The Belle II Experiment

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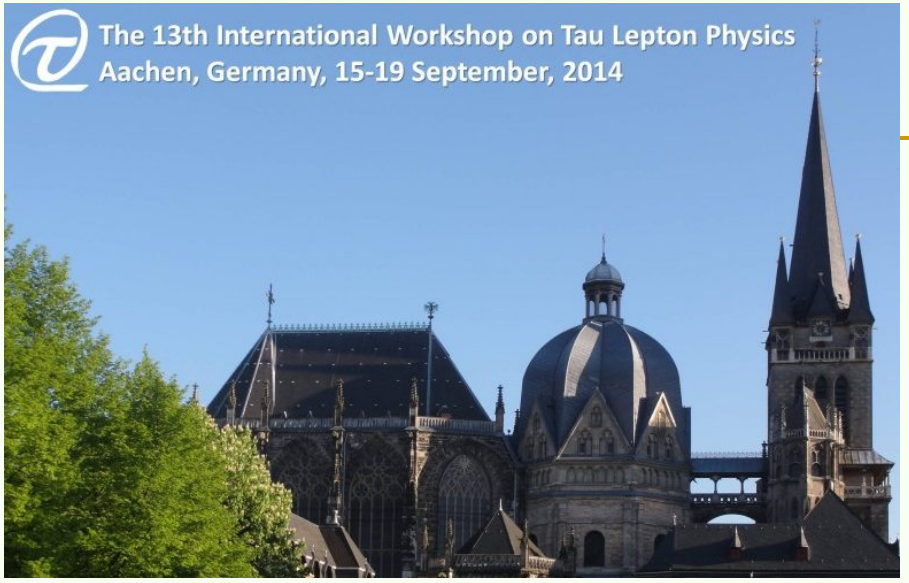
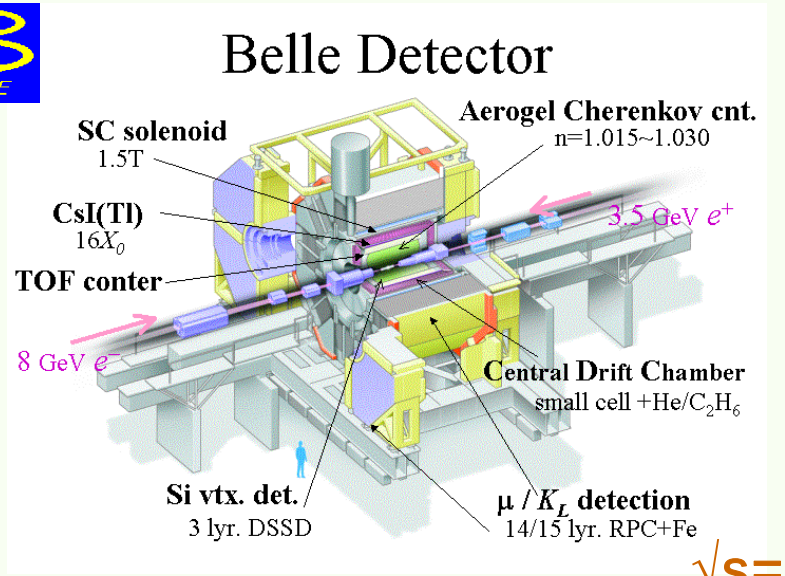
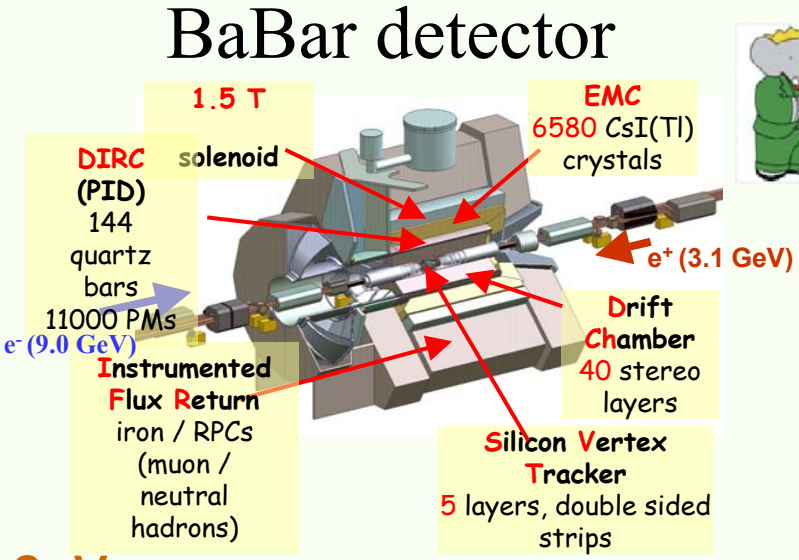


- Introduction
- B- and Super-B Physics
- Collider
- Detector

During last ten years a lot of physics results came from two B-factories – Belle and BaBar





$\sqrt{s}$=10.58 GeV

BaBar	$p(e^-)$=9 GeV	$p(e^+)$=3.1 GeV	$\beta\gamma$=0.56
Belle	$p(e^-)$=8 GeV	$p(e^+)$=3.5 GeV	$\beta\gamma$=0.42

Peak lumi record at KEKB: L=2.1 x 10^{34}/cm^2/sec with crab cavities

F/B asymmetric detectors

High vertex resolution, magnetic spectrometry, excellent calorimetry and sophisticated particle ID ability

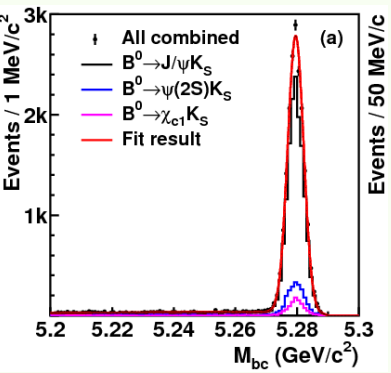
$$\sum_{BaBar}^{Belle} \int_{1999}^{2010} Ldt \approx 1.5ab^{-1}$$

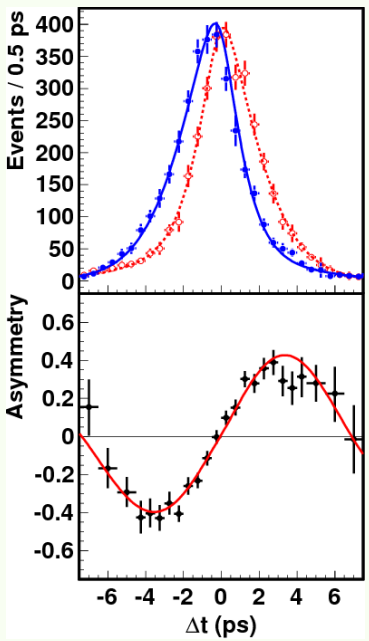
The primary goal of the Belle and BaBar experiments was to discover the CP violation in B mesons and to measure the parameters of CPV. This was achieved by both experiments in 2001

At present most precise result from Belle:

$\sin 2\varphi_1 = 0.667 \pm 0.023(\text{stat}) \pm 0.012(\text{syst})$
$A_f = 0.006 \pm 0.016(\text{stat}) \pm 0.012(\text{syst})$.

711 fb-1 (772M BB).





Belle and BaBar averaged (HFAG 2012)

Mode	Average
J/ ϕ KS (η CP=-1)	0.665 $\pm$ 0.024
J/ ϕ KL (η CP=+1)	0.663 $\pm$ 0.041
J/ ϕ K0	0.665 $\pm$ 0.022
ϕ (2S)KS (η CP=-1)	0.807 $\pm$ 0.067
ϕ (nS)K0	0.676 $\pm$ 0.021
χ c1KS (η CP=-1)	0.632 $\pm$ 0.099
All charmonium (incl. χ c0KS *etc.*)	0.679 $\pm$ 0.020

BaBar (PRD **79** (2009) 072009)
Belle (PRL **108** (2012) 171802)

However, a lot of other important results were obtained

- Observation of direct CP violation in B decays
- Measurements of the CPV parameters in different modes (ϕK^0, $\eta' K^0$, $K_S K_S K_S$, …)
- Measurements of rare decay modes (e.g., $B \to \tau\nu$, $D\tau\nu$)
- Observation of new charmonium-like and bottomonium-like hadronic states
- $b \to s$ transitions: probe for new sources of CPV and constraints from the $b \to s\gamma$ branching fraction
- Forward-backward asymmetry (A_{FB}) in $b \to s l^+ l^-$ has become a powerfull tool to search for physics beyond SM.
- Observation of D mixing
- Search for lepton flavour violation in τ decays
- Study of the hadronic τ decays
- Precise measurement of the hadronic cross sections in $\gamma\gamma$ and $e^+e^-(\gamma_{ISR})$ processes

So wide researches area become possible because of clean event environment and well defined initial state in the e^+e^- experiments as well as high luminosity and general purpose detectors

At present SuperKEKB collider and Belle II detector are under construction at KEK (Japan)

Target : $L_{peak} = 8 \times 10^{35}$ cm^{-2} s^{-1} [40 × KEKB]

$L_{int} > 50$ ab^{-1} by early 2020s [50 × Belle II]

Channel	Belle	BaBar	Belle II (per year)
$B\bar{B}$	7.7×10^8	4.8×10^8	1.1×10^{10}
$B(*)_S \bar{B}(*)_S$	7.0×10^6	–	6.0×10^8
$\Upsilon(1S)$	1.0×10^8	–	1.8×10^{11}
$\Upsilon(2S)$	1.7×10^8	0.9×10^7	7.0×10^{10}
$\Upsilon(3S)$	1.0×10^7	1.0×10^8	3.7×10^{10}
$\Upsilon(5S)$	3.6×10^7	–	3.0×10^9
$\tau\tau$	1.0×10^9	0.6×10^9	1.0×10^{10}

Search of New Physics – is a primary goal!

Examples of "Golden modes" to Search for New Physics at Belle II

a) **CPV in tree level and penguin decays:**
   - **sin $2\phi_1$(charm) vs. sin $2\phi_1$(strangeness)**

b) **CPV in radiative decays**
   - **sin $2\phi_1$ in $B \to K_S \pi^0 \gamma$**

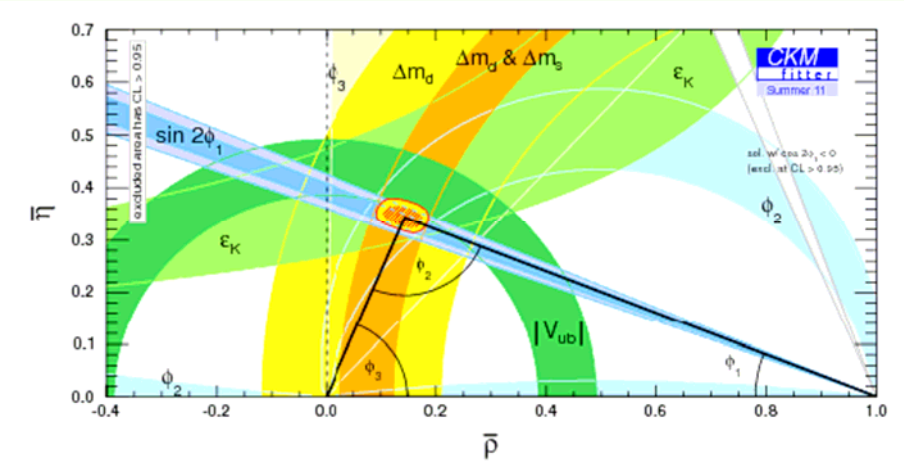
c) **Missing Energy**
   - **pure leptonic B decays: $B \to l\ \nu$ (l=e,m,t)**
   - **$B \to D(*)\ \tau\ \nu$**

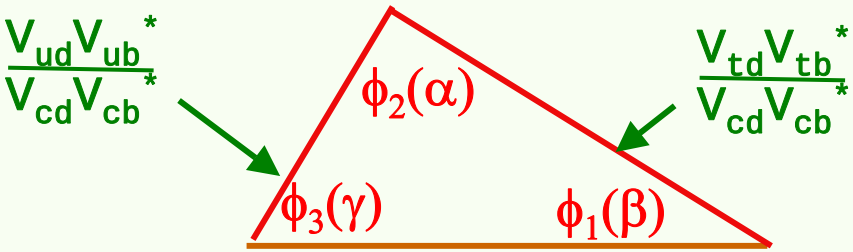
d) **Lepton Flavor Violation(LFV) in tau decays**
   - **$\tau \to \mu\gamma$, $\tau \to \mu\mu\mu$**

e) **CPV in D^0- $\bar{D}^0$ mixing**

CP violation in the B system and unitarity triangle

2011 [CKMfitter]

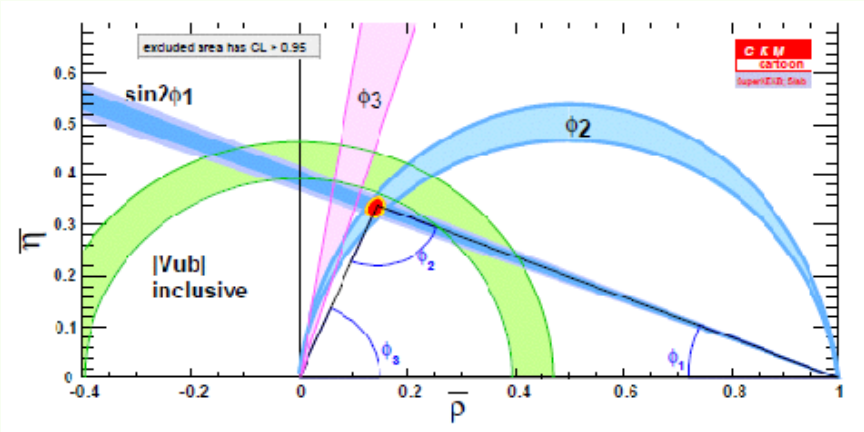


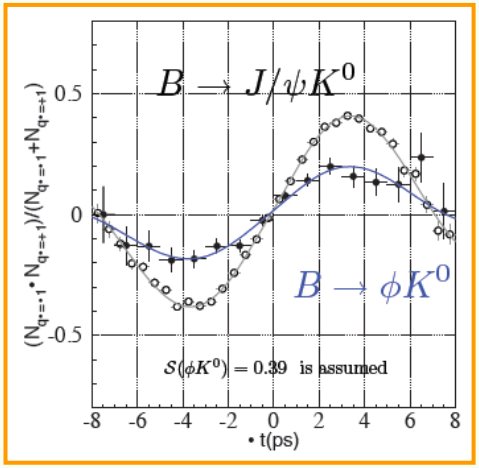


$\alpha + \beta + \gamma = \varphi_1 + \varphi_2 + \varphi_3 = (178\ ^{+11}_{-12})^\circ$ (PDG 2012) in a good agreement with SM and theoretical prediction of Euclid.

Still certain room for New Physics search exists…

202X@50/ab

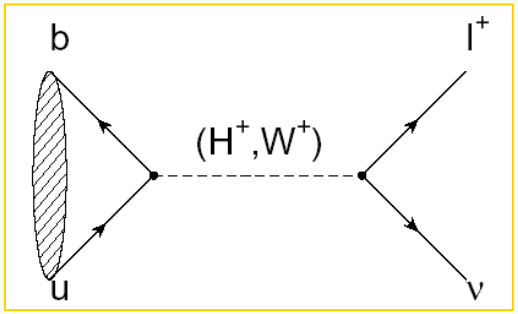


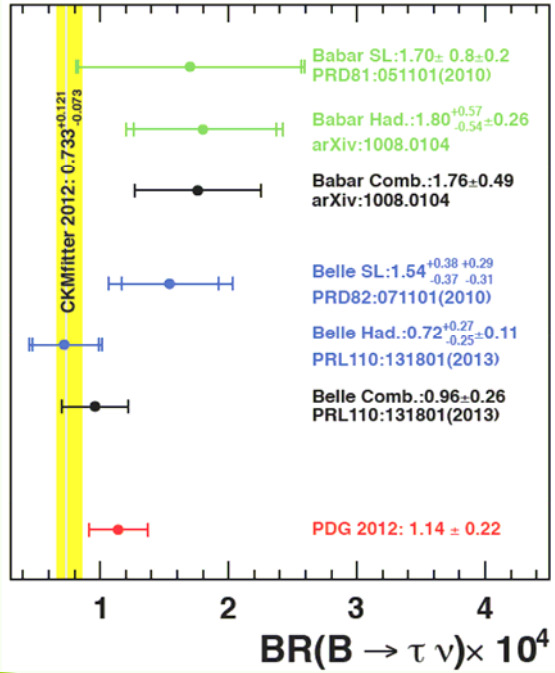


Physics at 50/ab, a few examples

$B^+ \rightarrow \tau^+ \upsilon_\tau$

Sensitivity to new physics with charged Higgs





In the SM

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

B → sγ direct CPV

ACP = (−0.8 ± 2.9)%
(HFAG, Aug 2012)

SM: ACP ~ (0.44±0.24)%
(T. Hurth et al., Nucl.Phys. B704 (2005) 56)

50 ab-1: O(0.1%) exp. sensitivity

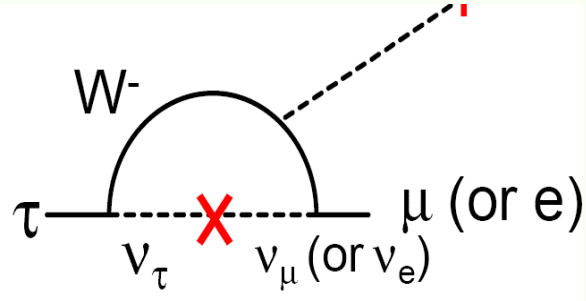
B → K*γ t-dependent CPV
SM: $S_{CP}^{K^*\gamma} \sim (2m_s/m_b)\sin 2\phi_1 \sim -0.04$

$S_{CP}^{Ks\pi 0\gamma} = -0.15 \pm 0.20$
$A_{CP}^{Ks\pi 0\gamma} = -0.07 \pm 0.12$

Expected sensitivity - 0.03 for

S in Ks pi0 gamma with 50 ab-1

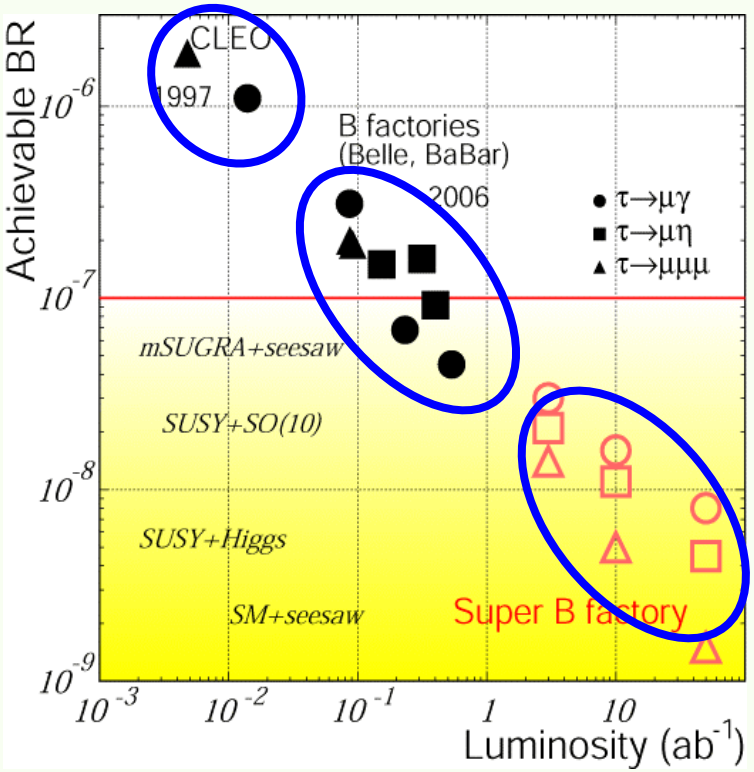
Searches for lepton flavour violation in tau decays

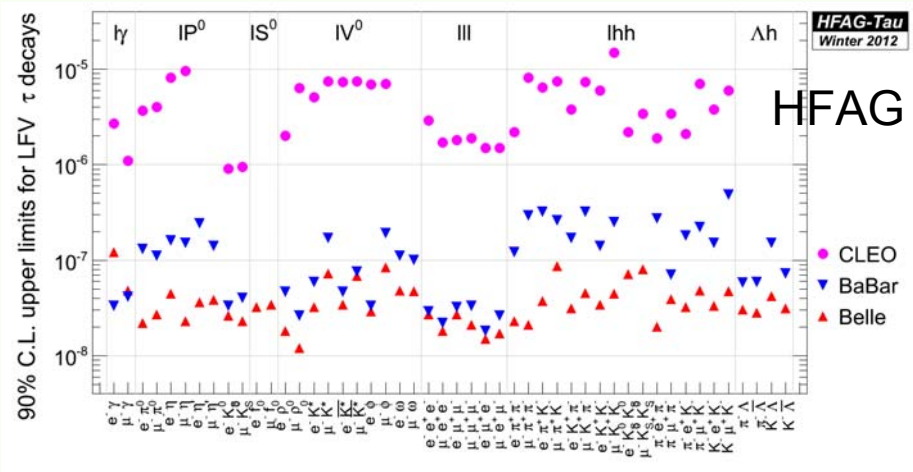


In the SM the lepton flavour violation decays are extremely small:

$Br(\tau \to l\gamma) \sim 10^{-54}$

$Br(\tau \to 3 \text{ leptons}) \sim 10^{-14}$





HFAG 2012

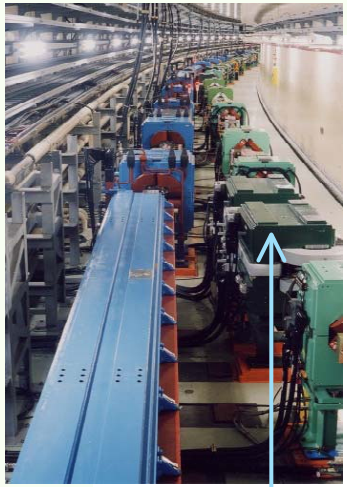
Expected sensitivity

$\tau \to \ell\gamma$ $Br \sim O(10^{-8\sim9})$

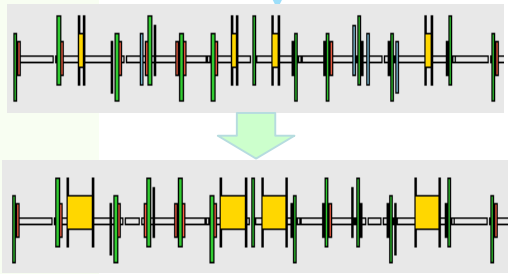
$\tau \to \ell\ell\ell$, l+meson $Br \sim O(10^{-9\sim10})$

How to do it?
→ upgrade KEKB and Belle

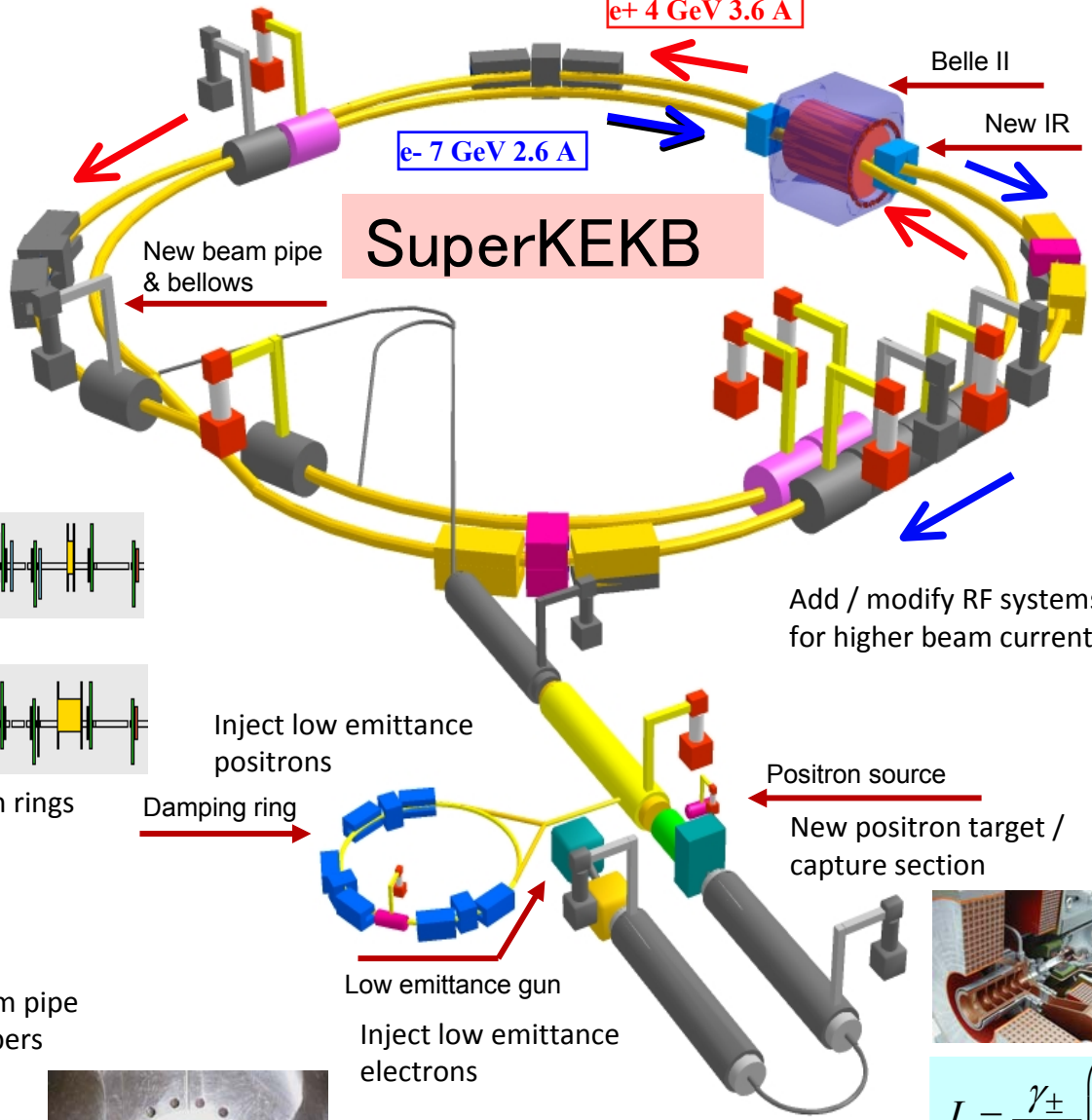
SuperKEKB

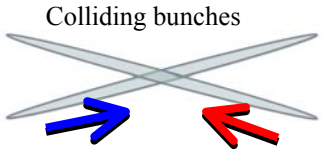


Replace short dipoles with longer ones (LER)

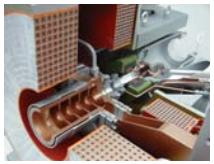


Redesign the lattices of both rings to reduce the emittance

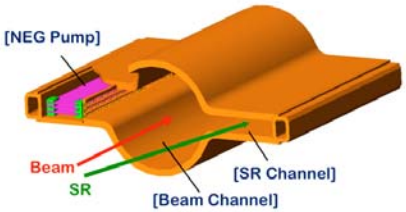


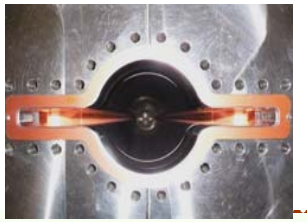


New superconducting /permanent final focusing quads near the IP



TiN-coated beam pipe with antechambers





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

x 40 Increase in Luminosity

Design Concept of SuperKEKB

- Increase the luminosity by 40 times based on "Nano-Beam" scheme, which was first proposed for SuperB by P. Raimondi.

Luminosity Gain

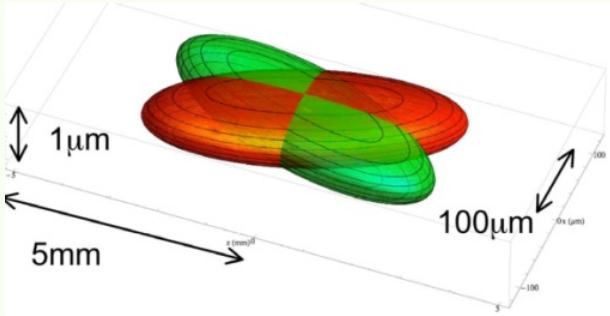
- Vertical β function at IP: 5.9 → 0.27/0.30 mm (× 20)
- Beam current: 1.7/1.4 → 3.6/2.6 A (× 2)
- Beam-beam parameter: .09 → .09 (× 1)

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right) = 8 \times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$$

- Beam energy: 3.5/8.0 → 4.0/7.0 GeV

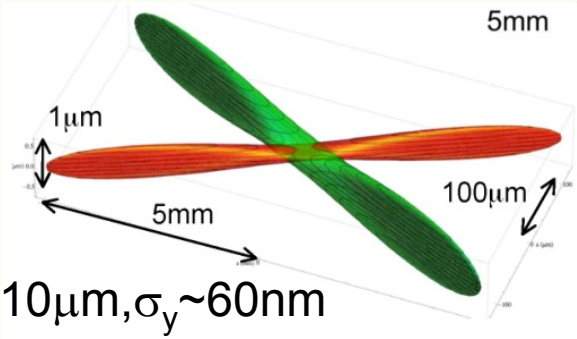
LER : Longer Touschek lifetime and mitigation of emittance growth due to the intra-beam scattering
HER : Lower emittance and lower SR power

KEKB



σ_x~100μm,σ_y~2μm

Nano-Beam SuperKEKB

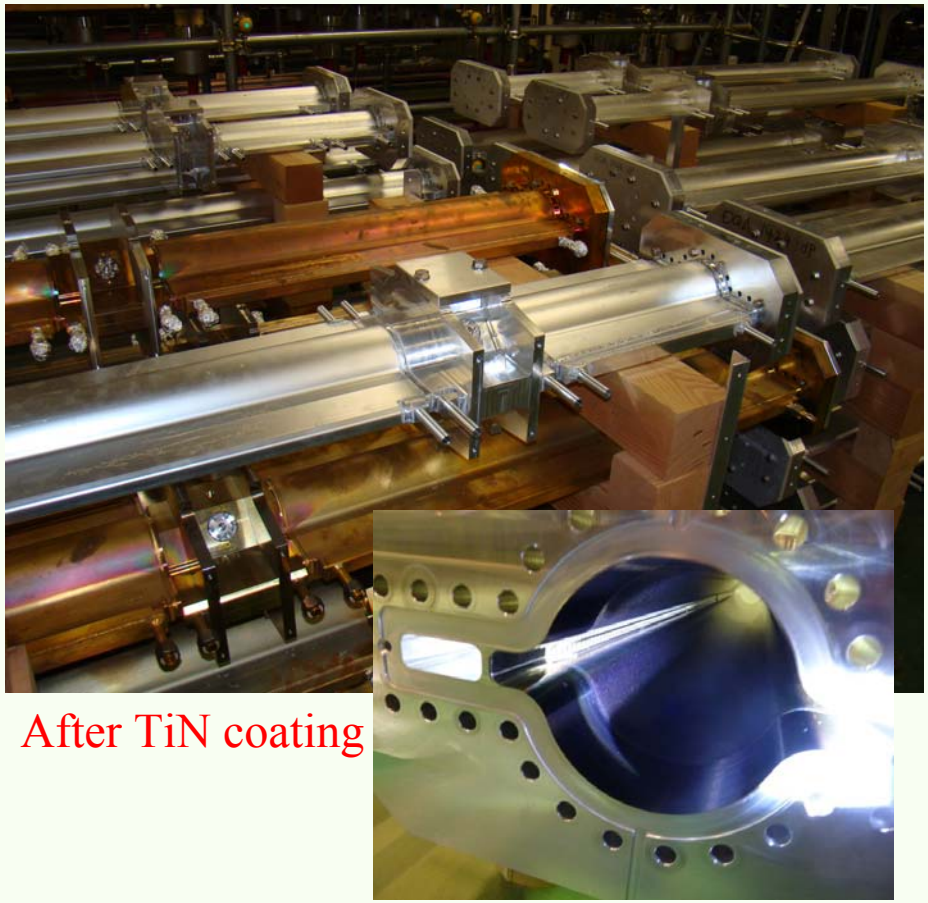


σ_x~10μm,σ_y~60nm

	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

Most of the accelerator components should be installed by the end of this year

Entirely new LER beam pipe with ante-chamber and Ti-N coating



After TiN coating

Demands on the detector

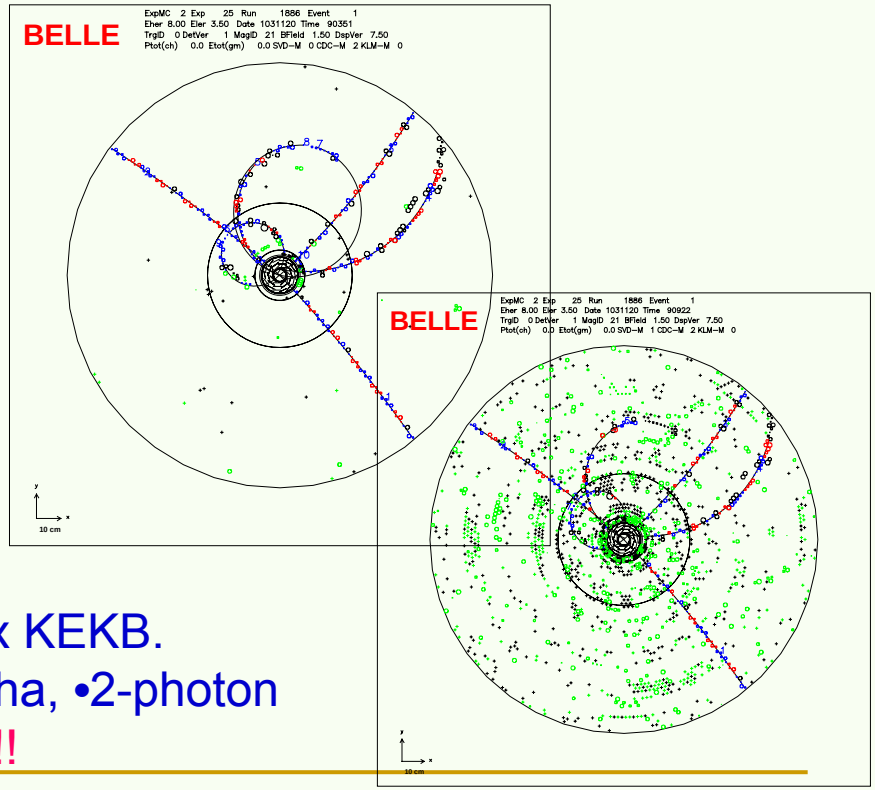
Total cross section and trigger rates with $L = 8\times10^{35}$ cm^{-2} s^{-1} from various physics processes at Υ(4S).

Physics process	Cross section (nb)	Rate (Hz)
Υ (4S) →BB	1.2	960
Hadron production from continuum	2.8	2200
$\mu^+\mu^-$	0.8	640
$\tau^+\tau^-$	0.8	640
Bhabha (θlab> 17°)	44	350[(a)]
γγ (θlab> 17°)	2.4	19 [(a)]
2γ processes (θlab> 17°, pt > 0.1GeV/c)	~80	~ 15000
Total	~130	~20000

(a) rate is pre-scaled by a factor of 1/100

The requirements for the trigger system are:

1. **high efficiency for hadronic events;**
2. **maximum average trigger rate of 30 kHz;**
3. **fixed latency of about 5 μs;**
4. **timing precision of less than 10 ns;**
5. **minimum two-event separation of 200 ns;**
6. **trigger configuration that is flexible and robust.**



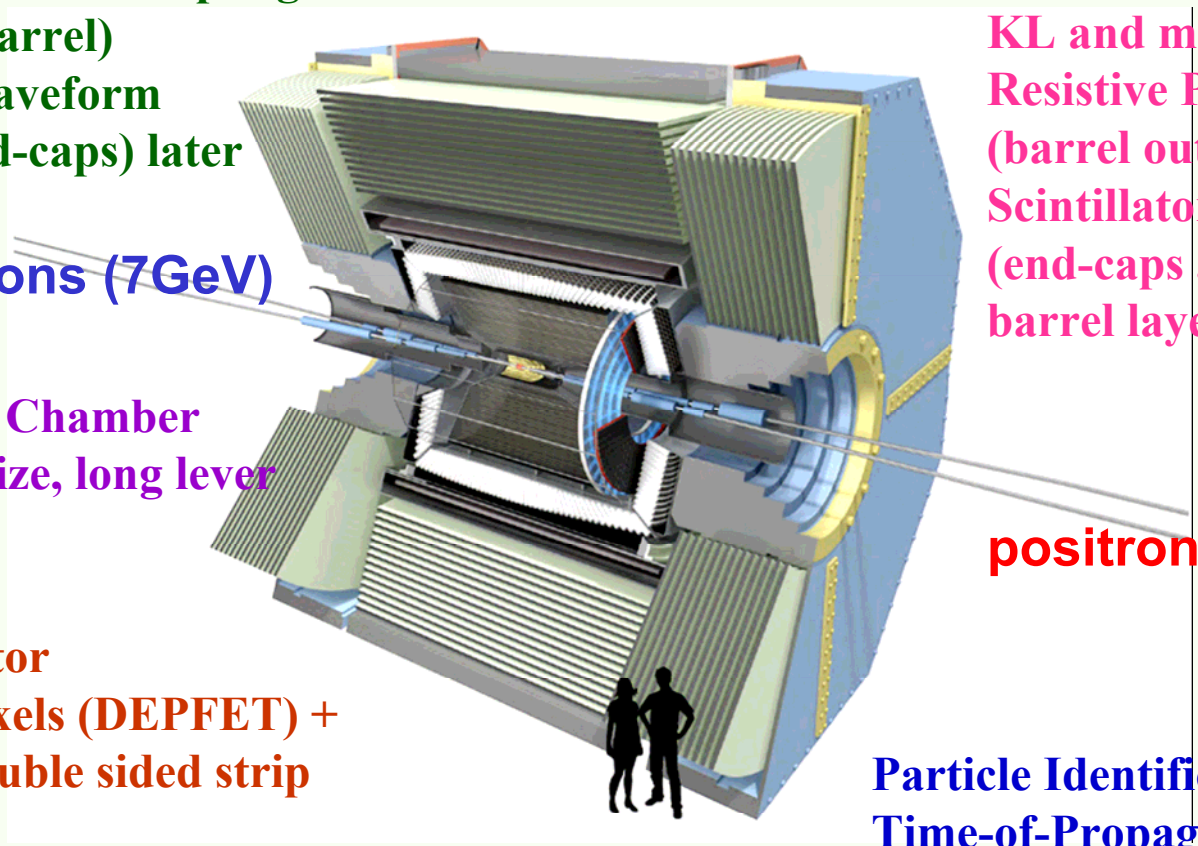
Beam-related backgrounds are 10-20 x KEKB.

•Touschek scattering, •Radiative Bhabha, •2-photon

Fake hits, pile up, radiation damage!!

Belle II Detector

EM Calorimeter:
CsI(Tl), waveform sampling electronics (barrel)
Pure CsI + waveform sampling (end-caps) later



KL and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps , inner 2 barrel layers)

Central Drift Chamber
Smaller cell size, long lever arm

Vertex Detector
2 layers Si Pixels (DEPFET) +
4 layers Si double sided strip DSSD

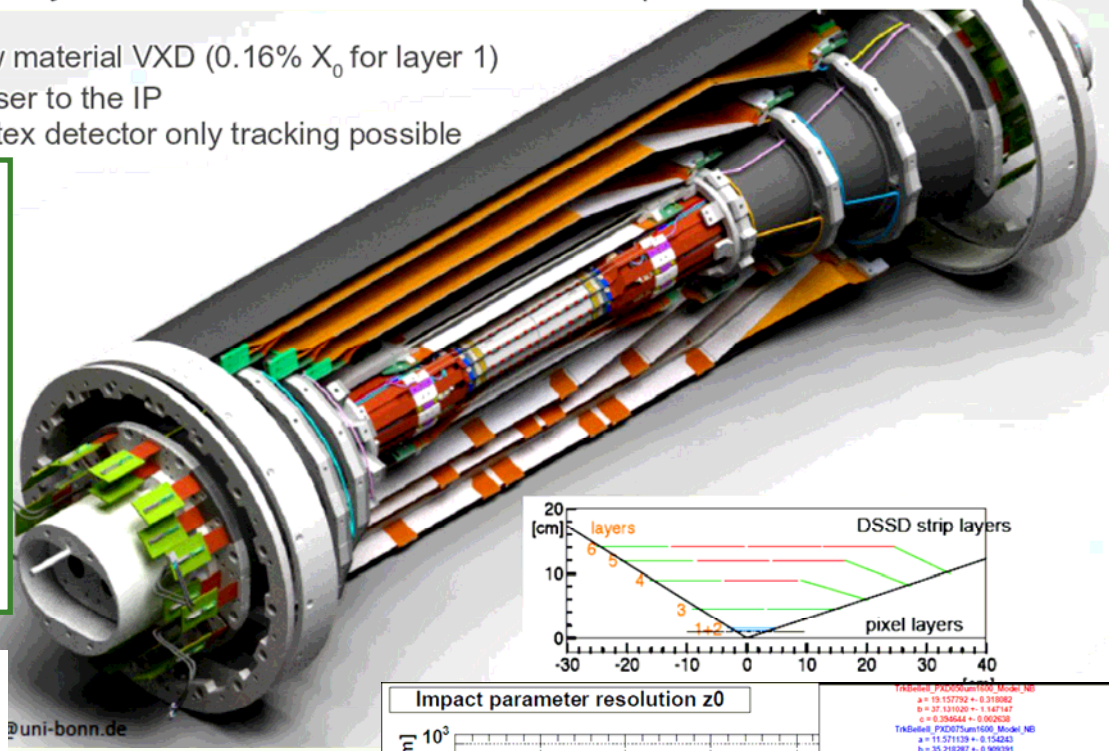
Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

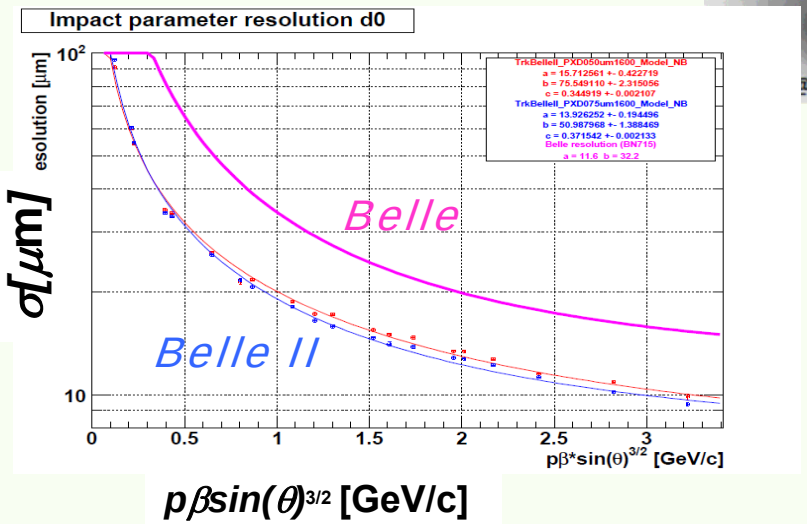
Vertex Detectors

- 2 layers of DEPFET pixel sensors in the innermost part
- 4 layers of double-sided silicon strip sensors

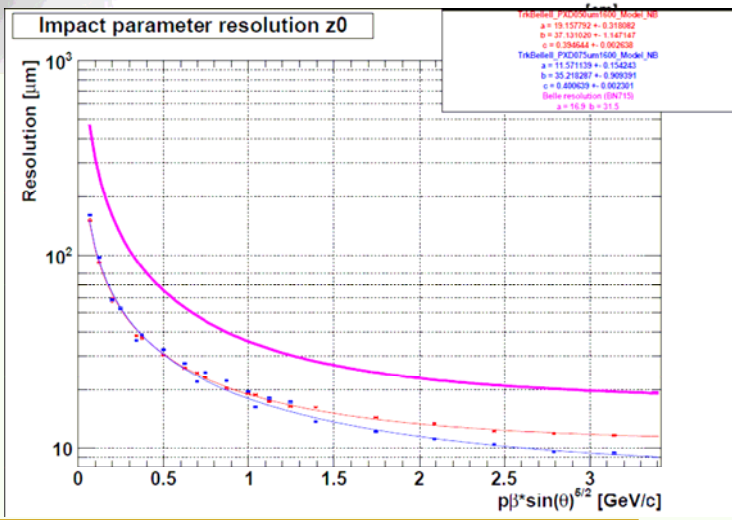
- Low material VXD (0.16% X_0 for layer 1)
- Closer to the IP
- Vertex detector only tracking possible

		Belle II	Belle
Beam Piper =		10mm	15mm
DEPFET			
	Layer 1	r = 14mm	
	Layer 2	r = 22mm	
DSSD			
	Layer 3	r = 38mm	20mm
	Layer 4	r = 80mm	43.5mm
	Layer 5	r = 104mm	70mm
	Layer 6	r = 135mm	88mm

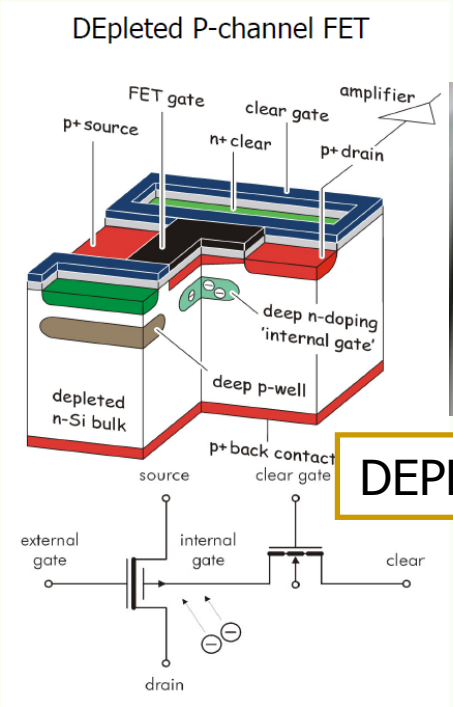




$p\beta\sin(\theta)^{3/2}$ [GeV/c]



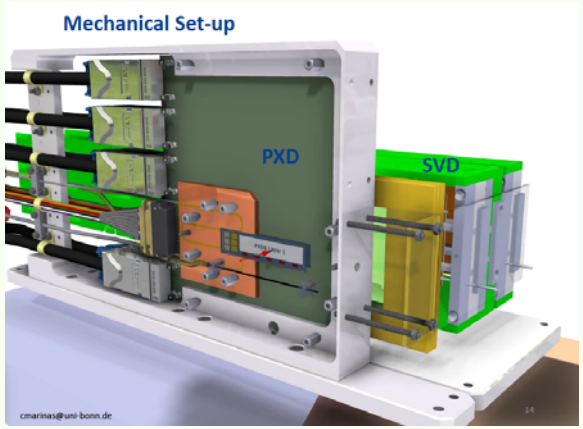
Pixel Vertex Detector

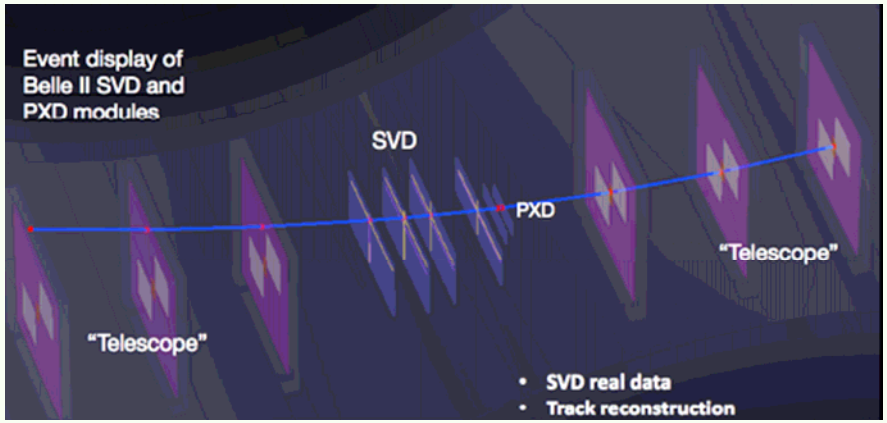


DEPFET pixel sensor

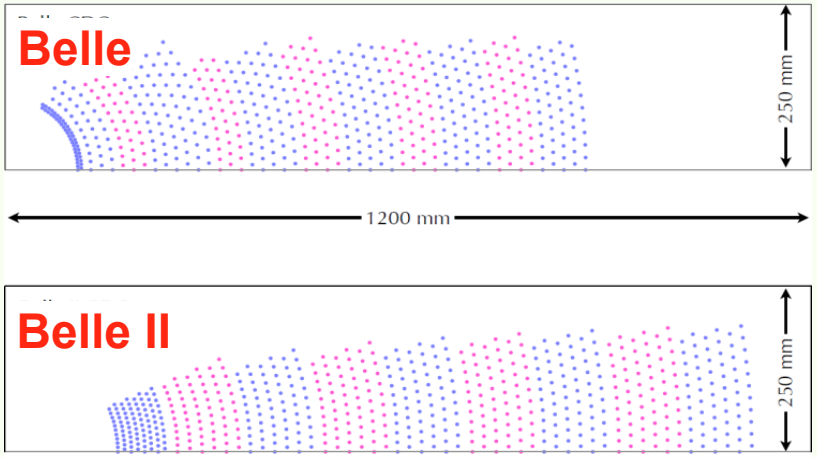
PXD: excellent spatial granularity (resolution ~15 μm)
low material (0.16%X0 for layer 1)
but significant amount of background hits, huge data rate.
SVD: precise timing (2–3 ns RMS)
but has **ambiguities in space** due to 1D strip.
Combining both yields a very powerful device!

Beam Test of the PXD and VXD prototypes were successfully performed at the DESY test beam in January '14





Central Drift Chamber



longer lever arm

Improved momentum resolution and dE/dx

$$\sigma_{P_t}/P_t = 0.19P_t \oplus 0.30/\beta$$

$$\sigma_{P_t}/P_t = 0.11P_t \oplus 0.30/\beta$$

new readout system

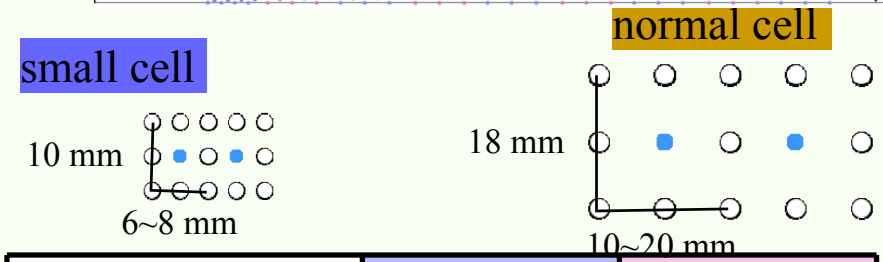
dead time 1-2μs → 200ns

small cell

smaller hit rate for each wire

shorter maximum drift time

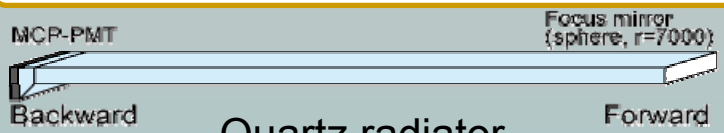
Stringing of all 51456 wires were completed the last summer.



	Belle	Belle II
inner most sense wire	r=88mm	r=168mm
outer most sense wire	r=863mm	r=1111.4mm
Number of layers	50	56
Total sense wires	8400	14336
Gas	He:C_2H_6	He:C_2H_6
sense wire	W(Φ30μm)	W(Φ30μm)
field wire	Al(Φ120μm)	Al(Φ120μm)

Particle Identification in Belle II

Barrel PID: Time of Propagation Counter (iTOP)



Quartz radiator

Focusing mirror

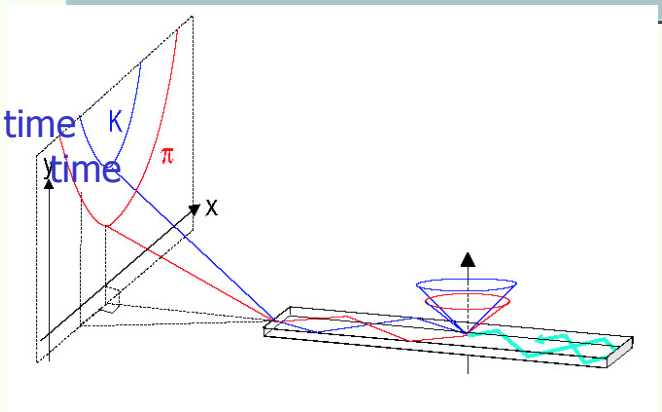
Small expansion block

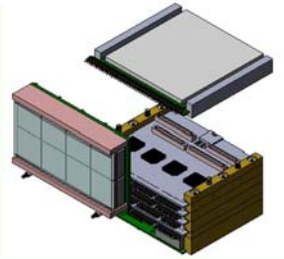
Hamamatsu MCP-PMT (measure t, x and y)

Cherenkov ring imaging with precise time measurement.

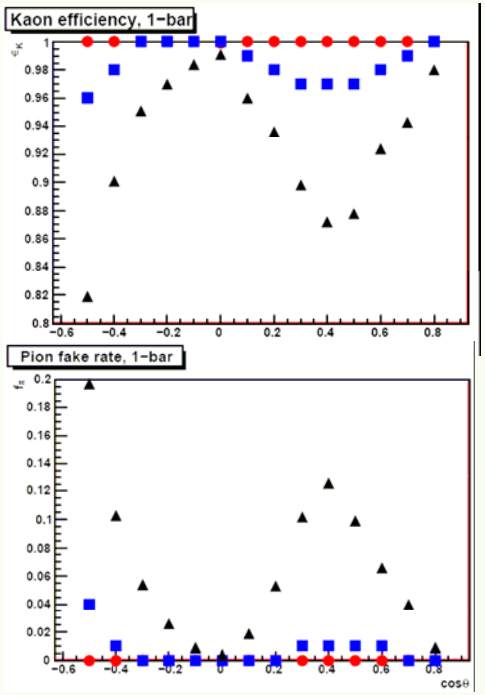
Device uses internal reflection of Cerenkov ring images from quartz like the BaBar DIRC

Cherenkov angle reconstruction from two hit coordinates and the time of propagation of the photon

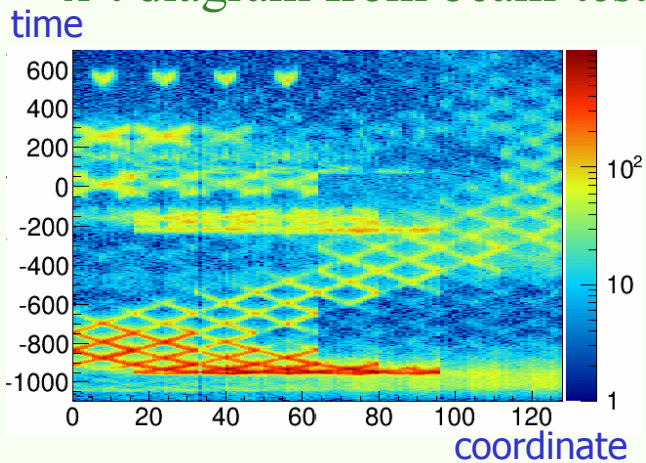




●1.5, ■2.5, ▲3.5 GeV/c



x-t diagram from beam-test



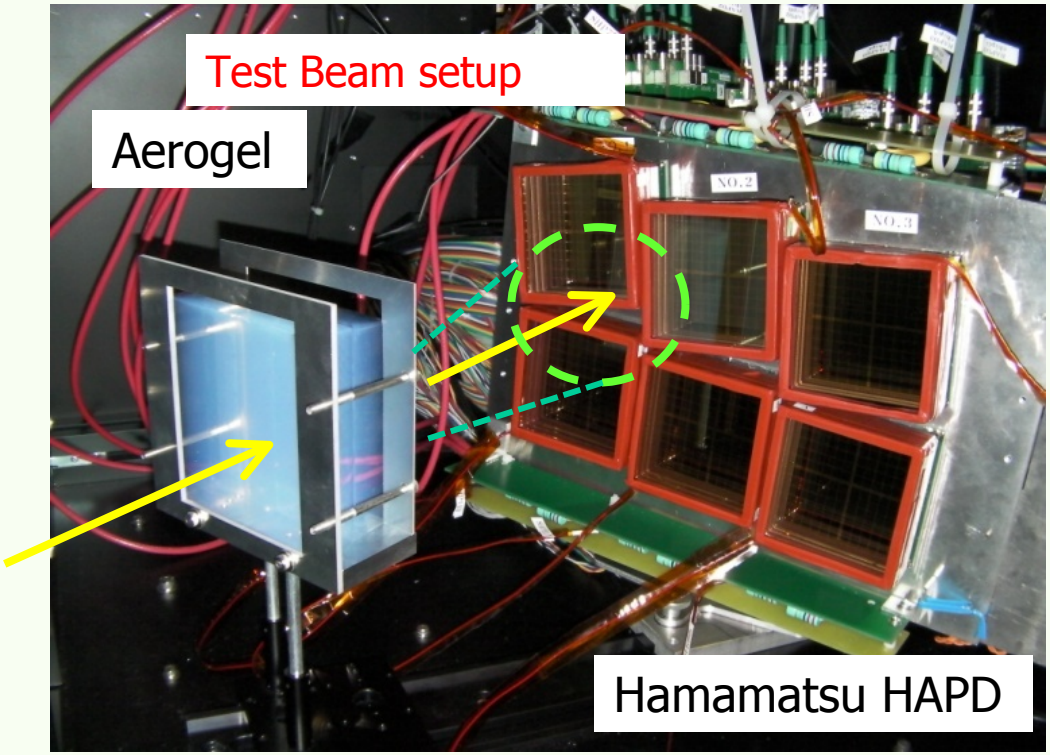
16 Quartz radiators

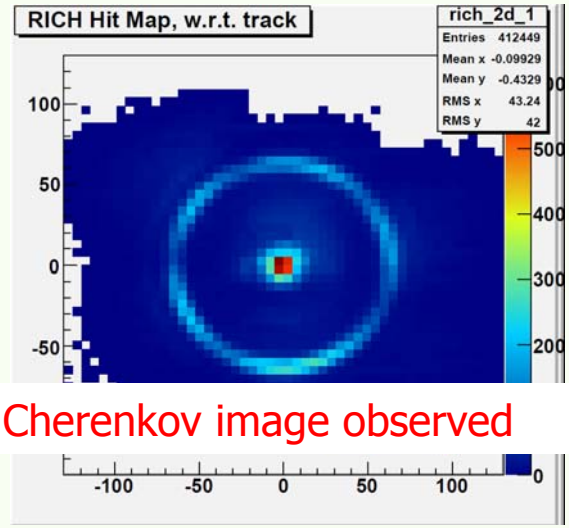
- **$2.6m^L$ x $45cm^W$ x $2cm^T$**
- **Excellent surface accuracy**

MCP-PMT

- **Hamamatsu 16ch MCP-PMTGood TTS (<35ps) & enough lifetime**
- **Multialkali photo-cathode → SBA**

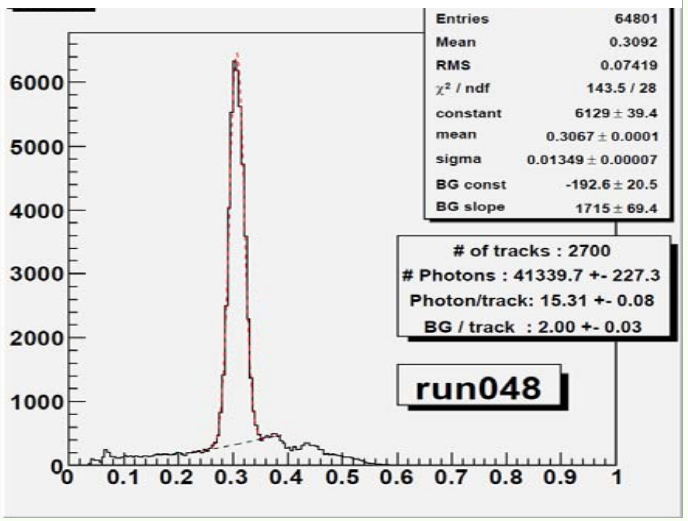
Aerogel RICH (endcap PID)





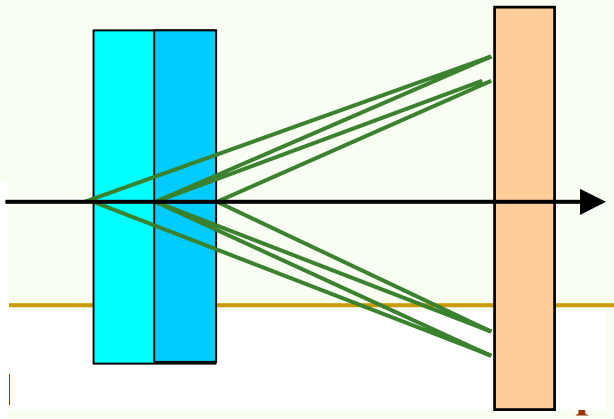
Clear Cherenkov image observed

Cherenkov angle distribution



RICH with a novel "focusing" radiator – a two layer radiator

Employ multiple layers with different refractive indices→ Cherenkov images from individual layers overlap on the photon detector.

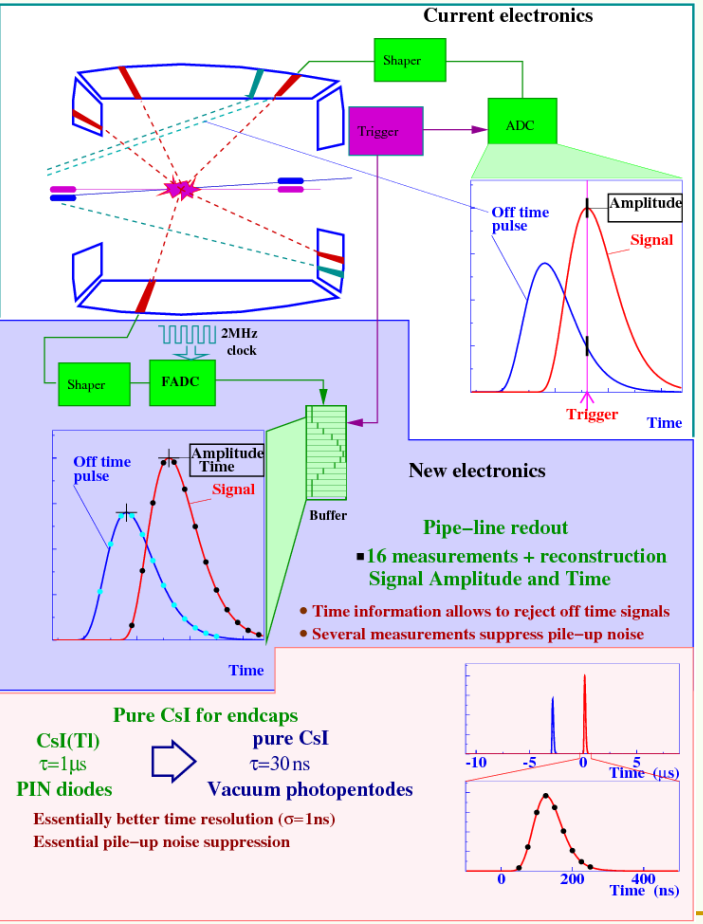


6.6 σ π/K at 4GeV/c !

ECL (Electromagnetic Crystal Calorimeter)

1. Upgrade electronics to do waveform sampling & fitting
2. Upgrade endcap crystal (baseline option: pure CsI + photomultipliers); upgrade will have to be staged.

About 400 ShaperDSP boards from 600 have been delivered to KEK and tested.



Modification of the electronics.

❖ Pipe-line readout with waveform analysis:

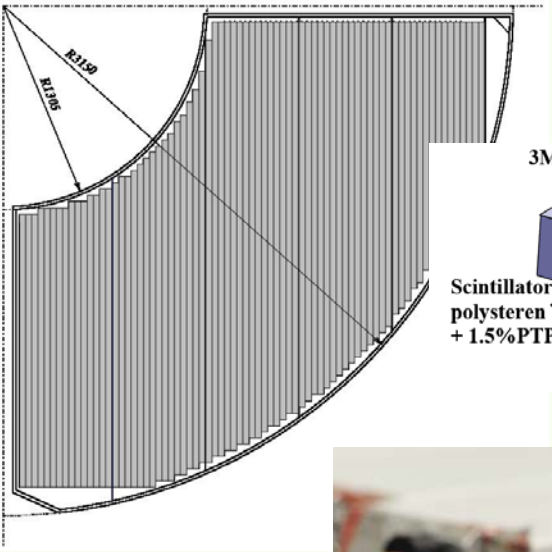
❖16 points within the signal are fitted by the signal function F(t):
$F(t) = H \cdot f(t-t_0)$

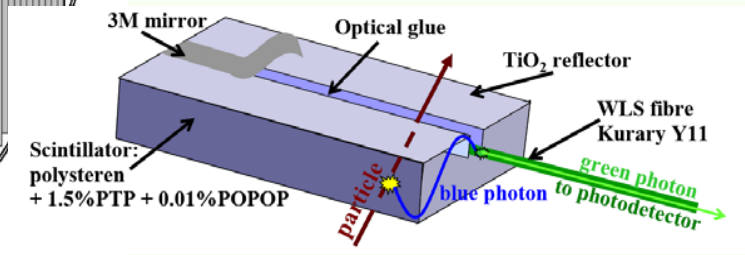
❖Both amplitude (H) and time (t_0) are obtained by the on-line shape fit:

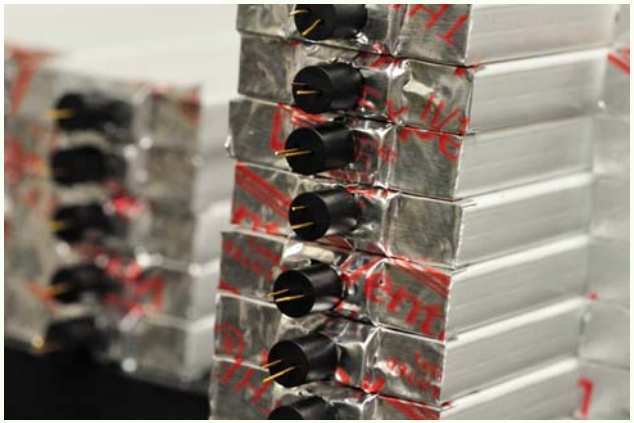
$$\chi^2 = \sum_{i,j} (A_i - F(t_i)) S_{ij} (A_j - F(t_j))$$

KLM: K_L&Muon detector

RPC → Scintillator (Endcap)
also inner 2 layers of Barrel(TBD)

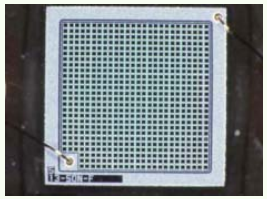






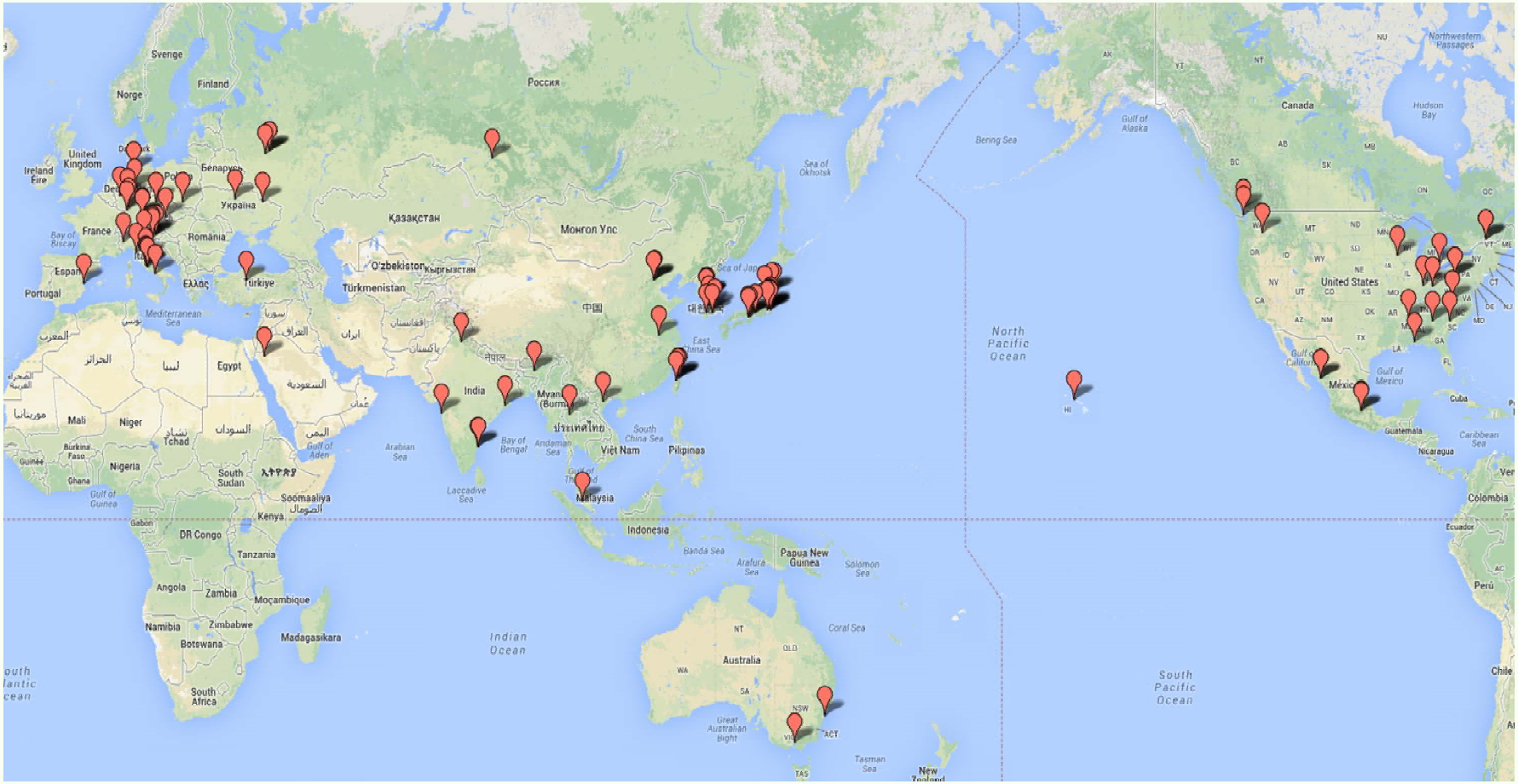
LAYOUT

- One layer: 75 strips (4 cm width)/sector
- 5 segments
  1 segment = 15strips
- Two orthogonal layer = superlayer
- F&B endcap KLM:
  - Total area ~1400 m^2
  - 16800 strips (total ~30000)
  - the longest strip 2.8 m; the shortest 0.6 m
- WLS fiber in each strip
- Hamamatsu MPPC at one fiber end
- mirrored far fiber end



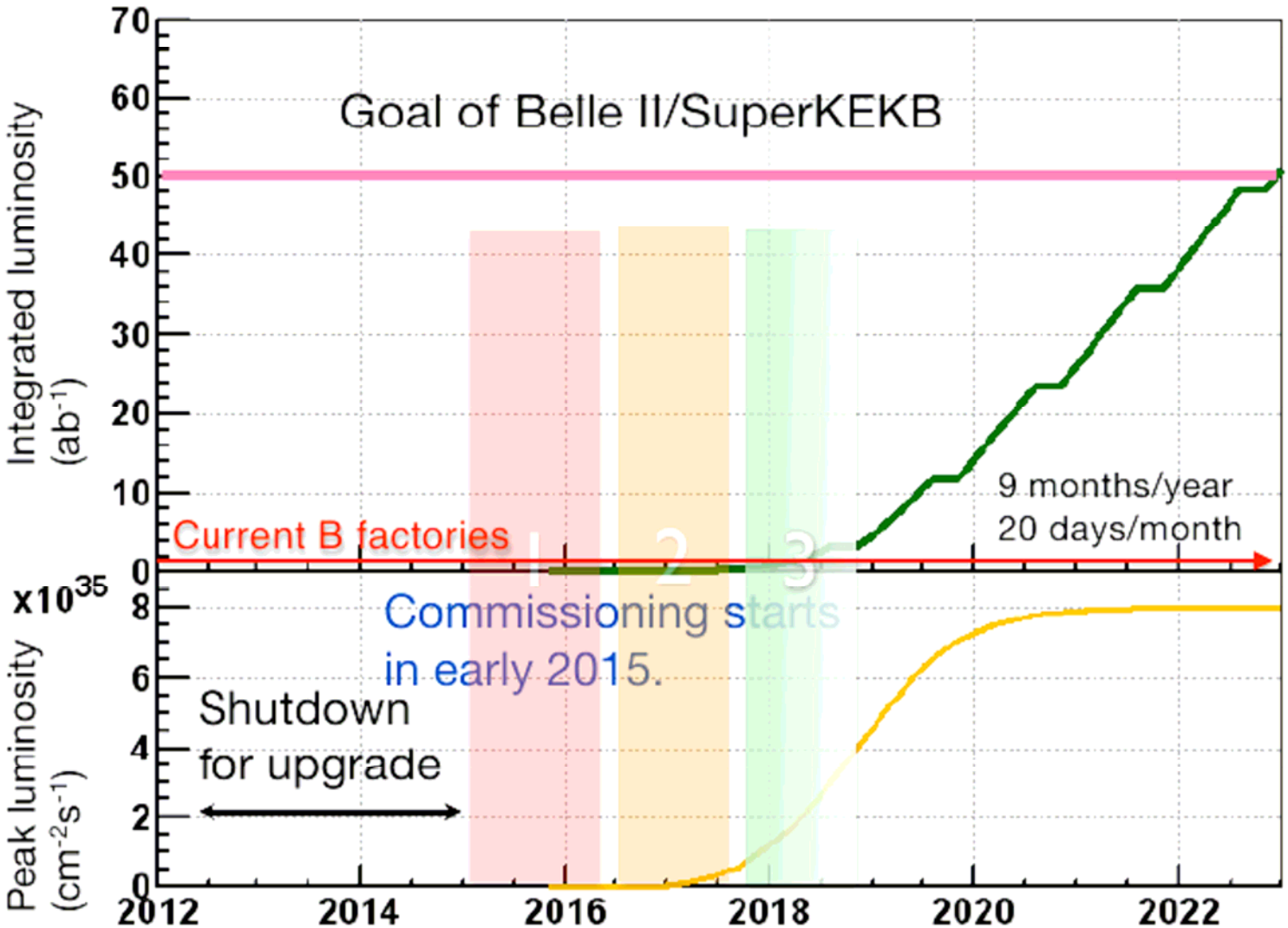
MPPC: Hamamatsu
1.3 × 1.3 mm 667 pixels
(used in T2K Near Detector)

Belle II Collaboration



23 countries/**regions**, 96 institutions, ~ 600 collaborators

1	2015	Accelerator commissioning
2	2016	Belle II “Beast” and partial detector commission
3	2017	First runs with full detector



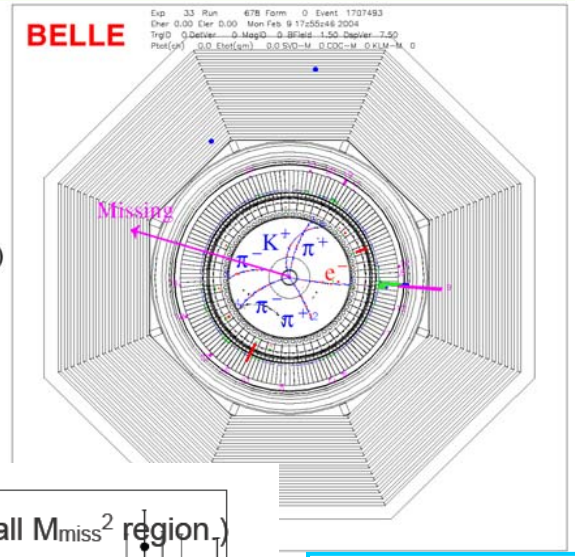
Conclusion

- Last decade demonstrated the fruitfulness and efficiency of the flavor “factory” approach in the particle physics.
- Huge amount of results was obtained at the B-factories, but many new questions appeared and the large field of researches will be opened by the super B factories.
- It is clear that the super B factories will produce the information complementary to the LHC.
- At present superKEKB/Belle II project is under construction
- We can wait for new exciting results in the next decade.

Back up

$B^- \rightarrow \tau^- \nu_\tau$

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



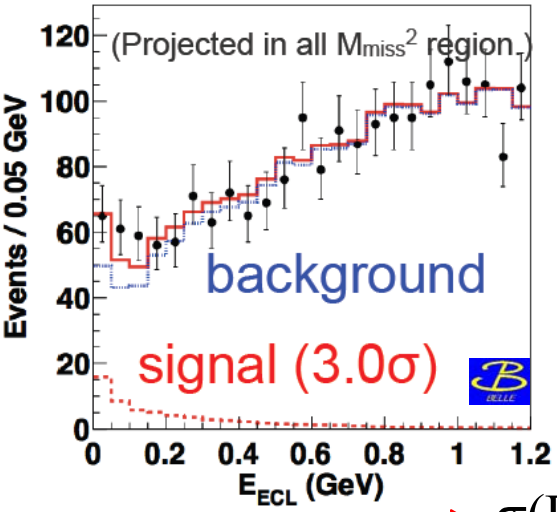
$BF(B \rightarrow \tau\nu)$

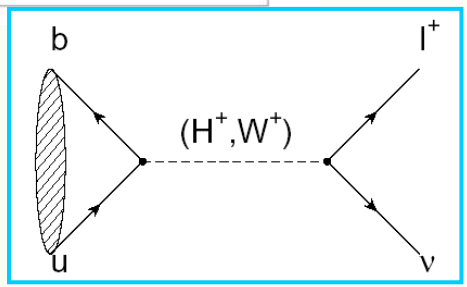
$$(0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$$

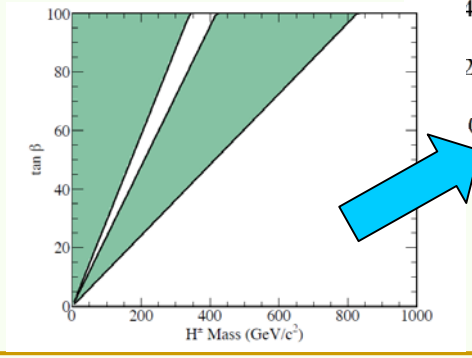
$$(1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$$

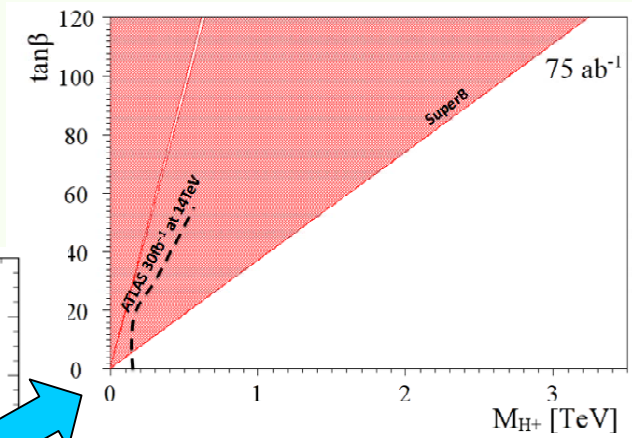
All measurements combined

$$r_H = \frac{BF(B \rightarrow \tau\nu)_{meas}}{BF(B \rightarrow \tau\nu)_{SM}} = 1.14 \pm 0.40$$





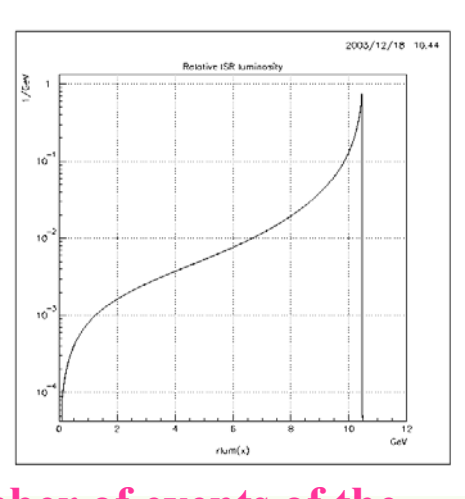




$\sigma(\Gamma/\Gamma_{SM}) \approx 0.08$

includes uncertainties from theory (on Vub and f_B), 0.04 purely exp.

Potential of ISR: competition or complementarity?



$$\frac{dl}{Ldm} = \frac{2\alpha m}{\pi s}\left\{\frac{s+m^4}{s(s-m^2)}\left(\ln\frac{s}{m_e^2}-1\right)\right\}$$

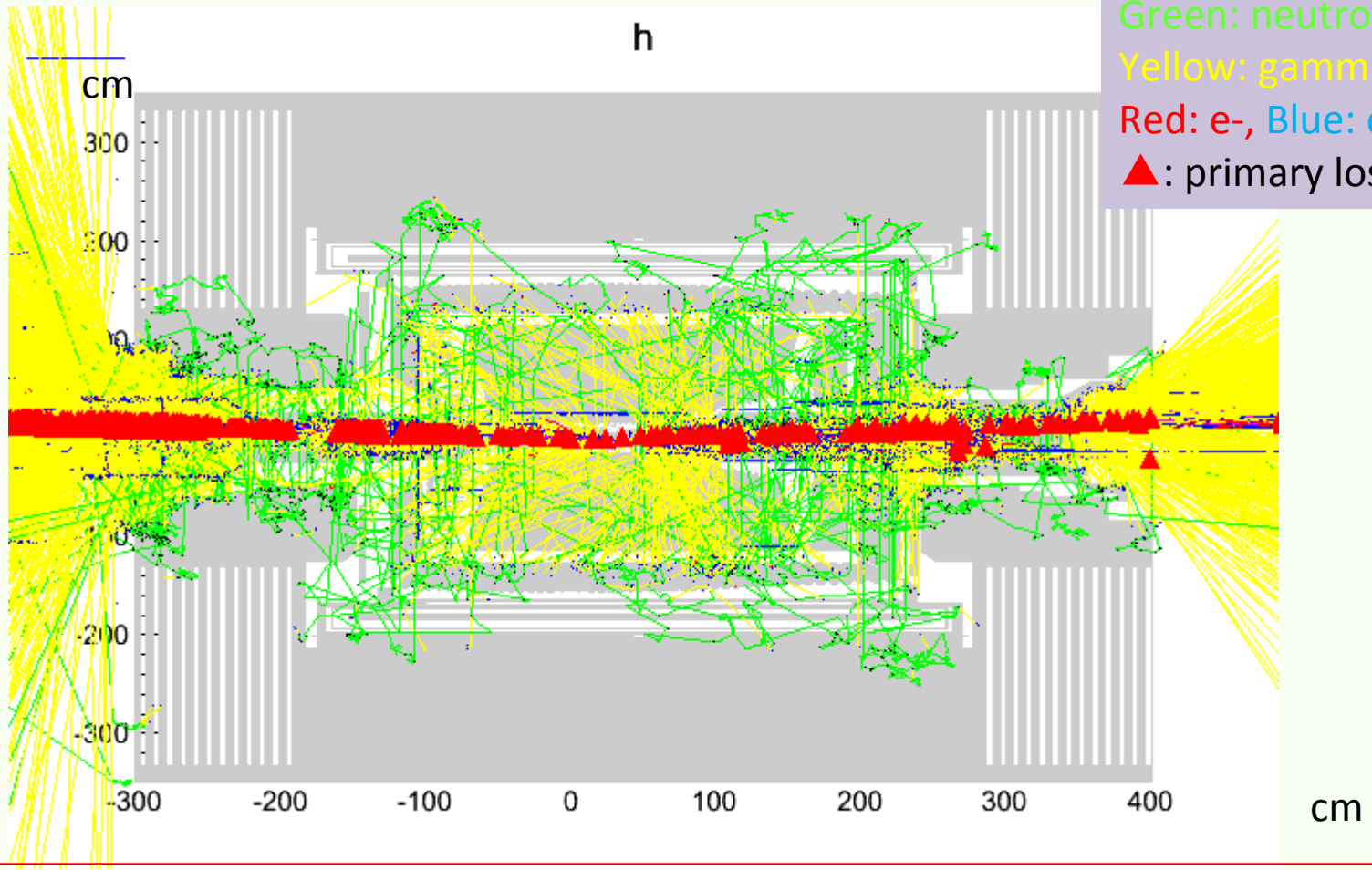
Number of events of the vector meson production at 8000 fb^{-1} (@Y(4s)

ϕ	1.5×10^8
ψ	2.3×10^8
$\psi(2S)$	7.8×10^7
$\psi(3770)$	9.7×10^6
$\Upsilon(1s)$	1.3×10^8
$\Upsilon(2s)$	1.2×10^8
$\Upsilon(3s)$	2.4×10^8

	KEKB	VEPP-2000	BEPC-II
Luminosity, см$^{-2}$ s^{-1}	$8\cdot10^{35}$	10^{32}	10^{33}
Integrated lum. (per 10^7 s)	8000 fb^{-1}	1 fb^{-1}	10 fb^{-1}
Integrated in the range [1-2] GeV	8 fb^{-1} (~0.8 @ θ>0.7)	1 fb^{-1}	
Integrated in the range [2-3] GeV	20 fb^{-1} (~2 @ θ>0.7)		10 fb^{-1}

Background event display

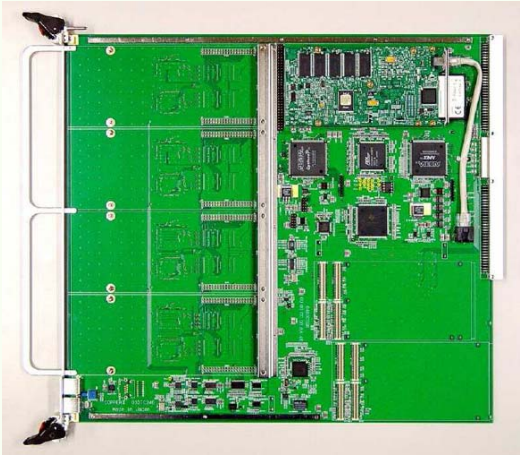
100ns, shown E>1MeV
Green: neutrons
Yellow: gammas
Red: e-, Blue: e+
▲: primary loss position



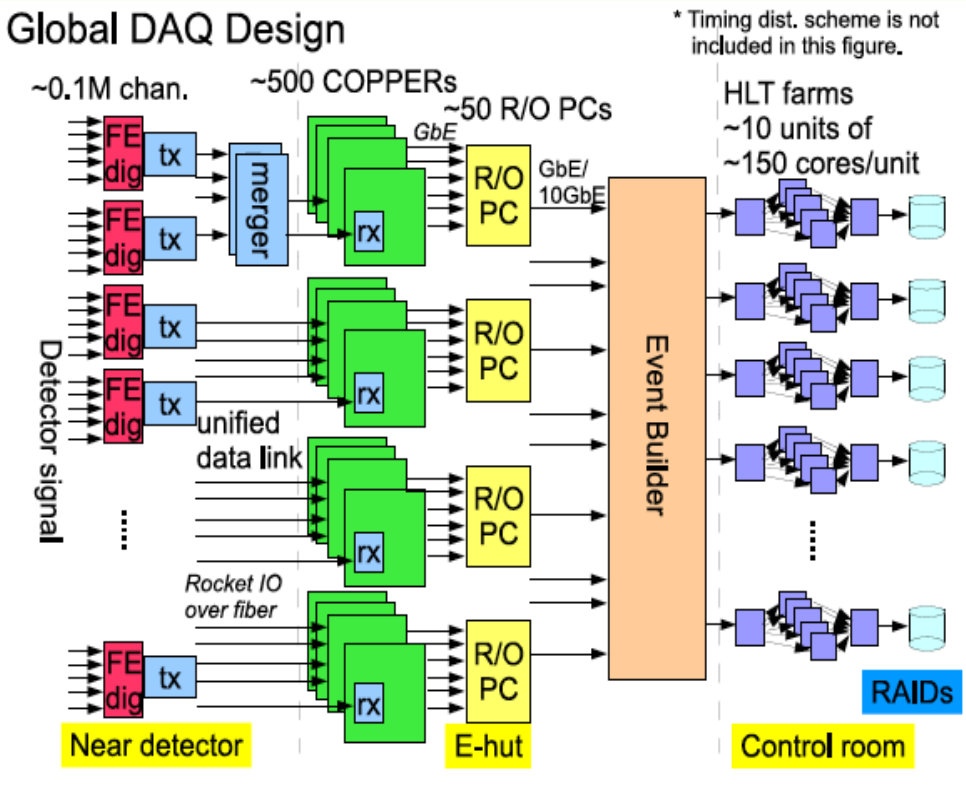
Neutrons: background hits in the muon and KL detection system (KLM) → reduce the efficiency of muon and KL detection → replace RPCs in the endcaps and 2 barrel layers.

DAQ Overview

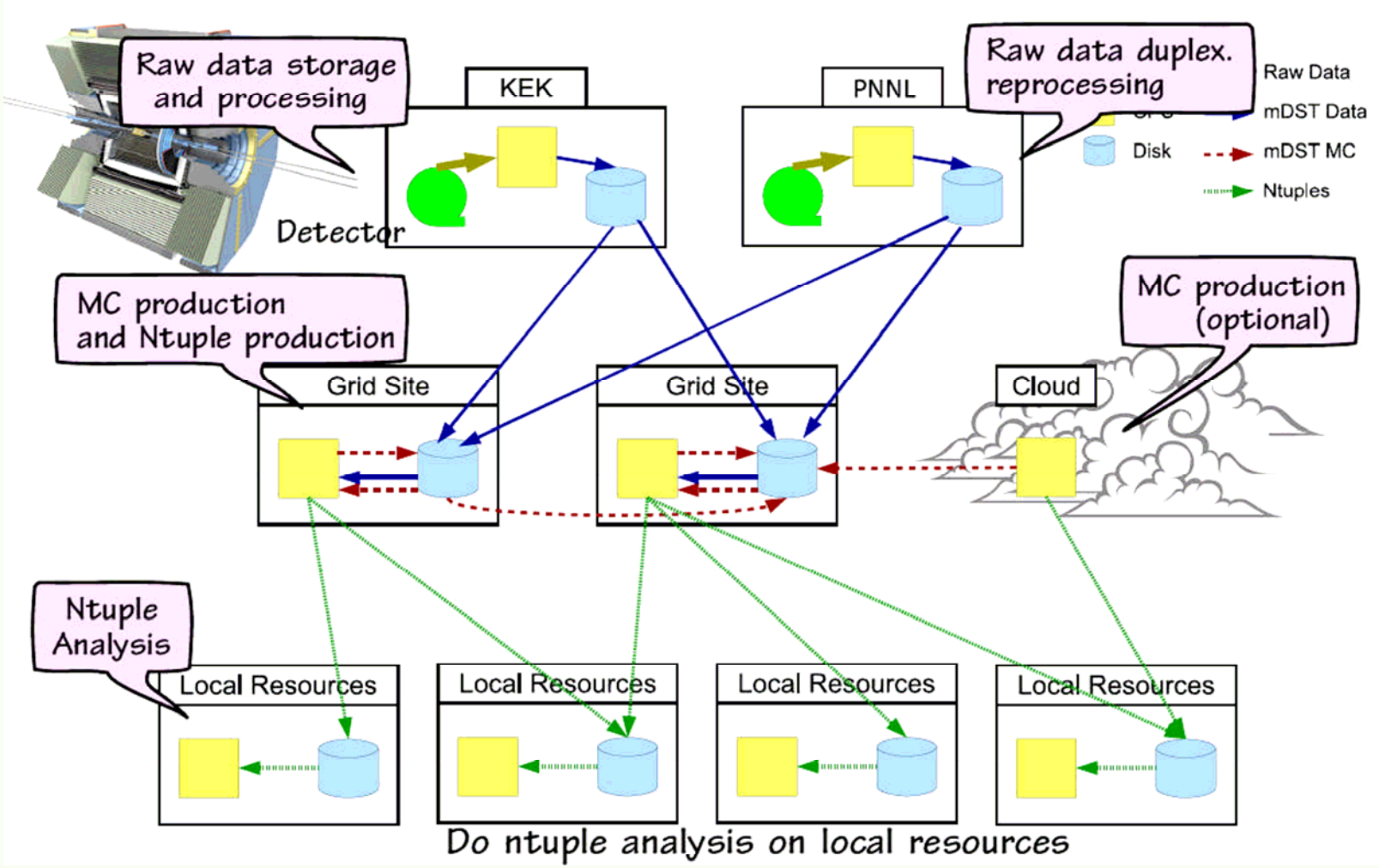
- At full luminosity, the data rate is 600 MB/sec.
- A high performance DAQ system is being designed by KEK and IHEP Beijing



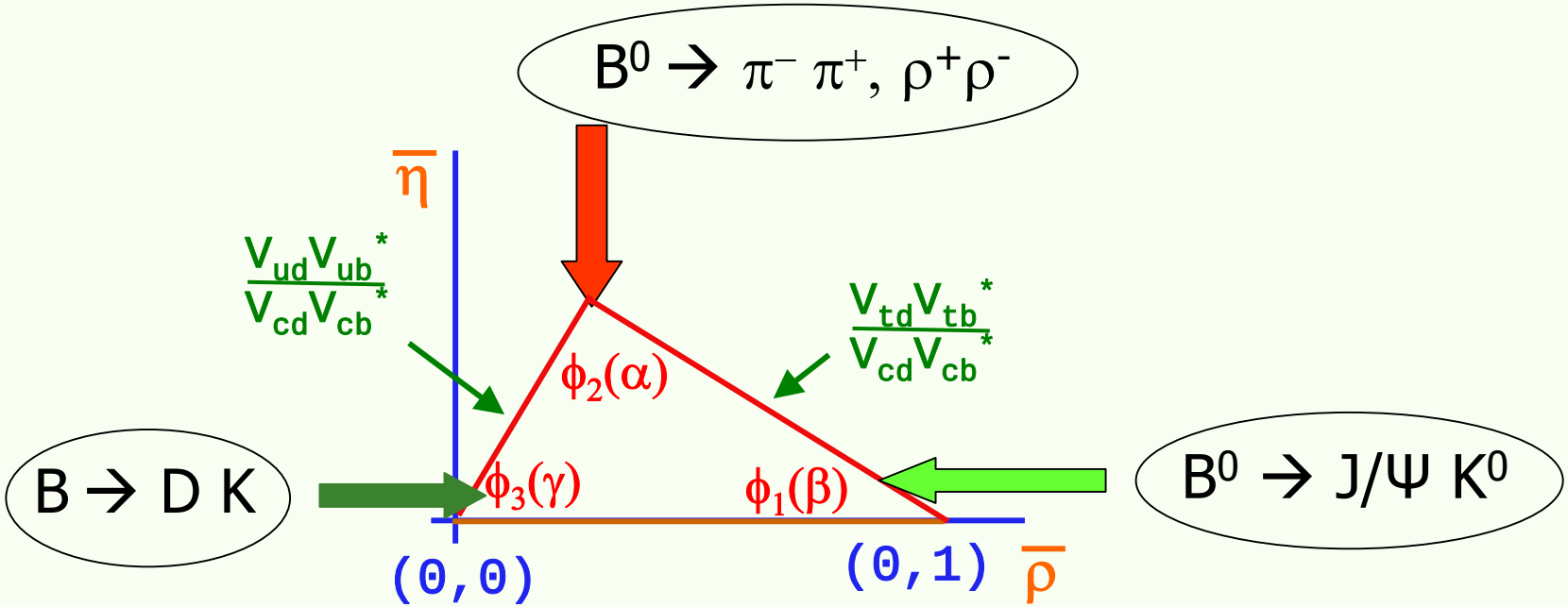
		Belle	Belle II
Level 1 Trigger	Trigger rate (kHz)	0.3-0.5	20-30
	Event size (kBytes)	40	300
	Data rate (MB/s)	20	6000
High Level Trigger	Reduction	1/ 2	1/10
	Storage Bandwidth (MB/s)	20	600



A snapshot of the Belle II computing model



CP violation in the B system and unitarity triangle



$\alpha + \beta + \gamma = \varphi_1 + \varphi_2 + \varphi_3 = (178\ ^{+11}_{-12})^\circ$ (PDG 2012) in a good agreement with SM and theoretical prediction of Euclid.

Still certain room for New Physics search exists…

In conclusion…

Complementarity

to other intensity frontiers experiments (LHCb, BES III, ...);

Super B factory

LHCb

K experiments

Observable	SM prediction	Theory error	Present result	Future error	Future Facility
$\lvert V_{us}\rvert$ $[K \to \pi \ell \nu]$	input	$0.5\% \to 0.1\%_{\rm Latt}$	0.2246 ± 0.0012	0.1%	K factory
$\lvert V_{cb}\rvert$ $[B \to X_c \ell \nu]$	input	1%	$(41.54 \pm 0.73) \times 10^{-3}$	1%	Super-B
$\lvert V_{ub}\rvert$ $[B \to \pi \ell \nu]$	input	$10\% \to 5\%_{\rm Latt}$	$(3.38 \pm 0.36) \times 10^{-3}$	4%	Super-B
γ $[B \to DK]$	input	$< 1^\circ$	$(70^{+27}_{-30})^\circ$	3°	LHCb
$S_{B_d \to \psi K}$	$\sin(2\beta)$	$\lesssim 0.01$	0.671 ± 0.023	0.01	LHCb
$S_{B_s \to \psi \phi}$	0.036	$\lesssim 0.01$	$0.81^{+0.12}_{-0.32}$	0.01	LHCb
$S_{B_d \to \phi K}$	$\sin(2\beta)$	$\lesssim 0.05$	0.44 ± 0.18	0.1	LHCb
$S_{B_s \to \phi \phi}$	0.036	$\lesssim 0.05$	—	0.05	LHCb
$S_{B_d \to K^* \gamma}$	few $\times$ 0.01	0.01	-0.16 ± 0.22	0.03	Super-B
$S_{B_s \to \phi \gamma}$	few $\times$ 0.01	0.01	—	0.05	LHCb
$A^d_{\rm SL}$	-5×10^{-4}	10^{-4}	$-(5.8 \pm 3.4) \times 10^{-3}$	10^{-3}	LHCb
$A^s_{\rm SL}$	2×10^{-5}	$< 10^{-5}$	$(1.6 \pm 8.5) \times 10^{-3}$	10^{-3}	LHCb
$A_{CP}(b \to s\gamma)$	< 0.01	< 0.01	-0.012 ± 0.028	0.005	Super-B
$\mathcal{B}(B \to \tau \nu)$	1×10^{-4}	$20\% \to 5\%_{\rm Latt}$	$(1.73 \pm 0.35) \times 10^{-4}$	5%	Super-B
$\mathcal{B}(B \to \mu \nu)$	4×10^{-7}	$20\% \to 5\%_{\rm Latt}$	$< 1.3 \times 10^{-6}$	6%	Super-B
$\mathcal{B}(B_s \to \mu^+\mu^-)$	3×10^{-9}	$20\% \to 5\%_{\rm Latt}$	$< 5 \times 10^{-8}$	10%	LHCb
$\mathcal{B}(B_d \to \mu^+\mu^-)$	1×10^{-10}	$20\% \to 5\%_{\rm Latt}$	$< 1.5 \times 10^{-8}$	[?]	LHCb
$A_{\rm FB}(B \to K^* \mu^+\mu^-)_{q^2_0}$	0	0.05	(0.2 ± 0.2)	0.05	LHCb
$B \to K \nu \bar{\nu}$	4×10^{-6}	$20\% \to 10\%_{\rm Latt}$	$< 1.4 \times 10^{-5}$	20%	Super-B
$\lvert q/p\rvert_{D-\rm mixing}$	1	$< 10^{-3}$	$(0.86^{+0.18}_{-0.15})$	0.03	Super-B
ϕ_D	0	$< 10^{-3}$	$(9.6^{+8.3}_{-9.5})^\circ$	2°	Super-B
$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$	8.5×10^{-11}	8%	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	10%	K factory
$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu})$	2.6×10^{-11}	10%	$< 2.6 \times 10^{-8}$	[?]	K factory
$R^{(e/\mu)}(K \to \pi \ell \nu)$	2.477×10^{-5}	0.04%	$(2.498 \pm 0.014) \times 10^{-5}$	0.1%	K factory
$\mathcal{B}(t \to cZ, \gamma)$	$\mathcal{O}(10^{-13})$	$\mathcal{O}(10^{-13})$	$< 0.6 \times 10^{-2}$	$\mathcal{O}(10^{-5})$	LHC (100 fb^{-1})

$B(B \to X_s\gamma)$	6%	Super-B	
$B(B \to X_d\gamma)$	20%	Super-B	
$S(B \to \rho\gamma)$	0.15	Super-B	
$B(\tau \to \mu\gamma)$	$3 \cdot 10^{-9}$	Super-B	(90% U.L.)
$B(B^+ \to D\tau\nu)$	3%	Super-B	
$B(B_s \to \gamma\gamma)$	$0.25 \cdot 10^{-6}$	Super-B	(5 ab^{-1})
$\sin^2\theta_W$ @ $\Upsilon(4S)$	$3 \cdot 10^{-4}$	Super-B	

G. Isidori et al., Ann.Rev.Nucl. Part.Sci. 60, 355 (2010)

B. Golob, KEK FF Workshop, Feb. 2012