Hot Topics at *Belle II*

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On Behalf of the Belle II Collaboration

Brookhaven Forum 2021
November 3, 2021

Belle II @ Super-KEKB

Intensity Frontier Flavor Factory Experiment
@ World's Highest-Luminosity Electron Positron Collider

KEK Tsukuba Campus

Successor to Belle at KEKB (1999-2010)

Belle II

e^- e^+

1 km

7 GeV e^- 4 GeV e^+

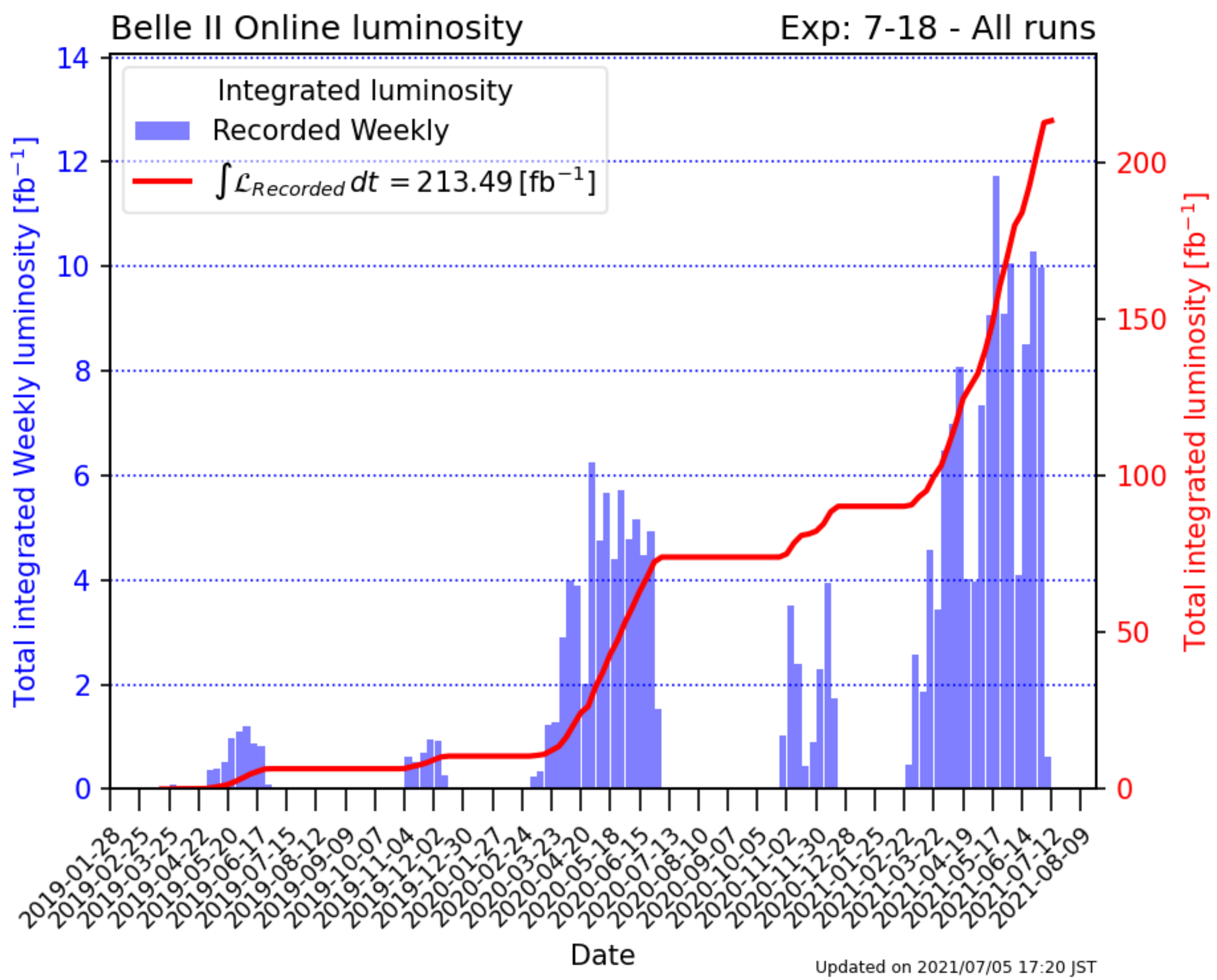
E_{CM} $\Upsilon(4S)$ = 10.58 GeV + scans

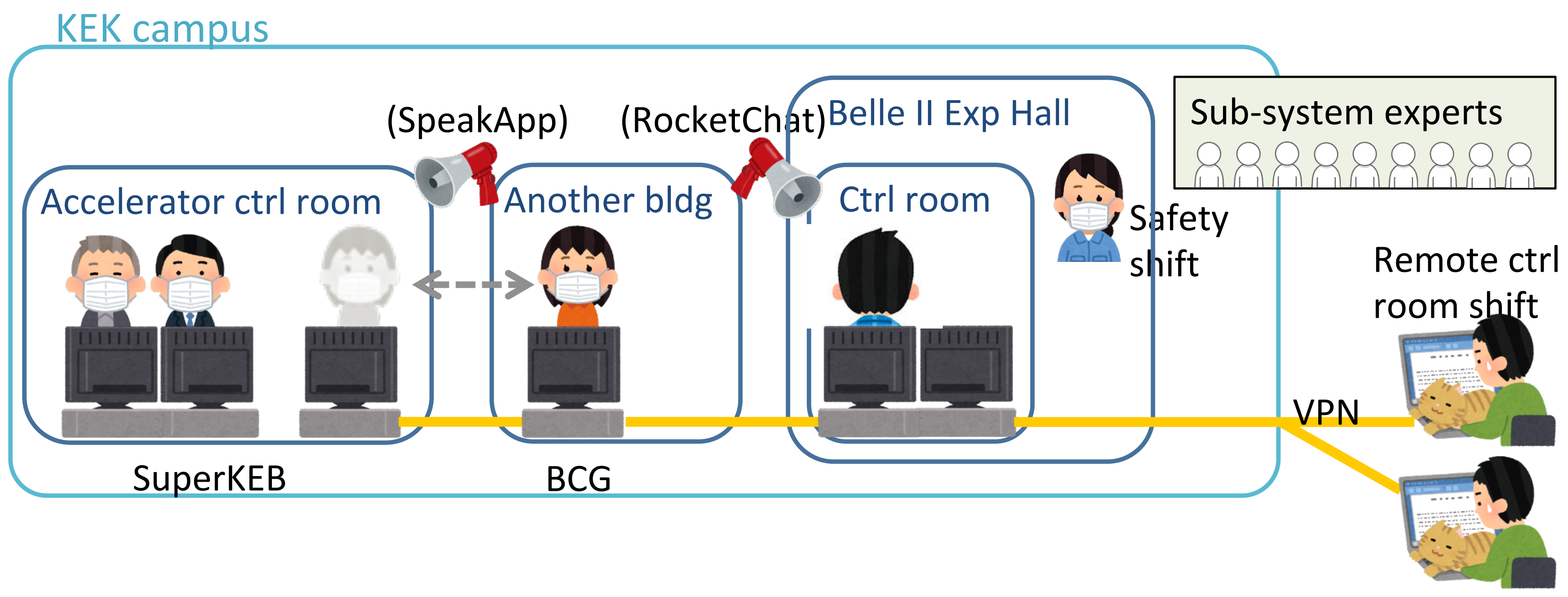
$\Upsilon(4S) \rightarrow B\bar{B}$

B + Charm + τ Factory

- **Low-background production of $\mathcal{O}$(100-1000) B/D/τ per second.**
- **Kinematic constraints from e^+e^- production: unique precision in final states with multiple π^0's or ν's.**

Belle II Data

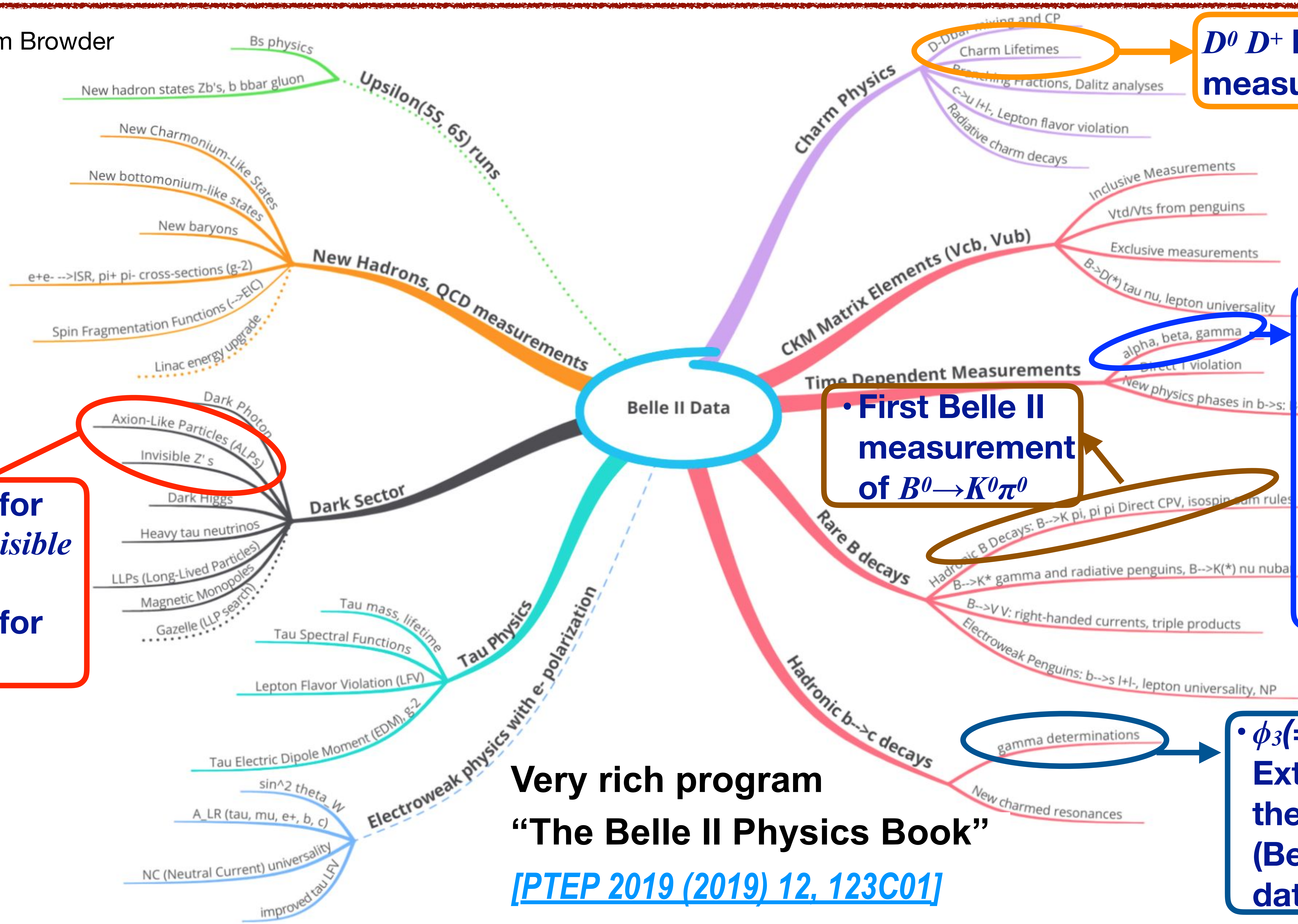




- As of today our recorded luminosity: ~213 fb^{-1} .
- Successful data taking throughout the pandemic.
- Record instantaneous luminosity **3.12×10^{34} $cm^{-2}s^{-1}$**.
- Data taking efficiency 89.5%
- Results use up to ~128 fb^{-1}.

Outline

Courtesy Tom Browder



D^0 D^+ **lifetime measurements**

- **First Belle II Measurements of $B \to J/\psi K_L$ and $B \to \eta' K$**
- **Towards (ϕ_2/α) :** $B^0 \to \pi^0\pi^0$, $B^+ \to \rho^+\rho^0$

- **First Belle II measurement of $B^0 \to K^0\pi^0$**

- **Search for $Z' \to invisible$**
- **Search for ALPs**

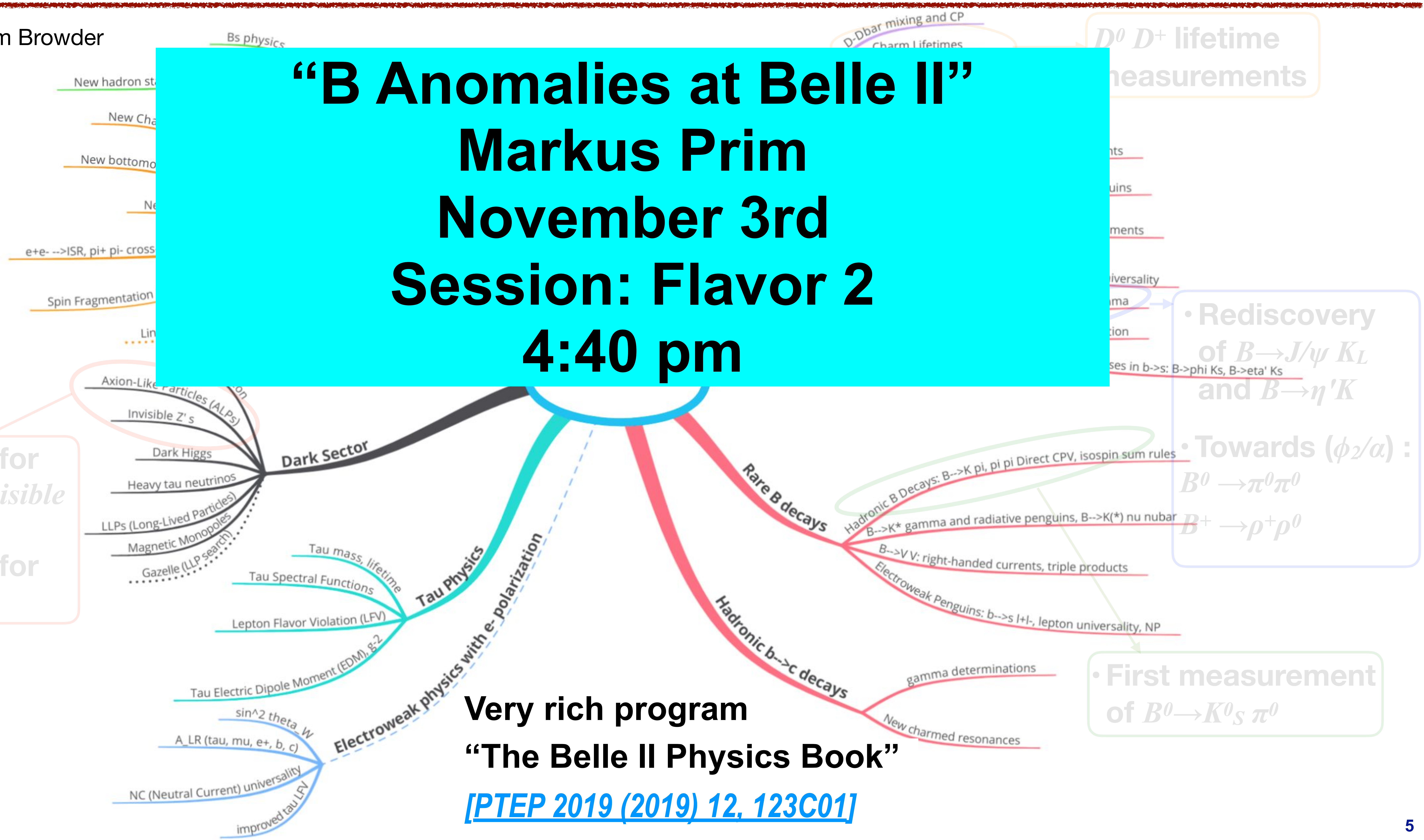
- **$\phi_3(=\gamma)$ Extraction on the Combined (Belle+Belle II) dataset**

Very rich program

"The Belle II Physics Book"

[PTEP 2019 (2019) 12, 123C01]

Courtesy Tom Browder



"B Anomalies at Belle II"
Markus Prim
November 3rd
Session: Flavor 2
4:40 pm

Very rich program

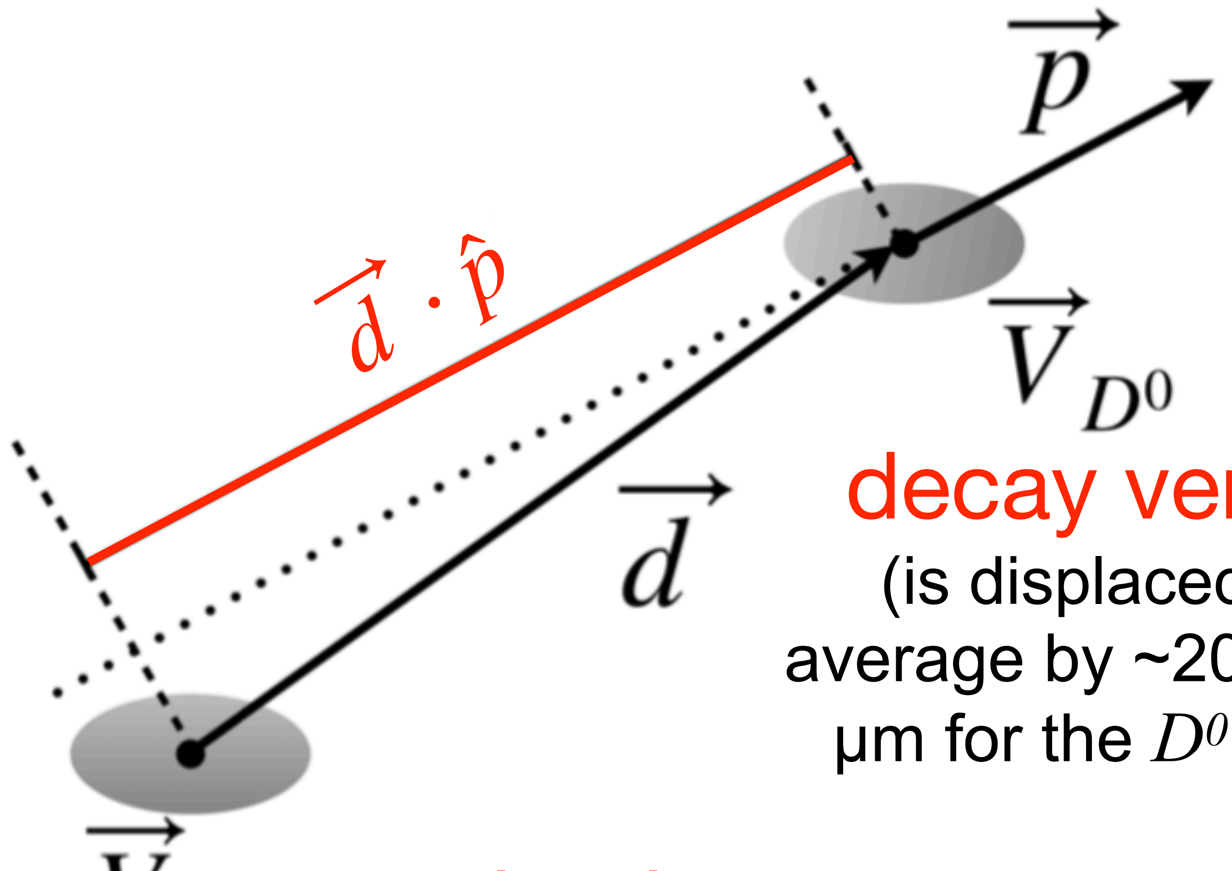
"The Belle II Physics Book"

[PTEP 2019 (2019) 12, 123C01]

D^0 and D^+ Lifetime Measurements

- Lifetime measurements provide excellent tests of effective models, such as the heavy-quark expansion *[arXiv:1405.3601]*.
- Most precise D^0 and D^+ lifetimes: FOCUS two decades ago *[arXiv:hep-ex/0203037]*.
  - No measurements from Belle, BaBar nor LHCb.
  - D^+ lifetime is being used as a reference.

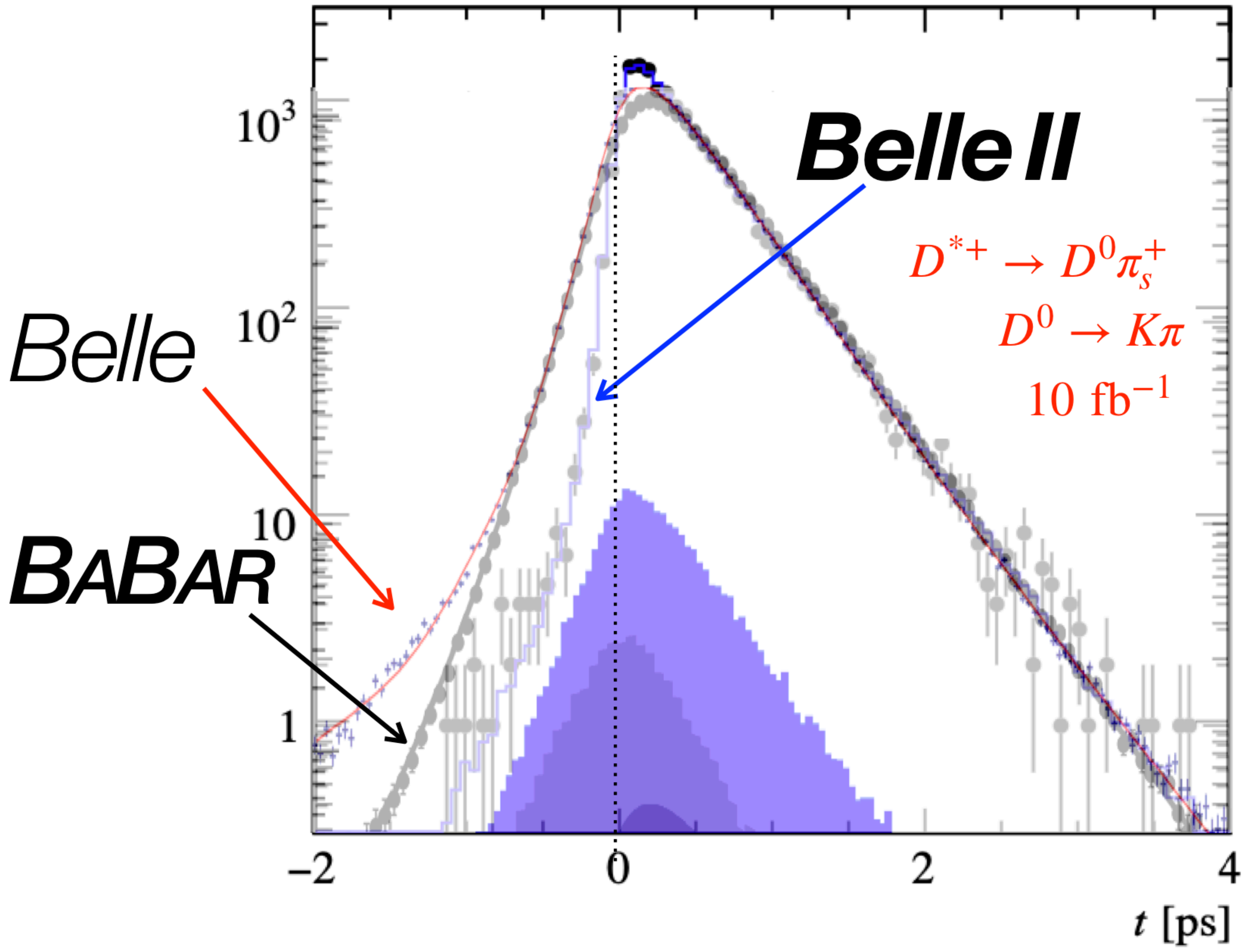
- **Belle II:** using $e^+ e^- \to c\bar{c} \to D^* X$ events :
  - select high-purity samples of D^*-tagged $D^0 \to K^-\pi^+$ and $D^+ \to K^- \pi^+ \pi^+$



decay vertex
(is displaced on average by ~200(500) μm for the $D^0(D^+)$)

production vertex
(lies inside the $e^+ e^-$ interaction region)

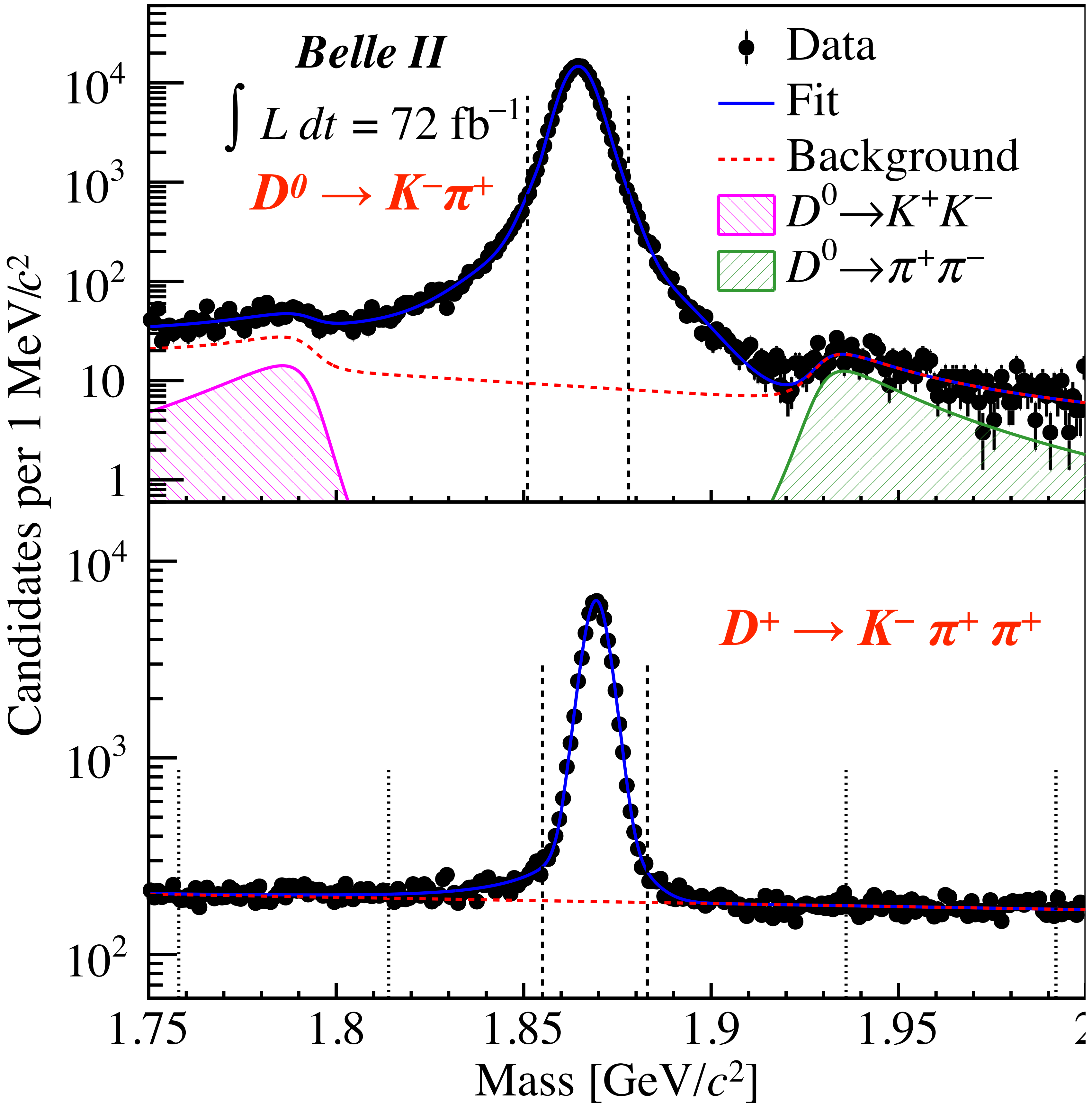
$$t = \frac{m_D \vec{d}\cdot\vec{p}}{(|\vec{p}|^2 c)}$$



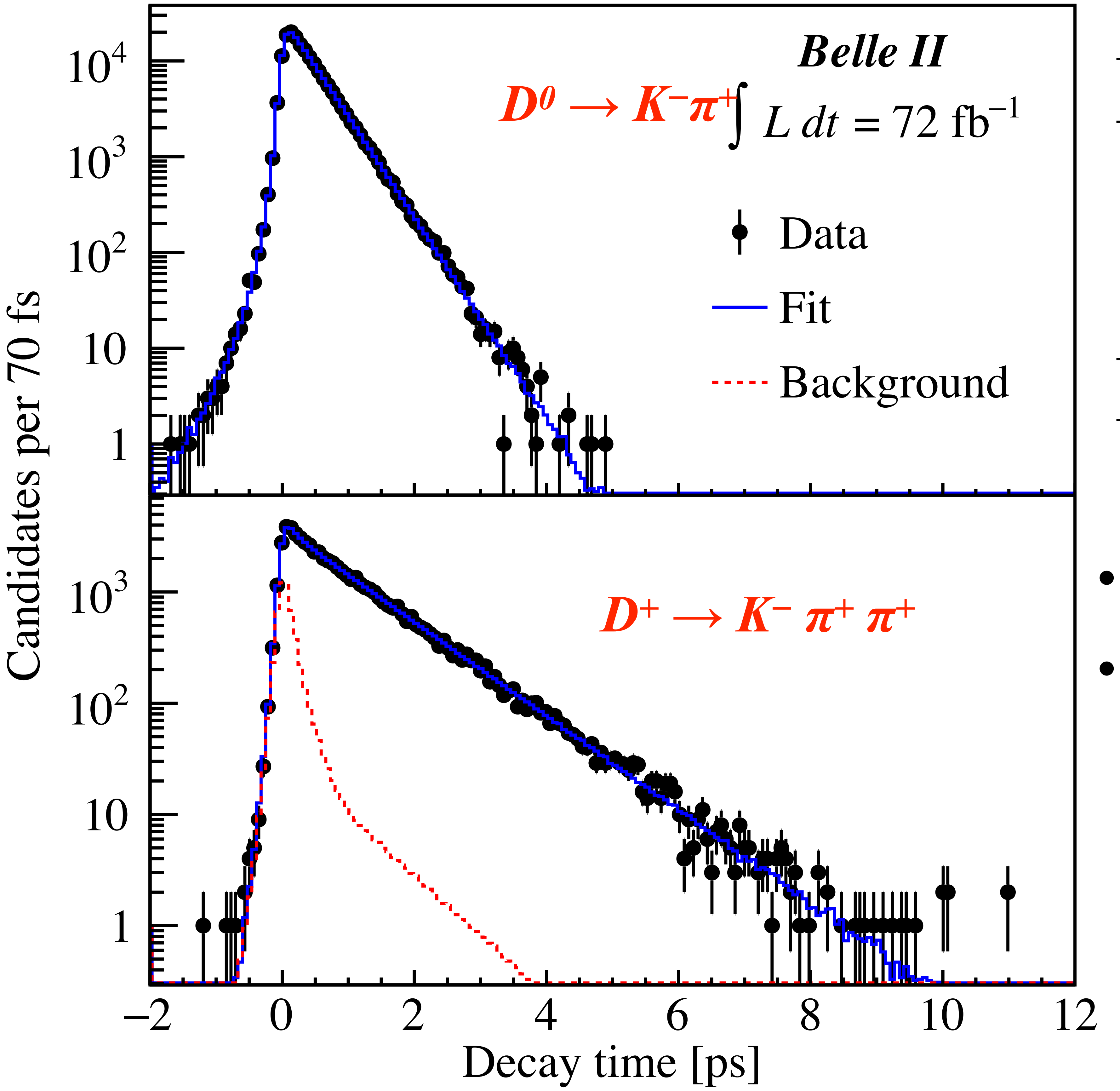
Belle II decay time resolution nearly twice as better as Belle's

D^0 and D^+ Lifetime Measurements

arXiv: 2108.03216 accepted by PRL



Belle II $\int \mathcal{L}dt$ = 72 fb^{-1}



Systematic Uncertainties

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

- Still limited by statistical uncertainty.
- The dominant systematics: from the detector alignment, and background modeling (for the D^+ only).

	Belle II	World Average Value
$\tau(D^0)$ =	(410.5 ± 1.1 ± 0.8) fs	(410.1 ± 1.5) fs
$\tau(D^+)$ =	(1030.4 ± 4.7 ± 3.1) fs	(1040 ± 7) fs

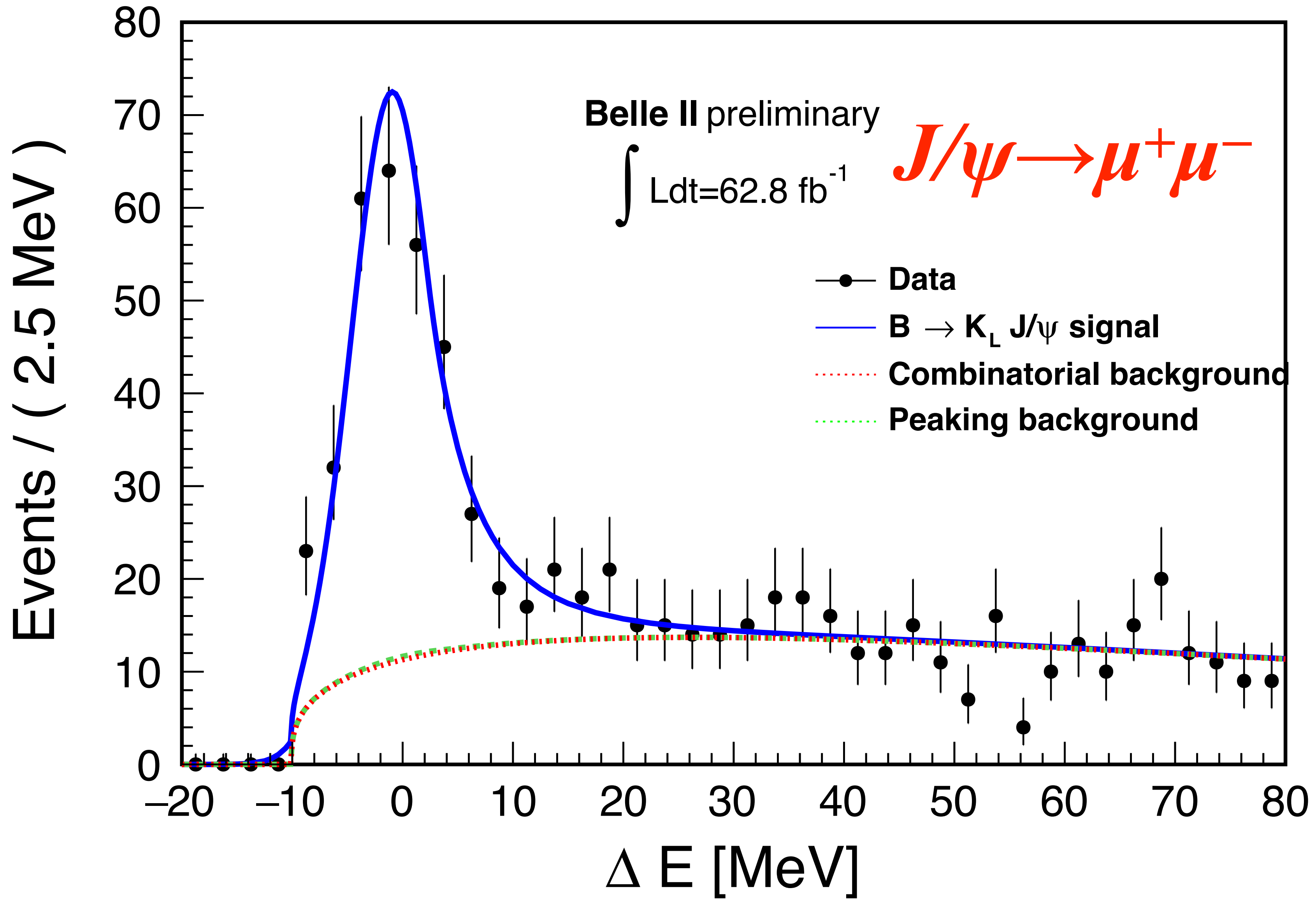
Our results are consistent with, and more precise than, the World Average!

Demonstration of excellent vertexing capabilities of Belle II.

First Belle II Measurements of $B \to J/\psi\, K_L$ and $B \to \eta' K$

Belle II $\int \mathcal{L}dt$ = 62.8 fb⁻¹

$B \to J/\psi\, K_L$



Energy difference: $\Delta E = E_B - E_{BEAM}$

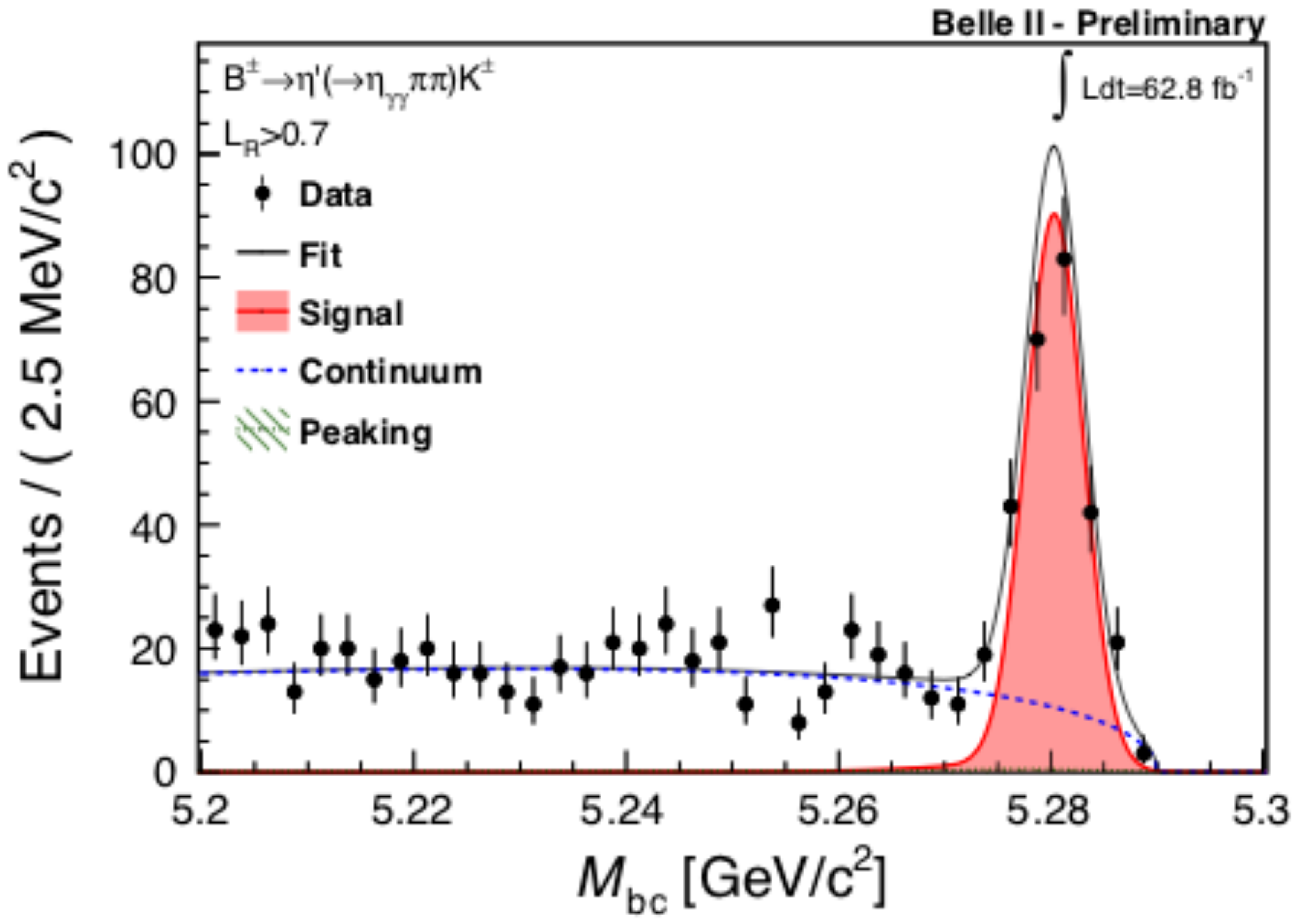
Beam-constrained mass: $M_{bc} = \sqrt{E_{BEAM}^2 - \vec{p}_B^{\,2}}$

$$N_{\text{sig}}\ (\mu^+\mu^-) = 267 \pm 21(\text{stat}) \pm 28(\text{peaking})$$
$$N_{\text{sig}}\ (e^+e^-) = 226 \pm 20(\text{stat}) \pm 31(\text{peaking}).$$

[arXiV:2106.13547]

- Next: precise measurement of B^0 lifetime and mixing frequency.

$B \to \eta' K$



Channel	This analysis $\mathcal{B}$ $(\times 10^6)$	World average [9]
$B^{\pm} \to \eta' K$	$63.4\ ^{+3.4}_{-3.3}(\text{stat}) \pm 3.4(\text{syst})$	70.4 ± 2.5
$B^0 \to \eta' K^0$	$59.9\ ^{+5.8}_{-5.5}(\text{stat}) \pm 2.7(\text{syst})$	66 ± 4

[arXiv:2104.06224]

- Next: to use the future large data sample collected at Belle II for a full time dependent CP violation analysis.

Towards Belle II Measurement of $\phi_2(=\alpha)$

- Accessible via $b \to u$ transitions, but $b \to d$ penguin diagrams contribute significantly.
- Penguin pollution from an isospin analysis of $B \to \pi\pi$ and $B \to \rho\rho$.

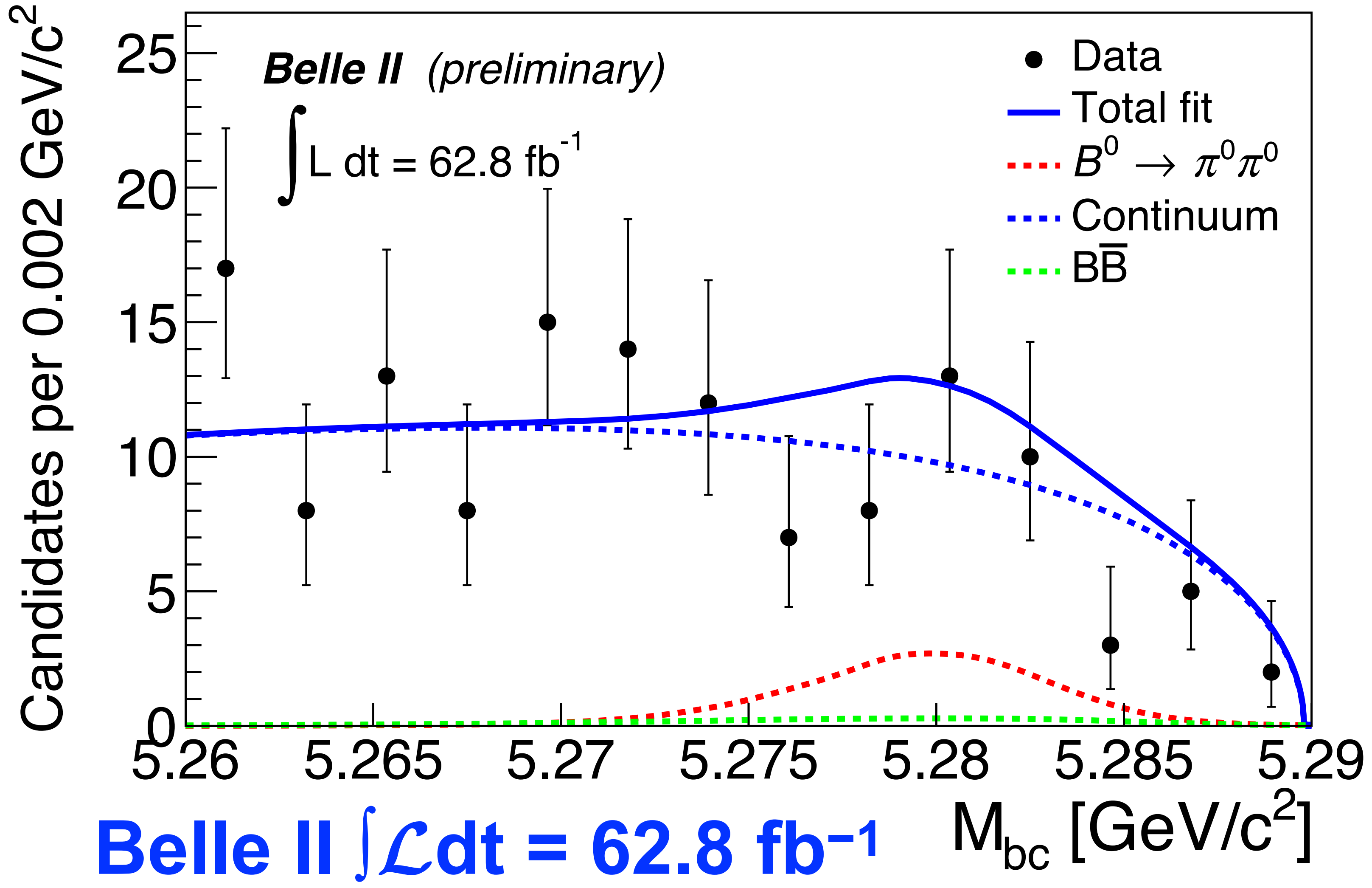
$$\mathcal{S} = -\xi_f \sqrt{1 - A^2} sin2\phi_2^{eff}$$
$$\phi_2^{eff} = \phi_2 - \Delta\phi_2 \quad (\text{"effective"}\ \phi_2)$$

$B^0 \to \pi^0\pi^0$

- Unique to Belle II : four photons in the final state.
- Dedicated MVA for optimized photon selection.
- Dominant background is coming from continuum π^0.
  - Suppressed with another MVA.

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = [0.98^{+0.48}_{-0.39}(stat) \pm 0.27(syst)] \times 10^{-6}$$

[arXiv:2107.02373]



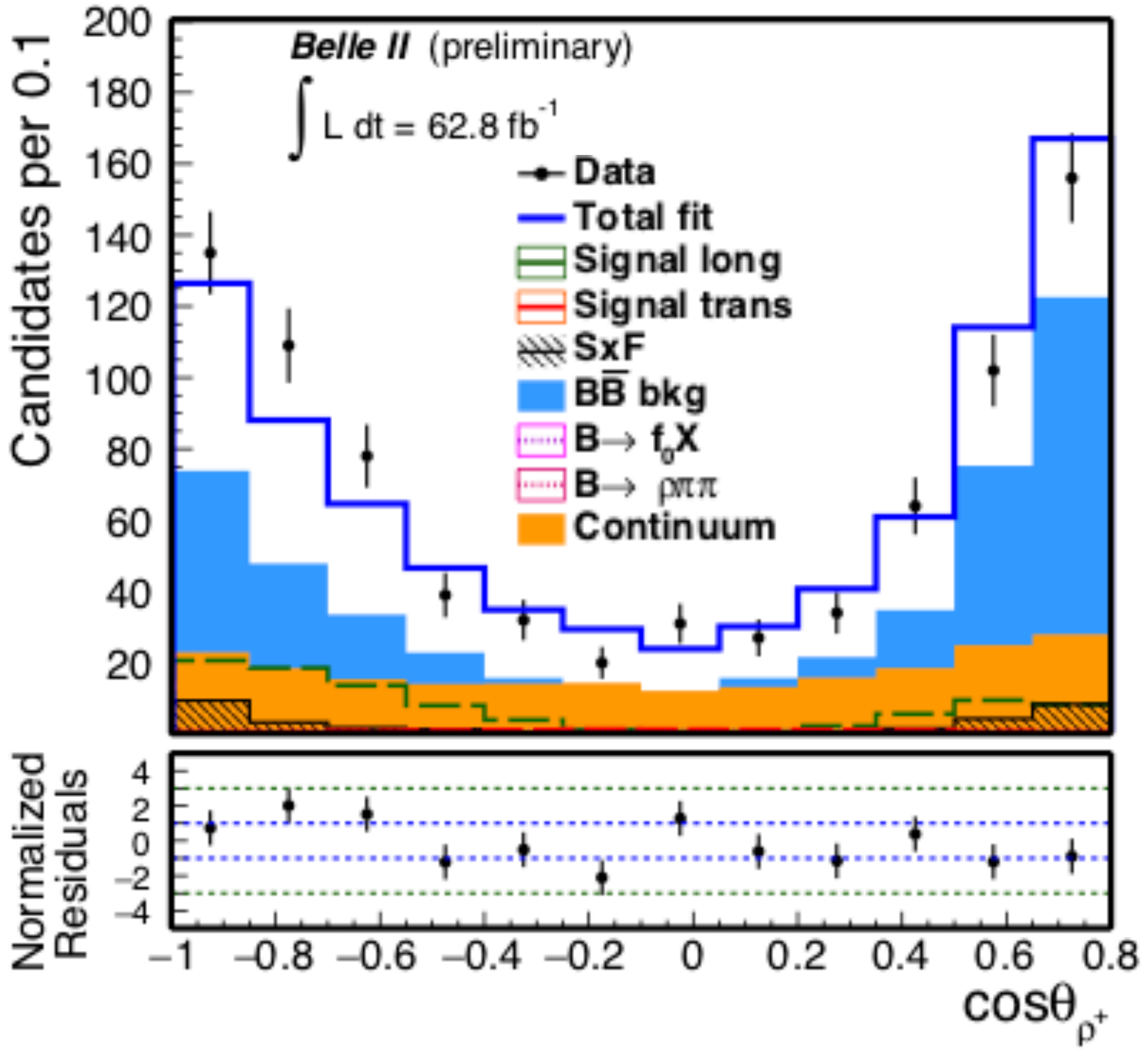
Belle II $\int\mathcal{L}dt$ = 62.8 fb^{-1}

$B^+ \to \rho^+\rho^0$

- pion only $(\pi^+\pi^0)(\pi^+\pi^-)$ final state.
- Large background because of broad ρ mass width.
- 6D fit including helicity angles.

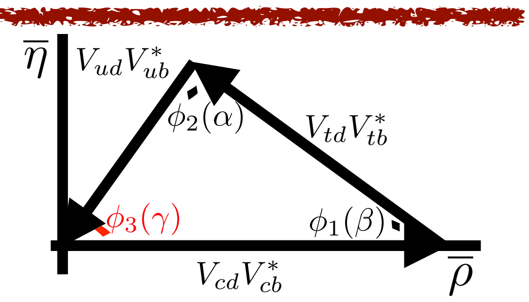
$$\mathcal{B}(B^+ \to \rho^+\rho^0) = [20.6 \pm 3.2(stat) \pm 4.0(syst)] \times 10^{-6}$$
$$f_L(B^+ \to \rho^+\rho^0) = 0.936^{+0.049}_{-0.041}(stat) \pm 0.021(syst)$$

[arXiv:2109.11456]



- 20% better precision than Belle on 78 fb^{-1} [PRL 91, 221801 (2003)].

$\phi_3(=\gamma)$ Extraction on the Combined (Belle and Belle II) Data Set



The first Belle and Belle II combined model-independent measurement of ϕ_3

- "**Golden**" mode: $B^-\rightarrow D^0(\rightarrow K^0_s\, h^+h^-)\, K^-$

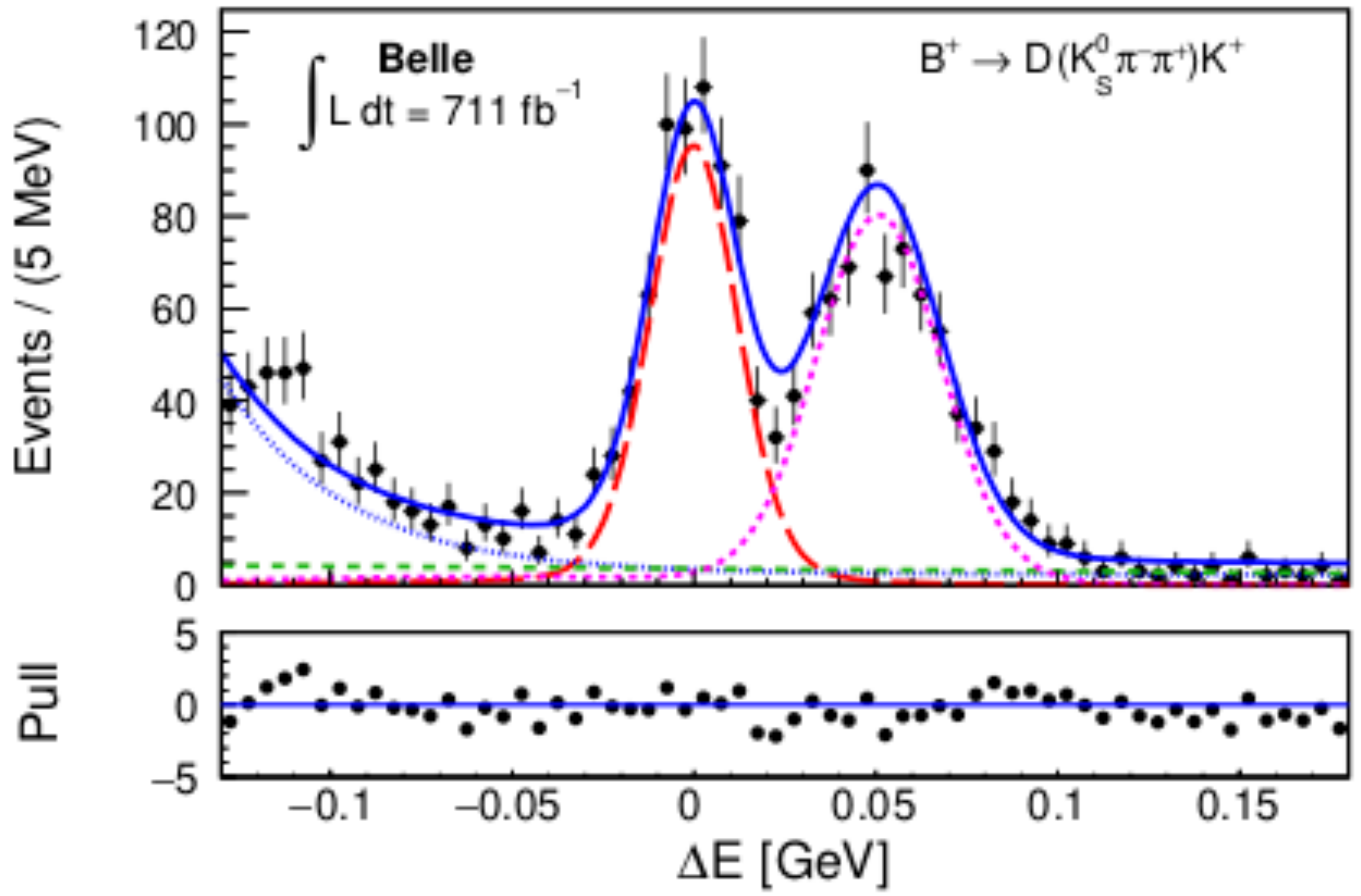
$$\frac{\mathcal{A}^{suppr.}(B^- \to \overline{D^0}K^-)}{\mathcal{A}^{favor.}(B^- \to D^0K^-)} = r_B e^{i(\delta_B+\phi_3)}$$

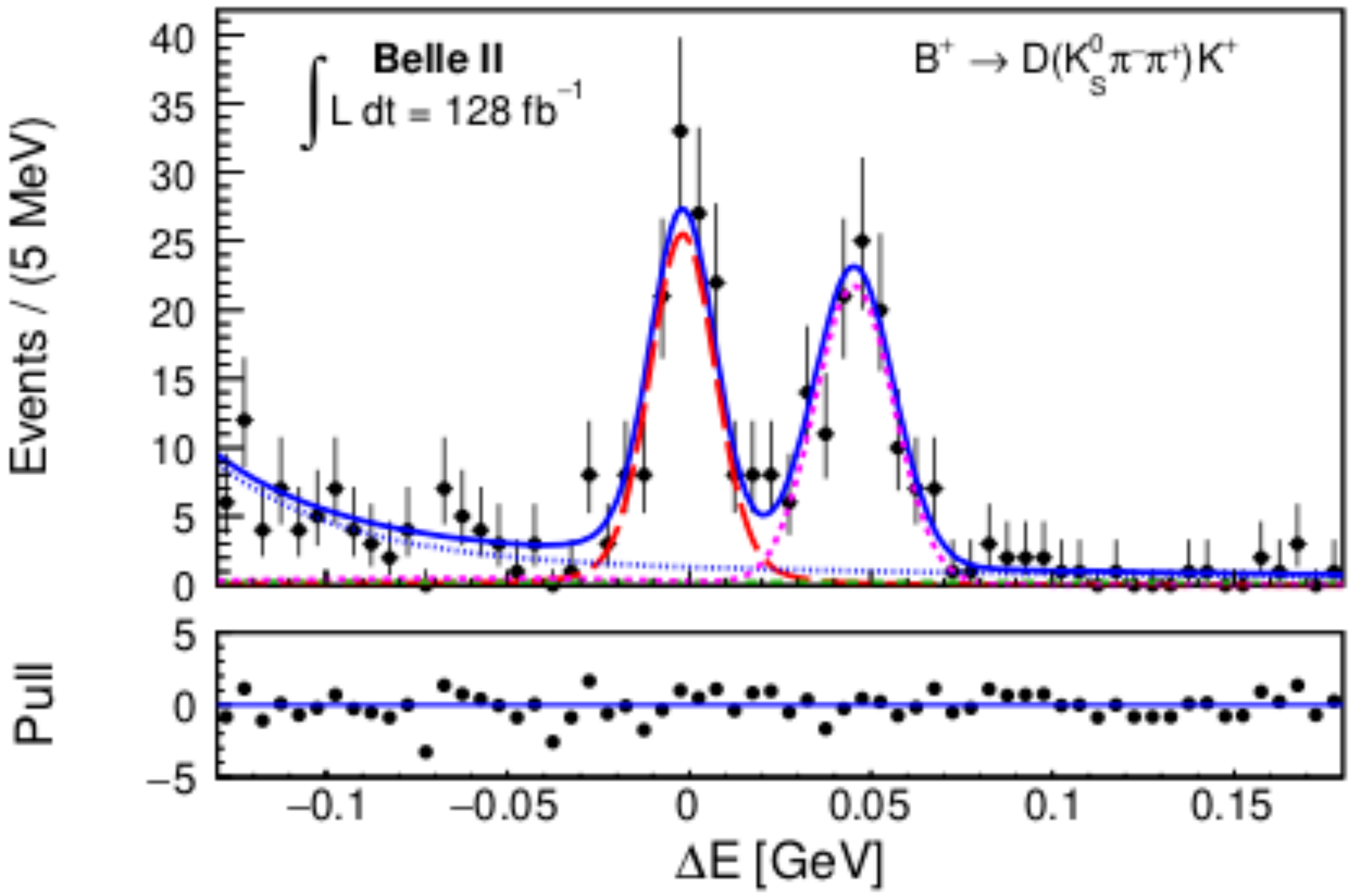
r_B : magnitude of the ratio of amplitudes
δ_B : strong phase difference

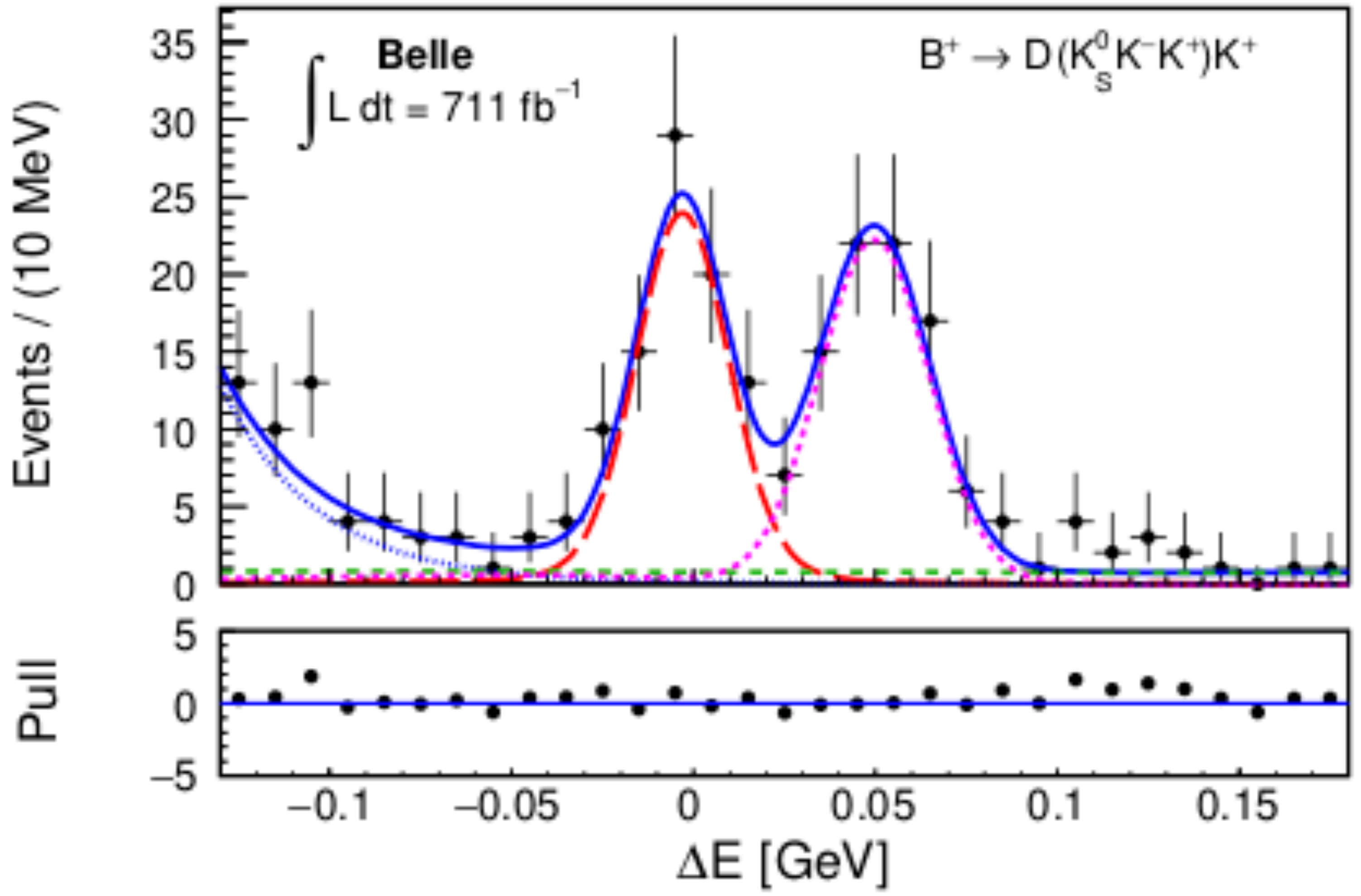
- BPGGSZ model-independent approach

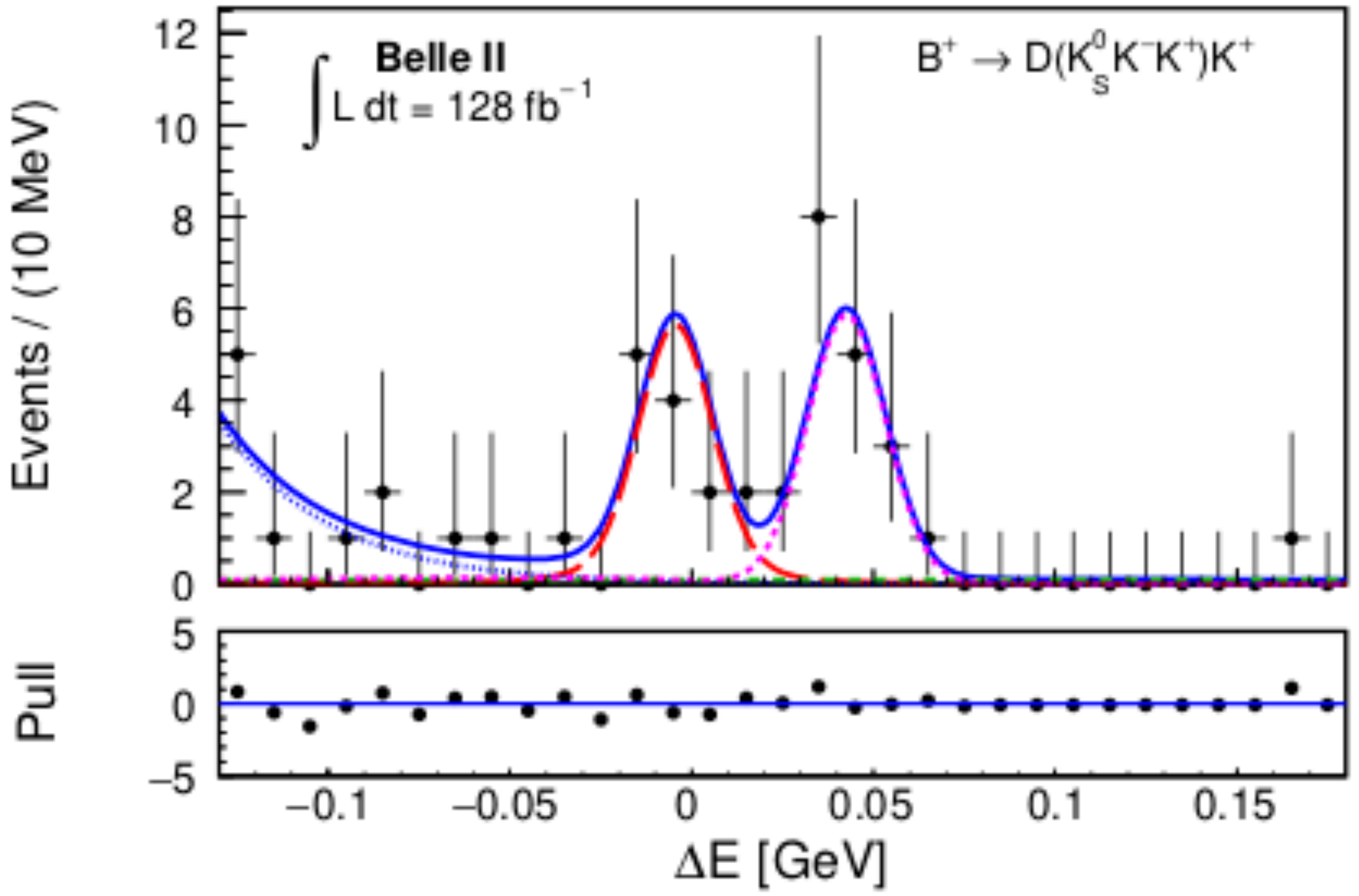
[Phys. Rev. D 68, 054018]

Belle ($\int\mathcal{L}dt$ = 711 fb^{-1}) **Belle II ($\int\mathcal{L}dt$ = 128 fb^{-1})**



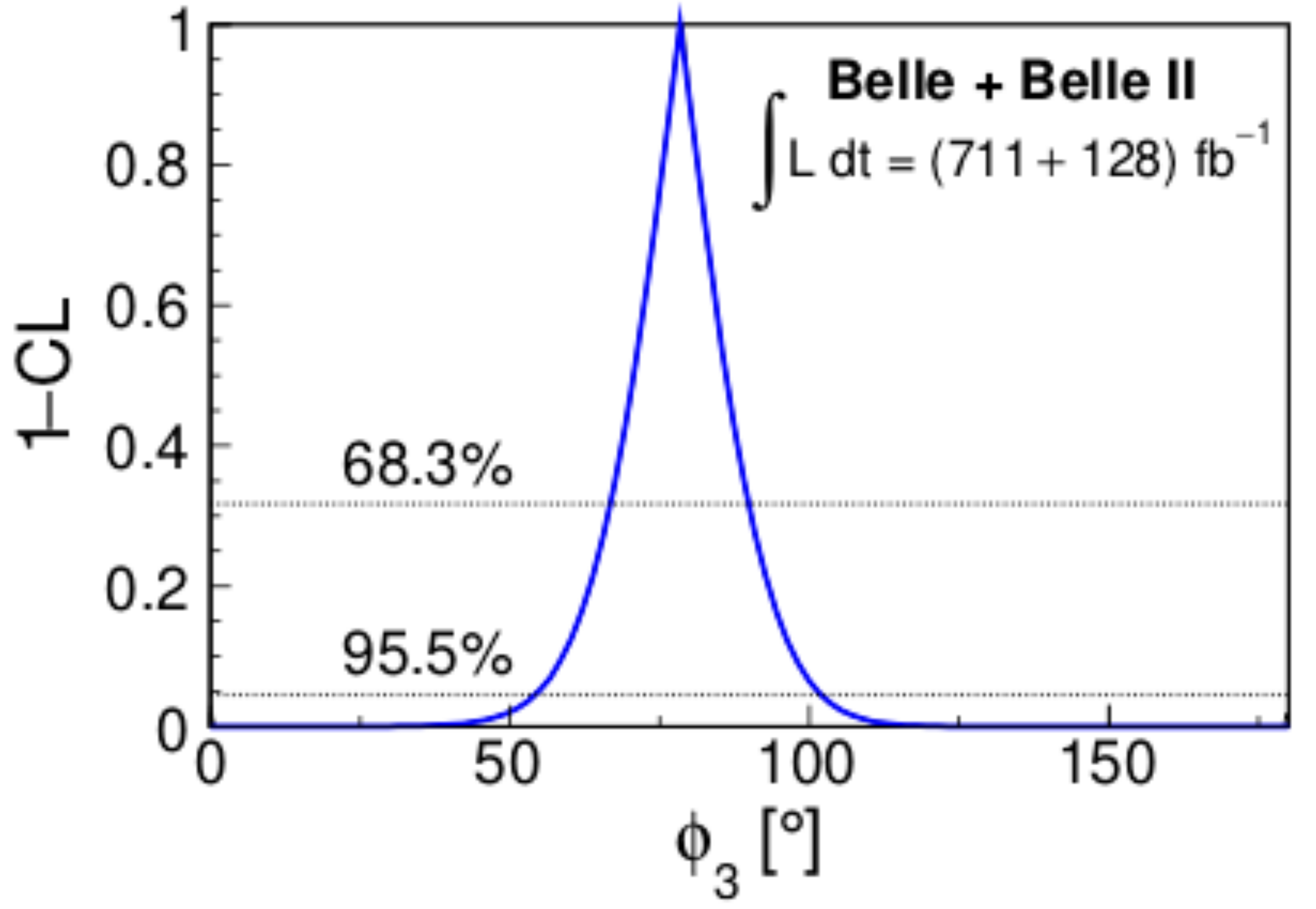


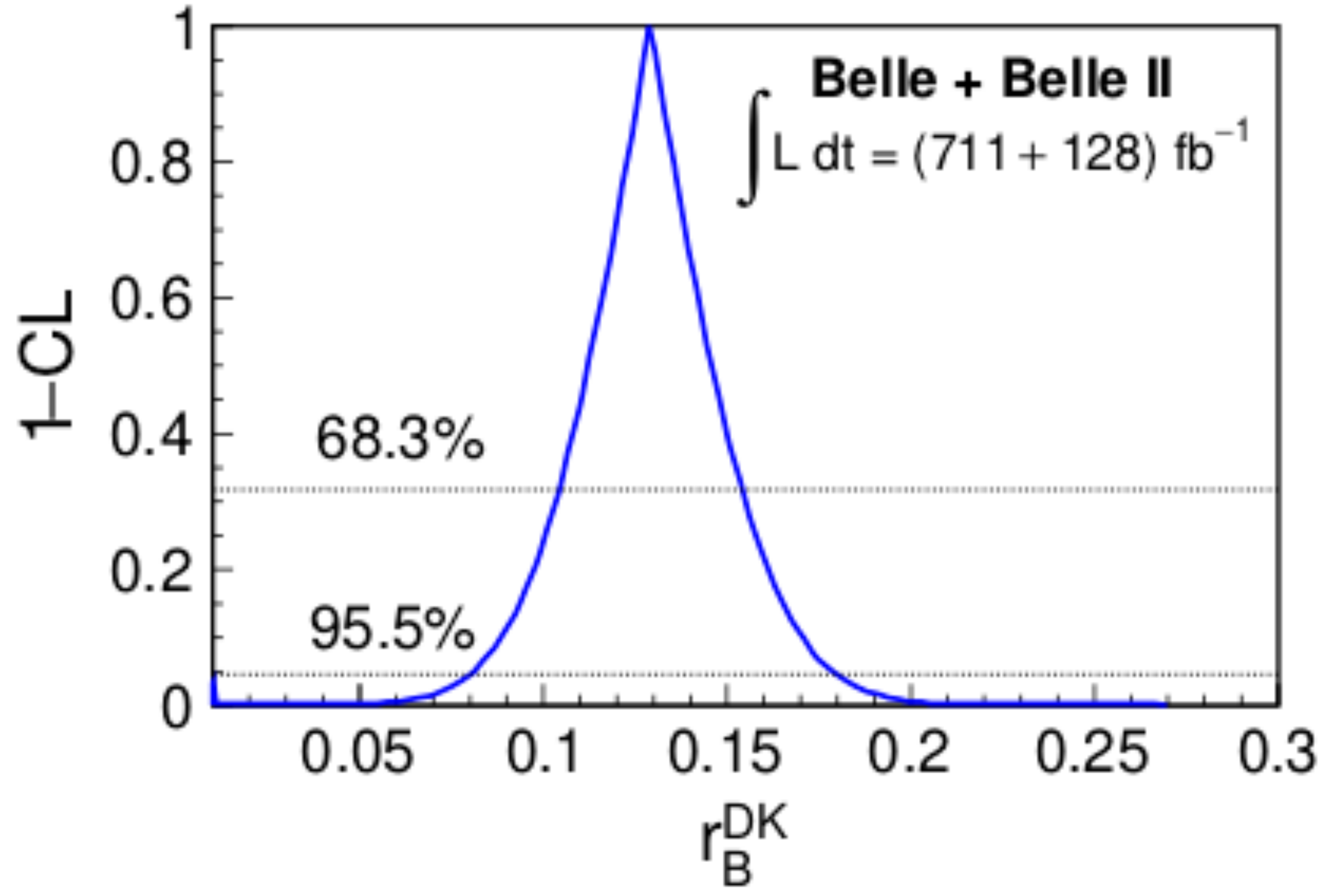




$\phi_3(=\gamma)$ Extraction on the Combined (Belle and Belle II) Data Set

Belle+Belle II $\int\mathcal{L}dt$ = (711 + 128) fb^{-1}





Belle previous analysis with 711 fb^{-1} : *[Phys. Rev. D 85, (2012) 112014]*

$$\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$$

Belle+Belle II $\int\mathcal{L}dt$ = (711 + 128) fb^{-1} *[arXiv.2110.12125] submitted to JHEP*

$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ\,,$$
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002,$$
$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ\,.$$

- Statistical uncertainty on ϕ_3 improved by 4° over Belle.
- Experimental systematics reduced from 4° to 0.5°.
- Input-related systematic reduced from 4° to 1° due to recent values provided by BESIII.
- Future analysis corresponding to 10 ab^{-1} will provide measurements with a precision of ~4° or so.

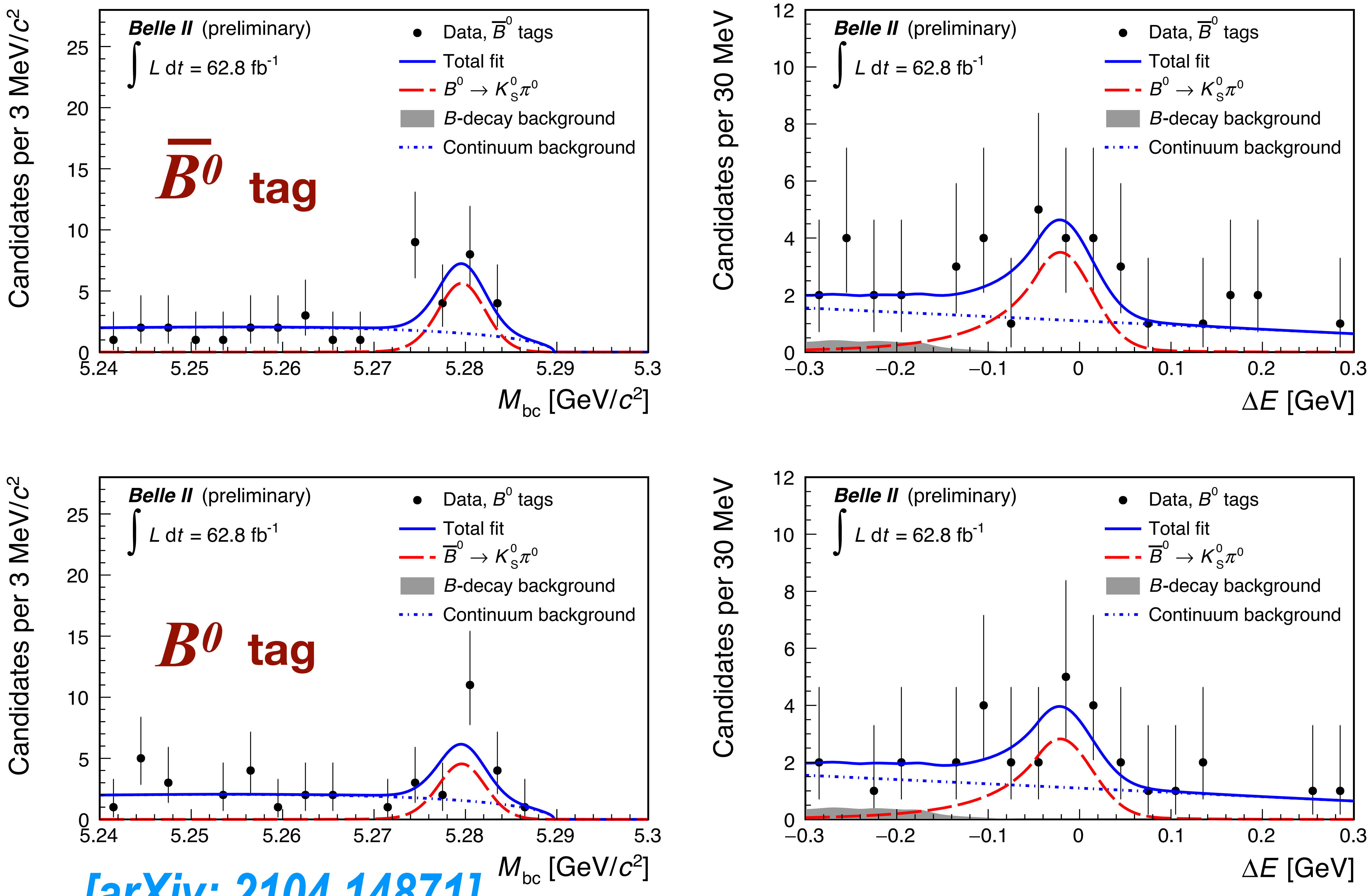
First Belle II Measurement of $B^0 \to K^0 \pi^0$

- Striking difference between the direct CP asymmetries of $B^0 \to K^+ \pi^-$ and $B^+ \to K^+ \pi^0$ (ΔA_{CP} = 0.115 ± 0.014).
- The isospin sum rule test: a sensitive null-test. *[PLB 627, 82 (2005)]*

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

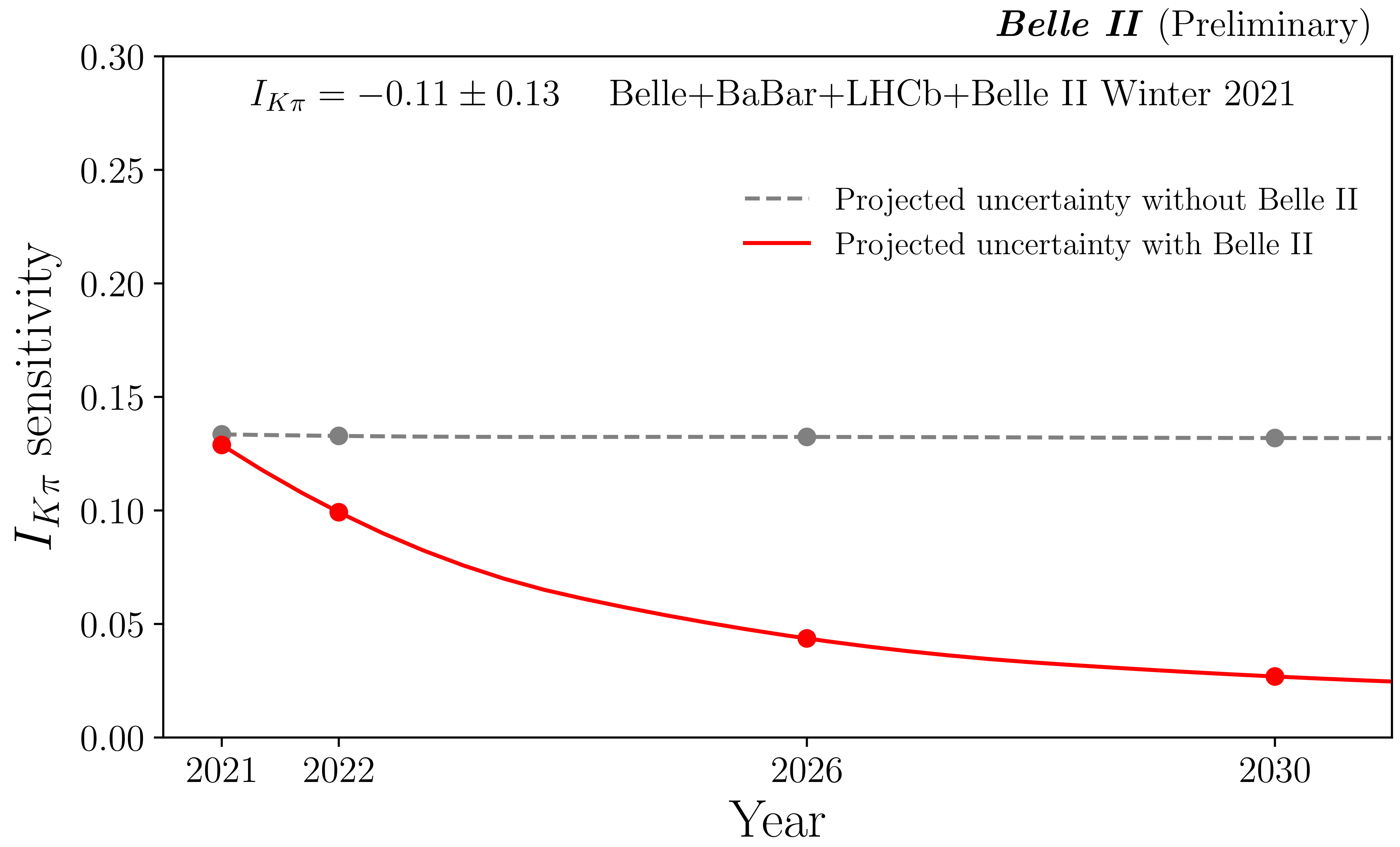
At Belle II we can measure all the inputs of the equation.

Belle II $\int\mathcal{L}dt$ = 62.8 fb^{-1}



[arXiv: 2104.14871]

$$\mathcal{A}_{K^0\pi^0} = -0.40^{+0.46}_{-0.44}(stat) \pm 0.04(syst), \text{and}$$
$$\mathcal{B}(B^0 \to K^0\pi^0) = [8.5^{+1.7}_{-1.6}(stat) \pm 1.2(syst)] \times 10^{-6}$$



Dark Sector Searches: *Z' → invisible*

[PRL 124, 141801 (2020)]

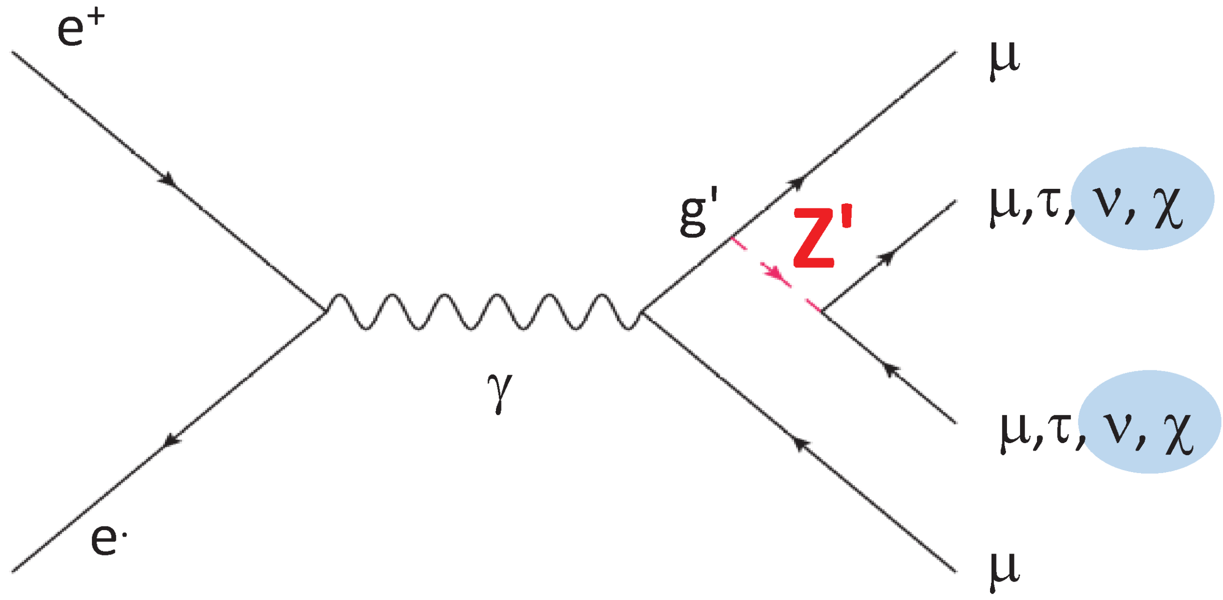
Searching in 0.276 fb^{-1} of commissioning data (April-July 2018)

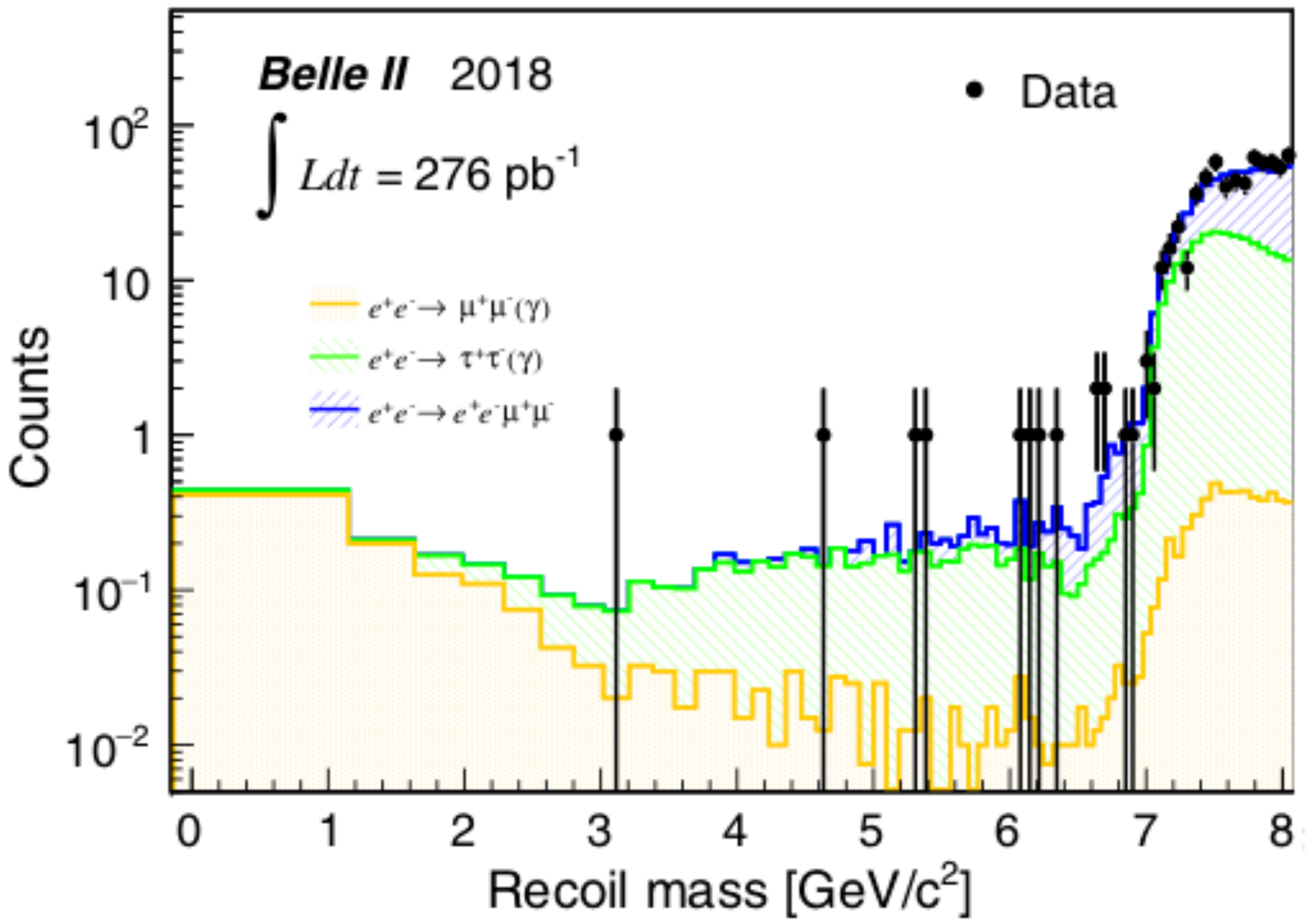
$e^+ e^- \to \mu^+ \mu^- Z'$, ($Z' \to$ invisible)

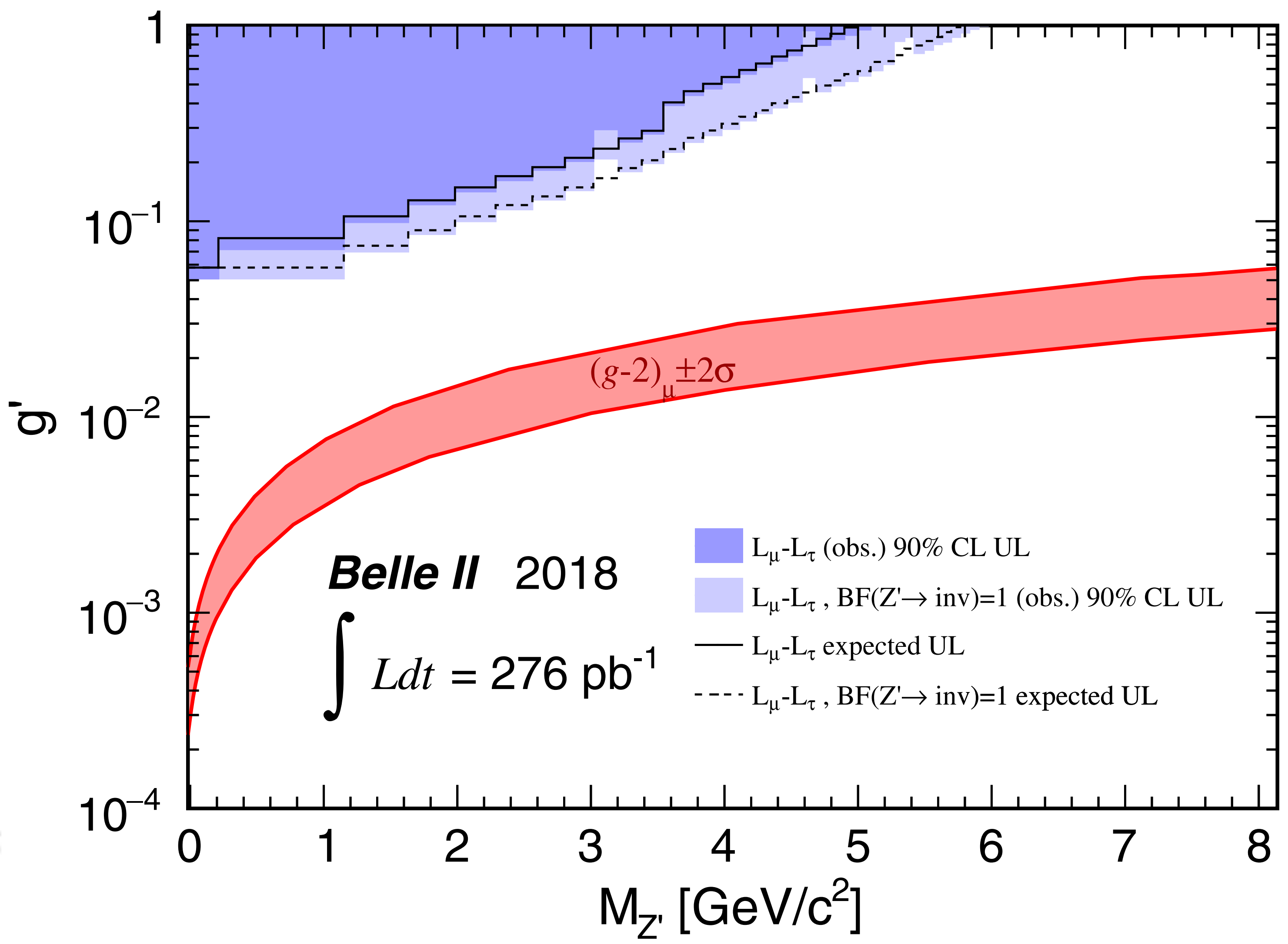
$L_\mu - L_\tau$ model

(coupling only to the 2nd and 3rd lepton generation)

[Phy.Rev D89,113004 (2014) JHEP12(2016)106]







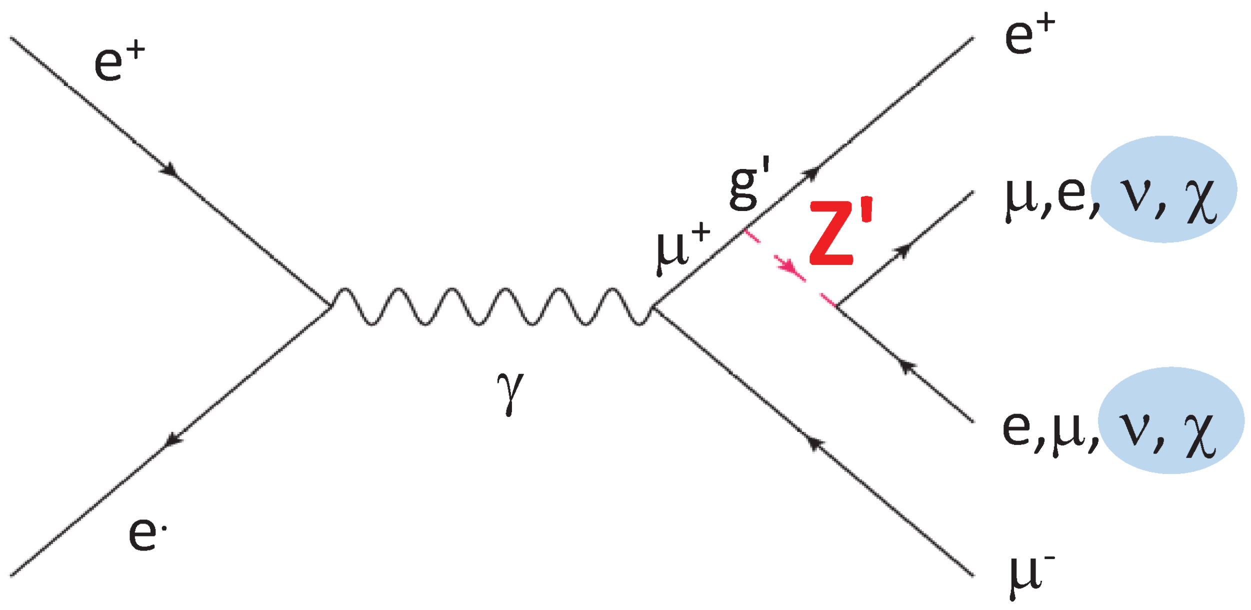
- The first experiment to set limits on Z' coupling, g'. Will soon probe the region interesting for the $(g\text{-}2)_\mu$ anomaly.

$e^+ e^- \to e^\pm \mu^\mp Z'$, ($Z' \to$ invisible)

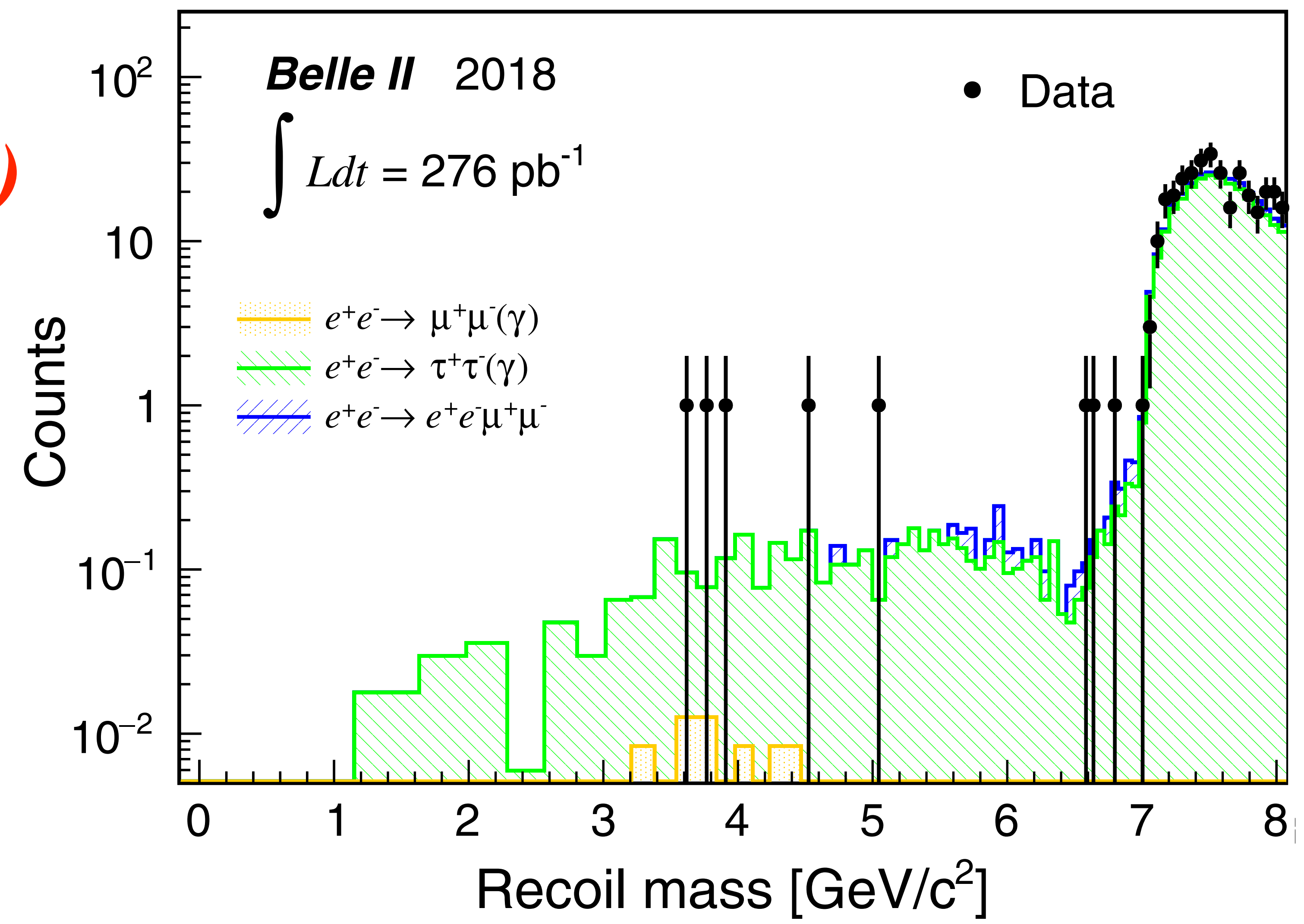
Z' with *LFV*

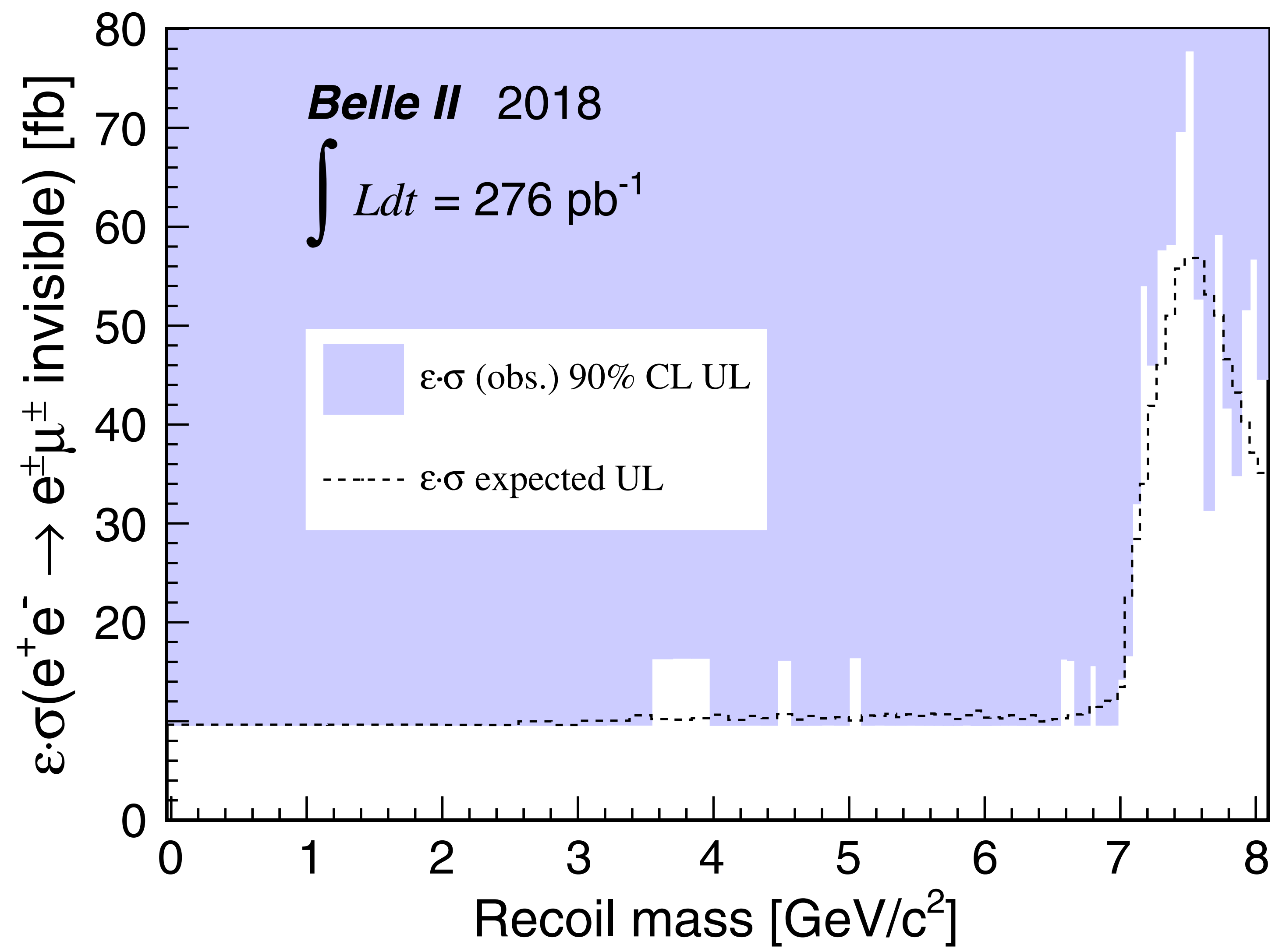
e–μ coupling

[JHEP05 (2017) 083, JHEP03 (2017) 064]



model independent search





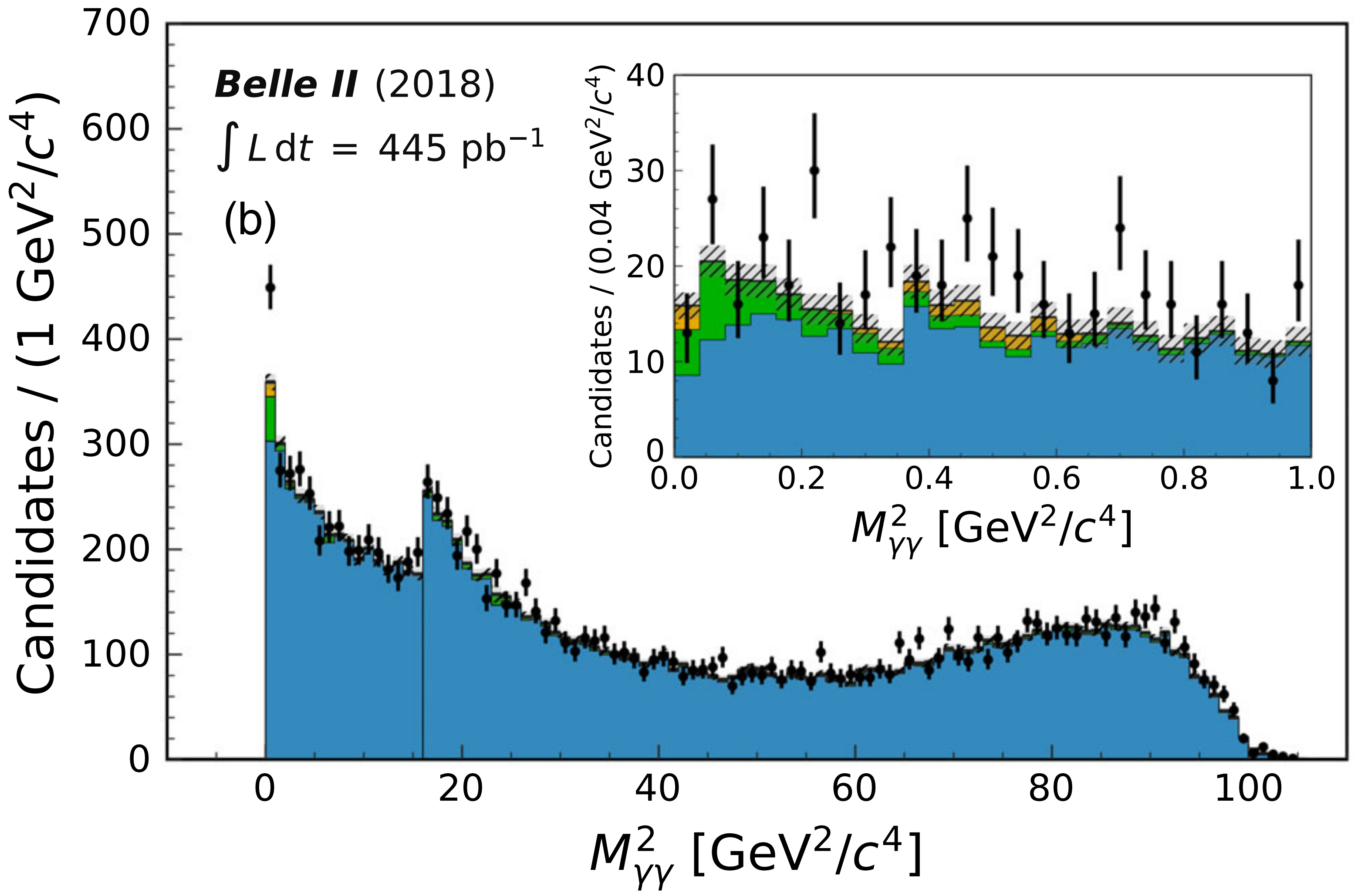
- No excess observed. The first experiment to set limits on cross-section for $e^+ e^- \to e^\pm \mu^\mp$ + *missing energy.*

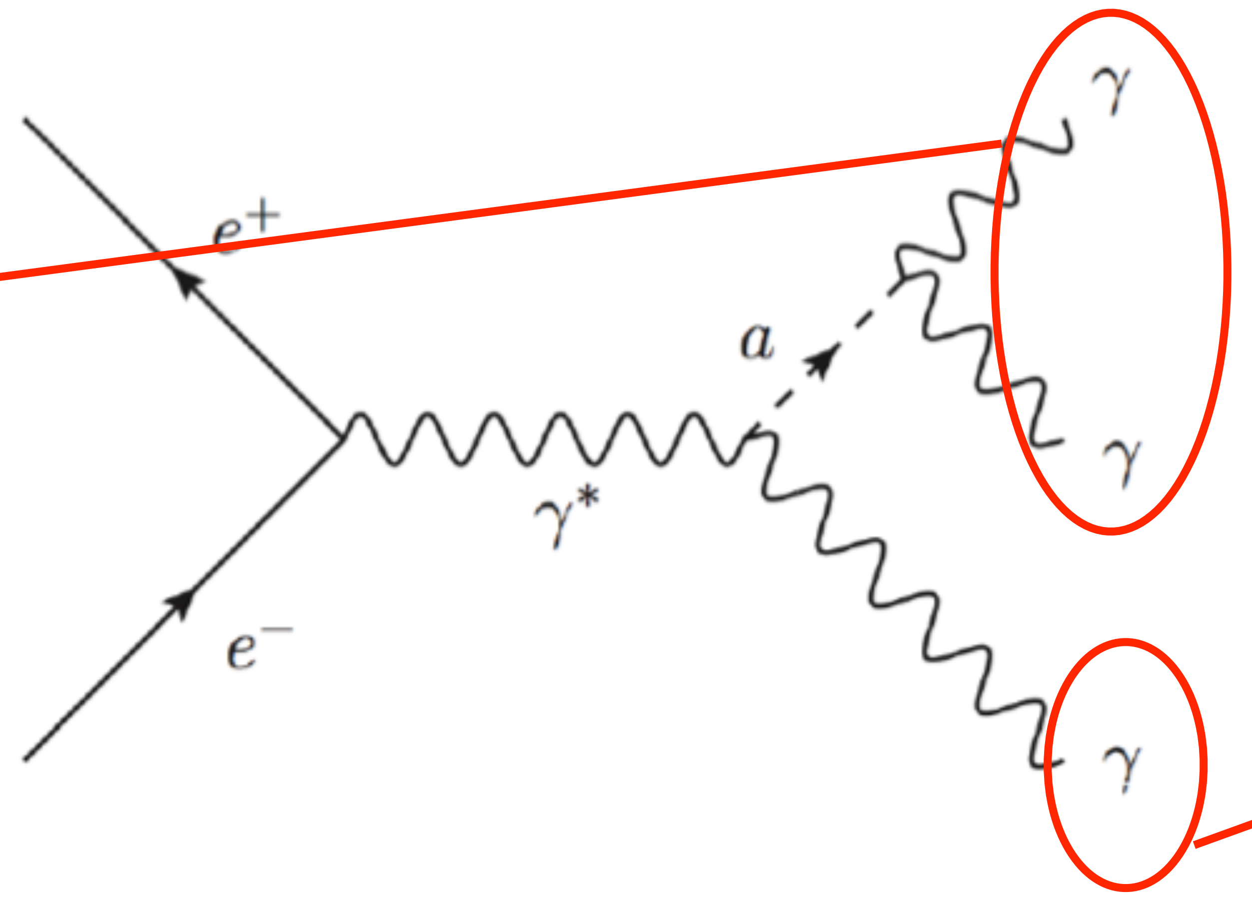
Dark Sector Searches: Search for Axion-Like Particles

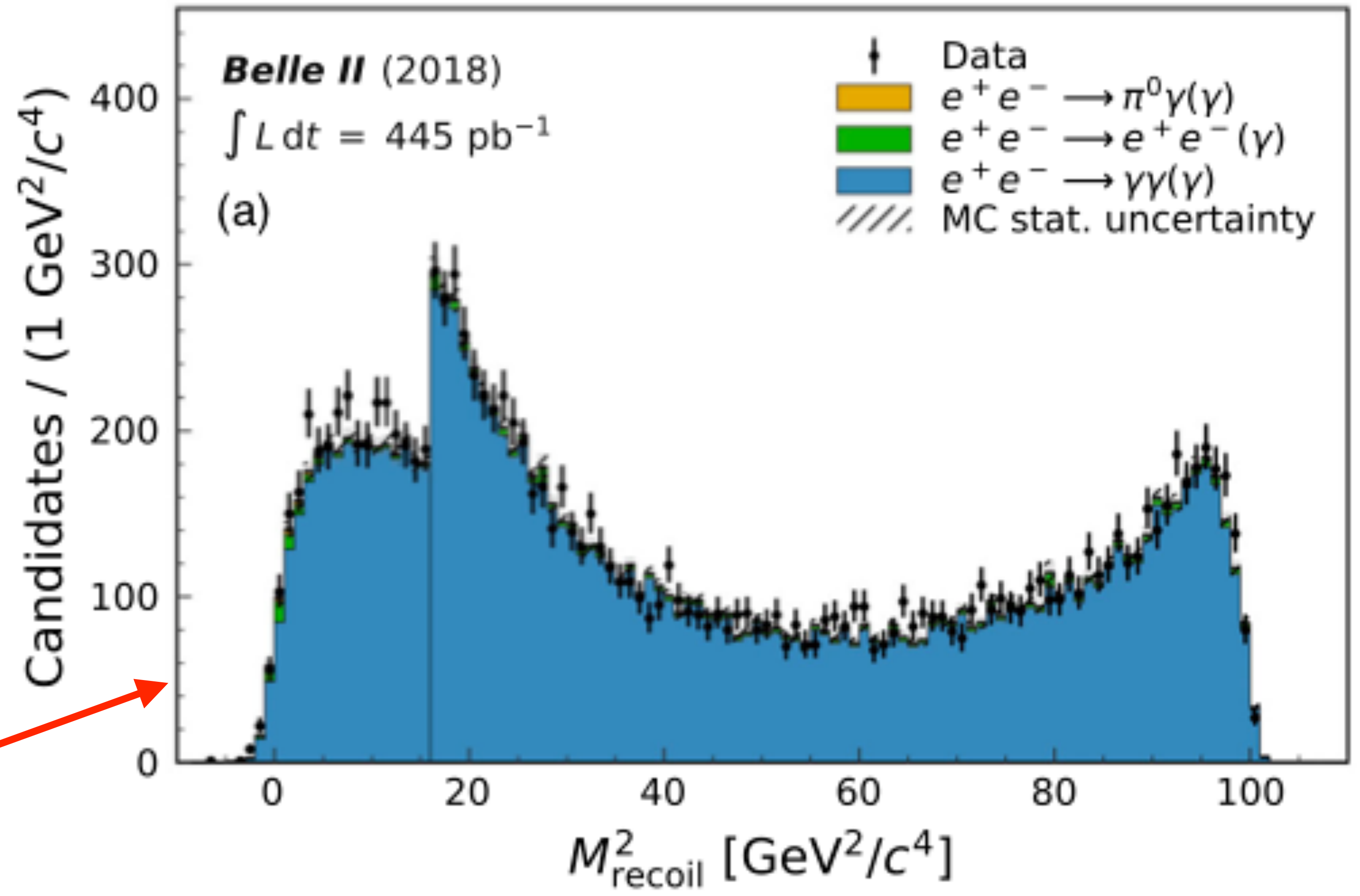
- Axion-Like Particles (ALPs) are pseudoscalars, a, which couple to SM bosons via $g_{a\gamma Z}$ and/or $g_{a\gamma\gamma}$.

Bell II focuses on $g_{a\gamma\gamma}$.

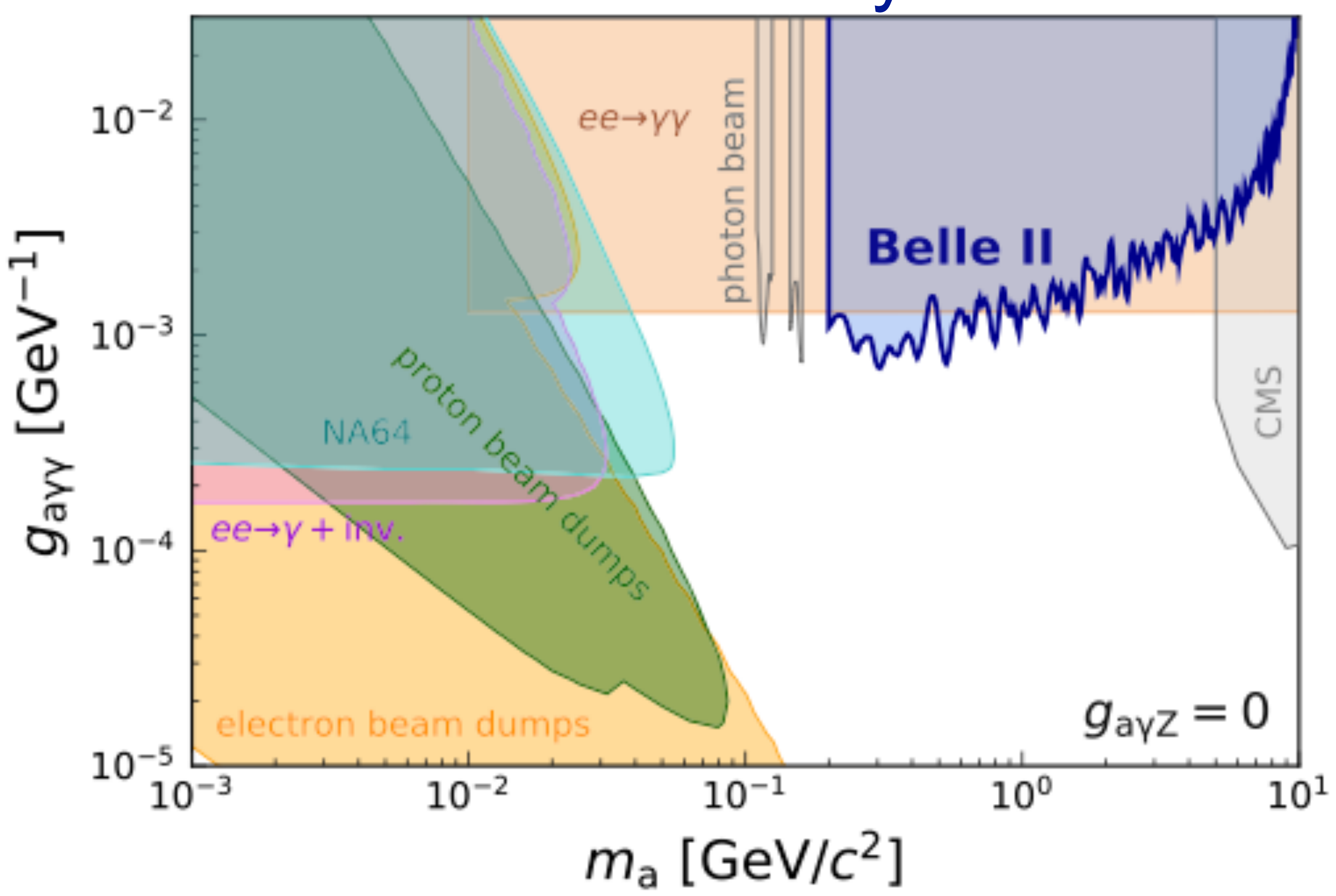
Searching in 0.445 fb^{-1} of commissioning data (April-July 2018)







New exclusions already with ~0.5 fb^{-1}



- A signal would be identified by a peak in the diphoton invariant mass ($M^2_{\gamma\gamma}$) (better for ALP masses < 6.5 GeV), or in the recoil invariant mass (M^2_{recoil}) (better for ALP masses > 6.5 GeV).
- No significant excess seen, limits set on ALP coupling to photons.

[PRL 125, 161806 (2020)]

Conclusion

- SuperKEKB has achieved $\mathcal{L}_{peak} = 3.1 \times 10^{34}\ cm^{-2}\ s^{-1}$, the world record on June 22nd.
- Despite the pandemic, Belle II collected up to 12 fb^{-1} per week.
- Belle II has a very diverse and exciting physics program *[The Belle II Physics Book Prog.Theor. Exp.Phys.2019,123C01 arXiv:18-8:10567]*.
- We have already world leading results on the first Dark Sector searches and on the D^0/D^+ charm lifetimes.
  - More charm lifetime measurements (Λ_C, D_s, Ω_C) are coming.
- We are looking forward to an exciting era of discoveries and we know the world is waiting for us.

Thank you for your attention!

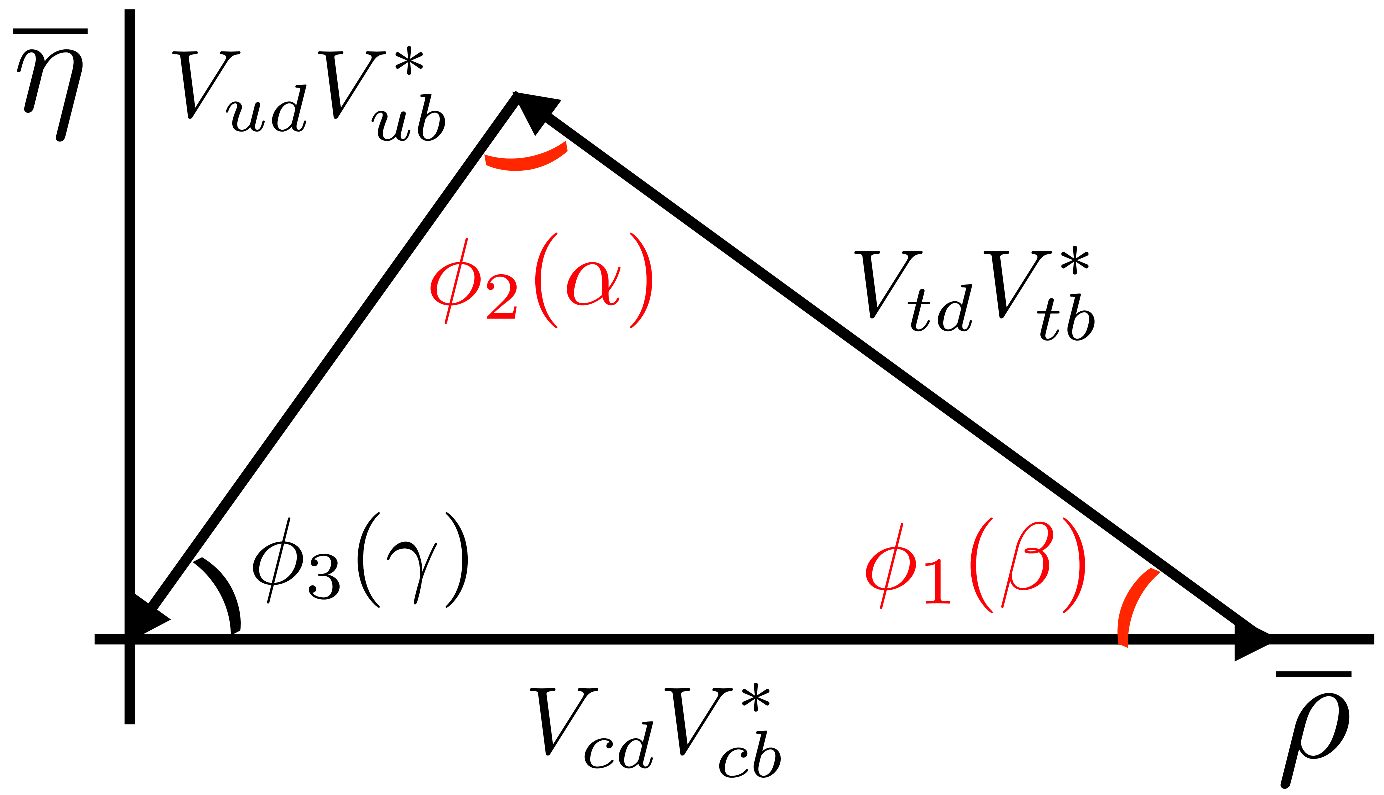
Courtesy Tom Browder

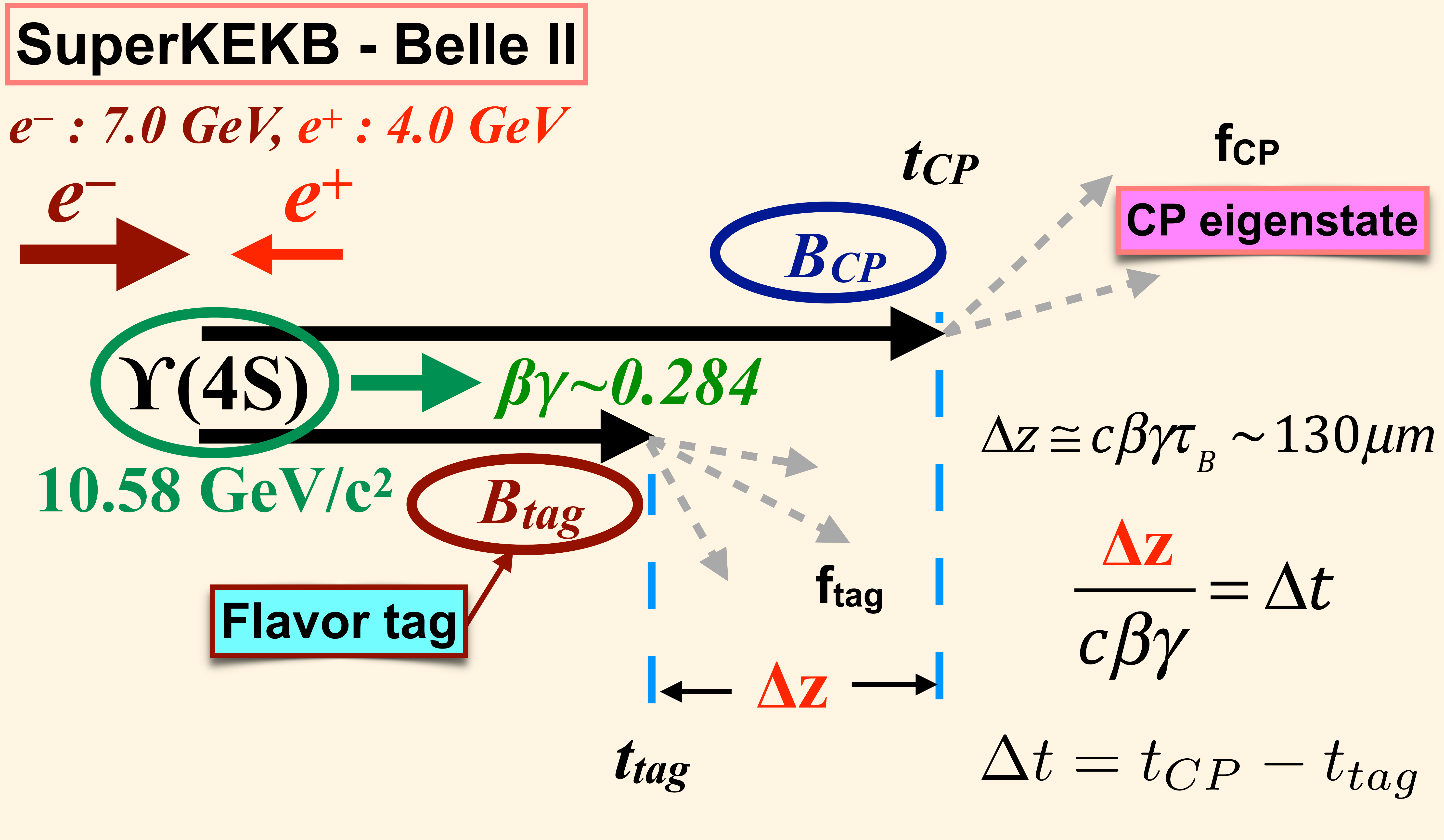
Backup

Time Dependent Charge Parity Violation (CPV) in B Decays

The flagship B factory measurement

- By measuring time evolution of B meson pairs, we can get constraints
  - for CP-violating angles, $\phi_1(=\beta)$ and $\phi_2(=\alpha)$
  - the B^0-$\overline{B^0}$ mixing parameter Δm_d.
- ϕ_1 , ϕ_2 are fundamental inputs of the CKM fit.
- Current precisions: ϕ_1/β ~0.7° and ϕ_2/α ~4.5°
- Belle II expects to improve by a factor ~5 on both.



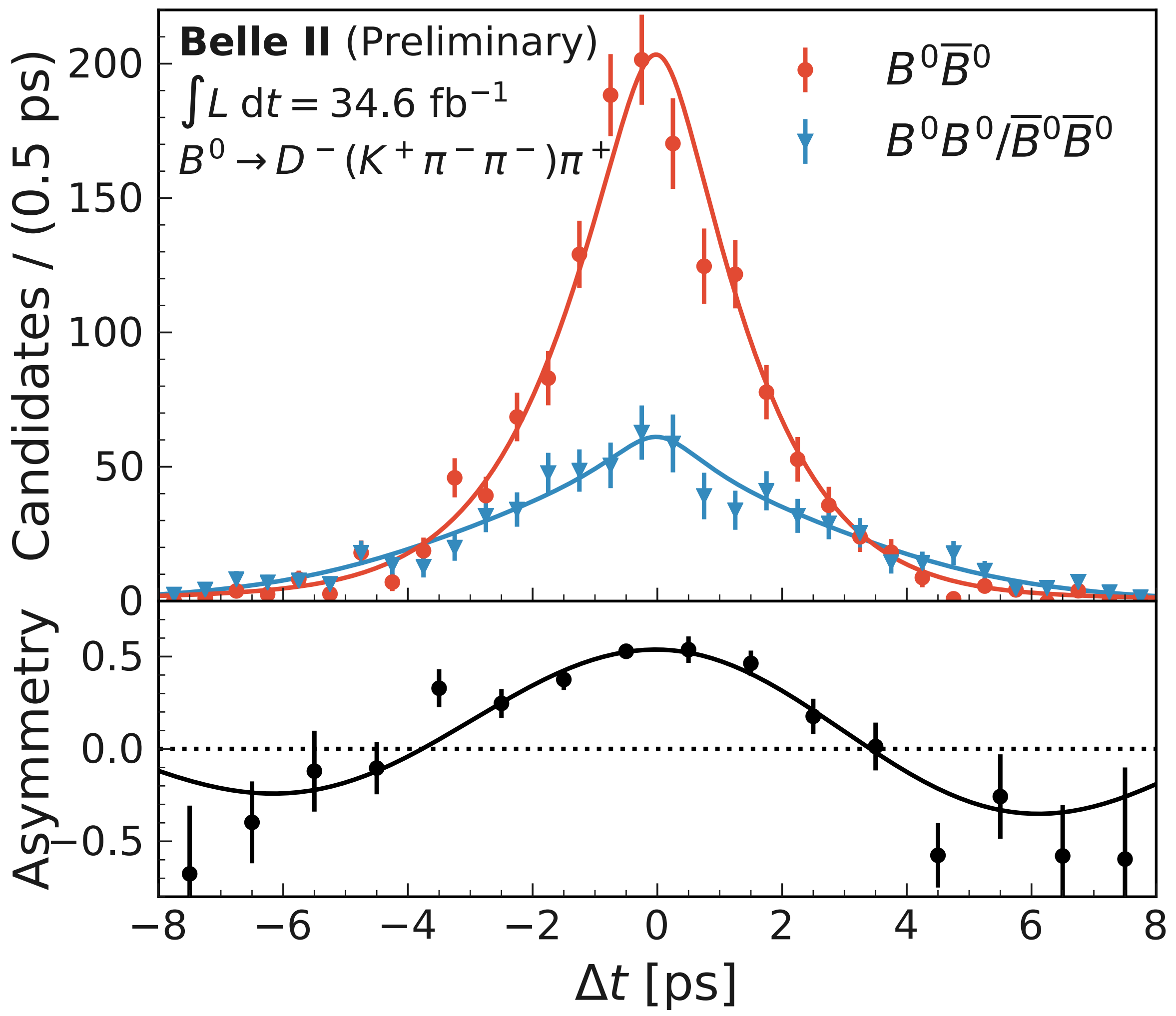


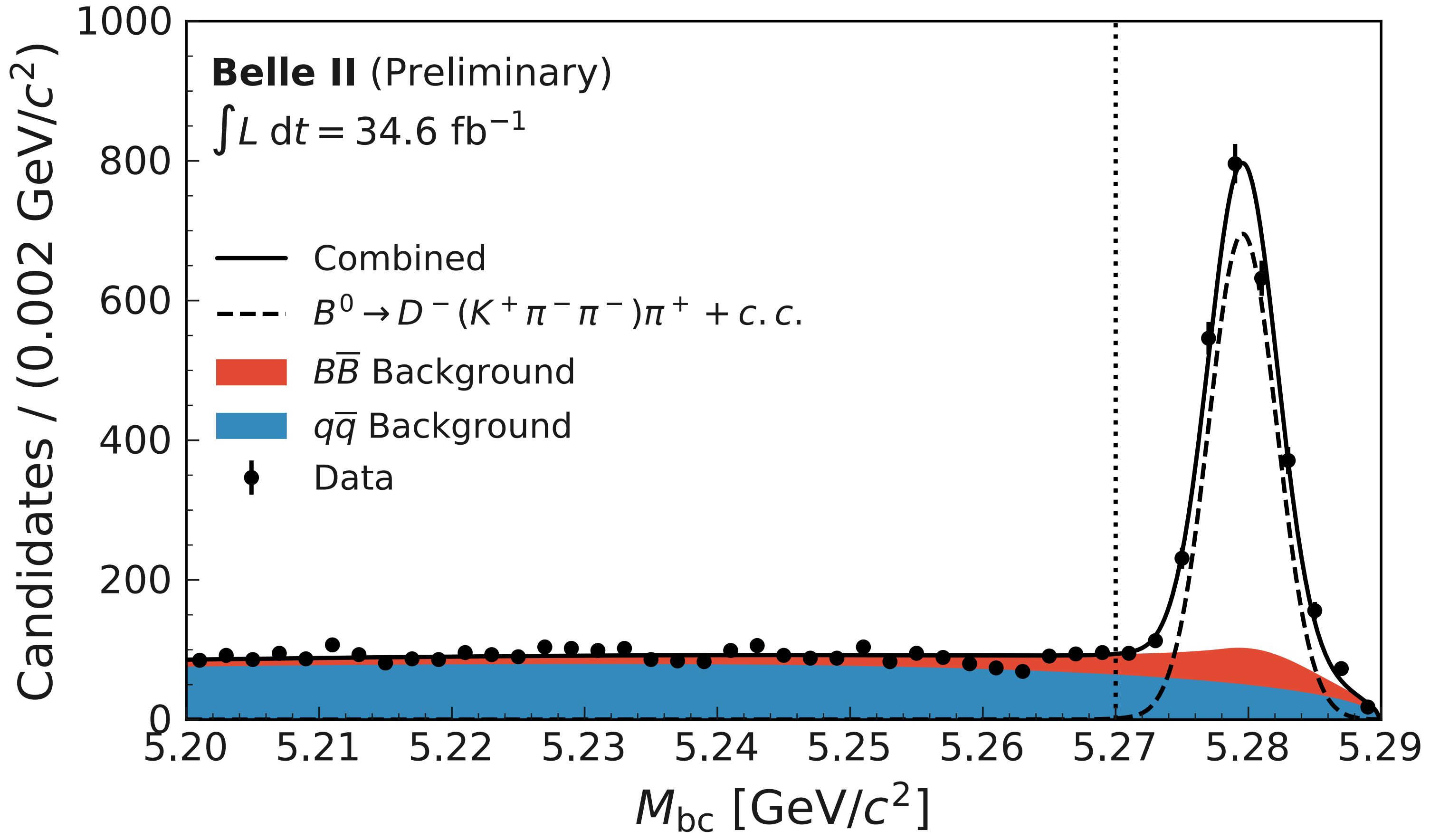
$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 + q[\mathcal{S}sin(\Delta m_d \Delta t) + \mathcal{A}cos(\Delta m_d \Delta t)]\}$$

$\mathcal{S}$ and $\mathcal{A}$: CP-violation parameters.

First Look at Time Dependent CPV in $B \to J/\psi\ K_s^0$

The measurement of $B\overline{B}^0$ mixing parameter using a sample of $B^0 \to D^-(\to K^+\pi^-\pi^-)\ \pi^+$





$\Delta m_d = (0.531 \pm 0.046 \pm 0.013)\ \text{ps}^{-1}$

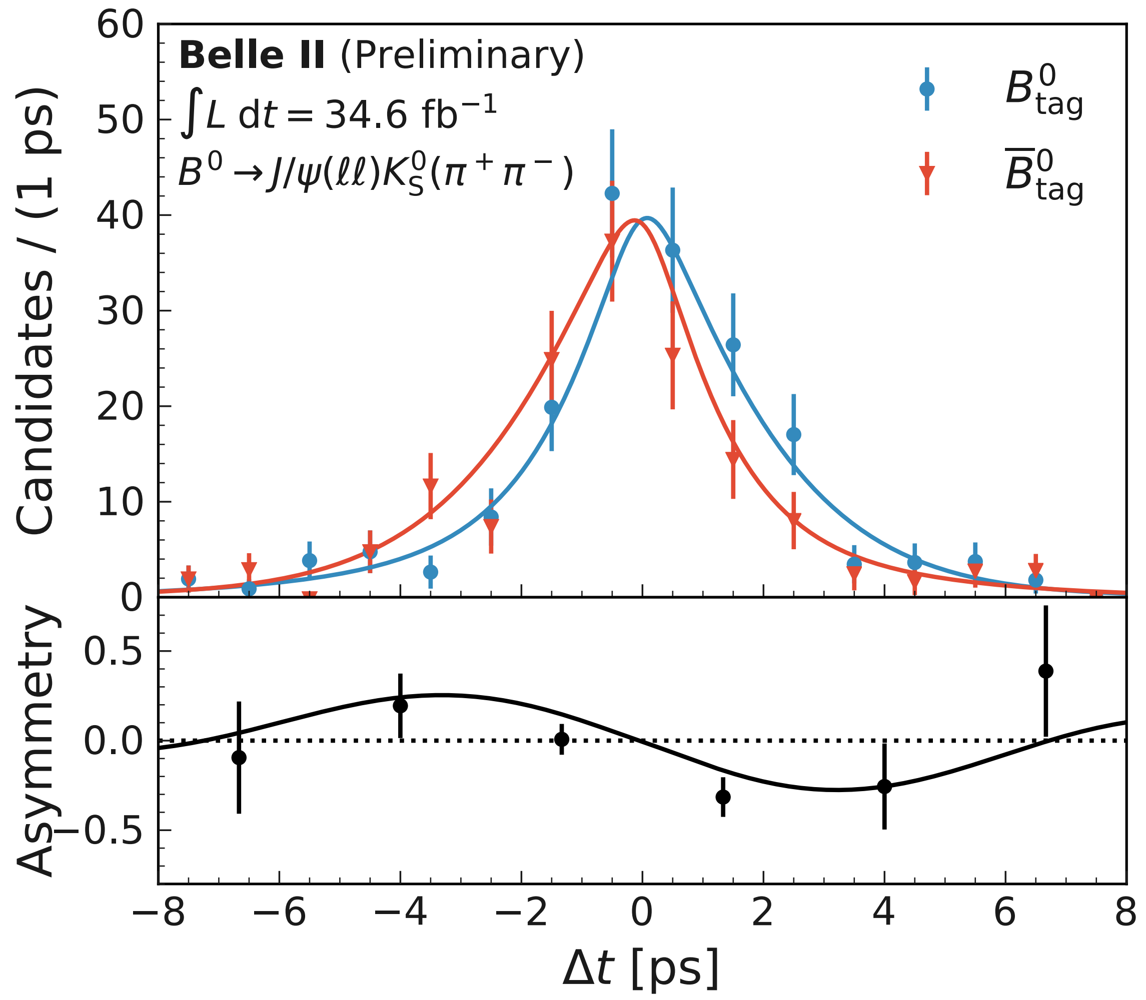
[BELLE2-NOTE-PL-2020-011]

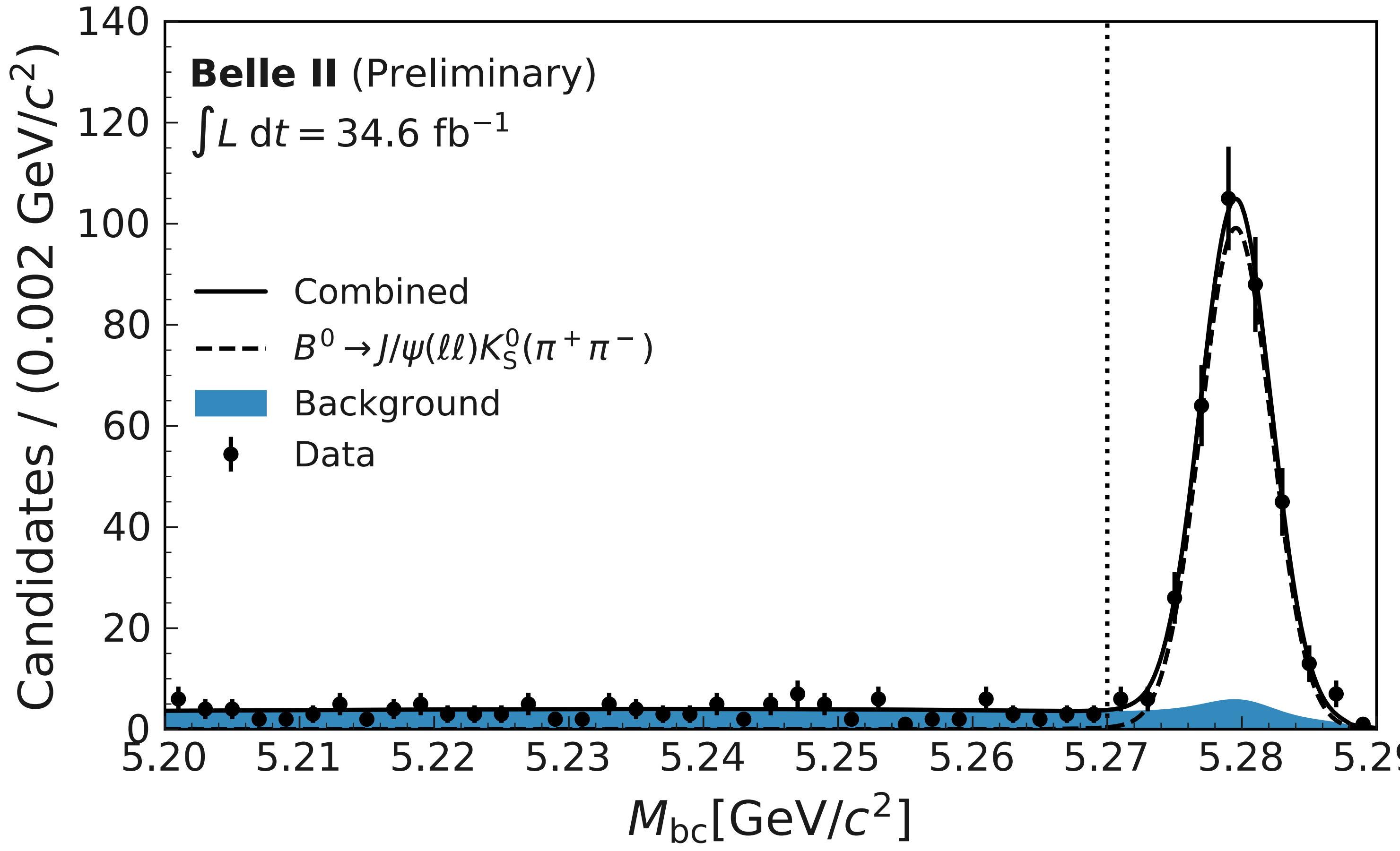
Belle II $\int \mathcal{L}dt = 34.6\ \text{fb}^{-1}$

PDG

B^0 lifetime = (1.519 ± 0.004) ps
$\Delta m_d = (0.5065 \pm 0.0019)\text{ps}^{-1}$

The measurement of time dependent CP violation on $B^0 \to J/\psi\ K_s^0$





$\mathcal{S} = (0.55 \pm 0.21 \pm 0.04)$

(significance ~2.7 σ)