Saving the B's at Belle II

WARNING: This is not a lecture
more a status report…
some material for discussion…

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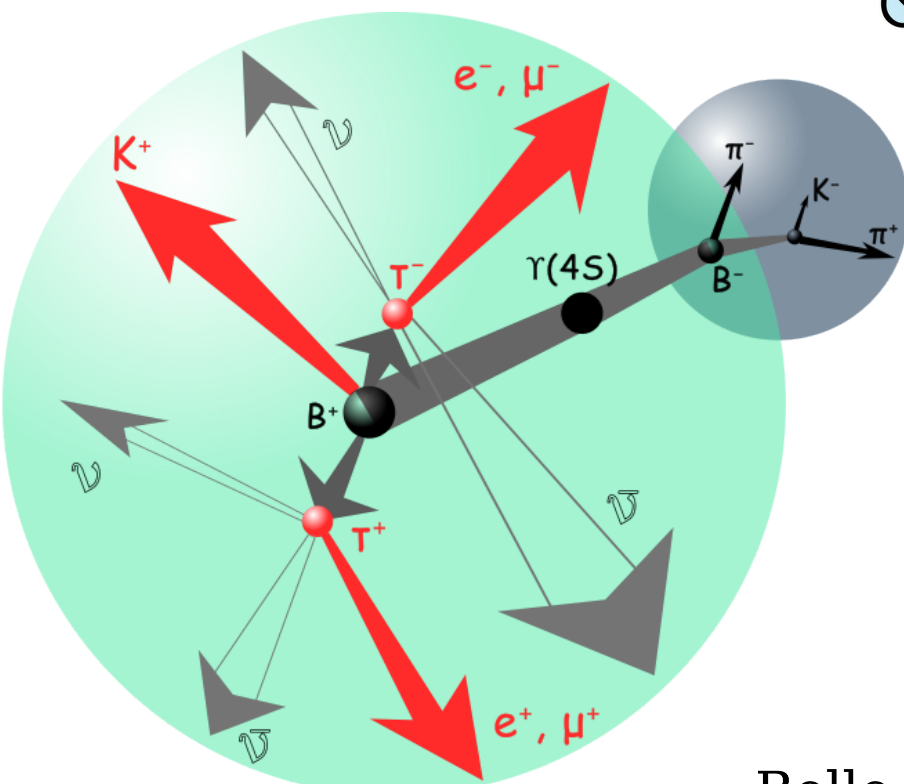
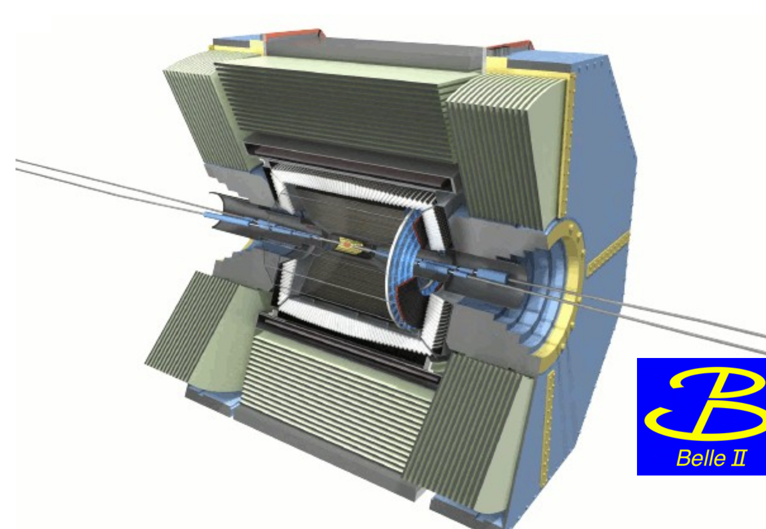




Belle II Physics Week
October 7, 2025

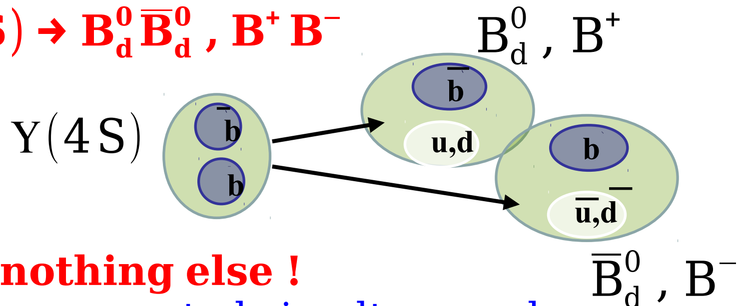
Belle II, a flavour-factory,

(Belle ~ 1 ab^{-1}) **a rich physics program…**

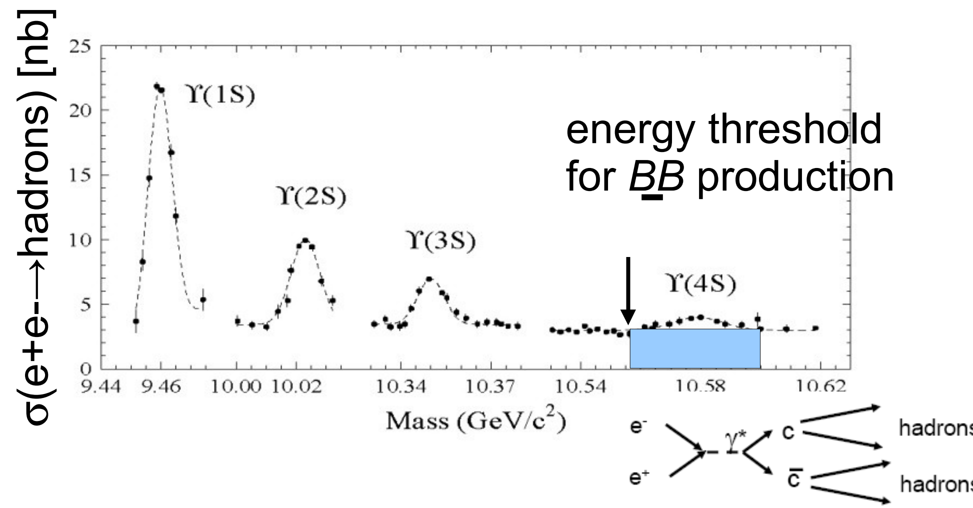
- We plan to collect (**at least**) 50 ab^{-1} of e^+e^- collisions at (or close to) the $\Upsilon(4S)$ resonance, so that we have:

– a (Super) B-factory ($\sim 1.1\times10^9$ $B\bar{B}$ pairs per ab^{-1})

"on resonance" production
$e^+e^- \to \Upsilon(4S) \to B_d^0\bar{B}_d^0$, B^+B^-



- **2 B's and nothing else !**
- 2 B mesons are created simultaneously in a L=1 coherent state



– a (Super) charm factory ($\sim 1.3\times10^9$ $c\bar{c}$ pairs per ab^{-1})
(but also charmonium, X, Y, Z, pentaquarks, tetraquarks, bottomonium…)

– a (Super) τ factory ($\sim 0.9\times10^9$ $\tau^+\tau^-$ pairs per ab^{-1})

– exploit the clean e^+e^- environment to probe the existence of exotic hadrons, dark photons/Higgs, light Dark Matter particles, ALPs, LLPs …

⇒ to reach few × 10^{35} $cm^{-2}s^{-1}$

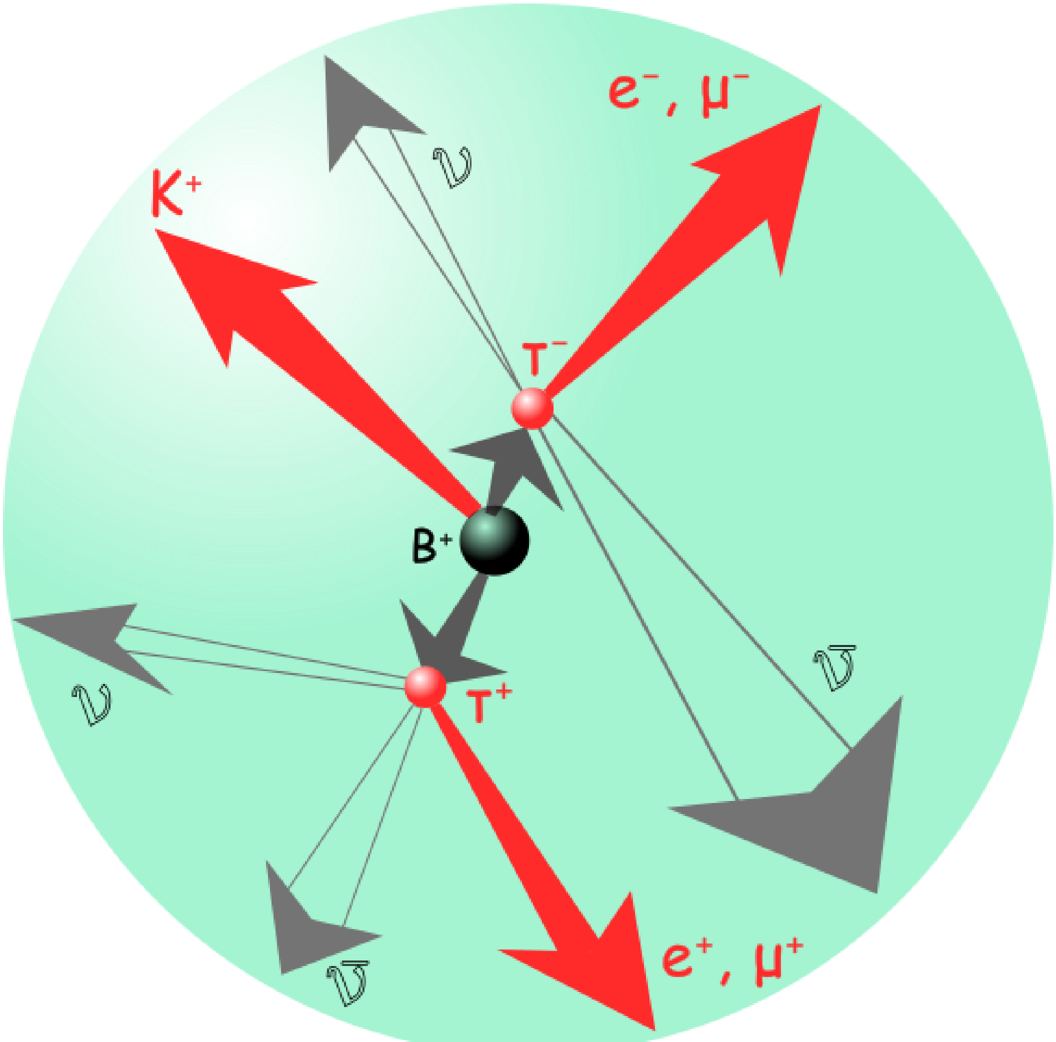
⇒ cumulate few 10 ab^{-1}

How do we search for B→Kττ ?

The neutrinos escape

Up to 4 neutrinos in $B^+ \to K^+\tau\tau$
⇒ Cannot reconstruct invariant mass or energy of the B

But, two B-mesons and nothing else in the event!



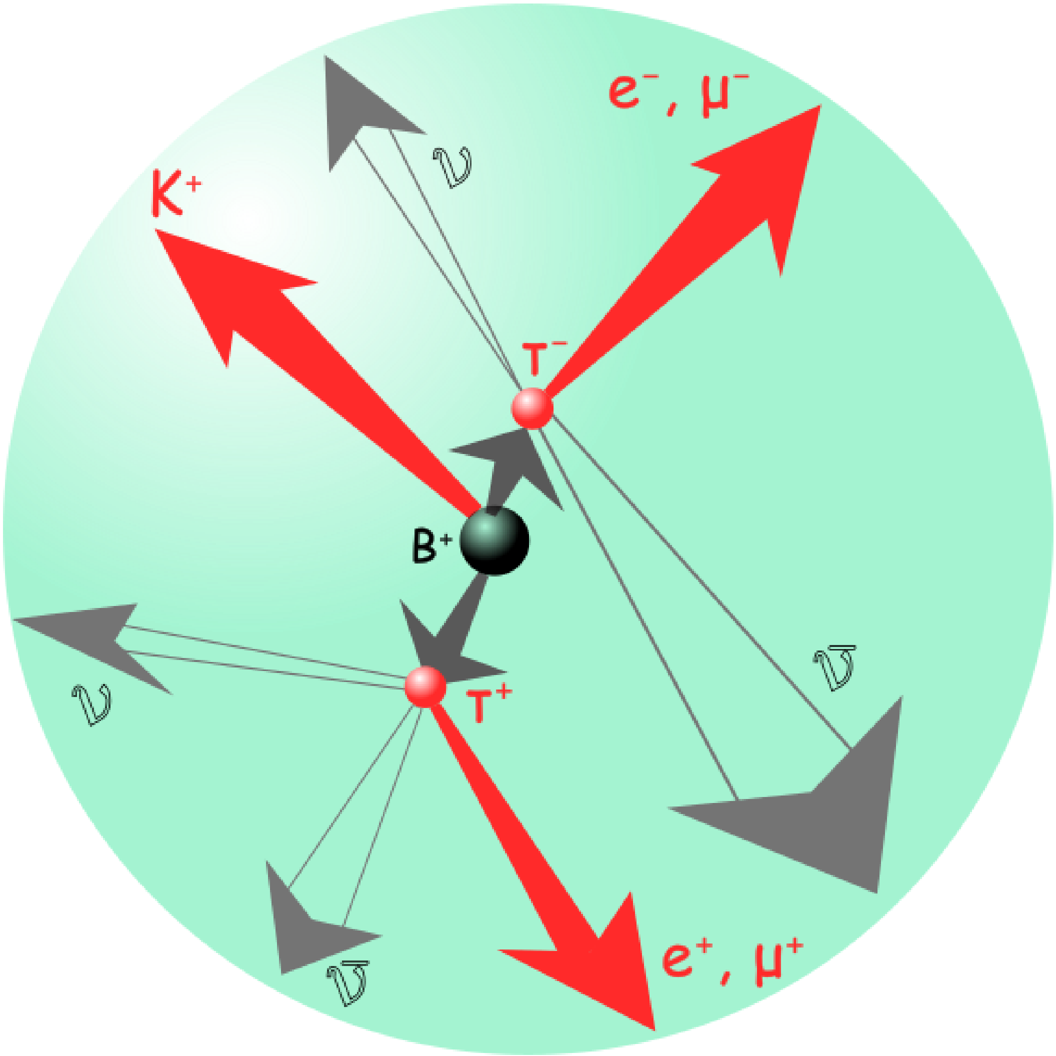
How do we search for B→Kττ ?

Using the other B (tag-side)

After reconstructing the 3 charged tracks on signal-side and the other B in the event, there will be no additional energy in the calorimeter (E_{ECL}).

⇒ In the rest of the event (ROE), sum of the energies of the clusters should peak at 0.

If the B_{tag} is reconstructed using hadronic decays : Hadronic B-tagging



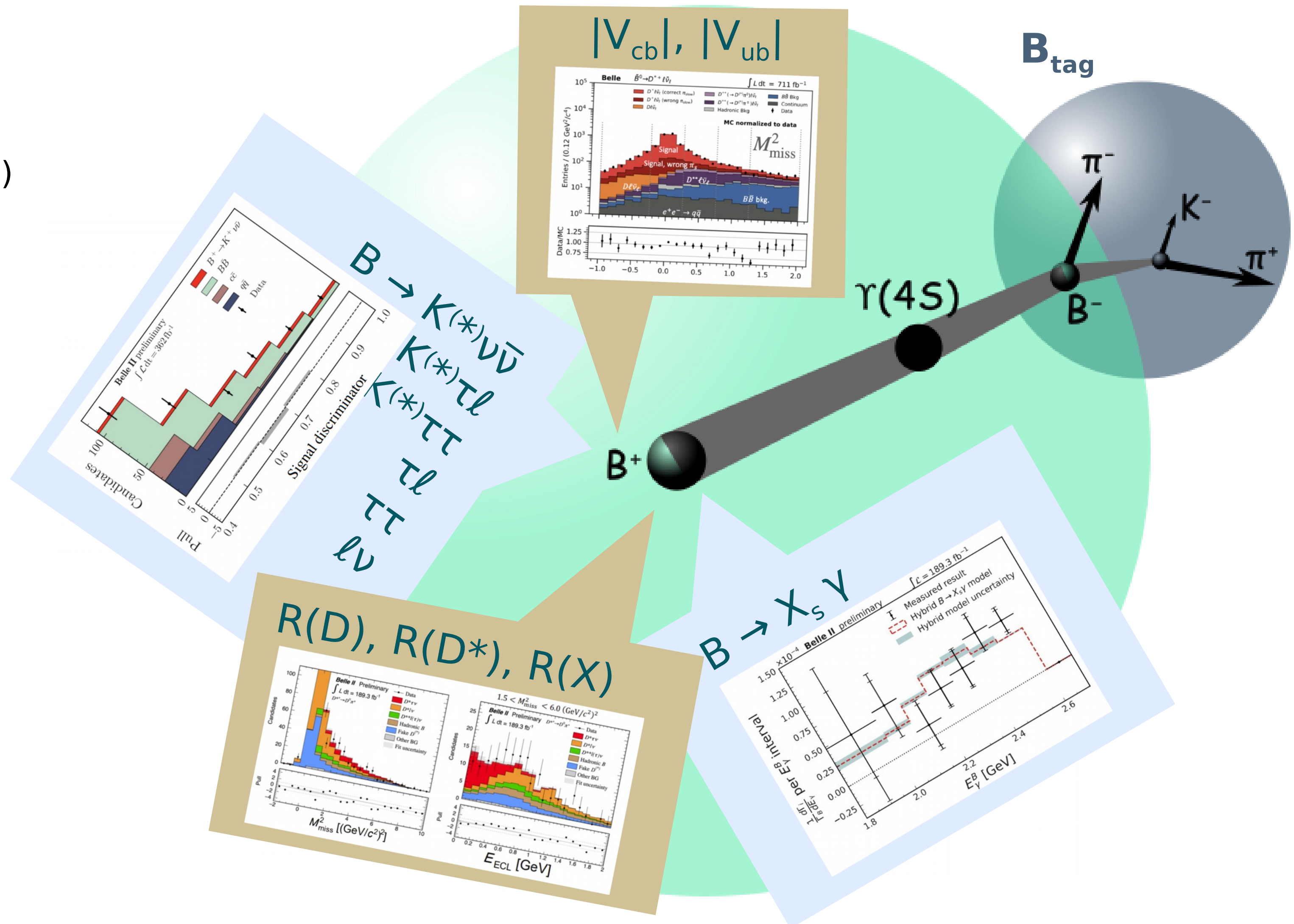
Hadronic B-tagging

is widely used in Belle II

It allows neutrino reconstruction at Belle II.

(equivalent to reconstructing inclusively)

Hadronic B-tagging is essential for a large part of Belle II’s physics program.



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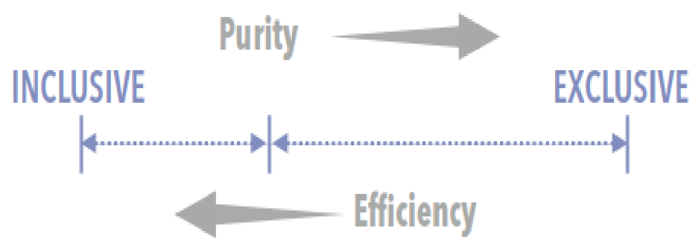
Missing energy modes and B-tagging

Many interesting B-physics studies involve missing energy: $R(D^{(*)})$, V_{cb}, $K^{(*)}\tau\ell$, $K^{(*)}\tau\tau$, $K^{(*)}\nu\nu$, $\pi l\nu$, $\tau\ell$, $\tau\nu$, $\mu\nu$… which require B-tagging.

FEI does exclusive B-tagging: Hadronic and Semileptonic



Hadronic B-tagging can provide the direction of the B.
Essential in some analysis and unique to B factories!

The 3 important metrics of B-tagging are:
- Efficiency
- Purity
- Data-MC agreement (Calibration factor)

Table 1 Summary of the maximum tag-side efficiency of the Full Event Interpretation and for the previously used exclusive tagging algorithms

Old measurement in MC	$B^{\pm}$ (%)	B^0 (%)
Hadronic		
FEI with FR channels	0.53	0.33
FEI	0.76	0.46
FR	0.28	0.18
SER	0.4	0.2
Semileptonic		
FEI	1.80	2.04
FR	0.31	0.34
SER	0.3	0.6

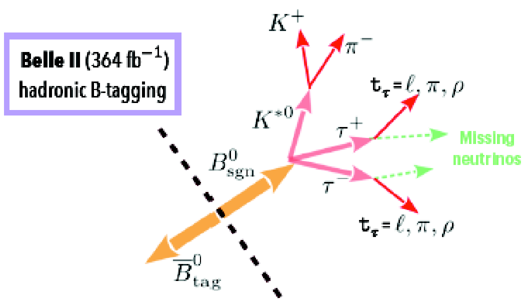
[T.Keck et. al, Comput Softw Big Sci (2019) 3: 6]

Exclusive B-tagging:
- **Advantages**: purity, direction of B_{tag}, but also…
  …official training, validation, skims, calibration, systematic (shared knowledge)
- **Disadvantages**: low efficiency…

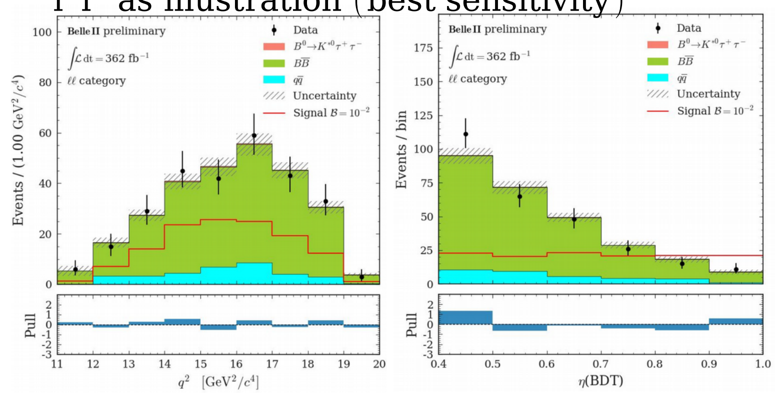
When/why do we use exclusive B-tagging ?

- signal side is reconstructed **exclusively** ... examples of 2025... [see Gaetano's talk]

Search for $B \to K^{*0}\tau\tau$



l^+l^- as illustration (best sensitivity)



[arXiv:2504.10042, submitted to PRL]

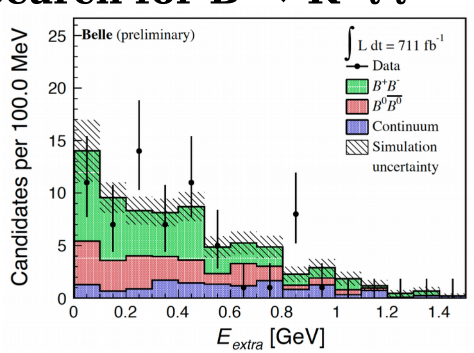
FCNC processes suppressed in SM at tree level

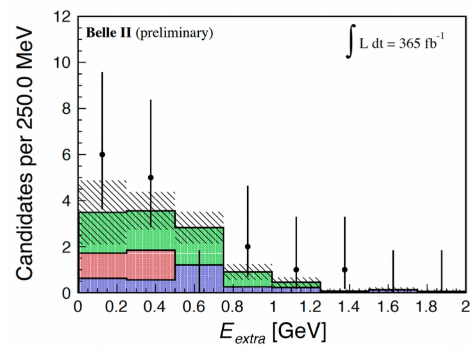
$BF_{SM} = (1.0 \pm 0.1) \times 10^{-7}$

BF $(B \to K^{*0}\tau\tau) < 1.8 \times 10^{-3}$ @ 90% C.L.

Twice better with only half sample wrt Belle !
Better tagging + more categories + BDT classifer...

Search for $B^+ \to K^+\tau\tau$





shown at CKM 2025, Sep 15-19 2025

$B_{SM}(B^+ \to K^+\tau\tau) = (1.5 \pm 0.1) \times 10^{-7}$

$$\mathcal{B}(B^+ \to K^+\tau^+\tau^-) = 3.13^{+3.70}_{-3.30} \times 10^{-4}$$

$$\mathcal{B}^{UL}(B^+ \to K^+\tau^+\tau^-) < 8.7 \times 10^{-4} \text{ at } 90\% \text{ CL}$$

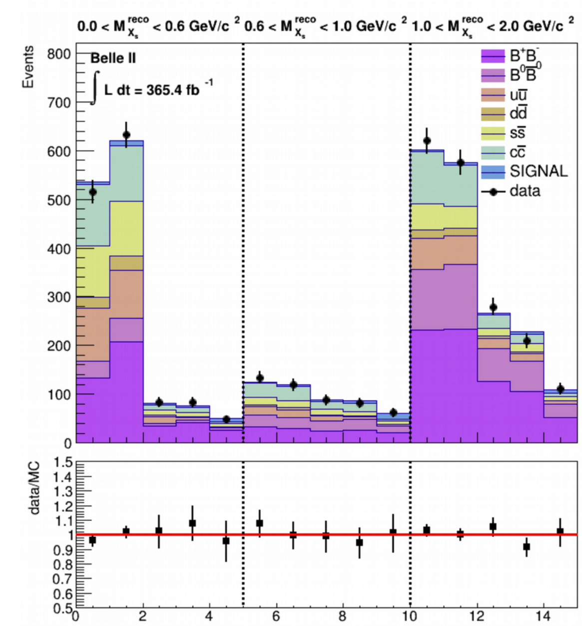
2.6 times better than current world best
Most stringent limit in $B^+ \to K^+\tau\tau$

Search for $B \to X_s \nu\bar{\nu}$

[PRELIMINARY]

- $B_{SM} = (2.9 \pm 0.3) \times 10^{-5}$ [JHEP 02 (2015) 184]
- $B < 6.4 \times 10^{-4}$ at 90% C.L. [ALEPH, EPJC 19 (2001) 213]
- Sum-of-exclusive from 30 decay modes (~90% of inclusive)

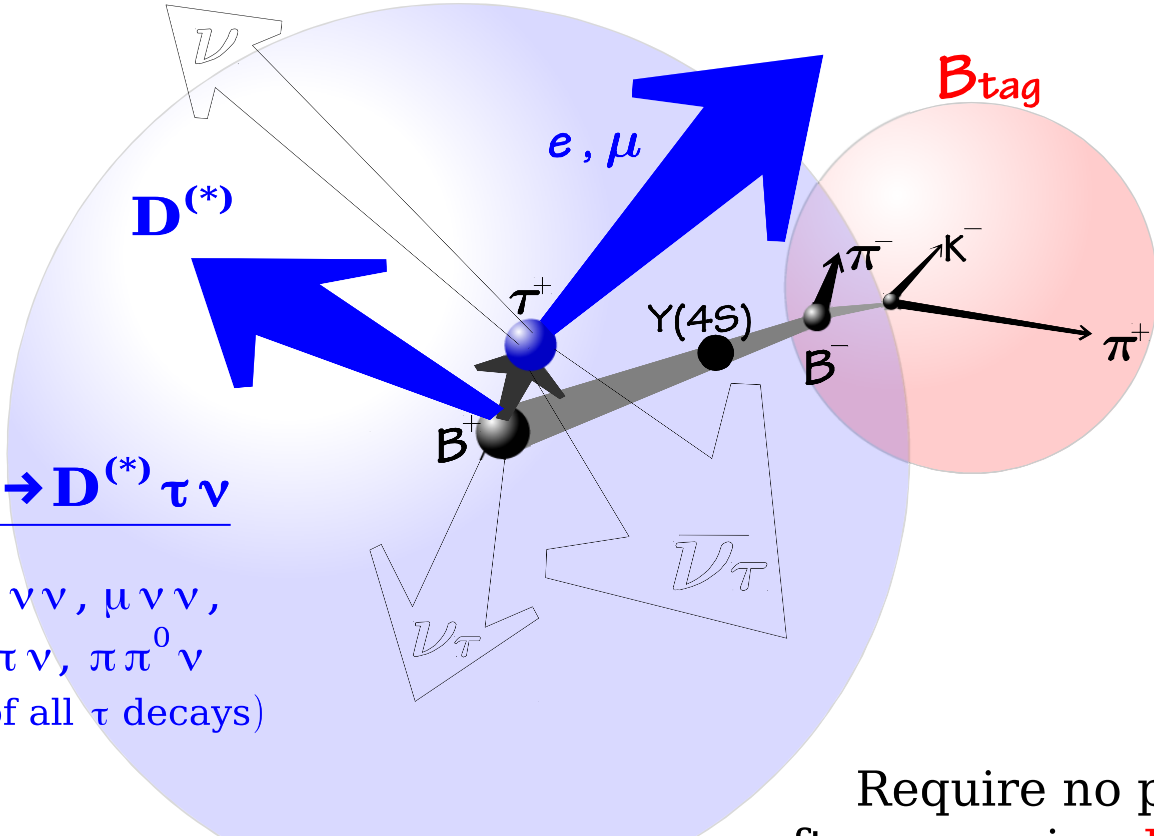
	$B^0\bar{B}^0$			$B^\pm$		
K	K^0_S			$K^\pm$		
$K\pi$	$K^\pm\pi^\mp$	$K^0_S\pi^0$		$K^\pm\pi^0$	$K^0_S\pi^\pm$	
$K2\pi$	$K^\pm\pi^\mp\pi^0$	$K^0_S\pi^\pm\pi^\mp$	$K^0_S\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm$	$K^0_S\pi^\pm\pi^0$	$K^\pm\pi^0\pi^0$
$K3\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp$	$K^0_S\pi^\pm\pi^\mp\pi^0$	$K^\pm\pi^\mp\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^0$	$K^0_S\pi^\pm\pi^\mp\pi^\pm$	$K^0_S\pi^\pm\pi^0\pi^0$
$K4\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^0$	$K^0_S\pi^\pm\pi^\mp\pi^\pm\pi^\mp$	$K^0_S\pi^\pm\pi^\mp\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^\pm$	$K^0_S\pi^\pm\pi^\mp\pi^\pm\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^0\pi^0$
$3K$	$K^\pm K^\mp K^0_S$			$K^\pm K^\mp K^\pm$		
$3K\pi$	$K^\pm K^\mp K^\pm\pi^\mp$	$K^\pm K^\mp K^0_S\pi^0$		$K^\pm K^\mp K^\pm\pi^0$	$K^0_S K^\pm K^\mp\pi^\pm$	



$B(B \to X_s \nu\bar{\nu}) < 3.6 \times 10^{-4}$ at 90% C.L.

⇒ The most stringent upper limit on $B \to X_s \nu\bar{\nu}$ decay

Event reconstruction in $B \to D^{(*)} \tau \nu$ at B factories



B_{tag}

hadronic tag

$B \to D^{(*)}\pi ,\ D^{(*)}\rho \ldots$

$\epsilon \sim 0.5\,\%$

semileptonic tag

$B \to D^{(*)} l \nu\ X$

$B_{sig} \to D^{(*)} \tau \nu$

$\tau \to e \nu \nu ,\ \mu \nu \nu ,$

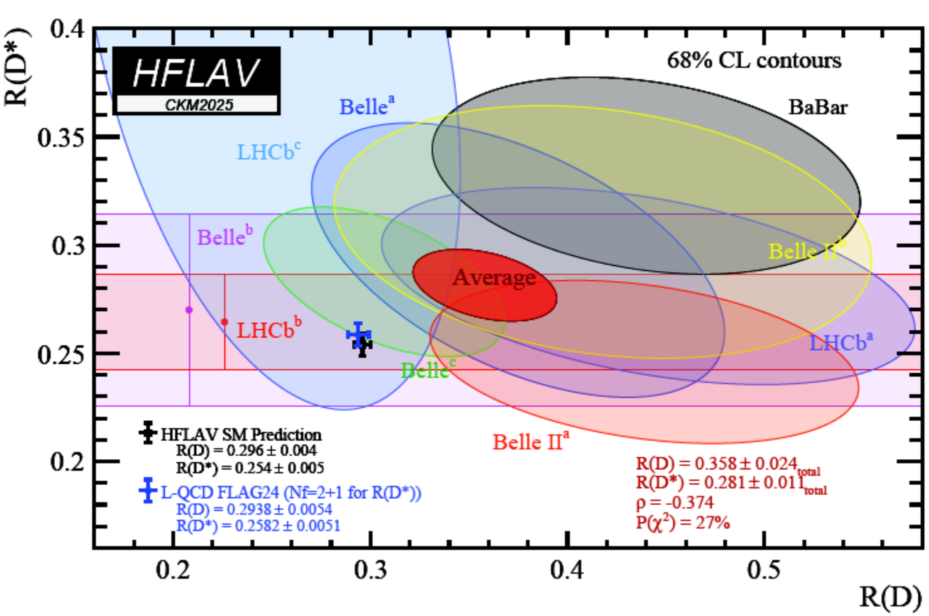
$\tau \to \pi \nu ,\ \pi \pi^0 \nu$

(70 % of all τ decays)

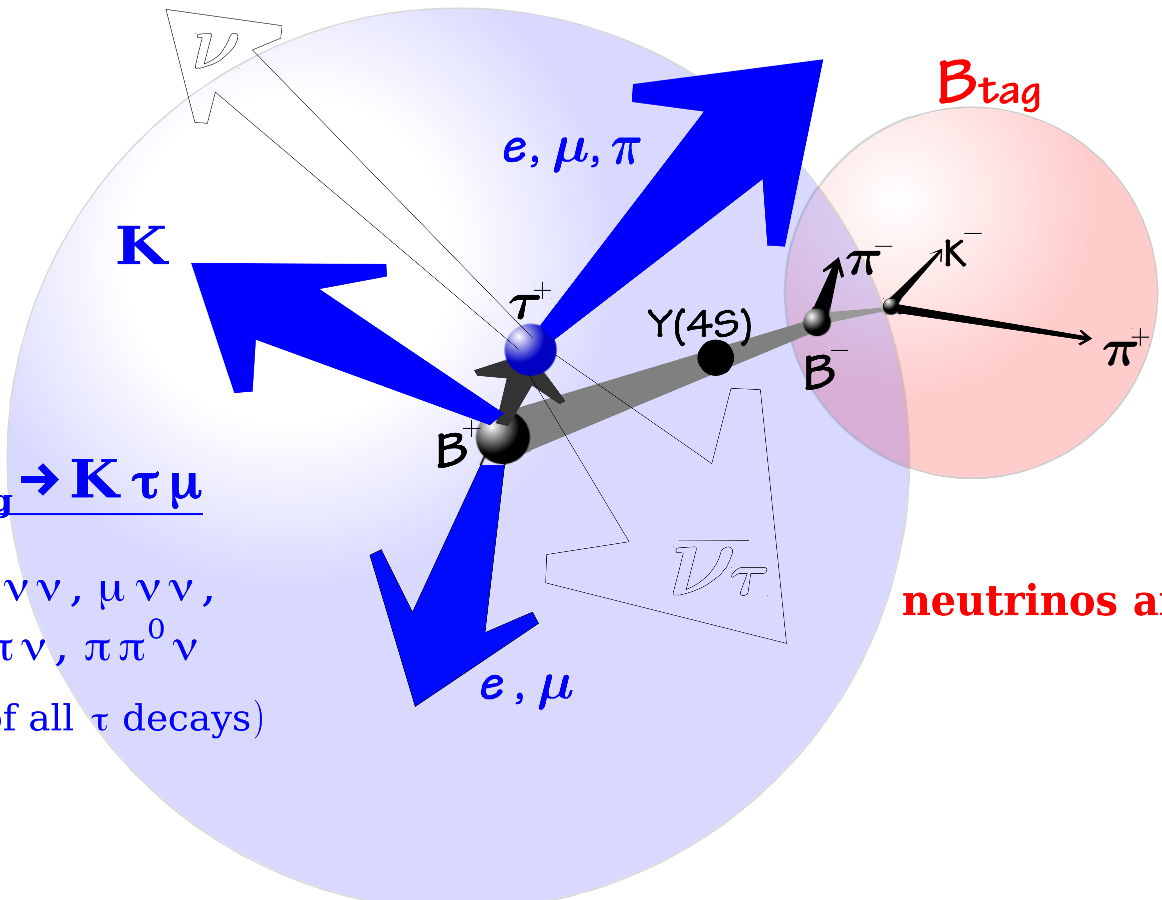
Require no particle and no energy left after removing B_{tag} and visible particles of B_{sig}

main signal - background discriminator

$$m^2_{miss} = (p_{ee} - p_{tag} - p_{D^{(*)}} - p_l)^2$$



Event reconstruction in B→K τ μ at B factories



B_{sig} → K τ μ

τ → e ν ν , μ ν ν ,
τ → π ν , π π^0 ν
(70 % of all τ decays)

B_{tag}

hadronic tag

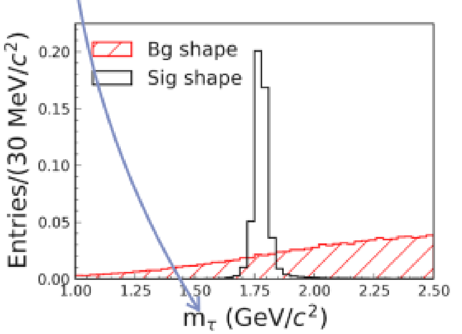
B → $D^{(*)}$ π , $D^{(*)}$ ρ …
ε ~ 0.5 %

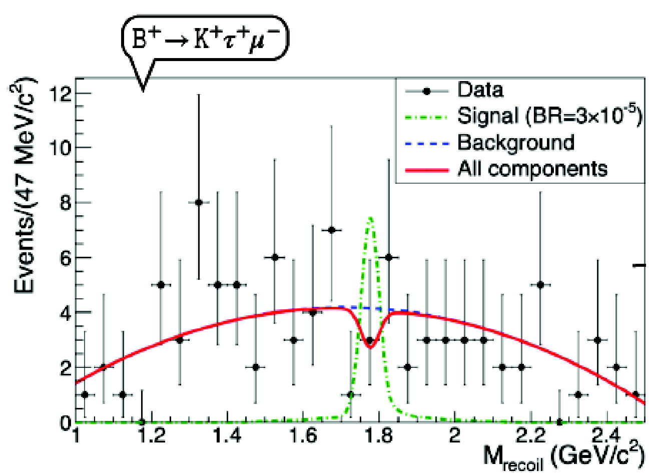
semileptonic tag

B → $D^{(*)}$ l ν X

neutrinos are all coming from the tau here !

$$m_\tau^2 = (p_{e^+e^-} - p_K - p_\ell - p_{B_{tag}})^2$$





[Belle , PRL 130, 261802 (2023)]

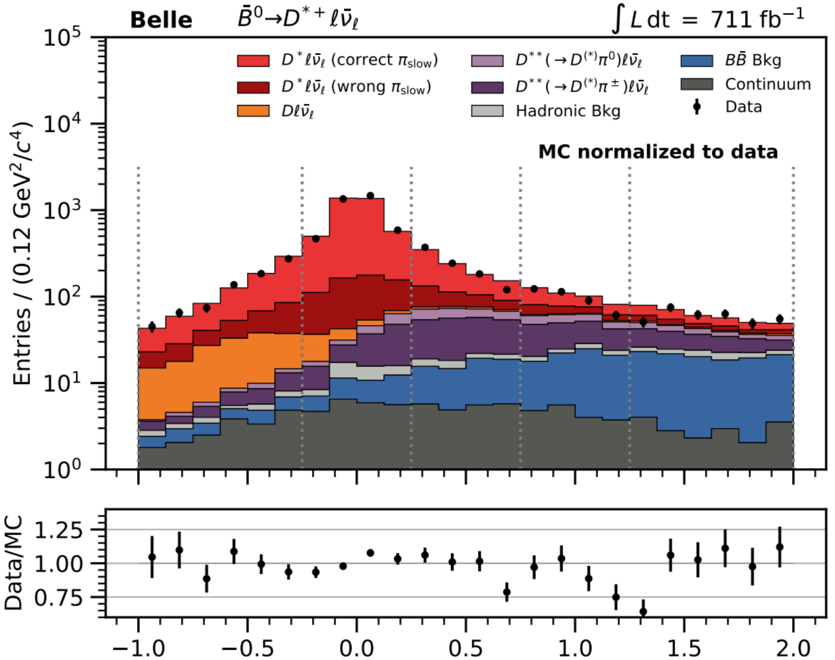
Mode	N_{sig}	ε (%)	$\mathcal{B}^{UL}$ (10^{-5})	$\mathcal{B}^{UL}_{NP}$ (10^{-5})
$B^+ \to K^+\tau^+\mu^-$	-2.1 ± 2.9	0.064	0.59	0.65
$B^+ \to K^+\tau^+e^-$	1.5 ± 5.5	0.084	1.51	1.71
$B^+ \to K^+\tau^-\mu^+$	2.3 ± 4.1	0.046	2.45	2.97
$B^+ \to K^+\tau^-e^+$	-1.1 ± 7.4	0.079	1.53	2.08

PHSP

When/why do we use exclusive B-tagging ?

- not only for search of rare/forbidden decays, or to have high purity…

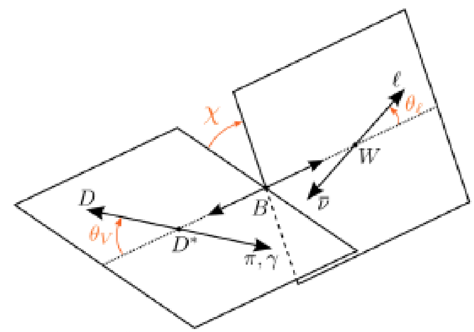
Measurement of angular coefficients with $D^* l \nu$ [Belle, PRD108(2023)1, 012002/PRL 133 (2024) 131801]

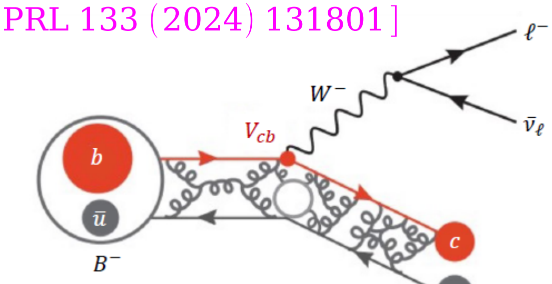


Extraction Method: Missing Mass Squared

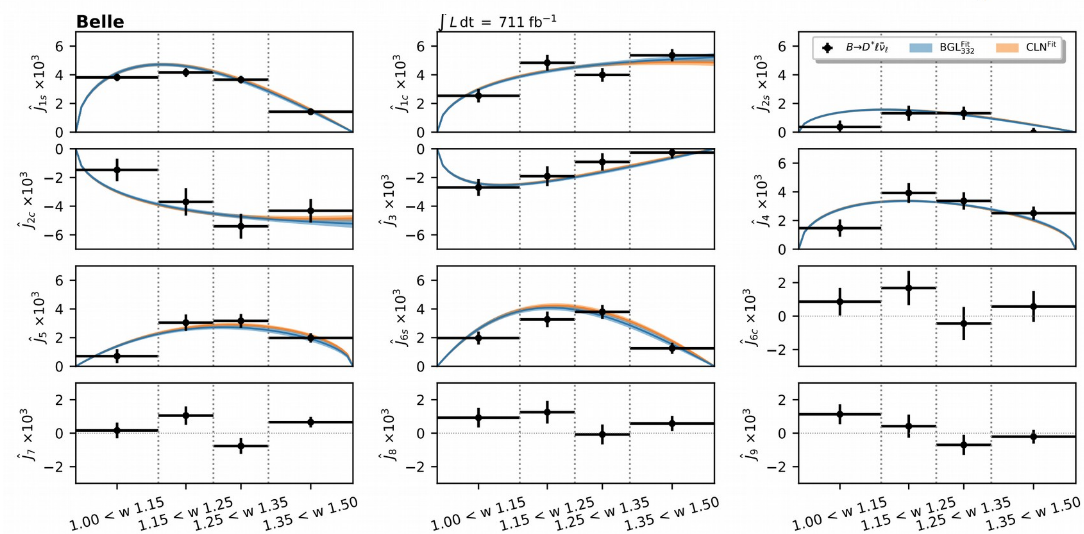
$$0 = m_\nu^2 = \mathrm{M}_{\text{miss}}^2 = (p_{e^+e^-} - \mathrm{p_B} - \mathrm{p_{D^*}} - \mathrm{p}_\ell)^2$$

$$w = v_B \cdot v_{D^{(*)}} = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}}$$





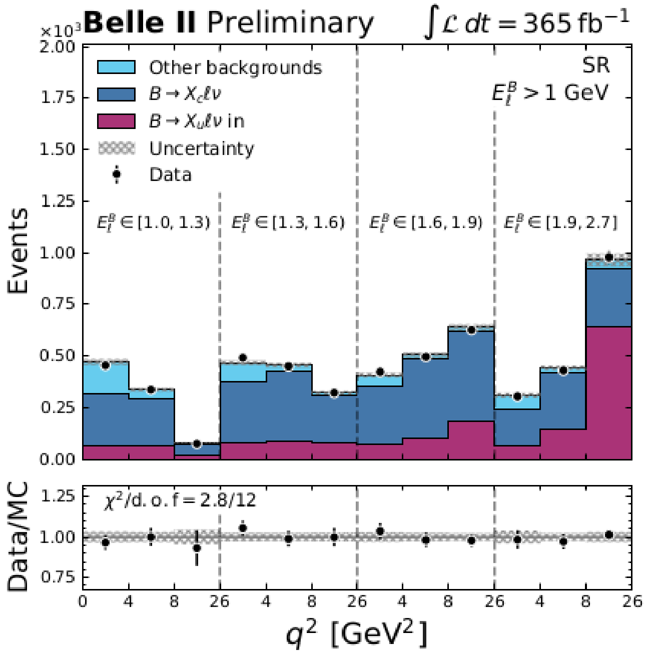
$$\frac{\mathrm{d}\Gamma(B \to D^* \ell \nu_\ell)}{\mathrm{d}w \mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_\mathrm{V} \mathrm{d}\chi} = \frac{2 G_\mathrm{F}^2 \eta_\mathrm{EW}^2 |V_\mathrm{cb}|^2 m_B^4 m_{\mathrm{D}^*}}{2\pi^4} \times \Big(J_{1s} \sin^2\theta_\mathrm{V} + J_{1c}\cos^2\theta_\mathrm{V} + (J_{2s}\sin^2\theta_\mathrm{V} + J_{2c}\cos^2\theta_\mathrm{V})\cos 2\theta_\ell + J_3 \sin^2\theta_\mathrm{V}\sin^2\theta_\ell \cos 2\chi + J_4 \sin 2\theta_\mathrm{V} \sin 2\theta_\ell \cos\chi + J_5 \sin 2\theta_\mathrm{V} \sin\theta_\ell \cos\chi + (J_{6s}\sin^2\theta_\mathrm{V} + J_{6c}\cos^2\theta_\mathrm{V})\cos\theta_\ell + J_7 \sin 2\theta_\mathrm{V} \sin\theta_\ell \sin\chi + J_8 \sin 2\theta_\mathrm{V} \sin 2\theta_\ell \sin\chi + J_9 \sin^2\theta_\mathrm{V} \sin^2\theta_\ell \sin 2\chi \Big).$$

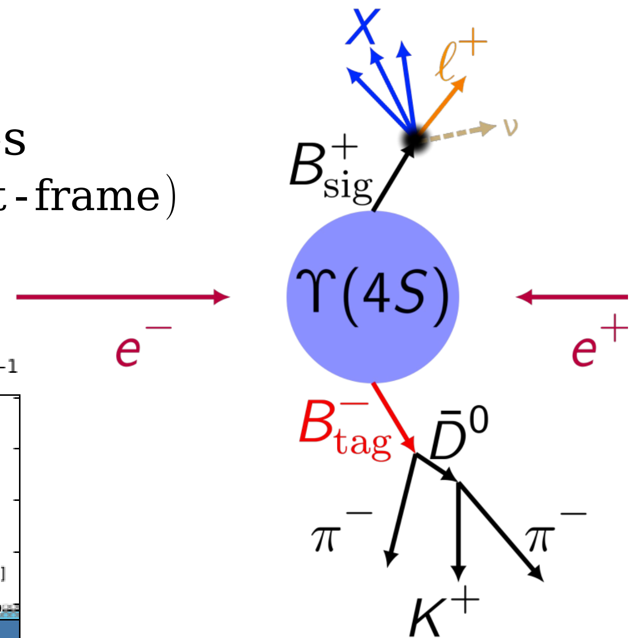


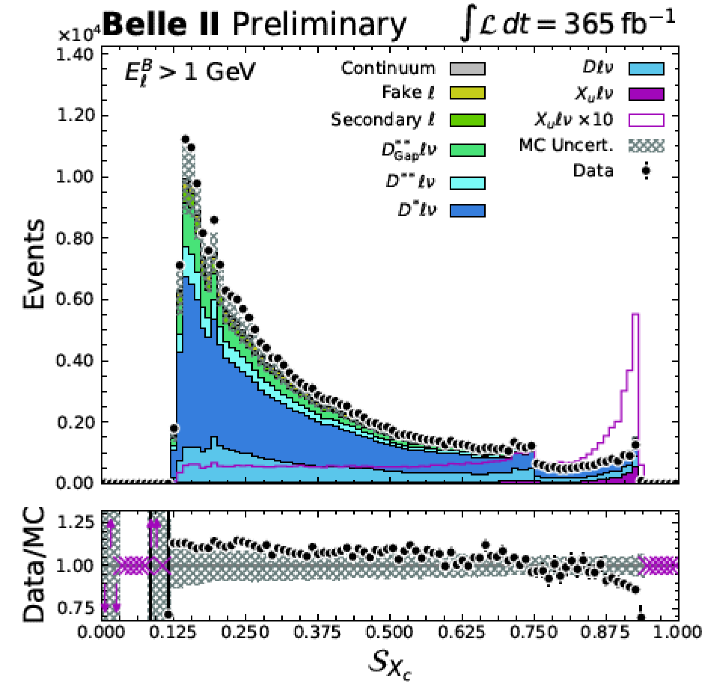
$|V_{ub}|$ from inclusive $B \to X_u l \nu$ decays (had tag)

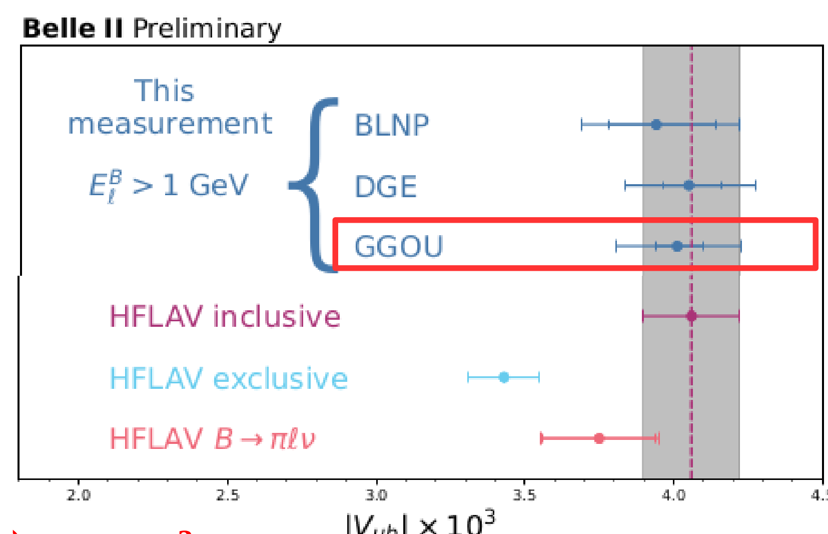
[PRELIMINARY]

- First Belle II measurement
- Hadronic B-tagging
- 3 main kinematical variables
  - $E_l^{(B)}$: lepton energy (in B_{sig} rest-frame)
  - M_X: mass of hadronic system
  - q^2: momentum transfer









Extract $|V_{ub}|$ from partial BR using the predicted partial decay rate over a given phase-space region

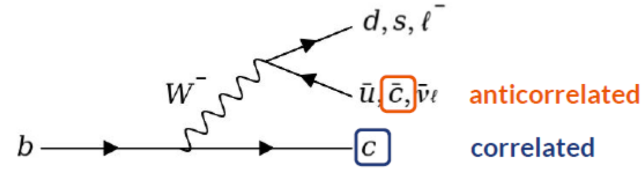
$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell \nu)}{\tau_B \Delta\Gamma(B \to X_u \ell \nu)}}$$

$$|V_{ub}|_{GGOU} = \left(4.01 \pm 0.11(\mathrm{stat}) \pm 0.16(\mathrm{syst})\ ^{+0.09}_{-0.07}(\mathrm{theo})\right) \times 10^{-3}$$

$$|V_{ub}|^{HFLAV}_{incl} = (4.06 \pm 0.16) \times 10^{-3}$$

When/why do we use exclusive B-tagging ?

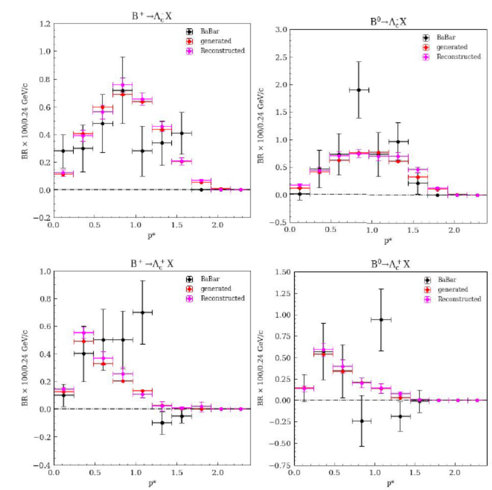
- signal side is **partially** reconstructed…
  - measurement of inclusive differential BFs:



$B^0 \to \Lambda_c^- X$, $B^0 \to \Lambda_c^+ X$, $B^+ \to \Lambda_c^- X$, $B^+ \to \Lambda_c^+ X$

Experimental results on inclusive (only BaBar hep-ex/0606026)

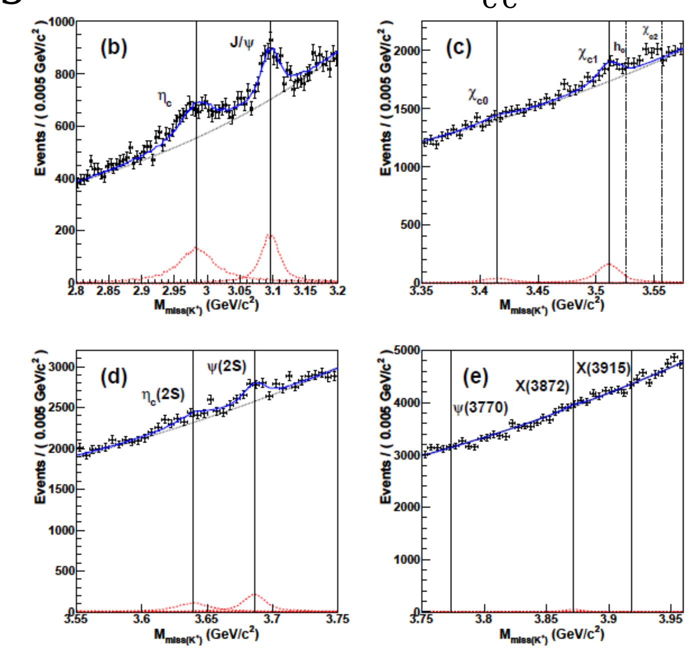
$B(B^+ \to D^0 X)$	=	$(8.6 \pm 0.7)\%$	$B(B^0 \to D^0 X)$	=	$(8.1 \pm 1.5)\%$
$B(B^+ \to \bar{D}^0 X)$	=	$(79 \pm 4)\%$	$B(B^0 \to \bar{D}^0 X)$	=	$(47.4 \pm 2.8)\%$
$B(B^+ \to D^+ X)$	=	$(2.5 \pm 0.5)\%$	$B(B^0 \to D^+ X)$	<	3.9%
$B(B^+ \to D^- X)$	=	$(9.9 \pm 1.2)\%$	$B(B^0 \to D^- X)$	=	$(36.9 \pm 3.3)\%$
$B(B^+ \to D_s^+ X)$	=	$(7.9^{+1.4}_{-1.3})\%$	$B(B^0 \to D_s^+ X)$	=	$(10.3^{+2.1}_{-1.8})\%$
$B(B^+ \to D_s^- X)$	=	$(1.10^{+0.40}_{-0.32})\%$	$B(B^0 \to D_s^- X)$	<	2.6%
$B(B^+ \to \Lambda_c^+ X)$	=	$(2.1^{+0.9}_{-0.6})\%$	$B(B^0 \to \Lambda_c^+ X)$	<	3.1%
$B(B^+ \to \Lambda_c^- X)$	=	$(2.8^{+1.1}_{-0.9})\%$	$B(B^0 \to \Lambda_c^- X)$	=	$(5.0^{+2.1}_{-1.5})\%$



- $B^{+/0} \to X_s \gamma$, $J/\psi X$…
- Measurements of the absolute branching fractions of $B^+ \to X_{c\bar{c}} K^+$

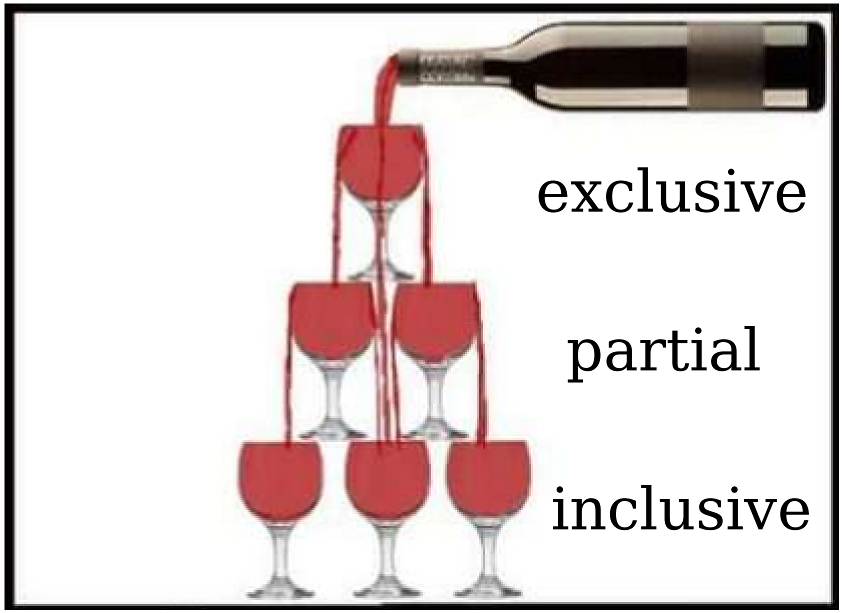
arXiv:1709.06108, Phys. Rev. D 97, 012005 (2018)

Mode	Yield	Significance (σ)	$\epsilon(10^{-3})$	$\mathcal{B}$ (10^{-4})	World average for $\mathcal{B}$ (10^{-4}) [10]
η_c	2590 ± 180	14.2	2.73 ± 0.02	$12.0 \pm 0.8 \pm 0.7$	9.6 ± 1.1
J/ψ	1860 ± 140	13.7	2.65 ± 0.02	$8.9 \pm 0.6 \pm 0.5$	10.26 ± 0.031
χ_{c0}	430 ± 190	2.2	2.67 ± 0.02	$2.0 \pm 0.9 \pm 0.1$ (< 3.3)	$1.50^{+0.15}_{-0.14}$
χ_{c1}	1230 ± 180	6.8	2.68 ± 0.02	$5.8 \pm 0.9 \pm 0.5$	4.79 ± 0.23
$\eta_c(2S)$	1050 ± 240	4.1	2.77 ± 0.02	$4.8 \pm 1.1 \pm 0.3$	3.4 ± 1.8
$\psi(2S)$	1410 ± 210	6.6	2.79 ± 0.02	$6.4 \pm 1.0 \pm 0.4$	6.26 ± 0.24
$\psi(3770)$	-40 ± 310	-	2.76 ± 0.02	$-0.2 \pm 1.4 \pm 0.0$ (< 2.3)	4.9 ± 1.3
$X(3872)$	260 ± 230	1.1	2.79 ± 0.01	$1.2 \pm 1.1 \pm 0.1$ (< 2.6)	(< 3.2)
$X(3915)$	80 ± 350	0.3	2.79 ± 0.01	$0.4 \pm 1.6 \pm 0.0$ (< 2.8)	-



Trickle down B-tagging

(ambition behind our work on B-tagging)



but focus on exclusive B-tagging in this presentation

References for FEI hadronic tag

- The Full Event Interpretation: An Exclusive Tagging Algorithm for the Belle II Experiment
  T. Keck et al, Computing and Software for Big Science Volume 3, article number 6, (2019)
  https://link.springer.com/article/10.1007/s41781-019-0021-8

- Everything you ever wanted to know about FEI
  Peter Lewis, 2022 Belle II Physics Week
  https://indico.belle2.org/event/7825/contributions/49619/

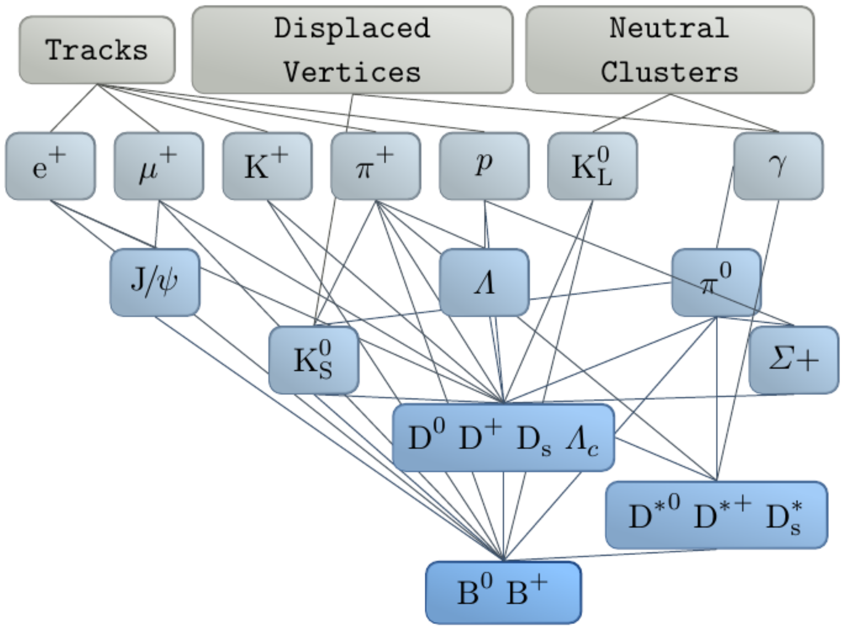
- FEI updates
  - Vidya Vobbilisetti, BELLE2-PTHESIS-2023-016
    https://docs.belle2.org/pub_data/documents/3919/
  - Vidya Vobbilisetti, Performance session @ 47th B2GM
    https://indico.belle2.org/event/10839/contributions/71798/

- Updates on FEI (with release08, MC16/proc16)
  Mattia Marfoli, Rahul Tiwary, 51st B2GM at KEK
  https://indico.belle2.org/event/14964/contributions/94610/

from release06 to release 08

Hadronic B-tagging tool at Belle/Belle II

called Full Event Interpretation (FEI)



Designed for Belle II software,
now used with Belle data also.

Hierarchical reconstruction…

$o(10^4)$ B total decay chains

Uses machine learning: over 200 BDTs **trained on simulated BB data**

Outputs:

- List of tagged B candidates (each in a specific B decay cascade)
- A "signal probability" for each…

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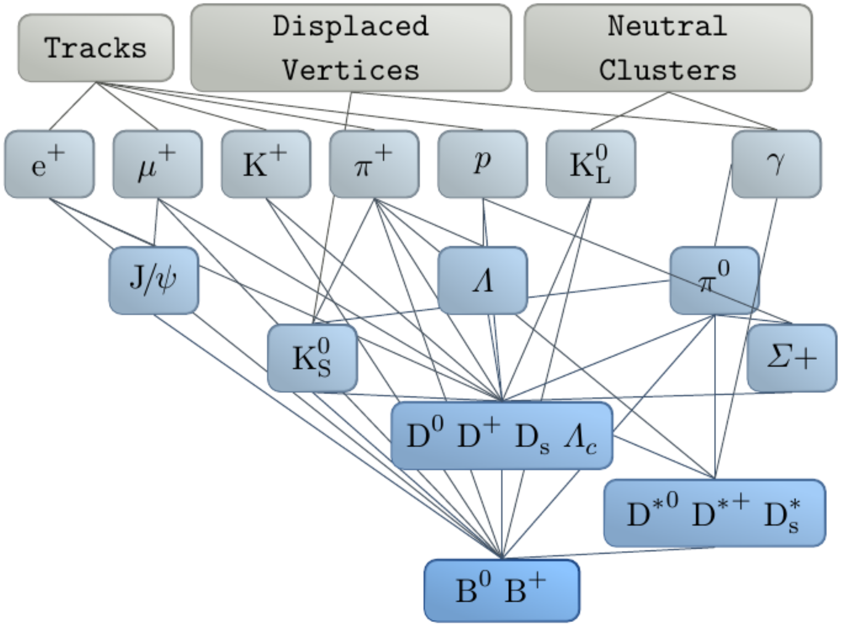


Designed for Belle II software,
now used with Belle data also.

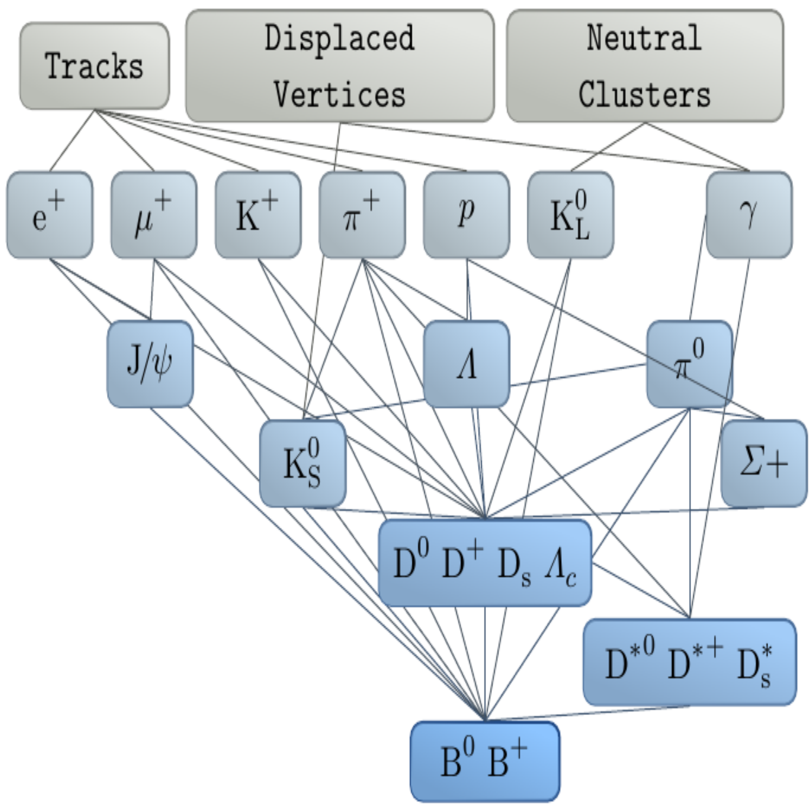
For each decay, BDTs trained on MC.

B^+-tagging uses 36 decays.
But only 12 of them, essentially $B \to D^{(*)}\, m\pi^\pm\, n\pi^0$, gives ~90% of the efficiency.

$\overline{D}^0\pi^+$
$\overline{D}^{*0}\pi^+$
$\overline{D}^0\pi^+\pi^0$
$\overline{D}^{*0}\pi^+\pi^0$
$\overline{D}^0\pi^+\pi^+\pi^-$
$\overline{D}^{*0}\pi^+\pi^+\pi^-$
$\overline{D}^0\pi^+\pi^0\pi^0$
$\overline{D}^{*0}\pi^+\pi^0\pi^0$
$\overline{D}^0\pi^+\pi^+\pi^-\pi^0$
$\overline{D}^{*0}\pi^+\pi^+\pi^-\pi^0$
$D^-\pi^+\pi^+$
$D^-\pi^+\pi^+\pi^0$

More $\pi \Rightarrow$ More complex,
but "high" Branching Fraction

FEI is a hierarchical combination of modes

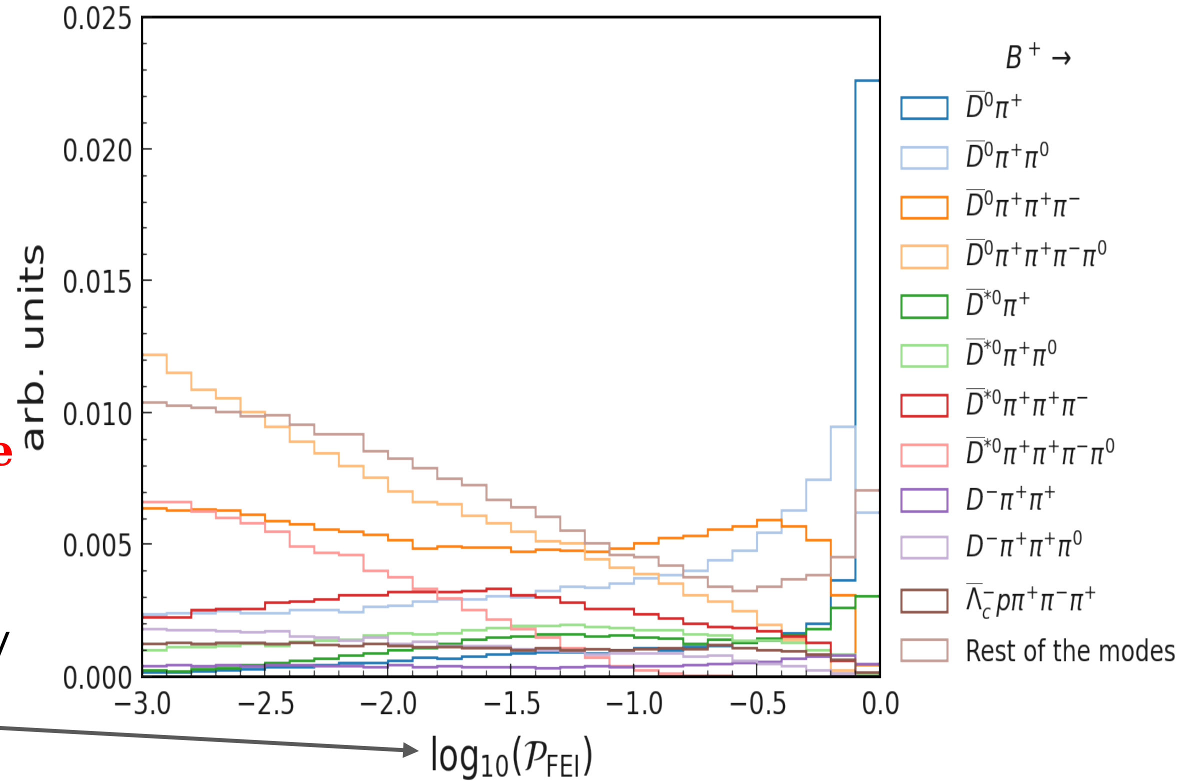


For each decay, BDTs trained on MC.

B^+-tagging uses 36 decays.
But only 12 of them, essentially $B \to D^{(*)}\ m\pi^{\pm}\ n\pi^0$,
gives ~90% of the efficiency.

Total efficiency < 1%.

Different modes have different signal probability
and different performance (efficiency, purity).
in MC

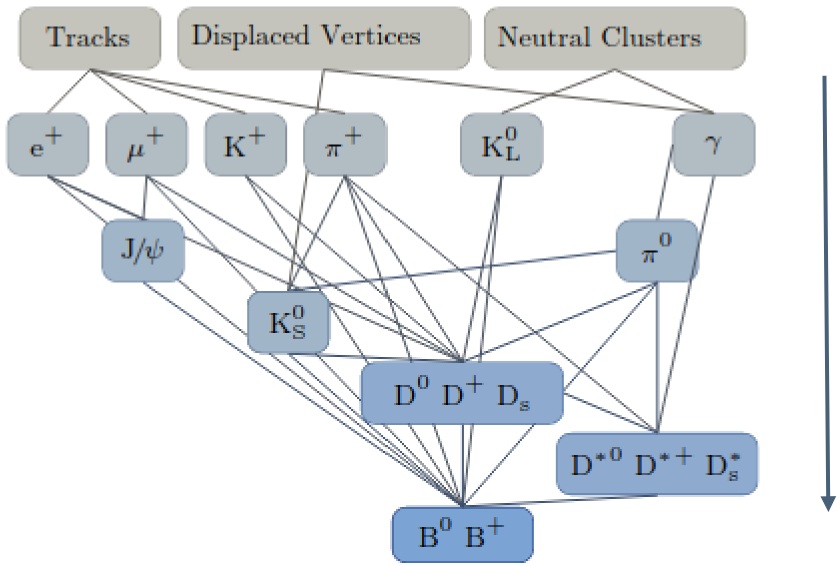


BDTs trained on MC , so performance is as good as the MC model…

Output of final BDTs called signal probability
(though it is not a probability)

Hadronic B-tagging tool at Belle/Belle II

''Full Event Interpretation'' package:

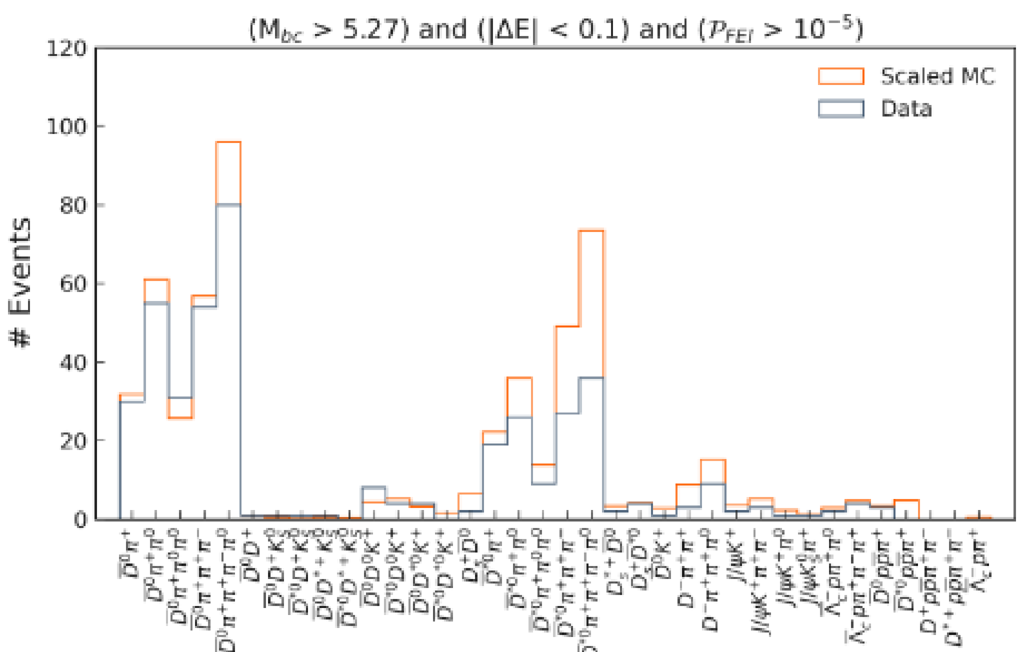


[T.Keck et. al, Comput Softw Big Sci (2019) 3: 6]

In FEI, Belle II's B-tagging algorithm: BDTs are trained on **MC** for some final states in a hierarchical structure starting from tracks and clusters.

⇒ any ML strategy will train on MC... assuming it is reproducing properly data

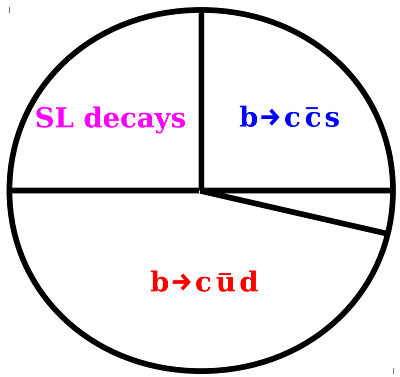
The hadronic FEI algorithm reconstructs B in 36 different B decays.



But 12 B decays among them account for ~90% of the efficiency, so we focused on them

Tagging efficiency in data (eff_{tag}= BF x eff_{reco}) is one of the limiting factors

Why is B-decay modeling so hard ?



Inclusive decays for b→c transition

A.Lenz et al, arXiv:1305.5390, 1404.6197

$B(b\to c\bar{u}d) = 0.446\pm0.014$

$B(b\to c\bar{c}s) = 0.232\pm0.007$

$B(b\to c e \nu_e) = 0.116\pm0.008$

$B(b\to c \mu \nu_\mu) = 0.116\pm0.008$

$B(b\to c \tau \nu_\tau) = 0.027\pm0.001$

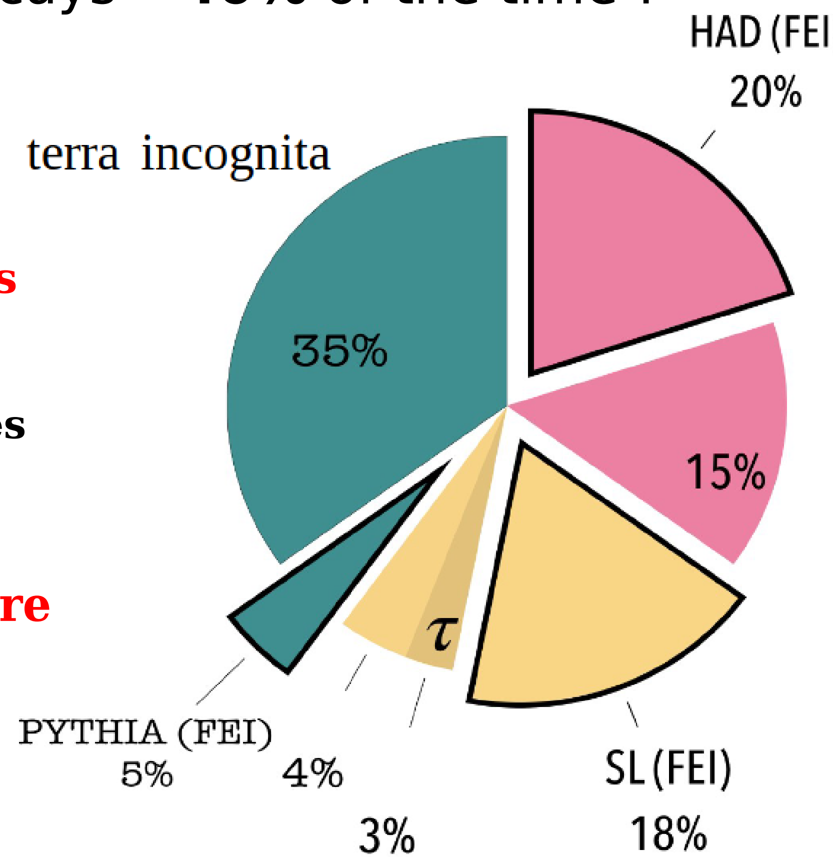
$B(b\to c\bar{u}s) = 0.024\pm0.001$

$B(b\to c\bar{c}d) = 0.0126\pm0.0005$

We will see that we (and PDG) use a 30-year-old measurement with ~75% uncertainty for one of the largest hadronic B-decays...

But on top of that, we don't know how B decays **~40%** of the time !

We ask **PYTHIA** to (poorly) generate them.



B-tagging is key tool for missing energy analyses

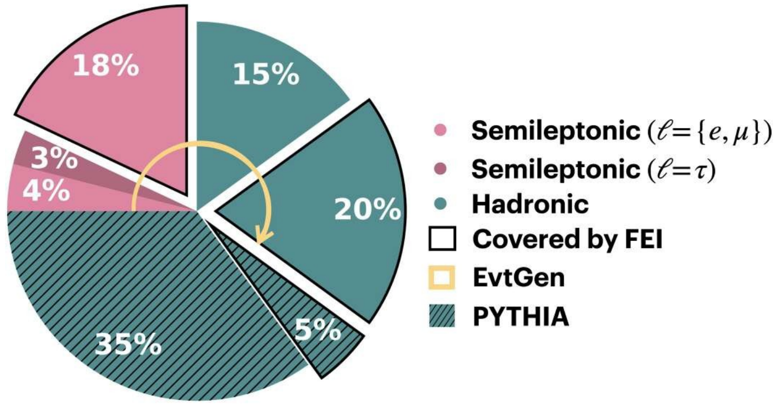
- low efficiency (efficiency for hadronic B-tagging < 1%)
- **and ML can't (always) save you...**
  B-tagging algorithms are trained using MC samples
- 40% of hadronic B decays generated by PYTHIA ...
- and even among the EvtGen part...

most BFs measured are old measurements from ARGUS, CLEO...

lot of hadronic B decays to understand/measure

⇒ new contributions to B-tagging ??

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;
              .
              .
```

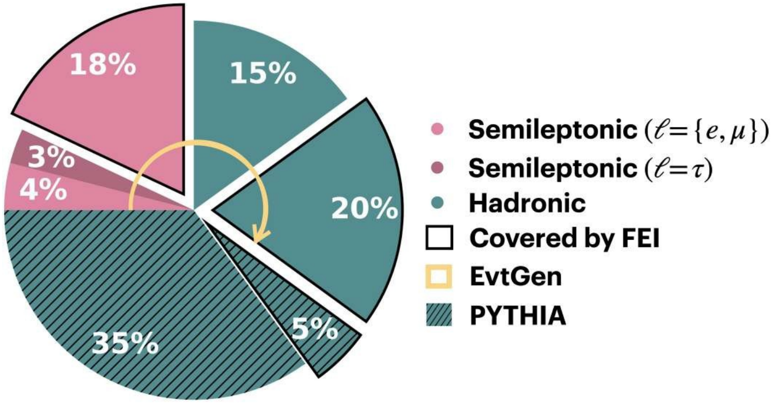
The largest decays are at 10^{-2}, 10^{-3}
so talking about $o(10^4)$ decay channels
we only list $o(10^3)$ explicitly

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 used 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 $a_1^{\pm}$, a_1^0, D^{**}...

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

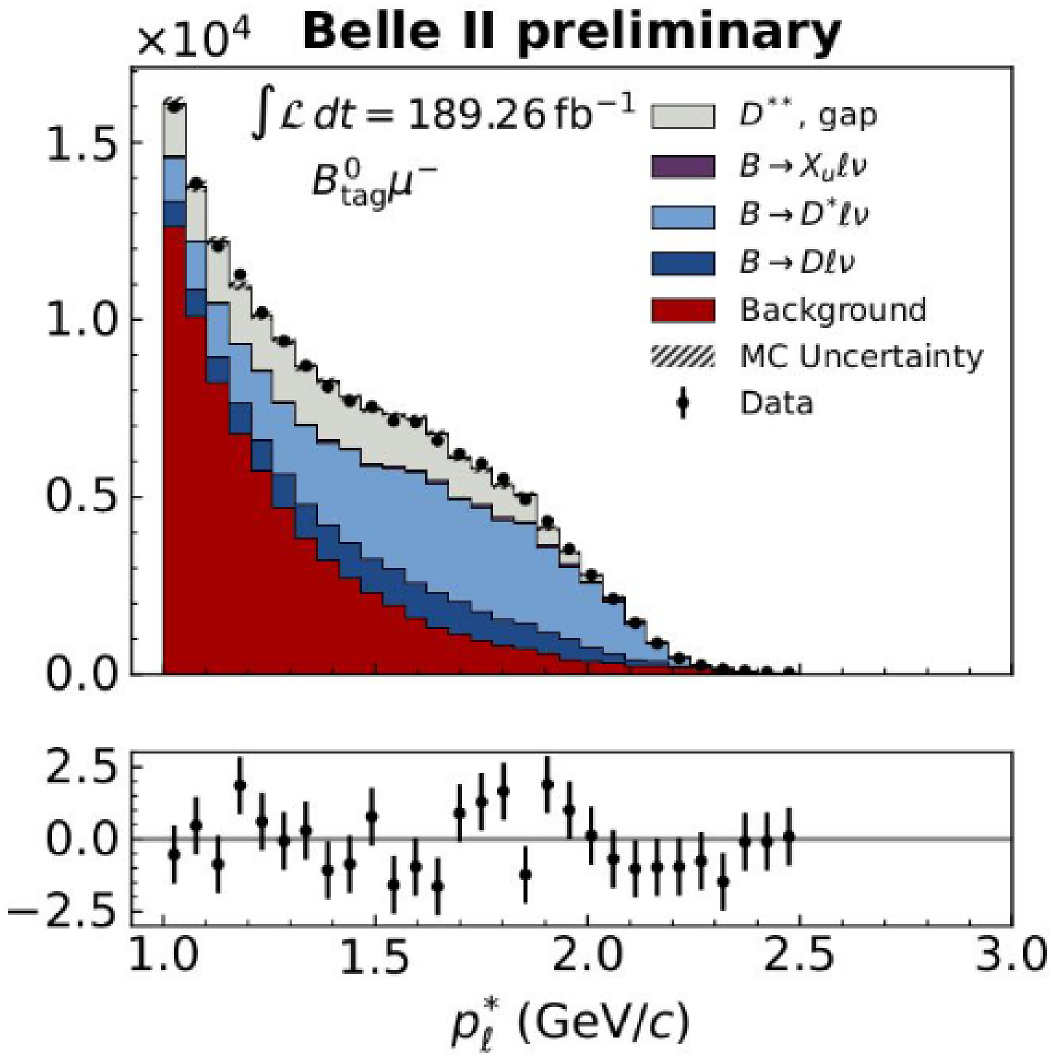
- Fragmentation compares the final state with the explicitly listed decays, and if found, performed again to produce an alternative final state
- Therefore, to exclude that a particular decay is generated by PYTHIA, it can be explicitly listed in DECAY.DEC with a branching fraction of 0%

Need to know what not to generate as well

How to calibrate FEI ?
or
FEI performance in MC and data

B^+-tagging: standard calibration sample

BDTs are trained on **MC**
⇒ The performance has to be calibrated with data.



Traditionally, this calibration is done with semi-leptonic B on the signal side because it has large branching fraction.

Fit the lepton momentum in B rest frame.
No clear peak
⇒ Complex template fitting strategy
⇒ Low signal-side purity

Systematically limited

- Highly dependent on the SL decay model including D** and SL gap components
- Significant cross-feed from B^0

But, if MC is not optimal, the BDT selection will not be optimal.

This cannot be easily studied with semi-leptonic B because there are no peaking structures.

An orthogonal sample is needed not only to provide calibration factors but to study the sources of discrepancy.

True lies and hard truths

(summarized by Peter Lewis)

In analysis

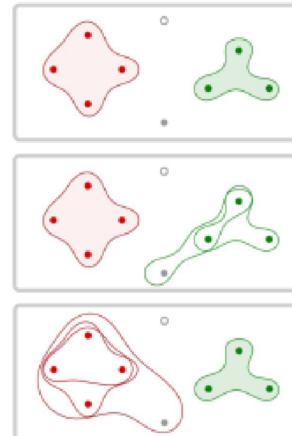
So you have your tags… *what do you do now?*

1. Build your *signal-side B* candidate
2. Combine *tag* and *signal Bs* to make $\Upsilon(4S)$ candidates

FEI efficiency ϵ_{FEI} enters in one of two ways:

Lies! →

- BF(signal): $\epsilon_{total} = \epsilon_{FEI} * \epsilon_{sig}$
- BF(signal)/BF(normalization): FEI efficiency *cancels*



But FEI is trained on MC: ϵ_{FEI} needs a *calibration*…

20

We now know that it is not possible to disentangle sig/tag efficiency, so a calibration may only be valid for the mode it is calibrated on (!)

Calibration

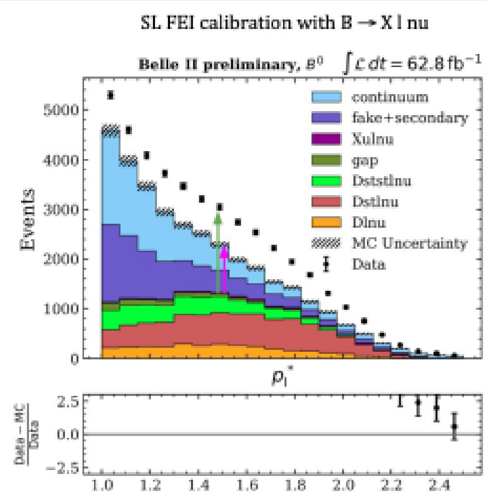
Measure *known decay* in FEI-tagged events

Lie → $N_{expected} = N_{\Upsilon(4S)} \epsilon_{FEI} \cdot \mathcal{B}\epsilon$

Calibration factors are **data**/MC ratios of measured yield

Oversimplification →

To use: correct simulated FEI efficiency with the calibration factor

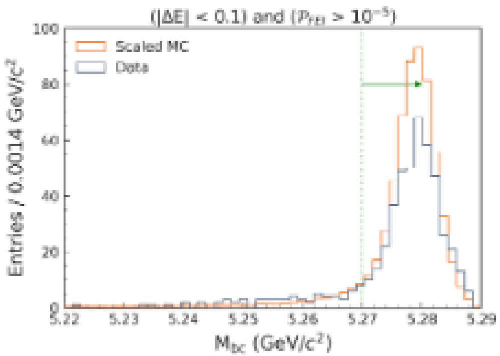


◦ having several calibration procedure (learn a lot about signal-side dependencies)

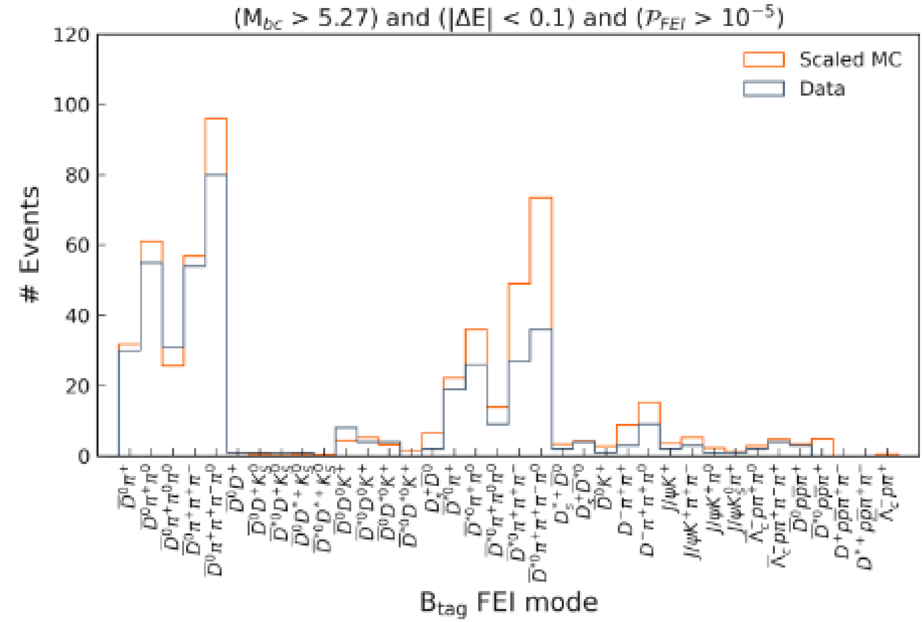
◦ the closer the calibration factors are from 1, the better is our MC (so is the cross-feed simulation, the signal-side dependencies…)

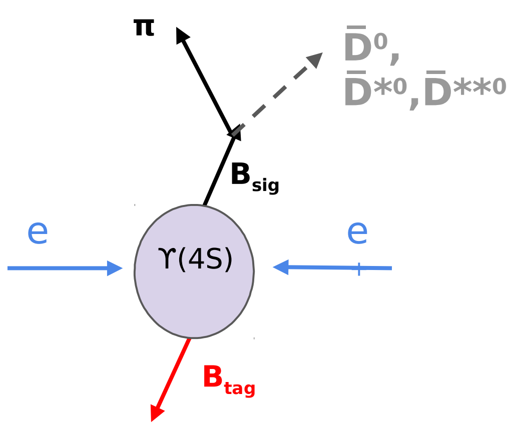
Ideal control sample to study B-tagging

First idea, use $B \to J/\psi K$:



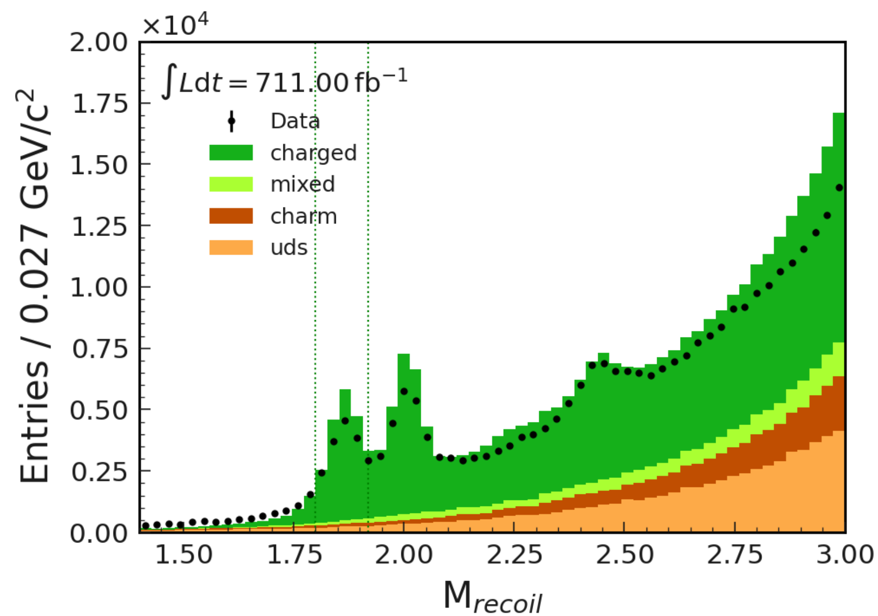
clean, allow first estimation (large MC/data differences)
⇒ but too limited stat (~ 400 evts after B-tagging)





We can look for D^0, D^{*0} and even D^{**0} in the recoil mass of a fully reconstructed B and a $\pi^\pm$

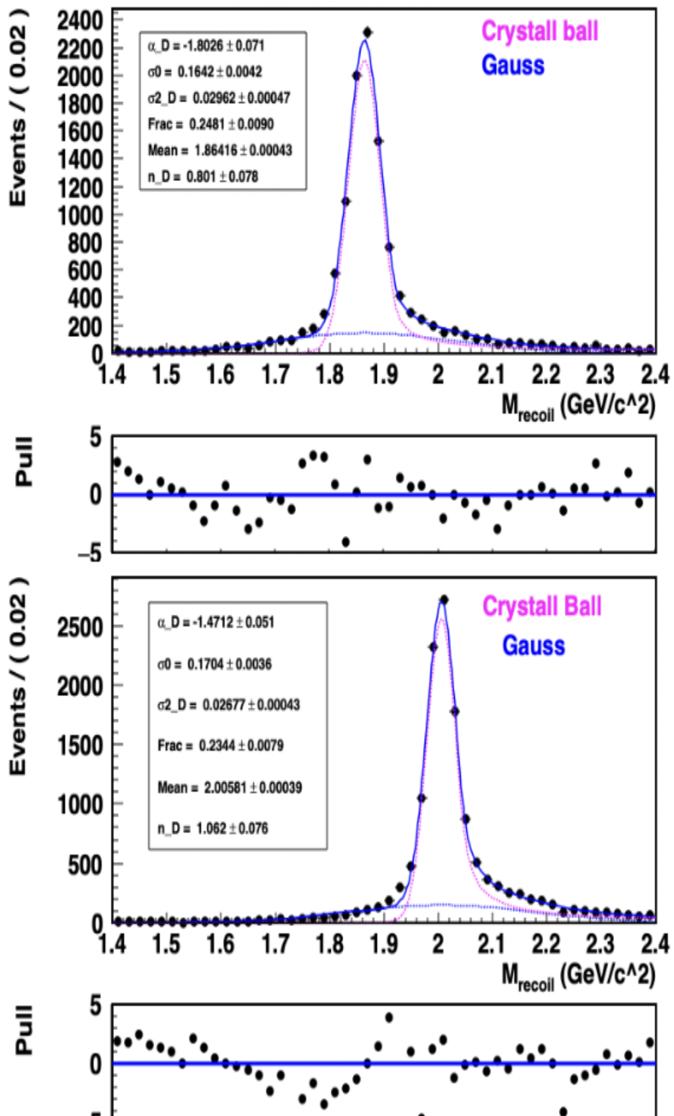
Within a narrow region around the peak, we know that one B decays to $D^0\pi^+$ and we can study the other B (decaying hadronically)



~16k events in a 3σ window around each peak in data.

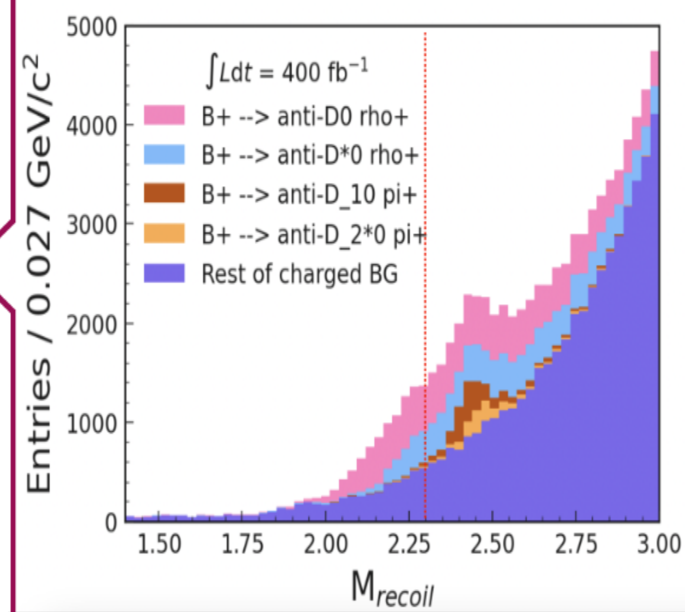
Need to calibrate the algorithm, but more importantly, need to improve MC for training.

Fitting D peak for yields



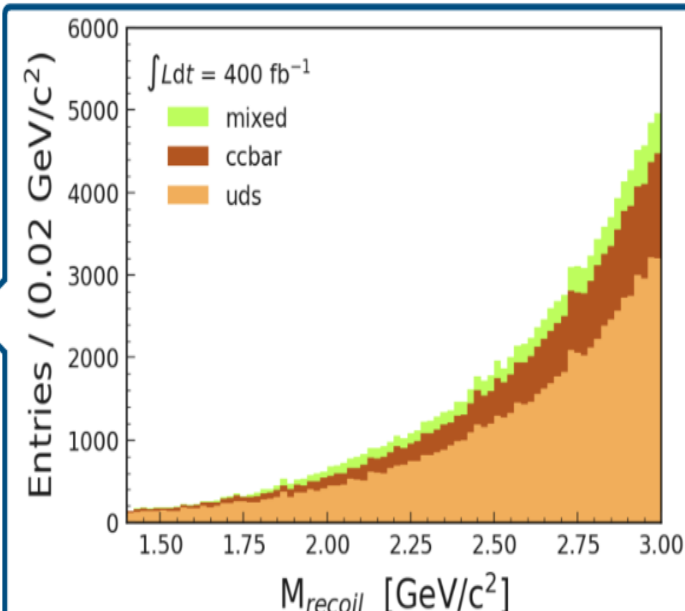
Fit range: [1.4, 2.3] to avoid the D** peaks at higher mass region

Rest of the $B \to D^{(*)}\rho$ candidates present are modelled with double Gaussian: systematics will be assigned for this component



Signal: common to both the peaks

Rest of the charged + mixed + continuum: exponential function



FEI metrics in data

Calculated directly on data:

- Calibration factor

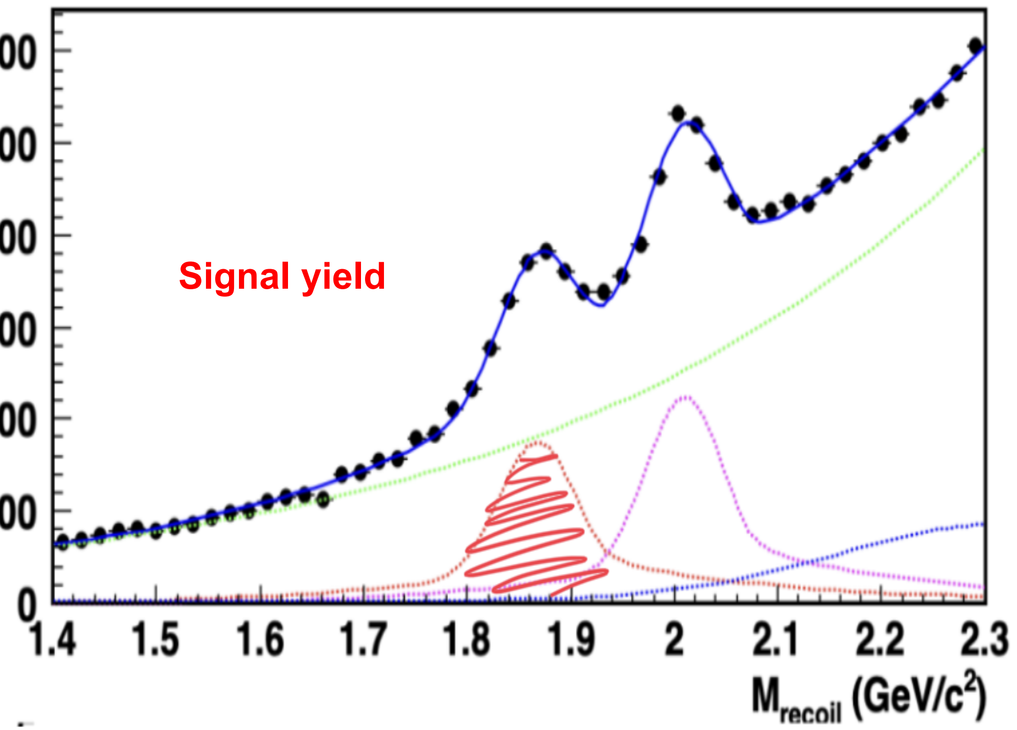
  = Signal yield in data / Signal yield in MC

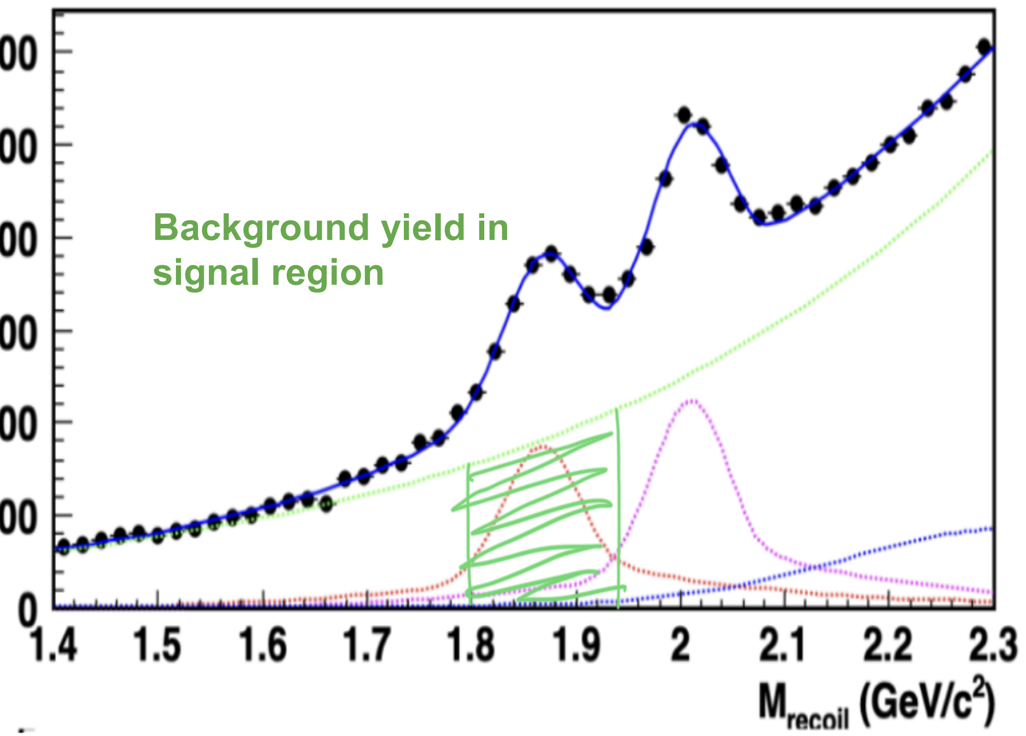
- Purity

  = Signal yield / (Signal yield + Background yield in signal region)

- Efficiency

  = Signal yield / (n_{BB} $BF_{B+ \to D\pi}$ ϵ_{π})

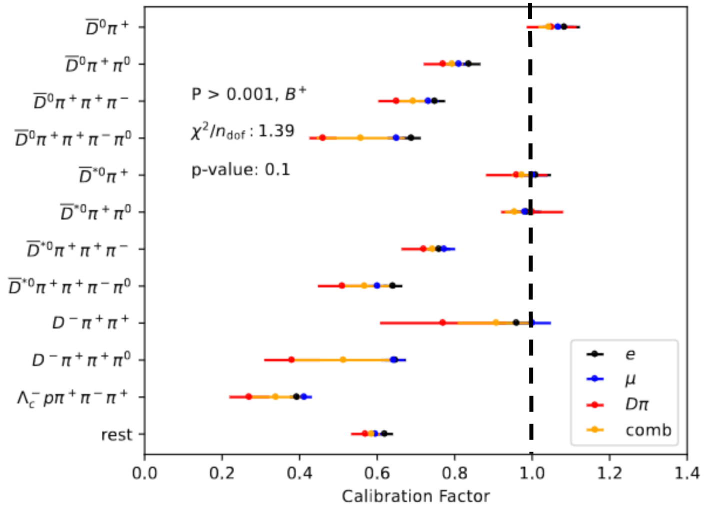




n_{BB} = 392.5 x 10^6
$BF_{B+ \to D\pi}$ = 0.467 x10^{-2}
ϵ_{π} = 90%

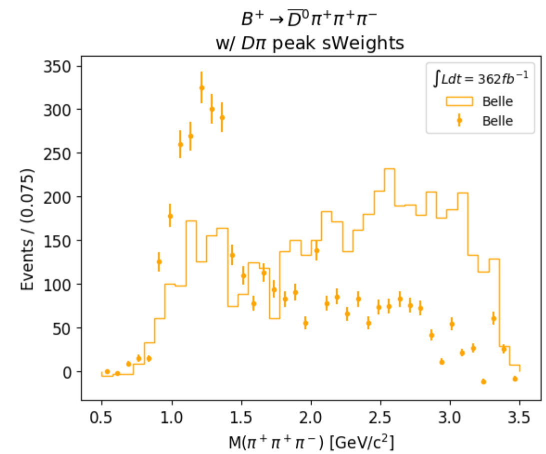
But why calibration factors are still far from 1 ?

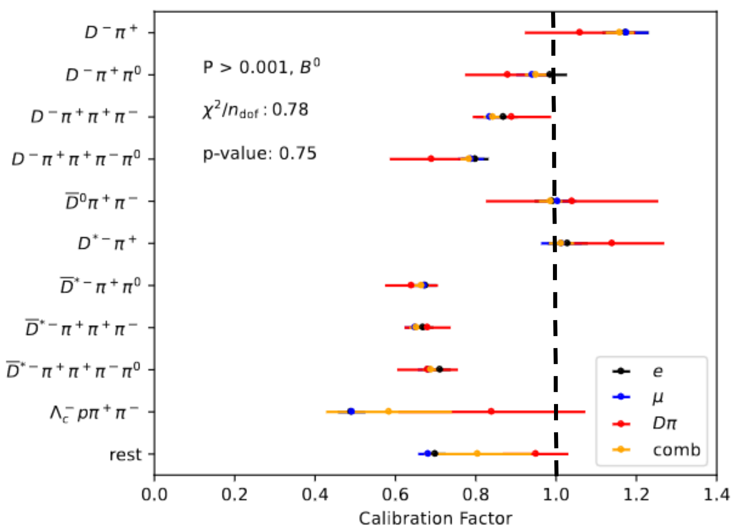
- The fit allows to obtain calibration factors but also thanks to splot, obtain the distributions for B_{tag} decays: invariant mass of intermediate states, sigprob…

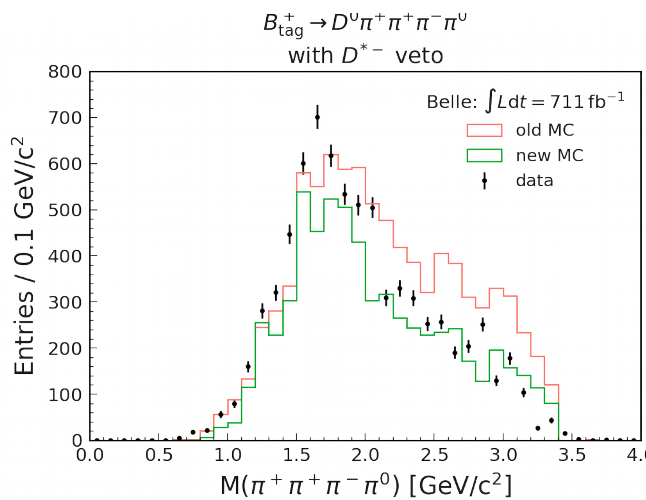


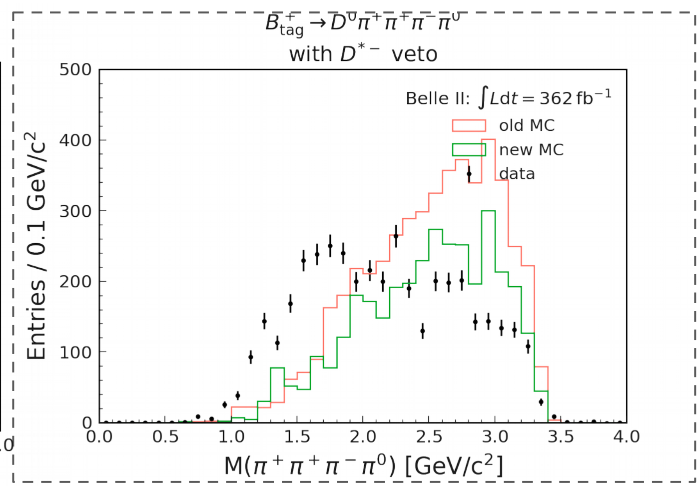
Understanding of $B \to D^{(*)} n\pi m\pi^0$ decays is essential for B-tagging…

⇒ significant differences between data and MC (e.g. $n+m \geq 3$)









Belle and Belle II have different PYTHIA.
But the distribution is different in the data itself
⇒ bias introduced by training on MC !!

⇒ Need to understand and improve the MC modeling of B decays

Improving MC model: an example

Let's take one final state for example: $B^+ \to \bar{D}^0 \pi^+ \pi^+ \pi^-$.
It can be produced through many intermediate states:

Decay	Belle	Belle II
$B^+ \to \overline{D}^0 \pi^- \pi^+ \pi^+$	0.46	0.51
$B^+ \to \overline{D}^0 \rho(770)^0 \pi^+; \rho(770)^0 \to \pi^+ \pi^-$	0.39	0.42
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to \rho(770)^0 \pi^+; \rho(770)^0 \to \pi^+ \pi^-$	0.13	0.14
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to f_0(600) \pi^+; f_0(600) \to \pi^+ \pi^-$	0.05	-
$B^+ \to \overline{D}_1(2420)^0 \pi^+; \overline{D}_1(2420)^0 \to D^*(2010)^- \pi^+; D^*(2010)^- \to \overline{D}^0 \pi^-$	0.04	0.02
$B^+ \to \overline{D}_1(2430)^0 \pi^+; \overline{D}_1(2430)^0 \to D^*(2010)^- \pi^+; D^*(2010)^- \to \overline{D}^0 \pi^-$	0.03	0.02
$B^+ \to \overline{D}_2^*(2460)^0 \pi^+; \overline{D}_2^*(2460)^0 \to D^*(2010)^- \pi^+; D^*(2010)^- \to \overline{D}^0 \pi^-$	0.01	0.01
$B^+ \to D^*(2010)^- \pi^+ \pi^+; D^*(2010)^- \to \overline{D}^0 \pi^-$	-	0.09
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to \pi^+ \pi^+ \pi^-$	-	0.07
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to f_0(500) \pi^+; f_0(500) \to \pi^+ \pi^-$	-	0.05
$B^+ \to \overline{D}_1(2420)^0 \pi^+; \overline{D}_1(2420)^0 \to \overline{D}^0 \pi^- \pi^+$	-	0.02
$B^+ \to \overline{D}^0 K^*(892)^+; K^*(892)^+ \to K^0 \pi^+; K^0 \to K_S^0; K_S^0 \to \pi^+ \pi^-$	-	0.01
Rest of Exclusive	0.03	0.03
Sum of Exclusive	1.12	1.38
Sum of Pythia	0	0
Total Sum	1.12	1.38

The $\pi^+ \pi^+ \pi^-$ could be directly generated, could come through $\rho^0\pi^+$ or through an intermediate a_1^+ resonance.

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$B^+ \to \overline{D}_1(2420)^0\pi^+; \overline{D}_1(2420)^0 \to D^*(2010)^-\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	0.04	0.02
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$B^+ \to D^*(2010)^-\pi^+\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	-	0.09
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to \pi^+\pi^+\pi^-$	-	0.07
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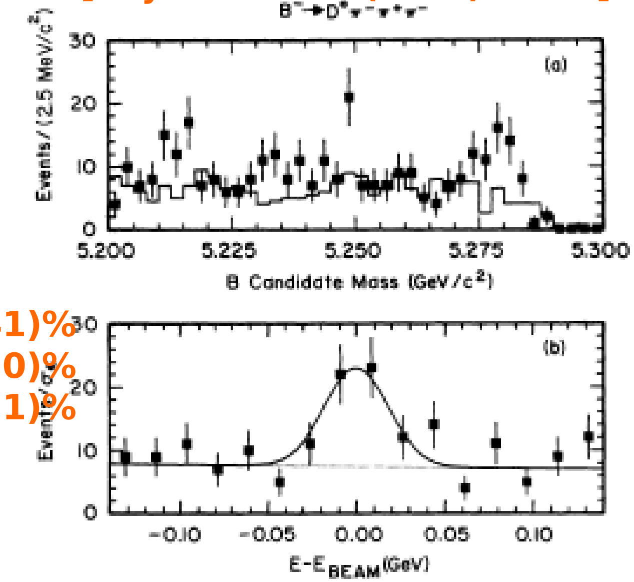
$B^+ \to \overline{D}_1(2420)^0\pi^+; \overline{D}_1(2420)^0 \to \overline{D}^0\pi^-\pi^+$	-	0.02
$B^+ \to \overline{D}^0 K^*(892)^+; K^*(892)^+ \to K^0\pi^+; K^0 \to K_S^0; K_S^0 \to \pi^+\pi^-$	-	0.01
Rest of Exclusive	0.03	0.03
Sum of Exclusive	1.12	1.38
Sum of Pythia	0	0
Total Sum	1.12	1.38

(0.51 ± 0.41)%
(0.42 ± 0.30)%
(0.14 ± 0.11)%

[Phys.Rev.D 45 (1992) 21-35]



In 1992, CLEO experiment measured these 3 values but with ~75% uncertainty!

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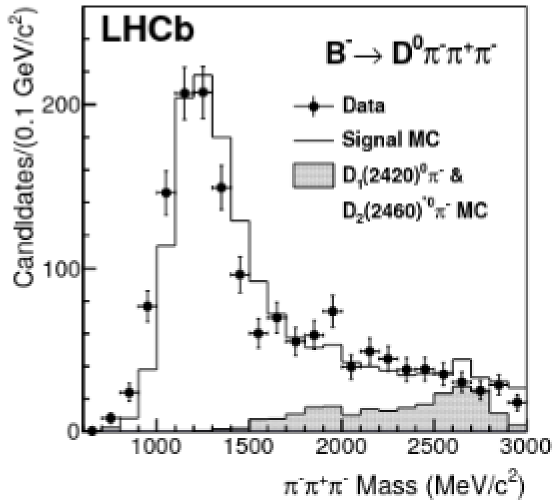
$B^+ \to \overline{D}^0 \rho(770)^0 \pi^+; \rho(770)^0 \to \pi^+\pi^-$	0.39	0.42
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to \rho(770)^0\pi^+; \rho(770)^0 \to \pi^+\pi^-$	0.13	0.14
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to f_0(600)\pi^+; f_0(600) \to \pi^+\pi^-$	0.05	-
$B^+ \to \overline{D}_1(2420)^0\pi^+; \overline{D}_1(2420)^0 \to D^*(2010)^-\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	0.04	0.02
$B^+ \to \overline{D}_1(2430)^0\pi^+; \overline{D}_1(2430)^0 \to D^*(2010)^-\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	0.03	0.02
$B^+ \to \overline{D}_2^*(2460)^0\pi^+; \overline{D}_2^*(2460)^0 \to D^*(2010)^-\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	0.01	0.01
$B^+ \to D^*(2010)^-\pi^+\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	-	0.09
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to \pi^+\pi^+\pi^-$	-	0.07
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to f_0(500)\pi^+; f_0(500) \to \pi^+\pi^-$	-	0.05
$B^+ \to \overline{D}_1(2420)^0\pi^+; \overline{D}_1(2420)^0 \to \overline{D}^0\pi^-\pi^+$	-	0.02
$B^+ \to \overline{D}^0 K^*(892)^+; K^*(892)^+ \to K^0\pi^+; K^0 \to K_S^0; K_S^0 \to \pi^+\pi^-$	-	0.01
Rest of Exclusive	0.03	0.03
Sum of Exclusive	1.12	1.38
Sum of Pythia	0	0
Total Sum	1.12	1.38

Phys.Rev.D 84 (2011) 092001



In 2011 (~20 years later), LHCb looked at this final state, but did not provide individual measurements.

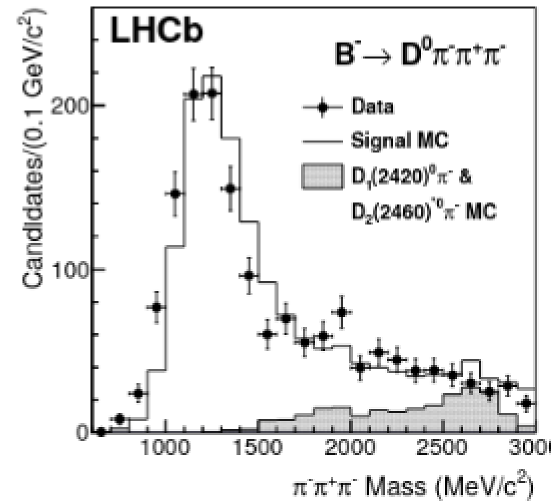
So we are still suck with a 30 year old CLEO measurement in PDG.

Improving MC model: an example

Let's take one final state for example: $B^+ \to \overline{D}^0 \pi^+ \pi^+ \pi^-$.
It can be produced through many intermediate states:

Decay	Belle	Belle II
$B^+ \to \overline{D}^0 \pi^- \pi^+ \pi^+$	0.46	0.51
$B^+ \to \overline{D}^0 \rho(770)^0 \pi^+; \rho(770)^0 \to \pi^+\pi^-$	0.39	0.42
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to \rho(770)^0\pi^+; \rho(770)^0 \to \pi^+\pi^-$	0.13	0.14
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to f_0(600)\pi^+; f_0(600) \to \pi^+\pi^-$	0.05	-
$B^+ \to \overline{D}_1(2420)^0\pi^+; \overline{D}_1(2420)^0 \to D^*(2010)^-\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	0.04	0.02
$B^+ \to \overline{D}_1(2430)^0\pi^+; \overline{D}_1(2430)^0 \to D^*(2010)^-\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	0.03	0.02
$B^+ \to \overline{D}_2^*(2460)^0\pi^+; \overline{D}_2^*(2460)^0 \to D^*(2010)^-\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	0.01	0.01
$B^+ \to D^*(2010)^-\pi^+\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	-	0.09
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to \pi^+\pi^+\pi^-$	-	0.07
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to f_0(500)\pi^+; f_0(500) \to \pi^+\pi^-$	-	0.05
$B^+ \to \overline{D}_1(2420)^0\pi^+; \overline{D}_1(2420)^0 \to \overline{D}^0\pi^-\pi^+$	-	0.02
$B^+ \to \overline{D}^0 K^*(892)^+; K^*(892)^+ \to K^0\pi^+; K^0 \to K_S^0; K_S^0 \to \pi^+\pi^-$	-	0.01
Rest of Exclusive	0.03	0.03
Sum of Exclusive	1.12	1.38
Sum of Pythia	0	0
Total Sum	1.12	1.38

Phys.Rev.D 84 (2011) 092001



But looking at this plot, it looks like most contribution comes through a_1^+ resonance (mass 1400 MeV/c²).

Improving MC model: an example

Let’s take one final state for example: $B^+ \to \bar{D}^0 \pi^+ \pi^+ \pi^-$.
It can be produced through many intermediate states:

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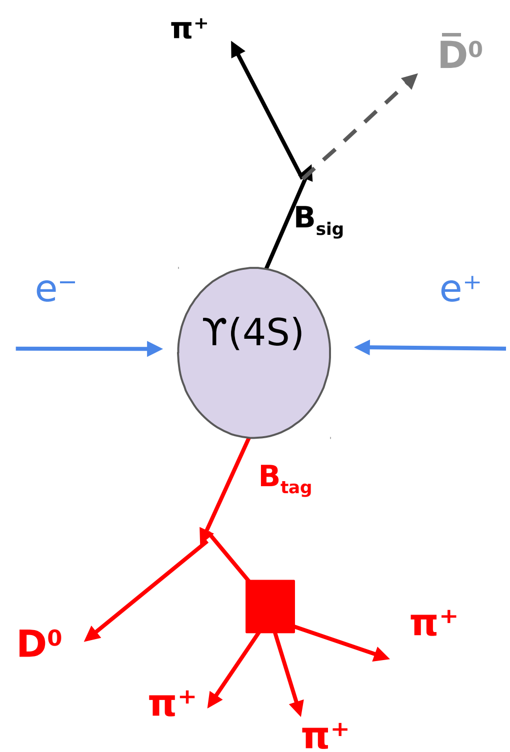
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to f_0(600)\pi^+; f_0(600) \to \pi^+\pi^-$	0.05	-
$B^+ \to \overline{D}_1(2420)^0\pi^+; \overline{D}_1(2420)^0 \to D^*(2010)^-\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	0.04	0.02
$B^+ \to \overline{D}_1(2430)^0\pi^+; \overline{D}_1(2430)^0 \to D^*(2010)^-\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	0.03	0.02
$B^+ \to \overline{D}_2^*(2460)^0\pi^+; \overline{D}_2^*(2460)^0 \to D^*(2010)^-\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	0.01	0.01
$B^+ \to D^*(2010)^-\pi^+\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	-	0.09
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to \pi^+\pi^+\pi^-$	-	0.07
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to f_0(500)\pi^+; f_0(500) \to \pi^+\pi^-$	-	0.05
$B^+ \to \overline{D}_1(2420)^0\pi^+; \overline{D}_1(2420)^0 \to \overline{D}^0\pi^-\pi^+$	-	0.02
$B^+ \to \overline{D}^0 K^*(892)^+; K^*(892)^+ \to K^0\pi^+; K^0 \to K_S^0; K_S^0 \to \pi^+\pi^-$	-	0.01
Rest of Exclusive	0.03	0.03
Sum of Exclusive	1.12	1.38
Sum of Pythia	0	0
Total Sum	1.12	1.38

Can be compared with data at Belle, if we reconstruct one B as $B^+ \to \bar{D}^0 \pi^+$ and other B as $B^- \to D^0 \pi^+ \pi^+ \pi^-$



Improving MC model: an example

Let's take one final state for example: $B^+ \to \bar{D}^0 \pi^+ \pi^+ \pi^-$.
It can be produced through many intermediate states:

Decay	Belle	Belle II
$B^+ \to \overline{D}^0 \pi^- \pi^+ \pi^+$	0.46	0.51
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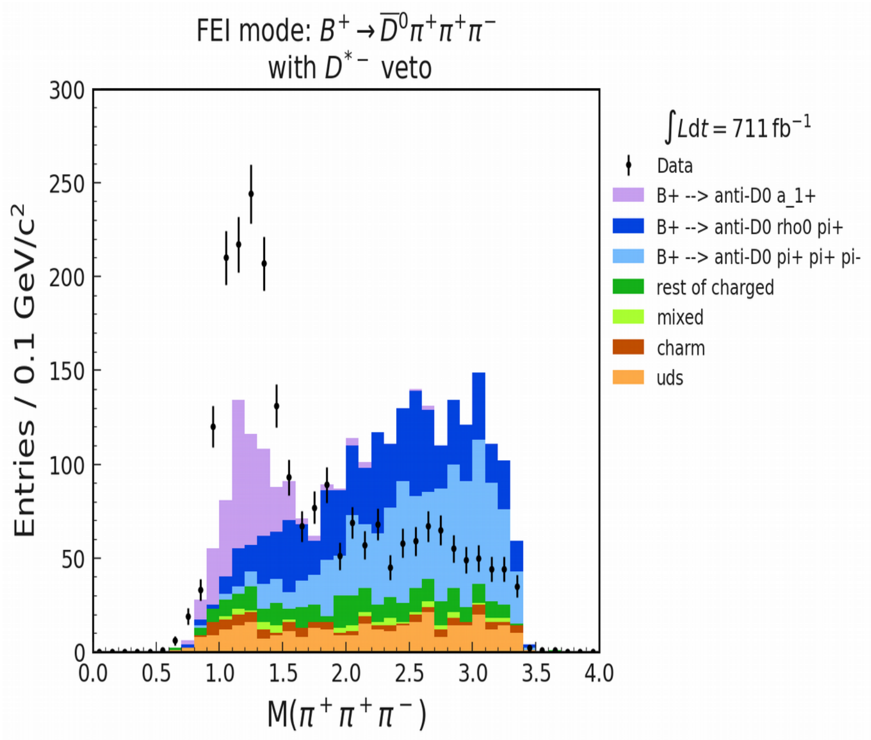
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to \rho(770)^0\pi^+; \rho(770)^0 \to \pi^+\pi^-$	0.13	0.14
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to f_0(600)\pi^+; f_0(600) \to \pi^+\pi^-$	0.05	-
$B^+ \to \overline{D}_1(2420)^0\pi^+; \overline{D}_1(2420)^0 \to D^*(2010)^-\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	0.04	0.02
$B^+ \to \overline{D}_1(2430)^0\pi^+; \overline{D}_1(2430)^0 \to D^*(2010)^-\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	0.03	0.02
$B^+ \to \overline{D}_2^*(2460)^0\pi^+; \overline{D}_2^*(2460)^0 \to D^*(2010)^-\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	0.01	0.01
$B^+ \to D^*(2010)^-\pi^+\pi^+; D^*(2010)^- \to \overline{D}^0\pi^-$	-	0.09
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to \pi^+\pi^+\pi^-$	-	0.07
$B^+ \to \overline{D}^0 a_1(1260)^+; a_1(1260)^+ \to f_0(500)\pi^+; f_0(500) \to \pi^+\pi^-$	-	0.05
$B^+ \to \overline{D}_1(2420)^0\pi^+; \overline{D}_1(2420)^0 \to \overline{D}^0\pi^-\pi^+$	-	0.02
$B^+ \to \overline{D}^0 K^*(892)^+; K^*(892)^+ \to K^0\pi^+; K^0 \to K_S^0; K_S^0 \to \pi^+\pi^-$	-	0.01
Rest of Exclusive	0.03	0.03
Sum of Exclusive	1.12	1.38
Sum of Pythia	0	0
Total Sum	1.12	1.38



Comparing with data clearly shows that a_1^+ component is underestimated, and the $\rho^0\pi^+$ and direct $\pi^+ \pi^+ \pi^-$ components are overestimated.

Similarly , for other final states

BELLE2-NOTE-PH-2022-002

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

Decay	Belle	Belle II
$B^+ \to \overline{D}^{*0} \pi^- \pi^+ \pi^+ \pi^0$	1.80	1.80
$B^+ \to \overline{D}^{*0} \omega(782) \pi^+;\ \omega(782) \to \pi^- \pi^+ \pi^0$	0.40	0.41
Rest of Exclusive	0.02	0.05
Sum of Exclusive	2.22	2.25
$B^+ \to \overline{D}^{*0} \rho(770)^0 \rho(770)^+;\ \rho(770)^0 \to \pi^+ \pi^-;\ \rho(770)^+ \to \pi^+ \pi^0$	0.49	0.20
$B^+ \to \overline{D}^{*0} \rho(770)^+ \pi^+ \pi^-;\ \rho(770)^+ \to \pi^+ \pi^0$	0.40	0.20
$B^+ \to \overline{D}^{*0} \rho(770)^0 \pi^+ \pi^0;\ \rho(770)^0 \to \pi^+ \pi^-$	0.40	0.20
$B^+ \to \overline{D}^{*0} \rho(770)^- \pi^+ \pi^+;\ \rho(770)^- \to \pi^- \pi^0$	0.20	0.10
$B^+ \to \overline{D}^{*0} \eta \pi^+;\ \eta \to \pi^- \pi^+ \pi^0$	0.14	0.07
$B^+ \to \overline{D}_1(2430)^0 \rho(770)^0 \pi^+;\ \overline{D}_1(2430)^0 \to \overline{D}^{*0} \pi^0;\ \rho(770)^0 \to \pi^+ \pi^-$	0.03	-
Rest of PYTHIA	0.02	0.01
Sum of PYTHIA	1.68	0.77
Total Sum	3.90	3.03

blue means generated by PYTHIA

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

TABLE VI: Contents of the DECAY file concerning the $B^+ \to \overline{D}^{*0} \pi^+ \pi^+ \pi^-$ final state and corresponding measurements in PDG [in %]. The rows in blue correspond to decays produced by Pythia.

Decay	Belle	Belle II	Marker	Ref
$B^+ \to \overline{D}^*(2007)^0 \pi^- \pi^+ \pi^+$	1.03	-	■	[2], [7]
$B^+ \to \overline{D}^*(2007)^0 a_1(1260)^+;\ a_1(1260)^+ \to \rho(770)^0 \pi^+;\ \rho(770)^0 \to \pi^+ \pi^-$	0.66	0.58	★	
$B^+ \to \overline{D}^*(2007)^0 a_1(1260)^+;\ a_1(1260)^+ \to f_0(600) \pi^+;\ f_0(600) \to \pi^+ \pi^-$	0.25	-	★	
$B^+ \to \overline{D}^*(2007)^0 a_1(1260)^+;\ a_1(1260)^+ \to \pi^+ \pi^+ \pi^-$	-	0.28	★	
$B^+ \to \overline{D}^*(2007)^0 a_1(1260)^+;\ a_1(1260)^+ \to f_0(500) \pi^+;\ f_0(500) \to \pi^+ \pi^-$	-	0.20	★	
$B^+ \to \overline{D}^*(2007)^0 \rho(770)^0 \pi^+;\ \rho(770)^0 \to \pi^+ \pi^-$	-	0.04	★	
Rest of Exclusive	0.02	0.05		
Sum of Exclusive	1.96	1.15		
$B^+ \to \overline{D}^*(2007)^0 f_0(980) \pi^+;\ f_0(980) \to \pi^+ \pi^-$	0.05	-	★	
$B^+ \to \overline{D}^*(2007)^0 \pi^+ \pi^+ \pi^-$	-	0.20	■	
Rest of Pythia	0.00	0.00		
Sum of Pythia	0.05	0.20		
Total Sum	2.01	1.35		

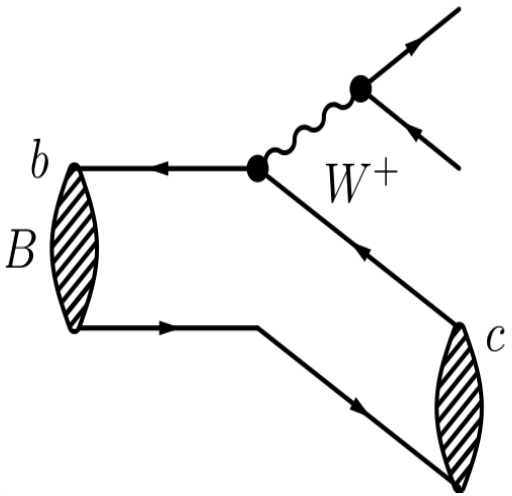
$B^+ \to \bar{D}^0 \pi^+ \pi^+ \pi^- \pi^0$

Marker convention:
- ★ : Old/No measurement
- ■ : Double counting

TABLE IX: Contents of the DECAY file concerning the $B^+ \to \overline{D}^0 \pi^+ \pi^+ \pi^- \pi^0$ final state and corresponding measurements in PDG [in %]. The rows in blue correspond to decays produced by Pythia.

Decay	Belle	Belle II	Markers	Ref
$B^+ \to D^*(2010)^- \pi^0 \pi^+ \pi^+;\ D^*(2010)^- \to \overline{D}^0 \pi^-$	1.02	1.03	★	[8]
$B^+ \to \overline{D}^*(2007)^0 \pi^- \pi^+ \pi^+;\ \overline{D}^*(2007)^0 \to \overline{D}^0 \pi^0$	0.64	-	■	
$B^+ \to \overline{D}^*(2007)^0 a_1(1260)^+;\ \overline{D}^*(2007)^0 \to \overline{D}^0 \pi^0;\ a_1(1260)^+ \to \rho(770)^0 \pi^+;\ \rho(770)^0 \to \pi^+ \pi^-$	0.41	0.38	★	
$B^+ \to \overline{D}^0 \omega(782) \pi^+;\ \omega(782) \to \pi^- \pi^+ \pi^0$	0.37	0.37	★	[9]
$B^+ \to \overline{D}^*(2007)^0 a_1(1260)^+;\ \overline{D}^*(2007)^0 \to \overline{D}^0 \pi^0;\ a_1(1260)^+ \to f_0(600) \pi^+;\ f_0(600) \to \pi^+ \pi^-$	0.16	-	★	
$B^+ \to D^*(2010)^- \rho(770)^+ \pi^+;\ D^*(2010)^- \to \overline{D}^0 \pi^-;\ \rho(770)^+ \to \pi^+ \pi^0$	0.14	0.14	★	
$B^+ \to \overline{D}^*(2007)^0 a_1(1260)^+;\ \overline{D}^*(2007)^0 \to \overline{D}^0 \pi^0;\ a_1(1260)^+ \to \pi^+ \pi^+ \pi^-$	-	0.18	★	
$B^+ \to \overline{D}^*(2007)^0 a_1(1260)^+;\ \overline{D}^*(2007)^0 \to \overline{D}^0 \pi^0;\ a_1(1260)^+ \to f_0(500) \pi^+;\ f_0(500) \to \pi^+ \pi^-$	-	0.13	★	
Rest of Exclusive	0.03	0.10		
Sum of Exclusive	2.75	2.32		
$B^+ \to \overline{D}^0 \rho(770)^+ \pi^+ \pi^-;\ \rho(770)^+ \to \pi^+ \pi^0$	0.20	0.30		
$B^+ \to \overline{D}^0 \rho(770)^0 \rho(770)^+;\ \rho(770)^0 \to \pi^+ \pi^-;\ \rho(770)^+ \to \pi^+ \pi^0$	0.20	0.20		
$B^+ \to \overline{D}^0 \rho(770)^- \pi^+ \pi^+;\ \rho(770)^- \to \pi^- \pi^0$	0.10	0.10		
$B^+ \to \overline{D}^0 \rho(770)^0 \pi^+ \pi^0;\ \rho(770)^0 \to \pi^+ \pi^-$	0.10	0.20		
$B^+ \to \overline{D}^0 \eta \pi^+;\ \eta \to \pi^- \pi^+ \pi^0$	0.05	0.07	★	
$B^+ \to \overline{D}_1(2430)^0 \pi^+ \pi^0;\ \overline{D}_1(2430)^0 \to D^*(2010)^- \pi^+;\ D^*(2010)^- \to \overline{D}^0 \pi^-$	0.05	-		
$B^+ \to \overline{D}_0^*(2300)^0 \rho(770)^0 \pi^+;\ \overline{D}_0^*(2300)^0 \to \overline{D}^0 \pi^0;\ \rho(770)^0 \to \pi^+ \pi^-$	0.03	-		
$B^+ \to \overline{D}^*(2007)^0 f_0(980) \pi^+;\ \overline{D}^*(2007)^0 \to \overline{D}^0 \pi^0;\ f_0(980) \to \pi^+ \pi^-$	0.03	-	■	
$B^+ \to \overline{D}_2^*(2460)^0 \rho(770)^0 \pi^+;\ \overline{D}_2^*(2460)^0 \to \overline{D}^0 \pi^0;\ \rho(770)^0 \to \pi^+ \pi^-$	0.02	-		
$B^+ \to \overline{D}_2^*(2460)^0 \pi^+ \pi^0;\ \overline{D}_2^*(2460)^0 \to D^*(2010)^- \pi^+;\ D^*(2010)^- \to \overline{D}^0 \pi^-$	0.01	-		
$B^+ \to \overline{D}^*(2007)^0 \pi^+ \pi^+ \pi^-;\ \overline{D}^*(2007)^0 \to \overline{D}^0 \pi^0$	-	0.13	■	
$B^+ \to \overline{D}^0 \pi^+ \pi^+ \pi^- \pi^0$	-	0.10		
Rest of Pythia	0.01	0.01		
Sum of Pythia	0.79	1.10		
Total Sum	3.54	3.42	★	

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



X = π, ρ, a$_1$, ωπ, ρππ, ηπ

Y = D, D*, D**

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

We 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 there is no signal).

2 primary rules:

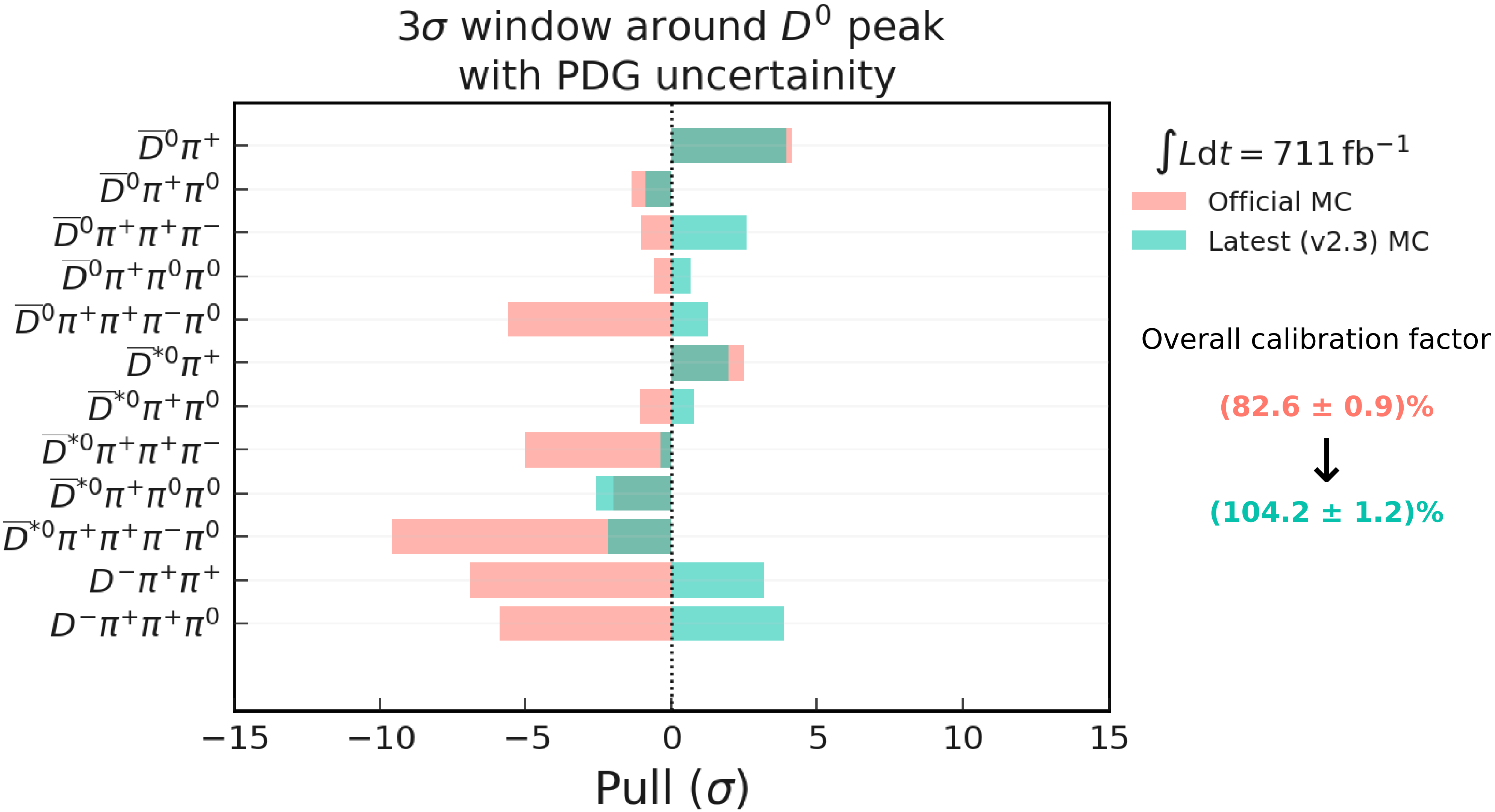
- D^0 X: D^{*0} X : D^{**0} X ~= 1 : 1 : 1
  (based on observation from D π^- : D* π^- : D** π^- and D ρ^- : D* ρ^-)
- Y π^- : Y ρ^- : Y a_1^- ~= 1 : 2.5 : 2.5
  (based on predictions and confirmed with $\tau \rightarrow h\ \nu$ decays)

Additional information:

- 3π π^0 is hard to model without some sort of ρ' resonance
  - For **ωπ** we fix from measurements.
  - For **ρππ** and **ηπ**, we let PYTHIA generate it**.**
- Decays of D** particles is synchronized with Belle II
- The fraction of 4 different D** is fixed based on observations.

Pulls of calibration factors

Another way to visualize the improvement in the calibration factors:

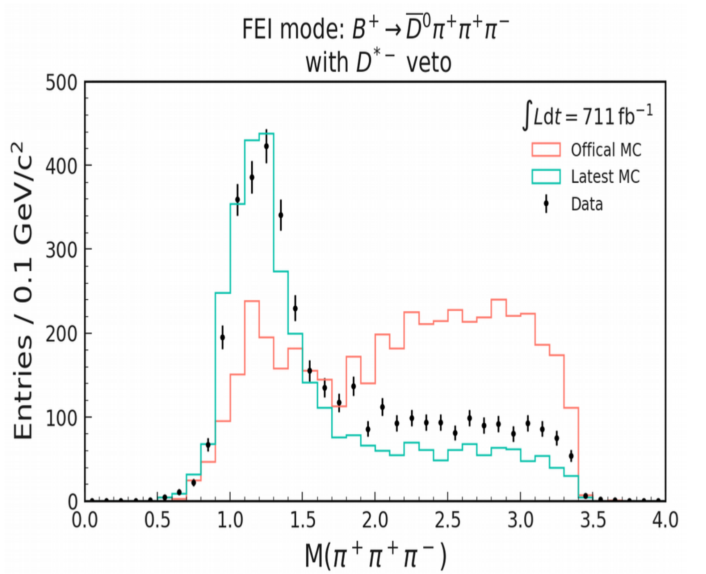


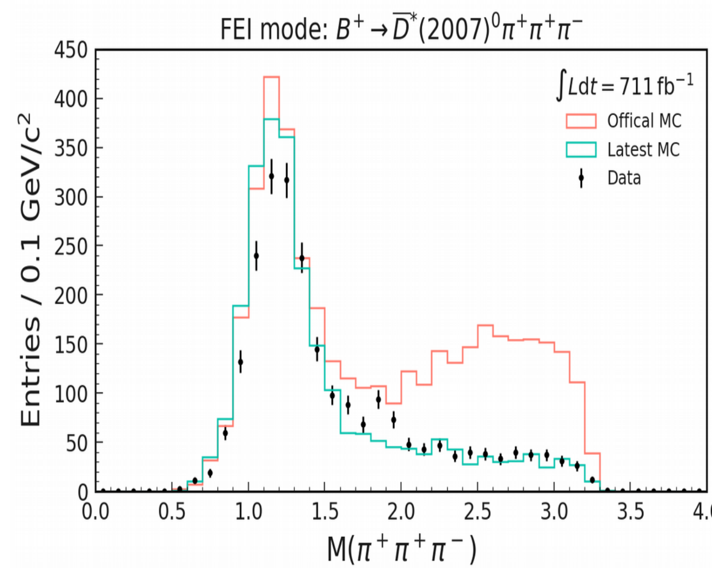
improving description of hadronic B decays ⇒ improve B-tagging efficiency

Decay description is improved !

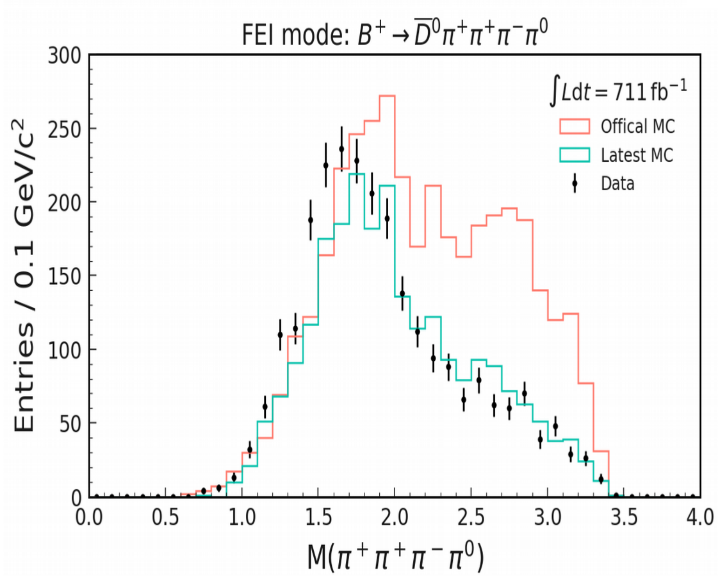
The improvement is not limited to calibration factors, but more importantly in the invariant masses (of intermediate particles), which are used as training variables in FEI

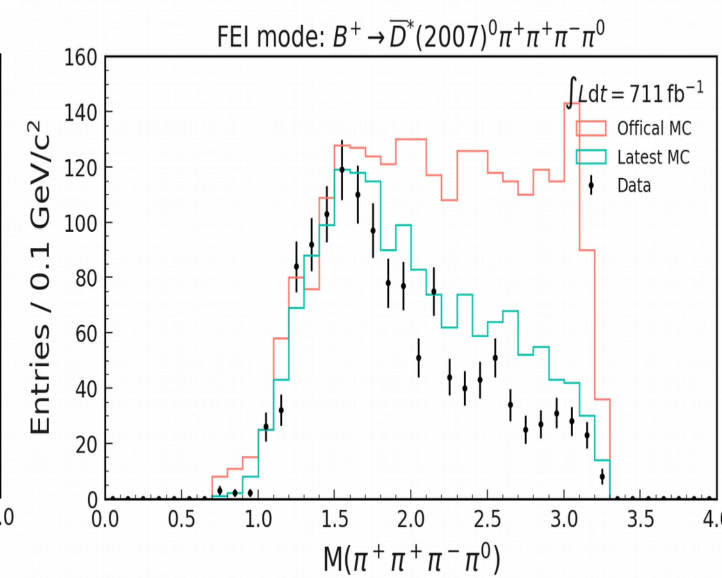
3π± case:





3π± π⁰ case:

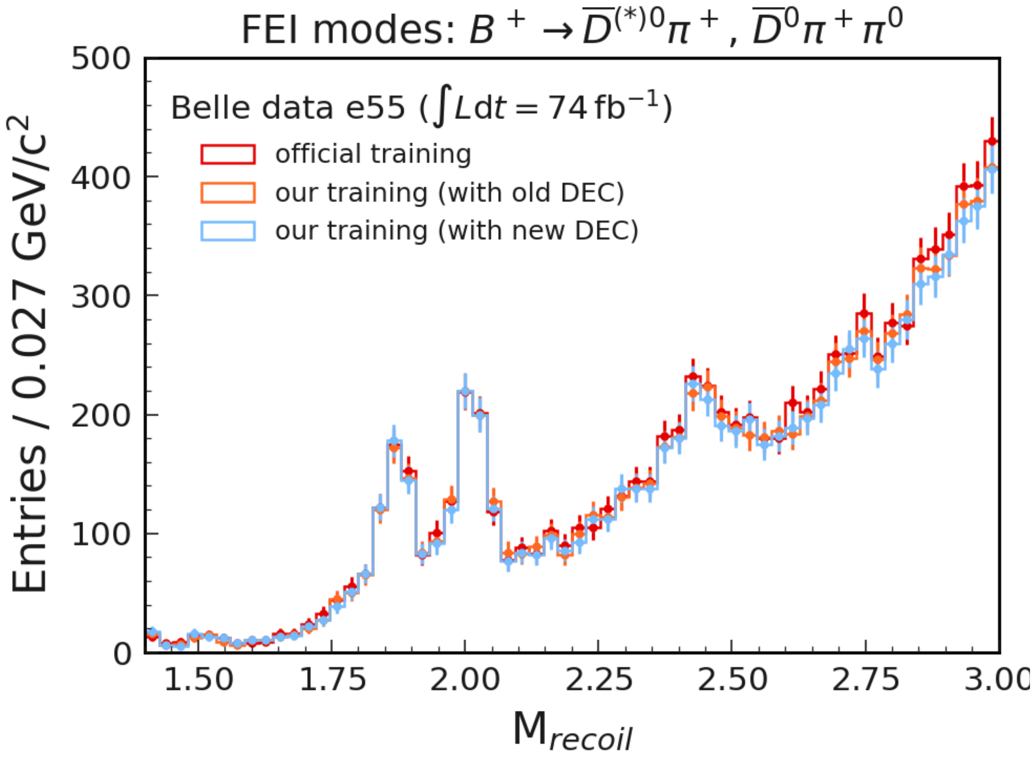


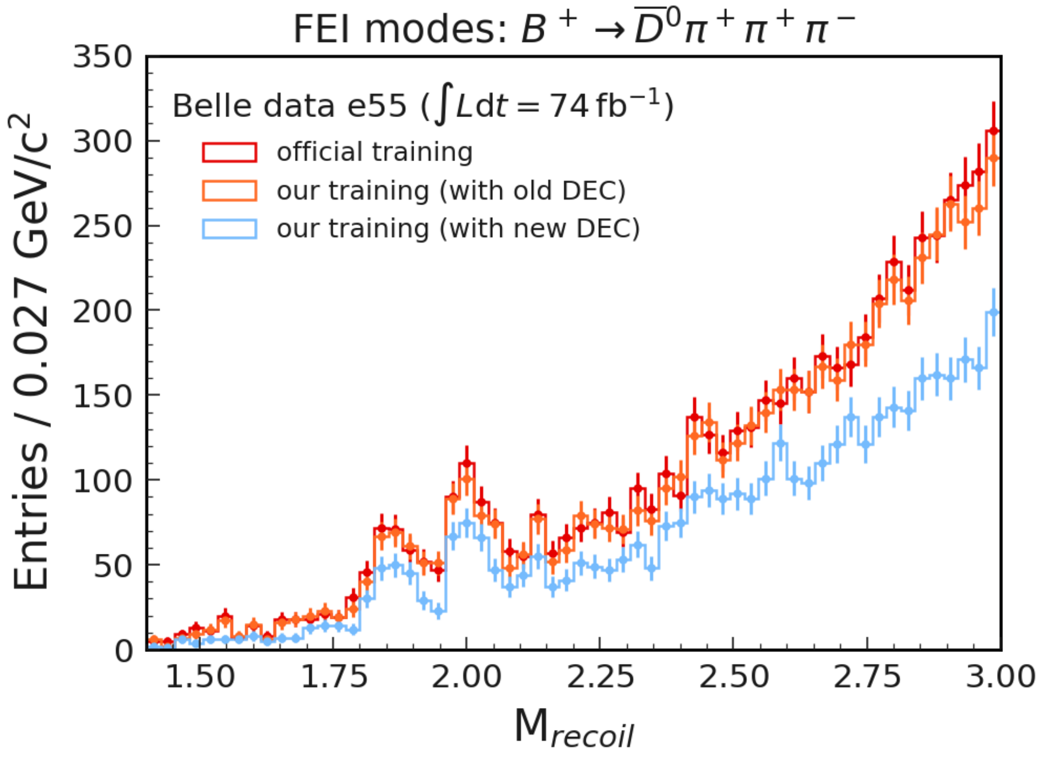


improving description of hadronic B decays ⇒ improve B-tagging efficiency

Retraining FEI: Validation

Once we have a new model for how the $B \rightarrow D^{(*)}\ (n\pi^+)\ (m\pi^0)$ decays, we can train BDTs again with it and see performance:

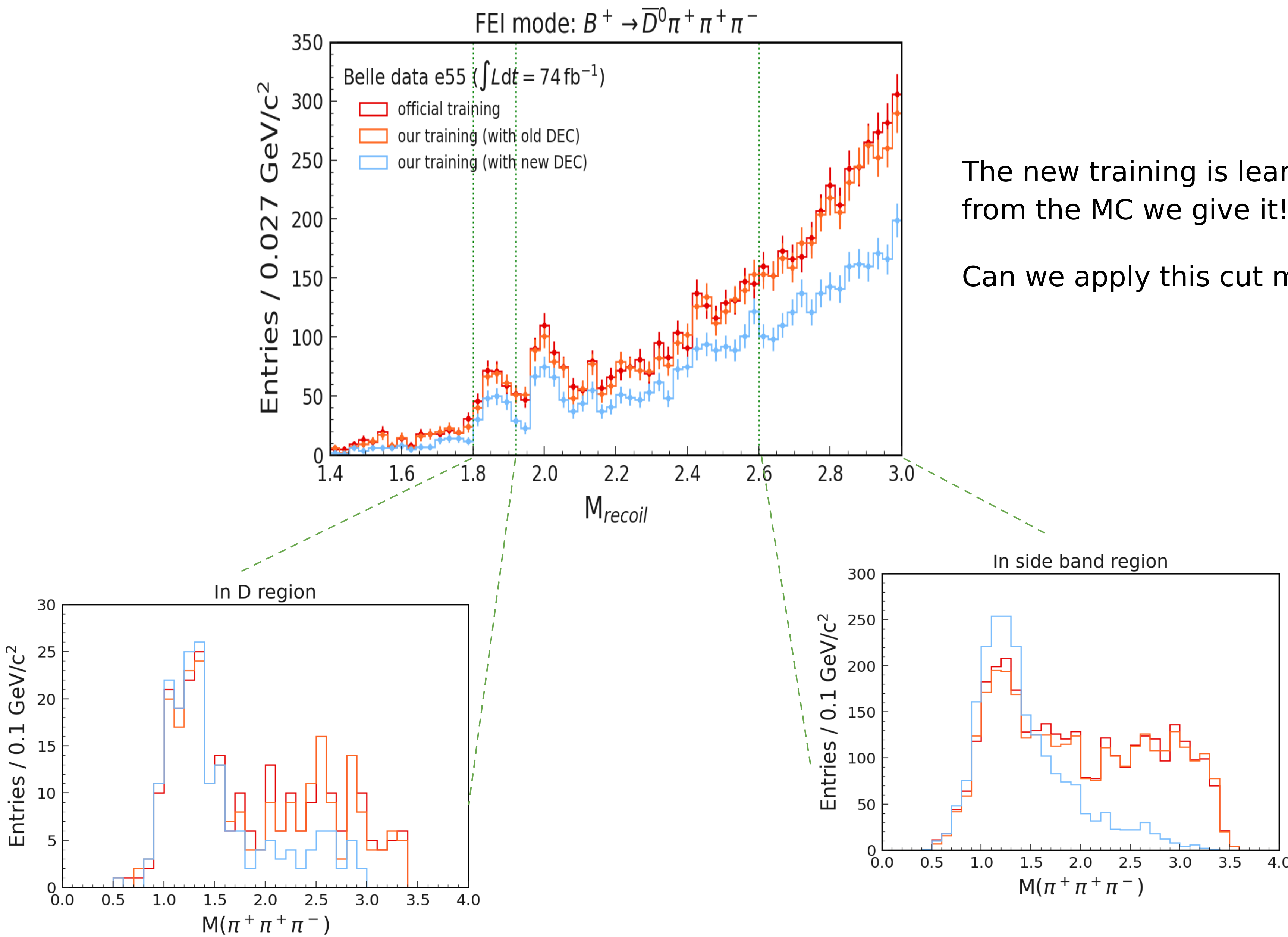




Nothing changes in the FEI modes where we did not change anything.

There is a significant background reduction in FEI modes where MC model is improved.

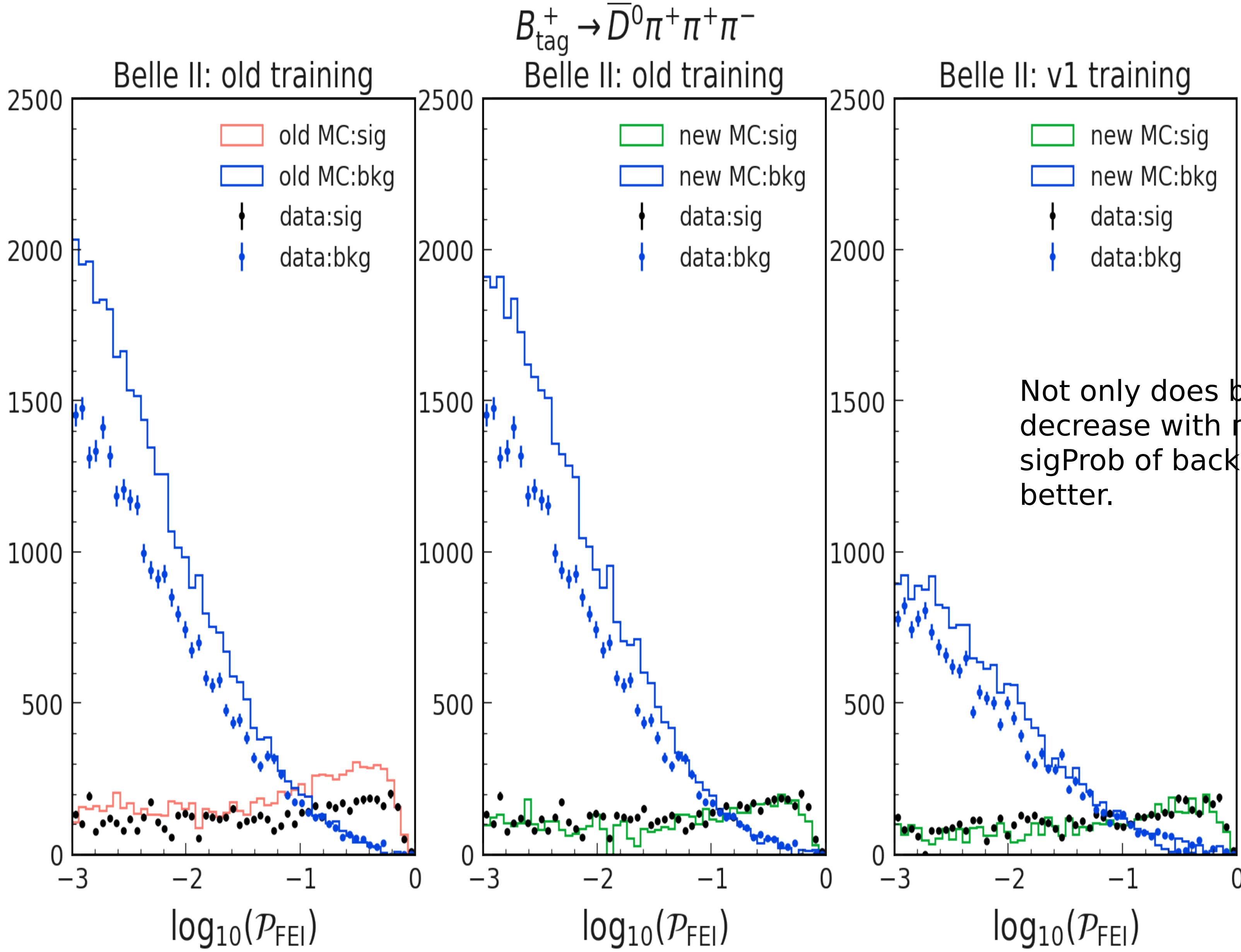
Retraining FEI: Effective cuts



The new training is learning the a_1+ cut from the MC we give it!

Can we apply this cut manually instead?

Training FEI with new MC ⇒ Better sigprob

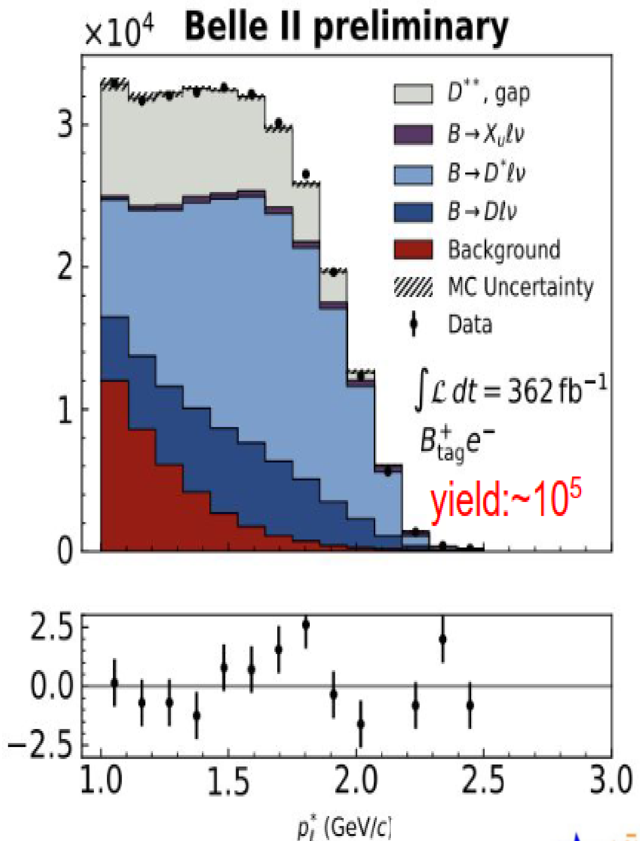


Not only does background decrease with retraining, but sigProb of background agrees better.

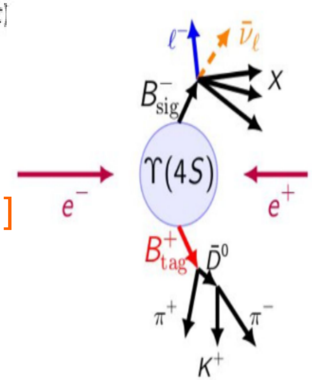
Reminder:
MC is modified independently and Dπ sample is used for validation

Had FEI calibration with Xlν and Dπ samples

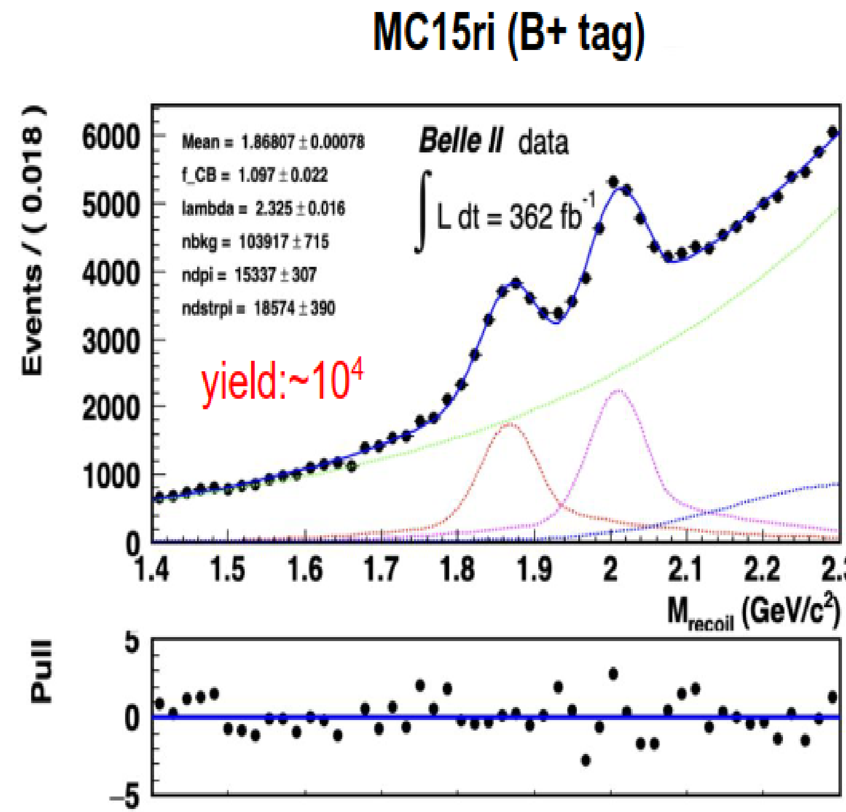
Xℓν sample:
High statistics, low purity



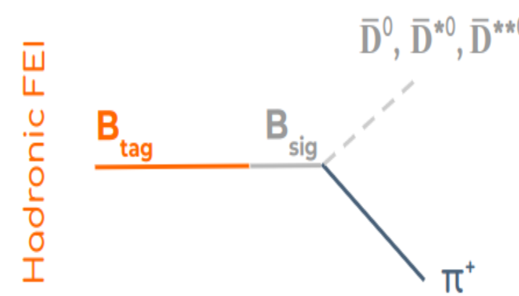
[Florian, William, Daniel Jacobi: BELLE2-NOTE-PH-2023-008]



Dπ sample:
Low statistics, high purity

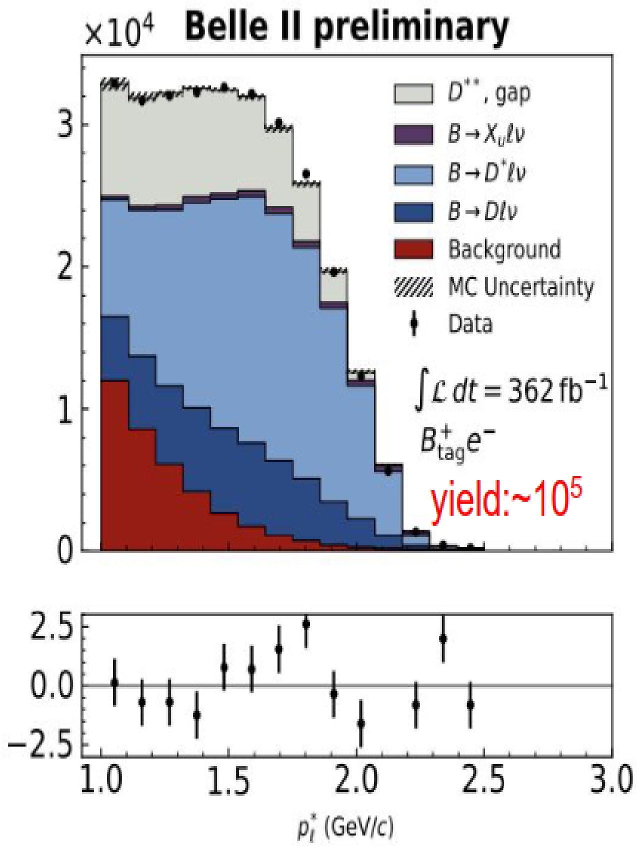


[Karim, Meihong, Niharika, Vidya: BELLE2-NOTE-PH-2023-004]

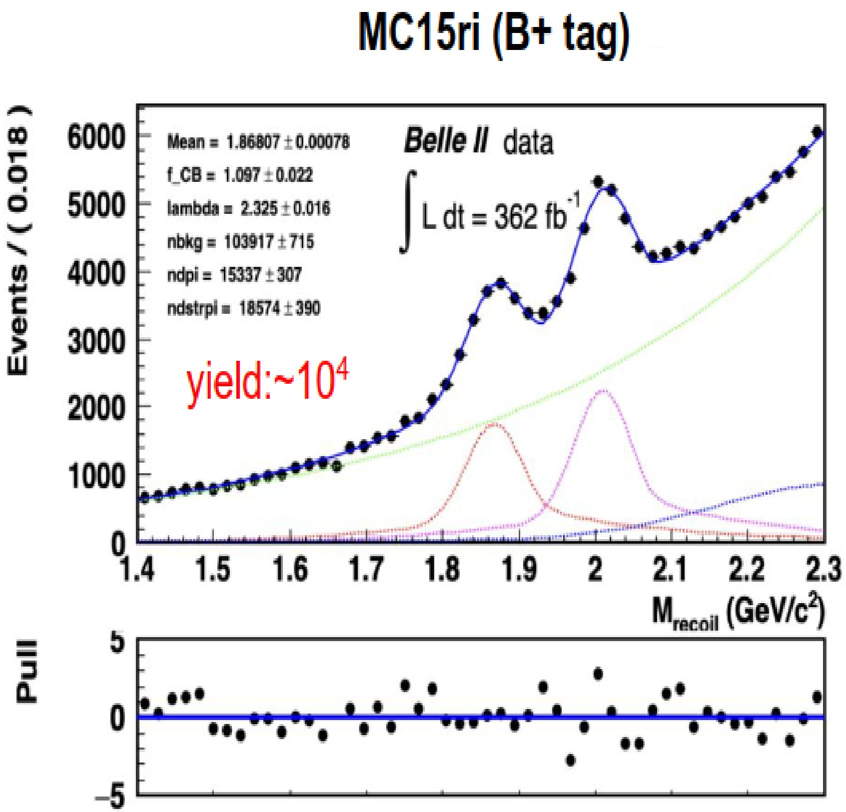


Had FEI calibration with $Xl\nu$ and $D\pi$ samples

$X\ell\nu$ sample:
High statistics, low purity



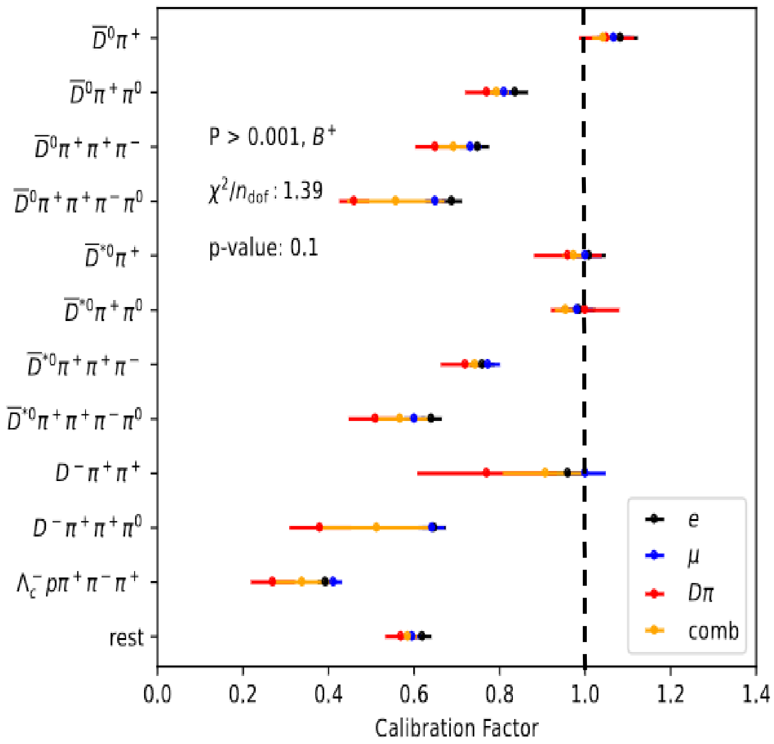
$D\pi$ sample:
Low statistics, high purity

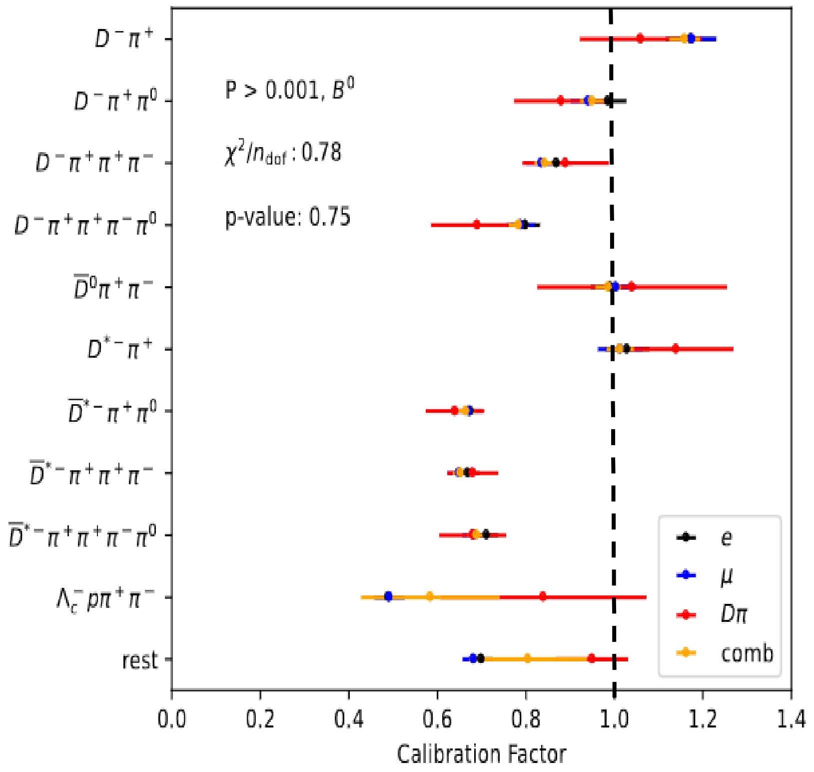


Calibration factors are calculated from signal yields i.e., correctly-reconstructed B_{tag}.
Hence, applicable on Signal MC.

Had FEI calibration: Combined for MC15ri

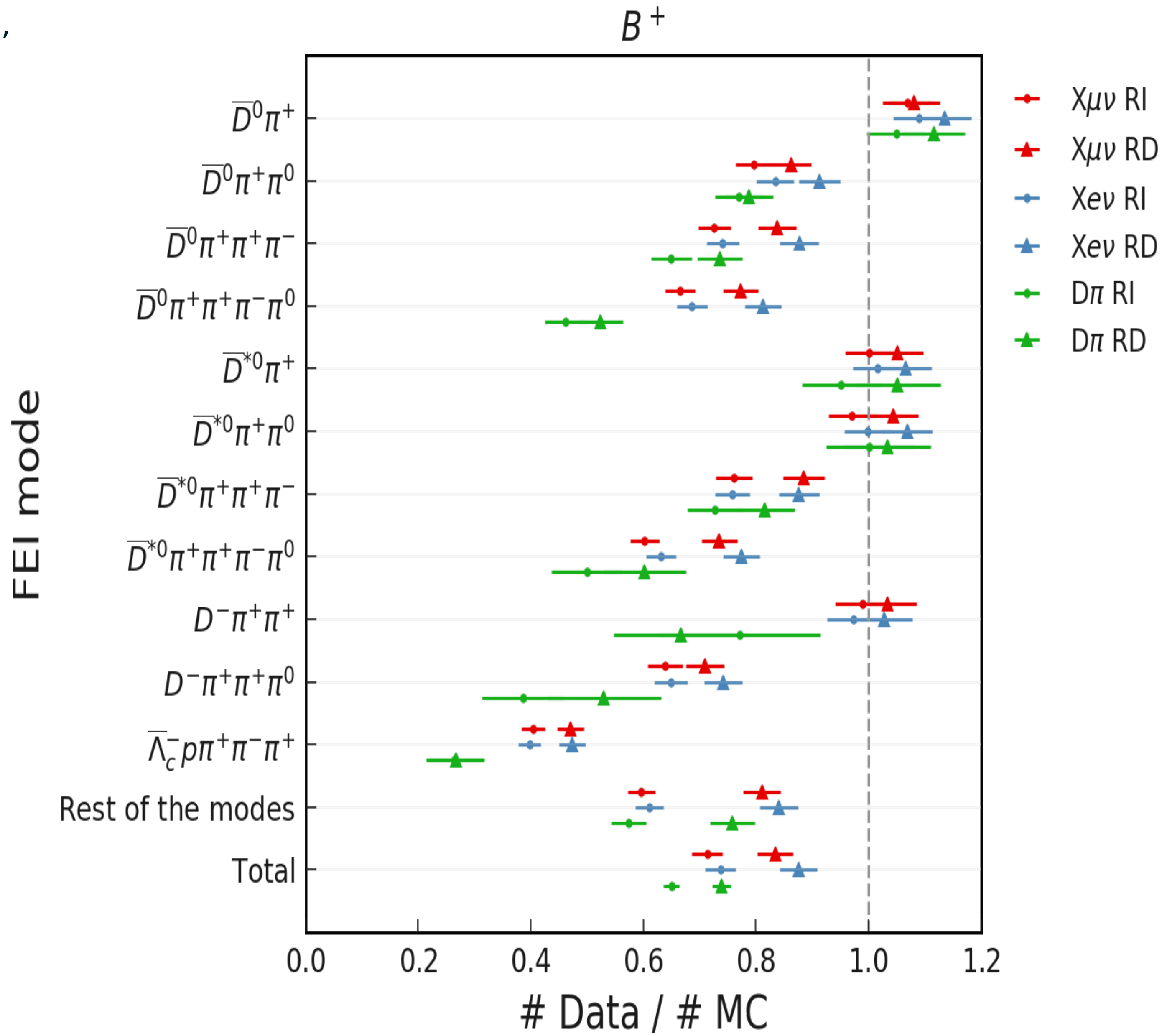
- CFs from both samples are combined, with an additional uncertainty added to cover the absolute discrepancies between both.
- For $\mathscr{P} > 0.001$ and $\mathscr{P} > 0.01$
- Results and procedure documented: BELLE2-NOTE-PH-2023-029
- Available on kekcc: /hsm/belle2/bdata/users/sutclw/fei_calibration/hadronic_FEI_calibration_factors/v1





Had FEI calibration: For MC15rd

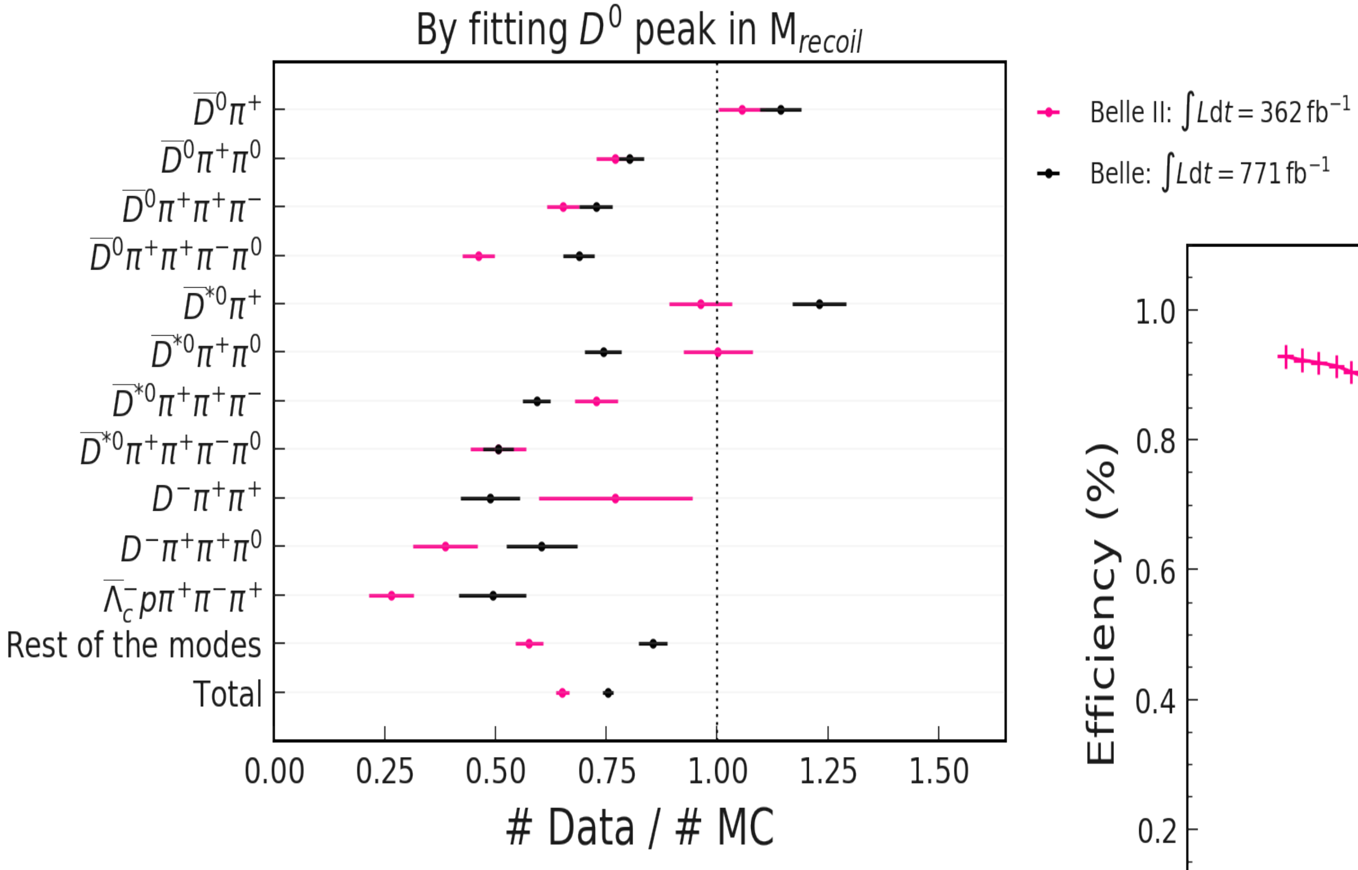
- Once correction tables available, we combine both samples through a chi² fit like for MC15ri.

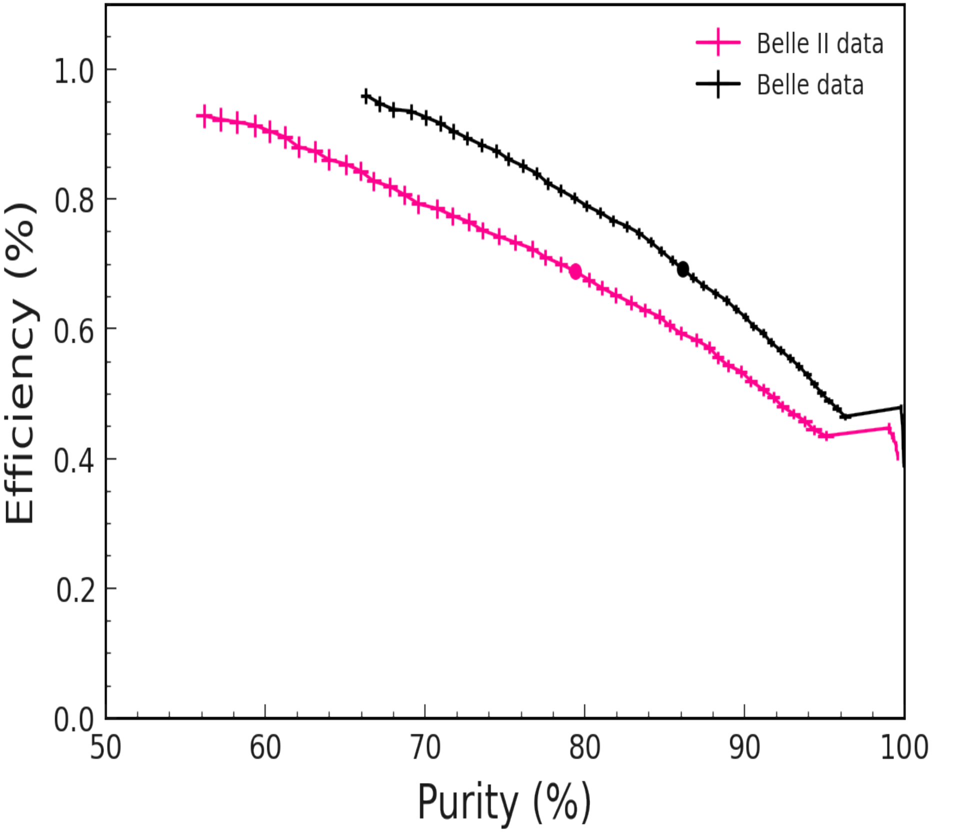


FEI metrics: comparison with Belle

The overall calibration factor in Belle II is ~65%, much lower than the ~75% in Belle.

Belle II has lower performance in terms of efficiency and purity too.





Belle and Belle II uses different MC
⇒ Different performance is expected!

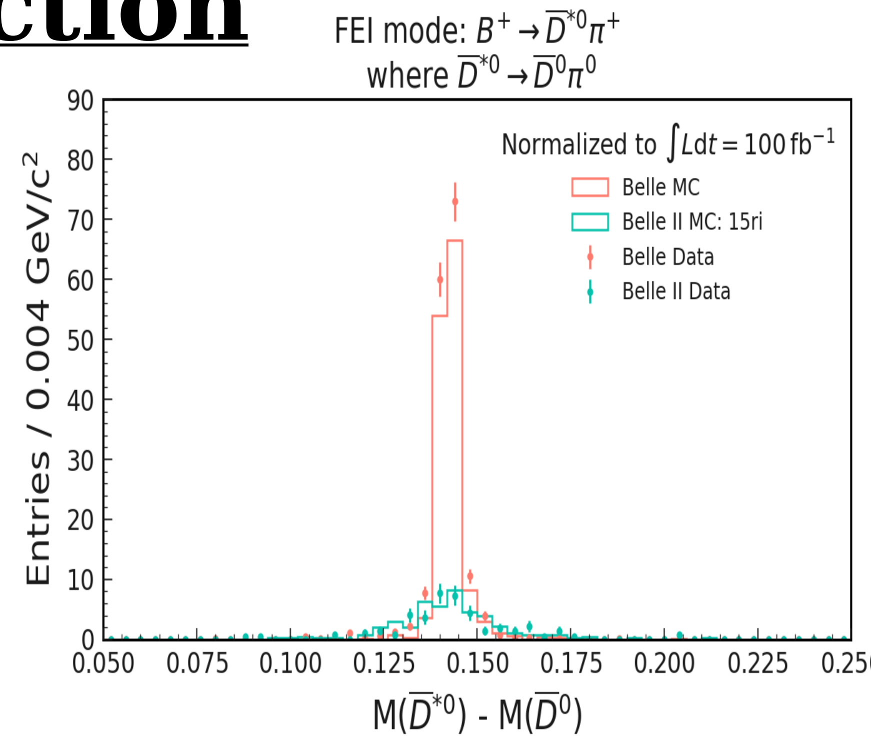
$D^{*0} \to D^0 \pi^0$ reconstruction

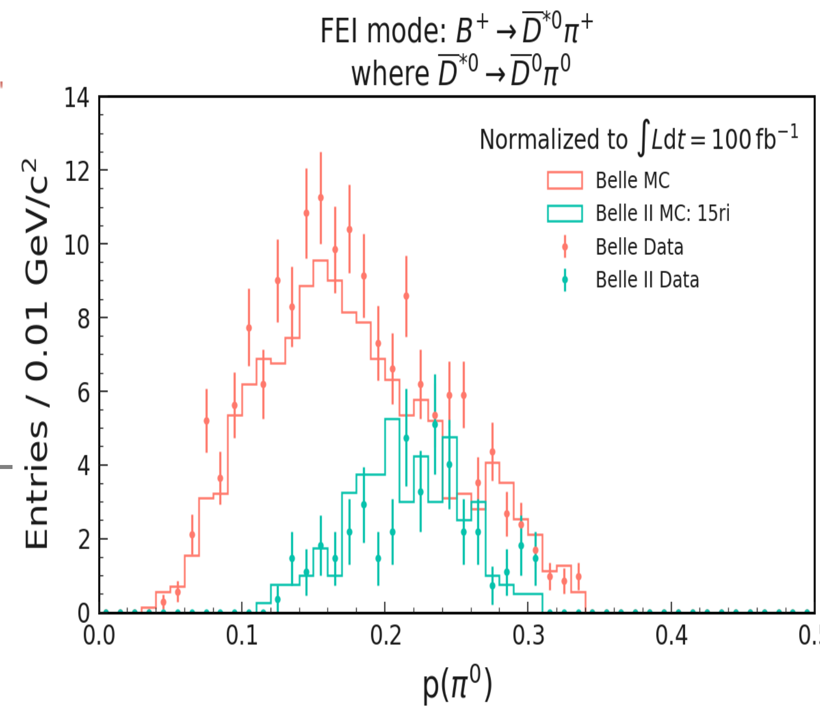
In Belle II, the yield of $D^{*0} \to D^0 \pi^0$ is much worse than Belle.

E > 0.09 GeV cut for γ is too tight for slow π^0
Should be loosened.

```
if convertedFromBelle:
    gamma_cut = 'goodBelleGamma == 1 and clusterBelleQuality == 0'
else:
    gamma_cut = '[[clusterReg == 1 and E > 0.10] or [clusterReg == 2 and E > 0.09] or [clusterReg == 3 and E > 0.16]]'
if specific:
    gamma_cut += ' and isInRestOfEvent > 0.5'

gamma = Particle('gamma',
                 MVAConfiguration(variables=['clusterReg', 'clusterNHits', 'clusterTiming', 'extraInfo(preCut_rank)',
                                             'clusterE9E25', 'pt', 'E', 'pz'],
                                  target='isPrimarySignal'),
                 PreCutConfiguration(userCut=gamma_cut,
                                     bestCandidateMode='highest',
                                     bestCandidateVariable='E',
                                     bestCandidateCut=40),
                 PostCutConfiguration(bestCandidateCut=20, value=0.01))
gamma.addChannel(['gamma:FSP'])
```

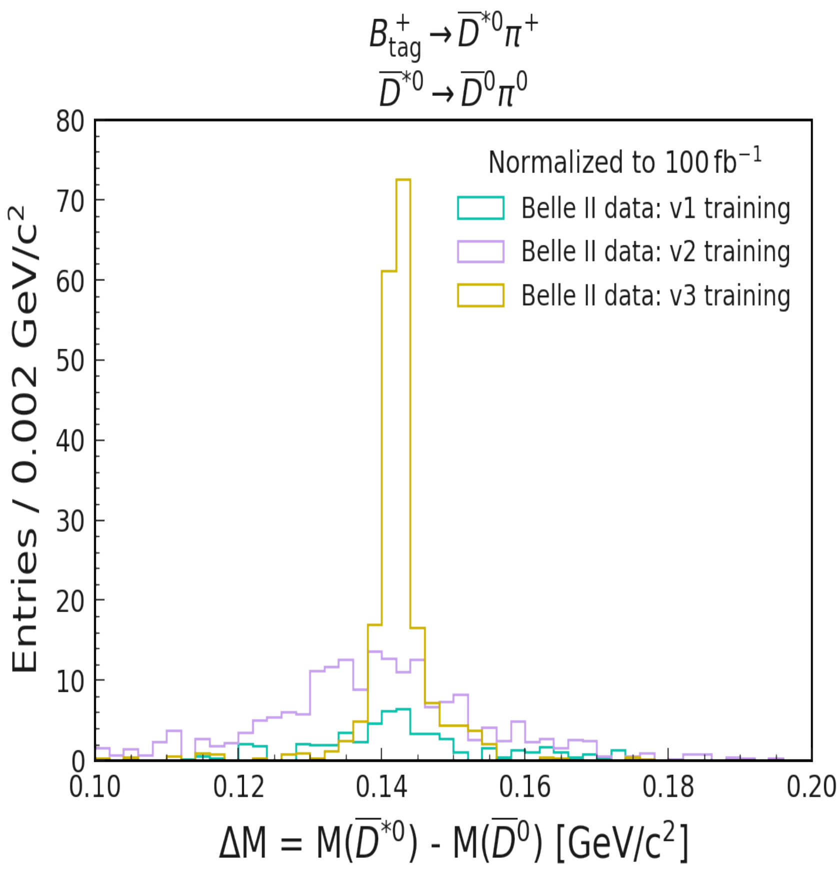


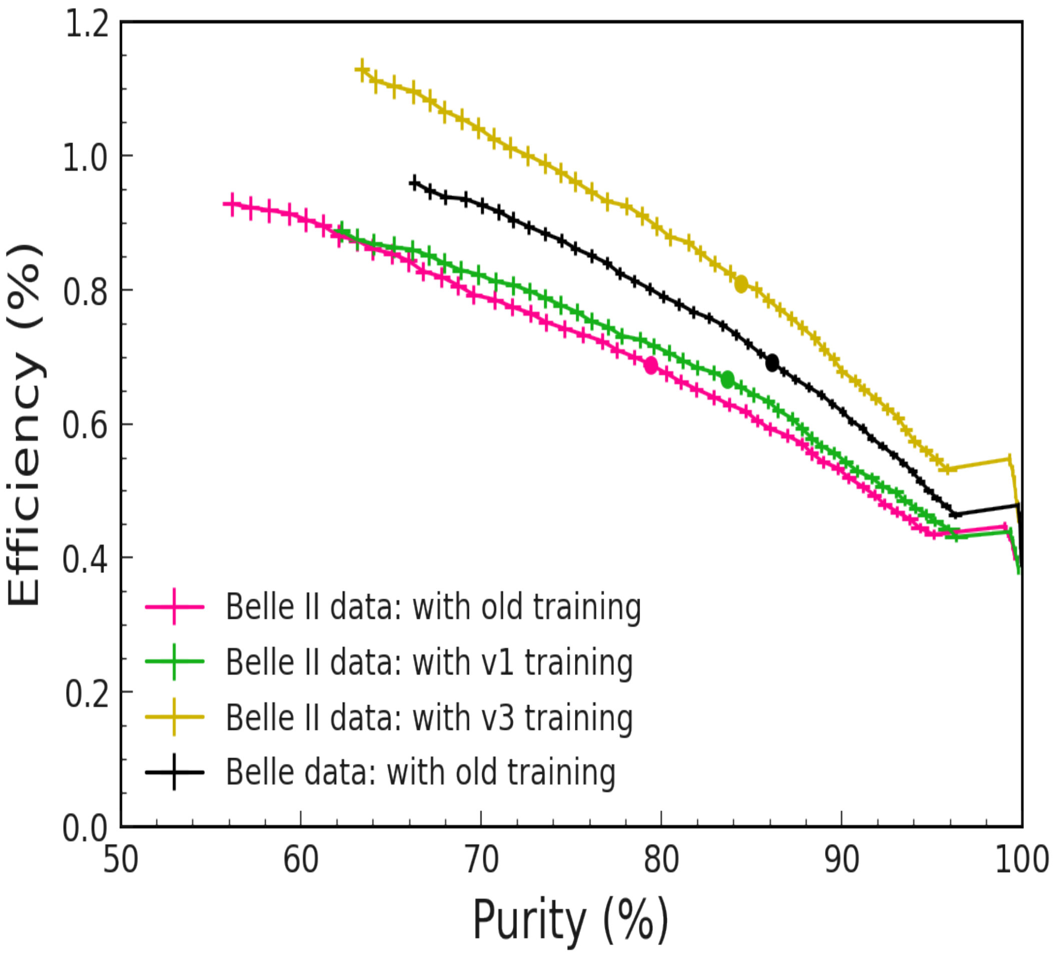


$D^{*0} \rightarrow D^0 \pi^0$ reconstruction

Optimize ΔM for D^{*0} reconstruction

Along with looser preselection for photons, mass-constraint is applied for π^0 candidates in Belle II.
This will improve ΔM distribution which is used in preselection and training for D^{*0}.
Retraining FEI provides expected results:





Improving metrics of FEI

For Hadronic B^+:

- ➢ Updated decay model for the 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 MCri-up (new DECAY.dec)

  56% → 63% : 12% ⬆ in purity

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

  0.93% → 1.13% : 21% ⬆ in efficiency

All these improvements are default for MC16/proc16 (shared knowledge)
still studying the impact on SL FEI

Trickle down B-tagging

(ambition behind our work on B-tagging)

implemented improvements:

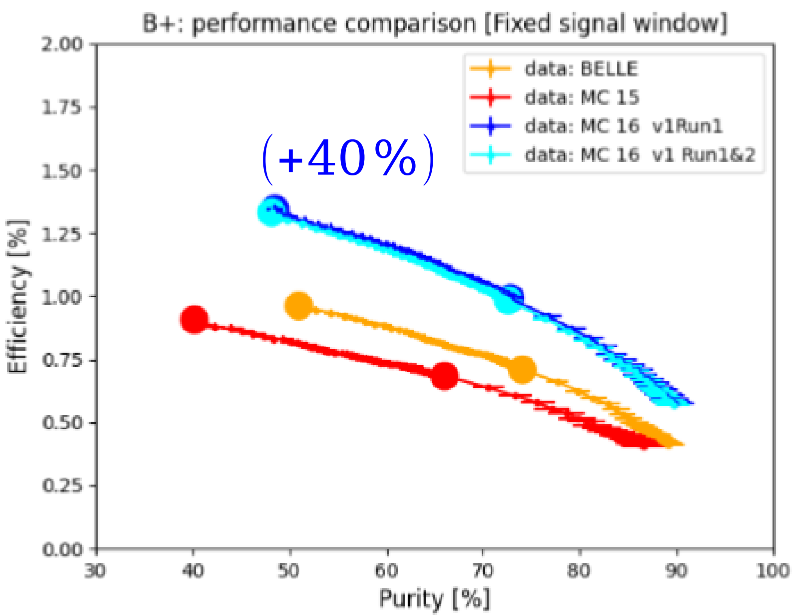
- better decay file for MC to improve calibration factors, training
- update precuts on γ to improve efficiency for modes with π^0
- add a mass constrain fit on π^0 to improve ΔM resolution

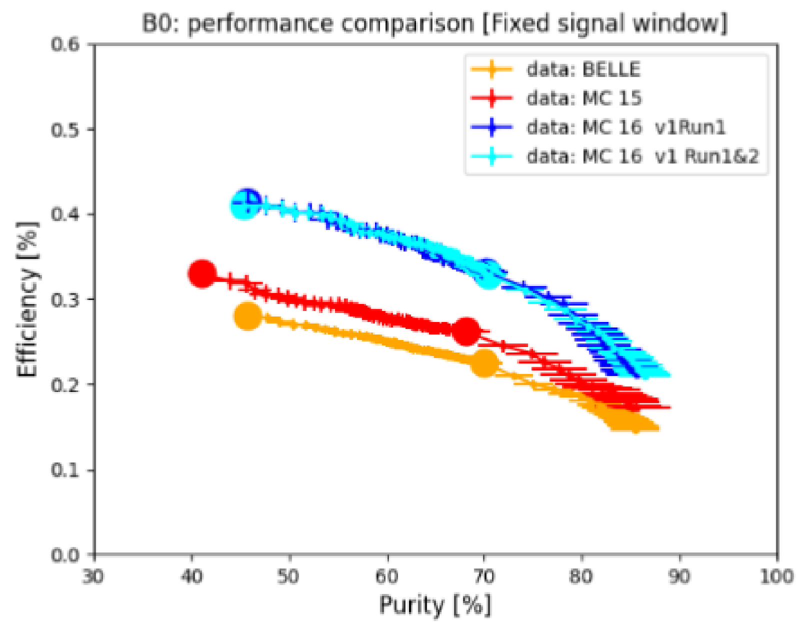
Hadronic B-tagging with proc16

see M.Marfoli's talk (+BELLE2-NOTE-PH-2025-033)

B^0:
- Purity: from 33% to 37% Efficiency: from 0.38% to 0.47%

B^+:
- Purity: from 34% to 39% Efficiency: from 1.06% to 1.54%



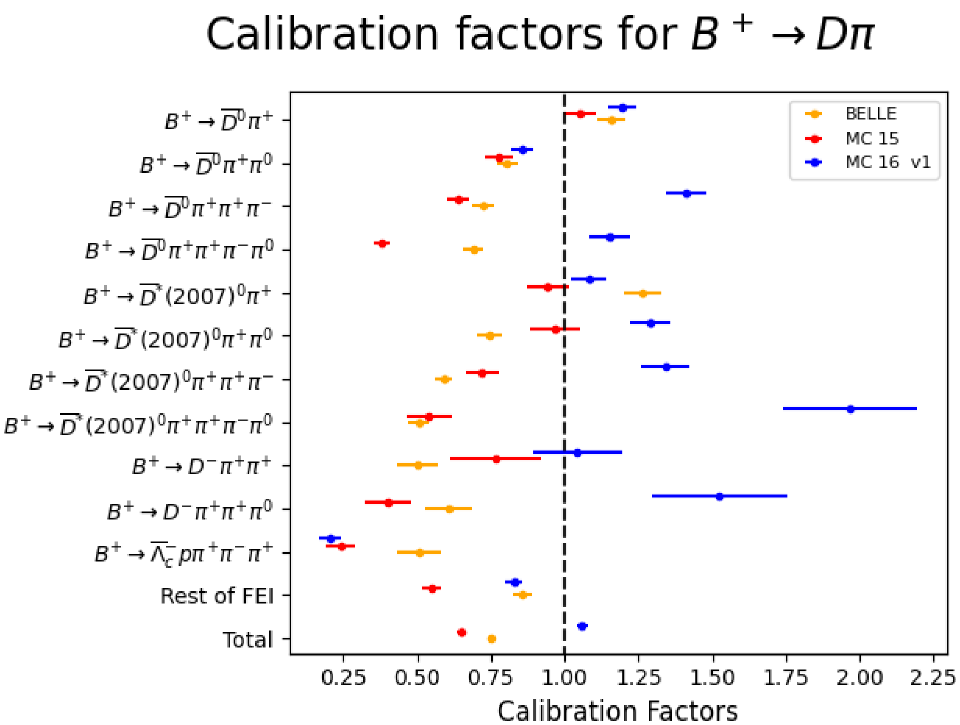


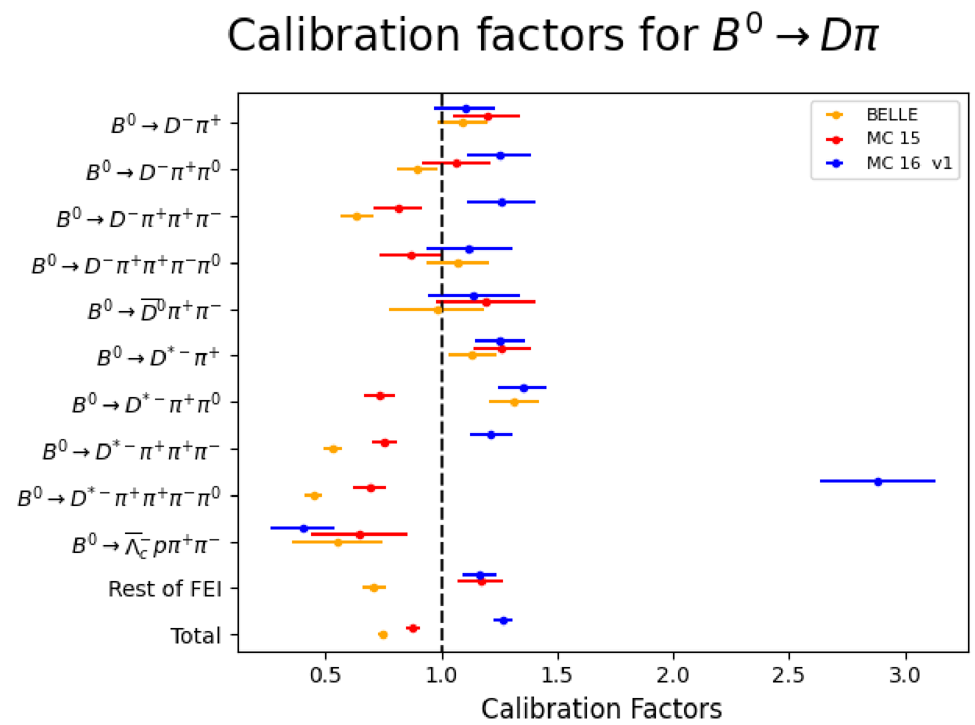
- improvement is clear ... and already available (proc16)
- now finally better than Belle
- run 2 seems to be of comparable quality

Hadronic B-tagging with proc16

see M.Marfoli's talk (+BELLE2-NOTE-PH-2025-033)

Calibration factors at P_{FEI}>0.001 for Belle - MC15 - MC16





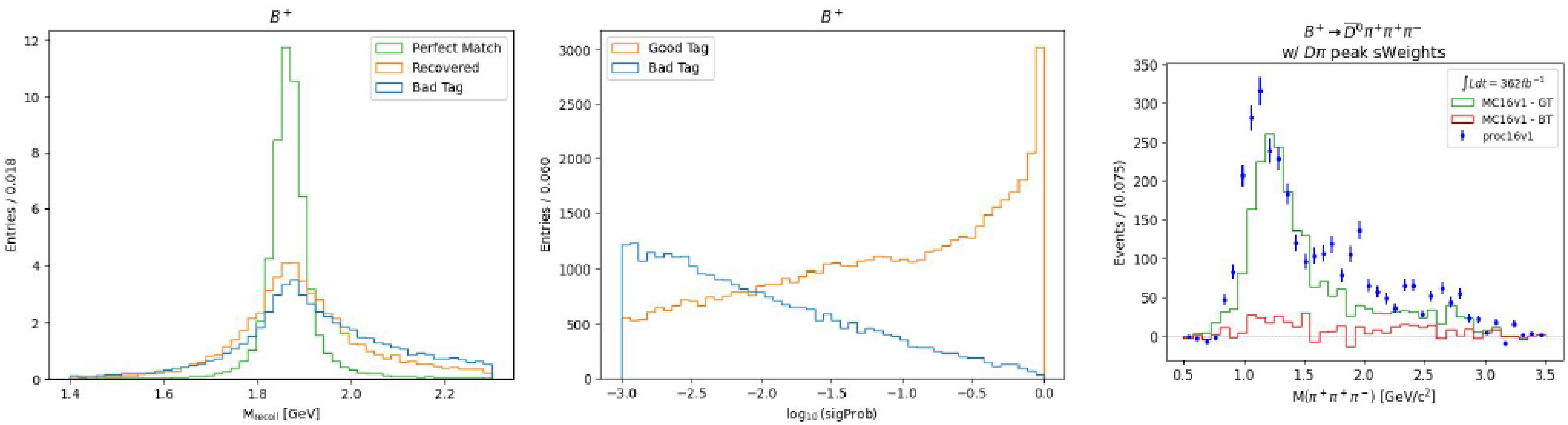
General improvements

B^+: from 0.65+/-0.01 to 1.04+/-0.02

B^0: from 0.88+/-0.03 to 1.22+/-0.04

Still some discrepancies, especially in $D^{(*)}3(^0)$ and Λ_c modes

Good Tags and Bad Tags



◦ To estimate how many events are tagged correctly for truth matched signal we consider a Good Tag (GT) event either as a:

- perfect match (isSig=1)
- recovered (isSig != 1) but with correct final state

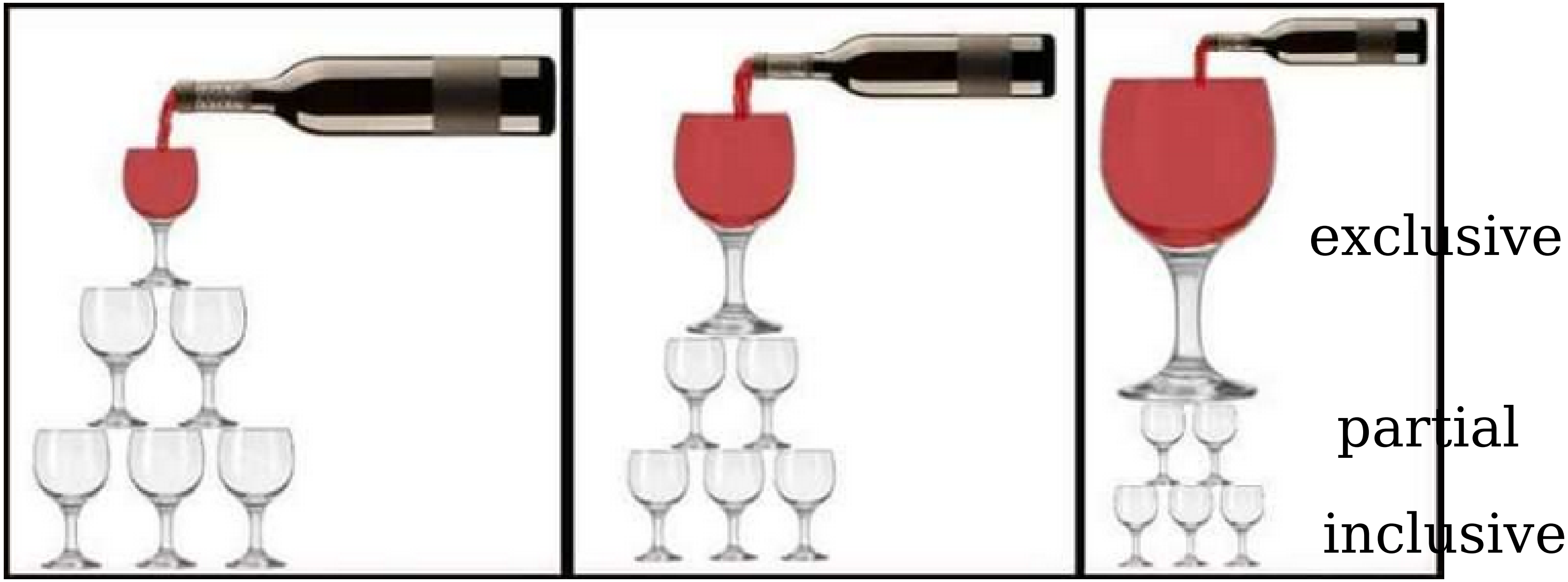
◦ It is also included as a systematic for the CFs but the effect is rather small (1%)

Trickle down B-tagging

(ambition behind our work on B-tagging)

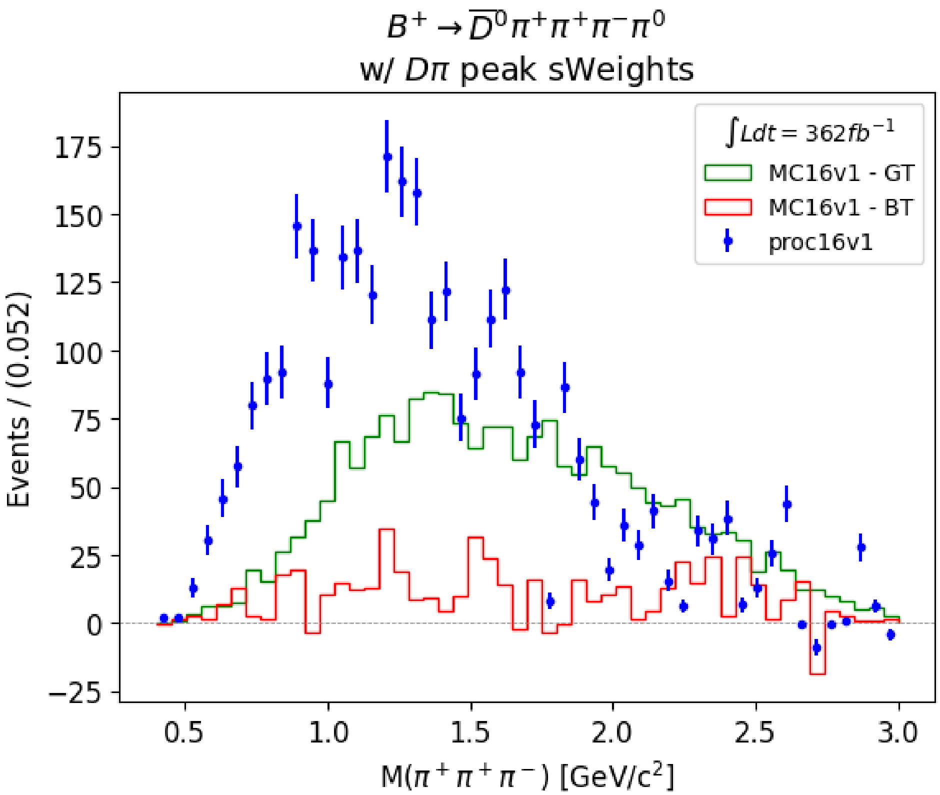
Still need improvements:

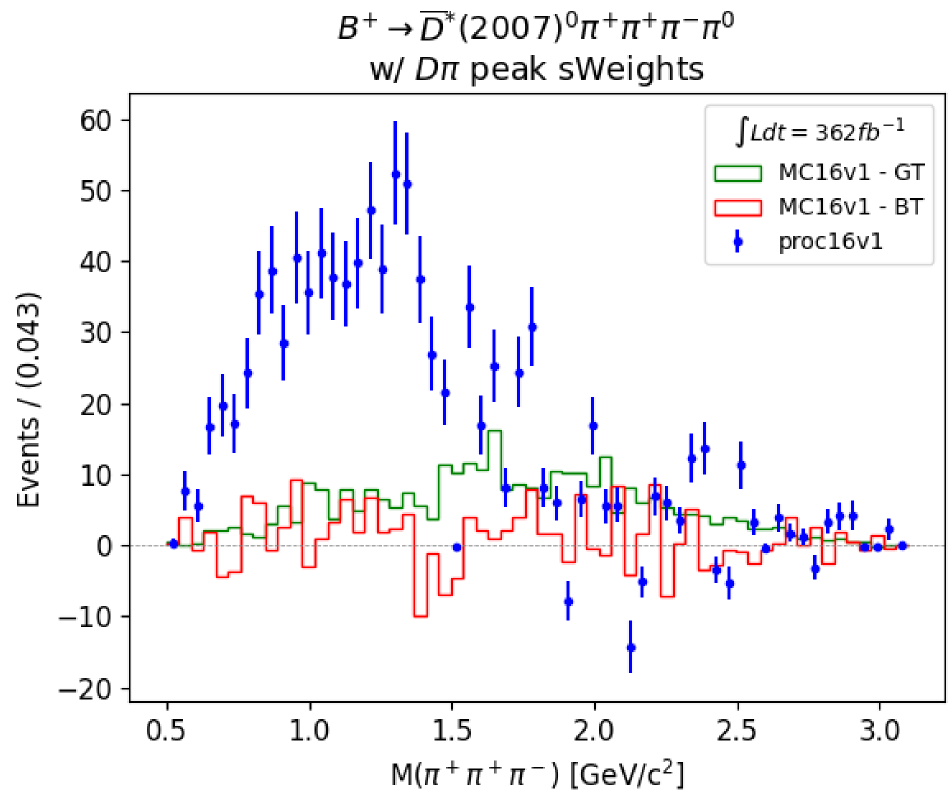
- improve our simulation of all B_{tag} modes included → better B-tagging performance
- also some opportunities to remeasure/study those B decays and intermediate states



Keep improving the modelisation

Remains some room for improving the modelisation of dominant B_{tag} modes, for for example $B \to D^{(*)} 3\pi\pi^0$ (see below), $B \to \Lambda_c p n \pi$...





- new modes: $B^+ \to D^{*-}(4\pi)^{++}$, $B^+ \to D^{*0}(5\pi)^+$ have large BFs
- improve the code: implement cuts based when obvious cases (narrow resonances), remove the ΔE from sigprob for a partial reconstruction

First, understand better the B decays…

CLEO 0.89 fb^{-1}

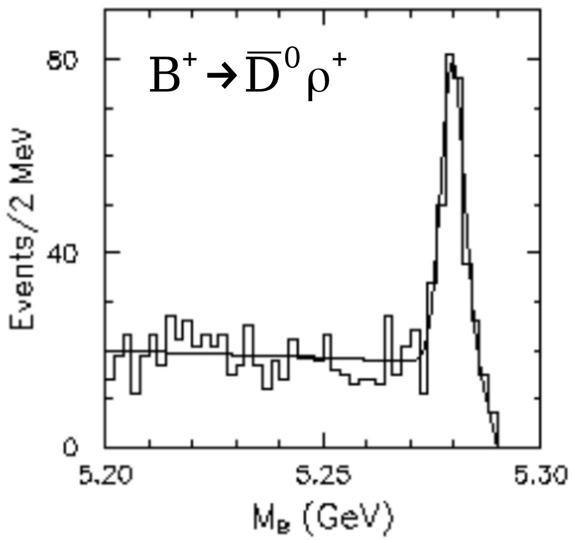
[PRD 50 (1994) 43]

30 years ago

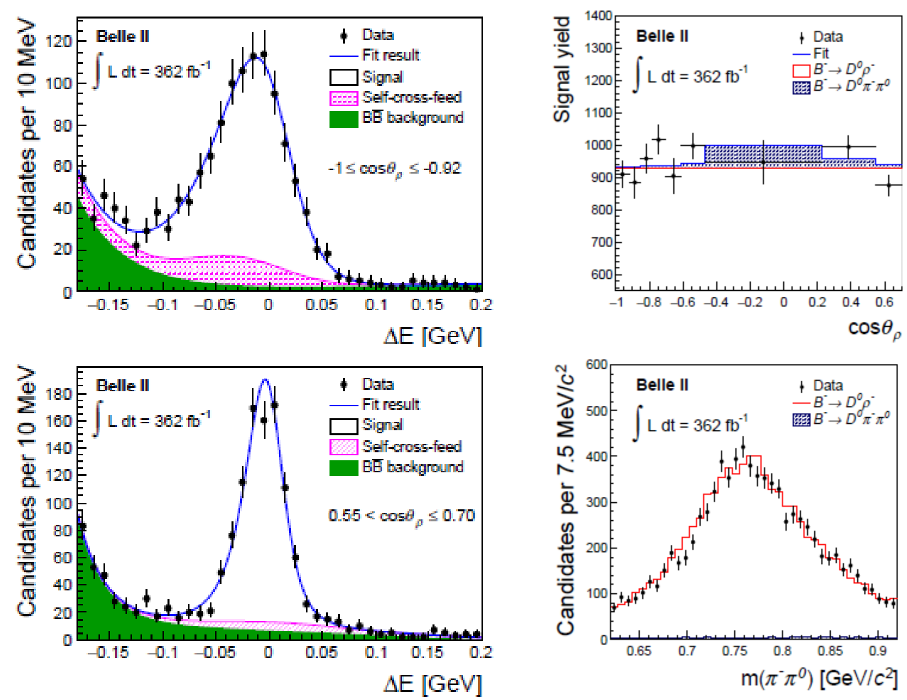
Uses M_{bc}

$B = (1.34 \pm 018)\%$

13% uncertainty !



[arXiv:2404.10874 , Phys Rev D. 109, L111103]



$B(B^+ \to D^0 \rho^+) = (0.94 \pm 0.02 \pm 0.05)\%$

- World's best result with more than 2× improvement
- Factorisation test: in agreement with prediction
- Systematically limited by uncertainty on π^0 efficiency

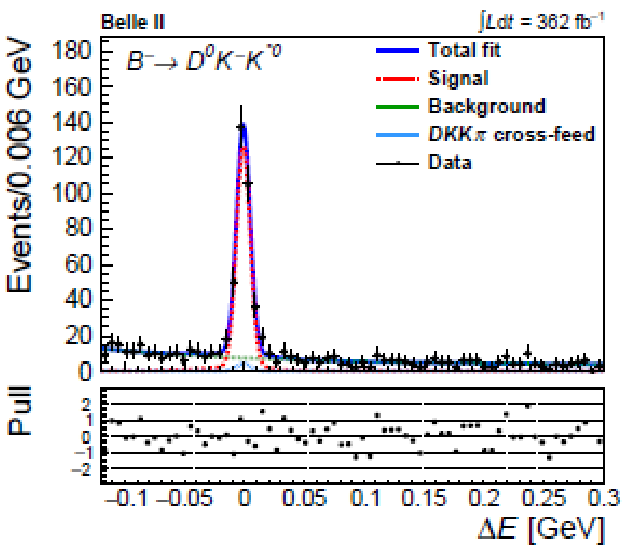
First, understand better the B decays…

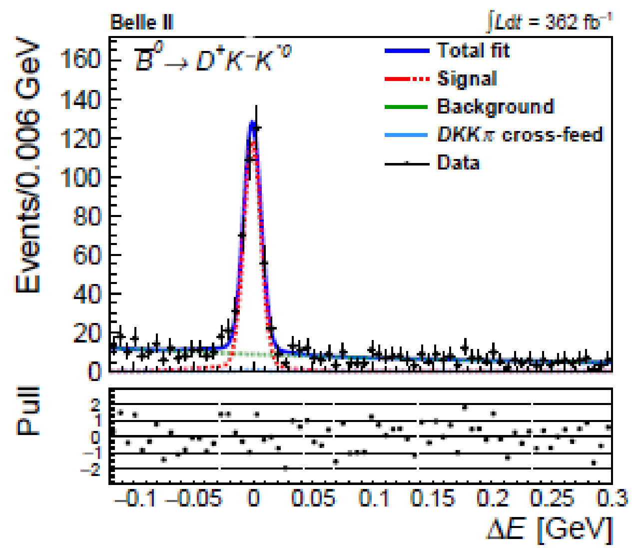
B→DKK: largely unexplored sector

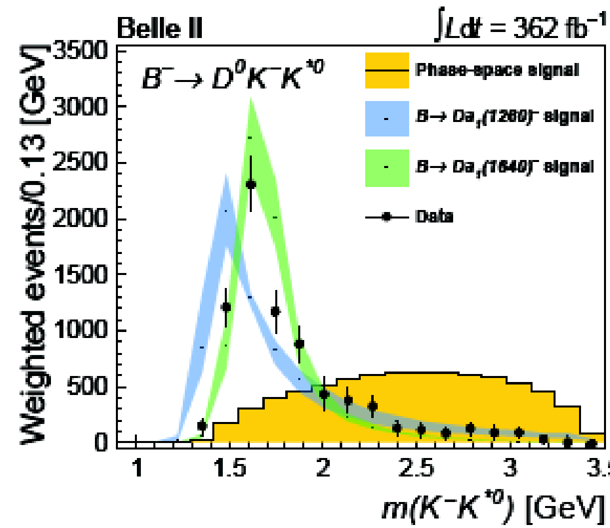
- few % of B branching fraction expected
- Only 0.3% measured so far

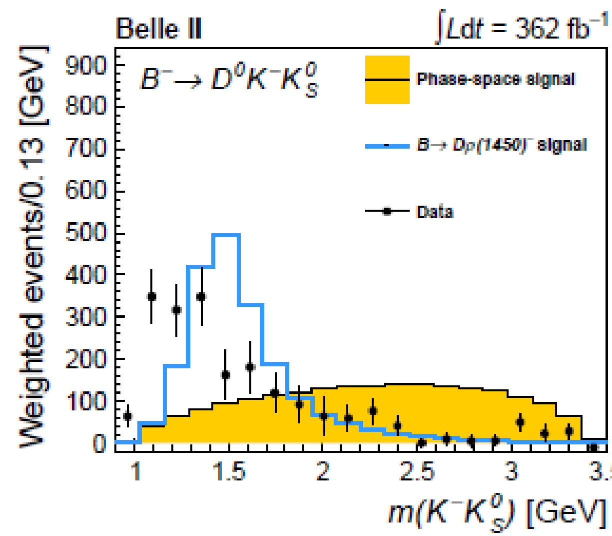
[arXiv:2406.06277, JHEP 08 (2024) 206]

Measurement of the branching fractions of $B \to D^{(*)} K K_S^{(*)}$…





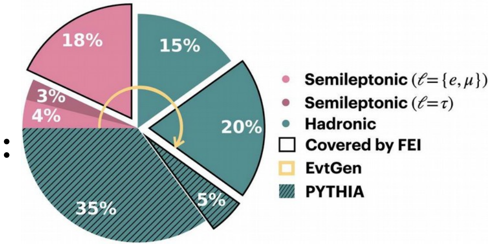




- Efficiency correction applied in the planes $m(D^{(*)}K^-)$ and $m(K^- K^{(*)0}_{(S)})$
- Extraction of bkg-subtracted and efficiency corrected invariant mass and helicity
- Dominant transitions $J^P = 1^{-/+}$
- $B \to D^{(*)} D_s(\to KK^{(*)})$ are used as control modes

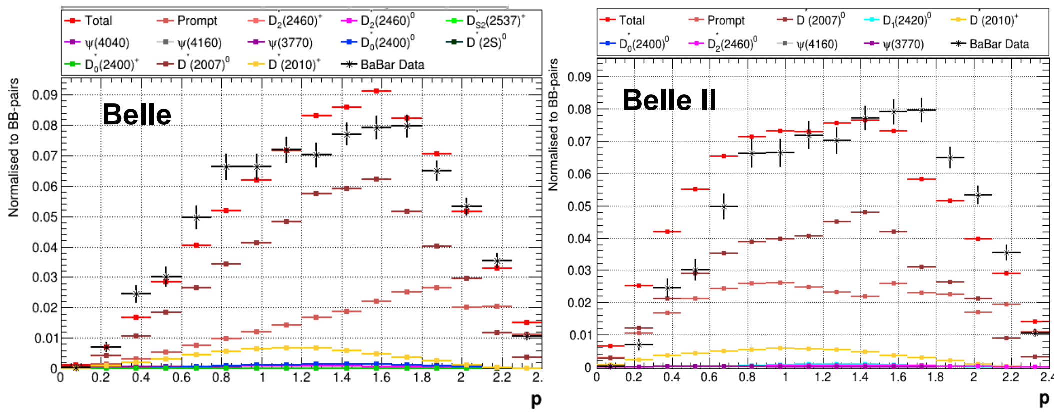
Further improvements → inclusive

- need more measurements to ''constrain'' our MC
- B→DX (**but also B→D*X**), on-going analysis...
- difference between Belle and Belle II MC shows room for improvement:



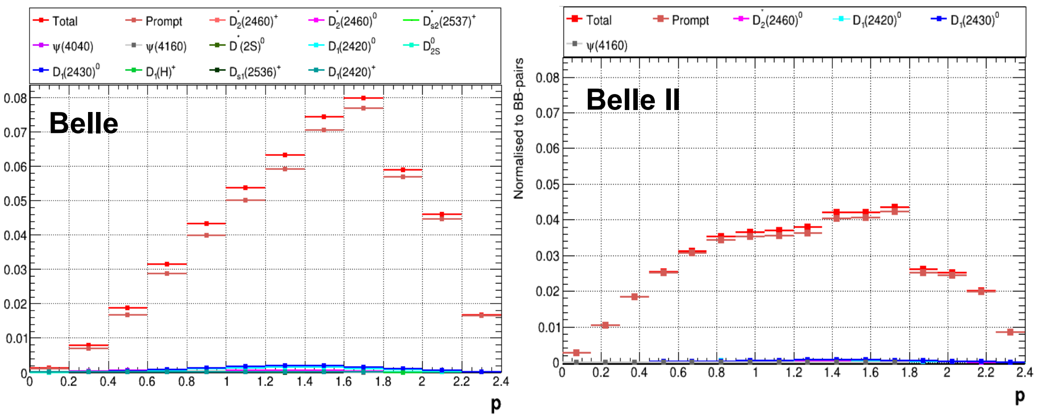
Correlated

$B^{+}\to \overline{D}^{0} X$



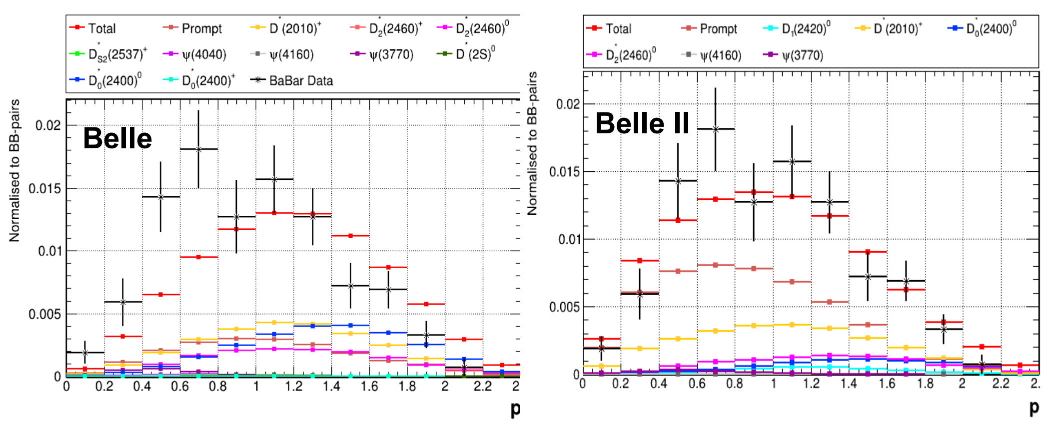
BR : $Belle$ = 0.791 ; $Belle\,II$ = 0.829
$BaBar$ = $0.786\pm0.016\pm0.027$

$B^{+}\to \overline{D}^{*0} X$



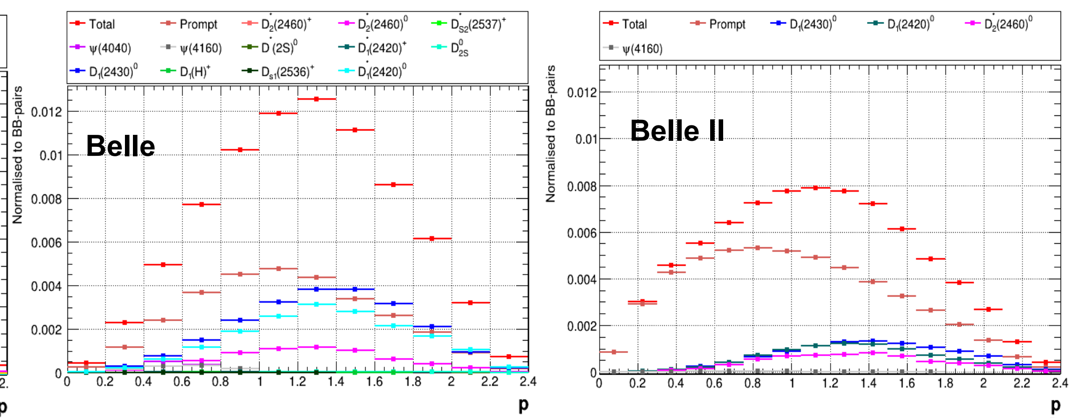
BR : $Belle$ = 0.496 ; $Belle\,II$ = 0.442

$B^{+}\to D X$



BR : $Belle$ = 0.087 ; $Belle\,II$ = 0.095
$BaBar$ = $0.099\pm0008\pm0.005$

$B^{+}\to D^{*} X$



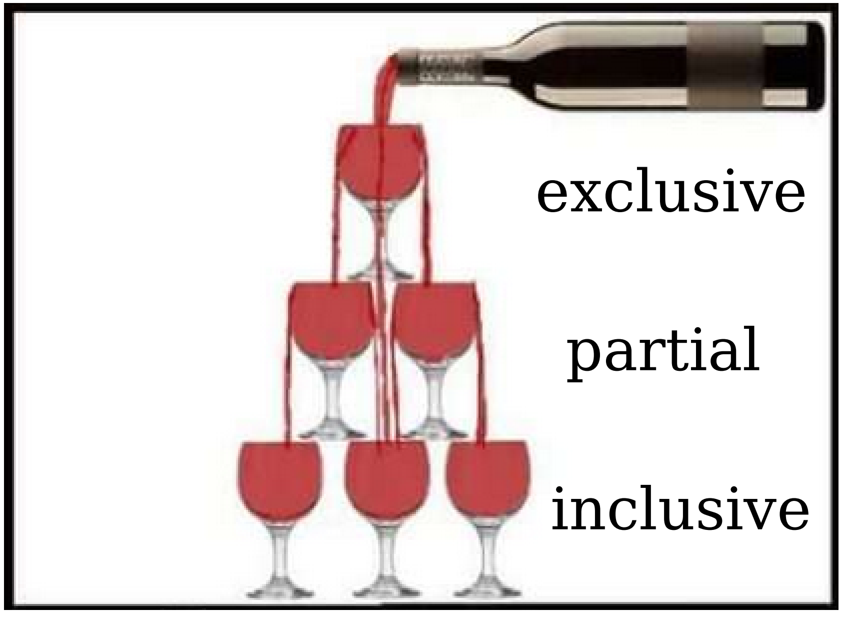
BR : $Belle$ = 0.080 ; $Belle\,II$ = 0.074

Momentum spectra, for correlated cases in the B to D$^{(*)}$ cases considering the B$^+$ rest frame.

Trickle down B-tagging

(ambition behind our work on B-tagging)

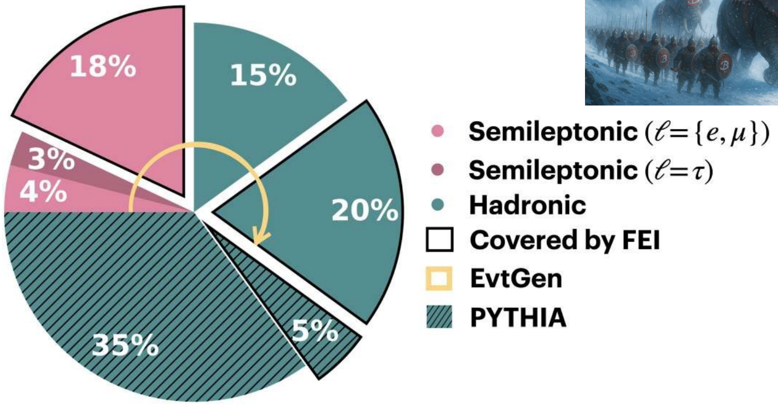
to get more inclusive, we need more inclusive measurements



Summary ''from rare to not understood''

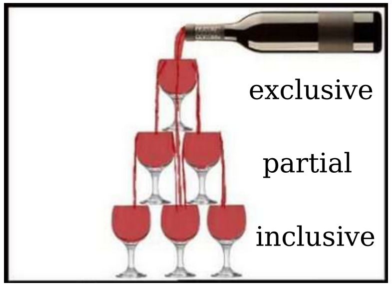
- knowledge of hadronic B-decays is essential for any B-tagging
- a large part (50%) of the hadronic B decays not measured...
- ...and PYTHIA is generating something...
- **clear overall improvement for proc16 thanks to long term efforts**

⇒ ambition is to provide (soon) a DECAY table without PYTHIA



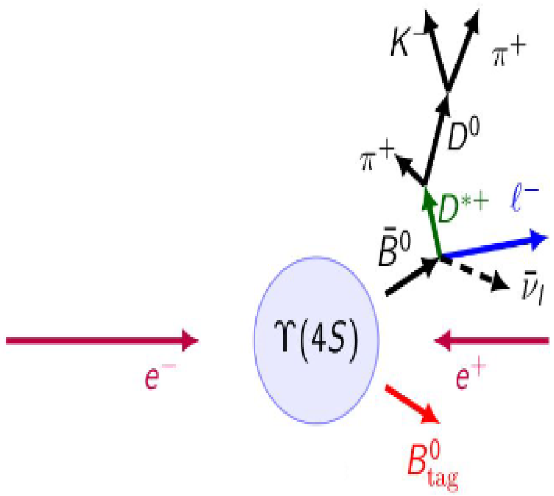
⇒ nice perspectives for using proc16 (run1+2 + Belle, had/SL B-tagging)...
...in missing energy modes searches

- further on-going inclusive measurements $B\to(D^0, D^+, D^{*0}, D^{*+})X$, but also $B\to(D_s, D_s^*)X$ and $B\to(\Lambda_c, \Sigma_c)X$ will keep improving our knowledge of B decays and improve exclusive/inclusive B-tagging



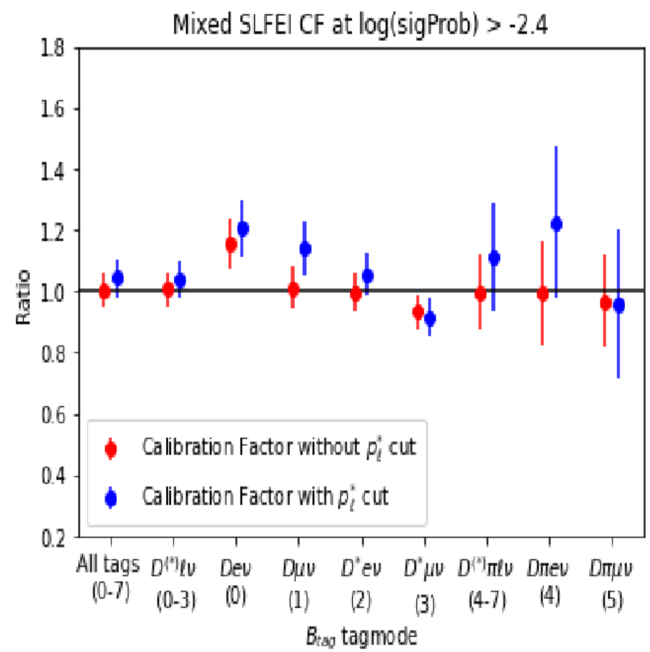
SL FEI calibration with $D^* l\nu$ sample

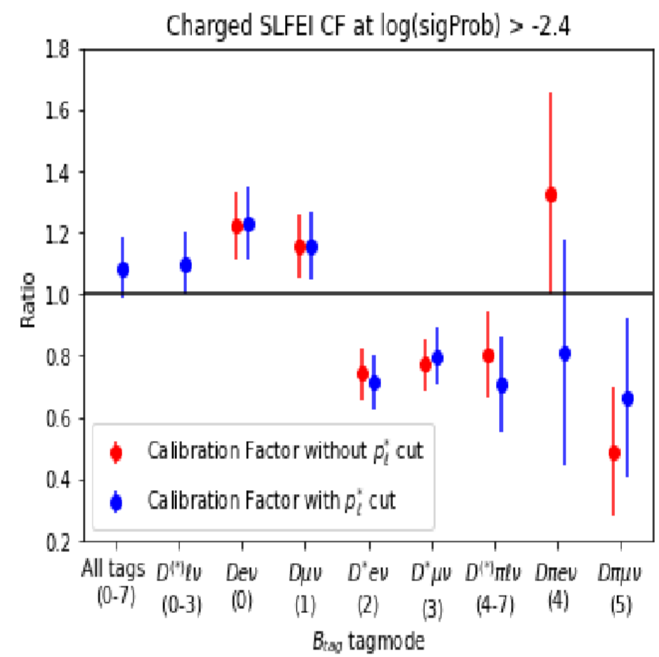
[Andre Huang, Kevin Varvell: BELLE2-NOTE-PH-2023-022]

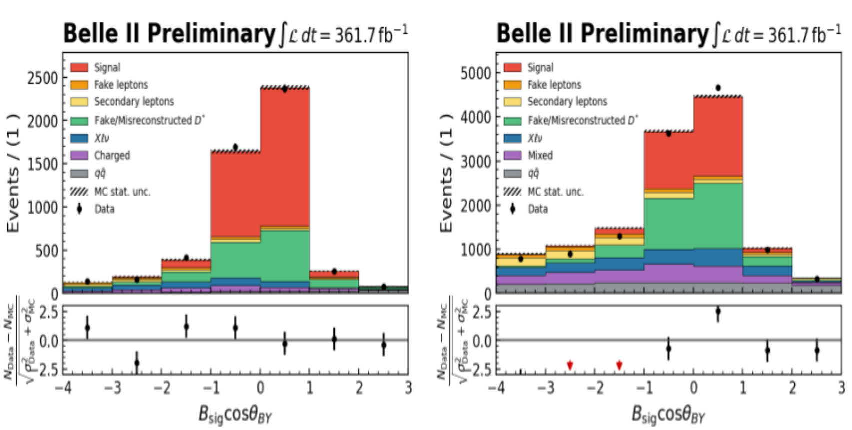


Consistent selection between B_{sig} and B_{tag}

The calibration factors for MC15ri:





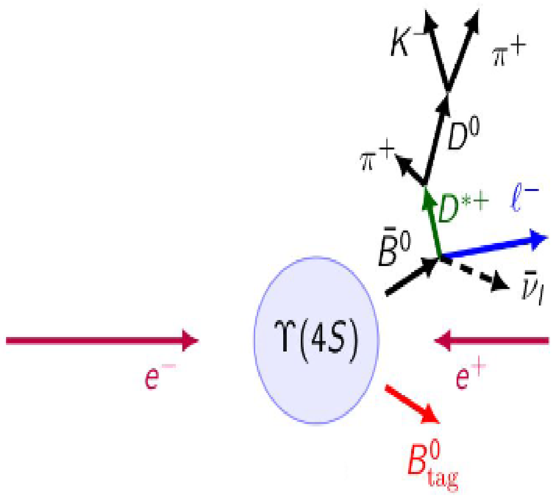


(a) $B^0 \to D^{*-}\ell^+\nu_\ell$ (b) $B^+ \to \bar{D}^{*0}\ell^+\nu_\ell$

FIG. 1: Data-MC $\cos\theta_{BY}$ distributions, following reconstruction of an $\Upsilon(4S)$ candidate and the additional selections listed in Table V with all dataset corrections.

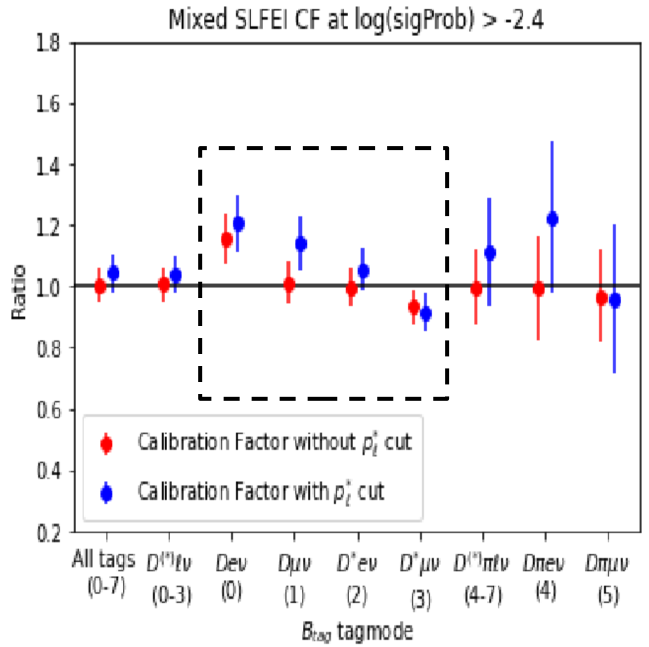
SL FEI calibration with $D^{*}l\nu$ sample

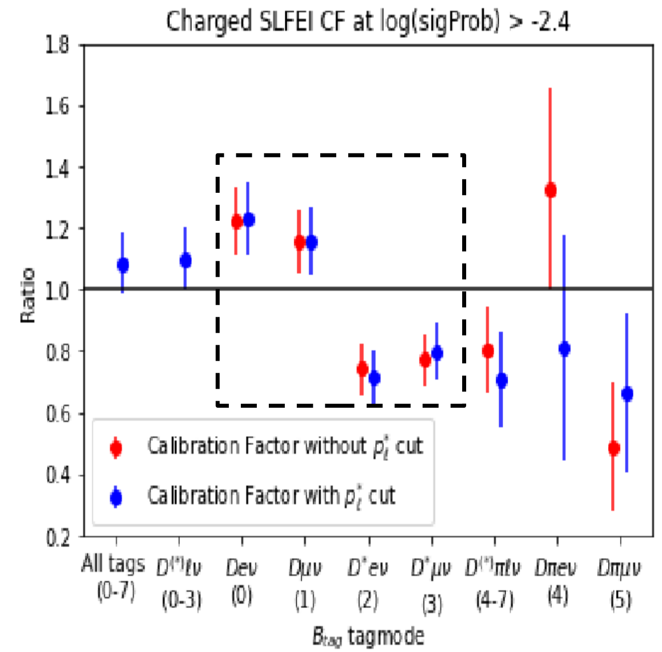
[Andre Huang, Kevin Varvell: BELLE2-NOTE-PH-2023-022]

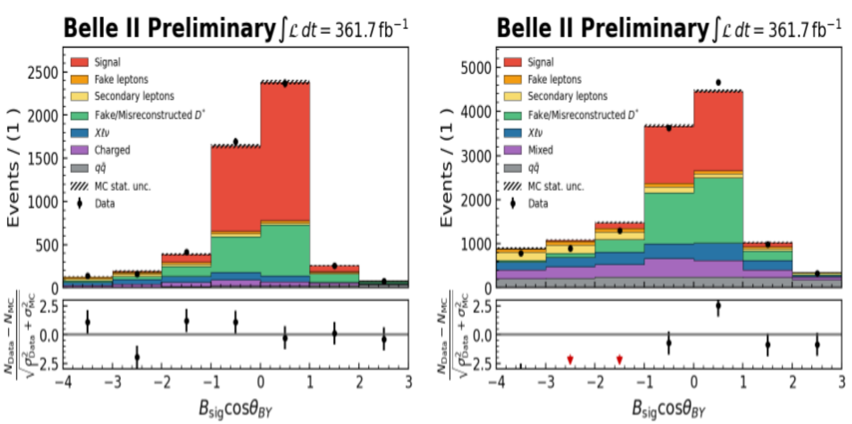


Consistent selection between B_{sig} and B_{tag}

The calibration factors for MC15ri:







(a) $B^0 \to D^{*-}\ell^+\nu_\ell$ (b) $B^+ \to \bar{D}^{*0}\ell^+\nu_\ell$

FIG. 1: Data-MC $\cos\theta_{BY}$ distributions, following reconstruction of an $\Upsilon(4S)$ candidate and the additional selections listed in Table V with all dataset corrections.

Recommendations:

- ➢ Use only the 4 $D^{(*)}\ell\nu$ modes (select after BCS).
- ➢ Apply mode-dependent CF, not the overall.
- ➢ The p_ℓ^* selection could be analysis dependant.

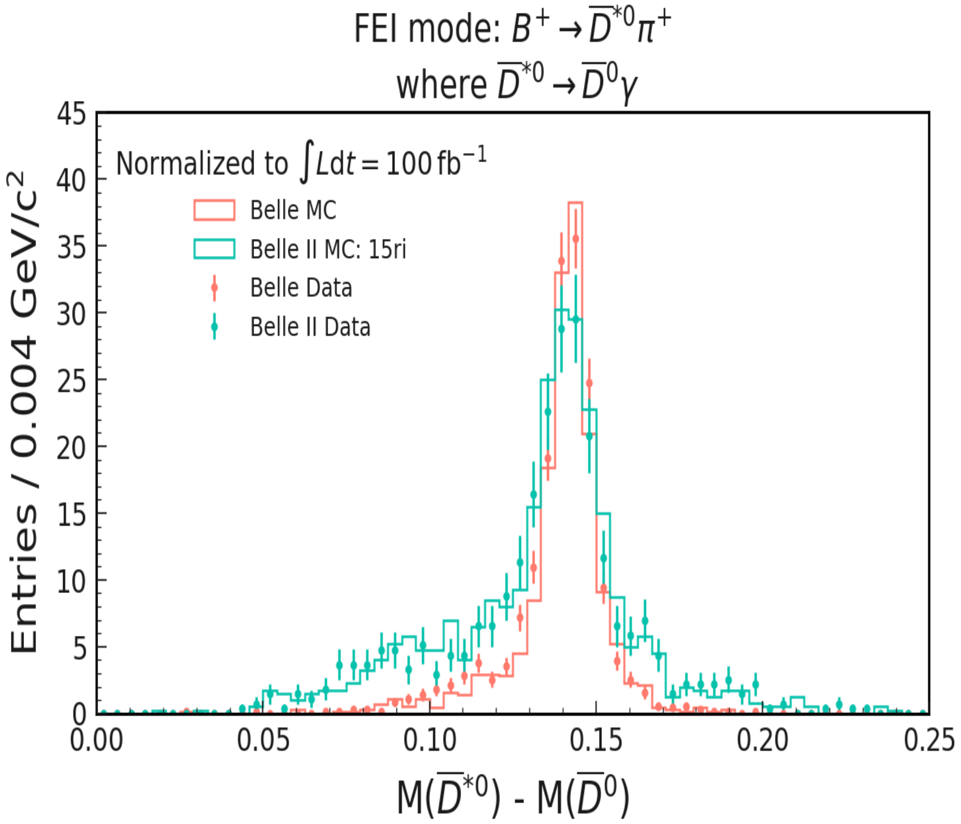
RC in progress to approve the procedure.
Yet to check for MC15rd (Not used for this winter).

$D^{*0} \to D^0 \gamma$ reconstruction

In Belle II, the yield of $D^{*0} \to D^0 \pi^0$ is much worse than Belle, because the tighter pre-cuts on γ hurts slow π^0 reconstruction.

A part of it is recovered in the tail of $D^{*0} \to D^0 \gamma$, but not ideal.

This also shows that a tight ΔM constraint, which could bring high purity is not effectively utilized.



Should tighten the ΔM pre-BDT cut?