Status and perspectives of the Belle II experiment

57th International Winter Meeting on Nuclear Physics

Bormio, January 23, 2019

Francesco Forti,
INFN and University, Pisa

A flavor suite

- Prelude: A brief history of flavor
- Allemande: The SuperKEKB upgrade
- Courante: The Belle II upgrade
- Sarabande: Phase 2 running (2018)
- Bourrée: Physics commissioning
- Gigue: Phase 3 running and perspectives

A musical section or movement introducing the theme or chief subject

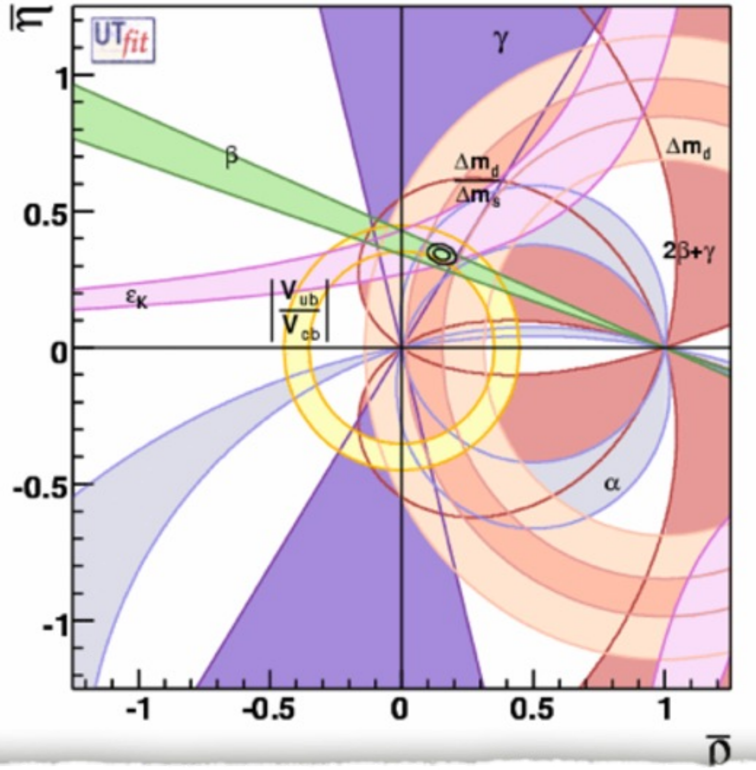
Prelude
A brief history of flavor

(Some) past successes of flavor

Indirect discoveries of flavor experiments

- suppression of $K_L^0 \to \mu^+\mu^-$ decays
  $\Rightarrow$ existence of charm quark by GIM mechanism
- $K^0\bar{K}^0$ oscillations, $B^0\bar{B}^0$ oscillations
  $\Rightarrow$ charm and top quark masses
- CPV in K^0 systems
  $\Rightarrow$ 3rd generation of quarks & KM mechanism

Precision measurement of CKM elements



First generation B Factories

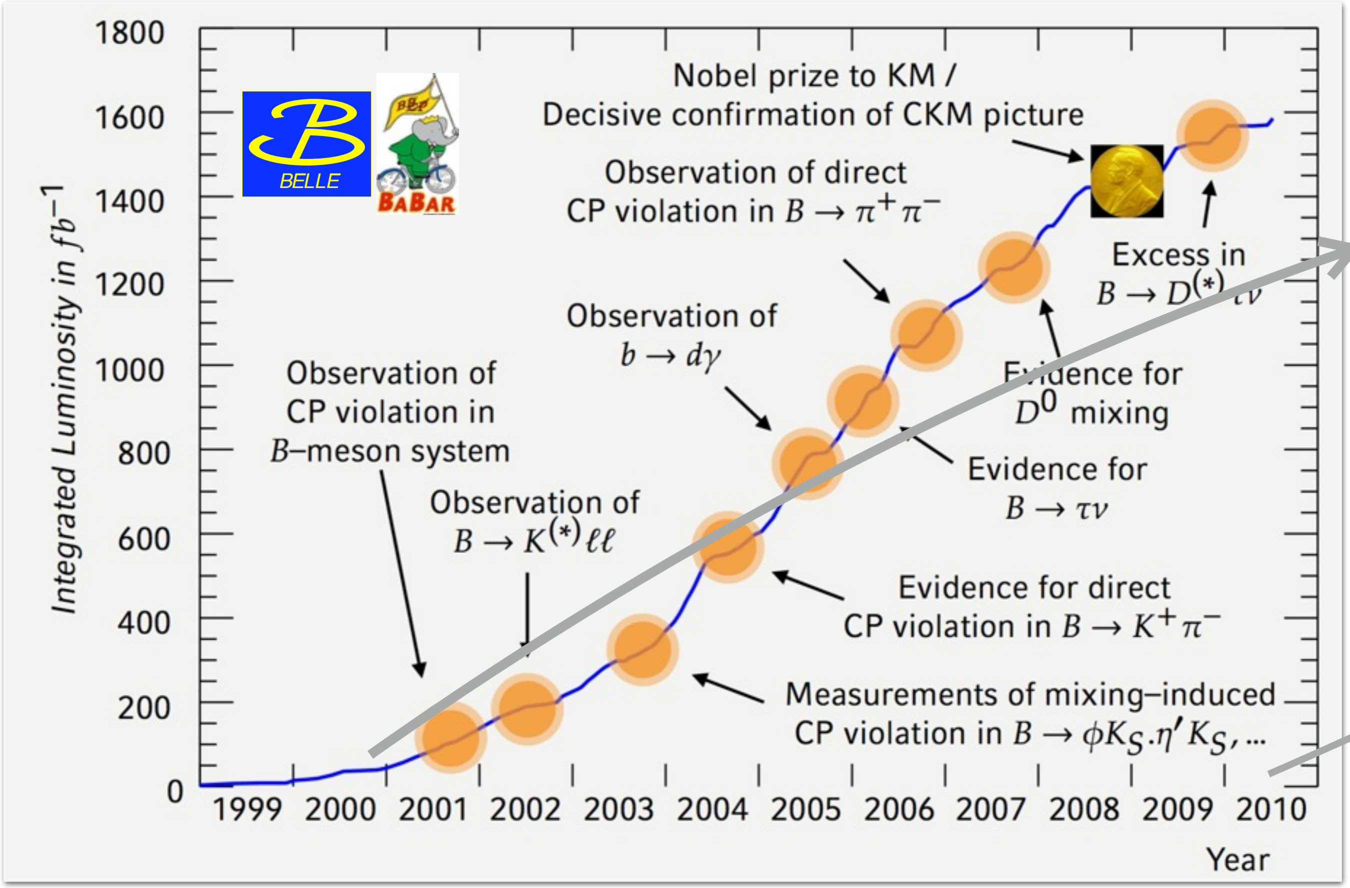
BABAR @ PEP-II: 1999-2008

BELLE @ KEKB: 1999-2010

Courtesy of A.Zupanc

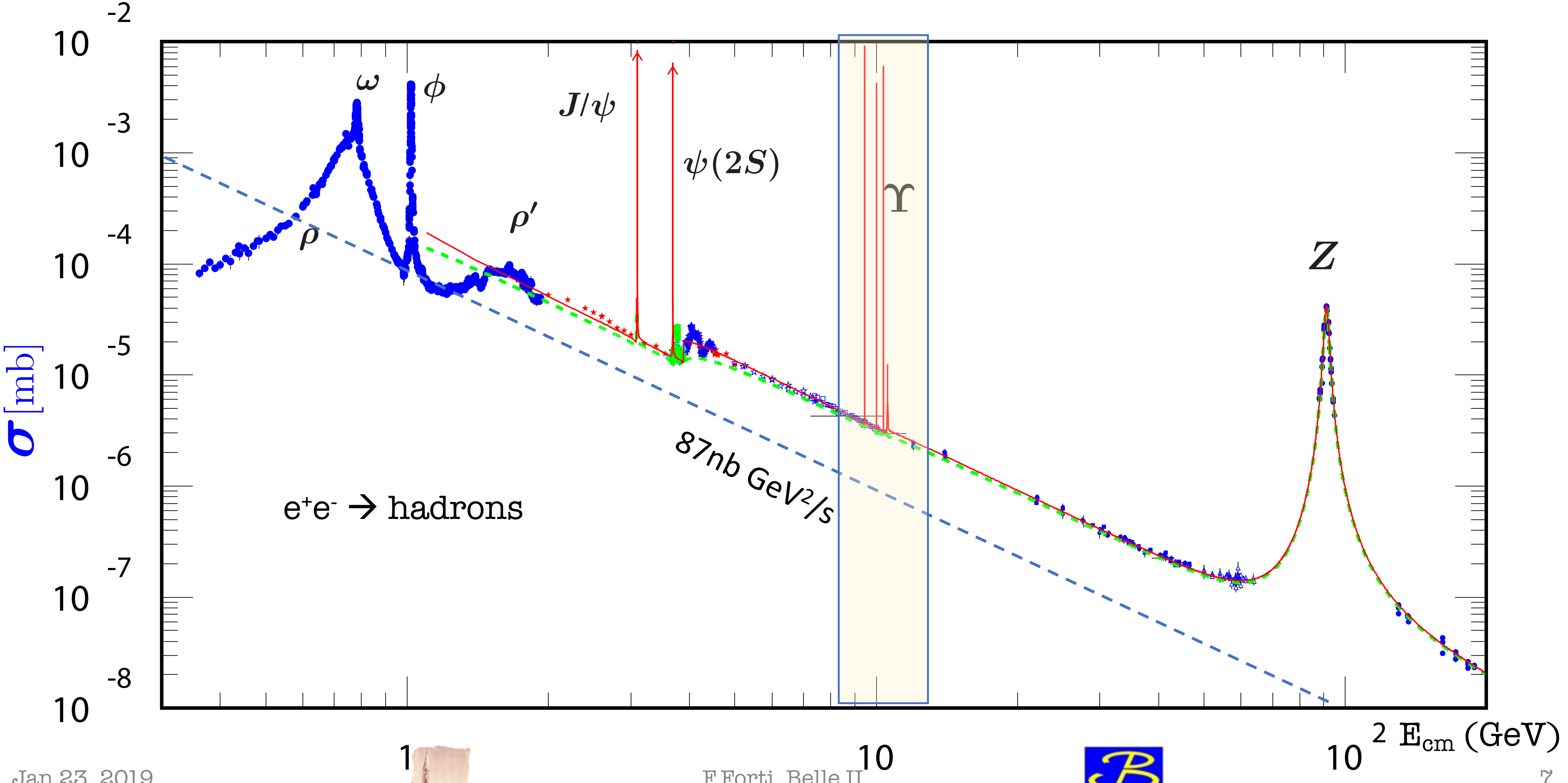
Asymmetric B factories: flavour physics at the intensity frontier

BaBar (PEPII@SLAC) and **Belle** (KEKB@KEK)



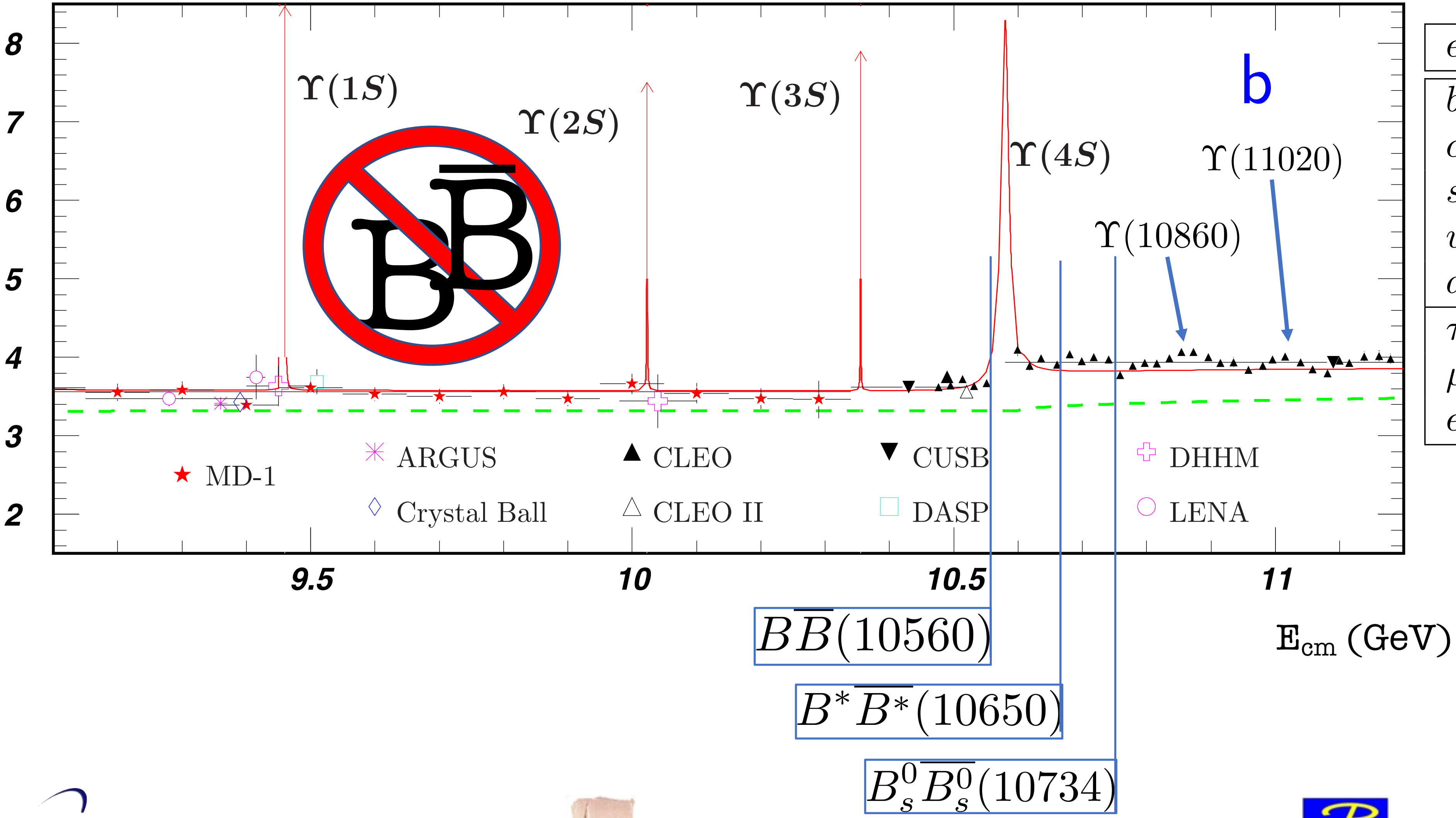
Physics of the B Factories
Ed. A.J. Bevan, B. Golob, Th. Mannel, S. Prell, and B.D. Yabsley,
Eur. Phys. J. C74 (2014) 3026,
arXiv:1406.6311 [hep-ex]

e+e- cross section



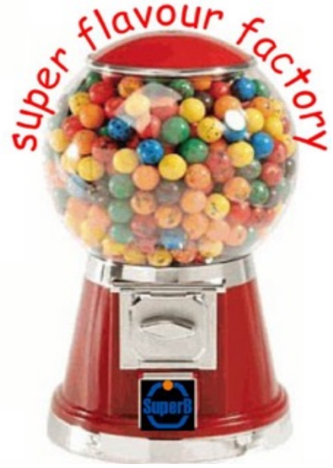
e+e- cross section in the bottomonium region

$R=\sigma(e^+e^- \to had)/\sigma(e^+e^- \to \mu^+\mu^-)$



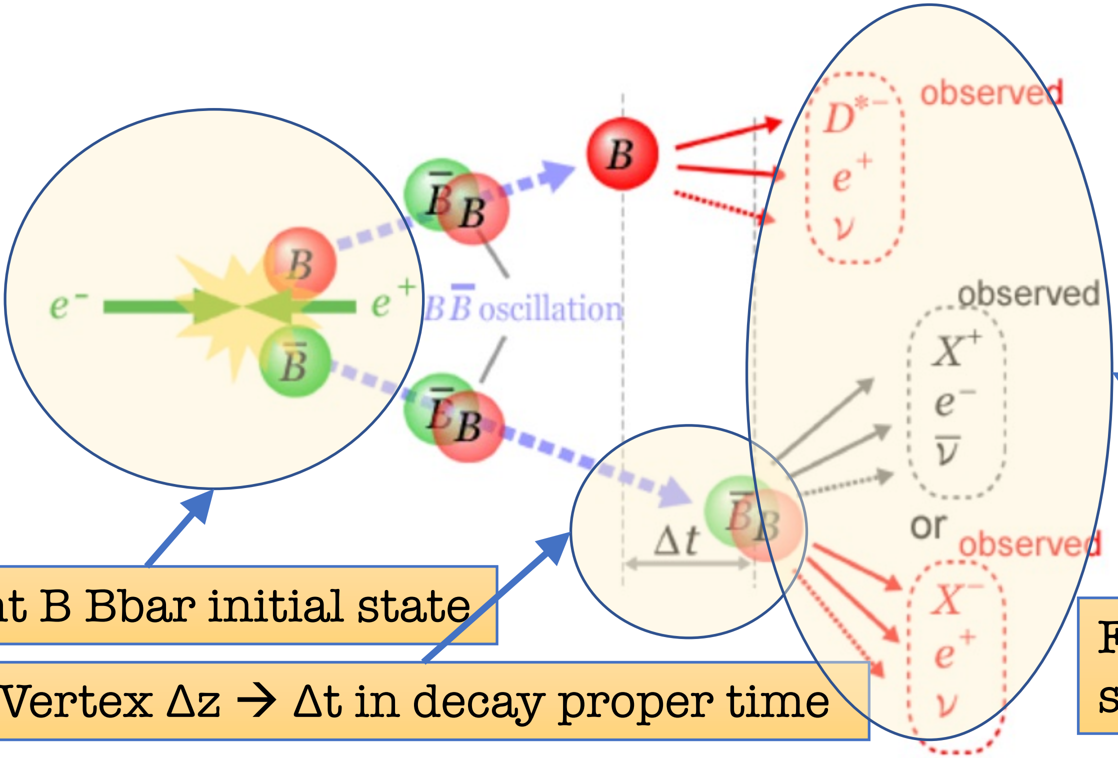
Cross section @ Υ(10580)

$e^+e^- \to$	Cross-section (nb)
$b\bar{b}$	1.05
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$u\bar{u}$	1.39
$d\bar{d}$	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	~ 40



Essence of asymmetric e+e- B-Factories

- Center of mass travels along beam direction (boost)
- Very clean events (only tens of particles in the final state)
- Open trigger (no specific state pre-selection)



Coherent B Bbar initial state

Vertex Δz → Δt in decay proper time

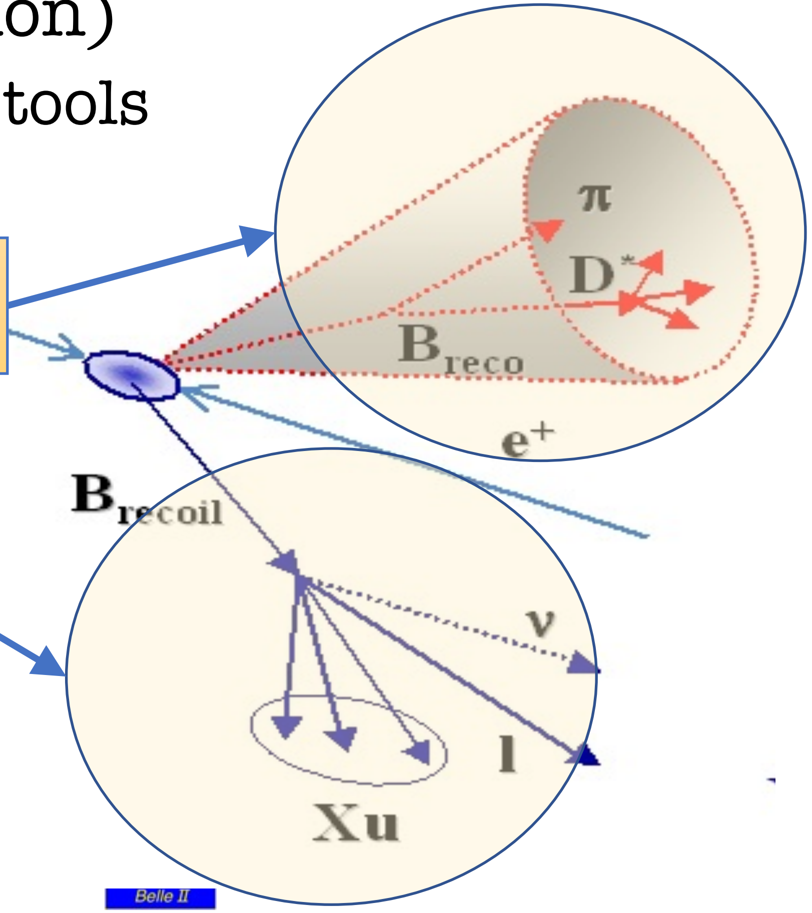
Final state can identify flavor, or select CP eigenstate

Essence of asymmetric e+e- B-Factories

- Center of mass travels along beam direction (boost)
- Very clean events (only tens of particles in the final state)
- Open trigger (no specific state pre-selection)
- Full Event Interpretation provides powerful tools

Fully reconstruct one B (thousands of modes)

The other B is completely known both kinematically and in flavor: it is a beam of B's



- Super clean B allows for analyses like B→ invisible

Essence of asymmetric e+e- B-Factories

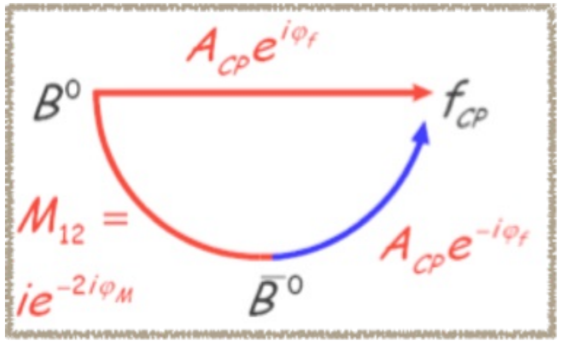
- Center of mass travels along beam direction (boost)
- Very clean events (only tens of particles in the final state)
- Open trigger (no specific state pre-selection)
- Full Event Interpretation provides powerful tools

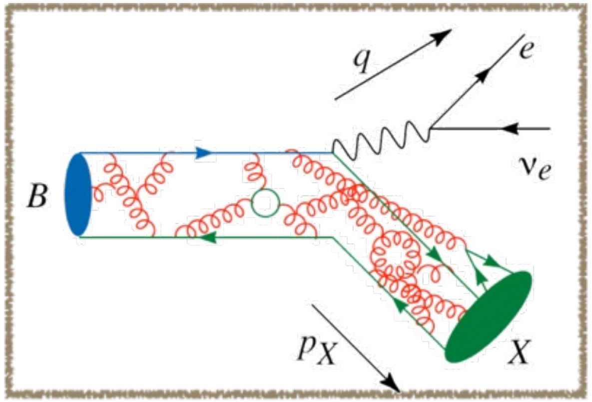
- Main limitations:
- e+e- Cross section is much smaller (~1000) than hadronic production
- Only B_d and B_u produced. B_s possible, but with smaller rate. B_c out of reach.

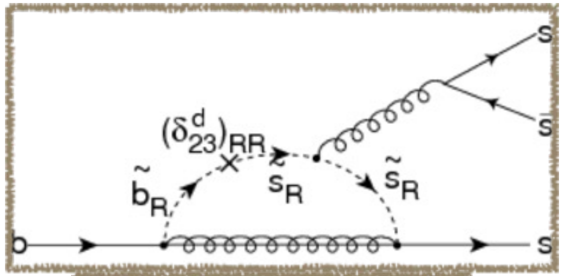
The power of flavor

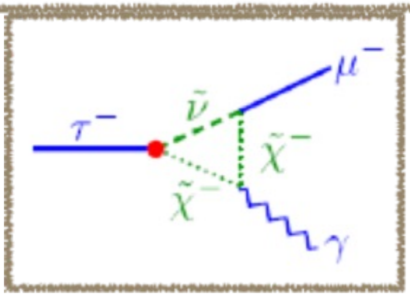
Statistics

- **Explore the origin of CP violation**
  - Key element for understanding the matter content of our present universe
  - Established in the B meson in 2001
  - Direct CPV established in B mesons in 2004
- **Precisely measure parameters of the standard model**
  - For example the elements of the CKM quark mixing matrix
  - Disentangle the complicated interplay between weak processes and strong interaction effects
- **Search for the effects of physics beyond the standard model in precision measurements**
  - Potentially large effects on rates of rare decays, time dependent asymmetries, lepton flavor violation
  - Sensitive to large New Physics scale, as well as to phases and size of NP coupling constants

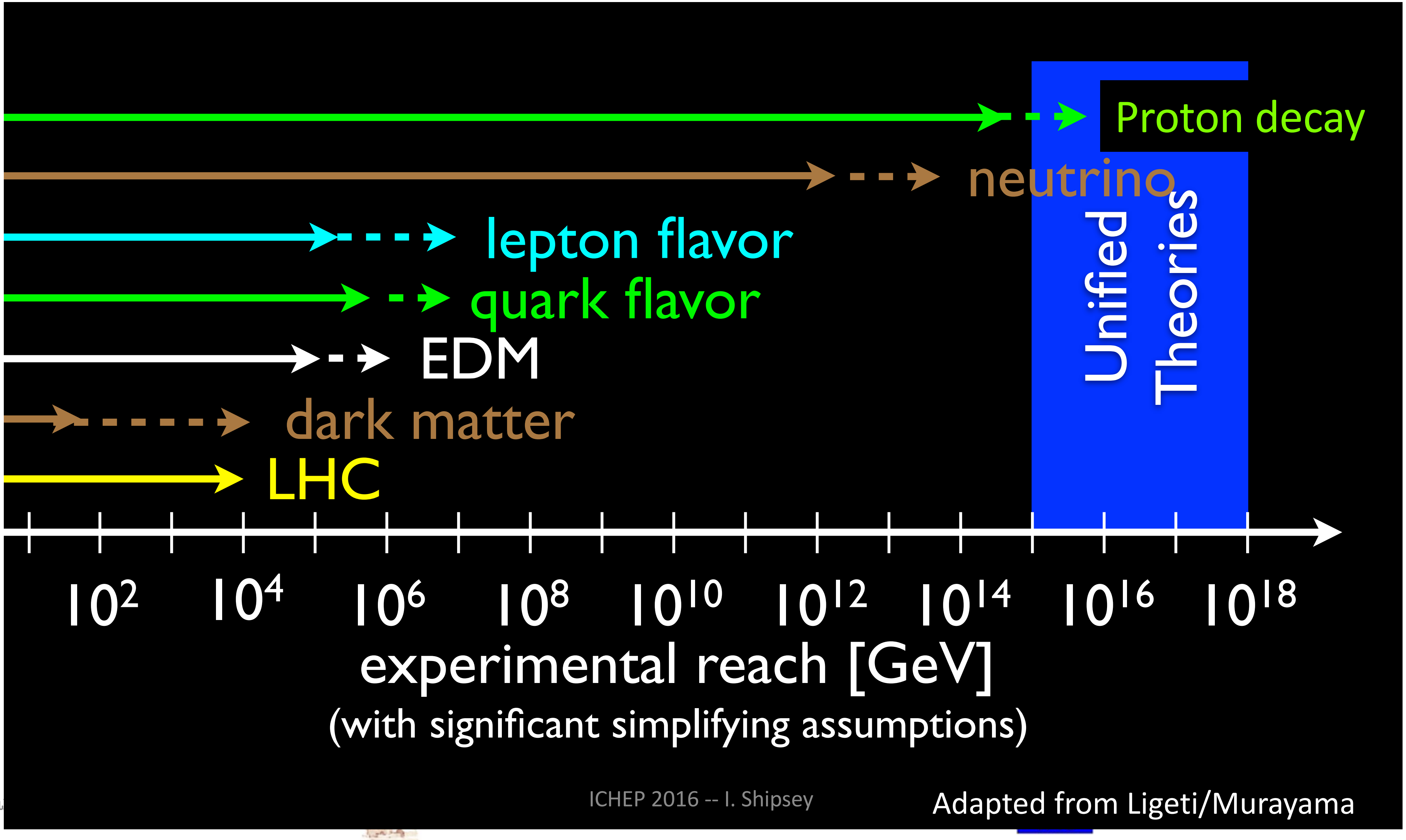




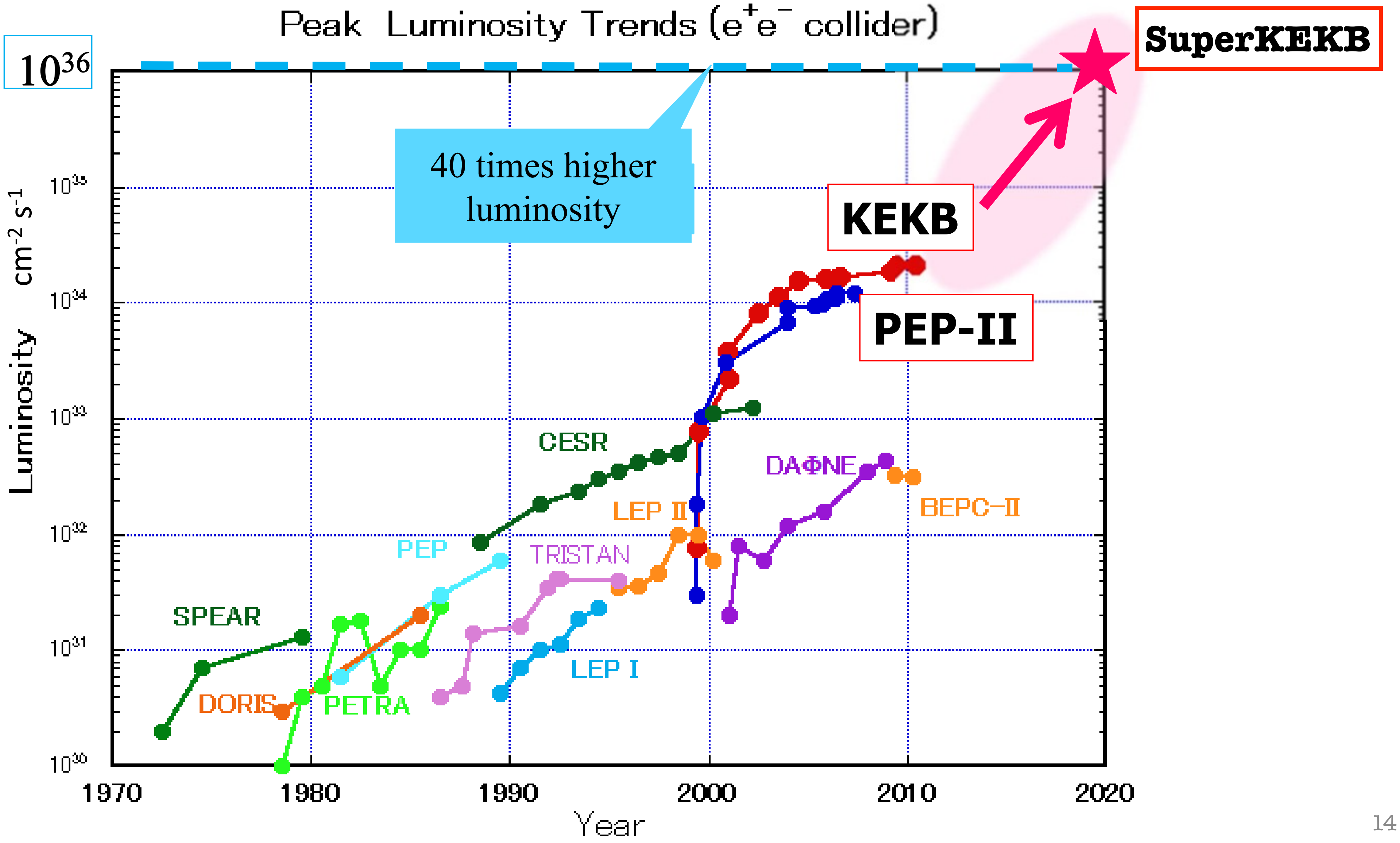




The next decade: the power of quantum loops



The intensity frontier



A musical composition or movement in moderate tempo and duple or quadruple time

Allemande
The SuperKEKB upgrade

How to increase the luminosity?

Lorentz factor

Beam current

Beam-beam parameter

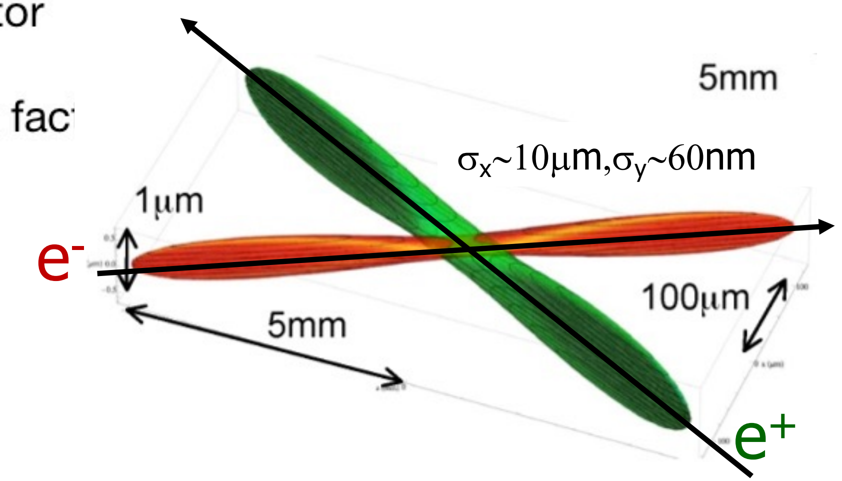
$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Classical electron radius

Beam size ratio@IP
1 - 2 % (flat beam)

Vertical beta function@IP

Lumi. reduction factor
(crossing angle)&
Tune shift reduction fac
(hour glass effect)
0.8 - 1
(short bunch)



(1) Smaller β_y^*
(2) Increase beam currents
(3) Increase ξ_y

"Nano-Beam" scheme

$$\sigma(s) = \sqrt{\epsilon \cdot \beta(s)}$$

Collision with very small spot-size beams

Invented by Pantaleo Raimondi for SuperB

SuperKEKB design parameters

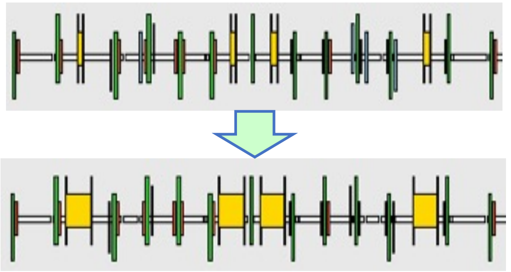
parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7	GeV
Half crossing angle	ϕ	11		41.5		mrad
Horizontal emittance	ε_x	18	24	3.2	4.6	nm
Emittance ratio	κ	0.88	0.66	0.37	0.40	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
Beam currents	I_b	1.64	1.19	3.60	2.60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

- **Nano-beams and a factor of two more beam current** to increase luminosity
- **Large crossing angle**

- **Change beam energies** to solve the problem of short lifetime for the LER
- Consequence β_y: decrease 0.42 → 0.28

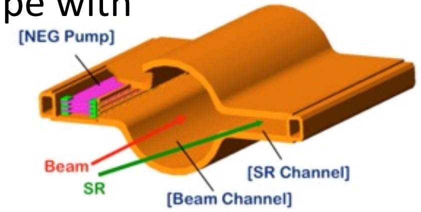
KEKB → SuperKEKB

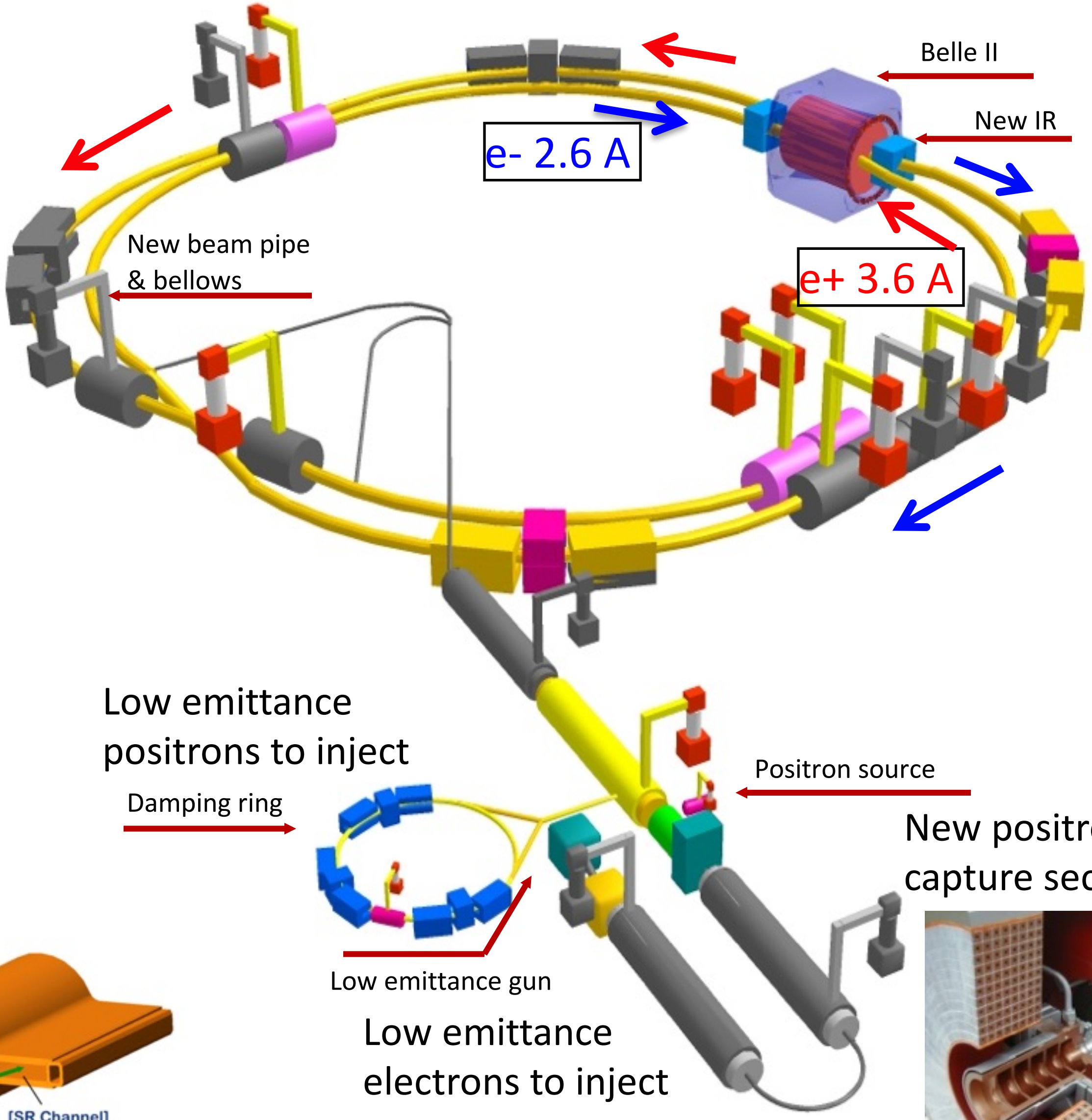
Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers

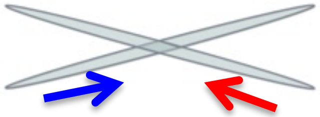




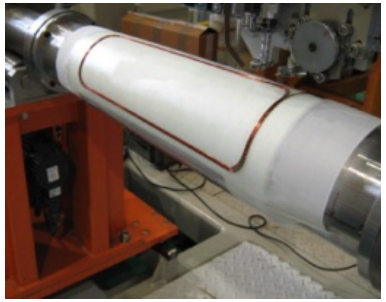
Low emittance positrons to inject

Low emittance electrons to inject

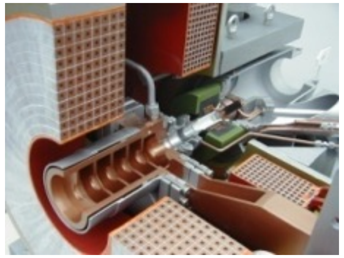
Colliding bunches



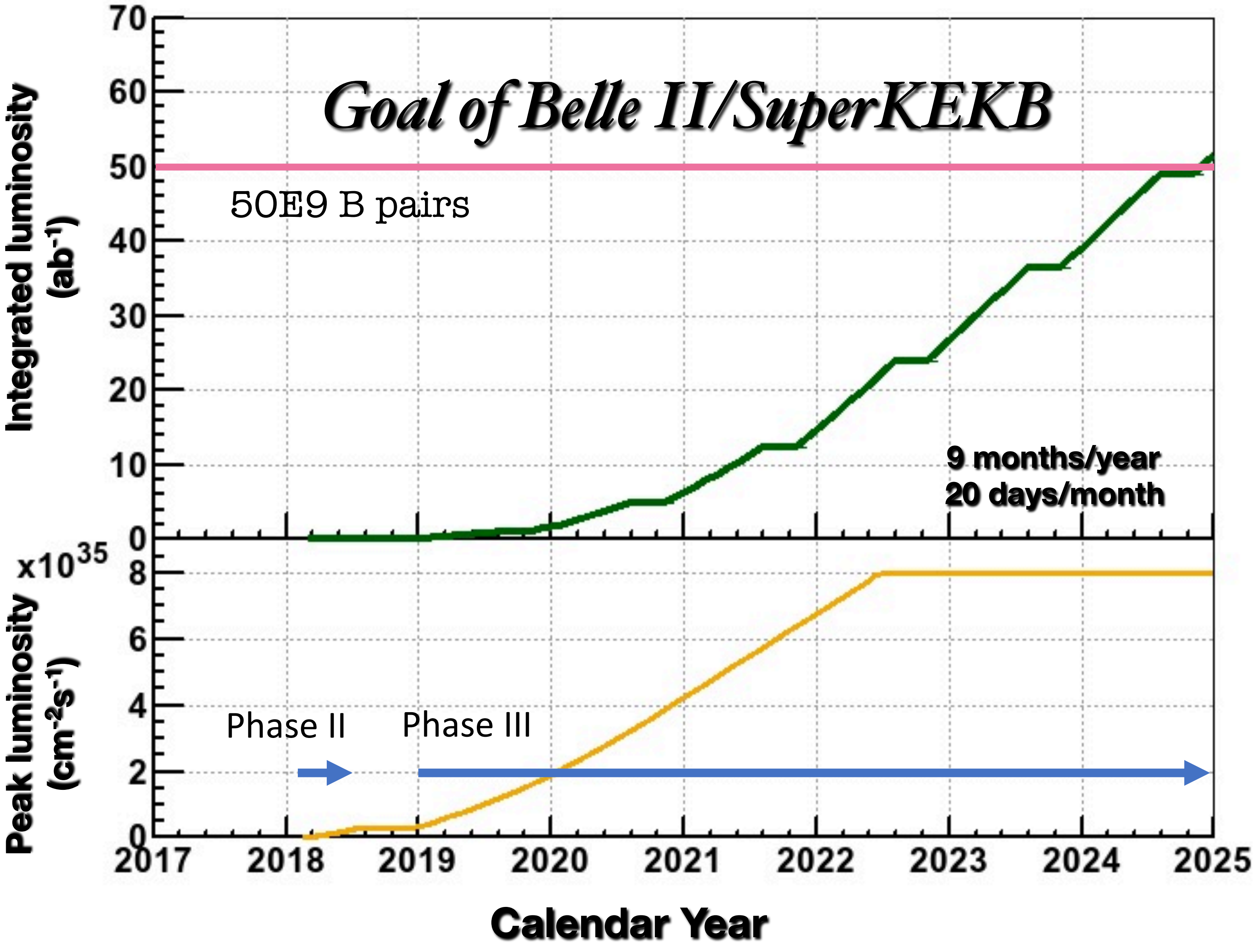
New superconducting /permanent final focusing quads near the IP



New positron target / capture section



Add / modify RF systems for higher beam current



Phase I (2016)

- NO final focus; NO damping ring
- Circulated both beams but no collisions;
- Tune accelerator optics, etc.; vacuum scrubbing
- Beam Background studies with dedicated BEAST II/1 detector

Phase II (2018)

- First collisions
- Beam Commissioning
- Background measurements with BEAST II/2
- Physics run with Belle II without Vertex Detector

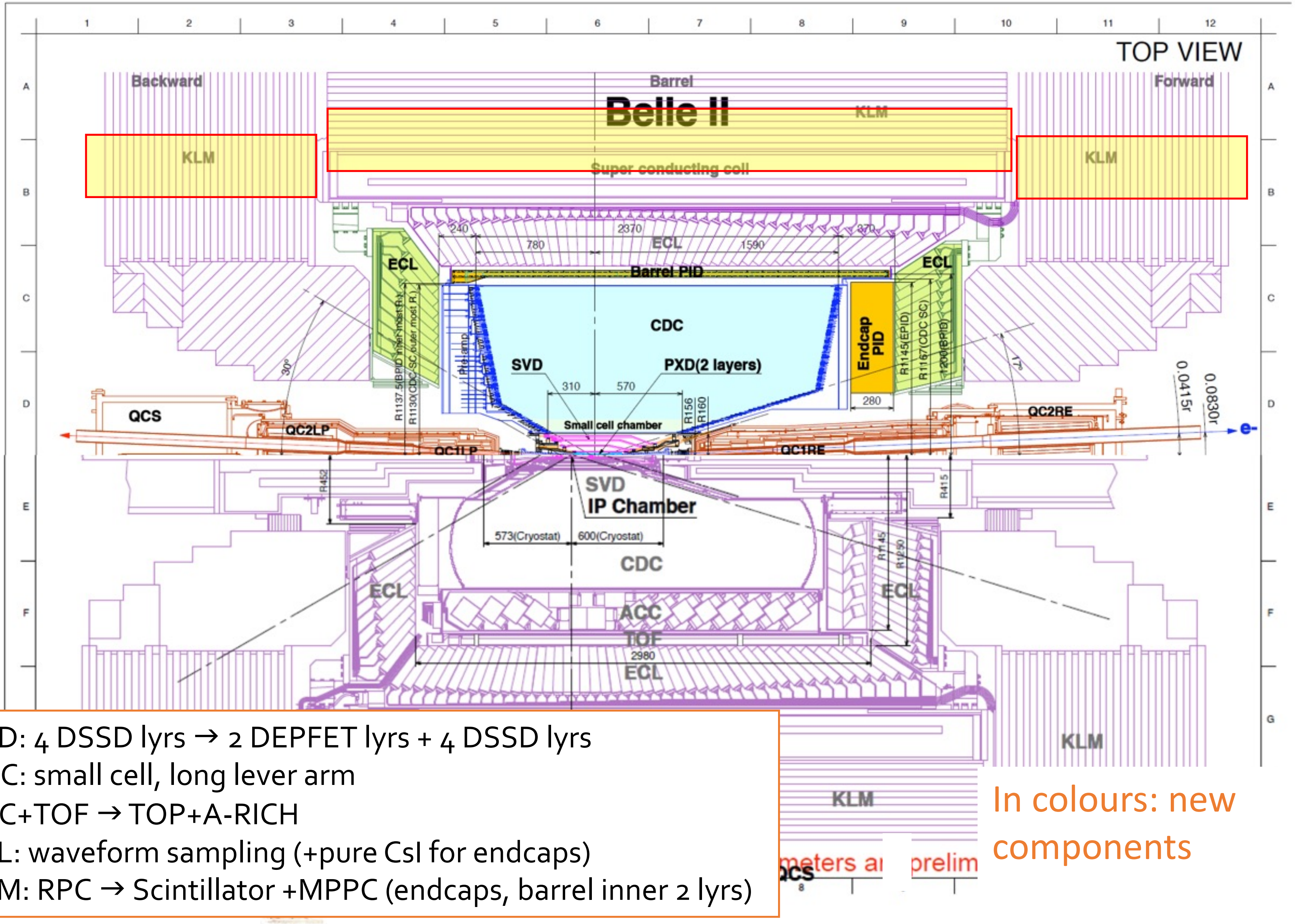
Phase III (2019→)

- Physics run

Music in quick triple time or in a mixture of $^{3}/_{2}$ and $^{6}/_{4}$ time

Courante
The Belle II upgrade

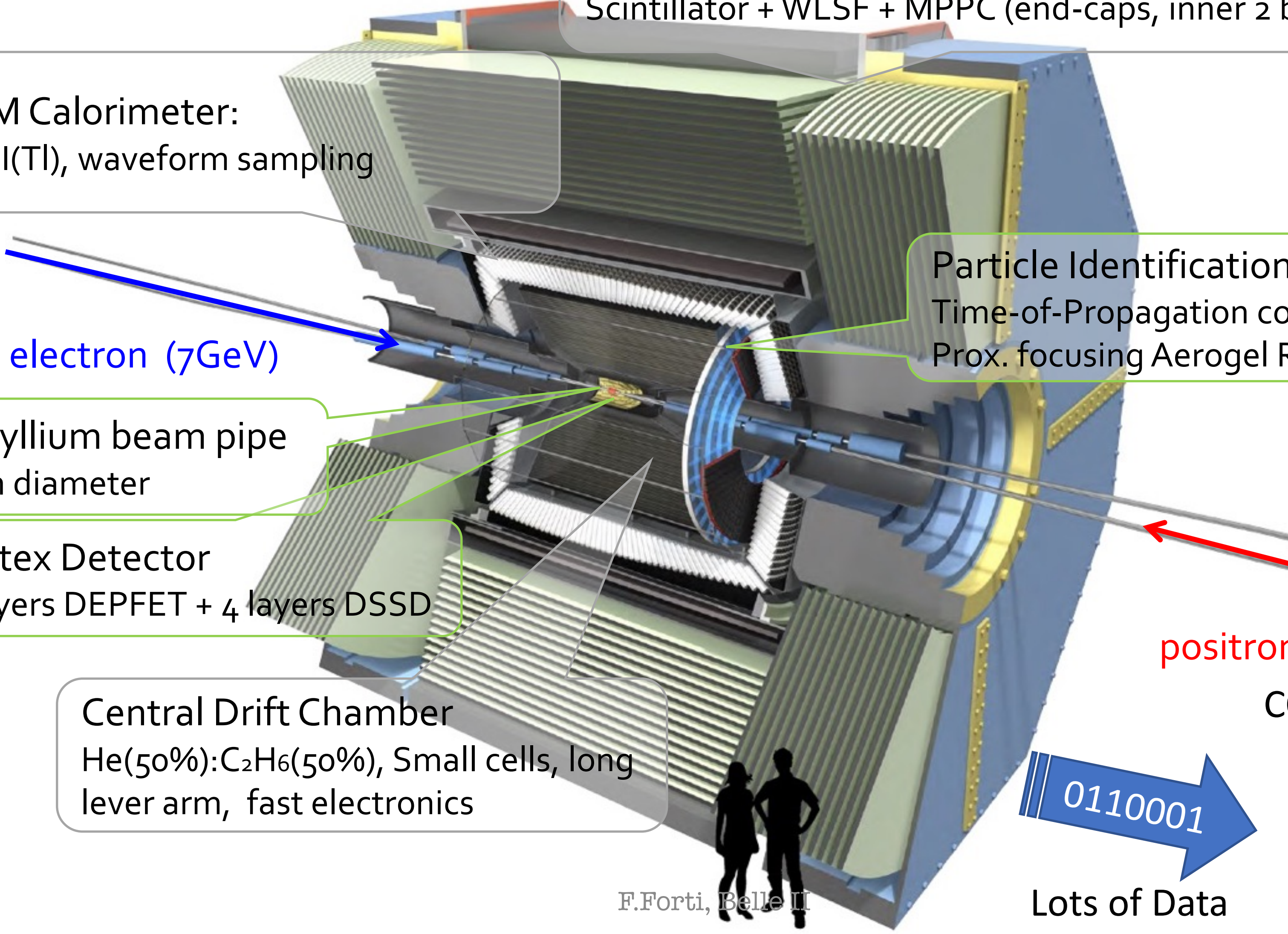
Belle II Detector (in comparison with Belle)



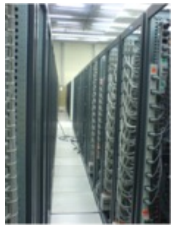
SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

In colours: new components

Belle II Detector



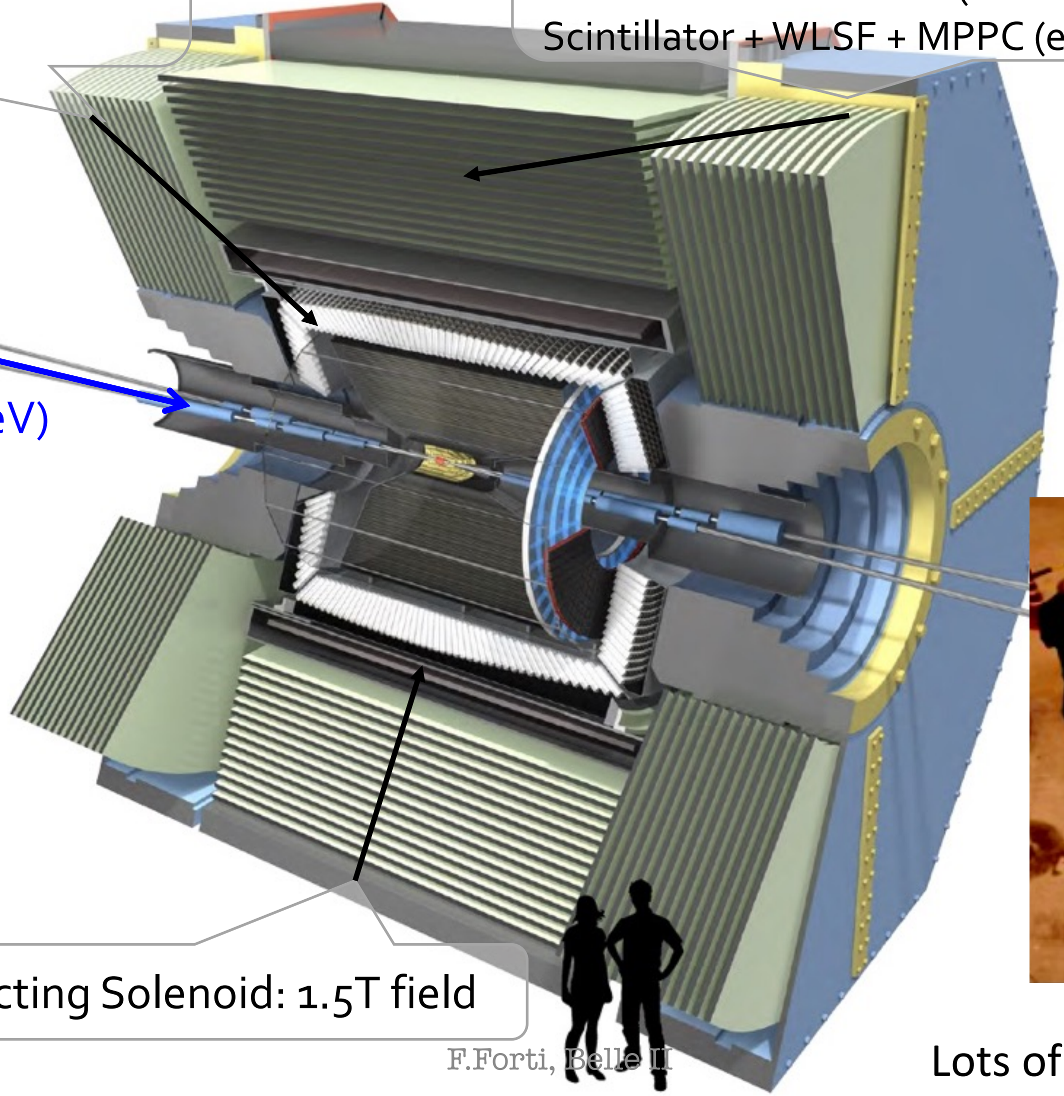
COMPUTING

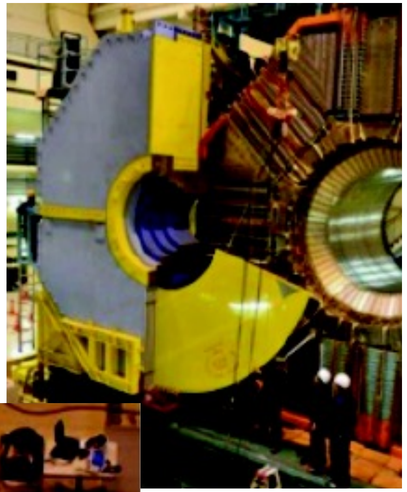


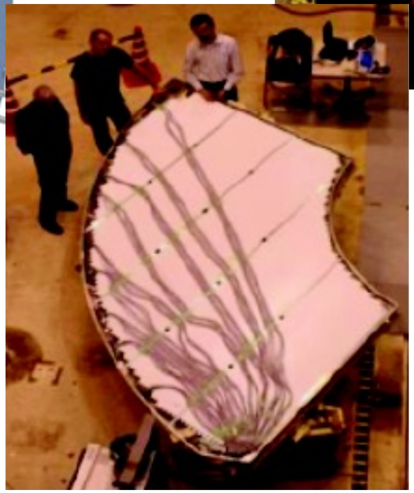
Belle II Detector – KLM and ECL

ECL: EM Calorimeter - Measure photons, identify electrons
CsI(Tl) crystals, waveform sampling

KLM: K_L and muon detector -
Identify muons (penetration) and KL (showers)
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)







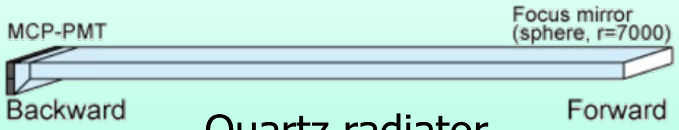
Superconducting Solenoid: 1.5T field

Lots of Data

Particle Identification Devices

Crucial to separate π from K

Barrel PID: Time of Propagation Counter (TOP)



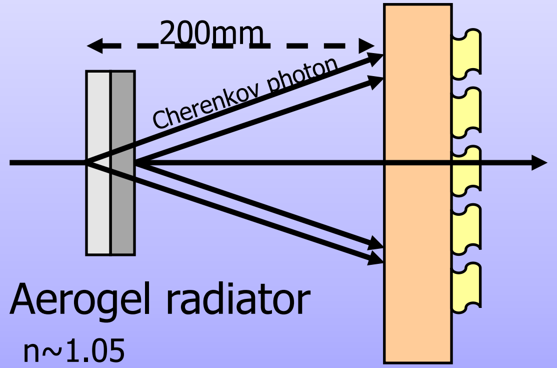
Quartz radiator

Focusing mirror

Small expansion block

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

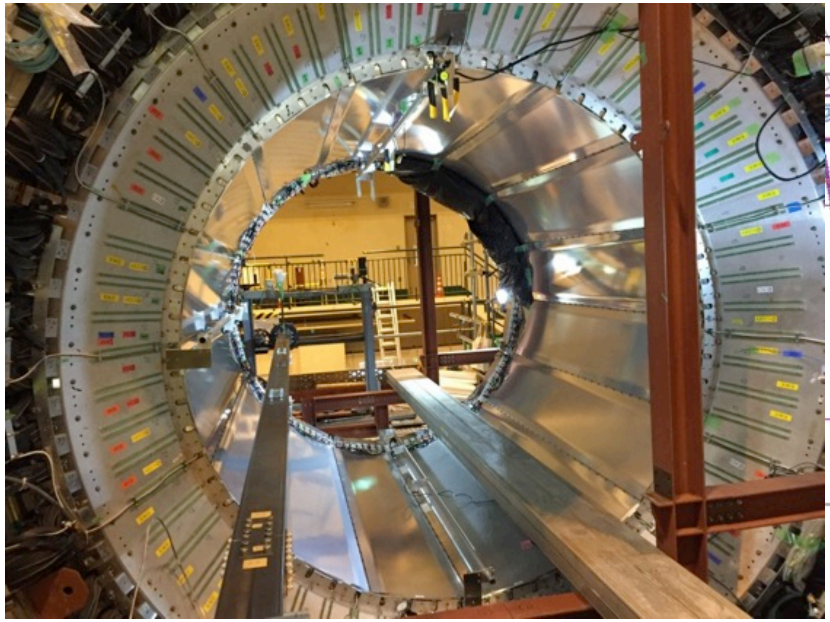
Endcap PID: Aerogel RICH (ARICH)

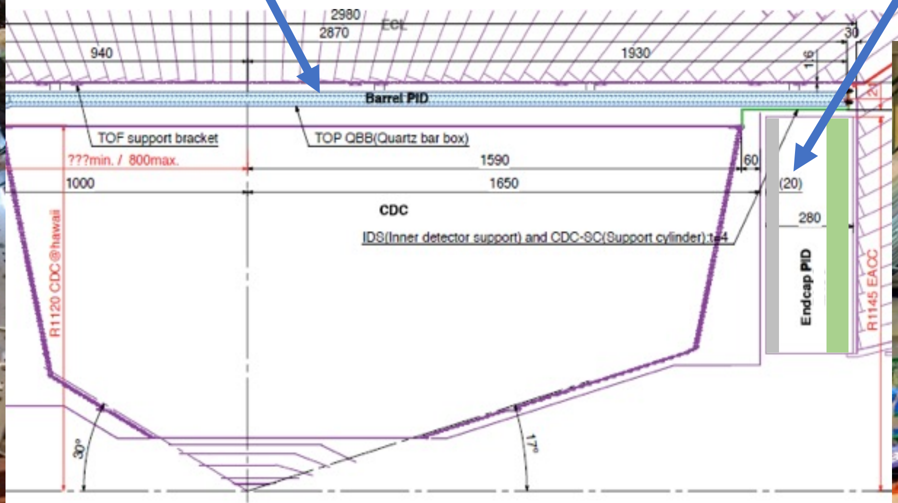


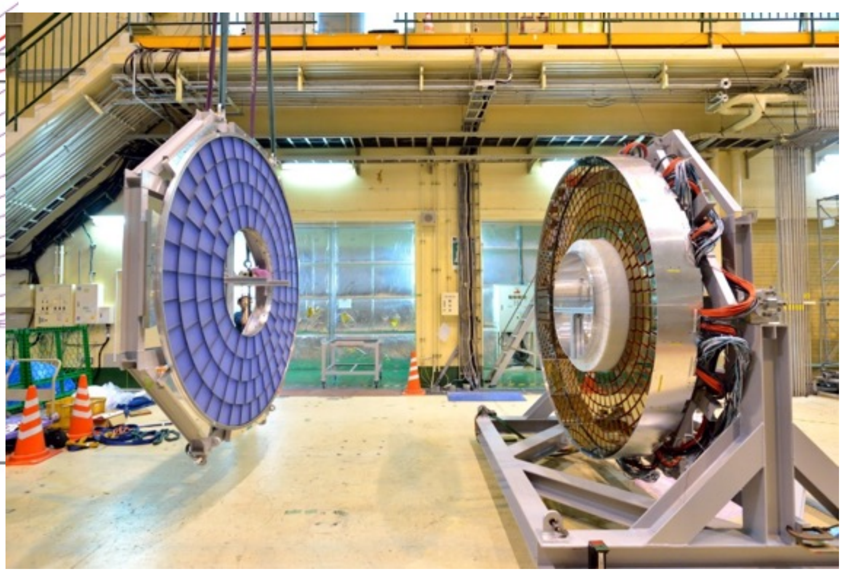
Aerogel radiator

n~1.05

Hamamatsu HAPD

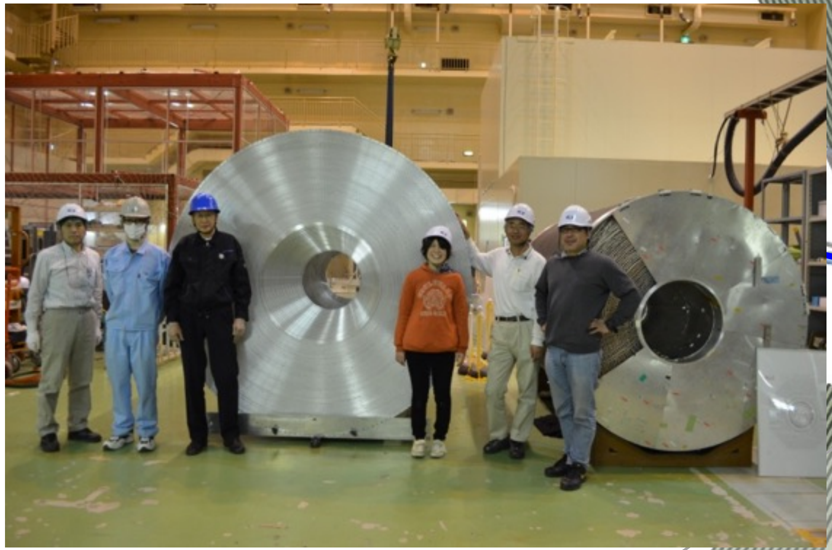


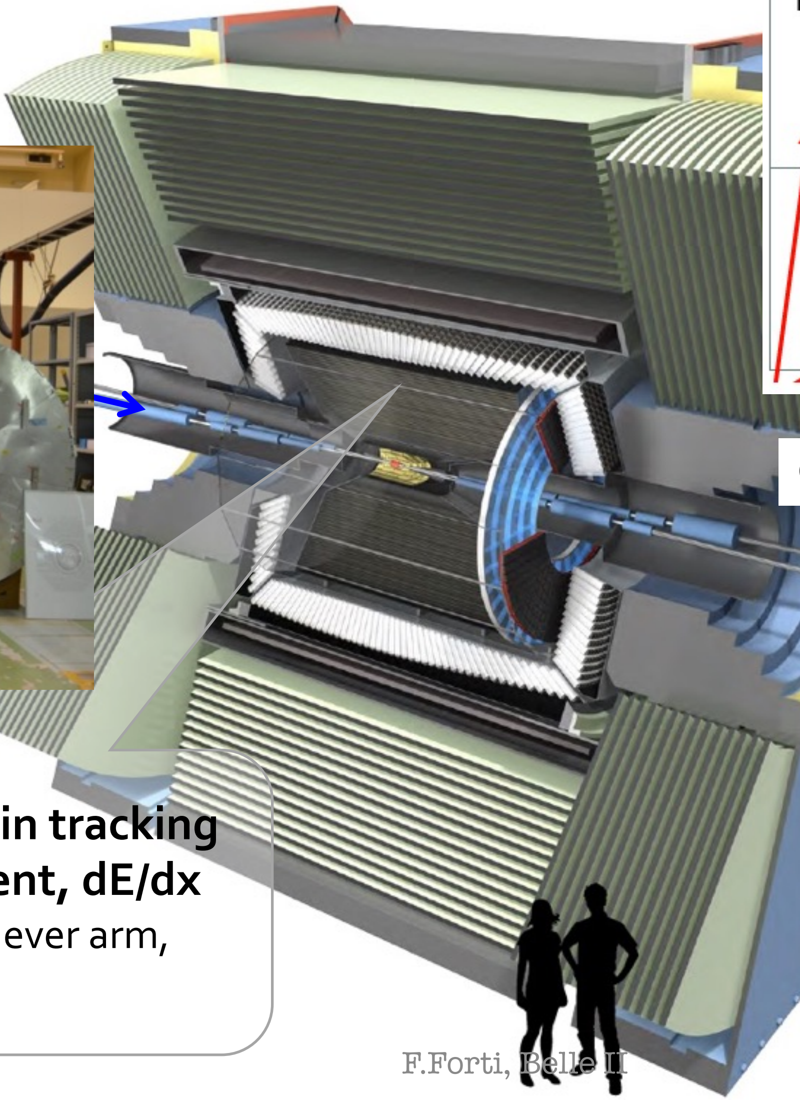


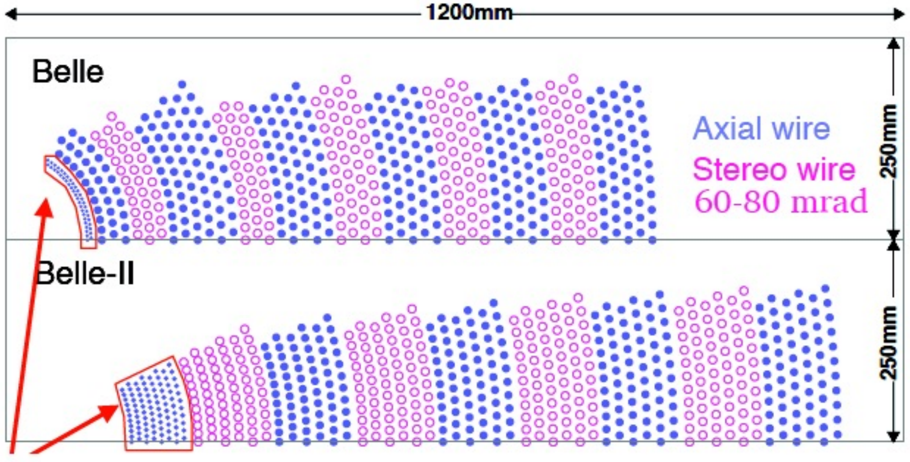


Belle II Detector Central Drift Chamber

Much bigger than in Belle!





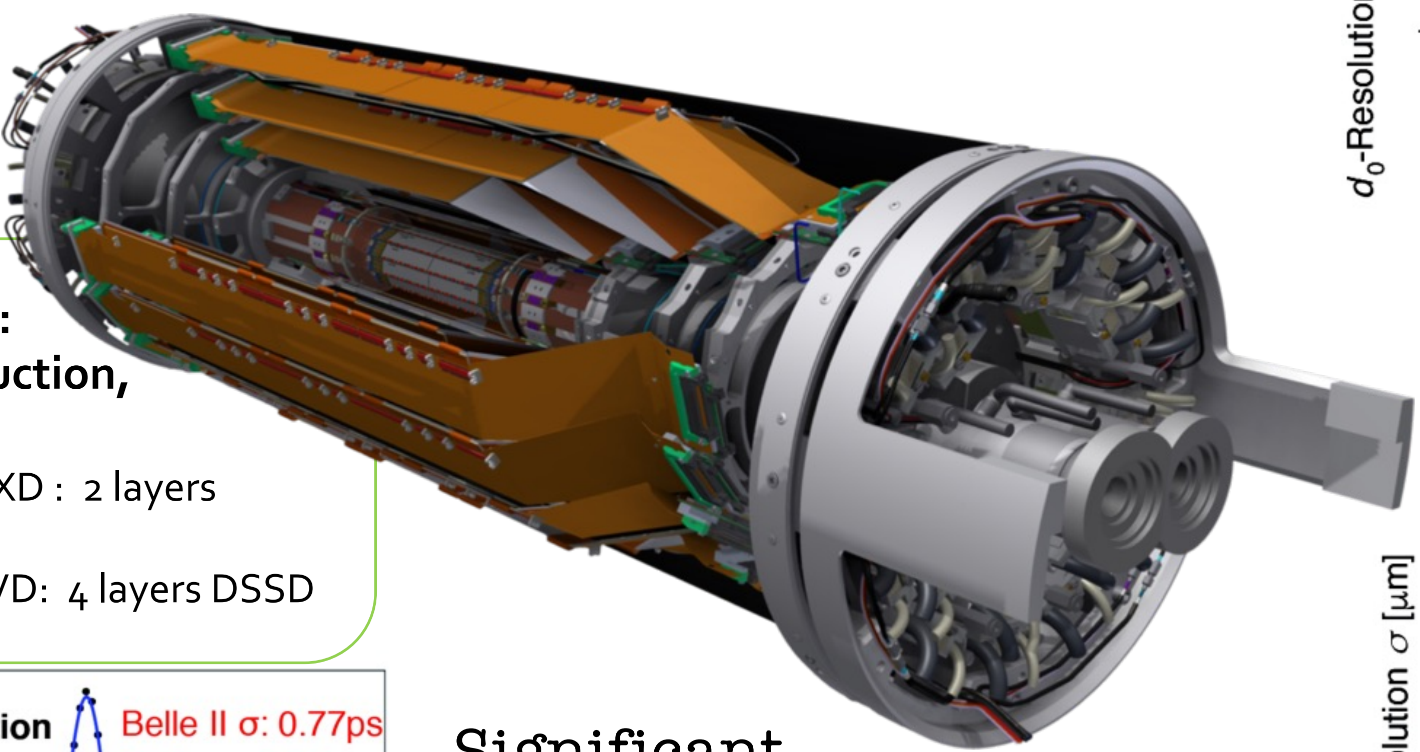


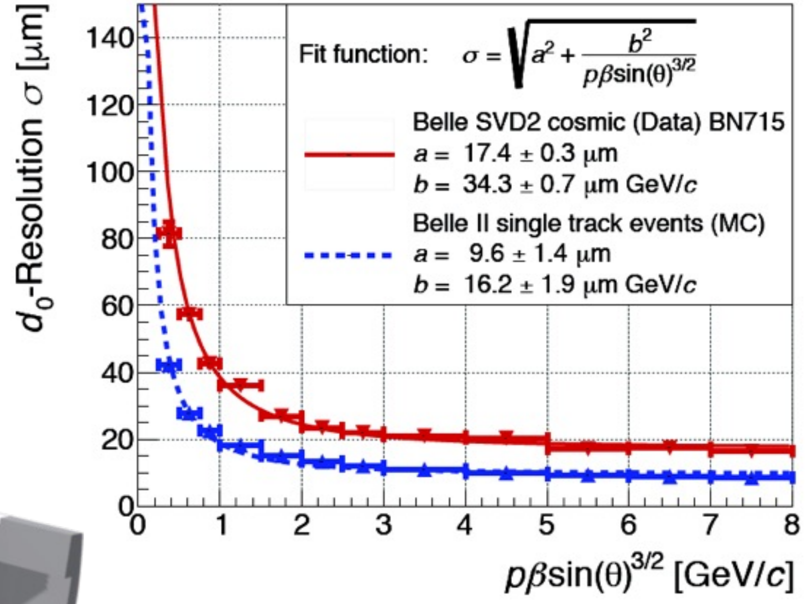
Oct 2016: Central Drift Chamber inside Belle II

CDC: Central Drift Chamber - Main tracking device - Momentum measurement, dE/dx

He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

Vertex Detector – PXD & SVD

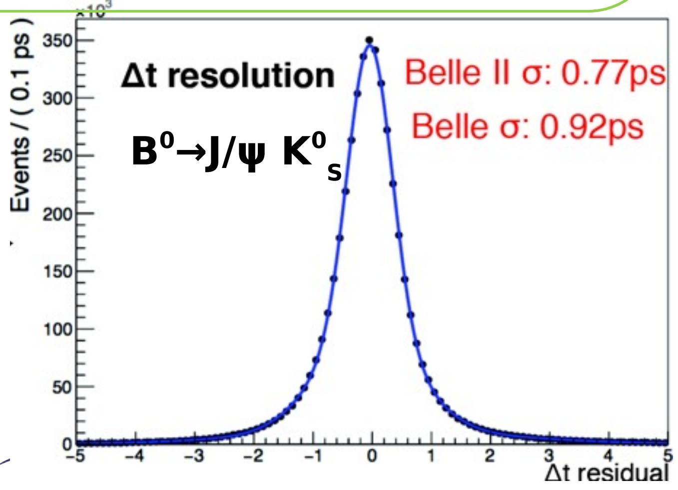




Vertex Detector:
Vertex reconstruction,
low p tracking

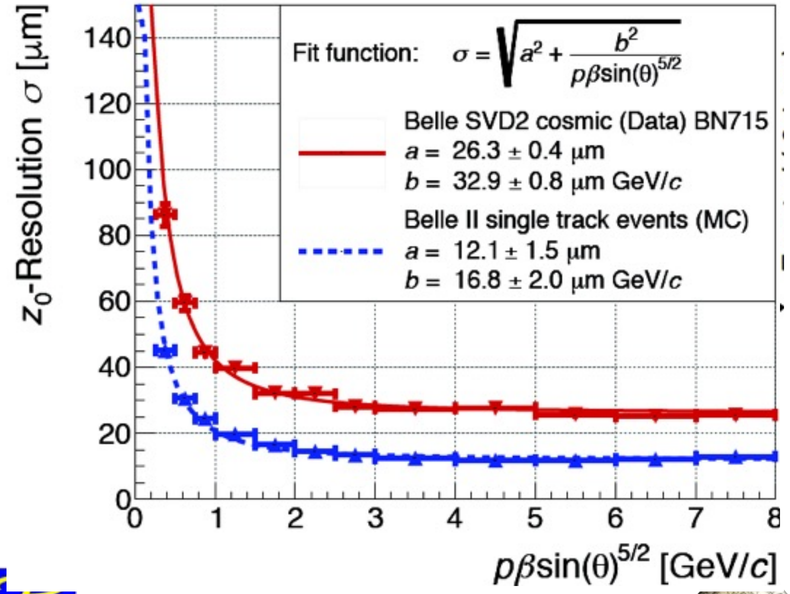
Pixel detectors – PXD : 2 layers DEPFET

Strip detectors - SVD: 4 layers DSSD



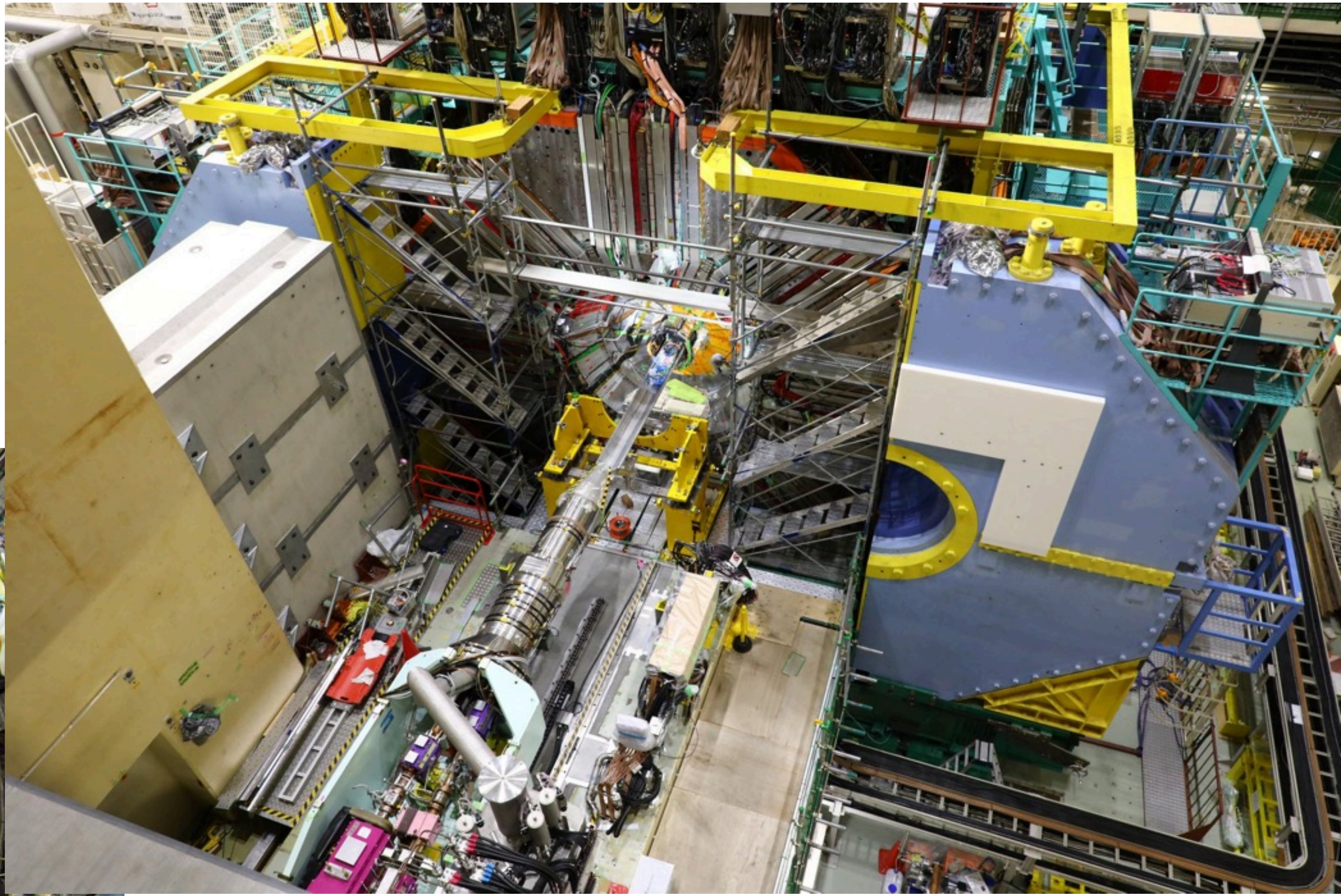
Significant improvements in vertex resolution w.r.t. Belle

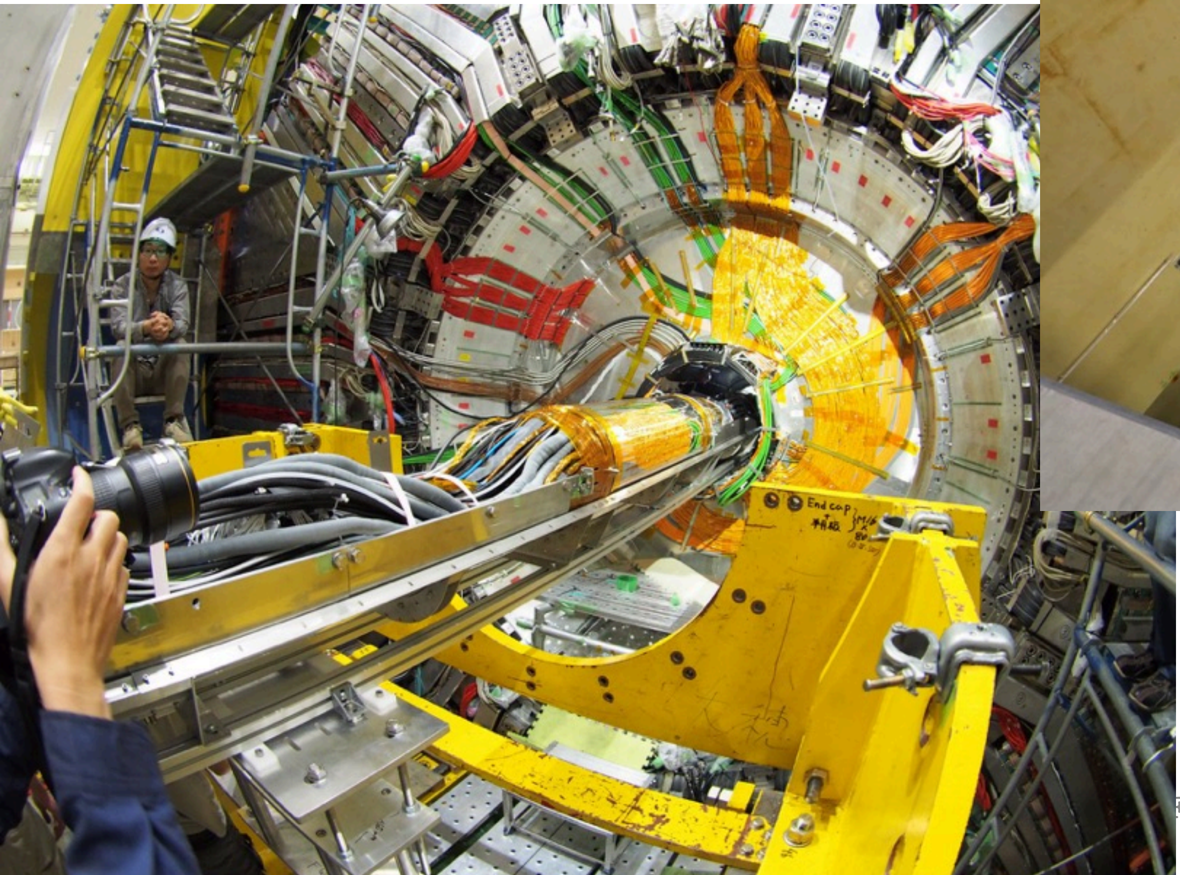
PXD: Only L1 + 1/6 of L2
Full detector in 2020



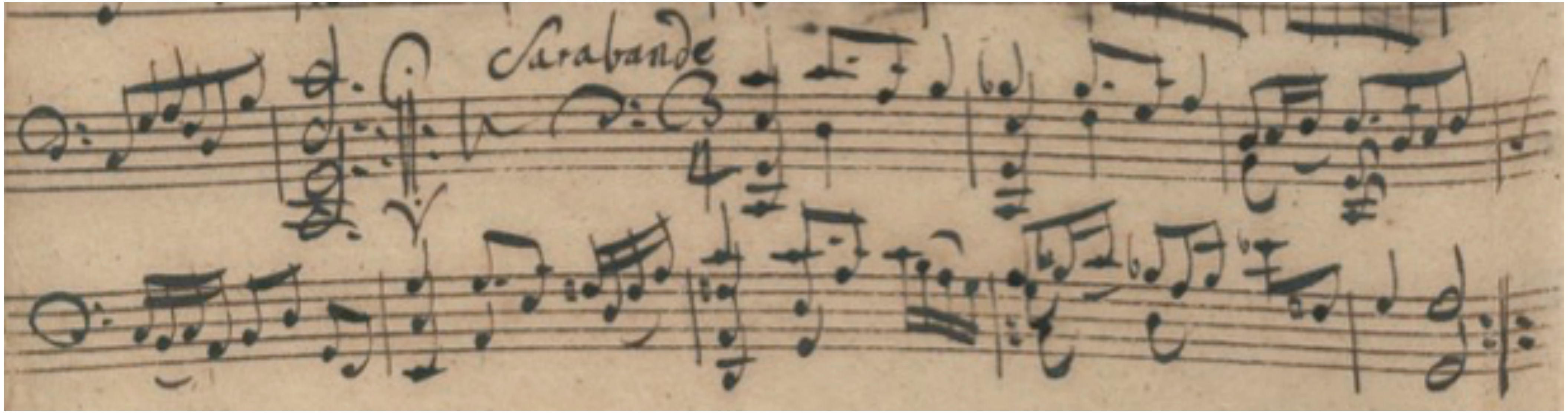
SVD – PXD Marriage Oct 3, 2018

VXD Installation Dec 2018





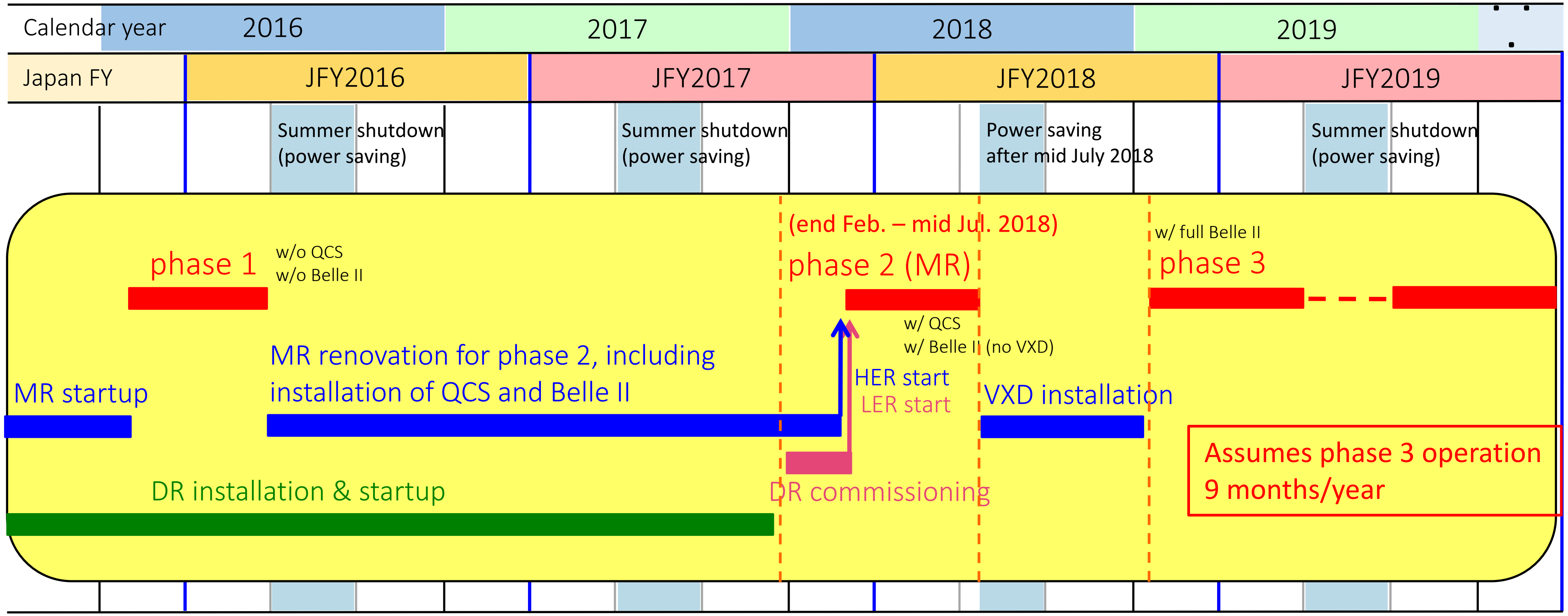
Belle II Collaboration



A music in slow triple time with accent on the second beat

Sarabande
Phase 2 running (2018)

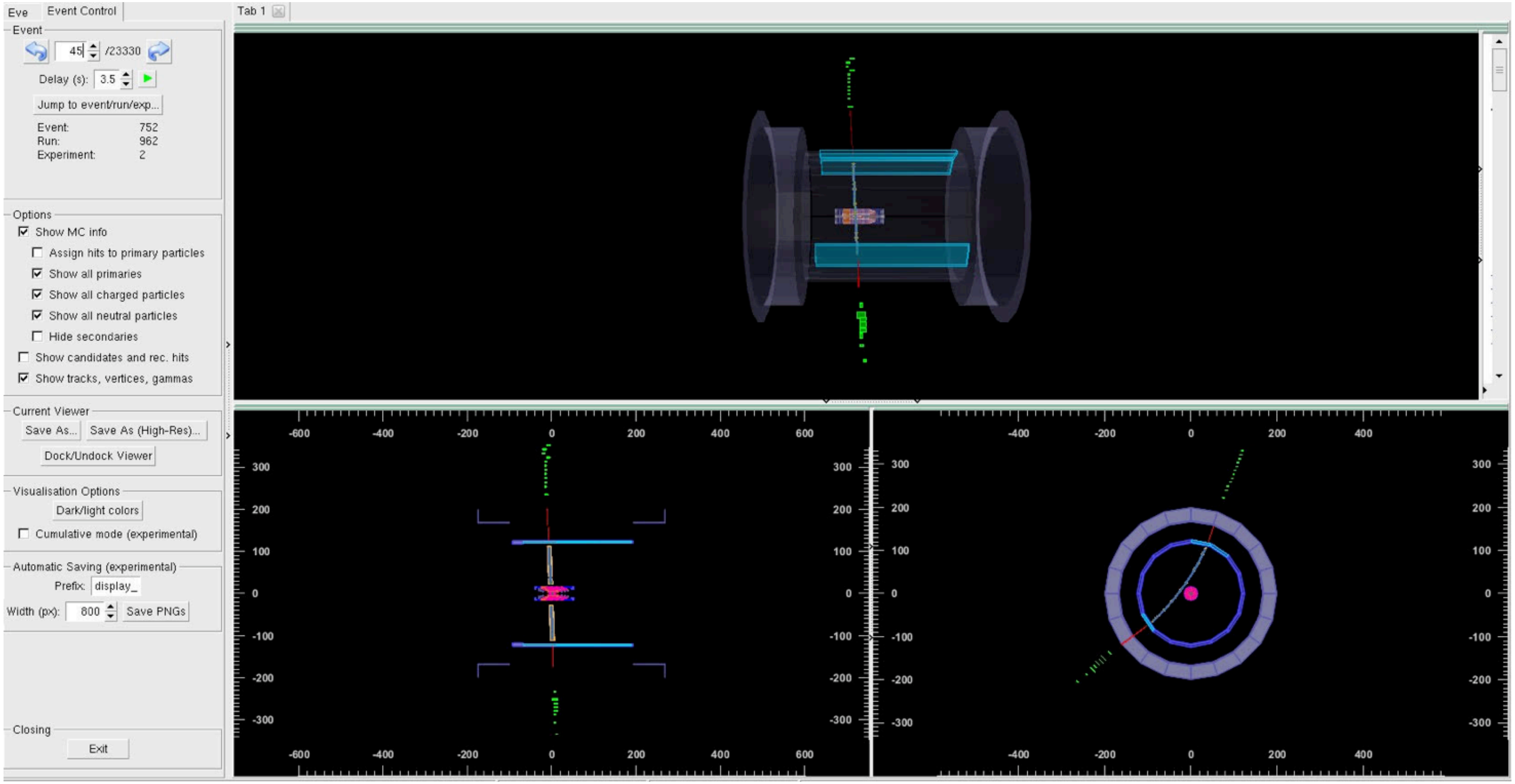
SuperKEKB/Belle II schedule



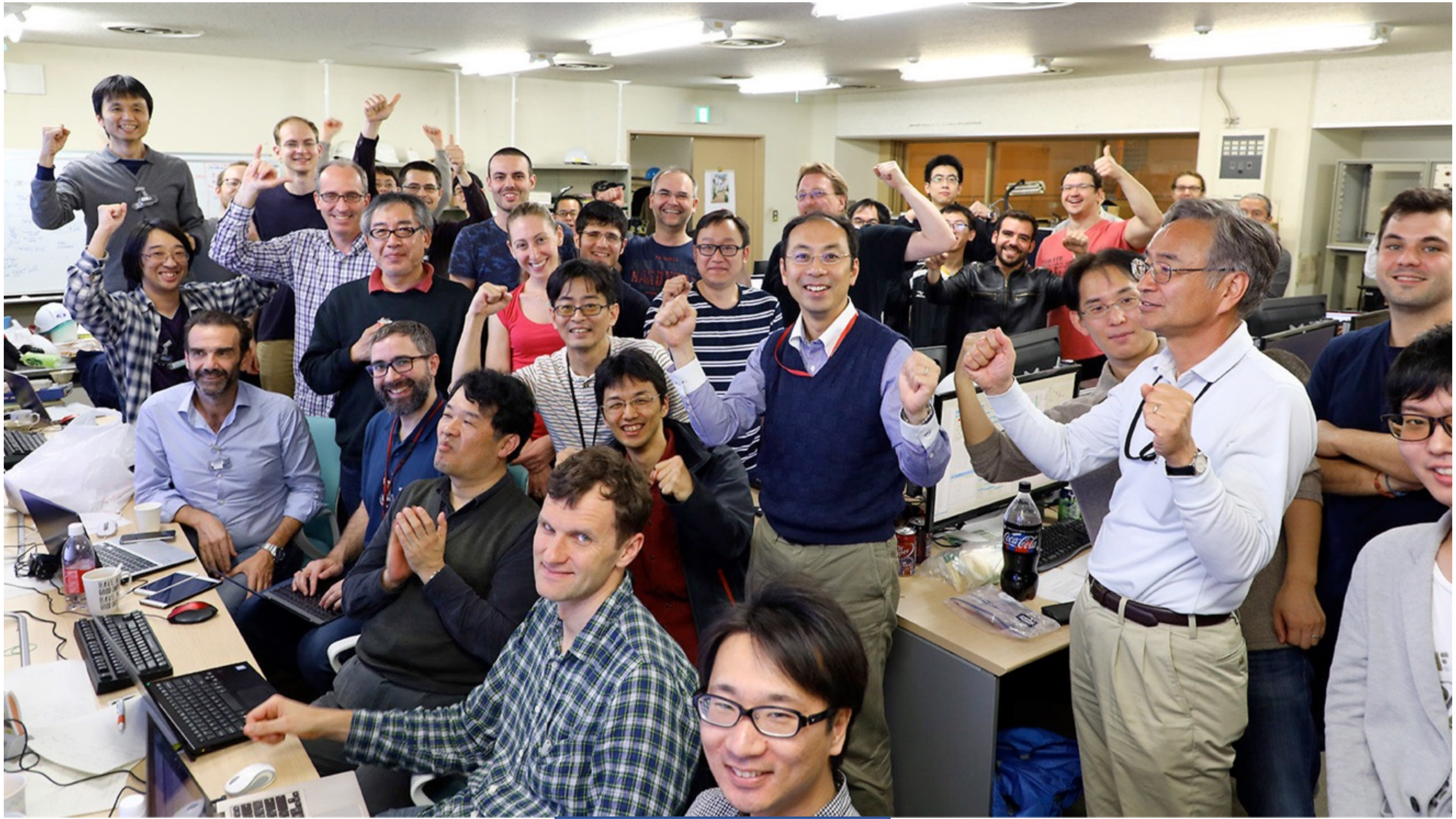
First collisions on Apr 26, 2018

Phase 3 will start in March 2019, slightly delayed from the original plan

First cosmic events – early 2018

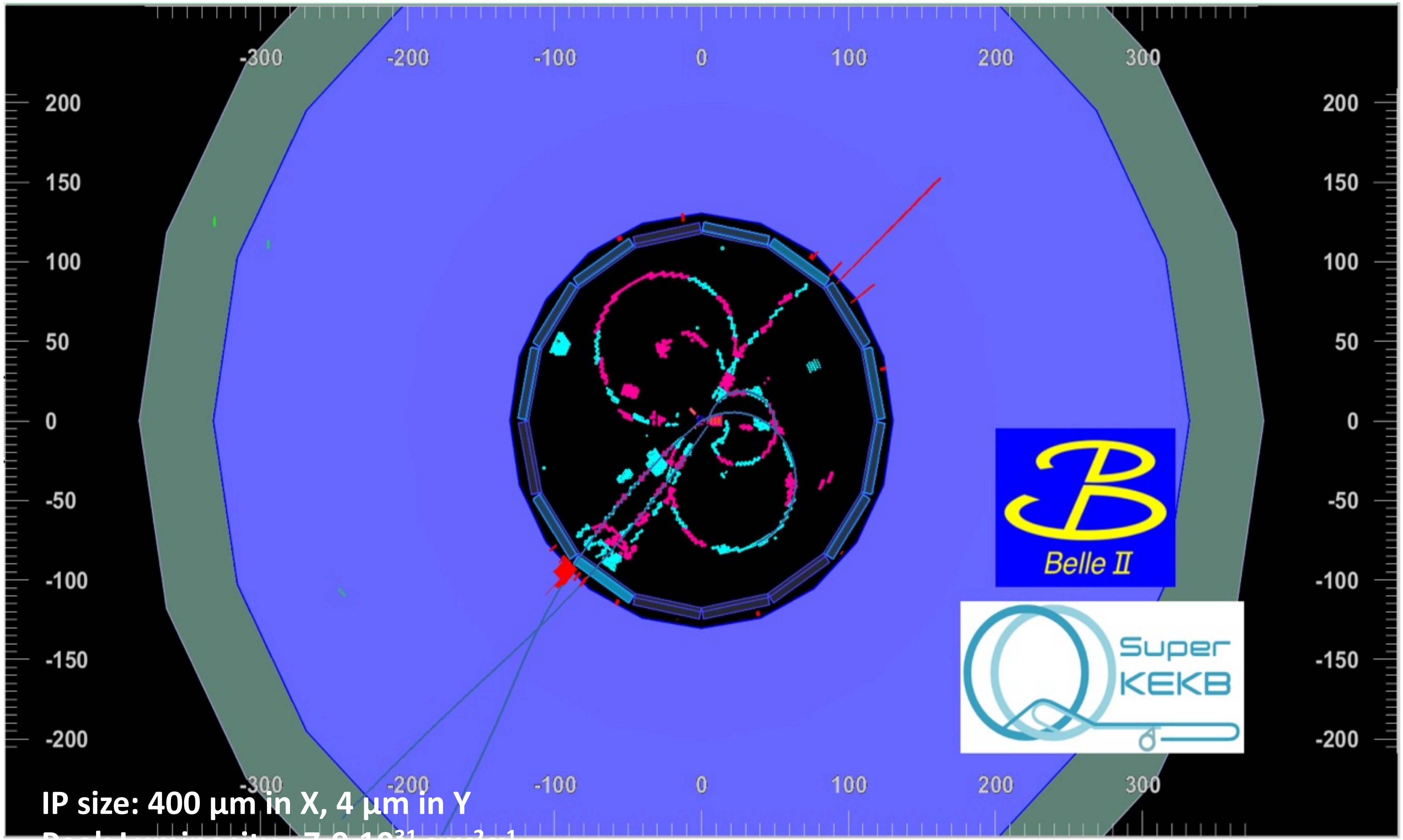


First collisions in Tsukuba Hall B3 Control Room



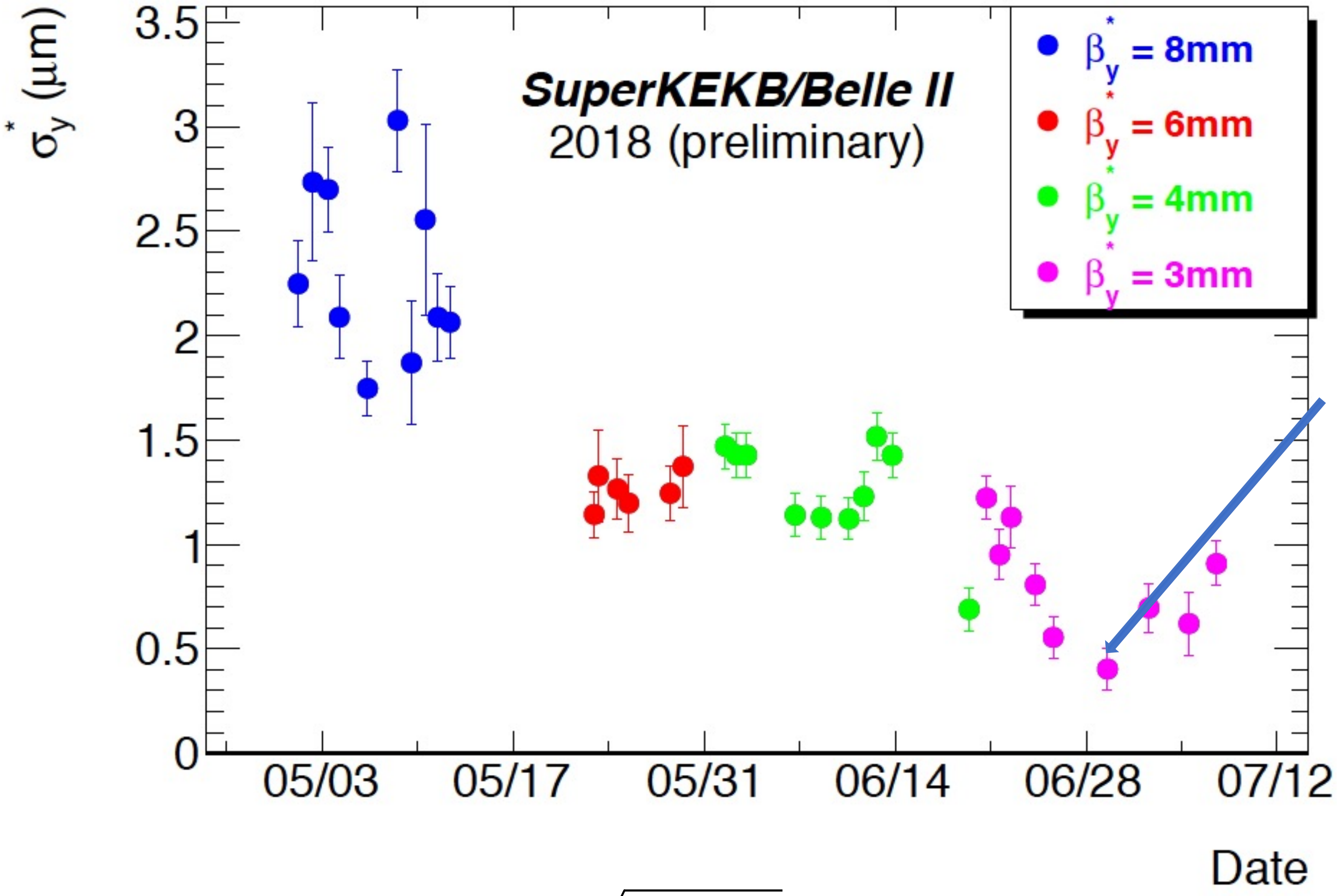
Apr 26, 2018

One of the first events, probably $e^+e^- \to \gamma^* \to q\bar{q}$



Nanobeams, how do we know ?

- Measure width of luminosity scan with diamond detectors
- Big improvements, but still struggling with beam blow-up



$$\sigma(s) = \sqrt{\epsilon \cdot \beta(s)}$$

1. For early Phase 3, we will continue with β_y^*=3mm

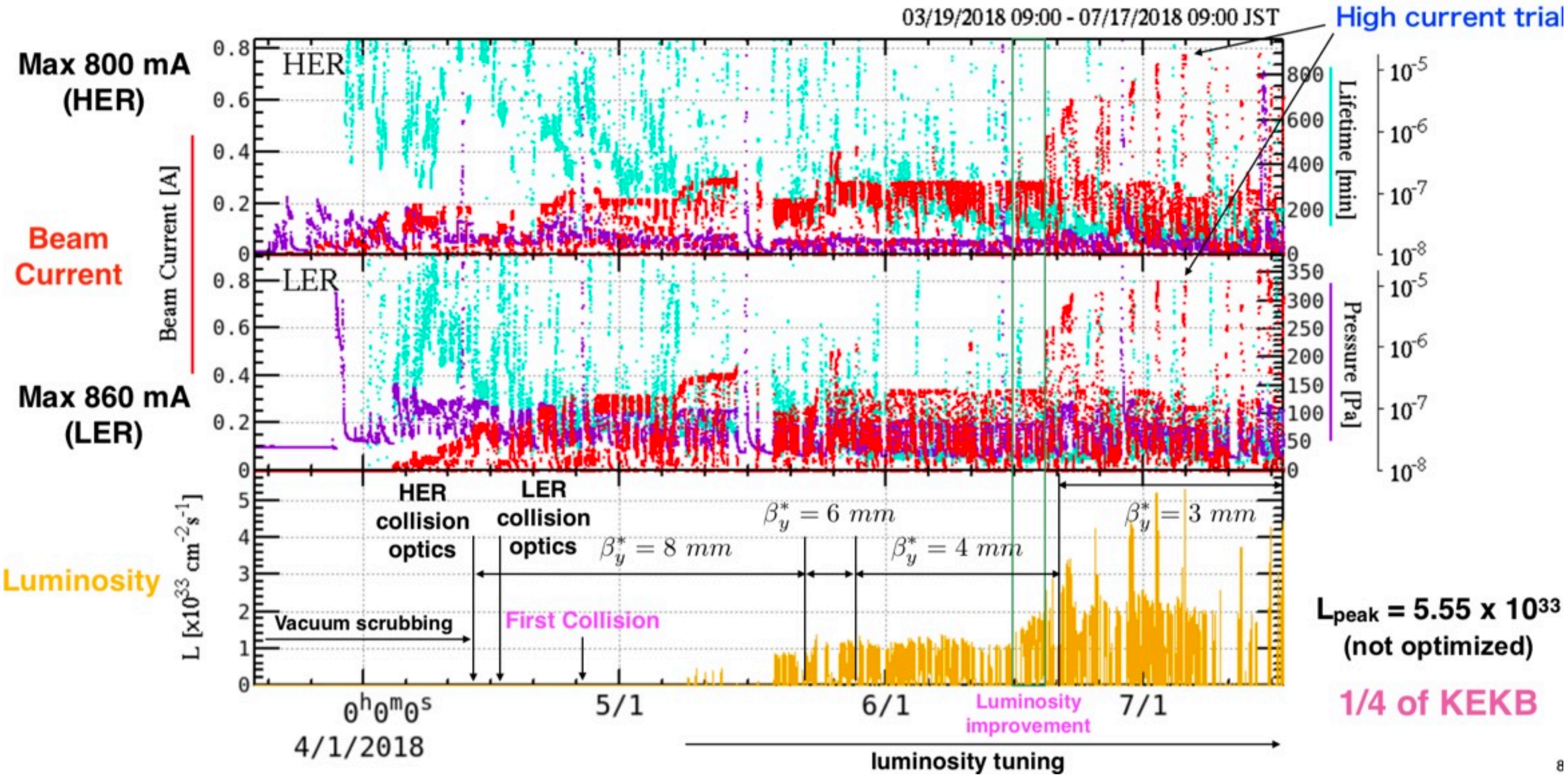
2. The record is $\sigma_y \sim$ 400 nm and beam currents of only ~15mA

3. Final Target is β_y^*=0.3mm, σ_y~60nm

Phase 2 in a nutshell

$$L_{peak} = 5.5 \times 10^{33} / cm^2 / \sec$$

Integrated luminosity ~ 500/pb
Measured with ee→ ee(γ), γγ, μμ(γ)

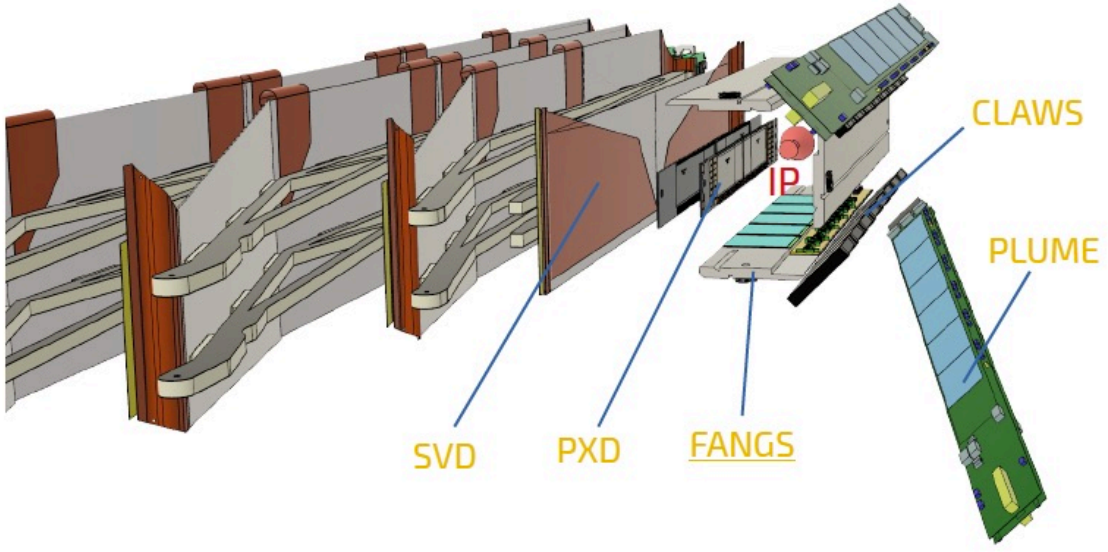


Priority given to machine tuning

N.B. Still a long way to go with the superconducting final focus (one order of magnitude in β_y^*)

PEP-II design luminosity 3 x 10^{33}

VXD Volume in Phase II



Beam backgrounds

Short story:

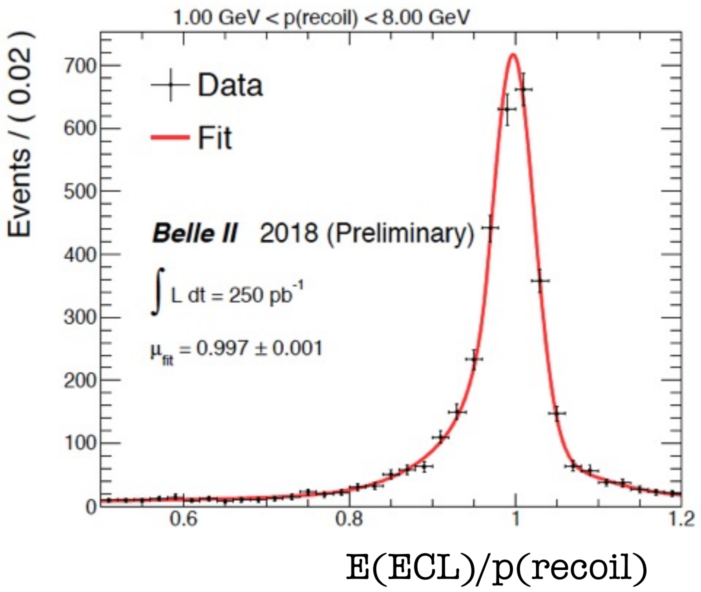
- Backgrounds during phase 2 running are larger than anticipated, but reasonably controllable and not dangerous for the detector.
- →Decision to complete detector installation
- New collimators in machine will give additional handles on background control
  - Large reduction factor (O(10) or more) needed to ramp up in luminosity → Significant challenge

A musical composition with the rhythm of quick duple time

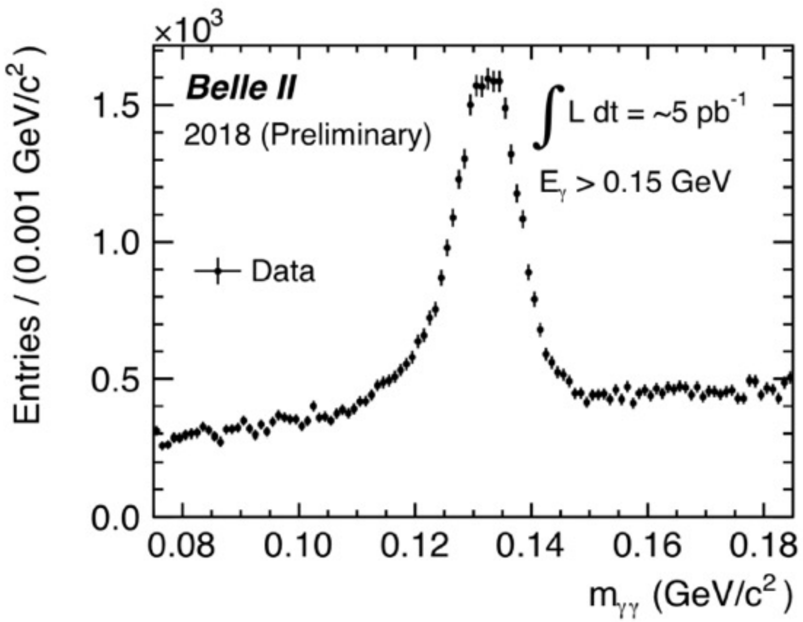
Bourrée
Physics commissioning

Signals involving photons

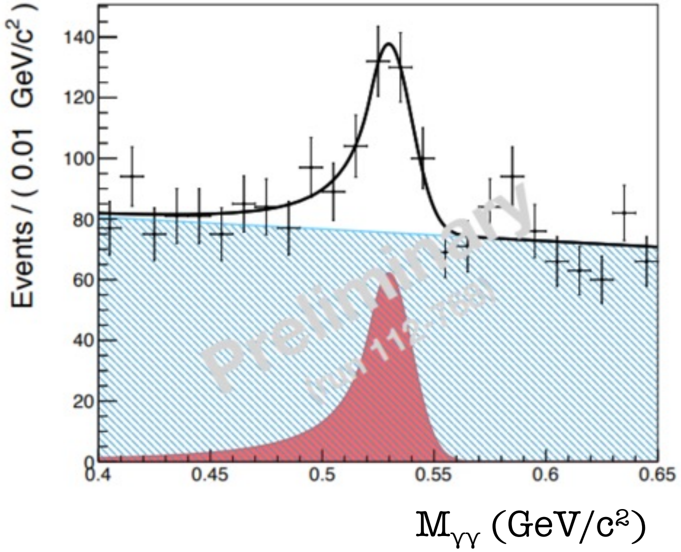
$e^+e^- \to \mu^+\mu^-\gamma$



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



$\eta \to \gamma\gamma$



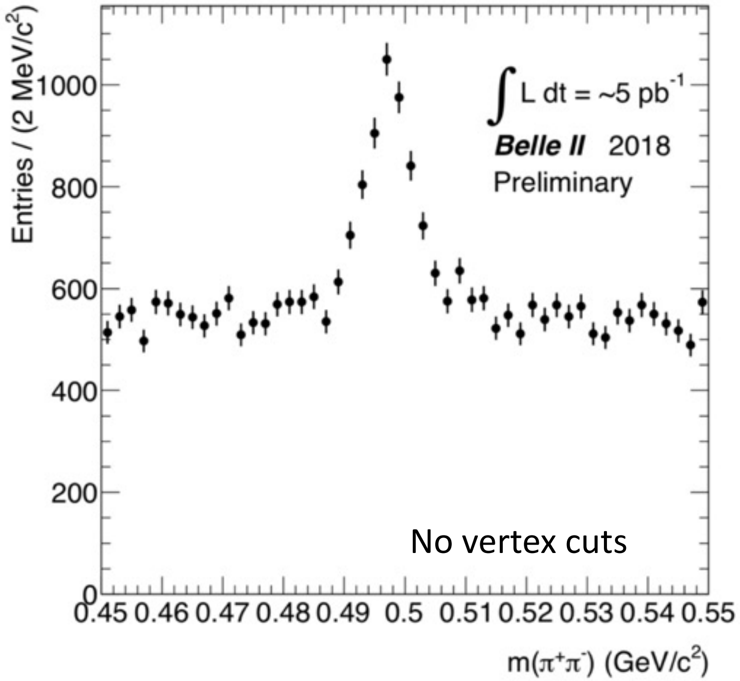
- Good reconstruction of both single photons and pairs
- Ready for the "dark sector" – single photons

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

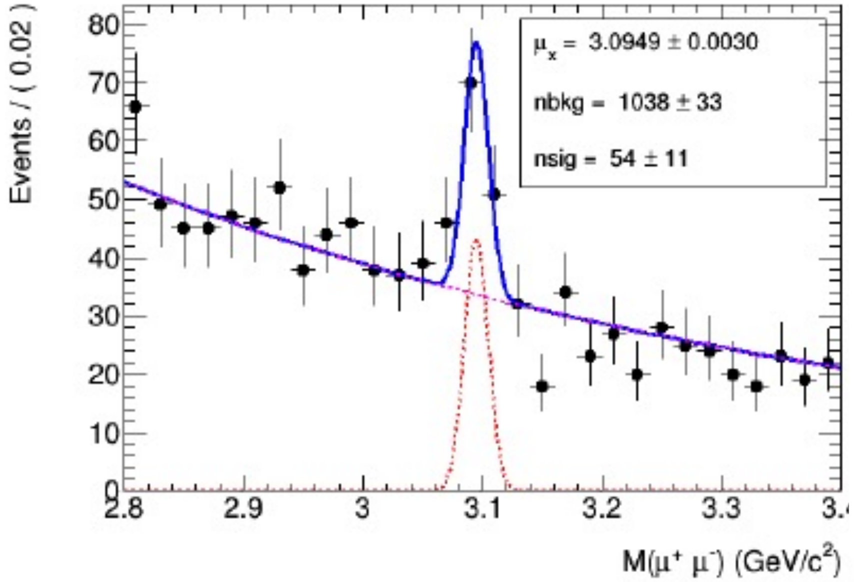
$$e^+e^- \to \gamma ALP \to \gamma(\gamma\gamma)$$

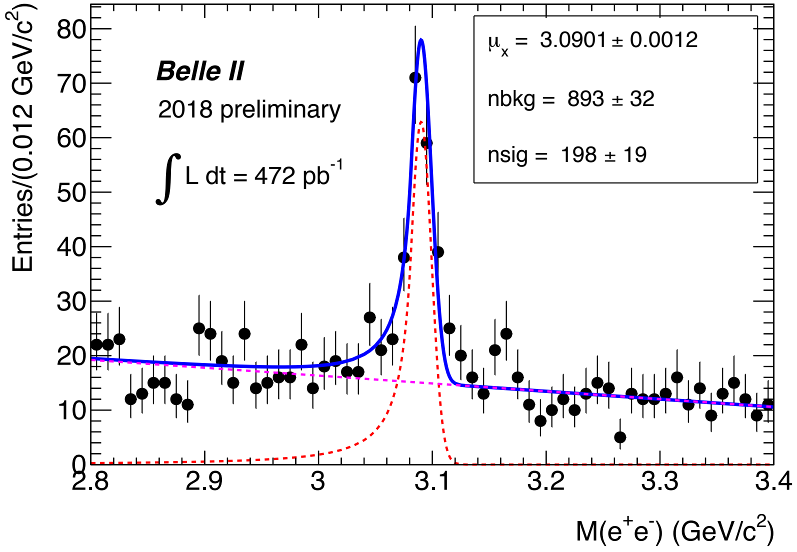
Signals involving charged tracks

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



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



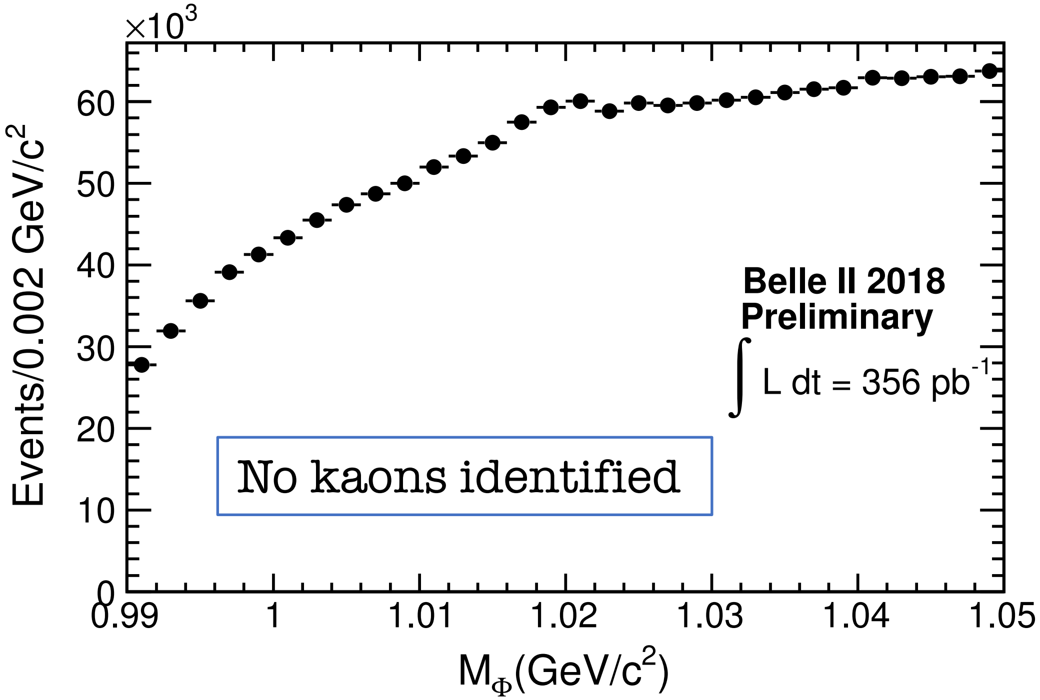


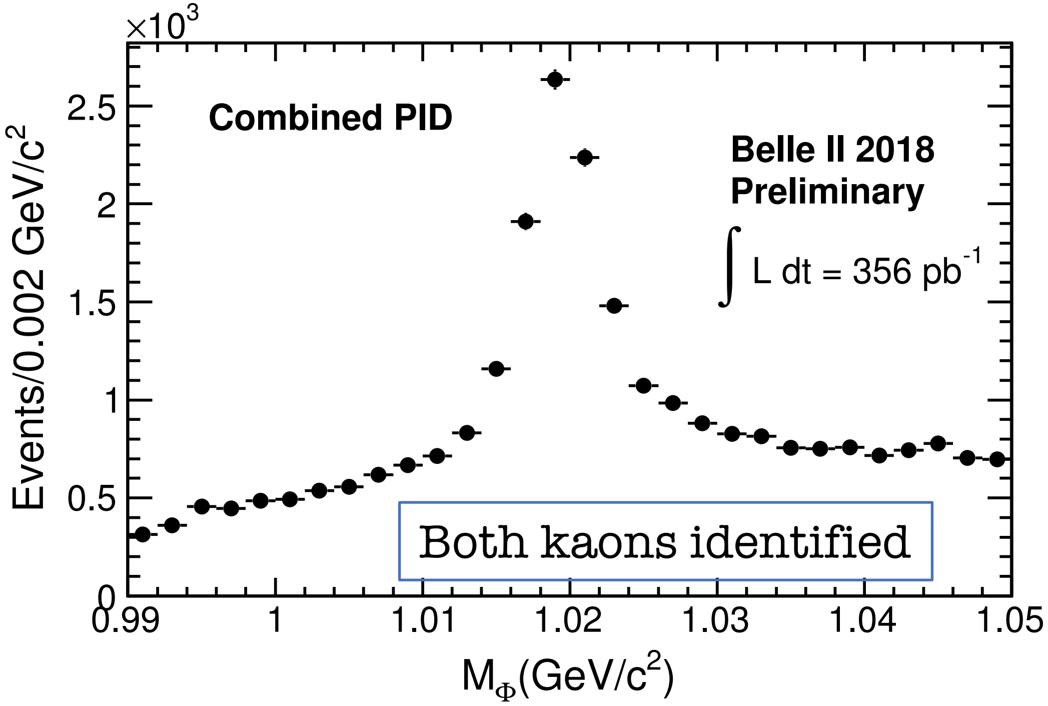
- Good tracking efficiency.
- Well understood with Montecarlo.

Marvels of Particle ID

- An example of Kaon identification capabilities with early calibration and alignment

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

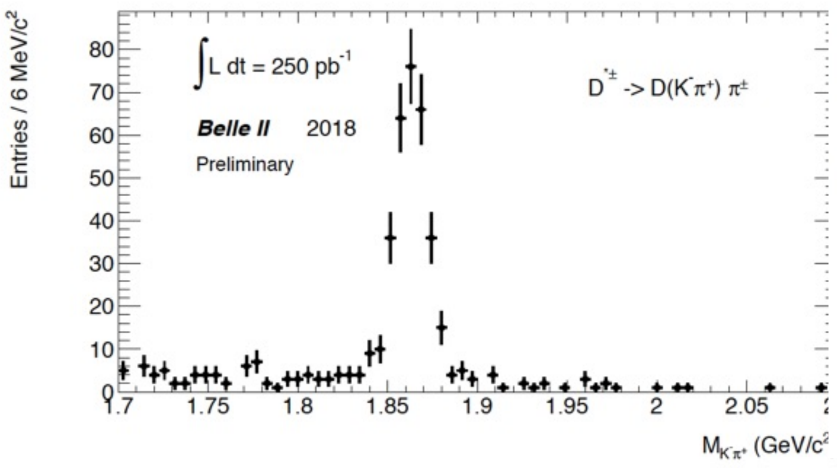


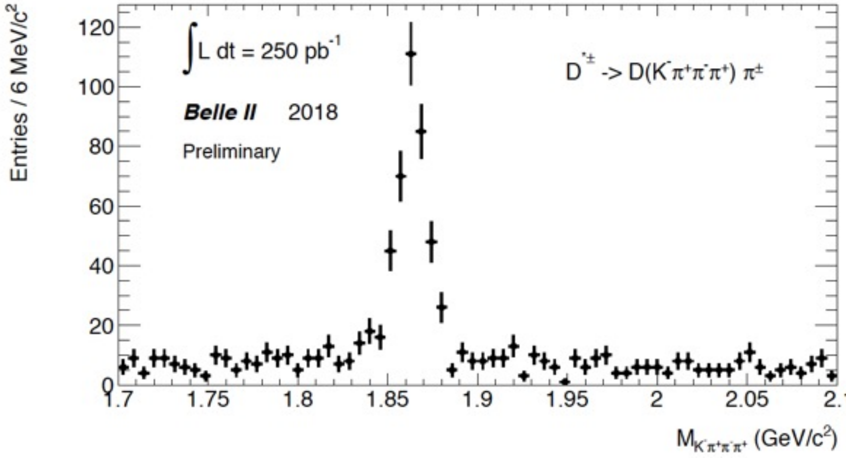


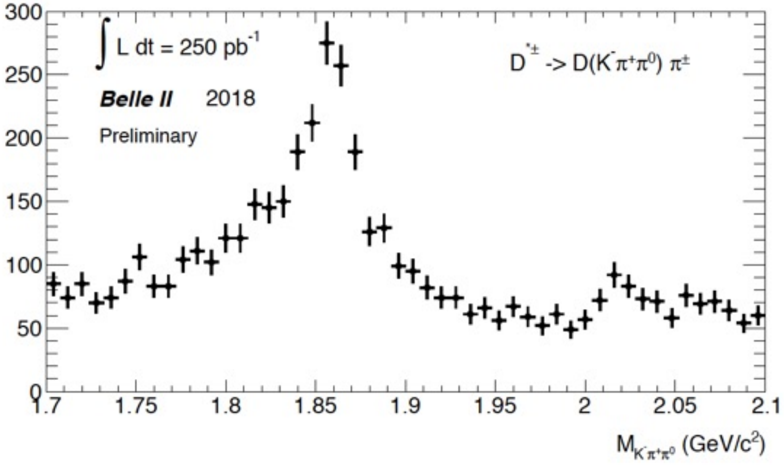
Charm $e^+e^- \to c\bar{c}$ $D^{*+} \to D^0\pi^+(\pi\,\mathrm{soft})$

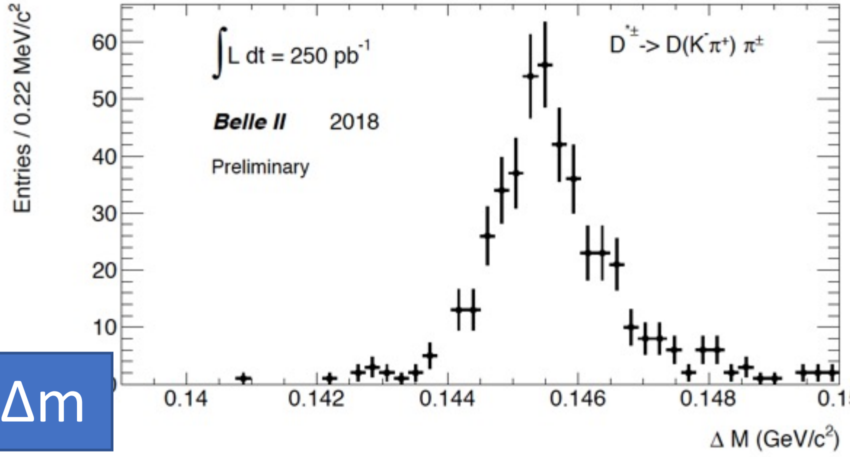
m(D*)

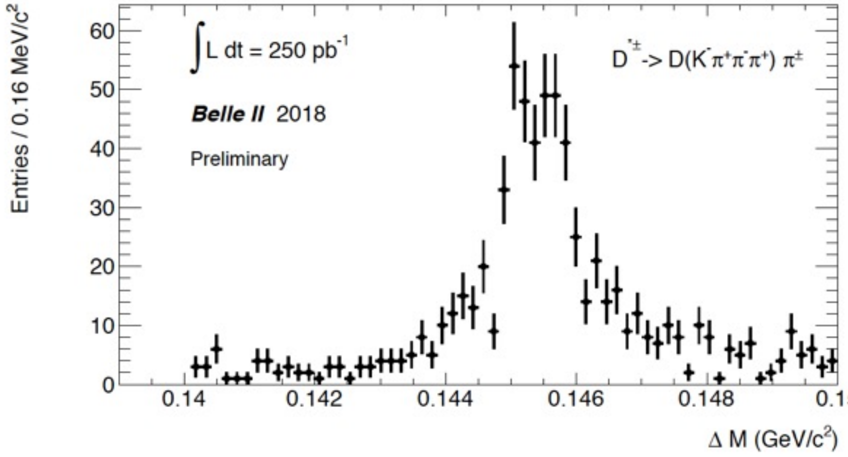
$D^0 \to K^-\pi^+$ $D^0 \to K^-\pi^+\pi^-\pi^+$ $D^0 \to K^-\pi^+\pi^0$

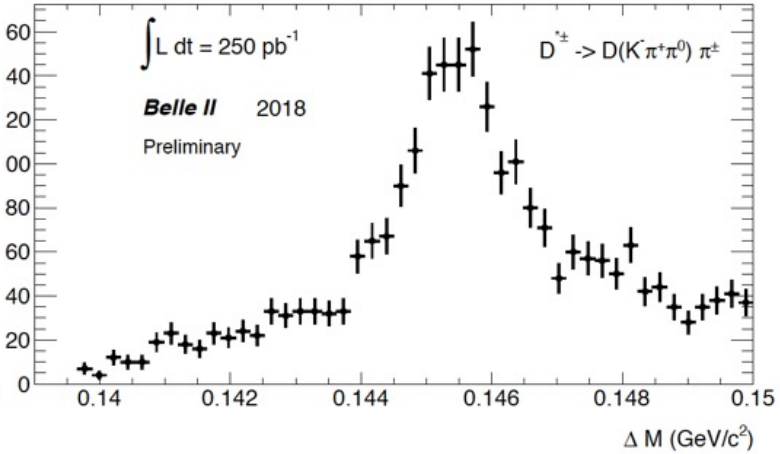










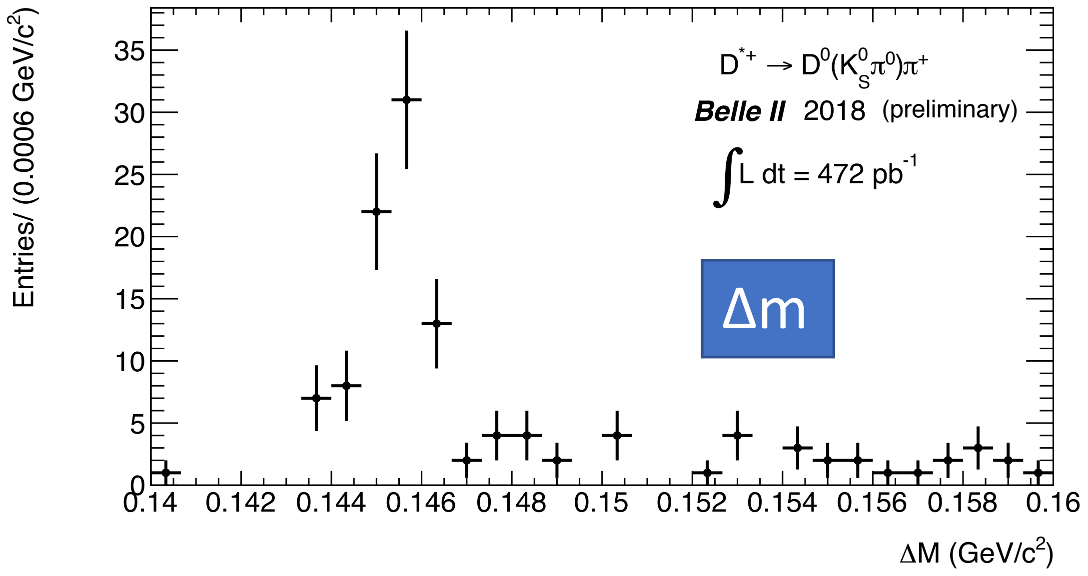


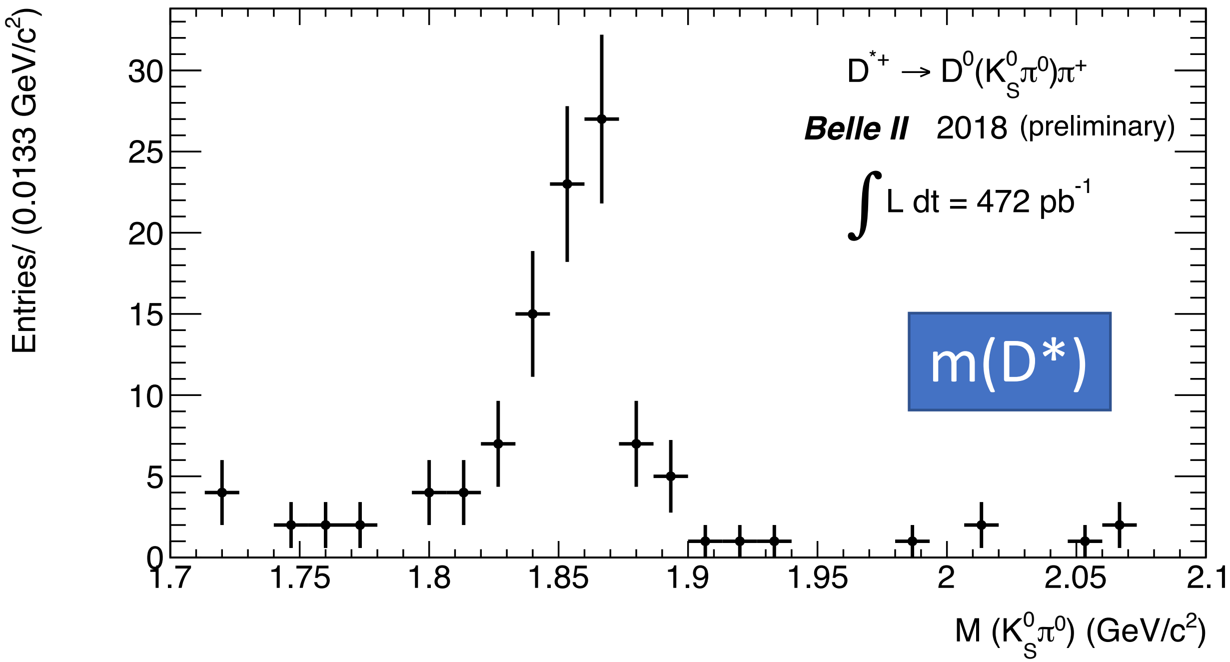
Δm

Unique capabilities. All neutral states

D^0 decaying in CP eigenstate

$$D^{*+} \rightarrow D^0(K_S\pi^0)\pi^+$$

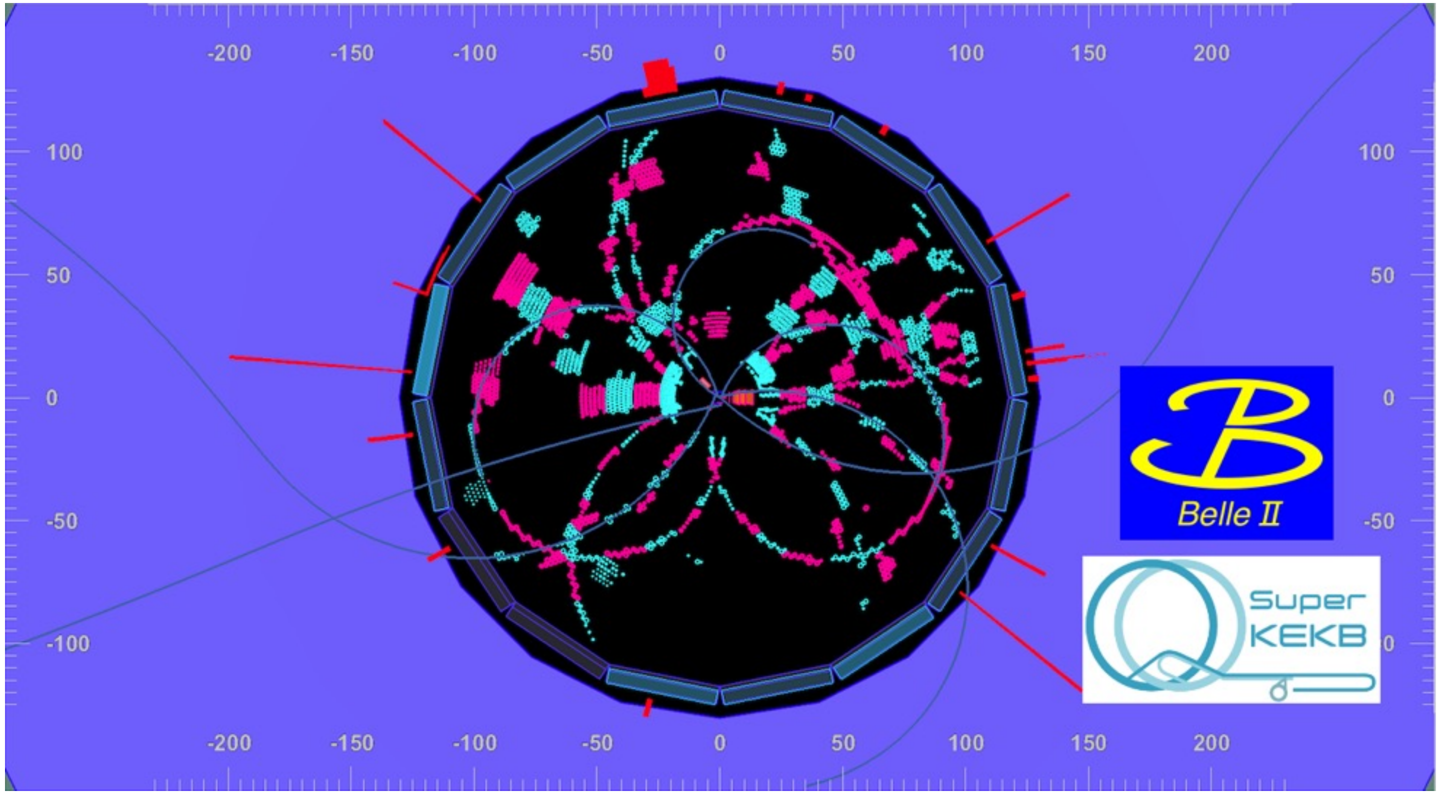




Need a pair of pions with a displaced vertex and two photons measured with good resolution and low background

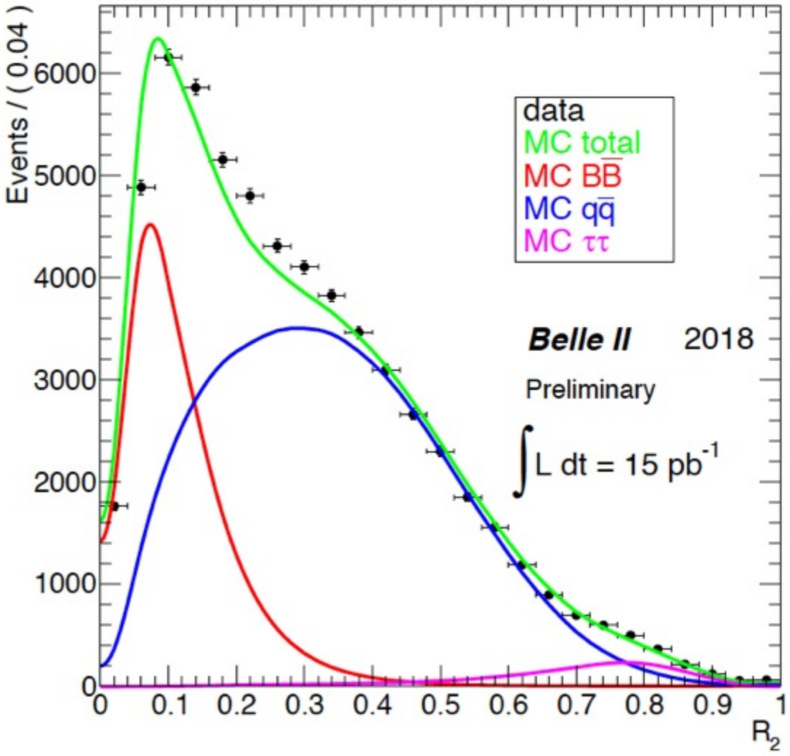
Another event from Belle II's first evening

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



A potential e+ e- →B anti-B candidate

Event shape

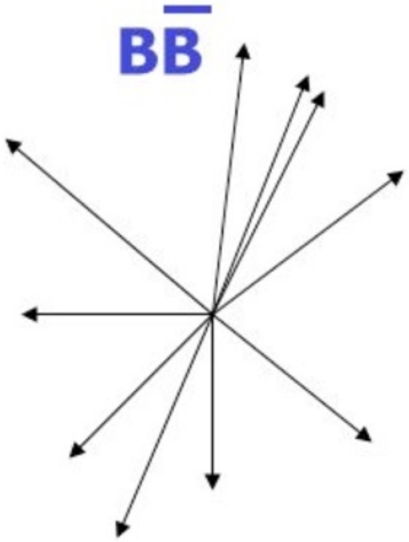


Spherical R_2 Jet-like

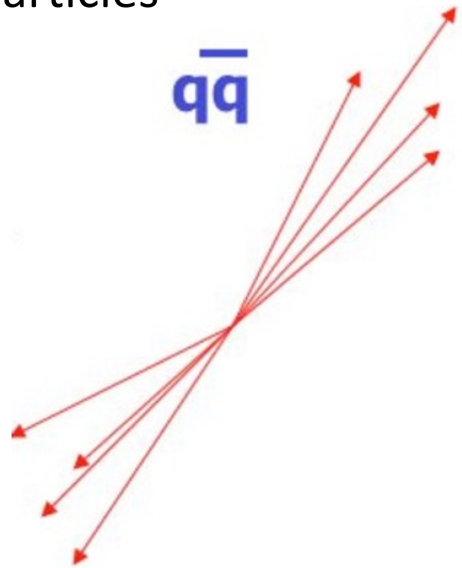
Event Topology (fits to R_2) tells us we are seeing B's

$R_2 = H_2/H_0$

$$H_l = \sum_{i,j} \frac{|\mathbf{p}_i||\mathbf{p}_j|}{E_{\text{vis}}^2} P_l(\cos\theta_{ij}) ,$$



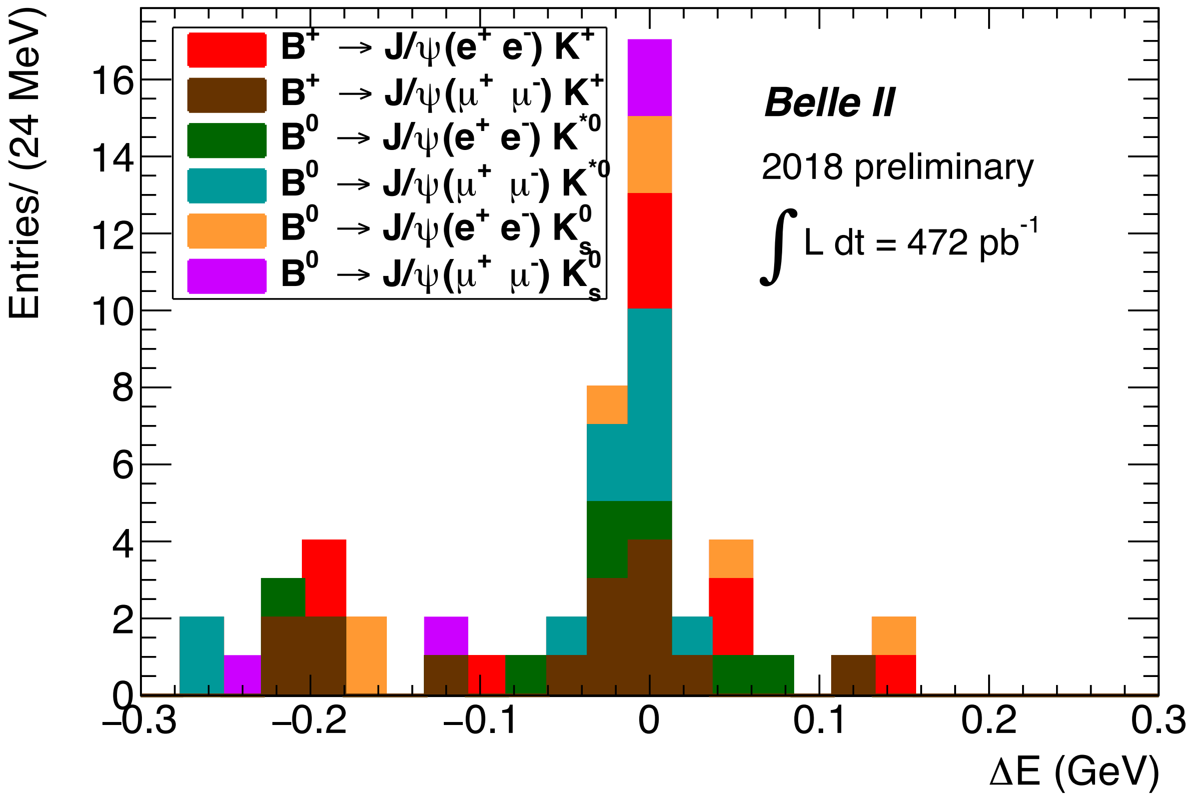
B pairs produced at rest in the CM with no extra particles

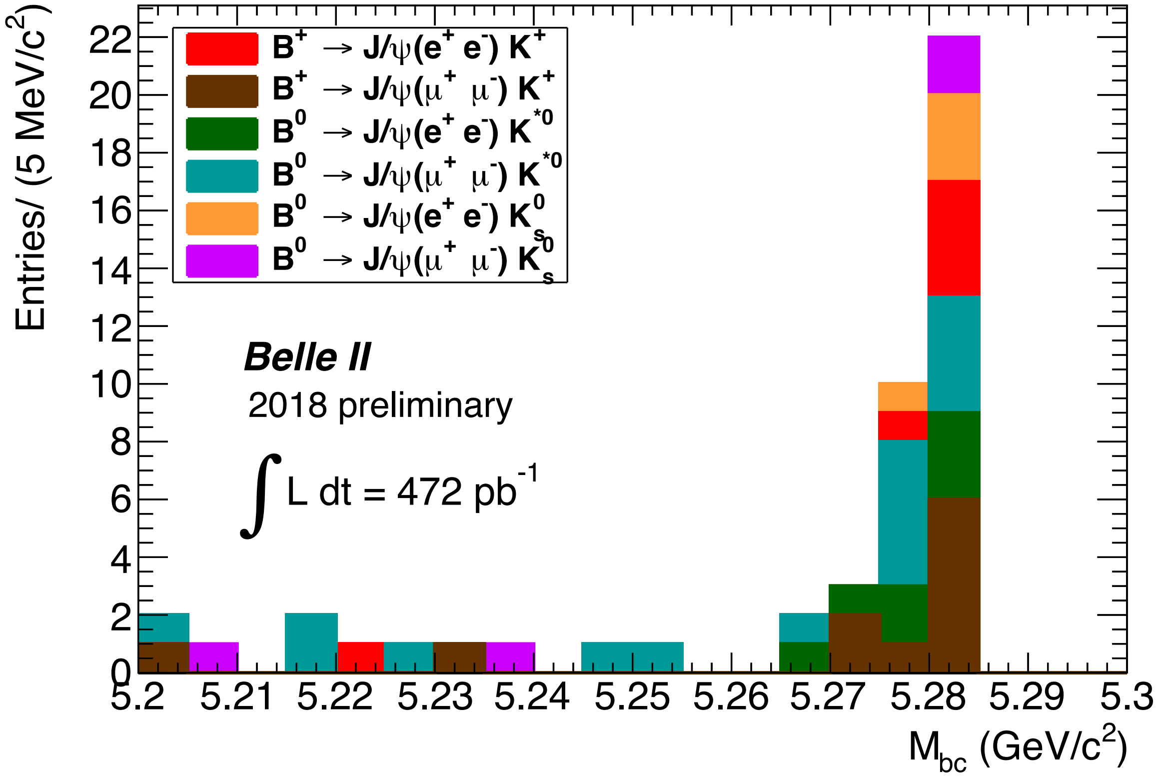


B meson "rediscovery"

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

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





A lively dance movement having compound triple rhythm and composed in fugal style

Gigue
Phase 3 running and perspectives

Early Phase 3 Physics

- Luminosity will depend on machine and detector performance
- Plausible assumption of about 10fb-1 by summer 2019

- Semileptonic
  - $B \to \pi l \nu$ and $\rho l \nu$ untagged (CLEO saw a signal with 2.66 fb^{-1})

- Time Dependent CP Violation/Charm
  - D lifetimes (2 fb^{-1})
  - Doubly Cabibbo suppressed $D^0 \to K^+ \pi^-$, $D^0 \to K^+ \pi^- \pi^0$ (10 fb^{-1})
  - B lifetimes (2-10 fb^{-1})
  - Time dependent B mixing (10 fb^{-1})

- Radiative/Electroweak Penguins
  - $B \to K^* \gamma$ ($b \to s$) (2 fb^{-1}) rediscover penguins
- - $B \to Xs\, \gamma$ ($b \to s$) (~10 fb^{-1} depending on off-resonance data taking)

Hadronic B decays (not time dependent)
- $B \to K \pi$ ($b \to u$) (10 fb^{-1})
- $B \to \Phi K$ ($b \to s$) (10 fb^{-1})
- $B \to J/\psi K$ (with more significance 2-10 fb^{-1})

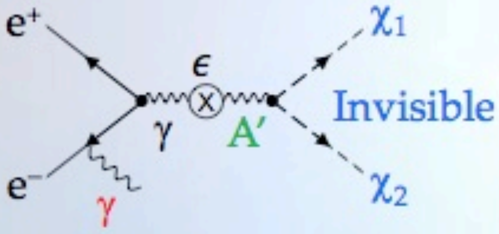
++ Dark Sector Physics Publications

Demonstrate full Belle II physics performance

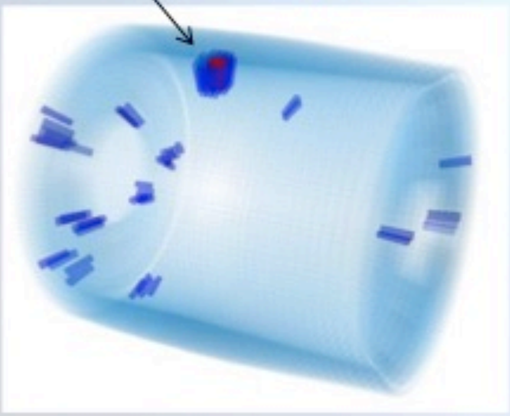
Dark Sector

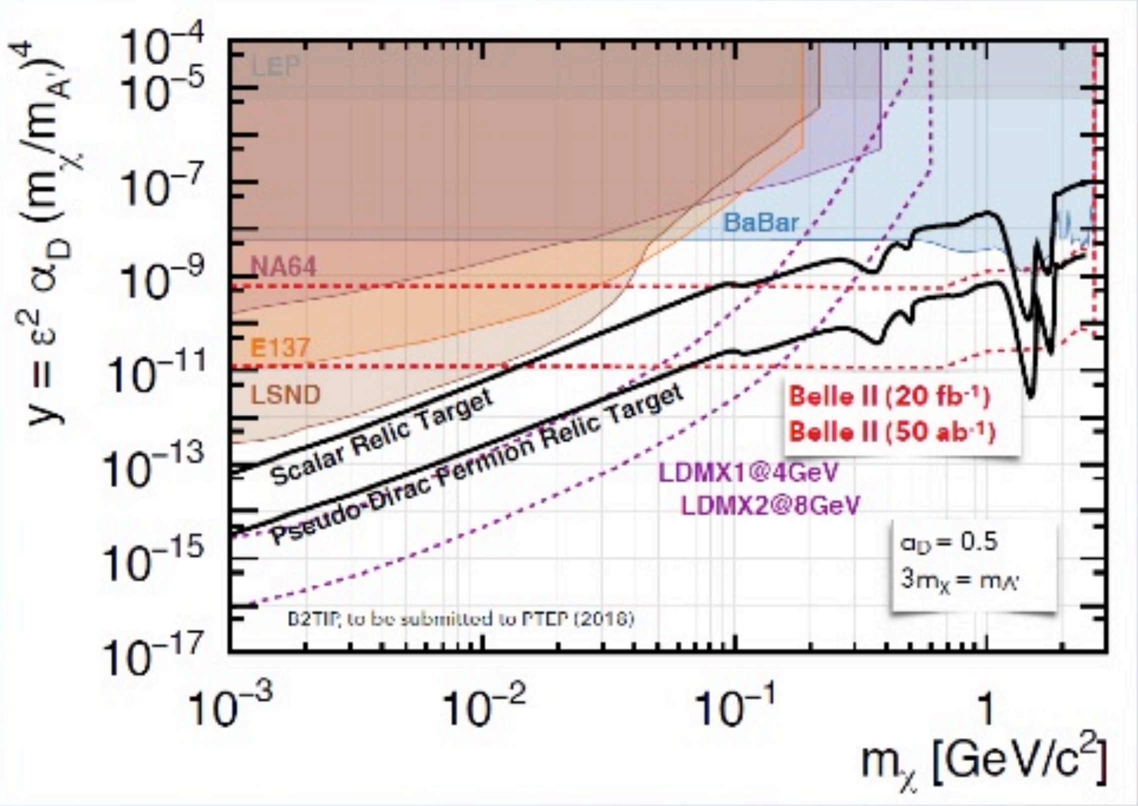
- May be possible to provide results even with very limited statistics.

- New triggers will be used in Belle II to search for dark matter and dark photons.
  - Single photon trigger with ~1 GeV threshold to search for dark photon decaying into light dark matter



$$E_\gamma = \frac{E_{CM}^2 - M_{A'}^2}{2E_{CM}}$$





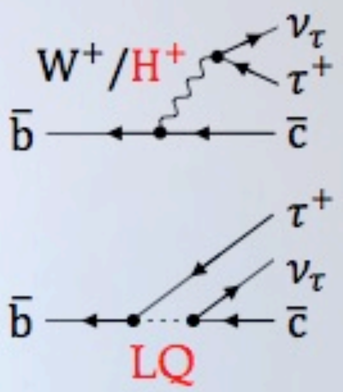
Lepton universality in B→D$^{(*)}$τν

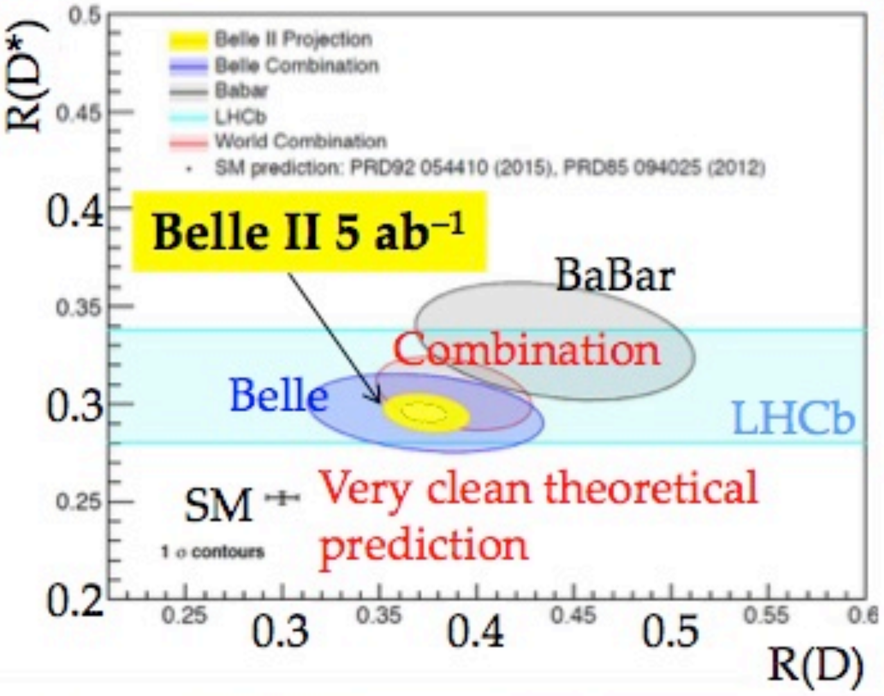
$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)} \quad (\ell = \text{e or } \mu)$$

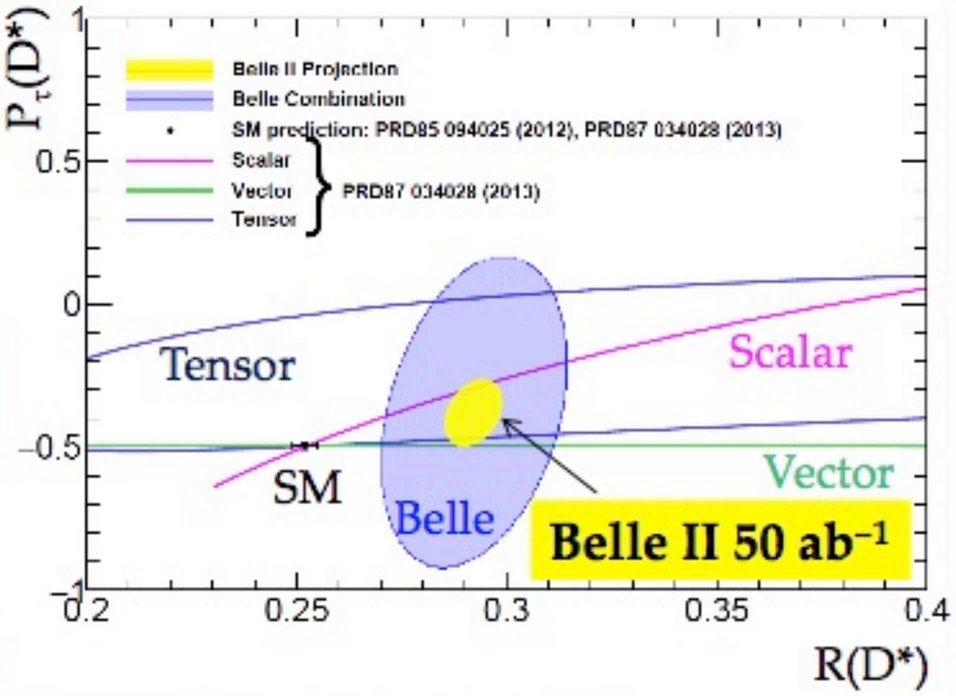
- Partial cancellation of theoretical uncertainties related to hadronic effects and measurement systematics.

$$P_\tau(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-} \quad (\Gamma^\pm\text{: decay rate of } \pm\,\tau\text{-helicity})$$

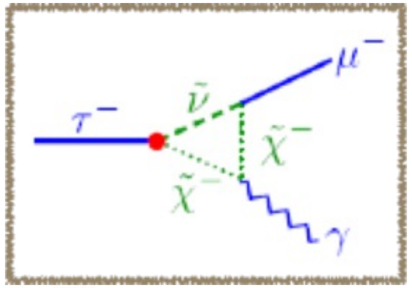
- Another probe of New Physics

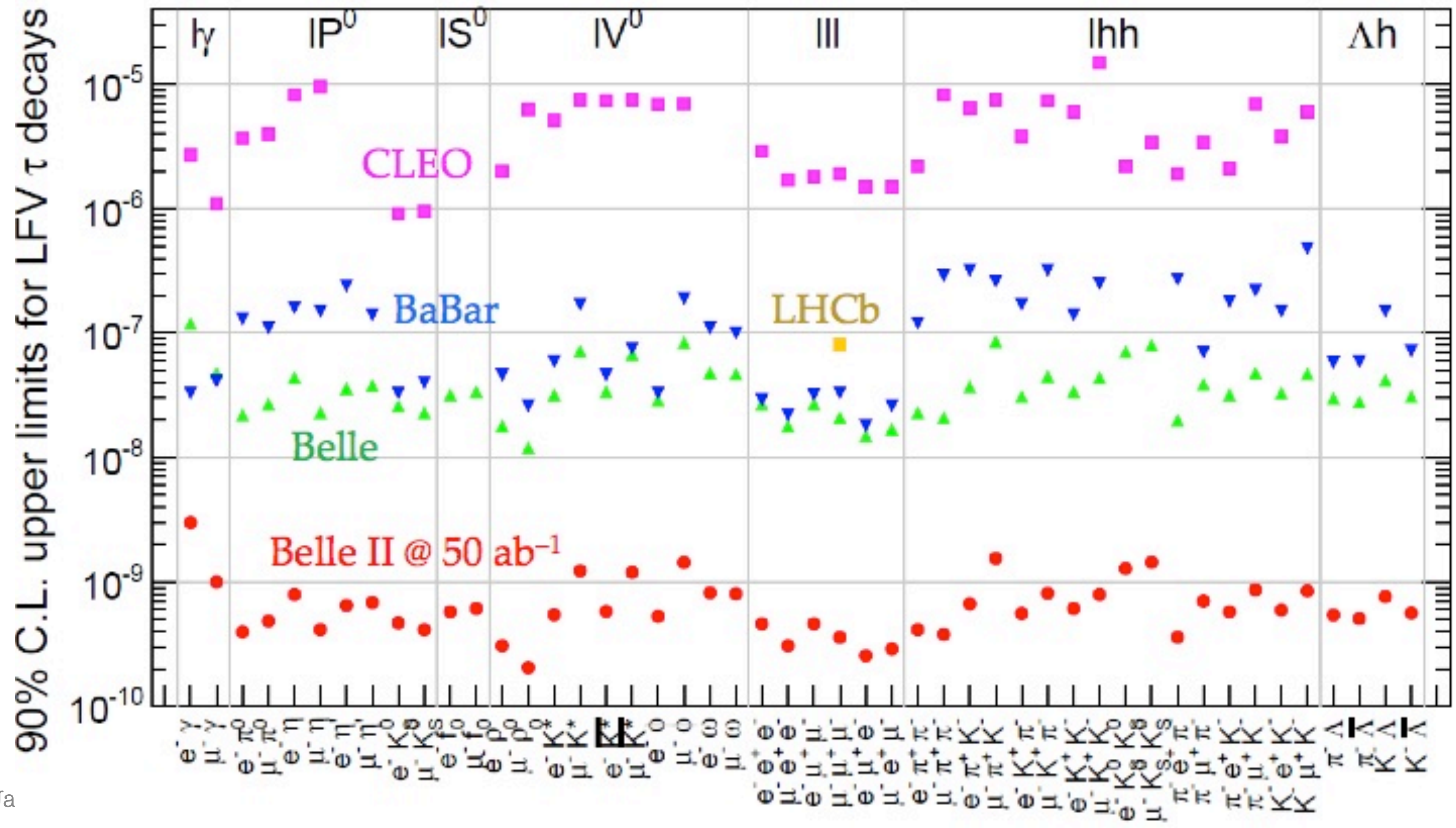






Lepton flavor violating τ decays

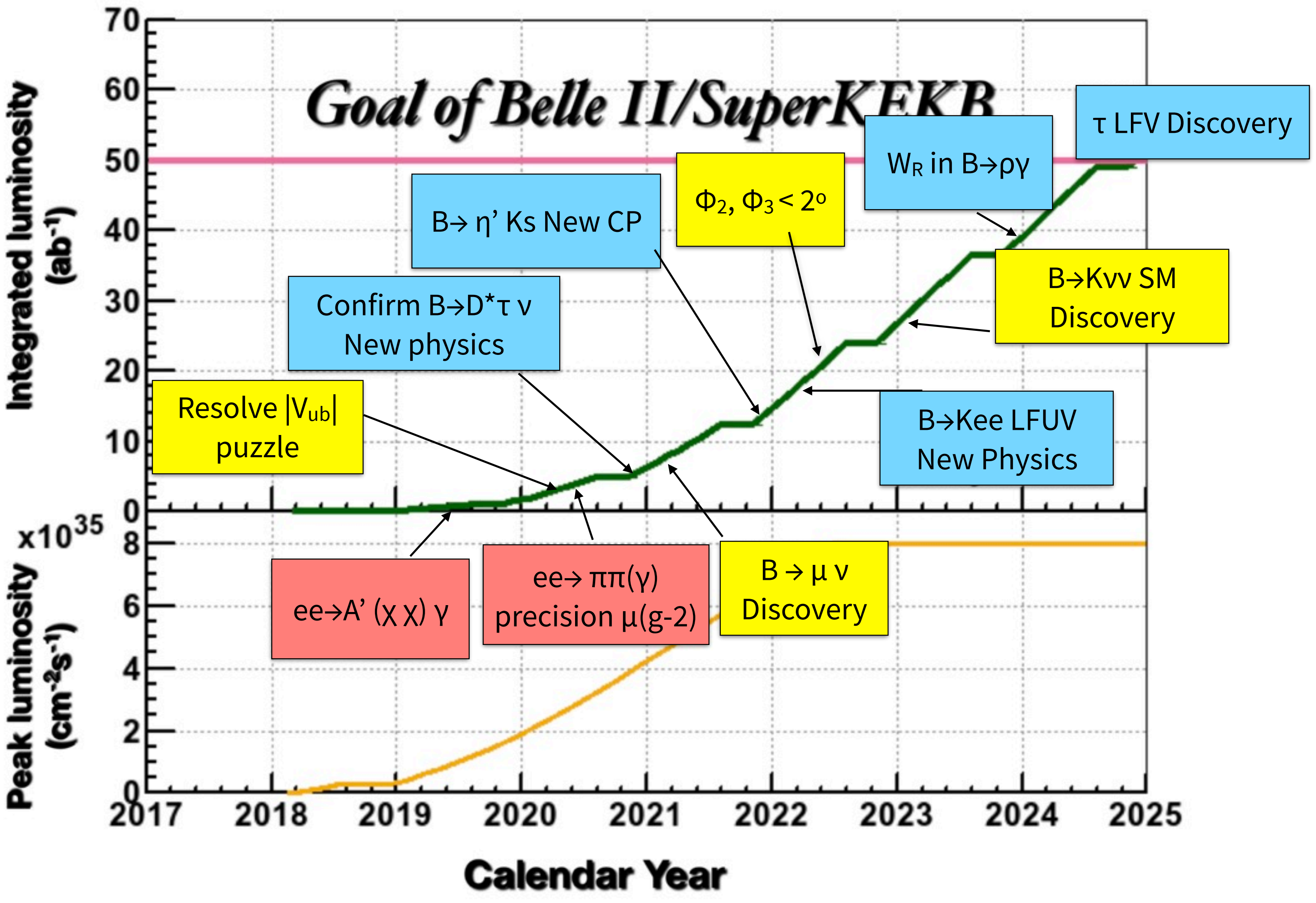




Time-dependent physics precision

- B2TIP: Belle2 Theory Interface Platform
- A series of joint workshops with theorists
- Belle II Physics book submitted to PTEP

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



Ultimate precision

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%	CKM	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	CPV	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			LEPT	
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%		Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	SL	Belle II
$R(B \to D\tau\nu)$	***	3%	LFUV	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	EWP	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
$\mathcal{B}(B \to K\nu\overline{\nu})$ $[10^{-6}]$	***	20%		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	CHARM	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03		Belle II
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***	4		Belle II
Tau				
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50		Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100	LFV	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3		Belle II/LHCb

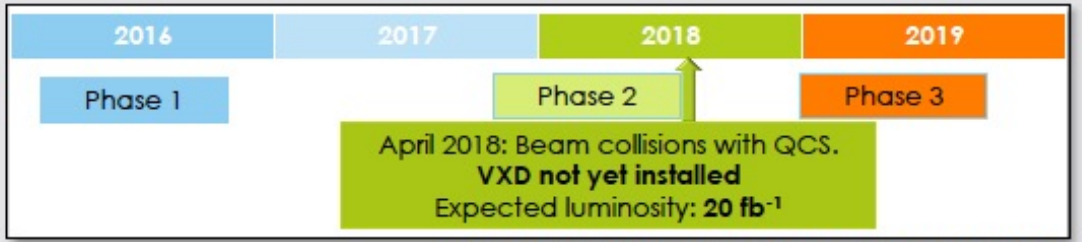
- Very rich physics program in the next few years

Global perspective

2019–2020	2021–2023	2024–2026	2027–2029	2030–2031	2032–203+
	Run III		Run IV		Run V
LS2		LS3		LS4	
LHCb 40 MHz **UPGRADE I**	$L = 2 \times 10^{33}$	**LHCb** Consolidate: Upgr Ib	$L = 2 \times 10^{33}$ 50 fb^{-1}	**LHCb UPGRADE II**	$L = 1\text{-}2 \times 10^{34}$ 300 fb^{-1}
ATLAS Phase I Upgr	$L = 2 \times 10^{34}$	**ATLAS** Phase II UPGRADE	**HL-LHC** $L = 5 \times 10^{34}$	**ATLAS**	**HL-LHC** $L = 5 \times 10^{34}$
CMS Phase I Upgr	300 fb^{-1}	**CMS** Phase II UPGRADE		**CMS**	3000 fb^{-1}
Belle II 5 ab^{-1}	$L = 8 \times 10^{35}$	50 ab^{-1}			

LHC schedule: Frederick Bordry, Jun 2015

- Belle II
  - $L = 5 \times 10^{33}\ cm^{-2}s^{-1}$ achieved!
  - Physics with VXD in 2019



R. Cheaib, Moriond, 12 Mar 2018, arXiv:1802.01366

Niels Tuning, ICHEP 2018

Global perspective -> future

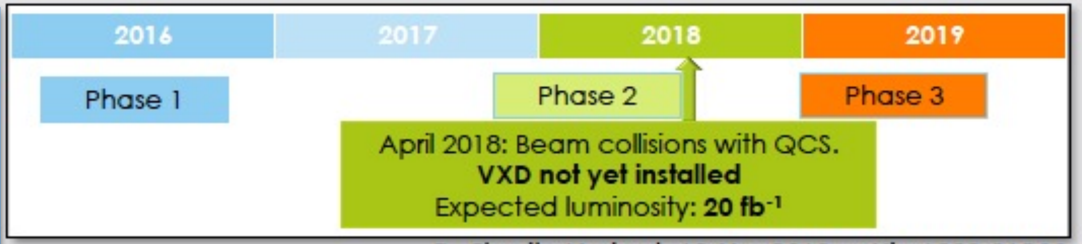
2019 2020	2021 2022 2023	2024 2025 2026	2027 2028 2029	2030 2031	2032 203+
	Run III		Run IV		Run V
LS2		LS3		LS4	
LHCb 40 MHz **UPGRADE I**	$L = 2 \times 10^{33}$	LHCb **Consolidate: Upgr Ib**	$L = 2 \times 10^{33}$ $50\ fb^{-1}$	LHCb **UPGRADE II**	$L=1\text{-}2 \times 10^{34}$ $300\ fb^{-1}$
ATLAS Phase I Upgr	$L = 2 \times 10^{34}$	ATLAS **Phase II UPGRADE**	**HL-LHC** $L = 5 \times 10^{34}$	ATLAS	**HL-LHC** $L = 5 \times 10^{34}$
CMS Phase I Upgr	$300\ fb^{-1}$	CMS **Phase II UPGRADE**		CMS	$3000\ fb^{-1}$
Belle II $5\ ab^{-1}$	$L = 8 \times 10^{35}$	$50\ ab^{-1}$	→		

LHC schedule: Frederick Bordry, Jun 2015

Upgrade studies are starting:
- Luminosity
- Polarization

Fantastic physics potential

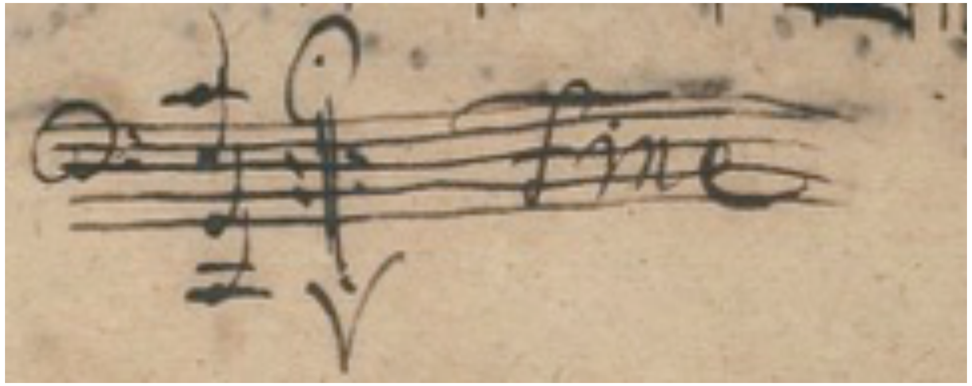
Niels Tuning, ICHEP 2018



R. Cheaib, Moriond, 12 Mar 2018, arXiv:1802.01366

Conclusions and outlook

- Belle II has completed the initial data taking (Phase 2)
  - Understanding the machine and the backgrounds
  - Detector and software checkout
  - Initial physics
- Detector completion is progressing well
  - VXD successfully installed a few weeks ago
- The physics run will start in March 2019
  - All efforts to ensure a rapid luminosity ramp up and a 9 months/year running period
- Hope to shed light on the new physics hints currently observed (and maybe more!)


Fine