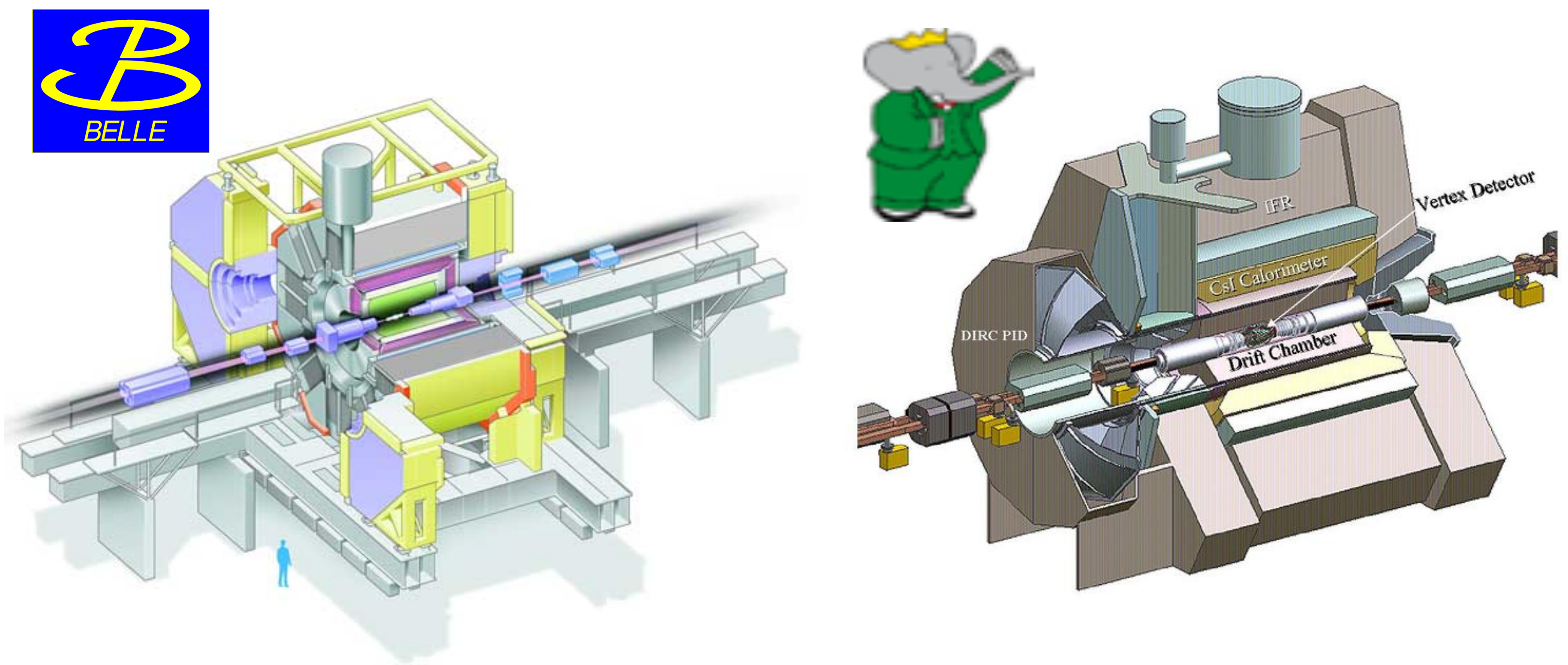
The use of weak reactions to learn about hadron interactions at Belle II

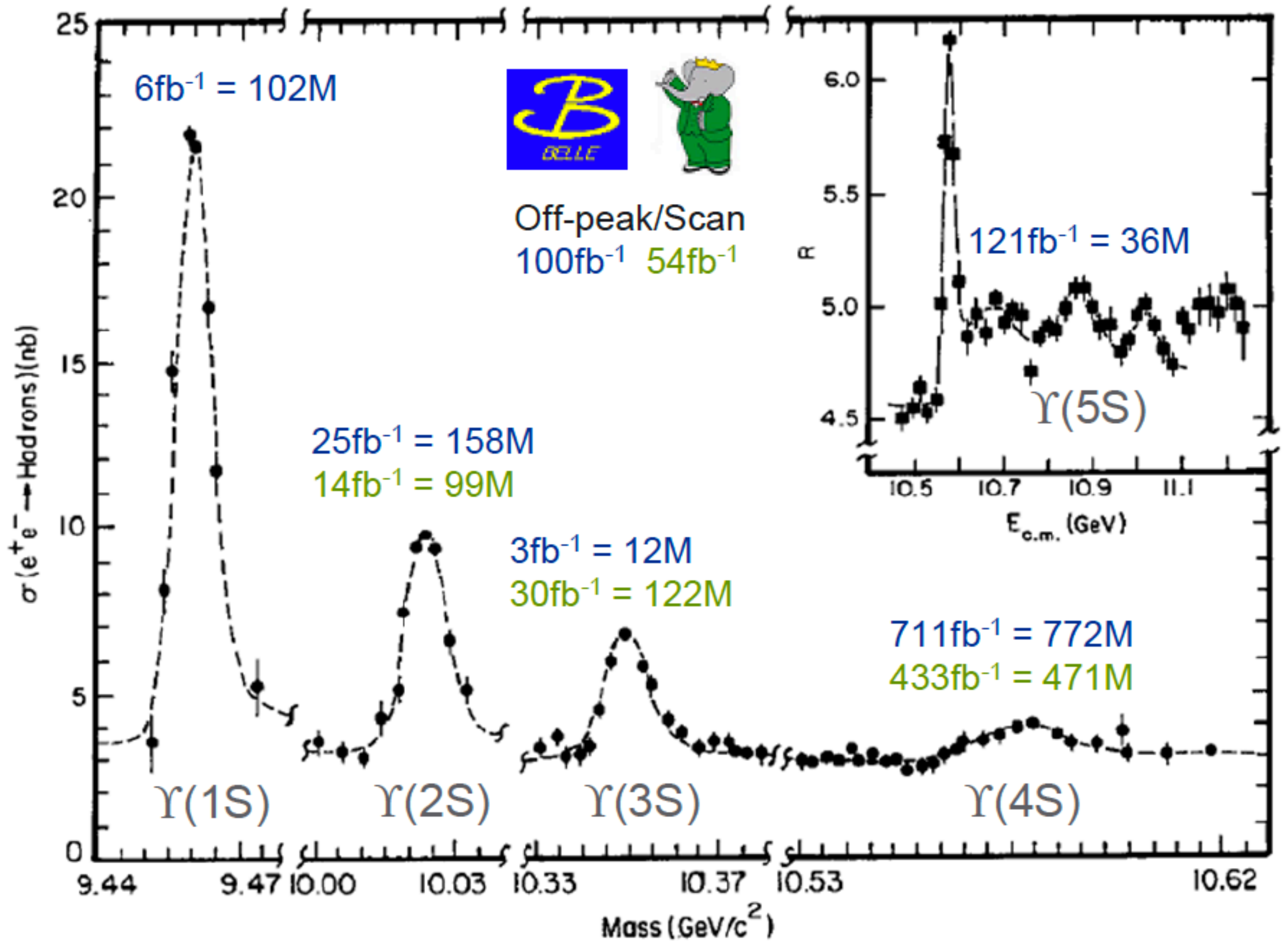
Jake Bennett, on behalf of the Belle II collaboration
The University of Mississippi
QNP 2022

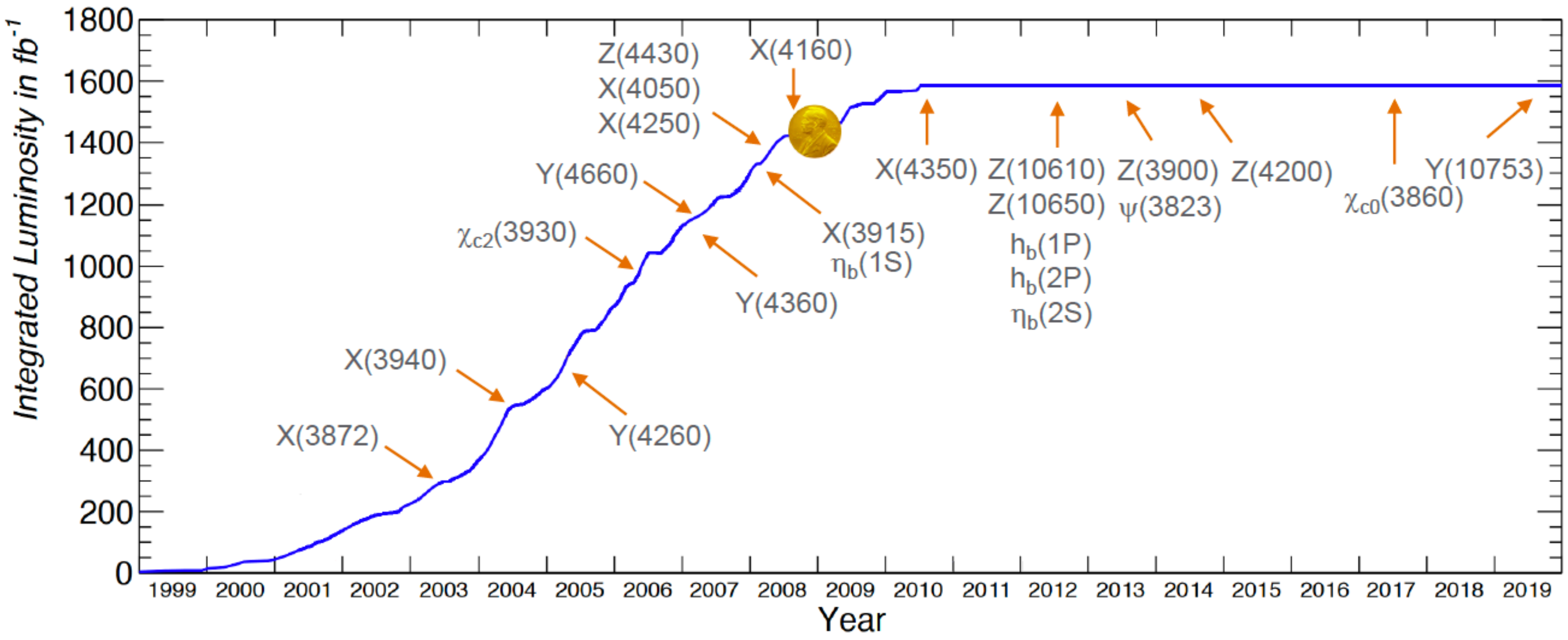
B factories



- Belle/KEKB (KEK) and BaBar/PEP-II (SLAC)
  - Very successful physics programs with a total recorded sample over 1.5 ab^{-1} (1.25×10^9 $B\bar{B}$ pairs)
  - Flavor physics (CKM/UT, CPV), NP in rare processes, new particle discoveries

More details in "The Physics of the B Factories", EPJC 74, 3026 (2014)

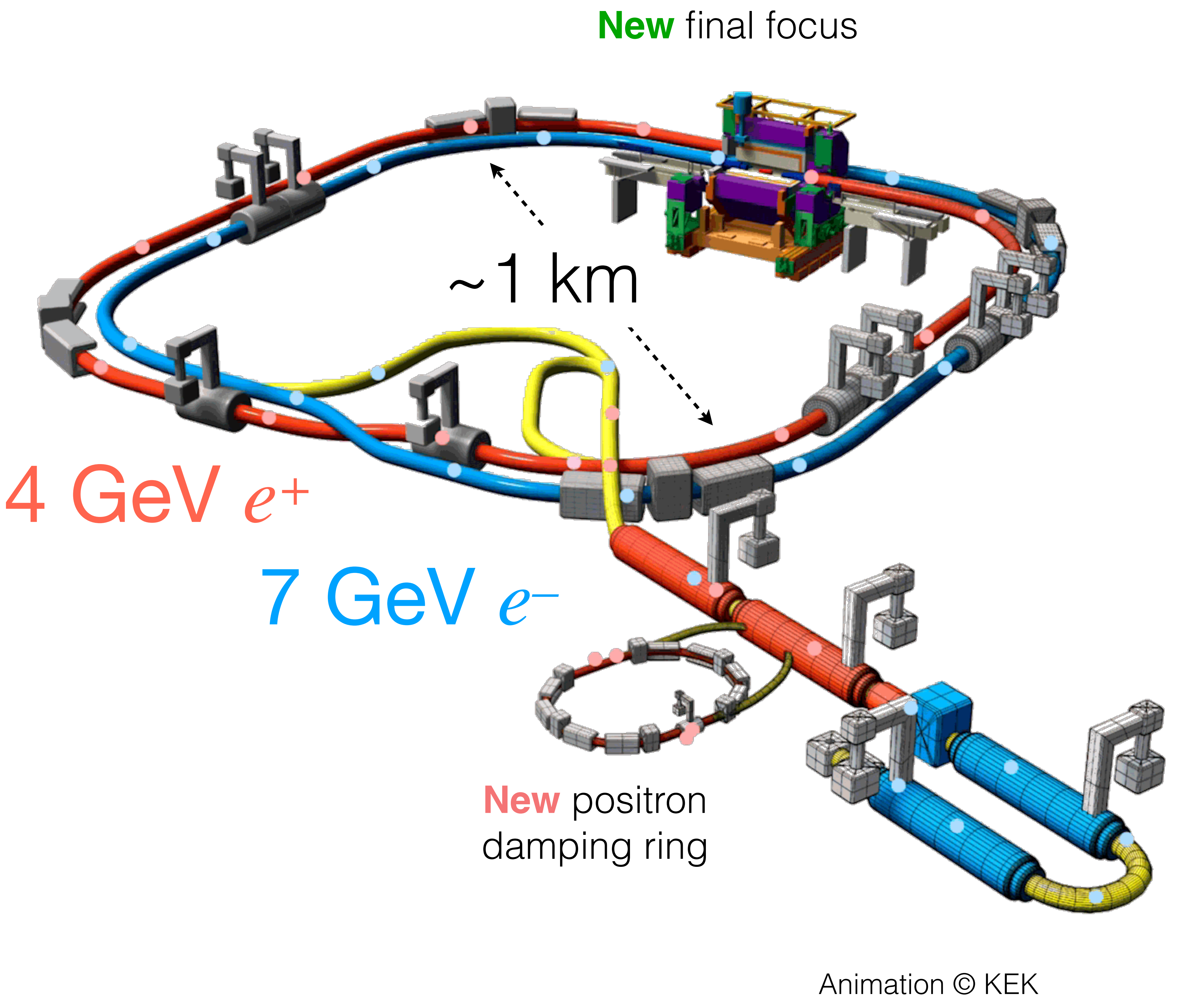


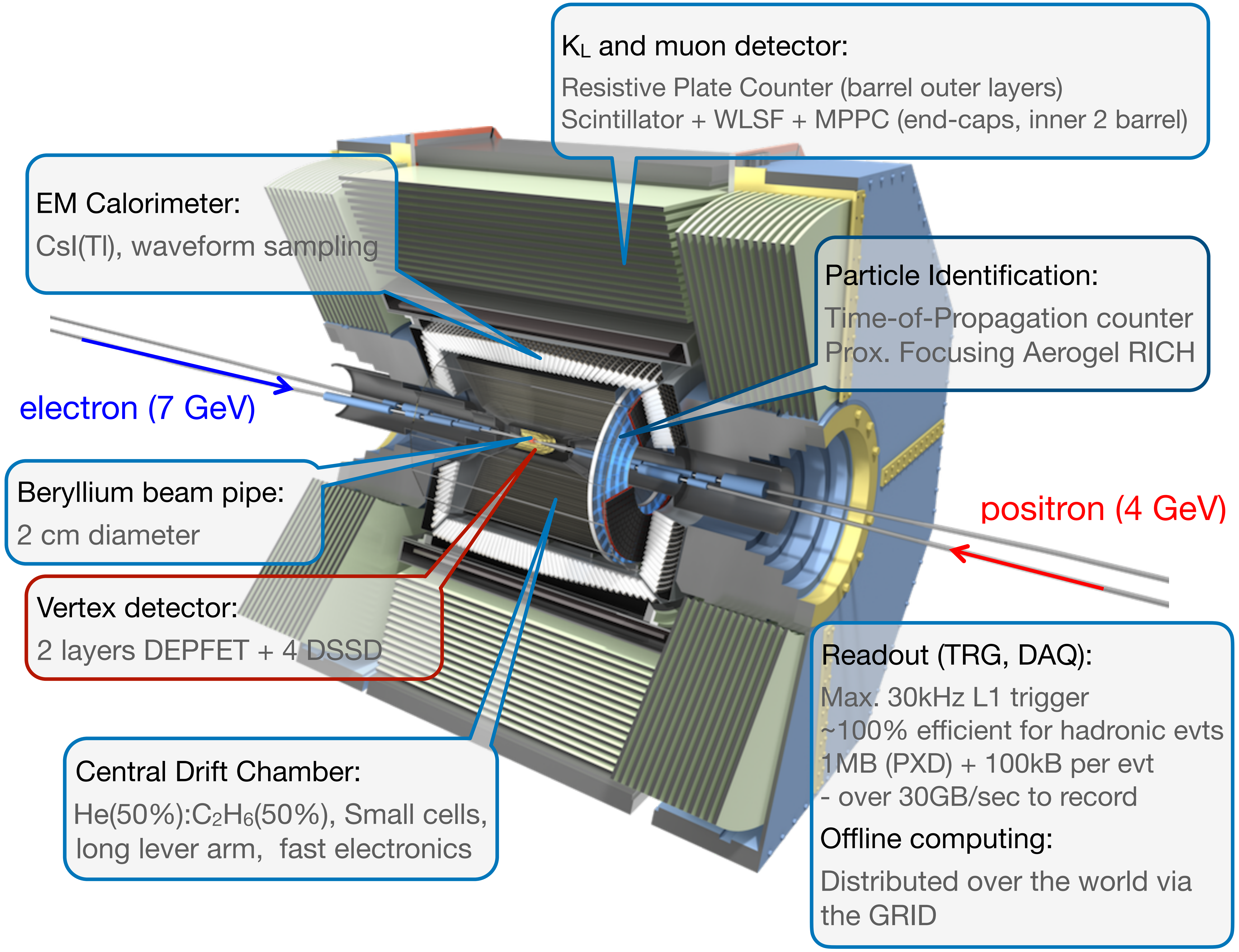


Even >10 years after data taking, still producing new results in hadron spectroscopy

>350 papers published since shutdown!

SuperKEKB and Belle II: 2nd generation “Super B Factory”

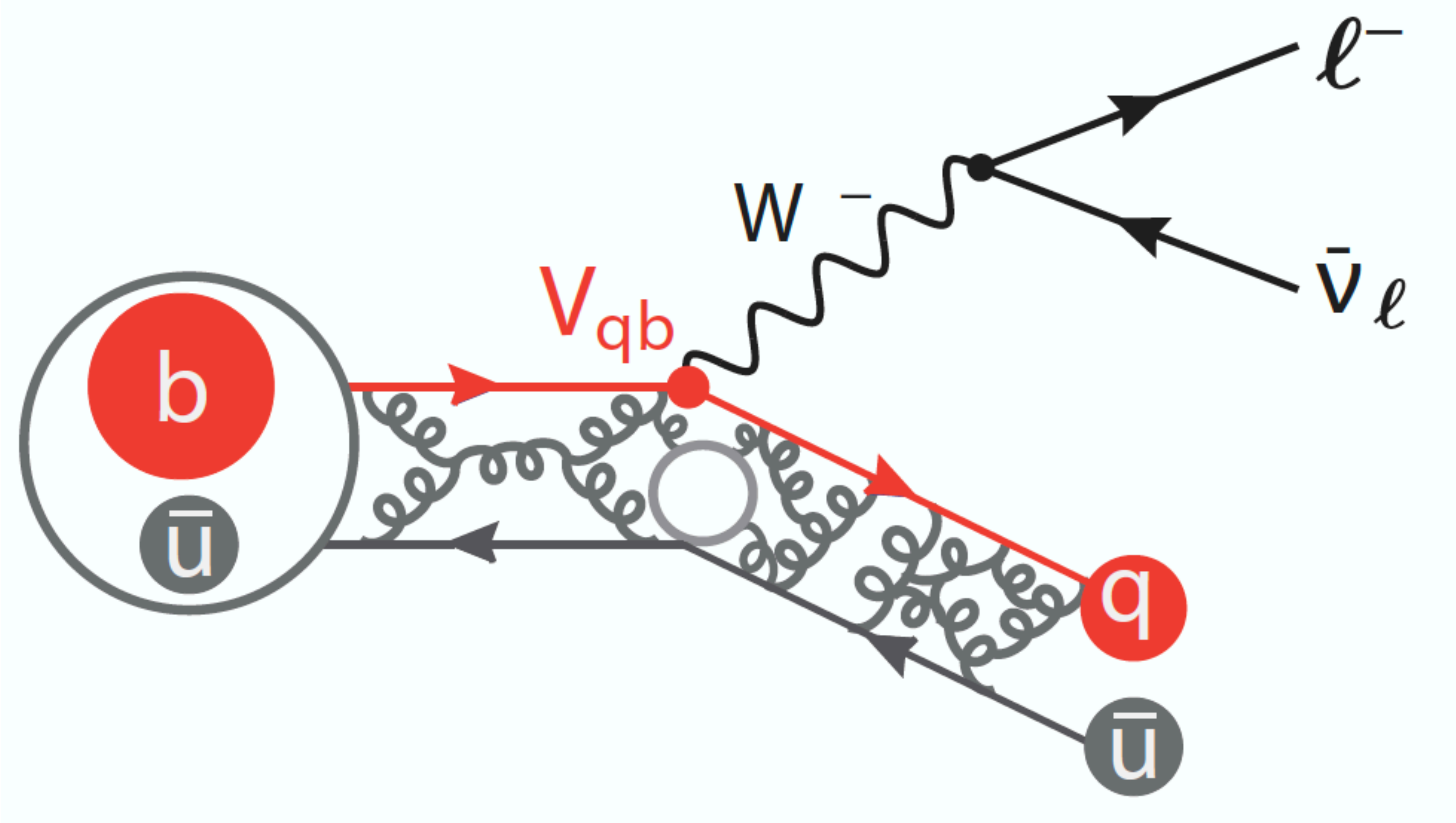




$$c\bar{c},\ u\bar{u},\ d\bar{d},\ \ell^+\ell^- \leftarrow e^+e^- \rightarrow \Upsilon(\mathrm{nS}) \rightarrow B^{(*)}\bar{B}^{(*)}$$

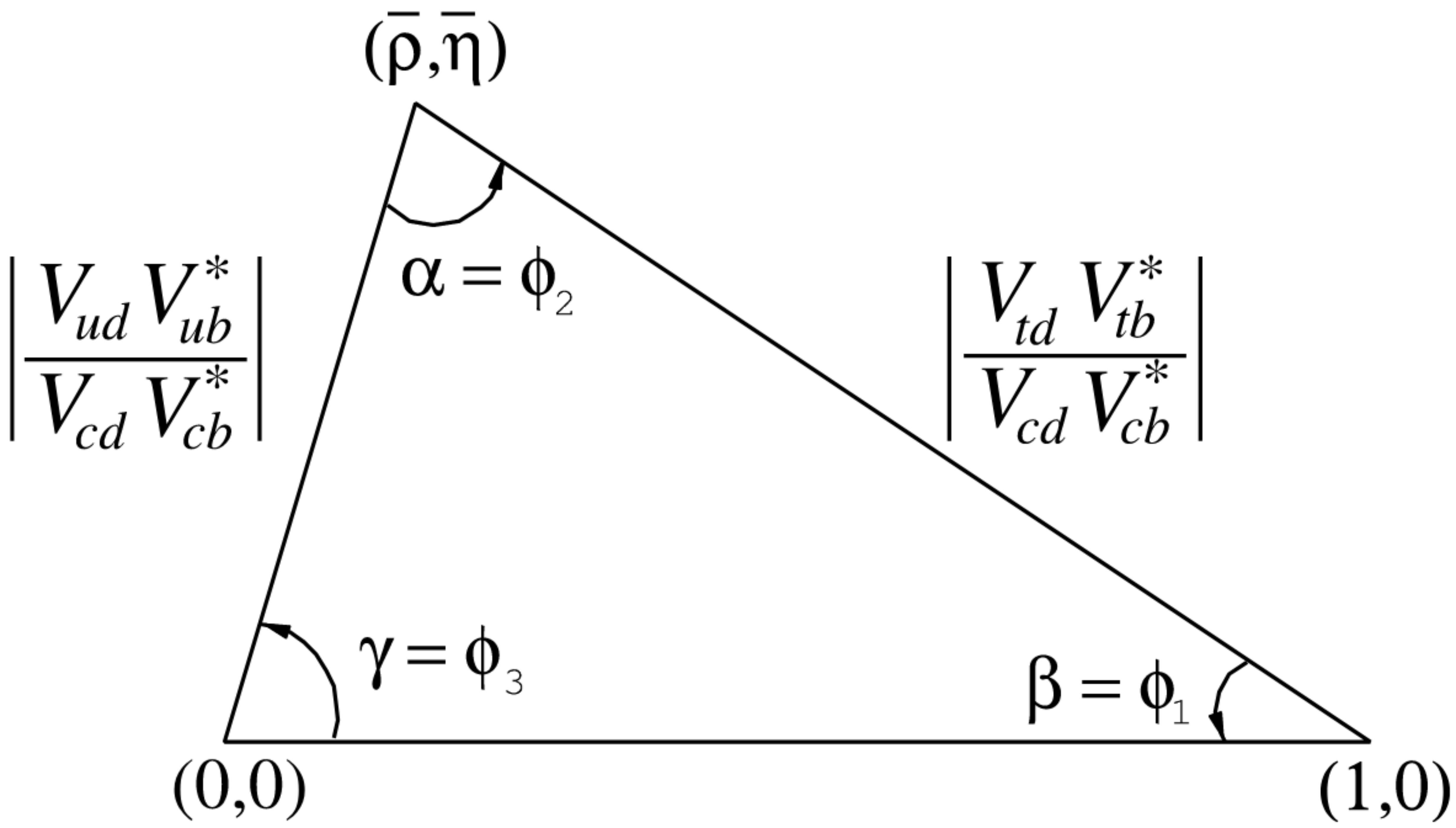
Weak decays and hadronic interactions

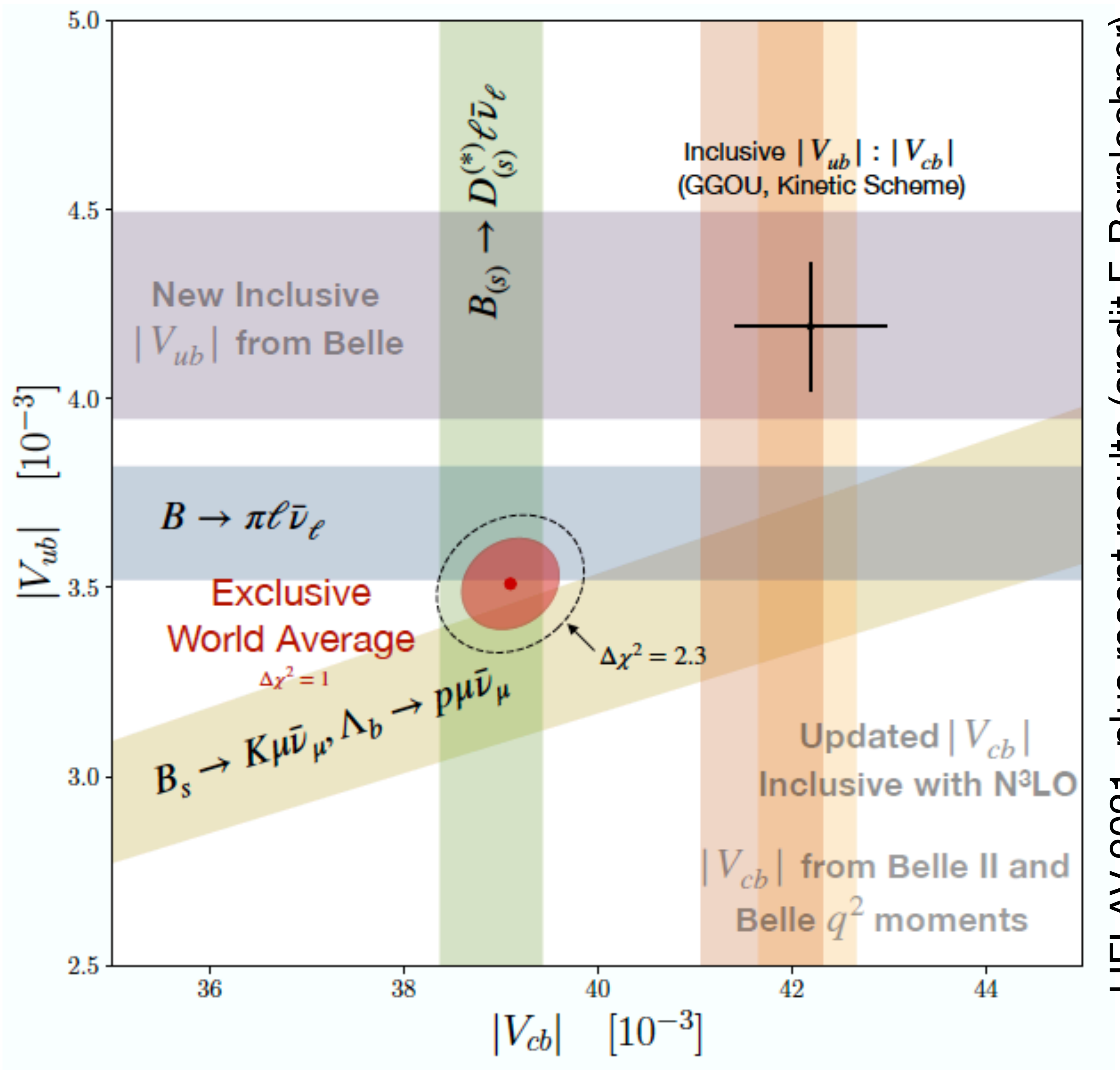
- Searches for BSM physics rely on accurate theory descriptions of strong interactions at low energy
  - Often rely on predictive models like the Heavy Quark Expansion (HQE)
    - A standard tool for theoretical description of inclusive decays of heavy hadrons
    - Decay widths calculated with expansion in terms of heavy quark mass



CKM metrology

- Measure $|V_{ub}|$ and $|V_{cb}|$ to overconstrain unitarity condition → potent test of Standard Model
- Long-standing discrepancy between inclusive and exclusive measurements
- We need new experimental and theoretical results that challenge existing knowledge





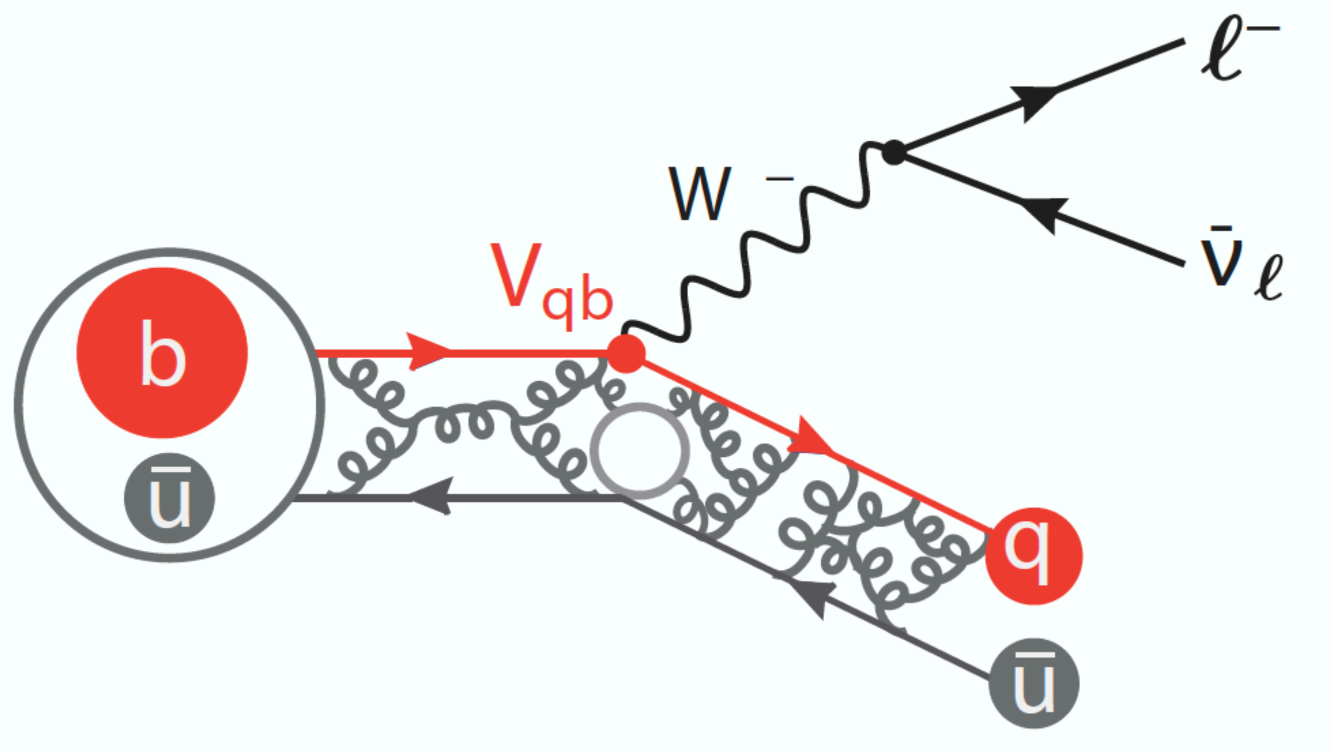
HFLAV 2021, plus recent results (credit F. Bernlochner)

$|V_{cb}|$ from exclusive $B \to X_c \ell \nu$ decays

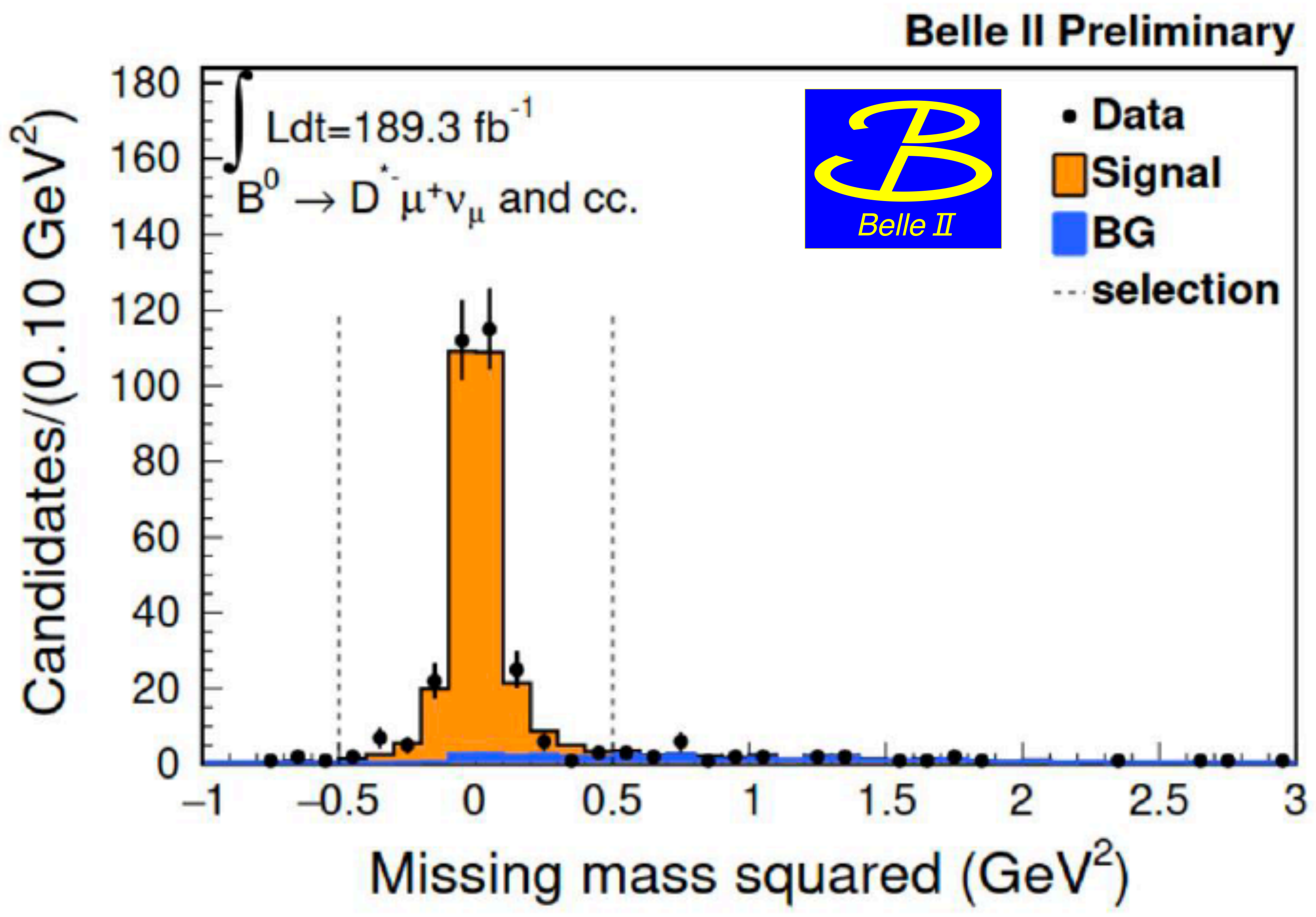
Short-distance radiative corrections

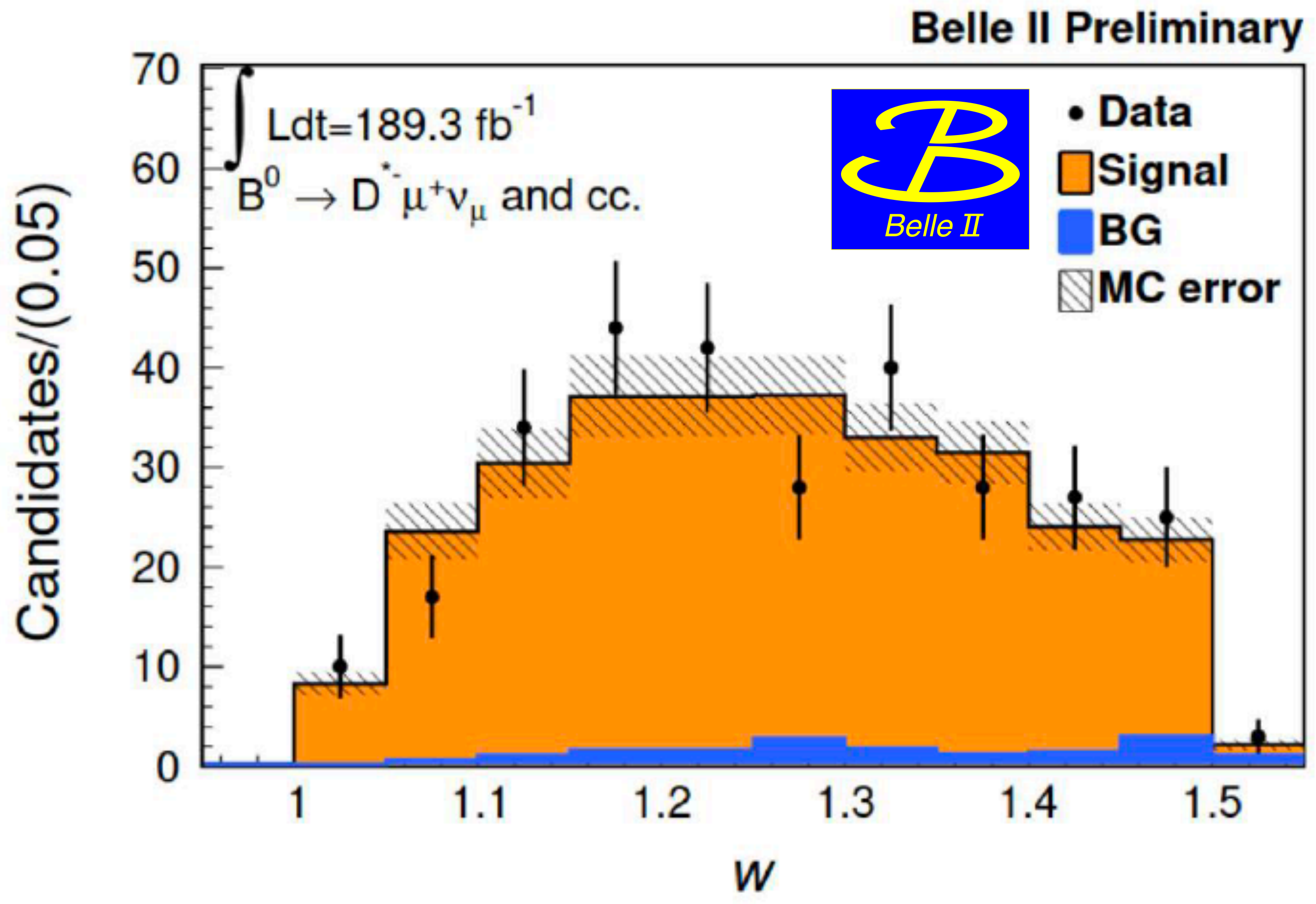
$$\frac{d\Gamma}{dw} \propto F(w)\ |V_{cb}|^2\ \eta_{EW}^2$$

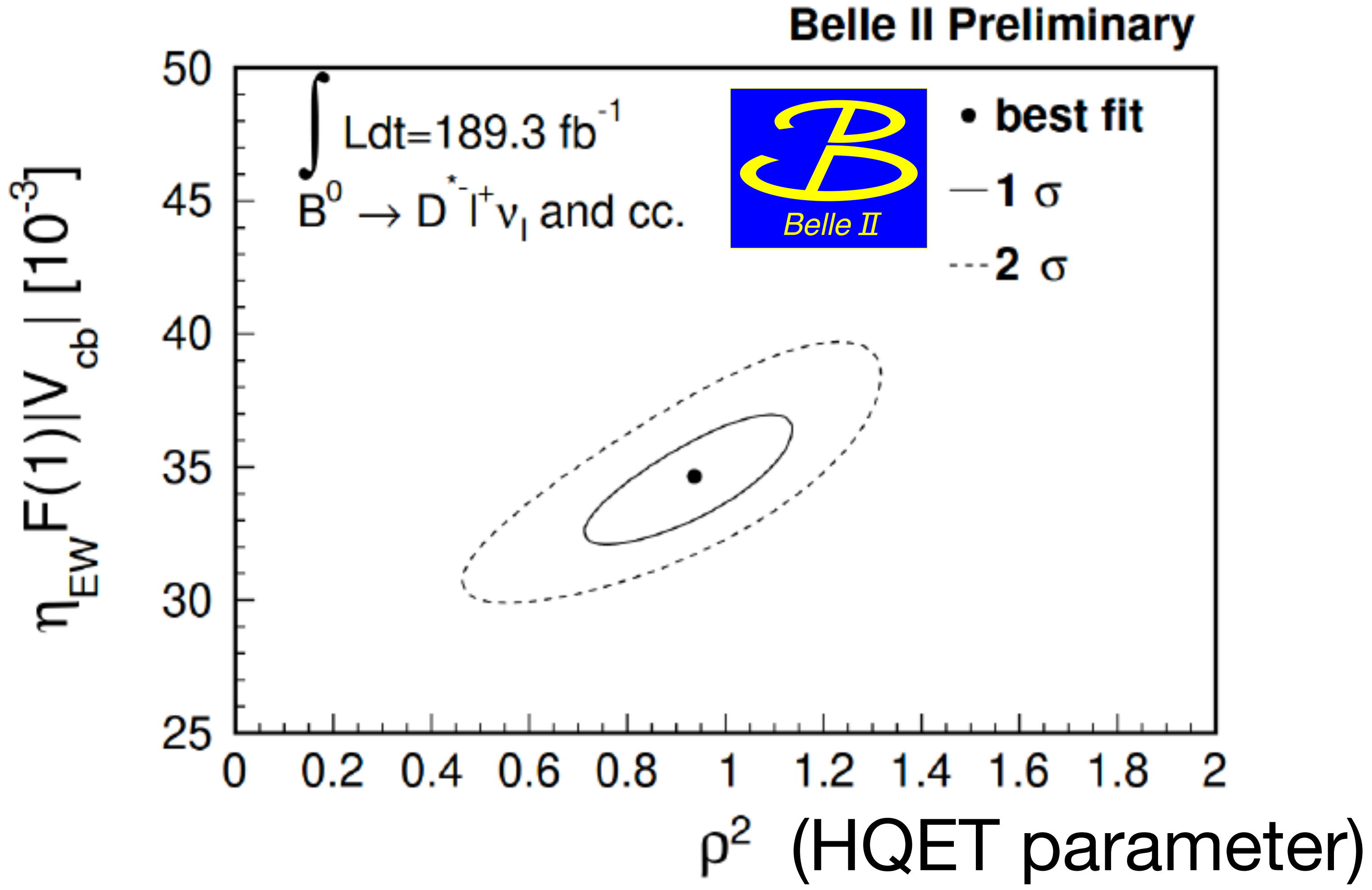
- Decay rate depends on product of CKM element and hadronic form factor
  - Global fit for CKM element, extract form factors (test theory predictions)
  - Theory prediction for form factor, extract CKM elements



- Exclusive measurement of $|V_{cb}|$
  - Now have LQCD predictions beyond zero recoil
  - LHCb measurements with $B_s \to D_s^{(*)} \mu \bar{\nu}_\mu$ [Phys. Rev. D 101, 072004]
  - Preliminary results for $|V_{cb}|$ in $B^0 \to D^{*-} \ell^+ \nu_\ell$ at Belle II



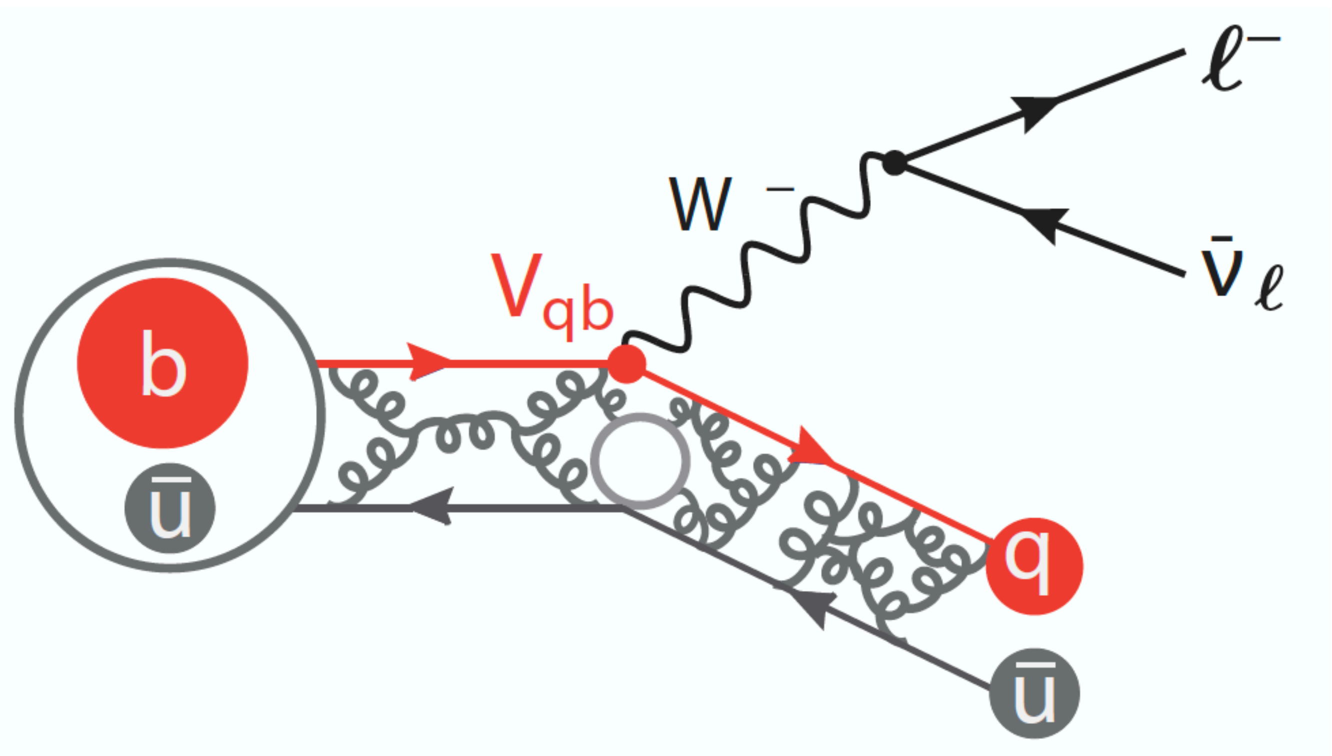




$|V_{cb}|$ from inclusive $B \to X_c \ell \nu$ decays

Operator Product Expansion

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 \left(1 + \frac{c_5(\mu) O_5(\mu)}{m_b^2} + \frac{c_6(\mu) O_6(\mu)}{m_b^3} + \mathcal{O}\left(\frac{1}{m_b^4}\right)\right)$$



- **Traditional approach**: Use hadronic mass moments, lepton energy moments, etc. to determine non-perturbative matrix elements of OPE and extract $|V_{cb}|$
  - Allows model-independent extraction of HQE parameters up to $\mathcal{O}(1/m_b^3)$
  - Extraction of higher order terms complicated by proliferation of hadronic parameters - rely on modeling

- **Alternative approach** [JHEP 02 (2019) 177] (M. Fael, T. Mannel, K. Vos): exploit relations between HQE parameters due to *reparameterization invariance* to reduce the number of independent parameters
  - Not true for every observable (e.g. not for $\langle M_X \rangle$), but holds for $\langle q^2 \rangle$
  - At $1/m_b^4$ the number of matrix elements reduces from 13 to 8

$$q^2 = (p_{sig} - p_{X_c})^2$$

q^2 moments from $B \to X_c \ell \nu$ decays

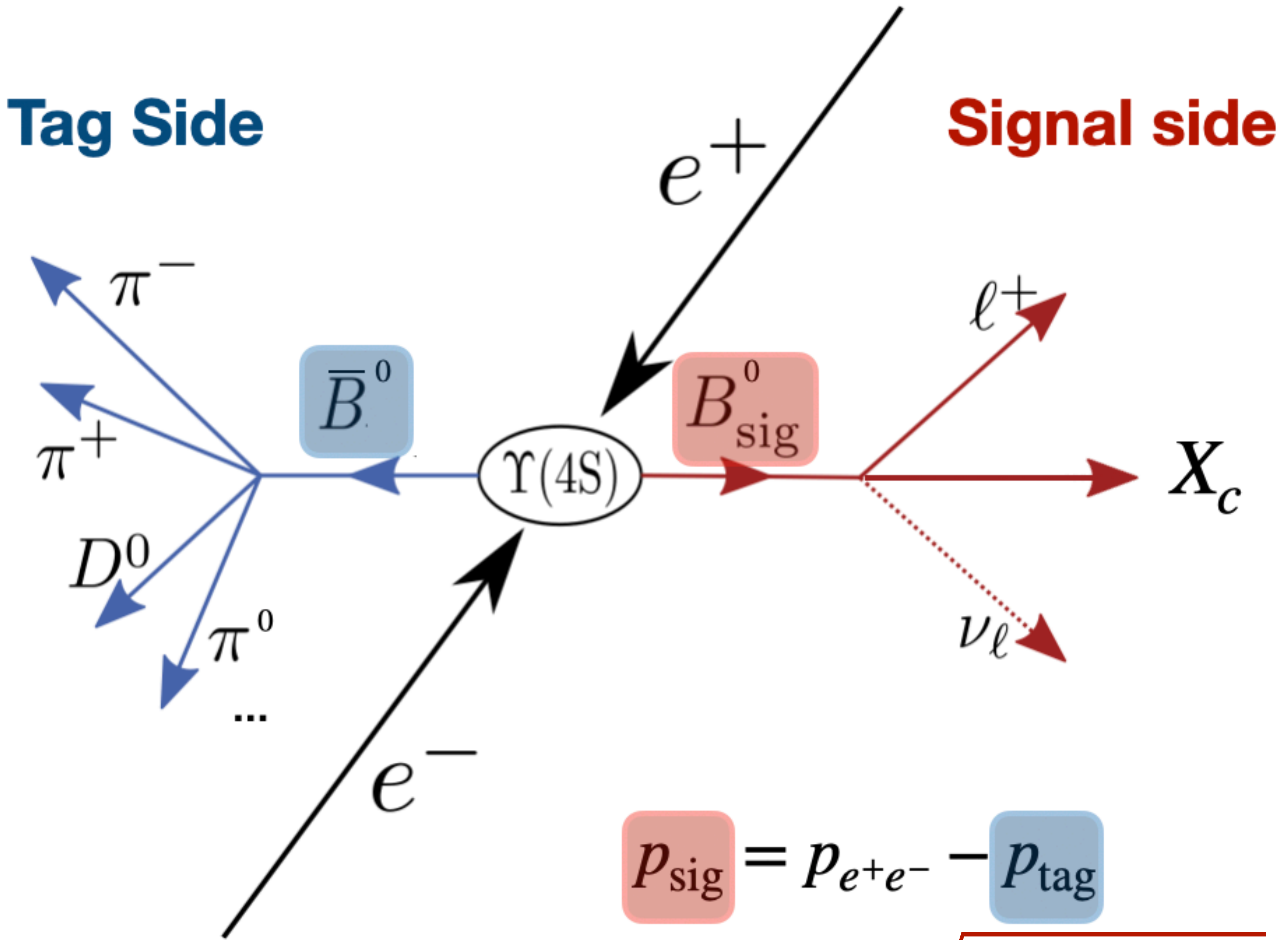
Improved Hadronic Tagging technique using Belle II algorithm (approximately twice better efficiency than Belle)

Acceptance corrected

Calibration factors

$$\langle q^{2n} \rangle = \frac{\sum_i^{N_{\rm data}} w(q_i^2) \times \boxed{q_{{\rm calib},i}^{2n}}}{\sum_j^{N_{\rm data}} w(q_j^2)} \times \boxed{\mathcal{C}_{\rm calib} \times \mathcal{C}_{\rm gen}}$$

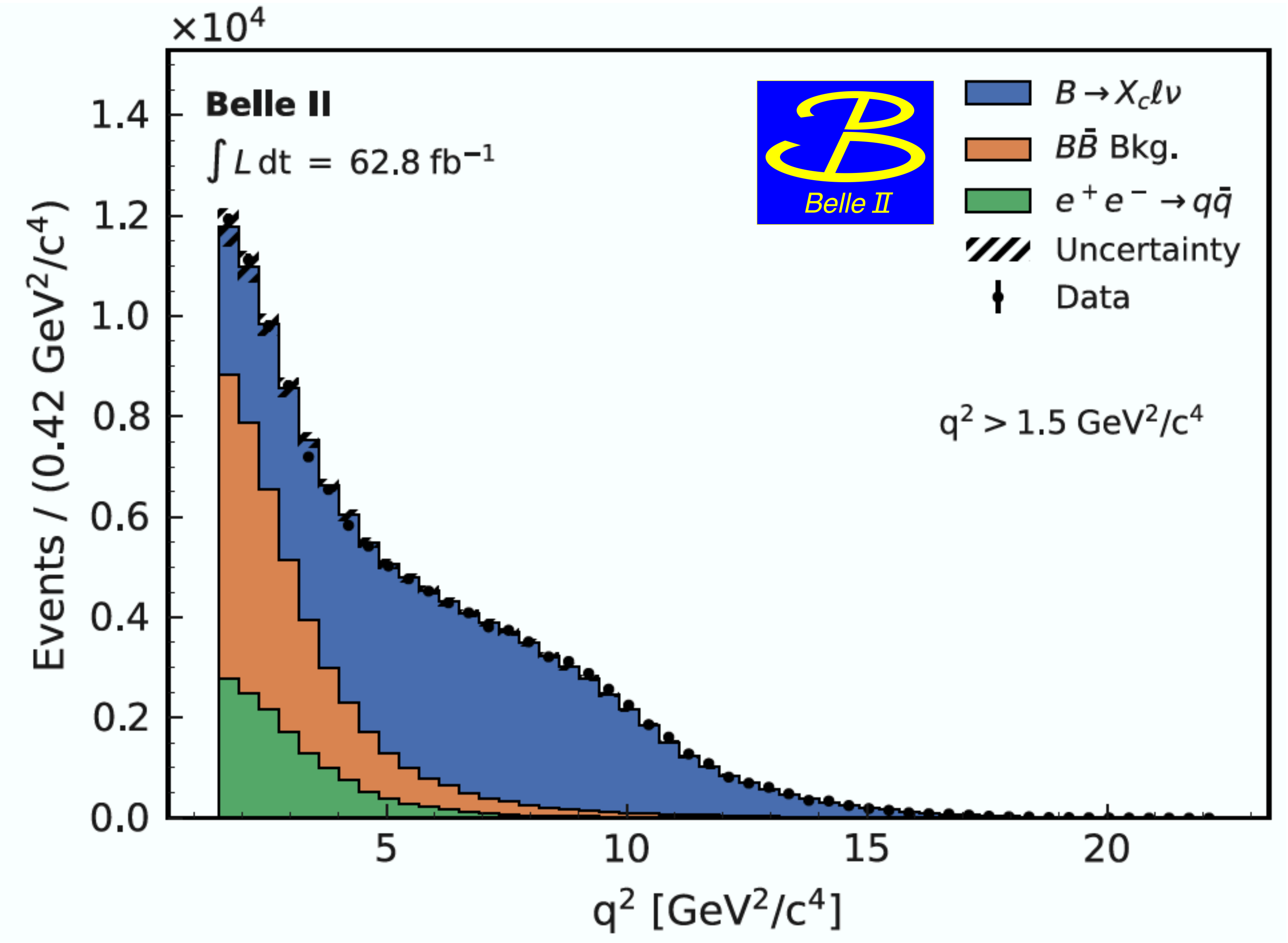
Event-wise signal probability

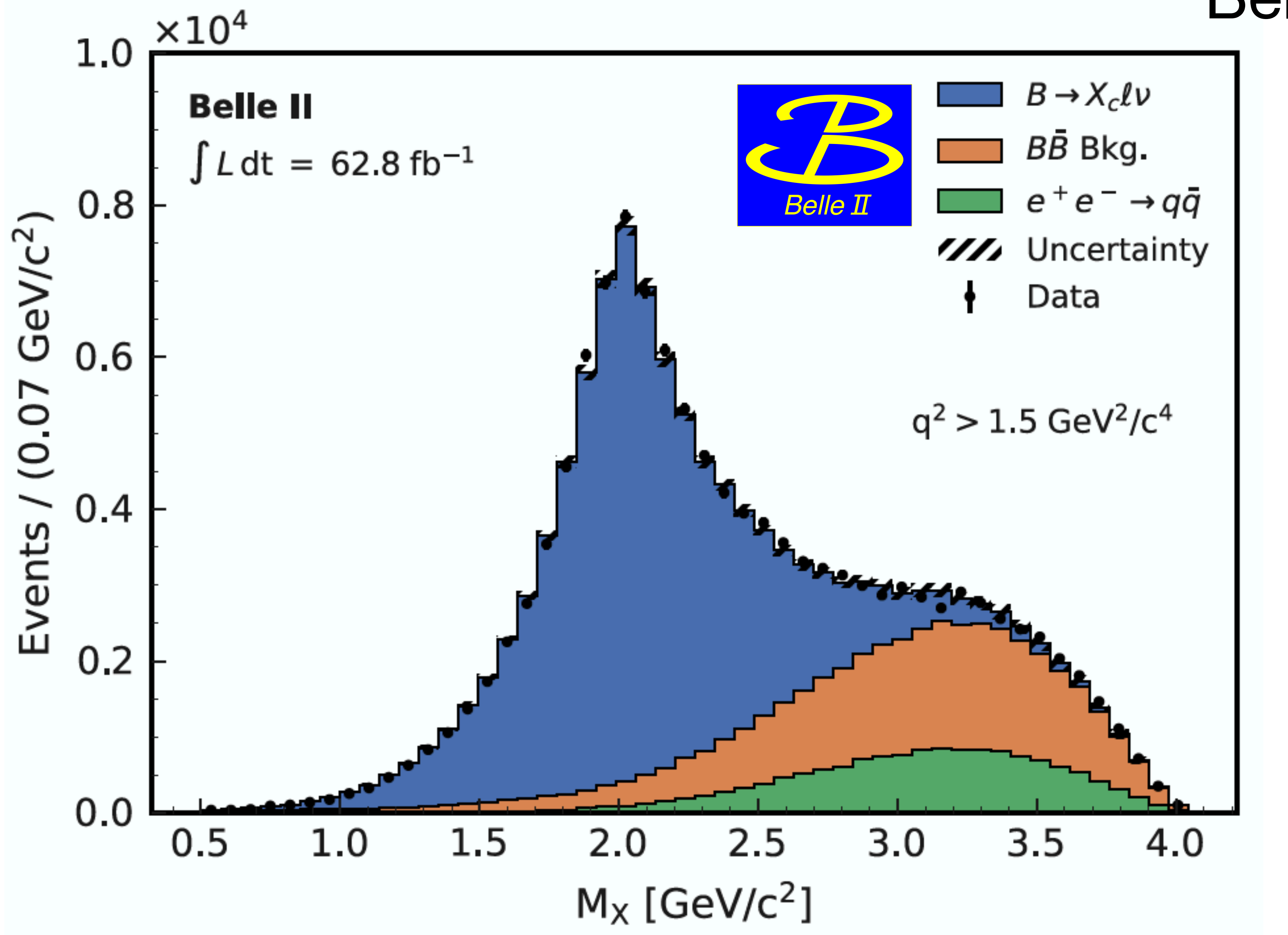


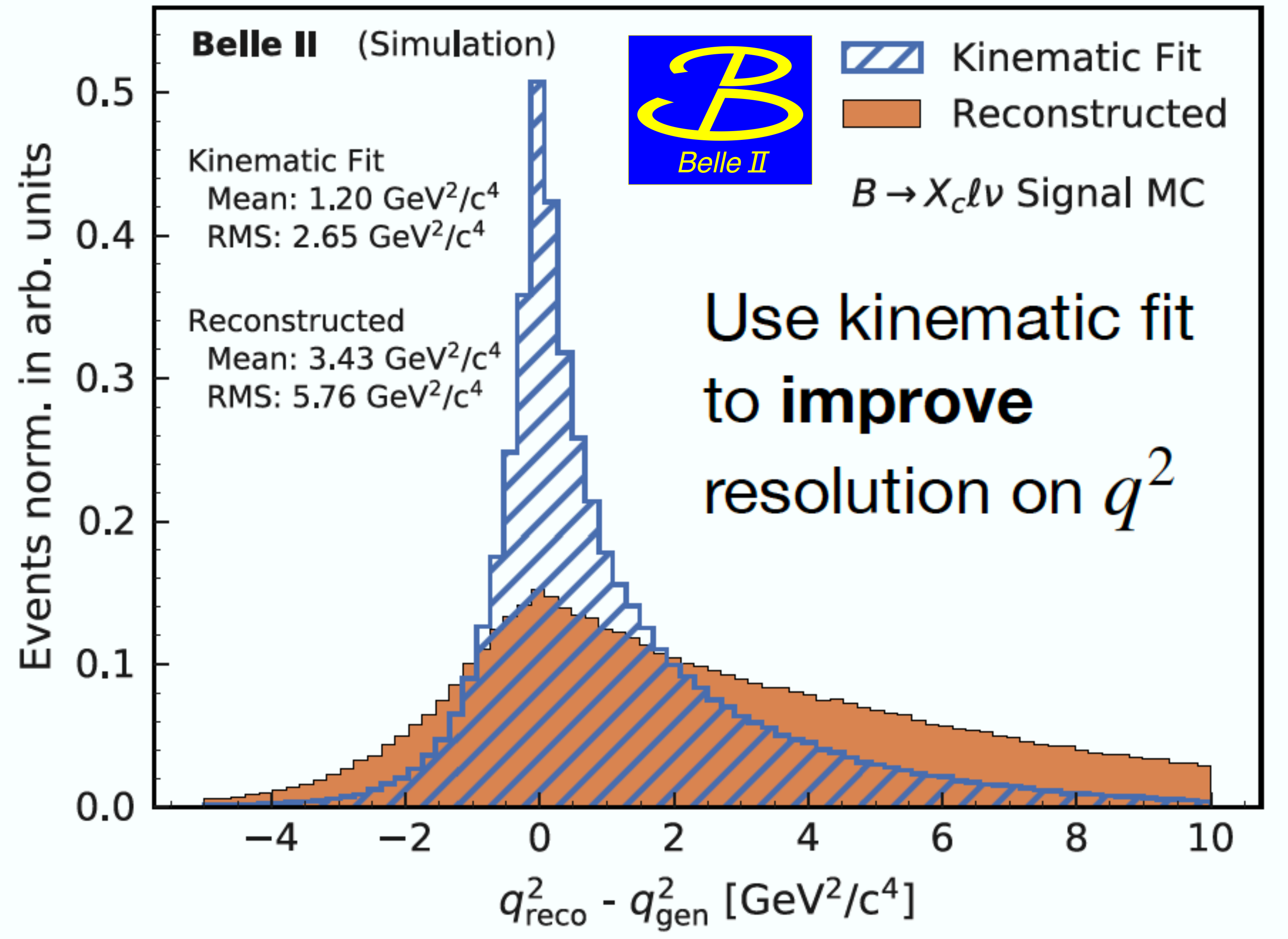
$$p_{\rm sig} = p_{e^+e^-} - p_{\rm tag}$$

$$q^2 = (p_{sig} - p_{X_c})^2 \qquad M_X = \sqrt{(p_{X_c})_\mu (p_{X_c})^\mu}$$

Belle II - arXiv:2205.06372 (Submitted to PRD)







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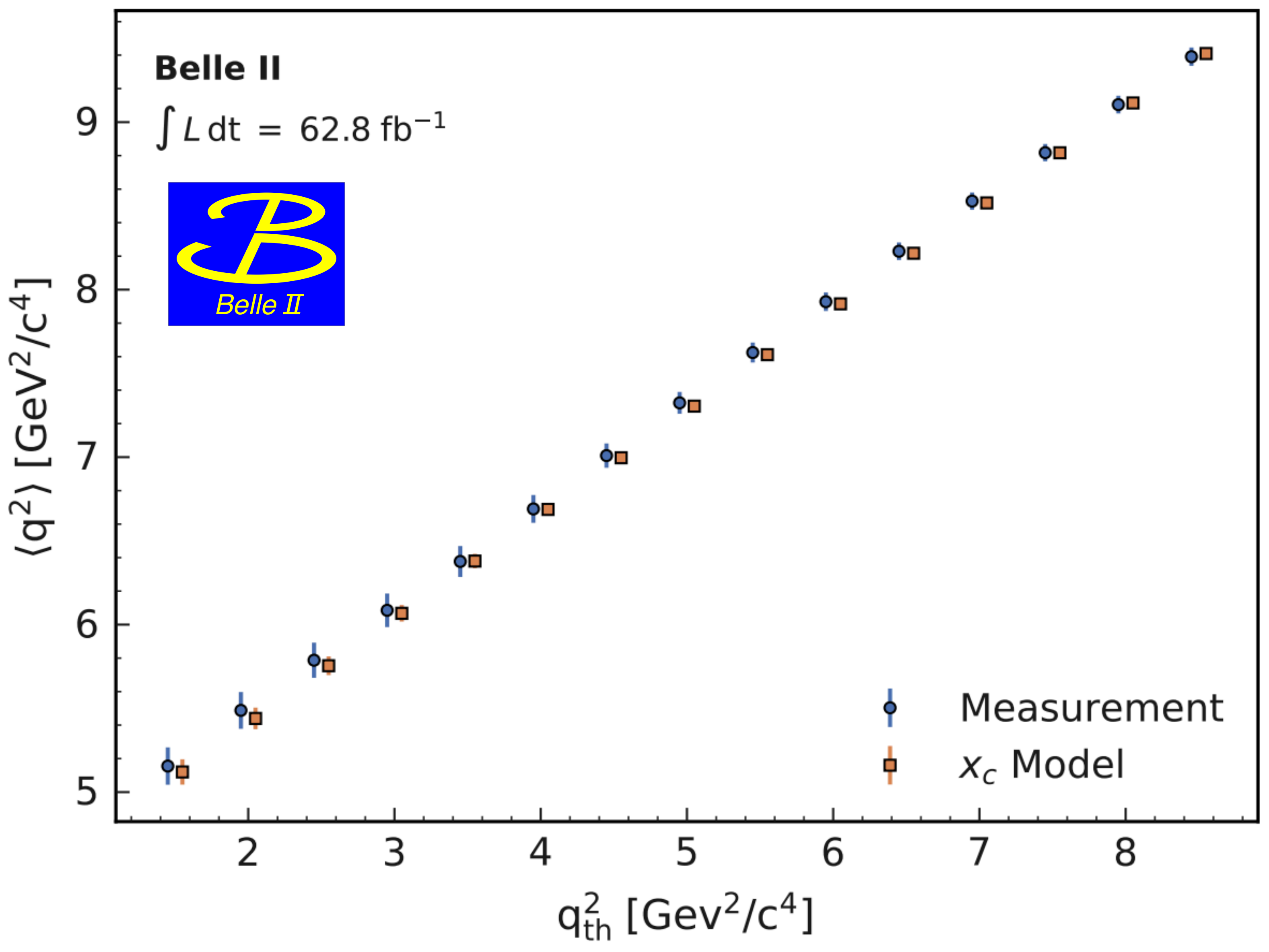
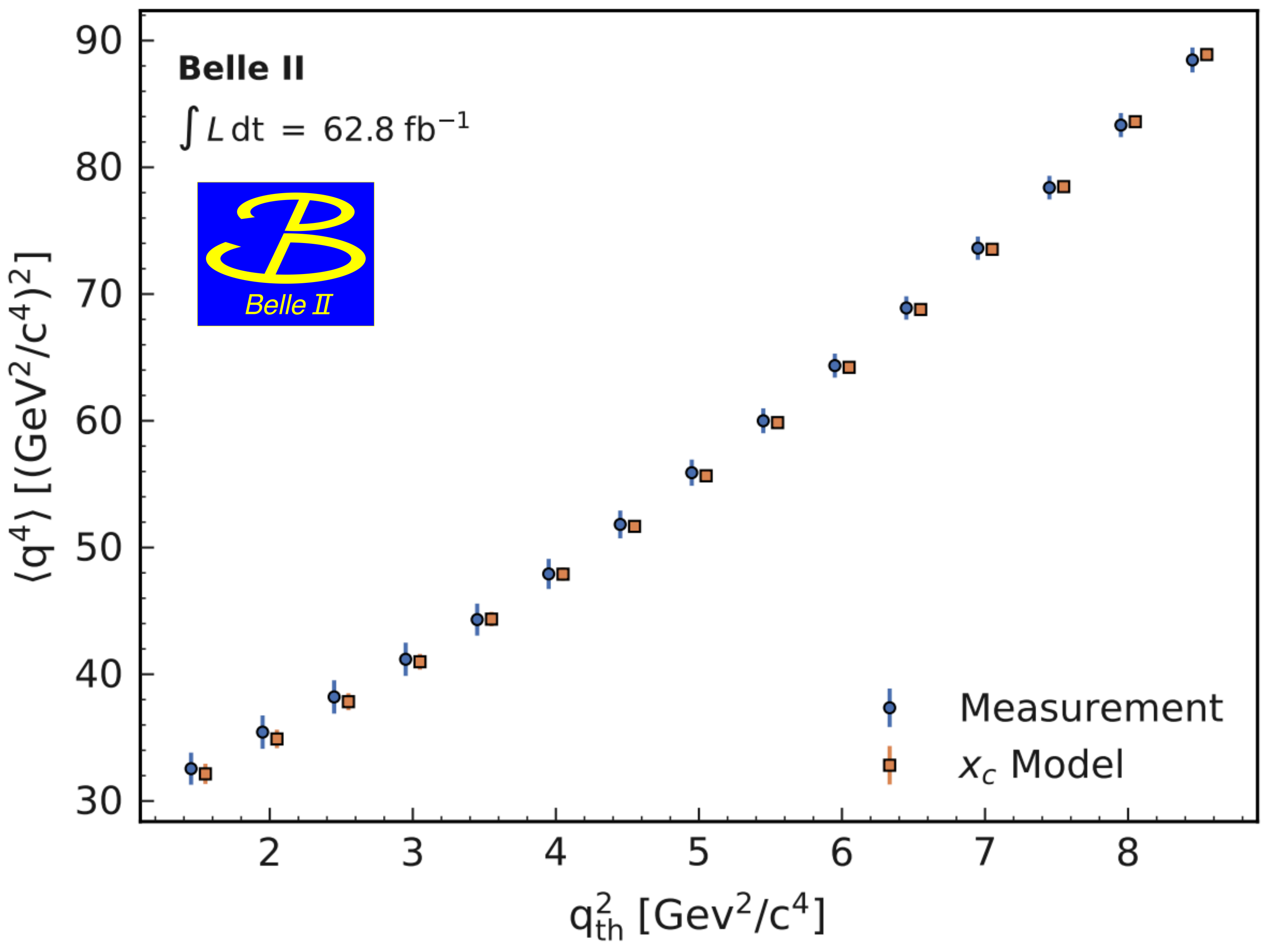
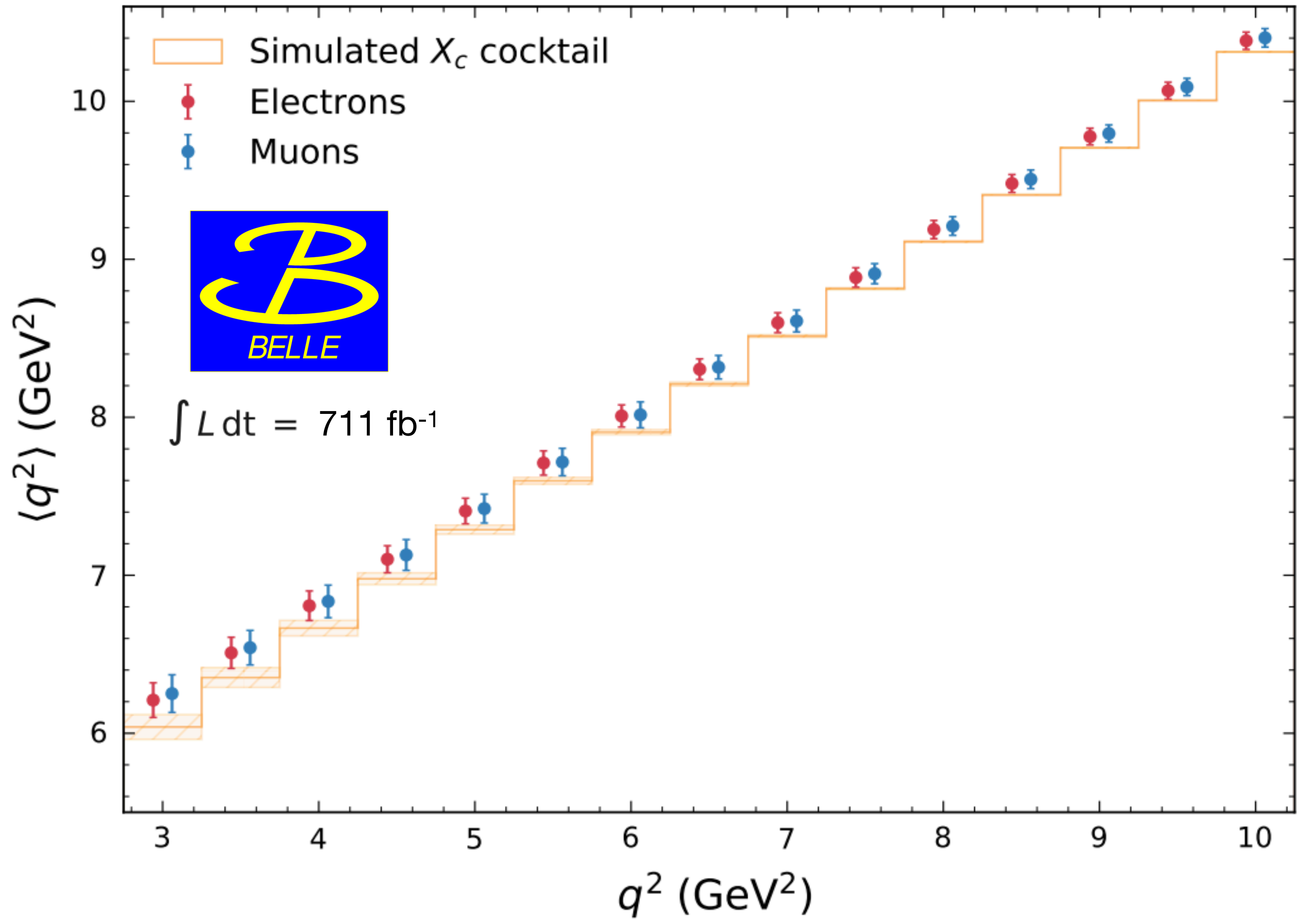
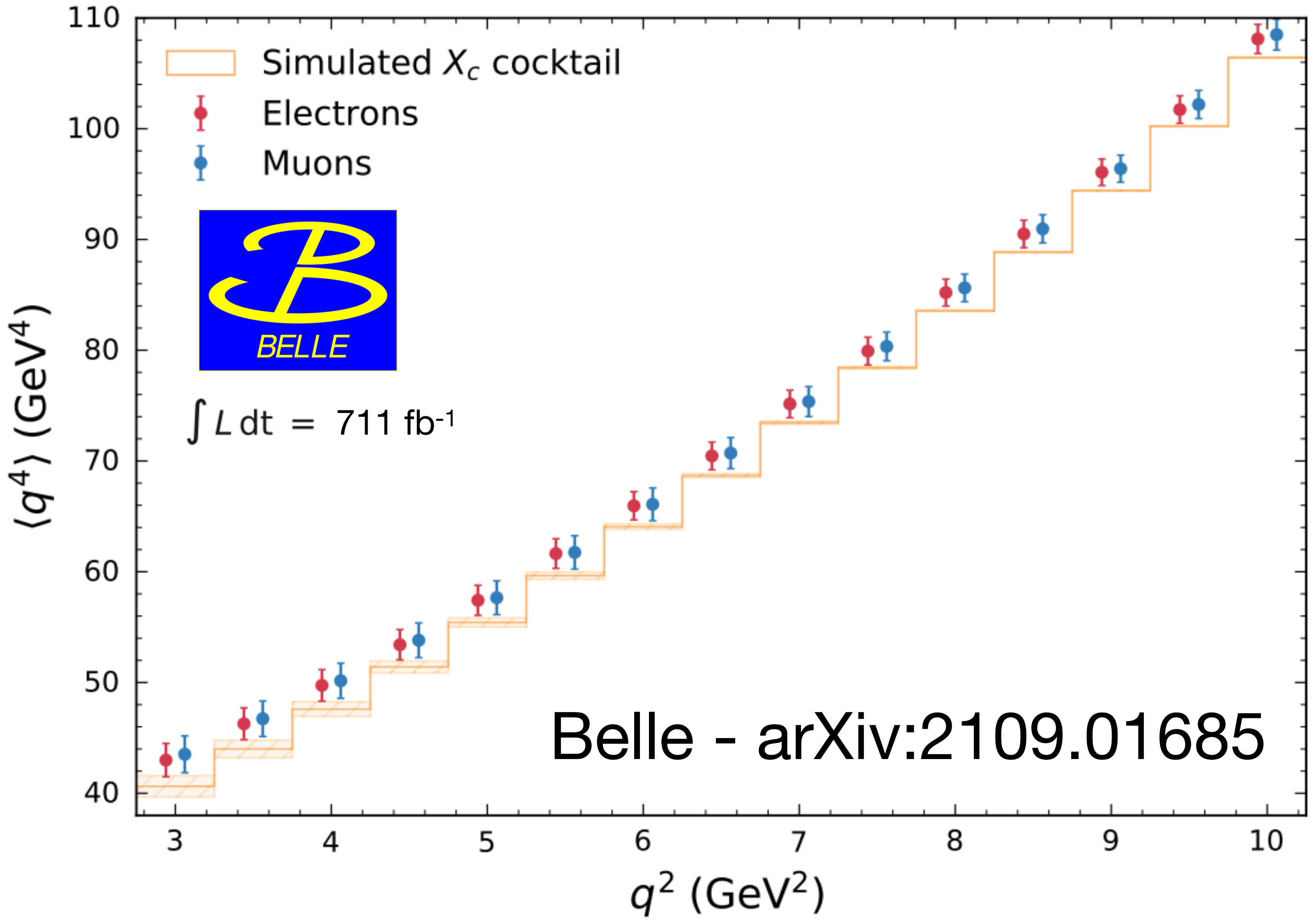
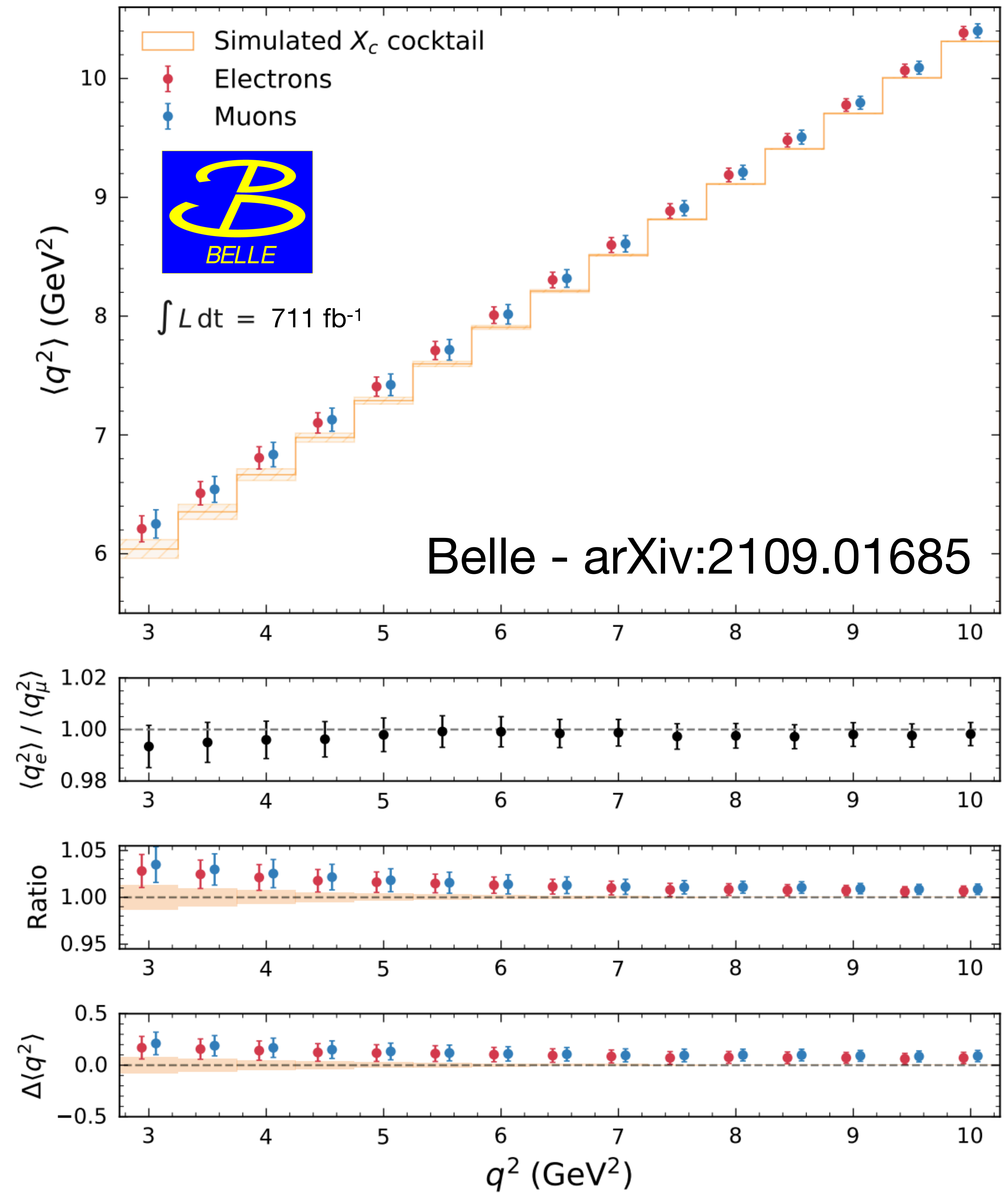








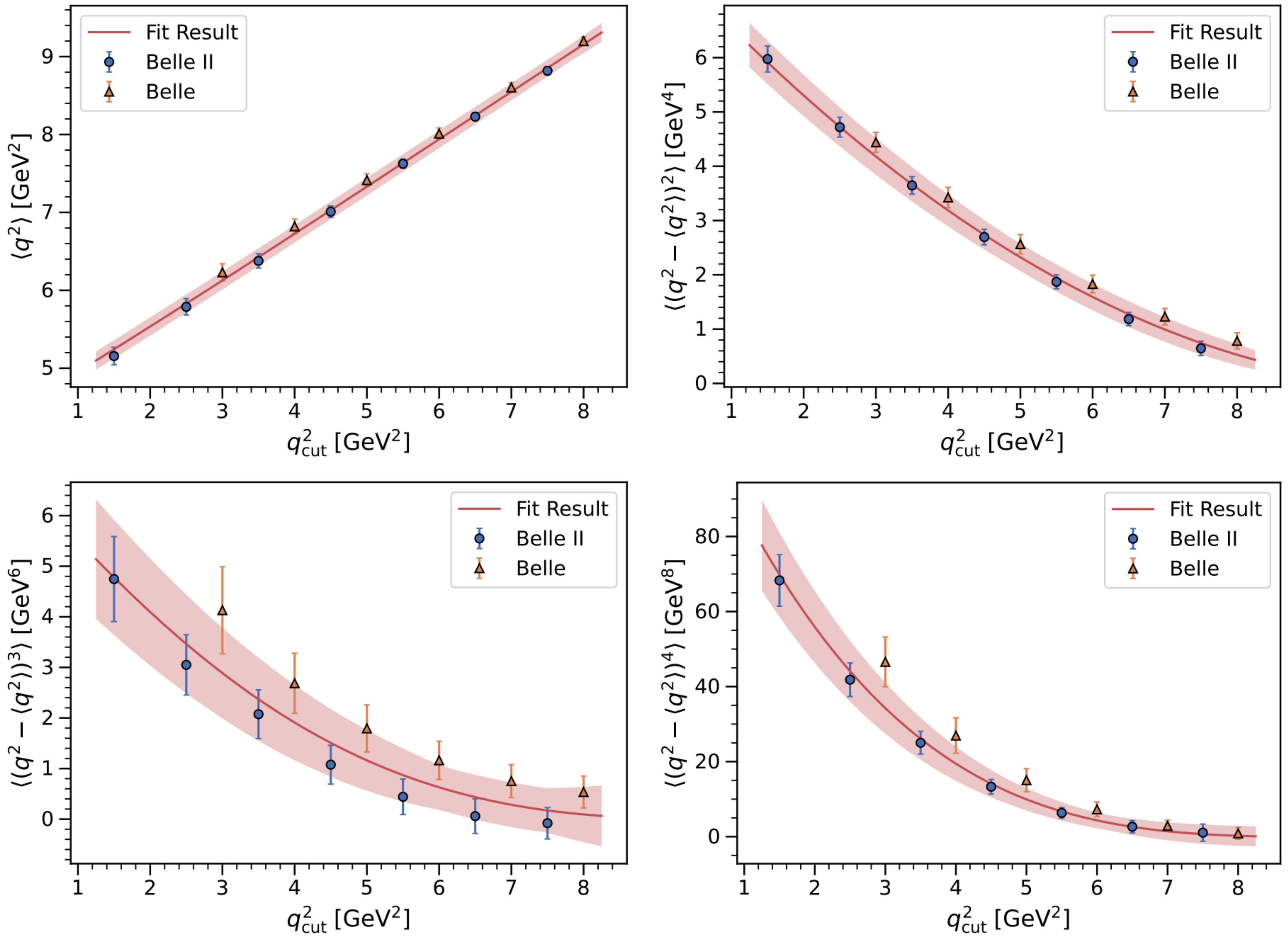


Belle II already reaches similar precision to Belle and can reach lower q^2 threshold

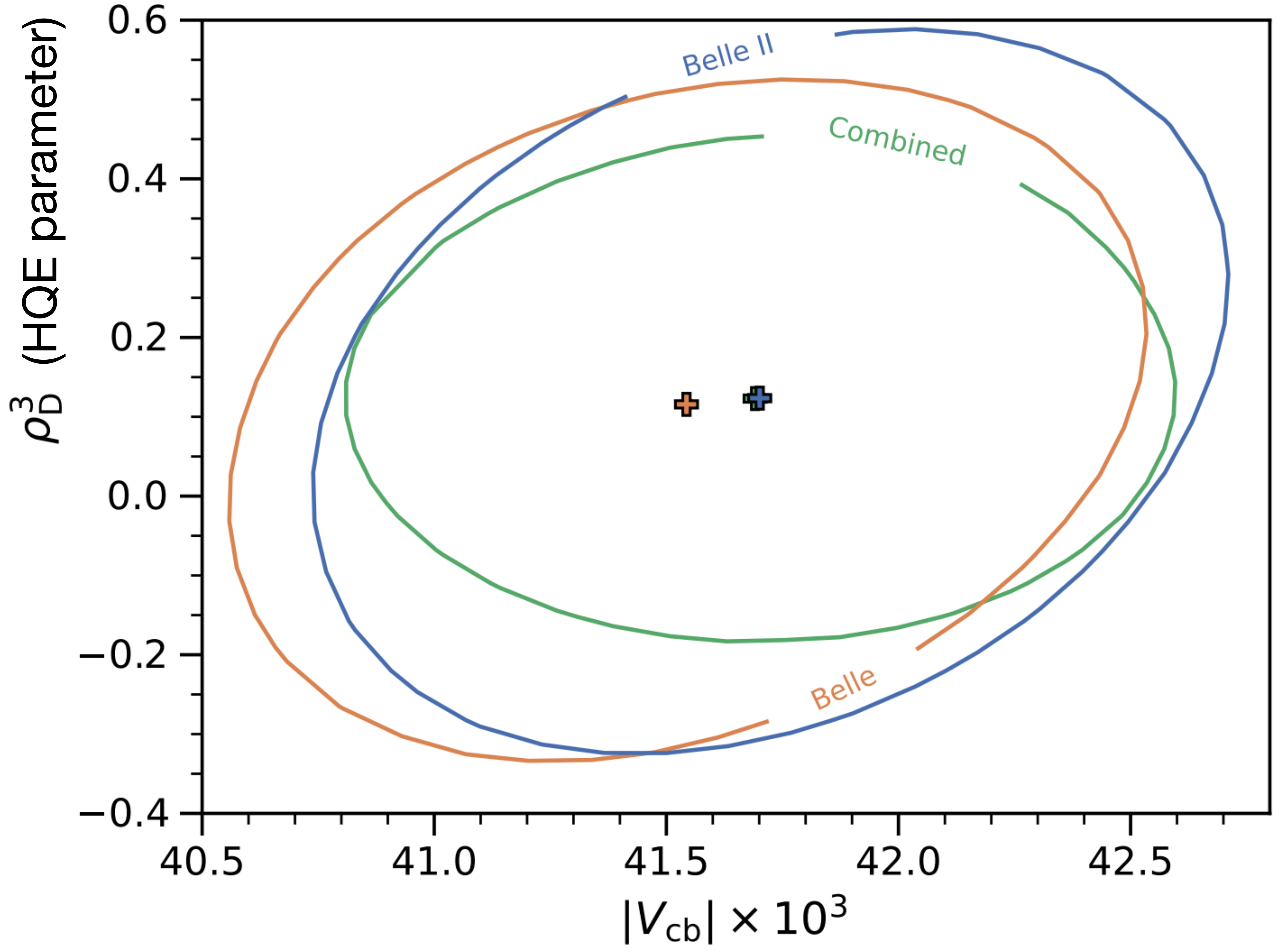
First extraction of inclusive $|V_{cb}|$ from q^2 moments

- Good agreement with the most precise previous measurement, $|V_{cb}| = 42.16(51) \times 10^{-3}$ [hep-ph/2107.00604]
- Provides strong evidence that inclusive $|V_{cb}|$ can be reliably obtained using the HQE
    - Uncertainties well under control

hep-ph/2205.10274



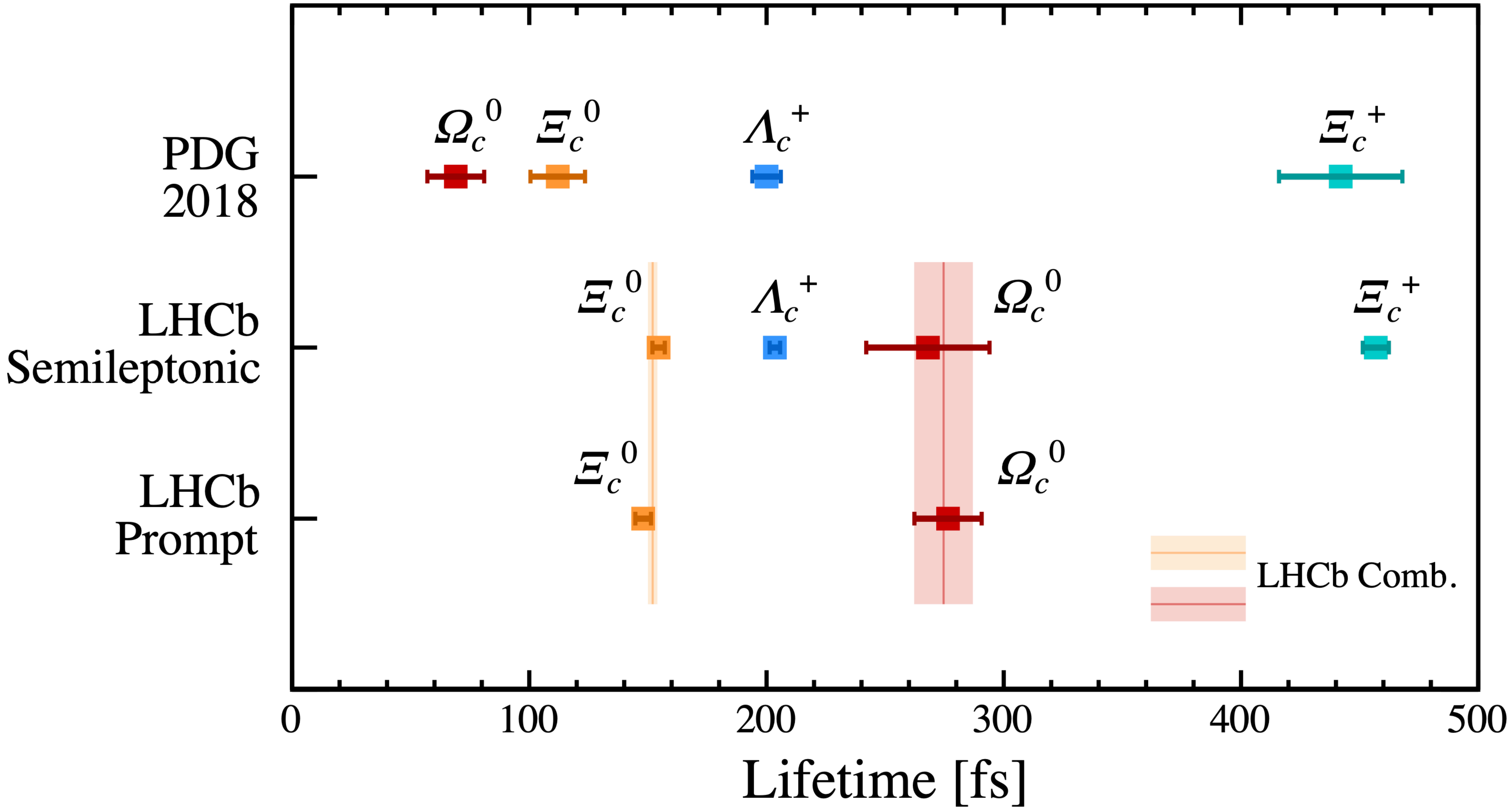
	$\lvert V_{cb}\rvert \times 10^3$	m_b^{kin}	$\overline{m}_c$	μ_G^2	μ_π^2	ρ_D^3	r_G^4	$r_E^4 \times 10$	ρ_{cut}	ρ_{mom}
Value	41.69	4.56	1.09	0.37	0.43	0.12	-0.21	0.02	0.05	0.09
Uncertainty	0.59	0.02	0.01	0.07	0.24	0.20	0.69	0.34	$^{+0.03}_{-0.01}$	$^{+0.10}_{-0.10}$



Other tests of theory predictions for hadronic interactions

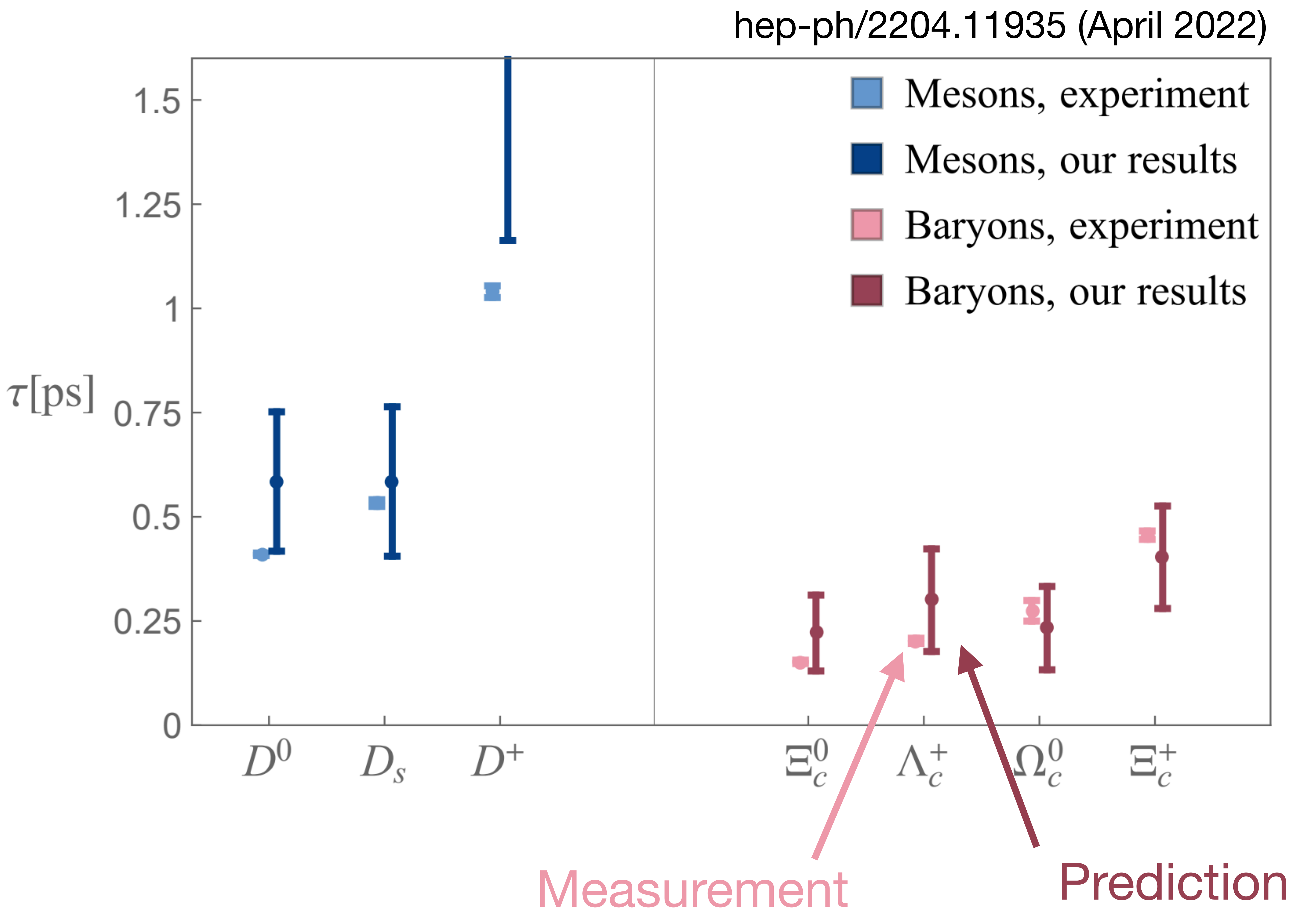
- Particle lifetimes sensitive to higher order terms in HQE
  - Charm hadrons complicated by poor performance of HQE to $\mathcal{O}(1/m_c^3)$ to describe non-perturbative effects
  - Recent charm lifetime measurements break established charm baryon lifetime hierarchy

LHCb - Sci. Bull. 67 (2022) 479



$$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$$

Charmed baryon lifetimes



- **Charm hadrons in particular provide excellent tests**
  - Charm quark mass is much less than that of the beauty quark
  - Higher order corrections and spectator effects more significant
  - Charmed baryons are most difficult to describe due to model-dependent spectator effects like weak W-annihilation and Pauli interference
  - **Provide stringent tests of theory predictions** that can be used to inform models used for BSM searches

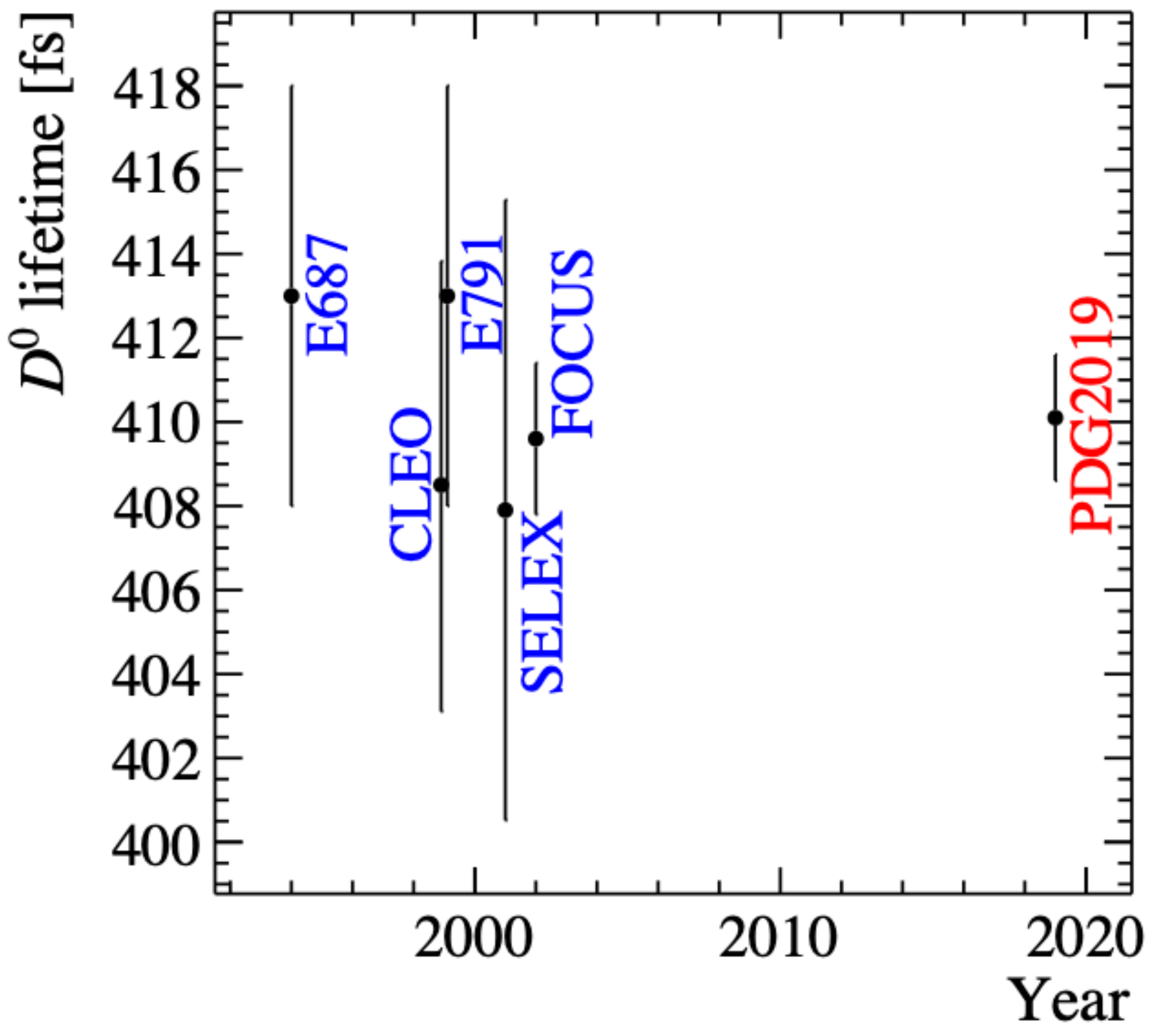
Charmed hadron lifetimes: experimental status

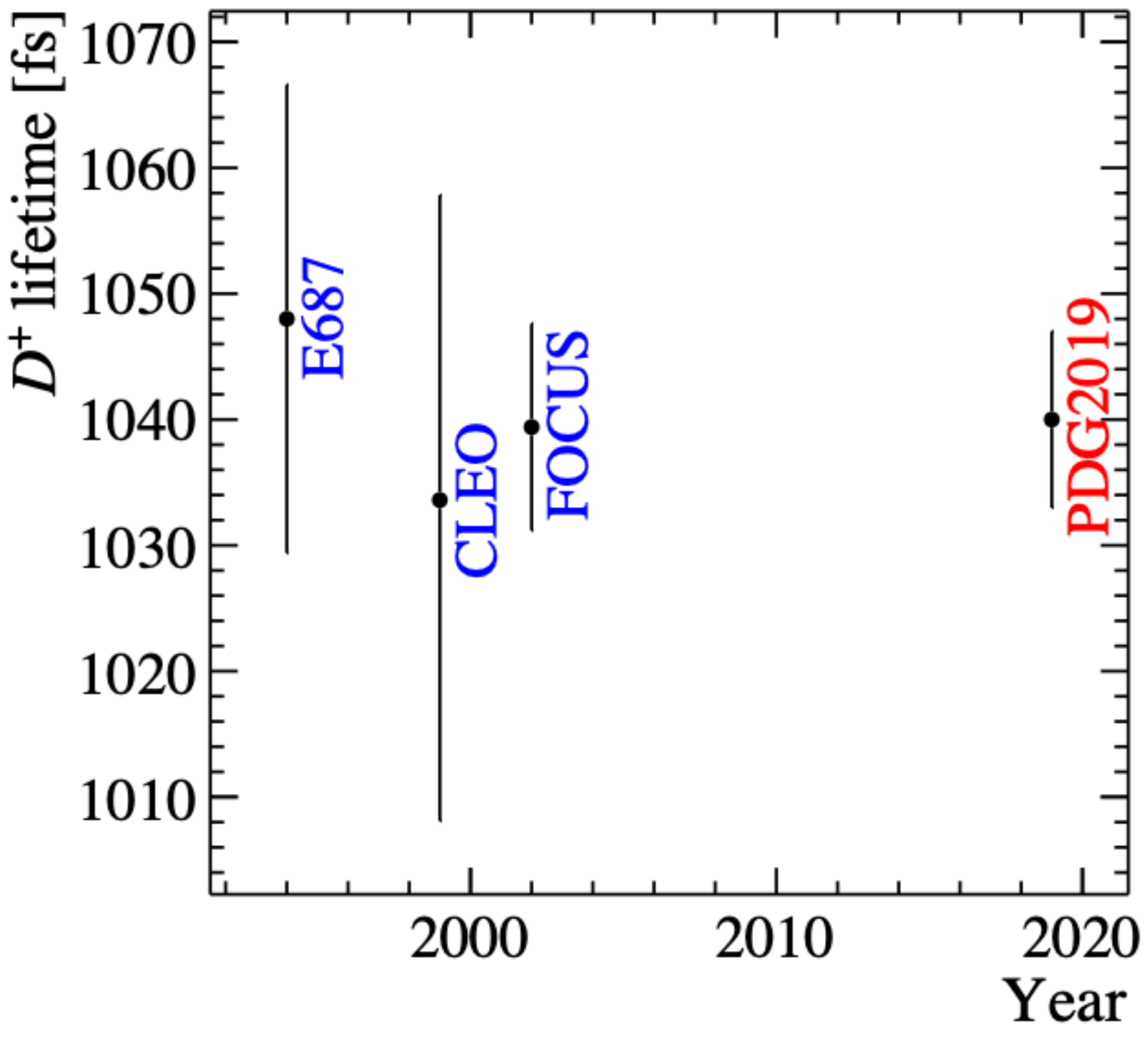
- D^0 and D^+ dominated by
  - FOCUS: photon beam experiment
  - SELEX: hyperon beam experiment
  - CLEO: the only e^+e^- measurements

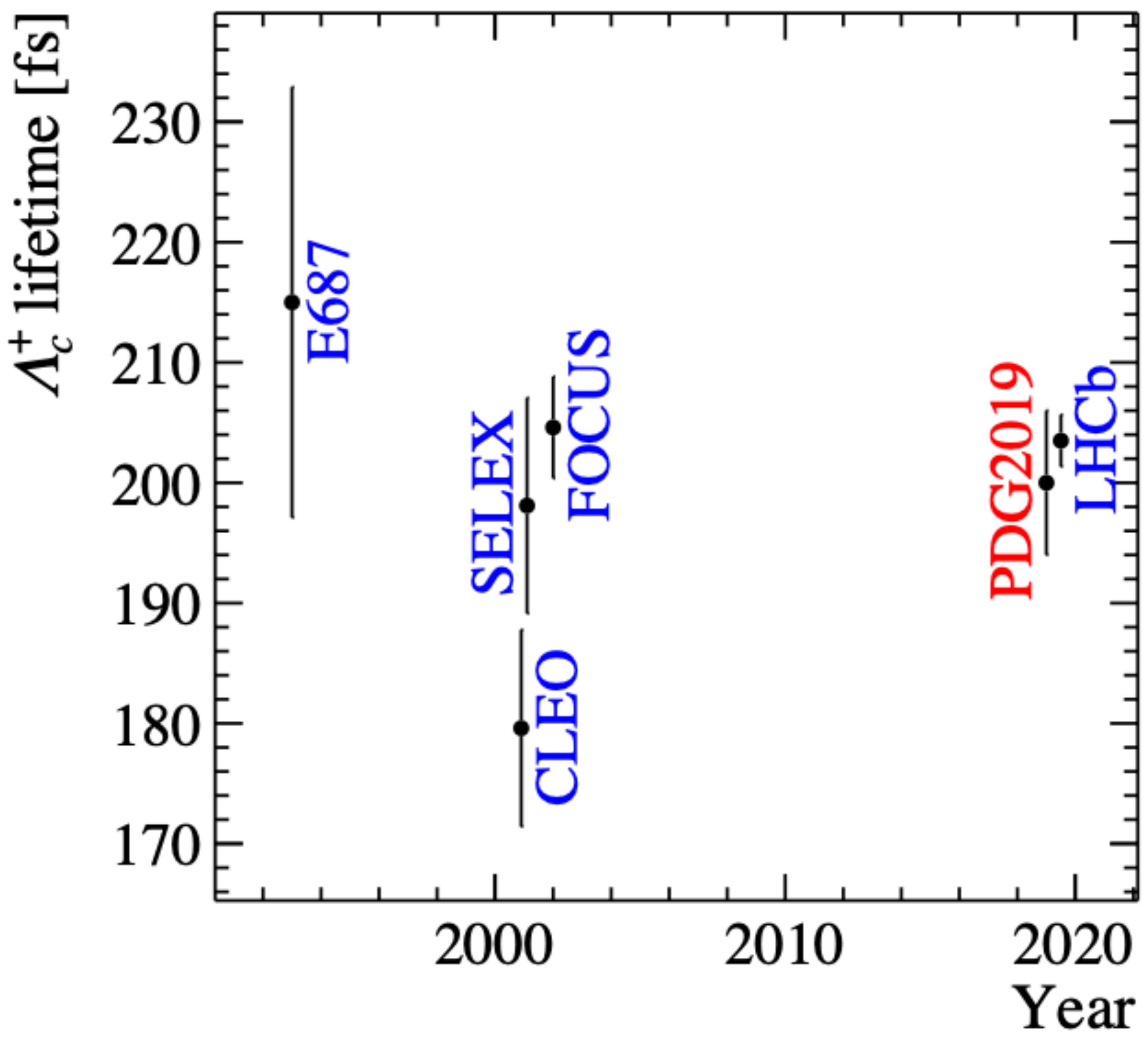
- Other charmed hadrons dominated by LHCb
  - All relative measurements with respect to D^+

$$\tau_{\Lambda_c^+} = 203.5 \pm 1.0 \text{ (stat)} \pm 1.3 \text{ (syst)} \pm 1.4 \ (\tau_{D^+})\ fs$$

LHCb - PRD 100 (2019) 032001

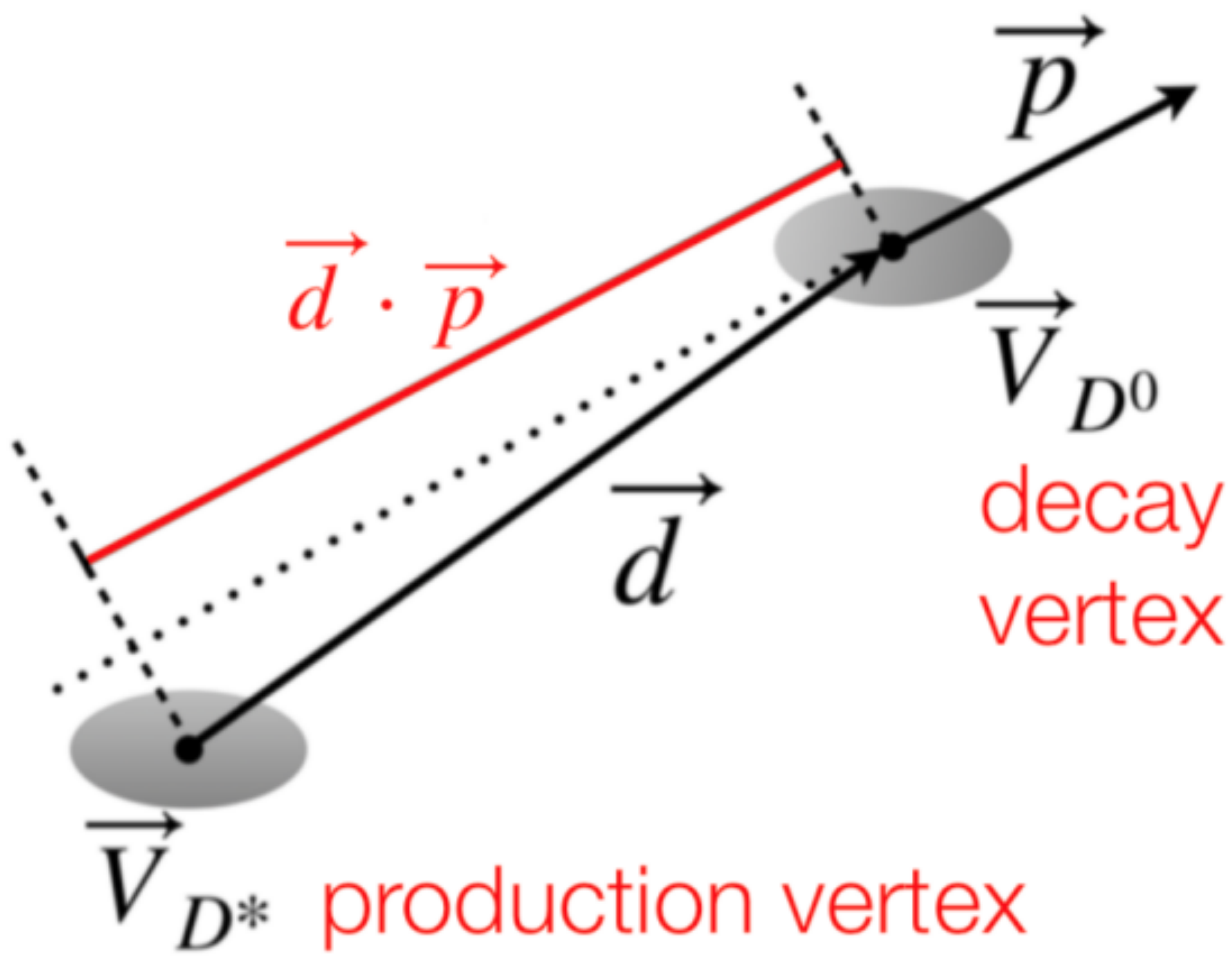




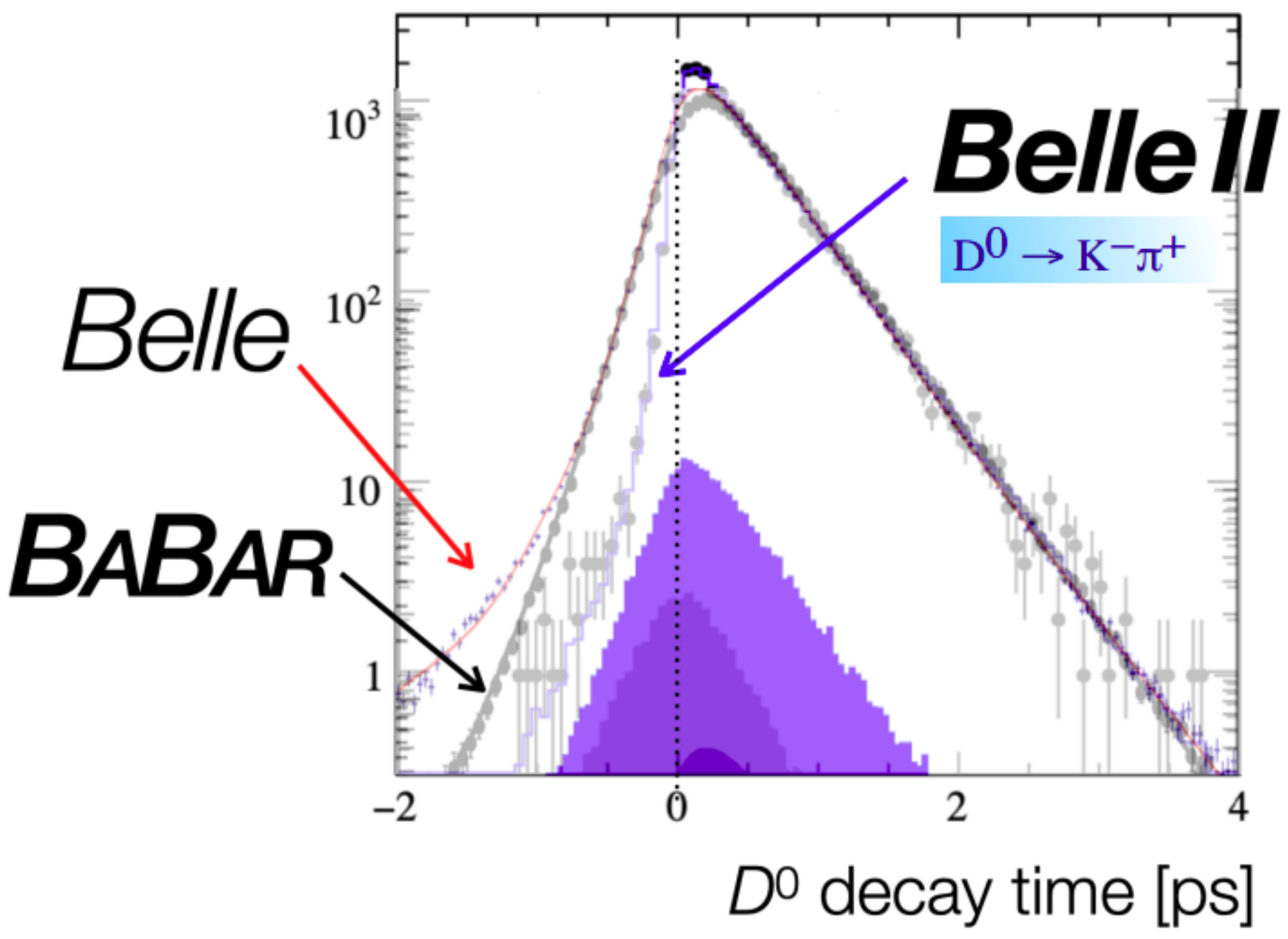


Precise lifetime measurements by Belle II

- Lifetimes calculated from distance between production and decay vertices
  - Decay times become negative due to resolution (tool to understand resolution)
  - High precision measurements probe beam spot and alignment calibration



$$t = \frac{m_D}{p}\left(\vec{d} \, . \, \hat{p}\right)$$



- Belle II can make precision, absolute lifetime measurements
  - Large samples of exclusive charm decays *without lifetime-biasing triggers and selections*
  - Precise calibration of final state particle momenta
  - Excellent vertex detector alignment
  - Very good vertex resolution, small beam size

Precise lifetime measurements by Belle II

Integrated luminosity goal: $50\ \mathrm{ab}^{-1}$

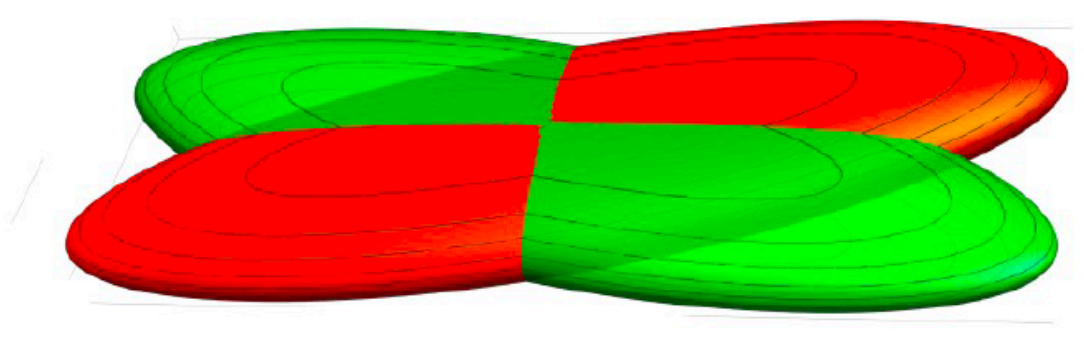
Target luminosity: $6.5 \times 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

June 22, 2022: $4.71 \times 10^{34}\ \mathrm{cm}^{-1}\ \mathrm{s}^{-1}$

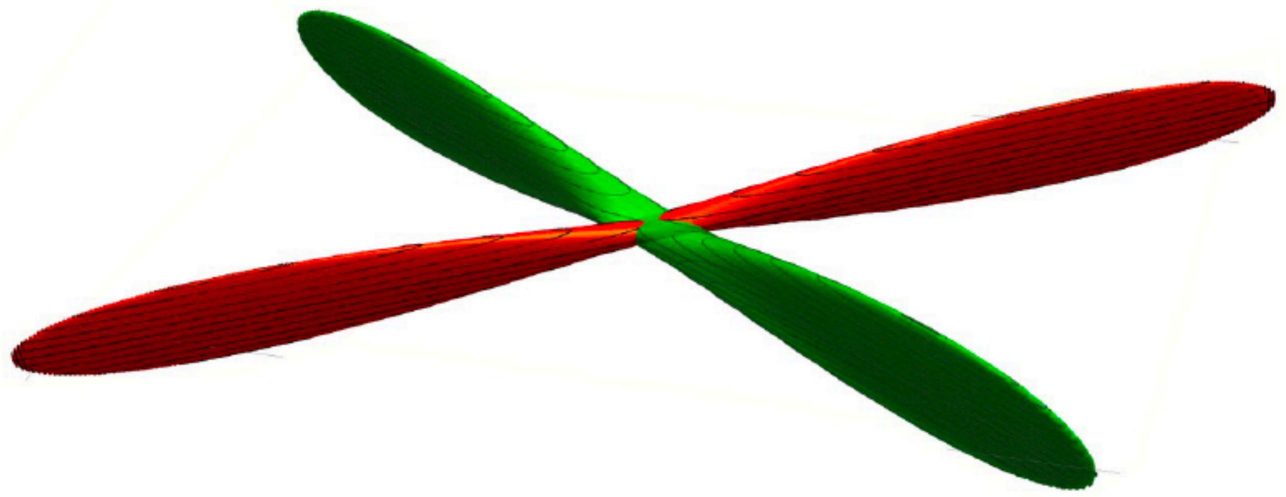
World record!

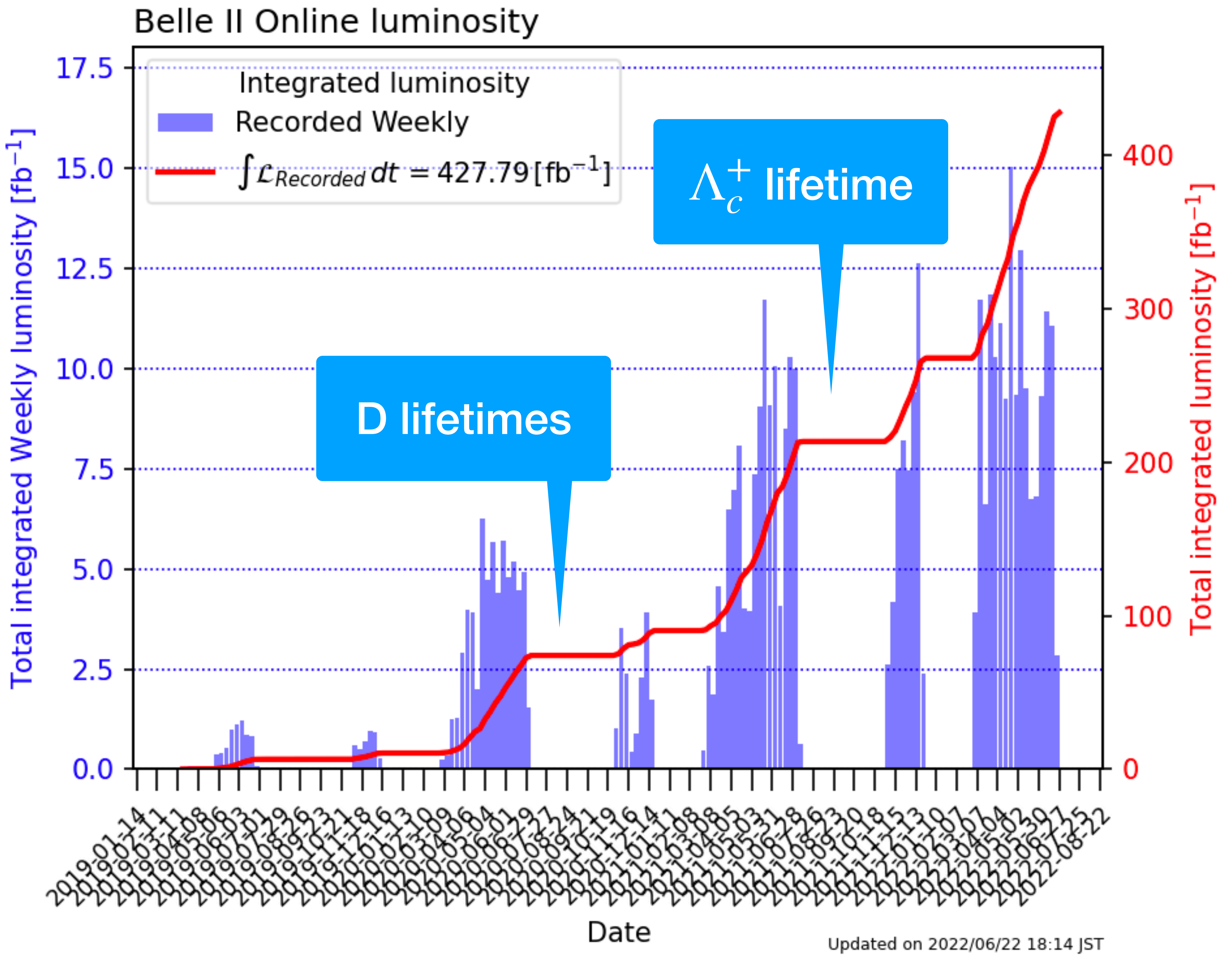
- High instantaneous luminosity via the "nano-beam" scheme
  - Small beam size better constrains event kinematics
  - Improved flight time resolution
- Beam spot calibrated continuously
  - Using $e^+e^- \to \mu^+\mu^-$ events

Belle



Belle II



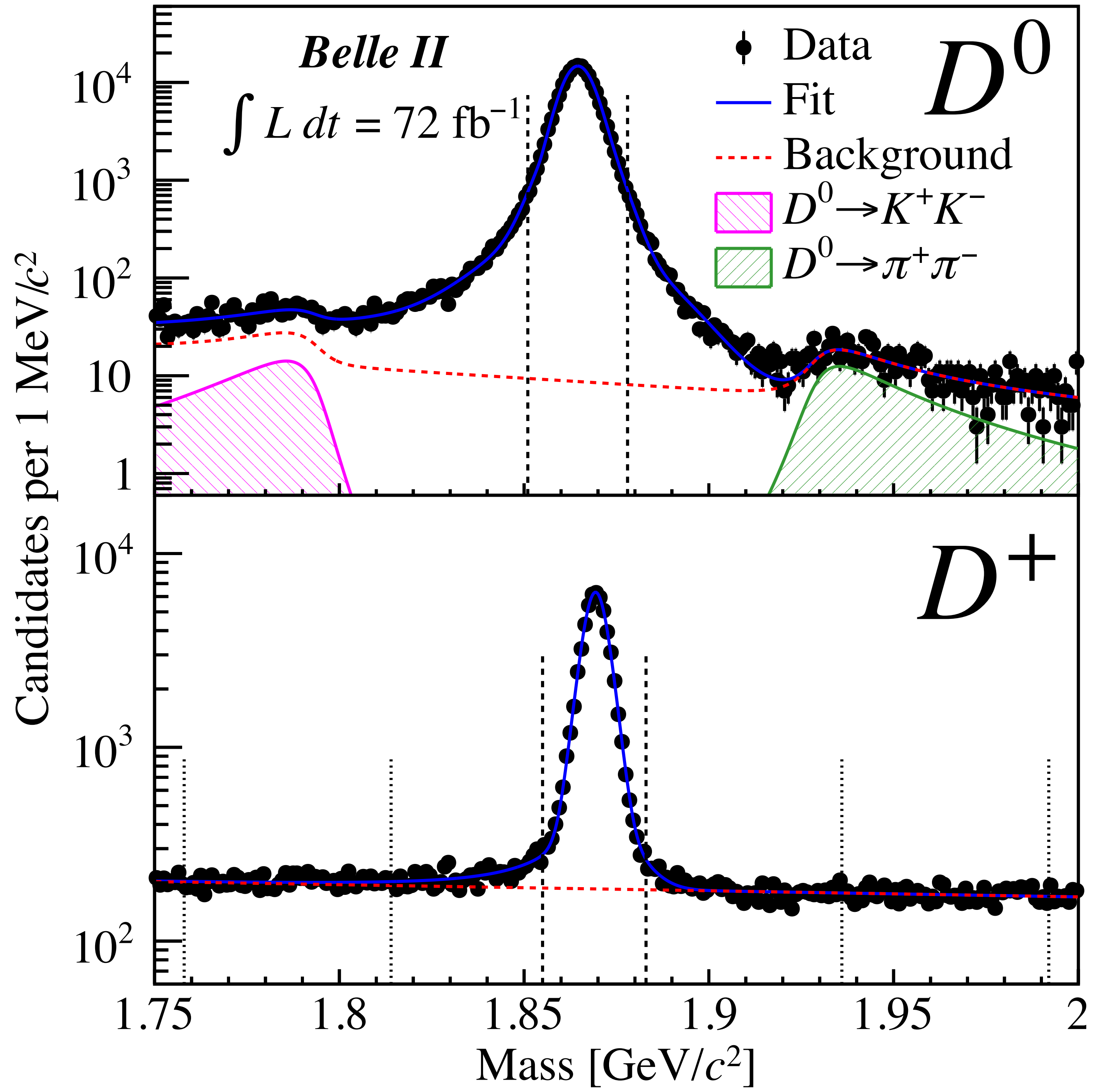


D^0 and D^+ measurements by Belle II

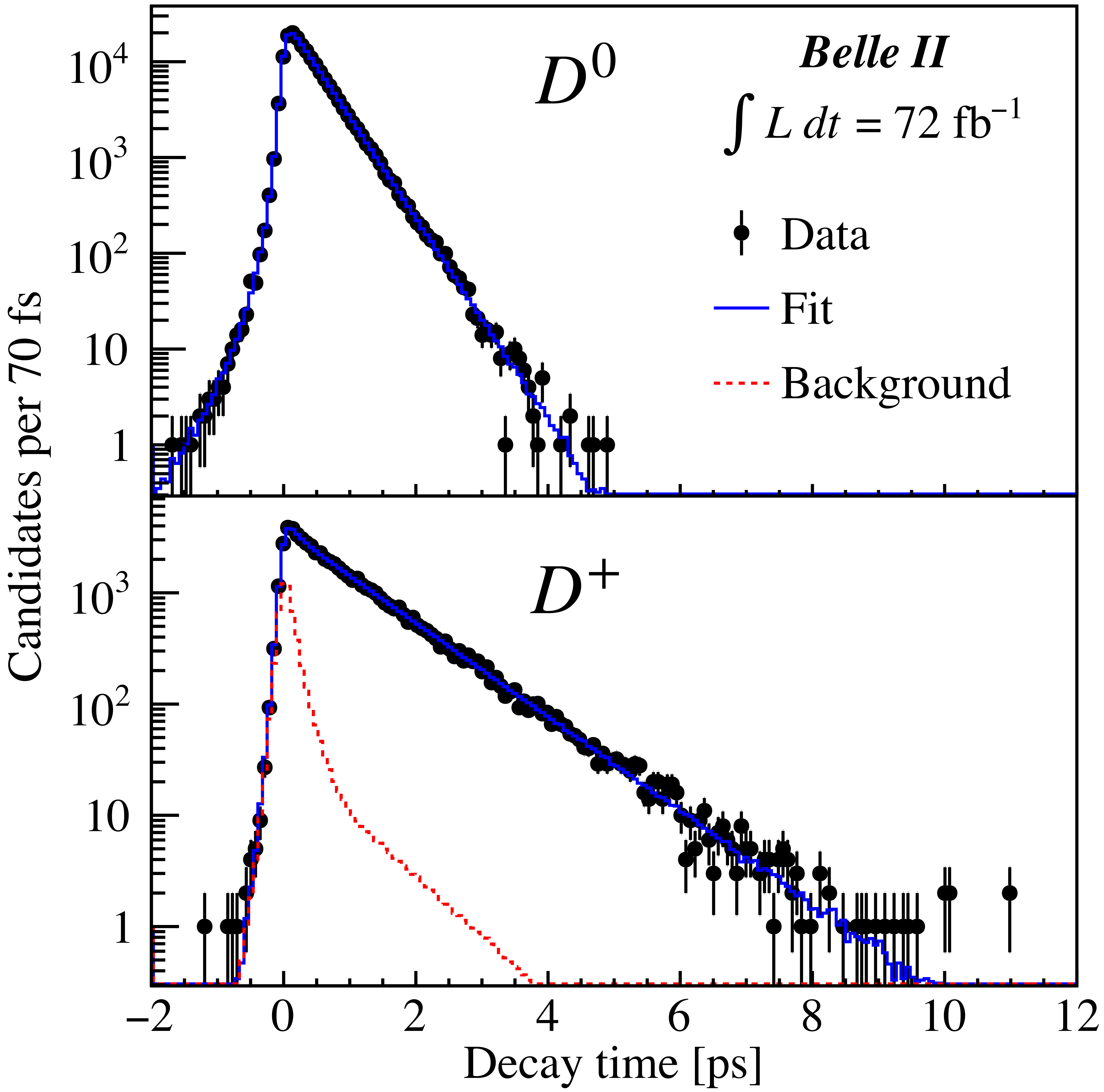
- Lifetime measured from an unbinned 2D fit to the (t, σ_t) distribution
  - Simultaneous fit to signal and sidebands
  - Background constrained from mass fit

Background neglected

9% backgrounds



Belle II - PRL 127 211801 (2021)



~70 ps resolution

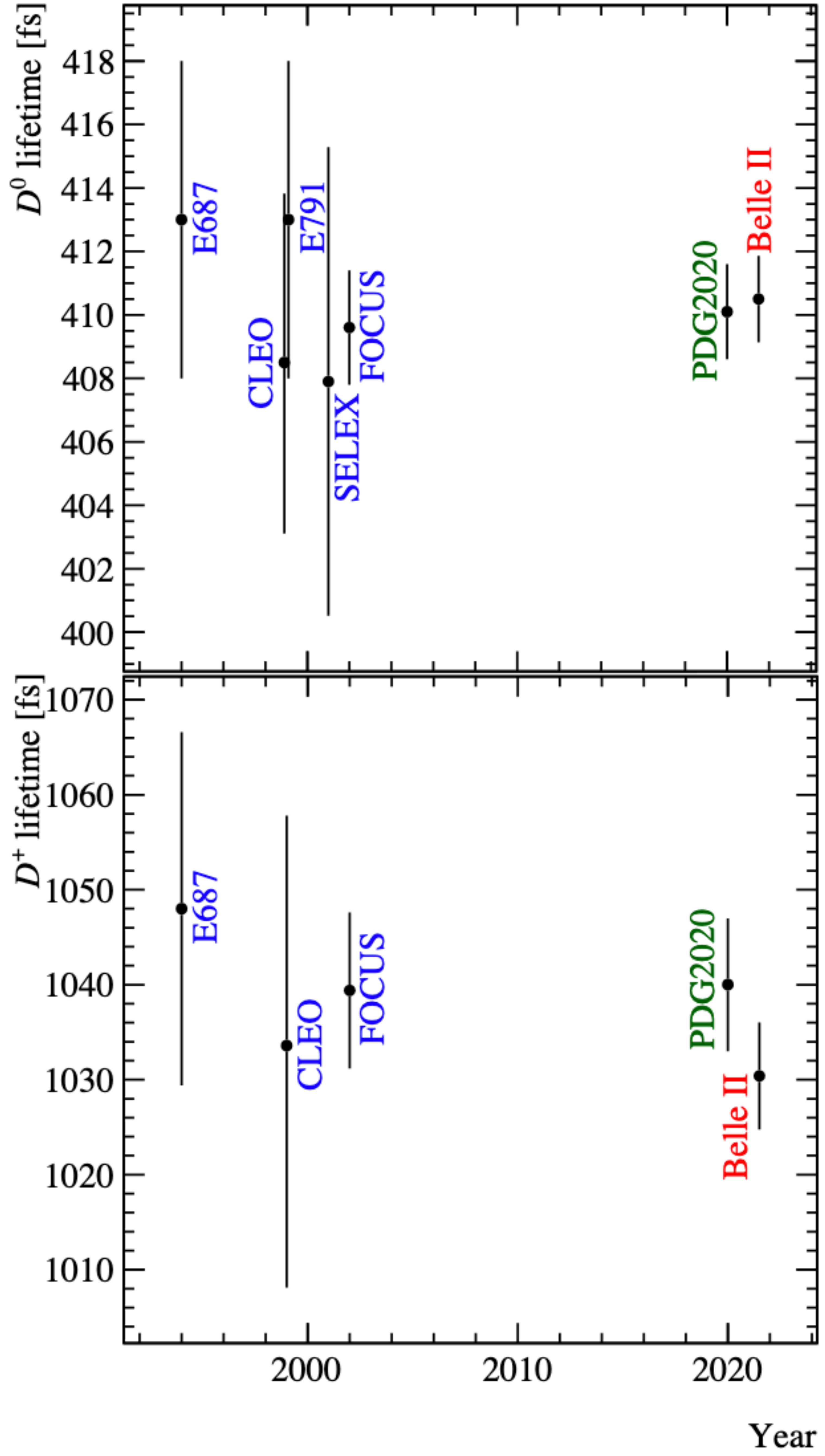
~60 ps resolution

D^0 and D^+ measurements by Belle II

$$\tau(D^0) = 410.5 \pm 1.1 \pm 0.8\,\text{fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1\,\text{fs}$$

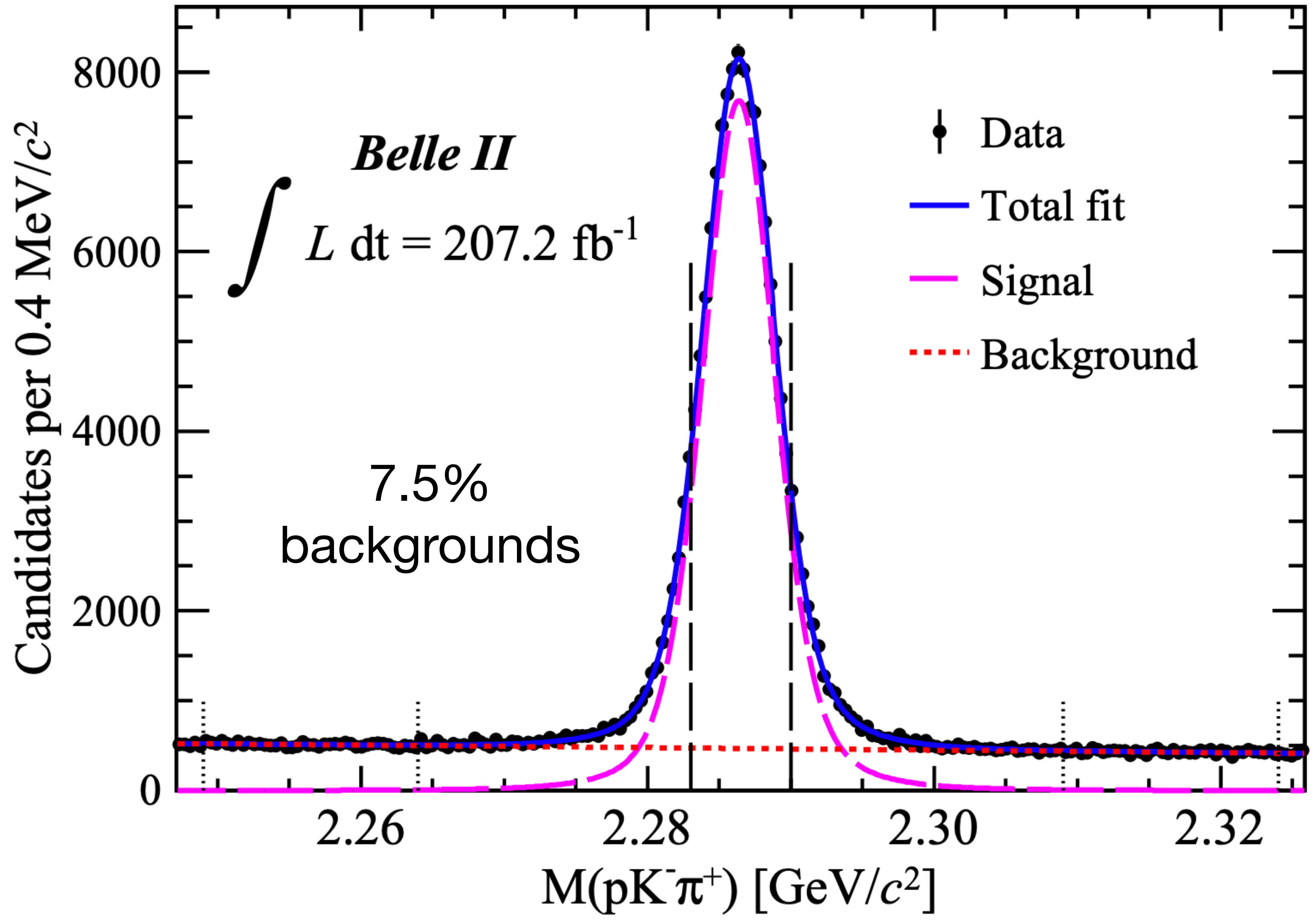
Source	$\tau(D^0)$ [fs]	$\tau(D^+)$ [fs]
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Total	0.80	3.10

- **World's best measurements of the D^0 and D^+ lifetimes**
  - Consistent with current world averages
  - Sub-1% accuracy establishes excellent detector performance
  - Paves the way for additional lifetime measurements

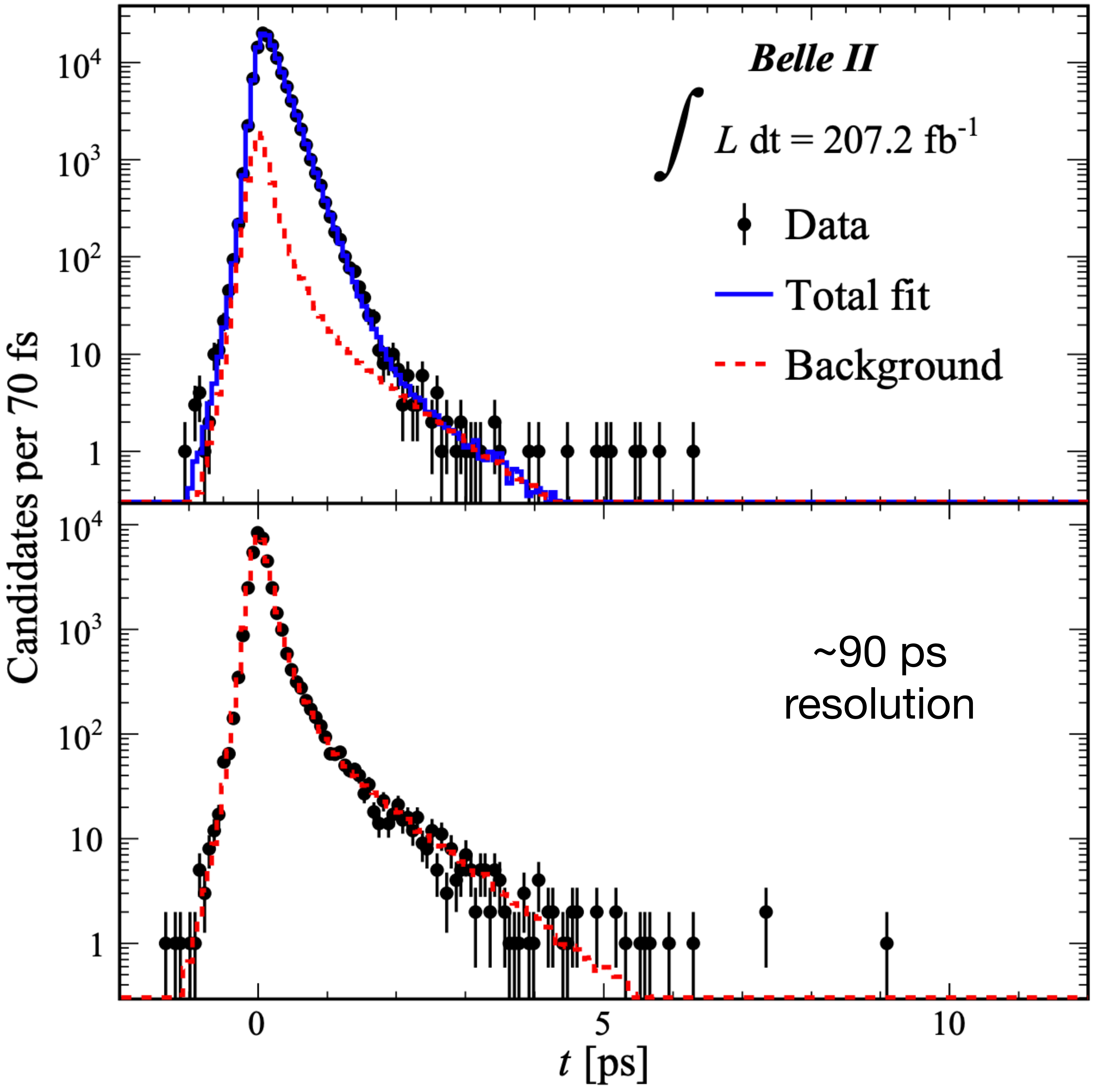


Λ_c^+ lifetime measurement at Belle II

- Relatively clean sample of $\Lambda_c^+ \to pK^-\pi^+$ events
  - Lifetime measured from a fit to the (t, σ_t) distribution
  - Reprocessing includes improved alignment calibration
  - Potential bias due to $\Xi_c^0 \to \Lambda_c^+\pi^-$ and $\Xi_c^+ \to \Lambda_c^+\pi^0$



Belle II - hep-ex/2206.15227, accepted at PRL



Ξ_c contamination

- Potentially problematic background from $\Xi_c^0 \to \Lambda_c^+\pi^-$ and $\Xi_c^+ \to \Lambda_c^+\pi^0$
  - Not accounted in previous Λ_c lifetime measurements
  - $BR(\Xi_c^0 \to \Lambda_c^+\pi^-) = 0.55 \pm 0.20\,\%$ (LHCb: PhysRevD.102.071101)
  - $BR(\Xi_c^+ \to \Lambda_c^+\pi^0) = 1.11\,\%$ (https://arxiv.org/pdf/2111.14111.pdf)

Lifetimes

$\tau(\Xi_c^0) = 153 \pm 6\ fs$

$\tau(\Xi_c^+) = 456 \pm 5\ fs$

No BF measurement (theory prediction made after LHCb measurement for $\Xi_c^0 \to \Lambda_c^+\pi^-$)

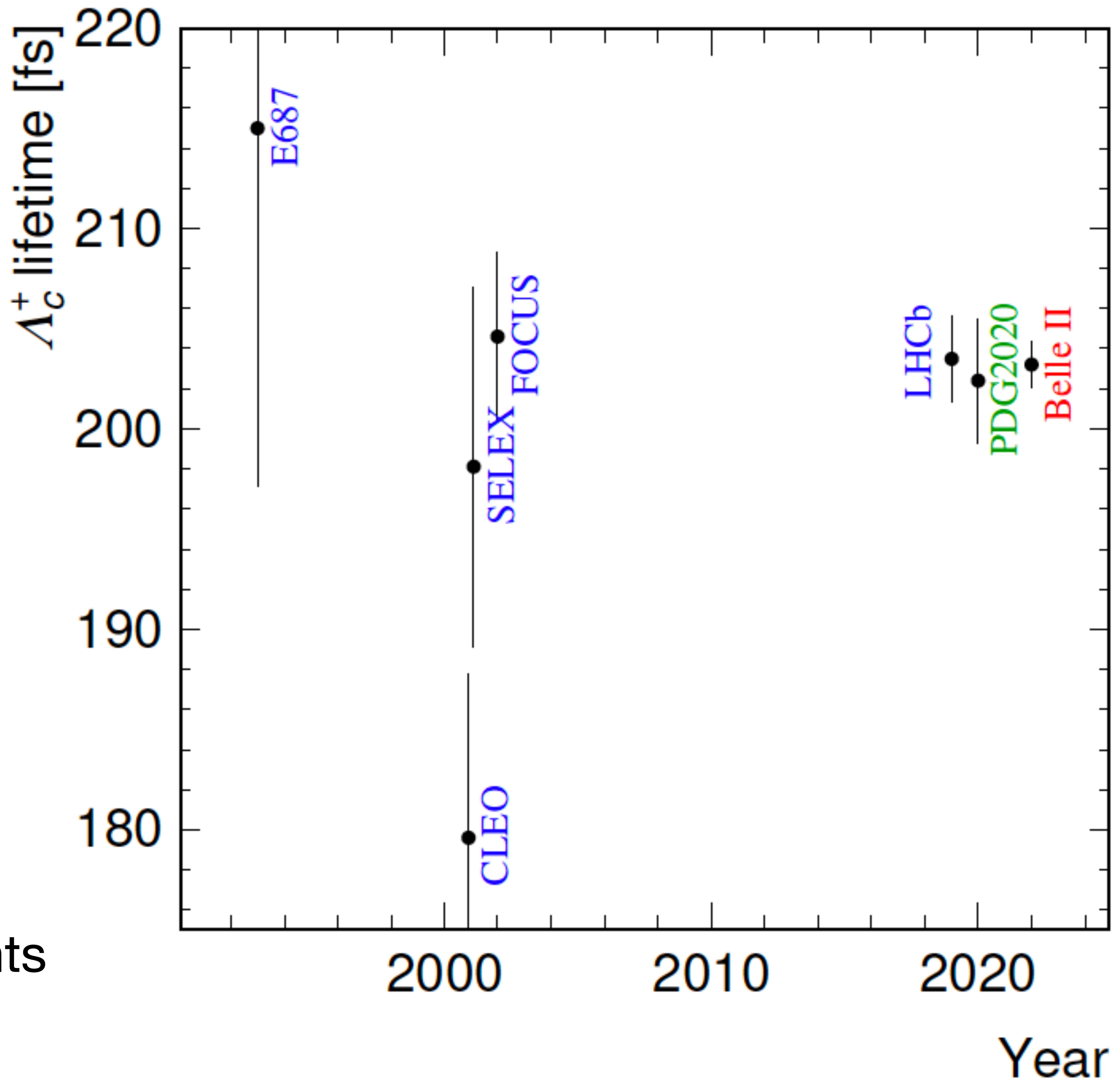
- Reduce backgrounds with veto and correct for remaining
  - Reject events with $M(\Lambda_c^+\pi^0) - M(\Lambda_c^+)$ within 2σ of expected value
  - Conservative estimate determined from fit to impact parameter for Λ_c^+
  - Mix signal events with generic MC to test potential remaining bias
  - Take half the shift as correction and systematic uncertainty

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

Λ_c^+ lifetime measurement at Belle II

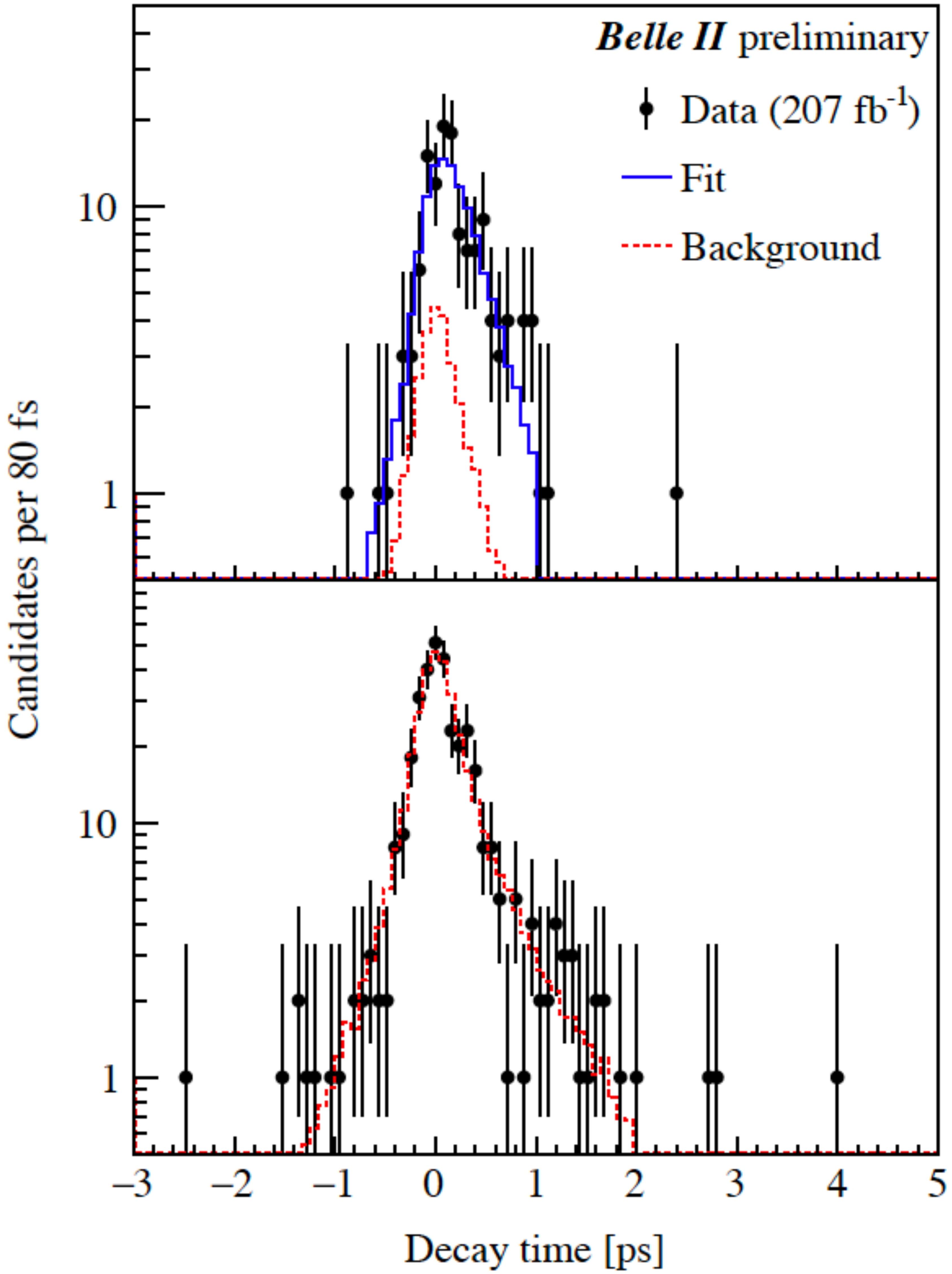
Experiment	Lifetime (fs)
This measurement	$203.20 \pm 0.89 \pm 0.77$
LHCb (2019)	$203.5 \pm 1.0 \pm 1.3 \pm 1.4$
FOCUS (2002)	$204.6 \pm 3.4 \pm 2.5$
SELEX (2001)	$198.1 \pm 7.0 \pm 5.6$
CLEO (2001)	$179.6 \pm 6.9 \pm 4.4$

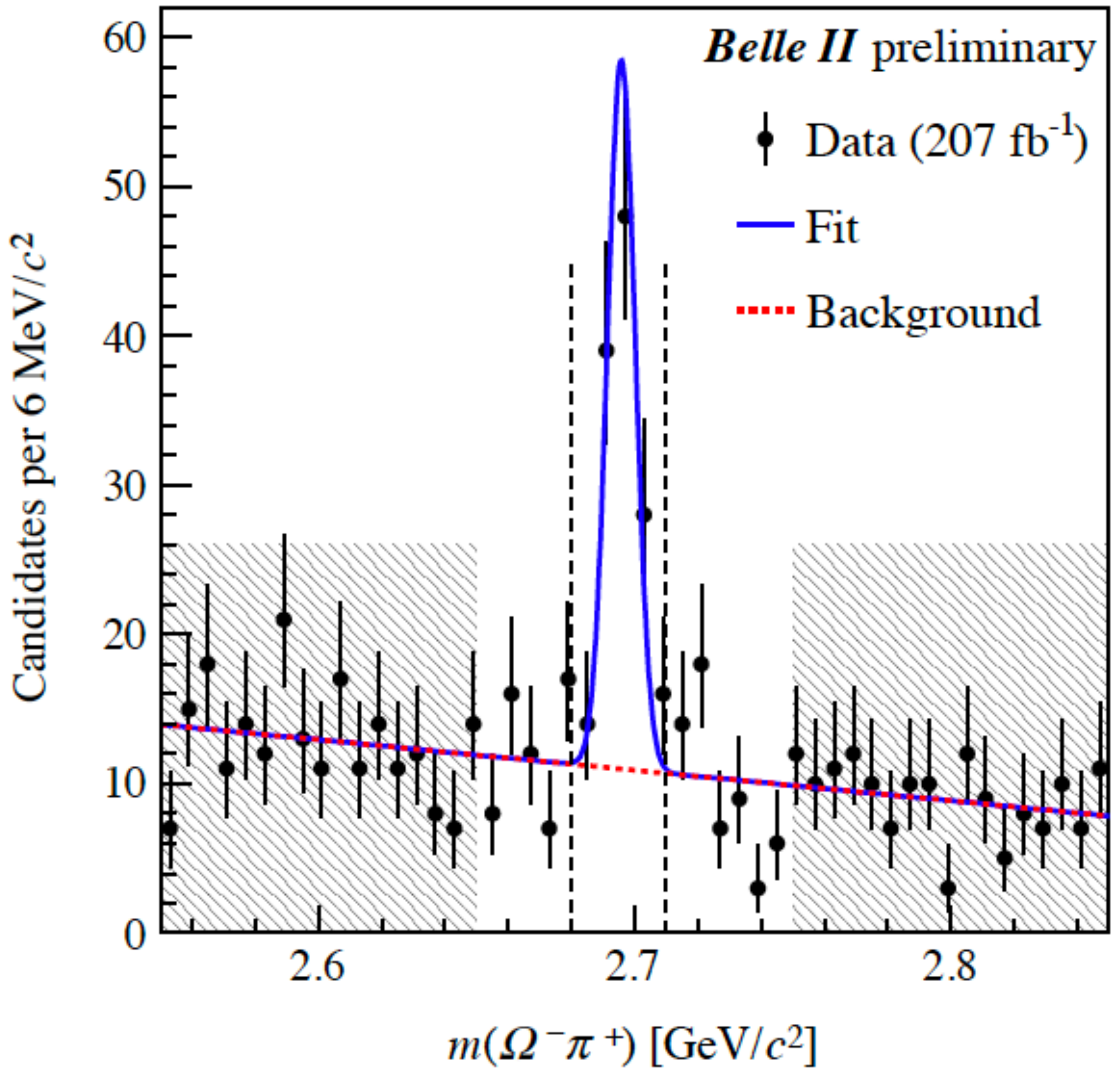
- **World's best measurements of the Λ_c^+ lifetime**
  - Consistent with current world averages
  - Slight tension with CLEO measurement remains
  - Benchmark for future baryon lifetime measurements



Measurement of the Ω_c lifetime at Belle II

Belle II - hep-ex/2208.08573, accepted at PRD(L)





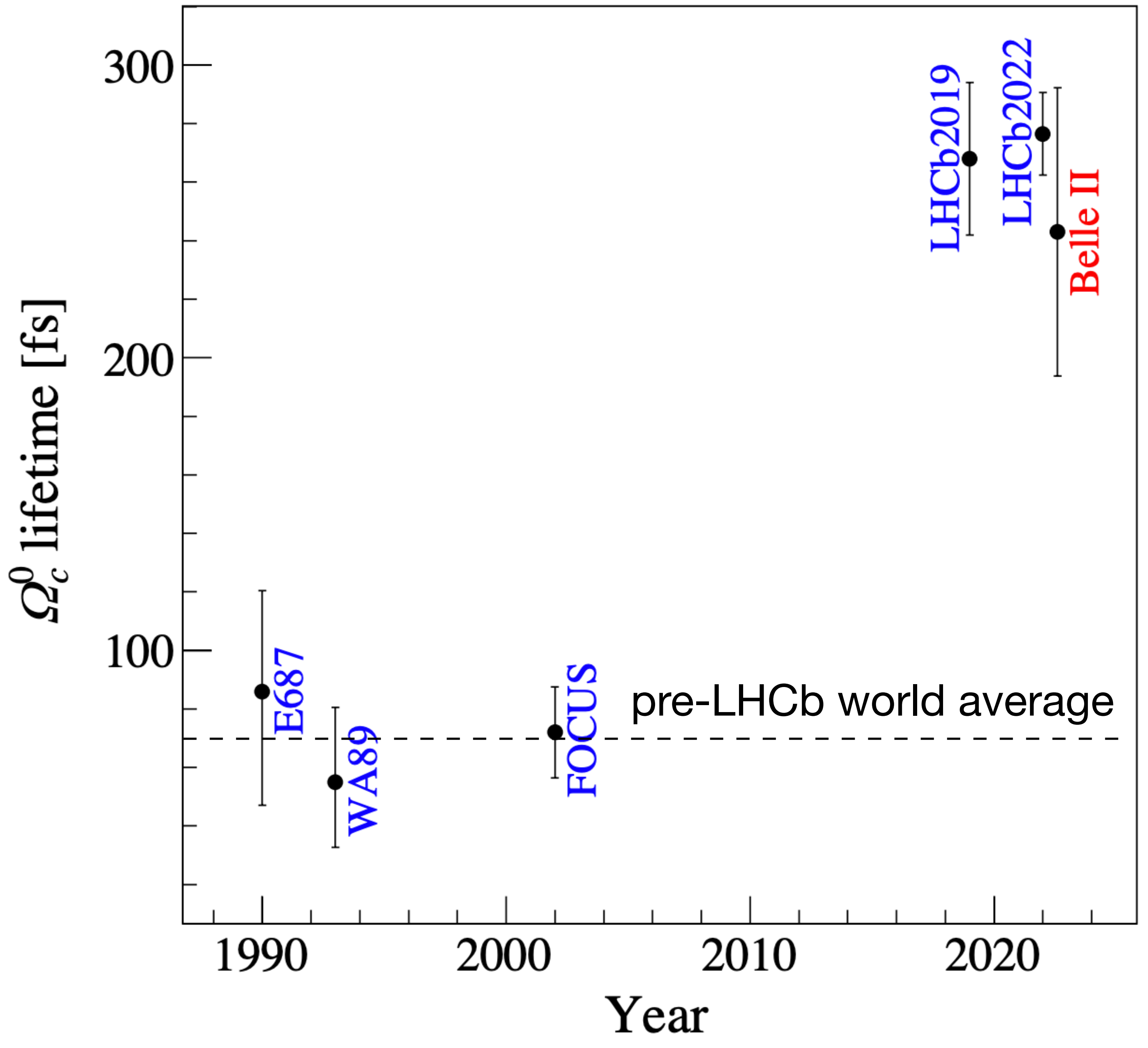
Belle II result:

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

Consistent with LHCb average of

$$274.5 \pm 12.4\ \text{fs}$$

- Inconsistent at 3.4σ with the pre-LHCb world average, $69 \pm 12\ \text{fs}$
  - confirmation that the Ω_c^0 is NOT the shortest lived charm baryon



Summary

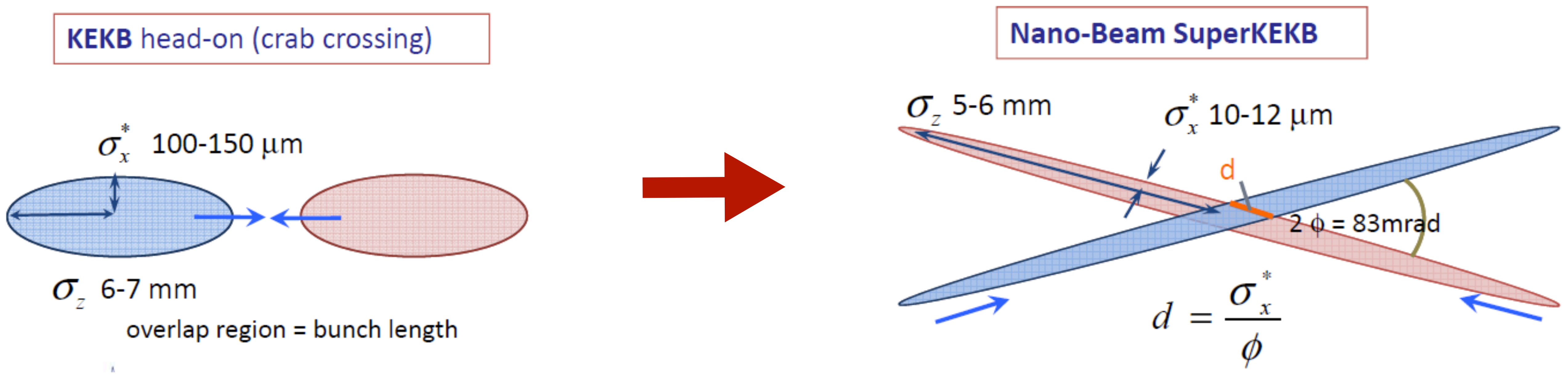
- Major upgrade at KEK for the next generation B-factory
  - Many detector components and electronics replaced, software and analysis tools also improved!
  - Rich physics program, complementary to existing experiments and the energy frontier program
  - Even with early data, excellent performance and good understanding of the Belle II detector

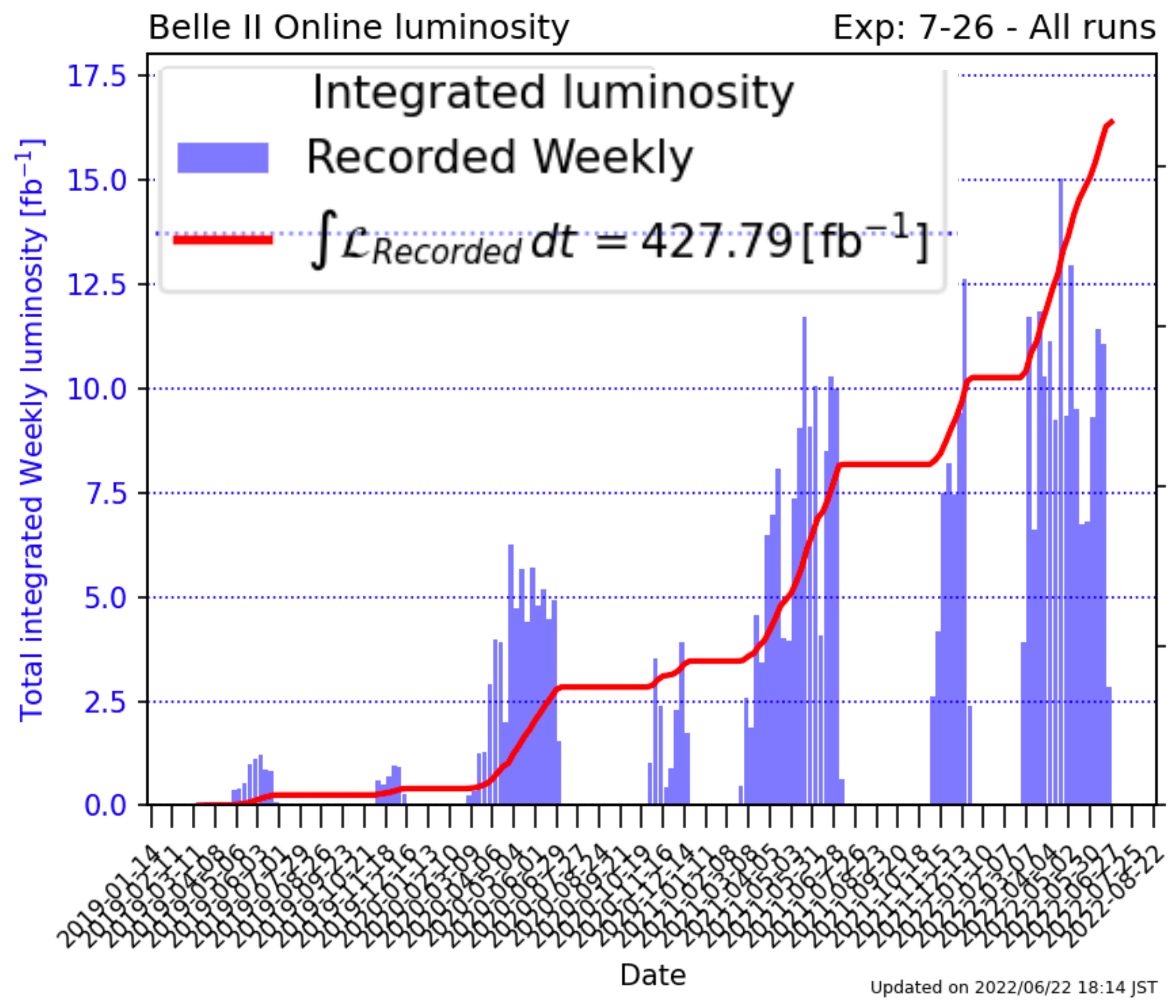
- **First high-precision results are here!**
  - q^2 **moments in** $B \to X_c \ell \nu$ **with comparable precision to Belle, but much smaller sample**
  - **World's best D lifetimes, establishes excellent vertexing**
  - **World's best** Λ_c **lifetime, benchmark for future baryon lifetimes**
  - **Confirmation that the** Ω_c^0 **is NOT the shortest lived charm baryon**

- Only 0.5% of target integrated luminosity collected so far - much more to come!

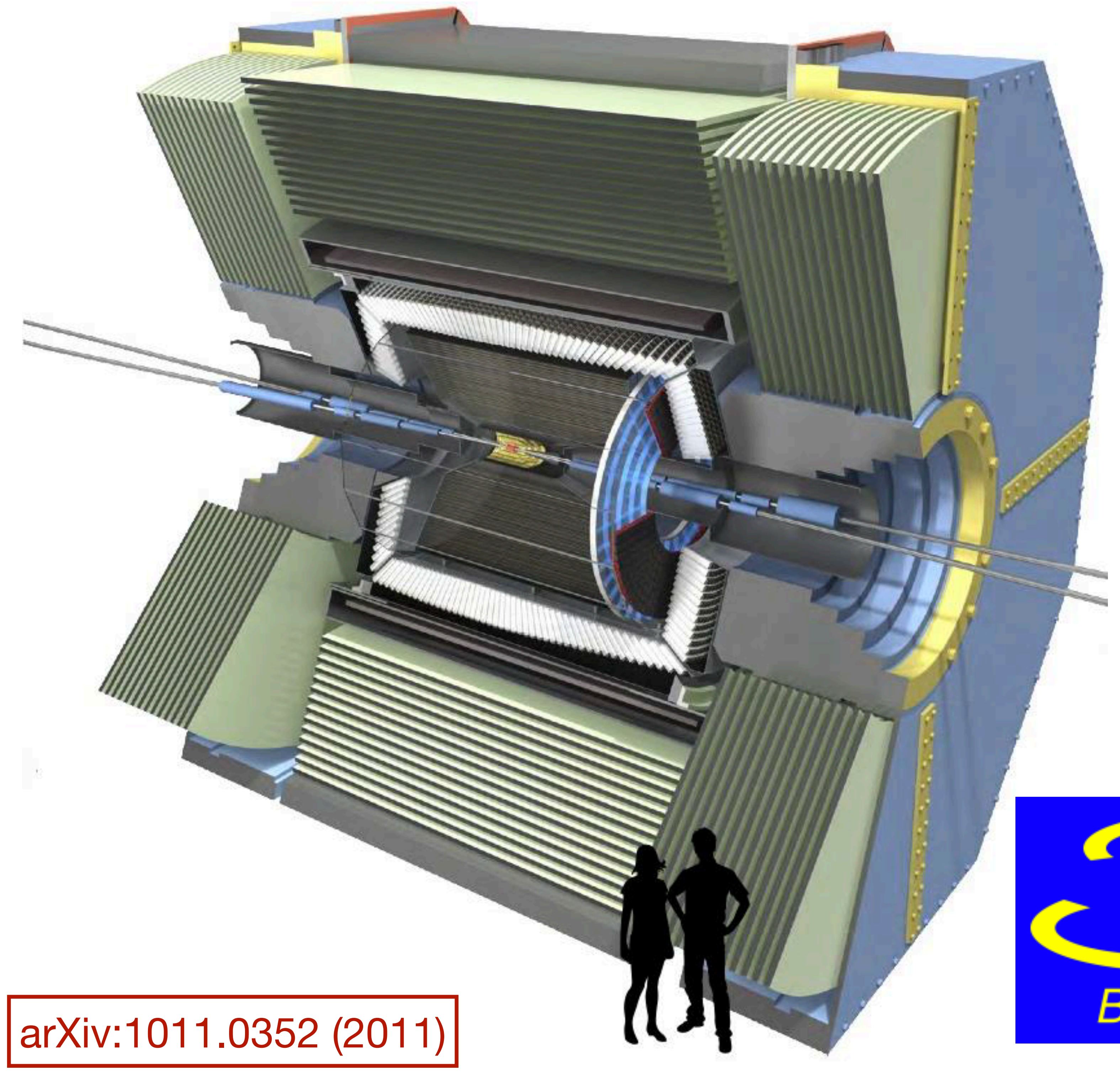
Extra

Belle II capabilities





- Advantages for quarkonium physics program
  - World record instantaneous luminosity (aiming for 50x Belle integrated luminosity)
  - High resolution, hermetic detector, good PID capability
  - Efficient reconstruction of neutrals (π^0, η, ...)
  - Reconstruct single resonance to explore recoiling system (e.g. $e^+e^- \to J/\psi\ X$)
  - Using tagged events (i.e. with a fully reconstructed partner B) to measure absolute branching fractions
  - Variety of production mechanisms accessible

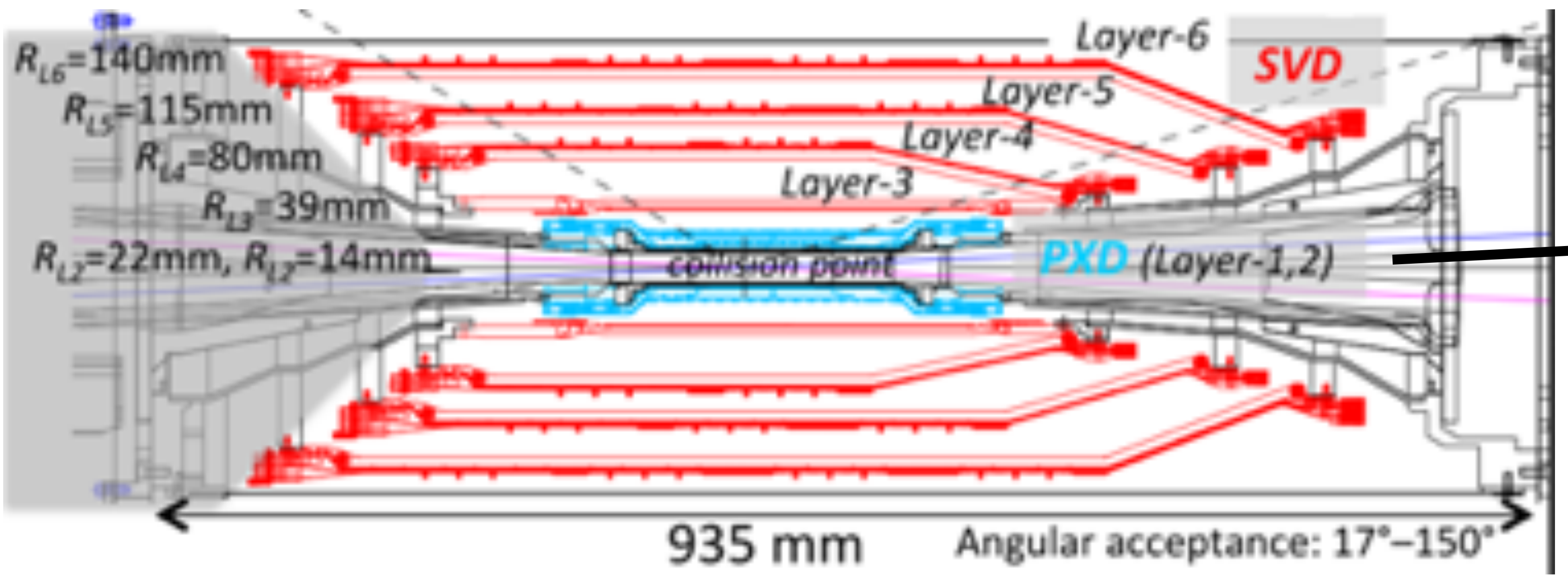


arXiv:1011.0352 (2011)

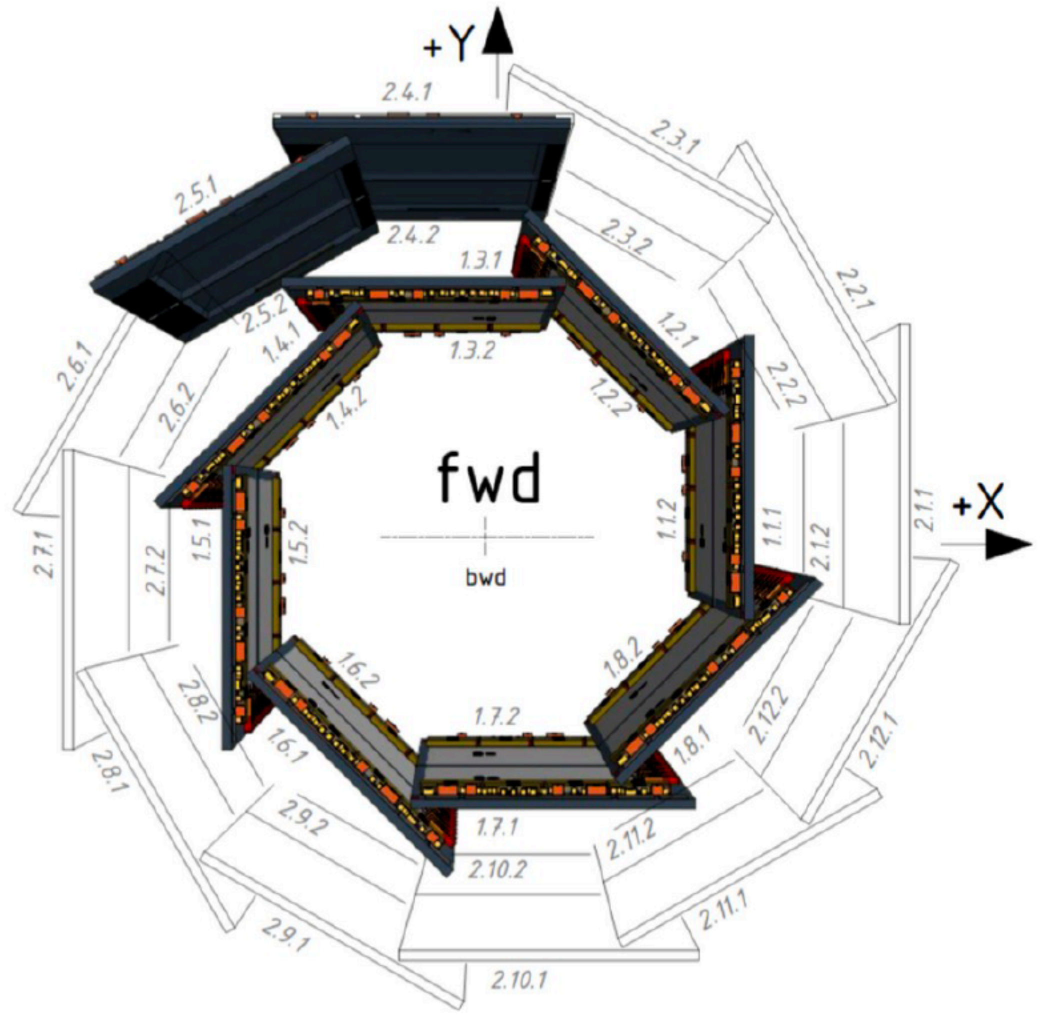
Belle II

Precise lifetime measurements by Belle II

- Upgraded vertex detector
  - More robust tracking
  - Better vertex resolution

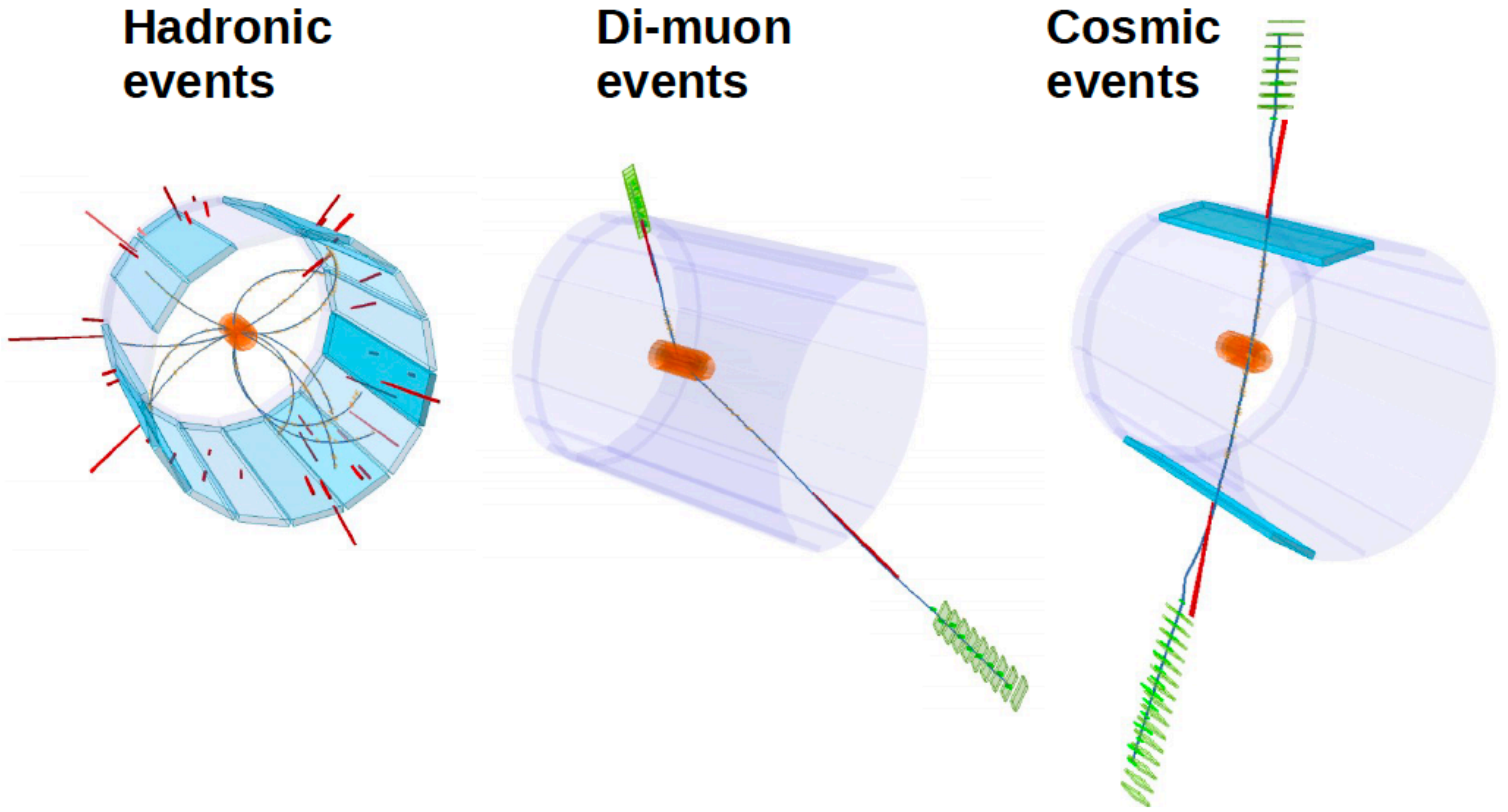


Silicon Vertex Detector (SVD)

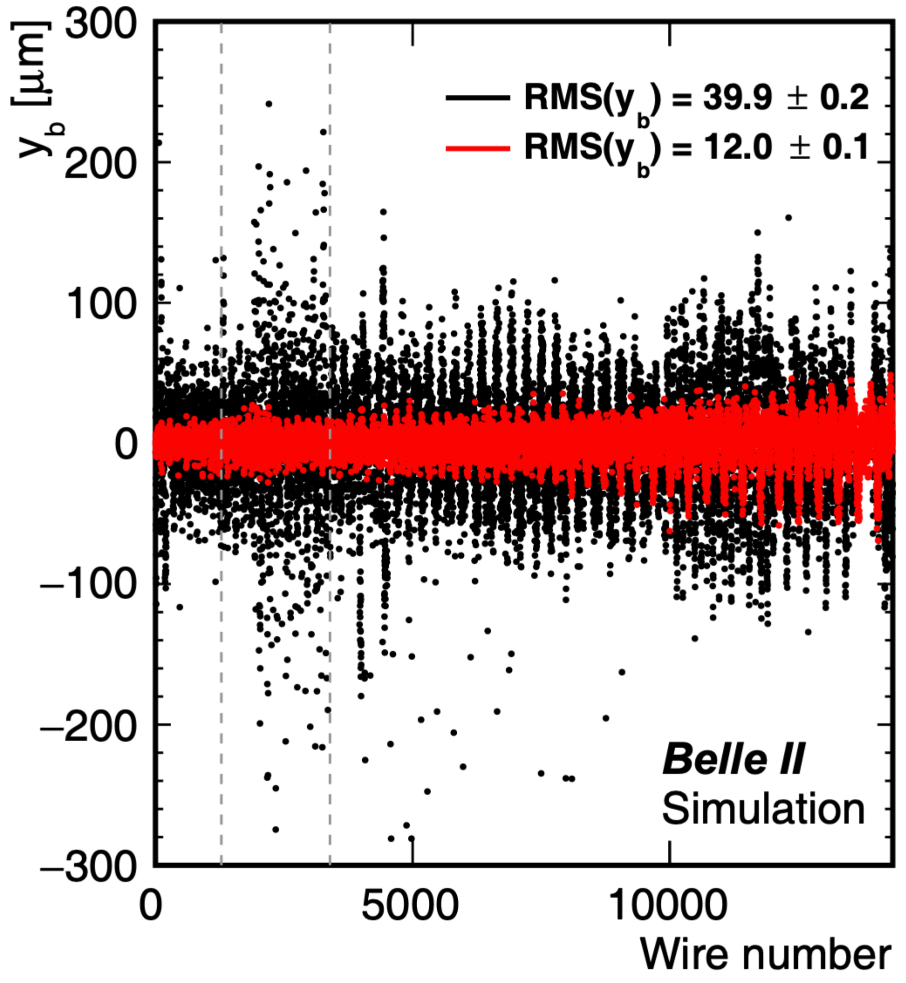


Pixel Detector (PXD)

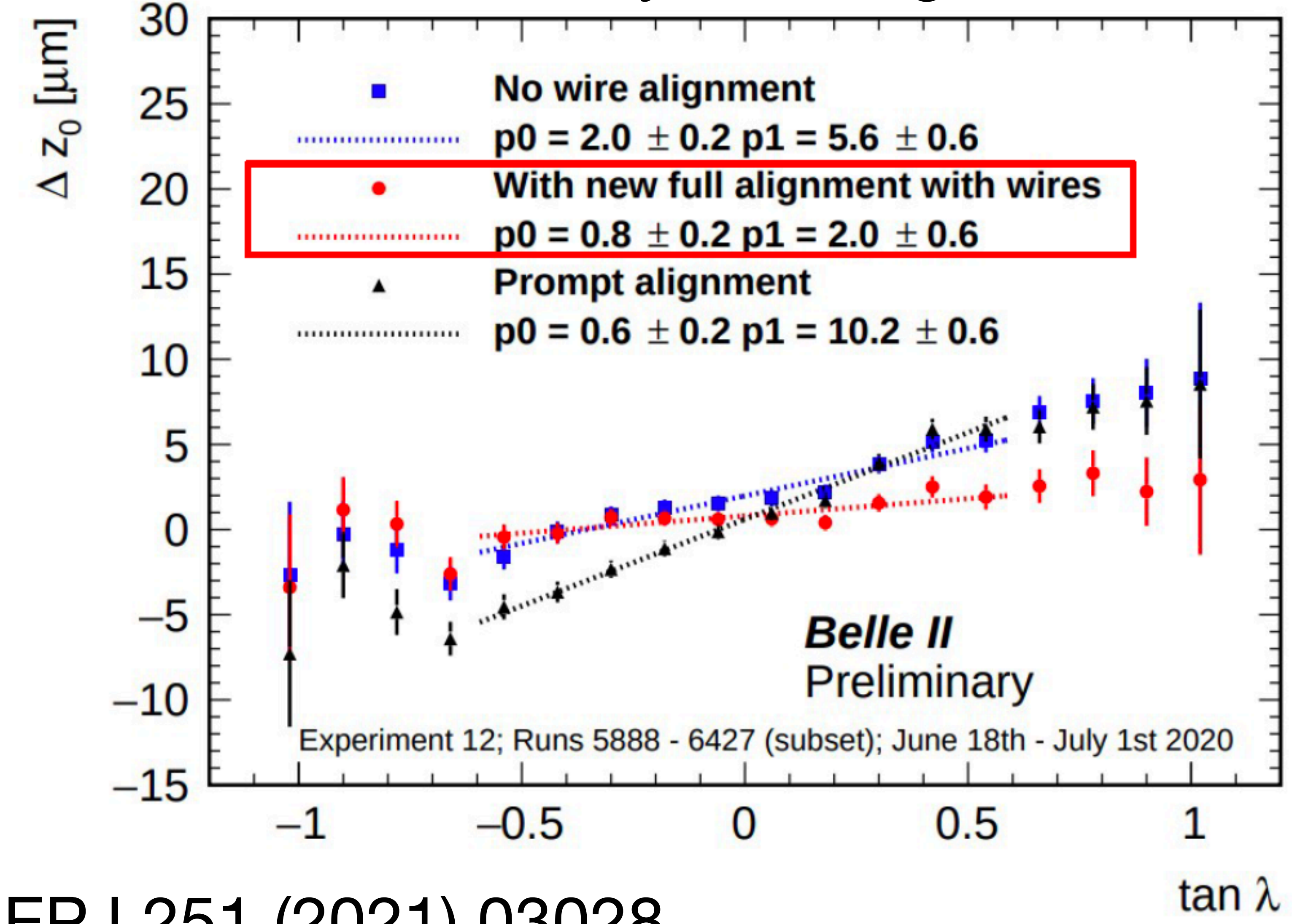
- Precise alignment crucial for precision measurements
  - Includes all 14336 wires in central drift chamber (60,000 parameters)



Realistic misalignment



Cosmic ray data alignment



CHEP2021: EPJ 251 (2021) 03028