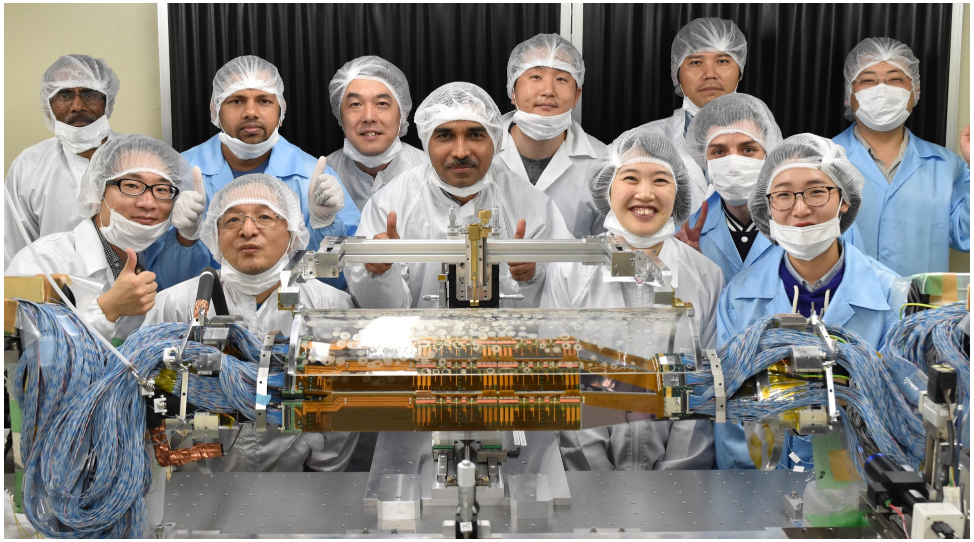
Flavor physics at Belle II



Gagan Mohanty

tifr

International Workshop on frontiers in high energy physics

FHEP 2019

14 -17 October 2019, Hyderabad, India

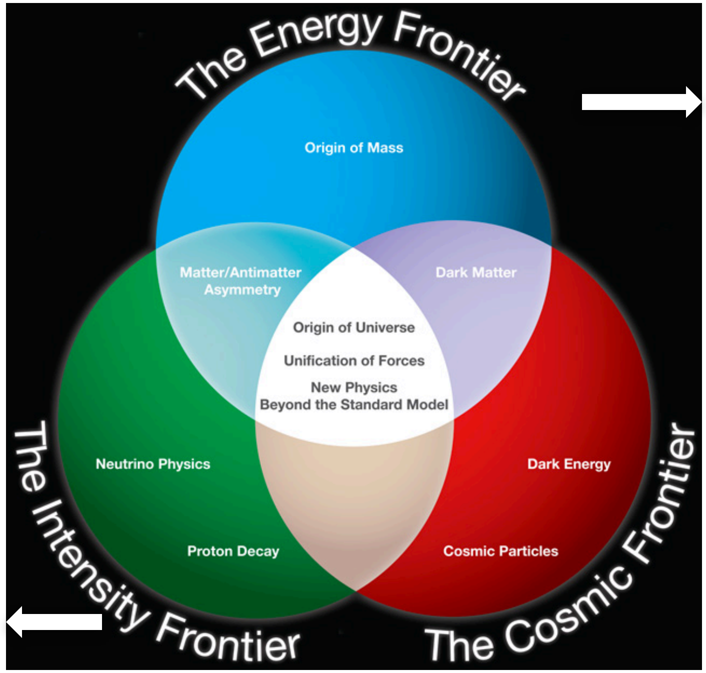
UNIVERSITY OF HYDERABAD

सा विद्या या विमुक्तये

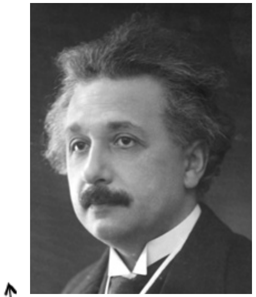
भारतीय प्रौद्योगिकी संस्थान हैदराबाद

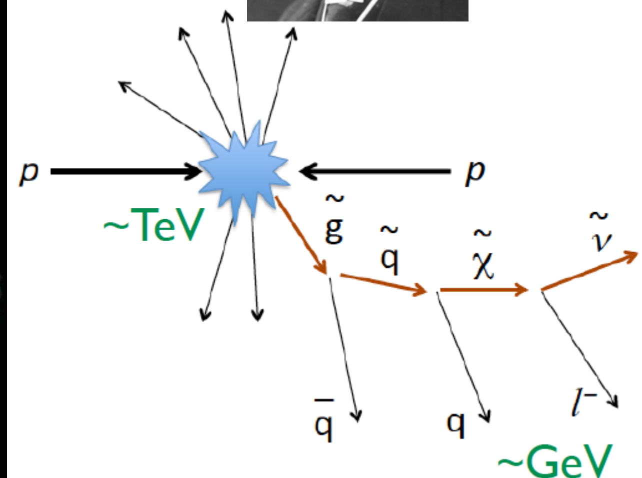
Indian Institute of Technology Hyderabad

Flavor physics: why?

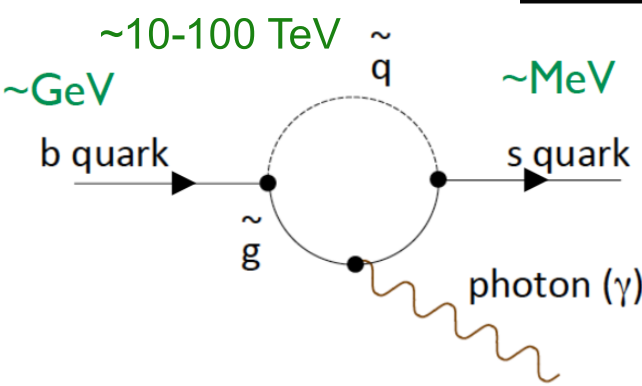


E ~ m



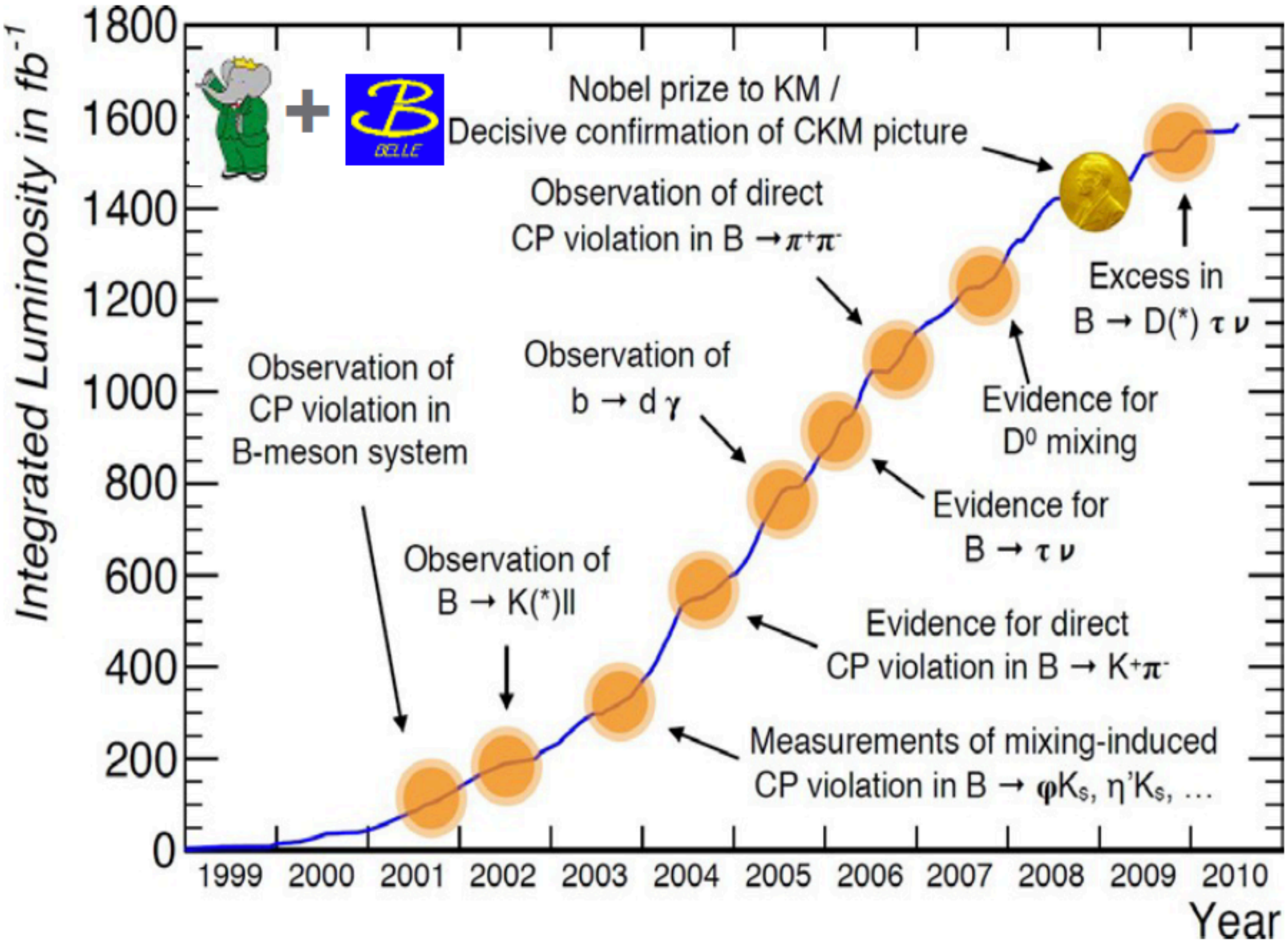


Δm.Δt ~ 1



- ❑ Provides a unique probe to unravel deeper mysteries of universe with intense sources and highly sensitive detectors

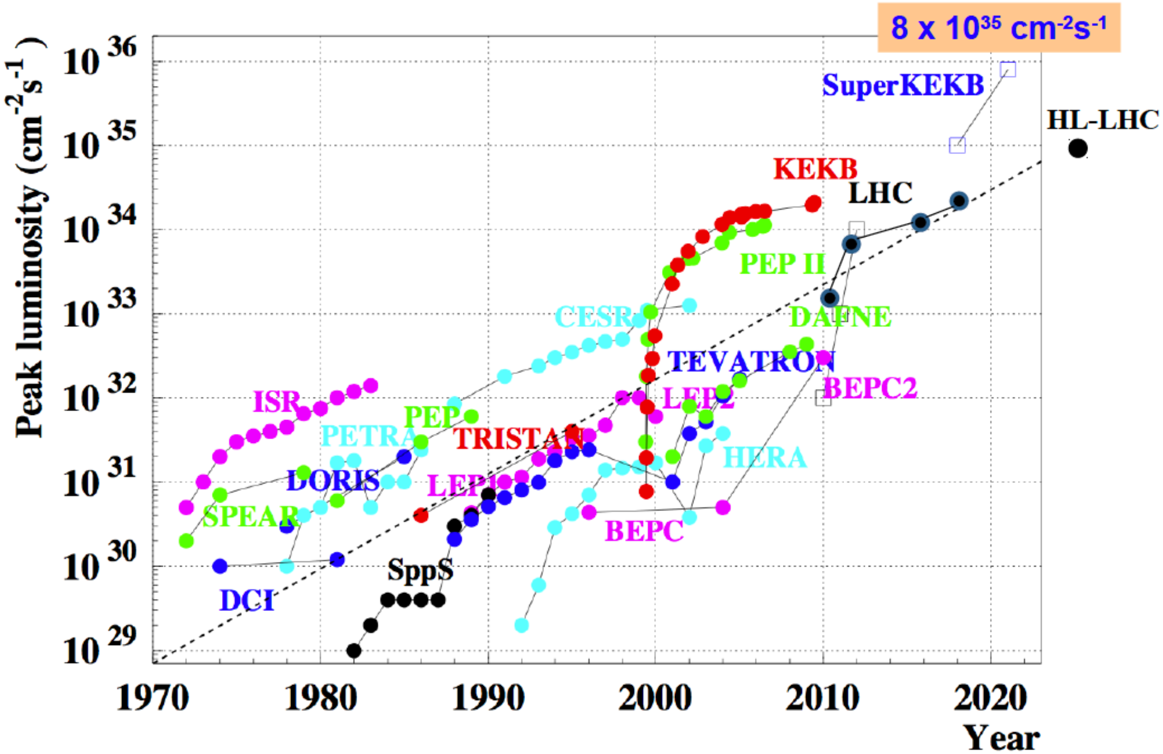
First-generation e^+e^- flavor factories



- Success culminated in 2008 Nobel prize in Physics
- Rich legacy left for next-gen expt. EPJ C74, 3026 (2014)

So, why another e^+e^- flavor factory?

- 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 $\tau\nu$ or $D^{(*)}\tau\nu$ final state
- New physics in tau sector ➔ search for lepton flavor violating (LFV) tau decays
- Can we probe dark matter from bottom? ➔ hidden dark sector (C. Hearty)



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

Snapshots of what Belle II can achieve?

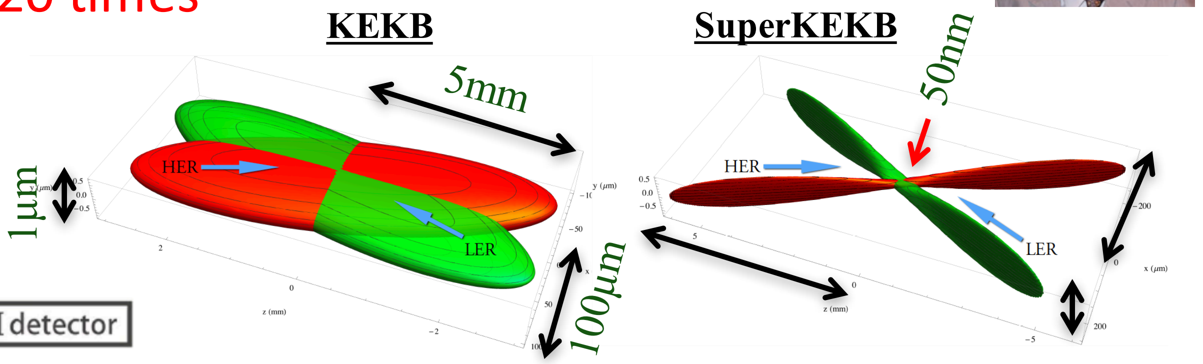
Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	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
$S(B \to K_S^0\pi^0\gamma)$	***	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
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***	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

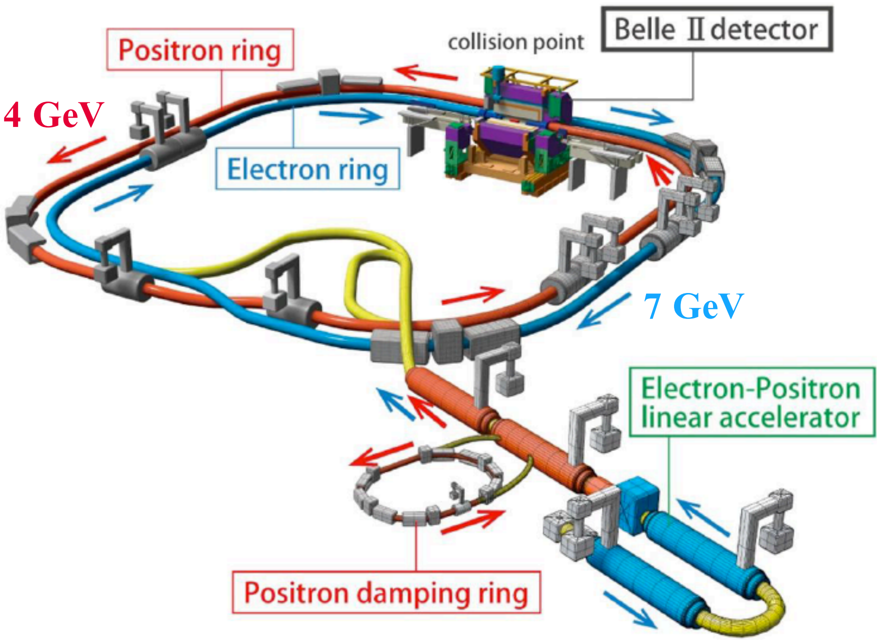
☞ From Belle II physics book arXiv:1808.10567 (to appear in PTEP)

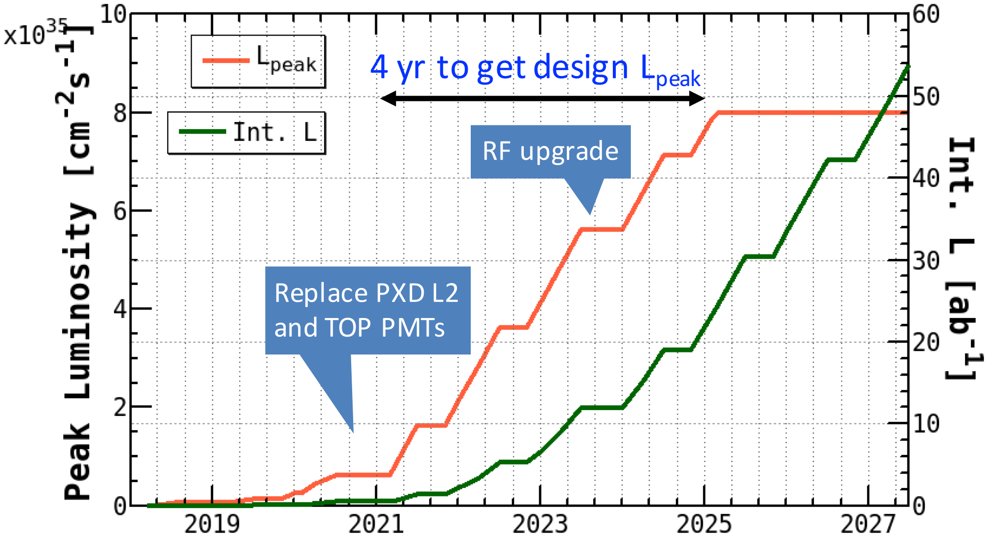
- Precision CKM metrology
- Direct and mixing-induced CP violation in B decays
- (Semi-)leptonic B decays
- Radiative & electroweak penguin decays
- Vibrant charm program
- Search of LFV tau decays

SuperKEKB: New Intensity Frontier machine

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

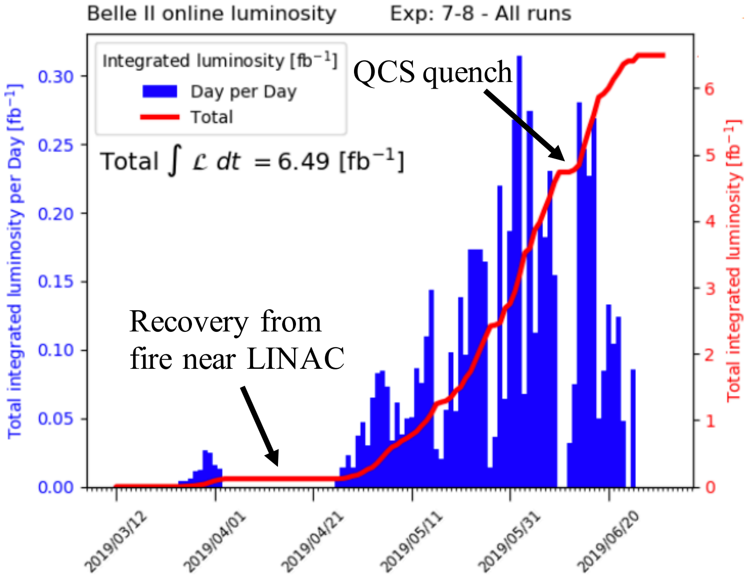






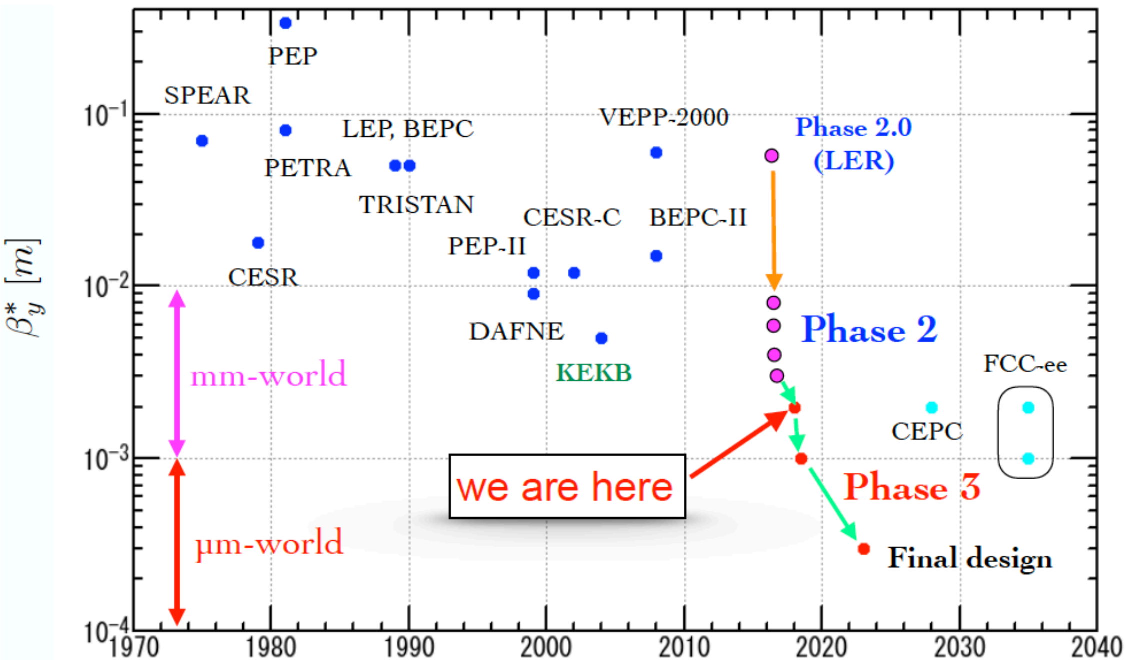
- ➢ First new particle collider after LHC!

How far have we gone?



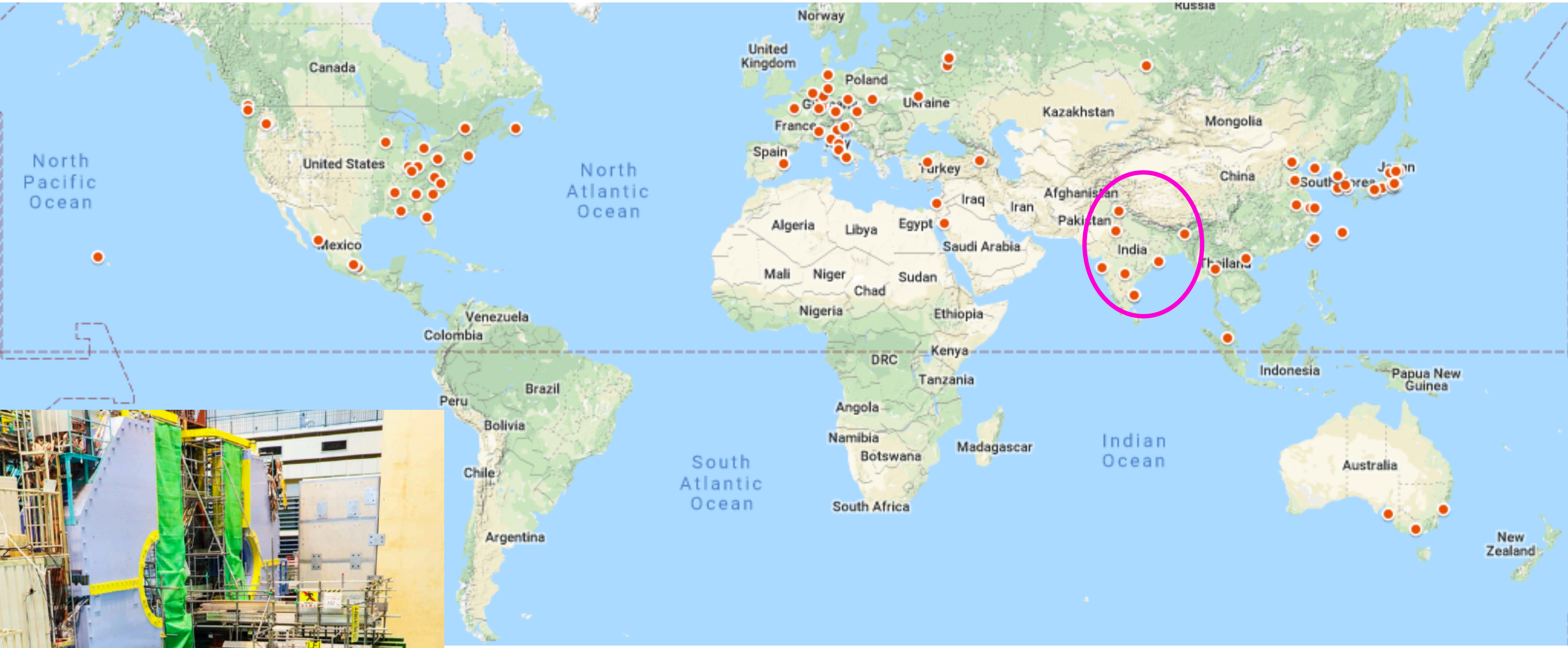
- Phase 1 (2016): single beam background study
- Phase 2 (2018): beam commissioning (establish nano-beam scheme, reach the KEKB luminosity, and measure beam backgrounds) as well as for doing some physics with partial vertex detector
- Phase 3 (2019 – …): physics run with complete vertex detector

- Reached β_y^* = 33 mm in 2018
- Went down β_y^* = 2 mm by end of Summer 2019 (with Belle II off) ➔ starting point for fall run
- ☞ Design luminosity requires one more order-of-magnitude jump to β_y^* = 0.3 mm



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

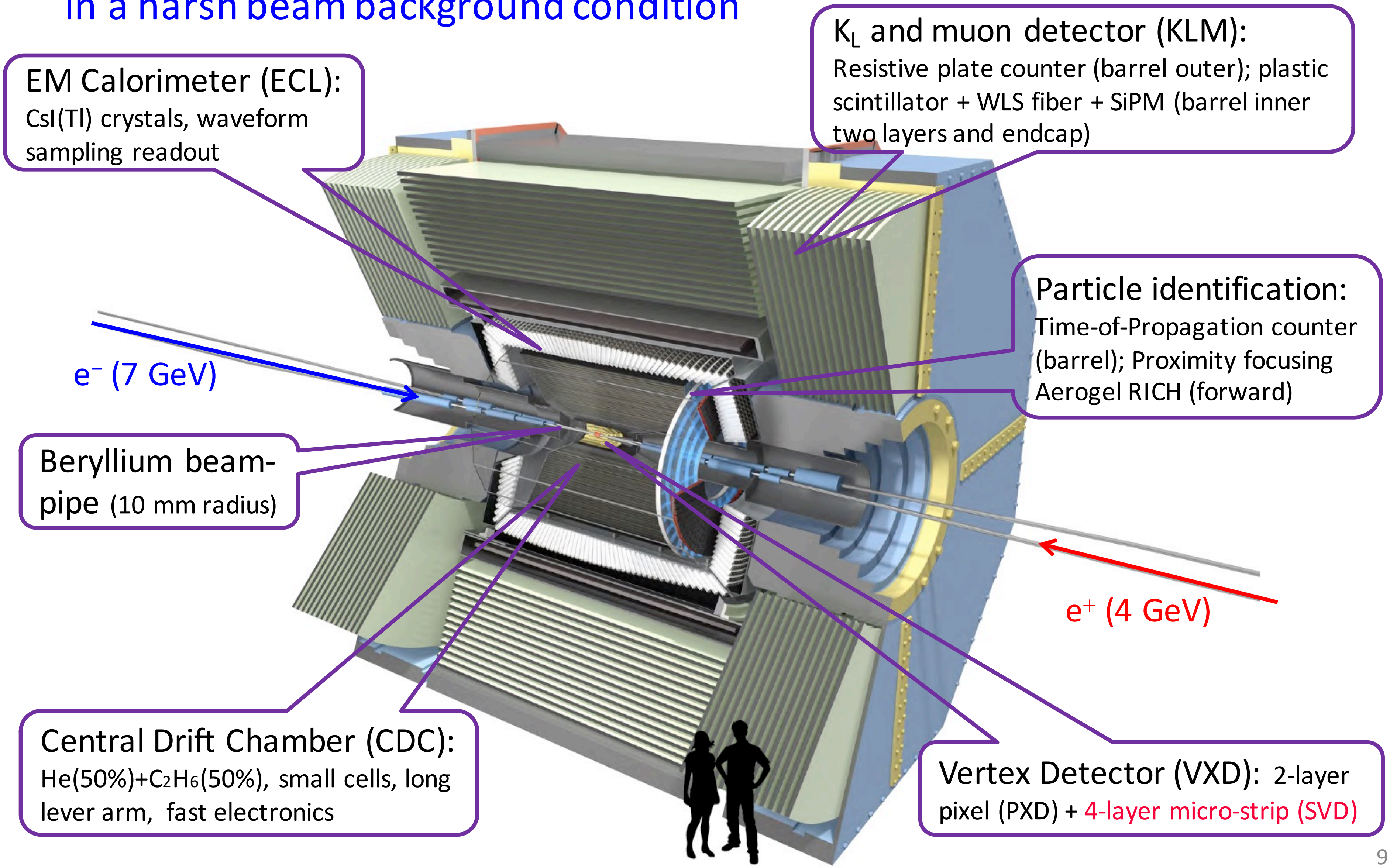
collaboration



- 950 researchers from 112 institutes in 26 countries
- The Indian team comprises ~50 members including five from IIT Hyderabad
  - Leadership positions as well as key contributions to the detector building, reconstruction software and computing

Belle II: A 21st century HEP experiment

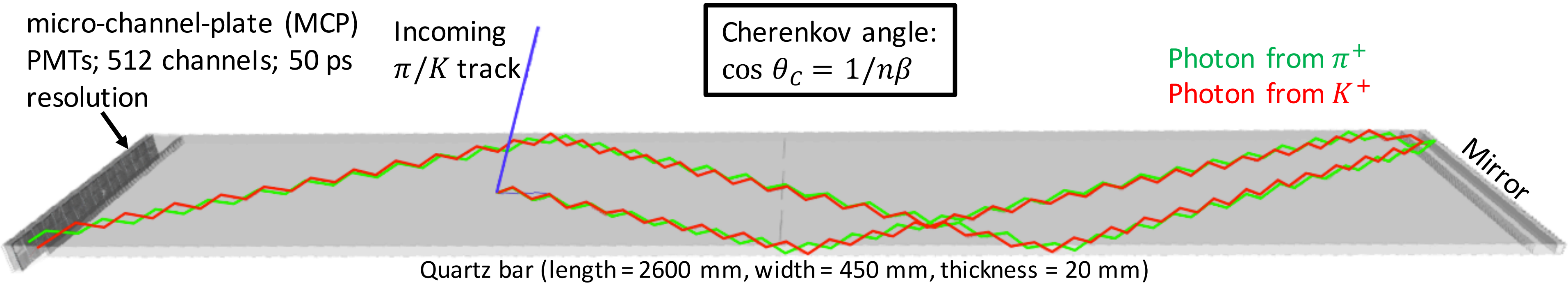
☞ Designed to operate with a performance similar or better than Belle, but in a harsh beam background condition



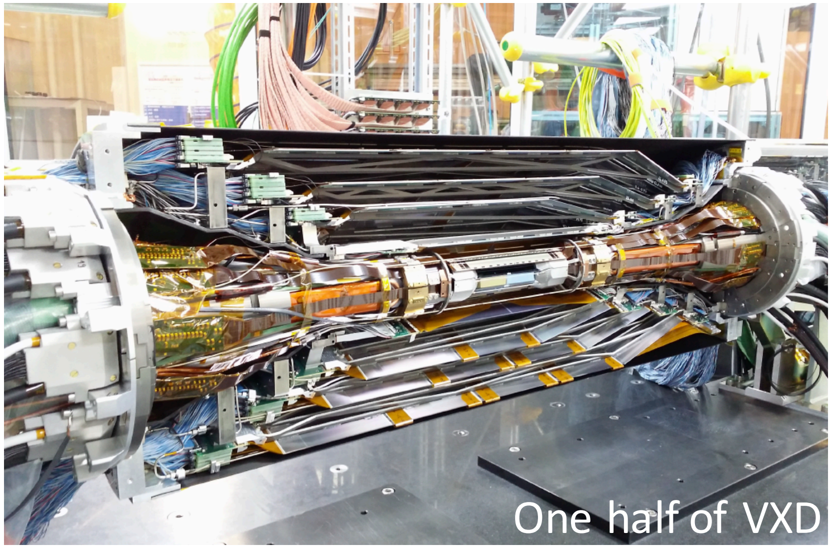
Two detector highlights

Barrel PID (imaging TOP): Japan, US, Slovenia and Italy

☞ 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)



Beam-pipe r = 10 mm

DEPFET pixels: Germany, Czech Republic, Spain…

Layer 1 r = 14 mm

Layer 2 r = 22 mm (2/12 now, rest in 2020)

DSSD (double sided micro-strips)

Layer 3 r = 38 mm (Australia)

Layer 4 r = 80 mm (India)

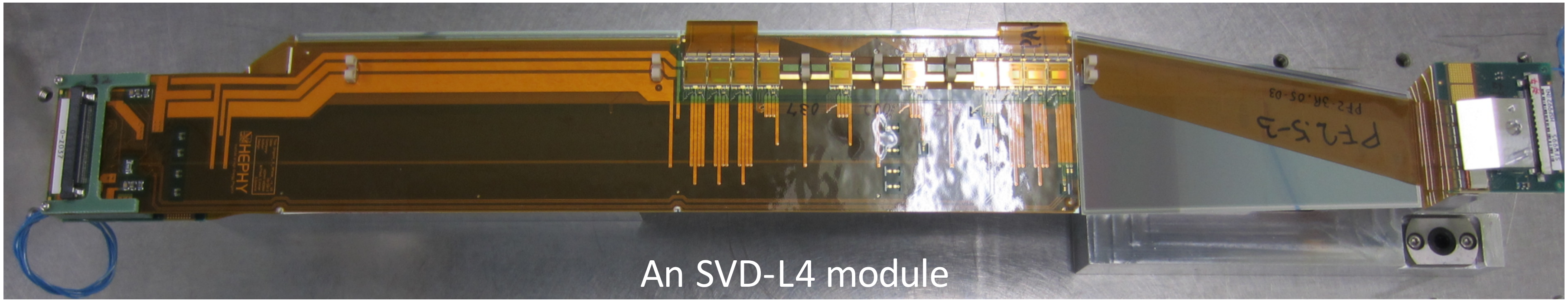
Layer 5 r = 115 mm (Austria)

Layer 6 r = 140 mm (Japan)

} FWD/BWD Italy

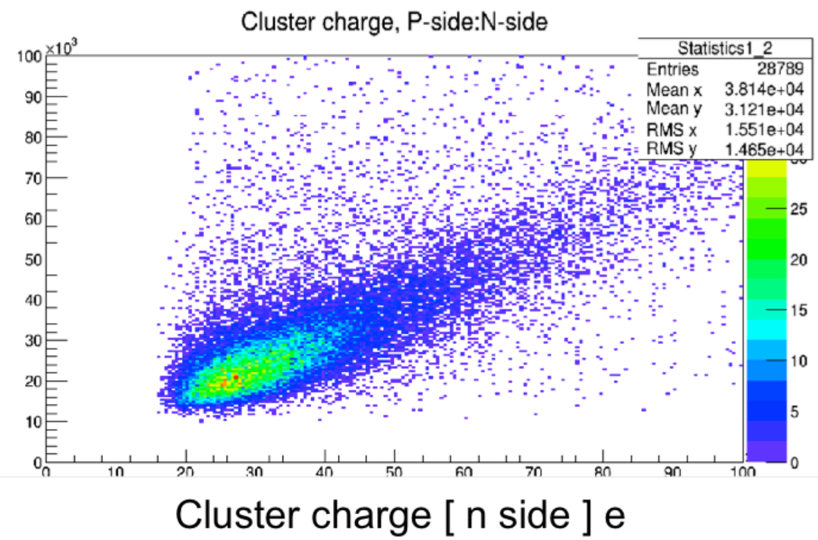
A bit on the SVD-L4 project

- tifr led the design, prototyping and construction of SVD layer-4


An SVD-L4 module

Sensor	ΔX (μm)	ΔY (μm)	ΔZ (μm)
Backward	-49	-35	-34
Central	-6	-15	-22
Forward	-7	-47	94

Design specs: ±150 μm (ΔX, ΔY), ±200 μm (ΔZ)

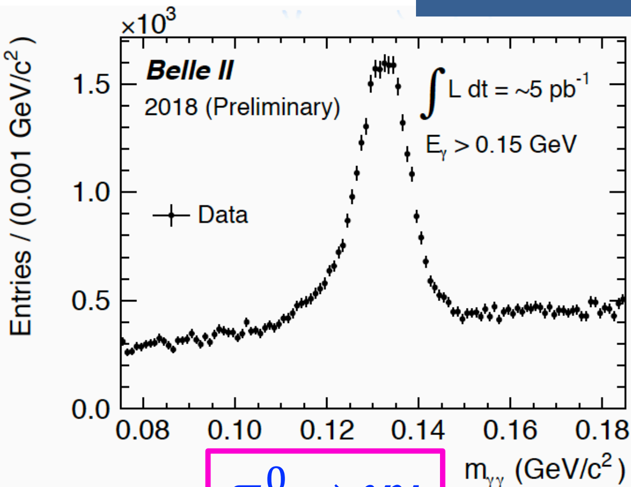


- Had to pass through several stages of a stringent international technical review and grapple with multiple challenges; finally delivered 12 SVD-L4 modules
- 8 students (3 outside TIFR) and 1 postdoc have been trained in this project

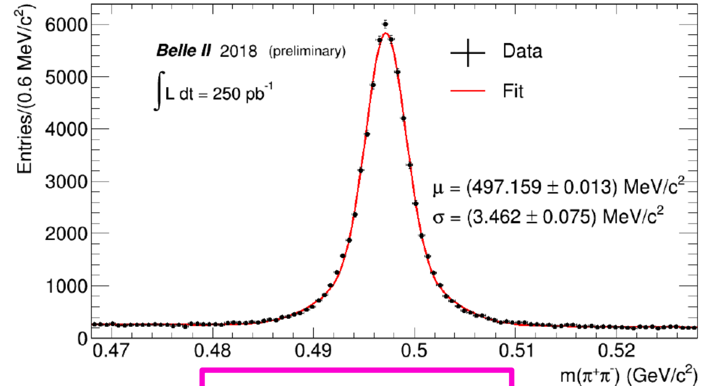
Early rediscovery at phase-2

- 472 fb^{-1} data used for the rediscovery of known processes

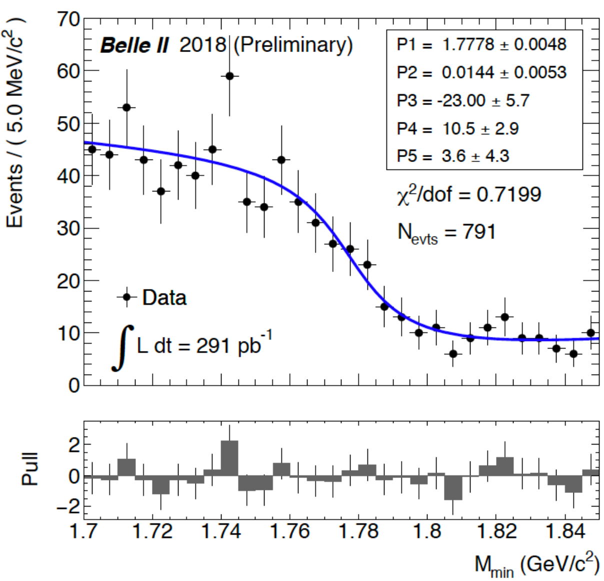
☞ Our team has made good contribution



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

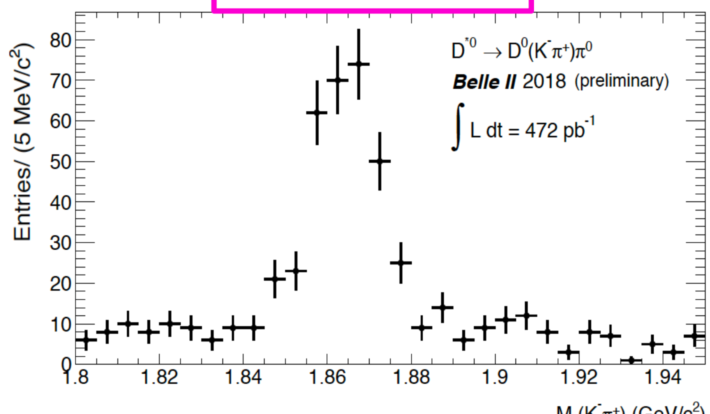


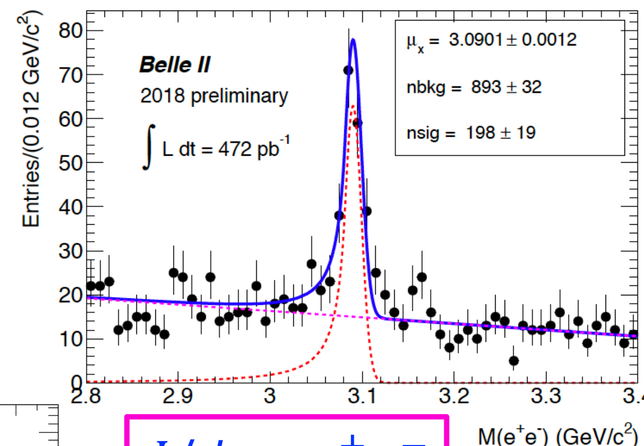
$K_S^0 \to \pi^+\pi^-$



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

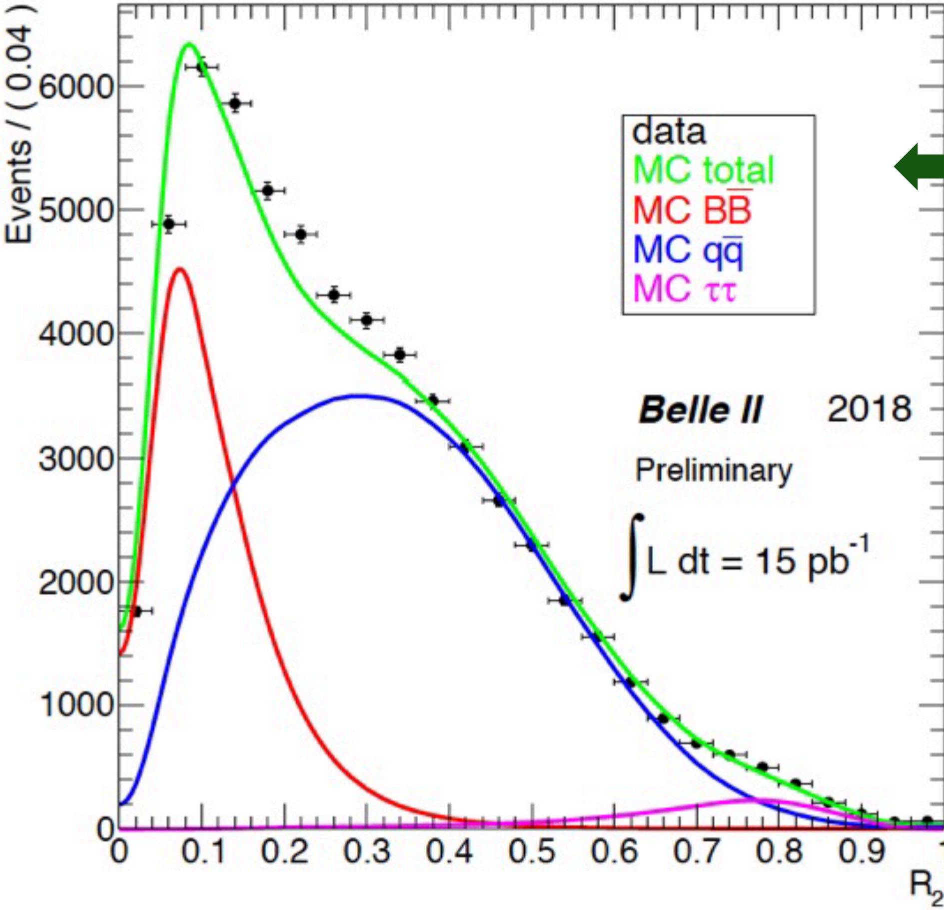
$D^0 \to K^-\pi^+$

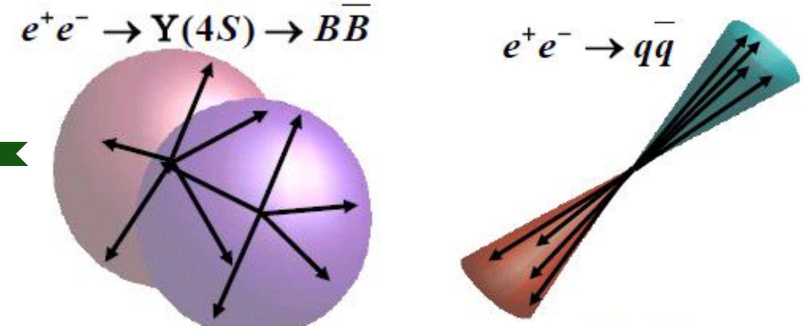




$J/\psi \to e^+e^-$

We also found B mesons...





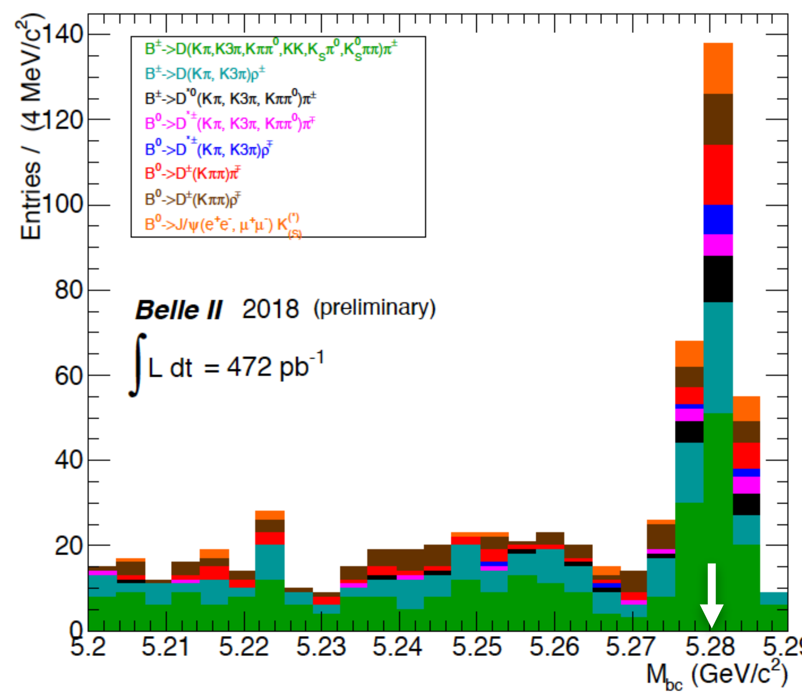
Spherical (R_2~ 0) **Jetlike** (R_2~ 1)

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

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

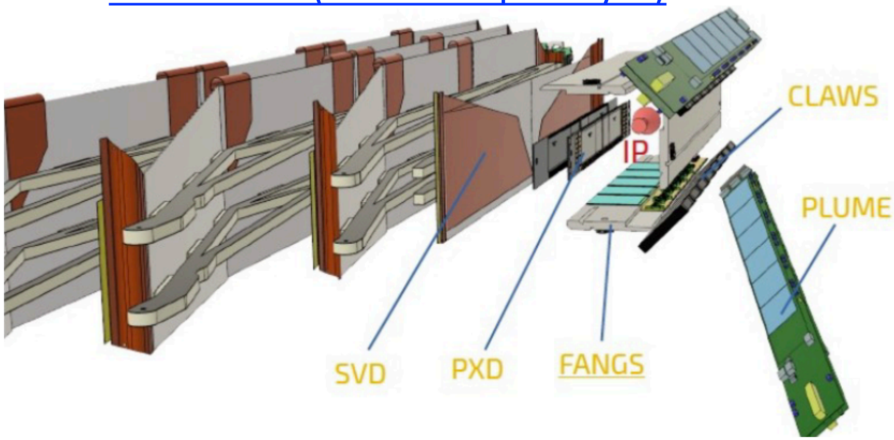
$$M_{\rm bc} = \sqrt{E_{\rm beam}^2 - \vec{p}_B^{*2}}$$

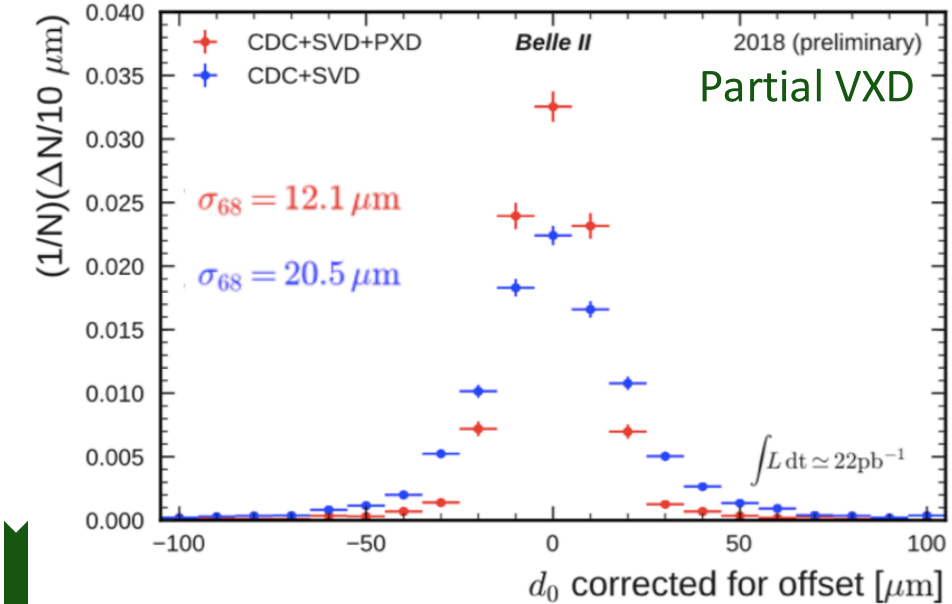
☞ Major contributions from us



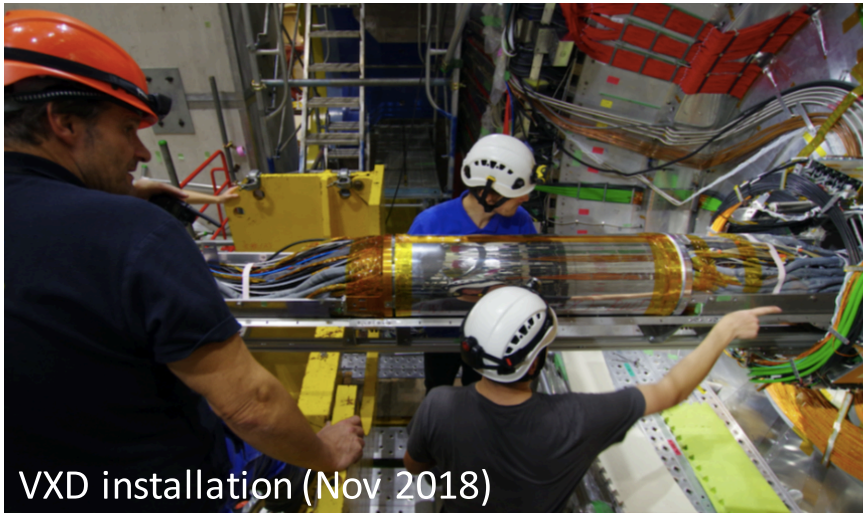
Going from phase-2 to phase-3

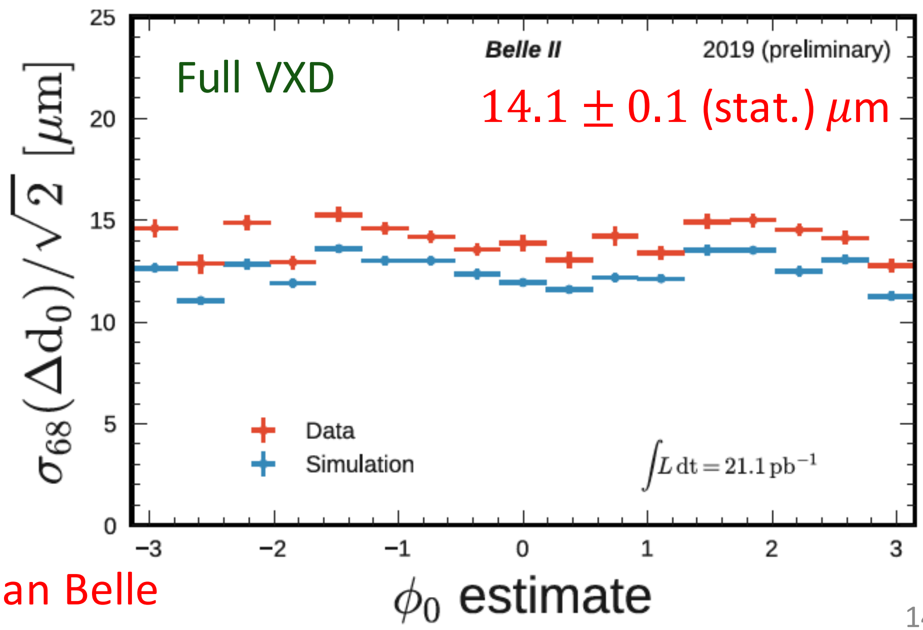
Partial VXD (1 module per layer)





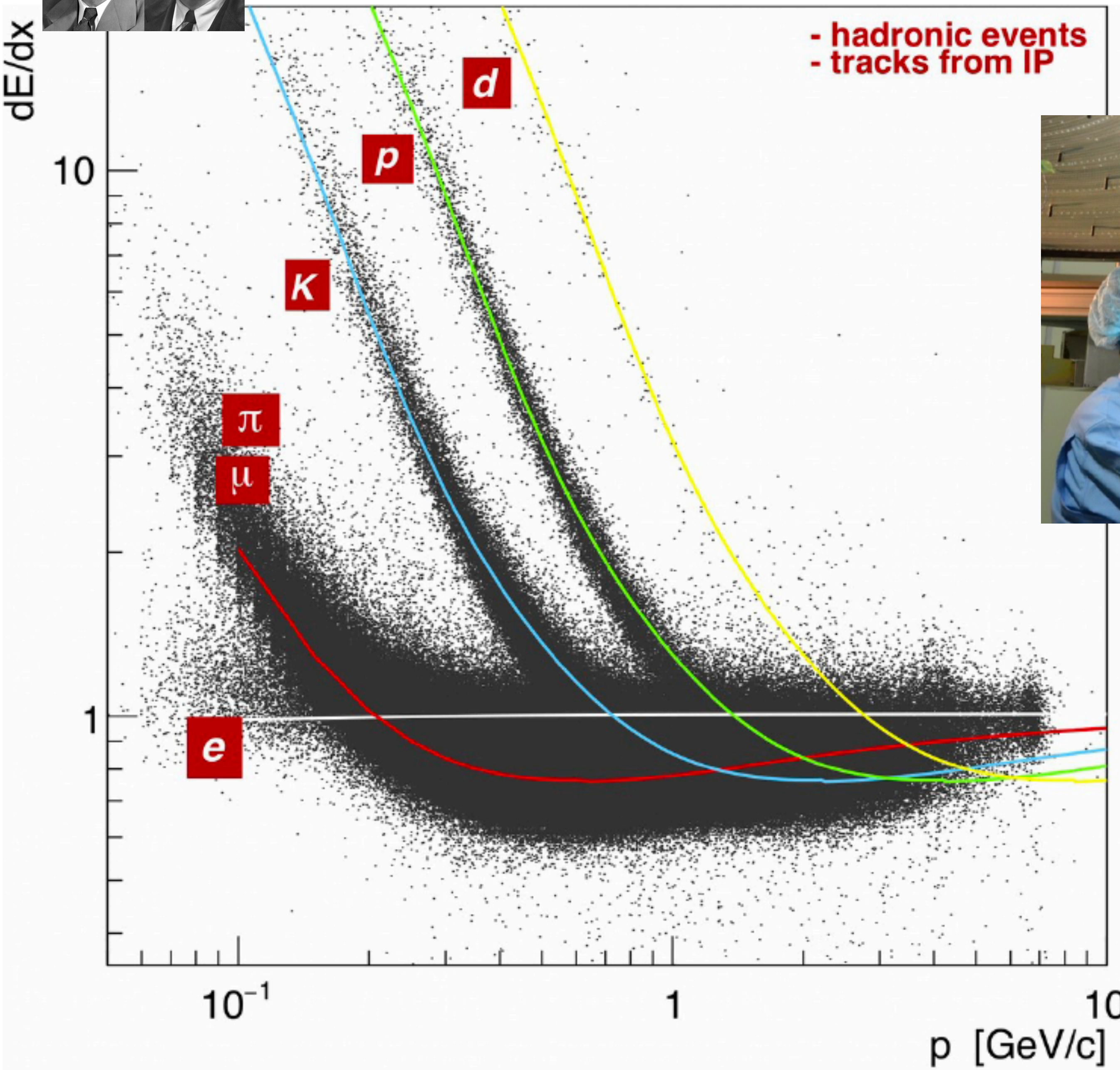
Full VXD (L2 has 2/12 modules)

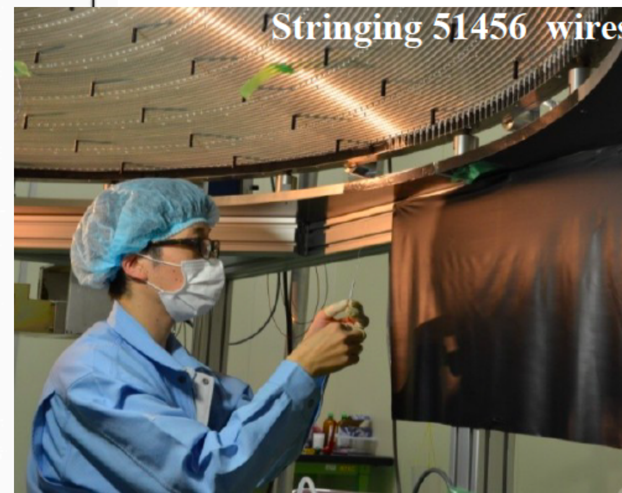




☞ Impact parameter resolution twice better than Belle

CDC dE/dx performance



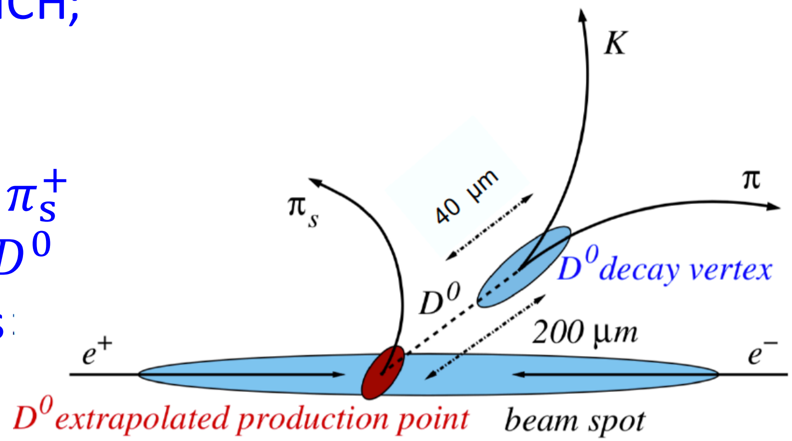


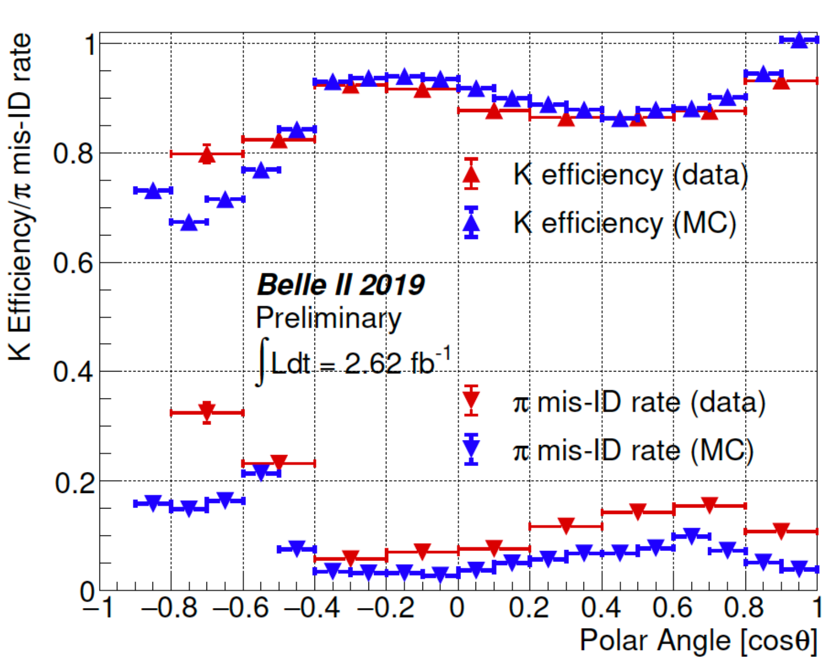
- Obtained with early calibrations in the hadronic event sample
- Key to identify the charged particles, especially at low momentum

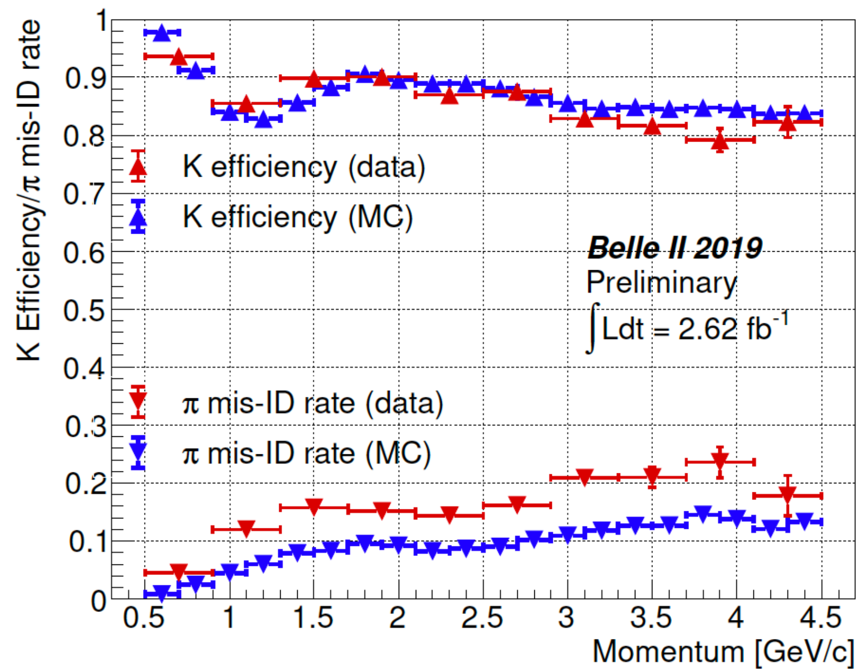
Charged kaon-pion separation

- Provided by the PID system: mainly TOP & ARICH; CDC also helps

- Performance is tested with $D^{*+} \to D^0[K^-\pi^+]\pi_s^+$ decay, where the slow pion tags the flavor of D^0 meson as well as identifies its daughter kaons and pions kinematically



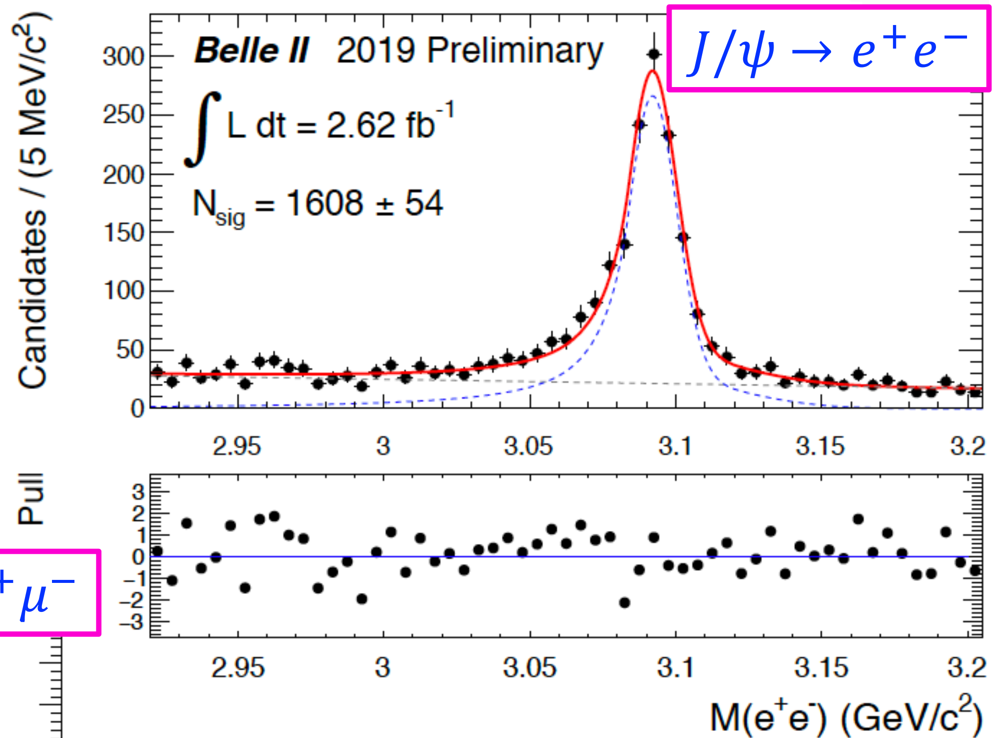


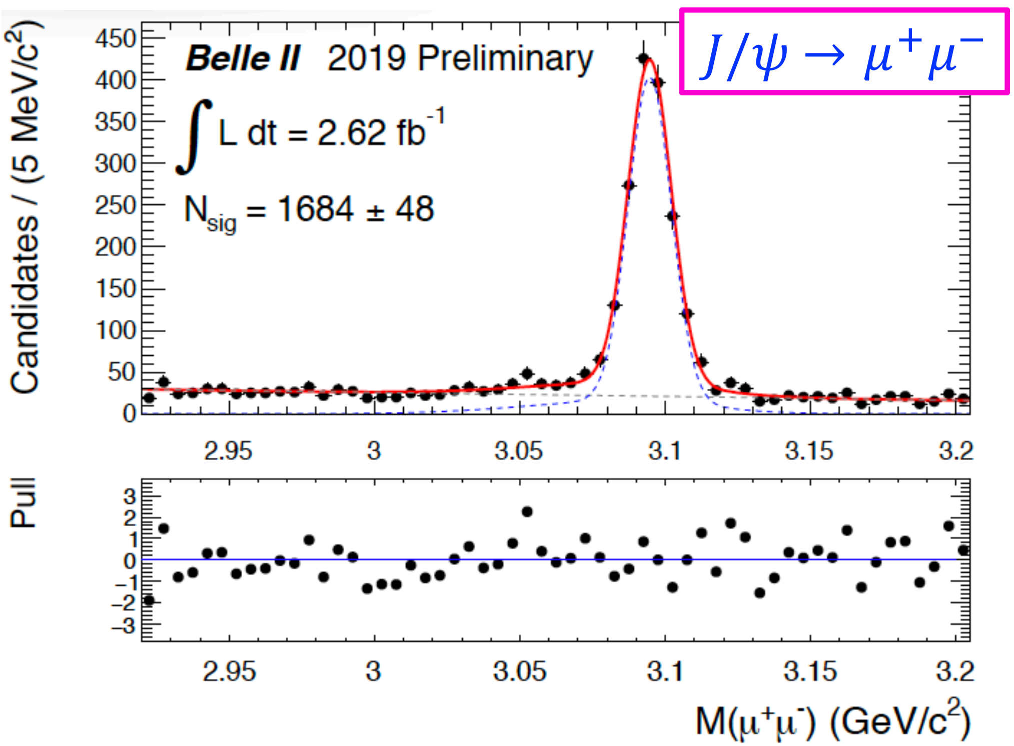


☞ MC simulations yet to include embedded random triggers to correctly represent beam background effects and electronic noise

Electron and muon identification

- Electron ID largely relies on the ECL and CDC (E/p, …)

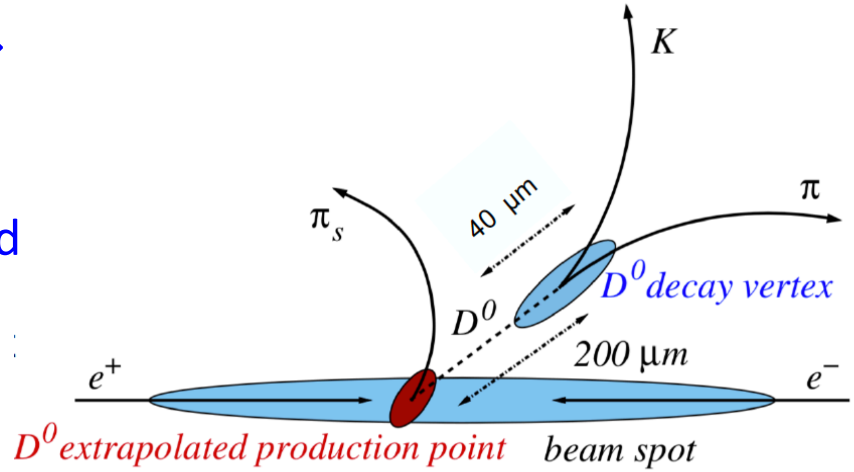


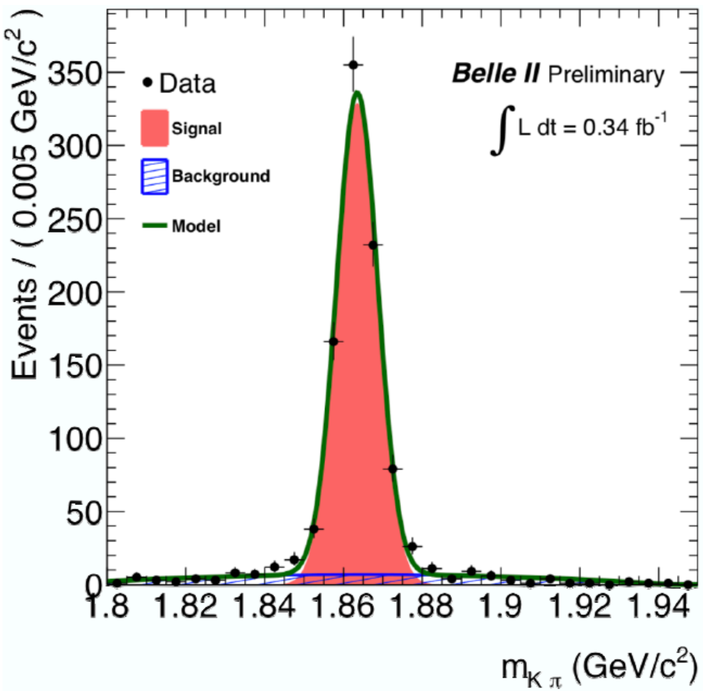


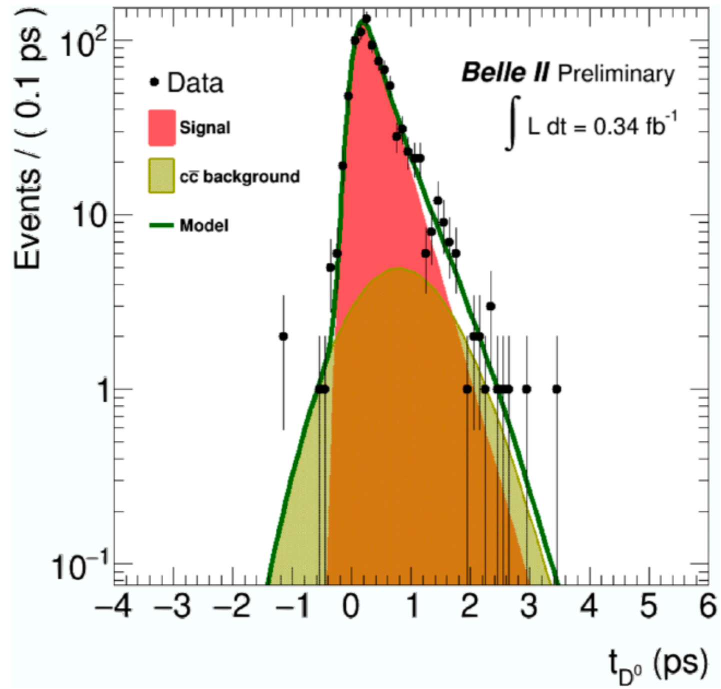
- Muons are identified mostly with information from the KLM

Measurement of D^0 lifetime

- ❑ Use the self-tagging decay channel $D^{*+} \to D^0[K^-\pi^+]\pi_s^+$
- ❑ 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



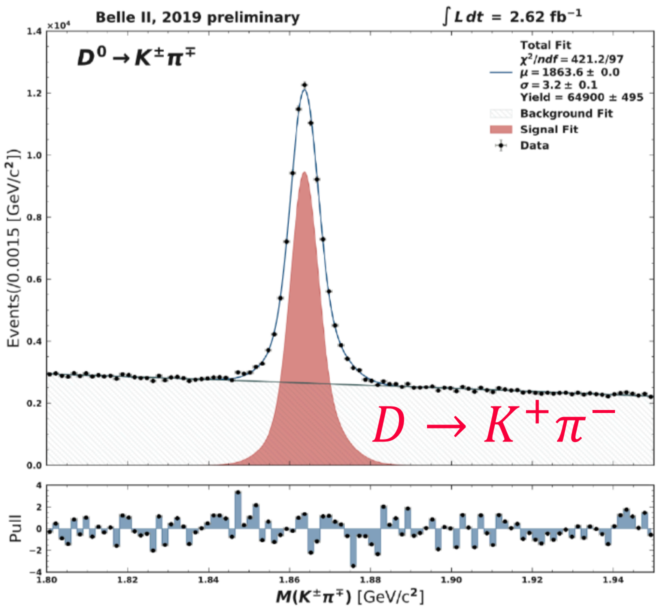


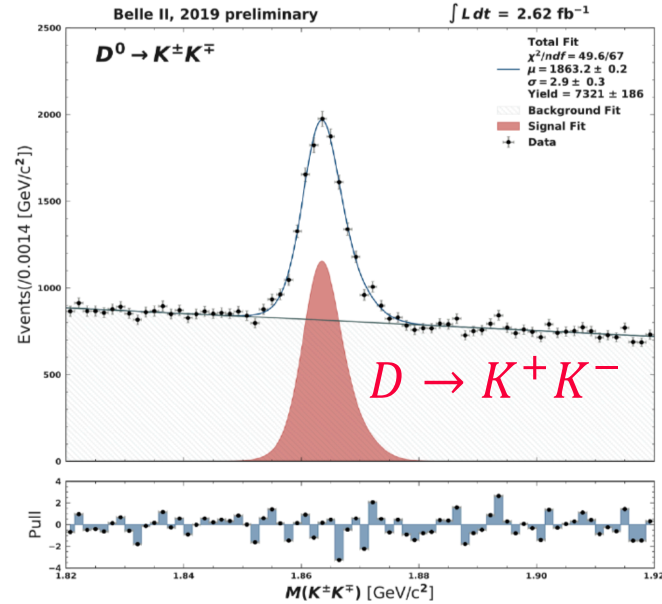


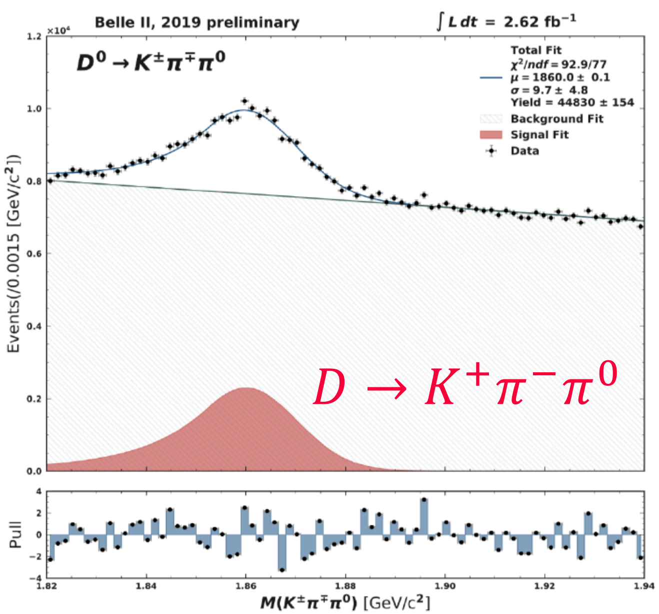
$\tau_D = 370 \pm 40$ fs

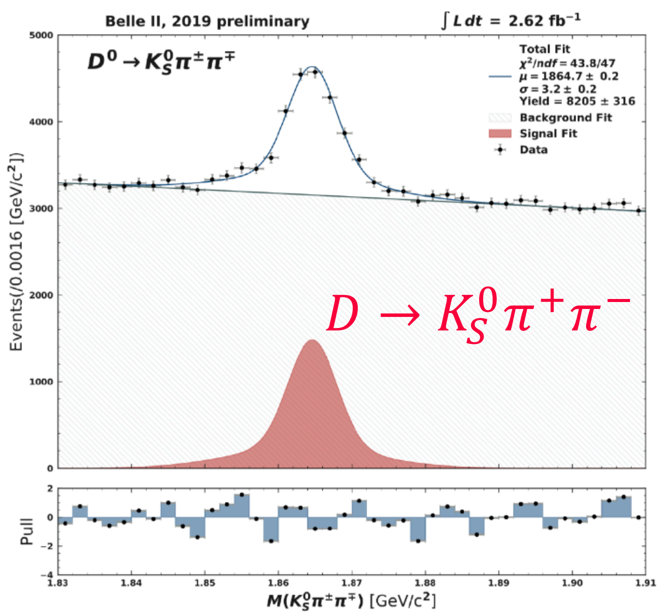
✓ Consistent with PDG (410 fs)

Warming up for charm physics



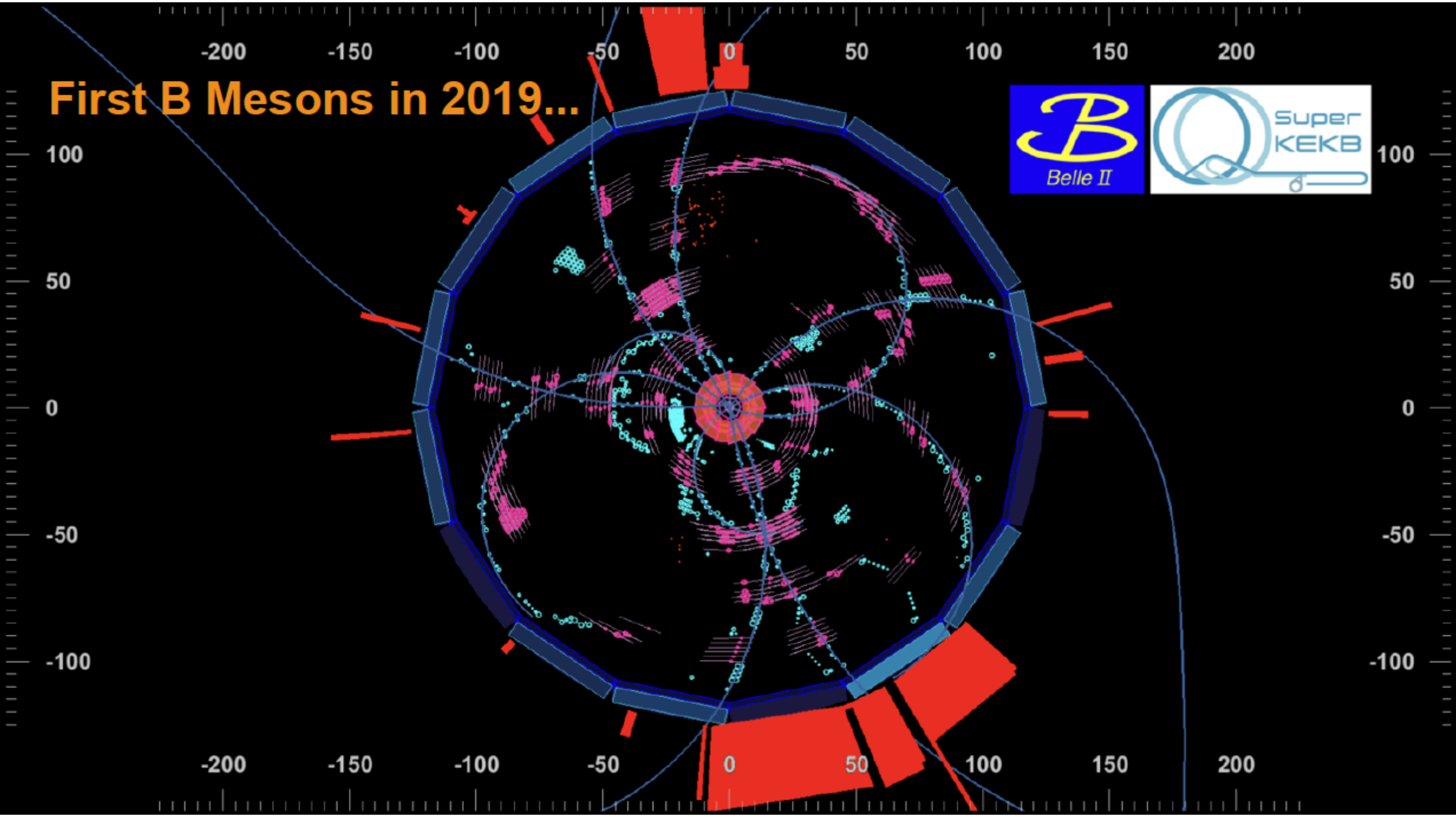






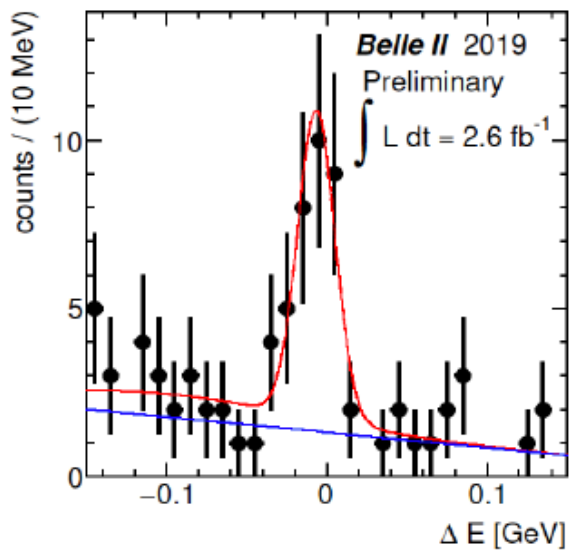
- Going from cleaner to not-so cleaner ones (in clockwise)

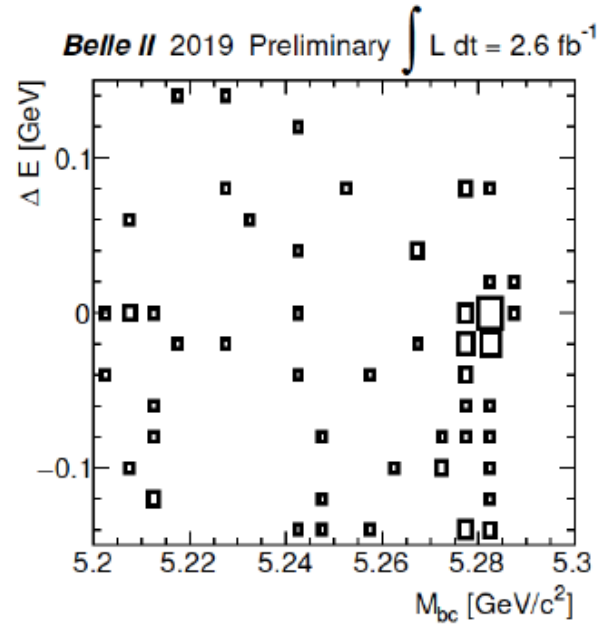
A picture for the office door



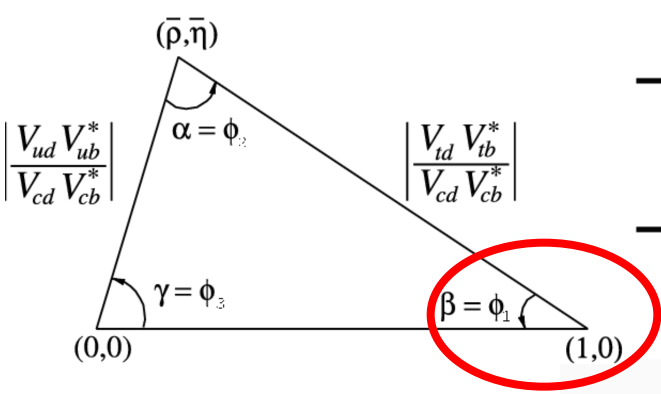
Getting ready for 

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

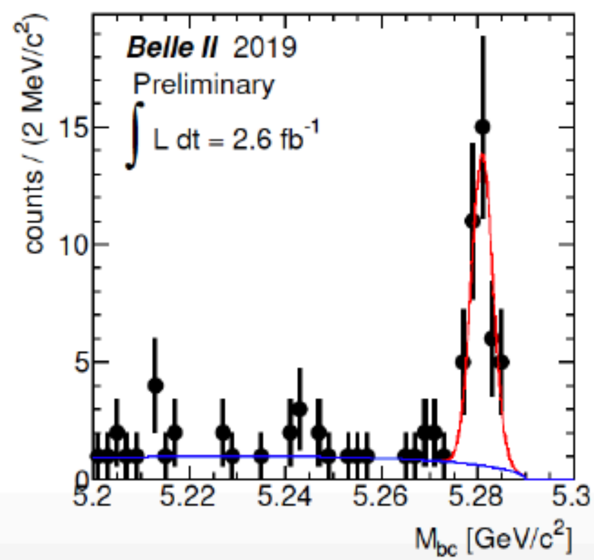




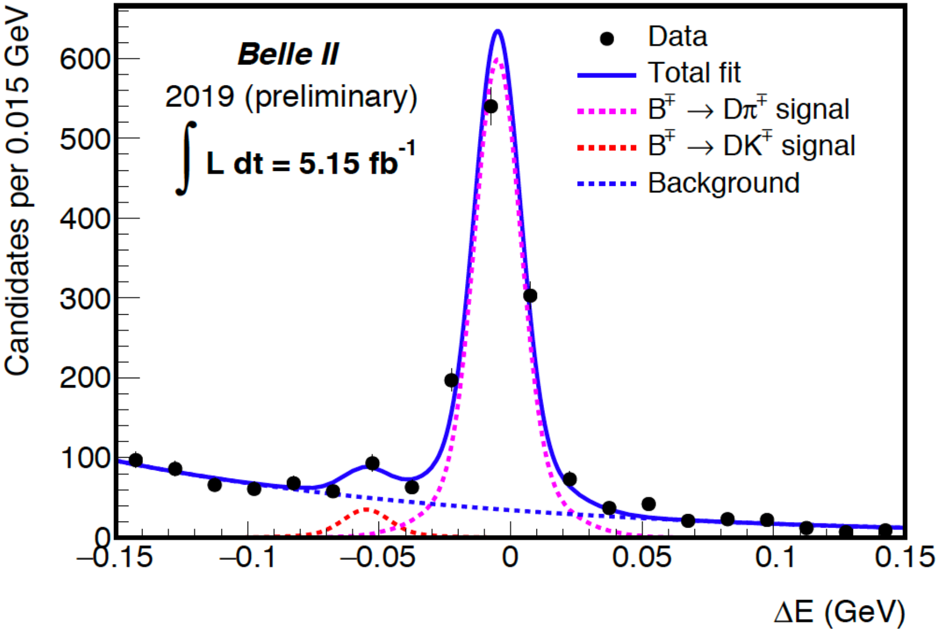
☞ "Golden channel" for the CKM angle $\phi_1 \equiv \beta$

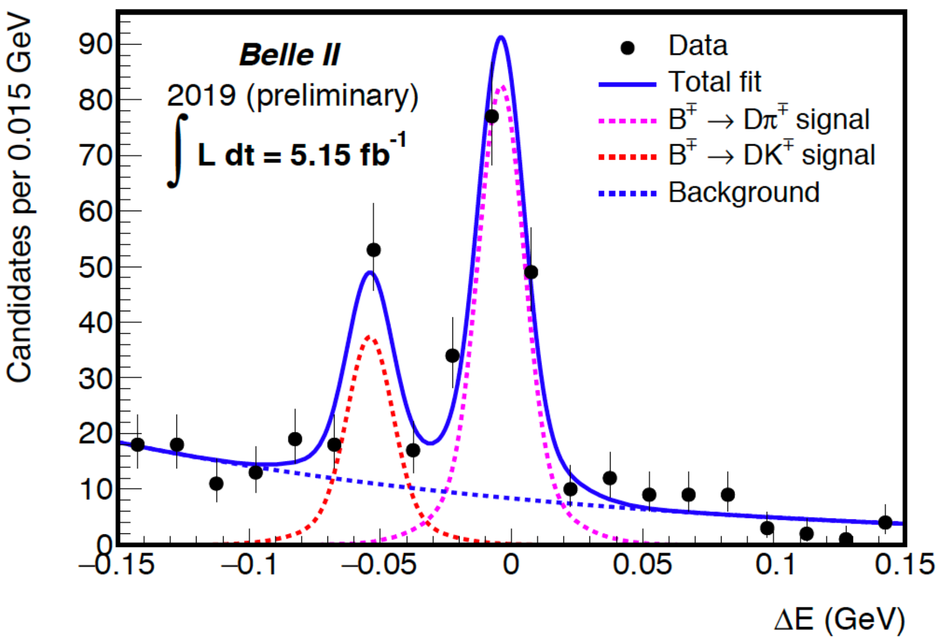


Type	Yield
N_{signal}	29.6 ± 5.3
$N_{\text{background}}$	1.6 ± 0.3



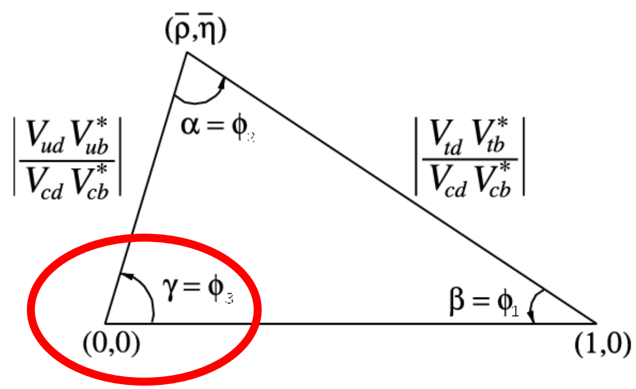
Study of charmed B decay





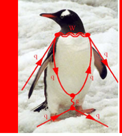
- ΔE distributions for $B^{\pm} \to Dh^{\pm}$ decays with $D \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+$
- Demonstrate importance of PID at high momentum towards improving the S/B ratio

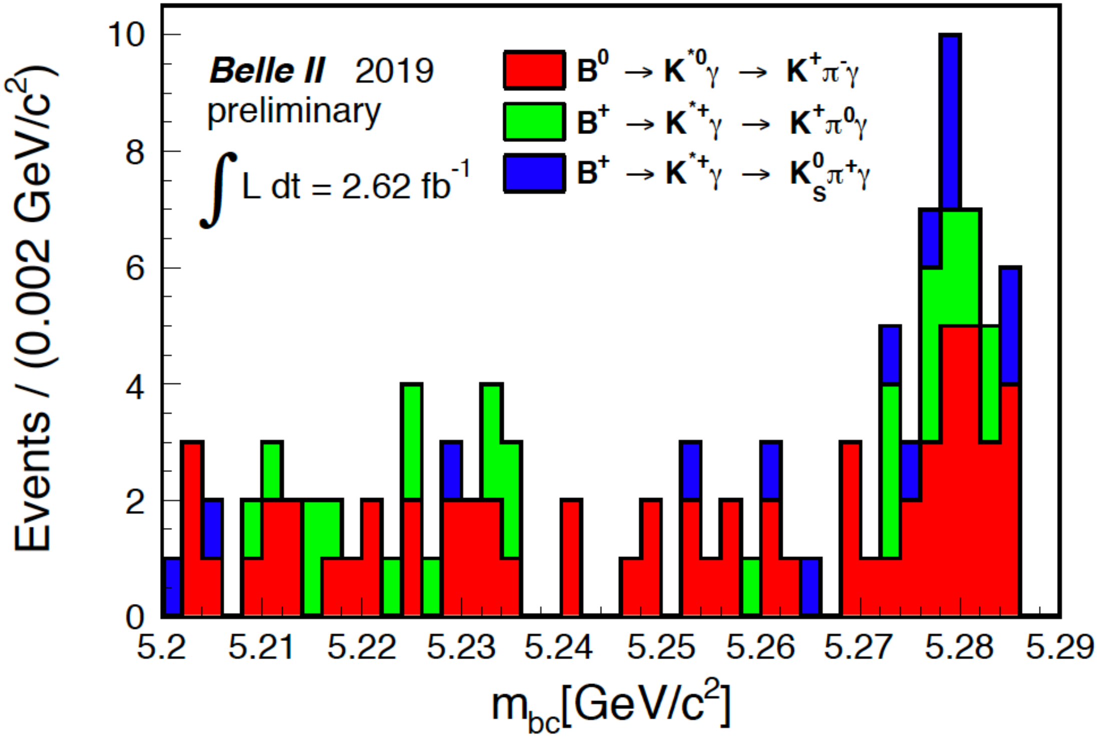
- This kind of decay channels will be essential to measure the CKM angle $\phi_3 \equiv \gamma$



☞ Major Indian contribution

Rediscovery of radiative



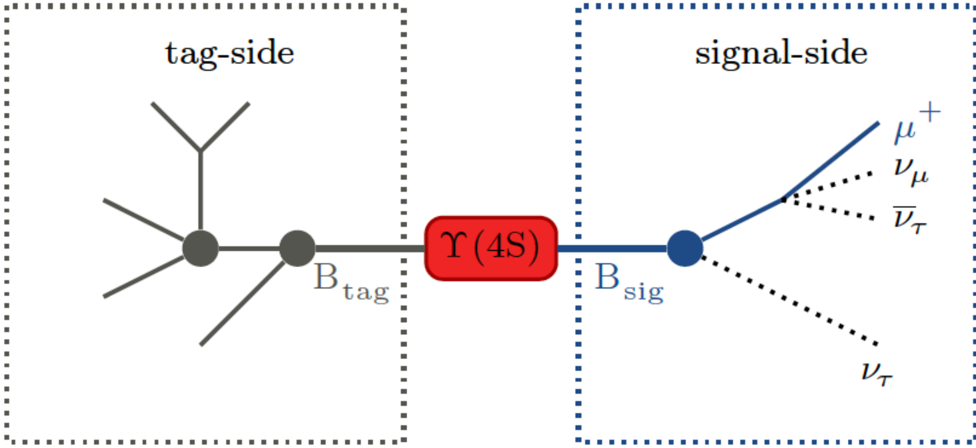


- Distributions of M_{bc} for:
  - $B^0 \to K^{*0}(\to K^+\pi^-)\gamma$
  - $B^+ \to K^{*+}(\to K^+\pi^0)\gamma$
  - $B^+ \to K^{*+}(\to K_S^0\pi^+)\gamma$

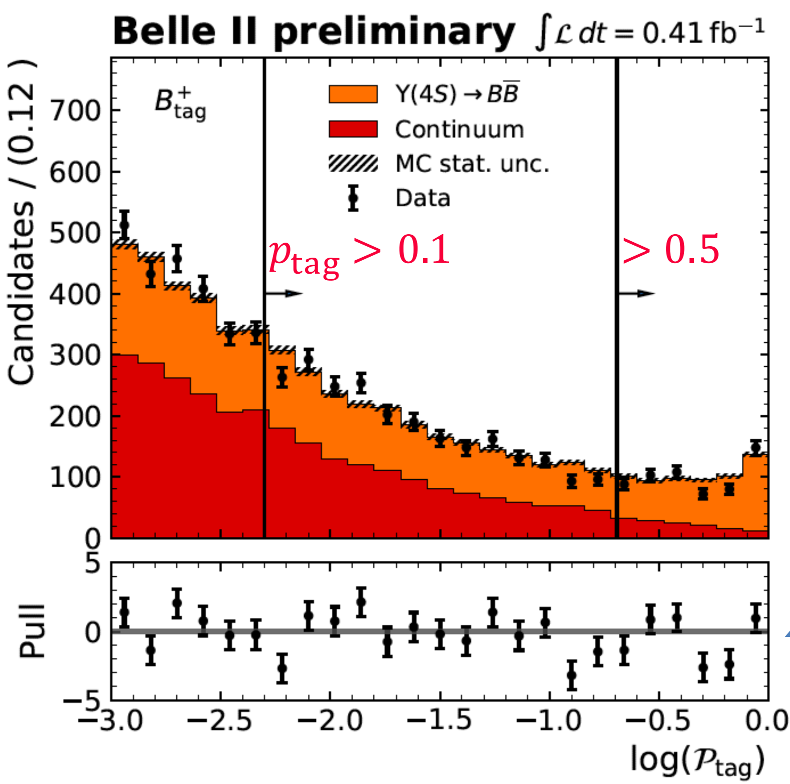
☞ Just made the beginning

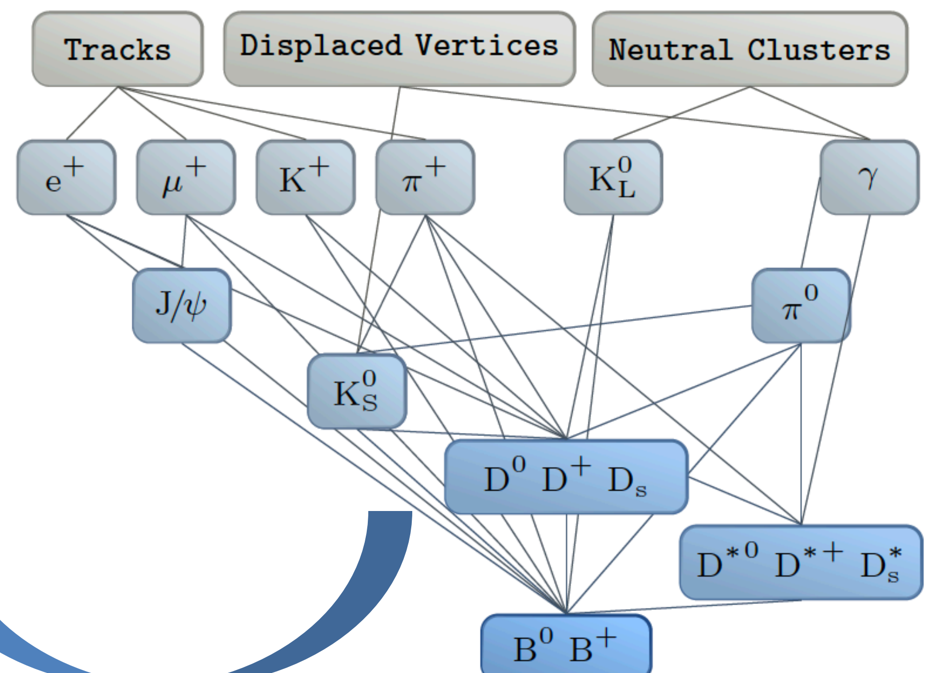
	signal yield (statistics only)	significance
$B^0 \to K^{*0}(\to K^+\pi^-)\gamma$	19.1 ± 5.2	4.4 σ
$B^+ \to K^{*+}(\to K^+\pi^0)\gamma$	9.8 ± 3.4	3.7 σ
$B^+ \to K^{*+}(\to K_S^0\pi^+)\gamma$	6.6 ± 3.1	2.1 σ

Novelty: full event interpretation

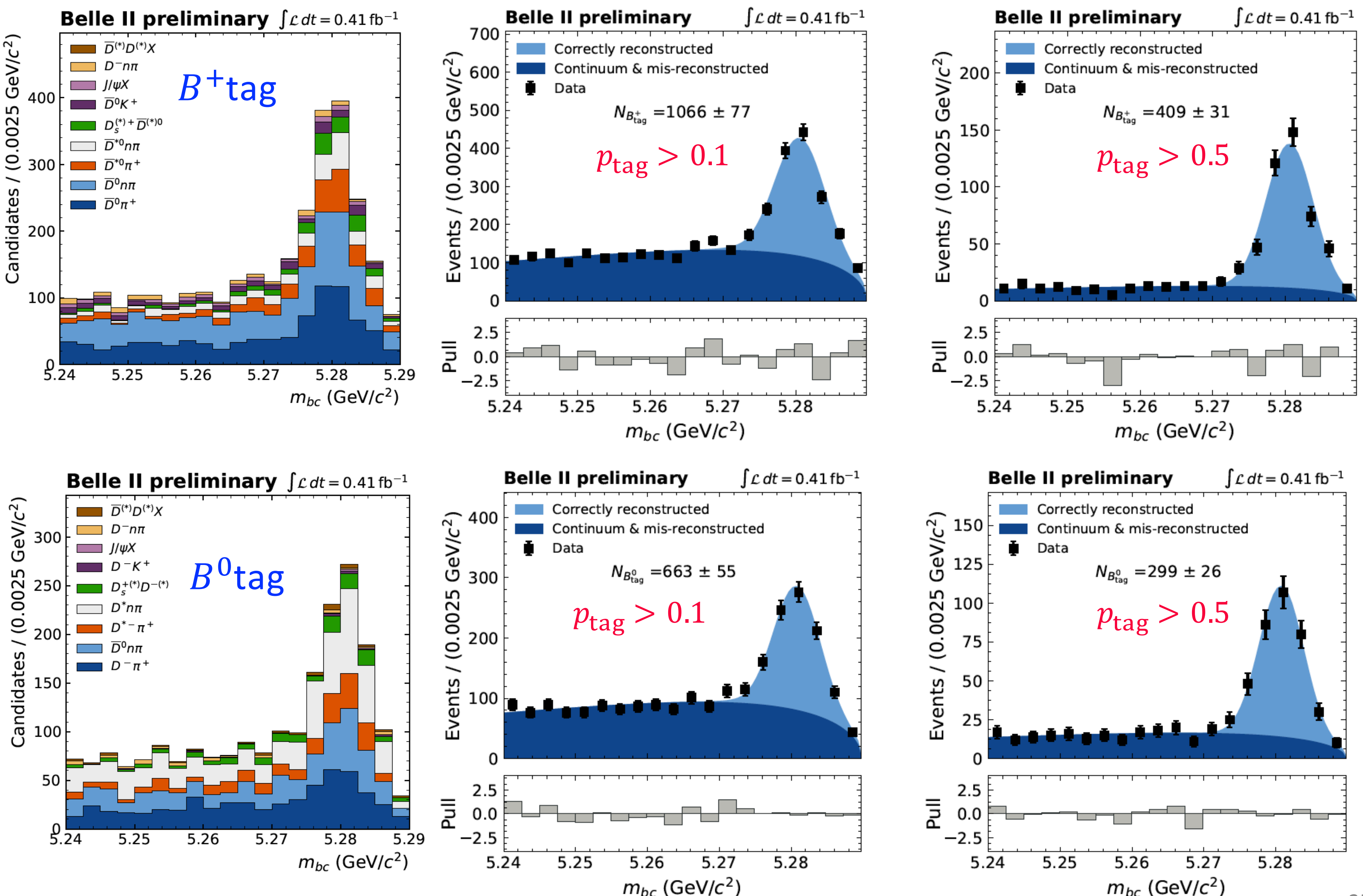


- Signal B decays with missing energy can be studied via the reconstruction of tag-side B candidates
  - ☞ USP of e^+e^- flavor factories
- Multistage classifier to reconstruct such candidates in 100+ exclusive decay channels
  - ☞ Significant improvement w.r.t. the previous method

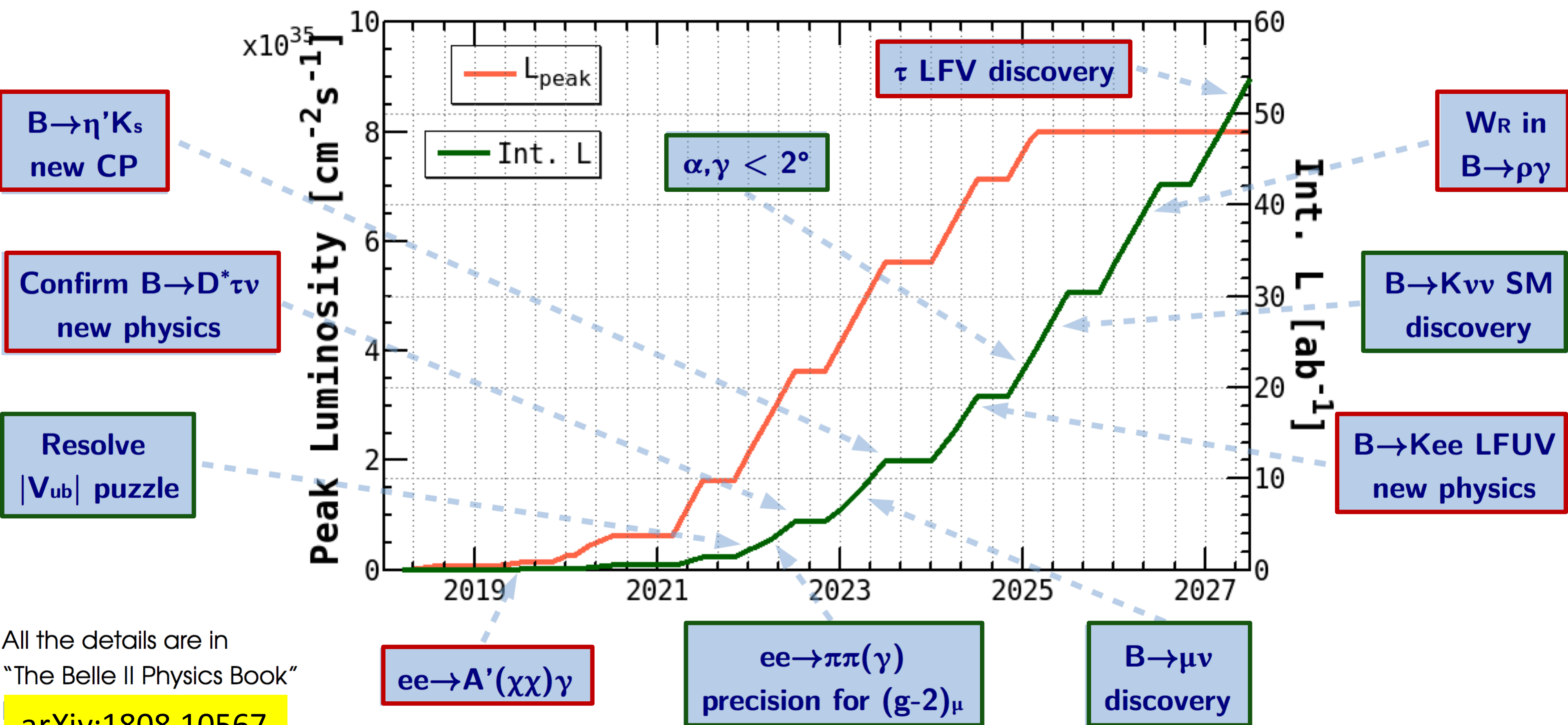




FEI performance with early 2019 data



Prospects for data & physics harvesting



All the details are in
"The Belle II Physics Book"
arXiv:1808.10567

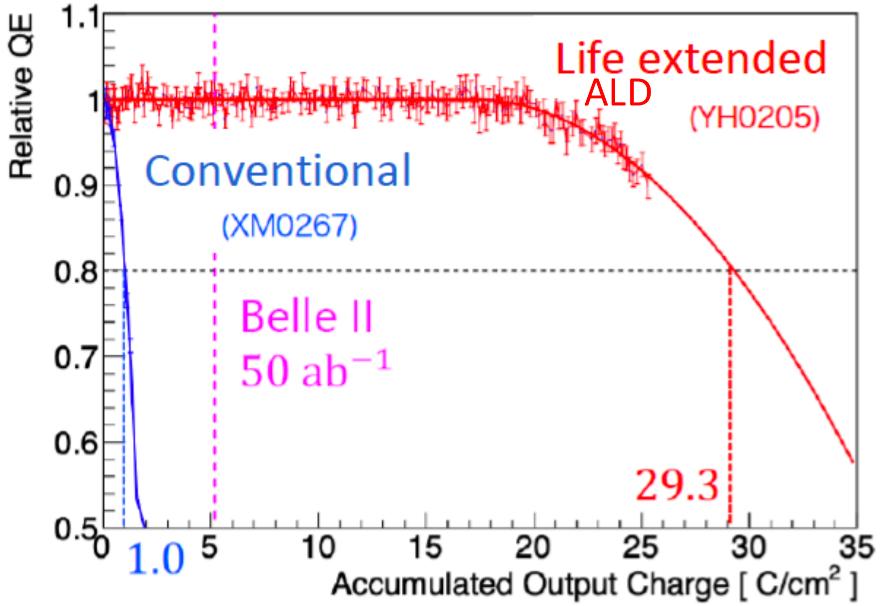
- 1 ab^{-1} (= Belle) in 2021
- 5 ab^{-1} in 2022
- 10 ab^{-1} by mid 2023

Sure shot
Wish list

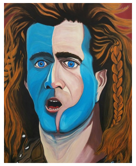
Courtesy: Giacomo De Pietro

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/

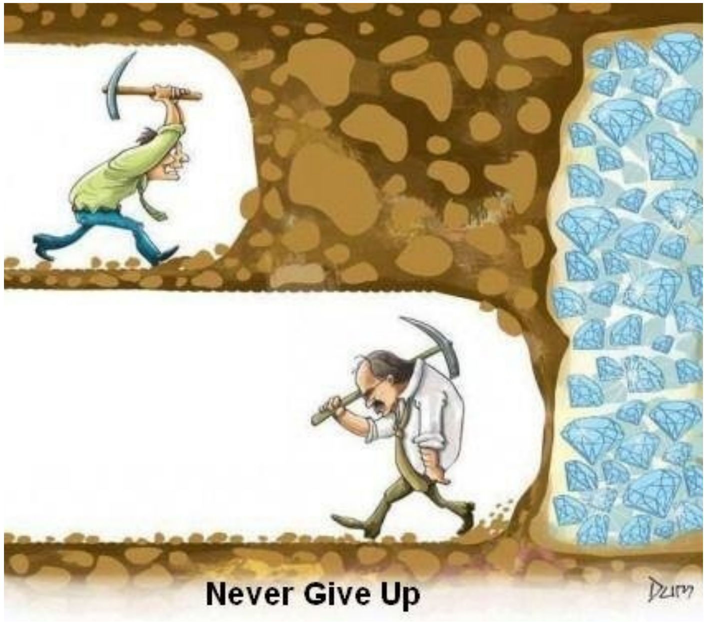
Closing words

- 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

- 1st physics run in Spring 2019 has completed delivering ~6.5 fb^{-1}➔ fall run is about to begin

- Detector and machine initial performances have been good; we expect the road ahead to be bit long before achieving our design goal

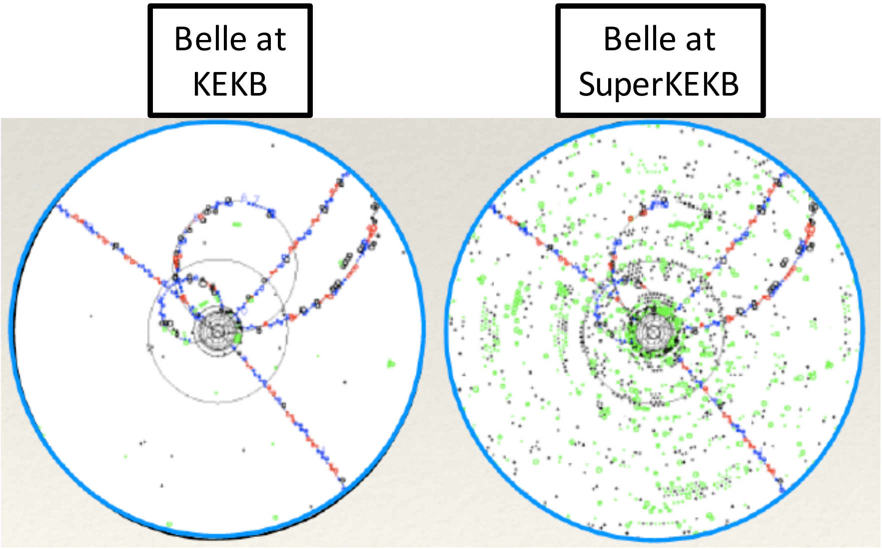


Additional information

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	ϕ	11		41.5		mrad
Horizontal emittance	ε_x	18	24	3.2	4.6	nm
Emittance ratio	κ	0.88	0.66	0.37	0.40	%
Beta functions at IP	β_x^*/β_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	ξ_y	0.129	0.090	0.0881	0.0807	
Luminosity	L	2.1×10^{34}		8×10^{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