First observation and branching fraction measurement of the $\Lambda_b^0 \to D_s^- p$ decay

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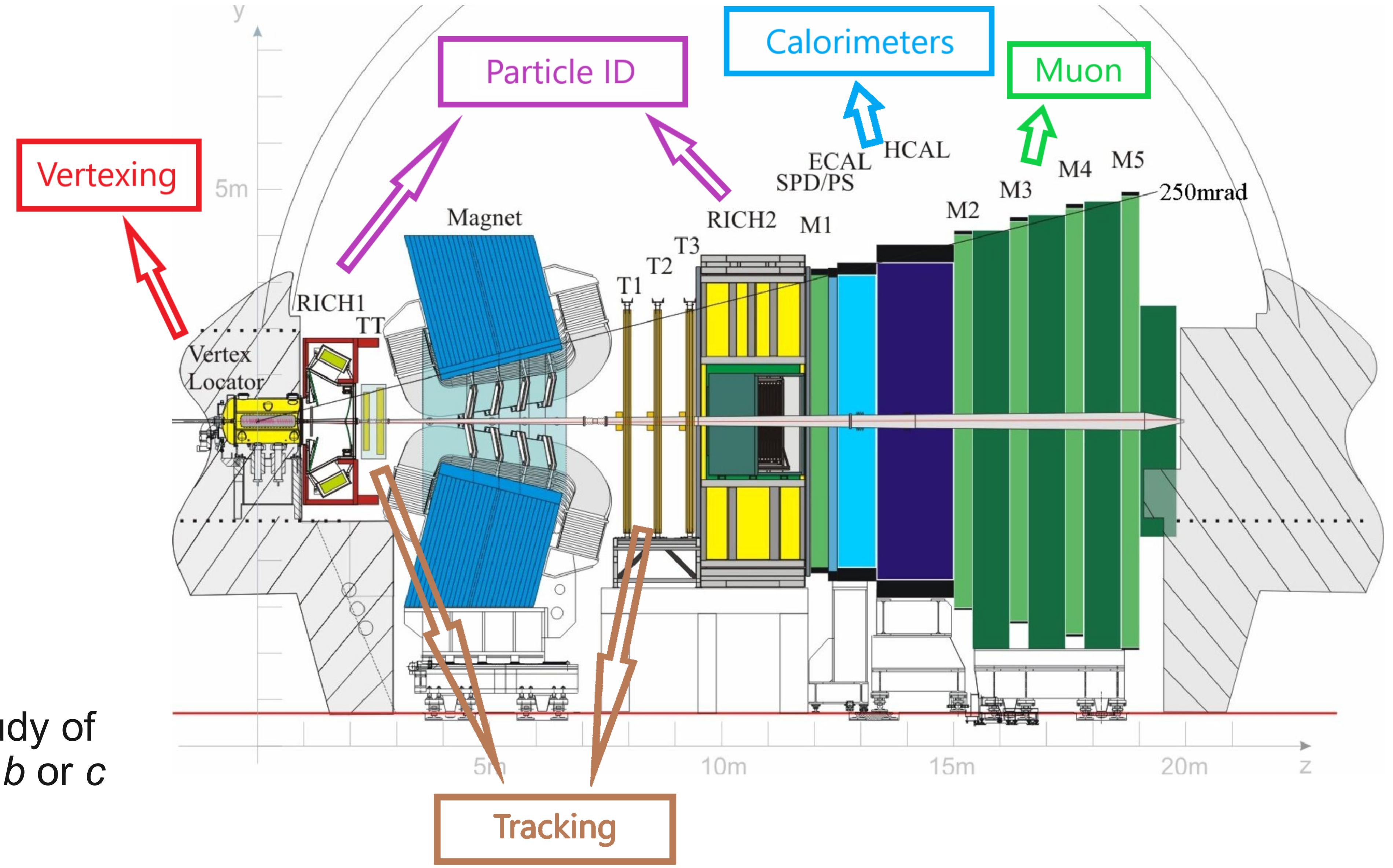
[arXiv:2212.12574]

LHCb

LHCb detector structure in yz plane, operational for Run1 and Run2

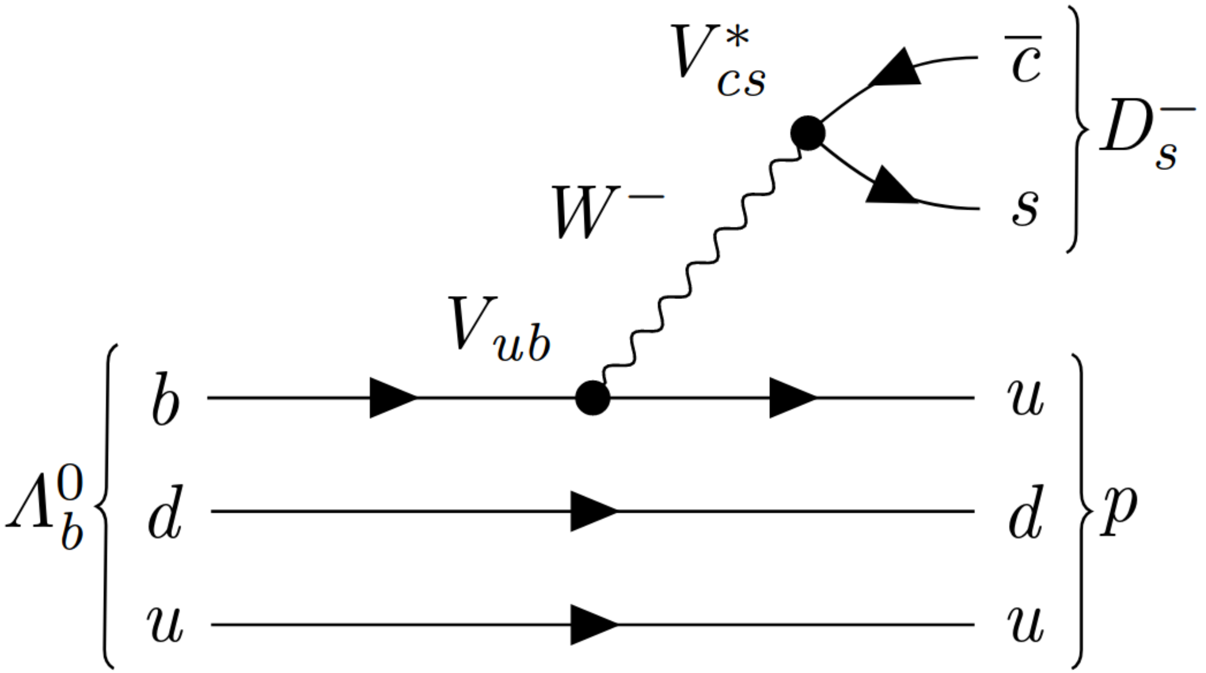
- Single-arm forward spectrometer
- $2 < \eta < 5$
- Designed for the study of particles containing *b* or *c* quarks



Introduction

Motivation

- $\Lambda_b^0 \to D_s^- p$ not yet observed
- Background in CKM γ angle measurement using $B_s^0 \to D_s^{\mp} K^{\pm}$ decays
- Hadronic decay probing amplitude of $b \to u$ transition
  - Only first order diagram
- $\mathcal{B}(\Lambda_b^0 \to D_s^- p) \propto |V_{ub}|^2 |a_{\mathrm{NF}}(D_s^- p)|^2 |F_{\Lambda_b^0 \to p}|^2 f_{D_s}^2$
  - f_{D_s} Decay constant
  - $F_{\Lambda_b^0 \to p}$ Form factor
  - a_{NF} Non-factorisable effects, due to QCD interactions between D_s meson and a proton
- Similar to $B^0 \to D_s^- \pi^+$ decay [Eur. Phys. J. C 81, 314 (2021)]



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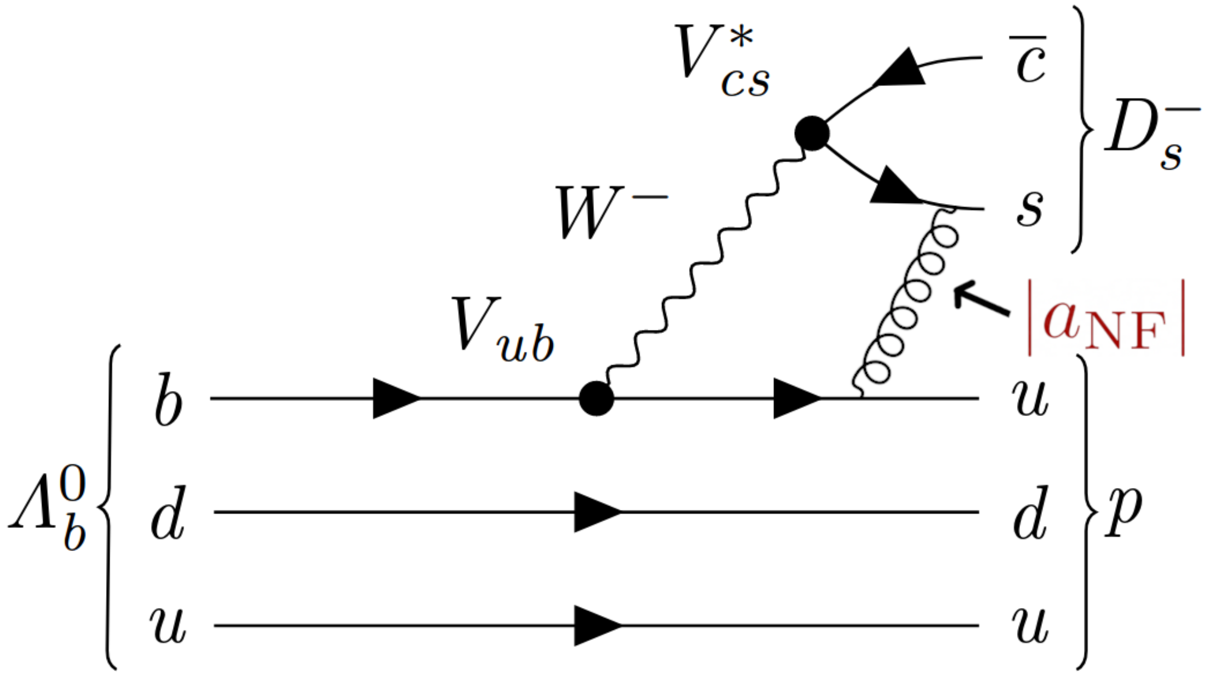


Method of branching fraction determination

- Normalisation channel: $\Lambda_b^0 \to \Lambda_c^+ \pi^-$
  - Topologically similar and high statistics decay

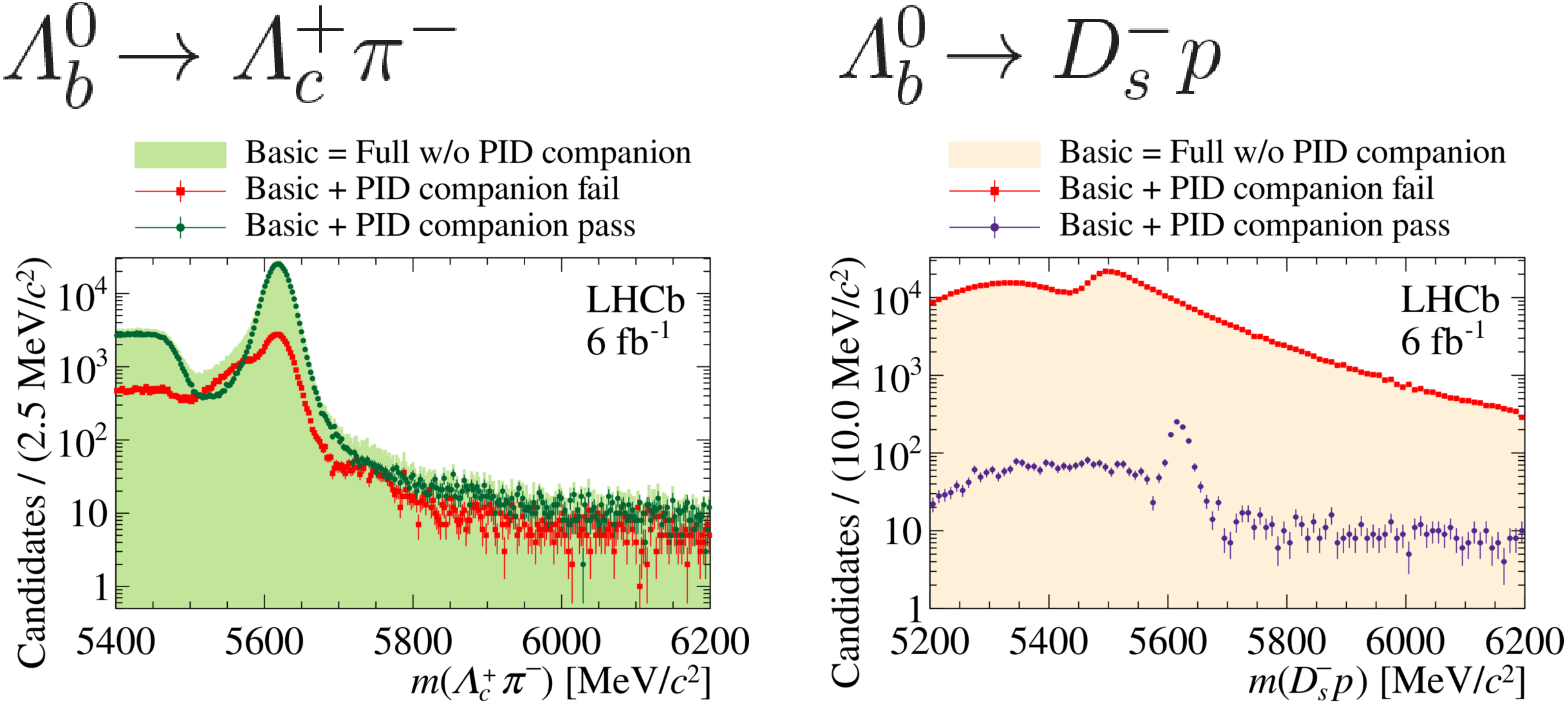
- $$\mathcal{B}(\Lambda_b^0 \to D_s^- p) = \frac{N_{\Lambda_b^0 \to D_s^- p}}{N_{\Lambda_b^0 \to \Lambda_c^+ \pi^-}} \frac{\epsilon_{\Lambda_b^0 \to \Lambda_c^+ \pi^-}}{\epsilon_{\Lambda_b^0 \to D_s^- p}} \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-) \frac{\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)}{\mathcal{B}(D_s^- \to K^- K^+ \pi^-)}$$

- Yields ⇒ Invariant mass fits
- Efficiencies ⇒ Calculate using MC corrected by data
- Branching fractions ⇒ PDG

Event selection

- Full Run 2 data-set (6 fb^{-1}) collected by the LHCb detector
- Preselection of tracks with high transverse momentum
- Good-quality of *b*-hadron and *c*-hadron vertices
- Combinatorial background suppressed by BDTG (Gradient-Boosted Decision Tree). Use of geometrical and kinematic variables like transverse momentum, vertex fit χ^2 and flight distance
- Explicit vetoes of cross-feed backgrounds
- Particle identification (PID) of the final state particles

Selection - particle identification



Selection efficiencies – intermediate results

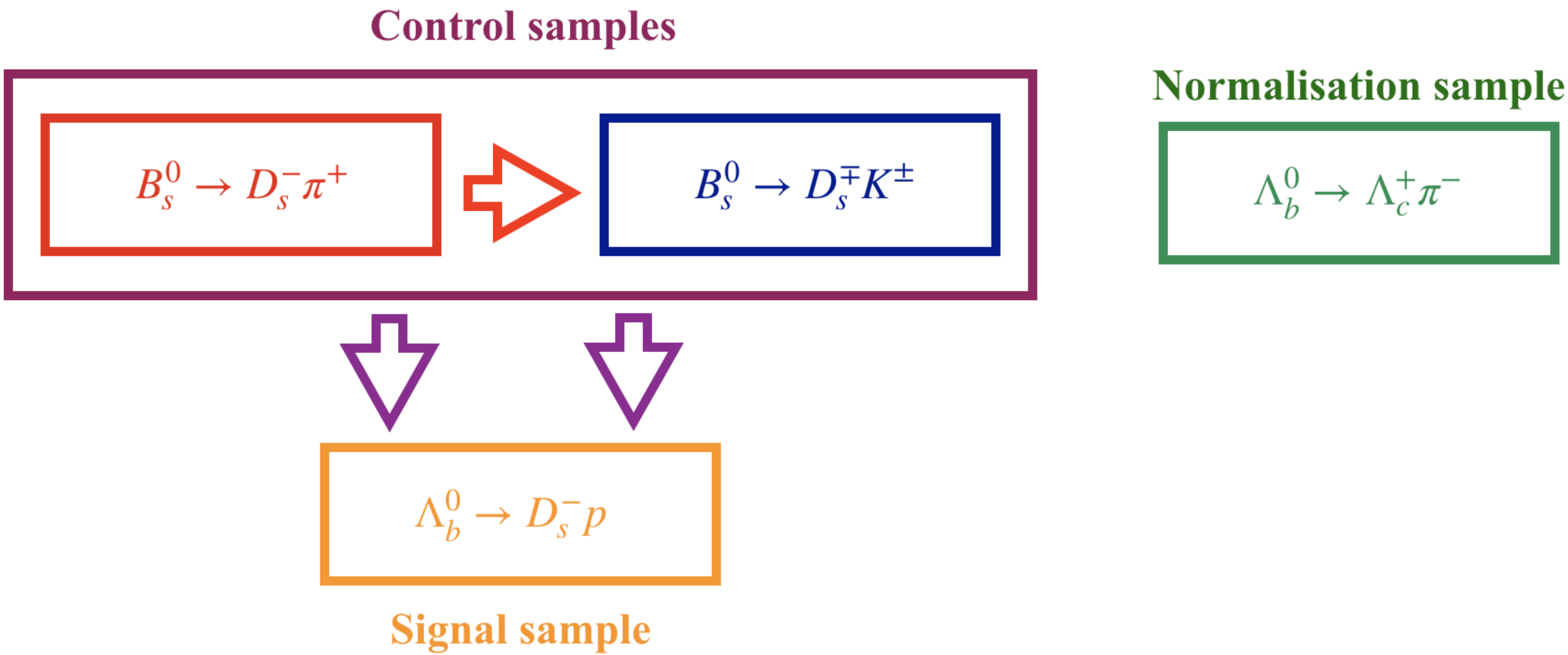
A breakdown of the relative efficiency ratios of the $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ and $\Lambda_b^0 \to D_s^- p$ decays, calculated after applying the preceding requirements.

Requirement	Ratio $\epsilon(\Lambda_b^0 \to \Lambda_c^+ \pi^-)/\epsilon(\Lambda_b^0 \to D_s^- p)$
LHCb acceptance	0.9625 ± 0.0016
Software trigger and preselection	1.1370 ± 0.0026
Kinematic and geometric selection	0.7580 ± 0.0018
Particle identification selection	1.278 ± 0.005
Hardware trigger	0.995 ± 0.006
Total	1.070 ± 0.010

Invariant mass fits

Control samples

- Use control samples to constrain misidentified backgrounds in signal sample

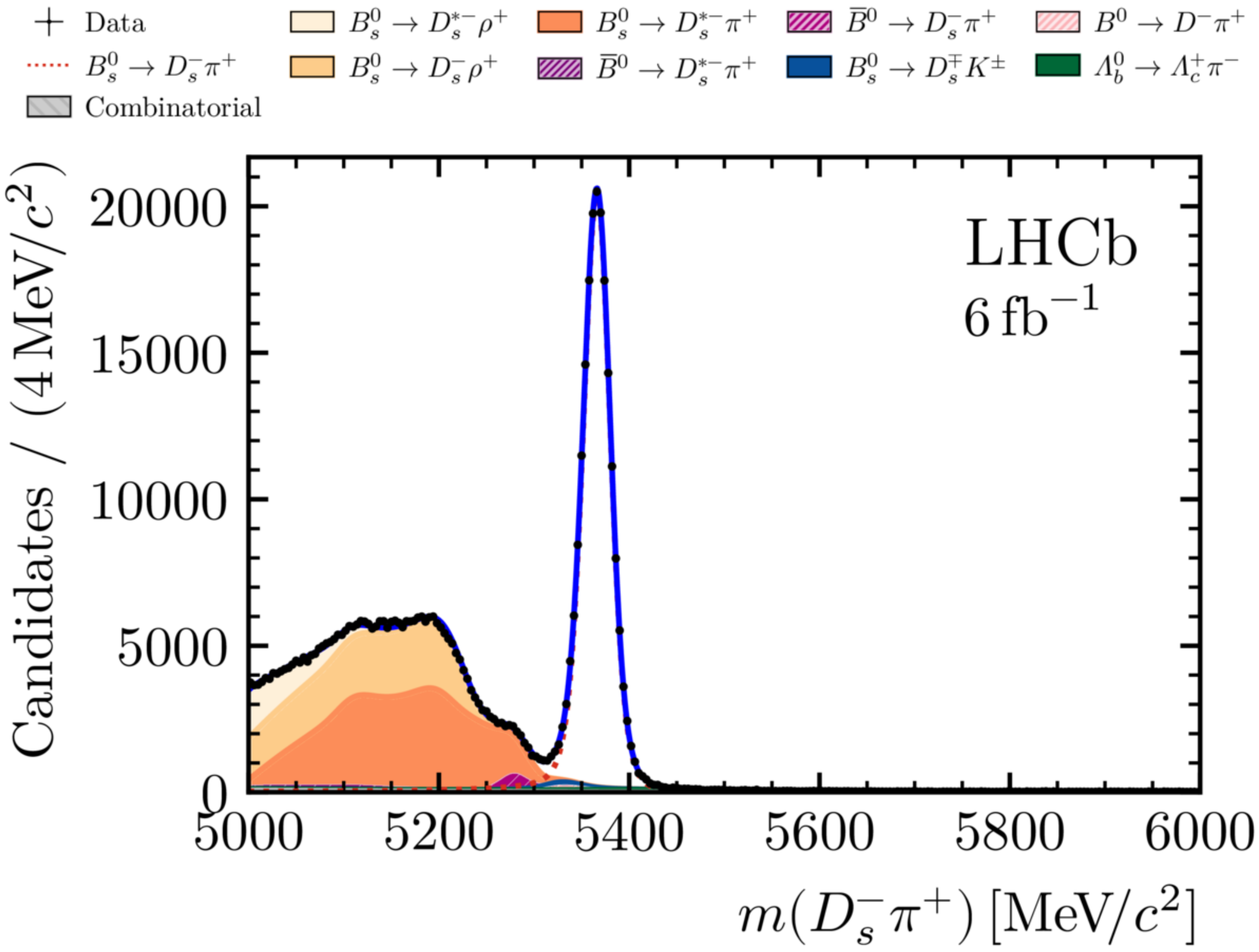


Fit to $\Lambda_b^0 \to D_s^- p$ candidates

Main components:

- $\Lambda_b^0 \to D_s^- p$ signal
- Combinatorial background
- Partially reconstructed background $\Lambda_b^0 \to D_s^{*-} p$
- Misidentified backgrounds
  - $D_s^- \pi^+$-like
    - $B_s^0 \to D_s^- \pi^+$
    - $B_s^0 \to D_s^- \rho^+$
    - $B_s^0 \to D_s^{*-} \pi^+$
    - $B_s^0 \to D_s^{*-} \rho^+$
  - $D_s^- K^+$-like
    - $B_s^0 \to D_s^\mp K^\pm$
    - $B_s^0 \to D_s^{*\mp} K^\pm$
    - $B_s^0 \to D_s^\mp K^{*\pm}$
    - $B_s^0 \to D_s^{*\mp} K^{*\pm}$
    - $B^0 \to D_s^- K^+$
    - $B^0 \to D_s^{*-} K^+$

Fit to $\Lambda_b^0 \to D_s^- p$ candidates - $D_s^- \pi^+$ sample



$D_s^- \pi^+$-like components

Misidentified backgrounds: $D_s^- \pi^+$-like

- Data-driven strategy
- Very clean, high statistic mode
- Same selection except companion PID cut
- Obtained yields of:
  - $B_s^0 \to D_s^- \pi^+$
  - $B_s^0 \to D_s^- \rho^+$
  - $B_s^0 \to D_s^{*-} \pi^+$
  - $B_s^0 \to D_s^{*-} \rho^+$

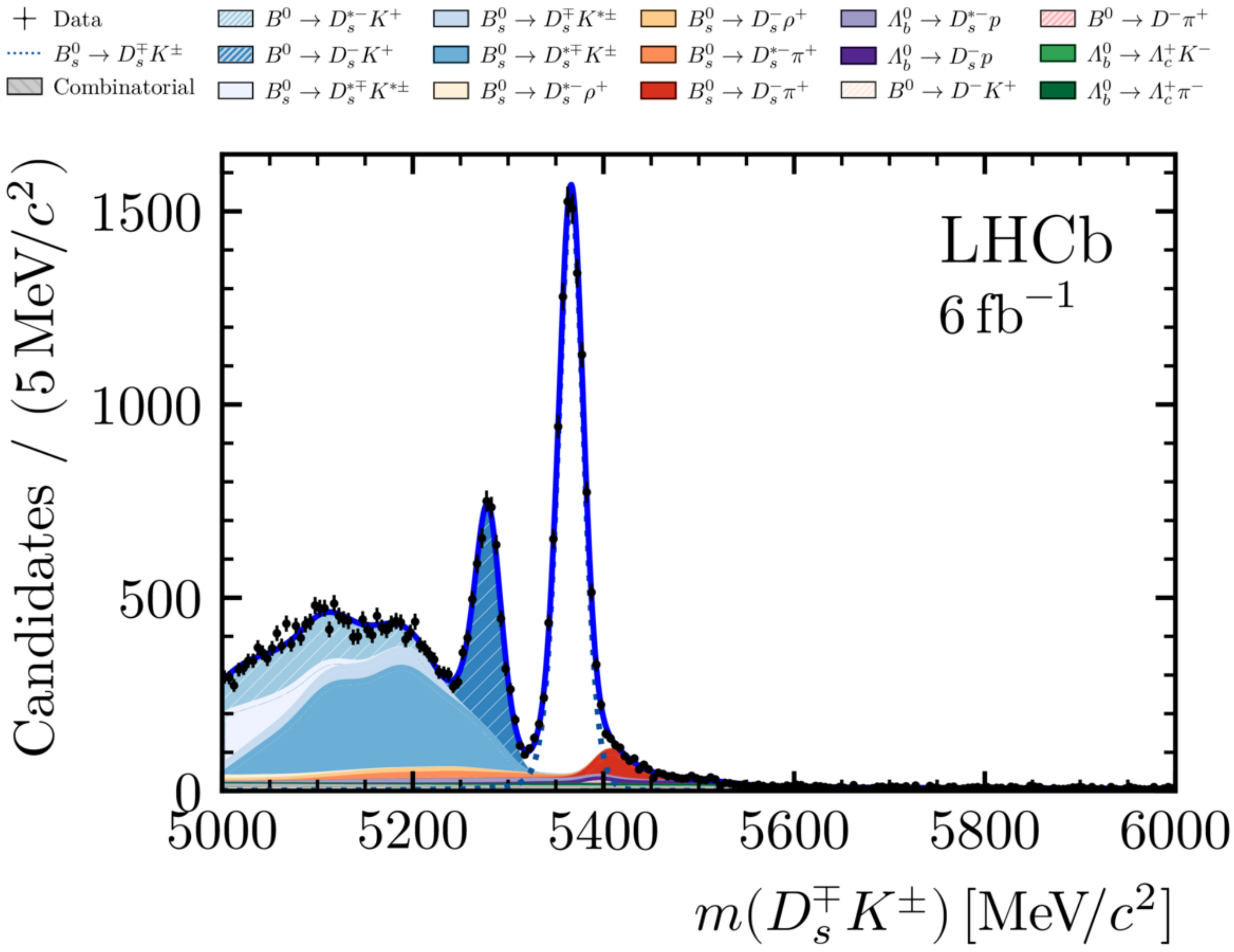
under the $\Lambda_b^0 \to D_s^- p$ hypothesis

Fit to $\Lambda_b^0 \to D_s^- p$ candidates - $D_s^- K^+$ sample

Misidentified backgrounds: $D_s^- K^+$-like

- Data-driven strategy
- Very clean, high statistic mode
- Same selection except companion PID cut
- Obtained yields of:
  - $B_s^0 \to D_s^\mp K^\pm$
  - $B_s^0 \to D_s^{*\mp} K^\pm$
  - $B_s^0 \to D_s^\mp K^{*\pm}$
  - $B_s^0 \to D_s^{*\mp} K^{*\pm}$
  - $B^0 \to D_s^- K^+$
  - $B^0 \to D_s^{*-} K^+$

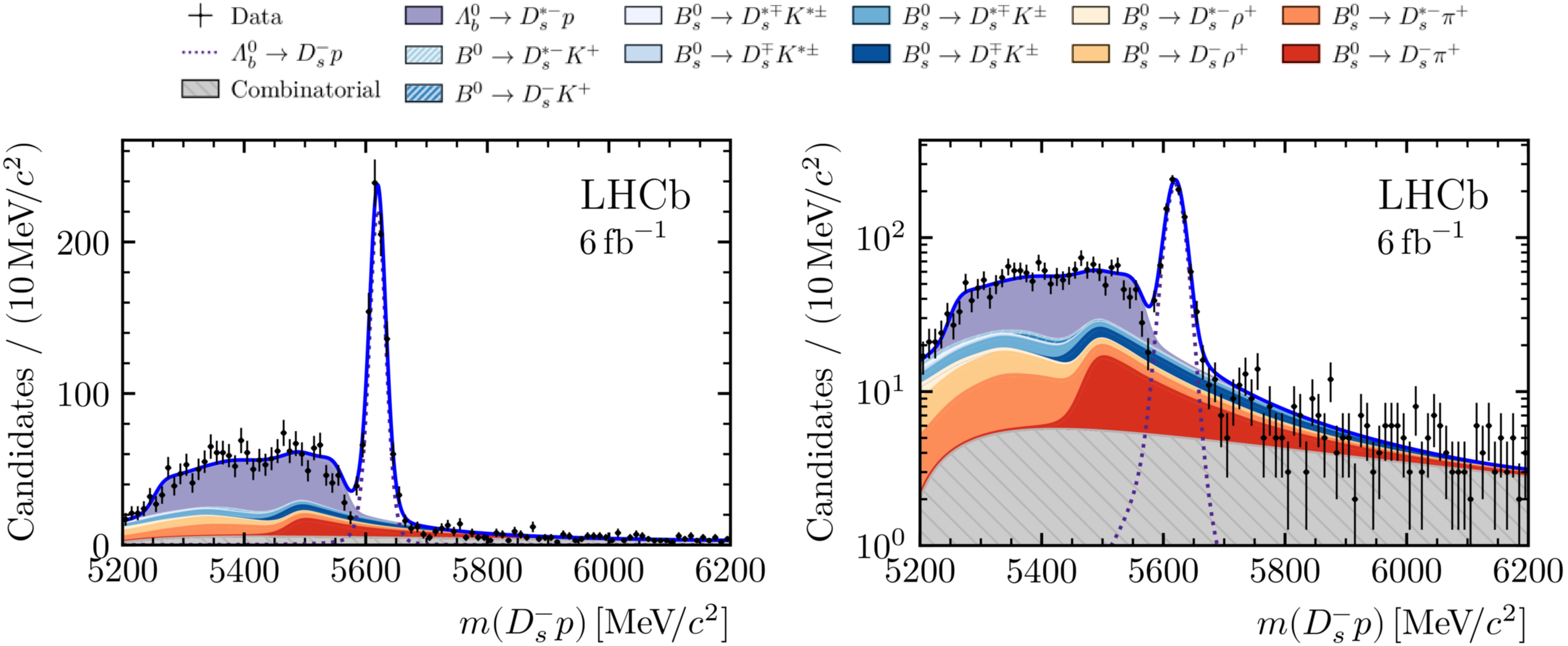
under the $\Lambda_b^0 \to D_s^- p$ hypothesis



$D_s^- K^+$-like components

Fit to $\Lambda_b^0 \to D_s^- p$ candidates - result

- $N_{\Lambda_b^0 \to D_s^- p}$ = 831 ± 32
- **Crystal clear discovery**



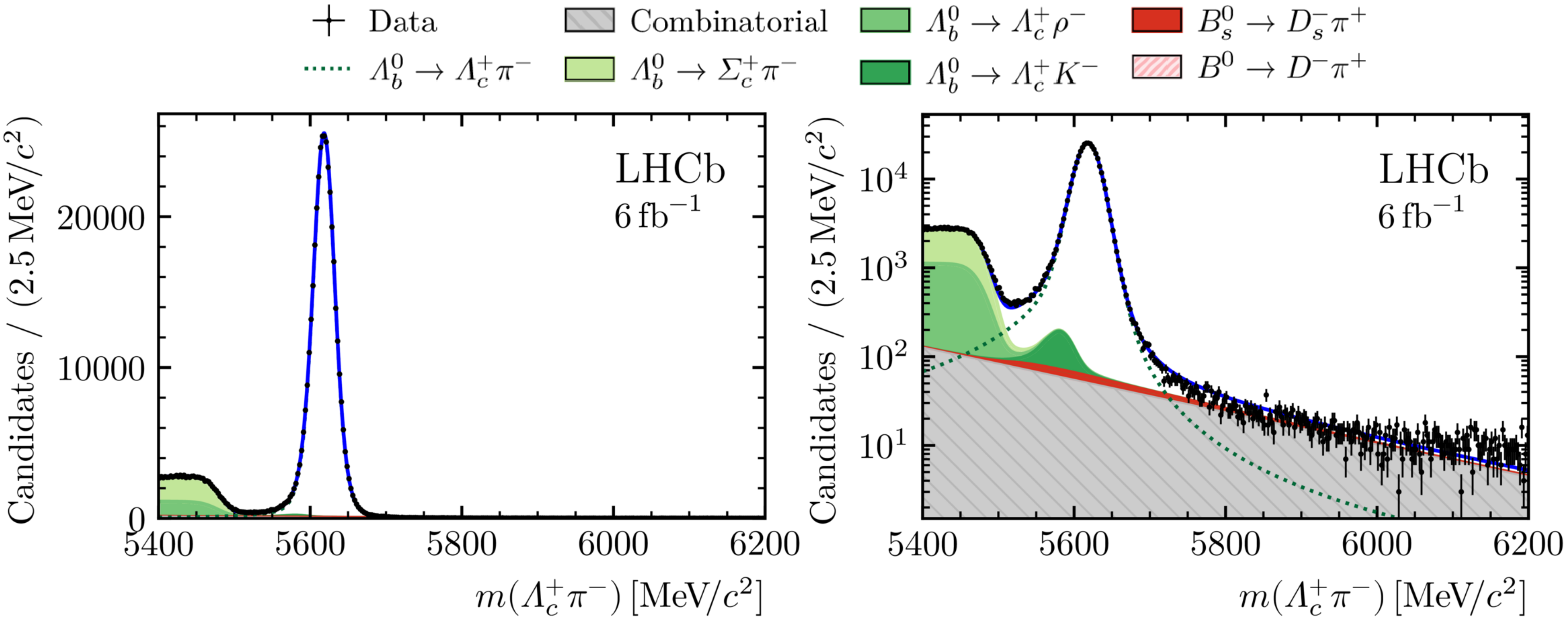
Normalisation channel: fit to $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ candidates

Main components:

- $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ signal
- Combinatorial background
- Partially reconstructed backgrounds
  - $\Lambda_b^0 \to \Lambda_c^+ \rho^-$ and $\Lambda_b^0 \to \Sigma_c^+ \pi^-$
- Misidentified backgrounds
  - $B^0 \to D^- \pi^+$ and $B_s^0 \to D_s^- \pi^+$ yields obtained in a data-driven way
  - $\Lambda_b^0 \to \Lambda_c^+ K^-$ yield calculated using corresponding branching fractions and efficiencies

Fit to $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ candidates - result

- Many signal events!
- $N_{\Lambda_b^0 \to \Lambda_c^+ \pi^-}$ = 404 700 ± 700



Systematic uncertainties

Source	Relative uncertainty (%)
Invariant-mass fits:	
$m(D_s^- p)$ fit:	
Signal parametrisation	0.54
Combinatorial background parametrisation	0.73
Constrained/fixed yields	0.71
Specific background parametrisation	0.89
$m(\Lambda_c^+ \pi^-)$ fit:	
Signal parametrisation	0.27
Combinatorial background parametrisation	0.04
Constrained/fixed yields	0.03
Specific background parametrisation	0.01
Efficiencies:	
PID efficiency	0.49
hardware trigger efficiency	1.15
Reconstruction efficiency	0.50
Total	2.01

Branching fraction result

Reminder (Obtaining the branching fraction)

- $$\mathcal{B}(\Lambda_b^0 \to D_s^- p) = \frac{N_{\Lambda_b^0 \to D_s^- p}}{N_{\Lambda_b^0 \to \Lambda_c^+ \pi^-}} \frac{\epsilon_{\Lambda_b^0 \to \Lambda_c^+ \pi^-}}{\epsilon_{\Lambda_b^0 \to D_s^- p}} \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-) \frac{\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)}{\mathcal{B}(D_s^- \to K^- K^+ \pi^-)}$$
- Yields ⇒ Invariant mass fits
- Efficiencies ⇒ Calculate using MC corrected by data
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Results

Inputs for the branching fraction measurement

	$\Lambda_b^0 \to D_s^- p$	$\Lambda_b^0 \to \Lambda_c^+ \pi^-$
Yield	831 ± 32	$(4.047 \pm 0.007) \times 10^5$
Efficiency	$(0.1819 \pm 0.0013)\%$	$(0.1947 \pm 0.0012)\%$
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)$	$(4.9 \pm 0.4) \times 10^{-3}$	
$\mathcal{B}(D_s^- \to K^- K^+ \pi^-)$	$(5.38 \pm 0.10) \times 10^{-2}$	
$\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)$	$(6.28 \pm 0.32) \times 10^{-2}$	

- $$\frac{\mathcal{B}(\Lambda_b^0 \to D_s^- p)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)} = (2.56 \pm 0.10 \pm 0.05 \pm 0.14) \times 10^{-3}$$
- $$\mathcal{B}(\Lambda_b^0 \to D_s^- p) = (12.6 \pm 0.5 \pm 0.3 \pm 1.2) \times 10^{-6}$$
- **World's first measurement of this branching fraction**

Thank you for your attention!

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Backup

Previous limit for $\Lambda_b^0 \to D_s^- p$ branching fraction:

Γ_{55}	pD_s^-	$< 4.8 \times 10^{-4}$	CL=90%	2364	

$\Gamma(\Lambda_b^0 \to pD_s^-)/\Gamma_{\text{total}}$ $\qquad$ Γ_{55}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$< \mathbf{4.8 \times 10^{-4}}$	90	AAIJ	2014Q	LHCB	pp at 7 TeV

References:

AAIJ 2014Q JHEP 1404 087 Searches for Λ_b^0 and Ξ_b^0 Decays to $K_S^0\, p\pi^-$ and $K_S^0\, pK^-$ Final States with First Observation of the $\Lambda_b^0 \to K_S^0\, p\pi^-$ Decay

Fit to $\Lambda_b^0 \to D_s^- p$ candidates

$\Lambda_b^0 \to D_s^- p$ signal:

- Sum of a double-sided Hypatia and a Johnson S_U distribution

Partially reconstructed background $\Lambda_b^0 \to D_s^{*-} p$:

- Used the sum of a `RooHORNSdini` and a `RooHILLdini` function

Combinatorial background:

- Not exponential
  - Due to changed mass hypothesis of companion $\pi^+ \to p$
- Described by `RooDstD0BG`:

$$\mathcal{C}(m|m_0, A, C) = (1 - exp(-\frac{m-m_0}{C})) \times (\frac{m}{m_0})^A$$

- Exponential used for determination of systematic uncertainty

Johnson S_U function:

Having defined the following parameters:

$$w = e^{\tau^2}$$

$$\omega = -\nu\tau,$$

$$c(\nu,\tau) = \frac{1}{\sqrt{\frac{1}{2}(w-1)\left(w\cosh 2\omega + 1\right)}} \,,$$

$$z(m|\mu,\sigma,\nu,\tau) = \frac{m - \left(\mu + c(\nu,\tau) + \sigma\sqrt{w}\sinh\omega\right)}{c\sigma} \,,$$

$$r(m|\mu,\sigma,\nu,\tau) = -\nu + \frac{\sinh^{-1} z(m|\mu,\sigma,\nu,\tau)}{\tau} \,,$$

where m is the observable, the Johnson S_U function is expressed as follows:

$$J(m|\mu,\sigma,\nu,\tau) \propto \frac{1}{2\pi c(\nu,\tau)\sigma} e^{-\frac{1}{2}r(m|\mu,\sigma,\nu,\tau)^2} \frac{1}{\tau\sqrt{z(m|\mu,\sigma,\nu,\tau)^2+1}} \,.$$

Double-sided Hypatia:

Having defined:

$$h(m|\mu,\sigma,\lambda,\zeta,\beta) \propto \left((m-\mu)^2 + A_\lambda^2(\zeta)\sigma^2\right)^{\frac{1}{2}\lambda-\frac{1}{4}} e^{\beta(m-\mu)} K_{\lambda-\frac{1}{2}}\left(\zeta\sqrt{1+\left(\frac{m-\mu}{A_\lambda(\zeta)\sigma}\right)^2}\right) \,,$$

where m is the observable and $(\mu,\sigma,\lambda,\zeta,\beta)$ denotes the set of parameters. Knowing that the first derivative with respect to m is given as h', the double-sided Hypatia function H is expressed as follows:

$$H(m|\mu,\sigma,\lambda,\zeta,\beta,a_1,n_1,a_2,n_2) \propto$$
$$\begin{cases} h(m|\mu,\sigma,\lambda,\zeta,\beta), & \text{if } \frac{m-\mu}{\sigma} > -a_1 \text{ or } \frac{m-\mu}{\sigma} < a_2 \,, \\ \frac{h(m|\mu-a_1\sigma,\mu,\sigma,\lambda,\zeta,\beta)}{\left(1-m/\left(n\frac{h(m|\mu-a_1\sigma,\mu,\sigma,\lambda,\zeta,\beta)}{h'(m|\mu-a_1\sigma,\mu,\sigma,\lambda,\zeta,\beta)}-a_1\sigma\right)\right)^{n_1}}, & \text{if } \frac{m-\mu}{\sigma} \leq -a_1 \,, \\ \frac{h(m|\mu-a_2\sigma,\mu,\sigma,\lambda,\zeta,\beta)}{\left(1-m/\left(n\frac{h(m|\mu-a_2\sigma,\mu,\sigma,\lambda,\zeta,\beta)}{h'(m|\mu-a_2\sigma,\mu,\sigma,\lambda,\zeta,\beta)}-a_2\sigma\right)\right)^{n_2}}, & \text{if } \frac{m-\mu}{\sigma} \geq a_2 \,. \end{cases}$$

The K_λ functions are special Bessel functions of third kind, whereas A_λ is defined as:

$$A_\lambda^2 = \frac{\zeta K_\lambda(\zeta)}{K_{\lambda+1}(\zeta)} \,.$$

HORNSdini and HILLdini:

The HORNSdini and HILLdini PDFs are defined as

$$\texttt{RooHORNSdini}(\mu|a,b,\xi,\sigma,f_g,R_g) = \int_a^b \left(x - \frac{a+b}{2}\right)^2 D(x|\mu,\sigma,f_g,R_\sigma)\left(\frac{1-\xi}{b-a}x + \frac{b\xi - a}{b-a}\right) dx \ ,$$

$$\texttt{RooHILLdini}(\mu|a,b,\xi,\sigma,f_g,R_g) = \int_a^b -(x-a)(x-b) D(x|\mu,\sigma,f_g,R_\sigma)\left(\frac{1-\xi}{b-a}x + \frac{b\xi - a}{b-a}\right) dx \ ,$$

where $D(x|\mu,\sigma,f_g,R_\sigma)$ is a double Gaussian function defined as

$$D(x|\mu,\sigma,f_g,R_\sigma) = G(x|\mu,\sigma) + f_g G(x|\mu,R_\sigma\sigma) \ .$$