Status and Recent Highlights of Belle II

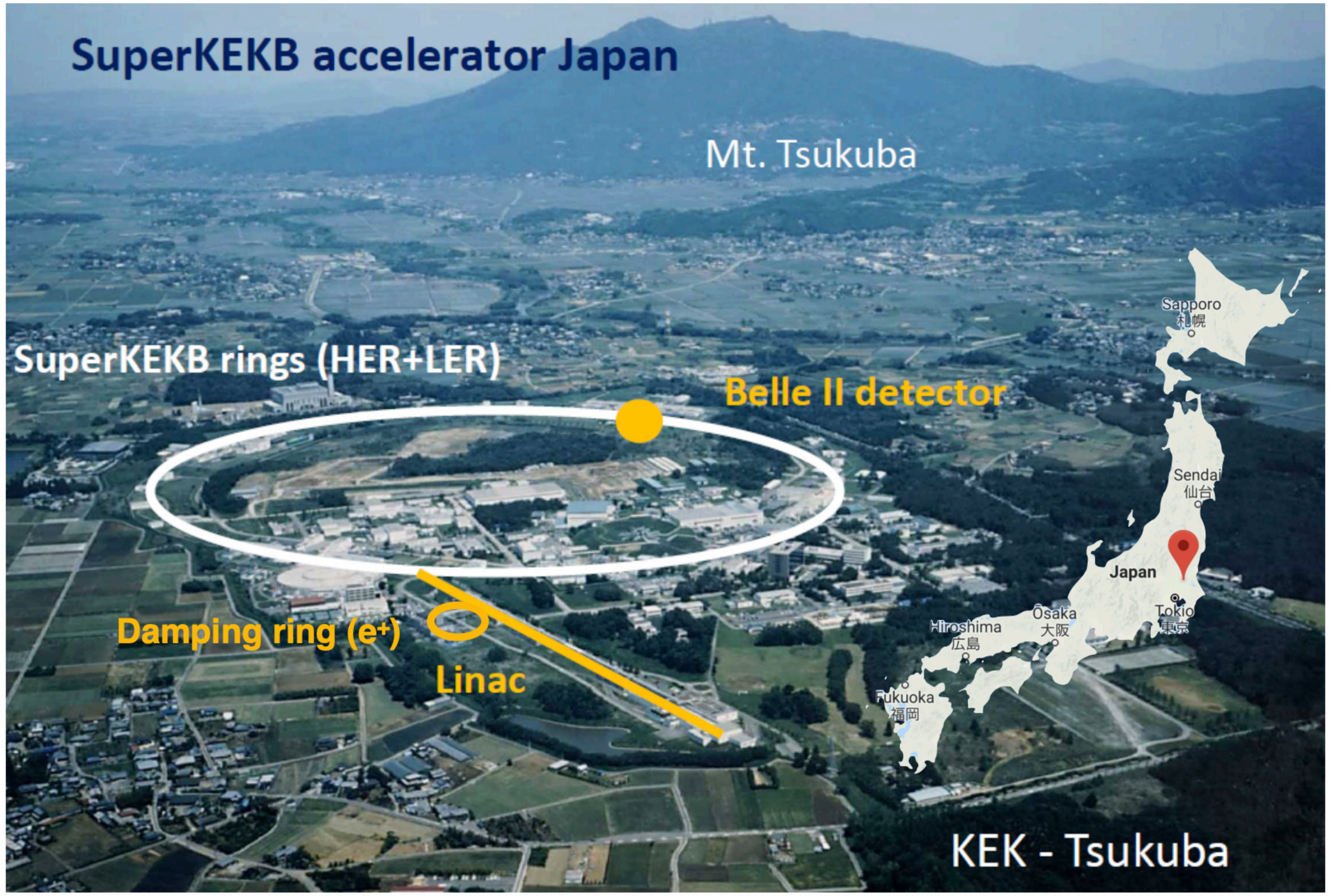
Lu Cao

(for the Belle II Collaboration)

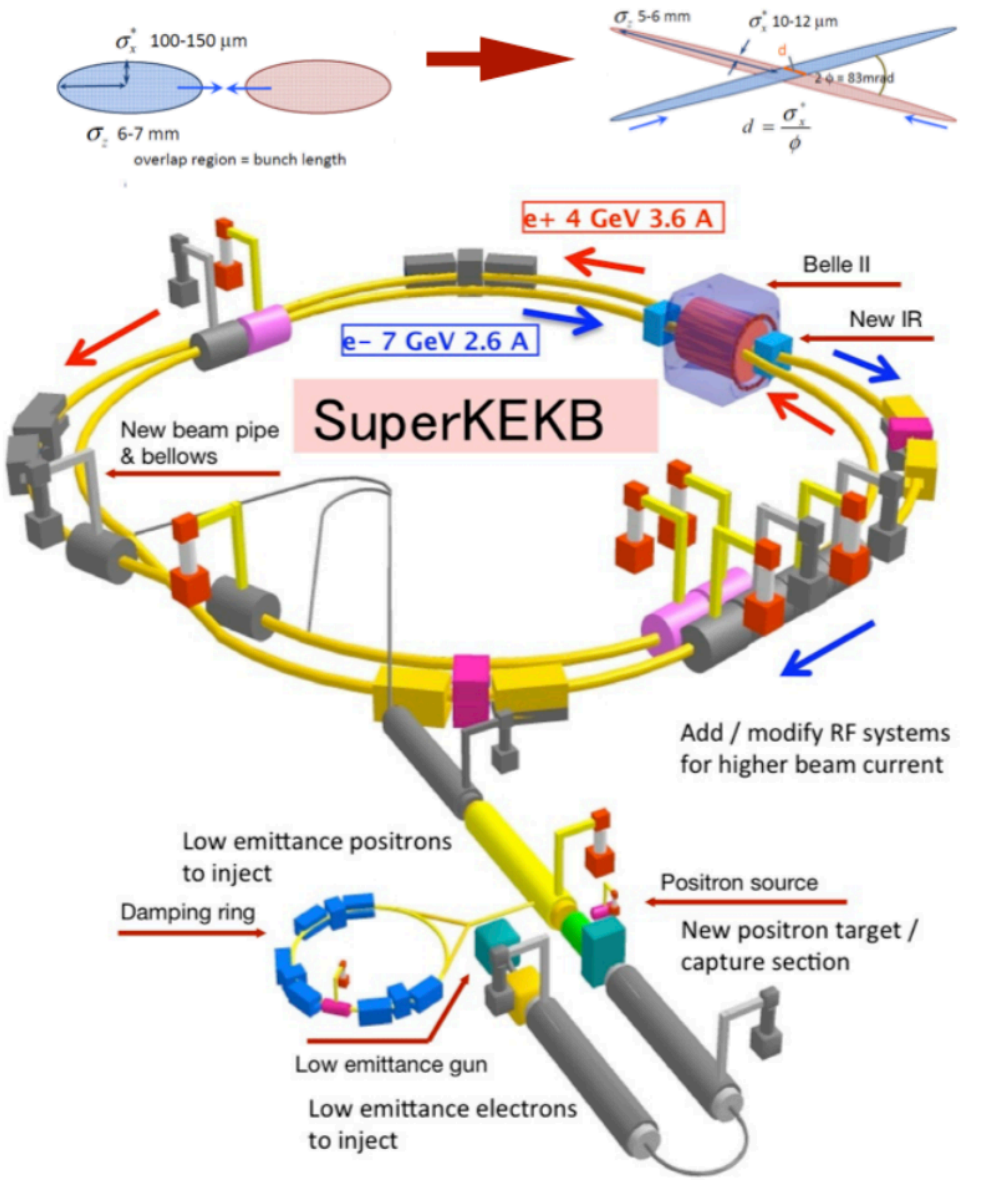
CEA (Paris-Saclay), 05-22-2023

Belle II Experiment @ SuperKEKB

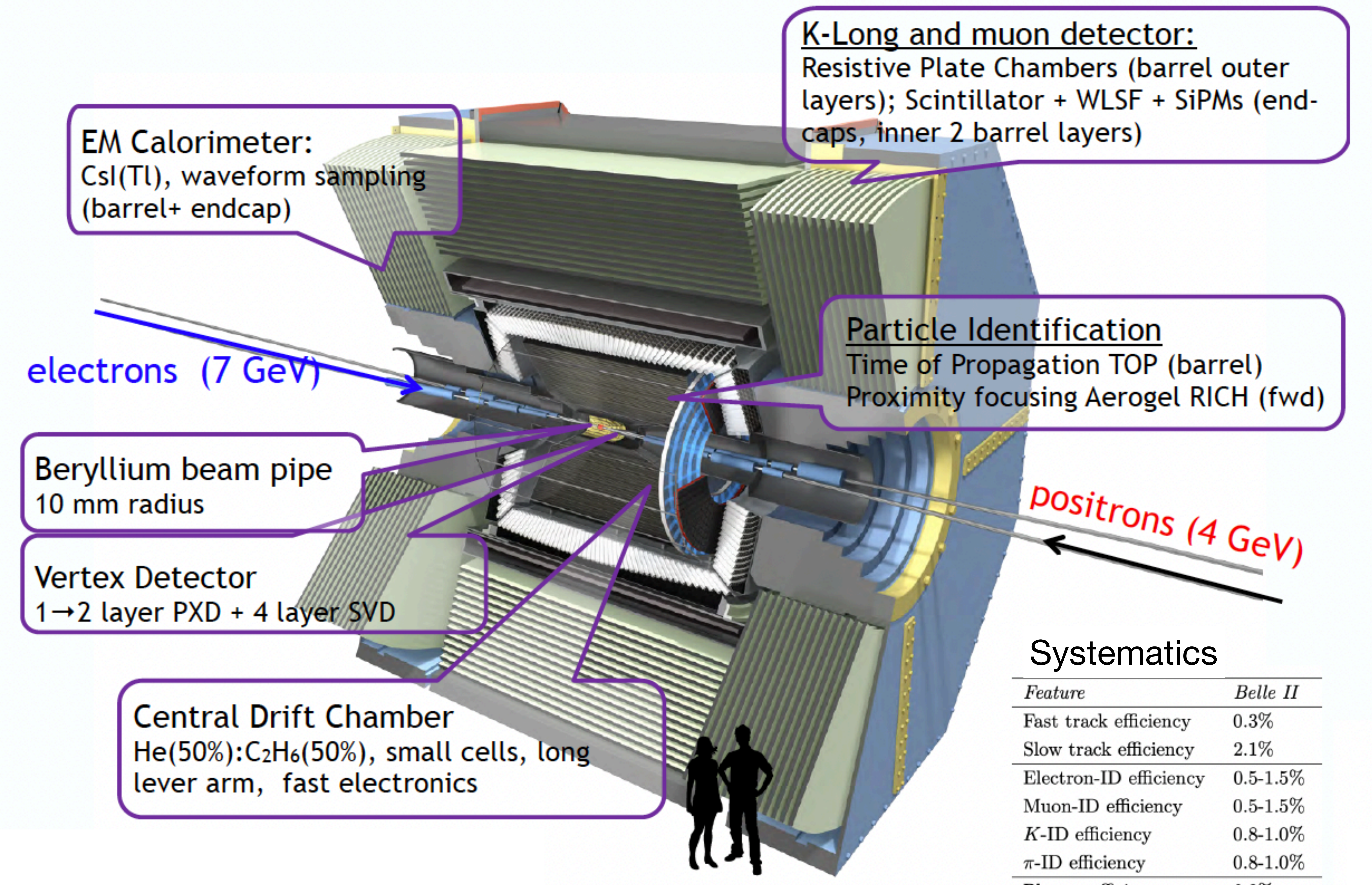
- Asymmetric-energy e^+e^- collider operating near $\Upsilon(4S)$ mass peak
- KEKB => **SuperKEKB**; Belle => **Belle II**
- Goal is to collect **50 billion $B\bar{B}$ pairs!**



Upgraded detector and accelerator



Belle II Detector

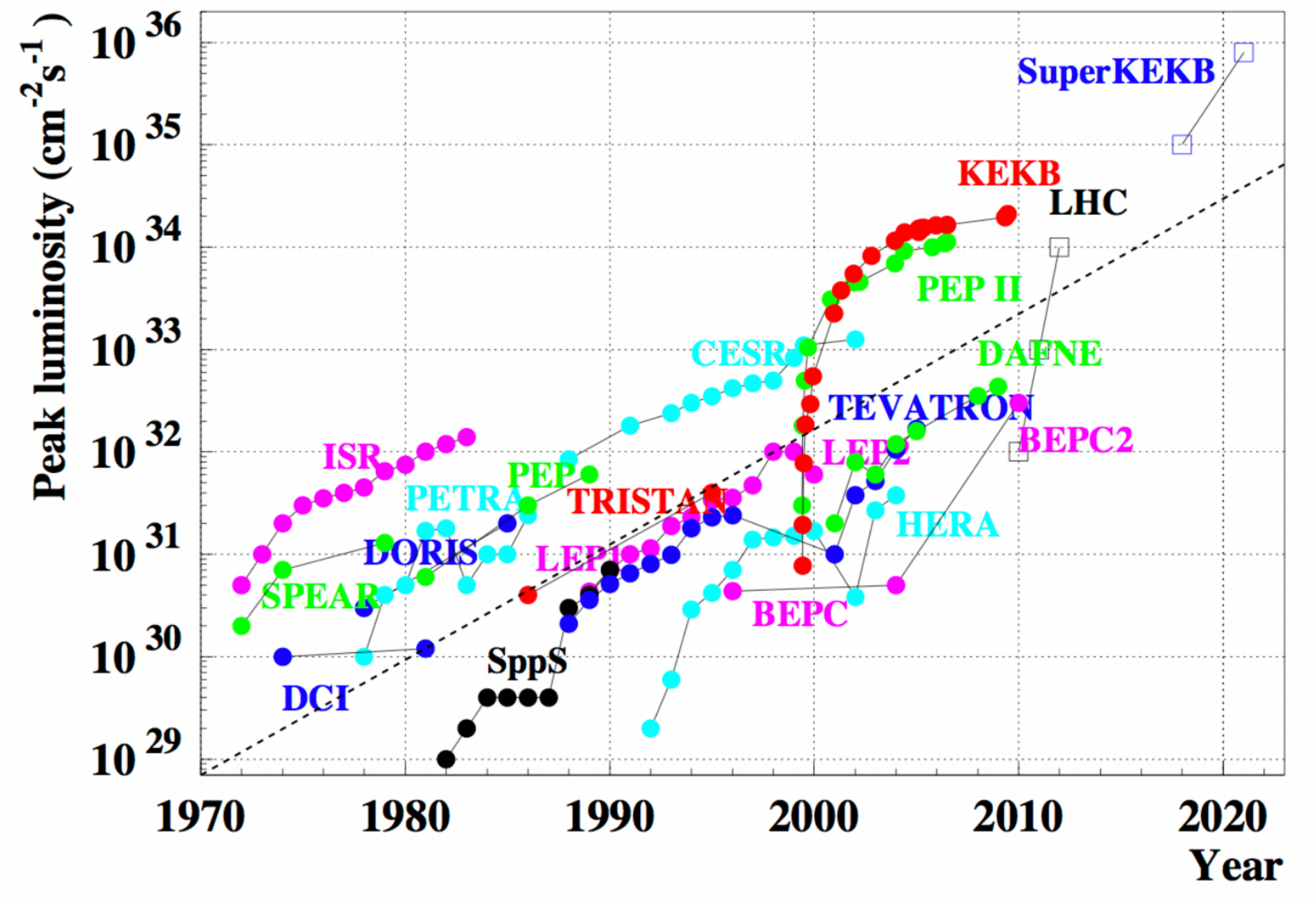


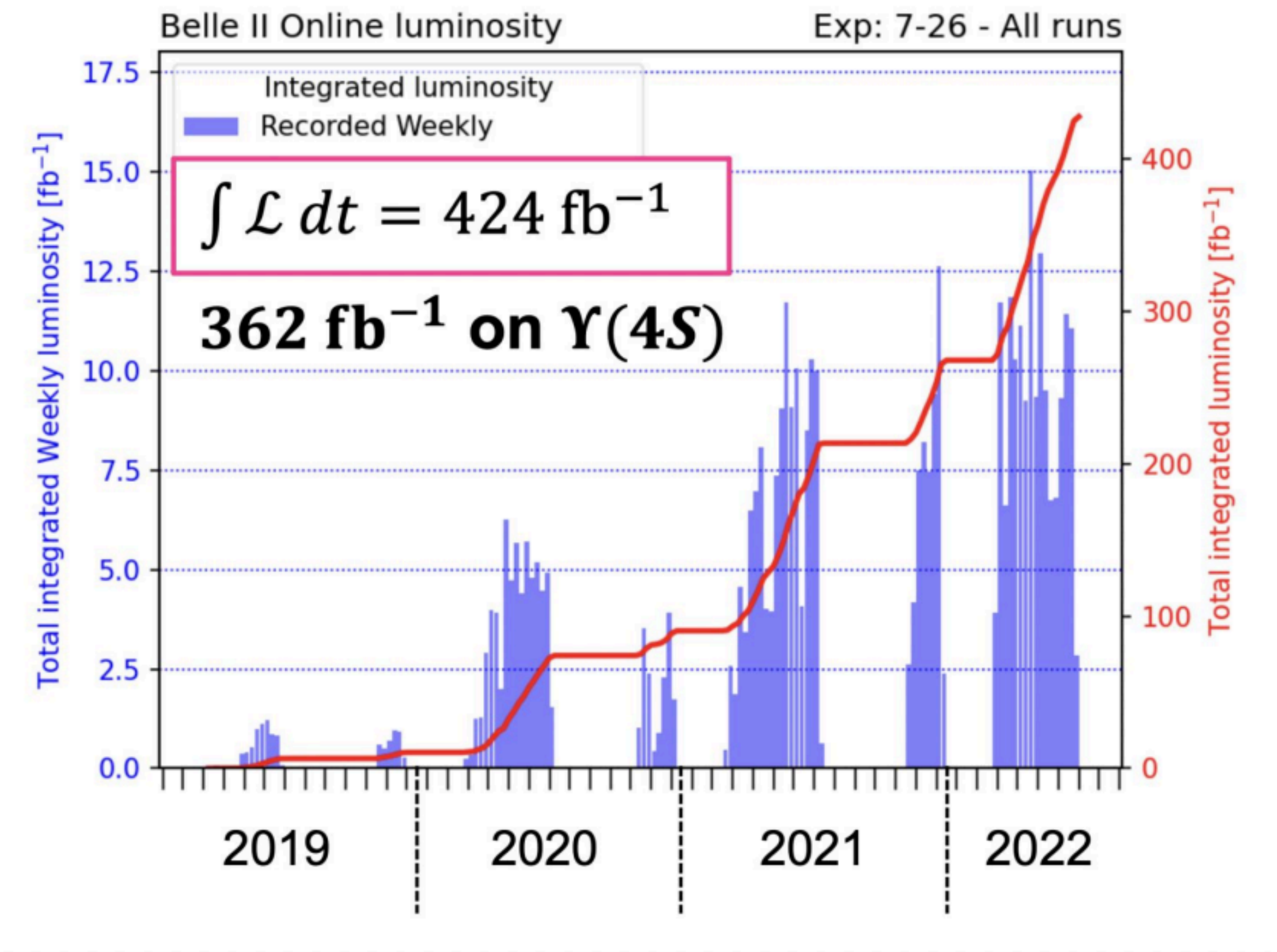
Systematics

Feature	*Belle II*
Fast track efficiency	0.3%
Slow track efficiency	2.1%
Electron-ID efficiency	0.5-1.5%
Muon-ID efficiency	0.5-1.5%
K-ID efficiency	0.8-1.0%
π-ID efficiency	0.8-1.0%
Photon efficiency	0.3%
π^0 efficiency	3.4-7.1%

Status of Belle II Experiment

- Max instantaneous luminosity $L_{\text{peak}} = 4.7 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ **(world record)**
- By summer 2022, $L_{\text{int}} = 424\,\text{fb}^{-1}$ accumulated (similar to full dataset of BaBar, ~1/2 of Belle's)
- Ultimate goal: reach $50\,\text{ab}^{-1}$ by operating at instantaneous lumi. of $6 \times 10^{35}\,\text{cm}^{-2}\text{s}^{-1}$





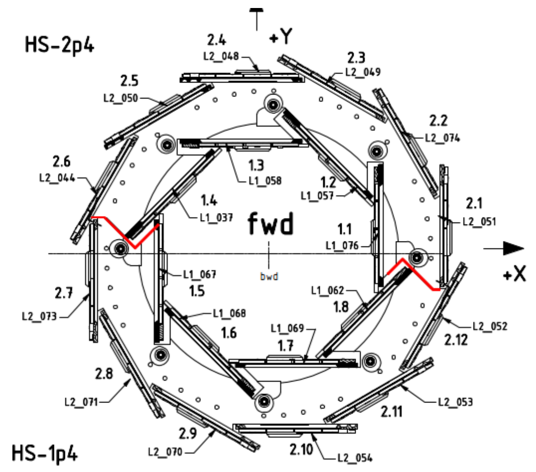
Status of Belle II Experiment

- Currently, we are in **LS1** (long shutdown 1) starting from summer 2022
- Operation will be resumed in the coming winter

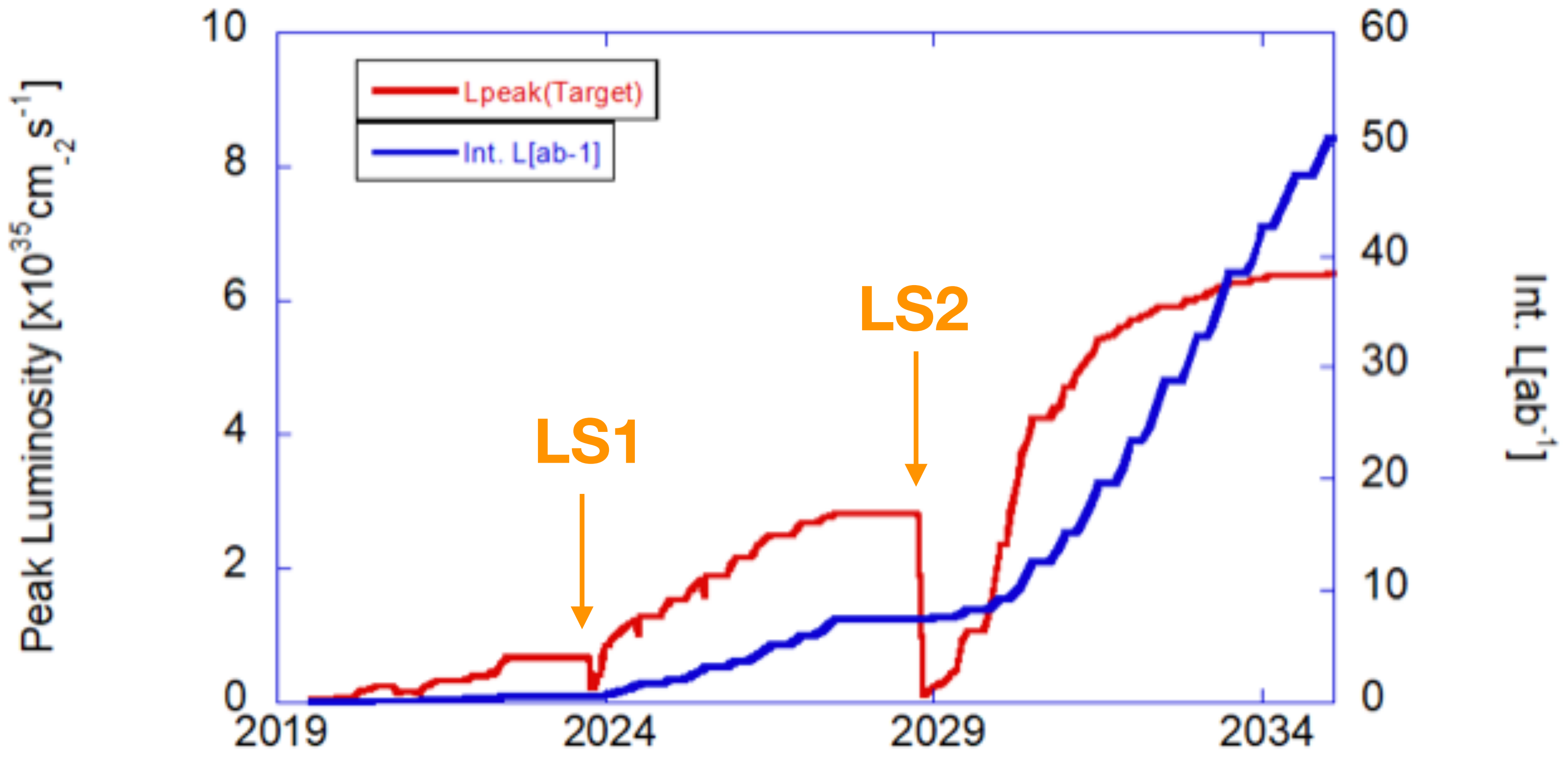
We are working on:

- Replacement of beam pipe
- Replacement of photomultipliers of the central PID detector (TOP)
- Installation of 2-layered pixel vertex detector
- Improvement of data-quality monitoring and alarm system
- Complete transition to new DAQ boards (PCIe40)
- Replacement of aging components
- Additional shielding and increased resilience against beam background

- Higher and more stable beam injection
- Longer beam lifetime and improved stability
- IR radiation shield modification, new collimation scheme and robust collimator head



PXD2 assembly completed in April @ KEK



Belle II is maybe (?) the only experiment that explains how it works via its logo:

Plenty of Puns

1) Belle collides electrons and their anti-particle positrons
2) B breaks the symmetry between el - le
   (i.e. between matter and antimatter)
3) Belle investigates beauty quarks, which are of course "belle"

Belle II is maybe (?) the only experiment that explains how it works via its logo:

BEAST

(**B**eam **E**xorcism for **A** **ST**able BELLE Experiment)

The BEAST experiment: a background detector for the commissioning of the BELLE experiment

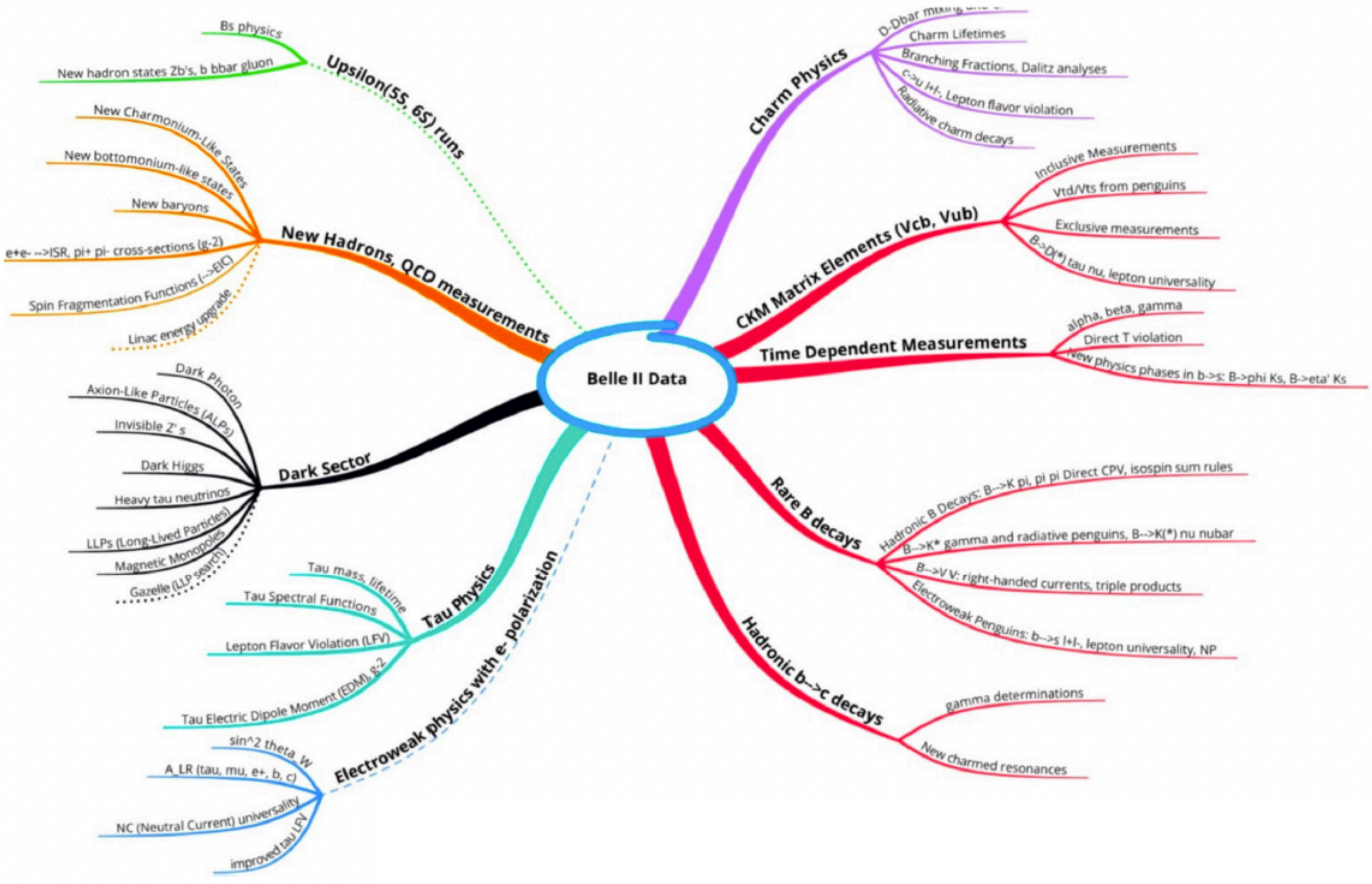
Plenty of Puns

1) Belle collides electrons and their anti-particle positrons
2) B breaks the symmetry between el - le
   (i.e. between matter and antimatter)
3) Belle investigates beauty quarks, which are of course "belle"

Picture: movies.disney.com

Belle II Physics Program

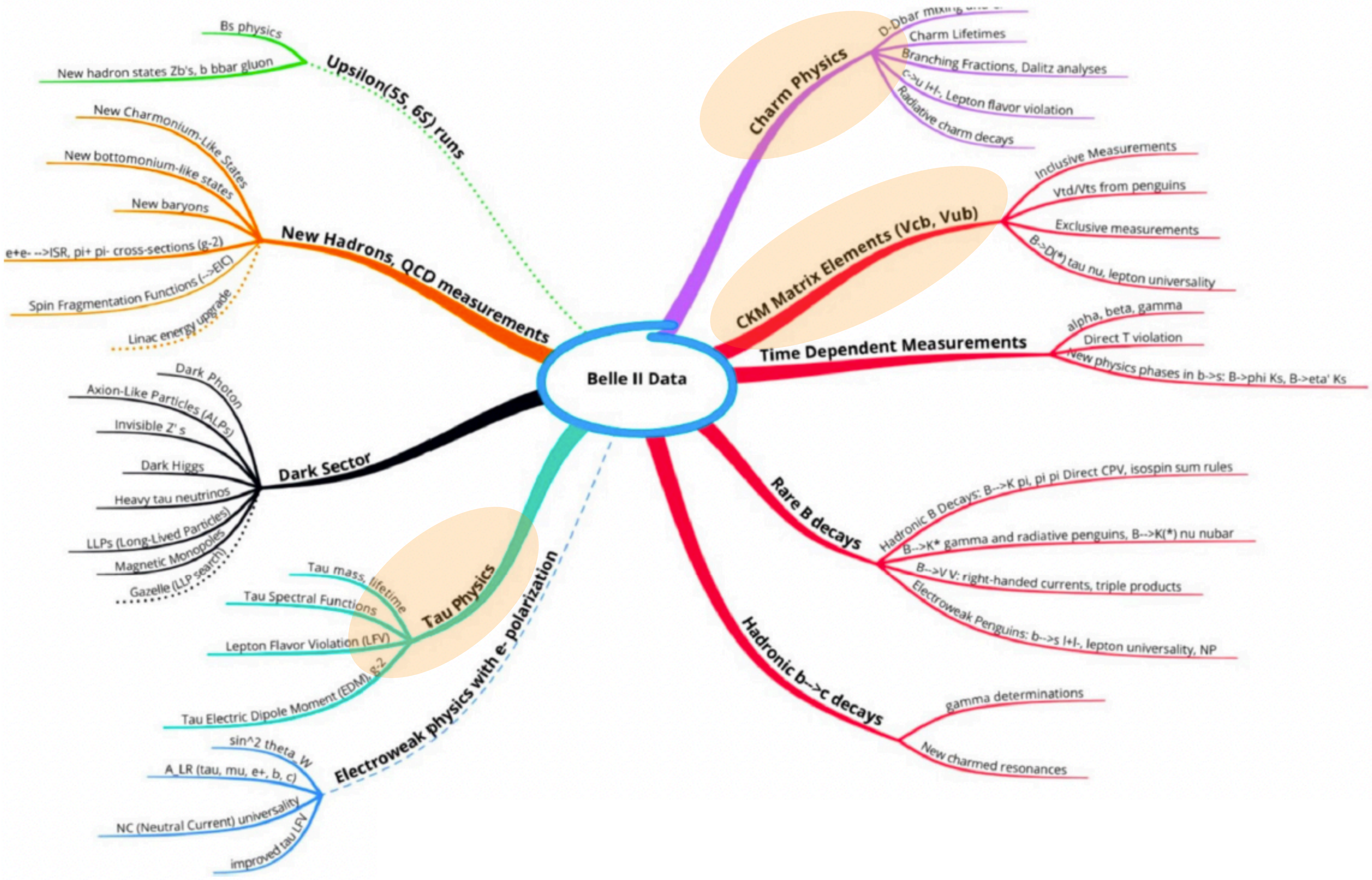
- Many sectors will be explored by analyzing Belle II data
- Unique advantages in inclusive analyses, decays involving multiple neutrals
- Full potential summarized in “Belle II Physics Book” [PTEP 2019 123C01, arXiv:1808.10567]



Belle II Physics Program

- Many sectors will be explored by analyzing Belle II data
- Unique advantages in inclusive analyses, decays involving multiple neutrals
- Full potential summarized in “Belle II Physics Book” [PTEP 2019 123C01, arXiv:1808.10567]

recent highlights covered in today’s talk

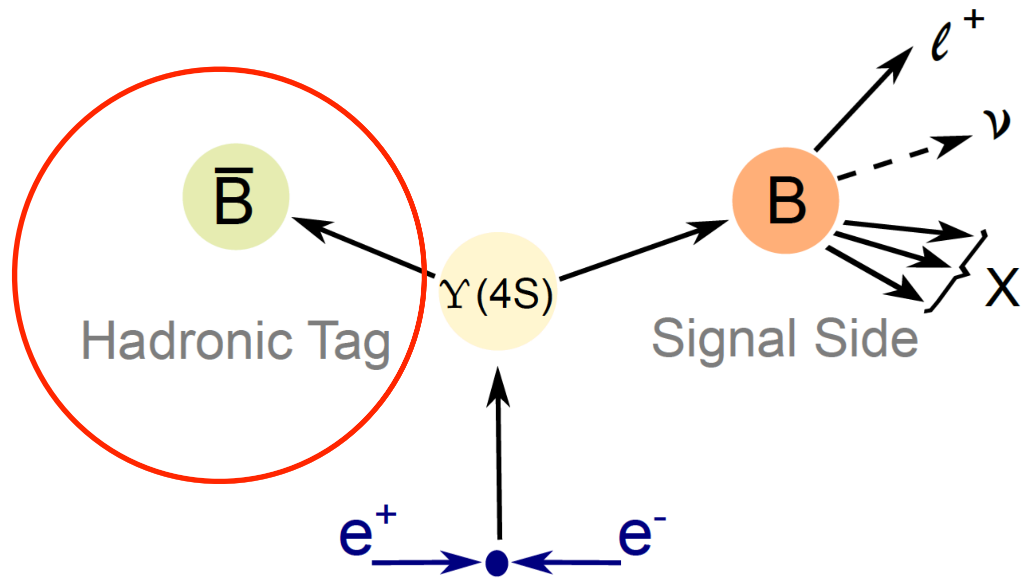


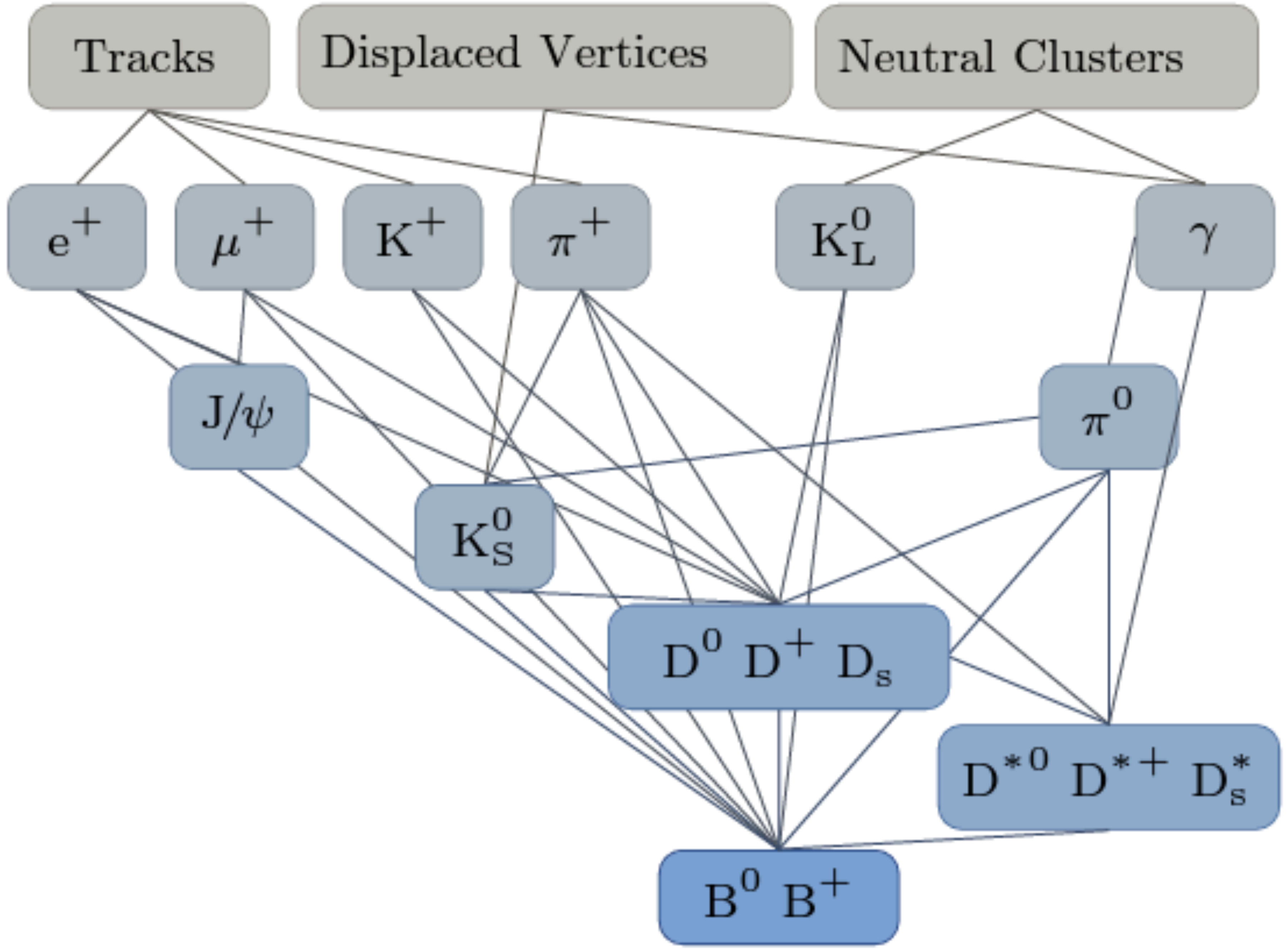
CKM matrix element $|V_{cb}|$

Inclusive $B \to X_c \ell \nu$ Decays and q^2 Moments

- Measurement of q^2 moments allows new approach to extract inclusive $|V_{cb}|$
- Analysis Belle II dataset of **62.8 fb^{-1}** , $\ell = e, \mu$
- Hadronic tagging with **Full Event Interpretation** algorithm [Comput Softw Big Sci 3, 6(2019)] to reconstruct B_{tag}
    - Reconstruct B candidate with all combination of daughters
    - Calculate signal probability with multivariate classifiers

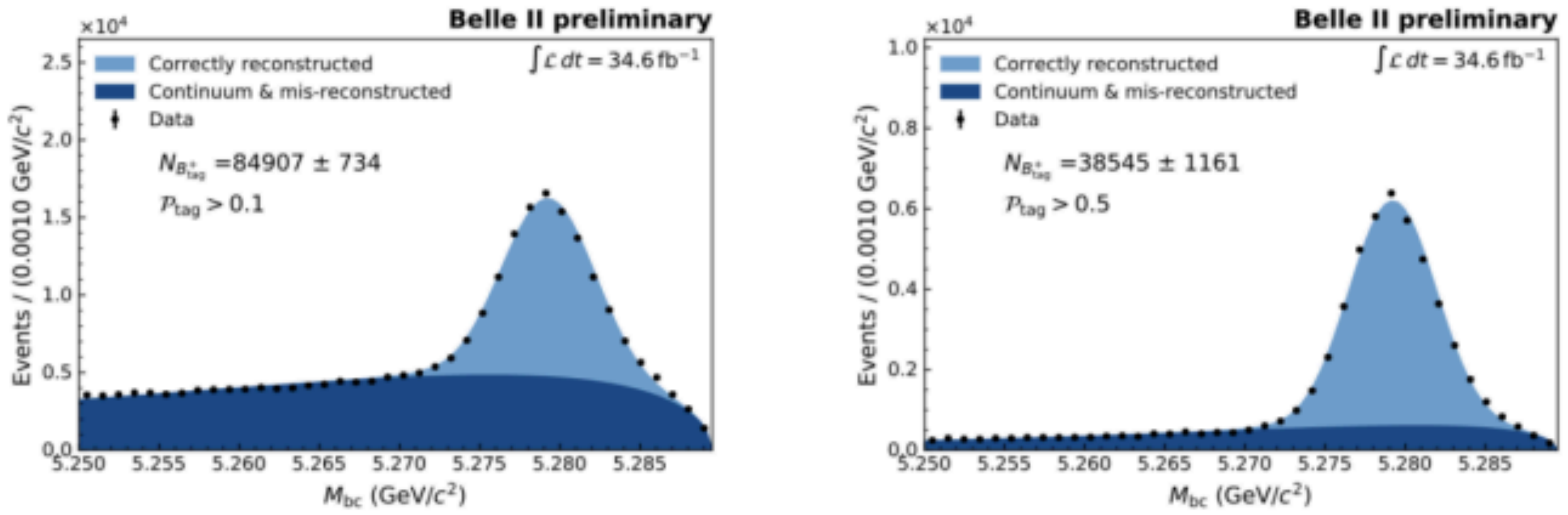
PRD 107, 072002 (2023)





Hadronic FEI

- Over 200 BDTs to reconstruct $\mathcal{O}(10000)$ distinct decay chains
- Efficiency $\epsilon_{B^+} \approx 0.5\,\%$, $\epsilon_{B^0} \approx 0.3\,\%$ at ~$15\,\%$ purity



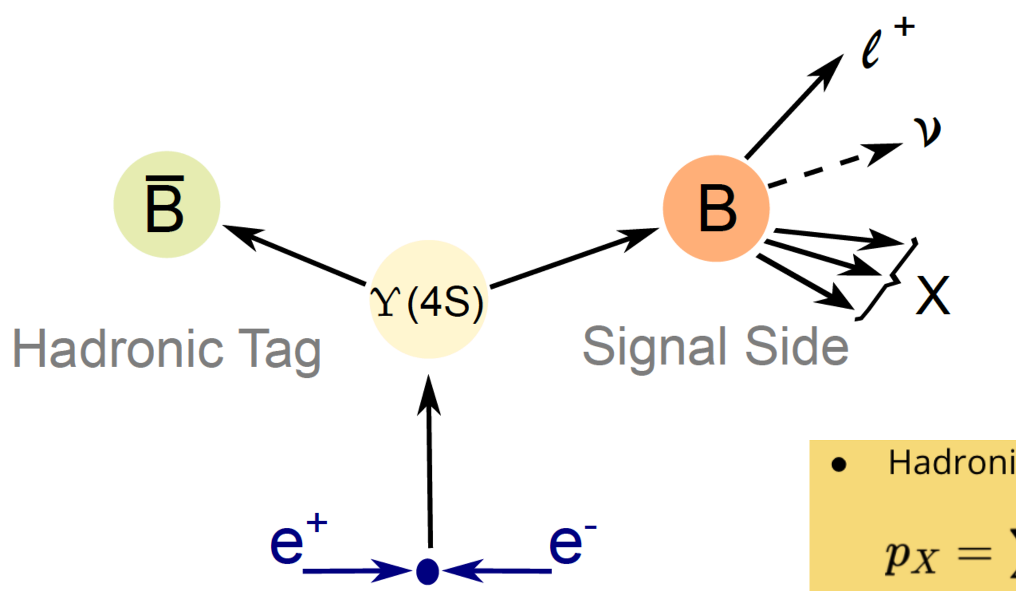
$$M_{bc} = \sqrt{E_{beam}^2/4 - (p_{B_{tag}}^{cm})^2} > 5.27\ \text{GeV}/c^2$$

Inclusive $B \to X_c \ell \nu$ Decays and q^2 Moments

- Measurement of q^2 moments allows new approach to extract inclusive $|V_{cb}|$

PRD 107, 072002 (2023)

- Analysis Belle II dataset of **62.8 fb^{-1}** , $\ell = e, \mu$
- Hadronic tagging with **Full Event Interpretation** algorithm [Comput Softw Big Sci 3, 6(2019)] to reconstruct B_{tag}
- Background suppressed in hadronic mass M_X and converted to signal prob. on q^2



Can fully assign each final state particle to either the tag or signal side

Allows to reconstruct *X*

- Hadronic system *X*:

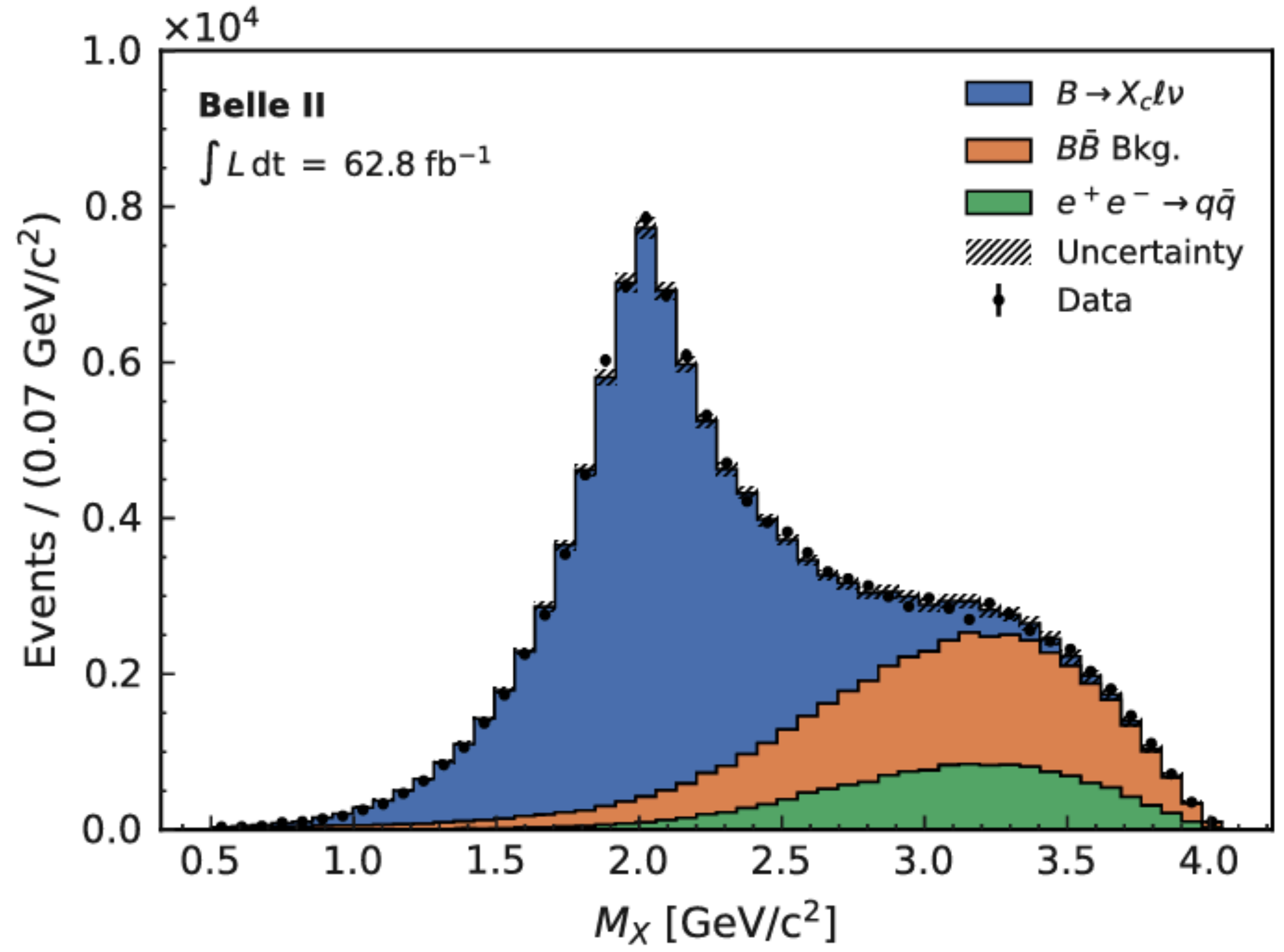
$$p_X = \sum_i \left(\sqrt{m_\pi^2 + |\mathbf{p_i}|^2}, \mathbf{p_i}\right) + \sum_i (E_i, \mathbf{k_i})$$

- Missing mass squared:

$$MM^2 = (P_{\Upsilon(4S)} - P_{\text{tag}} - P_X - P_\ell)^2$$

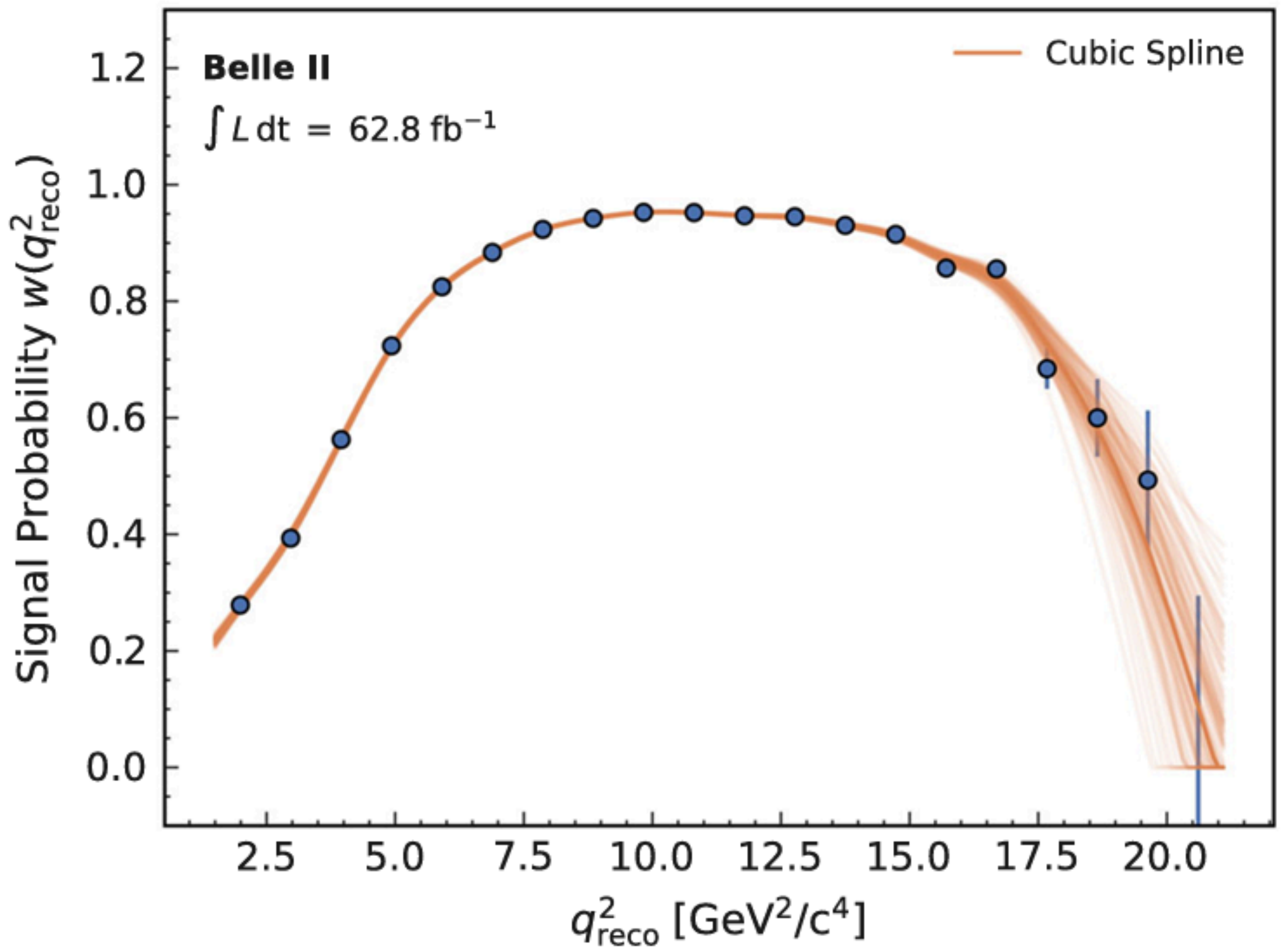
- Leptonic system:

$$q^2 = (P_B - P_X)^2 = (P_\ell + P_\nu)^2$$



- **First to fourth moments (m=1~4)** measured at a progression of cuts on q^2
- Spectra corrected for linear distortions, eff. & acc. & residual bias

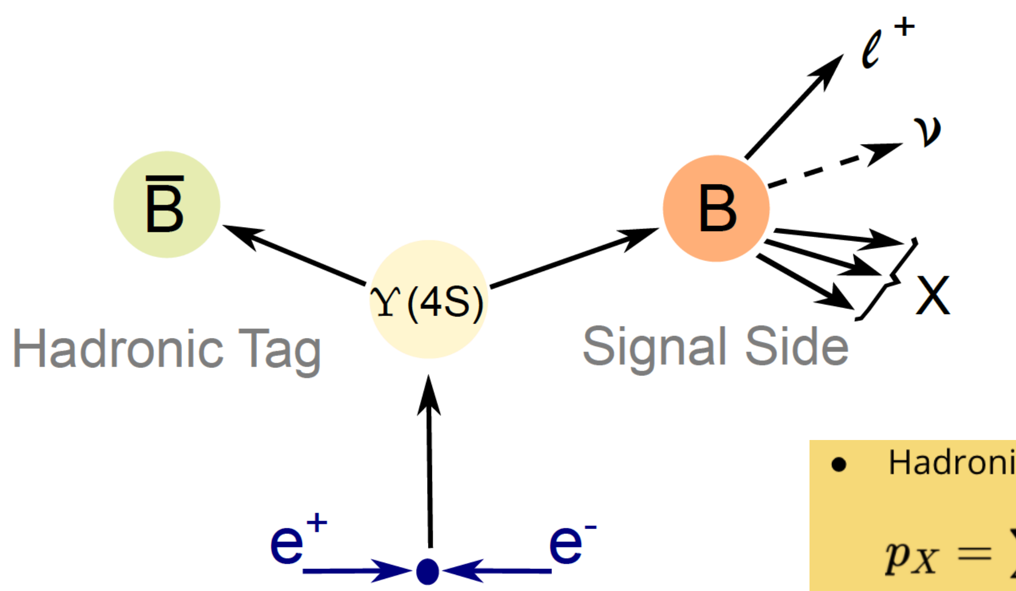
$$\langle q^{2m} \rangle = \frac{C_{\text{cal}} \cdot C_{\text{acc}}}{\sum_i^{\text{events}} w(q_i^2)} \times \sum_i^{\text{events}} w(q_i^2) \cdot q_{\text{cal}\,i}^{2m}$$



Inclusive $B \to X_c \ell \nu$ Decays and q^2 Moments

PRD 107, 072002 (2023)

- Measurement of q^2 moments allows new approach to extract inclusive $|V_{cb}|$
- Analysis Belle II dataset of **62.8 fb^{-1}**, $\ell = e, \mu$
- Hadronic tagging with **Full Event Interpretation** algorithm [Comput Softw Big Sci 3, 6(2019)] to reconstruct B_{tag}
- Background suppressed in hadronic mass M_X and converted to signal prob. on q^2
- Measured phase space of $q^2 = [1.5, 8.5]$ GeV^2



Can fully assign each final state particle to either the tag or signal side

Allows to reconstruct *X*

- Hadronic system *X*:

$$p_X = \sum_i \left(\sqrt{m_\pi^2 + |\mathbf{p}_i|^2}, \mathbf{p}_i\right) + \sum_i (E_i, \mathbf{k}_i)$$

- Missing mass squared:

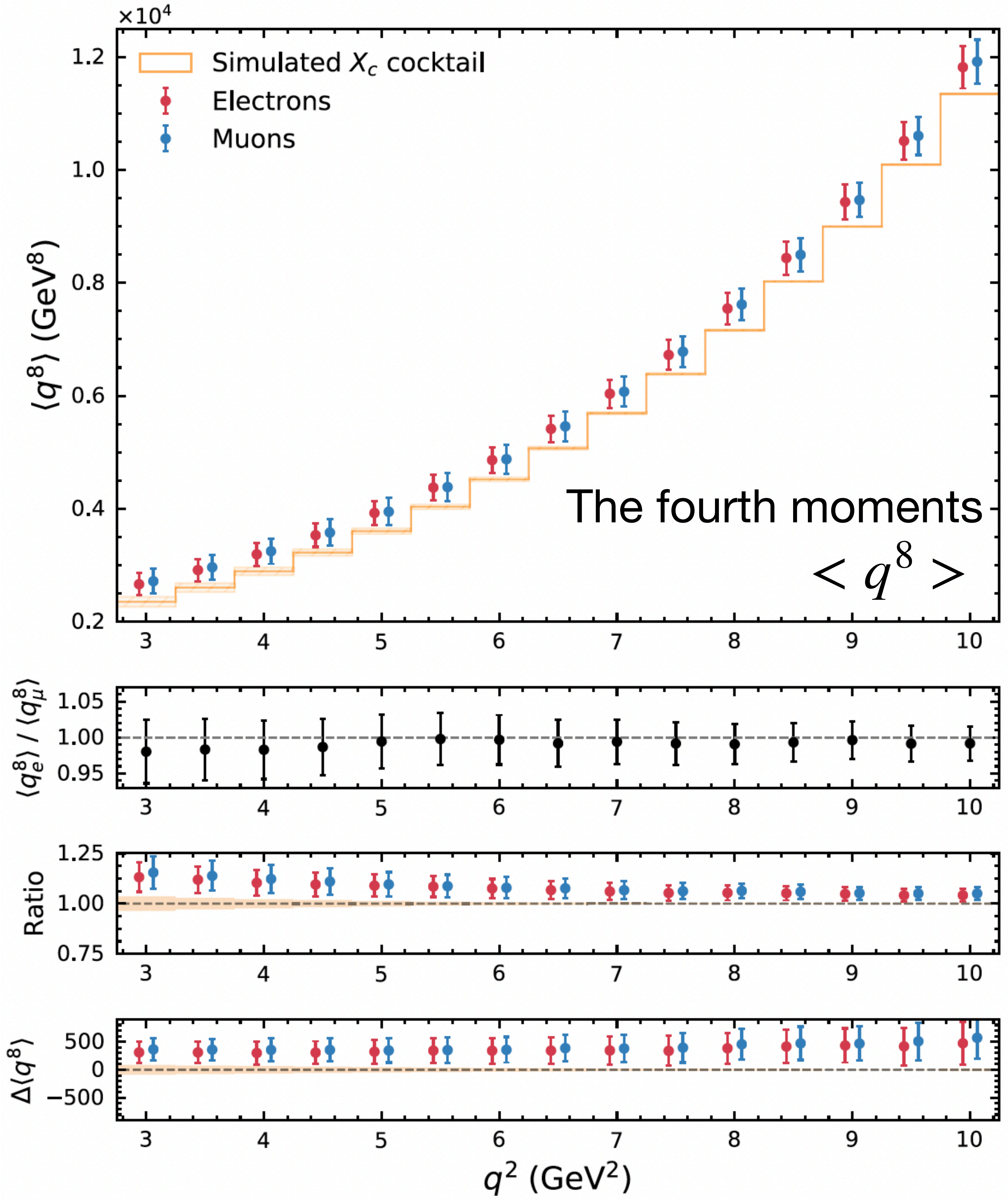
$$MM^2 = (P_{\Upsilon(4S)} - P_{\text{tag}} - P_X - P_\ell)^2$$

- Leptonic system:

$$q^2 = (P_B - P_X)^2 = (P_\ell + P_\nu)^2$$

- **First to fourth moments (m=1~4)** measured at a progression of cuts on q^2
- Spectra corrected for linear distortions, eff. & acc. & residual bias

$$\langle q^{2m} \rangle = \frac{C_{\text{cal}} \cdot C_{\text{acc}}}{\sum_i^{\text{events}} w(q_i^2)} \times \sum_i^{\text{events}} w(q_i^2) \cdot q_{\text{cal}\, i}^{2m}$$



← Extract $|V_{cb}|$

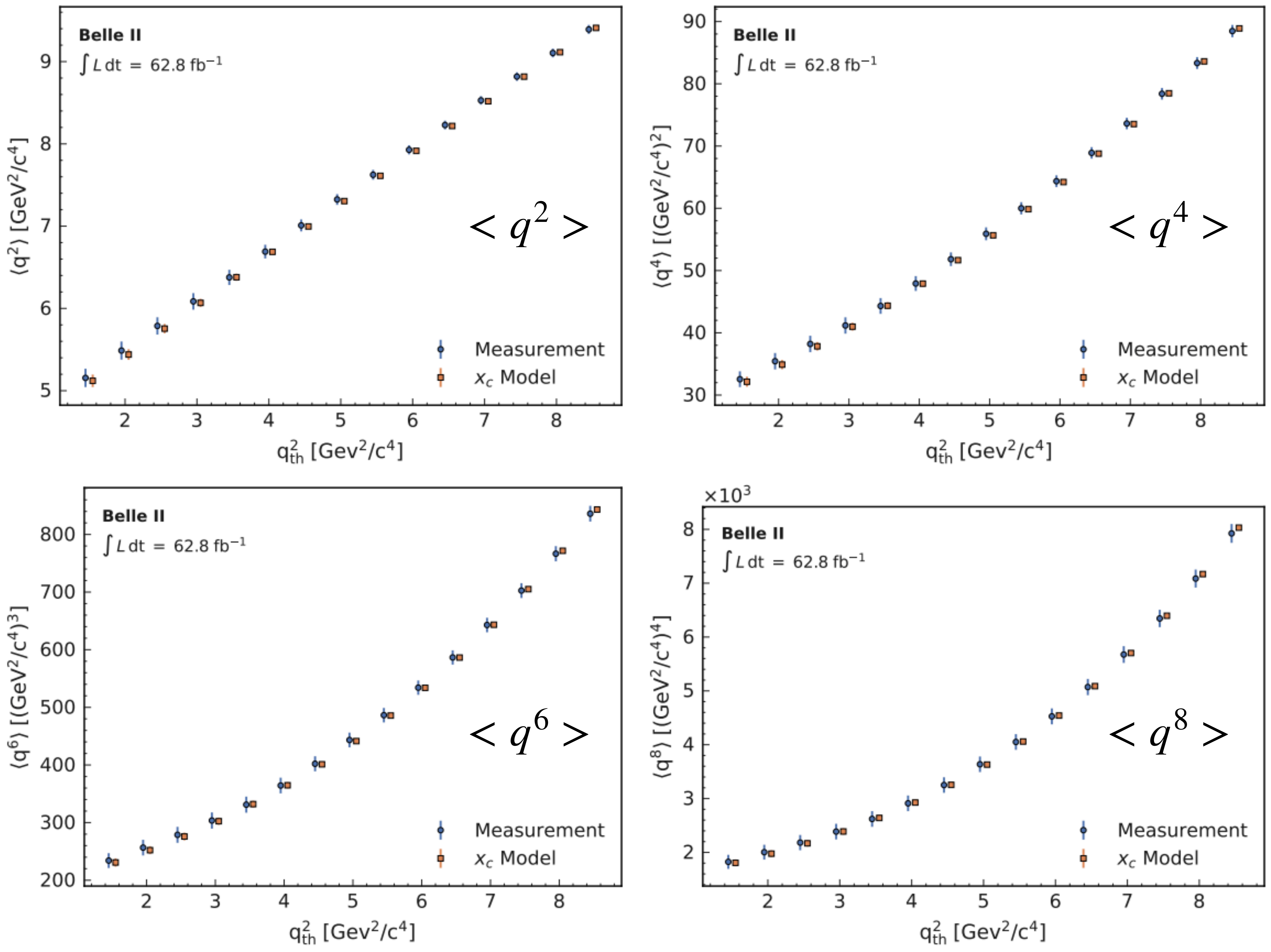
← LFUV test

← Mea. / Sim.

← Mea. - Sim.

Inclusive $B \to X_c \ell \nu$ Decays and q^2 Moments

PRD 107, 072002 (2023)



A side remark on Inclusive $|V_{cb}|$ determination

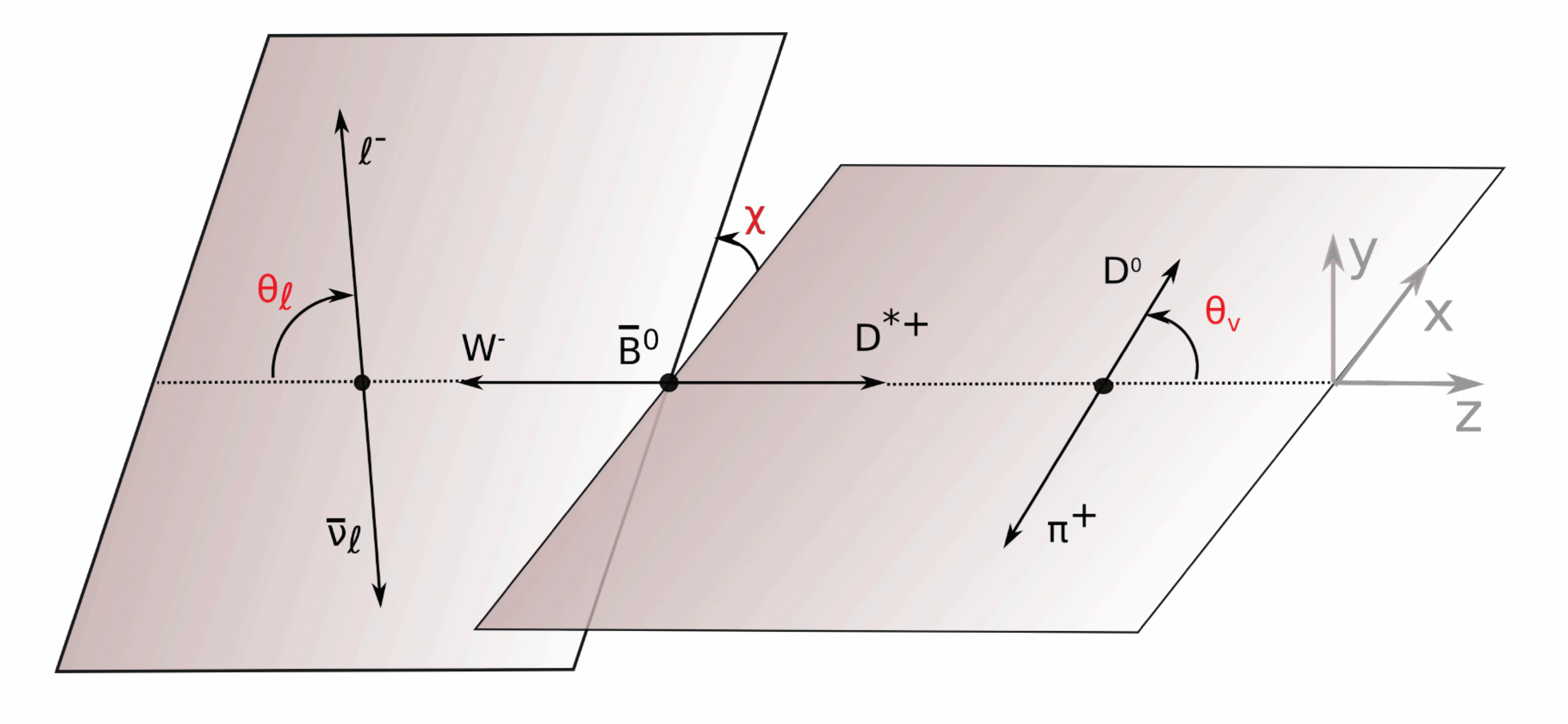
- Belle II & Belle $< q^{2m} >$ results are used in novel approach to extract $|V_{cb}|$ [JHEP 10 (2022) 068]
- Benefit from reduced number of non-perturbative matrix elements
- Obtained consistent $|V_{cb}|$ with previous results using M_X, E_ℓ^B moments

$$|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3}$$

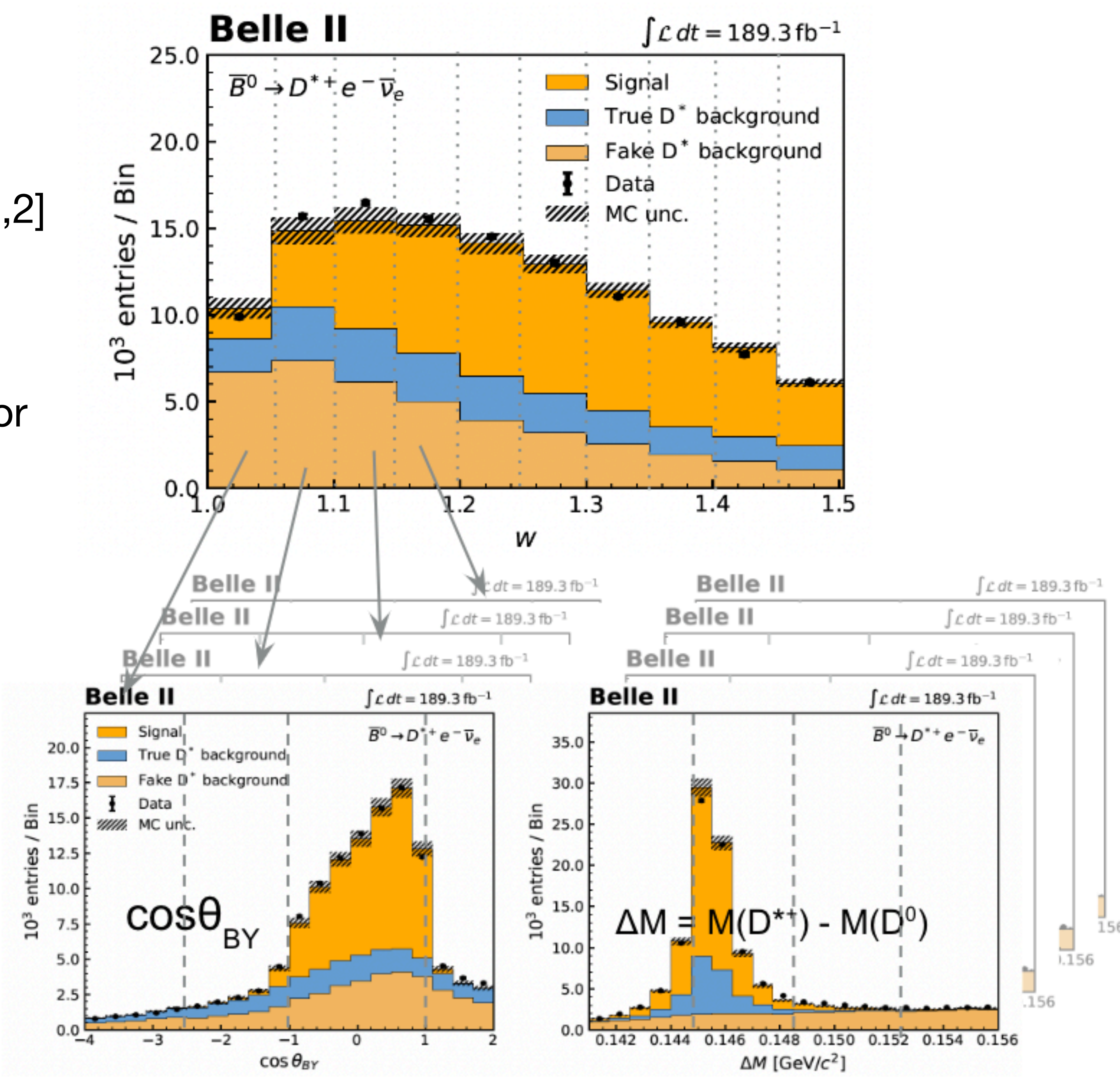
$|V_{cb}|$ in $B^0 \to D^*\ell\nu$ Decay

Preliminary

- Decay chain: **$B^0 \to D^{*+} \ell\nu$, $D^{*+} \to D^0\pi^+_{slow}$, $D^0 \to K^- \pi^+$**
- Untagged strategy (higher efficiency than tagged)
- Select energetic signal lepton $p^{CM} > 1.2$ GeV
- $M(D^0) = m_{PDG} \pm 15$ MeV, $M(D^{*+})-M(D^0) = [0.141,0.156]$ GeV, $\cos\theta_{BY} = [-4,2]$
- 2D binned linkelihood fit on ($\cos\theta_{BY}$, ΔM) for each bin of kinematic variables: recoil parameter **w**, and angles **$\cos\theta_\ell$**, **$\cos\theta_\nu$**, χ
- Systematic shape variations incorporated as bin-wise Nuisance para. for each fit template



$$\cos\theta_{BY} = \frac{2E_B^{CM}E_Y^{CM} - m_B^2 - m_Y^2}{2|\vec{p}_B^{\,CM}||\vec{p}_Y^{\,CM}|}$$



integral projection

|V$_{cb}$| in $B^0 \to D^*\ell\nu$ Decay

Preliminary

- Unfold signal yields using **singular-value-decomposition (SVD)** method within pyRooUnfold, regularization para. optimised for low bias & stable result

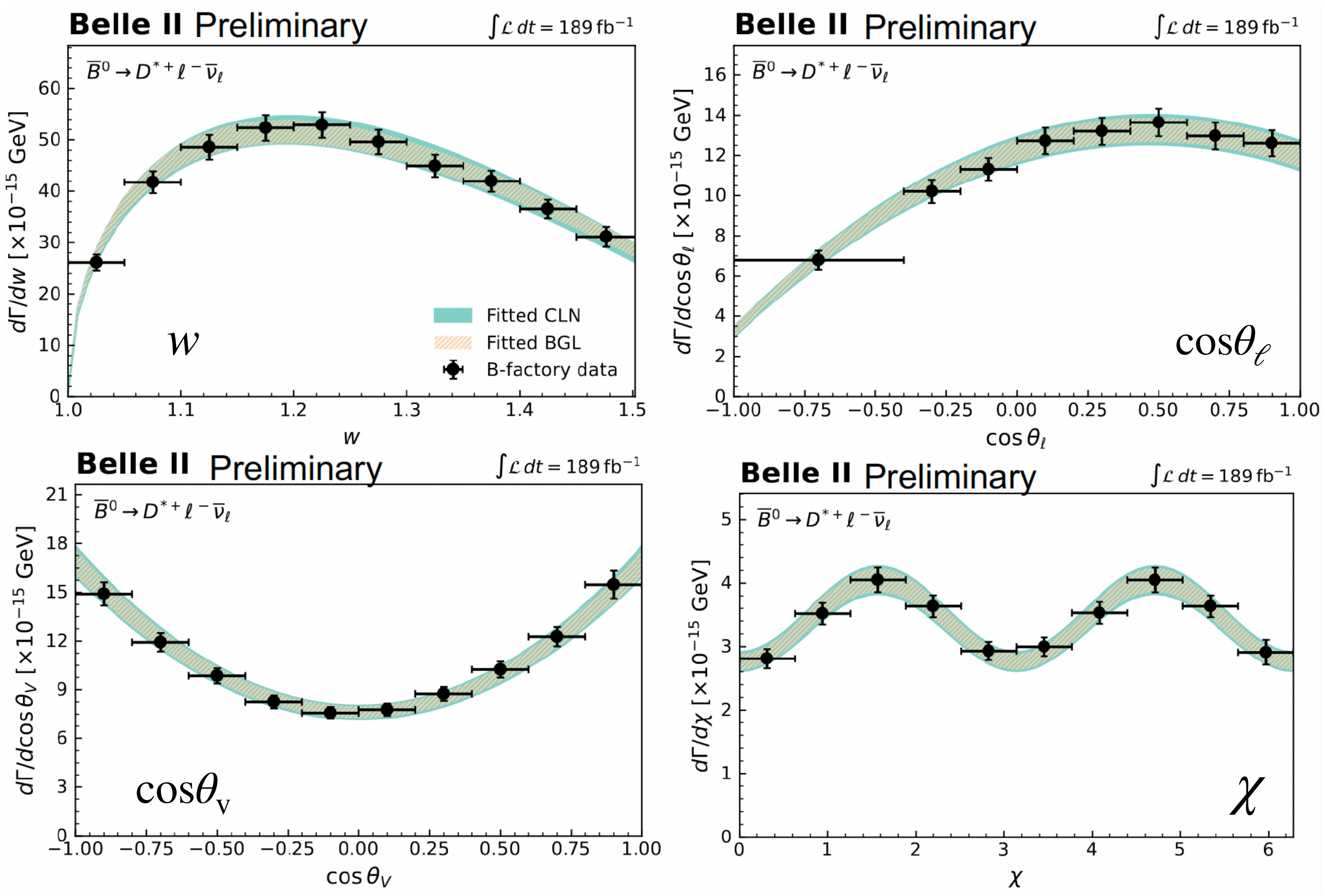
- Full post-unfolding stat. & syst. covariance propagated into partial decay rate

reco. eff & acc.

input of PDG2022

$$\Delta\Gamma_i = \frac{y_i^{\mathrm{unfolded}}}{\boxed{\epsilon_i} N_{B^0} \boxed{\mathcal{B}(D^{*+} \to D^0\pi^+)\mathcal{B}(D^0 \to K^-\pi^+)\tau_{B^0}}}$$

$$\Gamma = \left(\sum_{i=1}^{10} \Delta\Gamma_i^{w} + \sum_{i=1}^{8} \Delta\Gamma_i^{\cos\theta_\ell} + \sum_{i=1}^{10} \Delta\Gamma_i^{\cos\theta_V} + \sum_{i=1}^{10} \Delta\Gamma_i^{\chi} \right) /4$$

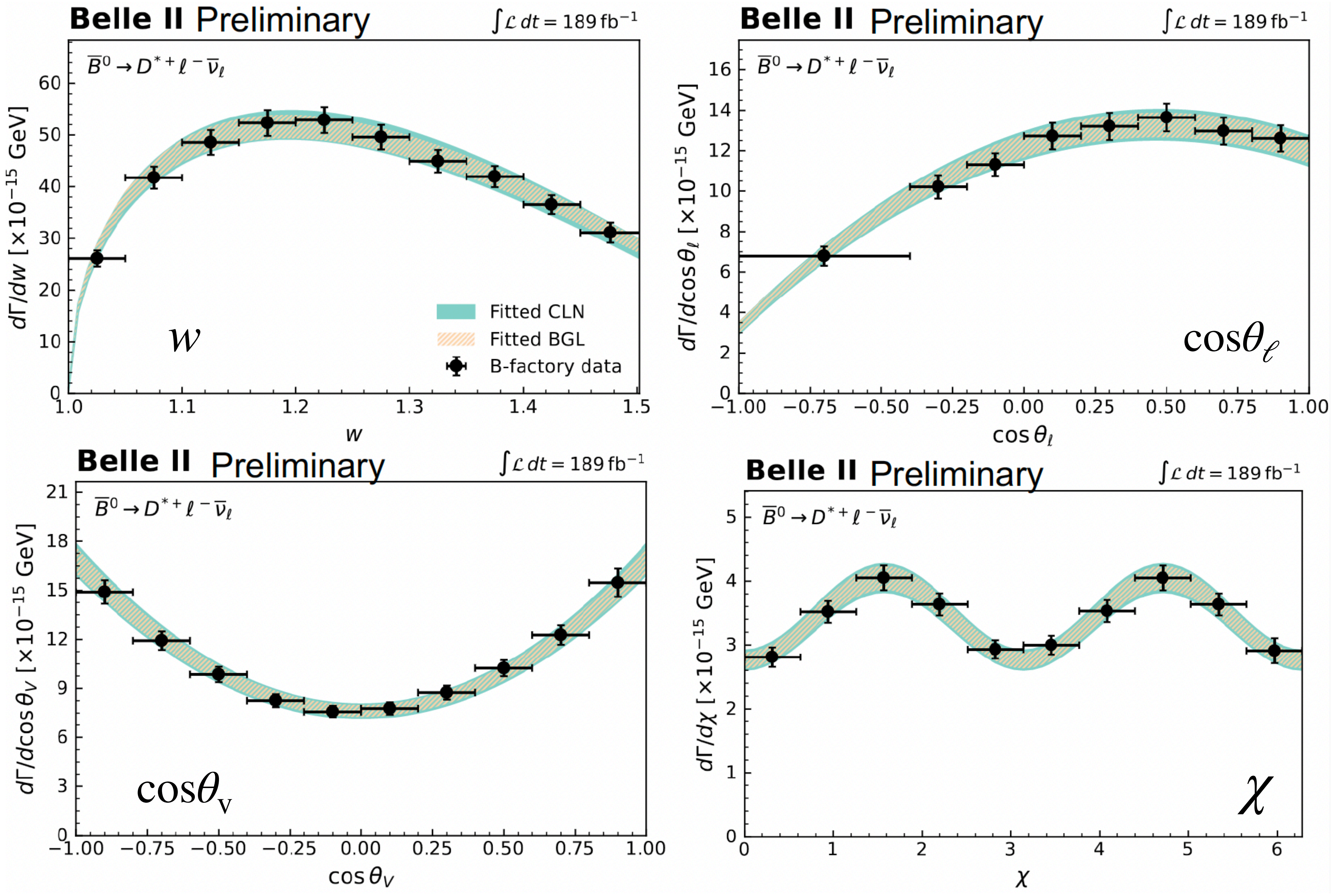


$|V_{cb}|$ in $B^0 \to D^*\ell\nu$ Decay

Preliminary

- Unfold signal yields using **singular-value-decomposition (SVD)** method within pyRooUnfold, regularization para. optimised for low bias & stable result

- Full post-unfolding stat. & syst. covariance propagated into partial decay rate



reco. eff & acc.

input of PDG2022

$$\Delta\Gamma_i = \frac{y_i^{\text{unfolded}}}{\boxed{\epsilon_i} N_{B^0} \boxed{\mathcal{B}(D^{*+} \to D^0\pi^+)\mathcal{B}(D^0 \to K^-\pi^+)\tau_{B^0}}}$$

$$\Gamma = \left(\sum_{i=1}^{10} \Delta\Gamma_i^{w} + \sum_{i=1}^{8} \Delta\Gamma_i^{\cos\theta_\ell} + \sum_{i=1}^{10} \Delta\Gamma_i^{\cos\theta_V} + \sum_{i=1}^{10} \Delta\Gamma_i^{\chi} \right) /4$$

Branching fraction extracted by the **total rate** summing over partial decay rates and averaging all kin. variables

e mode: $\mathcal{B}(\overline{B}^0 \to D^{*+}e^-\overline{\nu}_e) = (4.94 \pm 0.03 \pm 0.22)\%$

mu mode: $\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu) = (4.94 \pm 0.03 \pm 0.24)\%$

average: $\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell) = (4.94 \pm 0.02 \pm 0.22)\%$

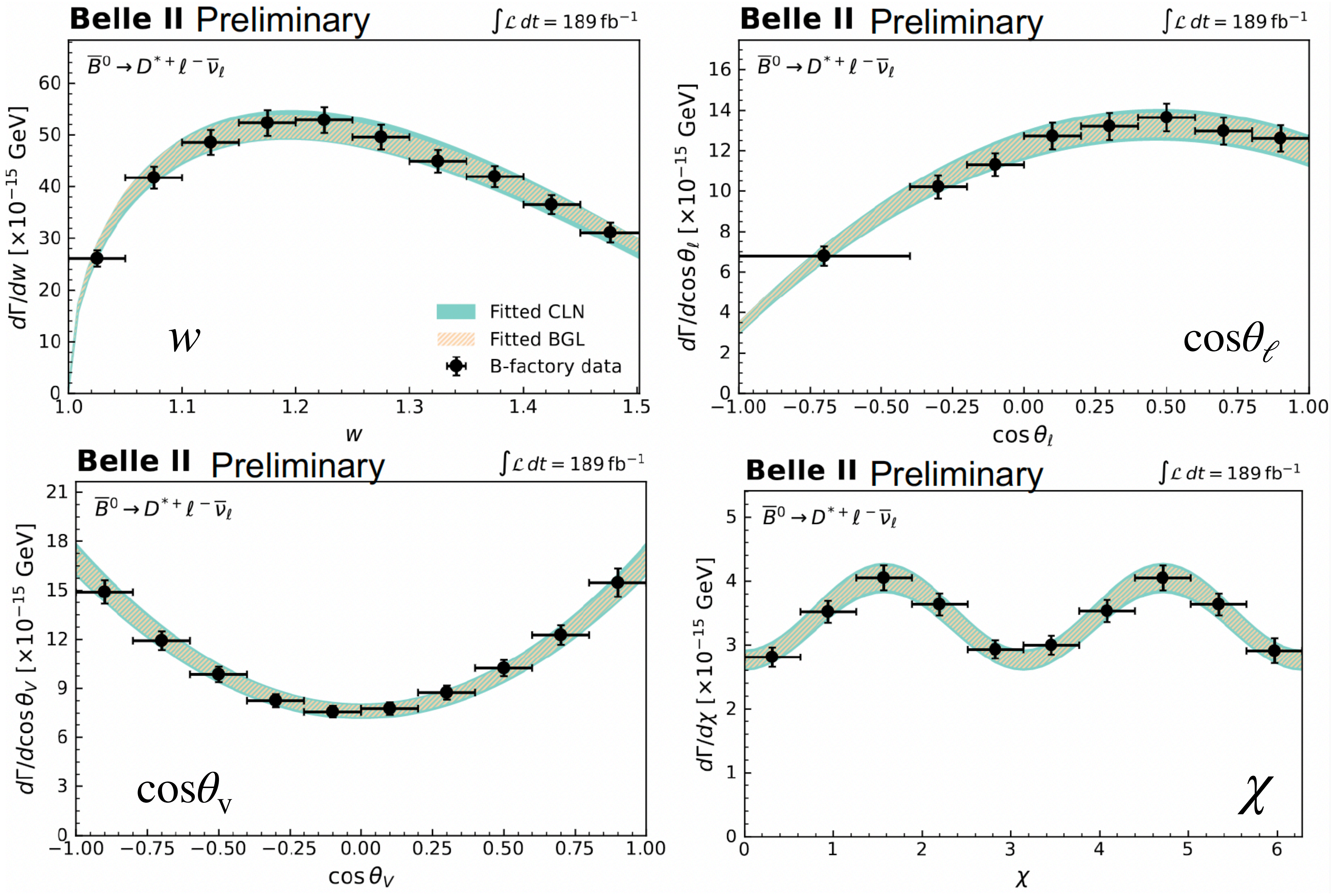
$|V_{cb}|$ in $B^0 \to D^*\ell\nu$ Decay

Preliminary

- Include all measured w, $\cos\theta_\ell$, $\cos\theta_V$, χ to extract form factor & $|V_{cb}|$
- Fit with form factor expansion based on **CLN** & **BGL (truncation tested)**
- Reredundant degrees of freedom removed by using **normalized partial rates** on each variable together with the **averaged total rate** (ndf = 34+1)

$$\chi^2 = \sum_{i,j}^{34} \left(\frac{\Delta\Gamma_i^{\rm obs}}{\Gamma^{\rm obs}} - \frac{\Delta\Gamma_i^{\rm pre}}{\Gamma^{\rm pre}} \right) C_{ij}^{-1} \left(\frac{\Delta\Gamma_j^{\rm obs}}{\Gamma^{\rm obs}} - \frac{\Delta\Gamma_j^{\rm pre}}{\Gamma^{\rm pre}} \right)$$

$$+ \frac{(\Gamma^{\rm obs} - \Gamma^{\rm pre})^2}{\sigma_\Gamma^2}$$



$$|V_{cb}|\eta_{\rm EW}\mathcal{F}(1) = \frac{1}{\sqrt{m_B m_{D^*}}} \left(\frac{|\tilde{b}_0|}{P_f(0)\phi_f(0)} \right)$$

$$|V_{cb}|_{\rm BGL} = (40.9 \pm 0.3 \pm 1.0 \pm 0.6) \times 10^{-3}$$

$$|V_{cb}|_{\rm CLN} = (40.4 \pm 0.3 \pm 1.0 \pm 0.6) \times 10^{-3}$$

Slow pion eff. plays leading role in syst.

Input from LQCD at zero-recoil F(1)

$|V_{cb}|$ in $B^0 \to D^*\ell\nu$ Decay

Preliminary

- Include all measured w, $\cos\theta_\ell$, $\cos\theta_V$, χ to extract form factor & $|V_{cb}|$
- Fit with form factor expansion based on **CLN** & **BGL (truncation tested)**
- Reredundant degrees of freedom removed by using **normalized partial rates** on each variable together with the **averaged total rate** (ndf = 34+1)
- Inclusion of LQCD constraint [arxiv:2105.14019] at beyond zero-recoil (w = [1.03, 1.10, 1.17]) in two scenarios

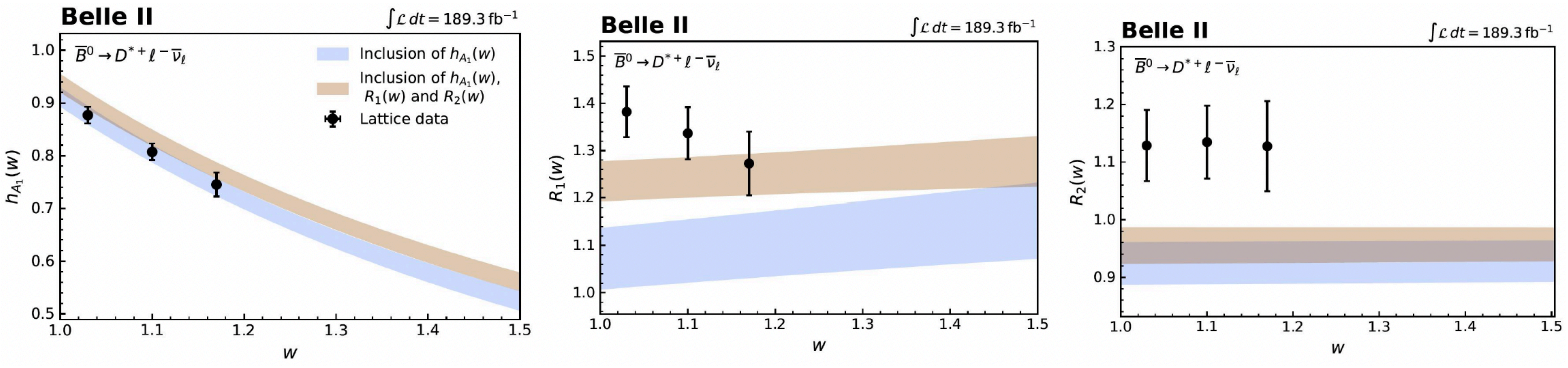
$$\chi^2 = \sum_{i,j}^{34} \left(\frac{\Delta\Gamma_i^{\rm obs}}{\Gamma^{\rm obs}} - \frac{\Delta\Gamma_i^{\rm pre}}{\Gamma^{\rm pre}} \right) C_{ij}^{-1} \left(\frac{\Delta\Gamma_j^{\rm obs}}{\Gamma^{\rm obs}} - \frac{\Delta\Gamma_j^{\rm pre}}{\Gamma^{\rm pre}} \right)$$

$$+ \frac{(\Gamma^{\rm obs} - \Gamma^{\rm pre})^2}{\sigma_\Gamma^2}$$

$$+ \sum_{ij} (F_i^{\rm LQCD} - F_i^{\rm exp}) C_{ij}^{-1} (F_j^{\rm LQCD} - F_j^{\rm exp})$$

BGL	Constraints on $h_{A_1}(w)$	Constraints on $h_{A_1}(w)$, $R_1(w)$, $R_2(w)$
$a_0 \times 10^3$	21.7 ± 1.4	25.7 ± 0.8
$b_0 \times 10^3$	13.20 ± 0.24	13.58 ± 0.23
$b_1 \times 10^3$	-7 ± 7	2 ± 6
$c_1 \times 10^3$	-1.1 ± 0.8	-0.5 ± 0.8
$\|V_{cb}\| \times 10^3$	40.5 ± 1.2	38.6 ± 1.1
χ^2/ndf	40/33	74/39
p-value	0.18	0.001

$|V_{cb}|$ shifts when include LQCD full constraints

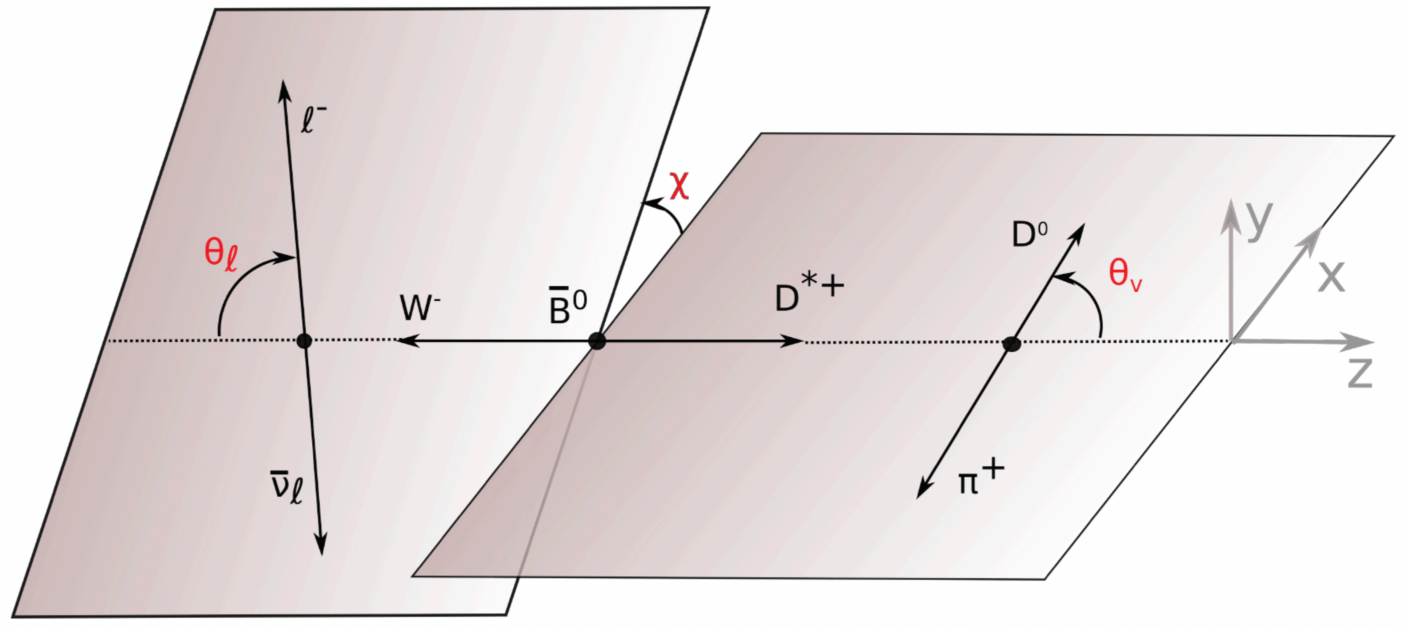


Consistent with recent Belle (2023) measurement [arXiv:2301.07529]
⇒ Both found large disagreements wrt LQCD results on R_2

|V$_{cb}$| in $B^0 \to D^*\ell\nu$ Decay

Preliminary

- Lepton-flavor-universality tested with separate results on e- & mu-mode
- All in **good agreement with SM expectations**



Test on branching fraction ratio: $R_{e/\mu} = 1.001 \pm 0.009 \pm 0.021$

Test on forward-backward asymmetry:

$$\mathcal{A}_{\mathrm{FB}} = \frac{\int_0^1 \mathrm{d}\cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell - \int_{-1}^0 \mathrm{d}\cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell}{\int_0^1 \mathrm{d}\cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell + \int_{-1}^0 \mathrm{d}\cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell}$$

$$\Delta\mathcal{A}_{\mathrm{FB}} = \mathcal{A}_{\mathrm{FB}}^{\mu} - \mathcal{A}_{\mathrm{FB}}^{e}$$

$$\mathcal{A}_{\mathrm{FB}}^{e} = 0.219 \pm 0.011 \pm 0.020\,,$$
$$\mathcal{A}_{\mathrm{FB}}^{\mu} = 0.215 \pm 0.011 \pm 0.022\,,$$
$$\boxed{\Delta\mathcal{A}_{\mathrm{FB}} = (-4 \pm 16 \pm 18) \times 10^{-3}}$$

Test on D* longitudinal polarization fraction:

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_V} = \frac{3}{2}\left(F_L\cos^2\theta_V + \frac{1-F_L}{2}\sin^2\theta_V\right)$$

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

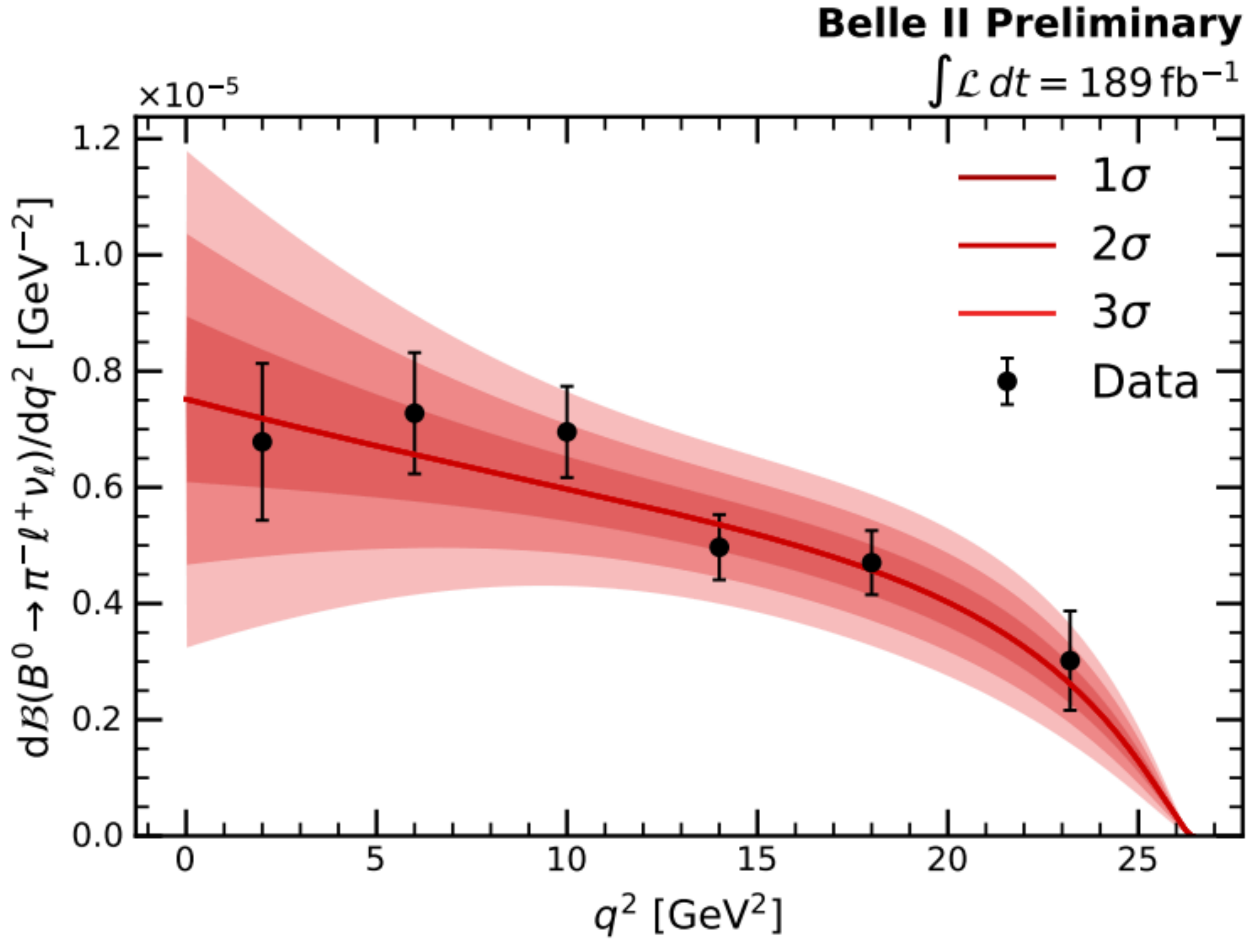
$$F_L^{e} = 0.521 \pm 0.005 \pm 0.007$$
$$F_L^{\mu} = 0.534 \pm 0.005 \pm 0.006$$
$$\boxed{\Delta F_L = 0.013 \pm 0.007 \pm 0.007}$$

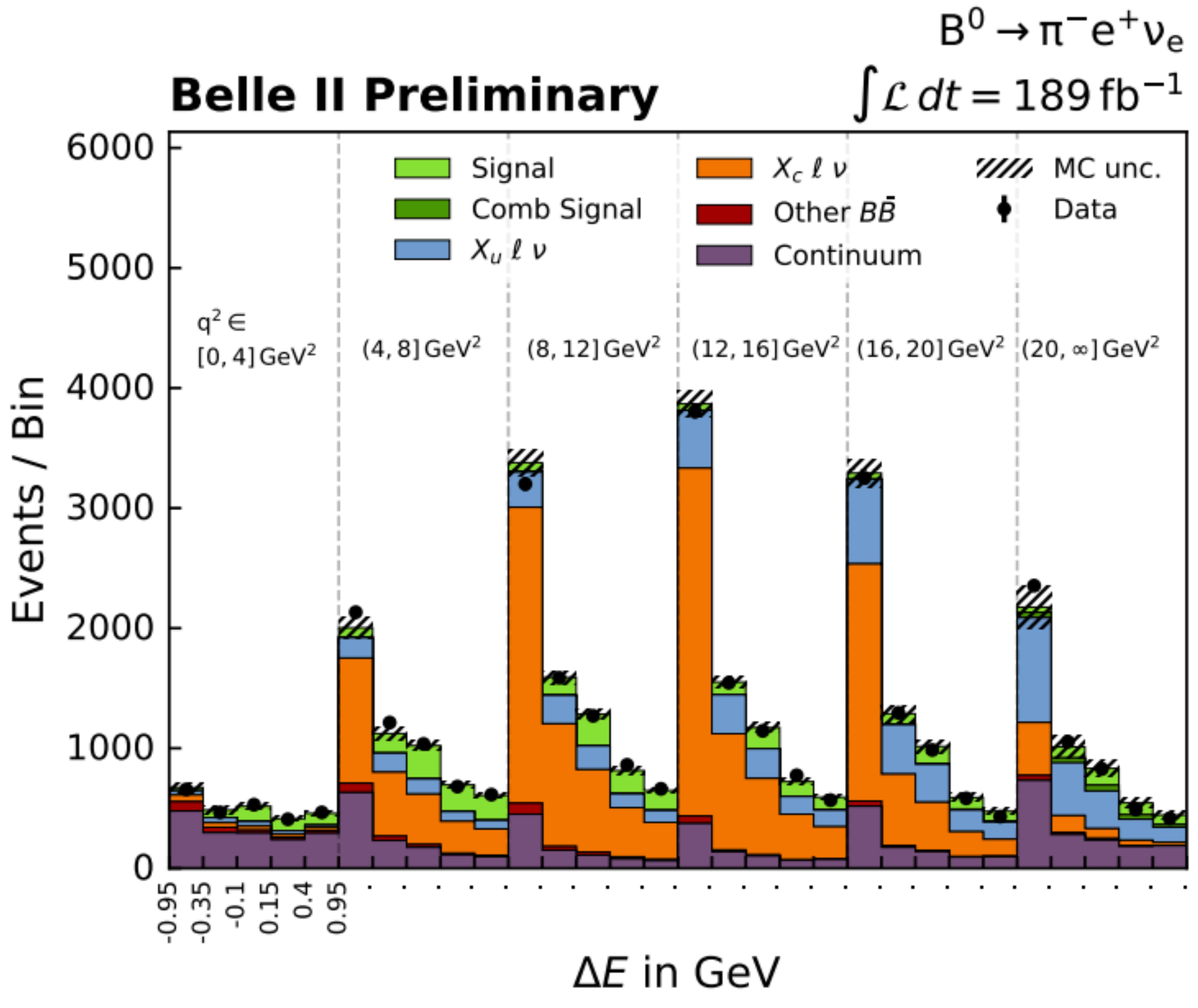
CKM matrix element $|V_{ub}|$

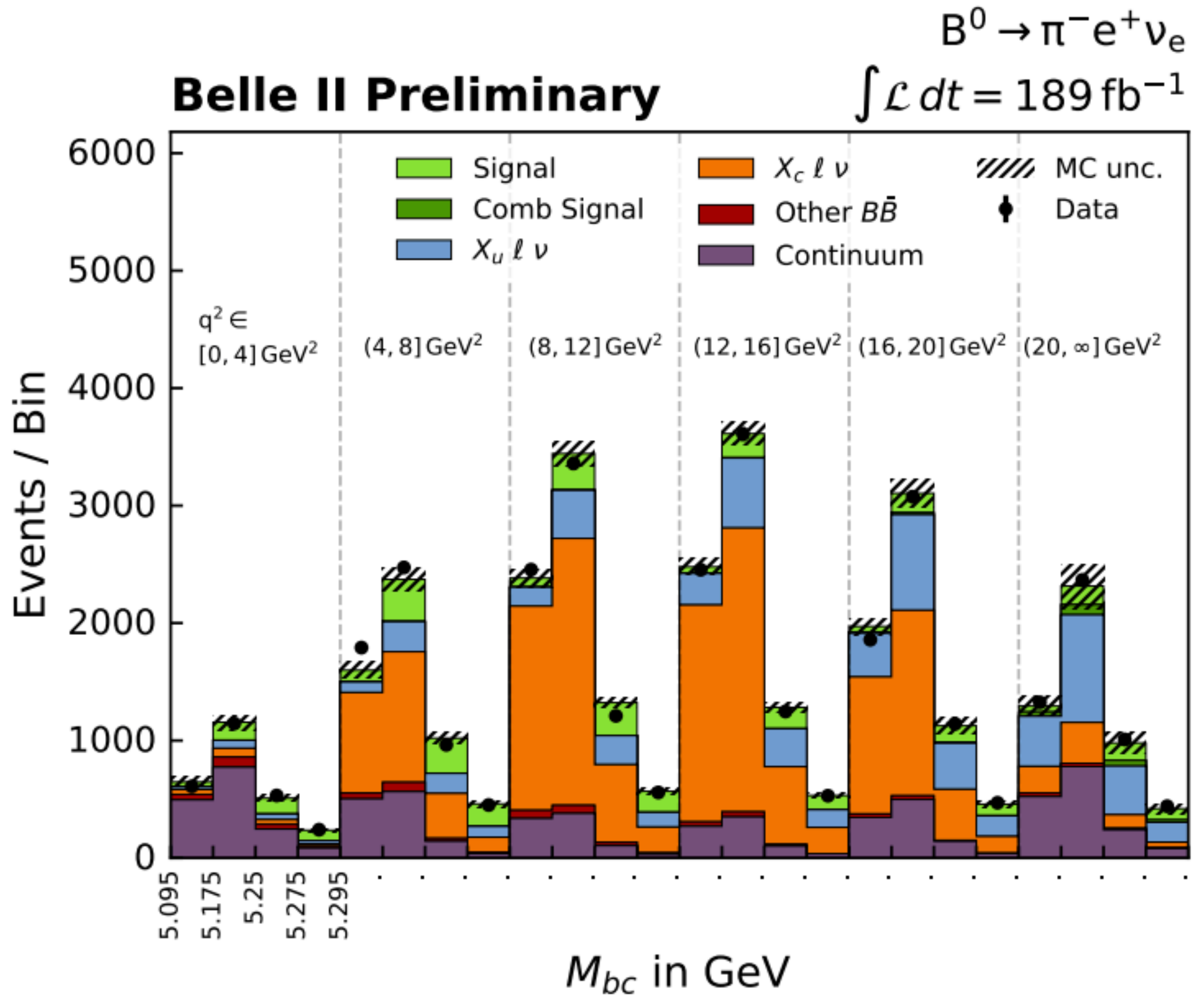
$|V_{ub}|$ in $B^0 \to \pi^- \ell^+ \nu$ with Belle II data

arXiv: 2210.04224

- Data set of 189.3 fb^{-1} with untagged analysis strategy
- Extract signal in beam-constrained mass M_{bc} and energy difference ΔE for each bin of q^2
- $|\mathbf{V_{ub}}|$ fitted with BCL expansion including LQCD constraints (FNAL/MILC)







$$\mathscr{B} = (1.426 \pm 0.056_{\text{stat}} \pm 0.125_{\text{syst}}) \times 10^{-4}$$

$$\Delta E = E_B^* - E_{\text{beam}}^* = E_B^* - \frac{\sqrt{s}}{2}$$

$$M_{bc} = \sqrt{E_{\text{beam}}^{*2} - |\vec{p}_B^{\,*}|^2} = \sqrt{\left(\frac{\sqrt{s}}{2}\right)^2 - |\vec{p}_B^{\,*}|^2}$$

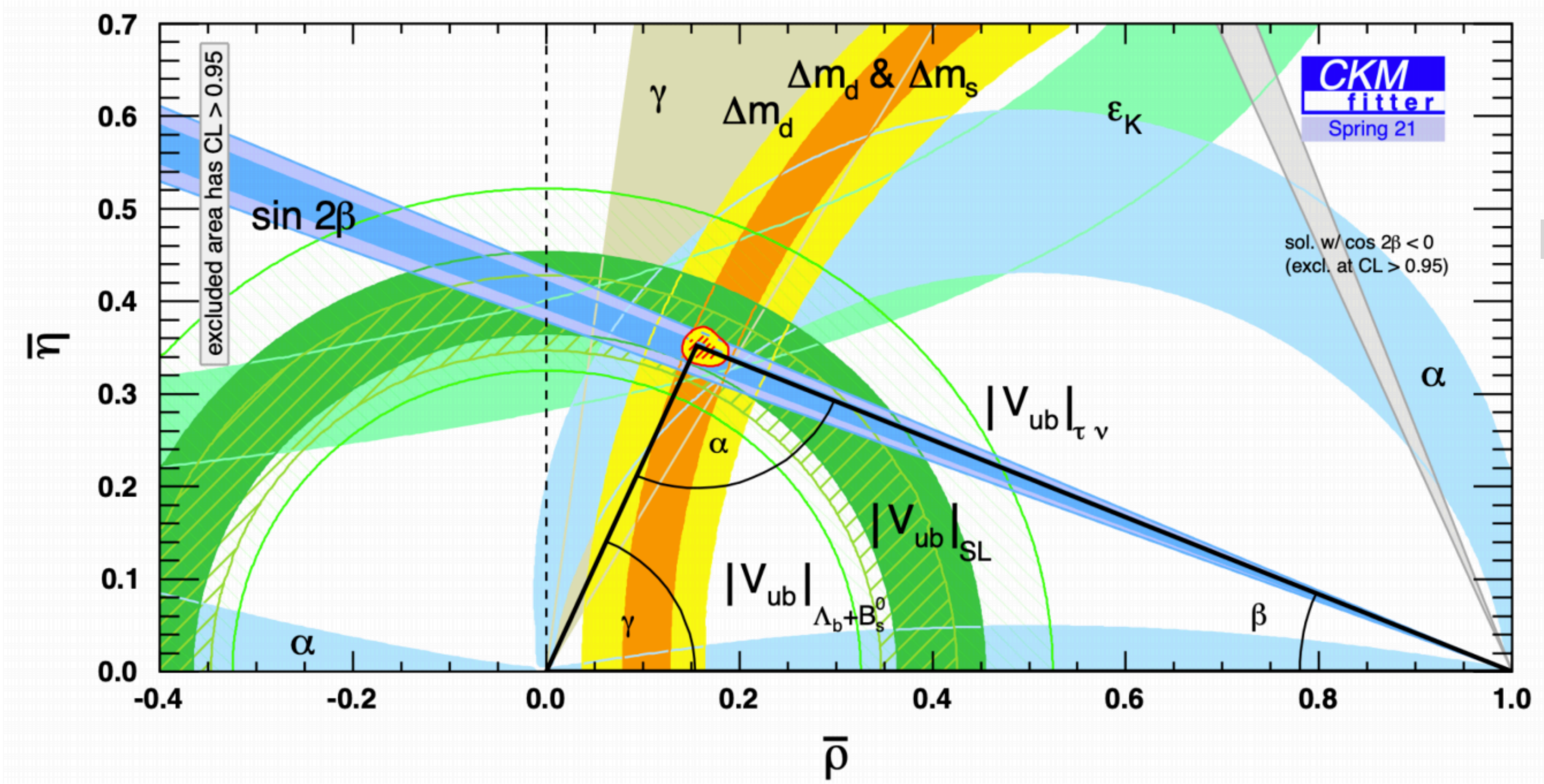
$$|V_{ub}| = (3.55 \pm 0.12_{\text{stat}} \pm 0.13_{\text{syst}} \pm 0.17_{\text{theo}}) \times 10^{-3}$$

dominated by background modelling (continuum, $B \to \rho \ell \nu$)

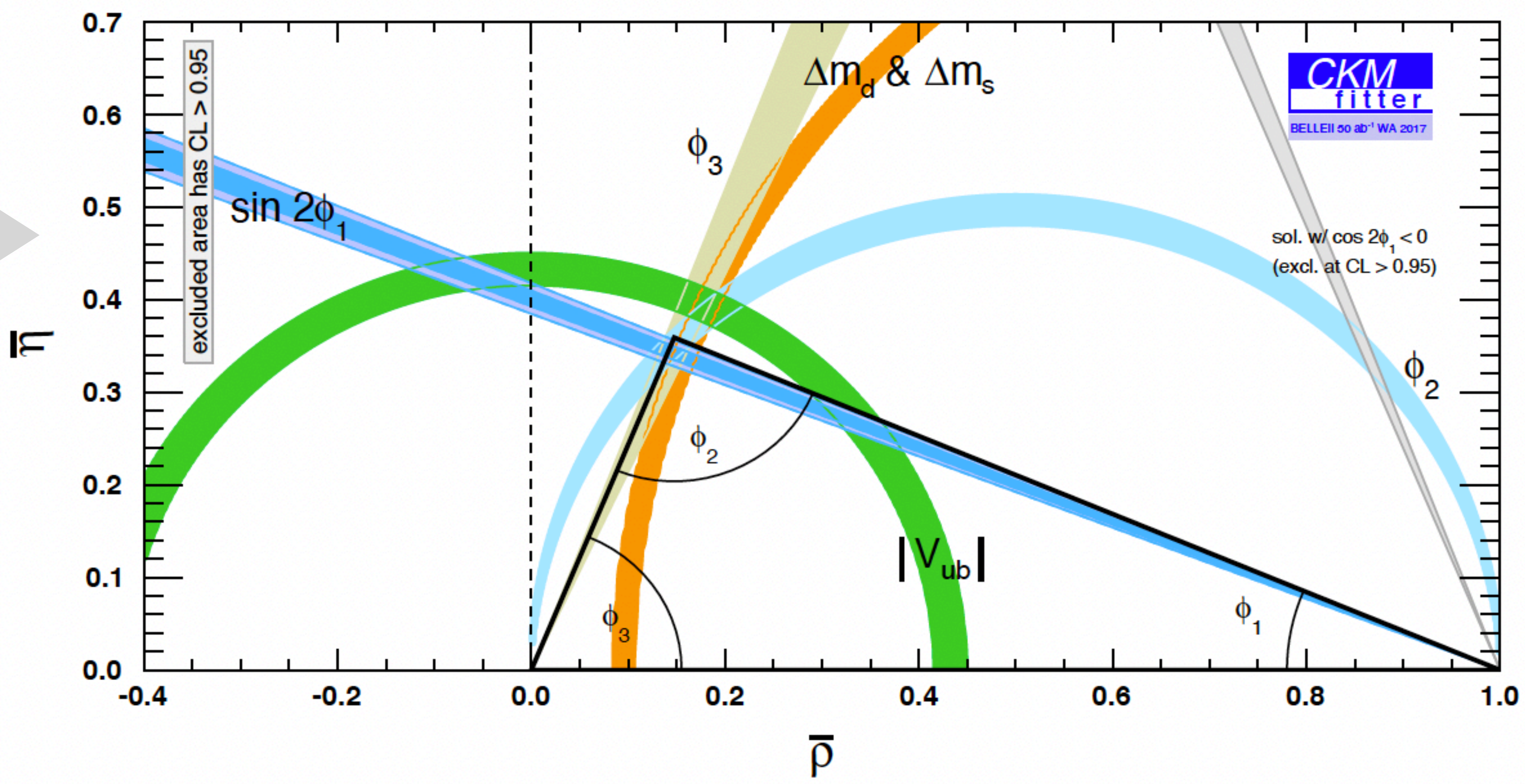
Ultimate Precision with Belle II

- UT lengths and angles can be explored with coming largest *B* dataset
- High statistics will shrink experimental uncertainties in global UT fit
- Many CKM measurements (|Vxb|, $\phi_{1,2,3}$) with Belle II data are on the way

Current



Projection to Belle II 50 ab^{-1} based on WA 2017

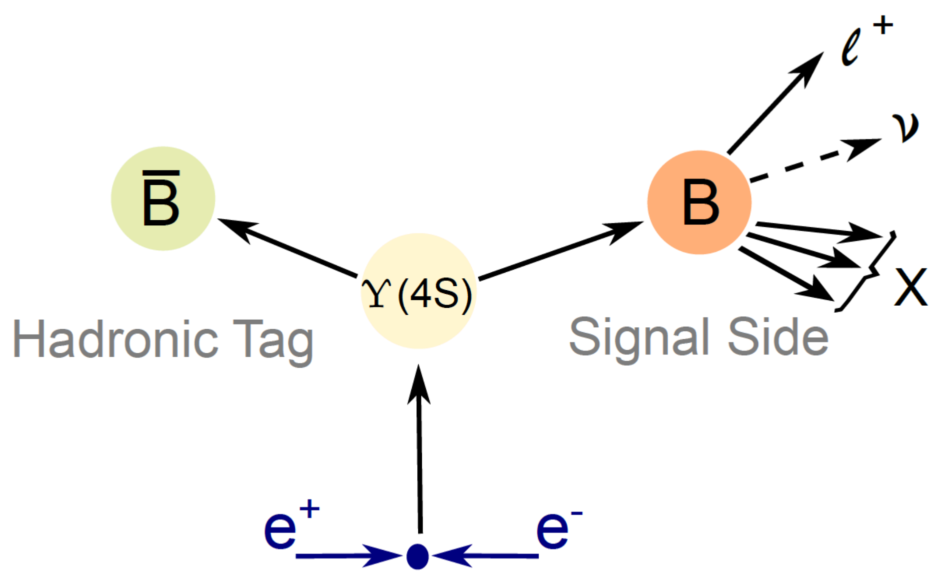


Light-lepton universality test in $B \to X\ell\nu$

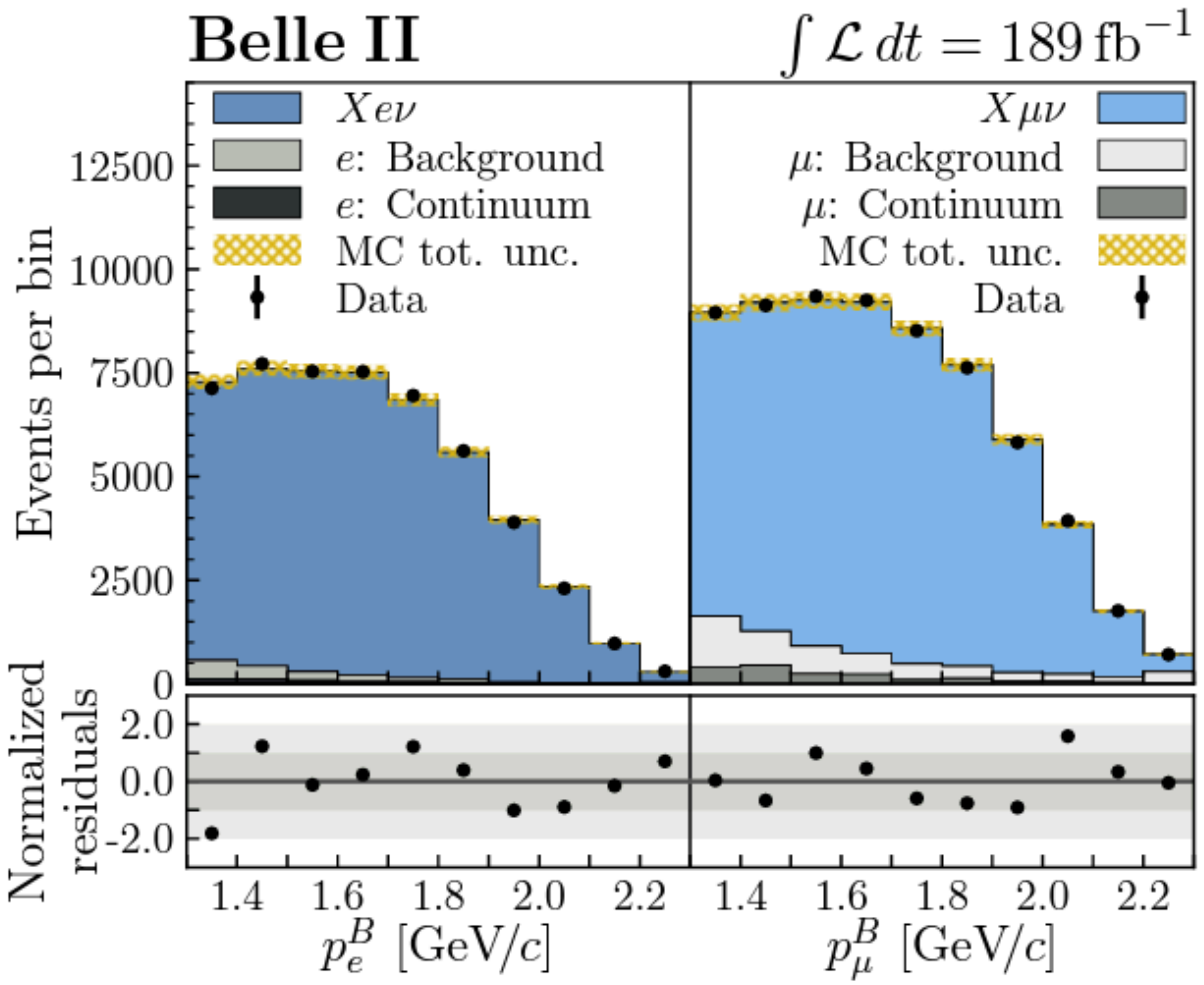
Measurement of $R(X)_{e/\mu}$

- Use 189 fb^{-1} dataset with hadronic tagging strategy
- Extract signal events above $p_\ell^B > 1.3$ GeV simultaneously for e- and μ-mode
- Calculate branching fraction ratio

$$R(X)_{e/\mu} = \frac{\mathscr{B}(B \to Xe\nu)}{\mathscr{B}(B \to X\mu\nu)}$$



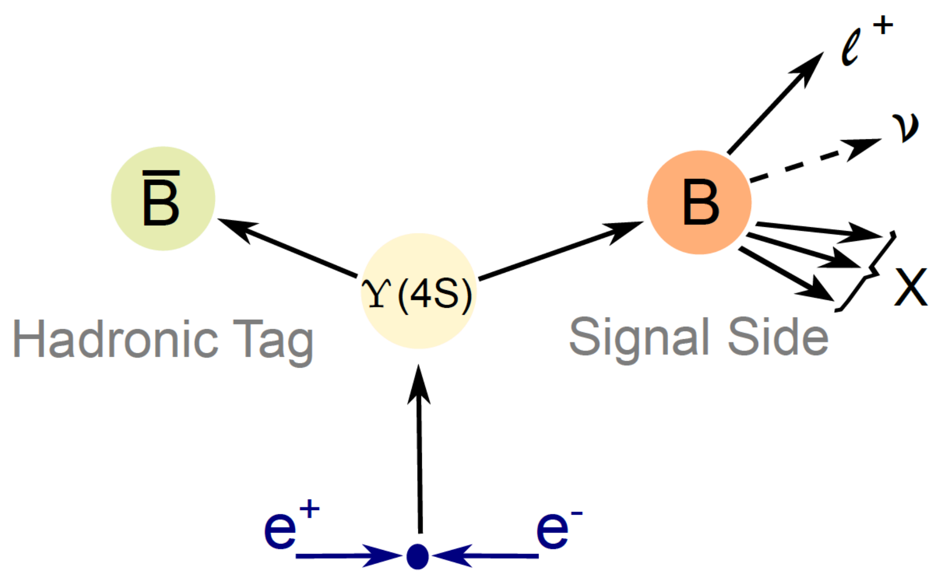
arXiv:2301.08266 (accepted by PRL)



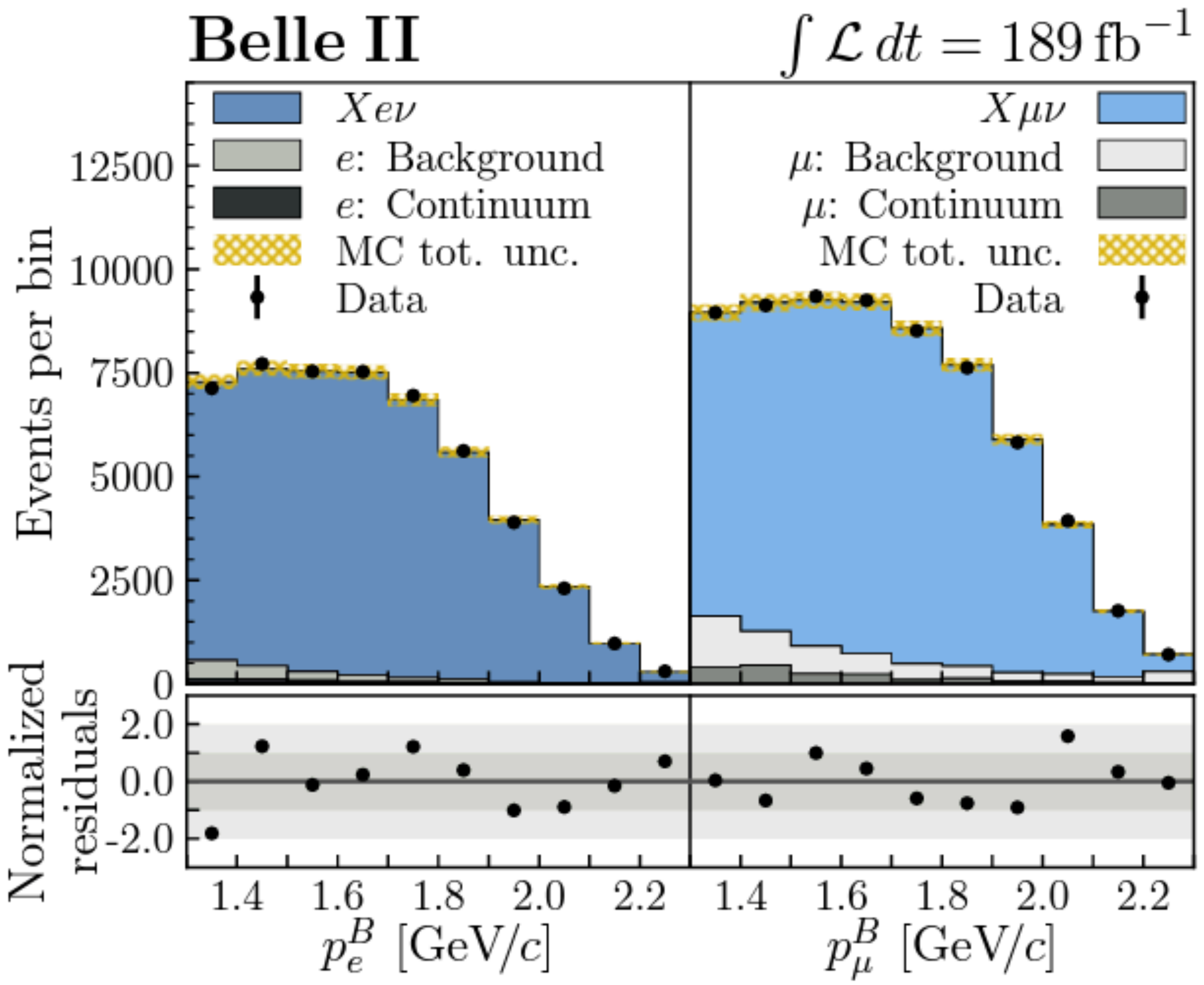
Measurement of $R(X)_{e/\mu}$

- Use 189 fb^{-1} dataset with hadronic tagging strategy
- Extract signal events above $p_\ell^B > 1.3$ GeV simultaneously for e- and μ-mode
- Calculate branching fraction ratio

$$R(X)_{e/\mu} = \frac{\mathscr{B}(B \to Xe\nu)}{\mathscr{B}(B \to X\mu\nu)}$$



arXiv:2301.08266 (accepted by PRL)



- **Most precise** $\mathscr{B}$ based LFU test in semileptonic B decays to date
- **World first** inclusive measurement
- Consistent with SM expectation within 1.2σ
- $R(X)_{\ell/\tau}$ is on the way

$$R(X)_{e/\mu} = 1.033 \pm 0.010_{\mathrm{stat}} \pm 0.019_{\mathrm{syst}}$$

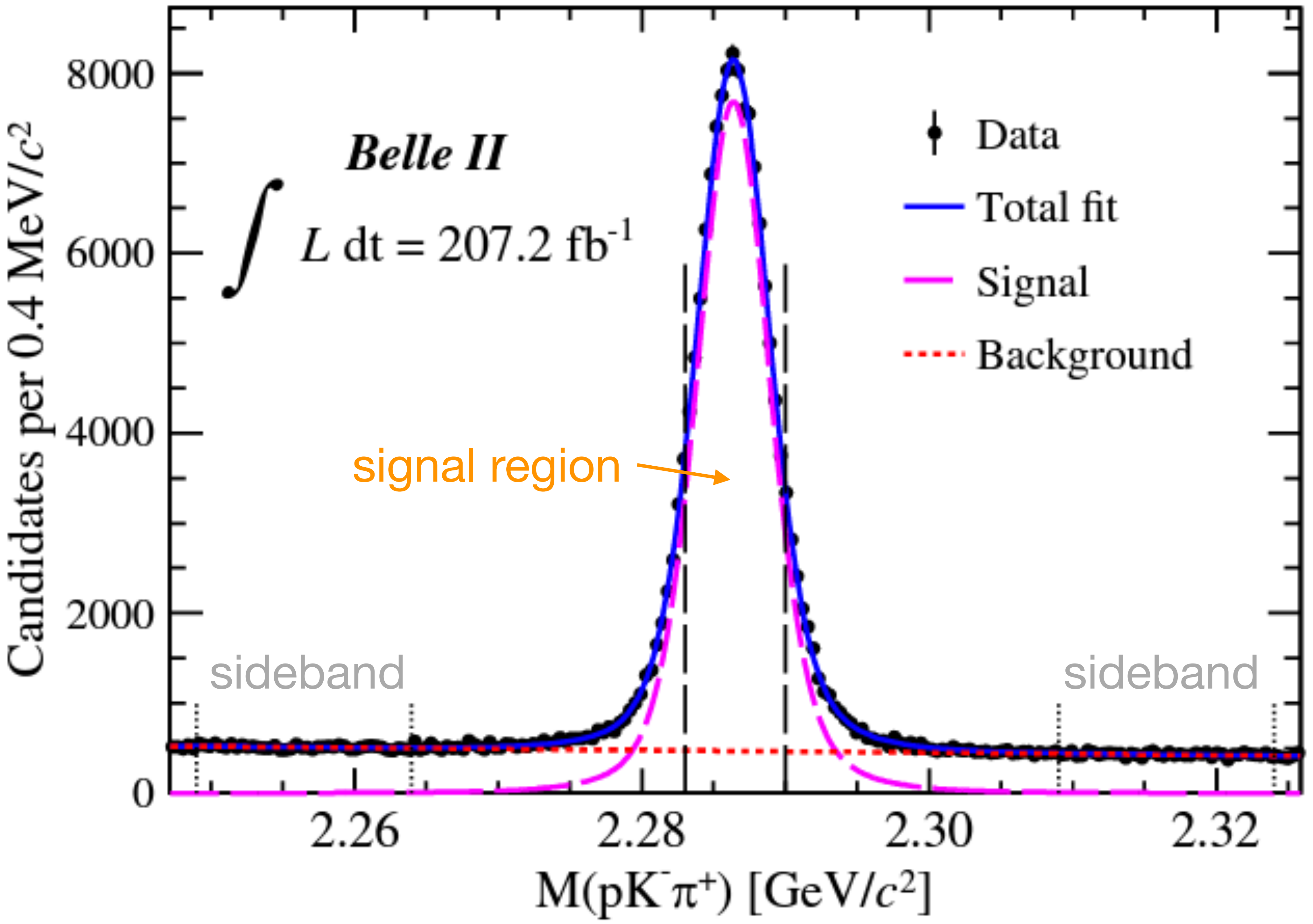
$$R(X\,|\,p_\ell^B > 1.3\,\mathrm{GeV})_{e/\mu} = 1.031 \pm 0.010_{\mathrm{stat}} \pm 0.019_{\mathrm{syst}}$$

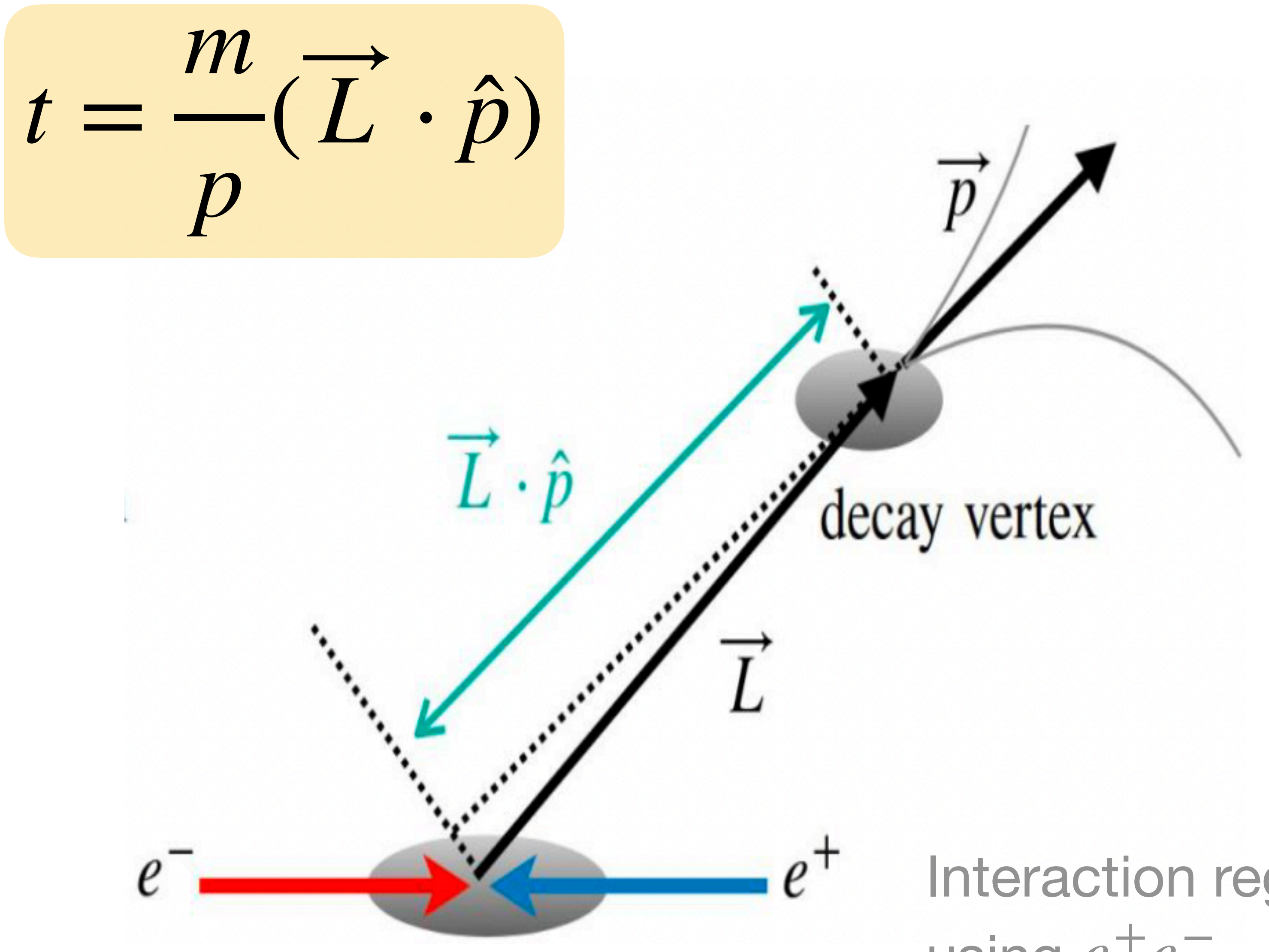
Lifetime measurements of Λ_c^+ and Ω_c^0

Measurement of Λ_c^+ Lifetime

PRL 130, 071802 (2023)

- Collision data of 207.2 fb^{-1} is used to reconstruct $\Lambda_c^+ \to pK^-\pi^+$
- Performed simultaneous fit to signal region and sidebands to better constrain bkg (Gaussian + Johnson functions with a common mode for signal shape)
- Decay time ***t*** calculated using displacement of Λ_c^+ decay vertex projected on its flying direction



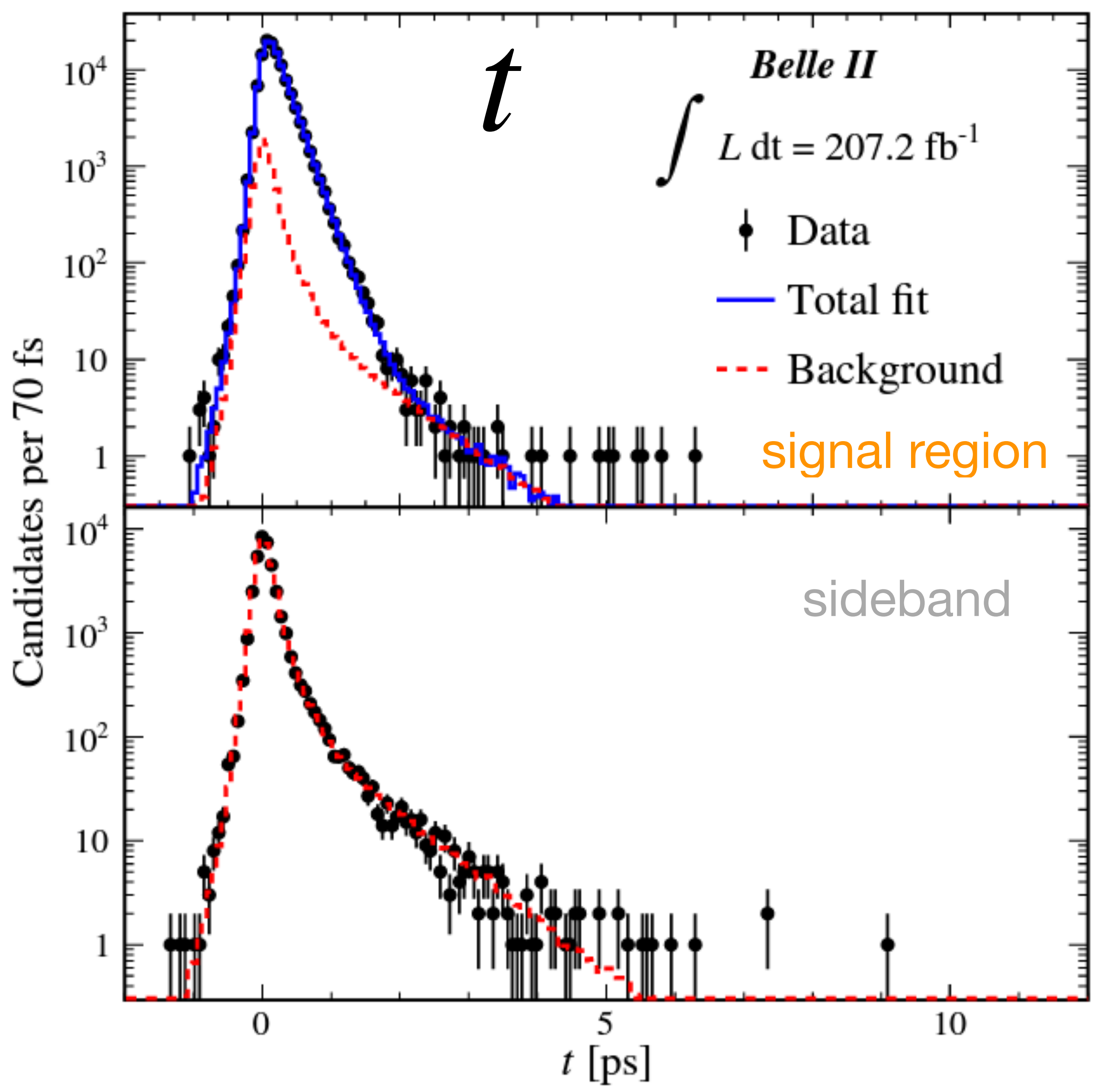


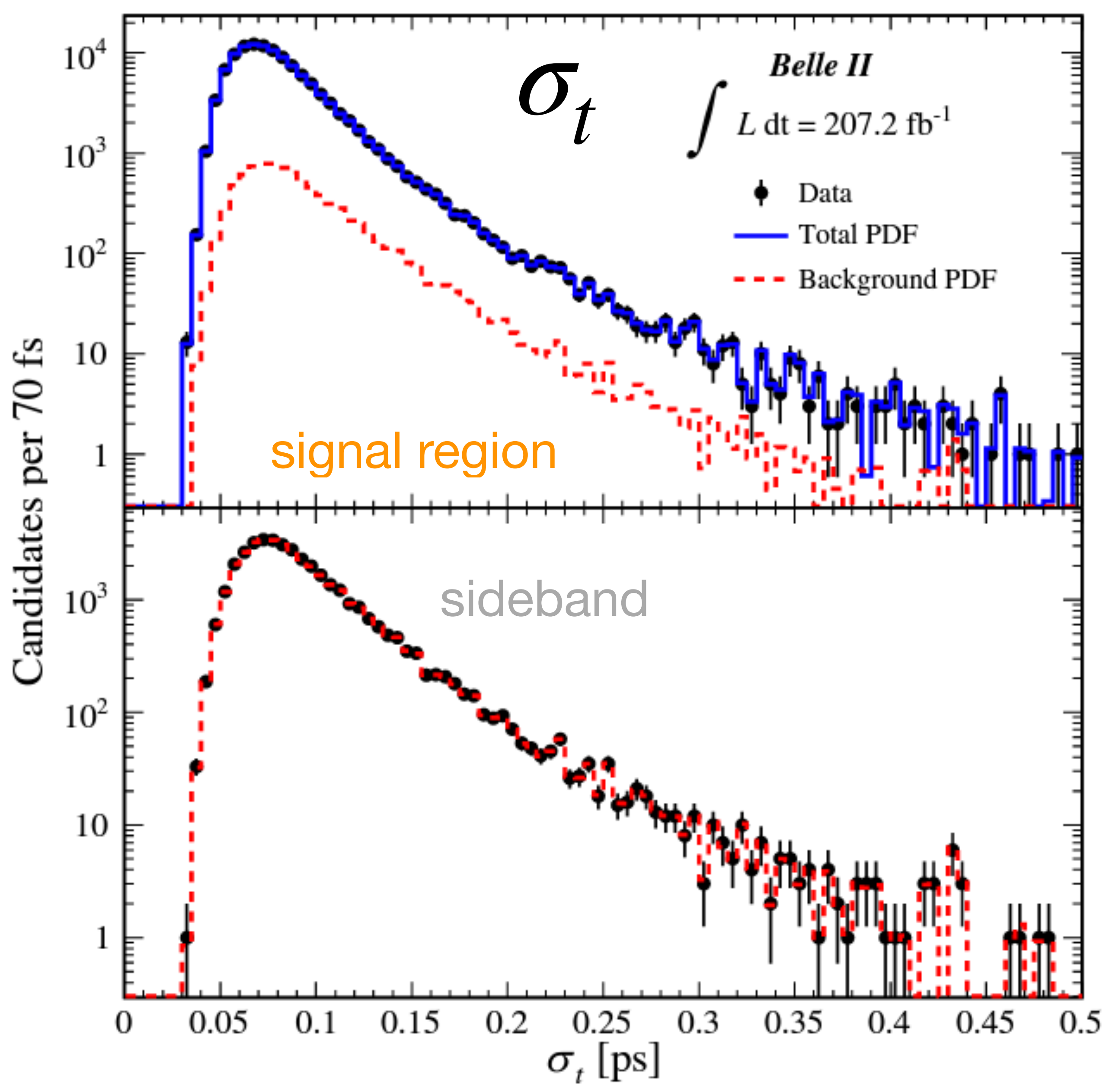
Interaction region determined using $e^+e^- \to \mu^+\mu^-$ events

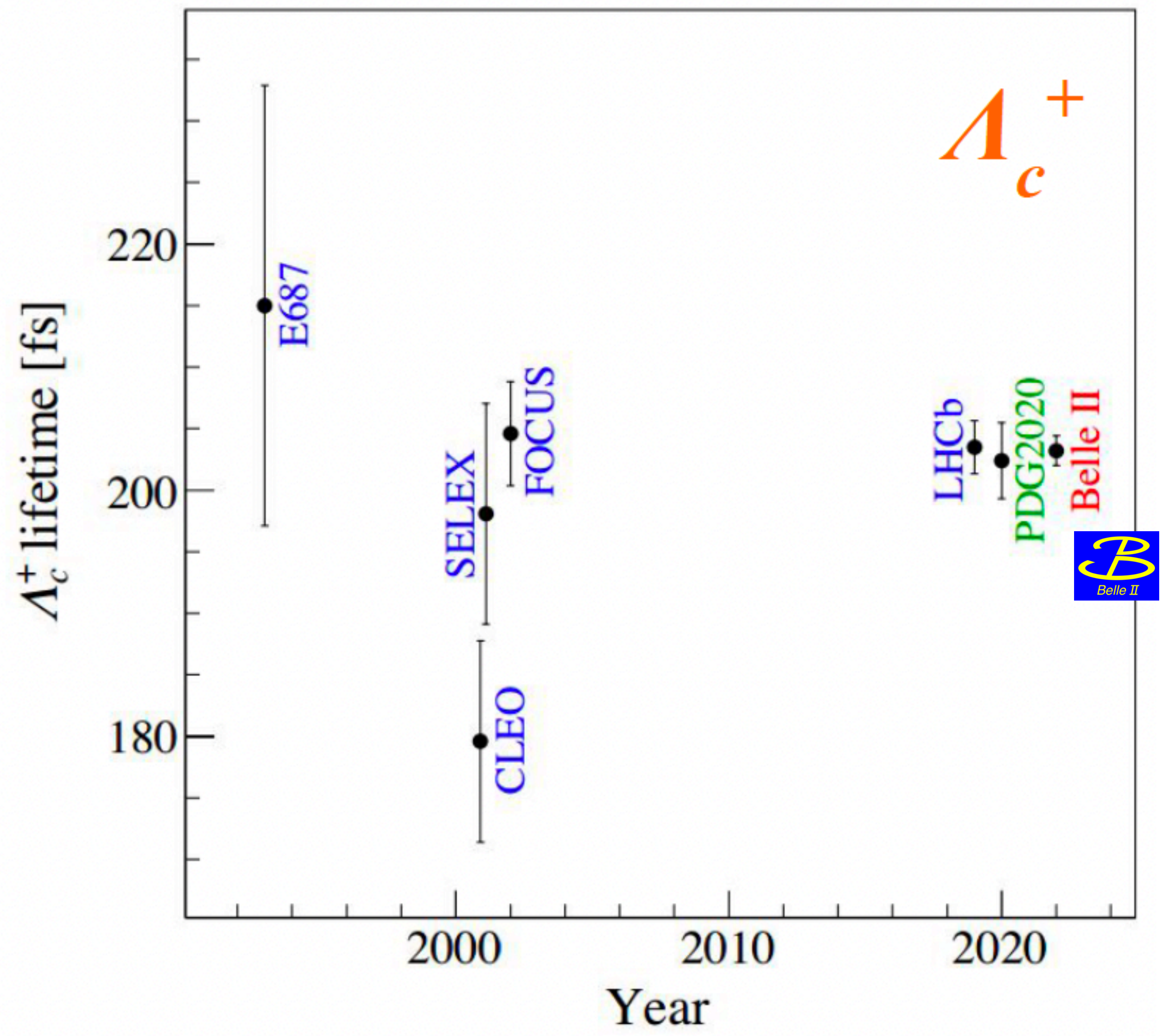
Measurement of Λ_c^+ Lifetime

PRL 130, 071802 (2023)

- Unbinned likelihood fit to (t, σ_t) to extract lifetime
- Result consistent with WA and recent LHCb relative measurement [PRD 100, 032001(2019)] while show tension versus CLEO's result [PRL 86,2232(2001)]







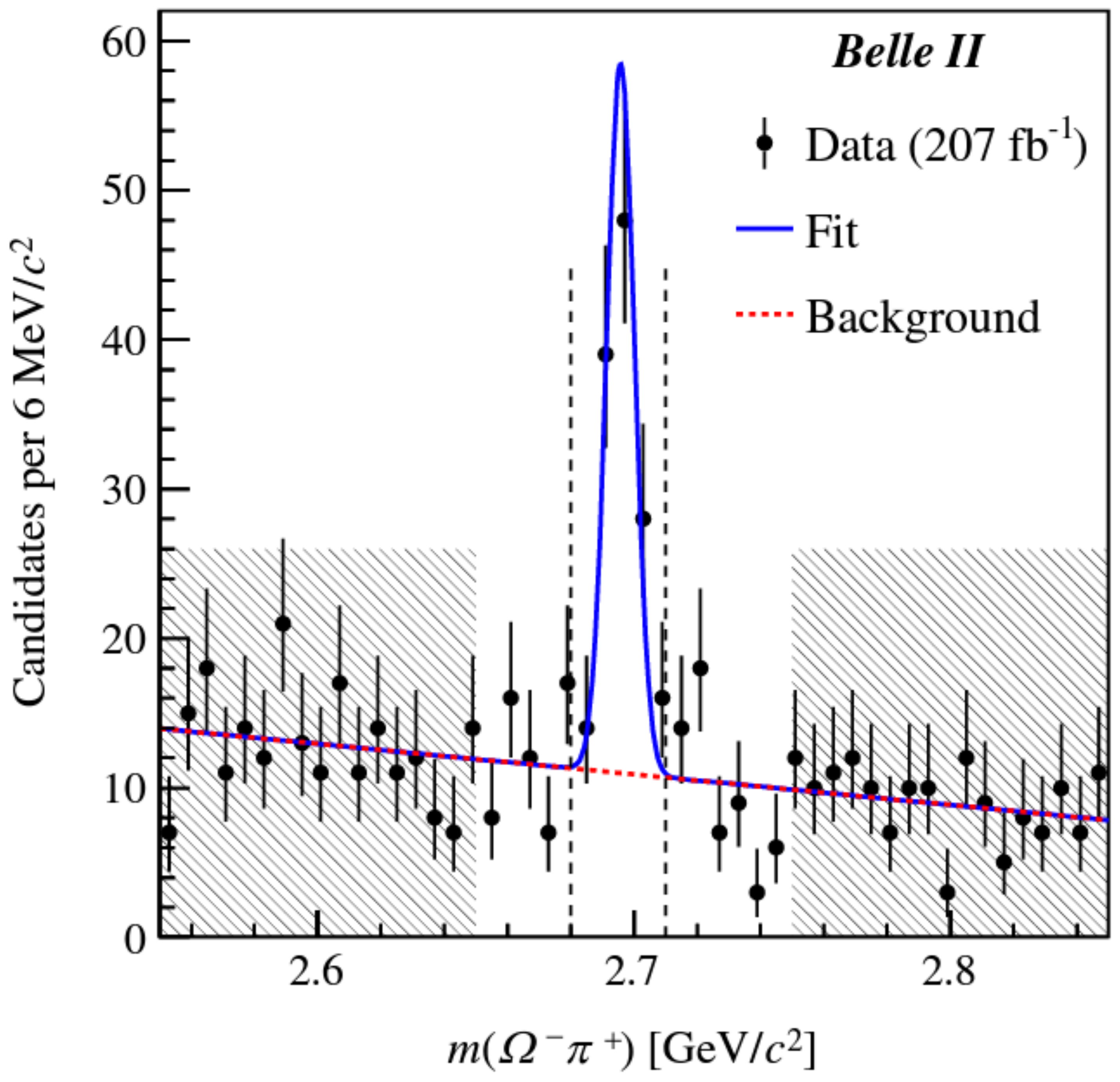
$$\tau(\Lambda_c^+) = 203.20 \pm 0.89_{\text{stat}} \pm 0.77_{\text{syst}}\ \text{fs}$$

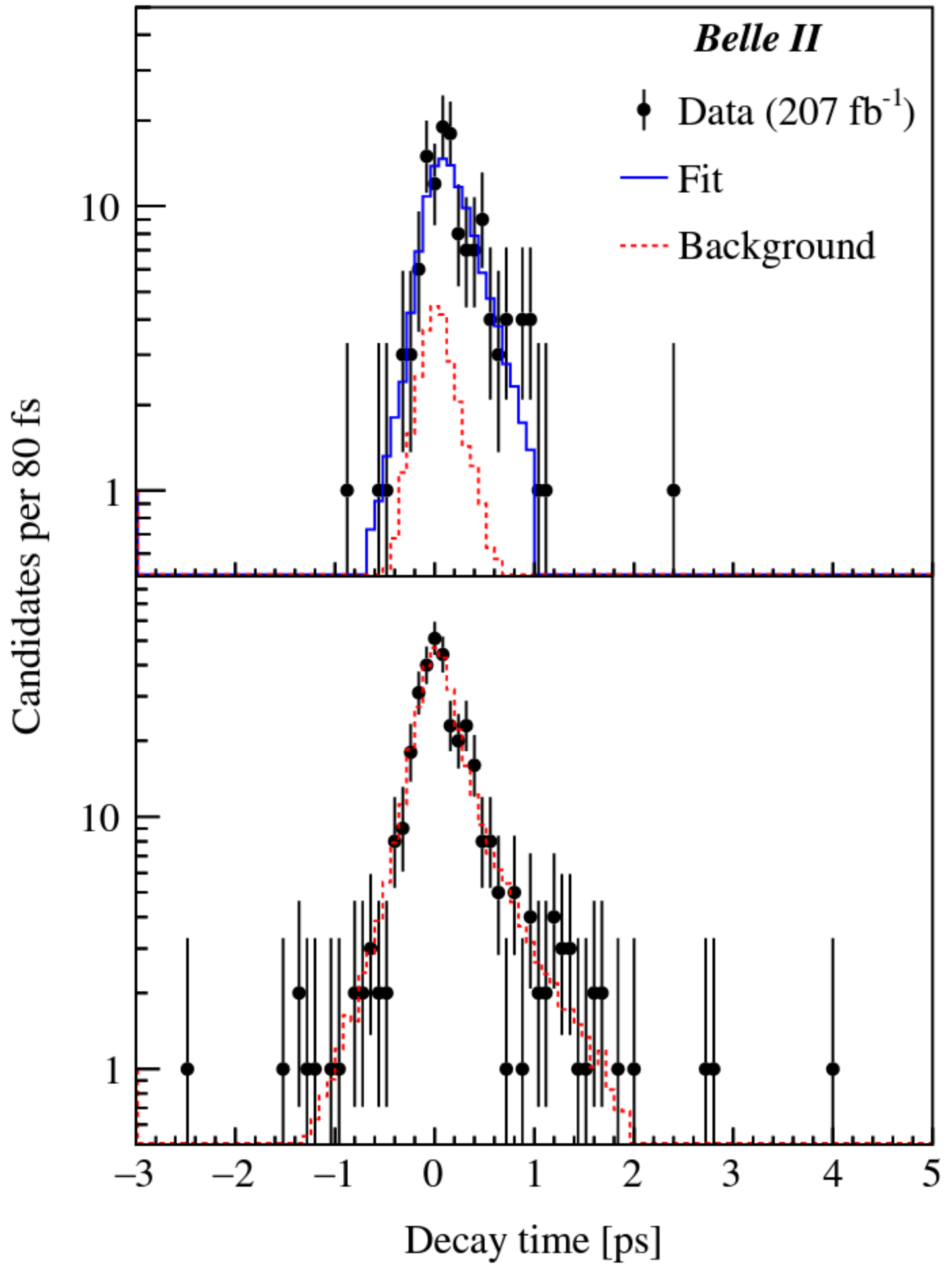
Most precise results to date!

Measurement of Ω_c^0 Lifetime

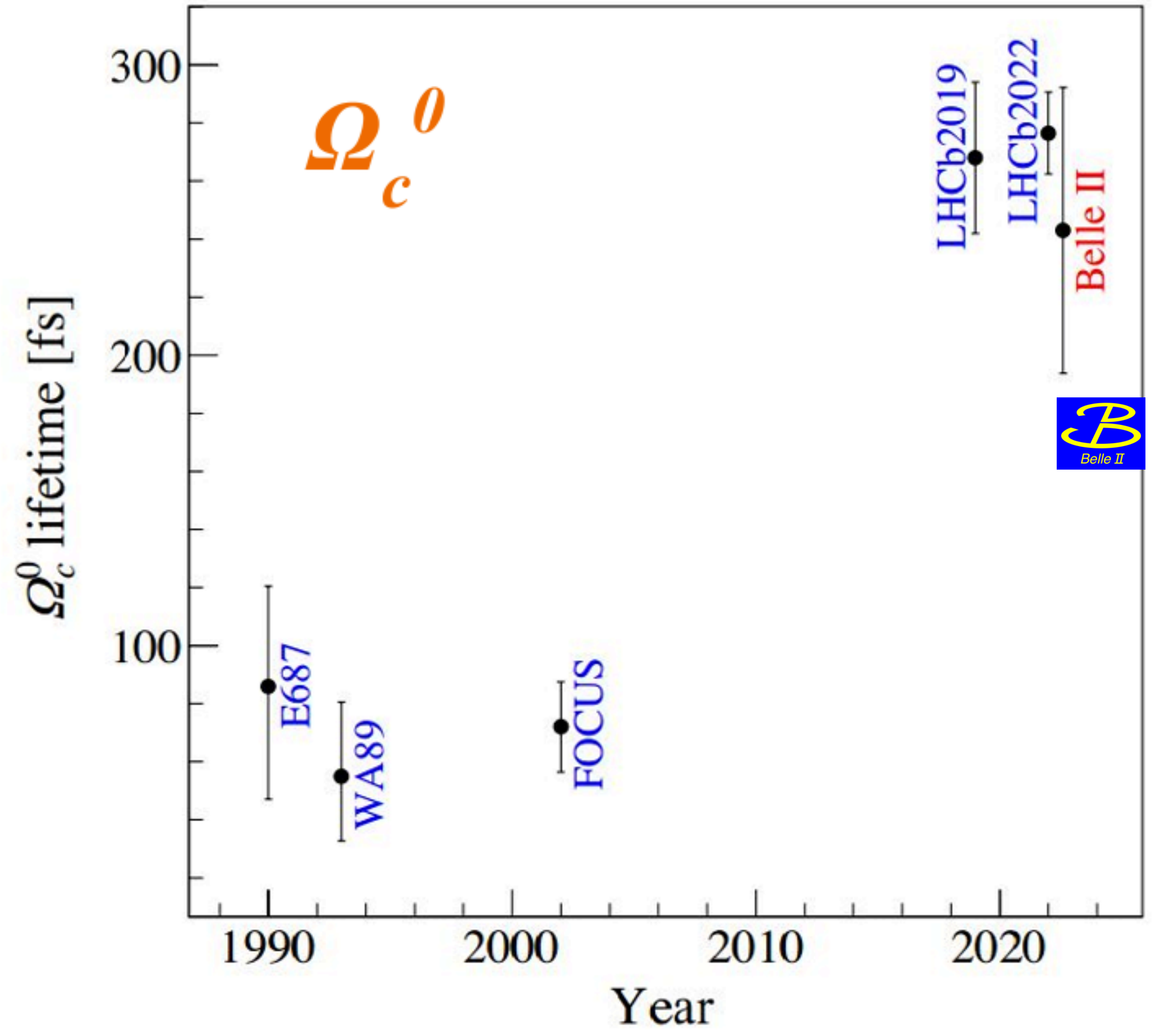
PRD 107, L031103 (2023)

- Dataset of 207.2 fb^{-1} is used to reconstruct $\Omega_c^0 \to \Omega^-\pi^+$, $\Omega^- \to \Lambda^0 K^-$, $\Lambda^0 \to p\pi^-$
- Applied unbinned likelihood fit to $m(\Omega^-\pi^+)$
- Derive lifetime from (t, σ_t) fit
- Result consistent with LHCb measurements but leave 3.4σ tension from old WA





$$\tau(\Omega_c^0) = 243 \pm 48_{\text{stat}} \pm 11_{\text{syst}}\ \text{fs}$$



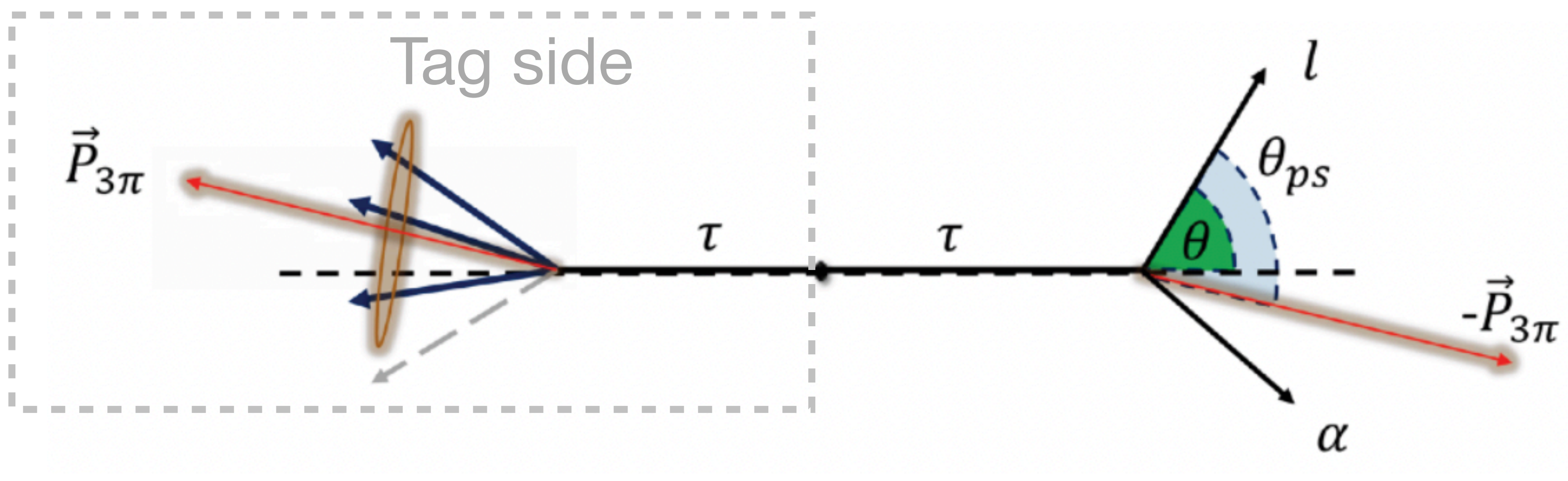
Lepton-flavor-violating $\tau \to \ell + \alpha$ decay

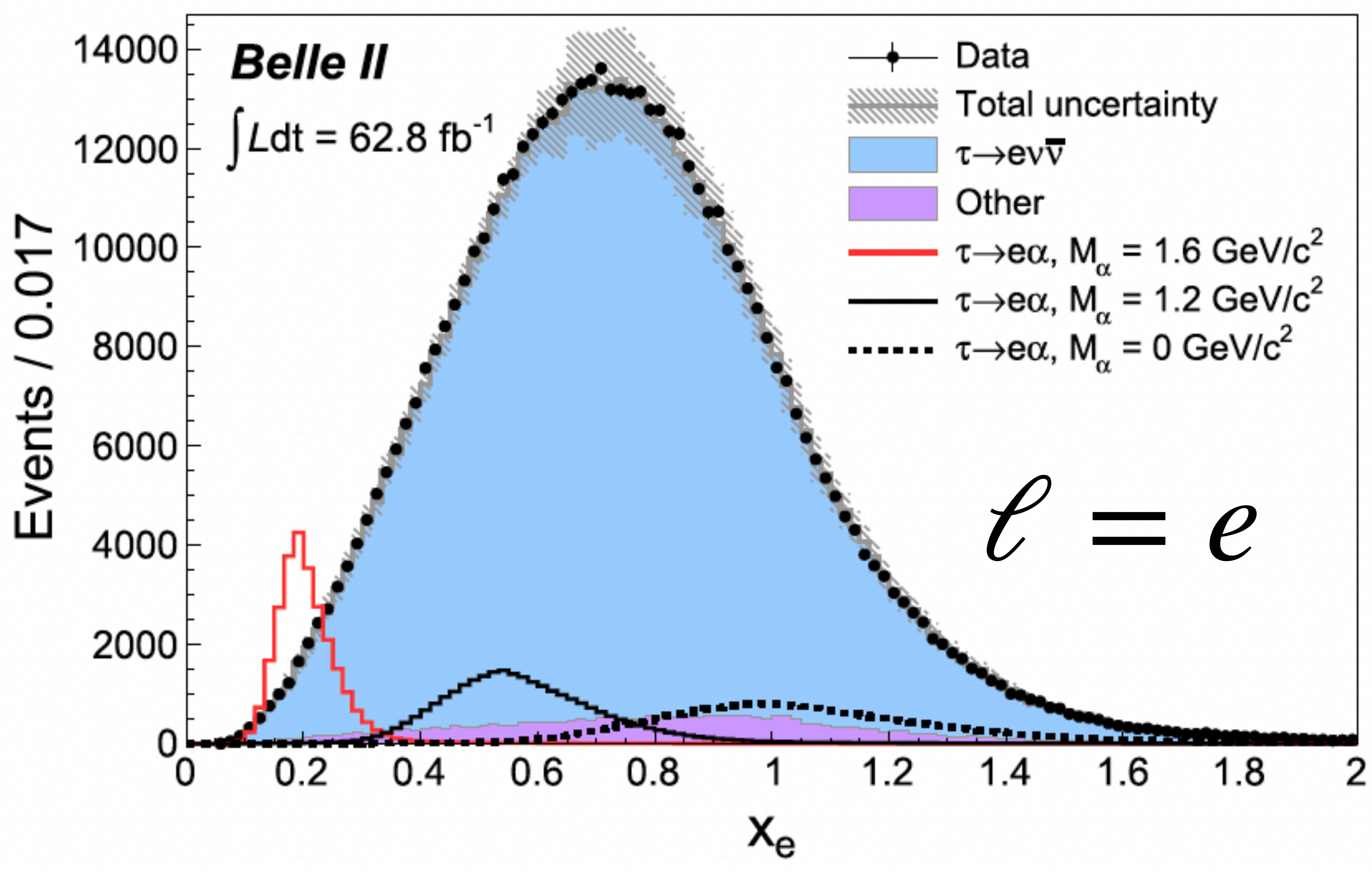
Search for LFV $\tau^- \to \ell^- + \alpha$

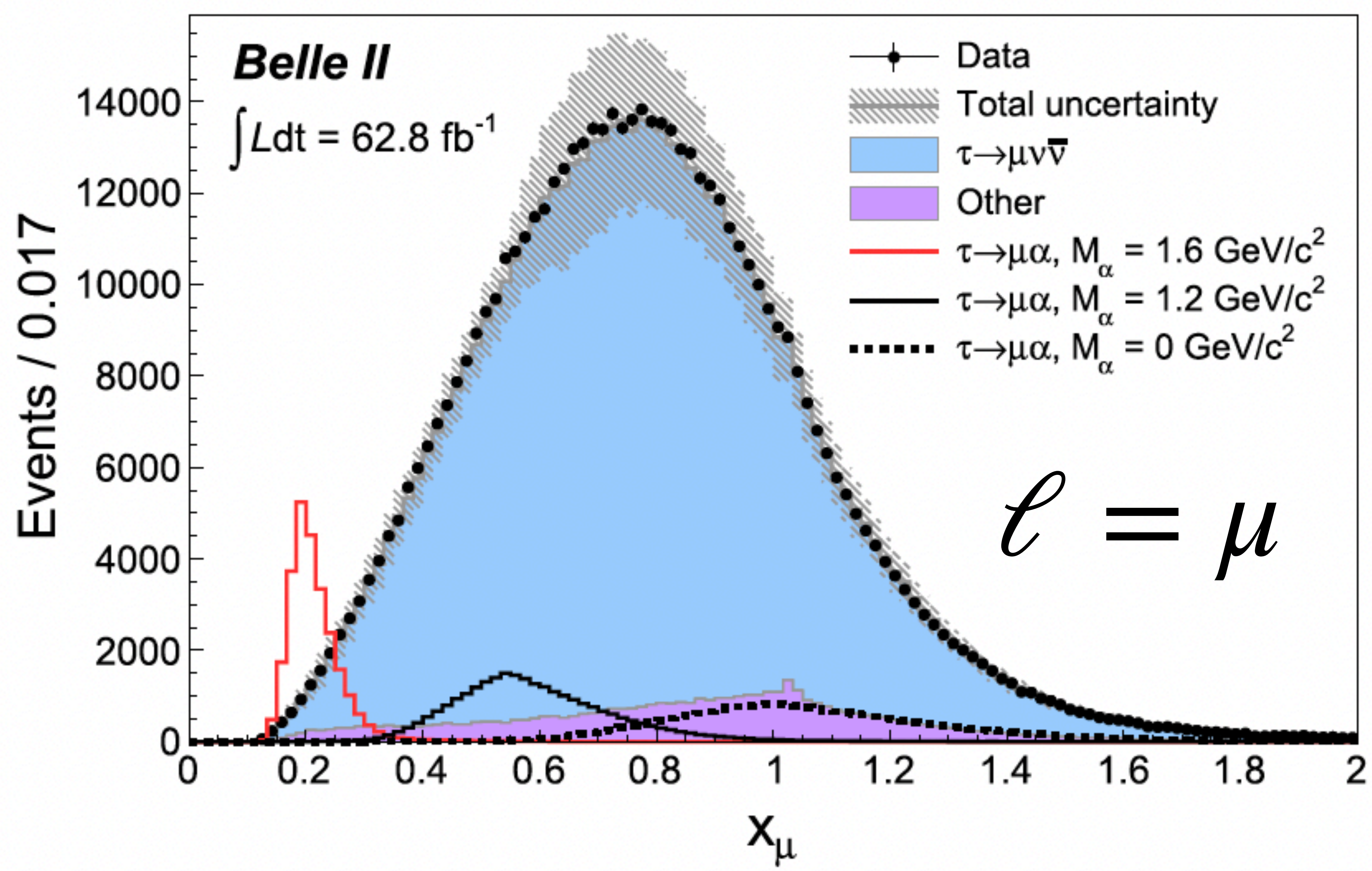
PRL 130, 181803 (2023)

- Use dataset of 62.8 fb^{-1} and tagged by $\tau \to h^- h^+ h^- \nu_\tau$
- Probe existence of a long-lived invisible gauge boson α
- Reconstruct τ pseudo rest frame based on $E_\tau = \sqrt{s}/2$, $\hat{p}_\tau \approx -\vec{p}_{3h}/|\vec{p}_{3h}|$
- Search for an excess of events on $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$ normalized lepton energy

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



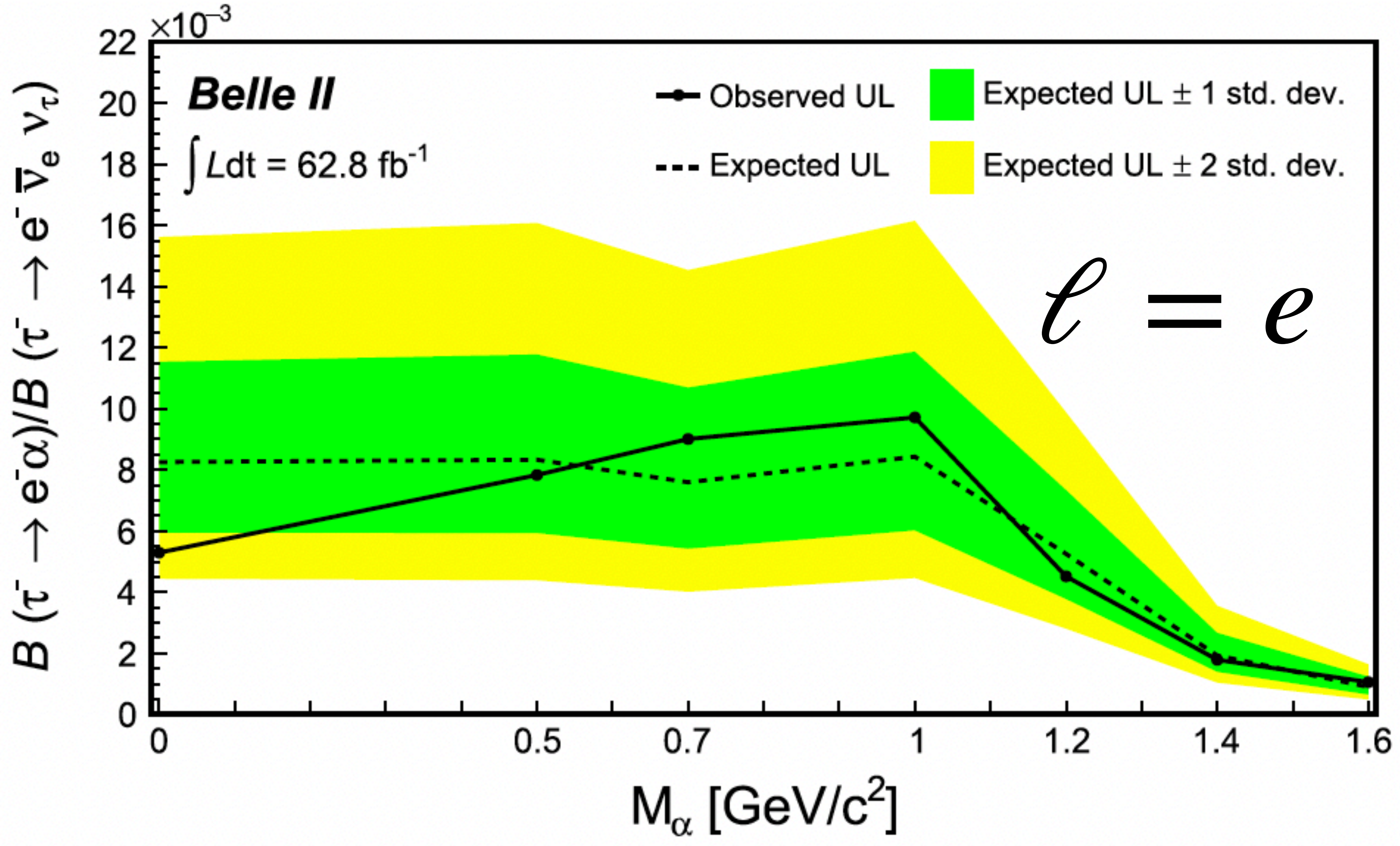


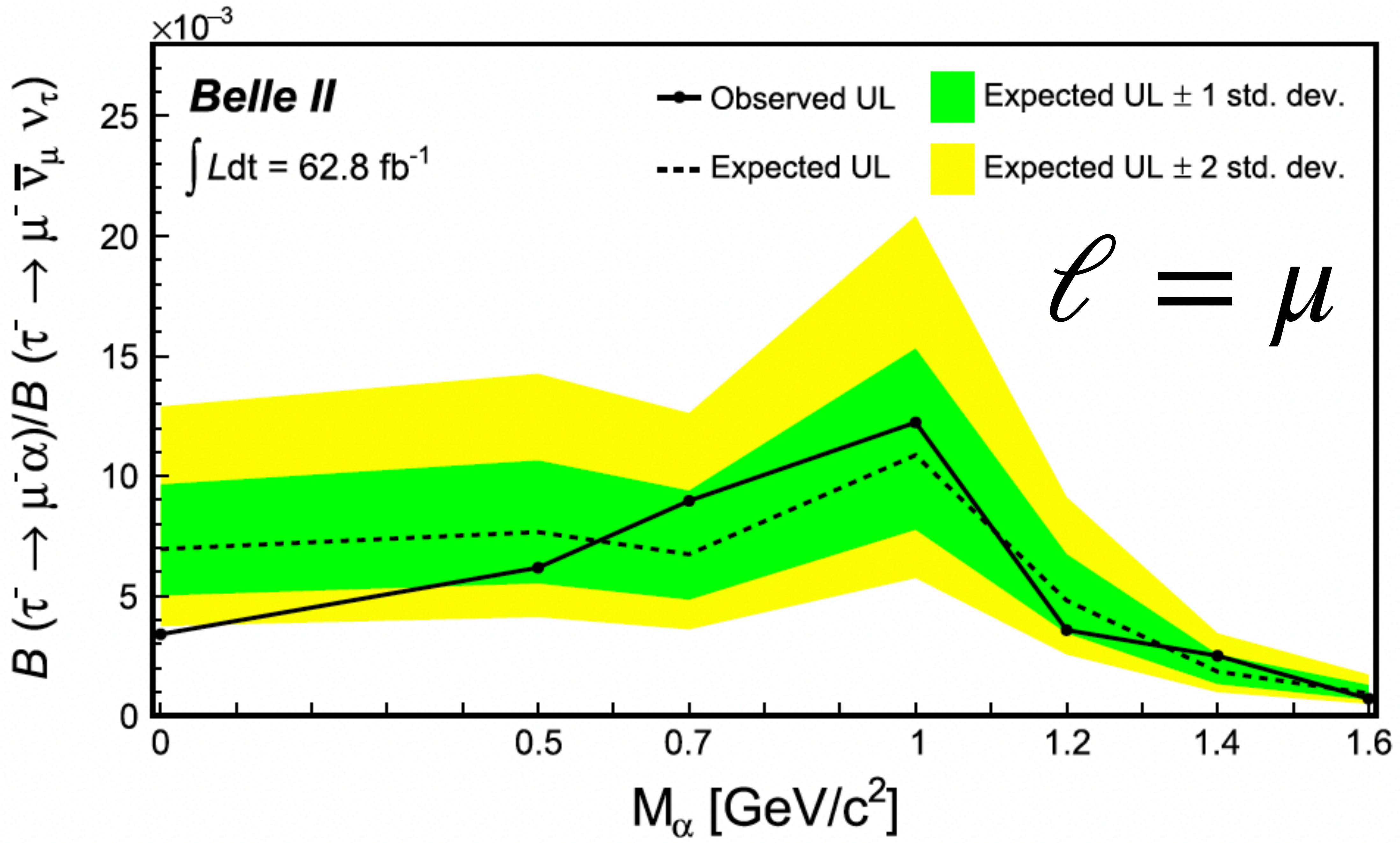


Search for LFV $\tau^- \to \ell^- + \alpha$

PRL 130, 181803 (2023)

- No signal observed
- Set upper limit at 95% C.L. for $\mathscr{B}(\tau \to \ell\alpha)/\mathscr{B}(\tau \to \ell\bar{\nu}_\ell\nu_\tau)$
- World **best** limits to date





Summary & Prospects

- As luminosity frontier project, SuperKEKB/Belle II will search for physics beyond SM with ultimate sensitivity
- By Summer 2022, Belle II has achieved

  $L_{\text{peak}} = 4.7 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ (world record)

  $L_{\text{int}} = 424\,\text{fb}^{-1}$ (similar to BarBar; ~ half of Belle)

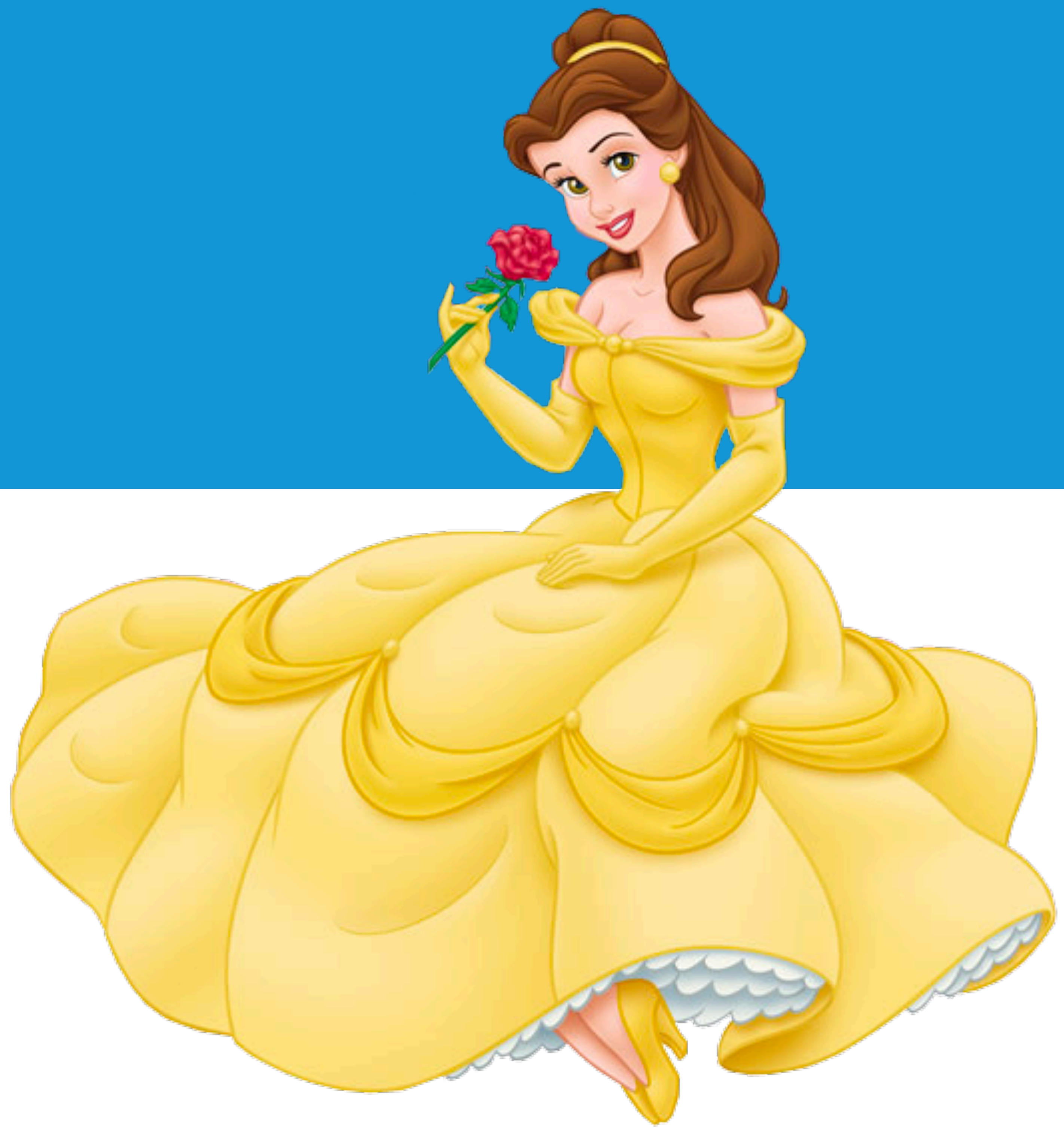
- Many exciting physics results are on the way
  - Benefited by improved detector performance & analysis technique
  - Some of them are already world-leading
- After current shutdown period, we will try to achieve higher luminosity
  - During LS1, many components are to be improved

Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP Violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\overline{\nu})$ $[10^{-6}]$	***	20%	Belle II
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle II
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***	4	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3	Belle II/LHCb

THANK YOU


Belle II Collaboration Meeting (February 13-17, 2023)

> 1100 active members
124 institutes
27 countries



Backup Slides

Measurement of $R(X)_{e/\mu}$

arXiv:2301.08266
(accepted by PRL)

Table I: Statistical and systematic uncertainties on the value of $R(X_{e/\mu})$ from the most significant sources.

Source	Uncertainty [%]
Sample size	1.0
Lepton identification	1.9
$X_c \ell \nu$ branching fractions	0.1
$X_c \ell \nu$ form factors	0.2
Total	2.2

Measurement of Λ_c^+ Lifetime

PRL 130, 071802 (2023)

Source	Uncertainty [fs]
Ξ_c contamination	0.34
Resolution model	0.46
Non-Ξ_c backgrounds	0.20
Detector alignment	0.46
Momentum scale	0.09
Total	0.77

Major sources of systematic error:

- $\Xi_c^{0/+}$ *contamination*
- *Resolution Model:* Correlations between the decay time and the decay-time uncertainty are neglected.
- *Background model:* Sideband data that differ from the background in the signal region. Systematic is estimated using the differences in data-MC.
- *Alignment of the detector:* Periodic calibrations are necessary to account for detector misalignment. Misalignment can can bias the measurement of the decay lengths.

Measurement of Λ_c^+ Lifetime

PRL 130, 071802 (2023)

Fit to (t, σ_t)

- Unbinned ML fit to $(\boldsymbol{t}, \boldsymbol{\sigma_t})$ for candidates in the signal region.
- PDF Model:
  - Signal PDF :

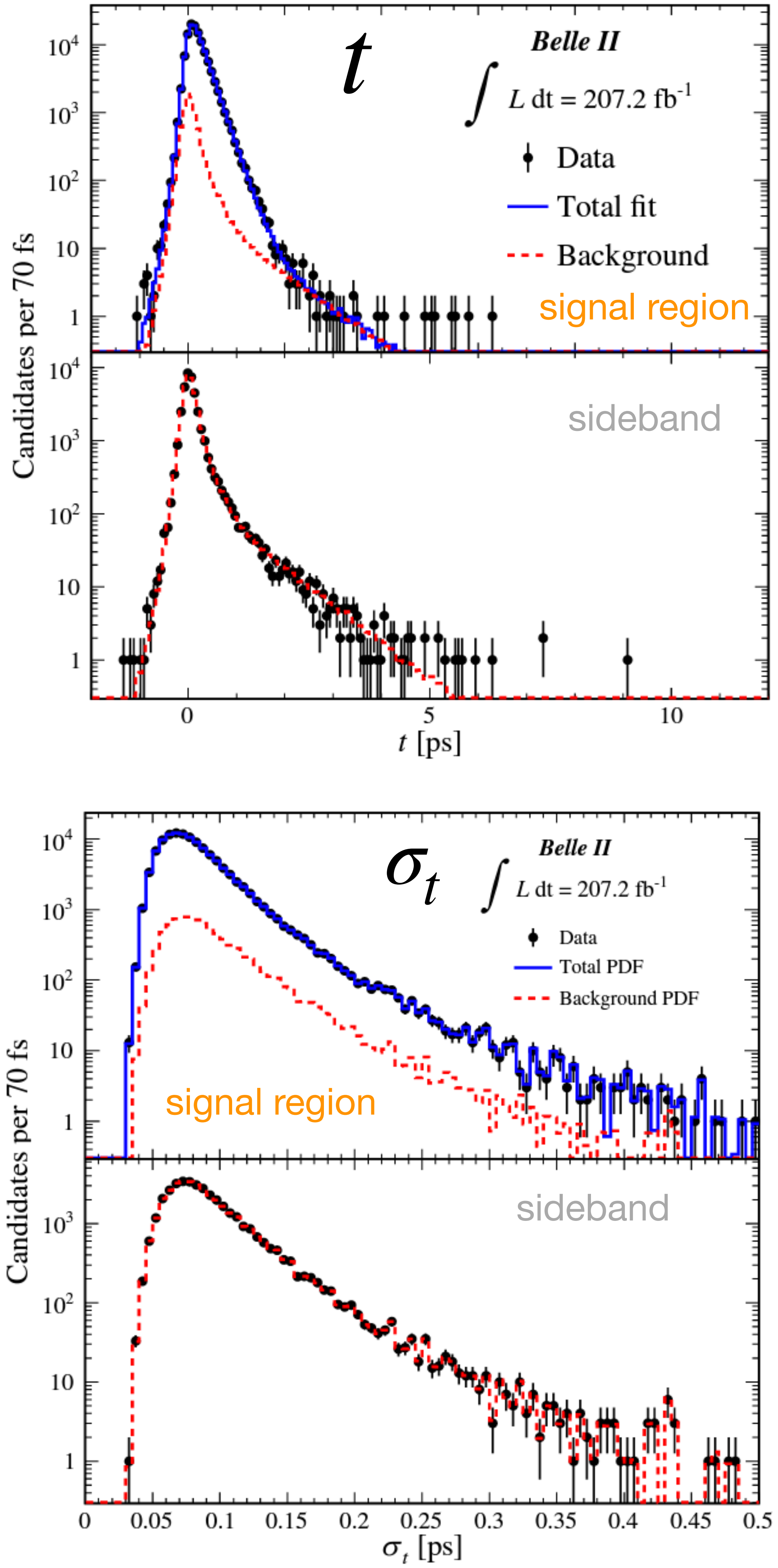
$$pdf(t,\sigma_t|\tau,f,b,s_1,s_2) = pdf(t|\sigma_t,\tau,f,b,s_1,s_2)\ pdf(\sigma_t)$$
$$\propto \int_0^\infty e^{-t_{true}/\tau} R(t-t_{true}|\sigma_t,f,b,s_1,s_2)dt_{true}\ pdf(\sigma_t)$$

f is the fraction of events in the Gaussian, and **b** is a mean parameter for a possible bias in **t**. **R** is the resolution function as:

$$R(t-t_{true}|\sigma_t,f,b,s_1,s_2) = f\ G(t-t_{true}|b,s_1\sigma_t) + (1-f)G(t-t_{true}|b,s_2\sigma_t)$$

$s_1\sigma_t$ and $s_2\sigma_t$ are the Gaussian widths.

  - Background PDF:
    - Empirical model of the sideband data, is the sum of two exponen functions convolved with Gaussian resolution functions.
    - A simultaneous fit to the events in the signal region and sidebands is also performed.



Measurement of Ω_c^0 Lifetime

PRD 107, L031103 (2023)

Source	Uncertainty (fs)
Fit bias	3.4
Resolution model	6.2
Background model	8.3
Detector alignment	1.6
Momentum scale	0.2
Input Ω_c^0 mass	0.2
Total	11.0

Major sources of systematic error are:

- *Background model:* Sideband data that differ from the background in the signal region. Systematic is estimated using the differences in data-MC.
- *Resolution model:* Simulation shows that the resolution function has tails that are inconsistent with a Gaussian model.
- *Fit Bias:* Due to small sample size.

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

TABLE III. Central values with their uncertainties, 95% C.L., and 90% C.L. upper limits (UL) for the branching-fraction ratios $\mathcal{B}_{e\alpha}/\mathcal{B}_{e\bar{\nu}\nu}$ (top) and $\mathcal{B}_{\mu\alpha}/\mathcal{B}_{\mu\bar{\nu}\nu}$ (bottom) for various masses of the α boson. Corresponding absolute upper limits for $\mathcal{B}(\tau^- \to \ell^-\alpha)$, computed using standard-model branching fractions from Ref. [35], are provided in parentheses for convenience.

M_α [GeV/c^2]	$\mathcal{B}_{e\alpha}/\mathcal{B}_{e\bar{\nu}\nu}$ ($\times 10^{-3}$)	UL at 95% C.L. ($\times 10^{-3}$)	UL at 90% C.L. ($\times 10^{-3}$)
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% C.L. ($\times 10^{-3}$)	UL at 90% C.L. ($\times 10^{-3}$)
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)