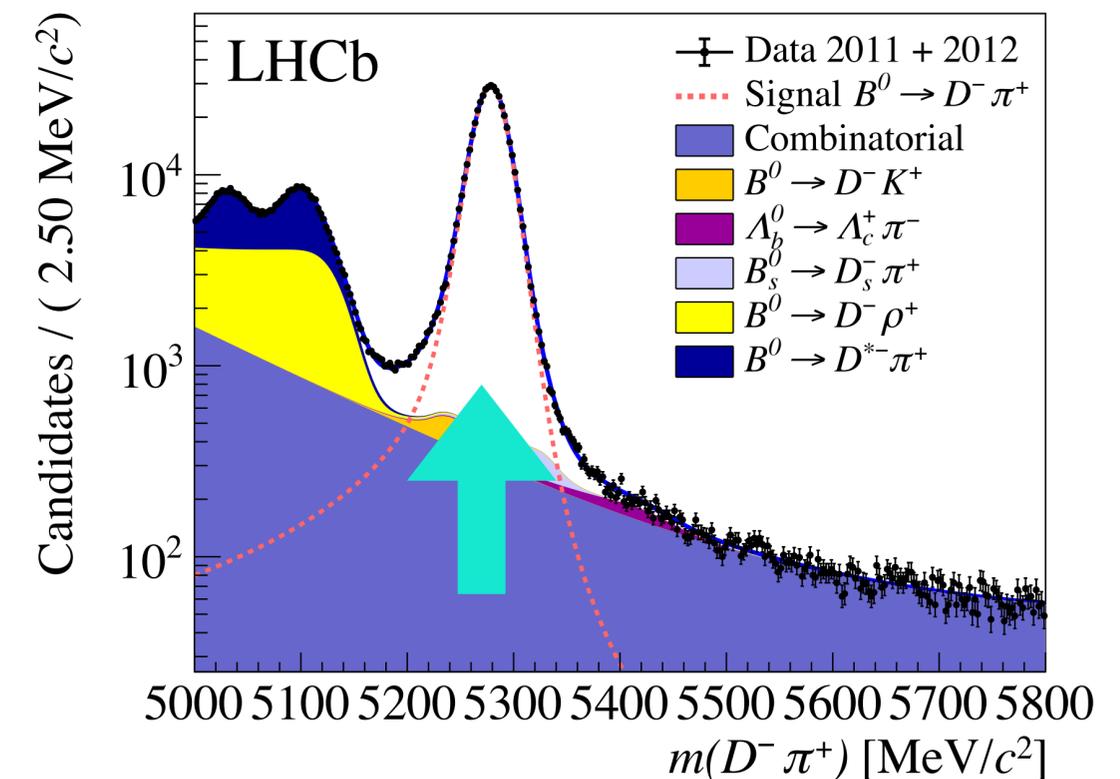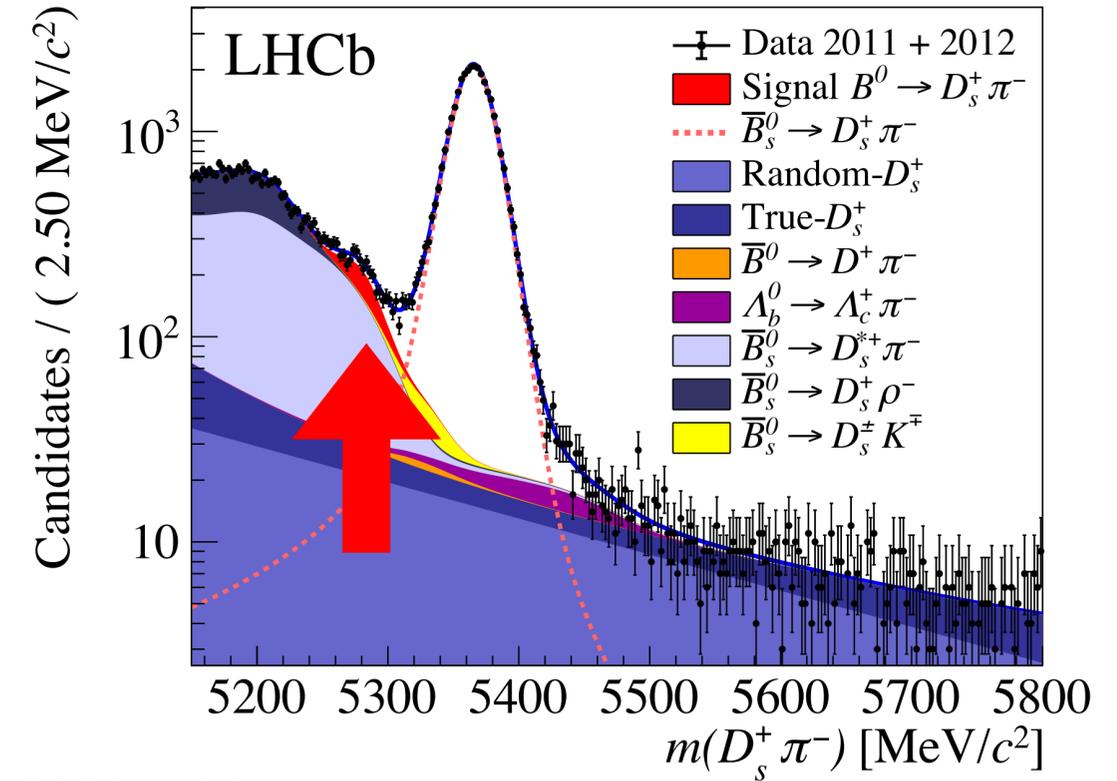
  ‣ Probing f_s/f_d

[*Eur. Phys. J. C* 81 (2021) 314]

Measurement of $\mathscr{B}(B^0 \to D_s^+ \pi^-)$

- **Precise counting measurement**

  ‣ Signal yield from fit to invariant mass

  ‣ Normalization from $B^0 \to D^- \pi^+$
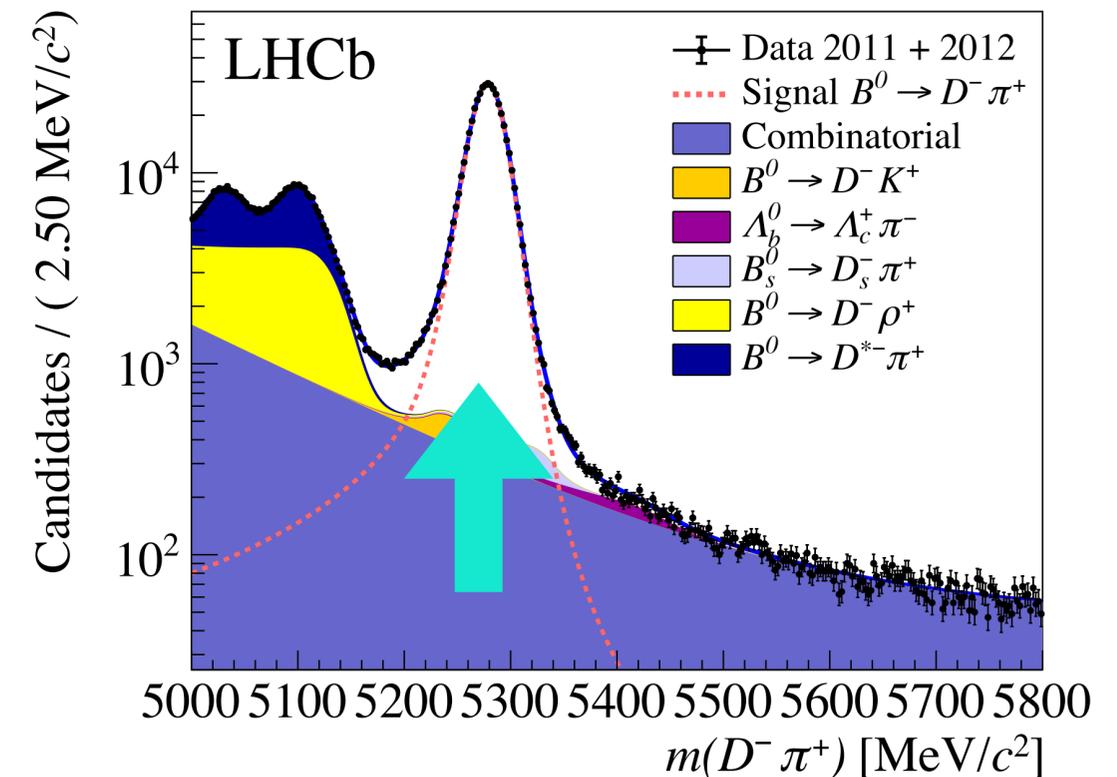
  ‣ Carefully determined efficiencies

[*Eur. Phys. J. C* 81 (2021) 314]

$$\frac{\mathscr{B}(B^0 \to D_s^+ \pi^-)}{\mathscr{B}(B^0 \to D^- \pi^+)} = (7.7 \pm 0.7 \pm 0.5 \pm 0.3) \cdot 10^{-3}$$

$$\frac{\mathscr{B}(B^0 \to D_s^+ \pi^-)}{\mathscr{B}(B^0 \to D^- \pi^+)} = \frac{N(B^0 \to D_s^+ \pi^-)}{N(B^0 \to D^- \pi^+)} \frac{\varepsilon(B^0 \to D^- \pi^+)}{\varepsilon(B^0 \to D_s^+ \pi^-)} \frac{\mathscr{B}(D^- \to K^- \pi^+ \pi^-)}{\mathscr{B}(D_s^+ \to K^+ K^- \pi^+)}$$

$$\mathscr{B}(B^0 \to D_s^+ \pi^-) = (19.4 \pm 1.8 \pm 1.3 \pm 1.2) \cdot 10^{-6}$$

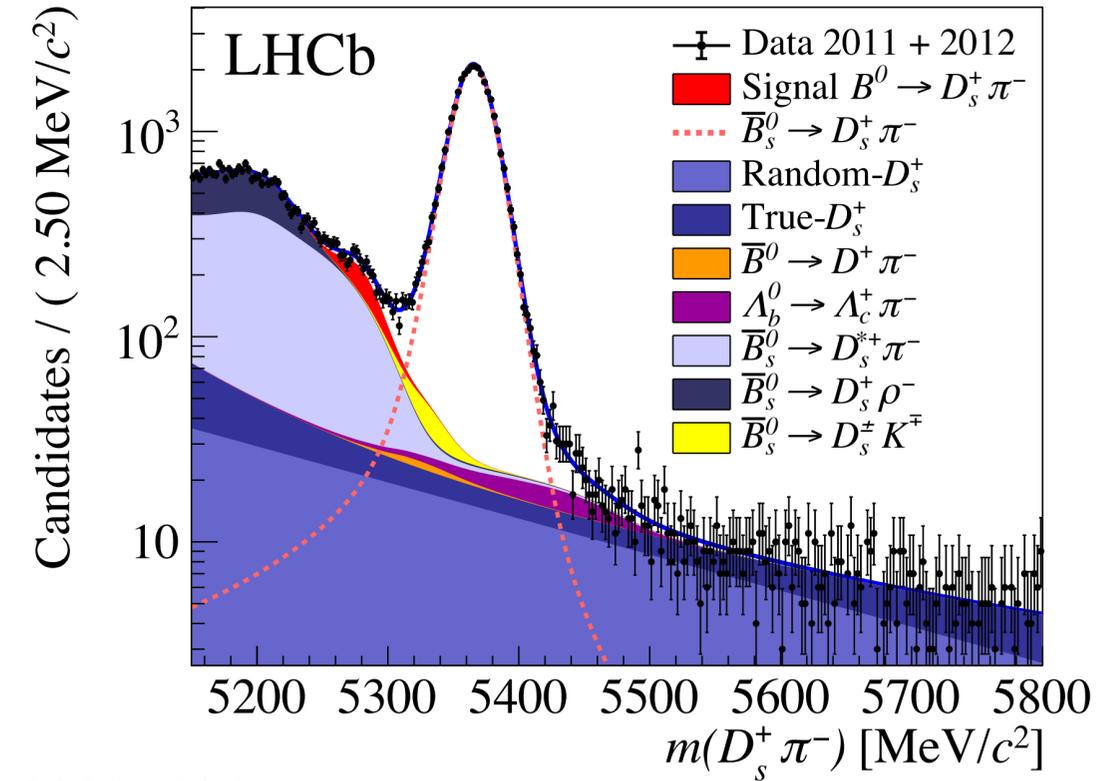# Measurement of $\mathscr{B}(B^0 \to D_s^+\pi^-)$

- **Precise counting measurement**

  ‣ Signal yield from fit to invariant mass

  ‣ Normalization from $B^0 \to D^-\pi^+$
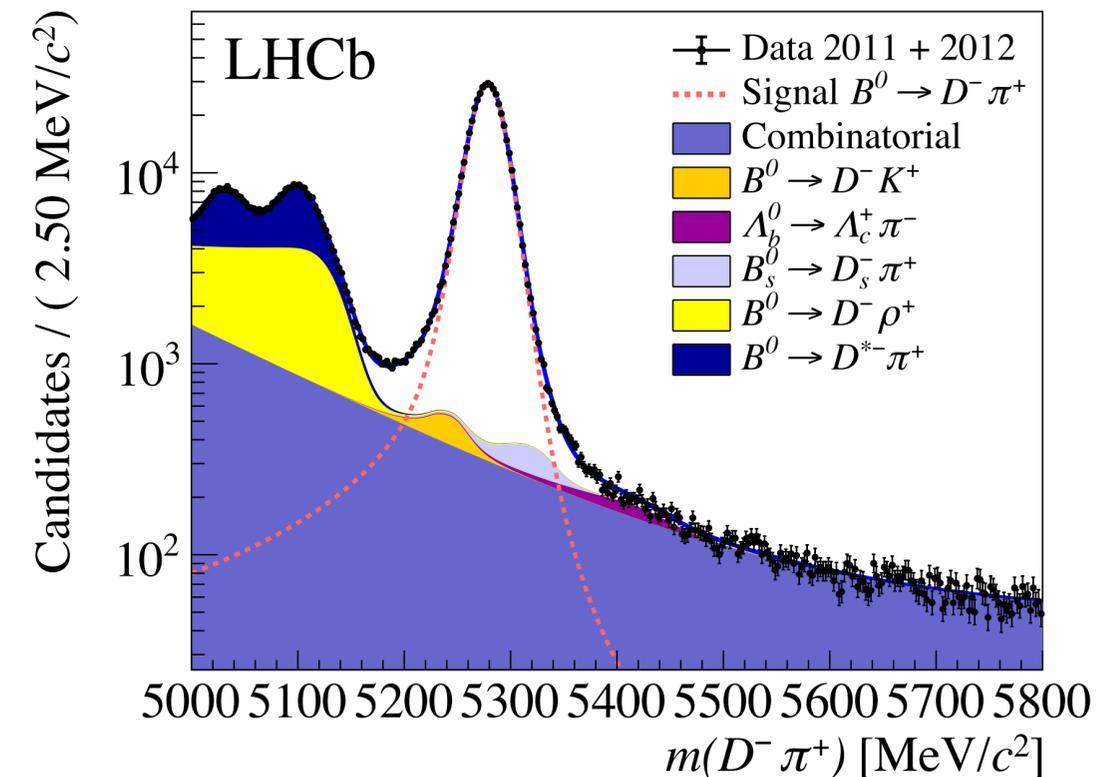
  ‣ Carefully determined efficiencies

[*Eur. Phys. J. C 81 (2021) 314*]

$$\frac{\mathscr{B}(B^0 \to D_s^+\pi^-)}{\mathscr{B}(B^0 \to D^-\pi^+)} = (7.7 \pm 0.7 \pm 0.5 \pm 0.3) \cdot 10^{-3}$$

$$\frac{\mathscr{B}(B^0 \to D_s^+\pi^-)}{\mathscr{B}(B^0 \to D^-\pi^+)} = \frac{N(B^0 \to D_s^+\pi^-)}{N(B^0 \to D^-\pi^+)} \frac{\varepsilon(B^0 \to D^-\pi^+)}{\varepsilon(B^0 \to D_s^+\pi^-)} \frac{\mathscr{B}(D^- \to K^-\pi^+\pi^-)}{\mathscr{B}(D_s^+ \to K^+K^-\pi^+)}$$

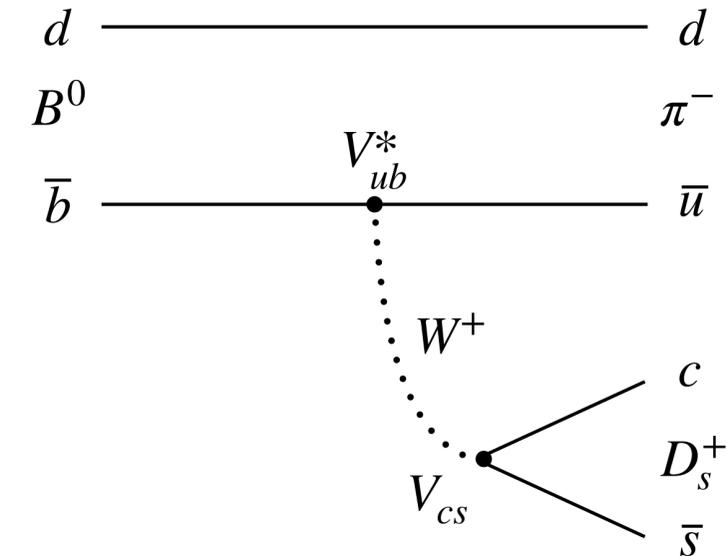$$\mathscr{B}(B^0 \to D_s^+\pi^-) = (19.4 \pm 1.8 \pm 1.3 \pm 1.2) \cdot 10^{-6}$$

Measurement of $\mathscr{B}(B^0 \to D_s^+ \pi^-)$
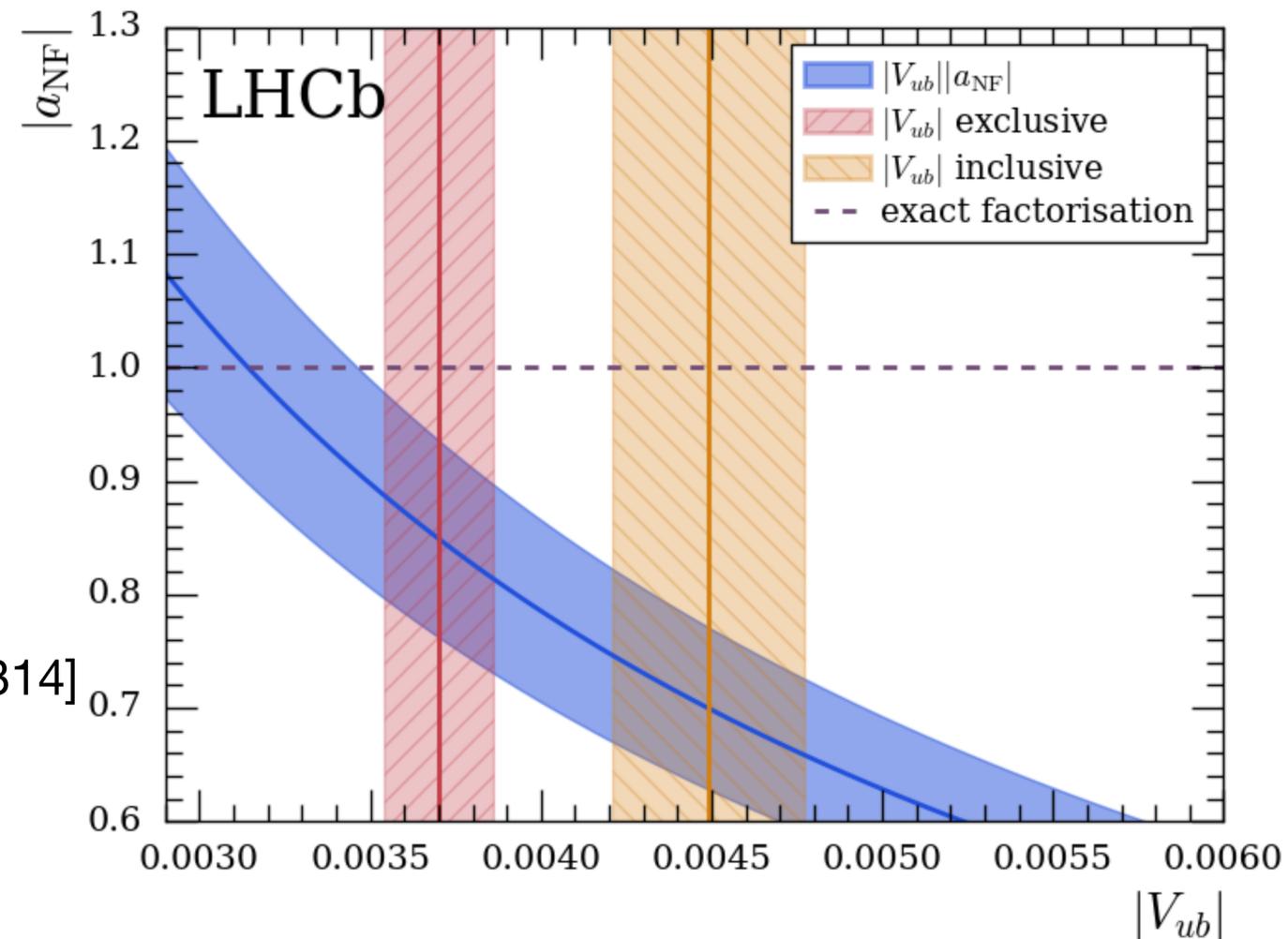

- **Sensitive to non-factorizing contributions**

  ‣ Precisely known theory inputs

  ‣ Externally constrained $|V_{ub}|$

$$\mathscr{B}(B^0 \to D_s^+ \pi^-) =$$

$$\Phi_{PS}\,|V_{ub}|^2\,|V_{cs}|^2\,|F(B^0 \to \pi^-)|^2\,f_{D_s^+}^2\,|a_{NF}|^2$$

$$|V_{ub}||a_{NF}| = (3.14 \pm 0.20 \pm 0.25) \cdot 10^{-3}$$

[*Eur. Phys. J. C* 81 (2021) 314]

Measurement of $\mathscr{B}(B^0 \to D_s^+\pi^-)$

- **Sensitive to non-factorizing contributions**

    ‣ Precisely known theory inputs

    ‣ Externally constrained $|V_{ub}|$

- **Amplitude ratio $r_{D\pi}$**

    ‣ Important for $C\!P$ in $B^0 \to D^{\mp}\pi^{\pm}$

    ‣ Limited by knowledge of $|a_{NF}|$

$$r_{D\pi} = \sqrt{\frac{\mathscr{B}(B^0 \to D^+\pi^-)}{\mathscr{B}(B^0 \to D^-\pi^+)}}$$

$$r_{D\pi} = \tan\theta_c \, \frac{f_{D^+}}{f_{D_s^+}} \sqrt{\frac{\mathscr{B}(B^0 \to D_s^+\pi^-)}{\mathscr{B}(B^0 \to D^-\pi^+)}}$$
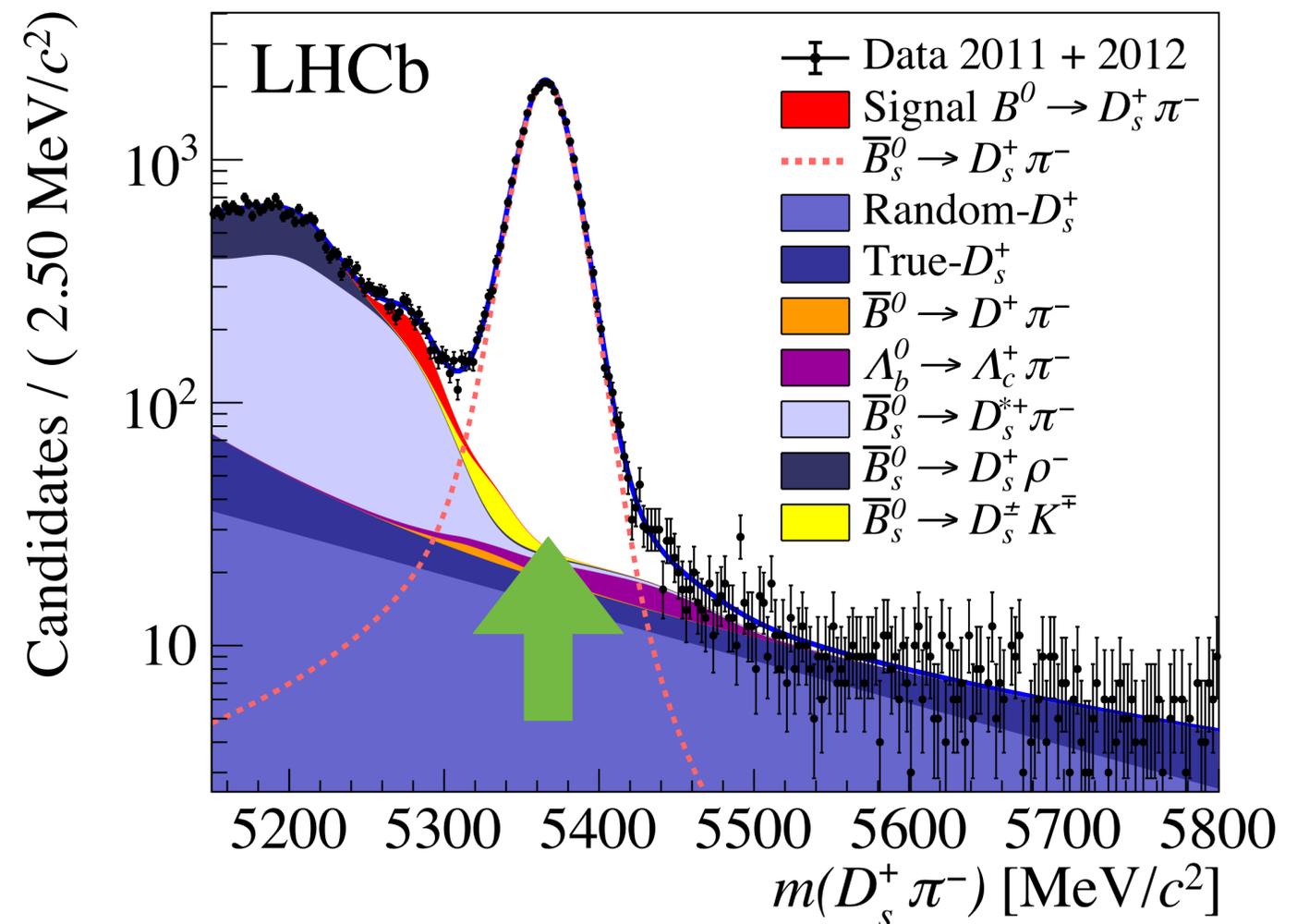
$$r_{D\pi} = 0.0163 \pm 0.0007 \pm 0.0007 \pm 0.0033$$

[*Eur. Phys. J. C* 81 (2021) 314]

Fitted $B_s^0 \to D_s^+ \pi^-$ yield

- **Sensitive to non-factorizing contributions**
  - Precisely known theory inputs
  - Externally constrained $|V_{ub}|$

- **Amplitude ratio $r_{D\pi}$**
  - Important for CP in $B^0 \to D^{\mp} \pi^{\pm}$
  - Limited by knowledge of $|a_{NF}|$

- **By-product: Probing f_s/f_d**
  - Fitted yields and efficiencies

$$\mathcal{R} = \frac{N_{\overline{B}_s^0 \to D_s^+ \pi^-}\, \varepsilon_{B^0 \to D^- \pi^+}}{N_{B^0 \to D^- \pi^+}\, \varepsilon_{\overline{B}_s^0 \to D_s^+ \pi^-}} \sim \frac{f_s}{f_d}$$

[*Eur. Phys. J.* C 81 (2021) 314]

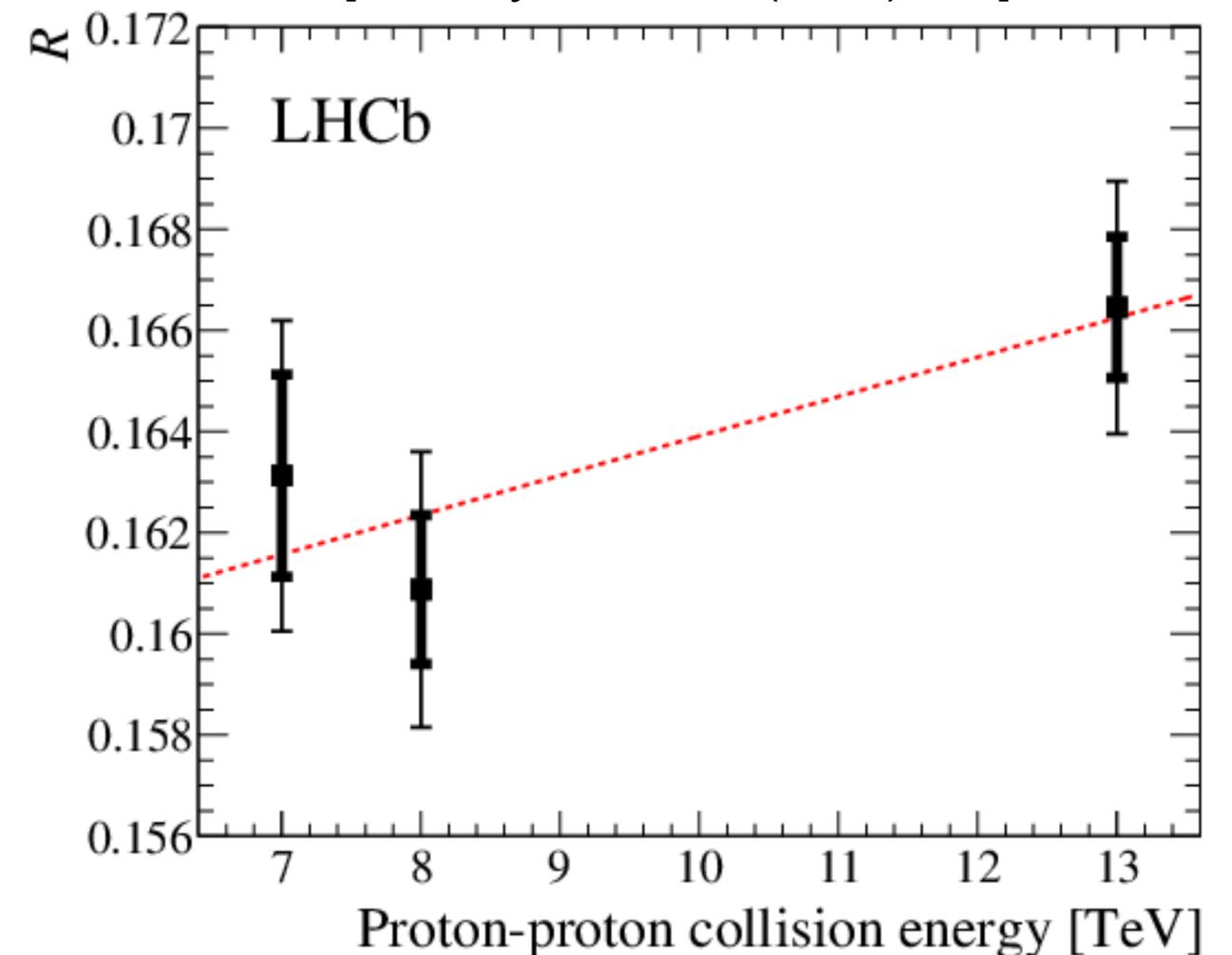# Fitted $B_s^0 \to D_s^+ \pi^-$ yield

- **Sensitive to non-factorizing contributions**

  ‣ Precisely known theory inputs

  ‣ Externally constrained $|V_{ub}|$

- **Amplitude ratio $r_{D\pi}$**

  ‣ Important for CP in $B^0 \to D^{\mp}\pi^{\pm}$

  ‣ Limited by knowledge of $|a_{NF}|$

- **By-product: Probing f_s/f_d**

  ‣ Fitted yields and efficiencies

$$\mathcal{R} = \frac{N_{\overline{B}_s^0 \to D_s^+ \pi^-} \; \varepsilon_{B^0 \to D^- \pi^+}}{N_{B^0 \to D^- \pi^+} \; \varepsilon_{\overline{B}_s^0 \to D_s^+ \pi^-}} \sim \frac{f_s}{f_d}$$

[*Eur. Phys. J.* C 81 (2021) 314]

Hadronization fraction

$$f_s / f_d$$

technische universität
dortmund

FSP LHCb
Erforschung von
Universum und Materie

LHCb

Fitting hadronization fraction f_s/f_d

$$\mathscr{R} = \frac{N_{\overline{B}_s^0 \to D_s^+ \pi^-}\ \varepsilon_{B^0 \to D^- \pi^+}}{N_{B^0 \to D^- \pi^+}\ \varepsilon_{\overline{B}_s^0 \to D_s^+ \pi^-}}$$

- **Fitting kinematic dependency**

  ‣ Relying on corrected yield ratios $\mathscr{R}$

  ‣ Input from 5 different measurements

  ‣ $\dfrac{\mathscr{B}(B^0 \to D^- \pi^+)}{\mathscr{B}(B_s^0 \to D_s^- \pi^+)}$ from theory or floating

Correction factors

$\mathscr{N}_a$: non-factorisable effects

$\mathscr{N}_F$: form factors

$\mathscr{N}_E$: exchange econtributions

$$\frac{f_s}{f_d} = \frac{\mathscr{B}(B^0 \to D^- \pi^+)}{\mathscr{B}(B_s^0 \to D_s^- \pi^+)} \mathscr{R}$$

$$= \Phi_{PS} \frac{\tau_{B^0}}{\tau_{B_s^0}} \frac{1}{\mathscr{N}_a \mathscr{N}_F \mathscr{N}_E} \frac{\mathscr{B}(D^- \to K^+ \pi^- \pi^-)}{\mathscr{B}(D_s^- \to K^+ K^- \pi^-)} \mathscr{R}$$

[*Phys. Rev. D* 104 (2021) 032005]

Fitting hadronization fraction f_s/f_d

- **Fitting kinematic dependency**

  ‣ Relying on corrected yield ratios $\mathscr{R}$

  ‣ Input from 5 different measurements

  ‣ $\dfrac{\mathscr{B}(B^0 \to D^- \pi^+)}{\mathscr{B}(B_s^0 \to D_s^- \pi^+)}$ from theory or floating

$$\mathscr{R} = \frac{N_{\overline{B}_s^0 \to D_s^+ \pi^-}\ \varepsilon_{B^0 \to D^- \pi^+}}{N_{B^0 \to D^- \pi^+}\ \varepsilon_{\overline{B}_s^0 \to D_s^+ \pi^-}}$$

[*Phys. Rev. D* 104 (2021) 032005]

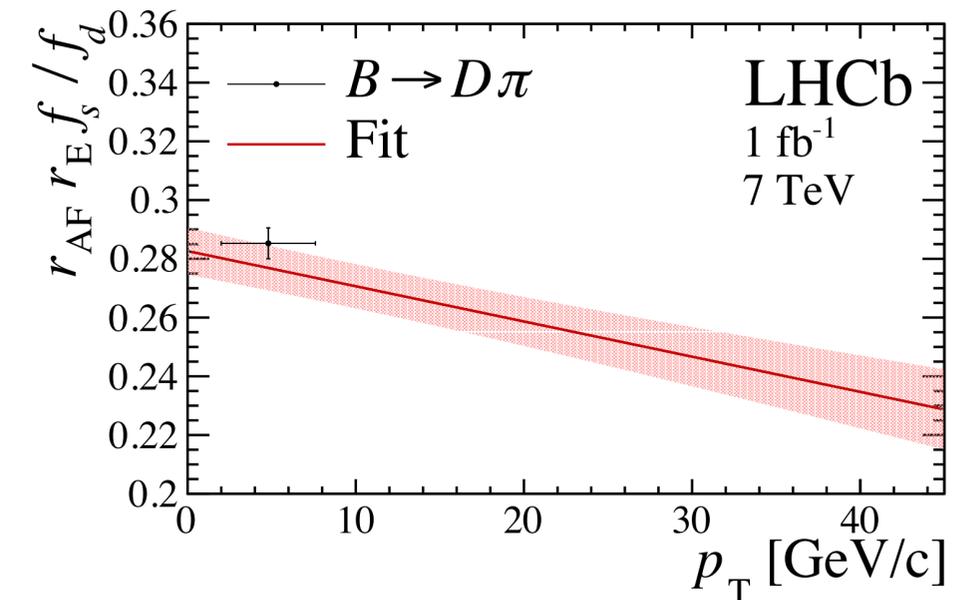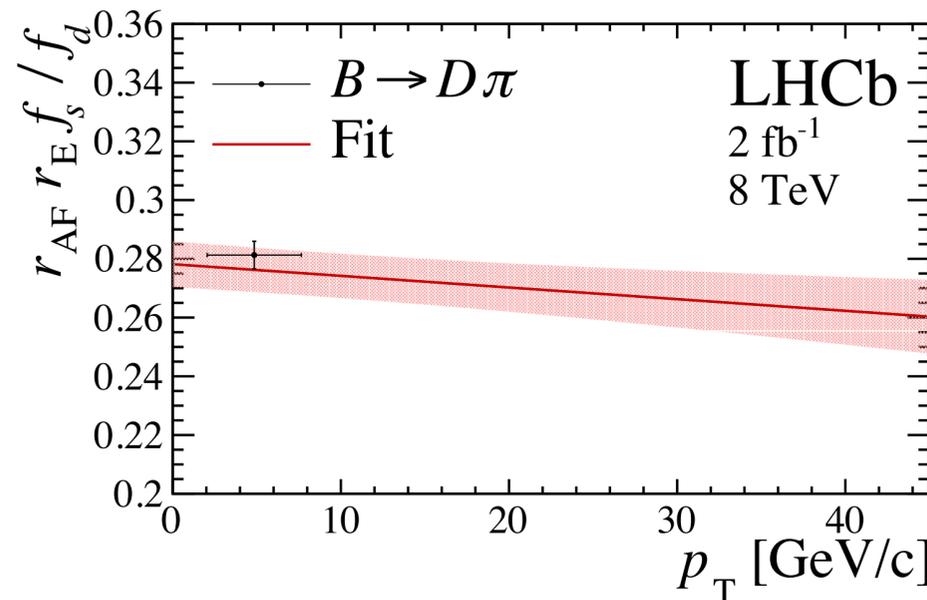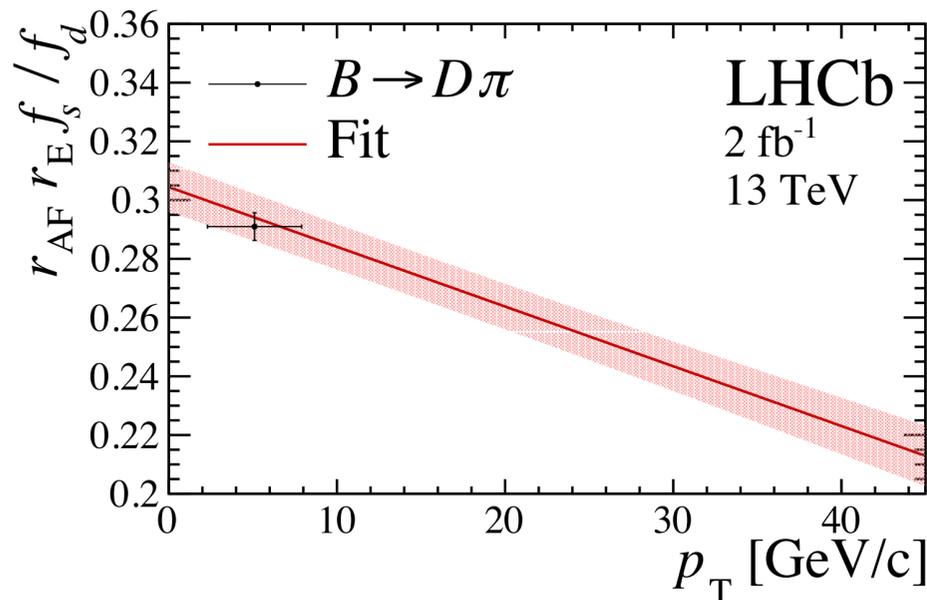| Final state	$\sqrt{s}$	Relative or absolute	Sensitivity	Reference
$B \to \overline{D} X \mu^+ \nu_\mu$	7 TeV	Absolute	f_s/f_d	[8]
$B \to \overline{D} X \mu^+ \nu_\mu$	13 TeV	Absolute	f_s/f_d	[23]
$B_s^0 \to D_s^- \pi^+, B^0 \to D^- K^+$	7 TeV	Absolute	f_s/f_d	[9]
$B_s^0 \to D_s^- \pi^+, B^0 \to D^- \pi^+$	7 TeV	Relative	f_s/f_d	[9]
$B_s^0 \to D_s^- \pi^+, B^0 \to D^- \pi^+$	7, 8, 13 TeV	Absolute	f_s/f_d , $\mathcal{B}(B_s^0 \to D_s^- \pi^+)$	[24]
$B_s^0 \to J/\psi\phi, B^+ \to J/\psi K^+$	7, 8, 13 TeV	Relative	$f_s/f_d, \mathcal{B}(B_s^0 \to J/\psi\phi)$	[10]

Fitting hadronization fraction f_s/f_d

- **Fitting kinematic dependency**

  ▸ Input from different channels

  ▸ Relying on corrected yield ratios $\mathscr{R}$

  ▸ Linear in p_T, no η dependency

[*Phys. Rev. D* 104 (2021) 032005]

Additional inputs from charmonia and semi-leptonics!

Fitting hadronization fraction f_s/f_d

- **Integrated fractions**

  ▸ Agreement with predictions

    [*Eur. Phys. J. C* 80 (2020) 951]

  ▸ Uncertainty halved cf. previous values

  ▸ Crucial input to BF measurements

  ▸ Many BF updated

$f_s/f_d(\ 7\,\text{TeV}) = 0.2390 \pm 0.0076$

$f_s/f_d(\ 8\,\text{TeV}) = 0.2385 \pm 0.0075$

$f_s/f_d(13\,\text{TeV}) = 0.2539 \pm 0.0079$

[*Phys. Rev. D* 104 (2021) 032005]

$\mathcal{B}(B_s^0 \to \mu\mu) = (3.0 \pm 0.6\,^{+0.2}_{-0.1} \pm 0.2) \cdot 10^{-9}$ (old)

$\mathcal{B}(B_s^0 \to \mu\mu) = (3.26 \pm 0.65\,^{+0.22}_{-0.11} \pm 0.10) \cdot 10^{-9}$

Fitting hadronization fraction f_s/f_d

- **Integrated fractions**

  ‣ Agreement with predictions
     [*Eur. Phys. J. C* 80 (2020) 951]

  ‣ Uncertainty halved cf. previous values

  ‣ Crucial input to BF measurements

  ‣ Many BF updated

[*Phys. Rev. D* 104 (2021) 032005]

$$\frac{\mathscr{B}(B_s^0 \to D_s^- \pi^+)}{\mathscr{B}(B^0 \to D^- \pi^+)} = 1.18 \pm 0.04$$

$$\frac{\mathscr{B}(B_s^0 \to D_s^- \pi^+)}{\mathscr{B}(B^0 \to D^- \pi^+)} = 1.19 \pm 0.19$$

PDG average [*Phys*. 2020 (2020) 083C01]

- **Fitted B_s^0 branching fraction ratios**

  ‣ More precise than PDG average

  ‣ $\mathscr{B}(B_s^0 \to D_s^- \pi^+)$ often as normalization

  ‣ Also improving many BF ratios

[*Phys. Rev. D* 104 (2021) 032005]

$$\mathscr{B}(B_s^0 \to D_s^- \pi^+) = (3.20 \pm 0.10 \pm 0.16) \cdot 10^{-3}$$

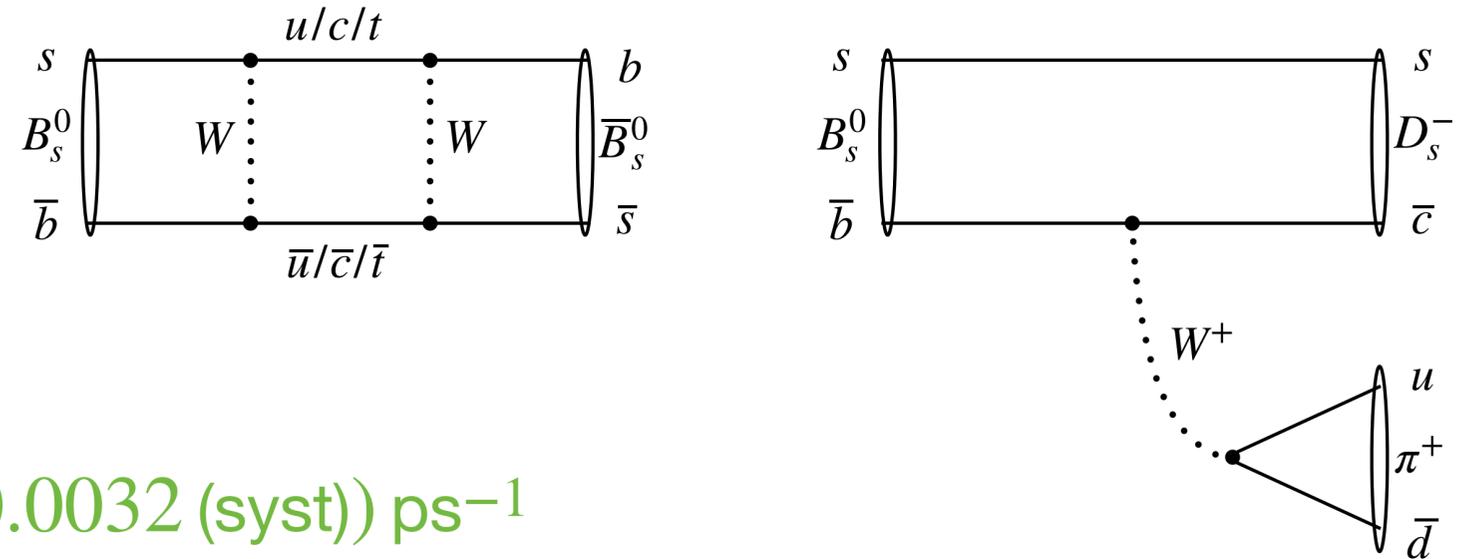$$\mathscr{B}(B_s^0 \to D_s^- \pi^+) = (3.00 \pm 0.23) \cdot 10^{-3}$$

PDG average [*Phys*. 2020 (2020) 083C01]

Mass difference / oscillation frequency Δm_s

from $B_s^0 \rightarrow D_s^- \pi^+$

Δm_s from $B_s^0 \rightarrow D_s^- \pi^+$
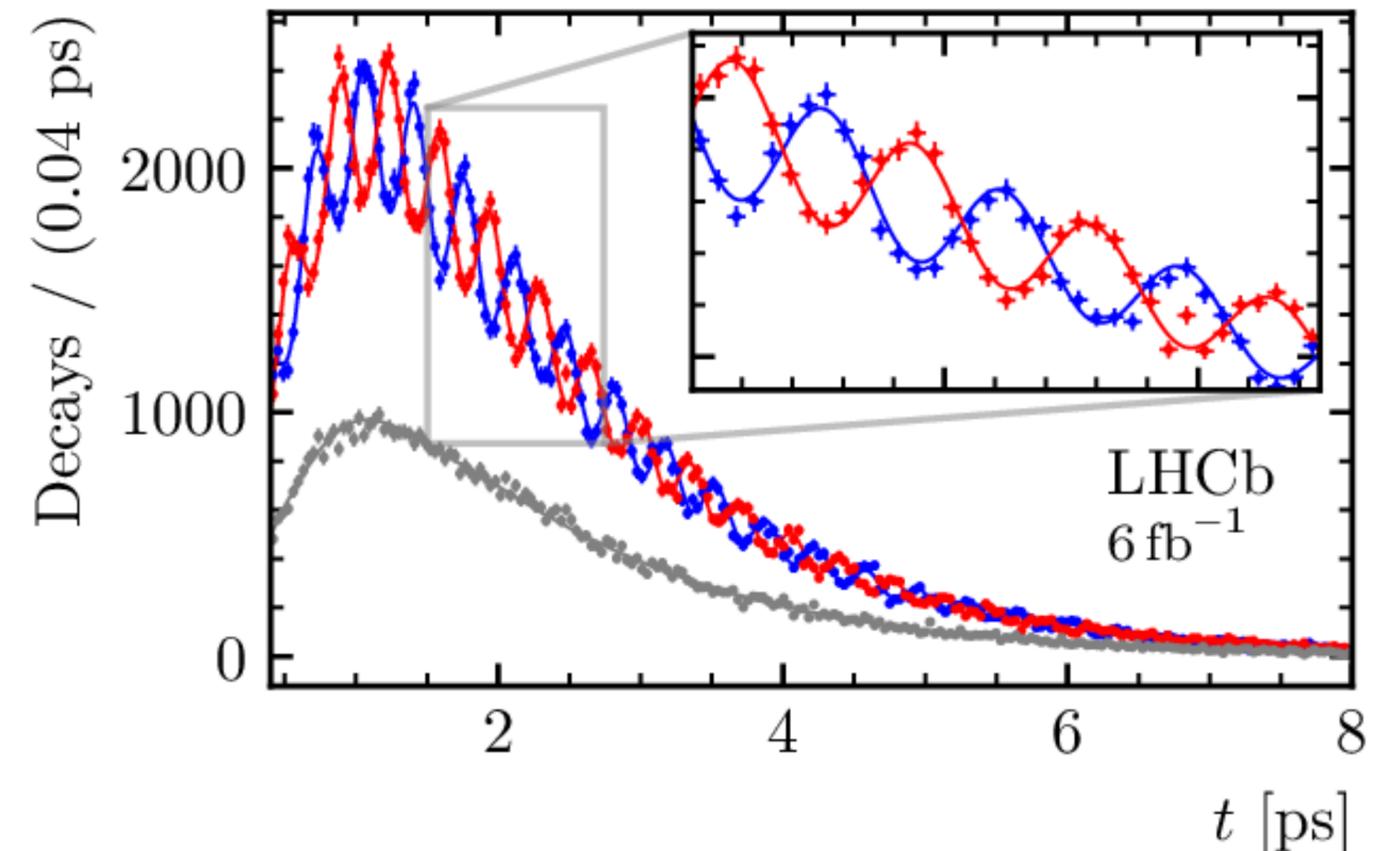

- **Very precise measurement**

  ‣ $\Delta m_s^{D_s \pi} = (17.7683 \pm 0.0051 \,(\text{stat}) \pm 0.0032 \,(\text{syst}))\,\text{ps}^{-1}$

  ‣ Expected to be long-standing result

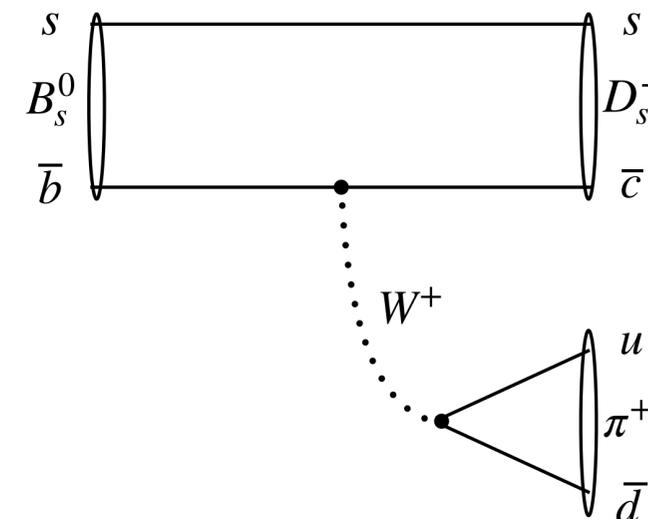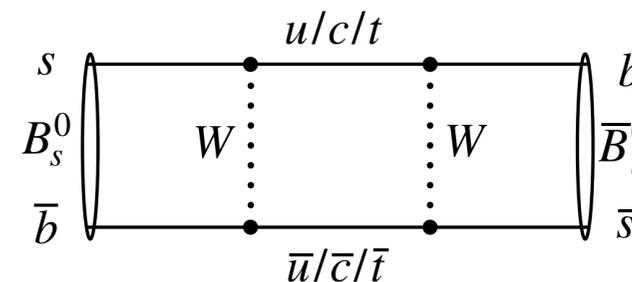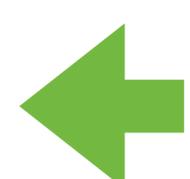 ‣ Dominating average

- **Crucial input for TD measurements**

  ‣ γ from $B_s^0 \rightarrow D_s^\mp K^\pm$, etc

[*Nature Phys.* 18 (2022) 1-5]

Δm_s from $B_s^0 \to D_s^- \pi^+$

- ## Very precise measurement

  - $\Delta m_s^{D_s \pi} = (17.7683 \pm 0.0051 \, \text{(stat)} \pm 0.0032 \, \text{(syst)}) \, \text{ps}^{-1}$

  - Expected to be long-standing result [*Nature Phys.* 18 (2022) 1-5]
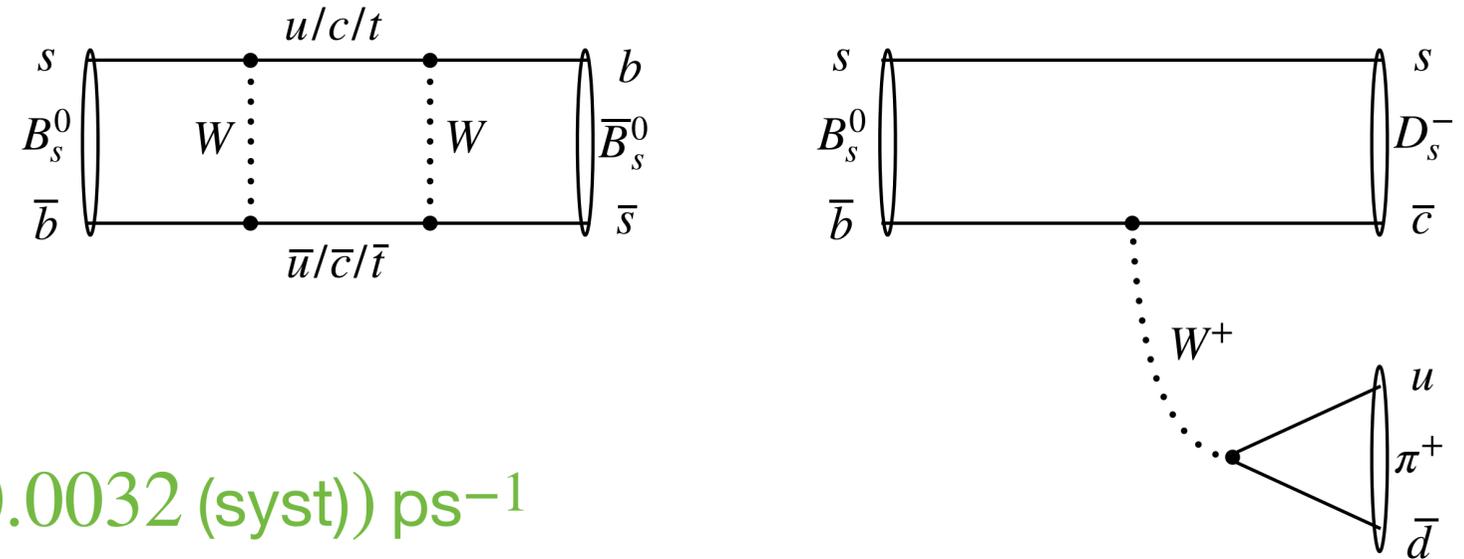
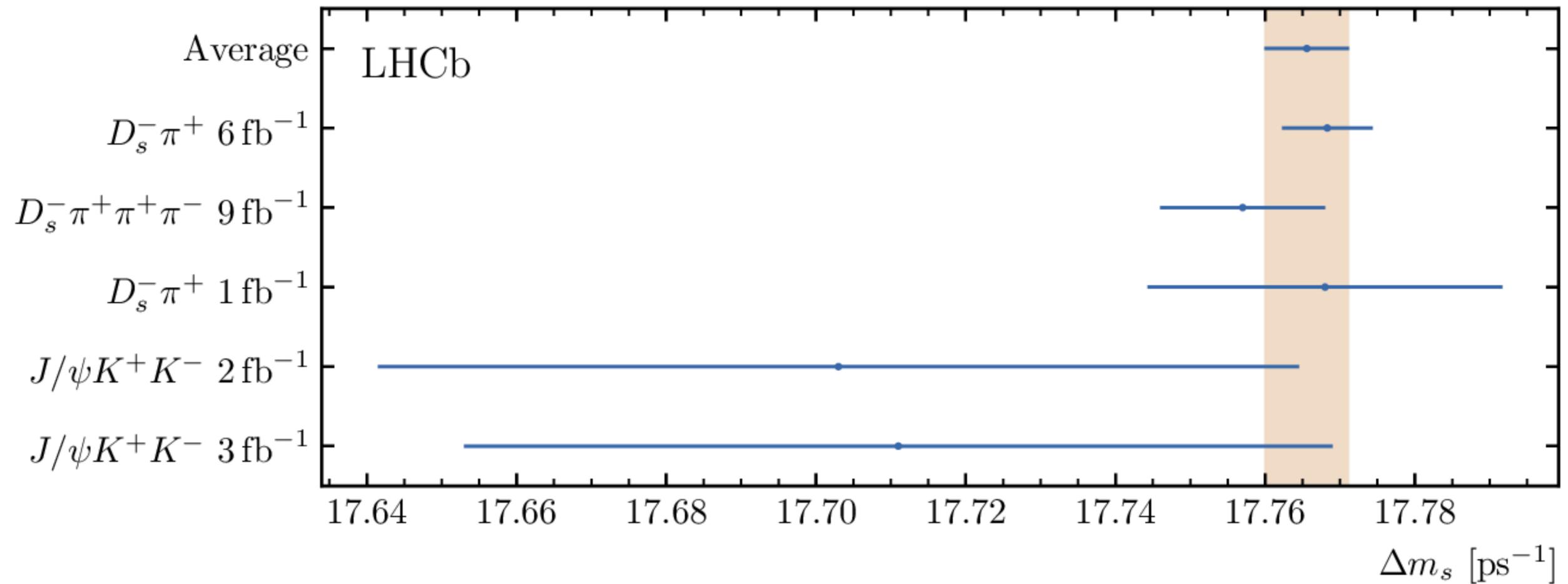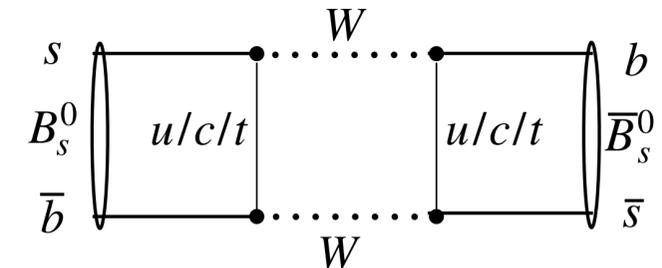| Description	Systematic uncertainty $[\text{ps}^{-1}]$
Reconstruction effects:	
momentum scale uncertainty	0.0007
detector length scale	0.0018
detector misalignment	0.0020
Invariant mass fit model:	
background parametrisation	0.0002
$B_s^0 \to D_s^{*-}\pi^+$ and $B^0 \to D_s^-\pi^+$ contributions	0.0005
Decay-time fit model:	
decay-time resolution model	0.0011
neglecting correlation among observables	0.0011
Cross-checks:	
kinematic correlations	0.0003
Total systematic uncertainty	0.0032

Leading systematics from detector (VELO)

$\sigma(z) = 100 \, \mu\text{m/m} = 0.01 \, \%$

technische universität dortmund

FSP LHCb
Erforschung von
Universum und Materie

LHCb
LHCP
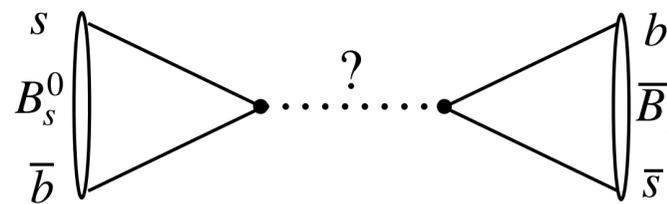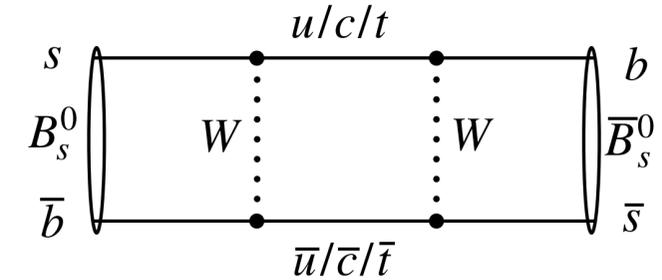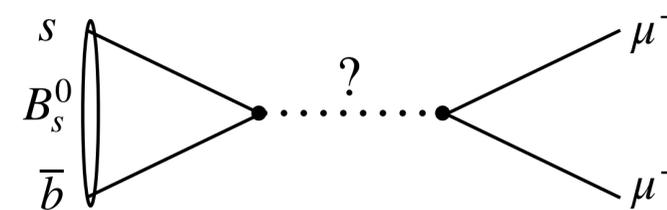
Δm_s from $B_s^0 \to D_s^- \pi^+$

- **Very precise measurement**

  ‣ $\Delta m_s^{D_s \pi} = (17.7683 \pm 0.0051 \,(\text{stat}) \pm 0.0032 \,(\text{syst})) \,\text{ps}^{-1}$

  ‣ Dominating average: $\Delta m_s^{exp} = (17.7656 \pm 0.0057) \,\text{ps}^{-1}$ *[Nature Phys. 18 (2022) 1-5]*

Implications of Δm_s

- B_s^0 **mixing can probe** $b \rightarrow sl^+l^-$ **anomalies**
  - ‣ Sensitive to BSM $b\bar{s}$ couplings
  - ‣ Oscillation frequency directly affected

- **Agreement is crumbling lately**
  - ‣ Precise measurements: $\Delta m_s^{exp} = (17.7656 \pm 0.0057)\,\text{ps}^{-1}$ [*Nature Phys.* 18 (2022) 1-5]

  - ‣ Prediction: $\Delta m_s^{avg} = (19.4 \pm 1.0)\,\text{ps}^{-1}$ [*JHEP* 05 (2019) 034]

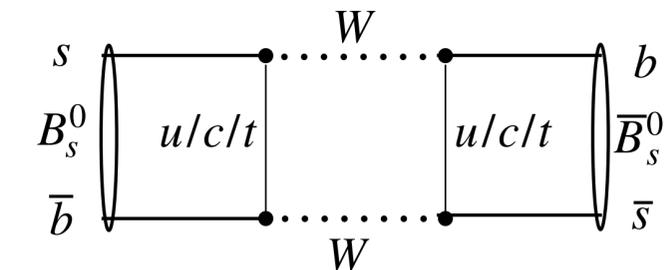 $= (19.4 \pm 0.9\,(\text{had.}) \pm 0.1\,(\text{scale})^{+0.3}_{-1.0}\,(\text{param.}))\,\text{ps}^{-1}$
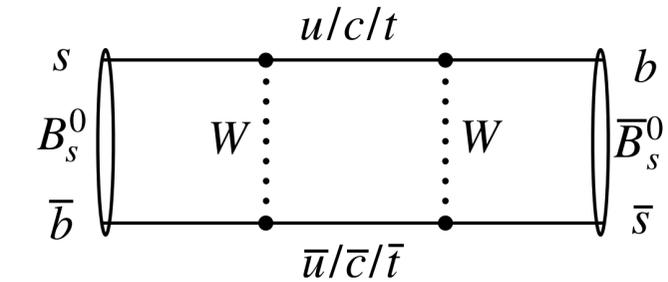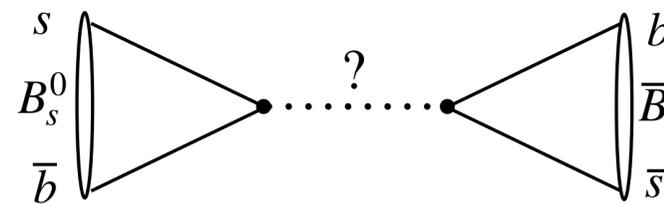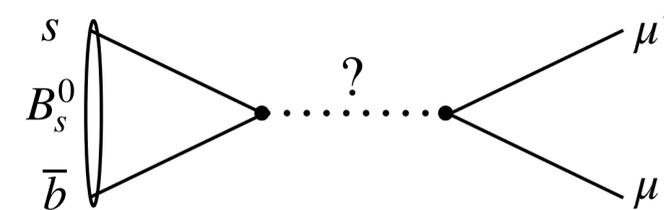
  (Combination of lattice and sum rule calculation)

- **Any possibility to improve prediction?**

Implications of Δm_s

- B_s^0 mixing can probe $b \to sl^+l^-$ anomalies

  ‣ Sensitive to BSM $b\bar{s}$ couplings

  ‣ Oscillation frequency directly affected

- **Hadronic uncertainty reduced in ratios**

  ‣ $(\Delta m_d / \Delta m_s)_{exp} = 0.0285 \pm 0.0001$ (Not yet including update)

  ‣ $(\Delta m_d / \Delta m_s)_{avg} = 0.0297\,^{+0.0006}_{-0.0009}$ [*JHEP* 05 (2019) 034]

  $\quad = 0.0297\,^{+0.0003}_{-0.0003}$ (had.) $^{+0.0005}_{-0.0008}$ (exp.)

  (Combination of lattice and sum rule calculation)

- **Where does this exp. uncertainty originate from? Only CKM elements?**

Prospects on a_{fs} from $B_s^0 \rightarrow D_s^- \pi^+$

- **Discrepancy in BF**

- **Flavour specific asymmetry**
  - Clean predictions
  $$a_{fs}^s = (2.06 \pm 0.18) \cdot 10^{-5}$$
  [JHEP 07 (2020) 177]*
  - Usually measured in SL
  $$a_{fs}^s = (-60 \pm 280) \cdot 10^{-5} = a_{sl}^s$$
  [Eur. Phys. J. C (2021) 81: 226]*
  - Null test due to exp. precision

- **NP could affect hadronic modes**
  - SM: no direct CPV in $B_s^0 \rightarrow D_s^- \pi^+$

[*JHEP* 10 (2021) 235]

Decay mode	LO	NLO	NNLO	NNLO$^\#$	Ref. [36]	Ref. [38]	Exp. [7, 8]
$\bar{B}^0 \rightarrow D^+\pi^-$	4.20	$4.45^{+0.25}_{-0.40}$	$4.58^{+0.22}_{-0.38}$	$4.74^{+0.61}_{-0.69}$	$3.93^{+0.43}_{-0.42}$		2.65 ± 0.15
$\bar{B}^0 \rightarrow D^{*+}\pi^-$	3.77	$4.00^{+0.29}_{-0.40}$	$4.13^{+0.27}_{-0.39}$	$4.26^{+0.75}_{-0.80}$	$3.45^{+0.53}_{-0.50}$		2.58 ± 0.13
$\bar{B}^0 \rightarrow D^+\rho^-$	10.98	$11.64^{+0.88}_{-1.18}$	$11.96^{+0.82}_{-1.15}$	$12.28^{+1.40}_{-1.63}$	$10.42^{+1.24}_{-1.20}$		7.6 ± 1.2
$\bar{B}^0 \rightarrow D^{*+}\rho^-$	10.32	$10.95^{+1.40}_{-1.55}$	$11.28^{+1.40}_{-1.56}$	$11.61^{+1.88}_{-2.01}$	$9.24^{+0.72}_{-0.71}$		6.0 ± 0.8
$\bar{B}^0 \rightarrow D^+K^-$	3.18	$3.37^{+0.17}_{-0.29}$	$3.48^{+0.14}_{-0.28}$		$3.01^{+0.32}_{-0.31}$	3.26 ± 0.15	2.19 ± 0.13
$\bar{B}^0 \rightarrow D^{*+}K^-$	2.82	$3.00^{+0.20}_{-0.29}$	$3.10^{+0.19}_{-0.28}$		$2.59^{+0.39}_{-0.37}$	$3.27^{+0.39}_{-0.34}$	2.04 ± 0.47
$\bar{B}^0 \rightarrow D^+K^{*-}$	5.48	$5.80^{+0.48}_{-0.62}$	$5.94^{+0.46}_{-0.61}$		$5.25^{+0.65}_{-0.63}$		4.6 ± 0.8
$\bar{B}_s^0 \rightarrow D_s^+\pi^-$	4.23	$4.49^{+0.27}_{-0.41}$	$4.61^{+0.23}_{-0.39}$		$4.39^{+1.36}_{-1.19}$	4.42 ± 0.21	3.23 ± 0.18
$\bar{B}_s^0 \rightarrow D_s^{*+}\pi^-$	3.51	$3.73^{+0.88}_{-0.84}$	$3.84^{+0.90}_{-0.85}$		$2.24^{+0.56}_{-0.50}$	$4.30^{+0.90}_{-0.80}$	$2.4^{+0.7}_{-0.6}$
$\bar{B}_s^0 \rightarrow D_s^+K^-$	3.21	$3.41^{+0.18}_{-0.30}$	$3.52^{+0.15}_{-0.29}$	$3.69^{+0.60}_{-0.65}$	$3.34^{+1.04}_{-0.90}$		2.41 ± 0.16
$\bar{B}_s^0 \rightarrow D_s^{*+}K^-$	2.62	$2.79^{+0.65}_{-0.61}$	$2.88^{+0.66}_{-0.63}$	$3.02^{+0.99}_{-0.97}$	$1.67^{+0.42}_{-0.37}$		1.63 ± 0.50

Table 3. Updated SM predictions for the branching ratios (in units of 10^{-3} for $b \rightarrow c\bar{u}d$ and 10^{-4} for $b \rightarrow c\bar{u}s$ transitions) of $\bar{B}_{(s)}^0 \rightarrow D_{(s)}^{(*)+}L^-$ decays at different orders in α_s, together with the results

Prospects on a_{fs} from $B_s^0 \rightarrow D_s^- \pi^+$

- **Discrepancy in BF**

- **Flavour specific asymmetry**
  - ▸ Clean predictions [*JHEP* 07 (2020) 177]
  $$a_{fs}^s = (2.06 \pm 0.18) \cdot 10^{-5}$$
  - ▸ Usually measured in SL [*Eur. Phys. J. C* (2021) 81: 226]
  $$a_{fs}^s = (-60 \pm 280) \cdot 10^{-5} = a_{sl}^s$$
  - ▸ Null test due to exp. precision

- **NP could affect hadronic modes**
  - ▸ SM: no direct CPV in $B_s^0 \rightarrow D_s^- \pi^+$

$$A_{fs}^q = \frac{\Gamma(\overline{B}_q(t) \rightarrow f) - \Gamma(B_q(t) \rightarrow \bar{f})}{\Gamma(\overline{B}_q(t) \rightarrow f) + \Gamma(B_q(t) \rightarrow \bar{f})}$$

$$= \frac{|\mathscr{A}_f|^2(1 + a_{fs}^q)) - |\overline{\mathscr{A}}_{\bar{f}}|^2(1 - a_{fs}^q)}{|\mathscr{A}_f|^2(1 + a_{fs}^q)) + |\overline{\mathscr{A}}_{\bar{f}}|^2(1 - a_{fs}^q)}$$

$$= a_{fs}^q \text{ ,if no direct CPV: } \overline{\mathscr{A}}_{\bar{f}} = \mathscr{A}_f$$

$$A_{fs}^q \approx a_{fs}^q - A_{dir}^q$$

$$A_{fs}^s(D_s^- l^+ \nu_l) - A_{fs}^s(D_s^- \pi^+) = A_{dir}^s(D_s^- \pi^+)$$

Conclusions

Summary

- **Wide span of colour-allowed trees at LHCb**

- **Variety of measurements, e.g.:**
  - BF, amplitude ratio $r_{D\pi}$, constraint on $|a_{NF}|$
  - Hadronization fraction f_s/f_d, very precise BF
  - Oscillation frequency Δm_s, constraint on $b\bar{s}$ coupling

- **Systematics and inputs often limiting**

- **Strong/important interplay between theory and experiment**

- **Excited for discussions**

BackUp

[*Phys. Rev. D* 104 (2021) 032005]