The Belle II Experiment at SuperKEKB

Leo Piilonen, Virginia Tech

... with an acknowledgement to my colleagues for their contributions

Brookhaven Forum May 2013

B factories: a success story

- Measurements of CKM matrix elements and angles of the unitarity triangle
- Observation of direct CP violation in B decays
- Measurements of rare decay modes (e.g., $B \to \tau\nu$, $D\tau\nu$)
- $b \to s$ transitions: probe for new sources of CPV and constraints from the $b \to s\gamma$ branching fraction
- Forward-backward asymmetry (A_{FB}) in $b \to sl^+l^-$ has become a powerfull tool to search for physics beyond SM.
- Observation of D mixing
- Searches for rare τ decays
- Observation of new hadrons

Possible also because of unique capabilities of B factories: detection of neutrals, neutrinos, clean event environment.

Belle physics output (compiled by Simon Eidelman)

# citations ➡	50-99	100-199	200-299	300-399	400-499	>500	Total
# papers ➡	64	37	10	2	–	2	115

N	Title	Year	Cites
1	X(3872)	2003	739
2	Large CPV	2001	618
3	$B \to X_s\gamma$	2001	381
4	CP in $B^0\bar{B}^0$	2002	326
5	D0 mixing	2007	292
6	Y(3945)	2005	290
7	$B \to \tau\nu$	2006	277
8	2$c\bar{c}$	2002	272
9	$b \to s\gamma$	2004	265
10	$D_s^*(2317)$, $D_{s1}(2460)$	2003	258
11	D^{**}	2004	249
12	Z(4430)	2008	235
13	D_{sJ}	2006	221
14	$X(3940)$ in 2$c\bar{c}$	2007	204

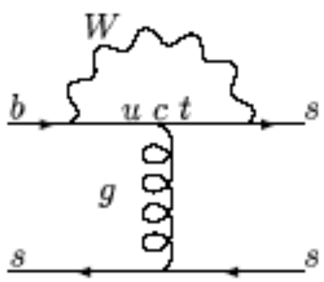
growing at ≈100/year

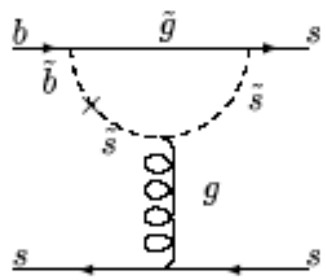
375 papers published plus ≈30/year

Searching for New Physics with Belle II

Indirect searches for New Physics complement direct searches at LHC

Flavor changing neutral currents
(virtual contributions of new, heavy particles in loops)





Precision test of **CKM unitarity**
(search for new CP-violating phases)

New Physics
???

Search for **New Physics**
in **B decays with τ leptons**
(charged Higgs, ...)

Search for **lepton flavor violation**
in **B and τ decays**

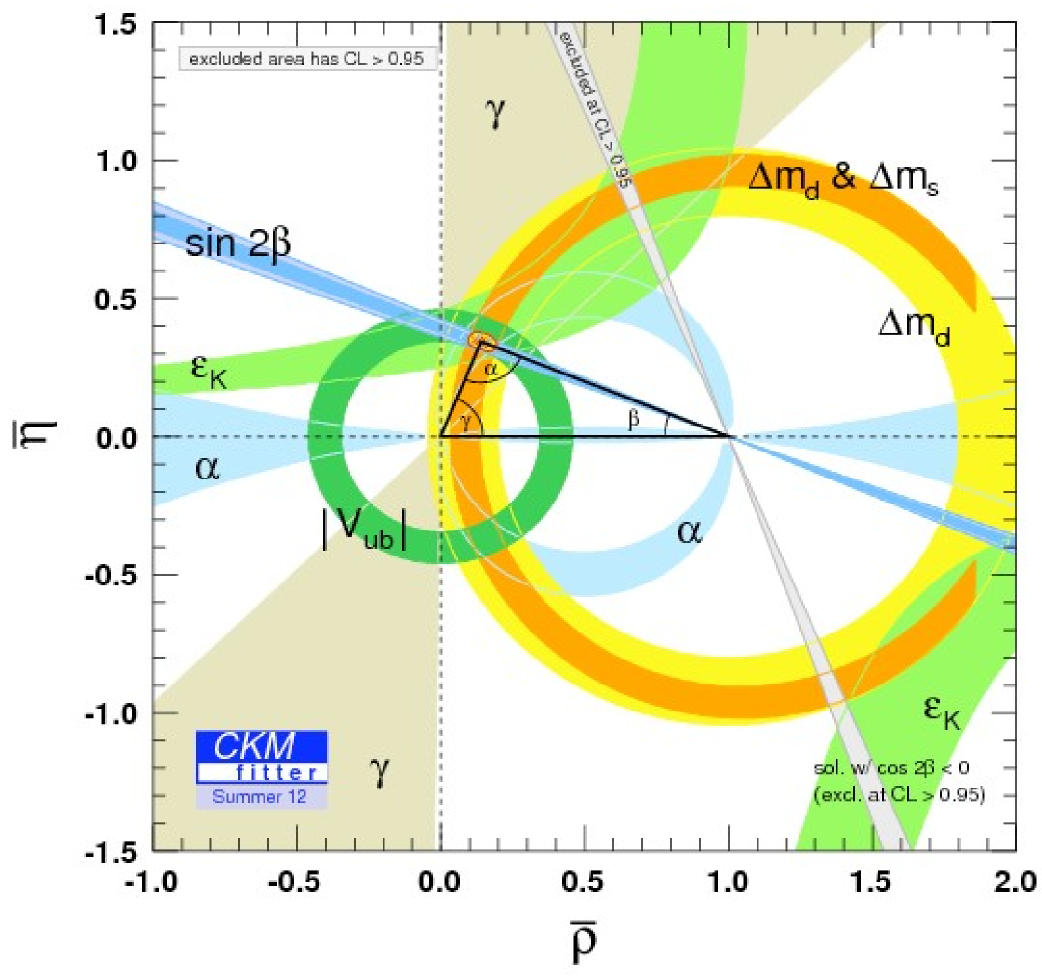
For sensitive New Physics searches, need **$O(10^2)$ times** more data

Belle / KEKB ⇒ Belle II / SuperKEKB

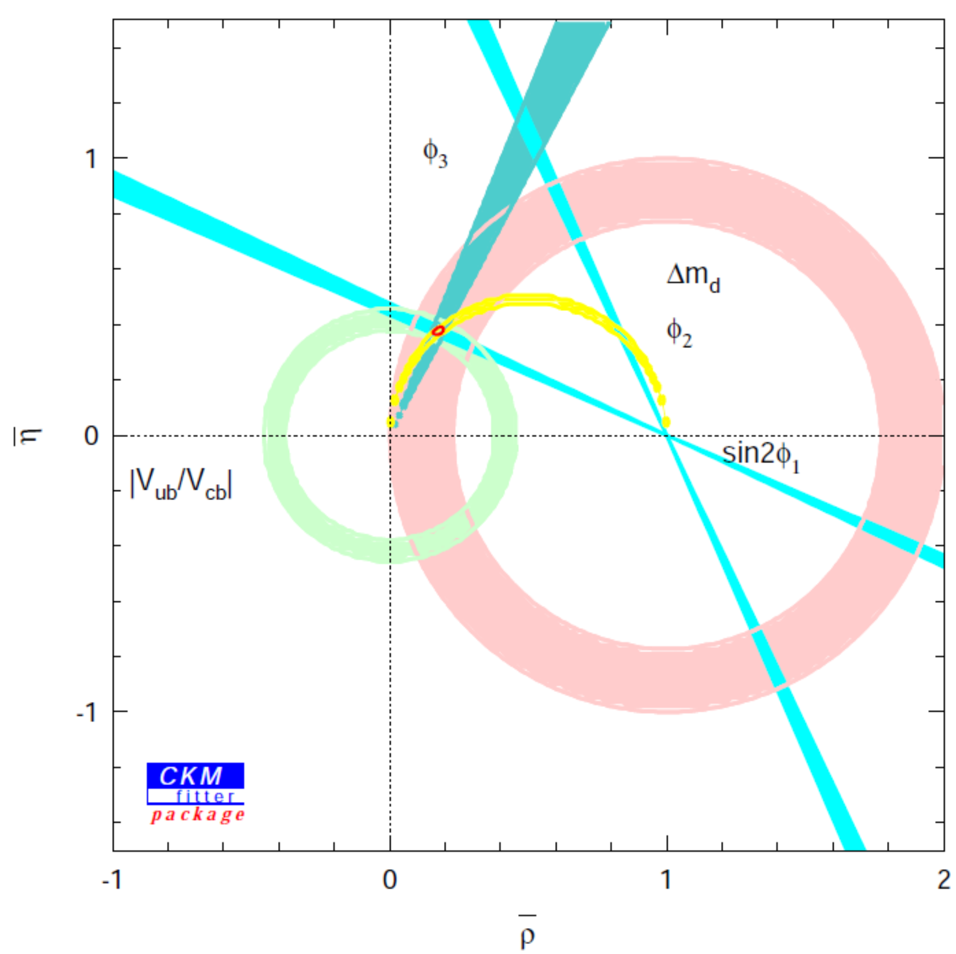
Precision Tests of CKM

- Much more improved measurements
- Overconstrain Unitarity Triangle
- Discrepancy between measurements → new physics?

2012 (~1000 fb^{-1} at Belle and BaBar)

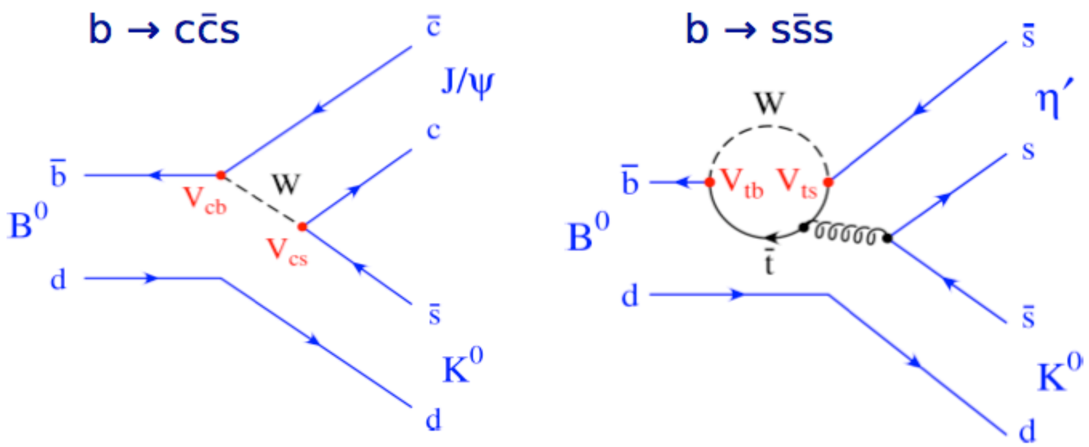


Expected constraint at 50 ab^{-1}



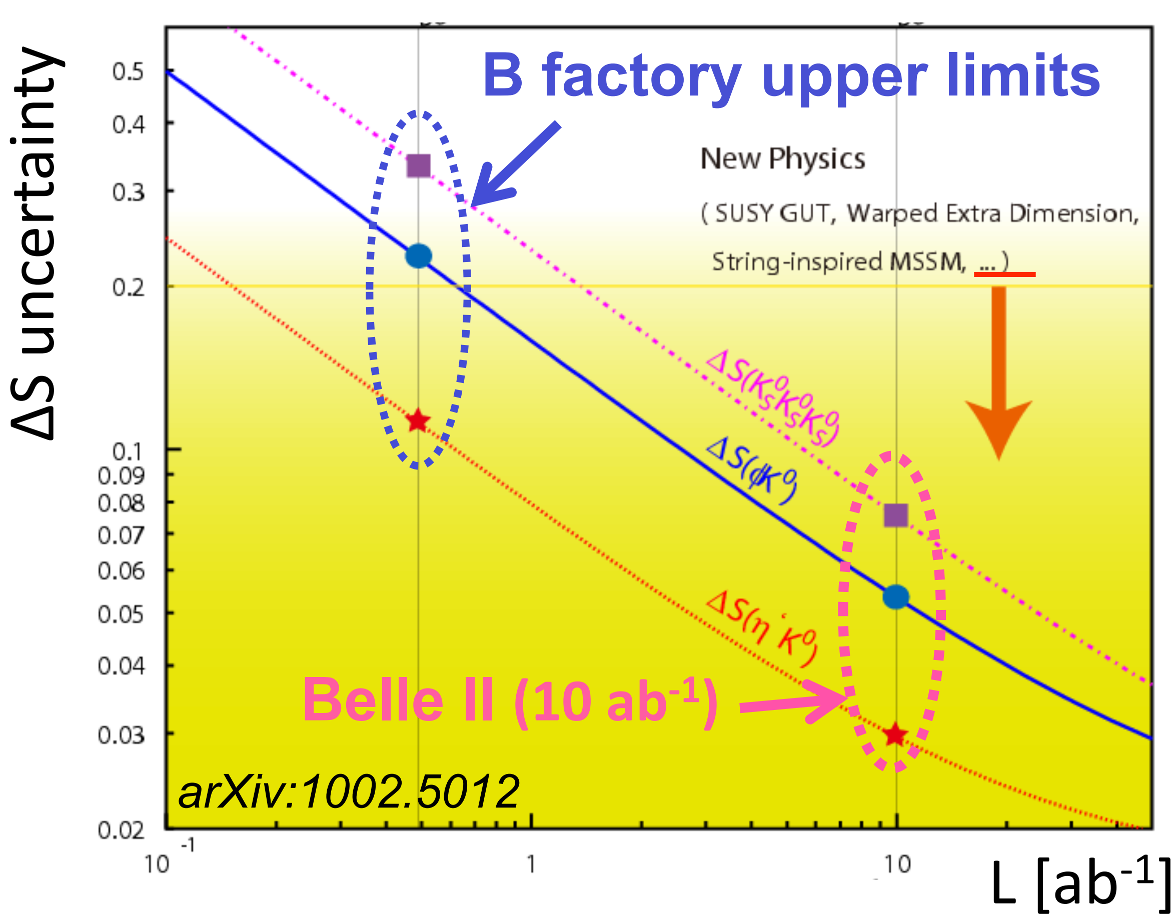
Belle II physics prospects: B decays

CP violation in s-Penguins

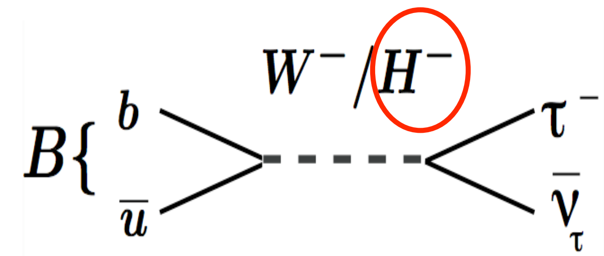


$\Delta S = S(b \to q\bar{q}s) - S(b \to c\bar{c}s) = -0.04 \pm 0.04$

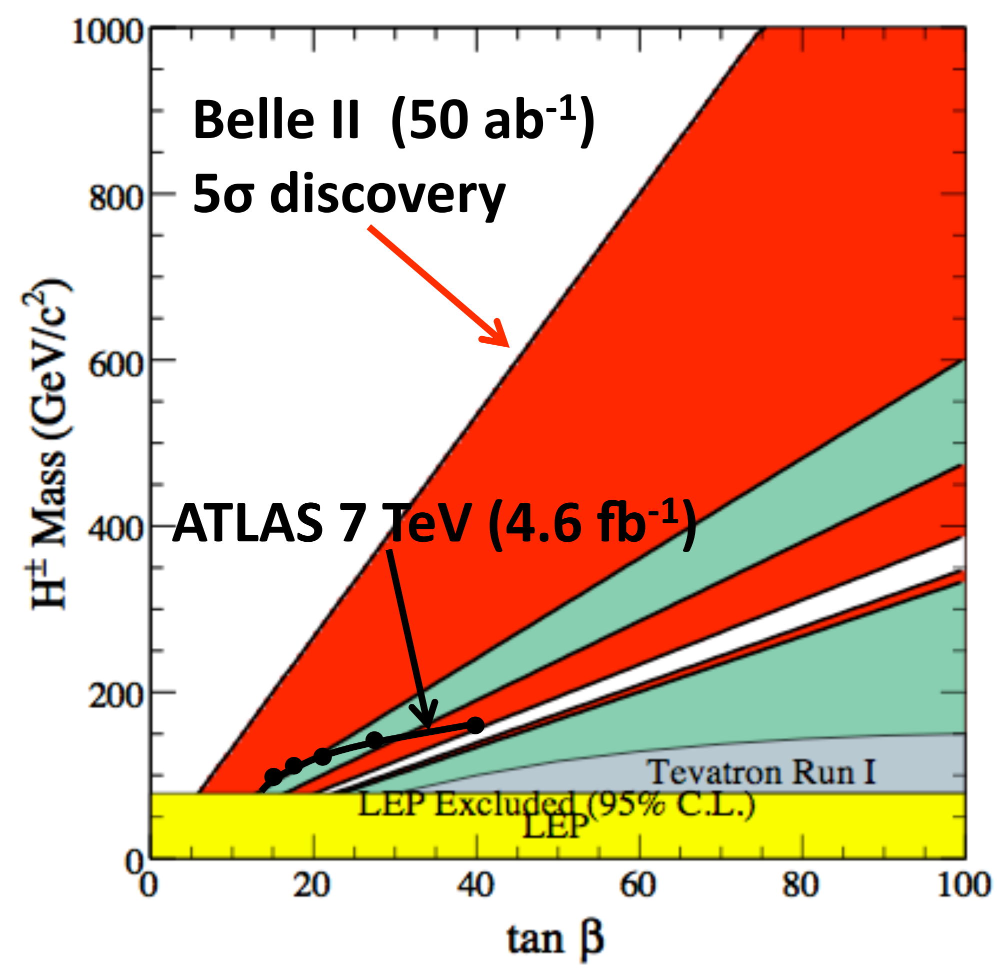
(HFAG, Summer 2012)



B decays with τ leptons



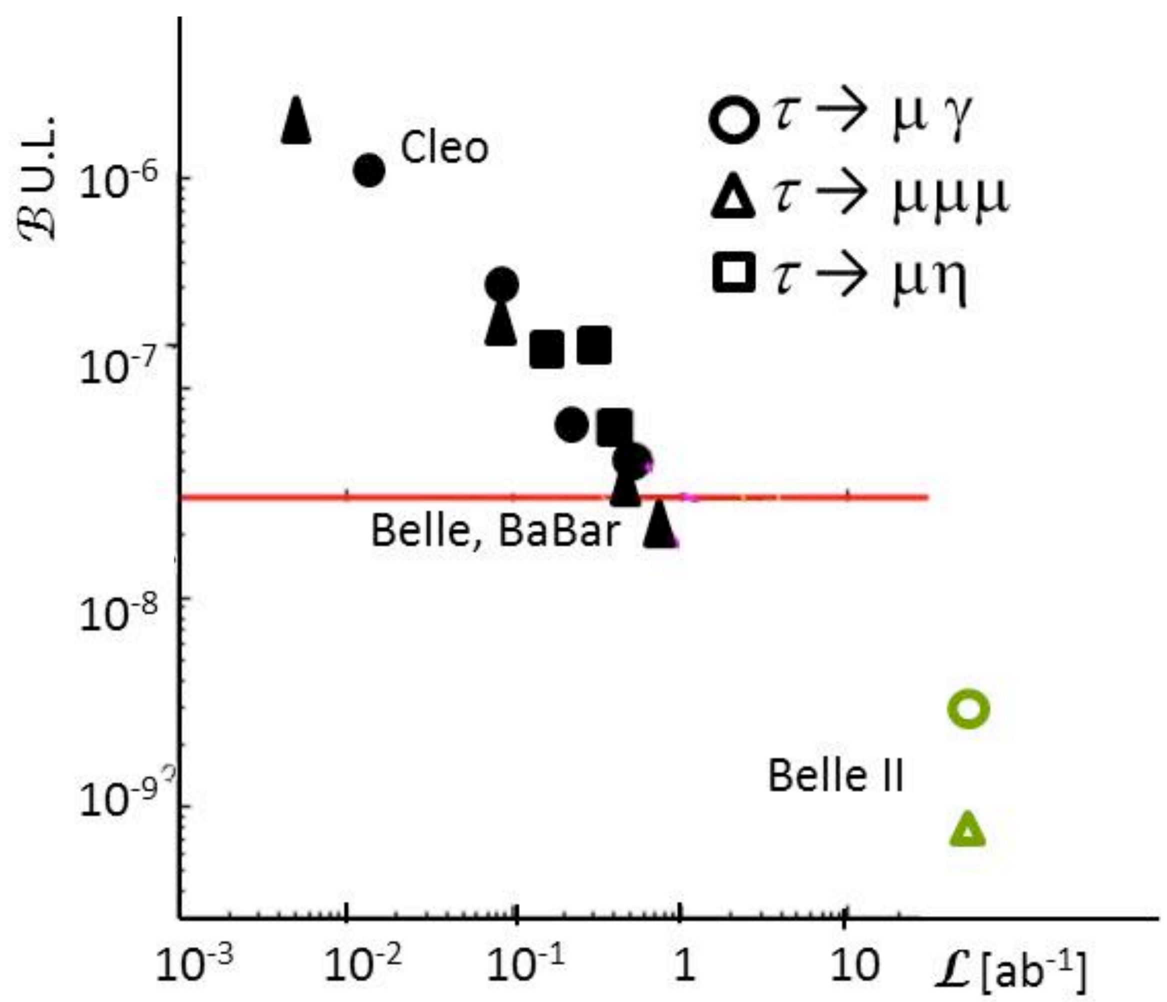
- $B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$
- Sensitive to charged Higgs



Belle II physics prospects: Tau and charm

Lepton flavor violation in τ decays

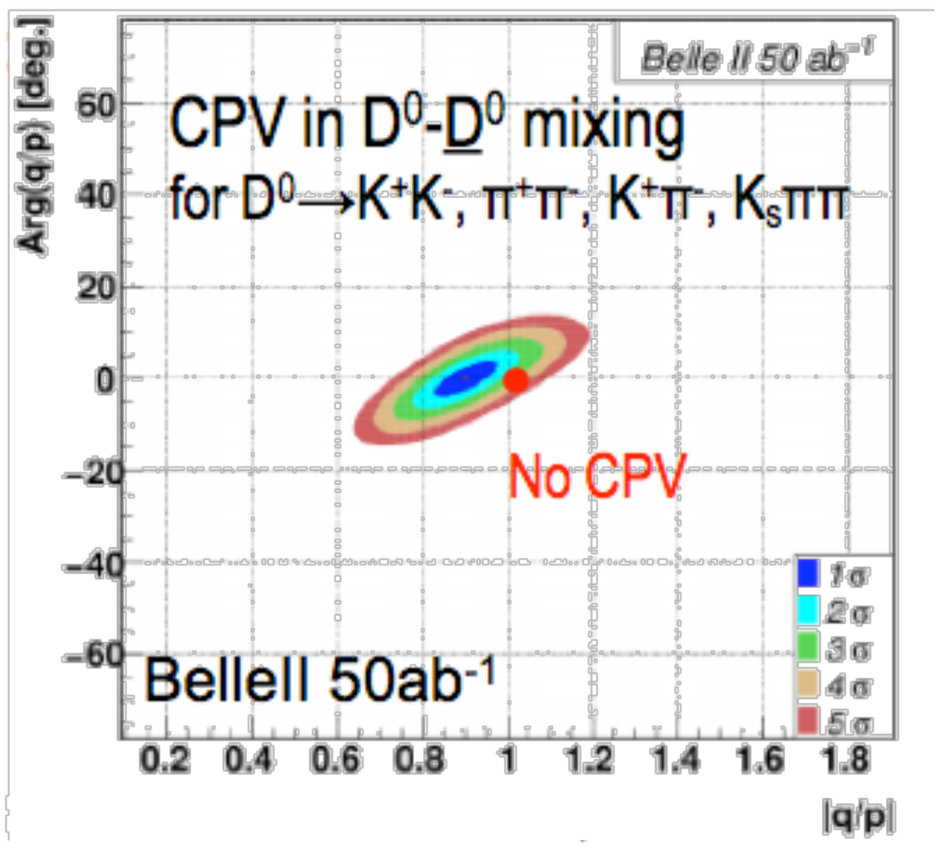
- strongly suppressed in SM: BF ~ 10^{-53}-10^{-49}
- Possible enhancements in NP models up to BF ~ 10^{-9}-10^{-7}



CP violation in D mixing

- Direct and indirect CPV in D^0-$\bar{D}^0$ mixing

Constraints on indirect CPV parameters



Current WA	Belle II (50 ab^{-1})
$\delta\|q/p\| = 0.17$	$\delta\|q/p\| = 0.05$
$\delta\phi = 9°$	$\delta\phi = 3°$

Complementary to LHCb

Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\|V_{us}\|$ $[K \to \pi \ell \nu]$	**	0.1%	K-factory
$\|V_{cb}\|$ $[B \to X_c \ell \nu]$	**	1%	Belle II
$\|V_{ub}\|$ $[B_d \to \pi \ell \nu]$	*	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
$\|q/p\|_D$	***	0.03	Belle II
$arg(q/p)_D$	***	1.5°	Belle II

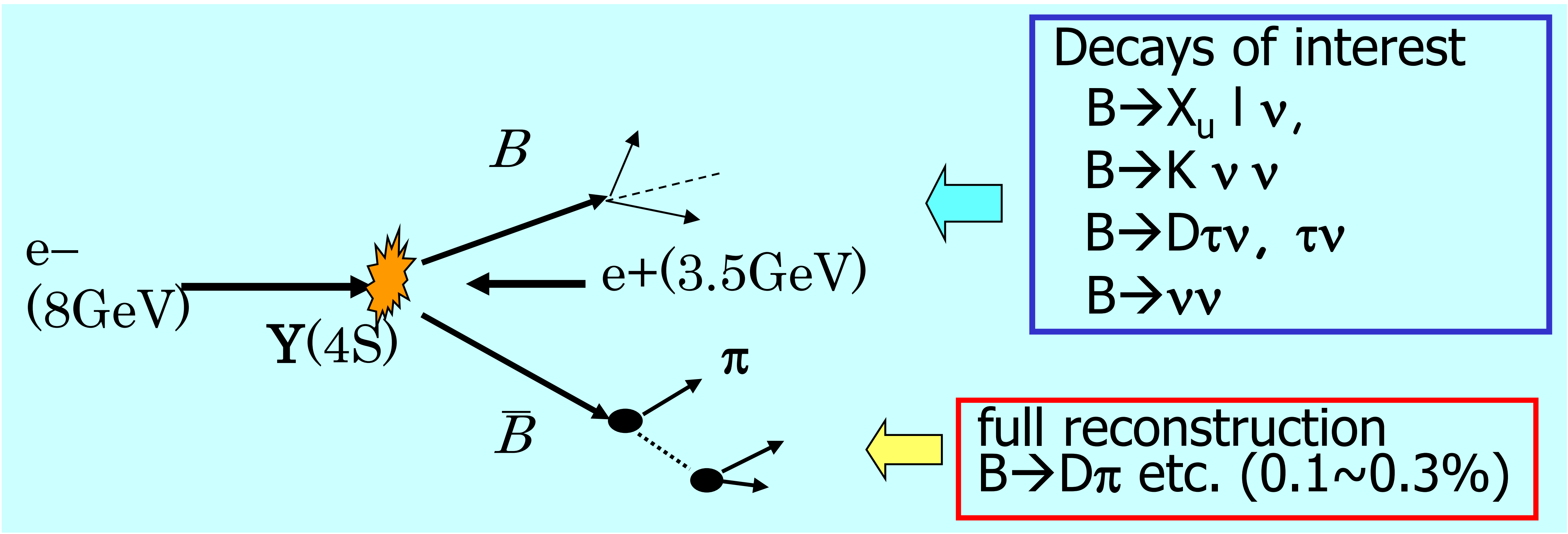
→Need both LHCb and super B factories to cover all aspects of precision flavour physics

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

B. Golob, KEK FF Workshop, Feb. 2012

Power of e^+e^-, example: Full Reconstruction Method

- Fully reconstruct one of the B mesons to
  - Tag B flavor/charge
  - Determine B momentum
  - Exclude decay products of one B from further analysis

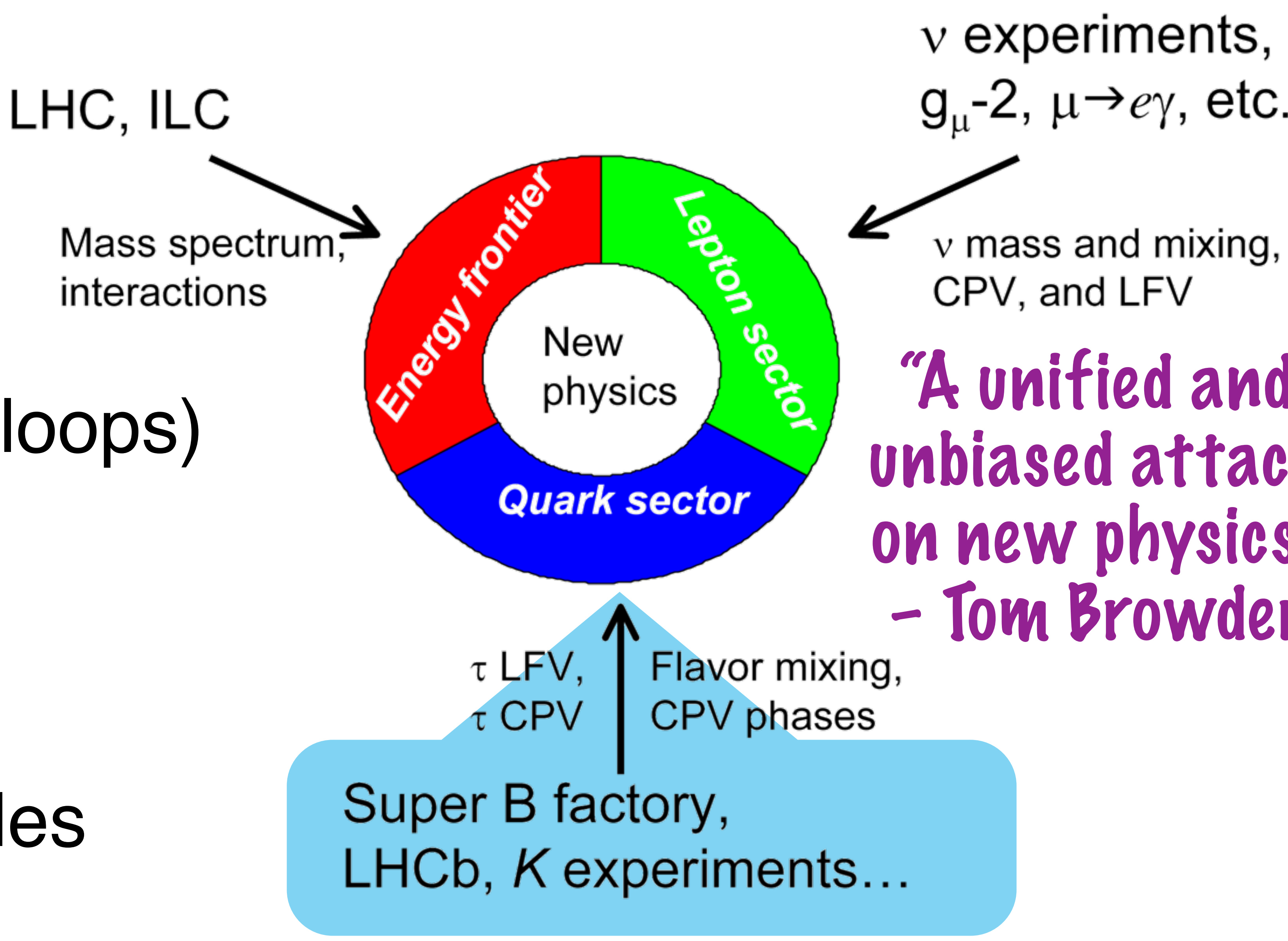


→ Offline B meson beam!

Powerful tool for B decays with neutrinos

Search for New Physics at Belle II

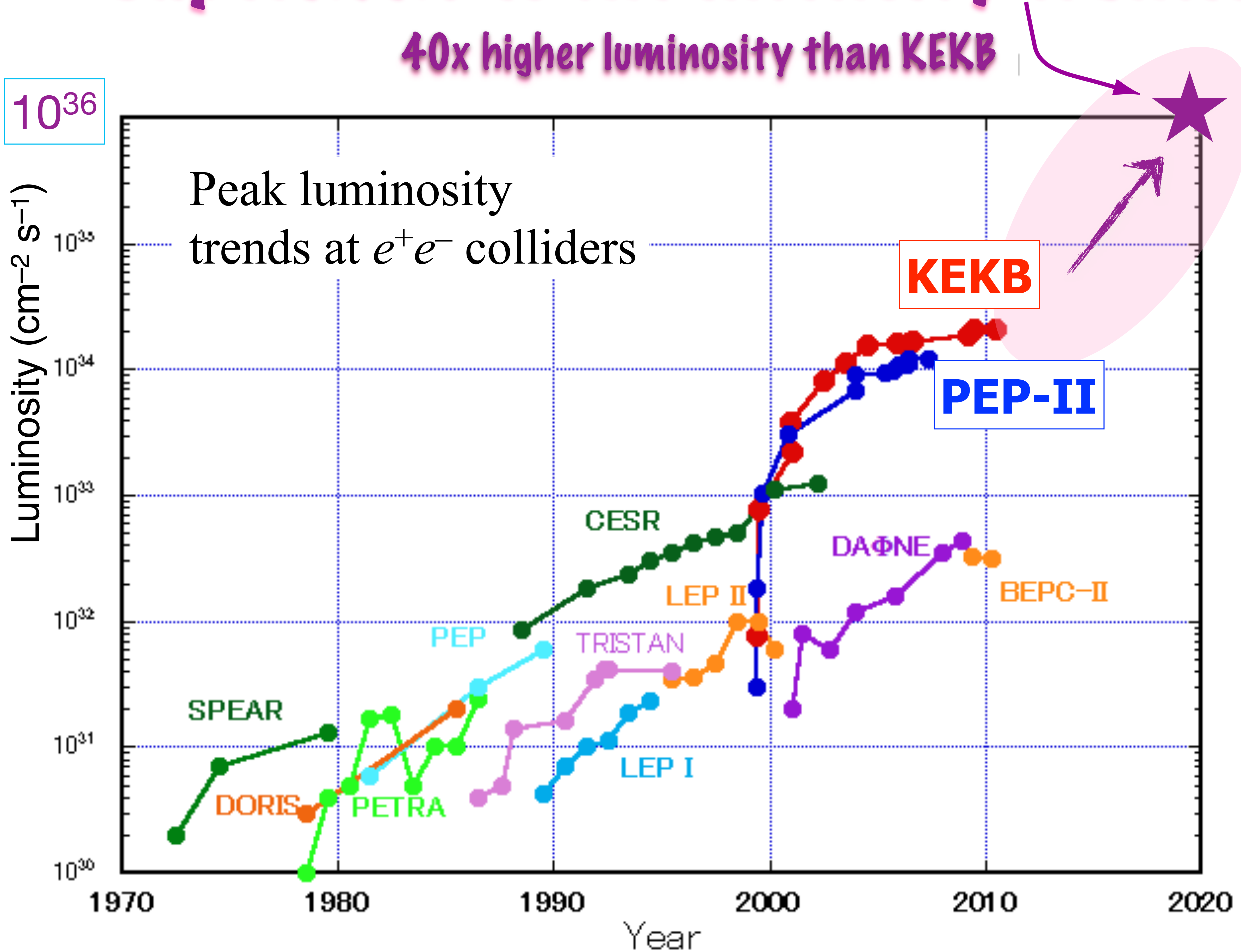
- ✓ Precision CKM unitarity tests
- ✓ NP effects in *B* decays with missing energy, such as $B \to \tau\nu,\ B \to D^{(*)}\tau\nu,\ B \to K\nu\nu,\ \ldots$
- ✓ LFV in *B* and τ decays
- ✓ FCNC (via virtual heavy particles in loops)
- ✓ Charm studies (including exotica)
- ✓ Dark-sector particles



"A unified and unbiased attack on new physics" – Tom Browder

SuperKEKB is the intensity frontier

40x higher luminosity than KEKB



Strategies for increasing luminosity

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

- Lorentz factor
- Beam current
- Beam-beam parameter
- Classical electron radius
- Beam size ratio@IP 1 - 2 % (flat beam)
- Vertical beta function@IP
- Lumi. reduction factor (crossing angle)& Tune shift reduction factor (hour glass effect) 0.8 - 1 (short bunch)

(1) Smaller β_y^*

(2) Increase beam currents

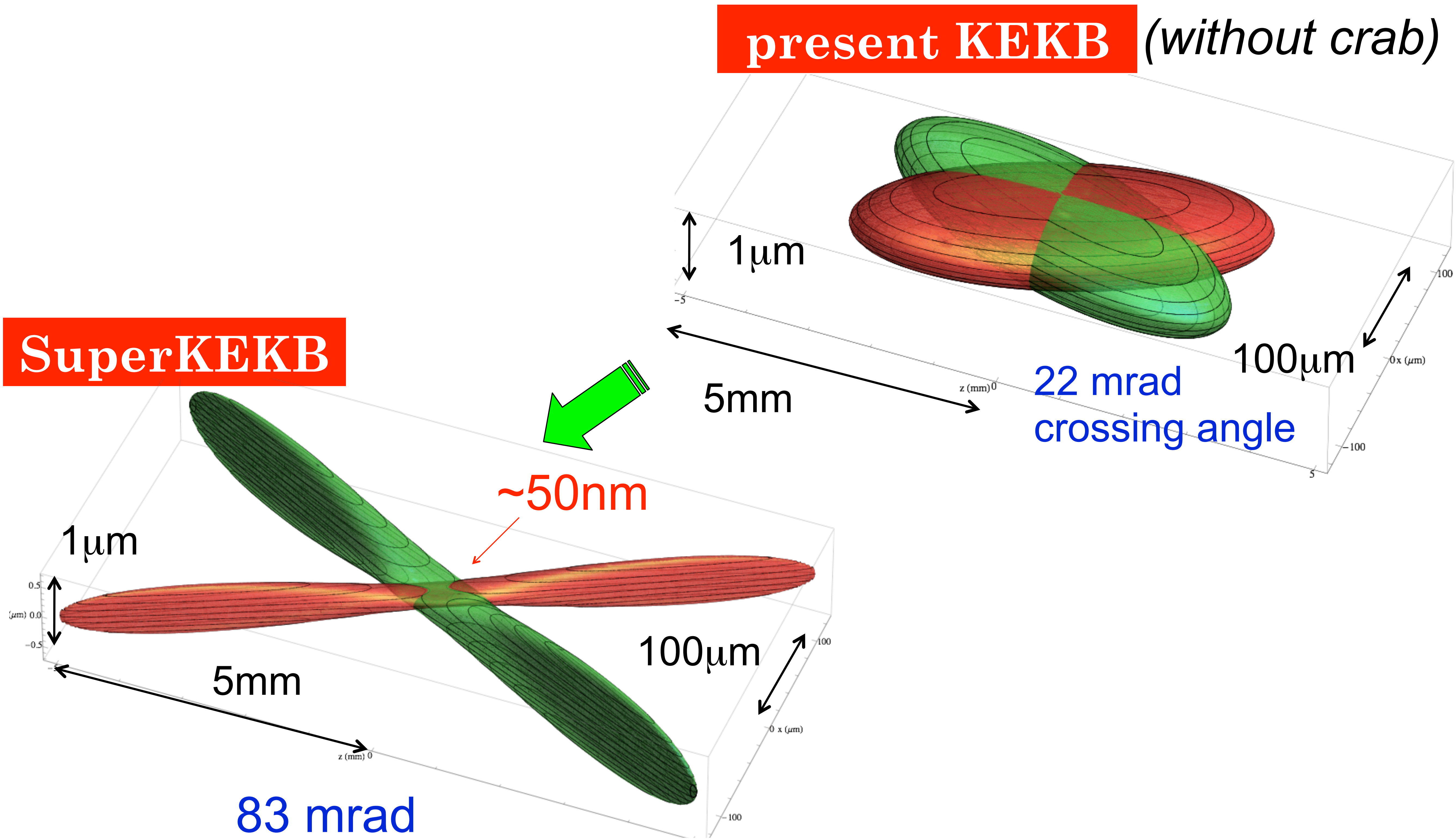
(3) Increase ξ_y

"Nano-Beam" scheme

Collision with very small spot-size beams

Invented by Pantaleo Raimondi for SuperB

Nano-Beam Scheme



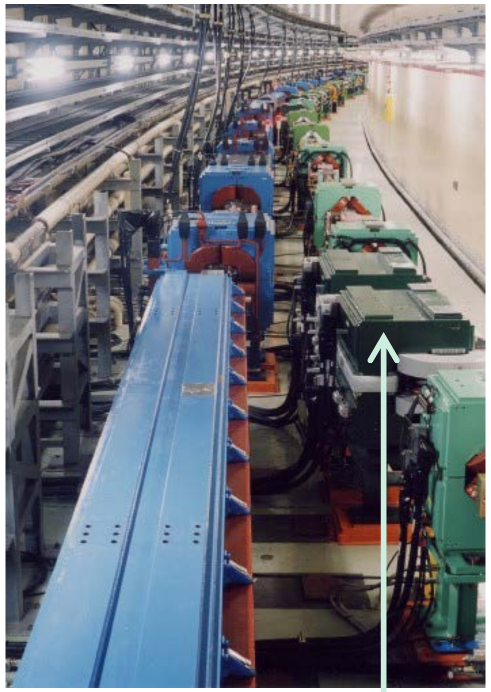
83 mrad
crossing angle

Machine design parameters

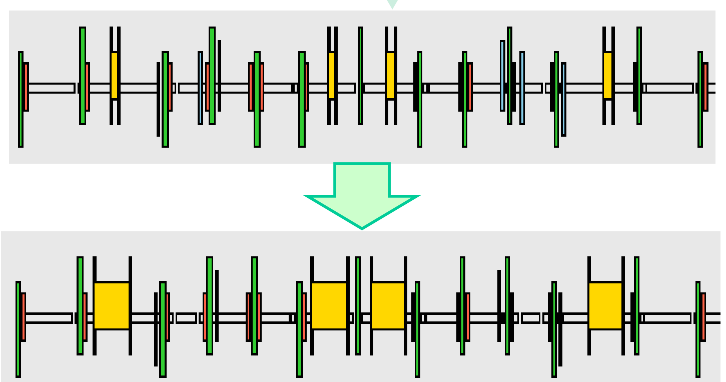
parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7	GeV
Half crossing angle	φ	11		41.5		mrad
Horizontal emittance	ε_x	18	24	3.2	4.6	nm
Emittance ratio	κ	0.88	0.66	0.37	0.40	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
Beam currents	I_b	1.64	1.19	3.60	2.60	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

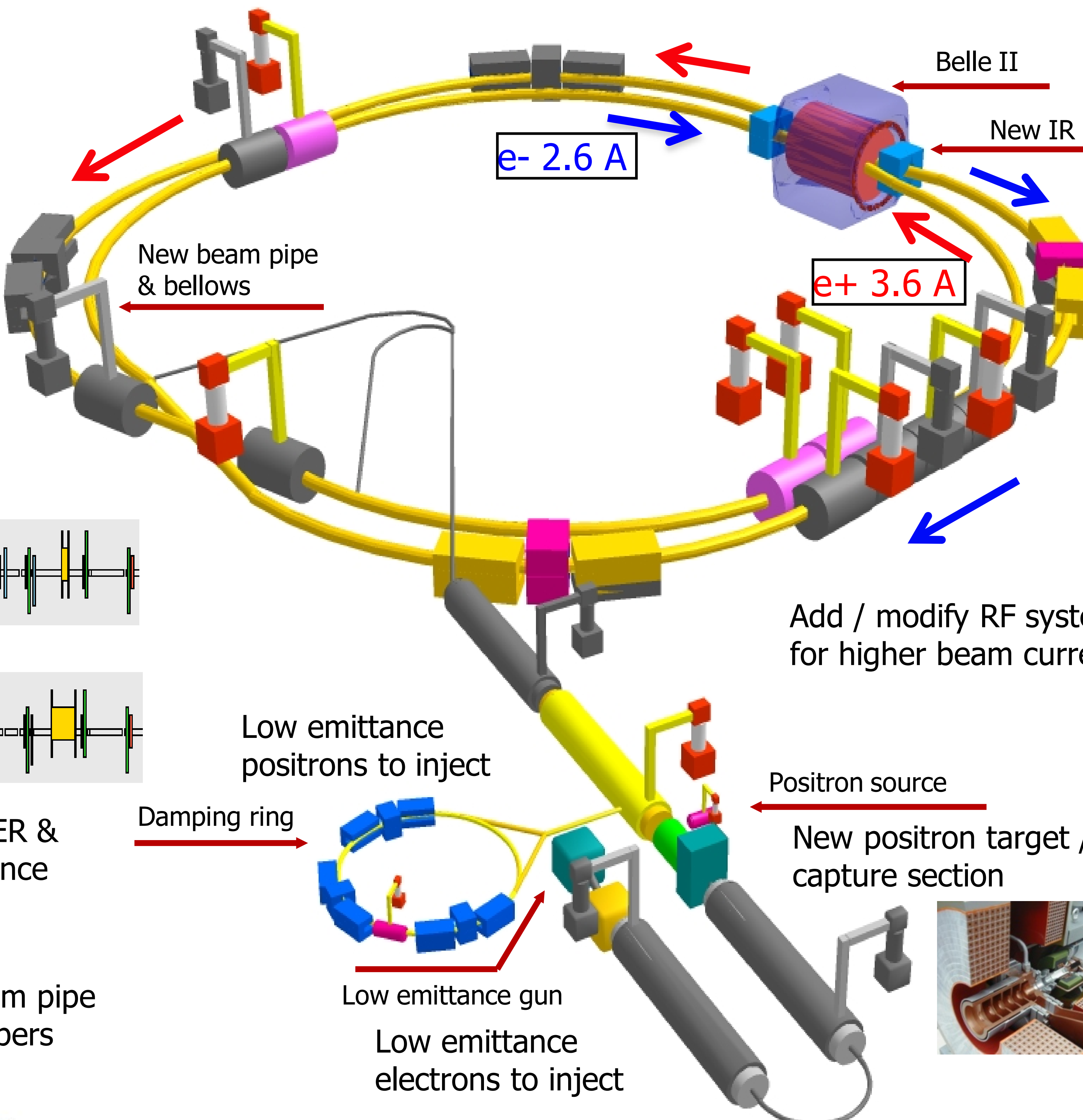
KEKB to SuperKEKB



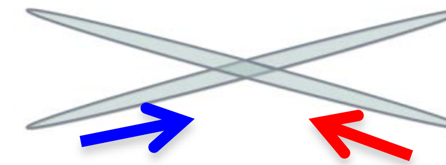
Replace short dipoles with longer ones (LER)



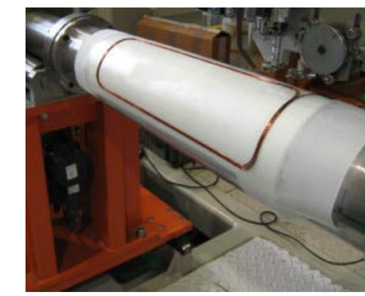
Redesign the lattices of HER & LER to squeeze the emittance



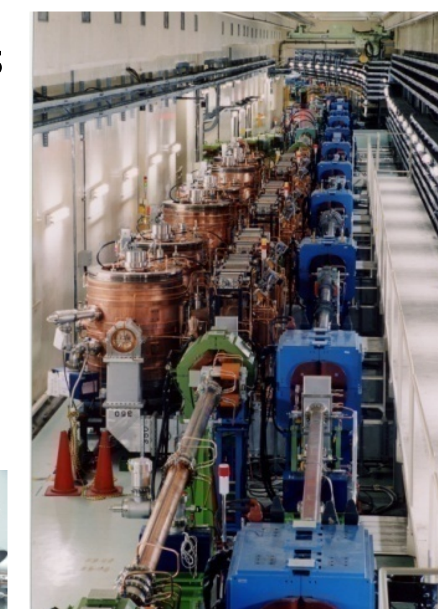
Colliding bunches



New superconducting /permanent final focusing quads near the IP



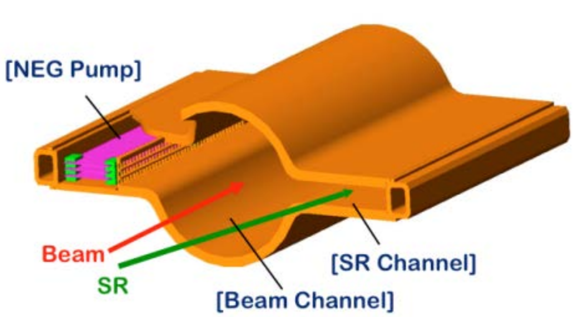
Add / modify RF systems for higher beam current



New positron target / capture section

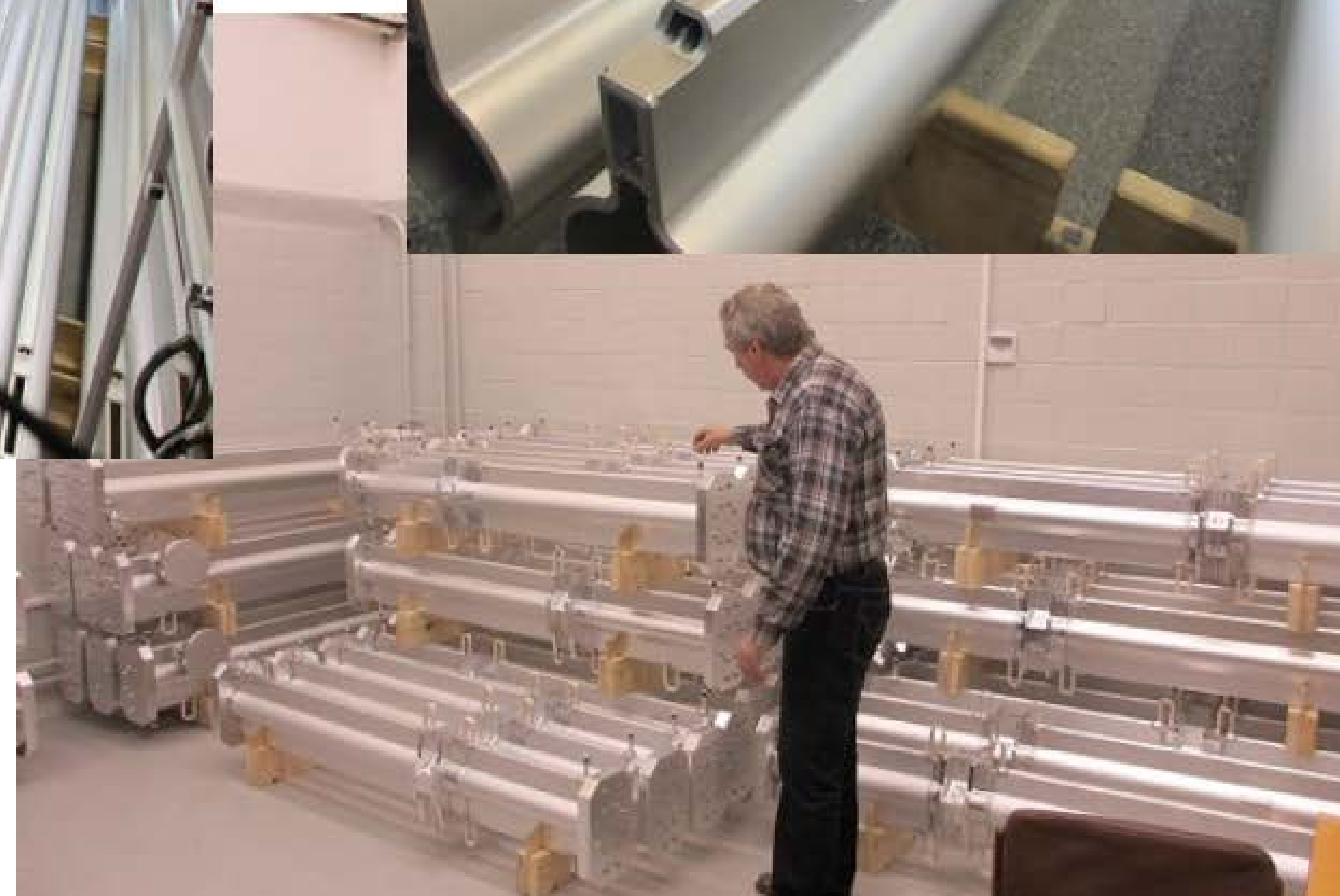
Low emittance electrons to inject

TiN-coated beam pipe with antechambers



To obtain x40 higher luminosity

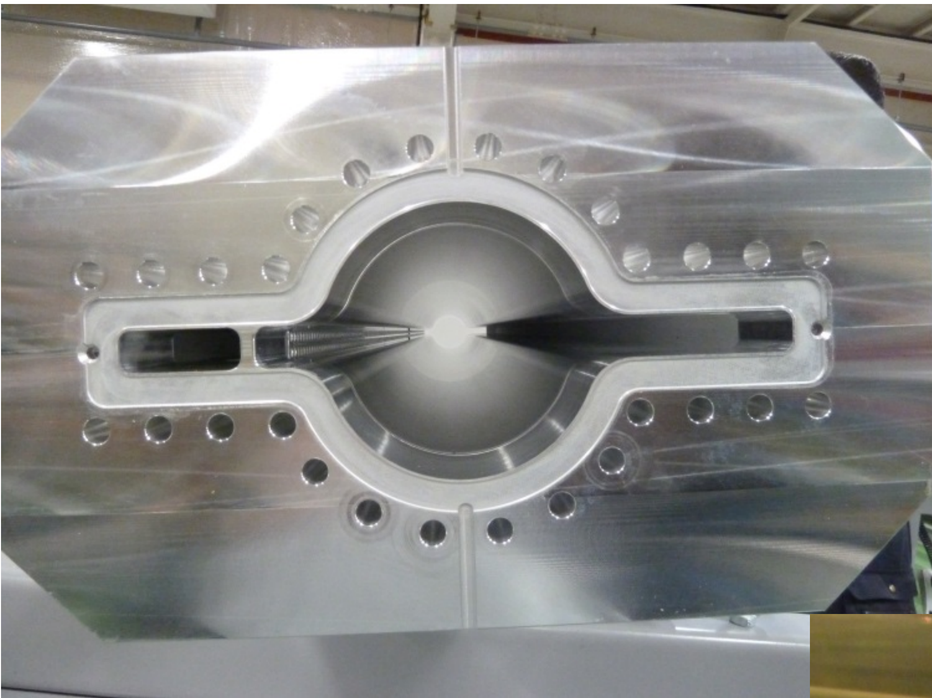
Entirely new LER beam pipe with ante-chamber and Ti-N coating

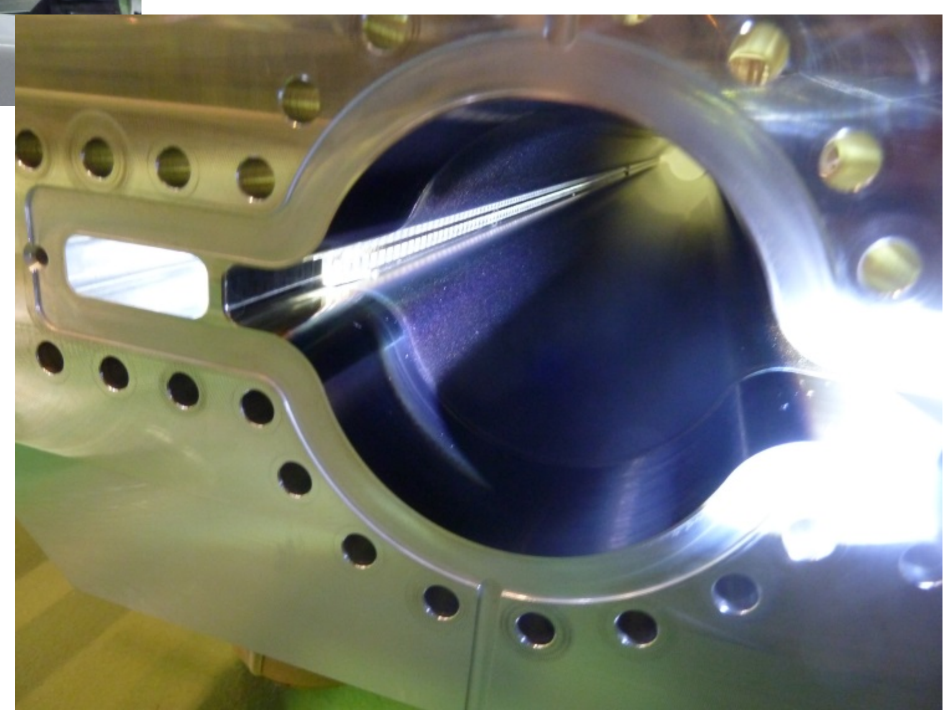


Beam pipe is made of aluminum.

Fabrication of the LER arc beam pipe section is completed

Al ante-chamber before coating





After TiN coating
before baking

After baking

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

Three magnets per day !

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

Magnet installation

field measurement

move into tunnel

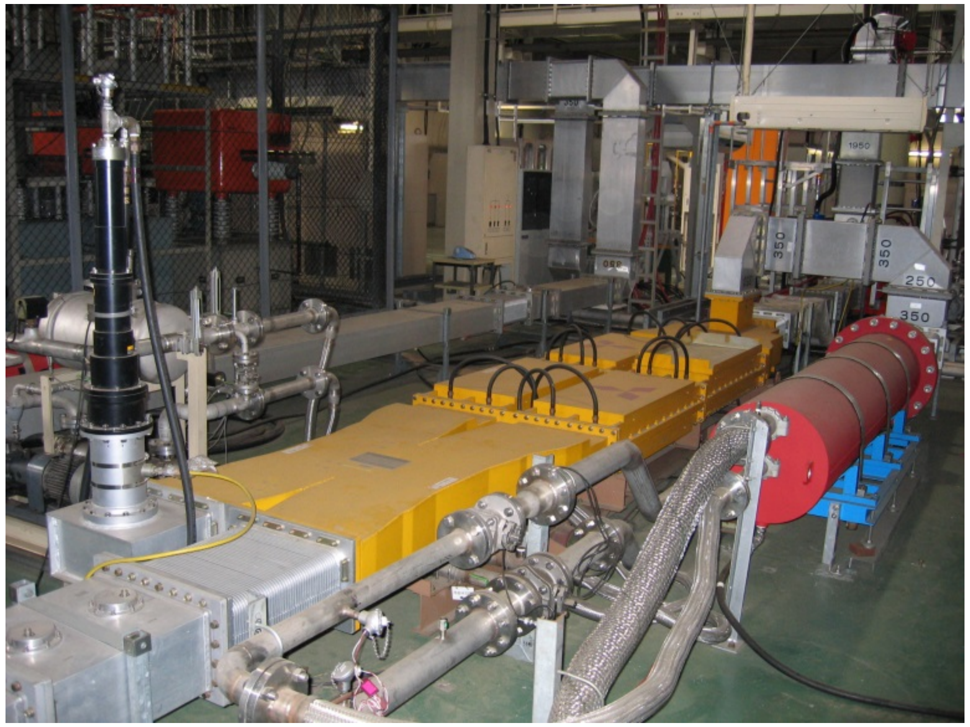
Installation of 100 new LER bending magnets done

carry on an air-pallet

carry over existing HER dipole

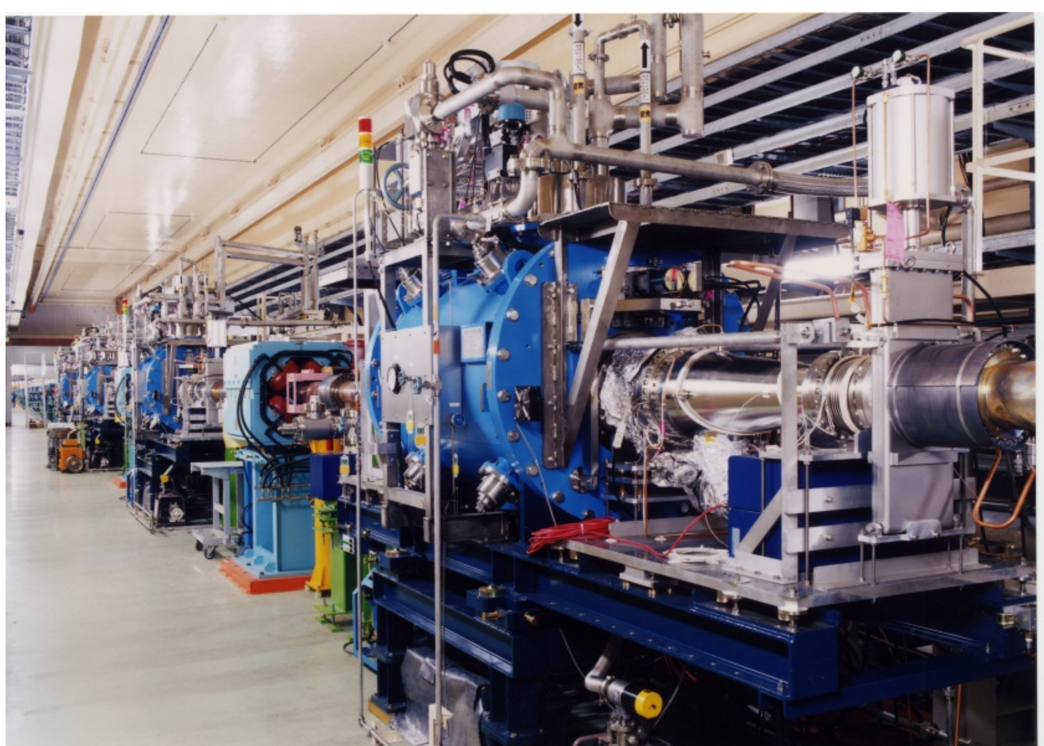
install done

Upgrade of RF system to cope with twice beam currents and 2.5 times beam power



RF high power system

1.2 MW CW klystron



Superconducting cavities

Six ARES cavities in D5 moved from HER to LER. HER wiggler magnets were installed close to the ARES.

Positron Damping Ring (new)

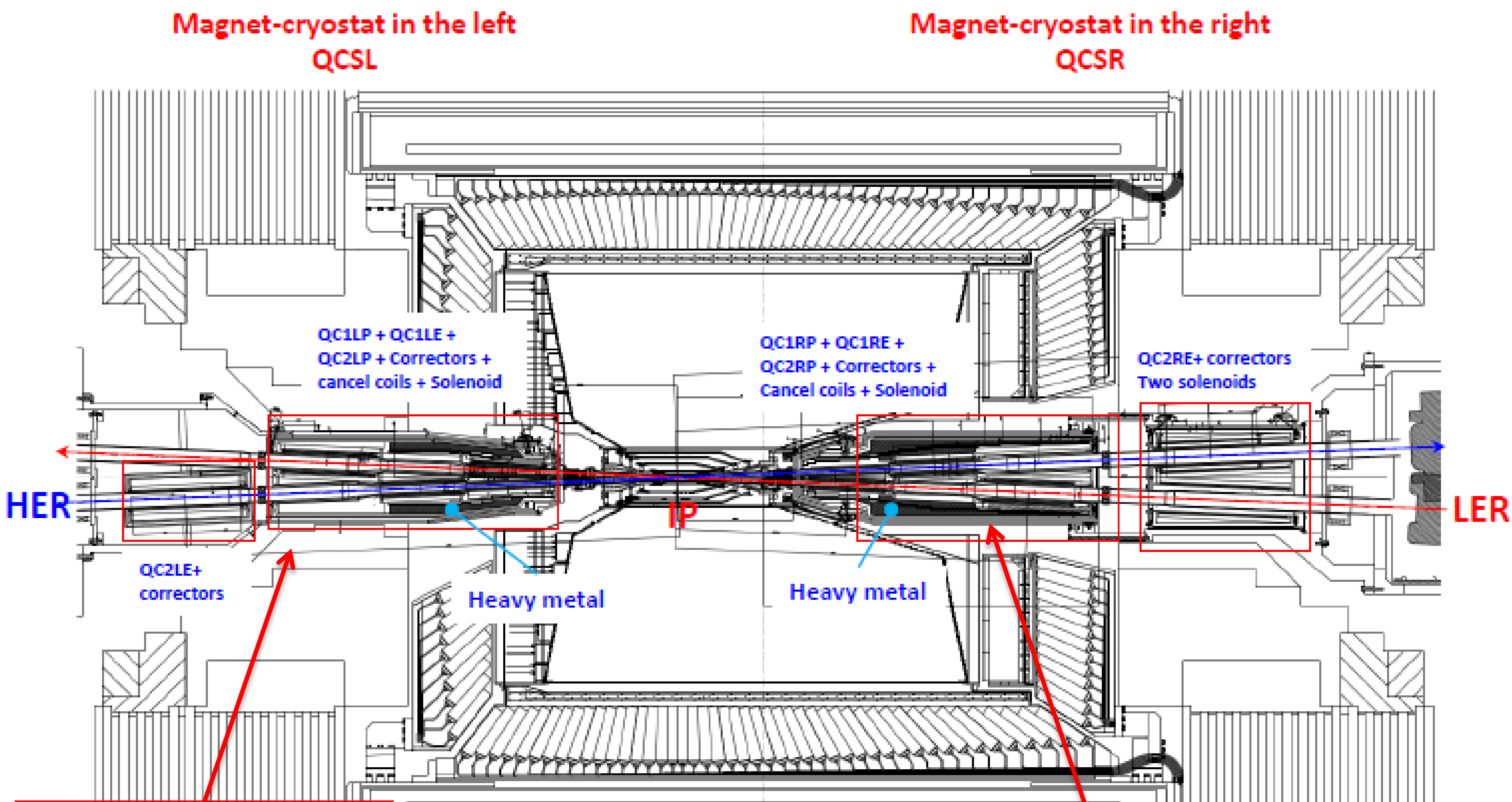
DR under construction on 18/Dec/2012

- Tunnel construction under way in 2012-13; half year delay due to budget suspend caused by the earthquake.
- Construction of buildings for DR will start in April this year.
- Fabrication of accelerator components ongoing. Installation starts in 2014.
- DR commissioning will start in 2015.

Inside DR tunnel

Now DR has been buried.

IR magnets overview

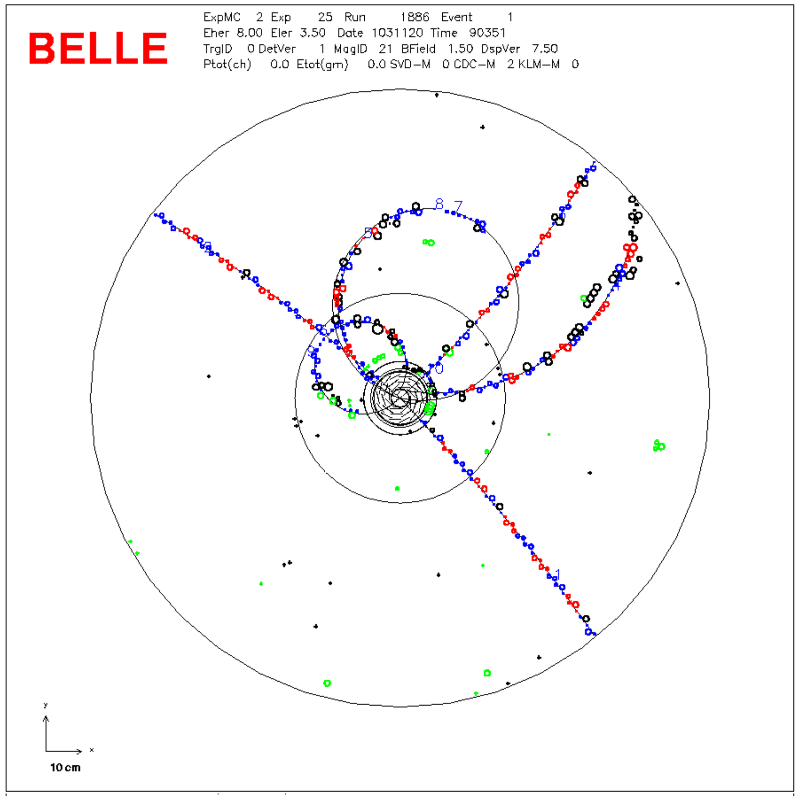


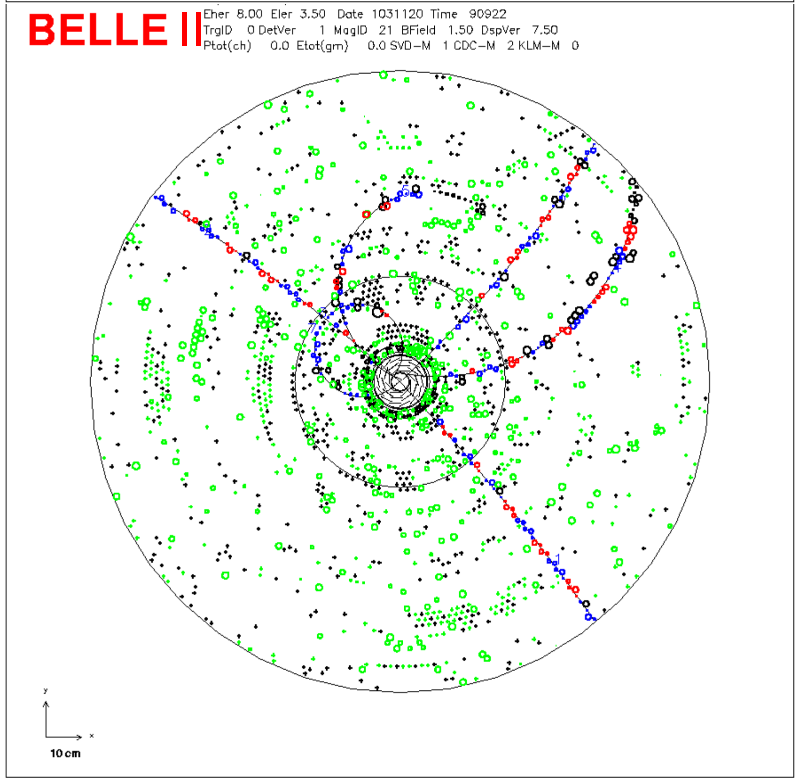
in production

design being finalized
→in production from summer

Experimental Challenges at High Luminosity

- High background (10-20 times higher than at Belle)
  - Fake hits, pile up, radiation damage
- Higher trigger rate
  - Typical Level1 trigger rate: 20kHz
  - High performance DAQ
- Important improvements
  - Hermeticity for full reconstruction analyses
  - IP and secondary vertex resolution
  - K_S and π^0 identification efficiency
  - Improve Kaon/pion separation
- Details in TDR *arXiv:1011.0352*



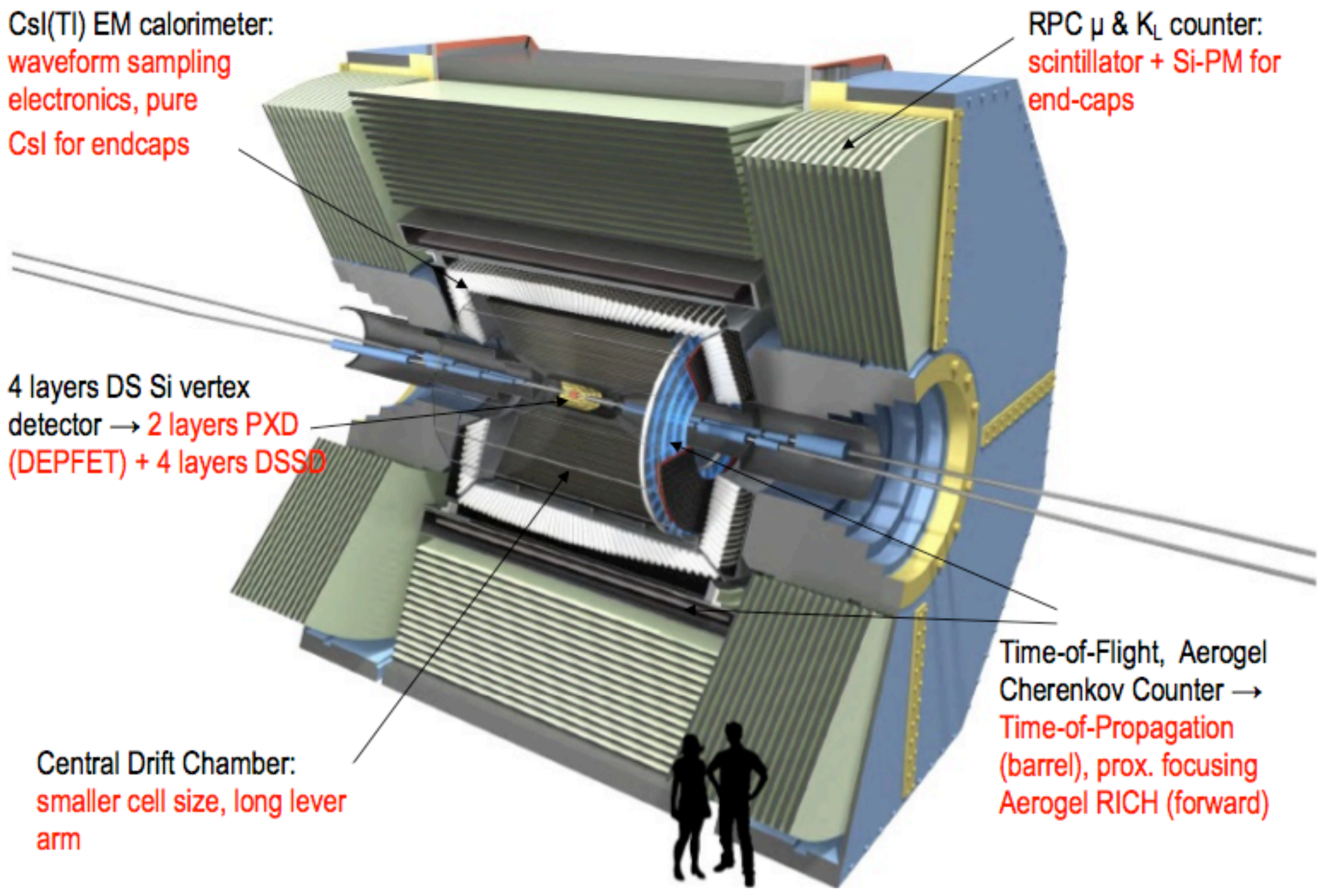


Belle II detector

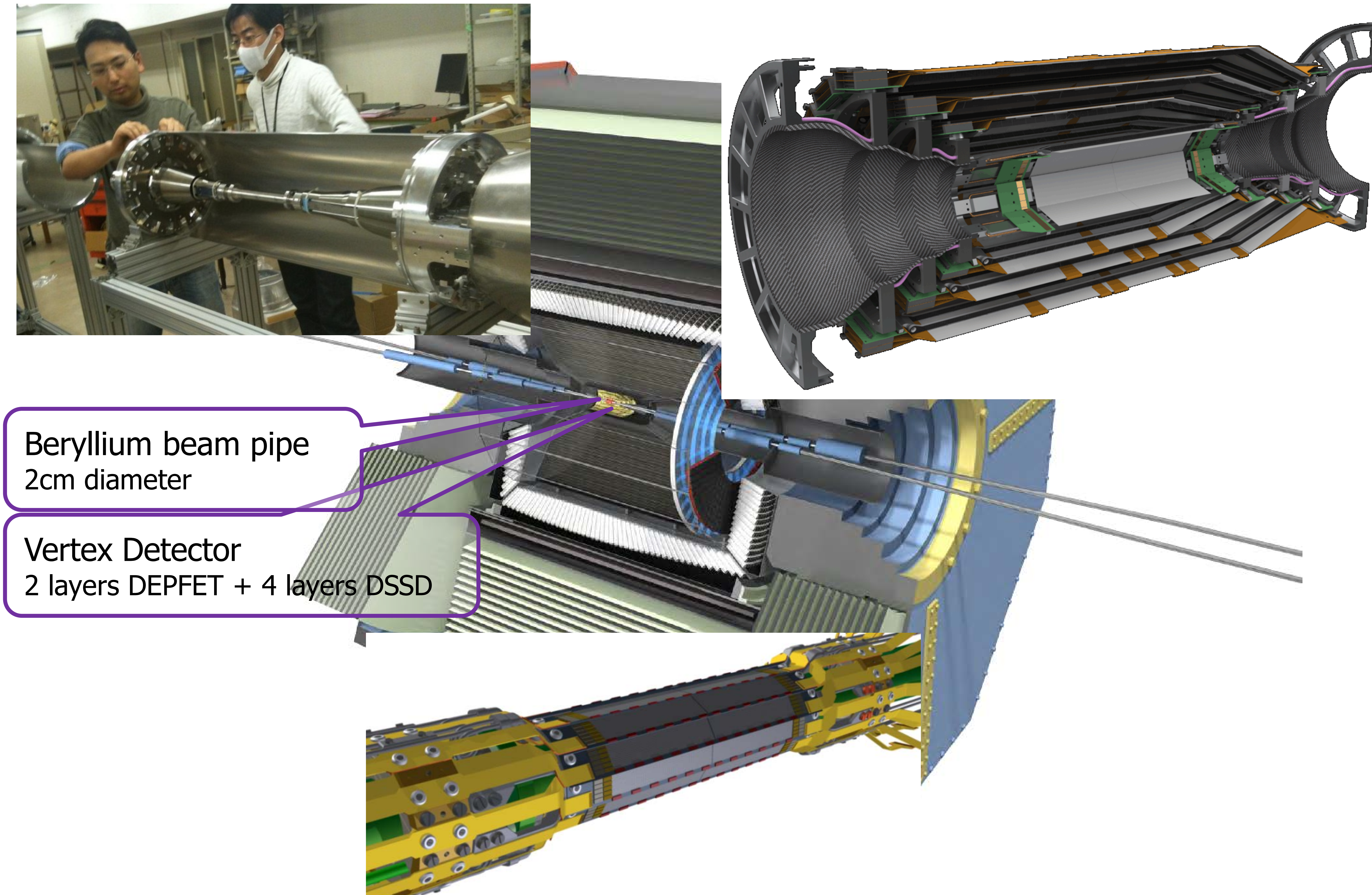
Higher backgrounds (× 20) ⇒ higher occupancy, radiation damage

Higher event rate ⇒ faster trigger, DAQ, computing

Special requirements, e.g. low-momentum μ ID (b→sμμ), hermeticity (ν reco.)

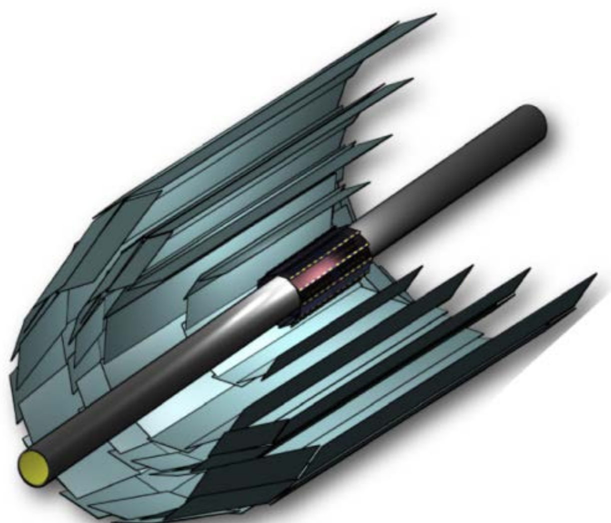


Belle II Detector – vertex region

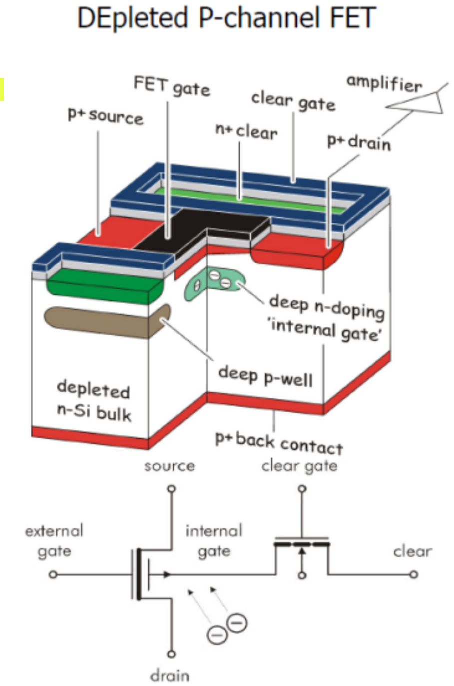


Vertex Detector

DEPFET:
http://aldebaran.hll.mpg.de/twiki/bin/view/DEPFET/WebHome

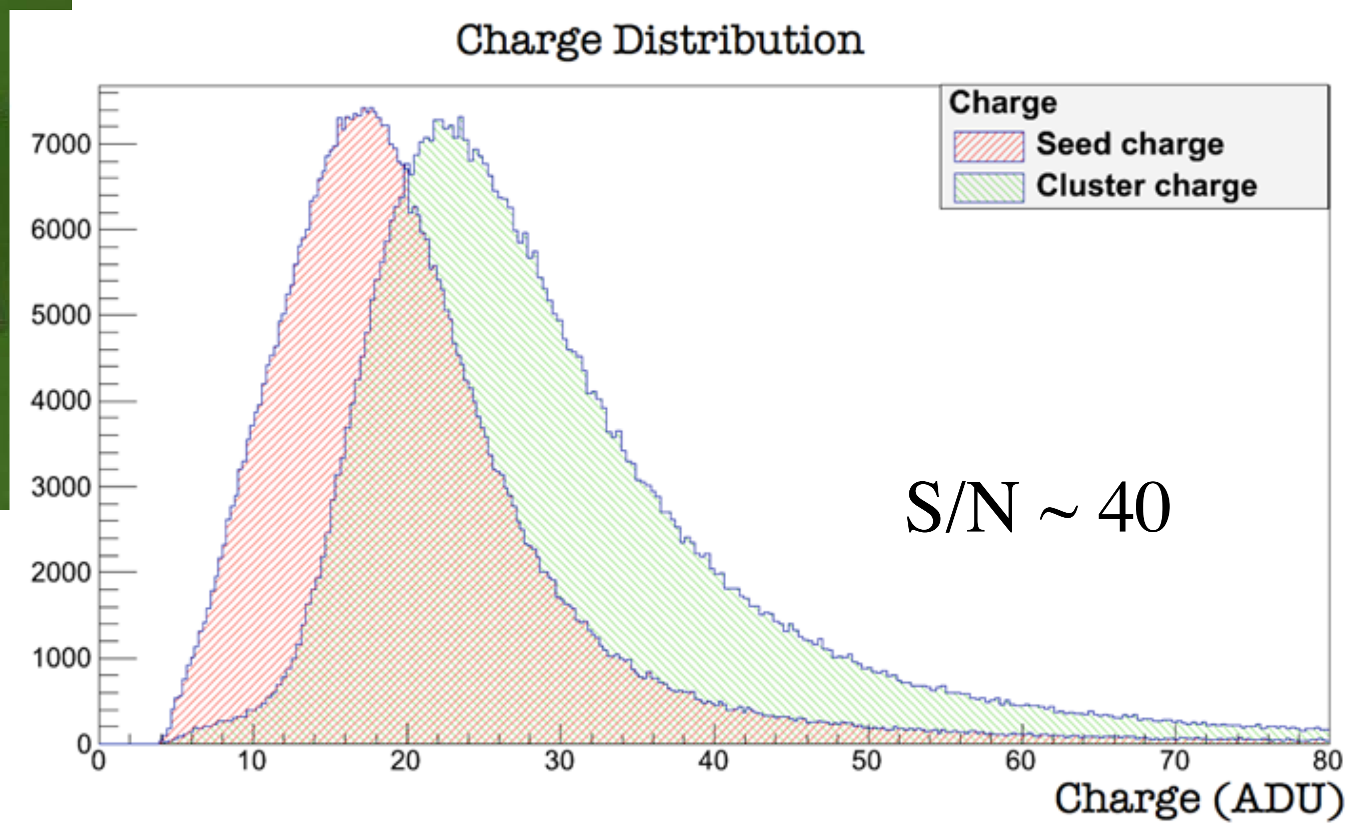


Beam Pipe		**r = 10mm**
DEPFET		
	Layer 1	**r = 14mm**
	Layer 2	**r = 22mm**
DSSD		
	Layer 3	**r = 38mm**
	Layer 4	**r = 80mm**
	Layer 5	**r = 115mm**
	Layer 6	**r = 140mm**



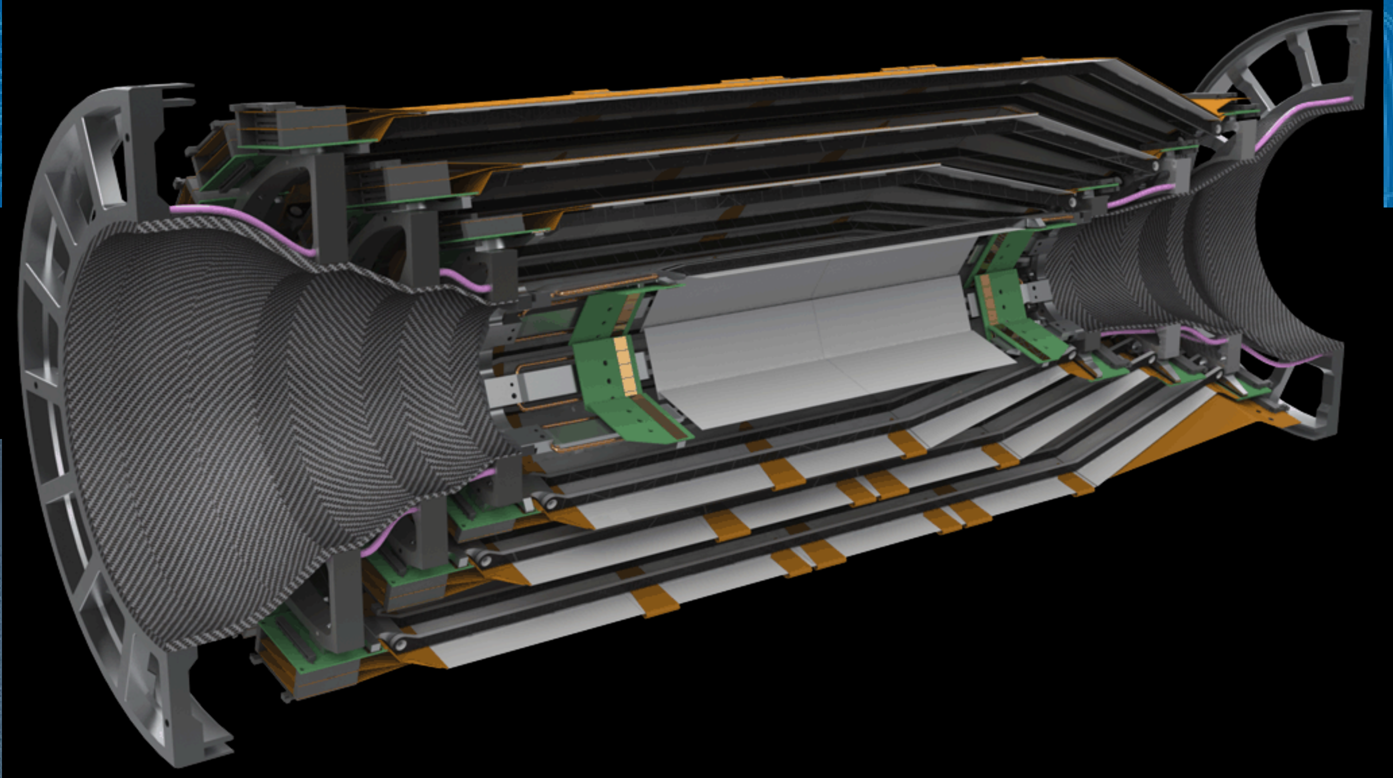
Mechanical mockup of pixel detector

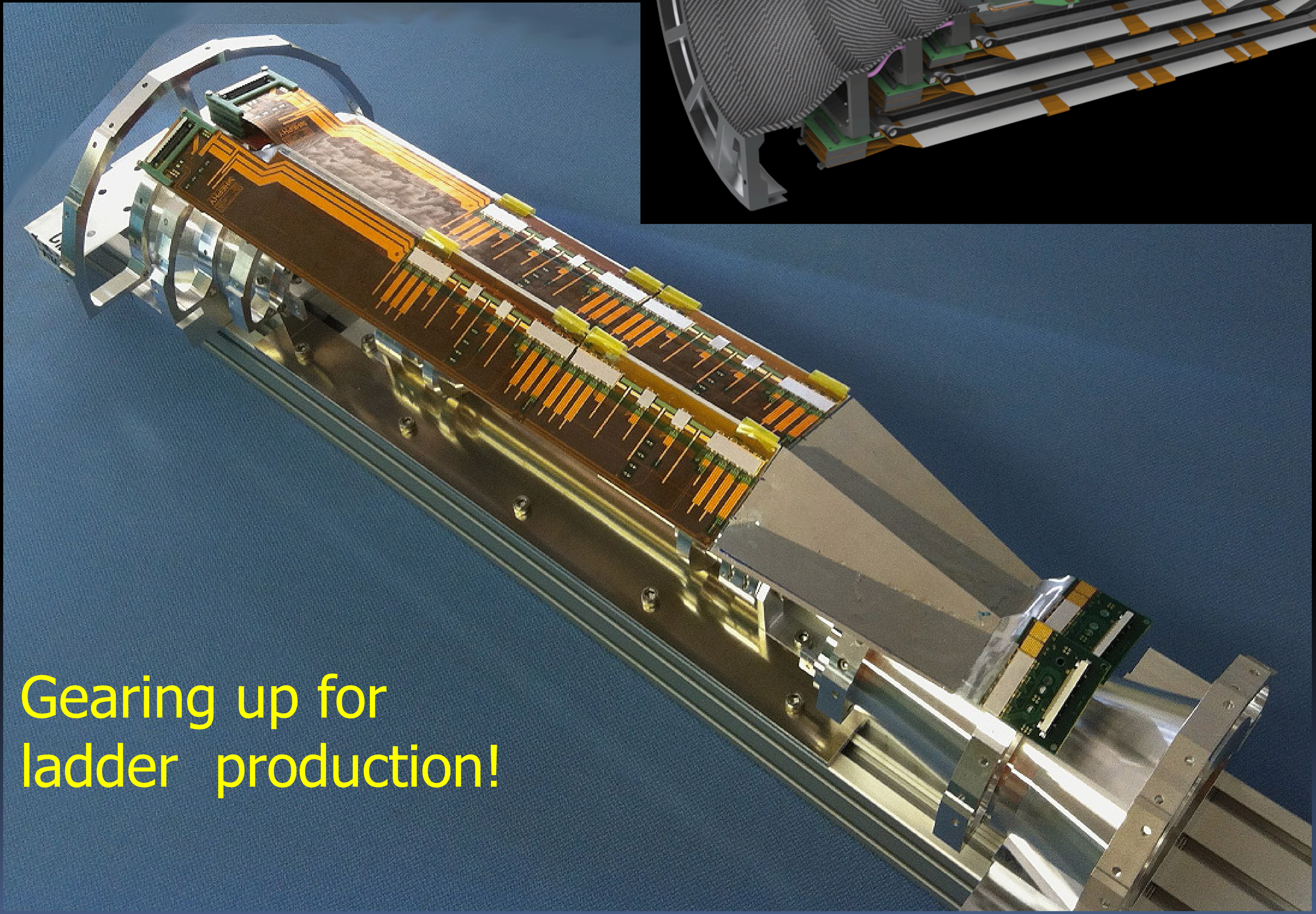
DEPFET pixel sensor



DEPFET sensor: very good S/N

SVD Mechanical Mockup



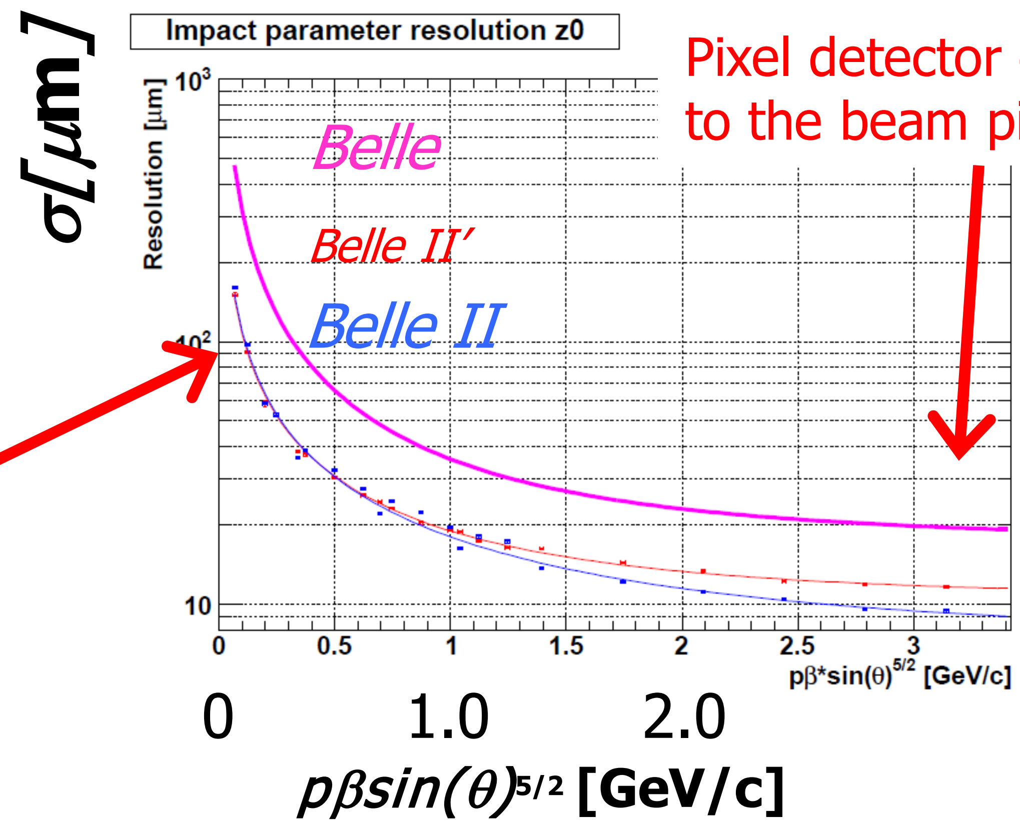


Gearing up for ladder production!

Expected performance

$$\sigma = a + \frac{b}{p\beta \sin^{\nu}\theta}$$

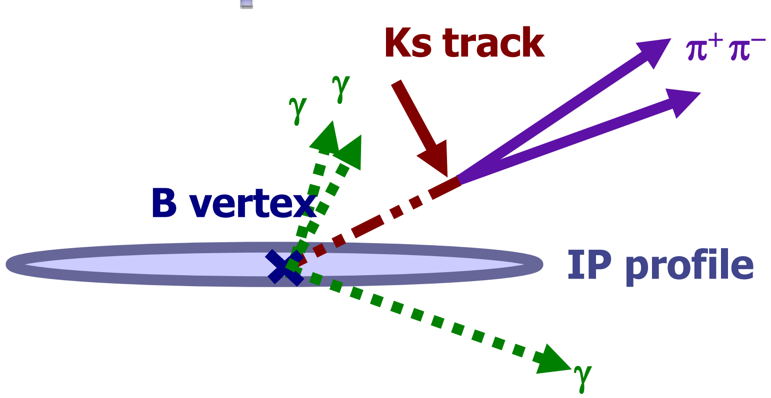
Significant improvement in vertex resolution!



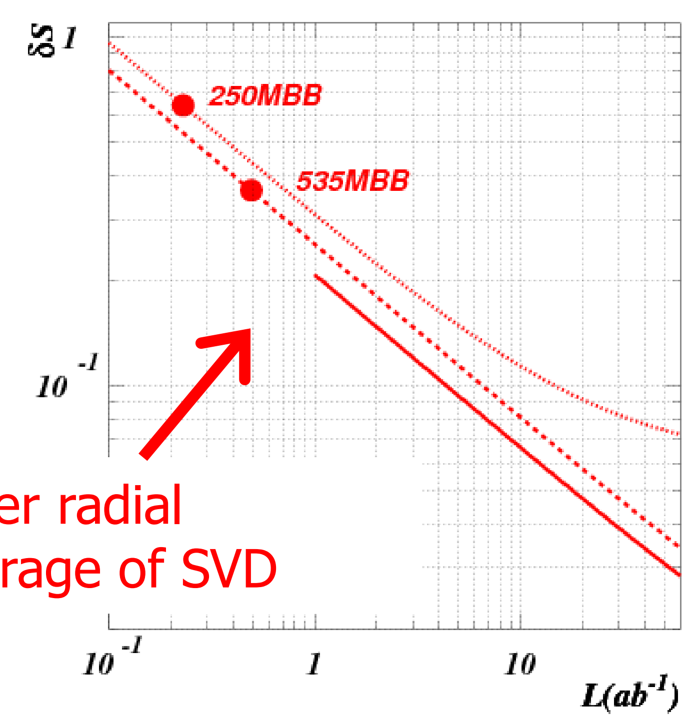
Pixel detector close to the beam pipe

Less Coulomb scattering

Significant improvement in $\delta S(K_S\pi^0\gamma)$

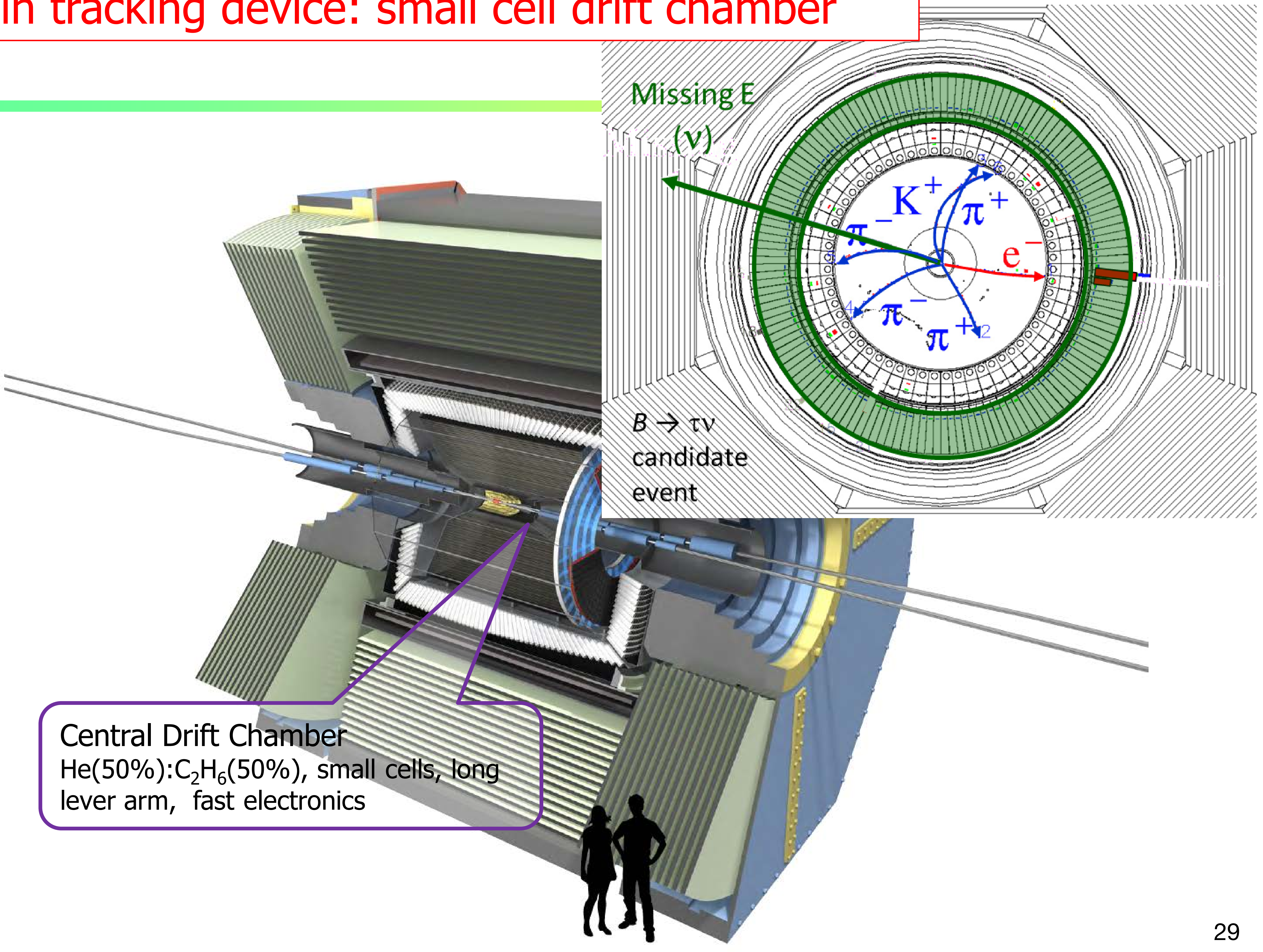


B decay point reconstruction with K_S trajectory



Larger radial coverage of SVD

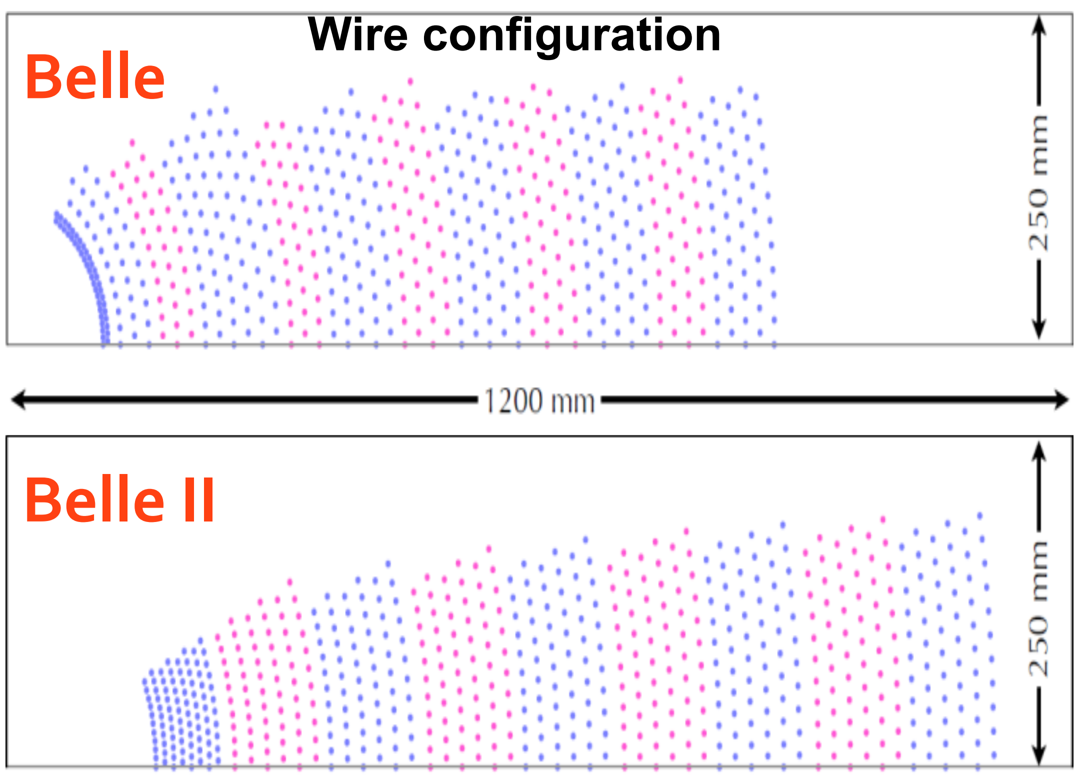
Main tracking device: small cell drift chamber

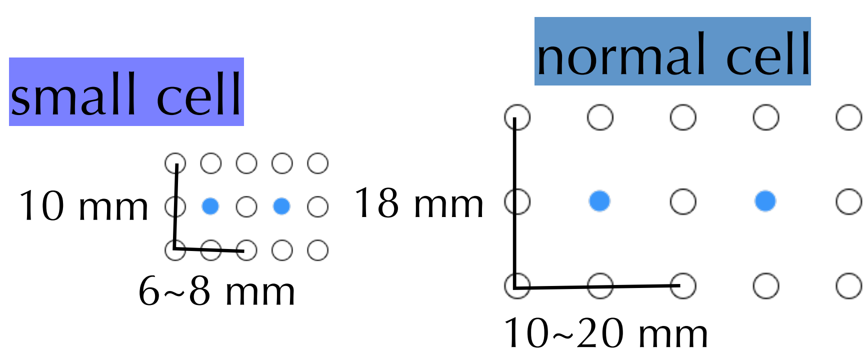


Central drift chamber

- **Extended** outer radius
- **Smaller cells** near beampipe
- **Faster** readout electronics

⇒ **Improved p and dE/dx resolution**



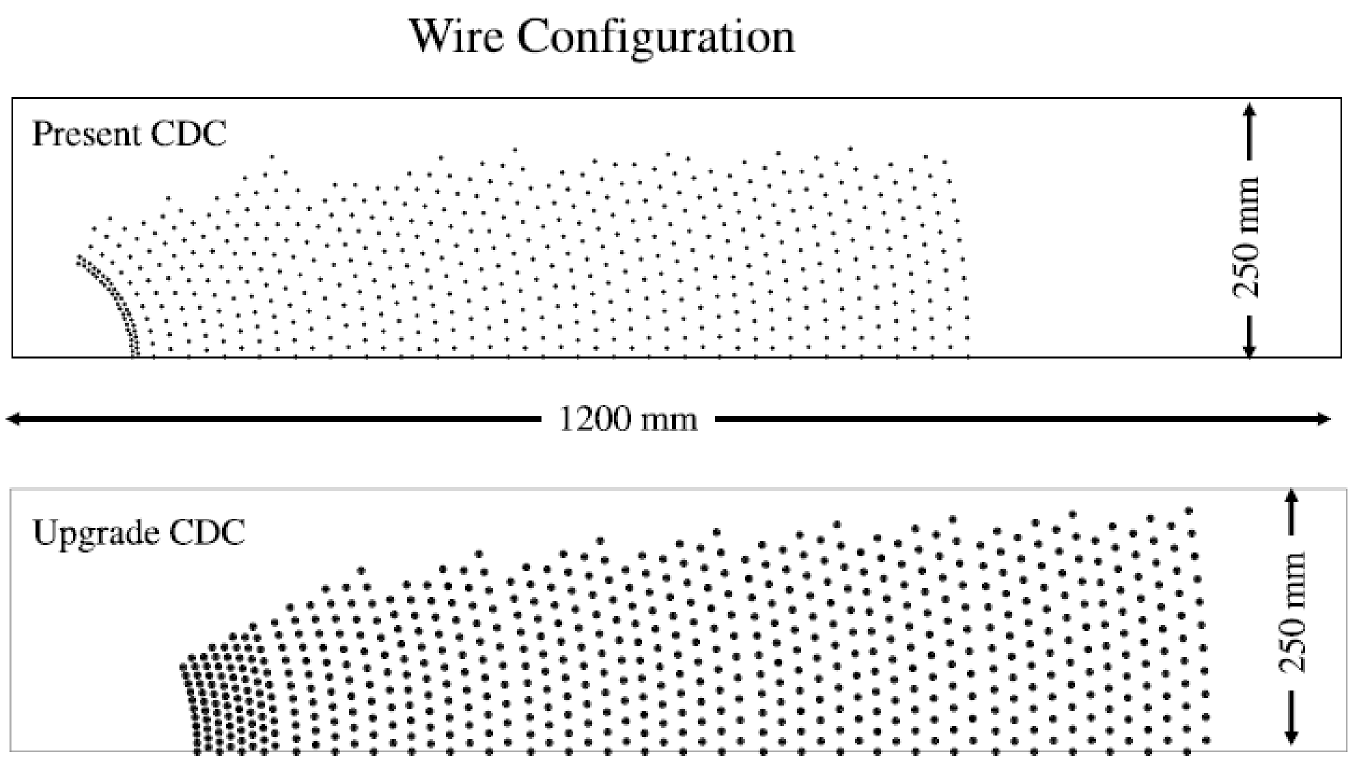


$\sigma_p/p \sim 0.3\% + 0.1\% \times p(\text{GeV})$ in B=1.5T

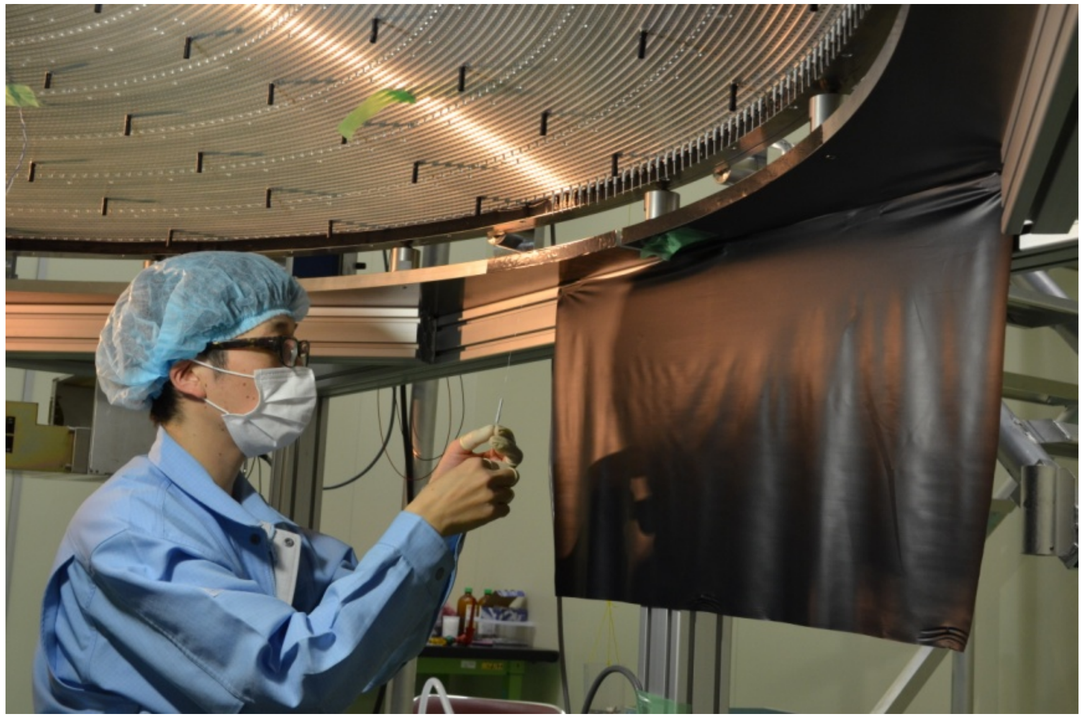
$\sigma\,(\mathrm{d}E/\mathrm{d}x) \sim 6\%$

	Belle	Belle II
Innermost sense wire	r=88mm	r=168mm
Outermost 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)

Belle II CDC



Much bigger than in Belle!

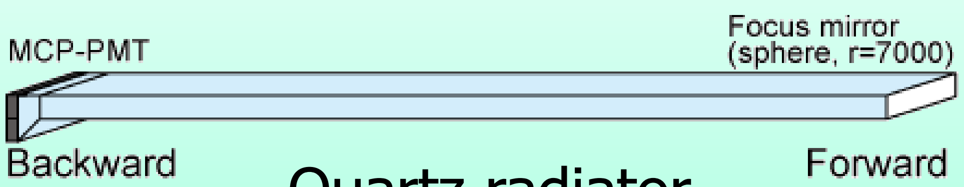


Wire stringing in a clean room

- thousands of wires,
- 1 year of work...

Particle Identification Devices

Barrel PID: Time of Propagation Counter (TOP)



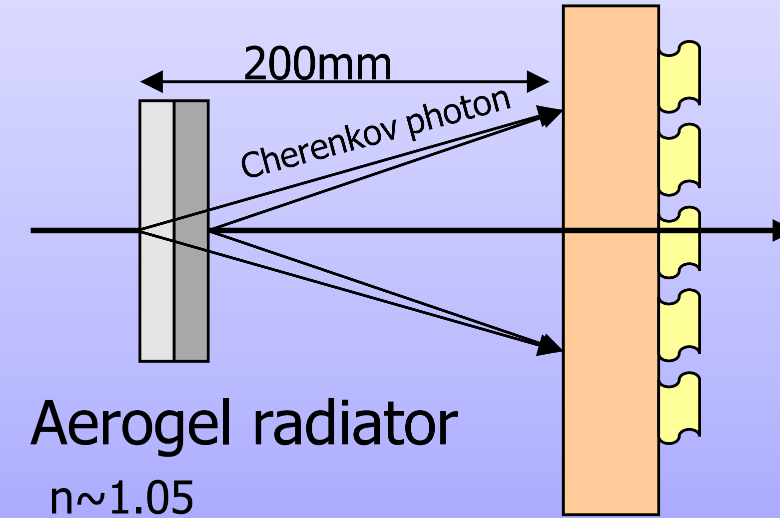
Quartz radiator

Focusing mirror

Small expansion block

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

Endcap PID: Aerogel RICH (ARICH)

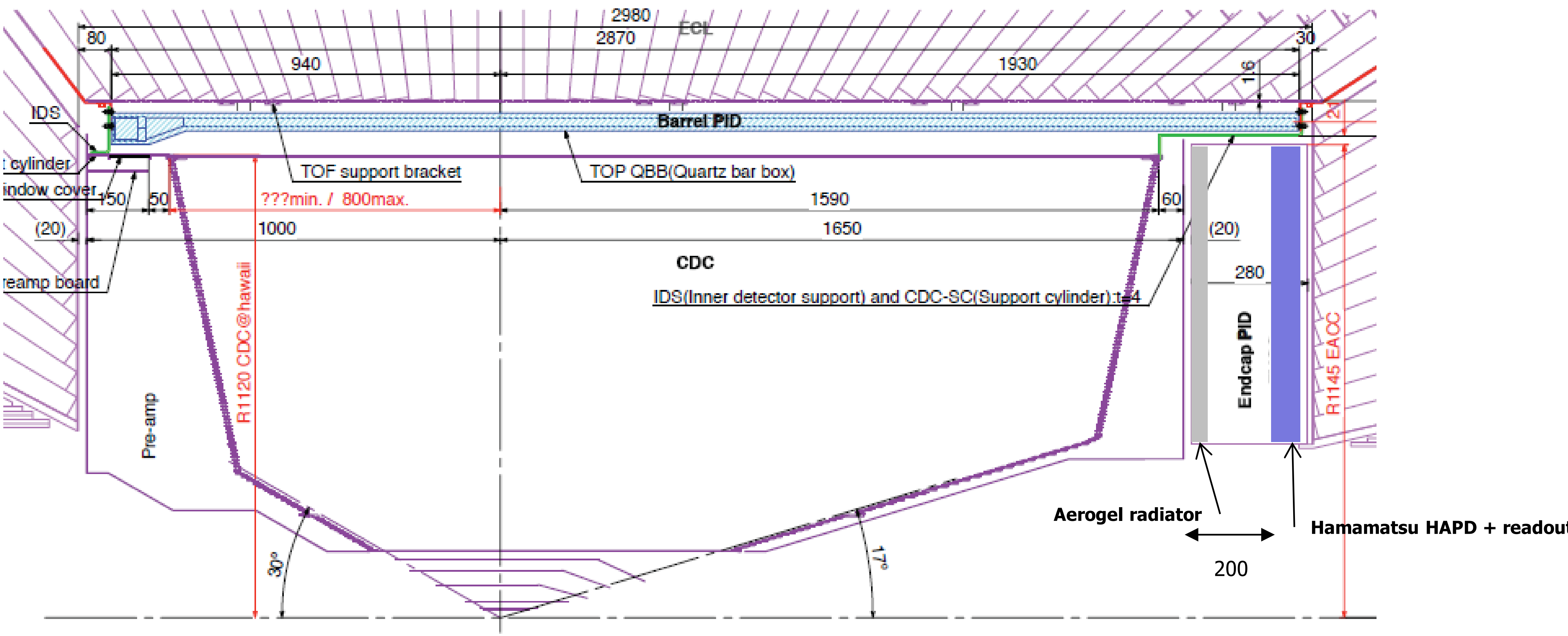


Aerogel radiator

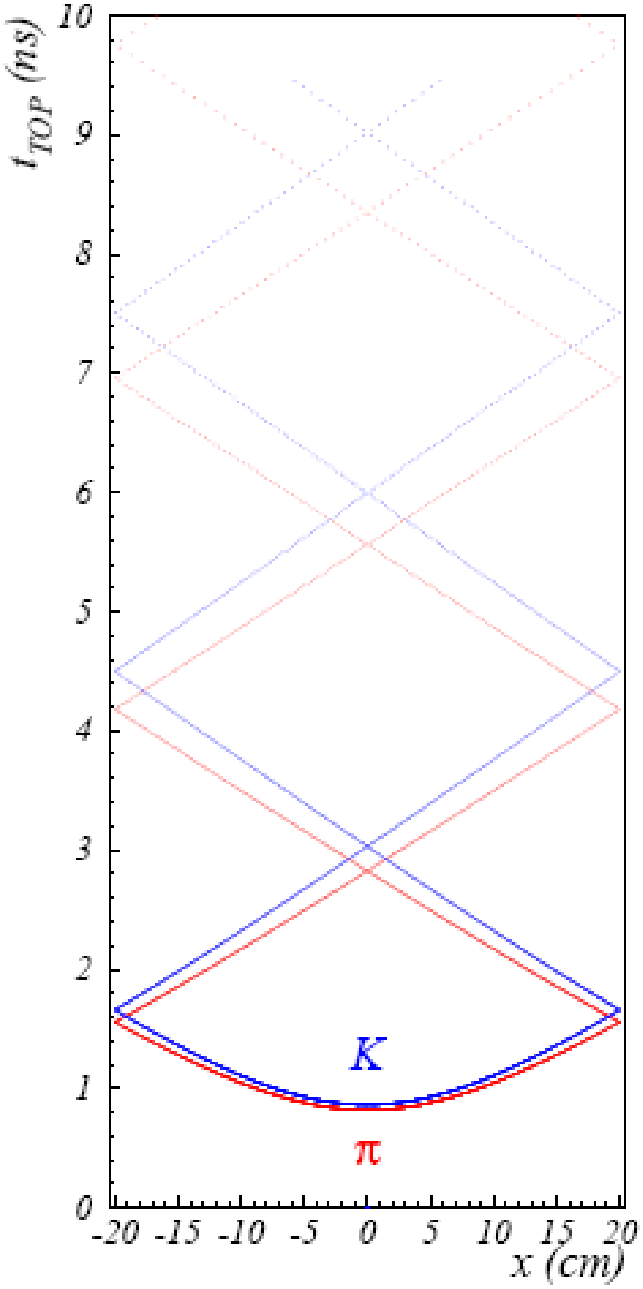
n~1.05

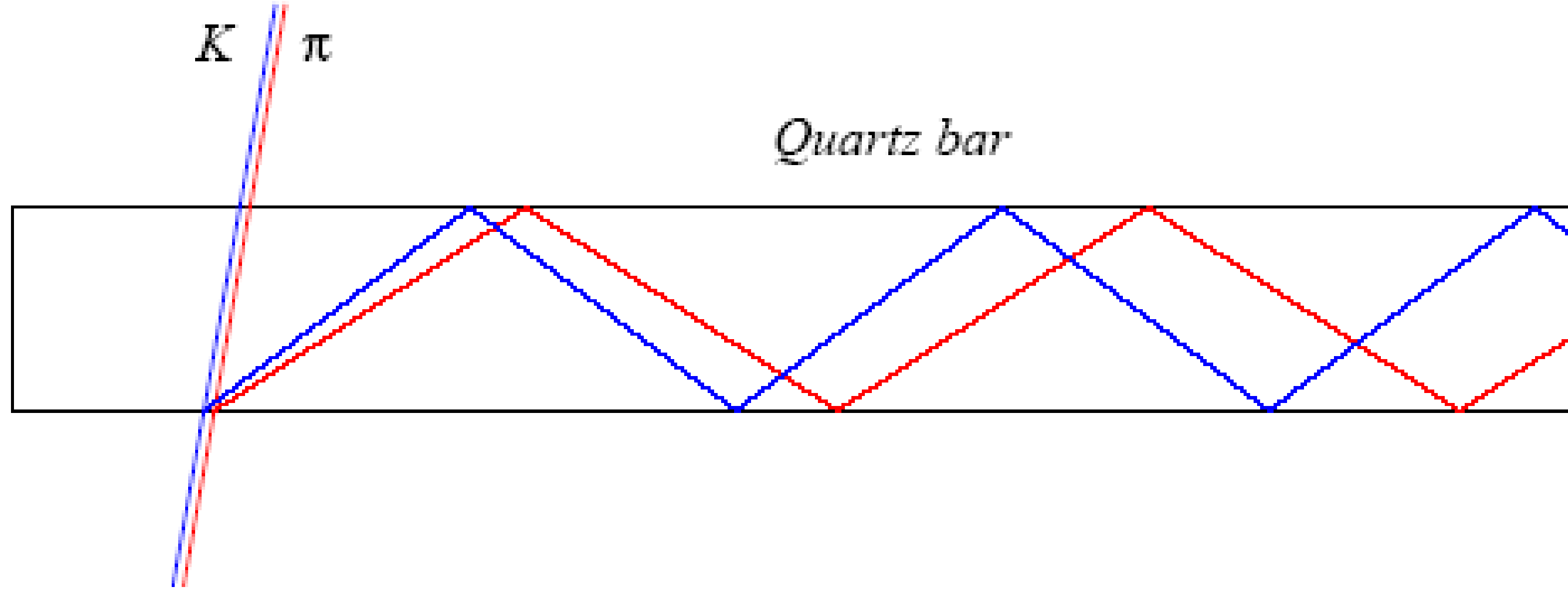
Hamamatsu HAPD

+ new ASIC

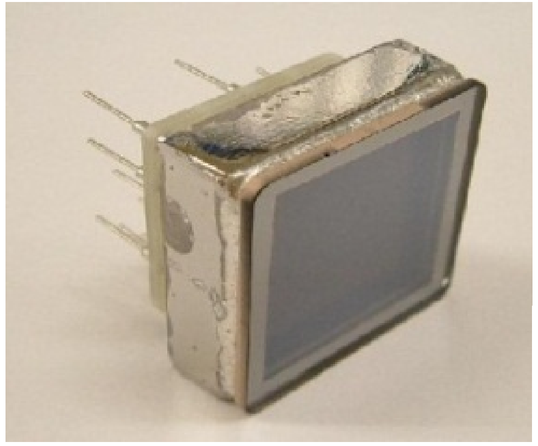


Barrel PID: Time of propagation (TOP) counter

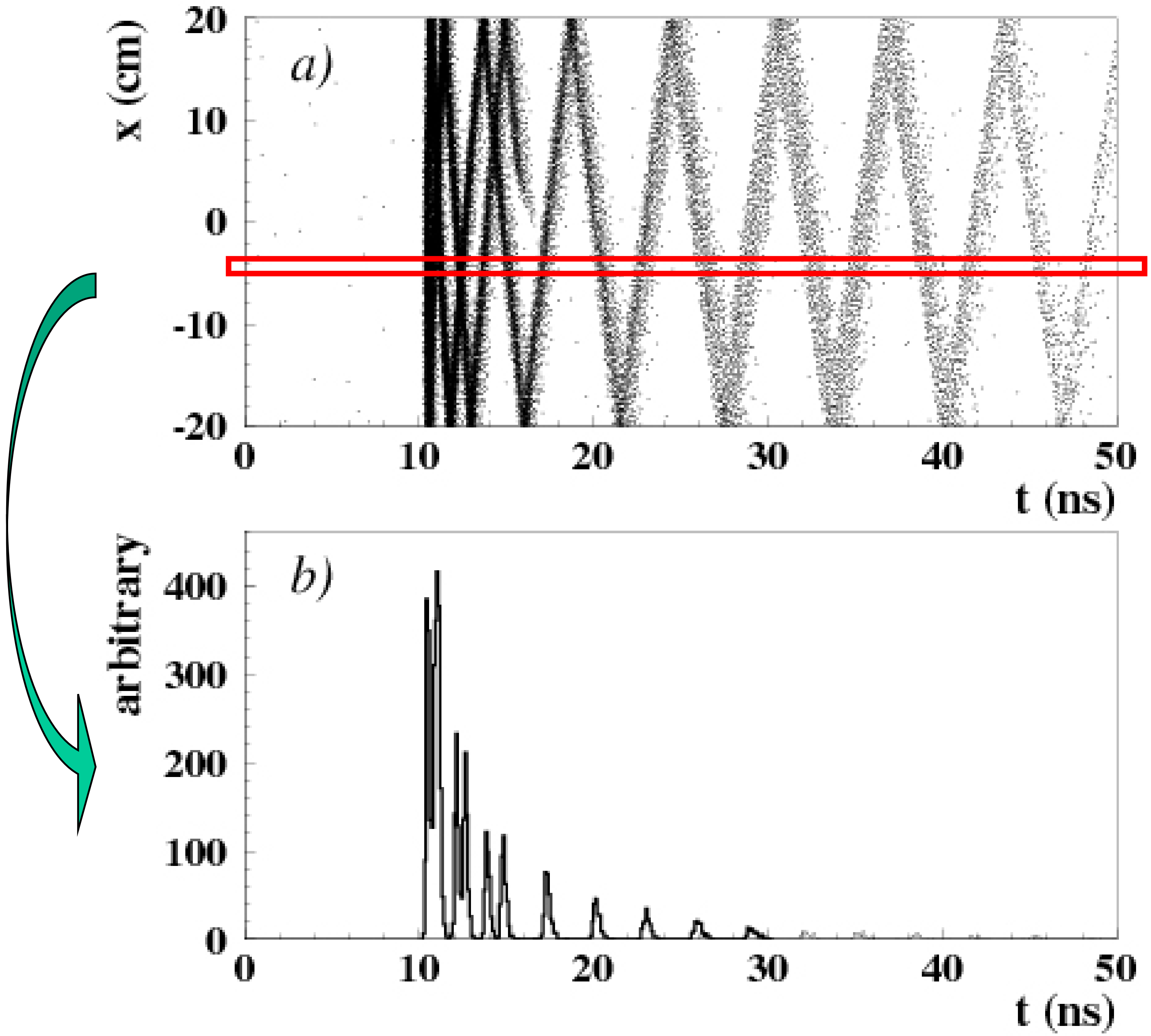




- Cherenkov ring imaging with precise time measurement.
- Device uses internal reflection of Cerenkov ring images from quartz like the BaBar DIRC
- Reconstruct Cherenkov angle from two hit coordinates and the time of propagation of the photon
  - Quartz radiator (2cm)
  - Photon detector (MCP-PMT)
    - Good time resolution ~ 40 ps
    - Single photon sensitivity in 1.5 T field
    - Hamamatsu SL10



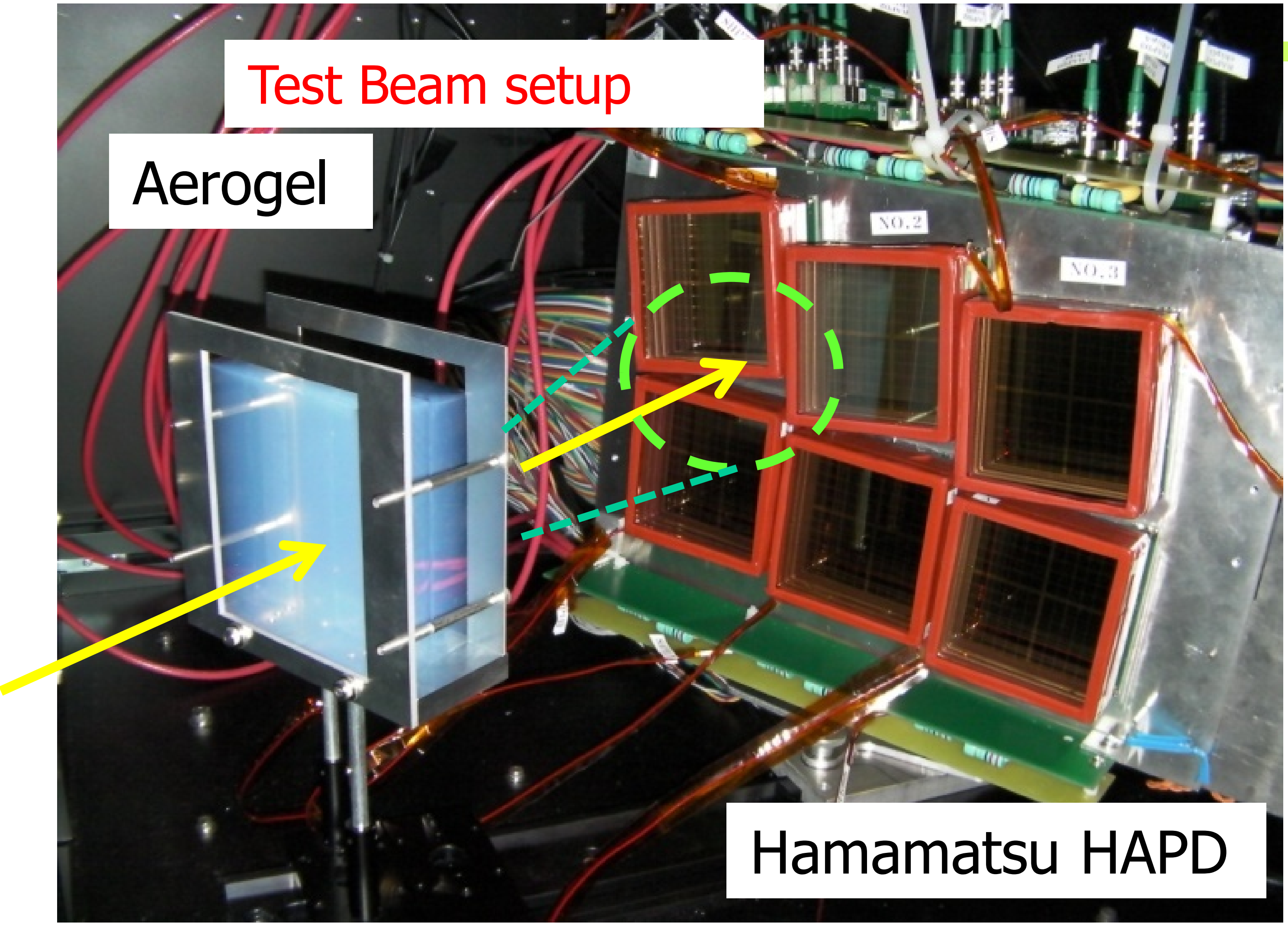
TOP image

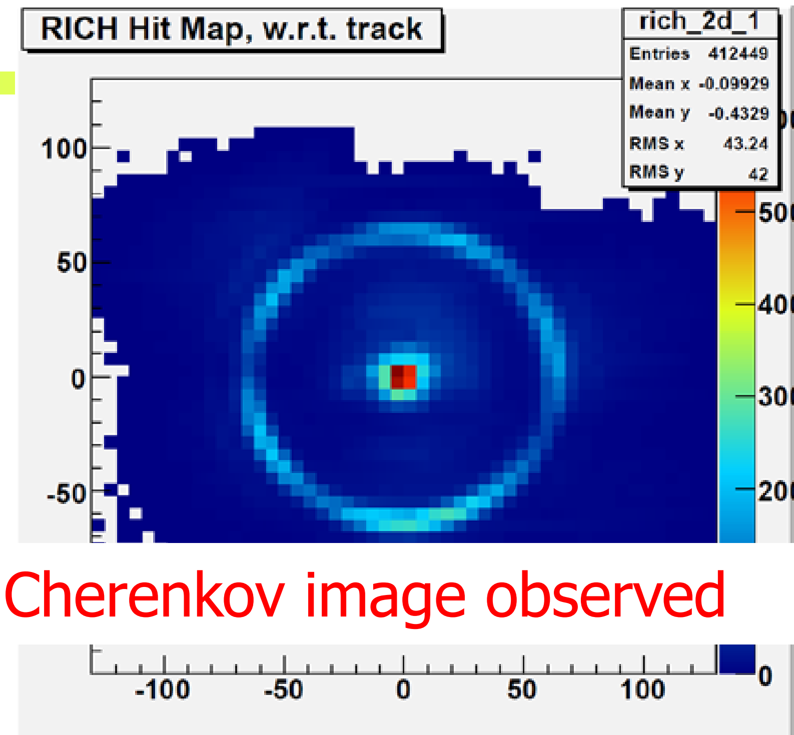


Pattern in the coordinate-time space (‘ring’) of a pion hitting a quartz bar with ~80 MAPMT channels

Time distribution of signals recorded by one of the PMT channels: different for π and K (~shifted in time)

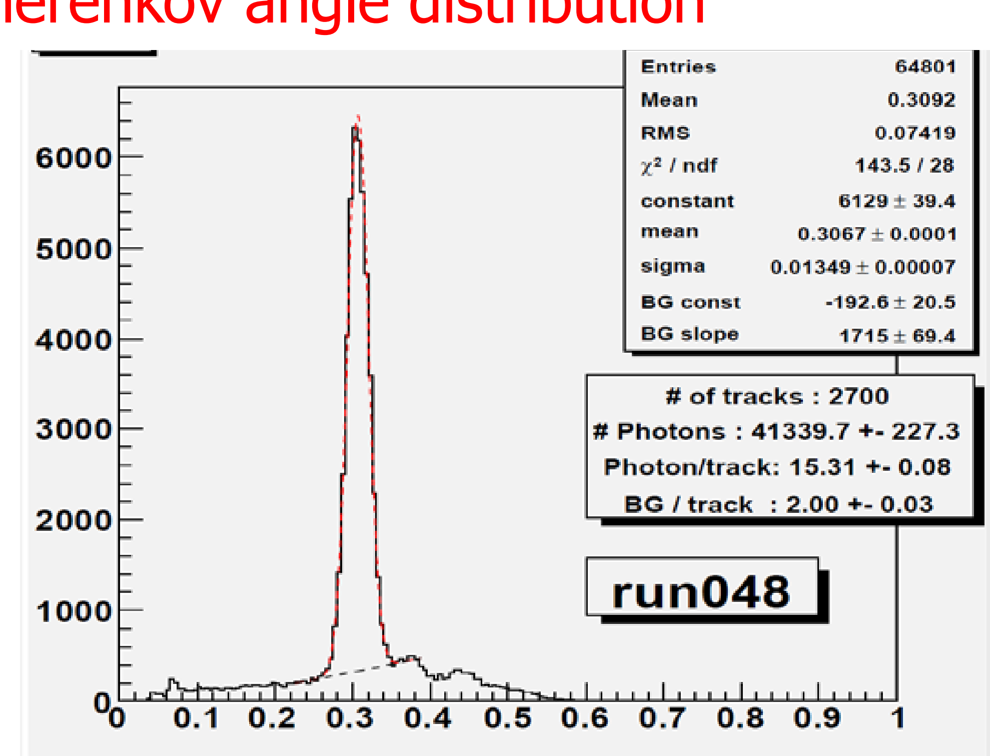
Aerogel RICH (endcap PID)





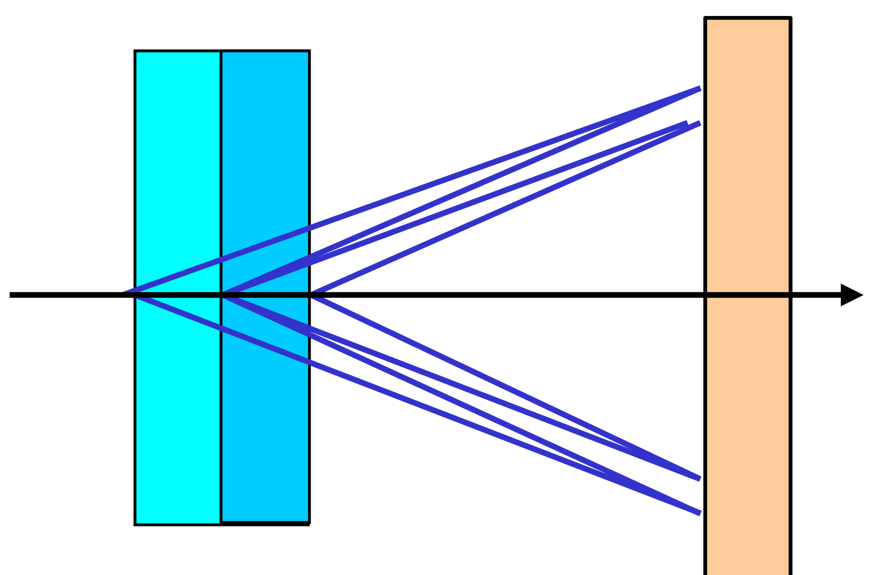
Clear Cherenkov image observed

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.

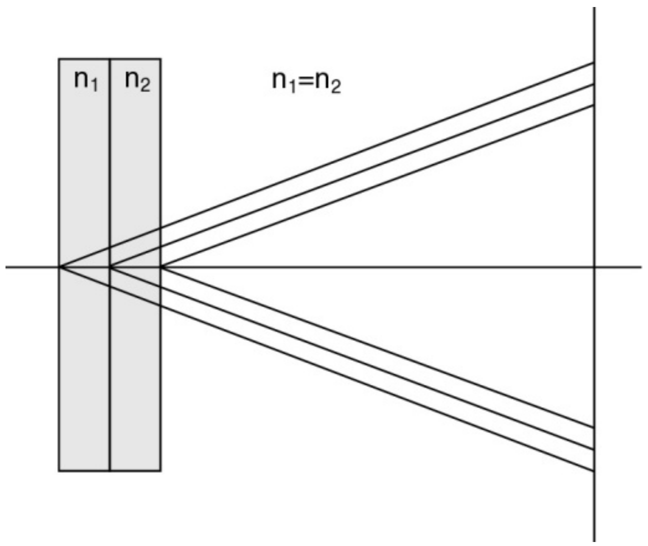


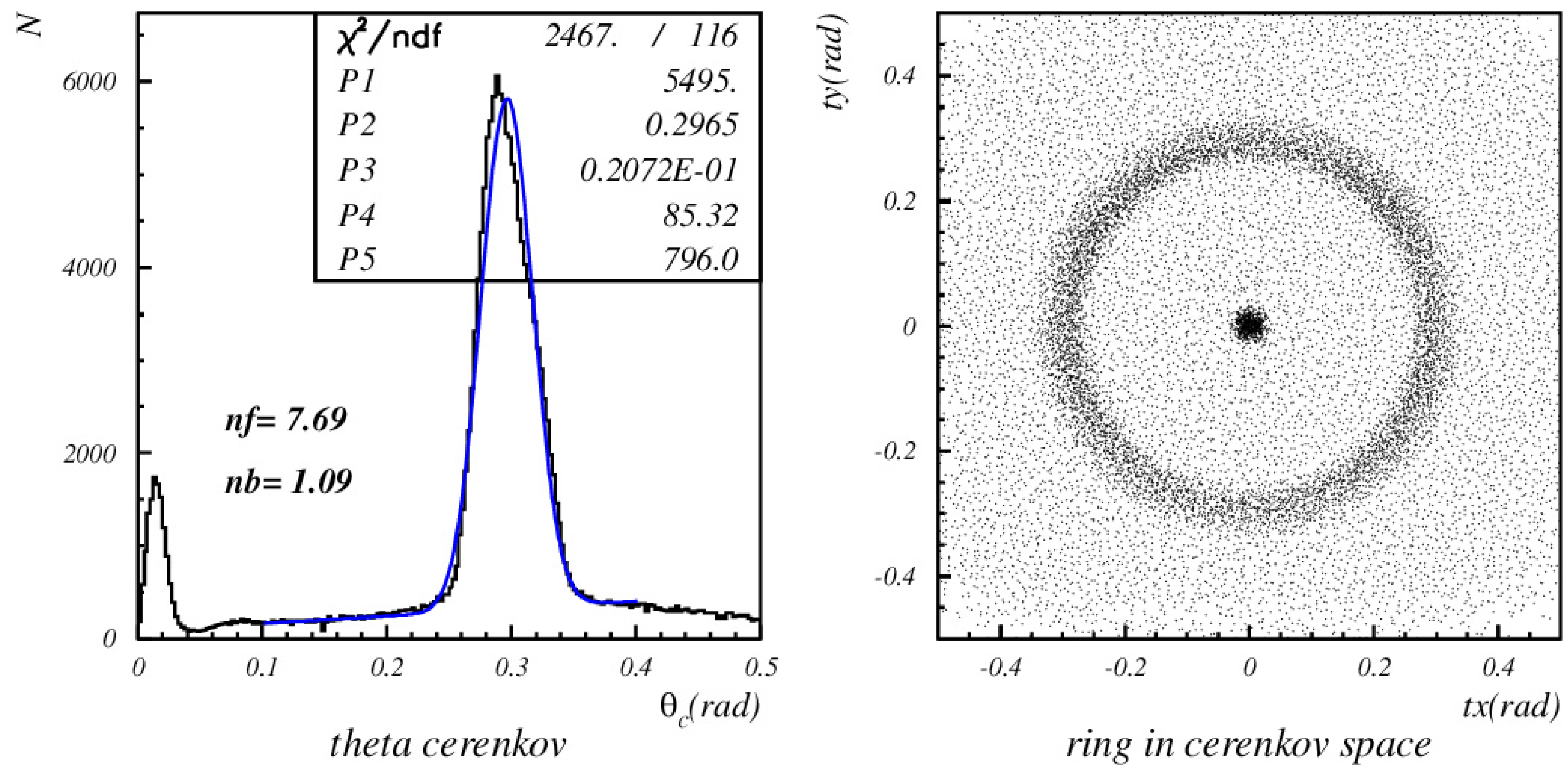
6.6 σ π/K at 4GeV/c !

RICH with a focusing radiator

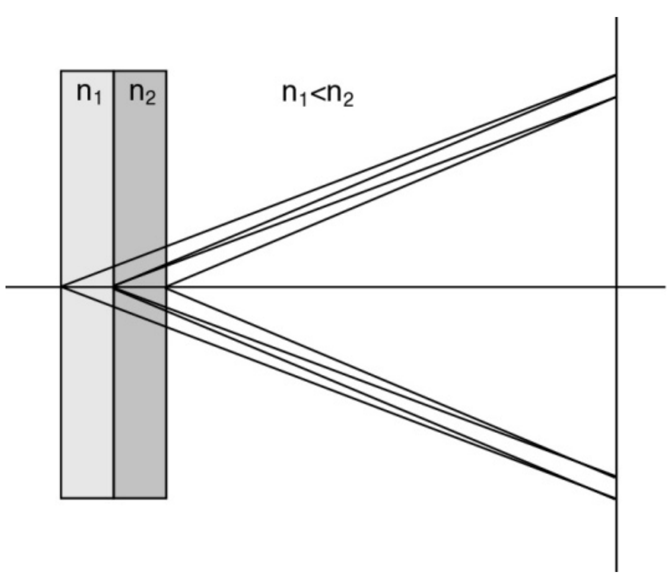
Increases the number of photons without degrading the resolution

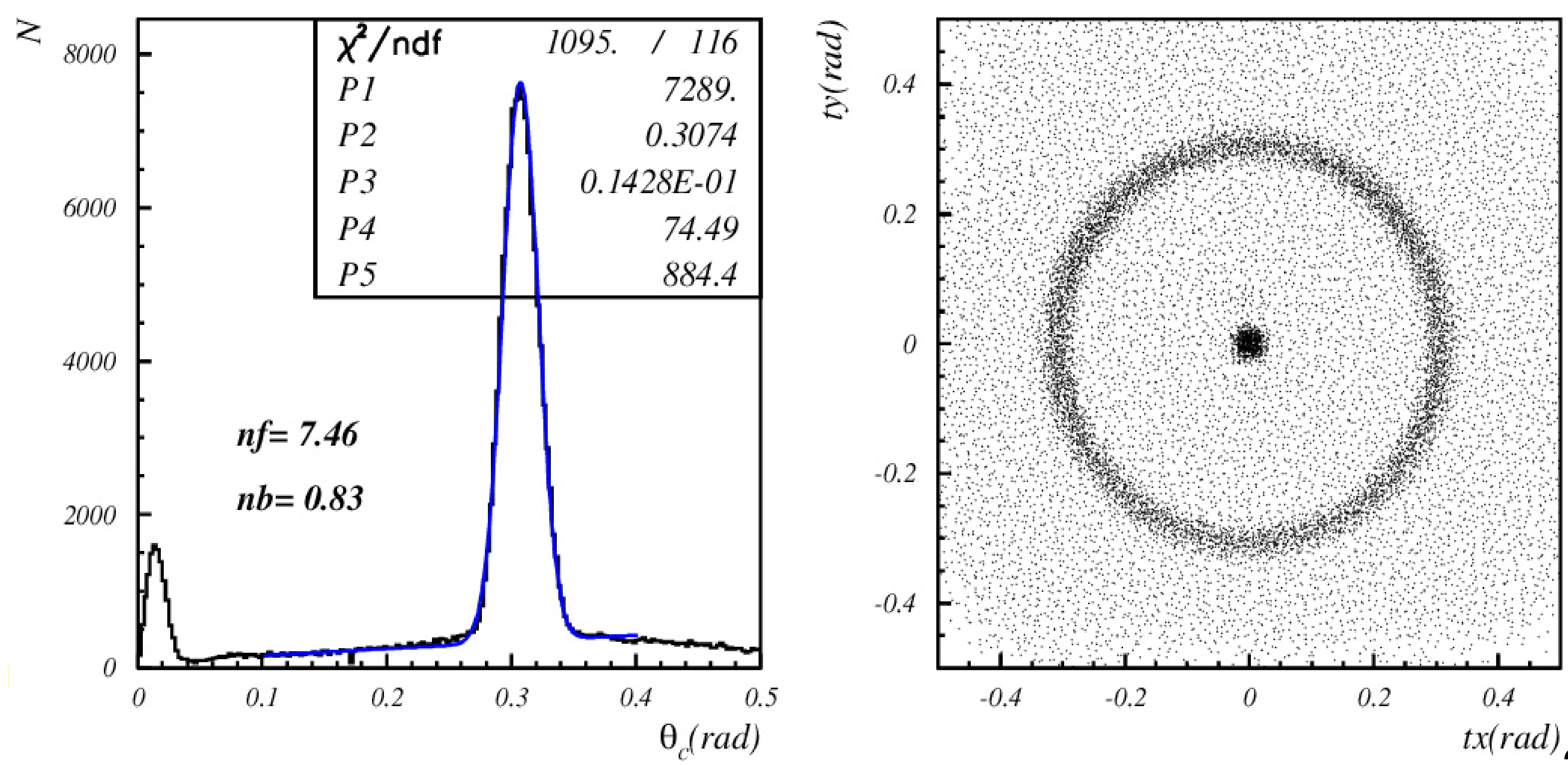
4cm aerogel single index





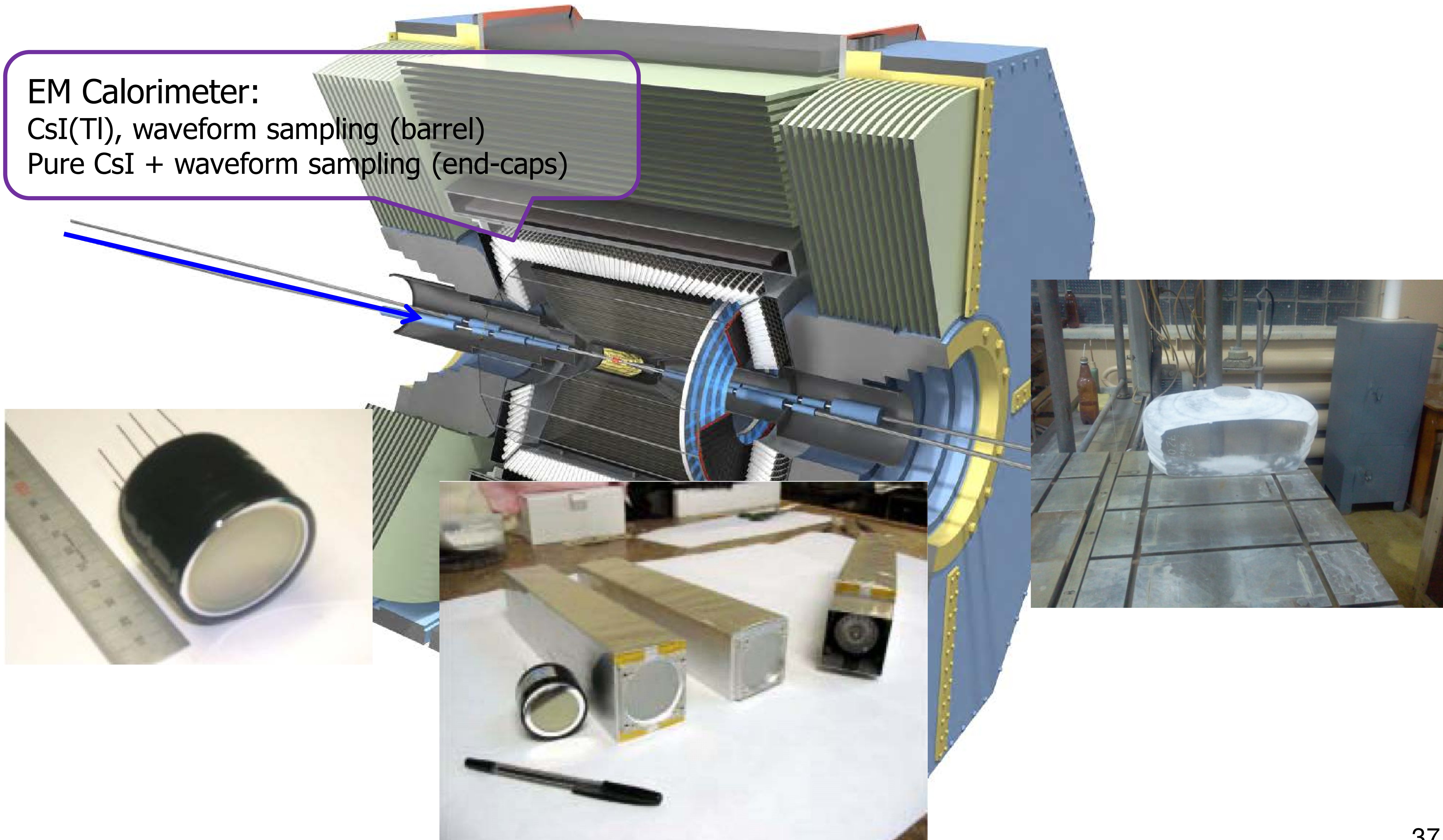
2+2cm aerogel





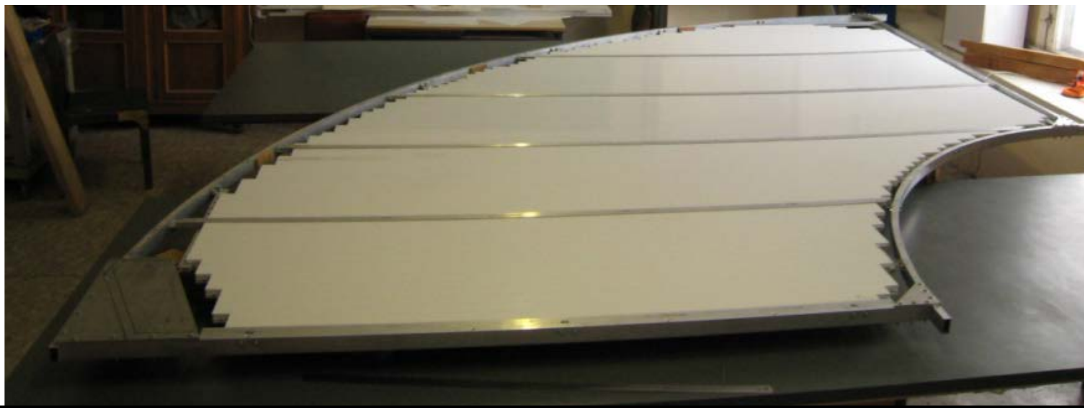
→NIM A548 (2005) 383

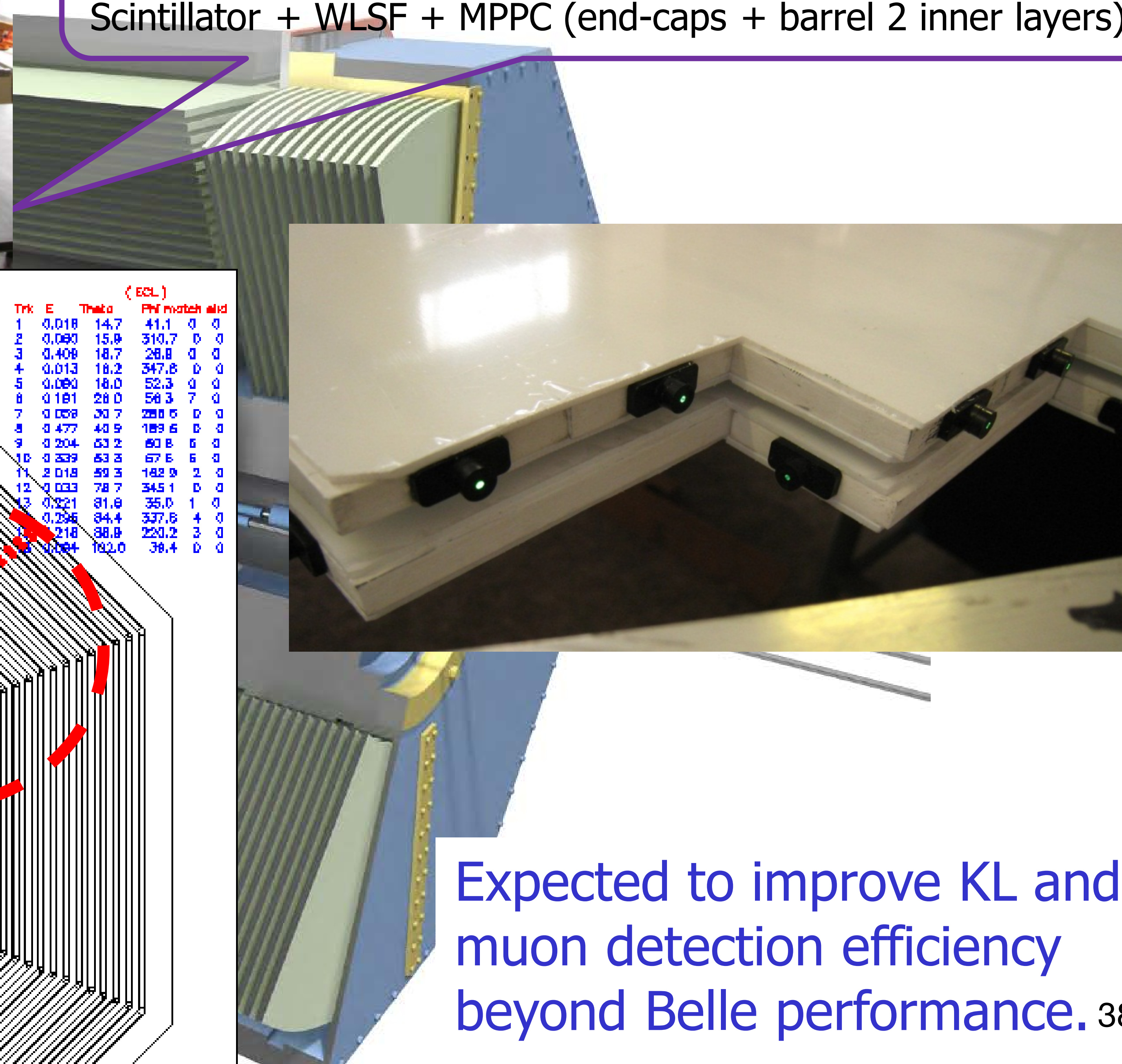
EM calorimeter: upgrade needed because of higher rates (barrel: electronics, endcap: electronics and CsI(Tl) → pure CsI) and radiation load (endcap: CsI(Tl) → pure CsI)

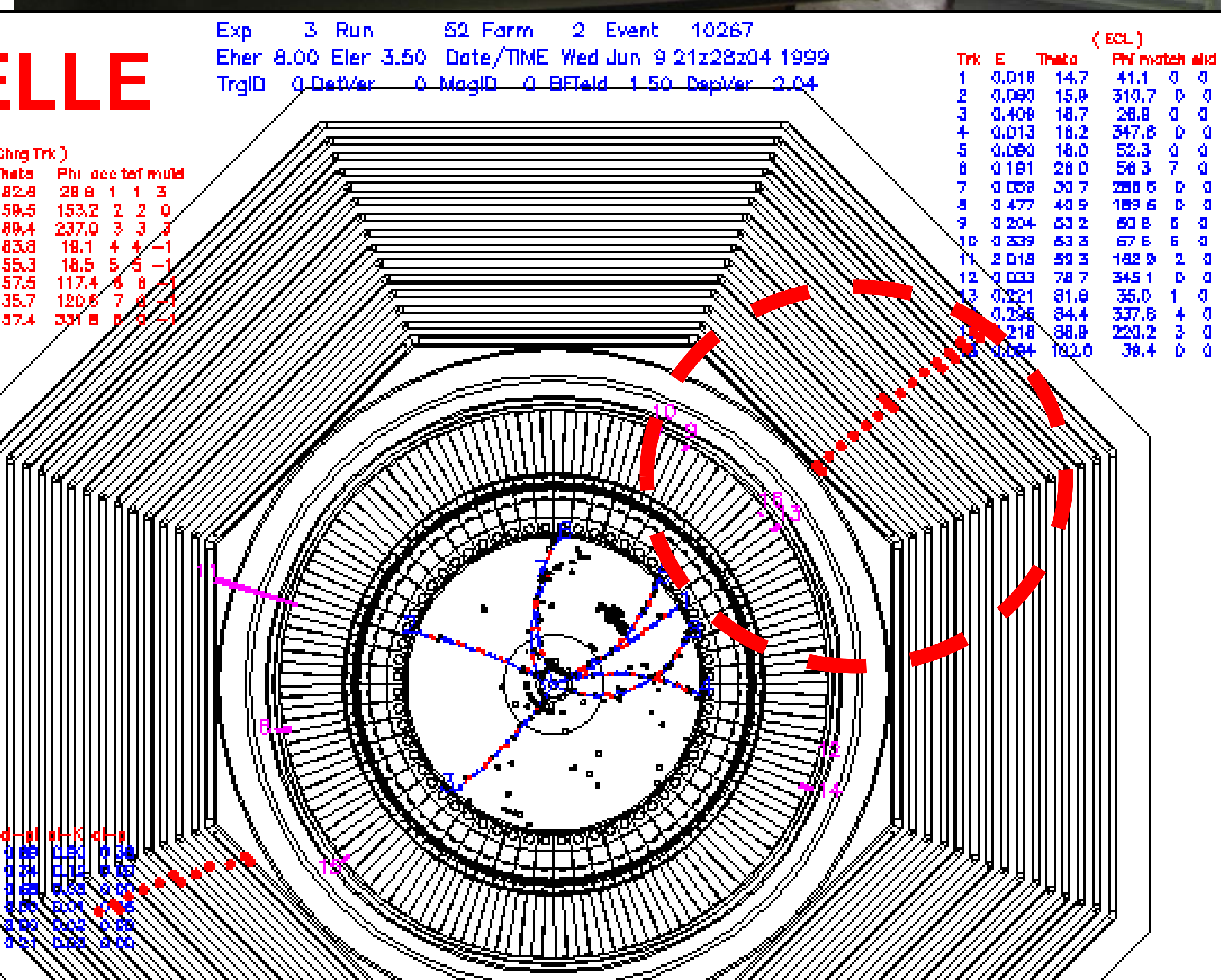


Detection of muons and KLs: Parts of the present RPC system have to be replaced to handle higher backgrounds (mainly from neutrons).

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



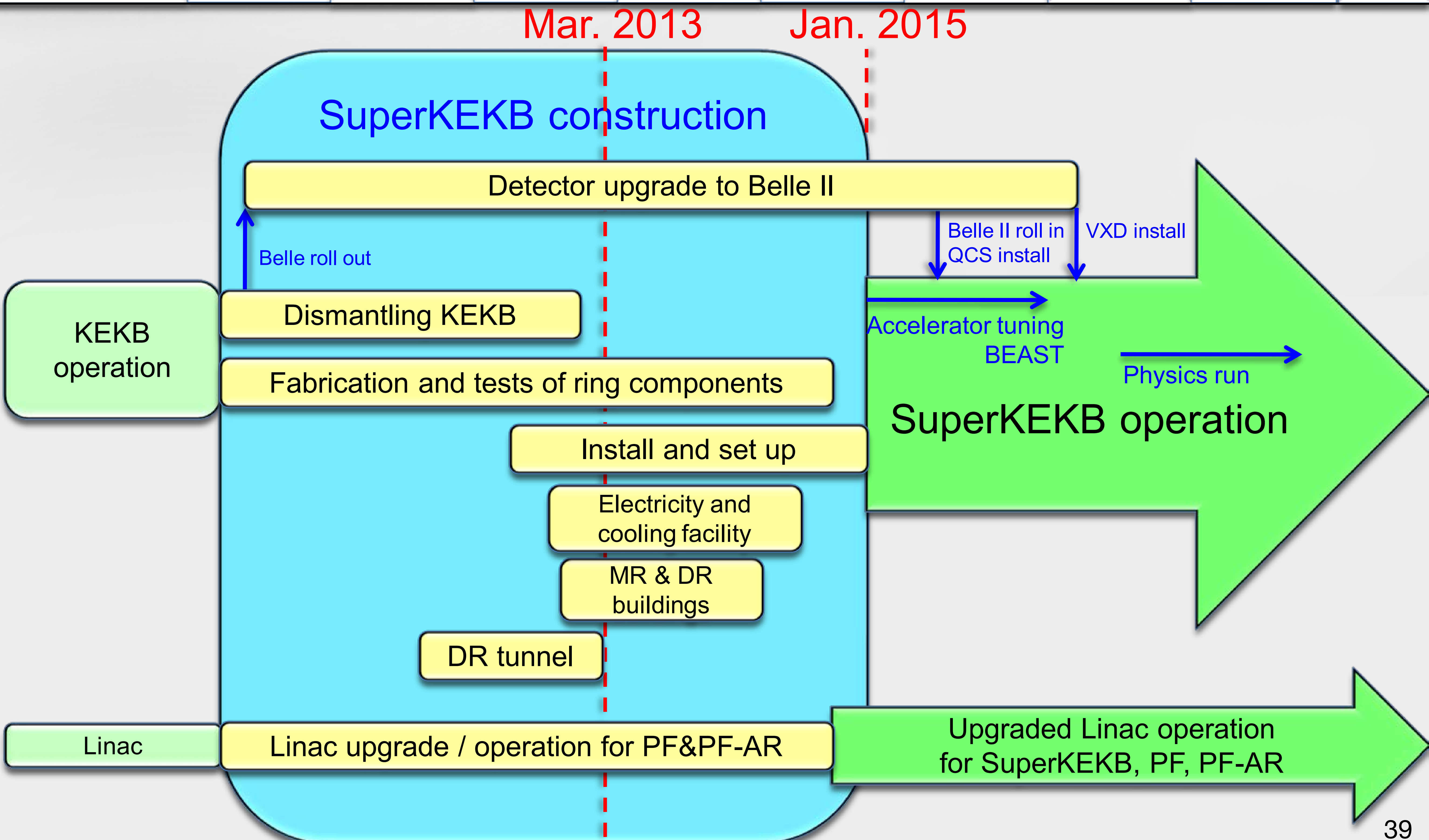




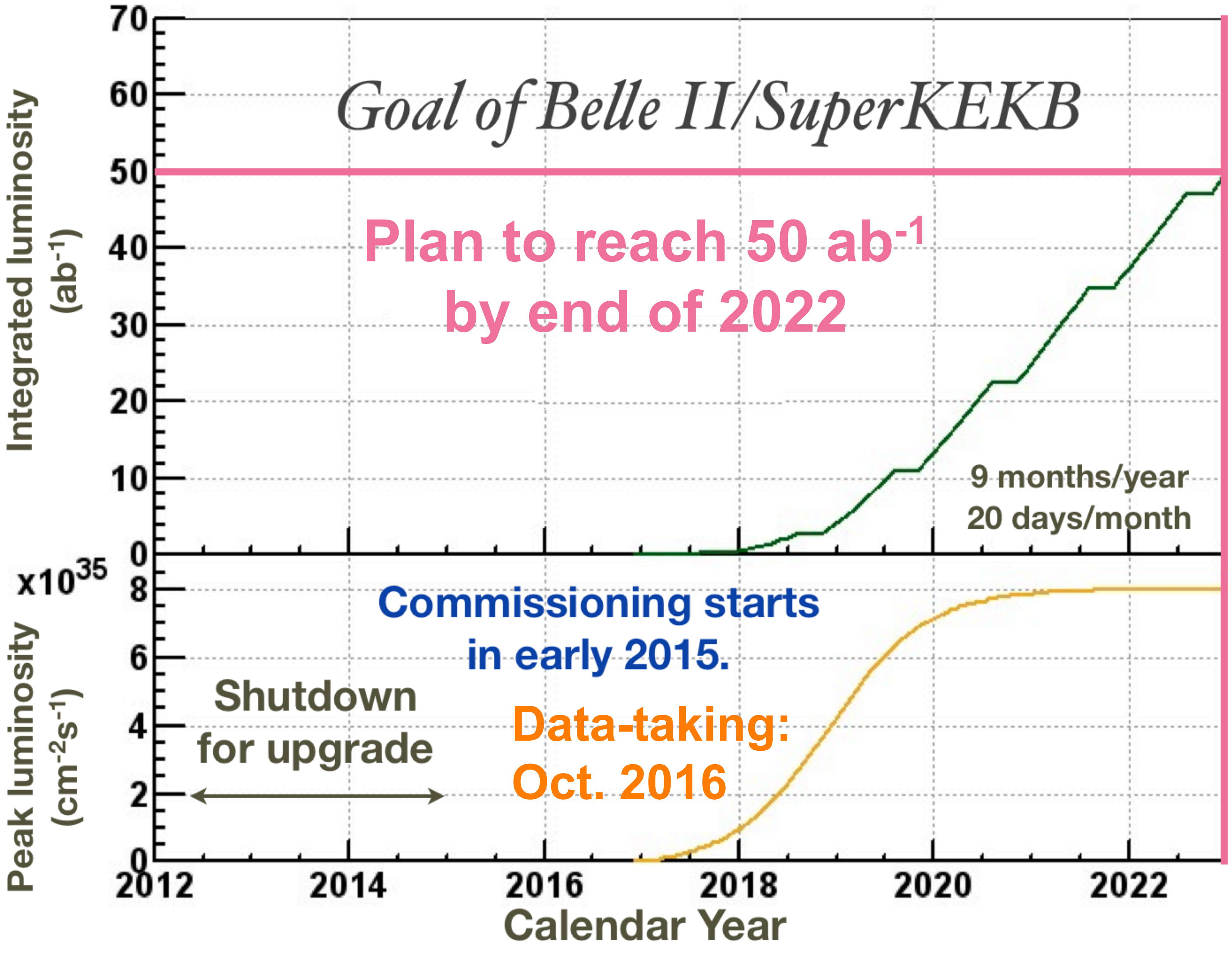
Expected to improve KL and muon detection efficiency beyond Belle performance.

SuperKEKB/Belle II schedule

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

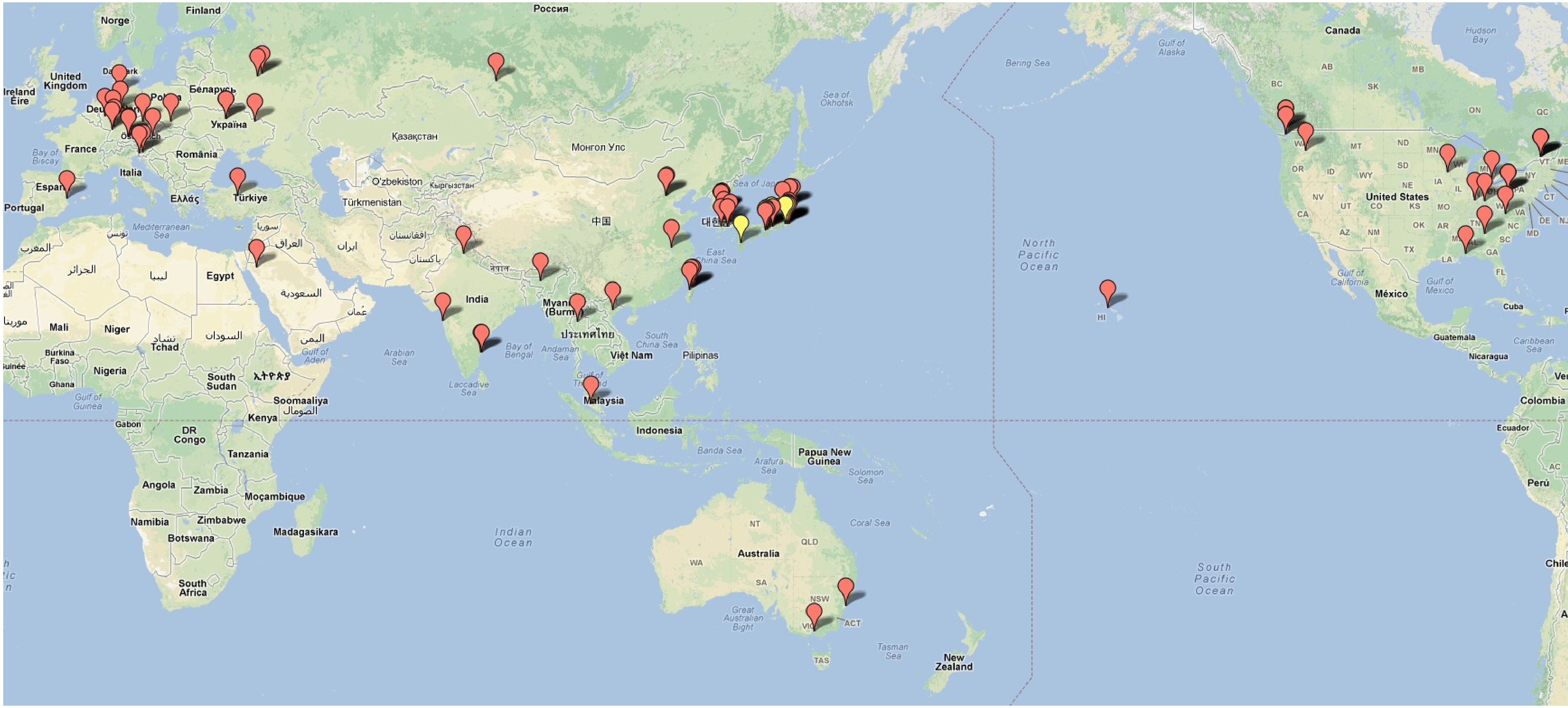


Timeline & goal



Groundbreaking Ceremony, November 18th, 2011

Belle II Collaboration



> 21 countries/regions, 76 institutions, ~480 collaborators

We welcome new collaborators!

<u>Open</u> collaboration meeting on July 4-7 at Virginia Tech

Summary

- Very successful e^+e^- B Factories: Belle and BaBar
- Major upgrade: SuperKEKB and Belle II
- 50 times larger integrated luminosity compared to Belle
  - Challenges to both accelerator and detector
- Fully approved and construction is ongoing
- First physics run in 2016
- New era of discoveries, complementary to LHC

We welcome new collaborators!

Open collaboration meeting on July 4-7 at Virginia Tech