The Belle II experiment: first data and physics prospect

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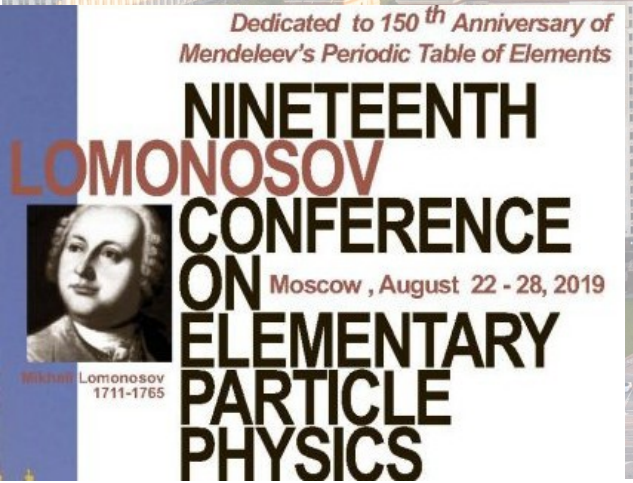
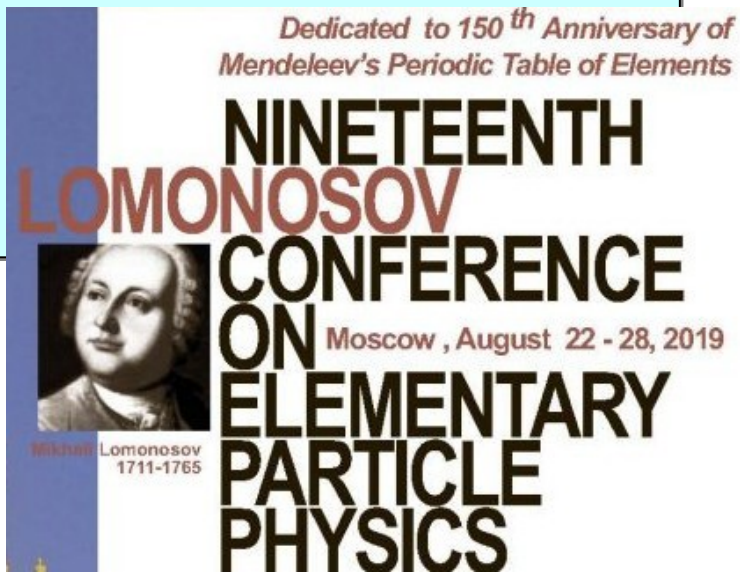
(On behalf of the Belle II Collaboration)



19th Lomonosov Conference on Elementary Particle Physics, Moscow, Russia, 22nd — 28th August 2019

Outline

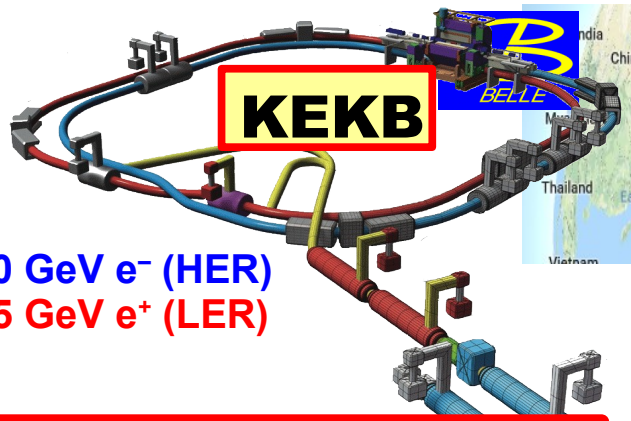
- Introduction, history
- Physics motivation
- The SuperKEKB accelerator and Belle II detector
- Results from early data
- Prospects
- Summary and conclusions



Legacy of B-Factories

- **B-Factories**: High luminosity asymmetric-energy e^+e^- colliders (PEP-II/BABAR, KEKB/Belle), (A clean environment)

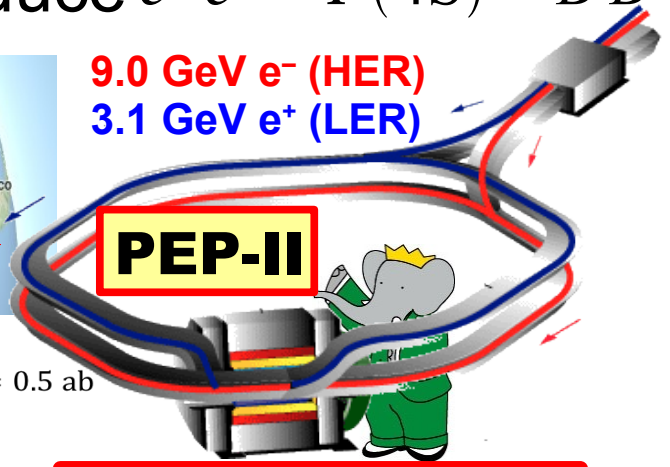
operating at $E_{CMS} \sim m_{\Upsilon(4S)} c^2 = 10.58\ GeV$ to produce $e^+e^- \to \Upsilon(4S) \to B\overline{B}$



8.0 GeV e^- (HER)
3.5 GeV e^+ (LER)

1999-2010
~1000 fb^{-1} = 1ab^{-1}

1999-2008
~500 fb^{-1} = 0.5 ab



9.0 GeV e^- (HER)
3.1 GeV e^+ (LER)

$2.11 \times 10^{34}\ cm^{-2}s^{-1}$ (WR!)

$1.21 \times 10^{34}\ cm^{-2}s^{-1}$

Step1 **Discovery of CPV in B decay**

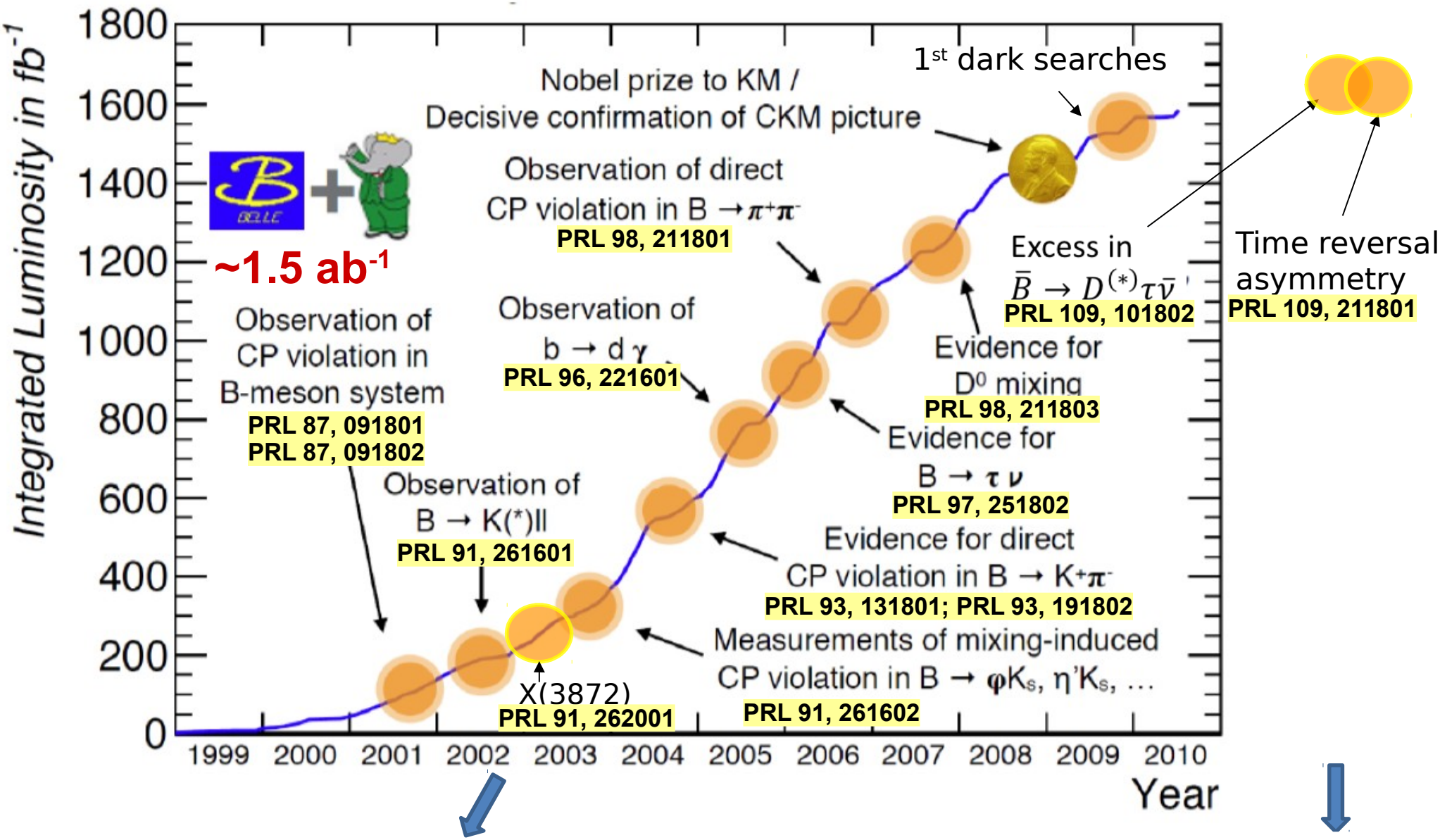
Step2 **Precise test of KM (CPV) and SM**

Step3 **Search/Evidence for New Physics**

B decays → QCD/Lattice, New Resonances
Also, excellent τ/charm factory

"The Physics of the B Factories"
Eur. Phys. J. C (2014) 74:3026

B-Factories physics milestones



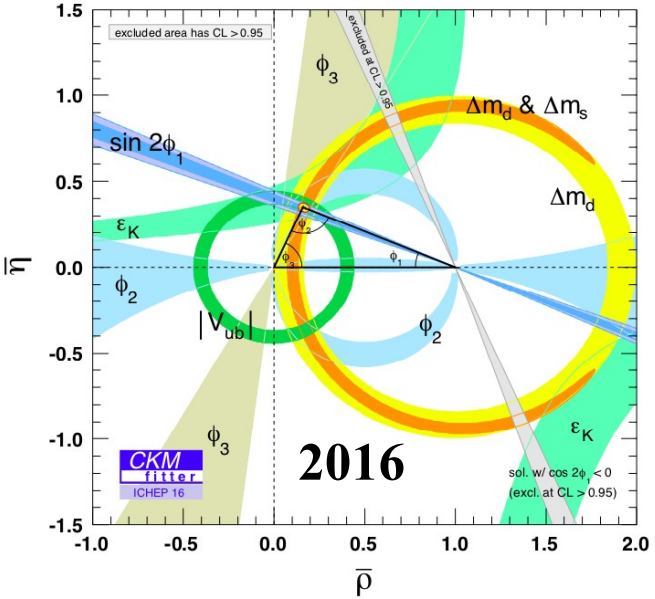
>100 unique CPV results

~380 papers published after shutdown; 18 in 2019

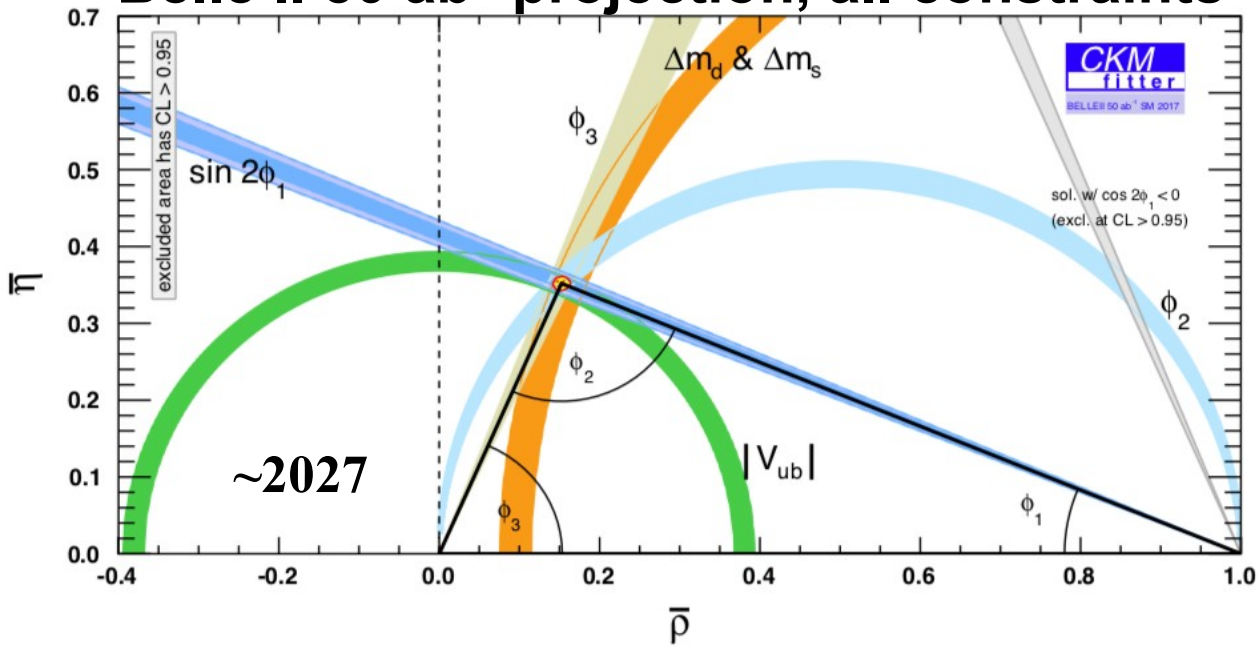
Physics motivation for increased luminosity

- B-Factories legacy, complementarity to the LHCb
  → The stage for the physics of Belle II:
  - Stress-testing the SM and sensitively probing new physics via, e.g.,
    - Precision CKM measurements: CP violation, meson mixing, decay rates;
    - Rare processes, e.g., flavour-changing neutral currents;
    - SM-forbidden processes, e.g., lepton-flavour non-universality, Lepton number/flavour violation;
    - Direct searches for light new states; Dark sector.

Precision of CKM unitarity triangle:

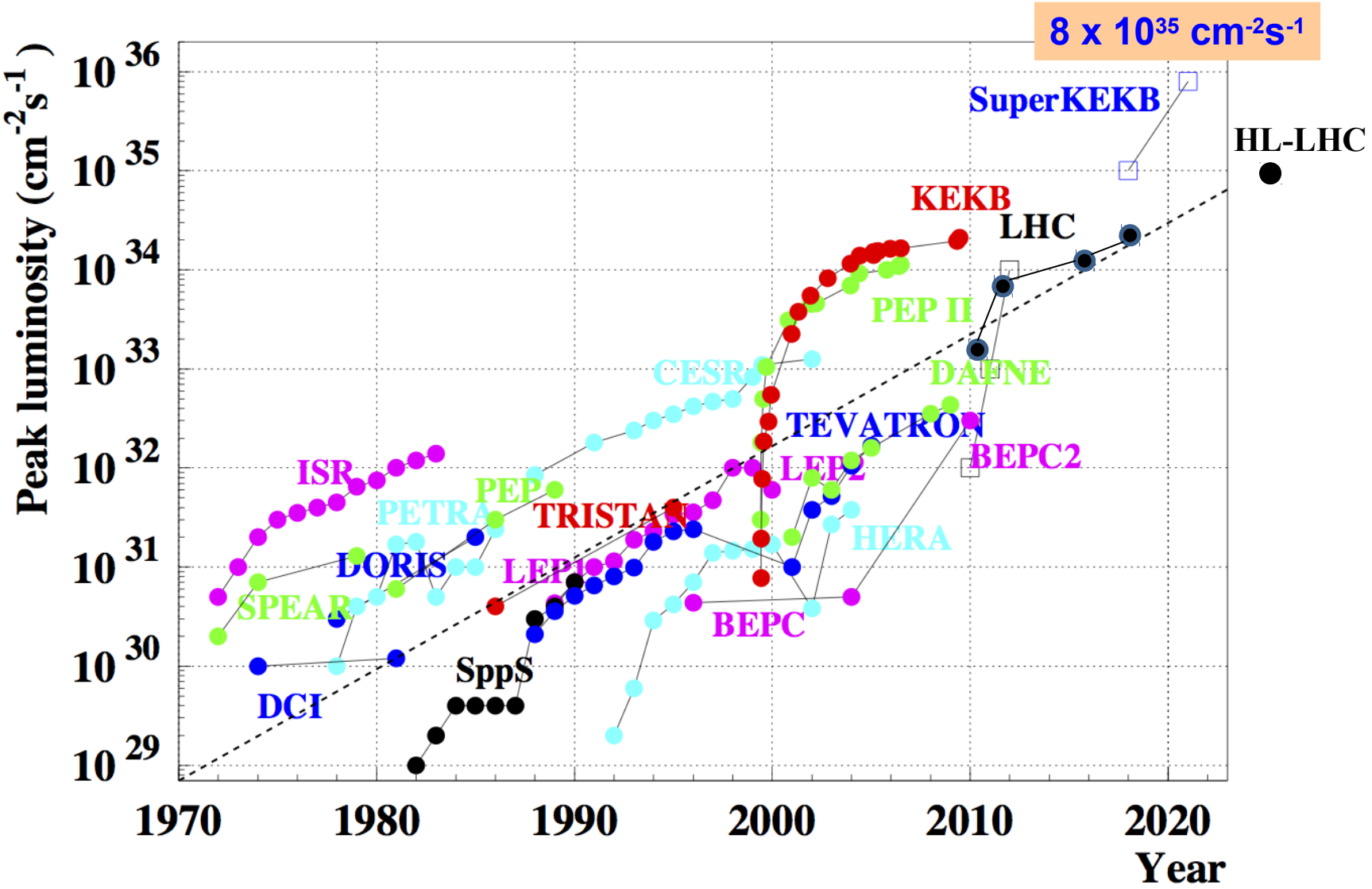


Belle II 50 ab^{-1} projection, all constraints



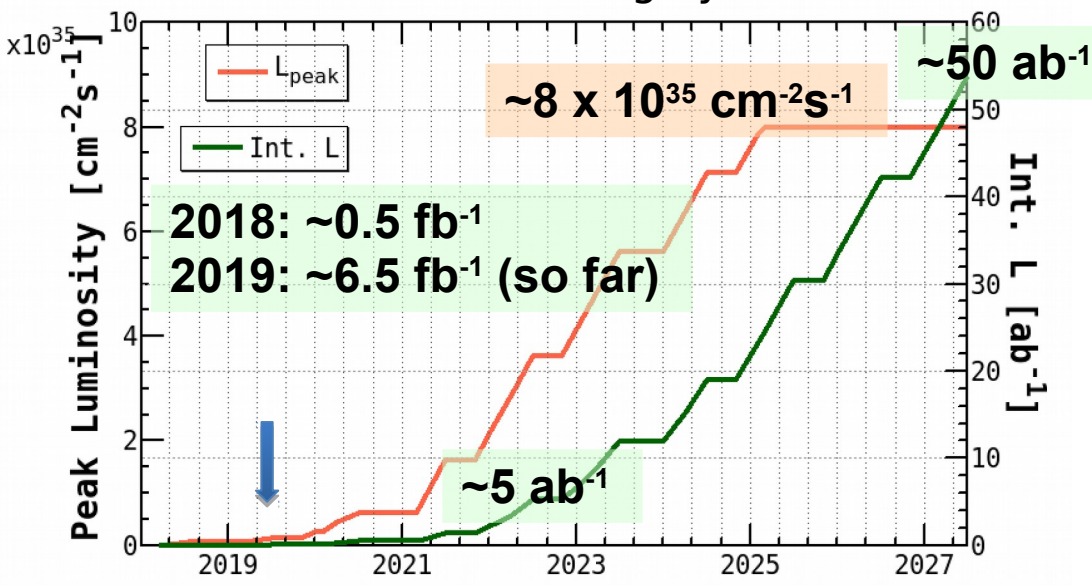
Intensity Frontier: new luminosity record

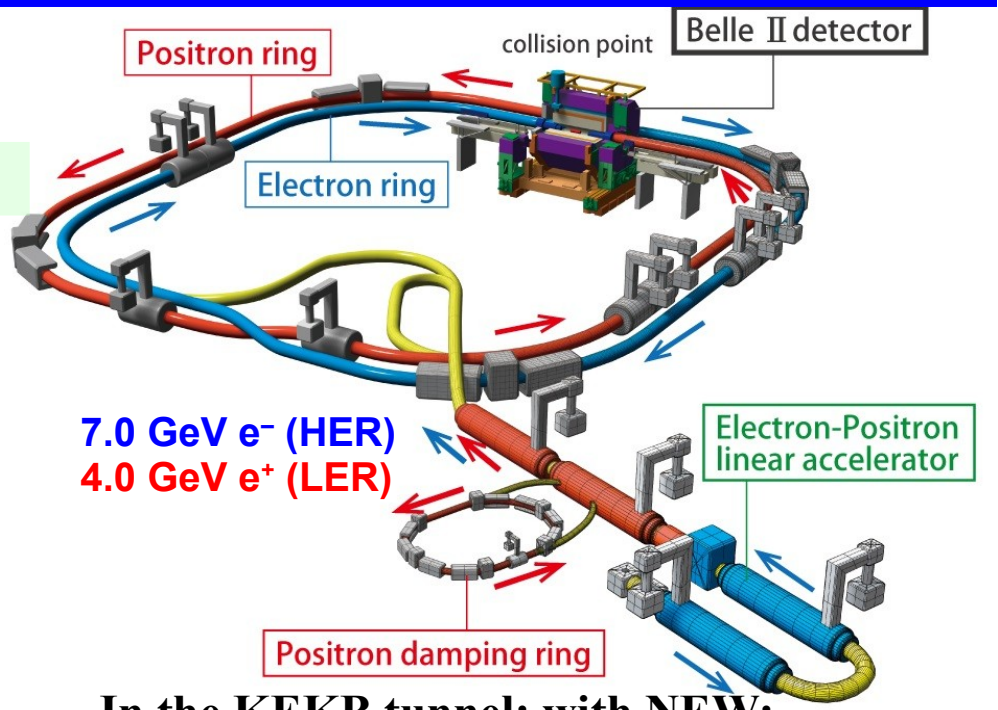
Increased sensitivity: Belle II data sample will be **50-times** larger than Belle's, by collecting data from the SuperKEKB collider with **40-times** higher luminosity



SuperKEKB Collider

Belle/KEKB recorded ~1000 fb^{-1}.
→ For Belle II Need to change y-axis units to ab^{-1}

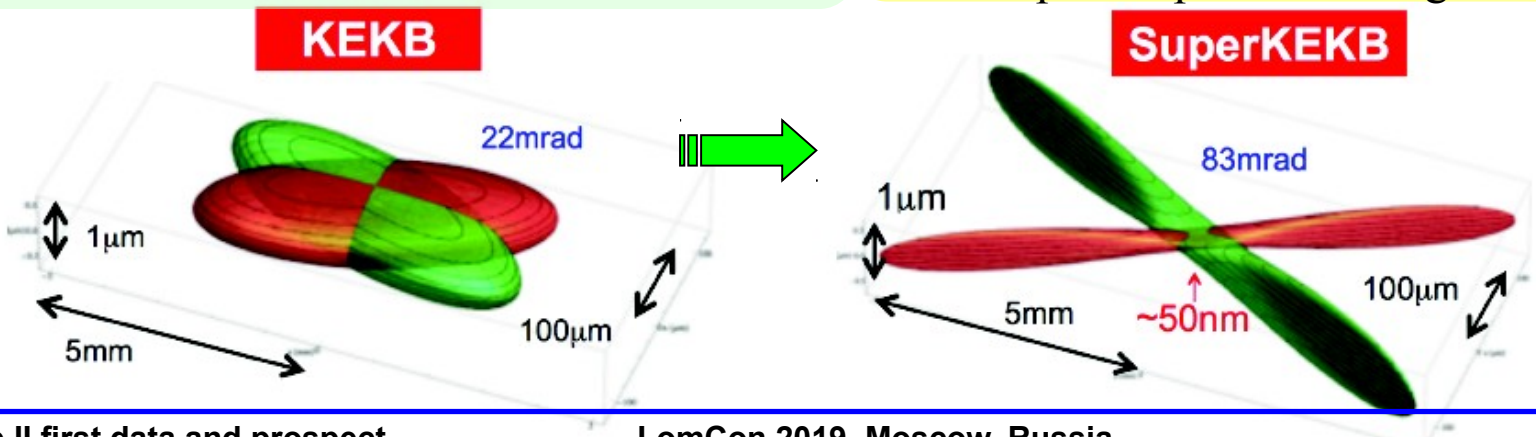




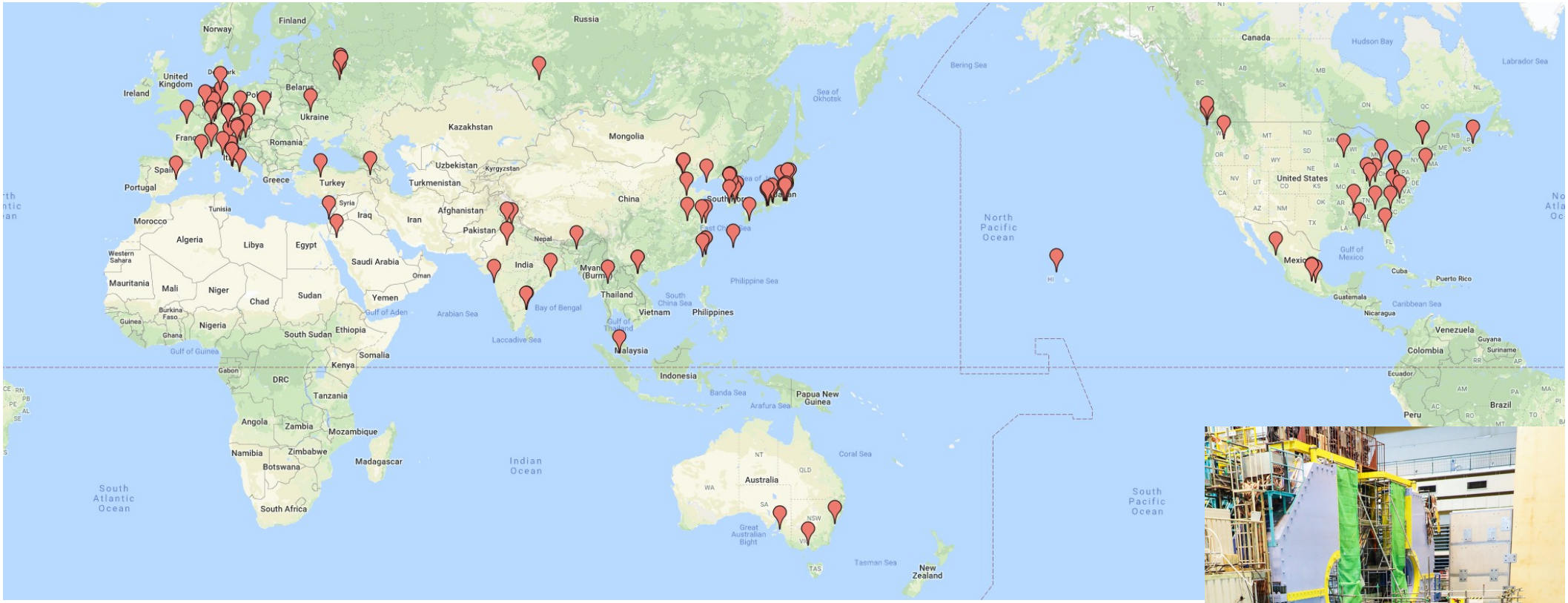
→ Beam currents are *only* a factor of ~2 higher than at KEKB (~PEPII).
→ "Nano-beam" scheme is the key to get to ~40.

In the KEKB tunnel; with NEW:

- 3-km-long positron ring vacuum chamber.
- Positron damping ring.
- Complex superconducting final focusing.



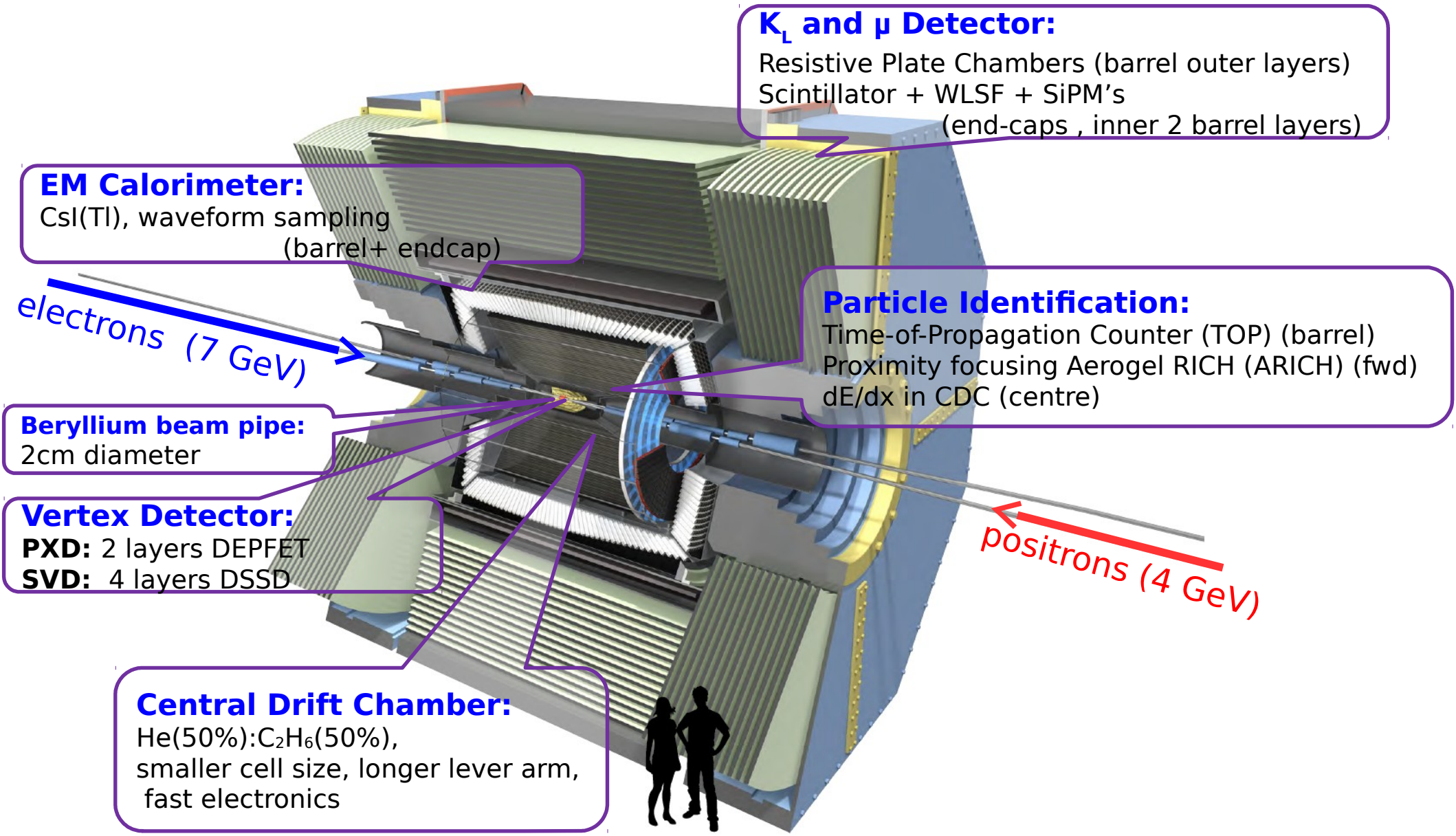
Belle II Collaboration



The Belle II collaboration:

- Almost **950 researchers** from **26 countries** (**115 institutions**) have joined efforts to built and operate the detector, and explore the physics potential of collected data;
- Russia: 48 members (BINP, MIPT, IHEP-Russia, LPI, MEPhI)

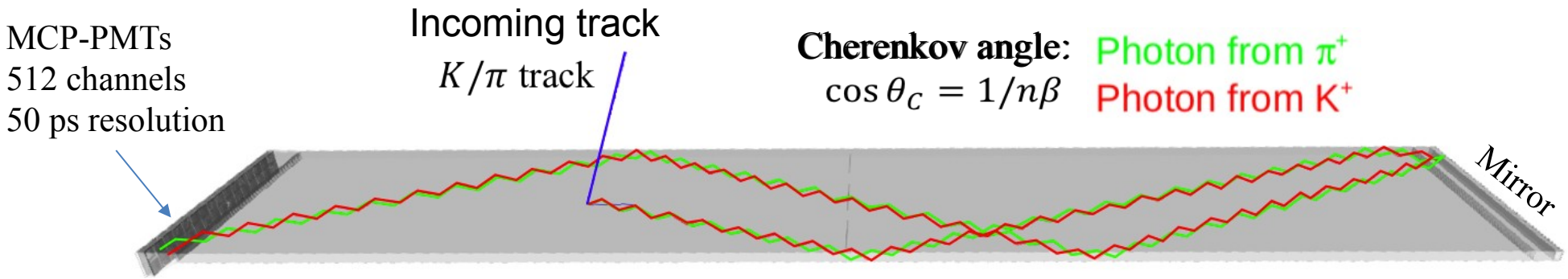
Belle II detector



Belle II detector highlights (I)

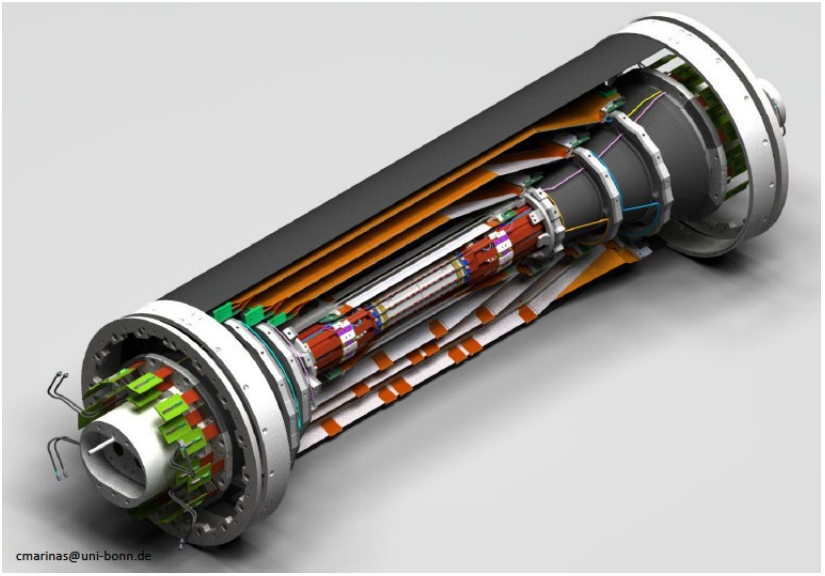
TOP: Barrel Particle Identification (uses Cherenkov radiation)

The paths of Cherenkov photons from a 2 GeV pion and kaon interacting in a TOP quartz bar.



Bar length = 2600 mm, width = 450 mm, thickness = 20 mm

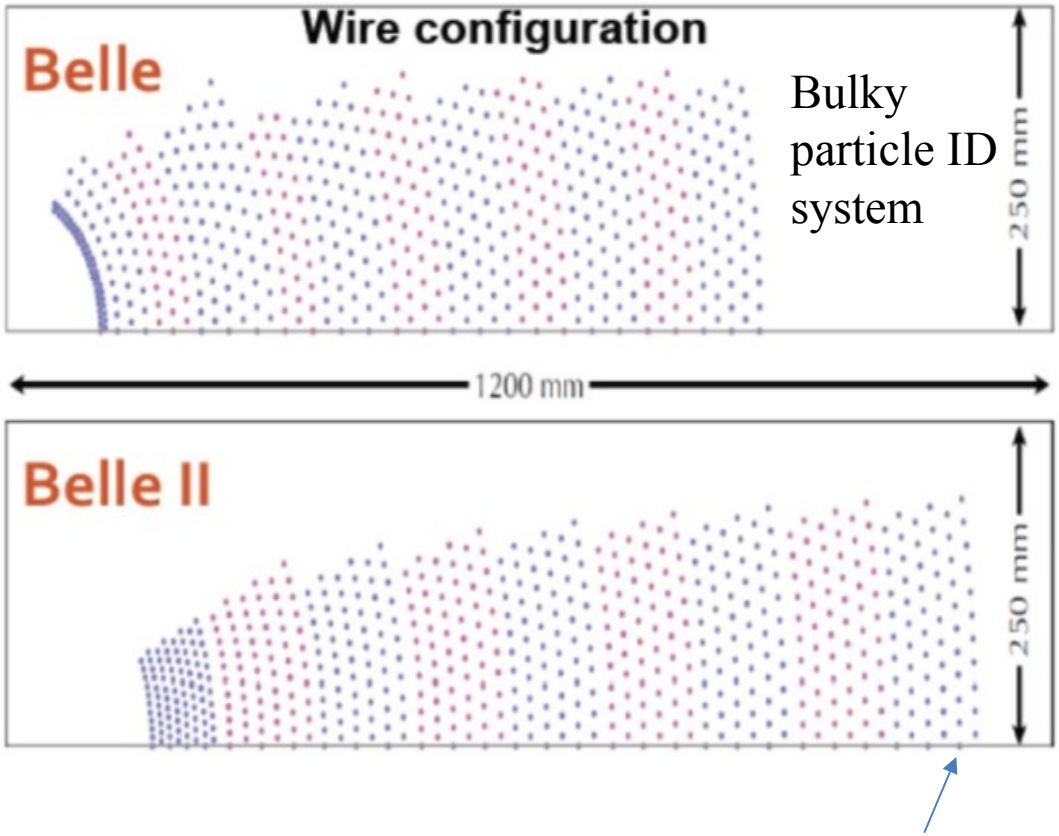
Vertexing/Inner Tracking (6 layers)



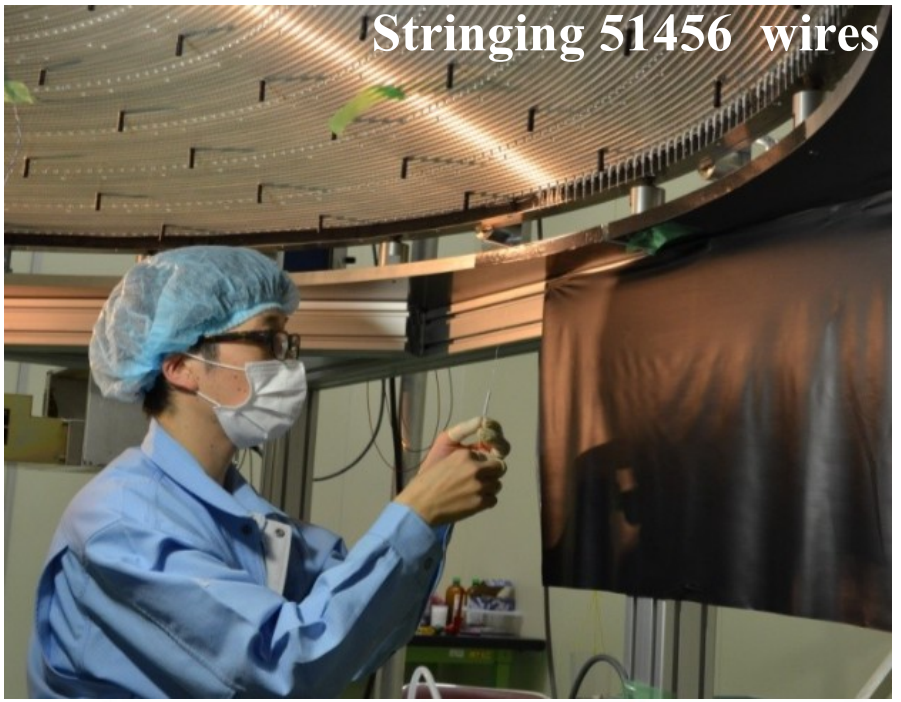
Beampipe r= 10 mm
DEPFET pixels
- Layer 1 r=14 mm
- Layer 2 r= 22 mm

DSSD (double sided silicon detectors)
- Layer 3 r=38 mm
- Layer 4 r=80 mm
- Layer 5 r=115 mm
- Layer 6 r=140 mm

Belle II detector highlights (II)



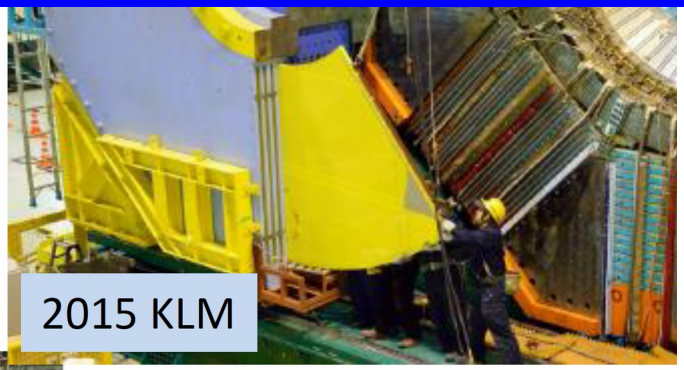
Note:
Outer radius almost ~20% larger than at BABAR/Belle:
Improved momentum resolution

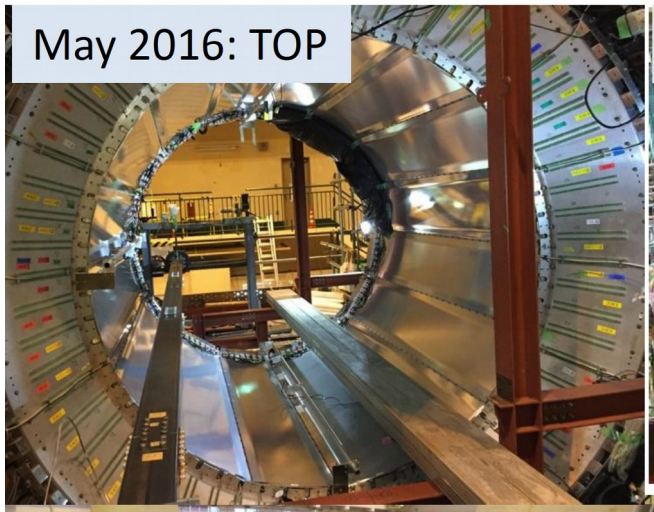


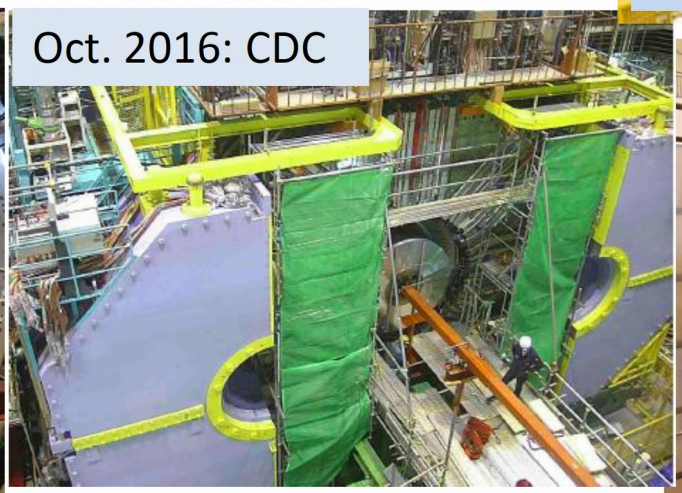
	Belle	Belle II
Innermost sense wire	r=88mm	r=168mm
Outermost sense wire	r=863mm	r=1111.4mm
Number of layers	50	56
Total sense wires	8400	14336
Gas	He:C_2H_6	He:C_2H_6
Sense wire	W(Φ30μm)	W(Φ30μm)
Field wire	Al(Φ120μm)	Al(Φ120μm)

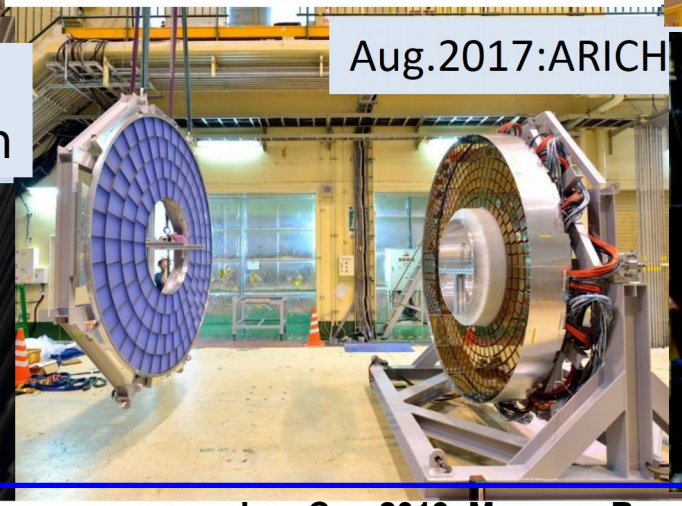
Belle II sub-detector installation

- In 2010 Belle/KEKB operation was completed;
- Upgrade to Belle II/SuperKEKB started;
- 2015 → Jan 2019: Sub-detector installation.

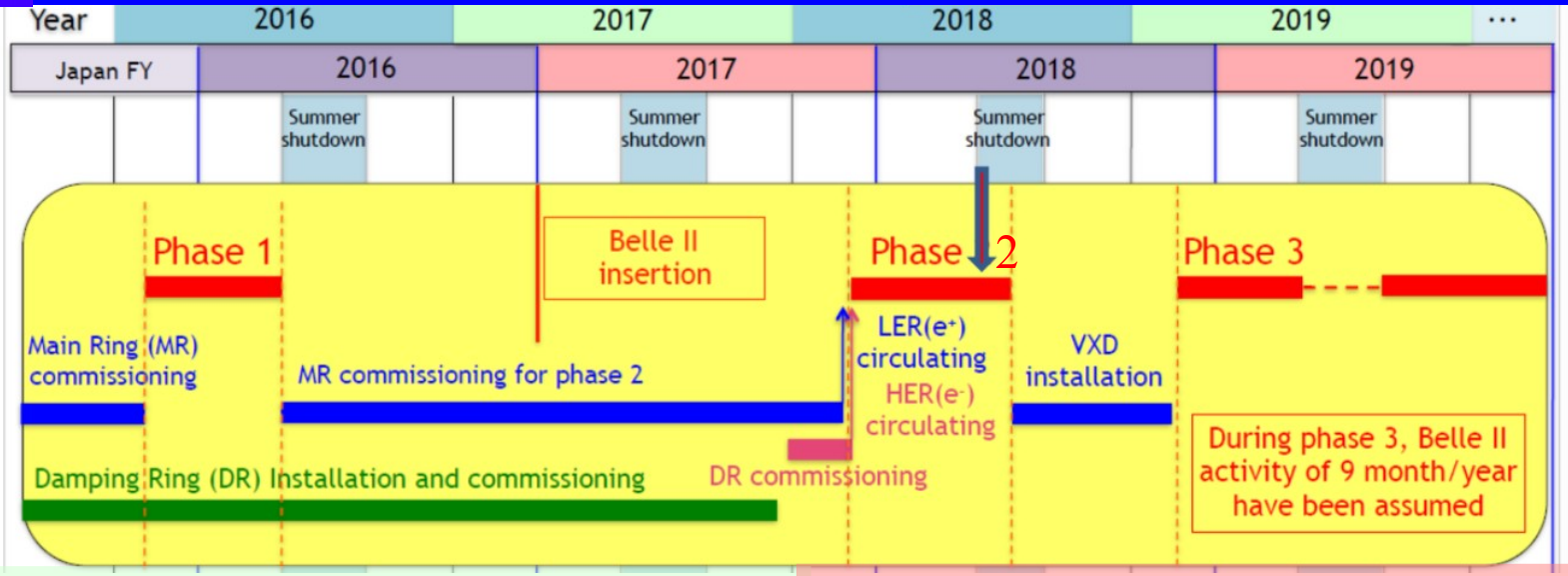








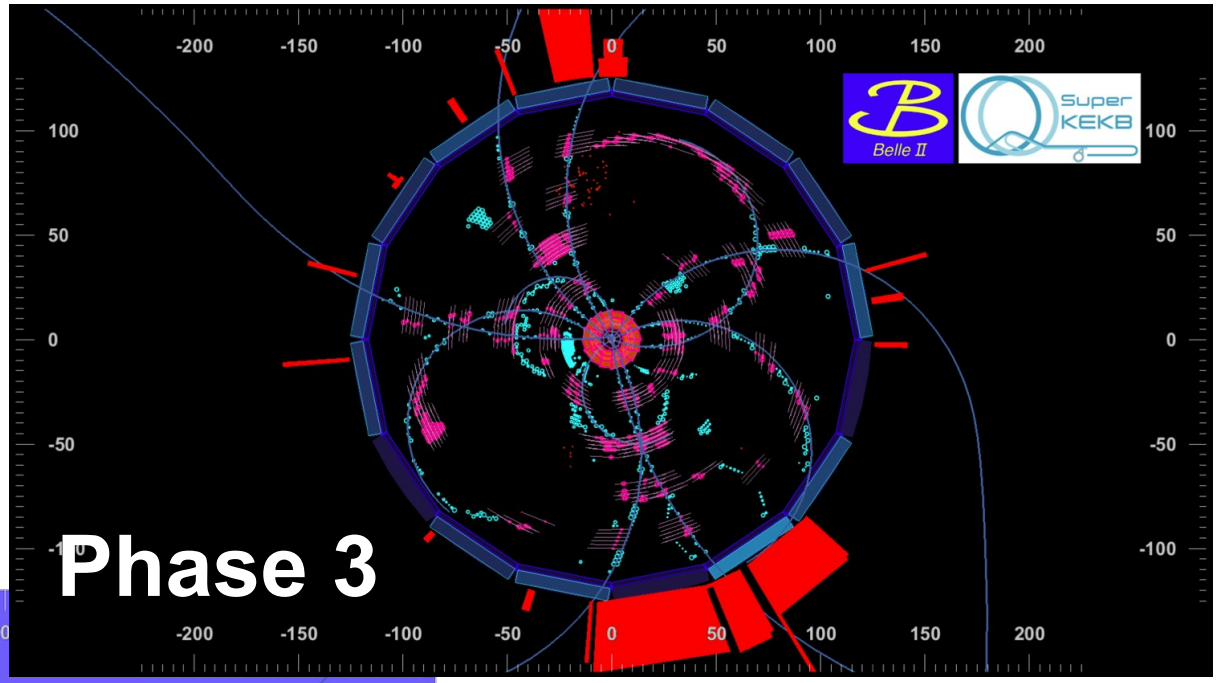
Startup of SuperKEKB/Belle II



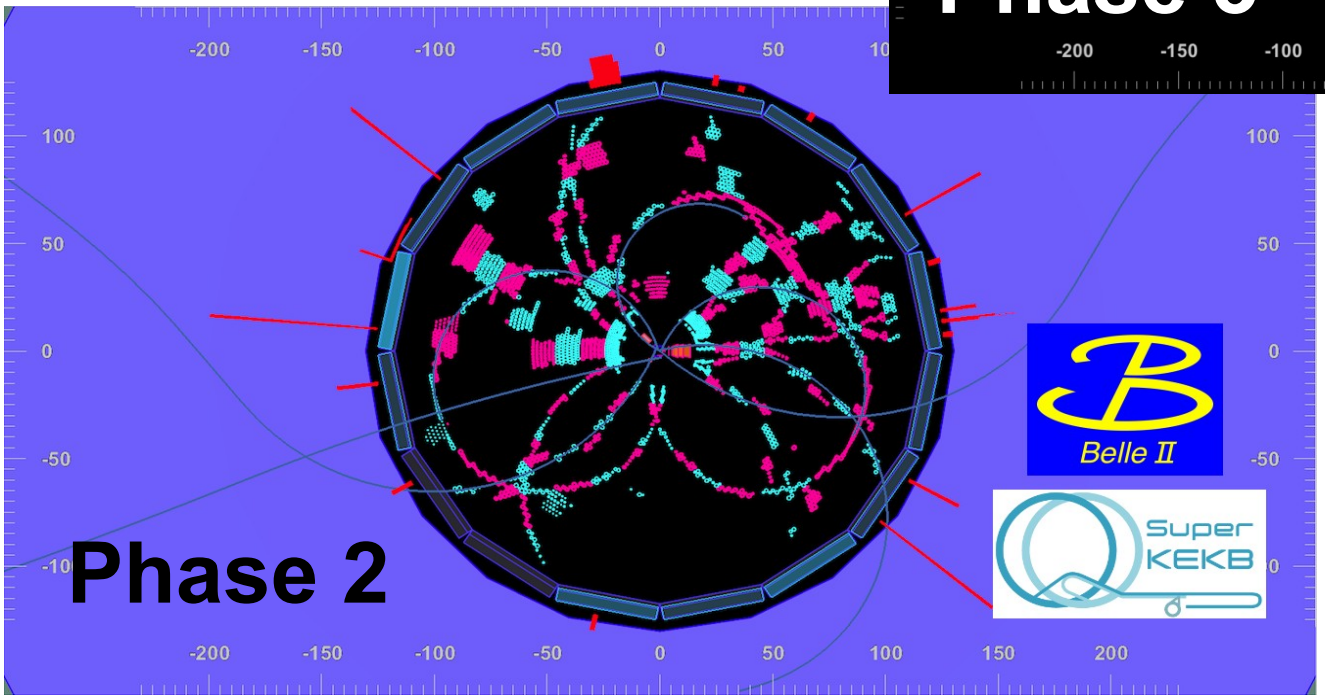
Phase 2: Full Belle II outer detector;
full superconducting final focus; no vertex detectors.
→ First collisions: 26 April, 2018

Phase 3: Full Belle II detector, including VXD
(Layer 2 PXD incomplete → to be installed in 2020)
→ First physics runs with collisions: 26 March, 2019

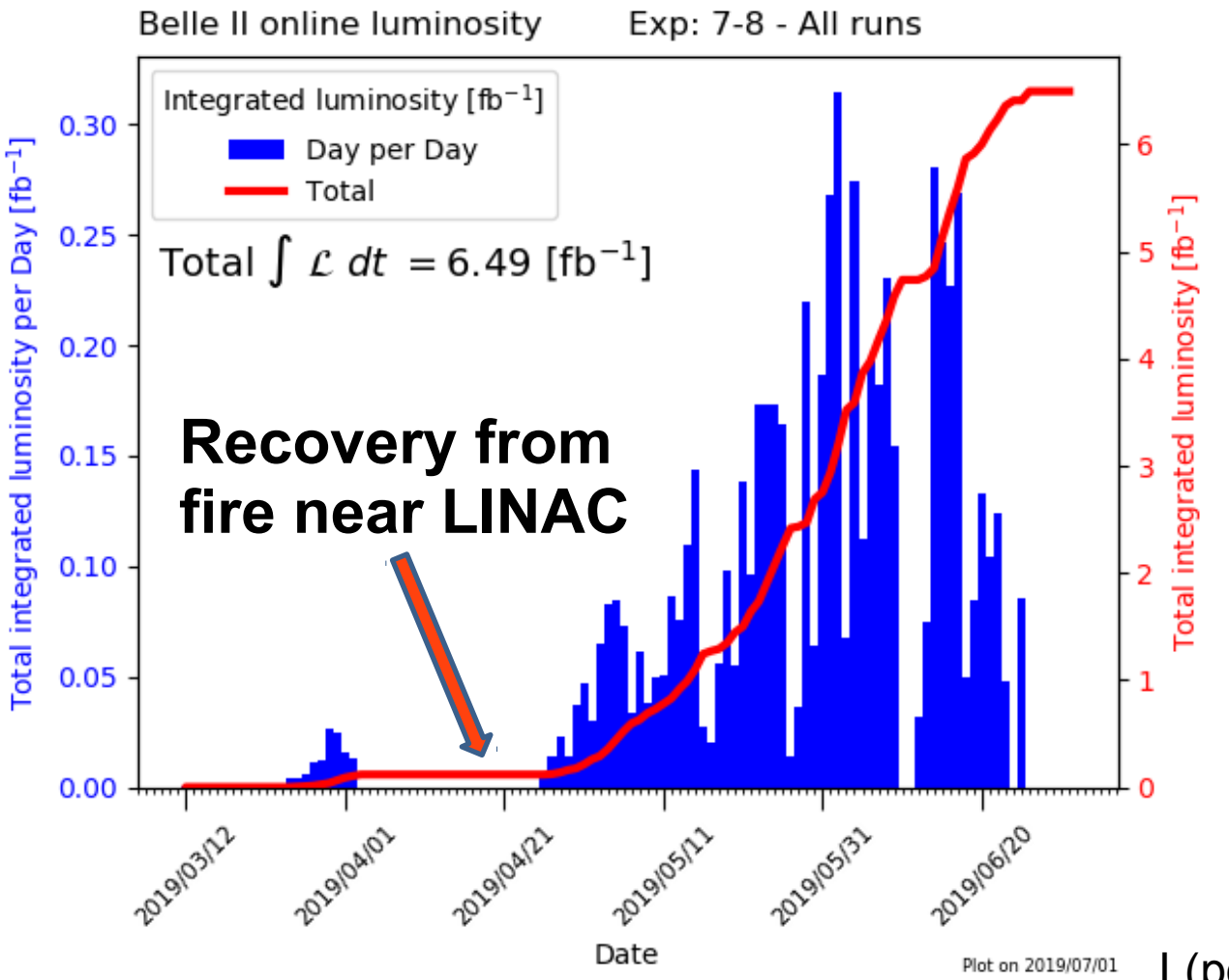
First collision events



A $B\bar{B}$-like event



Beginning of Phase 3 ...



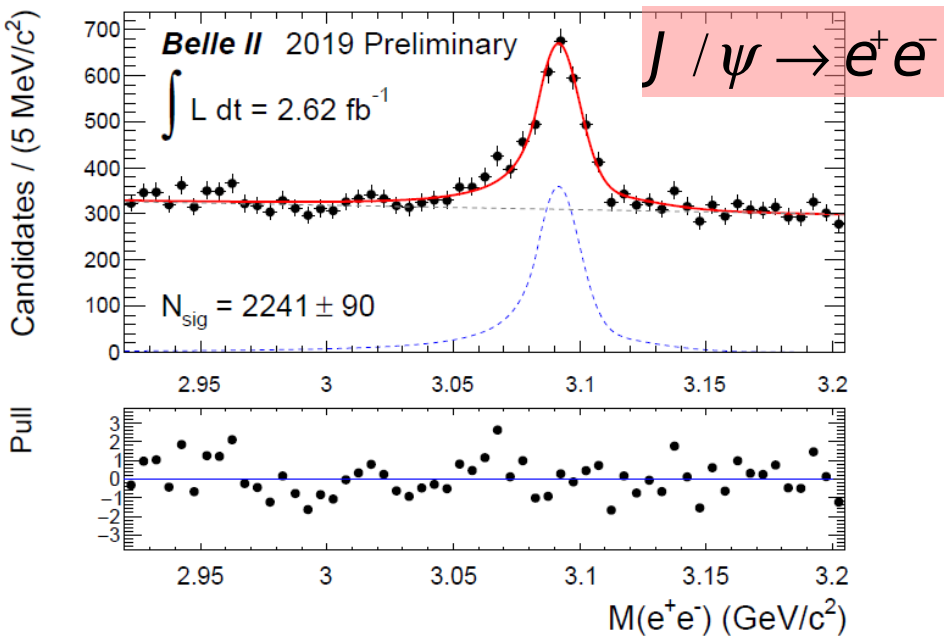
Unfortunately only 2 months of collisions (March-July 2019).

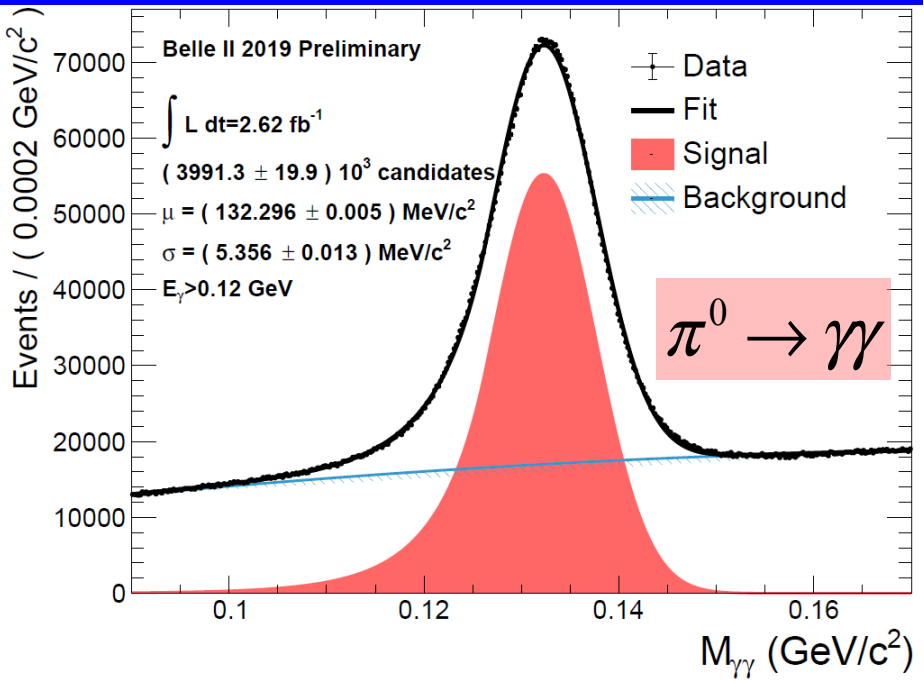
Parameter	Achieved	Target
I_{LER}(max)(A)	0.880	2.6
I_{HER}(max)(A)	0.940	3.6
β_y^* (mm)	2	0.3
# bunches	1576	2364
L_{peak}(cm^{-2} s^{-1})	6.1 x 10^{33}	8 x 10^{35}
L(det OFF)	12 x 10^{33}	

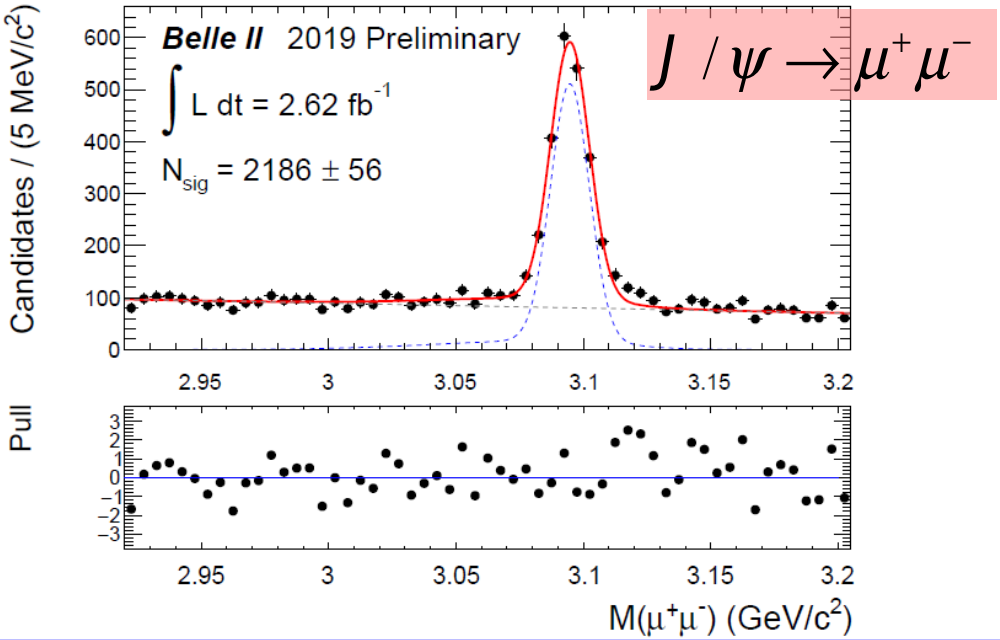
Results for early Phase 3 data: based on 2.62 fb^{-1} (on Y(4S) resonance)

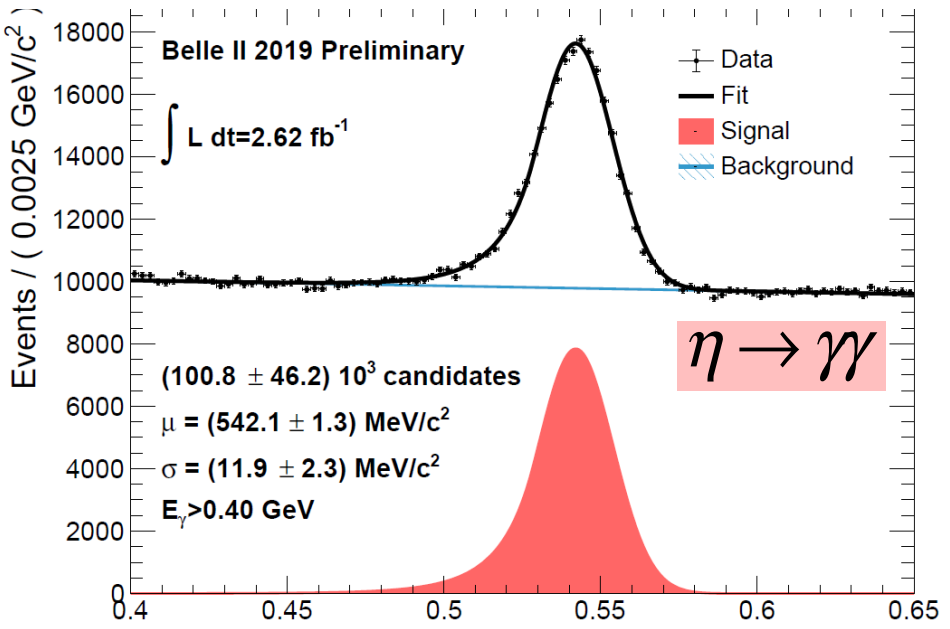
L(peak) ~5.5 x 10^{33}/cm^2/sec (β_y^*=3mm)
L(SuperKEKB peak, last week only)
~1.2 x 10^{34}/cm^2/sec (β_y^*=2mm)
→ This is comparable to PEP-II best,
but bkgs ~3x too large to turn on Belle II

Proof of principle: charged (lepton) tracks, photons







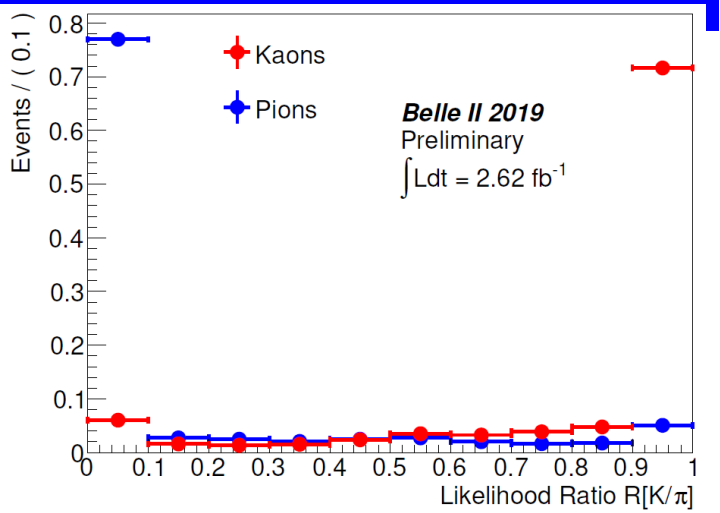


PID performance in Phase 3: global hadron ID

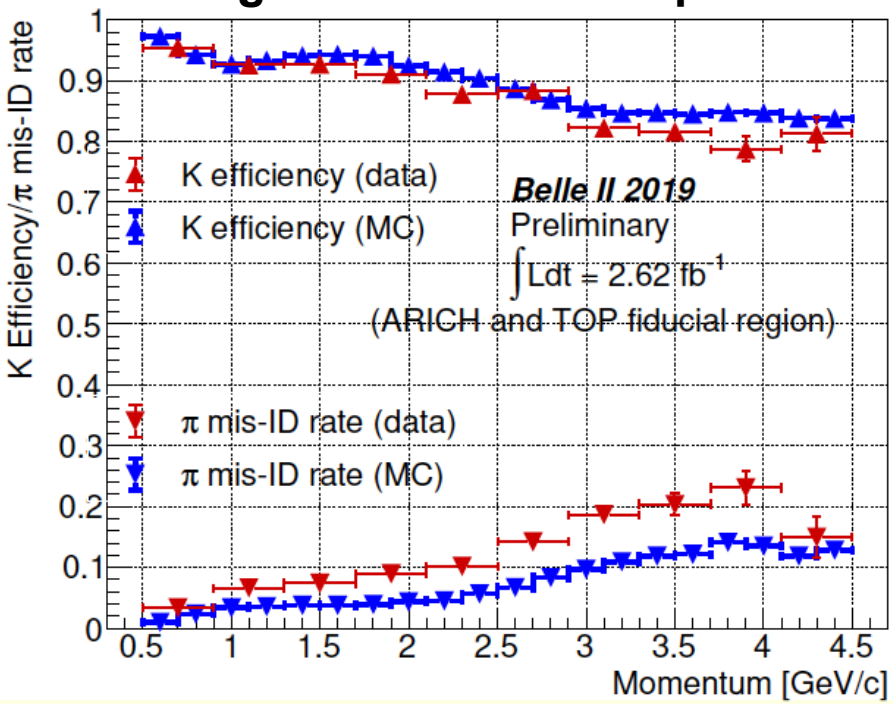
$$D^{*+} \to D^0 \pi_s^+ ; D^0 \to K^- \pi^+$$

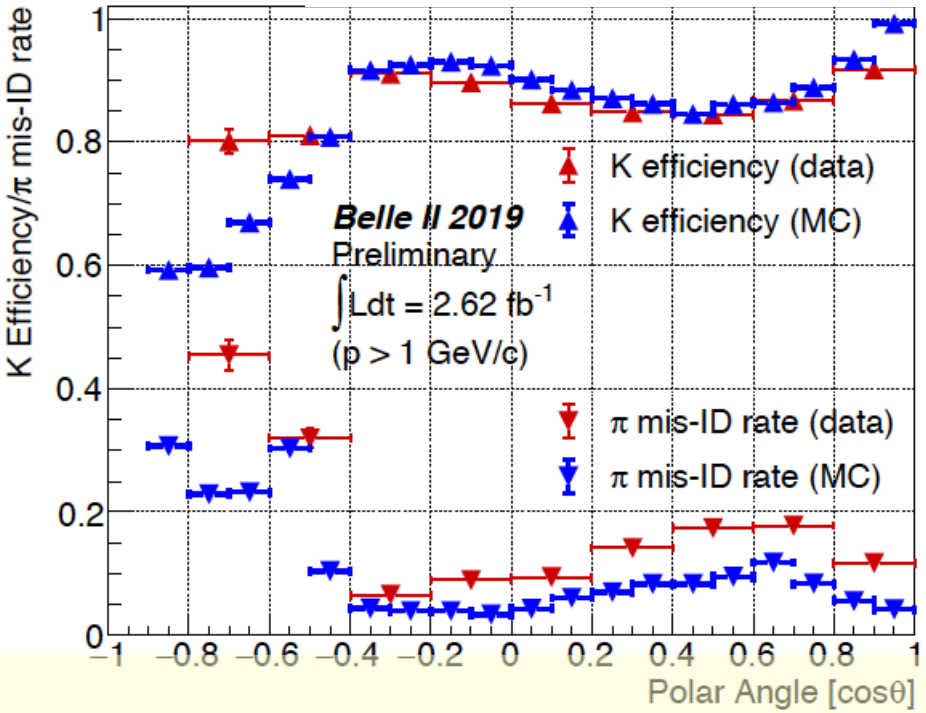
Kaon (pion) track is identified based on the charge correlation with the slow pion.

Combining information: CDC dE/dx (centre), ARICH (FW endcap) and TOP (barrel).



High momentum PID performance

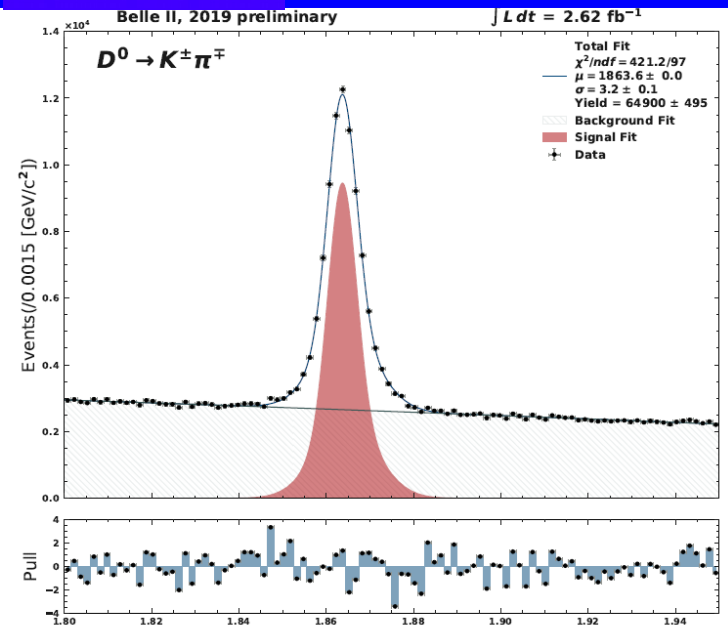


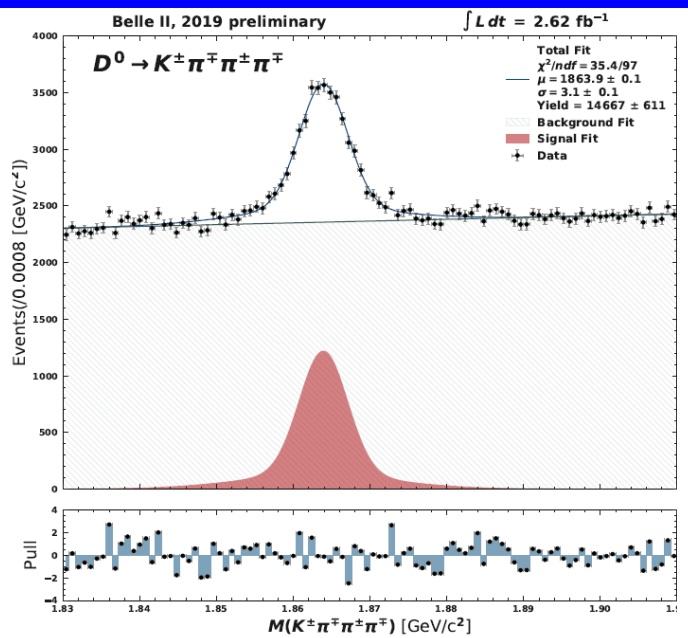


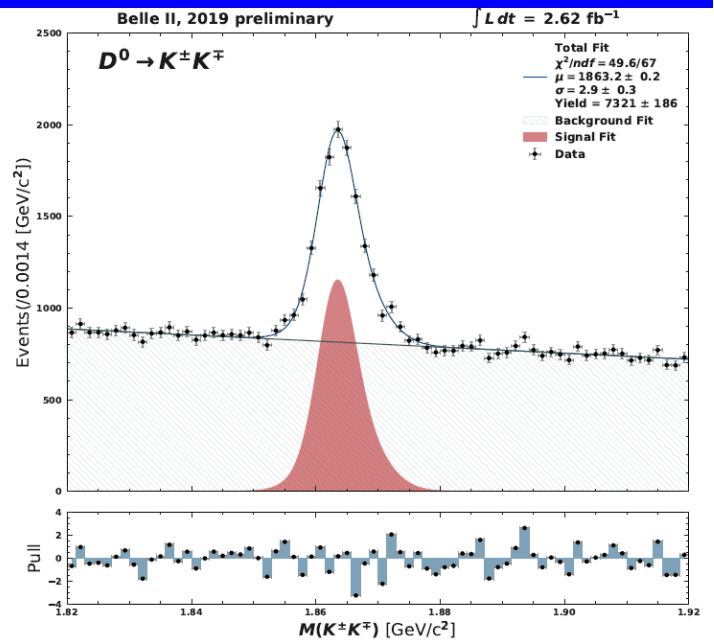
Performance is approaching MC expectations.

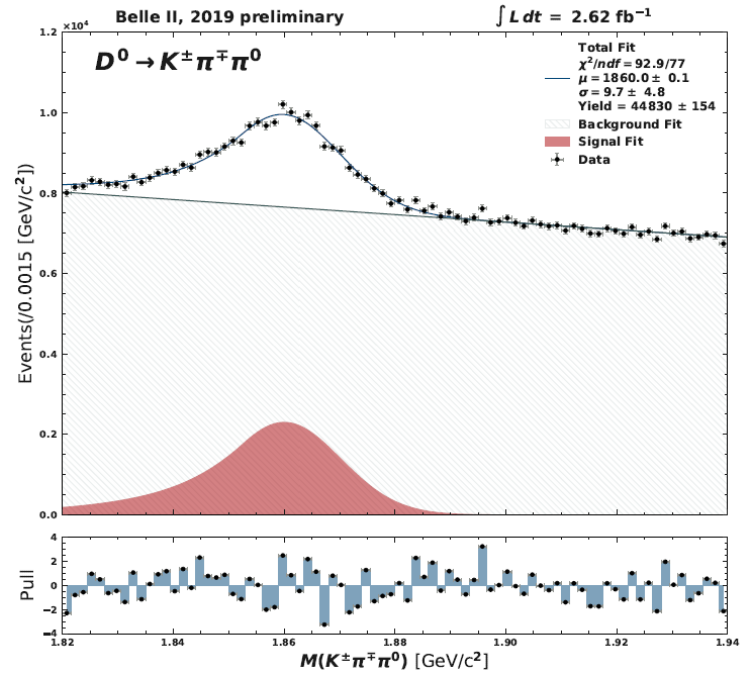
(**NB.** Current MC simulation (MC12, July 2019) does not include embedded random triggers, which correctly represent the effect of beam background and electronic noise in CDC, ARICH and TOP.)

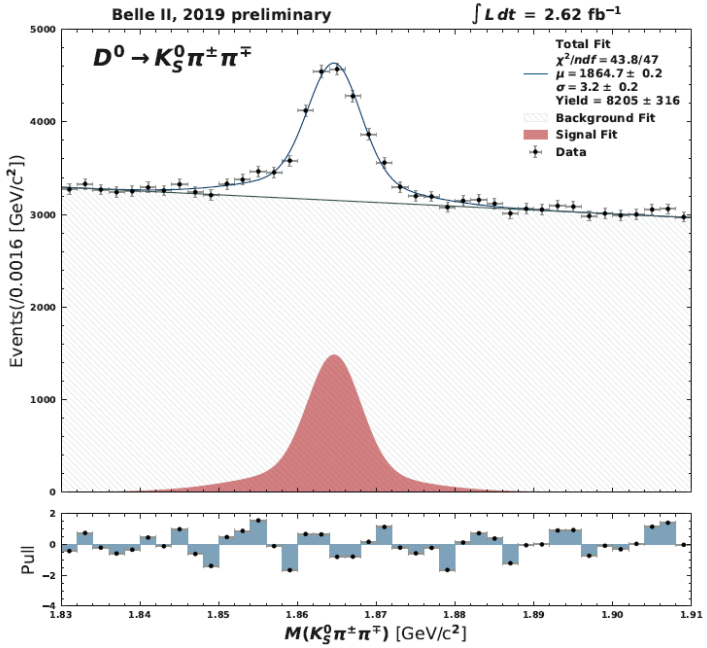
Proof of principle: Charm reconstruction







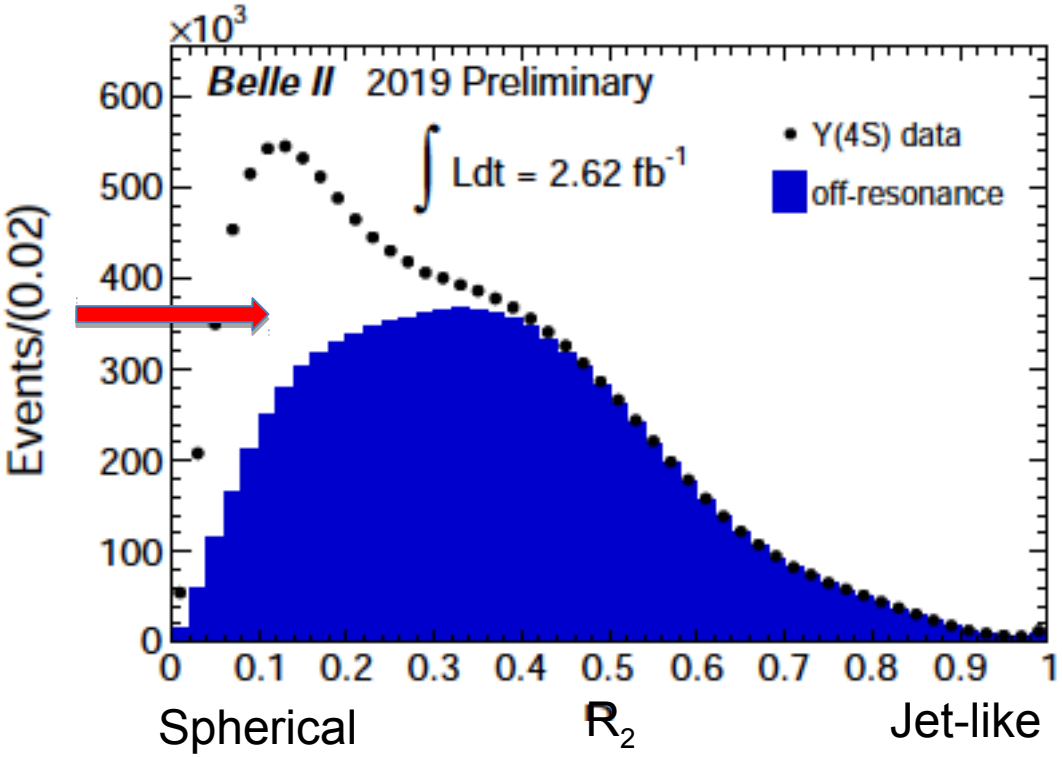


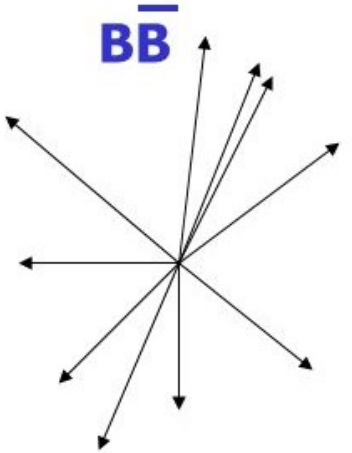


Belle II is ready for charm physics and for charm as a building block of B physics

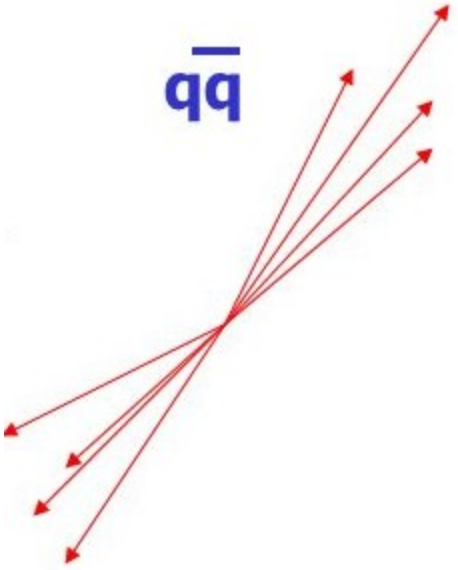
Finding $B\bar{B}$ pairs

The **Event Topology** indicates, if we are seeing B's or not:





B pairs are produced at rest in the CMS with no extra particles

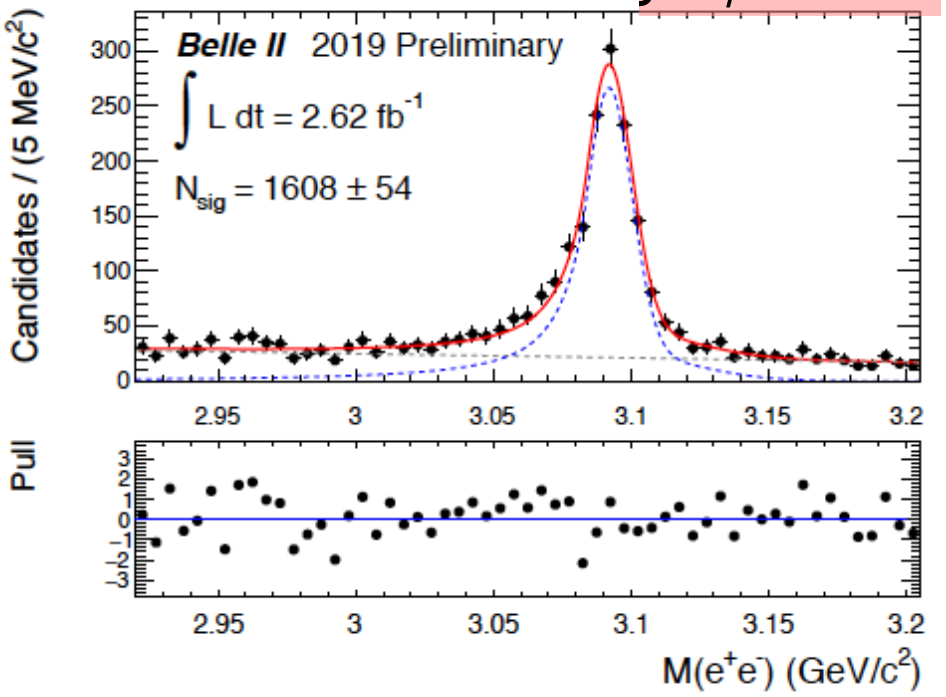


$$H_l = \Sigma_{ij} |p_i||p_j| P_l(\cos\theta_{ij}) \qquad R_2 = H_2/H_0$$

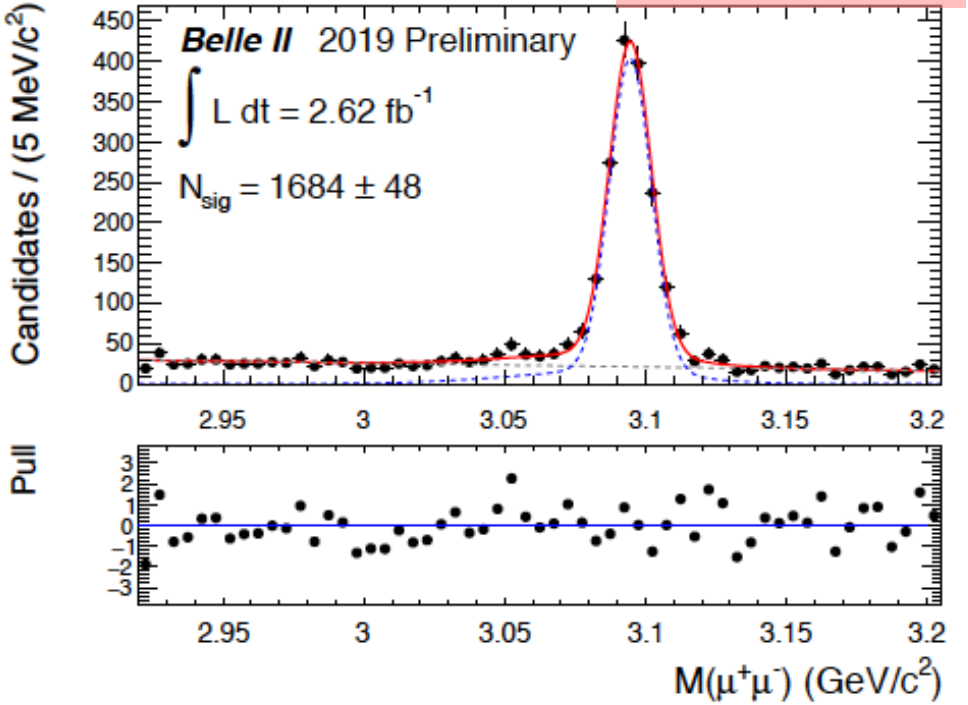
Running on the Y(4S) resonance and recording B anti-B pairs with ~99% efficiency.

Signal for $B \to J/\psi X$ in Phase 3 data

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



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



~1/2 of Phase 3 data: Clear signals for B→J/ψ X is seen.
(For e^+e^- pairs the bremsstrahlung recovery is included).

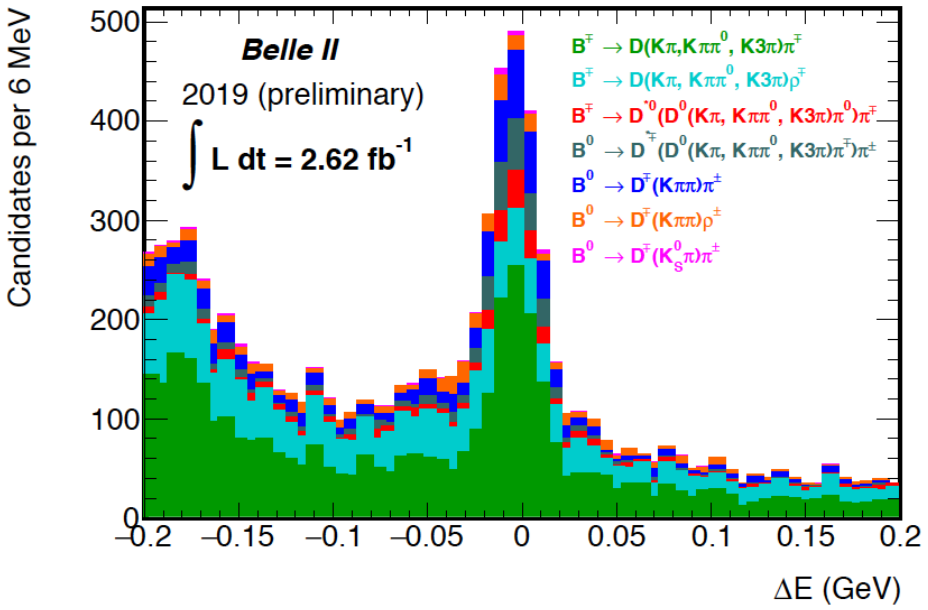
Belle II has good PID performance for both electrons and muons.

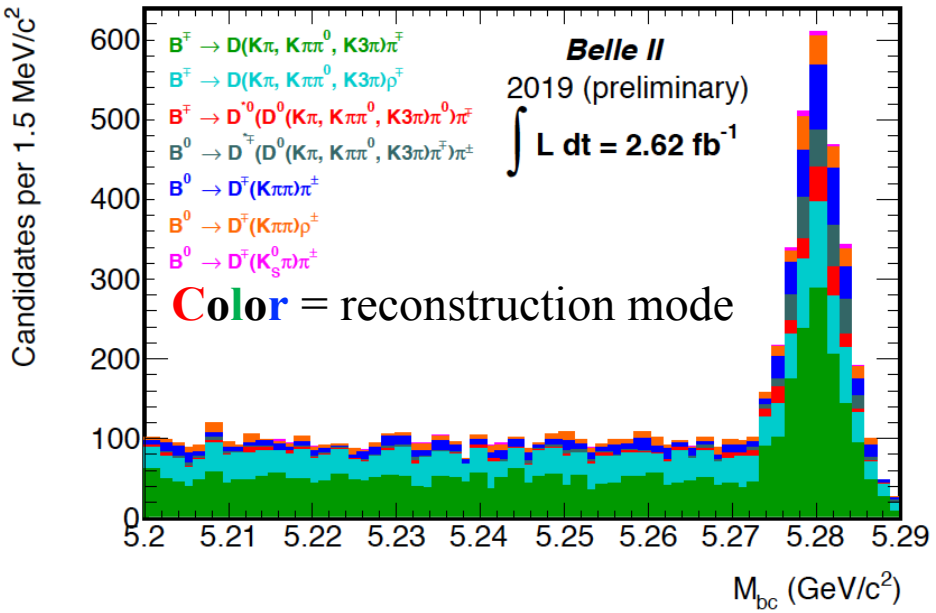
Finally: Hadronic B decays reconstructed

Re-discovery of B mesons (in ~1/2 of Phase 3 data)

$$\Delta E = E_{cm}/2 - E_{recon}$$

$$M_{bc} = \sqrt{(E_{cm}/2)^2 - p^2_{recon}}$$



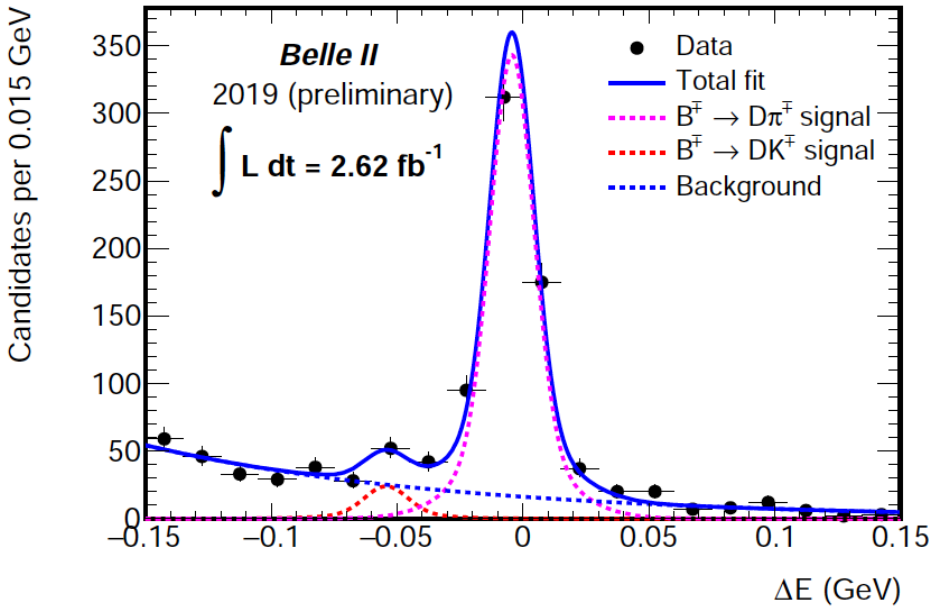


2200 Fully reconstructed hadronic B decays

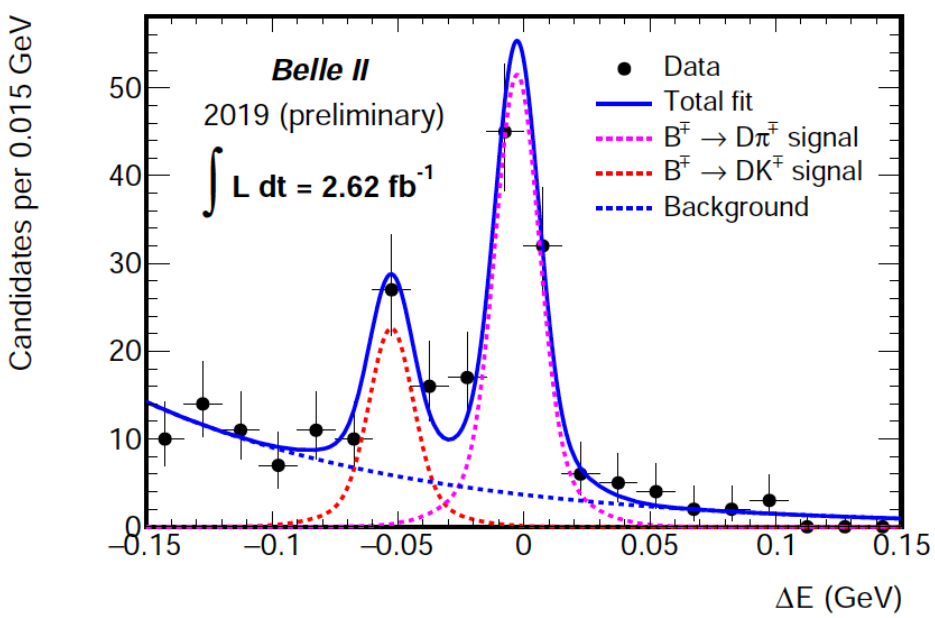
Clear demonstration of Belle II capabilities for doing B physics.
(**NB.** Modes with charged kaons and pions, as well as final states with K_S mesons and neutral particles are efficiently reconstructed.)

Evidence of $B^- \to D^0 K^-$

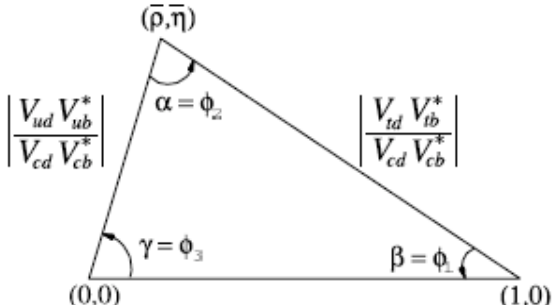
No PID



With high momentum PID



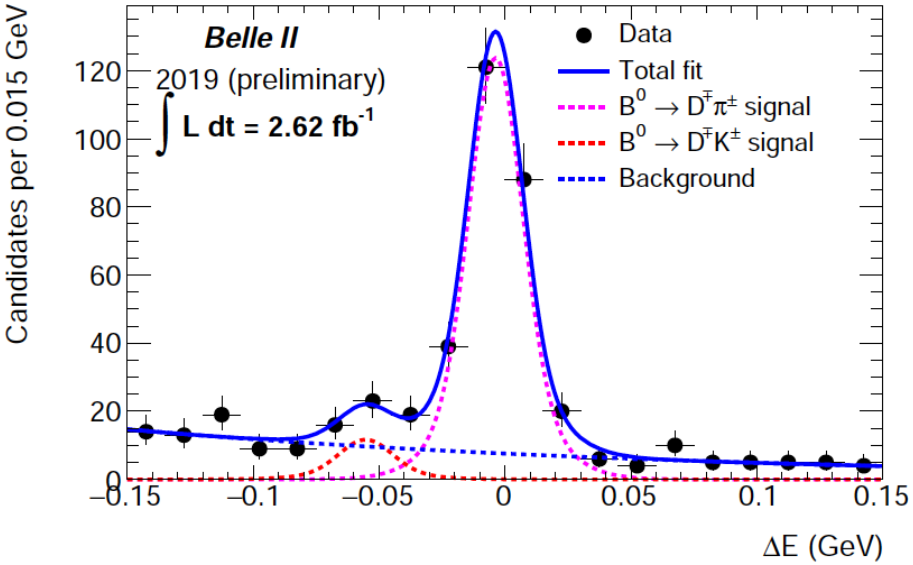
N(D K) = 38±8, fit gives 6σ



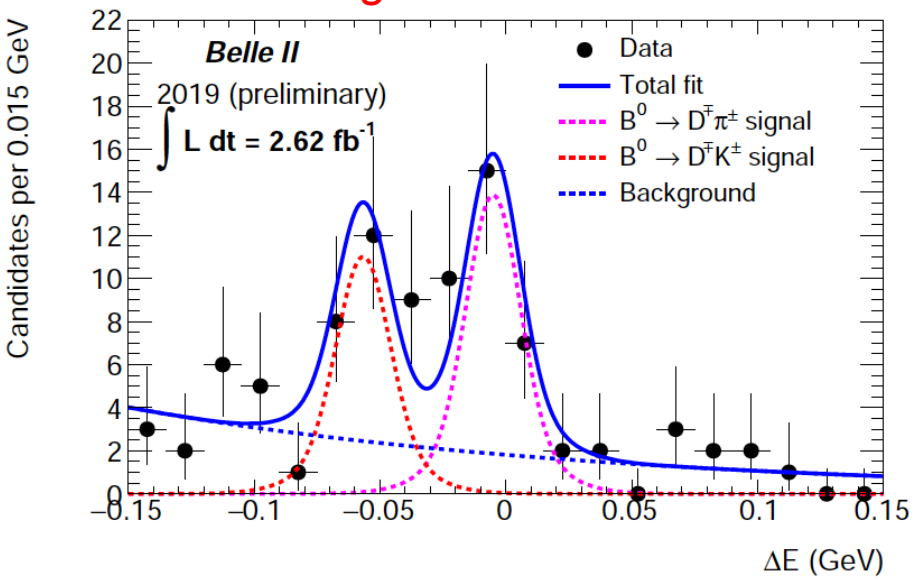
Demonstration of Belle II high momentum PID capability on a decay mode, which will be used for future determinations of the unitarity angle γ (or ϕ_3).

Evidence of $B^0 \to D^- K^+$

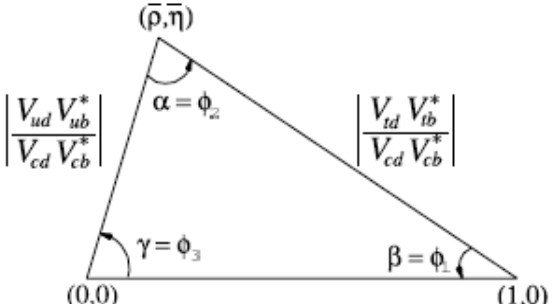
No PID



With high momentum PID

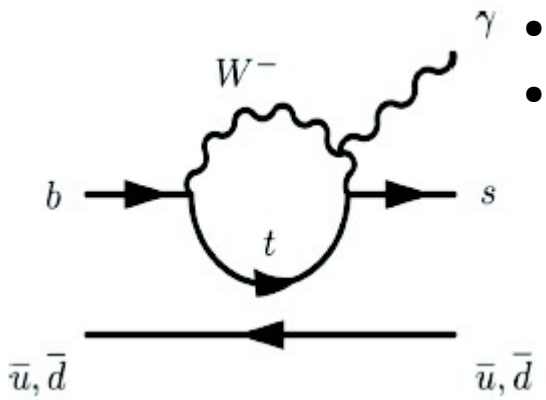


N(D K) = 23±6, fit gives 3.3σ



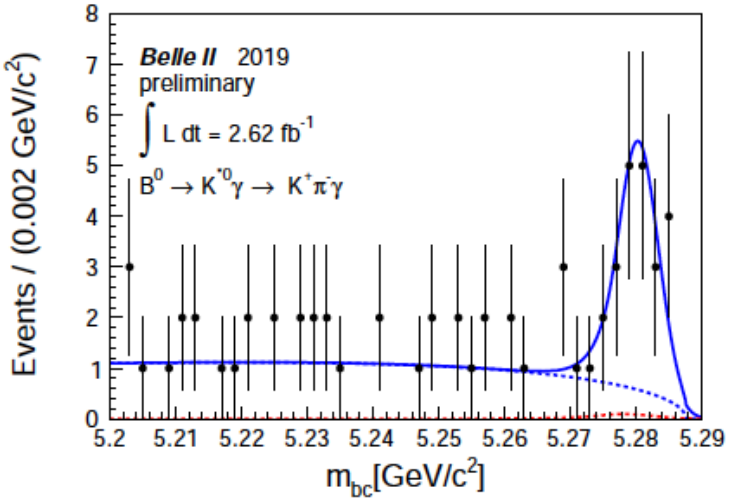
Demonstration of Belle II high momentum PID capability on a decay mode, which will be used for future determinations of the unitarity angle γ (or ϕ_3).

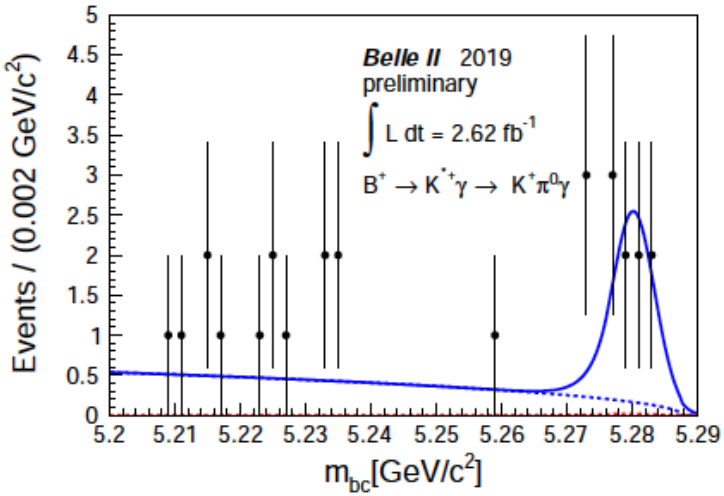
Study of a radiative B decay: $B^0 \to K^{*0}\gamma$

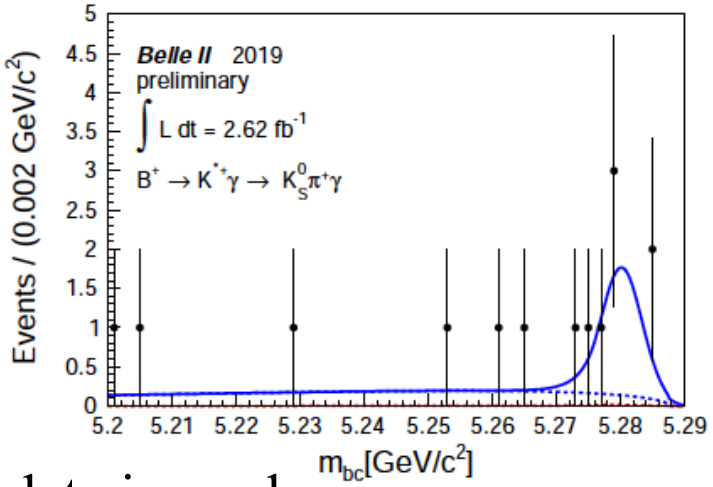


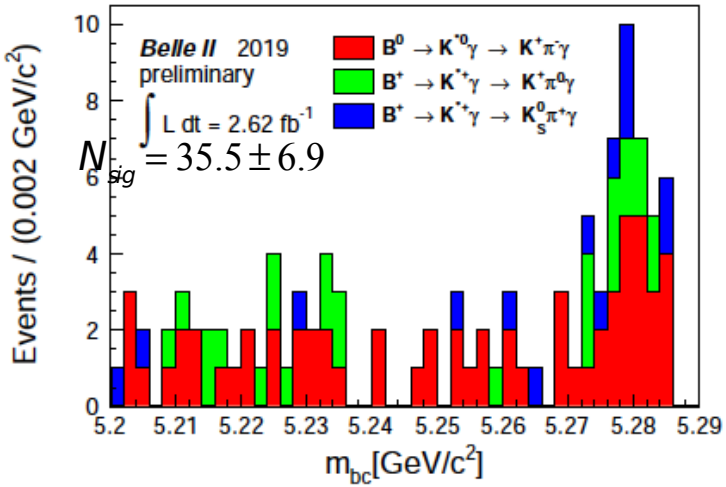
- Radiative penguin decay b→ sγ is a sensitive probe for NP;
- B→ K*γ is the cleanest exclusive decay to study

$$B^0 \to K^{*0}\gamma \to K^+\pi^-\gamma$$
$$B^0 \to K^{*+}\gamma \to K^+\pi^0\gamma$$
$$B^0 \to K^{*+}\gamma \to K^0_S\pi^+\gamma$$









First penguin for Belle II: Yields are consistent with the WA value.

Again: ~1/2 of Phase 3 data is used

Time-dependent measurements at Belle II

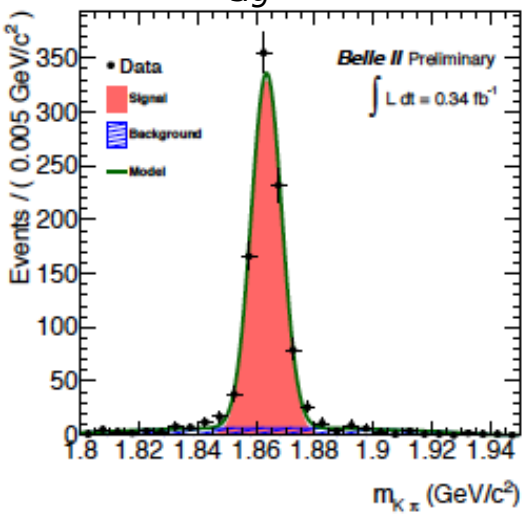
Example:
D^0 Lifetime in Belle II Phase 3 data

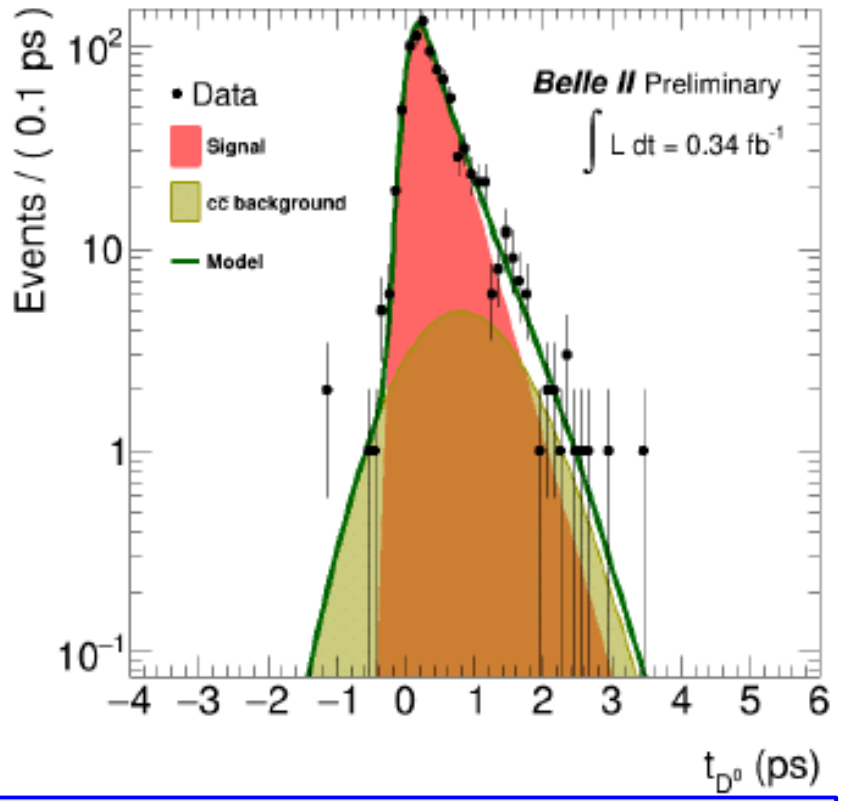
$$\tau_{D^0} = 370 \pm 40(stat)\ \text{fs}$$

- Using ~1/15 of the Phase 3 dataset.
- Clearly demonstrates the combined performance of the PXD and SVD (VXD system).

(**NB.** Accepted value 410 fs.)

$$N_{sig} = 860 \pm 30$$



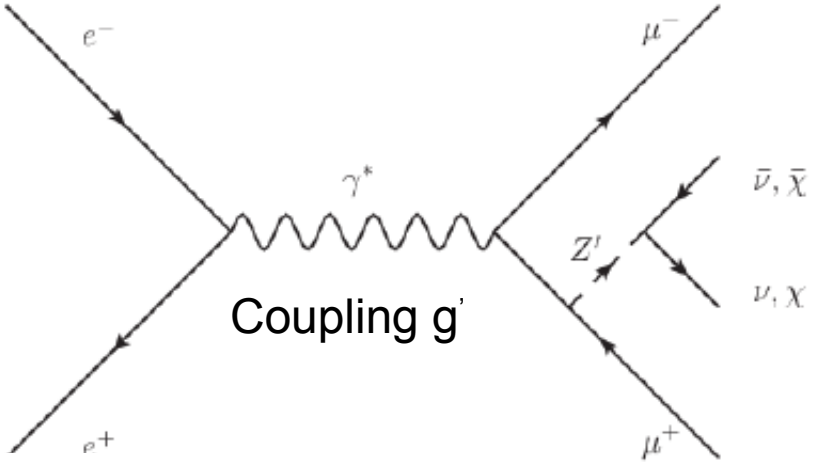


- **Belle II demonstrates also the capability to perform time-dependent studies;**
- **There will be a dedicated talk this afternoon (in Parallel sect. A): V.Chekelian: First look at the time-dependent CP violation using early Belle II data**

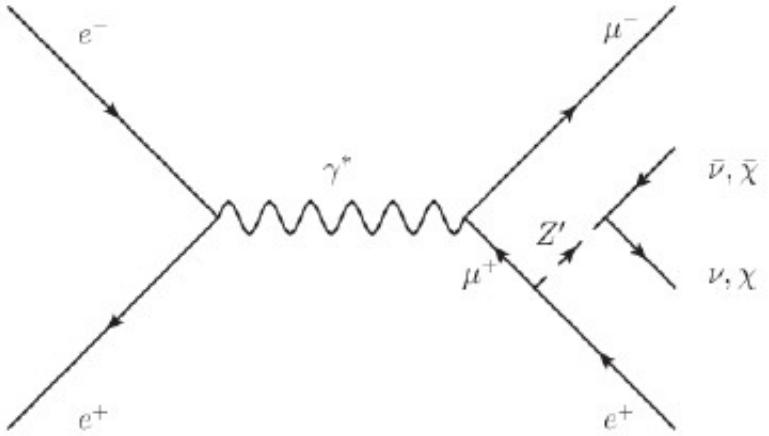
Dark sector at Belle II

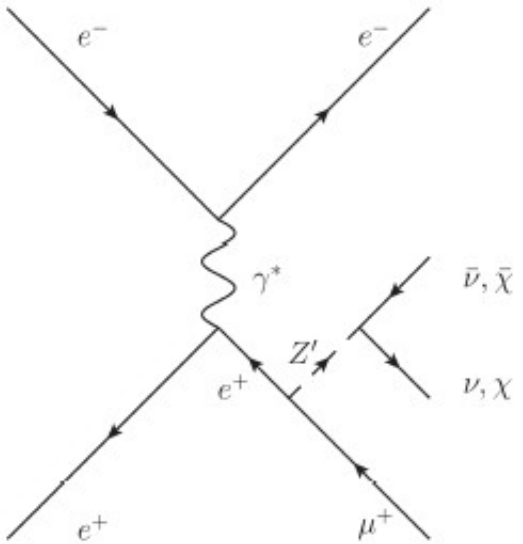
Dark Sector: Previously these studies were limited by triggering, QED backgrounds and theoretical imagination.
Now there are new possibilities of triggering, more bandwidth.

Belle II First Physics. A novel result on the dark sector (vector part. Z' → nothing) recoiling against a pair of muons *or* an electron-muon pair. (Both possibilities are poorly constrained at low Z' mass and in the first case, could explain the muon g-2 anomaly.)



Also examine a lepton-flavour-violating NP signature in the dark sector.



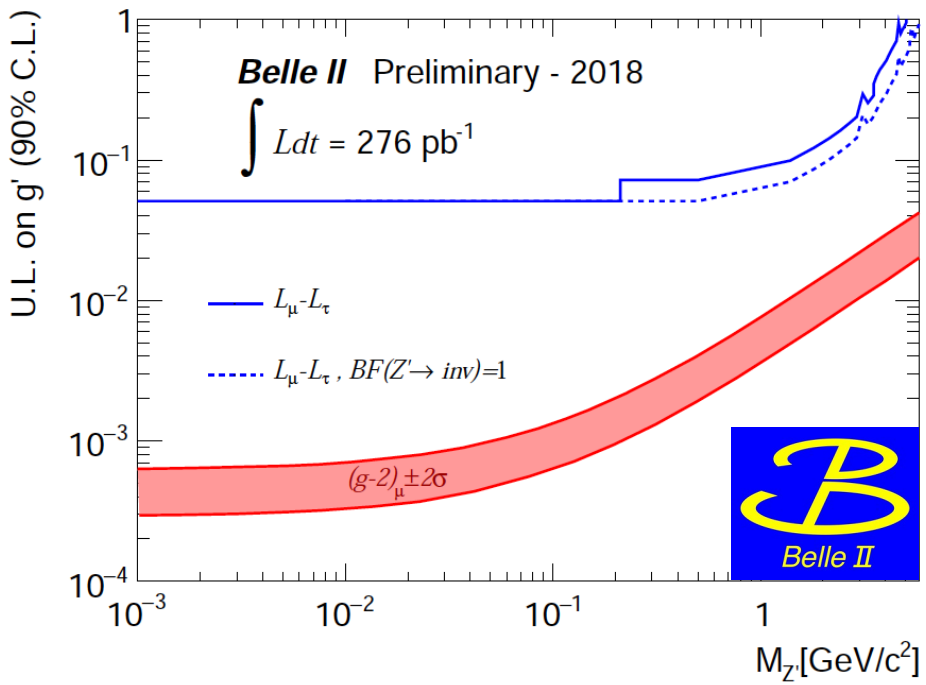


Dark sector at Belle II: Search for Z'

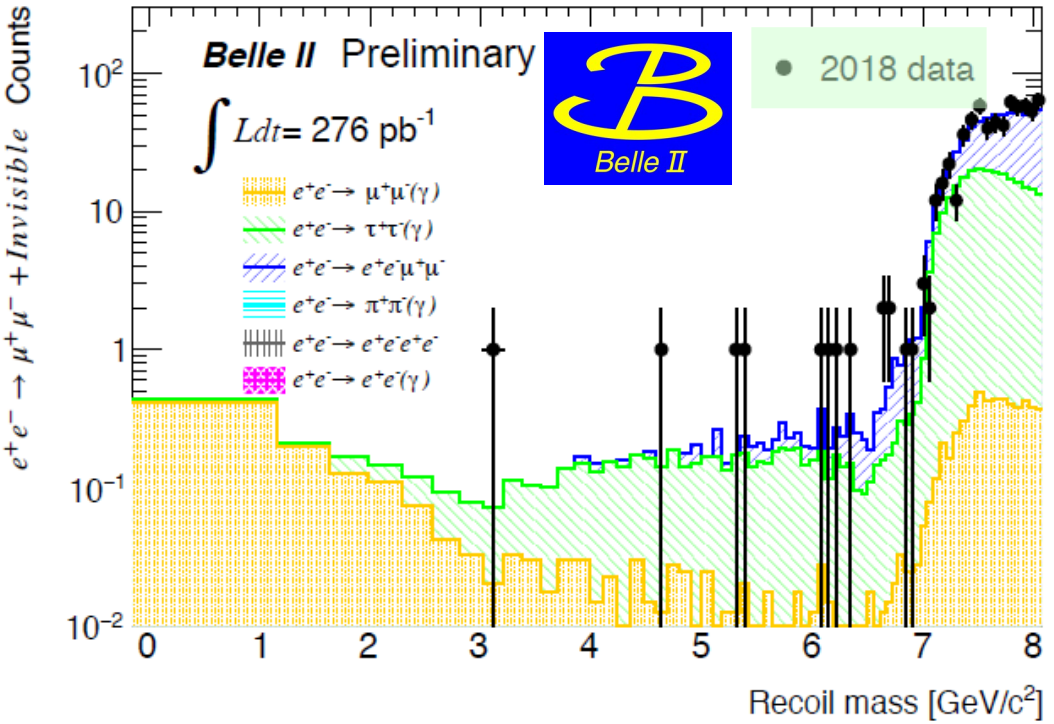
We search for Z' in

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

process.
Z' will create a bump in recoil mass of the event.



Search for $e^+e^- \to \mu^+\mu^- Z', Z' \to nothing$



→ After tau suppression cuts and unblinding.

Preliminary results are out → aiming at publication.

Results are compatible with backgrounds; No excess above 3σ is seen.
First upper limit on coupling g' is obtained.

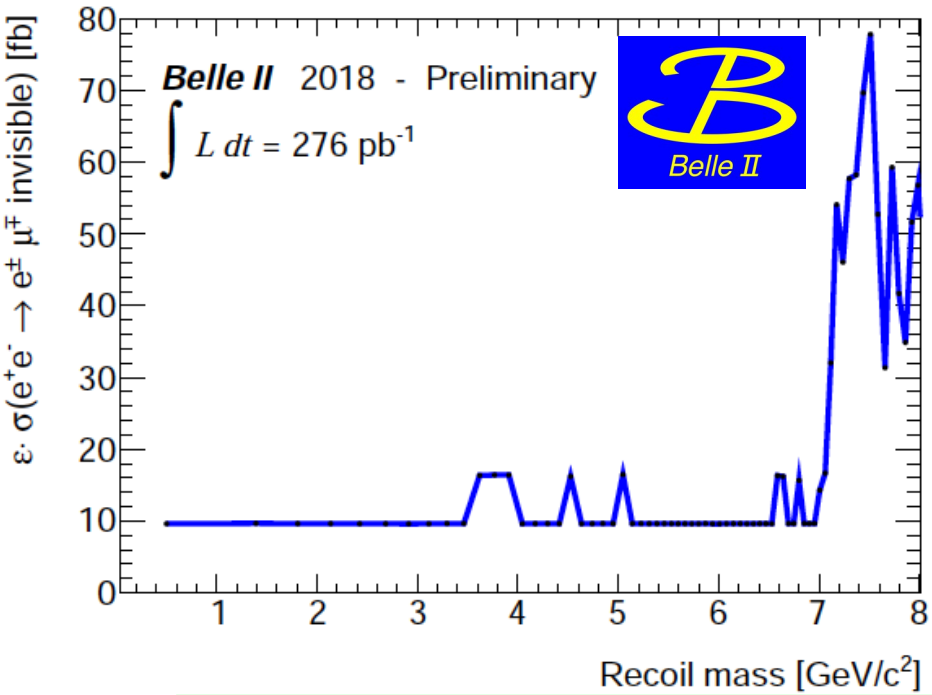
Dark sector at Belle II: Search for LFV Z'

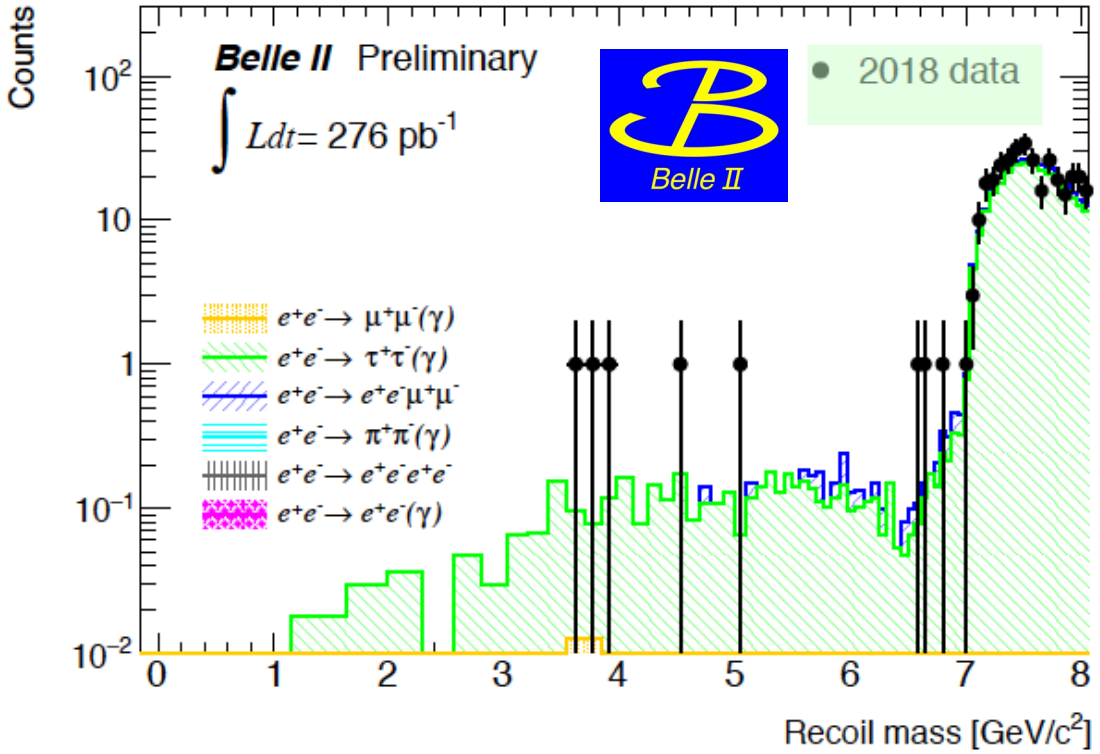
If we allow for Z' to have LFV couplings, we can also perform the search:

$$e^+e^- \to \mu^+ l^-(e,\tau)\ Z'(\to Invisible)$$

More theoretical input is needed for clear predictions

Search for $e^+e^- \to \mu^\pm e^\mp Z'_{LFV}, Z'_{LFV} \to nothing$





Preliminary results are out → aiming at publication.

Results are compatible with backgrounds; No excess seen.
Model-independent approach only: ε·σ is obtained.

Summary and Conclusions

- There has been highly successful program of machines with increased luminosity since the 1980s.
- The SuperKEKB colider and Belle II experiment aiming to continue the tradition with performance at a new level:
  - 40-times higher luminosity with respect to the previous record,
  - the most advanced, 21st-century detector technology.
- This will enable Belle II to explore NP on the Luminosity/Intensity Frontier, which is different/complementary to the LHC high p_T experiments (Energy Frontier).
- Competition and complementarity with the LHCb experiment.
- Phase 2 data-taking finished successfully: calibration, particle re-discoveries, tagging, ...
- Phase 3 started in March 2019 and finished on 1st July 2019:
Belle II collected data sample corresponding to L_{int} =6.49 fb^{-1}; first results shown.
- **Operation will resume in October 2019 and continue until July 2020.**

⇒ **Our results are eagerly awaited by the HEP community.**

Backup Slides

Long term prospects of Belle II

- Based on The Belle II Physics Book (https://arxiv.org/abs/1808.10567)
- Outcome of the B2TIP (Belle II Theory Interface) Workshops, with emphasis on New Physics (NP) reach.
  (Strong participation from theory community, *lattice QCD community* and Belle II members.
  689 pages, published by Oxford University Press)

KEK Preprint 2018-27
BELLE2-PAPER-2018-001
FERMILAB-PUB-18-398-T
JLAB-THY-18-2780
INT-PUB-18-047
UWThPh 2018-26

The Belle II Physics Book