Hadronic B to charm decays at Belle II

12^{th} CKM workshop

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for the Belle II collaboration

20 September 2023

Outline

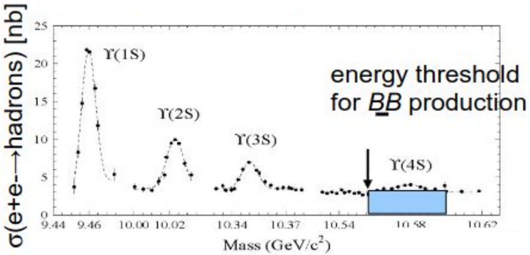
- The Belle II experiment
- Hadronic B-tagging built on B to charm decays
- $B \to D^{(*)}KK_S^0$ measurement
- $B \to D^{(*)}h$ BF puzzle
- SL gap

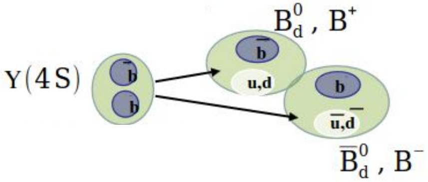
The Belle II detector

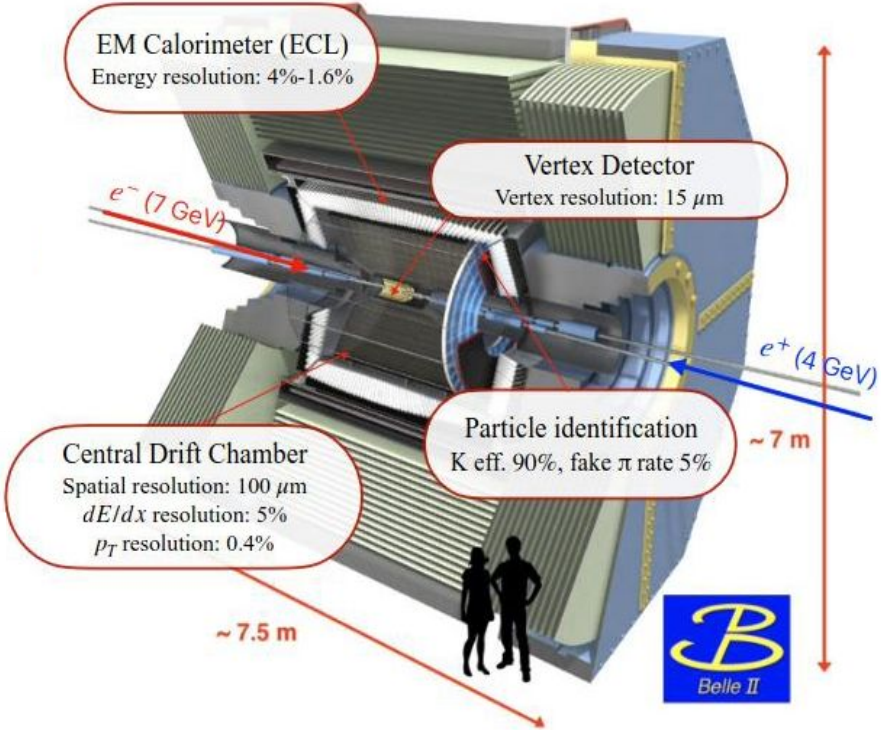
2 B’s and nothing else

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

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





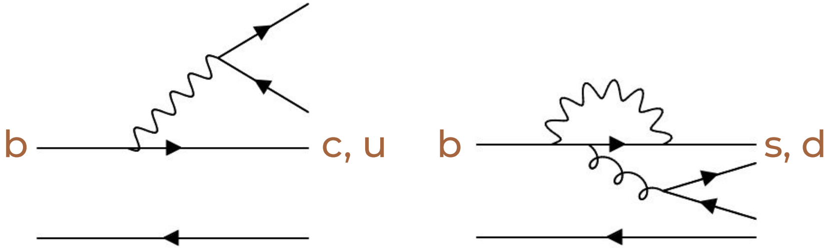


2 B’s and nothing else
⇒ B-tagging and flavour tagging

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

Hadronic B decays

can probe SM



b → c, u trees and b → s, d loops

Hadronic decays of B-mesons account for ~75% of the total branching fraction, dominated by the b → c trees.

Provides an opportunity to probe the SM:

- over-constrain CKM triangle
  - ϕ_1: via time-dependent analysis
  - ϕ_2: via isospin analysis of B → ππ, B → ρρ
  - ϕ_3: via B → Dh, B → D*K
- via isospin sum rules

See talks by
Yuma UEMATSU (Day 1: WG4)
Karim TRABELSI (Day 1: WG5) and
Mirco DORIGO (Day 2: WG5)

And plays another crucial role in B-factories...

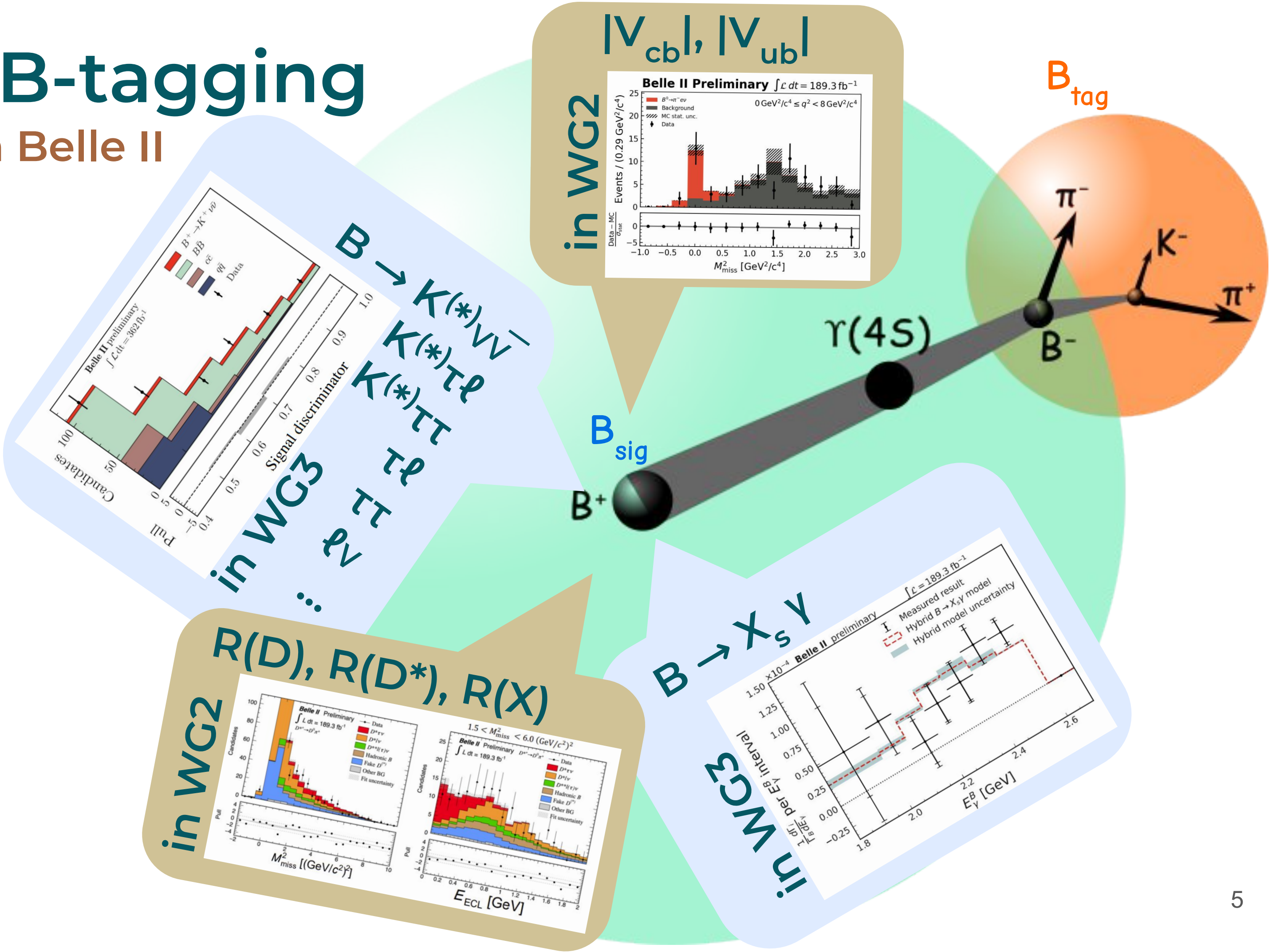
Hadronic B-tagging

is widely used in Belle II

It allows neutrino reconstruction at Belle II.

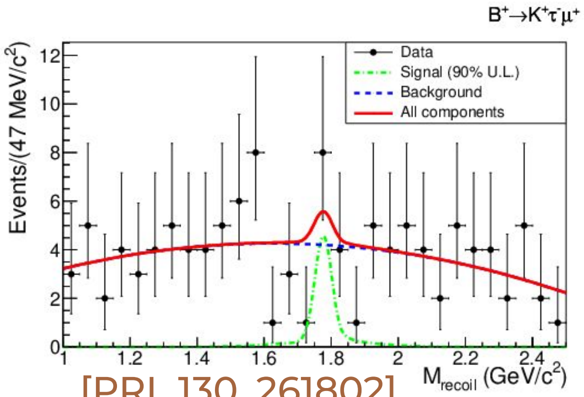
(equivalent to reconstructing inclusively)

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

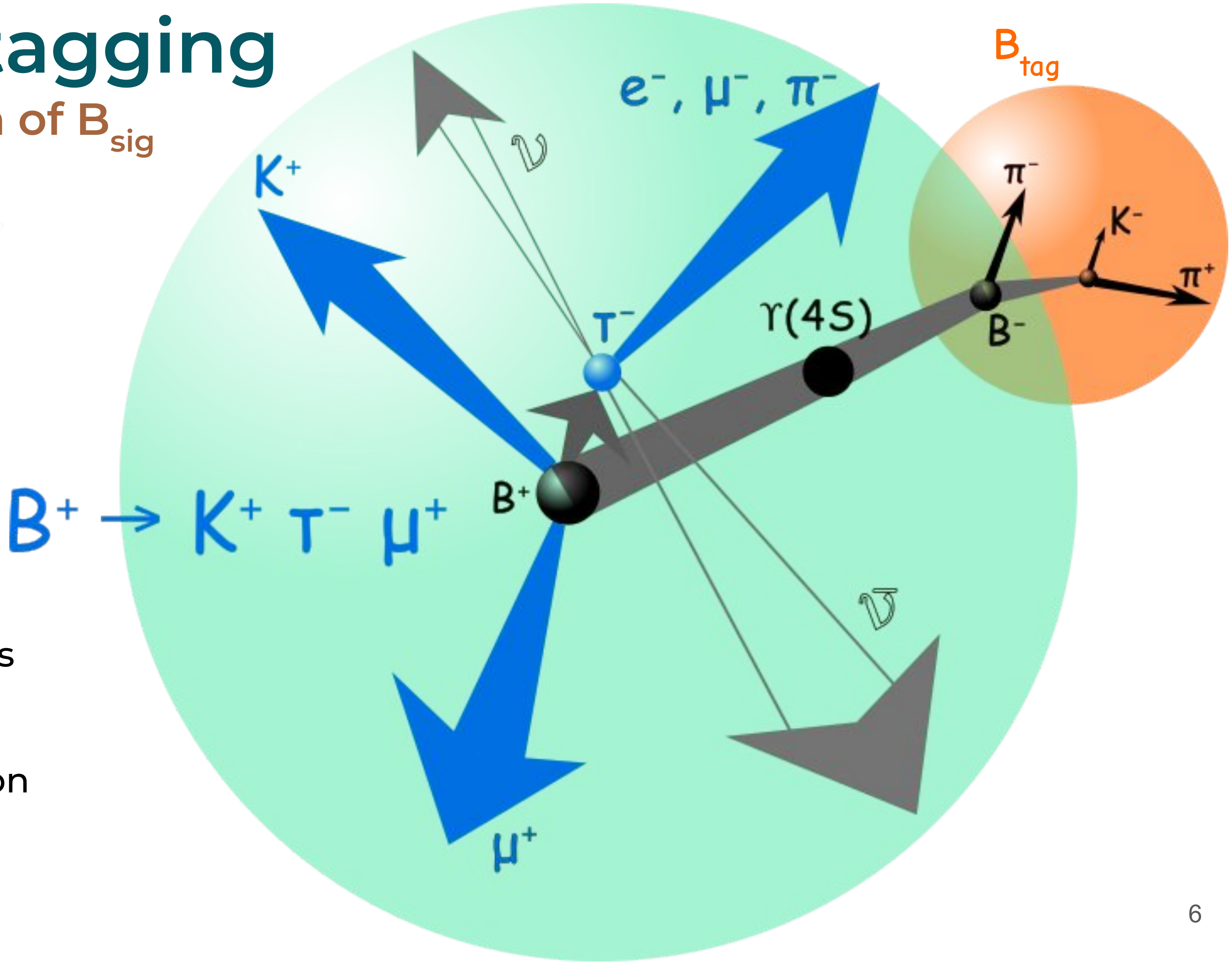


Hadronic B-tagging

can provide direction of B_{sig}



[PRL 130, 261802]

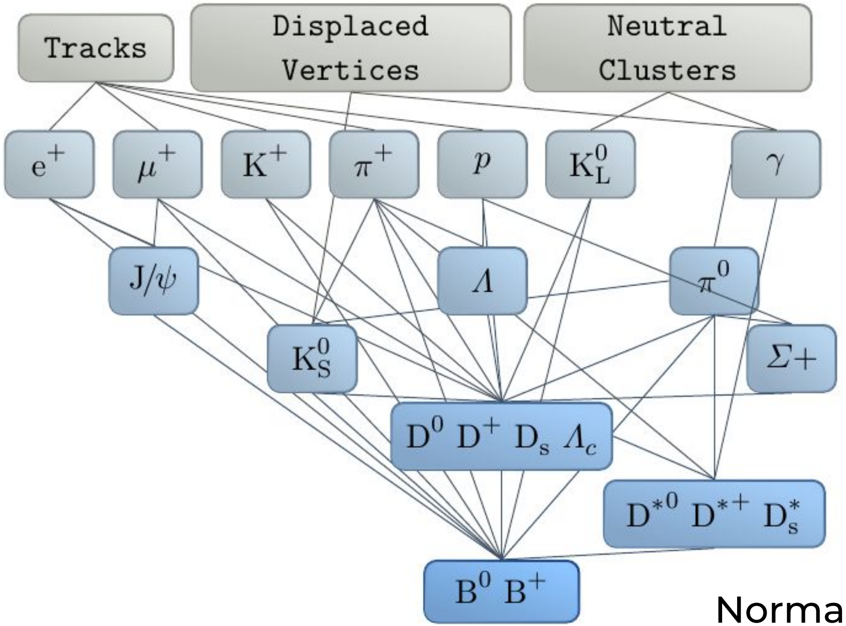


Along with filtering $B\bar{B}$ events with high purity, hadronic B-tagging can provide the direction of the signal B-meson (unique to e^-e^+ machines).

How does it work...?

Hadronic B-tagging tool at Belle II

Full Event Interpretation (FEI)



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

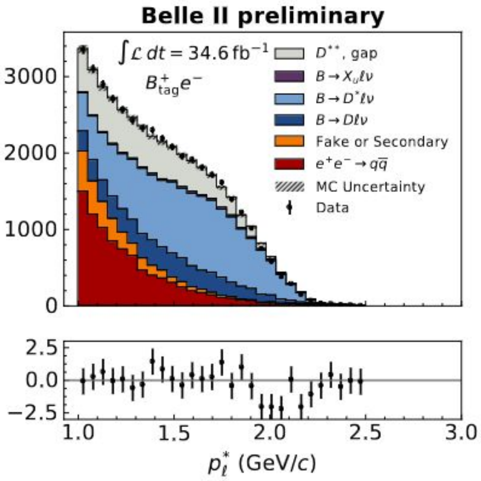
BDTs for each decay **trained on MC.**

Total efficiency < 1%.

But, large data-MC discrepancy

Calibration factors:
B^+: 0.65 ± 0.02
B^0: 0.83 ± 0.03

$B \to X\ell\nu$ sample [2008.06096]

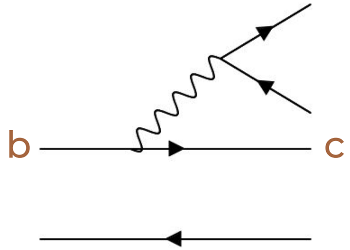


Normalization to account for it
⇒ large source of systematics
⇒ And also poor performance

But why the large discrepancy?

Hadronic B to charm decays

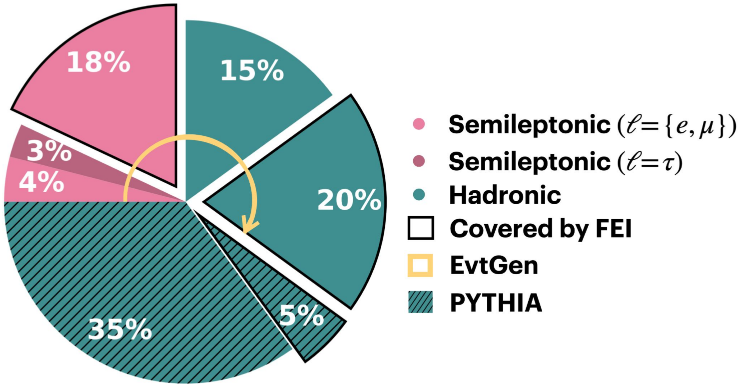
we don't know half of them!



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

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

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



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

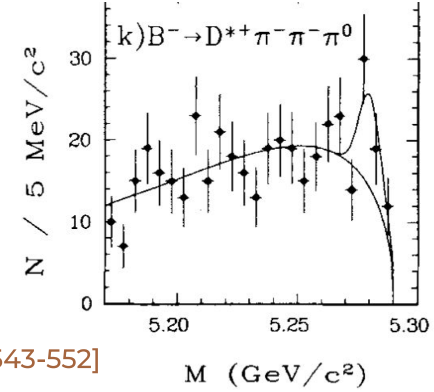
Is the MC really that bad?
room for improvements...

Modes in hadronic B-tagging

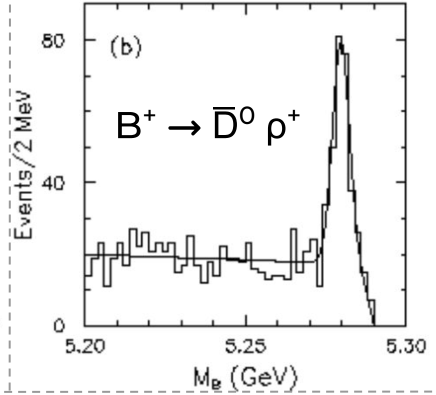
some of the largest $\mathcal{B}$ in PDG

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

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



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



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

[PRD 50 (1994) 43-68]

Not so great even with lower multiplicity

Old measurements with large uncertainties.
EvtGen only takes central value ⇒ MC contains unreliable information?

We need to remeasure with large statistics now.

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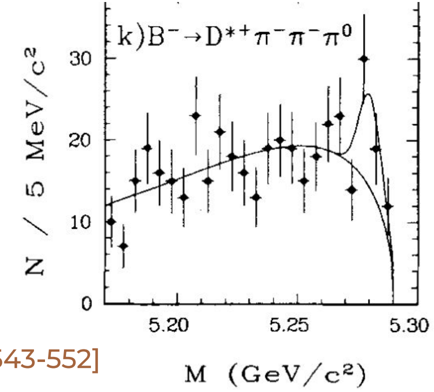

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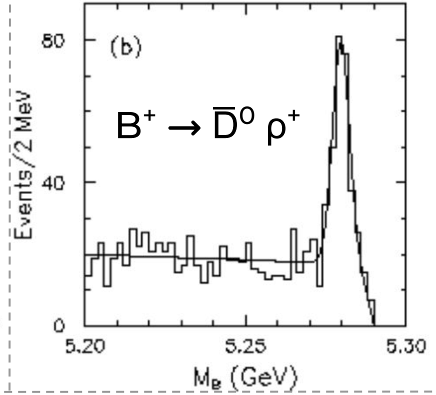

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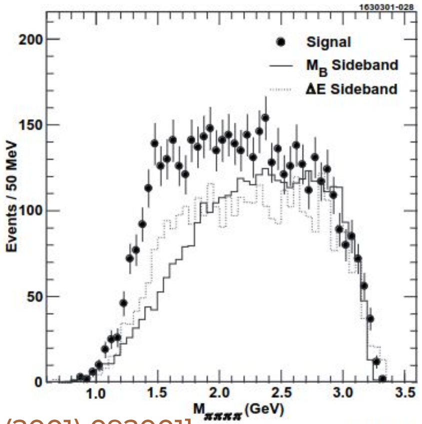
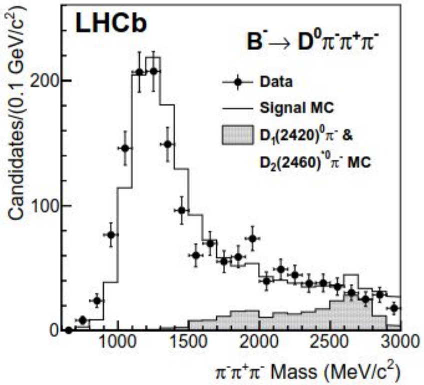
$B^+ \to \bar{D}^{*0} \pi^+\pi^+\pi^-\pi^0$

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

But model? ⇒ ρ'?



[PRD 64 (2001) 092001]



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

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

[PRD 84 (2011) 092001]

Modes in hadronic B-tagging

some of the largest $\mathcal{B}$ in PDG

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

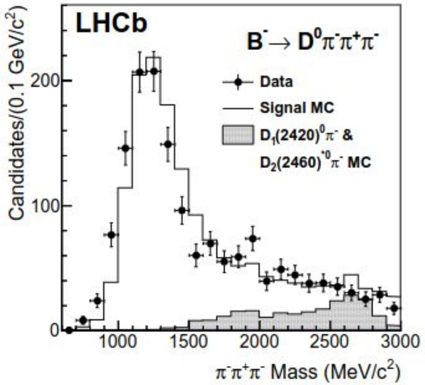
For decays with higher multiplicity, we need to know the decay model for MC.

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

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

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

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



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Modes in hadronic B-tagging

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

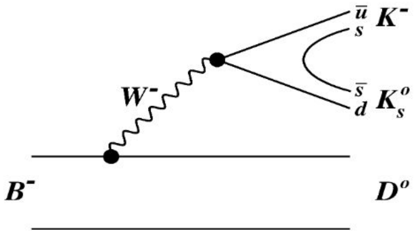
For decays with higher multiplicity, we need to know the decay model for MC.

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

Belle II is (re)measuring many modes with the intention of improving MC (understanding). → **Especially in the $B \to D^{(*)}\, m\pi^{\pm}\, n\pi^{0}$ sector usually $\mathcal{B} \sim 10^{-3}$**

An example of remeasurement shown today....
$\mathcal{B} \sim 10^{-4}$ but very pure ⇒ Addition to B-tagging?

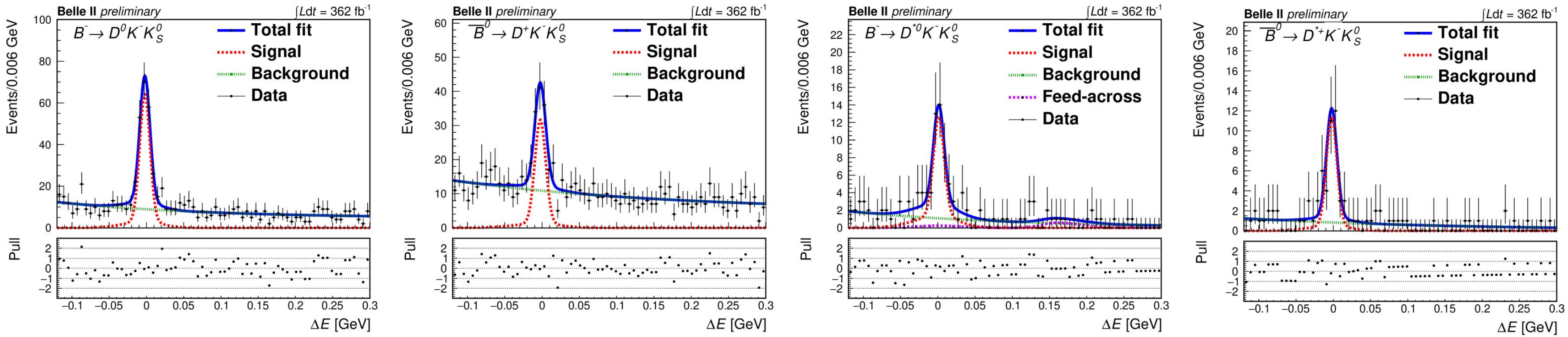
Observation of $B \to D^{(*)}K^{-}K_S^0$



362 fb^{-1}
[2305.01321]

$B \to D^{(*)}$ K K$^{(*)}$ sector is quite unexplored:
few % of the total BR, only 0.3% measured.

Last studied with 29.4 fb^{-1} by Belle. Now with 362 fb^{-1} by Belle II.



The high purity makes
it a good addition to
B-tagging too.

$$\mathcal{B}(B^- \to D^0 K^- K_S^0) = (1.89 \pm 0.16 \pm 0.10) \times 10^{-4},$$

$$\mathcal{B}(\bar{B}^0 \to D^+ K^- K_S^0) = (0.85 \pm 0.11 \pm 0.05) \times 10^{-4},$$

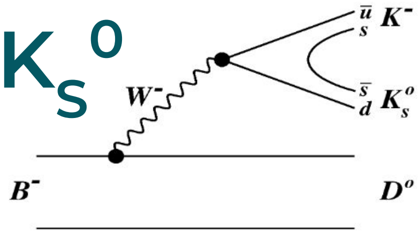
$$\mathcal{B}(B^- \to D^{*0} K^- K_S^0) = (1.57 \pm 0.27 \pm 0.12) \times 10^{-4},$$

$$\mathcal{B}(\bar{B}^0 \to D^{*+} K^- K_S^0) = (0.96 \pm 0.18 \pm 0.06) \times 10^{-4},$$

Use $B \to D^{(*)} D_s$ modes as control samples.

First observation for 3 modes!

Hadron physics in $B \to D^{(*)}K^-K_S^0$



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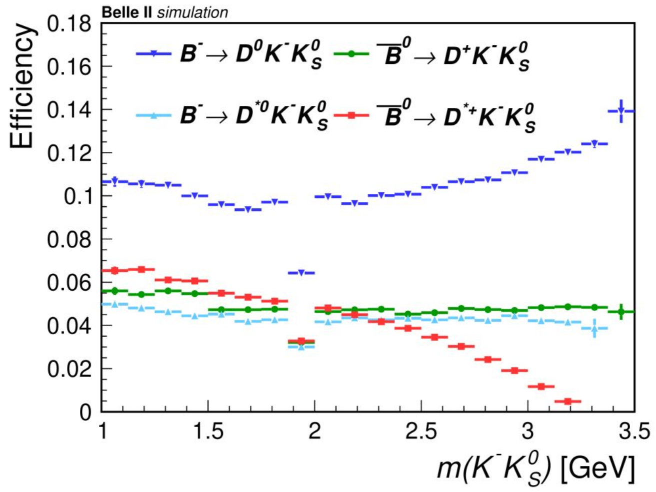
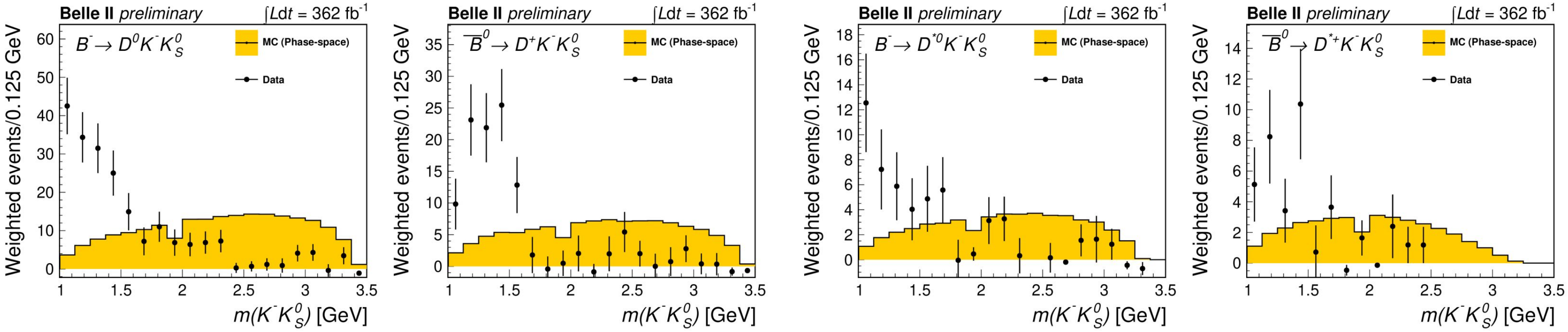


Can study the structures observed in $M(K^-K_S^0)$
Could be $\rho(1450)^-$ and $\rho(1700)^-$ resonances?
(see Ai-Jun Ma and Wen-Fei Wang: 2201.06881)



BF puzzle in B → $D^{(*)}$h decays

[S. Dubnička, et.al. : PRD 106 (2022) 3, 033006]

The theoretical predictions of $\mathcal{B}(B \to D^{(*)} h)$ from the CCQM does not agree with the measurements.

Seen in earlier predictions based on QCD factorization also.
[T. Huber, et.al. : JHEP 09 (2016) 112, M. Bordone, et.al. : EPJ C (2020) 80: 951, S. Iguro & T. Kitahara: PRD 102.071701 (2020)]

NP explanations are also being studied.
[Fang-Min Cai, et.al. : JHEP, 10:235, 2021]

	Process	Diagram	$\mathcal{B}_{\rm CCQM}/E$	$\mathcal{B}_{\rm PDG}/E$	E
1	$B^0 \to D^- + \pi^+$	D_1	5.34 ± 0.27	2.52 ± 0.13	10^{-3}
2	$B^0 \to \pi^- + D^+$	D_1	11.19 ± 0.56	7.4 ± 1.3	10^{-7}
3	$B^0 \to \pi^- + D_s^+$	D_1	3.48 ± 0.17	2.16 ± 0.26	10^{-5}
4	$B^+ \to \pi^0 + D_s^+$	D_1	1.88 ± 0.09	1.6 ± 0.5	10^{-5}
5	$B^0 \to D^- + \rho^+$	D_1	14.06 ± 0.70	7.6 ± 1.2	10^{-3}
6	$B^0 \to \pi^- + D_s^{*+}$	D_1	3.66 ± 0.18	2.1 ± 0.4	10^{-5}
7	$B^+ \to \pi^0 + D^{*+}$	D_1	0.804 ± 0.04	< 3.6	10^{-6}
8	$B^+ \to \pi^0 + D_s^{*+}$	D_1	0.197 ± 0.01	< 2.6	10^{-4}
9	$B^0 \to D^{*-} + \pi^+$	D_1	4.74 ± 0.24	2.74 ± 0.13	10^{-3}
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14	$B^+ \to \rho^0 + D_s^{*+}$	D_1	0.275 ± 0.01	< 4.0	10^{-4}
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21	$B^+ \to \overline{D}^{*0} + \pi^+$	D_3	7.60 ± 0.38	4.9 ± 0.17	10^{-3}
22	$B^+ \to \overline{D}^{*0} + \rho^+$	D_3	11.75 ± 0.59	9.8 ± 1.7	10^{-3}

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Seen in earlier predictions based on QCD factorization also.

NP explanations are also being studied.

Belle provided the most precise measurements for $B \to D\pi^+$.
[PRD 105 (2022) 1, 012003 and PRD 105 (2022) 7, 072007]

More to come in this sector.

Maybe complement with D-inclusive measurements also?

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Belle (II) can already contribute through the ongoing $B \to D \rho^+$ measurements (updating since CLEO).

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18	$B^0 \to \rho^0 + \overline{D}^{*0}$	D_2	1.50 ± 0.08	< 5.1	10^{-4}
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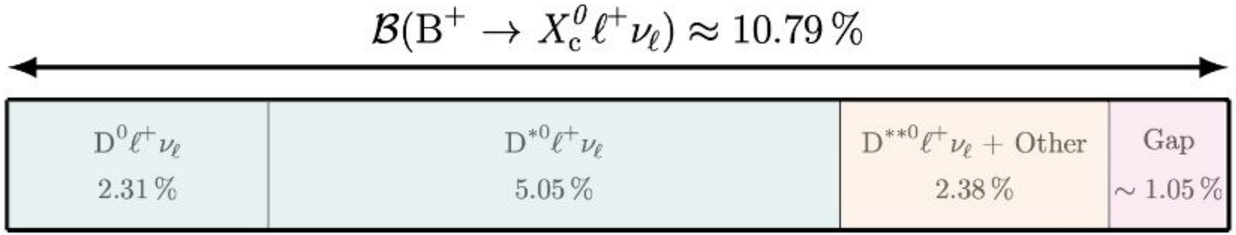
20	$B^+ \to \overline{D}^0 + \rho^+$	D_3	1.83 ± 0.09	1.34 ± 0.18	10^{-2}
21	$B^+ \to \overline{D}^{*0} + \pi^+$	D_3	7.60 ± 0.38	4.9 ± 0.17	10^{-3}
22	$B^+ \to \overline{D}^{*0} + \rho^+$	D_3	11.75 ± 0.59	9.8 ± 1.7	10^{-3}

SL gap

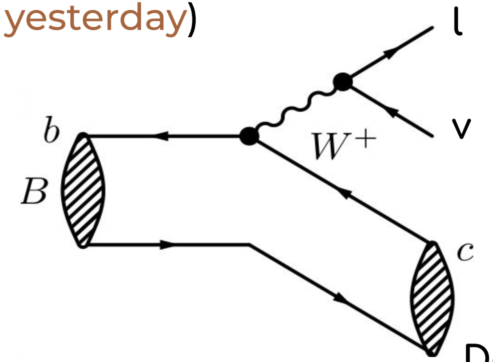
The SL gap impacts the $R(D^{(*)})$ measurement and the tension between inclusive and exclusive $|V_{cb}|$



Taken from [Raynette van Tonder]

The current workaround is to fill it with $B \to D^{(*)}\eta l \nu$,
either as a non-resonant state or through $(D^{(*)}\eta)$ from D** or D(2S) resonance.
[F. U. Bernlochner, Z. Ligeti, and S. Turczyk: PRD 85, 094033, 2012]
Maybe not through S-wave (see Florian Herren's talk yesterday)

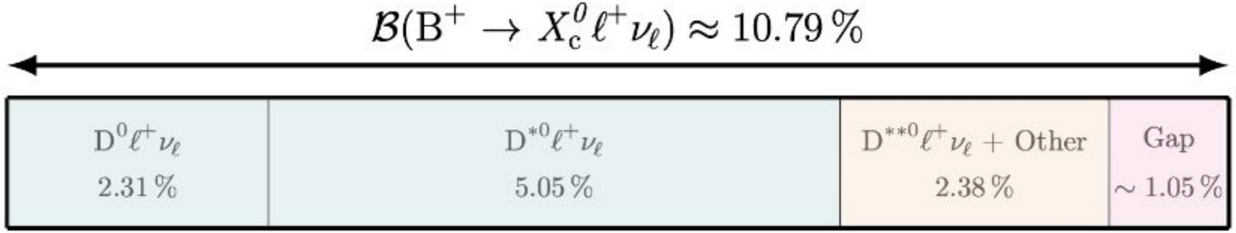
But SL decays are hard to measure.



$D^{(*)}\eta$ or
$D^{**} \to D^{(*)}\eta$ or
$D(2S) \to D^{(*)}\eta$

SL gap and search for $B \to D^{(*)}\eta\pi$

The SL gap impacts the $R(D^{(*)})$ measurement and the tension between inclusive and exclusive $|V_{cb}|$



Taken from [Raynette van Tonder]

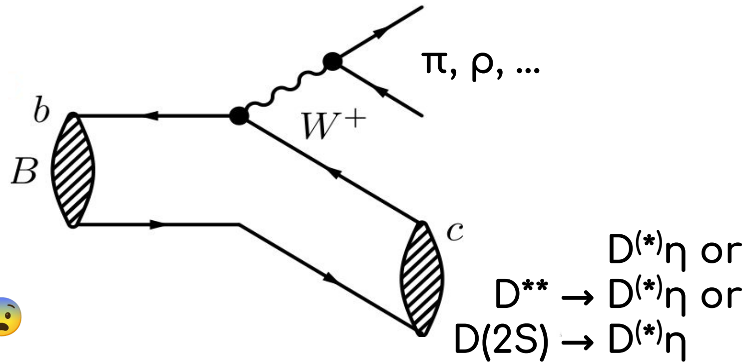
The current workaround is to fill it with $B \to D^{(*)}\eta l\nu$,
either as a non-resonant state or through $(D^{(*)}\eta)$ from D** or D(2S) resonance.

But SL decays are hard to measure.

Can be probed through (with sensitivity of 10^{-4})
the hadronic partner $B \to D^{(*)}\eta\pi$.

Unobserved so far ➪ Upcoming measurement.

This is generated by PYTHIA and used in B-tagging! 😨



Summary

- ➢ The Belle II experiment began contributing to exciting probes of the SM.
- ➢ Hadronic B-tagging built on B to charm decays plays a key role here.
  - ○ (Re)measurements are required to improve the MC (on which Hadronic B-tagging is trained on).
  - ○ Decay model should be studied, not necessarily complete amplitude with interferences, but simple intermediate resonances for MC.
- ➢ $B \to D^{(*)}KK_S^0$ measurement is a start of this, more to come.
- ➢ $B \to D^{(*)}h$ BF puzzle demands measurements from Belle II.
- ➢ SL gap can be probed through the hadronic partner $B \to D^{(*)}\eta\pi$?

Backup

Hadronic B to charm decays at LHCb

Can Belle II complement?

Some latest measurements from LHCb are helping build a better picture of the B → D decays.

Observation of the decays $B^0_{(s)} \to D_{s1}(2536)^{\mp} K^{\pm}$

LHCb Collaboration • Roel Aaij (Nikhef, Amsterdam) Show All(1107)

Aug 1, 2023

First observation of the $B^+ \to D_s^+ D_s^- K^+$ decay

R. Aaij *et al.* (LHCb Collaboration)

Phys. Rev. D **108**, 034012 – Published 14 August 2023

Amplitude analysis of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays

R. Aaij *et al.* (LHCb Collaboration)

Phys. Rev. D **108**, 012017 – Published 27 July 2023

Tetraquarks, pentaquarks, …hexaquarks?

Suggestions on how Belle II can complement (like measuring neutral partners) are welcome…

Hadronic B-tagging

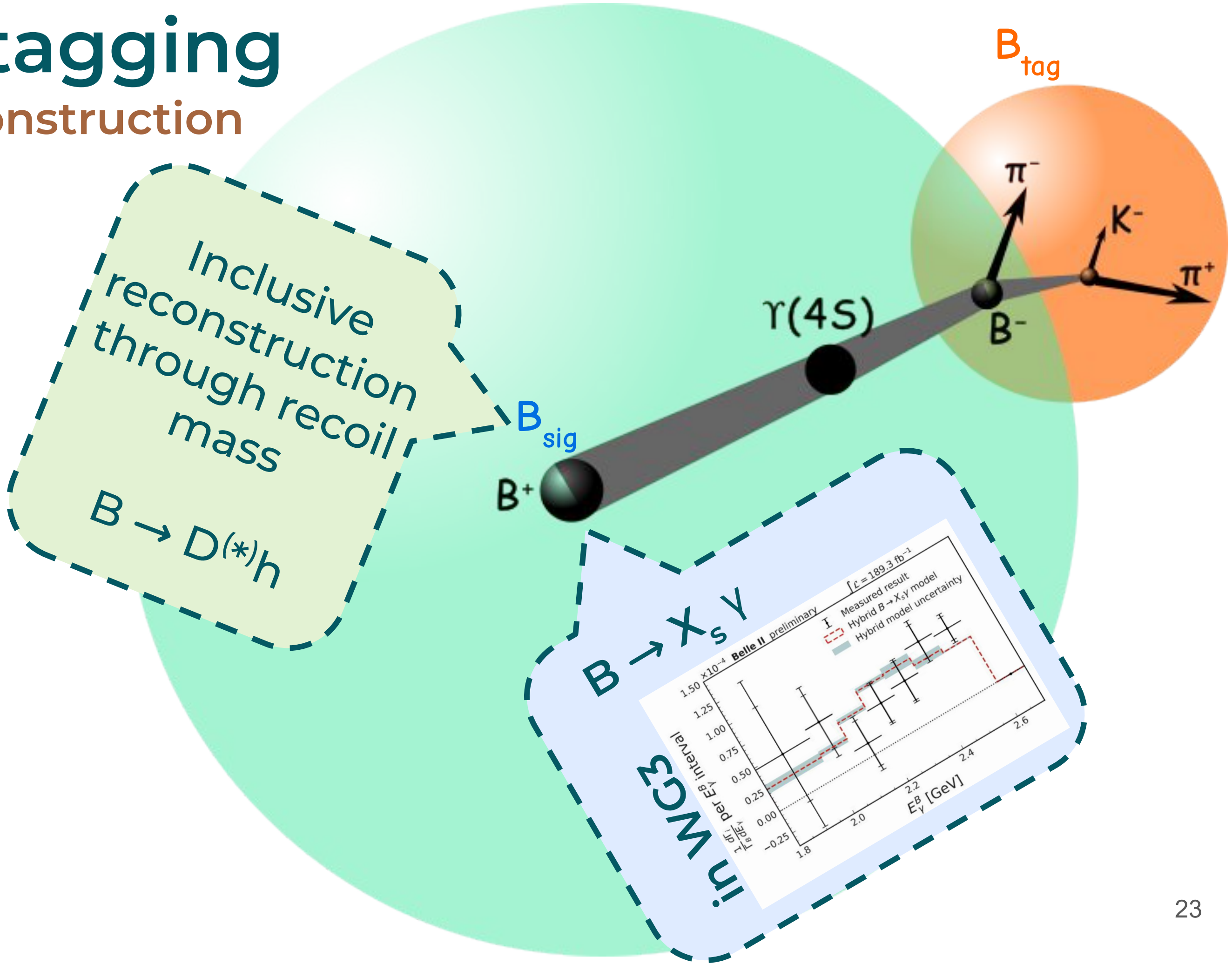
can do inclusive reconstruction

It allows to handle neutrinos at Belle II.

↓

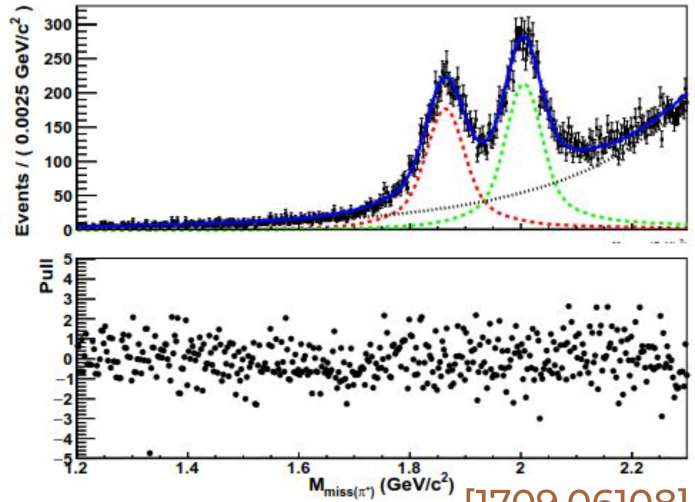
Equivalent to reconstructing inclusively

If only one particle is treated inclusively
⇒ peak in recoil mass!



B to charm decays in recoil mass

Recoil of $B_{tag} + \pi^{+} \Rightarrow D^{(*)}$



[1709.06108]

Inclusive D ⇒ No systematics from D decays.

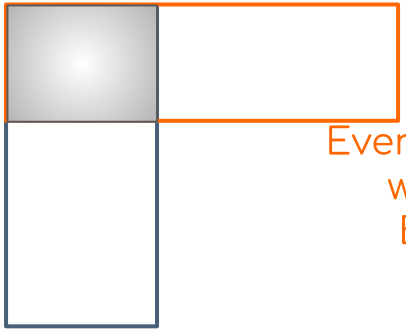
D and D* has same efficiency unlike exclusive.

Used to calibrate hadronic B-tagging in FEI now.

↓

with sPlot becomes the probe in tag-and-probe approach.

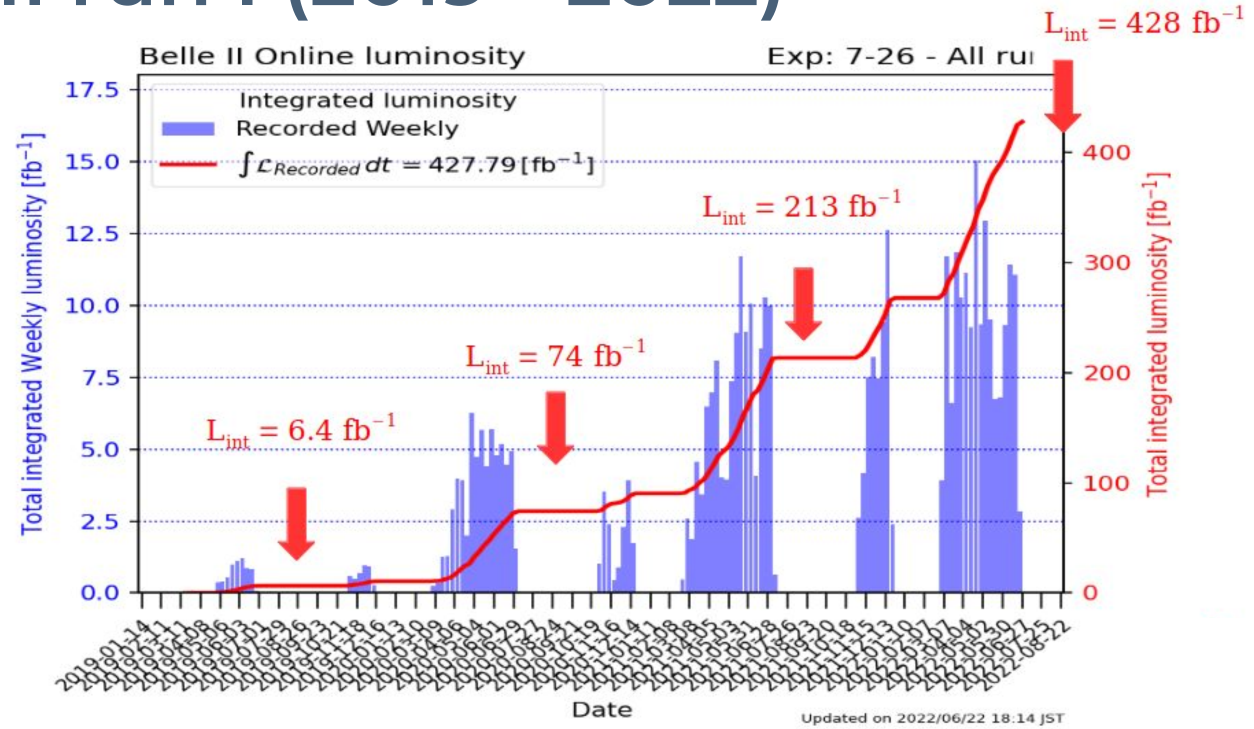
Can also study inclusive $B \to D^{**} \pi$
(BaBar, 210 fb^{-1}, [PRD 74 (2006) 111102])



Inclusive:
Events with $B \to D^{(*(*))} X$
where the other
$B \to$ Had B-tag

Exclusive:
Events with $B \to DX$
where $D \to K\pi$

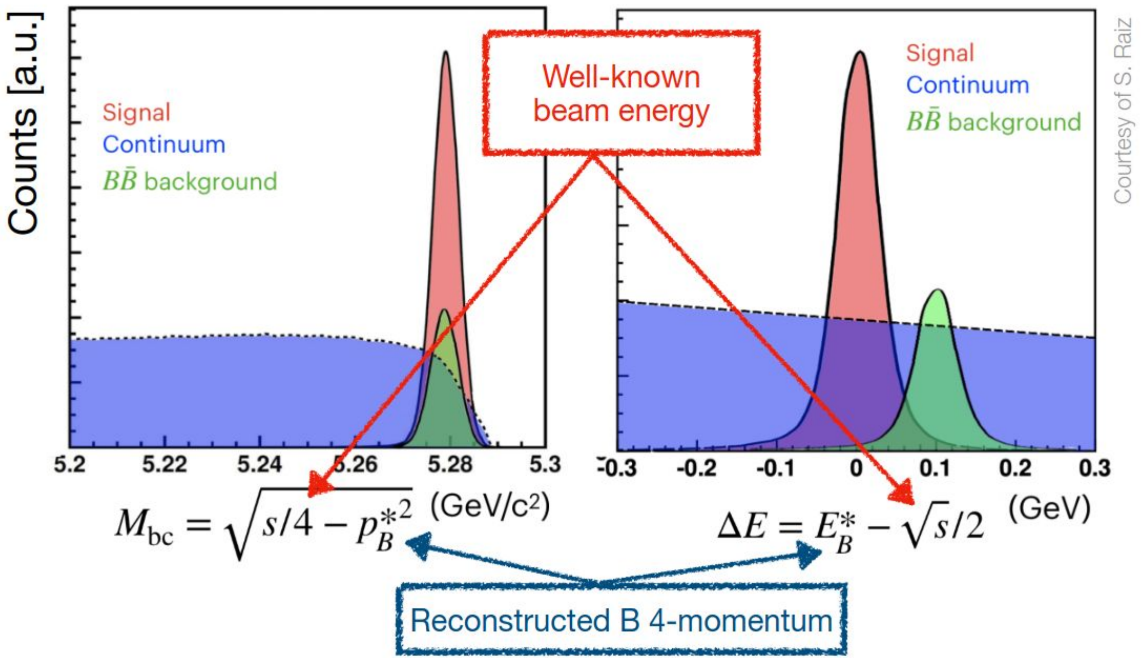
Belle II run I (2019 - 2022)

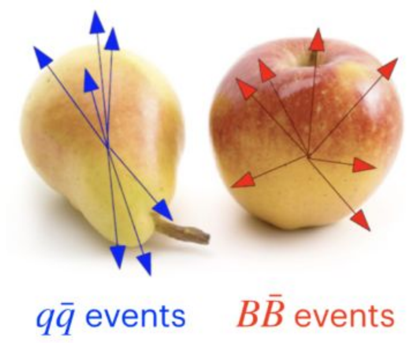


- 362 fb^{-1} on-resonance data collected so far (rest is off-resonance, and scan)
- Can be combined with Belle data sample (711 fb^{-1} on-resonance)
- Target: integrated luminosity of 50 ab^{-1}

Analysis workflow

Final state particles are combined to form B candidates and good candidates are selected (particle ID criteria, continuum suppression...). Then, yield is extracted from ΔE (preferably):





Control sample is used to validate and assess systematic uncertainties

Semi-Leptonic gap: Filled with η?

[Raynette van Tonder]

Model 1:
Equidistribution of all final state particles in phase space

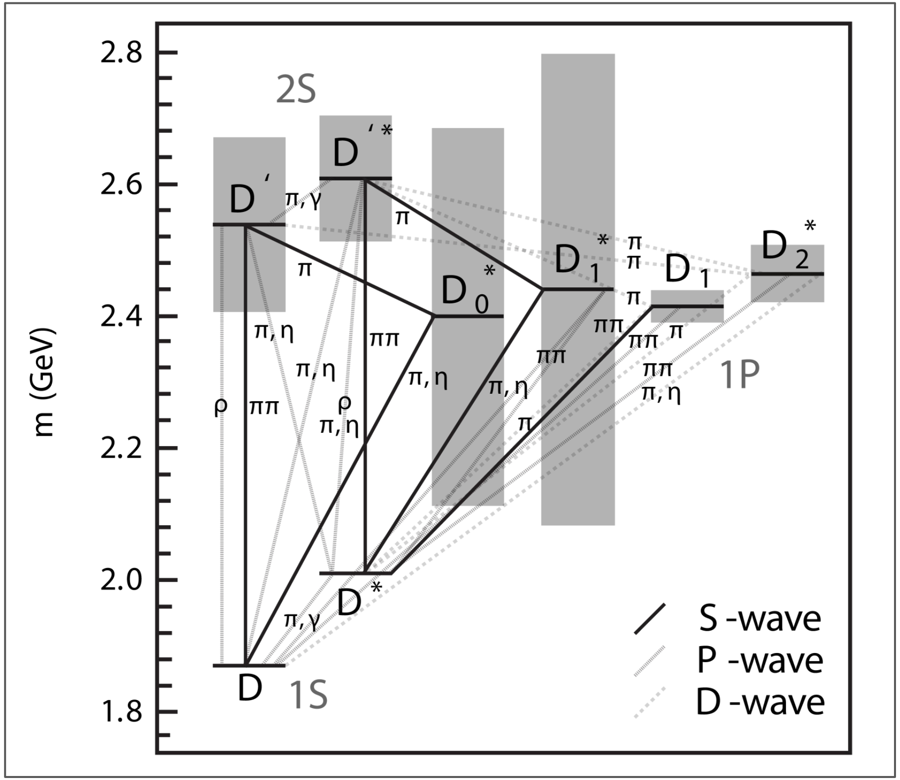
Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+\,\nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1) \times 10^{-3}$
$B \to D_2^*\,\ell^+\,\nu_\ell$	$(2.9 \pm 0.3) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$
$B \to D_0^*\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.8) \times 10^{-3}$	$(3.9 \pm 0.7) \times 10^{-3}$
$B \to D_1'\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$
$B \to D\pi\pi\,\ell^+\,\nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell^+\,\nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
$B \to D\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to D^*\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to X_c\ell\nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$

Model 2:
Decay via intermediate broad D^{**} state

Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D_0^*\,\ell^+\,\nu_\ell$ ($\hookrightarrow D\pi\pi$)	$(0.03 \pm 0.03) \times 10^{-2}$	$(0.03 \pm 0.03) \times 10^{-2}$
$B \to D_1^*\,\ell^+\,\nu_\ell$ ($\hookrightarrow D\pi\pi$)	$(0.03 \pm 0.03) \times 10^{-2}$	$(0.03 \pm 0.03) \times 10^{-2}$
$B \to D_0^*\pi\pi\,\ell^+\,\nu_\ell$ ($\hookrightarrow D^*\pi\pi$)	$(0.108 \pm 0.051) \times 10^{-2}$	$(0.101 \pm 0.048) \times 10^{-2}$
$B \to D_1^*\pi\pi\,\ell^+\,\nu_\ell$ ($\hookrightarrow D^*\pi\pi$)	$(0.108 \pm 0.051) \times 10^{-2}$	$(0.101 \pm 0.048) \times 10^{-2}$
$B \to D_0^*\,\ell^+\,\nu_\ell$ ($\hookrightarrow D\eta$)	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$
$B \to D_1^*\,\ell^+\,\nu_\ell$ ($\hookrightarrow D^*\eta$)	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$

The current workaround to explain the SL gap is to fill it with $D^{(*)}\eta l\nu$, either as a non-resonant state or through $(D^{(*)}\eta)$ resonance.
But never seen.

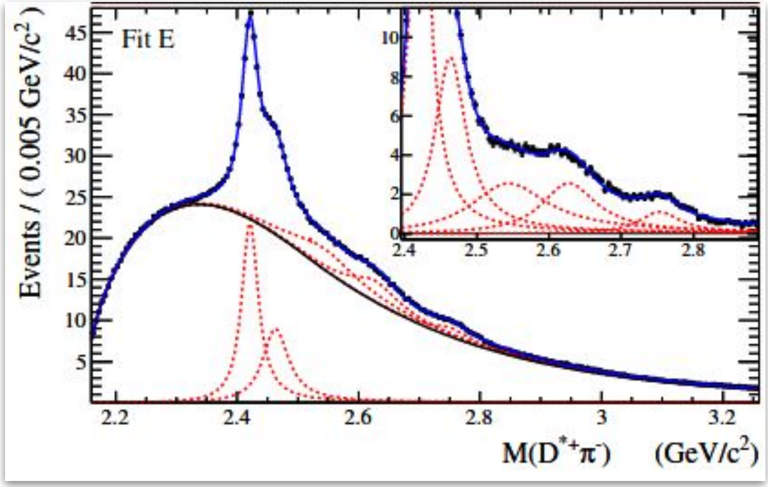
Source of η: D(2S)?



[arXiv:1202.1834]

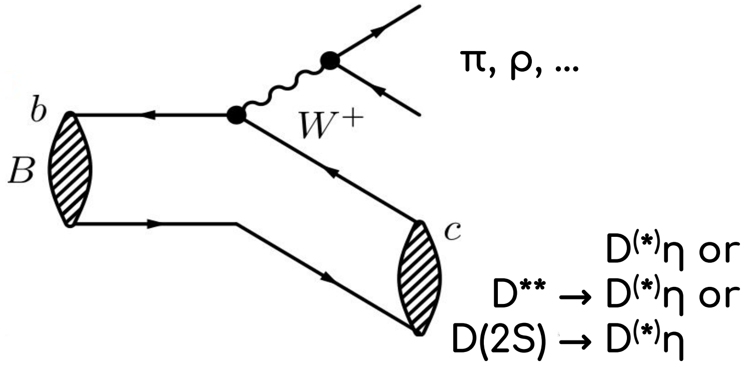
In 2010, BaBar observed even higher D resonances, consistent with L=2.

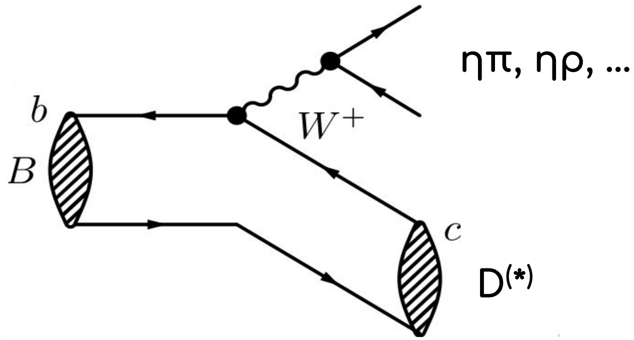
[1009.2076]



These D(2S) resonances have higher mass, and are potential candidates for sources of η filling the SL gap.

Hadronic $D^{(*)}\eta\pi$ vs $D^{(*)}\eta\rho$





In the alternative way of producing η through W, the ηπ contribution is suppressed.
G-parity violation ⇒ Second class current.
(also seen in τ decays)

But ηρ is still possible.

So, studying both $D^{(*)}\eta\pi$ vs $D^{(*)}\eta\rho$ simultaneously can also shed light on the source of η.