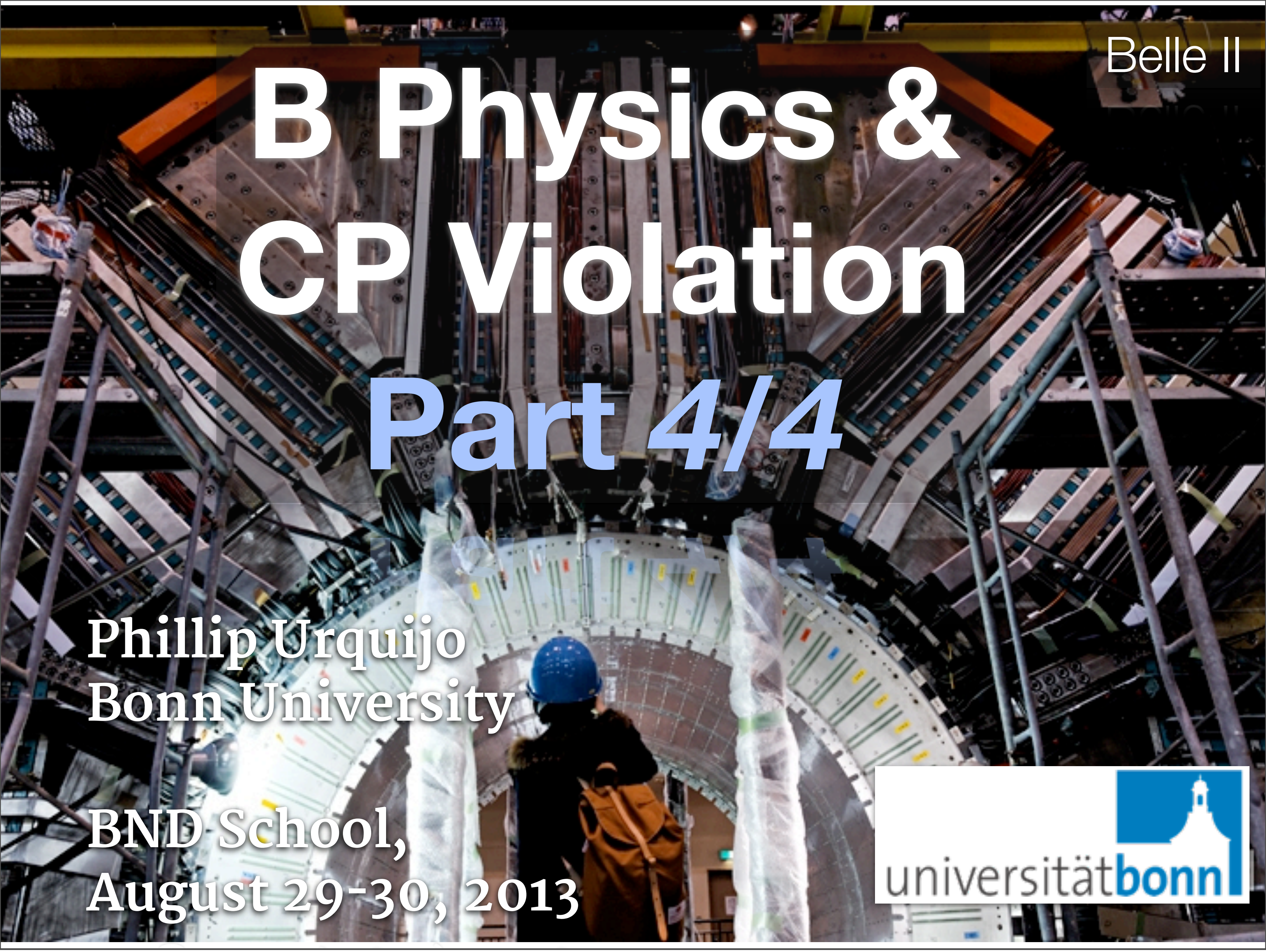


Belle II

B Physics & CP Violation

Part 4/4

Phillip Urquijo
Bonn University

BND School,
August 29-30, 2013

Outline

Part 1: Introduction to Flavour Physics

- What is flavour physics & why is it interesting?
- Brief history of discovery in flavour physics
- CKM mechanism and Unitarity Triangle (UT)
- B-physics Experiments

Part 2: CP violation & CKM measurements (Triumphs of the SM)

- Meson-antimeson oscillations
- Introduction to CP violation
- Measurement of UT angles
- Measurement of UT sides

Part 3: Search for New Physics

- Radiative Decays
- Tauonic Decays
- Purely Leptonic Decays

Part 4: The future

- The future experiments

Lesson from Flavour

- Unwise to assume ~10% (or even 0.1%) is ‘good enough’ with flavour

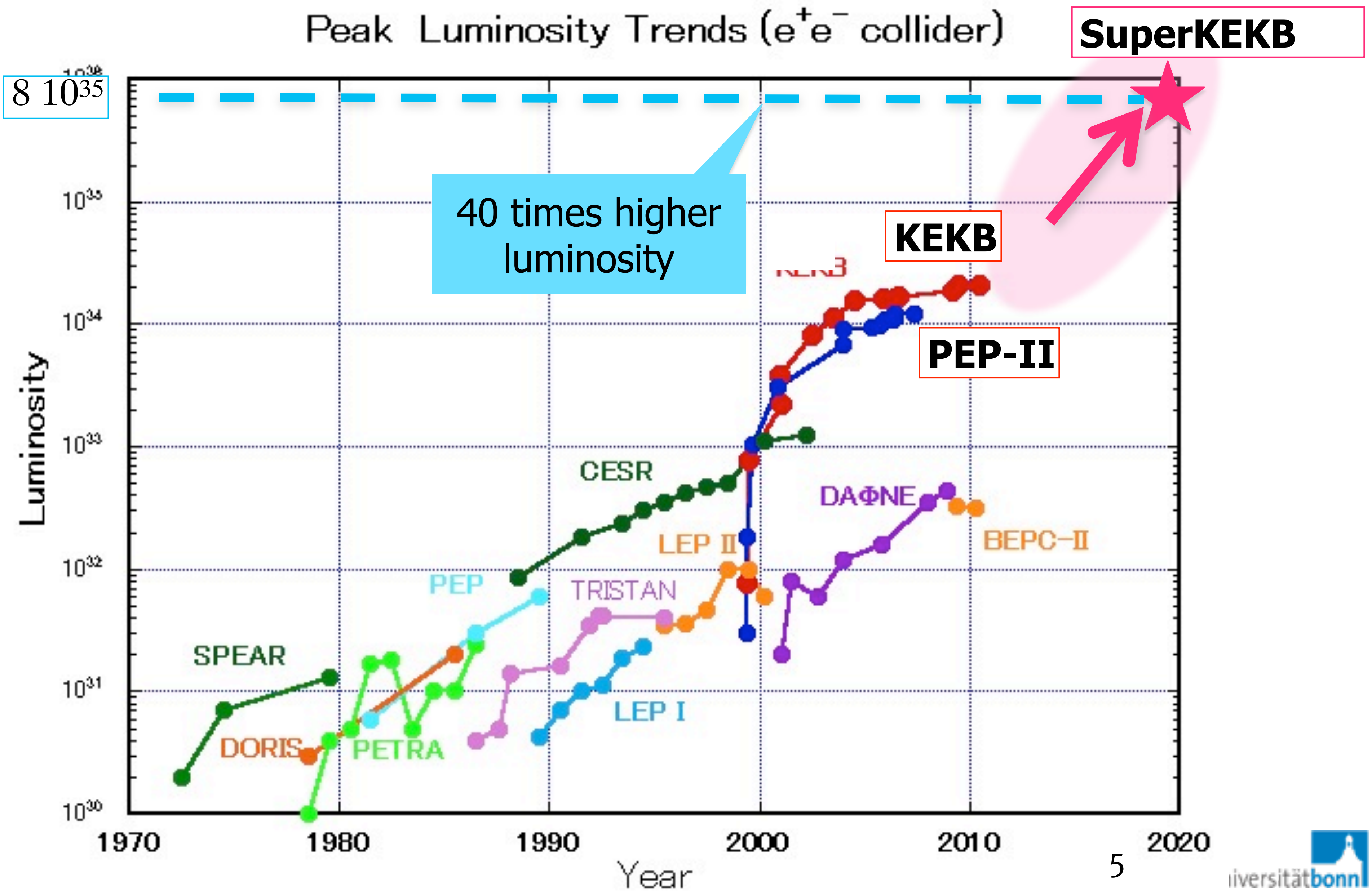
- **1962:** "A special search at Dubna was carried out by E. Okonov and his group. They did not find a single K_L to $\pi^+ \pi^-$ event among 600 decays into charged particles (Anikira *et al*, JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."
  -Lev Okun, "The Vacuum as Seen from Moscow"

- **1964**: BF= 2 x 10^{-3}, Cronin, Fitch et al. 1964.

Belle II

@SuperKEKB

Need 50x more data →Next generation B-factories



universitätbonn

Strategies for increasing luminosity

Beam-beam parameter

Lorentz factor

Beam current

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

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

Classical electron radius

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

Vertical beta function@IP

(1) Smaller ßy*

(2) Increase beam currents

(3) Increase xy

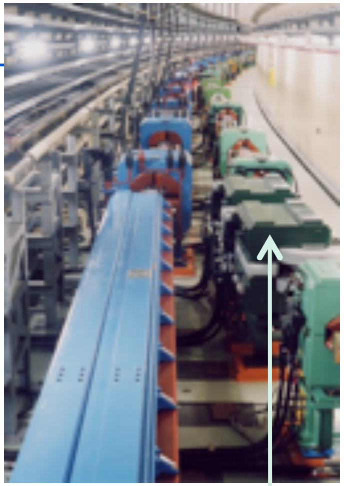
"Nano-Beam" scheme

Machine design parameters

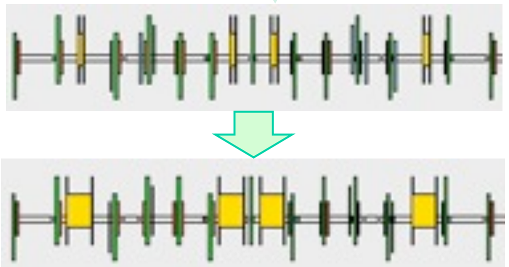
parameters		KEKB LER	KEKB HER	SuperKEKB LER	SuperKEKB HER	units
Beam energy	E_b	3.5	8	4	7	GeV
Half crossing angle	ϕ	11		41.5		mrad
Horizontal emittance	ε_x	18	24	3.2	4.6	nm
Emittance ratio	κ	0.88	0.66	0.37	0.40	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
Beam currents	I_b	1.64	1.19	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

KEKB to SuperKEKB

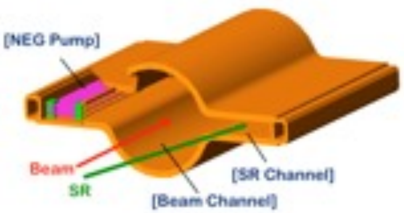


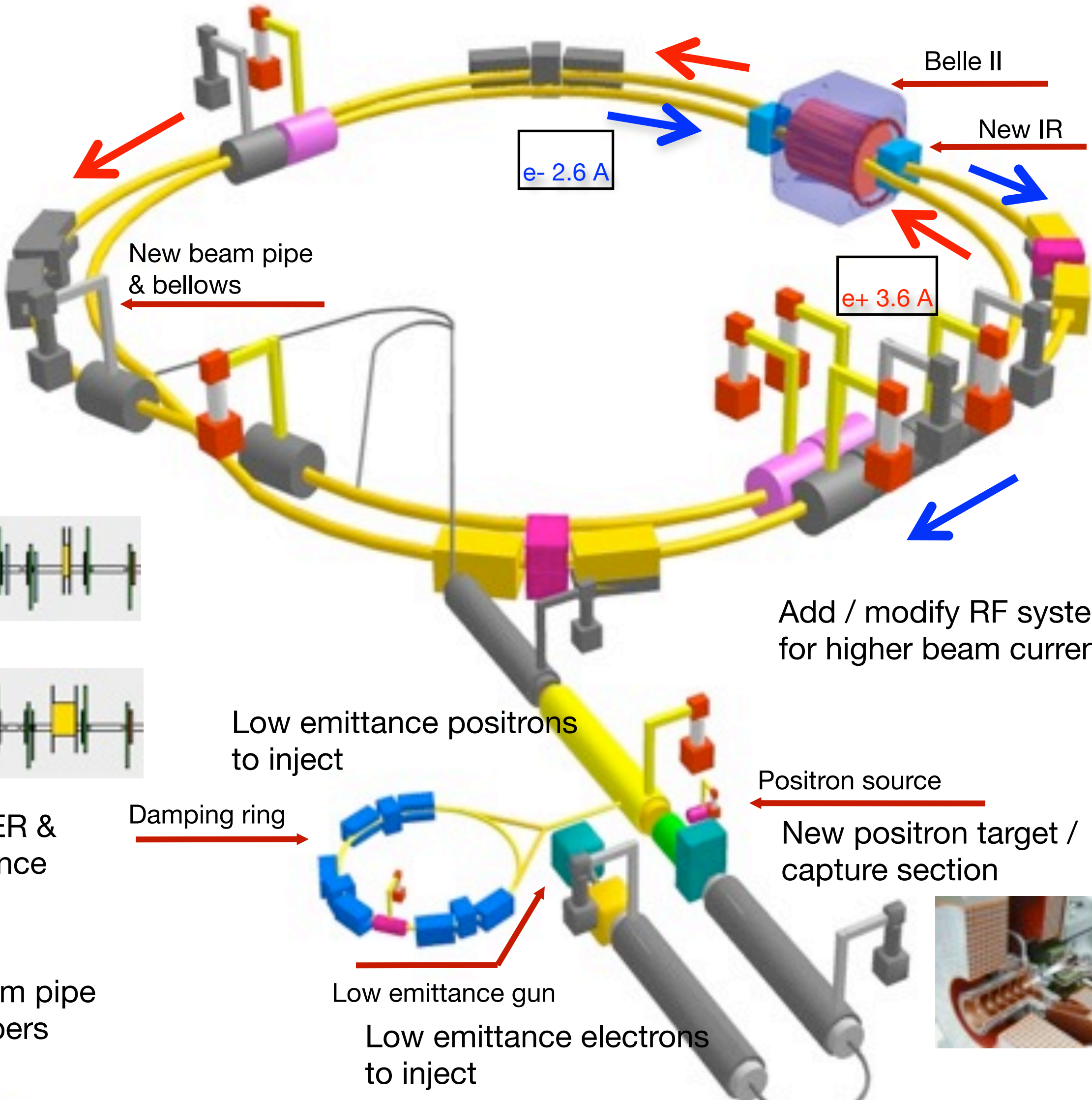
Replace short dipoles
with longer ones (LER)



Redesign the lattices of HER &
LER to squeeze the emittance

TiN-coated beam pipe
with antechambers

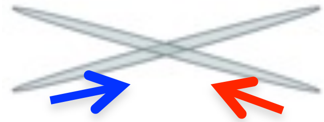




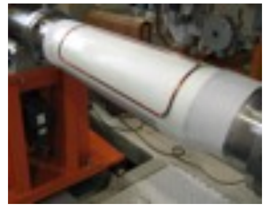
Low emittance positrons
to inject

Low emittance electrons
to inject

Colliding bunches



New superconducting /
permanent final focusing
quads near the IP



Add / modify RF systems
for higher beam current

New positron target /
capture section

To obtain x40 higher luminosity

All 100 4 m long dipole magnets have been successfully installed in the low energy ring (LER)!

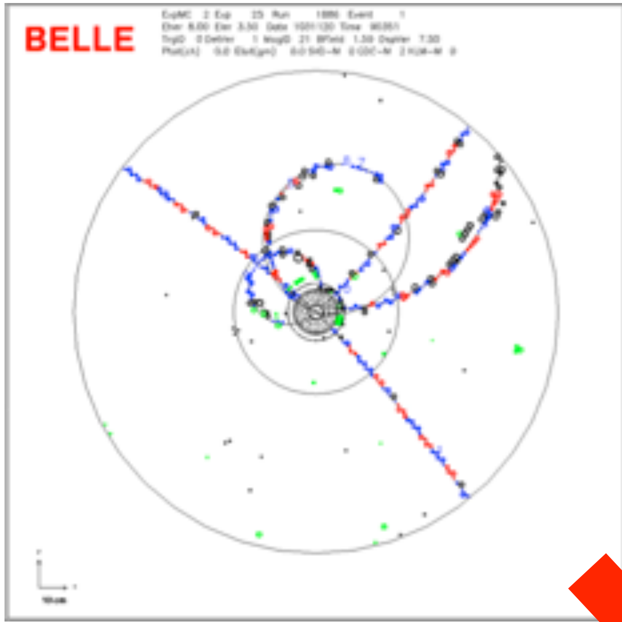
Three magnets per day !
Total ~100

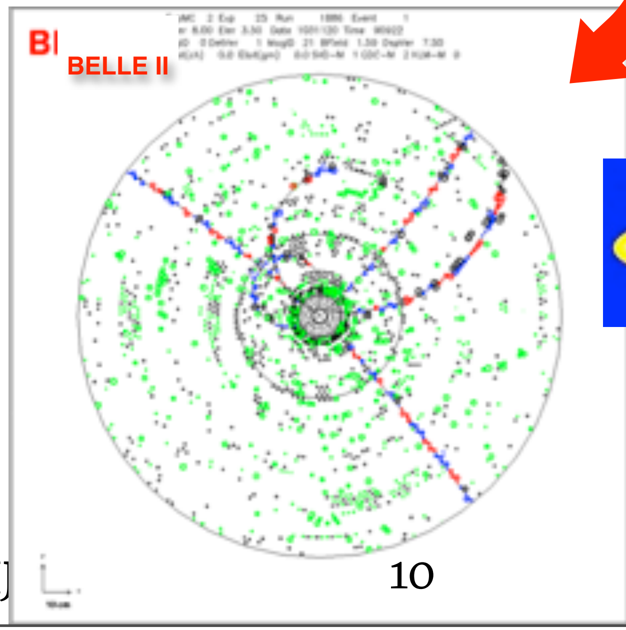
Installing the 4 m long LER dipole **over** the 6 m long HER dipole (remains in place).

Need to build a new detector to handle higher backgrounds

Critical issues at L= 8 x 10^{35}/cm^2/sec

- **Higher background ($\times$10-20)**
  - radiation damage and occupancy
  - fake hits and pile-up noise in the EM
- **Higher event rate ($\times$10)**
  - higher rate trigger, DAQ and computing
- **Require special features**
  - low p μ identification $\leftarrow$ $s\mu\mu$ recon. eff.
  - hermeticity $\leftarrow$ ν "reconstruction"



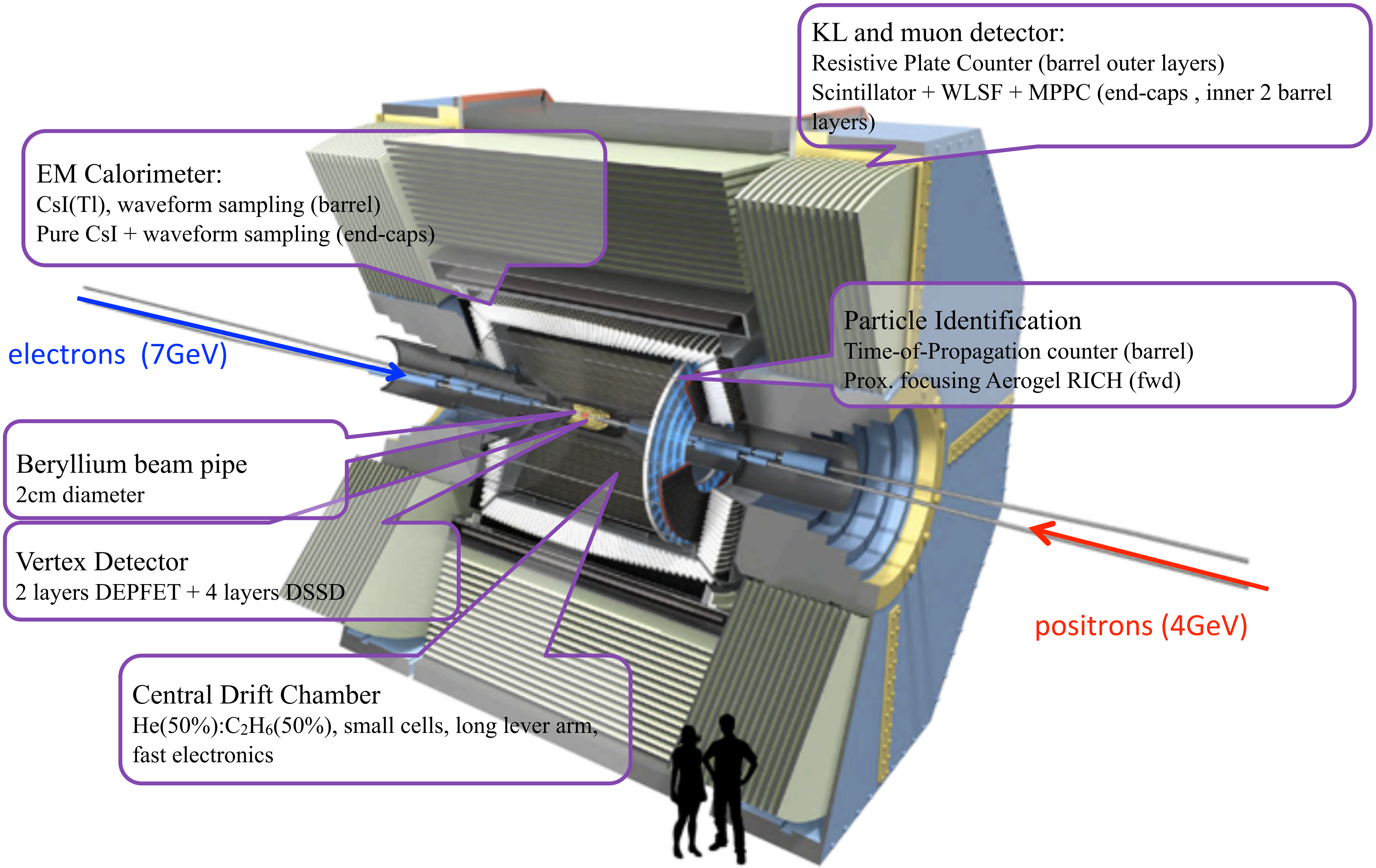


Have to employ and develop new technologies to make such an apparatus work!
$\rightarrow$

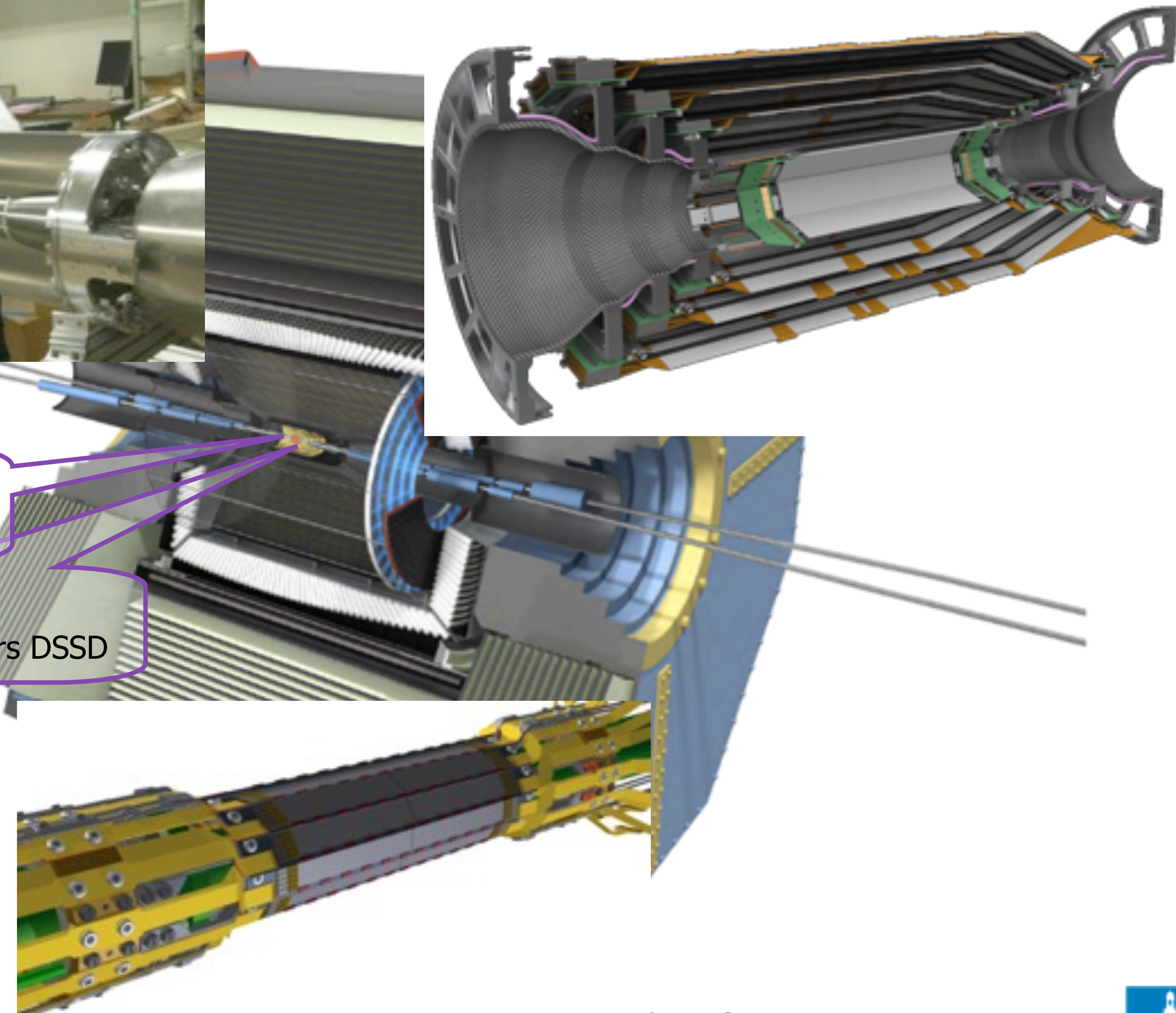
TDR published arXiv:1011.0352v1 [physics.ins-det]

Belle II

Belle II Detector



Vertex Region

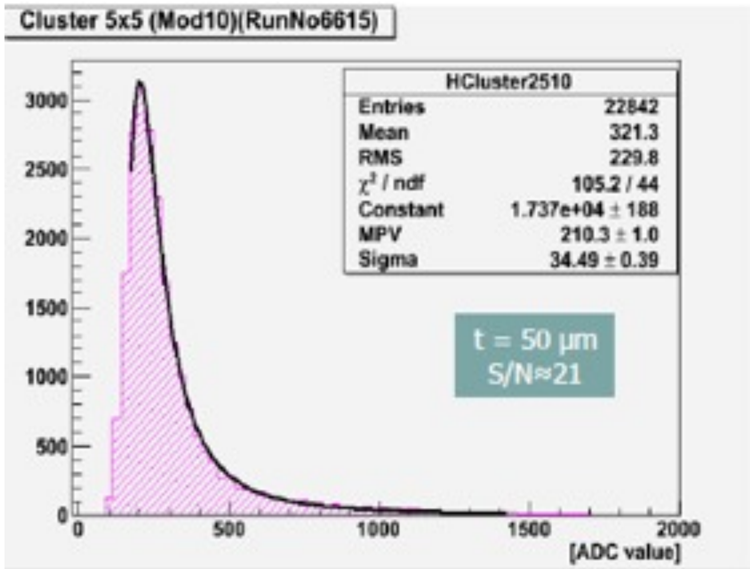


Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

VXD

Beam Pipe		**r = 10mm**
DEPFET		
	Layer 1	**r = 14mm**
	Layer 2	**r = 22mm**
DSSD		
	Layer 3	**r = 38mm**
	Layer 4	**r = 80mm**
	Layer 5	**r = 115mm**
	Layer 6	**r = 140mm**

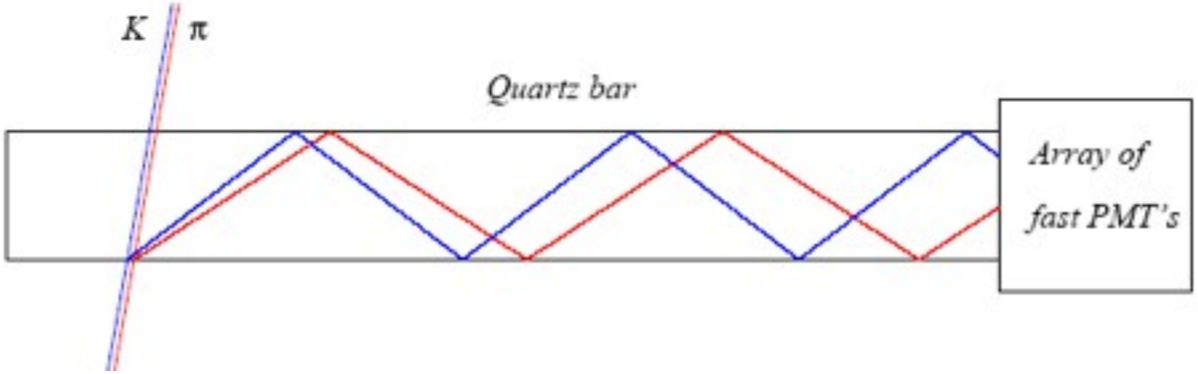


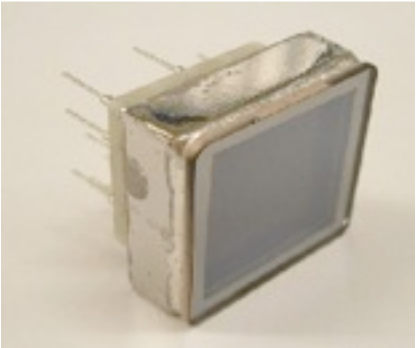
Mechanical mockup of pixel detector

DEPFET sensor: very good S/N

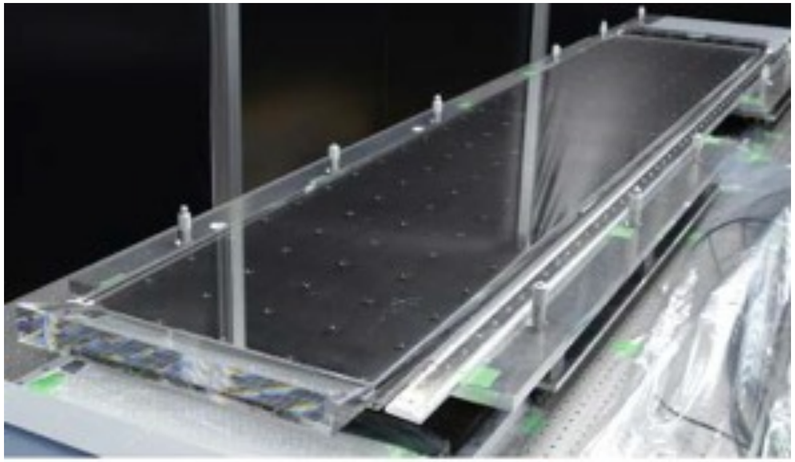
DEPFET pixel sensor

Barrel PID: Time of propagation (TOP) counter

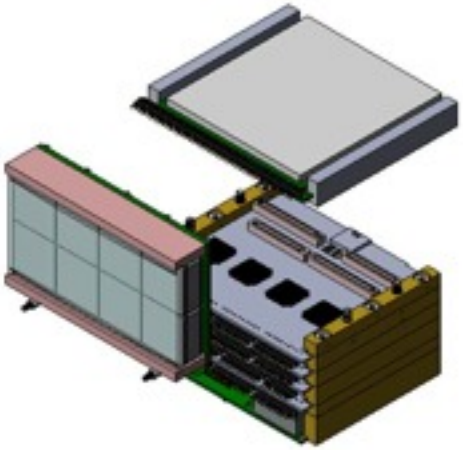




Hamamatsu SL10 MCP PMT



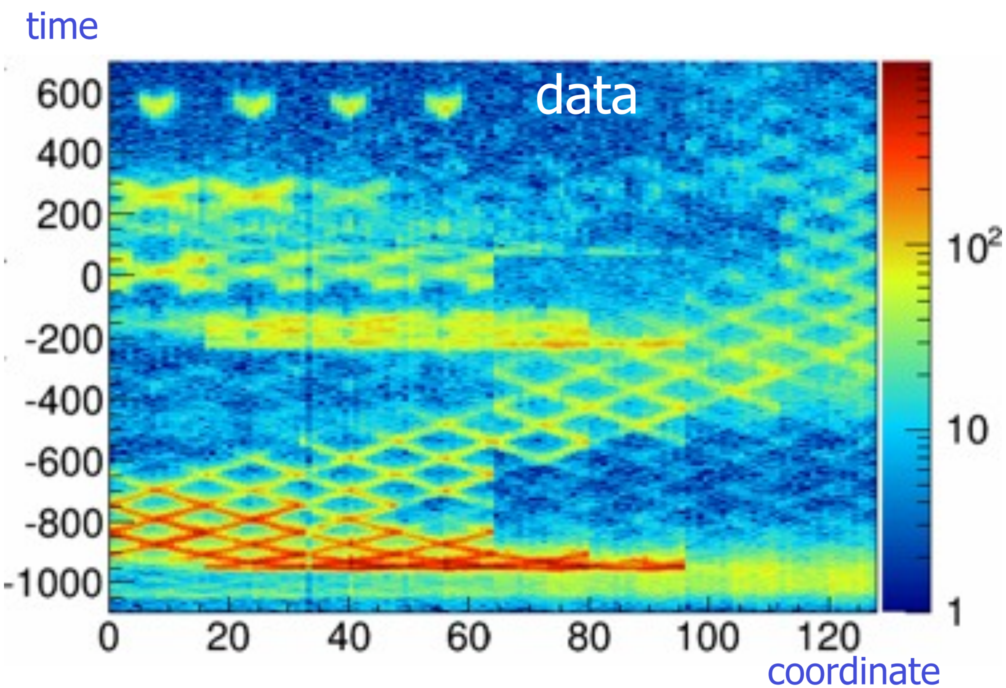
quartz bar

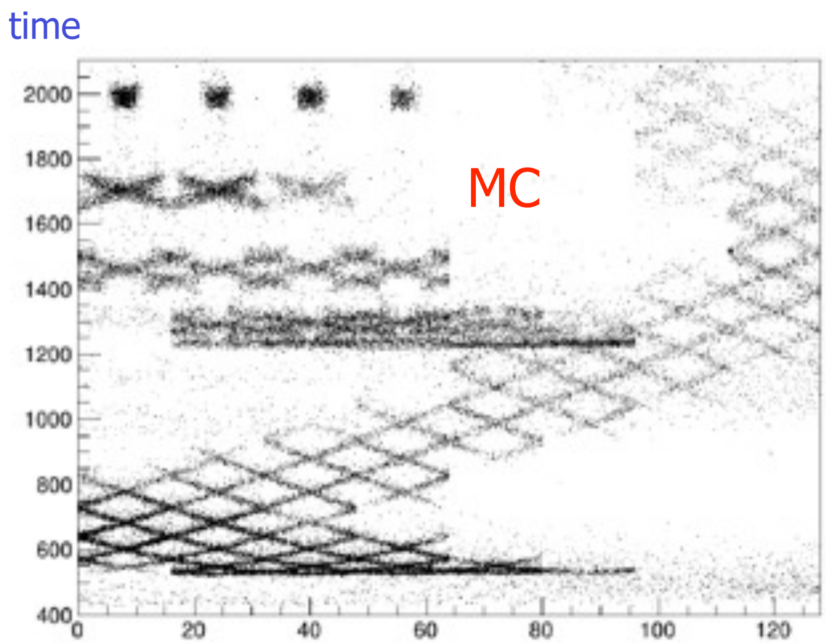


8 PMTs with read-out electronics

TOP image

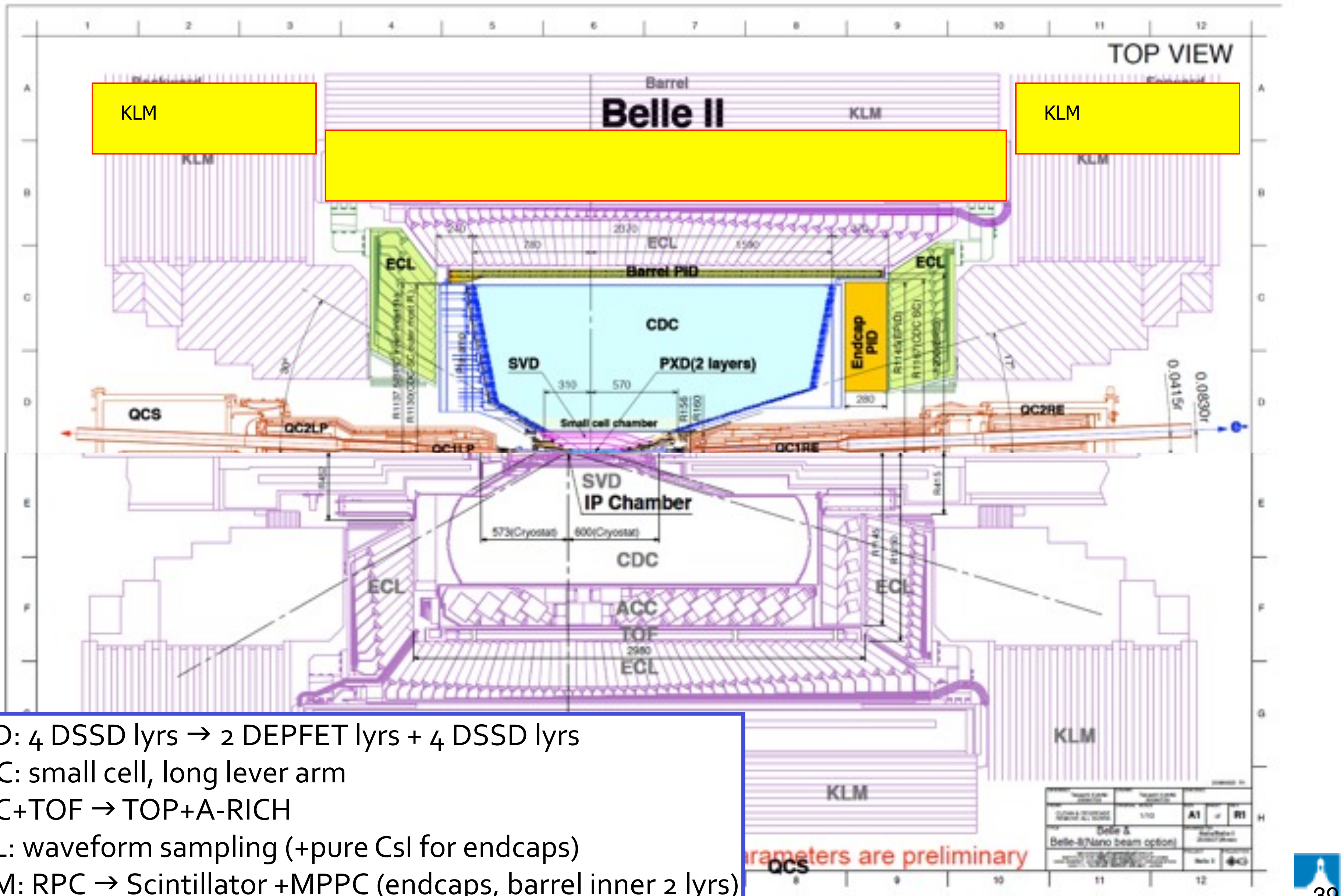
Pattern in the coordinate-time space ('ring') – different for kaons and pions.





Excellent agreement between beam test data and MC simulated patterns.

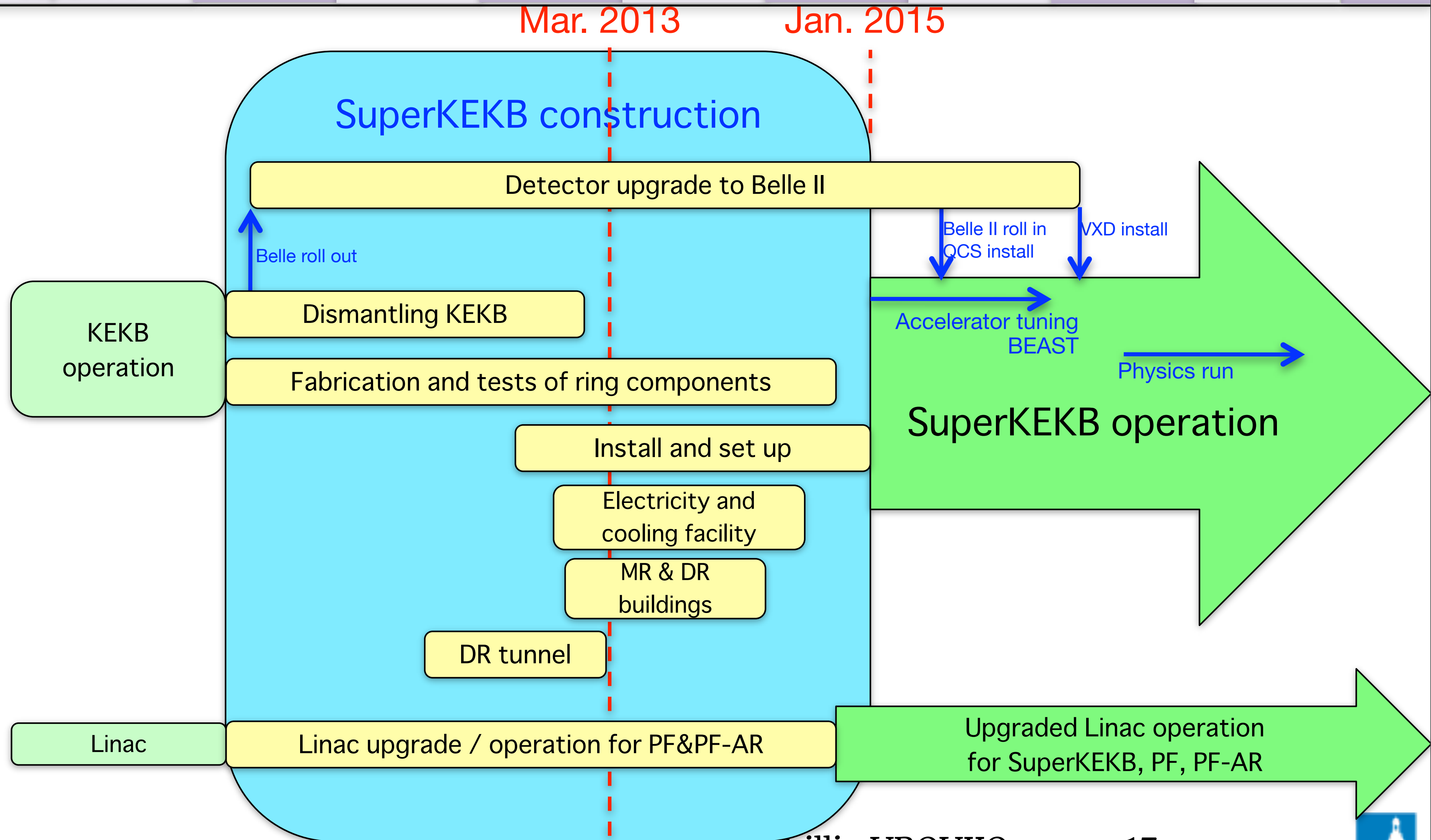
Belle II Detector (in comparison with Belle)



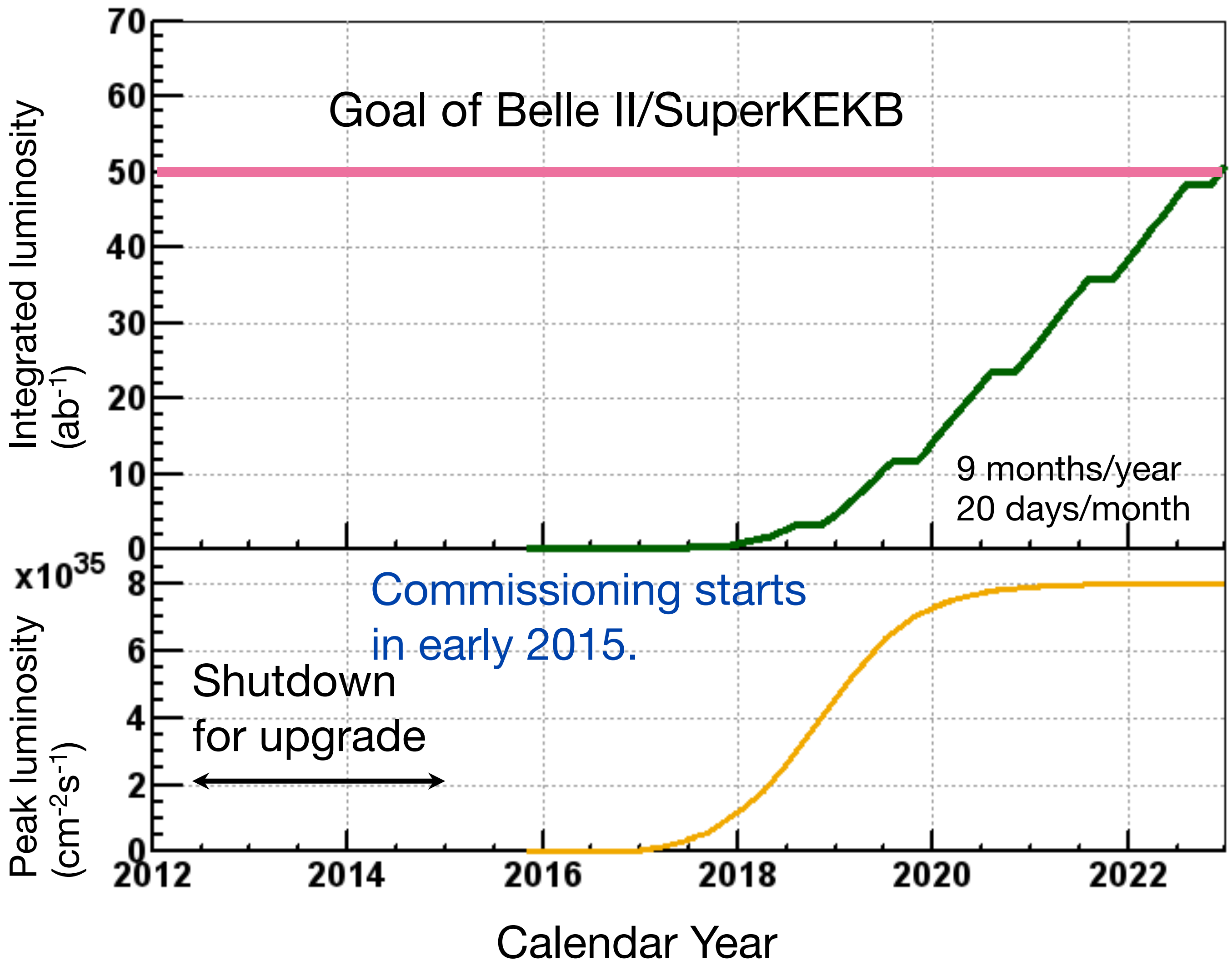
SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

SuperKEKB/Belle II schedule

Calendar	2010	2011	2012	2013	2014	2015	2016	2017	. . .
Japan FY	2010	2011	2012	2013	2014	2015	2016	2017	. .



SuperKEKB at the intensity frontier



Advantages of B factories in the LHC era

Unique capabilities of B factories:

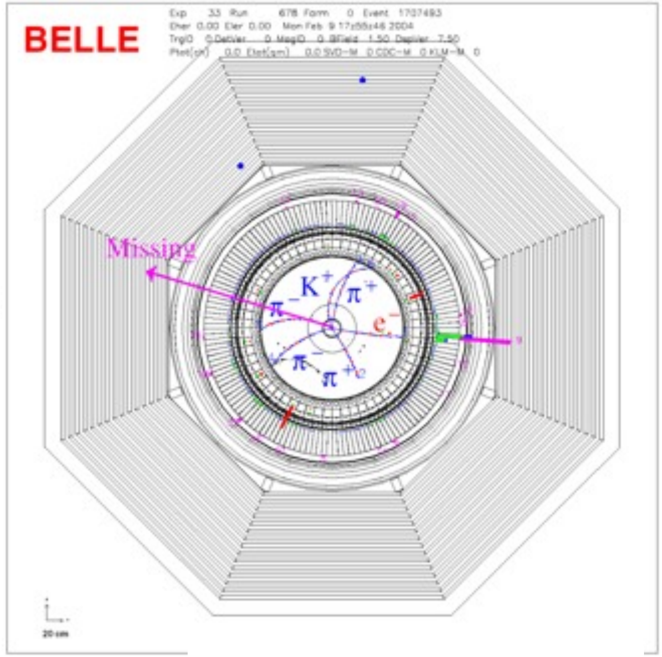
→Exactly two B mesons produced (at Y(4S))

→High flavour tagging efficiency

→Detection of gammas, π^0s, K_Ls

→Very clean detector environment (can observe decays with several neutrinos in the final state!)

→Well understood apparatus, with known systematics, checked on control channels



$$B^+ \to D^0\pi^+$$
$$(\to K\pi^-\pi^+\pi^-)$$
$$B^- \to \tau(\to e\nu\bar{\nu})\nu$$

LHCb Upgrade

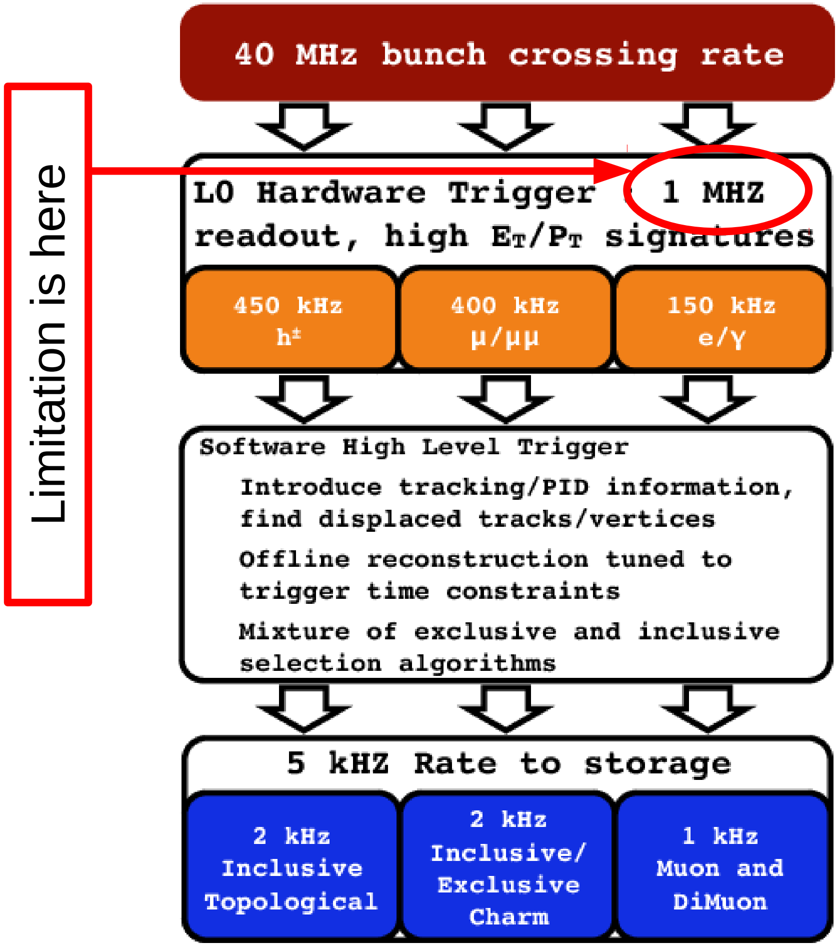
@LHC

LHCb Upgrade

- To fully exploit LHC potential for heavy flavour physics will require an upgrade to LHCb
  - full readout & trigger at 40 MHz to enable high L running
  - "high L" = $10^{33}/\text{cm}^2/\text{s}$ (independent of machine upgrade)
  - planned for 2018 shutdown

- Physics case:
  - "exploration" of 1st phase will become "precision studies"
  - new opportunities for exploration open up (e.g. testing consistency of CP violation in tree vs. loop processes)

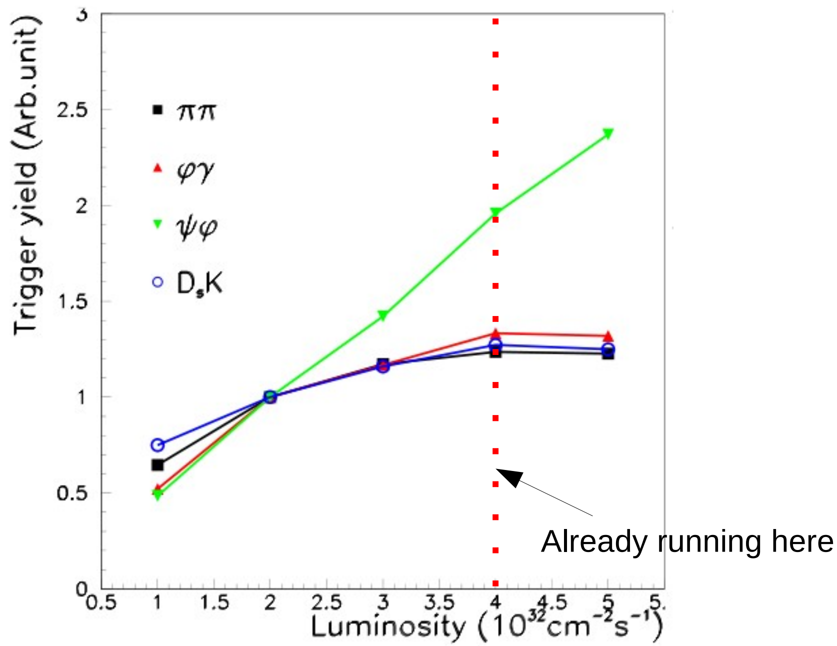
LHCb **Trigger** Upgrade



Higher luminosity

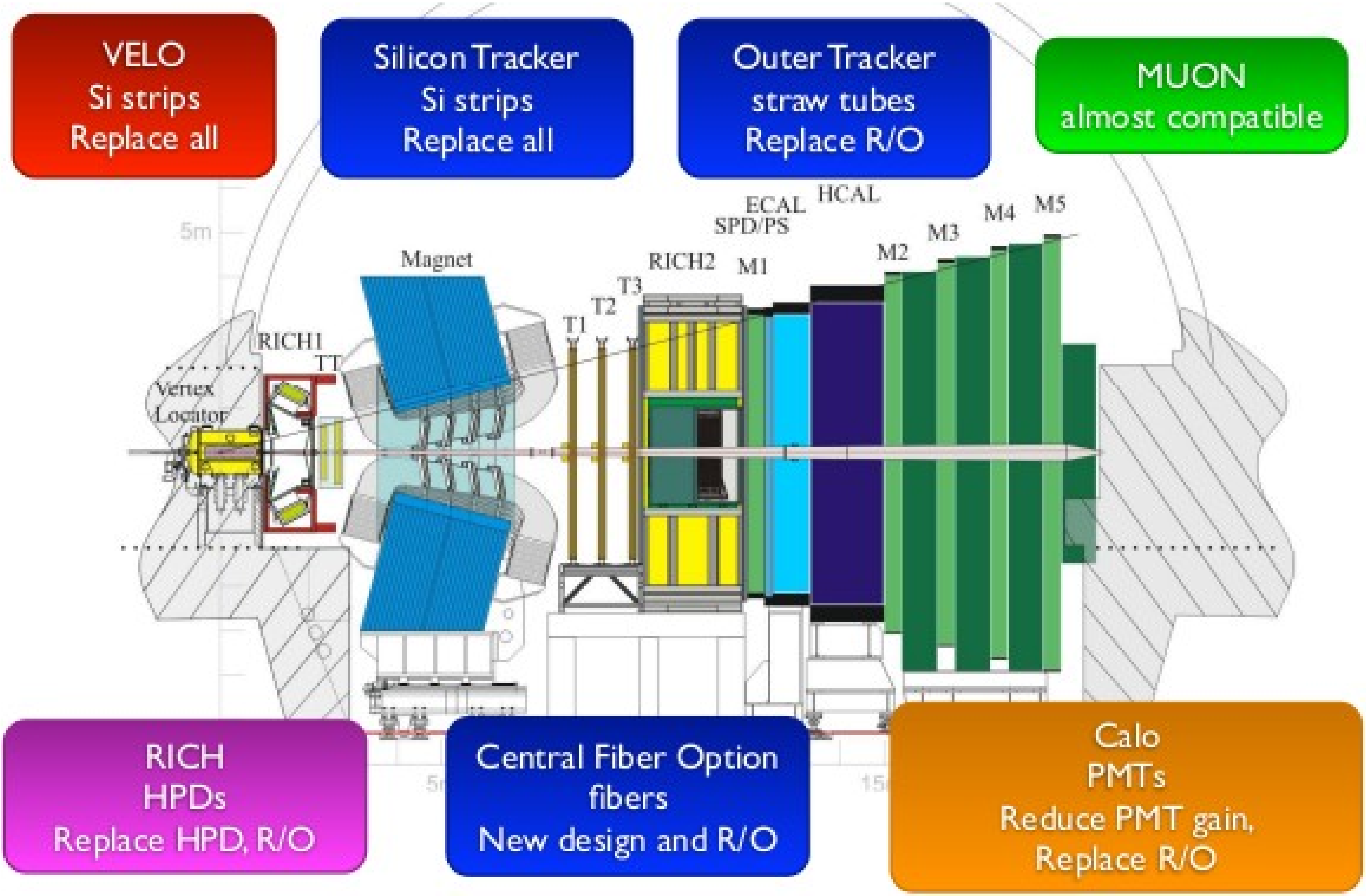
∴ need to cut harder at L0 to maintain rate at 1 MHz

→Efficiency loss



- Readout detector @ 40 MHz
- implement trigger fully in software! Unique for LHC experiments
- run L_{inst} up to 2E33 /cm²/s

LHCb **Detector** Upgrade



LHCb Upgrade **Timeline**

- **2011**
  - Letter of Intent: CERN-LHCC-2011-001
- **2012**
  - TDR: CERN-LHCC-2012-007
    - Endorsed by LHCC and approved by CERN Research Board
    - Features prominently in European Strategy for Particle Physics
  - Physics: arXiv:1208.3355
- **2013**
  - Sub-detector TDRs
- **2014–17**
  - Final R&D, production and construction
- **2018** (Long Shutdown 2)
  - Installation of upgraded LHCb detector (requires 18 months)

Prospects

Complementary to LHCb

Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\lvert V_{us}\rvert$ $[K \to \pi \ell \nu]$	**	0.1%	K-factory
$\lvert V_{cb}\rvert$ $[B \to X_c \ell \nu]$	**	1%	Belle II
$\lvert V_{ub}\rvert$ $[B_d \to \pi \ell \nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K_S^0$	***	$8 \cdot 10^{-3}$	Belle II/LHCb
ϕ_2		1.5°	Belle II
ϕ_3	***	3°	LHCb
CPV			
$S(B_s \to \psi\phi)$	**	0.01	LHCb
$S(B_s \to \phi\phi)$	**	0.05	LHCb
$S(B_d \to \phi K)$	***	0.05	Belle II/LHCb
$S(B_d \to \eta' K)$	***	0.02	Belle II
$S(B_d \to K^*(\to K_S^0\pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A_{SL}^d	***	0.001	LHCb
A_{SL}^s	***	0.001	LHCb
$A_{CP}(B_d \to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B \to \tau\nu)$	**	3%	Belle II
$\mathcal{B}(B \to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d \to \mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb
zero of $A_{FB}(B \to K^*\mu\mu)$	**	0.05	LHCb
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B \to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K \to \pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K \to e\pi\nu)/\mathcal{B}(K \to \mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\lvert q/p\rvert_D$	***	0.03	Belle II
$arg(q/p)_D$	***	1.5°	Belle II

- Belle II:
  - Decays with neutrinos, or multiple photons.
  - "Inclusive" decays.
- LHCb:
  - Decays to all charged particle final states.

Need both LHCb and super B factories to cover all aspects of precision flavour physics

Preparing for the next Nobel Prize…

James Watson Cronin — Val Logsdon Fitch

1964 Fitch and Cronin discover **CP violation** (indirect CP in K)

1970 $\Gamma(K^0\rightarrow\mu\mu) \ll \Gamma(K^+\rightarrow\mu\nu)$ Glashow-Iliopoulos–Maiani: No tree level FCNC ⇒ **Charm** inferred

1973 CPV in K due to **3rd generation**: Kobayashi & Maskawa (not a new force)

1987 Argus (DESY) *B* mixing

$\Delta m_B \Rightarrow \boldsymbol{m_t} \gg \boldsymbol{m_W}$

2002 BABAR/Belle establish indirect CP violation in B_d mesons, **confirming KM theory**

Makoto Kobayashi — Toshihide Maskawa

Wrap up 1/2

- **Flavour physics offers interesting avenues to explore the Standard Model and search for signals of New Physics with a huge energy scale sensitivity!**
  - Data in remarkable agreement with the CKM mechanism
  - But thats only a 5-10% agreement. New Physics must be lurking beneath.
  - Many unexplored aspects, and hints of discrepancies with the SM are starting to show.
- **Existing hints about the New Physics flavour signature suggest that only the combination of LHC and flavour experiments will give us the key to solving the puzzles of the Terascale**

Wrap up 2/2

- We still don't know:
  - why there are so many fermions in the SM
  - what causes the baryon asymmetry of the Universe
  - where exactly the new physics is ...
    ... and what it's flavour structure is
- Prospects are good for progress in the next few years
- We need a continuing programme of flavour physics into the 2020s
  - complementary to the high-pT programme of the LHC

End of Lectures

LHCb Upgrade: expected sensitivities

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\rm fs}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

Table 1: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with $50\,\text{fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured