Recent (non-*Rx*) Highlights from Belle

IBS-PNU Joint Wokrshop, Dec. 5, 2019

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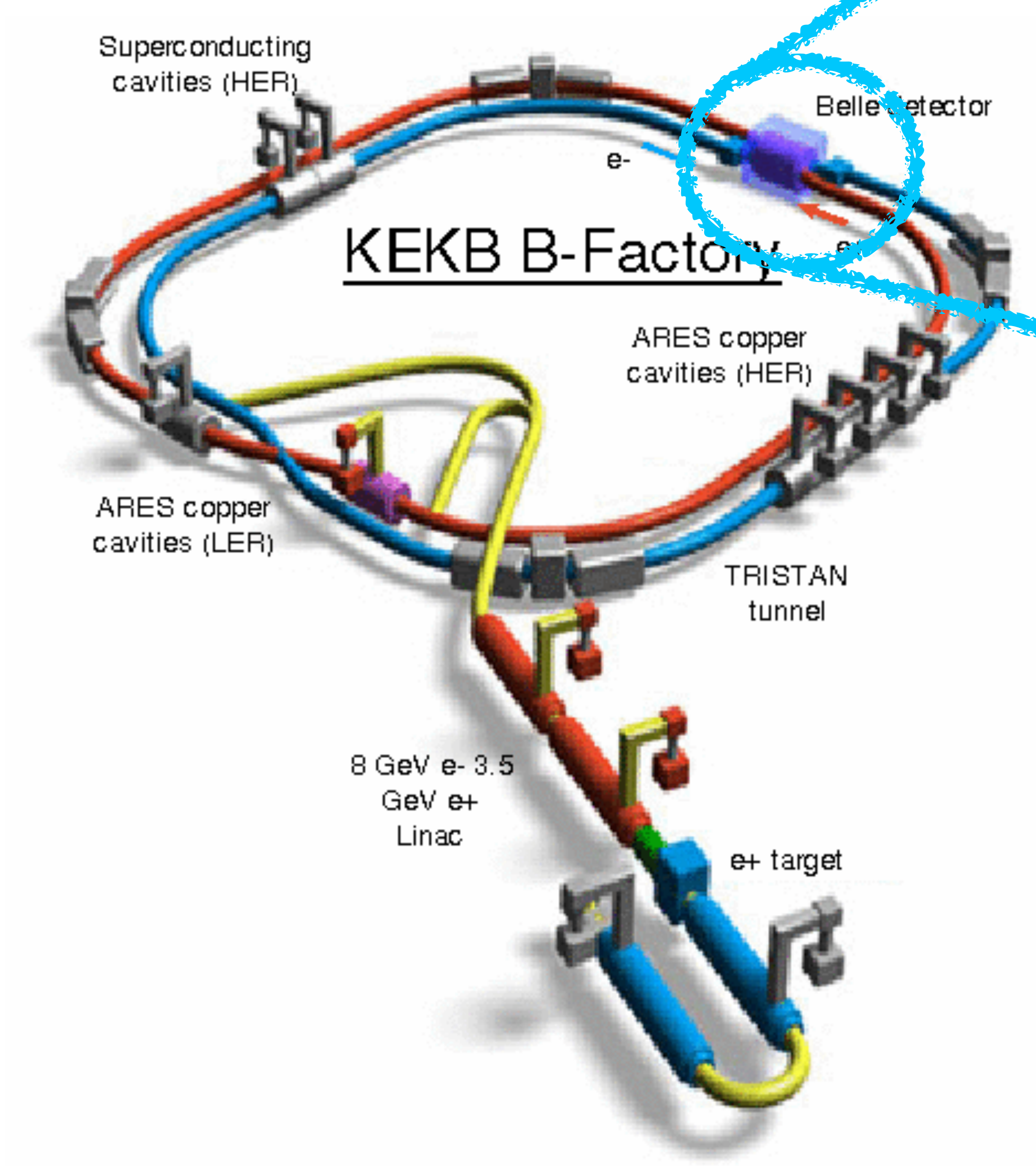
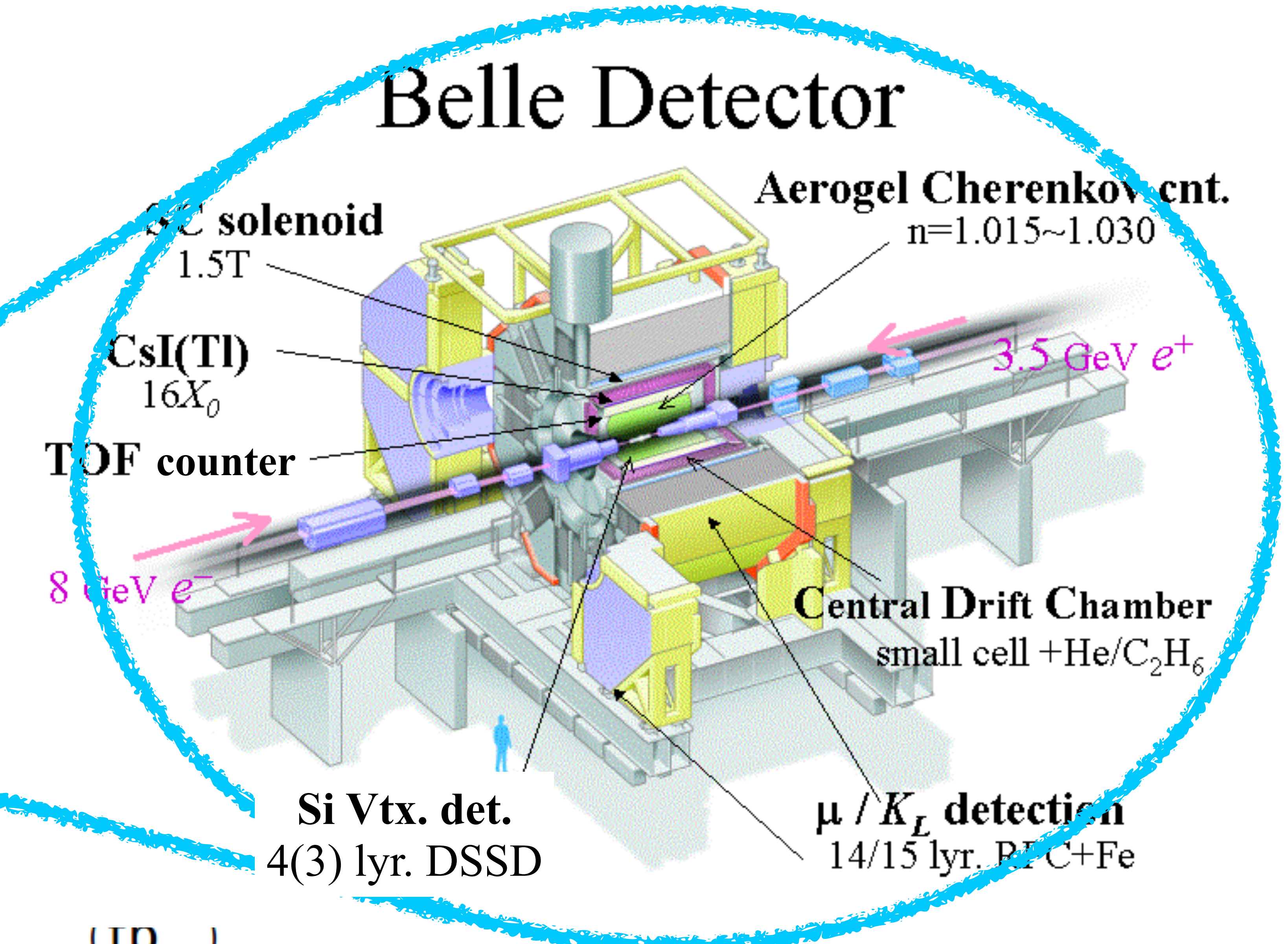
Overview

- *Leptonic B decays*
  - $B^+ \to \mu^+ \nu$
  - $B^+ \to \ell^+ \nu \gamma$
- *EWP and related*
  - $B \to K^* e^\pm \mu^\mp$
  - $B \to X_s \gamma$ *inclusive*
- *τ decays*
  - $\tau^+ \to \pi^+ \nu \ell^+ \ell^-$

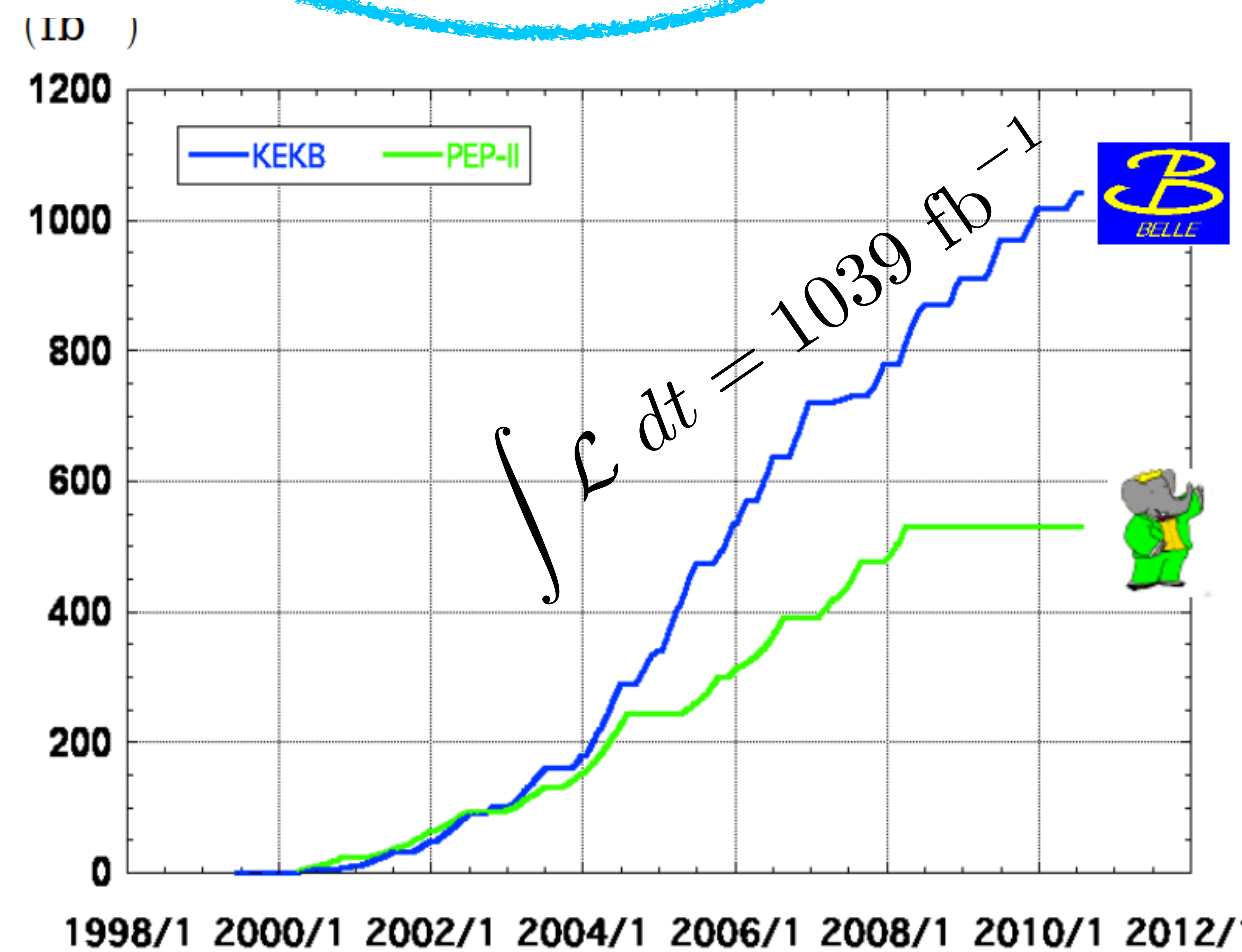
20 countries
90 institutions
~450 members

$$\mathcal{L}_{\rm peak} = 21.1\ {\rm nb}^{-1}{\rm s}^{-1}$$



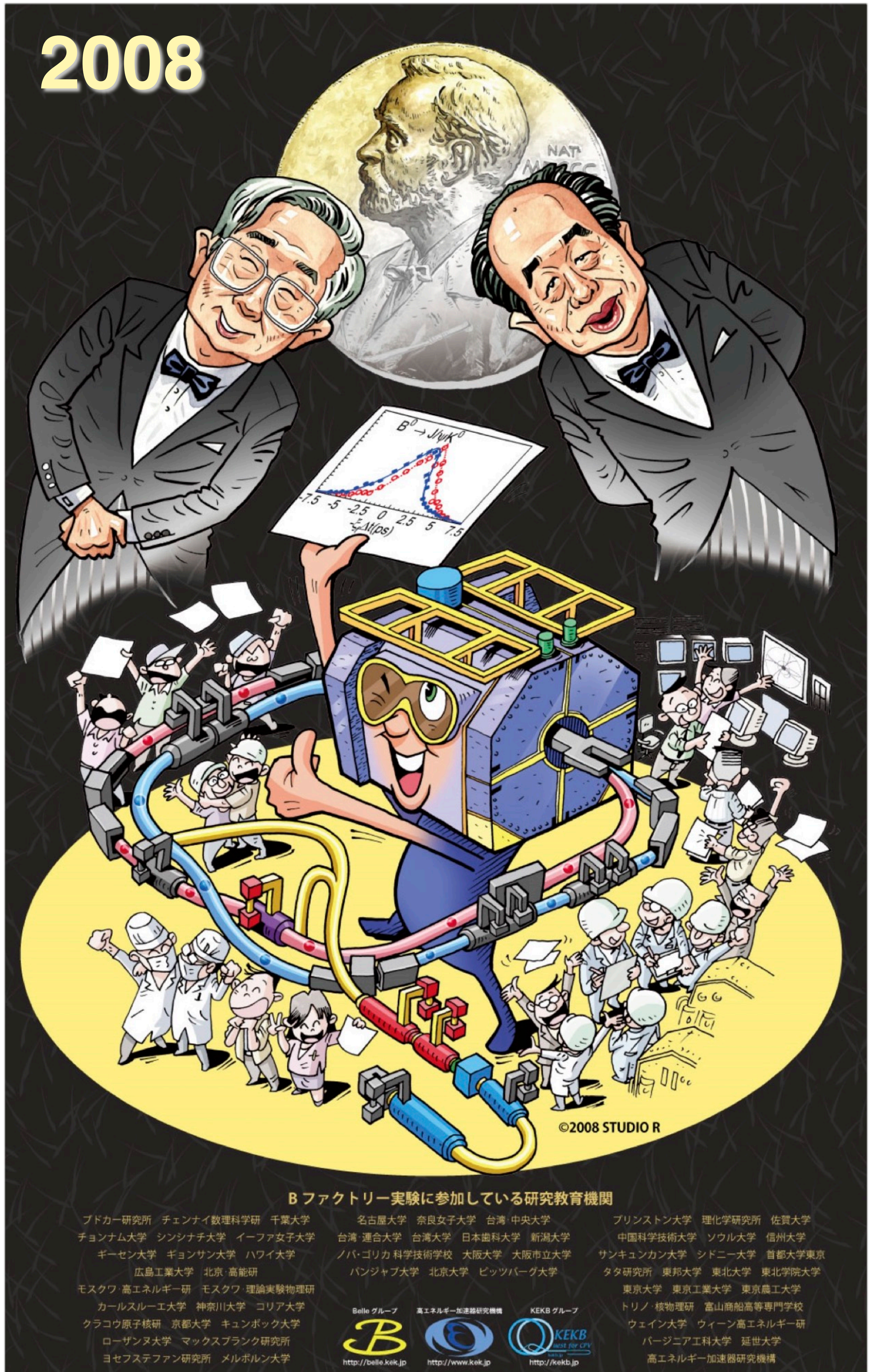


$$e^- \xrightarrow{\text{8 GeV}} (\star) \xleftarrow{\text{3.5 GeV}} e^+$$



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

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

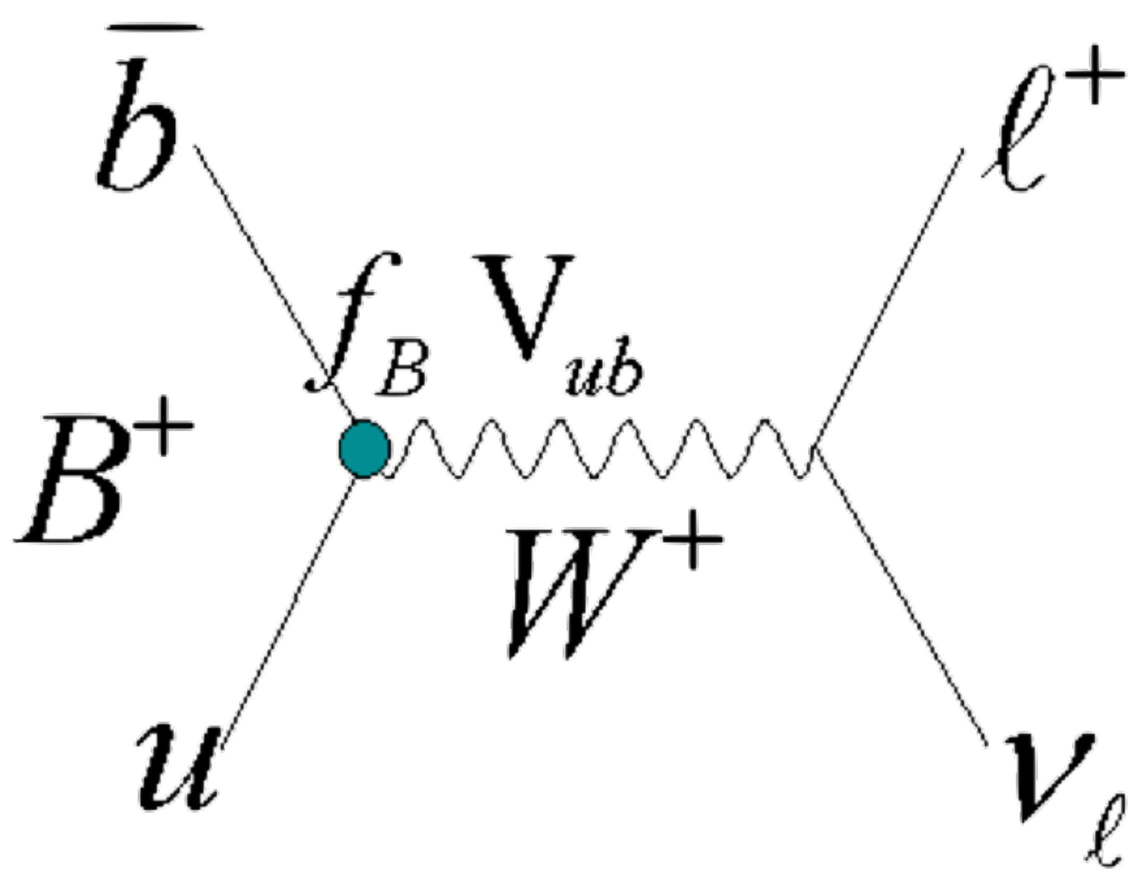


Belle (and BaBar, too) achievements include:

- CPV, CKM, and rare decays of B mesons (and B_s, too)
- Mixing, CP, and spectroscopy of charmed hadrons
- Quarkonium spectroscopy and discovery of (*many*) exotic states, e.g. $X(3872)$, $Z_c(4430)^+$
- Studies of τ and 2γ

$$B^+ \to \ell^+ \nu(\gamma)$$

For a clean test of lepton universality



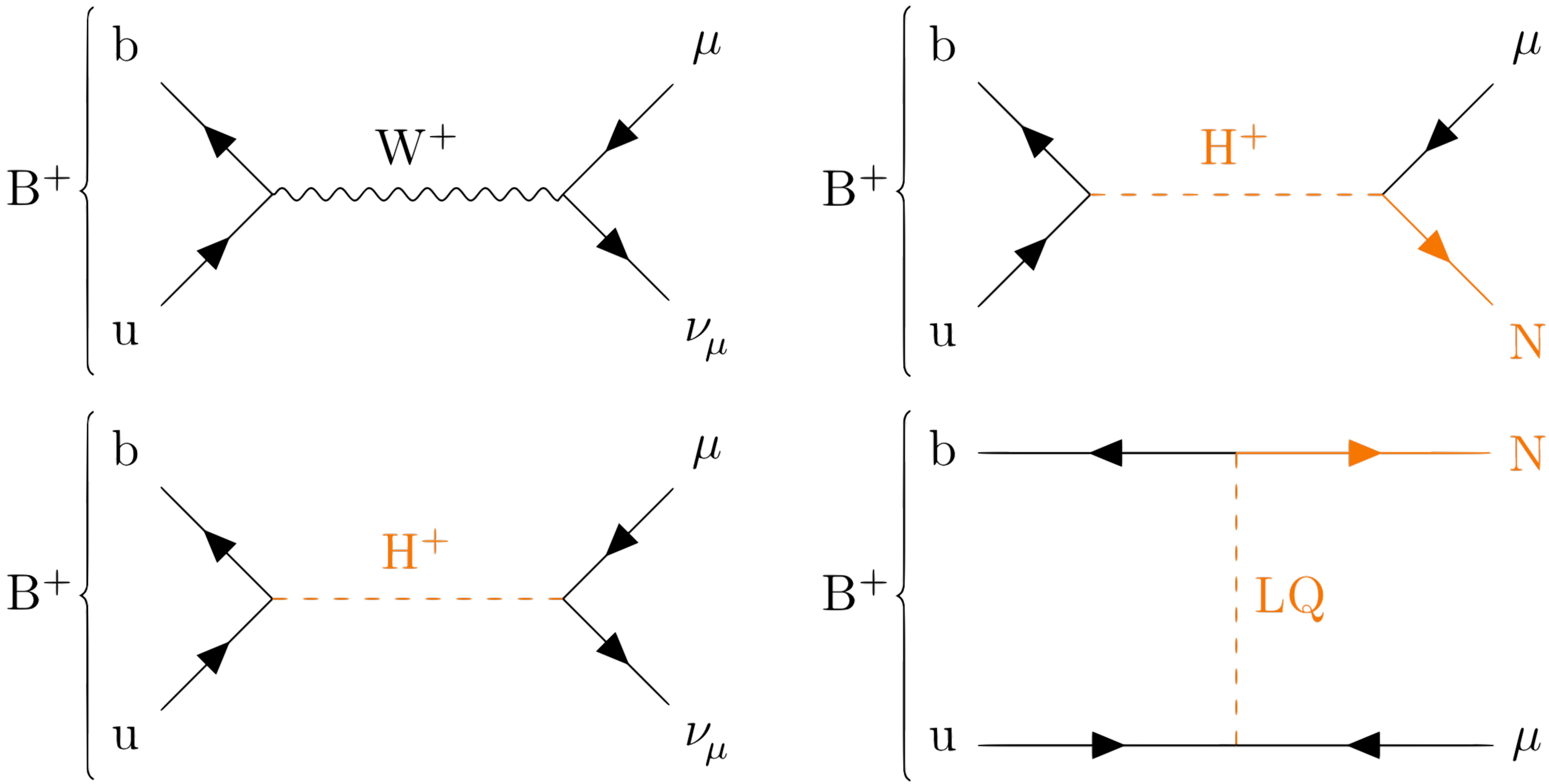
$$\Gamma(B^+ \to \ell^+\nu) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2$$

$$\frac{\Gamma(B^+ \to \ell^+\nu)}{\Gamma(B^+ \to \tau^+\nu)} = f(m_\ell^2, m_\tau^2)$$

and all other parameters cancel!

- Belle has measured $B^+ \to e^+\nu$, $\mu^+\nu$ with both inclusive tag and hadronic tag and updated $B^+ \to \mu^+\nu$ with inclusive tagging (2019)

SM and NP diagrams for $B^+ \rightarrow \mu^+\nu$



N = unknown neutral fermion (e.g. a sterile ν)

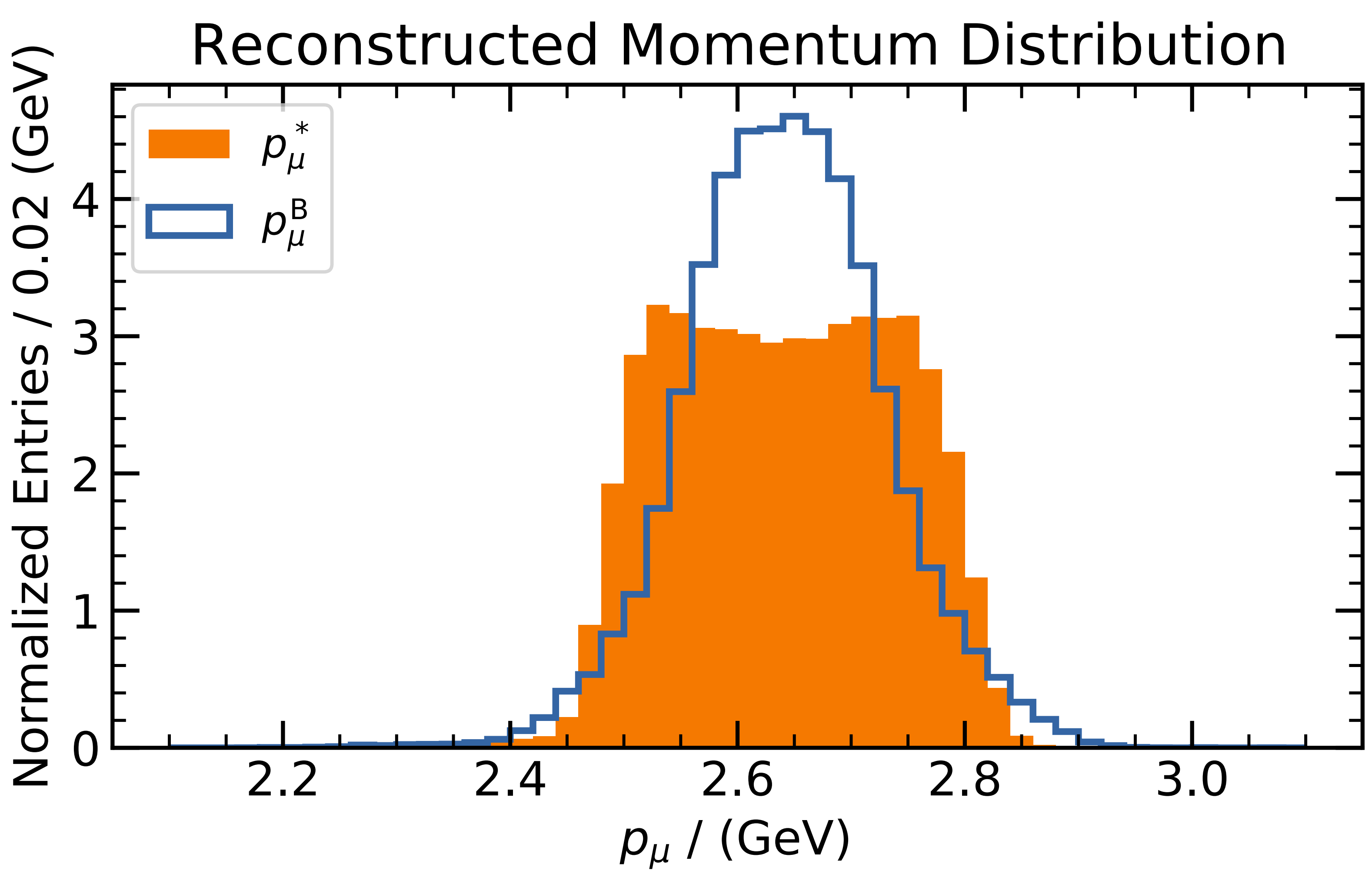
$B^+ \to \mu^+\nu$ and $B^+ \to \mu^+ N$

Features

- an <u>improved</u> search over Belle's PRL 2018
  - ✓ modeling of $b \to u \ell \nu$ and continuum background
  - ✓ use inclusive B tagging to maximize signal selection efficiency ($\Leftarrow$ $BF_{SM} \sim 4 \times 10^{-7}$)
- carry out the analysis in the <u>signal B rest frame</u>
  - ✓ $p_\mu^B = 2.64$ GeV
  - ✓ achieve better resolution and sensitivity than using p_μ^* (CM frame)
    $\Leftarrow$ tag-side momentum is calibrated by using MC

$$\mathbf{p}_{\mathrm{sig}} = -\mathbf{p}^*_{\mathrm{tag,cal}}$$

  - ✓ sensitive to $B^+ \to \mu^+ N$ search, for $m_N \in [0, 1.5)$ GeV



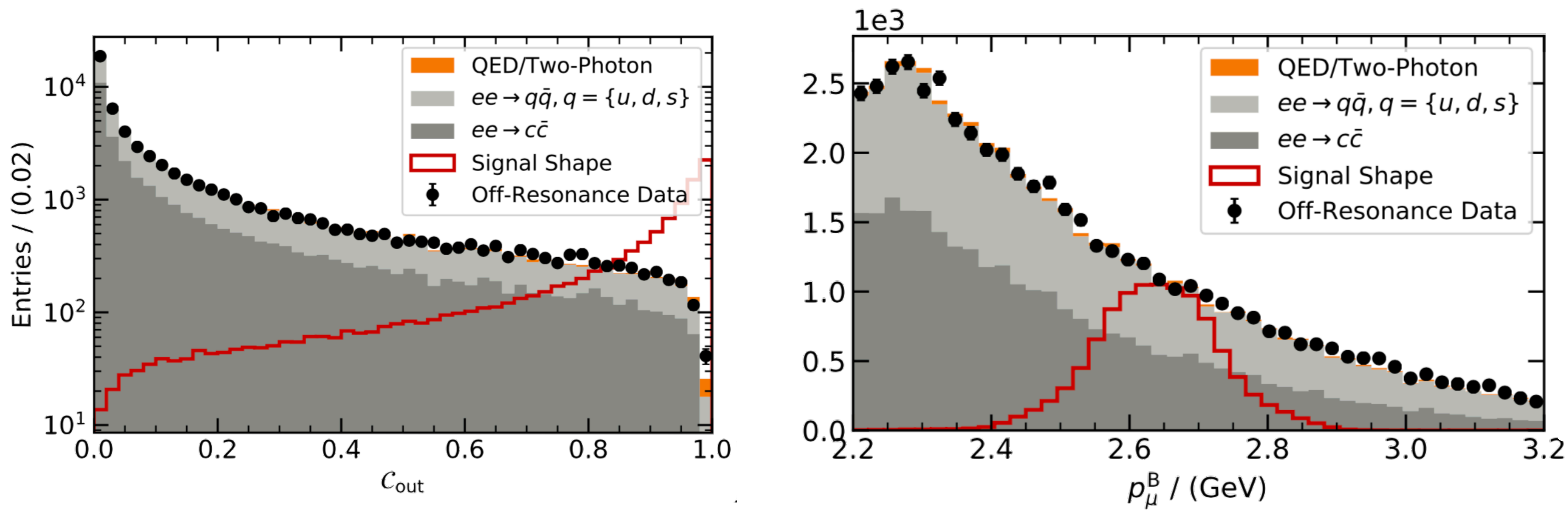
N = unknown neutral fermion (e.g. a sterile ν)

arXiv:1911.03186

$B^+ \to \mu^+\nu$ and $B^+ \to \mu^+ N$

Signal extraction

✓ by binned max. likelihood fit to p_μ^B in kinematic/BDT categories



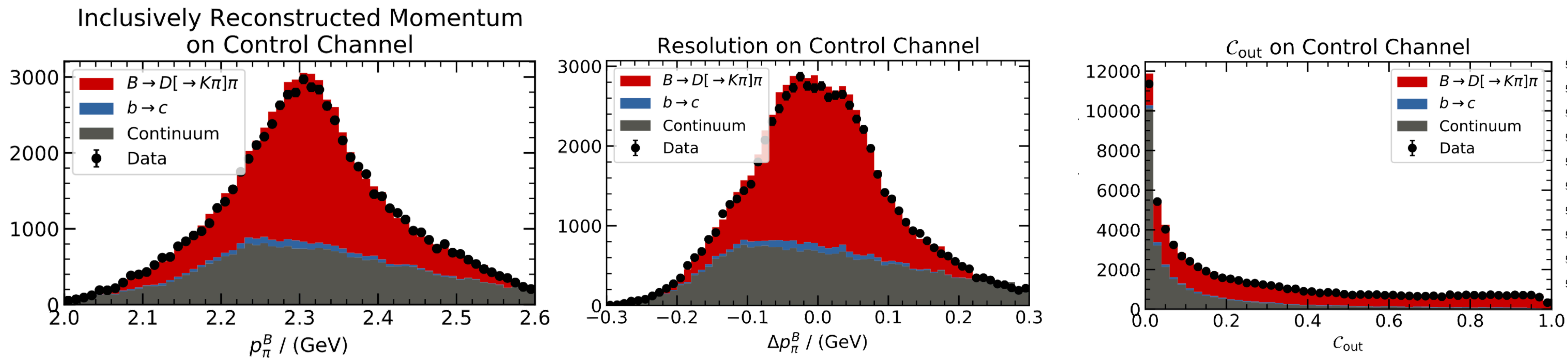
Category	C_{out}	$\cos\Theta_{B\mu}$	Signal Efficiency
I	[0.98,1.00)	[-0.13,1.00)	6.5 %
II	[0.98,1.00)	[-1.00,-0.13)	5.9 %
III	[0.93,0.98)	[0.04,1.00)	7.1 %
IV	[0.93,0.98)	[-1.00,0.04)	8.3 %

arXiv:1911.03186

$B^+ \to \mu^+\nu$ and $B^+ \to \mu^+N$

Validation

- ✓ The procedure is validated by measuring $B^+ \to \overline{D}^0\pi^+$
- ✓ Clean sample is reconstructed and selected by M_{bc}, $|\Delta E|$
- ✓ Prompt π^+ is treated as the signal μ^+
- ✓ Check Data vs. MC for p_μ^B, Δp_μ^B, $\mathcal{C}_{\rm out}$

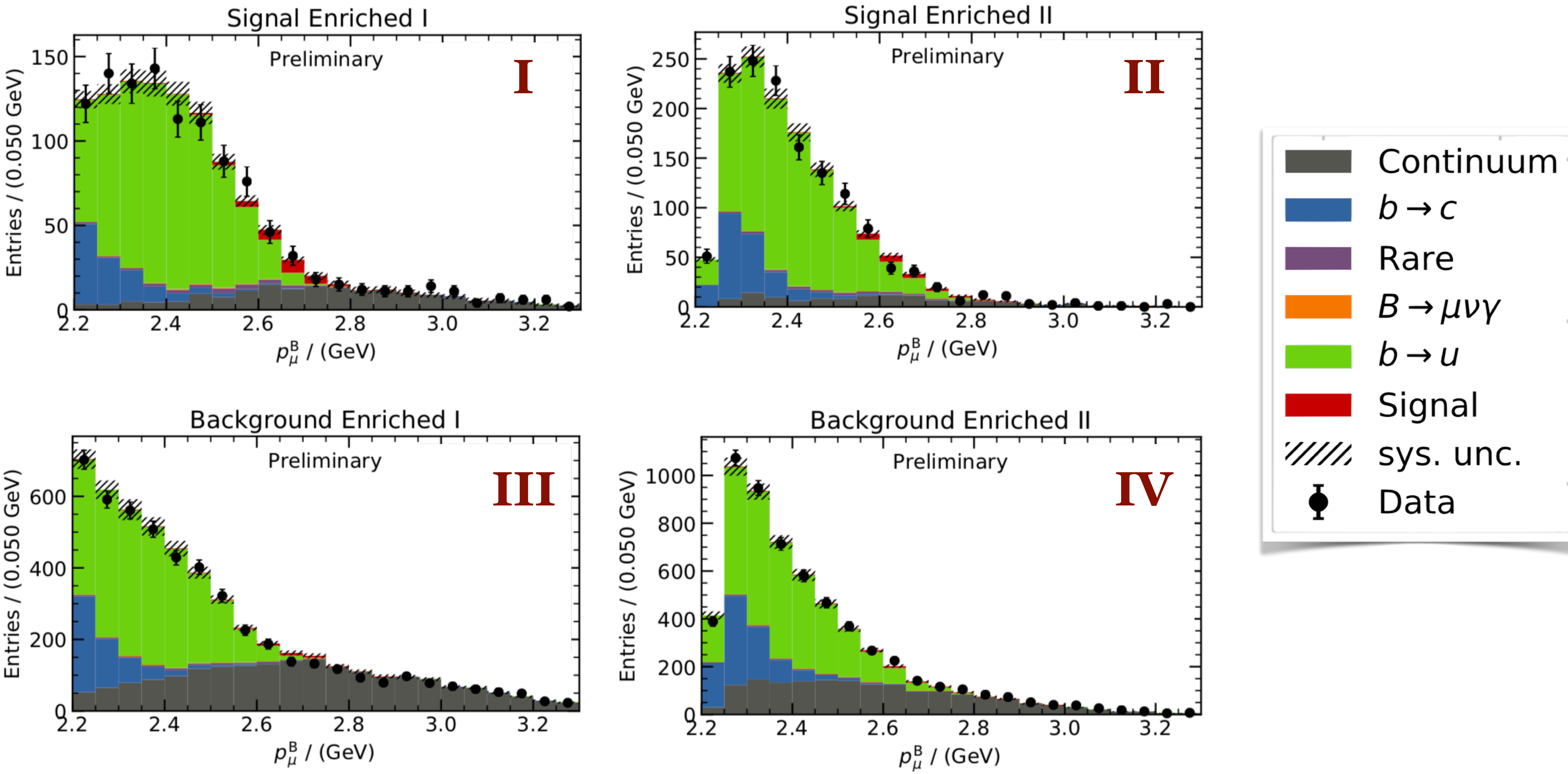


$$\Delta p_\mu^B = 0.11 \text{ GeV}$$

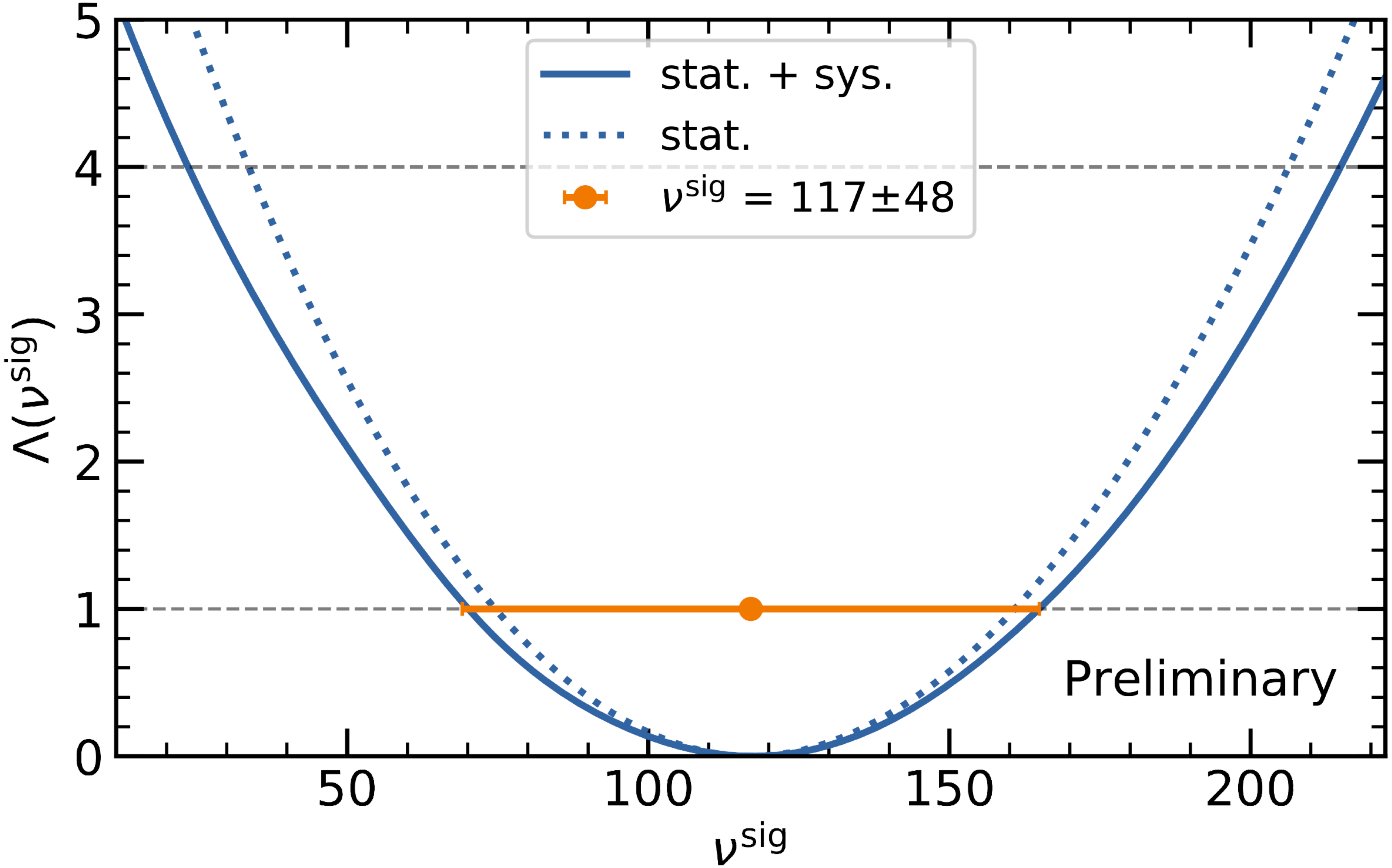
arXiv:1911.03186

$B^+ \to \mu^+\nu$ and $B^+ \to \mu^+ N$

Signal Extraction

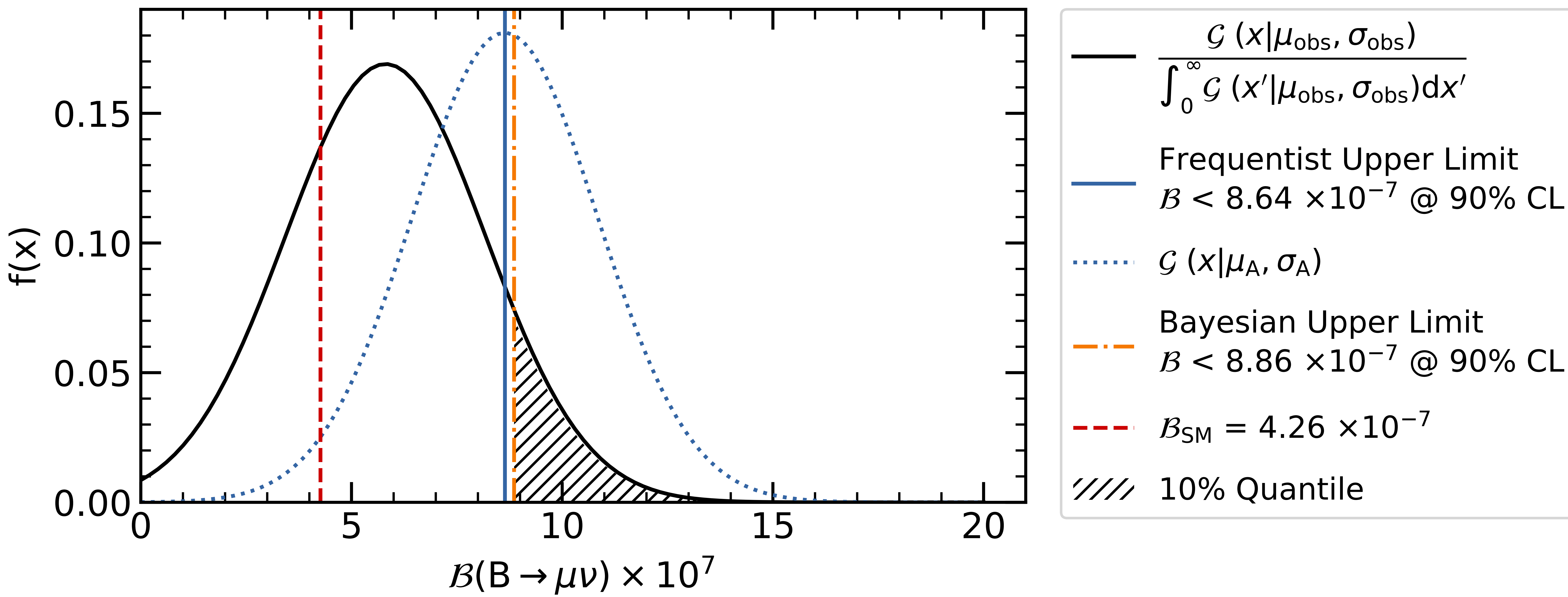


$B^+ \rightarrow \mu^+\nu$ Results



- $\mathcal{B}(B^+ \rightarrow \mu^+\nu) = (5.3 \pm 2.0 \pm 0.9) \times 10^{-7}$ @ 2.8σ

$B^+ \rightarrow \mu^+\nu$ Results

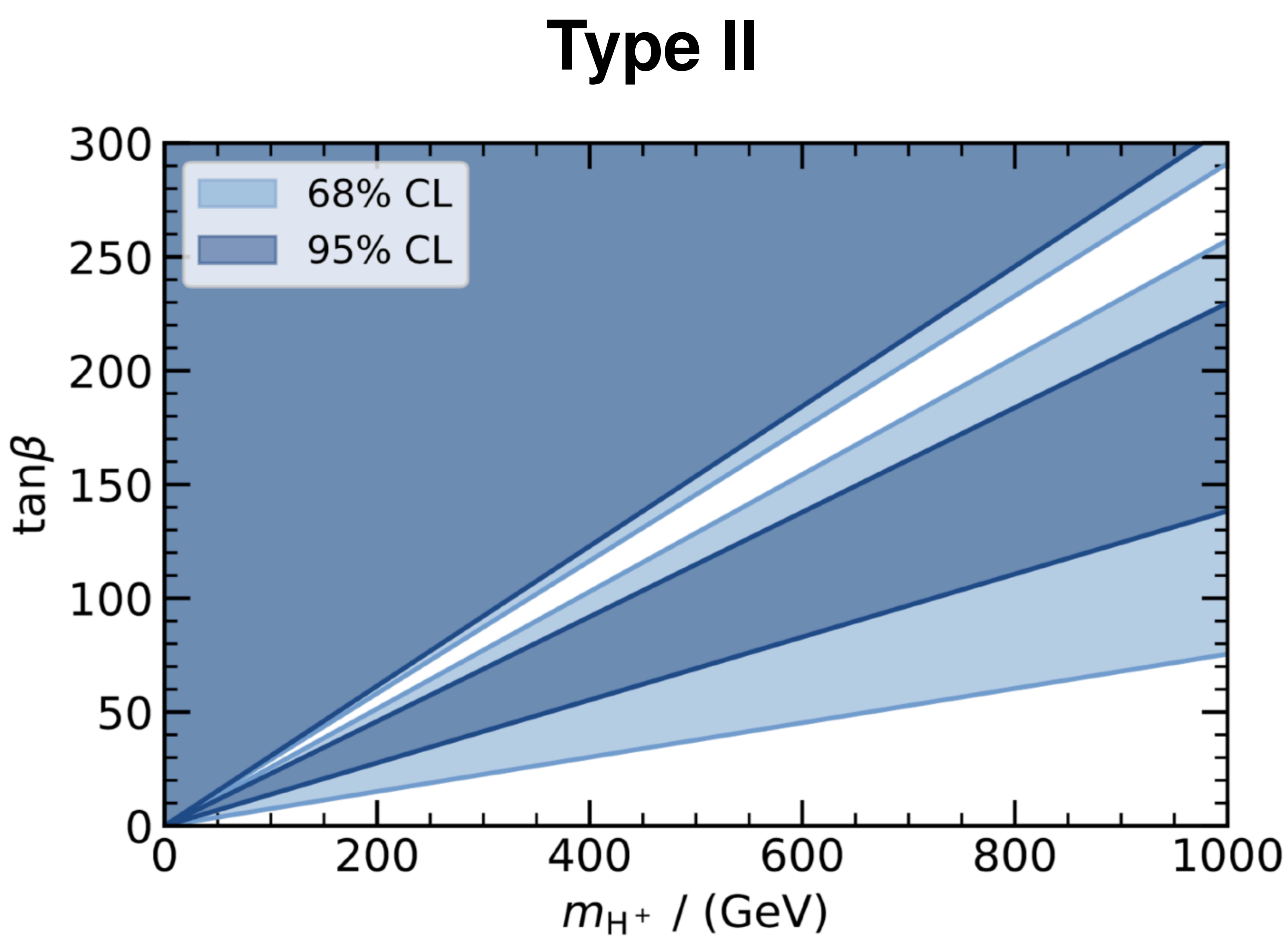


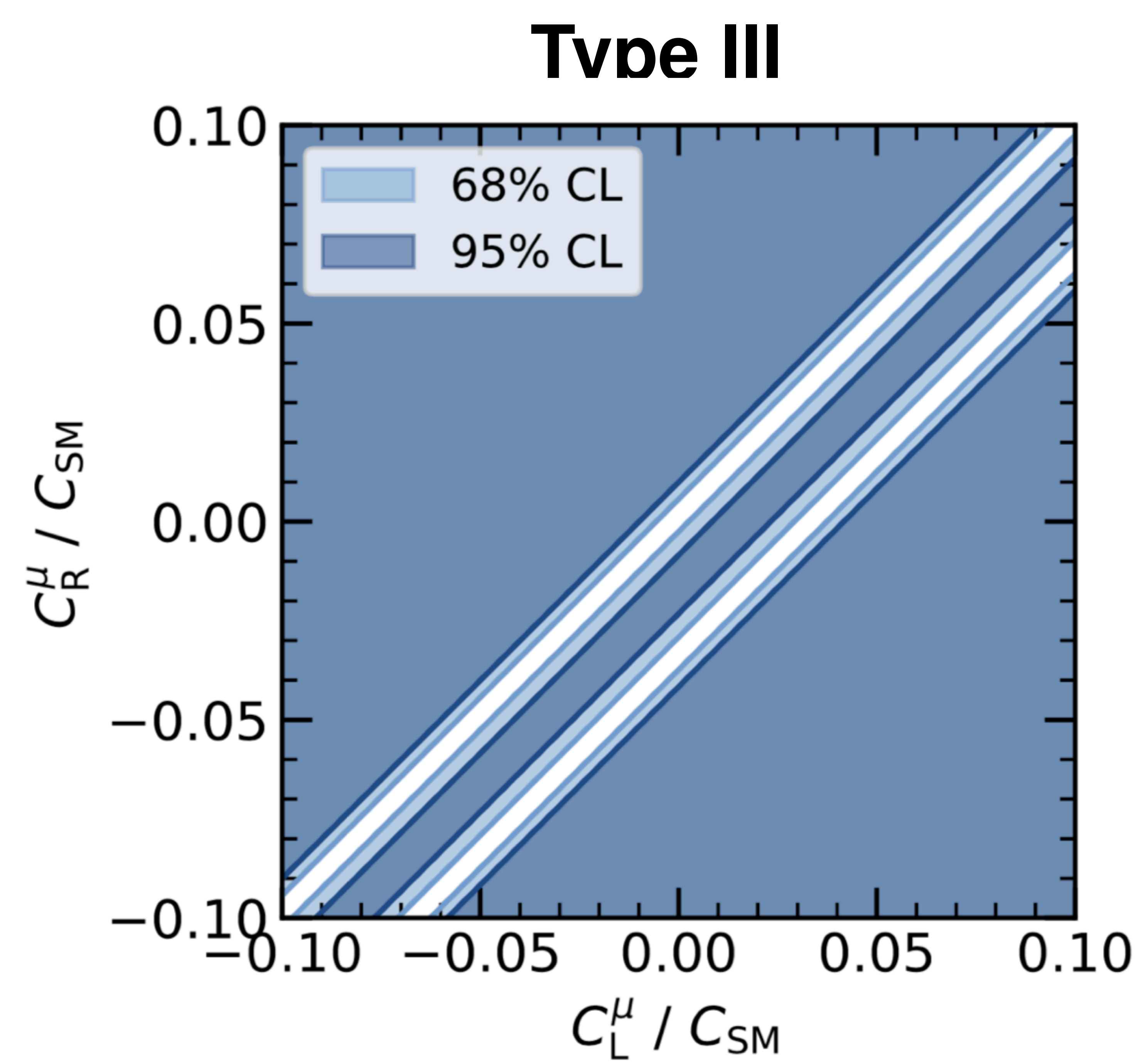
$$\mathcal{B}(B^+ \to \mu^+\nu) < 8.6 \times 10^{-7}$$ **Frequentist**

$$< 8.9 \times 10^{-7}$$ **Bayesian**

arXiv:1911.03186

$B^+ \rightarrow \mu^+\nu$ Interpretation with NP (2HDM) scenarios



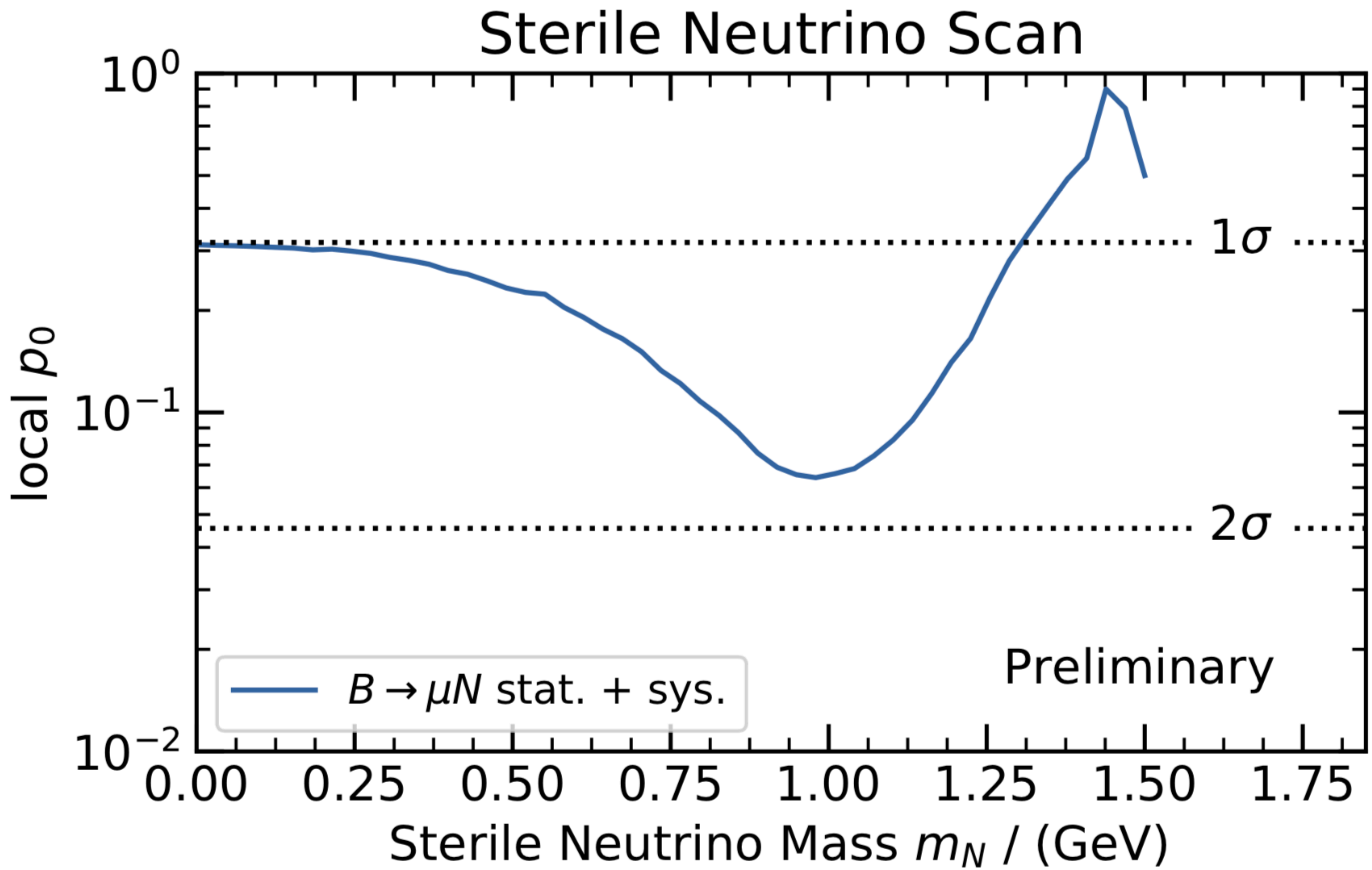


$$\mathcal{B}(\mathrm{B} \rightarrow \ell\nu_\ell) = \mathcal{B}^{\mathrm{SM}} \times \left| 1 - \frac{m_{\mathrm{B}}^2 \tan^2\beta}{m_{\mathrm{H}^+}^2} \right|^2$$

$$\mathcal{B}(\mathrm{B} \rightarrow \ell\nu_\ell) = \mathcal{B}^{\mathrm{SM}} \times \left| 1 + \frac{m_{\mathrm{B}}^2}{m_{\mathrm{b}}\, m_\ell} \frac{C_{\mathrm{R}} - C_{\mathrm{L}}}{C_{\mathrm{SM}}} \right|^2$$

arXiv:1911.03186

$B^+ \to \mu^+\nu$ and $B^+ \to \mu^+N$



$B^+ \to \ell^+\nu\gamma$

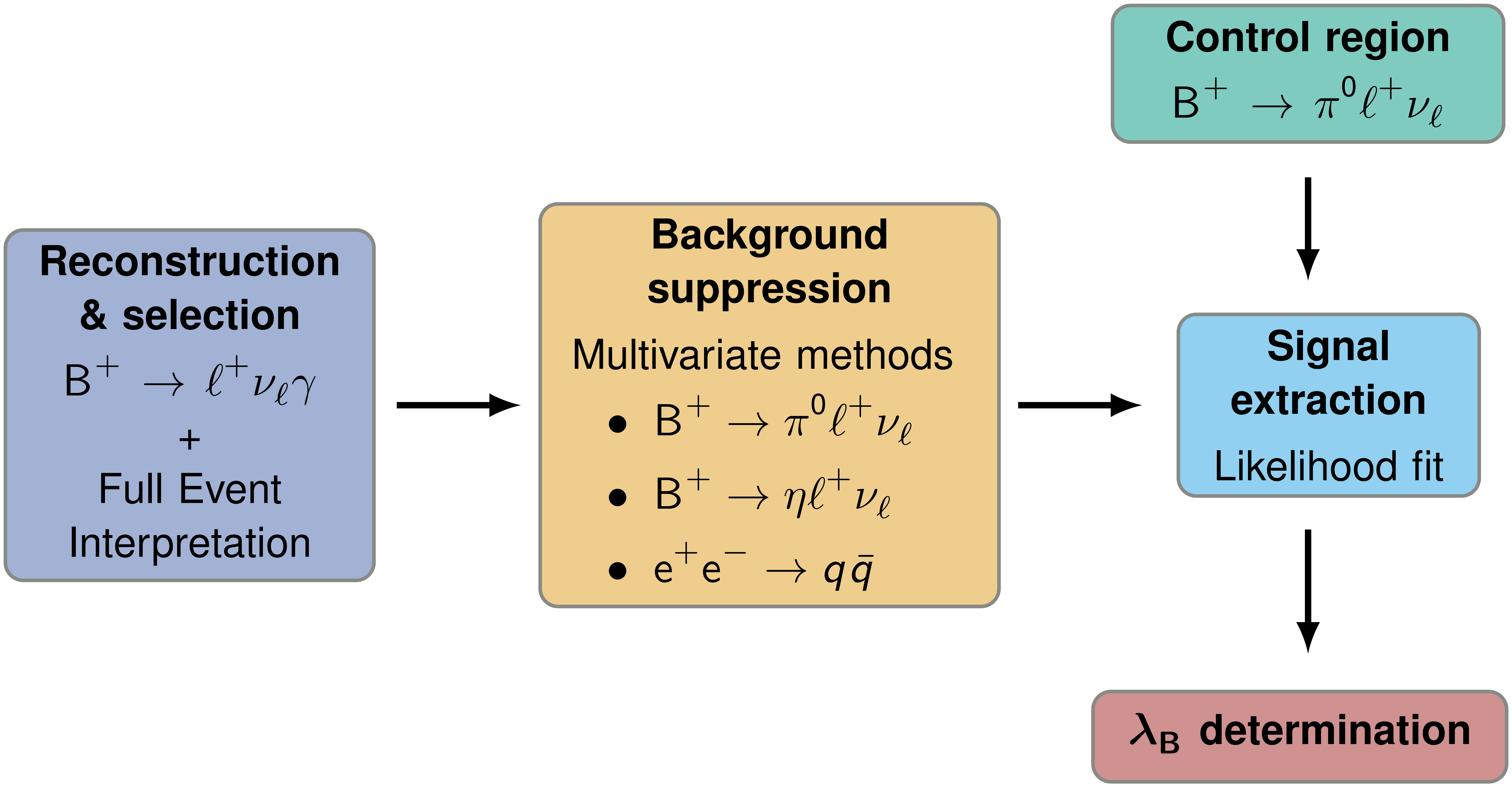
- Helicity suppression (of $B^+ \to \ell^+\nu$) is avoided by γ.

$$\frac{d\Gamma(B^+ \to \ell^+\nu\gamma)}{dE_\gamma} = \frac{\alpha_{\rm em} G_{\rm F}^2 |V_{ub}|^2}{6\pi^2} m_B E_\gamma^3 \left(1 - \frac{2E_\gamma}{m_B}\right) \left(\left|F_{\rm V}\right|^2 + \left|F_{\rm A} + \frac{e_\ell f_B}{E_\gamma}\right|^2 \right)$$

$$F_{\rm V}(E_\gamma),\ F_{\rm V}(E_\gamma) \sim \frac{e_u f_B m_B}{2E_\gamma \lambda_B} + \cdots$$

- λ_B is needed for QCDF to calculate, e.g., charmless hadronic B decays
- SM expectation: $\mathcal{B}(B^+ \to \ell^+\nu\gamma) \sim \mathcal{O}(10^{-6})$
  * Calculation is reliable only for $E_\gamma > 1$ GeV
- Previous Belle (2015): $\Delta\mathcal{B}(B^+ \to \ell^+\nu\gamma) < 3.5 \times 10^{-6}$
- Updated results from Belle (2018) with 'FEI' algorithm
  * a new B-tagging algorithm developed for Belle II

$B^+ \to \ell^+\nu\gamma$ Belle (2018) analysis strategy



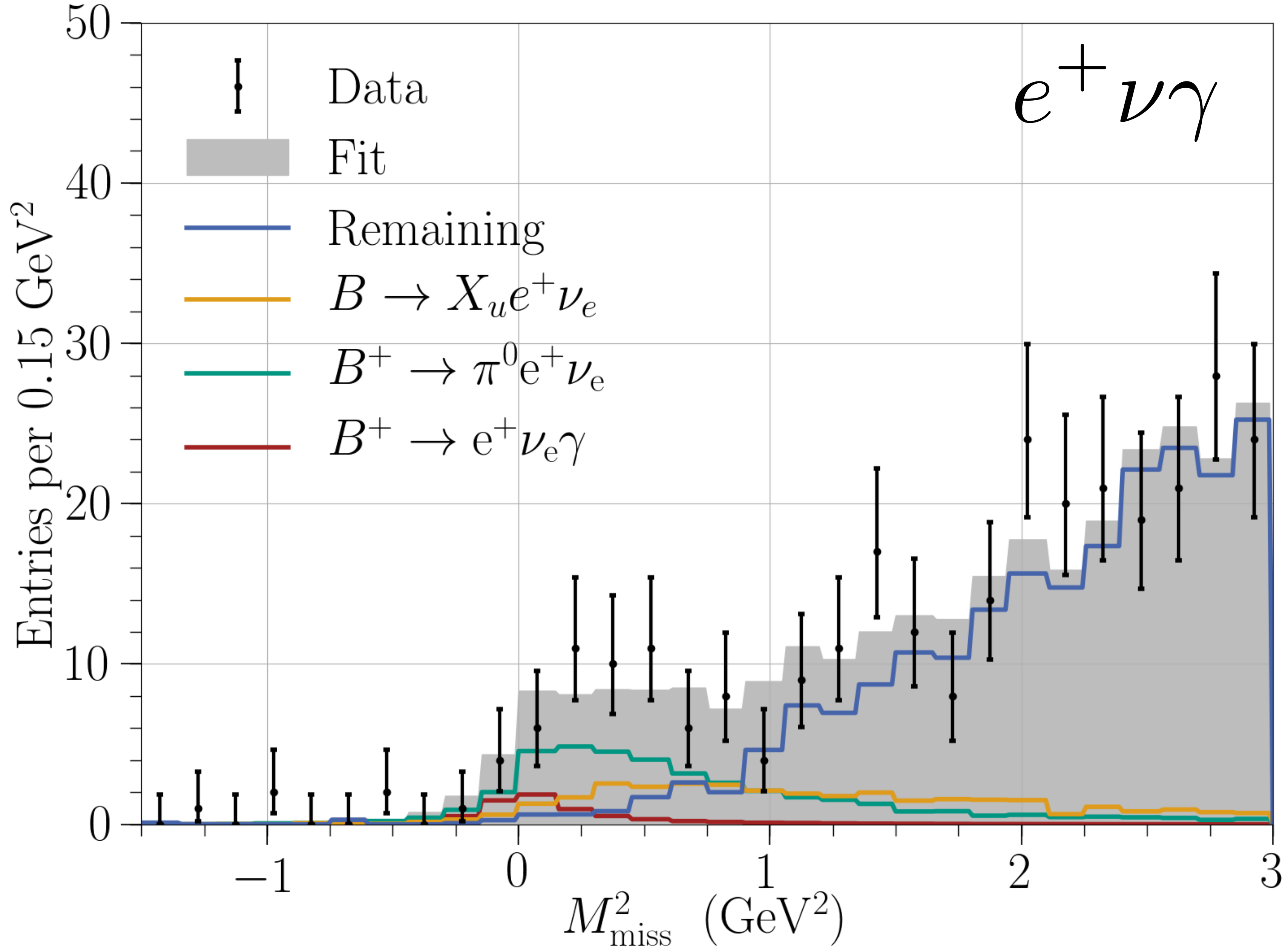
from M. Gelb talk at CKM2018

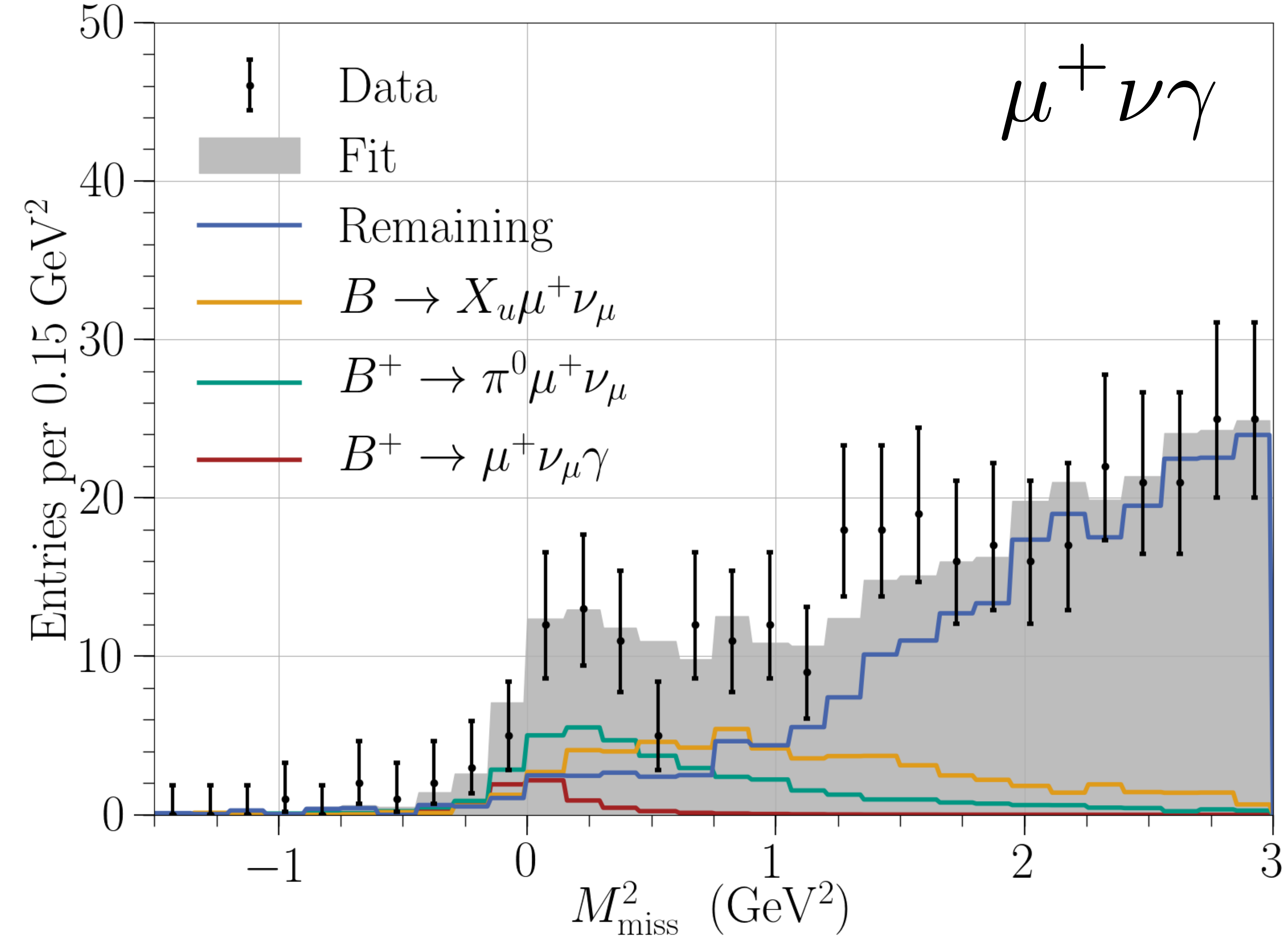
$B^+ \to \ell^+ \nu\gamma$ Belle (2018) features

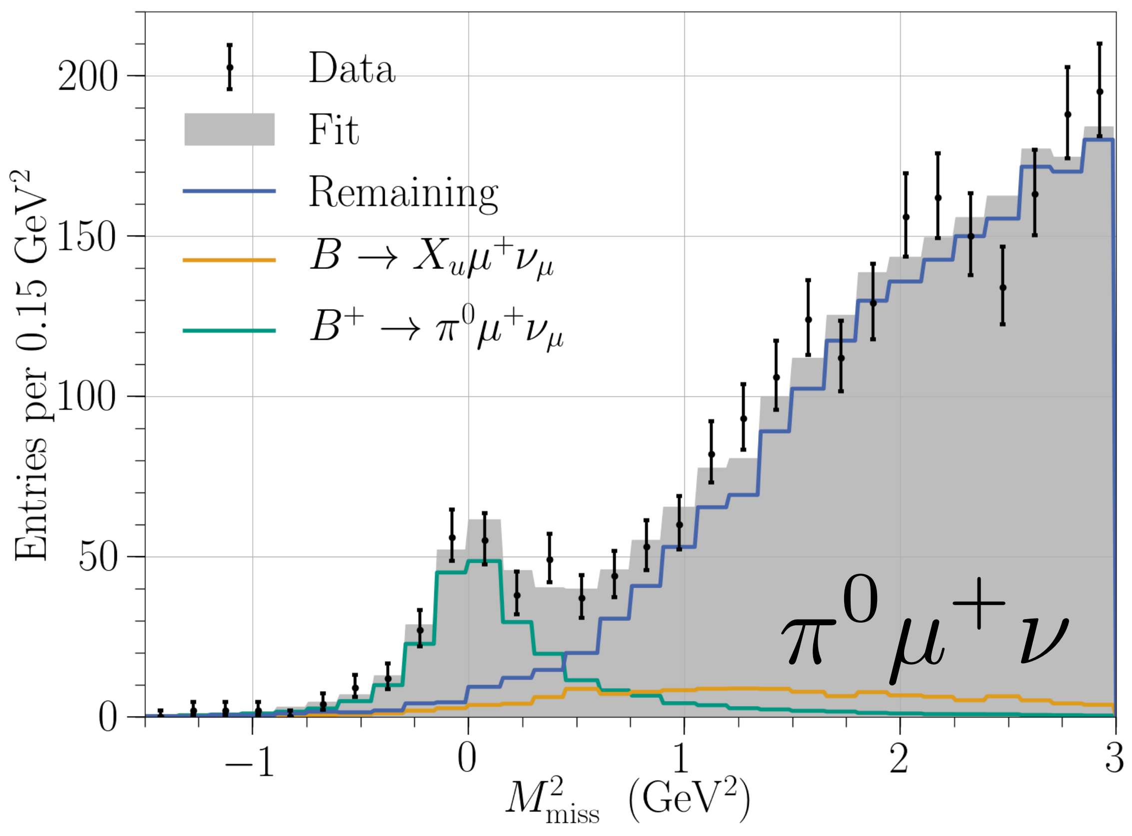
- Measure $B^+ \to \pi^0 \ell^+ \nu$ separately ("*control sample*"), to constrain the peaking background
- Two parameters
  * $\Delta\mathcal{B}(B^+ \to \ell^+ \nu\gamma)_{E_\gamma > 1.0\mathrm{GeV}}$
  * $R_\pi = \Delta\mathcal{B}(B^+ \to \ell^+ \nu\gamma)_{E_\gamma > 1.0\mathrm{GeV}} / \mathcal{B}(B^+ \to \pi^0 \ell^+ \nu)$
    $\Rightarrow$ This allows to extract λ_B independent of $|V_{ub}|$, and some systematics cancel in the ratio R_π.

$B^+ \to \ell^+\nu\gamma$ Belle (2018) results

PRD **98**, 112016 (2018)



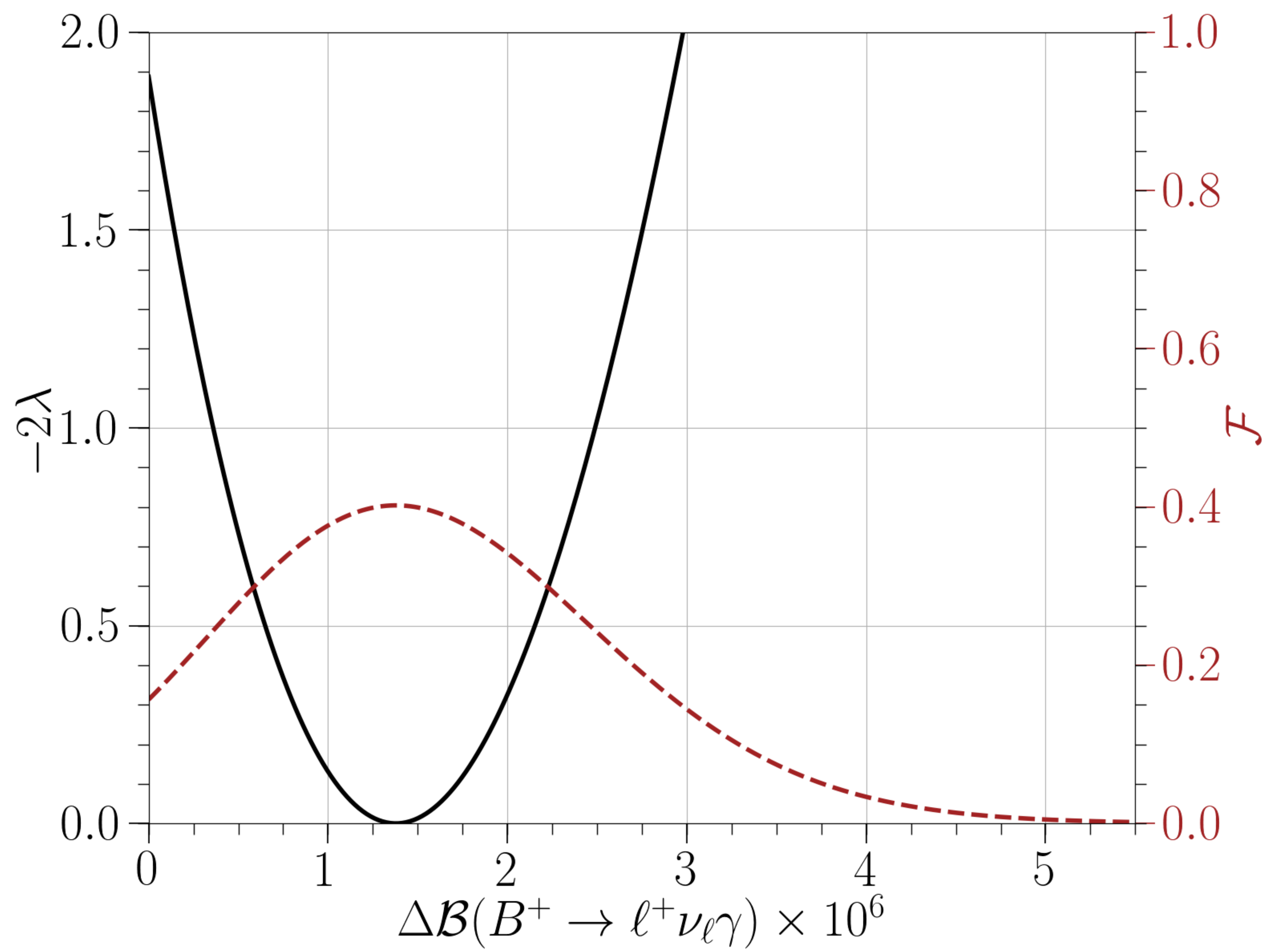




ℓ	$\mathcal{B}(B^+ \to \pi^0\ell^+\nu_\ell)$ (10^{-5})	σ	$\Delta\mathcal{B}(B^+ \to \ell^+\nu_\ell\gamma)$ (10^{-6})	σ
e	$8.3^{+0.9}_{-0.8} \pm 0.9$	8.0	$1.7^{+1.6}_{-1.4} \pm 0.7$	1.1
μ	$7.5^{+0.8}_{-0.8} \pm 0.6$	9.6	$1.0^{+1.4}_{-1.0} \pm 0.4$	0.8
e, μ	$7.9^{+0.6}_{-0.6} \pm 0.6$	12.6	$1.4^{+1.0}_{-1.0} \pm 0.4$	1.4

$B^+ \to \ell^+ \nu \gamma$ Upper Limits

PRD **98**, 112016 (2018)



Bayesian limit

$$0.9 = \frac{\int_0^{\mathrm{UL}} \mathcal{F}(\Delta\mathcal{B}) d\Delta\mathcal{B}}{\int_0^{\infty} \mathcal{F}(\Delta\mathcal{B}) d\Delta\mathcal{B}}$$

ℓ	**BaBar**	**Belle (2015)**	**Belle (2018)**
e	-	< 6.1	< 4.3
μ	-	< 3.4	< 3.4
e, μ	< 14	< 3.5	< 3.0

$B^+ \to \ell^+ \nu \gamma$ Discussion on λ_B

PRD **98**, 112016 (2018)

$$R_\pi^{\text{meas}} = (1.7 \pm 1.4) \times 10^{-2}$$

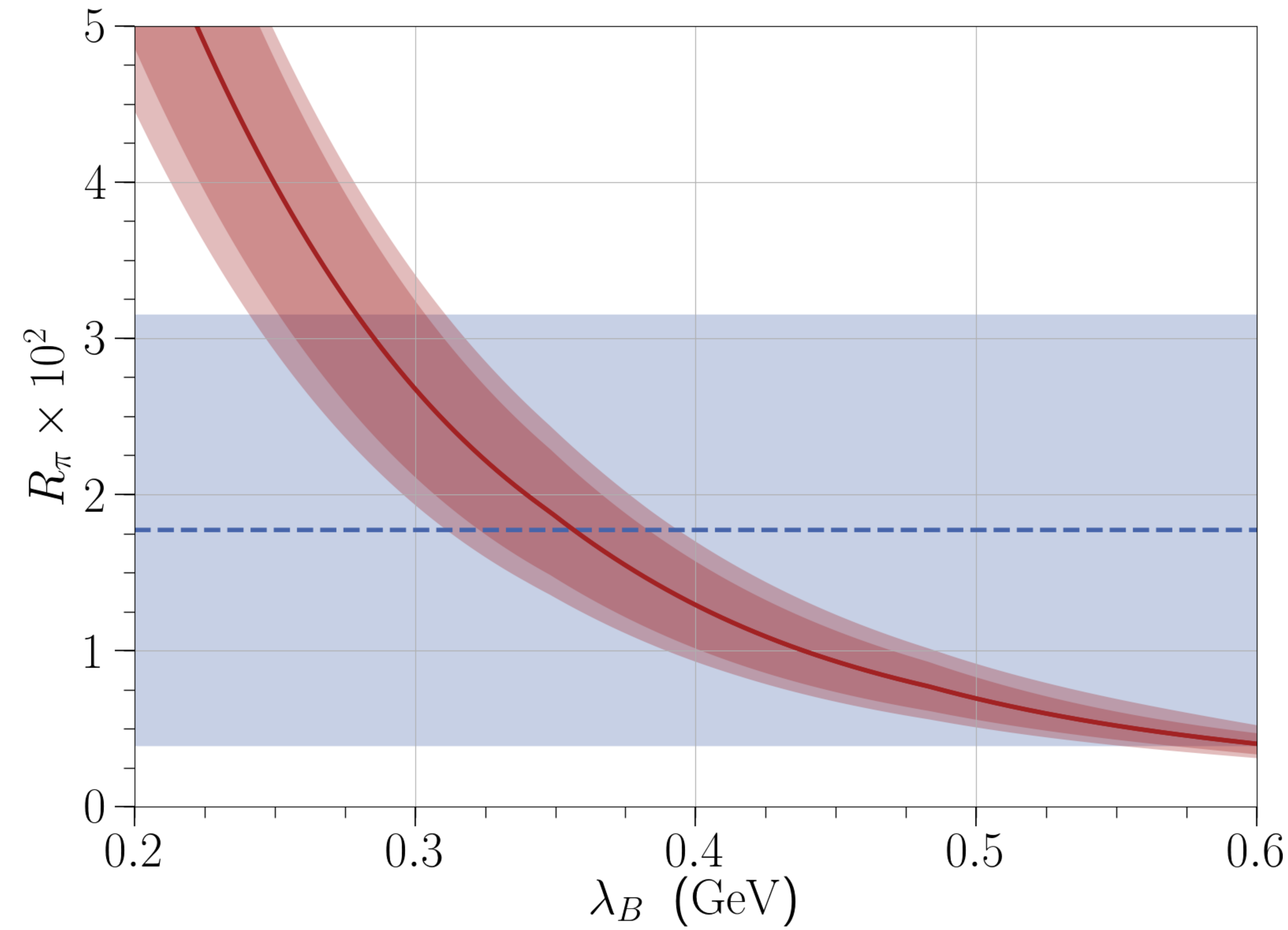
$$R_\pi = \frac{\Delta\Gamma(\lambda_B)}{\Gamma(B^+ \to \pi^0 \ell^+ \nu)}$$

Use theory to determine interval for λ_B

- Beneke, Braun, Ji, Wei, JHEP 1807, 154 (2018)
- HFLAV, EPJC 77, 895 (2017)

Two one-sided limits

$\lambda_B > 0.24$ GeV and $\lambda_B < 0.68$ GeV



EWP and related

$B^0 \to K^* e^\pm \mu^\mp$ Motivations

- Much renewed interests in $B \to K^{(*)} \ell^+\ell^-$ for $R_{K^{(*)}}$ anomalies and potential interpretations in lepton universality violation (LUV)
- LUV accompanied by LFV

"However, any departure from lepton universality is necessarily associated with the violation of lepton flavor conservation. *No known symmetry principle can protect the one in the absence of the other.*"*

- So, search for $B \to K^{(*)} \ell^+\ell'^-$ ($\ell \neq \ell'$)
  - Belle's search in 2018
  - using 2 sets of neural net to suppress continuum and BB backgrounds

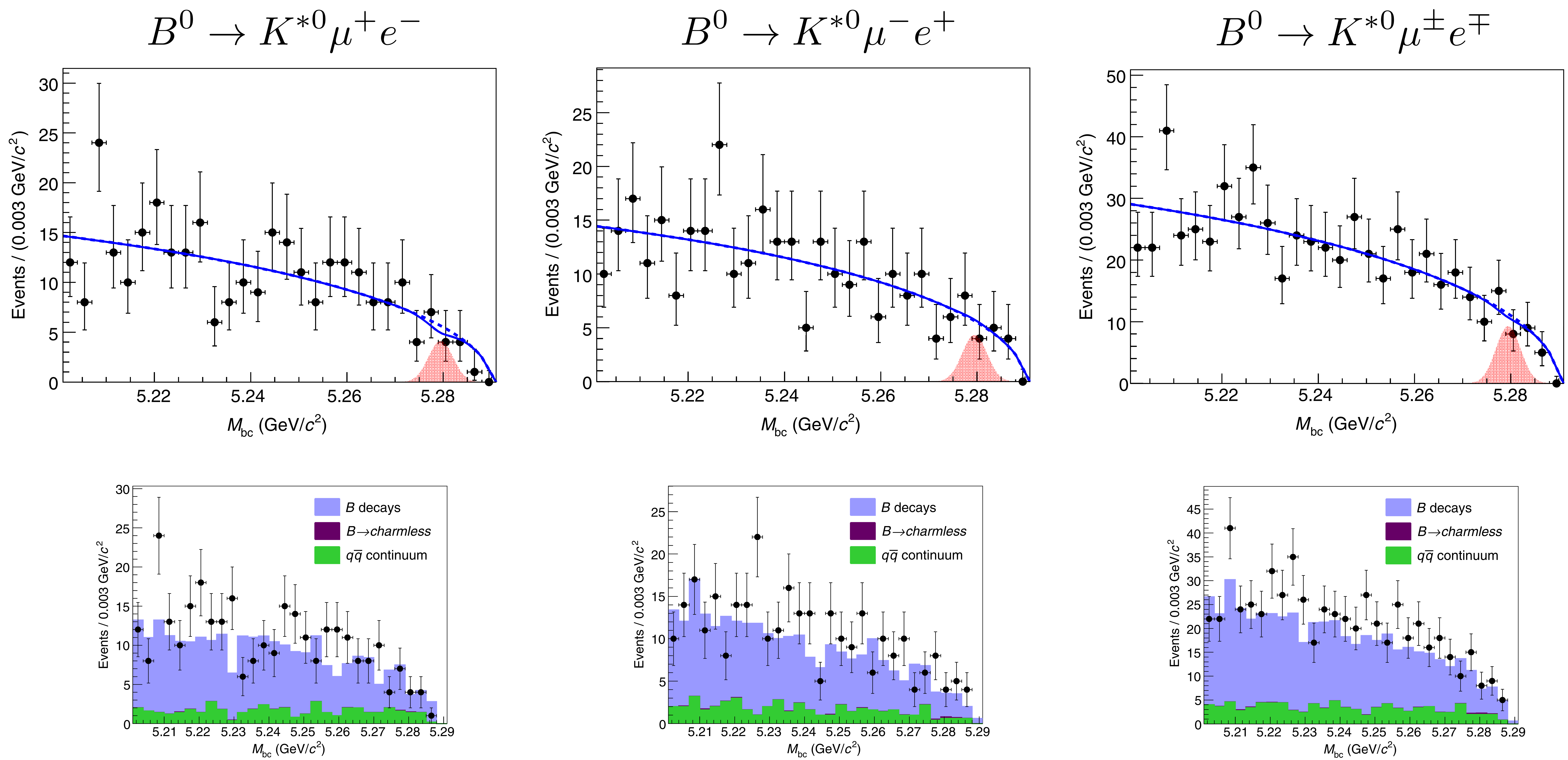
* *Lepton Flavor Violation in B Decays?* Glashow, Guadagnoli, Lane, PRL 114, 091801 (2015)

$B^0 \to K^* e^\pm \mu^\mp$ Backgrounds

- After 1st-stage signal selection (by M_{bc}, ΔE, etc.), the dominant background is continuum
  - neural net on event shape variables ➔ $\mathcal{O}_{\rm NN}^{q\bar{q}}$
  - optimizing $\varepsilon/\sqrt{N_B}$
- The remaining backgrounds are suppressed
  - 2nd set of neural net (vertex, ECL, Δz, etc.) ➔ $\mathcal{O}_{\rm NN}^{BB}$
  - optimizing (*again*) $\varepsilon/\sqrt{N_B}$

PHYS. REV. D **98,** 071101 (2018)

$B^0 \to K^* e^\pm \mu^\mp$ M_{bc} distributions



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$B^0 \to K^* e^\pm \mu^\mp$ Results

Mode	ε (%)	$N_{\rm sig}$	$N_{\rm sig}^{\rm UL}$	$\mathcal{B}^{\rm UL}$ (10^{-7})	BaBar (2006)
$B^0 \to K^{*0}\mu^+ e^-$	8.8	$-1.5^{+4.7}_{-4.1}$	5.2	1.2	5.3
$B^0 \to K^{*0}\mu^- e^+$	9.3	$0.4^{+4.8}_{-4.5}$	7.4	1.6	3.4
$B^0 \to K^{*0}\mu^\pm e^\mp$ (combined)	9.0	$-1.2^{+6.8}_{-6.2}$	8.0	1.8	5.8

$B \to X_s\gamma$ inclusive motivations

- $B \to X_s\gamma$ has played a powerful probe to search for NP in a loop

  $\mathcal{B}(B \to X_s\gamma) \Rightarrow$ strong constraint on NP, e.g. lower limit on $m(H^+)$

- Theory error on $\mathcal{B}(B \to X_s\gamma)$ (currently $\approx 7\%$)

  crucial to reduce it for Belle II test of NP in $B \to X_s\gamma$

- Resolved photon contribution is a significant portion of theory error via non-perturbative effects

  and depends on the spectator quark, hence related to isospin asymmetry

$$\frac{\mathcal{B}^{78}_{\rm RP}}{\mathcal{B}} \simeq -\frac{(1 \pm 0.3)}{3}\Delta_{0-} \qquad \Delta A_{CP} \approx 0.12\left(\frac{\tilde{\Lambda}_{78}}{100\ \mathrm{MeV}}\right)\mathrm{Im}\left(\frac{C_8}{C_7}\right)$$

null expected in SM;
sensitive to NP (e.g. SUSY)

- To measure Δ_{0-}, A_{CP}, and ΔA_{CP} of inclusive $B \to X_s\gamma$,

  $\Rightarrow$ "sum of the exclusive modes"

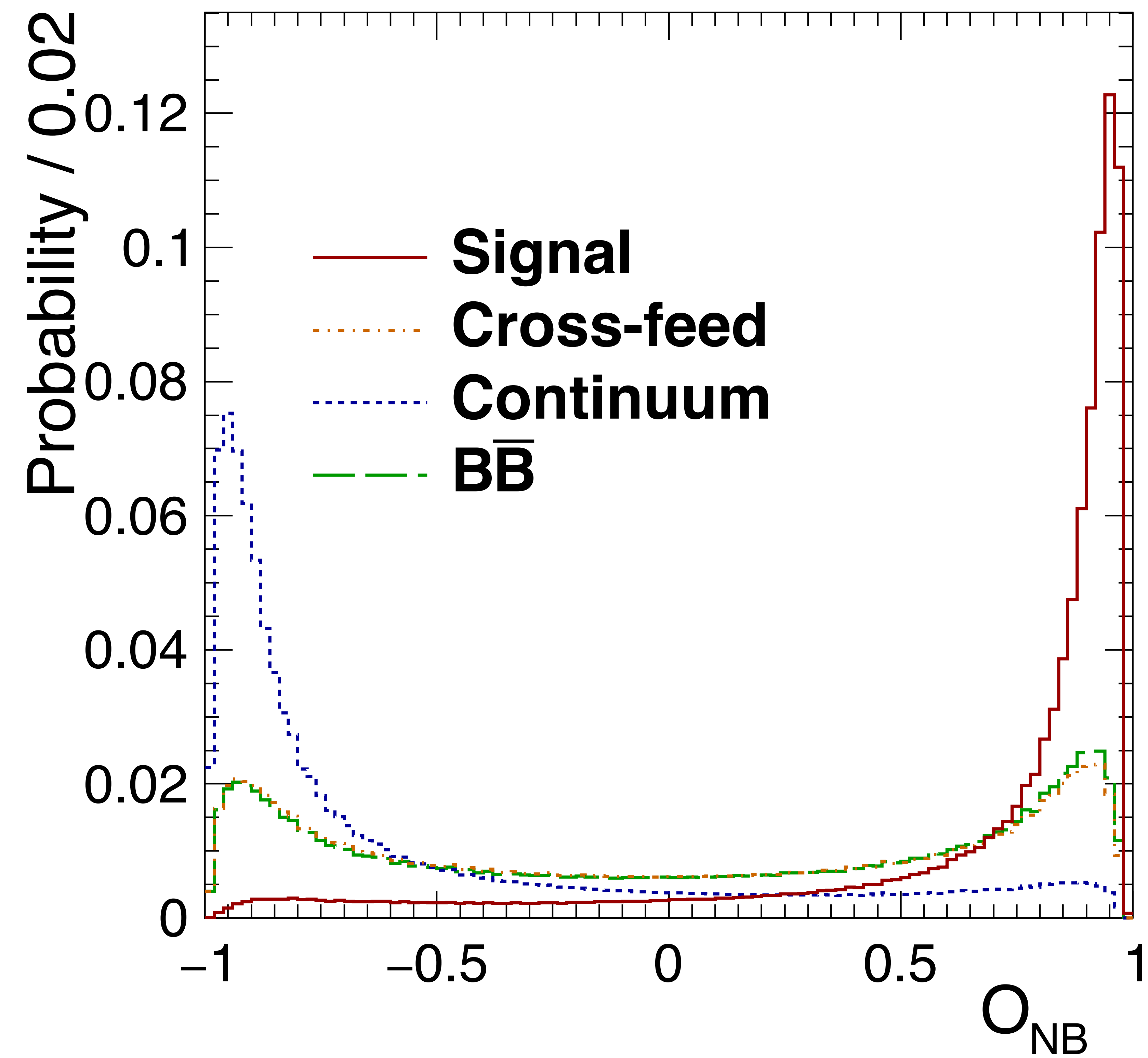
Final states for “sum of exclusives”

Mode ID	Final state	Mode ID	Final state
1	$K^+\pi^-$	20	$K_S^0\pi^+\pi^0\pi^0$
2	$K_S^0\pi^+$	21	$K^+\pi^+\pi^-\pi^0\pi^0$
3	$K^+\pi^0$	22*	$K_S^0\pi^+\pi^-\pi^0\pi^0$
4*	$K_S^0\pi^0$	23	$K^+\eta$
5	$K^+\pi^+\pi^-$	24*	$K_S^0\eta$
6*	$K_S^0\pi^+\pi^-$	25	$K^+\eta\pi^-$
7	$K^+\pi^-\pi^0$	26	$K_S^0\eta\pi^+$
8	$K_S^0\pi^+\pi^0$	27	$K^+\eta\pi^0$
9	$K^+\pi^+\pi^-\pi^-$	28*	$K_S^0\eta\pi^0$
10	$K_S^0\pi^+\pi^+\pi^-$	29	$K^+\eta\pi^+\pi^-$

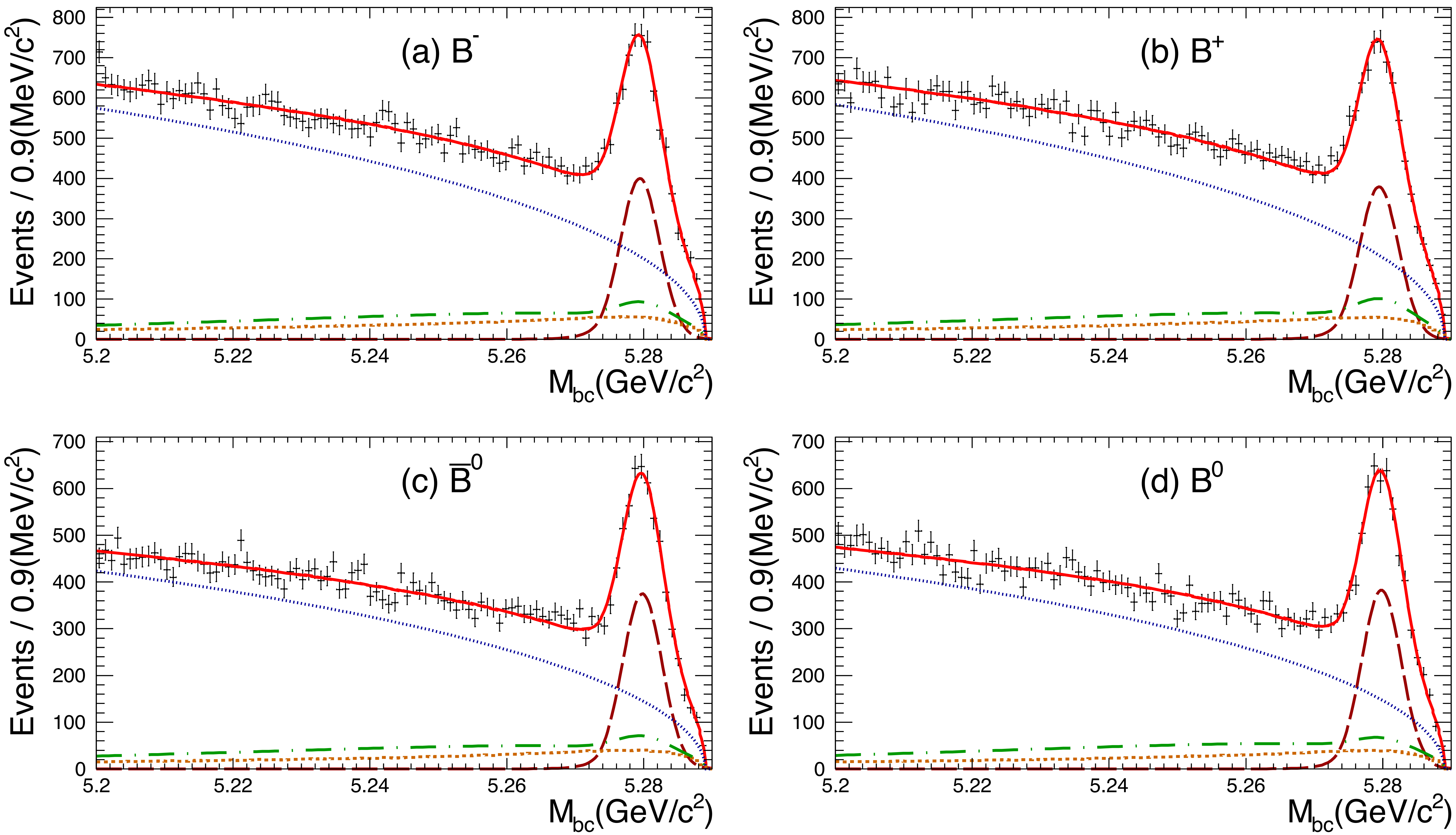
Mode ID	Final state	Mode ID	Final state
11	$K^+\pi^+\pi^-\pi^0$	30*	$K_S^0\eta\pi^+\pi^-$
12*	$K_S^0\pi^+\pi^-\pi^0$	31	$K^+\eta\pi^-\pi^0$
13	$K^+\pi^+\pi^+\pi^-\pi^-$	32	$K_S^0\eta\pi^+\pi^0$
14*	$K_S^0\pi^+\pi^+\pi^-\pi^-$	33	$K^+K^+K^-$
15	$K^+\pi^+\pi^-\pi^-\pi^0$	34*	$K^+K^-K_S^0$
16	$K_S^0\pi^+\pi^+\pi^-\pi^0$	35	$K^+K^+K^-\pi^-$
17	$K^+\pi^0\pi^0$	36	$K^+K^-K_S^0\pi^+$
18*	$K_S^0\pi^0\pi^0$	37	$K^+K^+K^-\pi^0$
19	$K^+\pi^-\pi^0\pi^0$	38*	$K^+K^-K_S^0\pi^0$

$B \to X_s \gamma$ inclusive backgrounds

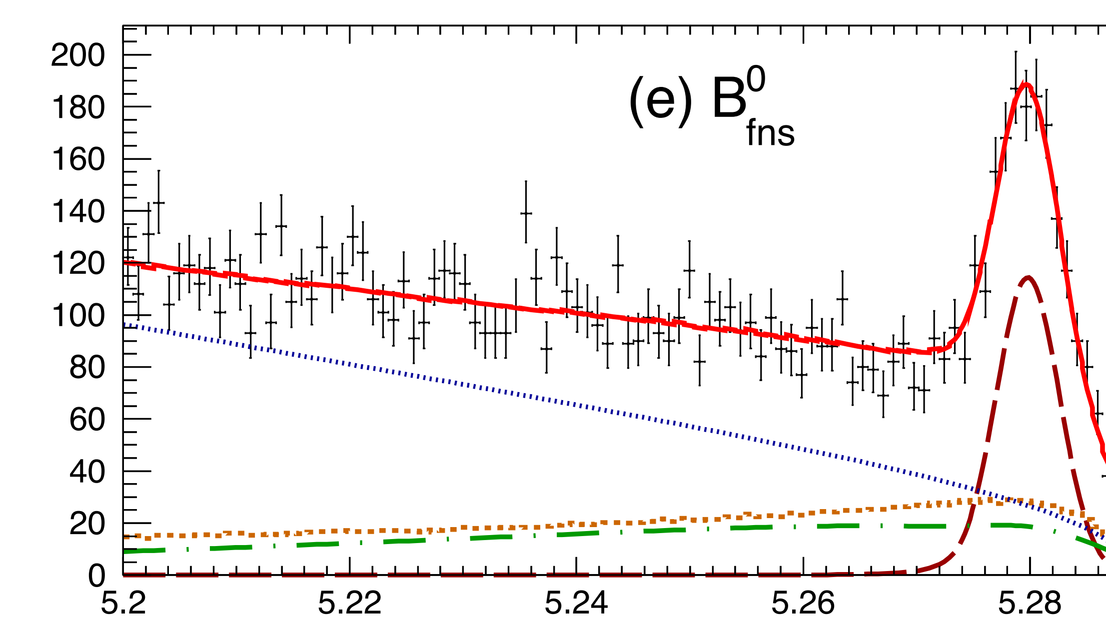
- Two dominant sources
  - $e^+e^- \to q\bar{q}$ continuum
  - $B \to D^{(*)}\rho^+$
- Suppression by
  - artificial NN (signal vs. $q\bar{q}$)
  - D veto



$B \to X_s\gamma$ inclusive signal yields



Mode	N_S	ϵ [%]
B^-	3243 ± 85	2.21 ± 0.12
B^+	3074 ± 86	2.23 ± 0.12
$\bar{B}^0$	3038 ± 78	2.42 ± 0.14
B^0	3102 ± 79	2.46 ± 0.14
$B_{\rm fns}$	902 ± 42	0.375 ± 0.023



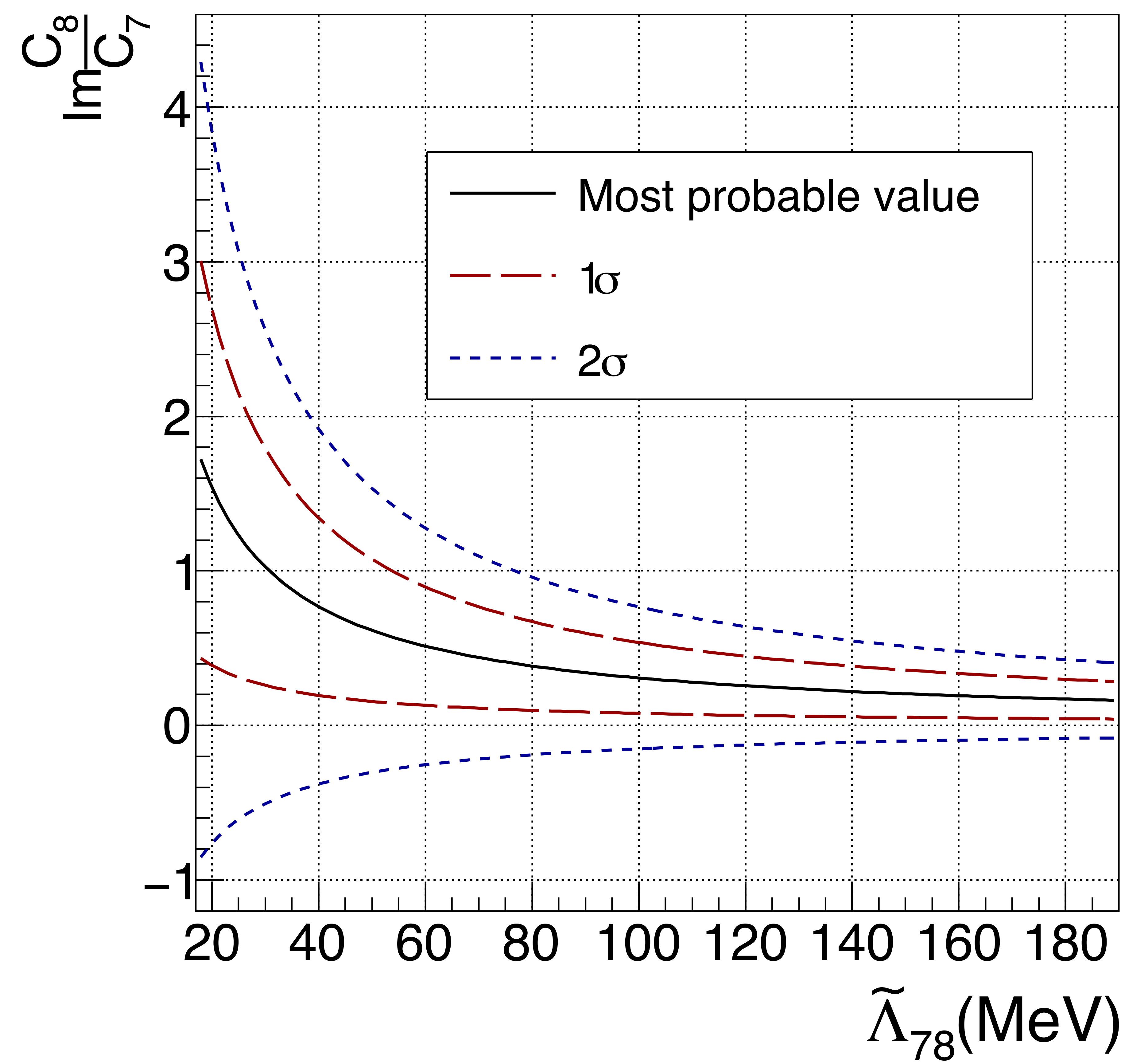
All
Signal
continuum
BB
cross-feed

$B_{\rm fns}$ = flavor-non-specific neutral B

$B \to X_s\gamma$ inclusive Results

$$\Delta_{0-} = (-0.48 \pm 1.49 \pm 0.97 \pm 1.15)\%,$$
$$\Delta A_{CP} = (+3.69 \pm 2.65 \pm 0.76)\%,$$
$$A_{CP}^{\mathrm{C}} = (+2.75 \pm 1.84 \pm 0.32)\%,$$
$$A_{CP}^{\mathrm{N}} = (-0.94 \pm 1.74 \pm 0.47)\%,$$
$$A_{CP}^{\mathrm{tot}} = (+1.44 \pm 1.28 \pm 0.11)\%,$$
$$\bar{A}_{CP} = (+0.91 \pm 1.21 \pm 0.13)\%,$$

$$\frac{\mathcal{B}_{\mathrm{RP}}^{78}}{\mathcal{B}} \simeq (+0.16 \pm 0.50 \pm 0.32 \pm 0.38 \pm 0.05)\%$$



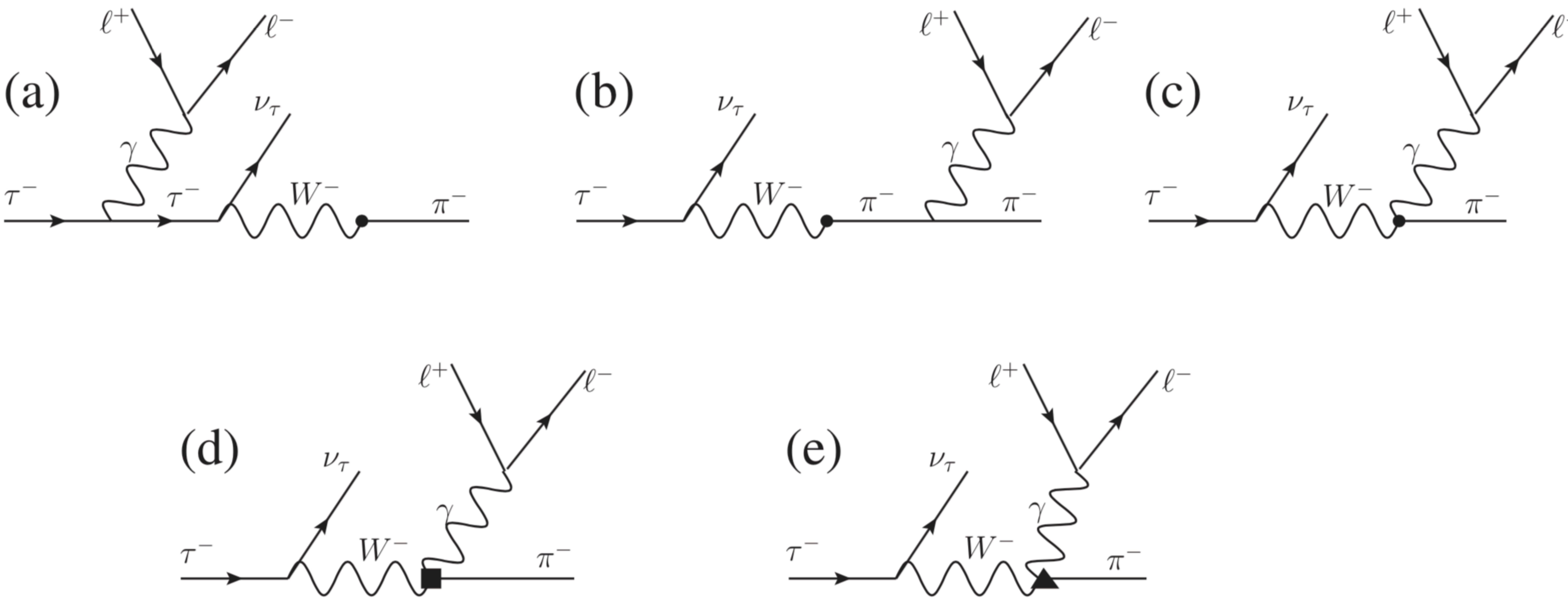
$$\tau \to \pi \nu \ell^+ \ell^-$$

$\tau^+ \to \pi^+ \nu \ell^+ \ell^-$ motivations

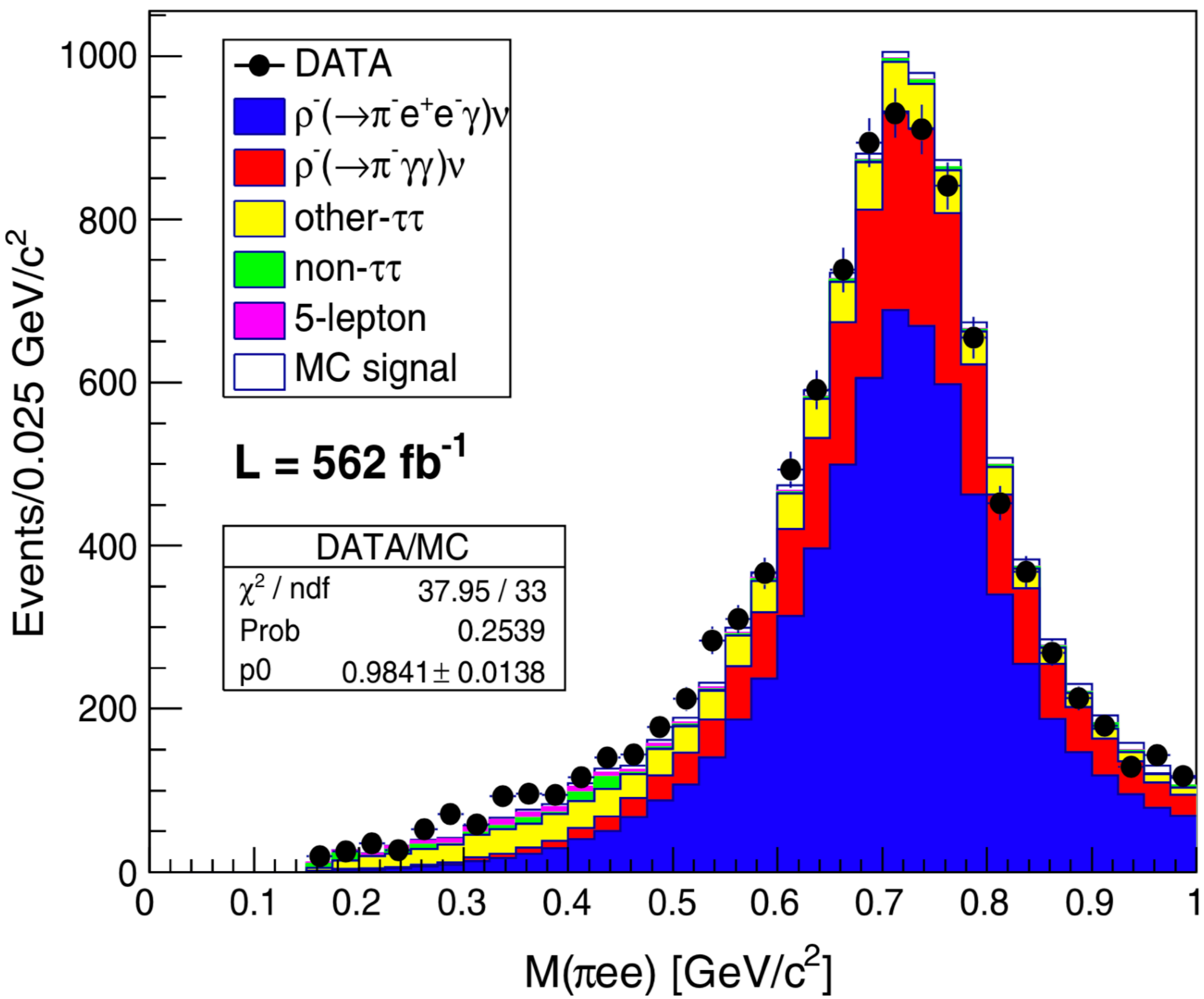
- hadronic final states of τ decays — a clean laboratory to study the dynamics of strong interactions
- study $\gamma^* W^* \pi$ vertex with two gauge bosons in the off-shells
- $\mathscr{B}(\tau^+ \to \pi^+ \nu \ell^+ \ell^-) \sim \mathcal{O}(10^{-5})$ in the SM
- useful for
  - radiative corrections to, e.g. $\tau^+ \to \pi^+ \nu$ decays, and
  - hadronic light-by-light scattering to $(g-2)_\mu$
  - background study for various LFV, LNV τ decays

PHYSICAL REVIEW D **100,** 071101(R) (2019)

$\tau^+ \to \pi^+ \nu \ell^+ \ell^-$ diagrams

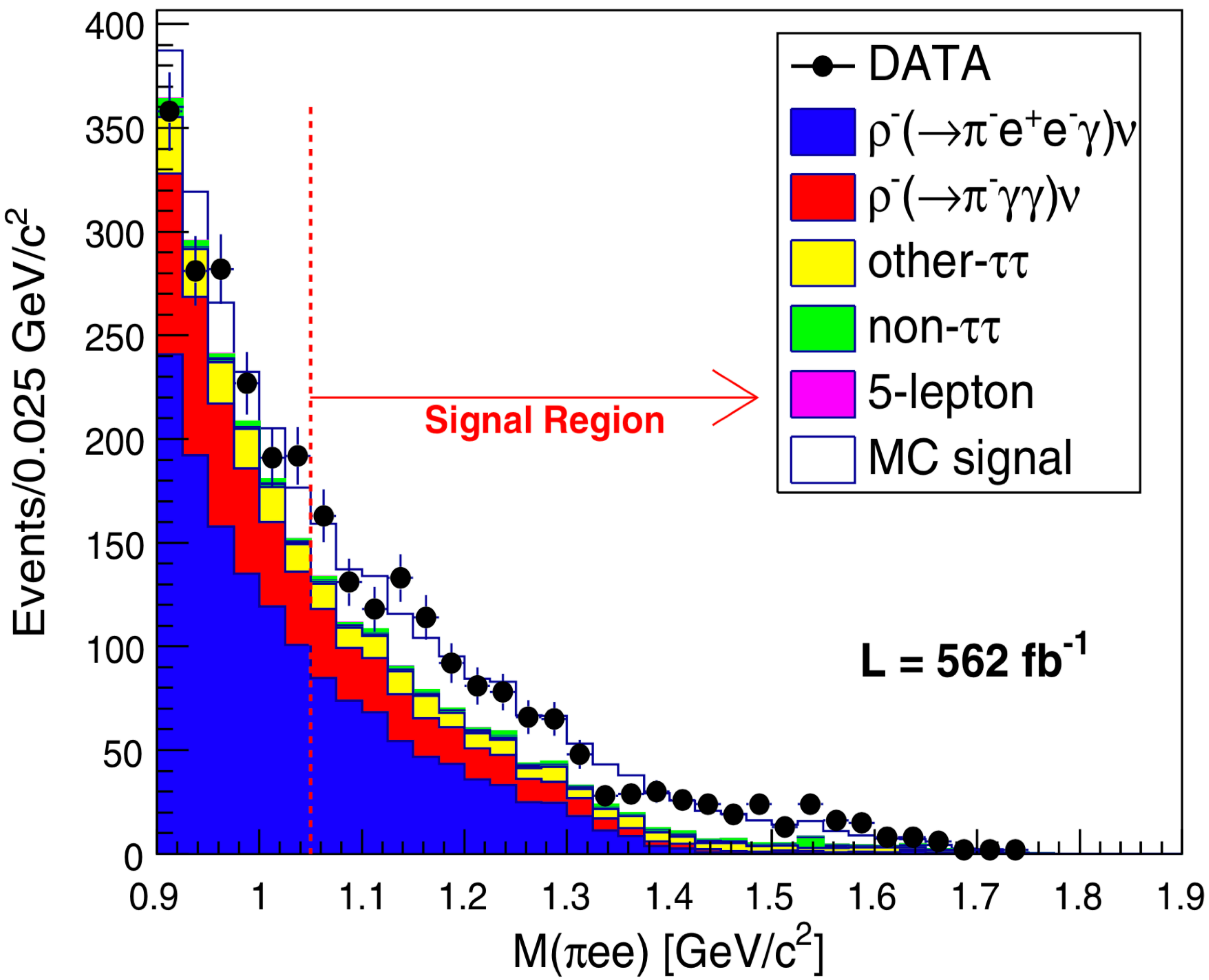


$\tau^+ \to \pi^+ \nu e^+ e^-$ control region



- $1.05 < M(\pi ee) < 1.8$ as the signal region
  - efficient for (d), (e), but insensitive for the others
- $M(\pi ee) < 1.05$ for the control region
  - check data vs. MC
- Blind analysis!

$\tau^+ \to \pi^+ \nu e^+ e^-$ signal region

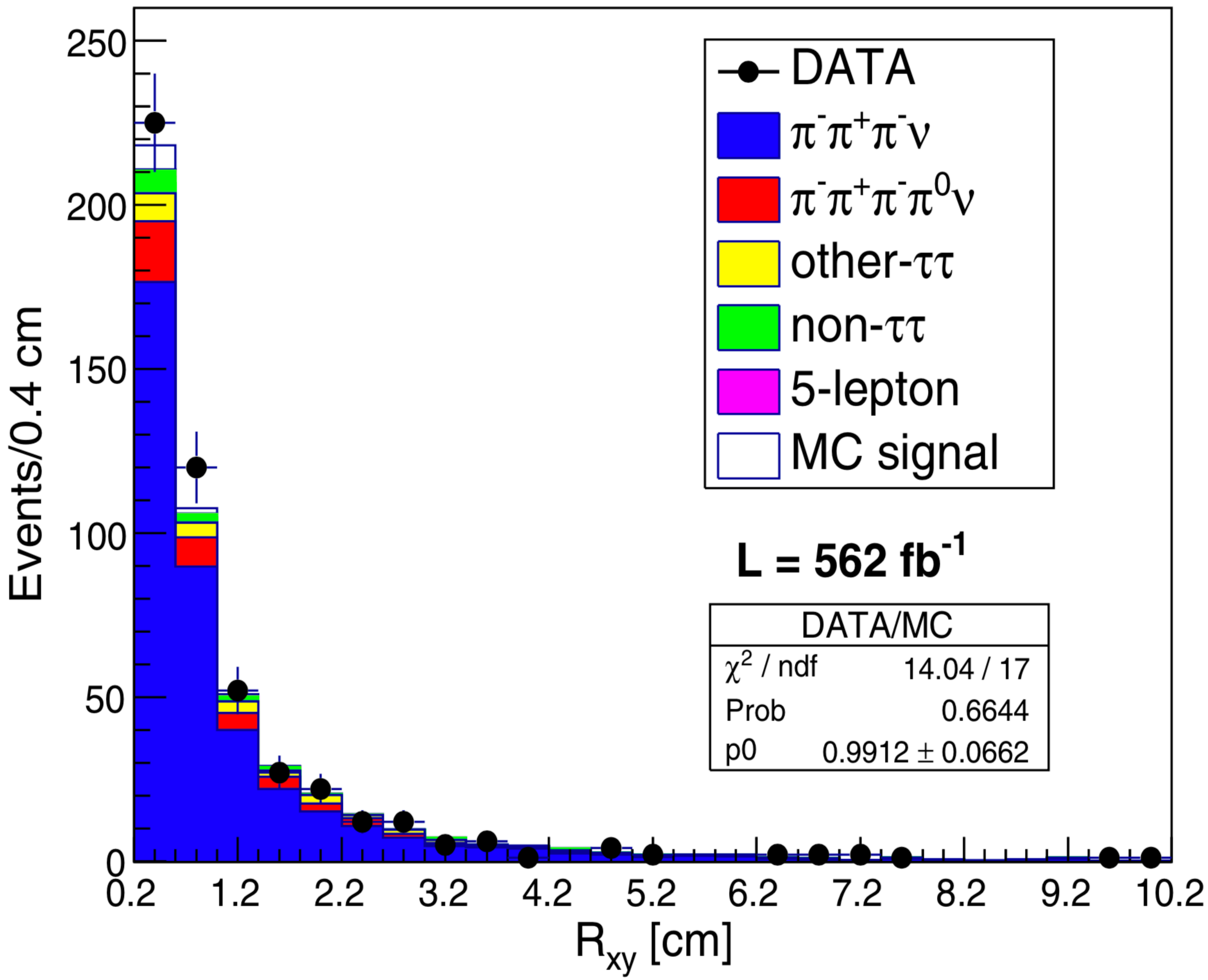


- $N_{\mathrm{event}} = 1365$
  - $N_{\mathrm{bkgd}} = 954 \pm 45$
  - 7σ excess
- Partial BF is measured
- For full BF, model-dependent for (a), (b), (c)

$$\mathscr{B}_A = (1.46 \pm 0.13 \pm 0.21) \times 10^{-5}$$

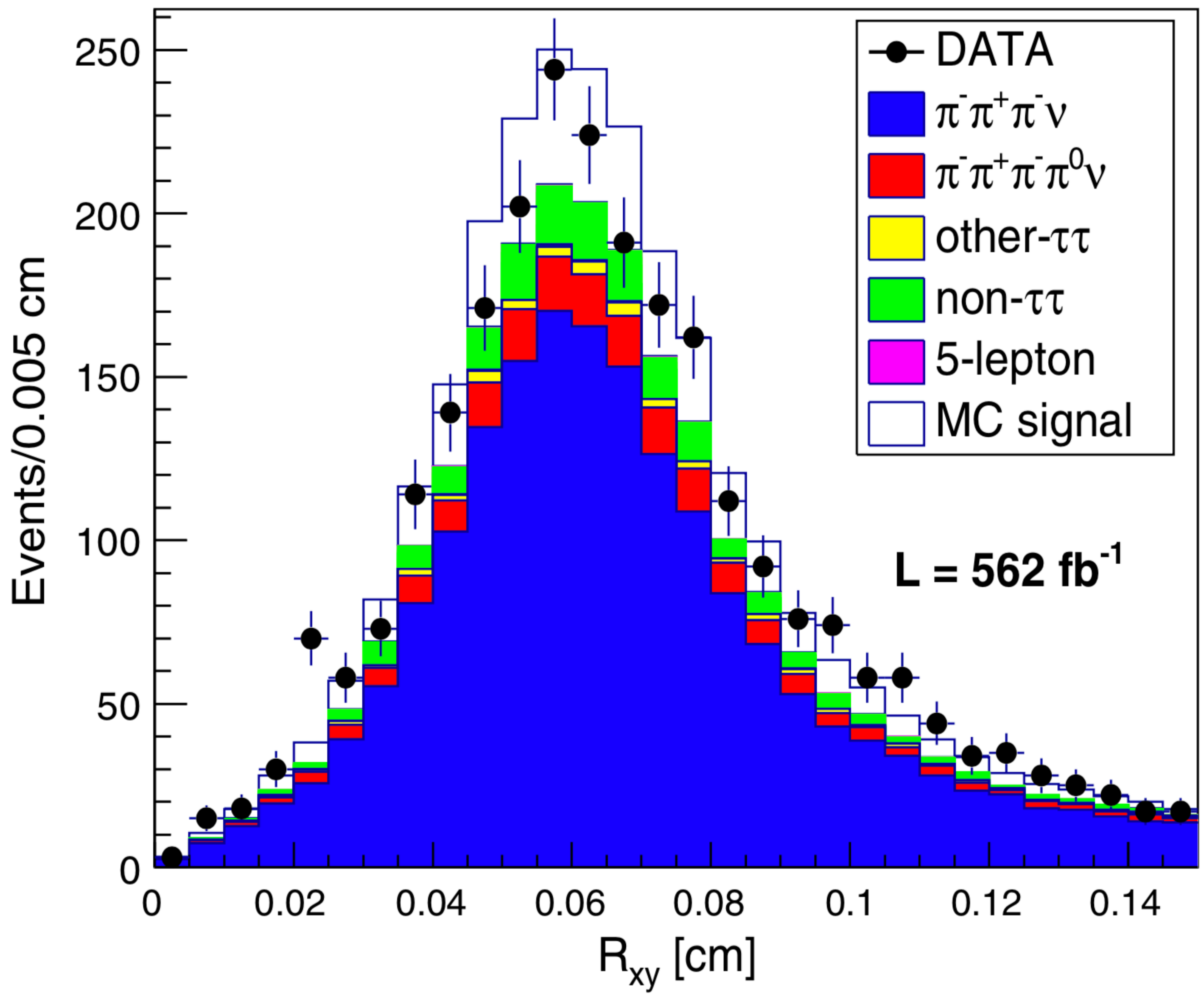
$$\mathscr{B}_V = (3.01 \pm 0.27 \pm 0.43) \times 10^{-5}$$

$\tau^+ \to \pi^+ \nu \mu^+ \mu^-$ control region



- R_{xy} = radial distance of $\mu\mu$ vertex from the IP
- $R_{xy} > 0.2$ cm as the control region
- $R_{xy} < 0.15$ cm for the signal region

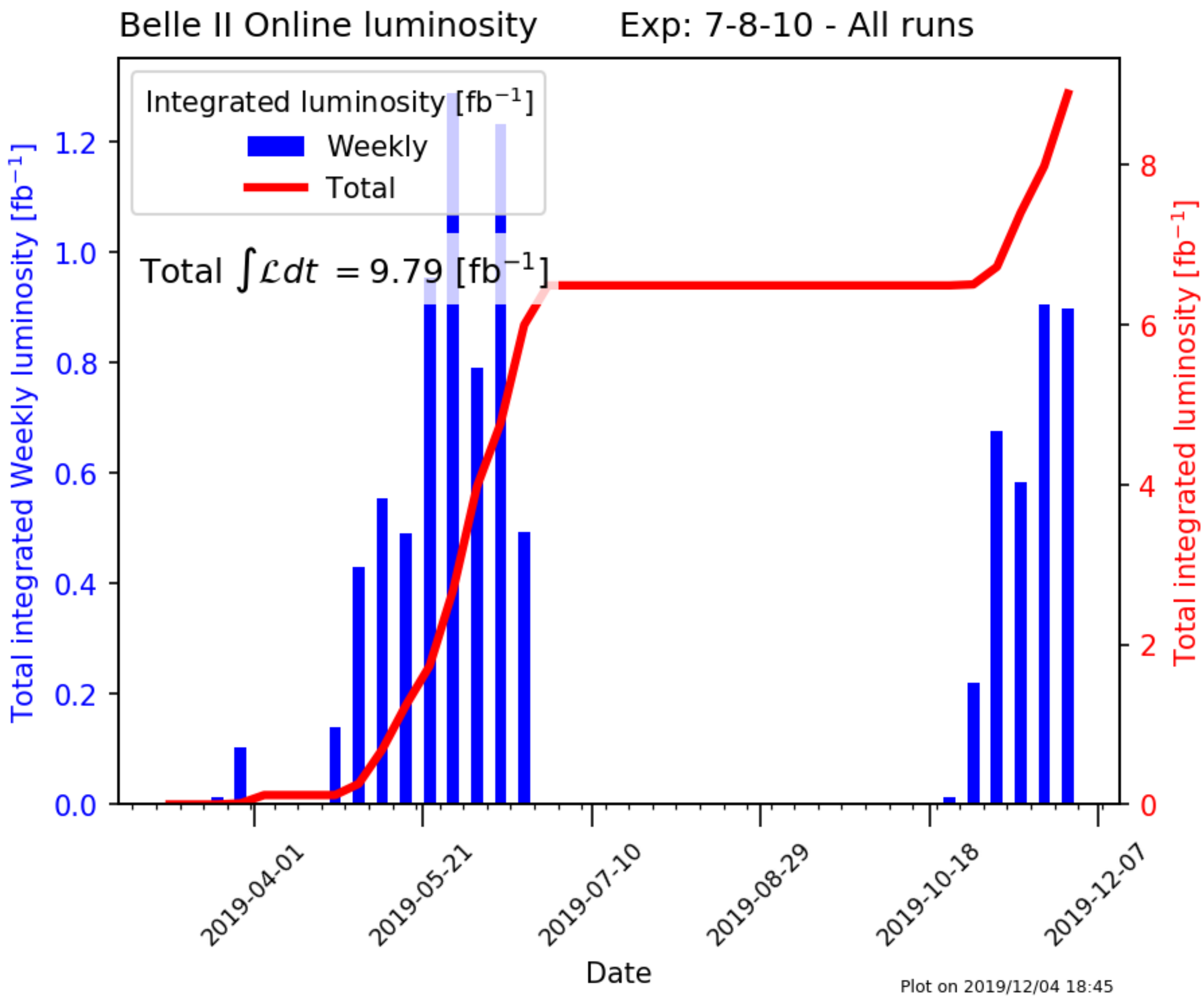
$\tau^+ \to \pi^+ \nu \mu^+ \mu^-$ signal region



- $N_{\text{event}} = 2578$
  - $N_{\text{bkgd}} = 2244 \pm 109$
  - 2.8σ excess $(334 \pm 51 \pm 109)$

$\mathscr{B}(\tau \to \pi\nu\mu\mu) < 1.14 \times 10^{-5}$

a Belle II update!

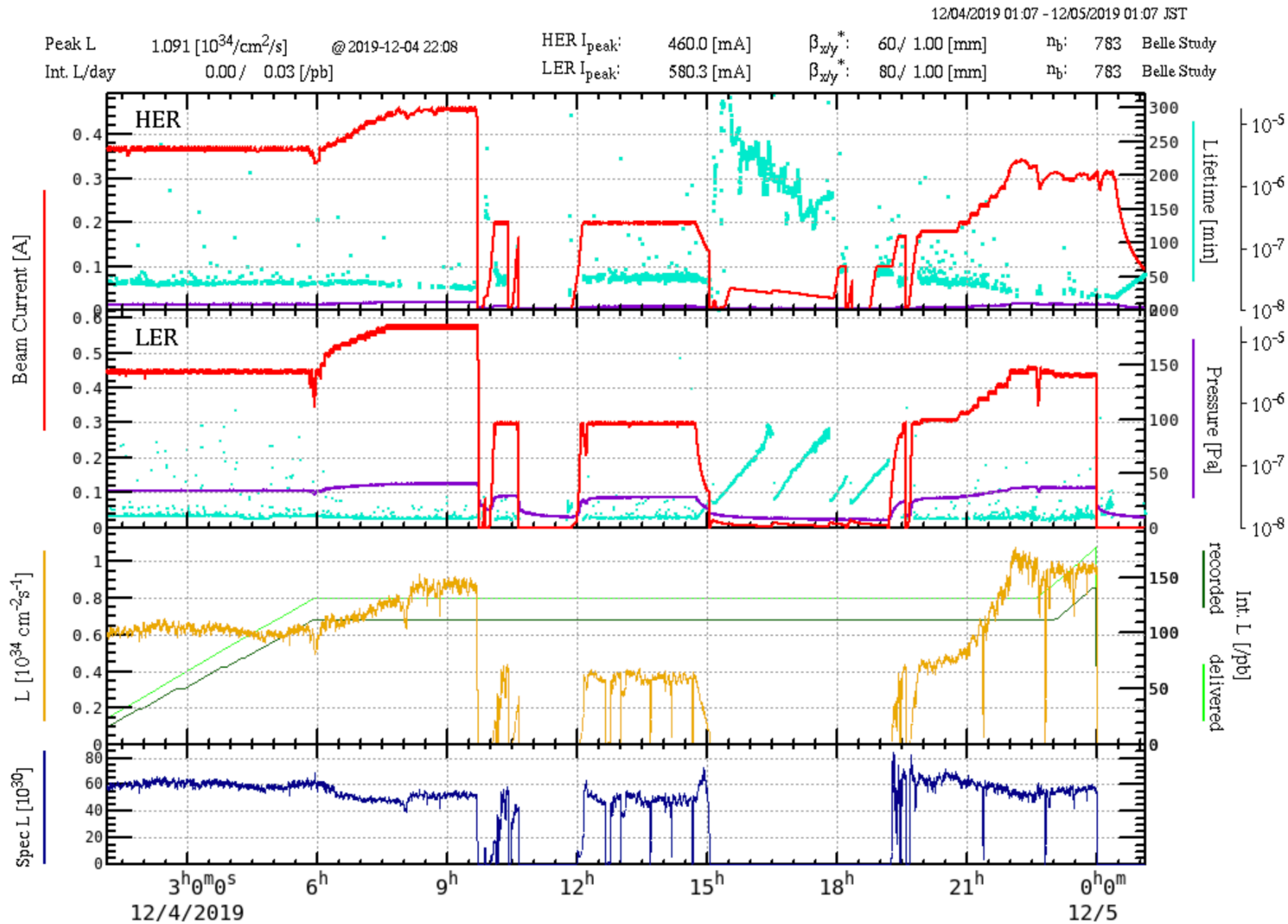


Belle II Online luminosity
Exp: 7-8-10 - All runs
Integrated luminosity [fb^{-1}]
Weekly
Total
Total $\int \mathcal{L} dt$ = 9.79 [fb^{-1}]
Total integrated Weekly luminosity [fb^{-1}]
Total integrated luminosity [fb^{-1}]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
2
4
6
8
2019-04-01
2019-05-21
2019-07-10
2019-08-29
2019-10-18
2019-12-07
Date
Plot on 2019/12/04 18:45

Not Secure | www-linac.kek.jp/skekb/snapshot/dailysnap.html

SuperKEKB 24-Hour Operation Summary

SuperKEKB Phase-3 operation.



Hulya Atmacan <hulya.atmacan@gmail.com>

Inbox - yjk...3@yonsei.ac.kr 3 December 2019 at 11:33 PM

HA

Details

[coll-members:5478] Peak Luminosity Record

To: Coll Members <coll-members@belle2.org>, Cc: Atmacan, Hulya (atmacaha) <atmacaha@ucmail.uc.edu>,

Reply-To: Hulya Atmacan <hulya.atmacan@gmail.com>

Dear Colleagues,

Many thanks to SuperKEKB accelerator group, tonight,
peak luminosity reached 1.05 x 10^34 1/(cm^2 sec) with
beta*y = 1.0 mm, beta*x=80 mm, I_HER = 370 mA and
I_LER = 450 mA. Belle II was collecting collision data
with acceptable backgrounds.

So we are happy to inform you that the story begins!

Thanks,
Kind regards,

Adachi-san, Matsuoka-san and Hulya

Closing remarks

- Belle is producing physics results nearly at a steady pace, even after 9 years past shut-down. Yes, we have things to show other than $R(D^{(*)})$, and/or $R_K^{(*)}$.
- In October, Belle II has resumed operation. On Dec.3, it has reached a meaningful milestone, $\mathscr{L} = 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. Please stay tuned, with a great expectation!