# Prospect of $B^+ \to \mu^+\nu$ and $B \to h\nu\bar{\nu}$

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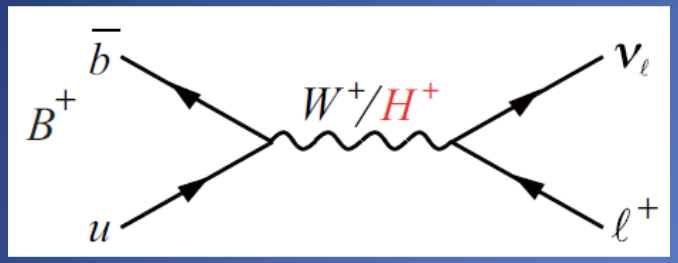
# Leptonic $B^+$ Decays




arXiv: 1712.04123

| $\ell$ | $\mathcal{B}_{\rm SM}$ |
|---|---|
| $\tau$ | $(8.45 \pm 0.70) \times 10^{-5}$ |
| $\mu$ | $(3.80 \pm 0.31) \times 10^{-7}$ |
| $e$ | $(8.89 \pm 0.73) \times 10^{-12}$ |

$$\mathcal{B}(B^+ \to \ell^+\nu_\ell)_{\rm SM} = \frac{G_F^2 M_B M_\ell^2}{8\pi}\left(1-\frac{M_\ell^2}{M_B^2}\right)^2 \times f_B^2 |V_{ub}|^2 \tau_B$$

$$\mathcal{B}(B^+ \to \ell^+\nu_\ell)_{\rm 2HDM\ II} = \mathrm{r_H}\, \mathcal{B}(B^+ \to \ell^+\nu_\ell)_{\rm SM}\,, \text{where}$$

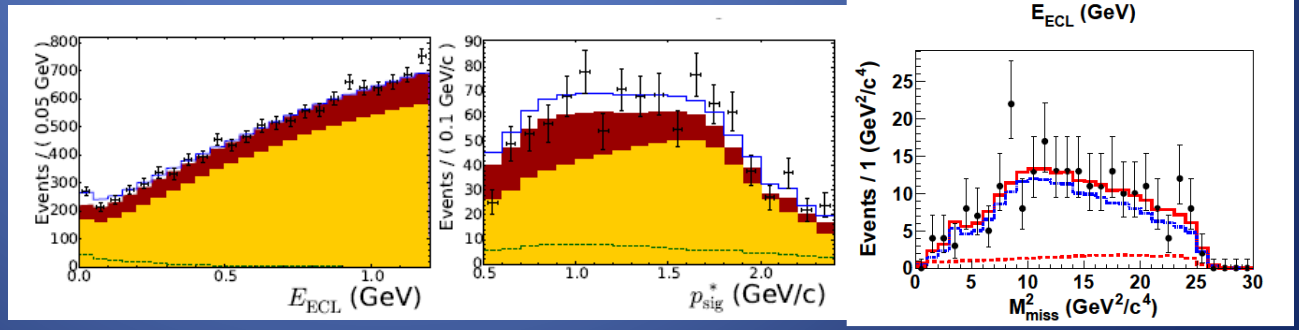
$$r_H = \left(1-\tan^2\beta \frac{M_b M_B^2}{(M_b+M_u)M_H^2}\right)^2 \approx \left(1-\tan^2\beta \frac{M_B^2}{M_H^2}\right)^2$$

- Clean processes with accurate theoretical branching fractions.
- Diagram involved in $W$ is helicity suppressed.
- Small SM BFs, enable good probe for new physics in tree.
- Possible enhancement only in $\mathcal{B}(B^+ \to \mu^+\nu_\mu)$

  $\Rightarrow$ See Masaya's talk: arXiv:1903.03016

# Analysis Strategy for $B^+ \to \tau^+ \nu_\tau$

- Tag accompanying B mesons using hadronic tags or semileptonic tags. Efficiency $\approx$ a few times $10^{-3}$
- $\tau^+$ candidates: $e^+\nu_e\bar{\nu}_\tau, \mu^+\nu_\mu\bar{\nu}_\tau, \pi^+\bar{\nu}_\tau, \rho^+(\pi^+\pi^0)\bar{\nu}_\tau$
- Veto events with additional charged particles, $K_L$ or $\pi^0$…
- Signal observables:
  - $E_{ECL}$ Extra energy in ECAL
  - $M^2_{miss}$ missing mass squared
  - $P^*_{sig}$



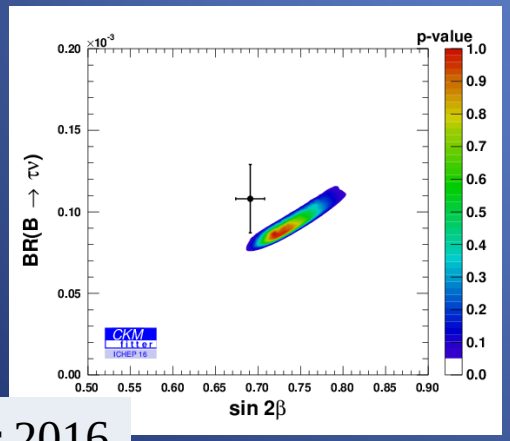
# Summary of $B^+ \to \tau^+ \nu_\tau$

| Exp. | Tag | B.F.$\times 10^4$ | Reference |
|---|---|---|---|
| Belle | Hadronic | $0.72^{+0.27}_{-0.25} \pm 0.11$ | PRL 110, 131801 (2013) |
| Belle | Semilept. | $1.25 \pm 0.28 \pm 0.27$ | PRD 92, 051102 (2015) |
| BaBar | Hadronic | $1.83^{+0.53}_{-0.49} \pm 0.41$ | PRD 88, 031102 (2013) |
| BaBar | Semilept. | $1.7 \pm 0.8 \pm 0.2$ | PRD 81, 051101 (2010) |

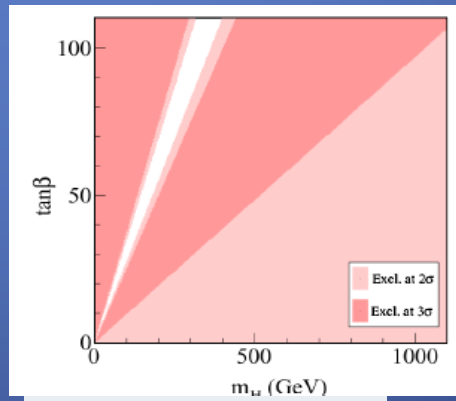
$\mathcal{B}(B^+ \to \tau^+ \nu_\tau)_{\text{avg}} = (1.09 \pm 0.24) \times 10^{-4}$ PDG 2016

$\mathcal{B}(B^+ \to \tau^+ \nu_\tau)_{\text{SM}} = (0.845 \pm 0.070) \times 10^{-4}$ arXiv: 1712.04123

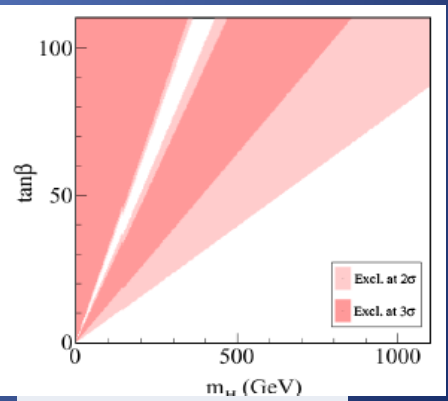
Test CKM




CKM fitter 2016




Exclusive $|V_{ub}|$

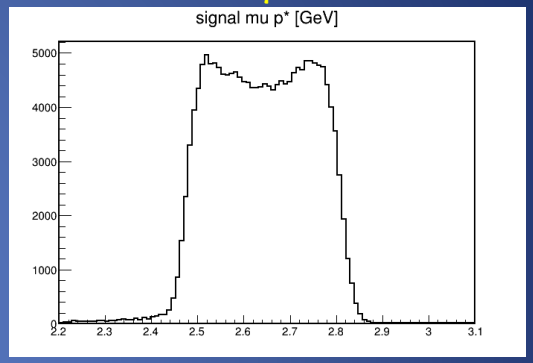


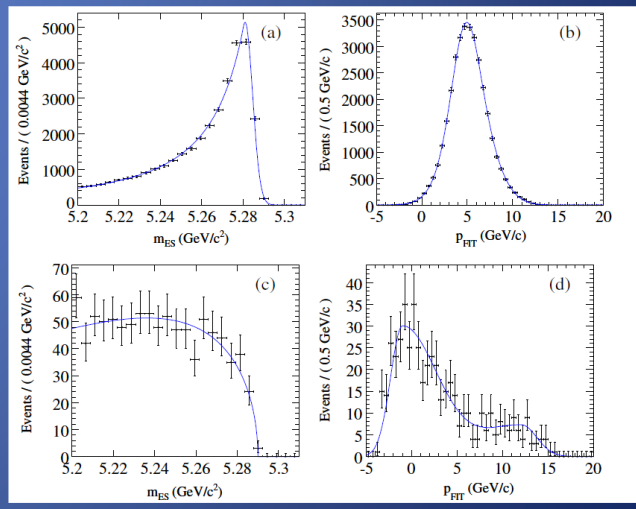

Inclusive $|V_{ub}|$

# Analysis strategy for $B^+ \to \mu^+ \nu_\mu$

- Unique feature: $P_\mu^B \approx \frac{M_B}{2}$ in B rest frame.
- Tagging efficiency ~ $o(10^{-3})$.
  $\Rightarrow$ Better not apply!
- BaBar $\mathcal{B} < 1.0 \times 10^{-6}$ PRD 79, 091101 (2009)
  - Select events with $2.4 < P_\mu^{cm} < 3.2$ GeV
  - Require $M_{ES} > 5.1$ GeV; $-2.0 < \Delta E < 0$
  - Employ shape variables to form fisher discri.
    Combine 1st fisher with $P_\mu^B$ boosted from $|P_B| = 350$ Mev/c and $P_\mu^*$ direction.
  - Fit on $M_{ES}$ and $P_{fit}$ (2nd fisher discriminant)

$P_\mu^*$



# $B^+ \to \mu^+\nu_\mu$, Belle 2018

- Belle recent result.
  - Full data sample 772M $B\bar{B}$
  - Loose kinematic selections
  - Combine 14 variables in to $O_{nn}$
  - Select events with high $P_\mu^*$
  - Consider $\pi\ell\nu$ & $\rho\ell\nu$ bkg.
  - Investigate $\mu^+\nu_\mu\gamma$ contrib.
  - Fit to extract yield ratio of signals and $B \to \pi\ell\nu$

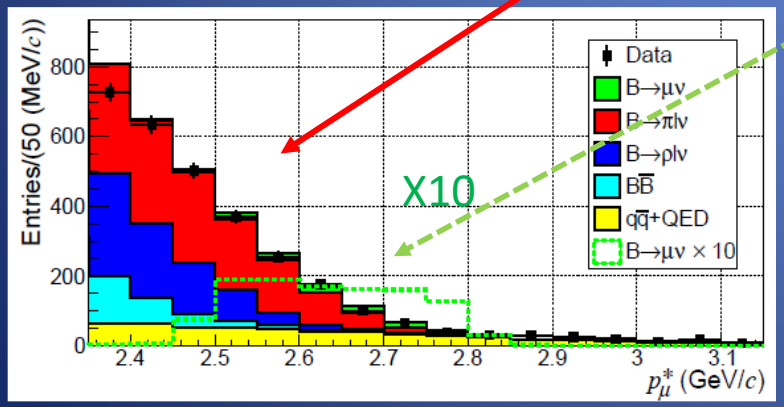
$\Rightarrow$ Yield = $195 \pm 67$, $\mathcal{B} = (6.46 \pm 2.22 \pm 1.60) \times 10^{-7}$ @ $2.4\sigma$

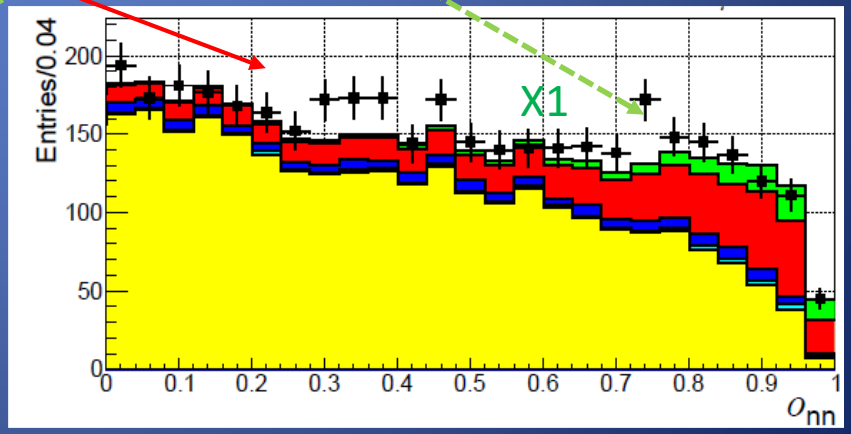
$\Rightarrow \mathcal{B}(B^+ \to \mu^+\nu_\mu) = [2.9, 10.7] \times 10^{-7}$ @ 90% CL. interval.

PRL 121, 031801 (2018)

$\pi\ell\nu$ bkg

$\mu\nu$ signal



# $B^+ \to \mu^+ \nu_\mu$ , New Improvement

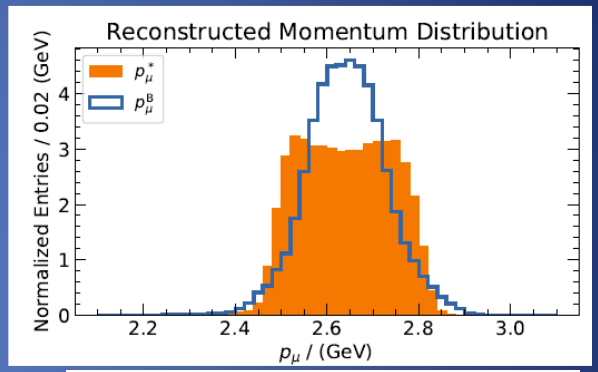
- Apply Belle II analysis software to Belle data.
- Convert $P_\mu^*$ to $P_\mu^B$ $\quad \zeta = 0.58$

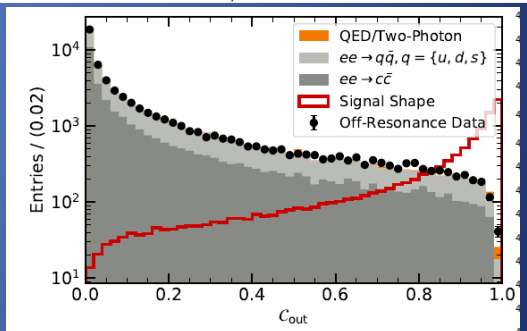
$$E^*_{\text{tag}} = \sqrt{(330\ \text{MeV})^2 + m_B^2}\ ;$$

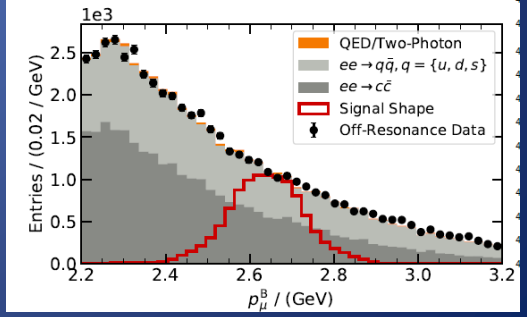
$$\left(\text{P}^*_{\text{tag,cal}}\right)_z = \zeta f \left[\left(P^*_{\text{tag}}\right)_z\right]$$

$$\left(\text{P}^*_{\text{tag,cal}}\right)_T = \zeta \sqrt{\left(P^*_{\text{tag}}\right)^2 - f\left(P^*_{\text{tag}}\right)_z{}^2}$$

- Understand backgrounds
  - continuum $\Rightarrow$ off-resonance data
  - $b \to u\ell\bar{\nu}_\ell$ $\Rightarrow$ generate various decays with appropriate factors



# $B^+ \to \mu^+ \nu_\mu$, continue

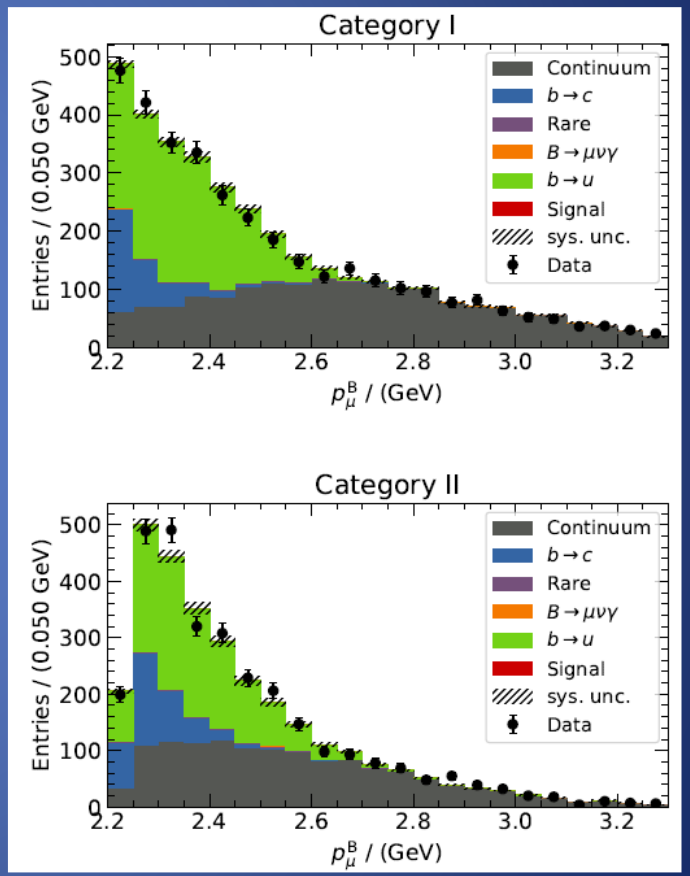
- Understanding $b \to u \ell \bar{\nu}_\ell$
  - Classifiers: $C_{out}$, $\cos\Theta_{B\mu}$, $P_\mu^B$

    $C_{out}$: shape variables, normalized $M_{\mathrm{bc}}/\Delta\mathrm{E}$
  - Continuum suppressed region.

- Four signal categories

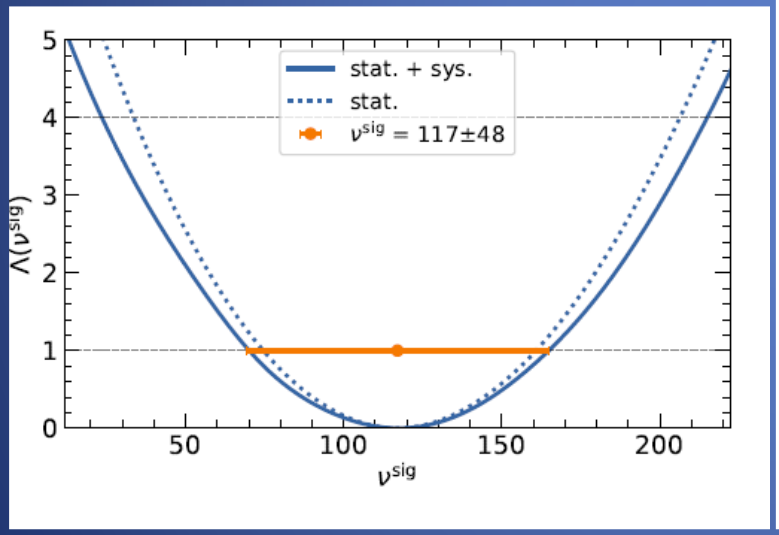
TABLE II. The definition of the four signal categories is shown.

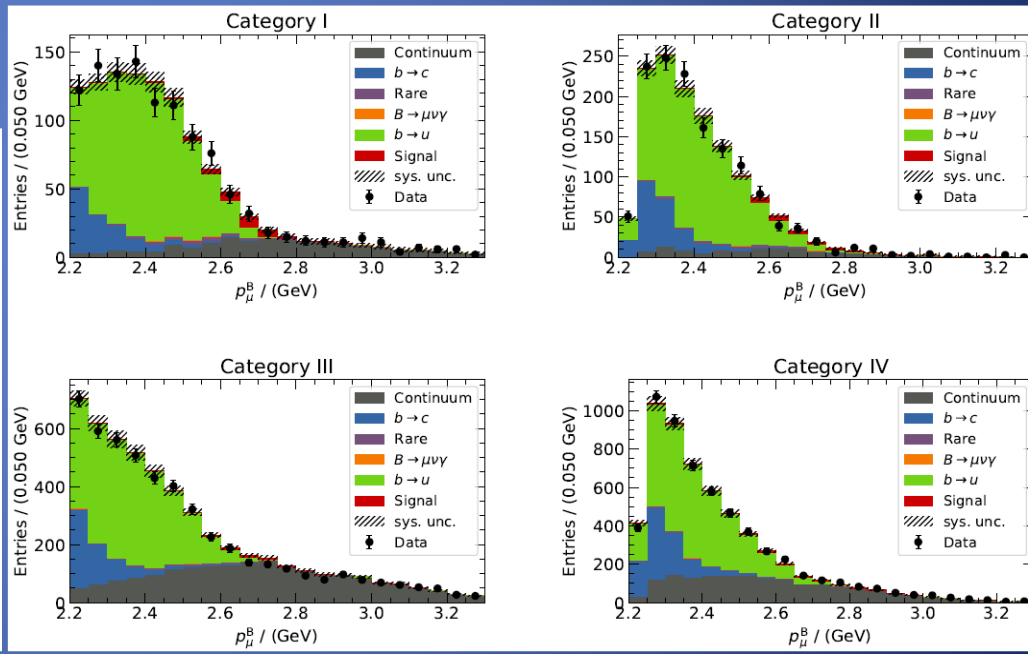
| Category | $C_{\mathrm{out}}$ | $\cos\Theta_{B\mu}$ | Signal Efficiency |
|---|---|---|---|
| I | [0.98,1.00) | [-0.13,1.00) | 6.5 % |
| II | [0.98,1.00) | [-1.00,-0.13) | 5.9 % |
| III | [0.93,0.98) | [0.04,1.00) | 7.1 % |
| IV | [0.93,0.98) | [-1.00,0.04) | 8.3 % |



# $B^+ \to \mu^+ \nu_\mu$ , 2019

- Fit on $P_B^\mu$ and $C_{out}$



# $B^+ \to \mu^+ \nu_\mu$ , New Results

$\mathcal{B}(\mathrm{B}^+ \to \mu^+ \nu_\mu) = (5.3 \pm 2.0 \pm 0.9) \times 10^{-7} @\ 2.8\ \sigma$

$= (6.46 \pm 2.22 \pm 1.60) \times 10^{-7} @ 2.4\ \sigma$ (2018)

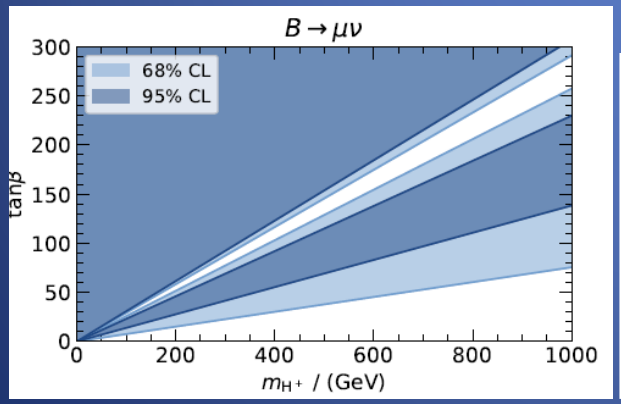
$\Rightarrow \mathcal{B}(\mathrm{B}^+ \to \mu^+ \nu_\mu) = 8.6 \times 10^{-7} @\ 90\%$ CL. level

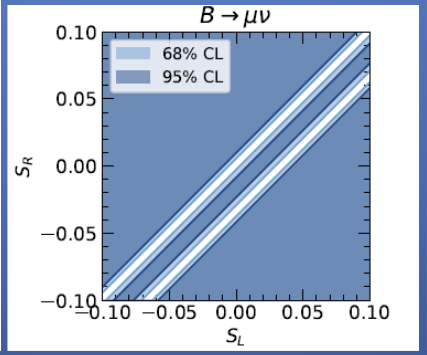
$\Rightarrow |\mathrm{V_{ub}}| = (4.4^{+0.8}_{-0.9} \pm 0.4 \pm 0.1) \times 10^{-3}$ using $f_B = 184 \pm 4$ MeV

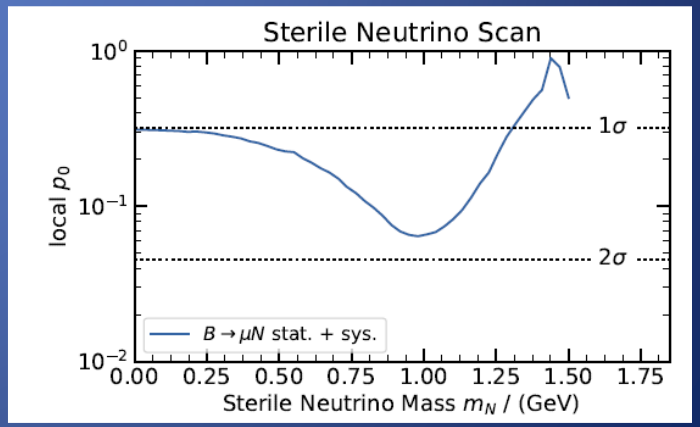
$\Rightarrow$ Exclude parameter space for 2HDM type II and type III

$\Rightarrow$ Perform sterile neutrino scan. $B^+ \to \mu^+ N$

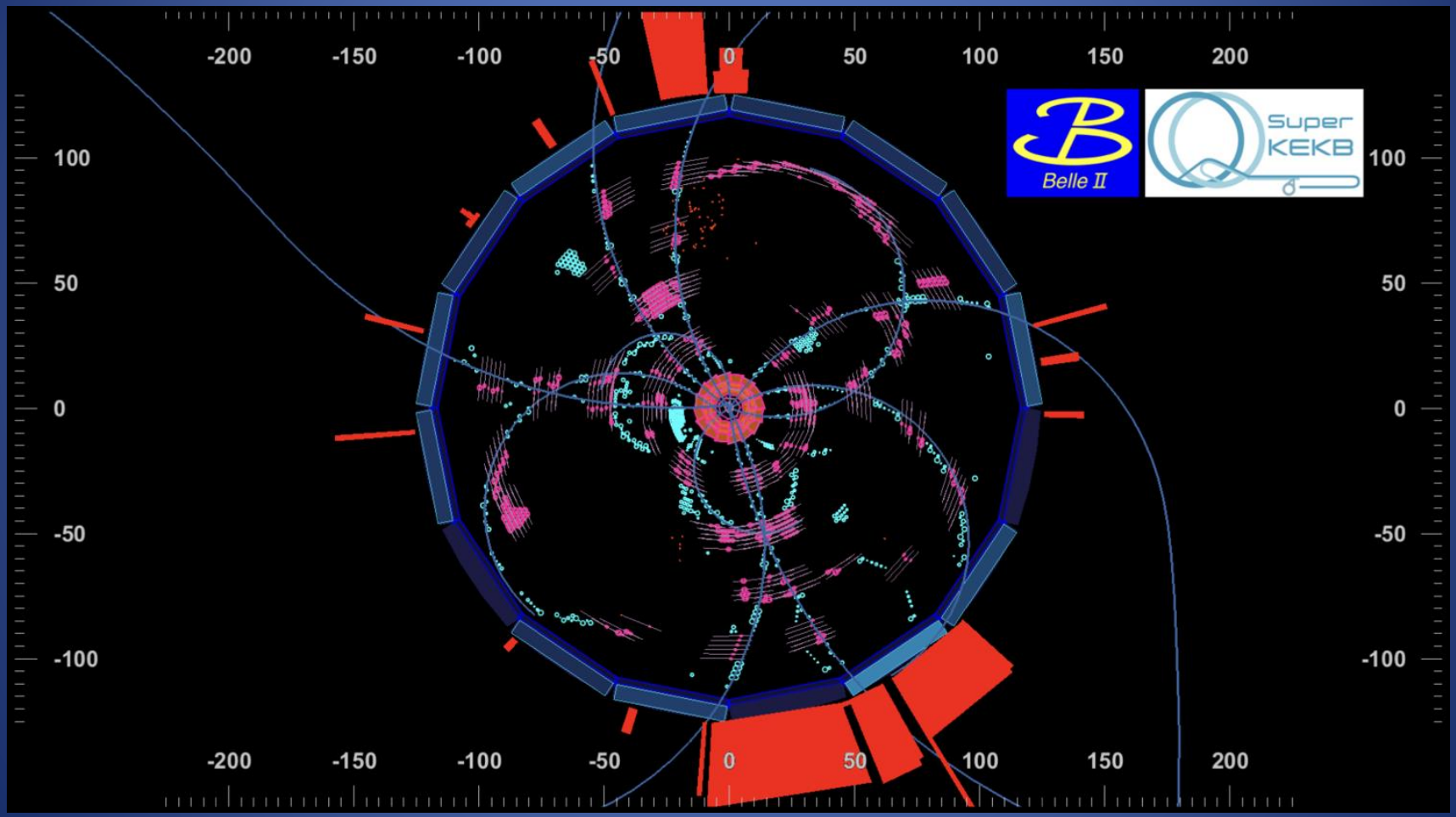
The largest deviation is at $m_N = 1.0$ GeV @ $1.8\sigma$



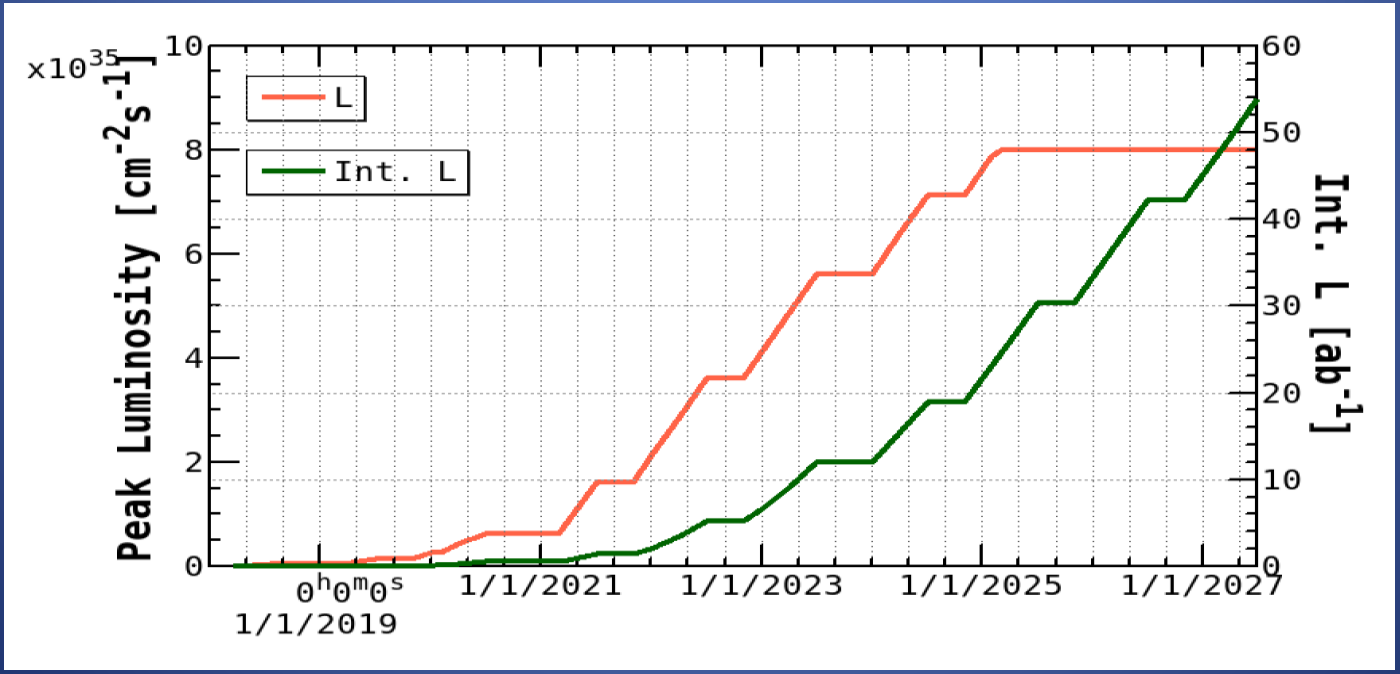



# A $B\bar{B}$ like event



# Belle II commission plan

- 8 months operation per year, except 7 months for 2019 JPY:
  - ✓ Phase 3: Mar. 11 to the end of June, 2019, expected to collect 10fb$^{-1}$ on resonance data
    - ➢ background study
    - ➢ beam energy scan
    - ➢ physics run
  - ✓ Physics run: Middle of Oct. ~ end of 2019.
  - ✓ Physics run: Early Feb. ~ March of 2020.
- 8 months shut down in 2020 for PXD and 6 months in 2023 for RF upgrade



# Milestones Foreseen for $B^+ \to \mu^+ \nu_\mu$

- 2020/12 Same data sample as Belle's

  Check if there is also an excess and publish results in 2021.
- 2022/7 5 $\mathrm{ab}^{-1}$

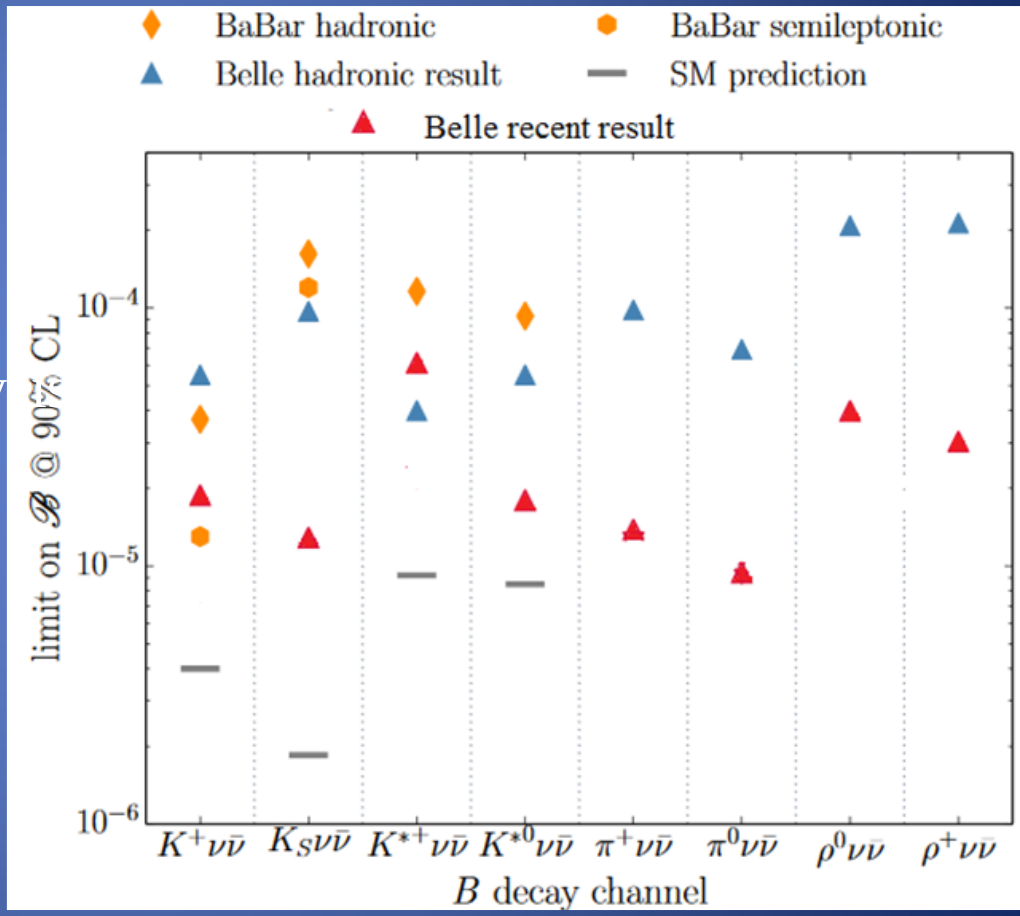
  Likely to claim observation and publish results in 2023.
- 2023/6 10 $\mathrm{ab}^{-1}$

  Examine deviation from SM and compare $B^+ \to \mu^+ \nu_\mu$ results.
- 2025/3 Reach $8 \times 10^{35}\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, 30 $\mathrm{ab}^{-1}$

# Search for $B \to h\nu\bar{\nu}$

- $h = K^{*+}, K^{*0}, K^{+}, K_S^0, \pi^{+}, \pi^{0}, \rho^{0}, \rho^{+}$
- Clean SM expectation on B.F.
  $\mathcal{B}(\mathrm{B}^{+} \to K^{*+}\nu\bar{\nu}) = 9.2 \times 10^{-6}$
  $\mathcal{B}(\mathrm{B}^{0} \to \pi^{0}\nu\bar{\nu}) = 1.2 \times 10^{-7}$
- Need a $B$ tag to perform the analy
  Signals are identified in $\mathrm{E_{ECL}}$
- References:

| Exp. | Tag | Reference |
|---|---|---|
| BaBar | Hadronic | PRD 87, 112005 |
| BaBar | Semilep. | PRD 82, 112002 |
| Belle | Hadronic | PRD 87, 111103 |
| Belle | Semilep. | PRD 92, 091101 |

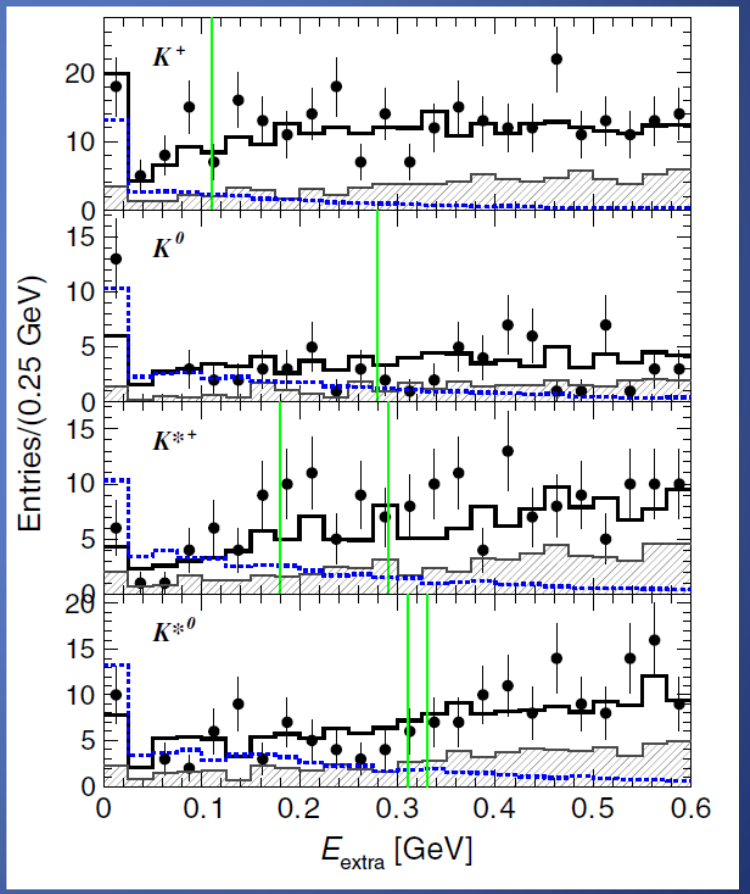



Good topics for Belle II

# Remark 1 on Analysis

- Lesson from $B^+ \to \tau^+ \nu_\tau$: Need to have at least one more variable to help distinguish backgrounds. $M^2_{miss}$, $P^*_{\mathrm{sig}}$
  - Data: points
  - Blue line : Signal PDF
  - Shaded area: Expected combinatorial ground
  - Background in the $m_{\mathrm{bc}}$-peaking region

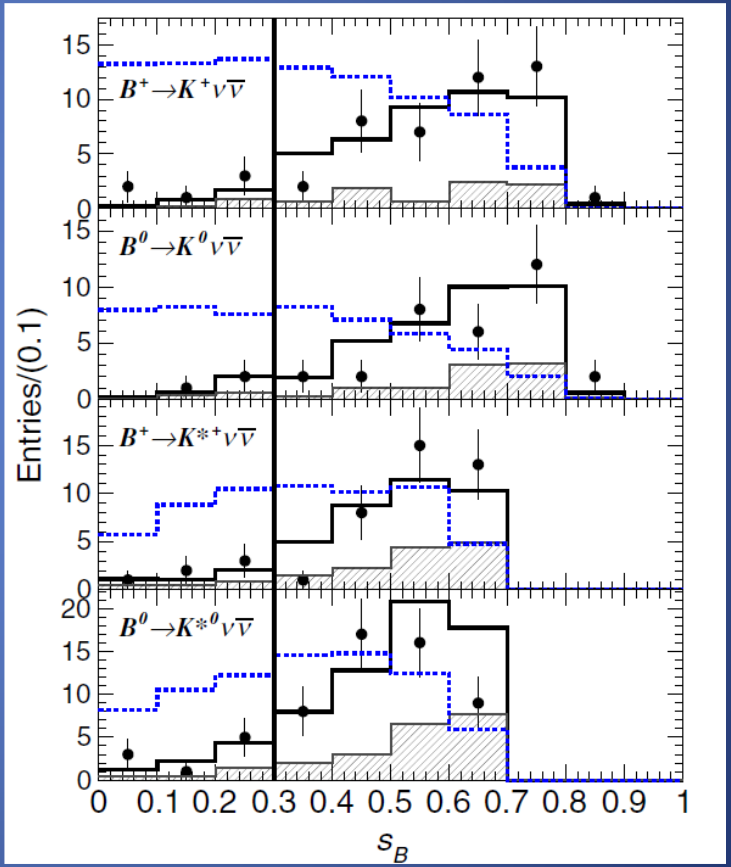
BaBar Hadronic



# Remark 2 on Analysis

BaBar Hadronic

- Low background in low $q^2$. Optimized in each $q^2$ bin.
- Excess in first bin?
  - Data: points
  - Blue line : Signals with 20~50 times data.
  - Shaded area: Expected combinatorial ground
  - Background in $m_{\mathrm{bc}}$ peaking region




$S_B = q^2/m_B^2$

# Summary

- Belle II has reached the phase III stage, entering Belle II era.
- Although the performance of SuperKEKB needs to be watched, it's very promising to observe the decay $B^+ \to \mu^+ \nu_\mu$ in 4 years.
- Hints or observations of $\mathrm{B} \to K^{(*)} \nu \bar{\nu}$ may be achieved with 10 $\mathrm{ab}^{-1}$ data.
- Manpower is crucial to our success.
  $\Rightarrow$ Recruiting posdoc and students.