Branching fraction measurement of $B^0 \to D_s^+ \pi^-$

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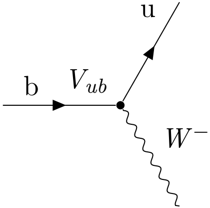
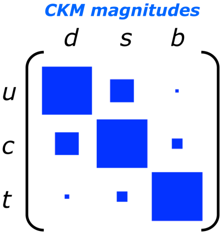
CKM matrix

- The Cabibbo-Kobayashi-Maskawa (CKM) Matrix gives the coupling strength of quark transitions

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & \boldsymbol{V_{ub}} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

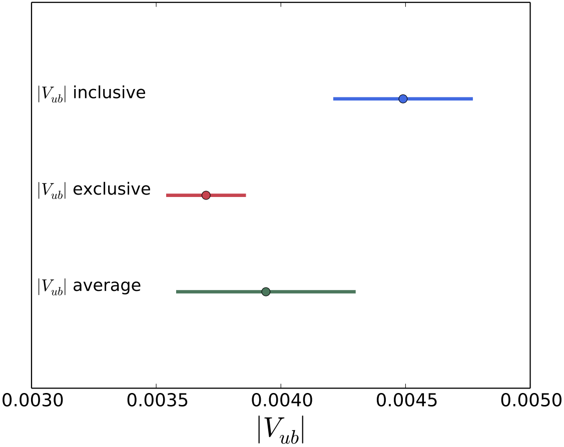
- Why is this matrix close to diagonal?
- Why do we have three generations of quarks?





CKM element $|V_{ub}|$

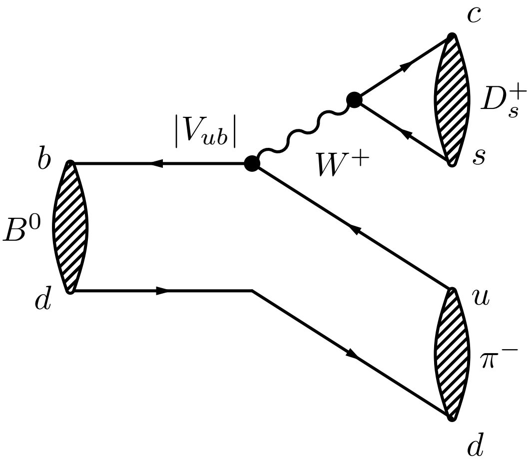
- V_{ub} CKM element with largest uncertainty
- Discrepancy between inclusive and exclusive measurements
    - Inclusive ⇒ $B \to X_u l \bar{\nu}_l$ decays
    - Exclusive ⇒ Specific decays (e.g. $B^0 \to \pi^- l^+ \nu$)
- More measurements help in solving this issue
    - This analysis: $B^0 \to D_s^+ \pi^-$



Motivation

Probing $|V_{ub}|$

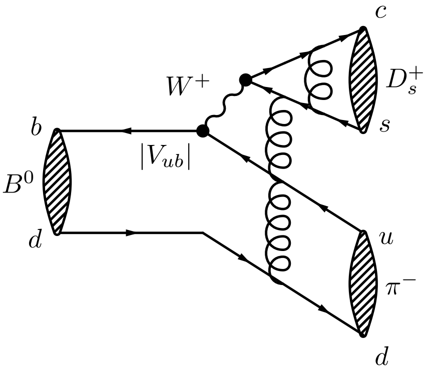
- This analysis looks at a hadronic decay probing the $b \to u$ quark transition
- Only first order tree diagram
- $\mathcal{B}(B^0 \to D_s^+ \pi^-) \propto |V_{ub}|^2$



Motivation

Probing $|a_{\mathrm{NF}}|$

- Hadronic decay → QCD important
- Known:
    - Form factor $F(B^0 \to \pi^-)$
    - Decay Constant: f_{D_s}
- Unknown:
    - Non-factorisation constant $|a_{\mathrm{NF}}(D_s^+\pi^-)|$
- $\mathcal{B}(B^0 \to D_s^+\pi^-) \propto |V_{ub}|^2 |a_{\mathrm{NF}}|^2 |F(B^0 \to \pi^-)|^2 f_{D_s}^2$



Motivation

Other motivations

Determining $r_{D\pi}$

The parameter

$$r_{D\pi} = \left| \frac{A(B^0 \to D^+\pi^-)}{A(B^0 \to D^-\pi^+)} \right|,$$

is necessary ingredient for CP asymmetry measurements in $B^0 \to D^\mp\pi^\pm$ decays. Assuming SU(3) flavour symmetry,

$$r_{D\pi} = \tan\theta_c \frac{f_{D^+}}{f_{D_s}} \sqrt{\frac{\mathcal{B}(B^0 \to D_s^+\pi^-)}{\mathcal{B}(B^0 \to D^-\pi^+)}}.$$

f_s/f_d dependence on collision energy

- Side result: relative event yield B^0/B_s^0
- Use data with collision energies of 7/8 TeV and 13 TeV to find out

$$\frac{f_s/f_d|_{\sqrt{s}=13\,\text{TeV}}}{f_s/f_d|_{\sqrt{s}=7/8\,\text{TeV}}}$$

- f_s/f_d is crucial for **all** B_s^0 branching fraction measurements at LHCb, most notably the famous $B_s^0 \to \mu^-\mu^+$

Strategy

How to calculate $\mathcal{B}(B^0 \to D_s^+\pi^-)$

- Branching fraction $\propto$ yield
- Normalisation channel $B^0 \to D^-\pi^+$ used
  - Unknown B^0 production
  - Topological similar to $B^0 \to D_s^+\pi^-$
  - Small uncertainty

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

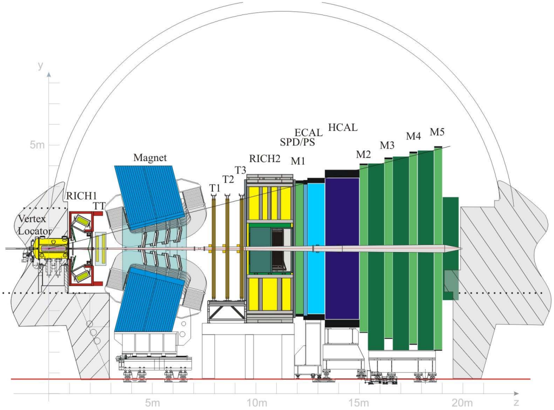
- My job:

$\Rightarrow$ Fit yields → Invariant mass fits

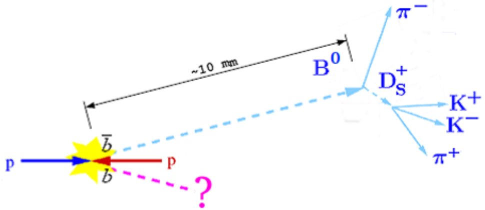
$\Rightarrow$ Determine efficiencies → Obtain from simulation

Detector

LHCb detector



Cross-section of the LHCb detector

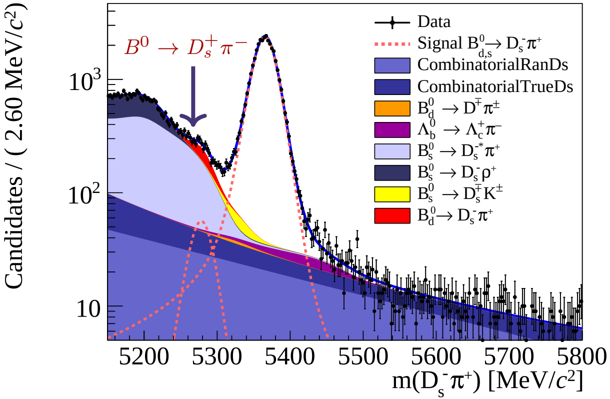


Decay signature $B^0 \to D_s^+ \pi^-$

Strategy

The $B^0 \to D_s^+\pi^-$ signal

- $B^0 \to D_s^+\pi^-$ signal is relatively small
- Need to control:
  - $B_s^0 \to D_s^-\pi^+$ shape
  - Partially reconstructed backgrounds
  - Misidentified backgrounds
  - Combinatorial background

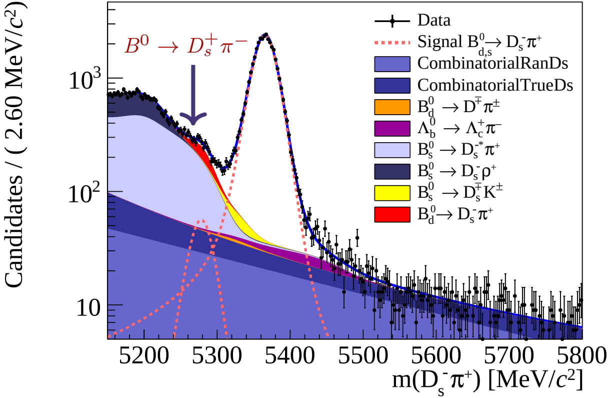


$D_s^+\pi^-$ data after full selection

Strategy

The $B^0 \to D_s^+\pi^-$ signal

- $B^0 \to D_s^+\pi^-$ signal is relatively small
- Need to control:
  - $\Rightarrow$ $\boldsymbol{B_s^0 \to D_s^-\pi^+}$ **shape**
    - Partially reconstructed backgrounds
    - Misidentified backgrounds
    - Combinatorial background

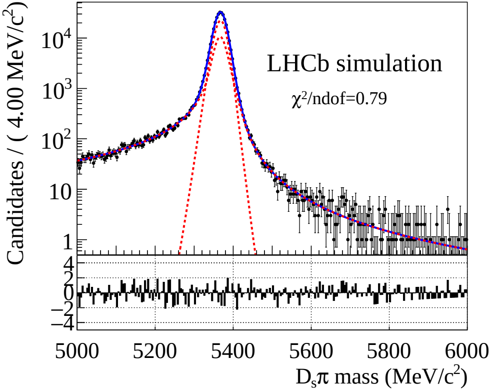


$D_s^+\pi^-$ data after full selection

Analysis steps

Signal shape

- Important to describe $B_s^0 \rightarrow D_s^- \pi^+$ accurately
- Fit to simulations of $B^0 \rightarrow D^- \pi^+$ and $B_s^0 \rightarrow D_s^- \pi^+$
  - Use normalisation channel $B^0 \rightarrow D^- \pi^+$ to check simulation/data differences and constrain $B_s^0 \rightarrow D_s^- \pi^+$ shape in data
  - Focus on left tail

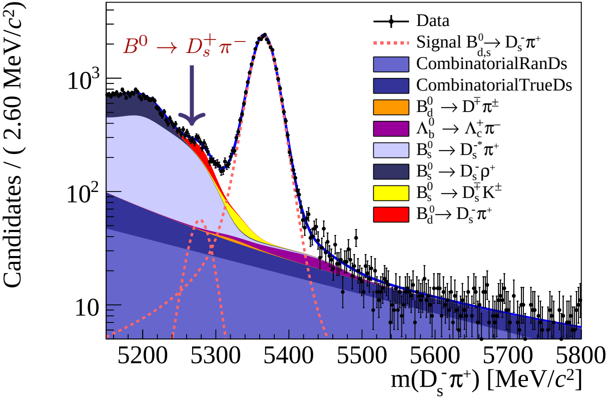


Fit to simulated $B_s^0 \rightarrow D_s^- \pi^+$ events

Analysis steps

Partially reconstructed backgrounds

- $B^0 \to D_s^+\pi^-$ signal is relatively small
- Need to control:
  - $B_s^0 \to D_s^-\pi^+$ shape
  - $\Rightarrow$ **Partially reconstructed backgrounds**
  - Misidentified backgrounds
  - Combinatorial background



$D_s^+\pi^-$ data after full selection

Analysis steps

Partially reconstructed backgrounds

- Excited state of D_s^+ meson or pion
- Describing the tails of these backgrounds correctly is crucial
- Analytical shape obtained from simulation fits
- Normalisation channel $B^0 \to D^-\pi^+$ to investigate simulation/data difference in resolution

In signal fit

- $B_s^0 \to D_s^{*-}\pi^+$ $(D_s^{*-} \to D_s^-\gamma/\pi^0)$
- $B_s^0 \to D_s^-\rho^+$ $(\rho^+ \to \pi^+\pi^0)$

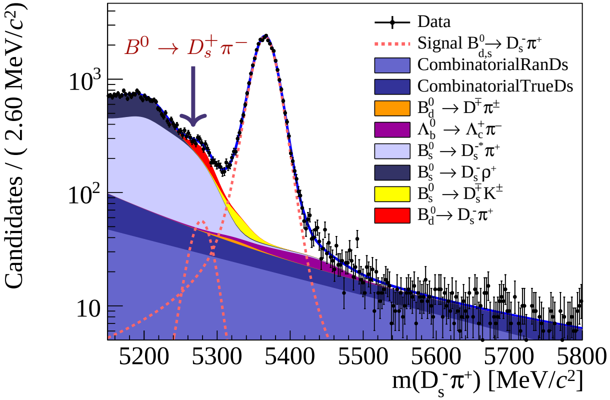
In normalisation channel fit

- $B^0 \to D^{*-}\pi^+$ $(D^{*-} \to D^-\pi^0)$
- $B^0 \to D^-\rho^+$ $(\rho^+ \to \pi^+\pi^0)$

Analysis steps

Misidentified backgrounds

- $B^0 \to D_s^+\pi^-$ signal is relatively small
- Need to control:
  - $B_s^0 \to D_s^-\pi^+$ shape
  - Partially reconstructed backgrounds
  - ⇒ **Misidentified backgrounds**
  - Combinatorial background



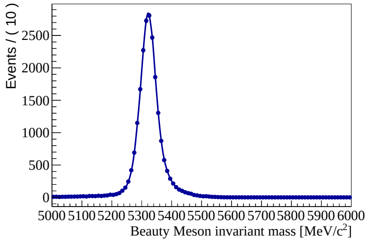
$D_s^+\pi^-$ data after full selection

Analysis steps

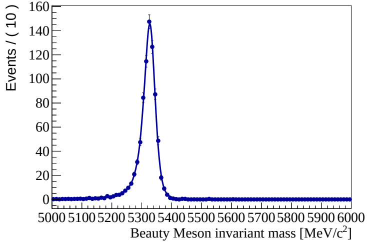
Misidentified backgrounds

- Other decays with one (or more) final-state particles misidentified
- Shape described by simulation
- Relative yields estimated using
    - Branching fractions of decays
    - Relative production B^0 and B_s^0 mesons
    - Efficiencies using simulation
- Relative yields constrained in fit

Misidentified
$B^0 \to D^- \pi^+$
$(D^- \rightsquigarrow D_s^-)$



Misidentified
$B_s^0 \to D_s^- K^+$
$(K^+ \rightsquigarrow \pi^+)$

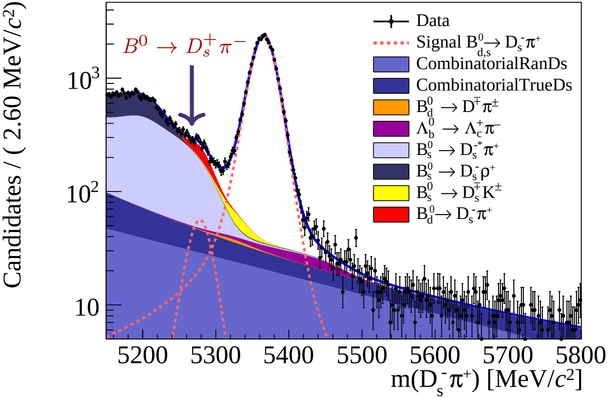


Analysis steps

Combinatorial background

- $B^0 \to D_s^+ \pi^-$ signal is relatively small
- Need to control:
  - $B_s^0 \to D_s^- \pi^+$ shape
  - Partially reconstructed backgrounds
  - Misidentified backgrounds

$\Rightarrow$ **Combinatorial background**



$D_s^+ \pi^-$ data after full selection

Analysis steps

Combinatorial background

- Random combinations of final-state particles of $B^0 \to D_s^+\pi^-(D_s^+ \to K^+K^-\pi^+)$
- Combinatorial background split in two components
- Simultaneous fit to $m(D_s^+\pi^-)$ and $m(K^+K^-\pi^+)$ necessary to separate

Random combinatorial

- Random combinations of final-state particles $K^+K^-\pi^+\pi^-$

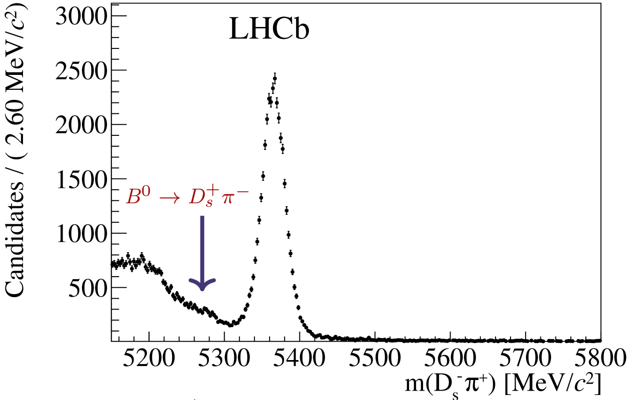
True-D_s^+ combinatorial

- Random combinations of a real D_s^+ meson with π^-

Fits to data

The data

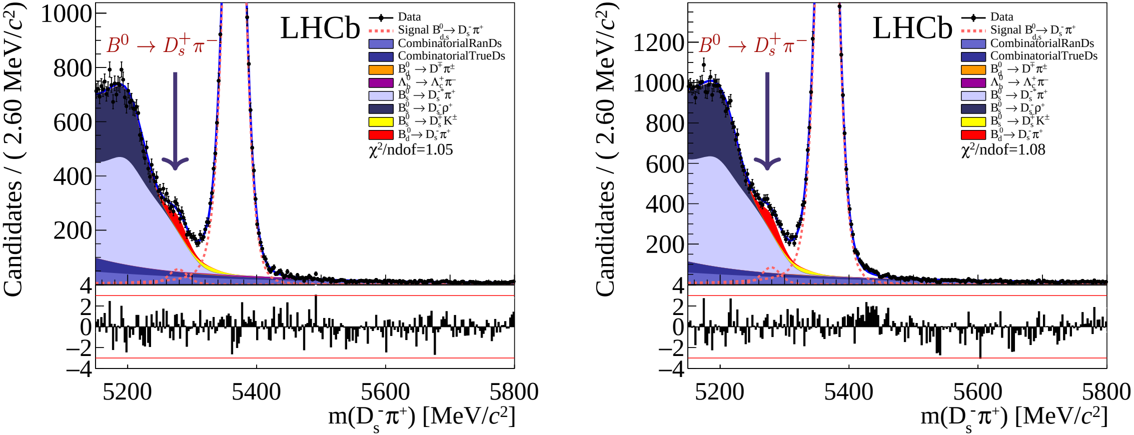
- All backgrounds and signals are studied
- It is time for the invariant mass fit!



$D_s^+\pi^-$ data after full selection

Fits to data

$B^0 \to D_s^+\pi^-$ mass fit



Fit to 2011 + 2012 data

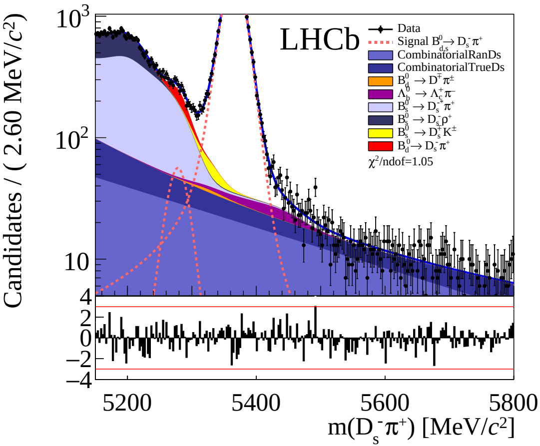
Fit to 2015 + 2016 data

Combined yield:

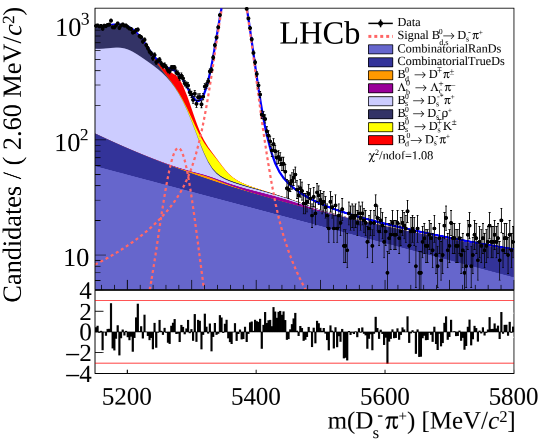
$$N_{B^0 \to D_s^+\pi^-} = 2190 \pm 198$$

Fits to data

$B^0 \to D_s^+ \pi^-$ mass fit



Fit to 2011 + 2012 data



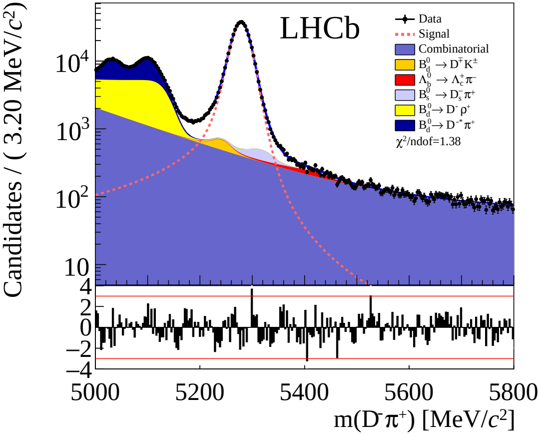
Fit to 2015 + 2016 data

Combined yield:

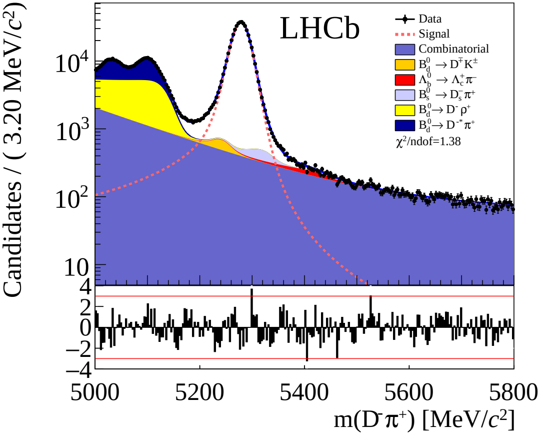
$$N_{B^0 \to D_s^+ \pi^-} = 2190 \pm 198$$

Fits to data

$B^0 \to D^-\pi^+$ mass fit (normalisation channel)



Fit to 2011 + 2012 data



Fit to 2015 + 2016 data

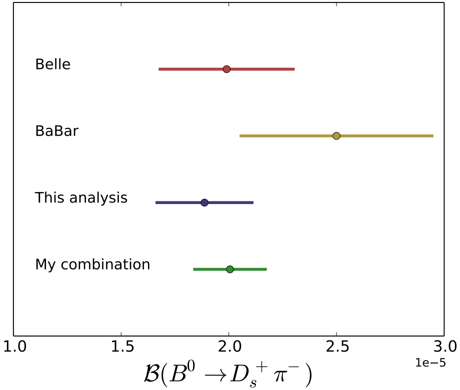
Combined yield:

$$N_{B^0 \to D^-\pi^+} = 1\,133\,035 \pm 2140$$

Results

Branching fraction calculation

- We now have all the ingredients to calculate the branching fraction[1]:
$$\Rightarrow \mathcal{B}(B^0 \rightarrow D_s^+\pi^-) = (18.9 \pm 1.7\,(\text{stat}) \pm 0.9\,(\text{syst}) \pm 1.2\,(\mathcal{B})) \cdot 10^{-6}$$
- Previous results
  - Belle $\Rightarrow \mathcal{B}(B^0 \rightarrow D_s^+\pi^-) = (19.9 \pm 3.2) \cdot 10^{-6}$
  - BaBar $\Rightarrow \mathcal{B}(B^0 \rightarrow D_s^+\pi^-) = (25 \pm 4.5) \cdot 10^{-6}$
- Single most precise measurement so far of this branching fraction



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[1] Details on relative efficiencies and systematic uncertainties are in the backup slides

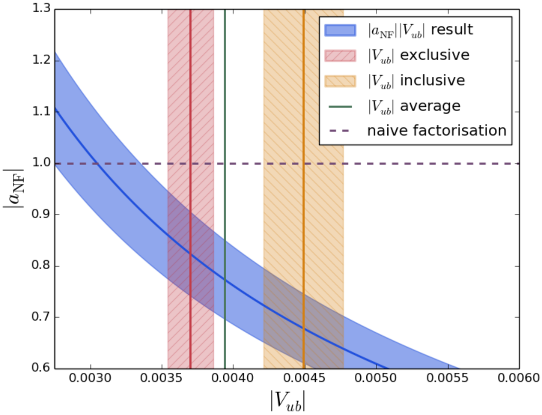
Results

Determination of $|V_{ub}||a_{\rm NF}|$

- Branching fraction probes $|V_{ub}||a_{\rm NF}|$

$$\mathcal{B}(B^0 \to D_s^+\pi^-) \propto |V_{ub}|^2|a_{\rm NF}|^2$$

- $|V_{ub}||a_{\rm NF}| = (3.05 \pm 0.30)\cdot 10^{-3}$
- Using average $|V_{ub}|$
  $\Rightarrow |a_{\rm NF}| = 0.77 \pm 0.10$



Results

Determination of $r_{D\pi}$

- Use branching fraction result:

$$\Rightarrow r_{D\pi} = \tan\theta_c \frac{f_{D^+}}{f_{D_s}} \sqrt{\frac{\mathcal{B}(B^0 \rightarrow D_s^+ \pi^-)}{\mathcal{B}(B^0 \rightarrow D^- \pi^+)}}$$

$$= 0.0168 \pm 0.0011 \pm 0.0034$$

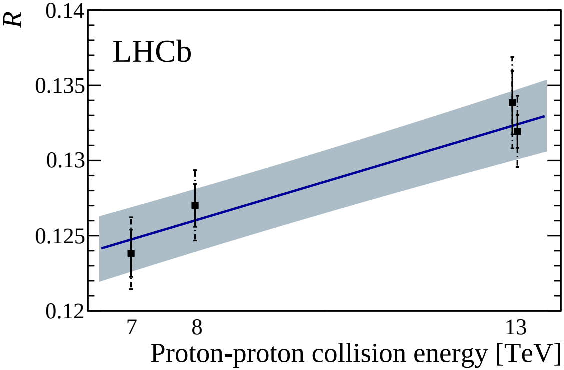
- Necessary for CP asymmetry measurements in $B^0 \rightarrow D^{\mp}\pi^{\pm}$ decays
- Value used in $B^0 \rightarrow D^{\mp}\pi^{\pm}$ analysis (using PDG for inputs) [1]:

$$\Rightarrow r_{D\pi} = 0.0182 \pm 0.0012 \pm 0.0036$$

Results

Hadronisation fraction f_s/f_d collision energy dependence

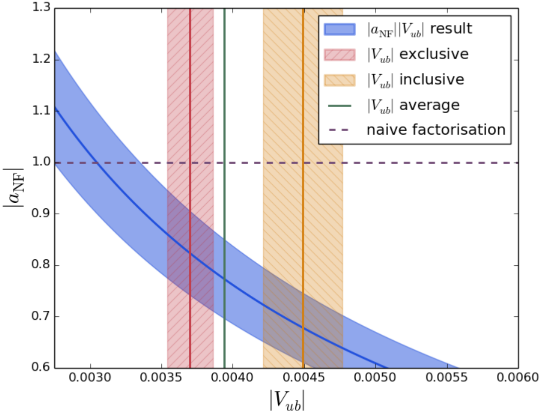
- Using ratio efficiency corrected $B_s^0 \to J/\psi\phi$ and $B^+ \to J/\psi K^+$ yields ($= R$) [2]:
  $\Rightarrow \frac{f_s/f_u|_{\sqrt{s}=13\text{ TeV}}}{f_s/f_u|_{\sqrt{s}=7\text{ TeV}}} = 1.068 \pm 0.016$
- Using my efficiency corrected yields of $B_s^0 \to D_s^-\pi^+$ and $B^0 \to D^-\pi^+$:
  $\Rightarrow \frac{f_s/f_d|_{\sqrt{s}=13\text{ TeV}}}{f_s/f_d|_{\sqrt{s}=7+8\text{ TeV}}} = 1.049 \pm 0.021$
- Relatively more B_s^0 wrt B^0 mesons at higher collision energies



Collision energy dependent hadronisation fraction [2]

Conclusion and outlook

- $B^0 \to D_s^+\pi^-$ is a challenging and interesting decay channel
- Single most precise measurement
  $\Rightarrow \mathcal{B}(B^0 \to D_s^+\pi^-) = (18.9 \pm 2.3) \cdot 10^{-6}$
- Probed $|V_{ub}||a_{\mathrm{NF}}|$
  $\Rightarrow |V_{ub}||a_{\mathrm{NF}}| = (3.05 \pm 0.30) \cdot 10^{-3}$
- Next steps:
  - Publish results



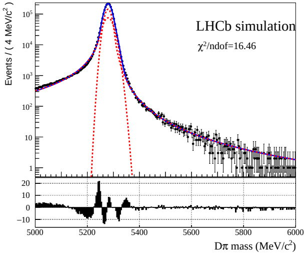
Conclusion

Thanks for your attention!

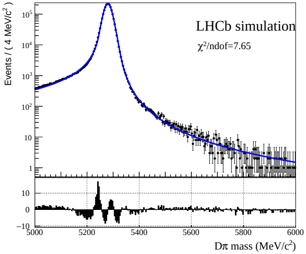
Backup slides

Determining the probability density function ($B^0 \to D^- \pi^+$ MC)

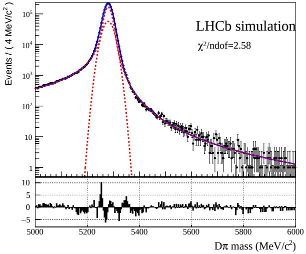
Double
Crystal Ball



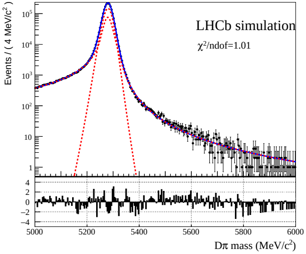
Ipatia



Ipatia plus
Gaussian



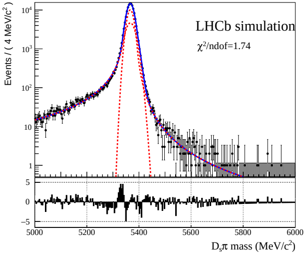
**Ipatia plus
Johnson SU**



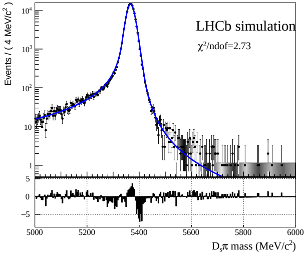
Backup slides

Determining the probability density function ($B_s^0 \to D_s^- \pi^+$ MC)

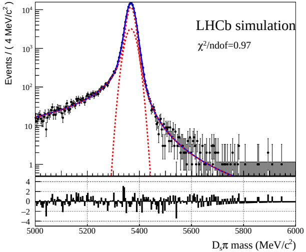
Double
Crystal Ball



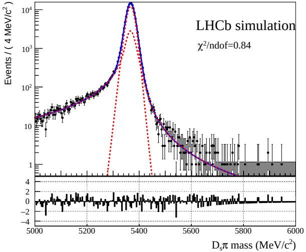
Ipatia



Ipatia plus
Gaussian

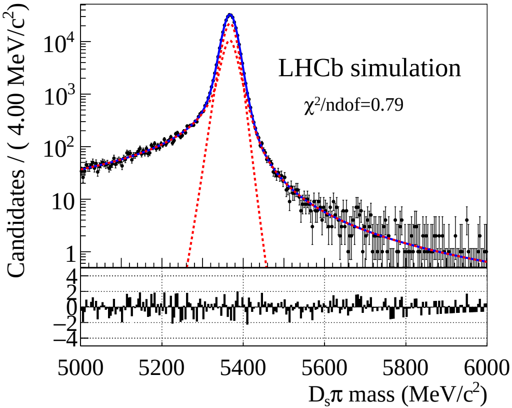


**Ipatia plus
Johnson SU**

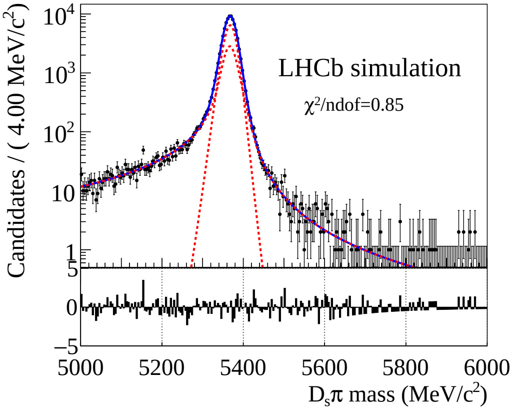


Backup slides

MC fits $B_s^0 \to D_s^- \pi^+$



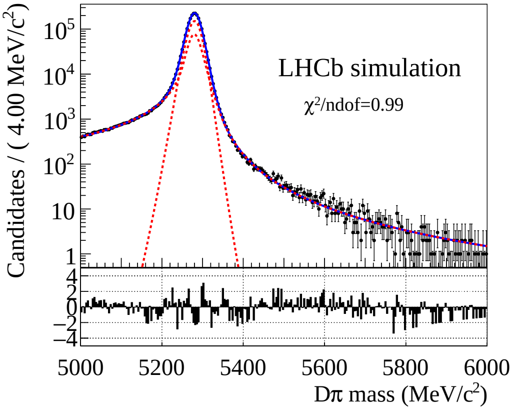
Run 1 fit to $B_s^0 \to D_s^- \pi^+$ MC using an Ipatia plus Johnson SU distribution



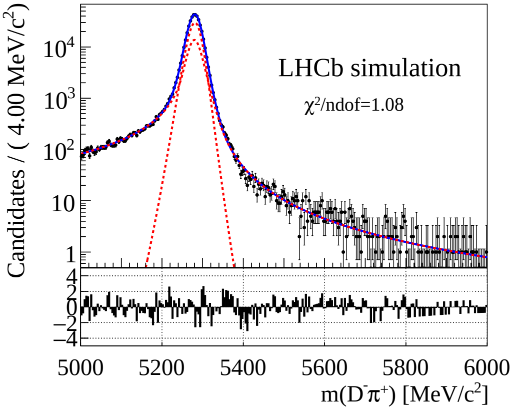
Run 2 fit to $B_s^0 \to D_s^- \pi^+$ MC using an Ipatia plus Johnson SU distribution

Backup slides

MC fits $B^0 \to D^-\pi^+$



Run 1 fit to $B^0 \to D^-\pi^+$ MC using an Ipatia plus Johnson SU distribution



Run 2 fit to $B^0 \to D^-\pi^+$ MC using an Ipatia plus Johnson SU distribution

Backup slides

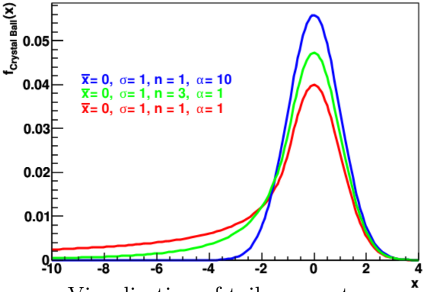
Left tail parameters in signal shape

- Left tail described by parameters a_1 and n_1
    - Found to be very correlated
    - Fix n_1 to $B^0 \to D^- \pi^+$ Run 1 MC result
- Also fixed λ and $\text{frac}_{\text{Ipatia}}$ to $B^0 \to D^- \pi^+$ Run 1 MC result to properly compare fit results
- Use $B^0 \to D^- \pi^+$ as control channel to measure tail in data
- Gaussian Constrain a_1 in $B^0_{(s)} \to D_s^+ \pi^-$ data mass fit:

Run 1	$B^0 \to D^- \pi^+$	$B^0_s \to D_s^- \pi^+$
MC	1.16 ± 0.20	1.20 ± 0.01
Data	0.97 ± 0.02	$\mathbf{1.1 \pm 0.1}^*$

Run 2	$B^0 \to D^- \pi^+$	$B^0_s \to D_s^- \pi^+$
MC	1.14 ± 0.01	1.14 ± 0.02
Data	1.02 ± 0.02	$\mathbf{1.1 \pm 0.1}^*$

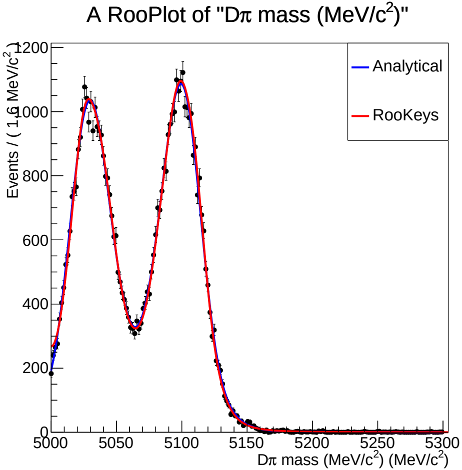
*Value and uncertainty chosen to cover differences MC and data



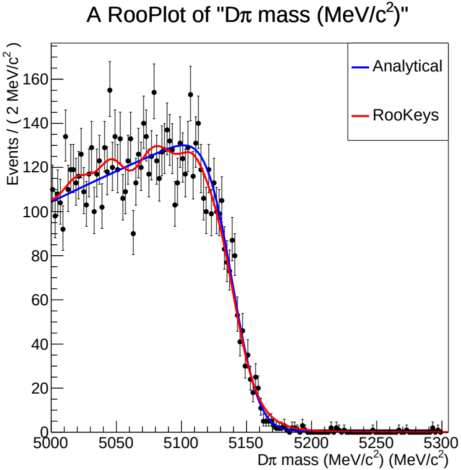
Visualisation of tail parameters

Backup slides

Partially reconstructed backgrounds in $B^0 \to D^- \pi^+$ mass fit



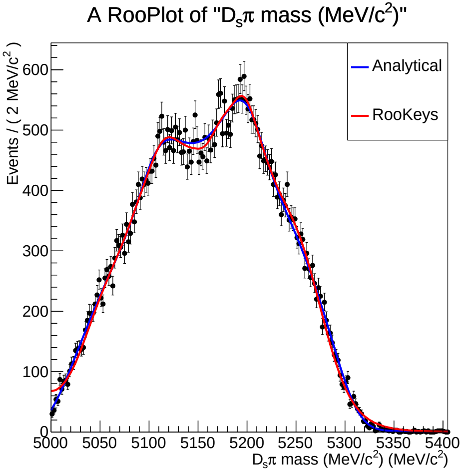
$B^0 \to D^{*-} \pi^+$ MC fits (2012)



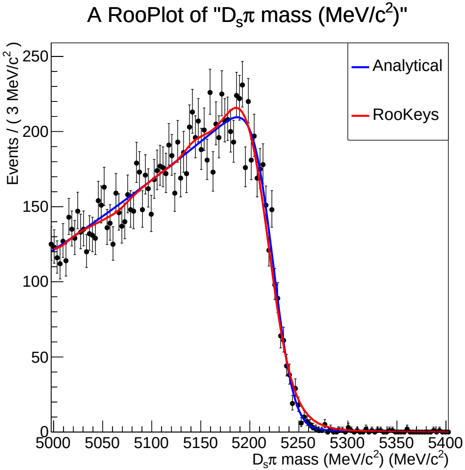
$B^0 \to D^- \rho^+$ MC fits (2012)

Backup slides

Partially reconstructed backgrounds in $B^0_{(s)} \to D_s^- \pi^+$ mass fit



$B^0_s \to D_s^{*-}\pi^+$ MC fits (2012)

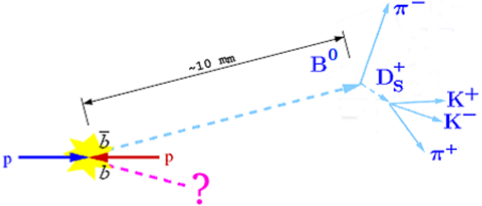


$B^0_s \to D_s^-\rho^+$ MC fits (2012)

Backup slides

Trigger and Stripping

- Trigger selection
  - Hardware trigger → high E_T or p_T
  - Software triggers → (partial) event reconstruction
  - `Hlt1TrackAllL0Decision` *(run1)*
  - `Hlt1TrackMVADecision` *(run2)*
  - `Hlt1TwoTrackMVADecision` *(run2)*
  - `Hlt2IncPhiDecision`
  - `Hlt2Topo2BodyBBDTDecision`
  - `Hlt2Topo3BodyBBDTDecision`
- Stripping → `B02DPiD2HHHBeauty2CharmLine`
  - Stripping versions `21r1`, `21`, `24r1` and `28r1` used



Backup slides

Offline selection

Description	Requirement
BDT value	> 0.1
$m(D_s^- \pi^+)$	$[5150, 5800]$ MeV/c^2
$m(K^- K^+ \pi^-)$	$[1930, 2065]$ MeV/c^2
DLL$_{\mu\pi}$ of companion pion	< 2
DLL$_{K\pi}$ of companion pion	< 0
D_s^- vertex separation χ^2 w.r.t. B_s^0	> 2
D_s^- lifetime w.r.t. B_s^0	> 0 ps
nTracks	$\in [0, 500]$
Momentum final-state particles	$\in [2, 650]$ GeV/c
D^0 veto:	
$m(K^- K^+)$	< 1840 MeV/c^2
D^- veto:	
pion veto, same-charge kaon	DLL$_{K\pi} > 10$
or	
D_s^- under $K^+\pi^-\pi^-$ hypothesis	$\notin [1840, 1900]$ MeV/c^2
Λ_c^+ veto:	
proton veto, same-charge kaon	DLL$_{K\pi}$ − DLL$_{p\pi} > 5$
or	
D_s^- under $pK^-\pi^+$ hypothesis	$\notin [2255, 2315]$ MeV/c^2

Table 1: $D_s^-\pi^+$ fit

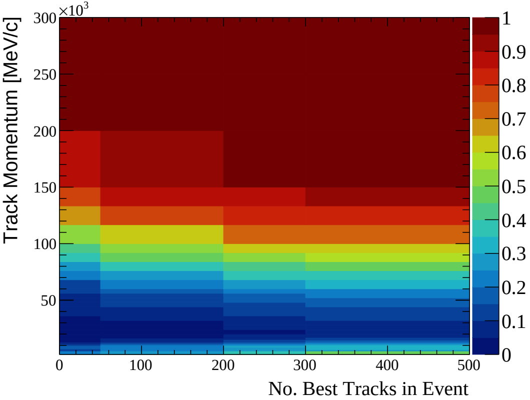
Description	Requirement
BDT value	> 0.1
$m(D^- \pi^+)$	$[5000, 5800]$ MeV/c^2
$m(K^+ \pi^- \pi^-)$	$[1830, 1920]$ MeV/c^2
DLL$_{\mu\pi}$ of companion pion	< 2
DLL$_{K\pi}$ of companion pion	< 0
D^- vertex separation χ^2 w.r.t. B^0	> 9
D^- lifetime w.r.t. B^0	> 0 ps
nTracks	$\in [0, 500]$
Momentum final-state particles	$\in [2, 650]$ GeV/c
Λ_c^+ veto:	
proton veto, pions	DLL$_{p\pi} < 0$
or	
D^- under $pK^-\pi^+$ hypothesis	$\notin [2255, 2315]$ MeV/c^2
D_s^- veto:	
kaon veto, pions	DLL$_{K\pi} < 0$
or	
D^- under $K^-K^+\pi^-$ hypothesis	$\notin [1950, 2030]$ MeV/c^2

Table 2: $D^-\pi^+$ fit

Backup slides

PID calibration

- RICH subdetectors used to assign the variables $\mathrm{DLL}_{K\pi}$, $\mathrm{DLL}_{p\pi}$, $\mathrm{DLL}_{\mu\pi}$ to charged hadrons
- Not well described in MC
- `PIDCalib` → data-driven method to solve this
- MC samples can be reweighted to take PID cuts into account



PID reweighting for $\mathrm{DLL}_{K\pi} > -2$ cut on pion

Backup slides

Fit Results $D_s^- \pi^+$ fit

Parameters	Fit Results		
	Run 1	Run 2	GC
$\mathrm{N}_{B^0 \to D_s^+ \pi^-}$	860 ± 126	1328 ± 153	
$\mathrm{N}_{B_s^0 \to D_s^- \pi^+}$	36517 ± 231	49959 ± 333	
$\mathrm{N}_{\text{RanDs Combinatorial}}$	4347 ± 146	5941 ± 165	
$\mathrm{N}_{\text{TrueDs Combinatorial}}$	2521 ± 492	3057 ± 757	
$\mathrm{N}_{\Lambda_b^0 \to \Lambda_c^+ \pi^-}$	316 ± 37	128 ± 15	✓
$\mathrm{relYield}_{B_s^0 \to D_s^{*-} \pi^+}$	0.456 ± 0.016	0.466 ± 0.014	
$\mathrm{relYield}_{B_s^0 \to D_s^- \rho^+}$	0.208 ± 0.014	0.214 ± 0.012	
$\mathrm{relYield}_{B_s^0 \to D_s^\mp K^\pm}$	0.00845 ± 0.00098	0.0086 ± 0.0011	✓
$B_s^0 \to D_s^- \pi^+$ BeautyMass:			
mean	5364.788 ± 0.097	5365.530 ± 0.084	
σ_I	23.34 ± 0.87	26.4 ± 1.2	
σ_J	17.02 ± 0.28	16.53 ± 0.31	
a_1	1.272 ± 0.070	1.203 ± 0.067	✓
$B_s^0 \to D_s^- \pi^+$ CharmMass:			
mean	1969.704 ± 0.029	1968.822 ± 0.024	
R	1.0463 ± 0.0054	1.0502 ± 0.0051	
RanDs Combinatorial BeautyMass:			
p_1	-0.00383 ± 0.00013	-0.00343 ± 0.00011	
RanDs Combinatorial CharmMass:			
p_1	-0.00656 ± 0.00057	-0.00702 ± 0.00049	
TrueDs Combinatorial BeautyMass:			
p_1	-0.0095 ± 0.0019	-0.0100 ± 0.0023	
f_1	0.782 ± 0.054	0.63 ± 0.10	
TrueDs Combinatorial CharmMass:			
R	1.60 ± 0.19	1.35 ± 0.14	

Backup slides

Efficiencies $B^0 \to D_s^+\pi^-$

	Run 1		Run2	
Cut	ϵ_{rel} (%)	ϵ_{cum} (%)	ϵ_{rel} (%)	ϵ_{cum} (%)
Generator level efficiency	17.368 ± 0.028	17.368 ± 0.028	18.055 ± 0.024	18.055 ± 0.024
Reconstruction and stripping	3.768 ± 0.006	0.6544 ± 0.0015	4.827 ± 0.007	0.8715 ± 0.0017
Trigger cuts	94.26 ± 0.09	0.6169 ± 0.0015	93.82 ± 0.08	0.8176 ± 0.0017
B_s^0 mass window cuts	98.04 ± 0.06	0.6048 ± 0.0015	98.08 ± 0.05	0.8019 ± 0.0018
$D_s^\pm$ mass window cuts	99.26 ± 0.04	0.6003 ± 0.0015	99.15 ± 0.03	0.7951 ± 0.0018
nTracks and Momentum cuts	99.90 ± 0.01	0.5997 ± 0.0015	99.83 ± 0.01	0.7938 ± 0.0018
Vertex separation cuts	88.03 ± 0.14	0.5279 ± 0.0016	85.82 ± 0.12	0.6812 ± 0.0018
Lifetime cut	98.38 ± 0.06	0.5193 ± 0.0016	98.61 ± 0.04	0.6718 ± 0.0018
BDT cuts	96.03 ± 0.09	0.4987 ± 0.0016	97.45 ± 0.06	0.6547 ± 0.0018
$D_s^- \to \phi\pi^-$ mode selection	41.24 ± 0.23	0.2057 ± 0.0013	41.59 ± 0.18	0.2723 ± 0.0014
PID cuts + vetoes	74.12 ± 0.14	0.1524 ± 0.0010	75.34 ± 0.19	0.2051 ± 0.0012

Table 3: Efficiencies $B^0 \to D^-\pi^+$ signal.

Backup slides

Efficiencies $B^0 \to D^-\pi^+$

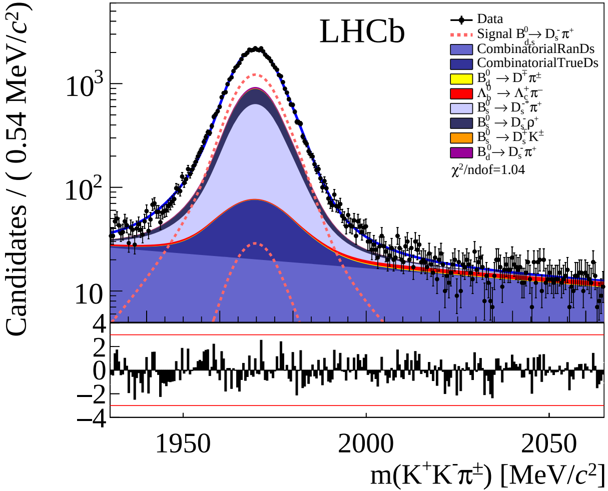
	Run 1		Run2	
Cut	ϵ_{rel} (%)	ϵ_{cum} (%)	ϵ_{rel} (%)	ϵ_{cum} (%)
Generator level efficiency	16.56 ± 0.05	16.56 ± 0.05	17.189 ± 0.024	17.189 ± 0.024
Reconstruction and stripping	3.7343 ± 0.0034	0.6184 ± 0.0020	4.5647 ± 0.0024	0.7846 ± 0.0012
Trigger cuts	94.14 ± 0.05	0.5821 ± 0.0019	96.29 ± 0.03	0.7555 ± 0.0011
B_s^0 mass window cuts	99.35 ± 0.02	0.5784 ± 0.0019	99.30 ± 0.01	0.7502 ± 0.0011
$D_s^\pm$ mass window cuts	98.52 ± 0.03	0.5698 ± 0.0018	98.34 ± 0.02	0.7377 ± 0.0011
nTracks and Momentum cuts	99.91 ± 0.01	0.5693 ± 0.0018	99.86 ± 0.01	0.7367 ± 0.0011
Vertex separation cuts	86.79 ± 0.08	0.4941 ± 0.0017	83.58 ± 0.05	0.6157 ± 0.0010
Lifetime cut	99.93 ± 0.01	0.4937 ± 0.0017	99.94 ± 0.00	0.6154 ± 0.0010
BDT cuts	95.98 ± 0.05	0.4739 ± 0.0016	97.55 ± 0.02	0.6003 ± 0.0010
PID cuts + vetoes	74.93 ± 0.16	0.3551 ± 0.0014	77.00 ± 0.15	0.4622 ± 0.0012

Table 4: Efficiencies $B^0 \to D^-\pi^+$ signal.

Backup slides

$B^0 \to D_s^- \pi^+$ mass fit

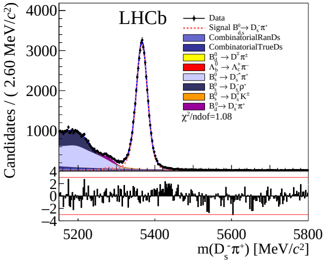
- Run 1 fit (2011+2012)
- Fitted yields, using **all** data:
  - $N_{B^0 \to D_s^+ \pi^-} = 2190 \pm 198$

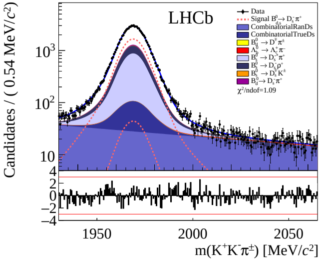


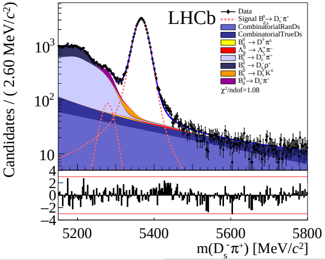
Backup slides

$B^0_{(s)} \to D_s^-\pi^+$ mass fit

- Run 2 fit (2015+2016)
- Fitted yields:
    - $N_{B^0\to D_s^+\pi^-} = 1328 \pm 153$







Backup slides

Systematic Uncertainties (1/2)

- Partially Reconstructed backgrounds
    - Vary resolution of anaytical shapes by ±1.0
    - Run 1 → 4.6%, Run 2 → 4.3%
- PID selection
    - Reduce/increase amount of bins with a third
    - Assign additional uncertainty to $p > 100\,\mathrm{GeV}/c$ and $p > 300\,\mathrm{GeV}/c$ final-state particles
    - 1.1 systematic uncertainty
- Offline selection
    - Compare variables between MC and sWeighted data
    - Reweight variable and check change in efficiency
    - Run 1 → 0.1%, Run 2 → 0.6%

Backup slides

Systematic Uncertainties (2/2)

- L0 trigger efficiency
  - Detection efficiency asymmetry between pions and kaons
  - $\sim 0.2\%$
- MisID backgrounds
  - Free yield of $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ misidentified background in $D_s^+ \pi^-$ fit
  - Run 1 $\to$ 0.6%, Run 2 $\to$ 1.4%
- $B^0 \to D_s^+ \pi^-$ signal width
  - Scale the $B^0 \to D_s^+ \pi^-$ signal width with B^0 and B_s^0 masses
  - Run 1 $\to$ 1.0%, Run 2 $\to$ 1.2%
- Total systematic uncertainty
  - Run 1 $\to$ 4.9%, Run 2 $\to$ 4.8%

Backup slides

Detailed branching fraction results

- We now have all the ingredients to calculate the branching fraction:

	Run 1	Run 2
$\epsilon_{B^0\to D_s^+\pi^-}$ (%)	0.1524 ± 0.0010	0.2051 ± 0.0012
$\epsilon_{B^0\to D^-\pi^+}$ (%)	0.3551 ± 0.0014	0.4622 ± 0.0012
$N_{B^0\to D_s^+\pi^-}$	860 ± 126	1328 ± 153
$N_{B^0\to D^-\pi^+}$	500908 ± 1315	632127 ± 1596

- Result:
  - $\mathcal{B}(B^0 \to D_s^+\pi^-) = (17.2 \pm 2.5\,(\text{stat}) \pm 0.8\,(\text{syst}) \pm 1.1\,(\mathcal{B})) \cdot 10^{-6}$ (Run 1)
  - $\mathcal{B}(B^0 \to D_s^+\pi^-) = (20.3 \pm 2.3\,(\text{stat}) \pm 1.0\,(\text{syst}) \pm 1.3\,(\mathcal{B})) \cdot 10^{-6}$ (Run 2)
  - $\mathcal{B}(B^0 \to D_s^+\pi^-) = (18.9 \pm 1.7\,(\text{stat}) \pm 0.9\,(\text{syst}) \pm 1.2\,(\mathcal{B})) \cdot 10^{-6}$ (Combined)

Backup slides

Fit Results $D_s^+\pi^-$ fit

Parameters	Fit Results		
	Run 1	Run 2	GC
$\mathrm{N}_{B^0\to D_s^+\pi^-}$	860 ± 126	1328 ± 153	
$\mathrm{N}_{B_s^0\to D_s^-\pi^+}$	36517 ± 231	49959 ± 333	
$\mathrm{N}_{\text{RanDs Combinatorial}}$	4347 ± 146	5941 ± 165	
$\mathrm{N}_{\text{TrueDs Combinatorial}}$	2521 ± 492	3057 ± 757	
$\mathrm{N}_{\Lambda_b^0\to \Lambda_c^+\pi^-}$	316 ± 37	128 ± 15	✓
$\mathrm{relYield}_{B_s^0\to D_s^{*-}\pi^+}$	0.456 ± 0.016	0.466 ± 0.014	
$\mathrm{relYield}_{B_s^0\to D_s^-\rho^+}$	0.208 ± 0.014	0.214 ± 0.012	
$\mathrm{relYield}_{B_s^0\to D_s^\mp K^\pm}$	0.00845 ± 0.00098	0.0086 ± 0.0011	✓
$B_s^0 \to D_s^-\pi^+$ BeautyMass:			
mean	5364.788 ± 0.097	5365.530 ± 0.084	
σ_I	23.34 ± 0.87	26.4 ± 1.2	
σ_J	17.02 ± 0.28	16.53 ± 0.31	
a_1	1.272 ± 0.070	1.203 ± 0.067	✓
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mean	1969.704 ± 0.029	1968.822 ± 0.024	
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f_1	0.782 ± 0.054	0.63 ± 0.10	
TrueDs Combinatorial CharmMass:			
R	1.60 ± 0.19	1.35 ± 0.14	

Backup slides

Fit Results $D^-\pi^+$ fit

Parameters	Fit Results		
	Run 1	Run 2	GC
$\mathrm{N}_{B^0\to D^-\pi^+}$	500908 ± 1426	632127 ± 1596	
$\mathrm{N}_{B^0\to D^{*-}\pi^+}$	164612 ± 5744	189315 ± 4391	
$\mathrm{N}_{B^0\to D^-\rho^+}$	169264 ± 6134	235087 ± 4655	
$\mathrm{N}_{\mathrm{Combinatorial}}$	112431 ± 2736	196906 ± 2876	
$\mathrm{relYield}_{B^0\to D^-K^+}$	0.0069 ± 0.0010	0.00679 ± 0.00093	✓
$\mathrm{relYield}_{B_s^0\to D_s^-\pi^+}$	0.00651 ± 0.00084	0.00803 ± 0.00081	✓
$\mathrm{relYield}_{\Lambda_b^0\to \Lambda_c^+\pi^-}$	0.00355 ± 0.00055	0.00243 ± 0.00028	✓
$B^0 \to D^-\pi^+$ BeautyMass:			
mean	5277.758 ± 0.030	5278.046 ± 0.028	
σ_I	27.05 ± 0.44	28.25 ± 0.41	
σ_J	16.91 ± 0.10	17.171 ± 0.090	
a_1	0.974 ± 0.021	1.028 ± 0.019	
Partially reconstructed BeautyMass:			
$\sigma_{B^0\to D^{*-}\pi^+}$	15.65 ± 0.29	15.05 ± 0.21	
$\sigma_{B^0\to D^-\rho^+}$	17.65 ± 0.35	18.15 ± 0.30	
shift	-1.95 ± 0.13	-1.66 ± 0.11	
Combinatorial BeautyMass:			
p_1	-0.00637 ± 0.00012	-0.006132 ± 0.000091	
f_1	0.8619 ± 0.0064	0.8030 ± 0.0048	