B Leptonic Decay

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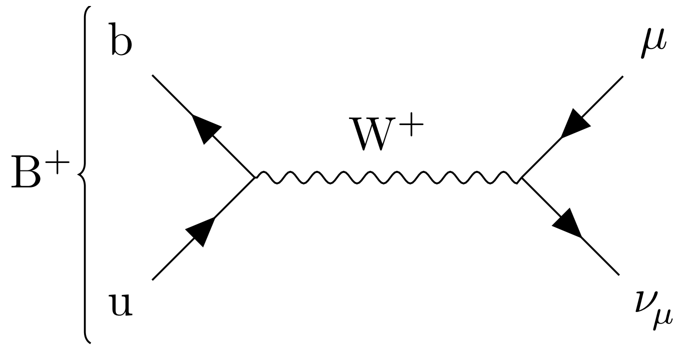
Introduction

- B meson leptonic decay : test the validity of the Standard Model of particle physics

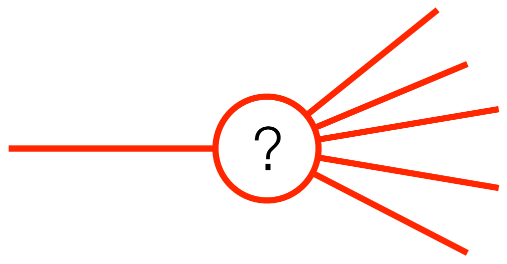


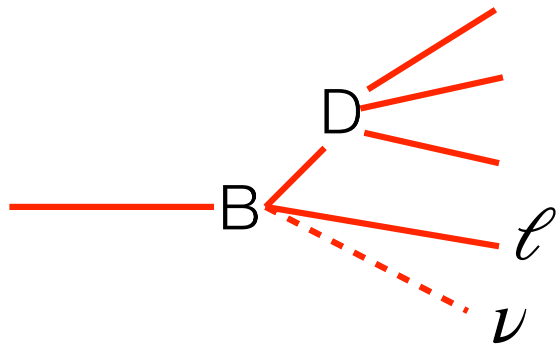
- $$Br(B^+ \to \ell^+ \nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B^2$$
    - G_F : Fermi constant, $m_{B/l}$: mass of B meson or lepton, V_{ub} : CKM matrix element, τ_B : B meson lifetime, f_B : B meson decay constant
    - *b*-*u* quark 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))

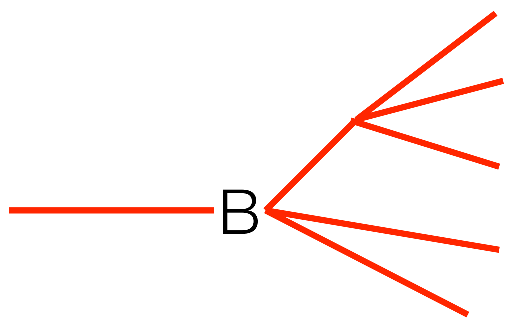
- improved search for $B^+ \to \mu^+\nu_\mu$ than previous our publish (Phys. Rev. Lett. 121, 031801 (2018))
- World Averaged values (PDG)
  - $|V_{ub}| = \left(4.49 \pm 0.16_{(\mathrm{stat.})} \ {}^{+0.16}_{-0.17} \ _{(\mathrm{sys.})} \pm 0.17_{(\mathrm{theo.})}\right) \times 10^{-3}$ (inclusive meas.)
  - $|V_{ub}| = \left(3.67 \pm 0.09 \pm 0.12\right) \times 10^{-3}$ (exclusive meas.)
  - $|V_{ub}| = \left(3.94 \pm 0.36\right) \times 10^{-3}$ combine inclusive and exclusive
- SM calculation with $f_B = 184 \pm 4 \ \mathrm{MeV}$
  - $Br(B^+ \to \mu^+\nu_\mu) = (4.3 \pm 0.8) \times 10^{-7}$ (inclusive $|V_{ub}|$)
  - $Br(B^+ \to \mu^+\nu_\mu) = (3.7 \pm 0.4) \times 10^{-7}$(exclusive $|V_{ub}|$)
  - ~300 events in full Belle data set at $\Upsilon(4s)$ ($= 711 \mathrm{fb}^{-1}$)

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

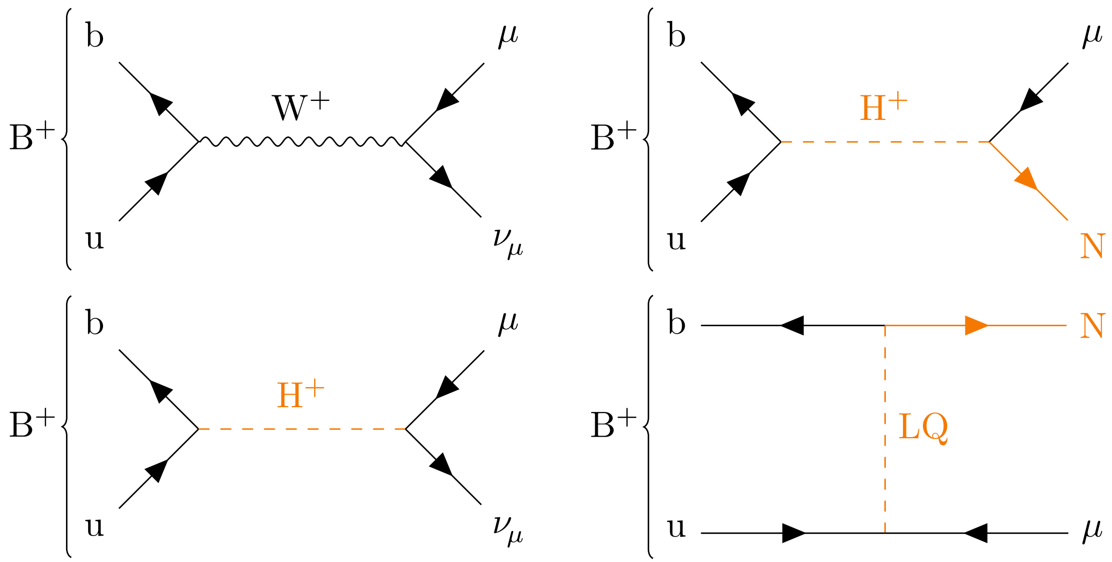






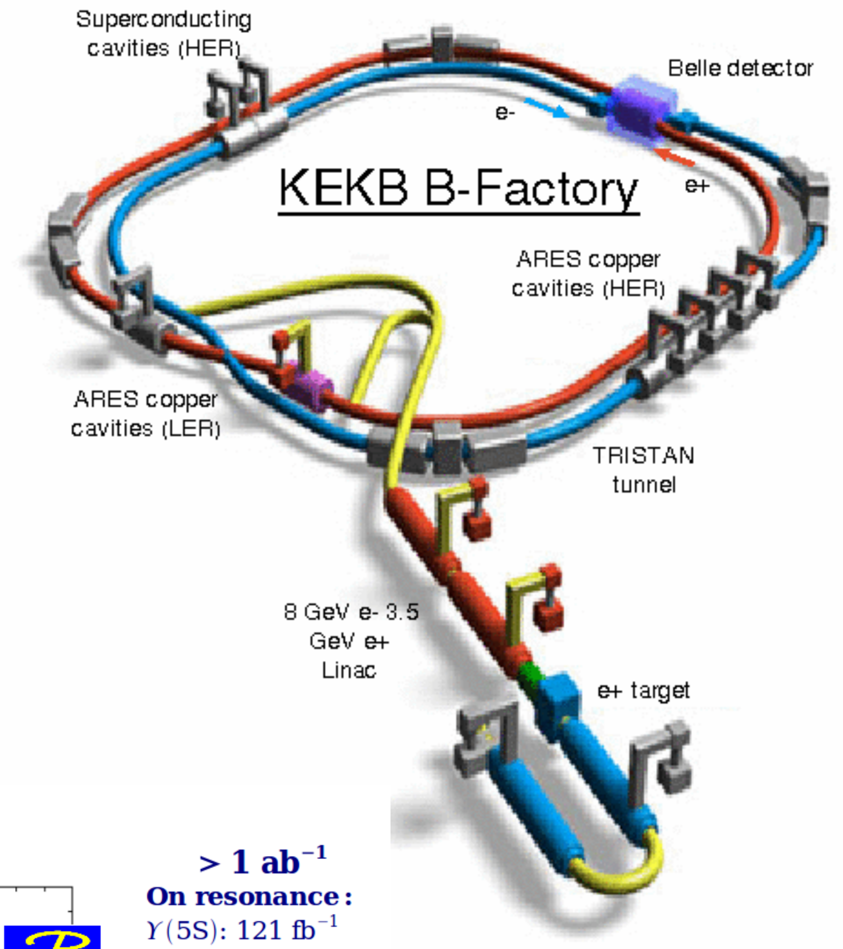
New Physics

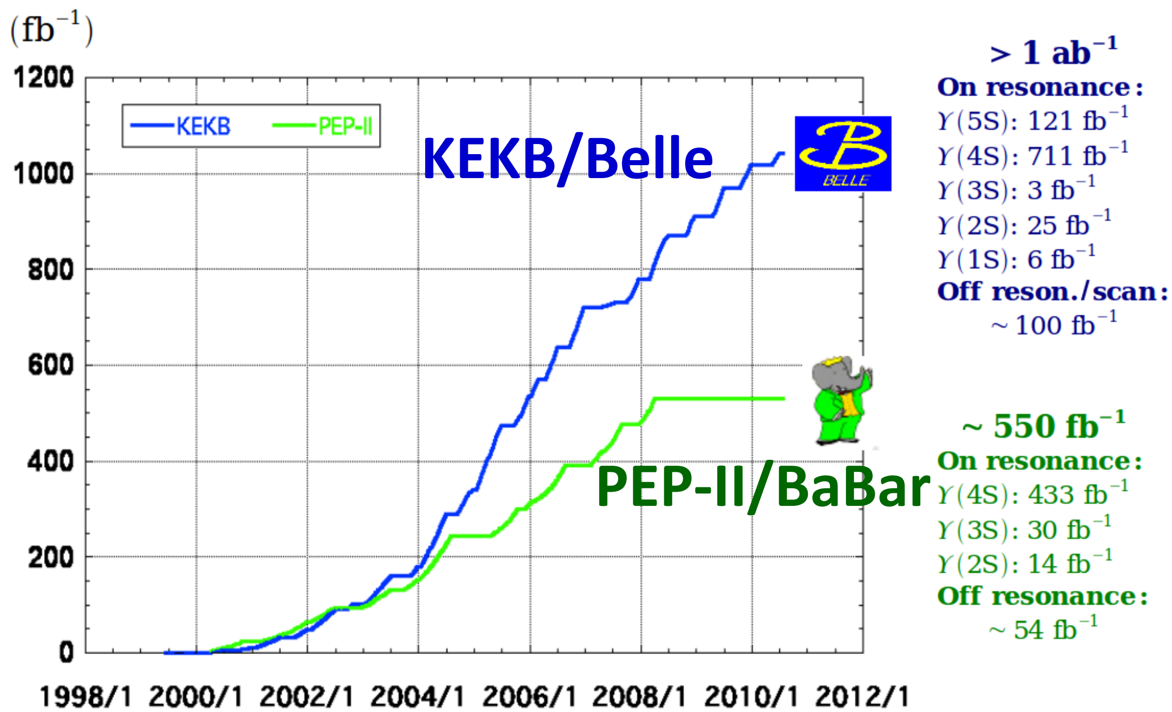
- deviates cross section from SM prediction
  - charged Higgs or LQ
  - sterile neutrino

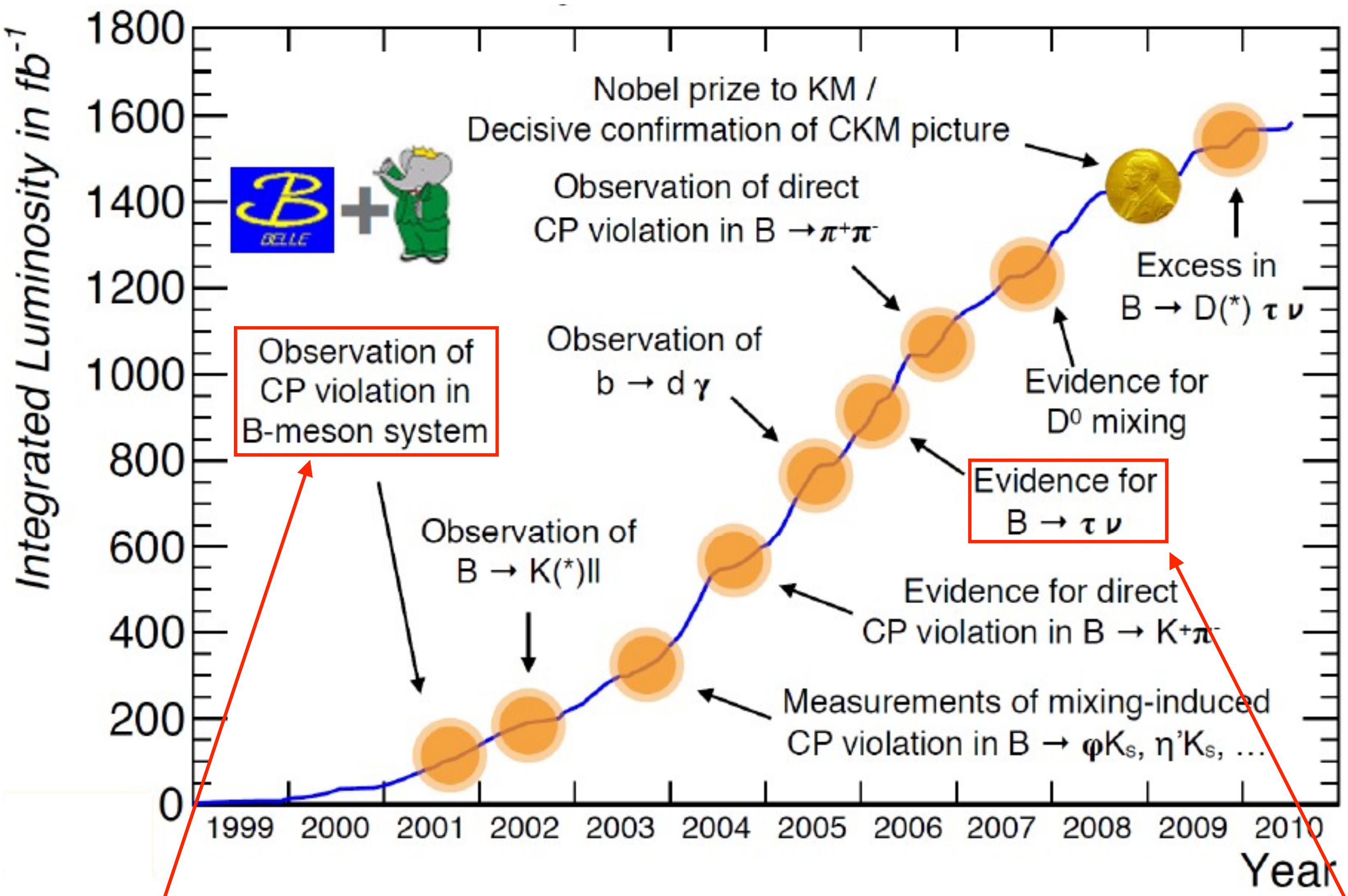


KEKB accelerator

- 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)





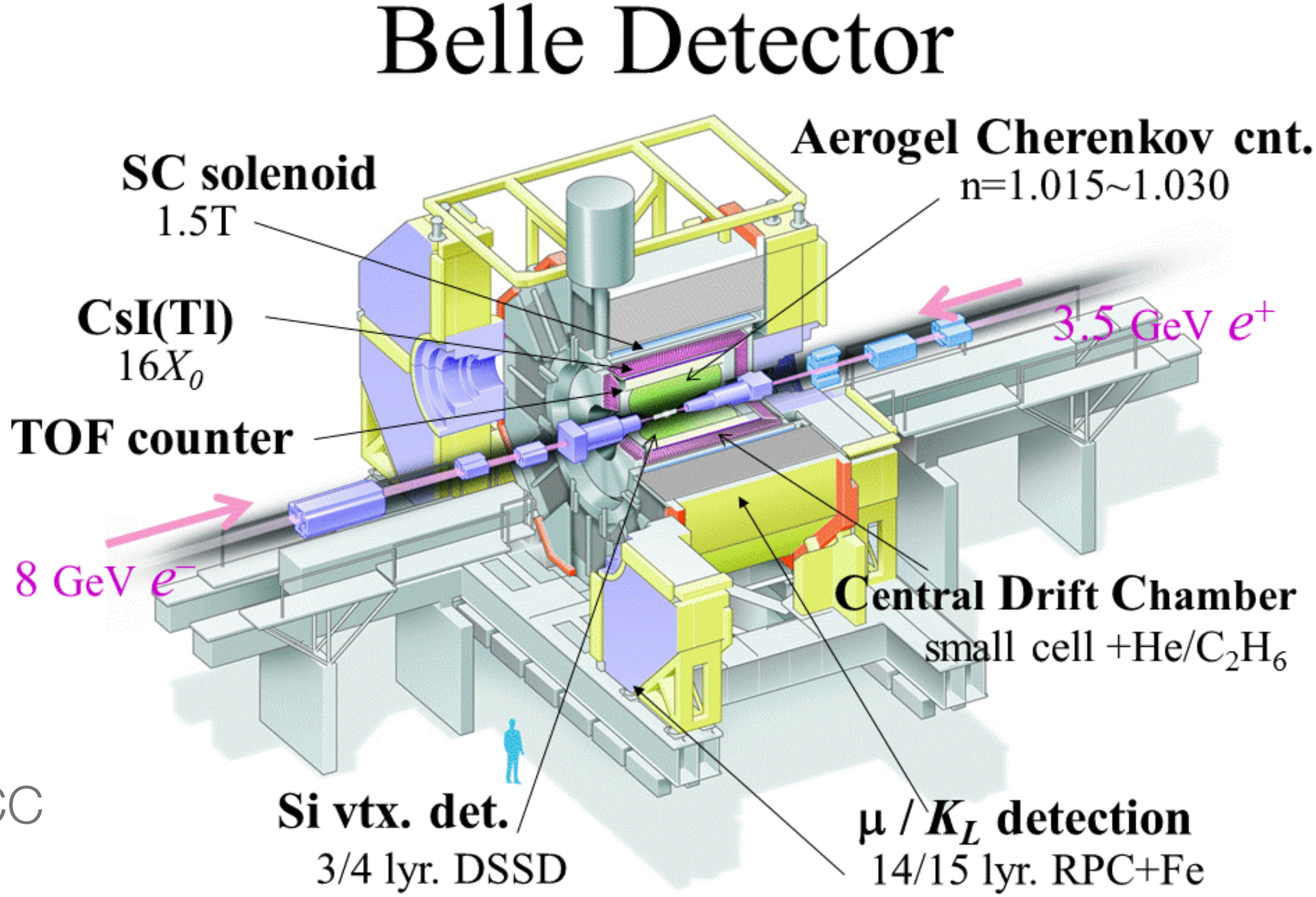


The 1st mile stone of
B-factory experiments

evidence for pure leptonic B decay
similar to this analysis

Belle detector

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

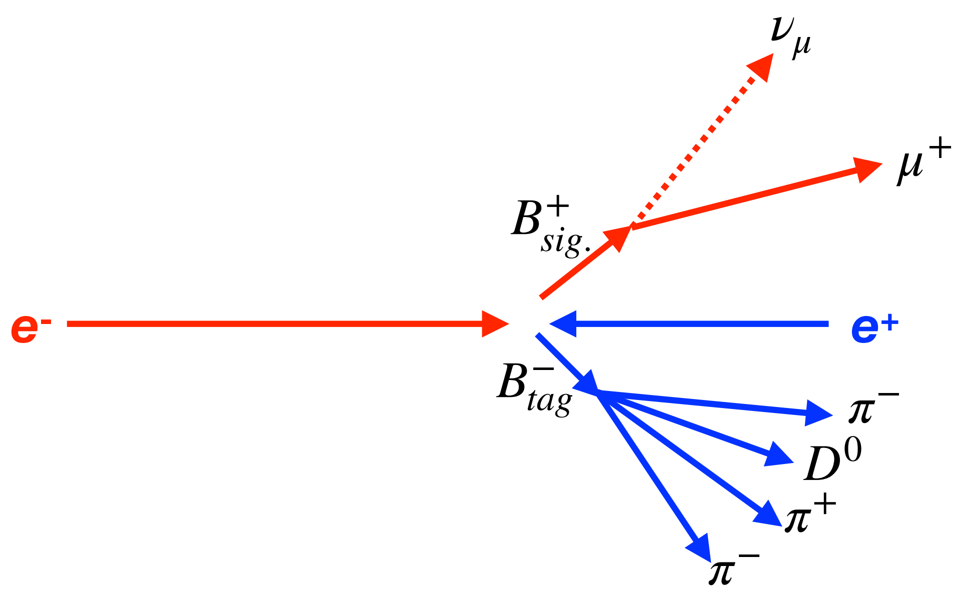


Analysis strategy

Select $B\bar{B}$ events
#charged ≥ 3
significant energy in ECL in c.m.s.

reconstruct signal side B
muon candidate
$p_\mu^* > 2.2~\mathrm{GeV}/c$
dr < 0.5 cm, |dz| < 2.0 cm

~99.8% eff.



reconstruct rest-of-the-evevnt(ROE)
remaining tracks(as pion)/clusters
dr < 10 cm, |dz| < 20 cm

$$\mathbf{p}^{\mathrm{lab}}_{\mathrm{tag}} = \sum_i^{\mathrm{tracks}} \mathbf{p}_i^{\mathrm{lab}} + \sum_j^{\mathrm{clusters}} \mathbf{E}_j^{\mathrm{lab}}$$

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

$$\mathbf{p}^{\text{lab}}_{\text{tag}} = \sum_i^{\text{tracks}} \mathbf{p}^{\text{lab}}_i + \sum_j^{\text{clusters}} \mathbf{E}^{\text{lab}}_j$$

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

lab. frame

$$E^*_{\text{tag}} = \sqrt{(\mathbf{p}^*_B)^2 + m_B^2} = \sqrt{(330\text{MeV}/c)^2 + m_B^2}$$

$$\mathbf{p}^*_{\text{tag}}$$

center-of-mass frame

detector acceptance leads

momentum uncertainty : bias to $\left(\mathbf{p}^*_{\text{tag}}\right)_z$

correct $\left(\mathbf{p}^*_{\text{tag}}\right)_z$ by applying calibration function *f*

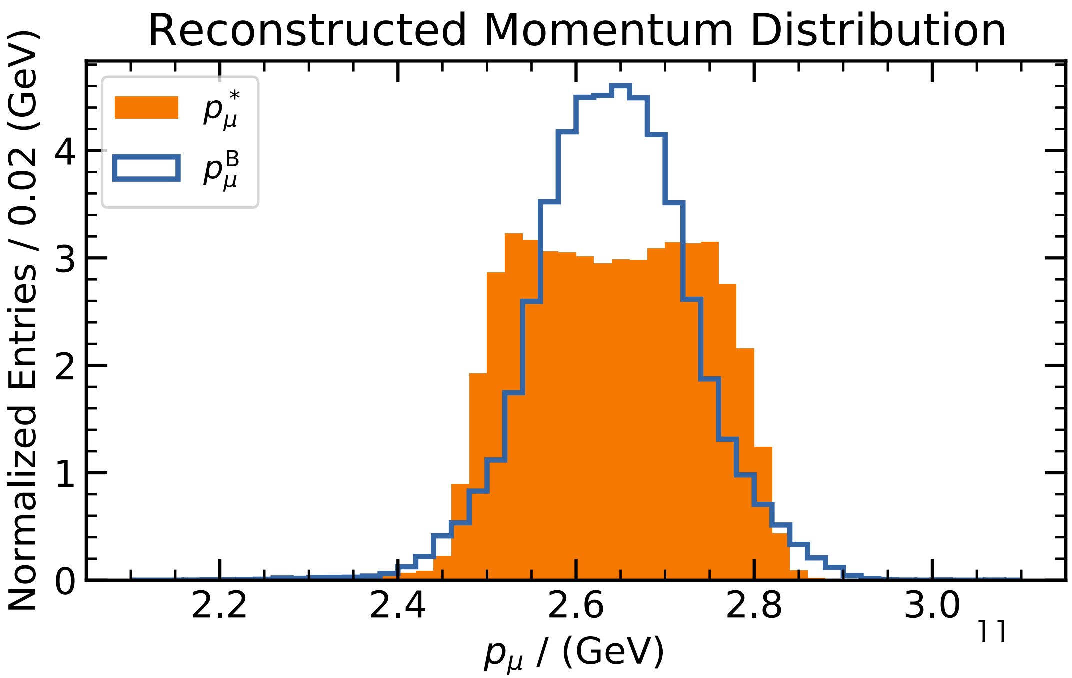
f shifts mean of $\left(\mathbf{p}^*_{\text{tag}}\right)_z$ to true distribution

f : calibrated using signal MC events

- overall correction factor ζ is also applied

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

- 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

- multivariable classifier C_{out} using gradient-BDTs
- input : event topology

magnitude of thrust, CLEO cones,
R_2, modified Fox-Wolfram moments

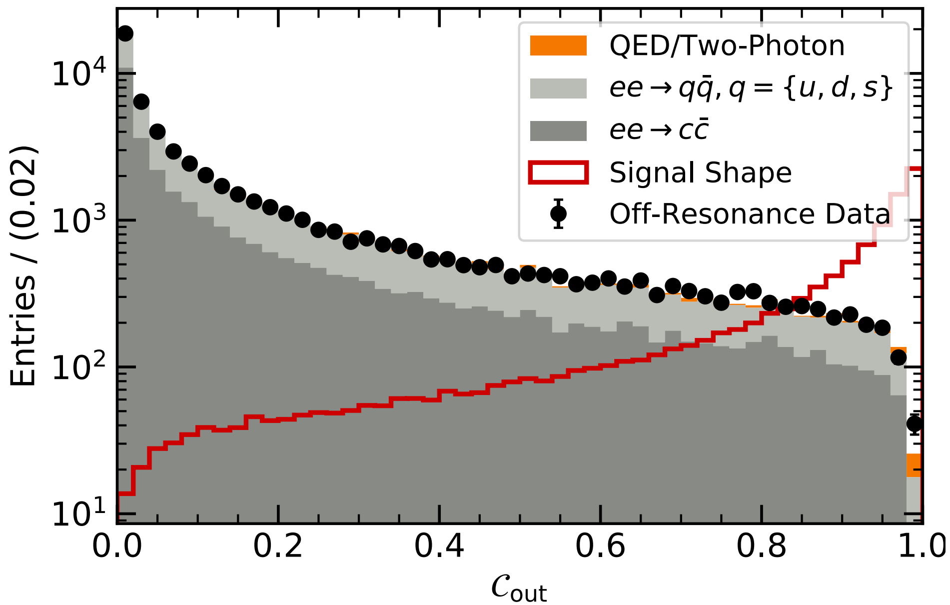
- #track and #leptons(electron or muon) in the ROE,
- normalized beam constrain mass of tag side B

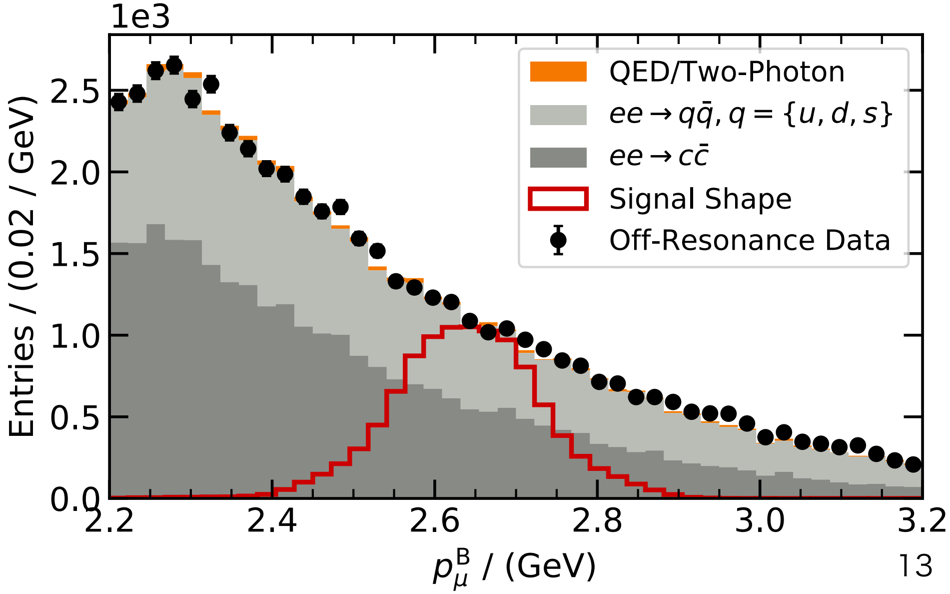
. $\hat{m}_{bc}^{\text{tag}} = \sqrt{s/4 - \left(\mathbf{p}^{*}_{\text{tag,cal}}\right)^2} / (\sqrt{s}/2)$

- normalized missing energy

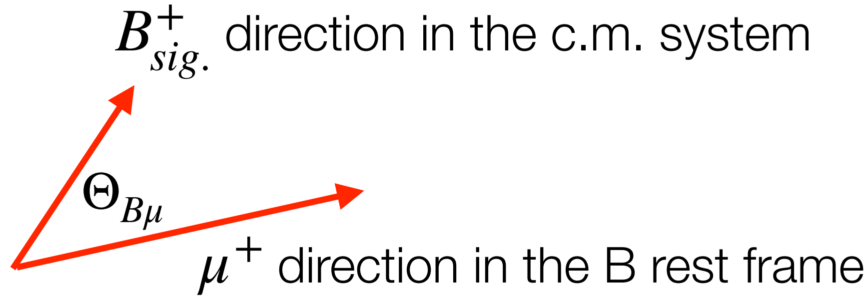
. $\Delta\hat{E} = \left(E^{*}_{\text{tag,reco}} - \sqrt{s}/2\right) / (\sqrt{s}/2)$, $E^{*}_{\text{tag,reco}}$: ROE momentum in c.m.s.

- apply loose selection to ROE
  - #tracks >= 2
  - #leptons < 3
  - $\hat{m}_{bc}^{\mathrm{tag}} > 0.96$
  - $-0.5 \leq \Delta\hat{E} < 0.1$
  - $R_2 < 0.2$
- continuum sim. vs
- off-resonance data
  - good agreement





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



four signal categories

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

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)

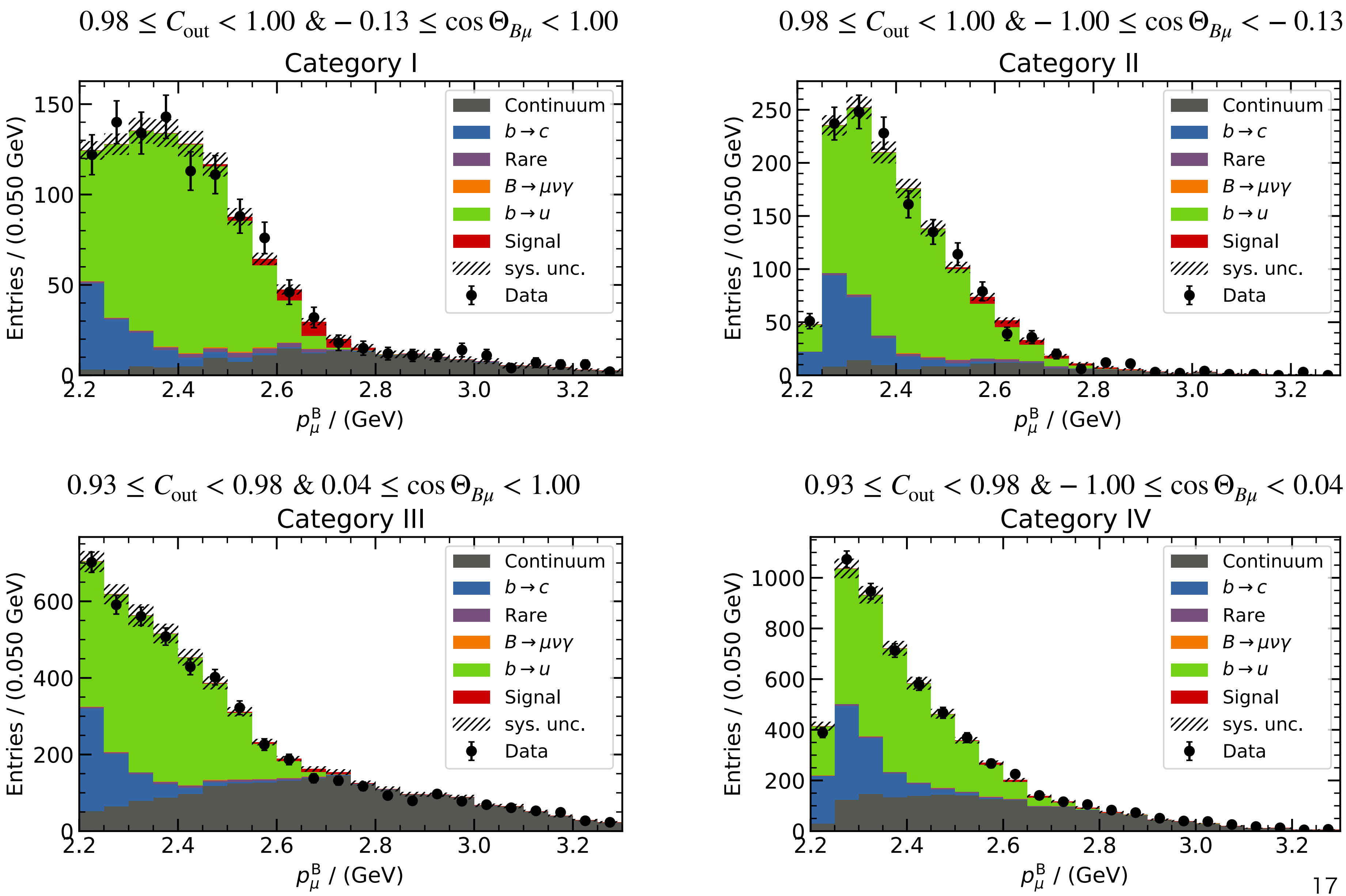
  - G_k : systematics (k : BG components)

- $2.2 \leq p_\mu^B < 3.3$ (GeV/c) : 22 bins (50 MeV/c each)

- four components : free
  - Signal $B^+ \to \mu^+ \nu_\mu$ events
  - BG $b \to u \ell \nu_\ell$ events
  - BG $b \to c \ell \nu_\ell$ events (dominated by $B \to D^{(*)} \ell^+ \nu_\ell$)
  - BG continuum
- two other BG : $B^+ \to \mu^+ \nu_\mu \gamma$, rare $b \to s$ processes
  - constrained in the fit
  - shape are allowed to vary within uncertainties

fit results

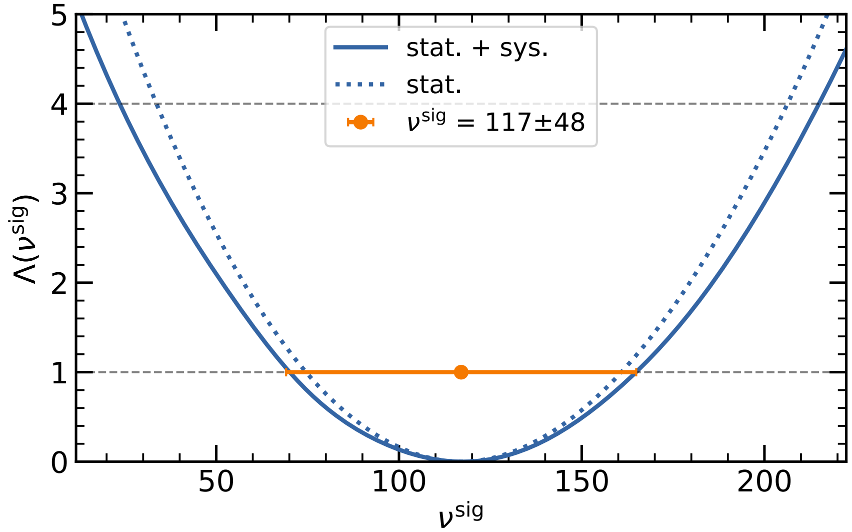
signal enriched



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%
$\mathcal{L}_{\mathrm{LID}}$ 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 : $2.4^{+0.8}_{-0.9}\ \sigma$)

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

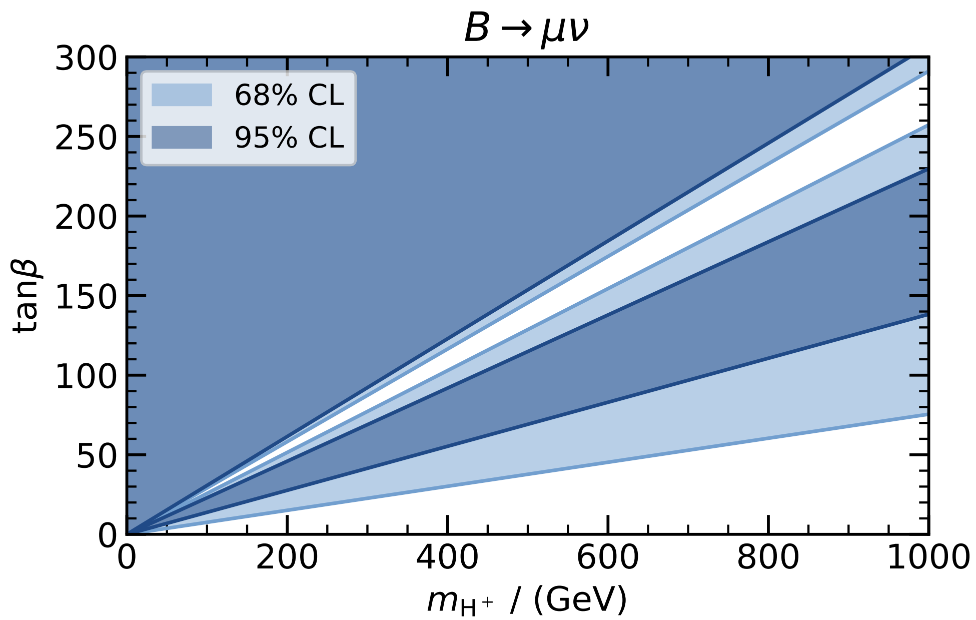
- compatible with both inclusive and exclusive measurements (PDG)

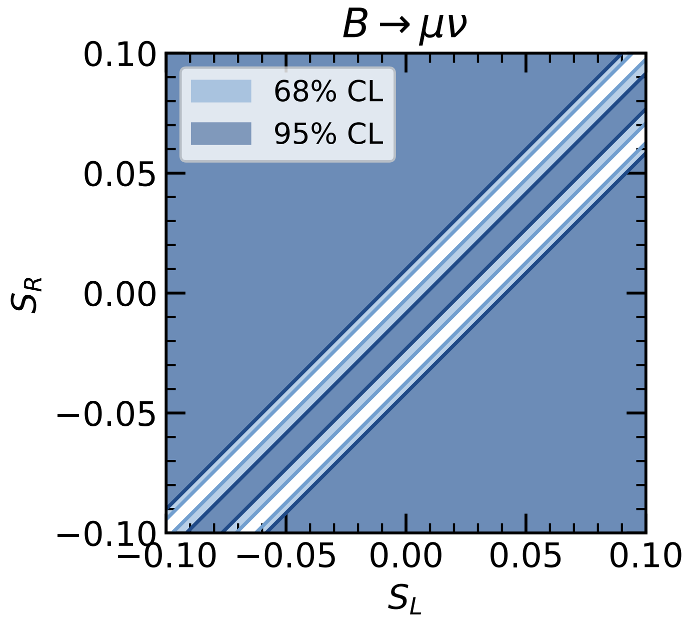
$$|V_{ub}| = \left(4.49 \pm 0.16_{(\text{stat.})}\ {}^{+0.16}_{-0.17}\ {}_{(\text{sys.})} \pm 0.17_{(\text{theo.})}\right) \times 10^{-3}$$

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

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

- constrain 2HDM of type II and type III
- type II
  - $$Br(B^+ \to \mu^+ \nu_\mu) = Br^{\mathrm{SM}} \times \left(1 - \frac{m_B^2 \tan^2 \beta}{m_{H^+}^2}\right)^2$$
  - $\tan \beta$: ratio of the vacuum expectation values of 2 Higgs fields
- type III
  - $$Br(B^+ \to \mu^+ \nu_\mu) = Br^{\mathrm{SM}} \times \left(1 + \frac{m_B^2}{m_b m_\mu}\left(S_R - S_L\right)\right)^2$$
  - $S_{R/L}$: size of new physics cont





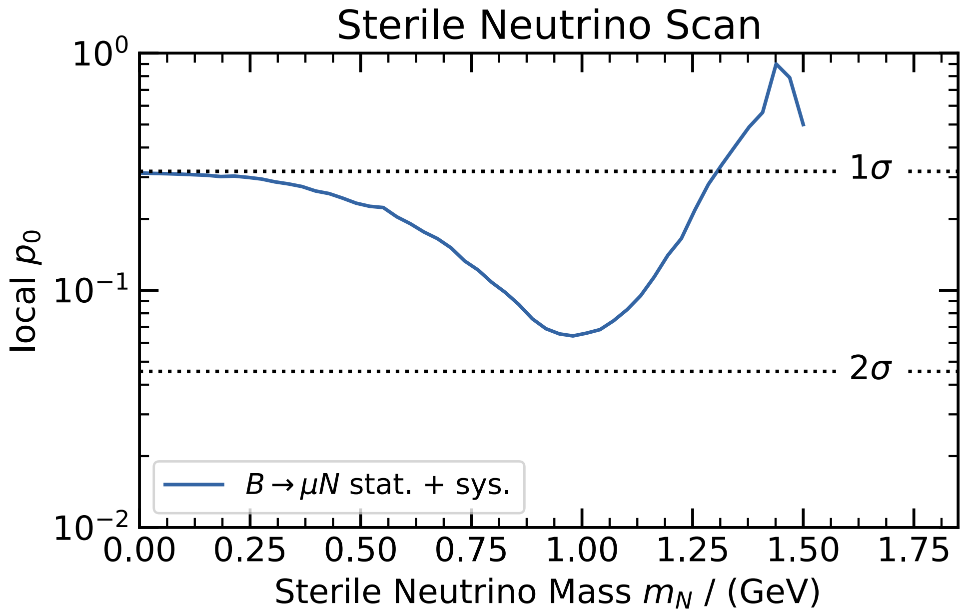
$$Br(B^+ \to \mu^+\nu_\mu) = Br^{\rm SM} \times \left(1 - \frac{m_B^2 \tan^2\beta}{m_{H^+}^2}\right)^2 \qquad Br(B^+ \to \mu^+\nu_\mu) = Br^{\rm SM} \times \left(1 + \frac{m_B^2}{m_b m_\mu}\left(S_R - S_L\right)\right)^2$$

$$Br^{\rm SM} = (4.3 \pm 0.8) \times 10^{-7} \qquad |V_{ub}| = (3.94 \pm 0.36) \times 10^{-3}$$

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

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/c²



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

spare

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

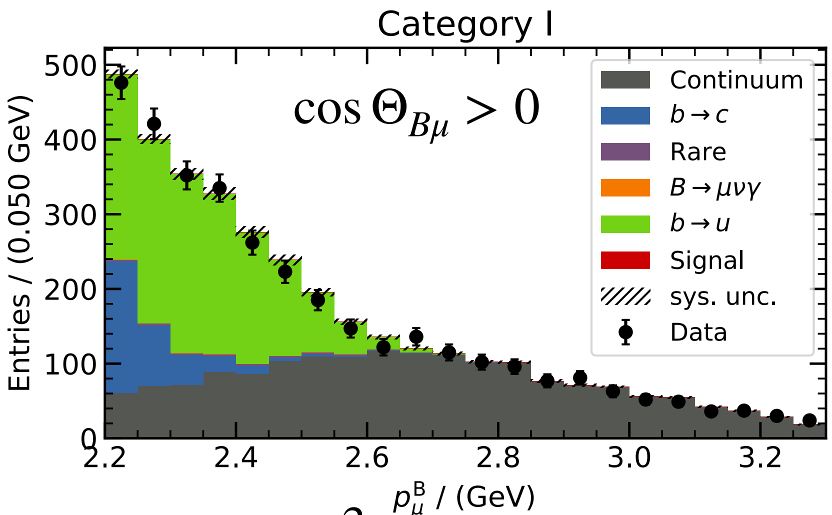
- test the simulation of crucial BG
- signal depleted region with moderate continuum contamination
    - $0.90 \leq C_{\text{out}} < 0.93$
- high p_μ^B region : validity for continuum description
- $2.2 < p_\mu^B$ $(\text{GeV}/c) < 2.6$: dominated by $b \to u\ell\nu_\ell$ and $b \to c\ell\nu_\ell$
-

- $B^+ \to \mu^+\nu_\mu$ yields : fixed to SM (~15 events each)

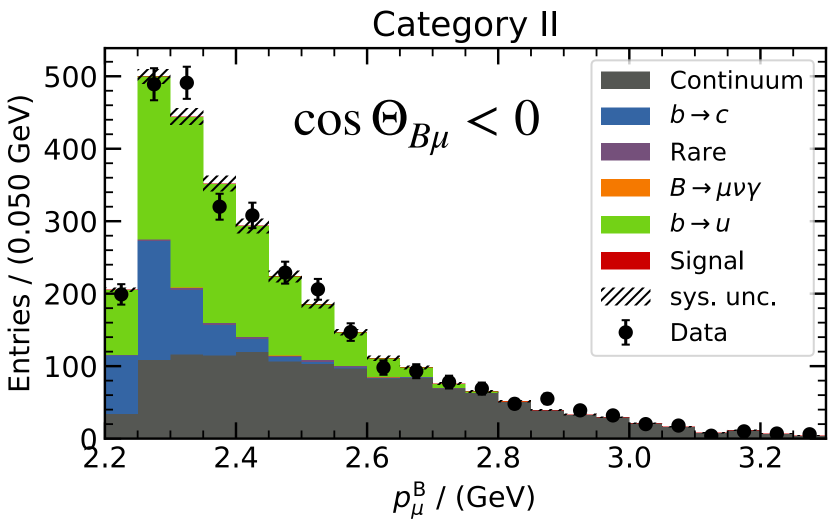
- templates describe data well

- $b \to c\ell\nu_\ell, b \to u\ell\nu_\ell$ and continuu

- signal is floated : yield is -31+-61



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



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

cumulative selection efficiencies

criteria	$B^+ \rightarrow \mu^+\nu_\mu$	$b \rightarrow ul\nu_l$	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

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

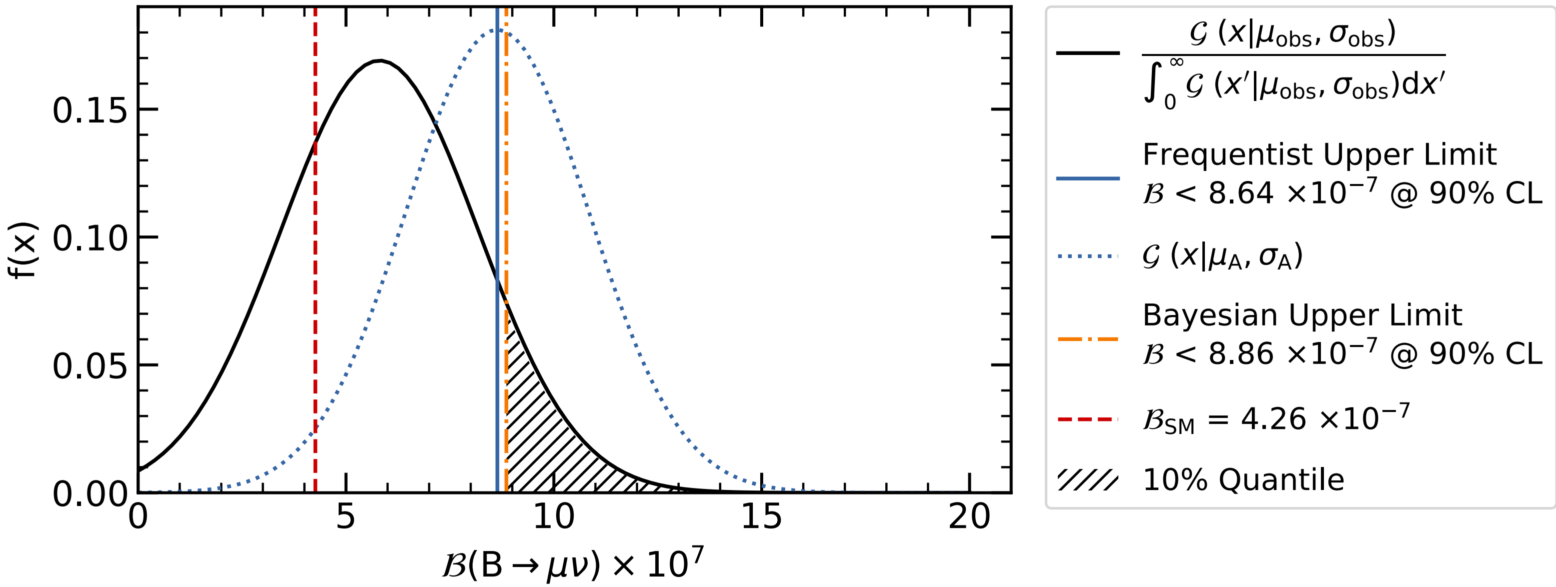
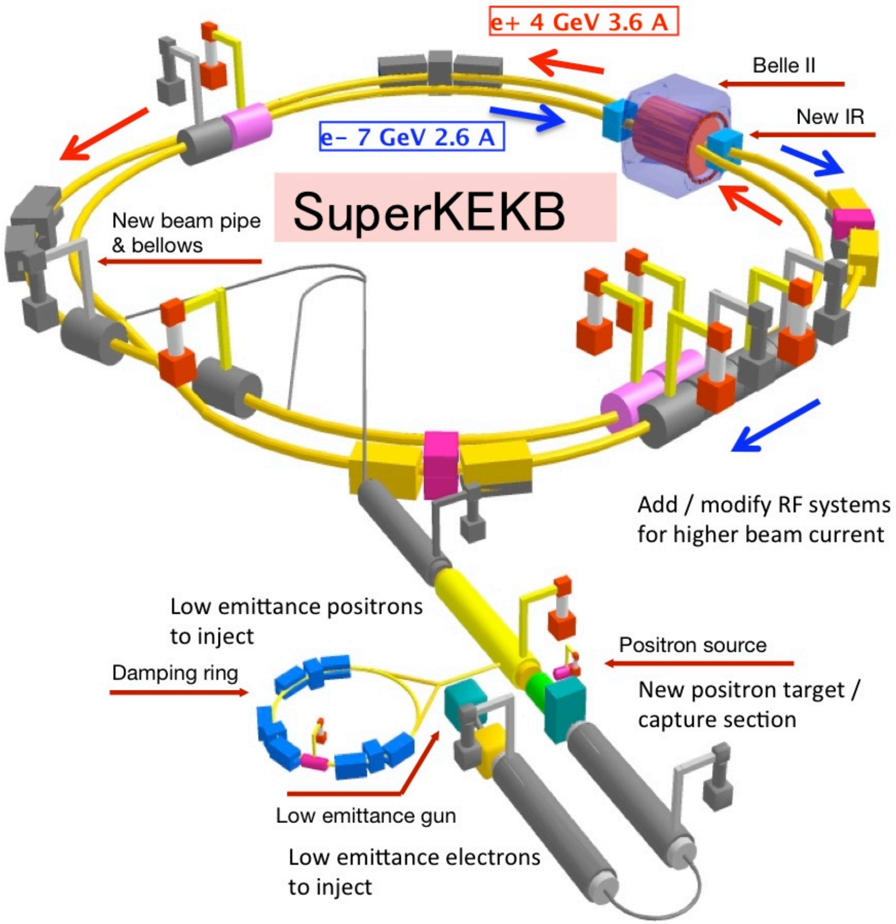


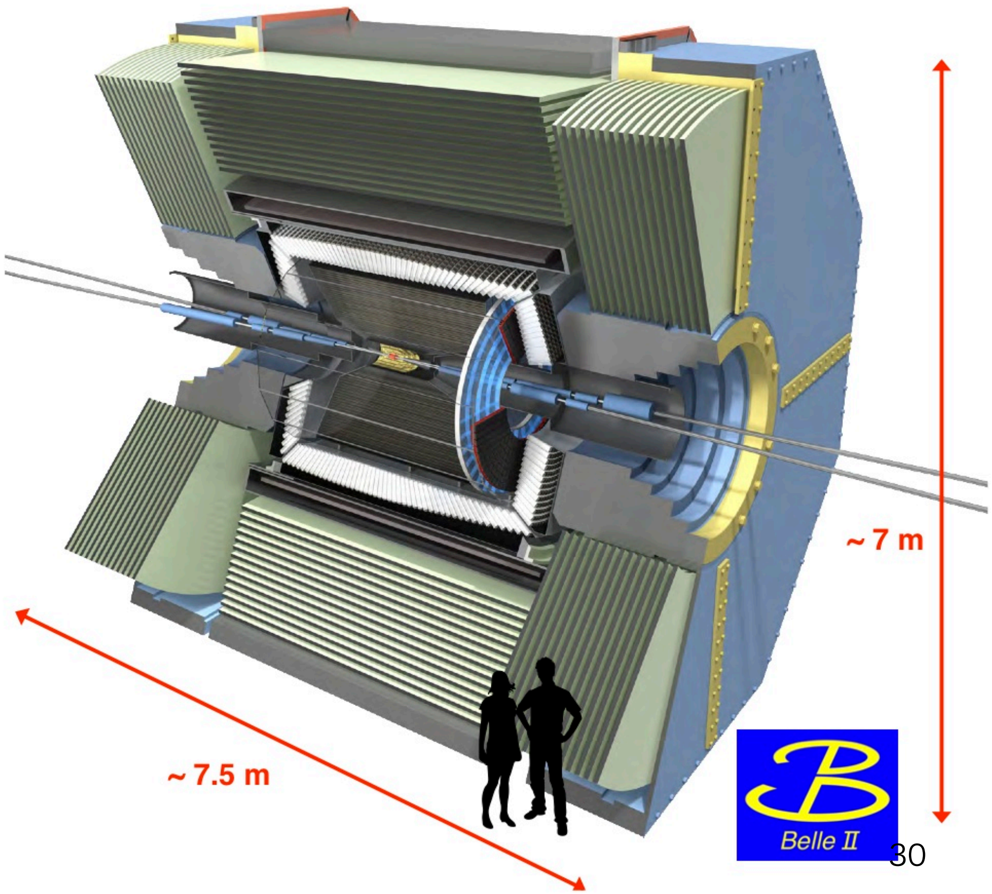
FIG. 9. The observed Bayesian (yellow dash-dotted) and Frequentist (blue) upper limits at 90% CL are shown, along with the SM expectation of the $B^+ \to \mu^+ \nu_\mu$ branching fraction and the Bayesian and Frequentist PDFs.

future prospects in Belle II

SuperKEKB : x40 luminosity of KEKB

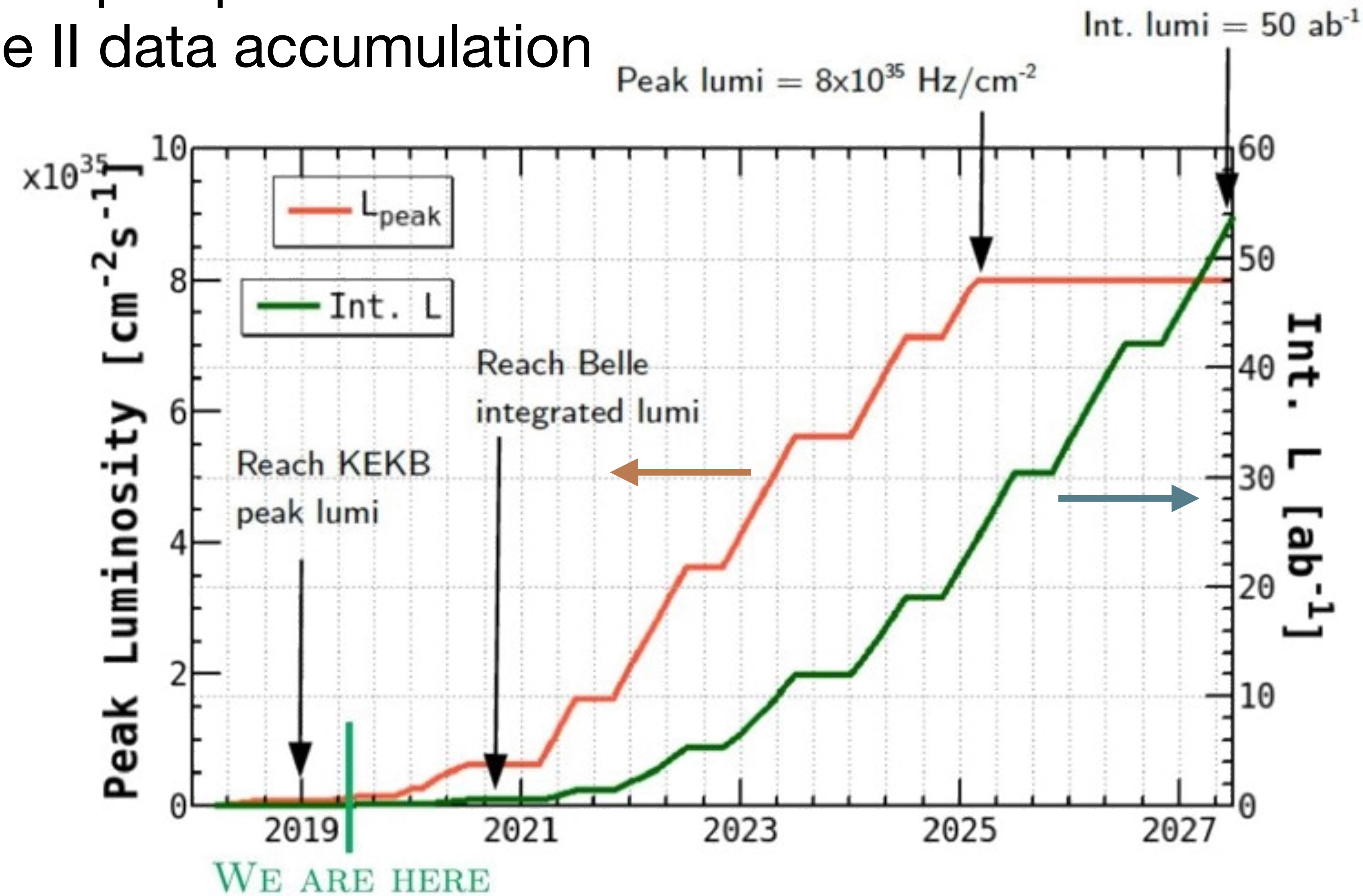


Belle II
upgraded for irradiation rate capability, data transfer



SuperKEKB / Belle II

prospect of
Belle II data accumulation



prospects

- search for $B^+ \to \mu^+\nu_\mu$
  - 2020 : reach to Belle integrated luminosity
    - combined analysis can be done, statistics will be about twice
    - excess 3 standard deviation can be expected
  - 2021 : accumulate 2-3 times more than Belle
    - excess 3 std. dev. only Belle II data will be expected
  - 2023 : accumulate ~5 times more than Belle
    - hope to excess 5 std. dev.