Jožef Stefan
Institute
Ljubljana, Slovenia

Belle II

Inclusive $B \to \Lambda_c X$ branching fraction measurement with hadronic tag

Paul Feichtinger

Strateško srečanje F9, Krvavec

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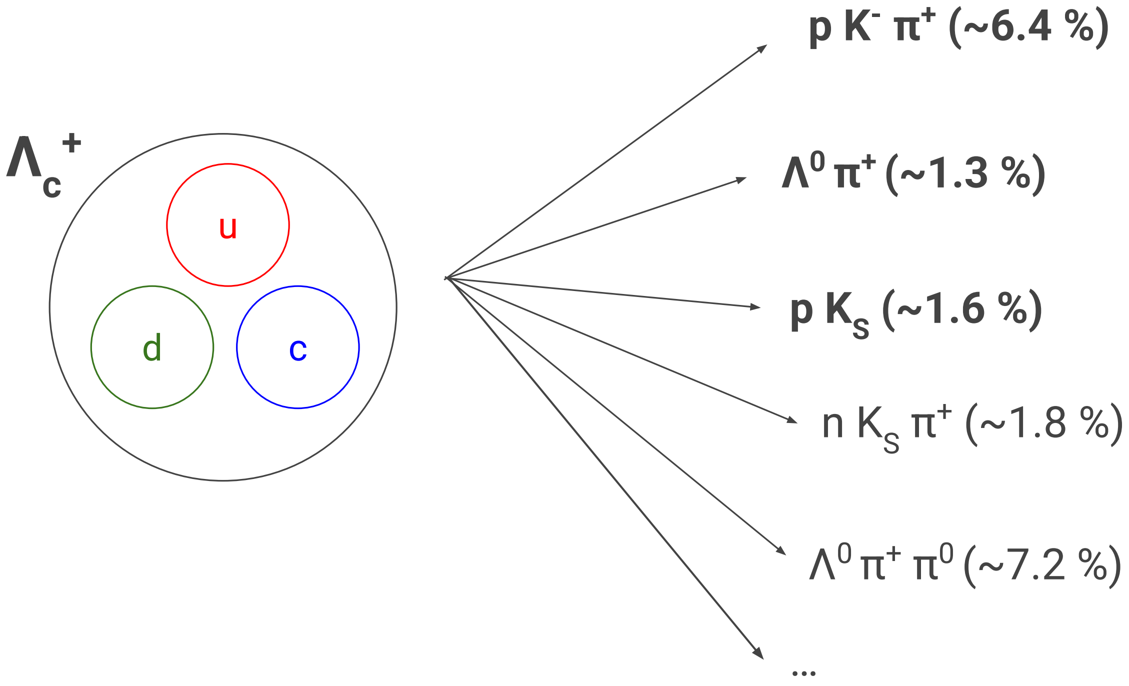
What is a Λ_c?



What is inclusive?

- $B \to \Lambda_c$ **X**
  - **X** can be **anything,** not exclusively reconstructed
  - also decay $B \to \Sigma_c X$ with $\Sigma_c \to \Lambda_c^+ \pi$
- only small fraction of inclusive BF measured exclusively!
  - **we don't know what is X**
  - measurement has to be data driven and independent of simulated X

▼ **Baryon modes**

Γ_{640}	$\overline{\Lambda}_c p\pi^+$	$(2.2 \pm 0.4) \times 10^{-4}$	S=2.7	1980
Γ_{641}	$\overline{\Lambda}_c pK^+$	$(8.8 \pm 1.6) \times 10^{-6}$		1849
Γ_{642}	$\overline{\Lambda}_c \Delta(1232)^{++}$	$< 1.9 \times 10^{-5}$	CL=90%	1928
Γ_{643}	$\overline{\Lambda}_c \Delta_X(1600)^{++}$	$(4.6 \pm 0.9) \times 10^{-5}$		
Γ_{644}	$\overline{\Lambda}_c \Delta_X(2420)^{++}$	$(3.7 \pm 0.8) \times 10^{-5}$		
Γ_{645}	$(\overline{\Lambda}_c p)_s \pi^+$	[8] $(3.1^{+0.7}_{-0.6}) \times 10^{-5}$		
Γ_{646}	$\overline{\Sigma}_c(2520)^0 p$	$< 3 \times 10^{-6}$	CL=90%	1904
Γ_{647}	$\overline{\Sigma}_c(2800)^0 p$	$(2.6 \pm 0.9) \times 10^{-5}$		
Γ_{648}	$\overline{\Lambda}_c p\pi^+\pi^0$	$(1.8 \pm 0.6) \times 10^{-3}$		1935
Γ_{649}	$\overline{\Lambda}_c p\pi^+\pi^+\pi^-$	$(2.2 \pm 0.7) \times 10^{-3}$		1880
Γ_{650}	$\overline{\Lambda}_c p\pi^+\pi^+\pi^-\pi^0$	<1.34 %	CL=90%	1823
Γ_{651}	$\Lambda_c^+ \Lambda_c^- K^+$	$(4.9 \pm 0.7) \times 10^{-4}$		739
Γ_{658}	$\overline{\Lambda}_c(2593)^- \overline{\Lambda}_c(2625)^- p\pi^+$	$< 1.9 \times 10^{-4}$	CL=90%	
Γ_{659}	$\overline{\Xi}_c^0 \Lambda_c^+$	$(9.5 \pm 2.3) \times 10^{-4}$		1144
Γ_{660}	$\Xi_c^0 \Lambda_c^+$	$< 2.6 \times 10^{-5}$	CL=95%	1144
Γ_{661}	$\overline{\Xi}_c^0 \Lambda_c^+ , \overline{\Xi}_c^0 \to \overline{\Xi}^+ \pi^-$	$(1.76 \pm 0.29) \times 10^{-5}$		1144
Γ_{662}	$\overline{\Xi}_c^0 \Lambda_c^+ , \overline{\Xi}_c^0 \to \Lambda K^+ \pi^-$	$(1.14 \pm 0.26) \times 10^{-5}$		1144
Γ_{663}	$\overline{\Xi}_c^0 \Lambda_c^+ , \overline{\Xi}_c^0 \to pK^- K^- \pi^+$	$(5.5 \pm 1.9) \times 10^{-6}$		
Γ_{664}	$\Lambda_c^+ \overline{\Xi}_c^{\prime 0}$	$< 6.5 \times 10^{-4}$	CL=90%	1023
Γ_{665}	$\Lambda_c^+ \overline{\Xi}_c(2645)^0$	$< 7.9 \times 10^{-4}$	CL=90%	
Γ_{666}	$\Lambda_c^+ \overline{\Xi}_c(2790)^0$	$(1.1 \pm 0.4) \times 10^{-3}$		
Γ_{667}	$\Lambda_c^+ \psi_{DS}$			

(exclusive B^+ decays in the PDG)

<<

▼ **Inclusive modes**

Γ_{48}	$D^0 X$	(8.6 ± 0.7) %
Γ_{49}	$\overline{D}^0 X$	(79 ± 4) %
Γ_{50}	$D^+ X$	(2.5 ± 0.5) %
Γ_{51}	$D^- X$	(9.9 ± 1.2) %
Γ_{52}	$D_s^+ X$	$(7.9^{+1.4}_{-1.3})$ %
Γ_{53}	$D_s^- X$	$(1.10^{+0.40}_{-0.32})$ %
Γ_{54}	$\Lambda_c^+ X$	$(2.1^{+0.9}_{-0.6})$ %
Γ_{55}	$\overline{\Lambda}_c^- X$	$(2.8^{+1.1}_{-0.9})$ %
Γ_{56}	$\overline{c} X$	(97 ± 4) %
Γ_{57}	$c X$	$(23.4^{+2.2}_{-1.8})$ %
Γ_{58}	$c\,\overline{c} X$	(120 ± 6) %

(inclusive B^+ decays in the PDG)

Motivation

- b → $\bar{c}$cs contributes a large portion (23%) to B decays which are not well measured
  - need more precise inclusive measurements to improve understanding of **charm quark hadronization**
- knowledge of hadronic B decays and accurate **modeling in MC** is essential for B tagging
- much better precision than old measurements, systematics start to dominate
  - we have more data + higher B tagging efficiency (hadronic FEI)

arXiv:1305.5390, arXiv:1404.6197

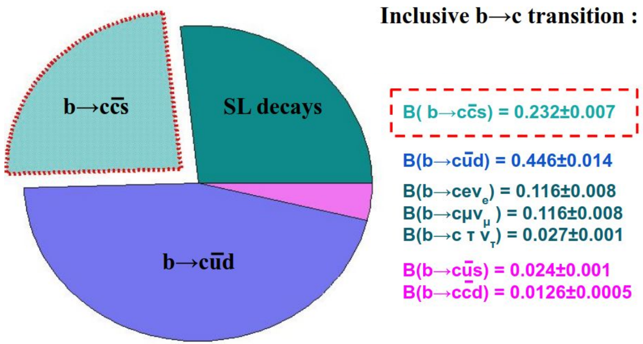
anti-correlated

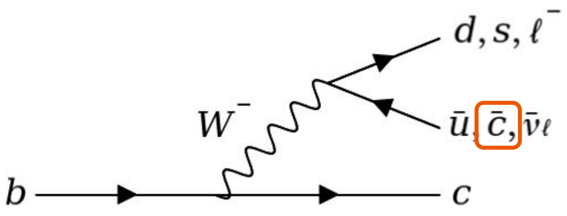
	B^+ (%)	B^0 (%)
D^0X	$8.6 \pm 0.7^{+0.2}_{-0.3}$	$8.1 \pm 1.5^{+0.2}_{-0.2}$
D^+X	$2.5 \pm 0.5^{+0.2}_{-0.2}$	< 3.9
D_s^+X	$7.9 \pm 0.7^{+1.3}_{-1.0}$	$10.3 \pm 1.3^{+1.7}_{-1.3}$
Λ_c^+X	$2.1 \pm 0.5^{+0.8}_{-0.4}$	< 3.1

correlated

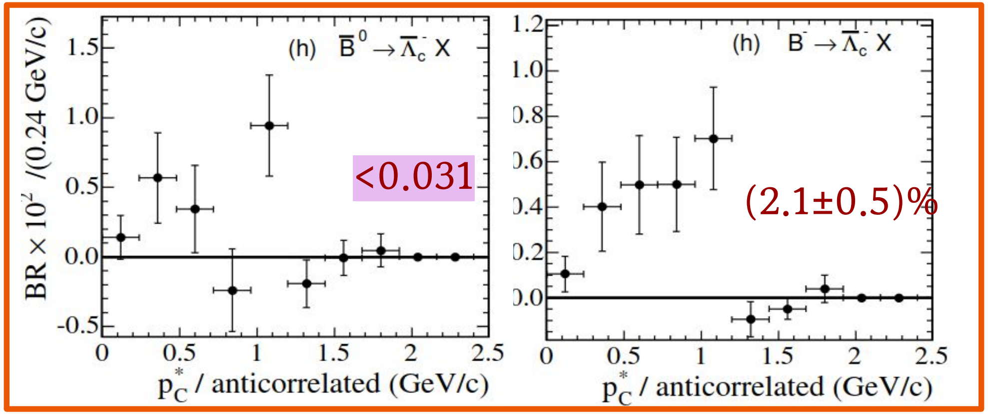
	B^+ (%)	B^0 (%)
$\bar{D}^0X$	$78.6 \pm 3.1^{+2.0}_{-1.9}$	$47.4 \pm 2.5^{+1.3}_{-1.2}$
D^-X	$9.9 \pm 0.9^{+0.8}_{-0.7}$	$36.9 \pm 2.1^{+2.6}_{-2.3}$
D_s^-X	$1.1 \pm 0.4^{+0.2}_{-0.1}$	< 2.6
Λ_c^-X	$2.8 \pm 0.6^{+1.0}_{-0.6}$	$5.0 \pm 1.1^{+1.8}_{-1.0}$

BaBar measurement from 2007 with 210 fb^{-1}
Phys.Rev.D75(2007)072002

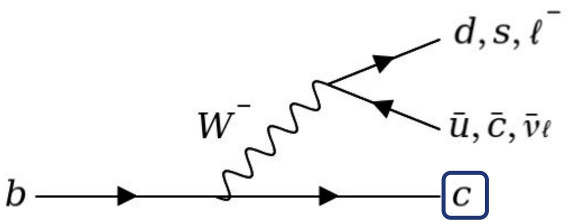




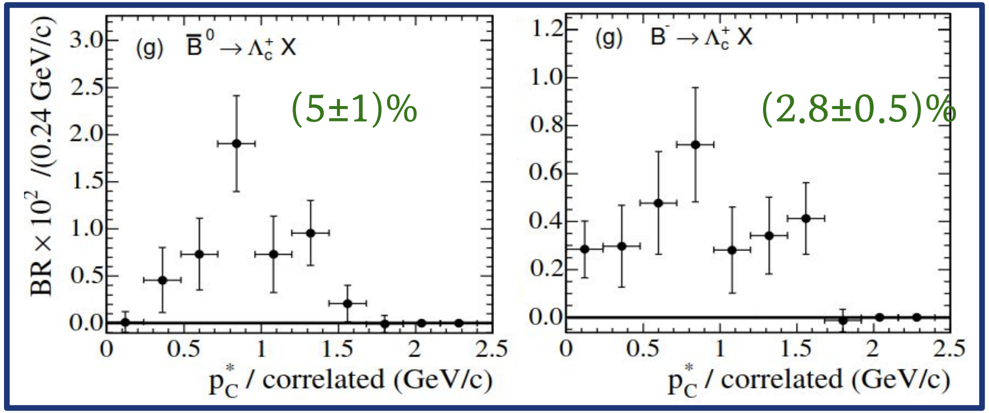
anticorrelated



BaBar, Phys. Rev. D 75, 072002(2007)



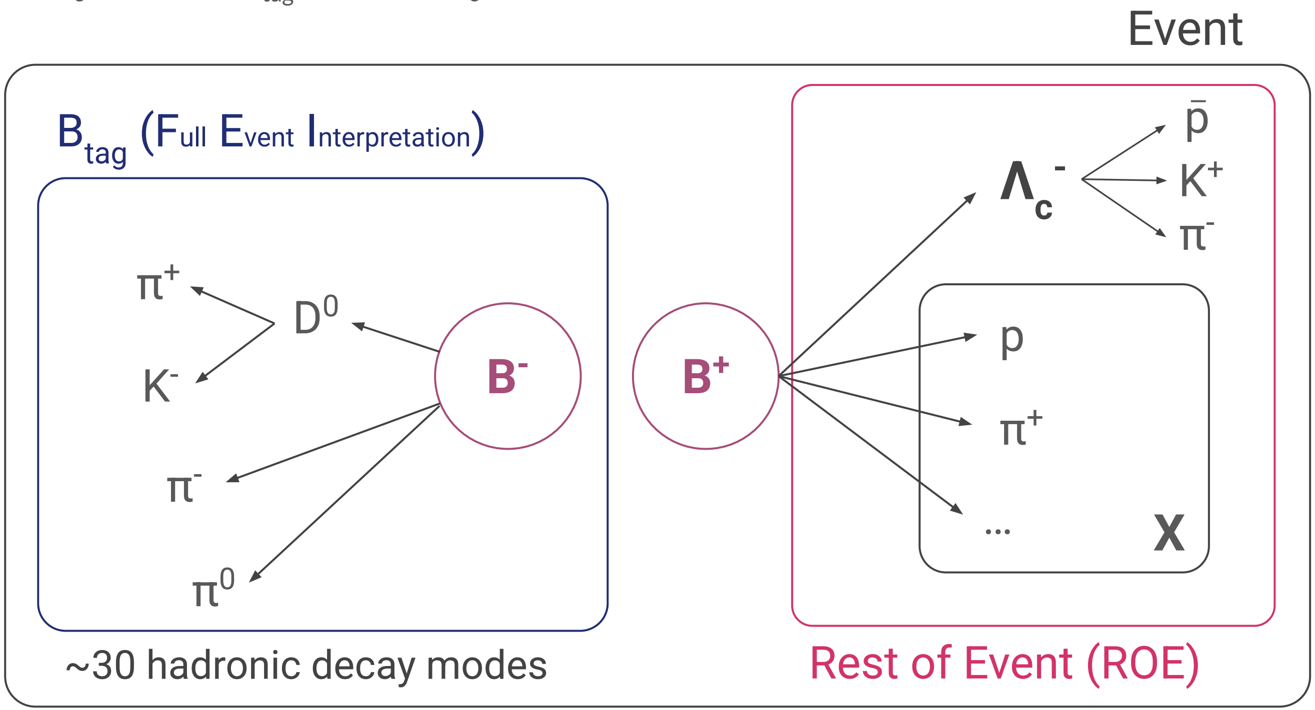
correlated



neutral B charged B

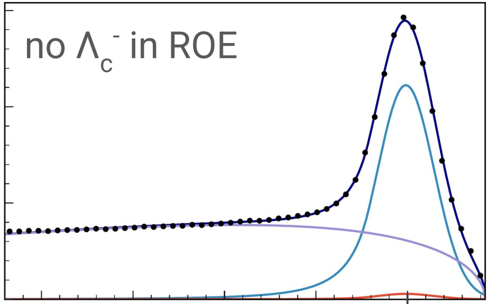
Strategy

- using **hadronic FEI** to fully reconstruct tag side B mesons
- reconstruct Λ_c in ROE of B_{tag}, e.g. from $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$



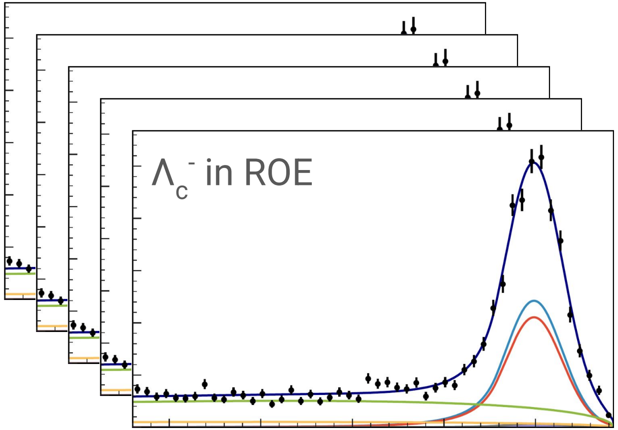
Strategy

2D fit in $p^*(\Lambda_c^-)$ bins

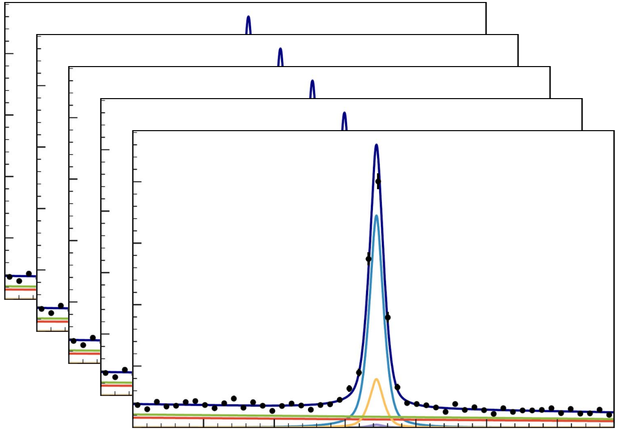


M_{bc} of B_{tag} 5.28 GeV

$$M_{\rm bc} = \sqrt{s/4 - |\vec{p}_B|^2}$$



M_{bc} of B_{tag}



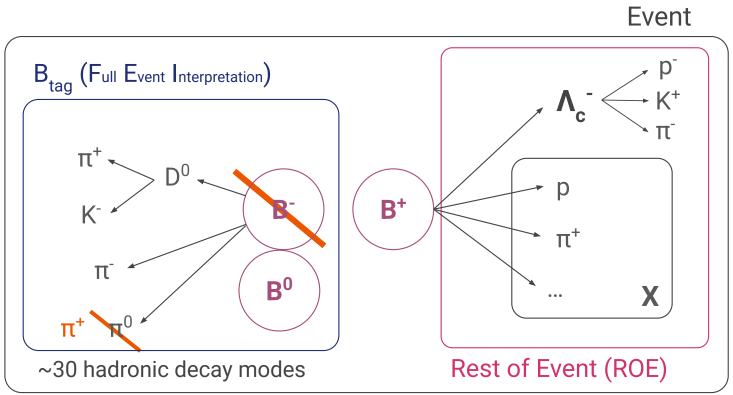
$M(\Lambda_c^-)$

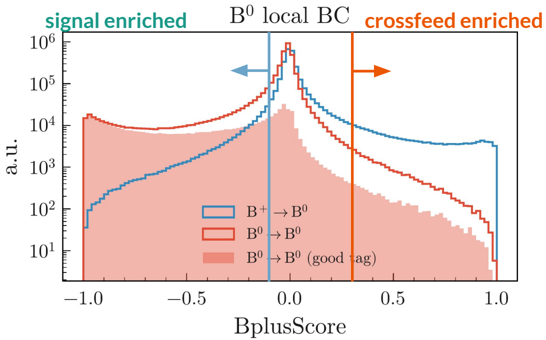
- unbinned, simultaneous fit to obtain yields of **correctly rec. B_{tag} + Λ_c^-** and **correctly rec. B_{tag}**
- BF obtained from ratio of yields, common normalisation uncertainties cancel

$$\tilde{\mathcal{B}}(B \to \Lambda_c X) = \frac{n_{B,\,\Lambda_c^{\rm rec} \to fs} / n_B}{\varepsilon_r \cdot \mathcal{B}(\Lambda_c^+ \to fs)}$$

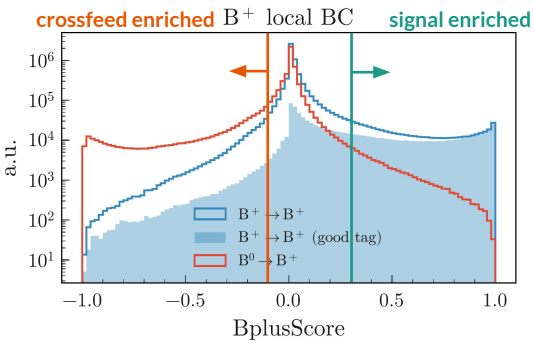
Crossfeed

- important to consider $B^+ \leftrightarrow B^0$ crossfeed
  - charged B_{tag} mis-reconstructed as neutral B_{tag} and vice versa
- crossfeed depends on X, which can cause bias if not calibrated
- neural network trained to classify charged and neutral B events
  - reduces crossfeed
  - define signal and crossfeed enriched samples to self-calibrate crossfeed using data with a simultaneous fit





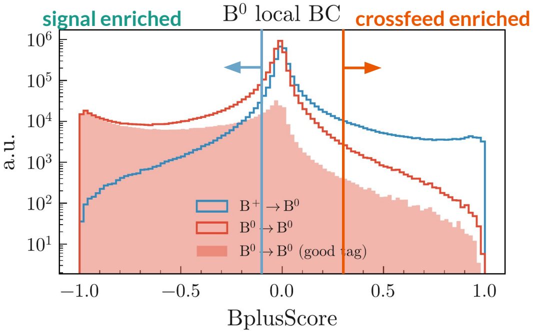
neutral B candidates

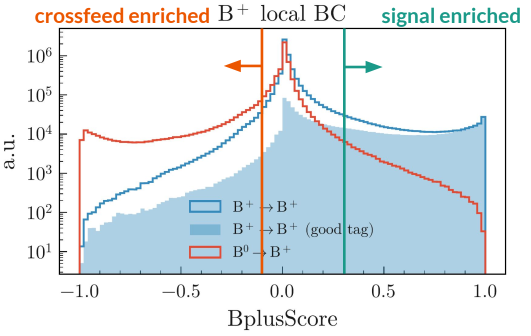


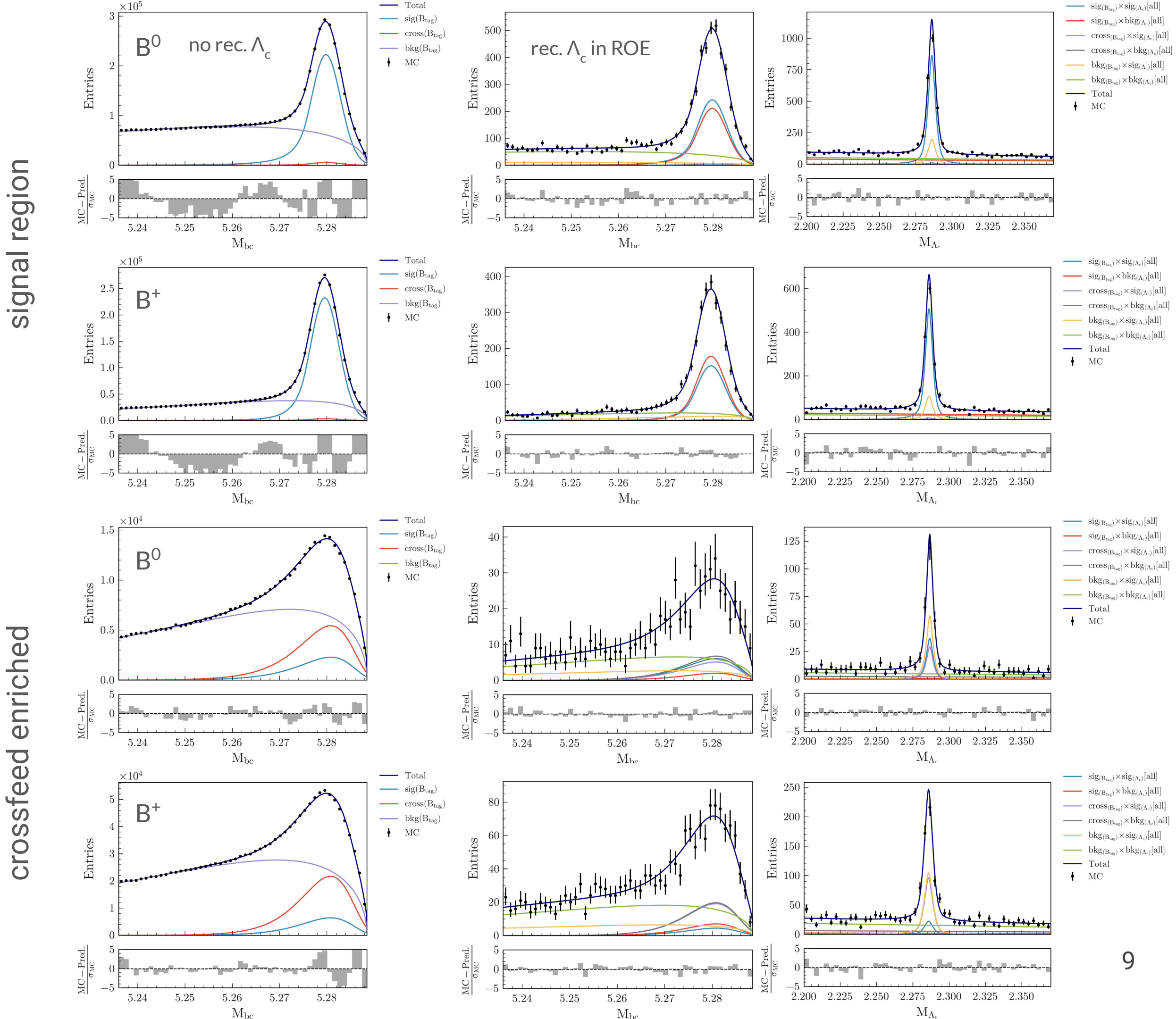
charged B candidates

simultaneous fit of

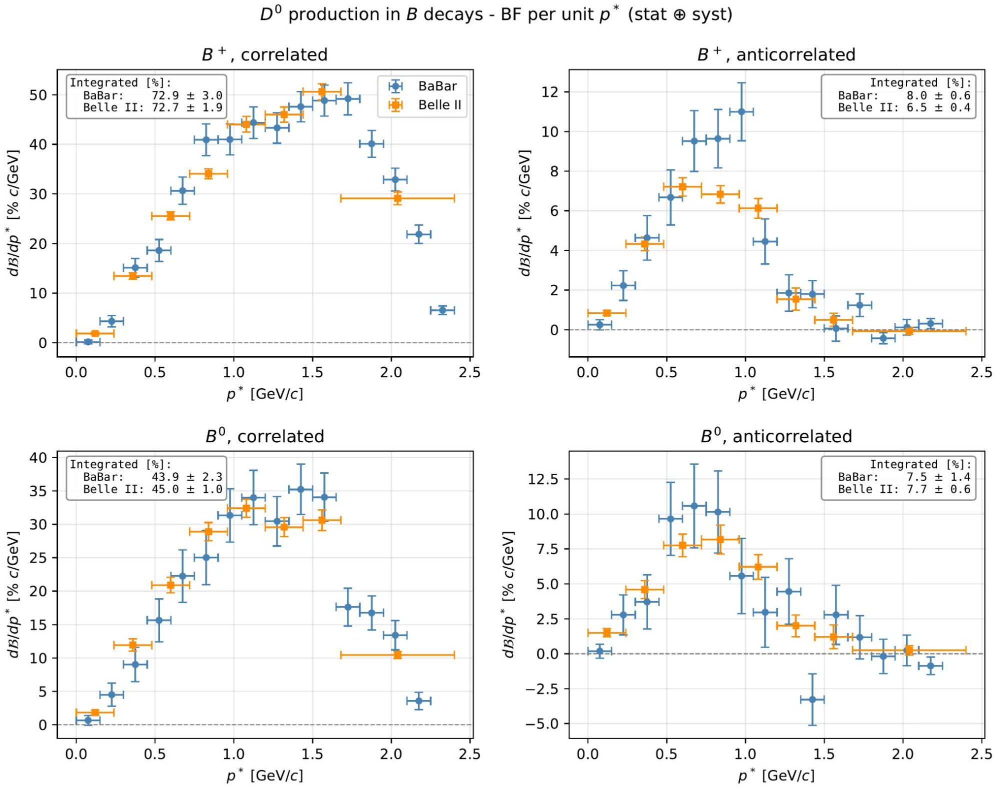
- crossfeed + signal enriched sample
- B^0 + B^+ channels





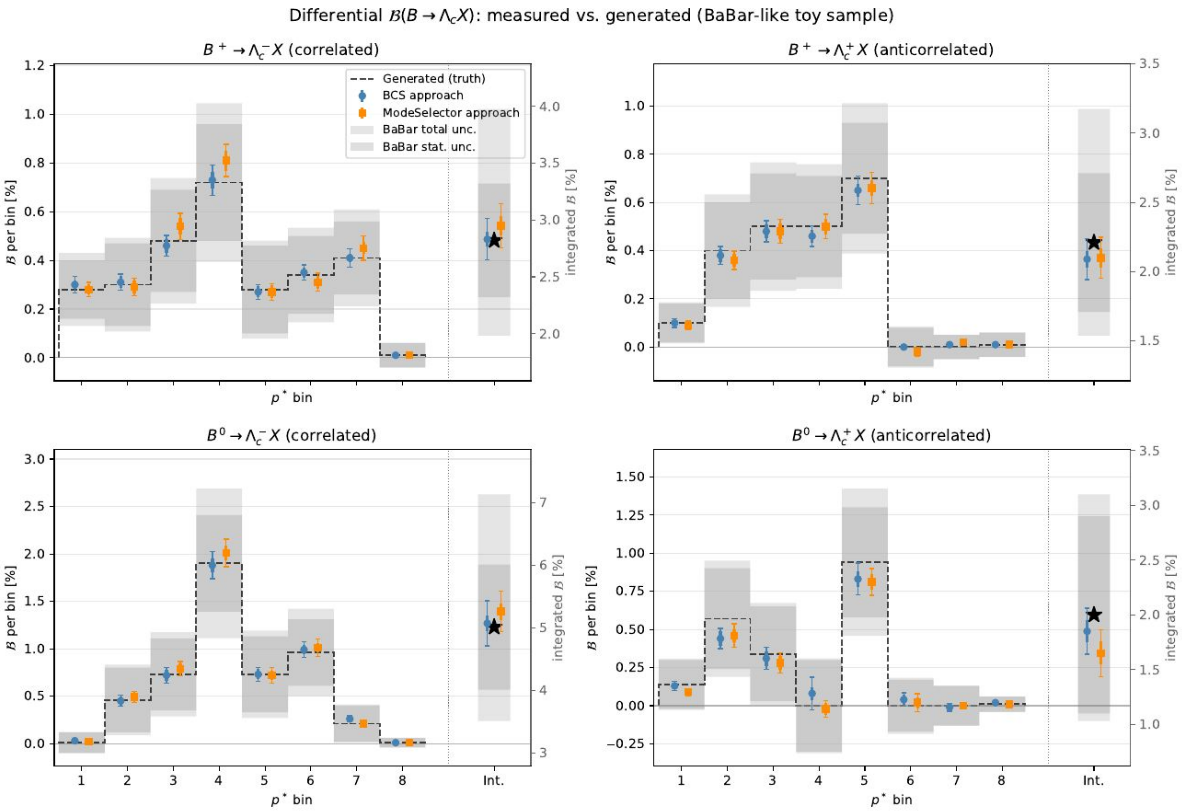


$B \rightarrow D^0X$ as validation channel



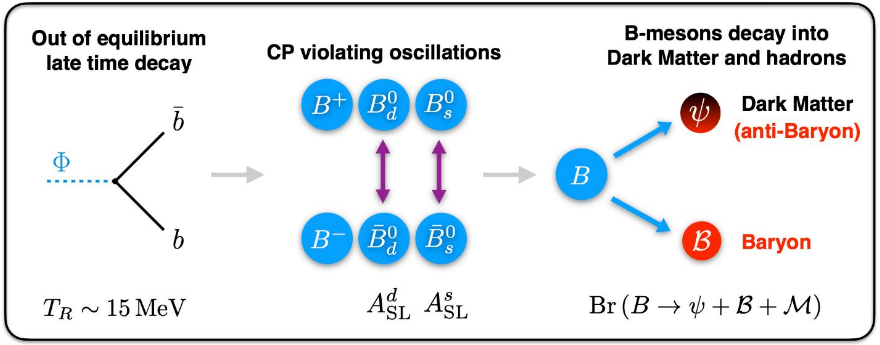
- much larger inclusive BF for $B \rightarrow D^0X$
- same strategy as the Λ_c analysis except reconstructing D^0 as $K^-\pi^+$
- good agreement with published BaBar measurement

Expected results



- analysis still blinded
- expect more than factor 5 improvement in precision with respect to previous measurement
  - mostly due to reduced stat. uncertainty
  - stat. ~ sys. uncertainty
- 2 strategies with different method and crossfeed treatment
- serve as independent cross checks with different fitting framework

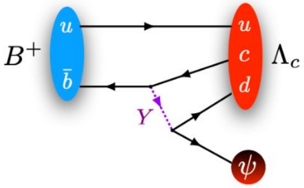
What about new physics?

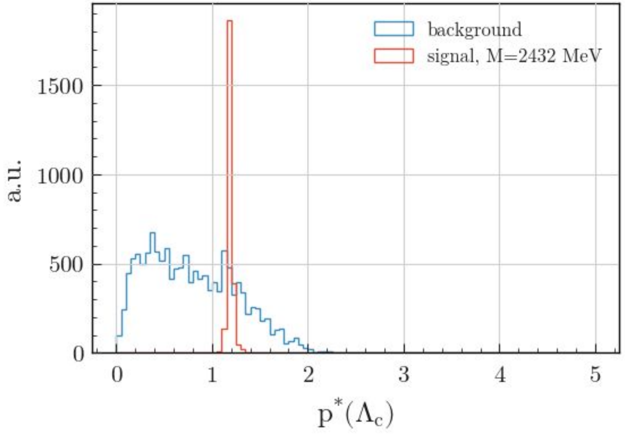


Some NP models such as B-Mesogenesis can be tested

- arXiv:1810.00880, arXiv:2101.02706

- B could decay into SM baryon such as Λ_c and dark (anti-)baryon ψ_D





- we can require that X = { }
- $B \to \Lambda_c \psi_D$ would appear as peak in momentum spectrum of Λ_c depending on mass of ψ_D

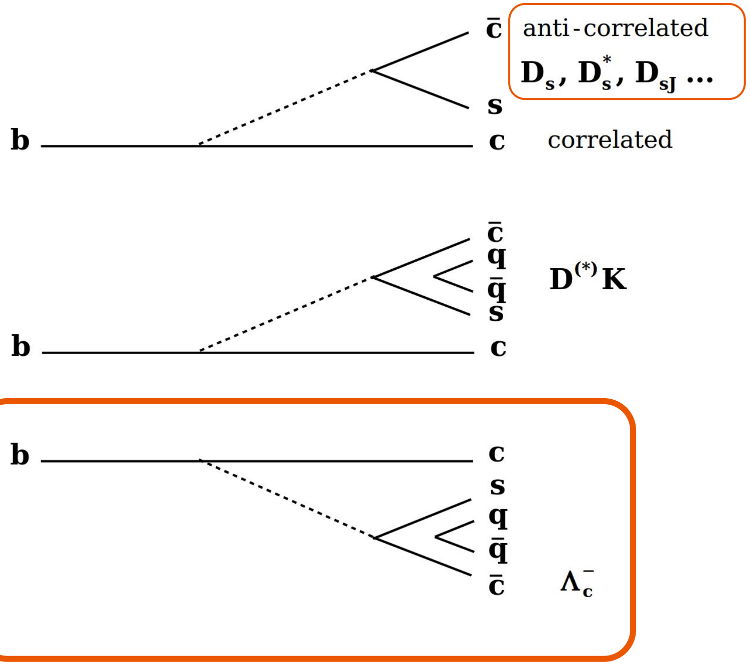
Outlook

- analysis in review stage, plan to unblind next month
- more inclusive measurements still coming from Belle II
    - $B \to D^{(*)}X$, $B \to D_s^{(*)}X$, $B \to p\,X$, $B \to \Lambda\,X$

spare slides ↴

$b \to c\bar{c}s$

	B^+	B^0	
$D_s^+ X$	7.9 ± 1.4 %	10.3 ± 2.1 %	BaBar PRD75:072002
- $D_{s(J)}^{(*)} D^{(*)}$	~5.9 %	~5.6 %	∑excl. (BaBar, CLEO, ARGUS, LHCb, Belle)
$D^{(*)}$ anti-$D^{(*)}$ K	~4 %	~3.7 %	∑excl.: BaBar, arXiv:1011.3929
$\Lambda_c^+ X$	2.1 ± 0.9 %	< 3.1 %	BaBar PRD75:072002
$b \to c\bar{c}s$ (pred.)	~23%	~23%	arXiv:1305.5390



- inclusive measurements of $B \to D^{+/0}$, $B \to D_s^+$, $B \to \Lambda_c^+$ (correlated + **anti-correlated**) will help to fill the gaps
  - including also the higher resonances ($B \to D^{*(*)}$, $D_{s(J)}^*$, Σ_c) for even more information

2 strategies

	BCS approach	ModeSelector approach
dataset	Belle + Belle II (1209/fb)	Belle II (498/fb)
crossfeed suppression	BCS	NN (ModeSelector, !5330), ~50% reduced crossfeed
B_{tag} modes	only selected modes (~80%)	all except flavour agnostic or with Λ_c
normalisation	not used	simultaneously fit all B_{tag} cand.
signal / CF shape	fixed to MC, different PDFs (sig-CF)	free parameters, same PDFs (sig-CF)
sim. fit	B^0_{corr}+B^0_{anti}+B^+_{corr} + B^+_{anti} (B+BII)	B^0_{corr}+B^+_{corr} and B^0_{anti}+B^+_{anti}
number of independent fits	**8**: 1 for each p(Λ_c) bin	**2**: corr / anti, sim. in p(Λ_c)
internal crossfeed (corr ↔ anti)	negligible	taking into account when converting FPRs to BFs

FPRs $$\tilde{\mathcal{B}}(B \to \Lambda_c X) = \frac{n_{B,\Lambda_c^{\rm rec}\to fs}/n_B}{\varepsilon_r \cdot \mathcal{B}(\Lambda_c^+ \to fs)}$$

BFs $$\mathcal{B}_a = \frac{\tilde{\mathcal{B}}_a \cdot (1 - f_{c\to a} - \delta_{B^0}\chi_d) - \tilde{\mathcal{B}}_c \cdot (f_{c\to a} + \delta_{B^0}\chi_d)}{1 - f_{a\to c} - f_{c\to a} - 2\delta_{B^0}\chi_d} \qquad \mathcal{B}_c = \frac{\tilde{\mathcal{B}}_c \cdot (1 - f_{a\to c} - \delta_{B^0}\chi_d) - \tilde{\mathcal{B}}_a \cdot (f_{a\to c} + \delta_{B^0}\chi_d)}{1 - f_{a\to c} - f_{c\to a} - 2\delta_{B^0}\chi_d}$$

Systematics

	BCS approach	ModeSelector approach
unfolding		50% of difference
absolute normalisation		cancels
FEI	from calibration	from calibration, largely cancels
continuum pdf	full difference between fits w/ and w/o (cont. yield+shape floating)	full difference between fits w/ and w/o (cont. yield+shape fixed from MC)
fit modelling / fit model	vary shape parameters within uncertainties from MC fit	bootstrap study, full bias as systematic
$B \rightarrow \Lambda_c X$ decay composition	efficiency difference of 2 signal samples	efficiency difference of 2 signal samples
crossfeed (B^+, B^0)	difference of 2 signal samples	nuisance parameter in fit
crossfeed (corr, anti)		stat uncertainty + 100% systematic

bin	1	2	3	4	5	6	7	8	integrated
central value	0.09	0.28	0.41	0.58	0.59	0.46	0.22	0.10	2.72
charm BFs	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
χ_d									
K_S	0.3	0.4	0.3	0.3	0.3	0.4	0.3	0.3	0.3
Λ^0	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.2	0.2
PID	2.9	3.1	3.0	2.9	2.9	2.7	2.7	2.6	2.9
FEI	0.3	0.2	0.1	0.2	0.1	0.2	0.1	0.1	0.2
tracking eff.	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
cont. modelling	0.7	1.7	0.6	2.0	2.2	2.2	2.3	4.4	1.9
decay composition	1.2	0.2	1.6	2.8	4.1	5.3	6.6	8.7	3.5
unfolding	0.5	0.1	0.3	0.4	0.2	0.1	0.3	0.8	0.0
crossfeed (corr, anti)	1.5	0.2	0.3	0.2	0.1	0.2	0.2	0.6	0.1
crossfeed (B^+, B^0)	5.6	3.4	3.1	2.3	2.3	2.4	3.6	4.9	1.3
MC stat. (eff.)	4.6	2.5	2.0	1.7	1.6	1.8	2.7	4.9	0.8
fit model	6.6	0.4	0.8	0.8	3.3	4.1	6.0	5.3	1.9
fit bias	0.4	0.0	0.1	0.1	0.1	0.6	0.2	0.1	0.0
total sys.	11.2	6.9	6.6	6.9	8.1	9.2	11.4	14.0	6.9
stat.	13.4	8.3	7.6	5.5	5.5	5.8	8.6	11.8	3.0
total	17.5	10.8	10.0	8.8	9.8	10.8	14.3	18.3	7.5

PDF parameters

(for fit of signal enriched sample)

- Crystal Ball (M_{bc})
- Argus (M_{bc})
- Gauss + Johnson ($M[\Lambda_c]$)
- Chebyshev ($M[\Lambda_c]$)
- Crossfeed fraction / calibration
- Yields

Parameter	Status
Normalisation fit	
$N_{\text{sig}}(B^0)$	floating
$N_{\text{sig}}(B^+)$	floating
$f_{\text{xfeed}}[\text{nrc}]$	fixed
$c_{\text{xfeed}}[\text{nrc}]$	floating
$N_{\text{bkg}}(B^0)$	floating
μ^{CB}	floating
σ^{CB}	floating
α^{CB}	floating
n^{CB}	floating
$m_0^{\text{Argus}}[\text{nrc}]$	fixed
$c^{\text{Argus}}[\text{nrc}]$	floating
$p^{\text{Argus}}[\text{nrc}]$	fixed

Parameter	Status
$\boldsymbol{bkg}_{(B_{tag})} \times \boldsymbol{sig}_{(\Lambda_c)}$	
$N_{\text{bkg}\times\text{sig}}(B^0)$	floating
$m_0^{\text{Argus}}[\text{trc}]$	fixed
$c^{\text{Argus}}[\text{trc}]$	floating
$p^{\text{Argus}}[\text{trc}]$	fixed
$f_{\text{Gauss/Johnson}}$	fixed
μ^{Gauss}	floating
σ^{Gauss}	floating
$f_{\text{width}}^{\text{Johnson}}$	fixed
λ^{Johnson}	derived
γ^{Johnson}	fixed
δ^{Johnson}	fixed

Parameter	Status
$\boldsymbol{sig}_{(B_{tag})} \times \boldsymbol{sig}_{(\Lambda_c)}$	
$N_{\text{sig}\times\text{sig}}(B^0)$	floating
μ^{CB}	floating
σ^{CB}	floating
α^{CB}	floating
n^{CB}	floating
$f_{\text{Gauss/Johnson}}$	fixed
μ^{Gauss}	floating
σ^{Gauss}	floating
$f_{\text{width}}^{\text{Johnson}}$	fixed
λ^{Johnson}	derived
γ^{Johnson}	fixed
δ^{Johnson}	fixed

Parameter	Status
$\boldsymbol{cross}_{(B_{tag})} \times \boldsymbol{sig}_{(\Lambda_c)}$	
$N_{\text{sig}\times\text{sig}}(B^+)$	floating
$f_{\text{xfeed}}[\text{trc}]$	fixed
$c_{\text{xfeed}}[\text{trc}]$	floating
μ^{CB}	floating
σ^{CB}	floating
α^{CB}	floating
n^{CB}	floating
$f_{\text{Gauss/Johnson}}$	fixed
μ^{Gauss}	floating
σ^{Gauss}	floating
$f_{\text{width}}^{\text{Johnson}}$	fixed
λ^{Johnson}	derived
γ^{Johnson}	fixed
δ^{Johnson}	fixed

Parameter	Status
$\boldsymbol{sig}_{(B_{tag})} \times \boldsymbol{bkg}_{(\Lambda_c)}$	
$N_{\text{sig}\times\text{bkg}}(B^0)$	floating
μ^{CB}	floating
σ^{CB}	floating
α^{CB}	floating
n^{CB}	floating
c_1^{bkg}	floating

Parameter	Status
$\boldsymbol{bkg}_{(B_{tag})} \times \boldsymbol{bkg}_{(\Lambda_c)}$	
$N_{\text{bkg}\times\text{bkg}}(B^0)$	floating
$m_0^{\text{Argus}}[\text{frc}]$	fixed
$c^{\text{Argus}}[\text{frc}]$	floating
$p^{\text{Argus}}[\text{frc}]$	fixed
c_1^{bkg}	floating

Parameter	Status
$\boldsymbol{cross}_{(B_{tag})} \times \boldsymbol{bkg}_{(\Lambda_c)}$	
$N_{\text{sig}\times\text{bkg}}(B^+)$	floating
$f_{\text{xfeed}}[\text{frc}]$	fixed
$c_{\text{xfeed}}[\text{frc}]$	floating
μ^{CB}	floating
σ^{CB}	floating
α^{CB}	floating
n^{CB}	floating
c_1^{bkg}	floating

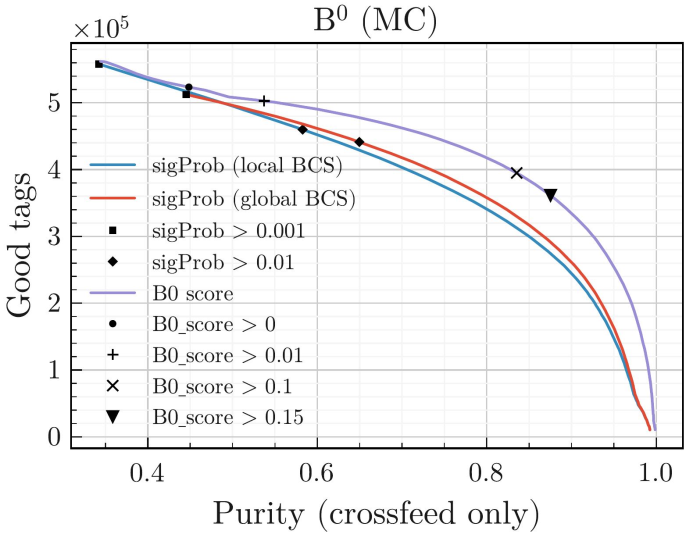
(cont. x bkg)

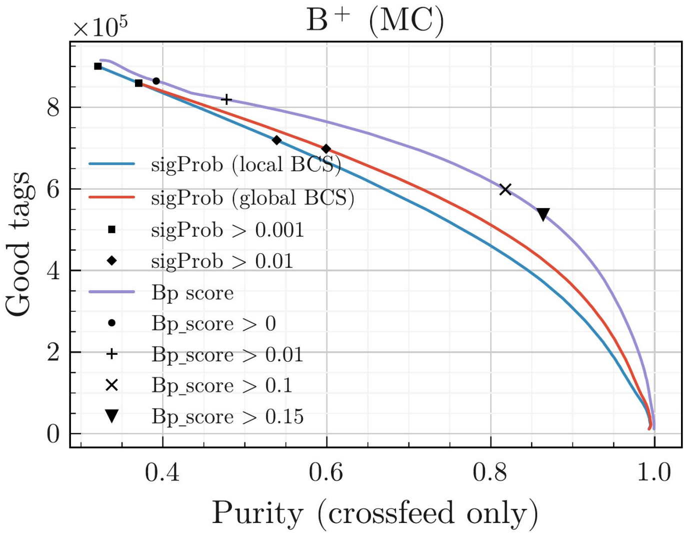
(cont. x sig)

cont. fixed from MC, fit performed with and without (nominal)

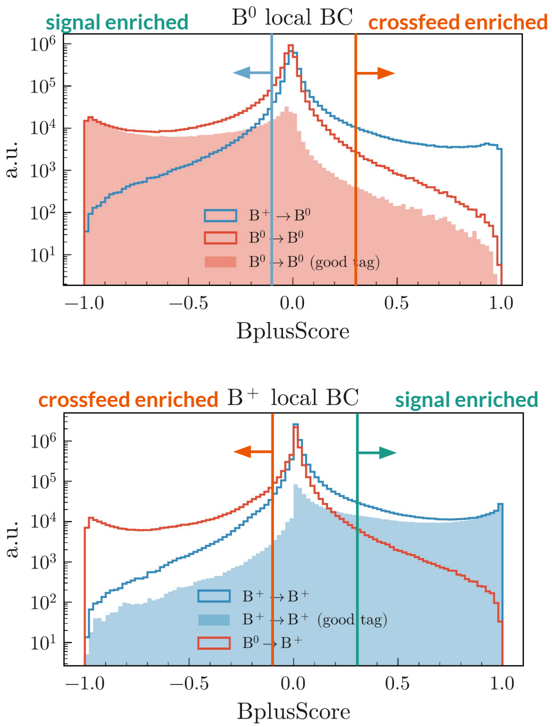
ROC curves

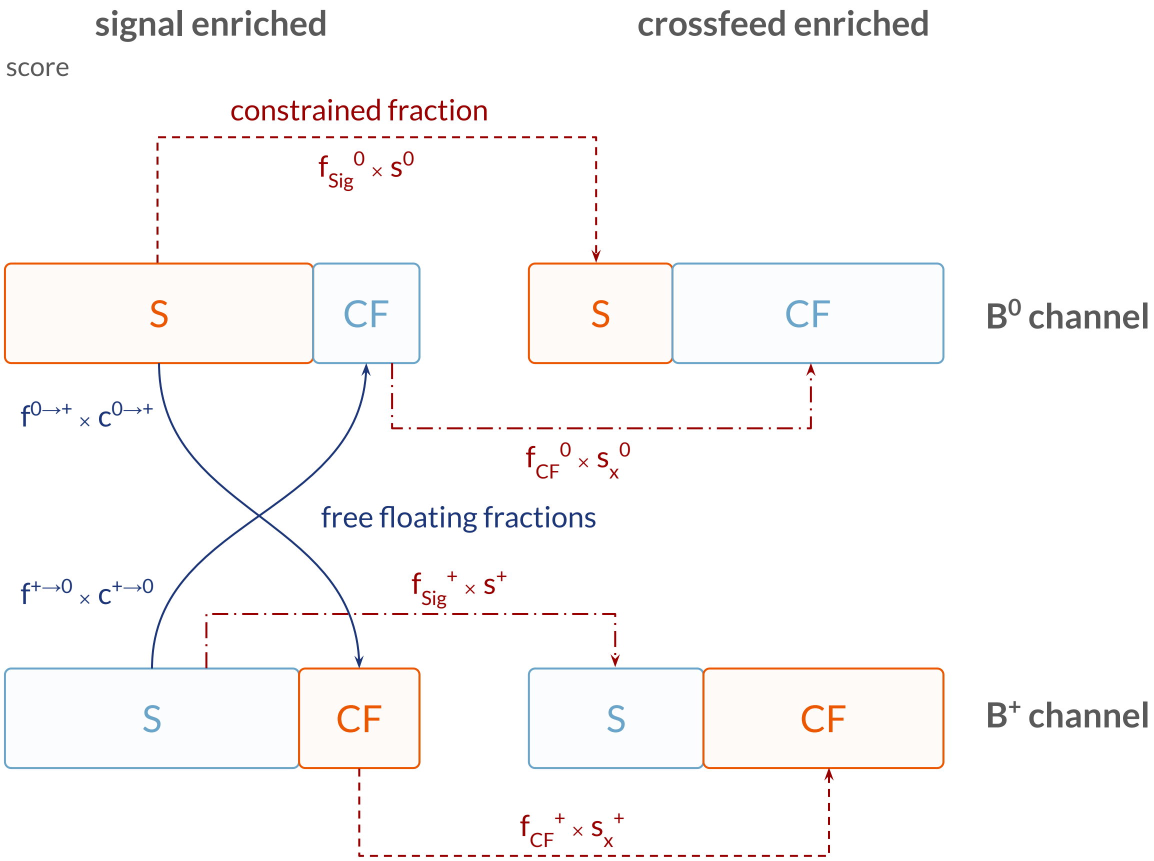
- with selections applied, requiring Λ_c candidate in ROE of B_{tag}





- f - fractions of yields, fixed from MC
- s^+/s^0 - parameters to account for mismodelling of Bp score
- $c^{0\to+}/c^{+\to0}$ - free parameters to calibrate crossfeed





individually for events with no rec. Λ_c in ROE / true rec. Λ_c [x8] / false rec. Λ_c [x8]