Modelling B meson decays at Belle (II)

LHC HF WG discussion on HEP simulations

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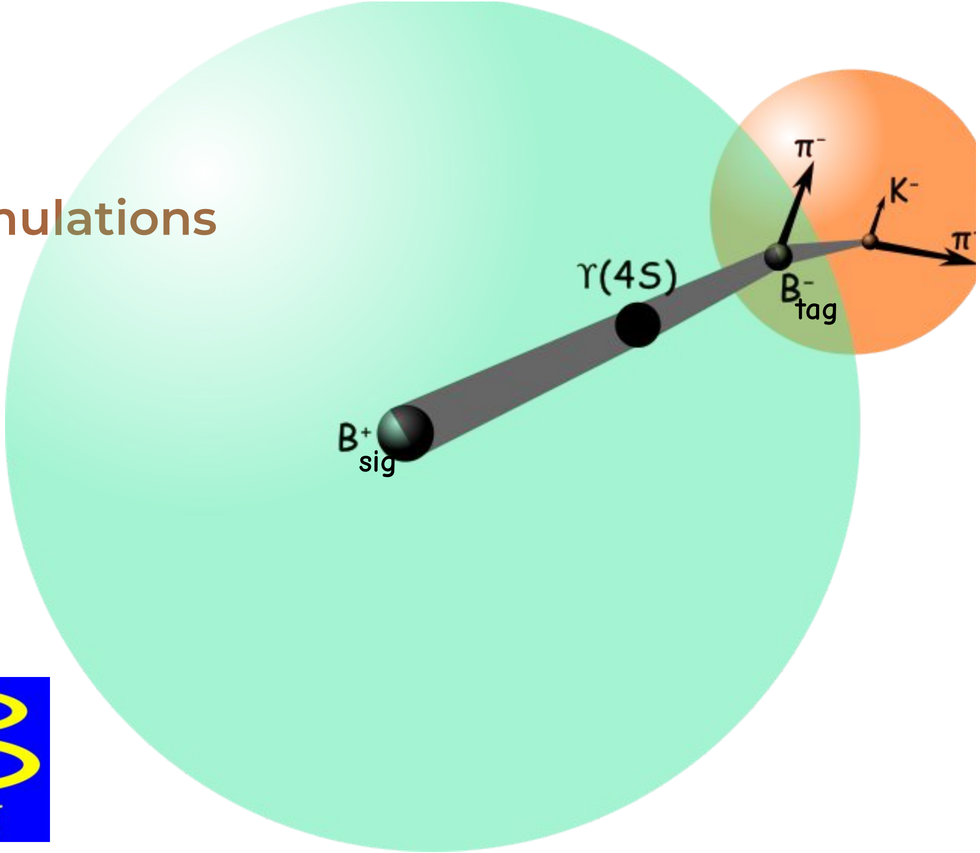
on behalf of the Belle II collaboration

28 June 2023



Outline

- ➢ Belle II experiment and B-tagging
- ➢ Hadronic B-tagging built on B to charm decays
- ➢ How are B decays generated? EvtGen + PYTHIA
- ➢ State of the measurements and interpretations in PDG
- ➢ What about D decays?
- ➢ Summary/Conclusion

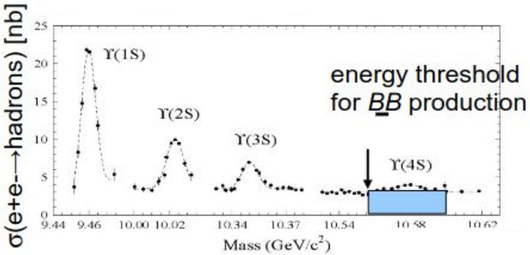
Realistic modelling of B decays is essential for many reasons like background estimation, but will focus on the studies performed in the context of B-tagging.

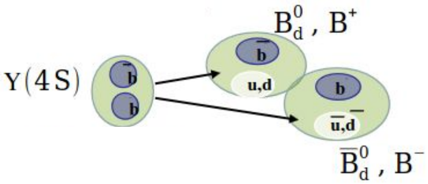
Belle II experiment

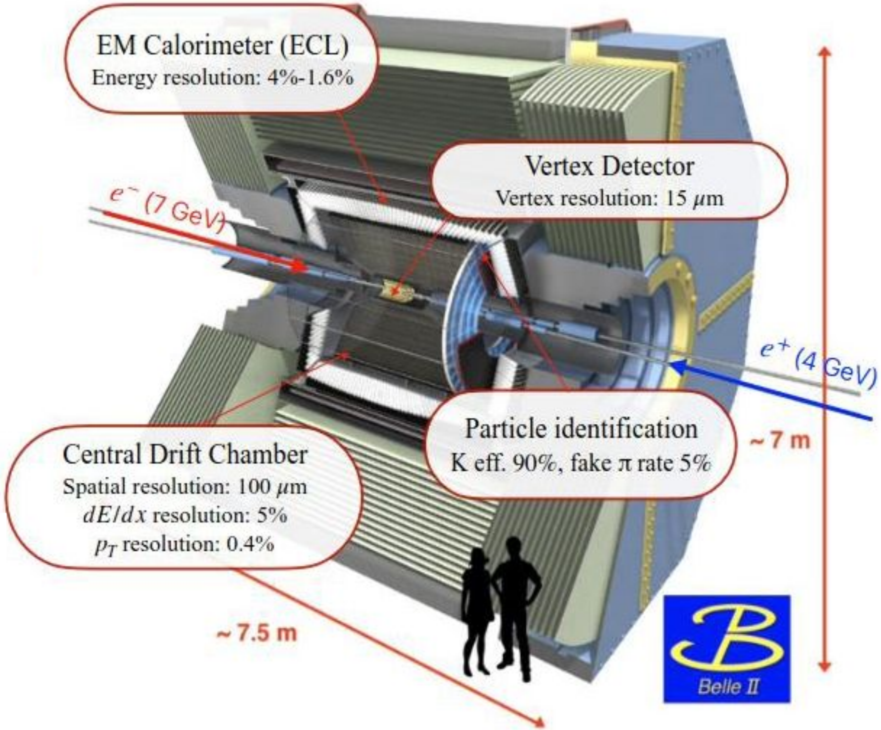
2 B's and nothing else

SuperKEKB: asymmetric e^-e^+ collisions at (or close to) $\Upsilon(4S)$ resonance.
World record peak luminosity: $4.7 \times 10^{34}\ cm^{-2}\ s^{-1}$

Belle II: B-factory ($\sim 1.1 \times 10^9$ $B\bar{B}$ pairs per ab^{-1})







2 B's and nothing else
⇒ B-tagging and flavour tagging

~500 fb^{-1} on-resonance data collected so far.
Can be combined with Belle (711 fb^{-1}).
Target: 50 ab^{-1}.

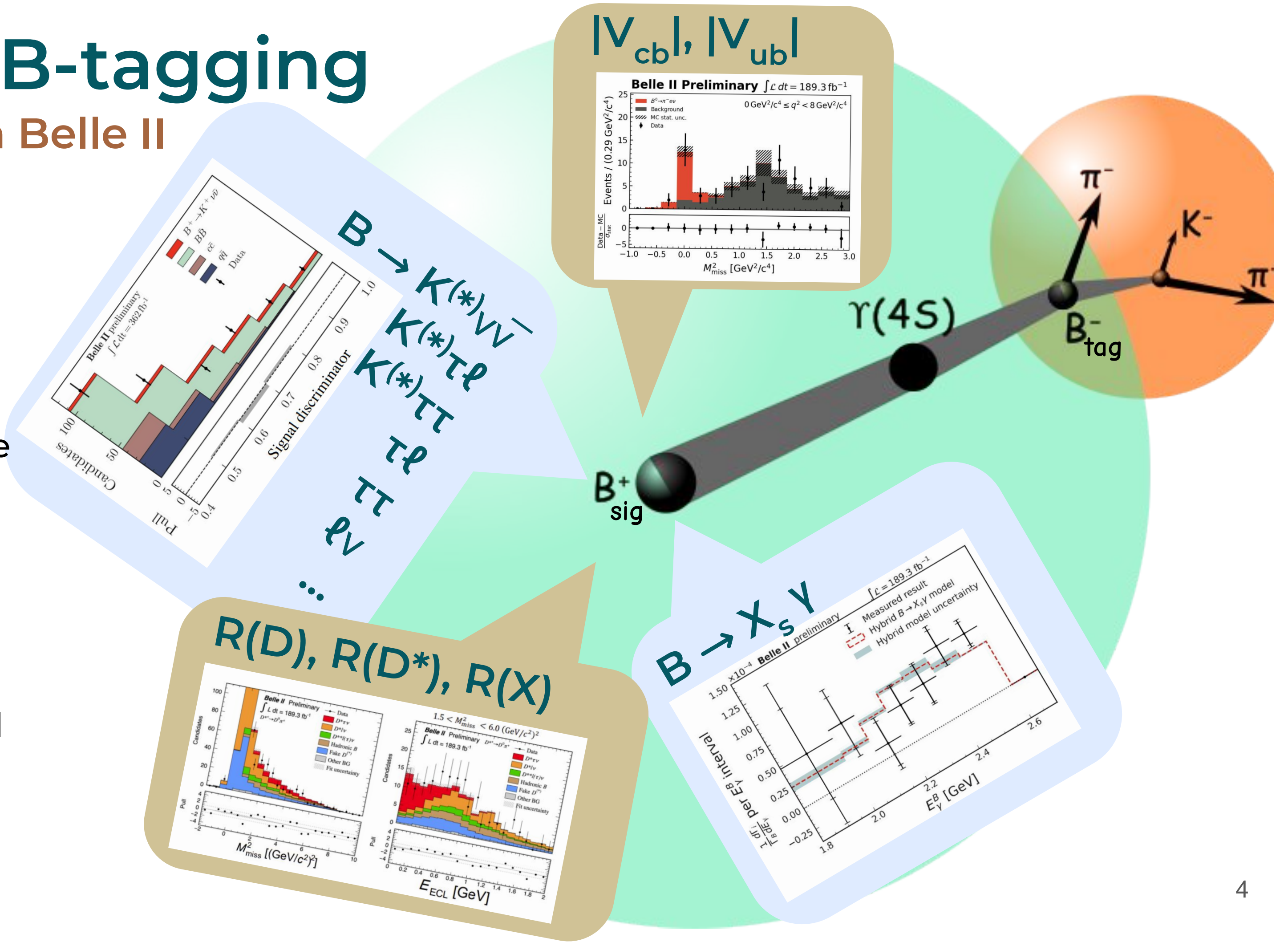
Hadronic B-tagging

is widely used in Belle II

It allows neutrino reconstruction like in $B \to D\ell\nu$ at Belle II.

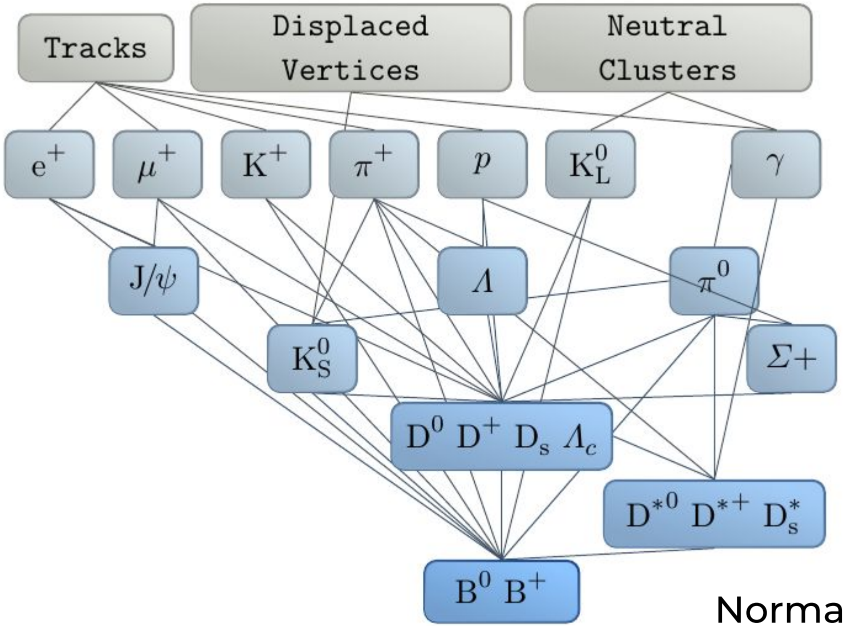
(Or to reconstruct a particle inclusively like in $B \to X_s\gamma$)

Effective hadronic B-tagging is essential for a large part of Belle II's physics program.



Hadronic B-tagging tool at Belle II

called Full Event Interpretation (FEI)



Essentially $B \to D^{(*)}\, m\pi^{\pm}\, n\pi^0$
(90% of efficiency)

BDTs for each decay **trained on MC.**

Total efficiency < 1% with high purity.

But, large data-MC discrepancy

Calibration factors:
B^+: (65 ± 2)%
B^0: (83 ± 3)%

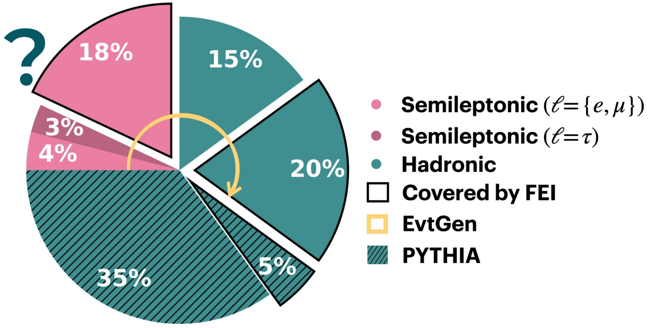
Normalization applied to account for it
⇒ large source of systematics
⇒ And also suboptimal performance?

But why such large discrepancy?

How are B decays generated?

EvtGen

Hadronic B-decays: ~75% of the total branching fraction.




```
Decay B+

0.054900000   anti-D*0  e+  nu_e      BGL 0.02596 -0.06049 0.01311 0.01713 0.00753 -0.09346,
0.023100000   anti-D0  e+  nu_e       BGL 0.0126 -0.094 0.34 -0.1 0.0115 -0.057 0.12 0.4;
0.007570000   anti-D_10  e+  nu_e     LLSW 0.71 -1.6 -0.5 2.9;
0.003890000   anti-D_0*0  e+  nu_e    LLSW 0.68 -0.2 0.3;
0.004310000   anti-D'_10  e+  nu_e    LLSW 0.68 -0.2 0.3;
0.003730000   anti-D_2*0  e+  nu_e    LLSW 0.71 -1.6 -0.5 2.9;
                 .
                 .
                 .
                 .
0.000383590   D+  anti-D0             PHSP;
0.000392390   D*+  anti-D0            SVS;
0.000630000   anti-D*0  D+            SVS;
0.000810000   anti-D*0  D*+           SVV_HELAMP 0.56 0.0 0.96 0.0 0.47 0.0;
                 .
                 .
```

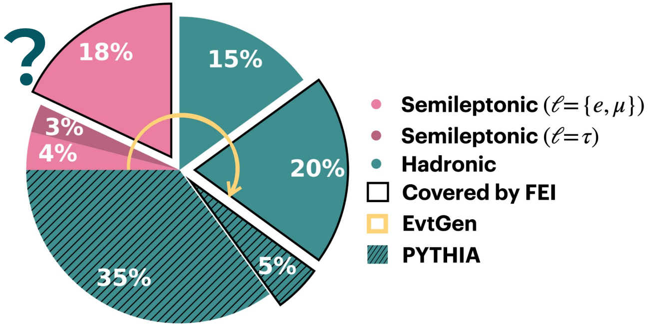
The largest decays are at 10^{-2}, 10^{-3} so we are talking about $O(10^4)$ decay channels.
We only list $O(10^3)$ explicitly

This is from PDG and some guestimates…
but what about the rest ?

How are B decays generated?

EvtGen + PYTHIA

Hadronic B-decays: ~75% of the total branching fraction.
But only about half of it is measured.
PYTHIA is employed to generate the other half in MC.



Quark transition	modeID in PYTHIA v8	$\mathcal{B}^{\text{Belle}}(\%)$	$\mathcal{B}^{\text{Belle II}}(\%)$
u anti-d anti-c u	23	31.23	20.26
u anti-d anti-c u	43	-	3.87
u anti-s anti-c u	43	2.23	2.02
c anti-s anti-c u	43	-	6.66
c anti-d anti-c u	43	-	0.36
u anti-d anti-u u	23	-	0.27
c anti-s anti-u u	23	-	0.36
u anti-u anti-d u	23	-	0.18
d anti-d anti-d u	23	-	$<$0.01
s anti-s anti-d u	23	-	0.01
u anti-u anti-s u	23	-	0.20
d anti-d anti-s u	23	-	0.16
s anti-s anti-s u	23	-	0.13
anti-s u	91	-	0.45
anti-cd_1 uu_1	63	3.40	2.97
anti-cd_1 uu_1	64	1.27	-
anti-cs_0 cu_0	63	0.85	-
anti-cs_1 uu_1	63	0.18	0.81
anti-cs_1 uu_1	64	0.04	-
anti-cd_0 cu_0	63	0.04	-
Total PYTHIA contribution		39.24	38.71

- ➢ PYTHIA is called for quark fragmentation according to relative rates determined by the parameters of the StringFlav class.
- ➢ We use the default values for most parameters, with the production of some excited mesons turned off, like $a^{\pm}_1$, a^0_1, D**.

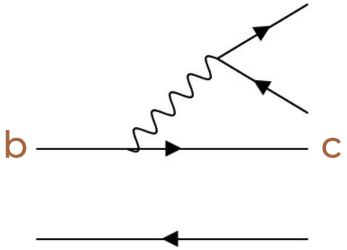
The StringFlav parameters as well as relative fractions assigned to different quark transitions need to be tuned.

- ➢ Fragmentation compares the final state with the explicitly listed decays, and if found, performed again to produce an alternative final state.
- ➢ Therefore, to exclude that a particular decay is generated by PYTHIA, it can be explicitly listed in DECAY.DEC with a branching fraction of 0%.

Need to know what not to generate as well.

Hadronic B to charm decays

we don’t know half of them!



Hadronic B-decays: ~75% of the total branching fraction.
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PYTHIA is employed to generate the other half in MC.

Understanding $B \rightarrow D^{(*)}h$ decays is essential for B-tagging.

Even among the measurements, most are performed with small data sets
⇒ Large statistical uncertainties.

Poor knowledge of hadronic B decays
⇒ Poor MC (significantly different from reality/data)
⇒ Poor hadronic B-tagging
⇒ Limits our reach to exciting physics

Is our understanding of these decays that bad?
room for improvements...

Examples in the following slides are based on the efforts related to B-tagging, but generation of hadronic B decays has impact in many places.

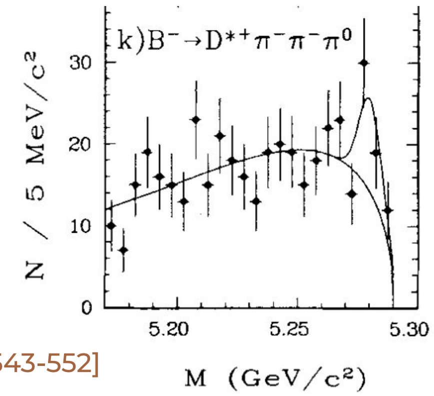
Decays in hadronic B-tagging

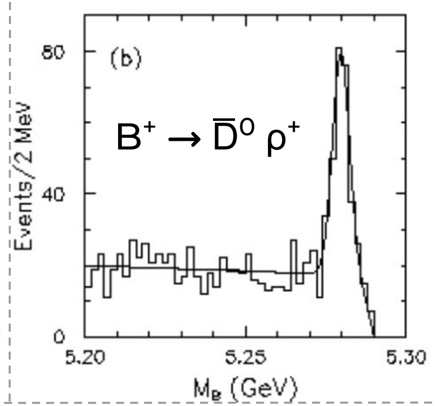
Some of the largest BF in PDG

Understanding
$B \to D^{(*)}h$ decays
is essential for
B-tagging.

ARGUS, 229 pb^{-1}
33 years ago
Uses M_{bc}
$\mathcal{B} = (1.5 \pm 0.7)\%$
47% uncertainty!

[Z.Phys.C 48 (1990) 543-552]





CLEO, 0.89 fb^{-1}
29 years ago
Uses M_{bc}
$\mathcal{B} = (1.34 \pm 0.18)\%$
13% uncertainty!

[PRD 50 (1994) 43-68]

Not so great even with lower multiplicity

Old measurements with large uncertainties not reflected in generation.
EvtGen only takes central value ⇒ MC contains unreliable information?

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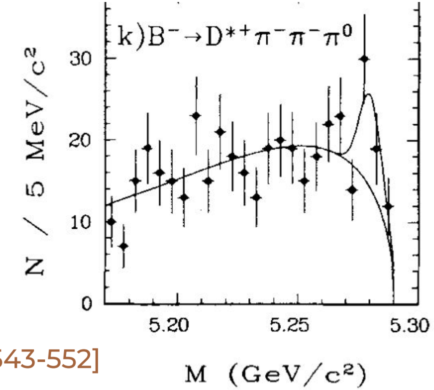

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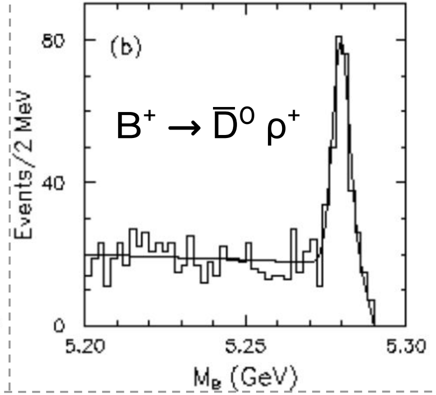

CLEO, 0.89 fb^{-1}
29 years ago
Uses M_{bc}
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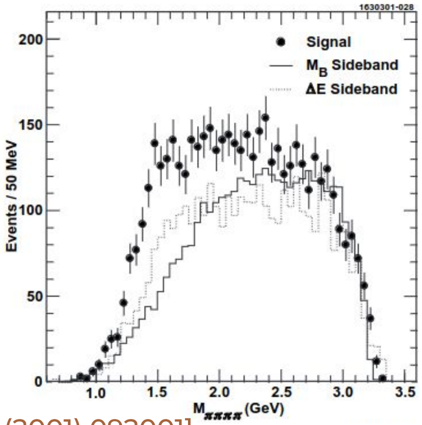
13% uncertainty!

[PRD 50 (1994) 43-68]

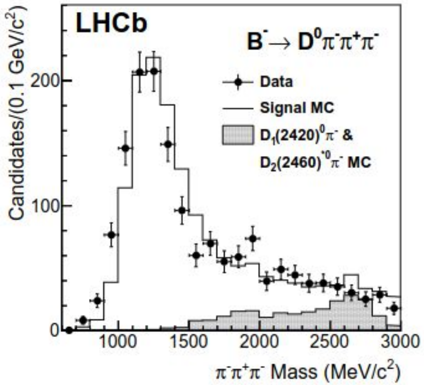
$B^+ \to \bar{D}^{*0}\pi^+\pi^+\pi^-\pi^0$

CLEO, 9 fb^{-1}
22 years ago
Uses M_{bc}
$\mathcal{B} = (1.8 \pm 0.4)\%$
22% uncertainty!

But model? ⇒ ρ'?



[PRD 64 (2001) 092001]



LHCb, 35 pb^{-1}
12 years ago

But
$\mathcal{B}(B^+ \to \bar{D}^0 a_1^+)$
not provided! 😥

[PRD 84 (2011) 092001]

Decays in hadronic B-tagging

Some of the largest BF in PDG

Understanding $B \to D^{(*)}h$ decays is essential for B-tagging.

For decays with higher multiplicity, we need to know the decay kinematics.

In MC, modelled as a coherent sum of decays through many intermediate resonances.

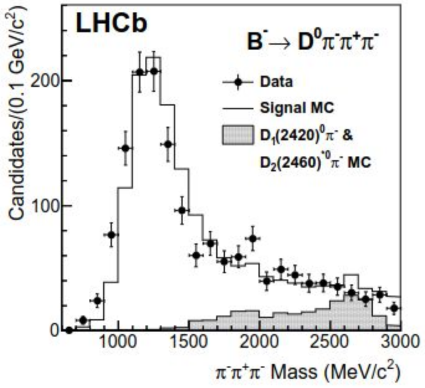
Measured:

Inclusive $D^0 \pi^- \pi^+ \pi^-$

$$\frac{\mathcal{B}(B^- \to D^0 \pi^- \pi^+ \pi^-)}{\mathcal{B}(B^- \to D^0 \pi^-)} = 1.27 \pm 0.06 \pm 0.11$$

and D** components

But LHCb does not explicitly provide information on a_1^+...
we are left with $\mathcal{B}(B^+ \to \bar{D}^0 a_1^+) = (0.4 \pm 0.4)\%$
and $\mathcal{B}(B^+ \to \bar{D}^0 \pi^+ \rho^0) = (0.4 \pm 0.3)\%$
from CLEO (1992, 212 pb^{-1}) in PDG.



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But
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not provided! 😥

Update the MC

Implement first, and then validate

Understanding $B \rightarrow D^{(*)}h$ decays is essential for B-tagging.

For decays with higher multiplicity, we need to know the decay model for MC.

Not necessarily the complete amplitude with interferences,
but something simple to set in MC, i.e., intermediate resonances.

B^+ FEI mode	Contribution	$\mathcal{B}^{\text{Belle}}(\%)$	$\mathcal{B}^{\text{Belle II}}(\%)$	$\mathcal{B}^{\text{proposed}}(\%)$
$\overline{D}^0\pi^+\pi^-\pi^+$	$\overline{D}^0\pi^+\pi^-\pi^+$ (NR)	0.46	0.51	0
	$\overline{D}^0\rho^0\pi^+$	0.39	0.42	0
	$\overline{D}^0 a_1^+$	0.18	0.26	0.58
	$\overline{D}_1^0\pi^+$	0.04	0.04	0.08
	$\overline{D}_1^{\prime 0}\pi^+$	0.03	0.02	0.03
	$\overline{D}_2^{*0}\pi^+$	0.01	0.01	0.01
	$D^{*-}\pi^+\pi^+$	-	0.09	0
		1.11	**1.36**	**0.70**

Reminder: If not explicitly set with 0% BF, PYTHIA will generate it and inflate.

For the relevant final states, we directly interpreted from the papers:

- Correcting misinterpretations of inclusive BF measurement as non-resonant component.
- Avoiding PYTHIA generating additional components
- Updating the decay model of D**
- Removing obviously wrong components

and produced new MC.

Update the MC

Implement first, and then validate

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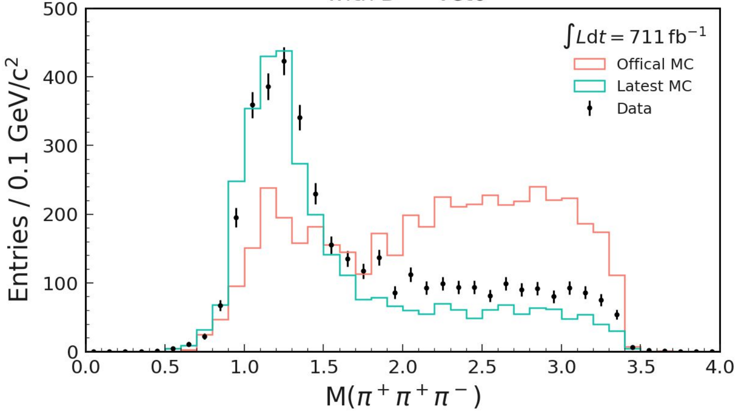
	$D^{*-}\pi^+\pi^+$	-	0.09	0
		1.11	**1.36**	**0.70**

With the help of a control sample with high signal-side purity, we validated our model via the B_{tag} reconstruction:



This not only improved the calibration factors of B-tagging, but also provided more realistic decay kinematics to train on, providing better purity.

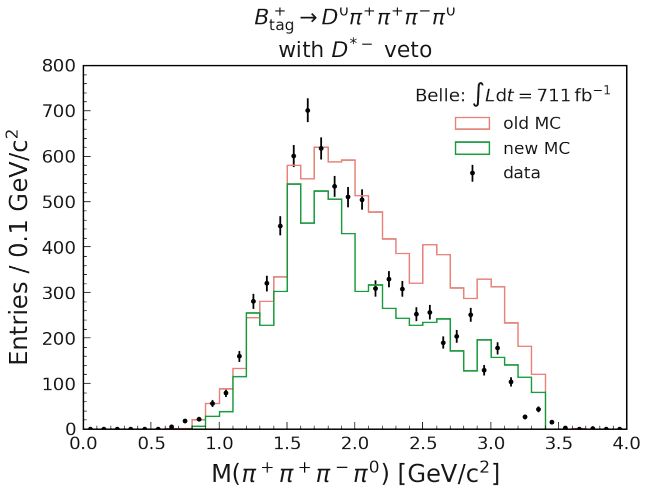
Detailed explanation on all the changes and validation in Ch4 of this thesis.

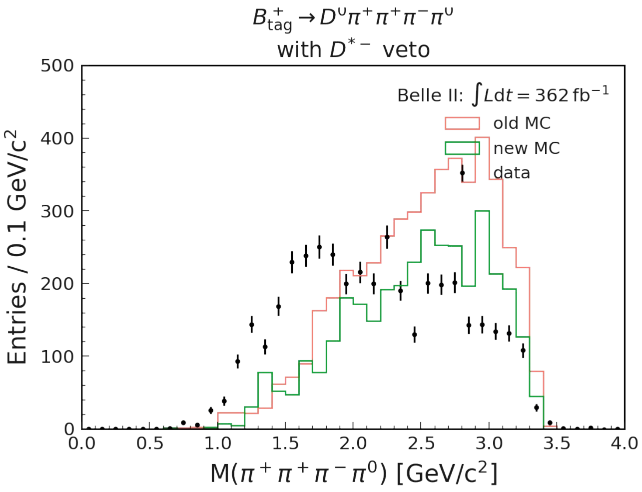
Limitations in these updates

Need more measurements!

- ➢ Old and statistically limited measurements like $\bar{D}^0\pi^+\pi^0$ and $\Lambda_c p^+\pi^+\pi^-\pi^+$
- ➢ And dependence on PYTHIA for $D^{(*)}\pi^+\pi^+\pi^-\pi^0$ which account for > 15% of the total efficiency.

Belle and Belle II have different PYTHIA (version, StringFlav params, relative composition of quark transitions). But the distribution is different in the data itself!

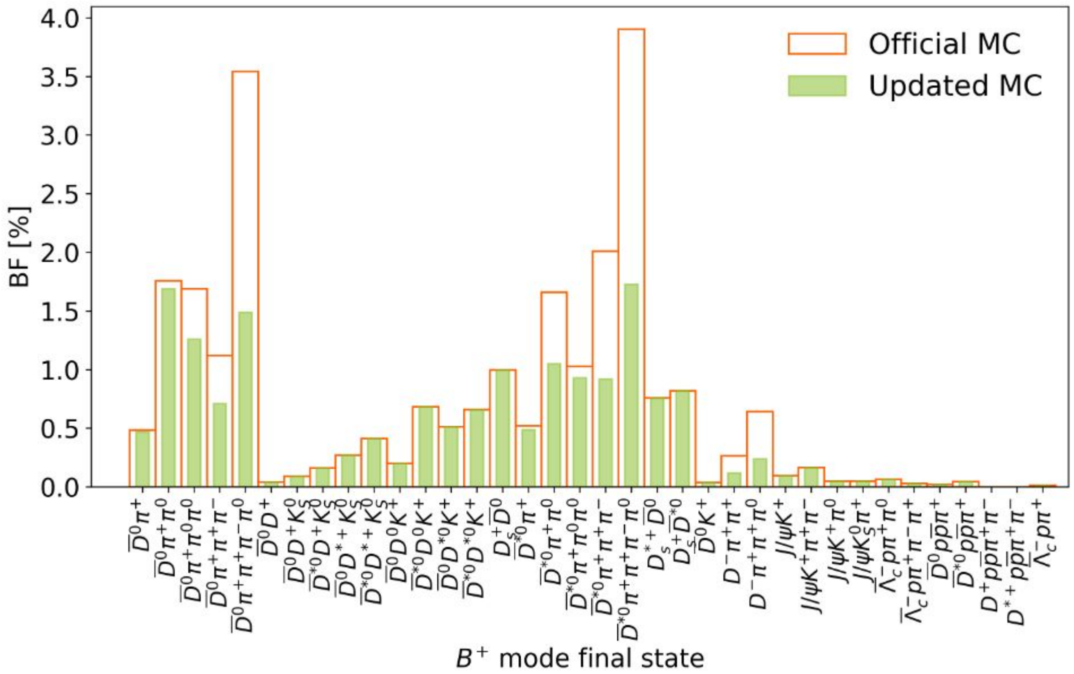


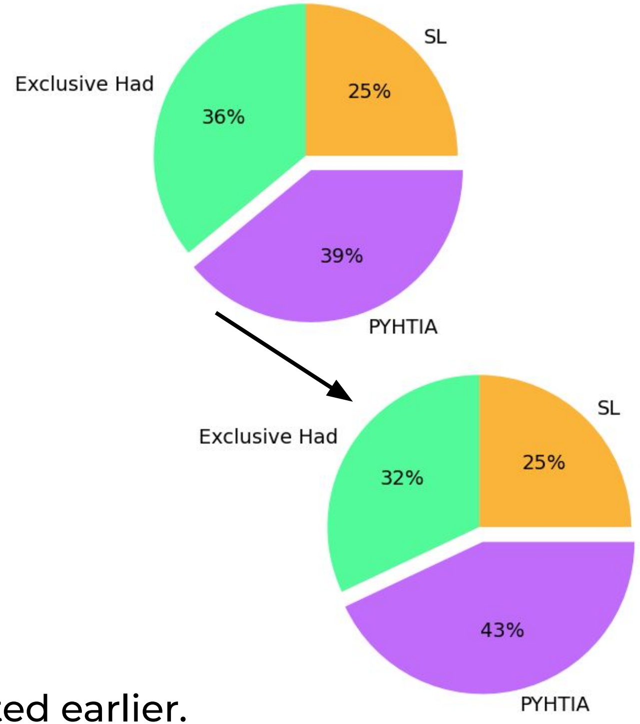


This is clear evidence of the bias introduced by training.

How does this impact the rest of MC?

After correcting the modes that contribute to the 12 main FEI final states:





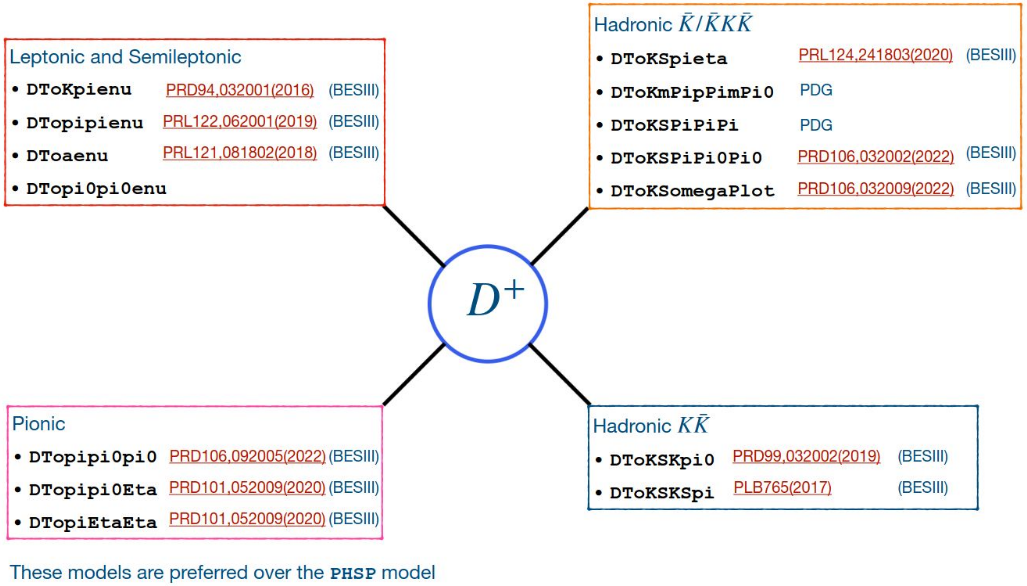
We seem to have mostly overestimated earlier.
Now, correcting shows the increase in the unknown (terra incognita) generated by PYTHIA!
In the spirit of filling the gaps, recently measurements B → Dρ (PRD) and $D^{(*)}KK^{(*)}$ (arXiv)...

What about D decays?

Taking inspiration from BESIII experiment

- ➢ Data-MC disagreements due to D decay modelling are also seen.
- ➢ There is a focused effort to update the branching fractions and improve physics models!
- ➢ Situation is relatively simpler here since there is no need for PYTHIA and Dalitz analyses (and corresponding EvtGen models) exist in some cases.

An extensive one-to-one comparison is being performed with BESIII DECAY.DEC where specific physics models are implemented over PHSP model and more multi-body decays are explored.



Other relevant changes

- Recently updated evt.pdl according to the PDG values (and we also "force" PYTHIA to use such values for coherence).
- We have (very few) additional EvtGen models, used mostly for signal productions.
- Whenever a new BF is added or a BF is touched, we rescale **all** the BFs of the decays handled by PYTHIA so that the sum is always 1 (validated by unit tests).
    - Ideally should only rescale the relevant quark transition, but this is easier.

In Belle II, we currently use:
EvtGen R02-00-00
PYTHIA 8.215
PHOTOS 3.64

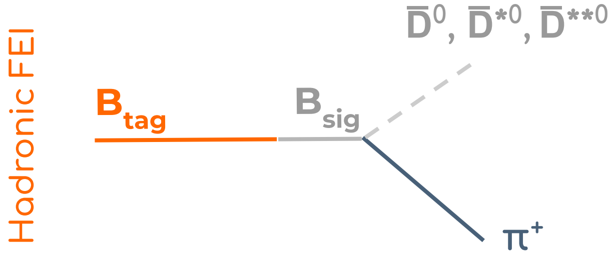
Summary

- ➢ Half of the hadronic B decays are unknown. PYTHIA is employed to generate them. More efforts needed to tune and avoid double-counting.
- ➢ Hadronic B-tagging built on B to charm decays plays a key role in Belle II's physics program.
  - ○ With better interpretation from the papers, we modified the dynamics of relevant decays and then validated.
  - ○ Latest DECAY.DEC can be found here, incorporate into EvtGen?
  - ○ (Re)measurements are required to further improve the MC. Priorities identified and reported to the collaboration.
  - ○ Decay model should be studied, not necessarily complete amplitude with interferences, but simple intermediate resonances for MC.
- ➢ B_{tag} is just one example, but also impacts the background estimation from MC in Belle II but also LHCb (poor description of $D^*(n\pi)$ affects the estimation of $D^*\tau\nu$, where $\tau \rightarrow 3\pi\nu$....).
- ➢ Efforts to improve the D decay modelling in underway, taking inspiration from BESIII DECAY.DEC.

Backup

$B \to D\pi$ sample to measure performance

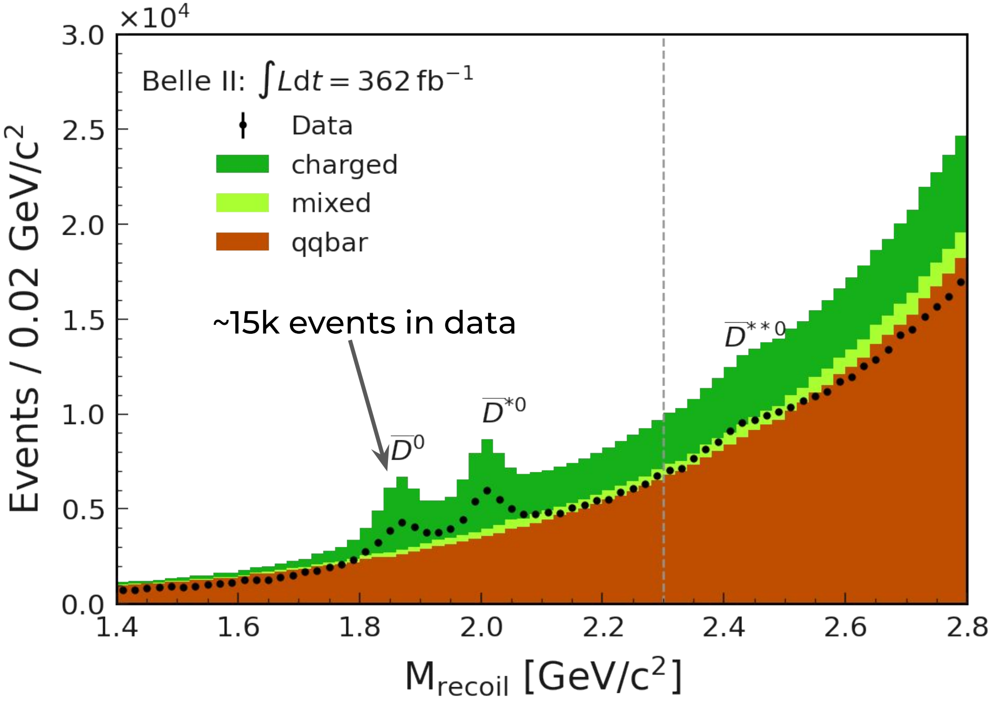
Statistically limited, but pure



Look for D^0, D^{*0} in the recoil mass of a $B^{\pm}$ reconstructed by FEI and a $\pi^{\mp}$

Statistically limited by $\mathscr{B}(B \to D\pi)$, gets better with more data.

But simple fit
⇒ Large signal-side purity



Metrics of B-tagging can be obtained from the yields , by fitting in the range 1.4 - 2.3 GeV/c^2

Quark transition	`modeID` in PYTHIA v8	$\mathcal{B}^{\text{Belle}}(\%)$	$\mathcal{B}^{\text{Belle II}}(\%)$
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Total PYTHIA contribution		39.24	38.71

- **48** (**23**): $n \geq 3$-body weak decays with phase space model; if there is a quark spectator system it collapses to one hadron[2],
- **13** (**43**): $n \geq 2$-body decays with phase space model; turn partons into a random number of hadrons with multiplicity based on a Poisson distribution,
- **23** (**63**), **24** (**64**): colour suppressed baryonic decays of fixed multiplicity with phase space model,
- **32** (**91**): decay to $q\bar{q}$ or $\gamma\gamma$, which should shower and hadronize.

Overall improvement

In all the metrics of B-tagging!

- ➢ Updated decay model for 11 most efficient B decay modes

  Belle 0.75 → 1.04 : 39% ⬆️ in Calibration factor

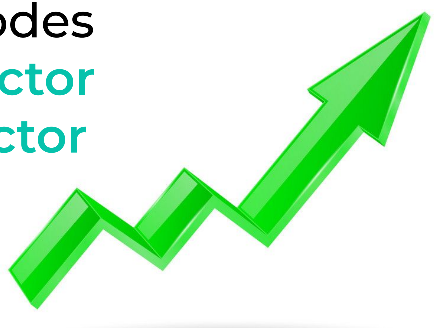
  0.65 → 0.81 : 25% ⬆️ in Calibration factor

- ➢ Training with the new MC

  56% → 63% : 12% ⬆️ in purity

- ➢ Loosen the γ preselection and mass-constraint π^0

  0.93% → 1.13% : 21% ⬆️ in efficiency

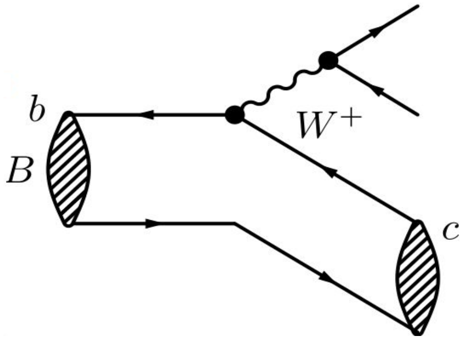


Reminder:

MC is first modified based on our best understanding.

And Dπ sample here is only used to validate.

Model for $B \to D^{(*,**)}\, n\pi\, m\pi^0$ decays



$X = \pi, \rho, a_1, \omega\pi, \rho\pi\pi, \eta\pi$

$Y = D, D^*, D^{**}$

Happens through 2 channels, one with spectator quarks (call Y) and one from the W (call X).

We want to modify the DECAY table to latest PDG/paper interpretations and this model to see the impact.

Essentially validation, we do not want to fine-tune (except set 0 when there is no signal*).

2 primary rules:

- $D^0 X : D^{*0} X : D^{**0} X$ ~= 1 : 1 : 1
  (based on observation from $D\pi^- : D^*\pi^- : D^{**}\pi^-$ and $D\rho^- : D^*\rho^-$)
- $Y\pi^- : Y\rho^- : Y a_1^-$ ~= 1 : 2.5 : 2.5
  (based on predictions and confirmed with $\tau \to h\nu$ decays)

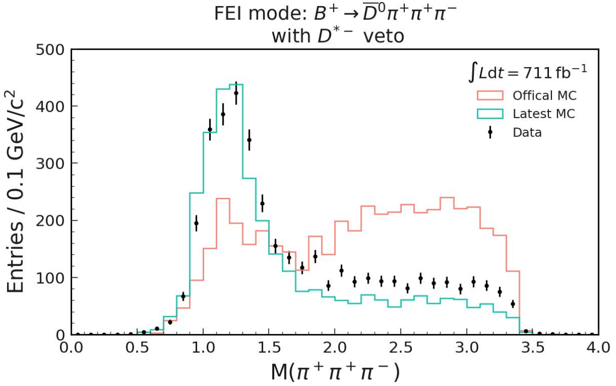
Additional information:

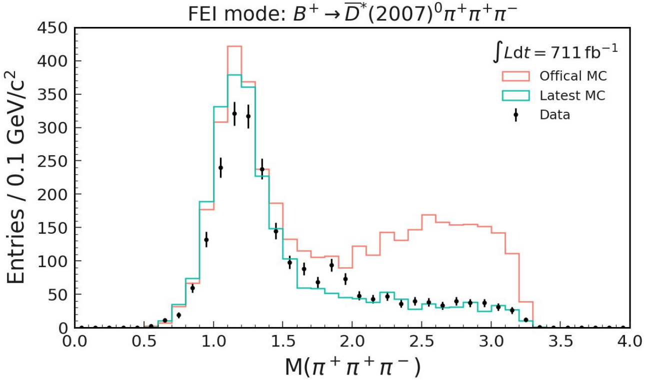
- $3\pi\, \pi^0$ is hard to model without some sort of ρ' resonance
  - For **ωπ**, we fix from measurements.
  - For **ηπ**, we fix based on prediction required to fill SL gap.
  - For **ρππ**, we let PYTHIA generate it.
- The fraction of 4 different D^{**} is fixed based on observations.

Decay description is improved!

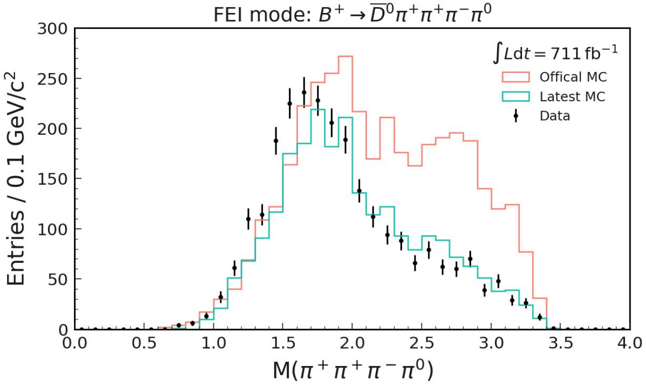
The improvement is not limited to calibration factors, but more importantly in the invariant masses (of intermediate particles), which are used as training variables in FEI

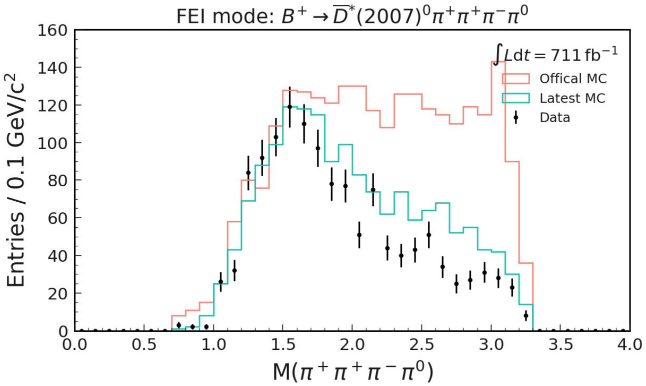
3π± case:





3π± π⁰ case:

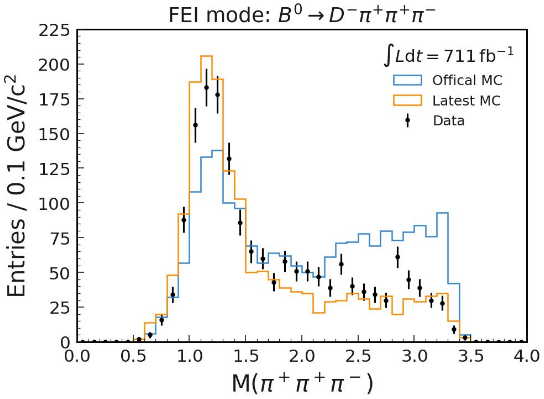


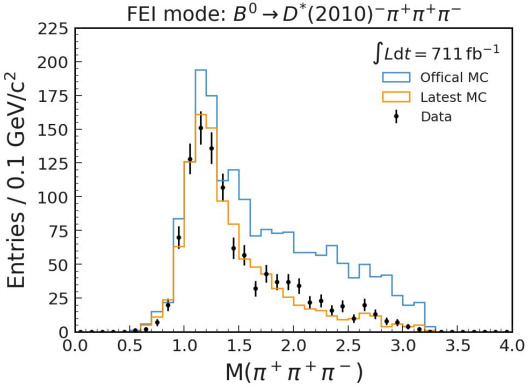


Decay description is improved in B^0!

The improvement is not limited to calibration factors, but more importantly in the invariant masses (of intermediate particles), which are used as training variables in FEI

$3\pi^\pm$ case:





$3\pi^\pm\ \pi^0$ case: