Belle II Results from the Phase II Run and Prospects for the Full Physics Runs

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Rencontres du Vietnam - Windows on the Universe

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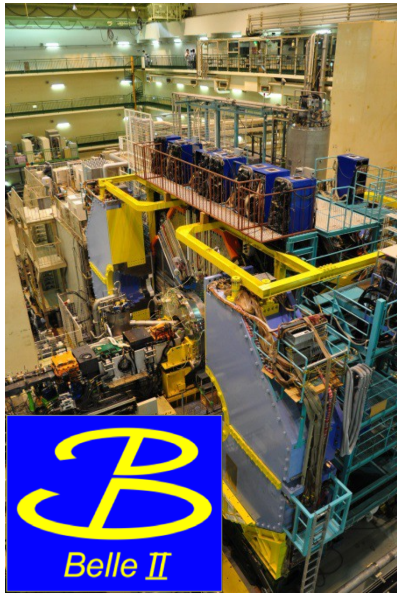
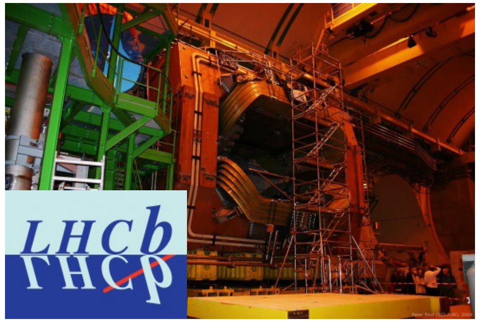
Outline

- Introduction
- The SuperKEKB collider
- The Belle II detector
- First Results
- Summary

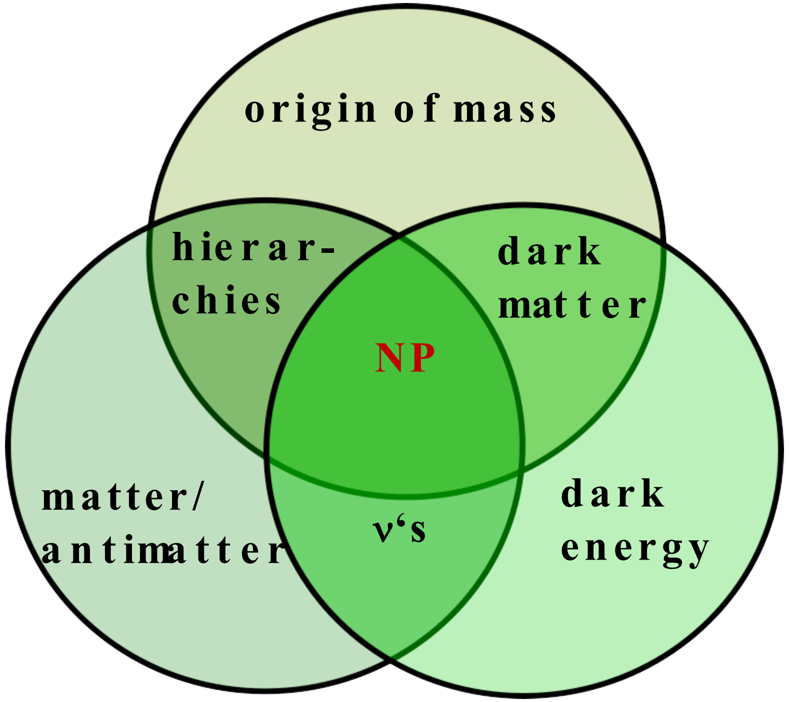
A Threefold Approach in the Quest for New Physics

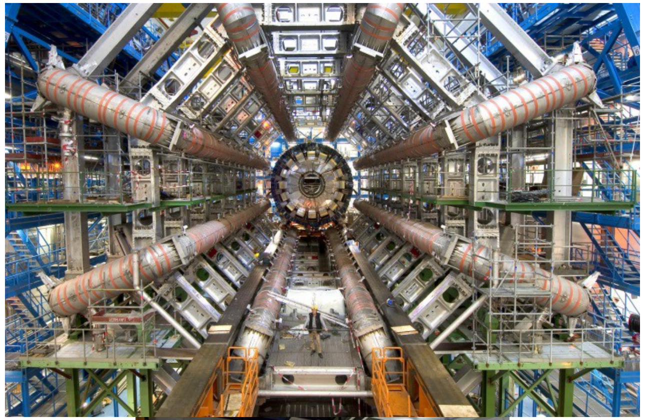


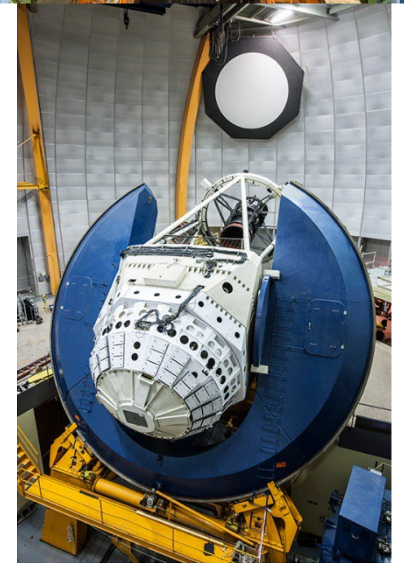


Intensity Frontier

Energy Frontier





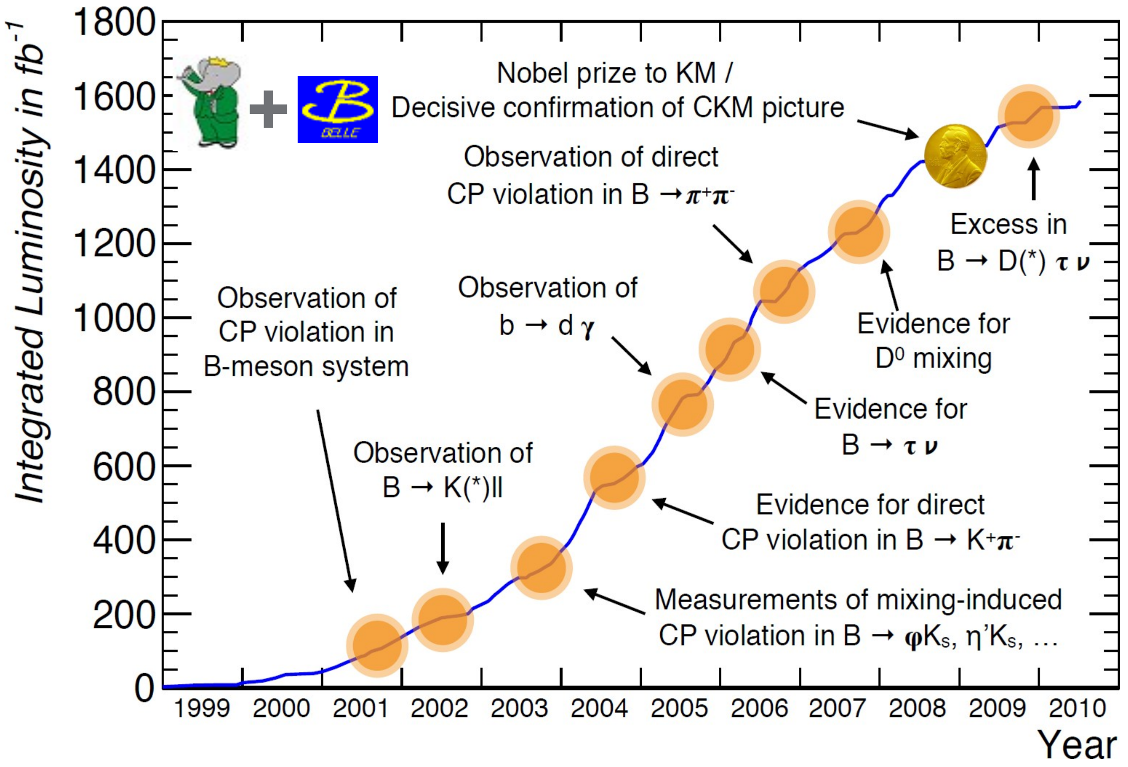


Cosmic Frontier

The Legacy of the B-factories

"The Physics of the B Factories", EPJC 74, 3026 (2014)

- Flavor physics
  - CKM matrix elements / Unitarity Triangle
  - CPV in B decays
- Spectroscopy
  - Exotic quarkonium
- Limits on BSM Physics
  - Rare decays
  - New physics search in loops $b \to s\gamma$, $b \to sll$
  - $B \to D^{(*)} \tau \nu$
  - Search for LFV in τ decays



"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature".

© The Nobel Foundation Photo: U. Montan

Makoto Kobayashi

© The Nobel Foundation Photo: U. Montan

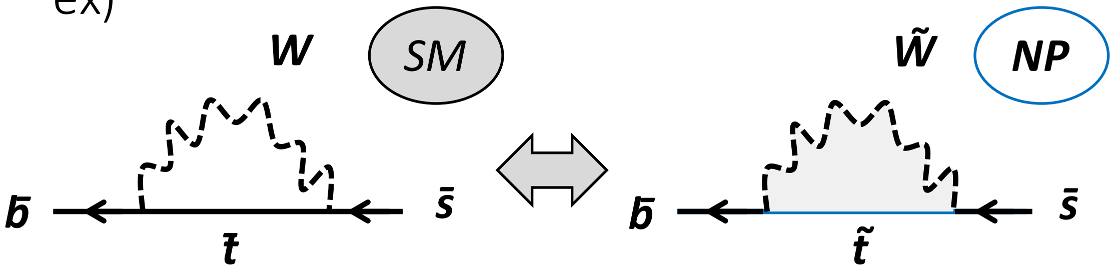
Toshihide Maskawa

2008

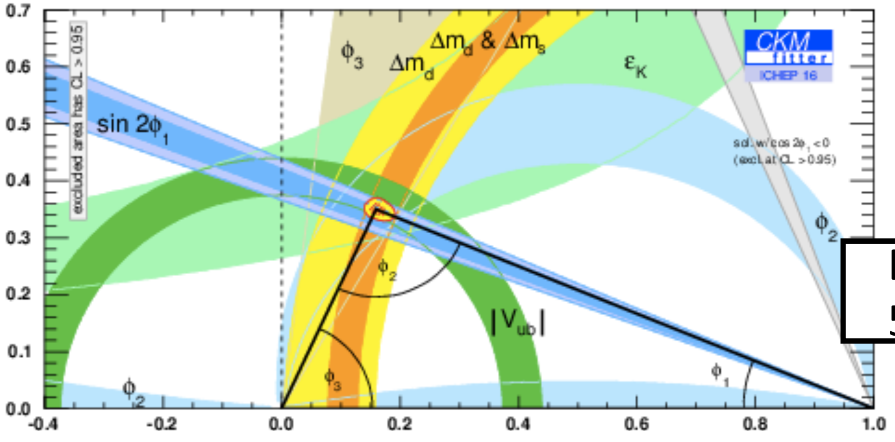
Belle II: an Experiment at the Intensity Frontier

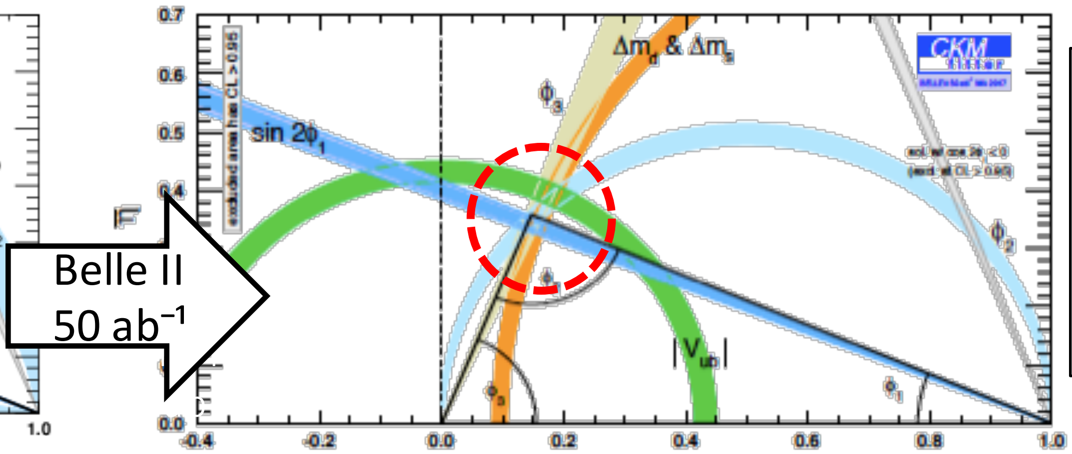
- Searches for effects of new particles in loop diagrams with huge data samples.
  - Related observables can deviate from the SM prediction.

ex)



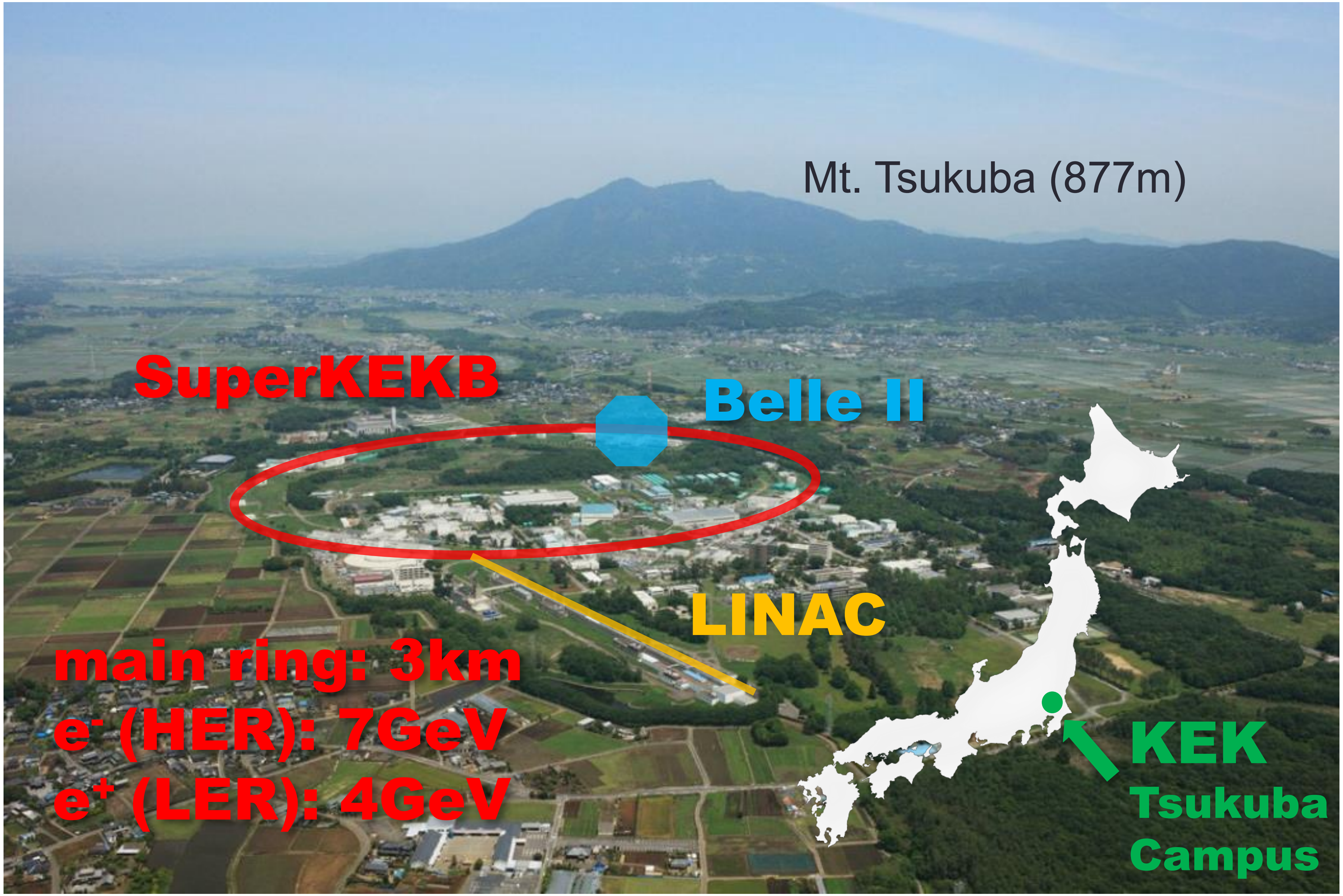
Belle II will collect 50 ab^{-1} of data, which is x50 of Belle (1 ab^{-1}).
Belle II is sensitive to new physics up to an energy scale of ~20 TeV.



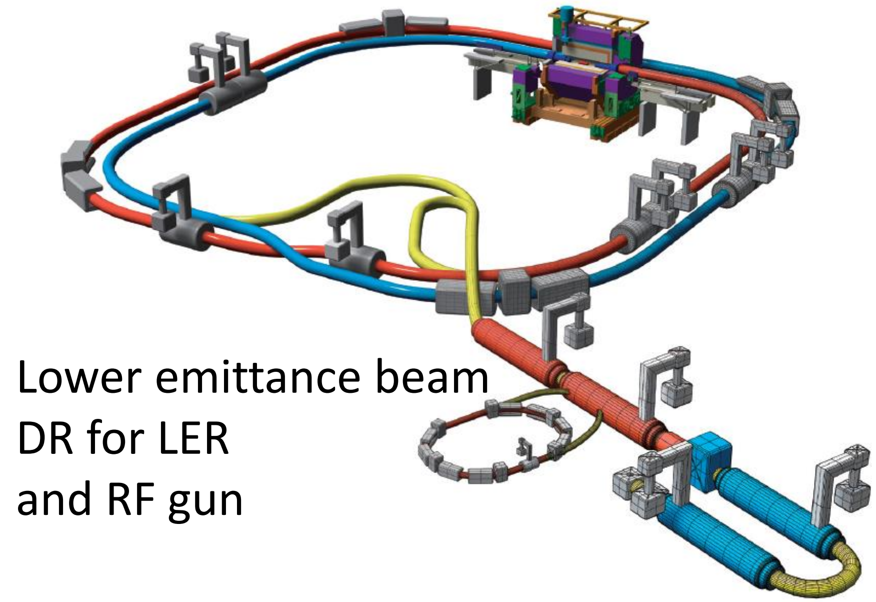


Any discrepancy will become statistical significant with 50 ab^{-1} of data at Belle II if the current central values hold.

SuperKEKB and Belle II



SuperKEKB: the Nano Beam Scheme



Lower emittance beam
DR for LER
and RF gun

Beam current

Beam-beam parameter

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

σ: beam size

β function

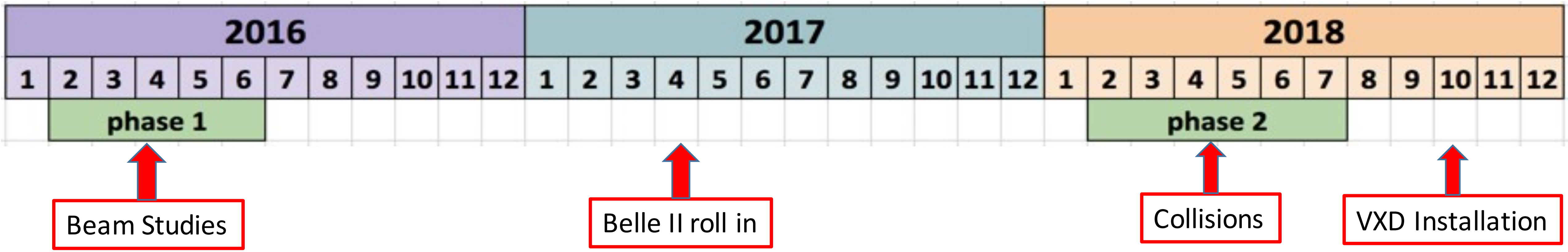
		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7.007	GeV
Beam crossing angle	φ	22		83		mrad
β function @ IP	β_x^*/β_y	1200/5.9		32/0.27	25/0.30	mm
Beam current	I_b	1.64	1.19	3.6	2.6	A
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

X 20

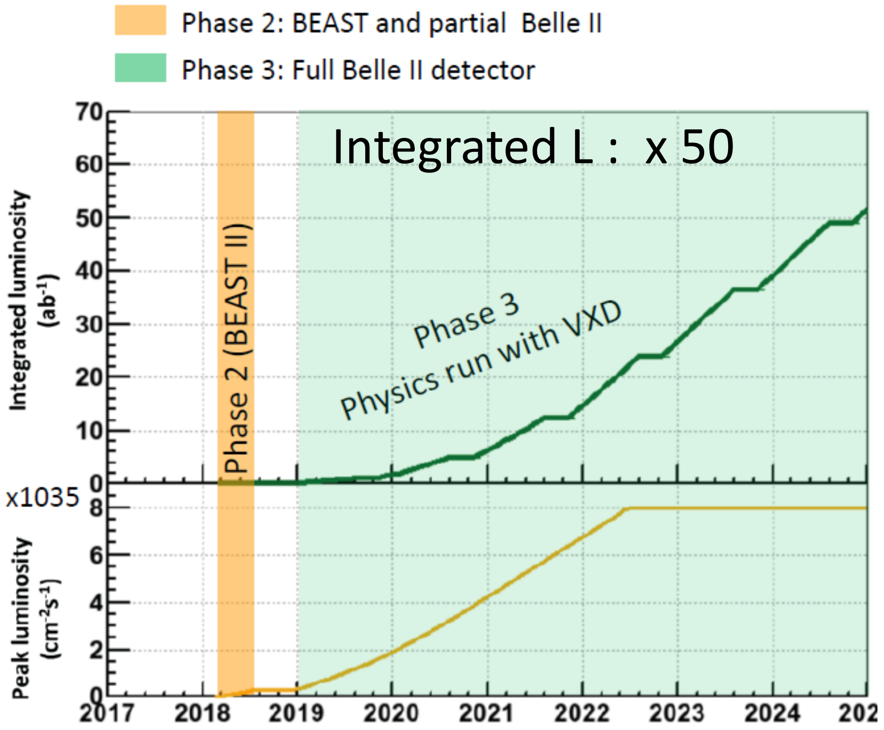
X 2

X 40

SuperKEKB Commissioning

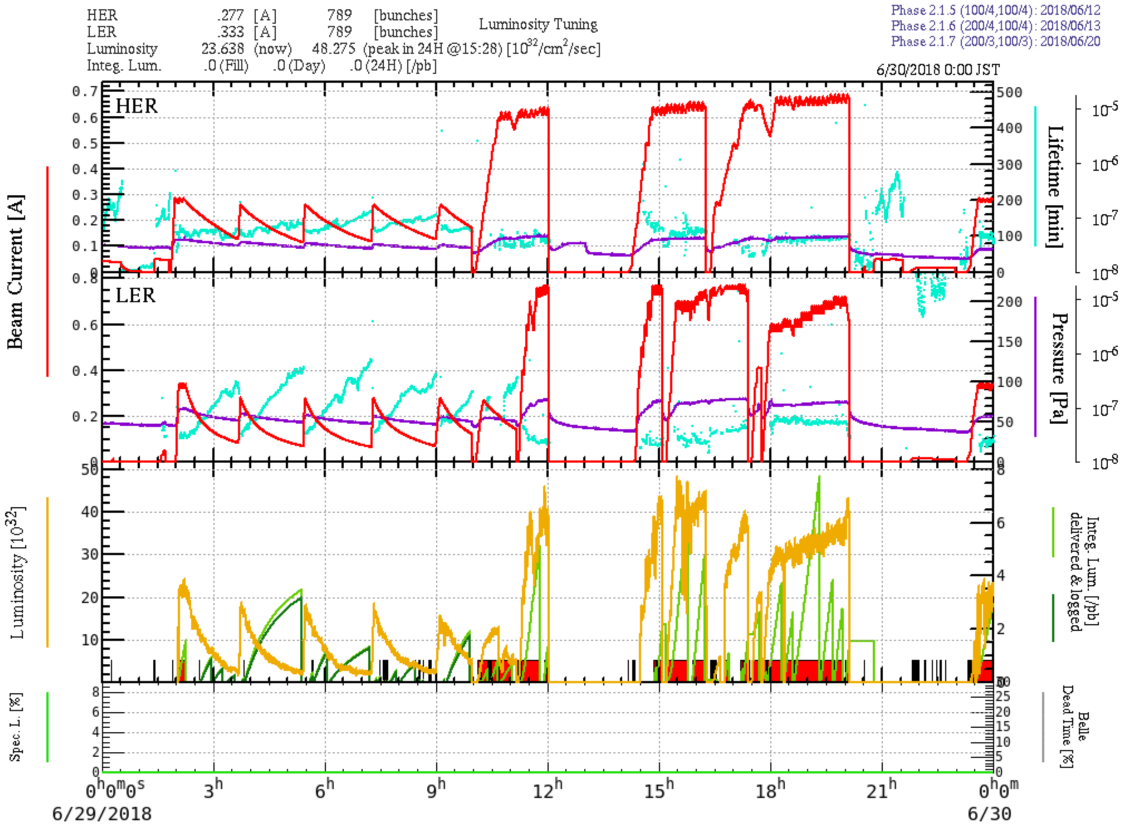


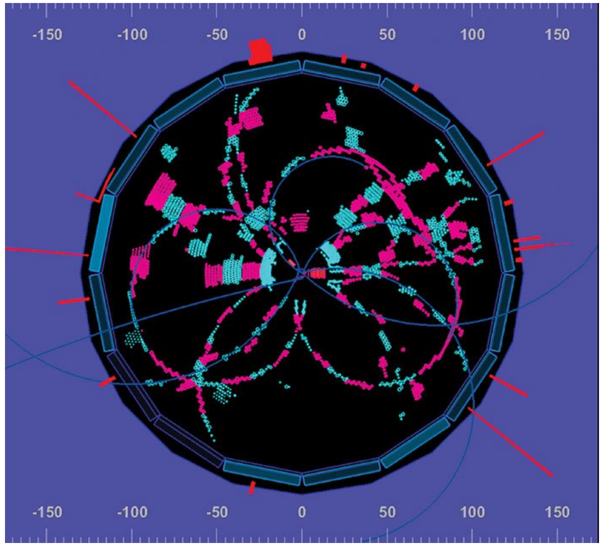
- Phase 1 (finished): Beam operation without final focus magnets and Belle II
  - Commissioning of beam transportation and vacuum scrubbing
  - Only single beam studies were possible
- Phase 2(4month): Start data taking with beam collision
  - Target Luminosity ~10^{34} $cm^{-2}s^{-1}$ which is comparable with KEKB
  - No final VXD but one ladder/layer with background sensors
- Phase 3 (2019): final detector configuration



Phase II Run: the Nano Beam Scheme in Action

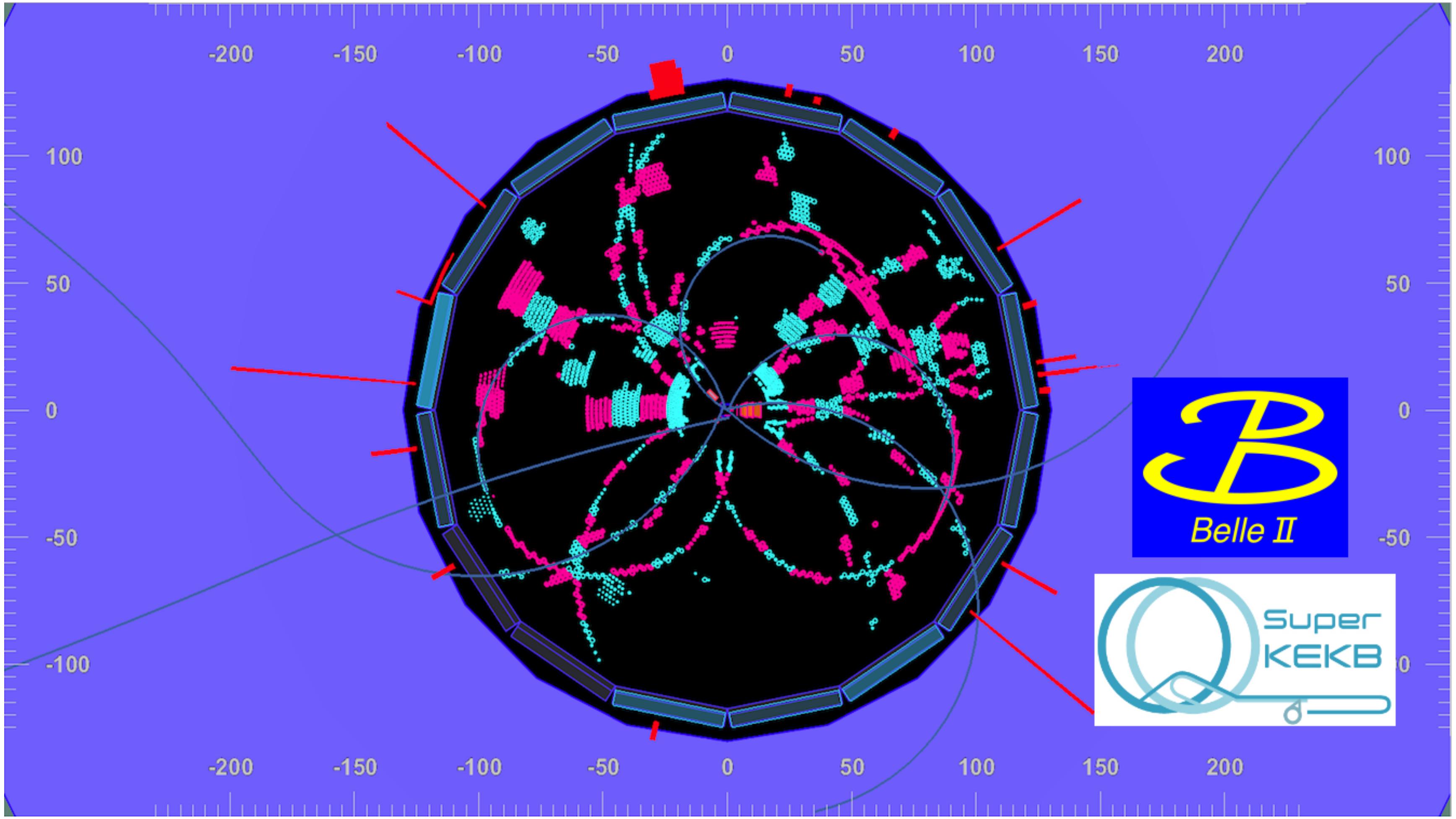
First collisions on April 26
β* successfully squeezed down to β*=2mm
$L = 5.54 \times 10^{33}\ cm^{-2}s^{-1}$
$L_{spec} = 2 \times 10^{31}\ cm^{-2}s^{-1}$
Integrated Luminosity (online): 500 pb^{-1}



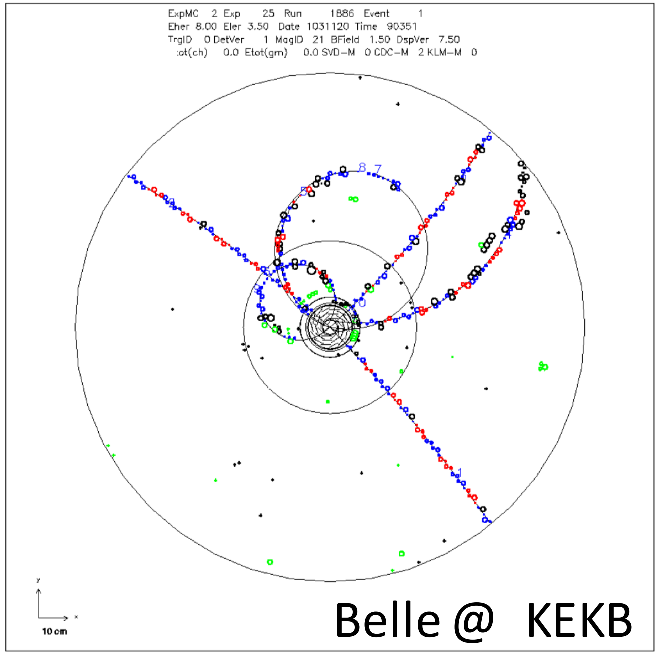


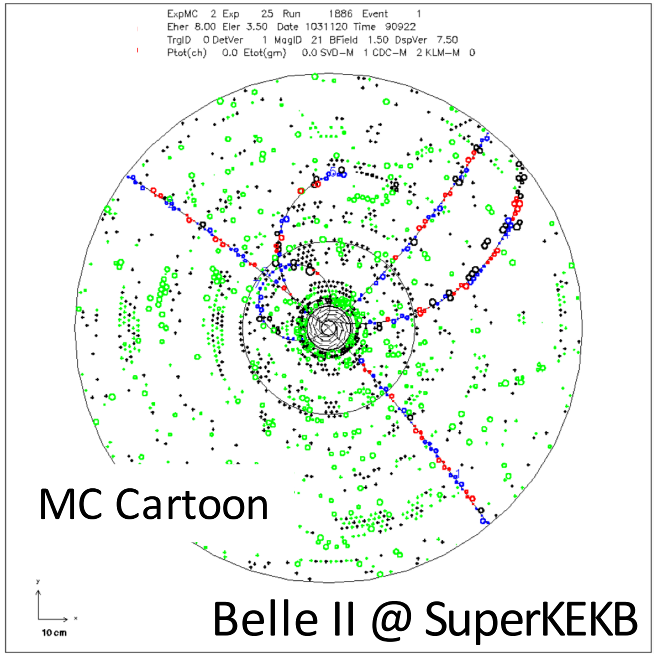
An Event from Belle II's First Evening

$$e^+e^- \to \gamma^* \to B\overline{B}$$



Detector Challenges @ High Luminosity

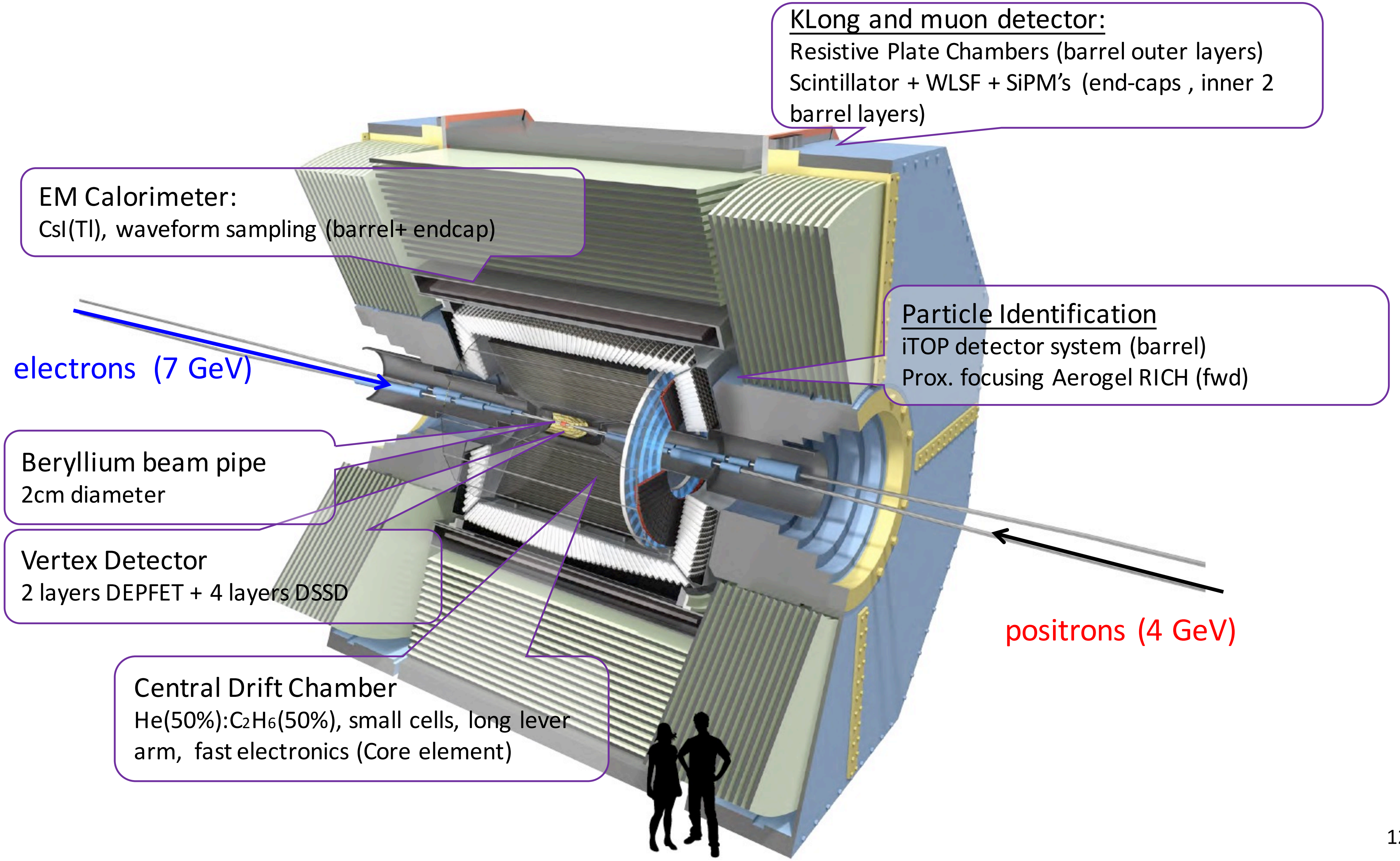




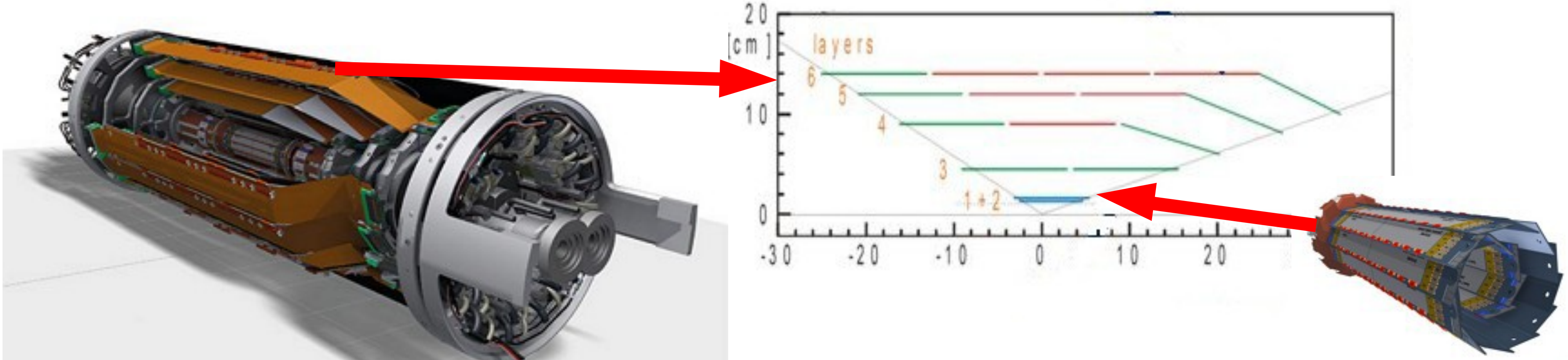
- Higher background:
- → radiation damage, occupancy → VTX (also closer to the beam pipe), background in EMC
- Higher event rate:
- → trigger, DAQ, computing
- Lesser boost of the B Mesons
- -> need a better vertex resolution
- Improvement to low momentum particle reconstruction and ID, and to hermeticity

- Detector had to be upgraded for SuperKEKB conditions to achieve equal or better performance than at KEKB

Belle II Detector



Vertex Detector

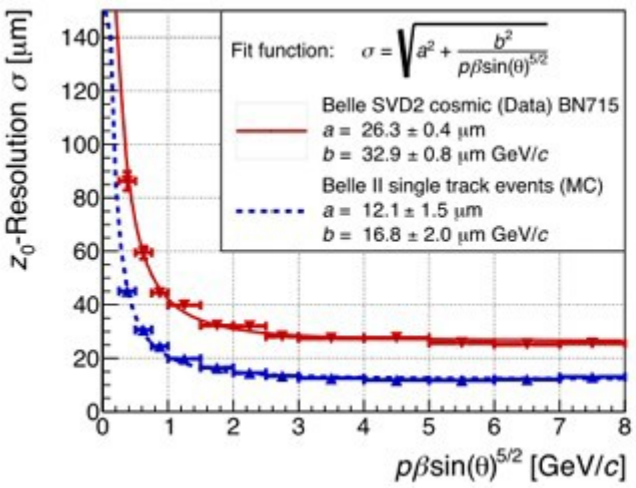


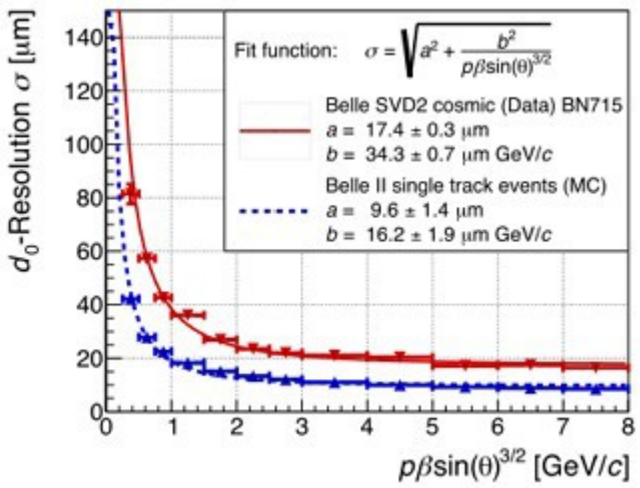
76 μm thickness DEPFET

4 layers DSSD (SVD)
2 layers DEPFET (PXD)

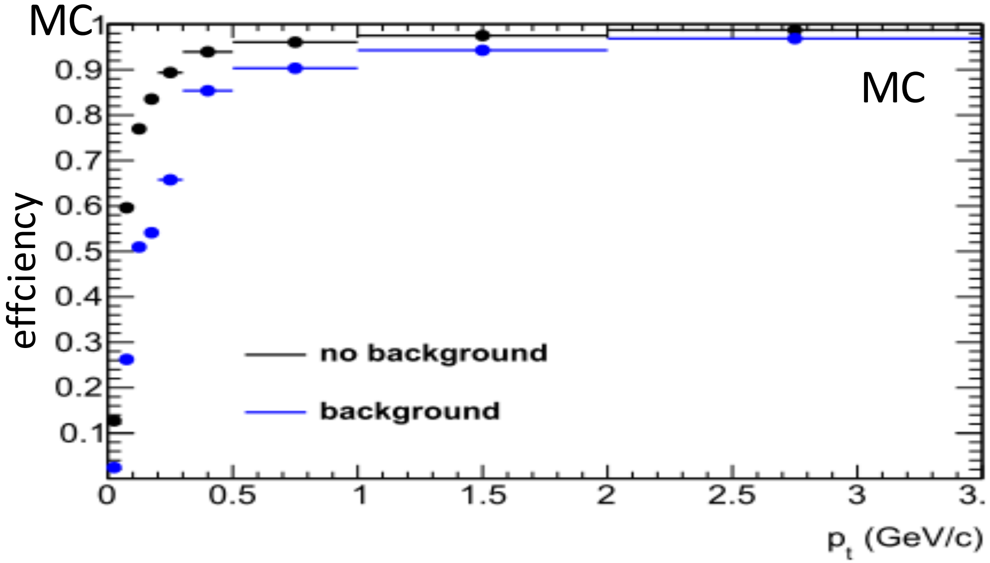
final focus quadrupole „integrated" into VXD

vertex resolution improved by a factor of 2 (compared to Belle)



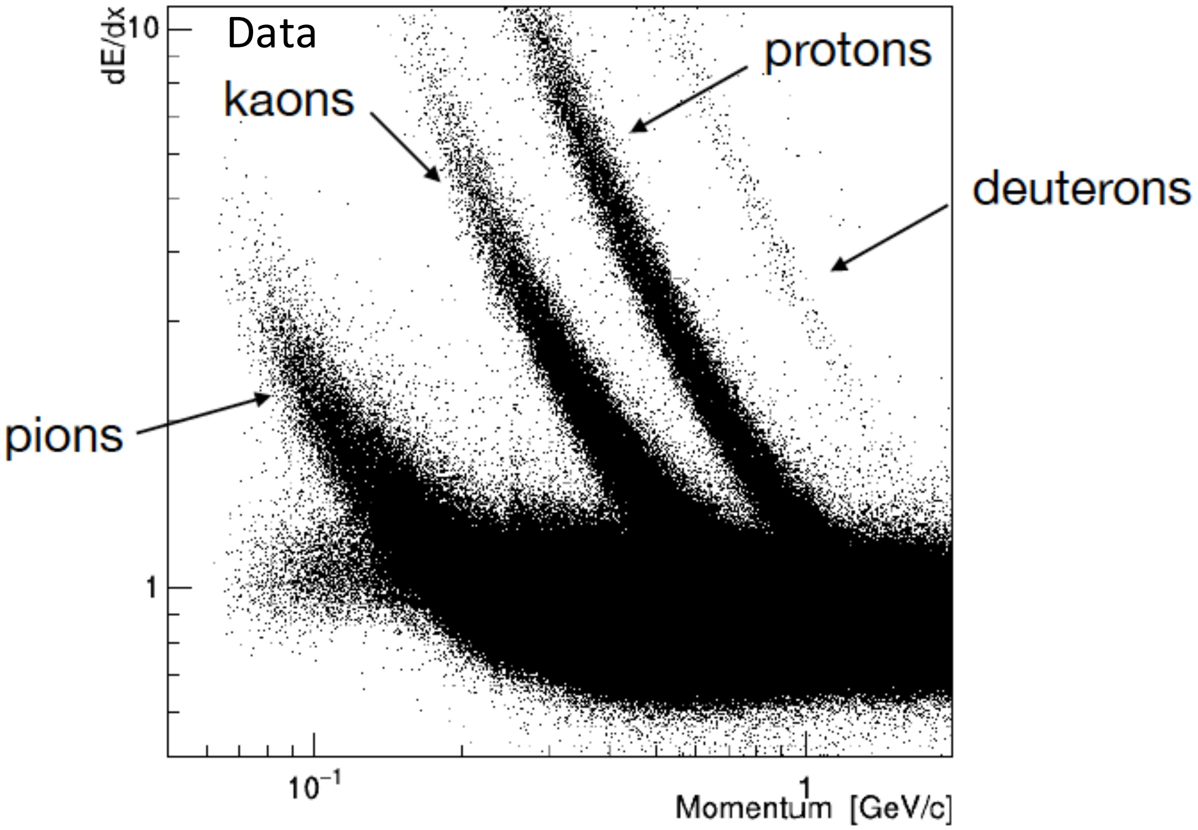


Central Drift Chamber



$$\frac{\sigma_{p_t}}{p_t} \sim 0.3\%/\beta \oplus 0.1\% \cdot p_t[GeV/c]$$

$$\sigma\left(\frac{dE}{dx}\right)\Big|_{\text{MIP}} \sim 5\%$$

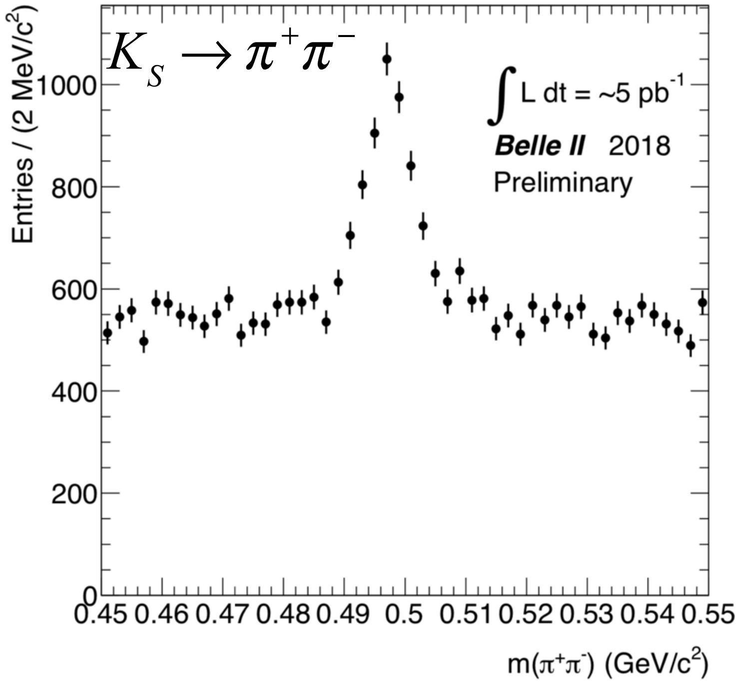


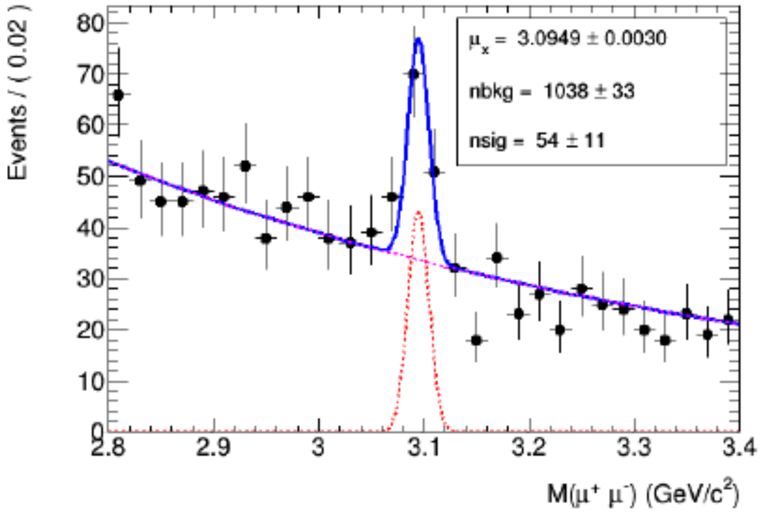
Extra cuts:

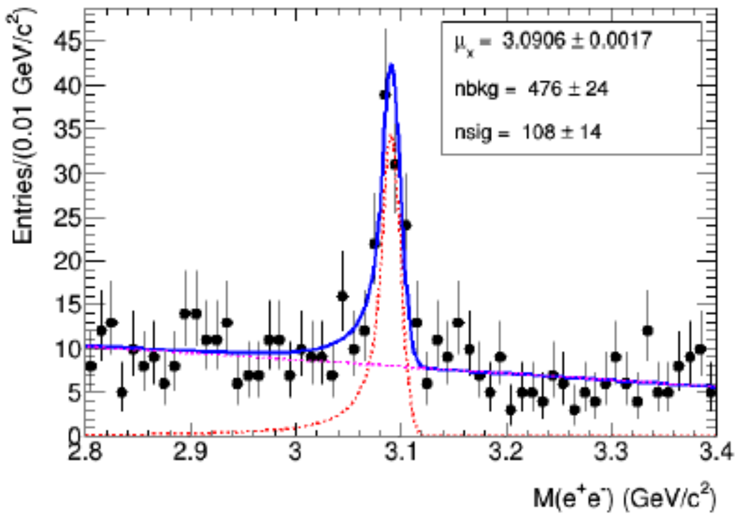
- |d0| < 1
- |dz| < 3
- # layers hit > 20

Most of the Belle II detector subsystems are working well
Here are some *signals* involving charged tracks.

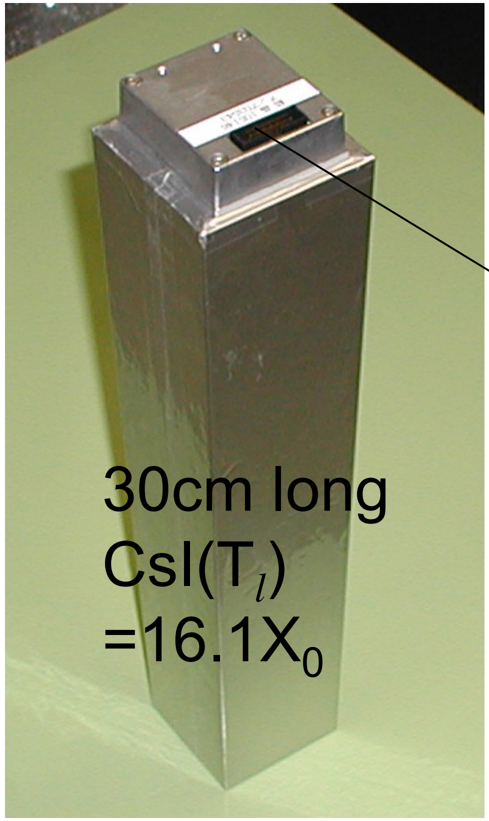
$J/\psi \to \mu^+\mu^-$, $J/\psi \to e^+e^-$

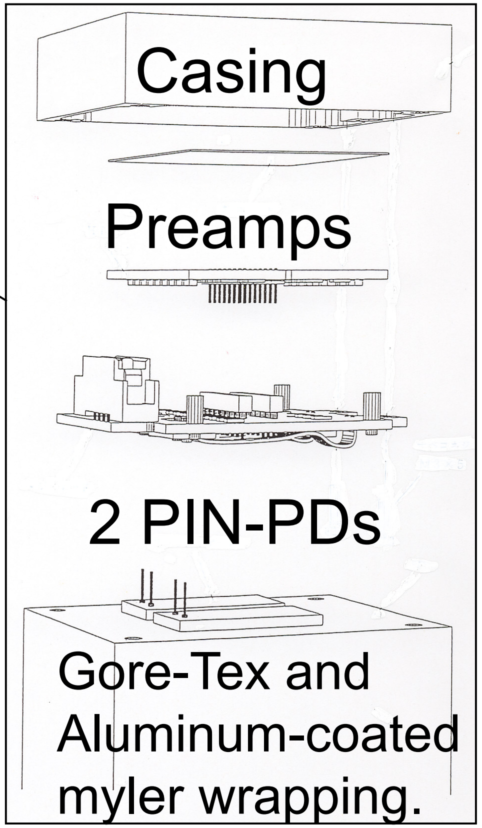


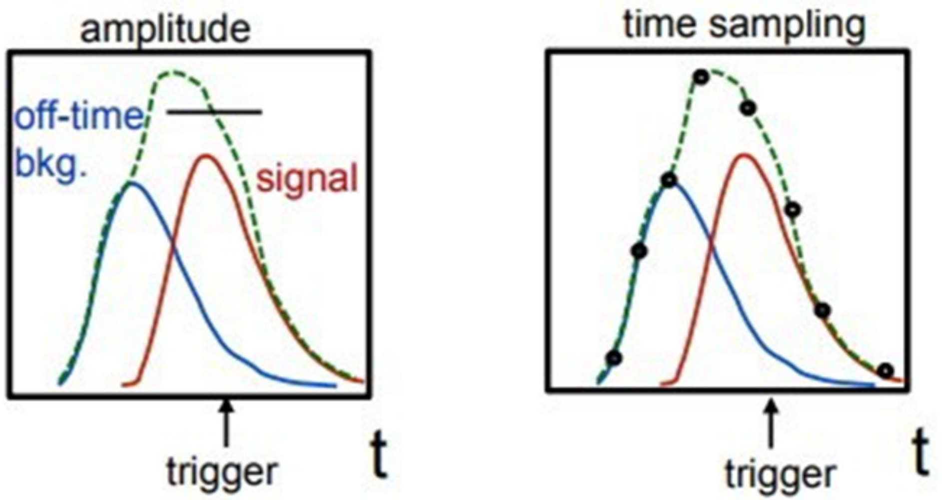




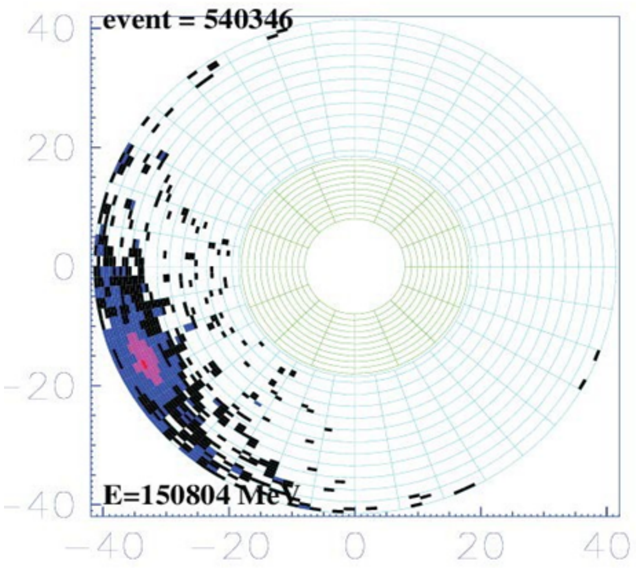
Electromagnetic Calorimeter

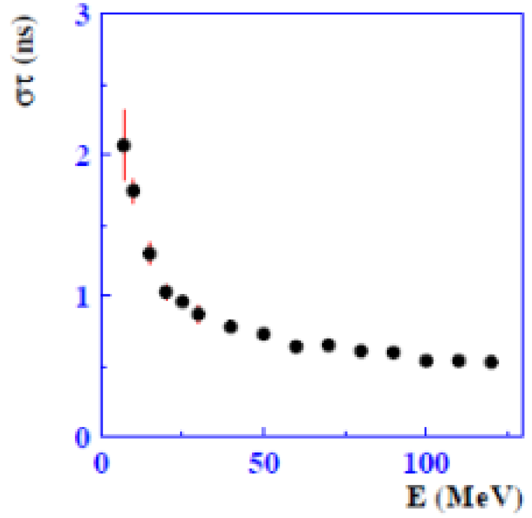






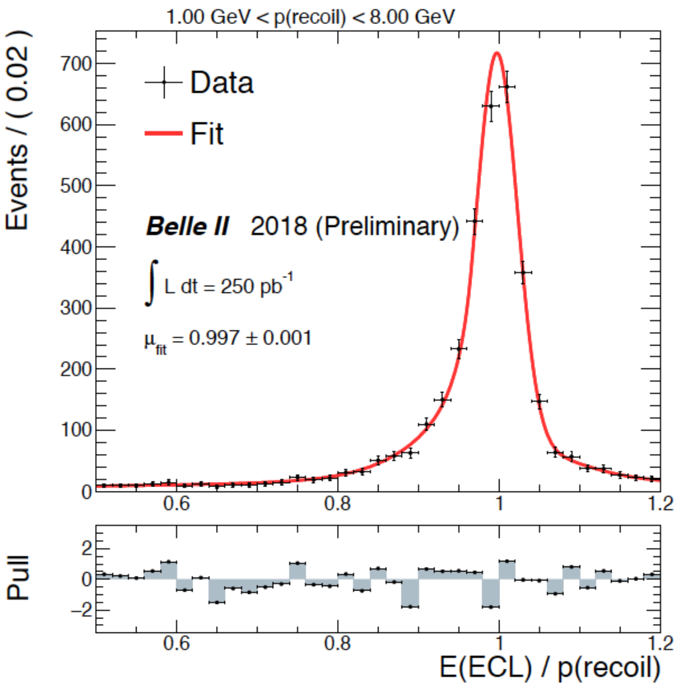
Waveform sampling to reject out of time hits



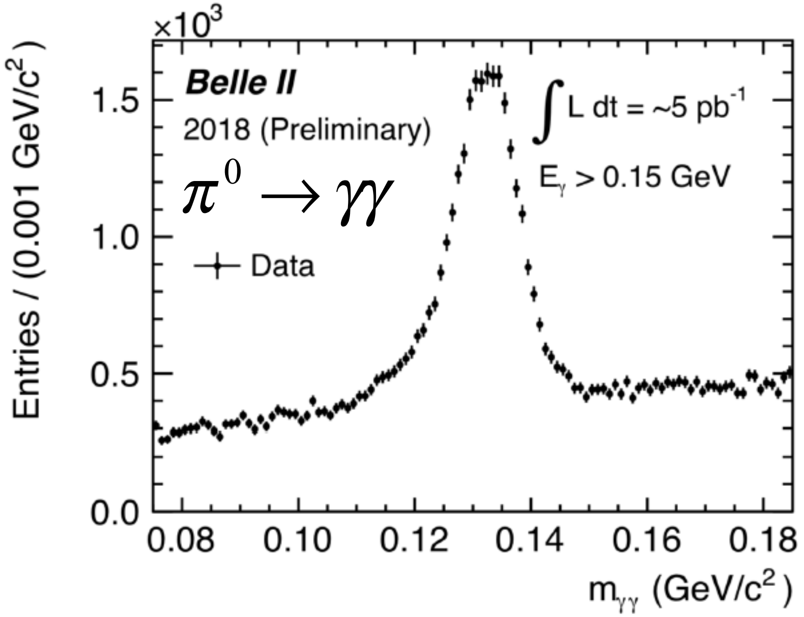


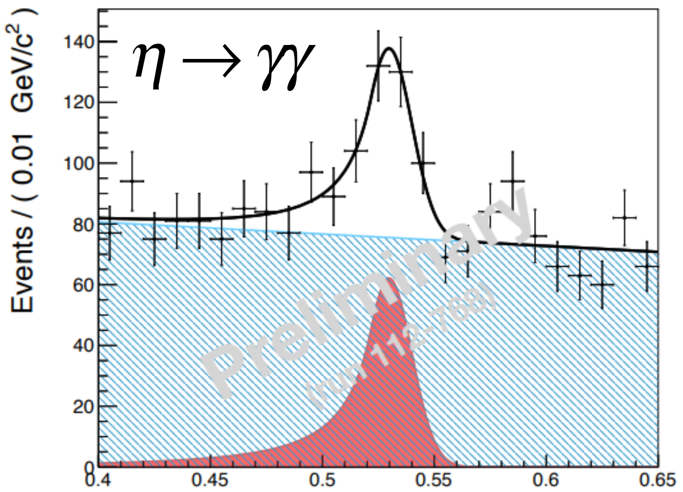
Most of the Belle II detector subsystems are working well.
Some nice examples of *signals* involving photons.

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



Single Photon Lines





Ready for the dark sector !

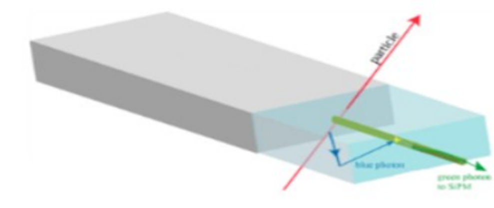
$$e^+e^- \to \gamma X$$

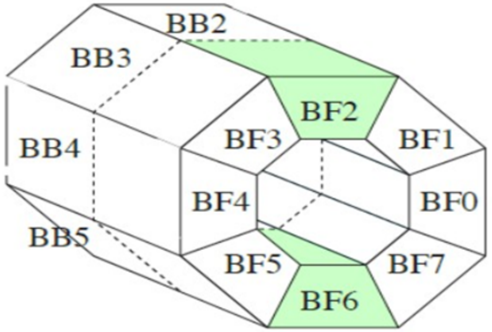
$$e^+e^- \to \gamma ALPS \to \gamma(\gamma\gamma)$$

K_L and μ Detector

- Barrel:

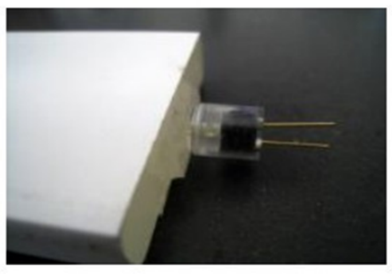
Belle RPCs reused
Two inner layers replaced by scintillator strips
Scintillator strips with WLS fibers
Hamamatsu SiPM S10362

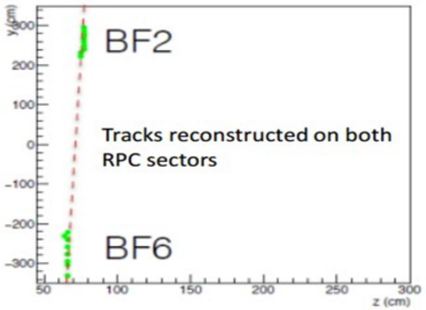


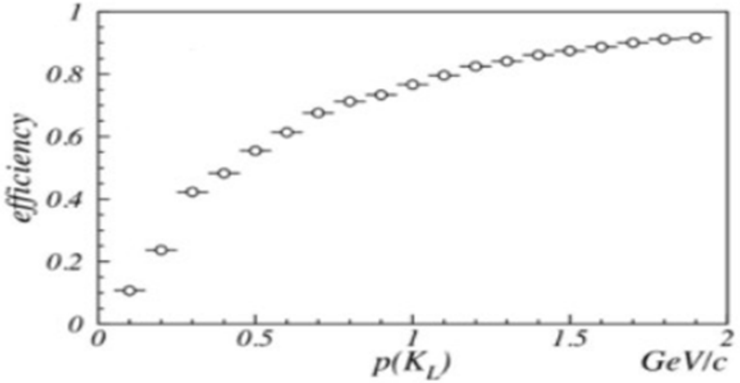


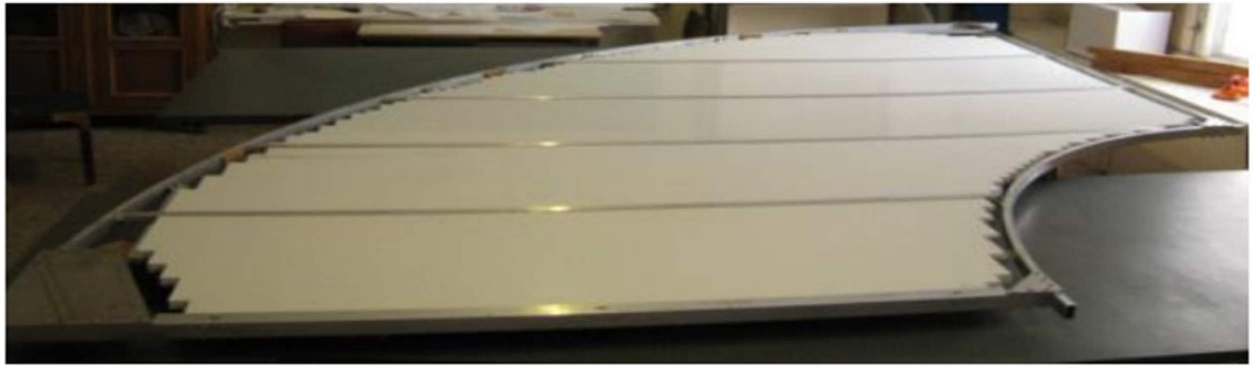
- Endcap:

RPCs replaced with polystyrene scintillators
99% geometrical acceptance. σ ~ 1ns









Particle Identification @ Belle II

Barrel PID: Time of Propagation Counter (TOP)

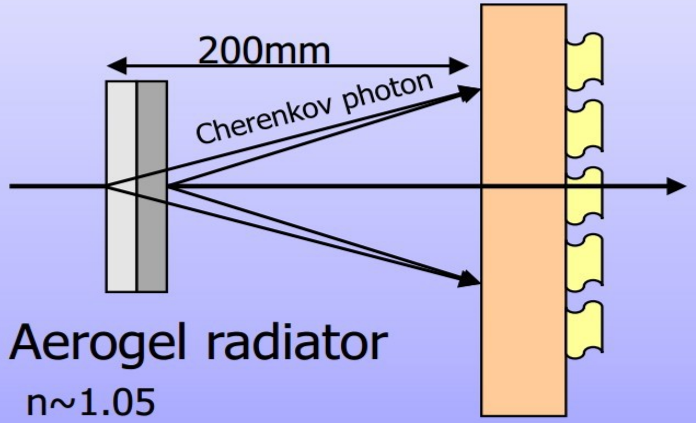
Quartz radiator

Focusing mirror

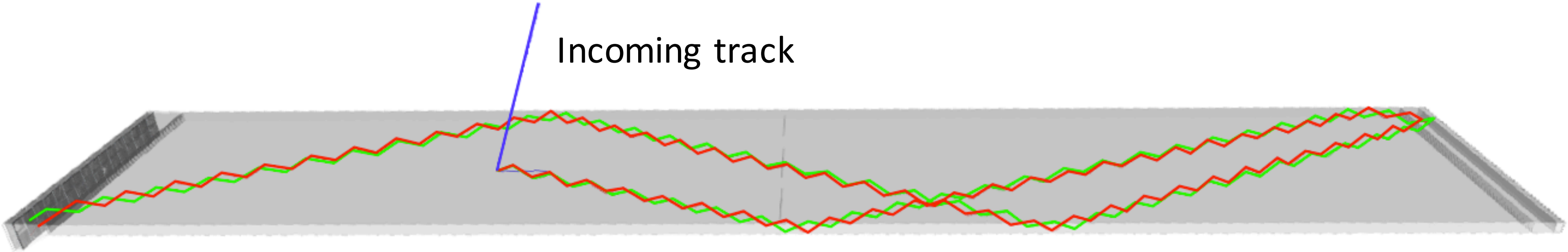
Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

Endcap PID: Aerogel RICH (ARICH)



Hamamatsu HAPD
+ new ASIC



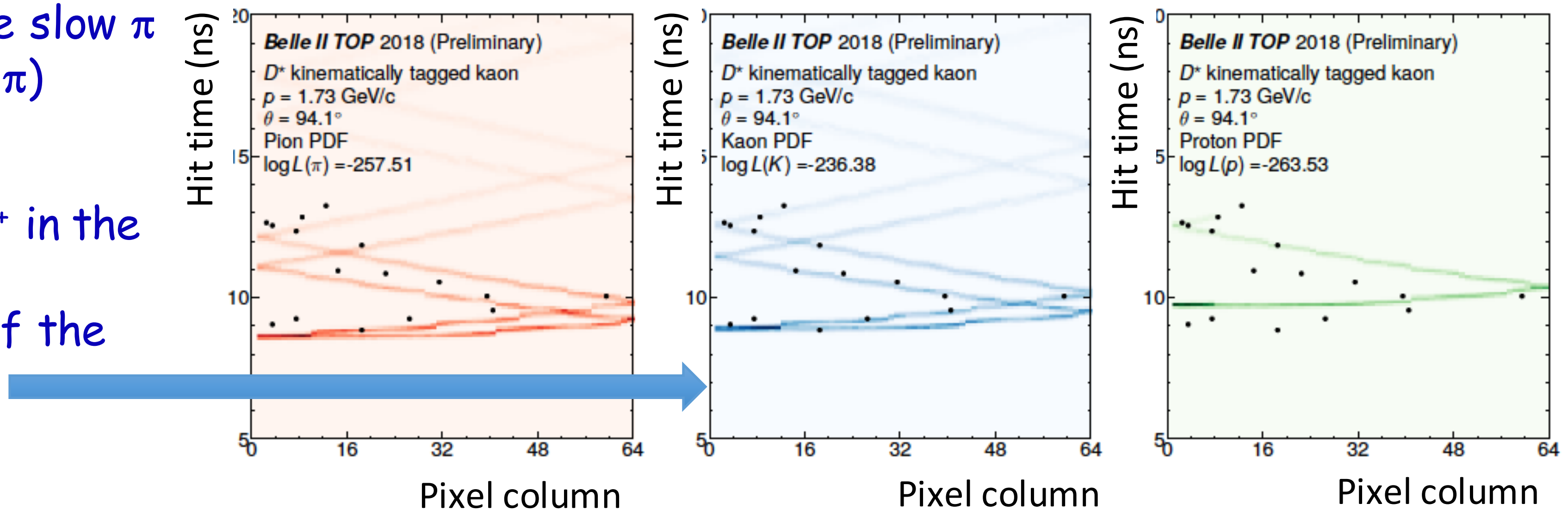
The paths of Cherenkov photons from a 2 GeV pion and kaon interacting in a TOP quartz bar.

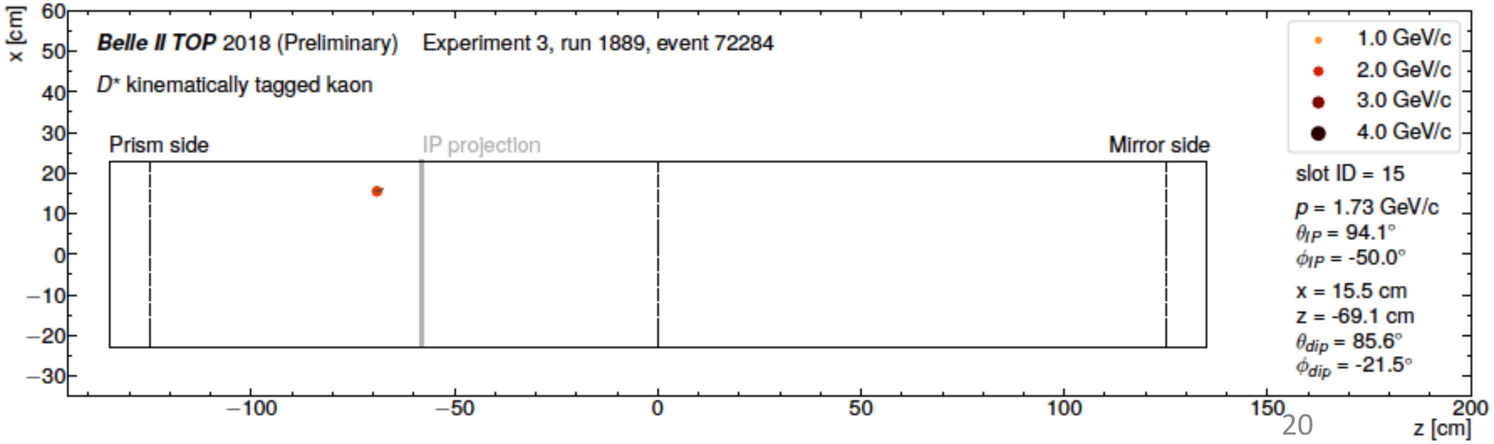
TOP Particle Identification

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

N.B. The charge correlation with the slow π determines which track is the K (or π)

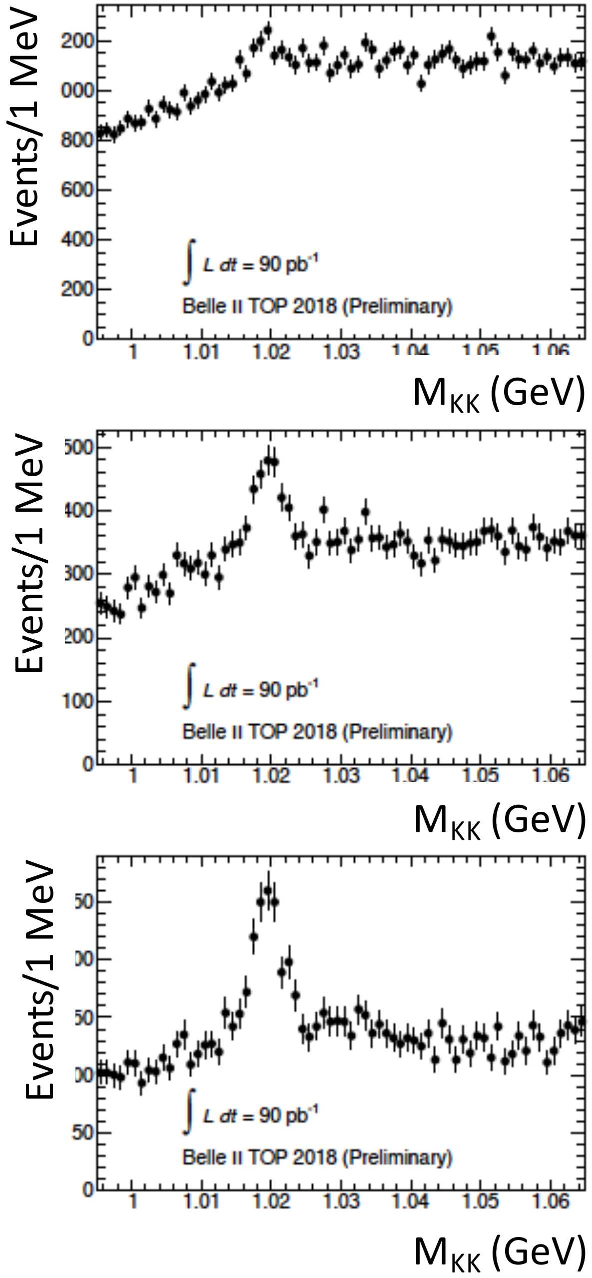
Kinematically identified K from a D^{*+} in the TOP;
Cherenkov x vs t pattern (mapping of the Cherenkov ring)





$\phi \to K^- K^+$ inclusive

An example of TOP particle identification with early calibration and alignment.

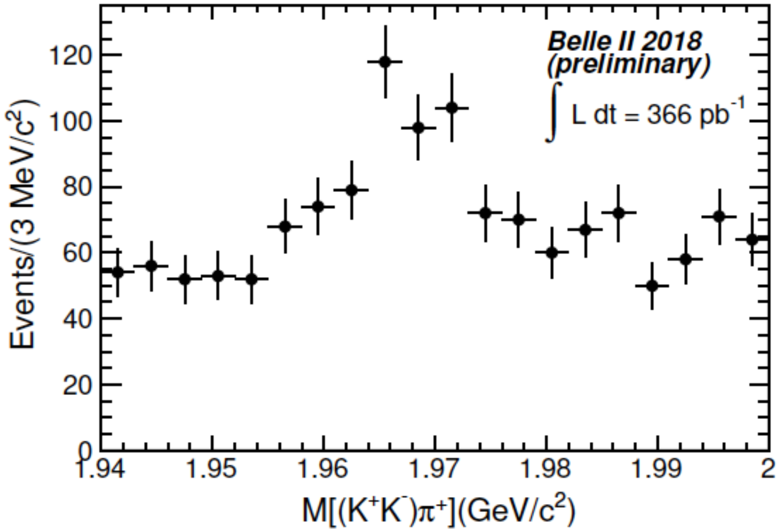


No kaons identified

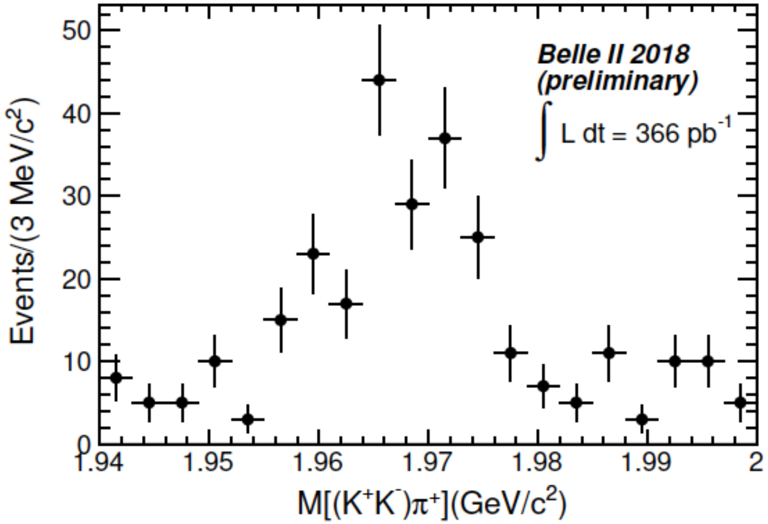
One kaon identified in the TOP.

Both kaons identified in the TOP.

Rediscovery of $D_s \to \phi\pi^+$, with $\phi \to K^+ K^-$

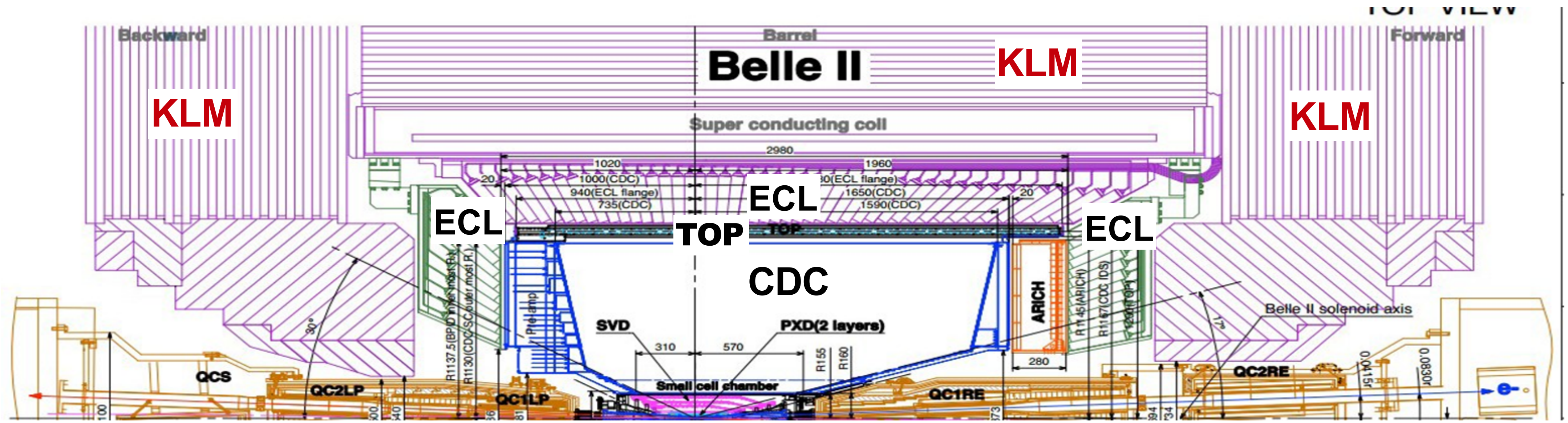


No PID



Two identified charged kaons

Trigger



Belle II Level 1 trigger (CDC + ECL +TOP + KLM)

beam bunch crossing 254 MHz (max.)

nominal beam background rate ~10 MHz

nominal L1 trigger rate ~20 KHz

L1 max. latency 5 μs

L1 z-vertex trigger

L1 Global Reconstruction Logic

HLT: software trigger on a dedicated farm

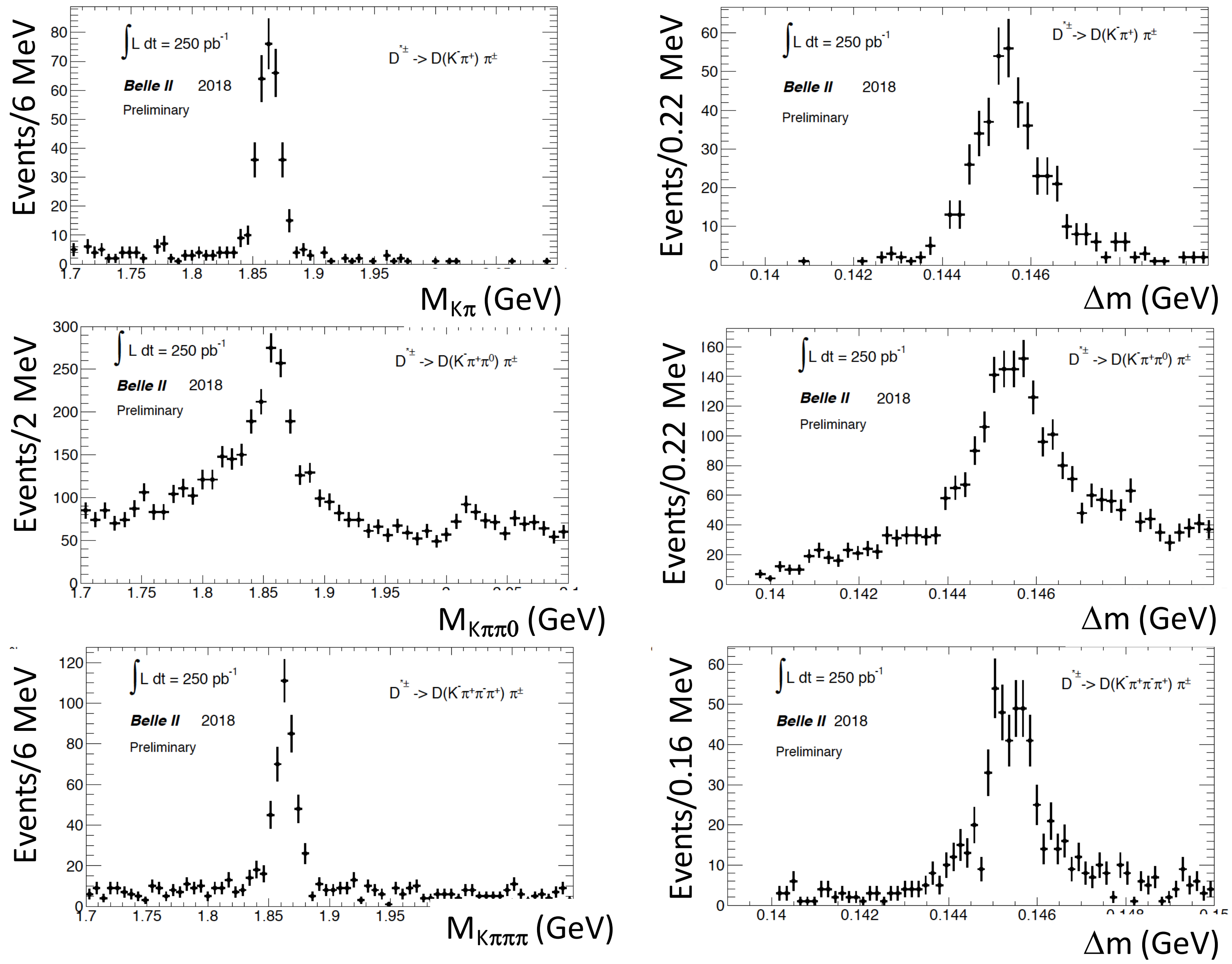
HLT output rate 6 KHz (1.8 GB/s)

$$e^+e^- \to c\bar{c}$$

$$D^{*+} \to D^0\pi^+,$$

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

The signal peaks are charm in continuum not from B's



Clearly illustrates the capabilities of Belle II and the potential for charm physics and the building blocks of B mesons.

CP Eigenstate: $D^0 \to K_S\pi^0$

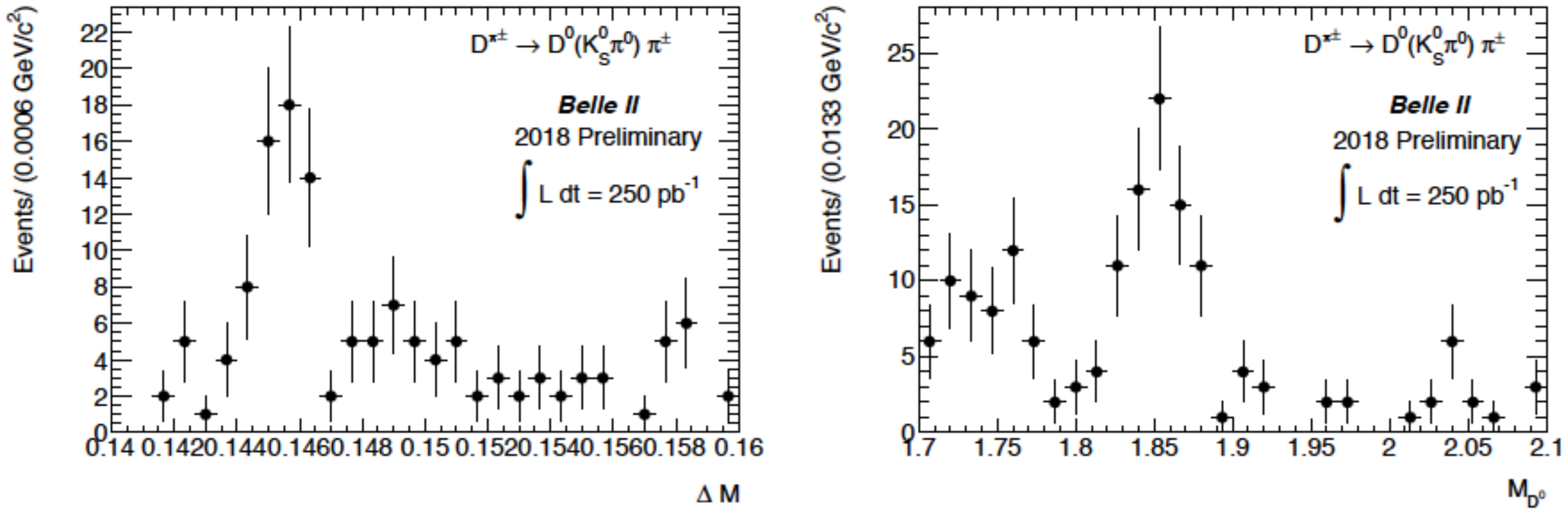
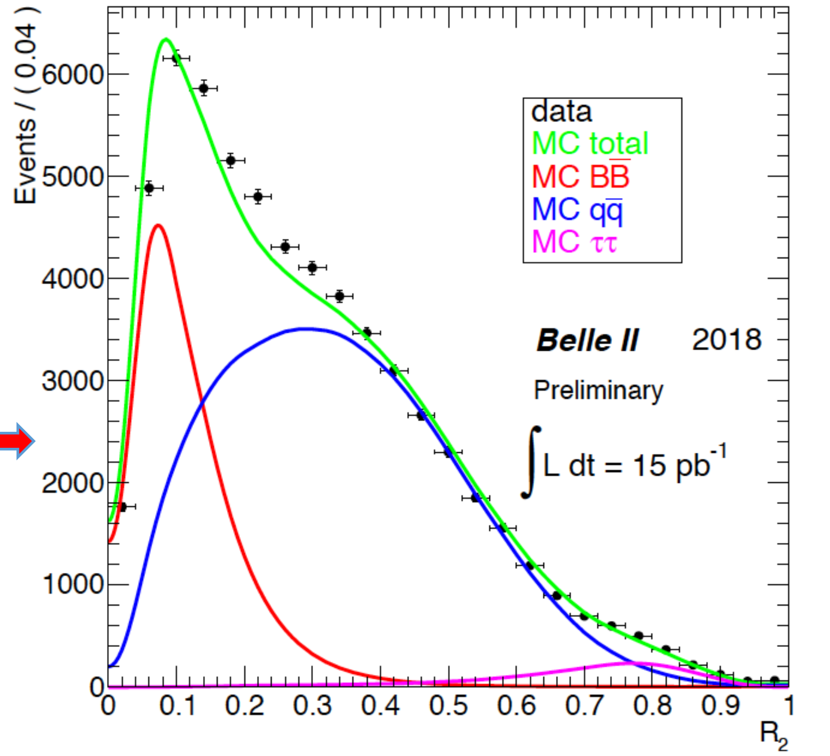


FIG. 36: ΔM (left) and M_D (right) signal-enhanced projections in 250 pb^{-1} prod4 data sample for $D \to K_S^0\pi^0$ final state.

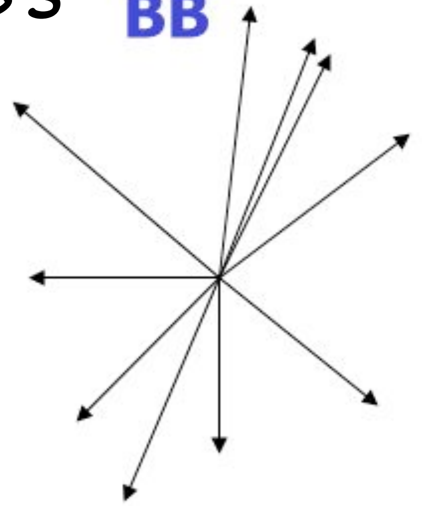
Also illustrates some of the important capabilities of Belle II.

Event Topology tells us we are seeing B's



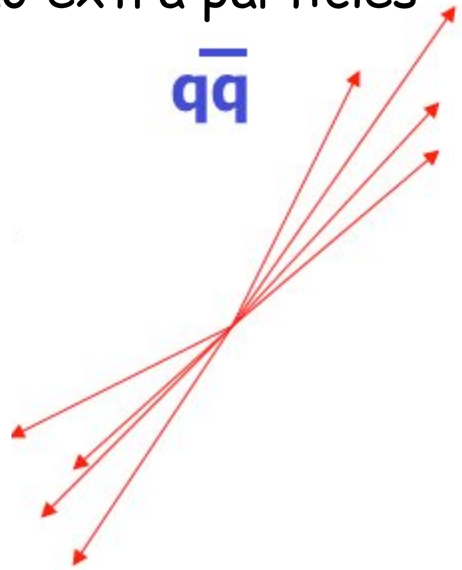
Spherical R_2 Jet-like

$B\bar{B}$



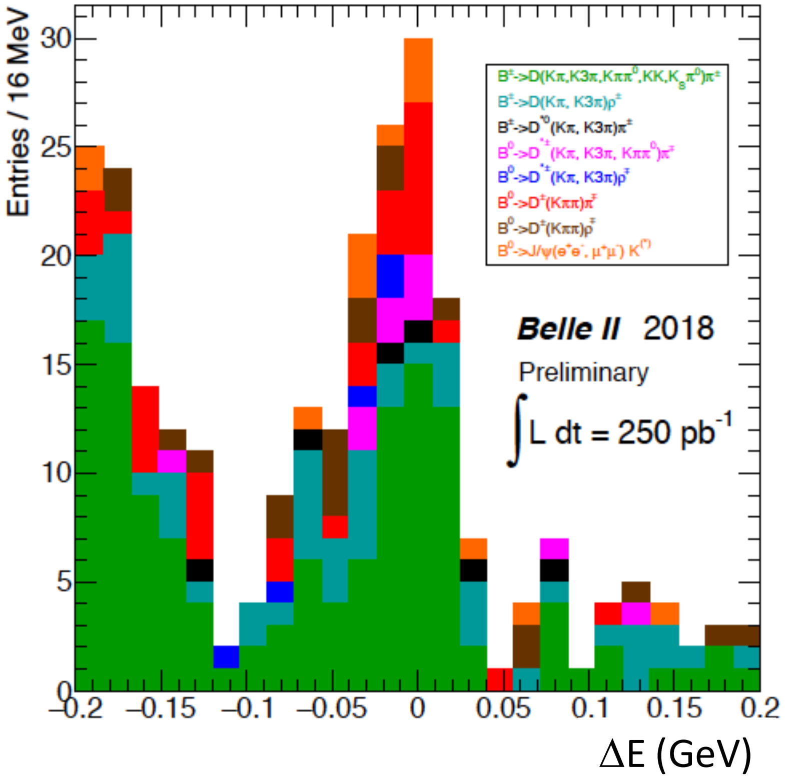
B pairs produced at rest in the CM with no extra particles

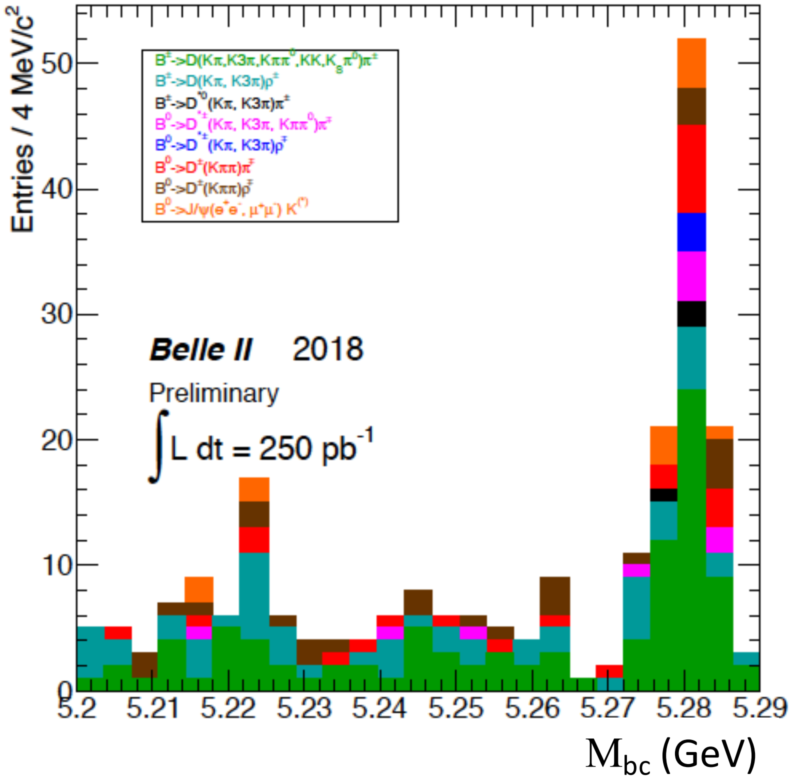
$q\bar{q}$



We are on the Υ(4S) resonance and recording B anti-B pairs with ~99% efficiency.

We have *rediscovered* the B meson !





$$\Delta E = E^*_B - E^*_{beam}$$

$$E_{bc} = \sqrt{(E^*_{beam})^2 + (p^*_B)^2}$$

History 1983:

VOLUME 50, NUMBER 12 PHYSICAL REVIEW LETTERS 21 MARCH 1983

Observation of Exclusive Decay Modes of *b*-Flavored Mesons $40.7\ pb^{-1}$

B-meson decays to final states consisting of a D^0 or $D^{*\pm}$ and one or two charged pions have been observed. The charged-B mass is $5270.8 \pm 2.3 \pm 2.0$ MeV and the neutral-B mass is $5274.2 \pm 1.9 \pm 2.0$ MeV.

Summary

- Belle II will explore New Physics on the Luminosity or Intensity Frontier. This is different and complementary to the LHC high p_T experiments, which operate on the Energy Frontier.

- There is competition and complementarity with LHCb

- We are ready to start a long physics run in the Super Factory mode. This requires *high-efficiency* data-taking by Belle II and *extensive running* by Super KEK-B, soon to be the world's highest luminosity accelerator.

Backup

The Geography of the International Belle II collaboration

Belle II now has grown to ~800 researchers from 25 countries

This is <u>rather unique</u> in Japan and Asia. The only comparable example is the T2K experiment at JPARC, which is also an <u>international collaboration</u>

Youth and potential: There are ~267 graduate students in the collaboration

Machine Parameters

2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.20×10^{-4}	4.55×10^{-4}		
σ_δ	$7.92(7.53) \times 10^{-4}$	$6.37(6.30) \times 10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	():zero current
ν_s	-0.0245	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

KEKB achieved

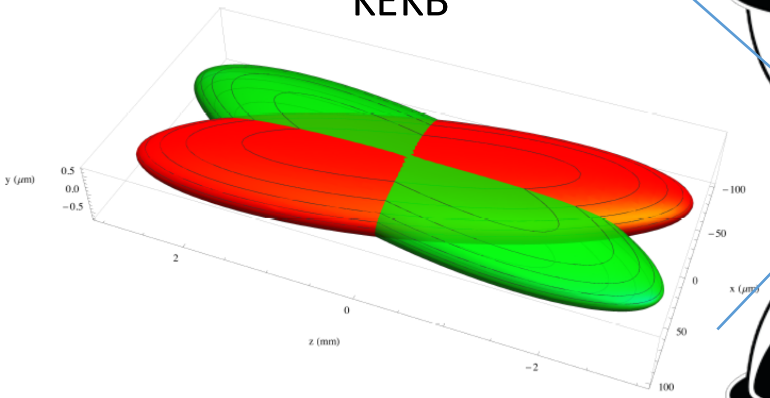
LER 1.8 A
HER 1.4 A

$\beta_y^* \sim 6mm$

2.1×10^{34}

Welcome to the world of large crossing angle nano-beams !

KEKB



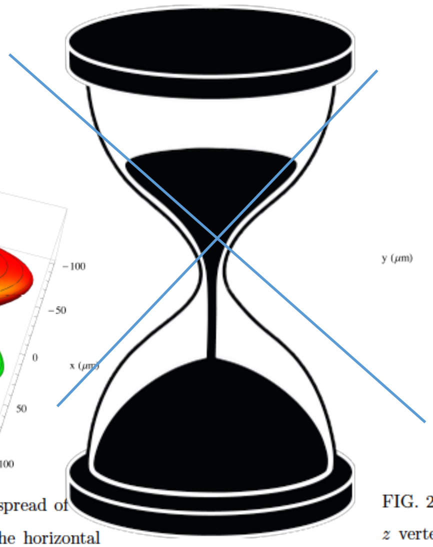


FIG. 1: Schematic view of Belle-I beam crossing at the interaction region. The spread of z vertex distribution can be estimated as $\sigma_z = \frac{\sqrt{\epsilon_x \beta_x^*}}{\sqrt{2}\phi_x}$ where for Belle-I optics the horizontal emittance $\epsilon_x = 20 \times 10^{-6}$ mm, $\beta_x^* = 1200$ mm, and the crossing angle $\phi_x = 11$ mrad leading to expected $\sigma_z = 1$ cm.

SuperKEKB

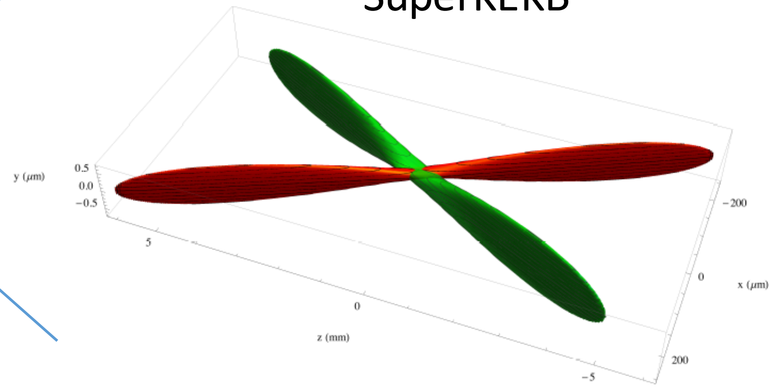
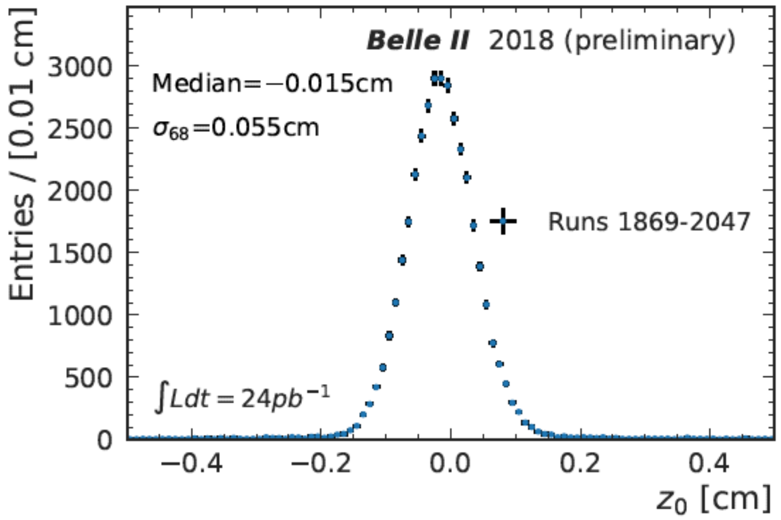


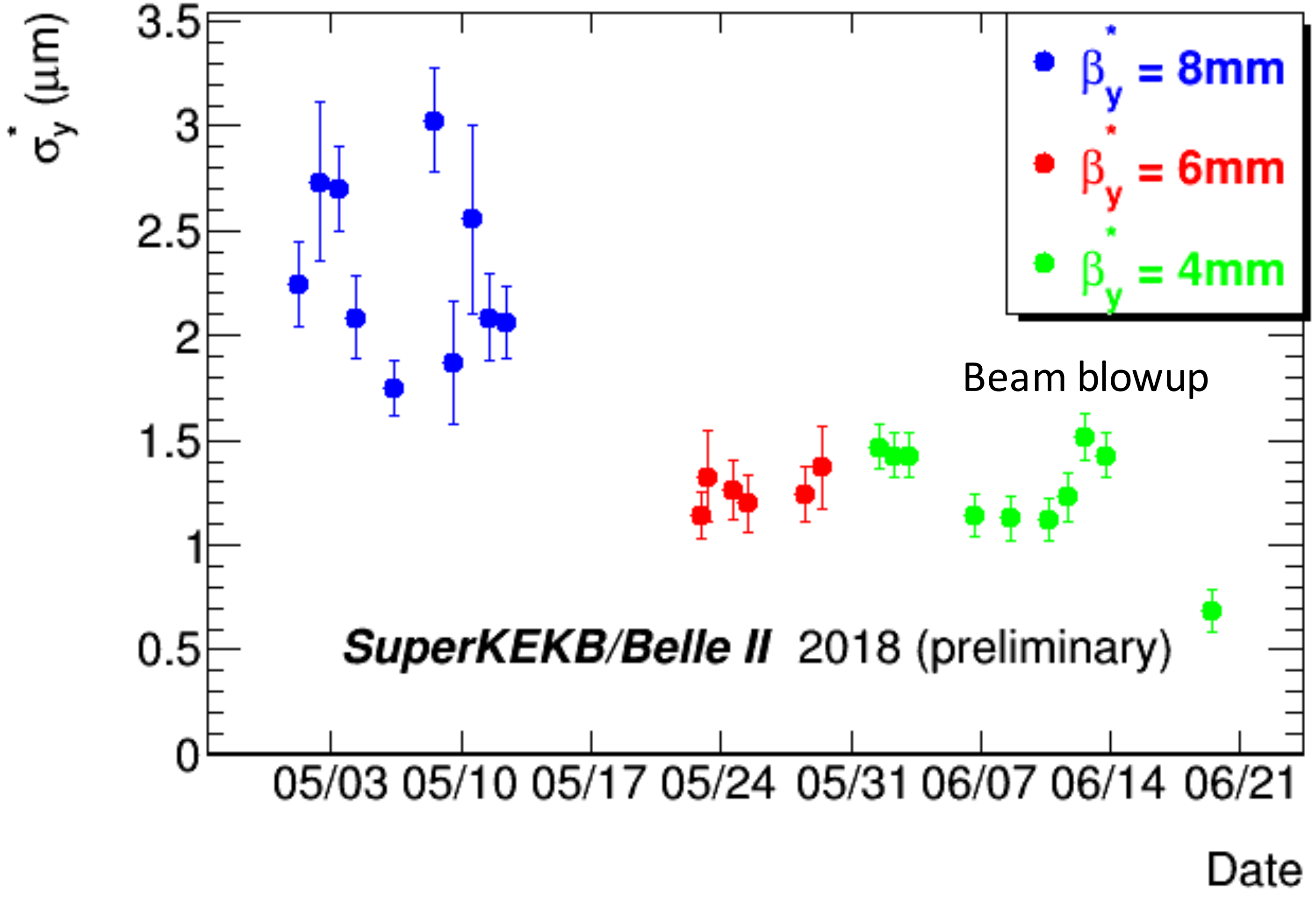
FIG. 2: Schematic view of Belle-II beam crossing at the interaction region. The spread of the z vertex distribution can be estimated as $\sigma_z = \frac{\sqrt{\epsilon_x \beta_x^*}}{\sqrt{2}\phi_x}$ where for Belle-II optics in phase 2 the horizontal emittance $\epsilon_x = 4 \times 10^{-6}$ mm, $\beta_x^* = 200$ mm, and the crossing angle $\phi_x = 41$ mrad leading to expected $\sigma_z = 0.049$ cm.

As expected, the effective bunch length is *reduced* from ~10 mm (KEKB) to 0.5 mm (SuperKEKB)

We measure this in two track events in Belle II data.



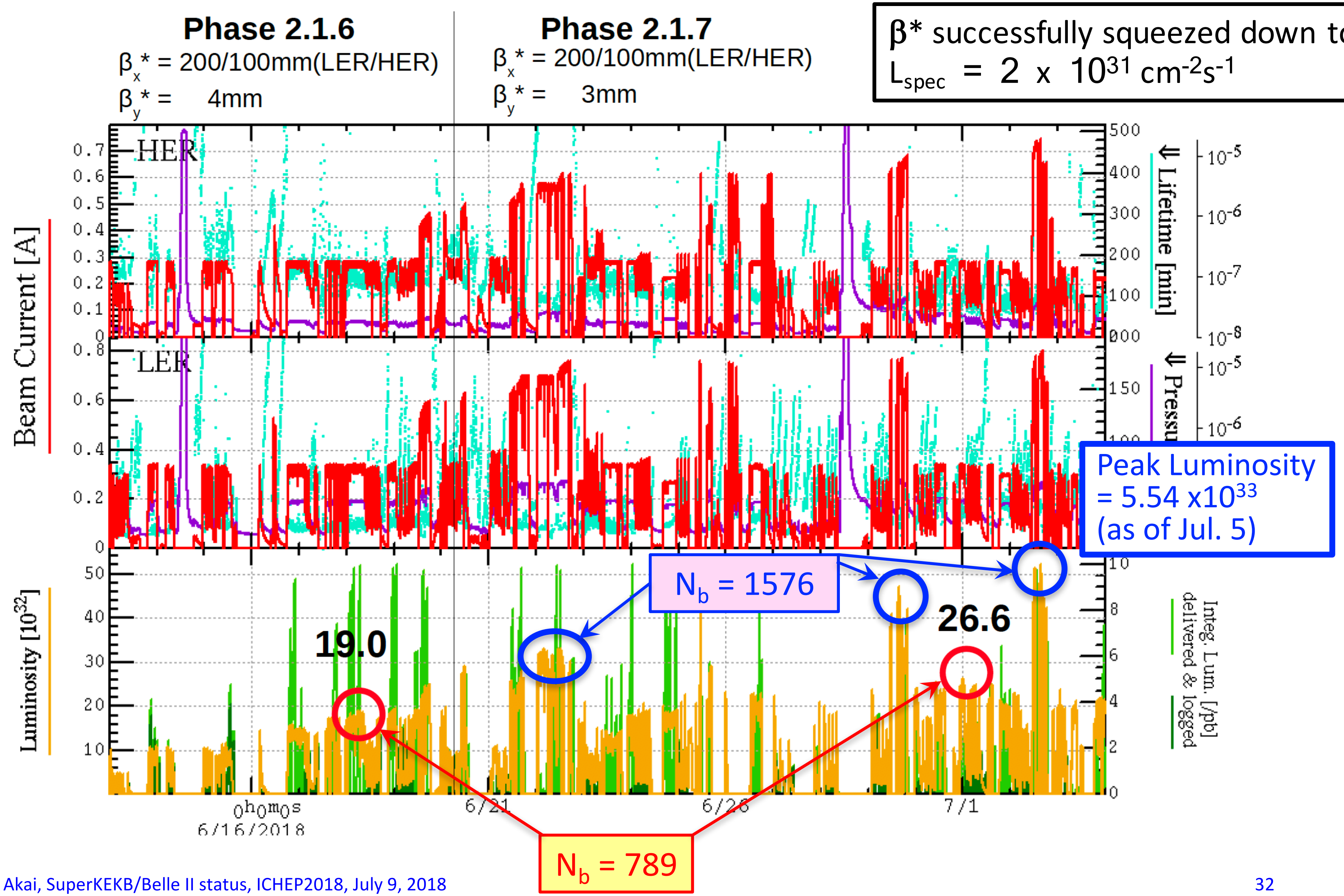
How do we measure the vertical height of nanobeams ?
Ans: Width of Luminosity scans with diamond detectors



At Phase 2 peak luminosity of 5 x 10^{33}/cm^2/sec, the vertical spot is ~700nm high. There is still beam-beam blowup at high currents. At low currents, the vertical spot size is 330 nm high (the final goal is O(50nm) with full capability of the QCS system).

Phase 2 Run

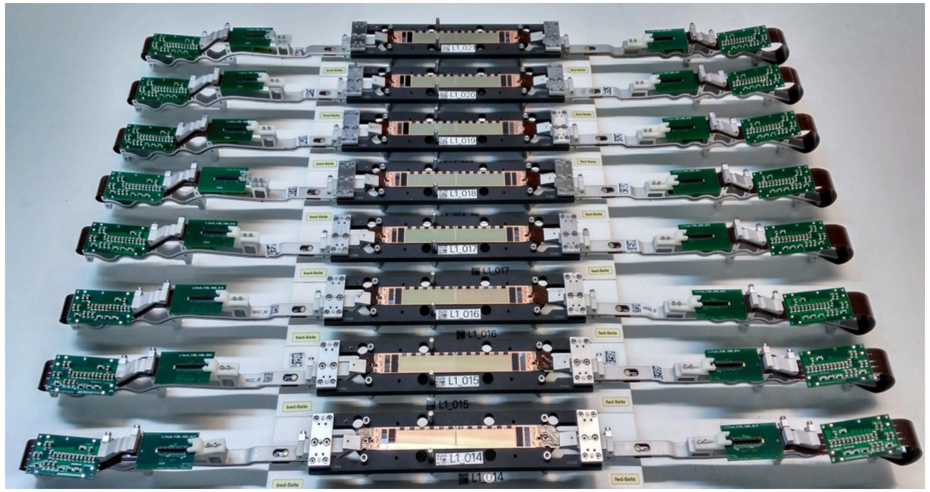
β* successfully squeezed down to β*=2mm
L_{spec} = 2 x 10^{31} $cm^{-2}s^{-1}$



. Akai, SuperKEKB/Belle II status, ICHEP2018, July 9, 2018

Onwards to Phase 3 and the Physics Run

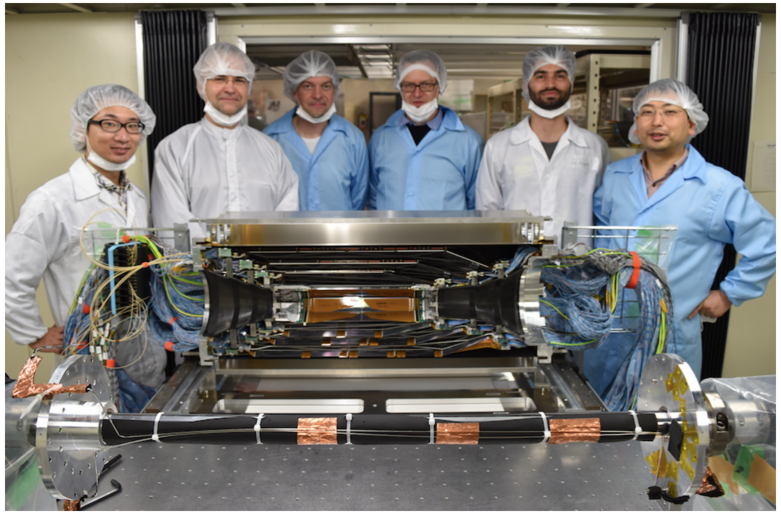
The VXD will be installed in Phase 3.
Restart Belle II data taking in February 2019.



PXD layer 1 ladders

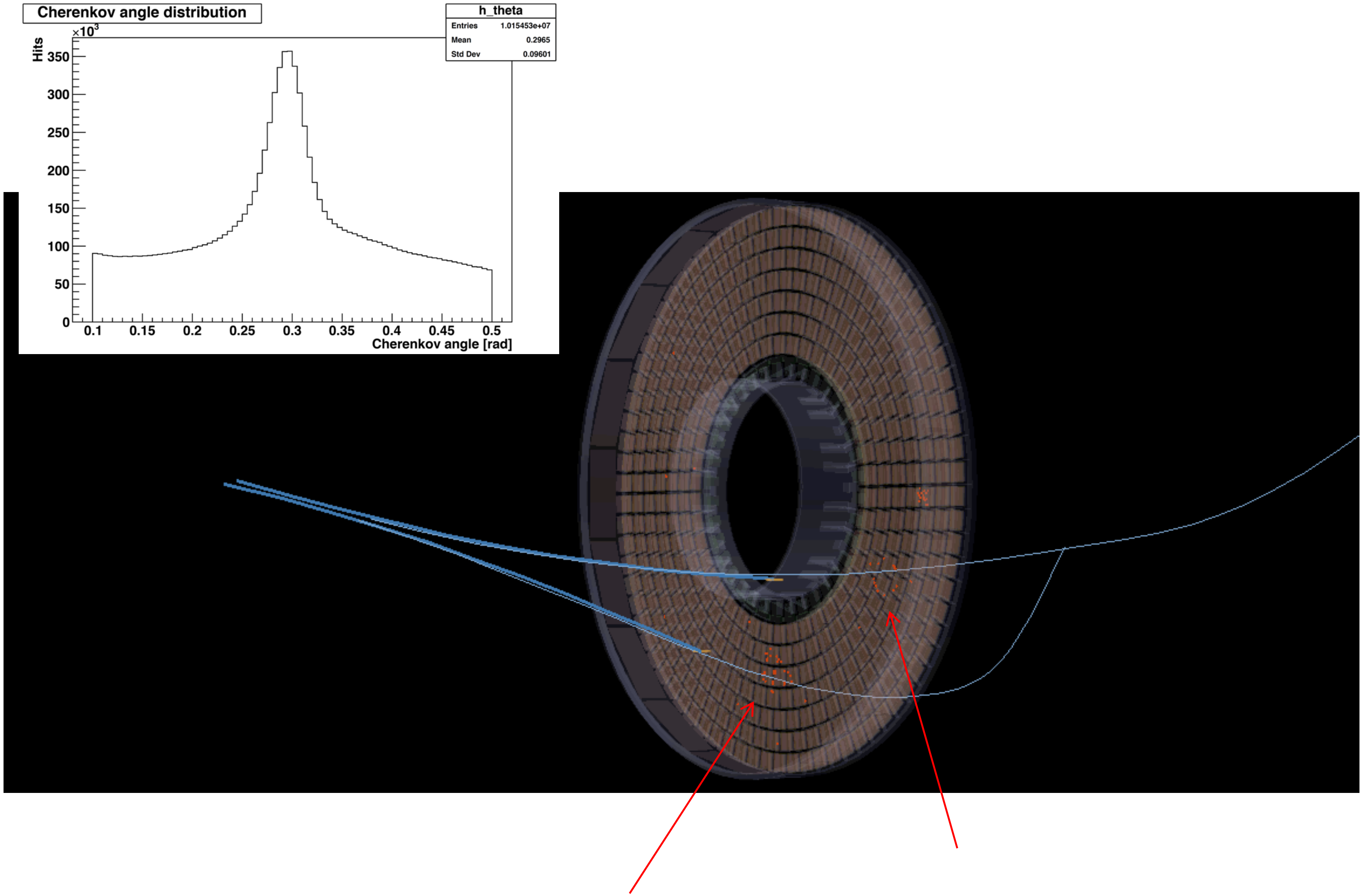
First PXD half-shell
being tested at DESY

SVD +x half-shell, Jan 2018



SVD -x half-shell, July 2018

Endcap particle identification via Aerogel RICH (ARICH)

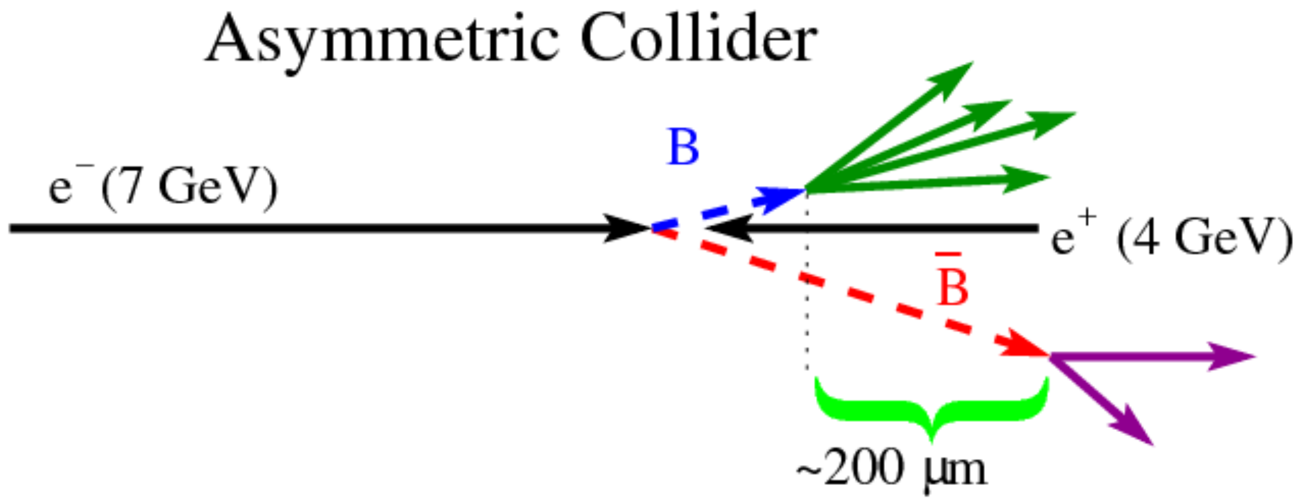


The B-anti B meson pairs at the Upsilon(4S) are produced in a coherent, *entangled* **quantum mechanical state**.

$$|\Psi>=|B^0(t_1,f_1)\overline{B^0}(t_2,f_2)>-|B^0(t_2,f_2)\overline{B^0}(t_1,f_1)>$$

Need to measure decay times to observe CP violation (particle-antiparticle asymmetry).

One B decays →collapses the flavor wavefunction of the other anti-B. (Exercise: Also one B must decay before the other can mix)

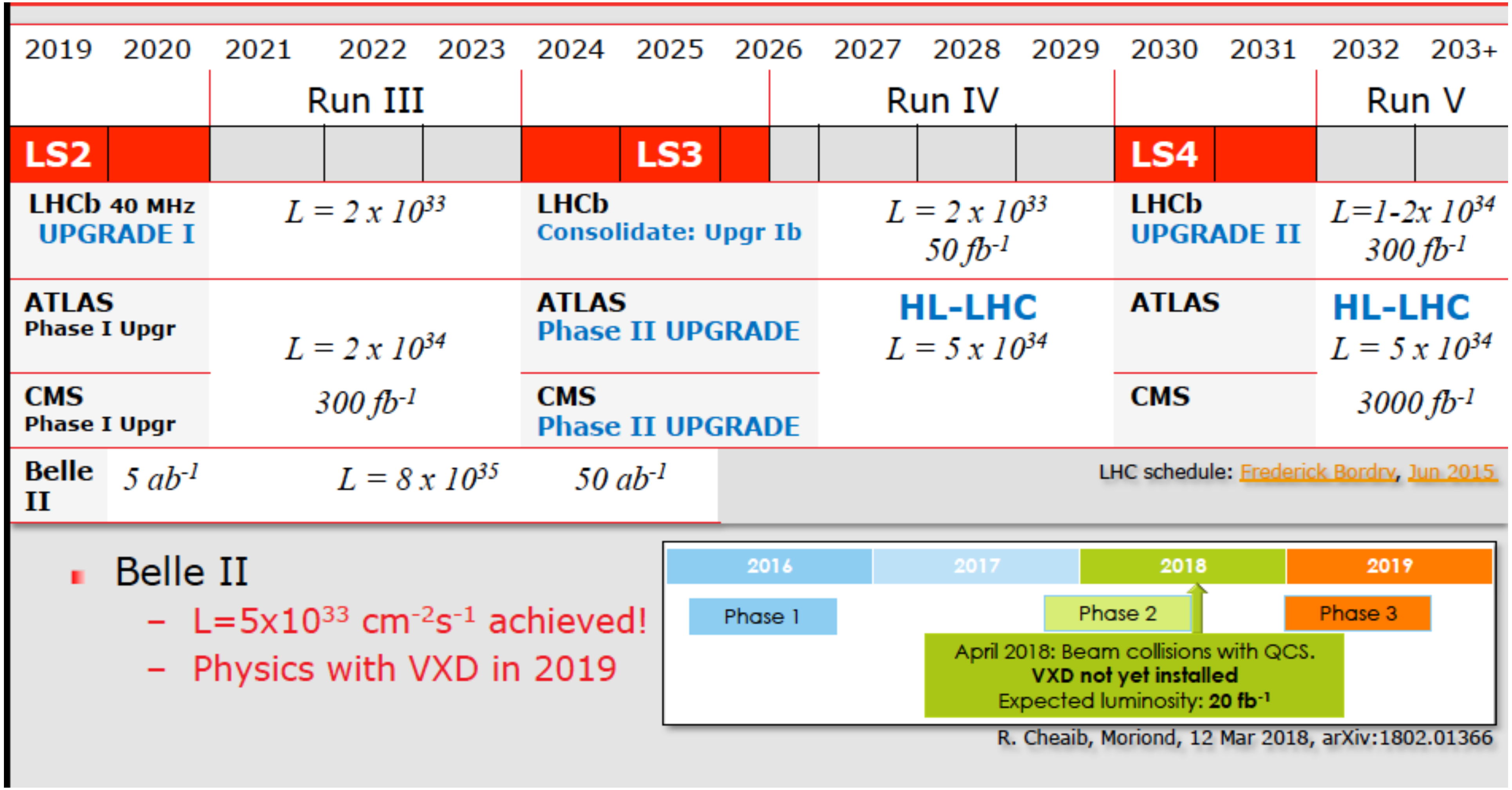


Not to scale

The beam energies are asymmetric (7 on 4 GeV)

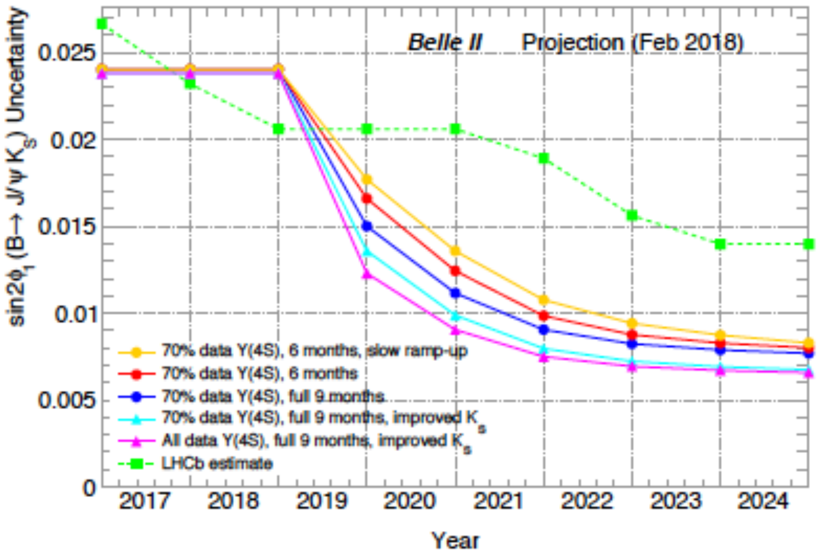
The decay distance is increased by around a factor ~7

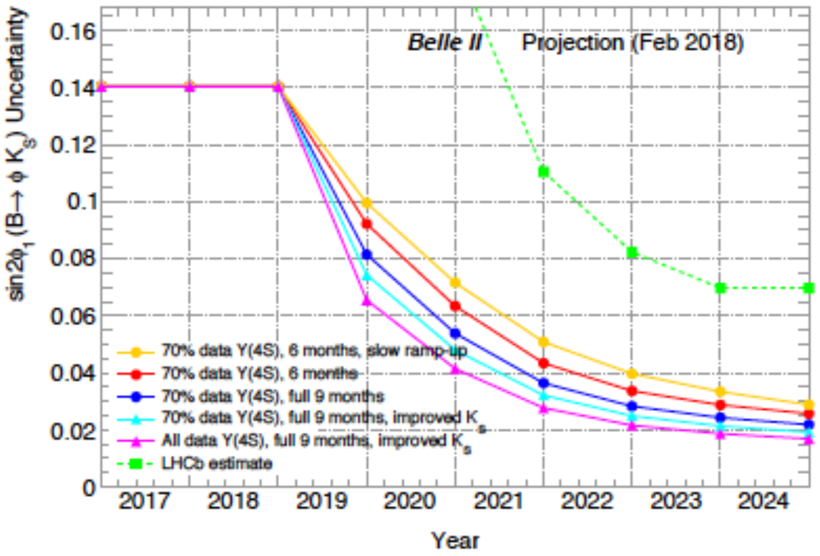
Physics Competition and Complementarity

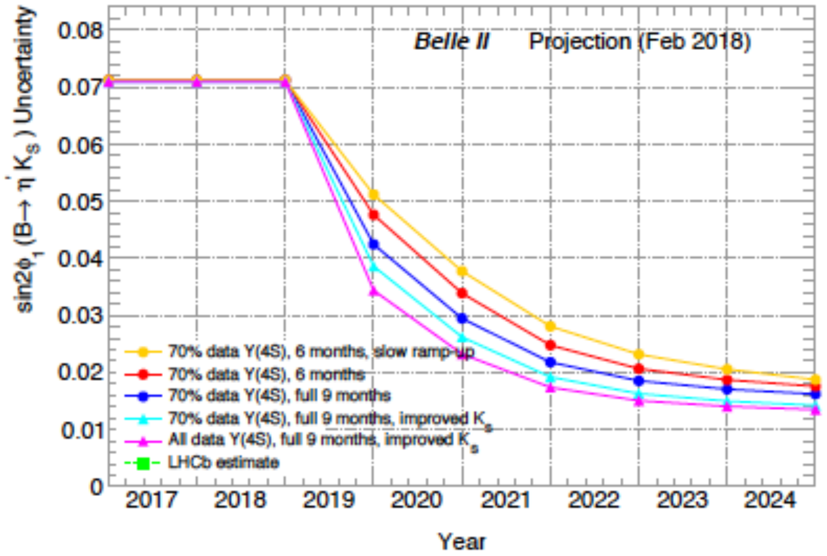


Outside perspective:
Plenary talk by Niels Tuning, ICHEP 2018 in Seoul, Korea

Examples of Physics Competition and Complementarity







Use publicly available LHCb projections.

How can we establish NP in $B \rightarrow K^* l^- l^+$?

Ans: Observe and measure the rate for $B \rightarrow s\nu\bar{\nu}$ and thus isolate the Z penguin (C_9) at *Belle II*

Answer from Buras et al.

TABLE I: Projections for the statistical uncertainties on the $B \to K^{(*)}\nu\bar{\nu}$ branching fractions.

Mode	$\mathcal{B}$ $[10^{-6}]$	Efficiency Belle $[10^{-4}]$	$N_{\text{Backg.}}$ 711 fb^{-1} Belle	$N_{\text{Sig-exp.}}$ 711 fb^{-1} Belle	$N_{\text{Backg.}}$ 50 ab^{-1} Belle II	$N_{\text{Sig-exp.}}$ 50 ab^{-1} Belle II	Statistical error 50 ab^{-1}	Total Error
$B^+ \to K^+\nu\bar{\nu}$	3.98	5.68	21	3.5	2960	245	23%	24%
$B^0 \to K^0_S\nu\bar{\nu}$	1.85	0.84	4	0.24	560	22	110%	110%
$B^+ \to K^{*+}\nu\bar{\nu}$	9.91	1.47	7	2.2	985	158	21%	22%
$B^0 \to K^{*0}\nu\bar{\nu}$	9.19	1.44	5	2.0	704	143	20%	22%
$B \to K^*\nu\bar{\nu}$ combined							15%	17%

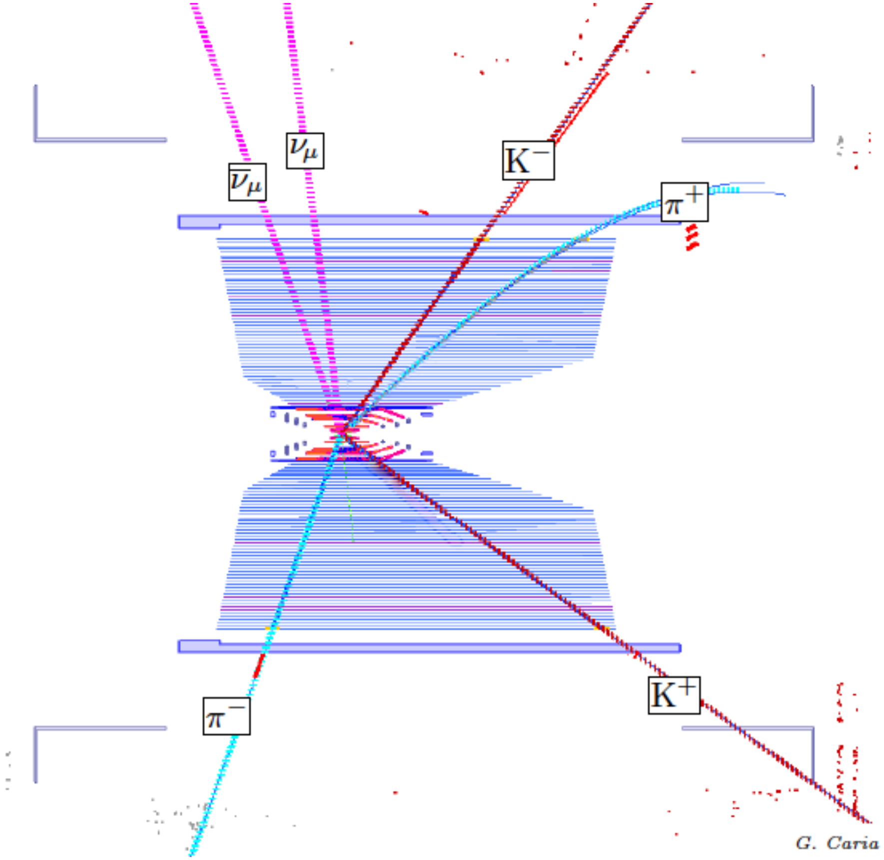
What's Ahead ?

"Missing Energy Decay" in a Belle II GEANT4 MC simulation

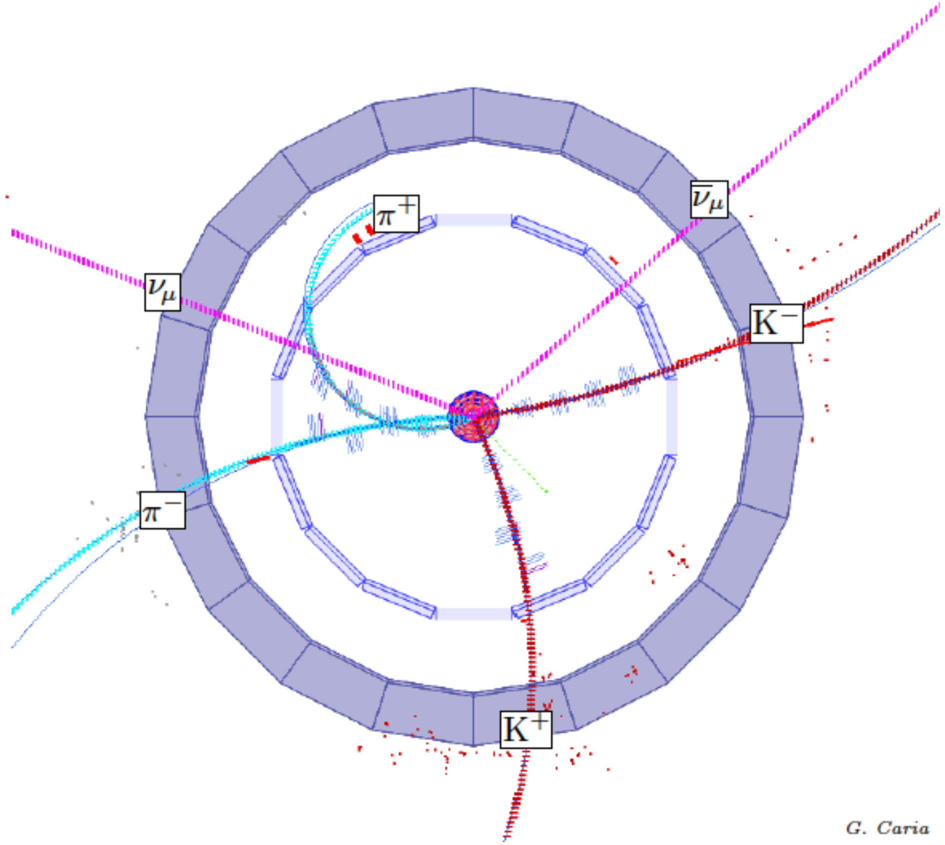
Signal: B→K ν ν

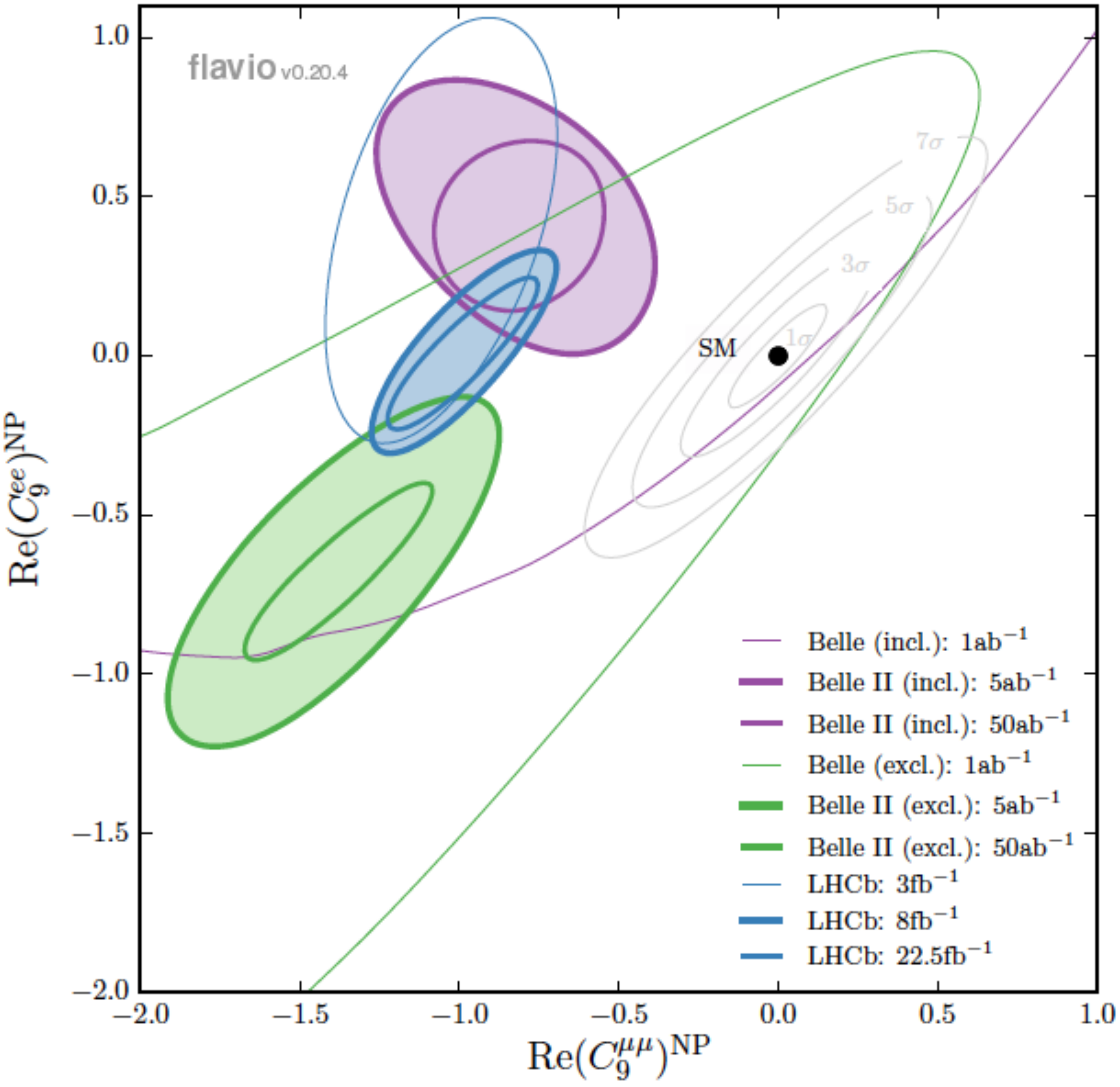
tag mode: B→Dπ; D→Kπ

View in r-z



Zoomed view of the vertex region in r--phi





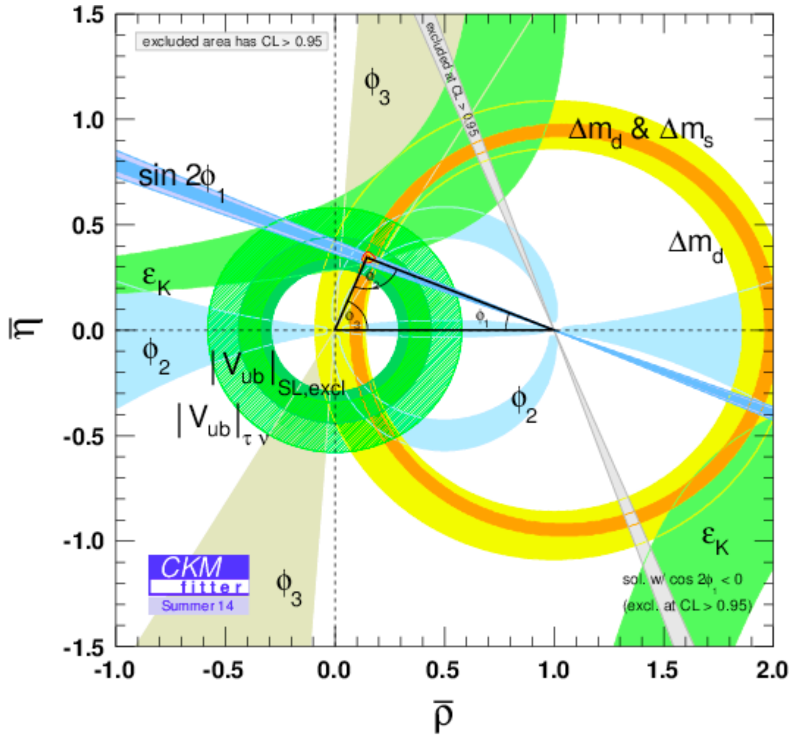
NP in b→s l^+l^-

Prepared by D. Straub et al. for the Belle II Physics Book (edited by P. Urquijo and E. Kou)

Belle II can do both inclusive and exclusive. Equally strong capabilities for electrons and muons.

Results from Global Fits to Data (CKMFitter Group)

Great progress on φ_3 or γ (first from B factories and now in the last four years from LHCb). *These measure the phase of V_{ub}*



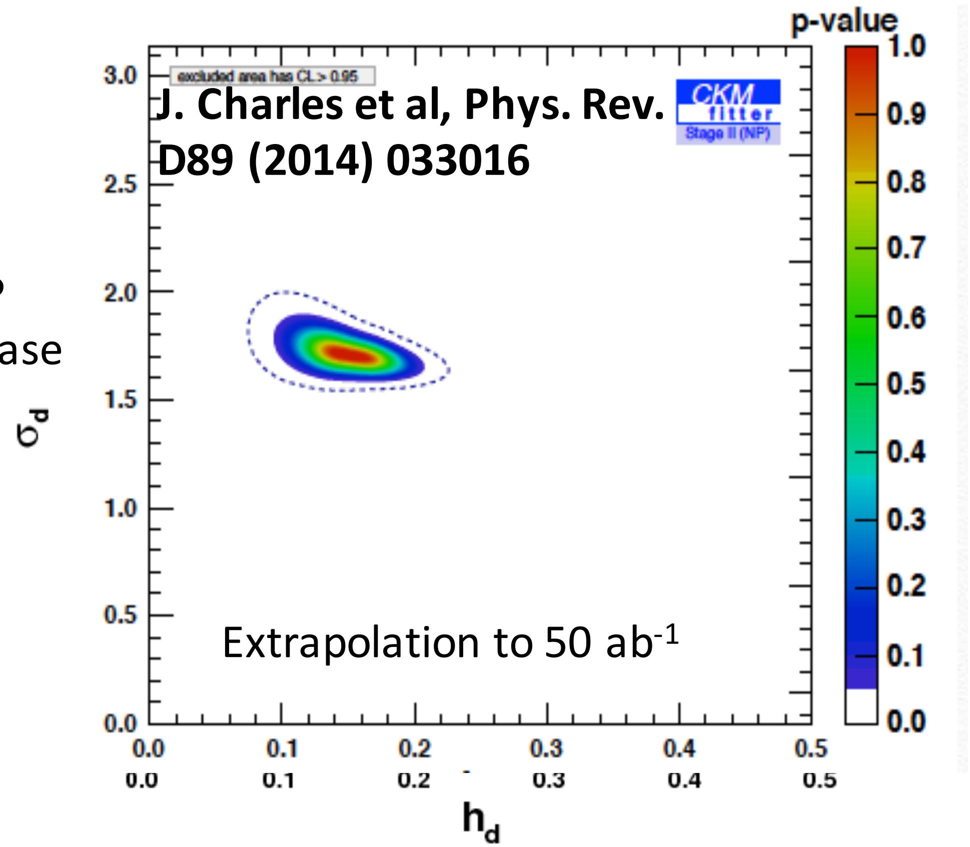
Looks good

(except for an issue with $|V_{ub}|$)

Similar results from UTFIT

NP

Phase



NP/SM amplitude ratio

But a 10-20% NP amplitude in B_d mixing is perfectly compatible with all current data.

More examples of Physics Competition and Complementarity

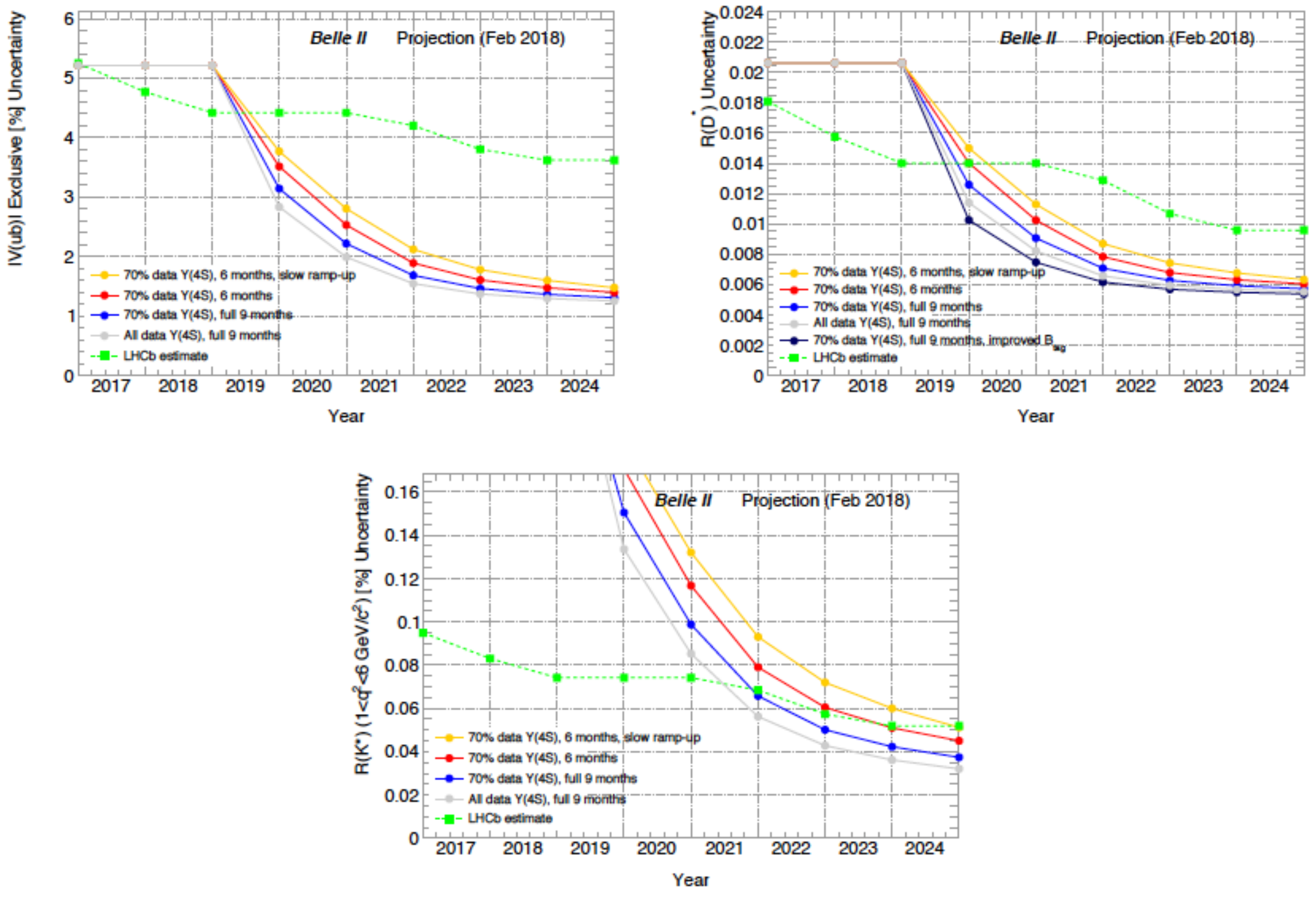
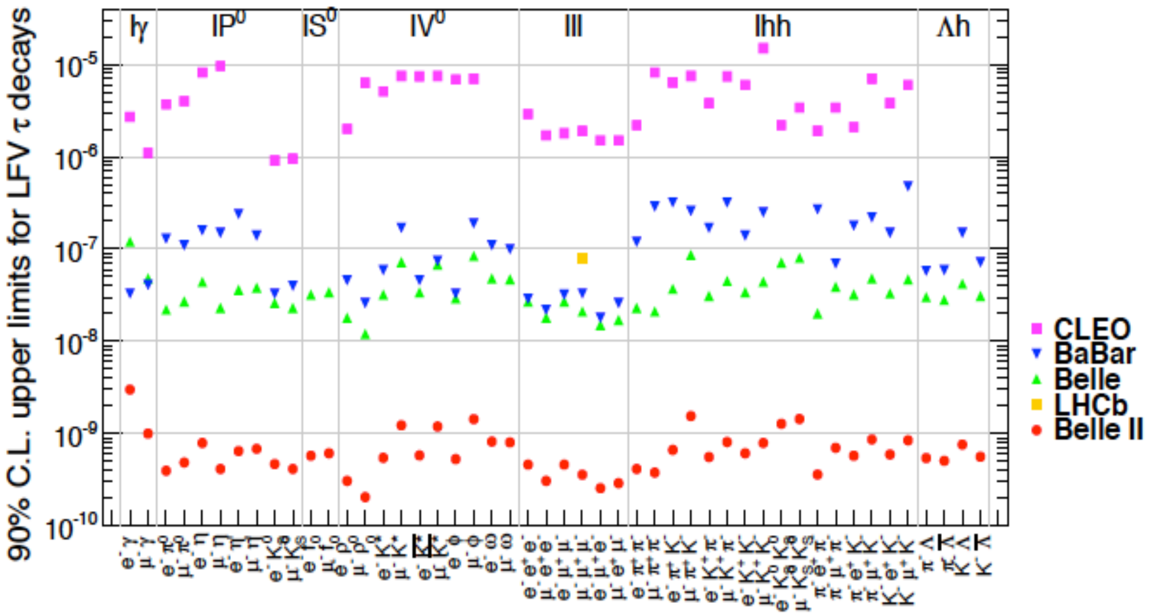


FIG. 6: Projected precision for various measurements of semileptonic B decays.

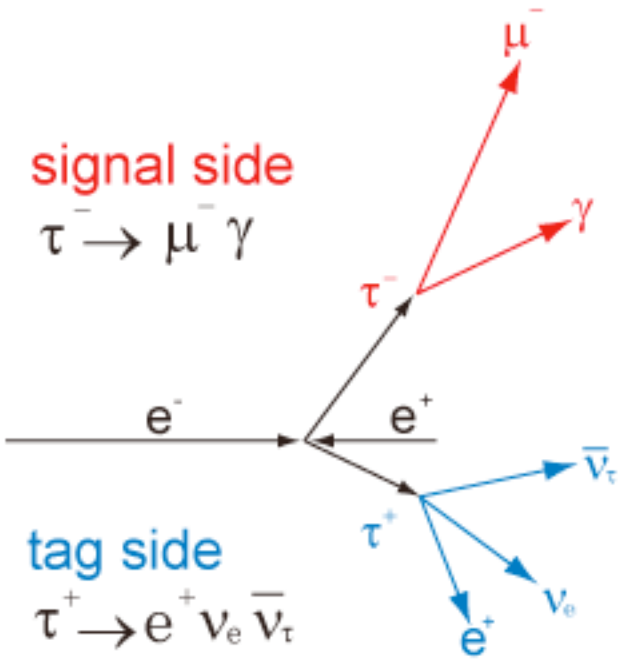
Uses publicly available LHCb projections.

epton Flavor Violation

Example of the decay topology



Note vertical log-scale (50 ab^{-1} assumed for Belle II; 3 fb^{-1} result for LHCb



__Belle II will push many limits below 10^{-9}__;

LHCb, CMS and ATLAS have very *limited* capabilities.

LHC high pt: The modes τ→μγ and τ →μ h+ h- provide important constraints on H→μτ

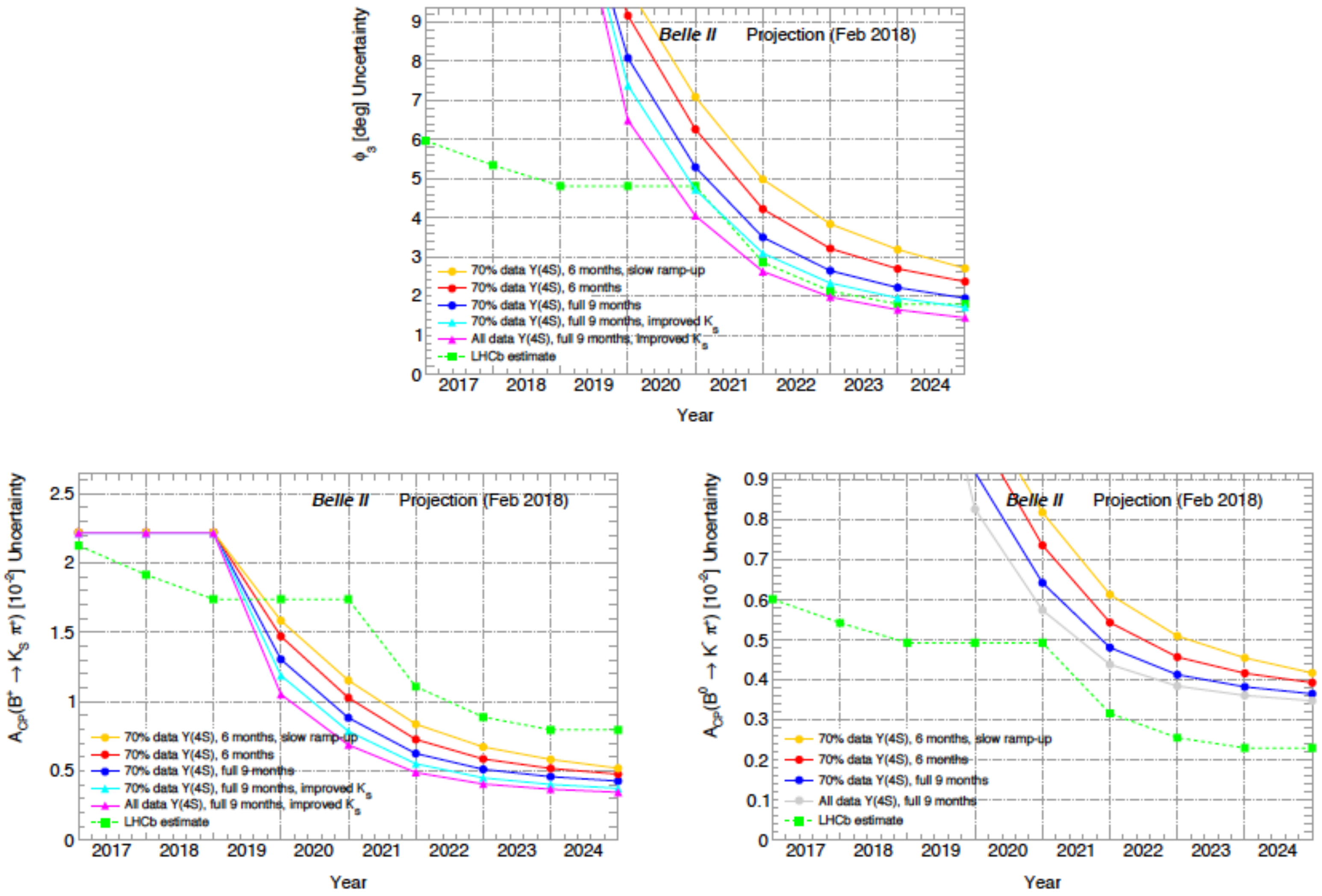


FIG. 5: Projected precision for various measurements of direct CP violation.

"Tsukuba, we have a Problem"

(apologies to Tom Hanks, Apollo 13)

WMAP data

$$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10}$$

KM Theoretical prediction

$$\left(\frac{n_b}{n_\gamma}\right)^{\rm SM} \propto \frac{J_{CP}}{T_c^{12}} \sim 10^{-20}$$

The CP Violation predicted by Kobayashi and Maskawa is too small by *~10 orders of magnitude* in the Standard Model.

What does this mean ?

→ New Physics