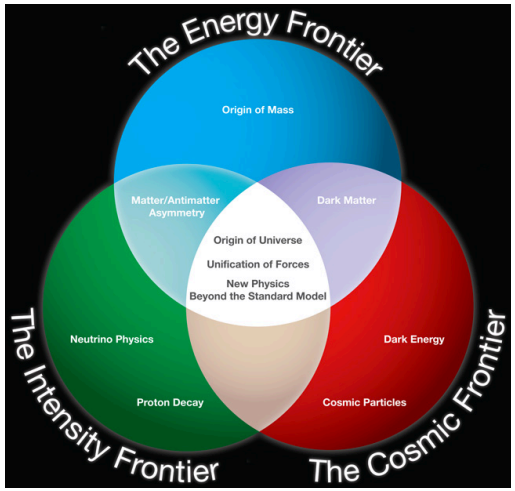
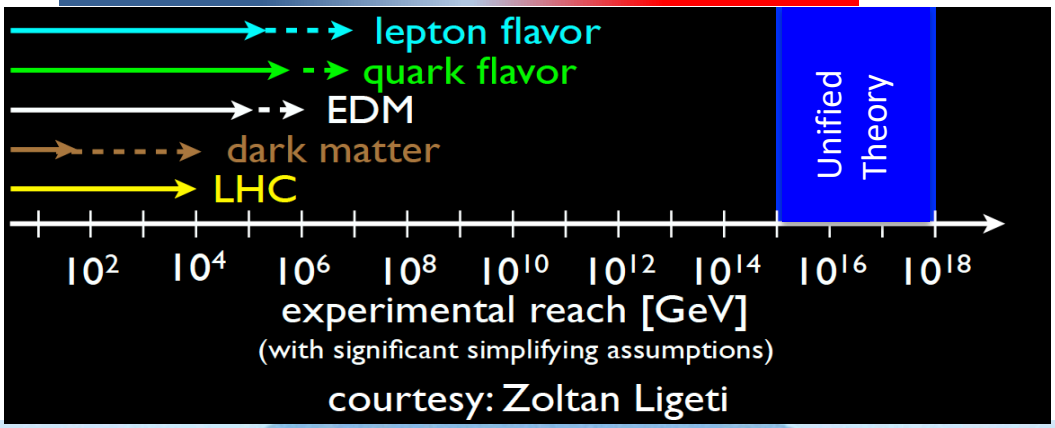
# Status and Prospects

Gagan Mohanty

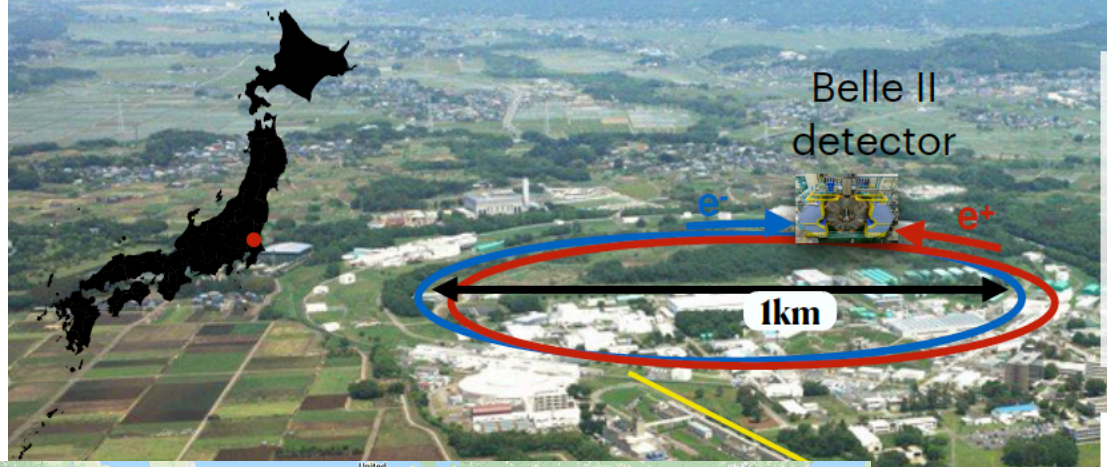
tifr

# Belle II: what & where?




Intensity frontier flavour-factory experiment, Successor to Belle @KEKB (1999-2010)



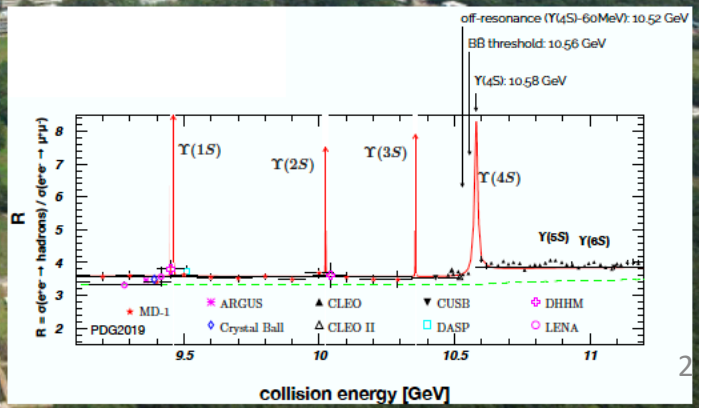

7 GeV $e^-$, 4 GeV $e^+$

$E_{CM}$ Υ(4S) = 10.58 GeV + scans

Υ(4S) → B anti-B

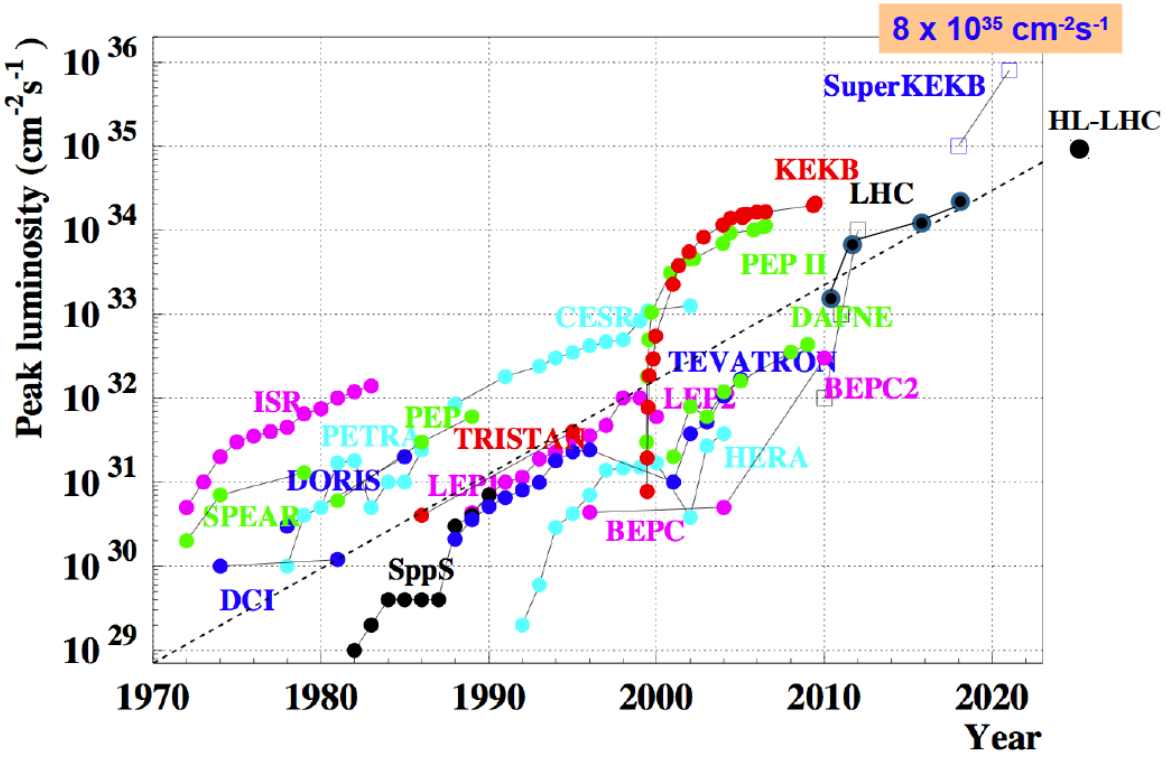
B + Charm + τ + Υ factory


>1000 members,
26 countries



# What science will it do?

- Precision CKM metrology ➔ Standard Model (SM) candle
- New CP violating phase? ➔ CP violation in B and D decays
- Any imprint of new physics in FCNC transitions? ➔ radiative and electroweak penguin decays
- How about charged Higgs boson? ➔ study tree-level B decay to the $\tau\nu$ or $D^{(\star)}\tau\nu$ final state
- New physics in tau sector ➔ search for lepton flavor violating (LFV) tau decays
- Can we probe dark matter from bottom? ➔hidden portal, axiflavons etc.




☞ Belle II @ SuperKEKB will address these questions with almost two orders of magnitude larger dataset than Belle+BABAR

# Why Belle II when LHCb is rocking?

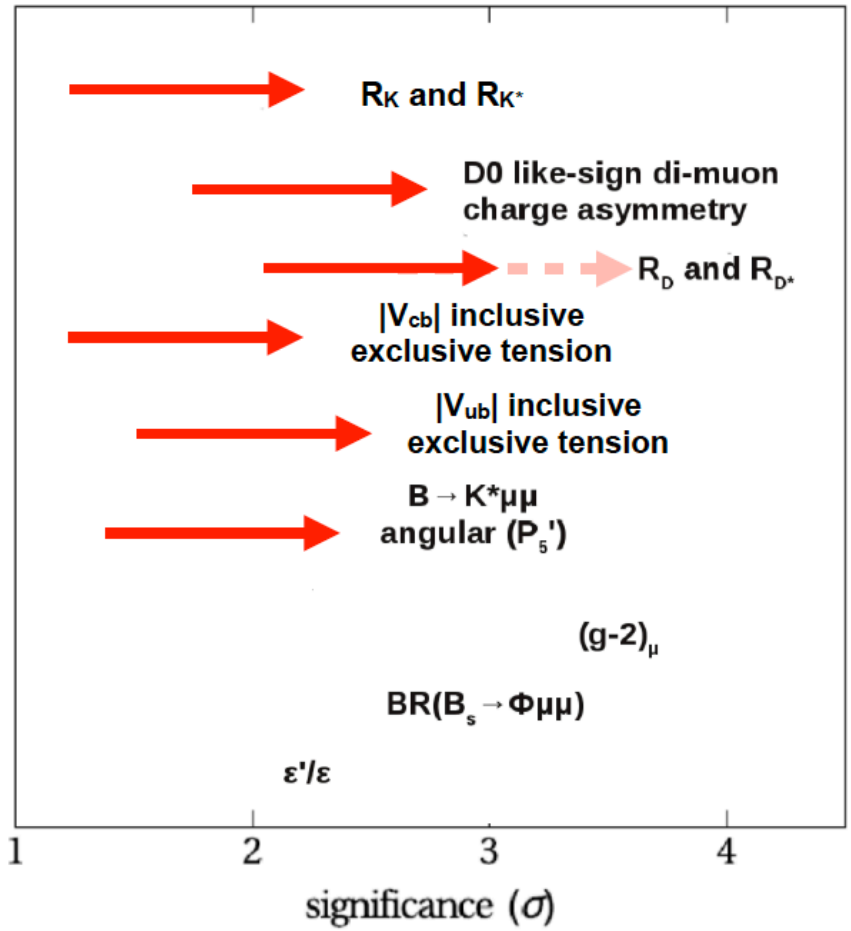
| Observables | Expected the. accuracy | Expected exp. uncertainty | Facility (2025) |
|---|---|---|---|
| UT angles & sides | | | |
| $\phi_1$ [°] | *** | 0.4 | Belle II |
| $\phi_2$ [°] | ** | 1.0 | Belle II |
| $\phi_3$ [°] | *** | 1.0 | LHCb/Belle II |
| $\|V_{cb}\|$ incl. | *** | 1% | Belle II |
| $\|V_{cb}\|$ 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 |
| $S(B \to K^0_S\pi^0\gamma)$ | *** | 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 |
| $R(B \to K^*\ell\ell)$ | *** | 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 |
| $A_{CP}(D^0 \to K^0_S\pi^0)$ $[10^{-2}]$ | ** | 0.03 | Belle II |
| $\|q/p\|(D^0 \to K^0_S\pi^+\pi^-)$ | *** | 0.03 | Belle II |
| $A_{CP}(D^+ \to \pi^+\pi^0)$ $[10^{-2}]$ | ** | 0.17 | 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 |

☞ Belle II physics book

arXiv:1808.10567
(10.1093/ptep/ptz106)

- Left table lists observables where Belle II has an edge over LHCb and vice versa
- Great for final states with $\gamma$, $\pi^0$ and $\nu$(s) ⇒ thanks to the clean $e^+e^-$ environment
- Good $K^0_S$ detection coverage
- Similar performance for the electron and muon channels ⇒ low-energy collisions
- Inclusive analysis possible ⇒ control on kinematics
- Advantageous to search for LFV tau decays

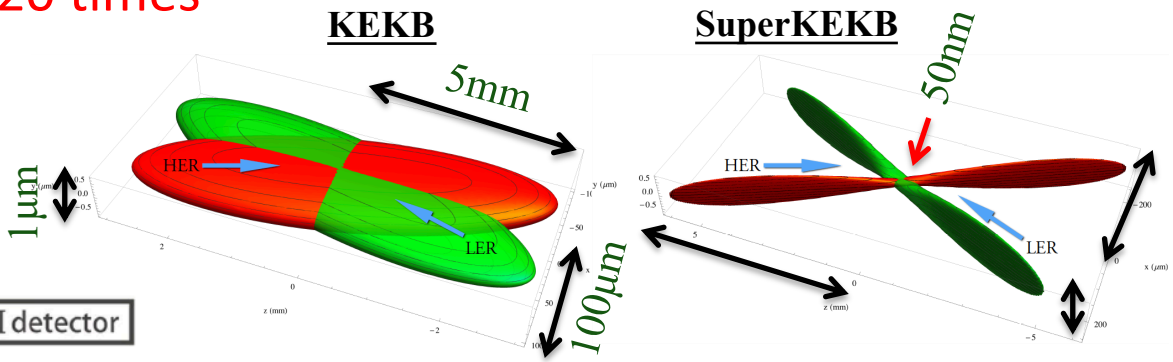
# Nature's hint or teasing?

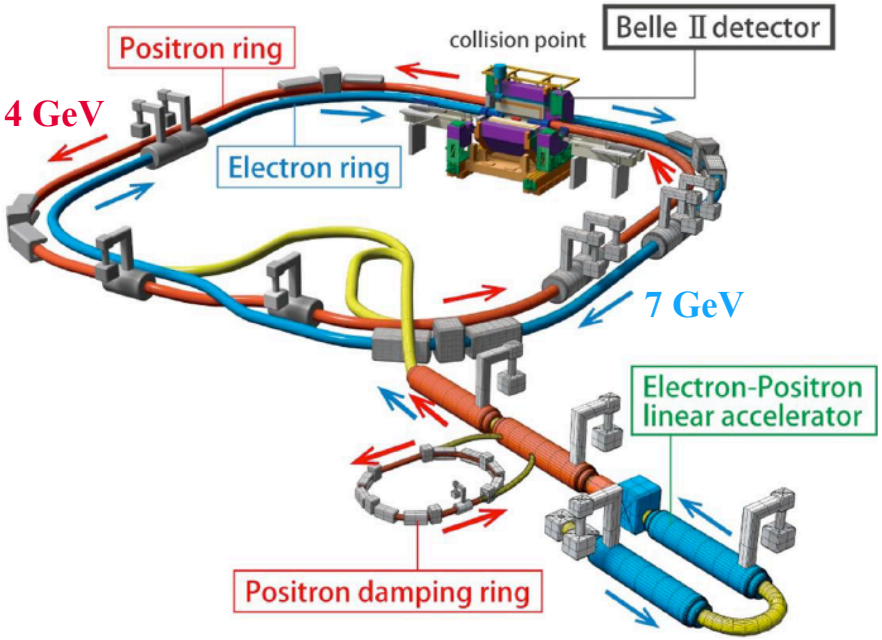


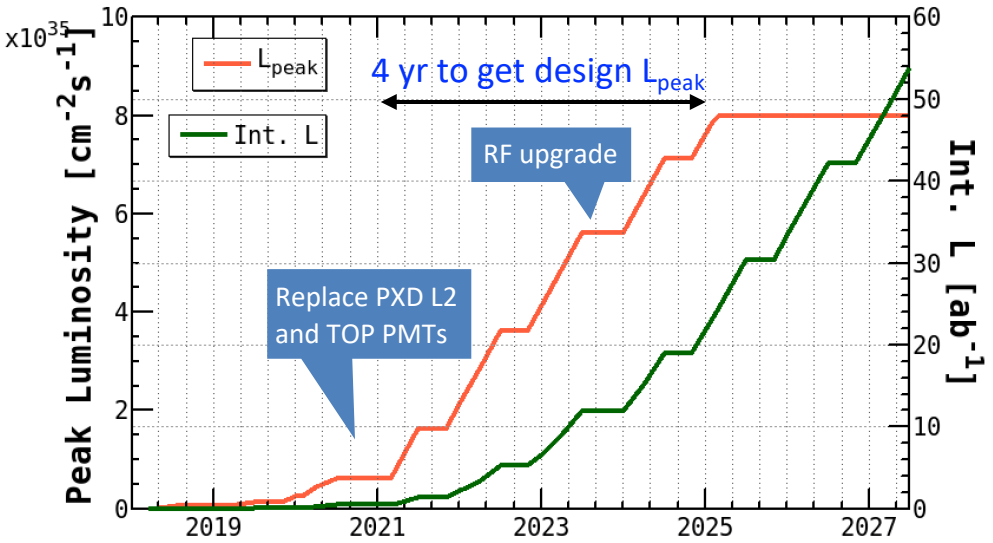

☞ Should be able to either confirm or refute many of the flavor anomalies, especially the IITH favorite one $R_{K^{(*)}}$

# Super KEKB : New Intensity Frontier machine

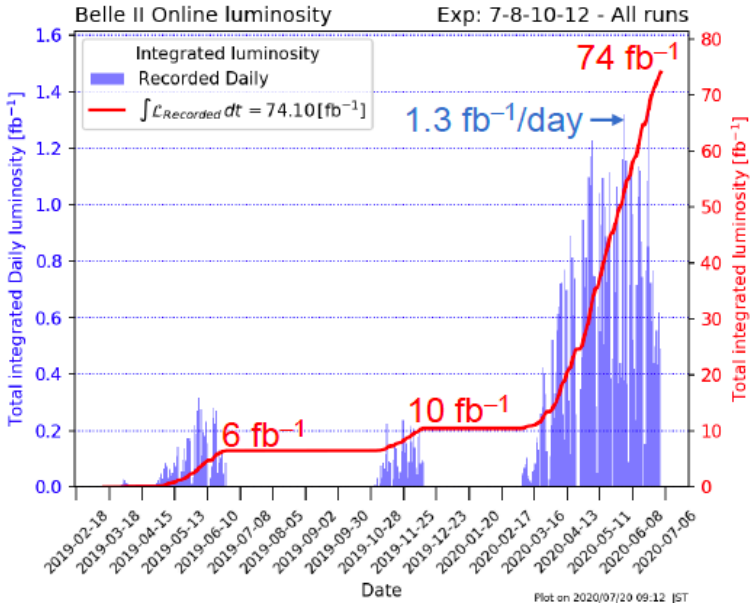
- Targets to deliver $e^+e^-$ collisions at a peak luminosity of $8 \times 10^{35}\ cm^{-2}s^{-1}$, 40 times that of KEKB
  - ✧ Increase beam currents twice
  - ✧ Reduce beam size by 20 times



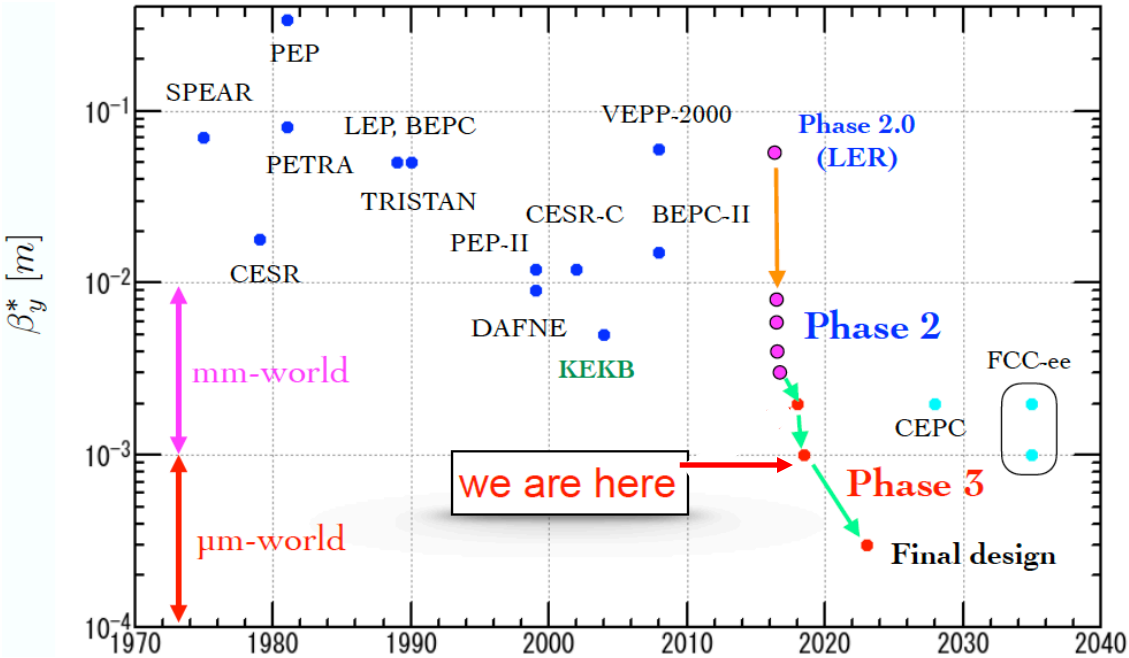



# How far have we gone?




- Reached $\beta_y^*$ = 0.8 mm by end of last run in July
- Aim at squeezing $\beta_y^*$ down to 0.6 mm in coming Autumn run
- ☞ Final design luminosity requires $\beta_y^*$ to jump to 0.3 mm

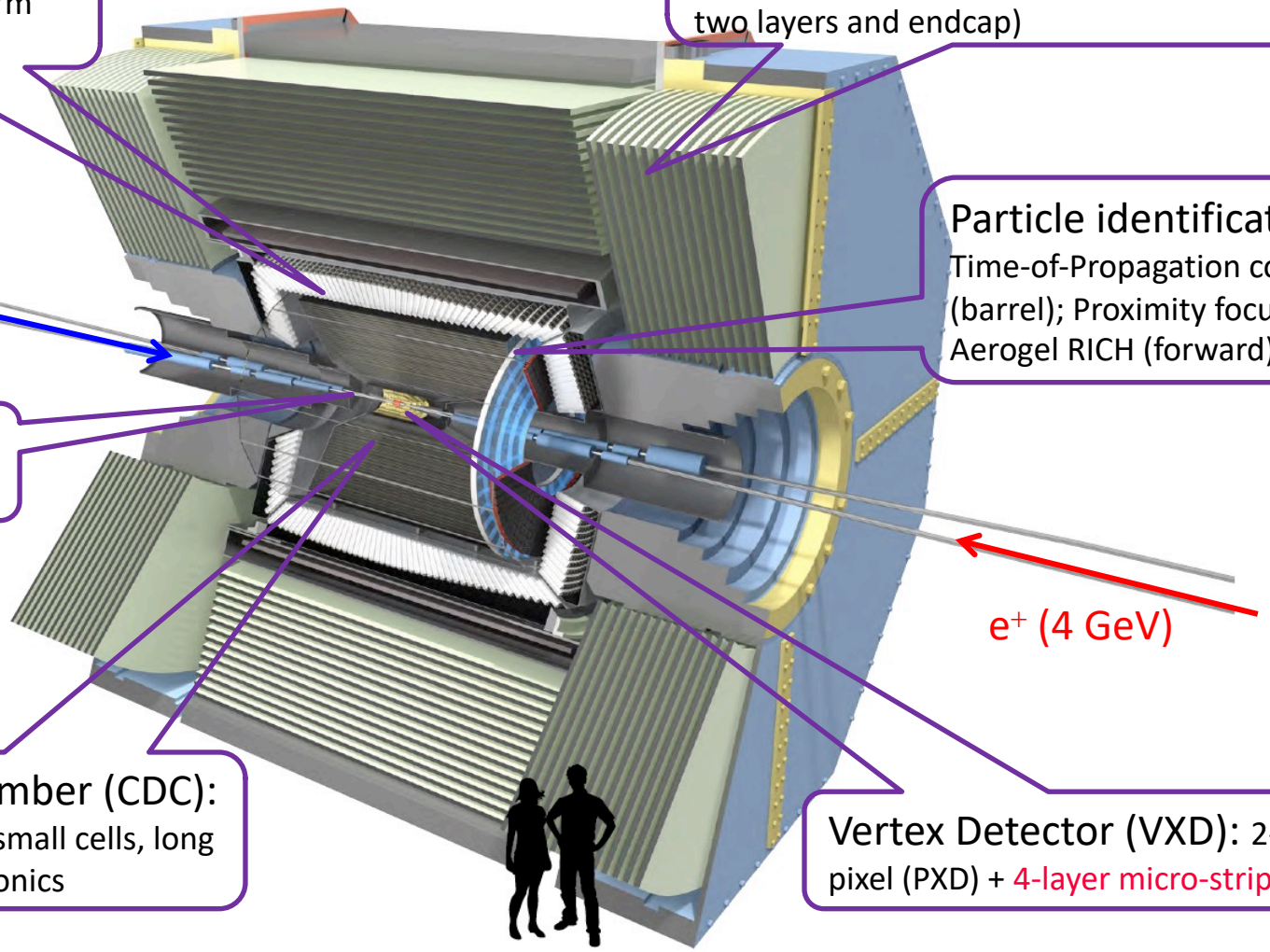
- ➢ Phase 1 (2016): single beam background study
- Phase 2 (2018): beam commissioning (establish nano-beam scheme, reach the KEKB luminosity, and measure beam backgrounds) as well as for doing some physics with partial vertex detector
- Phase 3 (2019 – …): physics run with complete vertex detector




- Currents achieved: 880 (940) mA for $e^+$ ($e^-$) beam ➔ need 3 (4)× scale up

# Belle II: A 21st century HEP experiment

☞ Designed to operate with a performance similar or better than Belle, but in a harsh beam background condition



EM Calorimeter (ECL): CsI(Tl) crystals, waveform sampling readout

$K_L$ and muon detector (KLM): Resistive plate counter (barrel outer); plastic scintillator + WLS fiber + SiPM (barrel inner two layers and endcap)

Particle identification: Time-of-Propagation counter (barrel); Proximity focusing Aerogel RICH (forward)

$e^-$ (7 GeV)

Beryllium beam-pipe (10 mm radius)

$e^+$ (4 GeV)

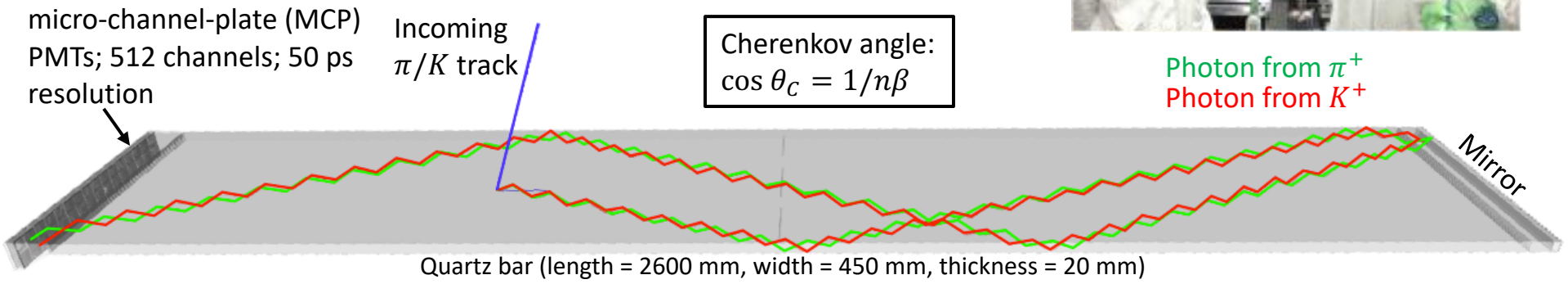
Central Drift Chamber (CDC): He(50%)+$C_2H_6$(50%), small cells, long lever arm, fast electronics

Vertex Detector (VXD): 2-layer pixel (PXD) + 4-layer micro-strip (SVD)

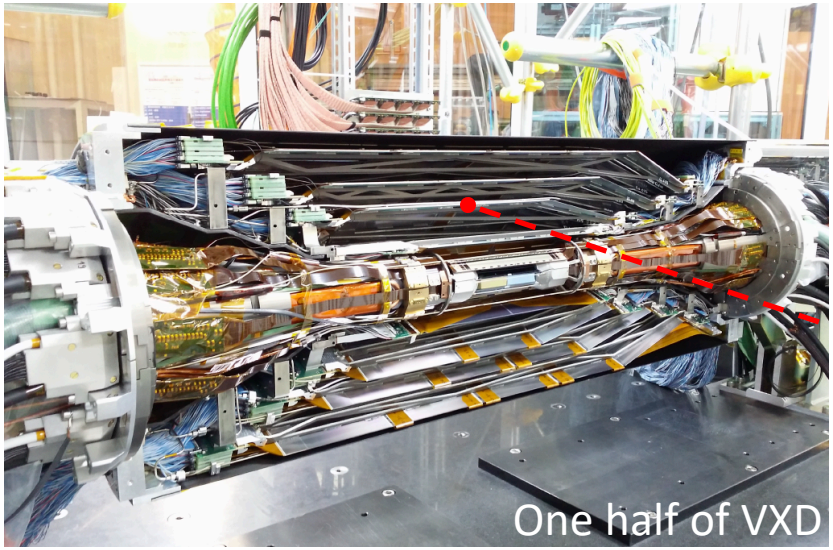
# Two detector highlights

## Barrel PID (imaging TOP): JP, US, SI and IT

☞ Example of Cherenkov-photon paths for 2 GeV pion and kaon traversing in a TOP quartz bar




## VXD (6 layer Si for vertexing & inner tracking) ☞ even useful for particle ID




Beam-pipe r = 10 mm

DEPFET pixels: DE, CZ, ES…

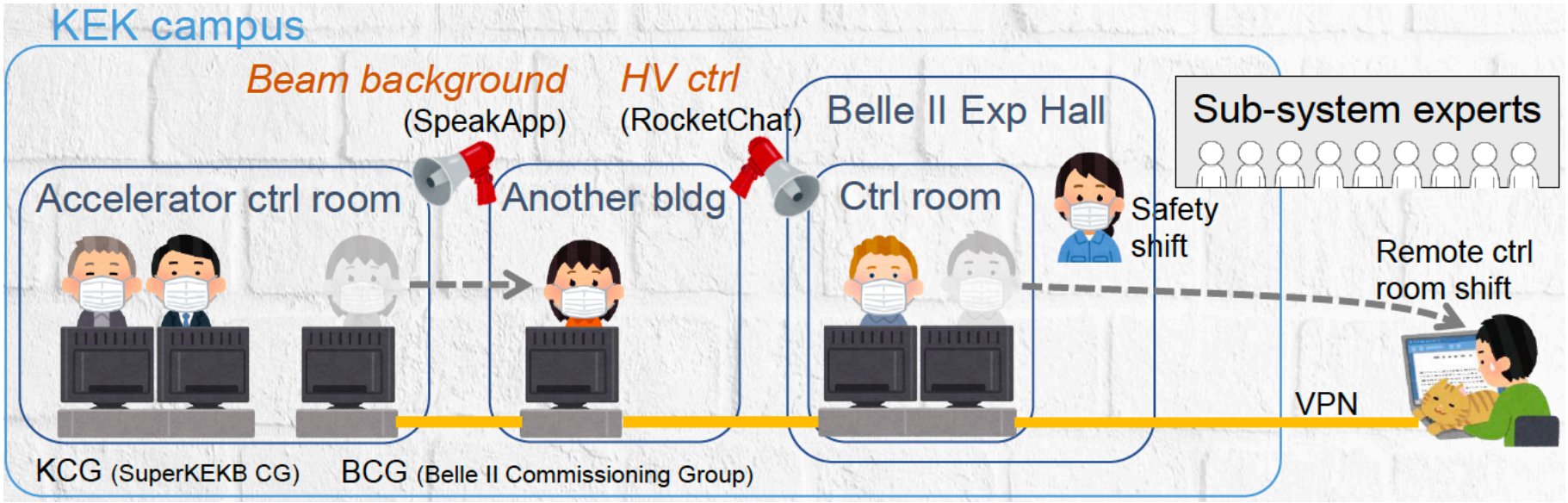
- Layer 1 r = 14 mm
- Layer 2 r = 22 mm (2/12 now, rest in 2021)

DSSD (double sided micro-strips)

- Layer 3 r = 38 mm (AU)
- Layer 4 r = 80 mm (IN)
- Layer 5 r = 115 mm (AT)
- Layer 6 r = 140 mm (JP)

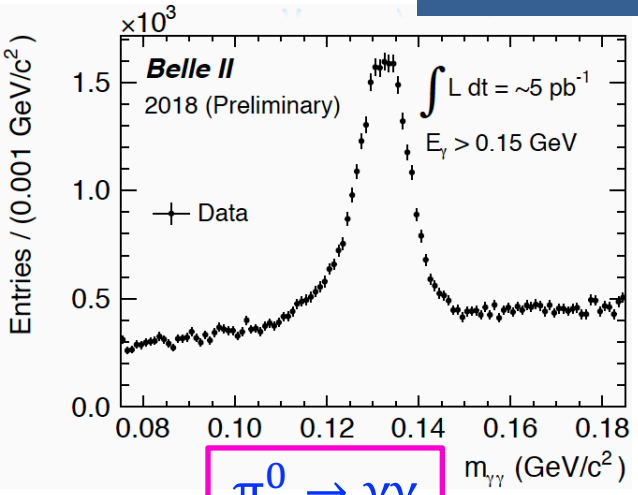
} FWD/BWD: IT

# worked during Covid-19



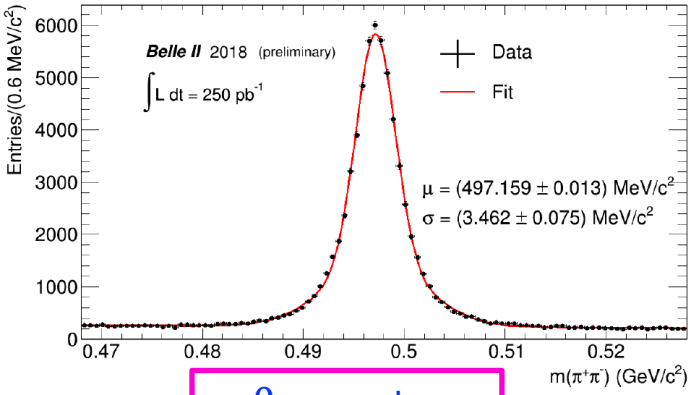

- SuperKEKB/Belle II continued to operate even under pandemic while ensuring a minimum risk of infection
- Minimize p-2-p contact and avoid 3C
  - Closed space
  - Closed places
  - Close-contact setting
  - Remote control room and expert shifts
  - Travel restrictions (~40 Belle II colleagues onsite)
  - Liberal online meetings
- Proper hygiene (face mask, alcohol disinfection, ventilation, …)

# Early rediscovery at phase-2

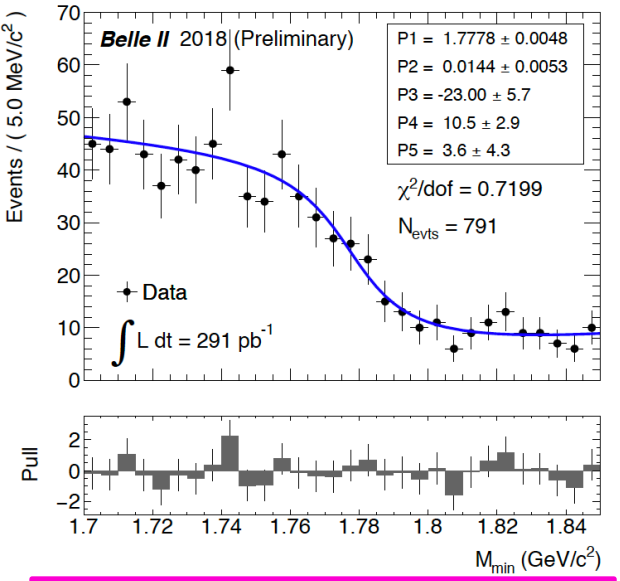



$\pi^0 \to \gamma\gamma$

- 472 $fb^{-1}$ data used for the rediscovery of known processes
- ☞ Our team has made good contribution

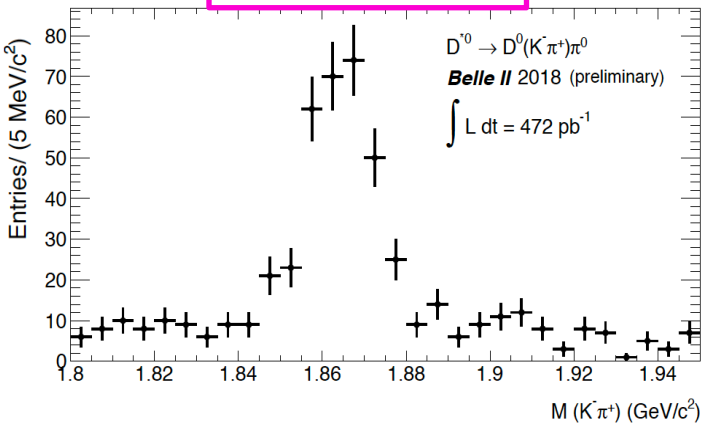


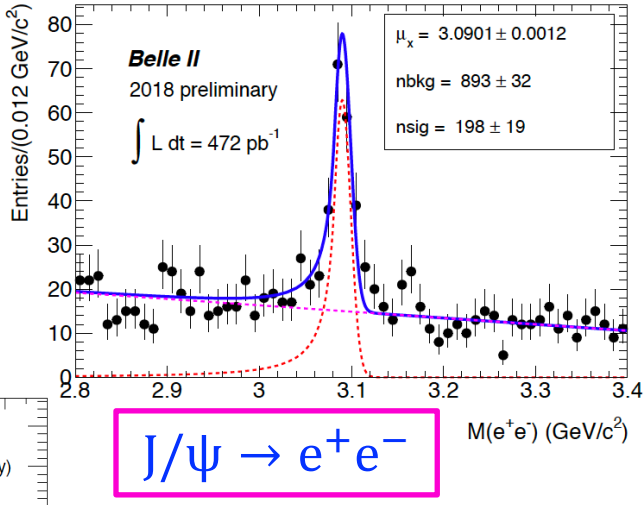

$K^0_S \to \pi^+\pi^-$




Pseudomass in $\tau \to 3\pi\nu_\tau$

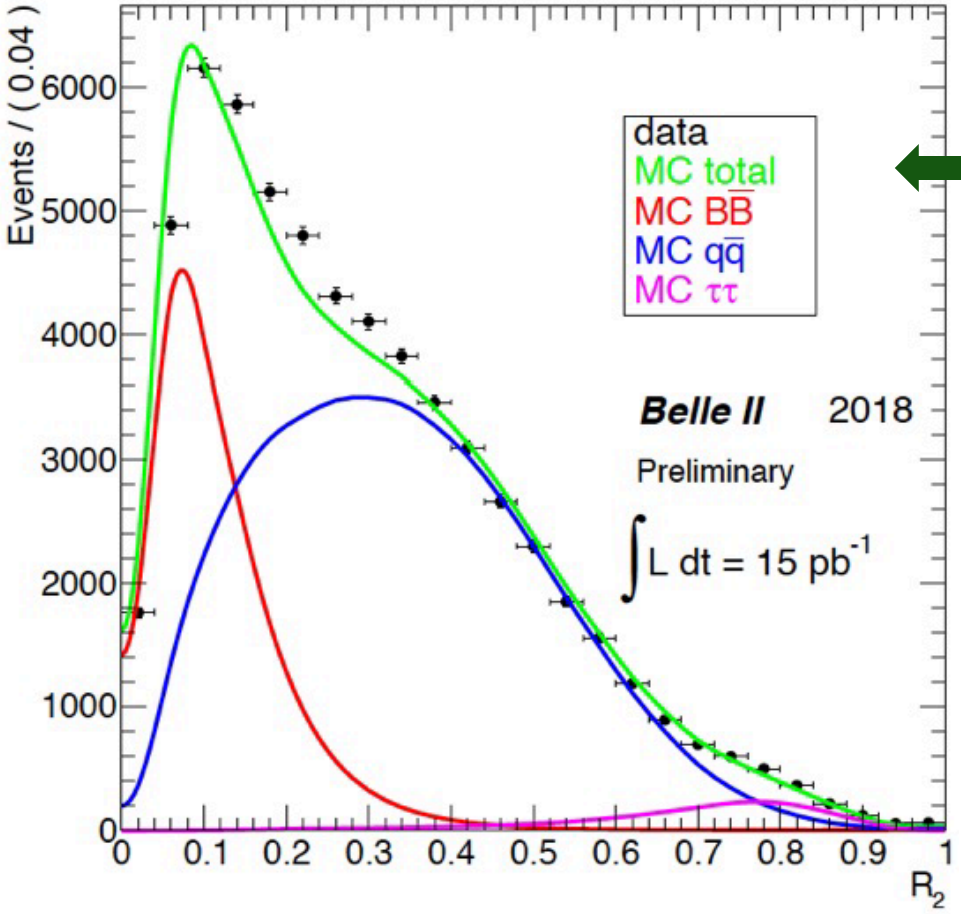
$D^0 \to K^-\pi^+$

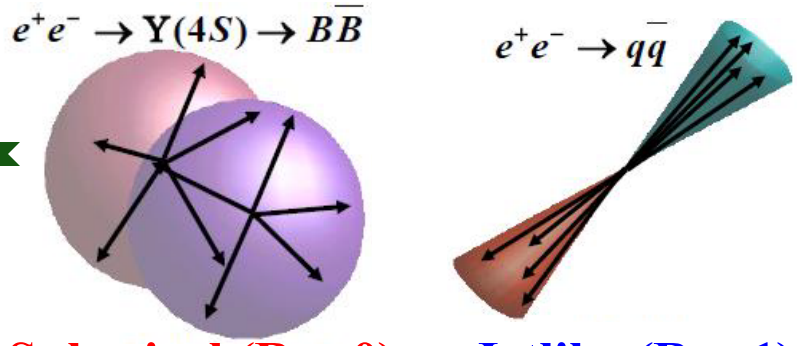



$J/\psi \to e^+e^-$

# We also found $B$ mesons…



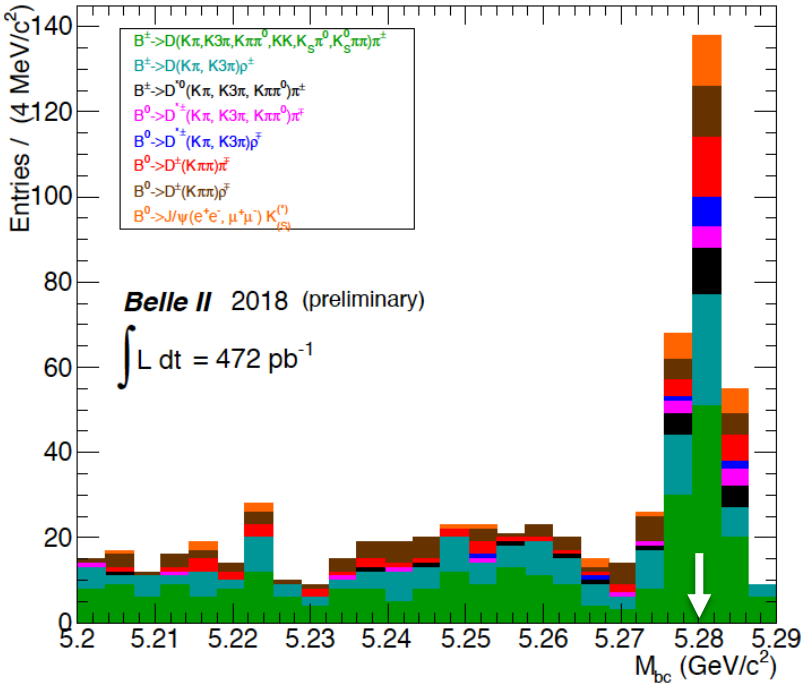

**Spherical** ($R_2 \sim 0$) **Jetlike** ($R_2 \sim 1$)

- Event topology tells us that we are seeing spherical $B\bar{B}$ events

- Further proof came from the plot of beam-energy constrained mass:

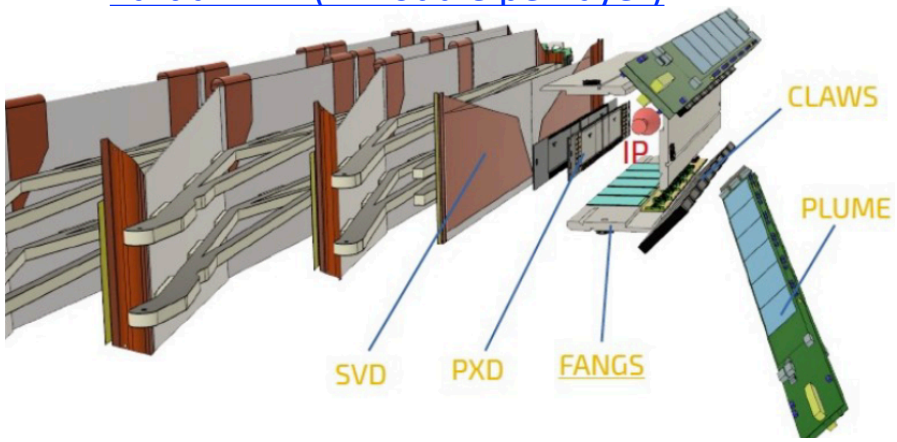
$$M_{\mathrm{bc}} = \sqrt{E_{\mathrm{beam}}^2 - \vec{p}_B^{*2}}$$

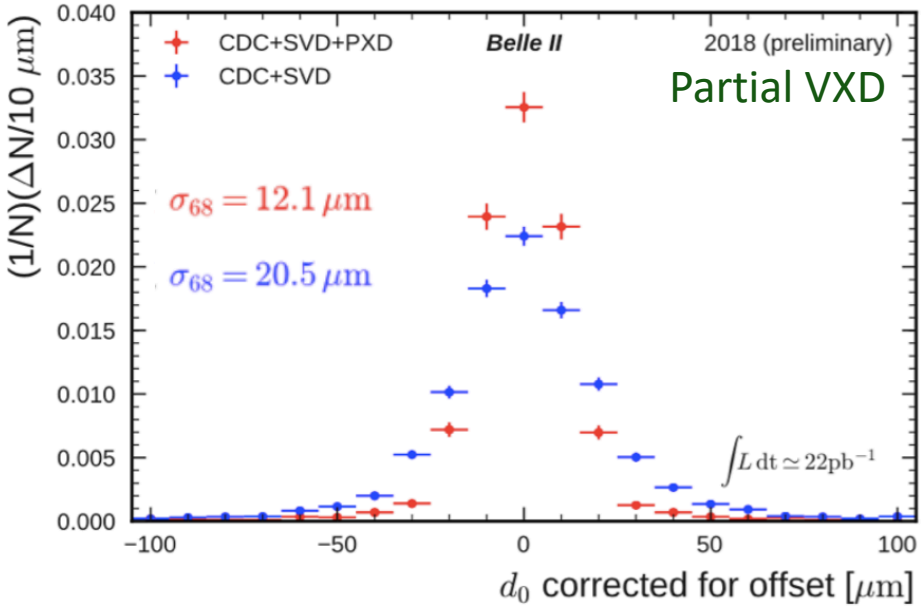
☞ Major contributions from us



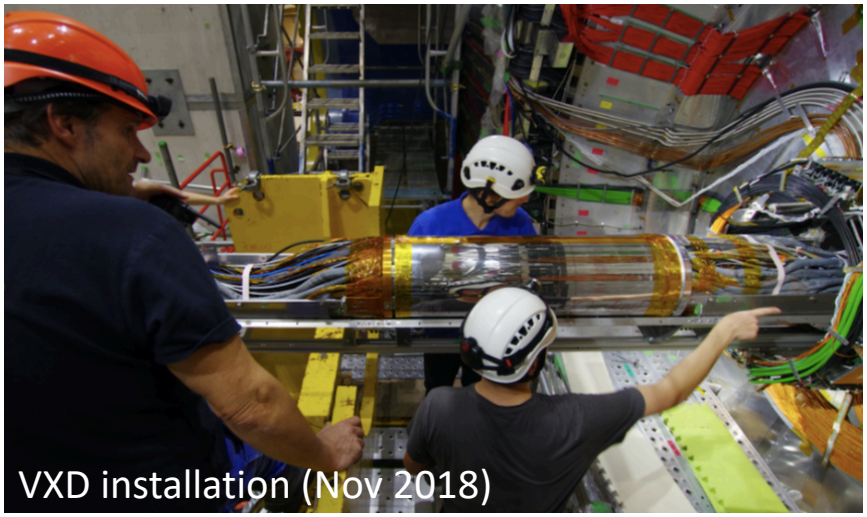
# Going from phase-2 to phase-3

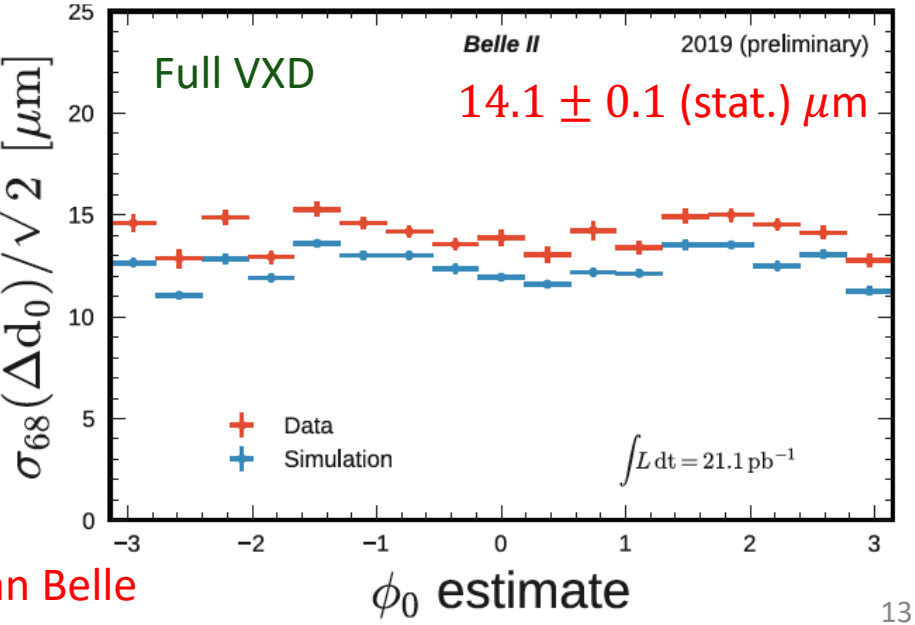
Partial VXD (1 module per layer)




Full VXD (L2 has 2/12 modules)

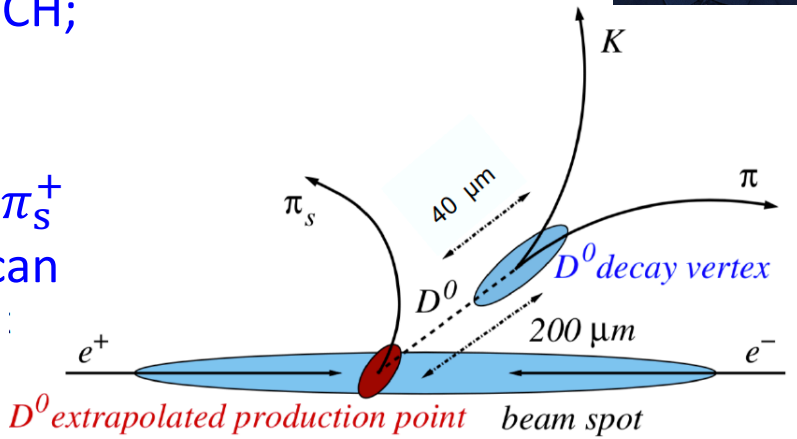


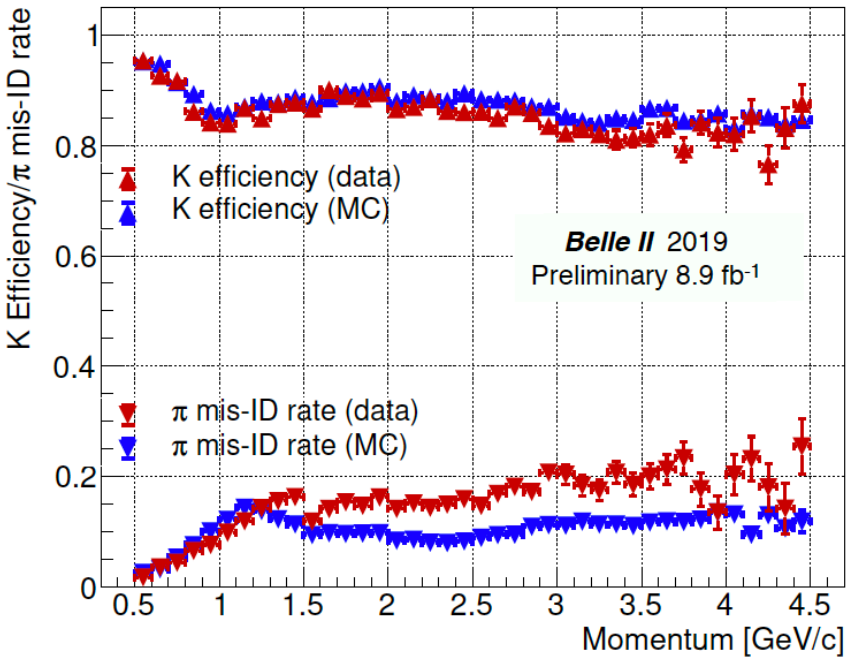



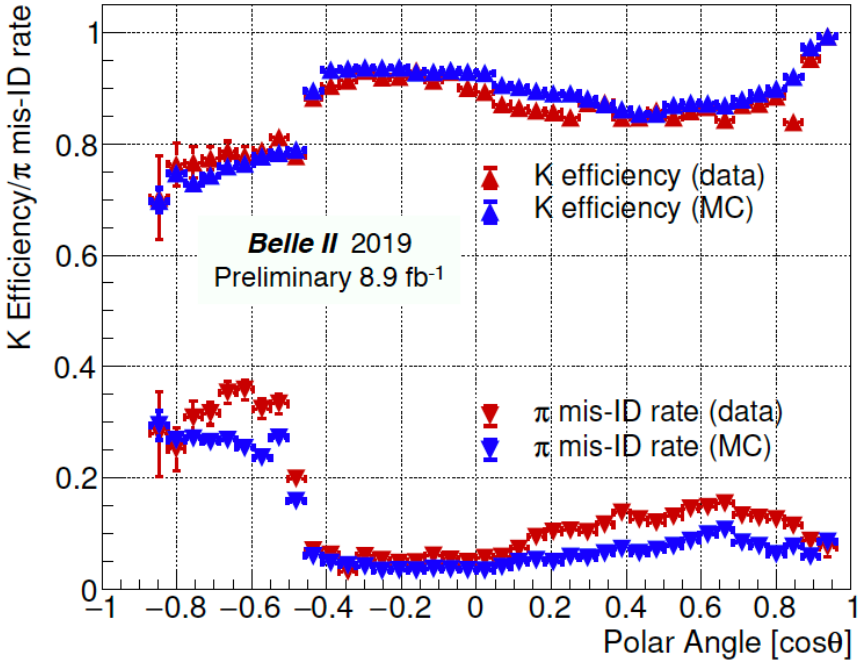

☞ Impact parameter resolution twice better than Belle

# Charged kaon-pion separation

- Provided by the PID system: mainly TOP & ARICH; CDC also helps (SVD will also come online!)
- Performance is tested with $D^{*+} \to D^0[K^-\pi^+]\pi_s^+$ decays, where the daughter kaons and pions can be identified kinematically

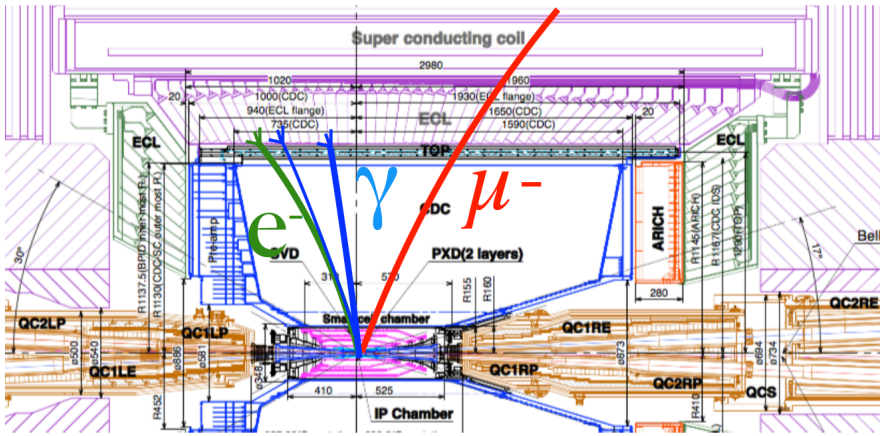


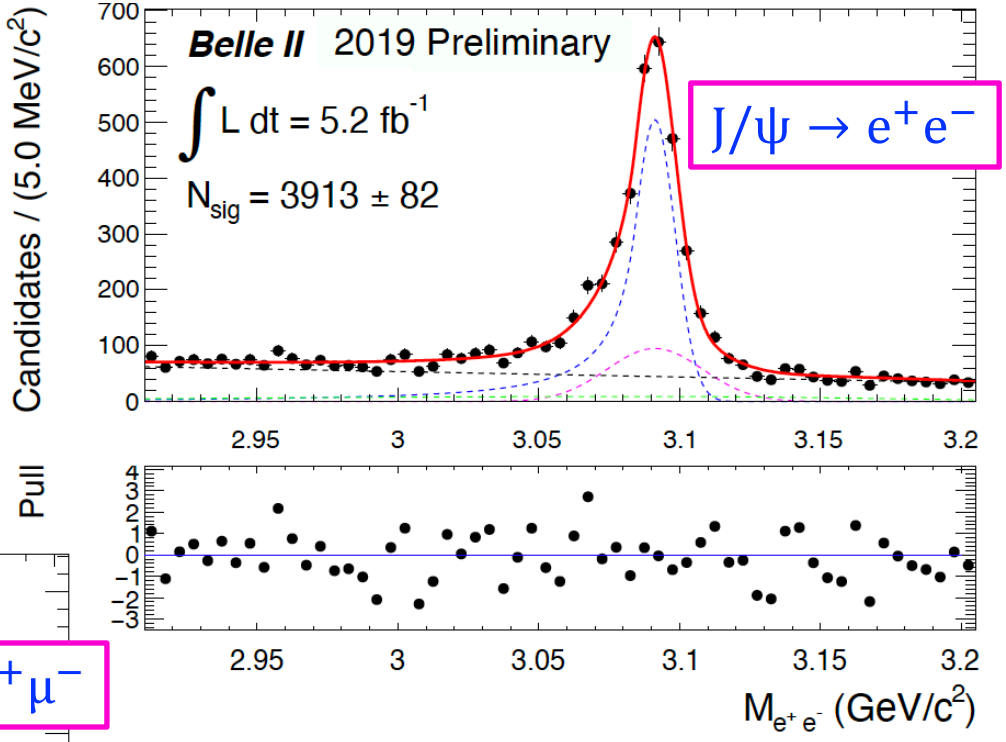



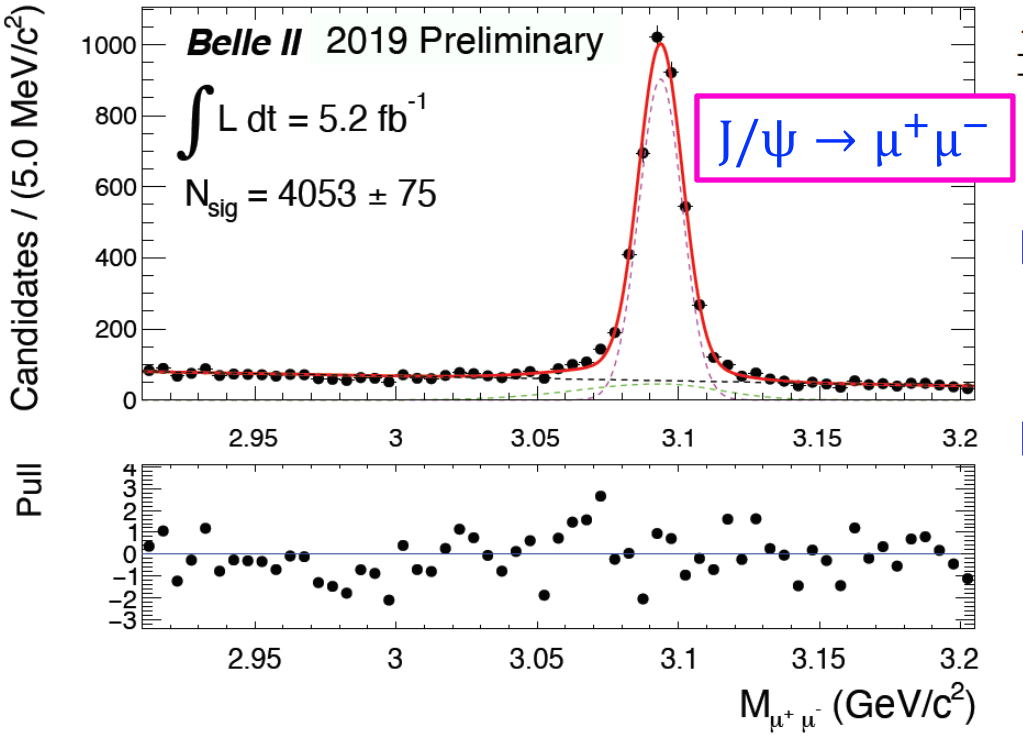




☞ MC simulations yet to include embedded random triggers to correctly represent beam backgrounds and electronic noise

# Electron and muon identification



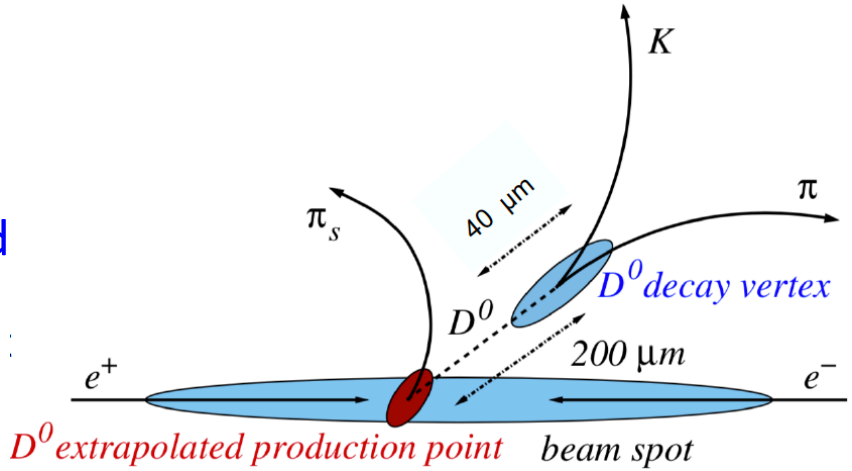



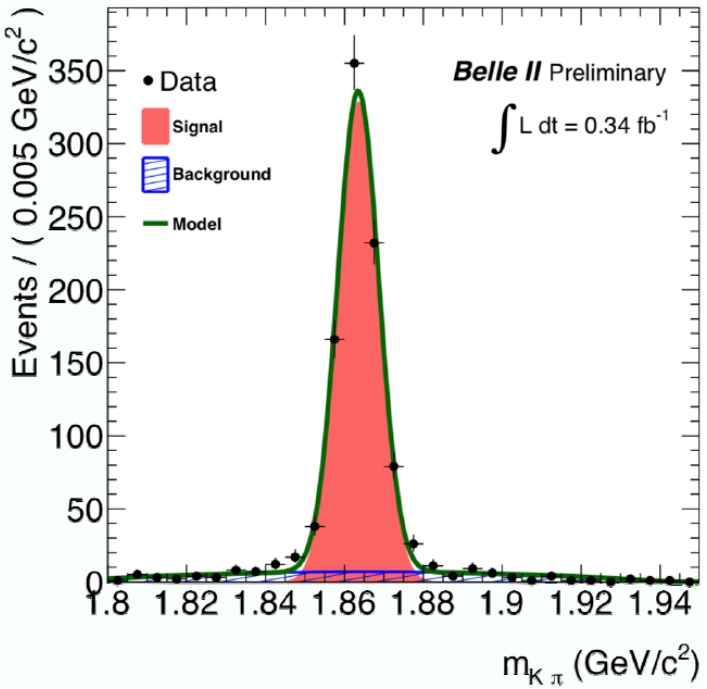



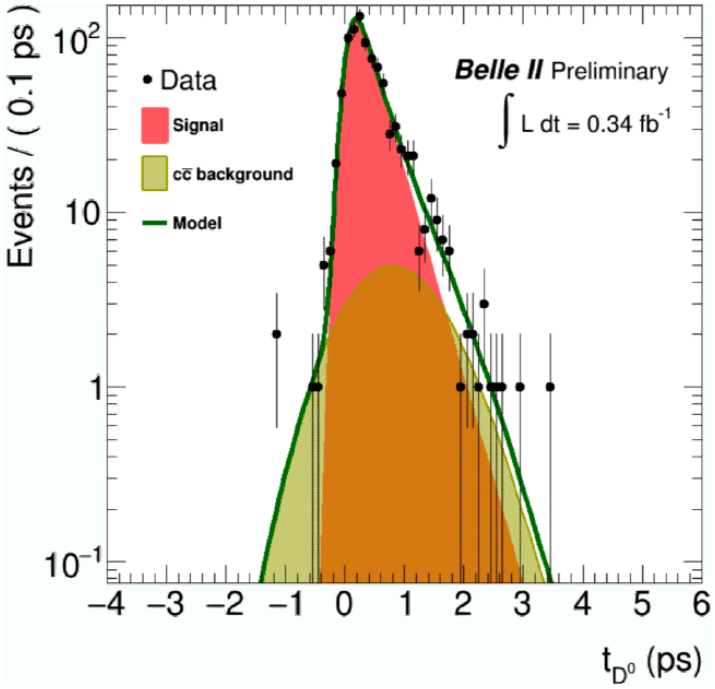

- Electron ID largely relies on the ECL and CDC (E/p, …)
- Muons are identified mostly with information from the KLM

# Measurement of $D^0$ lifetime

- Use the self-tagging decay channel $D^{*+} \rightarrow D^0[K^-\pi^+]\pi_s^+$
- Fit the full decay chain imposing $D^0$ mass constraint and $D^*$ production to measured beam spot region
- ☞ Constitutes a powerful test for the vertex fitting performance



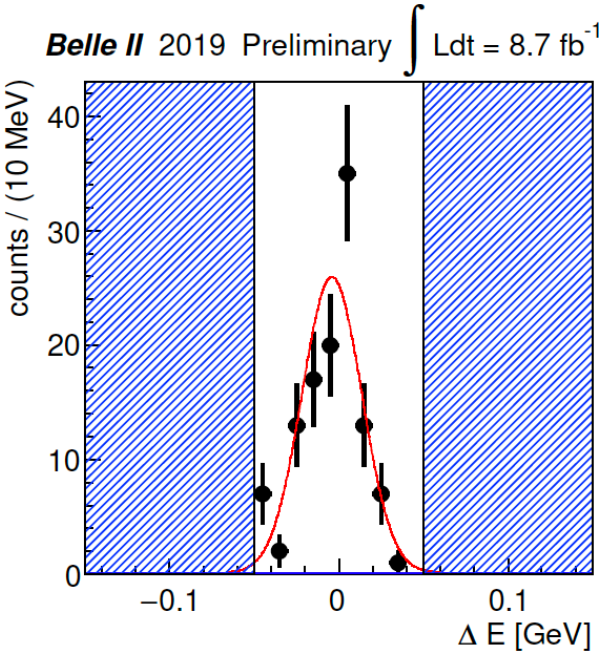



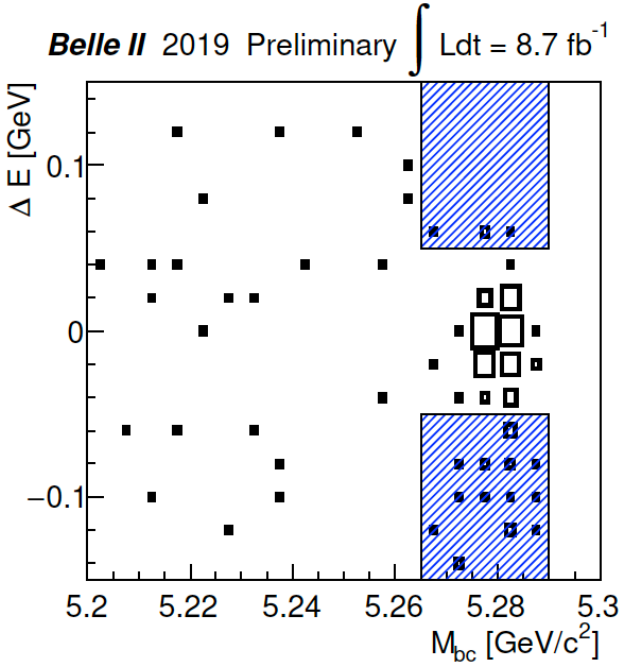




$\tau_D = 370 \pm 40$ fs ✓ Consistent with PDG (410 fs)

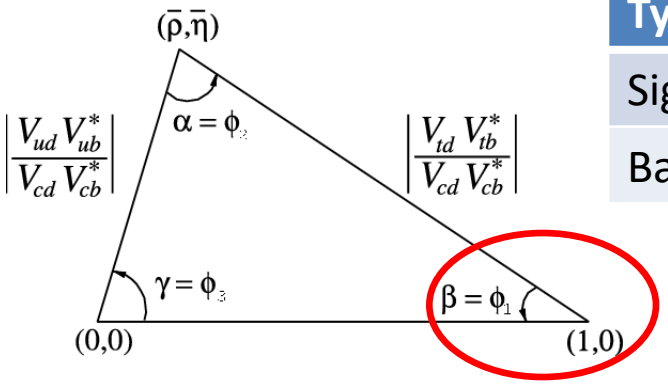
# Getting ready for

- Samples are being made available for time-dependent CP violation study
- $\Delta E$ is the difference between $E_{beam}$ and $E_B^*$

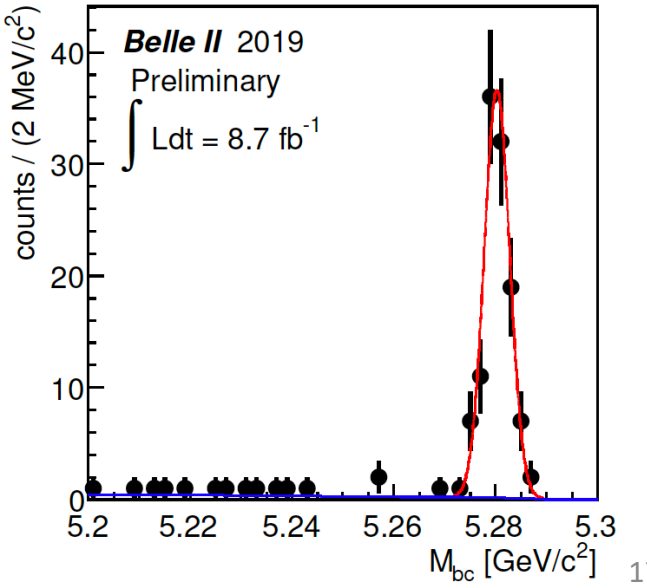


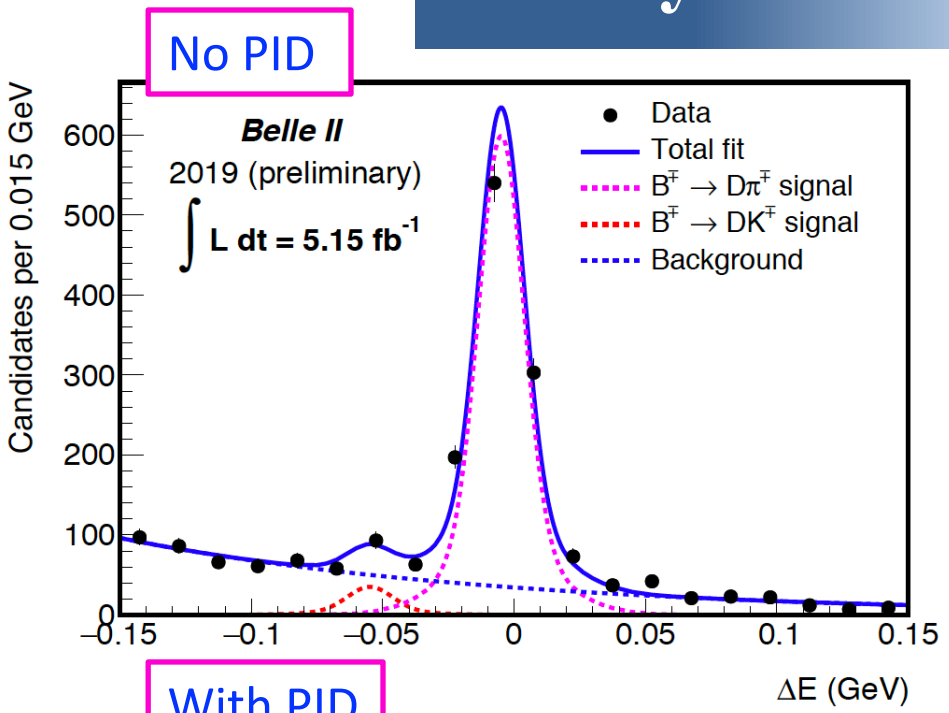

☞ "Golden channel" for the CKM angle $\beta \equiv \phi_1$

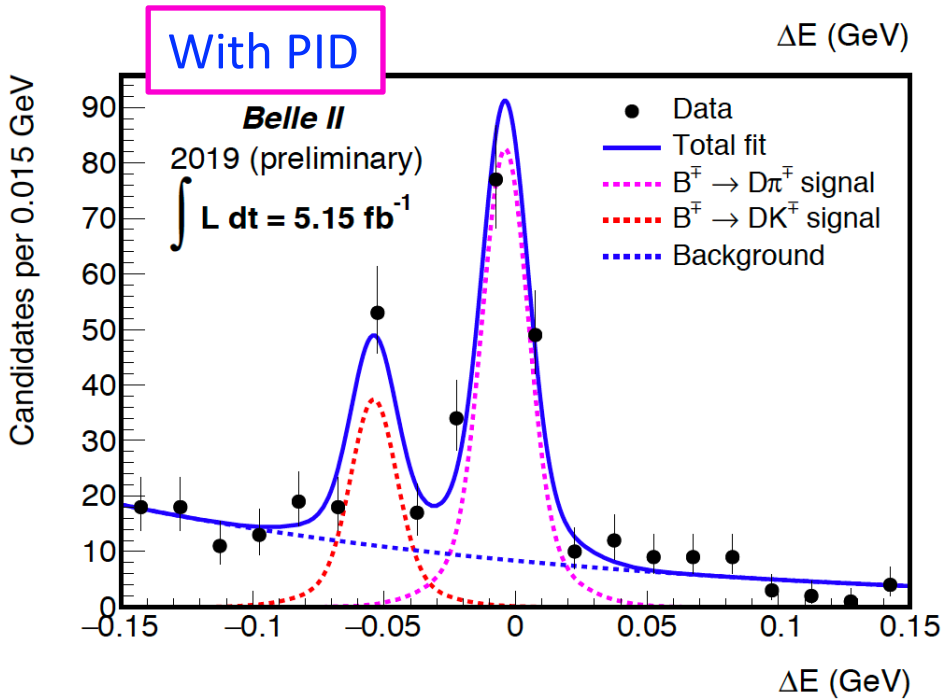



| Type | Yield |
|---|---|
| Signal | $113.9 \pm 11.1$ |
| Background | $1.3 \pm 0.3$ |



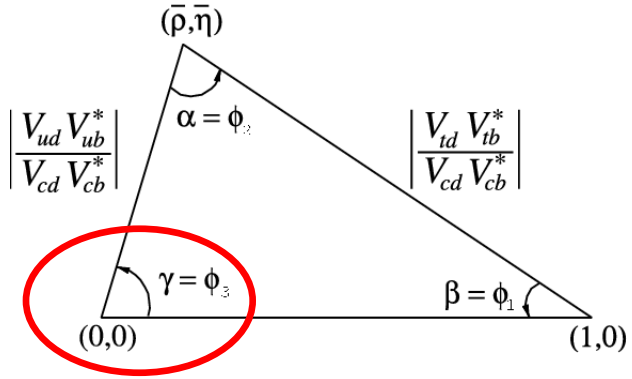
# Study of charmed B decay



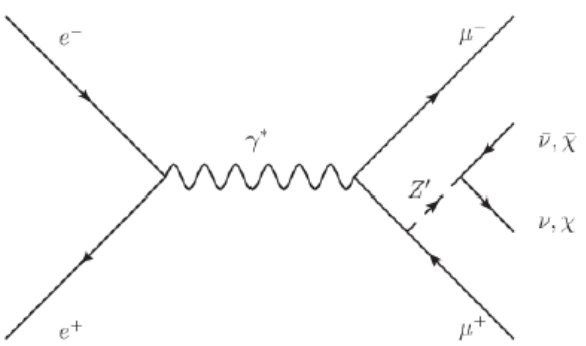

- $\Delta E$ distributions for $B^{\pm} \to Dh^{\pm}$ decays with $D \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+$
- Demonstrate importance of PID at high momentum towards improving the S/B ratio

- This kind of decay channels will be essential to measure the CKM angle $\gamma \equiv \phi_3$




☞ Major Indian contribution

# Probing the dark sector



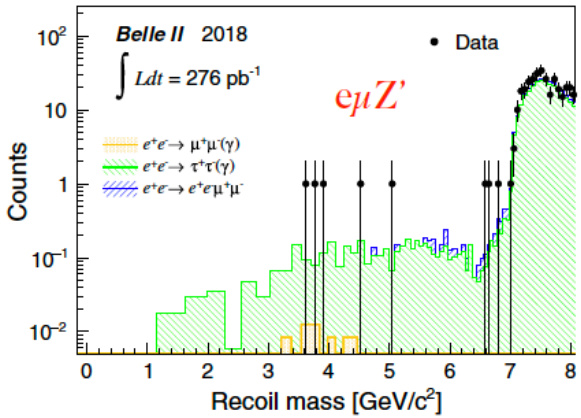

- Look for the vector boson Z′ that couples to second and third generation only
- Invisible decays to dark-matter particles or neutrinos
- Possible explanation for the (g-2) anomaly

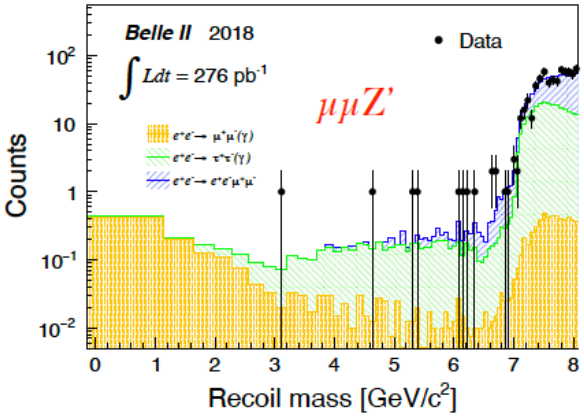
- First physics publication from Belle II

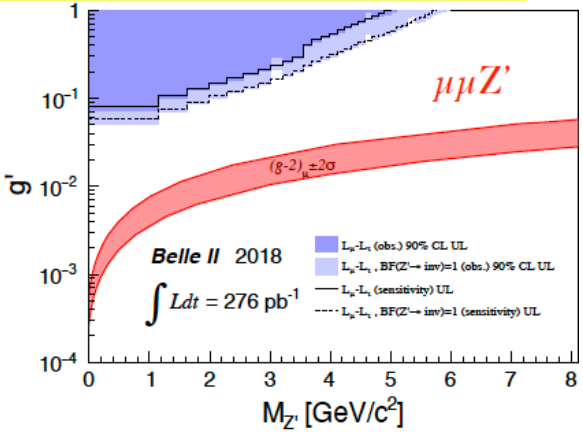
PRL 124, 141801 (2020)

More to come, e.g.
$e^+e^- \rightarrow \gamma X$
$e^+e^- \rightarrow \gamma$ ALP ($\rightarrow\gamma\gamma$)
$e^+e^- \rightarrow \gamma A'$ (dark photon)
Dark Z′, Magn. Monopoles

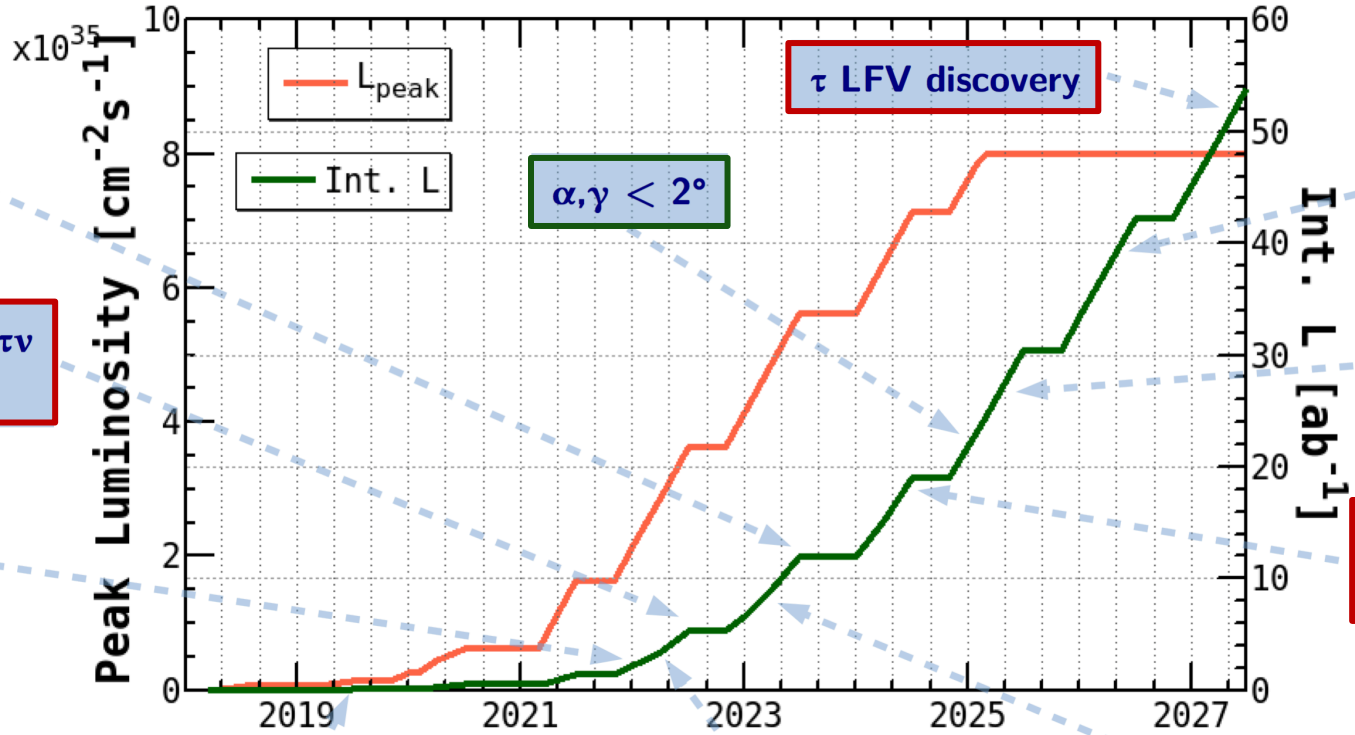
limits on the Z coupling constant at the level of $5\times10^{-2}$–1 for $M(Z^0) \leq 6$ GeV/$c^2$



# Prospects for data & physics harvesting




B→η'Ks new CP

Confirm B→D*τν new physics

Resolve |Vub| puzzle

WR in B→ργ

B→Kνν SM discovery

B→Kee LFUV new physics

ee→A'(χχ)γ

ee→ππ(γ) precision for (g-2)μ

B→μν discovery

All the details are in "The Belle II Physics Book"

arXiv:1808.10567 (10.1093/ptep/ptz106)

| | |
|---|---|
| 2021 | Integrated luminosity > 0.5 – 1.0 ab$^{-1}$ |
| 2022 | $\beta^*_y$ to reach 0.3 mm (design value) |
| 2023 | Integrated luminosity 5 ab$^{-1}$ |
| 2026 | Peak luminosity to reach ~8 x 10$^{35}$ cm$^{-2}$s$^{-1}$ (design value) |
| 2028 | Integrated luminosity 50 ab$^{-1}$ |

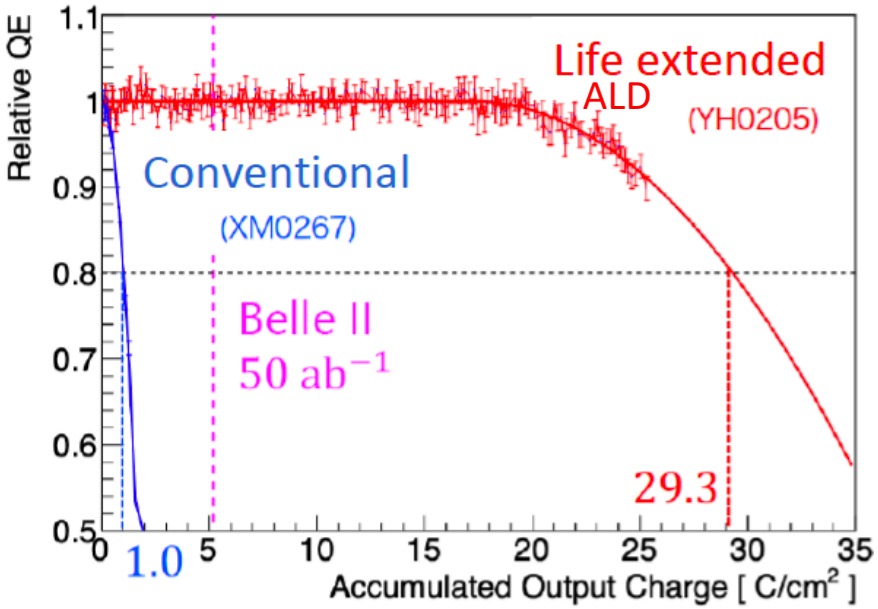
Sure shot

Wish list

Courtesy: G. De Pietro

# Prospects for detector improvements

- Short term:
  - Replace the conventional with atomic-layer-deposition (ALD) MCP-PMTs for the TOP counters
  - Complete installation of PXD layer-2
  - DAQ upgrade



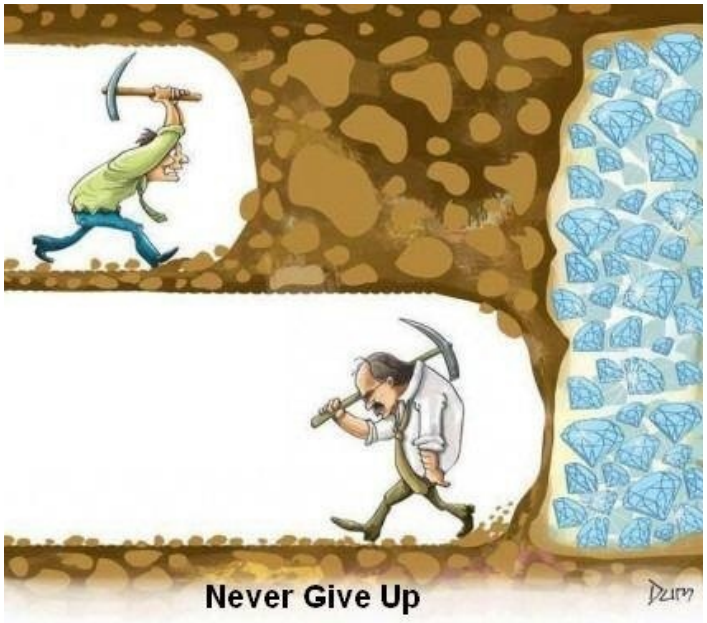

- Medium term:
  - Looking at options for making the detector more resilient against beam-induced background and radiation bursts

- Longer term:

  - Started to think about possibilities for luminosity upgrade; e.g., Belle II VXD open workshop http://indico.cern.ch/event/810687/

# Closing words

- Belle II has started to probe new physics beyond the SM at the intensity frontier ➔complementary to high-$p_T$ programs of ATLAS and CMS
- As for LHCb, there is healthy competition and complementarity between the two experiments
- Have already accumulated 74 $fb^{-1}$ data ➔ Autumn run begins in October
- Detector and machine initial performances have been good; we expect the road ahead to be bit long before achieving our design goal

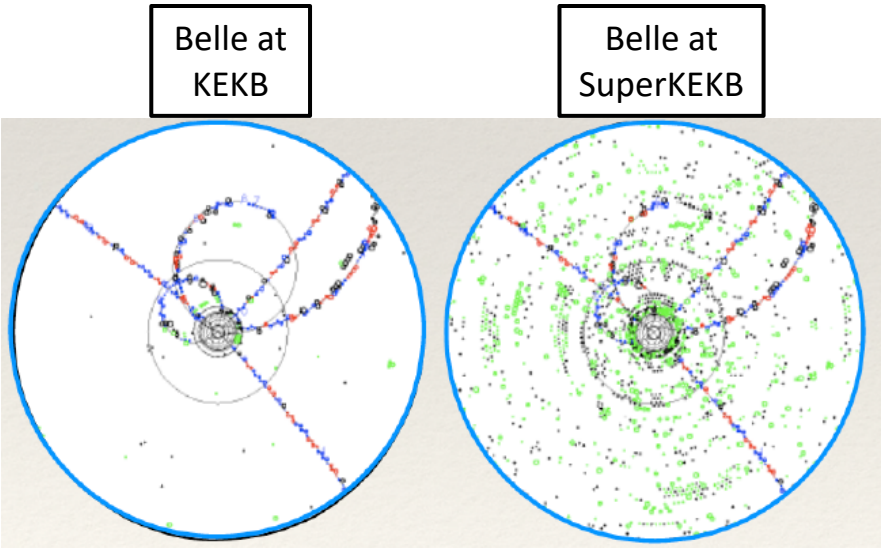


# Additional information

# Comparison: KEKB vs. SuperKEKB

| parameters | | KEKB | | SuperKEKB | | units |
|---|---|---|---|---|---|---|
| | | LER | HER | LER | HER | |
| Beam energy | $E_b$ | 3.5 | 8 | 4 | 7 | GeV |
| Half crossing angle | $\phi$ | 11 | | 41.5 | | mrad |
| Horizontal emittance | $\epsilon_x$ | 18 | 24 | 3.2 | 4.6 | nm |
| Emittance ratio | $\kappa$ | 0.88 | 0.66 | 0.37 | 0.40 | % |
| Beta functions at IP | $\beta_x^*/\beta_y^*$ | 1200/5.9 | | 32/0.27 | 25/0.30 | mm |
| Beam currents | $I_b$ | 1.64 | 1.19 | 3.60 | 2.60 | A |
| beam-beam parameter | $\xi_y$ | 0.129 | 0.090 | 0.0881 | 0.0807 | |
| Luminosity | L | $2.1 \times 10^{34}$ | | $8 \times 10^{35}$ | | $cm^{-2}s^{-1}$ |

# Beam backgrounds




- $e^+e^-$ colliders are clean, however at high $L_{peak}$ values beam backgrounds can become a challenge
- At the highest luminosities, QED processes e.g., $e^+e^- \rightarrow e^+e^-(\gamma)$ and $e^+e^- \rightarrow e^+e^-e^+e^-$ dominate

- Currently, single beam backgrounds are dominant, larger for the $e^+$ beam
  - beam-gas (residual gas in beam-pipe)
  - Touschek (intra-bunch scattering)
  - injection-induced
  - "dust events" (occasional large losses)
- CDC HV trips with large background
- Beam abort protection against spikes due to radiation
- Simulation and collimator studies