Higgsstrahlung, Invisible particles

at Belle & Belle II

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Dec. 16, 2022 @ Higgs and Cosmology Connection,YAFK SCP

Overview — a la my original plan

- Intro.
  - Belle & Belle II
- Dark photon via Higgsstrahlung
- Leptophilic Z' to invisible
- Invisibles in B decays
- Invisibles in τ decays

But, on Tuesday, we have heard

New approaches to semi-invisible τ and B decays

Chan Beom Park

- We devise a novel search strategy that we apply to pair productions of τ and B mesons,

$$\tau \to \ell\phi \quad (\phi: \text{ light invisible particle, } m_\phi \text{ in MeV–GeV})$$
$$B \to K\tau\mu \quad (\text{rare } B \text{ decay})$$

  at Belle II.

- Our strategy has a vast domain of applicability: $B \to K\nu\nu$, $B \to \tau\mu$, etc. at Belle II and LHCb.

Overview — *revised*

New approaches to semi-invisible τ and B decays

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- Intro.
  - Belle & Belle II
- A' via Higgsstrahlung & Z' ➔ invisible
- Invisibles in B decays along w/ $B \to K\tau\ell$, $B \to K\nu\bar{\nu}$
- Semi-invisible τ decay $\tau \to \ell\alpha$
- *one more thing!*

Belle & Belle II

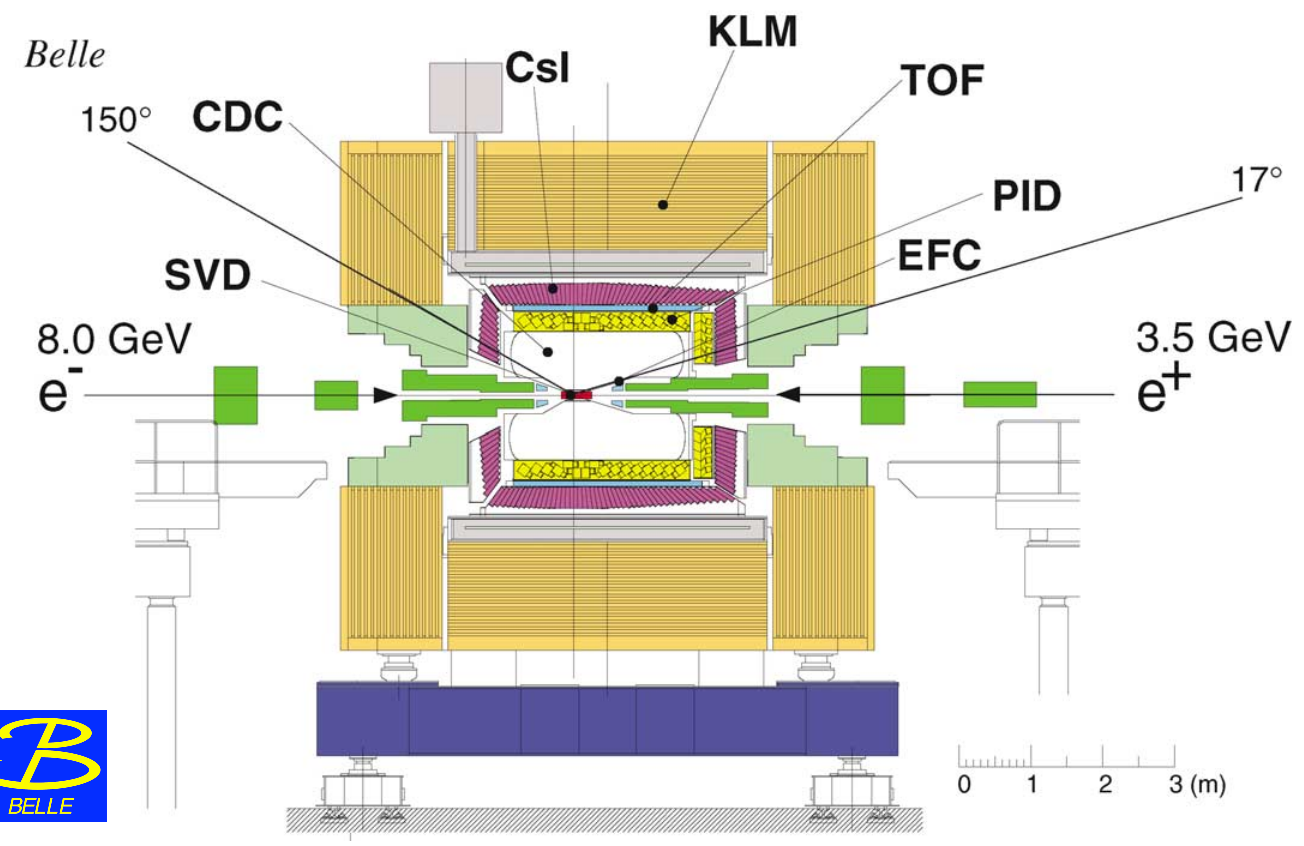
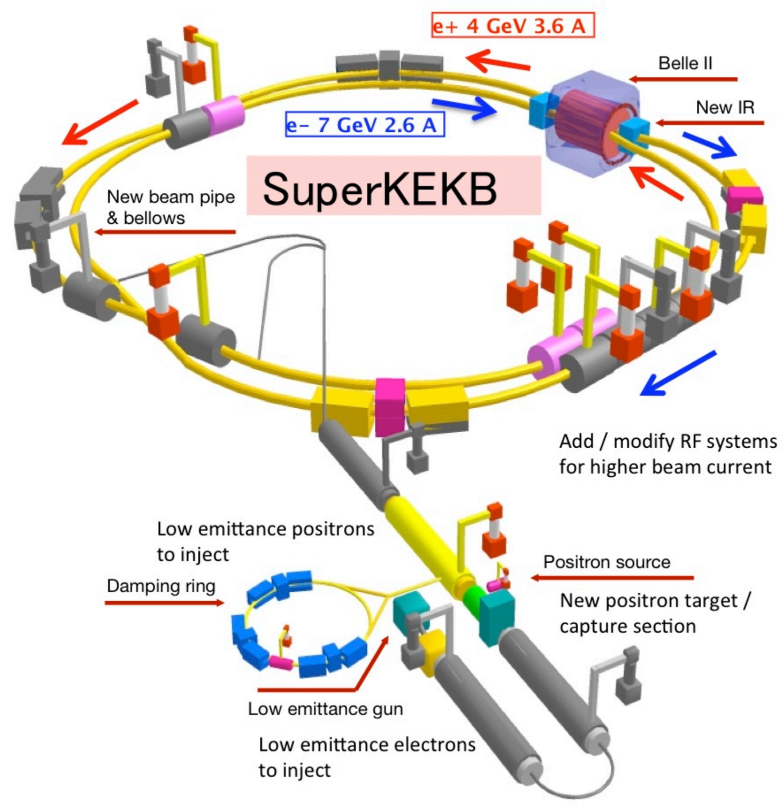
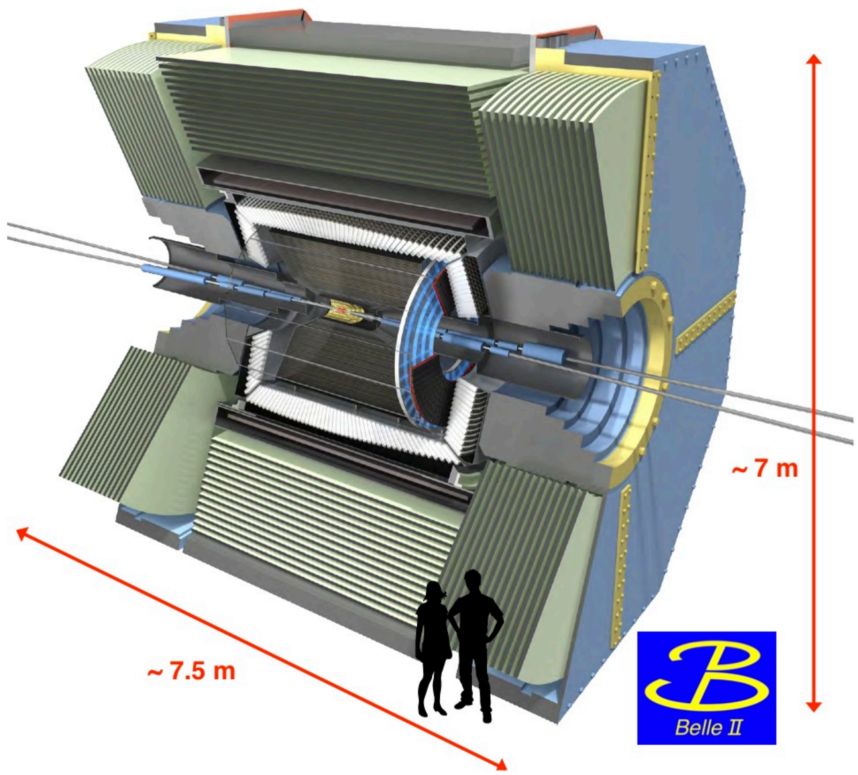


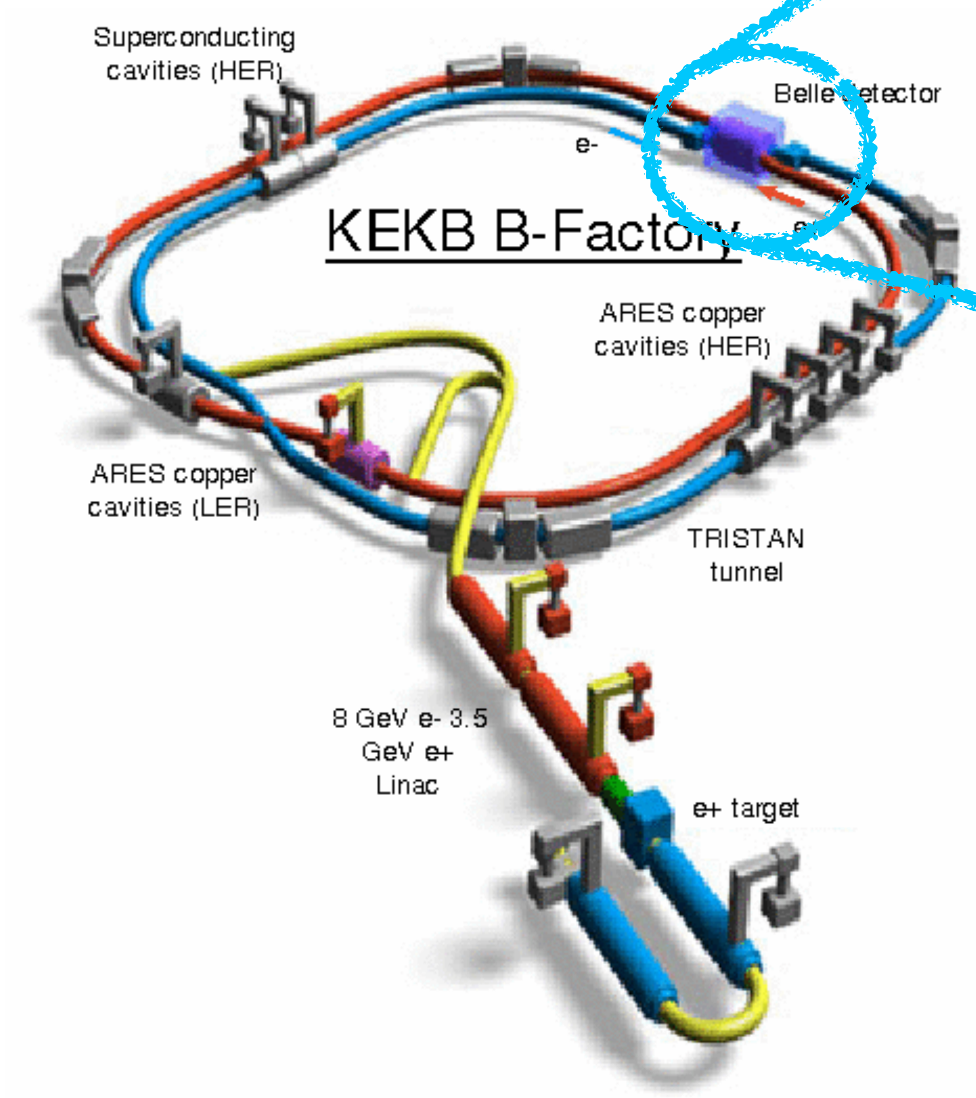
Fig. 1. Side view of the Belle detector.



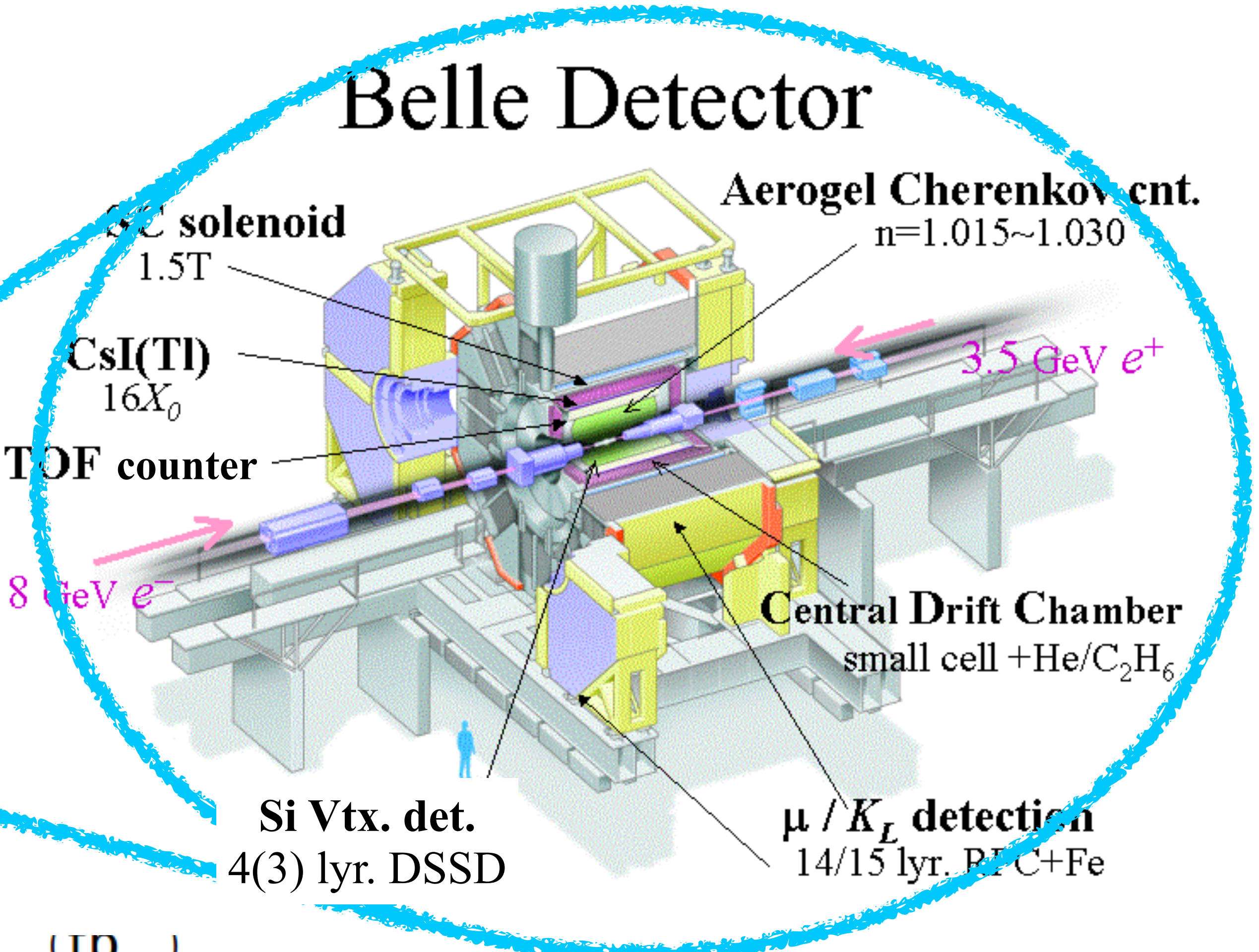


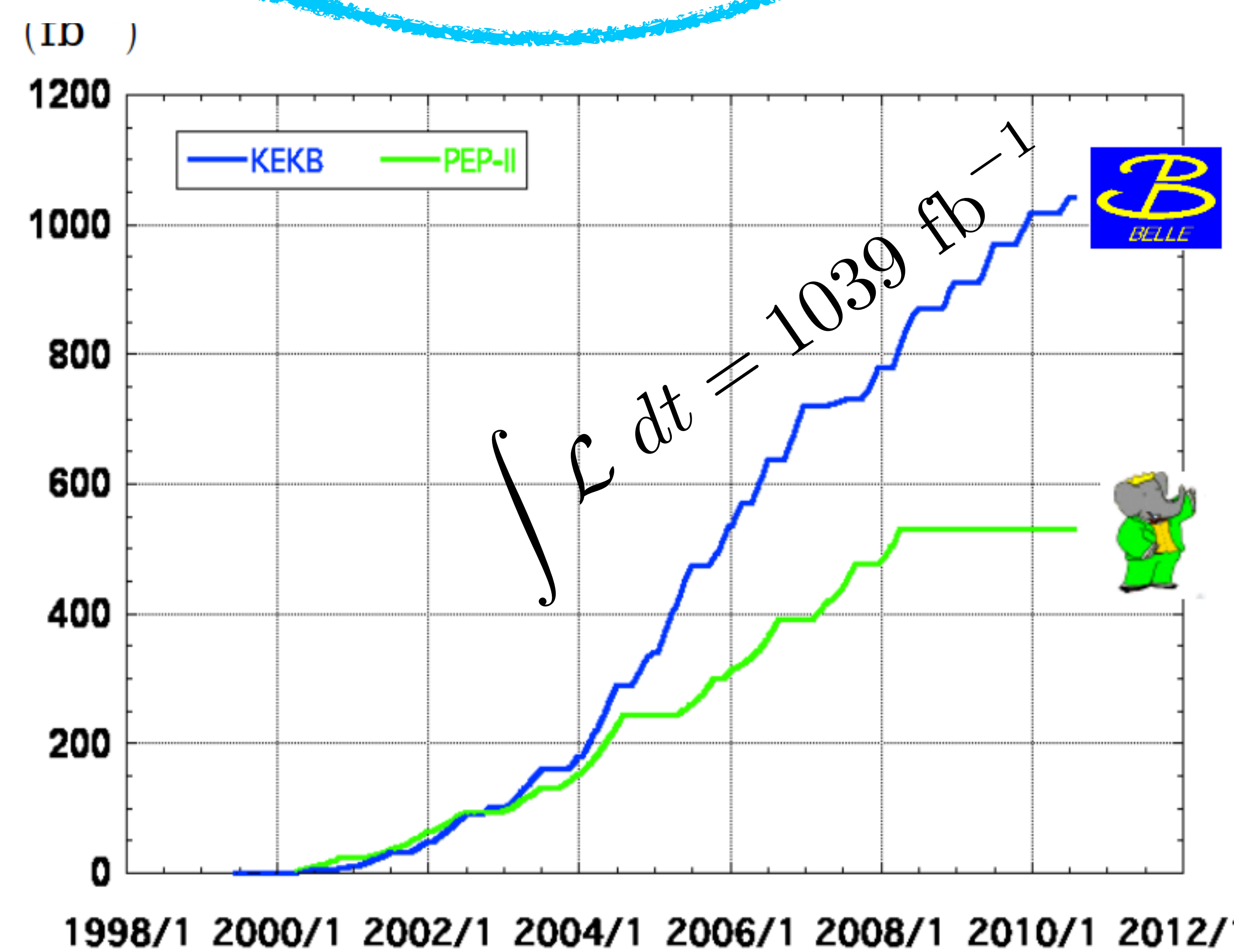
22 **countries**
100 **institutions**
~450 **members**

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



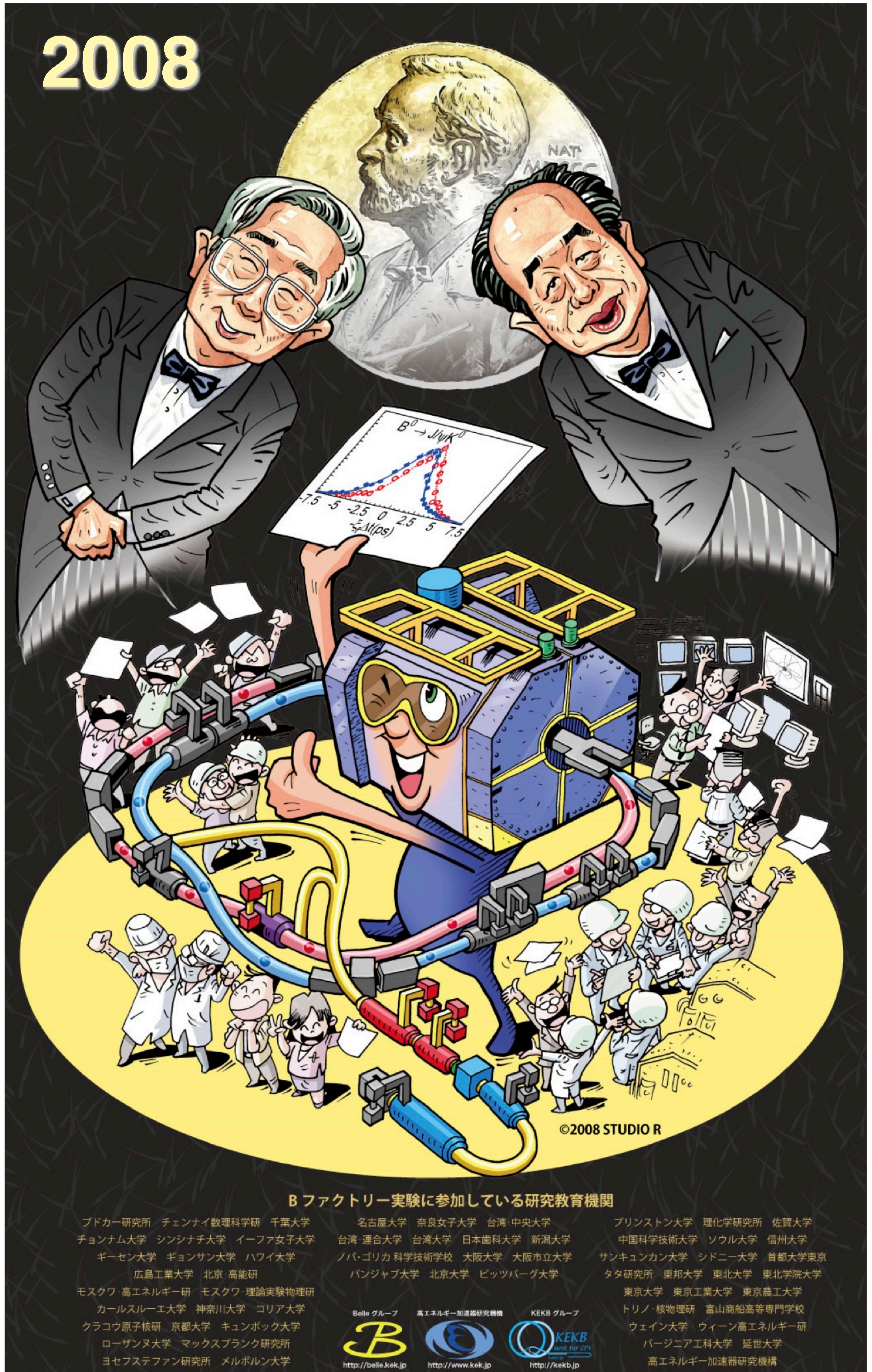
$$e^- \xrightarrow{\text{8 GeV}} (\star) \xleftarrow{\text{3.5 GeV}} e^+$$





> 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}

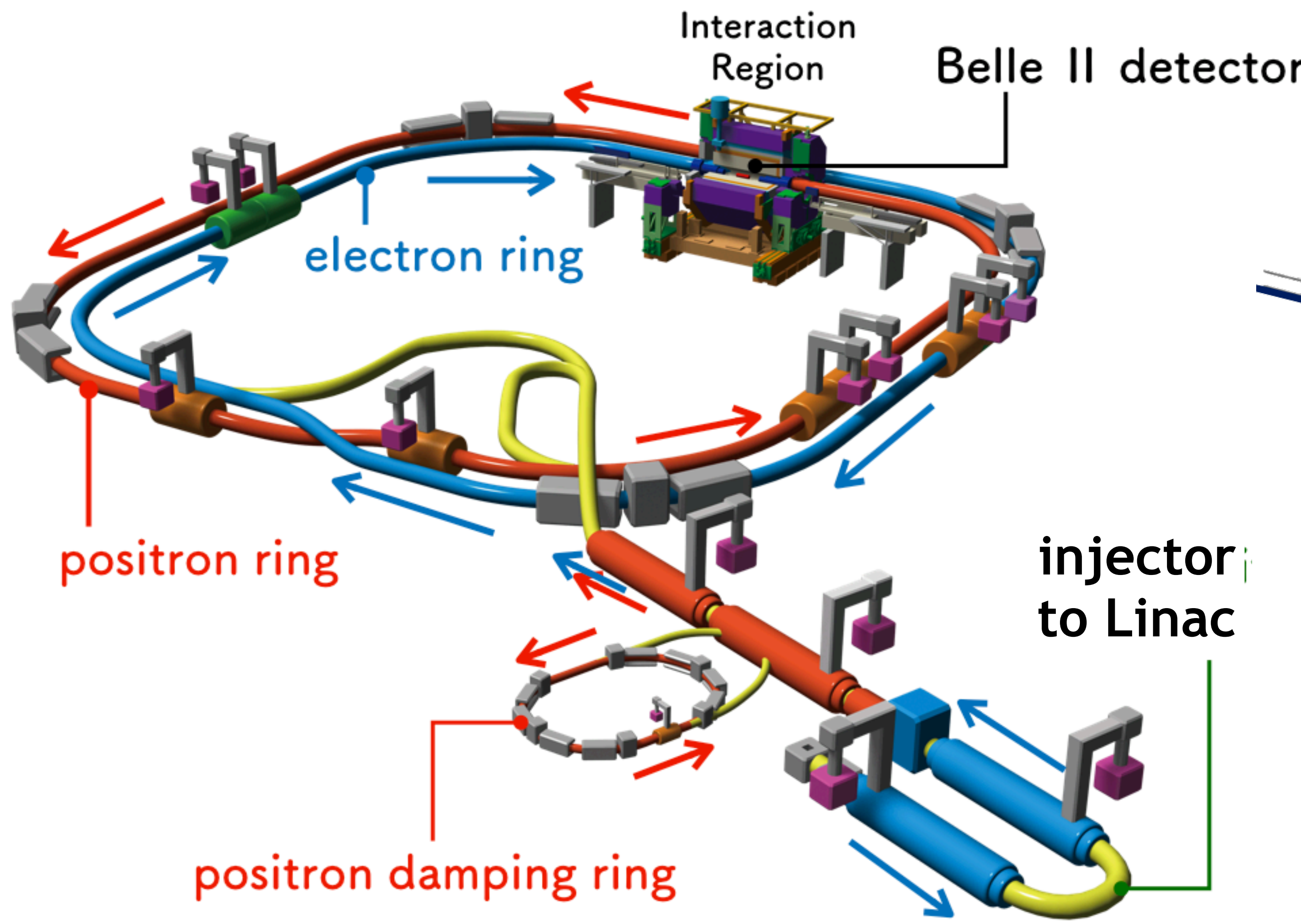
~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

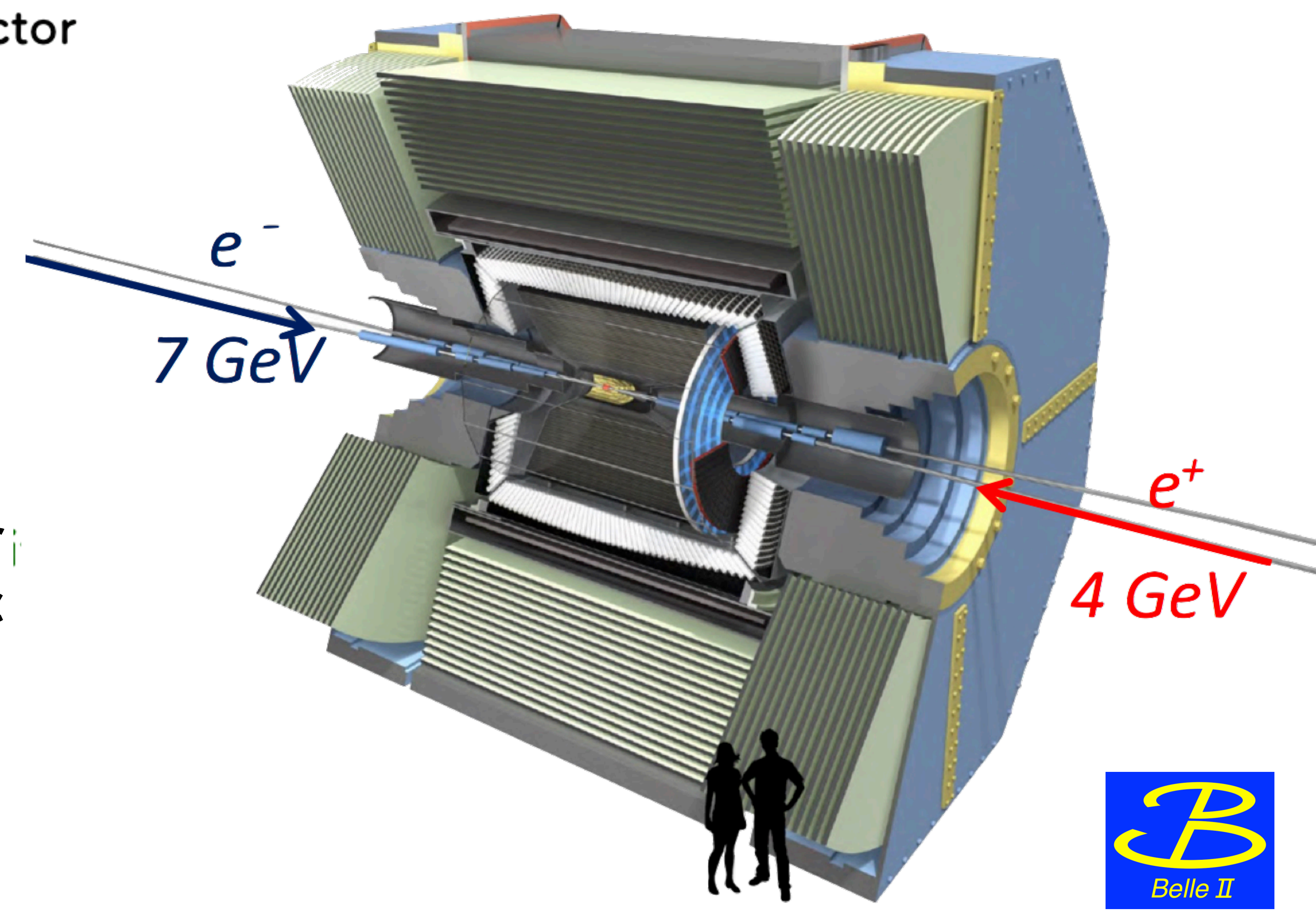


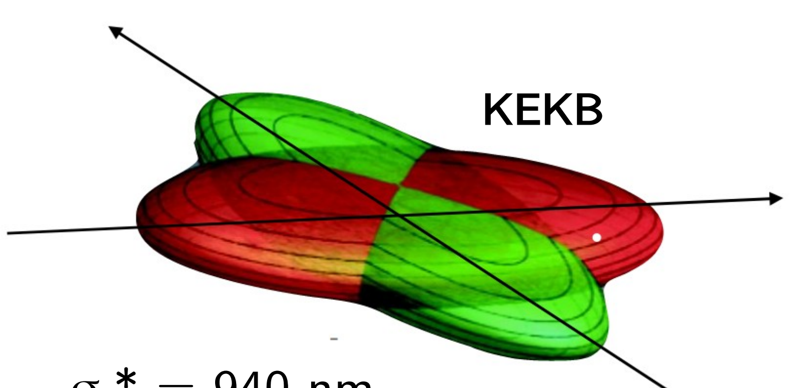
Belle (and BaBar, too) achievements include:

- CPV, CKM, and rare decays of B mesons (and B_s, too)
- Mixing, CP, and spectroscopy of charmed hadrons, 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

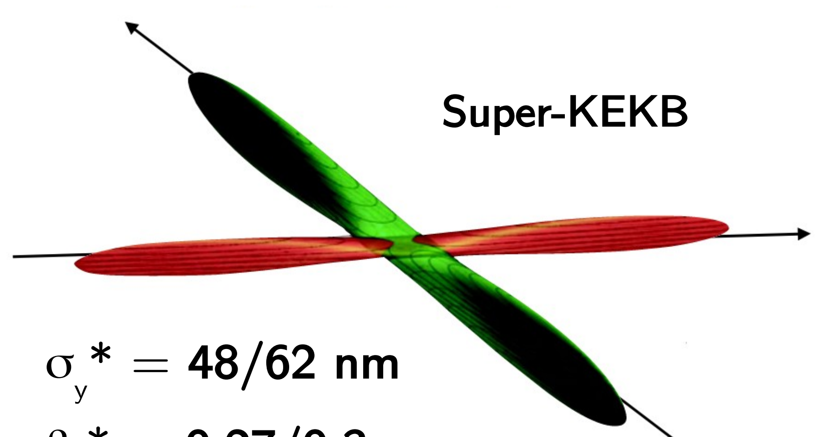
SuperKEKB $e^- \xrightarrow{7\text{ GeV}} (\star) \xleftarrow{4\text{ GeV}} e^+$ Belle II







$\sigma_y^* = 940$ 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

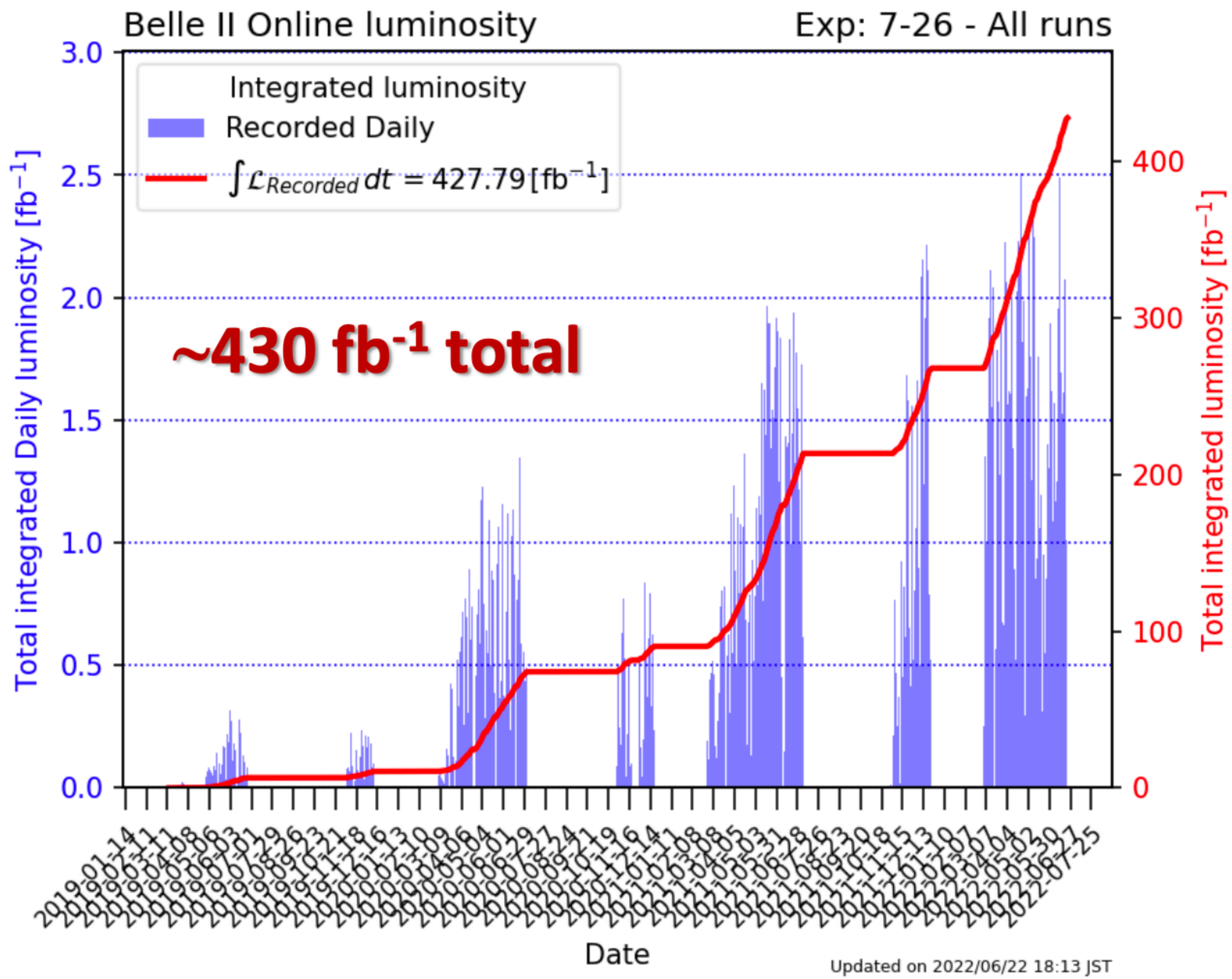
$$\mathcal{L}_{\mathrm{II}}^{\mathrm{peak}} \approx 30 \times \mathcal{L}_{\mathrm{I}}^{\mathrm{peak}}$$

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

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

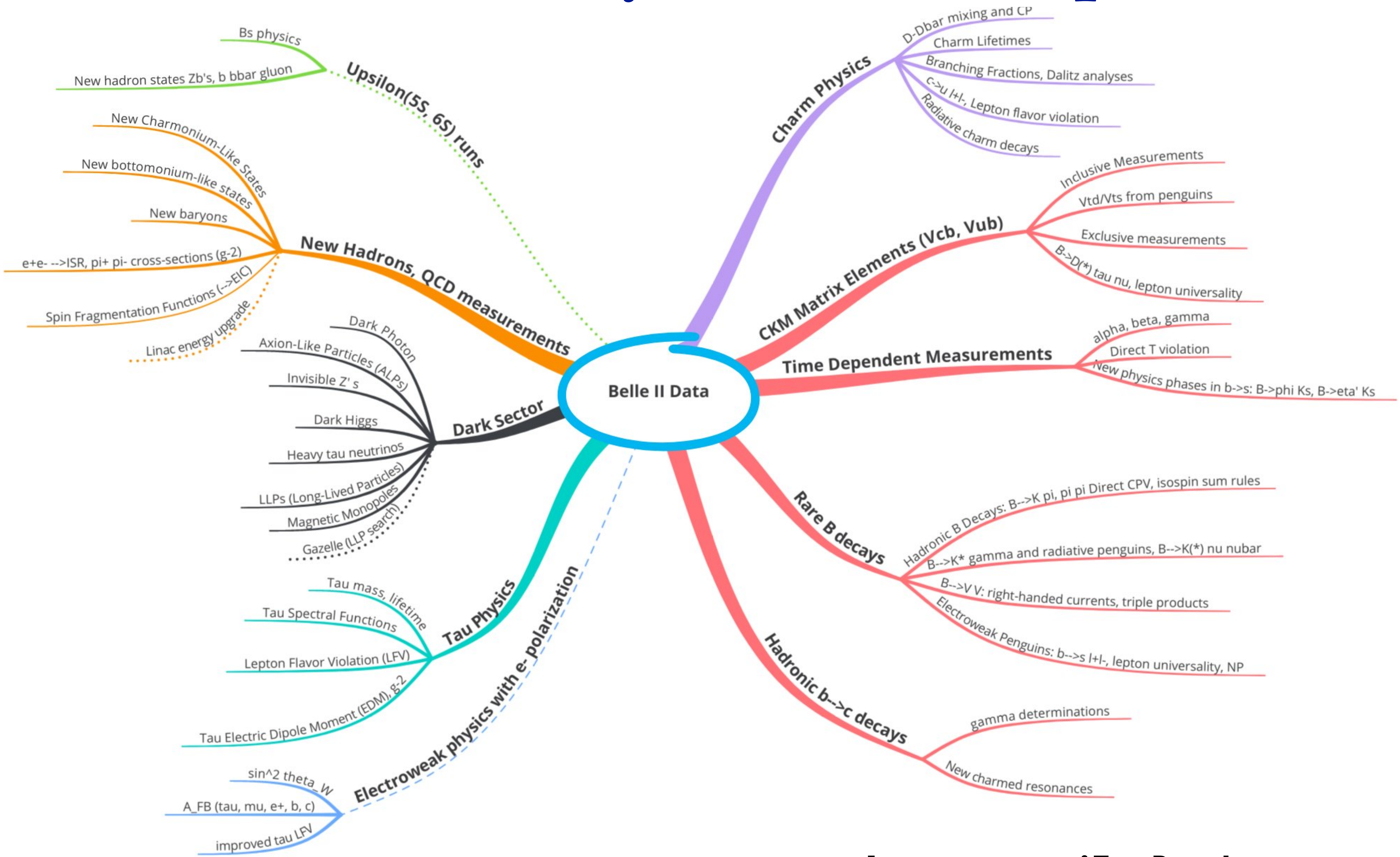


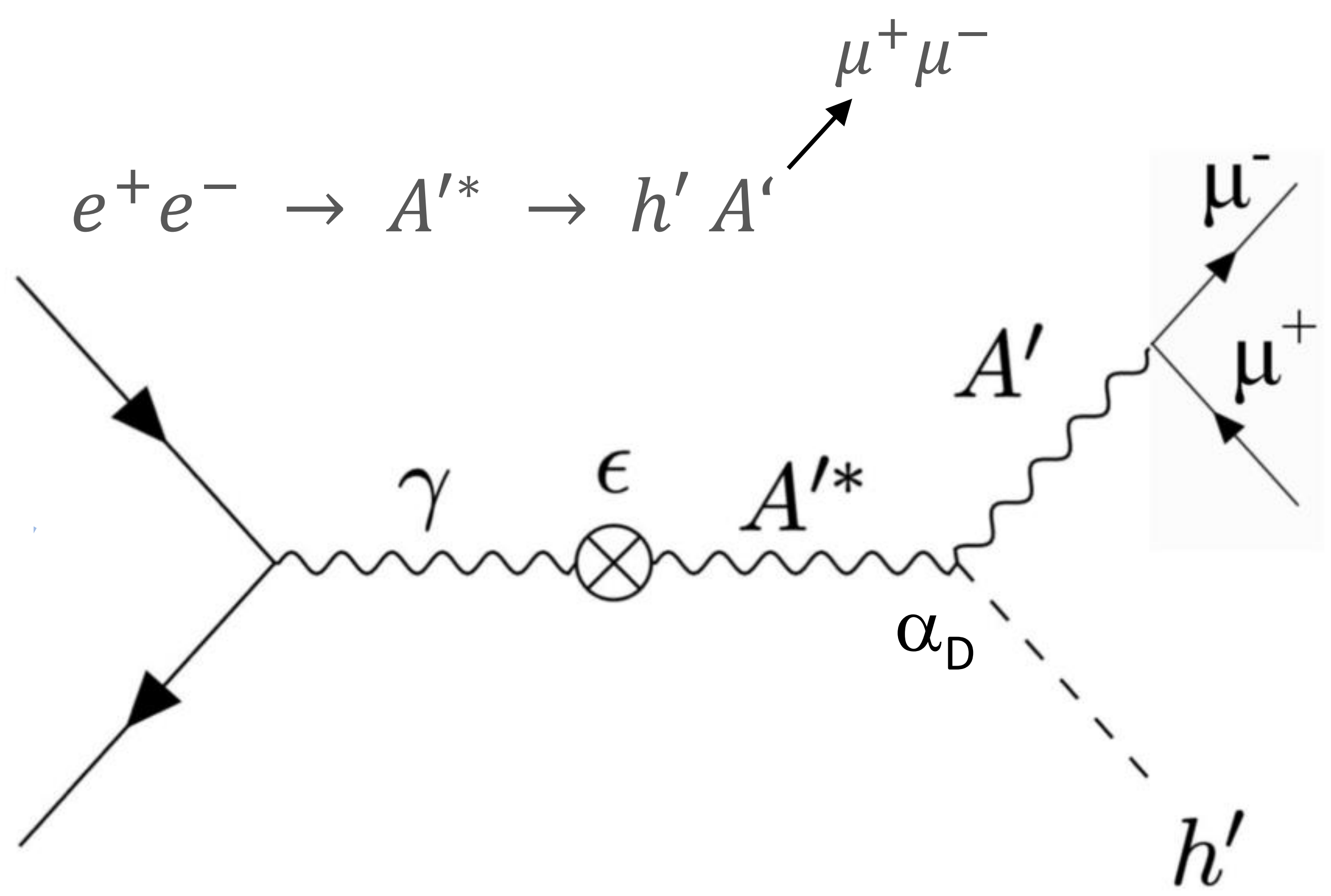
Image courtesy of Tom Browder

Dark photon via Higgsstrahlung

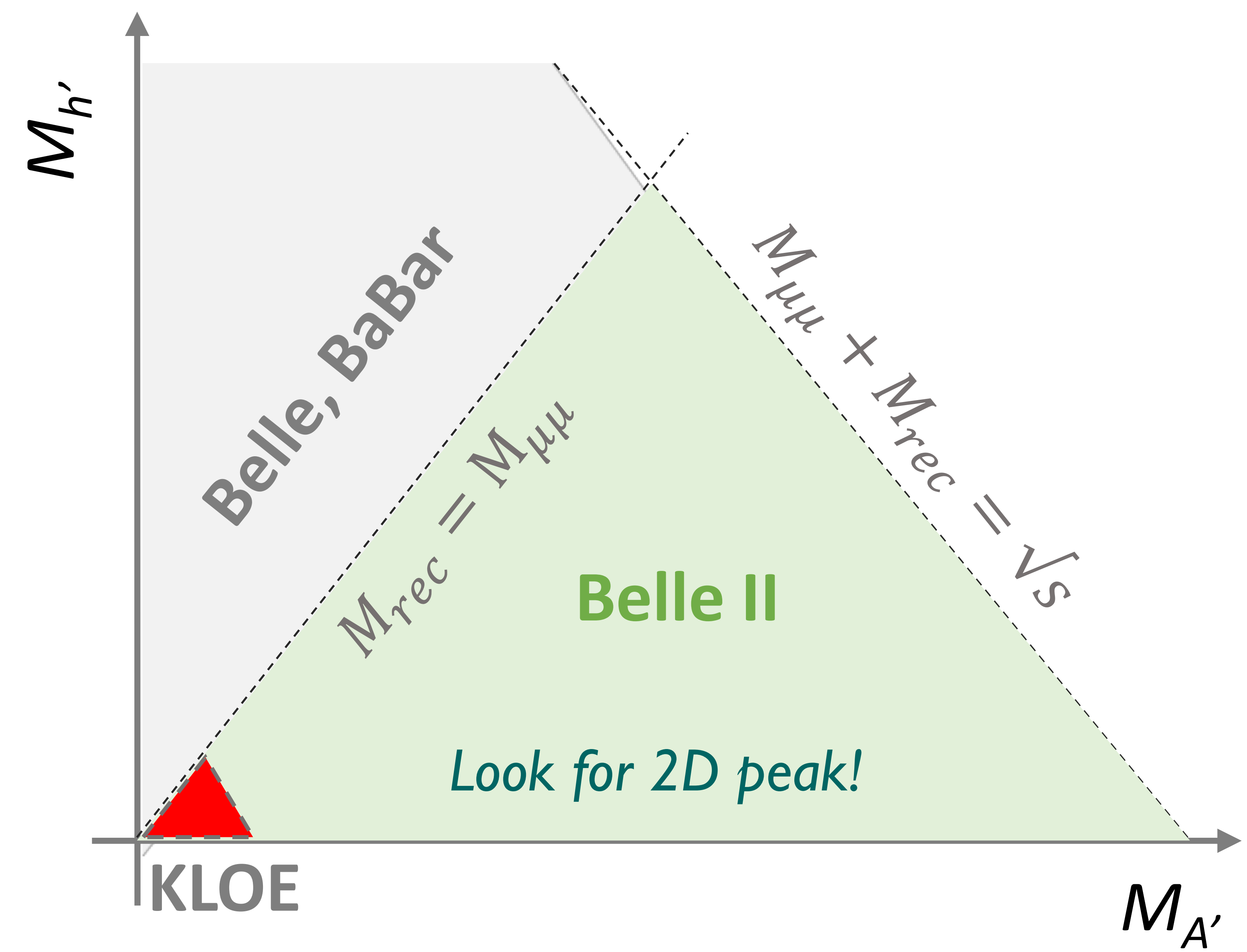
Belle II arXiv:2207.00509 (*accepted* to PRL)

arXiv:2207.00509
accepted to PRL

Dark Higgsstrahlung: $e^+e^- \to A'h'$



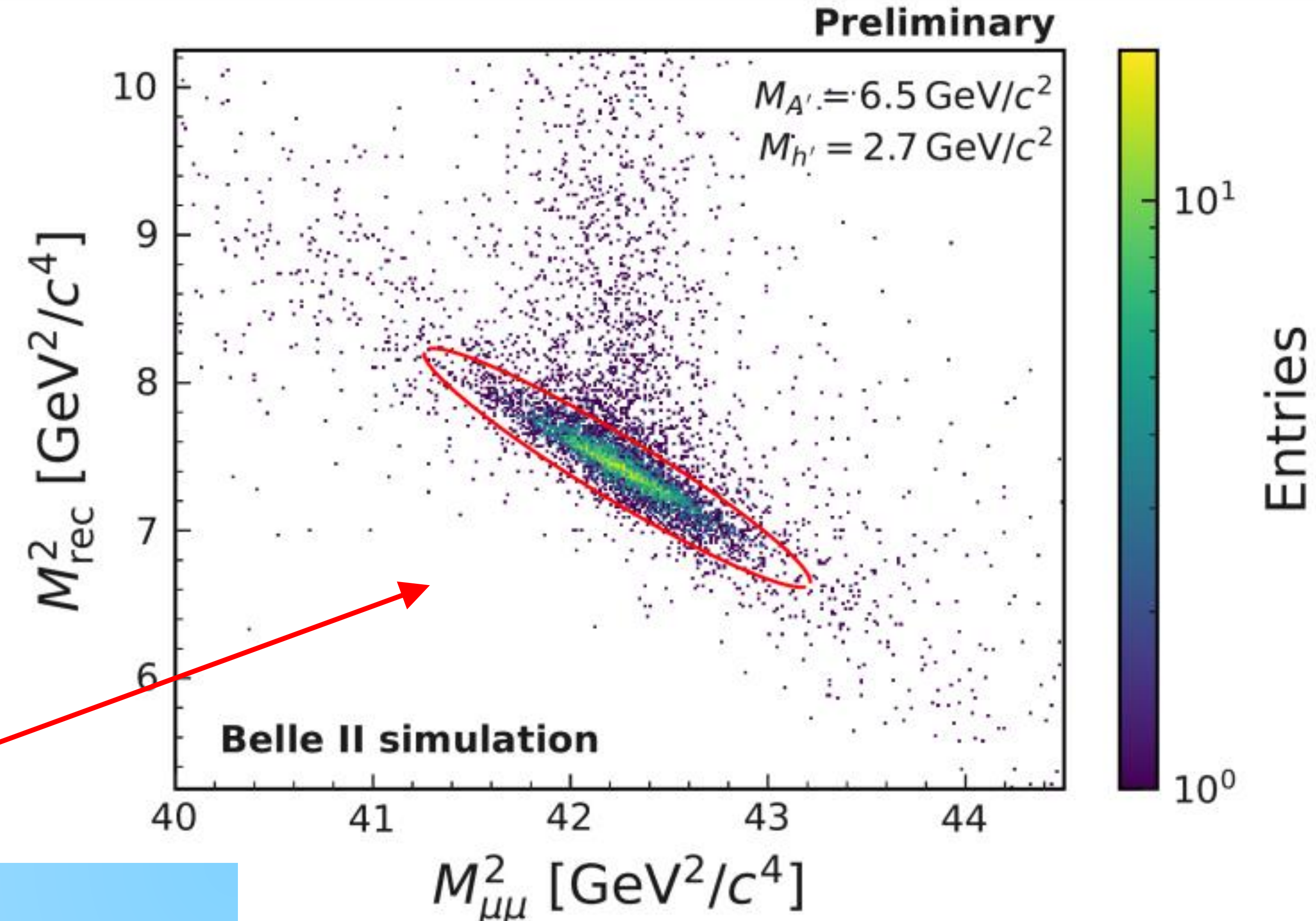
$e^+e^- \to \mu^+\mu^-$ + *missing energy*



arXiv:2207.00509
accepted to PRL

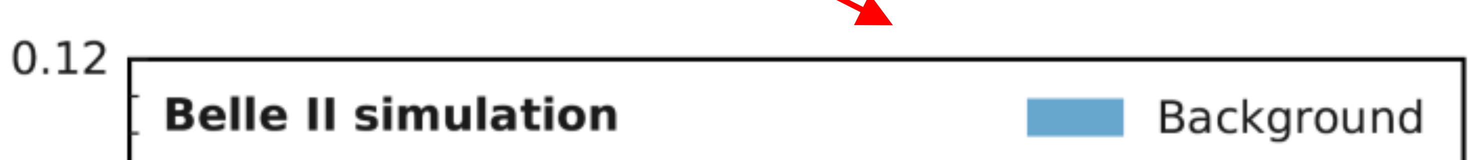
Dark Higgsstrahlung: $e^+e^- \to A'h'$

Two-track trigger
Two muons, $p_T^{\mu\mu} > 0.1$ GeV/c
Recoil points to barrel ECL
No extraenergy
Scan M_{recoil} vs $M_{\mu\mu}$



~9000 overlapping elliptical mass windows

Helicity angle



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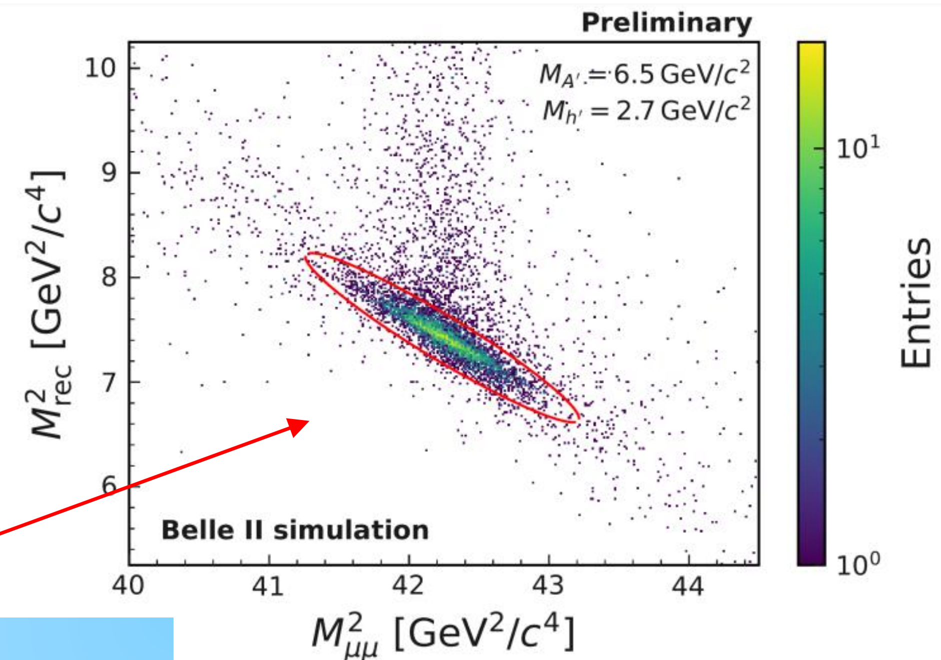

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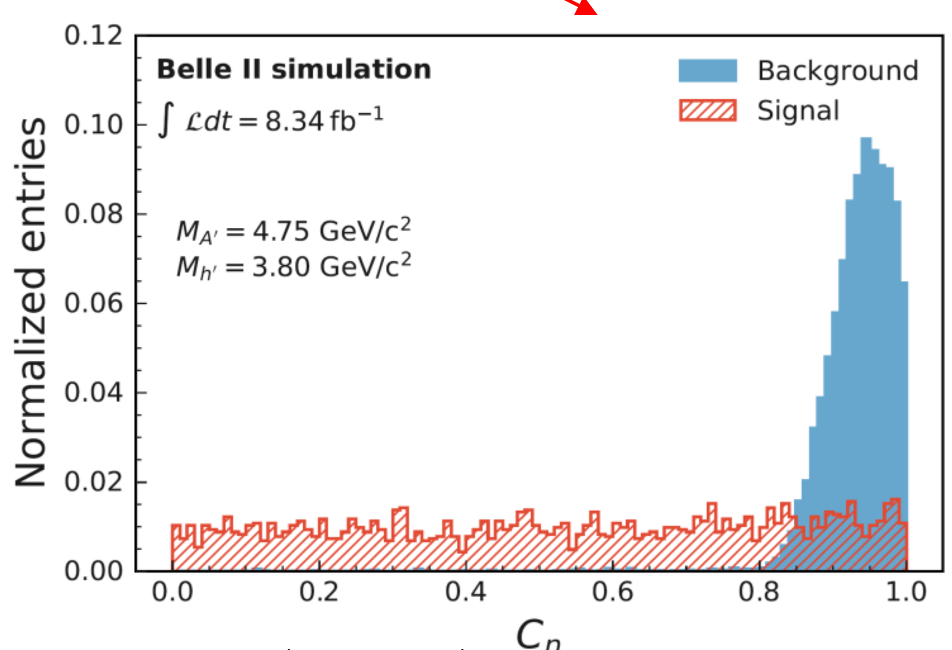
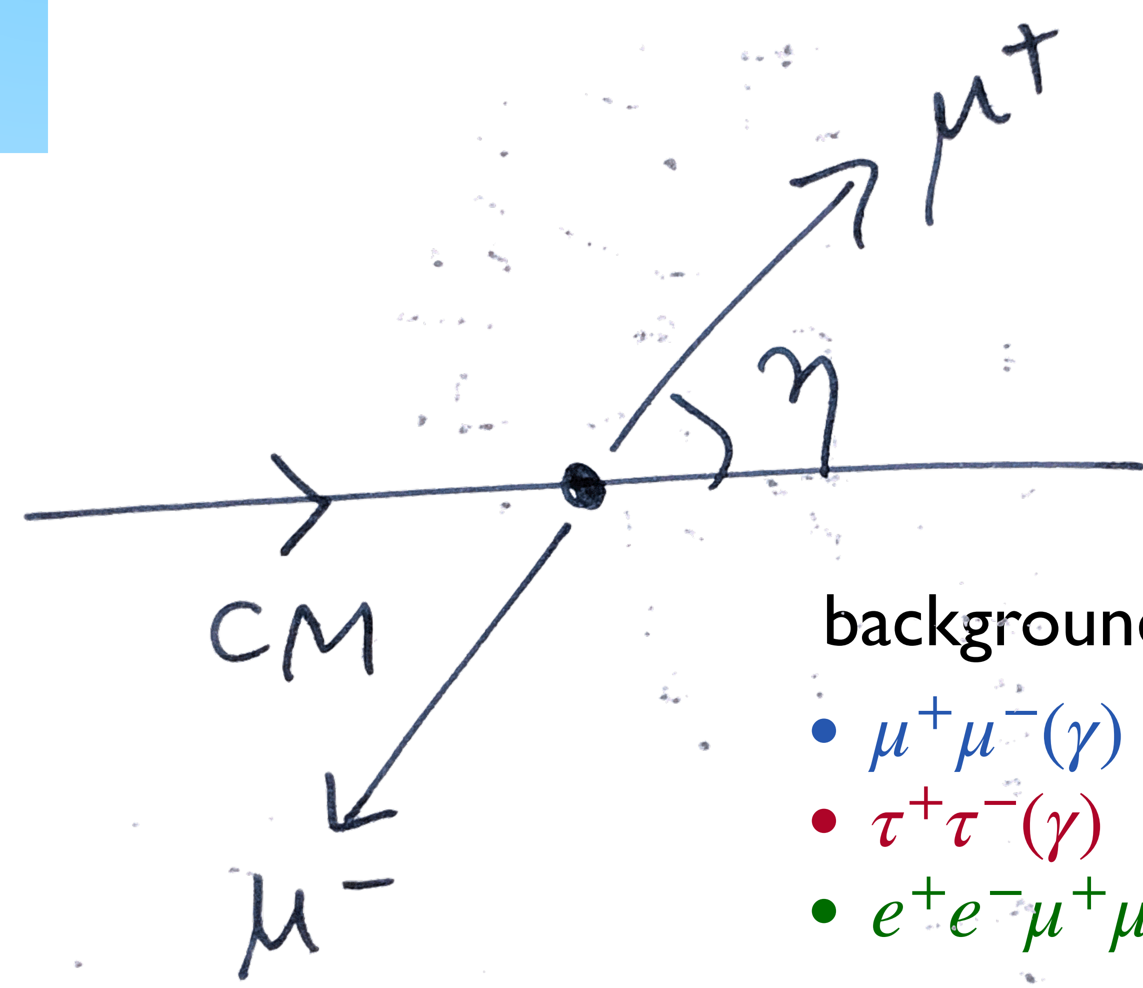


$$C_\eta = |\cos\eta|$$

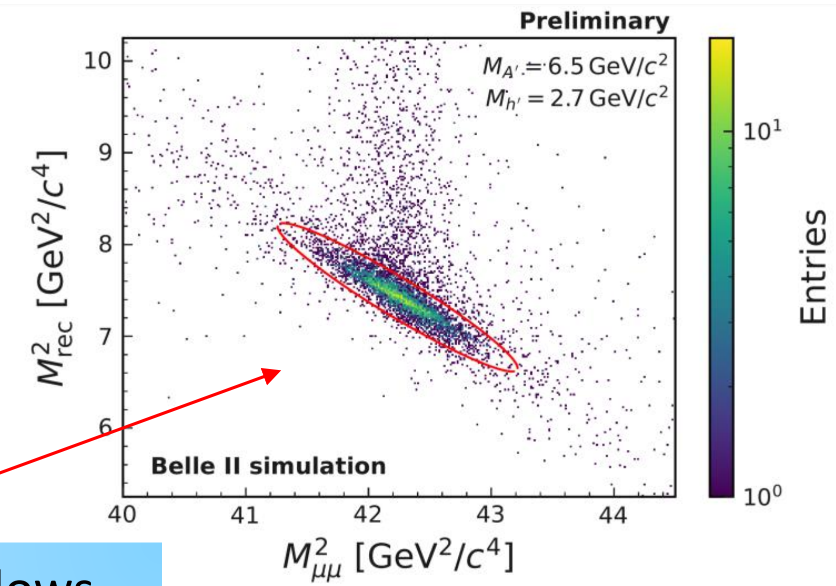


backgrounds

- $\mu^+\mu^-(\gamma)$ 79%
- $\tau^+\tau^-(\gamma)$ 18%
- $e^+e^-\mu^+\mu^-$ 3%

arXiv:2207.00509
accepted to PRL

Dark Higgsstrahlung: $e^+e^- \to A'h'$



- Two-track trigger
- Two muons, $p_T^{\mu\mu} > 0.1$ GeV/c
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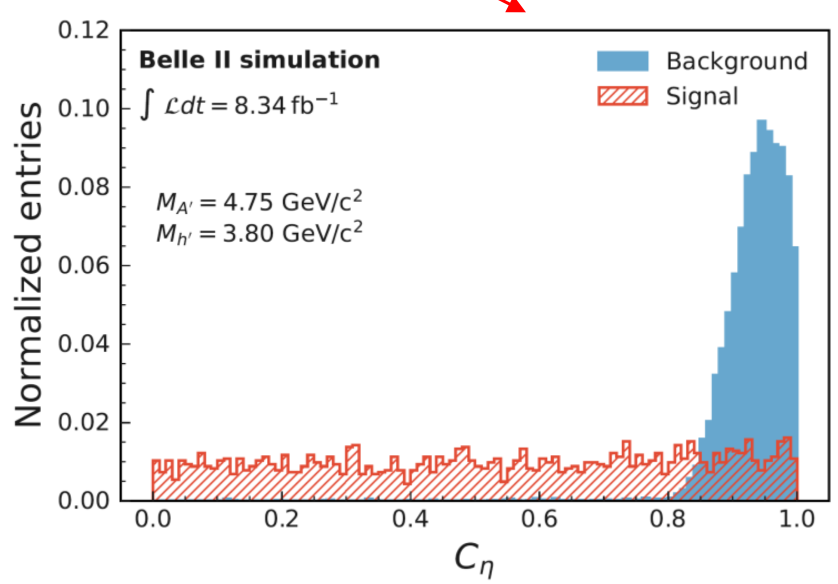

$$C_\eta = |\cos\eta|$$

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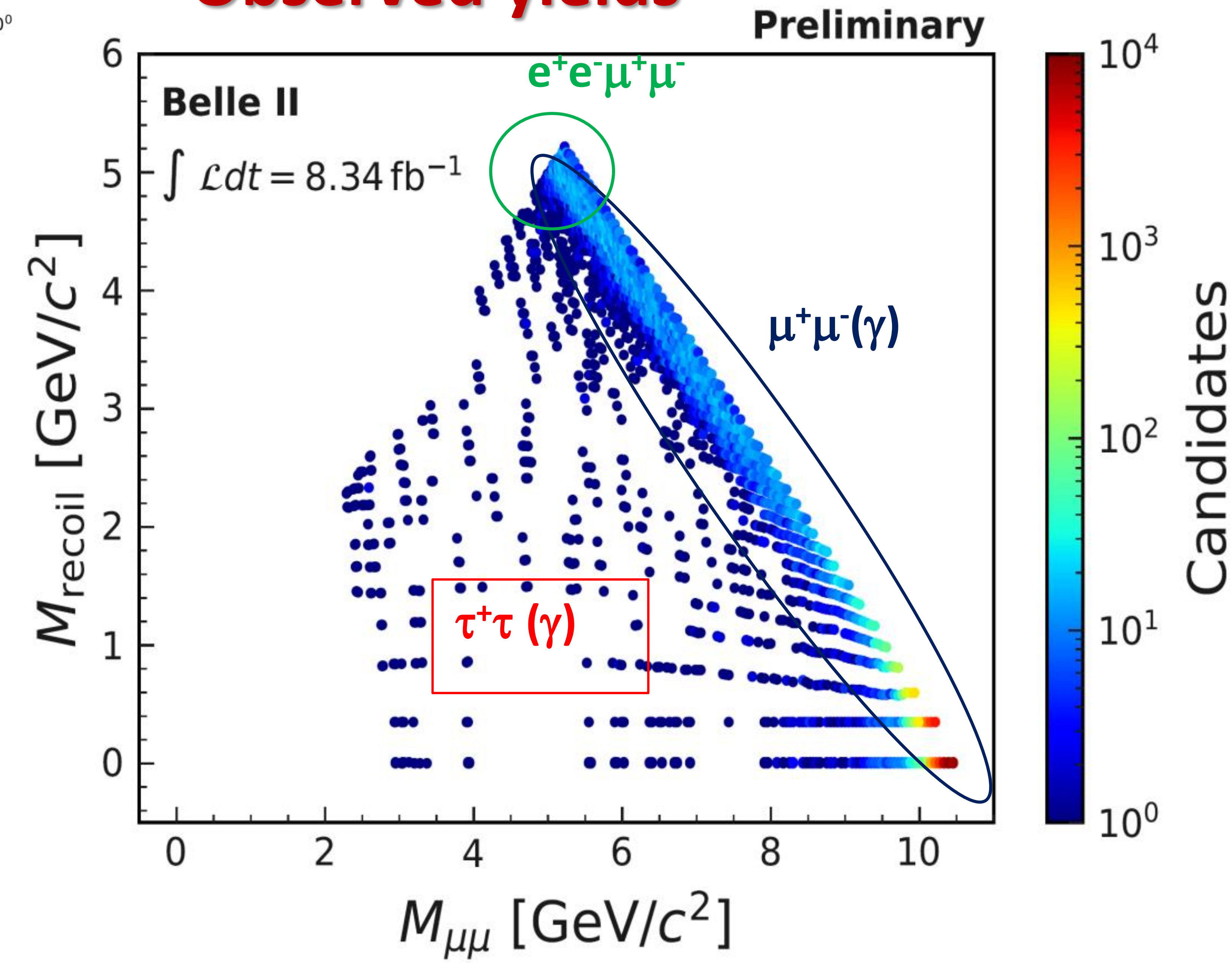
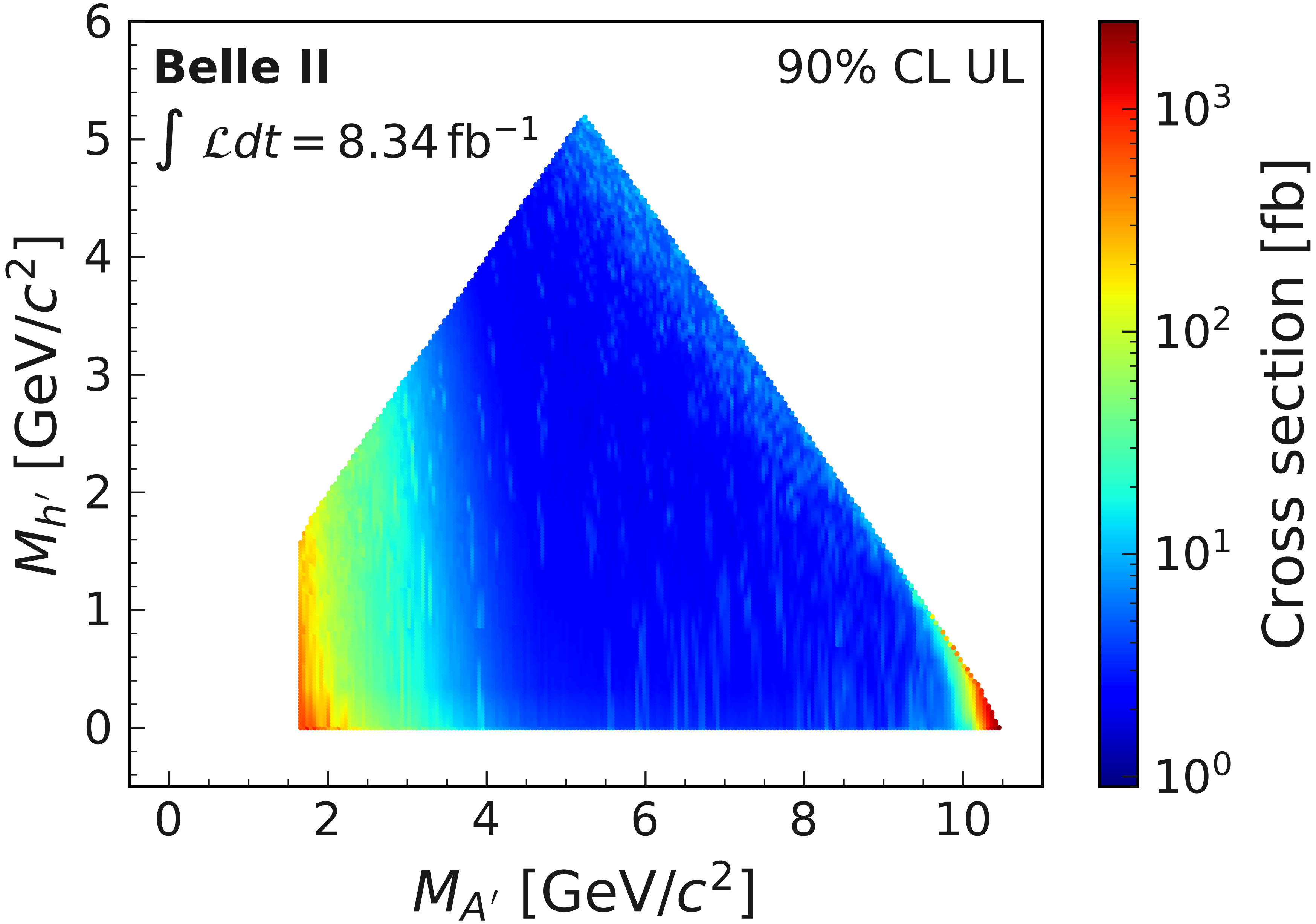
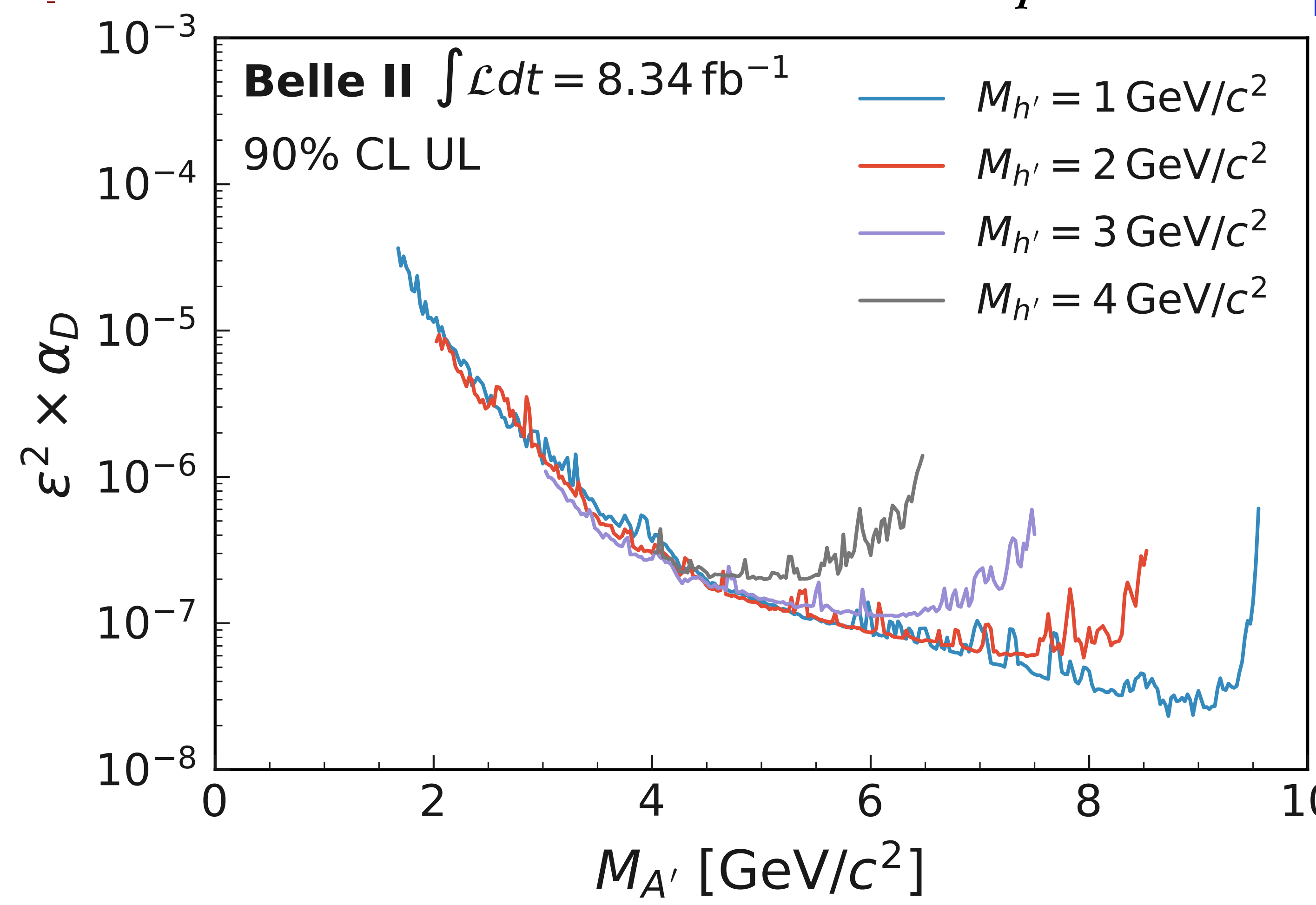
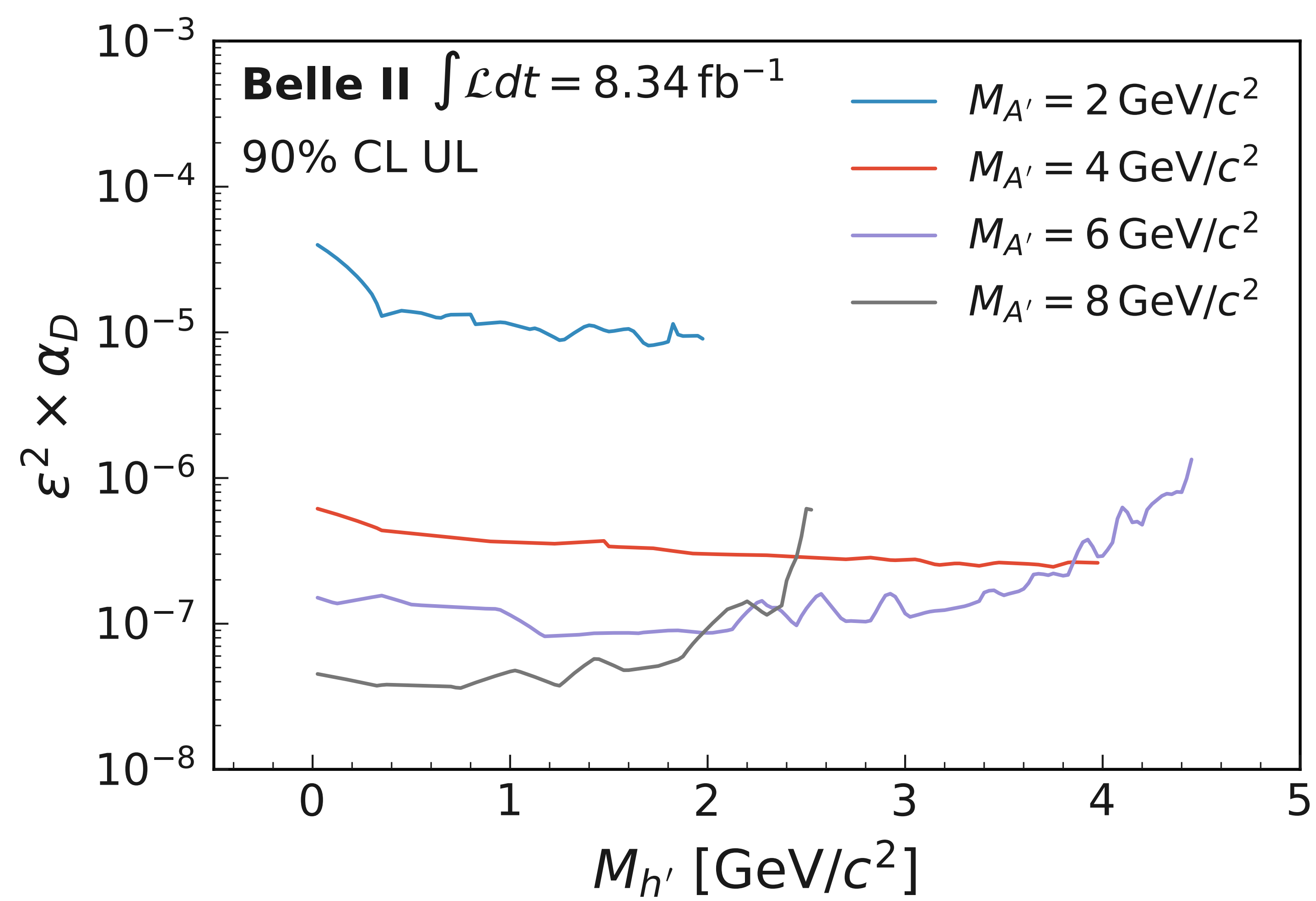
Observed yields



Dark Higgsstrahlung: *e*



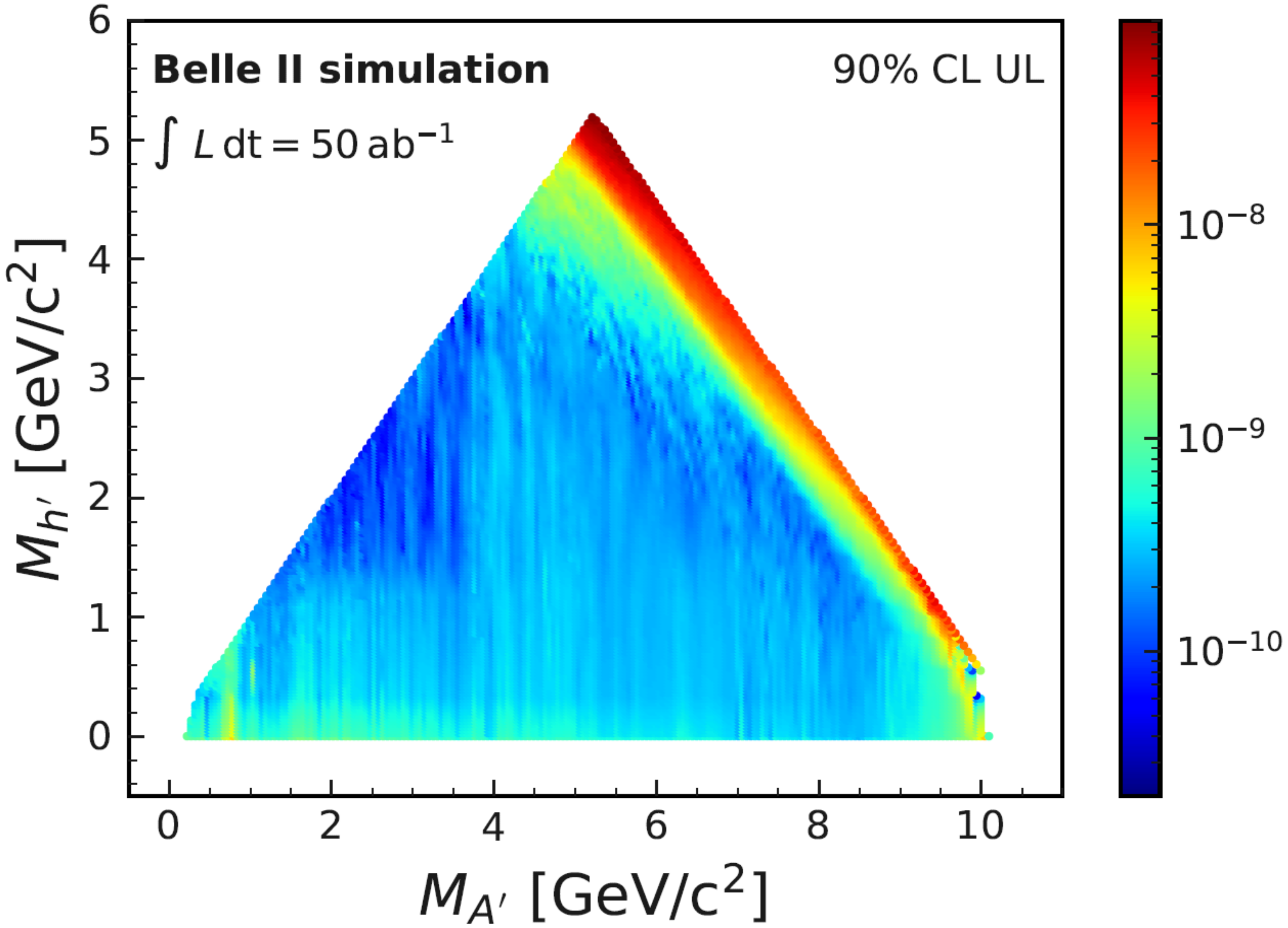


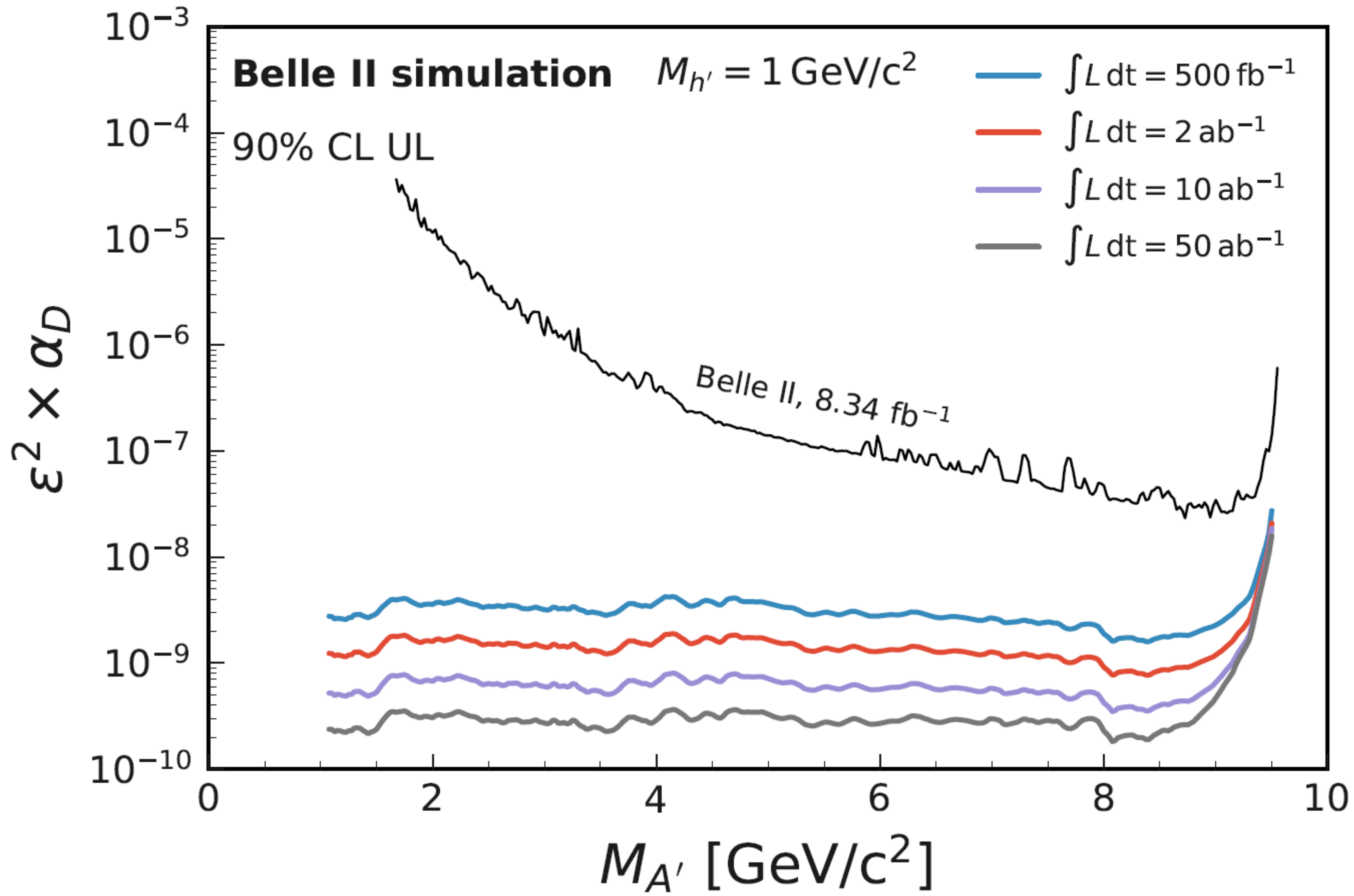


- No excess found
- upper limits on $\varepsilon^2\alpha_D$ as well
- most sensitive for $4 < M_{A'} < 9.7$ GeV/c²

arXiv:2207.06307
(Belle II, Snowmass)

Dark Higgsstrahlung (prospects)





Search for a dark photon and an invisible dark Higgs boson in $\mu^+\mu^-$ and missing energy final states with the Belle II experiment

F. Abudinén, I. Adachi, L. Aggarwal, H. Aihara, N. Akopov, A. Aloisio, N. Anh Ky, D. M. Asner, H. Atmacan, T. Aushev, V. Aushev, V. Babu, S. Bahinipati, P. Bambade, Sw. Banerjee, S. Bansal, J. Baudot, A. Baur, A. Beaubien, J. Becker, P. K. Behera, J. V. Bennett, E. Bernieri, F. U. Bernlochner, M. Bertemes, E. Bertholet, M. Bessner, B. Bhuyan, F. Bianchi, T. Bilka, D. Biswas, A. Bobrov, D. Bodrov, A. Bolz, A. Bozek, M. Bračko, P. Branchini, T. E. Browder, A. Budano, S. Bussino, M. Campajola, G. Casarosa, V. Chekelian, C. Chen, Y. Q. Chen, B. G. Cheon, K. Chilikin, K. Chirapatpimol, H.-E. Cho, K. Cho, S.-J. Cho, S.-K. Choi, S. Choudhury, D. Cinabro, L. Corona, S. Cunliffe, F. Dattola, G. de Marino, G. De Nardo, M. De Nuccio, G. De Pietro, R. de Sangro, M. Destefanis, S. Dey, A. De Yta-Hernandez, R. Dhamija, A. Di Canto, F. Di Capua, J. Dingfelder, Z. Doležal, I. Domínguez Jiménez, T. V. Dong, M. Dorigo, K. Dort, D. Dossett, S. Dreyer, S. Dubey, G. Dujany, M. Eliachevitch, D. Epifanov, P. Feichtinger, T. Ferber, D. Ferlewicz, T. Fillinger, C. Finck, G. Finocchiaro, K. Flood, A. Fodor, F. Forti, A. Frey, B. G. Fulsom, E. Ganiev, M. Garcia-Hernandez, V. Gaur, A. Gaz, A. Gellrich, R. Giordano, A. Giri, B. Gobbo, R. Godang, P. Goldenzweig, W. Gradl, S. Granderath, E. Graziani, D. Greenwald, T. Gu, K. Gudkova, J. Guilliams, C. Hadjivasiliou, K. Hara, T. Hara, K. Hayasaka, H. Hayashii, S. Hazra, C. Hearty, M. T. Hedges, I. Heredia de la Cruz, M. Hernández Villanueva, A. Hershenhorn, T. Higuchi, E. C. Hill, M. Hoek, M. Hohmann, C.-L. Hsu, T. Iijima, K. Inami, G. Inguglia, N. Ipsita, A. Ishikawa, S. Ito, R. Itoh, M. Iwasaki, P. Jackson, W. W. Jacobs, D. E. Jaffe, E.-J. Jang, Q. P. Ji, S. Jia, Y. Jin, H. Junkerkalefeld, H. Kakuno, A. B. Kaliyar, J. Kandra, K. H. Kang, R. Karl, G. Karyan, T. Kawasaki, C. Ketter, H. Kichimi, C. Kiesling, C.-H. Kim, D. Y. Kim, K.-H. Kim, Y.-K. Kim, K. Kinoshita, P. Kodyš, T. Koga, S. Kohani, K. Kojima, T. Konno, A. Korobov, S. Korpar, E. Kovalenko, R. Kowalewski, T. M. G. Kraetzschmar, P. Križan, P. Krokovny, T. Kuhr, R. Kumar, K. Kumara, T. Kunigo, Y.-J. Kwon, S. Lacaprara, Y.-T. Lai, T. Lam, J. S. Lange, M. Laurenza, R. Leboucher, S. C. Lee, L. K. Li, Y. B. Li, J. Libby

Leptophilic Z'

Belle II PRL 124, 141801 (2020)

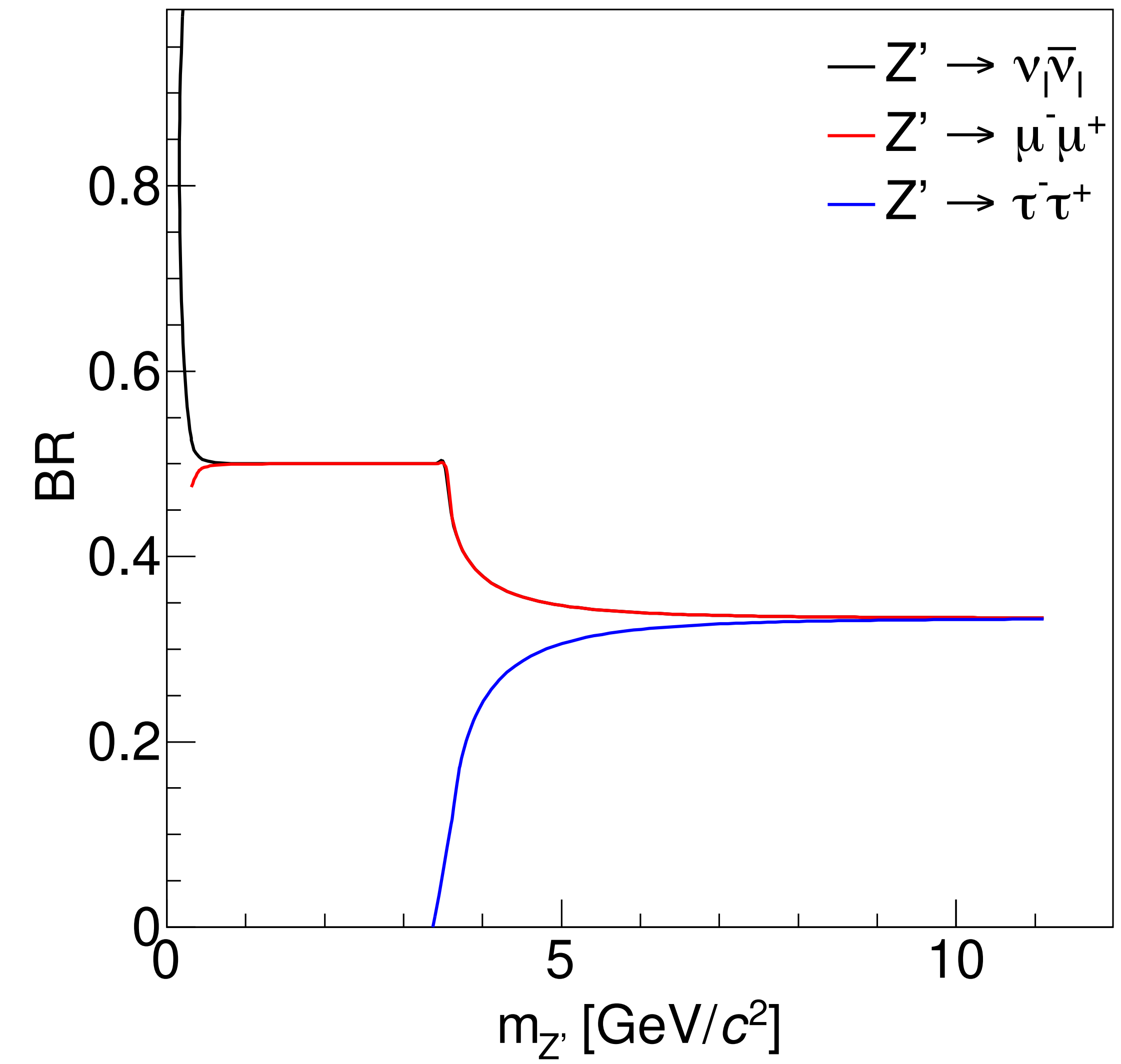
Belle PRD 106, 012003 (2022)

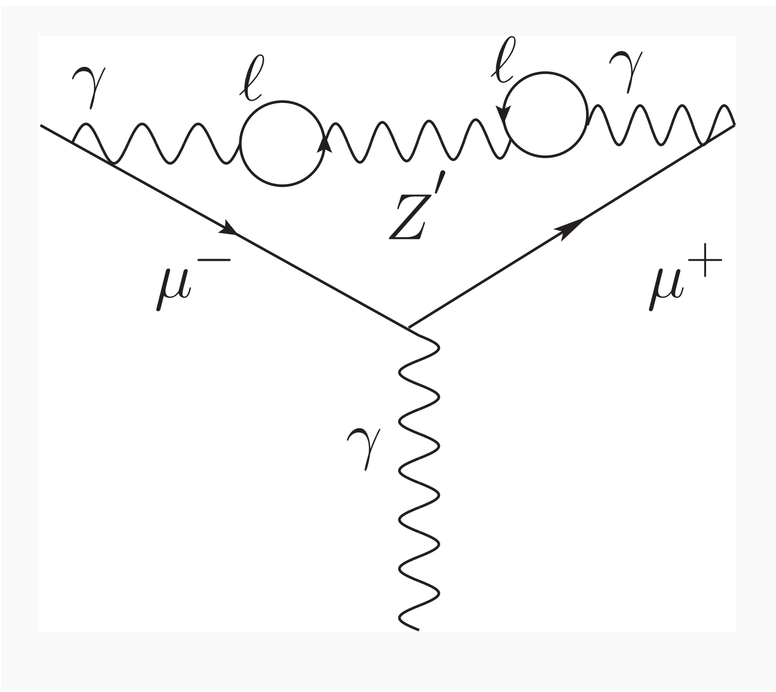
Belle II arXiv:2212.03066 (to PRL)

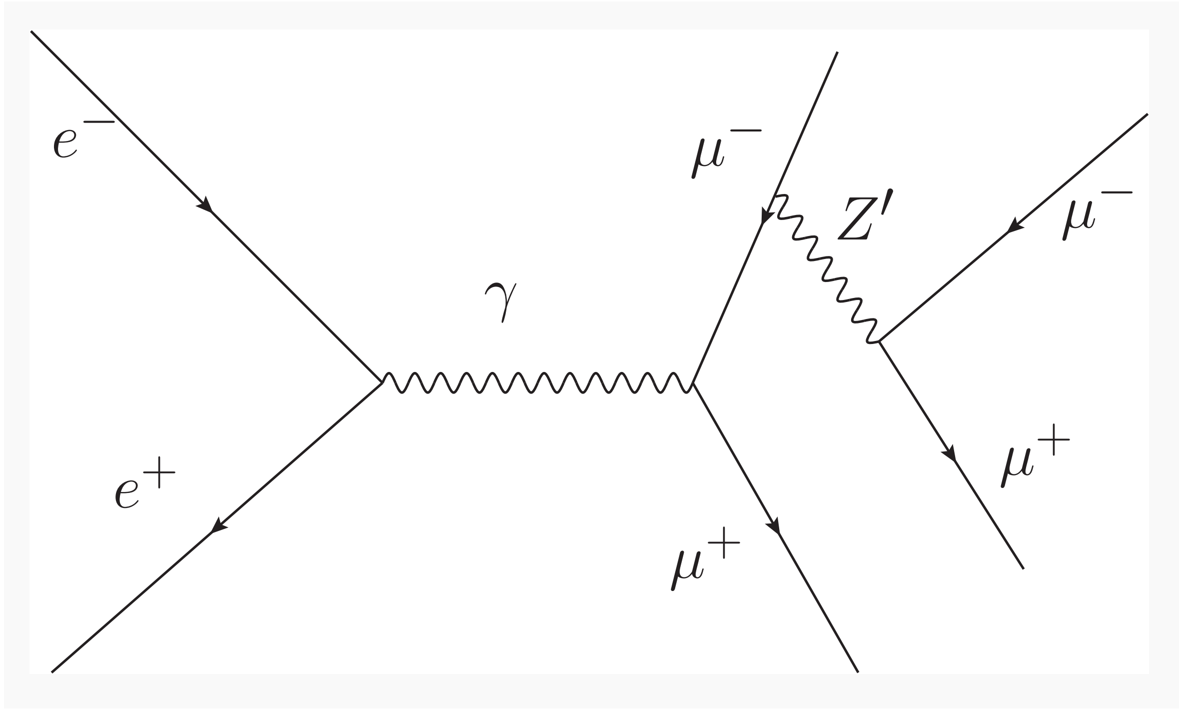
Leptophilic $Z' \to$ invis .

- $L_\mu - L_\tau$ model, initially motivated by $(g-2)_\mu$
- could also be a channel for sterile neutrinos as a dark matter candidate, as well as a potential sol. to $R_{K^{(*)}}$
- Search for $Z' \to \mu^+\mu^-$ (Belle)
- Search for $Z' \to$ "invisible" (Belle II)

  $Z' \to \tau^+\tau^-$ (Belle II)



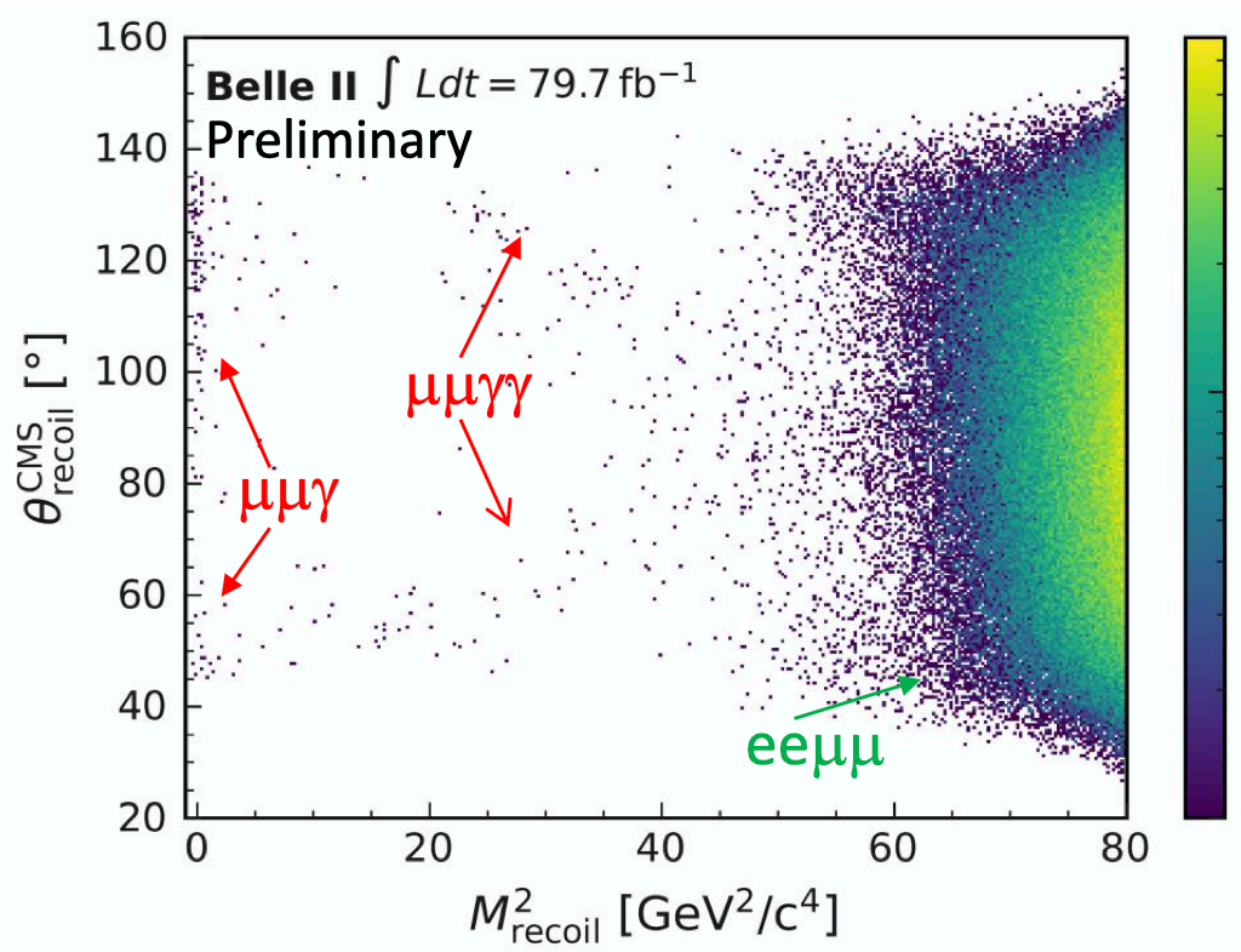




Leptophilic $Z' \to$ invis. (Belle II)

arXiv:2212.03066
submitted to PRL

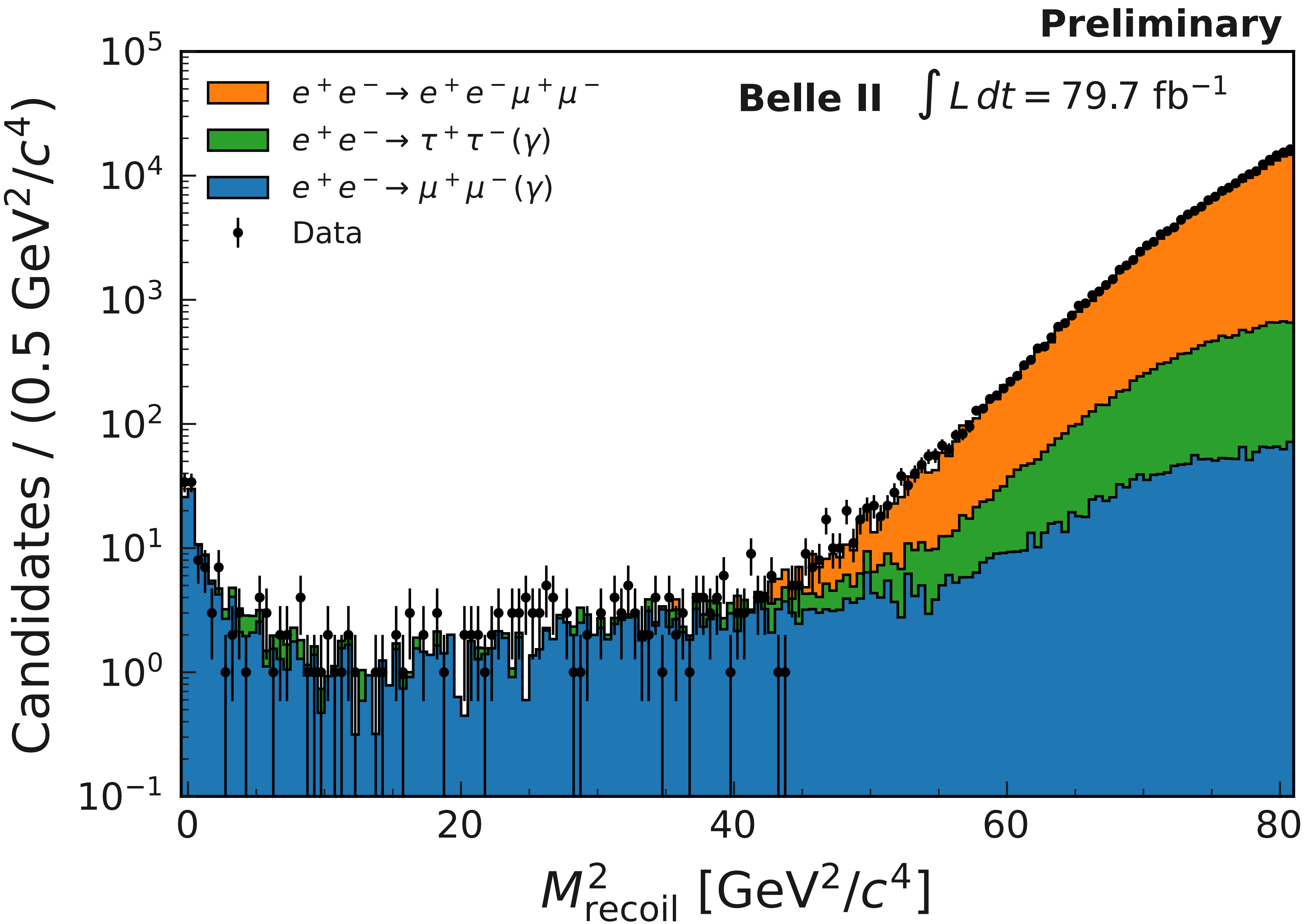
look for signal in $\theta_{\rm rec}$ vs. $M^2_{\rm rec}$



- $\tau^+\tau^-(\gamma)$ almost 100% suppressed
- $\mu^+\mu^-(\gamma)$ dominates up to ~7 GeV/c²
- $e^+e^-\mu^+\mu^-$ dominant in high $M^2_{\rm rec}$

Leptophilic $Z' \to$ invis. (Belle II)

arXiv:2212.03066
submitted to PRL



Leptophilic $Z' \to$ invis. (Belle II)

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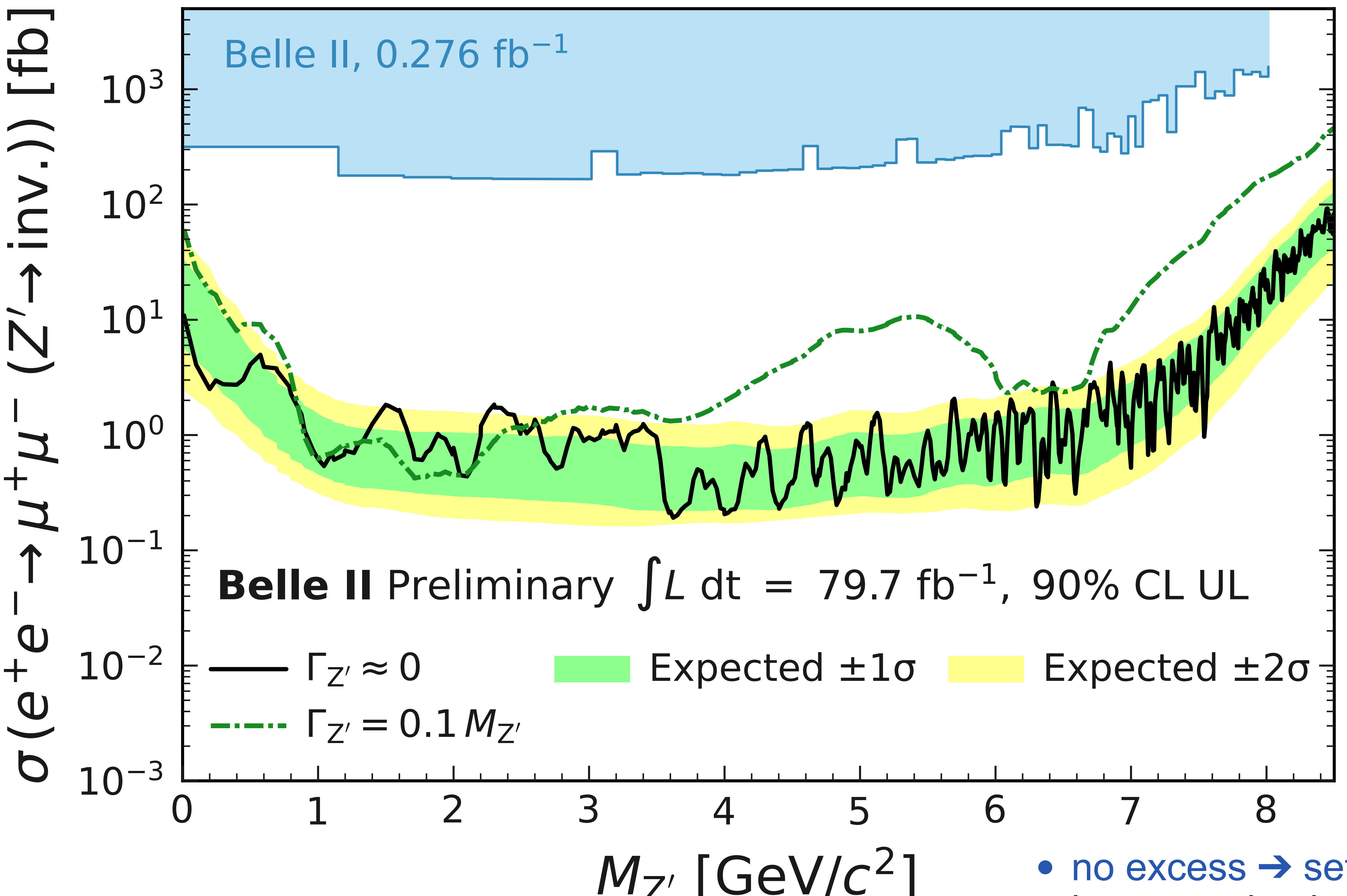
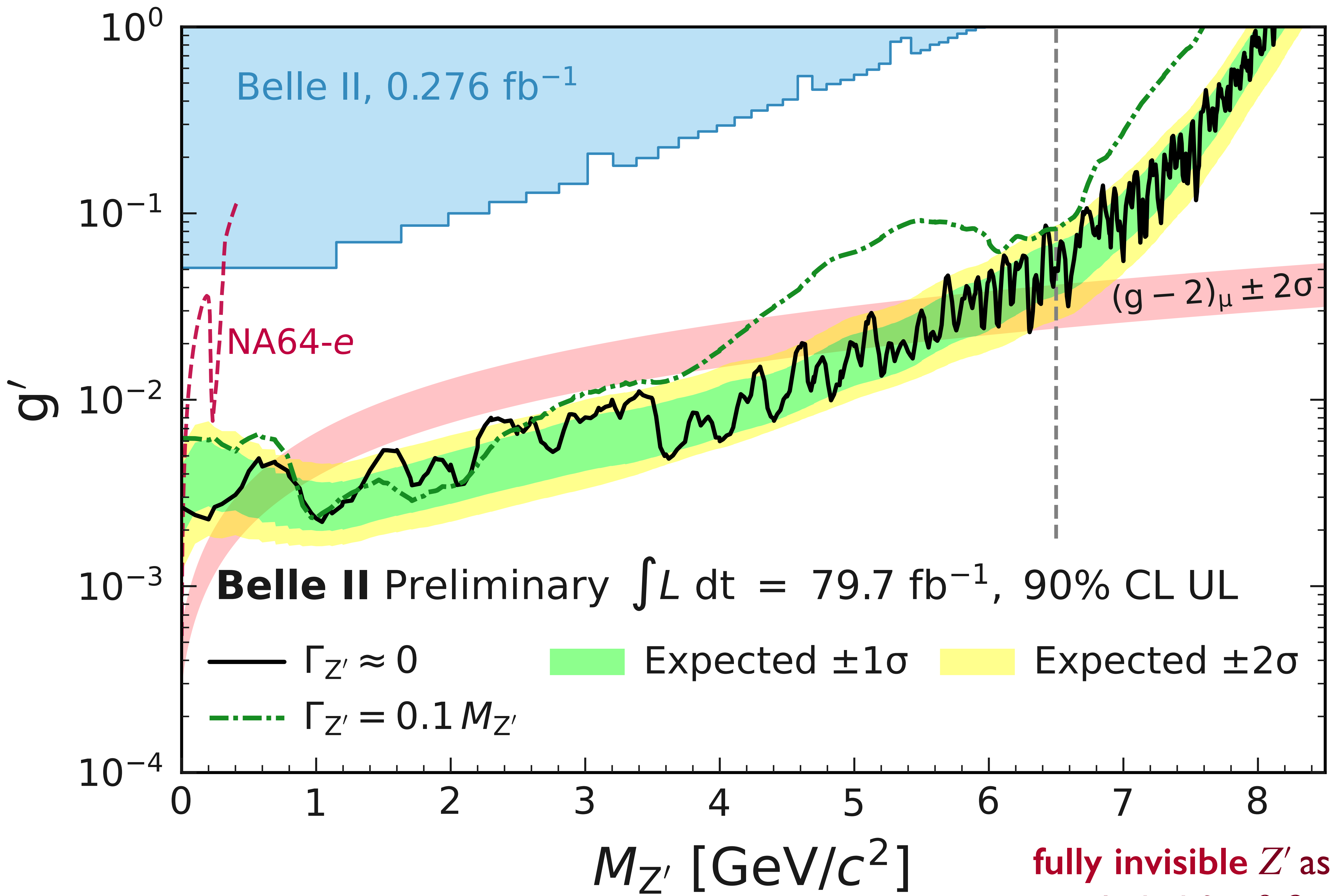


- no excess ➔ set 90% CL limits on σ and g'
- interpretation in two scenarios
  - ✓ "vanilla" scenario: Z' to SM only
  - ✓ "fully invisible" scenario

arXiv:2212.03066
submitted to PRL

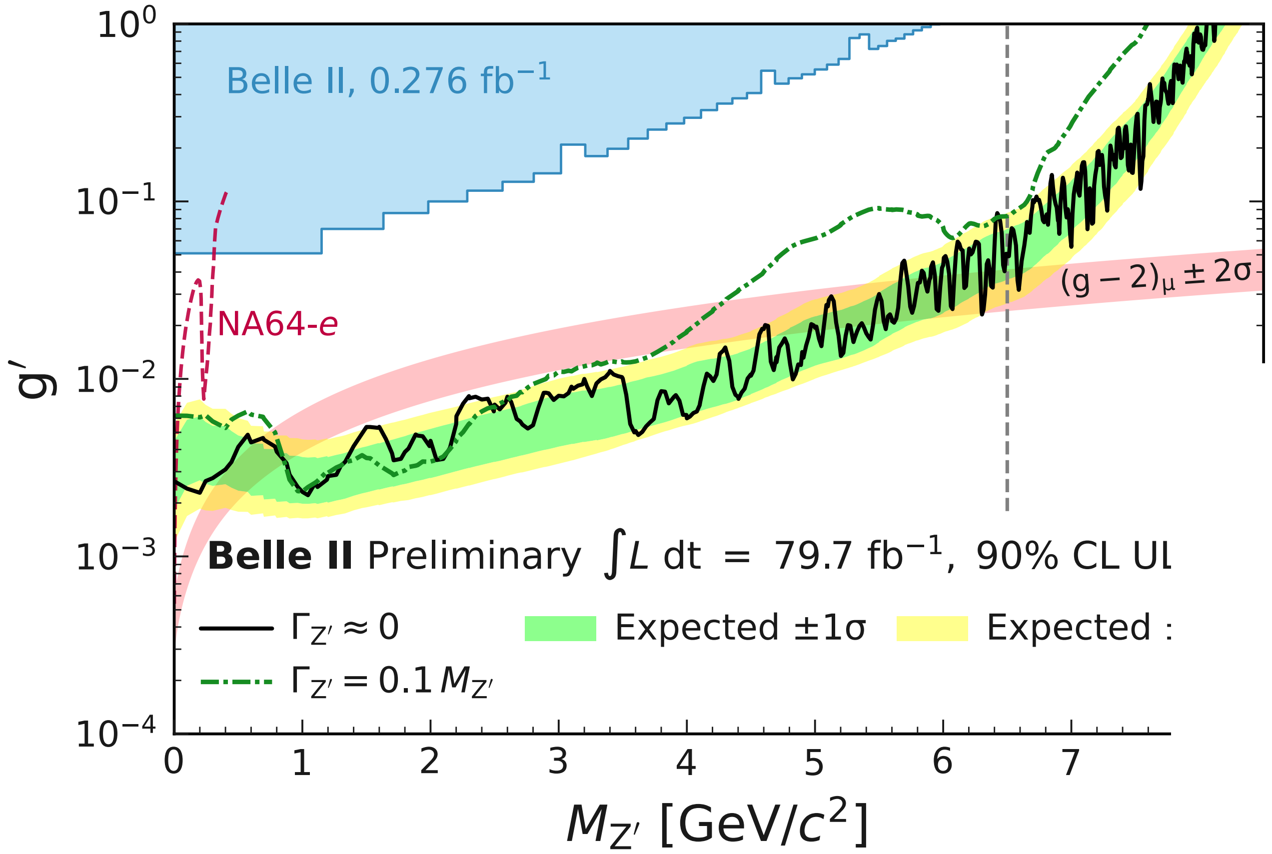
Leptophilic Z' search (Belle II)



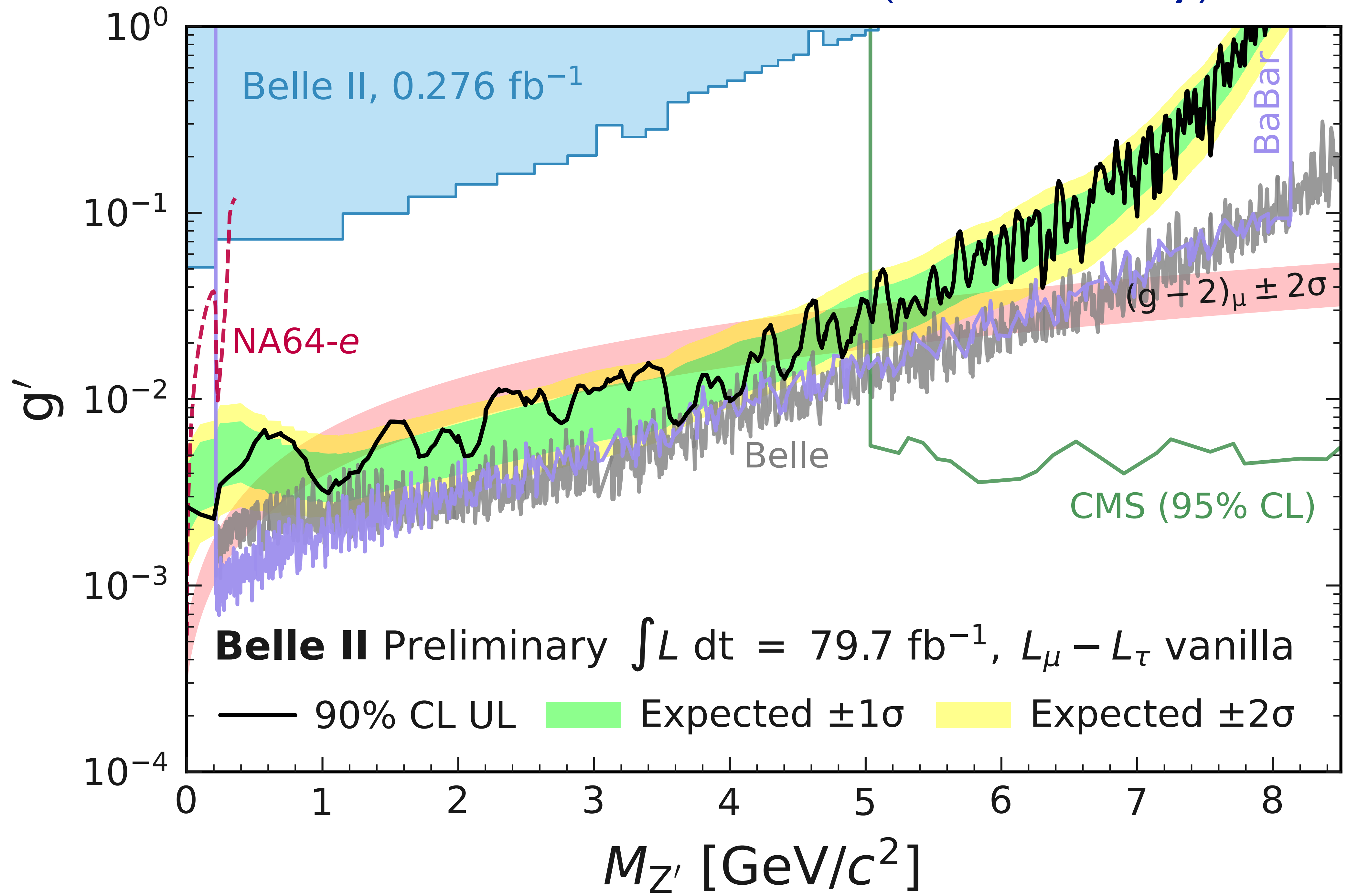
fully invisible Z' as origin of $(g-2)_\mu$ is excluded for $0.8 < M_{Z'} < 5.0$ GeV/c²

Leptophilic Z' search (Belle II)

arXiv:2212.03066
submitted to PRL

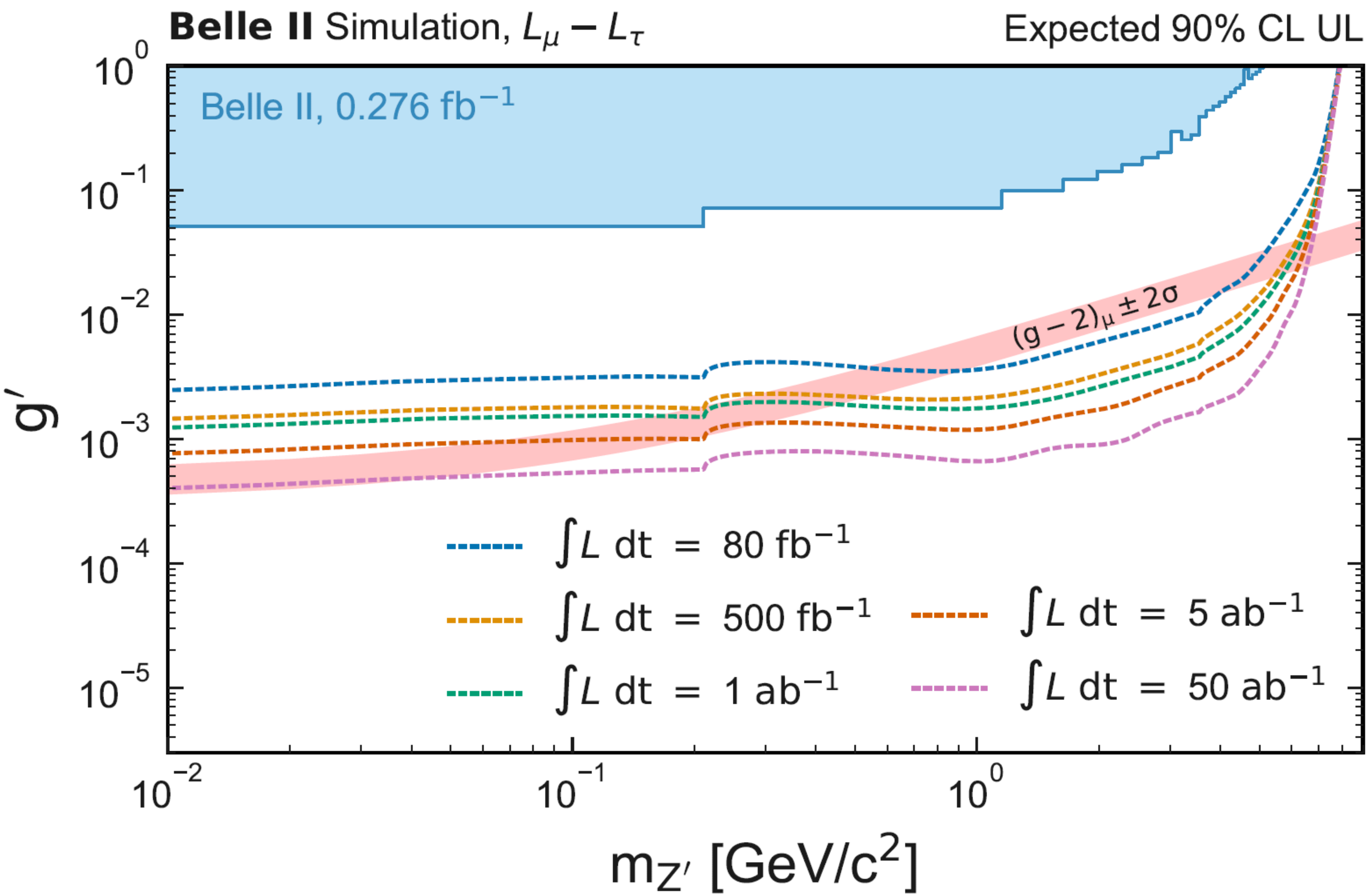


for the "*vanilla*" model (Z' to SM only)



Leptophilic Z' search (Belle II *prospects*)

arXiv:2207.06307
(Belle II, Snowmass)



Invisible particle search in B decays

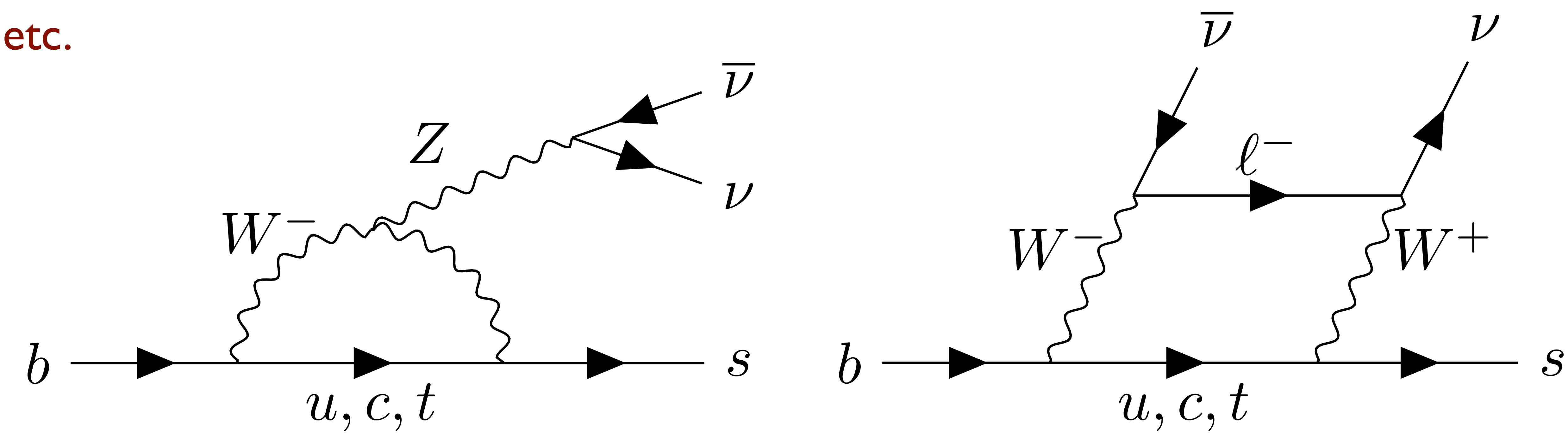
Belle II PRL 127, 181802 (2021)
Belle PRD 105, L051101 (2022)

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).

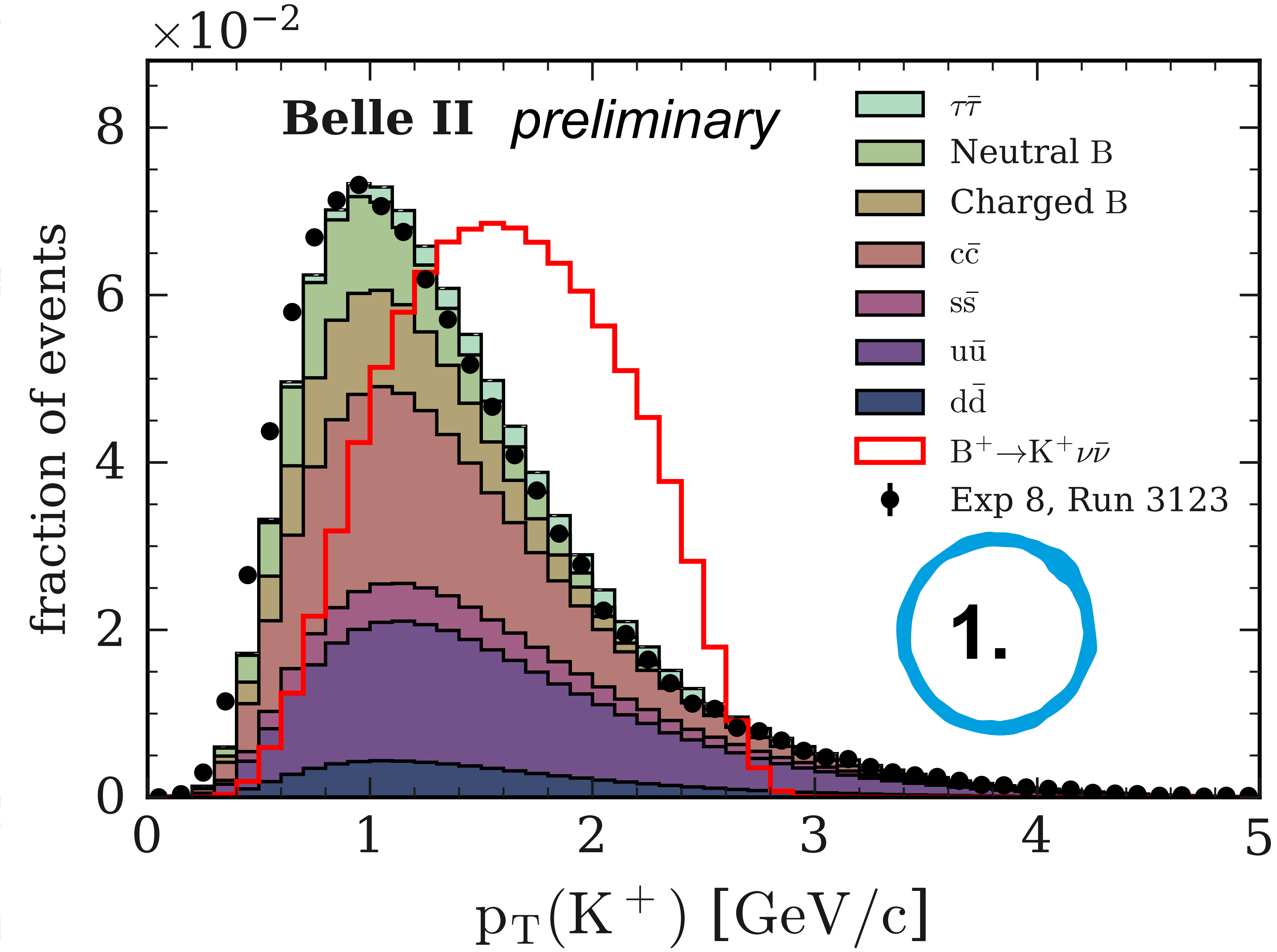
- sensitive to new physics BSM, e.g.
  - leptoquarks,
  - axions,
  - DM particles, etc.



(a) Penguin diagram (b) Box diagram

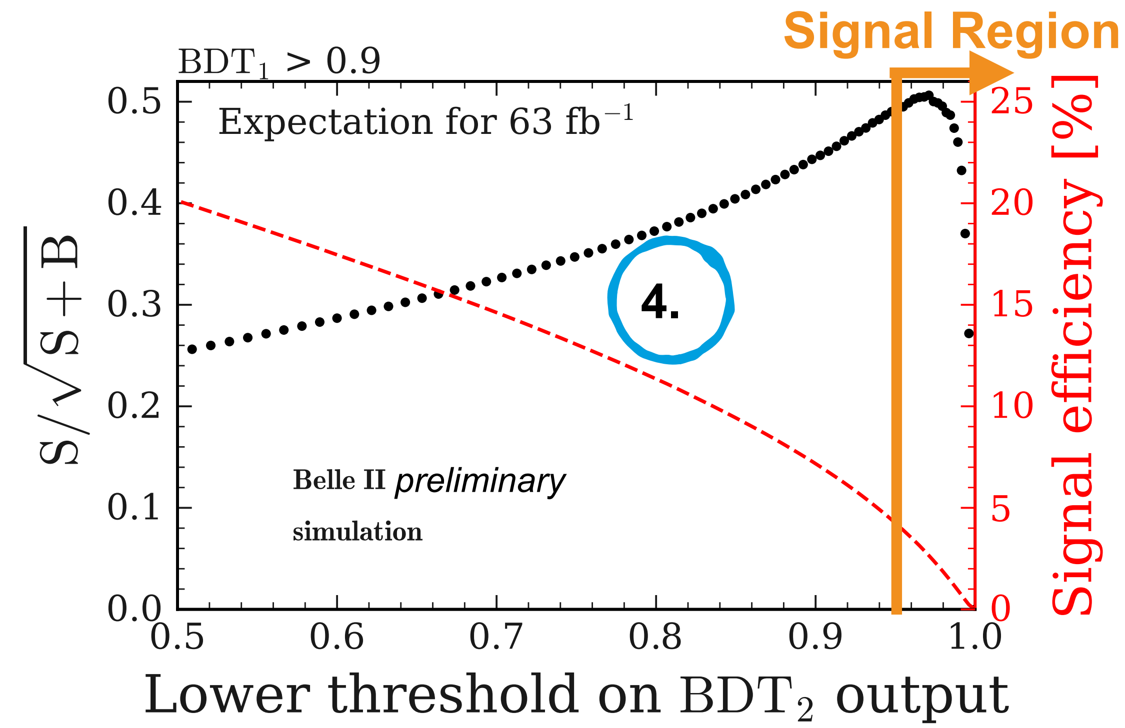
$B^+ \to K^+ \nu\bar{\nu}$ at Belle II

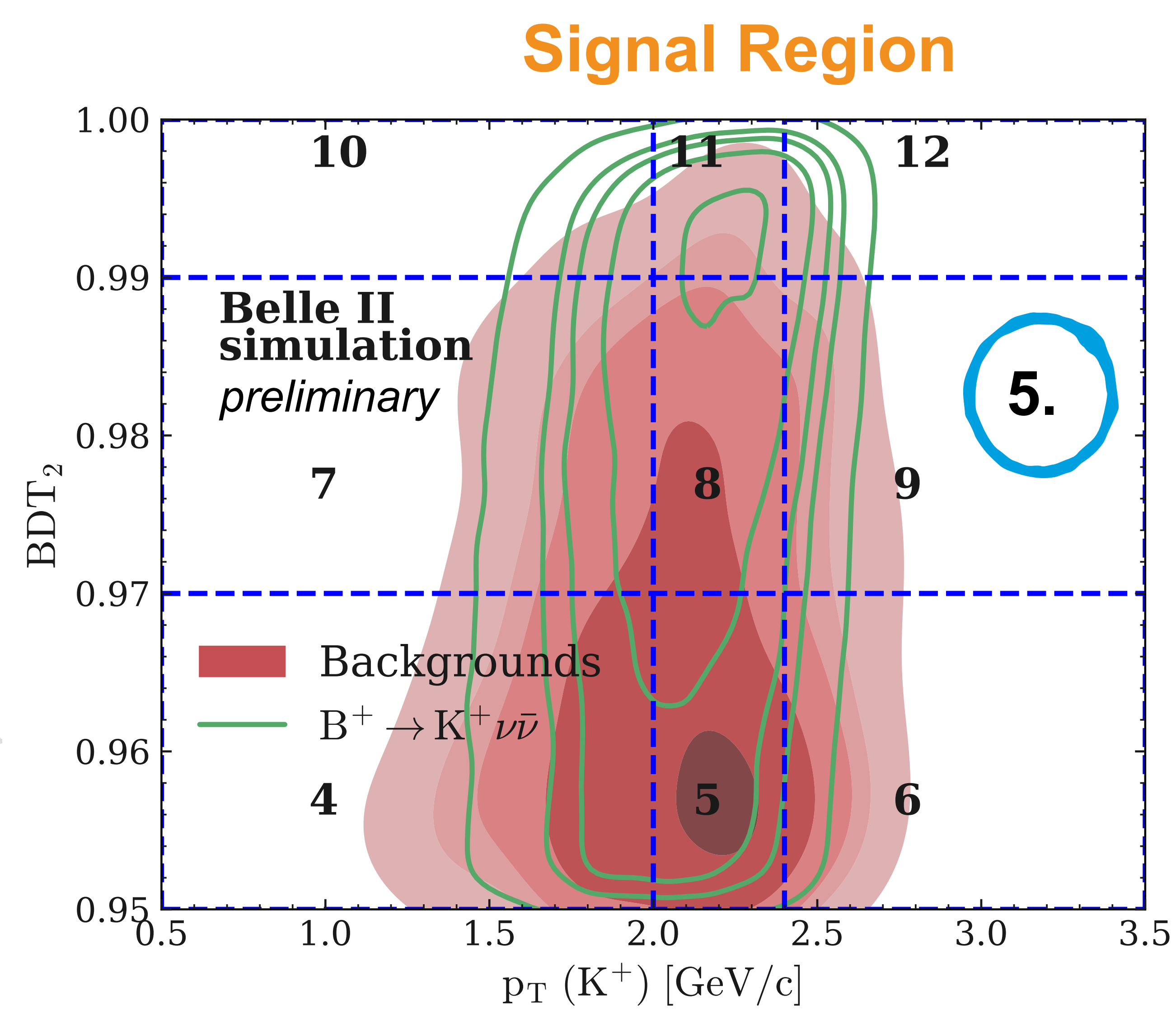
1. loose tagging ➔ find signal K^+ — track of highest p_T w/ at least 1 PXD hit ($\varepsilon \sim 80\,\%$)
2. all other tracks & clusters ⇒ "ROE" (rest of th
3. BDT for signal discrimination
   use event-shape, ROE dynamics, B_{sig} kinematics, ve
4. BDT_1 & BDT_2 (consecutive applications)
   ∵ to 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

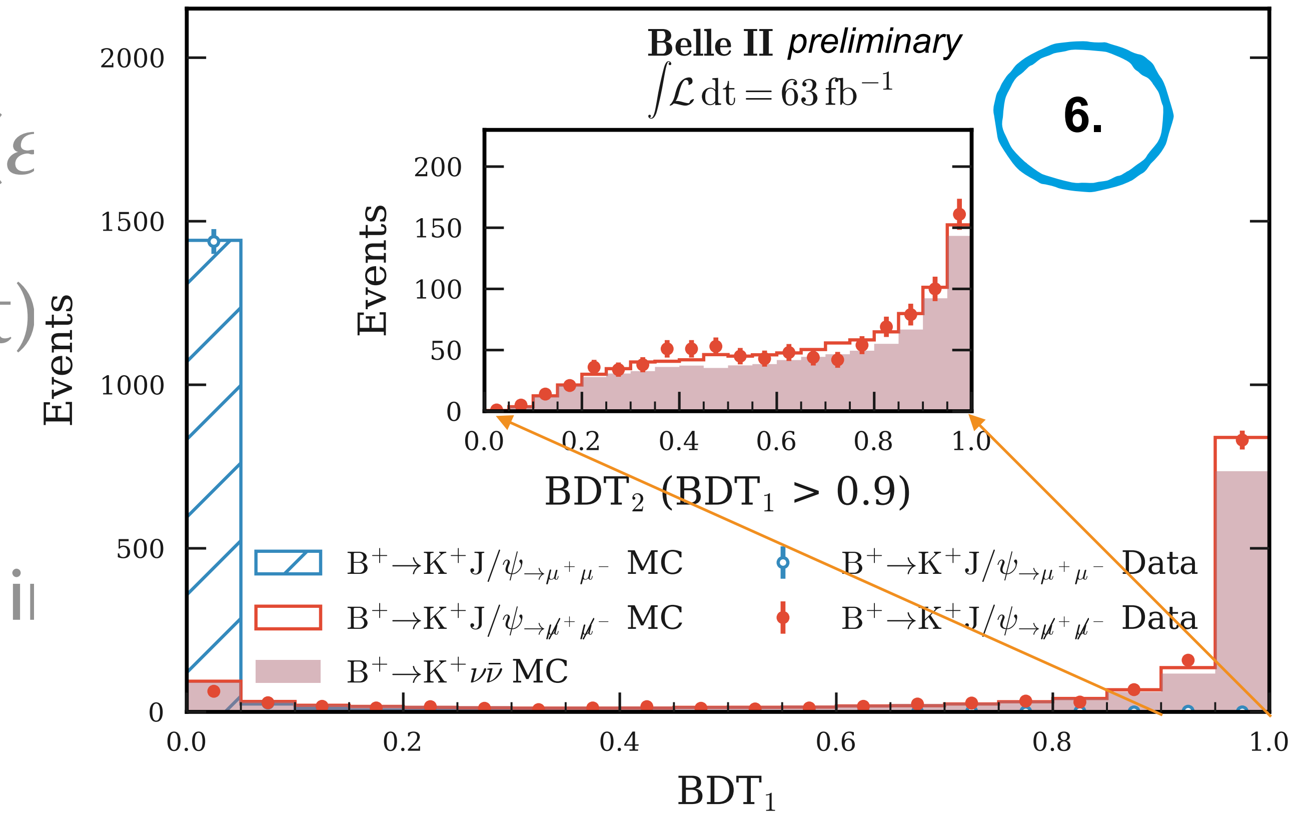
1. signal K^+ — track of highest p_T w/ at least 1 PXD hit ($\varepsilon \sim$
2. all other tracks & clusters ⇒ "ROE" (rest of the event)
3. BDT for signal discrimination
   use event-shape, ROE dynamics, B_{sig} kinematics, vertexing info.
4. BDT_1 & BDT_2 (consecutive applications)
   ∵ to suppress 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

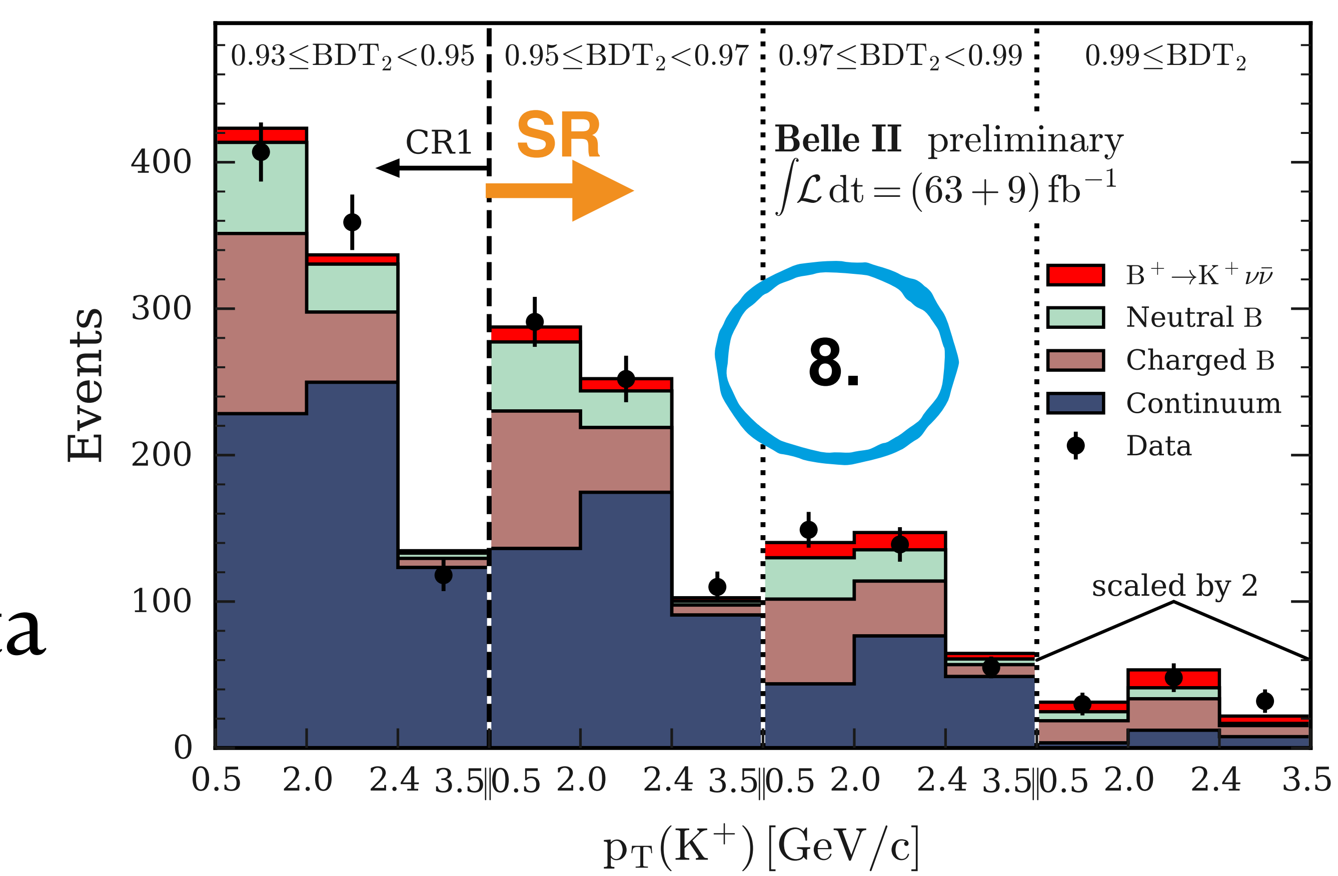




$B^+ \to K^+\nu\bar{\nu}$ at Belle II

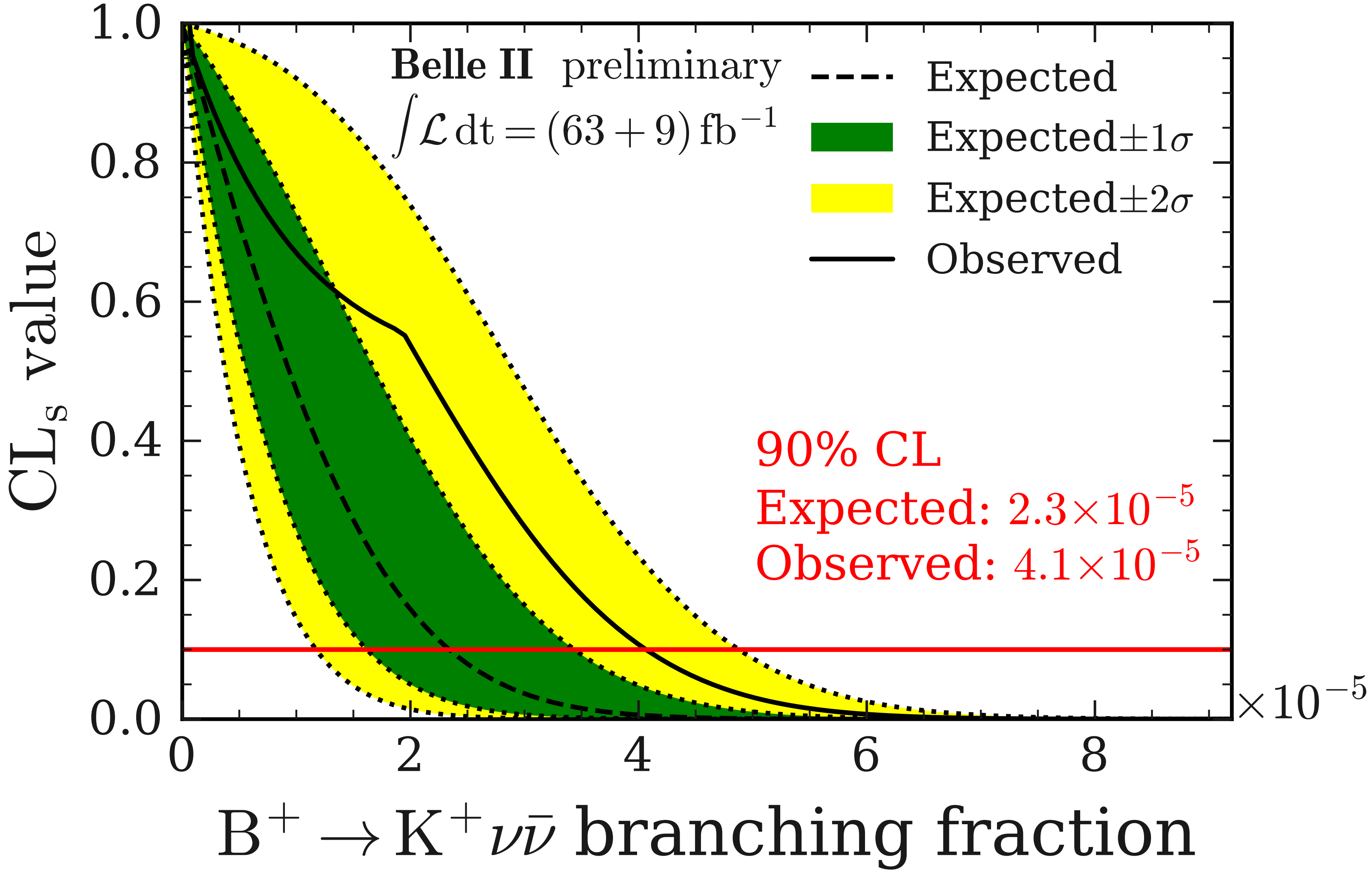
1. signal K^+ — track of highest p_T w/ at least 1 PXD hit (ε
2. all other tracks & clusters ⇒ "ROE" (rest of the event)
3. BDT for signal discrimination
   use event-shape, ROE dynamics, B_{sig} kinematics, vertexing i
4. BDT_1 & BDT_2 (consecutive applications)
   ∵ to suppress two different bkgds : 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

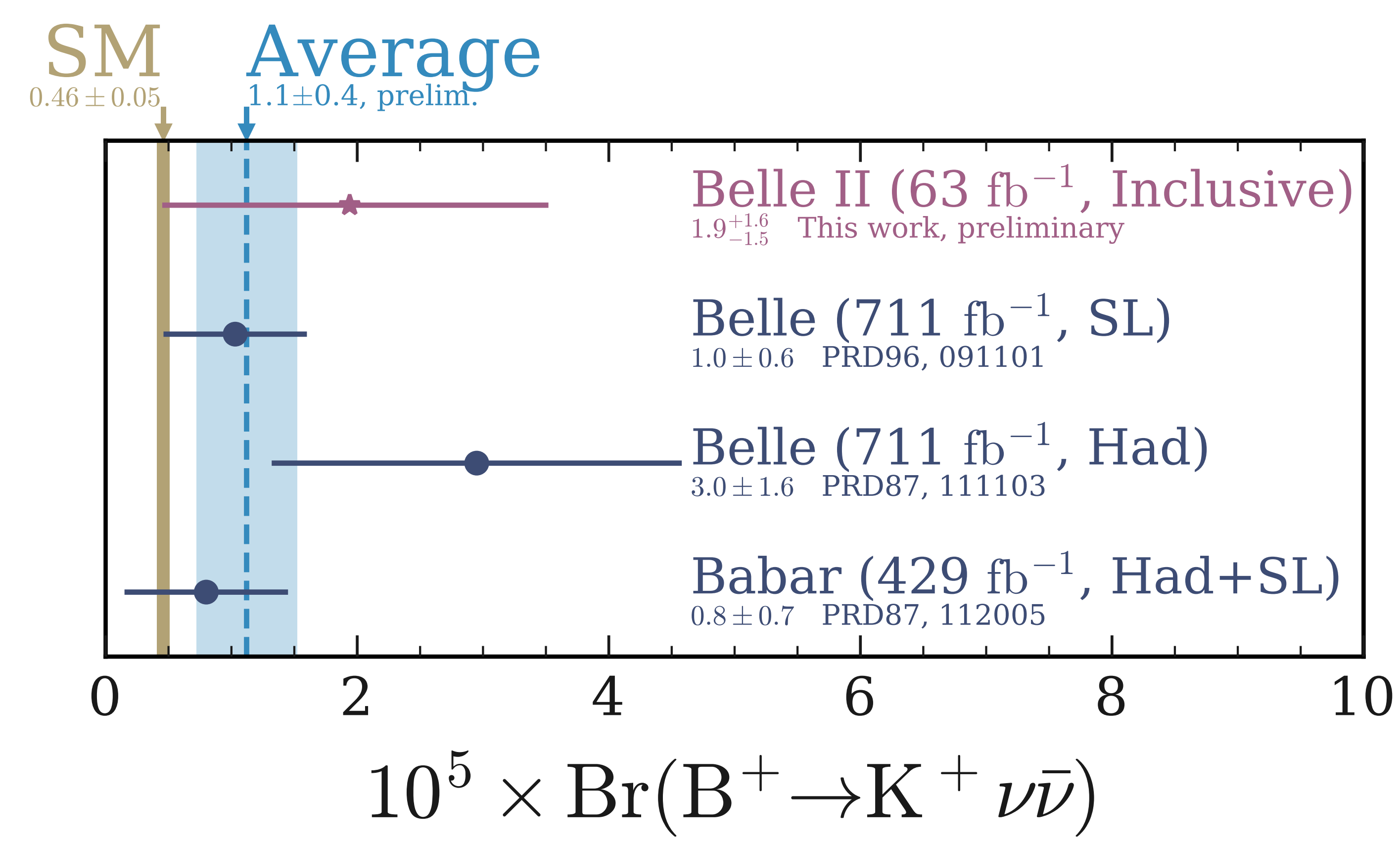




PRL 127, 181802 (2021)

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





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

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

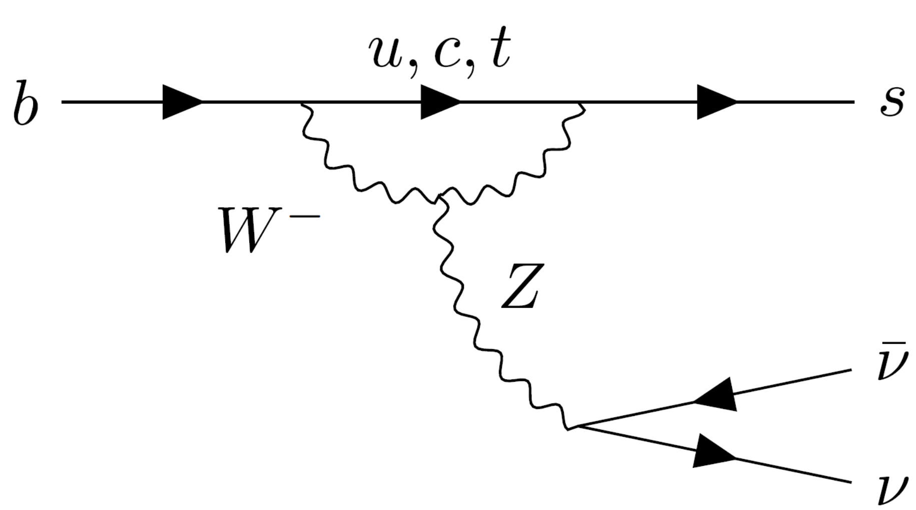
Junewoo Park
Yonsei HEP

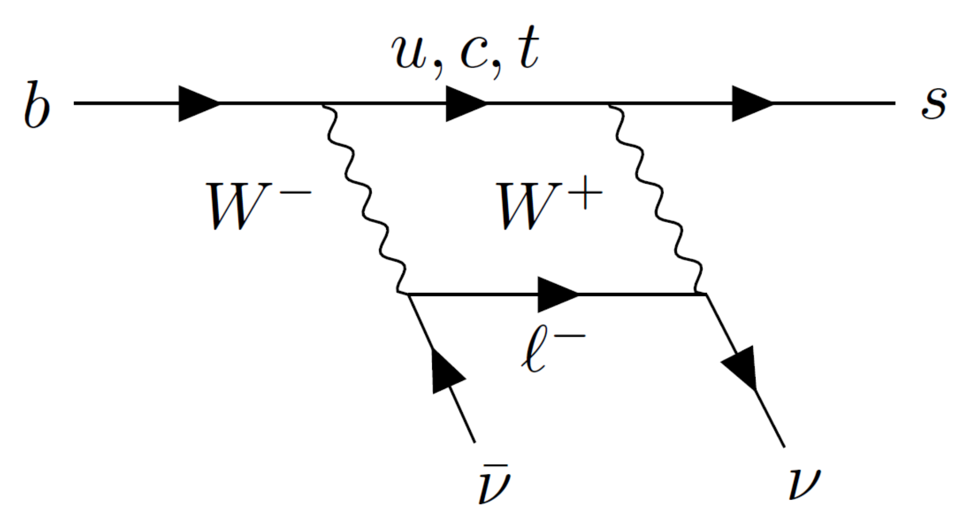
Search for $B \to X_s \nu\bar{\nu}$ (inclusive)

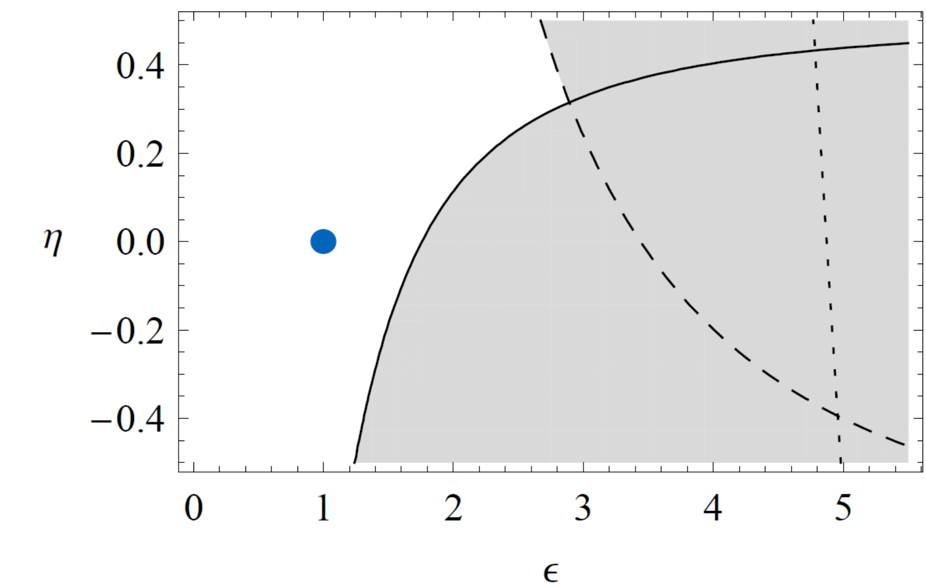
Motivation

- $B \to X_s \nu\bar{\nu}$ 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

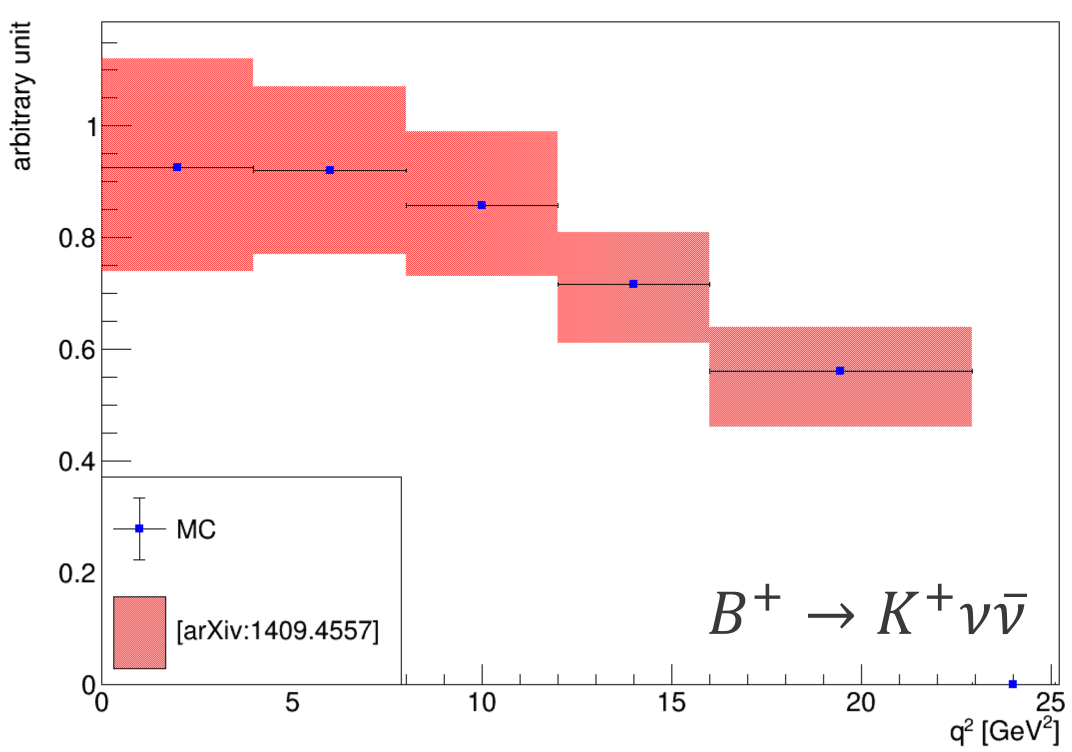
Event Generation

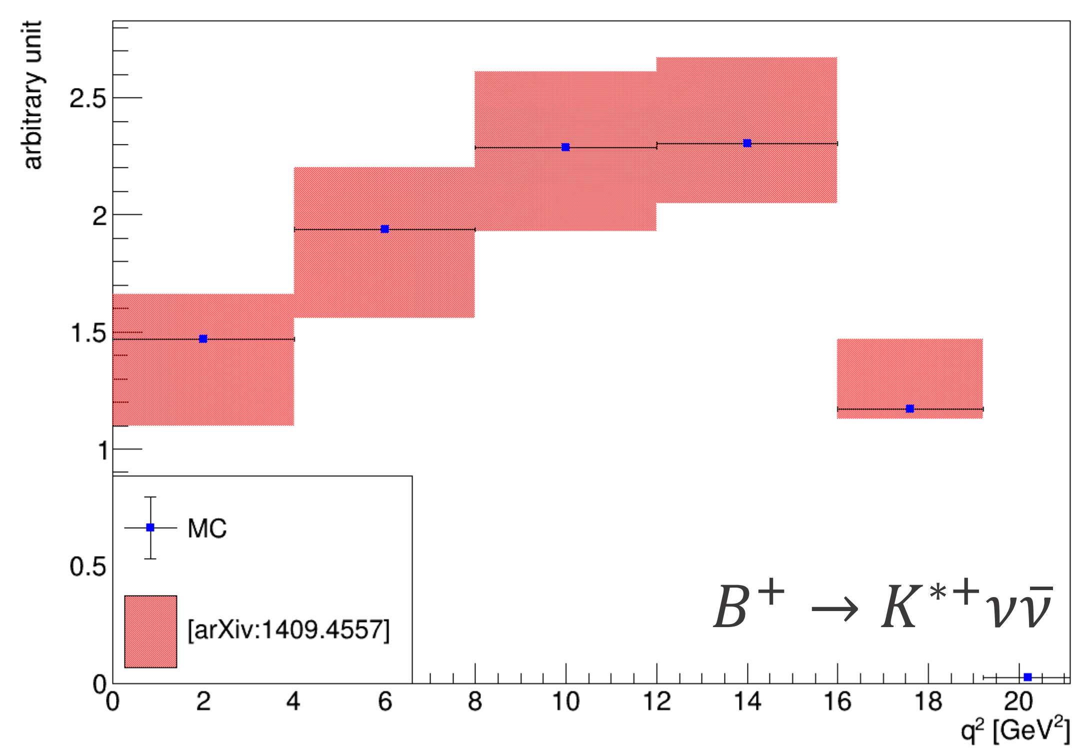
- For Monte-Carlo study, signal samples are produced according to SM *†‡

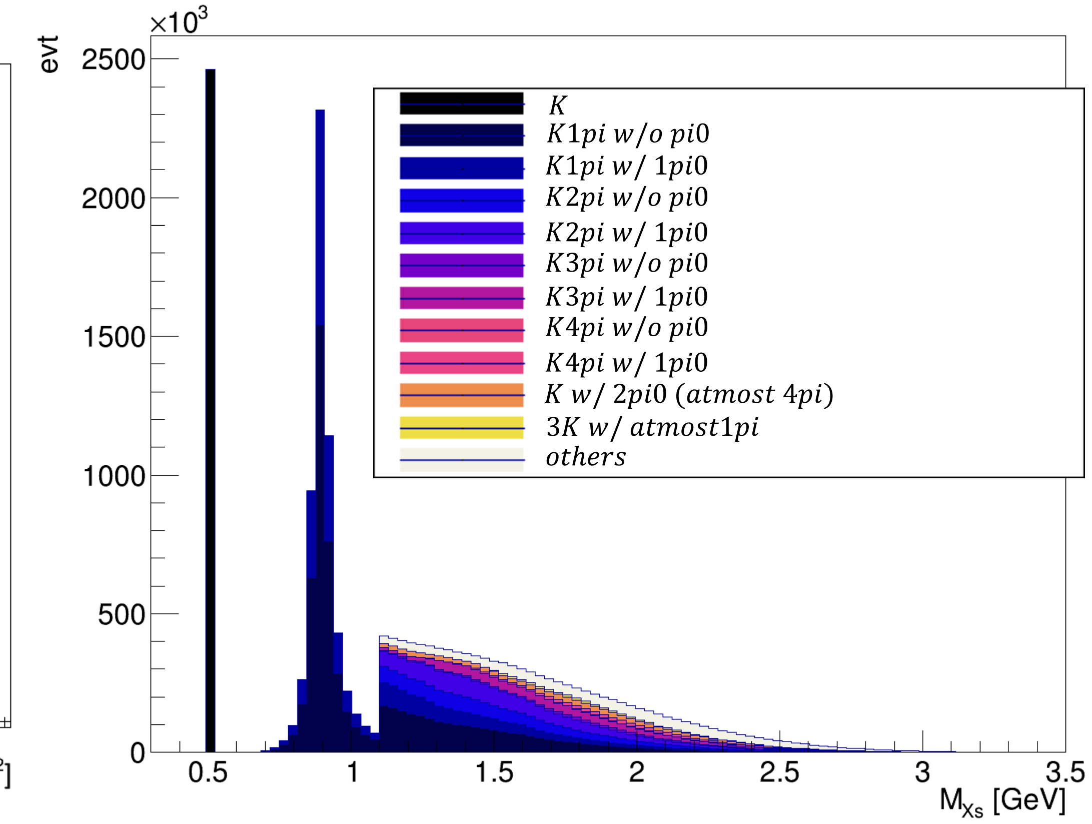
$$\mathcal{M}(B \to K\nu\bar{\nu}) \propto f_+(q^2)\left\{(p_B + p)_\mu - \frac{m_B^2 - m_K^2}{s} q_\mu\right\}(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)\text{, where } q^2 = (p_\nu + p_{\bar{\nu}})^2$$

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

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







* 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.

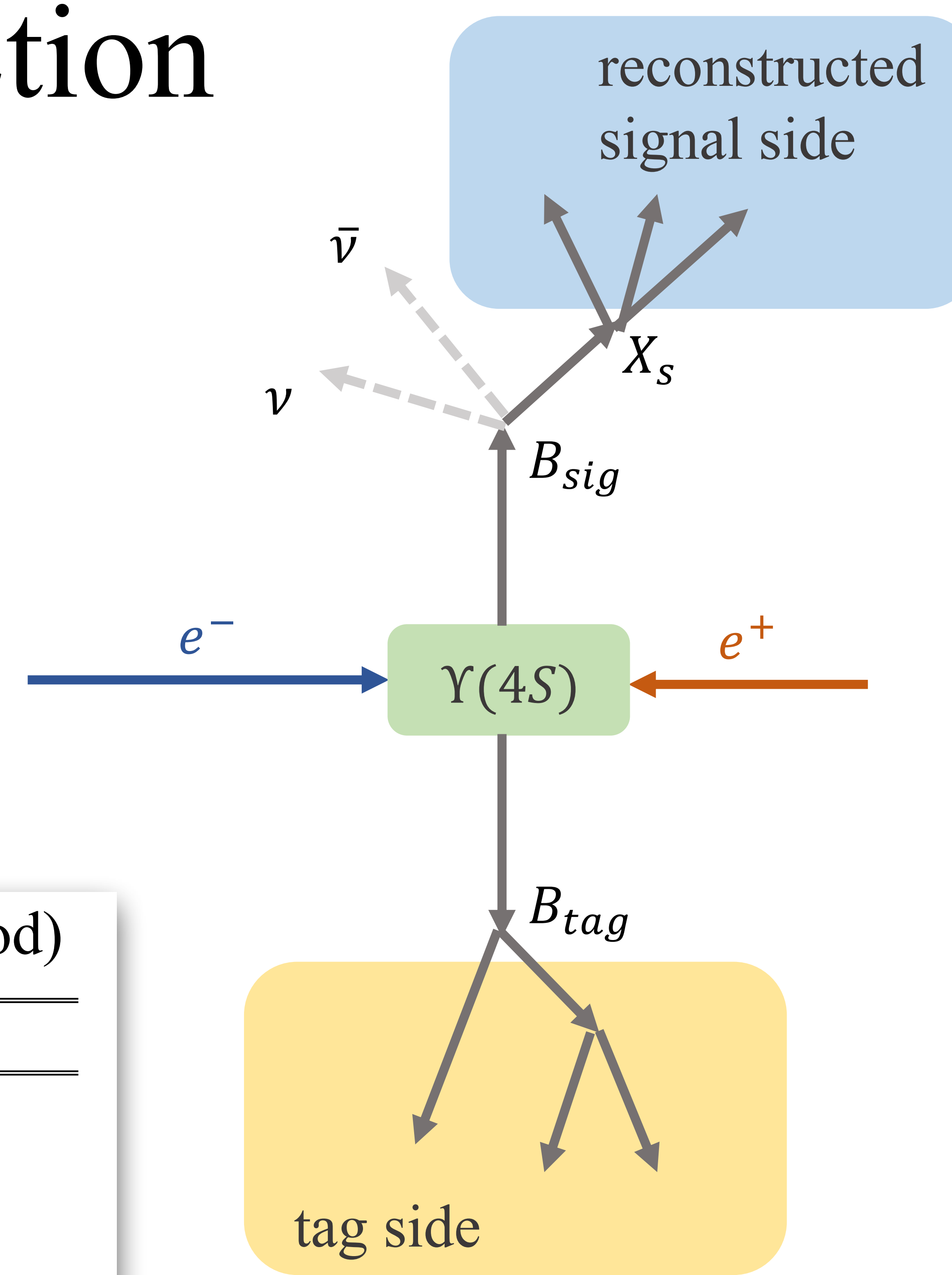
† Buras, Andrzej J., et al. " $B \to K^{(*)}\nu\bar{\nu}$ decays in the Standard Model and beyond." Journal of High Energy Physics 2015.2 (2015): 1-39.

‡ 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.

3

Reconstruction and Event Selection

- In $B \rightarrow X_s \nu \bar{\nu}$ 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

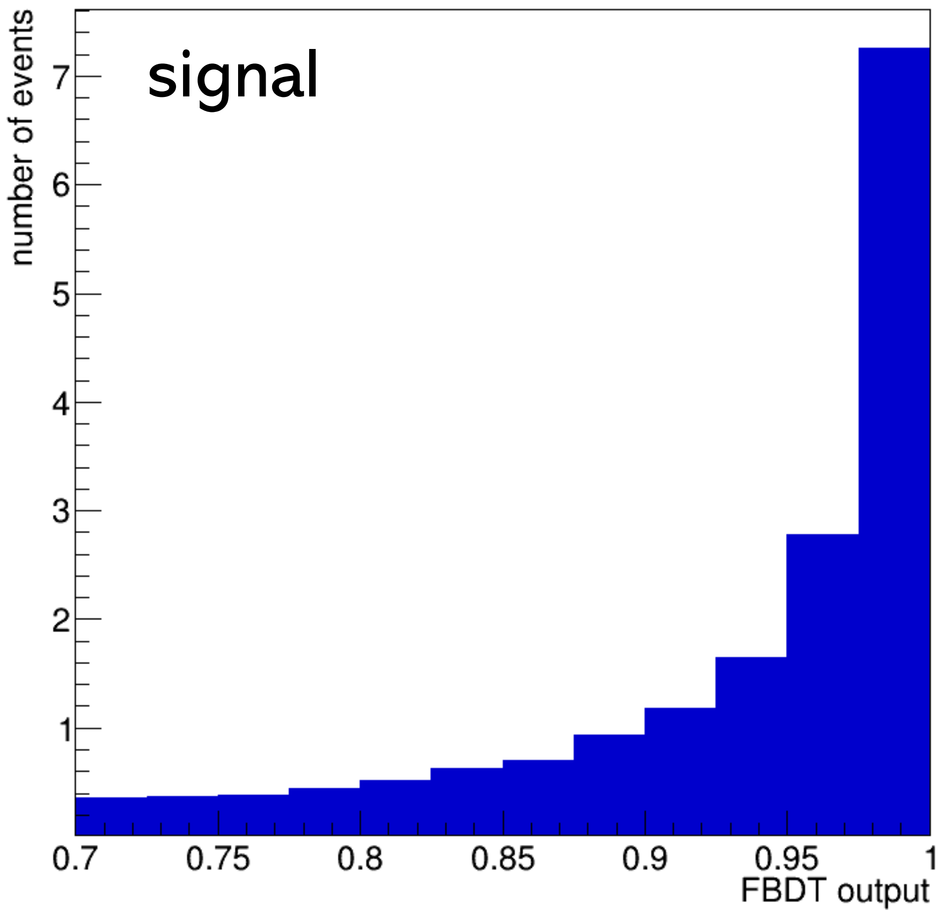


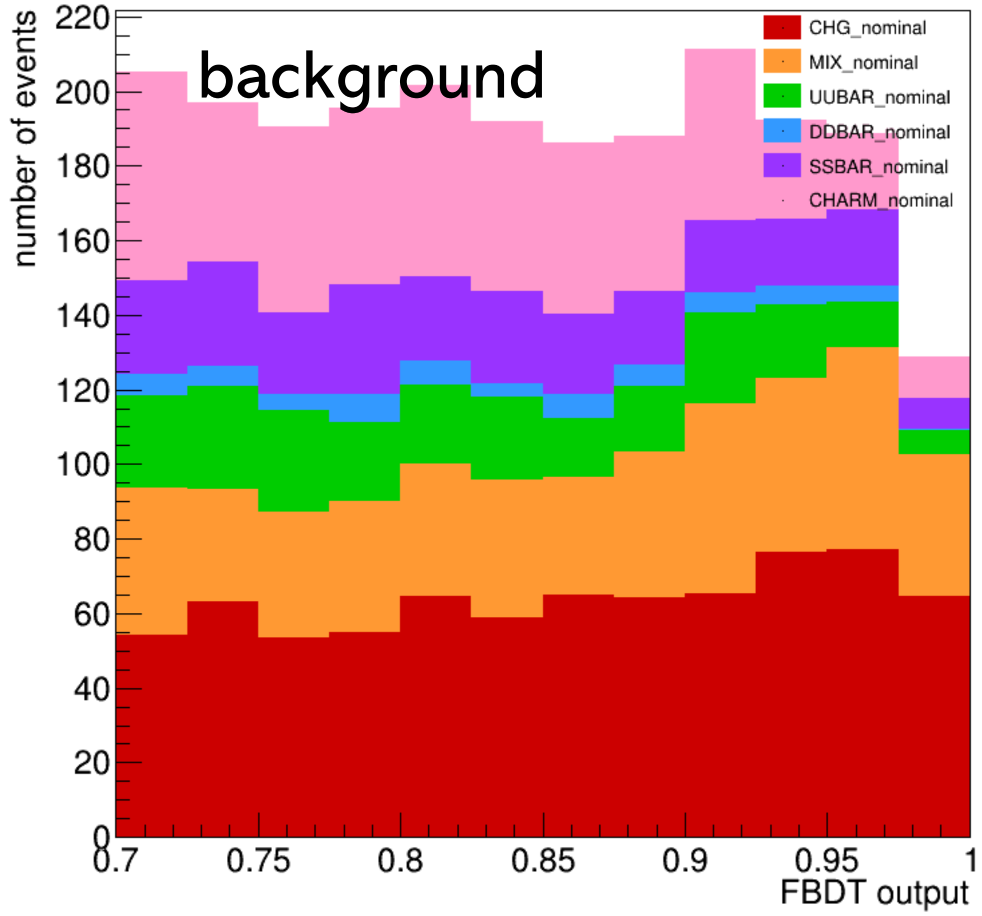
- X_s is reconstructed by 24 decay modes (sum of exclusive method)

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

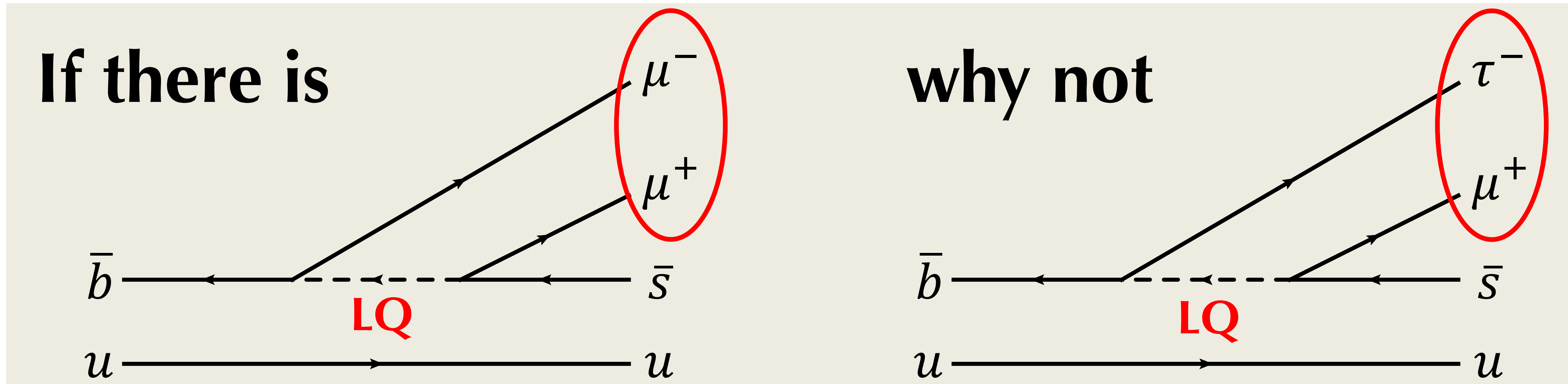
Fitting and Limit Setting

- 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





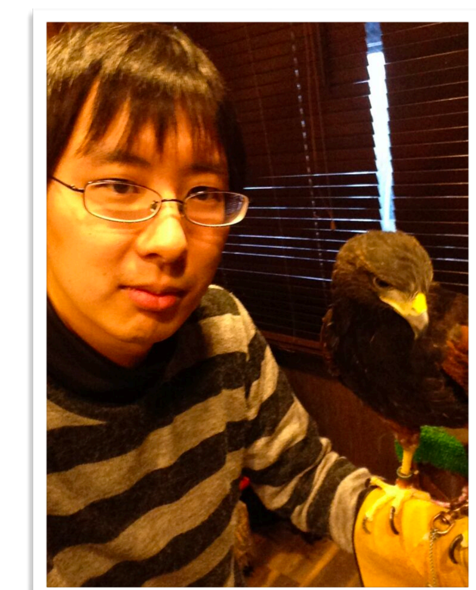
Search for $B^+ \to K^+\tau^\pm\ell^\mp$ (LFV)



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

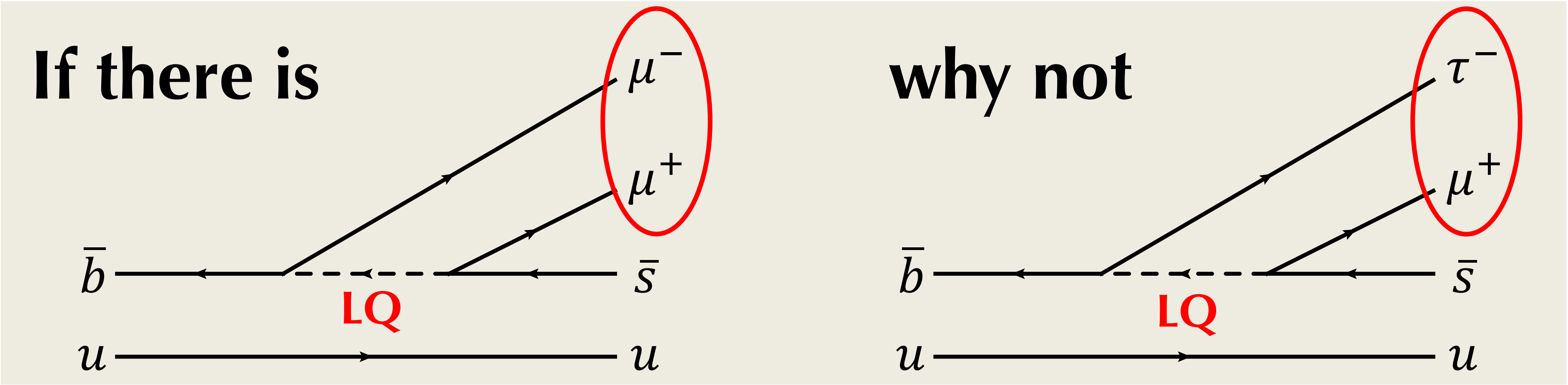
S. Watanuki, G. de Marino, K. Trabelsi, I. Adachi, H. Aihara, D. M. Asner, H. Atmacan, V. Aulchenko, T. Aushev, R. Ayad, V. Babu, Sw. Banerjee, M. Bauer, P. Behera, K. Belous, M. Bessner, V. Bhardwaj, B. Bhuyan, D. Biswas, D. Bodrov, G. Bonvicini, J. Borah, A. Bozek, M. Bračko, P. Branchini, T. E. Browder, 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,

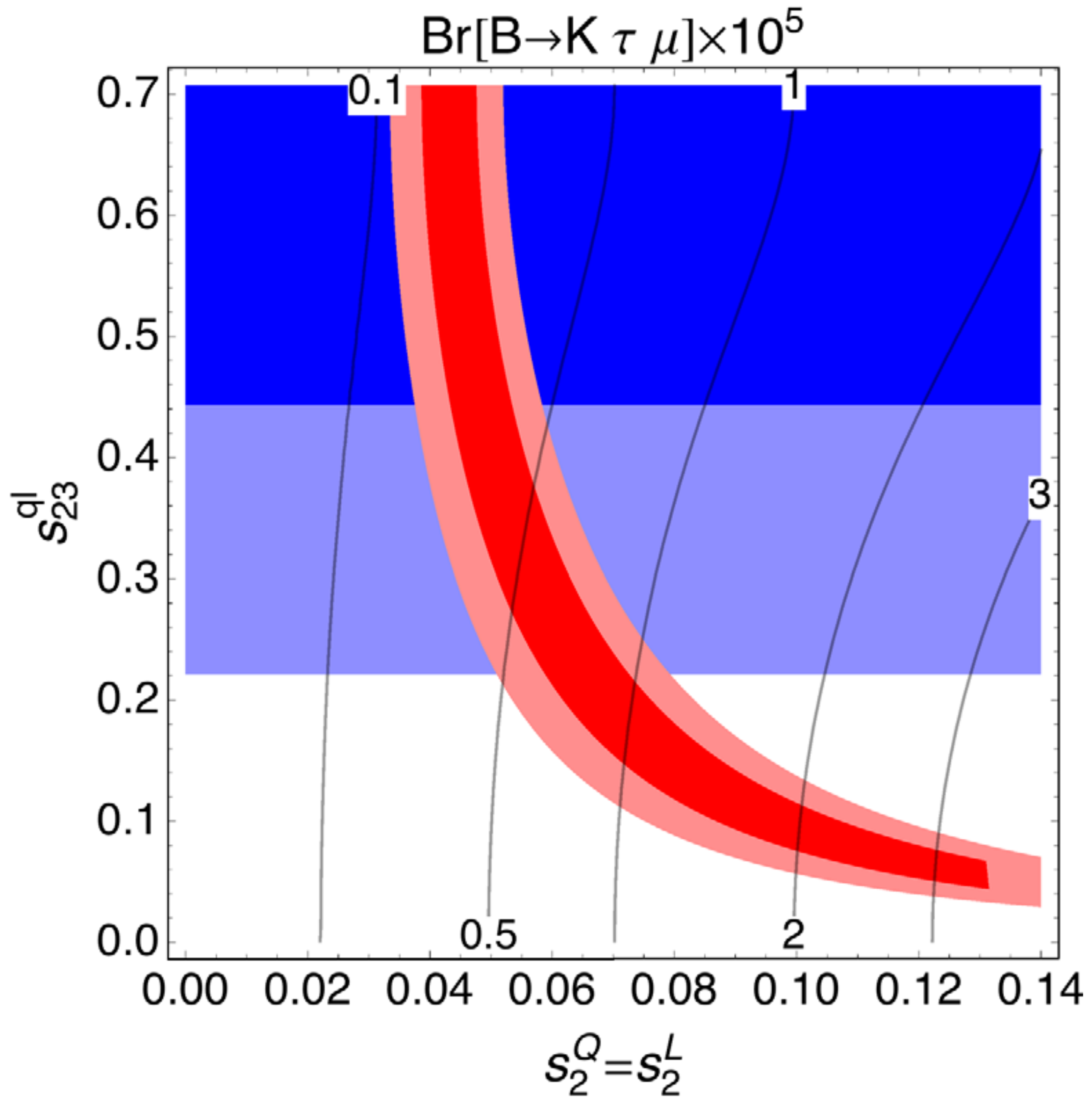


Shun Watanuki
(Yonsei HEP)

Karim Trabelsi

Search for $B^+ \to K^+\tau^\pm\ell^\mp$ (LFV)





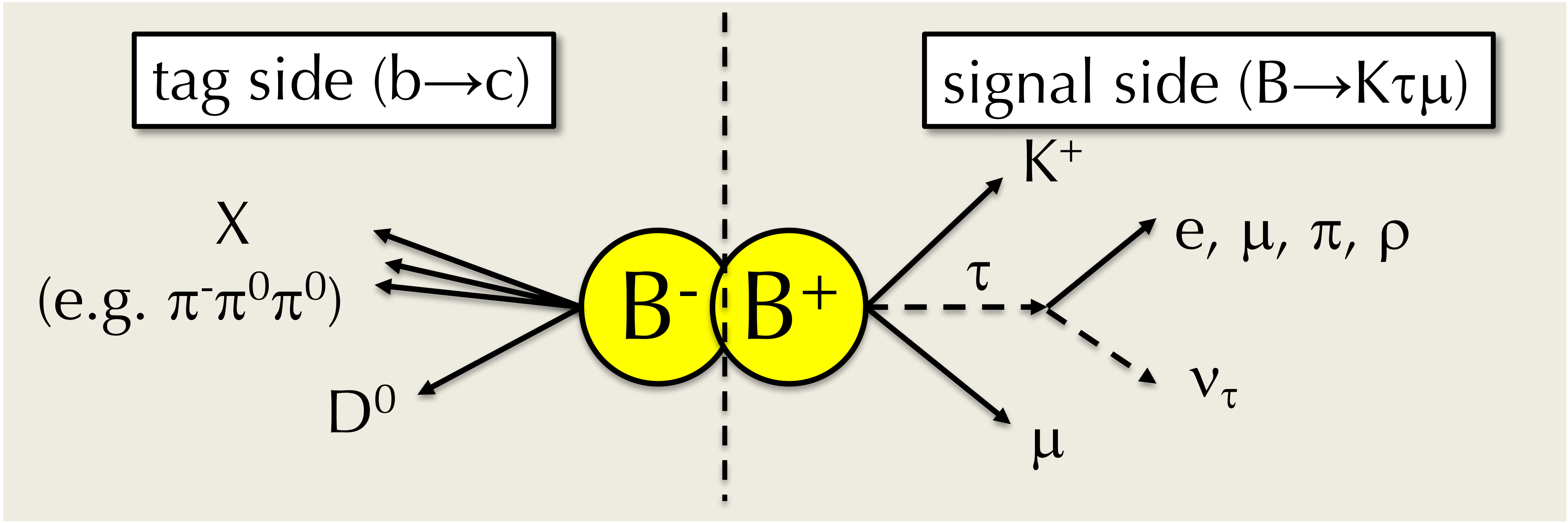
$\mathscr{B}(B \to K\tau\mu) \sim \mathcal{O}(10^{-6})$ is preferred in a certain VLQ model, for instance.

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

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

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

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



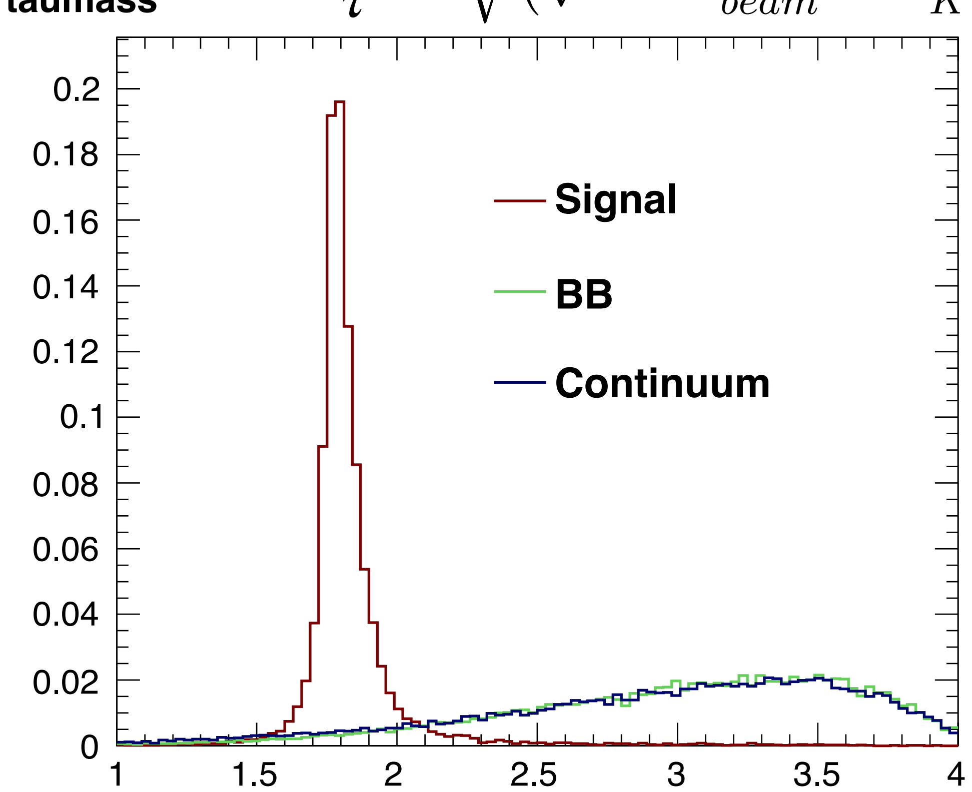
Charged tracks

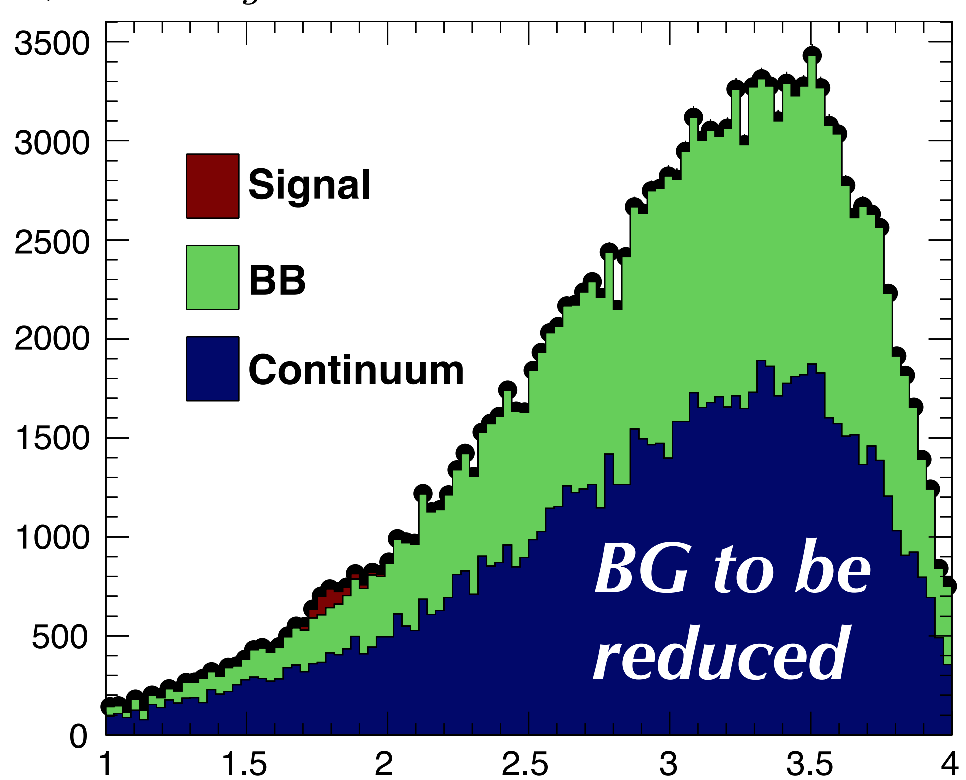
- $PID_\pi > 0.6$ for p^+, $PID_K > 0.6$ for K^+
- mID > 0.9 for μ
- eID > 0.9 for e

Primary tracks (K, μ/e)

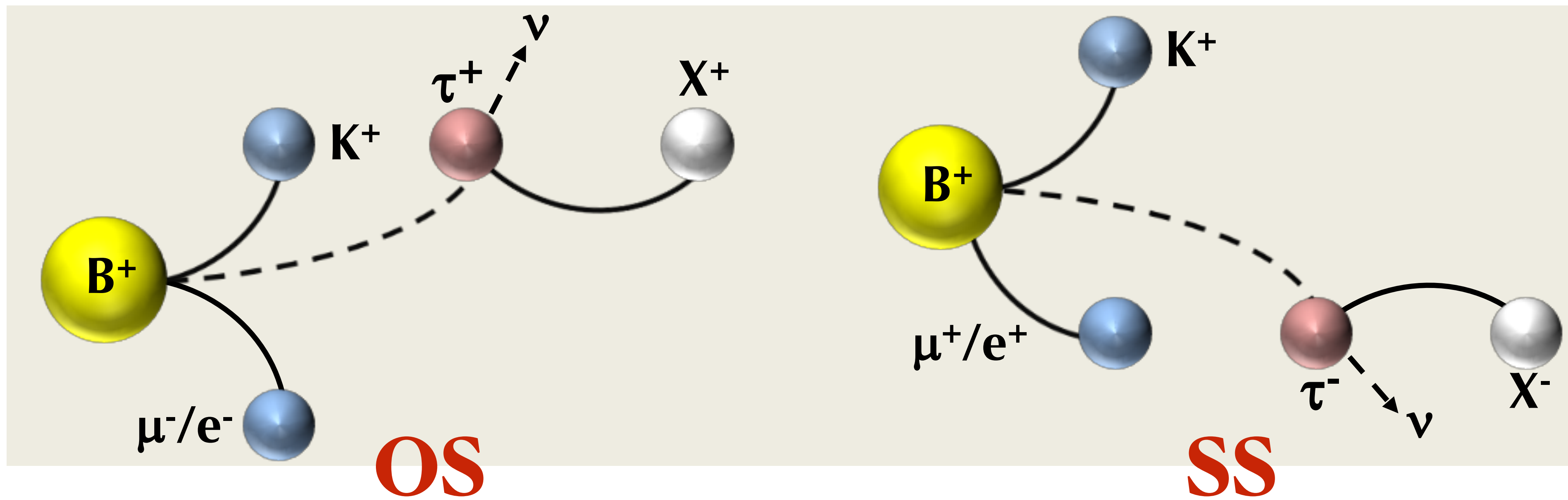
- $|d_0| < 0.5$cm
- $|z_0| < 5.0$cm

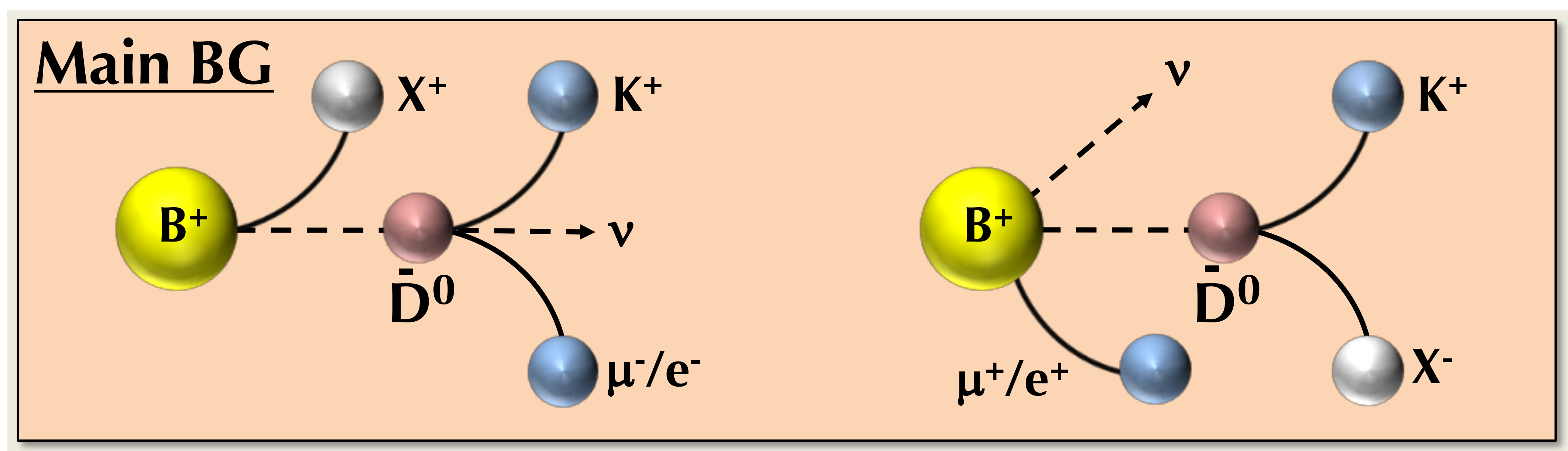
$$M_\tau \equiv \sqrt{(\sqrt{s} - E^*_{beam} - E^*_K - E^*_\ell)^2 - |\vec{p}^*_{tag} - \vec{p}^*_K - \vec{p}^*_\ell|^2}$$



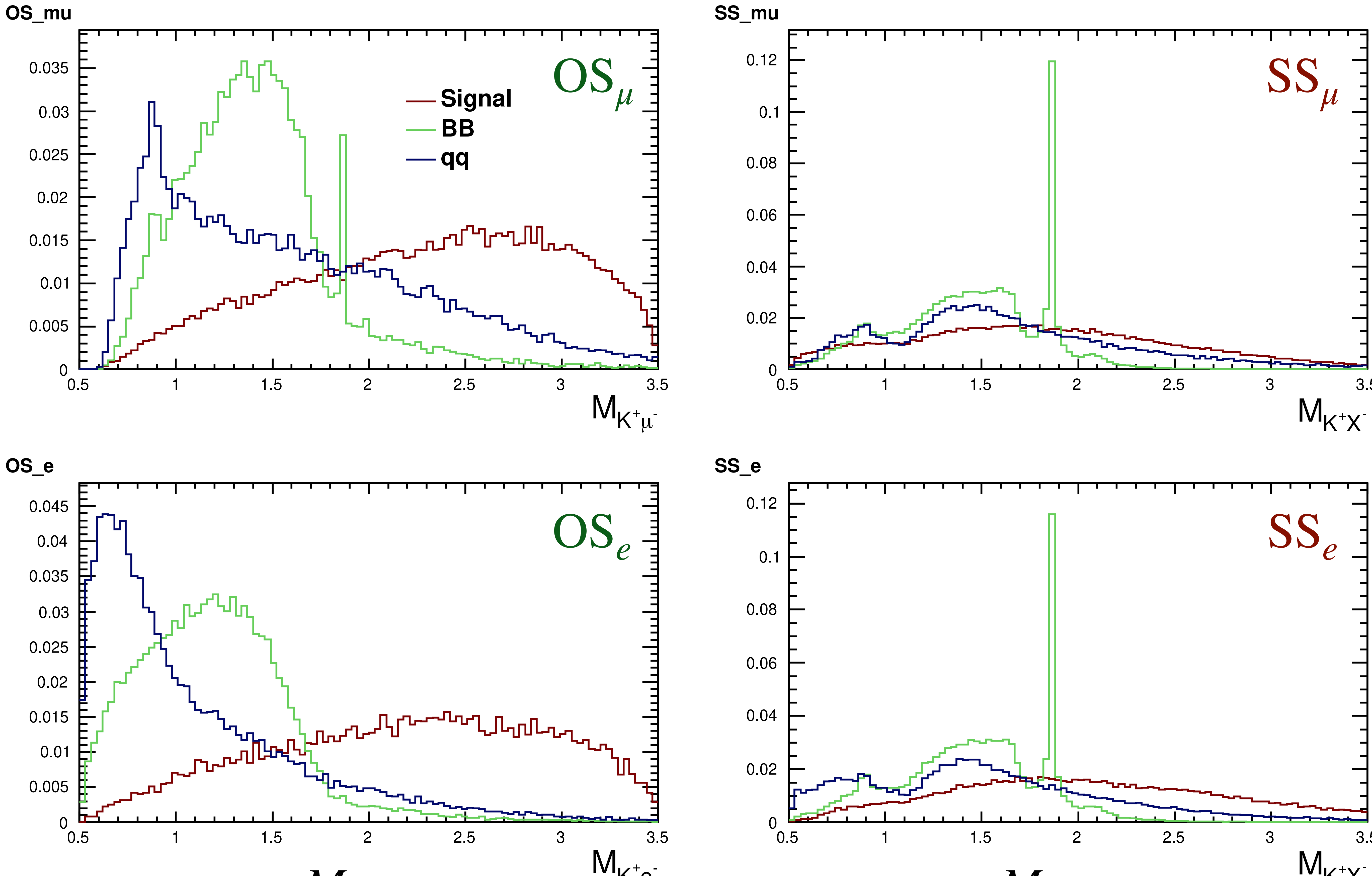


$B^+ \to K^+\tau^+\ell^-$ (OS) vs. $B^+ \to K^+\tau^-\ell^+$ (SS)



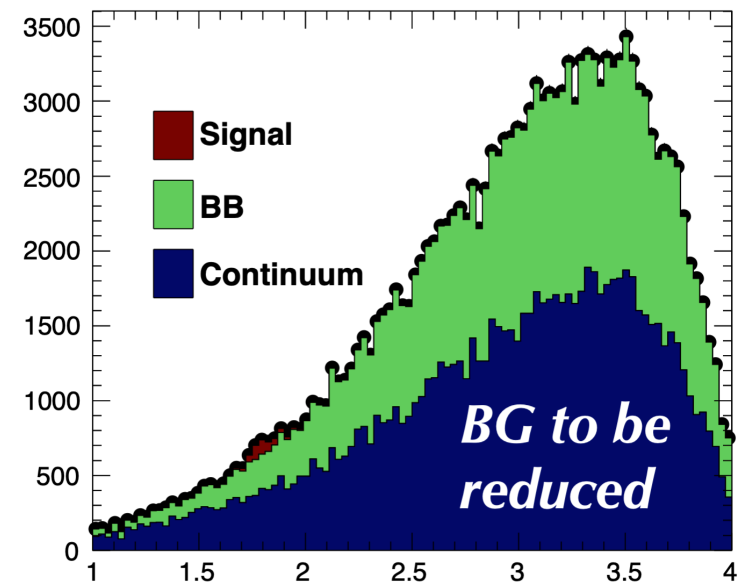


- We must do both (*if only for model independent search*)
- same reconstruction, but very different bkgd.
- Background for SS is much harder to handle


OS_mu
OS$_\mu$
Signal
BB
qq
$M_{K^+\mu^-}$
SS_mu
SS$_\mu$
$M_{K^+X^-}$
OS_e
OS$_e$
$M_{K^+e^-}$
SS_e
SS$_e$
$M_{K^+X^-}$

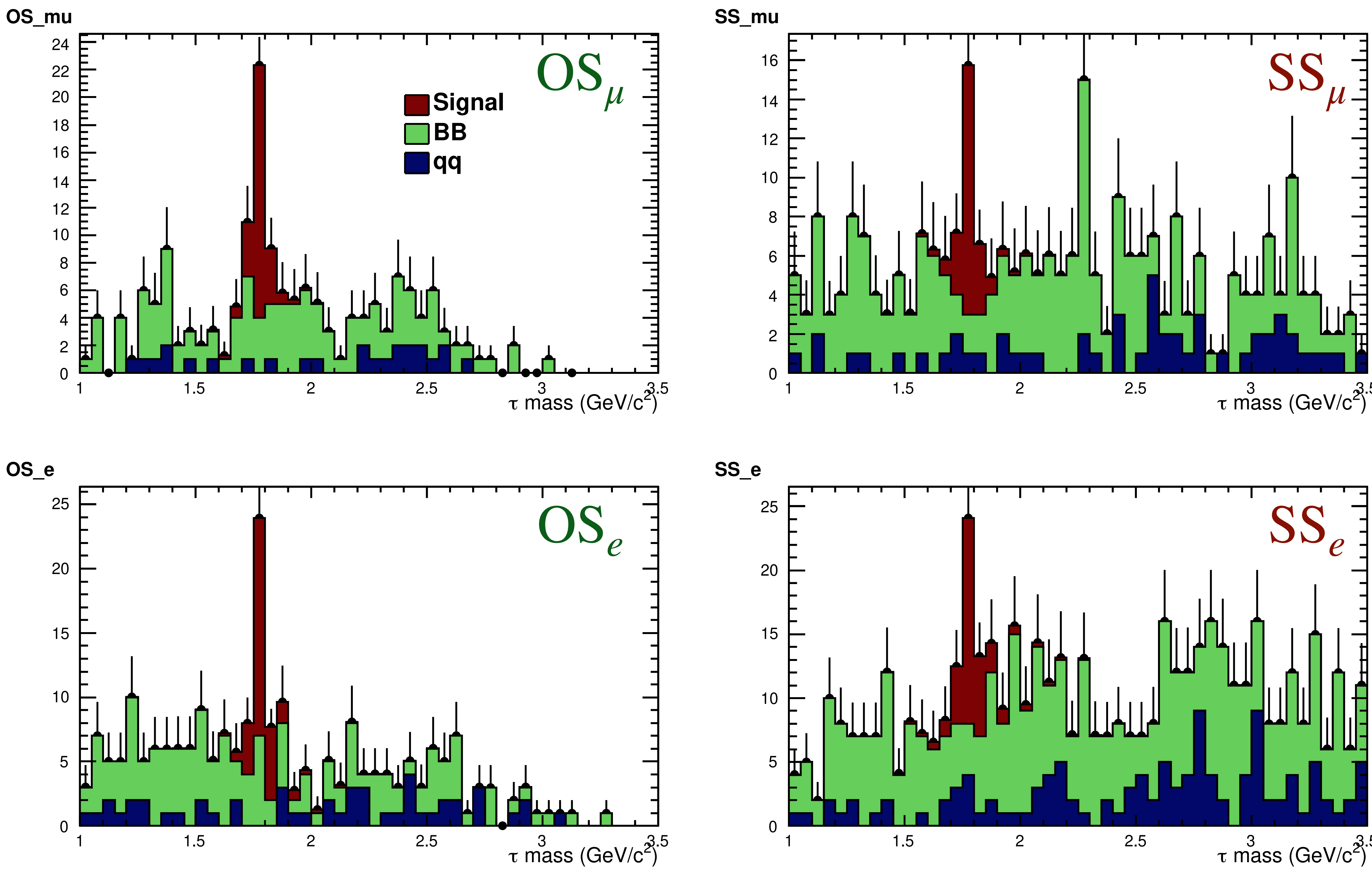
$M_{K^+\ell^-}$ $M_{K^+X^-}$

arXiv:2212.04128
submitted to PRL

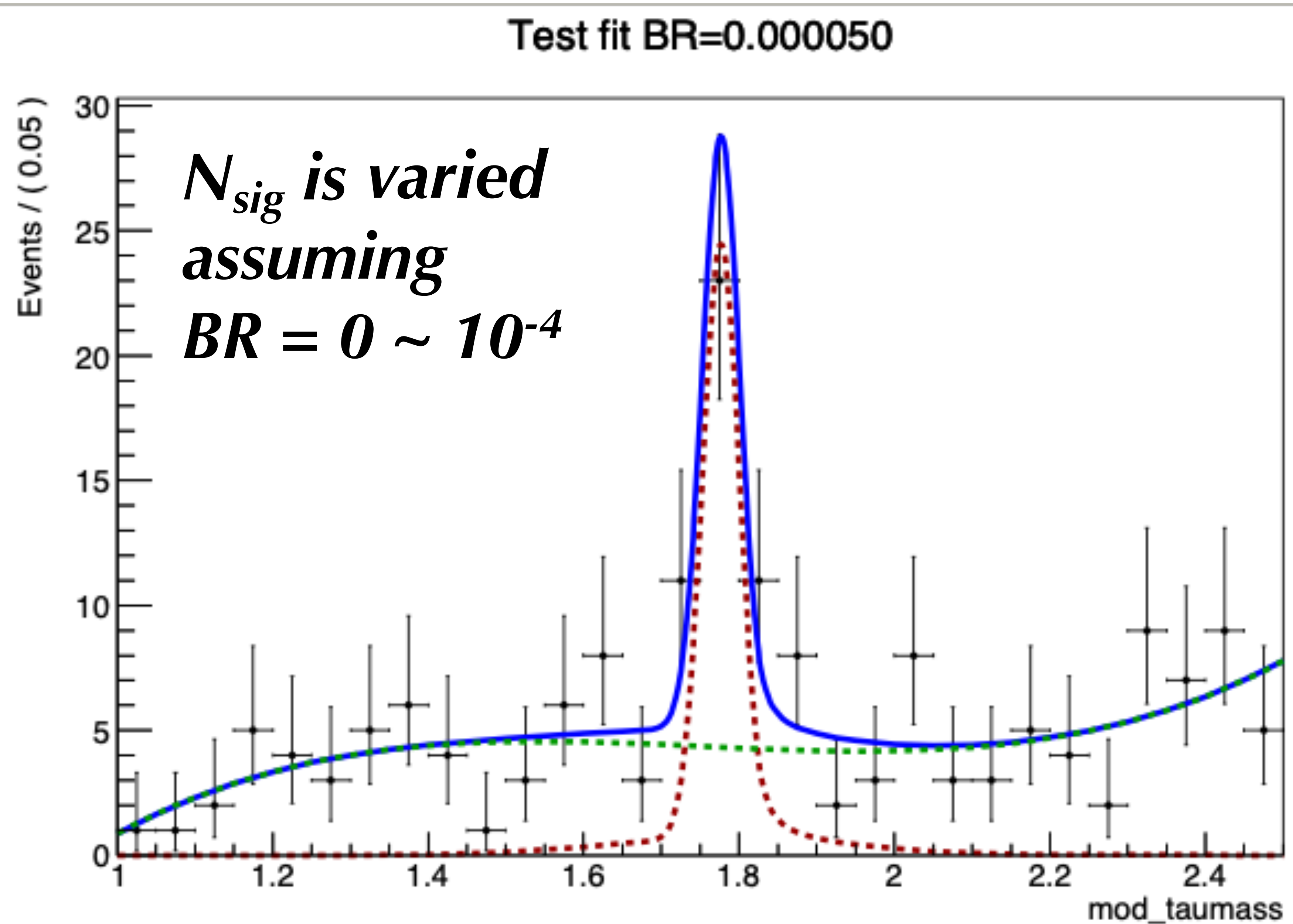


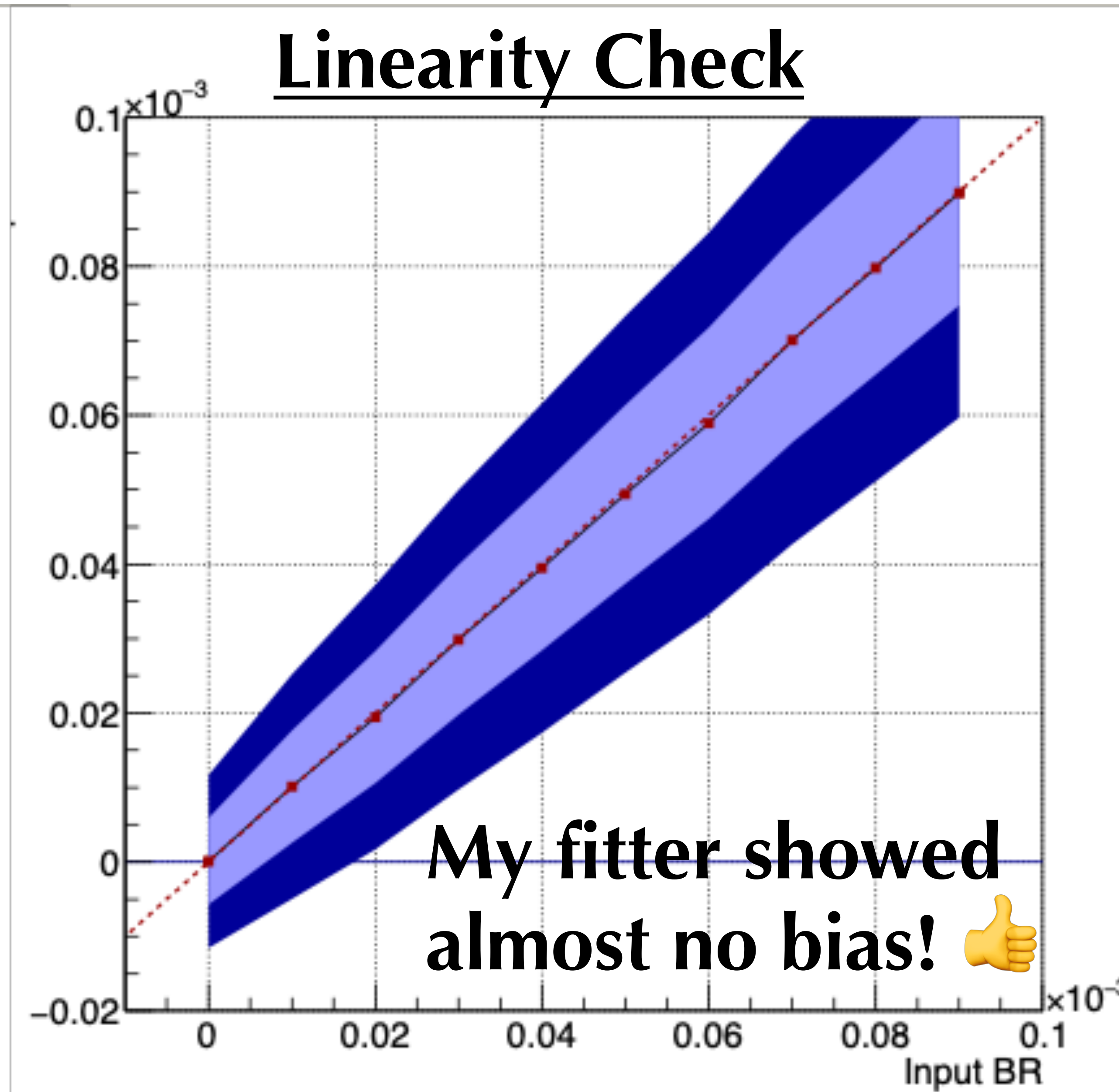
M_τ before FBDT

M_τ after FBDT

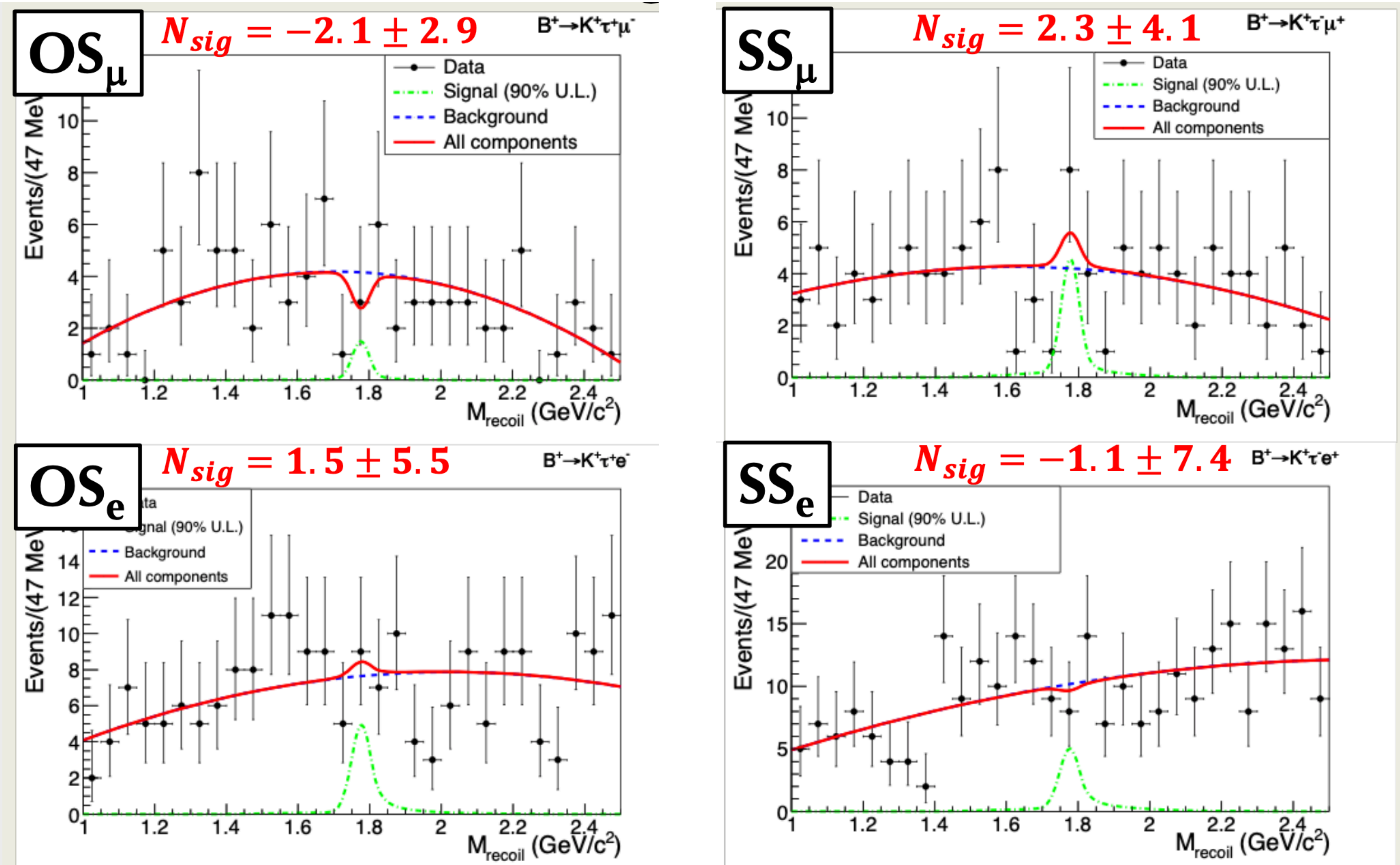


$B^+ \to K^+\tau^\pm\ell^\mp$ — linearity check





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



No signal excess in any mode!

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

BR U.L. (90% CL)	OS_μ x10^5	SS_μ x10^5	OS_e x10^5	SS_e x10^5
Babar	<2.8	<4.5	<1.5	<4.3
LHCb	<3.9	-	-	-
Belle (Preliminary)	**<0.65**	**<2.97**	**<1.71**	**<2.08**

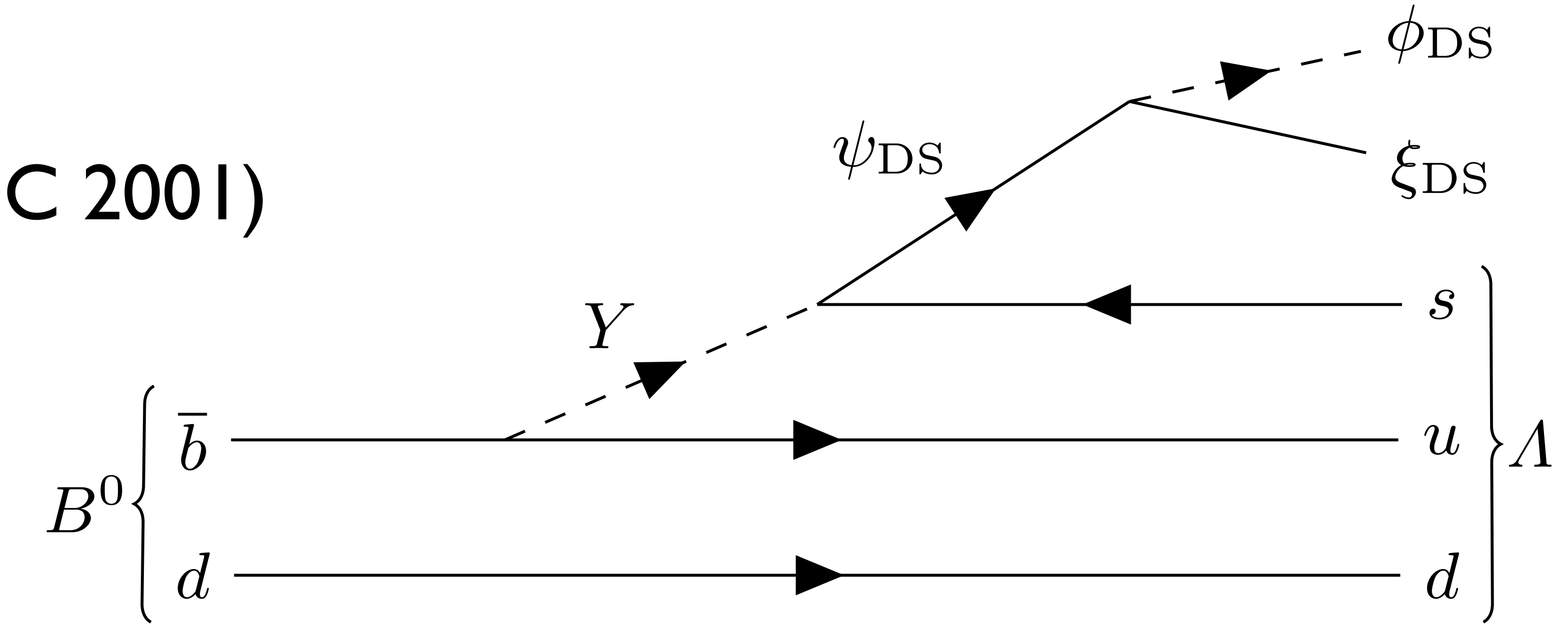
- The most stringent limit on $\mathscr{B}(B^+ \to K^+\tau\ell)$ except for OS_e
- a PRL paper submission is nearly ready ($\mathscr{O}$(week) or so)

FYI
Recently LHCb set U.L. on $\boldsymbol{B^0 \to K^{*0}\tau\mu}$ modes:
$BR(B^0 \to K^{*0}\tau^+\mu^-) < 1.0\times10^{-5}$ (90% CL)
$BR(B^0 \to K^{*0}\tau^-\mu^+) < 0.8\times10^{-5}$ (90% CL)
2022/10/20 S. Watanuki @KPS (Busan)

Our OS_μ *is more stringent!*

Search for $B^0 \to \Lambda\psi_{\rm DS}$

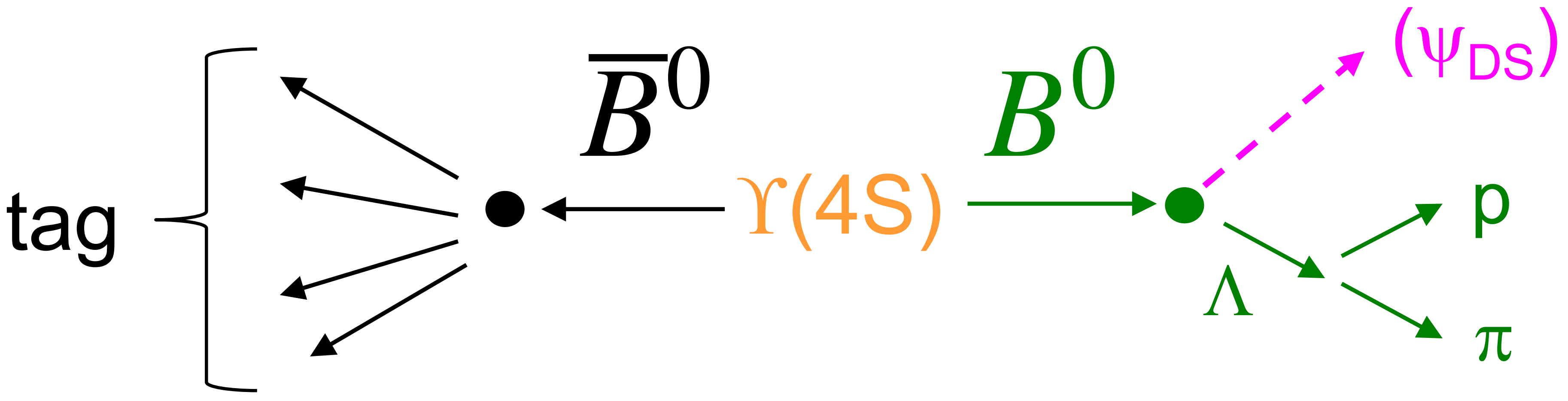
- B-mesogenesis — explains Baryogenesis and DM with B decays
  - ✓ Elor, Escudero, Nelson [PRD 99, 035031 (2019)]
  - ✓ predicts $\mathscr{B}(B^0 \to \Lambda\psi_{\rm DS} + \text{meson}) > 10^{-4}$
- Existing limits
  - ✓ $\mathscr{B}(B^0 \to \Lambda\psi_{\rm DS}) \lesssim 2 \times 10^{-4}$ by ALEPH (EPJC 2001)



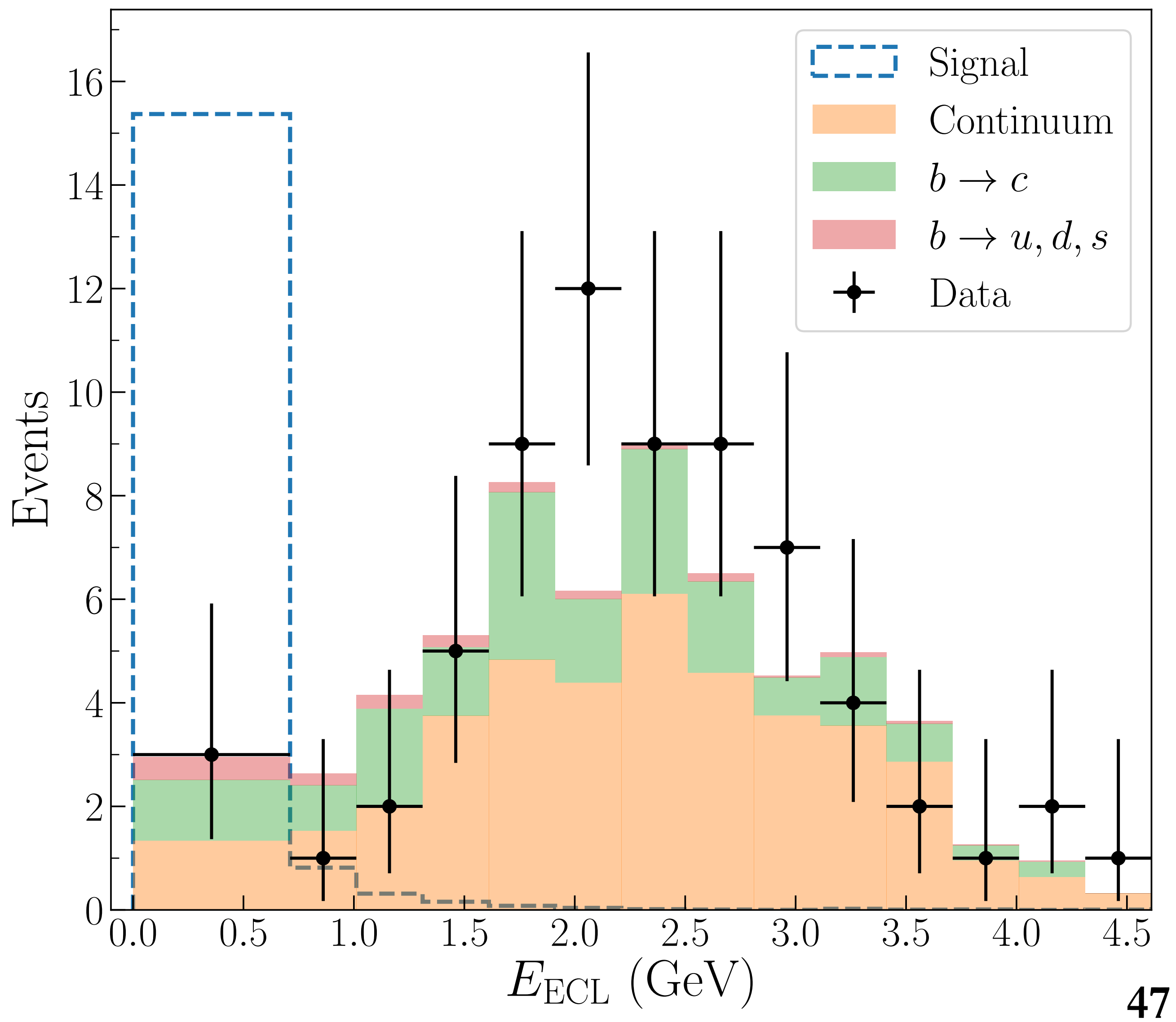
Search for $B^0 \to \Lambda\psi_{DS}$

- B-mesogenesis — explains Baryogenesis and DM with B decays
  - ✓ Elor, Escudero, Nelson [PRD 99, 035031 (2019)]
  - ✓ predicts $\mathscr{B}(B^0 \to \Lambda\psi_{DS} + \text{meson}) > 10^{-4}$

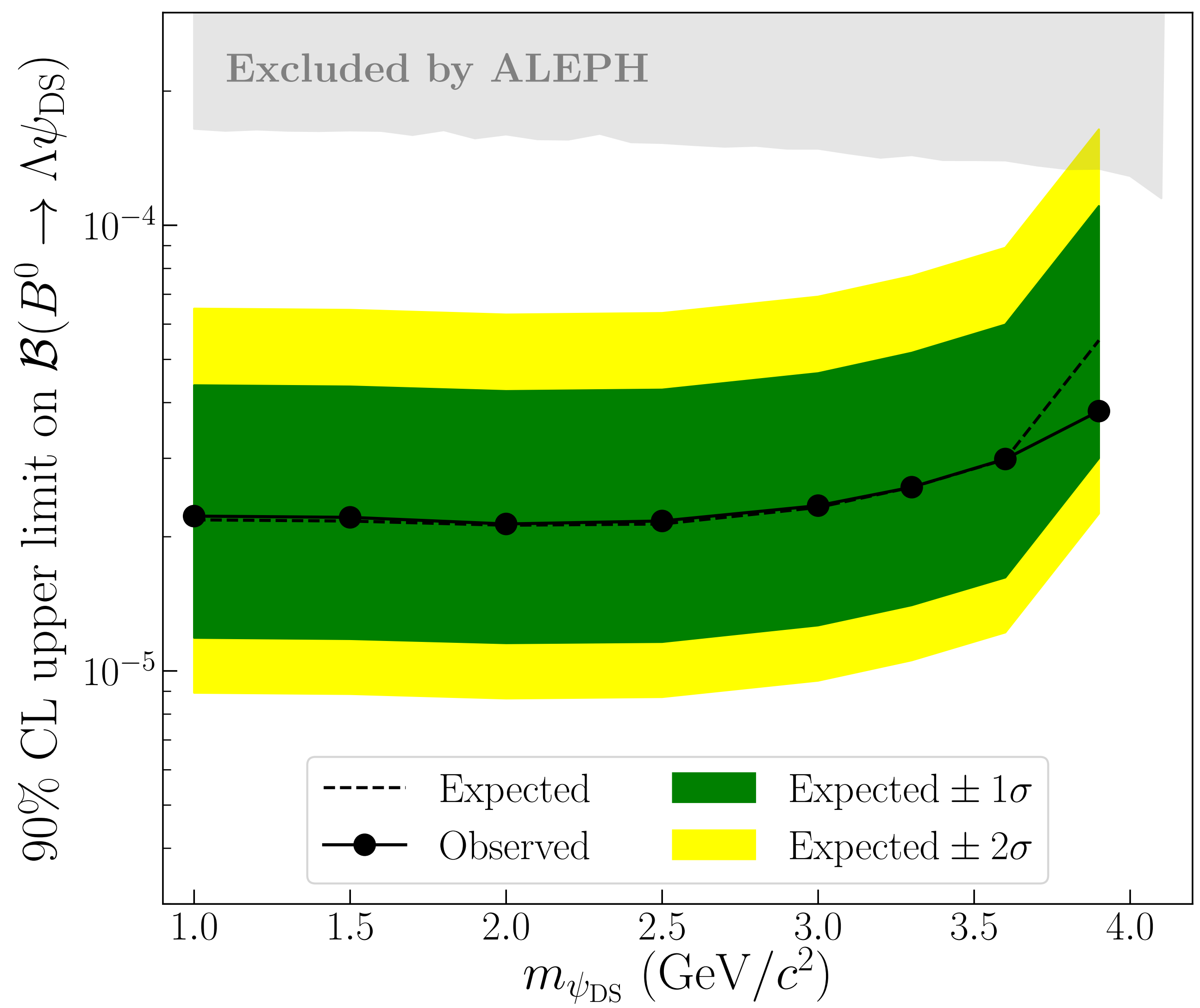
- Belle strategy
  - ✓ Hadronic B-tagging, and look for Λ + *nothing* in the signal-B
  - ✓ use E_{ECL} for background suppression
    $E_{ECL} < 0.57 \sim 0.74$ depending on $m_{\psi_{DS}}$

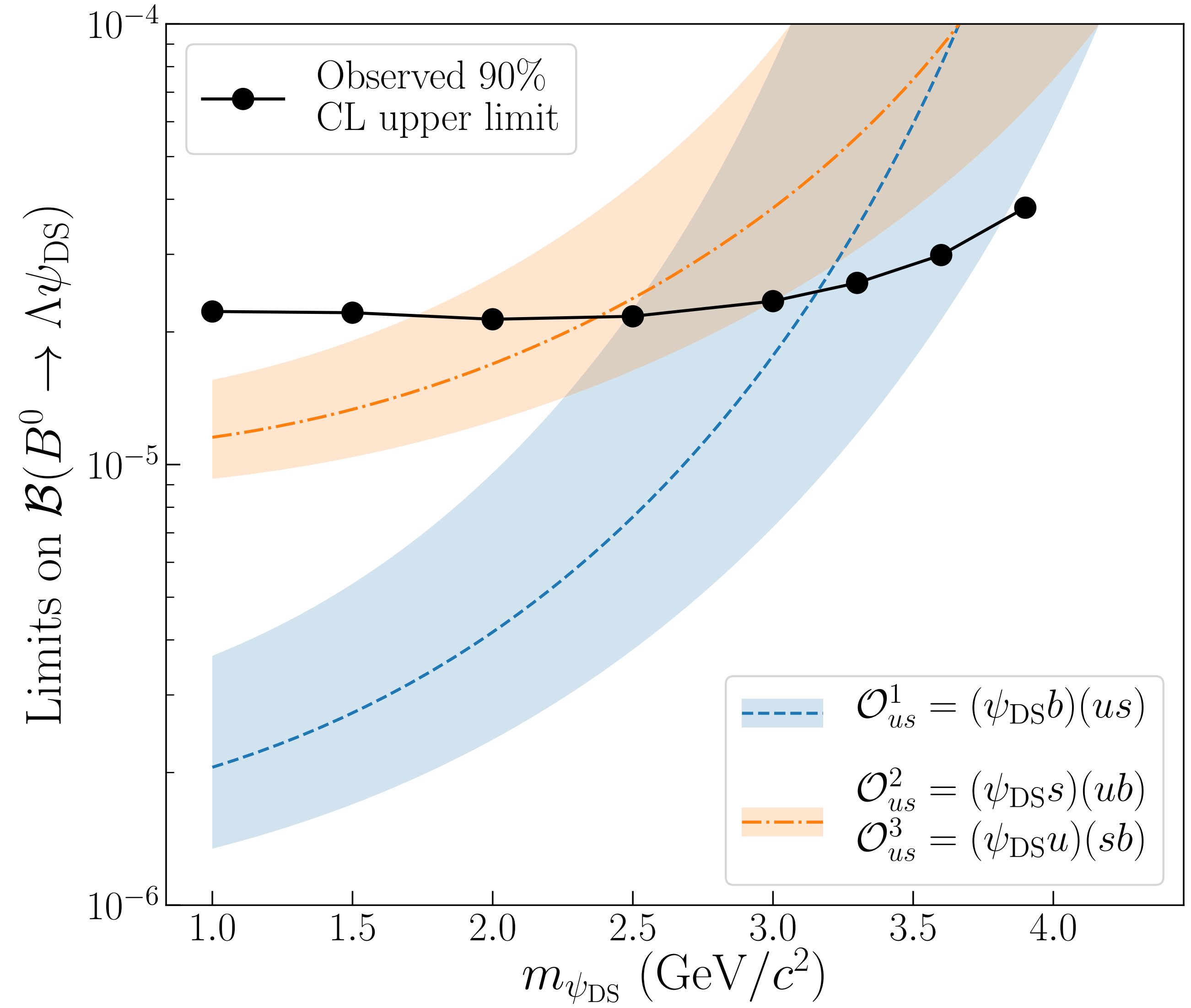


E_{ECL} distribution for
- $m_{\psi_{DS}} = 2.5$ GeV
- $\mathscr{B}(B^0 \to \Lambda\psi_{DS}) = 8 \times 10^{-5}$



Search for $B^0 \to \Lambda\psi_{\rm DS}$





- No signal; $\mathscr{B}(B^0 \to \Lambda\psi_{\rm DS}) < (2.1 \sim 3.8) \times 10^{-5}$
- Excludes $m_{\psi_{\rm DS}} \gtrsim 3.0$ GeV for "type-2" and "type-3" hypotheses[†]

[†] Alonso-Alvarez, Elor, Escudero, PRD 104, 035028 (2021)

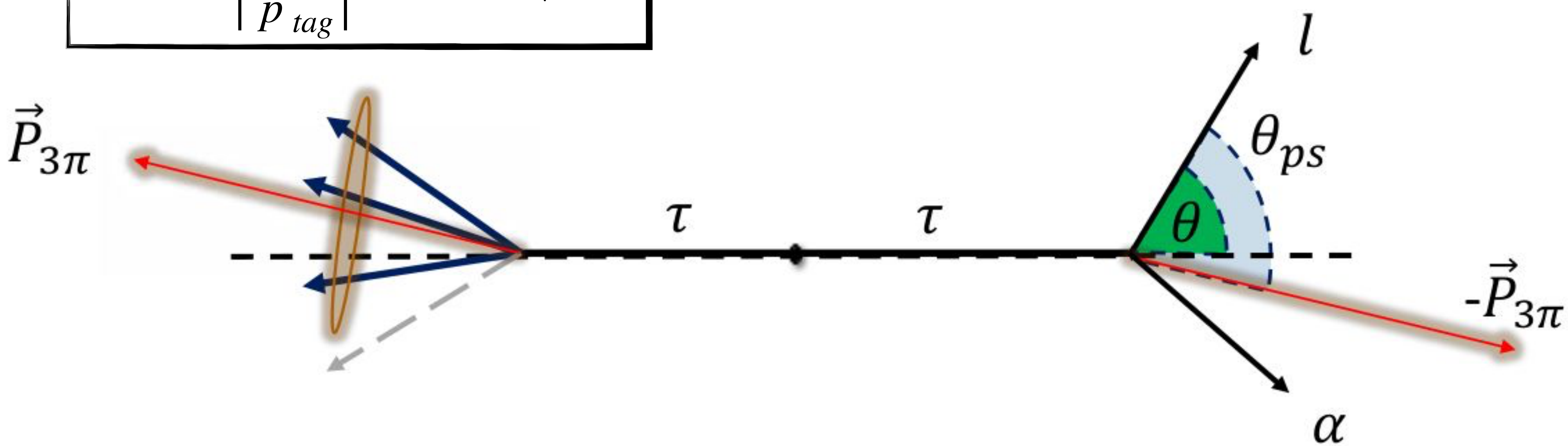
Invisible particle from τ

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. $E_\tau^{\mathrm{CM}} \simeq \sqrt{s}/2$

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



arXiv:2212.03634
submitted to PRL

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

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- 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. $E_\tau^{\mathrm{CM}} \simeq \sqrt{s}/2$

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

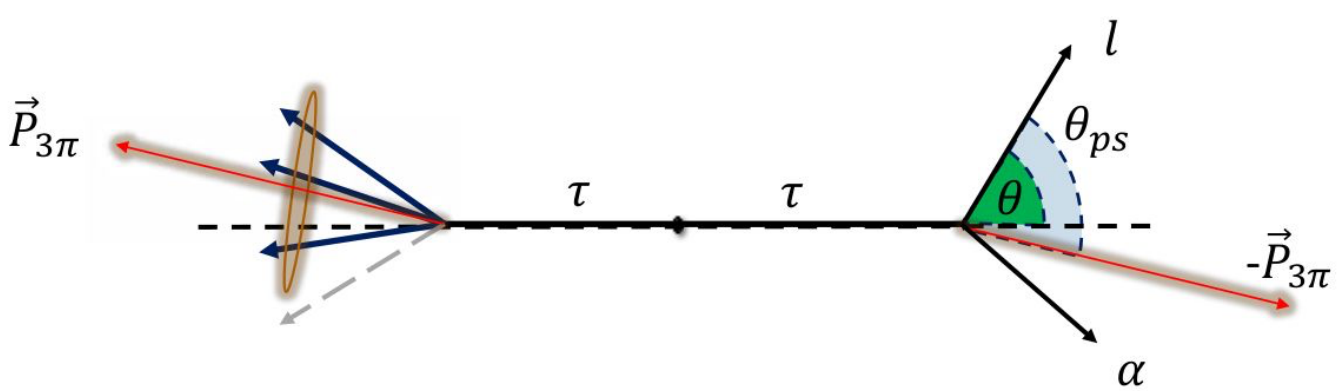
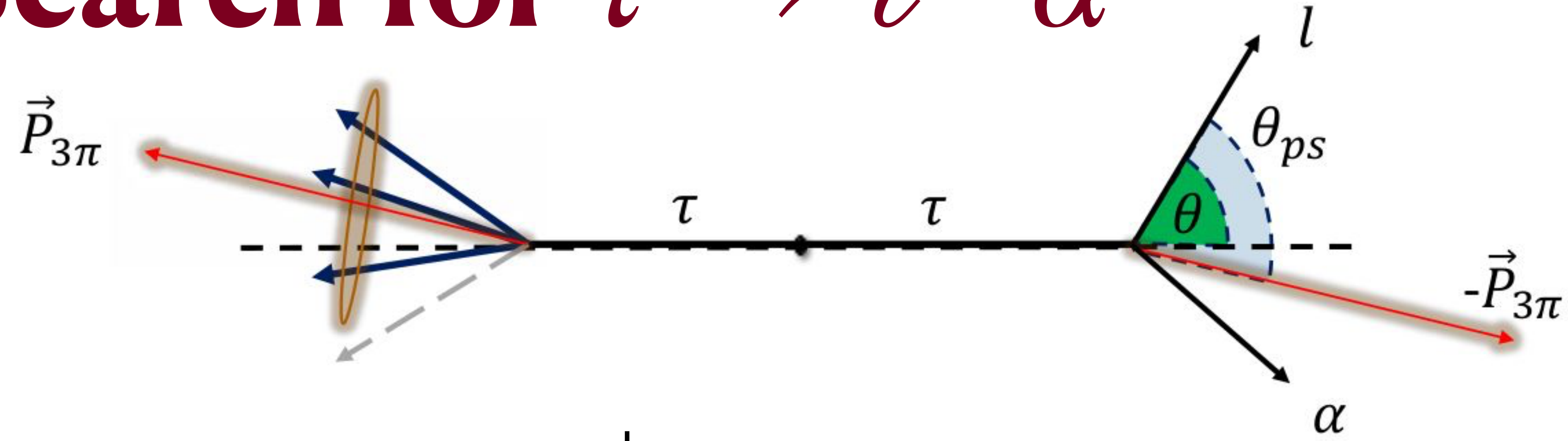


Table I: Requirements on event thrust, missing momentum polar angle, and tag hemisphere particles' total center-of-mass energy and mass.

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

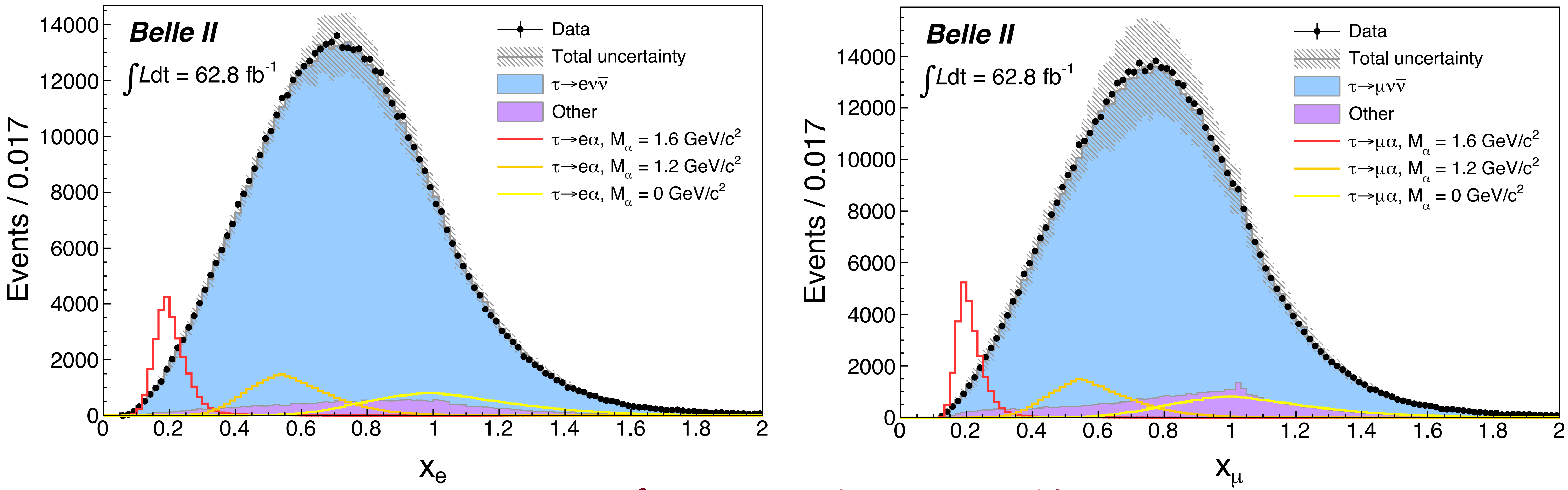
arXiv:2212.03634
submitted to PRL

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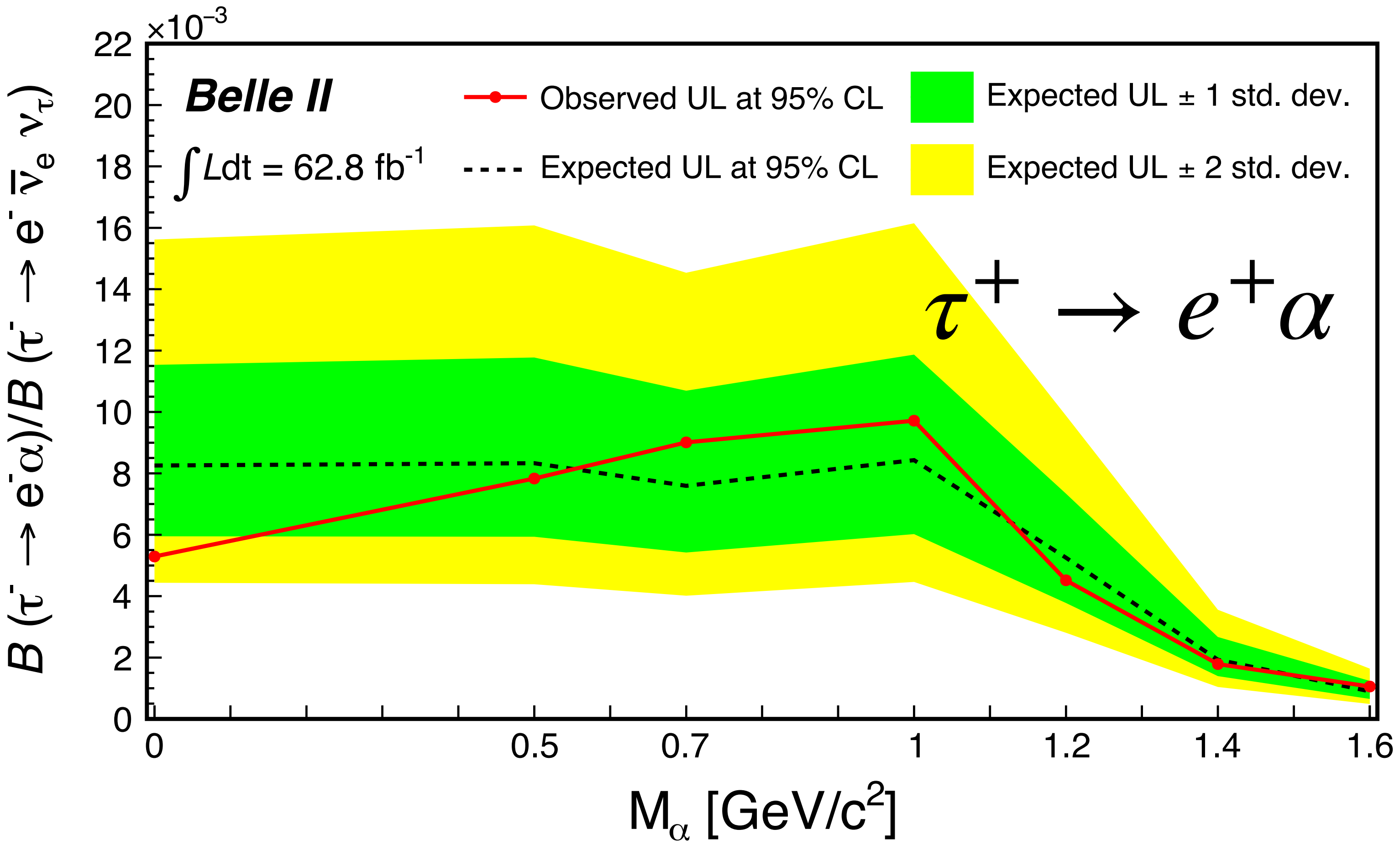
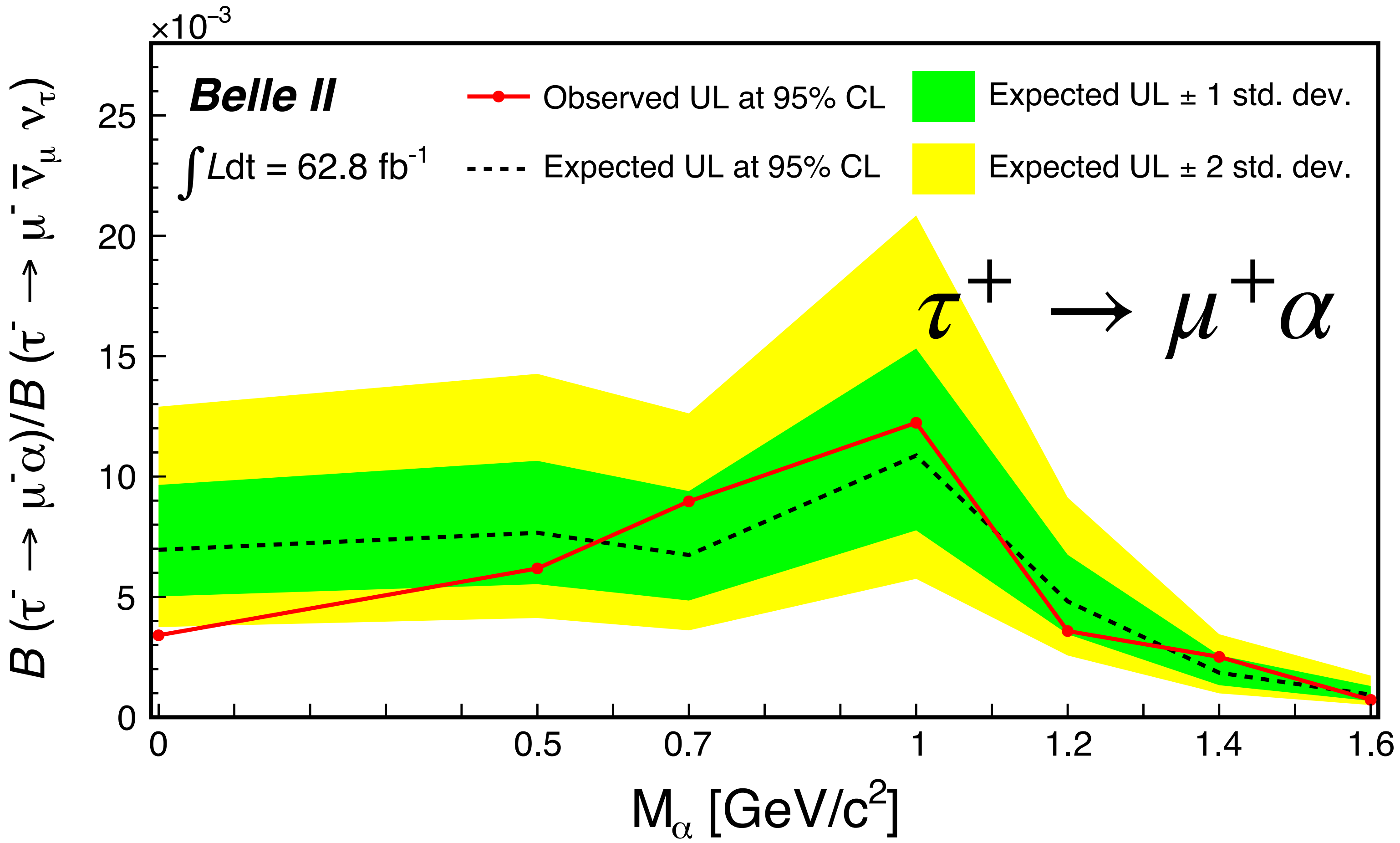
Results for $\tau \to \ell^+ \alpha$

- 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



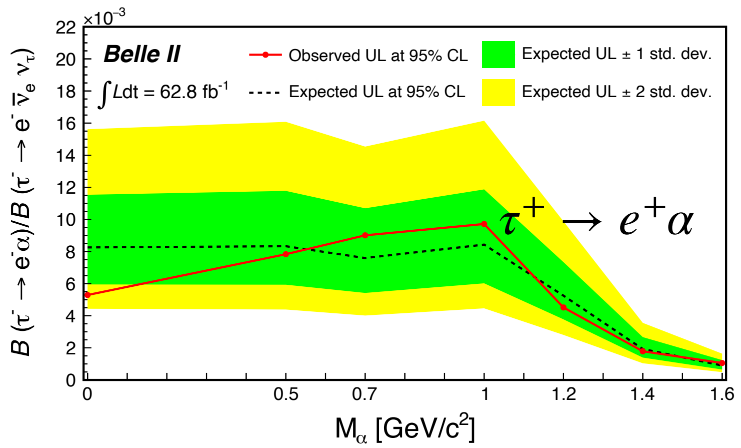


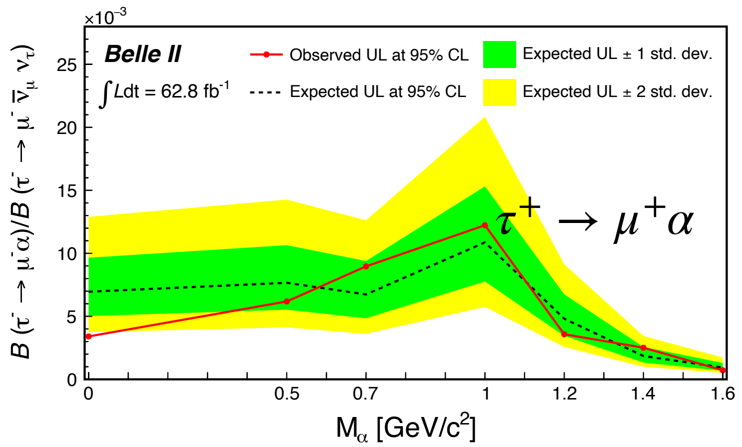
Results for $\tau \to \ell^+\alpha$

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

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

- Most stringent limits in these channels to date



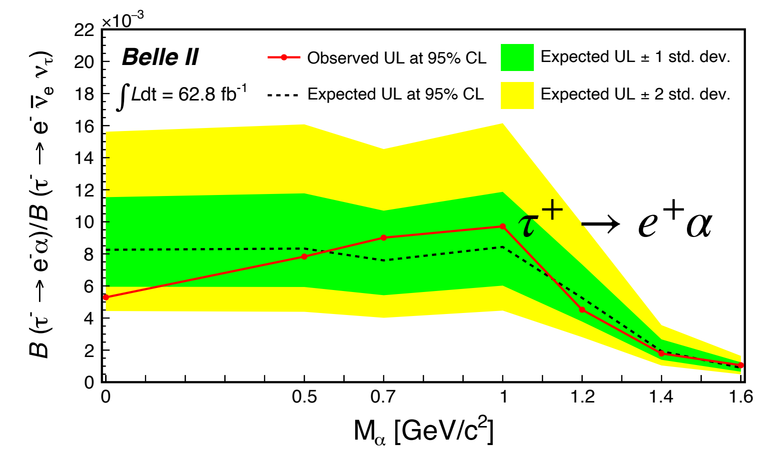


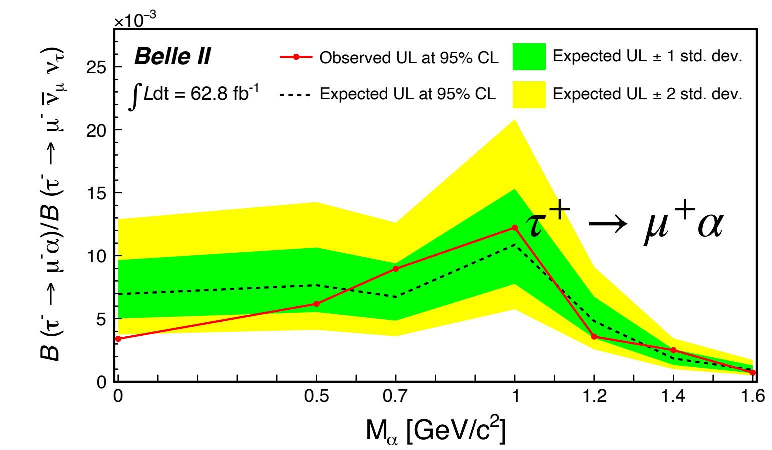
M_α [GeV/c^2]	$\mathcal{B}_{e\alpha}/\mathcal{B}_{e\bar{\nu}\nu}$ ($\times 10^{-3}$)	UL at 95% CL ($\times 10^{-3}$)	UL at 90% CL ($\times 10^{-3}$)
0.0	-8.1 ± 3.9	5.3 (0.94)	4.3 (0.76)
0.5	-0.9 ± 4.3	7.8 (1.40)	6.5 (1.15)
0.7	1.7 ± 4.0	9.0 (1.61)	7.6 (1.36)
1.0	1.7 ± 4.2	9.7 (1.73)	8.2 (1.47)
1.2	-1.1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

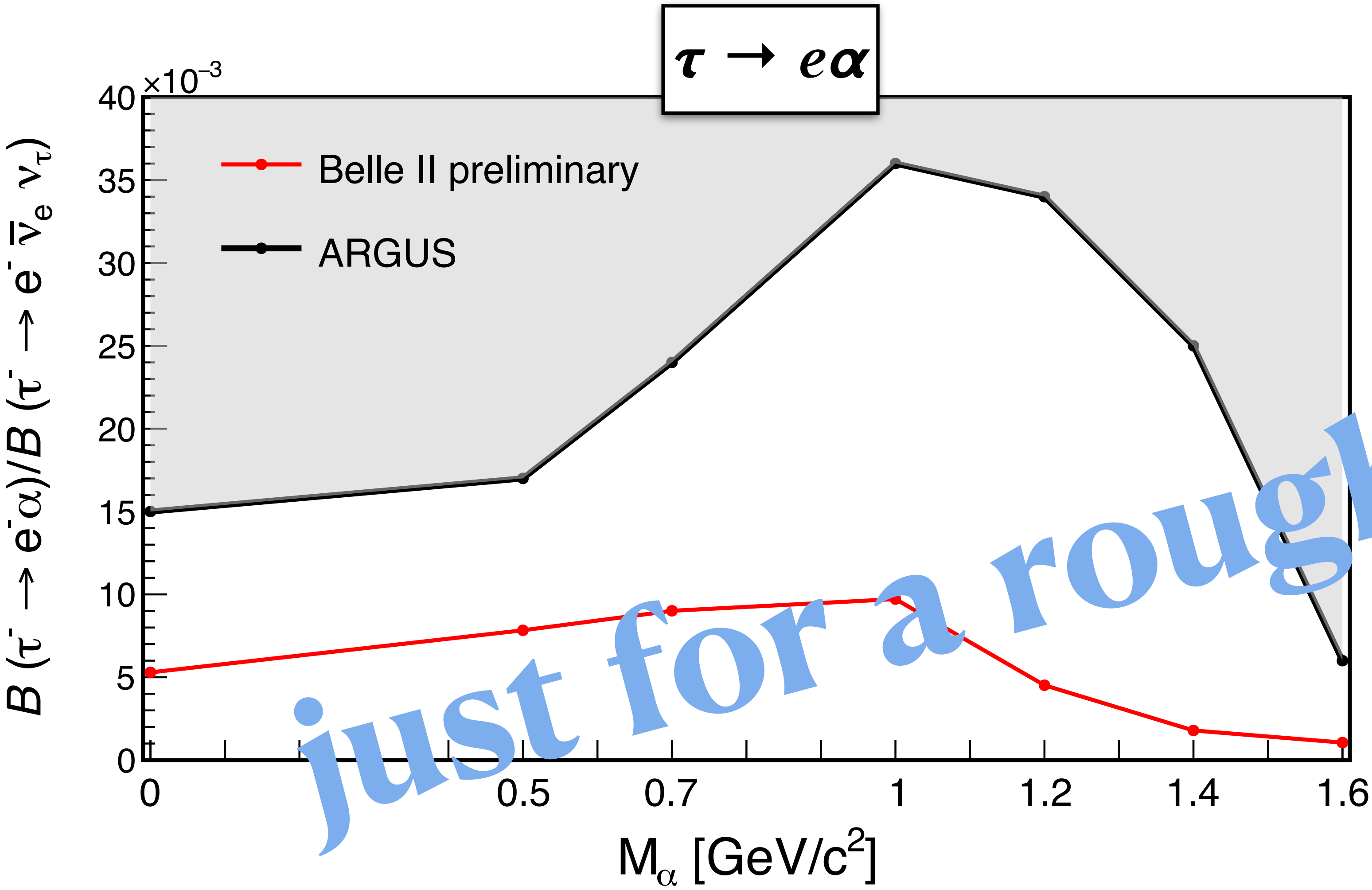
M_α [GeV/c^2]	$\mathcal{B}_{\mu\alpha}/\mathcal{B}_{\mu\bar{\nu}\nu}$ ($\times 10^{-3}$)	UL at 95% CL ($\times 10^{-3}$)	UL at 90% CL ($\times 10^{-3}$)
0.0	-9.4 ± 3.7	3.4 (0.59)	2.7 (0.47)
0.5	-3.2 ± 3.9	6.2 (1.07)	5.1 (0.88)
0.7	2.7 ± 3.4	9.0 (1.56)	7.8 (1.35)
1.0	1.7 ± 5.4	12.2 (2.13)	10.3 (1.80)
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)

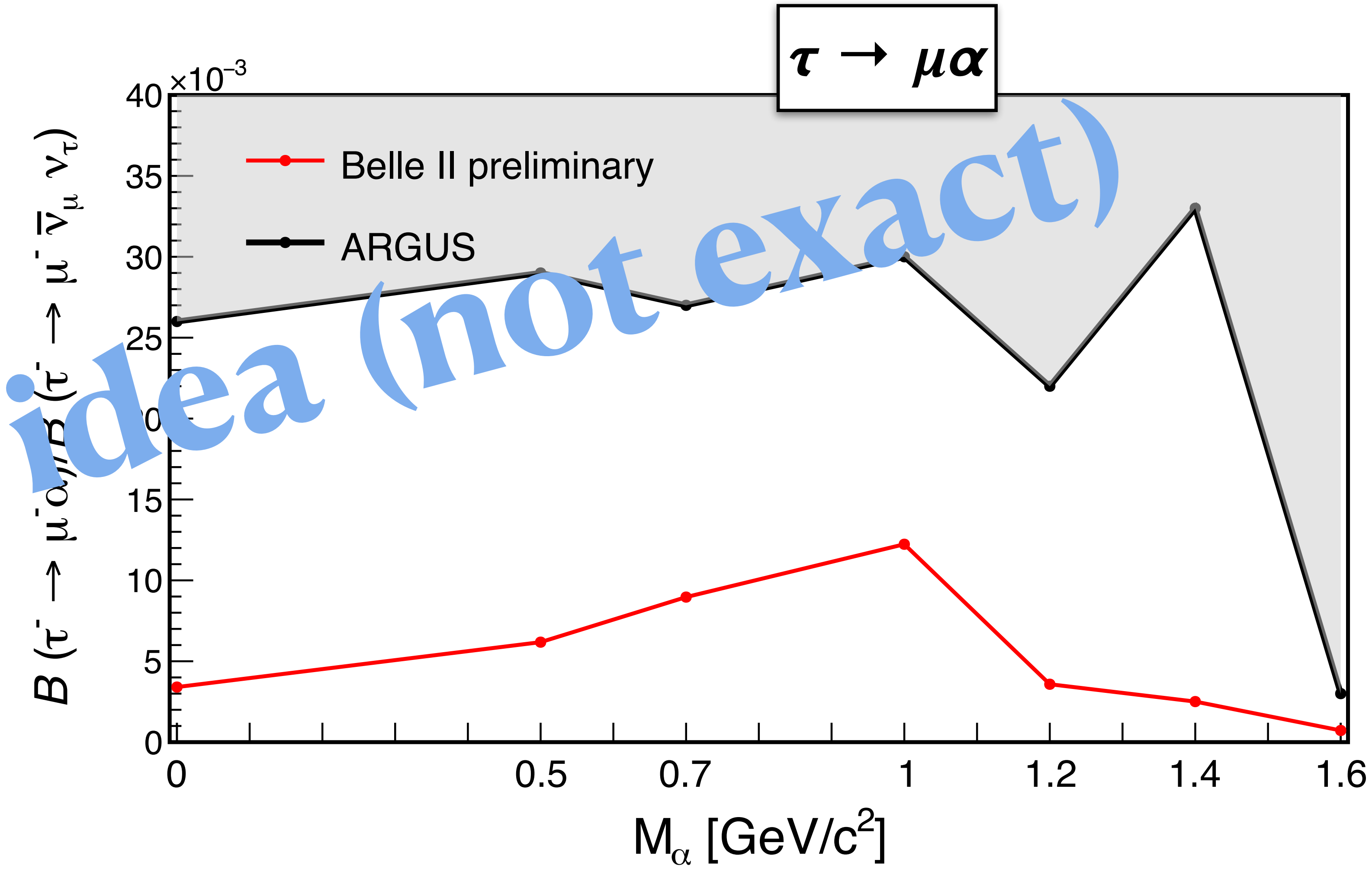
arXiv:2212.03634
submitted to PRL

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

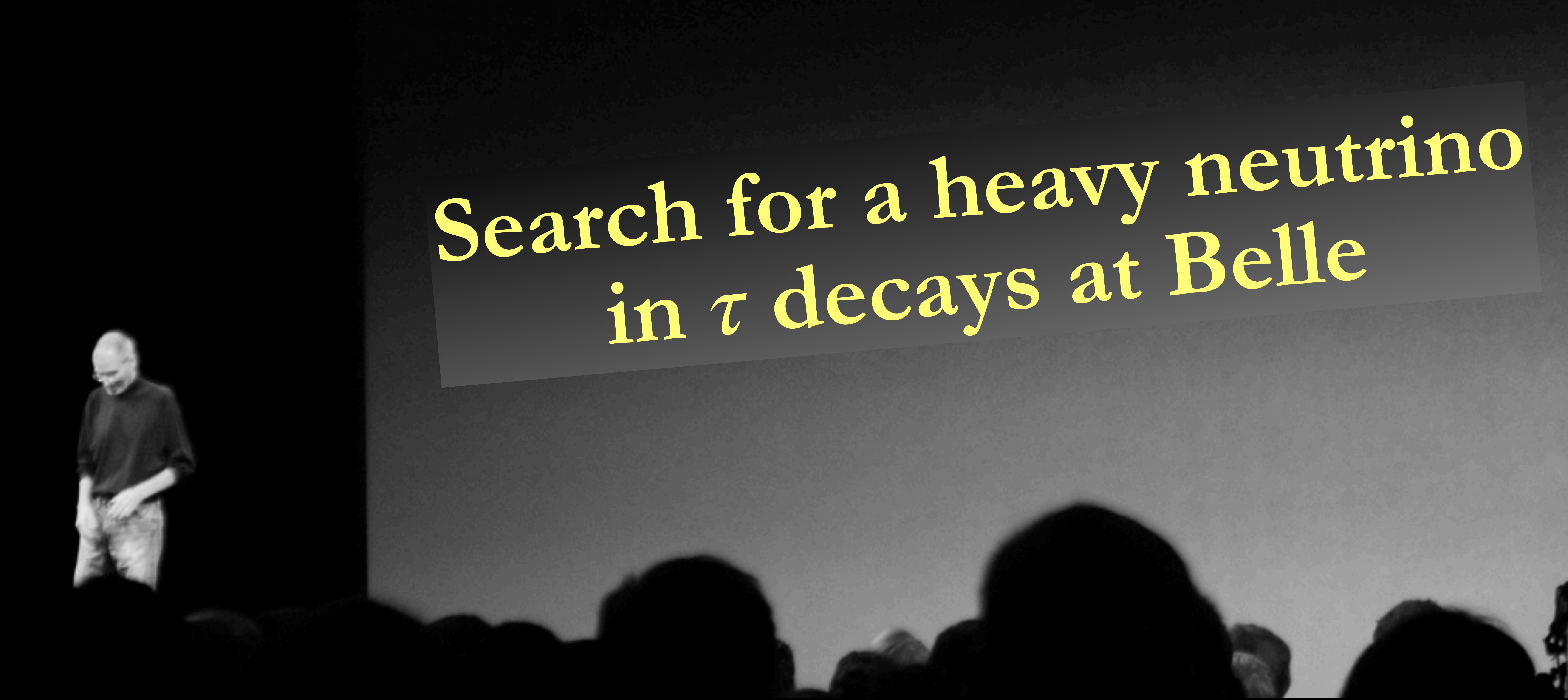


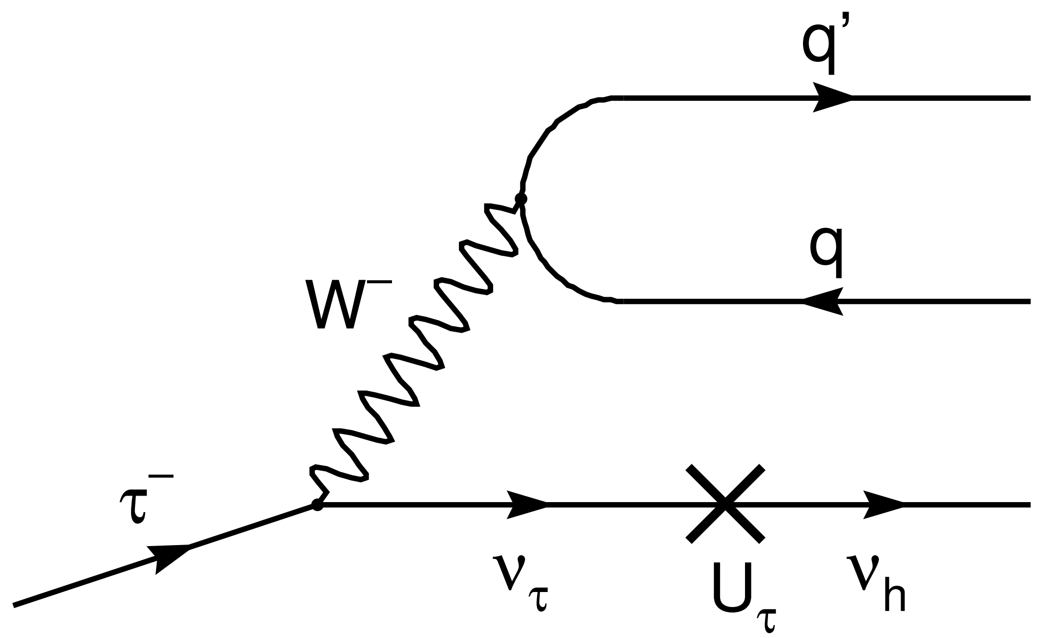




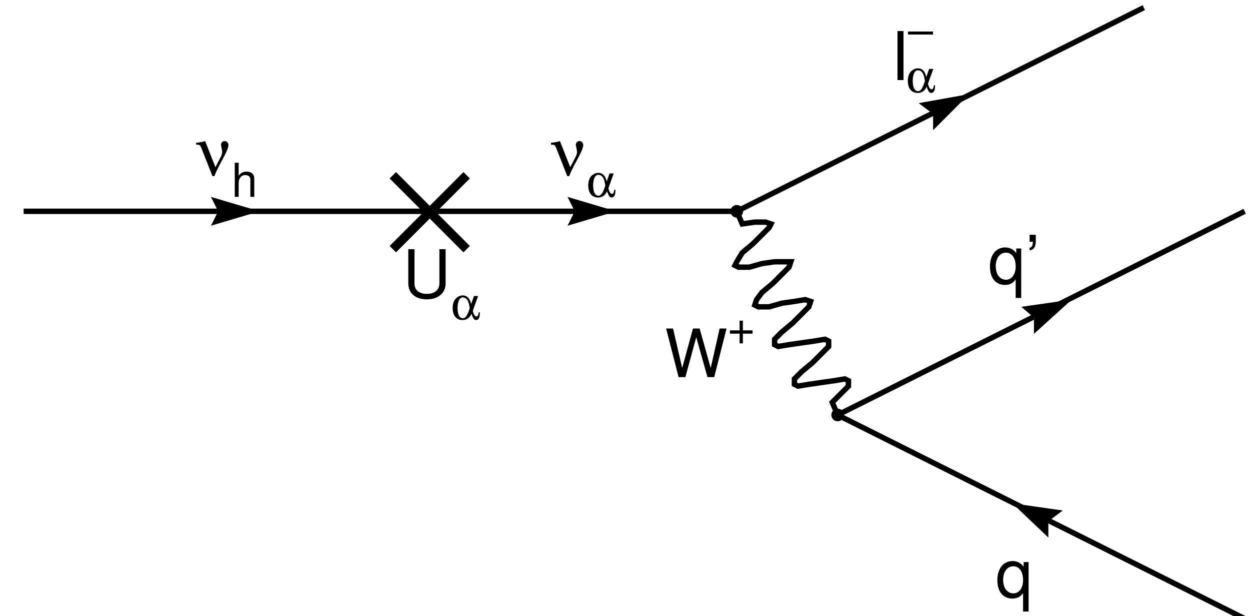


just for a rough idea (not exact)


Search for a heavy neutrino
in τ decays at Belle



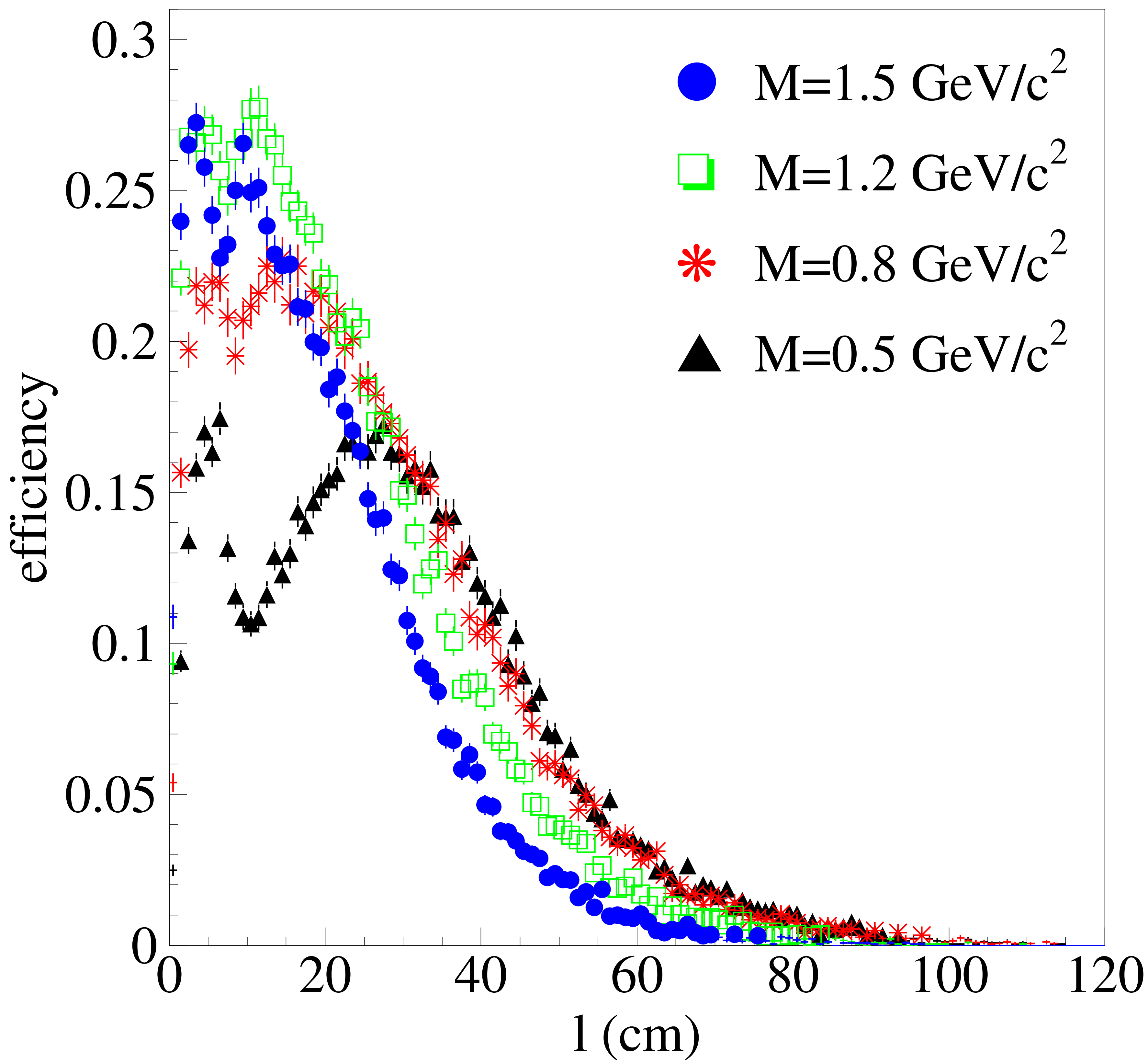
$$\nu_h \to \pi^{\pm}\ell^{\mp}$$



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

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

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



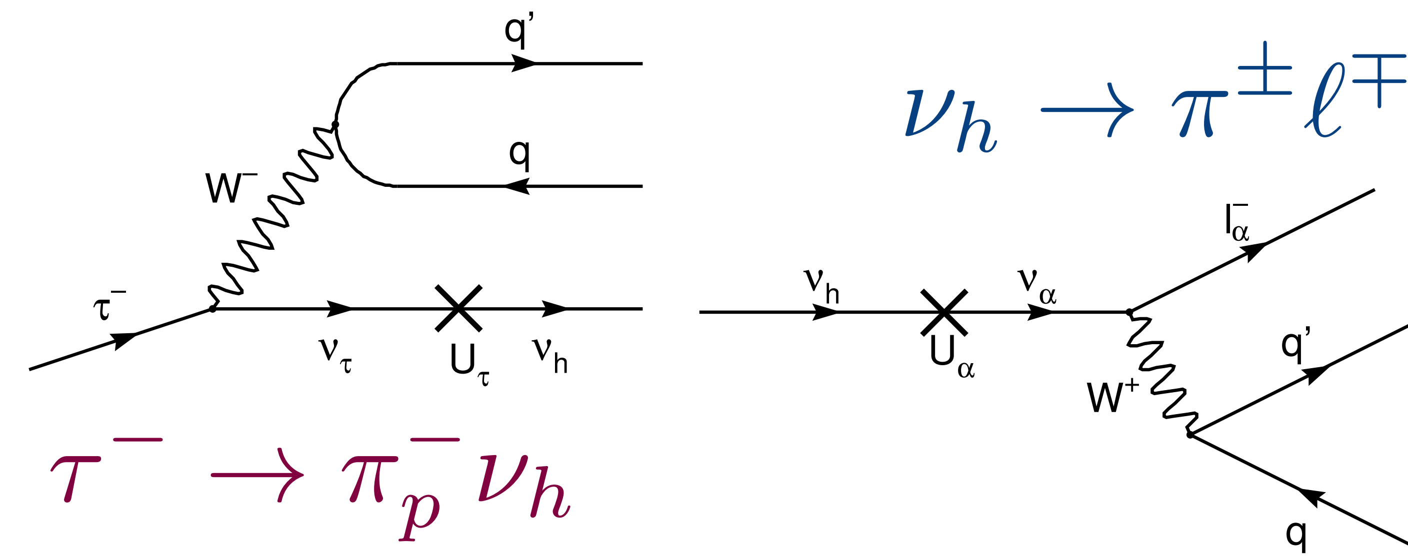


FIG. 2. Dependence of the HNL reconstruction efficiency on the neutrino travel distance l for different neutrino masses $M(\nu_h)$. Efficiency is almost identical for e and μ.

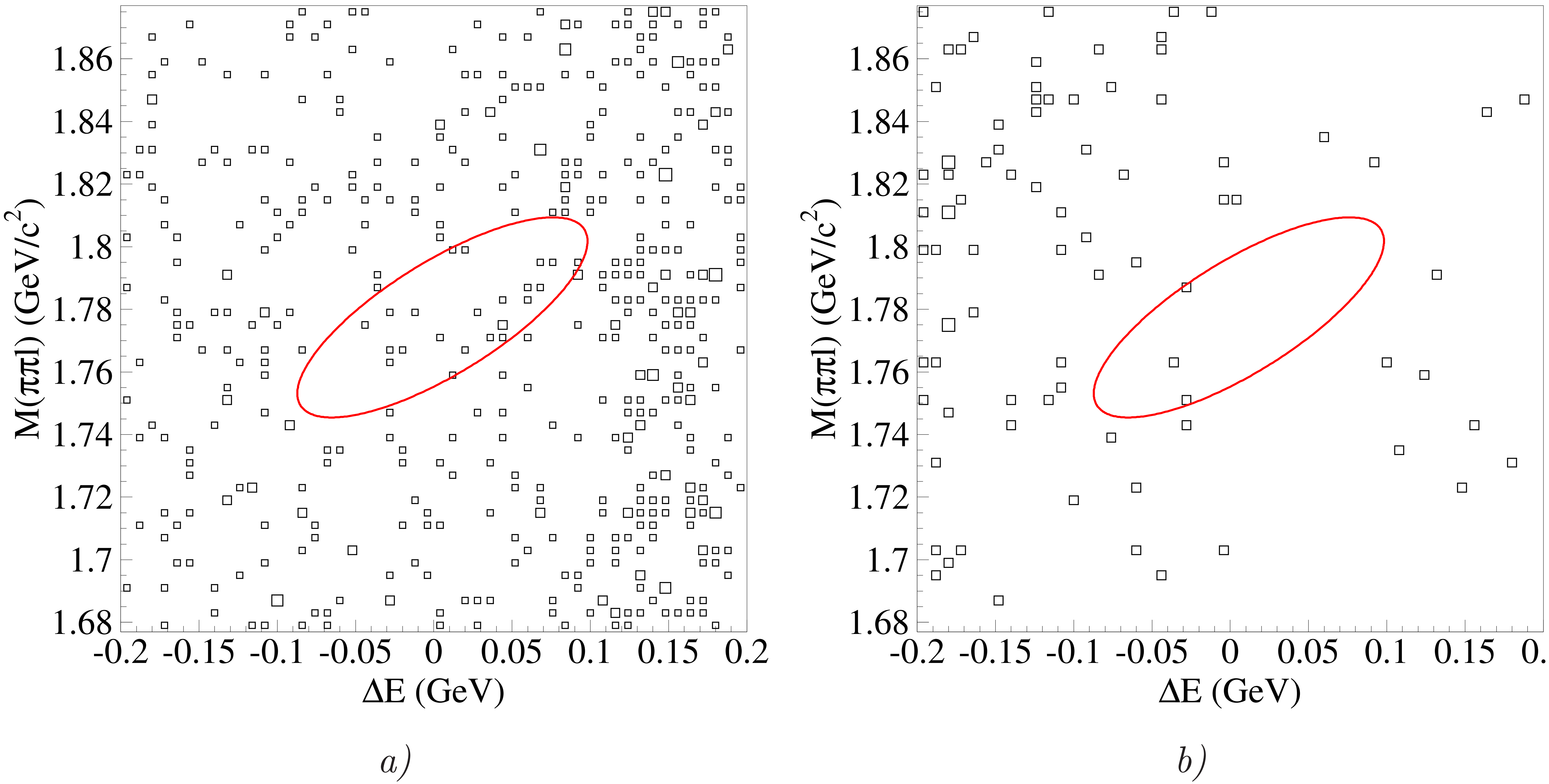


FIG. 3. ΔE vs $M(\pi\pi\ell)$ distributions with all requirements but ΔE and $M(\pi\pi\ell)$ imposed for $\pi\pi e$ (a) and $\pi\pi\mu$ (b) in data. The signal region is shown as a red ellipse.

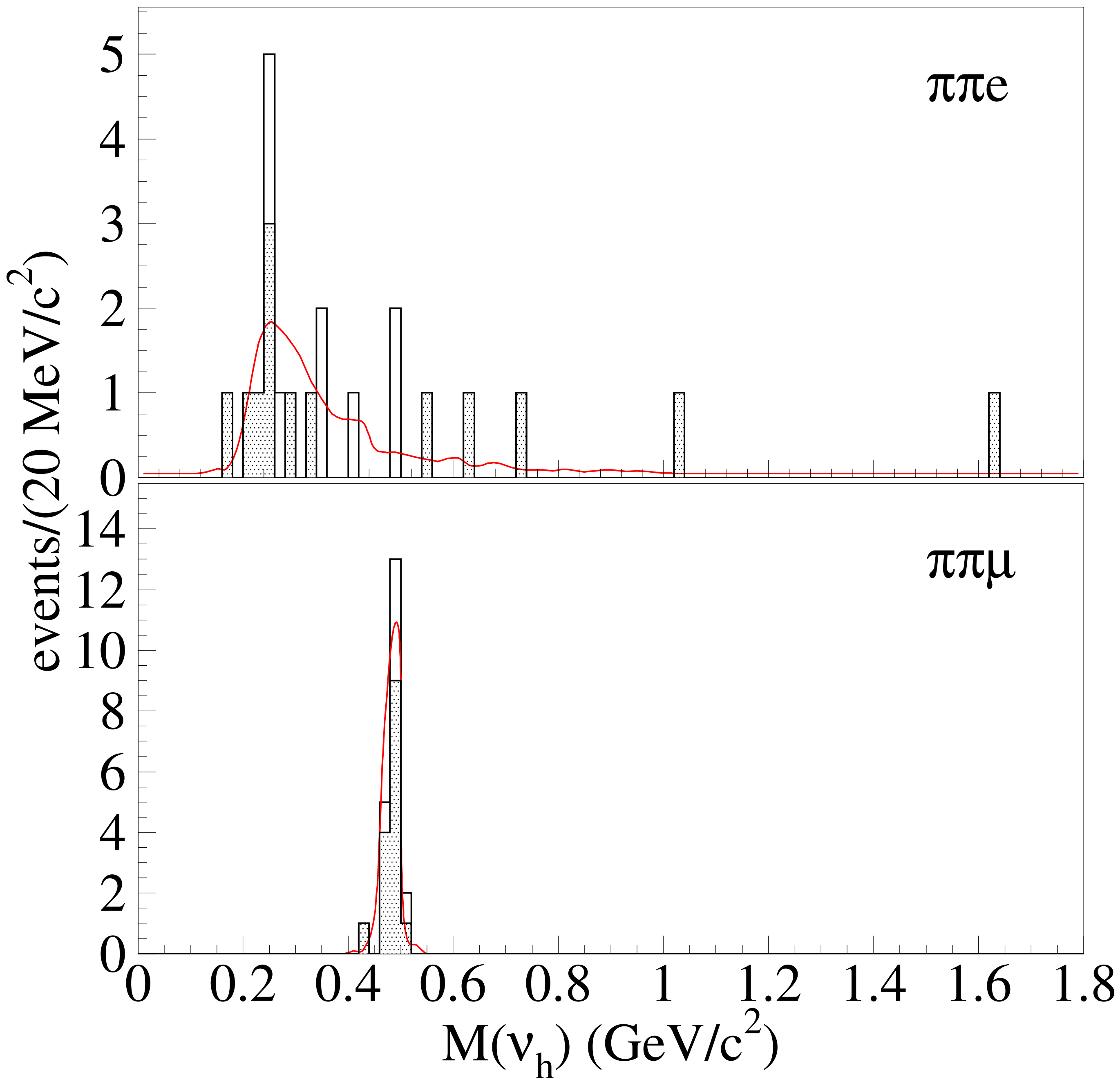


FIG. 4. Final distributions of $M(\nu_h)$ for $\pi\pi e$ and $\pi\pi\mu$ reconstruction modes in data. The filled histograms are for candidates with

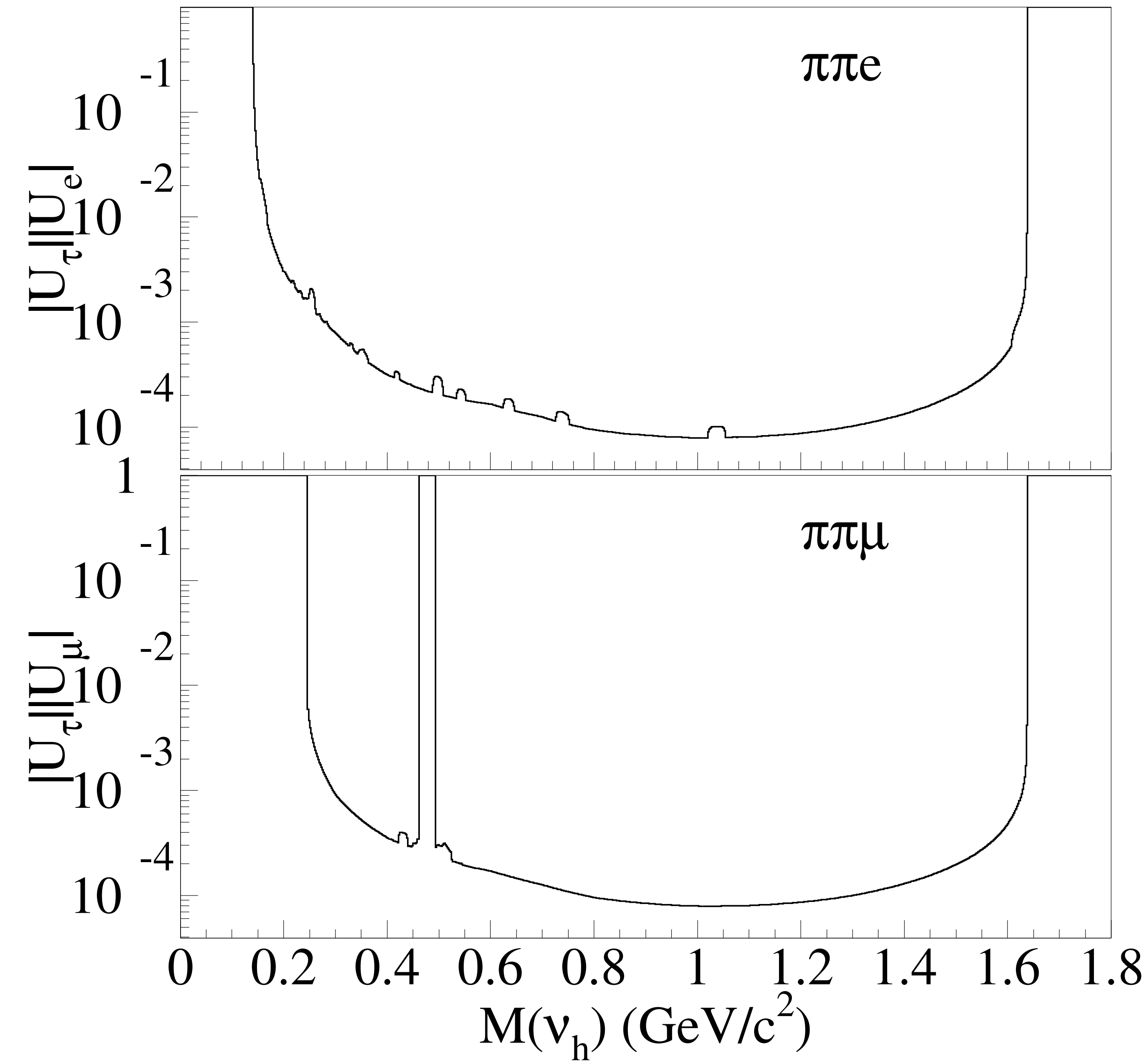


FIG. 5. Upper limits at 90% CL on $|U_\tau||U_e|$ and $|U_\tau||U_\mu|$.

Creativity is essential to particle physics, cosmology, and to mathematics, and to other fields of science, just as it is to its more widely acknowledged beneficiaries - the arts and humanities.

Lisa Randall


Thank you
and
Merry Christmas!