Colliders for b/c/tau production

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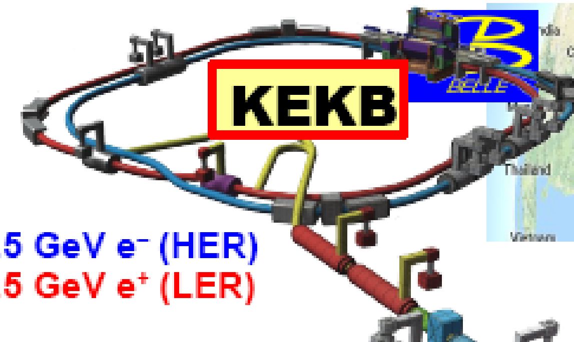
Budker INP/Novosibirsk State University
Novosibirsk

ECFA, 16 November, 2018, CERN

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

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

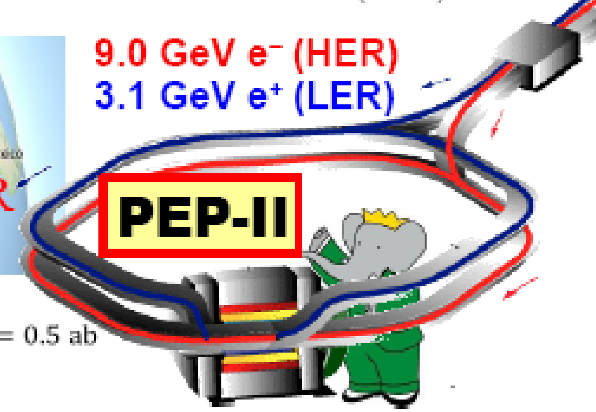


8.5 GeV e^- (HER)
3.5 GeV e^+ (LER)

1999-2010
$\sim 1000\ fb^{-1} = 1 ab^{-1}$

1999-2008
$\sim 500\ fb^{-1} = 0.5\ ab$

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



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

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

Step1
Discovery of CPV in B decay

Step2
Precise test of KM(CPV) and SM

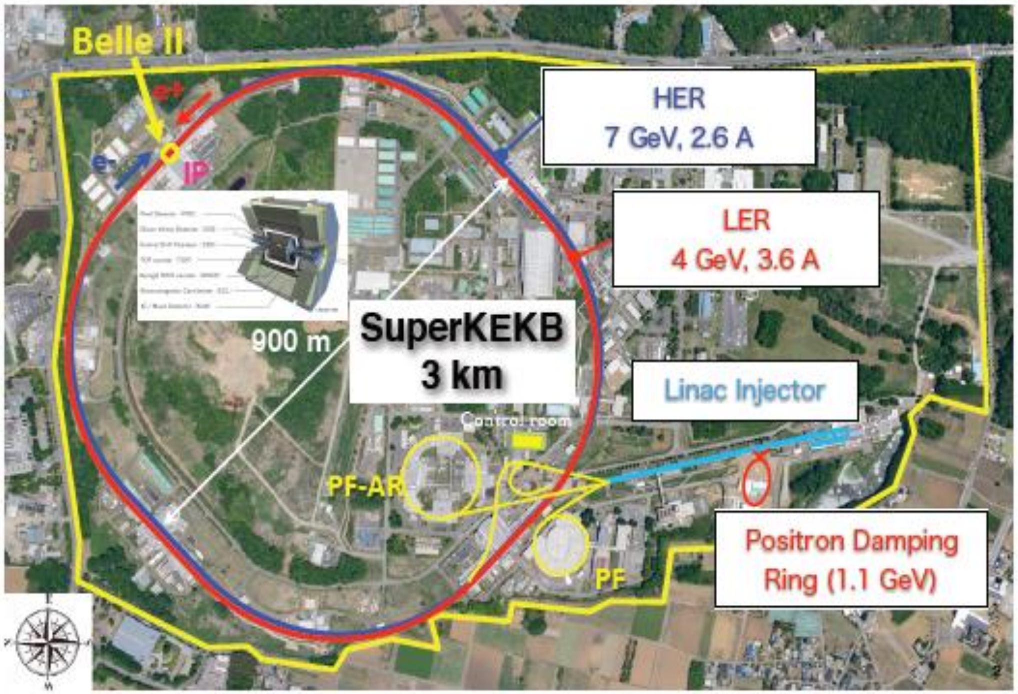
Step3
Search/Evidence for New Physics

New Resonances, τ Physics

Final Target

Target Luminosity: 8 x 10^{35} cm^{-2} s^{-1}

40 times luminosity as high as KEKB

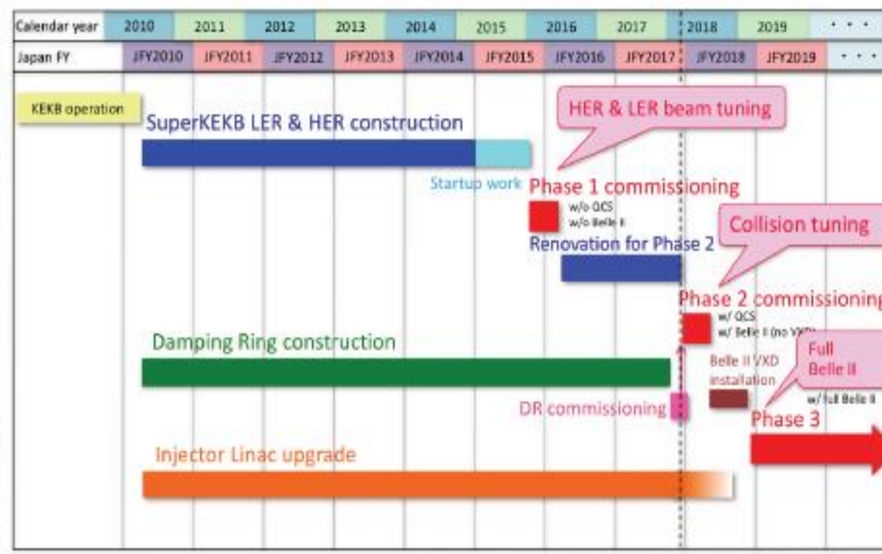


SuperKEKB project

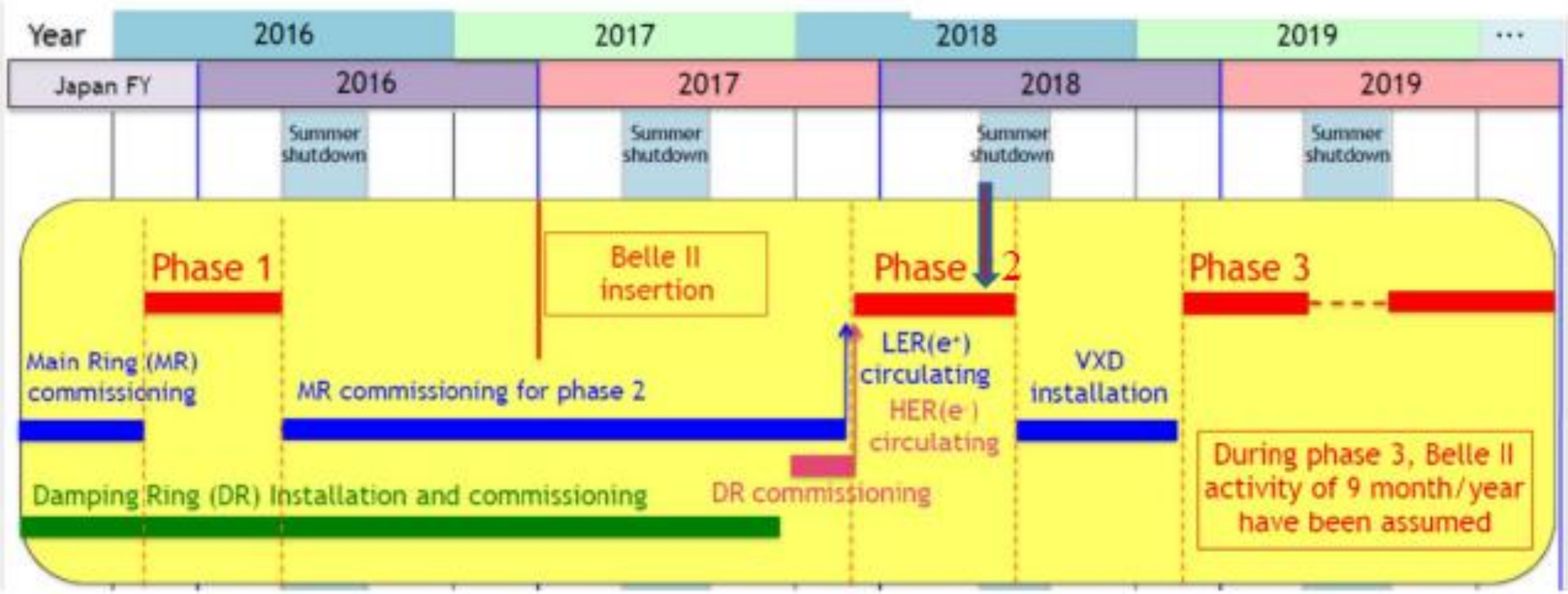
Phase 1 : Feb. 8 - June 28, 2016

Phase 2 : March 19 - July 17, 2018

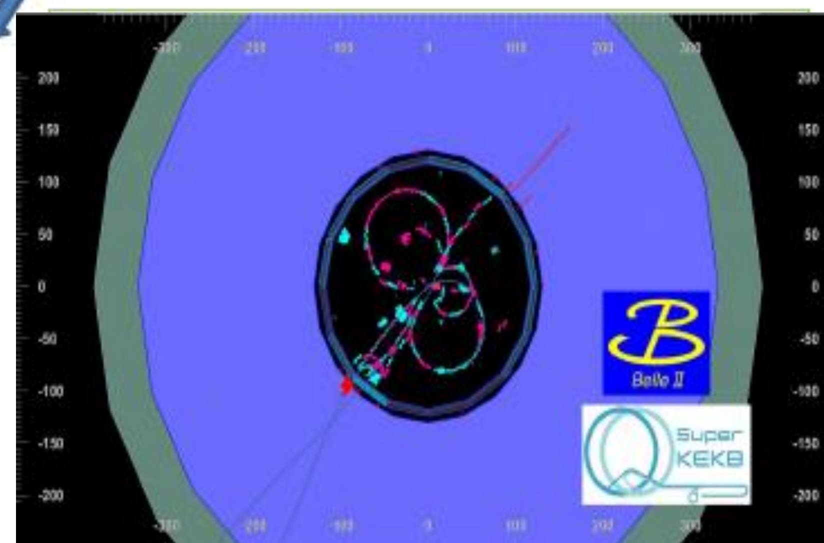
Phase 3 : March 11, 2019 ? - ?



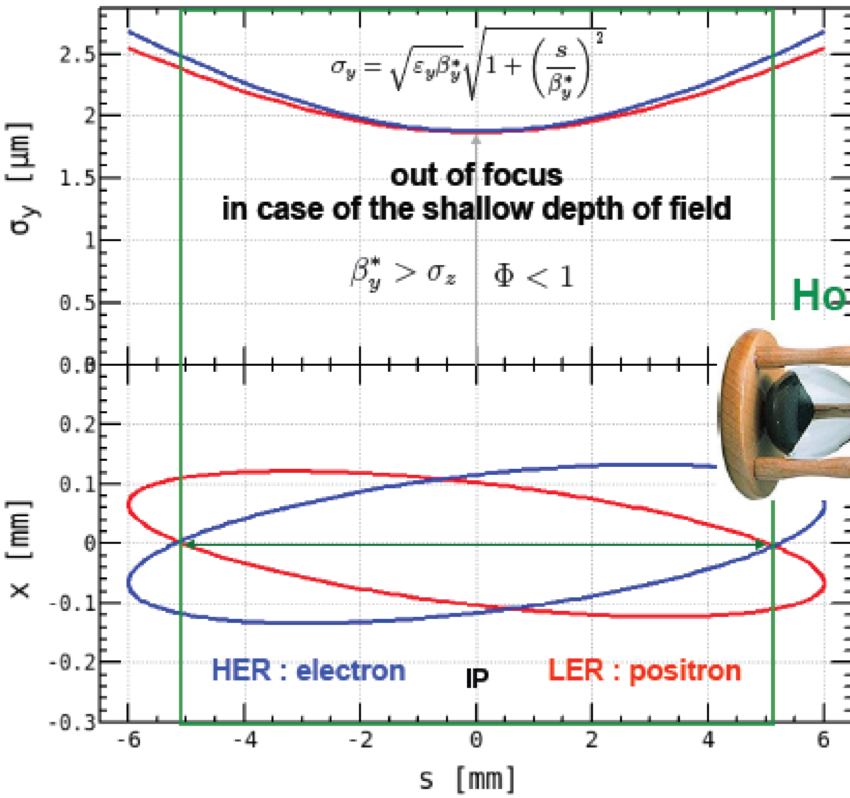
K. Akal



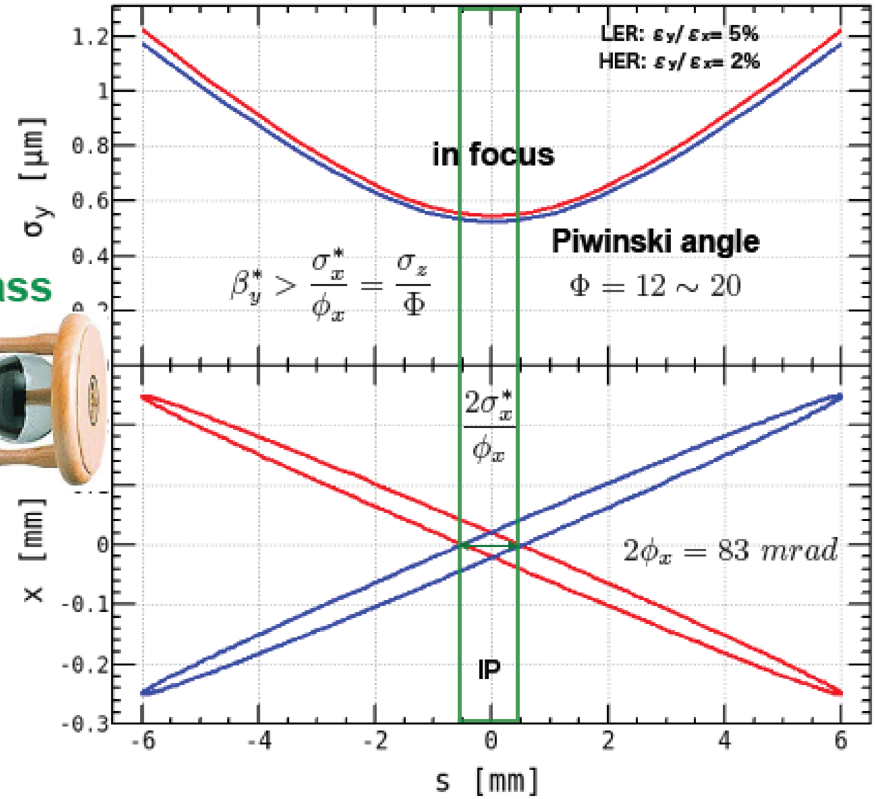
First collisions, 26 April, 2018



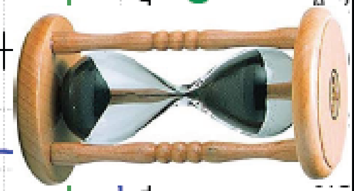
Ordinary collision (KEKB)



Nano-Beam (SuperKEKB Phase 2)

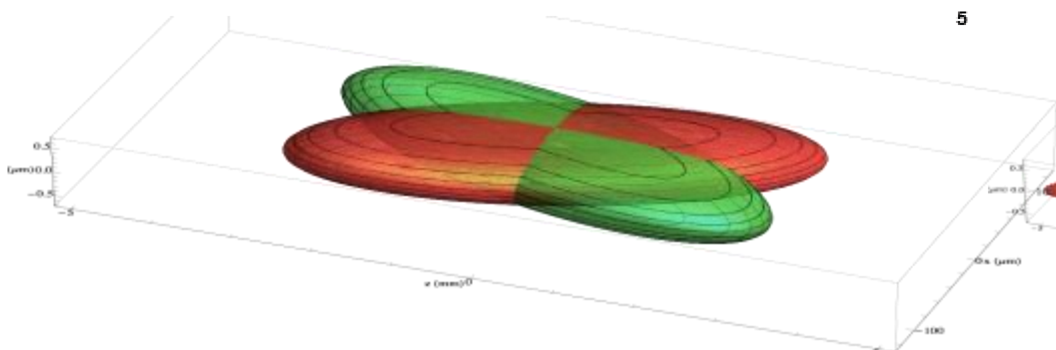


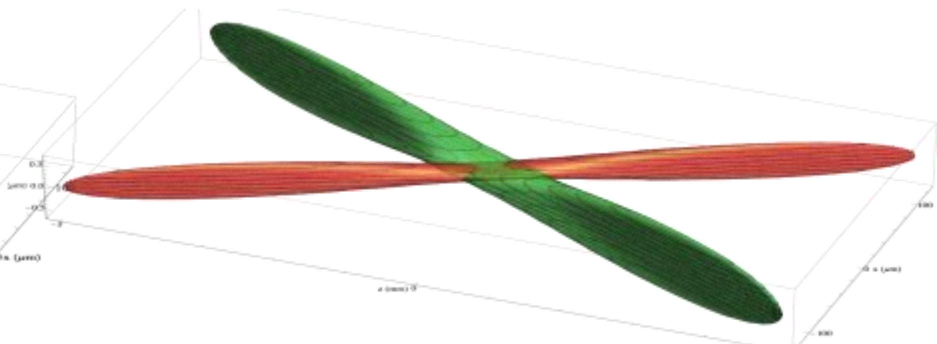
Hourglass



Large overlap region

Small overlap region





Beam-Beam Parameter

$$\xi_{y\pm} = \frac{r_e N_{\mp}}{2\pi\gamma_{\pm}(\sigma^*_{x,eff})}\sqrt{\frac{\beta^*_y}{\varepsilon_y}}$$

$$\beta^*_y \rightarrow \text{small} \Rightarrow \xi_y \rightarrow \text{small} \Rightarrow L \rightarrow \text{large}$$

Luminosity

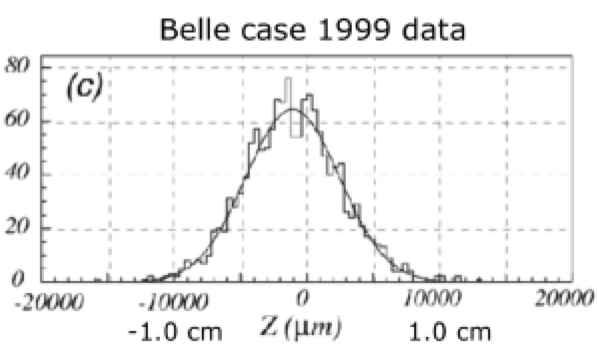
$$L = \frac{N_- N_+ n_b f_0}{4\pi(\sigma^*_{x,eff})\sqrt{\varepsilon_y \beta^*_y}} \simeq \frac{\gamma_\pm}{2er_e}\frac{I_\pm \xi_{y\pm}}{\beta^*_y}$$

$$\varepsilon_y \rightarrow \text{small}$$

Final Target $I_\pm \rightarrow \times 2$ $\beta^*_y \rightarrow \times 1/20$ $\xi_y \rightarrow \times 1$ $\Rightarrow$ $L \rightarrow \times 40$

3

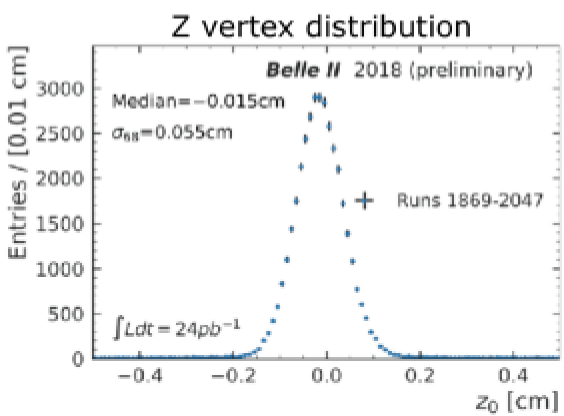
Ordinary collision (KEKB)



σ = 4.5 mm

measurement at Belle

Nano-Beam (SuperKEKB Phase2)



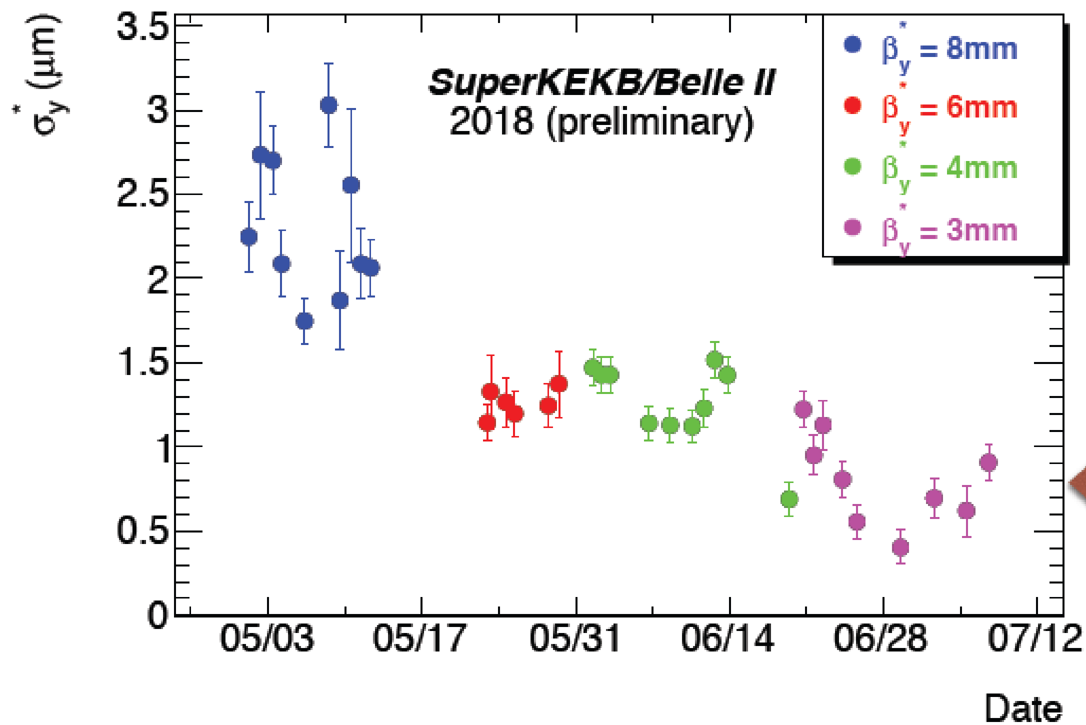
σ = 550 µm

I.Adachi, T.Iijima

Targets in Phase 2 Commissioning

Verification of nano-beam scheme

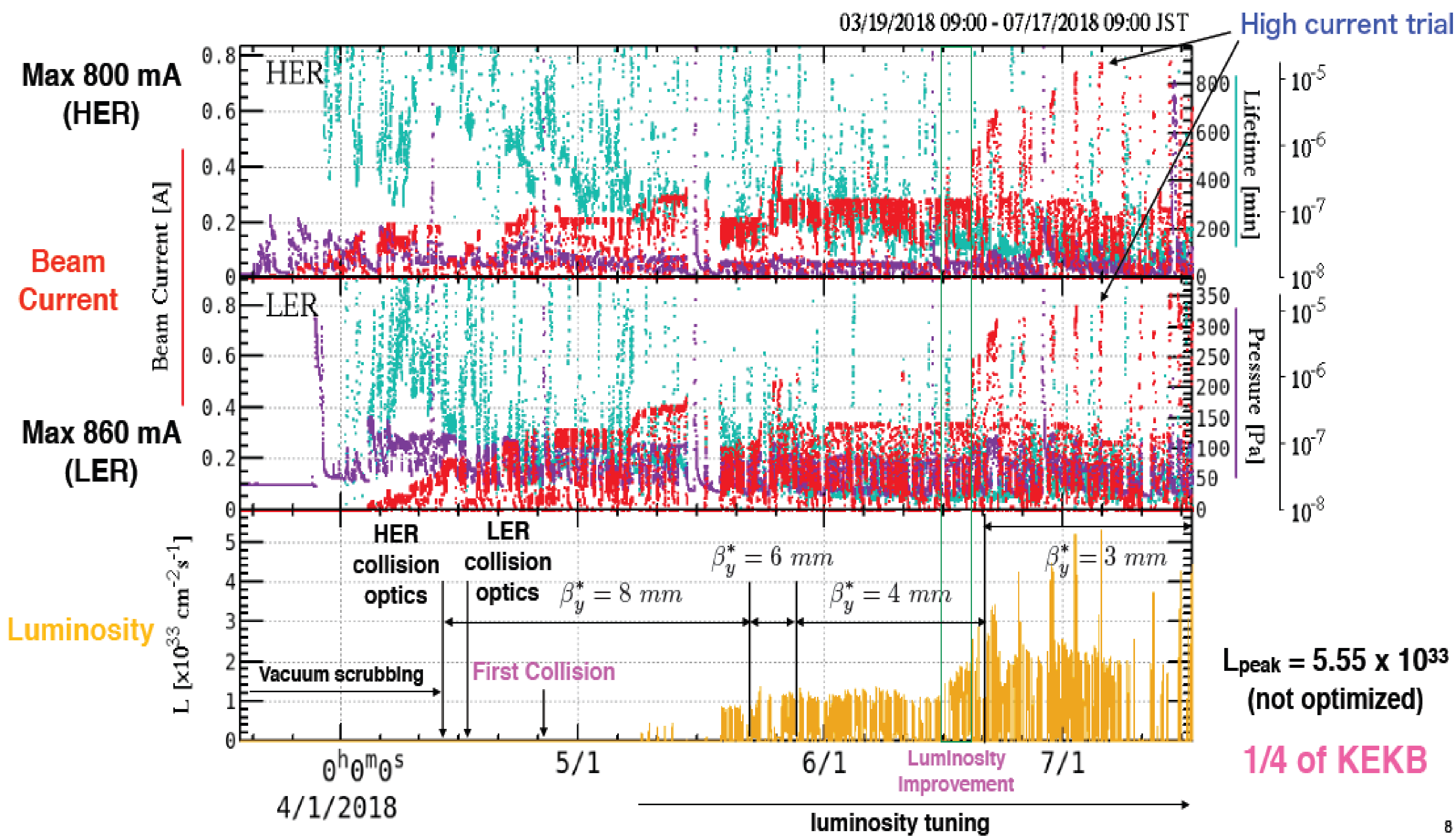
- Large crossing-angle, low emittance, and low beta at the IP
- Luminosity increases even though β_y^* is smaller than σ_z.
- Beam-Beam parameter, $\xi_y > 0.03$
- $L = 10^{34}$ $cm^{-2}s^{-1}$ at 1 [A] beam current in the LER



$$\sigma_y^\star = \sqrt{\beta_y^\star \varepsilon_y}$$

less than 500 nm achieved

History of Phase 2 Commissioning

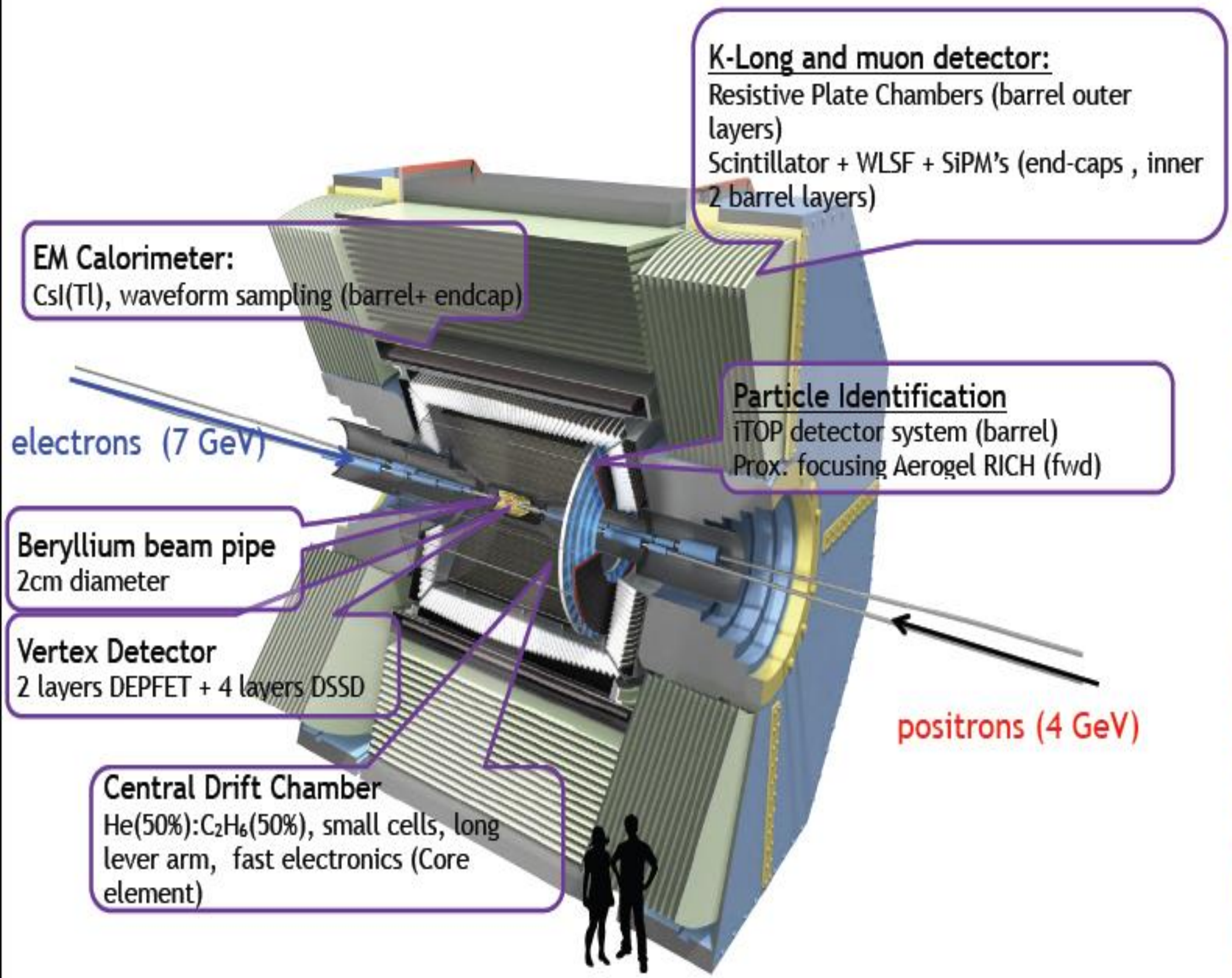


L_{peak} = 5.55 x 10^{33}
(not optimized)

1/4 of KEKB

Y.Ohnishi, eeFACT 2018, September 24, 2018

Belle II Detector



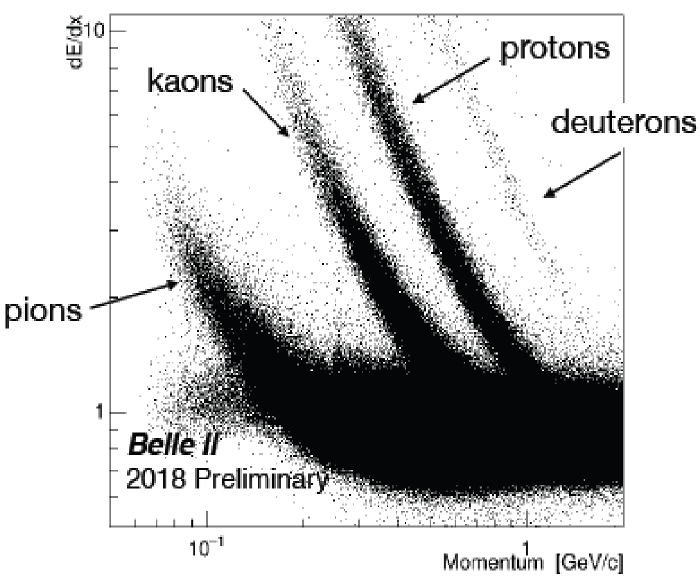
Particle identification in 2018

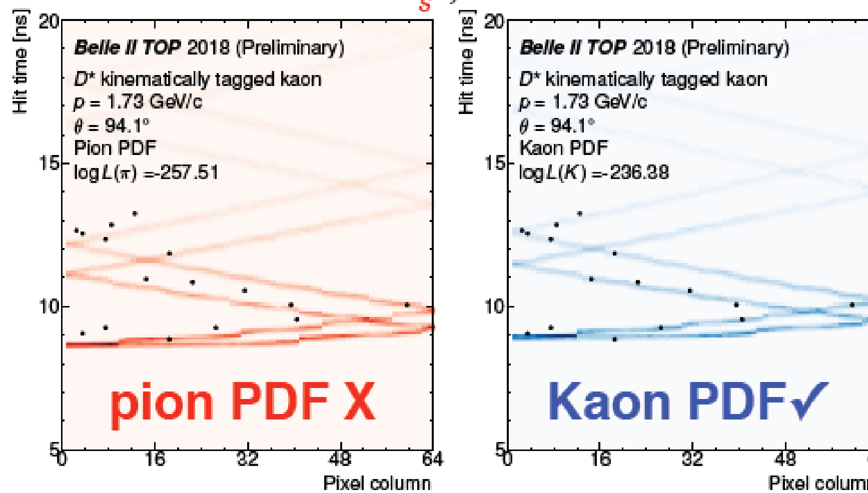
- Central Drift Chamber dE/dx & Time of propagation Cherenkov patterns - 2018 data

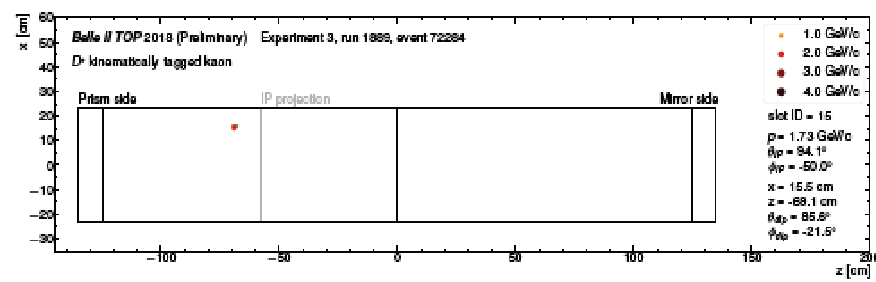
Kinematically identified kaon from D^{*+} in TOP; x vs t pattern (mapping of Cherenkov ring)

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

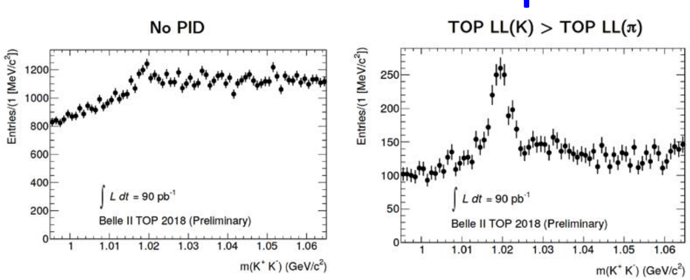
CDC dE/dx



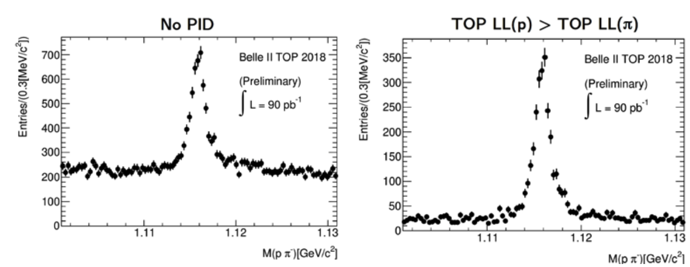




$\phi \rightarrow K^+K^-$ with both the tracks in the TOP acceptance **ϕ→KK**



$\Lambda \rightarrow p\pi$ with the **proton candidate** in the TOP acceptance **Λ→pπ**



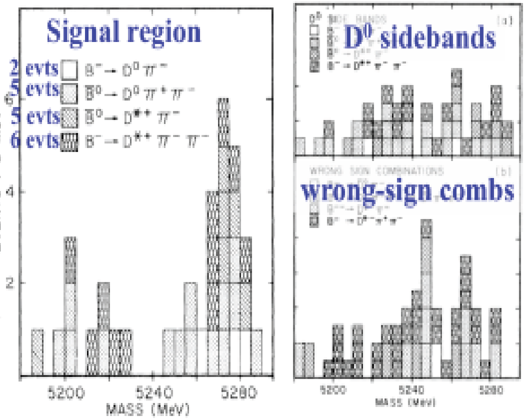
Beauty "Rediscovery" (cut-based analysis)

- Recreating CLEO & ARGUS
  - > 200 B candidates in hadronic modes (470/pb)
  - ~14 B → D* e ν found (250/pb)

VOLUME 50, NUMBER 12 PHYSICAL REVIEW LETTERS 21 MARCH 1983

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

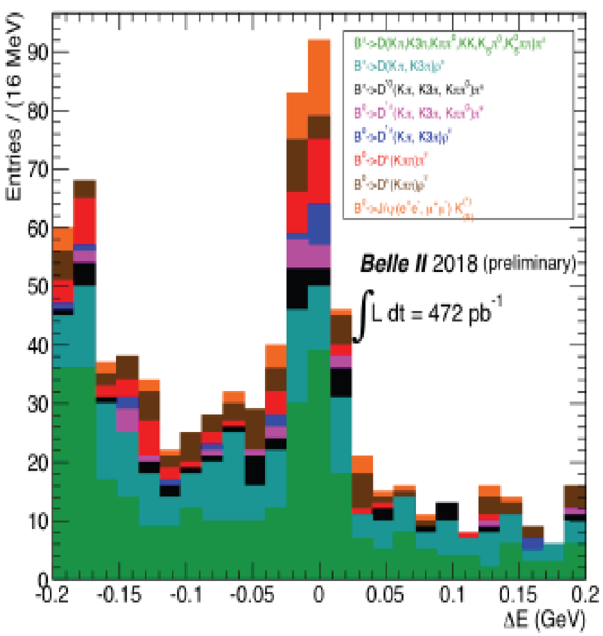
B-meson decays to final states consisting of a D^0 or $D^{*\pm}$ and one or two charged pions have been observed. The charged-B mass is 5270.8 ± 2.3 ± 2.0 MeV and the neutral-B mass is 5274.2 ± 1.9 ± 2.0 MeV.

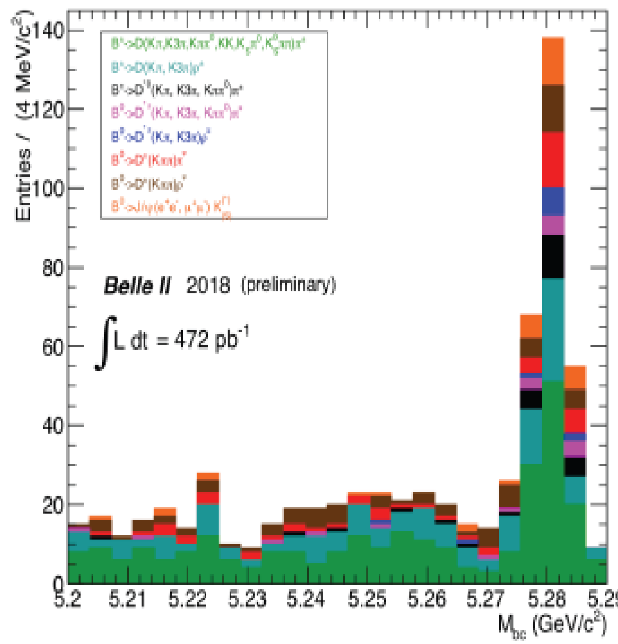


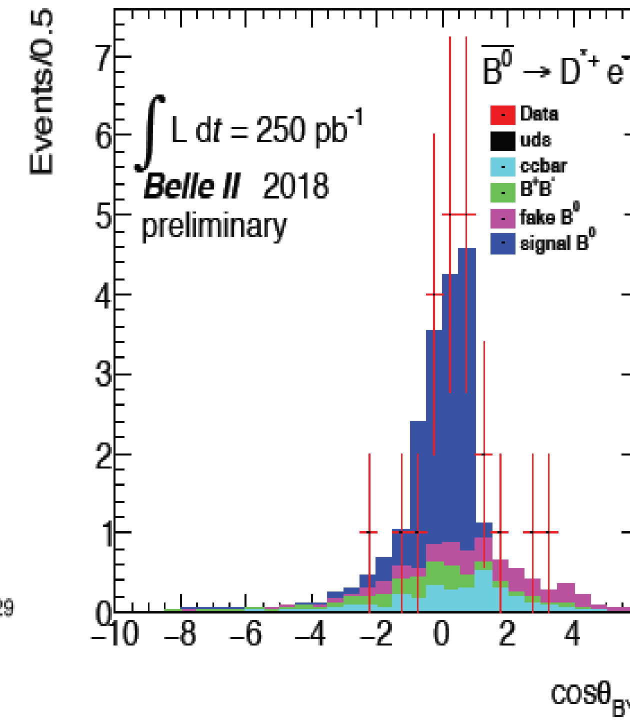
$$\Delta E = E_{cm}/2 - E_{recon}$$

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

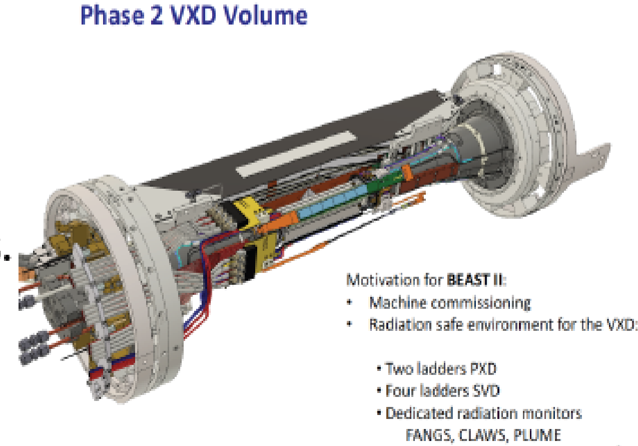
B→D* e ν



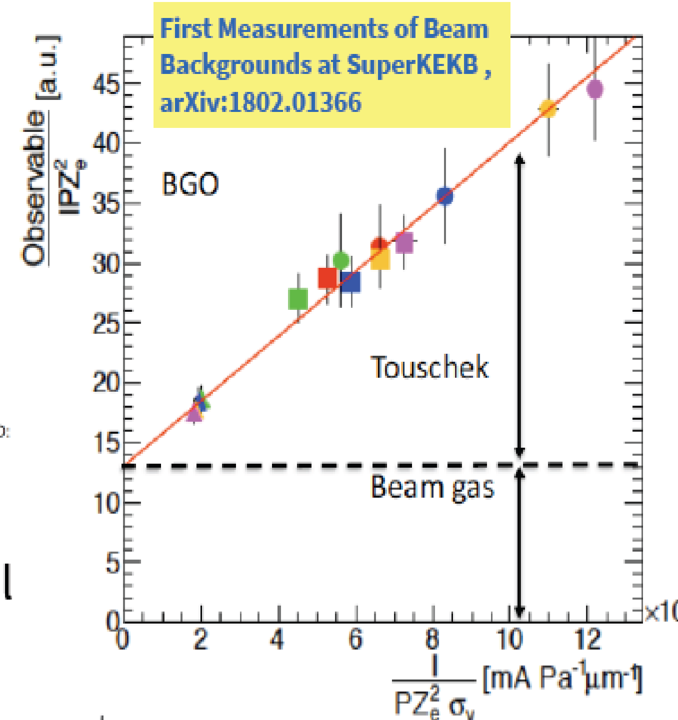




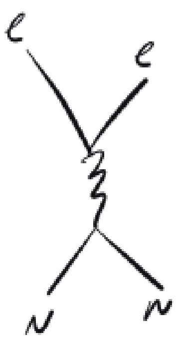
Beam background / Commissioning



<u>*Phase 1 2016*</u> : Simple background commissioning detector (diodes, diamonds TPCs, crystals…). No final focus. Only single beam studies.



<u>*Phase 2 2018*</u>: <u>Full Belle II outer detector</u>. Full superconducting final focus. *Collisions ! Result: Safe to install silicon detectors!*

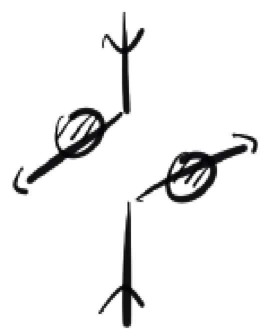


Coulomb scattering

Bremsstrahlung

Bhabha scattering σ~ 100 nb

2-photon σ~10⁷ nb



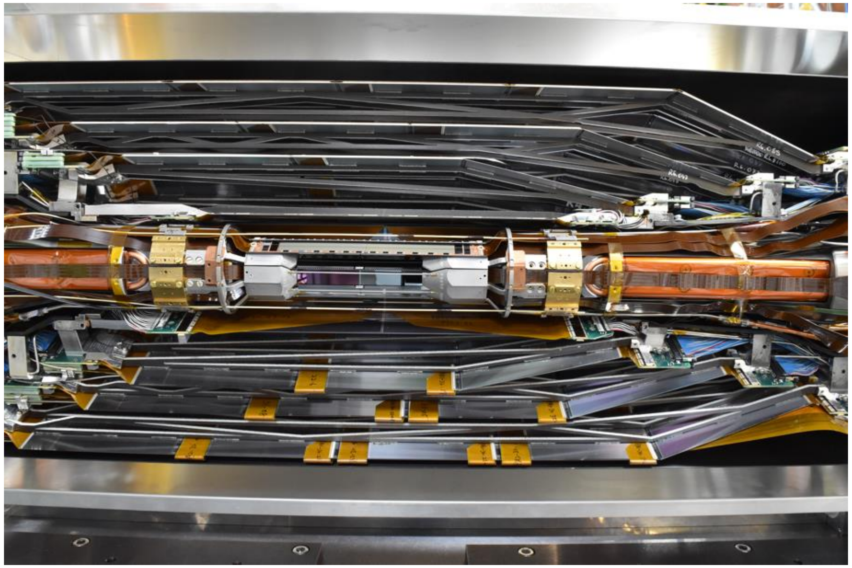
Intra-bunch Coulomb scattering, "Touschek scattering"

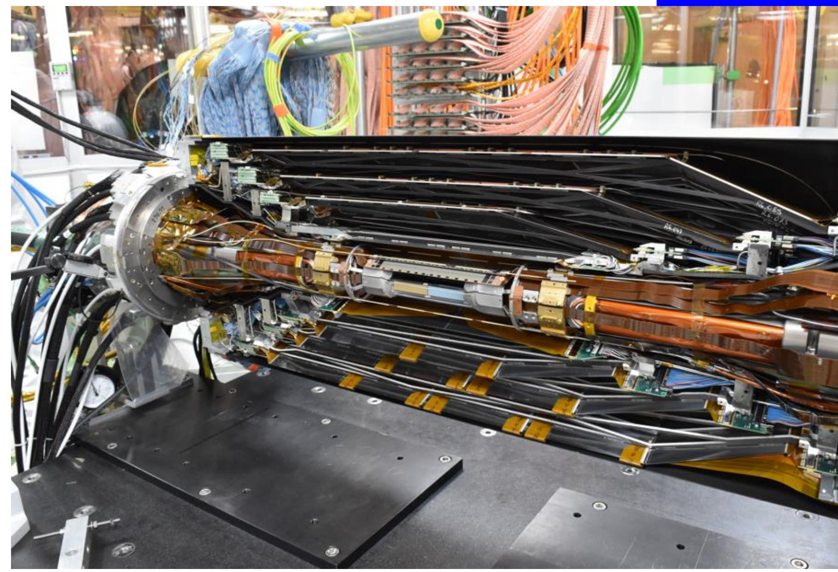
+ Synchrotron, beam gas …

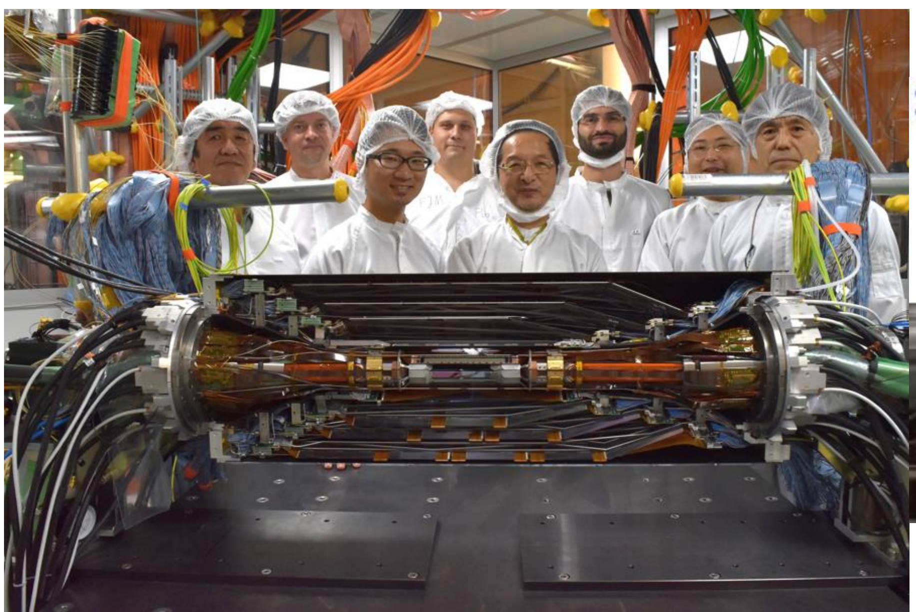
Targets in Phase 3

- Install additional collimators to reduce the backgrounds
- Install the whole silicon vertex tracker
- Restart the operations in March 2019
- Tune the optics
- Gradually increase the number of bunches and the bunch current
- Gradually decrease the vertical size of the bunches at the IP

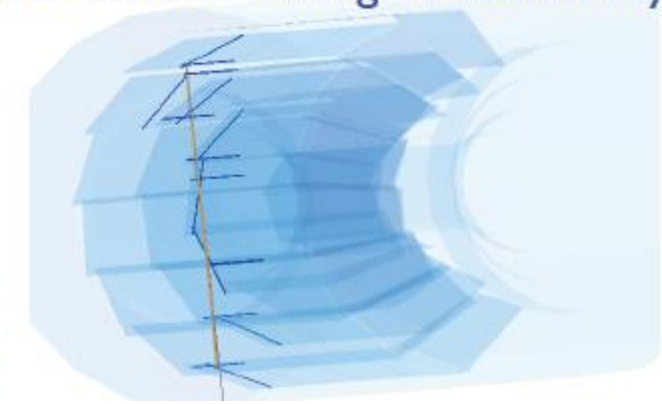
Successful marriage of PXD and SVD







SVD commissioning w/ cosmic ray



SuperKEKB/Belle II Plan

Phase 1 (w/o QCS/Belle II)

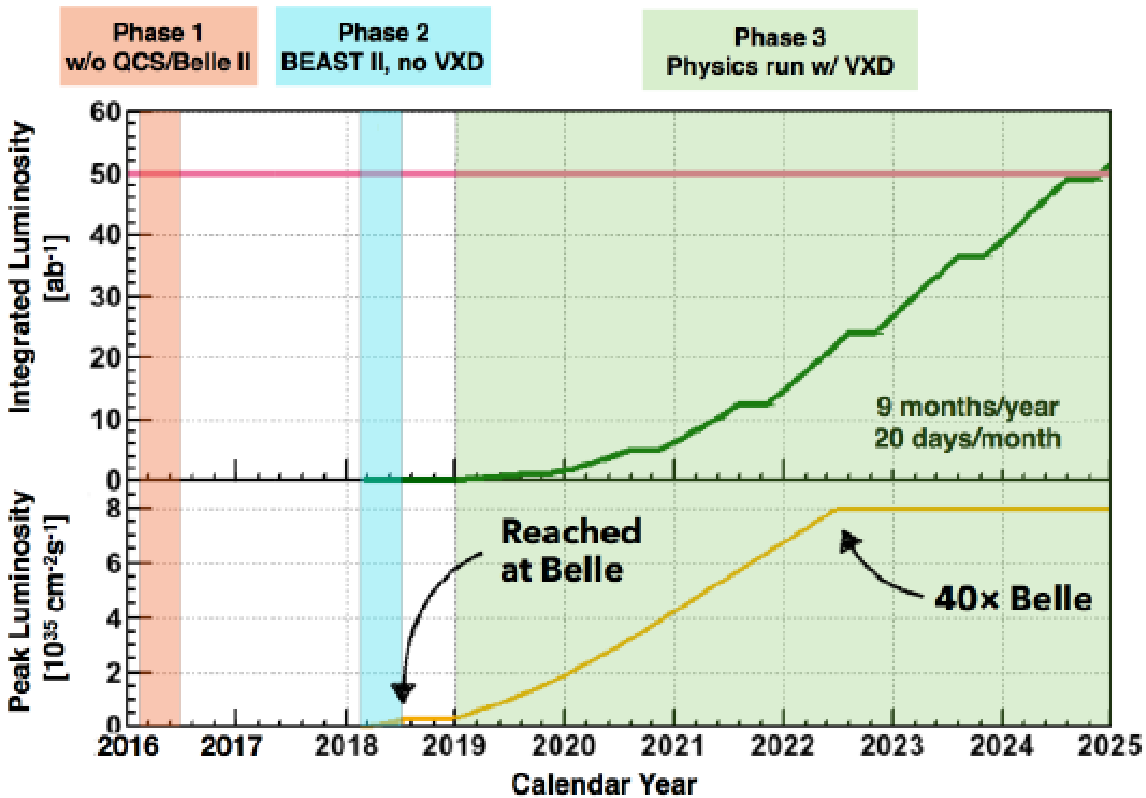
- Accelerator basic tuning with single beams

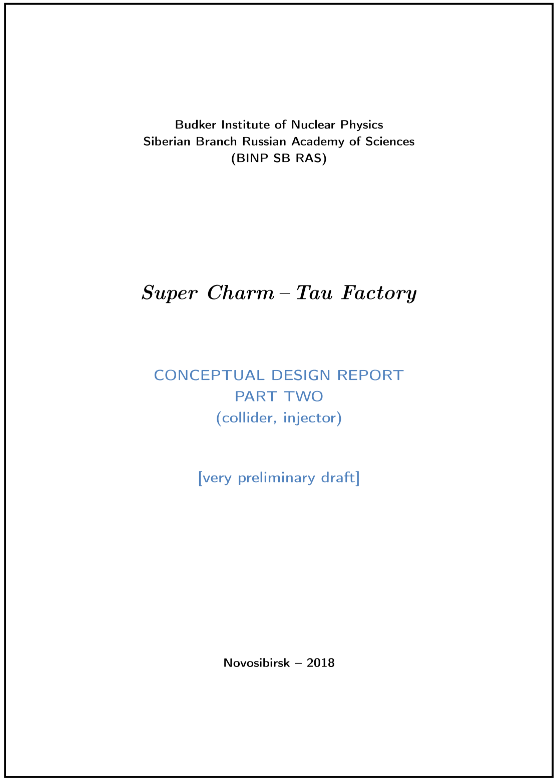
Phase 2 (w/ QCS/Belle II but w/o VXD)

- Verification of nano-beam scheme
- Understand beam background

Phase 3 (w/ full detector)

- $1ab^{-1}$ after 1 year
- $5ab^{-1}$ by ~2020
- $50ab^{-1}$ by ~2025




Budker Institute of Nuclear Physics
Siberian Branch Russian Academy of Sciences
(BINP SB RAS)

Super Charm – Tau Factory

CONCEPTUAL DESIGN REPORT
PART TWO
(collider, injector)

[very preliminary draft]

Novosibirsk – 2018

https://ctd.inp.nsk.su/wiki/index.php/CDR

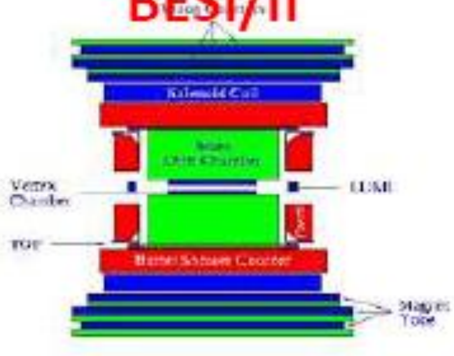
30 Years of τ-c facility in China

BEPCI (1988–2005)

$10^{31}cm^{-2}s^{-1} \Rightarrow 10^{33}cm^{-2}s^{-1}$

BEPCII (2006–now)

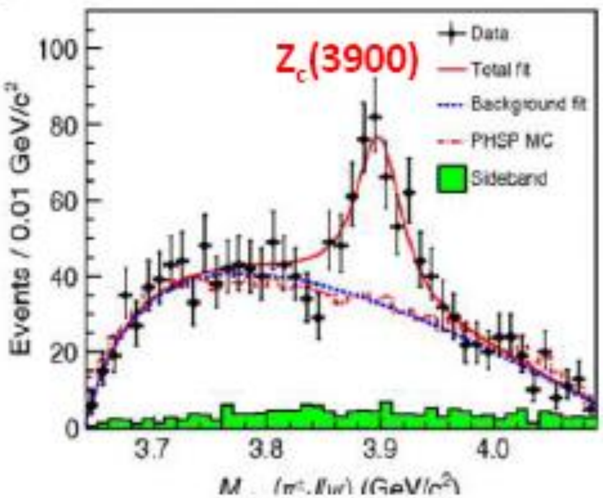
BESI/II

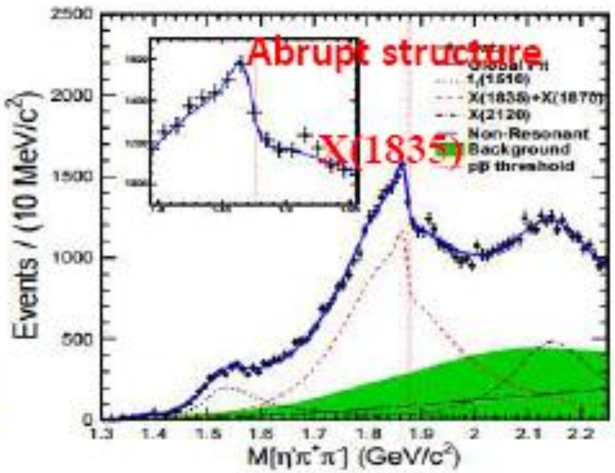


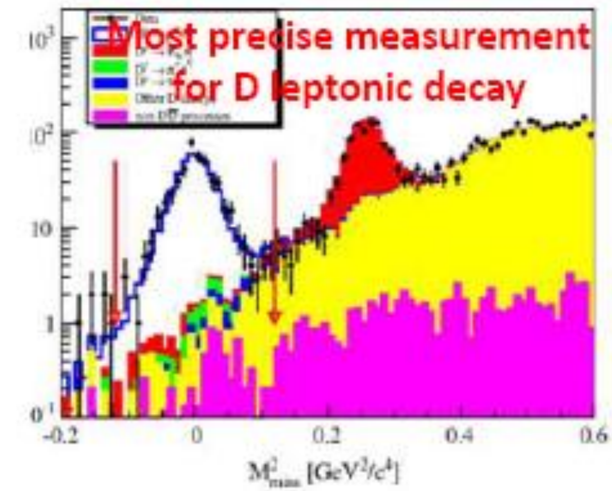
Side view of the BES detector

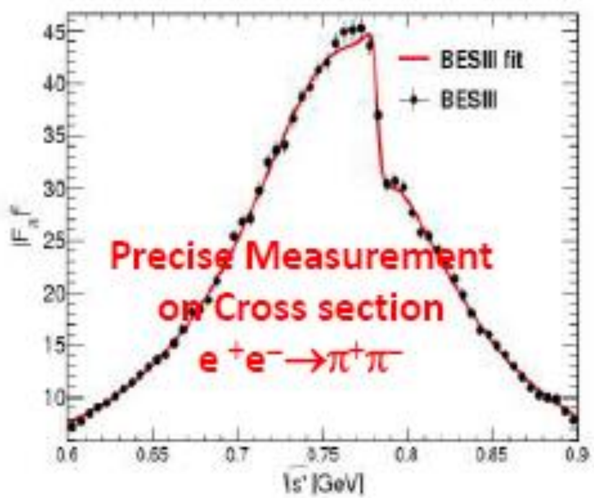
BESIII

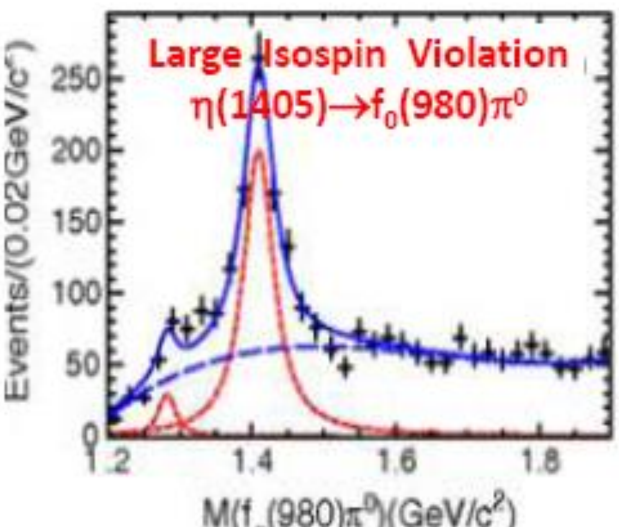
Fruitful BESIII Results

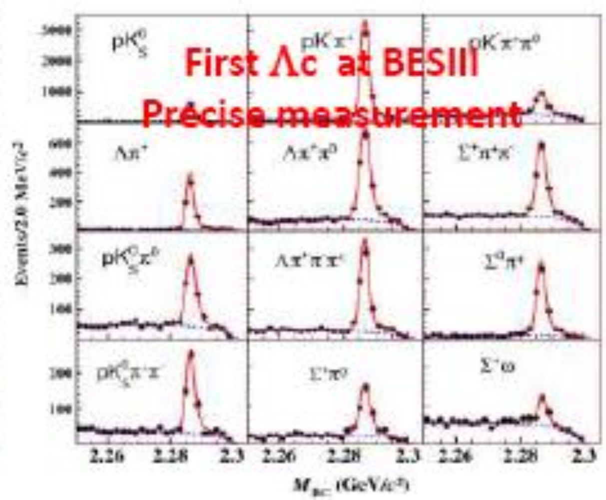












Features and limits of BEPCII/BESIII

- Threshold production
- Clean Signal, low background
- High efficiency and resolution
- ……….

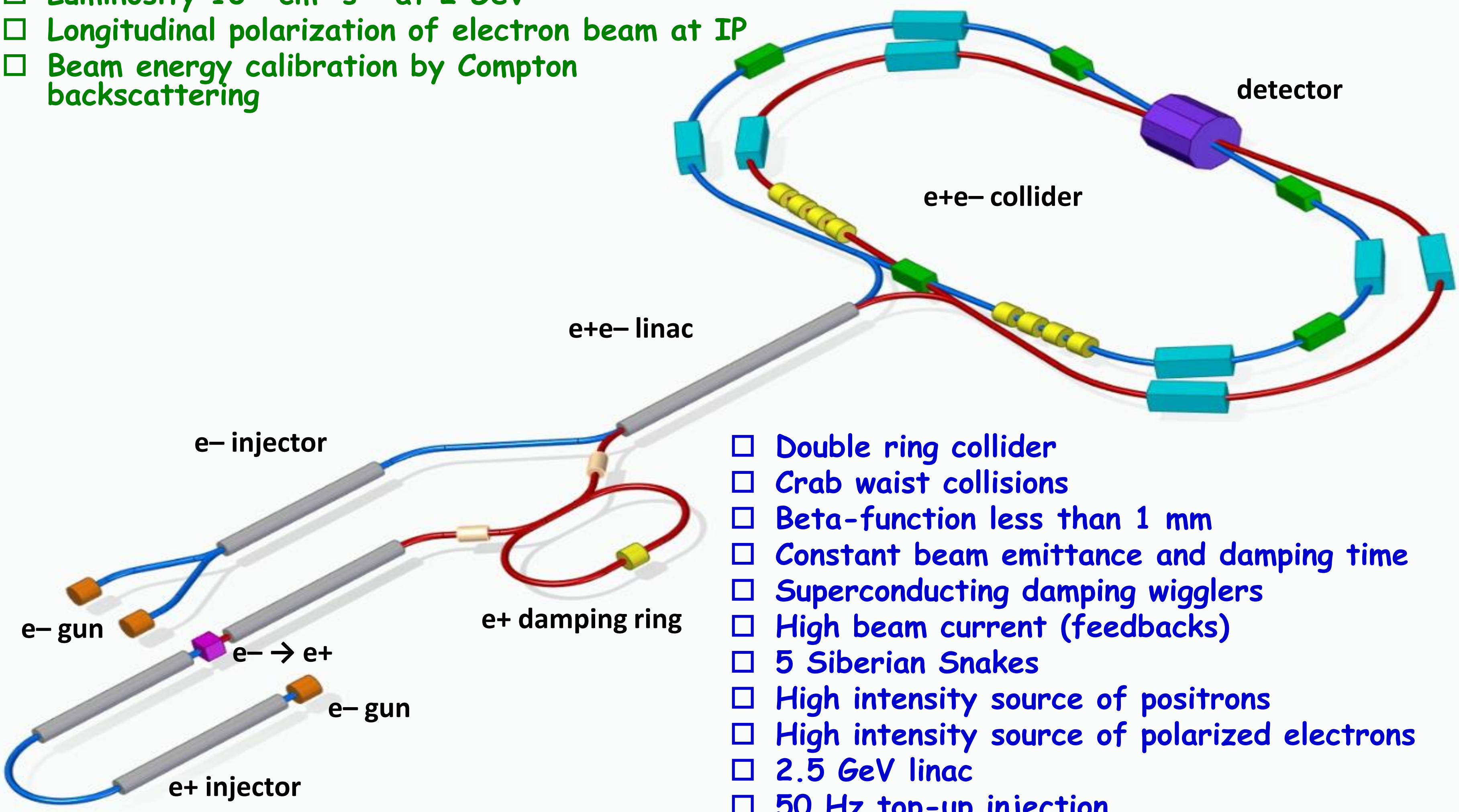
- limited Ecms range : 2-4.6 GeV
- Luminosity : 10^{33} cm^{-2} s^{-1}
- No major upgrade proposal to date

BEPCII/BESIII will end the mission in 8-10 years

Super C/Tau factory projects – Novosibirsk(Russia)/Hefei(China)

Layout & Solutions

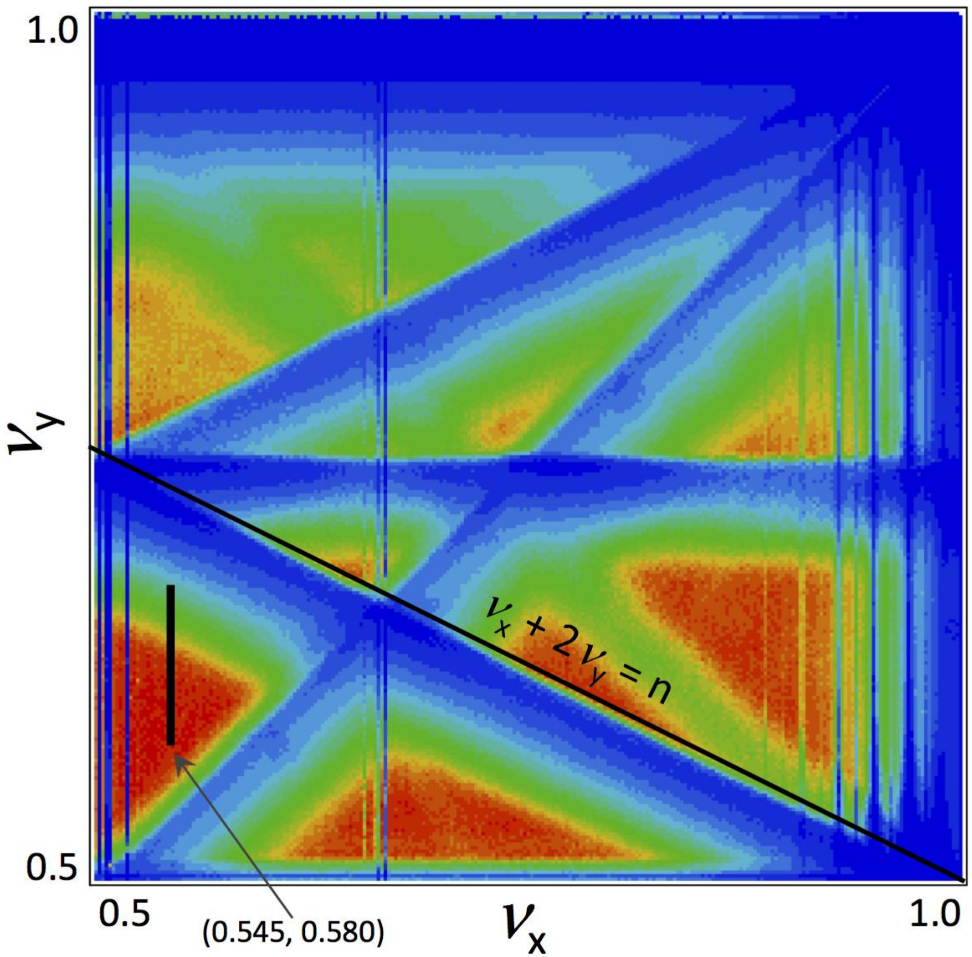
- Beam energy from 1.0 to 2.5 GeV (3.5 GeV !?)
- Luminosity 10^{35} $cm^{-2}s^{-1}$ at 2 GeV
- Longitudinal polarization of electron beam at IP
- Beam energy calibration by Compton backscattering



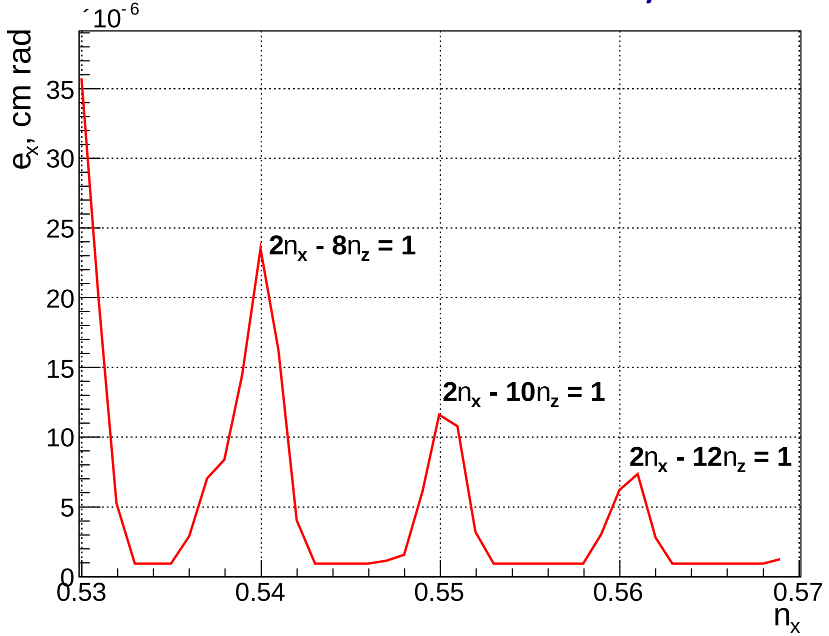
- Double ring collider
- Crab waist collisions
- Beta-function less than 1 mm
- Constant beam emittance and damping time
- Superconducting damping wigglers
- High beam current (feedbacks)
- 5 Siberian Snakes
- High intensity source of positrons
- High intensity source of polarized electrons
- 2.5 GeV linac
- 50 Hz top-up injection

Beam-Beam

10^{35} cm^{-2}s^{-1}, ξ_y~0.12, ξ_x~0.004 @ 2 GeV

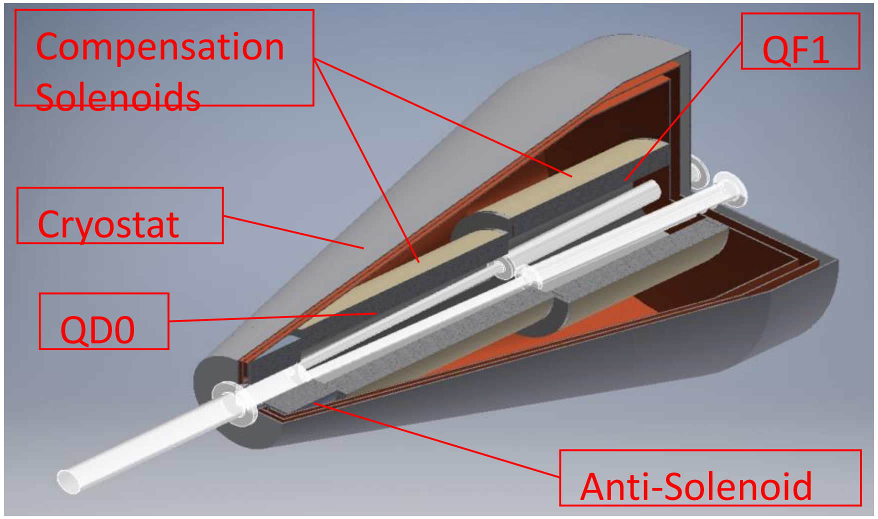


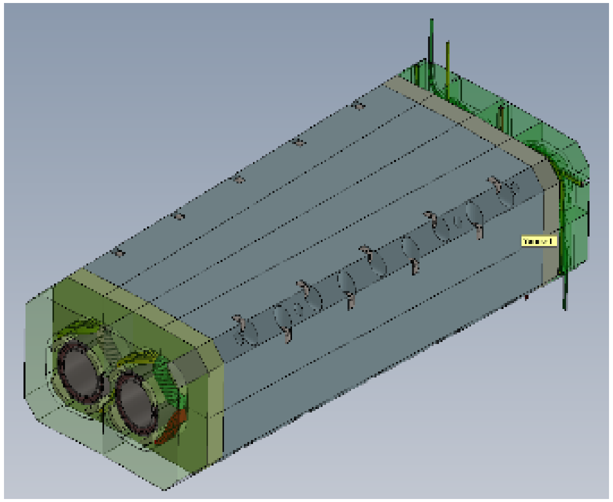
Quasi-strong-strong simulation of beam-beam XZ coherent instability

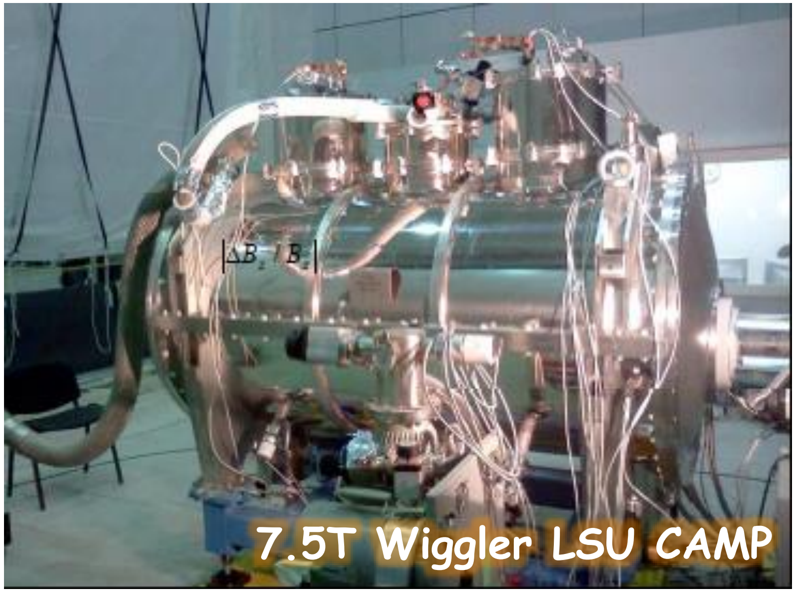


LIFETRAC by Shatilov

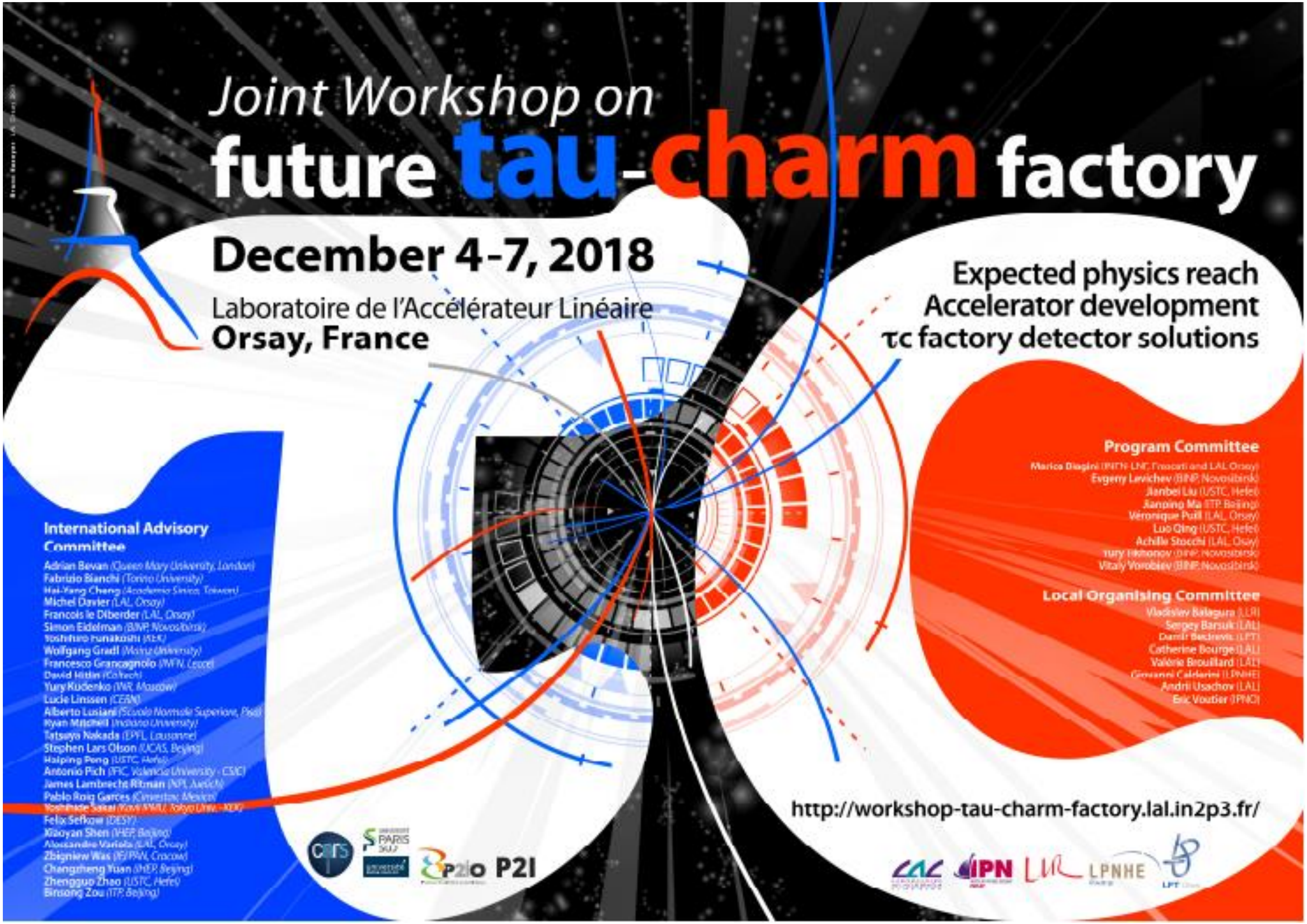
R&D activities







Infrastructure (BINP)



Joint Workshop on
future tau-charm factory
December 4-7, 2018
Laboratoire de l'Accélérateur Linéaire
Orsay, France
Expected physics reach
Accelerator development
τc factory detector solutions
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Luo Qing (USTC, Hefei)
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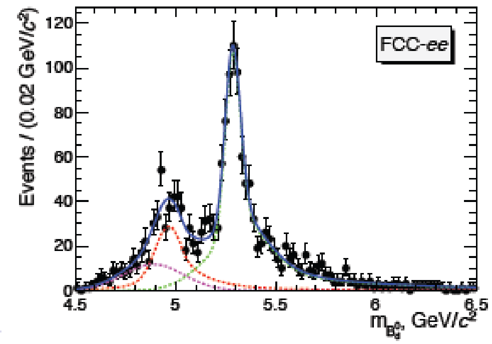
Zbigniew Was (IFJ PAN, Cracow)
Changzheng Yuan (IHEP, Beijing)
Zhengguo Zhao (USTC, Hefei)
Binsong Zou (ITP, Beijing)
http://workshop-tau-charm-factory.lal.in2p3.fr/

1) Heavy Flavours Production — Comparison w/ Belle II

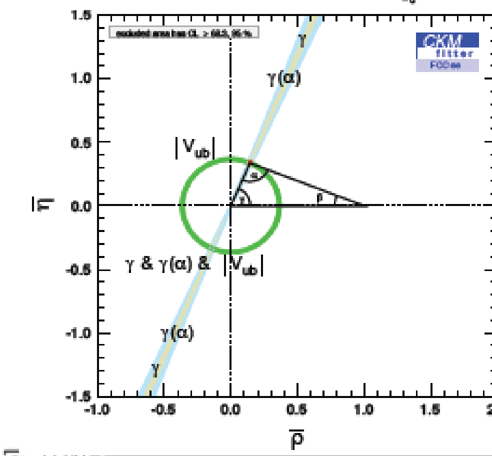
: Expected production yields of heavy-flavoured particles at Belle II (50 ab^{-1}) and FCC-ee.

Particle production (10^9)	$B^0 / \overline{B}^0$	B^+ / B^-	$B^0_s / \overline{B}^0_s$	$\Lambda_b / \overline{\Lambda}_b$	$c\overline{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	1000	1000	250	250	550	170



2) Flavour anomalies — b—> sll yields and $B^0 \to K^{*0}\ \tau^+\tau^-$

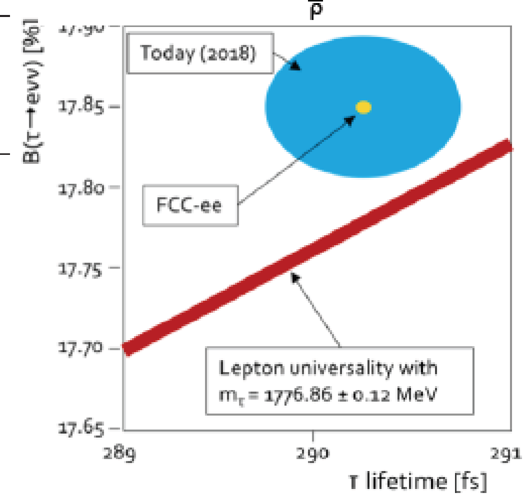
Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	$\sim$ 2 000	$\sim$ 10	n/a (5)
LHCb Run I	150	-	$\sim$ 15 (–)
LHCb Upgrade	$\sim$ 5000	-	$\sim$ 500 (50)
FCC-ee	$\sim$ 200000	$\sim$ 1000	$\sim$1000 (100)



3) CKM and *CP* violation in quark mixings

Observable / Experiments	Current W/A	Belle II (50 /ab)	LHCb-U1 (23/fb)	FCC-*ee*
CKM inputs				
γ (uncert., rad)	$1.296^{+0.087}_{-0.101}$	1.136 ± 0.026	1.136 ± 0.025	1.136 ± 0.004
$\|V_{ub}\|$ (precision)	5.9%	2.5%	6%	1%
Mixing-related inputs				
$\sin(2\beta)$	0.691 ± 0.017	0.691 ± 0.008	0.691 ± 0.009	0.691 ± 0.005
ϕ_s (uncert. rad 10^{-2})	-1.5 ± 3.5	n/a	-3.65 ± 0.05	-3.65 ± 0.01

4) Tau Physics

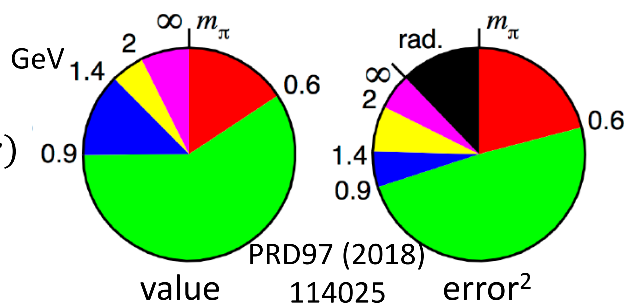


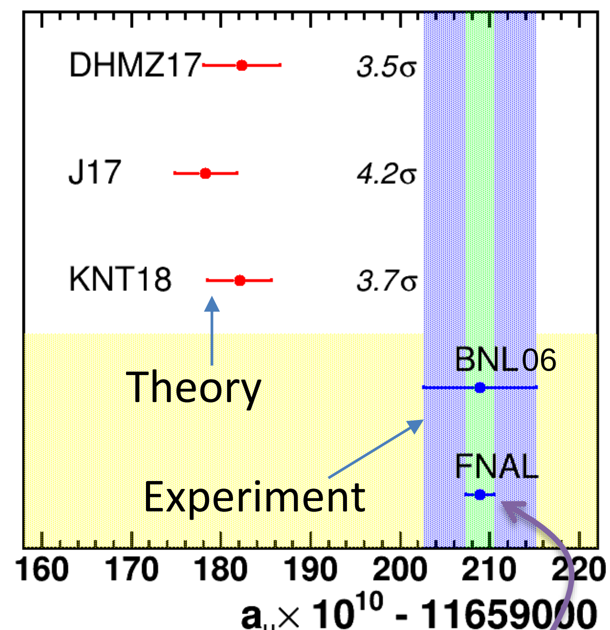
Muon (g-2) and VEPP-2000 (Novosibirsk)

Muon (g-2) is a long-standing question in flavor physics: $a_\mu(exp) - a_\mu(SM) = (3.5 \div 4)\sigma$

Theoretical precision is limited by measurement of $\sigma(e^+e^- \to hadrons)$ at low energies

$$a_\mu^{had,LO} = \frac{m_\mu^2}{12\pi^3}\int_{m_{thr}^2}^{\infty}\frac{ds}{s}\hat{K}(s)\sigma_{had}(s)$$

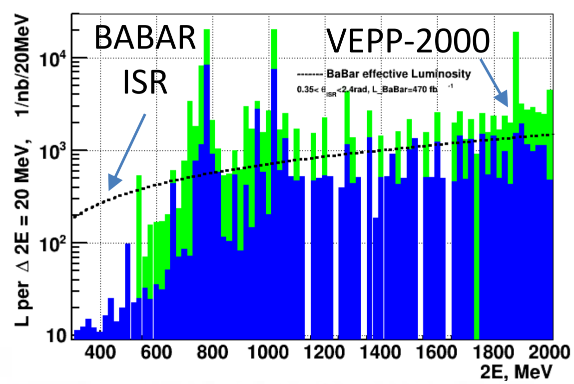


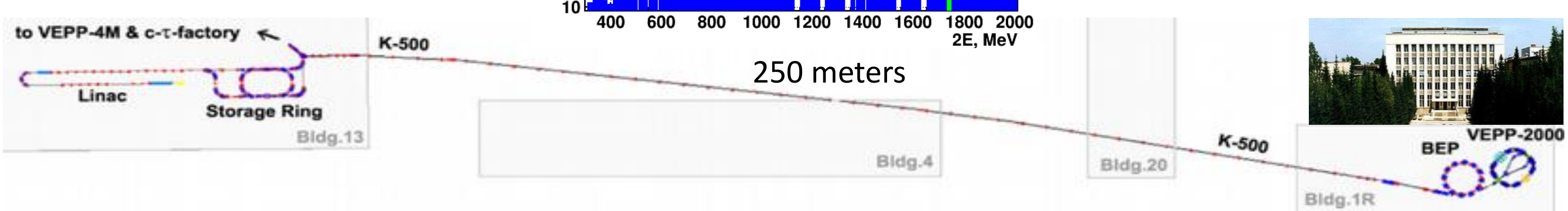


Expected final precision of FNAL measurement

New measurement at FNAL: 2018 – ~1.5-2 of BNL statistics

VEPP-2000 collider (e^+e^-, 0.36-2 GeV), now running at BINP (Novosibirsk), collected world-largest statistics at energies $\sqrt{s} \leq 2$ GeV





- There has been highly successful program of machines with increased luminosity since the 1980s.
- The SuperKEKB colider and Belle II experiment will continue the tradition with performance at a new level:
  - 40-times higher luminosity with respect to the previous record,
  - the most advanced, 21st-century detector technology.
- This will enable Belle II to explore New Physics on the Luminosity/Intensity Frontier, which is different and complementary to the LHC high p_T experiments, operating on the Energy Frontier.
- Competition and complementarity with the LHCb experiment.
- Phase-2 data-taking just finished: The data show that both the collider and detector are performing well.
- We are ready to start a long physics run (Phase 3) in 2019, operating in the Super Factory mode:
  - extensive running of SuperKEKB with world's highest luminosity,
  - high-efficiency data-taking with the complete Belle II detector.

Super C-Tau R&D is in progress.
The lattice, which meet all main requirements (800 um beta-y, chromatic correction and DA, momentum bandwidth, longitudinal polarization, luminosity optimization for wide energy range, etc.) is ready. Detailed machine design and beam dynamics simulation is in progress. Civil construction is under way.
We hope that funding of the project will start in 2020.

Thank you!

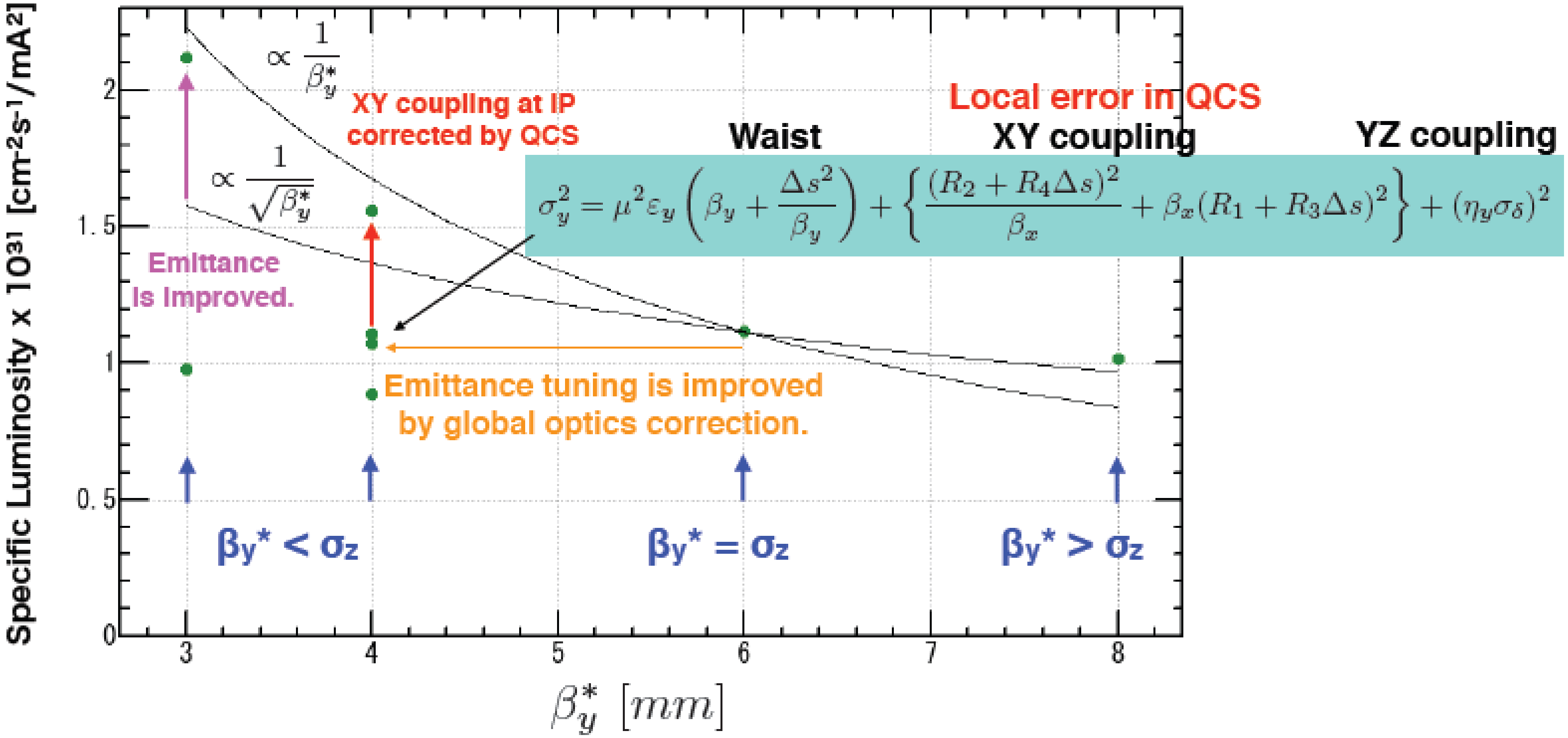
Heavy flavour data sets from colliders

- SuperKEKB is the first new collider since the LHC.
- Unique strengths in CKM metrology, rare and missing energy decays.

Expt.	$\int L\,dt$	σ(bb)	σ(cc)	Operation
Babar	530 fb^{-1}	1.1 nb	1.6 nb	1999-2008
Belle	1040 fb^{-1}	1.1 nb	1.6 nb	1999-2010
Belle II	**0.5 fb^{-1} (50 ab^{-1})**	**1.1 nb**	**1.6 nb**	**2018-**
BESIII	~16 fb^{-1}	-	6 nb (3770 MeV)	2008-
LHCb	1 + 2 + >5 fb^{-1}	250-500 μb	1200-2400 μb	2009-

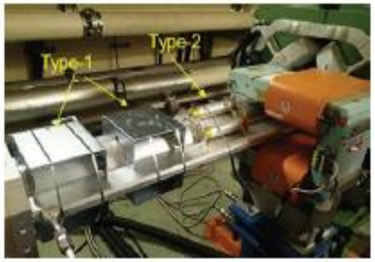
Observables	Expected the. accuracy		Expected exp. uncertainty	Facility (2025)
UT angles & sides				
ϕ_1 [°]	***		0.4	Belle II
ϕ_2 [°]	**		1.0	Belle II
ϕ_3 [°]	***	CKM	1.0	LHCb/Belle II
$\lvert V_{cb}\rvert$ incl.	***		1%	Belle II
$\lvert V_{cb}\rvert$ excl.	***		1.5%	Belle II
$\lvert V_{ub}\rvert$ incl.	**		3%	Belle II
$\lvert V_{ub}\rvert$ excl.	**		2%	Belle II/LHCb
CPV				
$S(B\to\phi K^0)$	***		0.02	Belle II
$S(B\to\eta' K^0)$	***	CPV	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
$R(B\to D\tau\nu)$	***	SL	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
$\mathcal{B}(B_s\to\gamma\gamma)$ $[10^{-6}]$	**	EWP	0.3	Belle II
$\mathcal{B}(B\to K^*\nu\bar{\nu})$ $[10^{-6}]$	***		15%	Belle II
$\mathcal{B}(B\to K\nu\bar{\nu})$ $[10^{-6}]$	***		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
$\mathcal{B}(D_s\to\tau\nu)$	***	D	2%	Belle II
$A_{CP}(D^0\to K_S^0\pi^0)$ $[10^{-2}]$	**		0.03	Belle II
$\lvert q/p\rvert(D^0\to K_S^0\pi^+\pi^-)$	***		0.03	Belle II
$\phi(D^0\to K_S^0\pi^+\pi^-)$ [°]	***		4	Belle II
Tau				
$\tau\to\mu\gamma$ $[10^{-10}]$	***	τ	< 50	Belle II
$\tau\to e\gamma$ $[10^{-10}]$	***		< 100	Belle II
$\tau\to\mu\mu\mu$ $[10^{-10}]$	***		< 3	Belle II/LHCb

$$L \propto \frac{1}{\sqrt{\varepsilon_y \beta_y^*}} \quad \text{or} \quad L \propto \frac{\xi_y}{\beta_y^*} \quad \xi_y \propto \sqrt{\frac{\beta_y^*}{\varepsilon_y}}$$



Additional permanent magnets

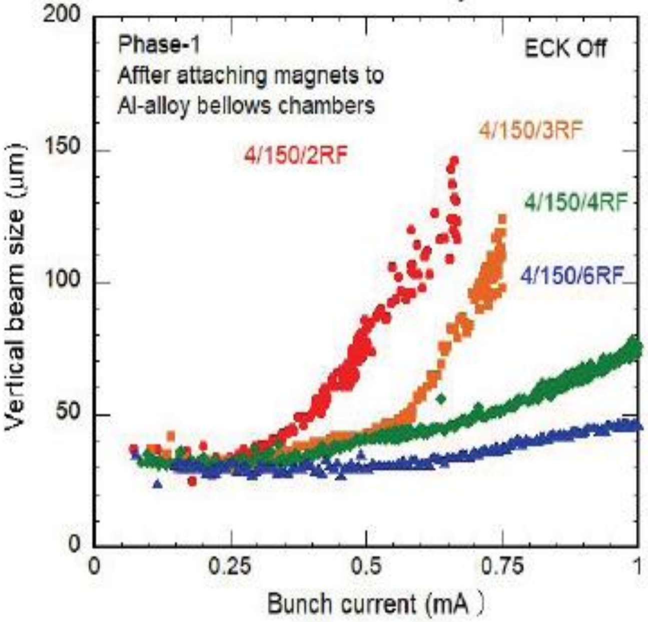
Y. Suetsugu et al.



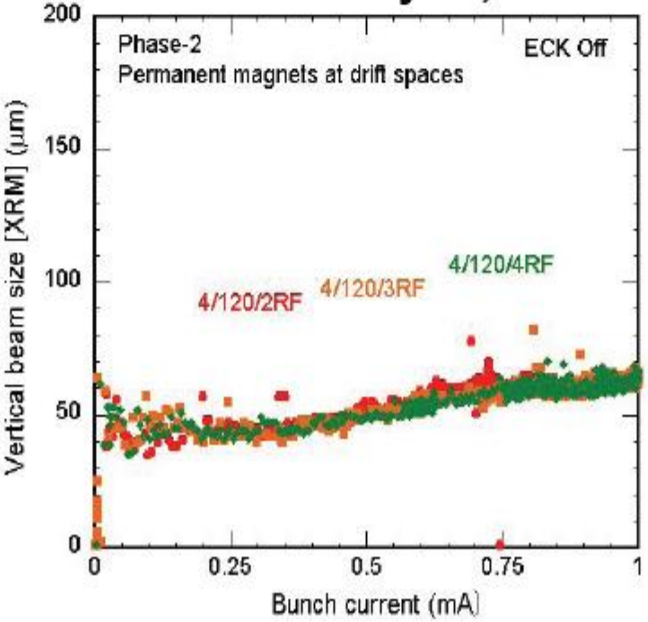
Threshold is much improved.
more than twice of 0.2 mA/bunch/RF bucket

Mode of CBI changes and the growth rate is reduced.

Phase 1: June 9, 2016



Phase 2: July 12, 2019



no blowup

Machine Parameters

	Phase 2 (high bunch current)		Phase 2 (high current)		Phase 3 (final)		
	LER	HER	LER	HER	LER	HER	Unit
$I\ @\ L_{peak}$	**265**	**217**	**788**	**778**	**3600**	**2600**	mA
n_b	395		1576		2500		
I/n_b	0.670	0.549	0.500	0.494	1.44	1.04	mA/bunch
ε_x	1.8	4.6	1.7	4.6	3.2	4.6	nm
β_x^*	200	100	200	100	32	25	mm
β_y^*	**3**	**3**	**3**	**3**	**0.27**	**0.3**	mm
α_c	2.9 x 10^{-4}	4.5 x 10^{-4}	2.9 x 10^{-4}	4.5 x 10^{-4}	3.2 x 10^{-4}	4.5 x 10^{-4}	
σ_δ	7.58 x 10^{-4}	6.31 x 10^{-4}	7.58 x 10^{-4}	6.31 x 10^{-4}	8.10 x 10^{-4}	6.37 x 10^{-4}	
U_0	1.76	2.43	1.76	2.43	1.76	2.43	NeV
V_c	8.4	12.8	8.4	12.8	9.4	15.0	MV
ν_s	-0.0220	-0.0258	-0.0220	-0.0258	-0.0244	-0.0280	
ν_x	44.562	45.542	44.561	45.545	44.53	45.53	
ν_y	46.617	43.609	46.614	43.612	46.57	43.57	
σ_y^* (X-ray)	883	652	1285*	528	48	62	nm
$\xi_y\ (\Sigma_y/\sqrt{2})$	**0.030**	**0.021**	**0.0244**	**0.0141**	**0.088**	**0.081**	
L	**2.29 x 10^{33}**		5.55 x 10^{33}		8 x 10^{35}		$cm^{-2}s^{-1}$

*ε_y enhancement in LER

Preliminary

Y.Ohnishi, eeFACT 2018, September 24, 2018

Milestones of BEPCII

Jan. 2004	Construction started
May. 4, 2004	Dismount of 8 linac sections
Dec. 1, 2004	Linac delivered e^- beams to BEPC
July 4, 2005	BEPC ring dismount started
Mar. 2, 2006	BEPCII ring installation started
Aug. 3, 2007	Shutdown for IR-SCQ installation
Mar. 28, 2008	Shutdown for BESIII installation
July 19, 2008	First hadron event observed
May 19, 2009	Luminosity reached $3.3\times10^{32}cm^{-2}s^{-1}$
July 17, 2009	Pass the National test & check
April 8, 2011	Luminosity reached $6.5\times10^{32}cm^{-2}s^{-1}$
April 2013	Zc(3900) found & confirmed
Nov. 20, 2014	Luminosity reached $8.53\times10^{32}cm^{-2}s^{-1}$
April 5, 2016	Luminosity reached $10.0\times10^{32}cm^{-2}s^{-1}$

2016/04/05 22:29:47

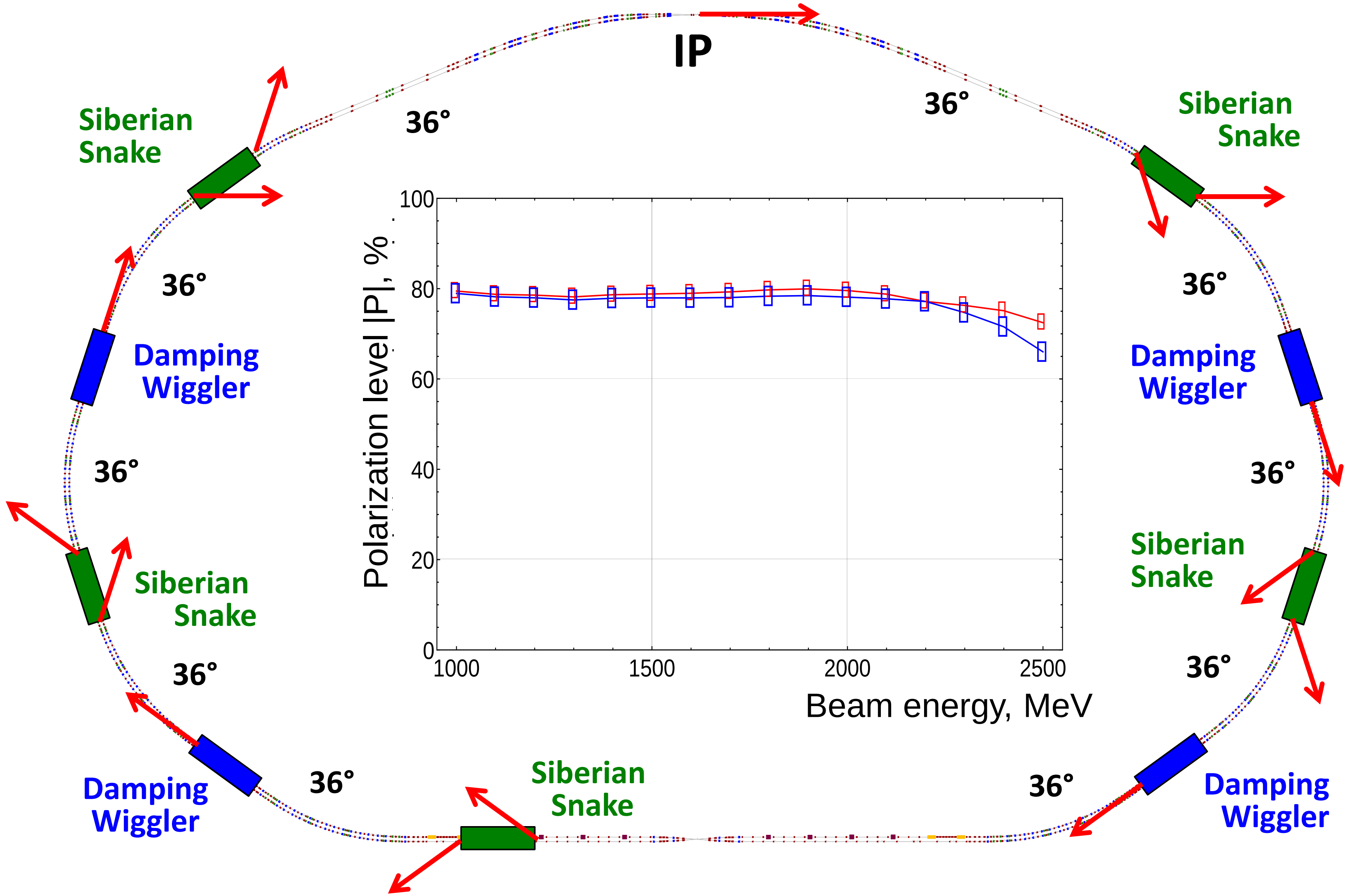
Luminosity 10.00 E32/cm^2/s

	e+	e−
Energy [GeV]	1.8831	1.8831
Current [mA]	849.18	852.31
Lifetime [hr]	1.53	2.30
Inj.Rate [mA/min]	0.00	0.00

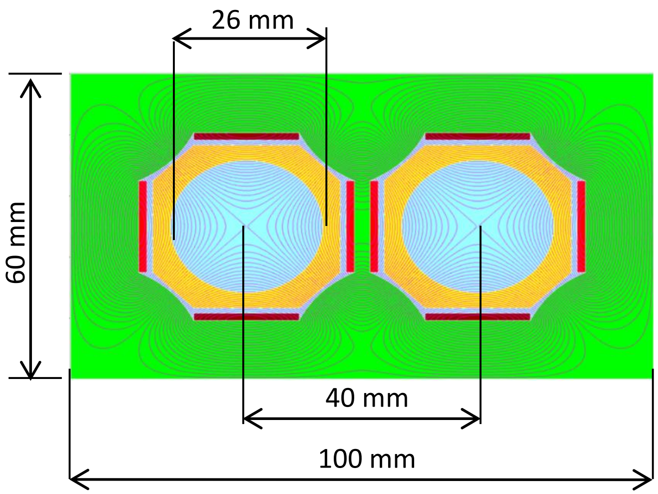
Main parameters

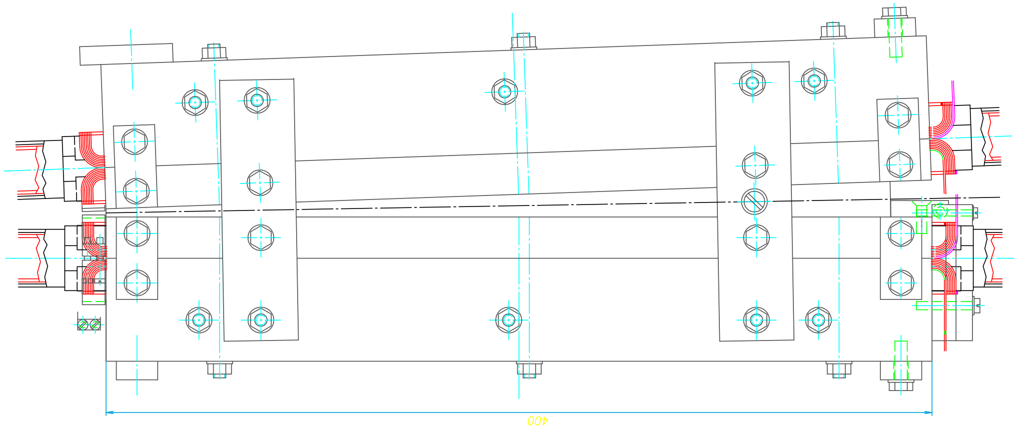
Energy	1.0 GeV	1.5 GeV	2.0 GeV	2.5 GeV
Circumference	813.1 m			
Emittance hor/ver	8 nm/0.04 nm @ 0.5% coupling			
Damping time hor/ver/long	50/50/25 ms	30/30/15 ms		
Bunch length	21 mm	12 mm	10 mm	10 mm
Energy spread	$8.7 \cdot 10^{-4}$	$11 \cdot 10^{-4}$	$9.3 \cdot 10^{-4}$	$7.2 \cdot 10^{-4}$
Momentum compaction	$8.73 \cdot 10^{-4}$	$8.81 \cdot 10^{-4}$	$8.82 \cdot 10^{-4}$	$8.83 \cdot 10^{-4}$
Damping wiggler field	50 kGs	50 kGs	35 kGs	10 kGs
Synchrotron tune	0.007	0.012	0.009	0.008
RF frequency	499.95 MHz			
Harmonic number	1356			
Particles in bunch	$7 \cdot 10^{10}$			
Number of bunches	406 (10% gap)			
Bunch current	4.2 mA			
Total beam current	1.7 A			
Beam-beam parameter	0.135	0.135	0.121	0.097
Luminosity	$0.6 \cdot 10^{35}$	$0.9 \cdot 10^{35}$	$1.0 \cdot 10^{35}$	$1.0 \cdot 10^{35}$

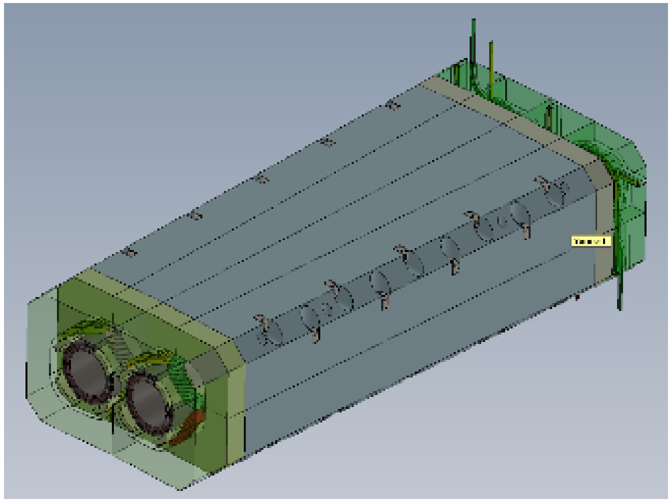
Polarization with 5 Siberian Snakes

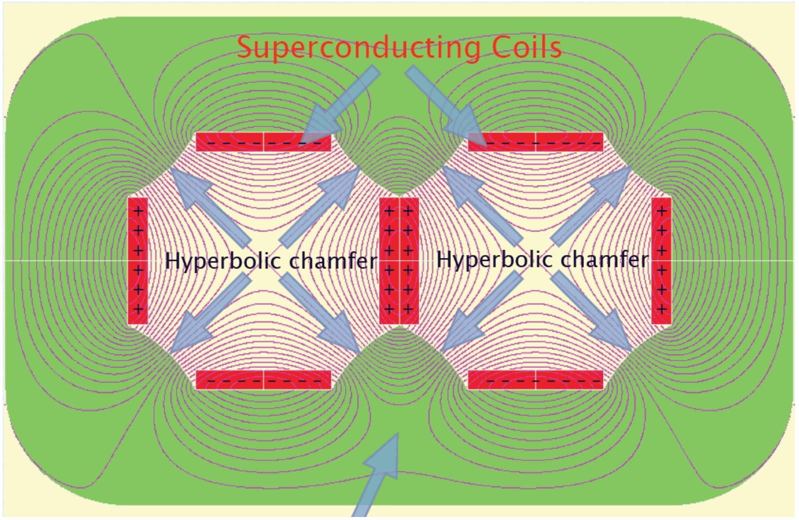


Double Aperture lens

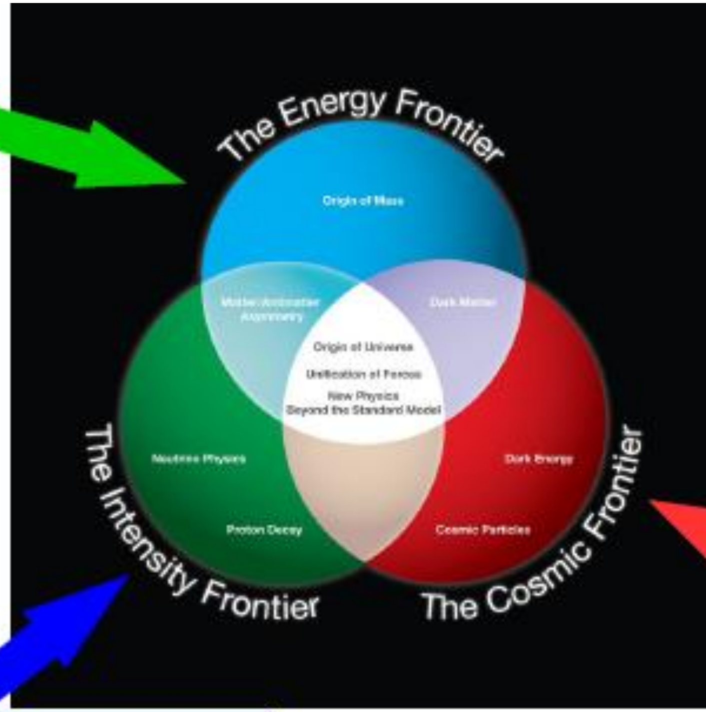








- LHC experiments



- Astroparticle experiments

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

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.

https://science.energy.gov/hep/research/