The Belle II experiment: status and prospects for BSM searches

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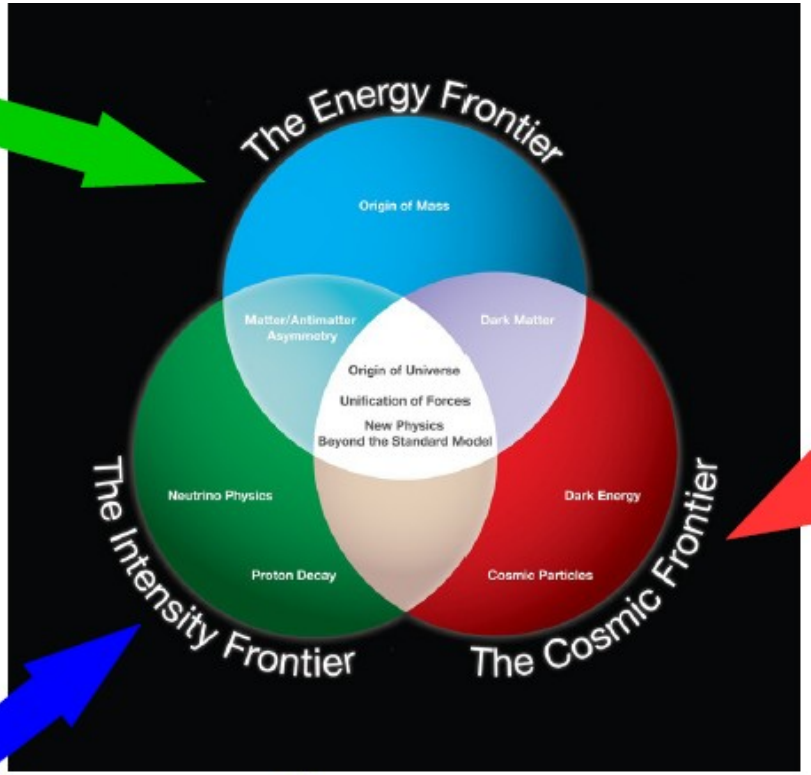
Budker INP & NSU

10-13 September **KAON 2019** **Perugia**

Frontiers of Particle Physics

- **LHC experiments**



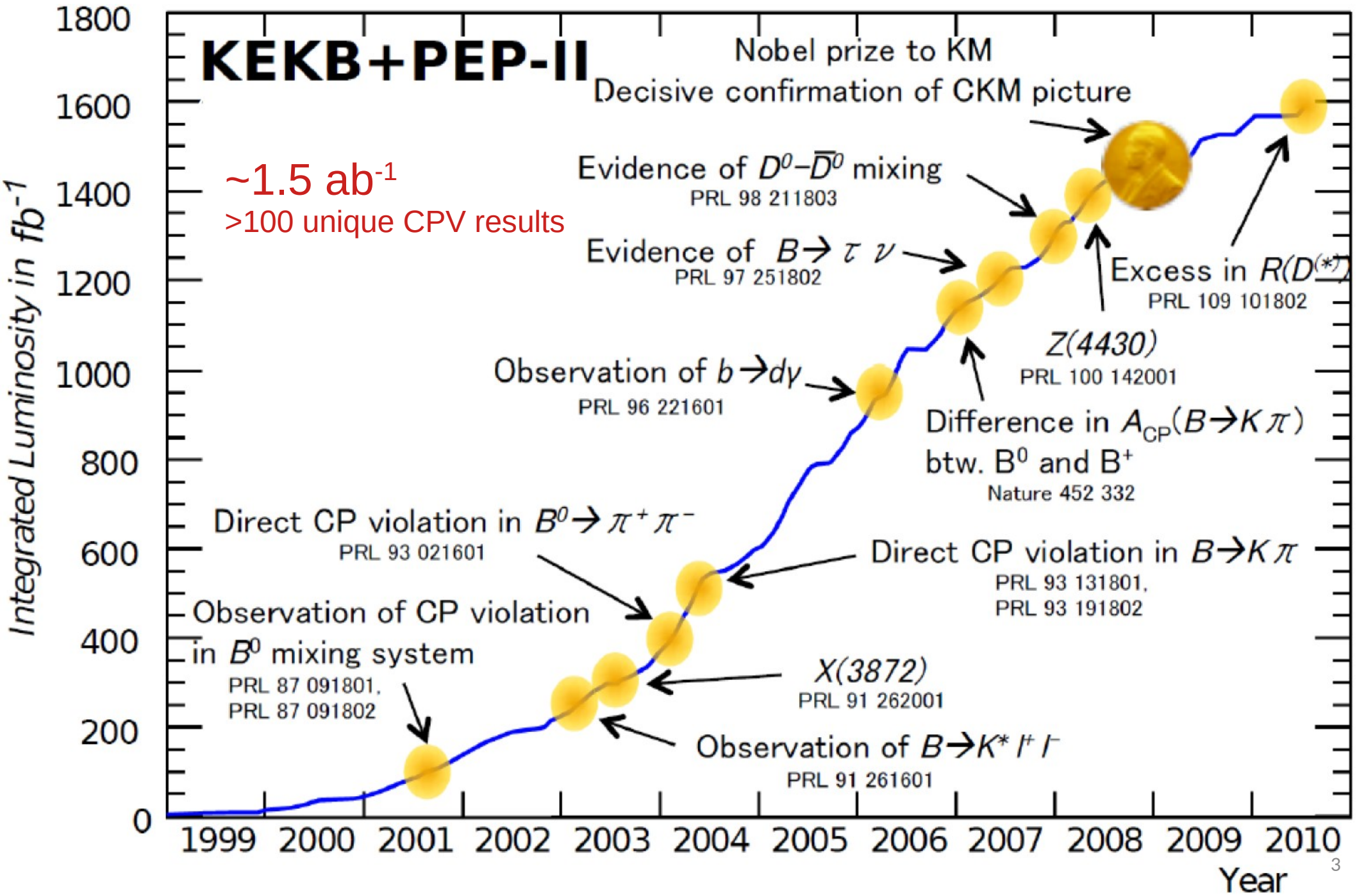
- **Astroparticle experiments**

- **Neutrino experiments**
- **Particle factories, such as Belle (II), and tau-charm factories**

NP searches:
indirect vs. **direct** approach

Intensity Frontier researchers use a combination of intense particle beams and highly sensitive detectors to make extremely precise measurements of particle properties, study some of the rarest particle interactions predicted by the Standard Model of particle physics, and search for New Physics.

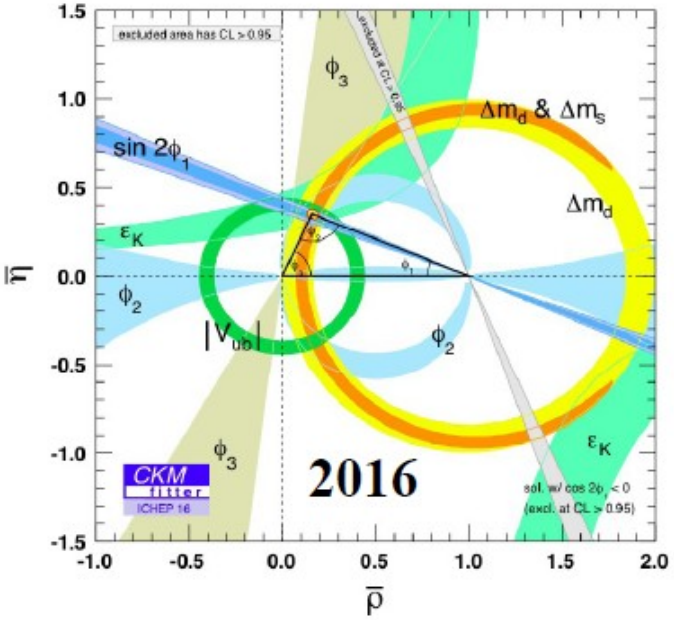
The B factories milestones

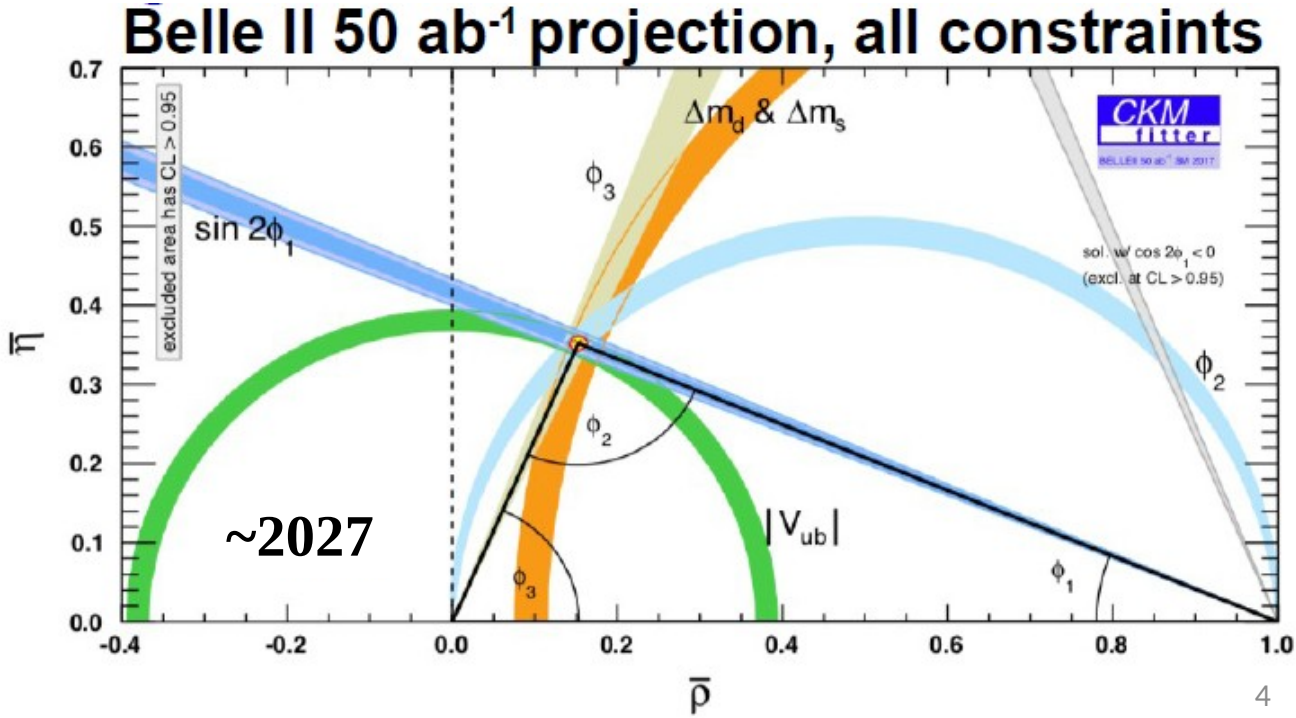


Physics motivation for increased luminosity

Stress-testing the SM and sensitively probing New Physics

- Precision CKM measurements: CP violation, meson mixing, decay rates;
- Rare processes, e.g., flavour-changing neutral currents;
- Search for New Physics in lepton-flavour non-universality, lepton flavour violation processes;
- Direct searches for new light states; Dark sector.

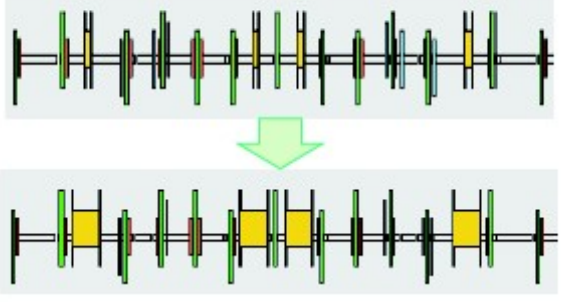




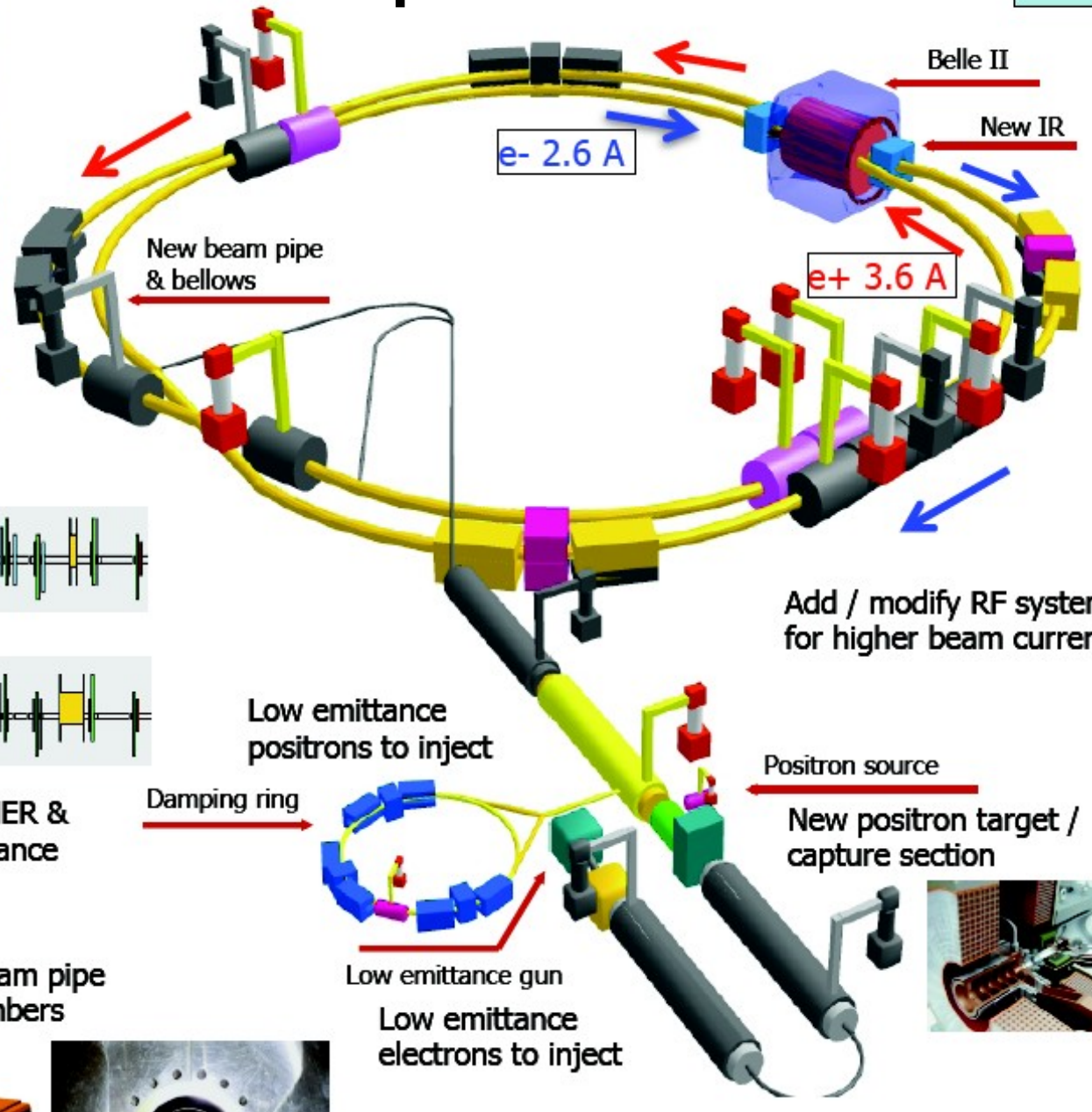
Super KEKB

Grey is recycled, coloured is new

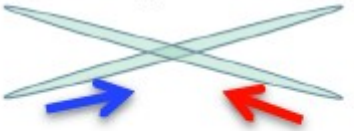
Replace short dipoles with longer ones (LER)



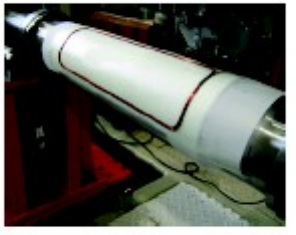
Redesign the lattices of HER & LER to squeeze the emittance



Colliding bunches



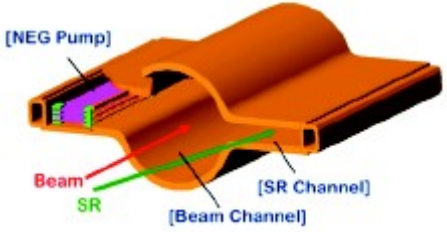
New superconducting / permanent final focusing quads near the IP

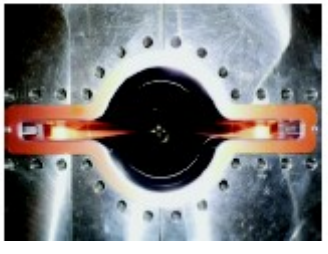


Add / modify RF systems for higher beam current

New positron target / capture section

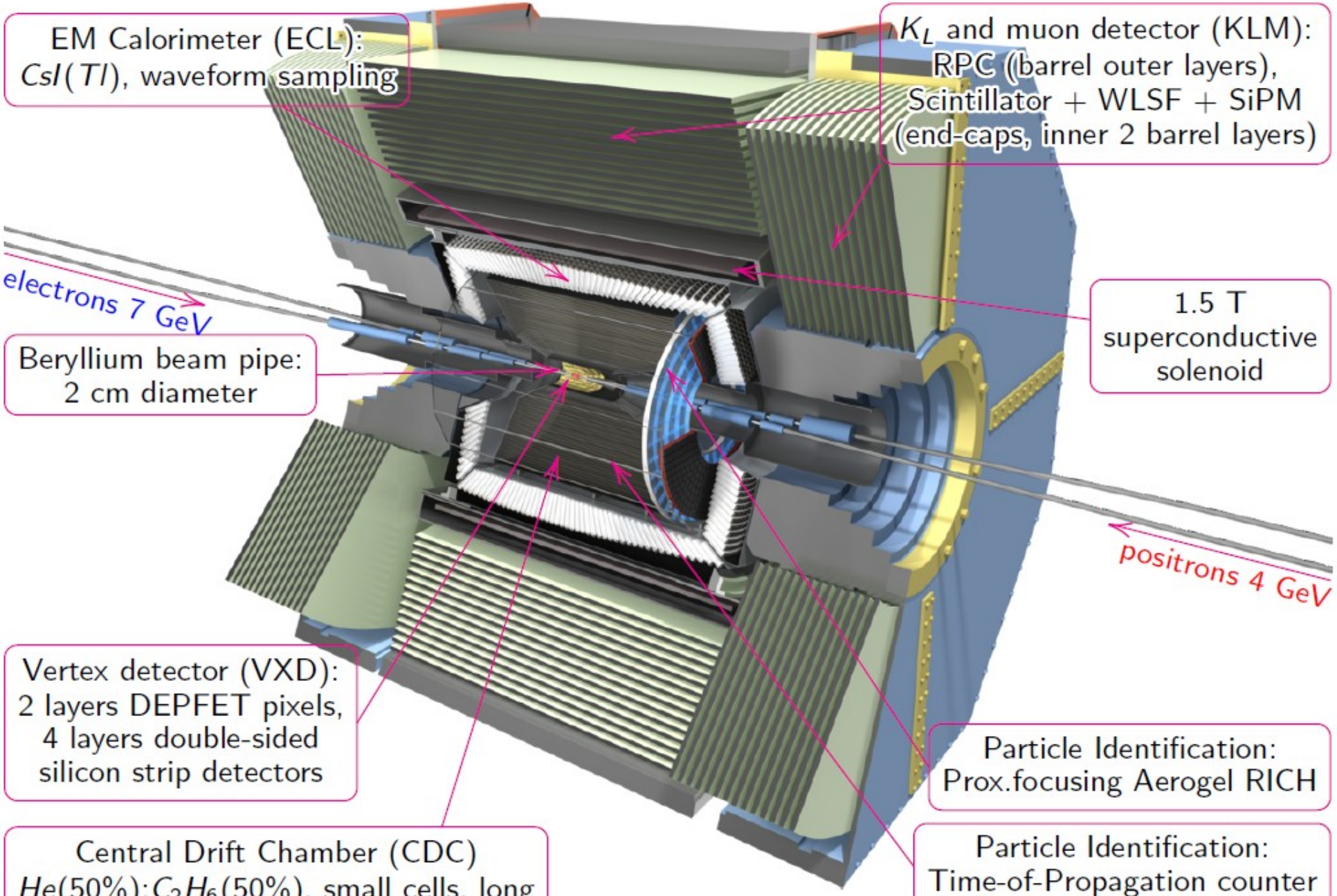
TiN-coated beam pipe with antechambers



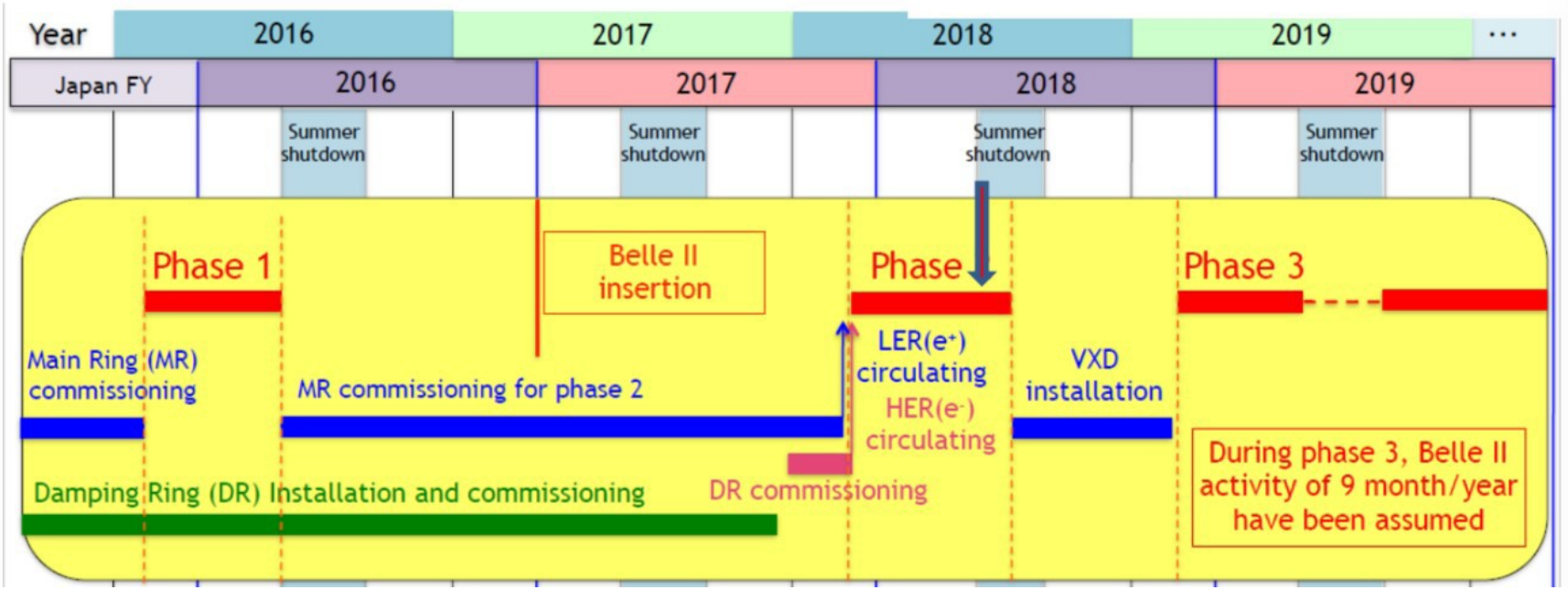


Almost entirely new machine!

Belle II detector

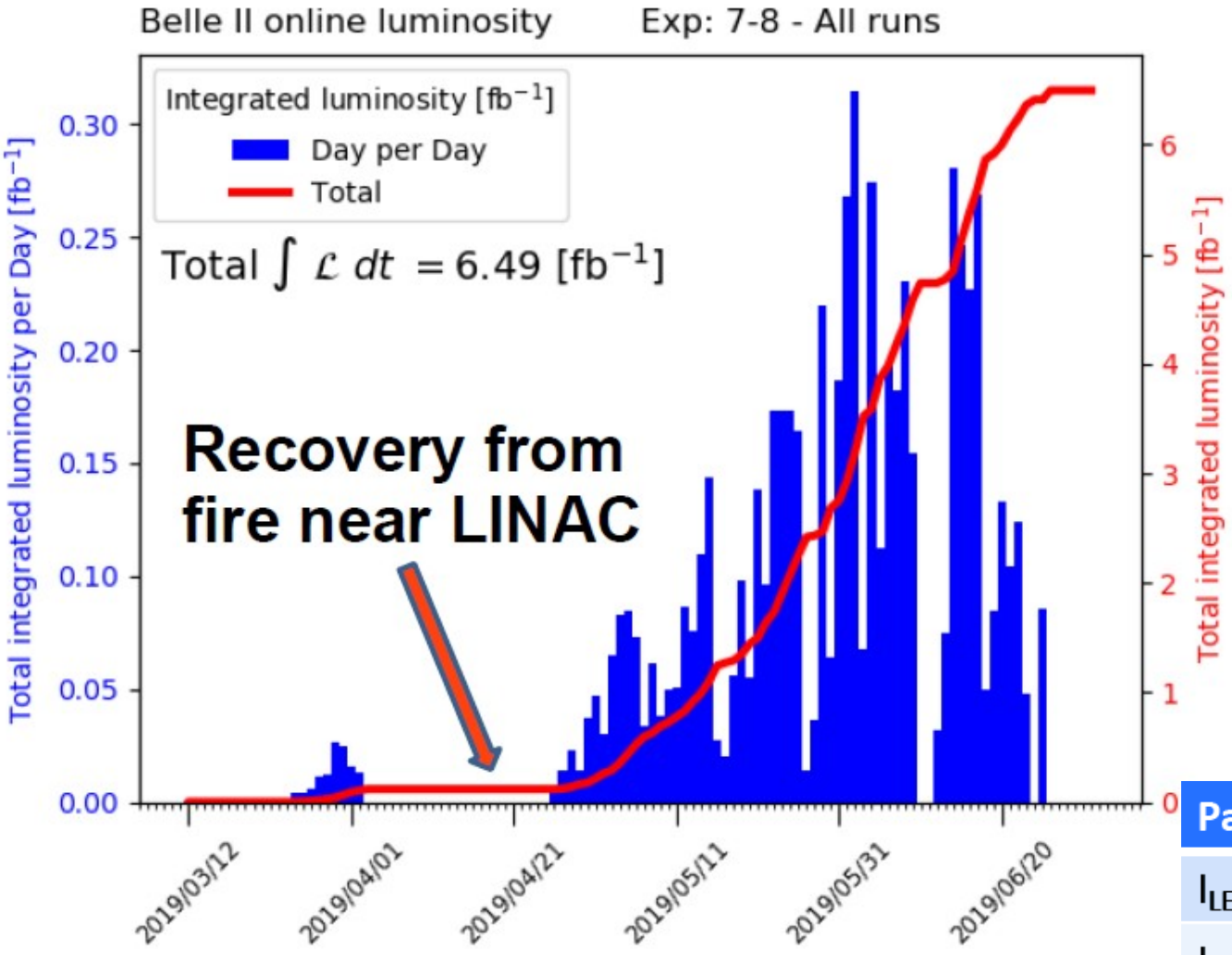


Belle II data taking



- Phase 1: [Feb – June 2016] Simple background commissioning detector BEAST II. No final focus. Single beam background studies.
- Phase 2: [April – July 2018] A pilot run with a more elaborate inner background commissioning detector. Belle II outer detector (partial vertex detector). Full superconducting final focus. Collisions.
- Phase 3: [March – June 2019] Installed the VXD in Belle II. First Physics Run with the full Belle II detector. Aims:
  - ✔ Tune SuperKEKB Physics running with acceptable backgrounds.
  - ✔ Test Belle II detector: readout, DAQ, vertexing, tracking, PID.
  - ✔ Make first measurements. Carry out dark sector searches as well.

Run 3



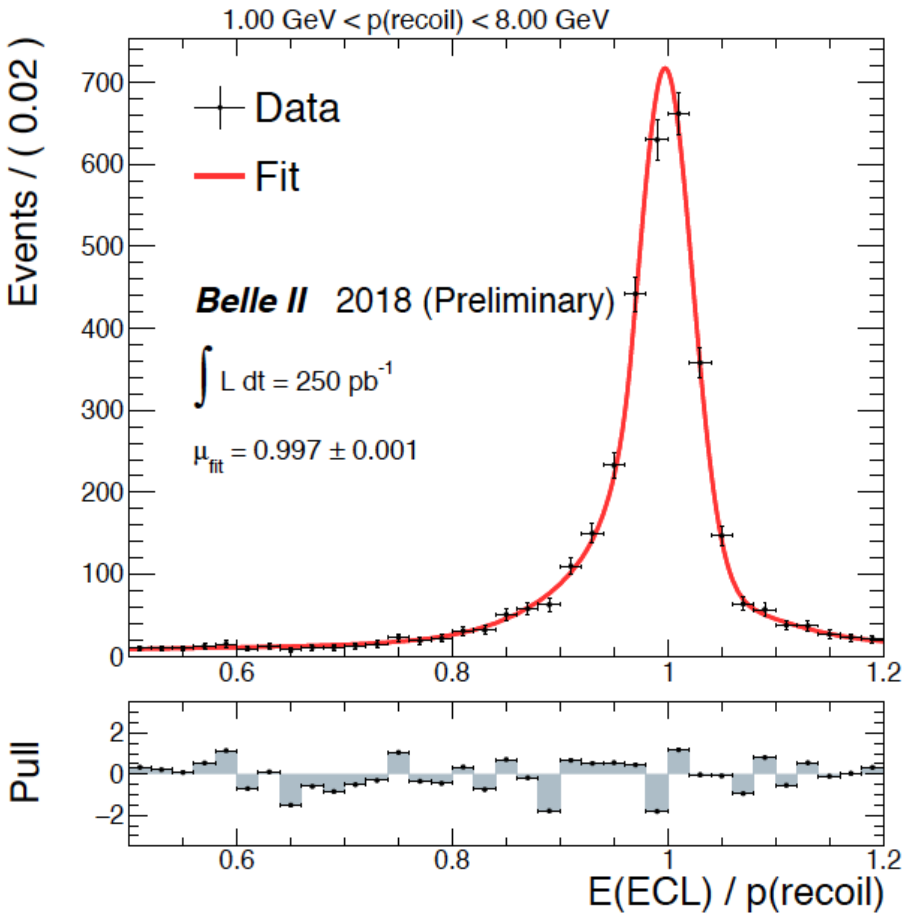
Results for early Phase 3 data: based on 2.62 fb^{-1}

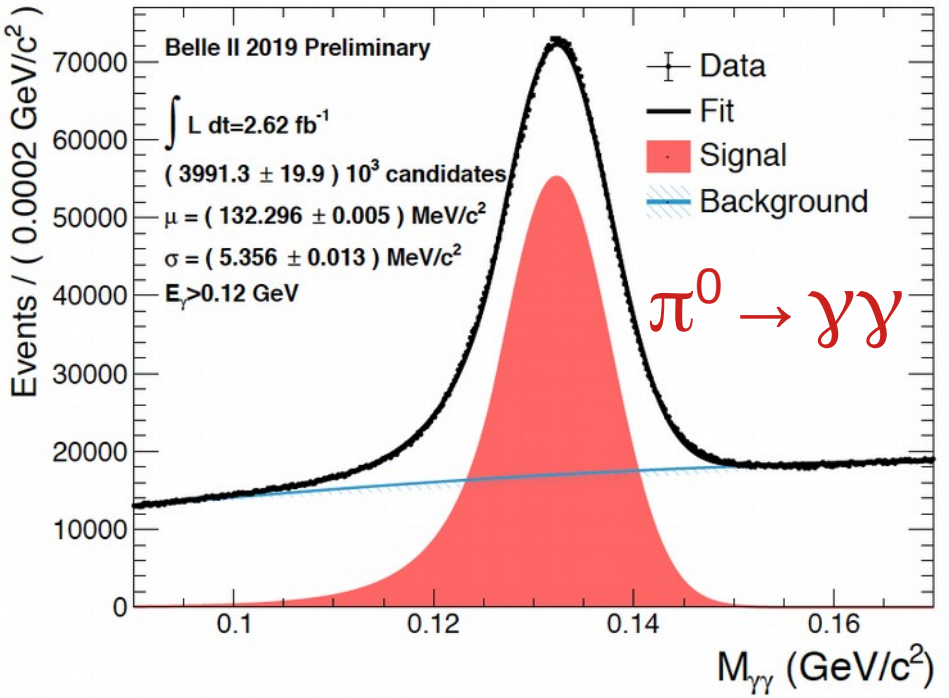
L_{peak}(normal)~5.5 x 10^{33}/cm^2/sec (βy^*=3mm)
L_{peak}(last week)~1.2 10^{34} (βy^*=2mm)
→ This is comparable to KEKB / PEP-II,
but background ~3 times higher to turn on Belle II

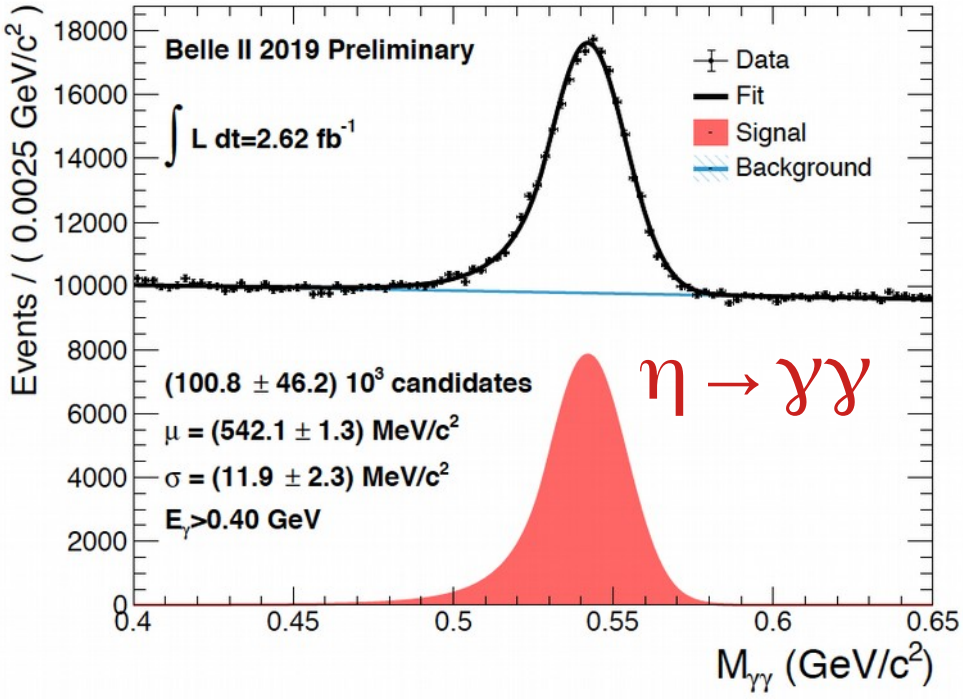
Parameter	Achieved	Target
I_{LER}(max)(A)	0.880	2.6
I_{HER}(max)(A)	0.940	3.6
β_y^* (mm)	2	0.3
# bunches	1576	2364
L_{peak}(cm^{-2} s^{-1})	6.1 x 10^{33}	8 x 10^{35}
L(det OFF)	12 x 10^{33}	

Photons reconstruction

$e^+e^- \to \mu^+\mu^-\gamma$





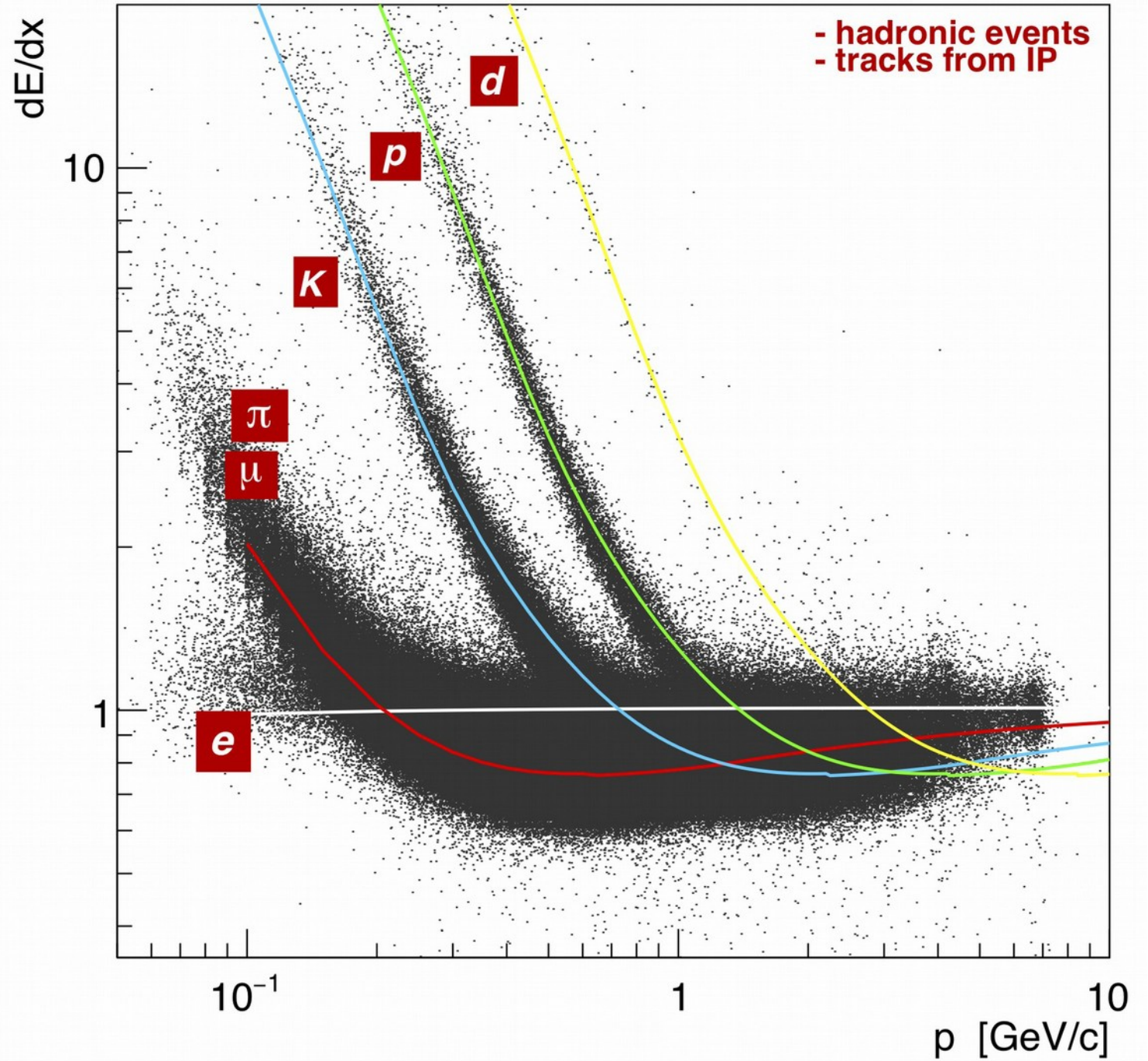


Ready for the dark sector:

$e^+e^- \to \gamma X$

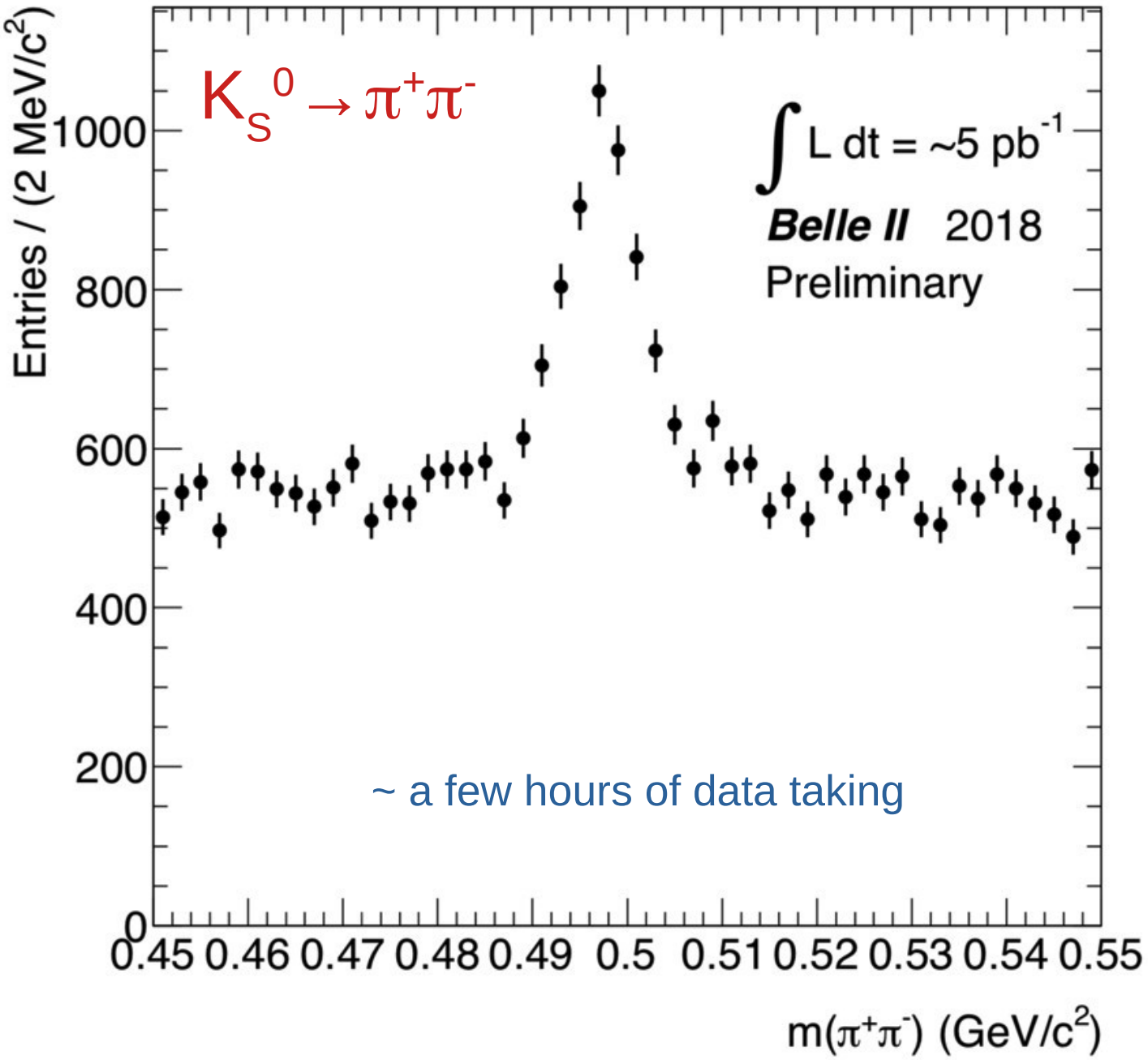
$e^+e^- \to \gamma ALPS \to \gamma(\gamma\gamma)$

PID: dE/dx in CDC

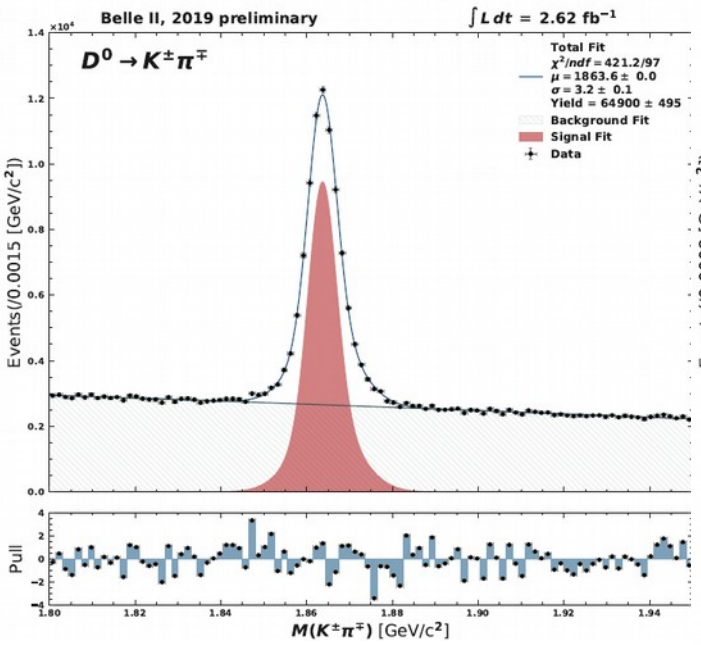


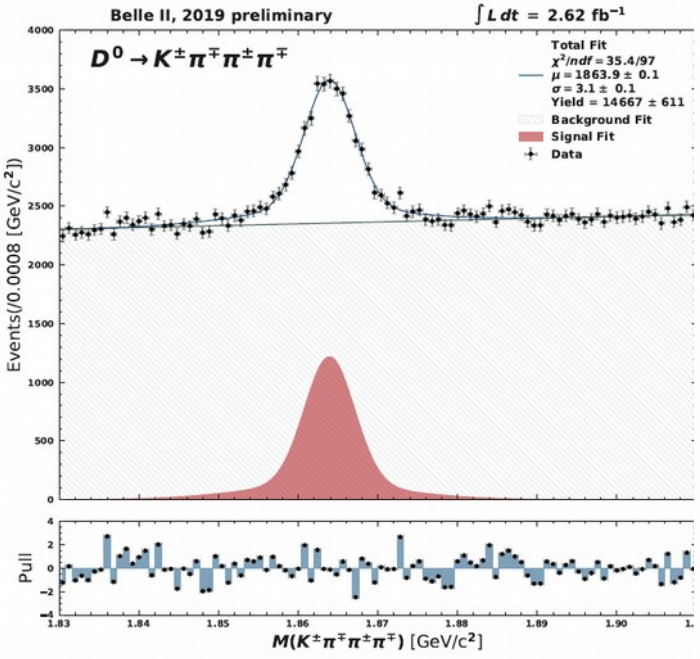
Performance of CDC dE/dx PID with early calibrations in the hadronic event sample.

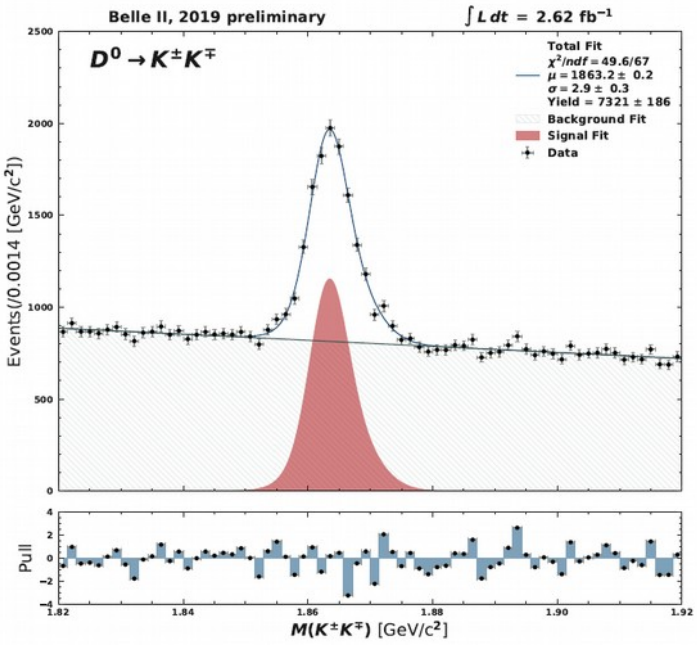
Reconstruction of charged tracks

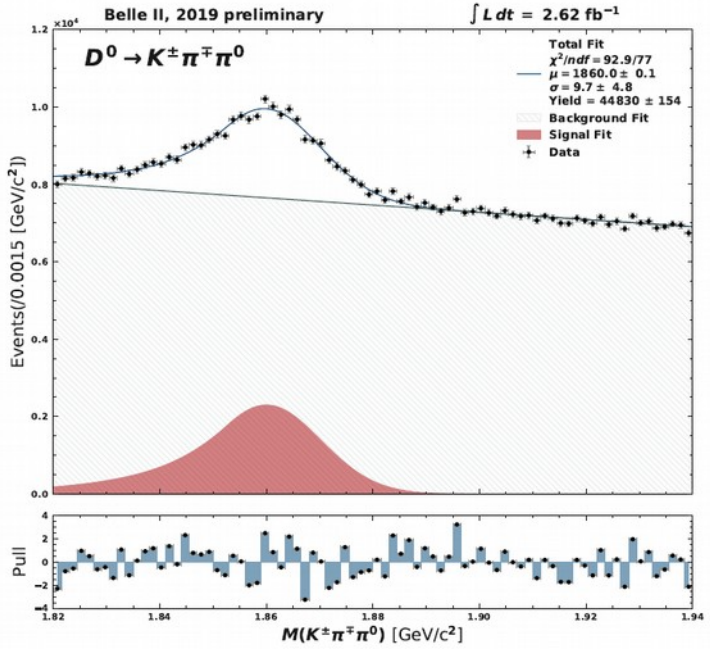


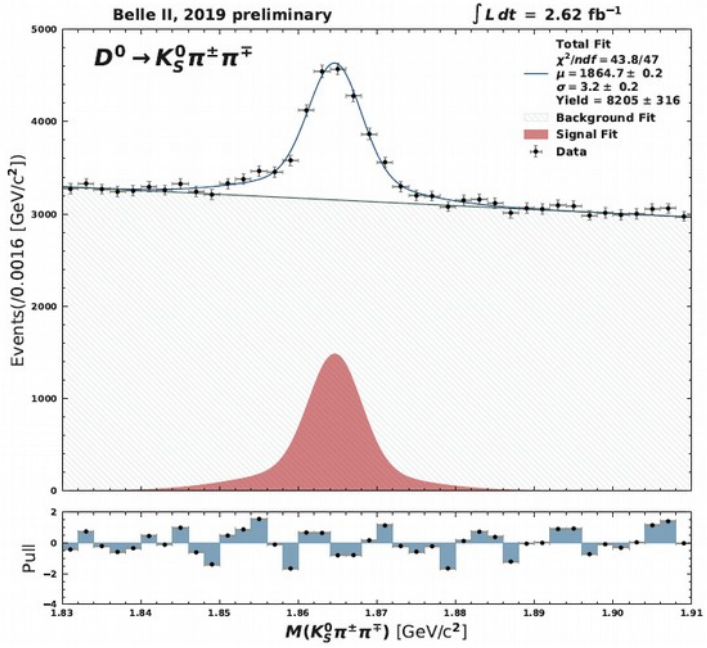
Charm reconstruction: $e^+e^- \to c\bar{c}$











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

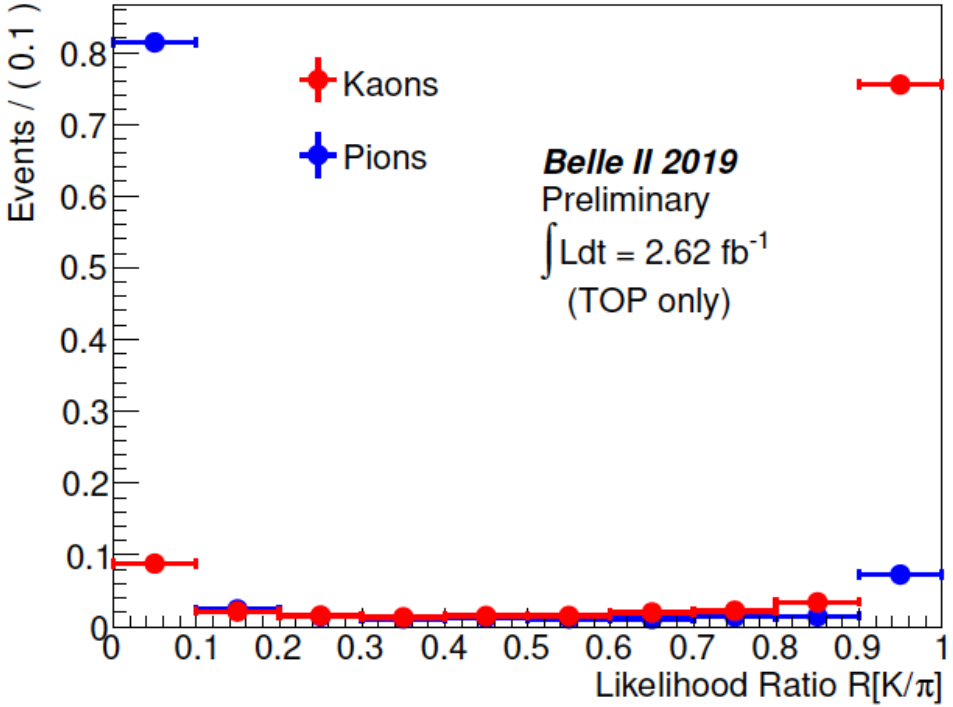
TOP PID

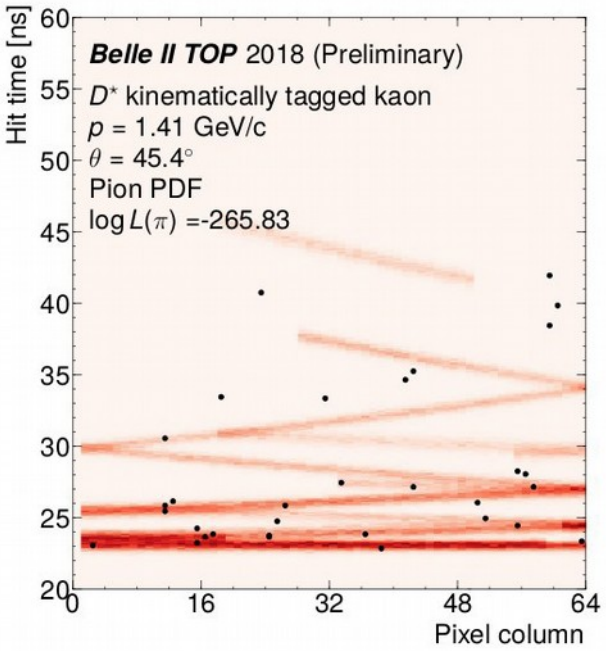
$D^{*+} \rightarrow D^0 \pi^+_{slow}$ $D^0 \rightarrow K^- \pi^+$

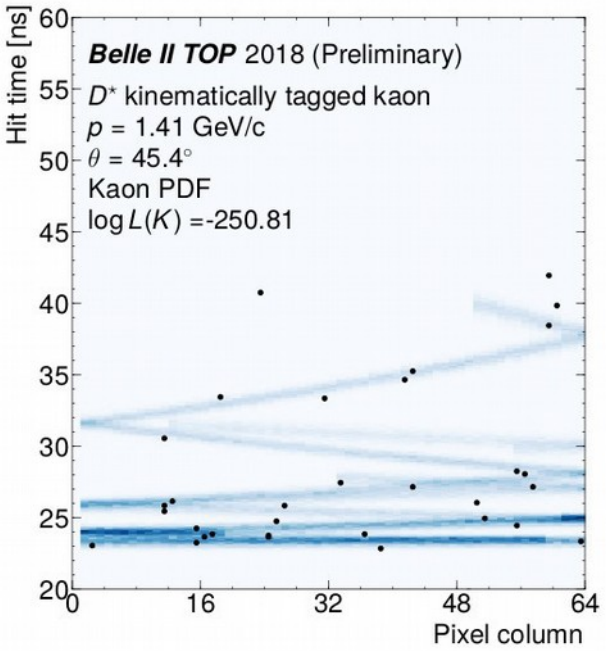
Kinematically identified kaon from a D^{*+} in the TOP.

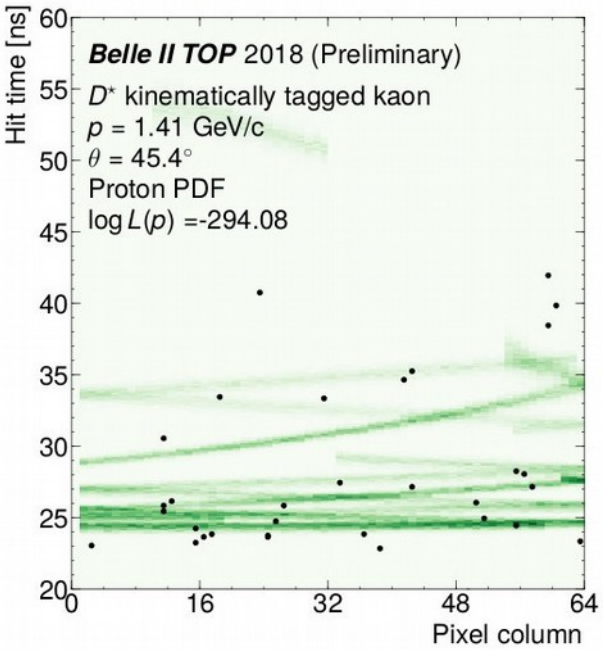
Cherenkov x vs t pattern (mapping of the Cherenkov ring)

Kaon hypothesis is favorable.





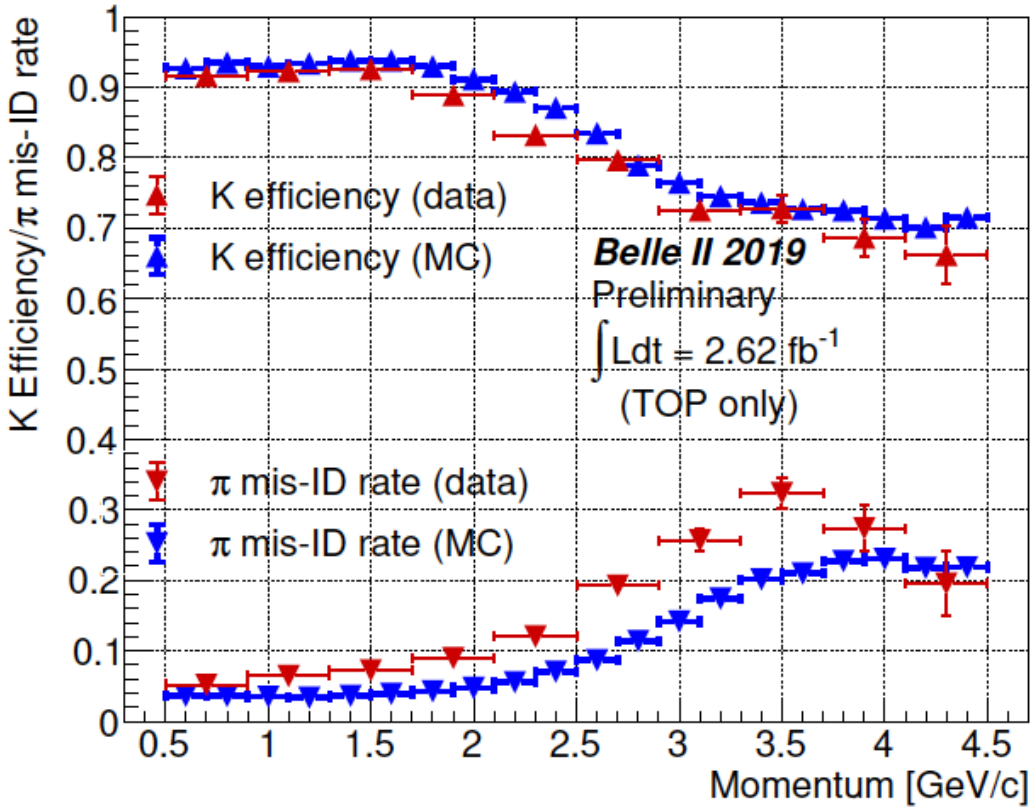


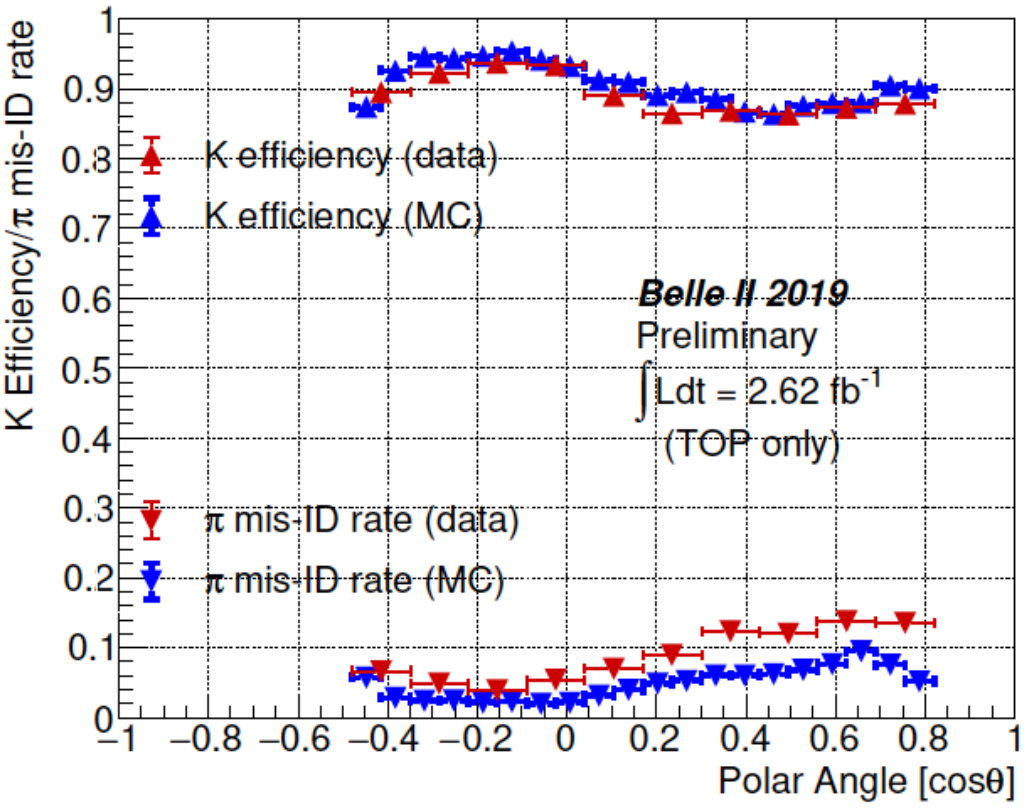


TOP performance

$D^{*+} \rightarrow D^0 \pi^+_{slow}$ $D^0 \rightarrow K^- \pi^+$

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

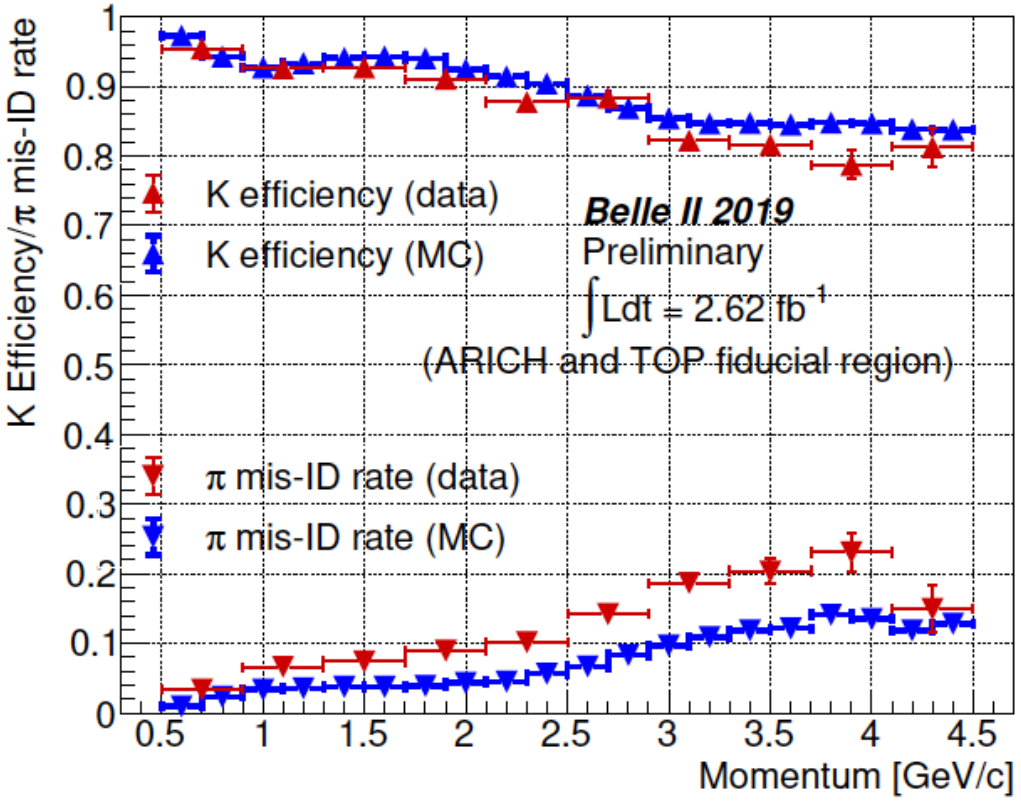


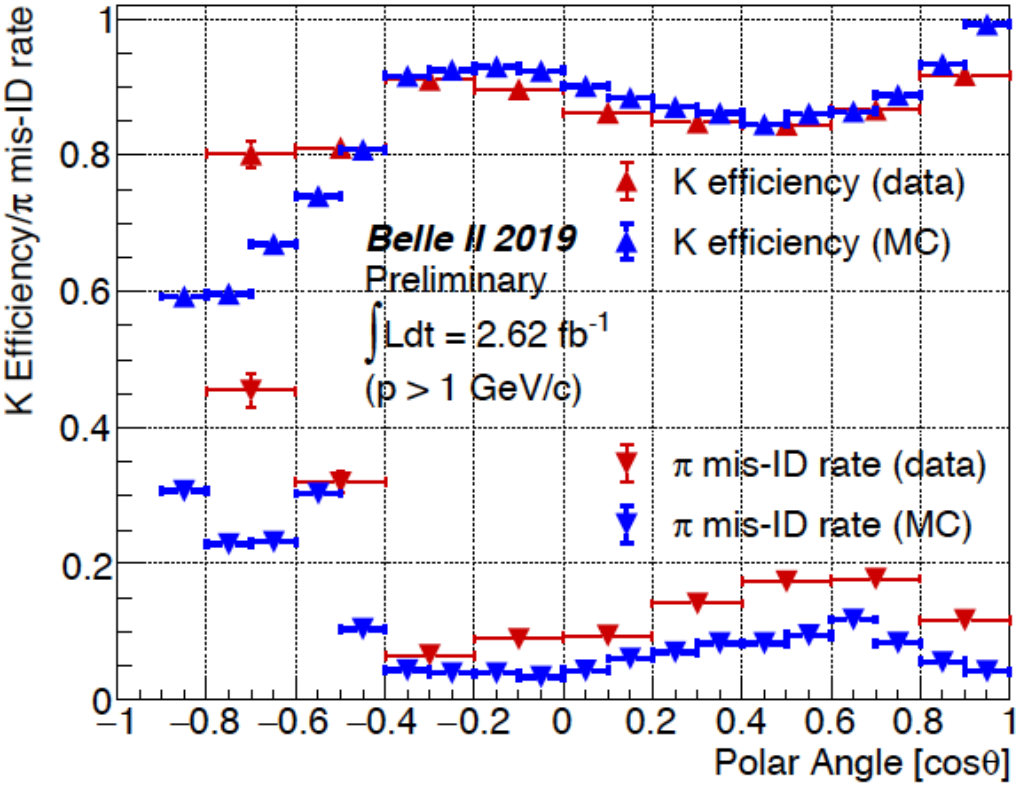


TOP performance is approaching MC expectations. ***NB.*** *The current MC simulation does not include embedded random triggers, which correctly represent the effect of beam background and electronic noise.*

Global PID performance

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

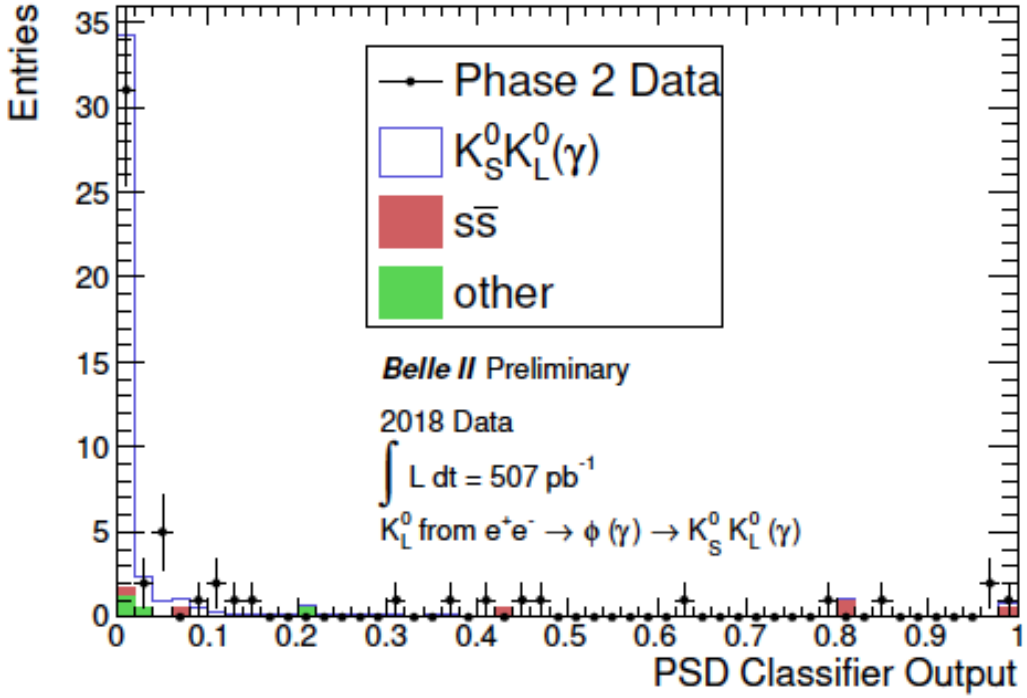




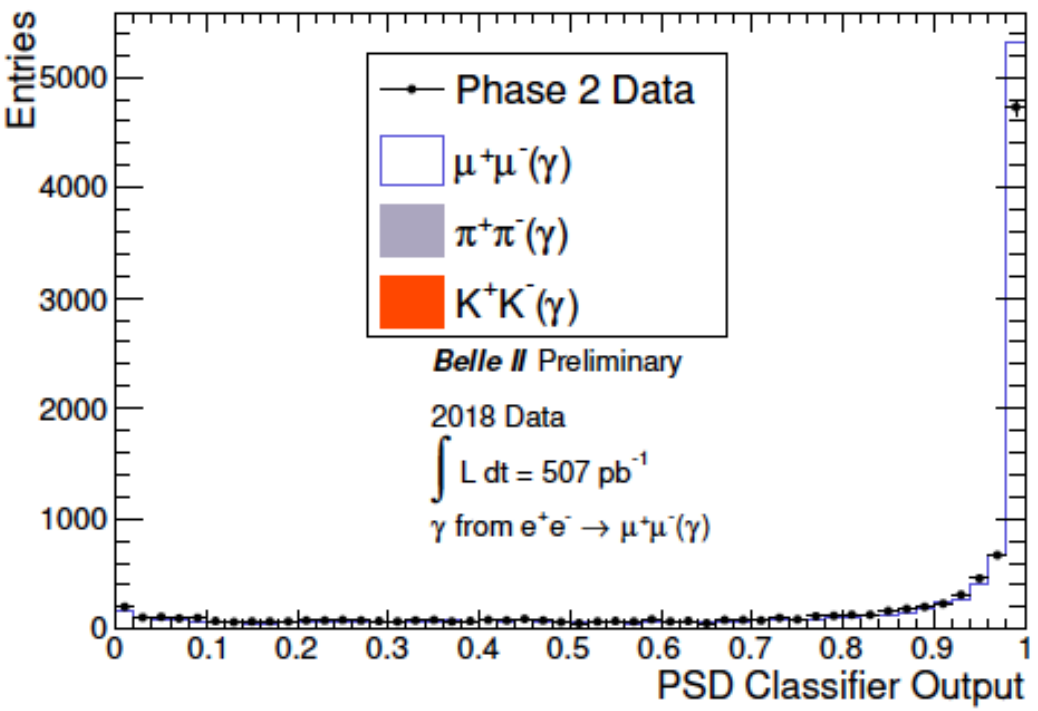
NB. *Current MC simulation does not include embedded random triggers, which correctly represent the effect of beam background and electronic noise in CDC, ARICH and TOP.*

K_L identification in ECL

K_L from e+e- → K_S K_L γ (ISR)

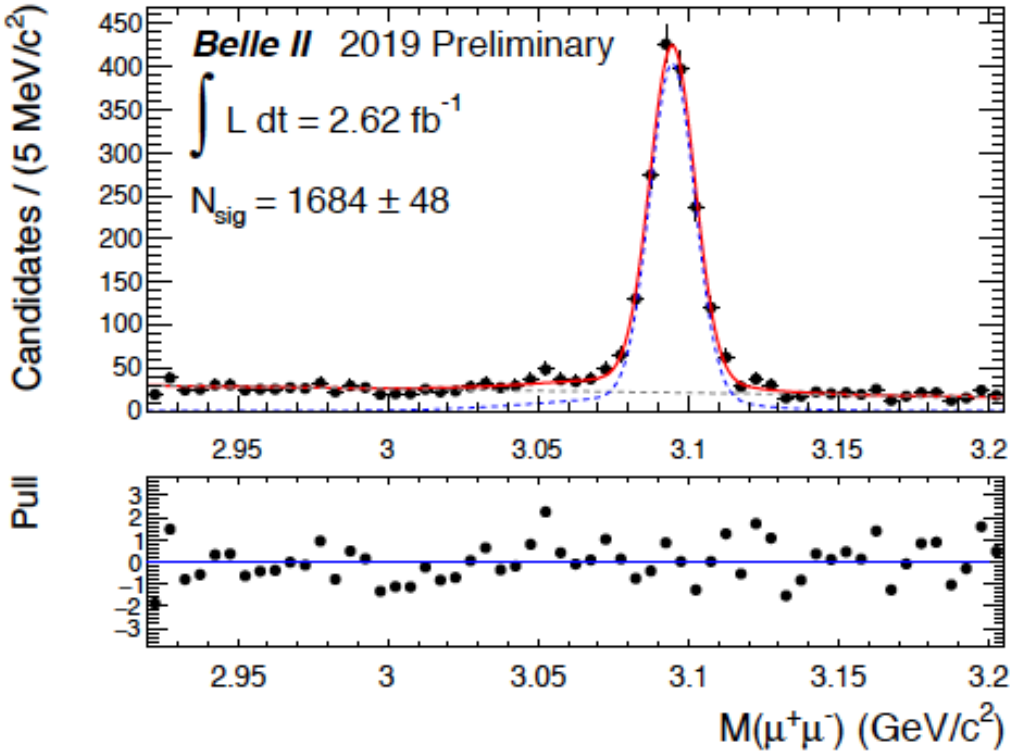


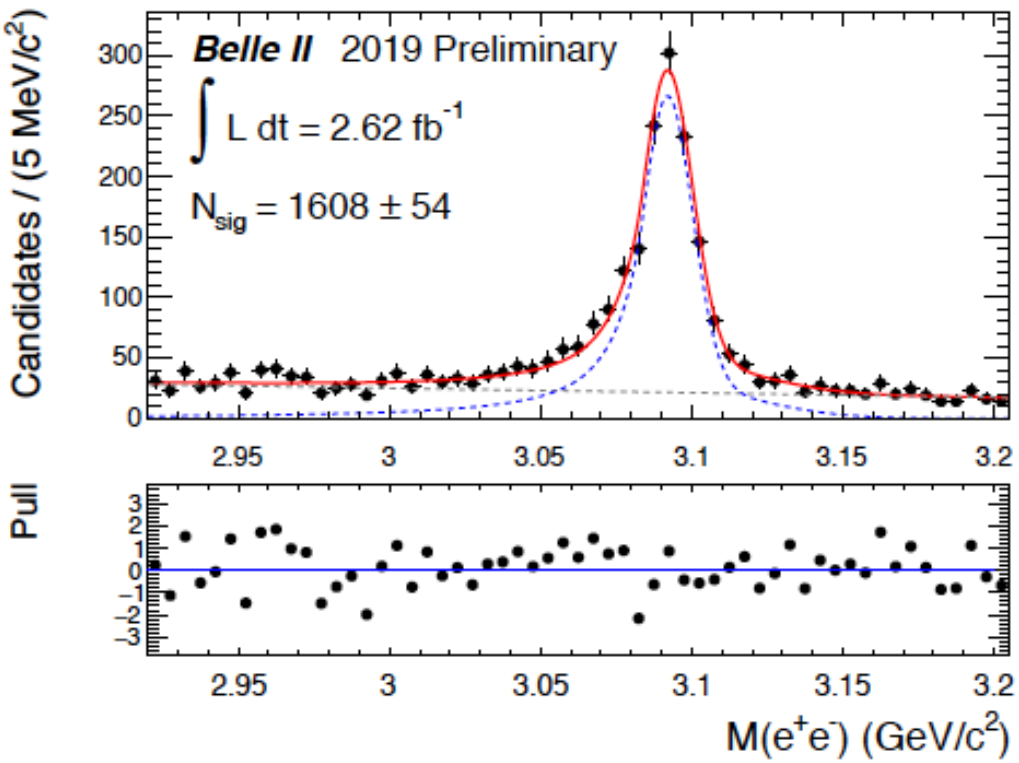
photons



K_L can be identified using ECL waveform sampling.

B → J/ψ X in Phase 3 data





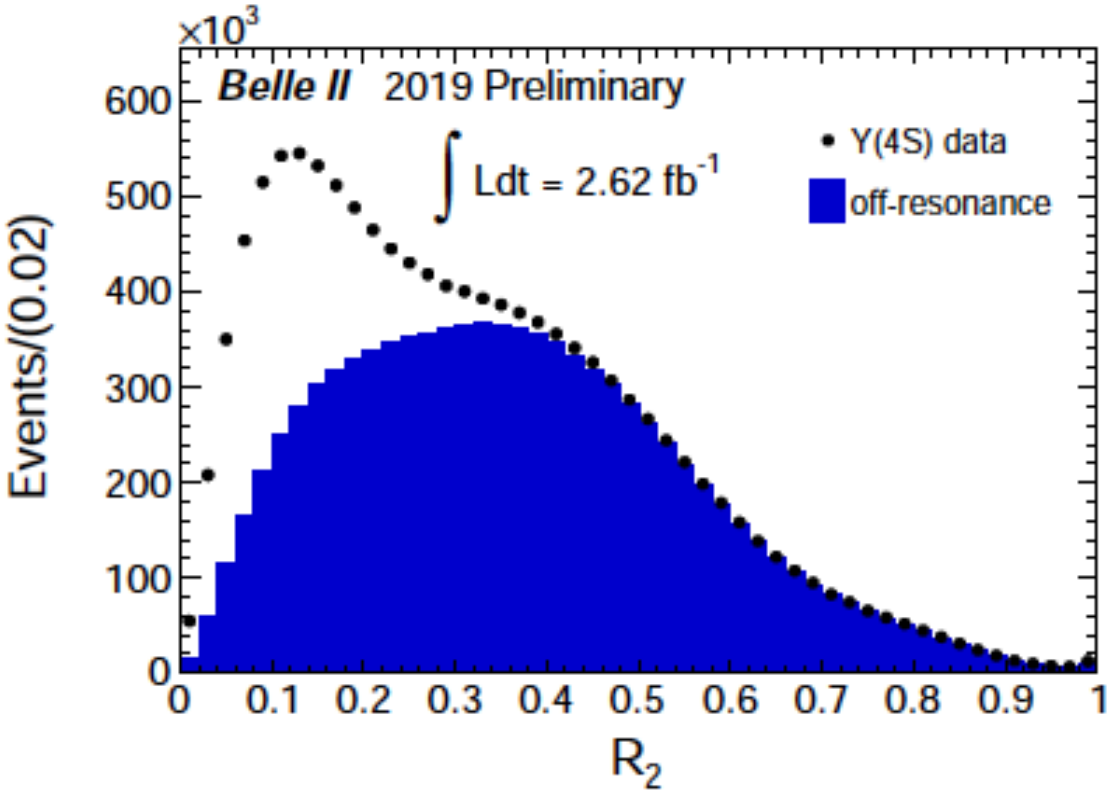
~½ of Phase 3 data: Clear signals for B → J/ψ X is seen.

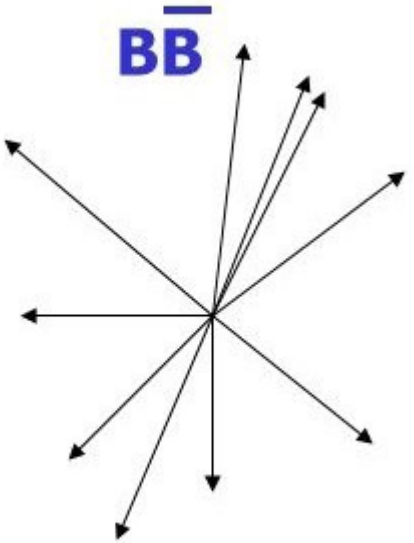
(For e+e- pairs the bremsstrahlung recovery is included).

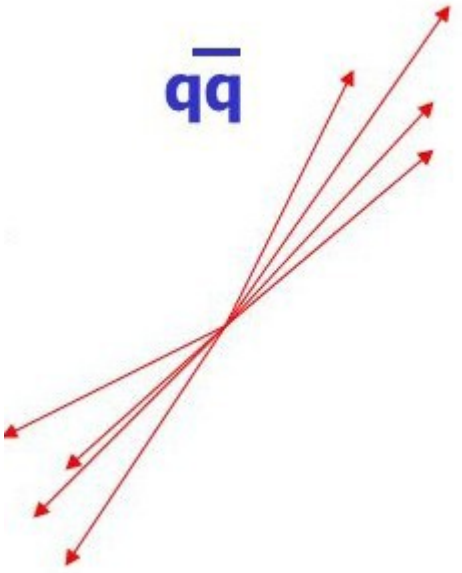
Belle II has good PID performance for both electrons and muons.

$B\bar{B}$

We can separate $B\bar{B}$ from $q\bar{q}$ using the Event Topology



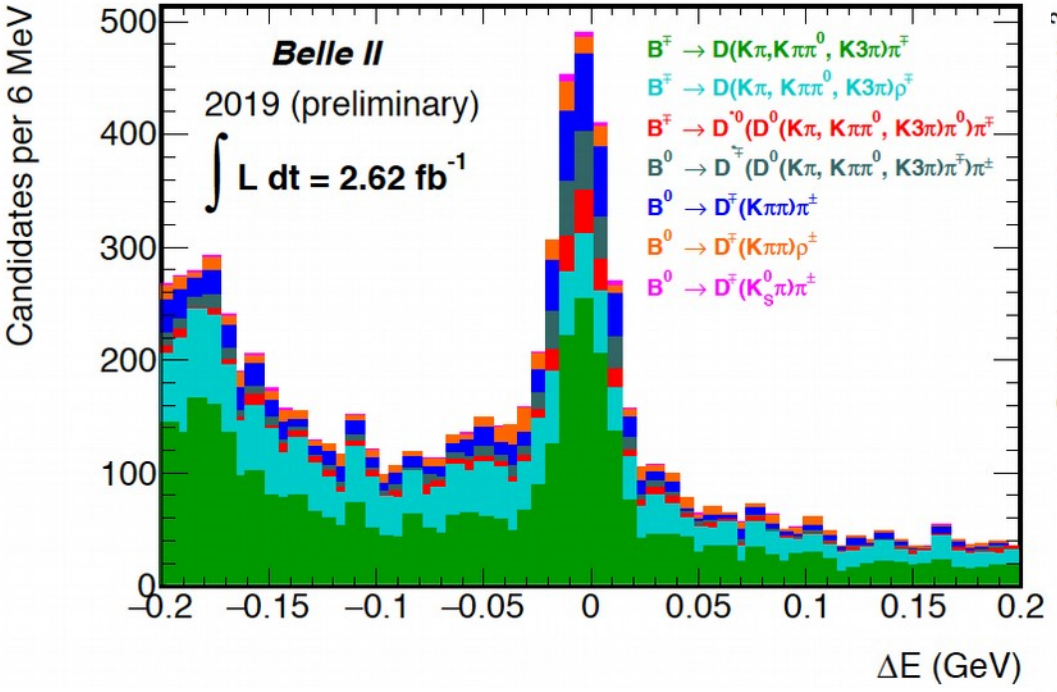




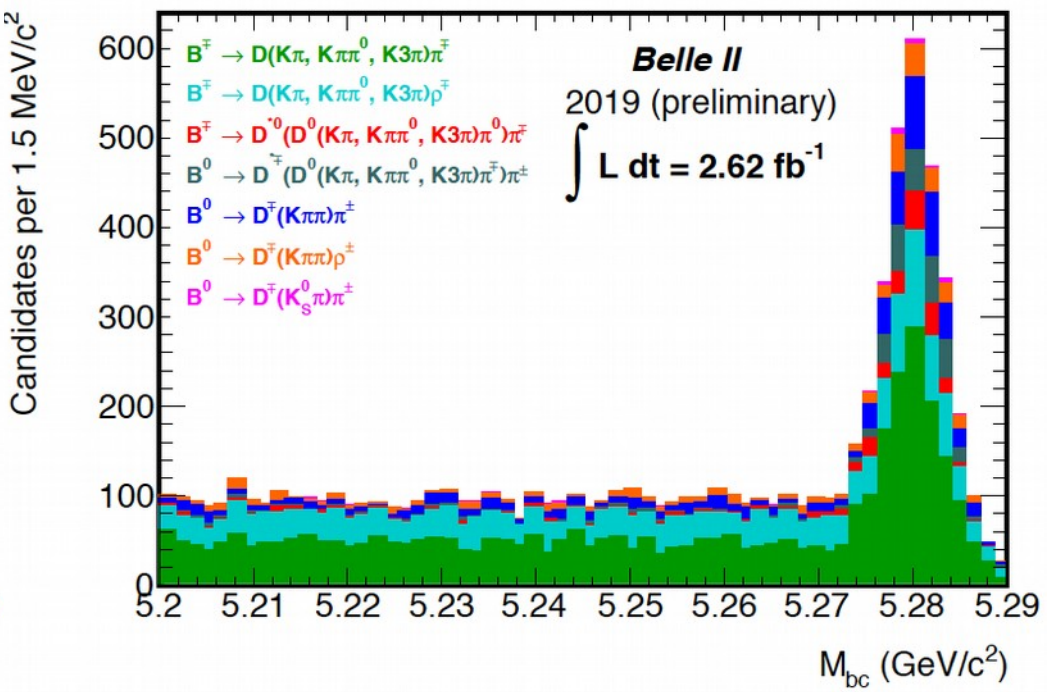
For many plots shown: $N_{B\bar{B}} \sim 2.8\ 10^6$

Reconstruction of B → hadrons

$\Delta E = E_{measured} - E_{CM}/2$



$m_{BC} = \sqrt{(E_{CM}/2)^2 - p^2_{measured}}$



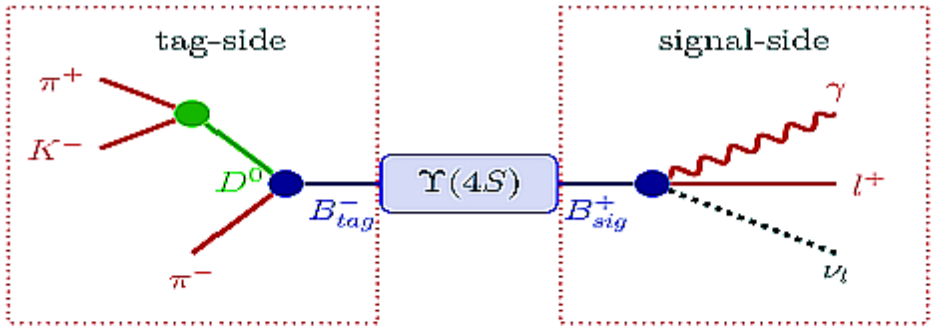
~2200 Fully reconstructed hadronic B decays

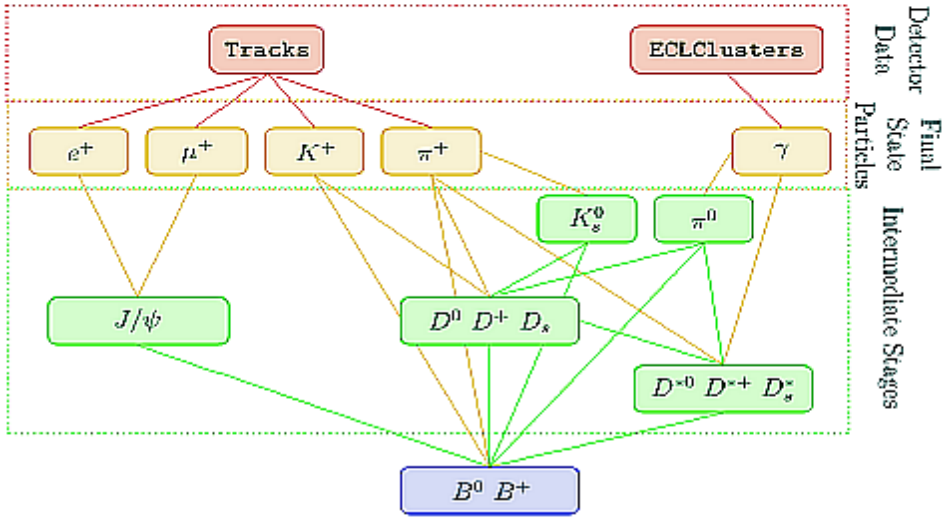
Clear demonstration of Belle II capabilities for doing B physics.

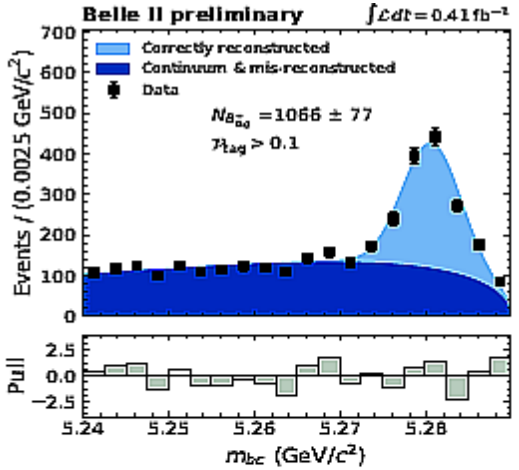
NB. Modes with charged kaons and pions, as well as final states with K^0_S mesons and neutral particles are efficiently reconstructed.

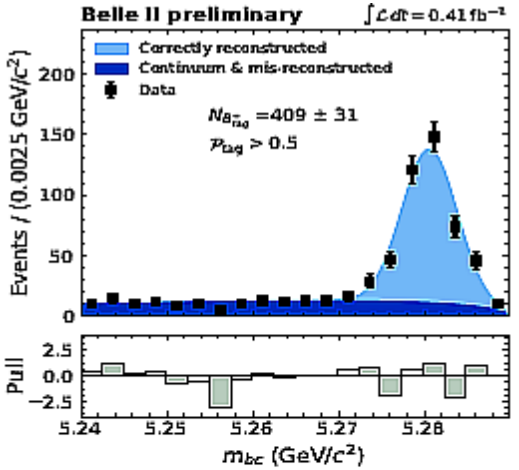
Full Event Interpretation

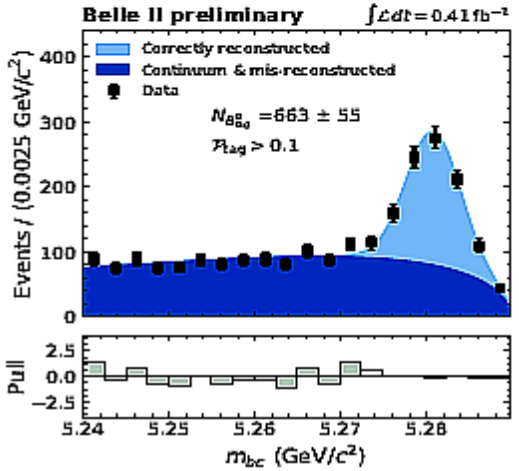
- Utilizing a machine learning technique (BDT - boosted decision trees) to fully reconstruct more than thousand B decay modes.
- Yields are increased by a factor of ~8 wrt the previous technique.
- The technique is particularly useful for channels with e.g. missing momentum (neutrinos).

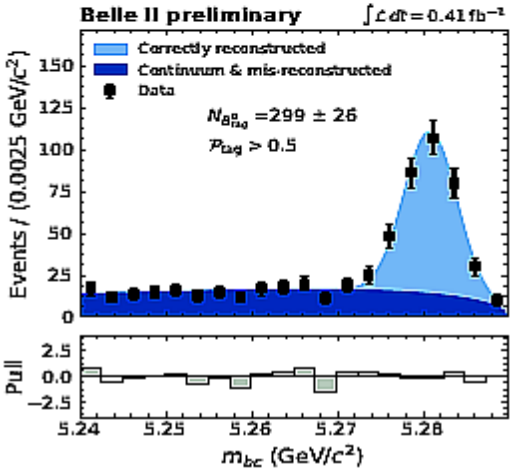








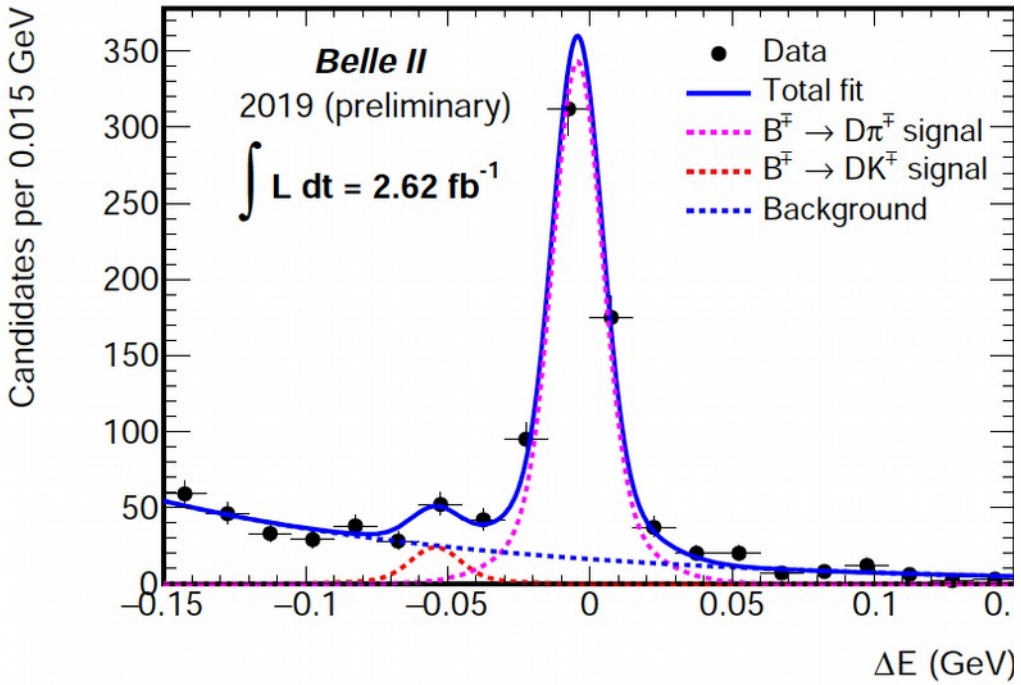




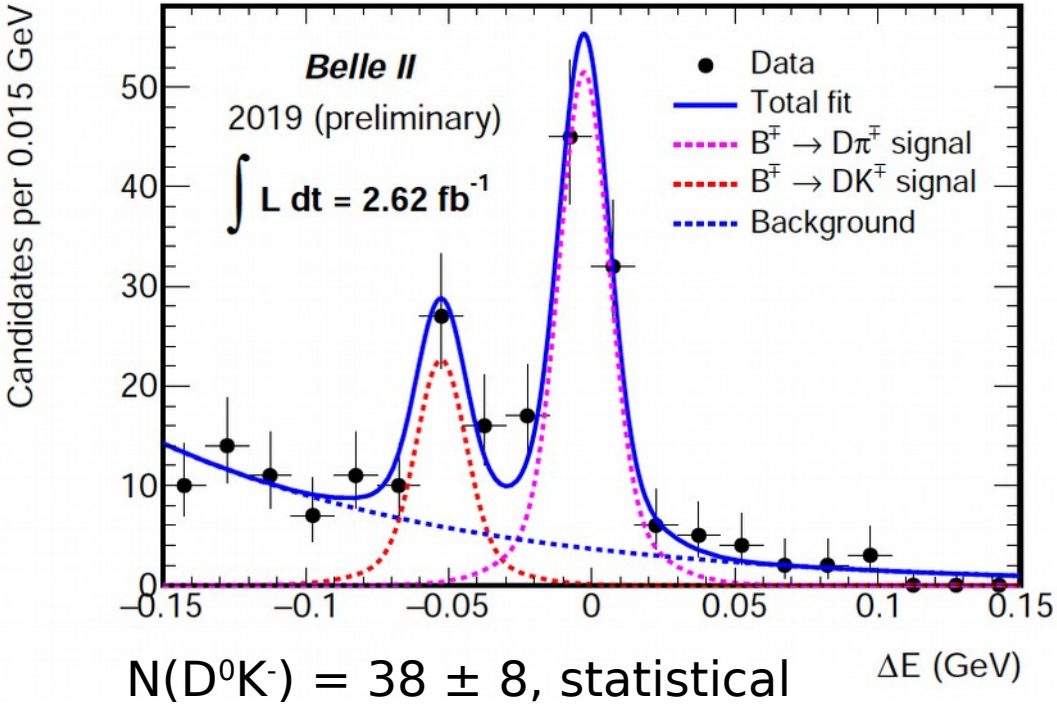
NB. *Only ~10% of the Phase 3 statistics is shown here.*

$B^- \rightarrow D^0 K^-$

No PID



High momentum PID



$N(D^0K^-) = 38 \pm 8$, statistical significance is 6σ

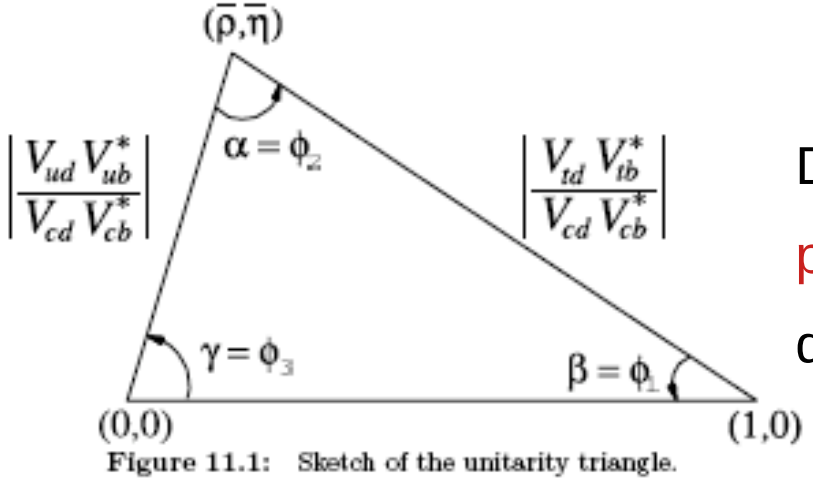


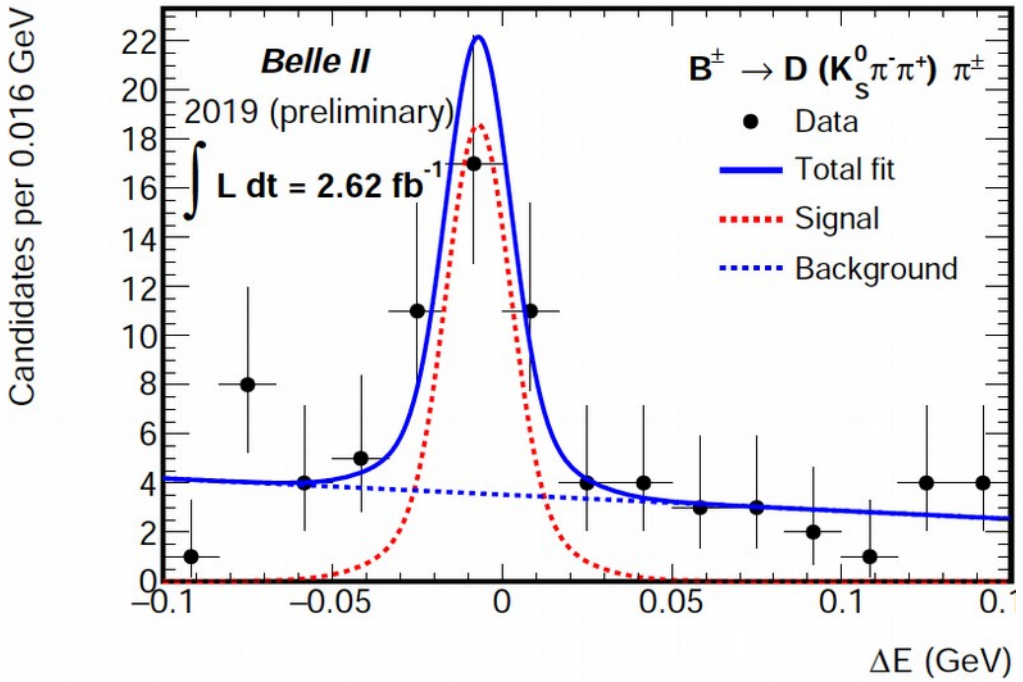
Figure 11.1: Sketch of the unitarity triangle.

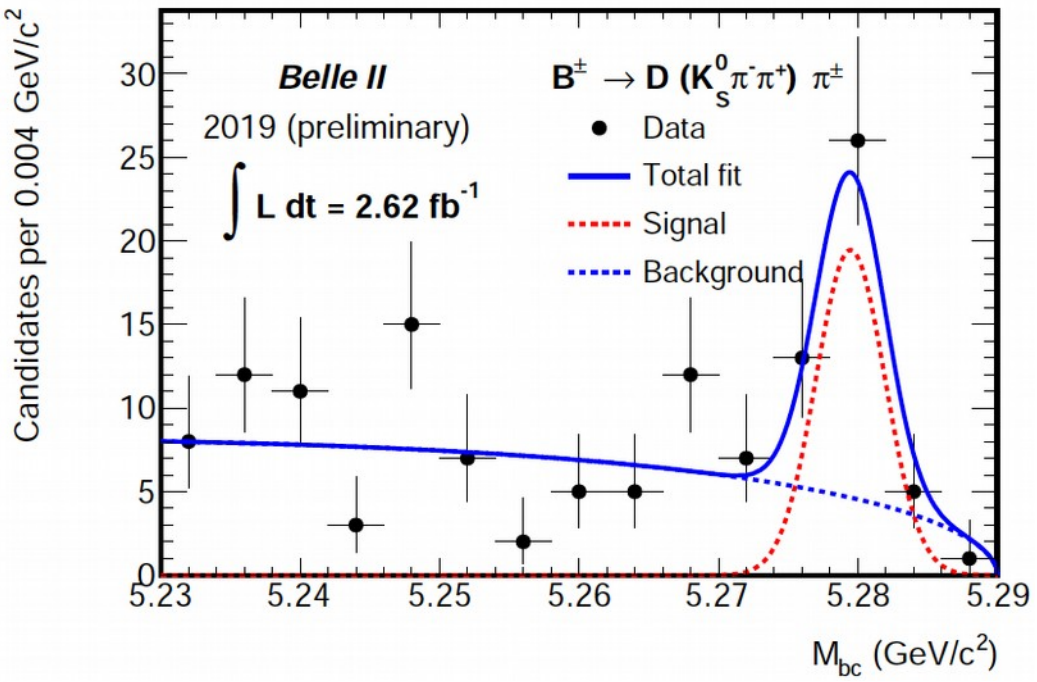
Demonstration of Belle II high momentum PID performance. This decay mode will be used for future determinations of the Unitarity angle ϕ3 (a.k.a. γ).

$B^- \to D^0[K_S^0\pi^+\pi^-]\,\pi^-$

$\Delta E = E_{measured} - E_{CM}/2$

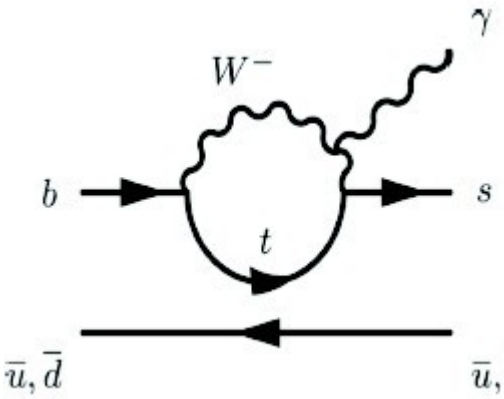
$m_{BC} = \sqrt{(E_{CM}/2)^2 - p^2_{measured}}$



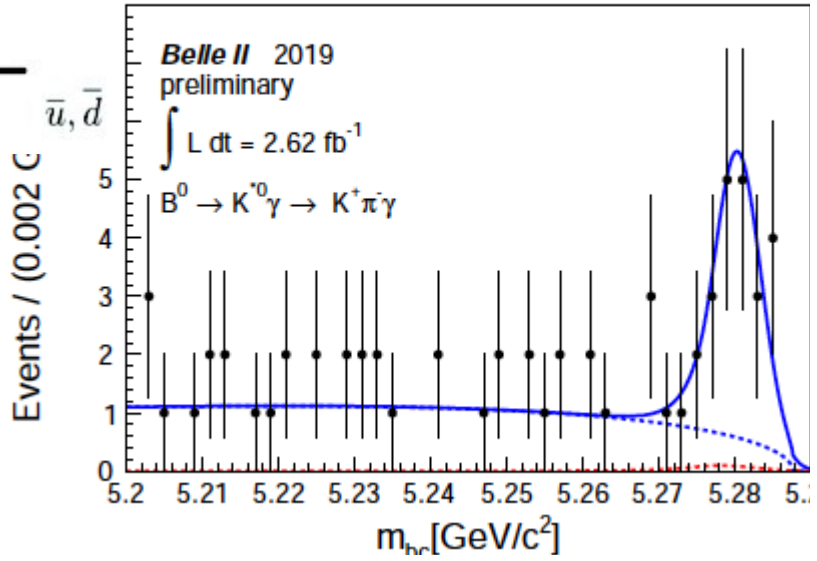


Belle II demonstrates capability to measure this important channel, which will be used in the Dalitz determination of the Unitarity angle ϕ_3 (γ).

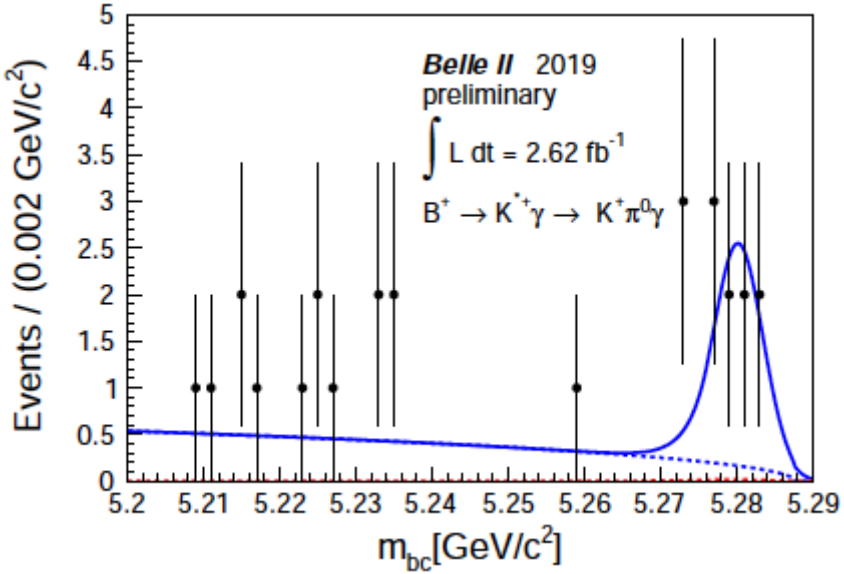
Radiative B decay: $B^0 \to K^{*0} \gamma$



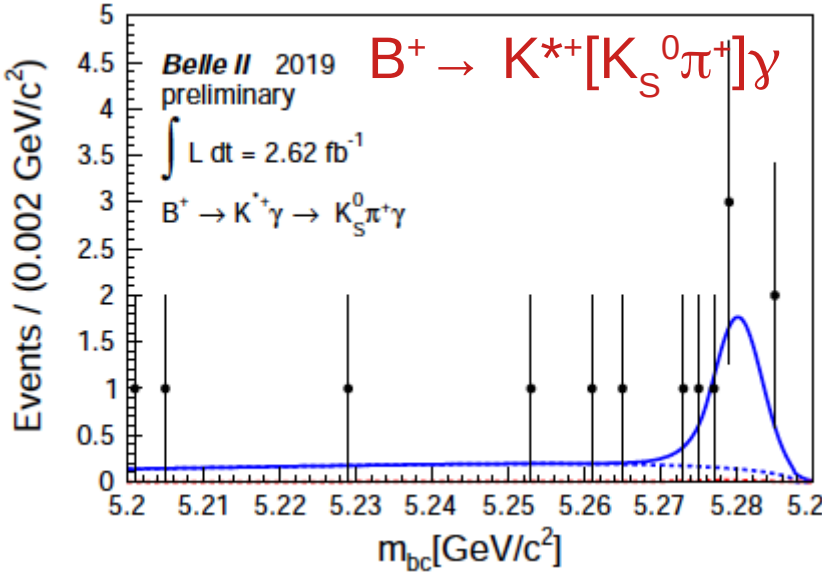
$B^0 \to K^{*0}[K^-\pi^+]\gamma$

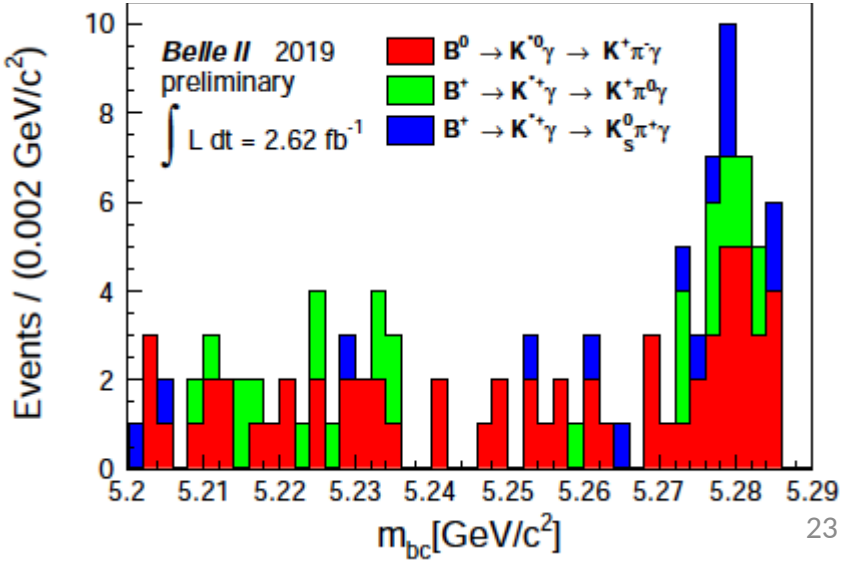


$B^+ \to K^{*+}[K^-\pi^0]\gamma$

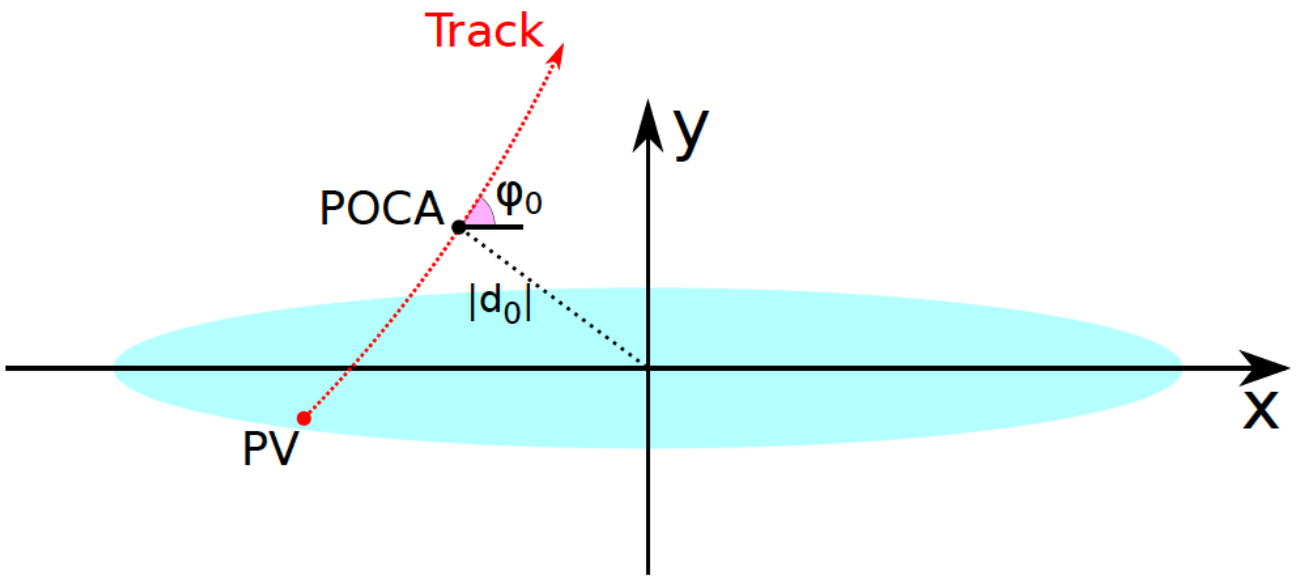


$B^+ \to K^{*+}[K_S^0\pi^+]\gamma$

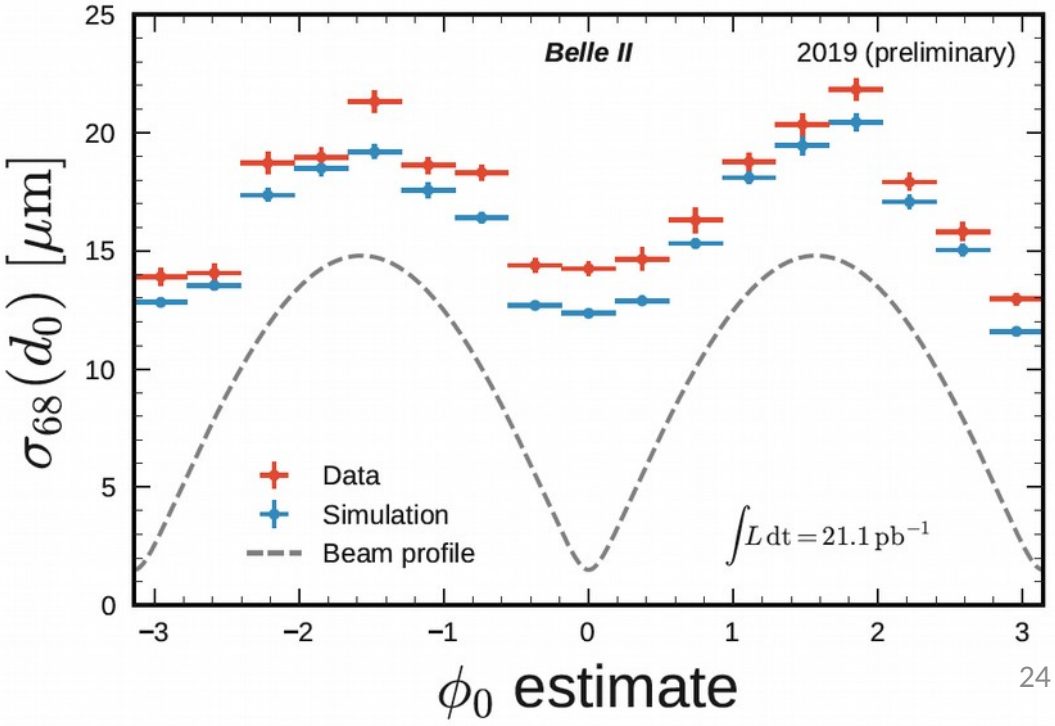




Time-dependent measurements

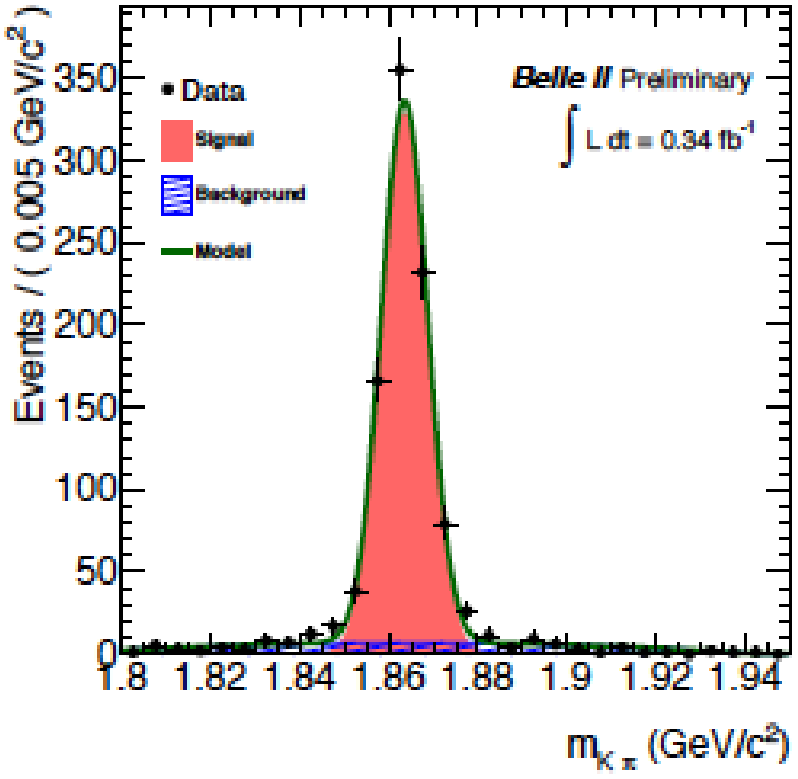


- Impact parameter distributions in two-track events.
- Width of impact parameter resolution distribution.
- VXD resolution in impact parameter ~14 microns
- Improved ~3 times in comparison with Belle

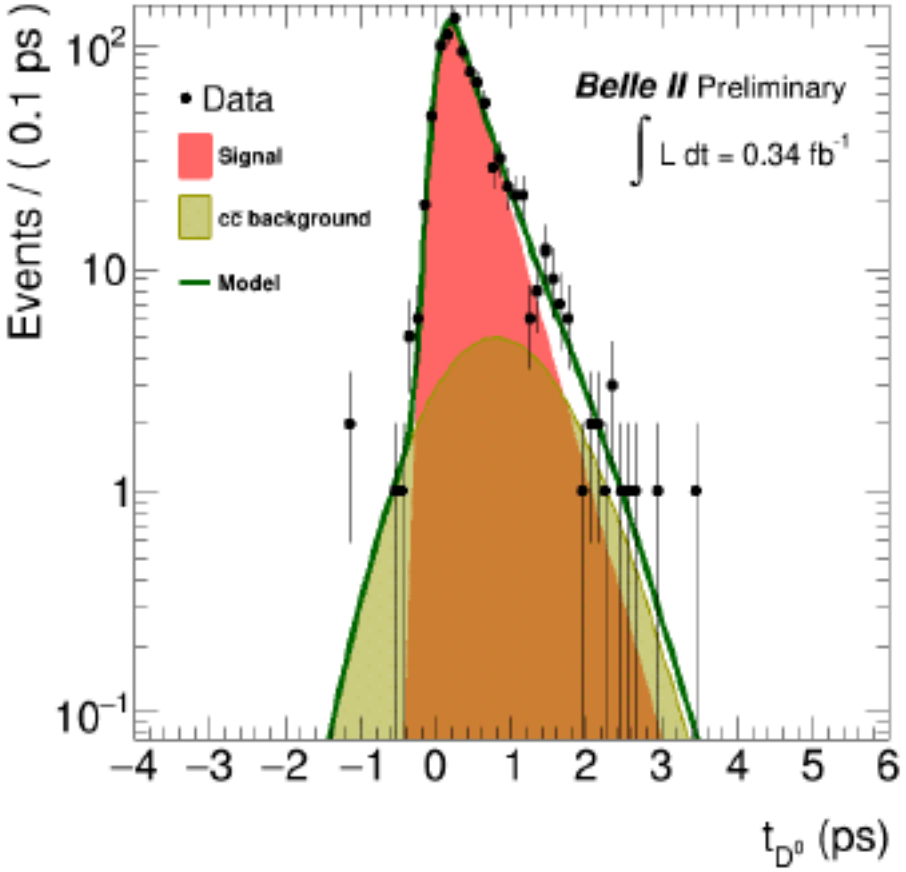


Time-dependent measurements

$N(D^0) = 860 \pm 30$

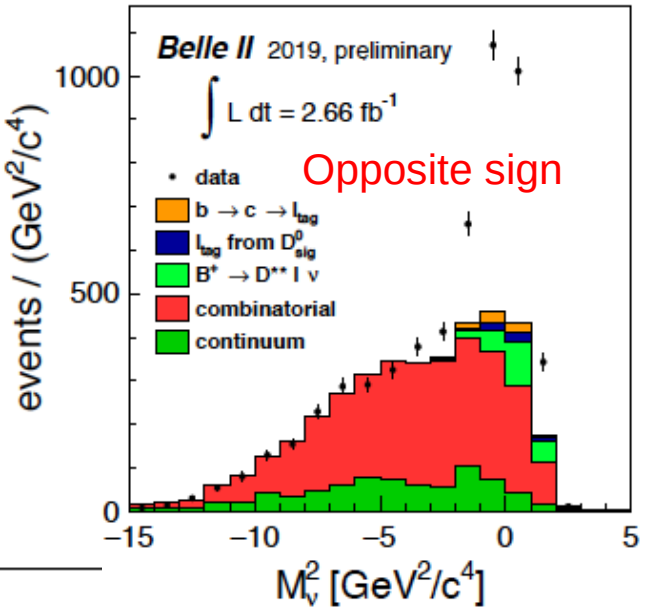


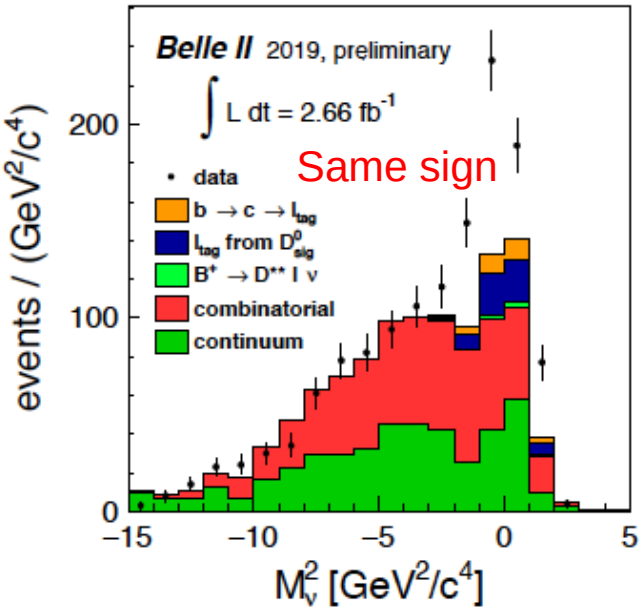
$\tau(D^0) = 370 \pm 40$ (stat) fs



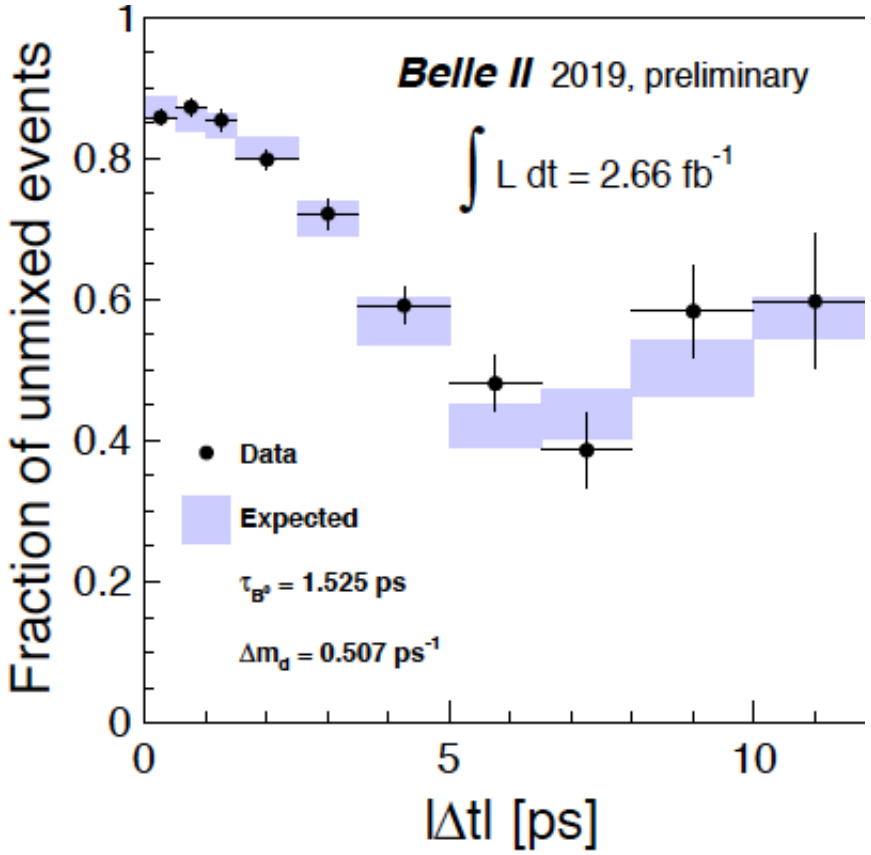
- Uses ~1/15 of the Phase 3 dataset.
- Clearly demonstrates the combined performance of the PXD and SVD.

B^0-$\bar{B}^0$ mixing



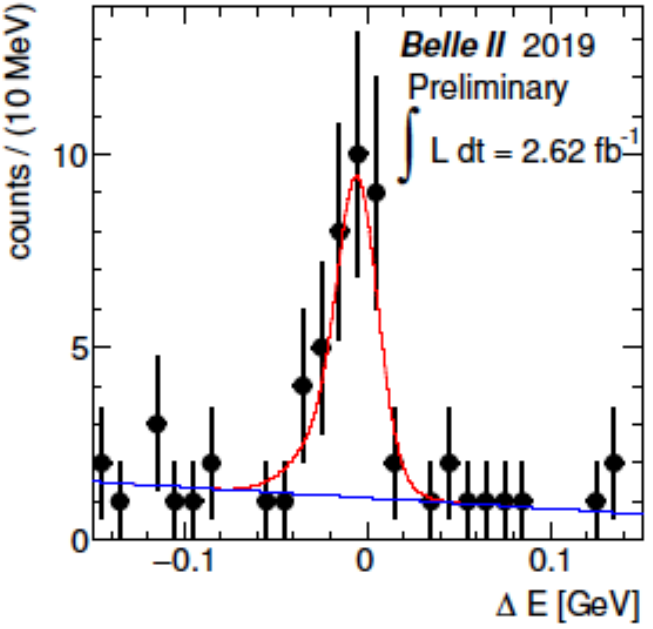


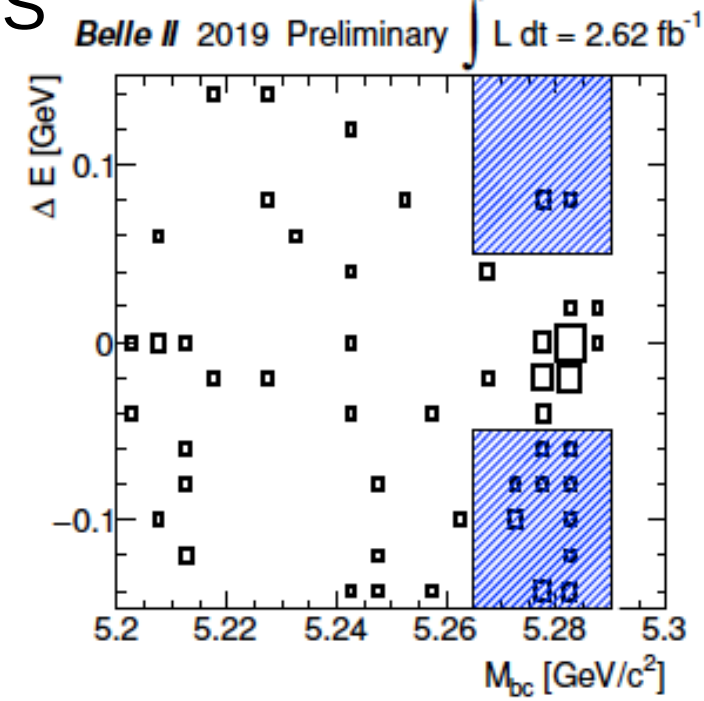
First oscillation



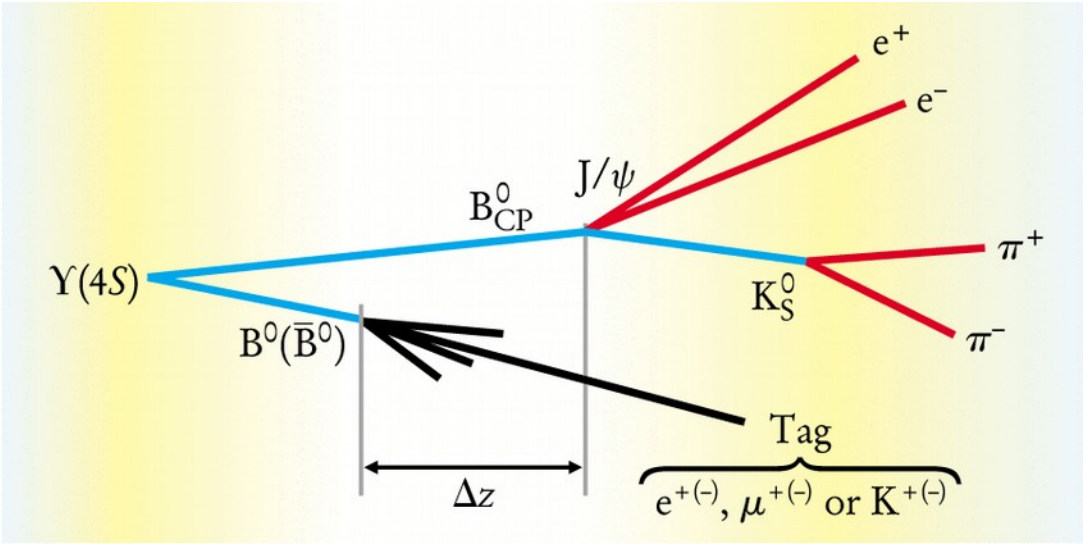
- Partial reconstruction and time determination uses only Lepton tagging.
- Check $M^2\nu$ sideband (consistent with MC) and continuum with loose cuts (no oscillation)
- Not CPV: $f_{unmix}(t) = K\,[1 + \cos(\Delta m_d\, \Delta t)]$
- Use flavor specific final states but requires tagging. Verifies Belle II VXD capabilities for CP violation measurements.

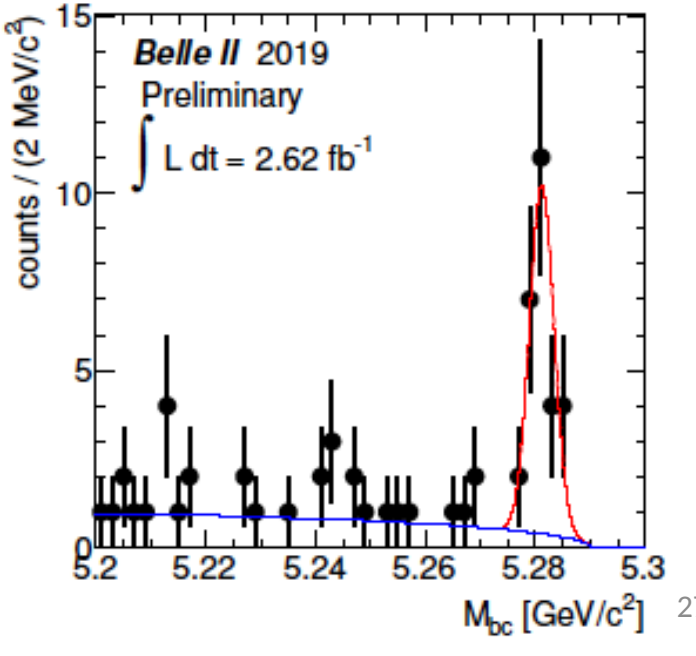
$B \to J/\psi K_S^0$



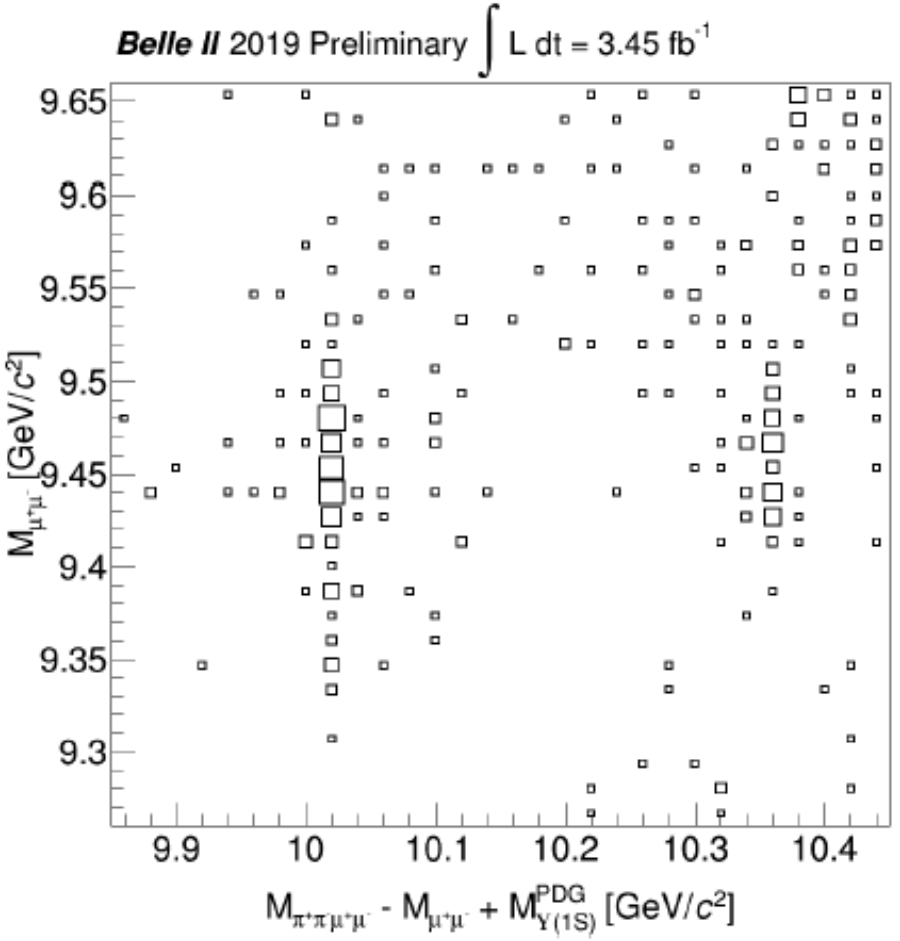


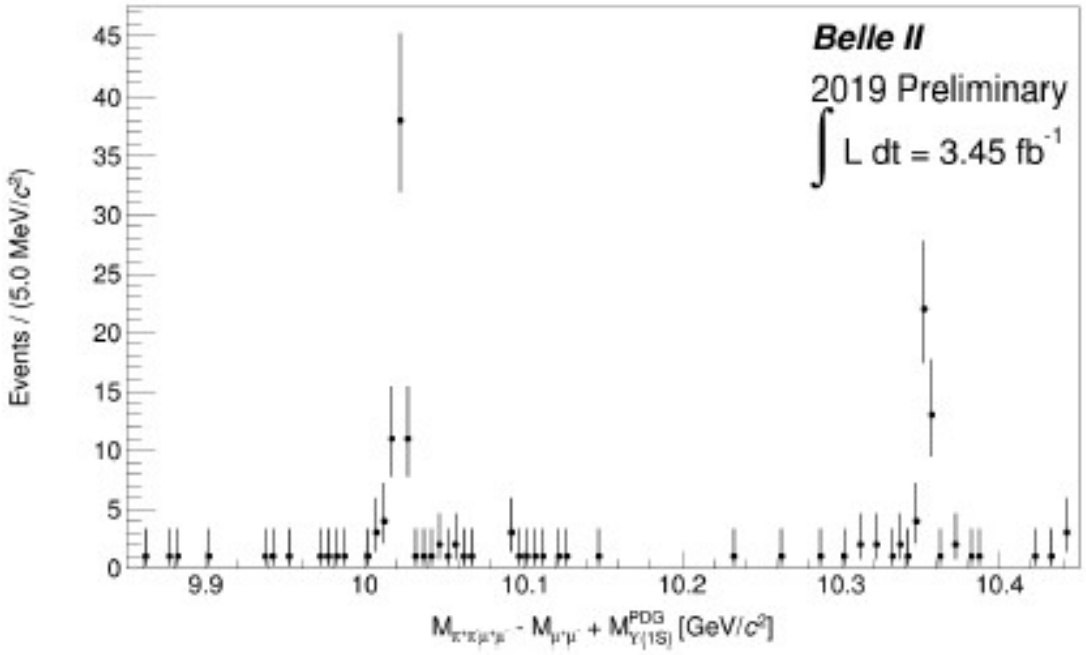
$N(B \to J/\psi K_S^0) = 26.7 \pm 5.2$





ISR measurements

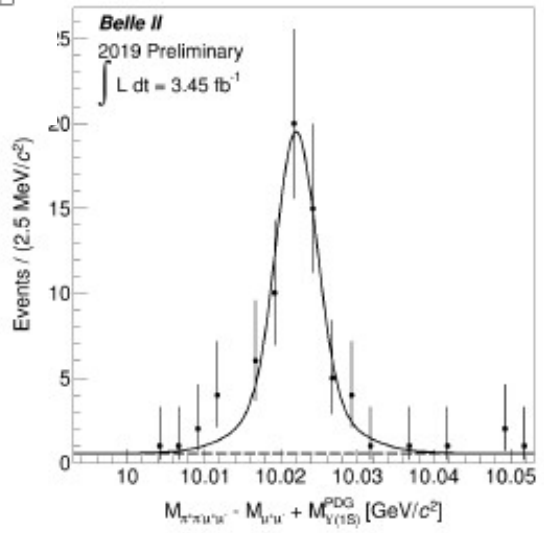


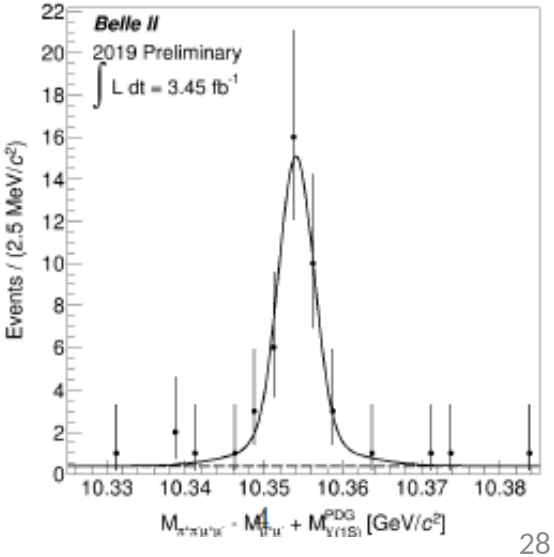


e+e- → Υ(2S, 3S) γ,

Υ(2S, 3S) → π⁺π⁻Υ(1S),

Υ(1S) → μ⁺μ⁻

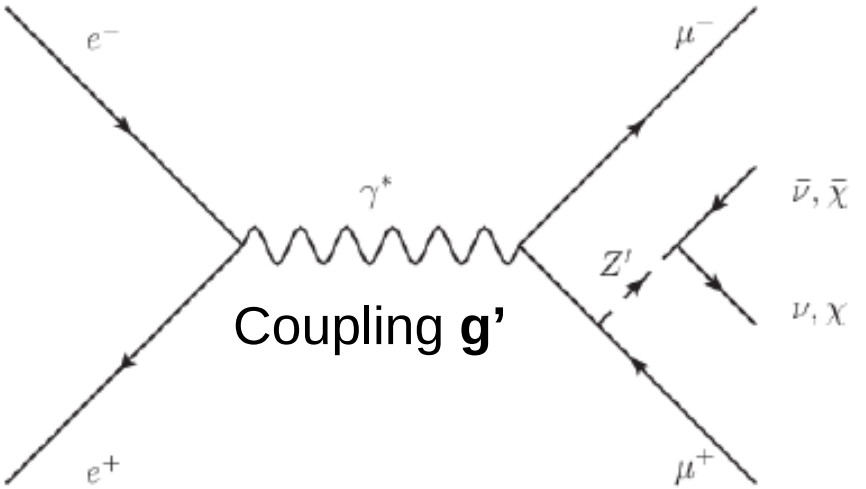




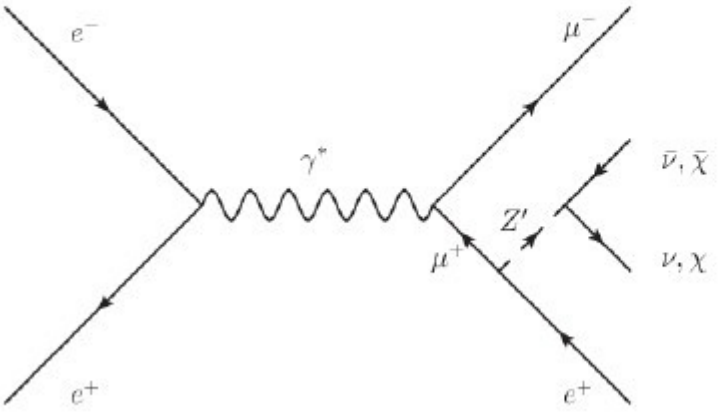
Dark sector

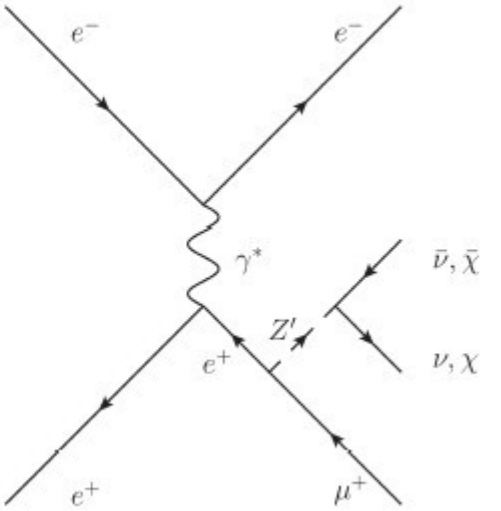
Previously limited by Triggering, QED backgrounds and theoretical imagination.
Now new possibilities of triggering, more bandwidth.

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



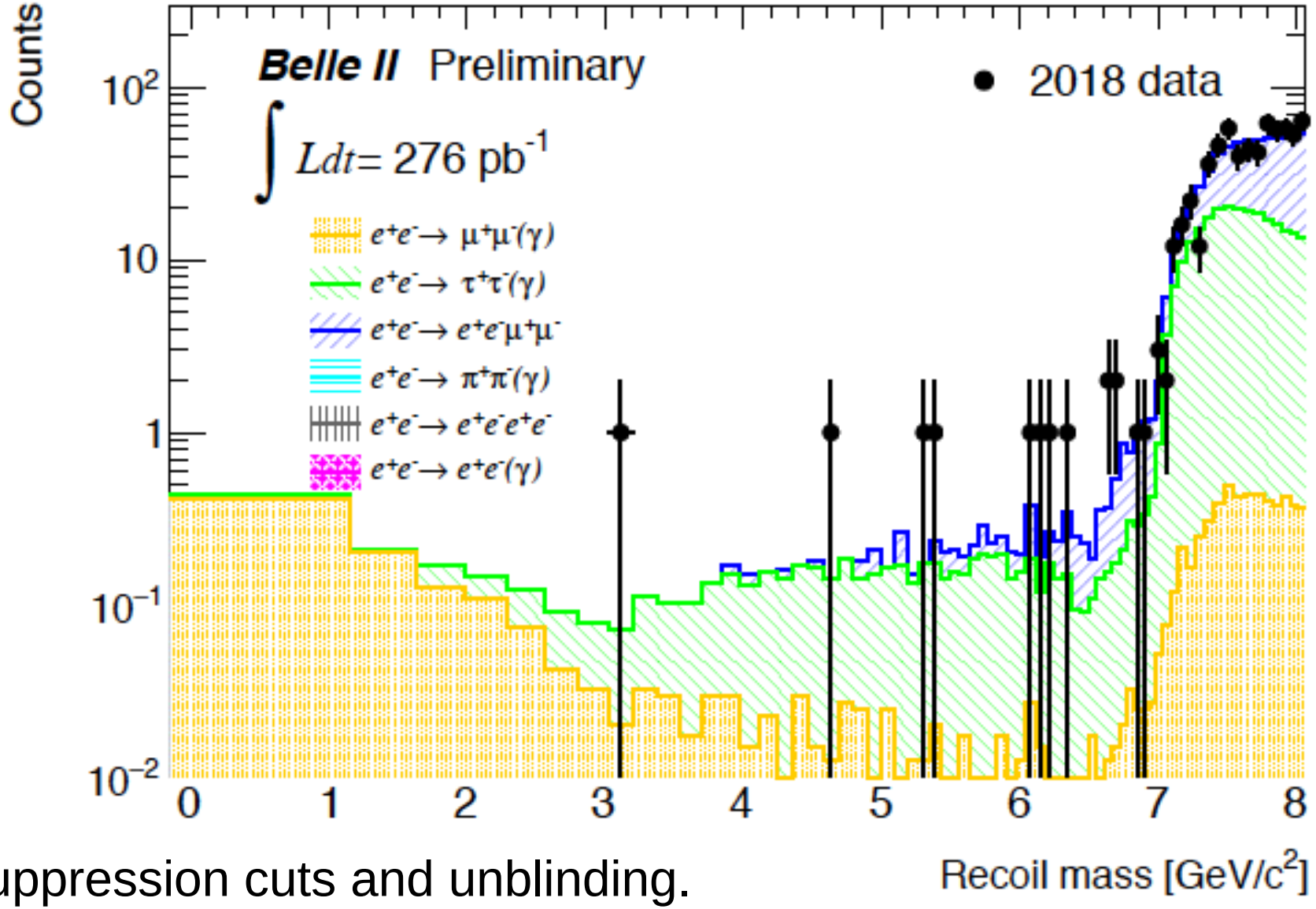
Also examine a lepton flavour violating NP signature in the dark sector





Dark sector: results

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



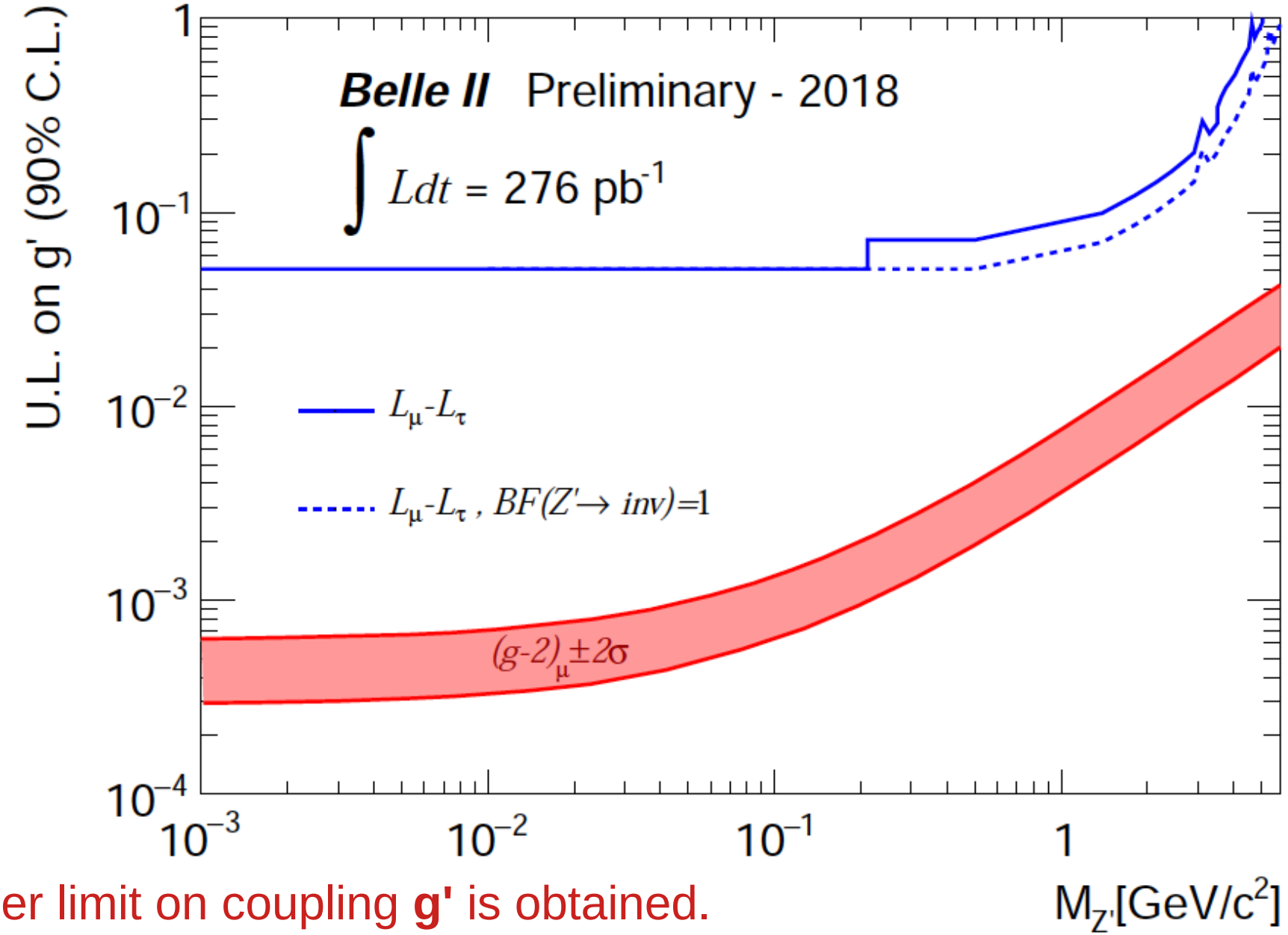
After tau suppression cuts and unblinding.

Results are compatible with backgrounds.

No excess above 3σ is seen.

Dark sector: results

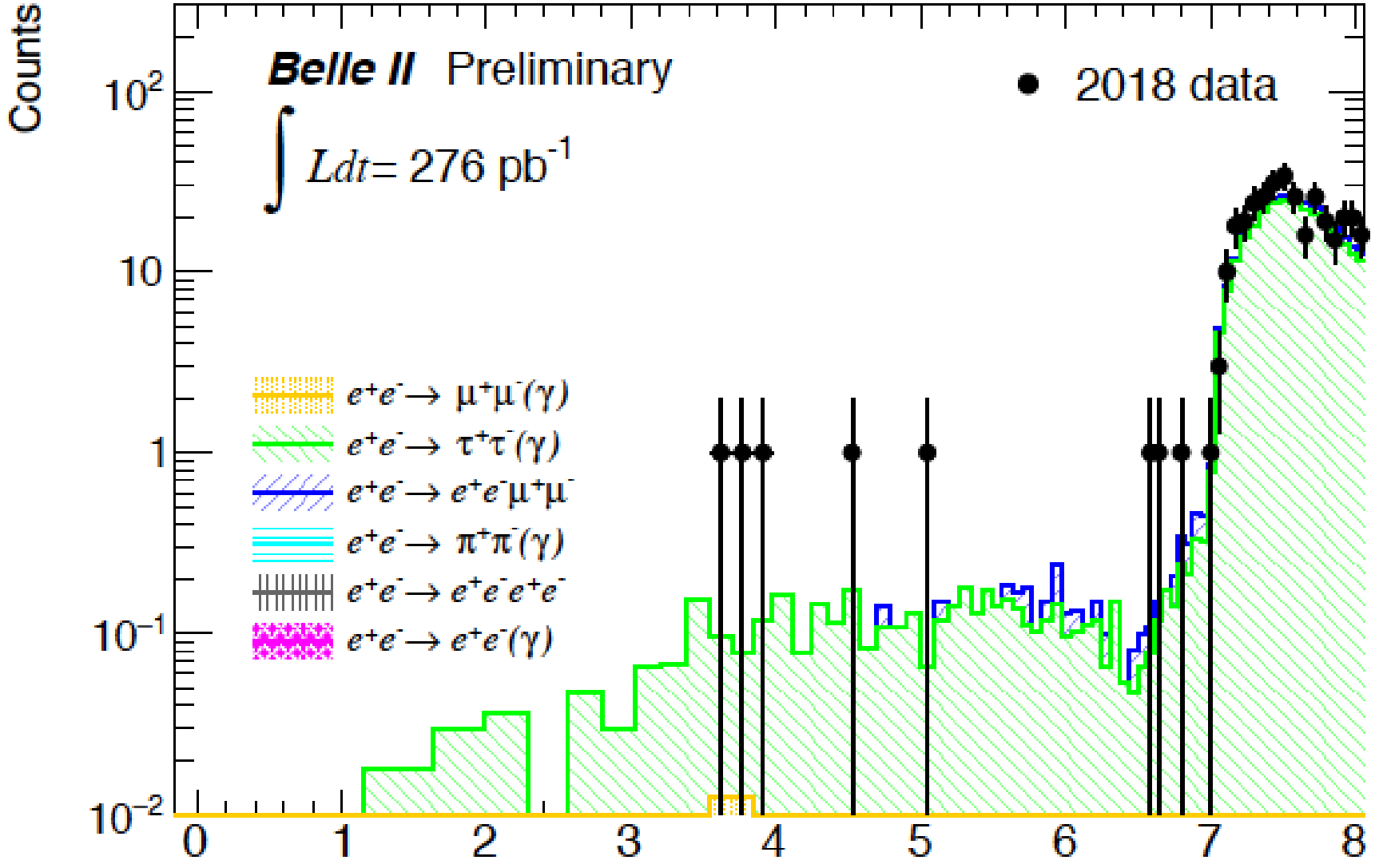
Search for $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to$ nothing



First upper limit on coupling **g'** is obtained.

Dark sector: results

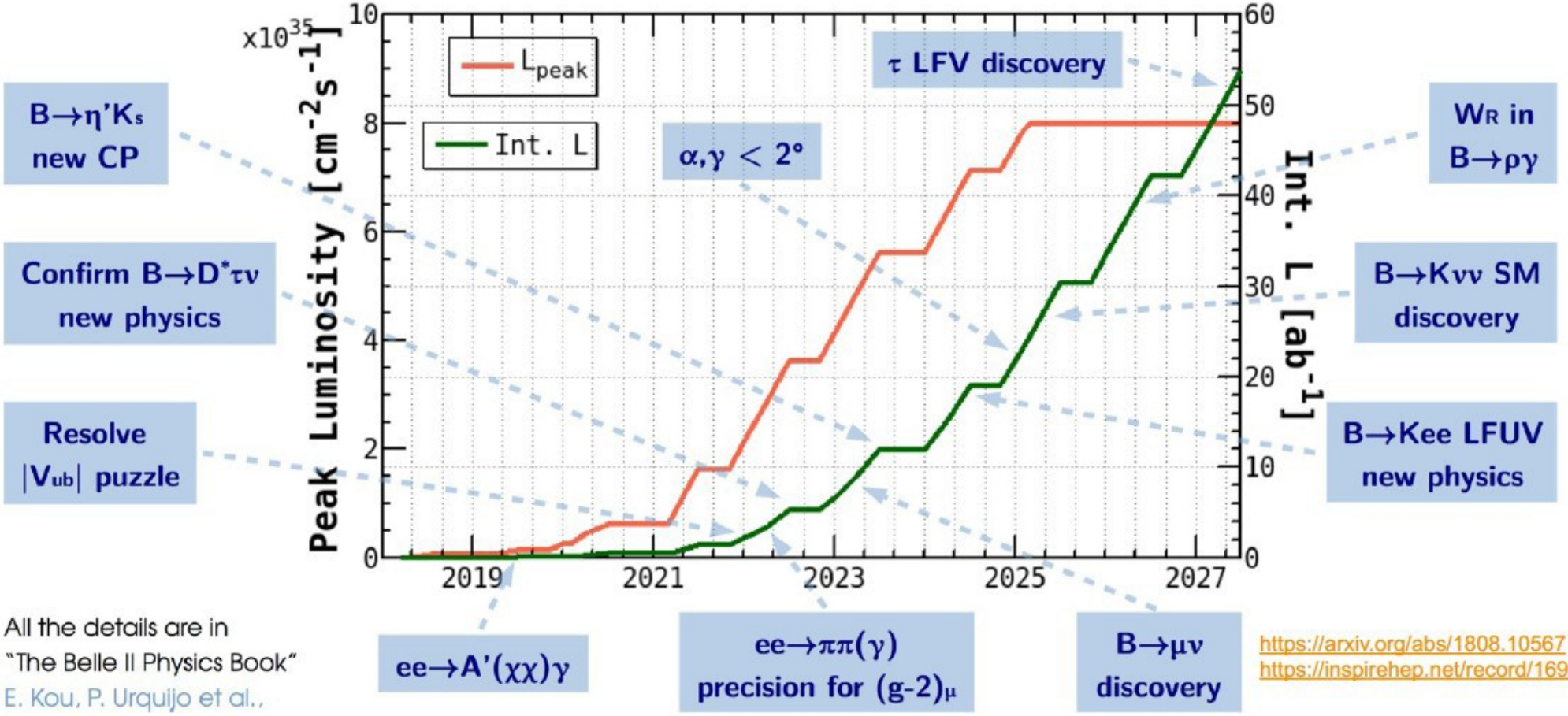
Search for $e^+e^- \to e^\pm\mu^\mp Z'_{LFV}$, $Z'_{LFV} \to$ nothing



Results are compatible with backgrounds.
No excess at any recoil mass can be seen.

Prospects of Belle II

- Based on The Belle II Physics Book, arxiv:1808.1056, published by Oxford University Press.
- Outcome of the Belle II Theory Interface Workshops, with emphasis on New Physics (NP) reach.
- Strong participation from theory community, lattice QCD community and Belle II members.



All the details are in
"The Belle II Physics Book"
E. Kou, P. Urquijo et al.,

https://arxiv.org/abs/1808.10567
https://inspirehep.net/record/1692393/

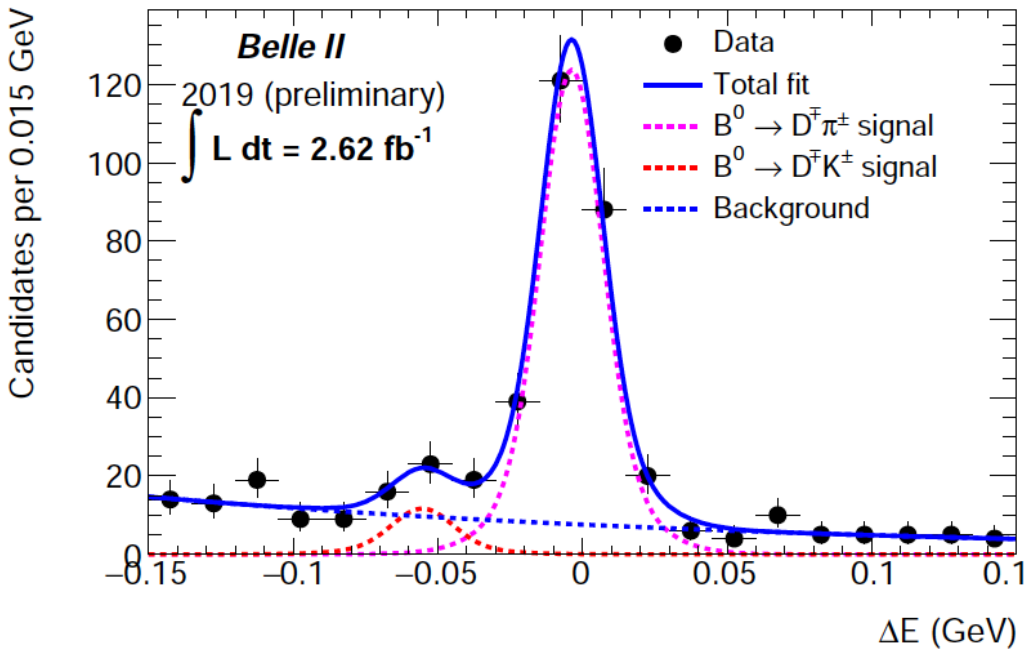
Summary

- The SuperKEKB colider and Belle II experiment aiming to search for New Physics with performance at a new level:
  - 40-times higher luminosity with respect to the previous record,
  - advanced detector technology.
- This will enable Belle II to explore NP on the Intensity Frontier, which is different/complementary to the LHC high p_T experiments (Energy Frontier).
- Competition and complementarity with the LHCb experiment.
- Phase 3 in March-June 2019: $L_{int} = 6.49\ fb^{-1}$ data is collected, first results are shown.
- Operation will resume in October 2019 and continue until July 2020.
- We are looking forward to the next decade of exiting new results in search for New Physics beyond the Standard Model.

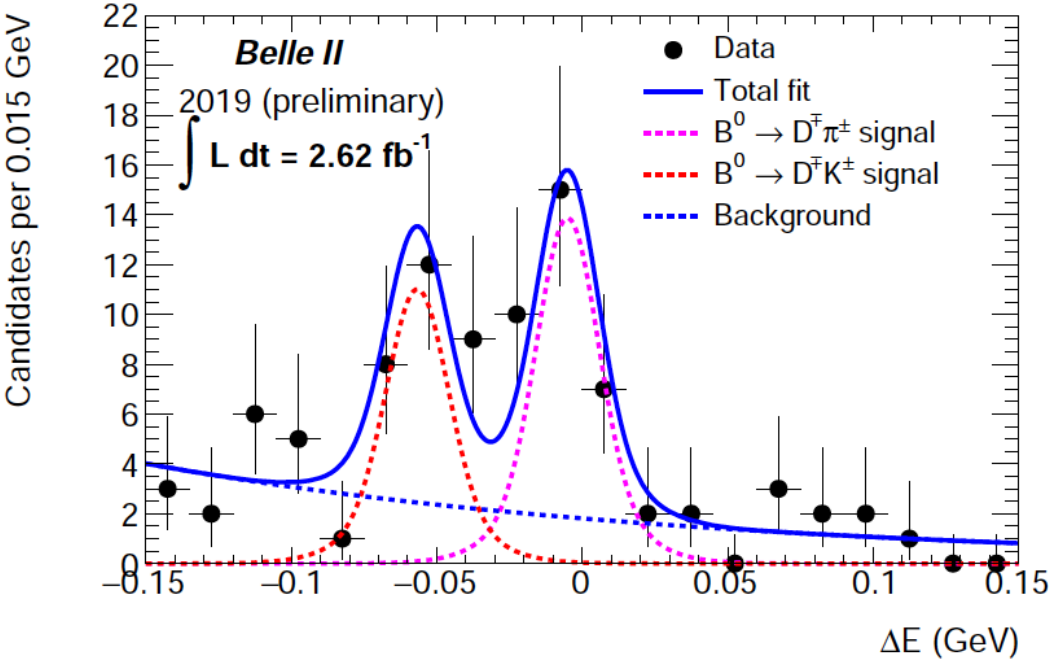
Backup

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

No PID



High momentum PID



$N(D^-K^+) = 23 \pm 6$, statistical significance is 3.3σ

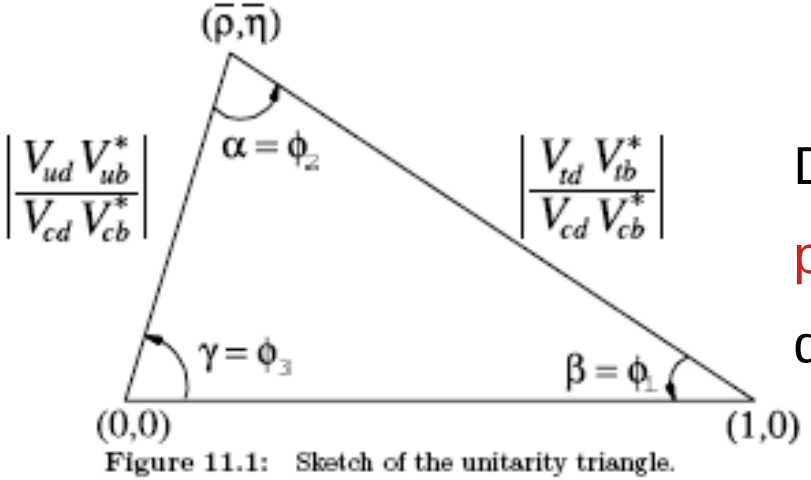
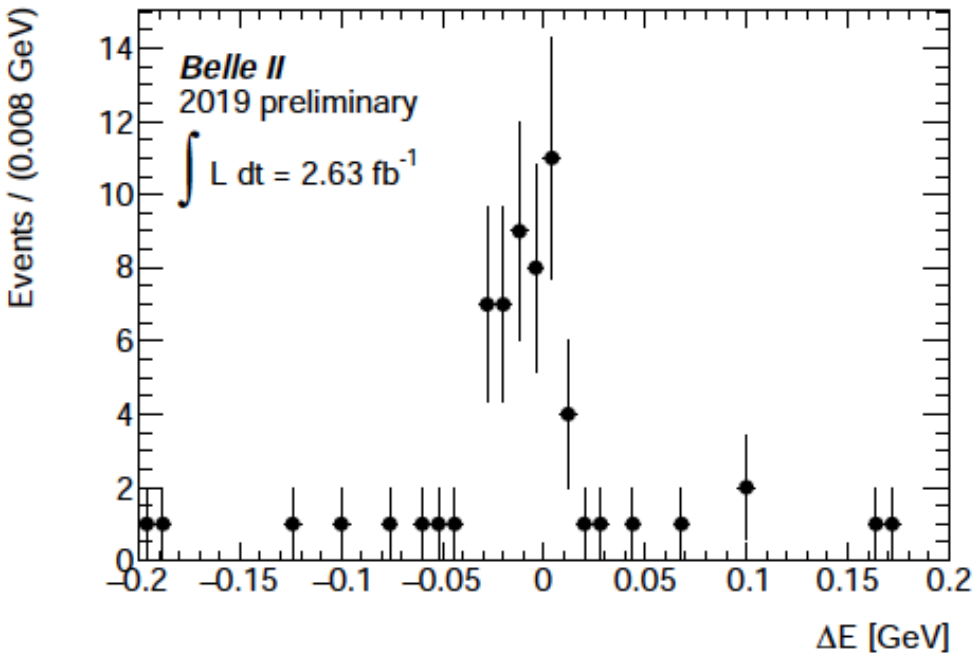
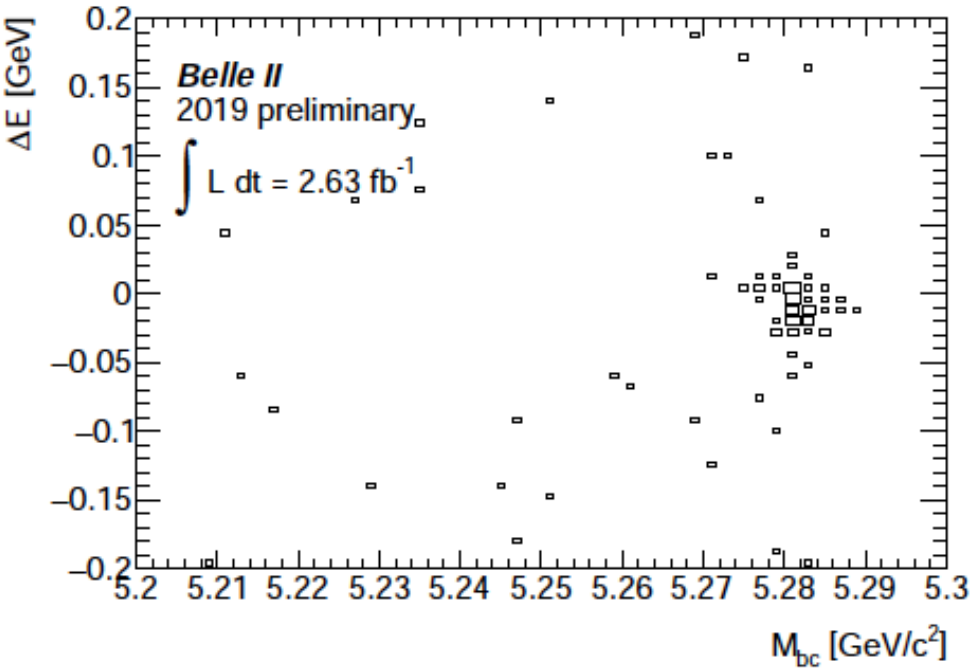


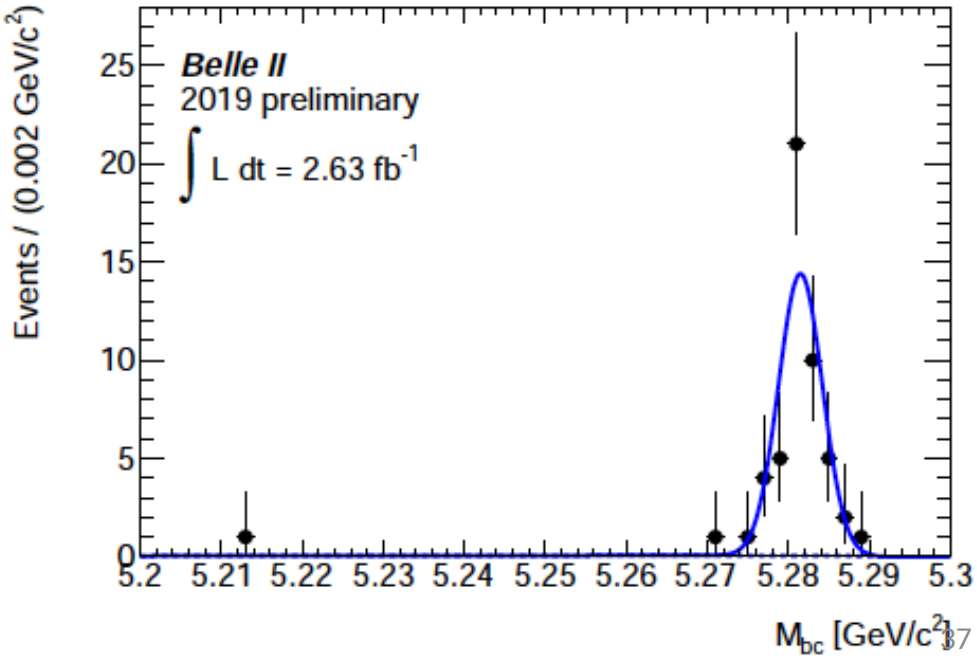
Figure 11.1: Sketch of the unitarity triangle.

Demonstration of Belle II high momentum PID performance. This decay mode will be used for future determinations of the Unitarity angle $\phi 3$ (a.k.a. γ).

$B \to J/\psi K^{*0}$

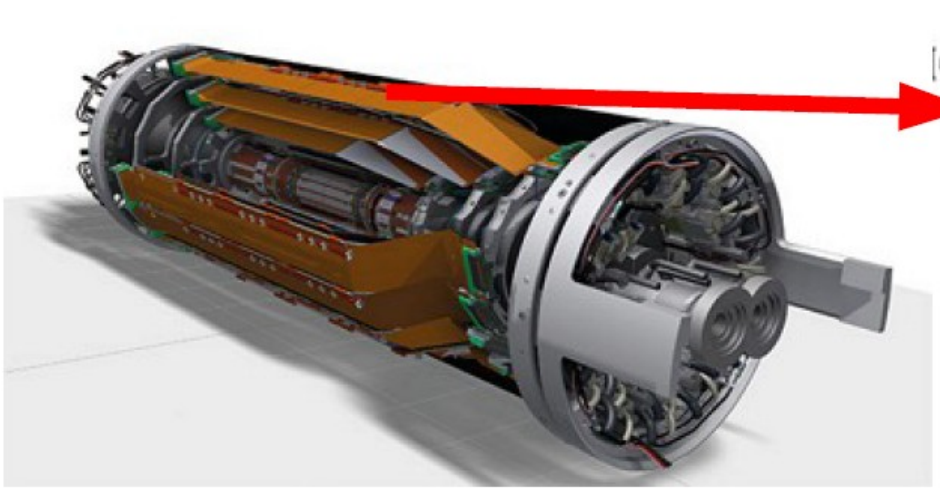


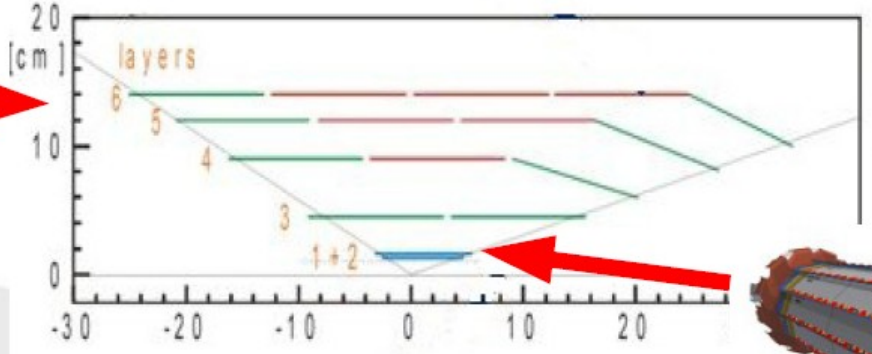


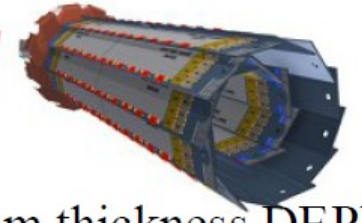


$N(B \to J/\psi K^{*0}) = 48.6 \pm 7.0$

Vertexing: SVD + PXD

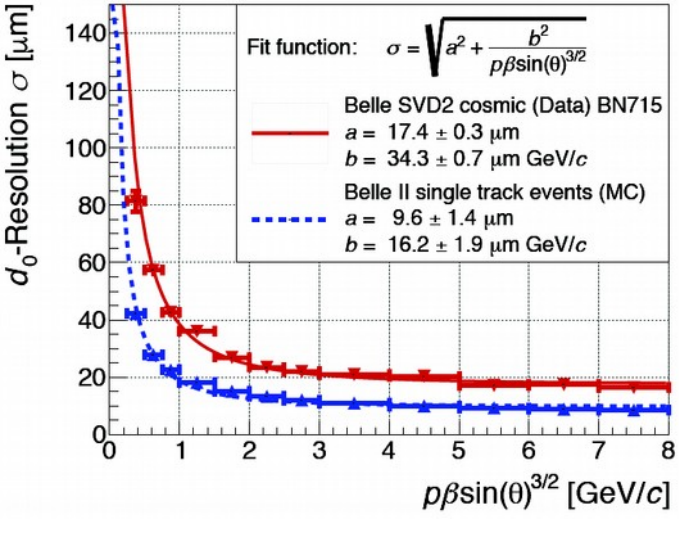


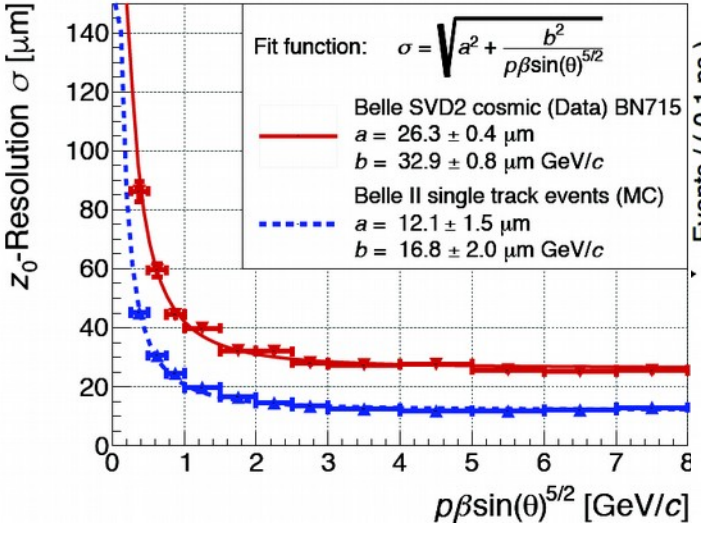


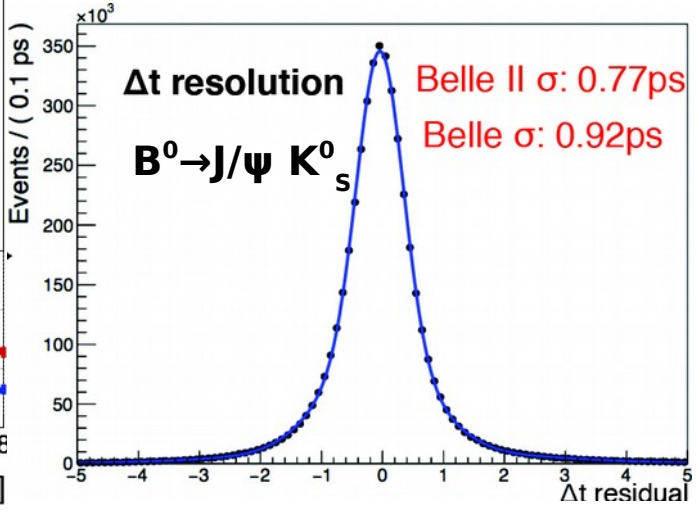


76 μm thickness DEPFET

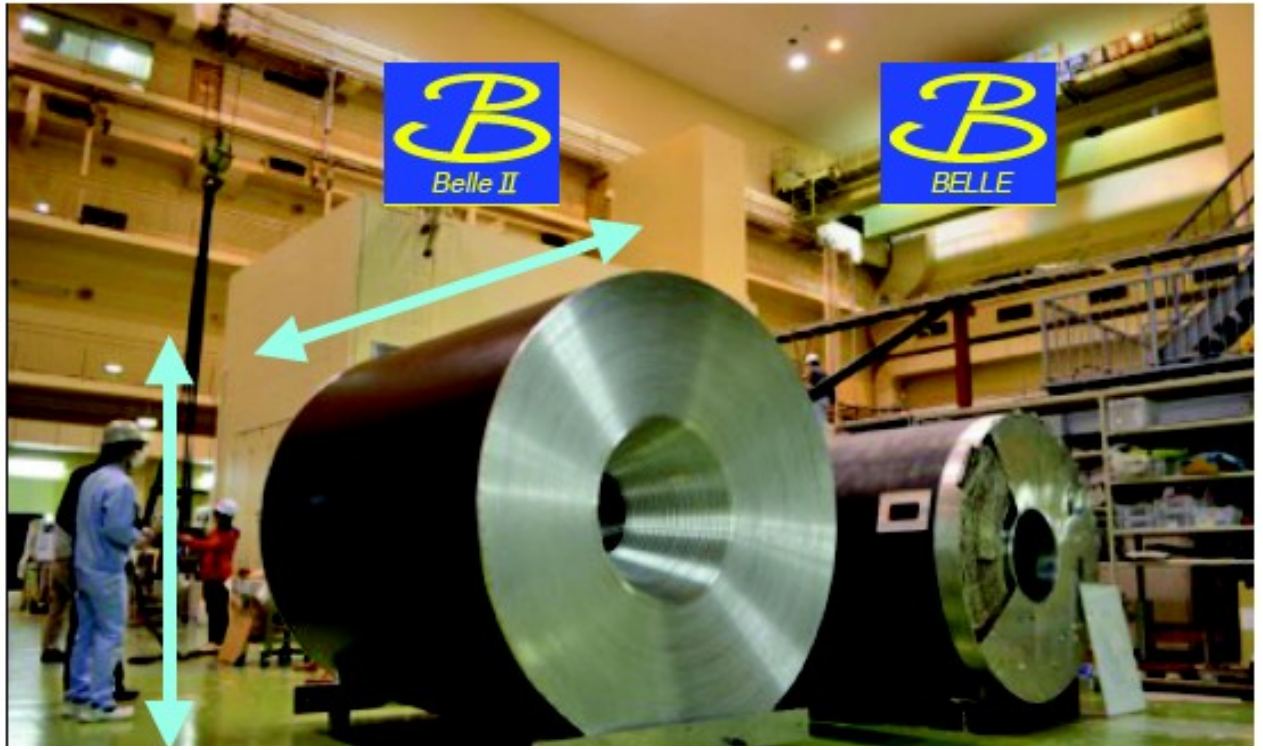
Belle II vertexing performance significantly improved in comparison with Belle

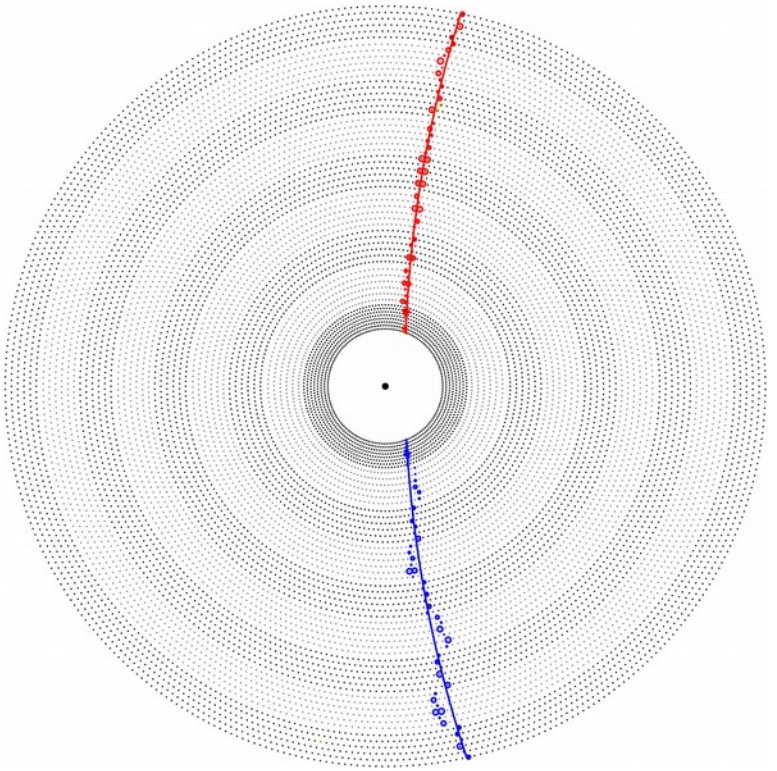


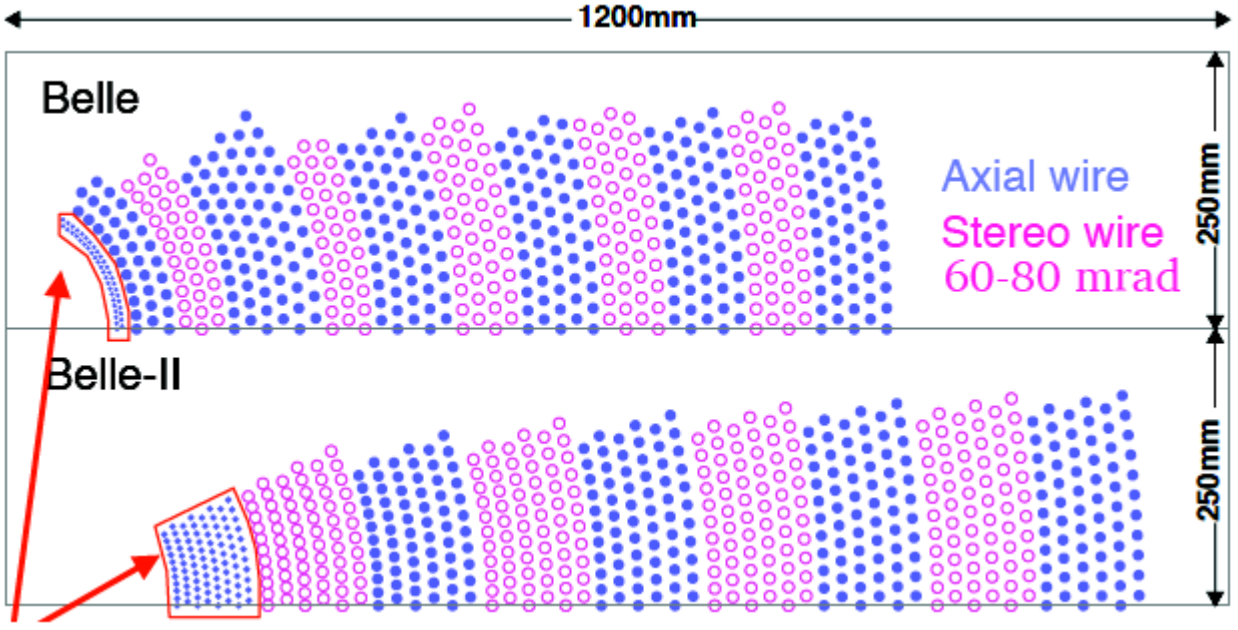


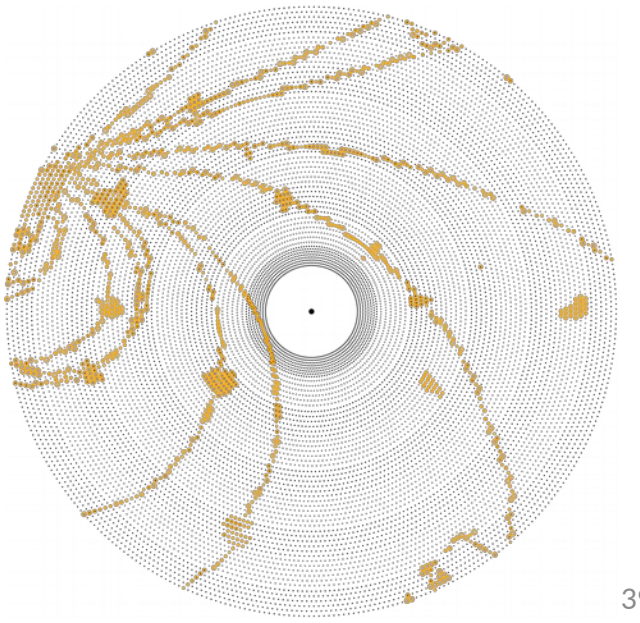


Central Drift Chamber

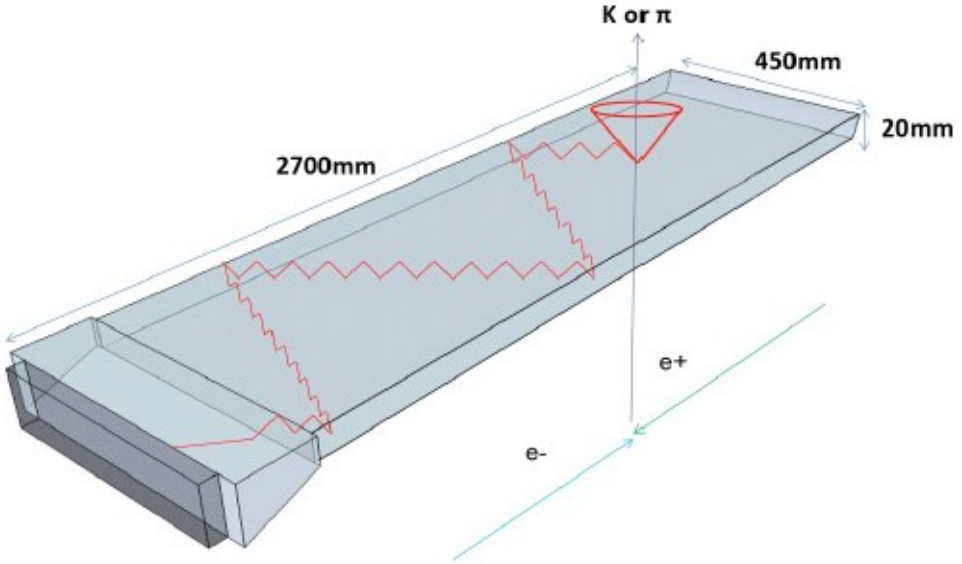


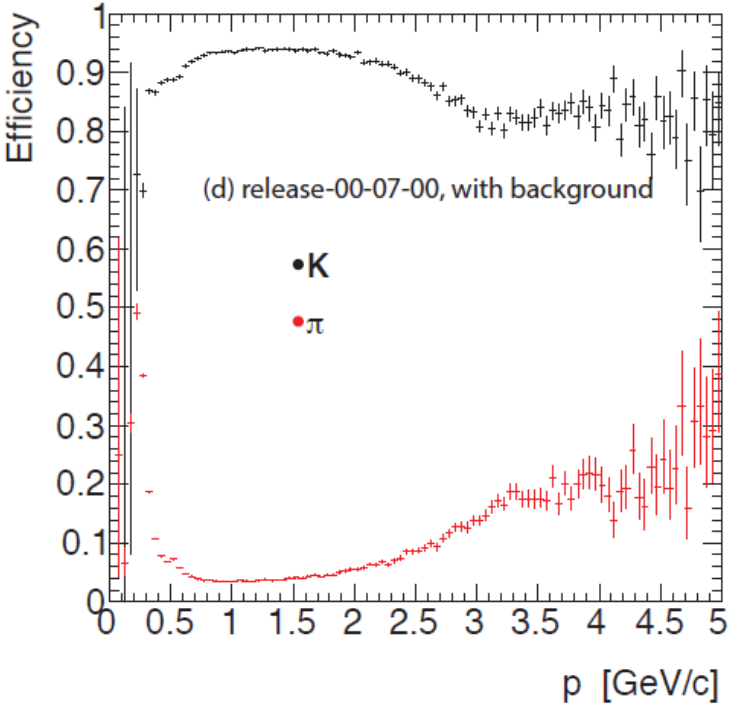


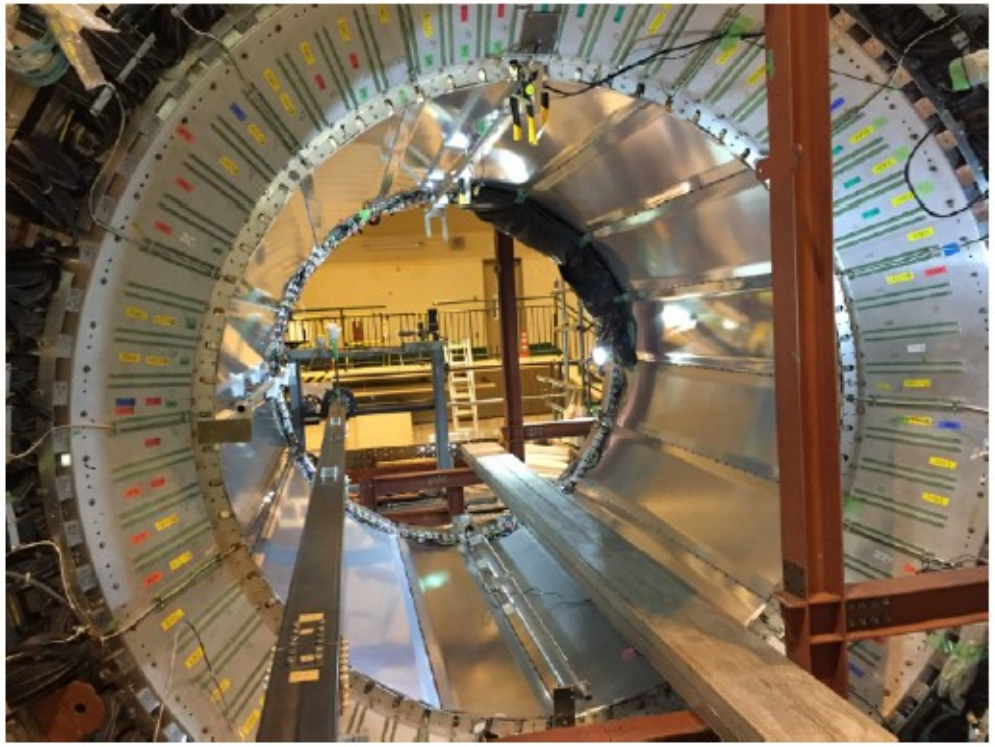




Barrel PID: Time of Propagation



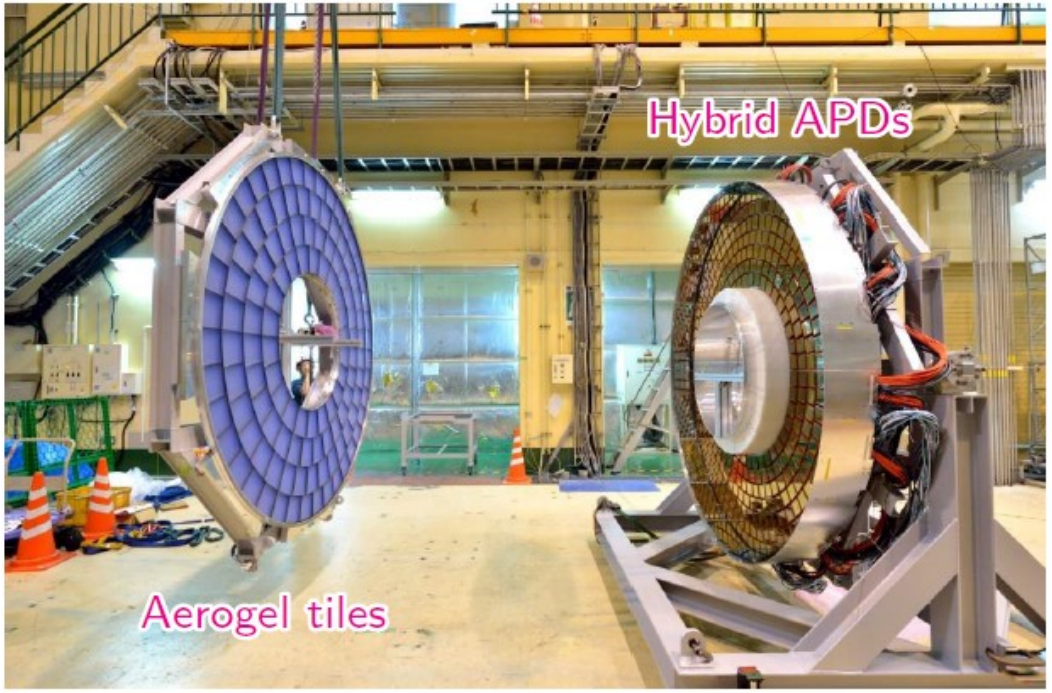


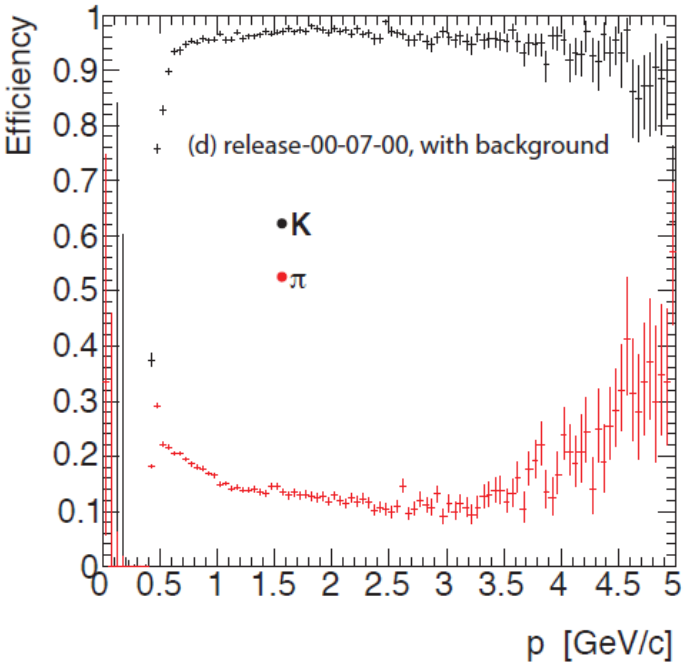


Cherenkov angle is reconstructed using hit position in the photo detector plane and time of propagation.

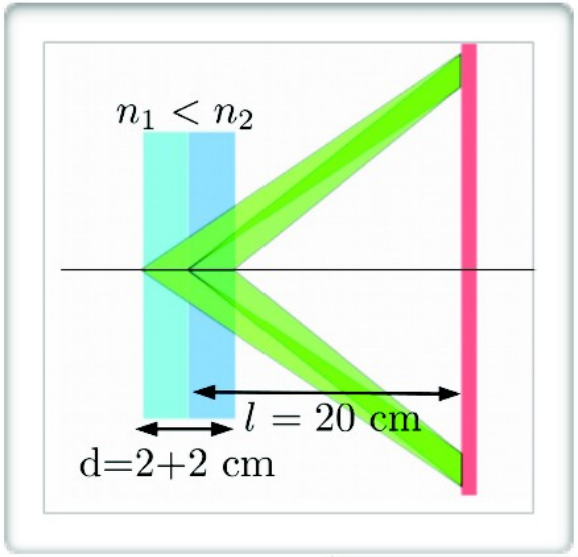
16 quartz bars: 125 x 45 x 2 cm
32 Micro-channel plate PMTs
Hamamatsu SL-10

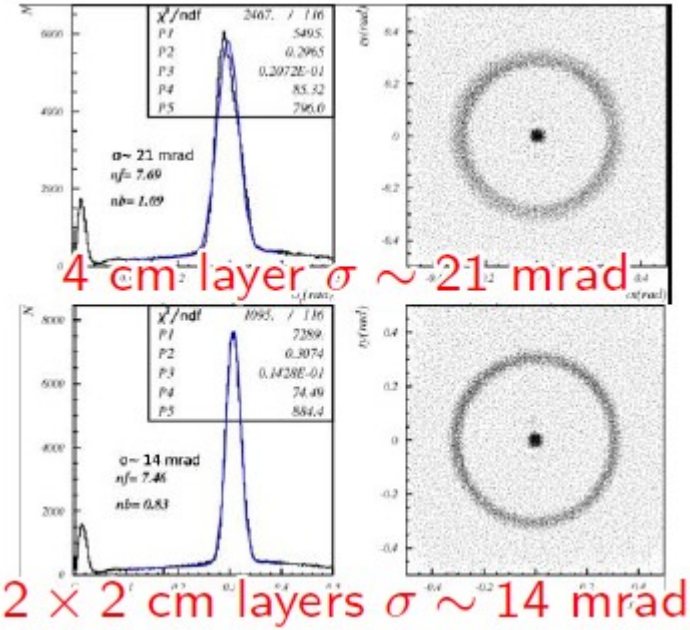
Forward PID: Aerogel RICH

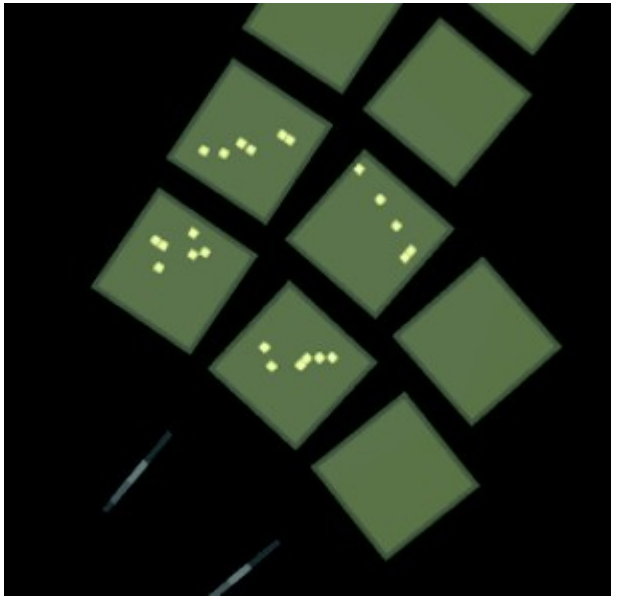




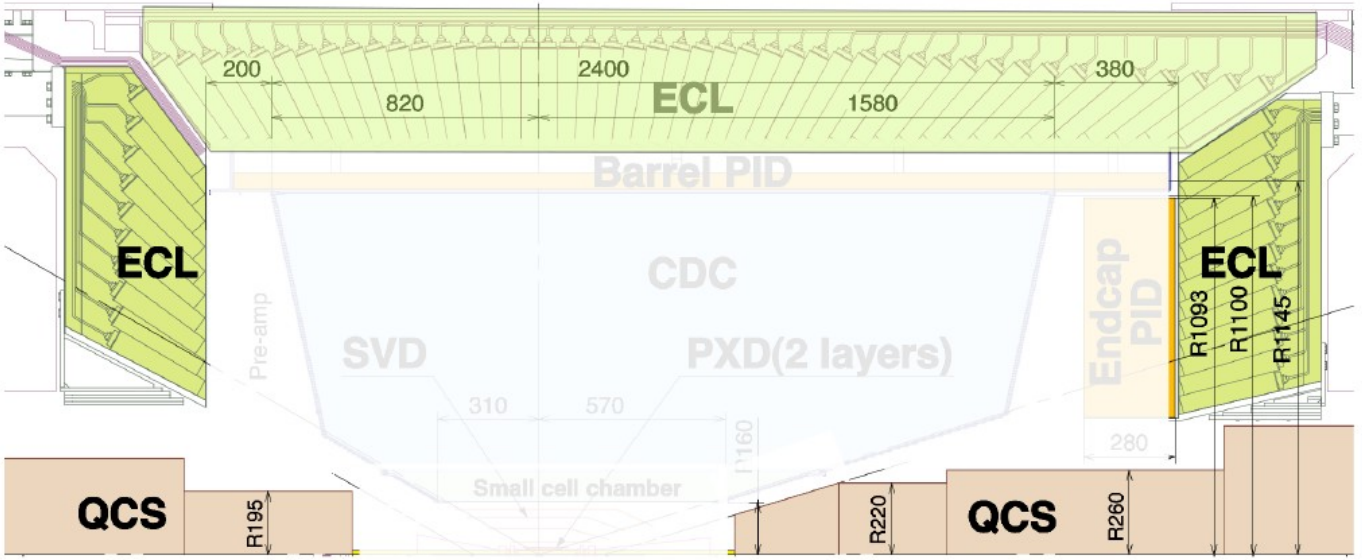
$n_1 = 1.045,\ n_2 = 1.055$







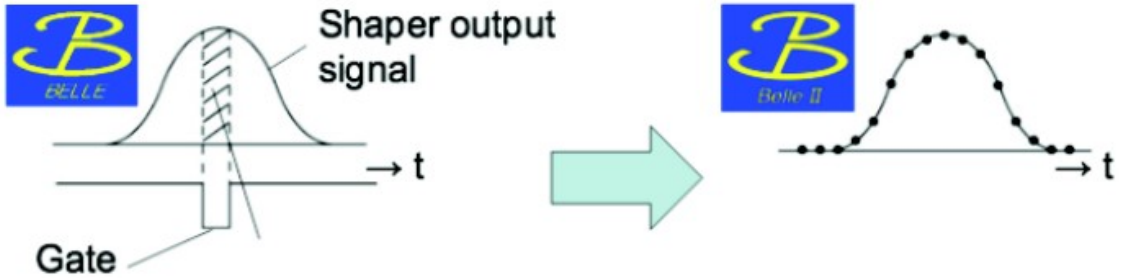
Electromagnetic Calorimeter

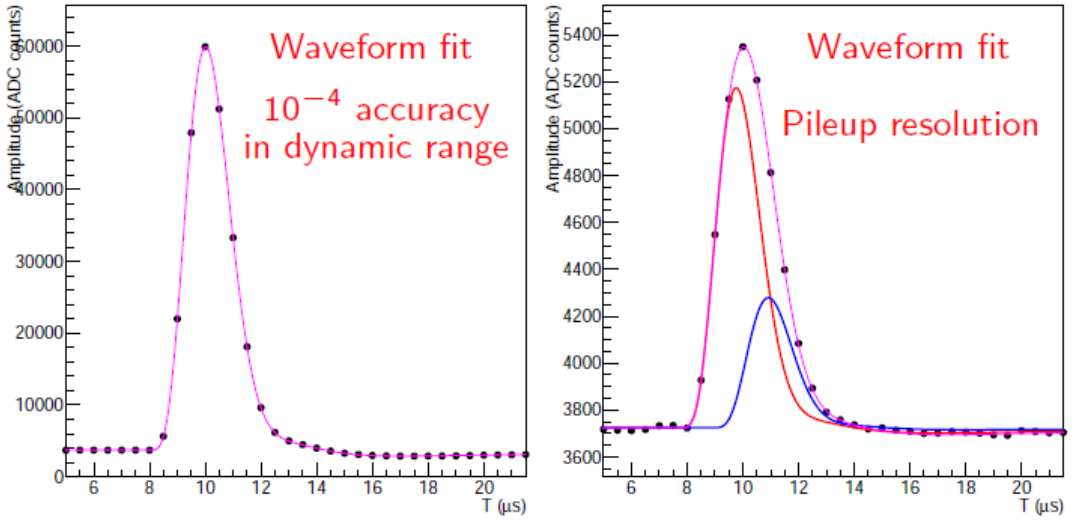


8736 CsI(Tl) crystals, 16 X_0

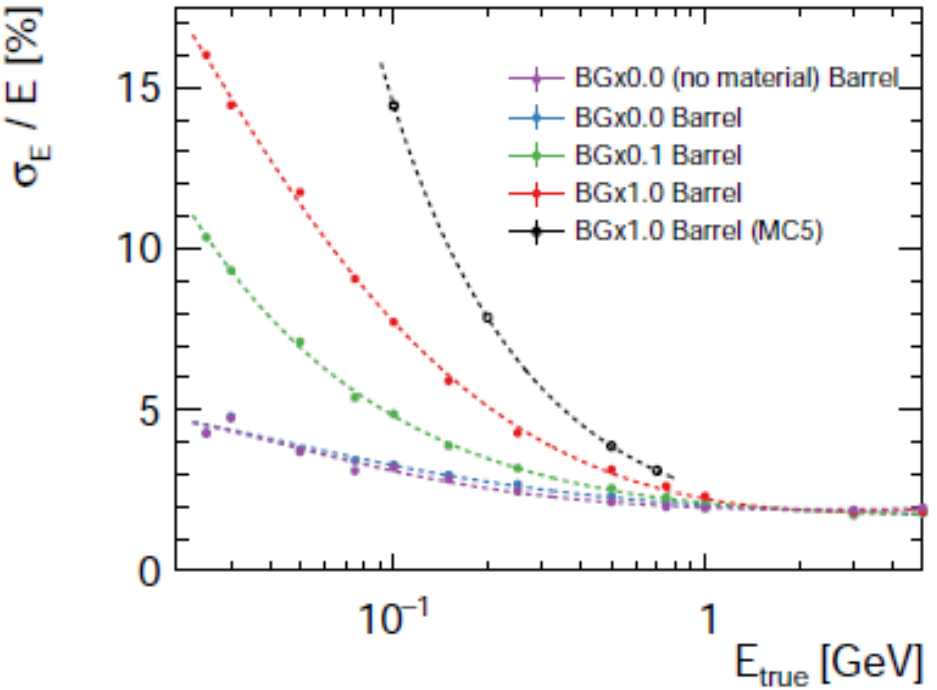
Upgrade of electronics

- Shorter signal sampling (1000 → 500ns)
- The waveform sampling (2 MHz)
- Fit form to extract amplitude and time

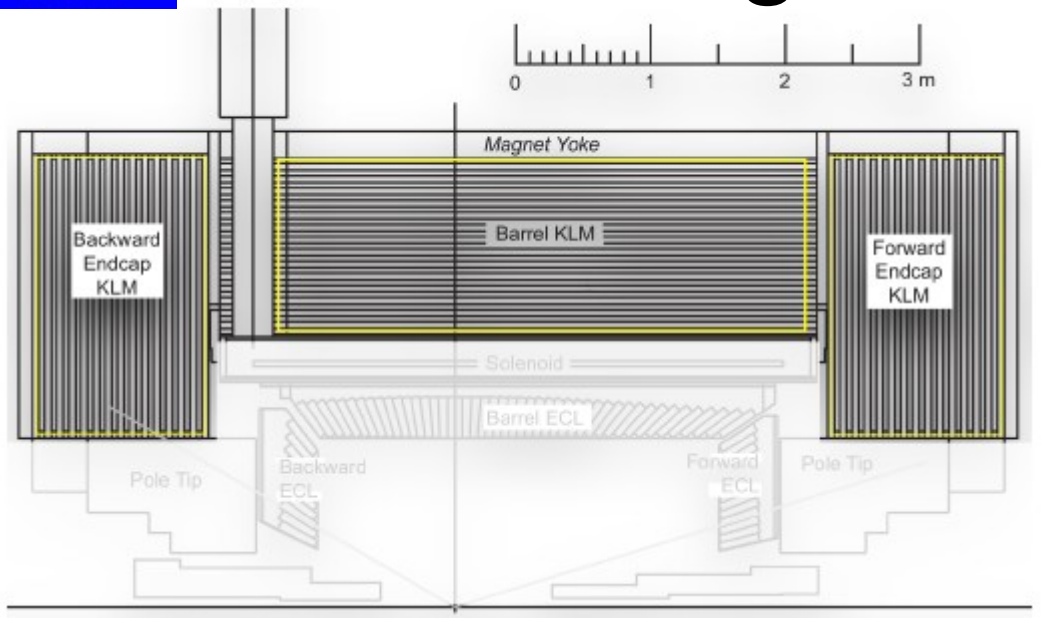


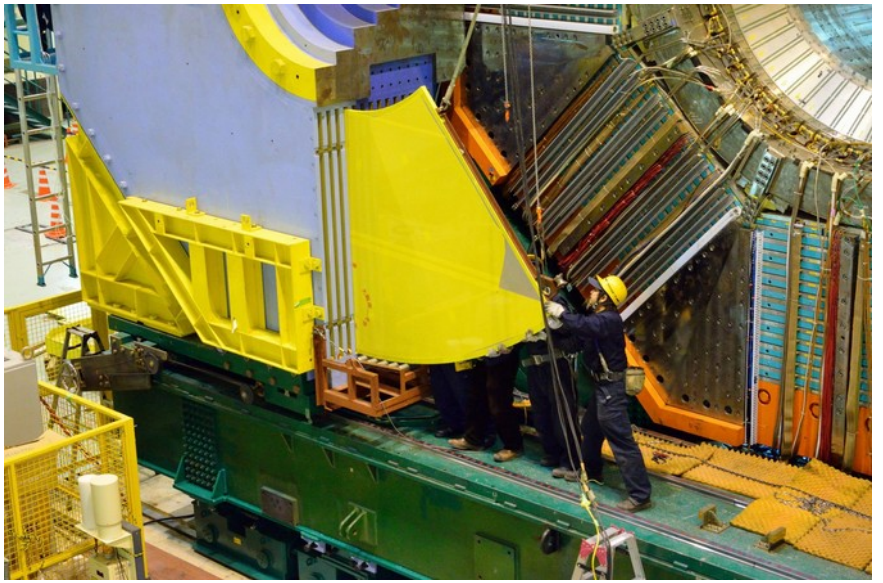


Energy resolution vs background



The KLong and Muon detector





RPCs in the endcaps and two inner barrel layers have been replaced with scintillator strips with WLS fibers and MPPC detectors in order to keep reasonable efficiency at high signal anf background rates.