B Leptonic Decays: Results at Belle and prospects at Belle II

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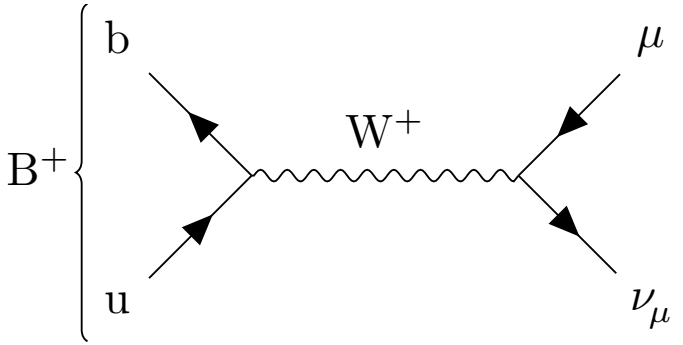
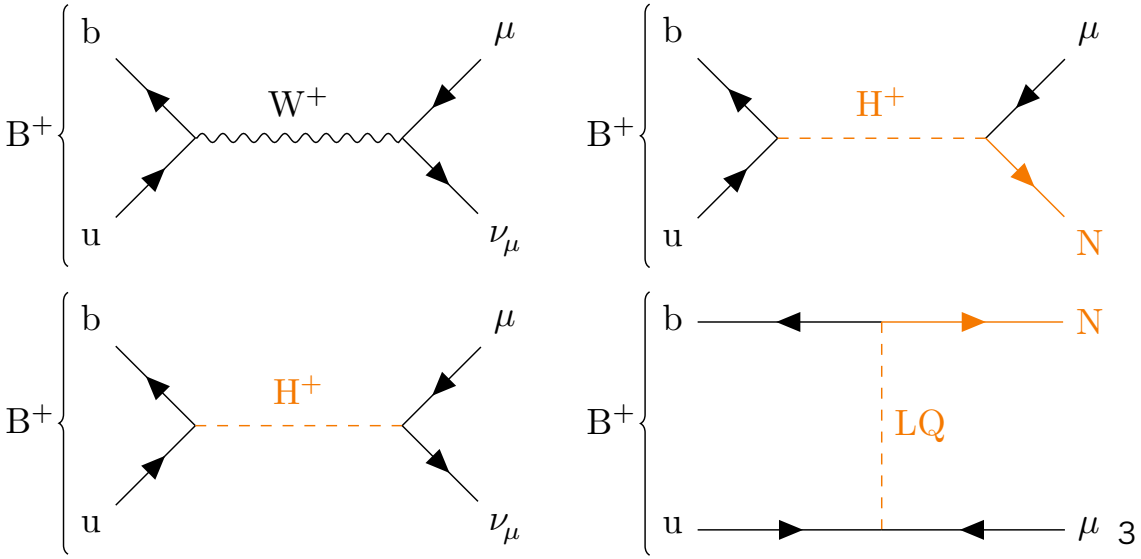
Introduction

- B meson leptonic decay : test the validity of the Standard Model of particle physics
- $Br(B^+ \to \ell^+ \nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B^2$



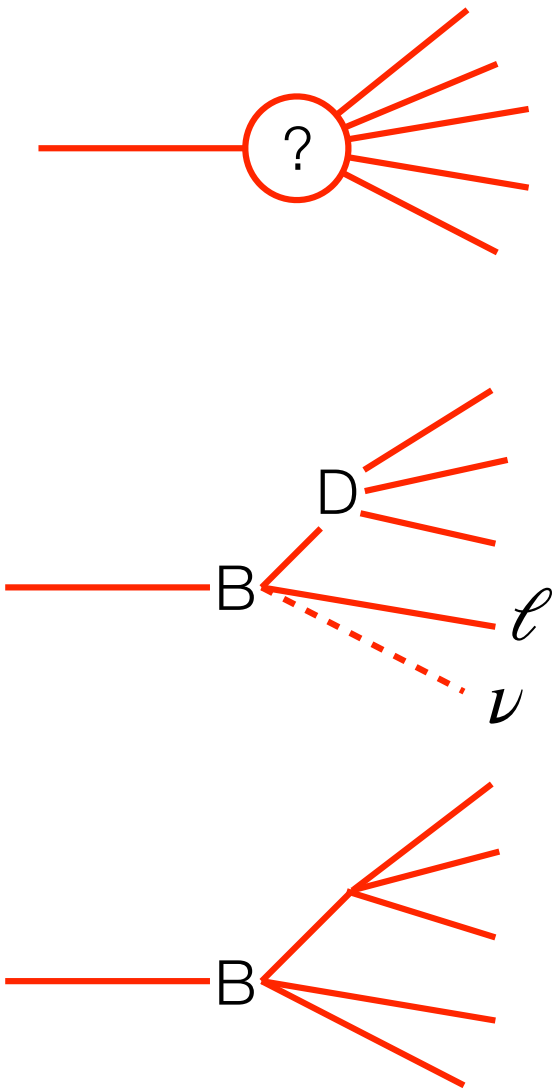
  - G_F : Fermi constant, $m_{B/l}$: mass of B meson or lepton, V_{ub} : CKM matrix element, τ_B : B meson lifetime, f_B : B meson decay constant
  - *b-u* quark annihilation : CKM suppression, $|V_{ub}|^2$
  - *W* decay into lepton-neutrino pair : helicity suppression, m_ℓ^2
  - f_B : determined by non-perturbative methods
- $Br(B^+ \to \mu^+ \nu_\mu) = \left(6.6 \pm 2.2 \pm 1.6\right) \times 10^{-7}$ (Belle 2018, Phys. Rev. Lett. 121, 031801 (2018))

- improved search for $B^+ \to \mu^+\nu_\mu$ than previous our publish (Phys. Rev. Lett. 121, 031801 (2018))
- SM calculation with $f_B = 184 \pm 4$ MeV
  - $Br(B^+ \to \mu^+\nu_\mu) = (4.3 \pm 0.8) \times 10^{-7}$ (inclusive PDG
    $|V_{ub}| = \left(4.49 \pm 0.16_{(\text{stat.})}\ ^{+0.16}_{-0.17}\ _{(\text{sys.})} \pm 0.17_{(\text{theo.})}\right) \times 10^{-3}$)
  - $Br(B^+ \to \mu^+\nu_\mu) = (3.7 \pm 0.4) \times 10^{-7}$(exclusive PDG
    $|V_{ub}| = \left(3.67 \pm 0.09 \pm 0.12\right) \times 10^{-3}$)
  - ~300 events in full Belle data set at $\Upsilon(4s)$ ($= 711\text{fb}^{-1}$)
  - sensitive to new physics
    - charged Higgs
    - LQ
    - sterile neutrino



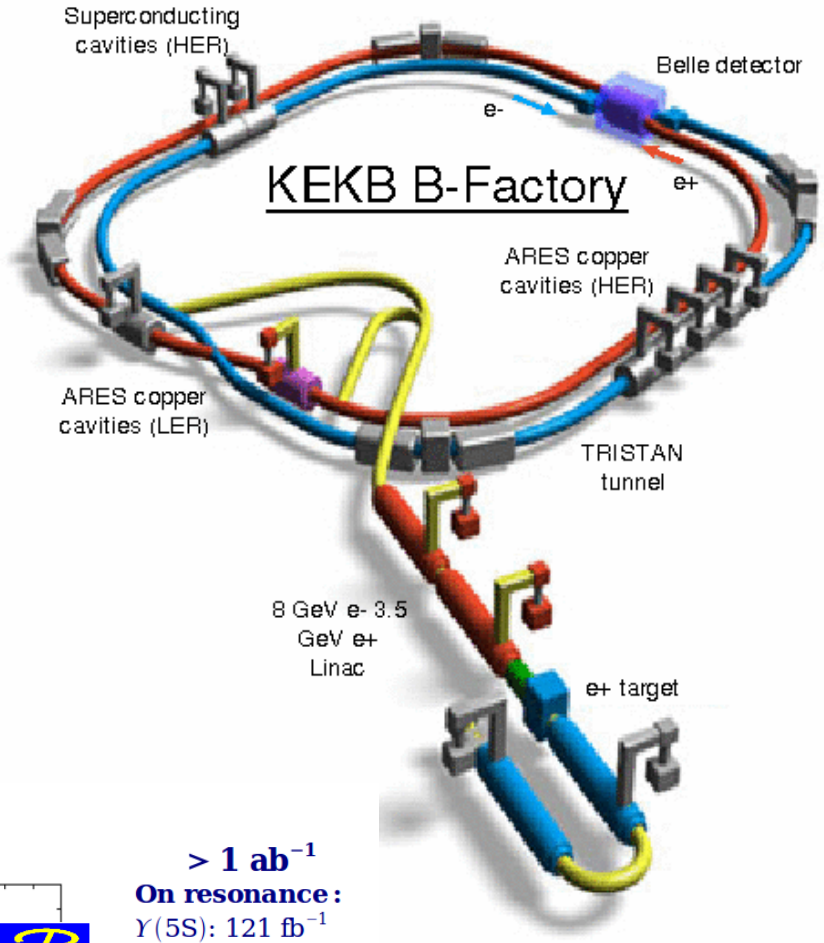
B tagging in Belle

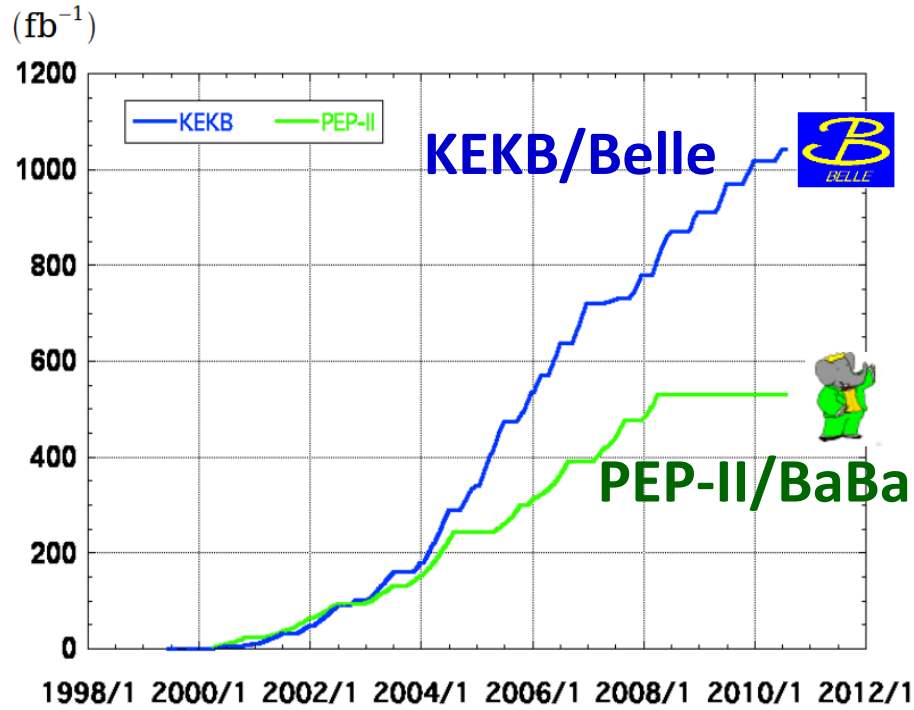
- inclusive tag : consistent with B meson
  - eff. = O(10%) : important in this case
  - low purity
- semi-leptonic tag : partial know B meson
  - eff. = O(1%)
  - moderate purity
- hadronic tag : exactly know B meson
  - eff. = O(0.1%)
  - high purity



KEKB accelerator

- 8 GeV e^-/3.5 GeV e^+
- operated during 1999 - 2010
- 711 fb^{-1} at $\sqrt{s} = 10.58$ GeV ($\Upsilon(4s)$ resonance)
- 79 fb^{-1} at 40 MeV below (off-resonance data)



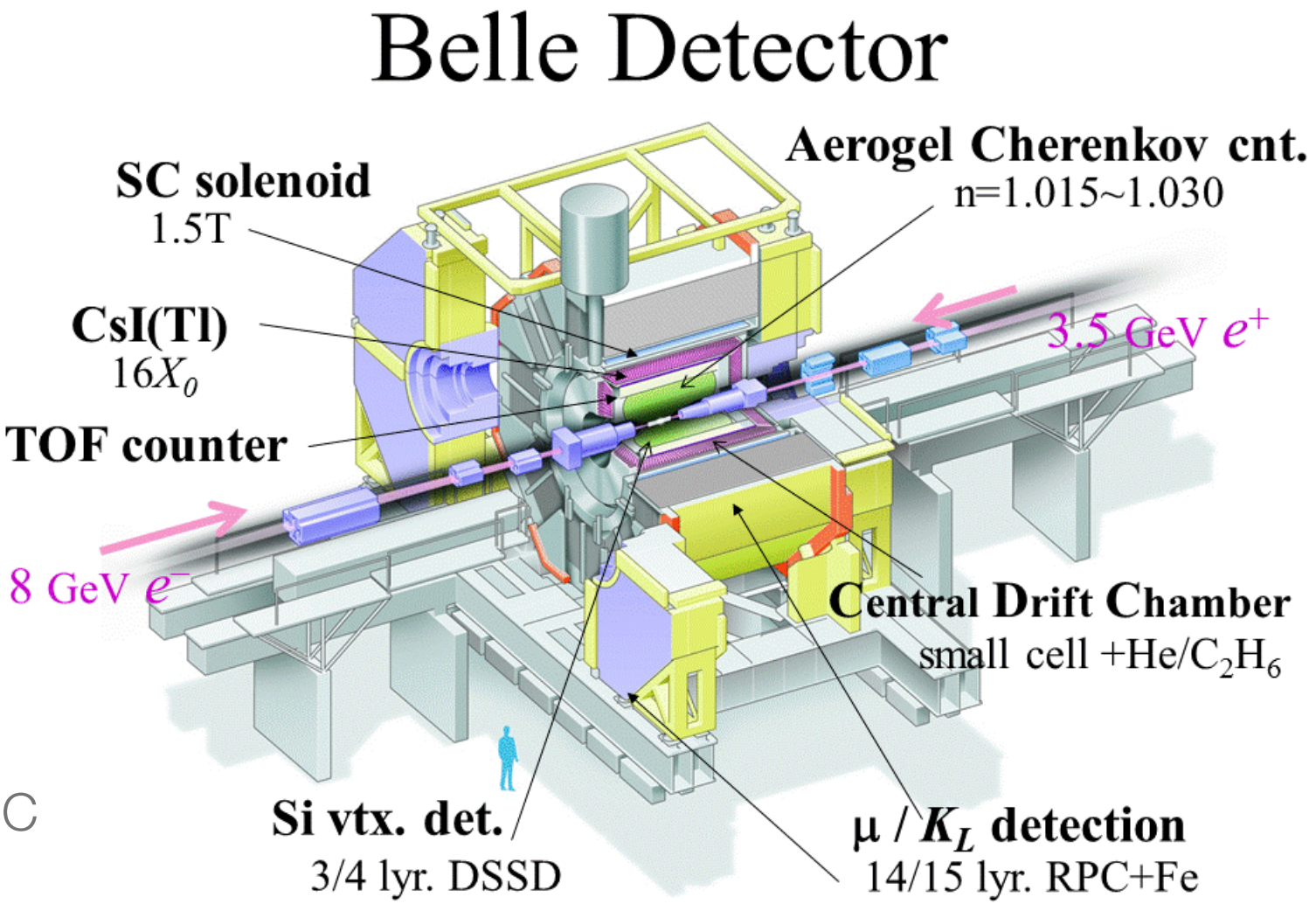


> 1 ab^{-1}
On resonance:
Υ(5S): 121 fb^{-1}
Υ(4S): 711 fb^{-1}
Υ(3S): 3 fb^{-1}
Υ(2S): 25 fb^{-1}
Υ(1S): 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
Υ(4S): 433 fb^{-1}
Υ(3S): 30 fb^{-1}
Υ(2S): 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

Belle detector

- charged tracking
  - SVD + CDC
- neutral cluster
  - ECL
- muon ID
  - KLM
- electron ID
  - ECL/CDC/ACC



Analysis strategy

Select $B\bar{B}$ events

#charged ≥ 3

significant energy in ECL in c.m.s.

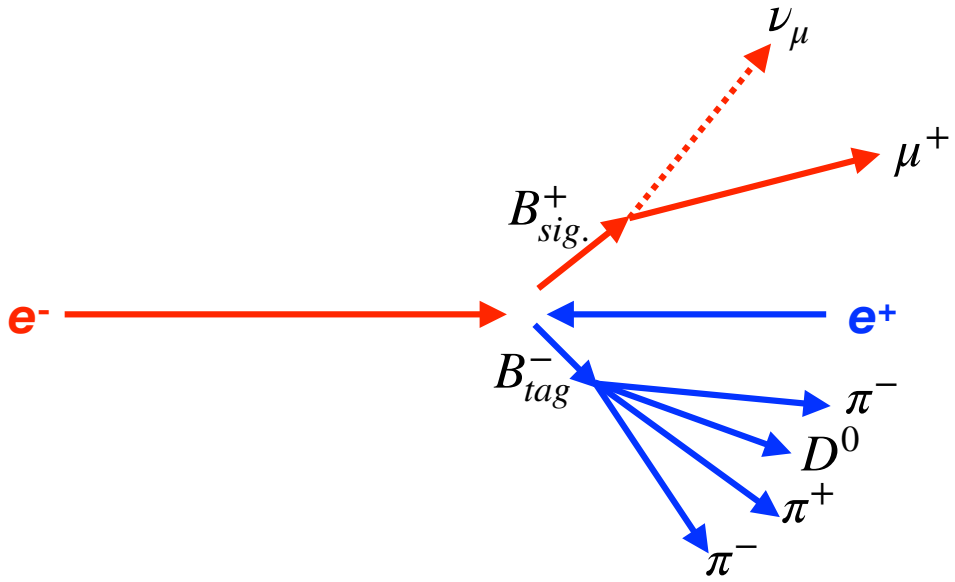
reconstruct signal side *B*

muon candidate

$p_\mu^* > 2.2$ GeV/c

dr < 0.5 cm, |dz| < 2.0 cm

~99.8% eff.



reconstruct rest-of-the-evevnt(ROE)

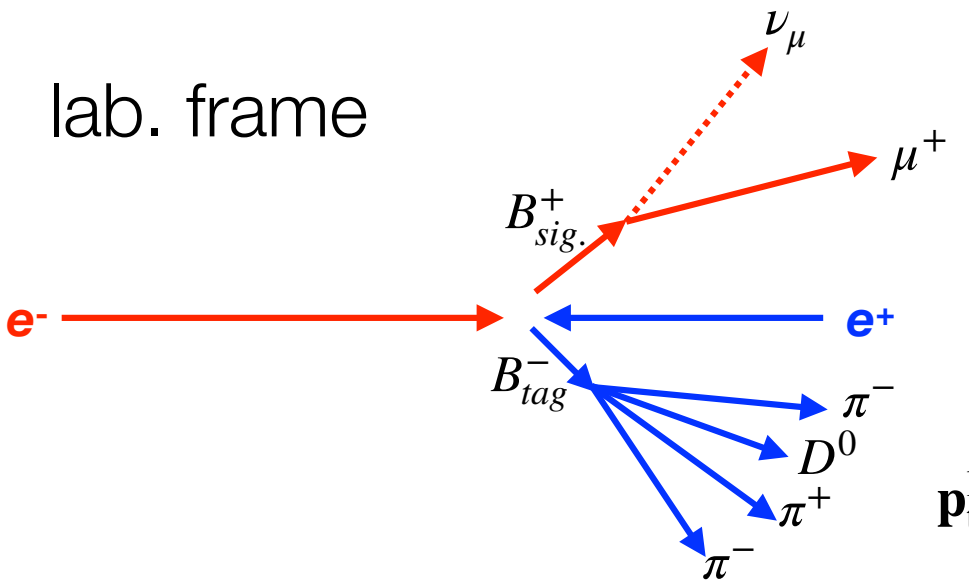
remaining tracks(as pion)/clusters (tag side *B*)

dr < 10 cm, |dz| < 20 cm

$$\mathbf{p}_{\text{tag}}^{\text{lab}} = \sum_{i}^{\text{tracks}} \mathbf{p}_i^{\text{lab}} + \sum_{j}^{\text{clusters}} \mathbf{E}_j^{\text{lab}}$$

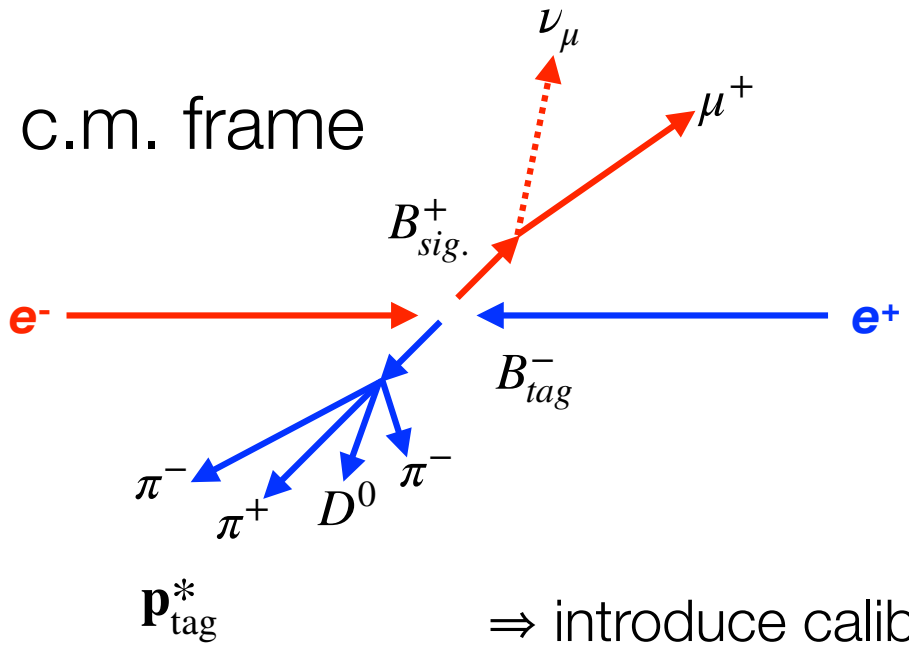
$$E_{\text{tag}}^{\text{lab}} = \sqrt{\left(\mathbf{p}_{\text{tag}}^{\text{lab}}\right)^2 + m_B^2}$$

lab. frame



$$\mathbf{p}^{\text{lab}}_{\text{tag}} = \sum_{i}^{\text{tracks}} \mathbf{p}^{\text{lab}}_{i} + \sum_{j}^{\text{clusters}} \mathbf{E}^{\text{lab}}_{j}$$

c.m. frame



(normalized or constrain to $|\mathbf{p}^*_{\mathbf{tag}}|$ = 330 MeV/c)

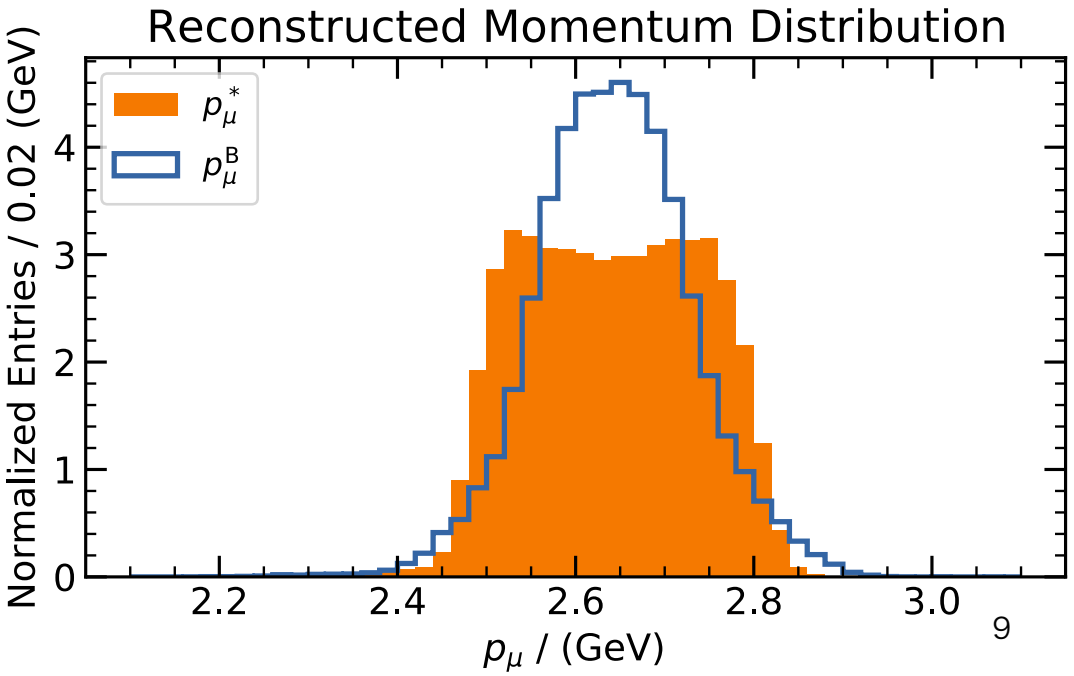
detector acceptance : $\left(\mathbf{p}^*_{\text{tag}}\right)_z$ has bias

$\Rightarrow$ introduce calibration function f : shifts mean of $\left(\mathbf{p}^*_{\text{tag}}\right)_z$

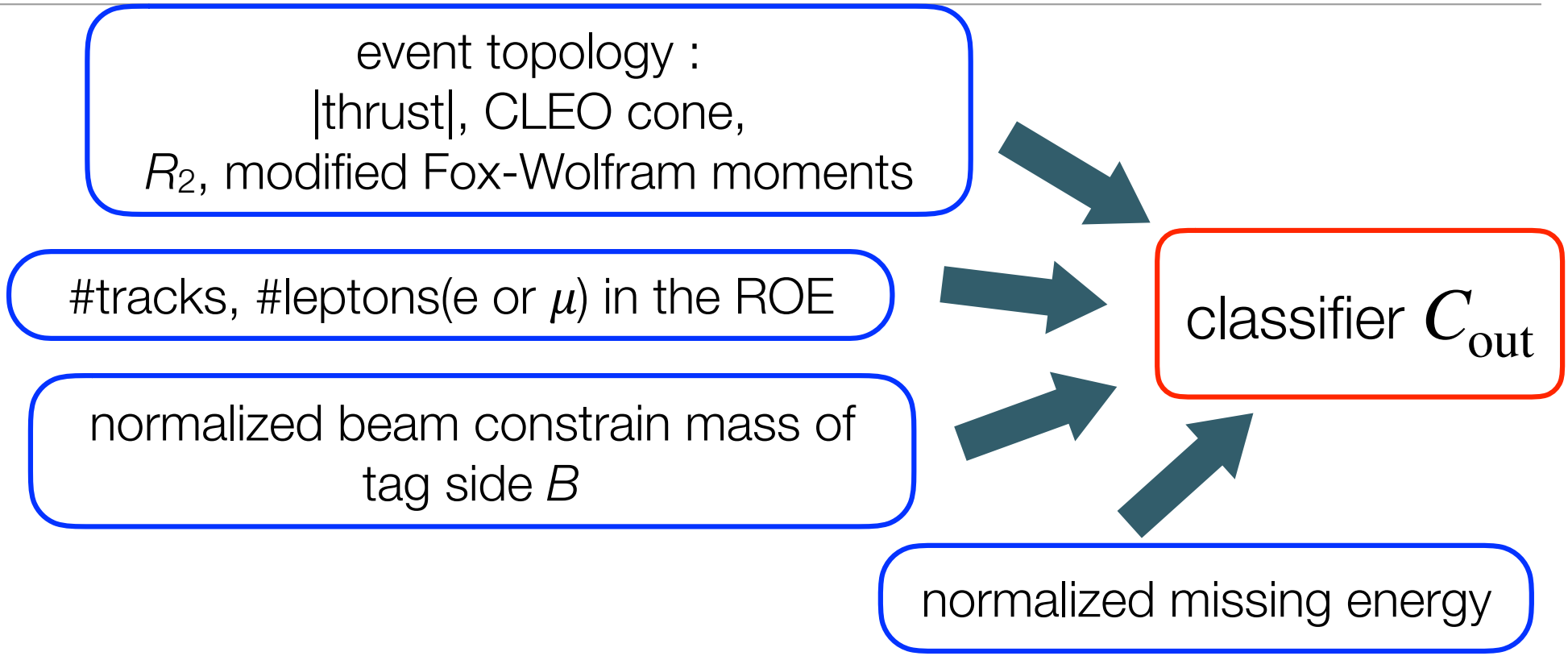
- overall correction factor ζ is also applied

$$\left(\mathbf{p}^*_{\mathrm{tag,cal}}\right)_z = \zeta f\left[\left(\mathbf{p}^*_{\mathrm{tag}}\right)_z\right] \qquad \left(\mathbf{p}^*_{\mathrm{tag,cal}}\right)_T = \zeta\sqrt{\left(\mathbf{p}^*_{\mathrm{tag}}\right)^2 - \left(\mathbf{p}^*_{\mathrm{tag,cal}}\right)^2_z}$$

- calculate tag-side *B* meson three-momentum $\mathbf{p}^*_{\mathrm{tag,cal}}$
- signal side *B* meson momentum $\mathbf{p}_{\mathrm{sig}} = -\mathbf{p}^*_{\mathrm{tag,cal}}$
- muon : boost back to *B* rest frame
- improve resolution and sensitivity
-

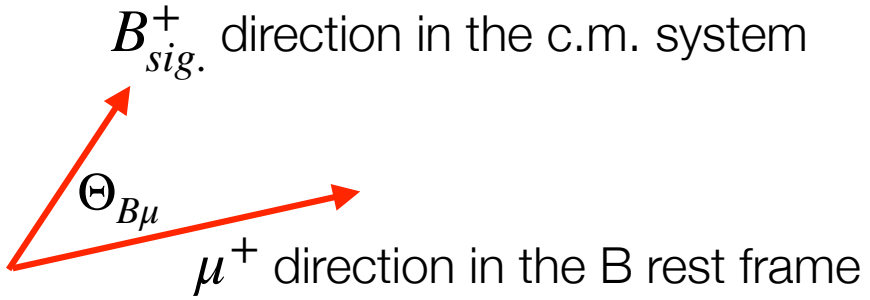


continuum BG suppression



- normalized beam constrain mass of tag side B $\hat{m}_{bc}^{\mathrm{tag}} = \sqrt{s/4 - \left(\mathbf{p}^*_{\mathrm{tag,cal}}\right)^2}/(\sqrt{s}/2)$
- normalized missing energy $\Delta\hat{E} = \left(E^*_{\mathrm{tag,reco}} - \sqrt{s}/2\right)/(\sqrt{s}/2)$, $E^*_{\mathrm{tag,reco}}$: ROE momentum in c.m.s.

- signal : $\cos\Theta_{B\mu}$ dist. is flat
- BG : $\cos\Theta_{B\mu}$ ~ 1
- using C_{out} and $\cos\Theta_{B\mu}$: define 4 categories



four signal categories

Category	C_{out}	$\cos\Theta_{B\mu}$	ε(signal)	
I	0.98 ≦ C_{out} <1.00	-0.13 ≦ $\cos\Theta_{B\mu}$ < 1.00	6.5%	signal enriched
II		-1.00 ≦ $\cos\Theta_{B\mu}$ < -0.13	5.9%	
III	0.93 ≦ C_{out} <0.98	0.04 ≦ $\cos\Theta_{B\mu}$ < 1.00	7.1%	BG enriched
IV		-1.00 ≦ $\cos\Theta_{B\mu}$ < 0.04	8.3%	

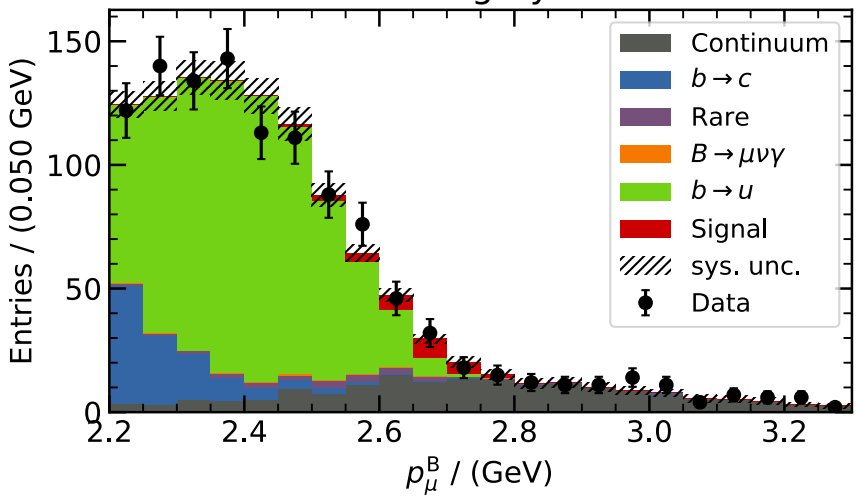
Signal fitting

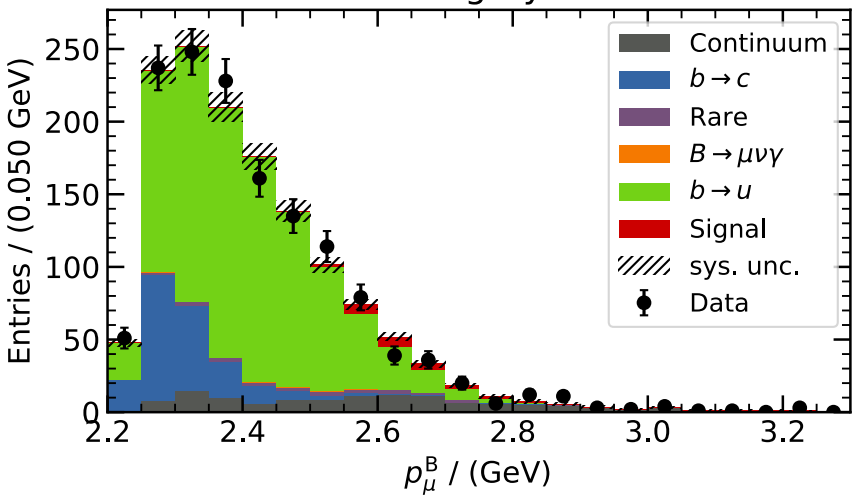
free
- Signal
- $b \to u l \nu_l$ BG
- $b \to c l \nu_l$ BG
- continuum BG

constrained
- $B^+ \to \mu^+ \nu_\mu \gamma$
- rare $b \to s$ process

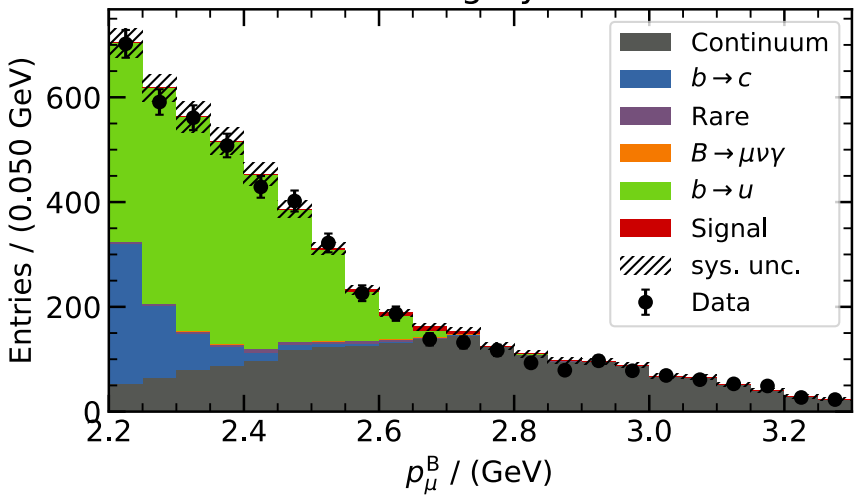
shape can be changed

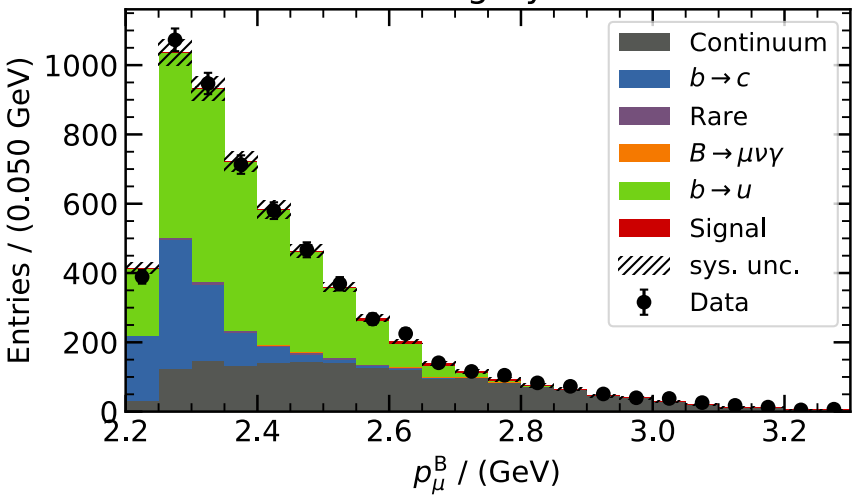
signal enriched





BG enriched



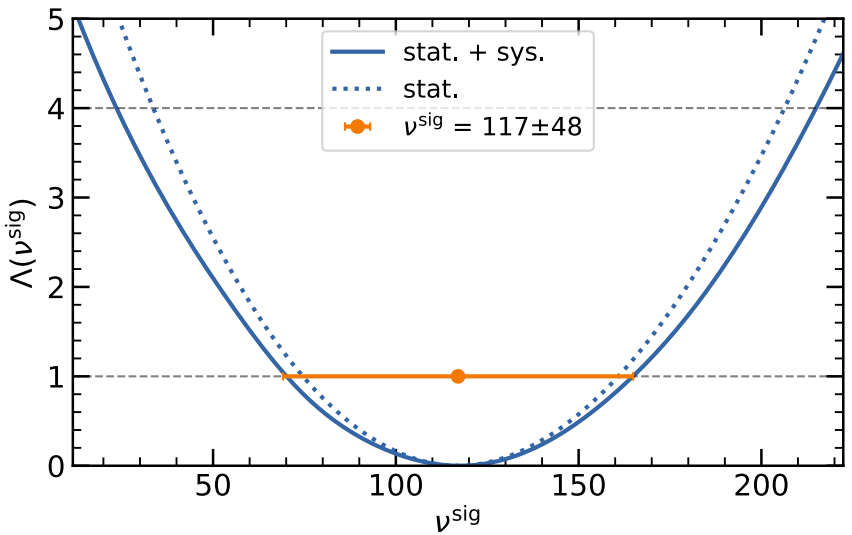


systematic uncertainties

- dominated by
  - $b \to u\ell\nu_\ell$ modeling
  - continuum modeling
    - low statistics of off-resonance data
- incorporated into likelihood function

source	uncertainty
Additive	
$B^+ \to \mu^+\nu_\mu$ MC statistics	1.0%
$b \to ul\nu_l$ modeling	11%
$b \to cl\nu_l$ modeling	2.5%
Br($b \to s$) process	1.0%
Br($B^+ \to \mu^+\nu_\mu\gamma$)	0.02%
Continuum modeling	13.3%
Multiplicative	
N_{BB}	1.4%
Tracking eff.	0.3%
$\mathcal{L}_{LID}$ eff.	2.0%
total	17%

- likelihood ratio contour
- expected #events : 117 ± 48



$$Br(B^+ \to \mu^+ \nu_\mu) = (5.3 \pm 2.0 \pm 0.9) \times 10^{-7}$$

- significance over the BG : 2.8σ (SM expectation : $2.4^{+0.8}_{-0.9}\ \sigma$)

$$|V_{ub}| = \left(4.4^{+0.8}_{-0.9(\text{stat.})} \pm 0.4_{(\text{sys.})} \pm 0.1_{(\text{theo.})}\right) \times 10^{-3} \quad \Leftarrow \quad f_B = 184 \pm 4 \text{ (MeV)}$$

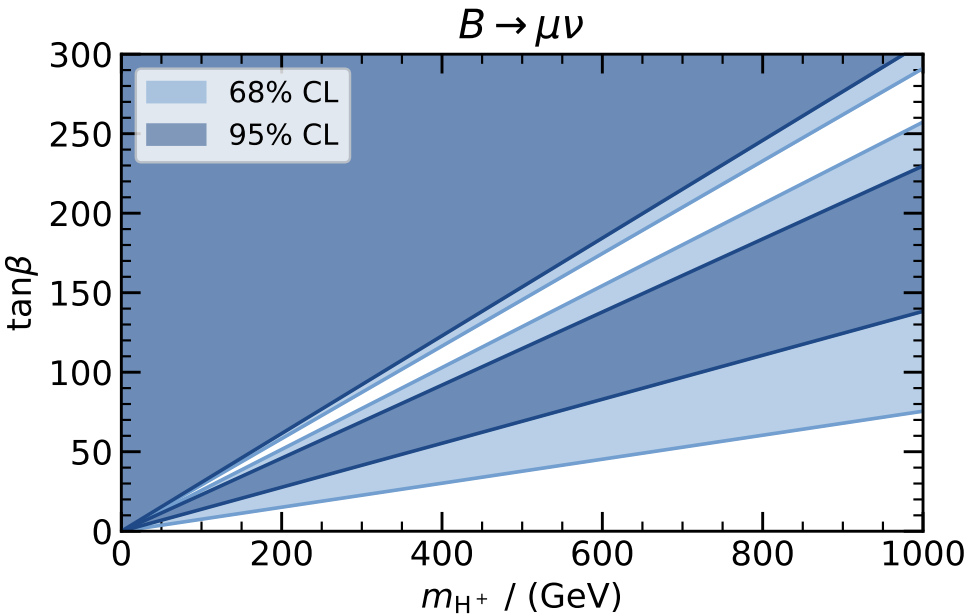
- compatible with both inclusive and exclusive measurements (PDG)

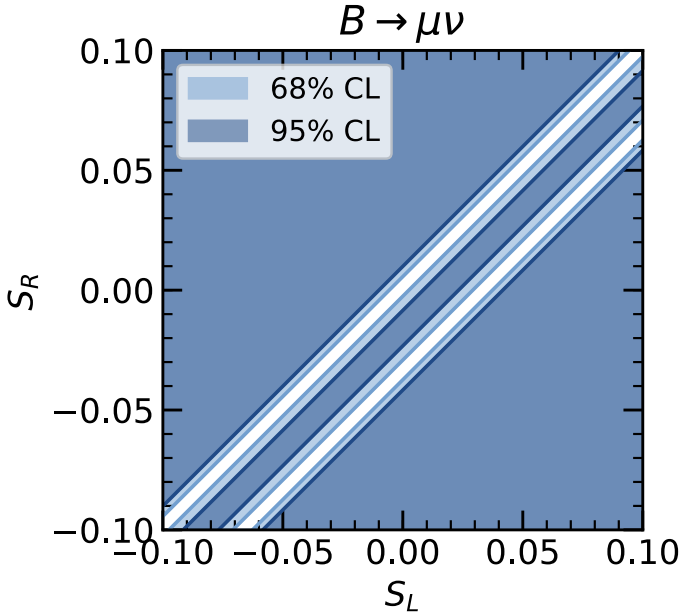
$$|V_{ub}| = \left(4.49 \pm 0.16_{(\text{stat.})}\ ^{+0.16}_{-0.17}\ _{(\text{sys.})} \pm 0.17_{(\text{theo.})}\right) \times 10^{-3}$$

$$|V_{ub}| = \left(3.67 \pm 0.09 \pm 0.12\right) \times 10^{-3}$$

- low significance : set upper limit
- $Br(B^+ \to \mu^+ \nu_\mu) < 8.6 \times 10^{-7}$ at 90 % CL . (Frequentist)

2HDM : type II and type III





$$Br(B^+ \to \mu^+\nu_\mu) = Br^{\mathrm{SM}} \times \left(1 - \frac{m_B^2 \tan^2\beta}{m_{H^+}^2}\right)^2$$

$$Br(B^+ \to \mu^+\nu_\mu) = Br^{\mathrm{SM}} \times \left(1 + \frac{m_B^2}{m_b m_\mu}\left(S_R - S_L\right)\right)^2$$

$\tan\beta$: ratio of the vacuum expectation values of 2 Higgs fields

$S_{R/L}$: sizes of new physics

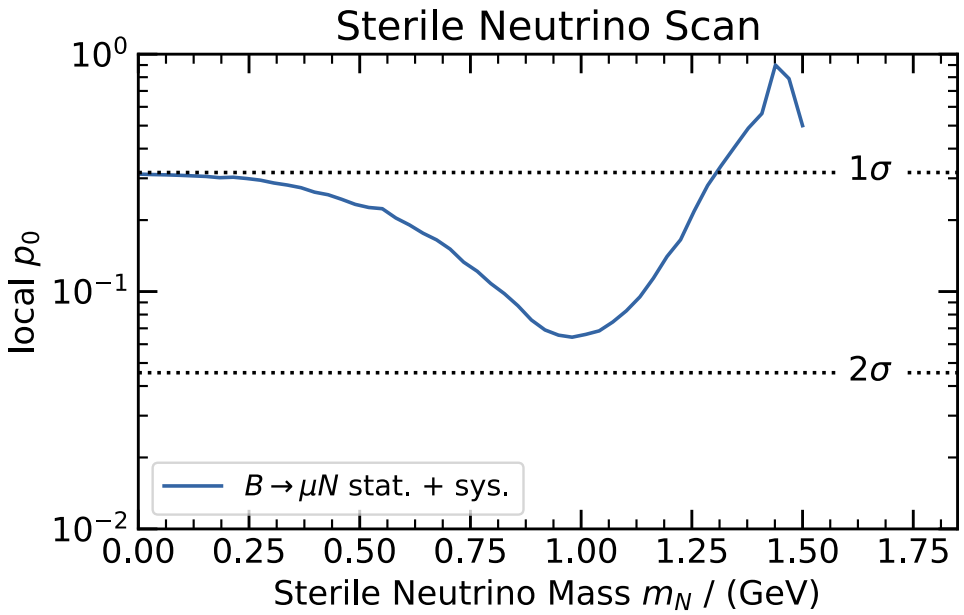
- more precise limit for type III than $B^+ \to \tau^+\nu_\tau$

$$Br^{\mathrm{SM}} = (4.3 \pm 0.8) \times 10^{-7}$$

$$|V_{ub}| = (3.94 \pm 0.36) \times 10^{-3}$$

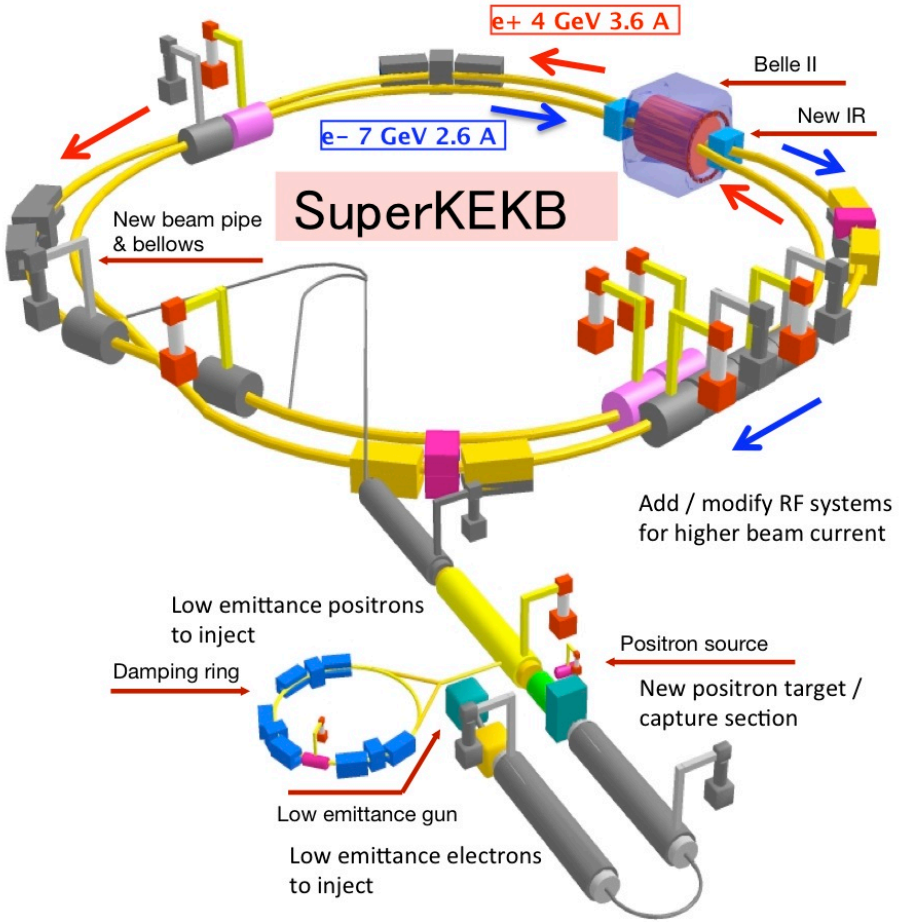
search for $B^+ \to \mu^+ N$

- $B^+ \to \mu^+ \nu_\mu$ contribution : fixed to Br^{SM}
- search excess in p_μ^B distribution
- No significant excess
  - $0 \leq m_N < 1.5$ GeV/c^2

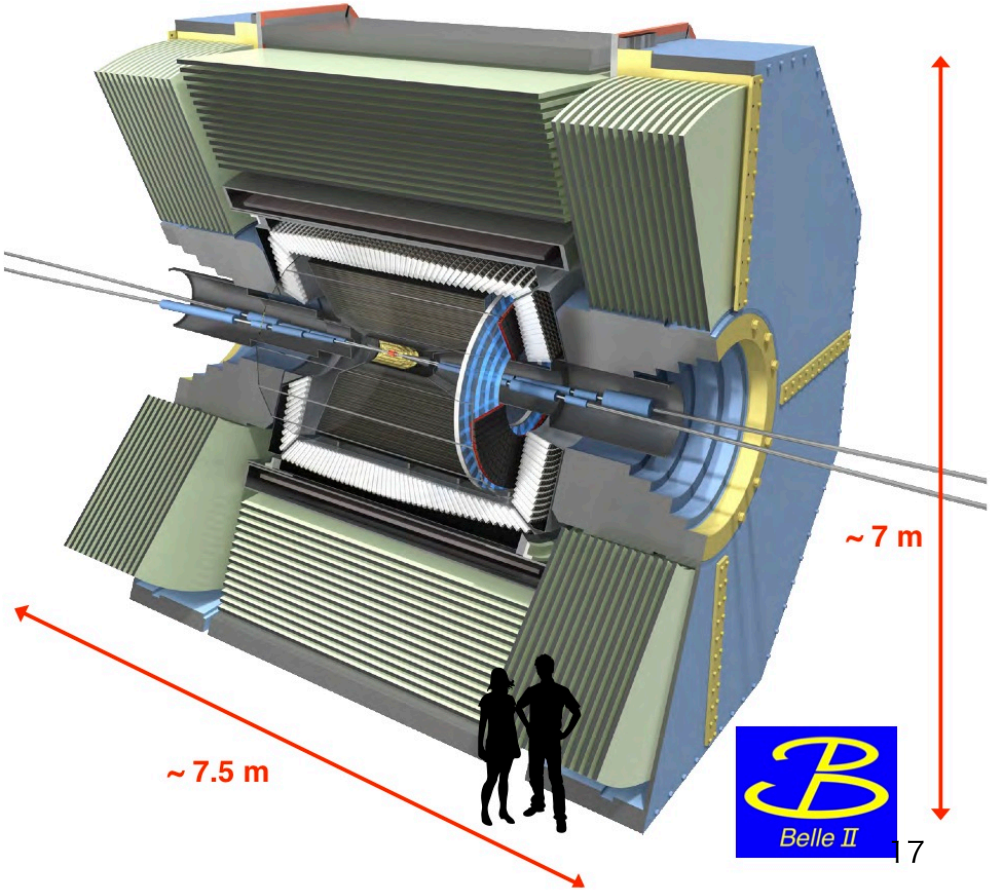


future prospects in Belle II

SuperKEKB : x40 luminosity of KEKB

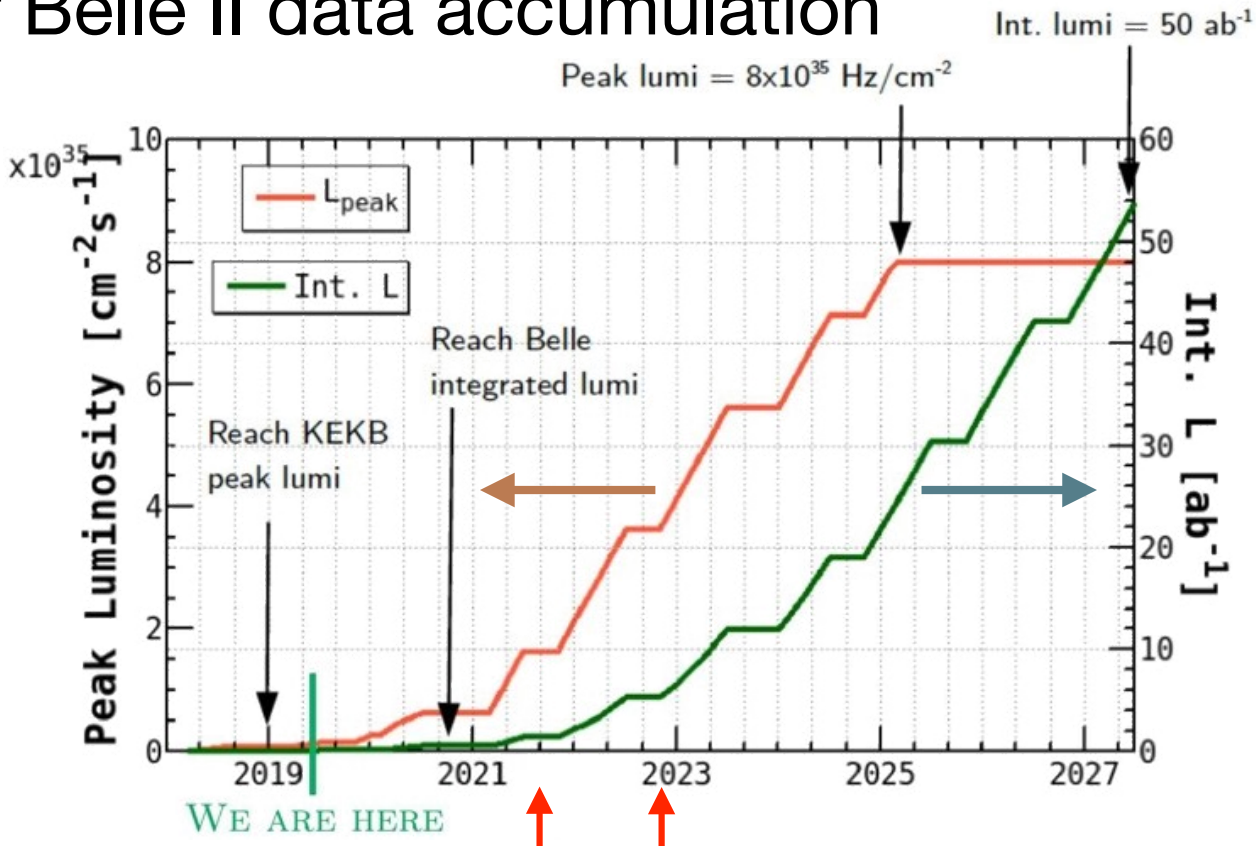


Belle II upgraded for irradiation rate capability, data transfer



prospect of $B^+ \to \mu^+ \nu_\mu$ search

prospect of Belle II data accumulation



~5 ab^{-1} (>x7 of Belle) : hope to be $> 5\sigma$

~2 ab^{-1} (x3 of Belle) : $> 3\sigma$ can be expected

Summary and Conclusions

- improved search of $B^+ \to \mu^+\nu_\mu$ and $B^+ \to \mu^+ N$ using full dataset of Belle with inclusive tagging
- analysis is carried out in the approximative *B* rest frame of signal side *B*
- This results in better signal resolution and improved sensitivity than CM frame analysis
- *Br* is determined using binned maximum likelihood fit of muon momentum spectrum
- $Br(B^+ \to \mu^+\nu_\mu) = (5.3 \pm 2.0 \pm 0.9) \times 10^{-7}$ (2.8σ significance)
- $Br(B^+ \to \mu^+\nu_\mu) < 8.6 \times 10^{-7}$ at $90\,\%$ CL. Frequentist
- limit to the type III 2HDM : most precise
- in near future, evidence or observation of $B^+ \to \mu^+\nu_\mu$ process can be expected

spare

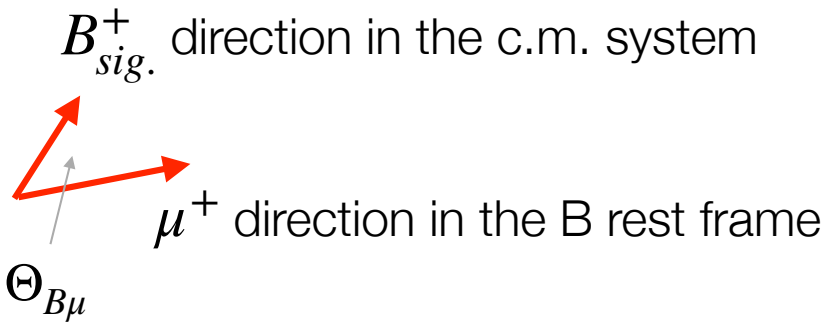
- $Br(B^+ \to \tau^+ \nu_\tau)$
  - $(1.09 \pm 0.24) \times 10^{-4}$ (PDG average)
  - $[1.25 \pm 0.28(\text{stat.}) \pm 0.27(\text{syst.})] \times 10^{-4}$ Belle semileptonic tag PRD92, 051102 (2015), 222 ±50, 3.8σ
  - $[0.72^{+0.27}_{-0.25}(\text{stat.}) \pm 0.11(\text{syst.})] \times 10^{-4}$ Belle hadronic tag PRL110, 131801 (2013), 62^{+23}_{-22}(stat) ±6(syst), 3.0σ
  - $[1.83^{+0.53}_{-0.49}(\text{stat.}) \pm 0.24(\text{syst.})] \times 10^{-4}$ BaBar hadronic tag PRD88, 031102 (2013), 62.1±17.3, 4.2σ
  - $[1.7 \pm 0.8(\text{stat.}) \pm 0.2(\text{syst.})] \times 10^{-4}$ BaBar semileptonic tag RPD81, 051101(2010), , 2.8σ

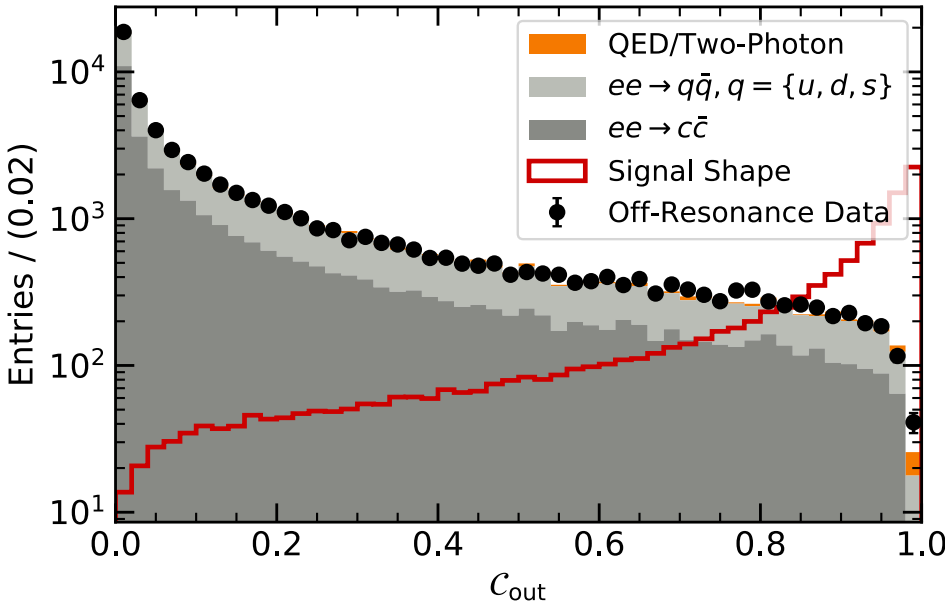
- Expected number of events in Belle II (Belle II P.B.)

	711 fb^{-1} (Belle)	5 ab^{-1} (Belle II)	50 ab^{-1} (Belle II)
$B^+ \to \tau^+\nu_\tau$	(612±50)x10^2	(430±35)x10^3	(430±35)x10^4
$B^+ \to \mu^+\nu_\mu$	275±23	1930±160	(193±16)x10^2

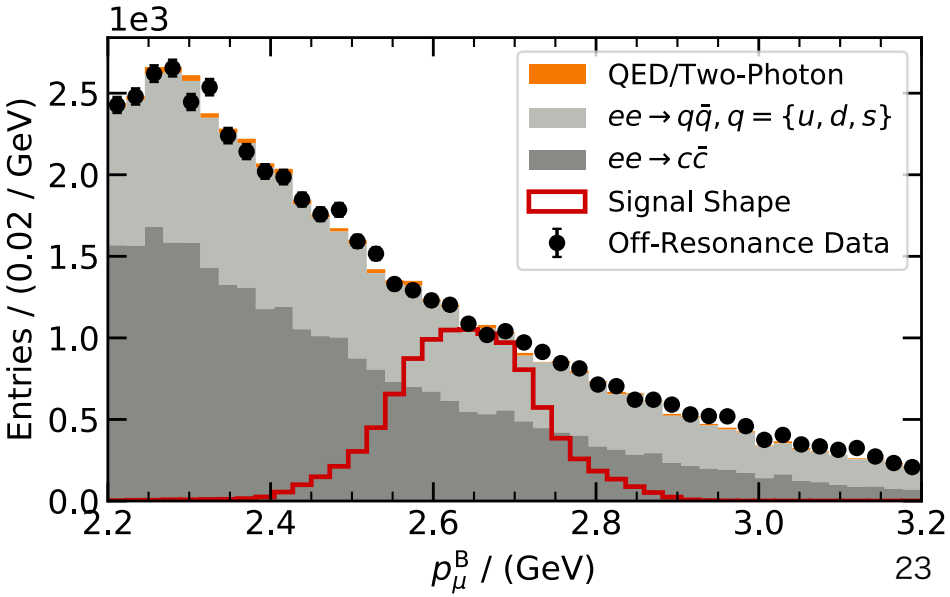
- assuming
  - $Br(B^+ \to \tau^+\nu_\tau) = (7.71 \pm 0.62) \times 10^{-5}$ and
  - $Br(B^+ \to \mu^+\nu_\mu) = (3.46 \pm 0.28) \times 10^{-7}$ with
  - $|V_{ub}| = (3.55 \pm 0.12) \times 10^{-3}$ and $f_B = 186 \pm 4$ MeV
- 3σ significance is expected at ~2 ab^{-1} for $B^+ \to \mu^+\nu_\mu$ process

- compare continuum sim. & off-resonance data
  - good agreement
- using C_{out} and $\cos\Theta_{B\mu}$





- signal : $\cos\Theta_{B\mu}$ dist. is flat
- BG : $\cos\Theta_{B\mu}$ ~ 1
- define 4 categories



Signal fitting

- simultaneous binned likelihood fit to the p_μ^B spectra of four categories
- total likelihood function

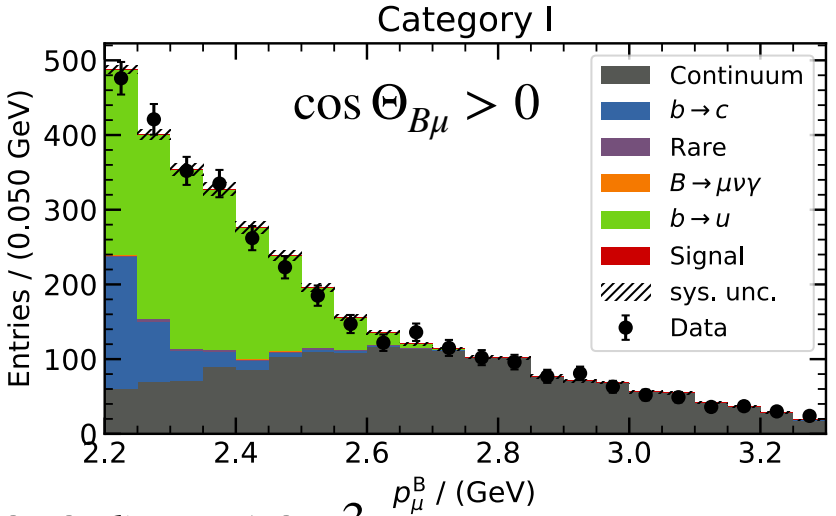
$$\mathcal{L} = \prod_c \mathcal{L}_c \times \prod_k \mathcal{G}_k$$

  - L_C : individual category likelihood (c : categories)
  - G_k : systematics (k : BG components)
- $2.2 \leq p_\mu^B < 3.3$ (GeV/c) : 22 bins (50 MeV/c each)

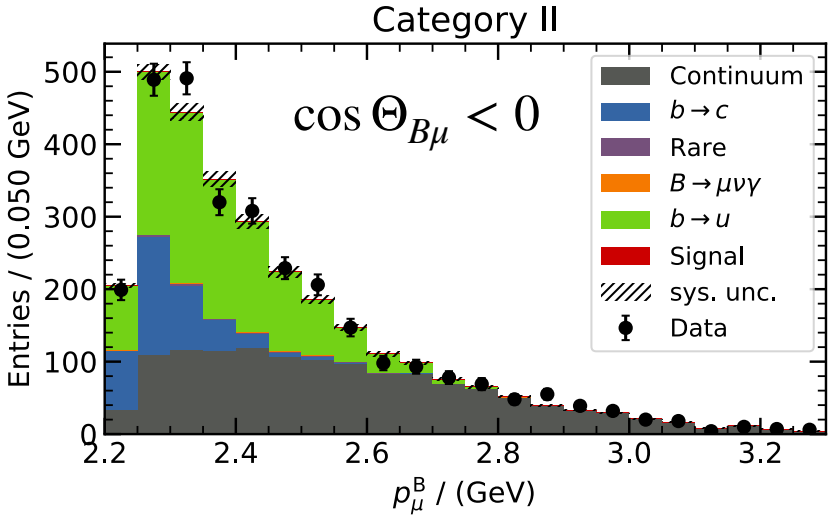
$b \to u\ell\nu_\ell$ control region

- test the simulation of crucial BG
- signal depleted region with moderate continuum contamination
  - $0.90 \leq C_{\text{out}} < 0.93$
- high p_μ^B region : validity for continuum description
- $2.2 < p_\mu^B\ (\text{GeV}/c) < 2.6$: dominated by $b \to u\ell\nu_\ell$ and $b \to c\ell\nu_\ell$
-

- $B^+ \to \mu^+ \nu_\mu$ yields : fixed to SM (~15 events each)
- templates describe data well
- $b \to c\ell\nu_\ell$, $b \to u\ell\nu_\ell$ and continu
- signal is floated : yield is -31+-61



$$Br(B \to X_u \ell^+ \nu_\ell) = (2.04 \pm 0.10 \pm 0.06) \times 10^{-3}$$



- $$Br(B \to X_u \ell^+ \nu_\ell) = (2.13 \pm 0.31) \times 10^{-3}$$

cumulative selection efficiencies

criteria	$B^+ \to \mu^+ \nu_\mu$	$b \to u l \nu_l$	Continuum
BB & muon reco.	99%	10%	0.9%
ROE Presel.	55%	1.4%	0.03%
C_{out} cut	28%	0.2%	0.001%

off-resonance control region

- $0.93 \leq C_{\text{out}} < 1$ of off-resonance data
- two components fit
  - signal yield : 1.8 ± 7
  - continuum yield : 37 ± 10