BELLE Belle II

Semi-invisible B and τ decays at Belle (II)

Youngjoon Kwon
Yonsei University

for CAU BSM 2023

Overview

2:40 PM	**Semi-invisible B and tau decays at Belle & Belle II** **Speaker**: Prof. Youngjoon Kwon (Yonsei Univ)
3:20 PM	**New approaches to semi-invisible tau and B decays** **Speaker**: Prof. Chan Beom Park (Chonnam National University)

- Introduction
  - Belle & Belle II
- Semi-invisibles in B decays $B \to K\tau\ell$, $B \to K\nu\bar{\nu}$
- Semileptonic B decays $B \to X\ell^+\nu_\ell$
- Semi-invisible τ decay $\tau \to \ell\alpha$
- *one more thing!*

Belle & Belle II

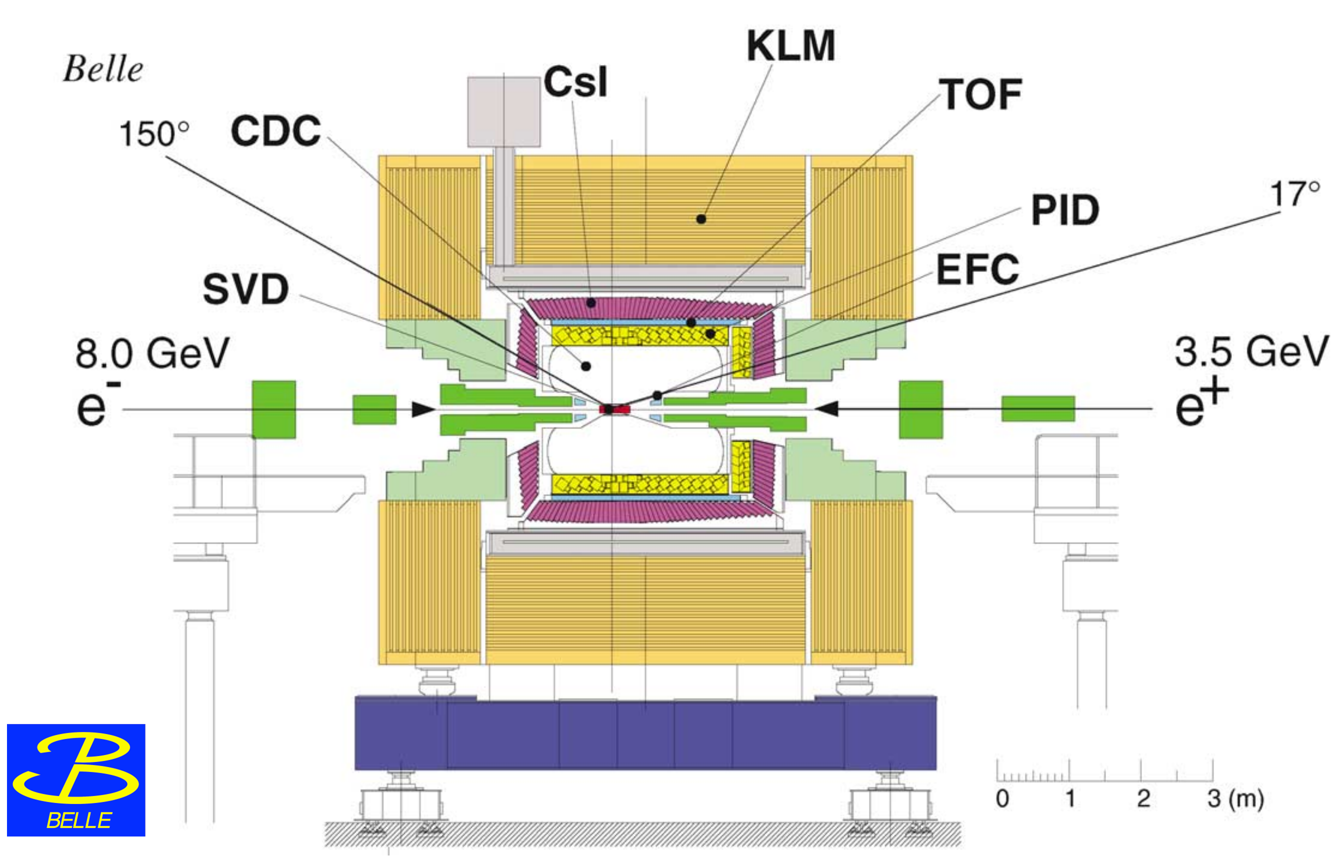
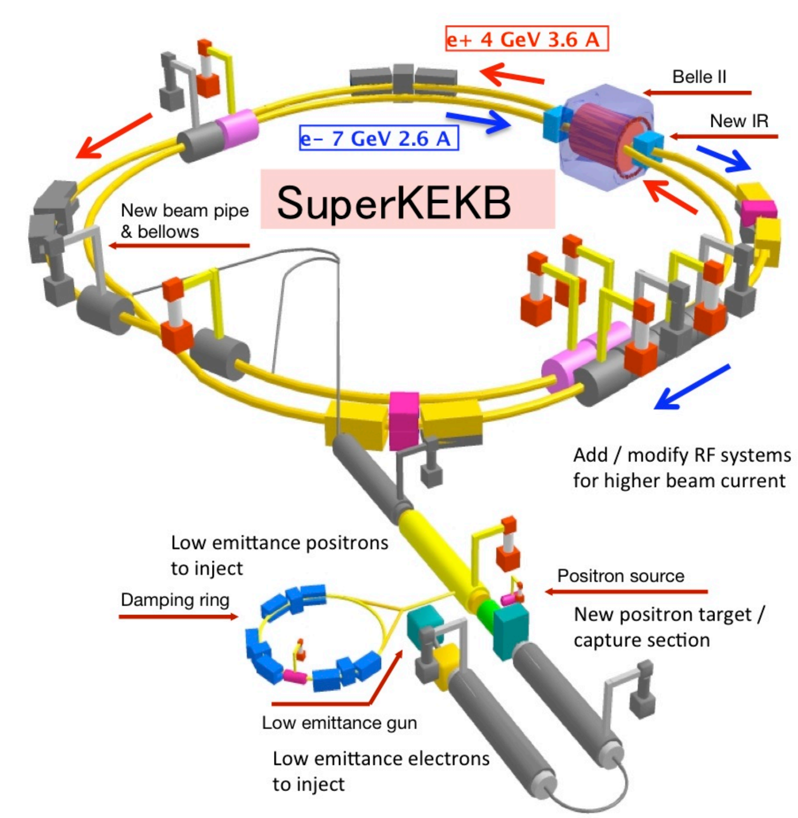
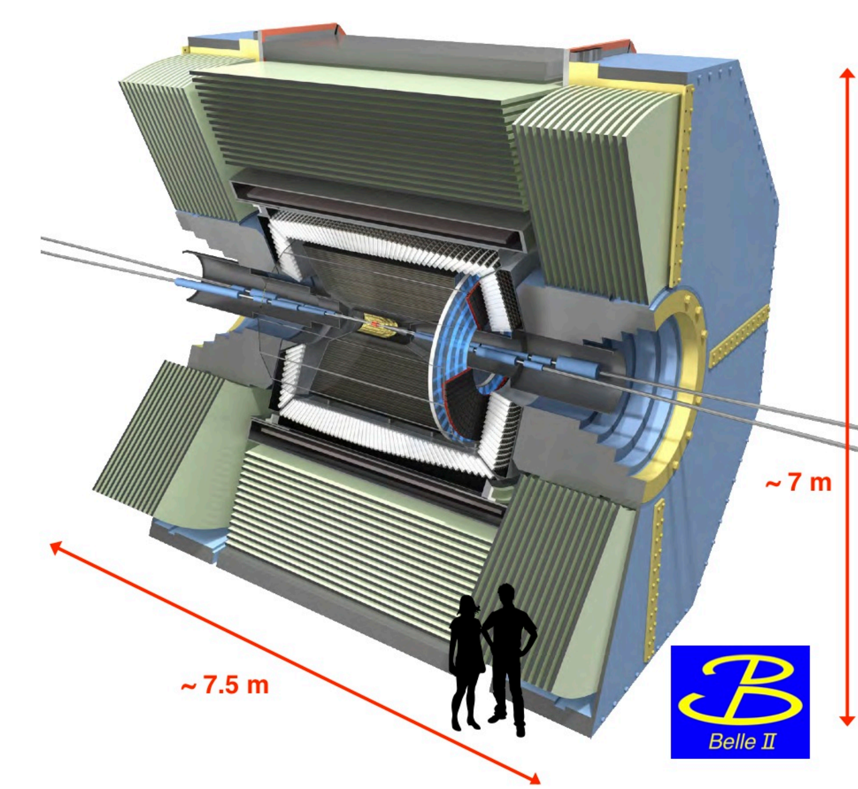


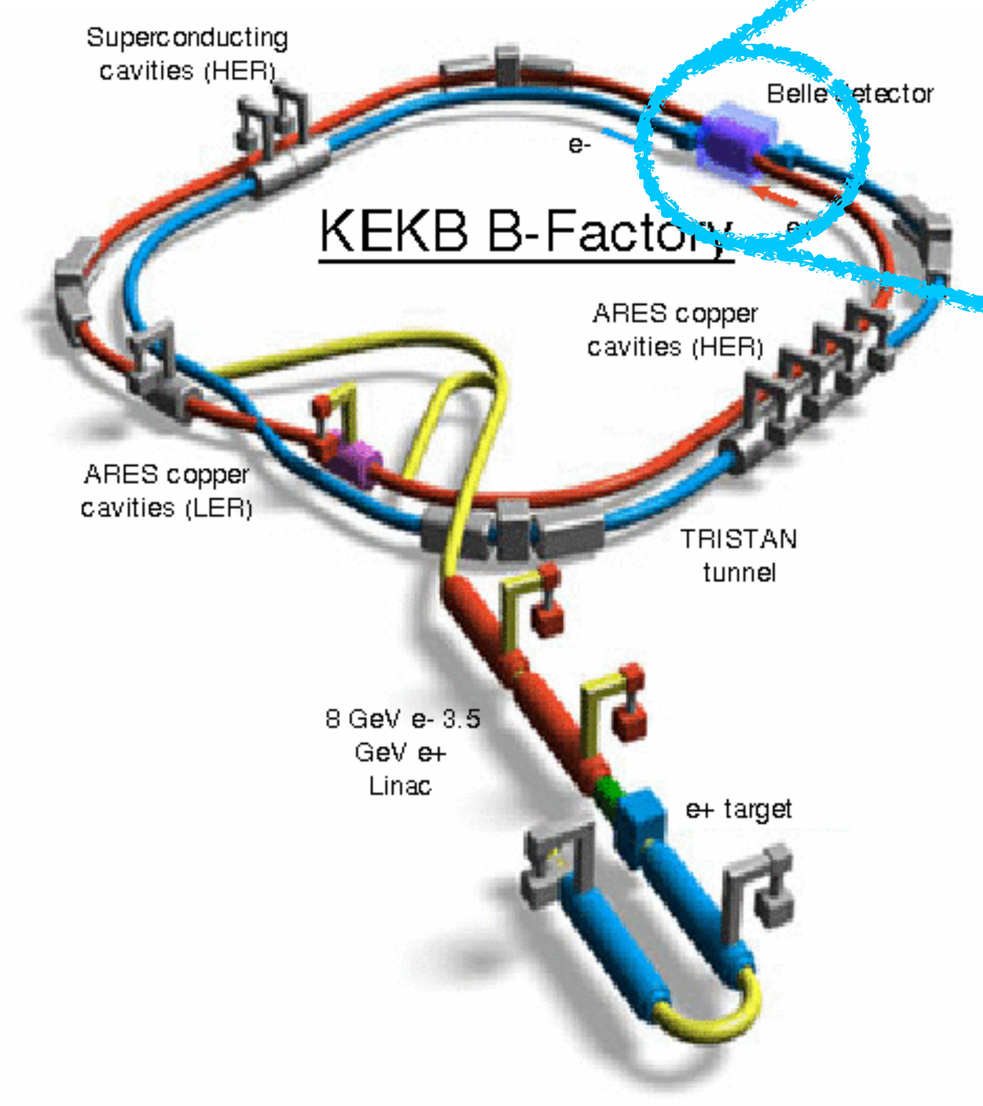
Fig. 1. Side view of the Belle detector.

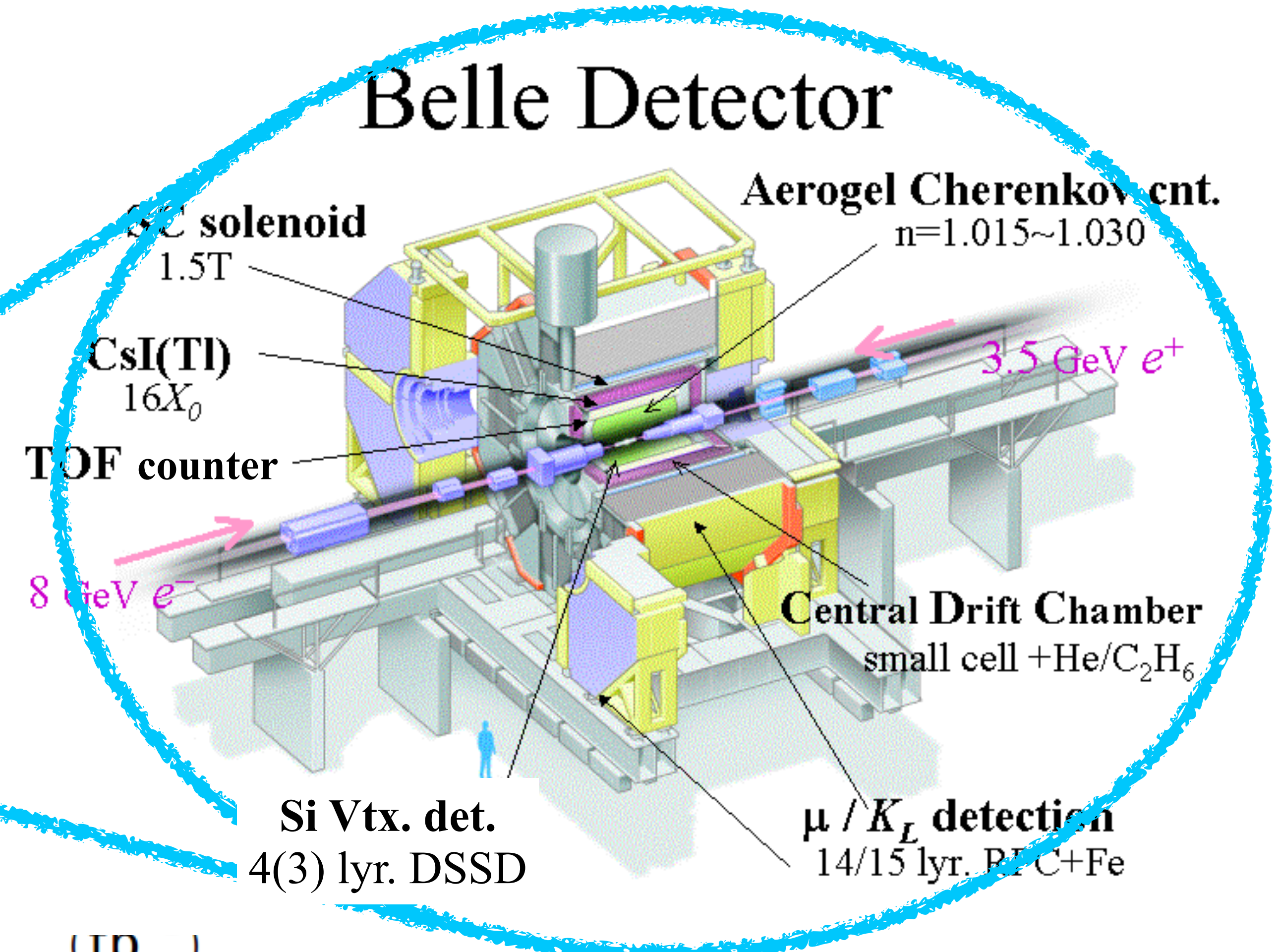


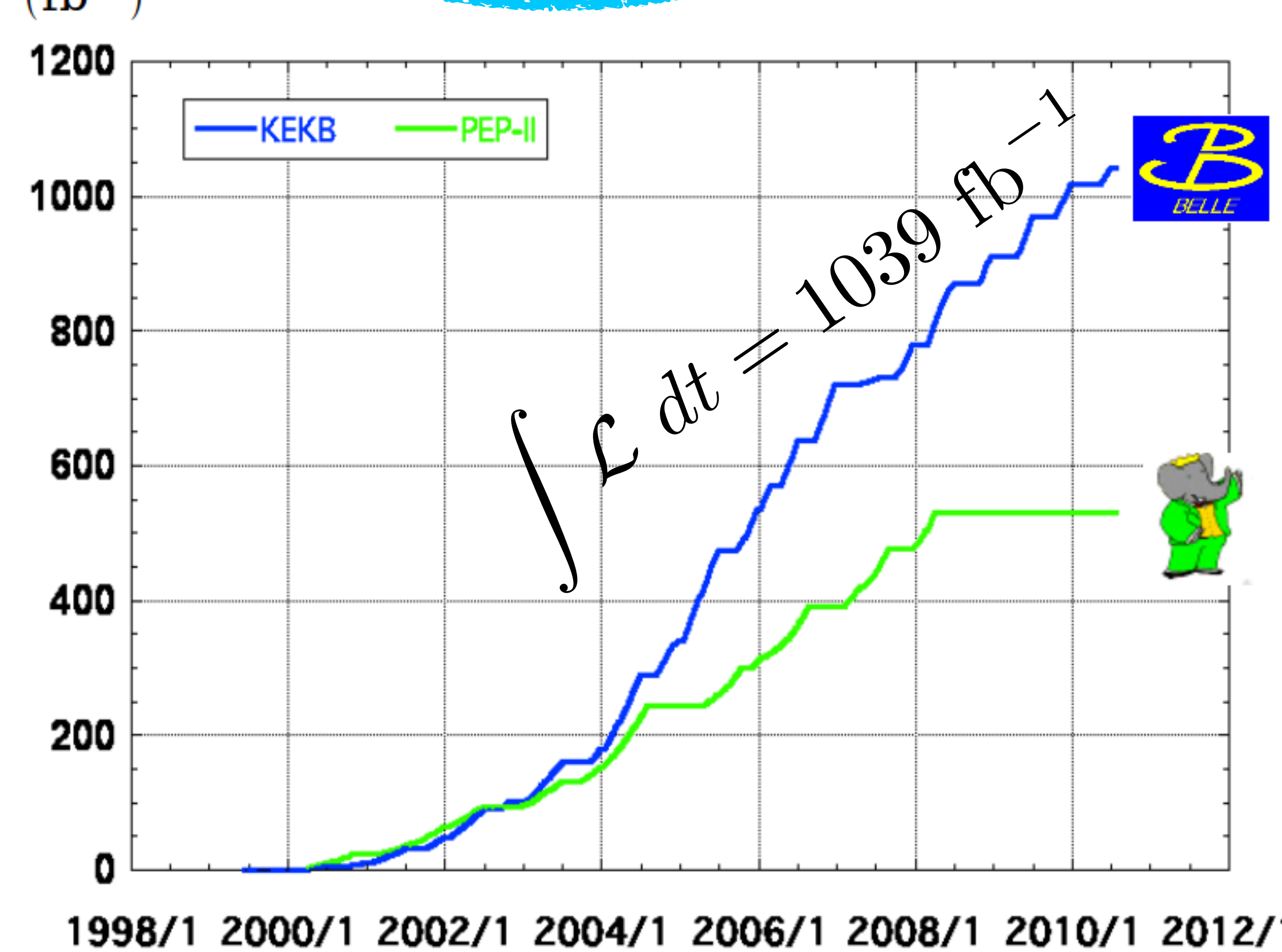


22 **countries**
100 **institutions**
~450 **members**

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



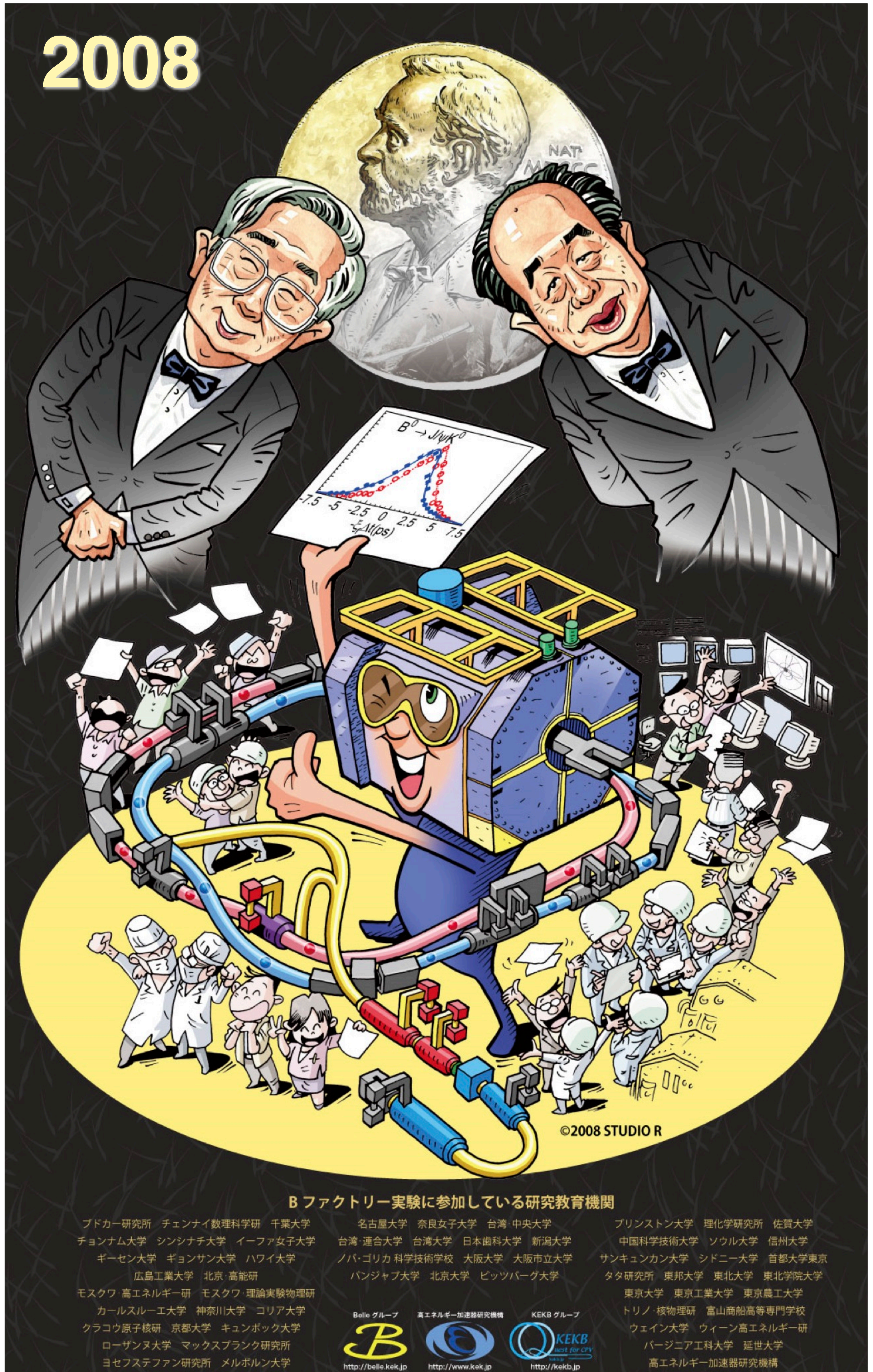




> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 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}

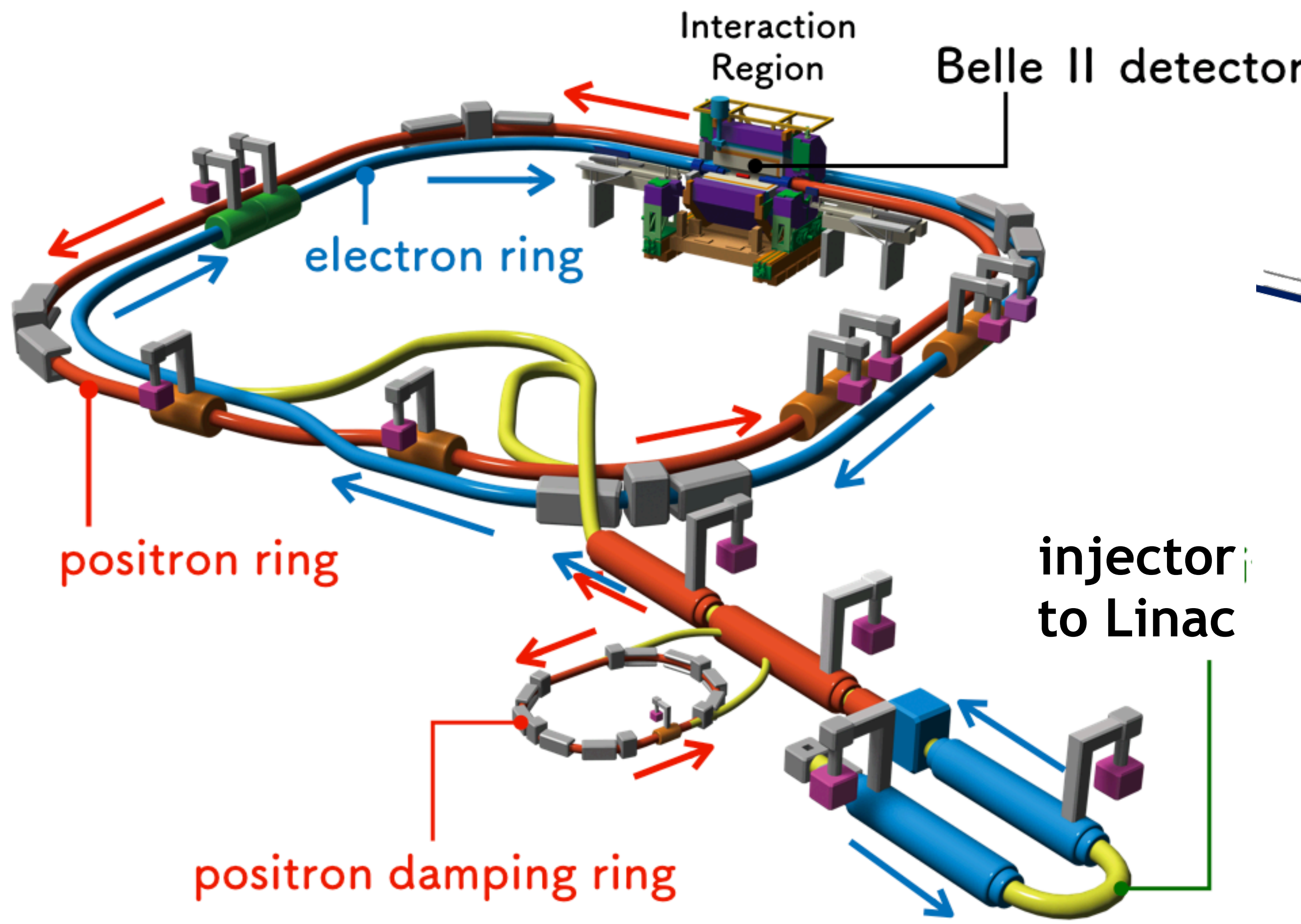
$$e^- \xrightarrow{\textbf{8 GeV}} (\star) \xleftarrow{\textbf{3.5 GeV}} e^+$$

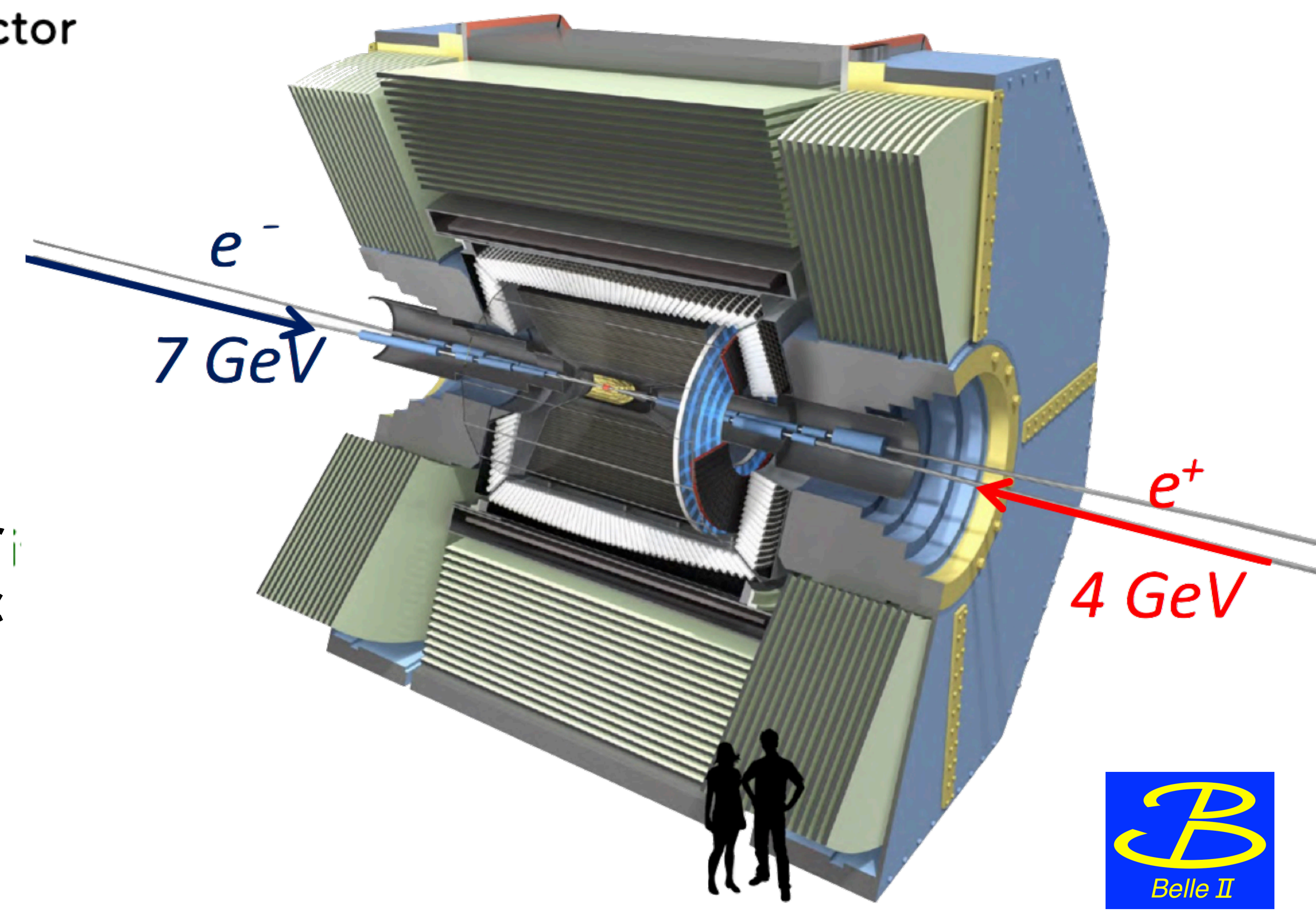


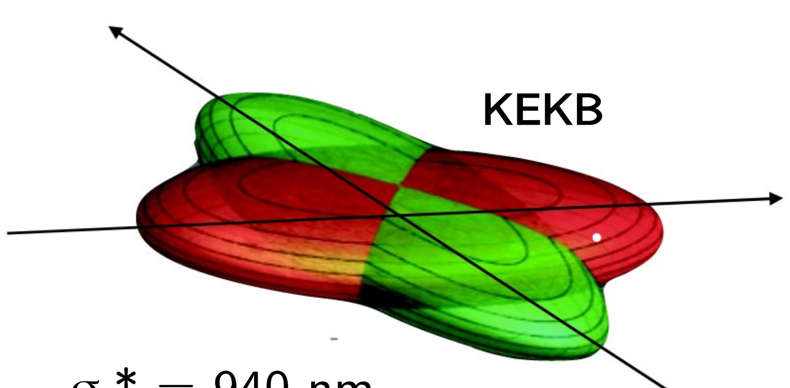
Belle (and BaBar, too) achievements include:

- CPV, CKM, and rare decays of B mesons (and B_s, too)
- Mixing, CP, and spectroscopy of charmed hadrons, e.g. $D_{s0}^{*}(2317)^{+}$
- Quarkonium spectroscopy and discovery of (*many*) exotic states, e.g. $X(3872)$, $Z_c(4430)^+$
- Studies of τ and 2γ

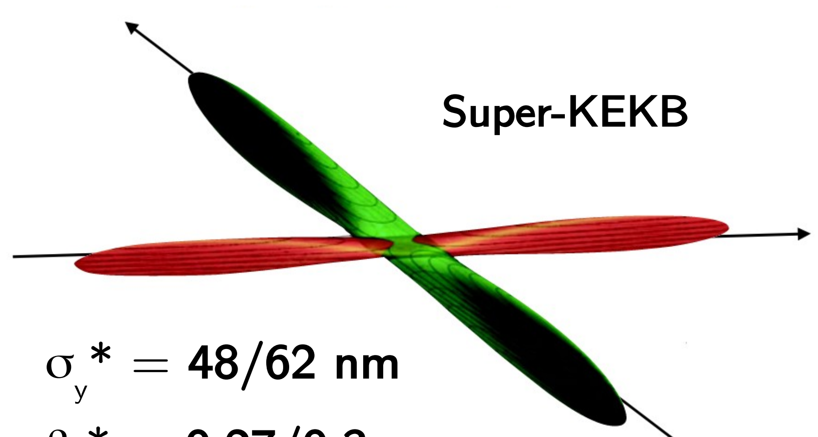
SuperKEKB $e^- \xrightarrow{7\text{ GeV}} (\star) \xleftarrow{4\text{ GeV}} e^+$ Belle II







$\sigma_y{}^* = 940$ nm
$\beta_y{}^* = 5.9$ mm
$\sigma_x{}^* = 147/170$ μm



$\sigma_y{}^* = 48/62$ nm
$\beta_y{}^* = 0.27/0.3$ mm
$\sigma_x{}^* = 10.1/10.7$ μm

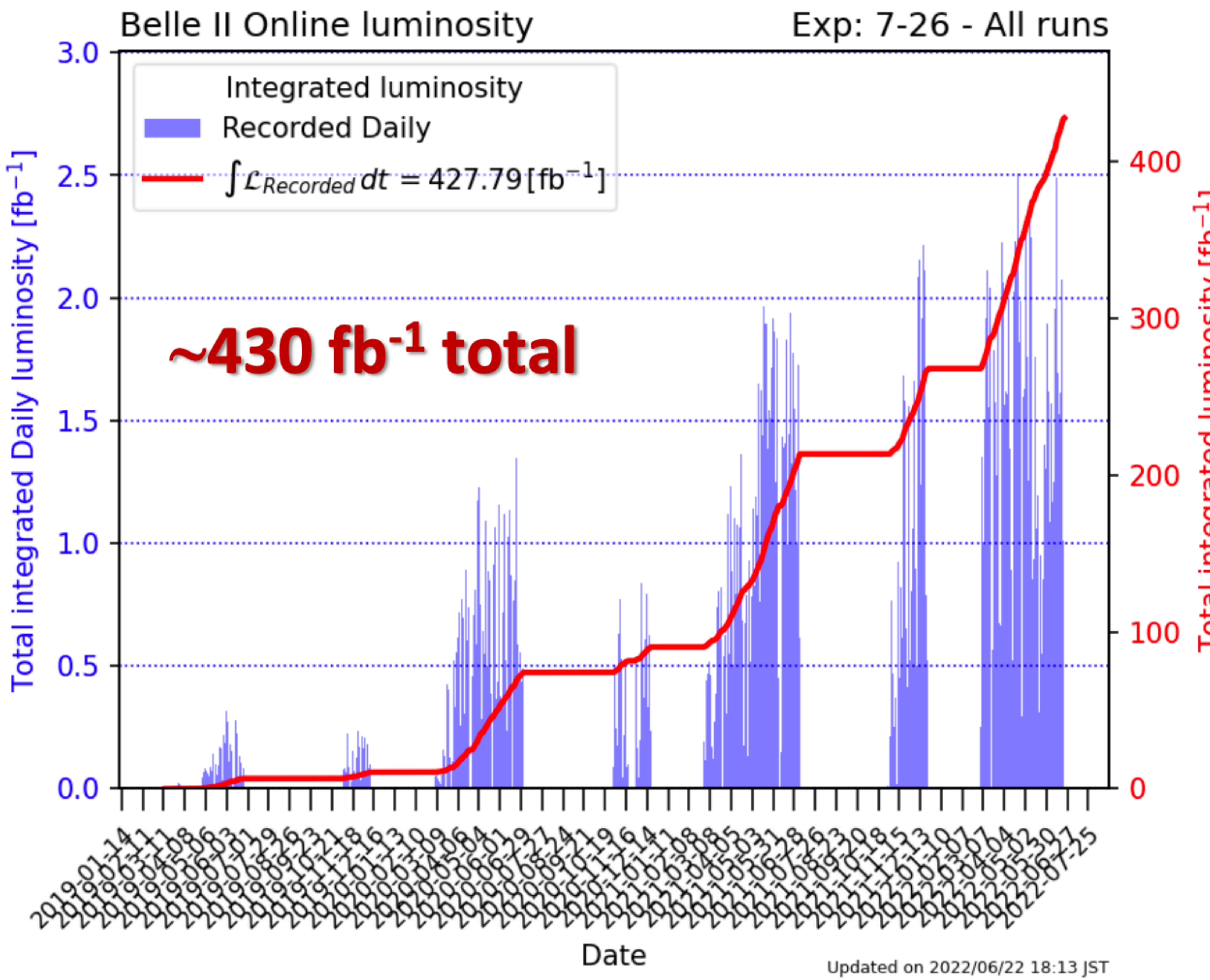
$$\mathcal{L}_{\rm II}^{\rm peak} \approx 30 \times \mathcal{L}_{\rm I}^{\rm peak}$$

$$\int^{\rm goal} \mathcal{L}_{\rm II}\, dt = 50\ {\rm ab}^{-1} \approx 50 \int \mathcal{L}_{\rm I}\, dt$$

Belle II Collected luminosity before LS1 (2019-2022)

Belle II has been in operation through the Pandemic era, with modified working mode in accordance with the anti-pandemic policy. (*See back-up slide!*)

peak luminosity world record
$4.7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



Belle II Physics Mind-map

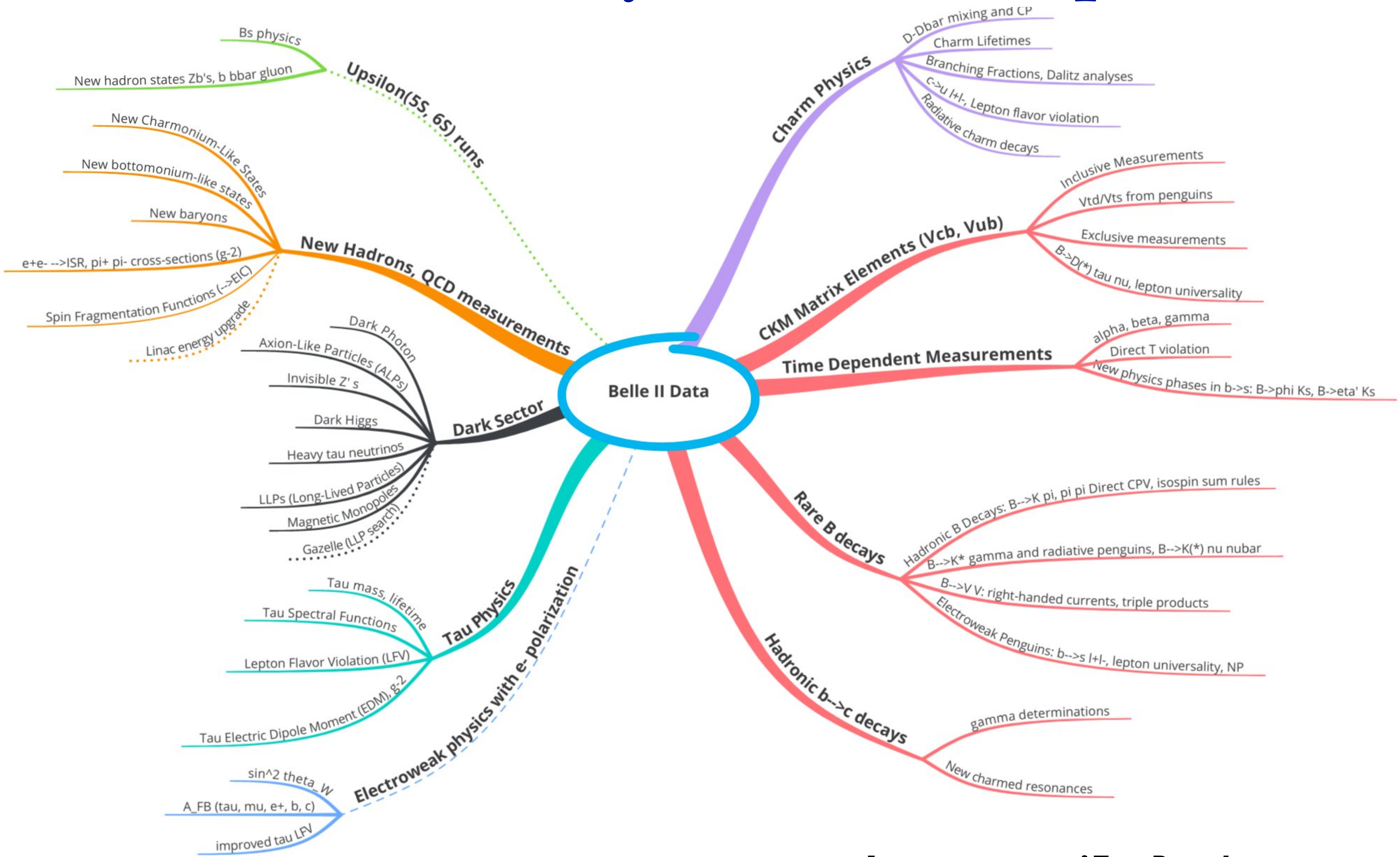


Image courtesy of Tom Browder

Semi-invisible modes of B decays

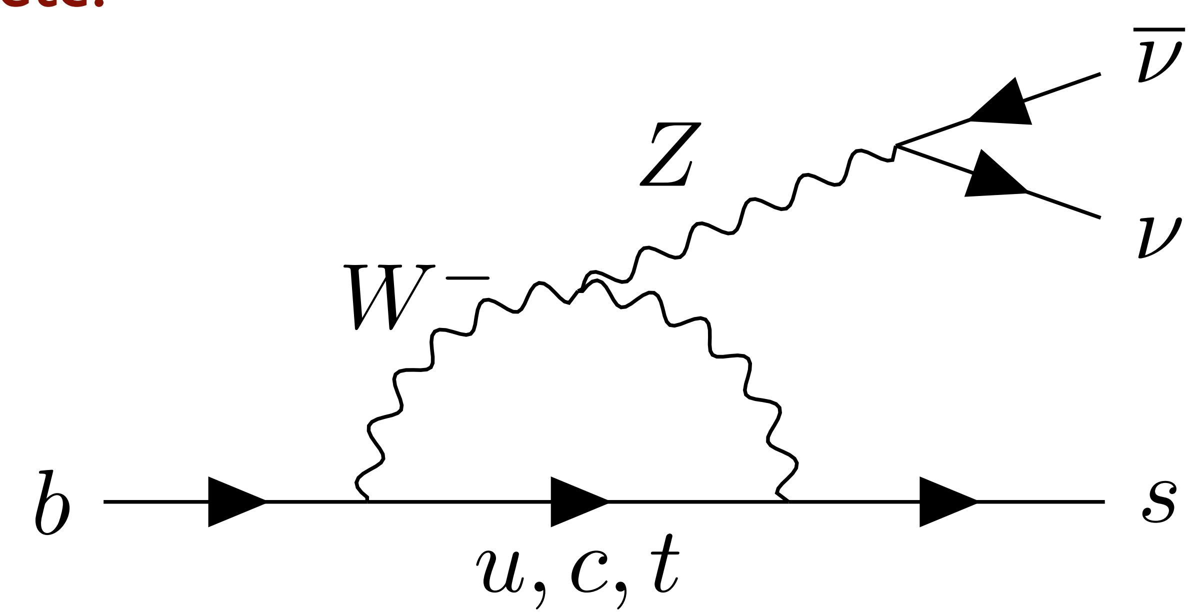
Belle II PRL 127, 181802 (2021)
Belle arXiv:2212.04128 (to PRL)

Search for $B^+ \to K^+\nu\bar{\nu}$ at Belle II

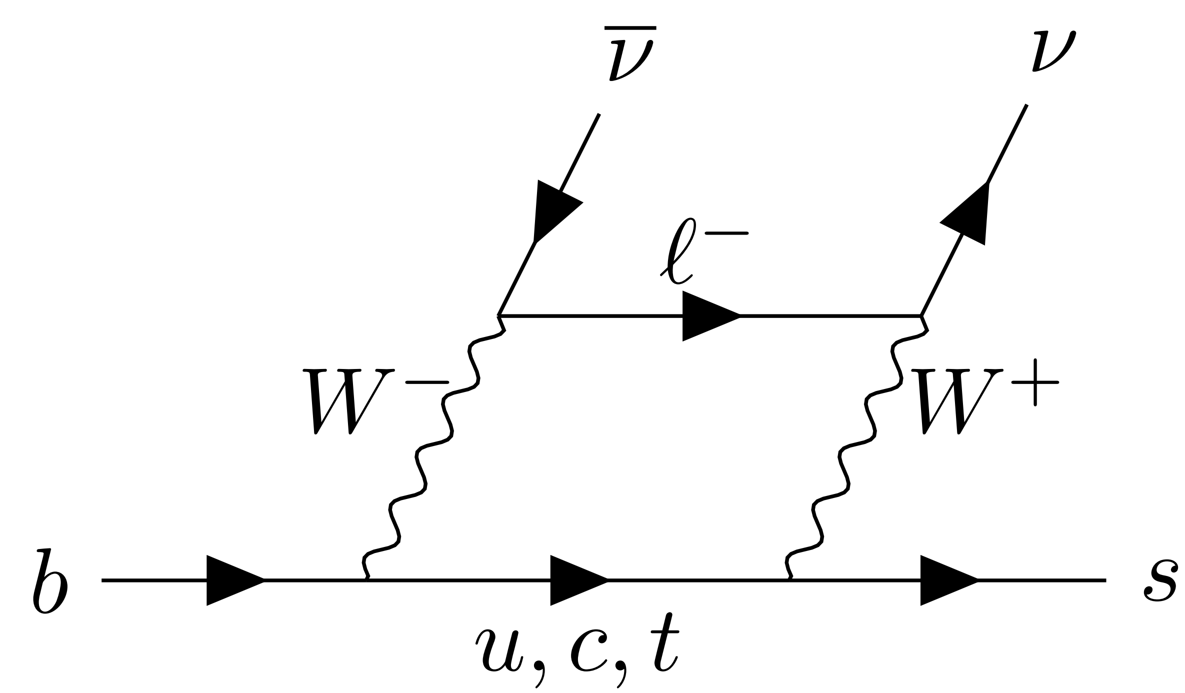
- In the SM,
  - $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$ [4]

[4] T. Blake, G. Lanfranchi, and D. M. Straub, Prog. Part. Nucl. Phys. **92**, 50 (2017).

- sensitive to new physics BSM, e.g.
  - leptoquarks,
  - axions,
  - DM particles, etc.



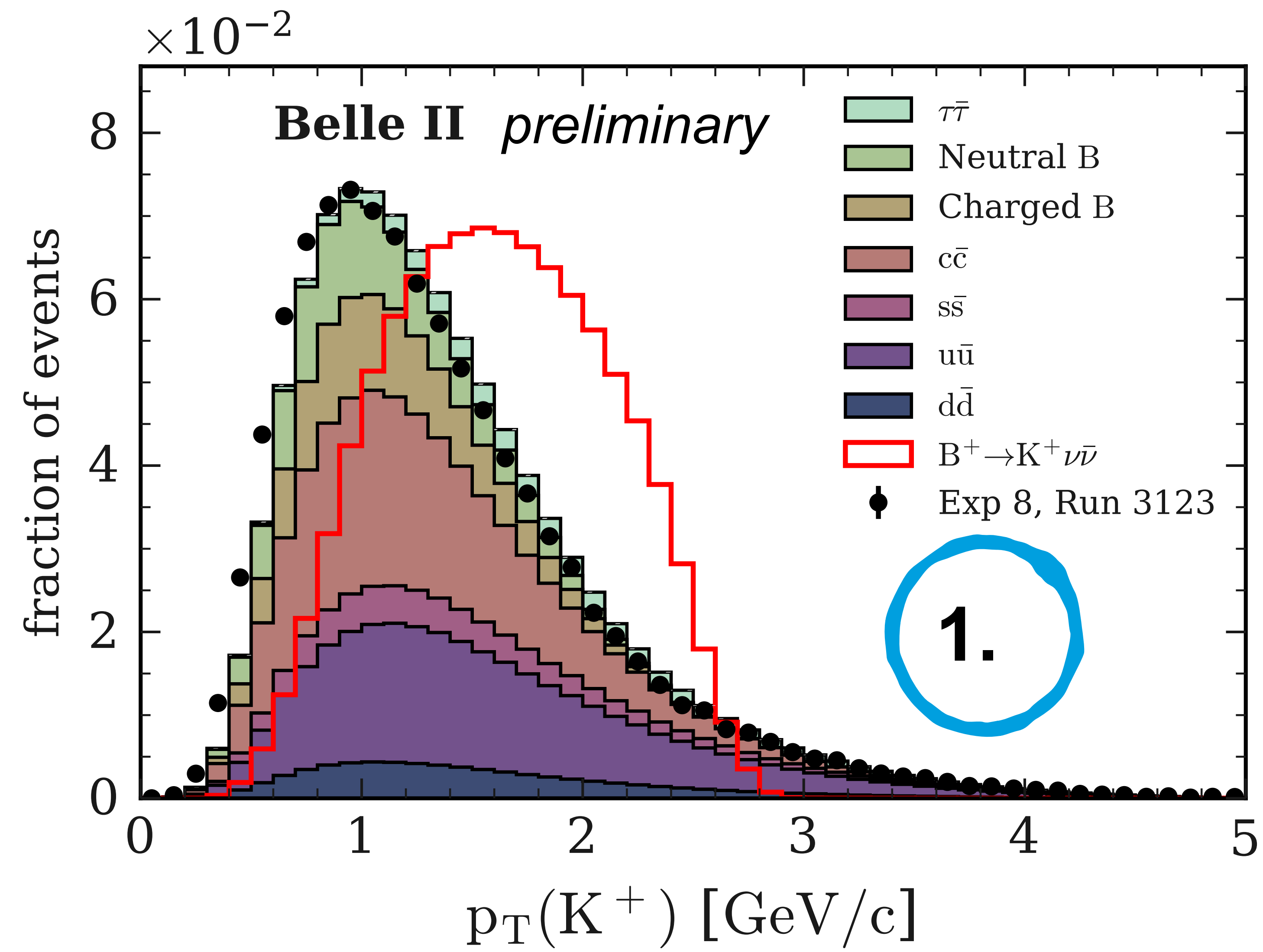
(a) Penguin diagram



(b) Box diagram

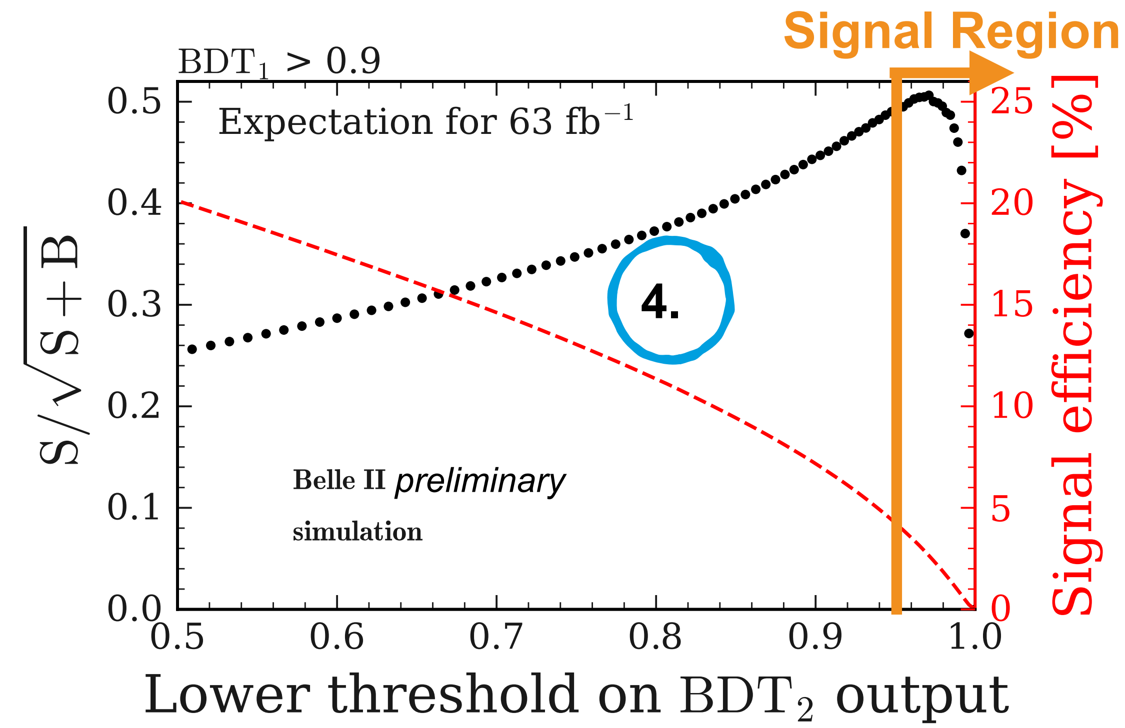
$B^+ \to K^+\nu\bar{\nu}$ at Belle II

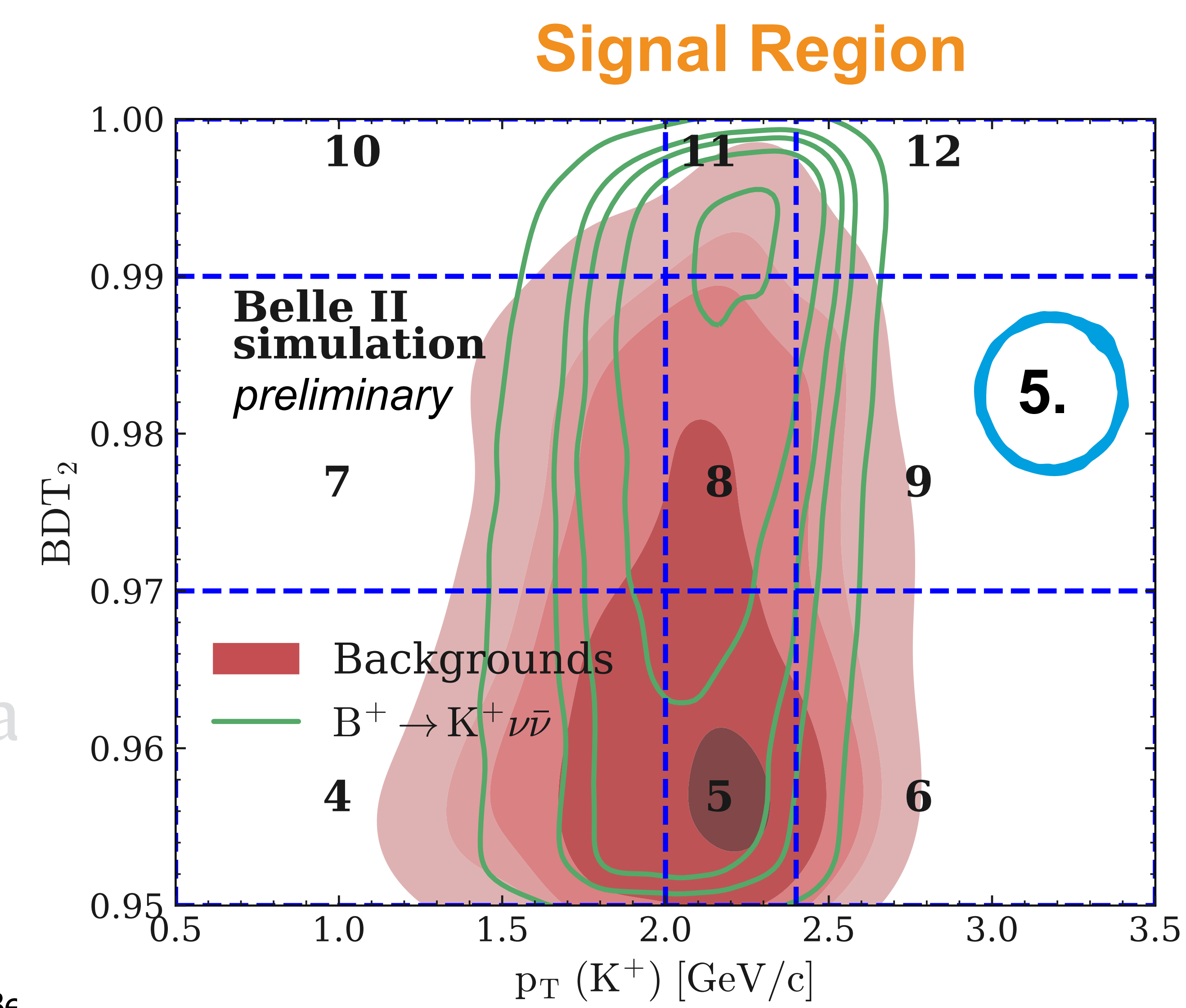
1. loose tagging ➔ find signal K^+ — track of highest p_T w/ at least 1 PXD hit ($\varepsilon \sim 80\,\%$)
2. all other tracks & clusters ⇒ "ROE" (rest of tl
3. BDT for signal discrimination
   use event-shape, ROE dynamics, B_{sig} kinematics, ve
4. BDT_1 & BDT_2 (consecutive applications)
   ∵ to suppress two different bkgds : BB and contin
5. signal region in 2D (BDT_2 vs. $p_T(K^+)$)
6. check BDT output with $B^+ \to J/\psi K^+$ sample
   for both signal and bkgd (*see back-up slide for deta*
7. check Data/MC agreement using Off-resonance data



$B^+ \to K^+\nu\bar{\nu}$ at Belle II

1. signal K^+ — track of highest p_T w/ at least 1 PXD hit ($\varepsilon \sim$
2. all other tracks & clusters ⇒ "ROE" (rest of the event)
3. BDT for signal discrimination
   use event-shape, ROE dynamics, B_{sig} kinematics, vertexing info.
4. BDT_1 & BDT_2 (consecutive applications)
   ∵ to suppress two different bkgds : BB and continuum
5. signal region in 2D (BDT_2 vs. $p_T(K^+)$)
6. check BDT output with $B^+ \to J/\psi K^+$ samples
   for both signal and bkgd (see *back-up slide for details*)
7. check Data/MC agreement using Off-resonance da





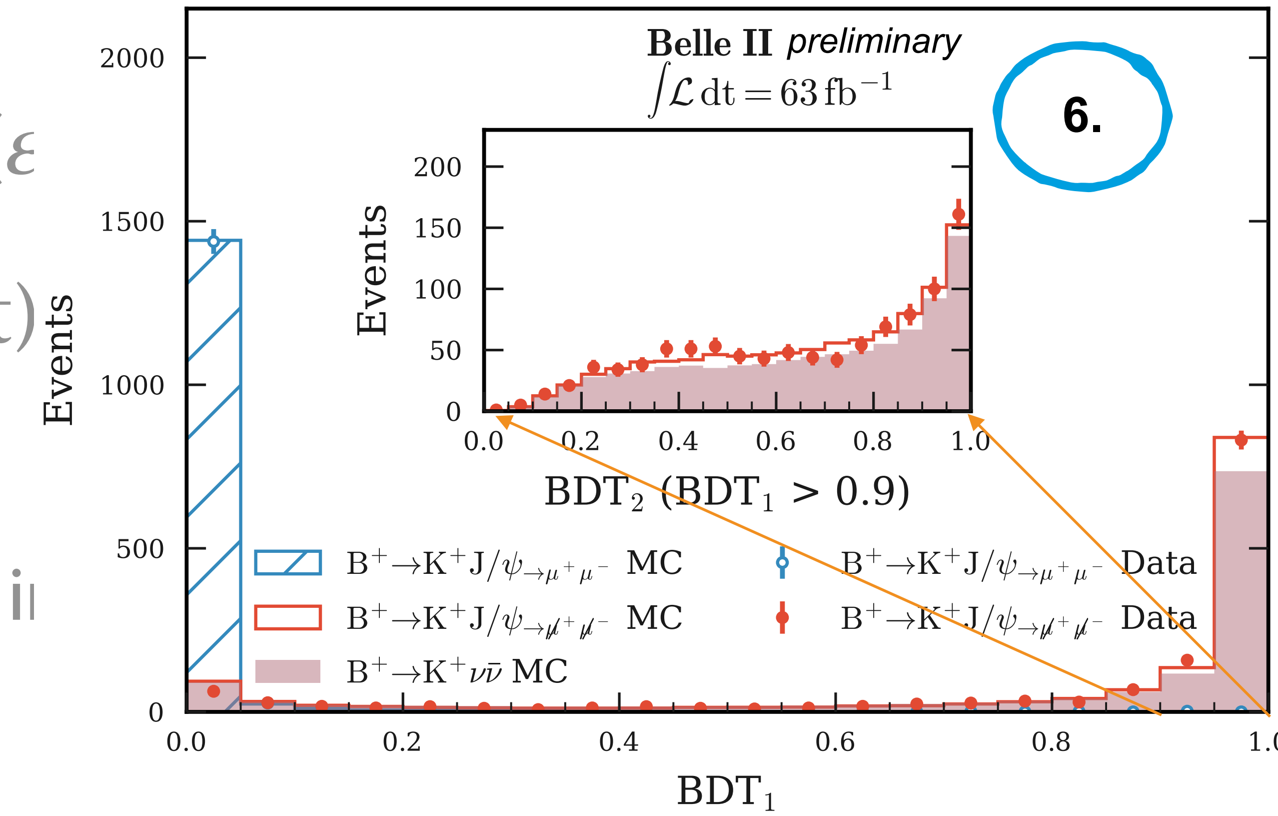
$B^+ \to K^+\nu\bar{\nu}$ at Belle II

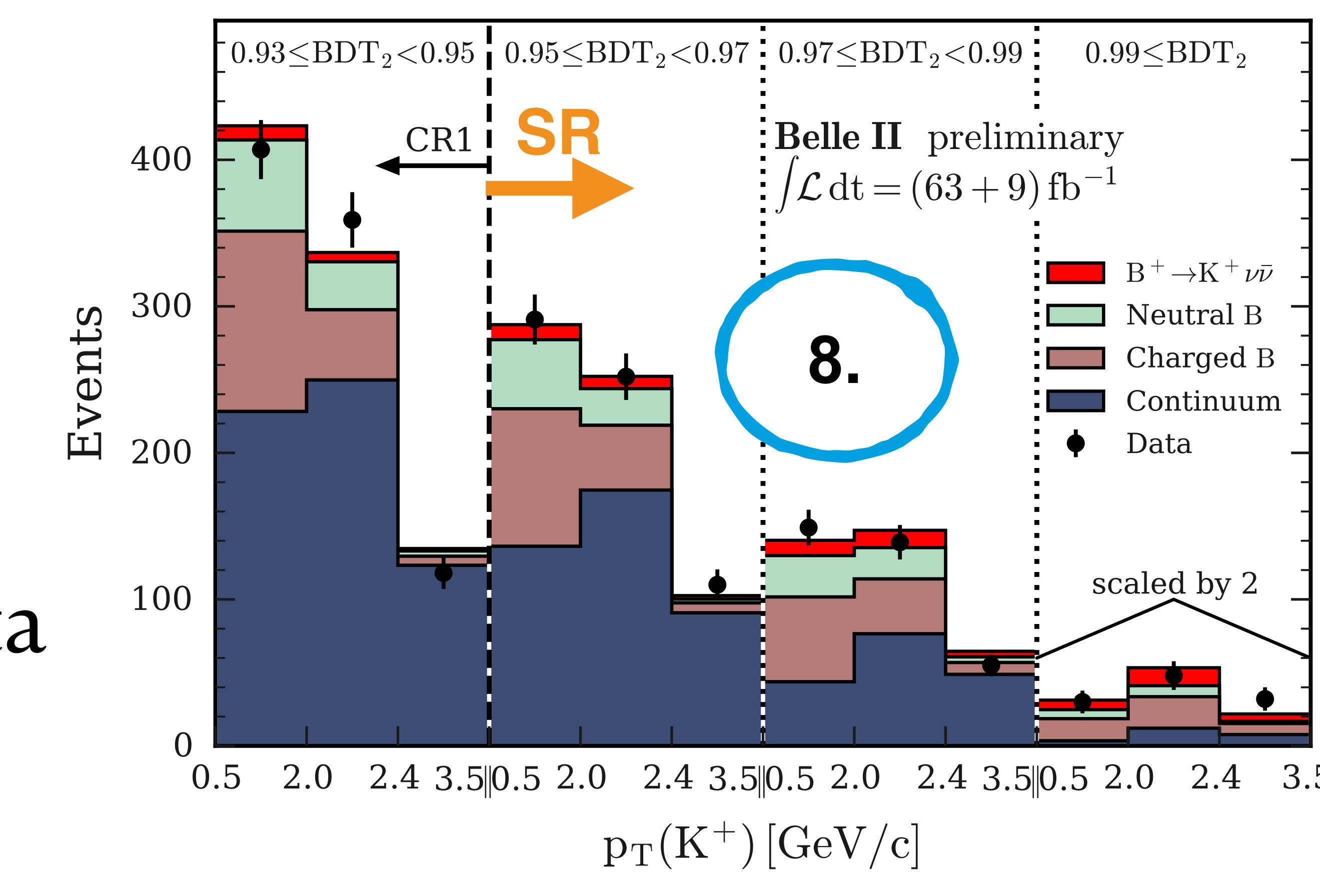
1. signal K^+ — track of highest p_T w/ at least 1 PXD hit (ε
2. all other tracks & clusters ⇒ "ROE" (rest of the event)
3. BDT for signal discrimination

   use event-shape, ROE dynamics, B_{sig} kinematics, vertexing i
4. BDT_1 & BDT_2 (consecutive applications)

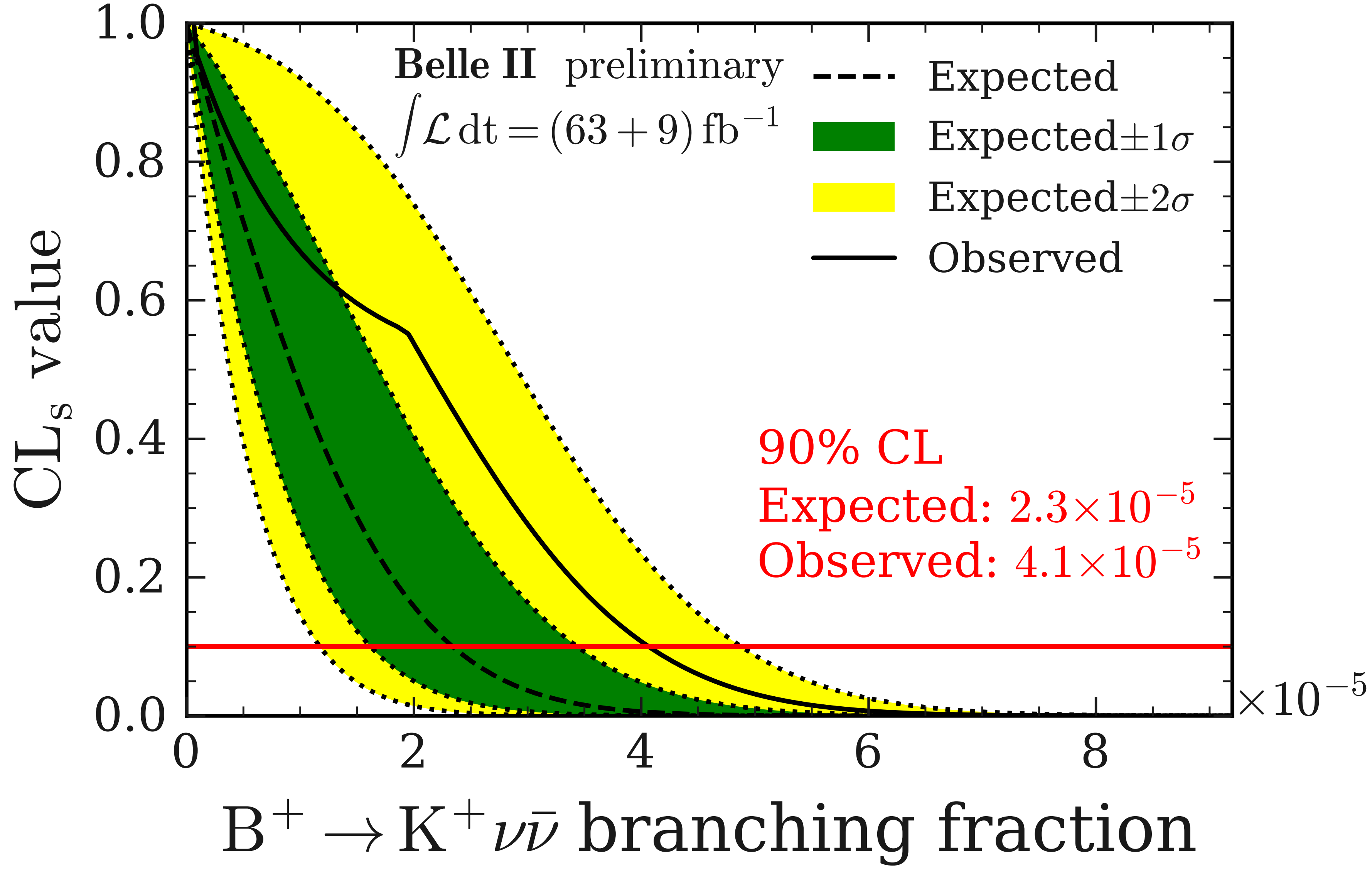
   ∵ to suppress two different bkgds : BB and continuum
5. signal region in 2D (BDT_2 vs. $p_T(K^+)$)
6. check BDT output with $B^+ \to J/\psi K^+$ samples

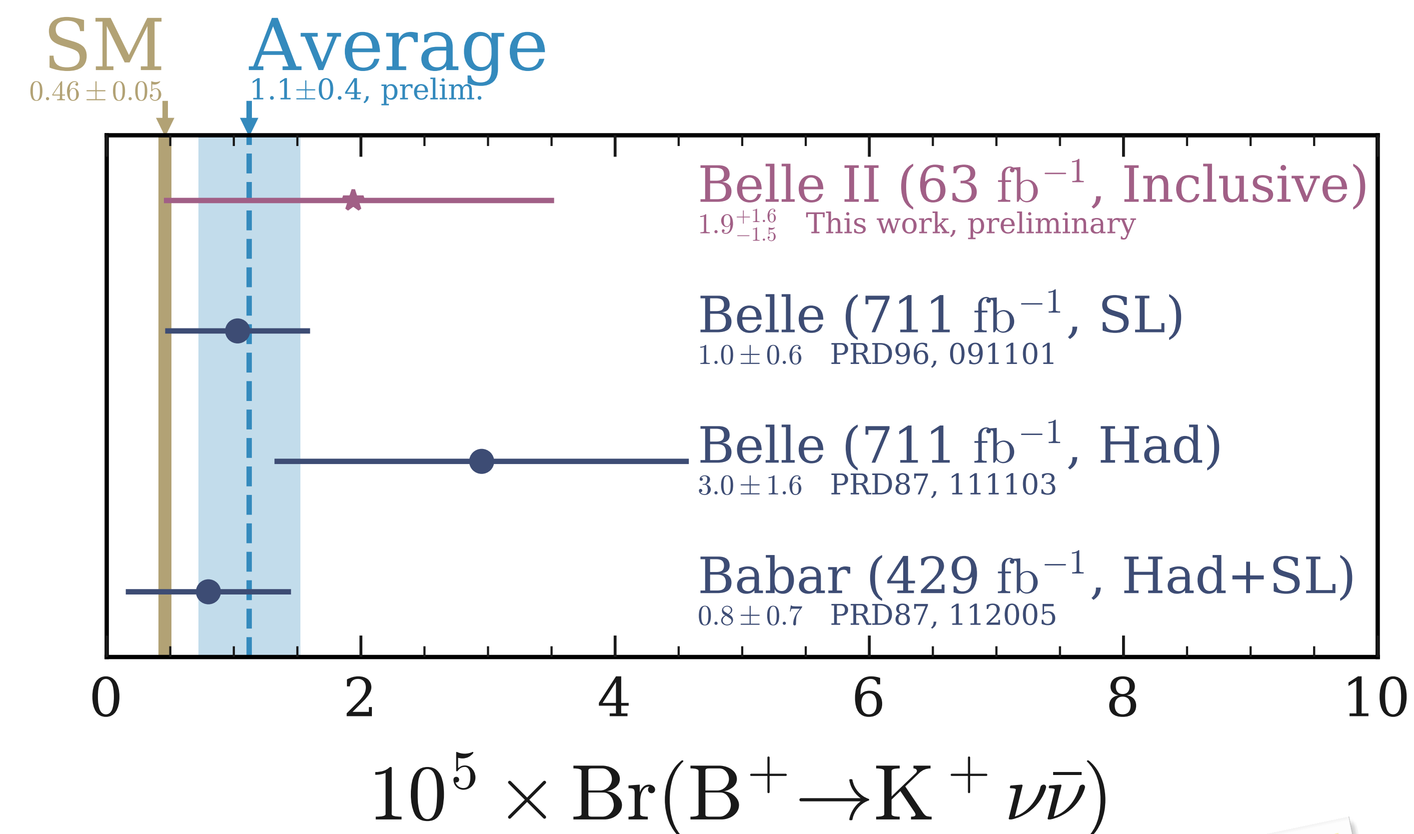
   for both signal and bkgd
7. check Data/MC agreement using Off-resonance data
8. simultaneous ML fit to ON- & OFF-resonance data





$B^+ \to K^+\nu\bar{\nu}$ at Belle II

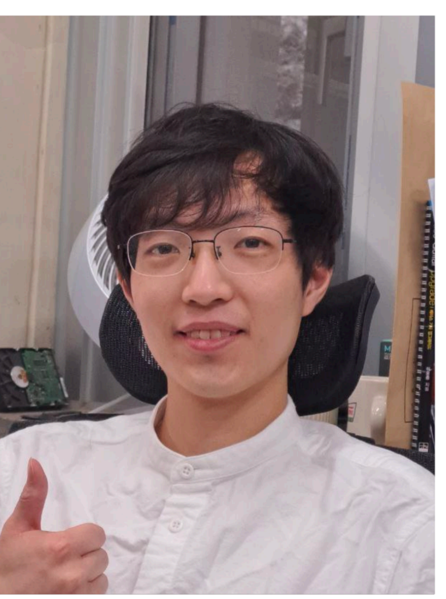




$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (1.9^{+1.3+0.8}_{-1.3-0.7}) \times 10^{-5}$$

$$< 4.1 \times 10^{-5} \quad @ \ 90\% \ CL$$

Please stay tuned for $K\nu\bar{\nu}$ update!



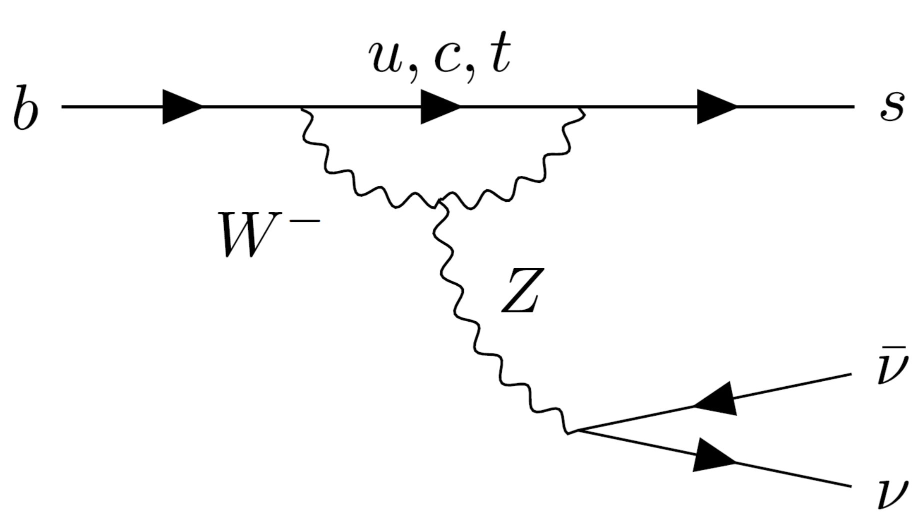
Junewoo Park
Yonsei HEP

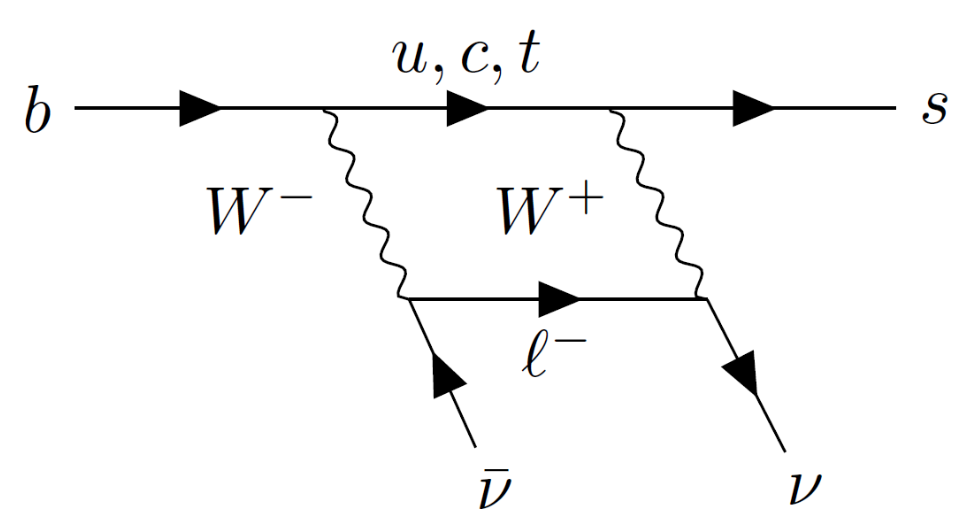
Search for $B \to X_s \nu\bar{\nu}$ (inclusive)

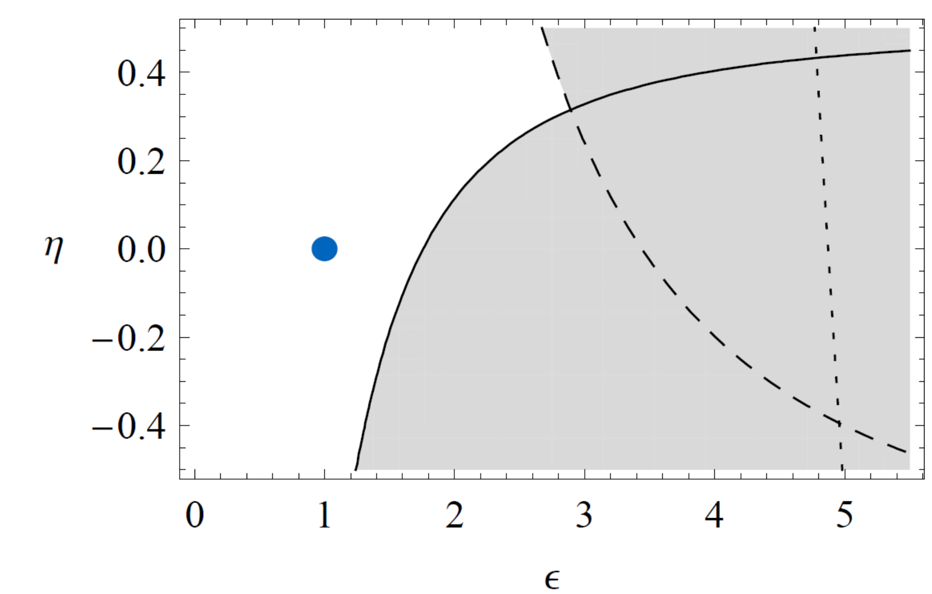
Motivation

- $B \to X_s \nu\bar{\nu}$ decay is theoretically clean
- Its branching ratio depends on right-handed currents
- Therefore, Measuring its branching ratio is important for new physics which has non-zero right-handed current ($C_R^\nu \neq 0$)

※ $\eta = -\frac{Re(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}$, $\epsilon = \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|(C_L^\nu)^{SM}|}$







Wolfgang Altmannshofer *et al* JHEP04(2009)022

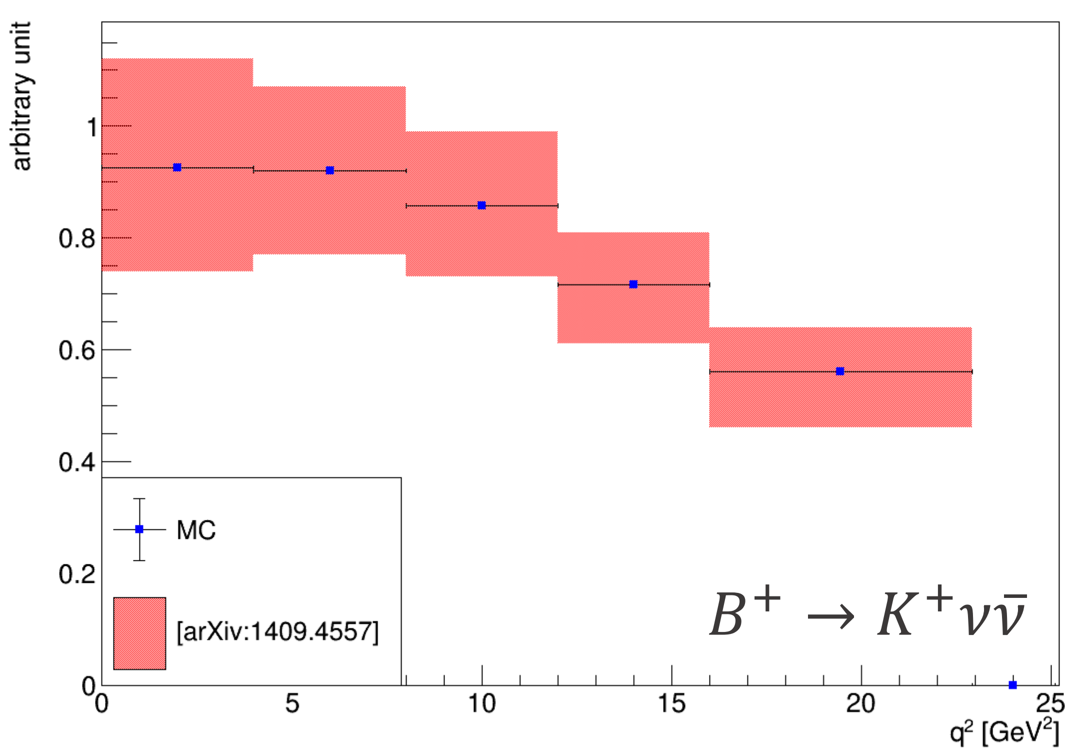
Event Generation

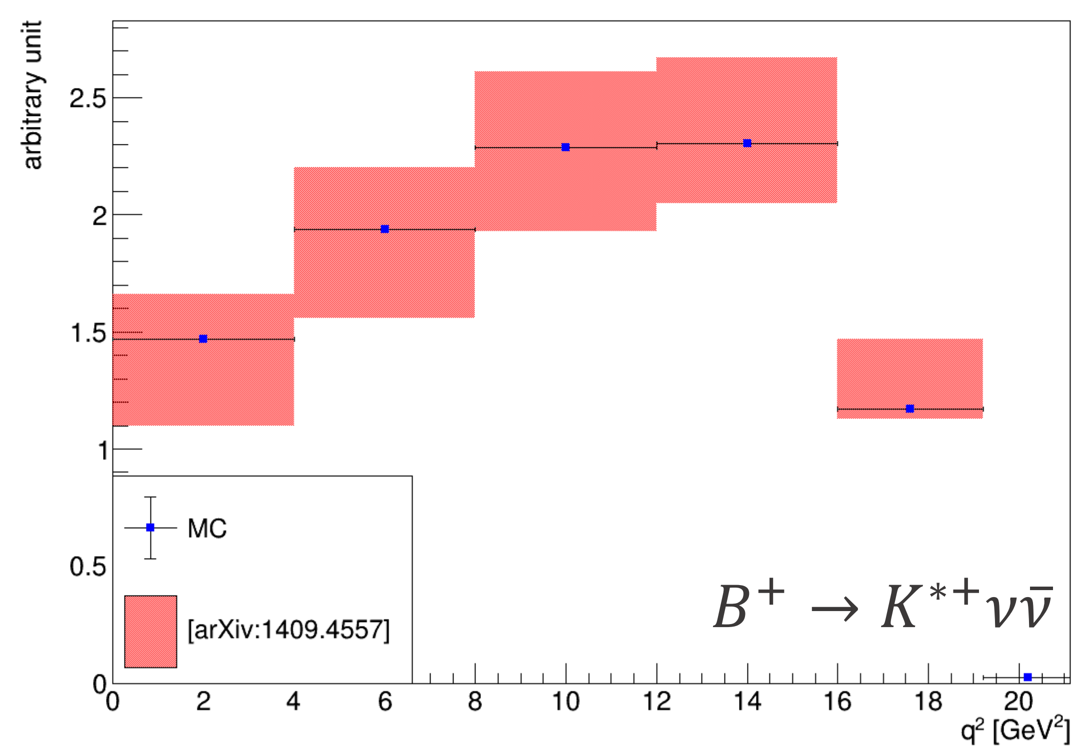
- For Monte-Carlo study, signal samples are produced according to SM *†‡

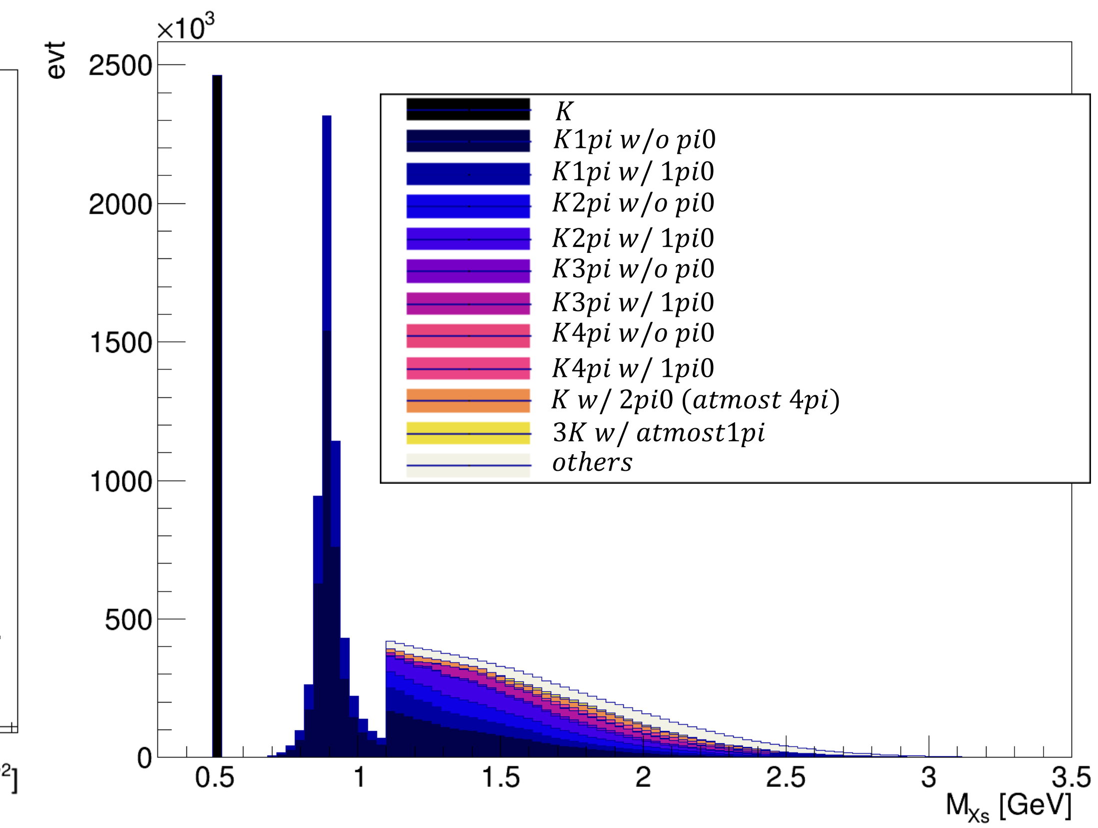
$$\mathcal{M}(B \to K\nu\bar{\nu}) \propto f_+(q^2)\left\{(p_B+p)_\mu - \frac{m_B^2-m_K^2}{s}q_\mu\right\}(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)\text{, where } q^2=(p_\nu+p_{\bar{\nu}})^2$$

$$\mathcal{M}(B \to K^*\nu\bar{\nu}) \propto T_\mu(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)\text{, where } T_\mu=(m_B+m_{K^*})A_1(q^2)\epsilon^*_\mu - A_2(q^2)\frac{\epsilon^*\cdot q}{m_B+m_{K^*}}(p+p_{K^*})_\mu + i\frac{2V(q^2)}{m_B+m_{K^*}}\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p^\rho p^\sigma_{K^*}$$

$$\frac{d\Gamma(B\to X_s\nu\bar{\nu})}{dq^2} \propto \sqrt{\lambda(1,\hat{m}_s,s_b)}\left[3s_b\left(1+\hat{m}_s^2-s_b-4\hat{m}_s+\lambda(1,\hat{m}_s,s_b)\right)\right]\text{, where } \hat{m}_s=m_s/m_b \text{ and } s_b=q^2/m_b^2$$







* Altmannshofer, Wolfgang, et al. "New strategies for new physics search in B→ K* ν ν¯, B→ K ν ν¯ and B→ Xs ν ν¯ decays." *Journal of High Energy Physics* 2009.04 (2009): 022.

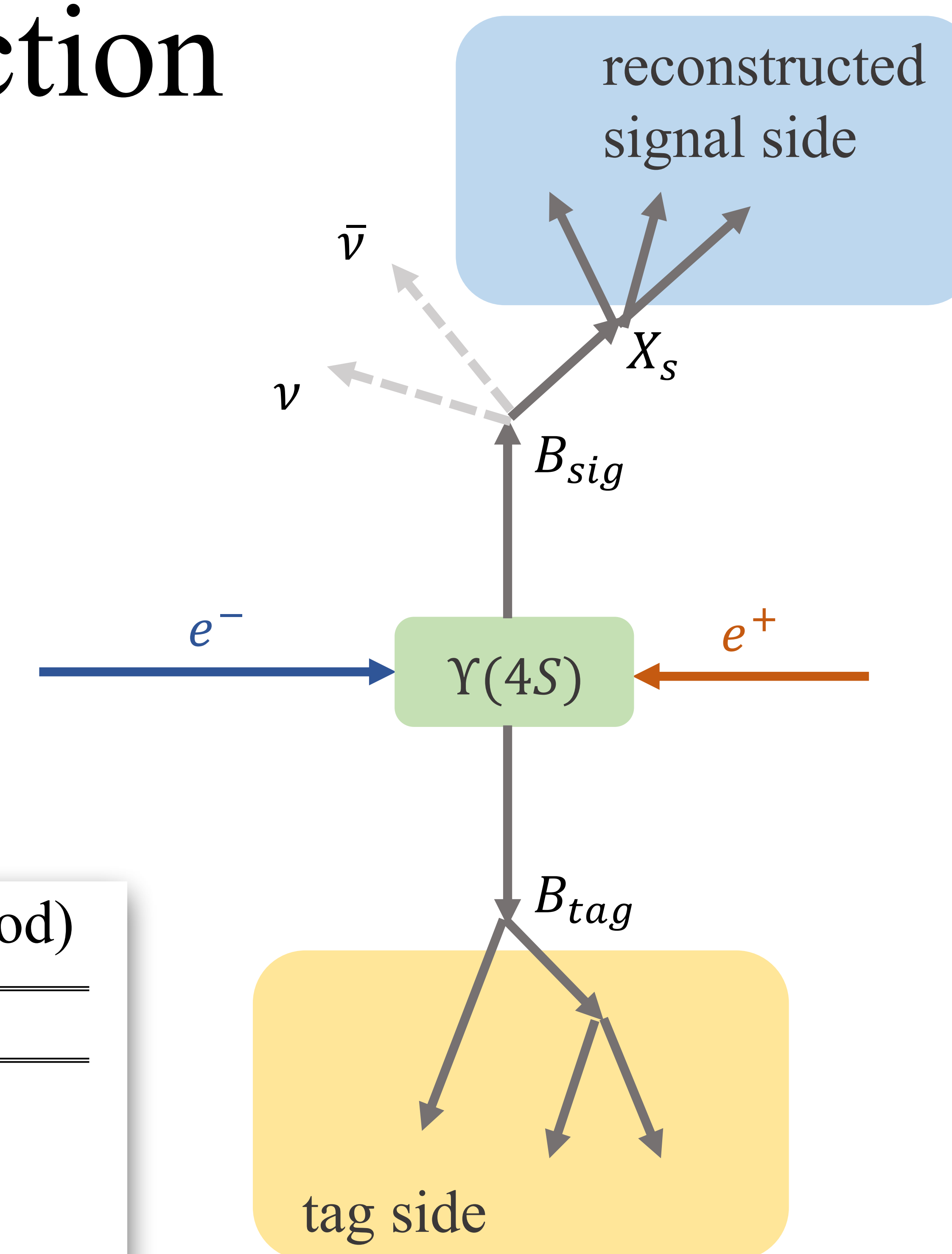
† Buras, Andrzej J., et al. " $B \to K^{(*)}\nu\bar{\nu}$ decays in the Standard Model and beyond." Journal of High Energy Physics 2015.2 (2015): 1-39.

3

‡ Bharucha, Aoife, David M. Straub, and Roman Zwicky. " $B \to V\ell^+\ell^-$ in the Standard Model from light-cone sum rules." Journal of High Energy Physics 2016.8 (2016): 1-64.

Reconstruction and Event Selection

- In $B \to X_s \nu\bar{\nu}$ decay, there are two neutrinos, which leads to large amount of background
- One side of B meson (B_{tag}) is reconstructed by hadronic decay modes
- Information of B_{tag} can be used to remove background

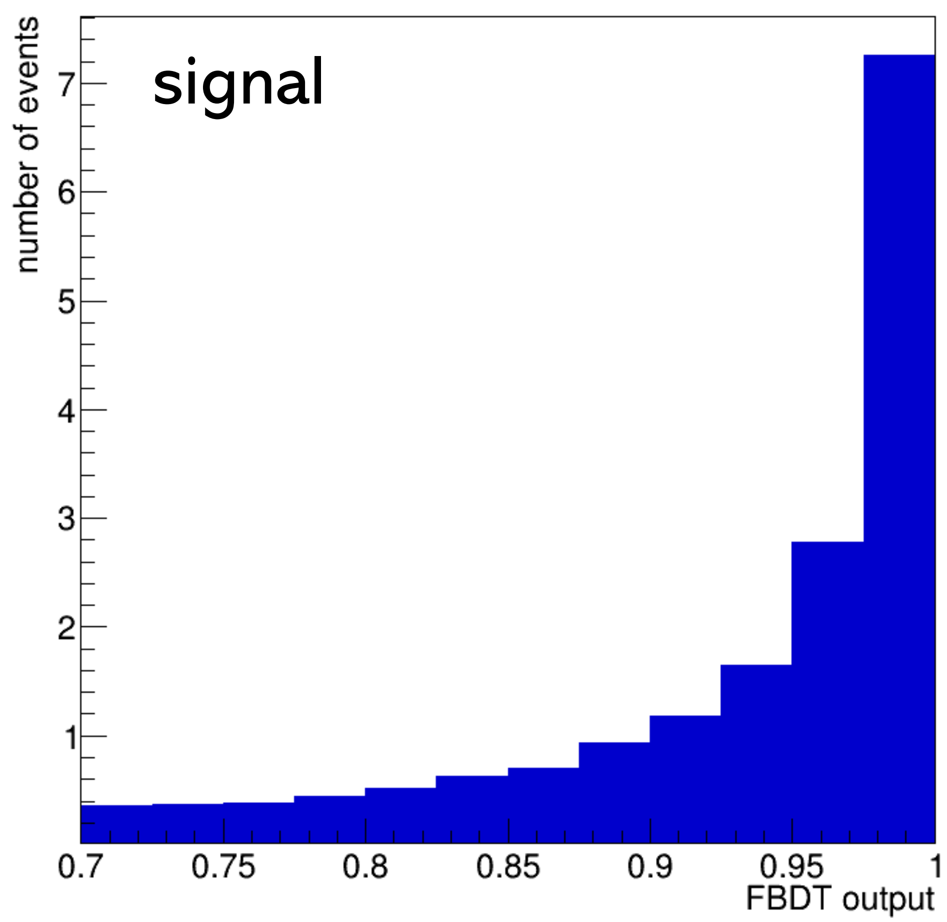


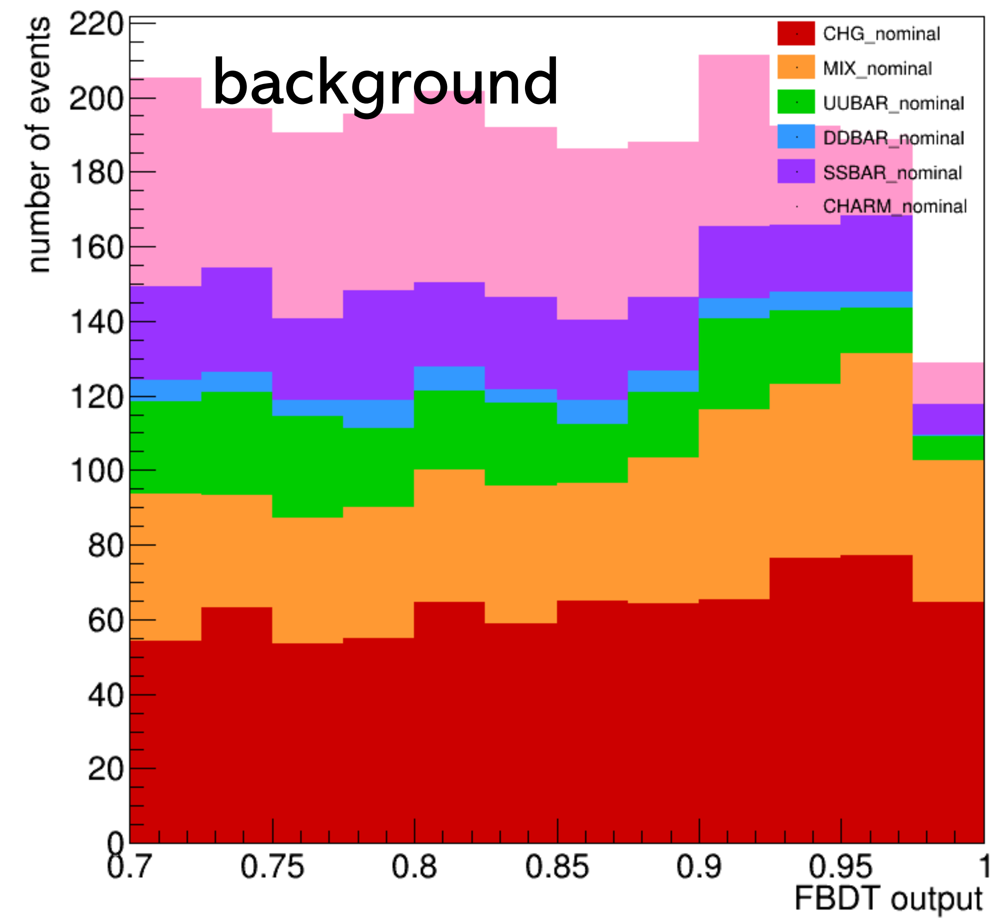
- X_s is reconstructed by 24 decay modes (sum of exclusive method)

	$B^0, \bar{B}^0$		$B^\pm$	
K	K_S^0		$K^\pm$	
$K\pi$	$K^\pm\pi^\mp$	$K_S^0\pi^0$	$K^\pm\pi^0$	$K_S^0\pi^\pm$
$K2\pi$	$K^\pm\pi^\mp\pi^0$	$K_S^0\pi^\pm\pi^\mp$	$K^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^0$
$K3\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp$	$K_S^0\pi^\pm\pi^\mp\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^0$	$K_S^0\pi^\pm\pi^\mp\pi^\pm$
$K4\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^0$	$K_S^0\pi^\pm\pi^\mp\pi^\pm\pi^\mp$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^\mp\pi^\pm\pi^0$
$3K$	$K^\pm K^\mp K_S^0$		$K^\pm K^\mp K^\pm$	
$3K\pi$	$K^\pm K^\mp K^\pm\pi^\mp$	$K^\pm K^\mp K_S^0\pi^0$	$K^\pm K^\mp K^\pm\pi^0$	$K_S^0 K^\pm K^\mp\pi^\pm$

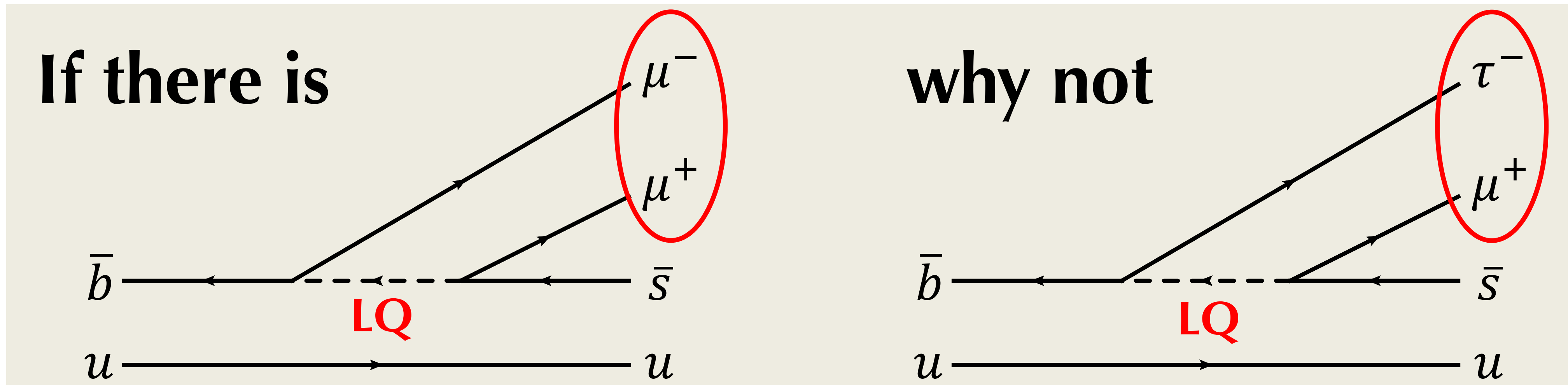
Fitting and Limit Setting

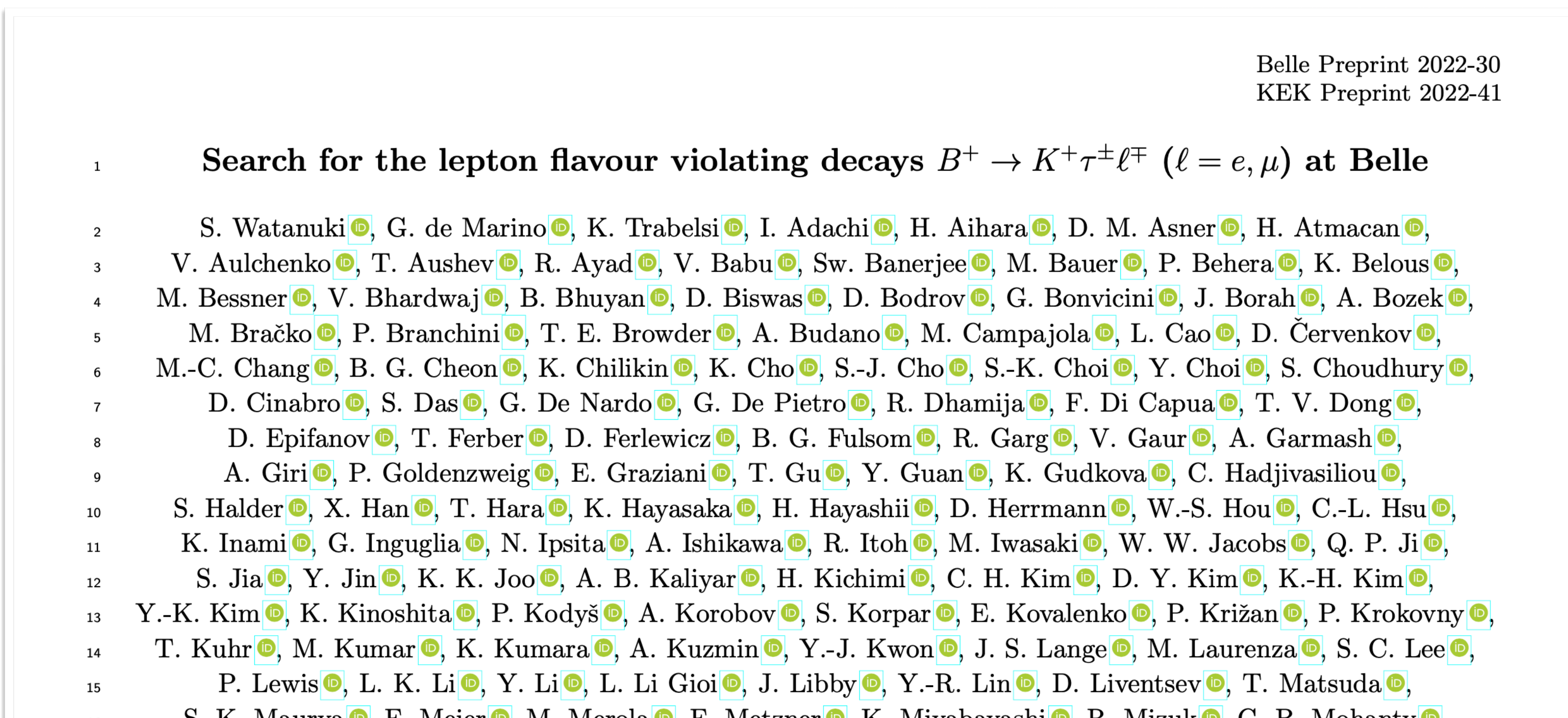
- Multivariate analysis (MVA) technique is used to suppress background
- About 30 variables are used for MVA
  - $\cos\theta$ of momentum of B meson
  - missing energy/momentum
  - the number of muon candidates in event
- MVA output value is used for a fitting and limit setting to extract signal yields





$B^+ \to K^+\tau^\pm\ell^\mp$

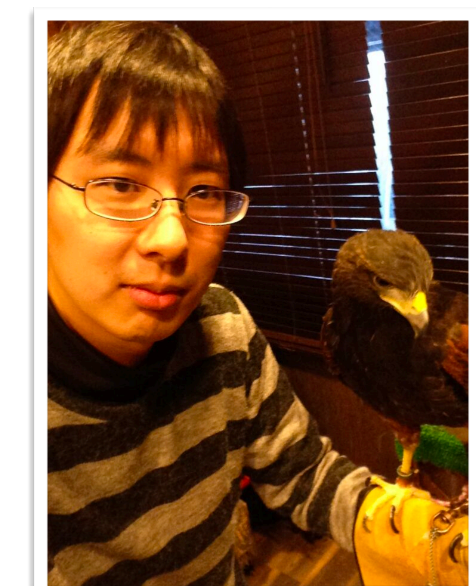




Belle Preprint 2022-30
KEK Preprint 2022-41

Search for the lepton flavour violating decays $B^+ \to K^+\tau^\pm\ell^\mp$ $(\ell = e, \mu)$ at Belle

S. Watanuki, G. de Marino, K. Trabelsi, I. Adachi, H. Aihara, D. M. Asner, H. Atmacan, V. Aulchenko, T. Aushev, R. Ayad, V. Babu, Sw. Banerjee, M. Bauer, P. Behera, K. Belous, M. Bessner, V. Bhardwaj, B. Bhuyan, D. Biswas, D. Bodrov, G. Bonvicini, J. Borah, A. Bozek, M. Bračko, P. Branchini, T. E. Browder, A. Budano, M. Campajola, L. Cao, D. Červenkov, M.-C. Chang, B. G. Cheon, K. Chilikin, K. Cho, S.-J. Cho, S.-K. Choi, Y. Choi, S. Choudhury, D. Cinabro, S. Das, G. De Nardo, G. De Pietro, R. Dhamija, F. Di Capua, T. V. Dong, D. Epifanov, T. Ferber, D. Ferlewicz, B. G. Fulsom, R. Garg, V. Gaur, A. Garmash, A. Giri, P. Goldenzweig, E. Graziani, T. Gu, Y. Guan, K. Gudkova, C. Hadjivasiliou, S. Halder, X. Han, T. Hara, K. Hayasaka, H. Hayashii, D. Herrmann, W.-S. Hou, C.-L. Hsu, K. Inami, G. Inguglia, N. Ipsita, A. Ishikawa, R. Itoh, M. Iwasaki, W. W. Jacobs, Q. P. Ji, S. Jia, Y. Jin, K. K. Joo, A. B. Kaliyar, H. Kichimi, C. H. Kim, D. Y. Kim, K.-H. Kim, Y.-K. Kim, K. Kinoshita, P. Kodyš, A. Korobov, S. Korpar, E. Kovalenko, P. Križan, P. Krokovny, T. Kuhr, M. Kumar, K. Kumara, A. Kuzmin, Y.-J. Kwon, J. S. Lange, M. Laurenza, S. C. Lee, P. Lewis, L. K. Li, Y. Li, L. Li Gioi, J. Libby, Y.-R. Lin, D. Liventsev, T. Matsuda, S. K. Maurya, F. Meier, M. Merola, F. Metzner, K. Miyabayashi, R. Mizuk, G. B. Mohanty,

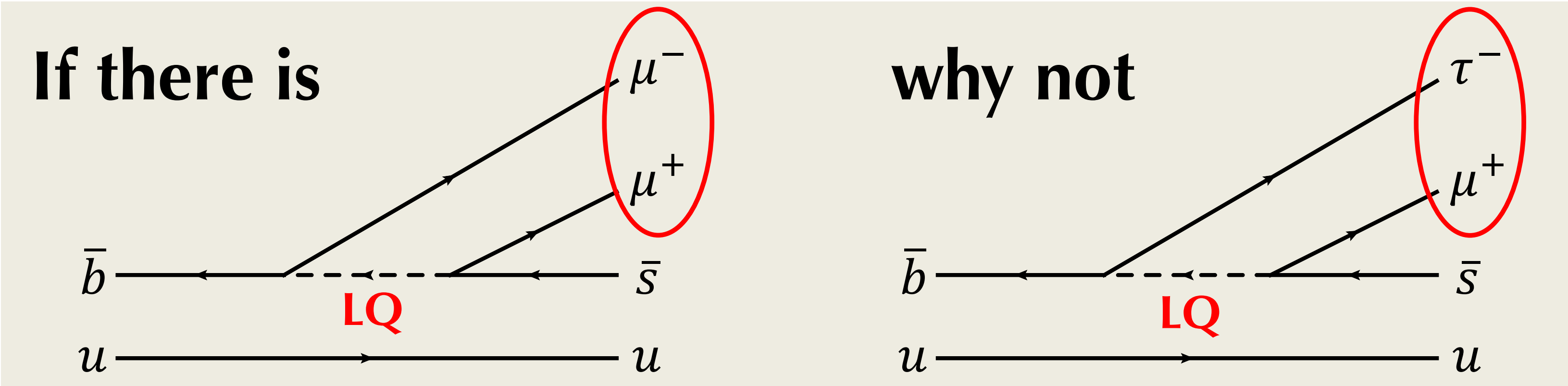


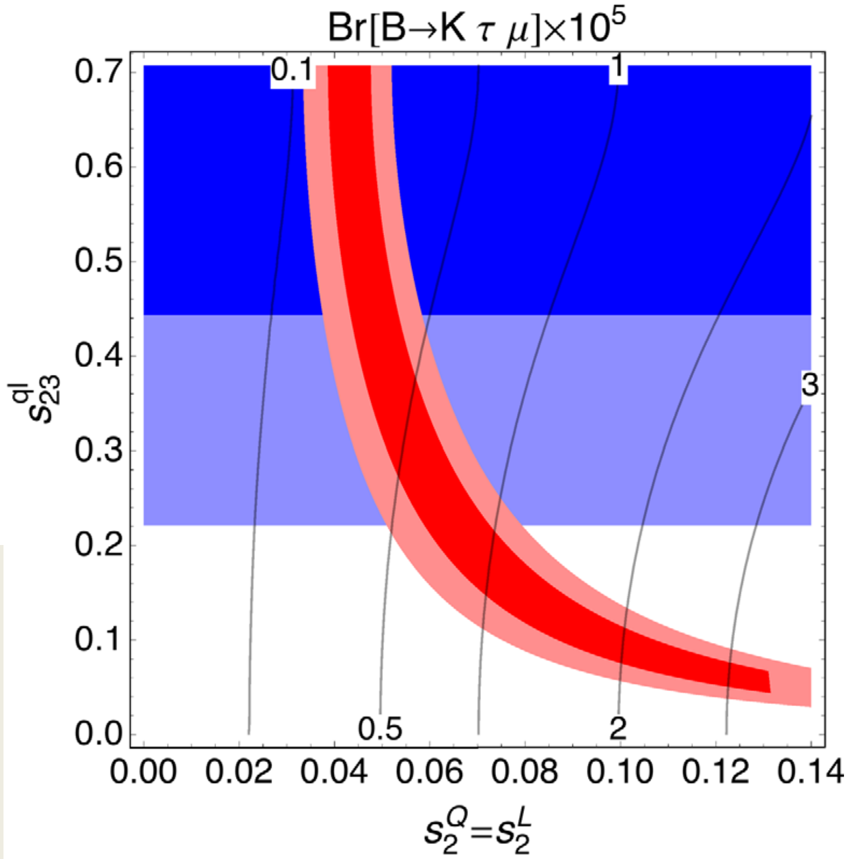
Shun Watanuki
(Yonsei HEP)

$B^+ \to K^+ \tau^\pm \ell^\mp$

Motivation

- If there is LUV, there is no natural mechanism to prevent LFV





$\mathscr{B}(B \to K\tau\mu) \sim \mathcal{O}(10^{-6})$ is preferred in a certain VLQ model, for instance.

- $R(D^{(*)})$ 2σ
- $R(D^{(*)})$ 1σ
- $C_9^{\mu\mu} = -C_{10}^{\mu\mu}$ 2σ
- $C_9^{\mu\mu} = -C_{10}^{\mu\mu}$ 1σ

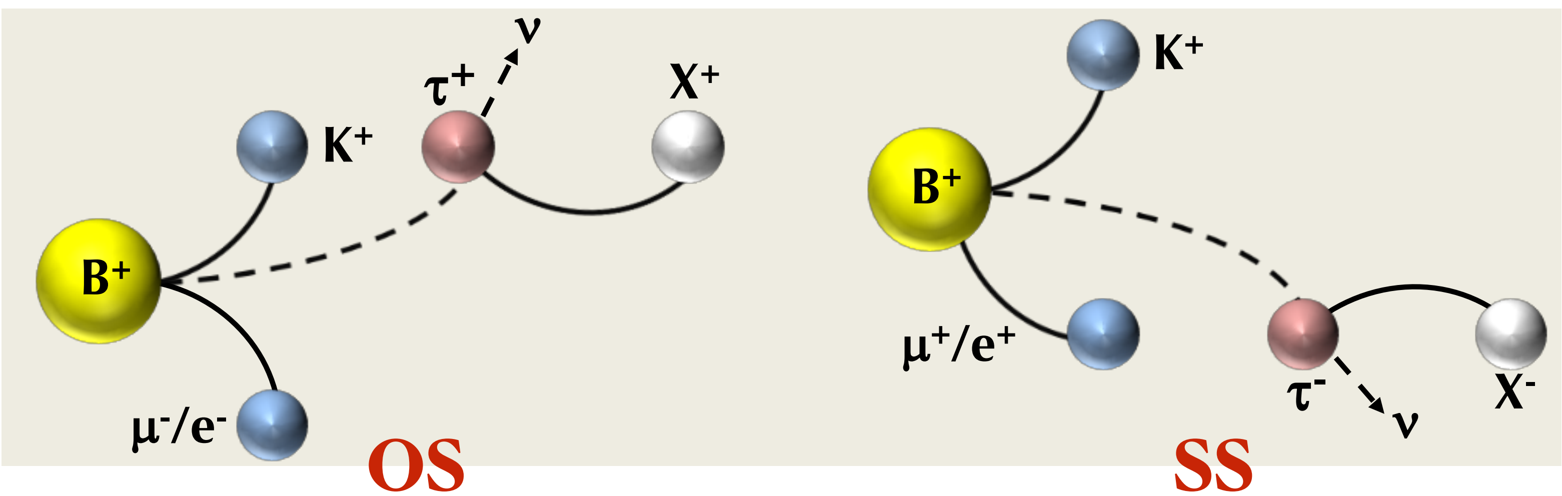
Calibbi, Crivellin, Li
PHYS. REV. D **98,** 115002 (2018)

$$\begin{pmatrix} q_{iL} \\ Q_{iL} \end{pmatrix} \to \begin{pmatrix} c_{iQ} & -s_{iQ} \\ s_{iQ} & c_{iQ} \end{pmatrix} \begin{pmatrix} q_{iL} \\ Q_{iL} \end{pmatrix}$$

$$\begin{pmatrix} \ell_{iL} \\ L_{iL} \end{pmatrix} \to \begin{pmatrix} c_{iL} & -s_{iL} \\ s_{iL} & c_{iL} \end{pmatrix} \begin{pmatrix} \ell_{iL} \\ L_{iL} \end{pmatrix}.$$

Analysis feature

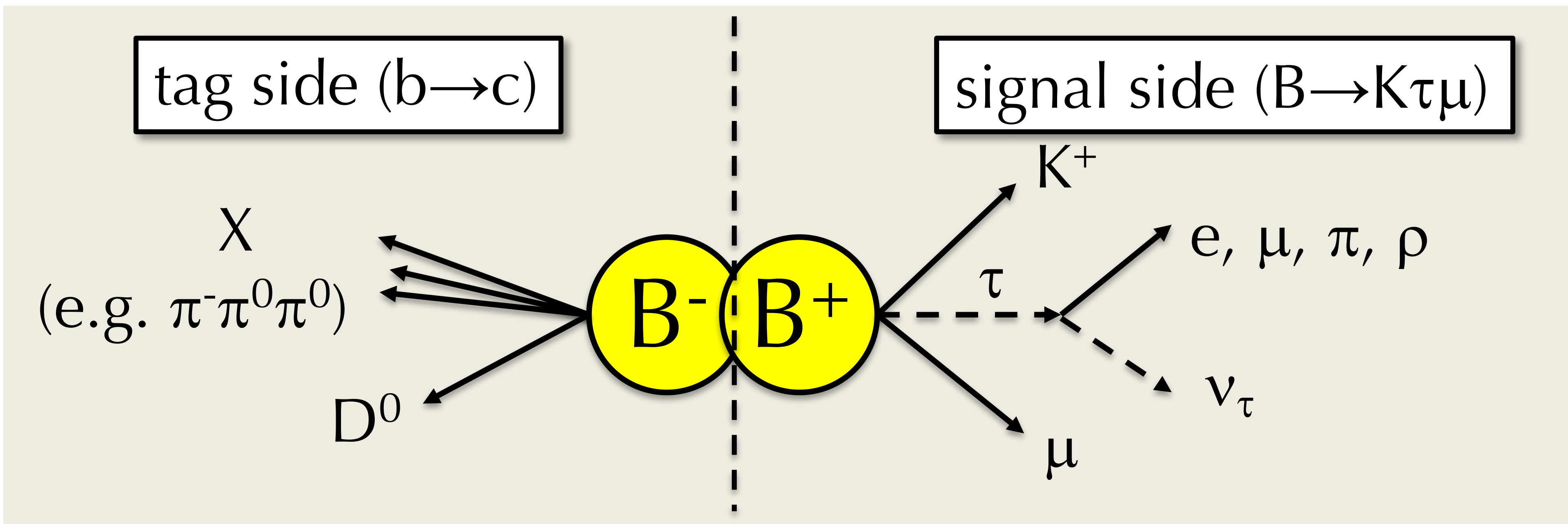
- hadronic B-tagging (FEI)
- OS vs. SS (very different bkgd.



- fit for recoil mass for M_τ
- use FBDT to suppress bkgd.

arXiv:2212.04128
submitted to PRL

$B^+ \to K^+\tau^\pm\ell^\mp$ — analysis feature



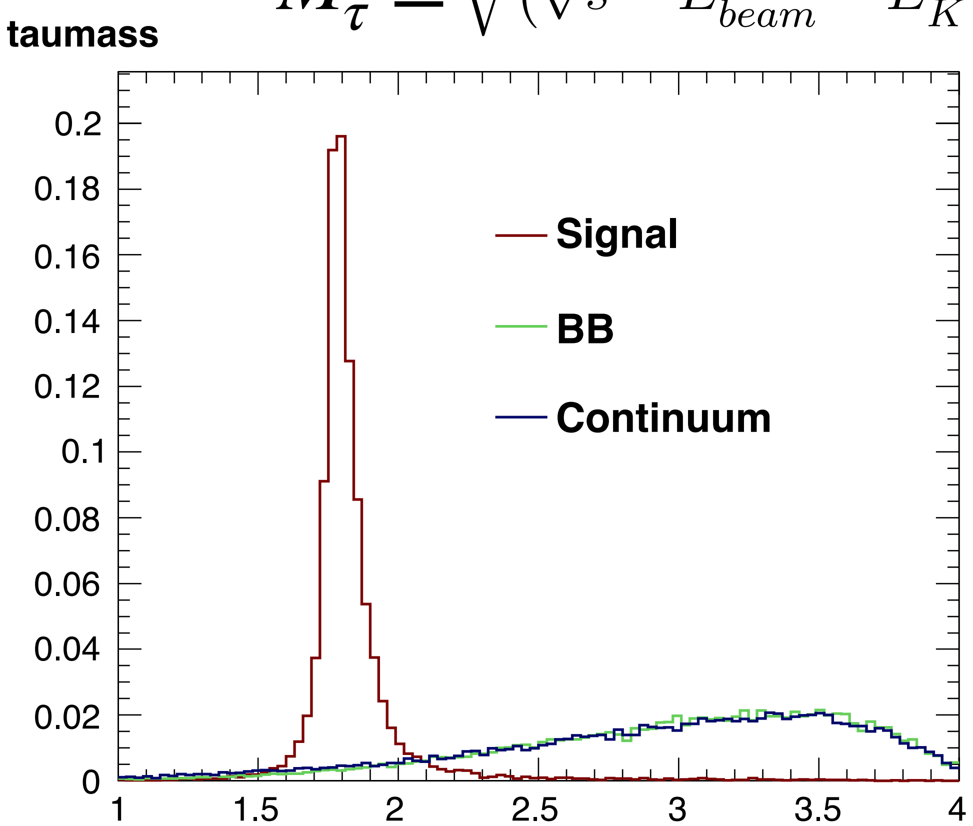
Charged tracks

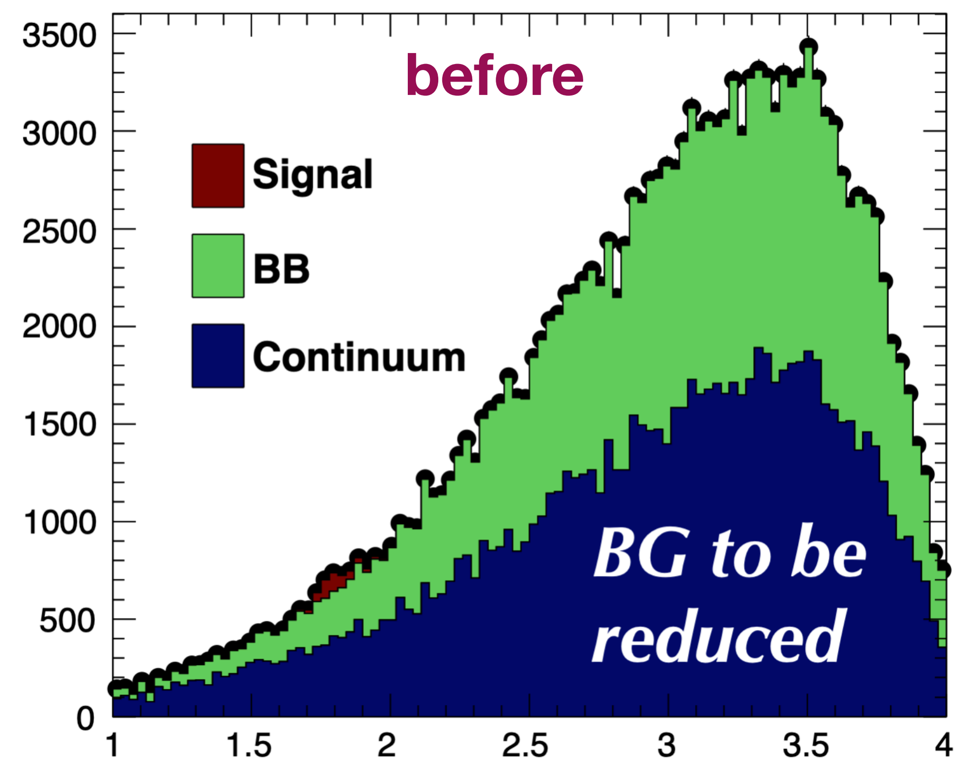
- $PID_\pi > 0.6$ for p^+, $PID_K > 0.6$ for K^+
- $mID > 0.9$ for μ
- $eID > 0.9$ for e

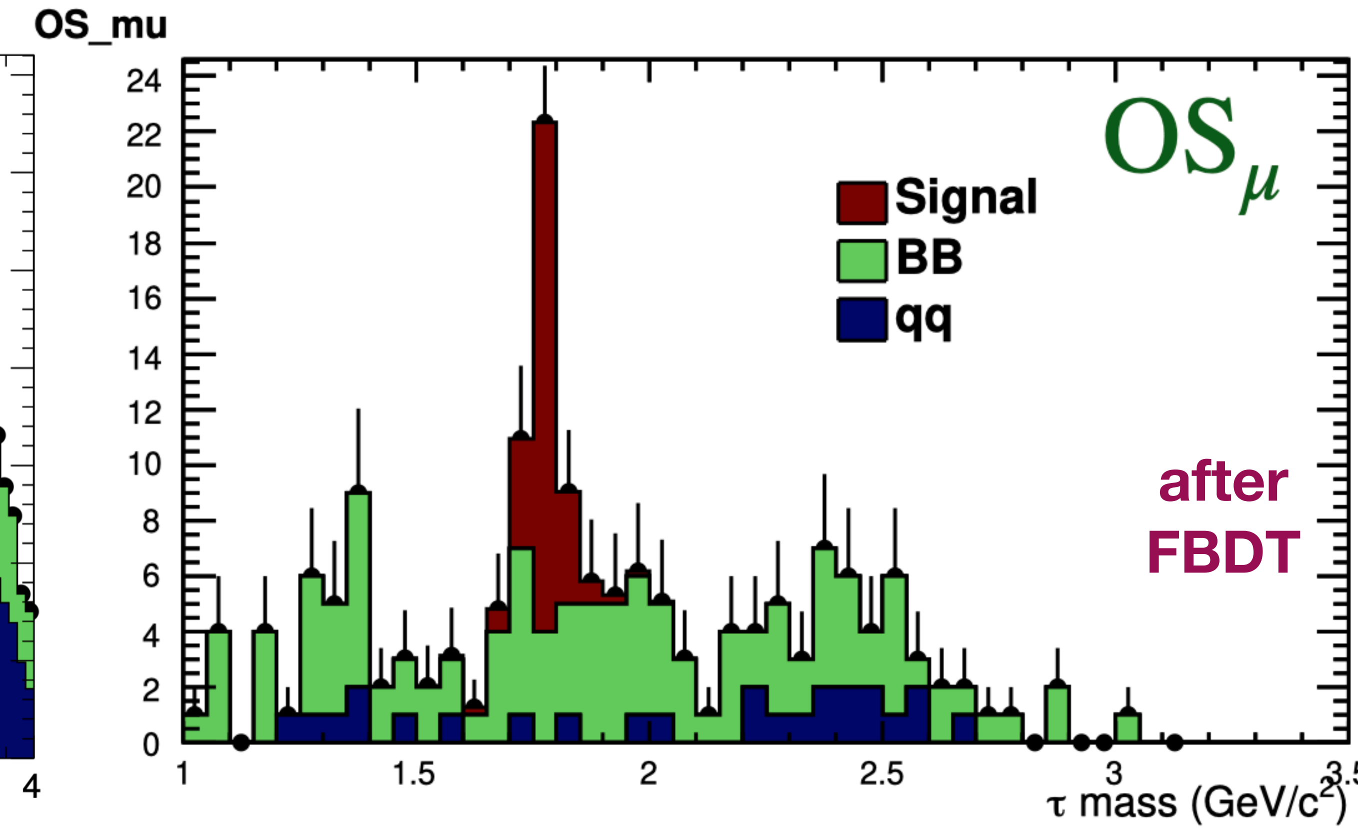
Primary tracks (K, μ/e)

- $|d_0| < 0.5$cm
- $|z_0| < 5.0$cm

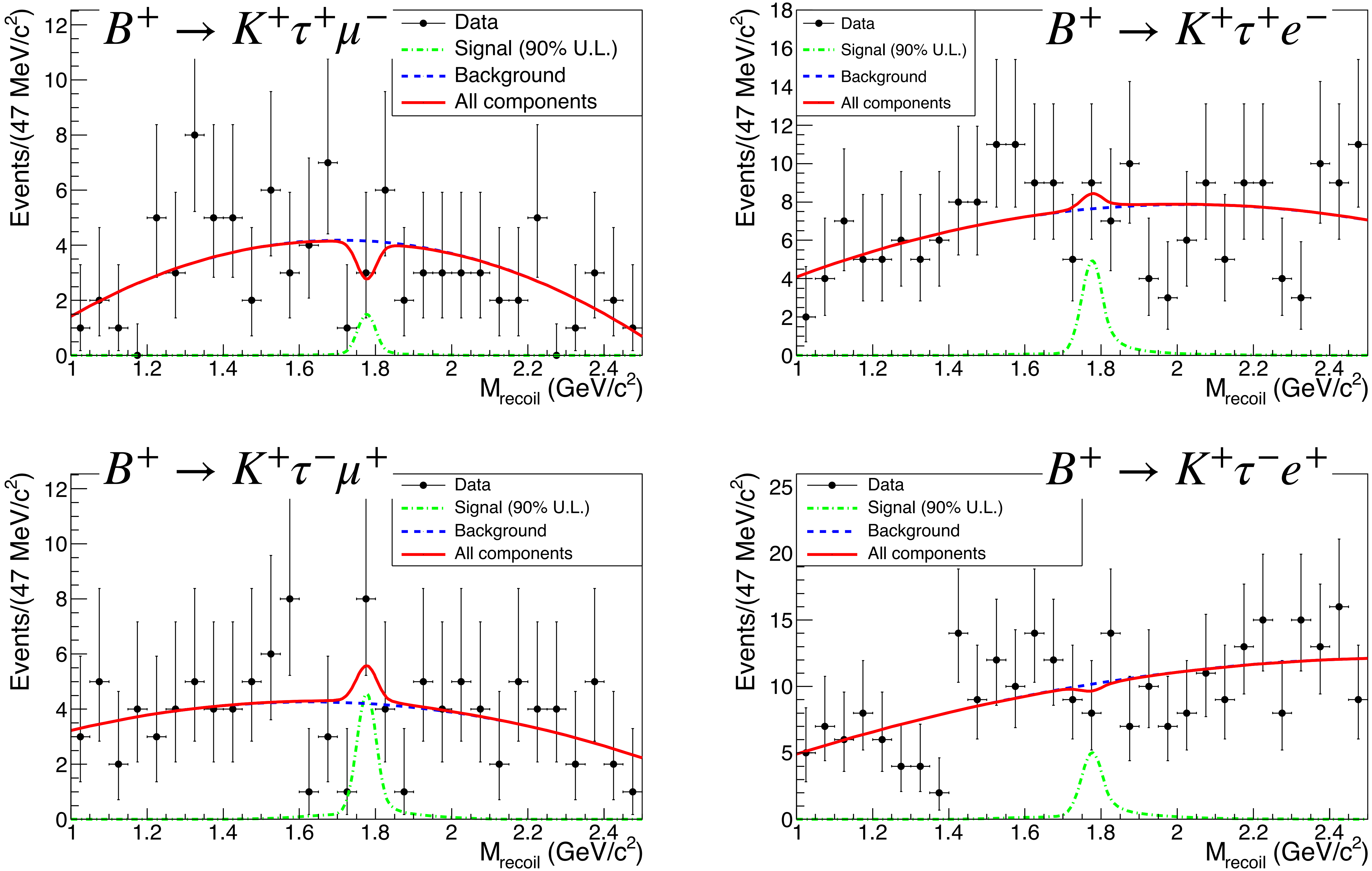
$$M_\tau \equiv \sqrt{\left(\sqrt{s} - E^*_{beam} - E^*_K - E^*_\ell\right)^2 - |\vec{p}^{\,*}_{tag} - \vec{p}^{\,*}_K - \vec{p}^{\,*}_\ell|^2}$$







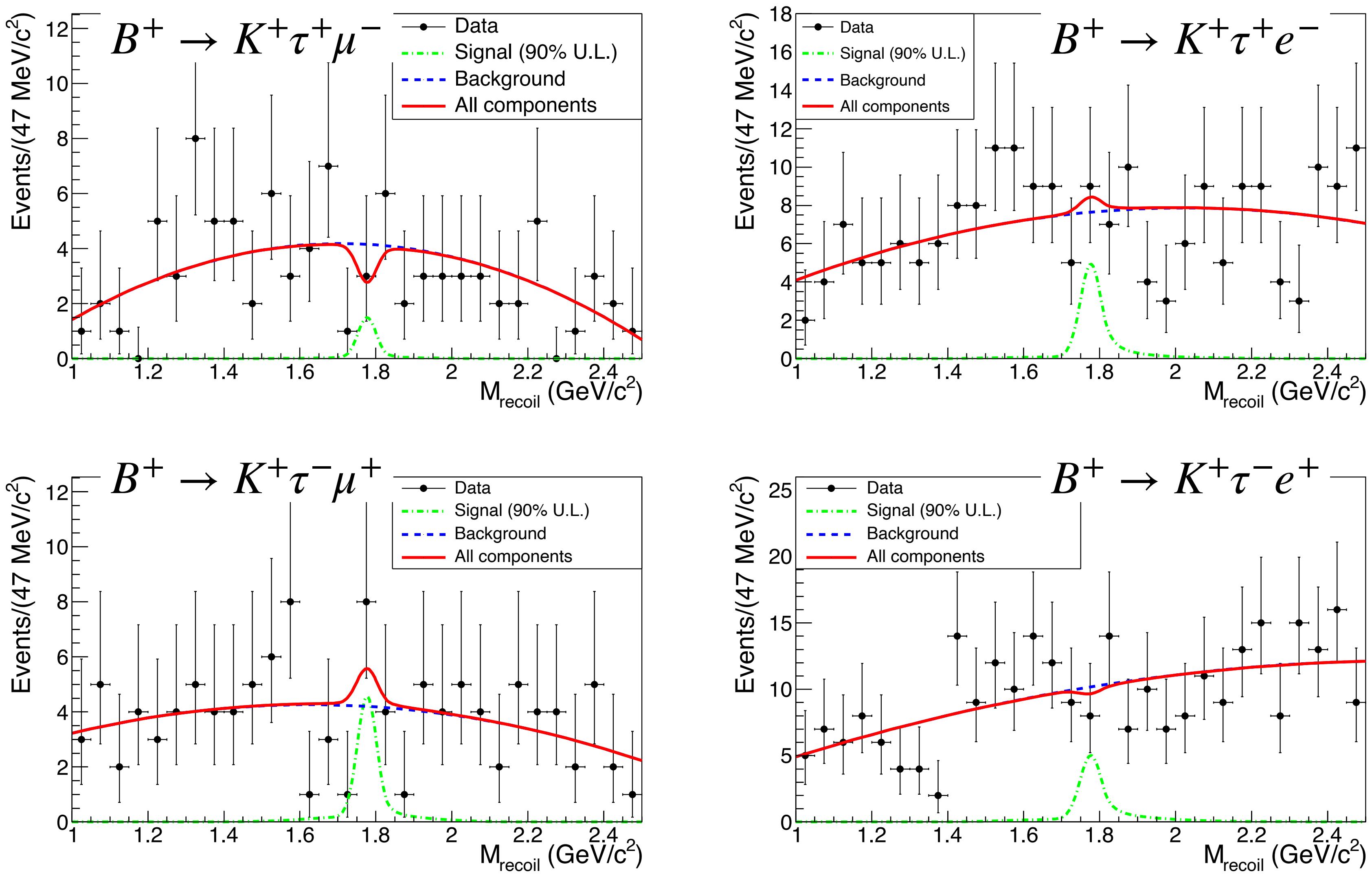
$B^+ \to K^+\tau^\pm\ell^\mp$ Results



No signal excess in any mode!

arXiv:2212.04128
submitted to PRL

$B^+ \to K^+\tau^\pm\ell^\mp$ Results



Mode	ε (%)	$\varepsilon^{\rm NP}$ (%)	$N_{\rm sig}$
$B^+ \to K^+\tau^+\mu^-$	0.064	0.058	-2.1 ± 2.9
$B^+ \to K^+\tau^+e^-$	0.084	0.074	1.5 ± 5.5
$B^+ \to K^+\tau^-\mu^+$	0.046	0.038	2.3 ± 4.1
$B^+ \to K^+\tau^-e^+$	0.079	0.058	-1.1 ± 7.4

$$\mathcal{B}(B^+ \to K^+\tau^+\mu^-) < 0.59 \times 10^{-5}$$

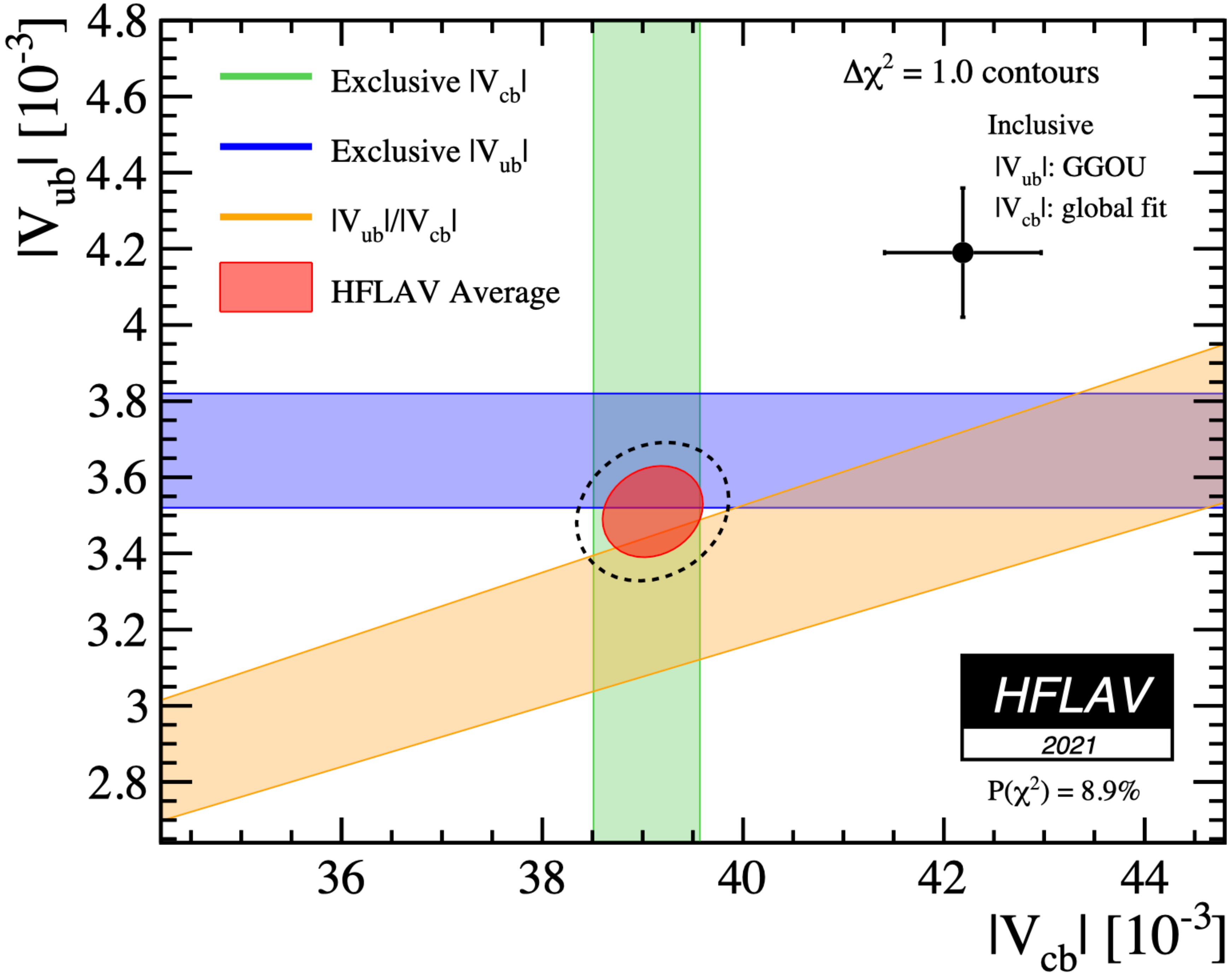
$$\mathcal{B}(B^+ \to K^+\tau^+e^-) < 1.51 \times 10^{-5}$$

$$\mathcal{B}(B^+ \to K^+\tau^-\mu^+) < 2.45 \times 10^{-5}$$

$$\mathcal{B}(B^+ \to K^+\tau^-e^+) < 1.53 \times 10^{-5}$$

- The most stringent limit on $\mathcal{B}(B^+ \to K^+\tau\ell)$ in all four modes, based on PHSP model
- NP upper limits are estimated for models that give lowest efficiency
- paper has been submitted to PRL

B semileptonic (1)



$$|V_{ub}|_{\text{incl.}} = (4.19 \pm 0.12^{+0.11}_{-0.12}) \times 10^{-3}$$

$$|V_{ub}|_{\text{excl.}} = (3.51 \pm 0.12) \times 10^{-3}$$

$\sim 3\sigma$ tension for each $(|V_{cb}|, |V_{ub}|)$

$$|V_{cb}|_{\text{excl.}} = (39.10 \pm 0.50) \times 10^{-3}$$

$$|V_{cb}|_{\text{incl.}} = (42.19 \pm 0.78) \times 10^{-3}$$

$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$

Differential shapes (*normalized*) of $B \to D^* \ell^+ \nu$

- provide necessary experimental input to determine the non-perturbative form factor
- once FF shape is known, it can be combined with L-QCD (or other methods) for the absolute normalization to determine $|V_{cb}|$

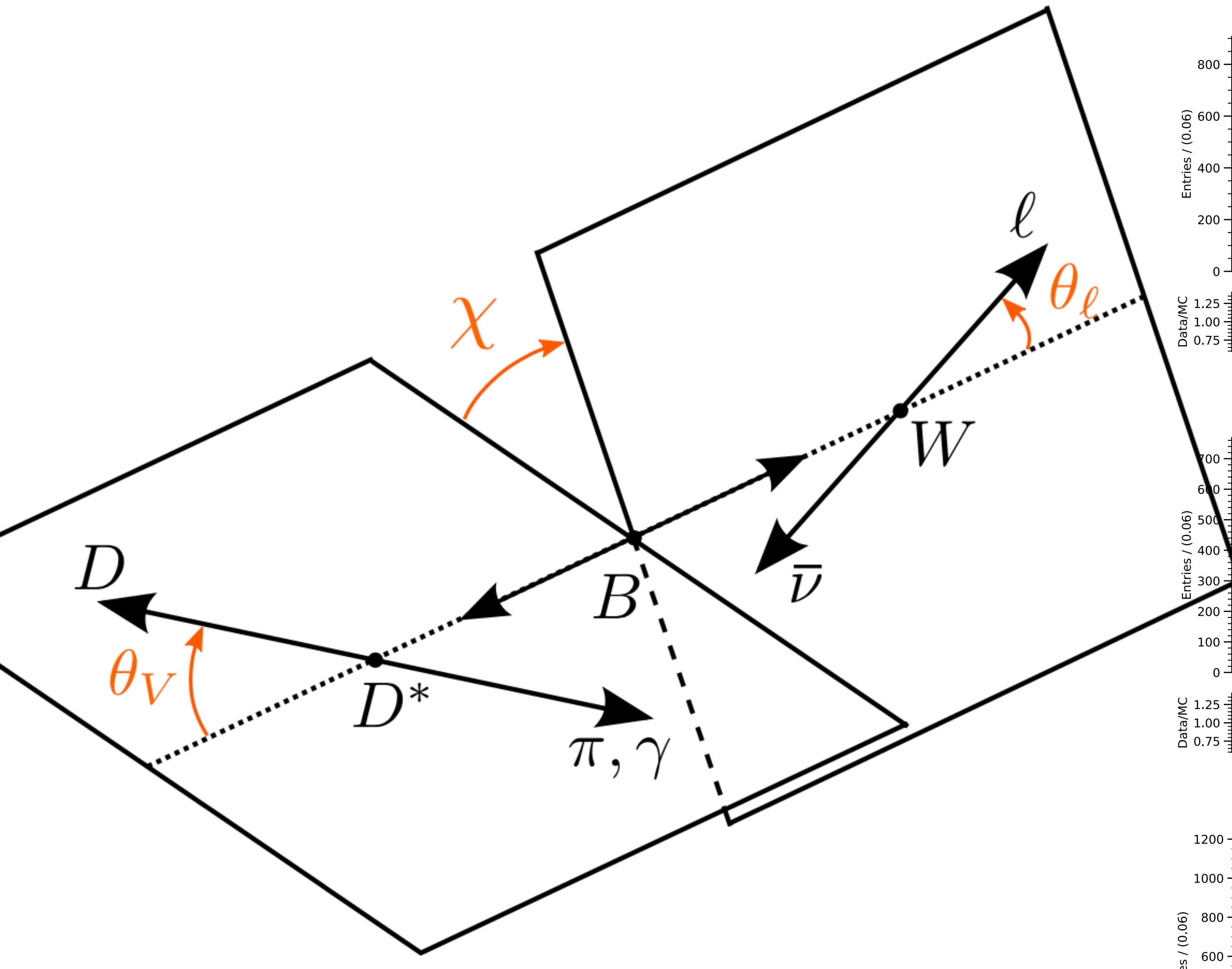
$$|V_{cb}| = \sqrt{\frac{\mathcal{B}(B \to D^* \ell \bar{\nu}_\ell)}{\tau_B\, \Gamma(B \to D^* \ell \bar{\nu}_\ell)}}$$

$\mathcal{B}$ – externally determined

Γ = decay width/$|V_{cb}|^2$ (theory)

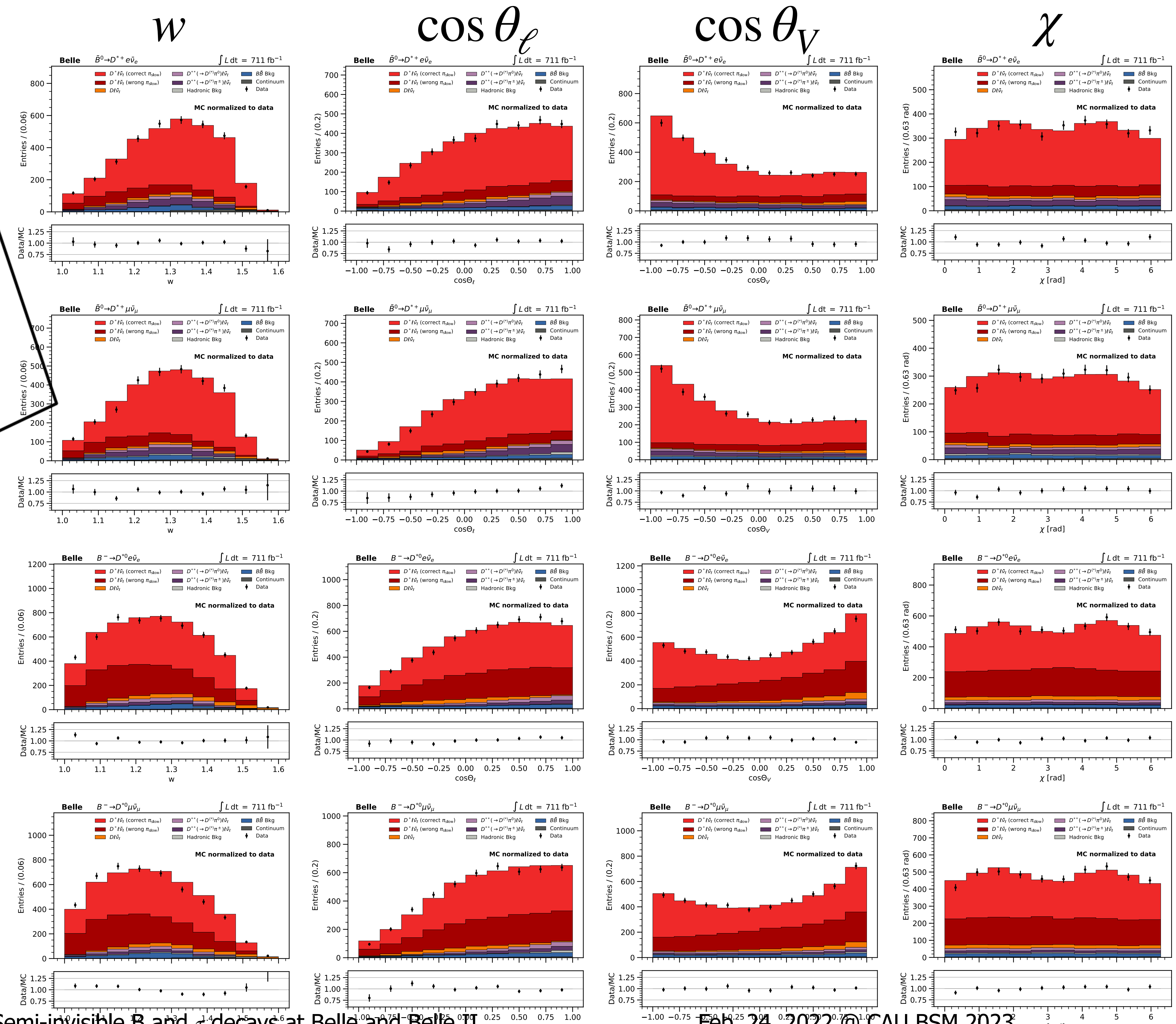
- use hadronic B-tagging via FEI
- characterize the 1D projections in $(w,\ \cos\theta_\ell,\ \cos\theta_V,\ \chi)$
- full correlations b/w the projections are determined
- L-QCD at zero recoil ($w = 1$) is used for $|V_{cb}|$

$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$



$$w = v \cdot v'$$

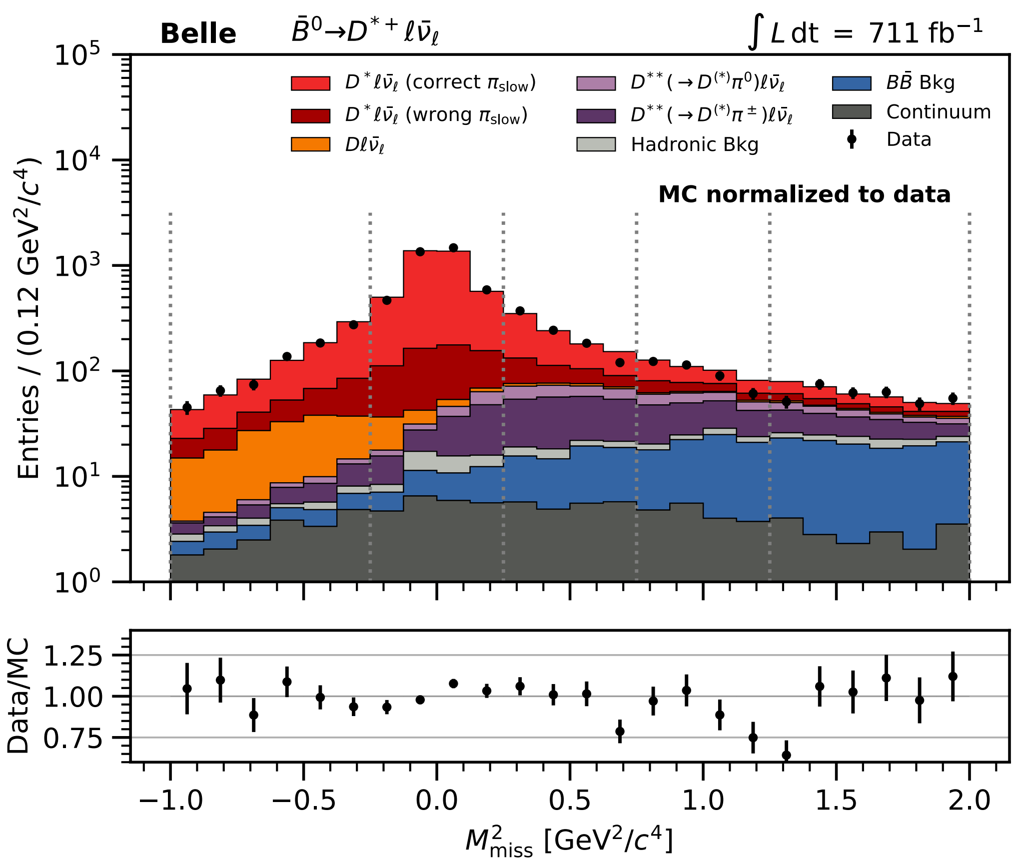
$$= \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

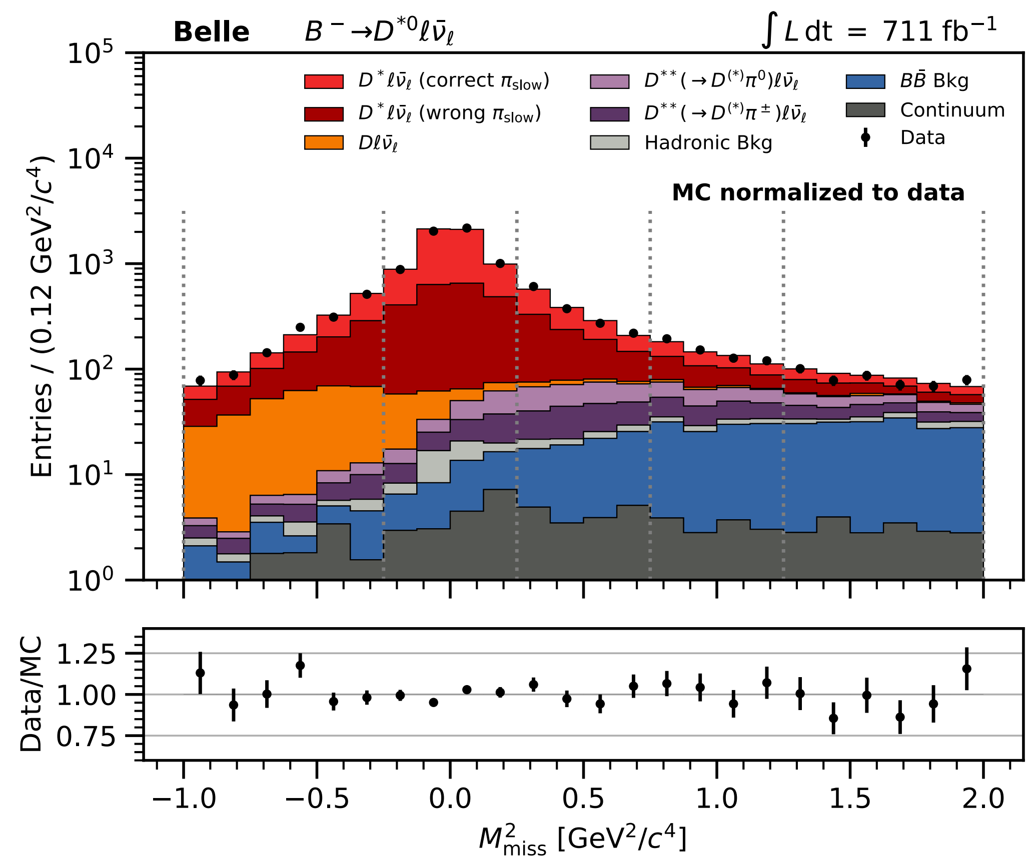


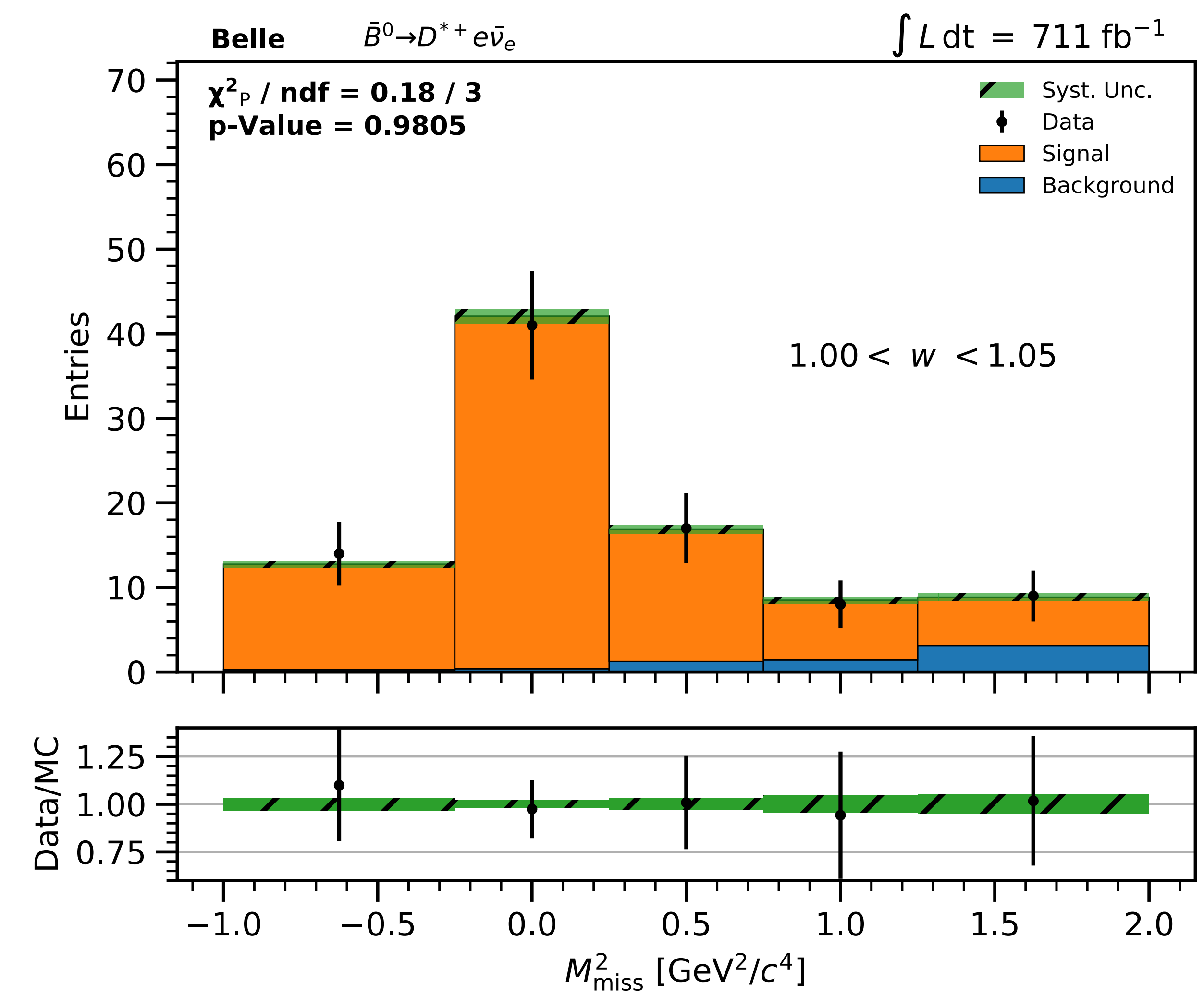
arXiv:2301.07529
submitted to PRD

$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$

background subtraction, with binned likelihood fits to $M^2_{\rm miss}$



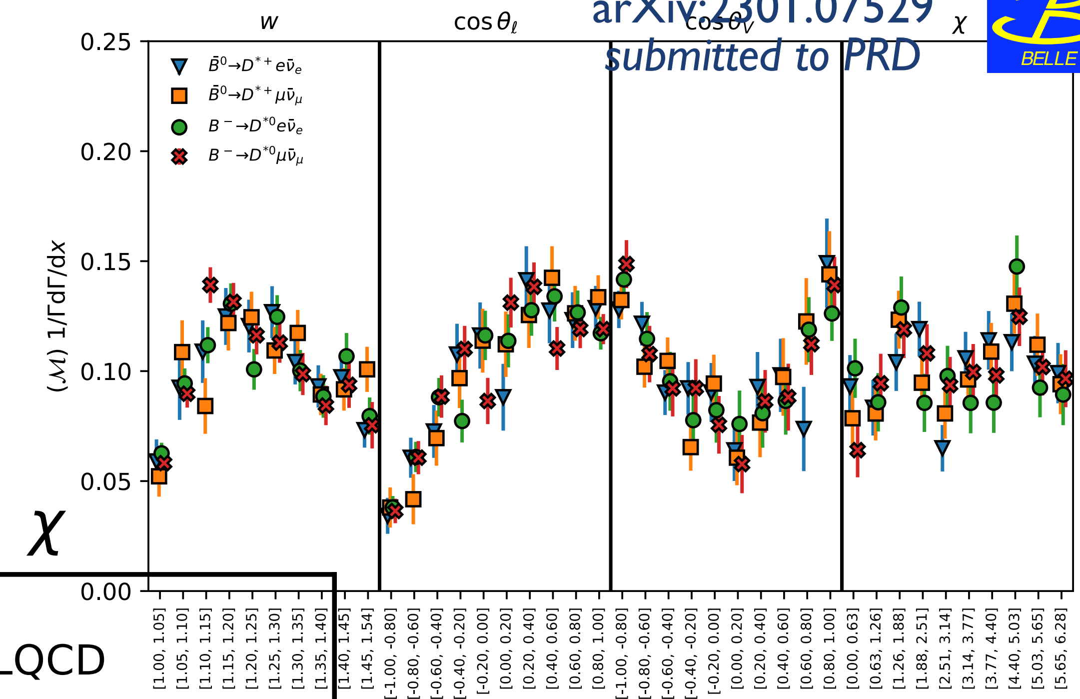


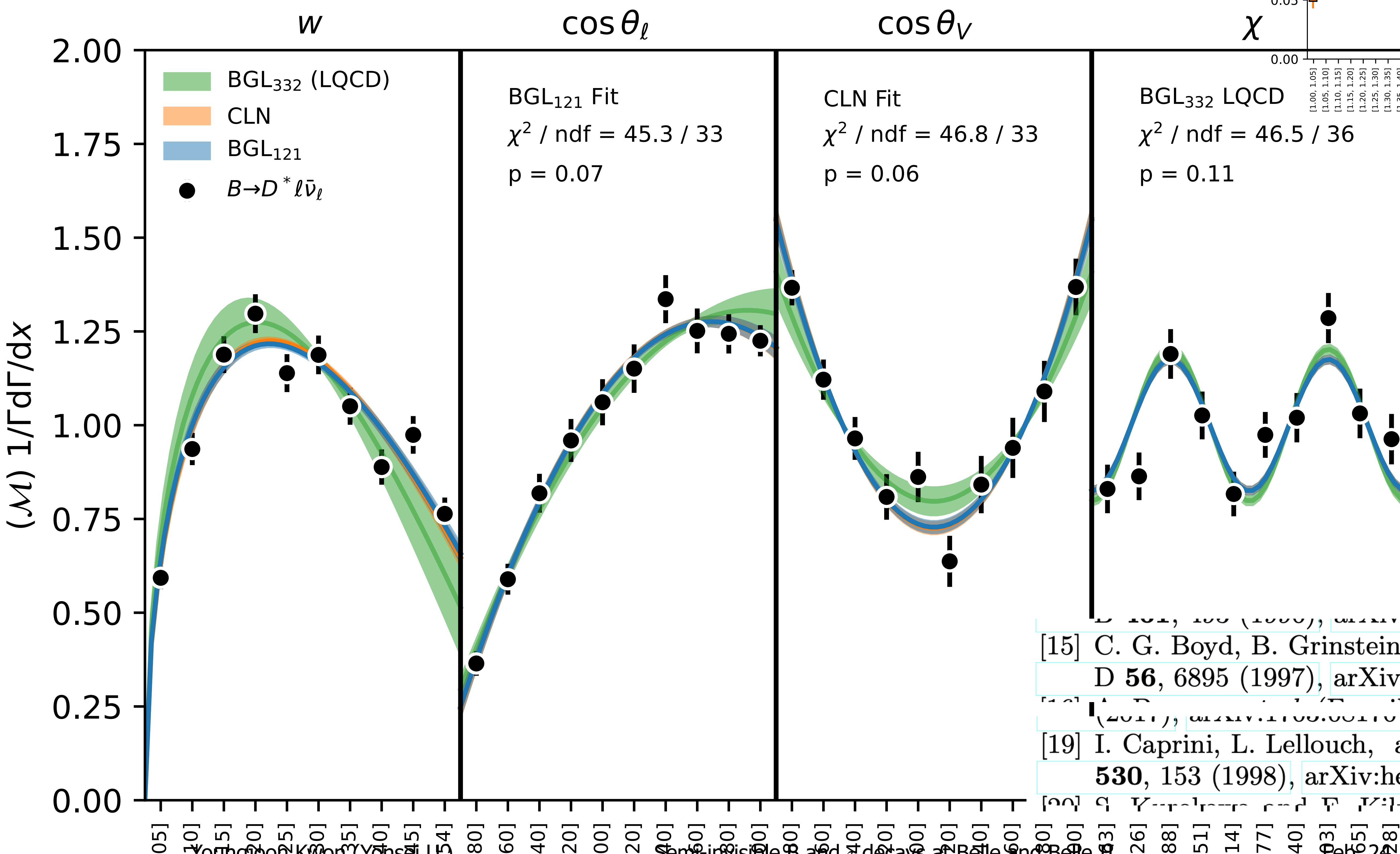


arXiv:2301.07529
submitted to PRD

$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$

fitted shapes to BGL & CLN models





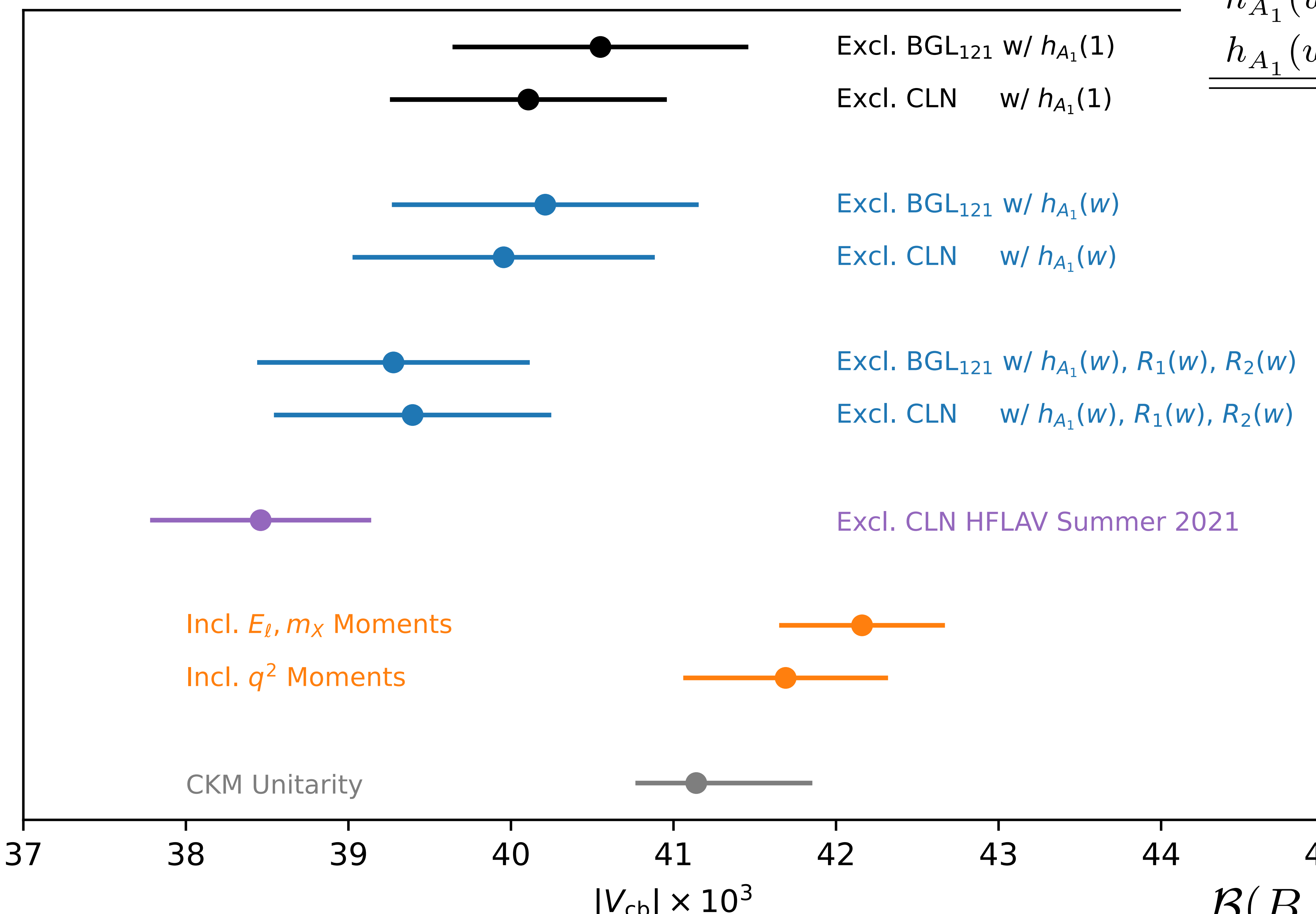
[15] C. G. Boyd, B. Grinstein, and R. F. Lebed, Phys. Rev. D **56**, 6895 (1997), arXiv:hep-ph/9705252.

[19] I. Caprini, L. Lellouch, and M. Neubert, Nucl. Phys. B **530**, 153 (1998), arXiv:hep-ph/9712417.

arXiv:2301.07529
submitted to PRD

$B \to D^{*}\ell^{+}\nu$ shapes & $|V_{cb}|$

$|V_{cb}|$ and other results



	BGL$_{121}$	CLN
$h_{A_1}(1)$	40.6 ± 0.9	40.1 ± 0.9
$h_{A_1}(w)$	40.2 ± 0.9	40.0 ± 0.9
$h_{A_1}(w),\ R_1(w),\ R_2(w)$	39.3 ± 0.8	39.4 ± 0.9

$$\Delta A_{\rm FB} = A^{\mu}_{\rm FB} - A^{e}_{\rm FB}$$

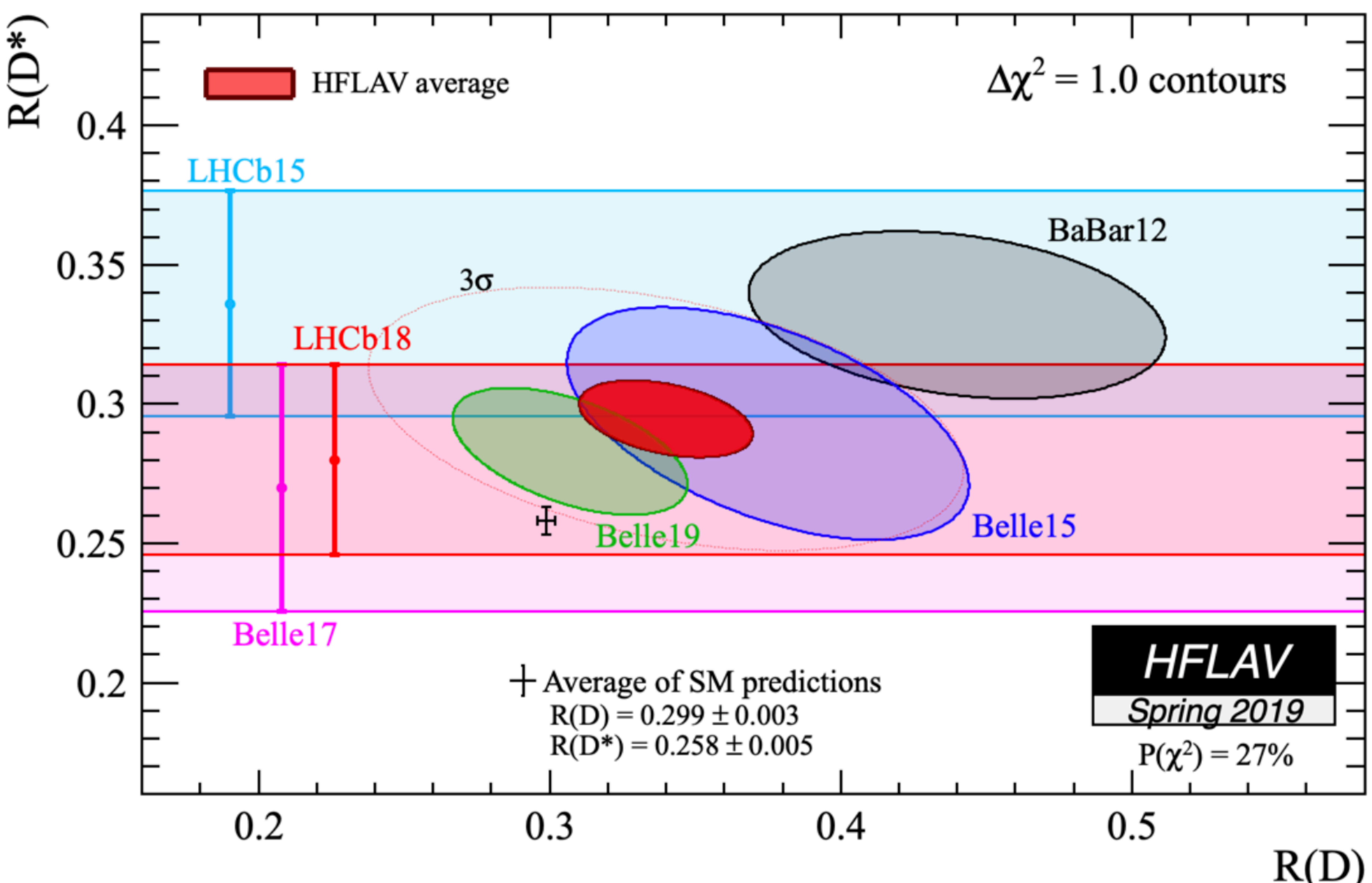
	$\Delta A_{\rm FB}$
$\bar{B}^0 \to D^{*+}\ell\bar{\nu}_\ell$	$0.062 \pm 0.044 \pm 0.011$
$B^- \to D^{*0}\ell\bar{\nu}_\ell$	$-0.003 \pm 0.033 \pm 0.009$
$B \to D^{*}\ell\bar{\nu}_\ell$	$0.022 \pm 0.026 \pm 0.007$

$$\Delta F_L = F^{\mu}_L - F^{e}_L$$

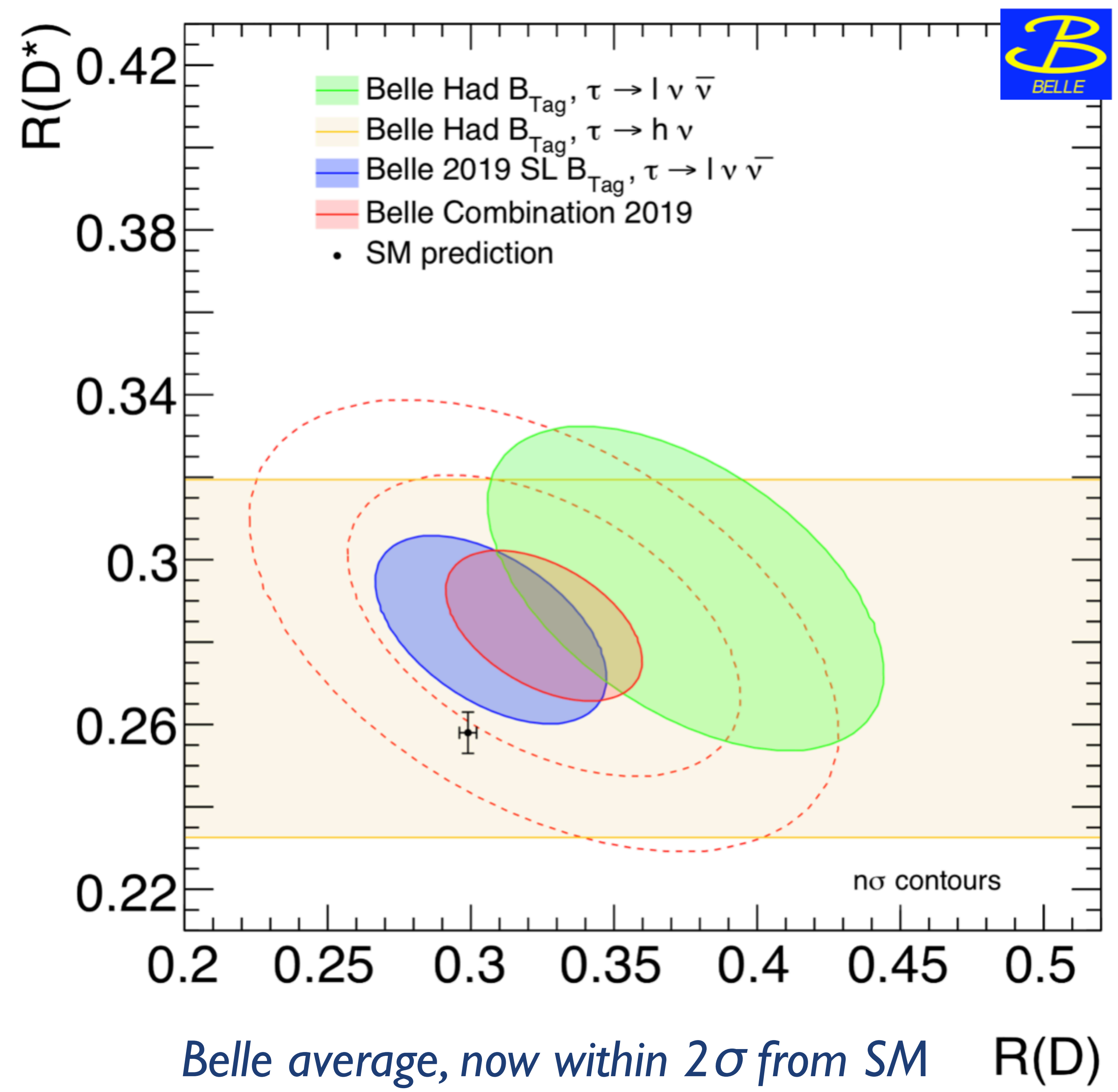
	$\Delta F_L^{D^*}$
$\bar{B}^0 \to D^{*+}\ell\bar{\nu}_\ell$	$0.032 \pm 0.033 \pm 0.010$
$B^- \to D^{*0}\ell\bar{\nu}_\ell$	$0.025 \pm 0.035 \pm 0.010$
$B \to D^{*}\ell\bar{\nu}_\ell$	$0.034 \pm 0.024 \pm 0.007$

$$R_{e\mu} = \frac{\mathcal{B}(B \to D^{*} e\bar{\nu}_e)}{\mathcal{B}(B \to D^{*} \mu\bar{\nu}_\mu)} = 0.990 \pm 0.021 \pm 0.023$$

B semileptonic (2)



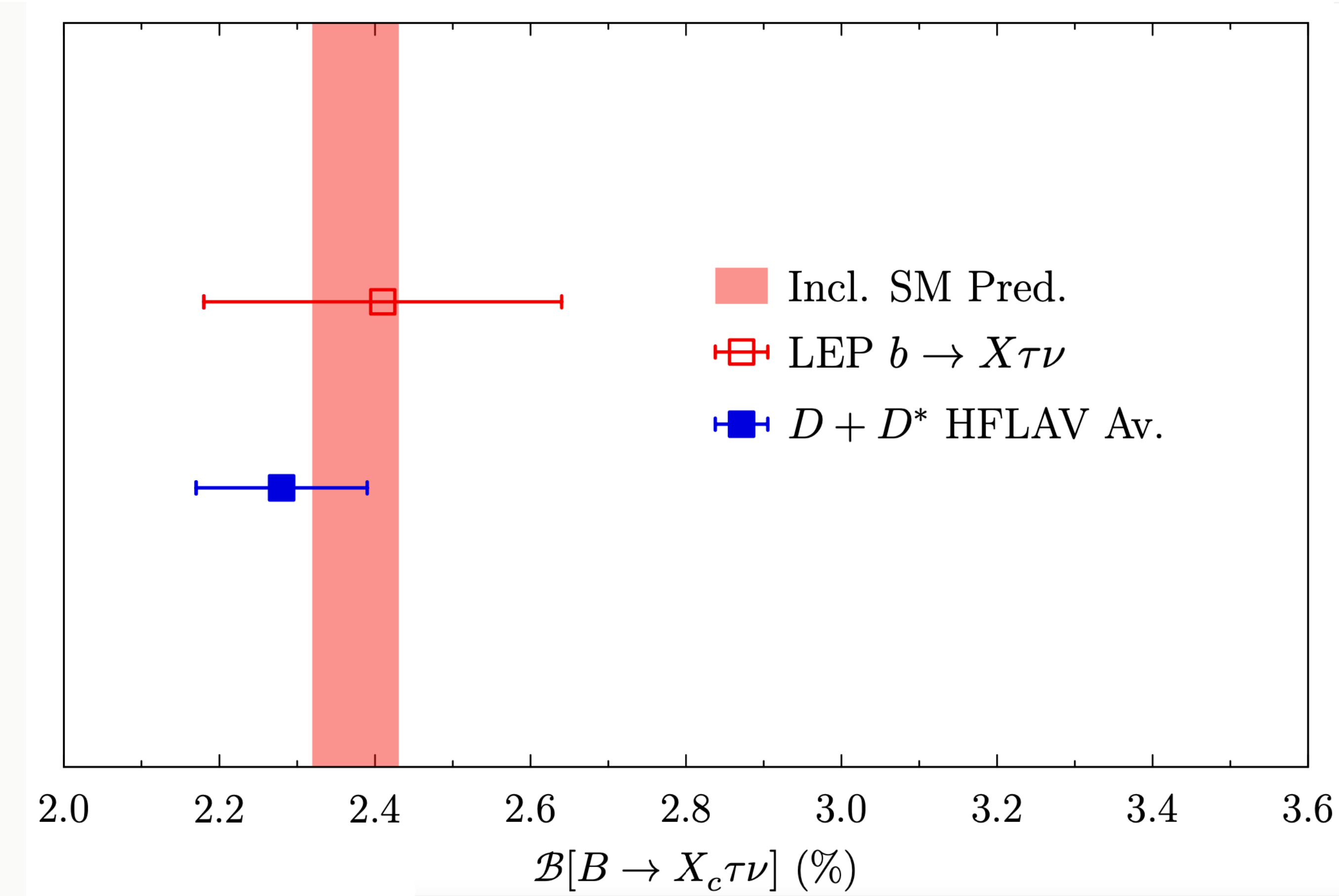
World average — tension with SM, now ~3.1σ



Belle average, now within 2σ from SM

LFU test with inclusive $B \to X\ell\nu$

- ***inclusive*** study — complementary to ***exclusive*** studies
- one of the unique and high-profile goals of Belle II
- last measured by LEP (!)
- very challenging — larger bkgd. & much less constrained
- precise modeling of $B \to X\ell\nu$ is critical



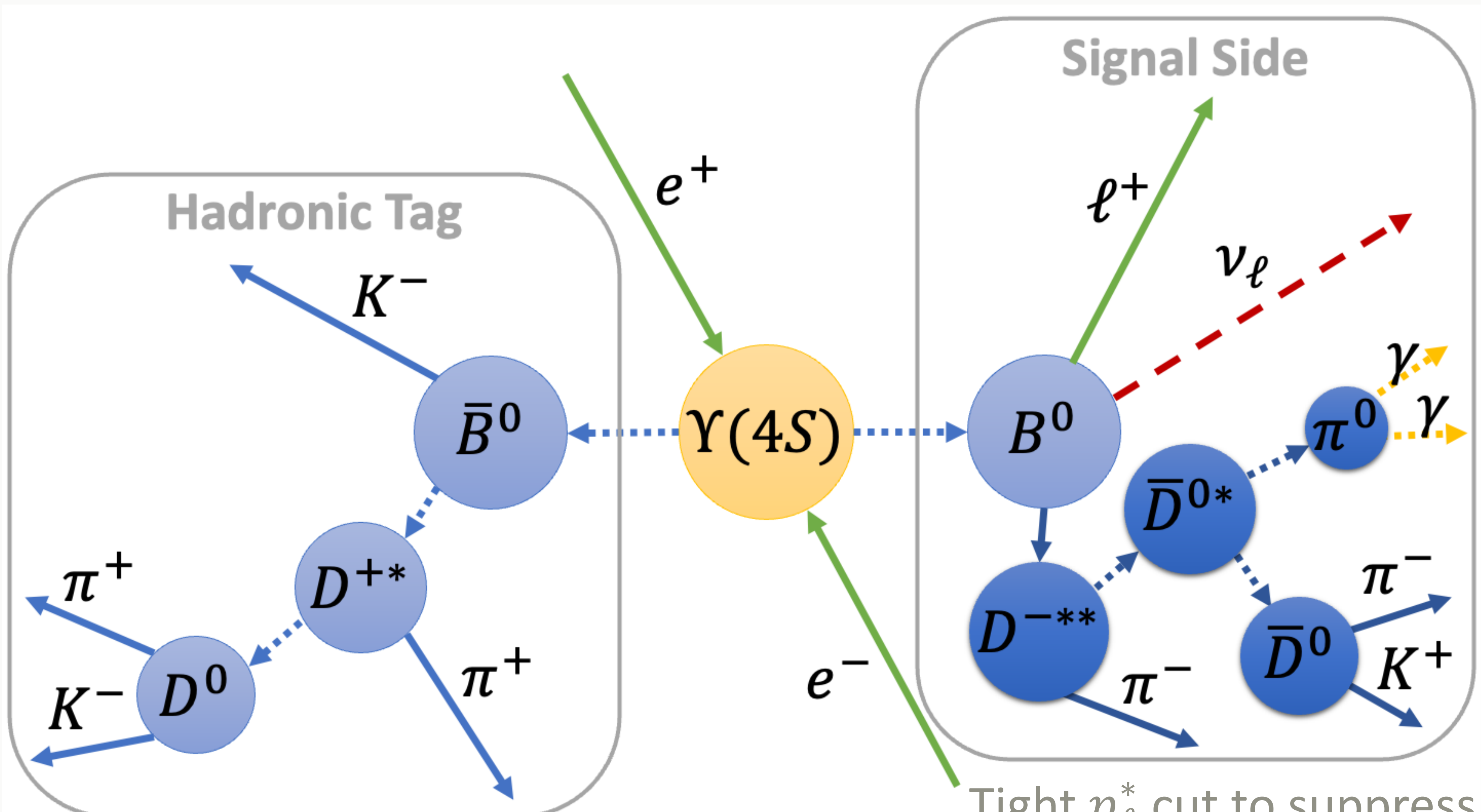
- $R(X_{c,\tau/\ell})_{SM} = 0.223 \pm 0.004$

  Phys. Rev. D 92, 054018 (2015)

- $R(X_{e/\mu})_{SM} = 1.006 \pm 0.001$

  K. Vos, M. Rahimi, in progress

LFU test with inclusive $B \to X\ell\nu$



- **Reconstruct**
  $\Upsilon(4S) \to B^-_{\text{tag}}\ell^+ X$
  $\Upsilon(4S) \to \bar{B}^0_{\text{tag}}\ell^+ X$
- **$p^*_\ell > 1.3$ GeV**
- **Only basic quality cuts on tracks and calorimeter signals**
- **Tight constraints on tag quality**

$\epsilon = \mathcal{O}(0.1\%)$

Precise knowledge of
B_{tag} kinematics

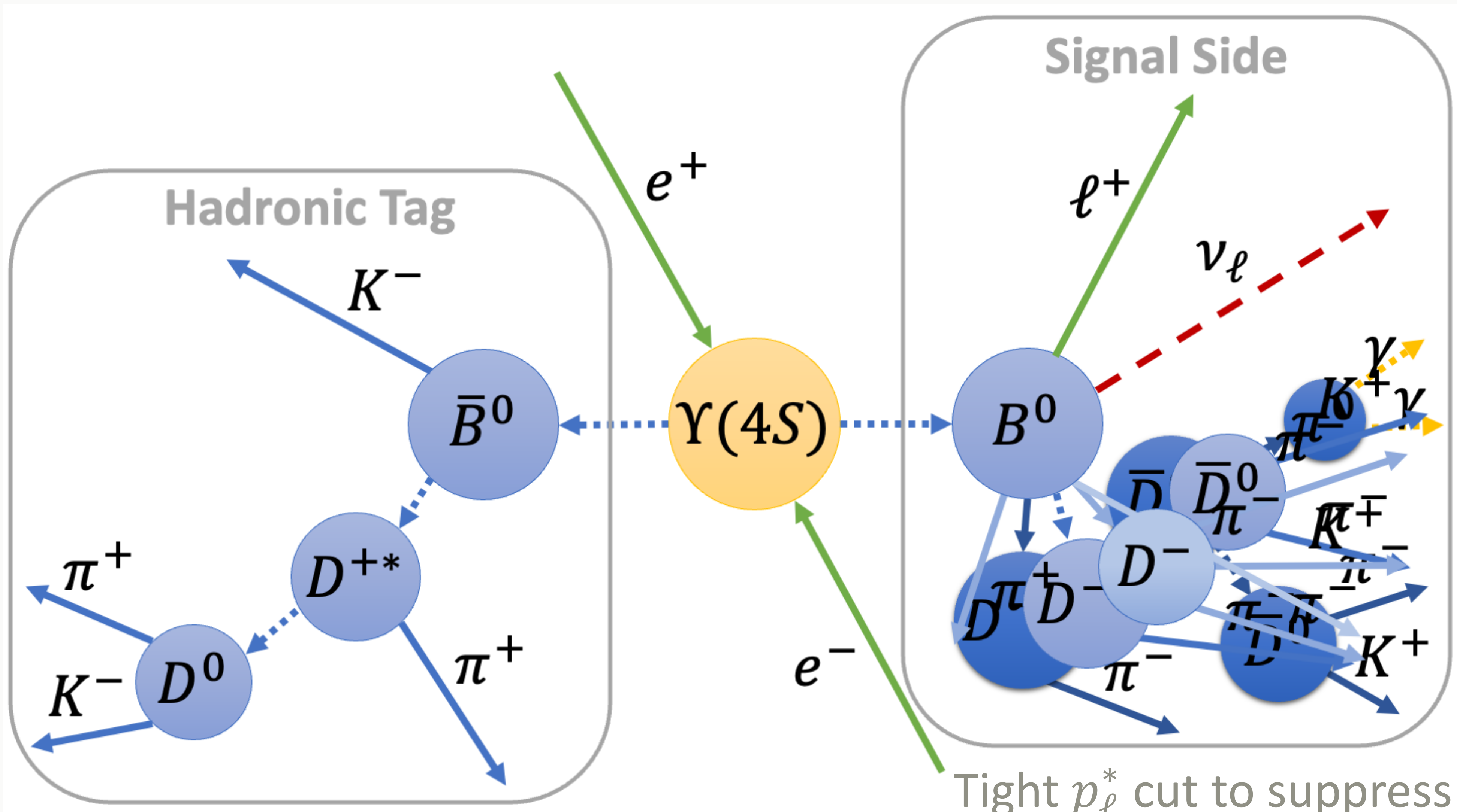
Tight p^*_ℓ cut to suppress

- hadrons faking leptons ("**fakes**")
- secondary leptons from $b \to c \to (\ell, s)$ cascades ("**secondaries**")
- $B \to X\tau\nu$

[53% (e) / 66% (μ) of selected B $\to X\ell\nu$ is retained]

slide taken from Belle II ICHEP2022 talk by H. Junkerkalefeld

LFU test with inclusive $B \to X\ell\nu$



$\epsilon = \mathcal{O}(0.1\%)$

Precise knowledge of B_{tag} kinematics

Tight p_ℓ^* cut to suppress

- hadrons faking leptons ("**fakes**")
- secondary leptons from $b \to c \to (\ell, s)$ cascades ("**secondaries**")
- $B \to X\tau\nu$

[53% (e) / 66% (μ) of selected B $\to X\ell\nu$ is retained]

- **Reconstruct**
  $\Upsilon(4S) \to B^-_{\text{tag}}\ell^+X$
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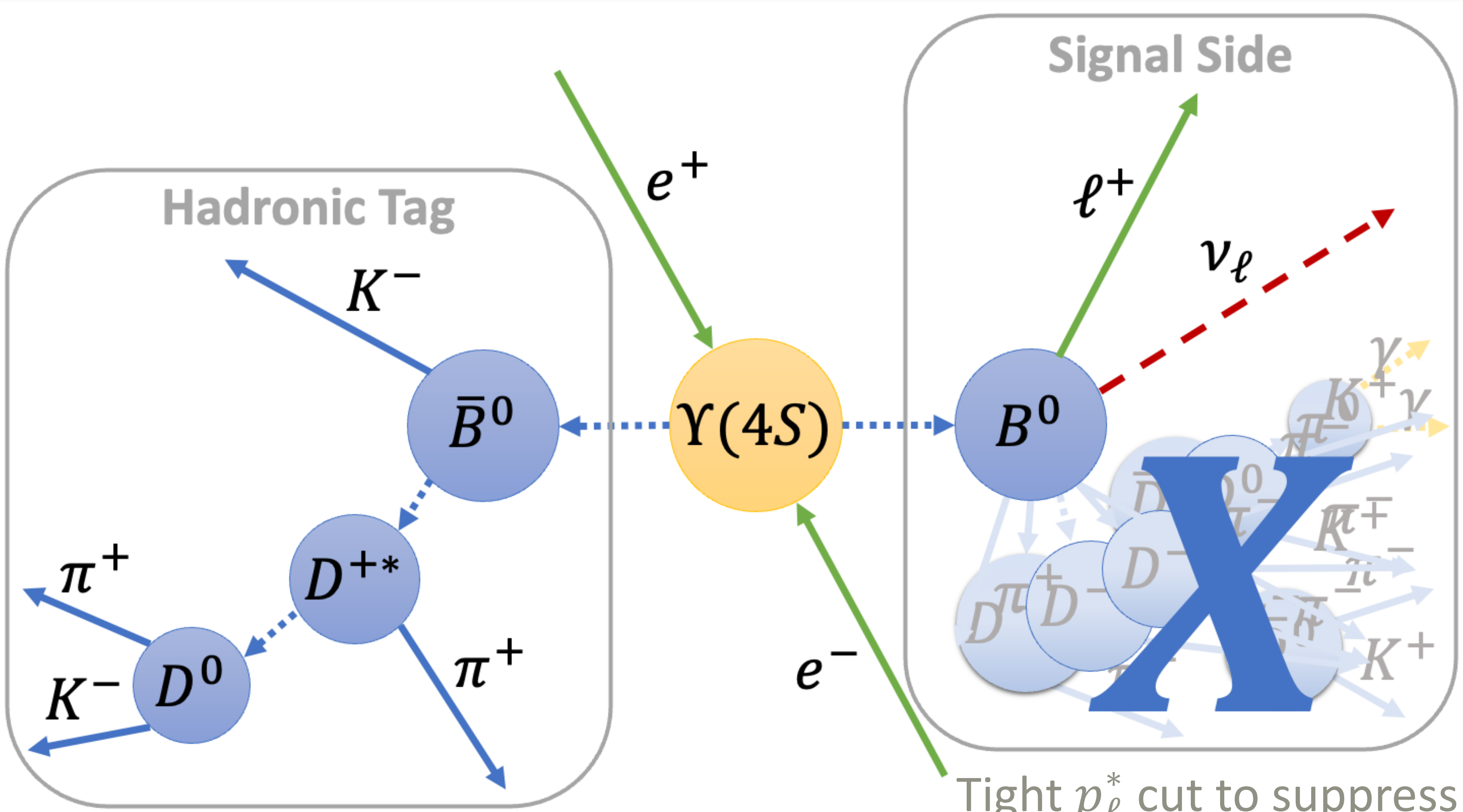
slide taken from Belle II ICHEP2022 talk by H. Junkerkalefeld

LFU test with inclusive $B \to X\ell\nu$



$\epsilon = \mathcal{O}(0.1\%)$

Precise knowledge of B_{tag} kinematics

Tight p_ℓ^* cut to suppress

- hadrons faking leptons ("**fakes**")
- secondary leptons from $b \to c \to (\ell, s)$ cascades ("**secondaries**")
- $B \to X\tau\nu$

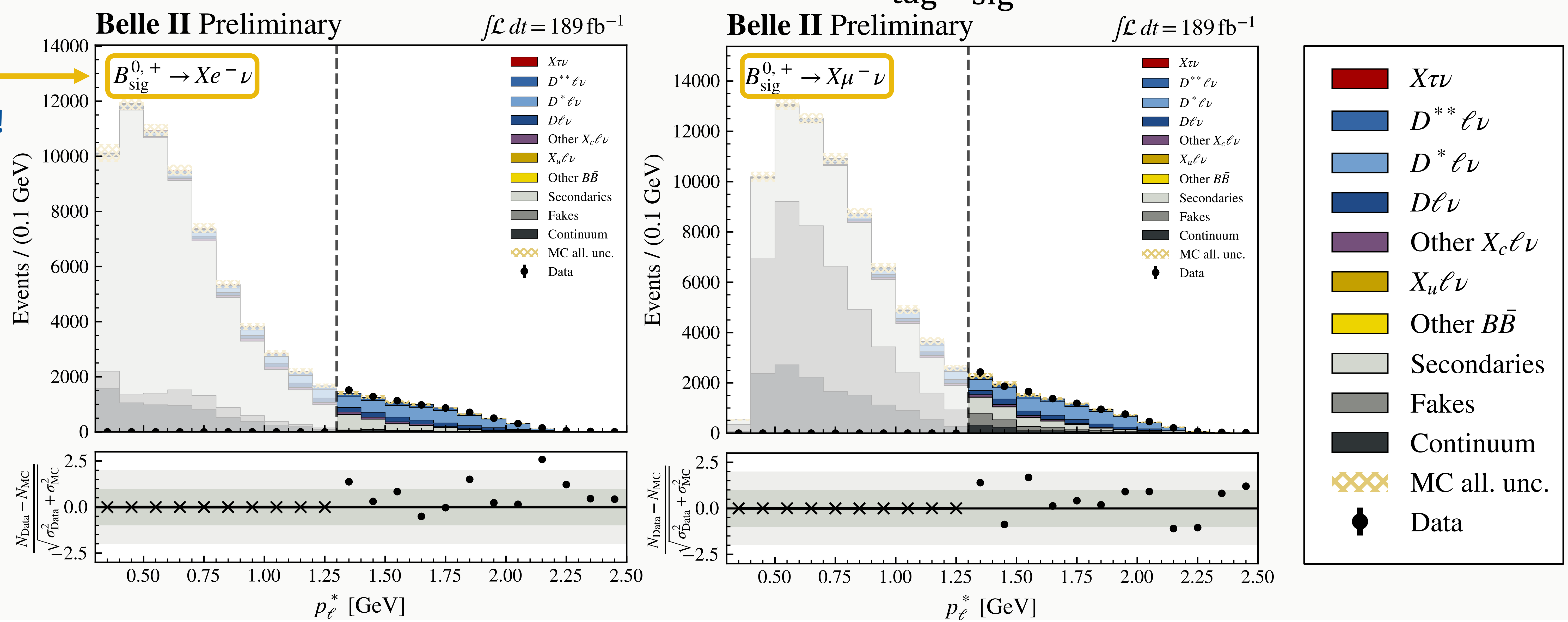
[53% (e) / 66% (μ) of selected B $\to X\ell\nu$ is retained]

- **Reconstruct** $\Upsilon(4S) \to B^-_{\text{tag}}\ell^+X$ $\Upsilon(4S) \to \bar{B}^0_{\text{tag}}\ell^+X$
- $p_\ell^* > 1.3$ **GeV**
- **Only basic quality cuts on tracks and calorimeter signals**
- **Tight constraints on tag quality**

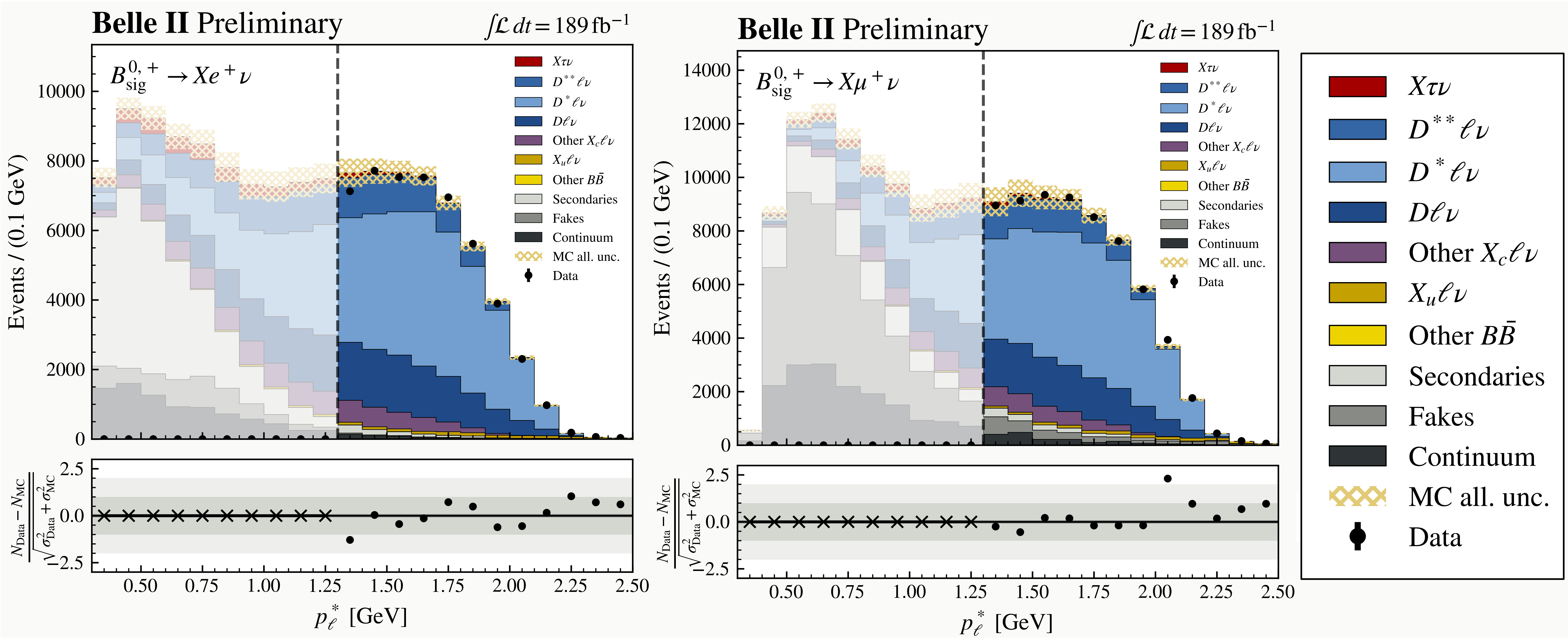
slide taken from Belle II ICHEP2022 talk by H. Junkerkalefeld

- **Fakes + secondaries** are normalized to data with correction factors derived from fits in the **"incorrect lepton charge"** control region: $\Upsilon(4S) \to B^{0,-}_{\mathrm{tag}} B^{0,+}_{\mathrm{sig}} (\to X \ell^- \nu) + \text{c.c.}$

Incorrect charge sideband!



LFU test with inclusive $B \to X\ell\nu$



Background is constrained by wrong-sign lepton charge samples (BU)

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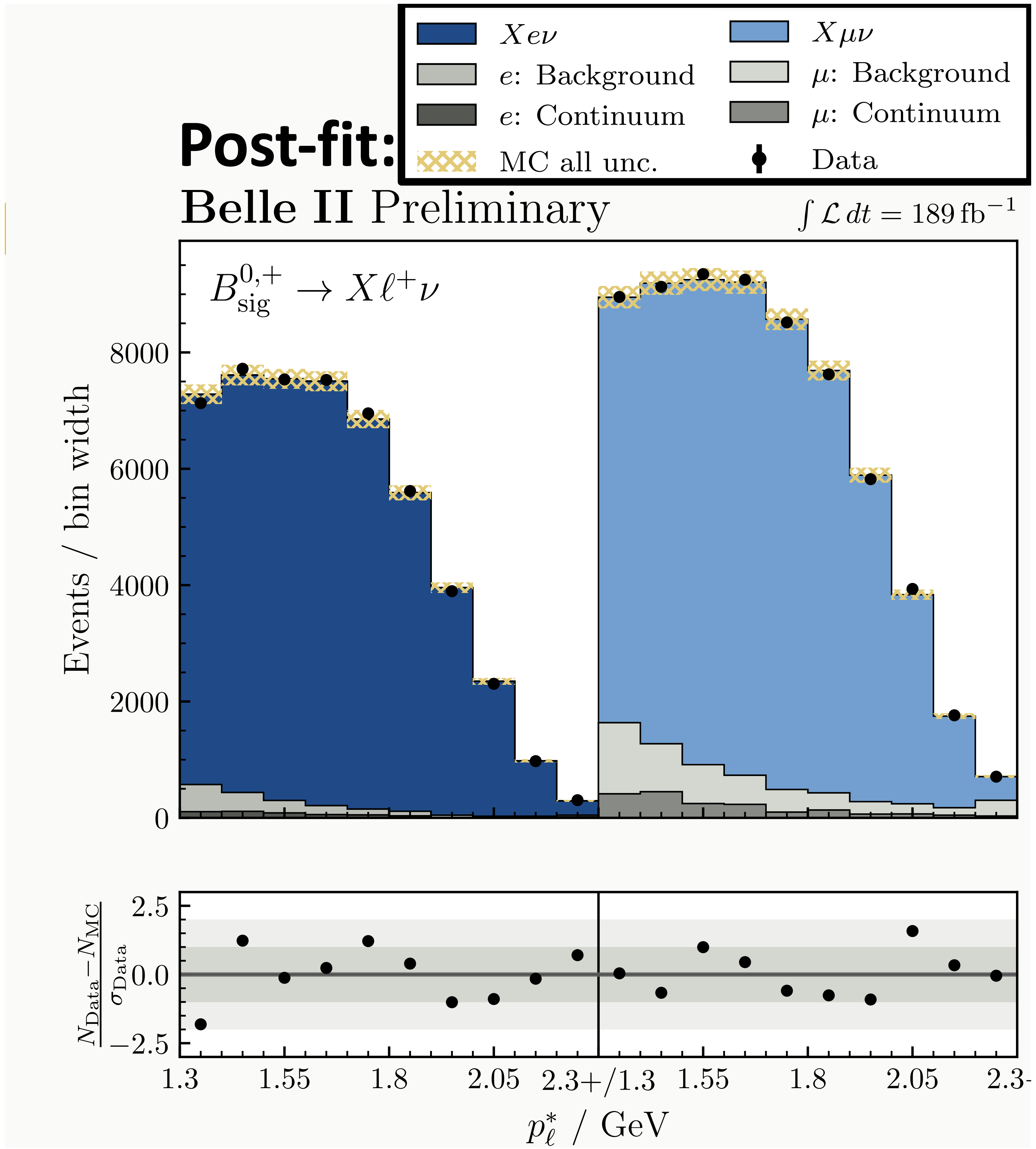
LFU test with inclusive $B \to X\ell\nu$

Post-fit:



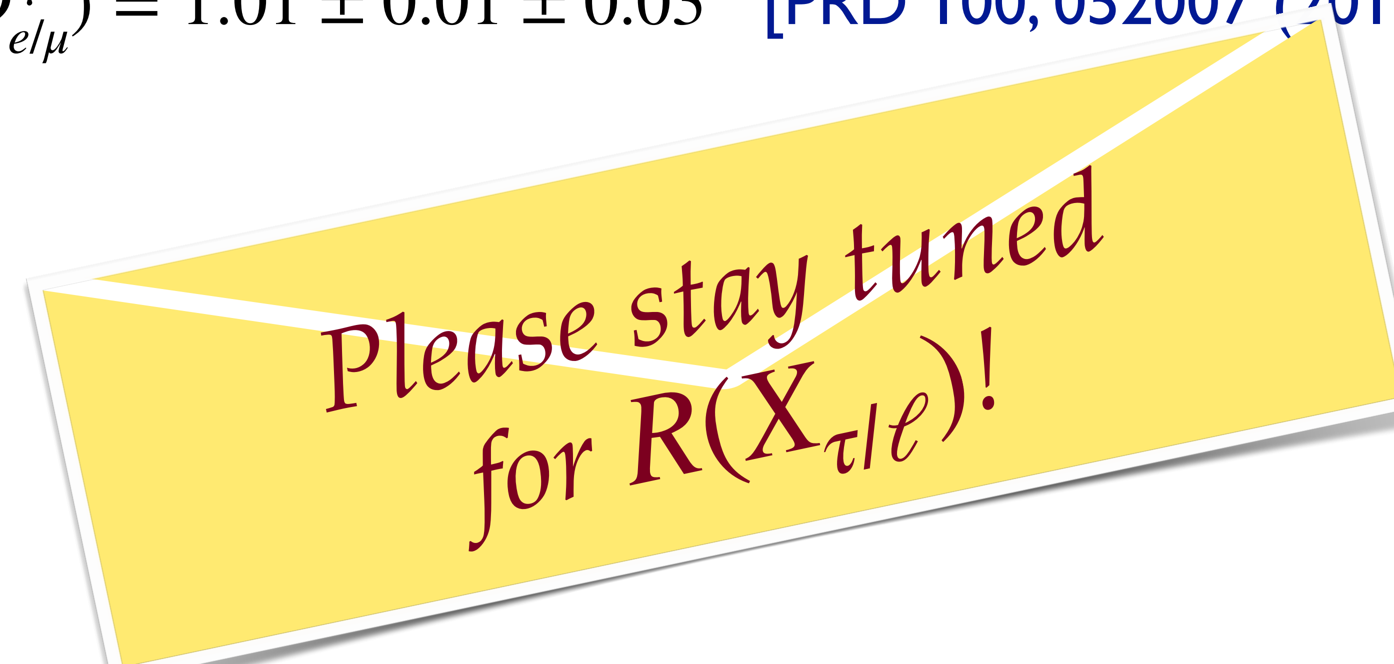
$$R(X_{e/\mu}) = \frac{N_{Xe\nu}\cdot\epsilon_{X\mu\nu}}{N_{X\mu\nu}\cdot\epsilon_{Xe\nu}} \quad \text{with}$$

$$\epsilon_{X\ell\nu} = \frac{N^{\ell}_{sel}\cdot(\epsilon^{data}_{B\,tag}/\epsilon^{MC}_{B\,tag})}{2\cdot N_{BB}\cdot BR(B\to X\ell\nu)}$$

$$R(X_{e/\mu})^{p^*_\ell>1.3} = 1.033 \pm 0.010 \pm 0.020$$

Source of uncertainty	Lepton ID	$X_c\ell\nu$ BFs	$X_c\ell\nu$ FFs	Statistical	Total
Rel. unc. of $R(X_{e/\mu})$	1.8%	0.1%	0.2%	1.0%	2.2%

compatible within 0.6σ with exclusive Belle measurement:
$R(D^*_{e/\mu}) = 1.01 \pm 0.01 \pm 0.03$ [PRD 100, 052007 (2019)]



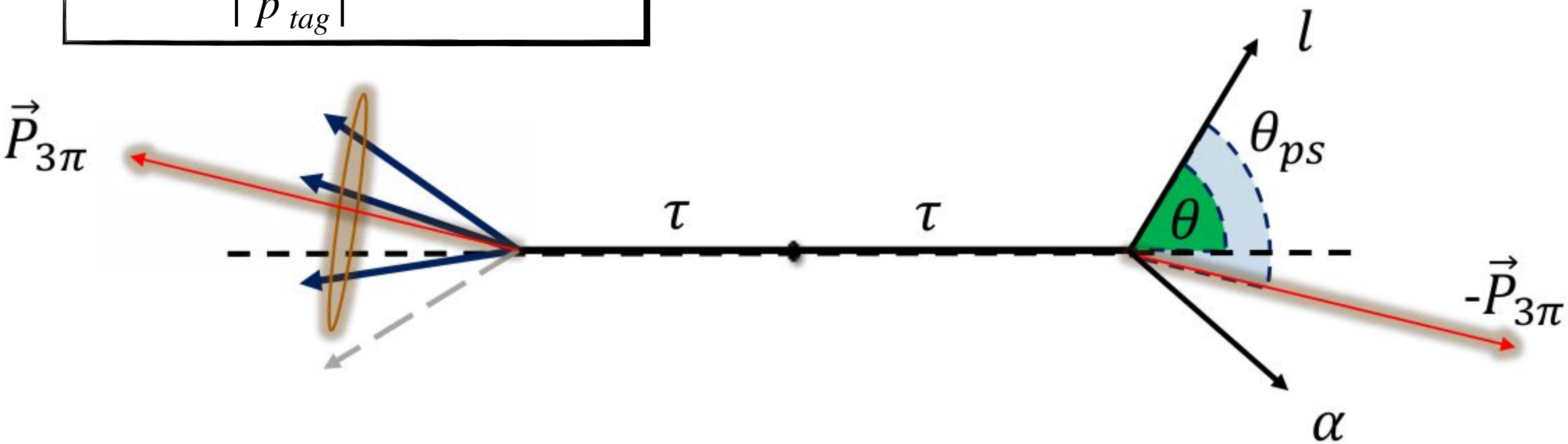
Semi-invisible τ decays

Belle II arXiv:2212.03634 (*to* PRL)

Search for $\tau \to \ell^+\alpha$

- for α being an ***invisible*** particle
- previous searches by Mark III (1985) and ARGUS (1995)
- event topology
  - ✓ 1-vs-3 (3-prong for tag side)
- τ pseudo-rest-frame by approx. $E_\tau^{\mathrm{CM}} \simeq \sqrt{s}/2$

$$\hat{p}_\tau \approx -\frac{\vec{p}_{tag}}{|\vec{p}_{tag}|}, \quad E_\tau \approx \sqrt{s}/2$$



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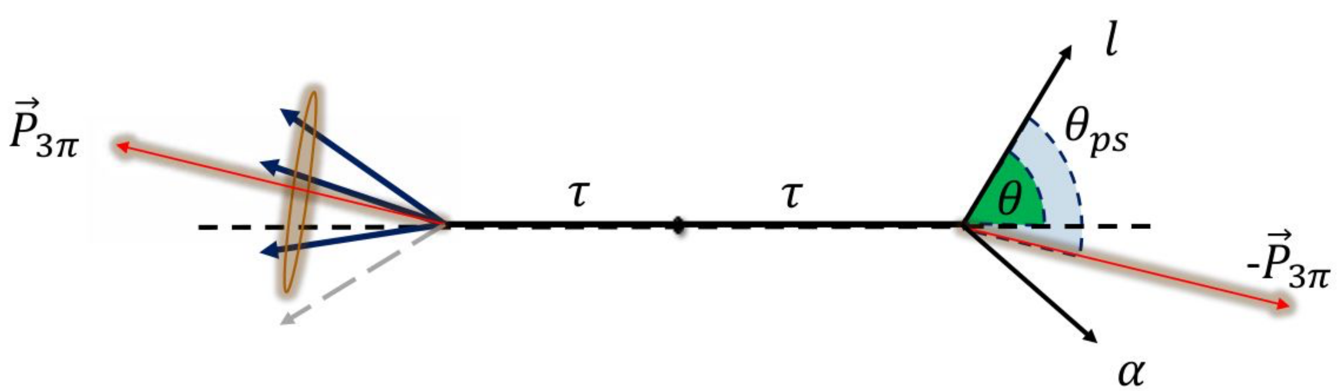
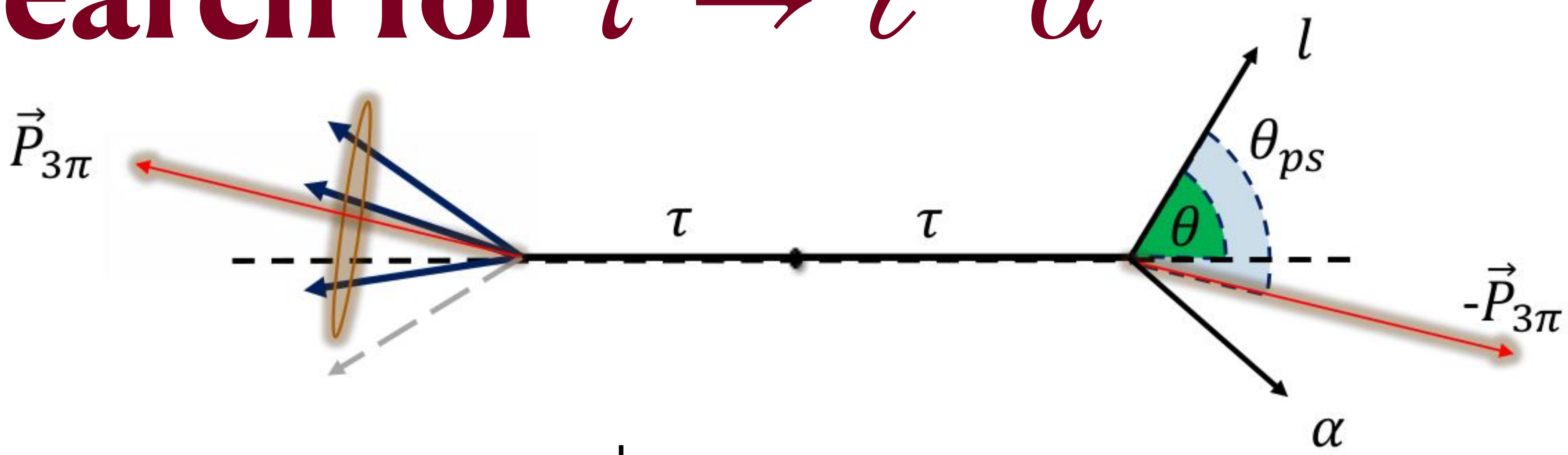


Table I: Requirements on event thrust, missing momentum polar angle, and tag hemisphere particles' total center-of-mass energy and mass.

	$\tau^- \to e^- \alpha$	$\tau^- \to \mu^- \alpha$
Thrust	$[0.90, 0.99]$	$[0.90, 1.00]$
θ_{miss}	$[20^\circ, 160^\circ]$	$[20^\circ, 160^\circ]$
E_{3h}^{CM}	$[1.2, 5.3]$ GeV	$[1.1, 5.3]$ GeV
M_{3h}	$[0.5, 1.7]$ GeV/c^2	$[0.4, 1.7]$ GeV/c^2

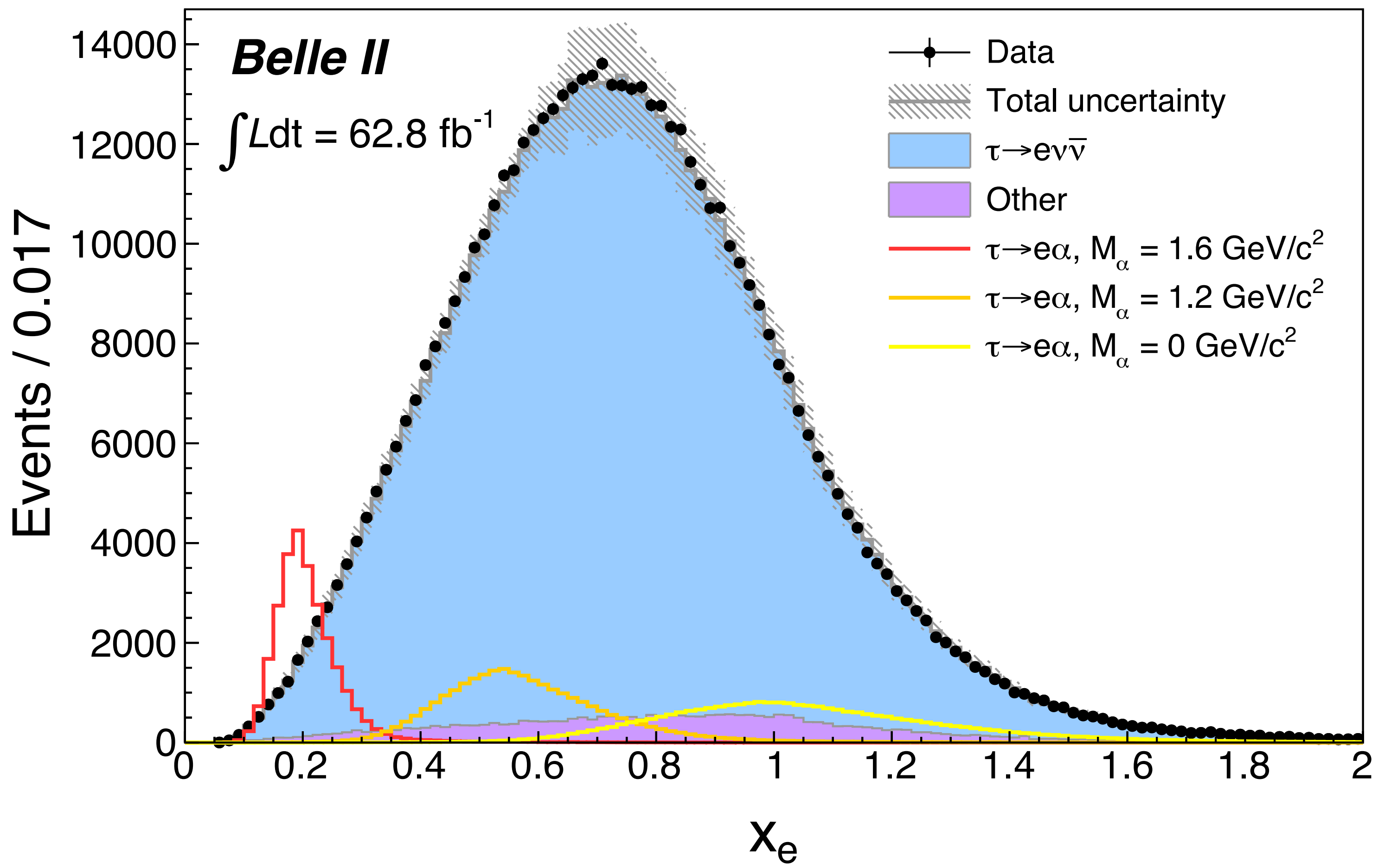
arXiv:2212.03634
submitted to PRL

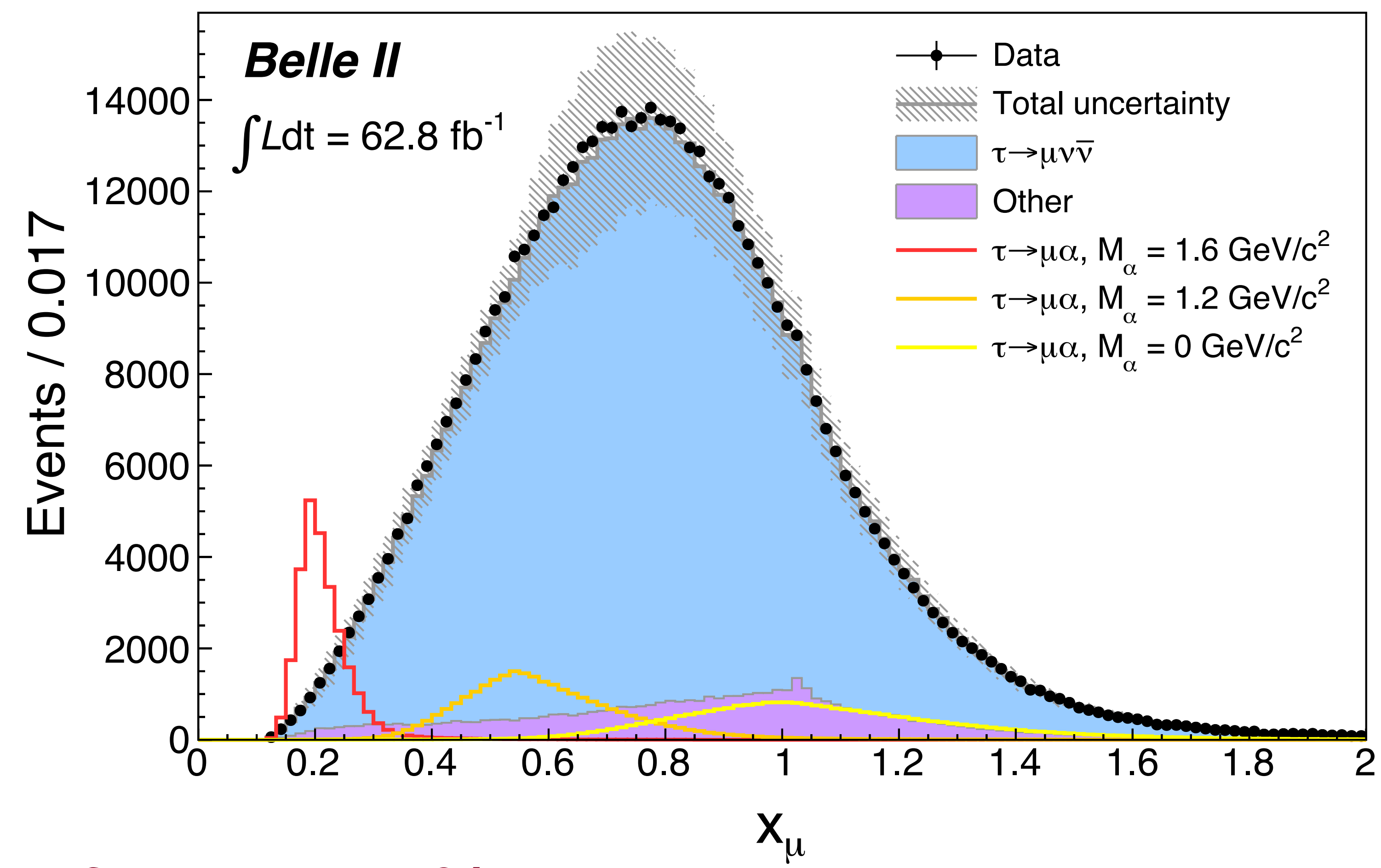
Search for $\tau \to \ell^+\alpha$



$$x_\ell \equiv \frac{E^*_\ell}{m_\tau c^2/2}$$

$\tau \to e^+\alpha$ $\tau \to \mu^+\alpha$





$\tau \to \ell\alpha$ shown for BF = 5%

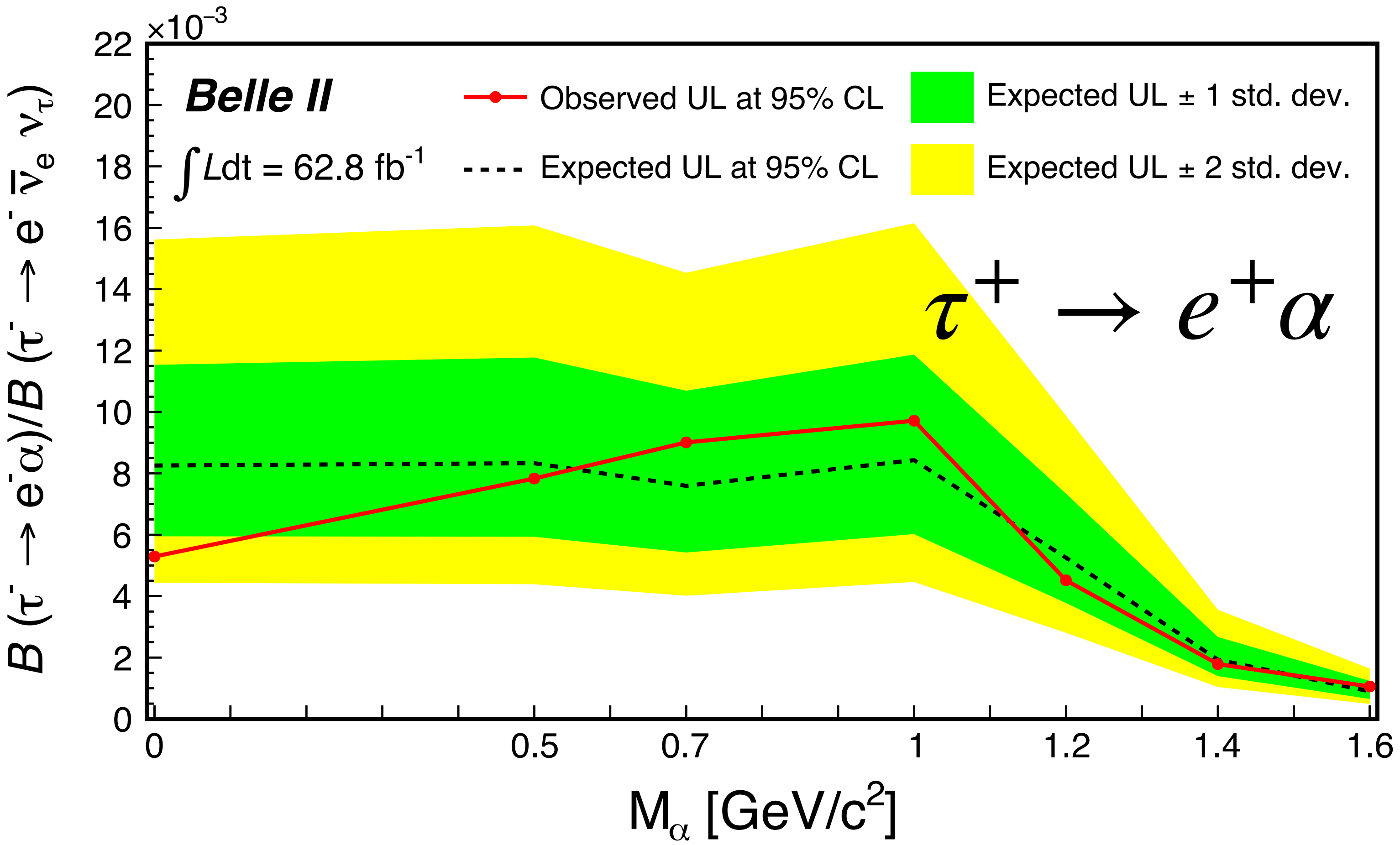
arXiv:2212.03634
submitted to PRL

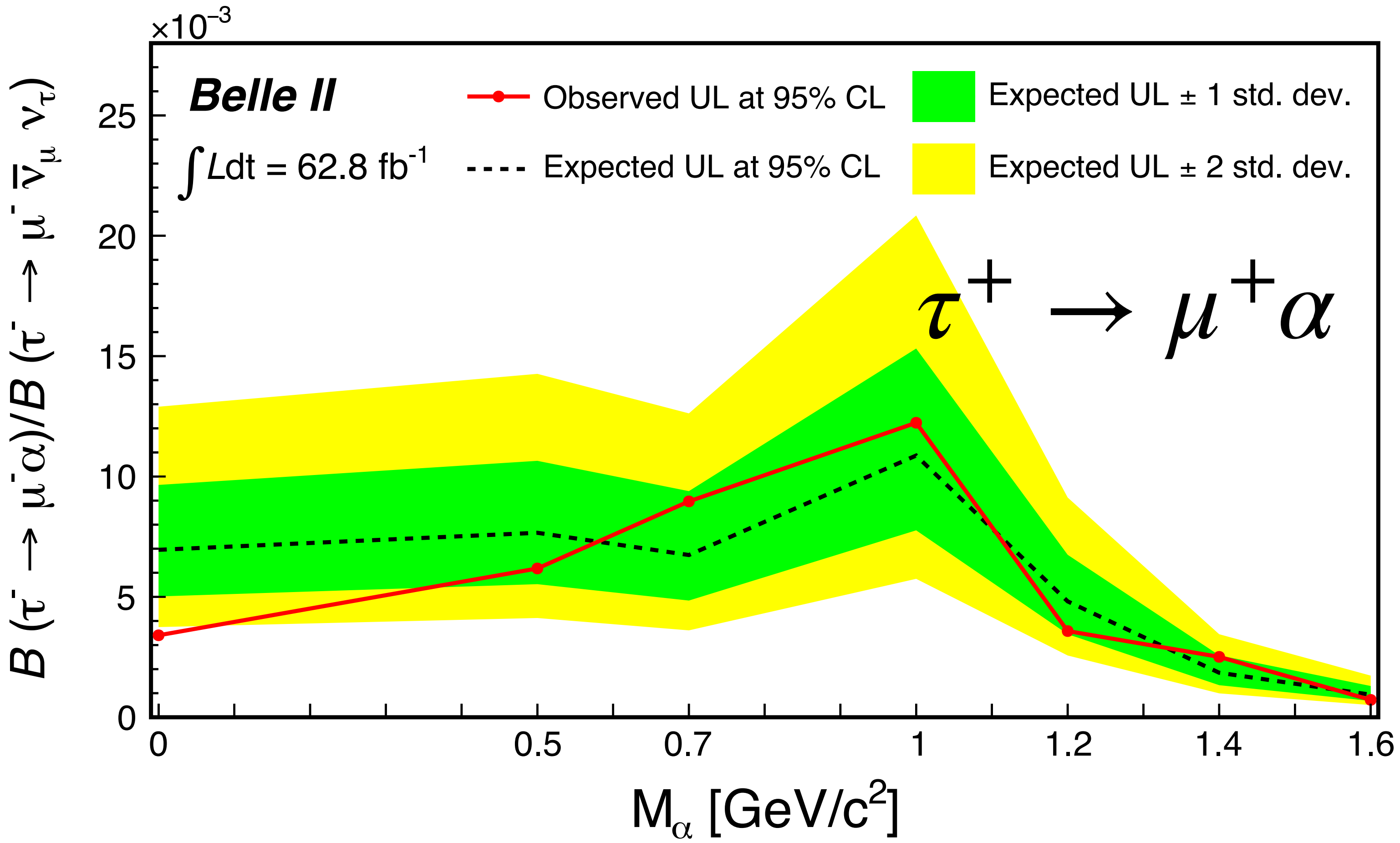
Results for $\tau \to \ell^+\alpha$

- We find no signal excess and set 95% CL upper limits on $\mathscr{B}(\tau \to \ell\alpha)/\mathscr{B}(\tau \to \ell\nu\bar{\nu})$

$\mathcal{B}(\tau \to \mu\nu\bar{\nu}) = (17.39 \pm 0.04)\%$

- Most stringent limits in these channels to date





Results for $\tau \to \ell^+\alpha$

- We find no signal excess and set 95% CL upper limits on $\mathscr{B}(\tau \to \ell\alpha)/\mathscr{B}(\tau \to \ell\nu\bar{\nu})$

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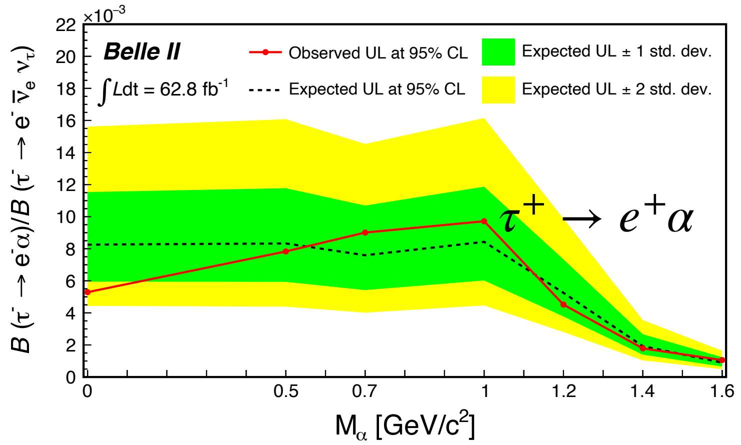
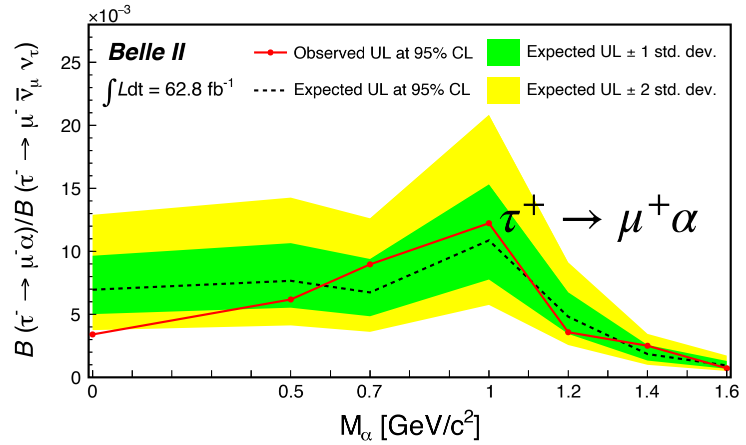


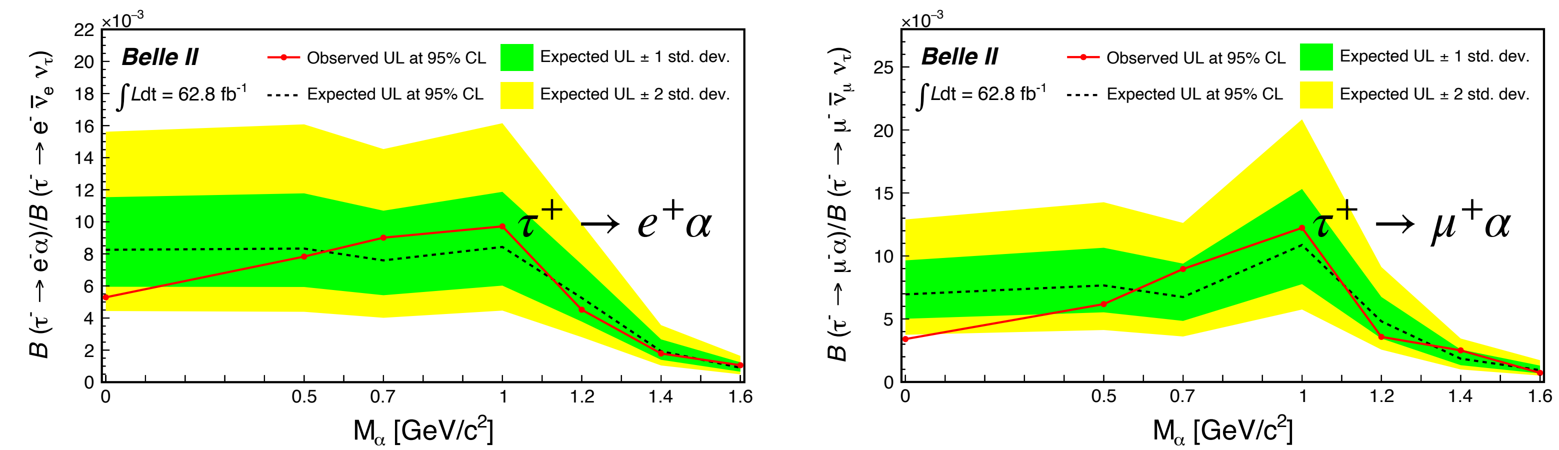


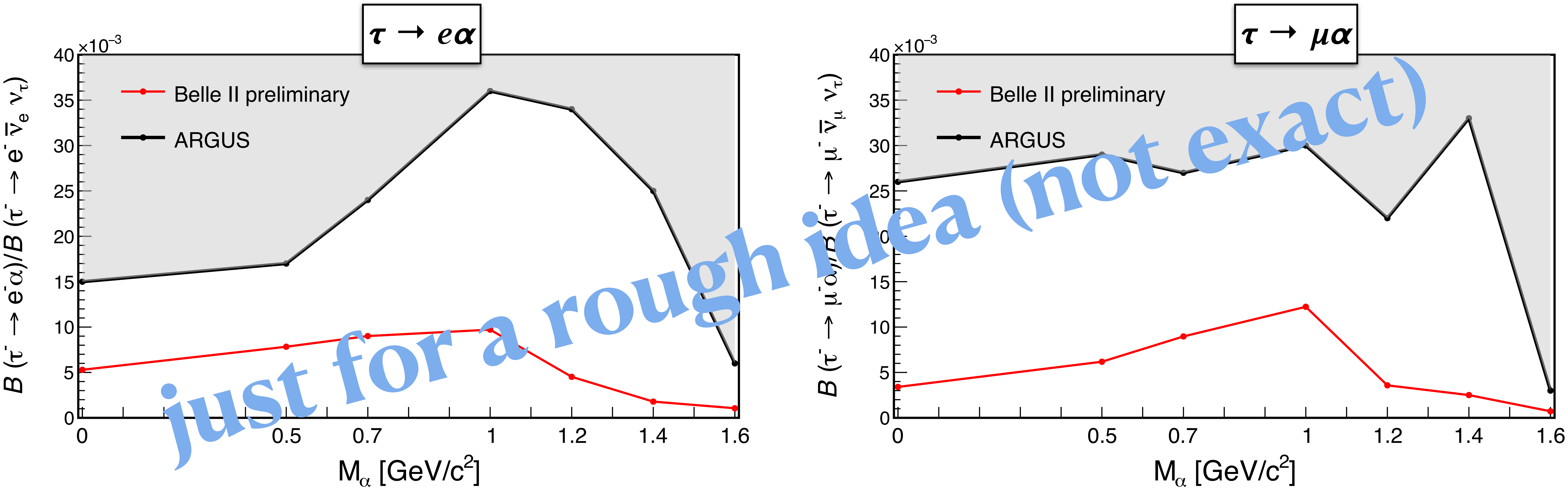
M_α [GeV/c^2]	$\mathcal{B}_{e\alpha}/\mathcal{B}_{e\bar{\nu}\nu}$ ($\times 10^{-3}$)	UL at 95% CL ($\times 10^{-3}$)	UL at 90% CL ($\times 10^{-3}$)
0.0	-8.1 ± 3.9	5.3 (0.94)	4.3 (0.76)
0.5	-0.9 ± 4.3	7.8 (1.40)	6.5 (1.15)
0.7	1.7 ± 4.0	9.0 (1.61)	7.6 (1.36)
1.0	1.7 ± 4.2	9.7 (1.73)	8.2 (1.47)
1.2	-1.1 ± 2.6	4.5 (0.80)	3.7 (0.66)
1.4	-0.3 ± 1.0	1.8 (0.32)	1.5 (0.26)
1.6	0.2 ± 0.5	1.1 (0.19)	0.9 (0.16)

M_α [GeV/c^2]	$\mathcal{B}_{\mu\alpha}/\mathcal{B}_{\mu\bar{\nu}\nu}$ ($\times 10^{-3}$)	UL at 95% CL ($\times 10^{-3}$)	UL at 90% CL ($\times 10^{-3}$)
0.0	-9.4 ± 3.7	3.4 (0.59)	2.7 (0.47)
0.5	-3.2 ± 3.9	6.2 (1.07)	5.1 (0.88)
0.7	2.7 ± 3.4	9.0 (1.56)	7.8 (1.35)
1.0	1.7 ± 5.4	12.2 (2.13)	10.3 (1.80)
1.2	-0.2 ± 2.4	3.6 (0.62)	2.9 (0.51)
1.4	0.9 ± 0.9	2.5 (0.44)	2.2 (0.38)
1.6	-0.3 ± 0.5	0.7 (0.13)	0.6 (0.10)

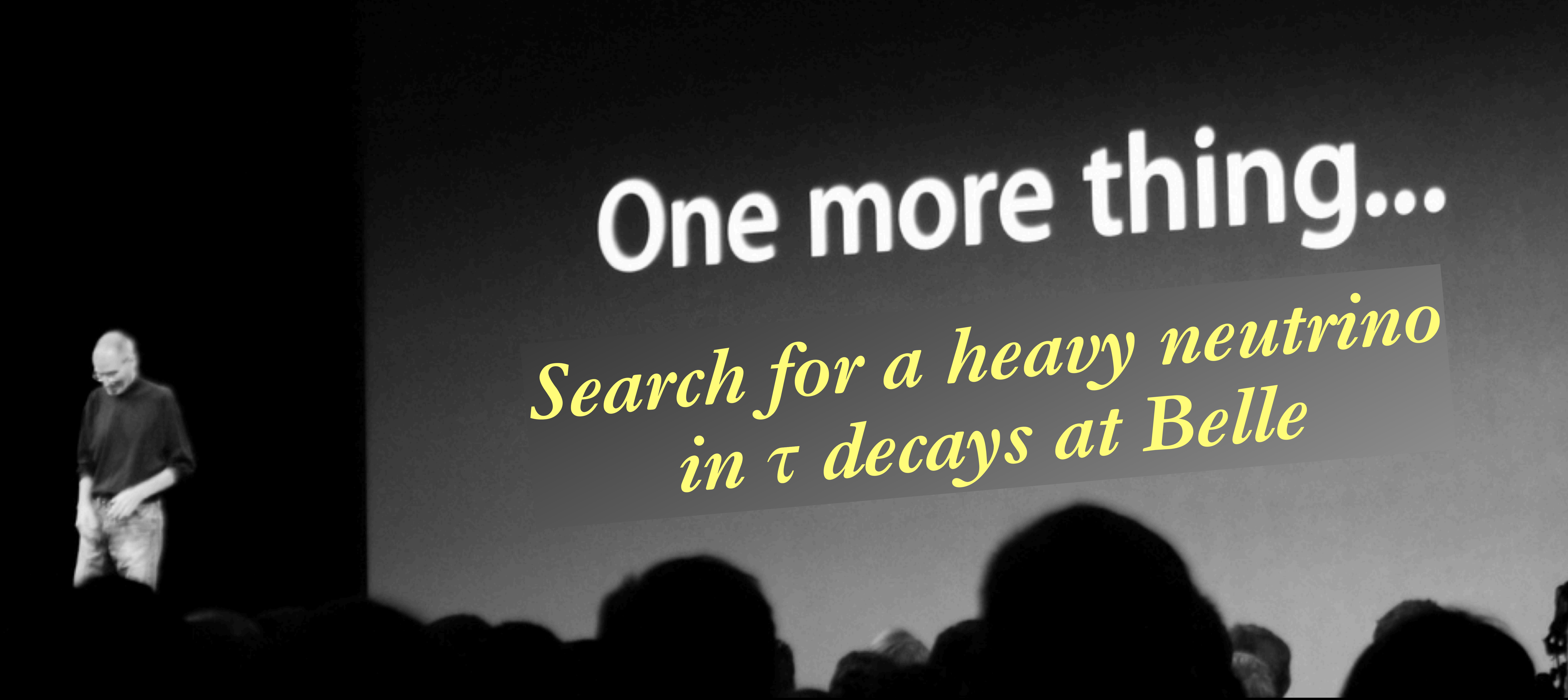
arXiv:2212.03634
submitted to PRL

Results for $\tau \to \ell^+\alpha$ — compared with old



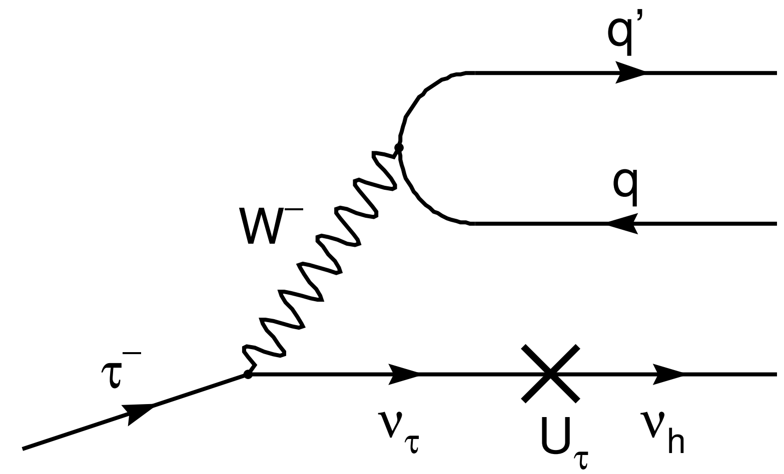


just for a rough idea (not exact)


One more thing...
Search for a heavy neutrino in τ decays at Belle

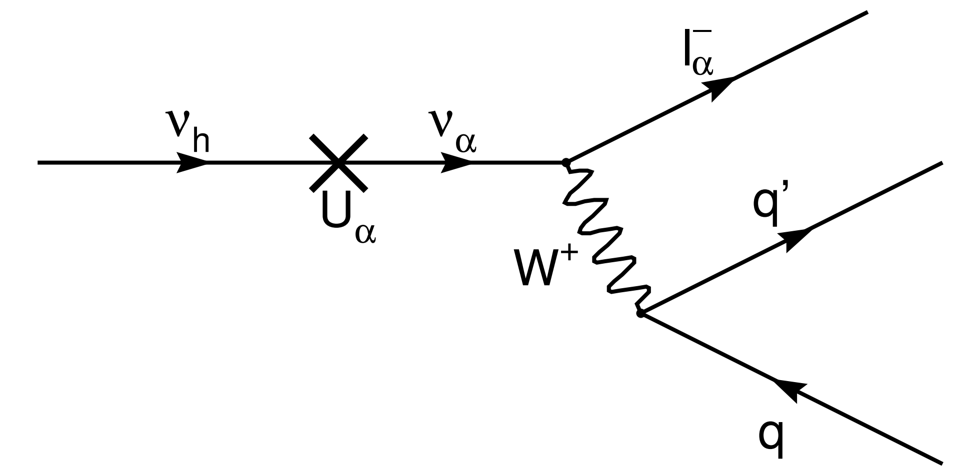
$\tau^- \to \pi^- \nu_h \ (\nu_h \to \pi^\pm \ell^\mp)$

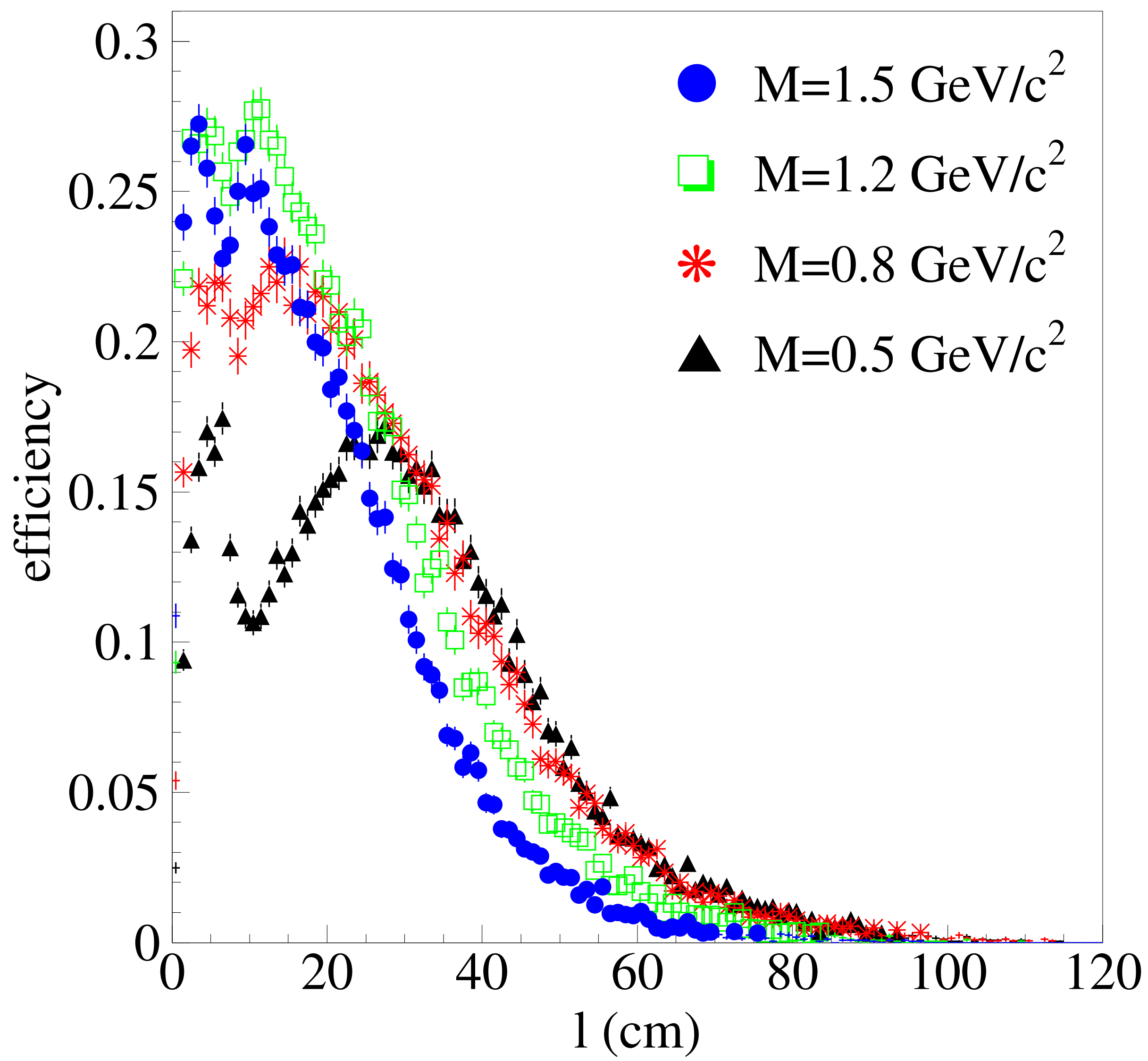
- Full Belle sample of 988 fb^{-1} $(N_{\tau\tau} = (912 \pm 13) \times 10^6)$
- Use $M(\pi_p \pi \ell)$ vs. $\Delta E \left(= E_{\pi_p\pi\ell} - \sqrt{s} \right)$



$\tau^- \to \pi_p^- \nu_h$

$\nu_h \to \pi^\pm \ell^\mp$





$$n(\nu_h) = 2N_{\tau\tau}\ \mathcal{B}(\tau \to \pi\nu_h)\ \mathcal{B}(\nu_h \to \pi\ell)\ \frac{m\Gamma}{p} \int \exp\left(-\frac{m\Gamma l}{p}\right)\varepsilon(m,l)dl$$
$$= |U_\tau|^2|U_\alpha|^2\ 2N_{\tau\tau}\ f_1(m)\ f_2(m)\ \frac{m}{p} \int \exp\left(-\frac{m\Gamma l}{p}\right)\varepsilon(m,l)dl,$$

FIG. 2. Dependence of the HNL reconstruction efficiency on the neutrino travel distance l for different neutrino masses $M(\nu_h)$. Efficiency is almost identical for e and μ.

$\tau^- \to \pi^- \nu_h \ (\nu_h \to \pi^\pm \ell^\mp)$ ***Results***

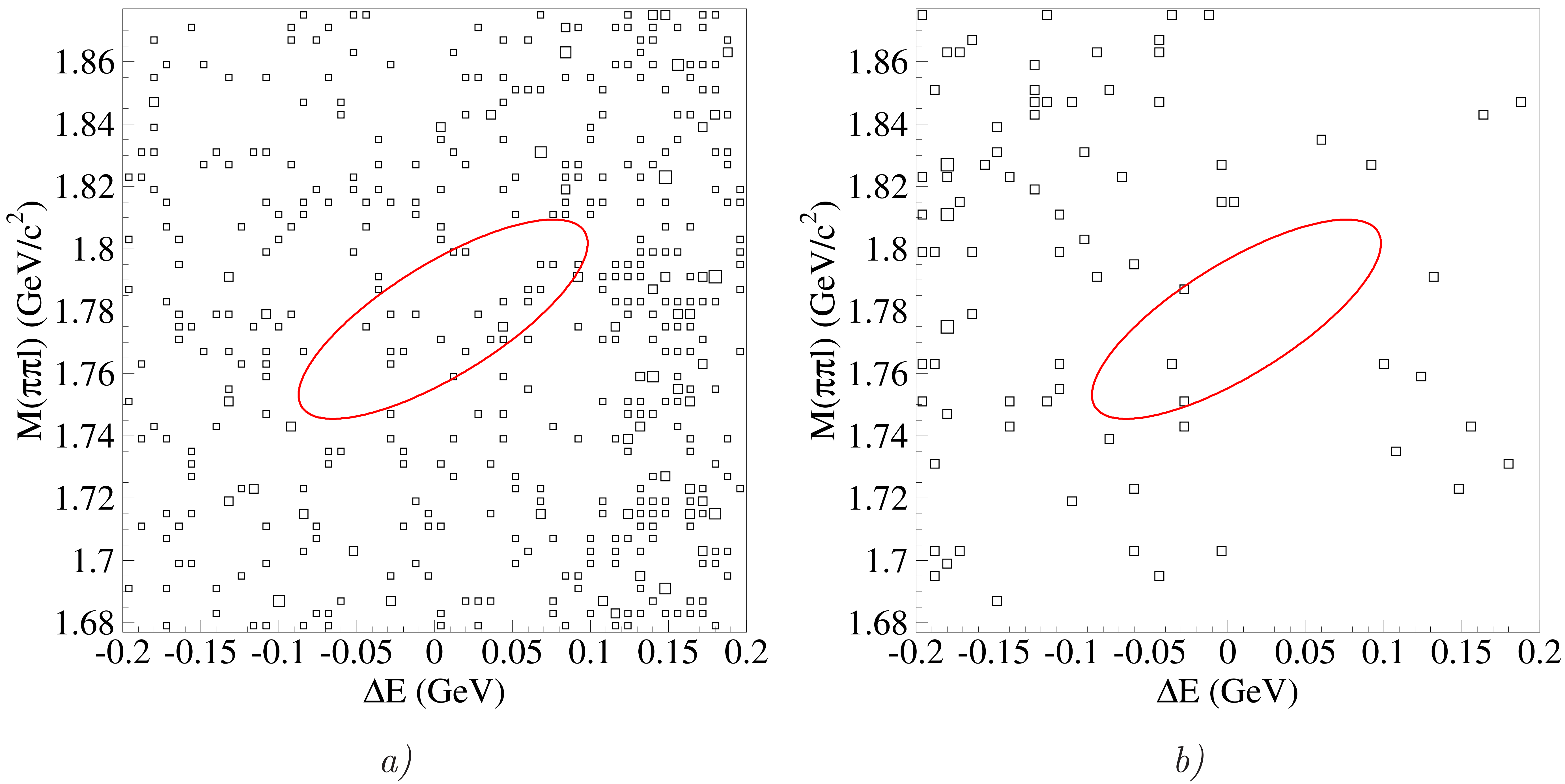


FIG. 3. ΔE vs $M(\pi\pi\ell)$ distributions with all requirements but ΔE and $M(\pi\pi\ell)$ imposed for $\pi\pi e$ *(a)* and $\pi\pi\mu$ *(b)* in data. The signal region is shown as a red ellipse.

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submitted to PRL

$\tau^- \to \pi^- \nu_h \; (\nu_h \to \pi^\pm \ell^\mp)$ *Results*

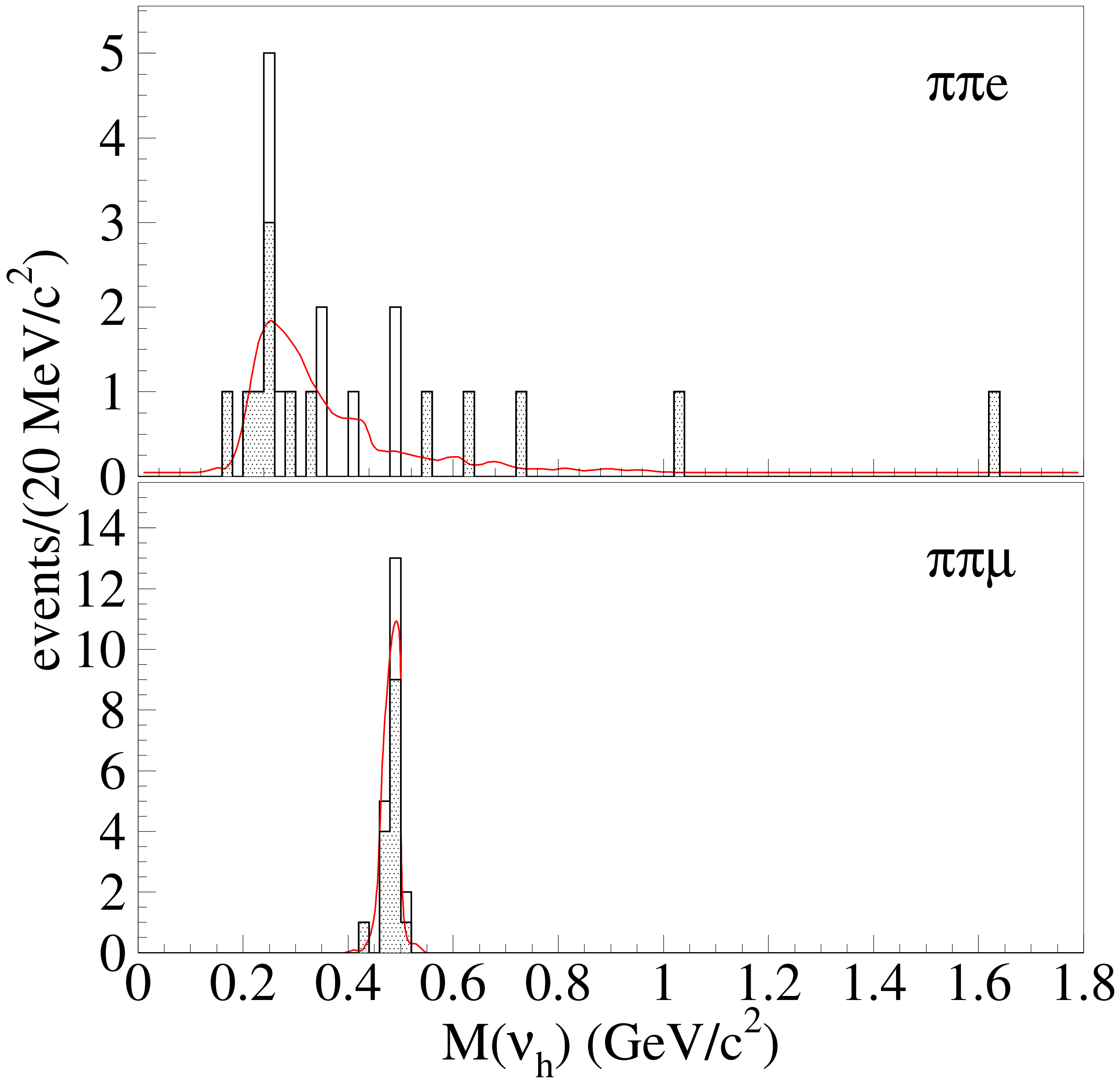


FIG. 4. Final distributions of $M(\nu_h)$ for $\pi\pi e$ and $\pi\pi\mu$ reconstruction modes in data. The filled histograms are for candidates with

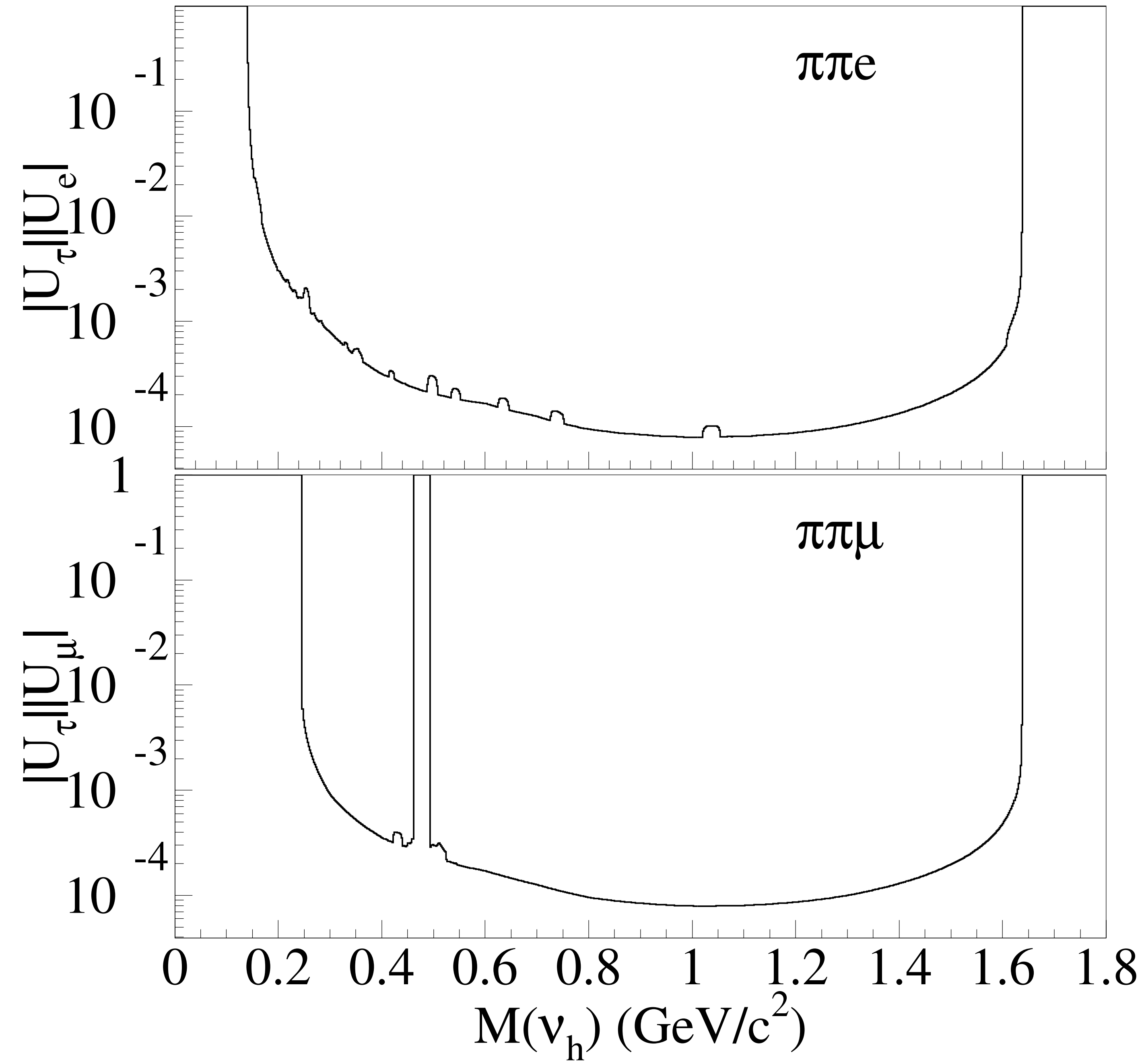


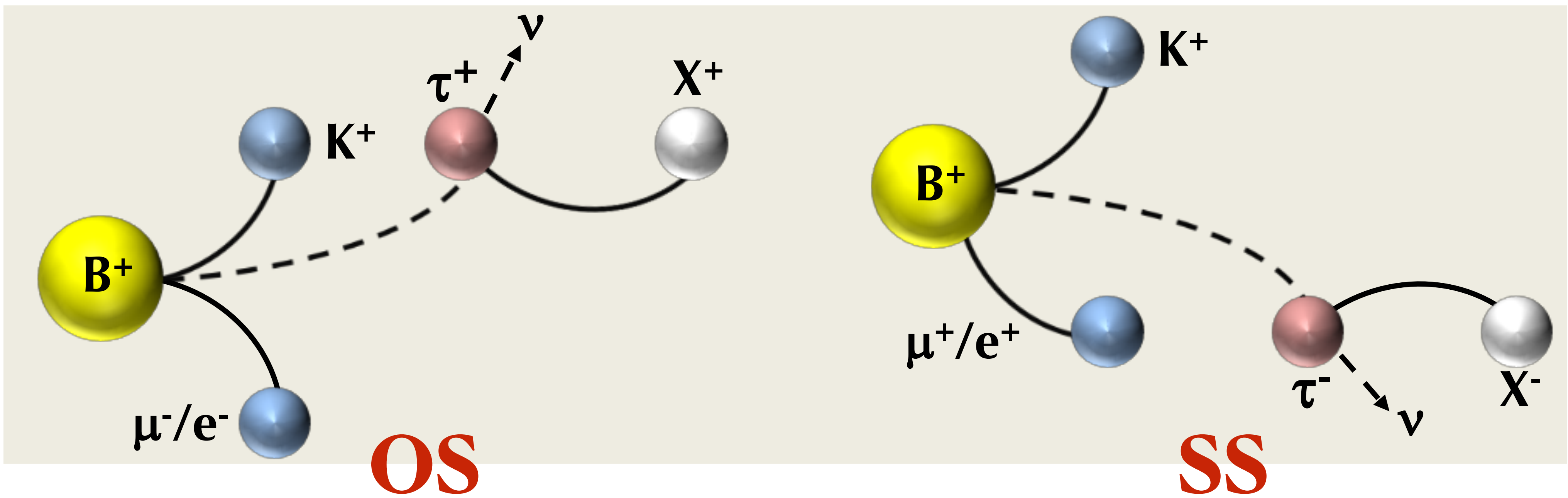
FIG. 5. Upper limits at 90% CL on $|U_\tau||U_e|$ and $|U_\tau||U_\mu|$.

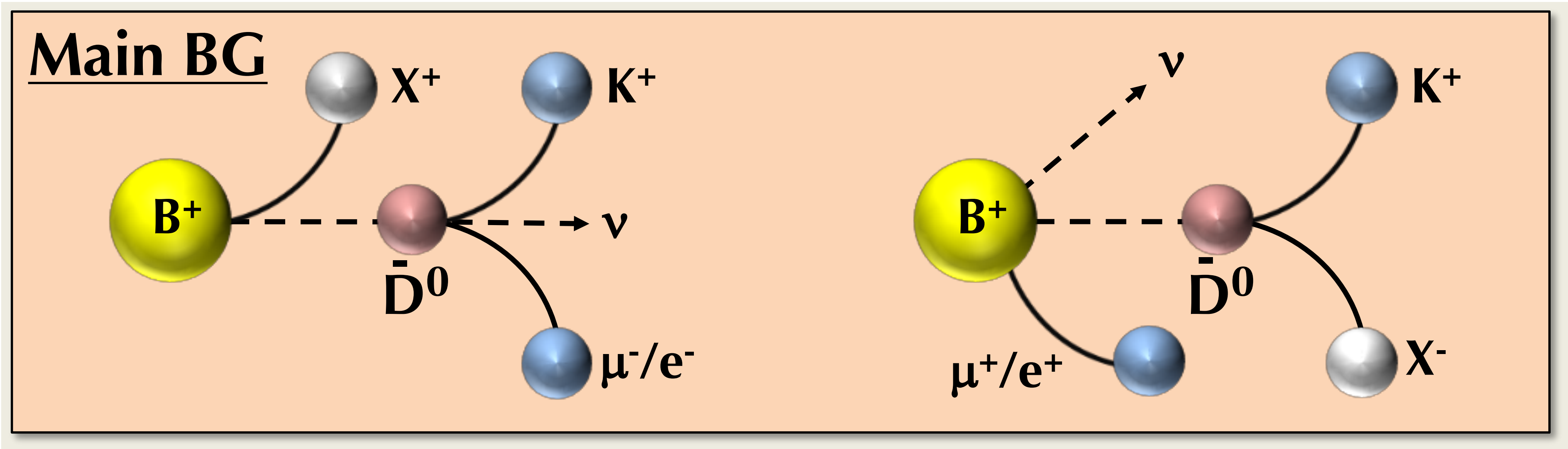
Closing remarks

- After > 12 years since shut-down, Belle is still producing > 20 papers per year.
- In 2022, there was a tentative interruption (due to …) of paper publication, but now it is resumed with ORCID.
- Belle II has collected data sample of $\sim 430\ \mathrm{fb}^{-1}$, and currently in Long Shutdown 1. Combining Belle & Belle II, we have $\sim 1.1\ \mathrm{ab}^{-1}$ at $\Upsilon(4S)$. Analyses based on combined data set will become more active.
- Please stay tuned for more news in semi-invisible *B* decays from Belle II.

Back-up slides

$B^+ \to K^+\tau^+\ell^-$ (OS) vs. $B^+ \to K^+\tau^-\ell^+$ (SS)





- We must do both (*if only for model independent search*)
- same reconstruction, but very different bkgd.
- Background for SS is much harder to handle