Flavour at Belle II

Carlos Mariñas and
Vidya Sagar Vobbilisetti
(IFIC/CSIC-UV)

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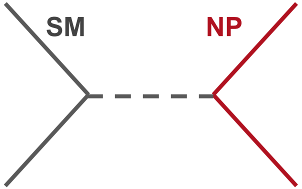
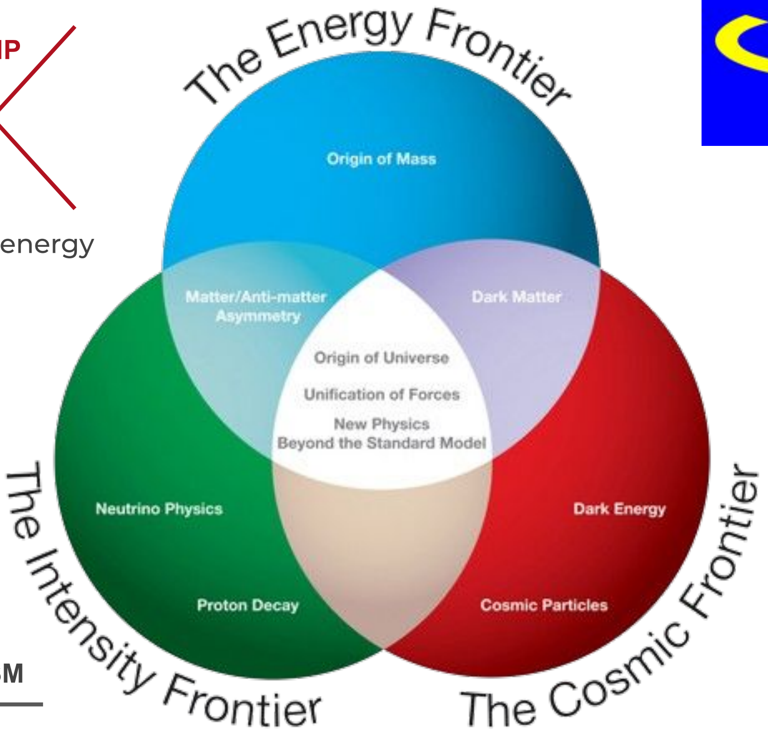
vidya.sagar.vobbilisetti@belle2.org

The intensity frontier



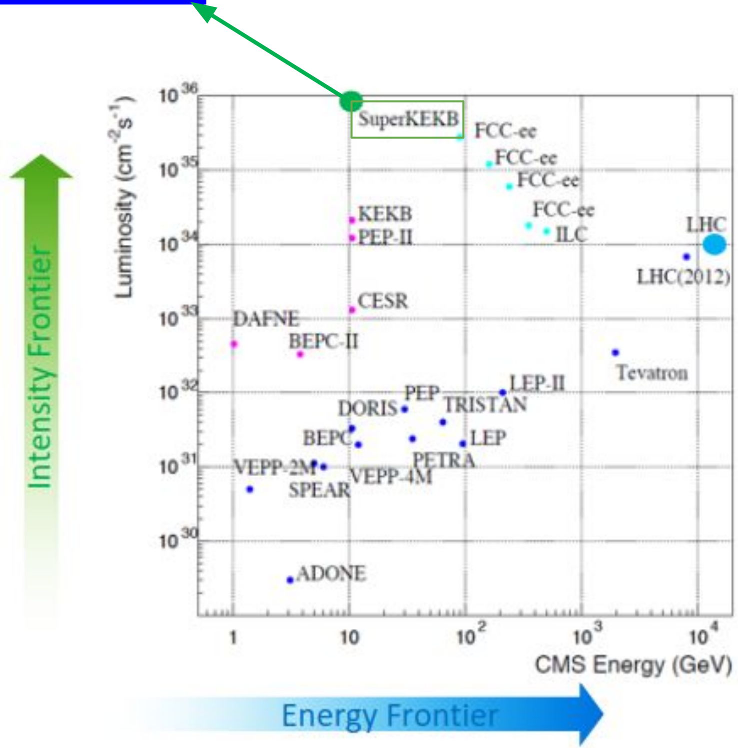
Limited by beam energy



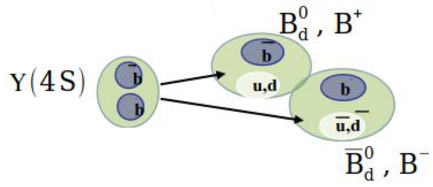
Limited by statistics

Search for rare new phenomena using medium-energy high-luminosity machines.

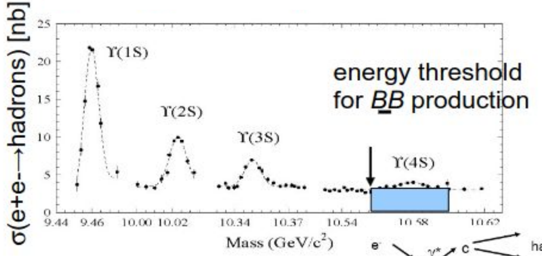
Belle II is at the forefront with the intention to study B physics.

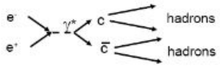


Why study B physics at $\Upsilon(4S)$?



The process $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ has comparable cross section to $e^+e^- \to q\overline{q}$, where q = u, d, s, c a.k.a. continuum





Provides complementarity wrt LHCb

Advantages compared to proton-proton

- Low average multiplicity – neutral reconstruction
- Constrained kinematics – good missing momentum reconstruction
- Correlated $B^0\overline{B}^0$ - high flavour-tagging efficiency
- Open trigger – 100% efficient for almost all B decays

Disadvantages compared to proton-proton

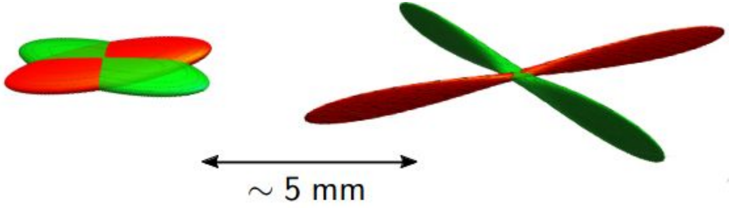
- Cross section – 150,000 times smaller
- No B_s, B_c, or Λ_b produced – can run at $\Upsilon(5S)$ for B_s
- No boost in the c.m. frame – partially overcome by the asymmetric beams

(Super) B factories

- The B factories, Belle with KEKB + BaBar with SLAC, collected 0.71 + 0.43 = 1.14 ab^{-1} $\Upsilon(4S)$ samples.
- Led to many achievements: confirmation of KM mechanism, $b \to c\tau\nu$, direct CPV in B decays
- To search for physics phenomena beyond SM in B, D and τ decays with even larger statistics, major upgrades were performed to Belle and KEKB.

SuperKEKB: Asymmetric e^+e^- collisions at (or close to) $\Upsilon(4S)$ resonance.

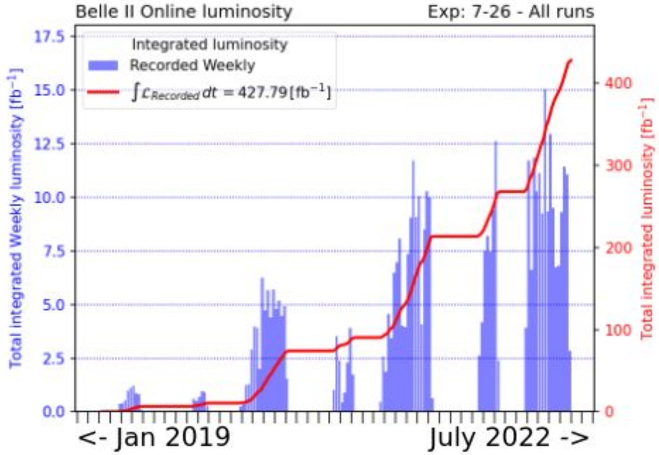
Higher instant luminosity achieved with increased currents and using so-called nano beam scheme:

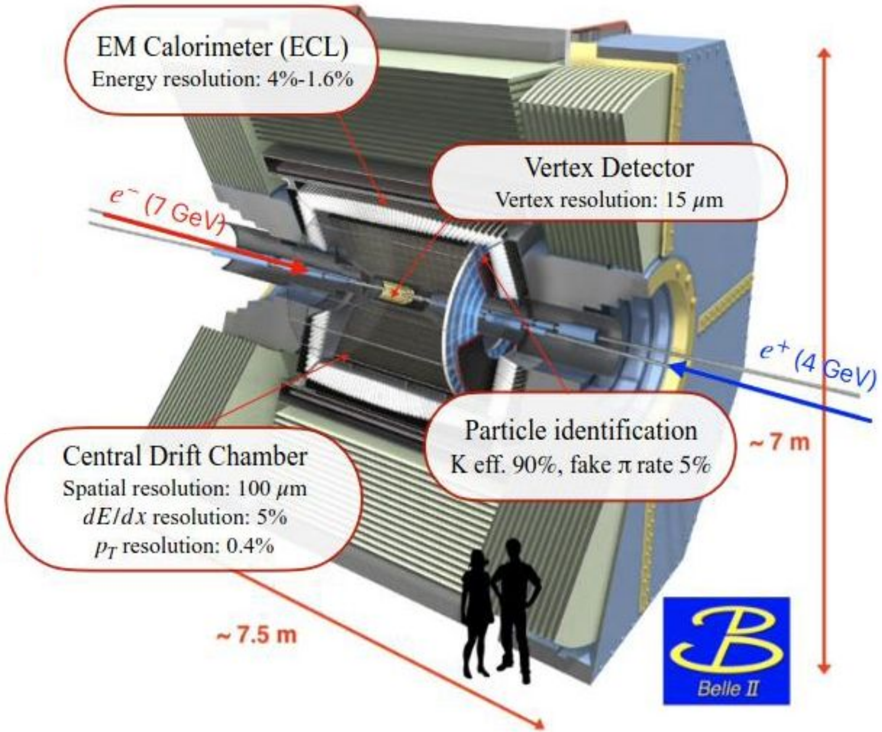


$\sigma_x \approx 9\ \mu m$, $\sigma_y \approx 50$ nm

SuperKEKB and Belle II

2 B's and nothing else





- ➢ World record peak luminosity: 4.7×10^{34} cm^{-2} s^{-1} (2x KEKB)
- ➢ 362 fb^{-1} on-resonance data collected so far
- ➢ Can be combined with Belle (711 fb^{-1})
- ➢ Target: 50 ab^{-1}
- ➢ ~1.1×10^9 $B\bar{B}$ pairs per ab^{-1}

- ➢ High-resolution and large-coverage detector
- ➢ Clean environment: 2 B's and nothing else in the event
  ⇒ B-tagging and flavour tagging

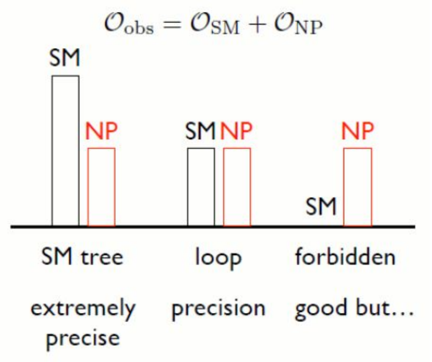
Physics at Belle II

On top of the rich B physics program, Belle II is also a (Super) charm factory:
~1.3×10^9 $c\bar{c}$ pairs per ab^{-1}
a (Super) τ factory:
~0.9×10^9 $\tau^+\tau^-$ 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.....

B flavour physics at Belle II

Along with the precision measurements of the CKM sector, many rare and forbidden processes:
– FCNC
– LFV, LFUV
– B → τ tree level
– new sources of CPV
 are being studied.



Here, B-tagging is a key tool for missing energy analyses.

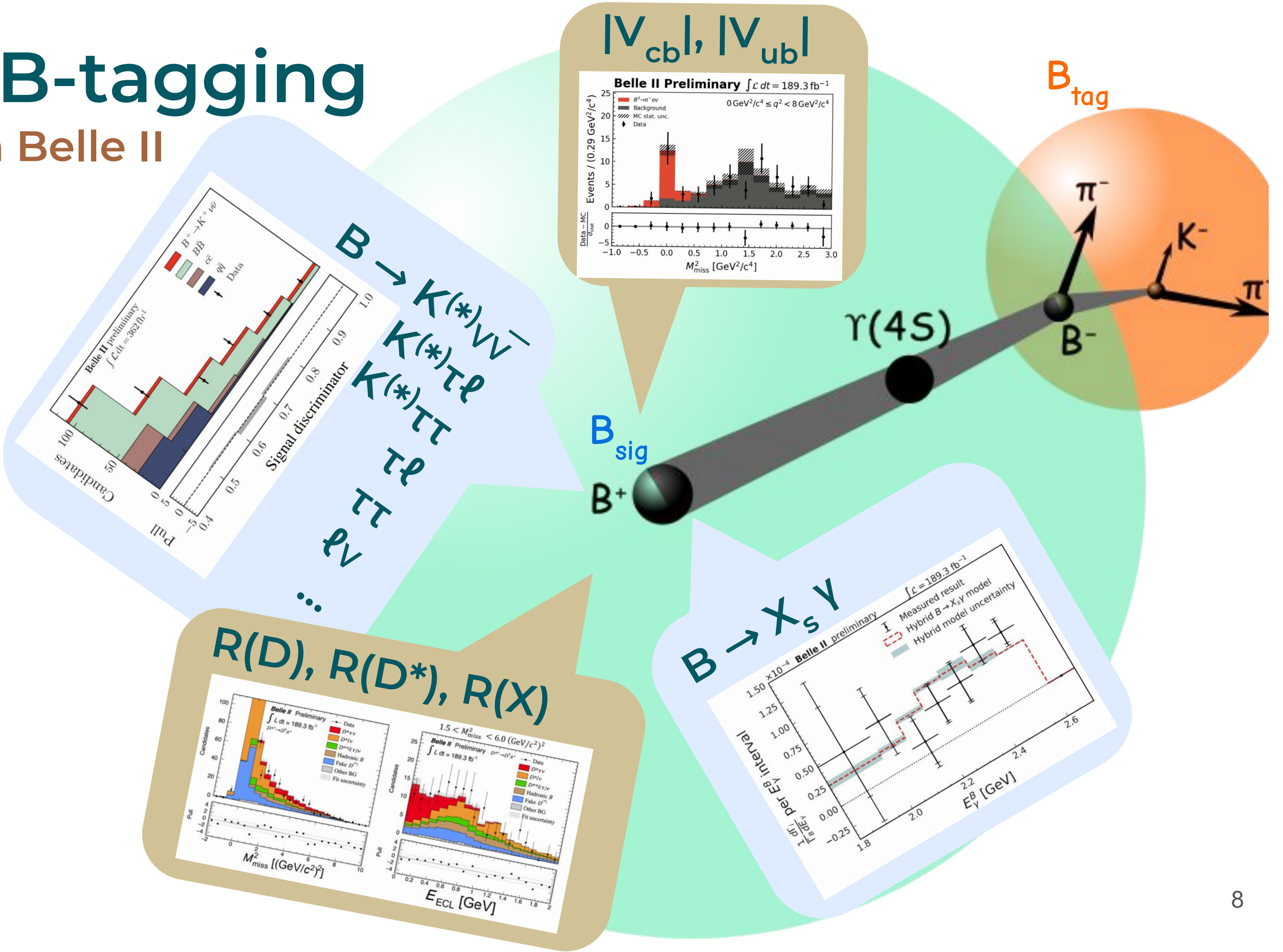
Hadronic B-tagging

is widely used in Belle II

It allows neutrino reconstruction at Belle II.

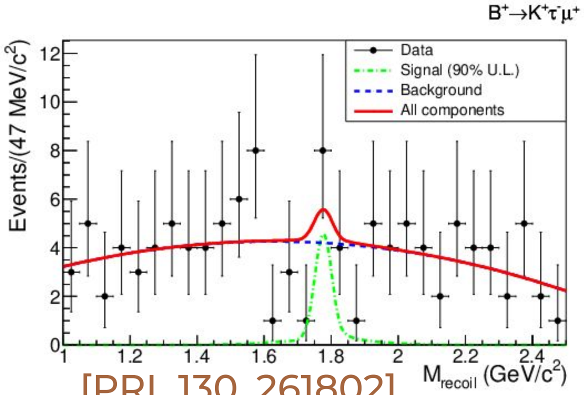
(equivalent to reconstructing inclusively)

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



Hadronic B-tagging

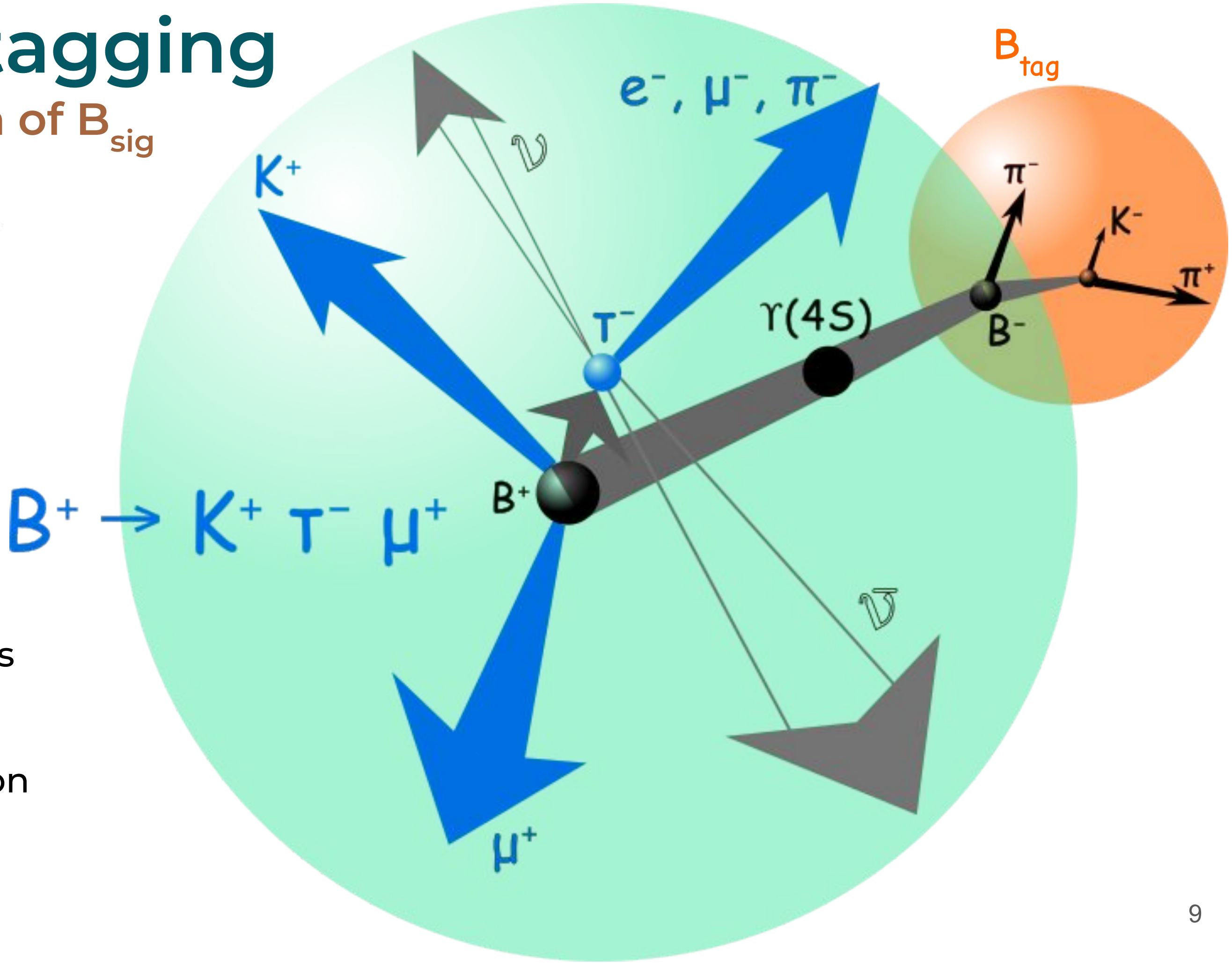
can provide direction of B_{sig}



[PRL 130, 261802]

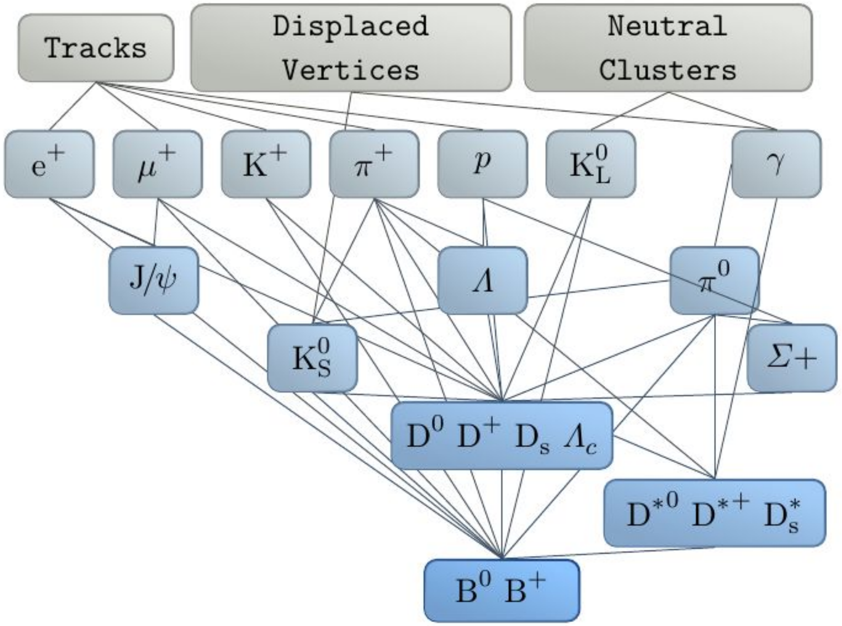
Along with filtering $B\bar{B}$ events with high purity, hadronic B-tagging can provide the direction of the signal B-meson (unique to e^-e^+ machines).

How does it work...?



Hadronic B-tagging tool at Belle II

Full Event Interpretation (FEI)



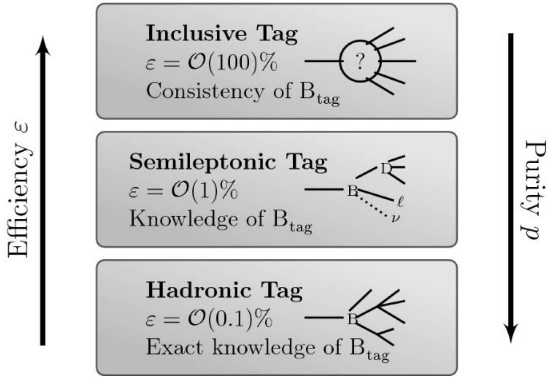
Designed for Belle II software, now used with Belle data also.

For each decay, BDTs trained on MC.

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

Total efficiency < 1%.

Using semi-leptonic decays or inclusively reconstructing can provide higher efficiency, but at the cost of purity.



Hadronic B-tagging tool at Belle II

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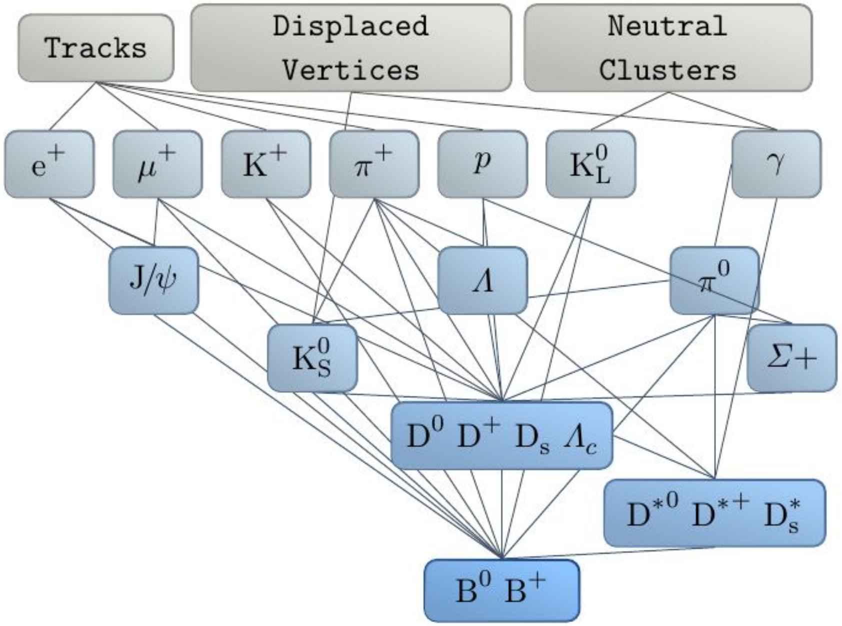

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For each decay, BDTs trained on MC.

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

Total efficiency < 1%.

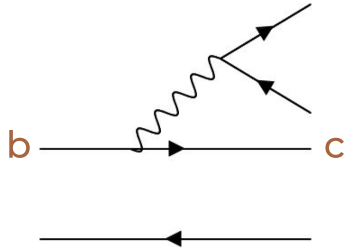
But, large data-MC discrepancy was observed (even larger in Belle II)

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

But why the large discrepancy?

Hadronic B to charm decays

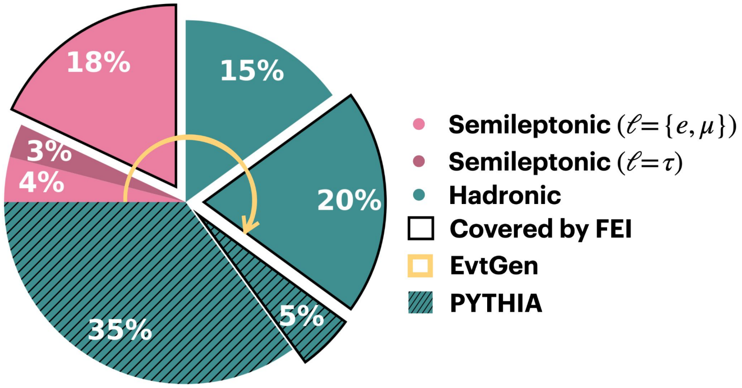
we don't know half of them!



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.

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

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



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

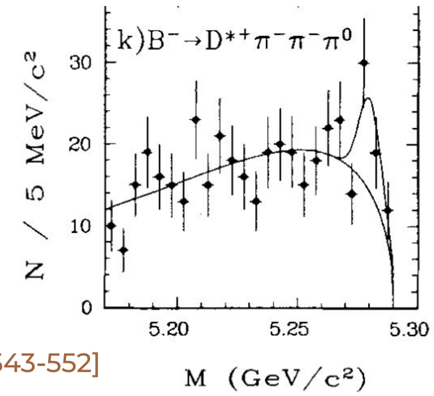
Is the MC really that bad?
room for improvements…

Modes in hadronic B-tagging

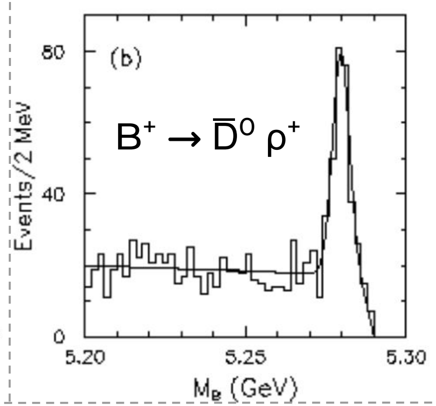
some of the largest $\mathcal{B}$ in PDG

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.

Modes in hadronic B-tagging

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

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

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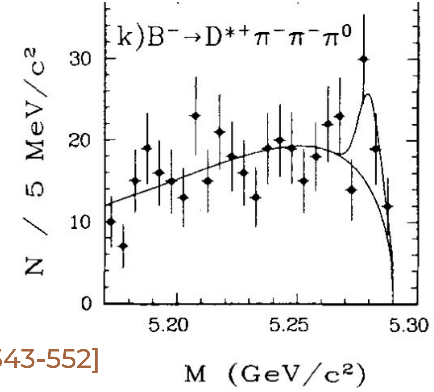

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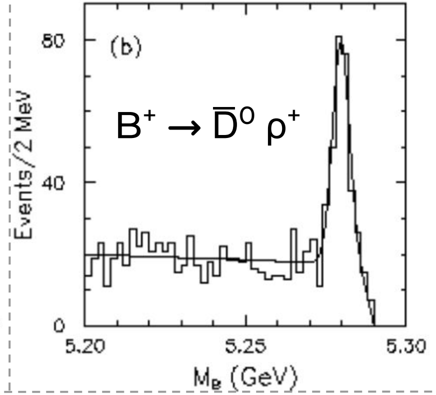


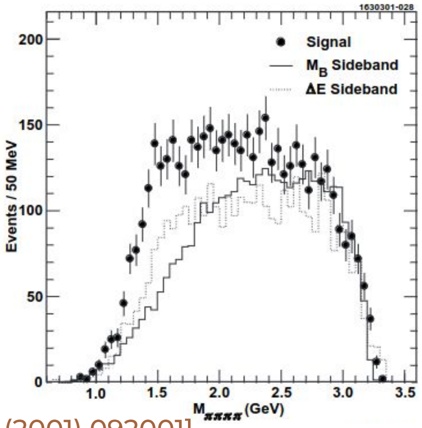
CLEO, 0.89 fb^{-1}
29 years ago
Uses M_{bc}
$\mathcal{B} = (1.34 \pm 0.18)\%$
13% uncertainty!

[PRD 50 (1994) 43-68]

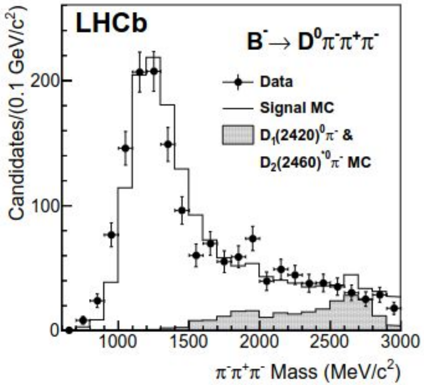
$B^+ \to \bar{D}^{*0} \pi^+\pi^+\pi^-\pi^0$

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]



[PRD 84 (2011) 092001]

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

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

Modes in hadronic B-tagging

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

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

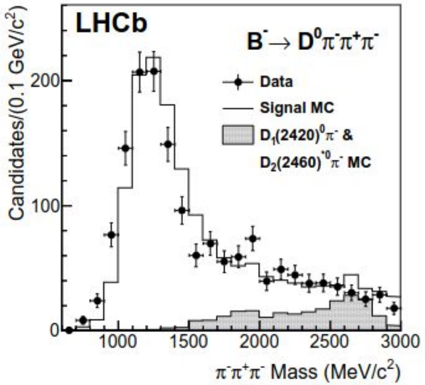
For decays with higher multiplicity, we need to know the decay model for MC.

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

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



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

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 $\mathcal{B} \sim 10^{-3}$

In the meantime, we updated the relevant decay description of our MC, and
noticed significant improvements in the agreement with data, as well as the purity.

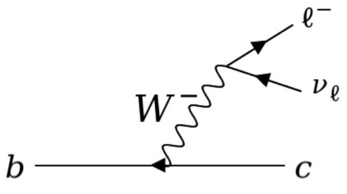
Going back to using hadronic B-tagging for searching missing energy modes...

Flavor in Standard Model

Lepton Flavor Universality (LFU): e, μ and τ have identical coupling strength.
Only difference comes from their masses.

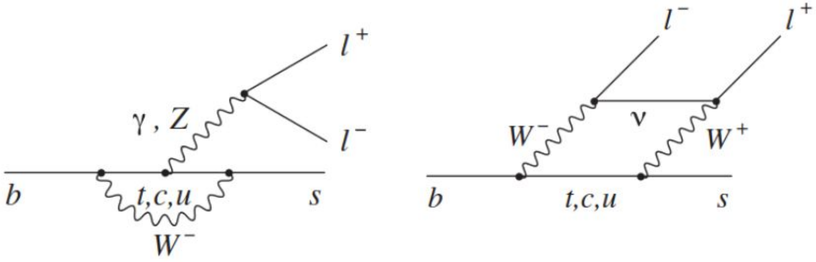
Can be tested in B decays:

SL decays



$$R_{D^{(*)}}^{\tau/\ell} = \frac{\Gamma\left(\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau\right)}{\Gamma\left(\bar{B} \to D^{(*)}\ell^- \bar{\nu}_\ell\right)} \qquad (\ell = e, \mu)$$

FCNC decays



$$R_H^{e/\mu} = \frac{\Gamma\left(B \to He^+e^-\right)}{\Gamma\left(B \to H\mu^+\mu^-\right)}\bigg|_{q^2 \in (q^2_{\rm min}, q^2_{\rm max})}$$

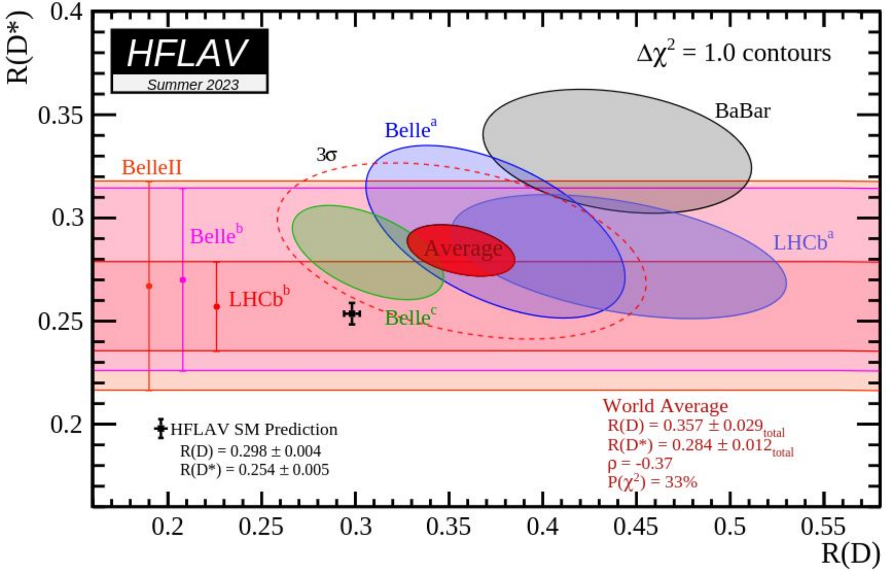
Deviation from SM ⇒ powerful probe for new physics living at higher energy scales.

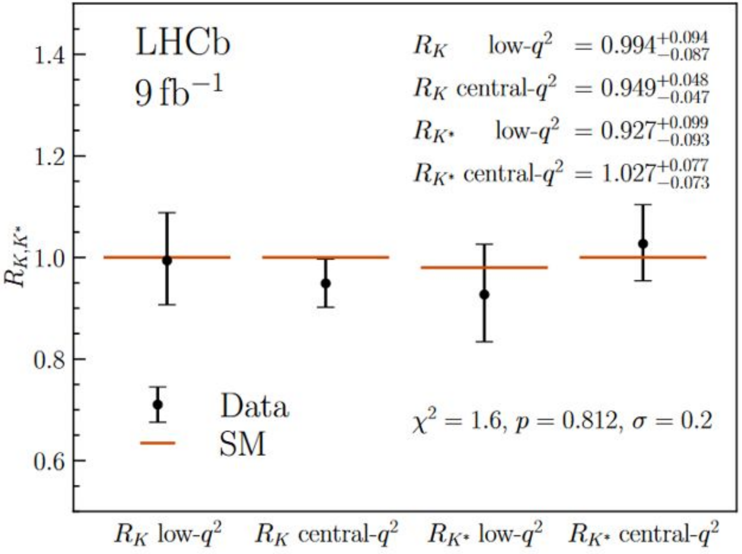
Experimental status of LFU tests

A precision era

$$R^{\tau/\ell}_{D^{(*)}} = \frac{\Gamma\left(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau\right)}{\Gamma\left(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell\right)} \qquad (\ell = e, \mu)$$

$$R^{e/\mu}_H = \frac{\Gamma\left(B \to He^+e^-\right)}{\Gamma\left(B \to H\mu^+\mu^-\right)}\Bigg|_{q^2\in(q^2_{\min},q^2_{\max})}$$



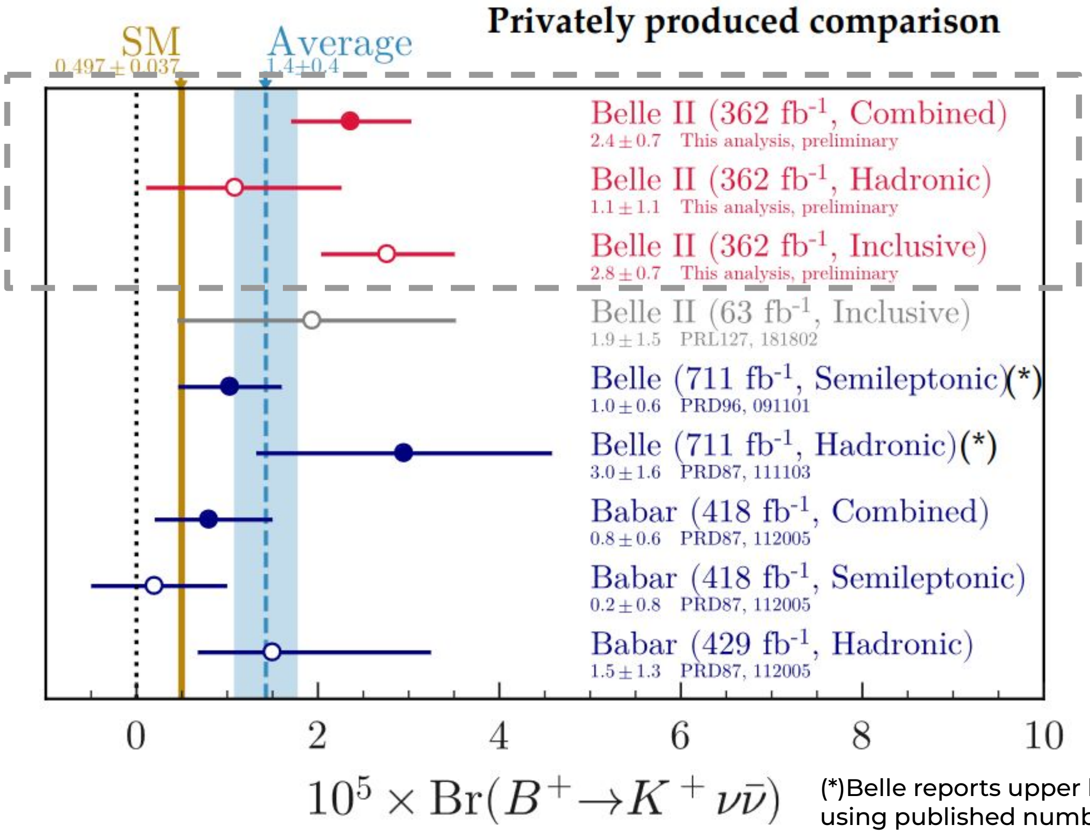


Combined deviation of 3.3σ from SM.
⇒ Larger coupling to τ

Now agrees with SM.
Also $B^+ \to K^+\nu\bar{\nu}$...

Evidence of $B^+ \to K^+\nu\bar{\nu}$

Saga of $b \to s$ transitions



Latest!
Shown at EPS-HEP 2023.

Combining results from hadronic and inclusive-tag methods, a 2.8σ excess is observed wrt SM!

What does it all mean for $B^+ \to K^+\tau\tau$ decays?

(*)Belle reports upper limits only; branching fractions are estimated using published number of events and efficiency

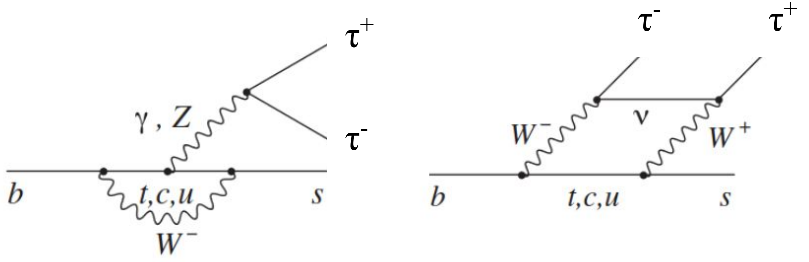
Probe through B → Kττ

Enhancement in b → sττ?

$R_{D(*)}$ ⇒ Larger coupling to τ?

- ★ Third generation
- ★ Heavier mass

Should also be seen in FCNC b → sττ transitions?



NP prediction for B → Kττ

Enhancement upto 1000x!

$R_{D^{(*)}}$ ⇒ Larger coupling to τ?

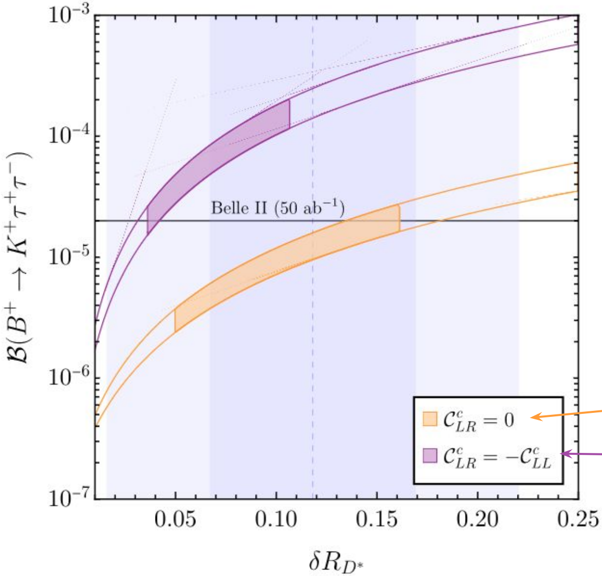
★ Third generation

★ Heavier mass

SM prediction $\mathcal{B} : \mathcal{O}(10^{-7})$

NP prediction $\mathcal{B} : \mathcal{O}(10^{-4})$

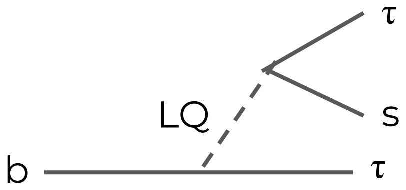
1000x!



Purely left-handed U_1 LQ

Equally left-handed and right-handed U_1 LQ

Should also be seen in FCNC b → sττ transitions?



NP particles can be present in the loops, enhancing the amplitude significantly.

For example, the U_1 leptoquark (LQ) model can explain both the low-energy constraints and the direct searches at the LHC.

J. Aebischer, G. Isidori, M. Pesut, B. A. Stefanek and F.Wilsch
EPJ C 83 (2023) 2, 153

Experimental status of B → Kττ

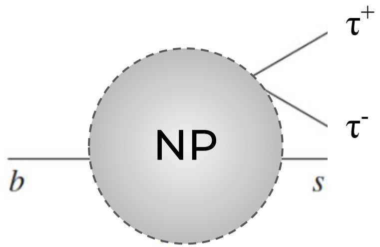
We are not there yet

$R_{D(*)}$ ⇒ Larger coupling to τ?
★ Third generation
★ Heavier mass

SM prediction $\mathcal{B}$: $\mathcal{O}(10^{-7})$
NP prediction $\mathcal{B}$: $\mathcal{O}(10^{-4})$
Exp. $\mathcal{B}$ UL : $\mathcal{O}(10^{-3})$

1000x!
10x!

Should also be seen in FCNC b → sττ transitions?



τ leptons have short lifetime producing neutrinos
⇒ Can't be fully reconstructed

Using Hadronic B-tagging techniques at e^+e^--collision experiments:

$$\mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 2.2 \times 10^{-3}$$

	e^+e^-	$\mu^+\mu^-$	$e^+\mu^-$
$N^i_{\rm bkg}$	49.4±2.4±2.9	45.8±2.4 ±3.2	59.2±2.8 ±3.5
$\epsilon^i_{\rm sig}(\times 10^{-5})$	1.1 ±0.2±0.1	1.3±0.2±0.1	2.1±0.2±0.2
$N^i_{\rm obs}$	45	39	92
Significance (σ)	−0.6	−0.9	3.7

BaBar (469 fb^{-1}, 2017) : PRL 118 3, 031802

τ → e, μ considered.
3.7σ excess is reported in the $e^{\pm}\mu^{\mp}$ channel.

Can Belle & Belle II do better?

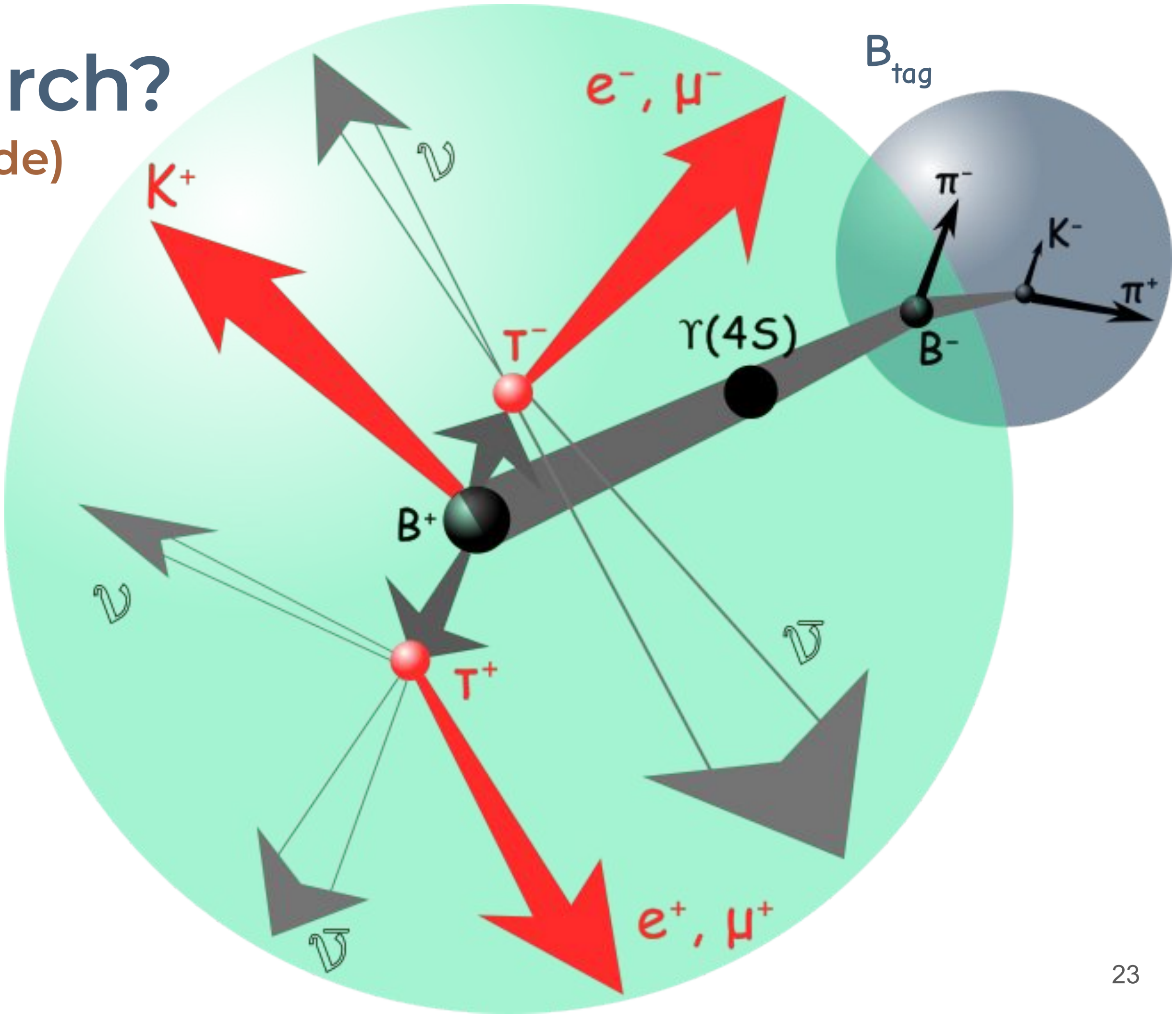
How do we search?

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.

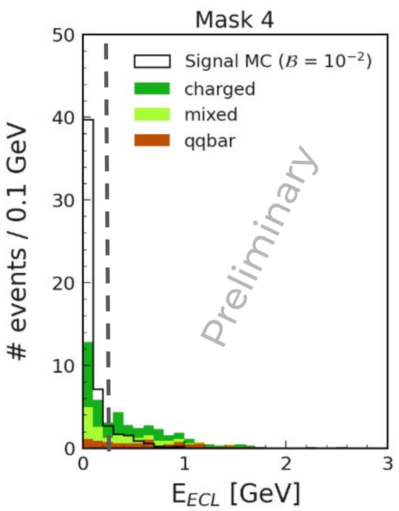
If the B_{tag} is reconstructed using hadronic decays :
Hadronic B-tagging



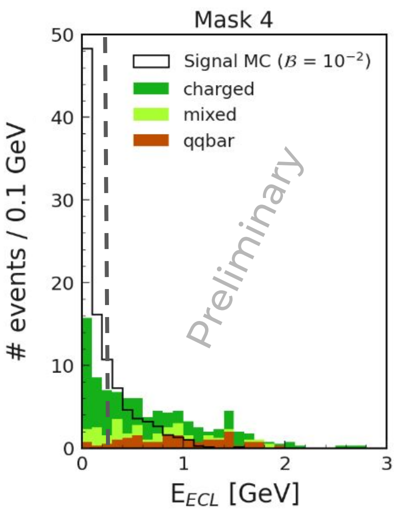
UL extraction with Belle + Belle II

That’s 1.1 ab^{-1}

Belle



Belle II



Normalized to 100 fb^{-1}

Signal region: 0 - 0.25 GeV

In collaboration with Trieste.

After B-tagging calibration:

	$K^+e^+e^-$	$K^+\mu^+\mu^-$	$K^+e^\pm\mu^\mp$
Signal efficiency (10^{-5})	1.6 ± 0.3	1.1 ± 0.2	2.8 ± 0.3
Background yields	82.2 ± 9.1	64.7 ± 8.0	153.2 ± 12.4

N^{UL} calculated using Rolke method

[W. A. Rolke, A. M. López, J. Conrad
Nucl. Instrum. Meth. A 551 (2005) 493–503]

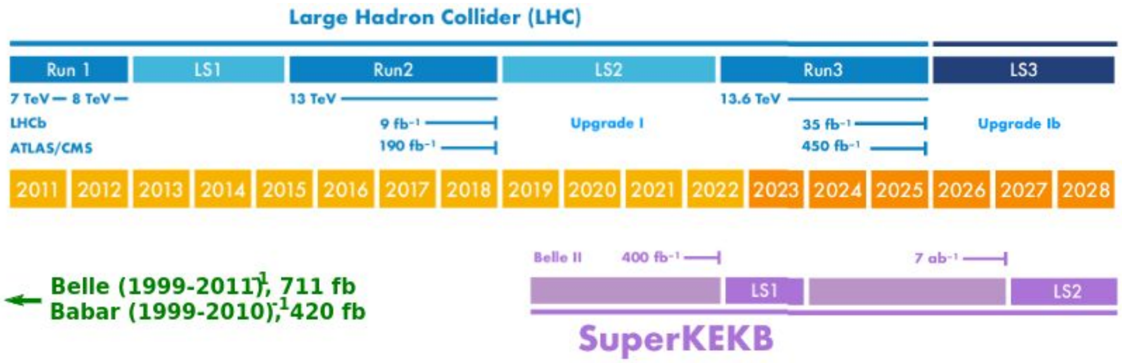
$$\mathcal{B}\left(B^+ \to K^+\tau^+\tau^-\right) < \frac{N^{UL}}{\epsilon_s \cdot 2 \cdot f^\pm \cdot N(B\bar{B})}$$

$\mathcal{B}(B^+ \to K^+\tau\tau) < 6 \times 10^{-4}$ at 90% CL

Huge improvement compared to the previous, 2×10^{-3}!
Entering the realm of New Physics...

Summary and future

- ➢ Belle (II) is a unique environment to study modes with missing energy
  $B \to K\nu\nu$, $K\tau\tau$, $K\tau l$, $\tau\tau$, τl , $D^{(*)}\tau\nu$, $\tau\nu$, $\mu\nu$ ..... and many other opportunities.
- ➢ Important contrast and cross-check to LHCb studies.
- ➢ B-tagging plays an essential role, improvements require more and better measurements of hadronic B mesons.
  - Ongoing measurements: $B \to D^{(*)}KK^{(*)}$, $D\pi^+\pi^0$, $\Lambda_c p^+ n\pi$, $D^{(*)}\eta\pi^+$ sprung from this effort. And more ideas to take form.
- ➢ Currently ongoing search for $B^+ \to K^+\tau\tau$ looks promising, entering the realm of new physics.
- ➢ Many more analysis and more data to come



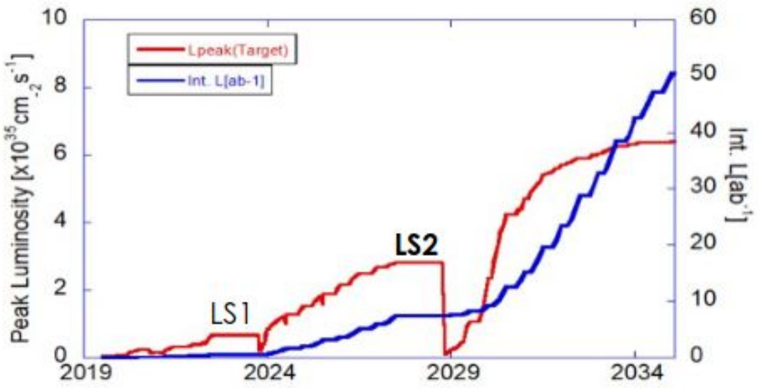
Summary and future

- ➢ Belle (II) is a unique environment to study modes with missing energy
  $B \rightarrow K\nu\nu$, $K\tau\tau$, $K\tau l$, $\tau\tau$, τl , $D^{(*)}\tau\nu$, $\tau\nu$, $\mu\nu$ ..... and many other opportunities.
- ➢ B-tagging plays an essential role, improvements require more and better measurements of hadronic B mesons.
  Ongoing measurements: $B \rightarrow D^{(*)}KK^{(*)}$, $D\pi^+\pi^0$, $\Lambda_c p^+ n\pi$, $D^{(*)}\eta\pi^+$ sprung from this effort. And more ideas to take form.
- ➢ Currently ongoing search for $B^+ \rightarrow K^+\tau\tau$ looks promising, entering the realm of new physics.

The increasing instantaneous luminosity demands a robust trigger system to not limit the physics reach.

IFIC participates in the vertex detector upgrade (LS2) for running safely at higher luminosity with enhanced performance. Working on trigger integration.

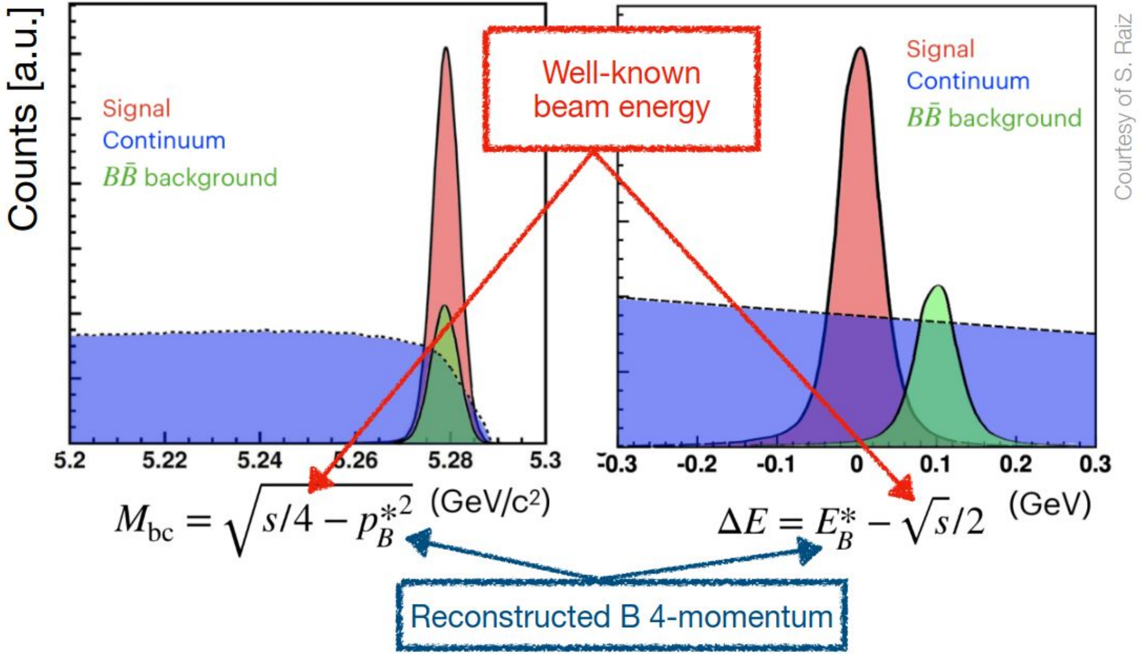
More on upgrade by Carlos Mariñas on Line 7 day soon.

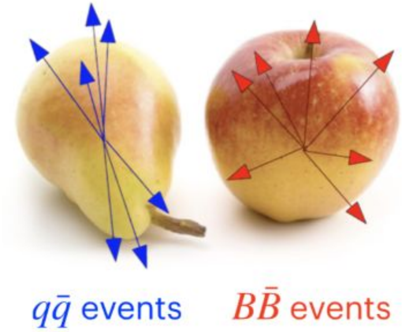


Backup

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