Search for new phenomena beyond the Standard Model at Belle II

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on behalf of the Belle II collaborations

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Belle and Belle II Experiments

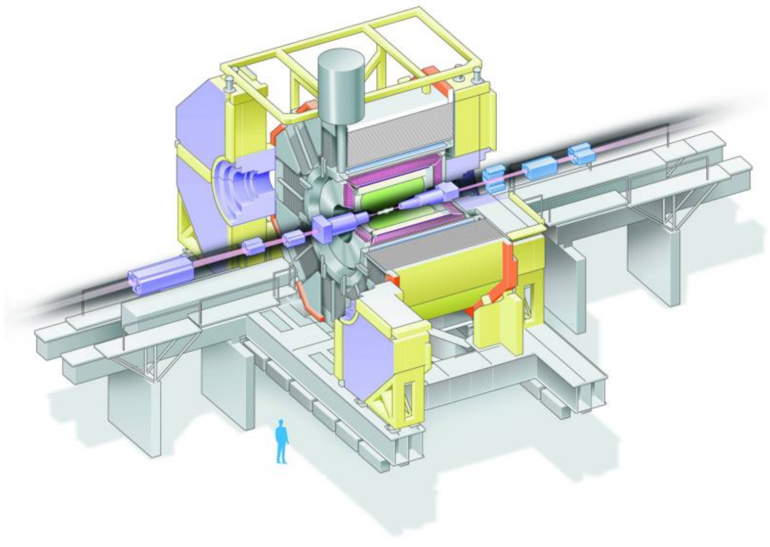
- Asymmetric energy collisions of electrons and positrons
- Its energy corresponds to $\sqrt{s} = 10.58\ \text{GeV}$, which is the resonance of $\Upsilon(4S)$
  - $\Upsilon(4S)$ mainly decays into B meson pair

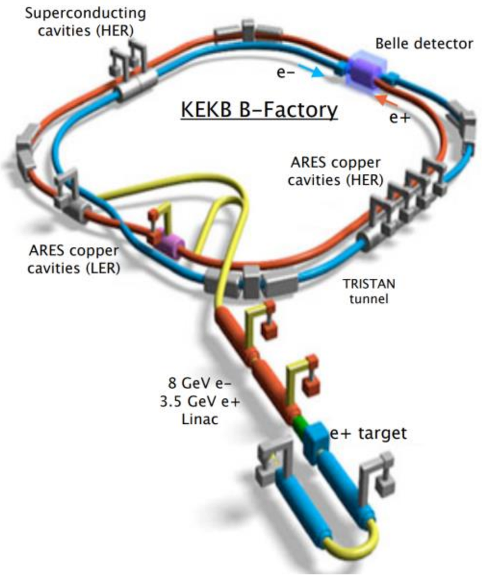
Belle experiment

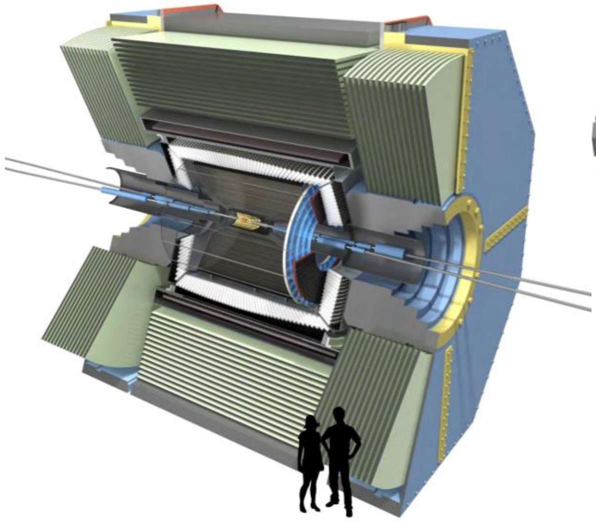
- 1999 - 2010
- $\mathcal{L}_{int} = 1\ ab^{-1}$
- $e^{+}(3.5\ \text{GeV})\ e^{-}(8\ \text{GeV})$ accelerated by KEKB

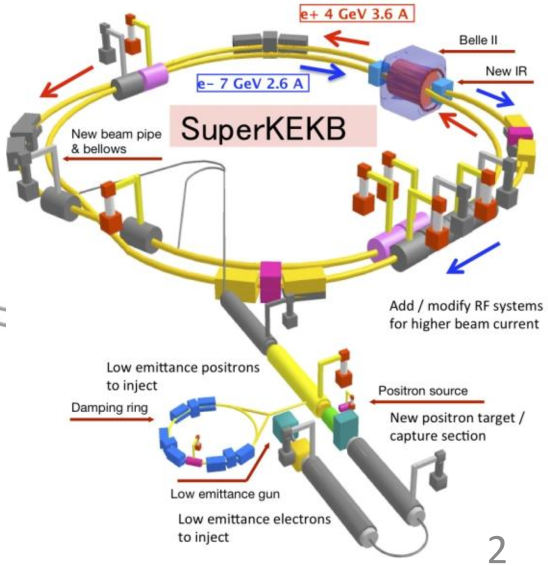
Belle II experiment

- 2019 - current
- $\mathcal{L}_{int} = 0.42\ ab^{-1}$ by 2023
- $e^{+}(4\ \text{GeV})\ e^{-}(7\ \text{GeV})$ accelerated by SuperKEKB









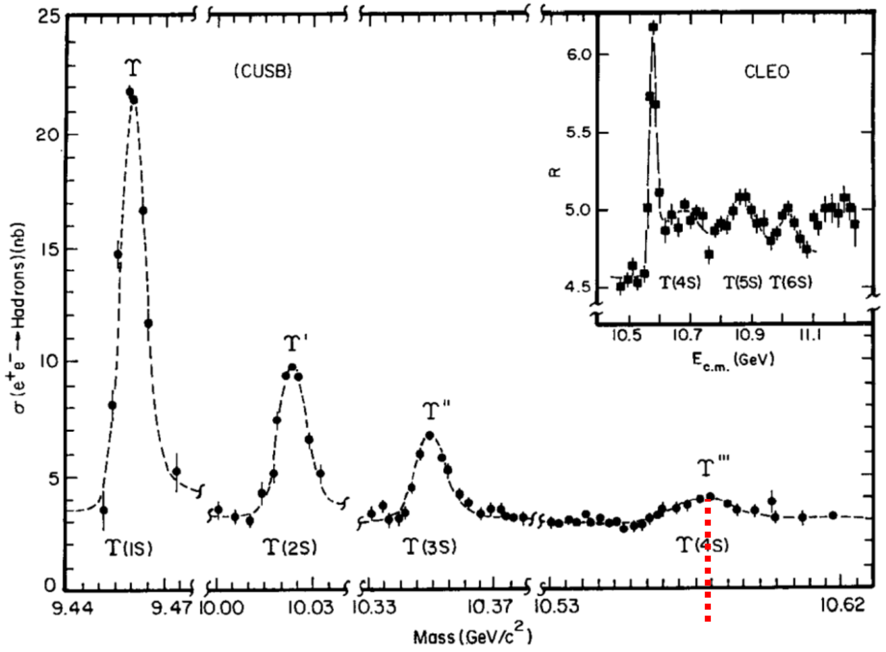
Belle and Belle II Experiments

- The entire kinematics are known in Belle II experiment.
  - c.m. energy is 10.58 GeV and two B mesons are produced

    → Belle II has an advantage on the decay modes with invisible particles, like neutrino

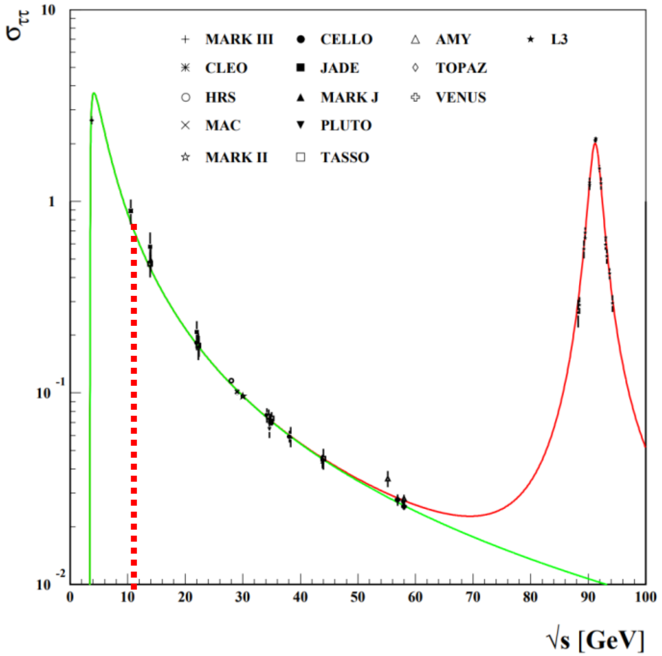
- Belle II experiment is not only B factory, but also tau factory

[Ann Rev Nucl Part Sci 43:333–378.]



$\sigma(e^+e^- \to \Upsilon(4S)) \sim 1.1$ nb @ 10.58 GeV

[*Phys.Rept.* 274 (1996) 287-376]



$\sigma(e^+e^- \to \tau^+\tau^-) \sim 0.9$ nb @ 10.58 GeV

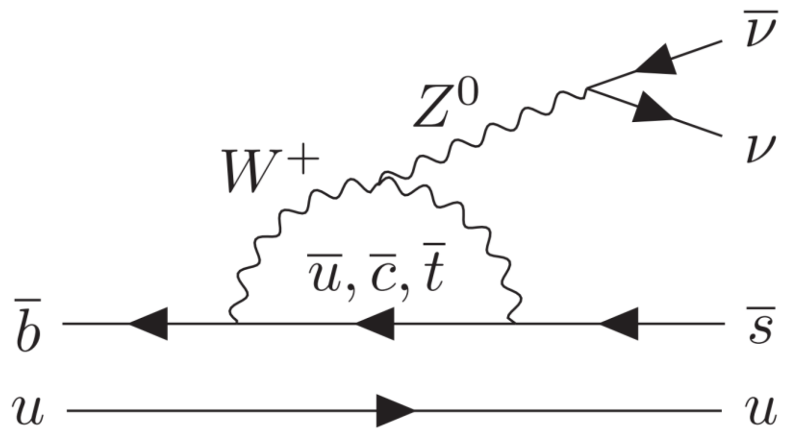
- we can also enjoy tau physics!

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

[Phys. Rev. D 109, 112006]

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

- $B^+ \to K^+ \nu\bar{\nu}$ decay
  - Flavour-changing neutral currents process
  - $\mathrm{BR} = (5.6 \pm 0.4) \times 10^{-6}$ at SM [Phys. Rev. D 107, 119903 (2023)]



- This decay can give a clue for non-SM particles
  - Leptoquark [Phys. Rev. D 98, 055003]
  - Axion [Phys. Rev. D 102, 015023]
  - Dark sector mediator [Phys. Rev. D 101, 095006]

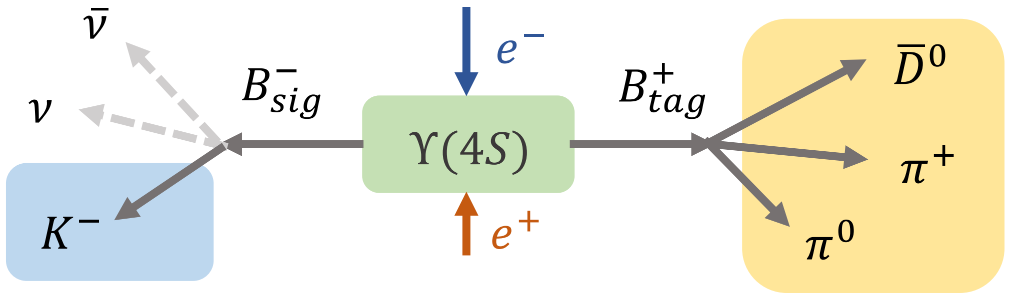
- There are previous studies in Babar, Belle, and Belle II experiments

experiment	Upper limit (90% CL)	$\mathcal{L}_{int}$	Tagging method	reference
BABAR	3.7×10^{-5}	$429\ fb^{-1}$	hadronic	Phys. Rev. D 87, 112005
BABAR	1.3×10^{-5}	$418\ fb^{-1}$	semileptonic	Phys. Rev. D 82, 112002
Belle	5.5×10^{-5}	$711\ fb^{-1}$	hadronic	Phys. Rev. D 87, 111103
Belle	1.9×10^{-5}	$711\ fb^{-1}$	semileptonic	Phys. Rev. D 96, 091101
Belle II	4.1×10^{-5}	$63\ fb^{-1}$	inclusive	Phys. Rev. Lett. 127, 181802

[Phys. Rev. D 109, 112006]

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

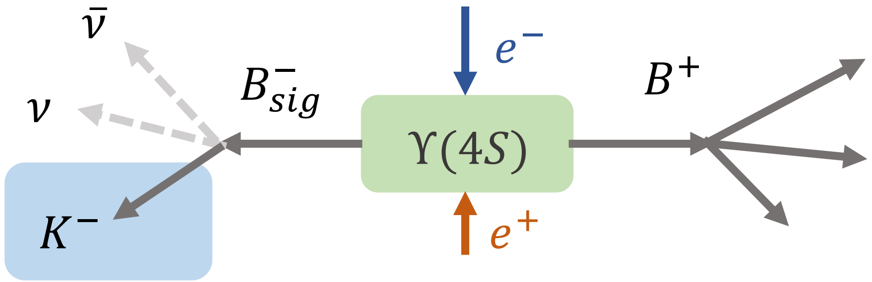
- $362\ fb^{-1}$ on-resonance data is used for this analysis
- Two tagging methods are done
  - hadronic tagging analysis (HTA)
  - inclusive tagging analysis (ITA)
- In HTA, one side of B meson is reconstructed by hadronic decay modes



  - Exact kinematics of B_{tag} is known
  - high purity
  - low efficiency

- In ITA, the second B meson is not explicitly reconstructed

* ROE: rest of event



  - Information of remaining particles (ROE) is used
  - low purity
  - high efficiency

[Phys. Rev. D 109, 112006]

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

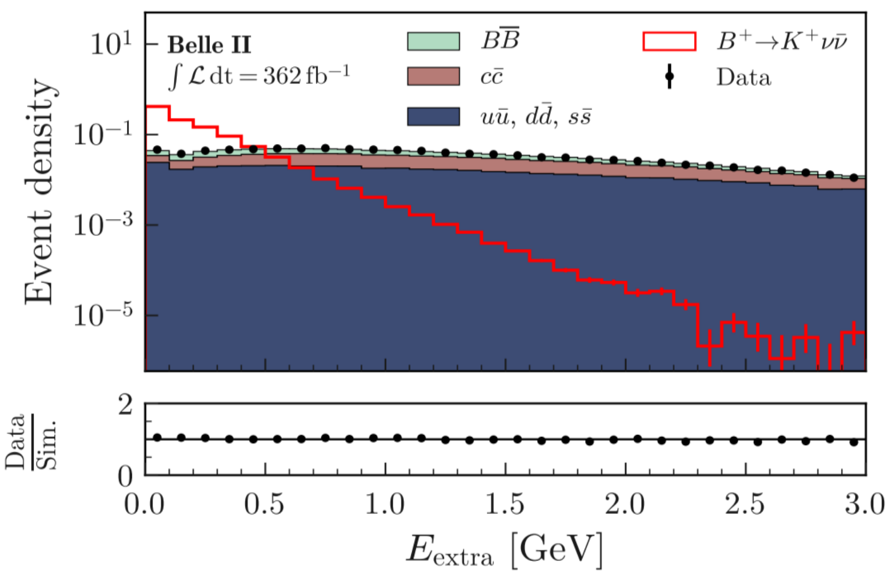
- For the background suppression, boosted decision tree (BDT) is used as the multivariate analysis technique
  - For HTA, total 12 variables are used
    - most powerful variable:

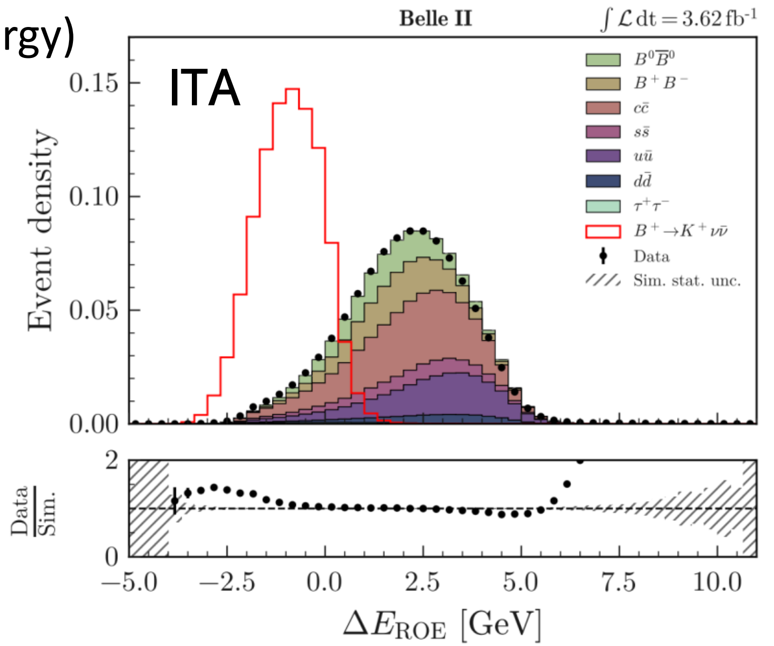
    → sum of remaining energy in the electromagnetic calorimeter (E_{extra})
  - For ITA, total 12 and 32 variables are used for two consecutive BDTs
    - most powerful variables:

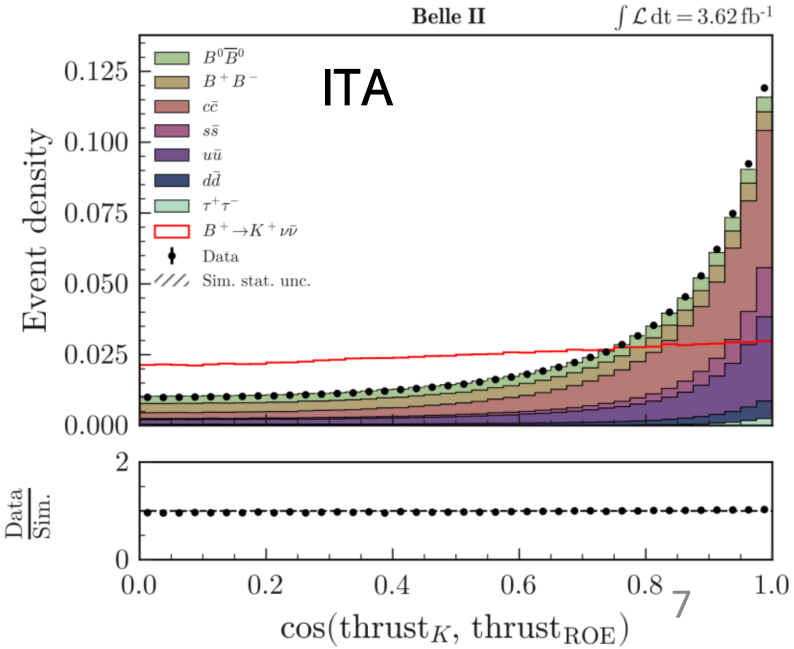
    → (Energy of ROE − a half of beam energy) in c.m. frame

    → event shape variable

HTA



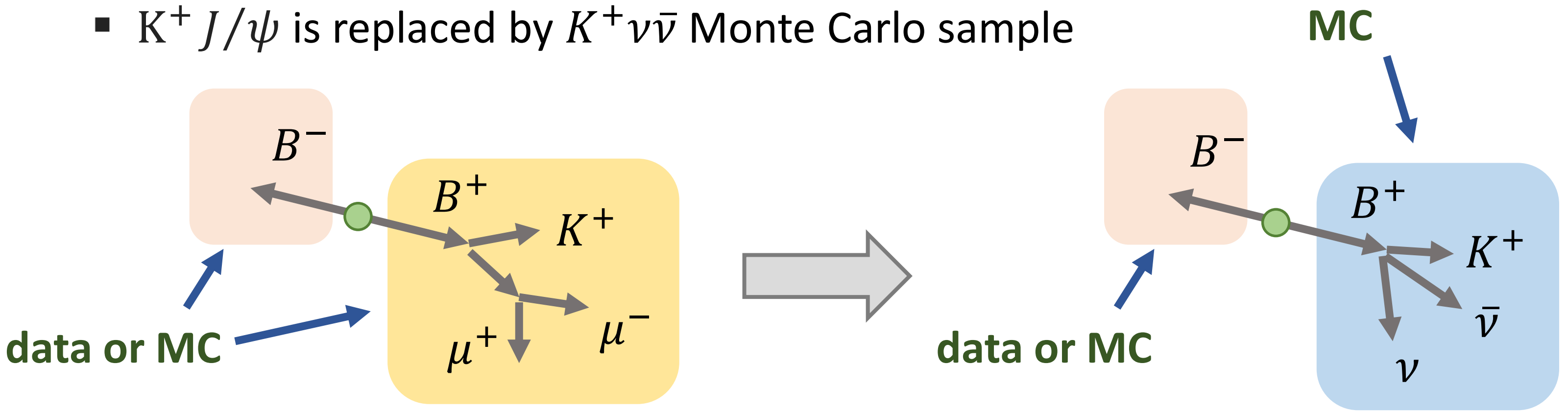


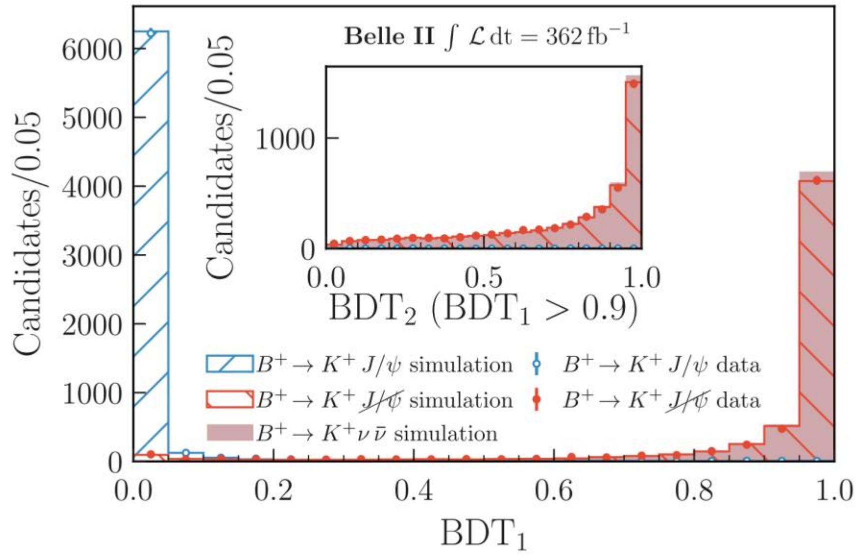


[Phys. Rev. D 109, 112006]

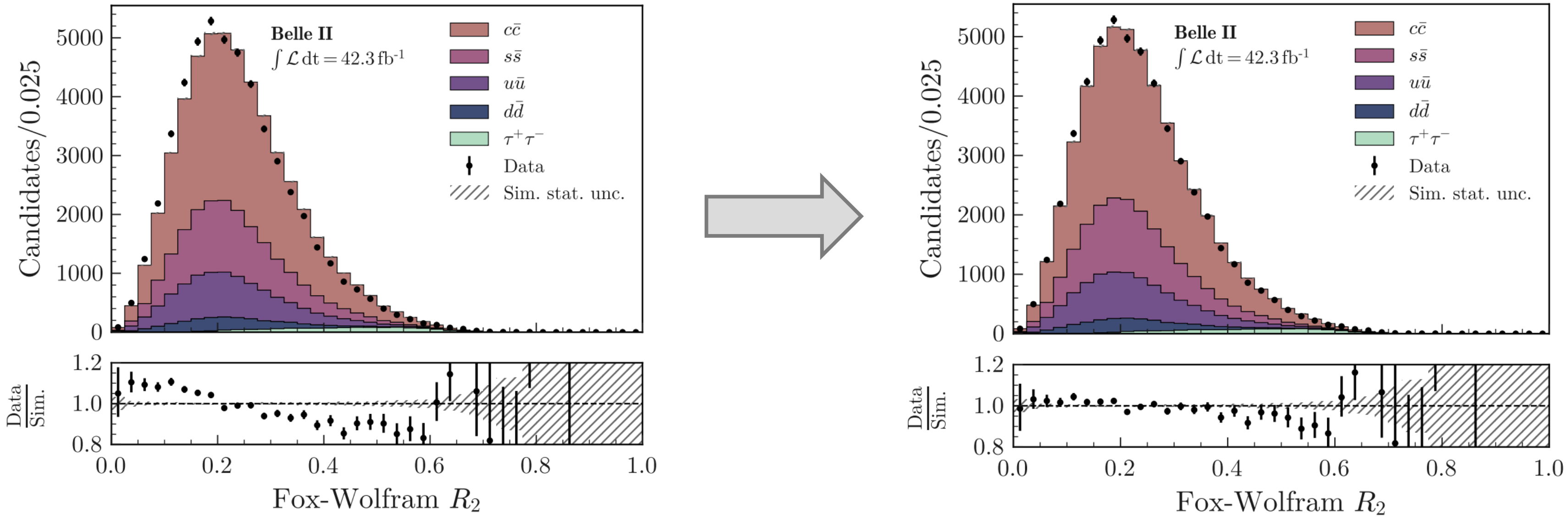
$B^+ \to K^+ \nu\bar{\nu}$

- $B^+ \to K^+ J/\psi\,(\to \mu^+\mu^-)$ is used for the signal efficiency validation
  - $K^+ J/\psi$ is replaced by $K^+\nu\bar{\nu}$ Monte Carlo sample





- The lower beam energy sample is used to correct the $e^+e^- \to q\bar{q}\ (q = u, d, s, c)$ background

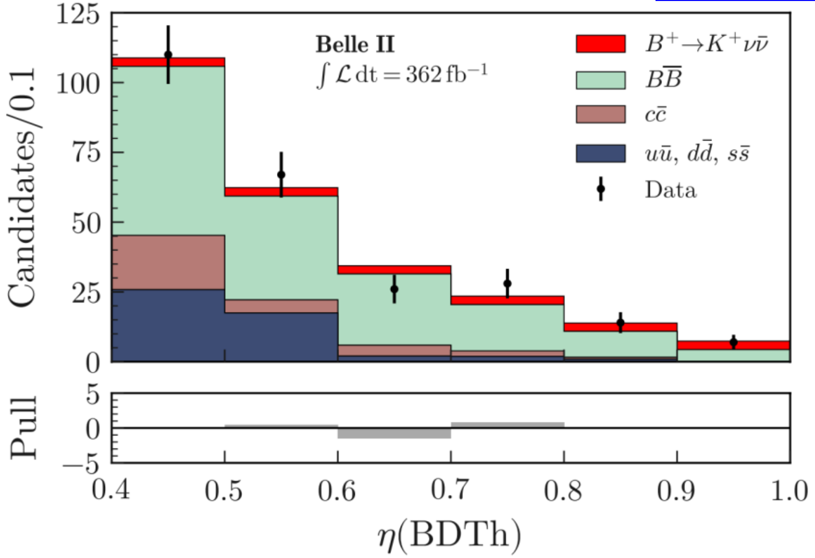


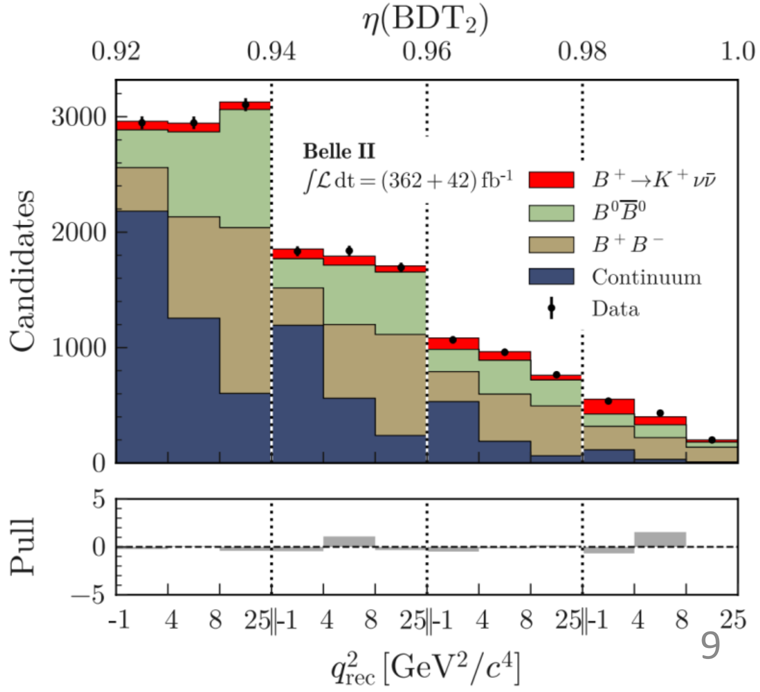
- Another BDT is trained to distinguish data vs MC
- Output of this BDT is used as a correction factor

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

[Phys. Rev. D 109, 112006]

- binned maximum likelihood fit is done to extract the signal yield
- Signal regions
  - For HTA, signal yield extraction is done on $\boldsymbol{\eta(BDT_h)}$ space
    - $\eta(\mathrm{BDT_h})$: variables related to the efficiency as a function of BDT cut
  - For ITA, signal yield extraction is done on $\boldsymbol{\eta(\mathrm{BDT_2})} \times \boldsymbol{q^2_{\mathrm{rec}}}$ space
    - $\eta(\mathrm{BDT_2})$: variables related to the efficiency as a function of BDT cut
    - q^2_{rec}: invariant mass square of the neutrino pair



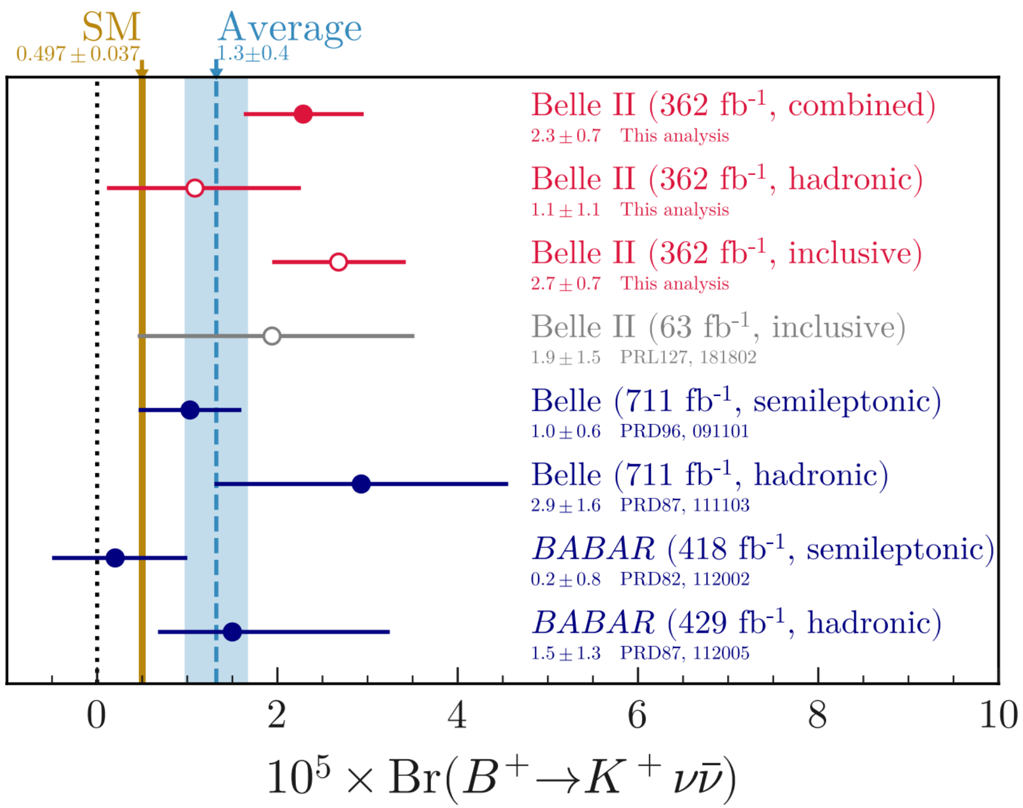


[Phys. Rev. D 109, 112006]

Belle II

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

- result



- Hadronic tag:

$$BR(B^+ \to K^+\nu\bar{\nu}) = \left[1.1^{+0.9}_{-0.8}(\mathrm{stat})^{+0.8}_{-0.5}(\mathrm{syst})\right] \times 10^{-5}$$

- Inclusive tag:

$$BR(B^+ \to K^+\nu\bar{\nu}) = [2.7 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{syst})] \times 10^{-5}$$

- Combined result:

$$BR(B^+ \to K^+\nu\bar{\nu}) = \left[2.3 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})\right] \times 10^{-5}$$

→ first evidence for the $B^+ \to K^+\nu\bar{\nu}$ decay (3.5σ) 🎉

- Compatibility with SM: 2.7σ

$$\tau^- \to \mu^+\mu^-\mu^-$$

[JHEP09(2024)062]

$\tau^- \to \mu^+\mu^-\mu^-$

[JHEP09(2024)062]

Belle II

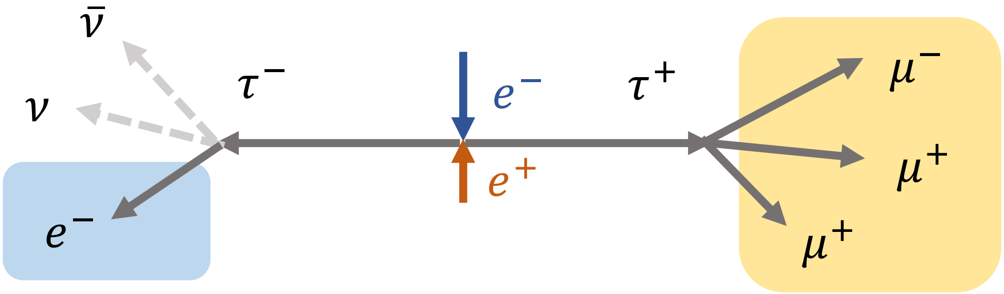
- Belle experiment is not only B factory but also tau factory
- $\tau^- \to \mu^+\mu^-\mu^-$ decay
  - Hard to occur in SM (smaller than $\mathcal{O}(10^{-50})$) [Eur. Phys. J. C 79 (2019) 84]
- This decay can be enhanced by new physics
  - Inverse Seesaw [J. Phys. Conf. Ser. 888 (2017) 012029]
- $424\ fb^{-1}$ data is used for the analysis
- There are previous studies

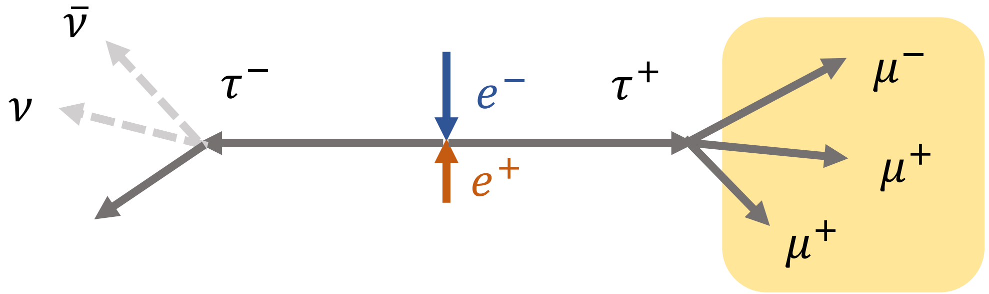
experiment	Upper limit (90% CL)	$\mathcal{L}_{int}$	Tagging method	reference
CLEO	1.9×10^{-6}	$4.79\ fb^{-1}$	one-prong	Phys. Rev. D 57 (1998) 5903
BABAR	3.3×10^{-8}	$468\ fb^{-1}$	one-prong	Phys. Rev. D 81 (2010) 111101
LHCb	4.6×10^{-8}	$3\ fb^{-1}$	-	JHEP 02 (2015) 121
ATLAS	3.8×10^{-7}	$20.3\ fb^{-1}$	-	Eur. Phys. J. C 76 (2016) 232
CMS	8.0×10^{-8}	$33.2\ fb^{-1}$	-	JHEP 01 (2021) 163

[JHEP09(2024)062]

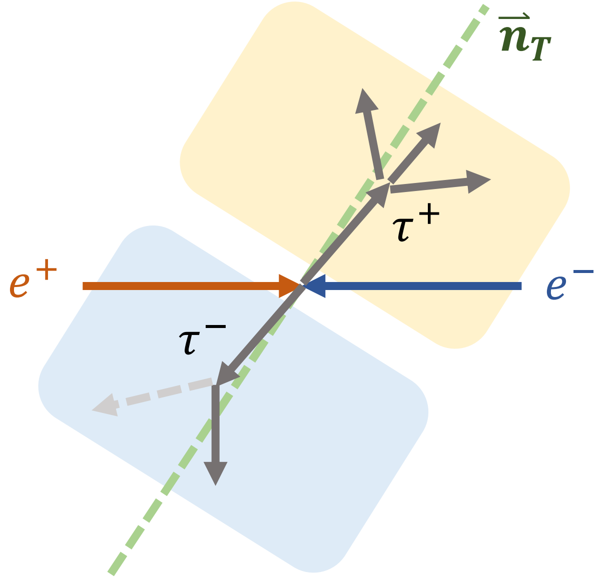
$\tau^- \to \mu^+\mu^-\mu^-$

- Two analysis methods are done in this analysis
  - one-prong tagging analysis (for the validation)
  - inclusive tagging analysis



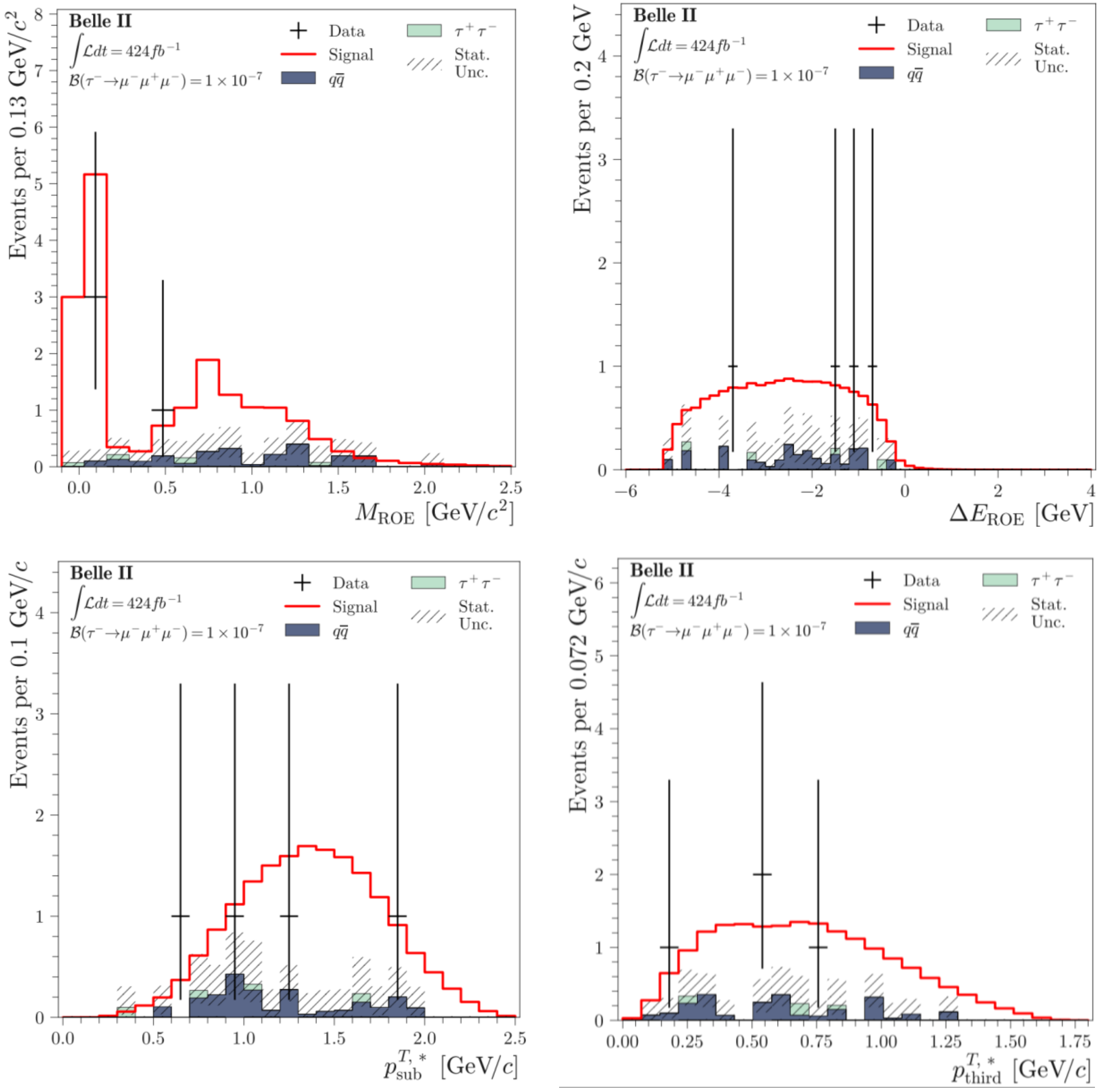


- The space is divided into two hemispheres
  - determine a vector $\vec{n}_T$ that the sum of inner products with particles' momentum is maximized
  - Then, we can define two hemispheres by the plane perpendicular to $\vec{n}_T$
  - All three μ are required to be included in the same hemisphere



$\tau^- \to \mu^+\mu^-\mu^-$

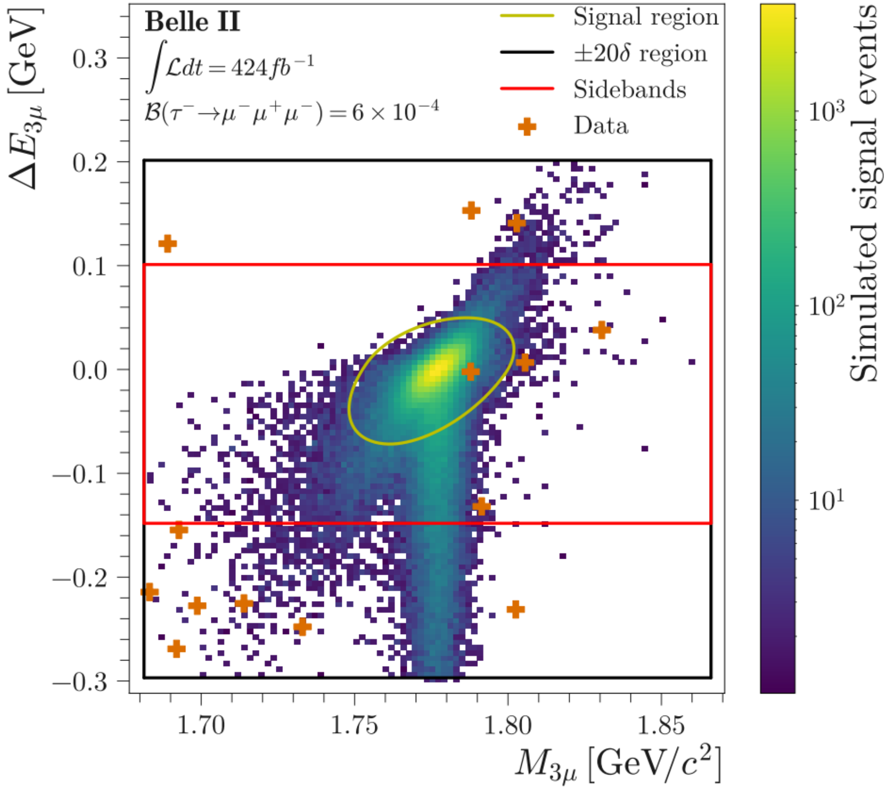
- BDT is used to suppress backgrounds
  - total 32 variables are used
  - the most discriminating variables:
    - mass of ROE
    - (Energy of ROE – a half of beam energy) in c.m. frame
    - transverse momentum of the second highest momentum muon
    - transverse momentum of the lowest momentum muon
  - cross-validation (k-folding) algorithm is used to reduce the impacts from the statistical fluctuation



$\tau^- \to \mu^+\mu^-\mu^-$

[JHEP09(2024)062]

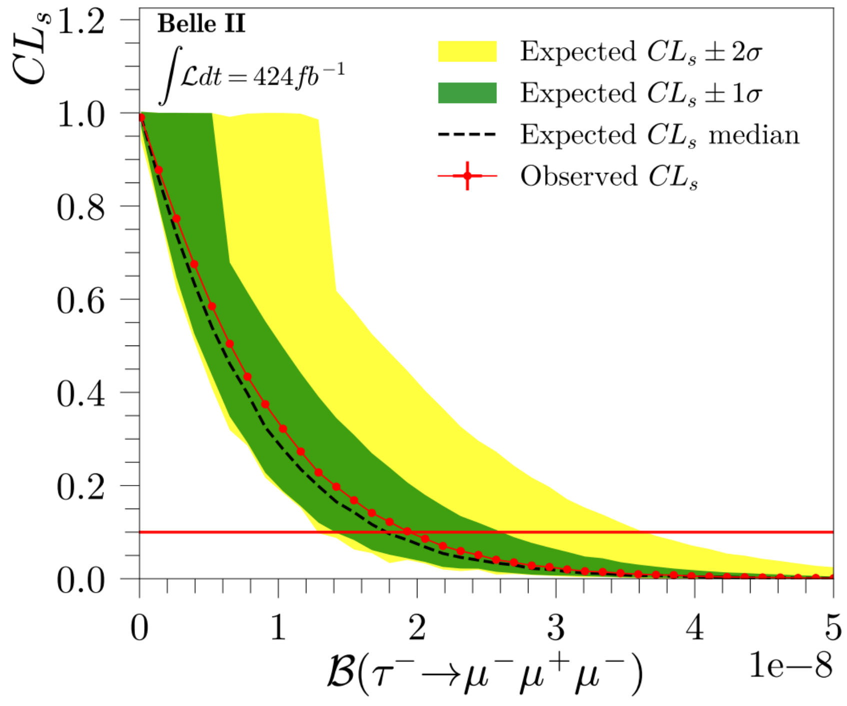
- Counting method is used in $(M_{3\mu}, \Delta E_{3\mu})$ plane
  - $M_{3\mu}$: invariant mass of three muons
  - $\Delta E_{3\mu}$: (Energy of three muons - a half of beam energy) in c.m. frame
- The signal region and sideband region are defined
  - The signal region (yellow line):
    - elliptical region is obtained from the MC sample
  - The sideband region (region between red and yellow lines)
    - $\pm 20\ \delta_M$, $\pm 10\ \delta_{\Delta E}$ wide rectangular region, where δ is expected resolution
- The number of expected background is obtained from the 2D plane (BDT output) X (distance from signal peak)



$\tau^- \rightarrow \mu^+\mu^-\mu^-$

- Result
  - $N_{\text{exp}} = 0.7^{+0.6}_{-0.5}$: the expected number of background events
  - $N_{obs} = 1$: the number of observed events
  - $BR(\tau^- \rightarrow \mu^+\mu^-\mu^-) = \left(2.1^{+5.1}_{-2.4} \pm 0.4\right) \times 10^{-9}$
    - $BR(\tau^- \rightarrow \mu^+\mu^-\mu^-) = \frac{N_{obs} - N_{exp}}{\mathcal{L} \times 2\sigma_{\tau\tau} \times \epsilon_{3\tau}}$
  - Upper limit of branching ratio = 1.9×10^{-8} at 90% confidence level

→ World's best limit 🎉



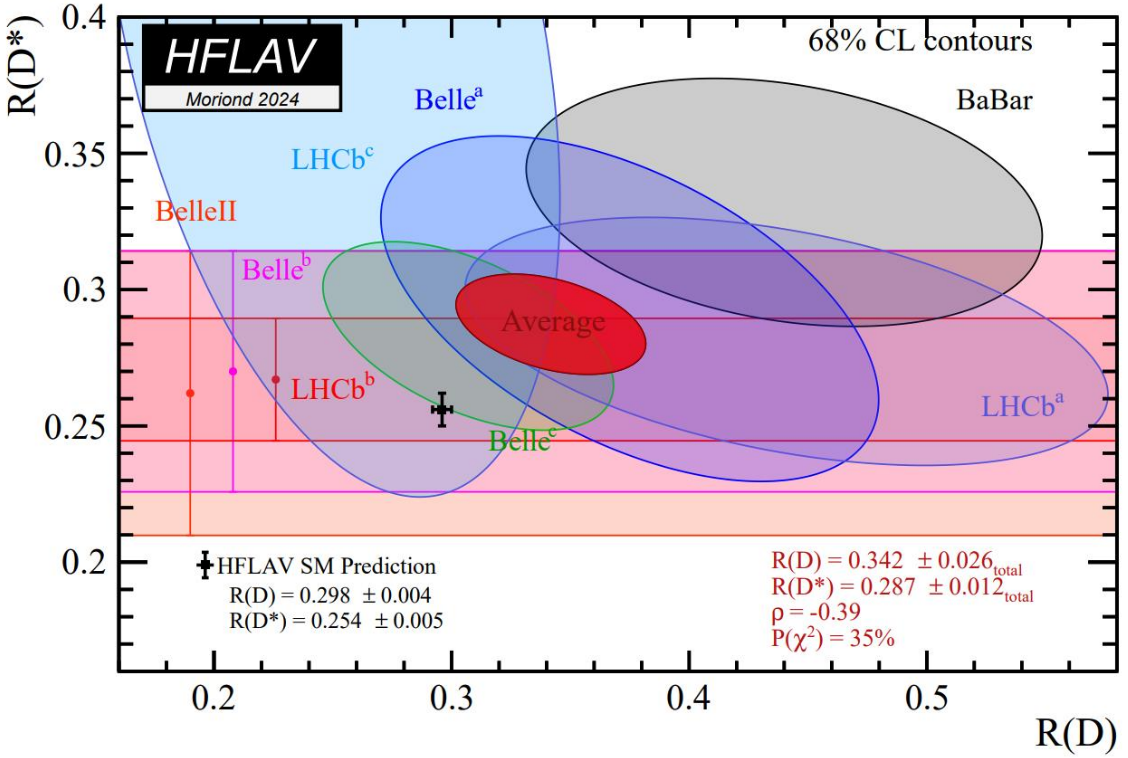
$R(D^*)$

[Phys. Rev. D 110, 072020]

$R(D^*)$

- Measuring $R(D^{(*)})$ is the direct test for the lepton flavour universality (LFU)
  - $R\left(D^{(*)}\right) = \frac{BR(\bar{B}\to D^{(*)}\tau\bar{\nu}_\tau)}{BR(\bar{B}\to D^{(*)}\ell\bar{\nu}_\ell)}$
  - In SM, [Phys. Rev. D 107, 052008]
    - $R(D) = 0.298 \pm 0.004$
    - $R(D^*) = 0.254 \pm 0.005$
  - Several systematic uncertainties are canceled for $R\left(D^{(*)}\right)$, like quark mixing element $|V_{cb}|$
  - $R\left(D^{(*)}\right)$ can be changed by new physics
    - Leptoquark [Phys. Rev. D 104, 055017]
    - W' boson [JHEP12(2016)059]

[Moriond 2024]

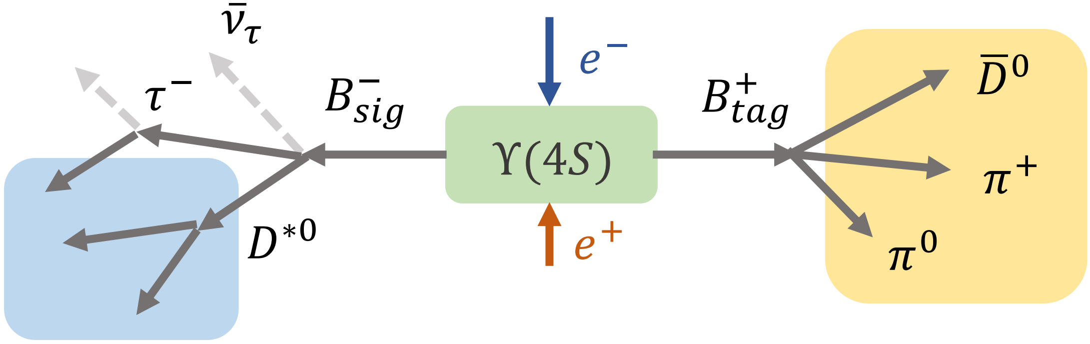


- Currently, it shows some tension from SM prediction: $\sim 3.17\sigma$

[Phys. Rev. D 110, 072020]

$R(D^*)$

- $189\ fb^{-1}$ on-resonance data is used for this analysis
- Hadronic tagging method is used



- The following decay modes are reconstructed for the signal side

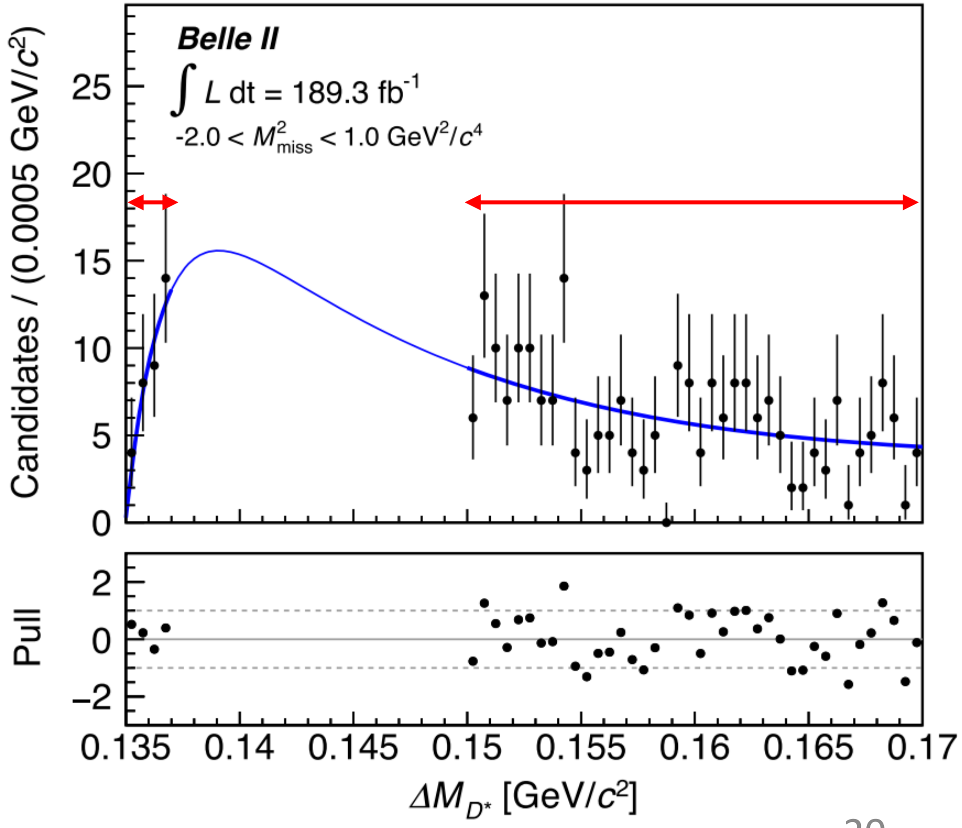
particle	Decay modes	remark
τ	$e^-\bar{\nu}_e\nu_\tau$ $\mu^-\bar{\nu}_\mu\nu_\tau$	Leptonic mode
D^{*+}	$D^0\pi^+$ $D^+\pi^0$	
D^{*0}	$D^0\pi^0$	
D^+	$K^-\pi^+\pi^+$ $K^0_S\pi^+$ $K^-K^+\pi^+$	
D^0	$K^-\pi^+\pi^0$ $K^-\pi^+\pi^-\pi^+$ $K^0_S\pi^+\pi^-\pi^0$ $K^-\pi^+$ $K^0_S\pi^+\pi^-$ $K^0_S\pi^0$ K^-K^+ $\pi^-\pi^+$	

[Phys. Rev. D 110, 072020]

$R(D^*)$

- Dominant background comes from the misreconstructed D^* candidates:
  - (Correctly reconstructed D) + (low-momentum pion not from D^*)
  - misreconstructed D with low-momentum pion
- This fake D^* yield is calibrated from the sideband for each D^* mode
  - The sideband region is defined in ΔM_{D^*} region, where $\Delta M_{D^*} = M_{D^*} - M_D$
  - The fit is done on the sideband, to obtain the data-simulation ratio of yield of fake D^*

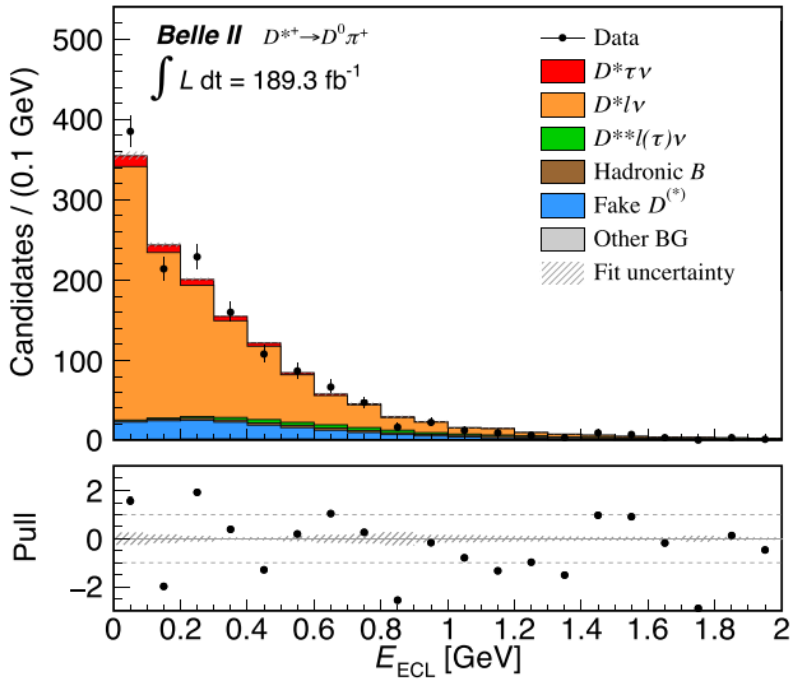
$D^{*0} \to D^0\pi^0$



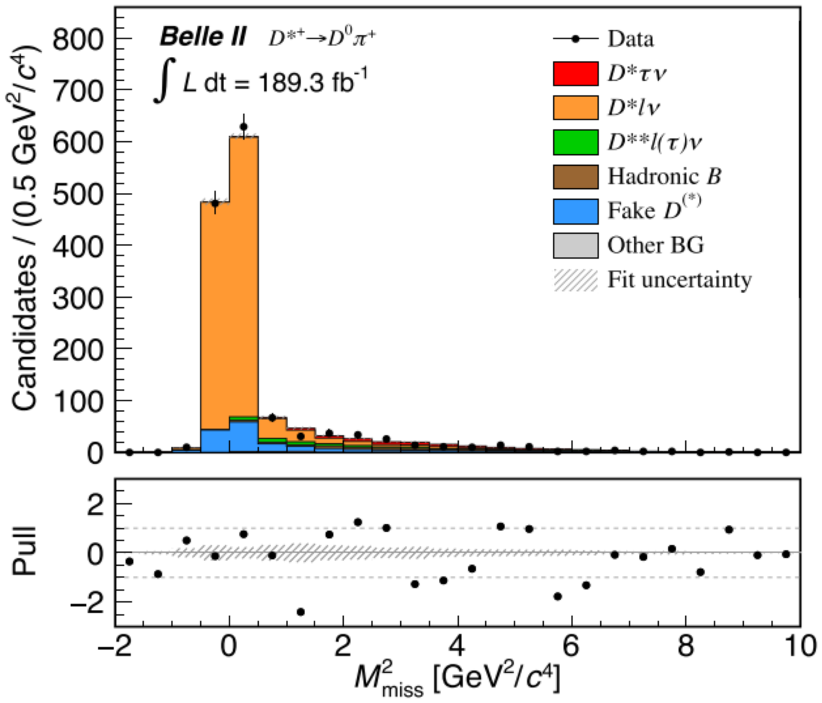
$R(D^*)$

- To extract the signal yield, extended binned maximum likelihood fit is done
- Signal region
  - (the remaining energy on the electromagnetic calorimeter) × (missing mass square)
- The probability density functions are constructed for each D^* modes

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



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

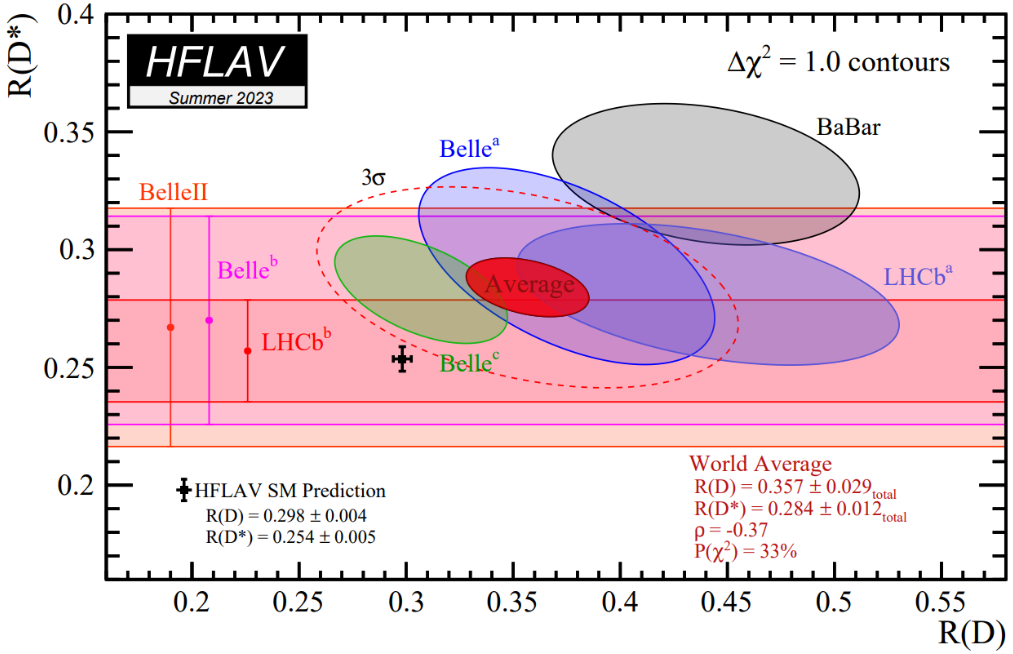


$R(D^*)$

- Result
  - $R(D^*) = 0.262^{+0.041}_{-0.039}(\text{stat})^{+0.035}_{-0.032}(\text{syst})$

    → Statistical uncertainty ($^{+15.7\%}_{-14.7\%}$) is comparable to Belle result (13.0%), even though this analysis uses much smaller data size (189 fb^{-1} vs 711 fb^{-1}) 🎉
  - consistent with SM prediction

[HFLAV]



Summary

- Belle II experiment has advantages to B and tau physics
  - Target energy is appropriate for B and tau production
  - decays with invisible particles can be analyzed
- Broad range of analysis have been successfully done in Belle II experiment
  - EWP: $B^+ \to K^+\nu\bar{\nu}$

    → first evidence for the $B^+ \to K^+\nu\bar{\nu}$ decay (3.5σ)
  - LFV: $\tau^- \to \mu^+\mu^-\mu^-$

    → World's best result
  - LFU: $R(D^*)$

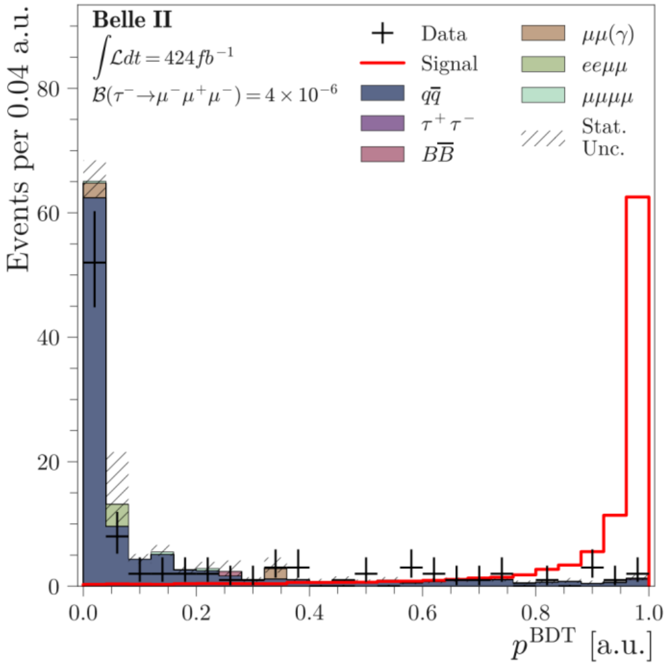
    → comparable statistical uncertainty, with much smaller data size, compared to Belle experiment

Backup

[JHEP09(2024)062]

$\tau^- \rightarrow \mu^+\mu^-\mu^-$

- The validation is done on the sideband region
  - Agreement on (BDT output) is checked
  - After the BDT selection,
    - The expected number of event in sideband = $2.0^{+0.7}_{-0.5}$
    - The observed number of event in sideband = 3



- The number of expected background is obtained from (BDT output) and distance from signal peak
  - expected $N_D = N_C \times \frac{N_B}{N_A}$