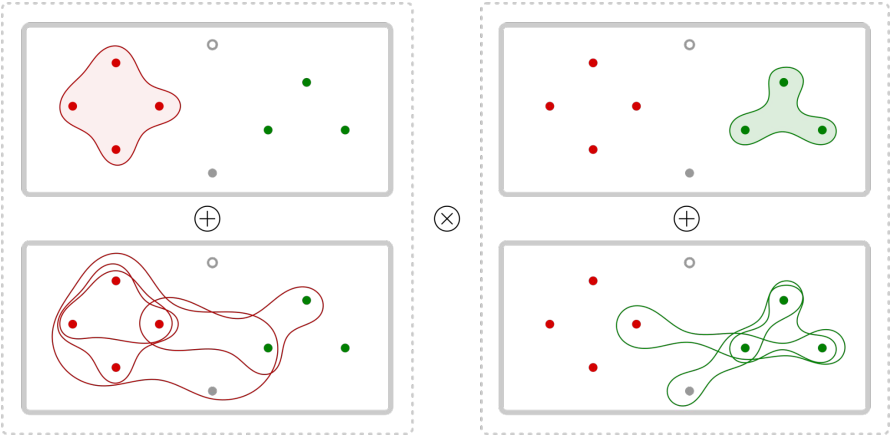

Everything you ever wanted to know about the **F**ull **E**vent **I**nterpretation

But half of it is *lies*

Peter Lewis | University of Bonn
1 Dec 2022
Belle II Physics week | Valencia

Two parts:

Keep your eyes out!
Can you spot them?

I. **Pleasing lies**
   A. Why?
   B. Basic introduction
   C. Usage

II. **Hard truths**
   A. Uncovering the lies
   B. Tagging logic
   C. A few hard truths
   D. How to use the FEI safely

Two parts:

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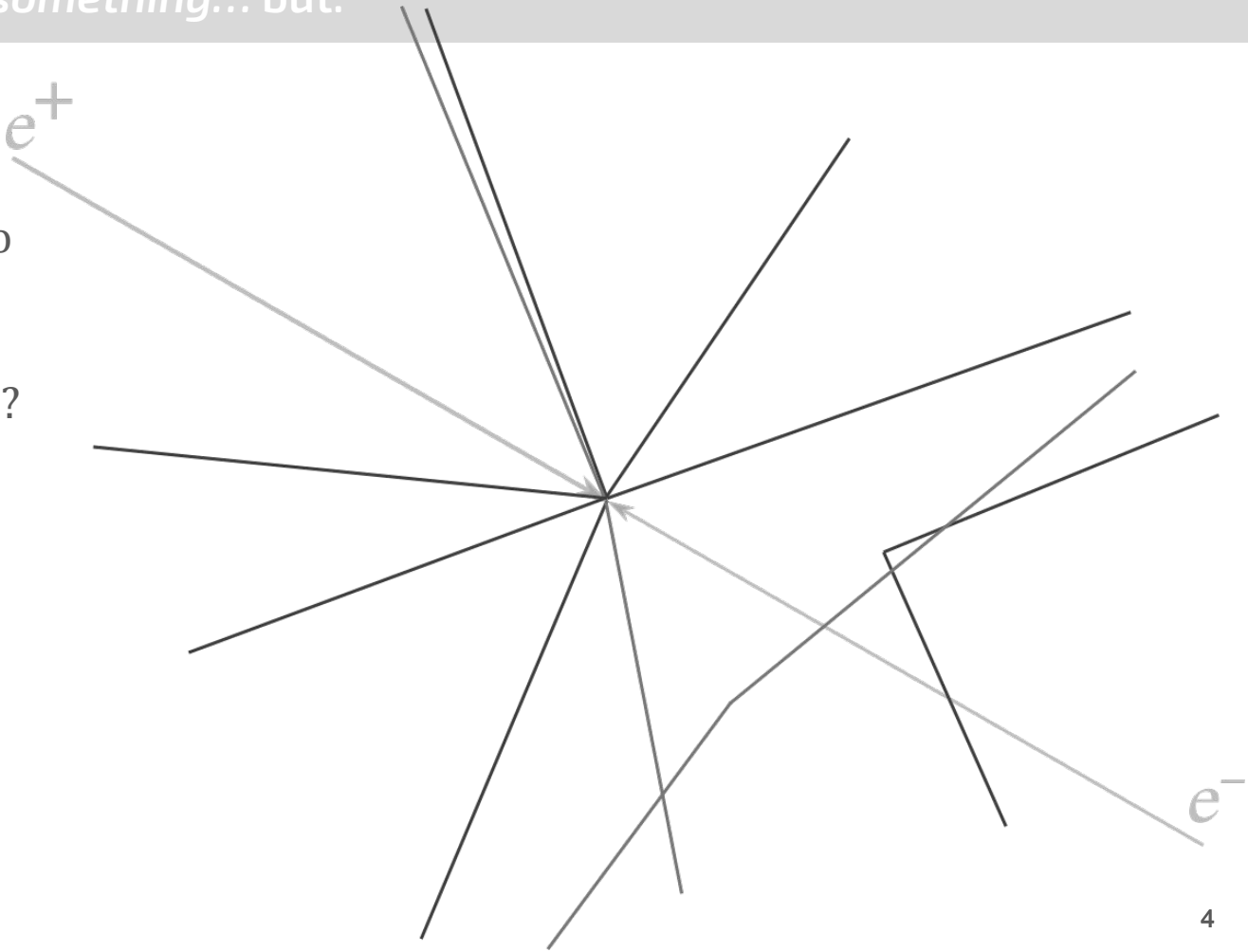
So you're looking for $B \rightarrow$ *something*… but:

Is the event BB?

Which particles belongs to which B?

What *frames* are the B*'s* in?



A solution?

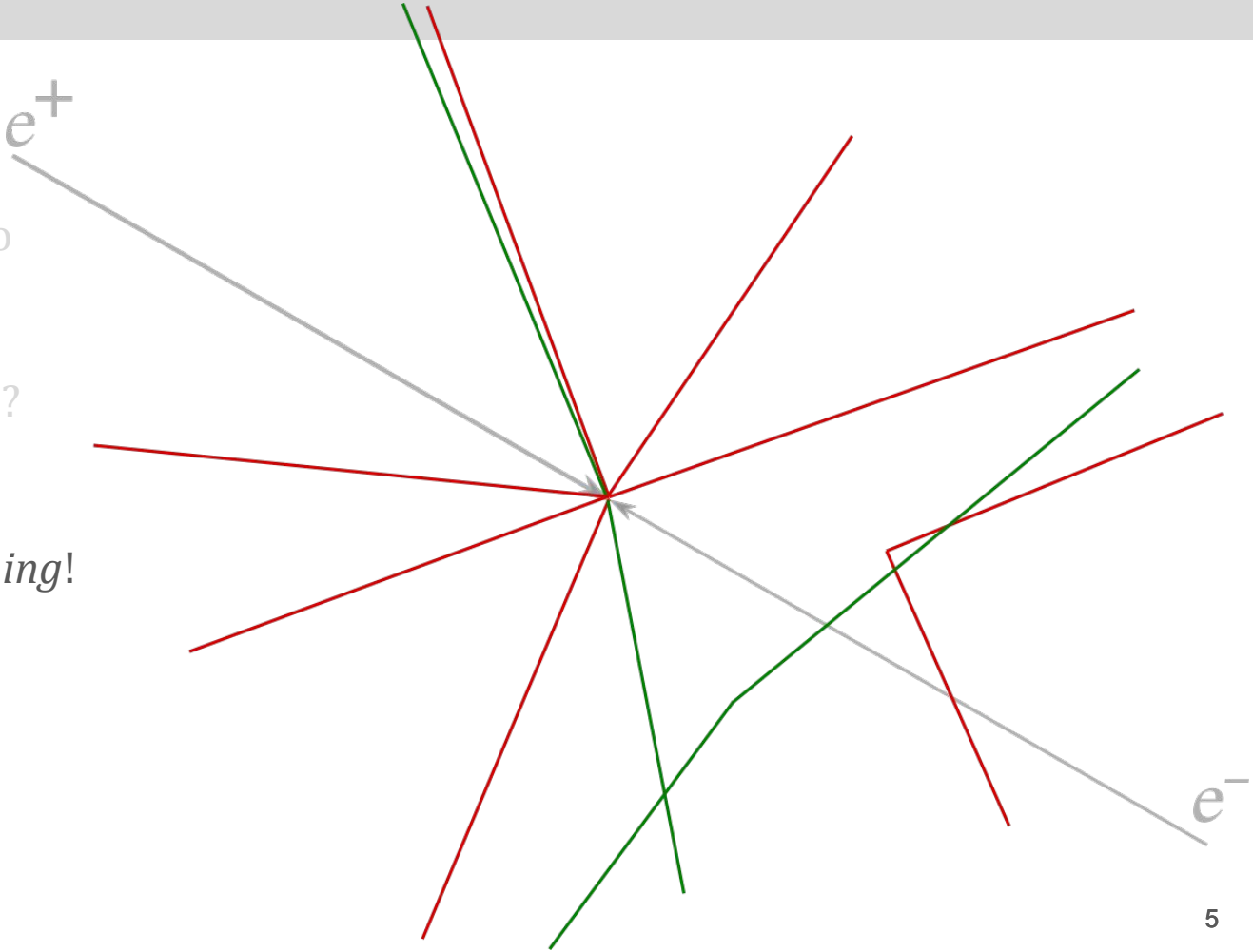
Is the event BB?

Which particles belongs to which B?

What *frames* are the B*'s* in?

→ Reconstruct one B explicitly… solves *everything*!

…but…



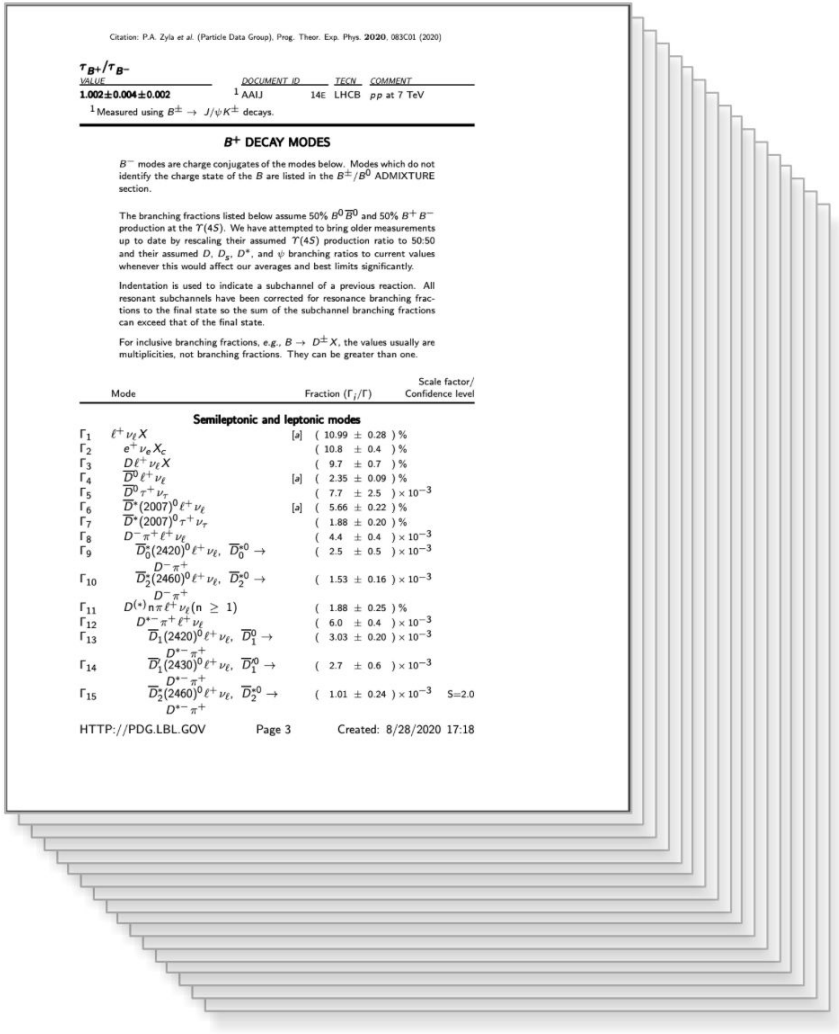
…there are **a *lot*** of *B* decay channels:

$\mathcal{O}(1000)$ *B* decays $\otimes$ $\mathcal{O}(100)$ *D* decays

$\rightarrow \mathcal{O}(10^5)$ possible channels

That's ok, we have computers! Should be no problem…

…but first let's agree on some *metrics* and *objectives* for such a "tagging" algorithm



Citation: P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

τ_{B^+}/τ_{B^-}

VALUE	DOCUMENT ID		TECN	COMMENT
1.002±0.004±0.002	[1] AAIJ	14E	LHCB	pp at 7 TeV

[1] Measured using $B^\pm \to J/\psi K^\pm$ decays.

B^+ DECAY MODES

B^- modes are charge conjugates of the modes below. Modes which do not identify the charge state of the B are listed in the $B^\pm/B^0$ ADMIXTURE section.

The branching fractions listed below assume 50% $B^0\overline{B}^0$ and 50% B^+B^- production at the $\Upsilon(4S)$. We have attempted to bring older measurements up to date by rescaling their assumed $\Upsilon(4S)$ production ratio to 50:50 and their assumed D, D_s, D^*, and ψ branching ratios to current values whenever this would affect our averages and best limits significantly.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

For inclusive branching fractions, *e.g.*, $B \to D^\pm X$, the values usually are multiplicities, not branching fractions. They can be greater than one.

	Mode		Fraction (Γ_j/Γ)	Scale factor/ Confidence level
	Semileptonic and leptonic modes			
Γ_1	$\ell^+ \nu_\ell X$	[a]	(10.99 ± 0.28) %	
Γ_2	$e^+ \nu_e X_c$		(10.8 ± 0.4) %	
Γ_3	$D \ell^+ \nu_\ell X$		(9.7 ± 0.7) %	
Γ_4	$\overline{D}^0 \ell^+ \nu_\ell$	[a]	(2.35 ± 0.09) %	
Γ_5	$\overline{D}^0 \tau^+ \nu_\tau$		(7.7 ± 2.5) $\times 10^{-3}$	
Γ_6	$\overline{D}^*(2007)^0 \ell^+ \nu_\ell$	[a]	(5.66 ± 0.22) %	
Γ_7	$\overline{D}^*(2007)^0 \tau^+ \nu_\tau$		(1.88 ± 0.20) %	
Γ_8	$D^- \pi^+ \ell^+ \nu_\ell$		(4.4 ± 0.4) $\times 10^{-3}$	
Γ_9	$\overline{D}_0^*(2420)^0 \ell^+ \nu_\ell$, $\overline{D}_0^{*0} \to D^- \pi^+$		(2.5 ± 0.5) $\times 10^{-3}$	
Γ_{10}	$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$, $\overline{D}_2^{*0} \to D^- \pi^+$		(1.53 ± 0.16) $\times 10^{-3}$	
Γ_{11}	$D^{(*)} n\pi \ell^+ \nu_\ell$(n $\geq$ 1)		(1.88 ± 0.25) %	
Γ_{12}	$D^{*-} \pi^+ \ell^+ \nu_\ell$		(6.0 ± 0.4) $\times 10^{-3}$	
Γ_{13}	$\overline{D}_1(2420)^0 \ell^+ \nu_\ell$, $\overline{D}_1^0 \to D^{*-} \pi^+$		(3.03 ± 0.20) $\times 10^{-3}$	
Γ_{14}	$\overline{D}_1'(2430)^0 \ell^+ \nu_\ell$, $\overline{D}_1'^0 \to D^{*-} \pi^+$		(2.7 ± 0.6) $\times 10^{-3}$	
Γ_{15}	$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$, $\overline{D}_2^{*0} \to D^{*-} \pi^+$		(1.01 ± 0.24) $\times 10^{-3}$	S=2.0

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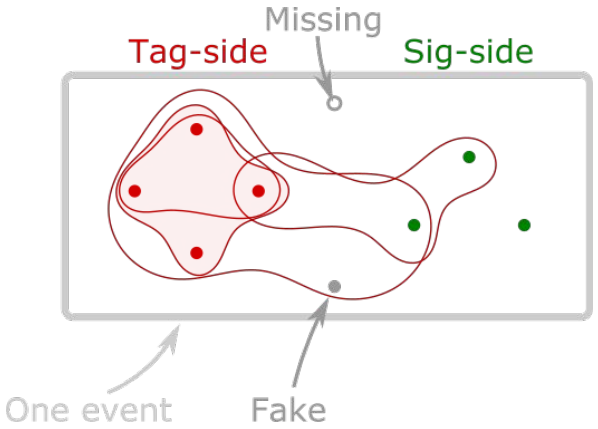
Tagging *metrics* and *objectives*:

- **High *efficiency***: fraction of events with a "good" tag
- **High *purity***: fraction of identified tags that are "good"
- Good kinematic information (minimize missing/fake)

A schematic view of an event with 4 tag candidates

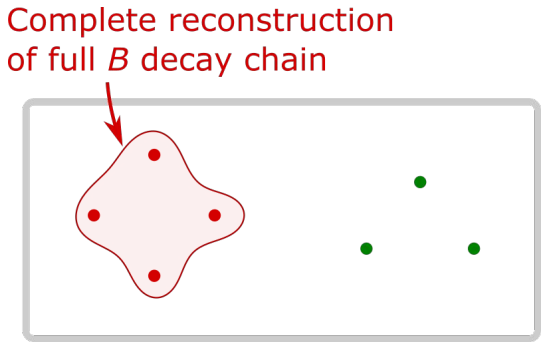


The FEI is an algorithm specifically designed to maximize these things, with two flavors…

The two flavors of FEI

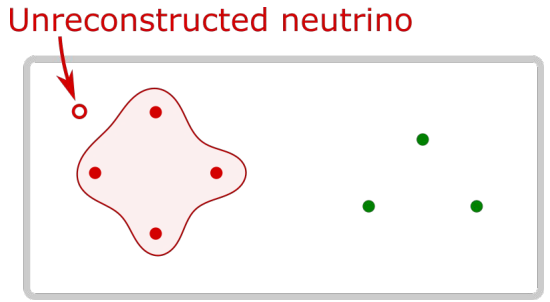
Hadronic tagging

- Very low efficiency: $\mathcal{O}(10^{-3})$
- Very high purity
- Excellent kinematic information



Semileptonic tagging

- Fairly low efficiency $\mathcal{O}(10^{-2})$
- Fairly high purity
- Fair kinematic information



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   - C. Usage

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   - B. *Rules* of usage
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   - D. The future

Basic introduction: what is it?

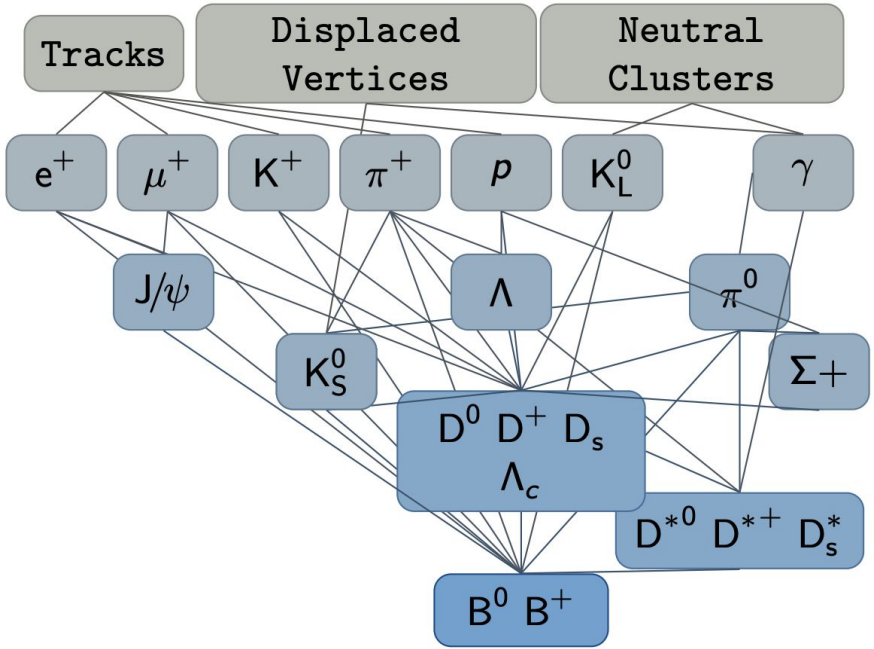
Hierarchical reconstruction…

$\mathcal{O}(10^4)$ *B* total decay chains

Uses machine learning: over 200 BDTs (Boosted Decision Trees) trained on simulated *BB* data

Outputs:

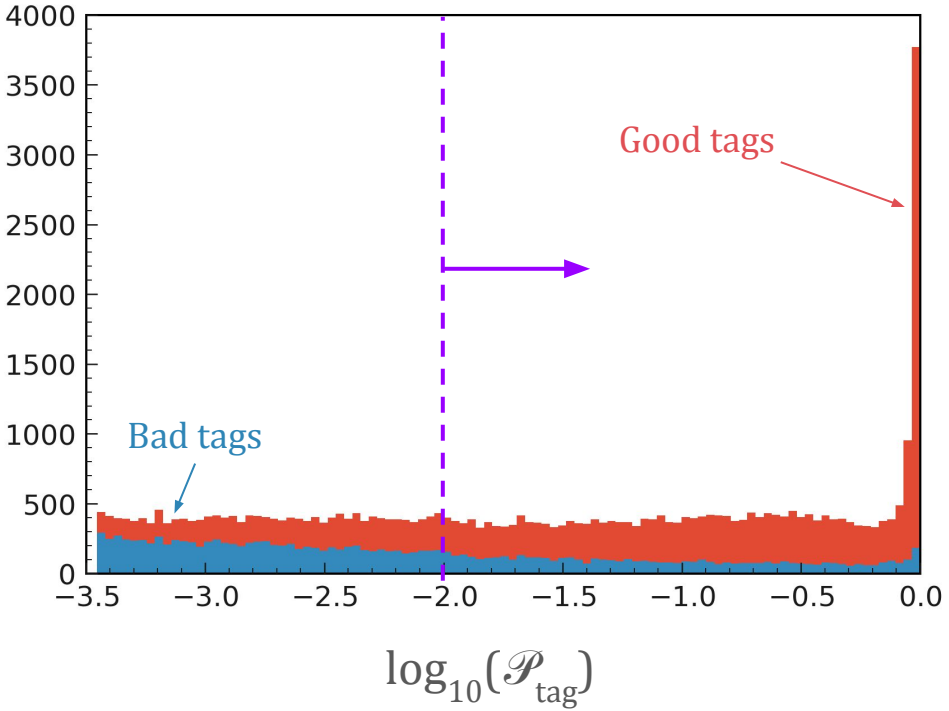
- List of tag candidates (each in a *specific* B decay cascade)
- A "signal probability" for each…

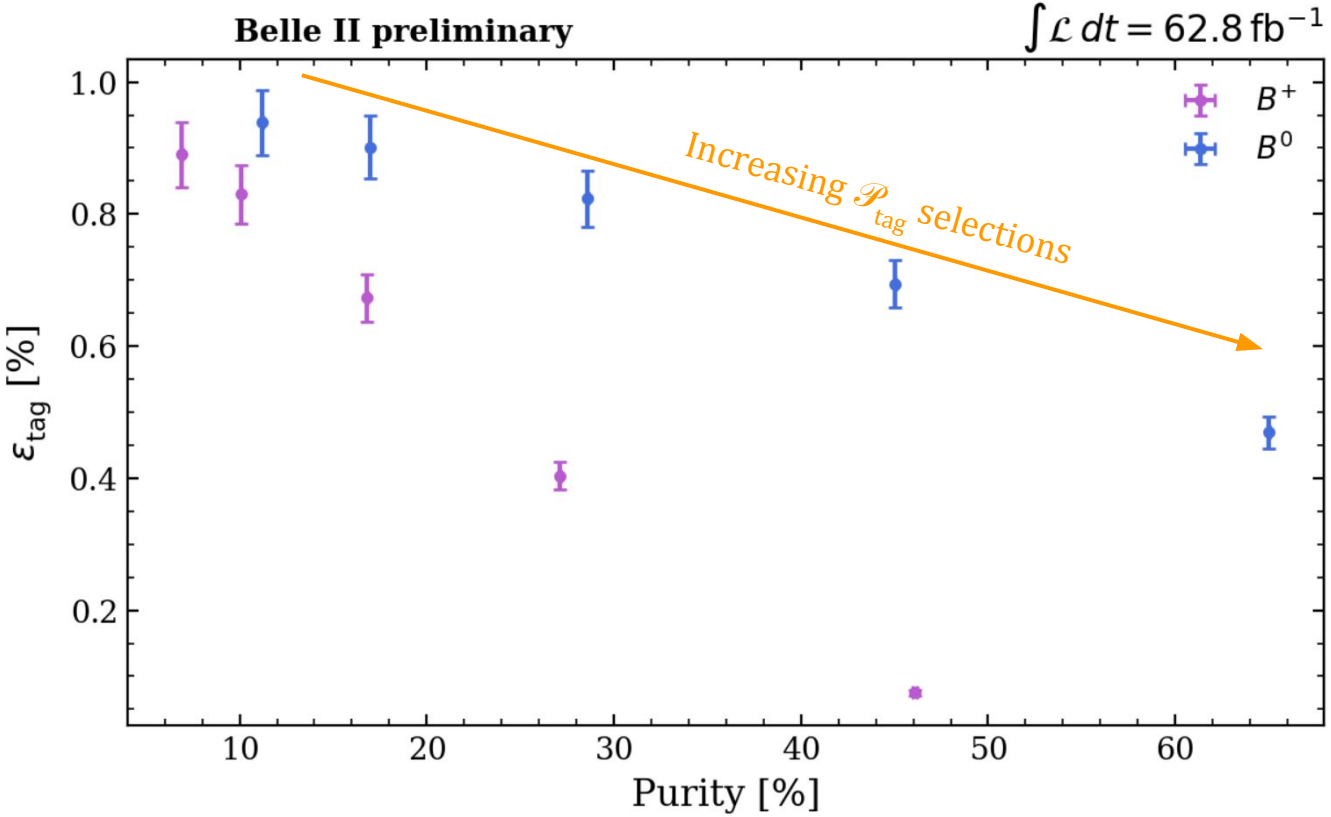


$\mathscr{P}_{\text{tag}}$ rates confidence that the tag is "good"

Full-chain classifier

Enhance *purity* via a **selection**…





There are other ways to purify your tags…

Measures of *kinematic consistency*:

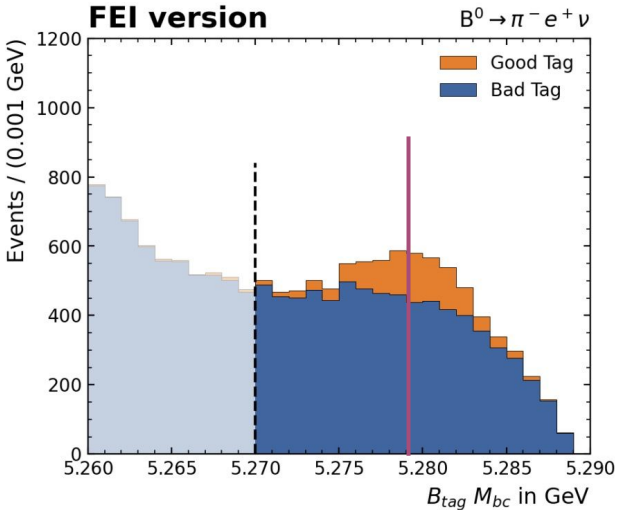
For good *hadronic* tags:

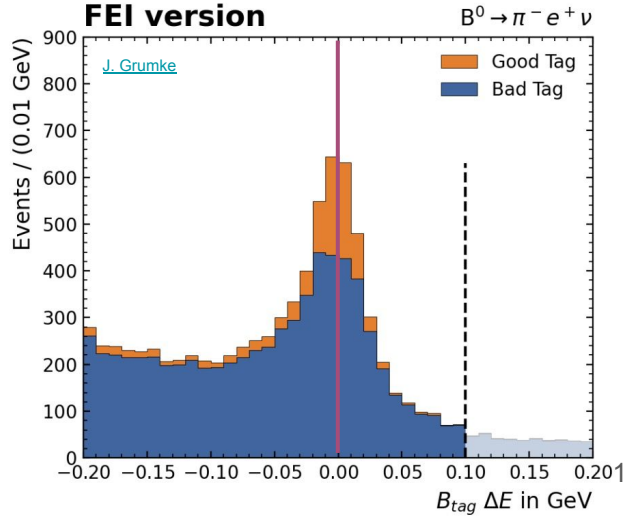
- Beam-constrained mass $M_{\mathrm{bc}} \sim m_B$
- Energy difference $\Delta E \sim 0$

For good *semileptonic* tags:

- $\cos\theta_{\mathrm{BY}} \in [-1,1]$

But what you get *more than one* tag candidate in an event?



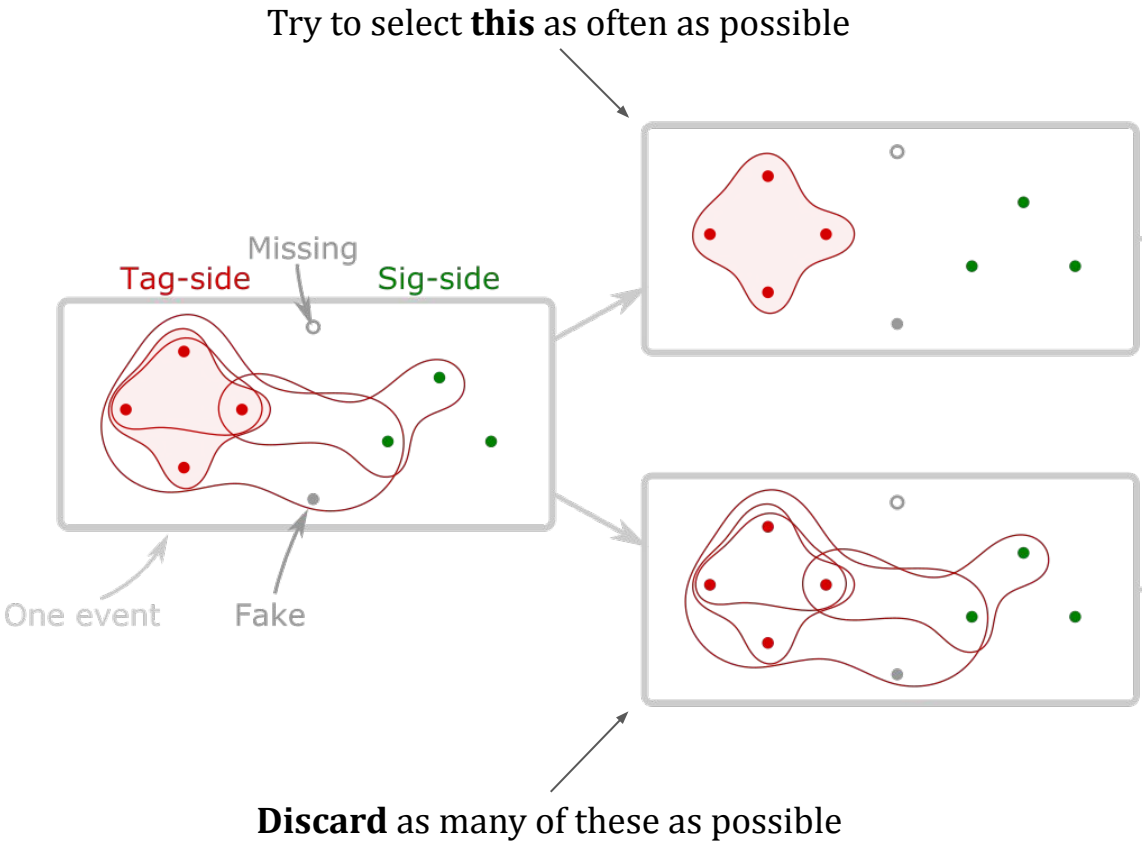


Best tag selection (BTS)

Can be helpful to select the “best” tag candidate in each event

Typically: highest $\mathscr{P}_{\text{tag}}$ in an event…

…*after* other selections.



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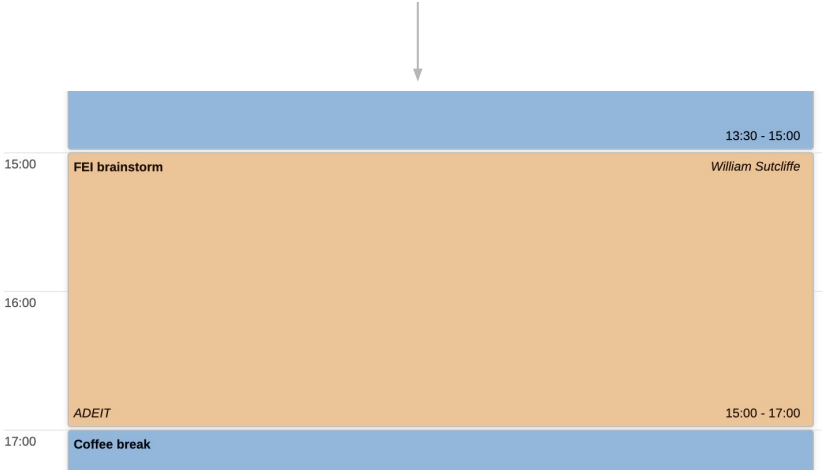
Training

Typically, you do **not** train the FEI yourself

FEI training weights are *magically** uploaded to the conditions database

*a.k.a. William Sutcliffe, but it could be you!!

No picture to show here, so I'll just invite you to brainstorm at 3pm



FEI is *trained* and *validated* and waiting for you to use…

Load the FEI

Get the tag list you want:

- `B+:generic`, `B0:generic` — Hadronic tag candidates
- `B+:semileptonic`, `B0:semileptonic` — Semileptonic tag candidates

Get the variables you want:

- `Mbc` $\rightarrow M_{bc}$
- `deltaE` $\rightarrow \Delta E$
- `extraInfo(SignalProbability)` $\rightarrow \mathscr{P}_{\text{tag}}$
- `extraInfo(decayModeID)`
- `cosThetaBetweenParticleAndNominalB` $\rightarrow \cos\theta_{\text{BY}}$

0 :	$B^0 \to D^- \pi^+$
1 :	$B^0 \to D^- \pi^+ \pi^0$
2 :	$B^0 \to D^- \pi^+ \pi^0 \pi^0$
3 :	$B^0 \to D^- \pi^+ \pi^+ \pi^-$
4 :	$B^0 \to D^- \pi^+ \pi^+ \pi^- \pi^0$
5 :	$B^0 \to \overline{D}^0 \pi^+ \pi^-$
6 :	$B^0 \to D^- D^0 K^+$
7 :	$B^0 \to D^- D^{*0} K^+$
8 :	$B^0 \to D^{*-} D^0 K^+$
9 :	$B^0 \to D^{*-} D^{*0} K^+$
10 :	$B^0 \to D^- D^+ K_S^0$
11 :	$B^0 \to D^{*-} D^+ K_S^0$
12 :	$B^0 \to D^- D^{*+} K_S^0$
13 :	$B^0 \to D^{*-} D^{*+} K_S^0$
14 :	$B^0 \to D_s^+ D^-$
15 :	$B^0 \to D^{*-} \pi^+$
16 :	$B^0 \to D^{*-} \pi^+ \pi^0$
17 :	$B^0 \to D^{*-} \pi^+ \pi^0 \pi^0$
18 :	$B^0 \to D^{*-} \pi^+ \pi^+ \pi^-$
19 :	$B^0 \to D^{*-} \pi^+ \pi^+ \pi^- \pi^0$
20 :	$B^0 \to D_s^{*+} D^-$
21 :	$B^0 \to D_s^+ D^{*-}$
22 :	$B^0 \to D_s^{*+} D^{*-}$
23 :	$B^0 \to J/\psi K_S^0$
24 :	$B^0 \to J/\psi K^+ \pi^-$
25 :	$B^0 \to J/\psi K_S^0 \pi^+ \pi^-$
26 :	$B^0 \to \overline{\Lambda}_c^- p^+ \pi^+ \pi^-$
27 :	$B^0 \to \overline{D}^0 p^+ \overline{p}^-$
28 :	$B^0 \to D^- p^+ \overline{p}^- \pi^+$
29 :	$B^0 \to D^{*-} p^+ \overline{p}^- \pi^+$
30 :	$B^0 \to \overline{D}^0 p^+ \overline{p}^- \pi^+ \pi^-$
31 :	$B^0 \to \overline{D}^{*0} p^+ \overline{p}^- \pi^+ \pi^-$
32 :	No B^0 FEI decay

0 :	$B^+ \to \overline{D}^0 \pi^+$
1 :	$B^+ \to \overline{D}^0 \pi^+ \pi^0$
2 :	$B^+ \to \overline{D}^0 \pi^+ \pi^0 \pi^0$
3 :	$B^+ \to \overline{D}^0 \pi^+ \pi^+ \pi^-$
4 :	$B^+ \to \overline{D}^0 \pi^+ \pi^+ \pi^- \pi^0$
5 :	$B^+ \to \overline{D}^0 D^+$
6 :	$B^+ \to D^+ \overline{D}^0 K_S^0$
7 :	$B^+ \to D^+ \overline{D}^{*0} K_S^0$
8 :	$B^+ \to D^{*+} \overline{D}^0 K_S^0$
9 :	$B^+ \to D^{*+} D^{*0} K_S^0$
10 :	$B^+ \to \overline{D}^0 D^0 K^+$
11 :	$B^+ \to \overline{D}^{*0} D^0 K^+$
12 :	$B^+ \to \overline{D}^0 D^{*0} K^+$
13 :	$B^+ \to \overline{D}^{*0} D^{*0} K^+$
14 :	$B^+ \to D_s^+ \overline{D}^0$
15 :	$B^+ \to \overline{D}^{*0} \pi^+$
16 :	$B^+ \to \overline{D}^{*0} \pi^+ \pi^0$
17 :	$B^+ \to \overline{D}^{*0} \pi^+ \pi^0 \pi^0$
18 :	$B^+ \to \overline{D}^{*0} \pi^+ \pi^+ \pi^-$
19 :	$B^+ \to \overline{D}^{*0} \pi^+ \pi^+ \pi^- \pi^0$
20 :	$B^+ \to D_s^{*+} \overline{D}^0$
21 :	$B^+ \to D_s^+ \overline{D}^{*0}$
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23 :	$B^+ \to D^- \pi^+ \pi^+$
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26 :	$B^+ \to J/\psi K^+ \pi^+ \pi^-$
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28 :	$B^+ \to J/\psi K_S^0 \pi^+$
29 :	$B^+ \to \overline{\Lambda}_c^- p^+ \pi^+ \pi^0$
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31 :	$B^+ \to \overline{D}^0 p^+ \overline{p}^- \pi^+$
32 :	$B^+ \to \overline{D}^{*0} p^+ \overline{p}^- \pi^+$
33 :	$B^+ \to D^0 p^+ \overline{p}^- \pi^+ \pi^-$
34 :	$B^+ \to D^{*0} p^+ \overline{p}^- \pi^+ \pi^-$
35 :	$B^+ \to \overline{\Lambda}_c^- p^+ \pi^+$
36 :	No B^+ FEI decay

Save electrons and only run over *FEI skims*

Subset of all events pre-identified with FEI tag candidates

Access skims on the NAF and bypass the Grid!

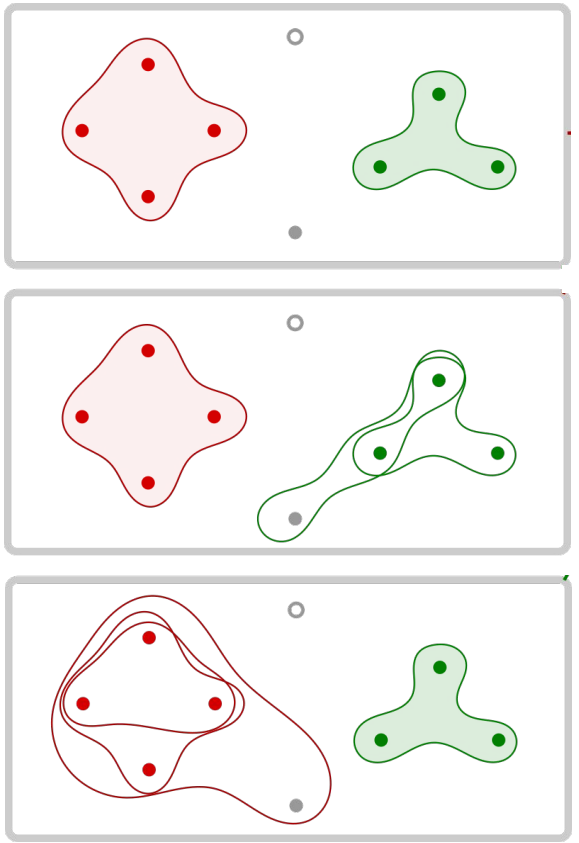
WG & JIRA tickets	Combined Skim	Skim	Skim Code	Gen Skim	MC15ri	proc13	prompt	MC15rd
SL&ME Liaison: @Shanette Anne De Lamotte Prep: BIIDP-5737 Requests: BIIDP-6059	FEI	feiHadronic	11180500	Hadron	Ready	Ready	Ready	
		feiSL	11180600					

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:

- *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*…

Calibration

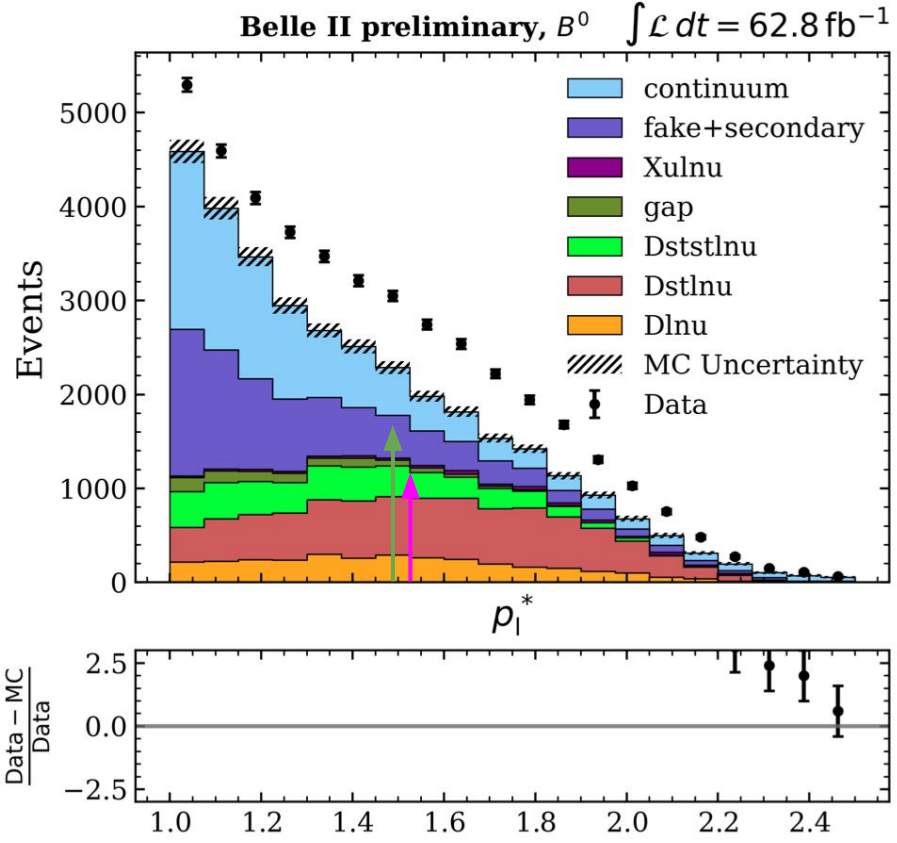
Measure *known decay* in FEI-tagged events

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

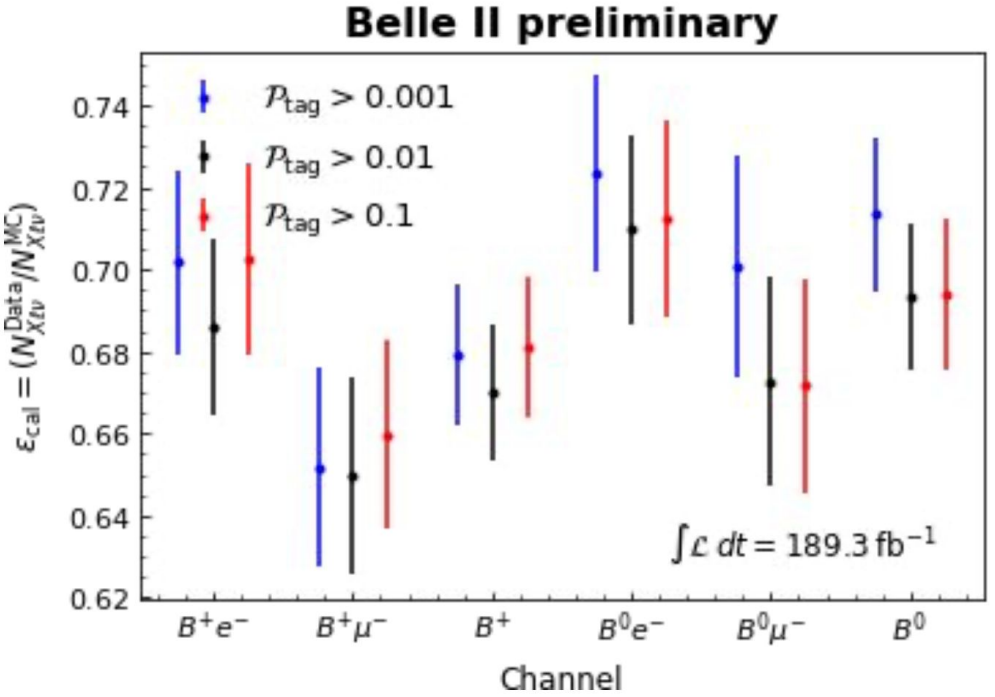
Calibration factors are **data**/MC ratios of signal yield

To use: correct simulated FEI efficiency with the calibration factor

SL FEI calibration with B → X l nu



The current official calibration…



…and that's all you need to know about the FEI! …

An obvious lie

Two parts:

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Half truths: these are *completely inadequate* definitions that hide some **extremely important** points

Tagging *metrics* and *objectives*:

- **High *efficiency***: fraction of events with a "good" tag
- **High *purity***: fraction of identified tags that are "good"
- Good kinematic information (minimize missing/fake)

A schematic view of an event with 4 tag candidates

The FEI is an algorithm specifically designed to maximize these things, with two flavors…

Basic introduction: what is it?

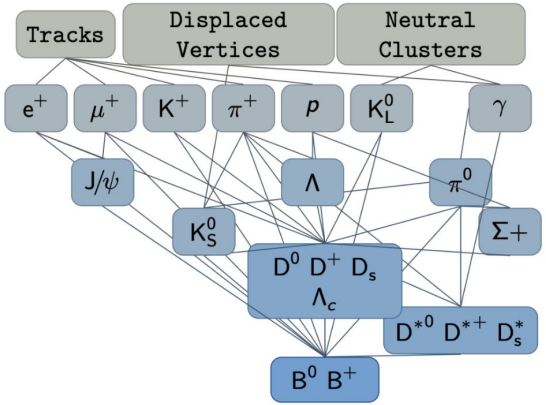
Hierarchical reconstruction…

$\mathcal{O}(10^4)$ B total decay chains

Uses machine learning: over 200 BDTs (Boosted Decision Trees) trained on simulated BB data

Outputs:

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



11

Misleading name: this isn't a probability

In analysis

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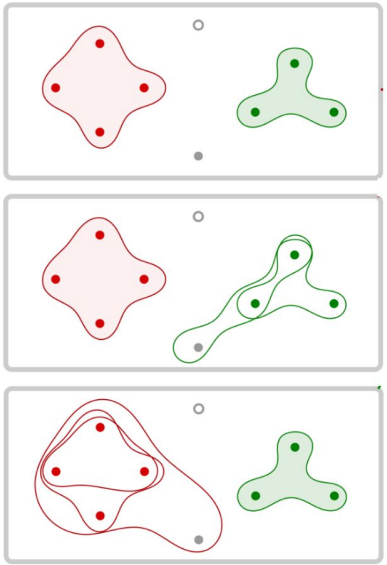
Lies!

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



The very concept of "*the*" FEI calibration is a **lie**!

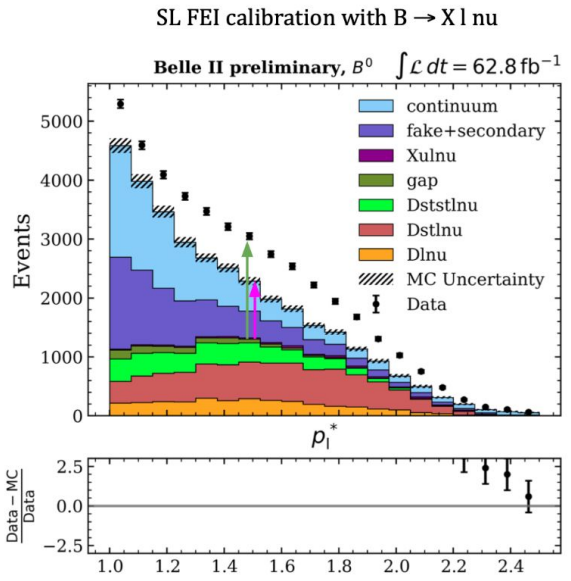
Calibration

Measure ***known decay*** in FEI-tagged events

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

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

Oversimplification → To use: correct simulated FEI efficiency with the calibration factor



But first let's think harder about what the FEI does…

Two parts:

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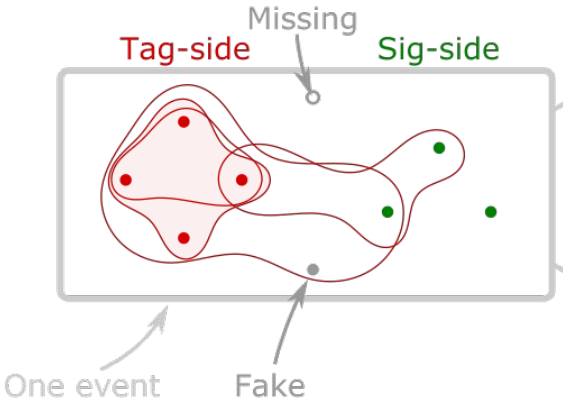
   A. Why?
   B. Basic introduction
   C. Usage

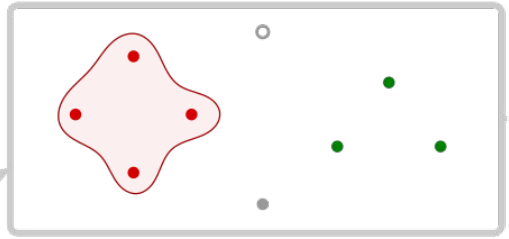
II. **Hard truths**
   A. Uncovering the lies
   B. Tagging logic
   C. A few hard truths
   D. How to use the FEI safely

Step 1:
Get FEI tag candidates

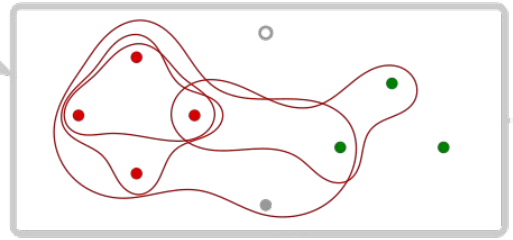
Step 2:
Cut and choose best tag

Step 3
Get li





Number of events with 1 or 2 good tags of **either flavor**: N_{t_1}



Bad tags include:
- Uncaptured tag-side particles
- Sig-side donors
- Fake particles
- Mis-reco tag particles

Good tags selected: N_{t_2}

Bad tags selected include:
- Events with no good tag
- Events with unselected good tag

Step 1:
Get FEI tag candidates

Step 2:
Cut and choose best tag

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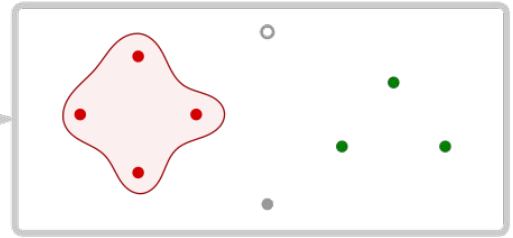
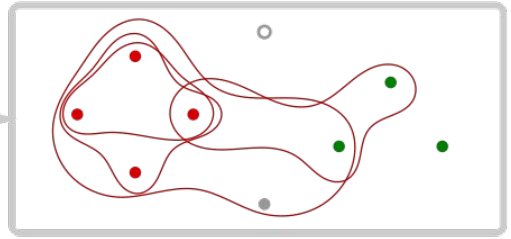
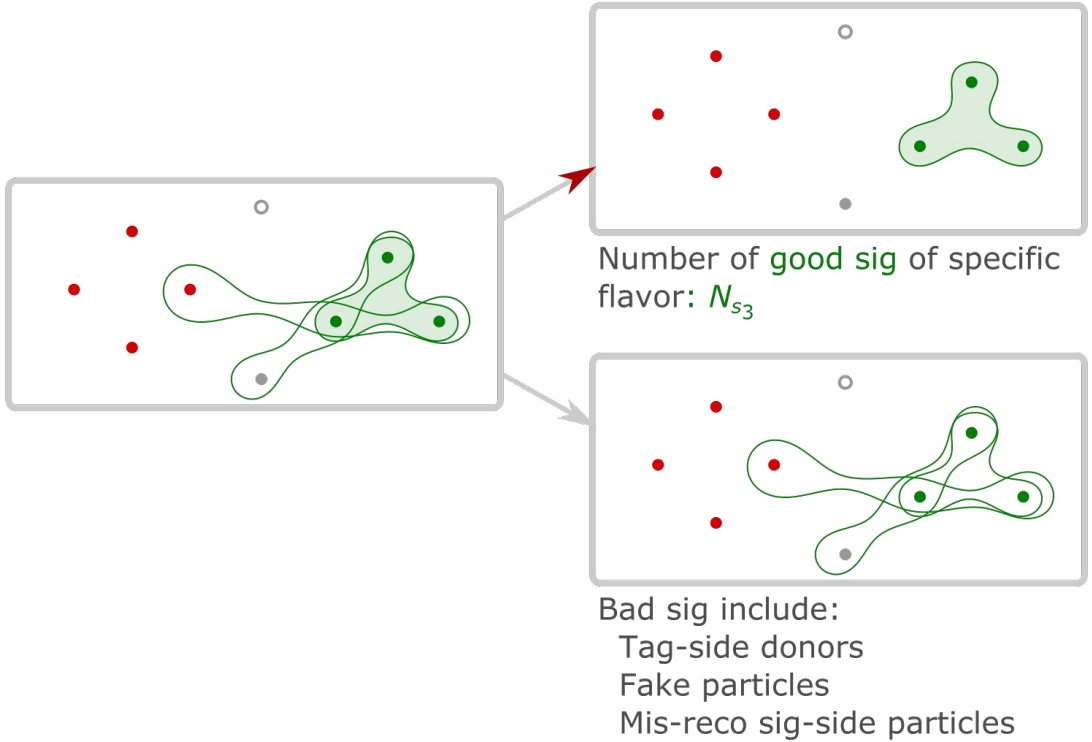


Good tags selected: N_{t_2}



Bad tags selected include:
- Events with no good tag
- Events with unselected good tag

Step 3:
Get list of signal candidates



Step 4:
Combine best tag and sig candidates

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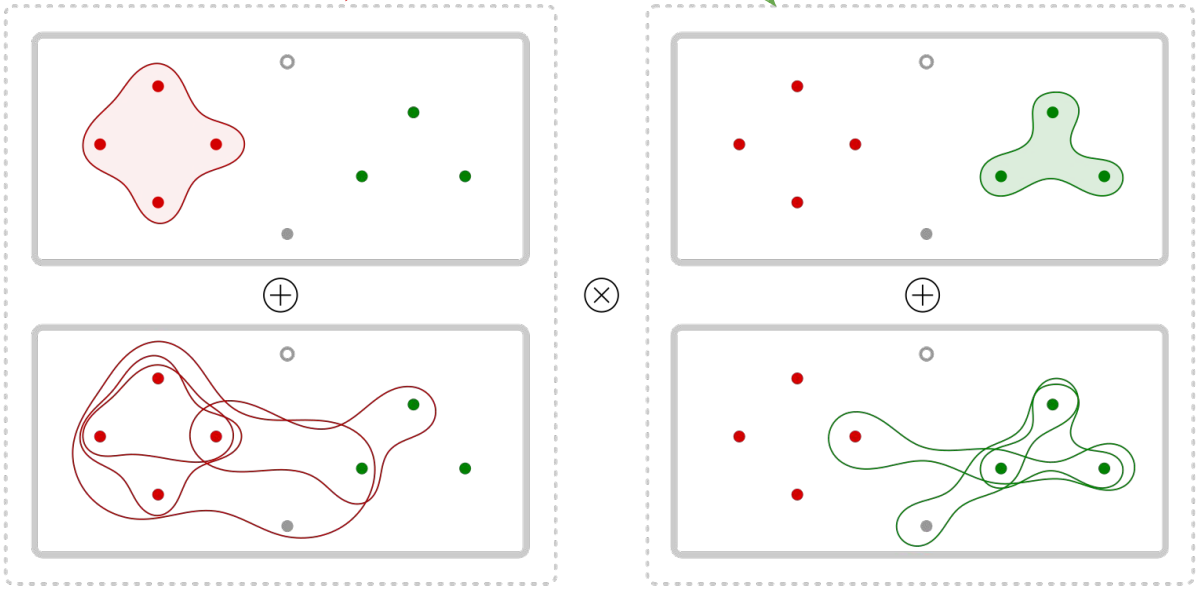
Combine best tag and sig candidates

With BTS, one per event
here but not **here**



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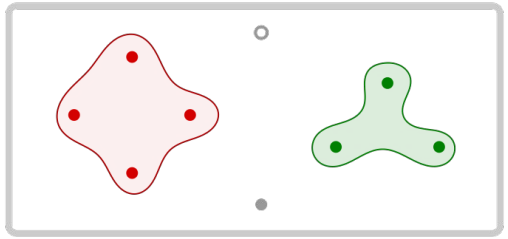
Assumption: 100% of good-good candidates survive

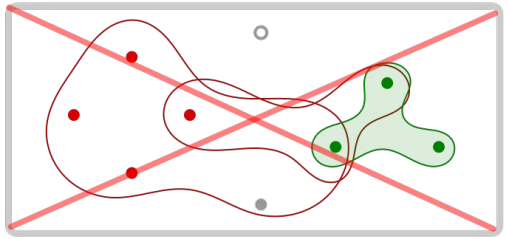
Valid combinations with good tags or good signal

idates

Valid combinations with
good tags or good signal

Invalid combinations with
good tags or good signal





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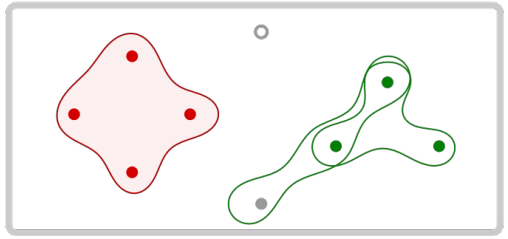
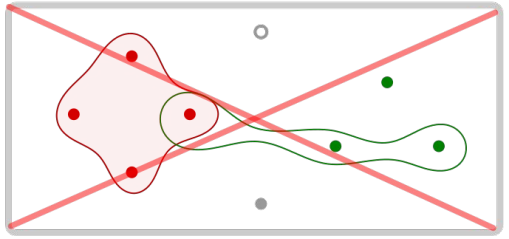
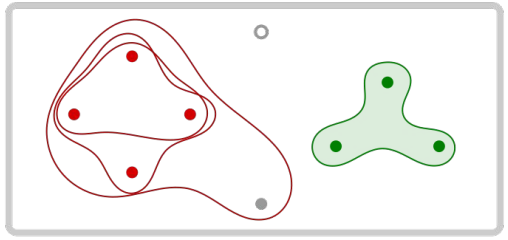
=





Lost good tags



Remaining:
N_{t_4} good *unique* tags
N_{s_4} good sig

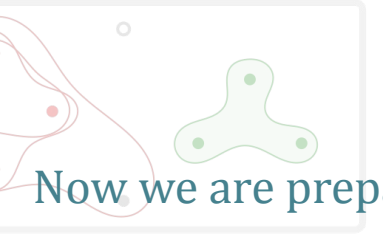
ombinations with
gs or good signal

Invalid combinations with
good tags or good signal

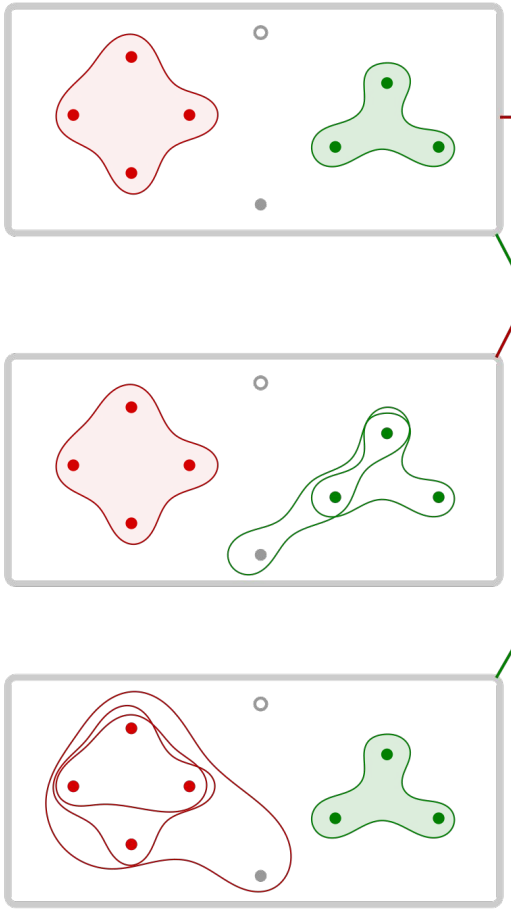
Step 5:
Cut and select best sig

ption: 100% of
ood candidates survive

Lost good tags



Remaining:
N_{t4} good *unique* tags
N_{s4} good sig



Now we are prepared to understand the lies…

Two parts:

I. **Pleasing lies**
   A. Why?
   B. Basic introduction
   C. Usage

II. **Hard truths**
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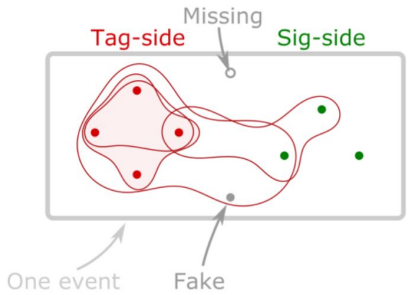
Let's address these lies one-by-one…

Tagging *metrics* and *objectives*:

- **High *efficiency***: fraction of events with a "good" tag
- **High *purity***: fraction of identified tags that are "good"
- Good kinematic information (minimize missing/fake)

The FEI is an algorithm specifically designed to maximize these things, with two flavors…

A schematic view of an event with 4 tag candidates



What exactly do we mean by "good tag" and "efficiency"?

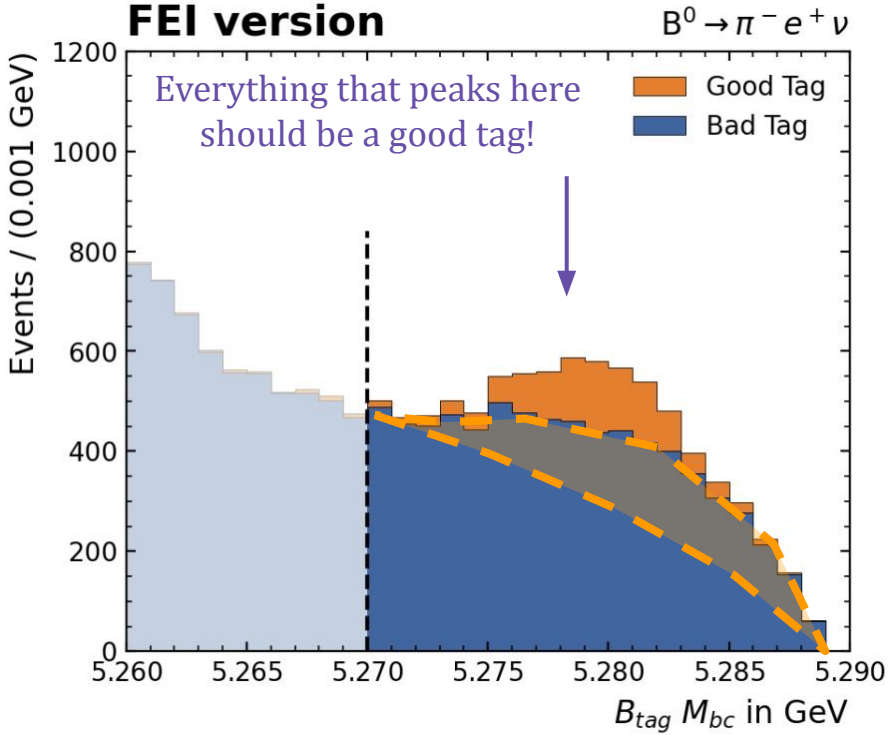
What is a “good tag”?

`isSignal`?

Very easy…

…but often *too strict*…

…is it *really* a “bad tag” if all the FSPs are correct?



…how about “*the peaking stuff*”?

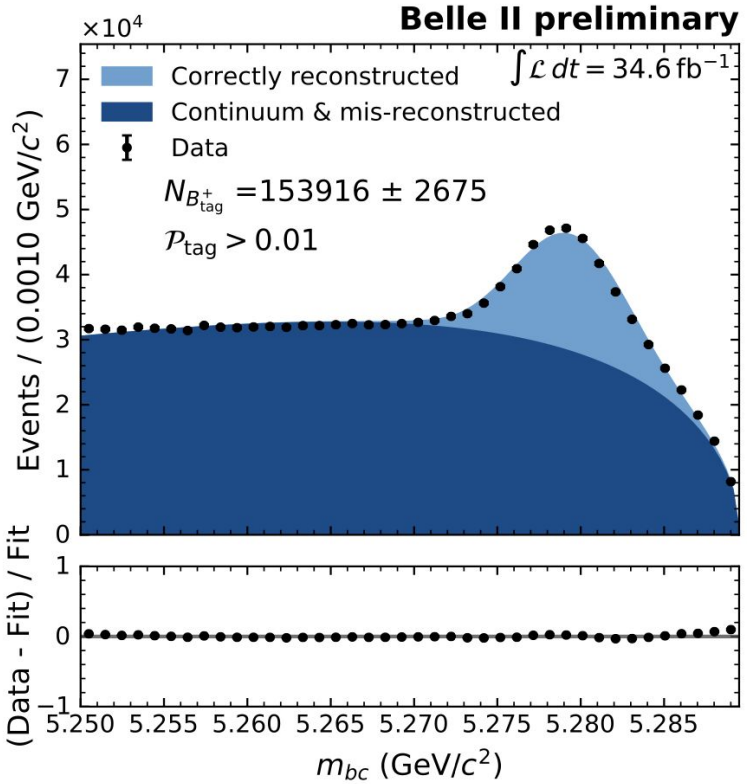
What is a “good tag”?

“The peaking stuff”

For example: fit M_{bc} with Argus+Crystal Ball

Yield of CB is good tag yield

But: we can’t identify **a given candidate** as a good or bad tag--we just know yields



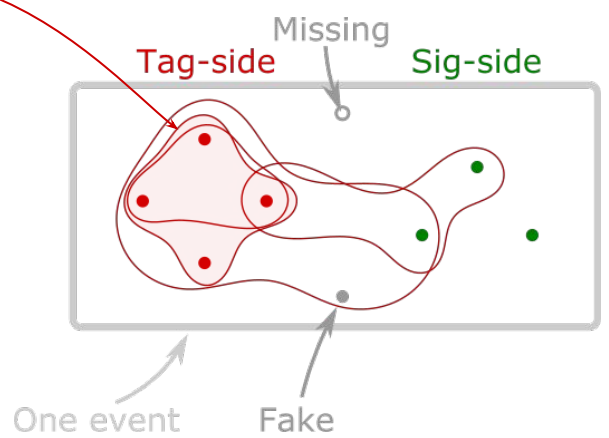
Can we do a better job with truth-matching?

What is a “good tag”?

A definition I like:

`mcPDG(B`$_{\texttt{tag}}$`)` is B (no sig particles in tag), and

All B daughters are in tag



Regardless, consider:

Tag *efficiency* depends on your definition

The *calibration factor* might too!

In analysis

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

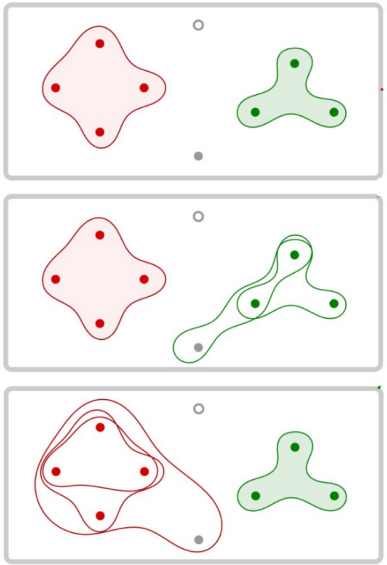
1. Build your *signal-side B* candidate
2. Combine *tag* and *signal Bs* to make $\Upsilon(4S)$ candidates

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

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

Lies!

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



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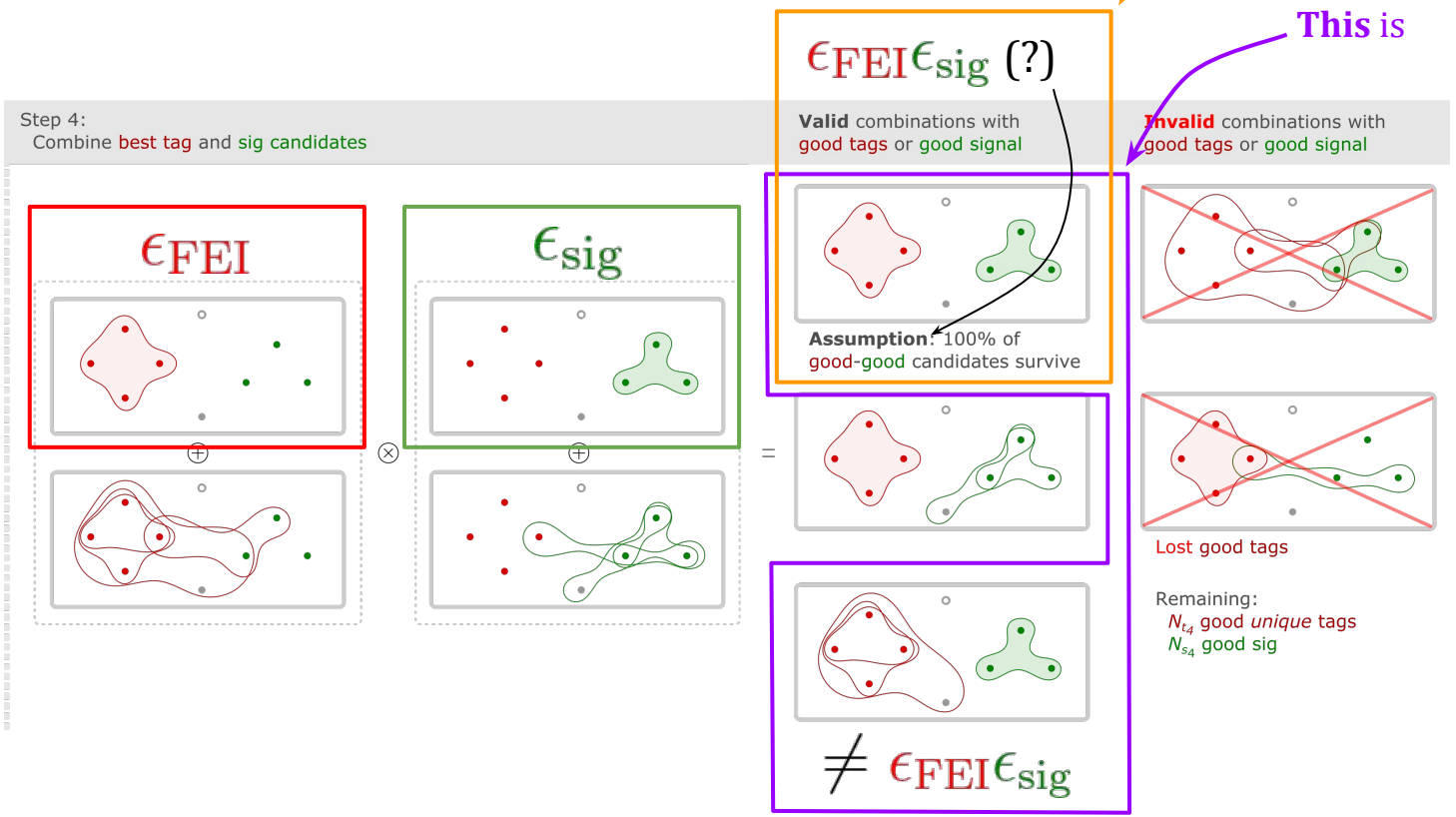
Consider the *combination* stage



The tag/sig combinations are *not random*… and depend on a lot of factors

There is no such thing as *the* FEI efficiency…

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

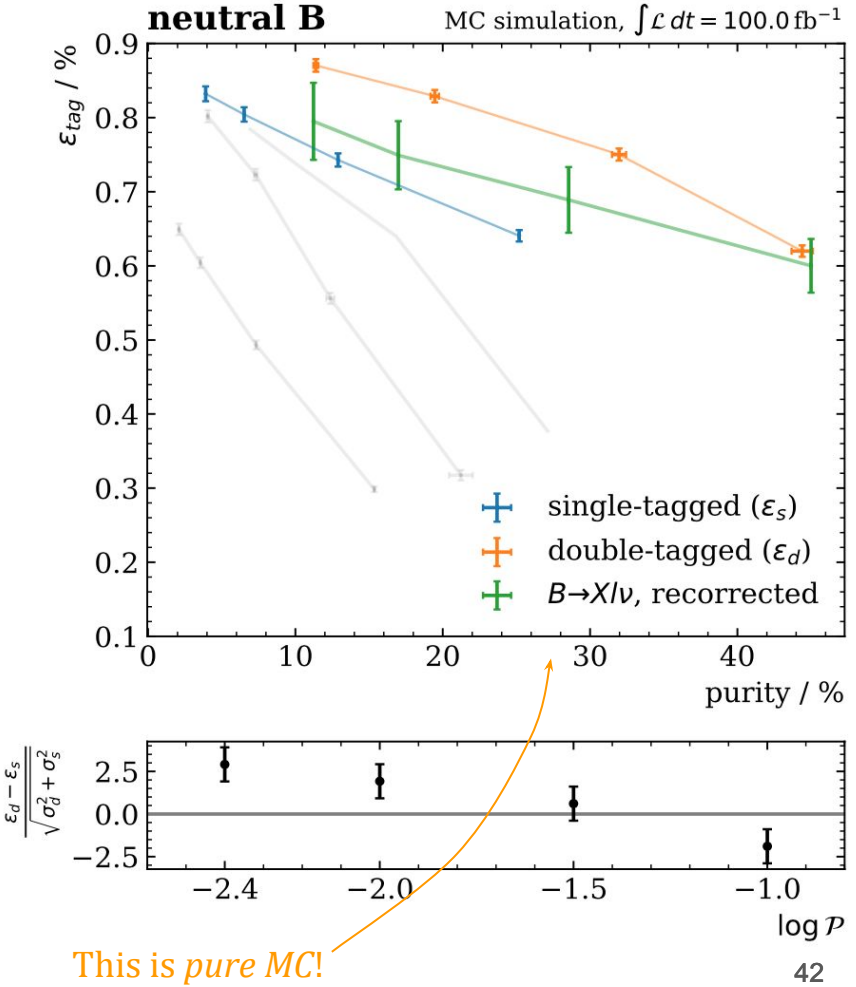
There is *only* ϵ_{total}…

…and it depends on what happens in the *tag-signal combination* so…

- *BF*(signal)/*BF*(normalization): FEI efficiency *cancels*

…*only if you are lucky*!

What factors affect this?

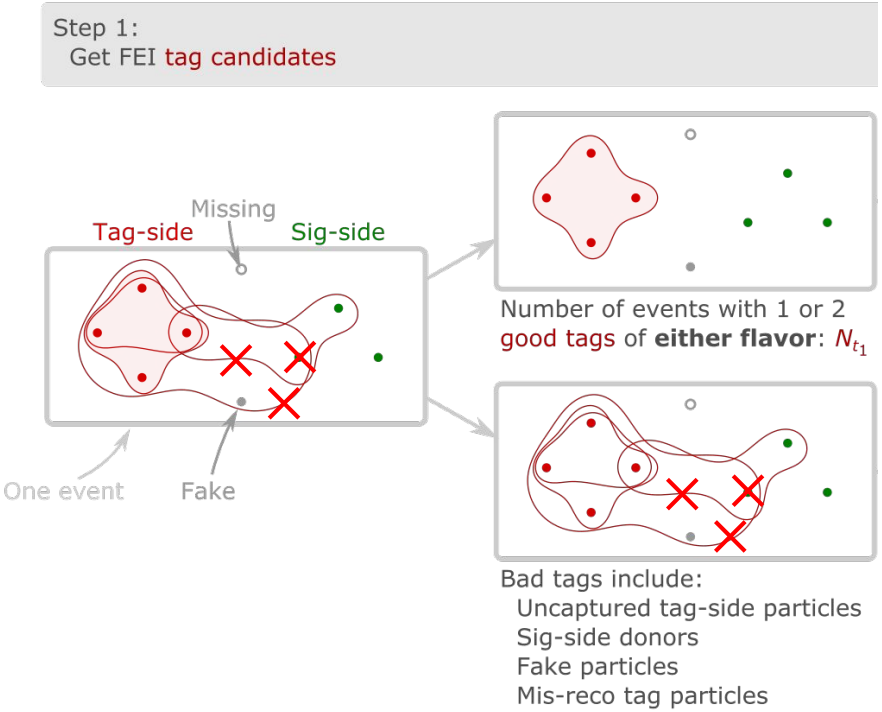


This is *pure MC*!

Consider *multiplicity*

Low multiplicity → fewer wrong tag candidates → fewer *entanglement* opportunities

But **other things can matter**… theses to be written!



Fewer bad tags → *higher BTS efficiency*

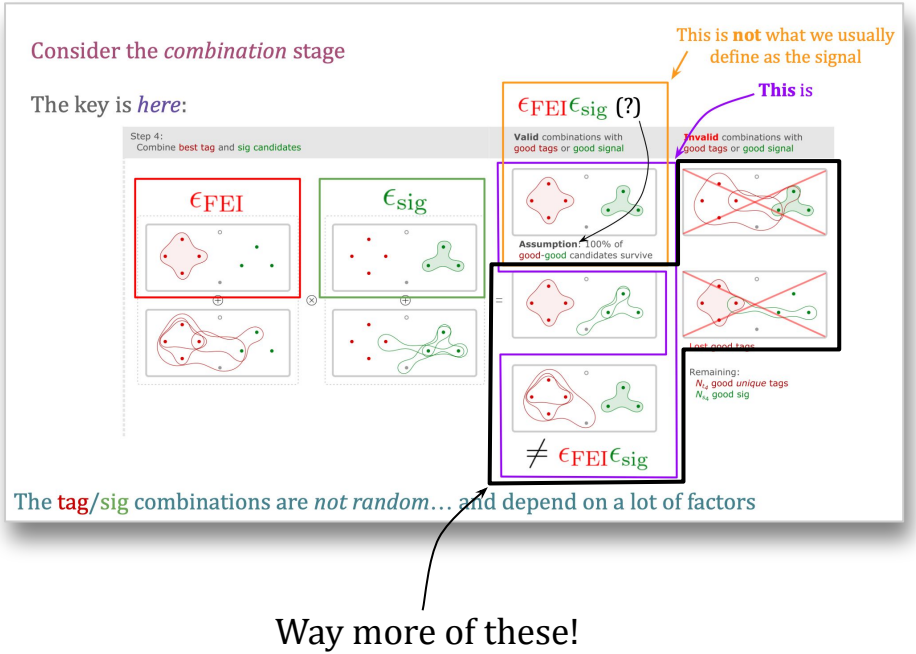
Things only get worse if you don't do BTS…

Skip best tag selection?

Try this:

- Select **no** best tag
- Throw *all* tags together with sigs
- Perform a selection on the $\Upsilon(4S)$ or sig
- We have now *multiplied* the problem!

Same problem if you select best tag after building combinations!



…but isn't this effect *modeled* in simulation?

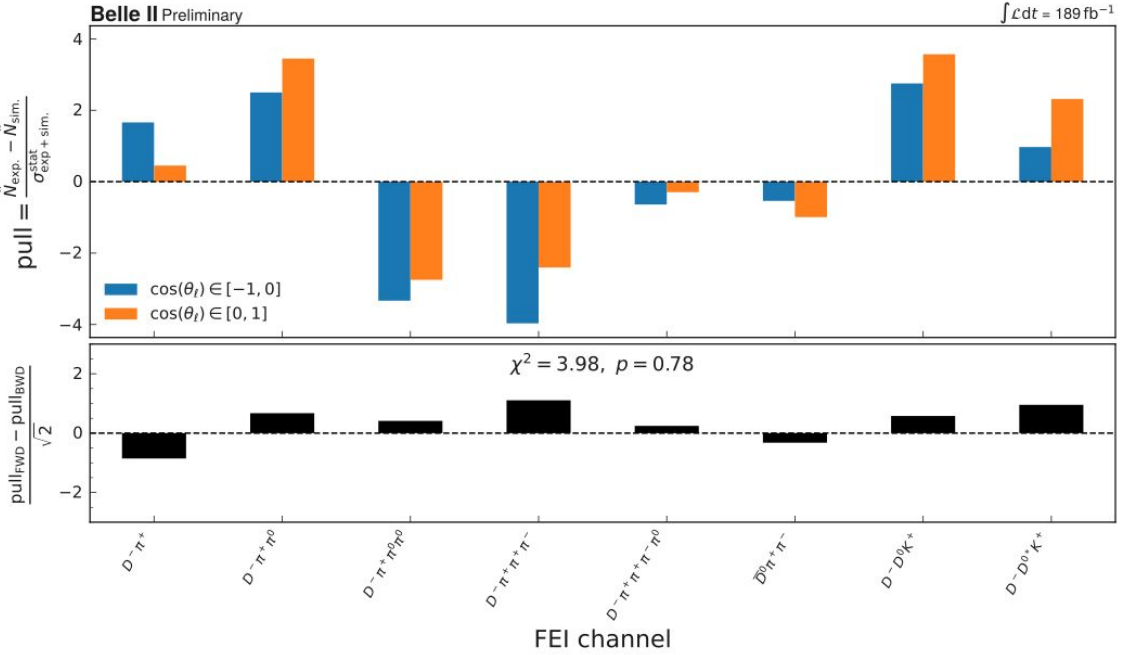
Yes, this is simulated, but…

What if the *signal-side efficiency dependence* is mismodeled?

Check decay mode ID distribution:

It's **ok** if it's mismodeled…

…as long as it's not *differentially* mismodeled in your signal categories



If this test applies to your analysis, you *should* do it…

But, can you come up with something better?

We have one last lie…

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 (!)**

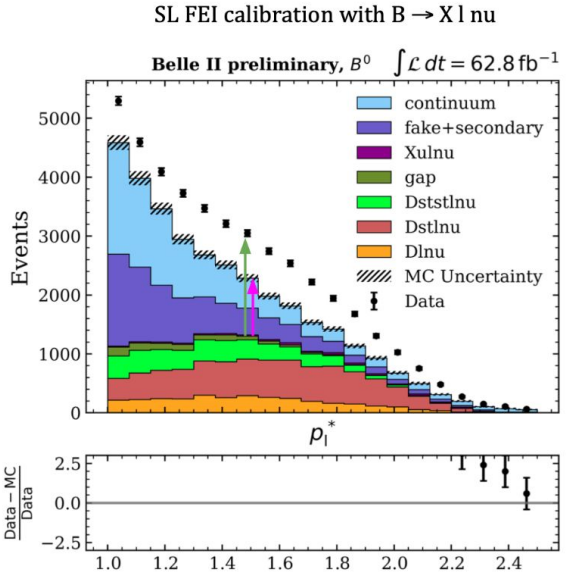
Calibration

Measure *known decay* in FEI-tagged events

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

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

To use: correct simulated FEI efficiency with the calibration factor



Lie

Oversimplification

…but calibration is still *very important*

Calibrations

Several groups calibrating in orthogonal ways

Should learn a lot about signal-side dependencies

It's important that these calibrations are *tag mode-dependent*

Current official calibration is not

Responsible / interested parties	Tag-side modes	Calibration channel / Performance study	Reference
@William Sutcliffe	Hadronic FEI (B+, B0)	B→Xlnu (inclusive, pl fit)	BELLE2-NOTE-PH-2019-031
@Taichiro Koga @Qidong Zhou @Michele Aversano @William Sutcliffe	Hadronic FEI (B+, B0)	B->D(*)lnu	
@Niharika Rout @Vidya Vobbilisetti @Trabelsi Karim	Hadronic FEI (B+)	B+ → D(*)pi+ (partial reco)	BELLE2-NOTE-PH-2022-002
@Meihong Liu @Trabelsi Karim @Vidya Sagar Vobbilisetti	Hadronic FEI (B0)	B0 → D(*)pi+ (partial reco)	BELLE2-NOTE-PH-2022-046
@William Sutcliffe	Hadronic FEI (B+, B0)	Mbc fitting in Data (ROC curves)	
@Andre Hao Yuan Huang @Kevin Varvell	Semileptonic FEI (B+, B0)	B→D(*) l nu	
	Semileptonic FEI (B+, B0)	B → X l nu (inclusive)	
	Semileptonic FEI (B+, B0)	cos theta BY fits in Data (ROC curves)	

If we are *very* lucky, all calibrations will agree… (but two early SL calibration efforts already don't)

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WARNING:

MY PERSONAL OPINION

(only vaguely scientific)

…until we have *official* usage guidelines from the task force…

Recommended procedure

1. (measure a ratio if you can)
2. Start with FEI skim
3. Build your tag list *first*
   a. Apply *standardized tag selections** [if you are using calibration, you ***must*** match its selections. If not, *it still may be a good idea.*]
   b. Apply best tag selection via $\mathscr{P}_{\text{tag}}$ [this does not *solve* tag/sig entanglement, but I believe that it **minimizes** it]
4. Build signal side and combine with tags
   a. Good tag definition must match calibration if using it [*probably*: isSignal!]
5. Always check for *differential* mismodeling in `decayModeIDs`…

*[*Request for task force*: provide FEI skims at multiple working points with **official** tag reconstruction, selection, and BTS]

Two complementary paths:

1. Improve/calibrate/validate/characterize FEI *as-built*
   a. **Understand mismodeling → *fix it***
   b. Develop usage guidelines, standardizations, and skims
   c. Quantify signal-side dependencies
   d. … (see brainstorming session)
2. Rethink, from the beginning, our fundamental assumptions and approach to tagging

A large amount of critical ongoing work.
See: the task force.

Me, screaming into the void. You could too!

Conclusion

The FEI is *awesome*…

…but it's not magic. You still have to *think*.