b hadronisation tagging at FCC (and LHC)

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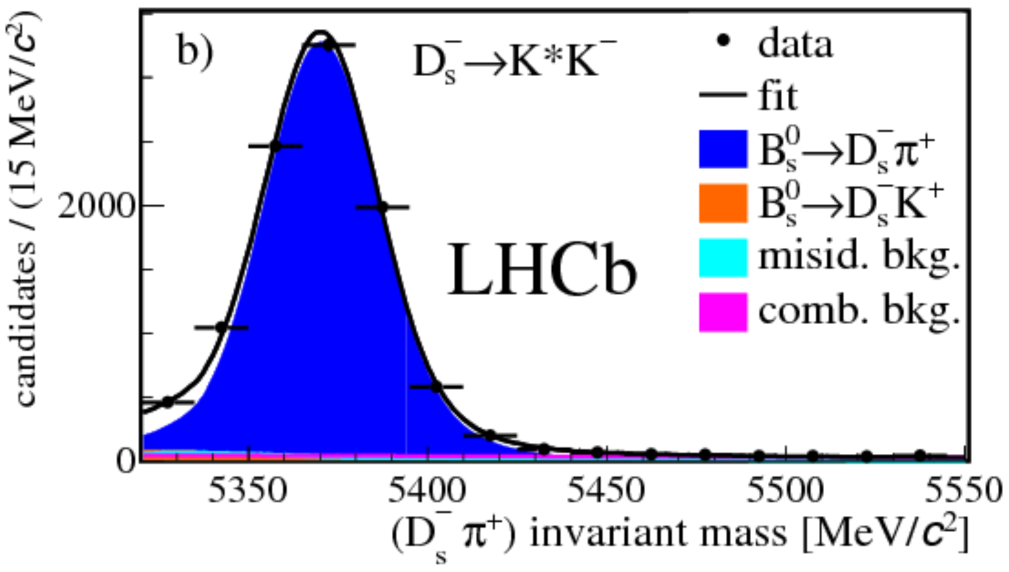
MITP 2026

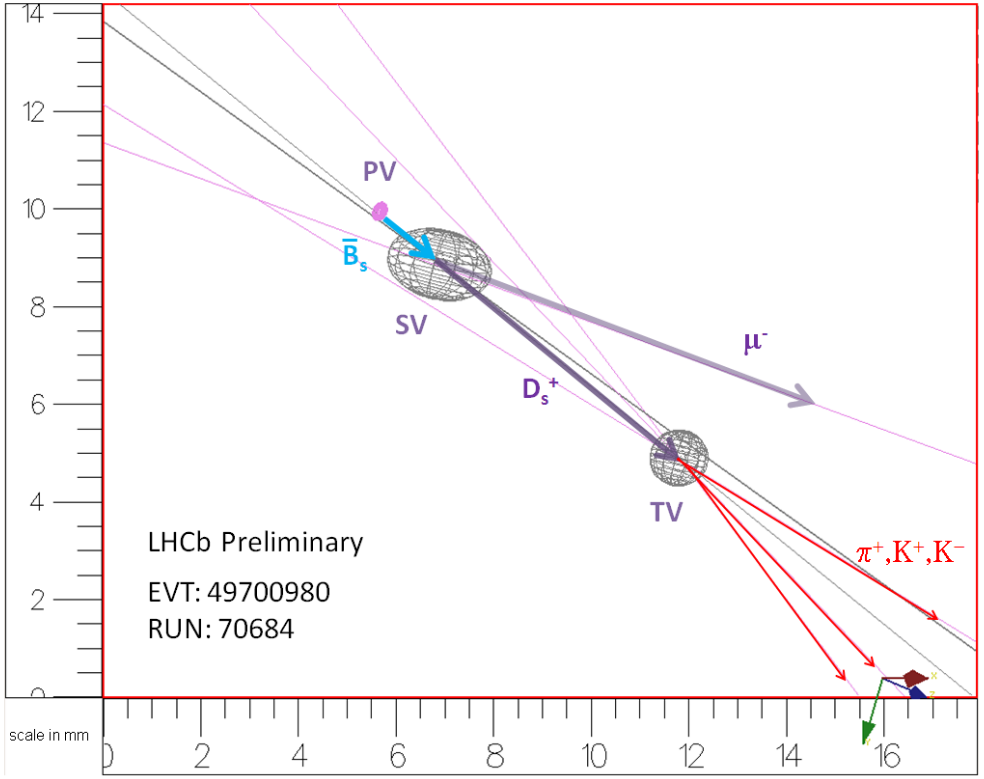
B physics at a hadron collider

Mass peaks



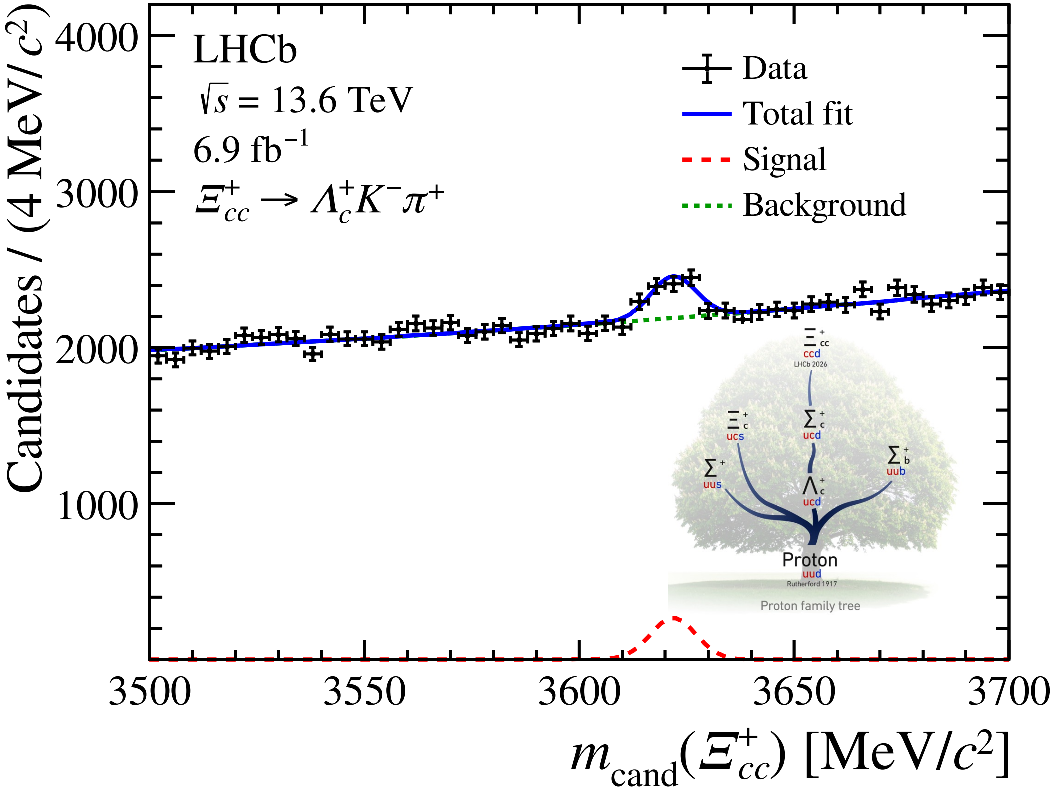
New J.Phys. 15 (2013) 053021

Displaced vertices

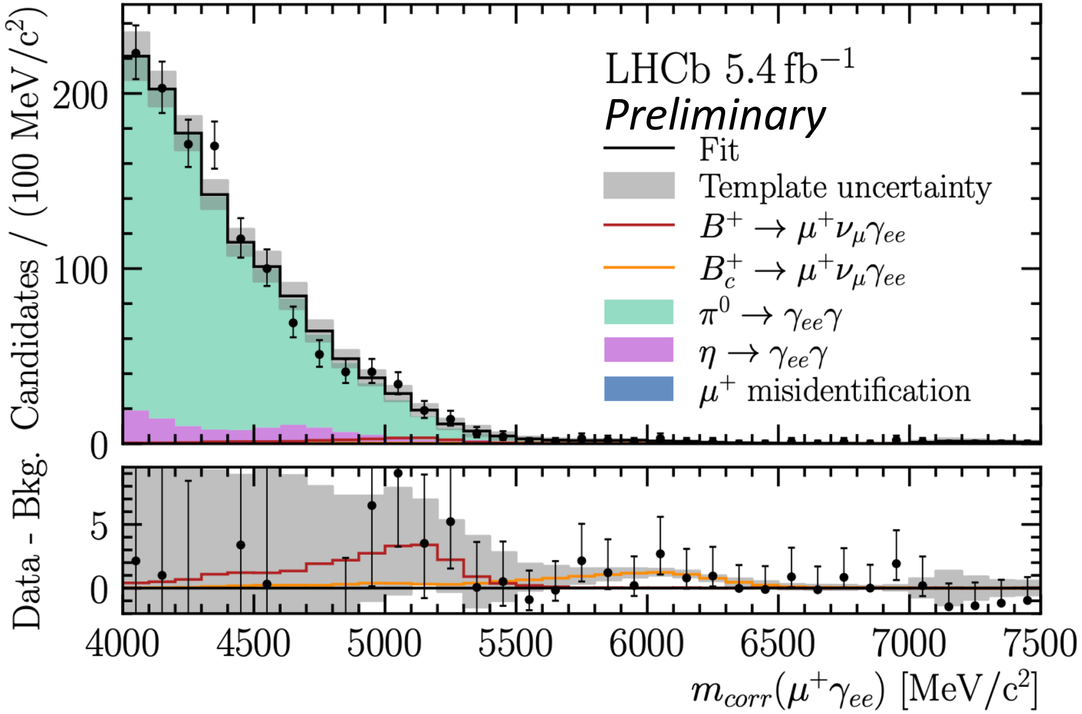


LHCb 2010

If no displacement or no mass peak: tough life + innovative methods



45 fs lifetime ~ 0.1 mm (almost prompt)

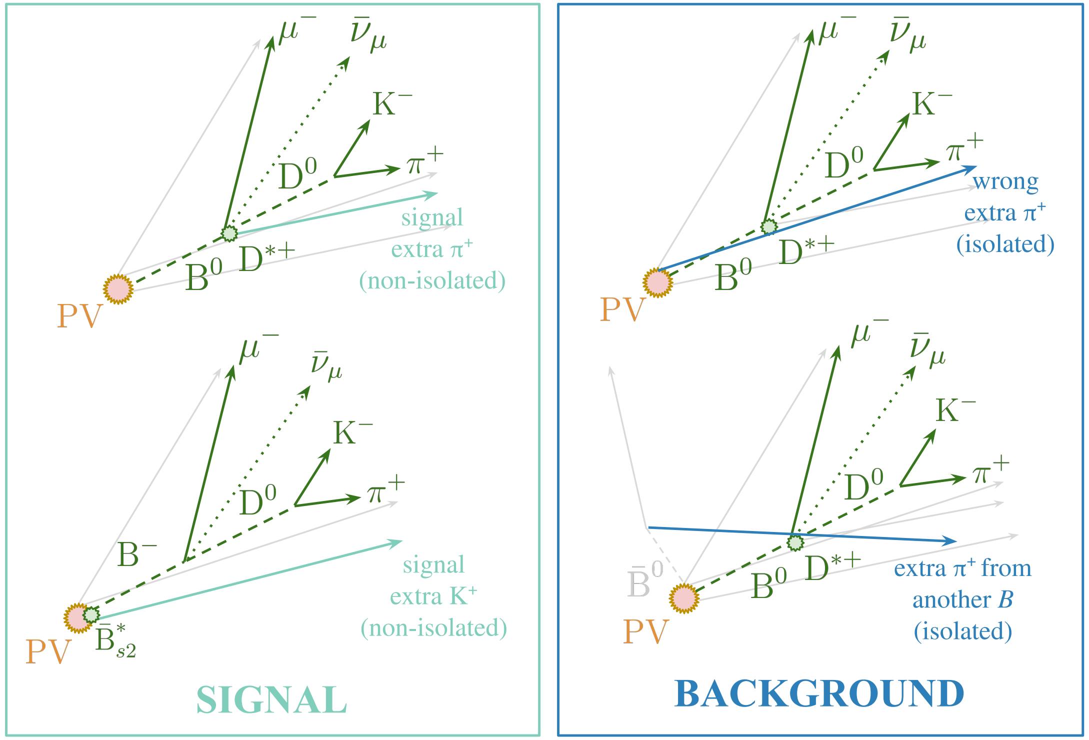


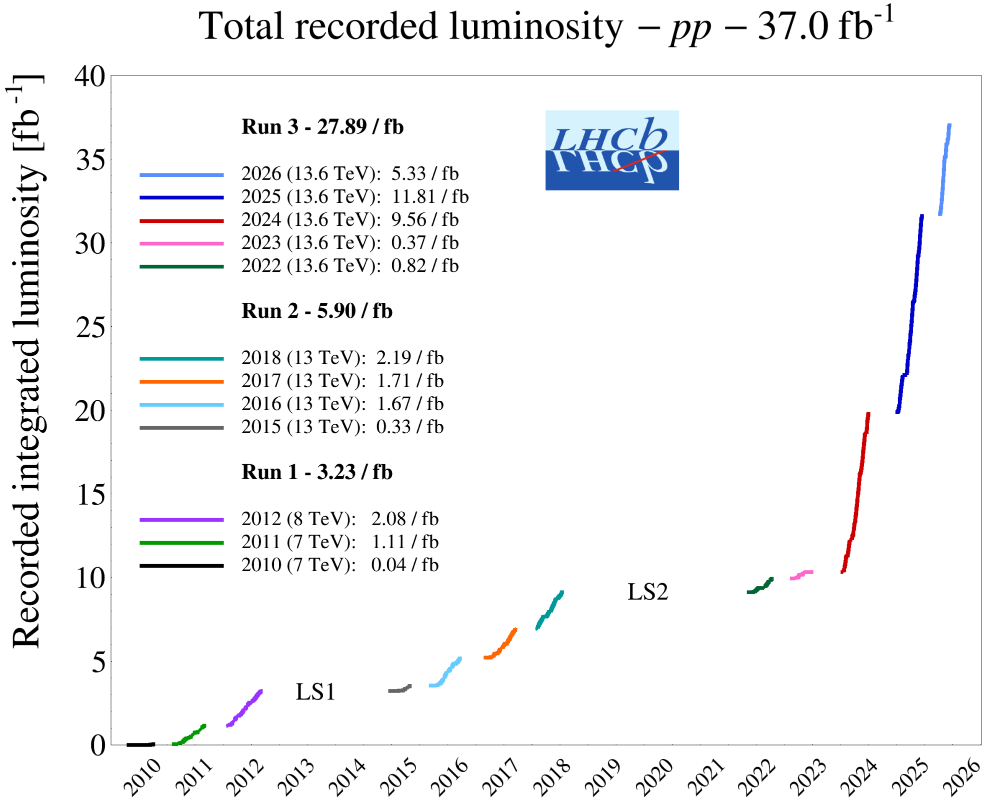
$B^+ \to \mu^+\nu\gamma$: use γ conversions to fight bkg

[2603.28456](2603.28456)

LHCb-PAPER-2026-020

Data collection optimization: signal-centric



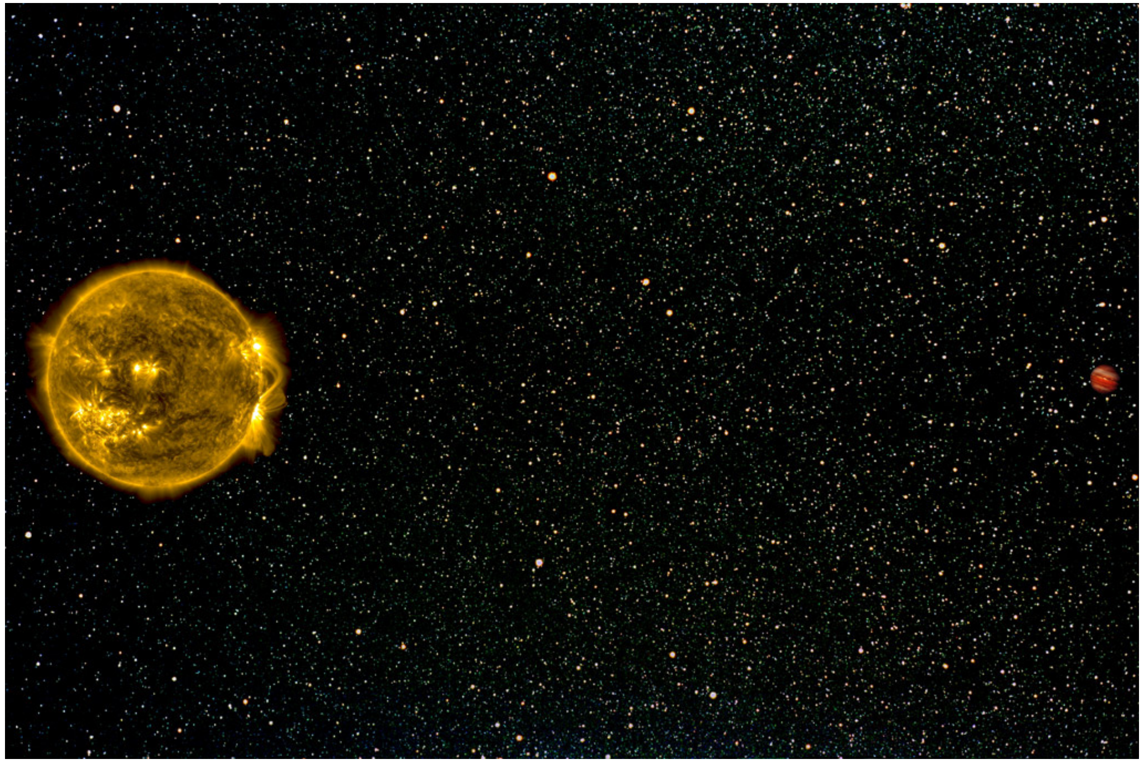


EPJC 86 (2026) 241

More and more rely on storing only signal tracks to overcome bandwidth explosion

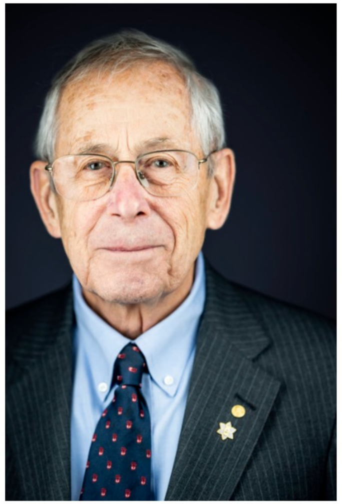
Discoveries with looking outside

[51 Pegasi exoplanet]



Do not observe the planet but infer it from the slight and regular velocity changes in the star's spectral lines of around 70 metres per second

Nobel Prize in Physics 2019



© Nobel Prize Outreach. Photo: A. Mahmoud

James Peebles

Prize share: 1/2

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Michel Mayor

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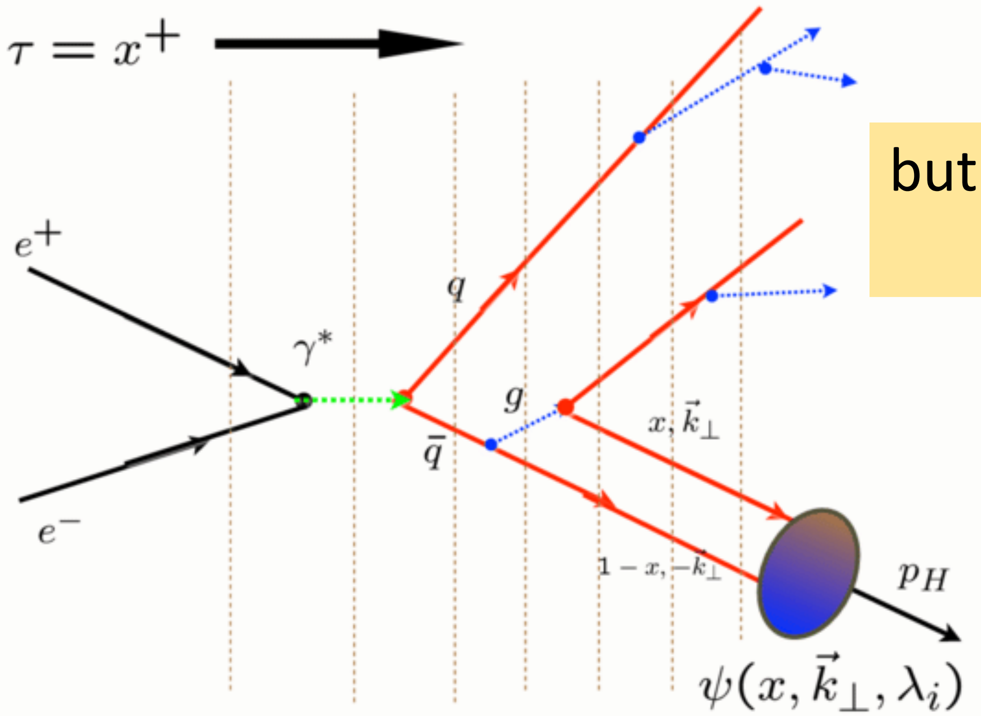
Didier Queloz

Prize share: 1/4

[NobelPrize.org]

Outside of the box in particle collisions?



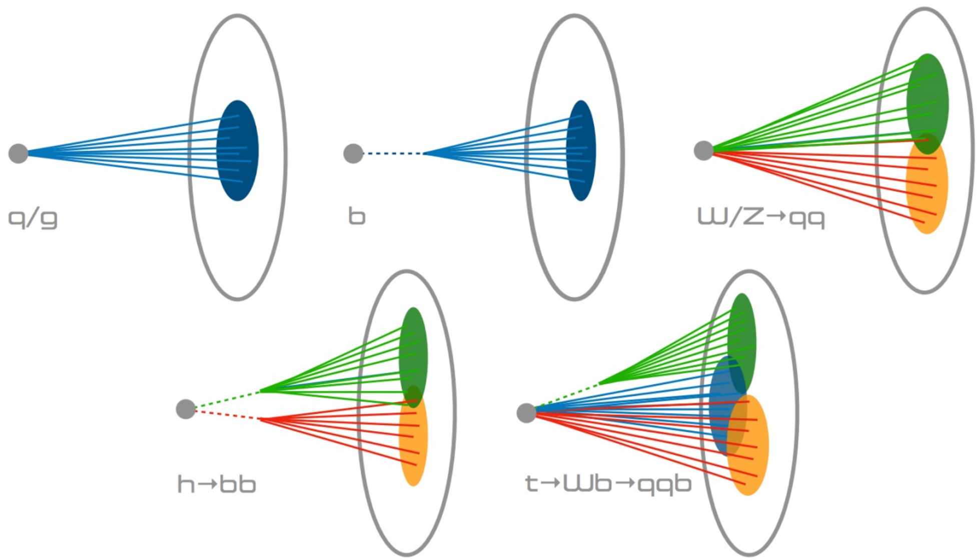
but: hadronization remnants ???

our focus: signal

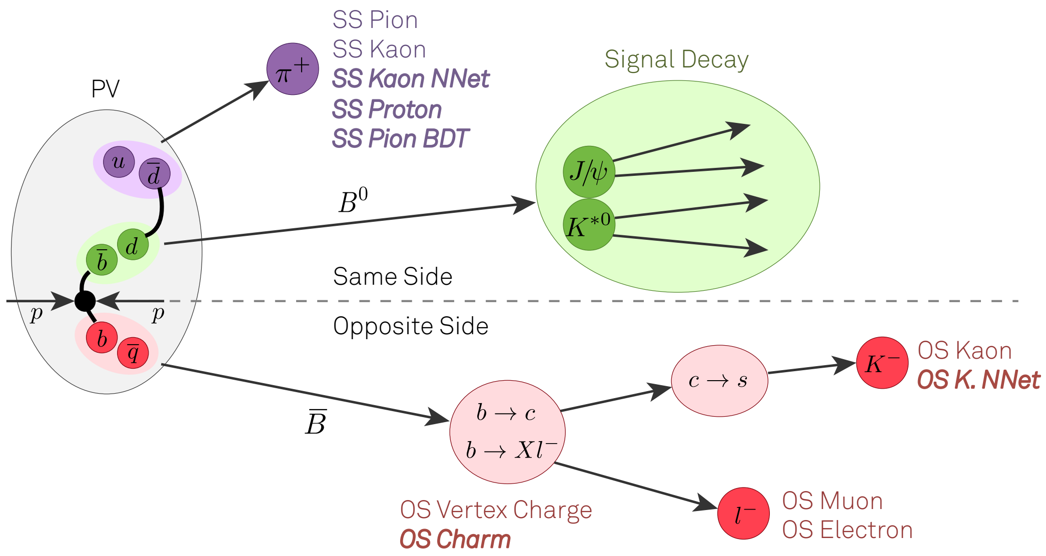
AIP Conf. Proc. 1348 (2011) 11

Building upon existing types of flavor tagging

#1: jet flavor tagging

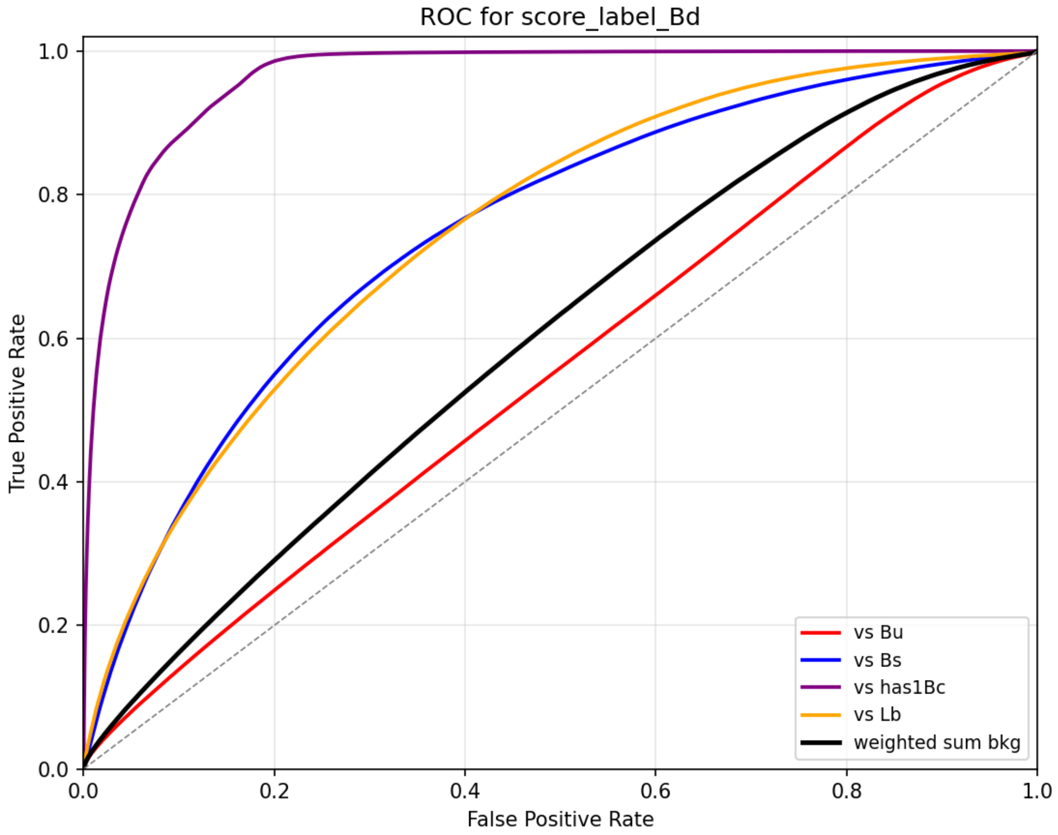


#2: b quark charge tagging



New #3: b hadron species tagging

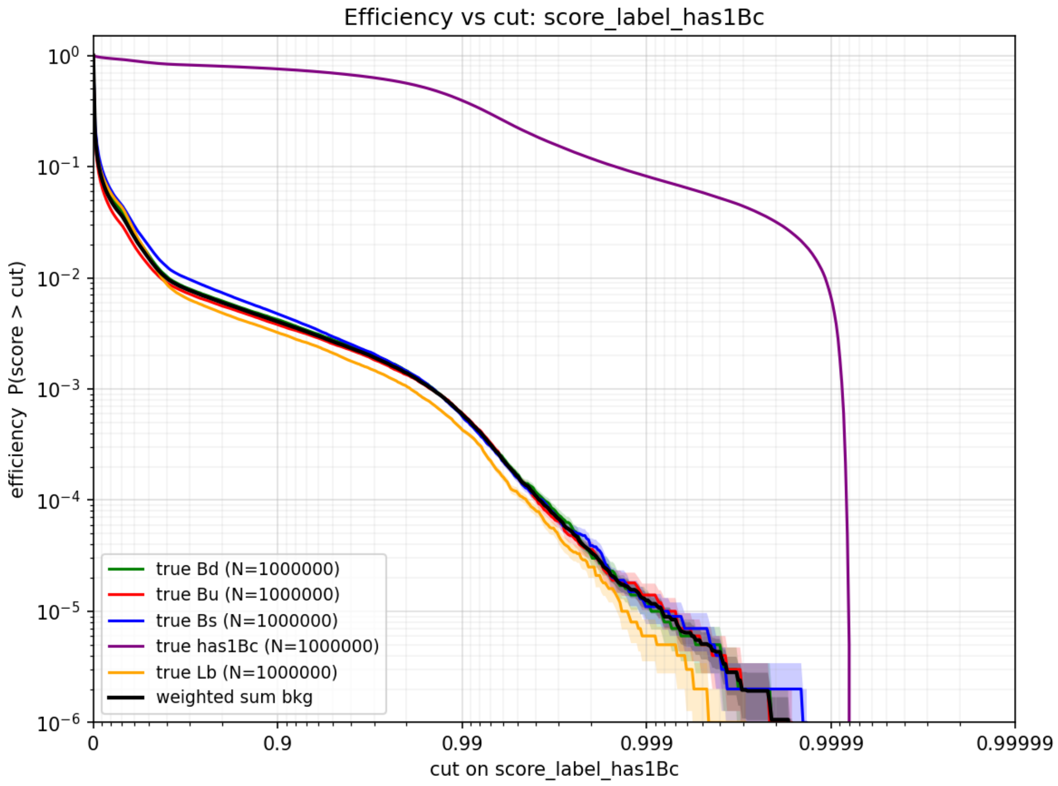
B_x identification for "hopeless" B_x decays



FCC-ee, one hemisphere, non-signal tracks only

- infer the type of quark with which b hadronized
  - use only non-signal tracks
- response is independent of the B hadron decay mode
  - can be calibrated in data with fully reconstructed decay modes
- from better to worse:
  - B_c, Λ_b, B_s, (B^+, B^0)
- performance at LHCb is expected to be similar or worse

Use cases



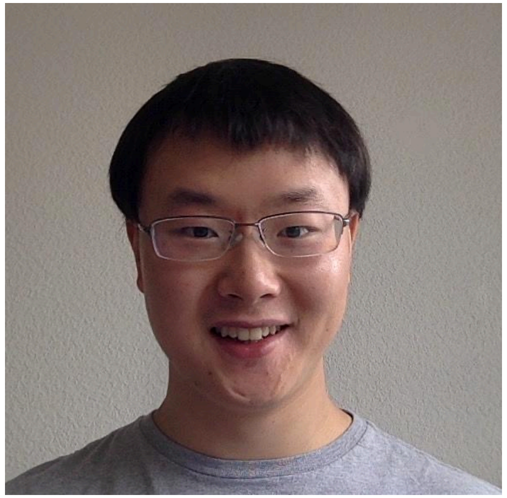
- suppress background for non-peaking final states:
  - $B_c \rightarrow \ell\nu(\gamma)$, $B_s \rightarrow \phi\nu\nu$
- design inclusive measurements:
  - $b \rightarrow s\ell\ell$ (?)
- hadronization fraction measurement w/o external inputs
- ….?

CHEF

B_c hadronization at the FCC

The most developed use-case as of now,

by Xunwu Zuo and Vasilisa Guliaeva




Presented at the Flavours at FCC Workshop by Xunwu:
[“Hadron species tagger at FCC-ee”]

Motivated by Patrick's talk at the 1st FCC flavor workshop

B_c fragmentation fractions

- Most of the time, B_c production is measured with respect to B^+

$$\mathcal{R}_{c/u} = \frac{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+) \times \mathcal{B}(B^+ \to J/\psi K^+)}$$

$$R_{c/u} = (0.683 \pm 0.018 \pm 0.009)\%$$

[LHCb, PRL 114 (2015) 132001]

- $\sigma(B^+)$ (or $f(B^+)$) is known with good precision at LHC or Z, $Br(B^+ \to J/\psi K^+)$ also (2% precision [PDG])
- But there is no measurement of $\sigma(B_c^+)$ (or $f(B_c^+)$) nor $Br(B_c^+ \to J/\psi\pi^+)$, and theoretical computations vary by a factor ~10.
  - So a precise measurement of $f(B_c)$ is not possible
  - Equivalently no absolute measurement of a branching fraction for B_c^+ is available

8

from the talk by Patrick Robbe

But: LHCb measurement with $B_c \to J/\psi\mu\nu$

Thanks to Marcello!

$$f_c = \begin{cases} (2.58 \pm 0.05 \pm 0.62 \pm 0.09) \cdot 10^{-3} & (7\,\mathrm{TeV}) \\ (2.61 \pm 0.03 \pm 0.62 \pm 0.06) \cdot 10^{-3} & (13\,\mathrm{TeV}) \end{cases},$$

stat.

hadronization of Bs and Λb

syst. + theoretical BF of $B_c \to J/\psi\mu\nu$

24%

New lattice calculation 5% uncertainty in the BF:

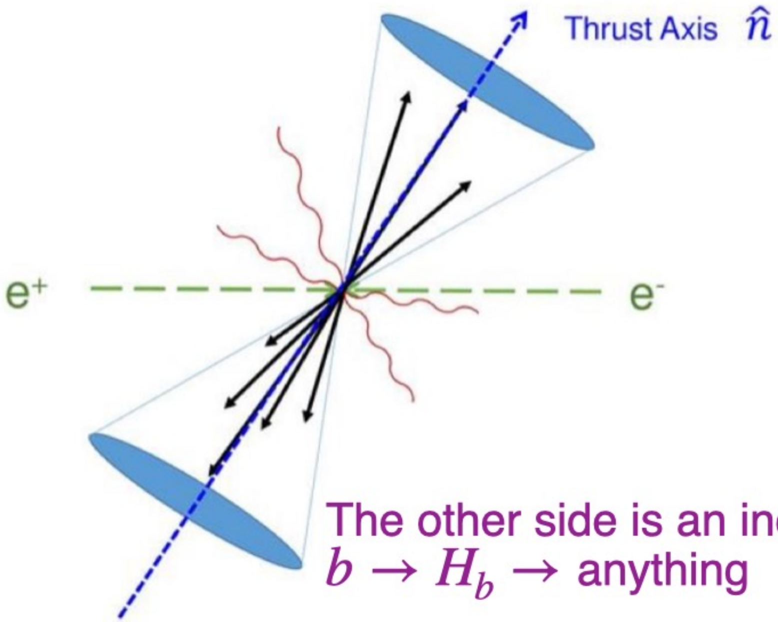
[*Phys. Rev. D* 112 (2025) 034503]

[*Phys. Rev. D* 100 (2019) 112006]

Training setup at the FCC

$Z \to qq$ events always 2 back-to-back jets

If one side is tagged a b-jet



The other side is an inclusive $b \to H_b \to$ anything

Truth assigned per hemisphere

- exactly 1 (truth level) b-hadron
- consider 5 labels $B^0, B^\pm, B_s^0, B_c^\pm, \Lambda_b$, i.e. Bd, Bu, Bs, Bc, Lb
- $Z \to bbbb$ not considered

Remark:

- $B_s^* \to B_s\gamma$ is labeled Bs
- $B_{s2}^* \to B^+K^-$ is labeled Bu
- $B_c \to B_s\pi$ is labeled Bc

Input information

Standard Particle Transformer architecture

use all available reconstructed info as input

reconstructed particles

- 4-vec, charge, true mass,
- angles relative to thrust axis
- full track parameters
- PID (dN/dx, mass from TOF)

reconstructed vertices (PV+SV)

- 4-vec momentum
- 3-vec position
- number of tracks
- Chi2, significance of displacement
- angle relative to thrust axis

Several types of the tagger

Consider 6 setups to understand performance

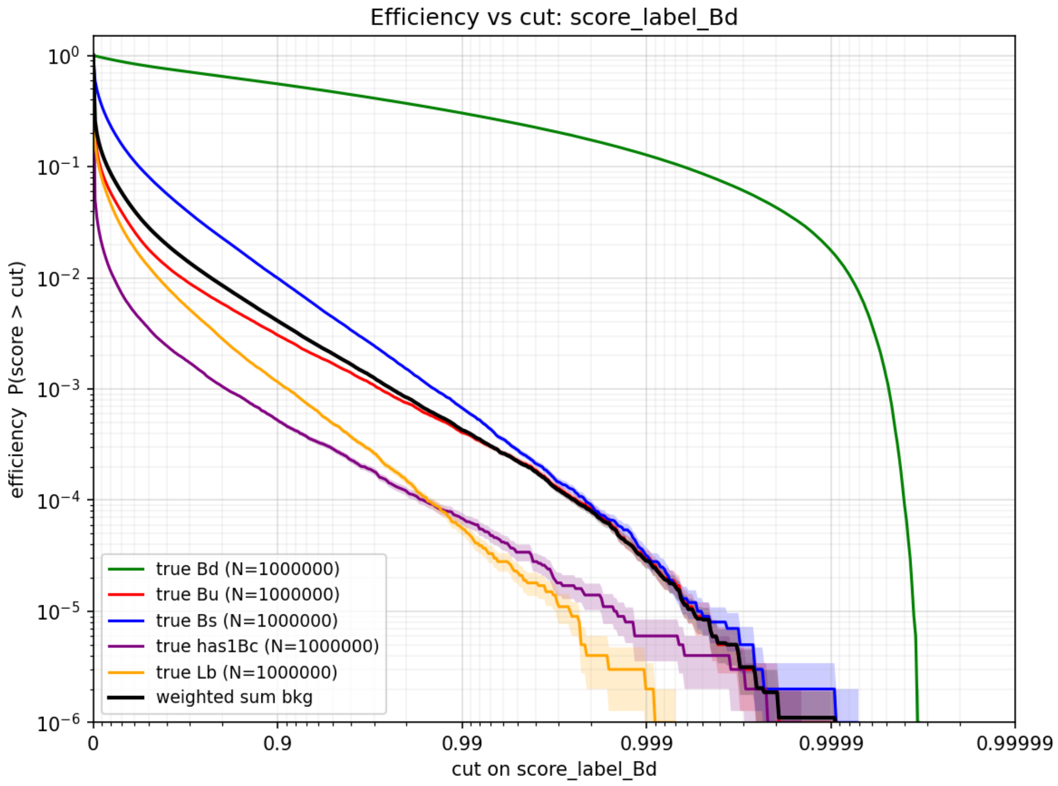
- **One hemisphere**: input info from a chosen hemisphere
- **Full event**: choose 1 hemisphere for tagging, but also include info from other hemisphere

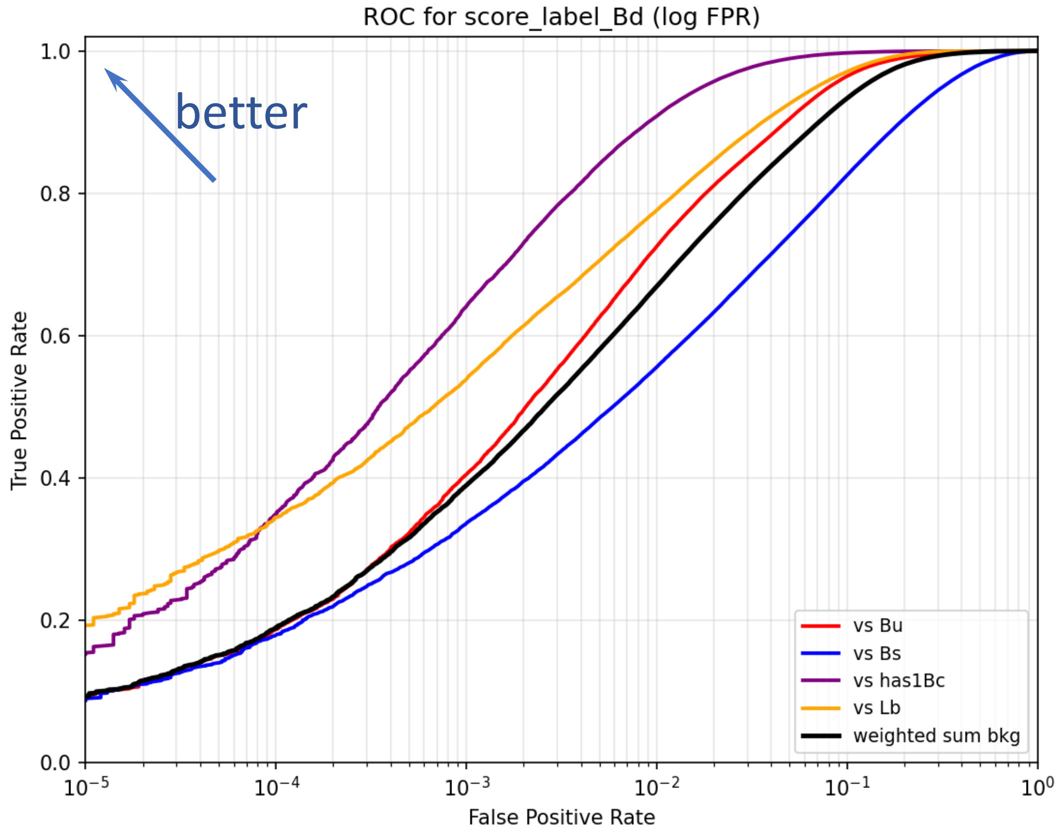
$\otimes$

- **All reco particles**: complete reconstructed info (including signal decay)
- **Excluding signal**: based on truth, mask all particles and vertices from signal decay chain, use everything else
- **Excluding signal excluding neutral**: based on truth, use only non-signal tracks

All-inclusive (+signal) tagger performance: Bd

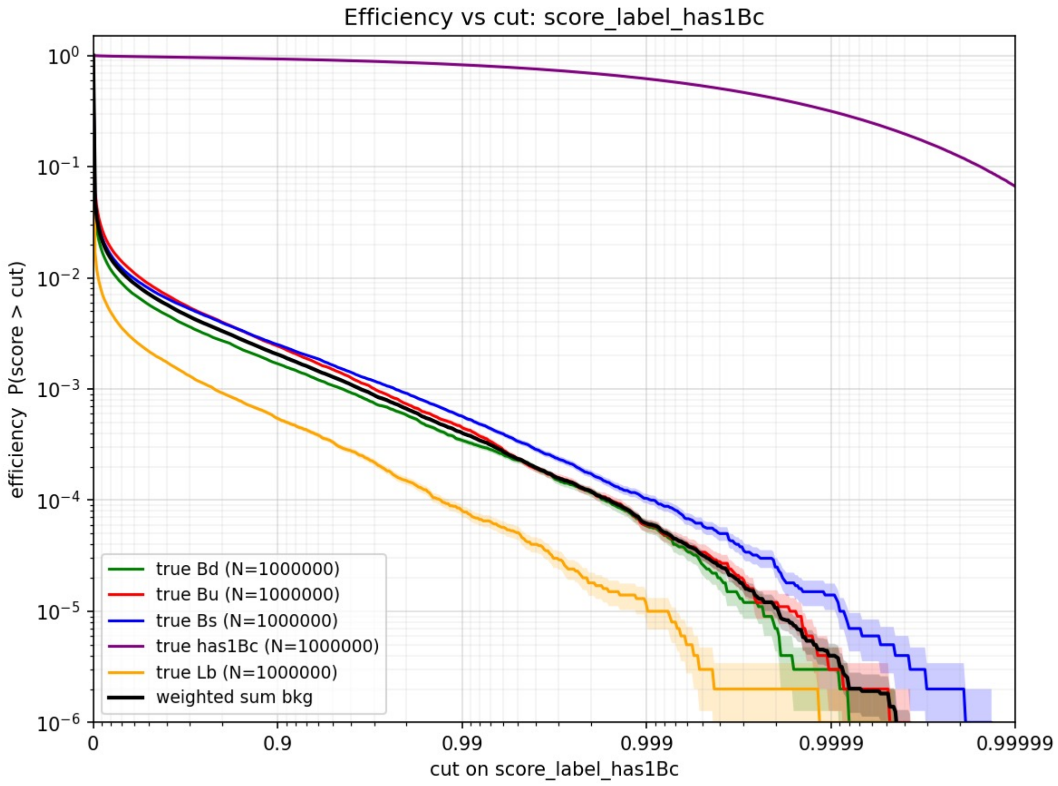
Setup: hemisphere ⊗ all particles

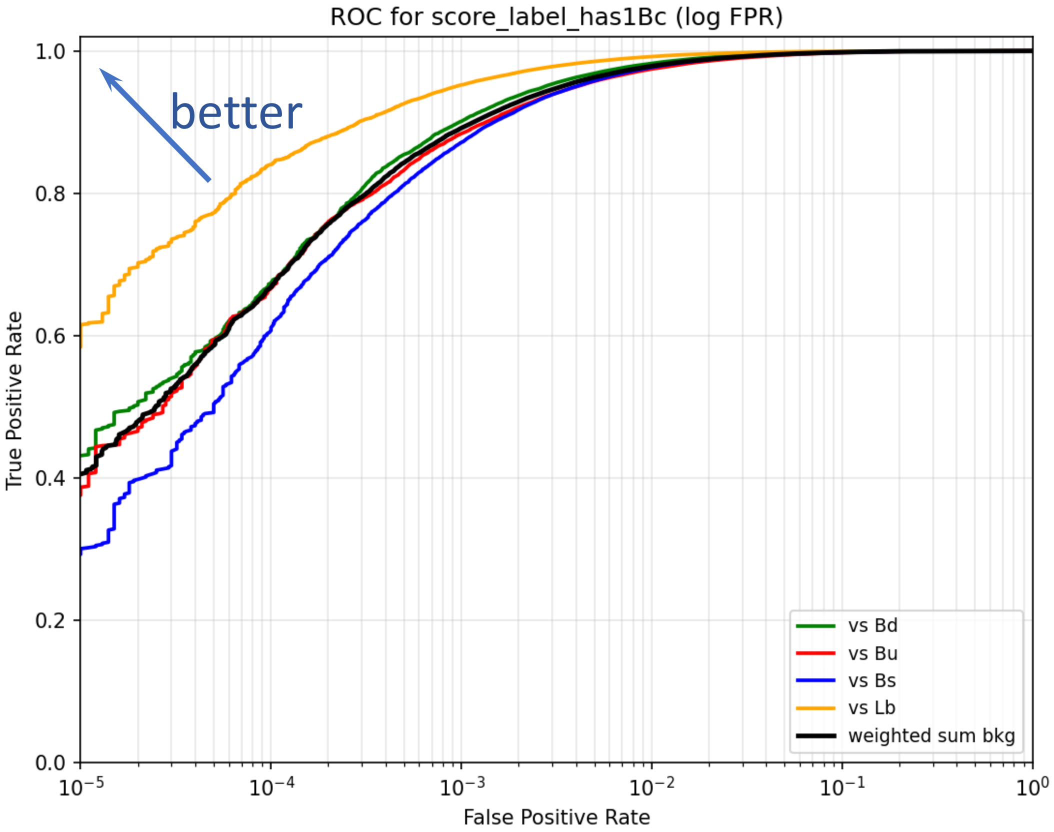




All-inclusive (+signal) tagger performance: Bc

Setup: hemisphere ⊗ all particles





Partial summary (1/3)

- All b-hadrons can be well-separated from others
- Worst case is Bs vs Bd (10^{-2} bkg rejection for 50% signal eff)
- Great performance for Bc and Λb (better than 10^{-4} bkg rejection for 50% signal eff)

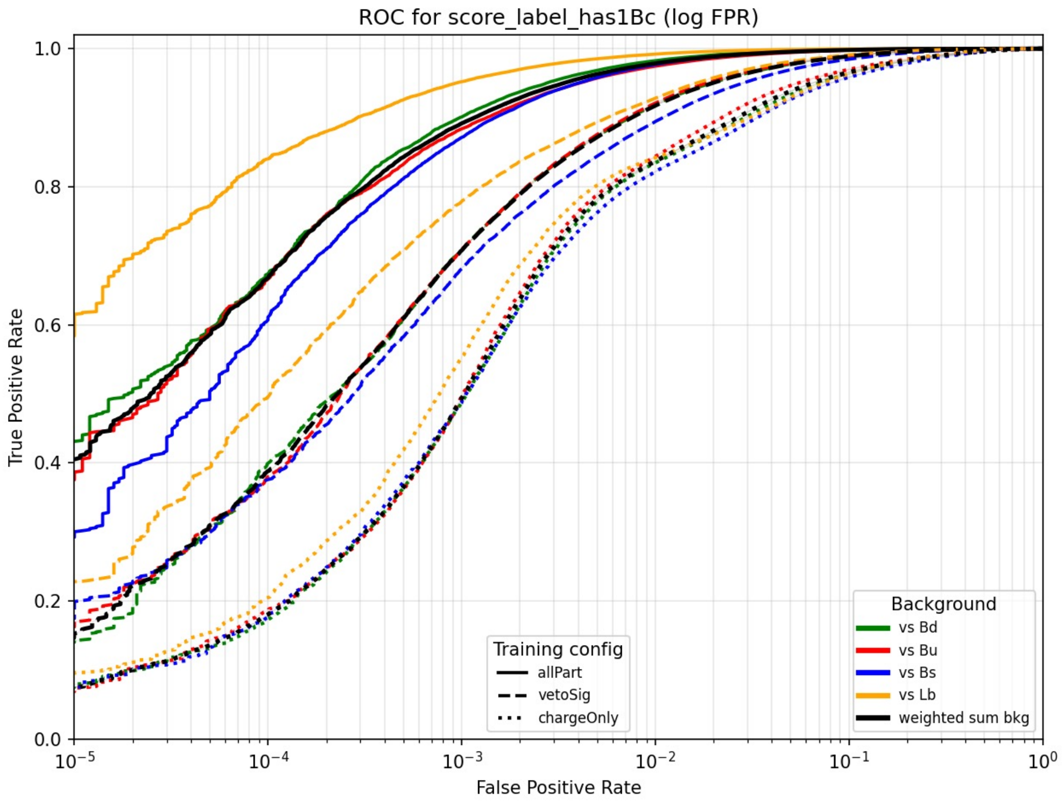
Include vs Veto signal: Bc tag

hemisphere ⊗

complete info

vs veto signal

vs veto signal & veto neutral



significant reduction of separation power

But in case of Bc vs others, a good separation still retained

Include vs Veto signal: Bd tag

hemisphere ⊗

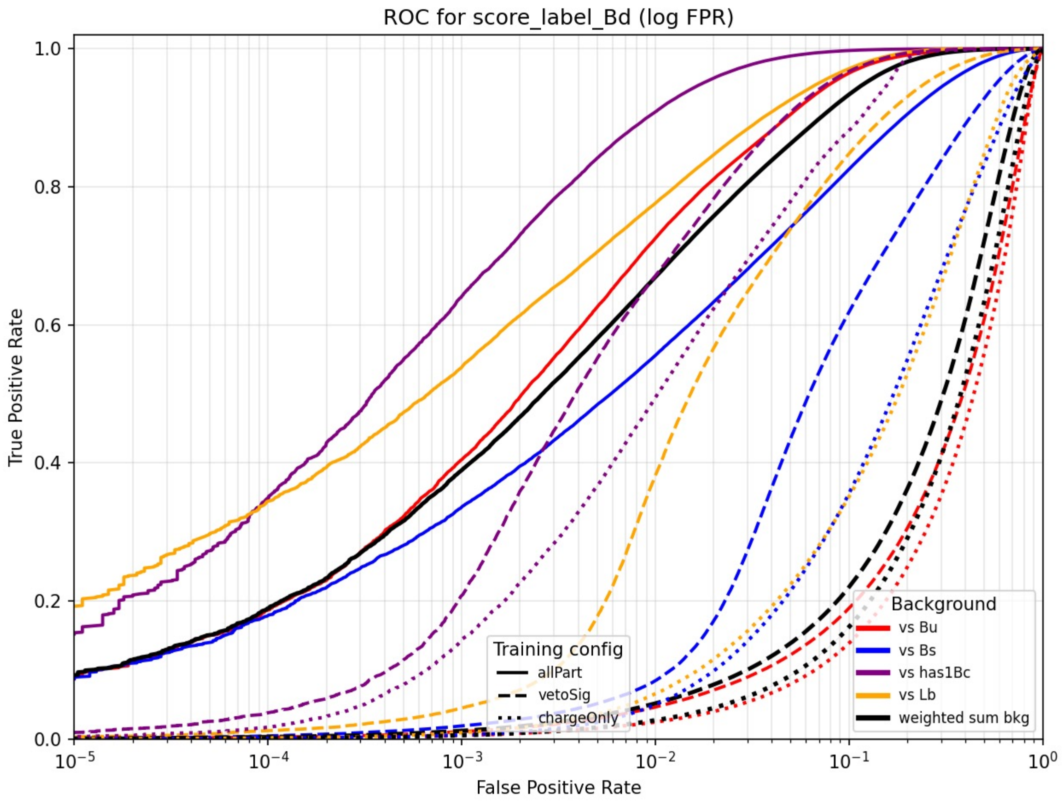
complete info

vs veto signal

vs veto signal & veto neutral

significant reduction of separation power

In case of Bd vs others, tagging info almost purely come from signal itself



Partial summary (2/3)

- All b-hadrons can be well-separated from others
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- Tagging power comes from both signal decay itself and hadronization. Hadronization info is more useful in case of Bc than Bd

Why compare all these setups?

Let’s take a step back…

and think about why we wanted a tagger in the first place

What kind of tagger?

We wanted to have an **inclusive tagger** to break circular logic

$$N_{B_c}^{obs} = \Sigma N_b f_{B_c} \epsilon_i^{tag} \mathcal{B}(B_c \to X_i) \epsilon_i^{reco} \xrightarrow[\text{independent of decay}]{\text{uniform } \epsilon_i} N_{B_c}^{obs} = N_b f_{B_c} \epsilon^{tag} \epsilon^{reco} \boxed{\Sigma \mathcal{B}(B_c \to X_i)} = 1$$

Decay-aware tagger

Decay-agnostic tagger

Exclude signal decay from tagger training

uniform ϵ by construction

But…… another circular logic:

without knowing the signal, which particles to exclude?

What kind of tagger?

We wanted to have an **inclusive tagger** to break circular logic

$$N_{B_c}^{obs} = \Sigma N_b f_{B_c} \epsilon_i^{tag} \mathscr{B}(B_c \to X_i) \epsilon_i^{reco} \xrightarrow[\text{independent of decay}]{\text{uniform } \epsilon_i} N_{B_c}^{obs} = N_b f_{B_c} \epsilon^{tag} \epsilon^{reco} \boxed{\Sigma \mathscr{B}(B_c \to X_i)} = 1$$

Decay-aware tagger

tagger uses decay info

Straightforward application

ϵ decay-dependent

Need to address 2 questions:

- To what extend is it decay-dependent?
- How to calibrate tagging eff?

Decay-agnostic tagger

Exclude signal decay from tagger training

uniform ϵ by construction

easy to calibrate, with candle modes

But…… another circular logic:

without knowing the signal, which particles to exclude?

- To what extend is it decay-dependent?
- How to calibrate tagging eff?

A solution to break the loop

uncertainty estimate

$$\epsilon^{tot} = \Sigma\mathscr{B}(B_c \to X_i)\epsilon_i^{tag}$$

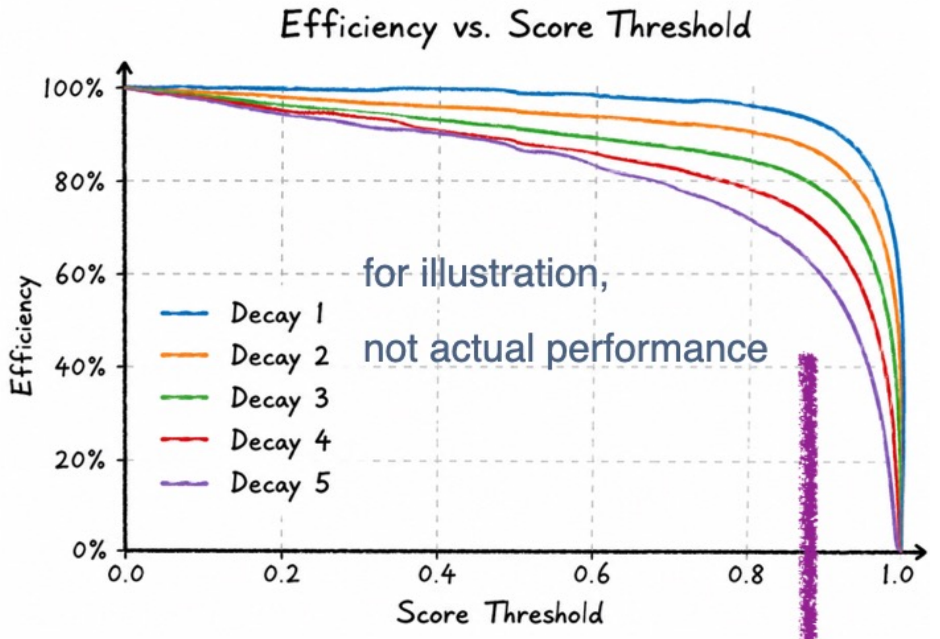
$$\delta\epsilon^{tot} \qquad \delta\mathscr{B}_i \qquad \delta\epsilon_i^{MC} + \delta\epsilon_i^{calib}$$

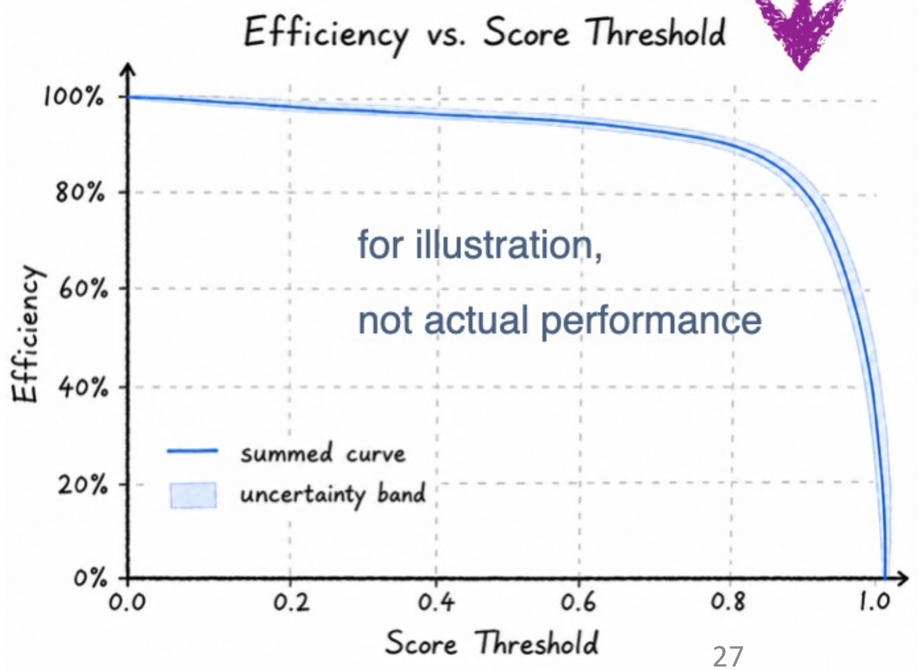
theo unc, can be conservative

MC stats unc, approaches 0 with big enough sample

per-object unc, can be calibrated in other ways with high precision

Vary all uncertainties randomly, take the envelope of variation as a (conservative) total uncertainty band.



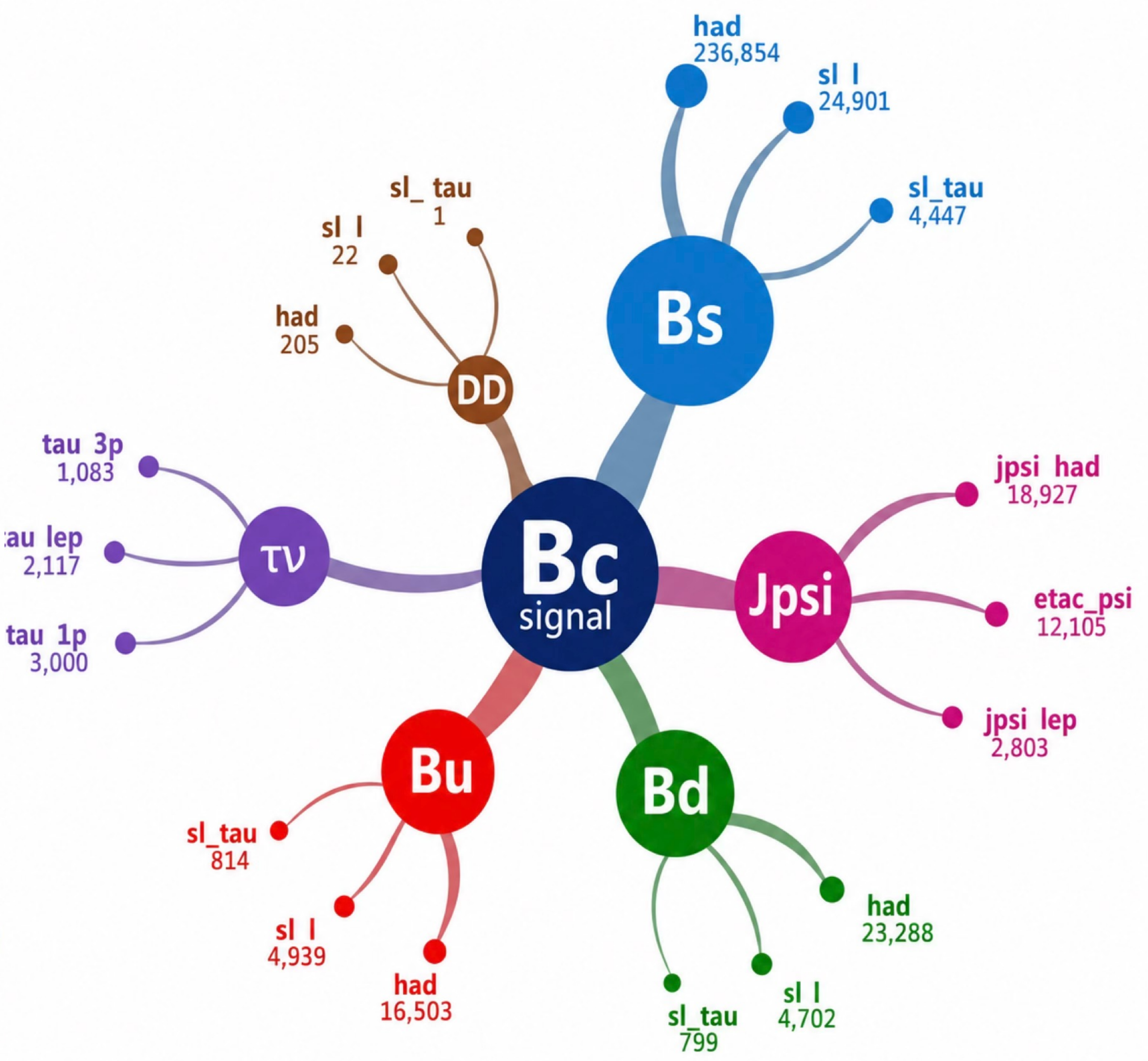


Explicit Bc decays

- A zoology of decay modes
- 12776 explicit decay modes found in sample
- 75% are $B_c \to B_s$
- Only a small fraction are fully reconstructable

4 level of categories

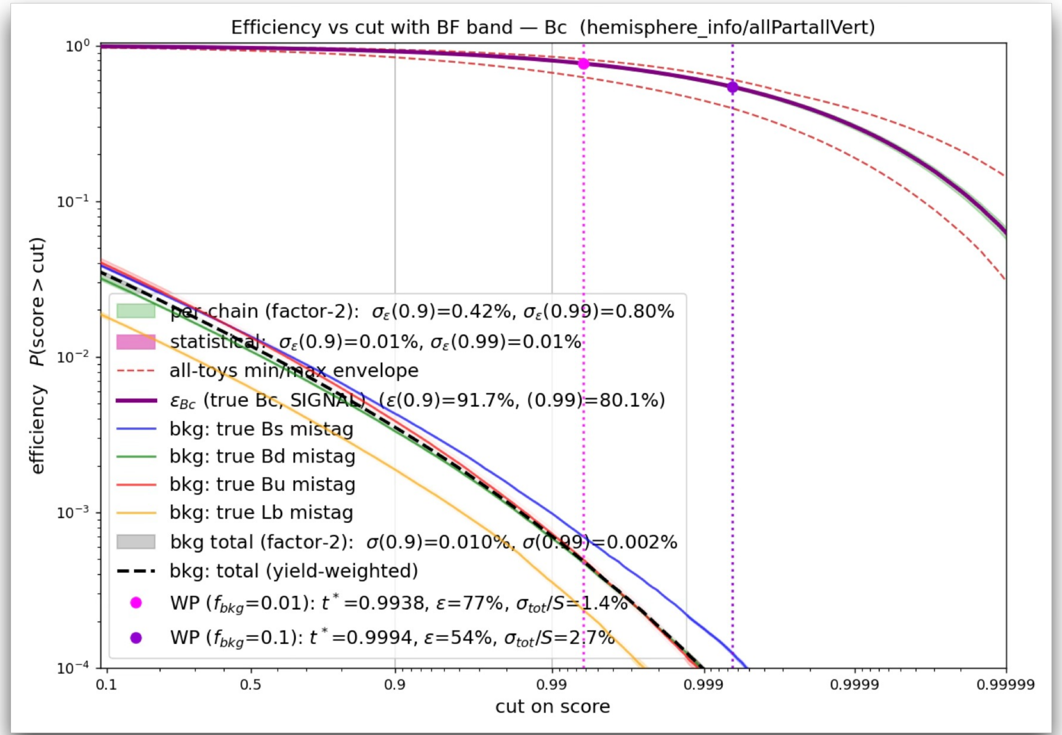
1. Direct daughters of Bc ($\to B_s, B_d, B_u, DD, J/\psi$)
2. Sub modes (daughter decay type, hadronic, semilep)
3. Vertex topology (whether each vertex is reconstructable)
4. Individual decay chain

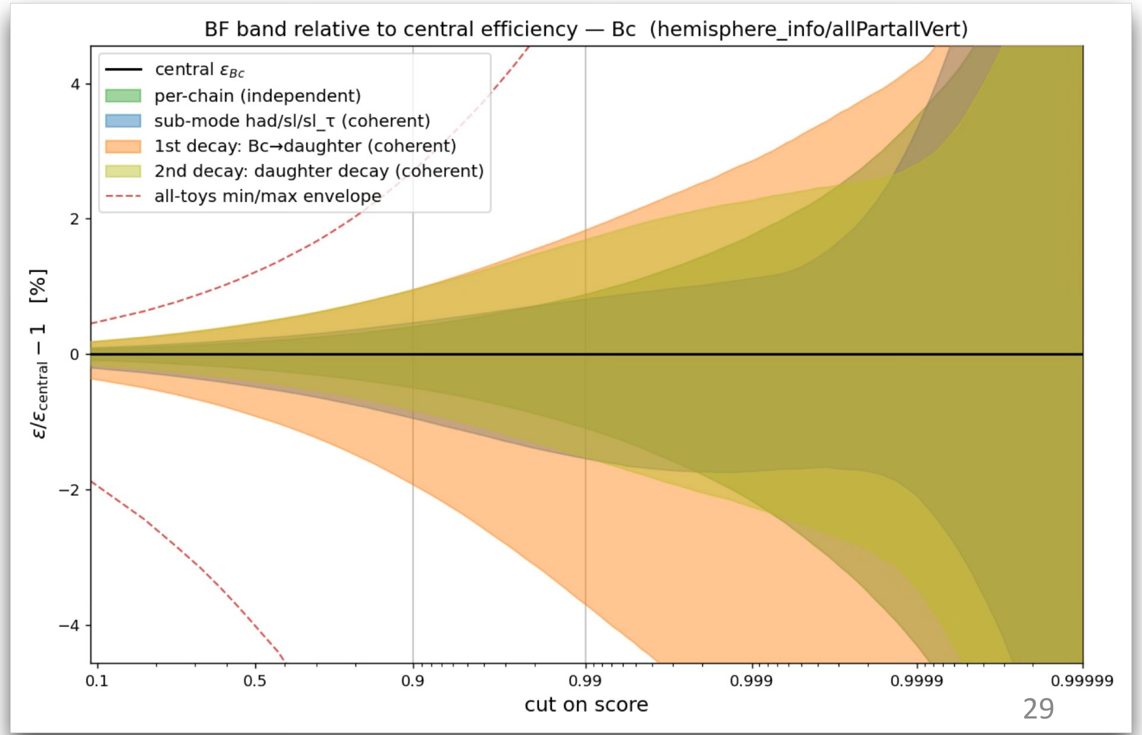


by Vasilisa Guliaeva

Uncertainty estimate for a simple scenario

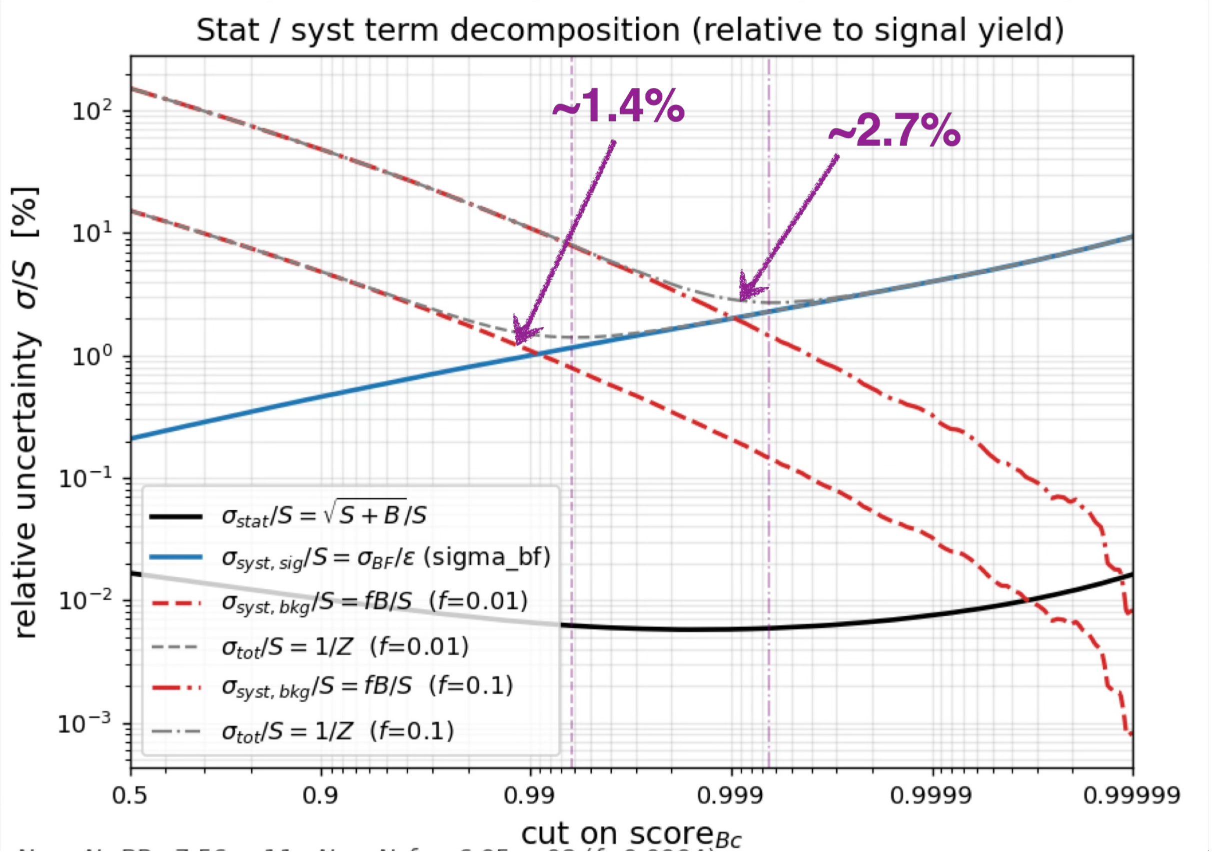
- Each BR is allowed to vary independently by +100%/-50%, keeping total = 1
- Ensemble of toys to make envelope
- The min/max line is the one toy where all 14,197 chains fluctuate to their extreme in the same direction at once
- since the chains are independent (per-chain the whole basis of the scheme), the probability of this joint configuration is ~(tail)^{14000} ≈ 0





Estimate of the total uncertainty in f_{Bc}

- apply the same envelope estimate to other b-hadrons (likely conservative)
- consider other hadronization fractions are known up to 10% (1%) for syst scenarios
- **a precision in f_{Bc} at percent level seems very achievable**



Informed BF variations for Bc decay chains

BF variation scheme · knobs × scenarios

Bc factorises Bc → X + Y then X → U V · columns = the level each knob takes in that scenario

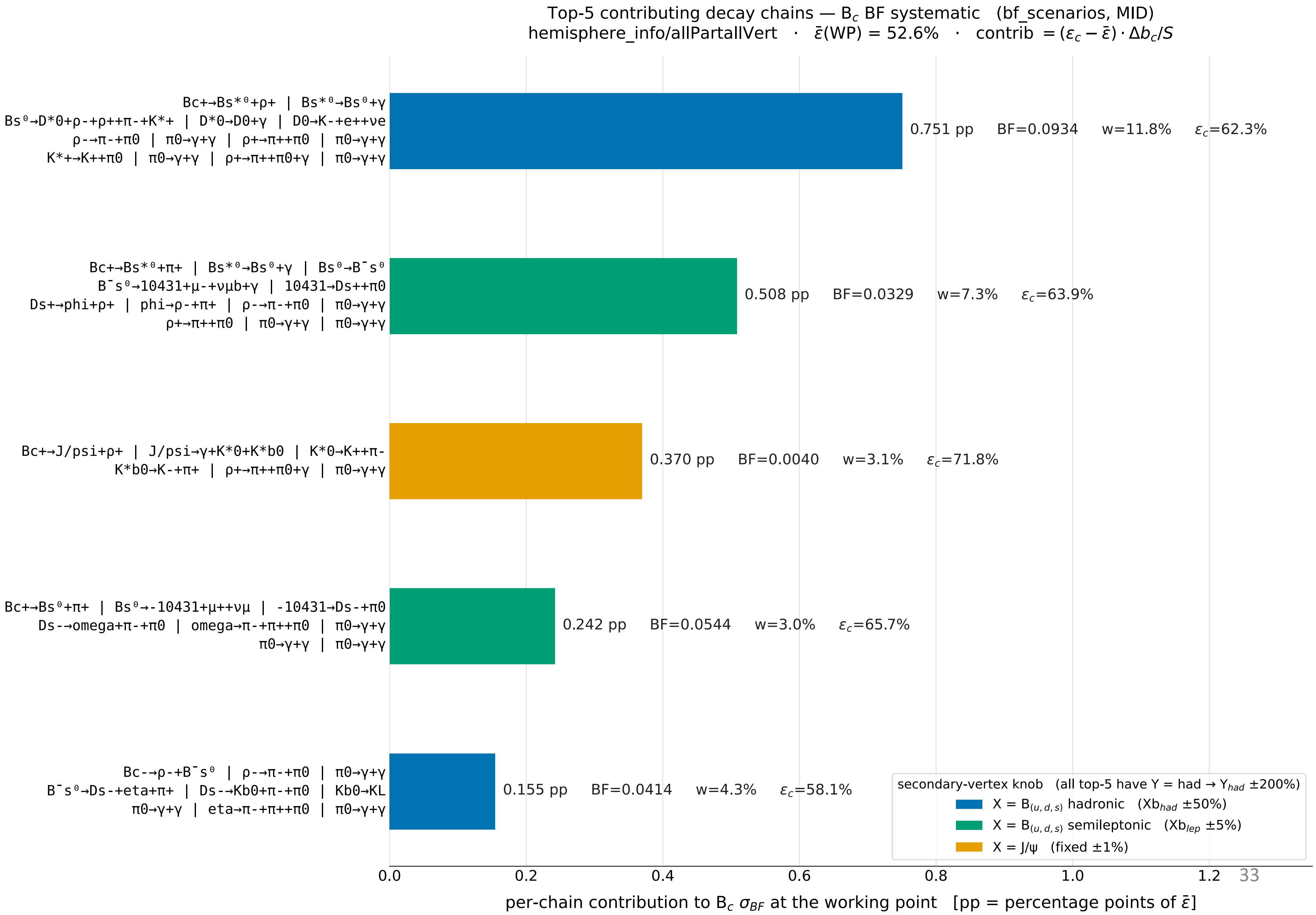
		MEASURED (what-if)		SCENARIO (theory)		
KNOB	APPLIES TO			TIGHT	MID	LOOSE
PRIMARY VERTEX — Bc → X + Y (companion Y)						
Y_had	Bc companion Y — hadronic	±10%	±30%	±100%	±200%	±500%
Y_lep	Bc companion Y — semileptonic / leptonic			±5%	±10%	±50%
SECONDARY VERTEX X → U V & ORDINARY B (same Xb knobs, per each particle's own decay)						
Xb_had	Bc remnant X = Bu/Bd/Bs or primary ordinary B — hadronic			±10%	±50%	±100%
Xb_lep	Bc remnant X = Bu/Bd/Bs or primary ordinary B — semileptonic			±1%	±5%	±10%
Xjpsi	secondary X = J/ψ (fixed, not an axis)			±1%	±1%	±1%

Bc: BF-variation grid

		$Y_{\rm lep} = \pm 50$			± 10			± 5		
$Y_{\rm had}$	$X_{b,\rm had}$	$X_{b,\rm lep}$=10	5	1	10	5	1	10	5	1
±500	±100	**3.47**	3.46	3.46	3.46	3.45	3.45	3.46	3.45	3.45
	±50	3.40	3.39	3.39	3.39	3.39	3.38	3.39	3.38	3.38
	±10	3.37	3.36	3.36	3.36	3.35	3.35	3.36	3.35	3.35
±200	±100	2.58	2.58	2.57	2.56	2.55	2.55	2.56	2.55	2.55
	±50	2.46	2.46	2.46	2.44	**2.43**	2.43	2.44	2.43	2.43
	±10	2.41	2.40	2.40	2.38	2.37	2.37	2.38	2.37	2.37
±100	±100	2.05	2.05	2.04	2.01	2.01	2.00	2.01	2.01	2.00
	±50	1.87	1.86	1.86	1.82	1.81	1.81	1.82	1.81	1.81
	±10	1.77	1.77	1.76	1.72	1.71	1.70	1.71	1.70	**1.70**
±30*	±100	1.58	1.57	1.57	1.51	1.50	1.49	1.51	1.50	1.49
	±50	1.28	1.27	1.26	1.15	1.13	1.13	1.14	1.13	1.12
	±10	1.07	1.06	1.05	0.88	0.86	0.85	0.88	0.85	0.84
±10*	±100	1.49	1.48	1.48	1.40	1.39	1.39	1.40	1.39	1.38
	±50	1.14	1.12	1.12	0.97	0.95	0.94	0.96	0.94	0.94
	±10	0.89	0.87	0.86	0.55	0.51	0.49	0.53	0.48	0.47

per-chain, 20k toys, $f_{\rm bkg} = 10\%$; cell = $\sigma_{\rm tot}/S$ [%] at the optimal WP; labels = ± variation in %. **Bold**: tight/mid/loose scenarios. * what-if: hadronic Bc BFs measured.

Worst offenders



Summary (3/3)

- All b-hadrons can be well-separated from others
- Worst case is Bs vs Bd (10^{-2} bkg rejection for 50% signal eff)
- Great performance for Bc and Λb (better than 10^{-4} bkg rejection for 50% signal eff)
- Tagging power comes from both signal decay itself and hadronization. Hadronization info is more useful in case of Bc than Bd
- A totally **inclusive, theory-independent** f_{Bc} measurement better than 2%

Next (ongoing) steps

- Application/development of other use-cases
- Training and application to LEP data
- Training on LHCb MC and testing on LHCb data!