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From Belle to Belle II

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Contents

- Highlights from B factories (+ a little bit of history)
- Physics case for a super B factory
- Accellerator and detector upgrade → SuperKEKB + Belle-II
- Status and outlook

A little bit of history...

CP violation: difference in the properties of particles and their anti-particles – first observed in 1964 in the decays of neutral kaons.

M. Kobayashi and T. Maskawa (1973): CP violation in the Standard model – related to the weak interaction quark transition matrix

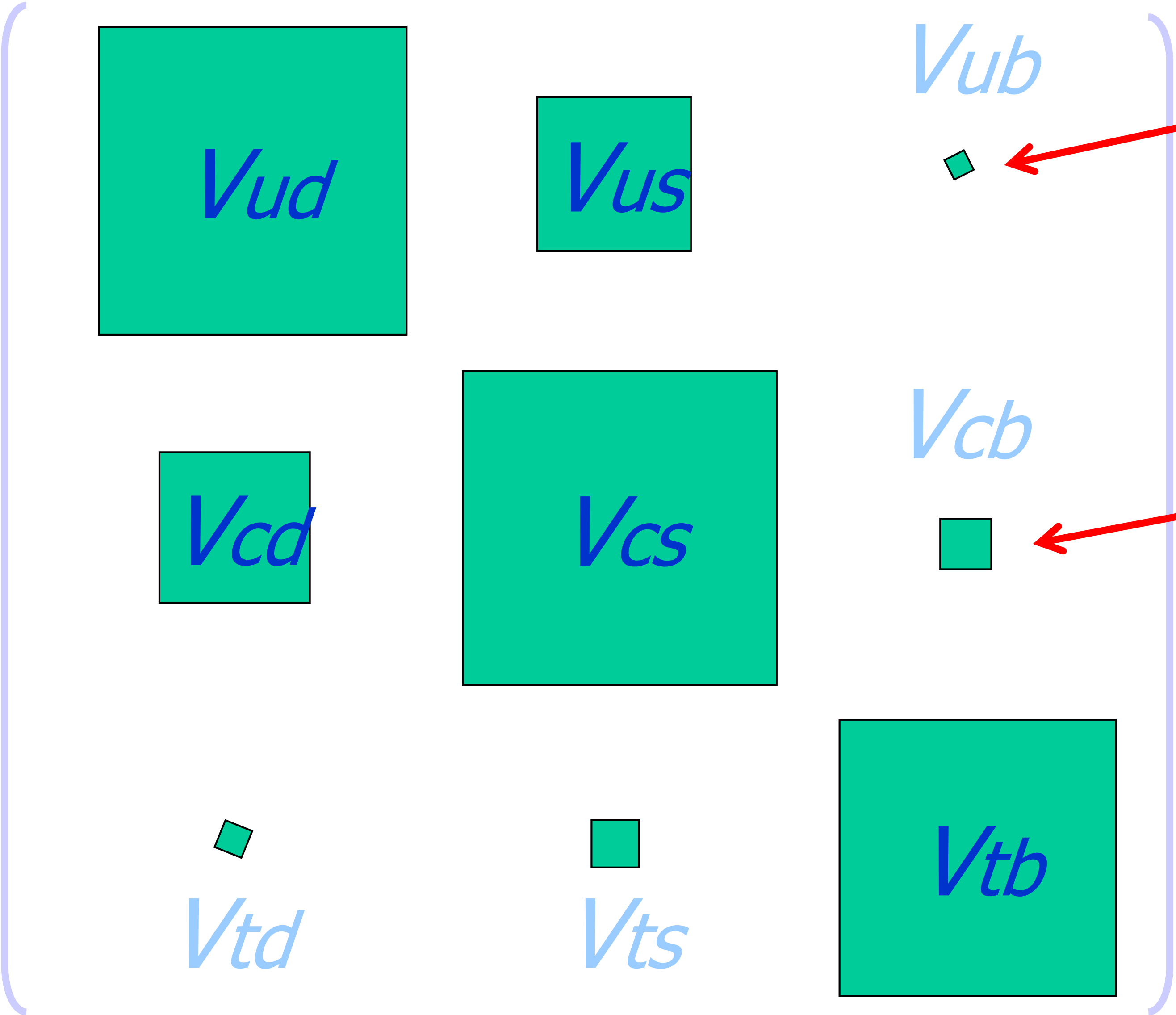
Their theory was formulated at a time when three quarks were known – and they requested the existence of three more!

The last missing quark was found in 1994.

... and in 2001 two experiments – Belle and BaBar at two powerfull accelerators (B factories) - have further investigated CP violation and have indeed proven that it is tightly connected to the quark transition matrix

CKM - Cabibbo-Kobayashi-Maskawa (quark transition) matrix:

almost real and diagonal, but not completely!



Amplitude for the b → u transition

Amplitude for the b → c transition

CKM: unitary matrix

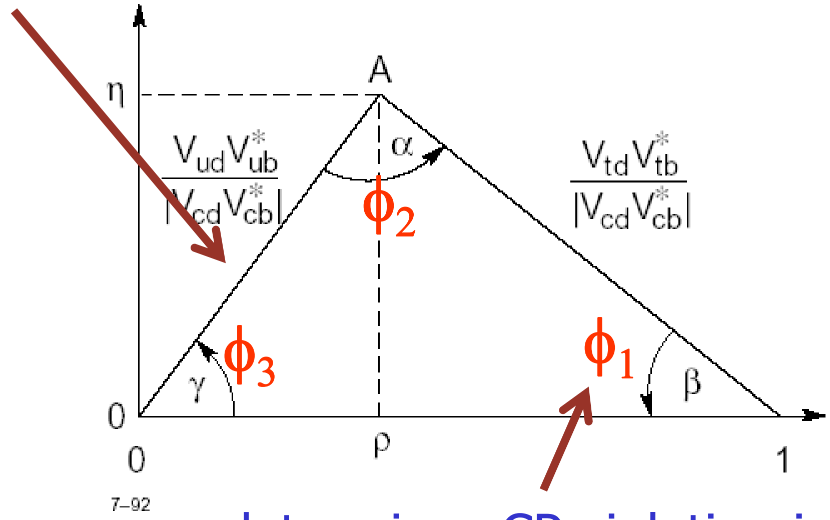
CKM matrix: determines charged weak interaction of quarks

Wolfenstein parametrisation: expand the CKM matrix in the parameter λ (=$\sin\theta_c$=0.22)

A, ρ and η: all of order one

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

determines probability of b→u transitions



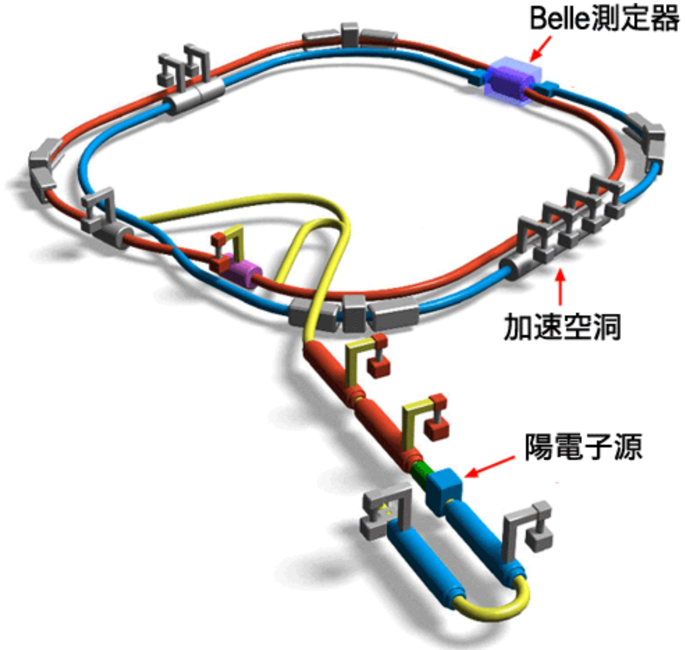
determines CP violation in B→J/ψ K_S decays

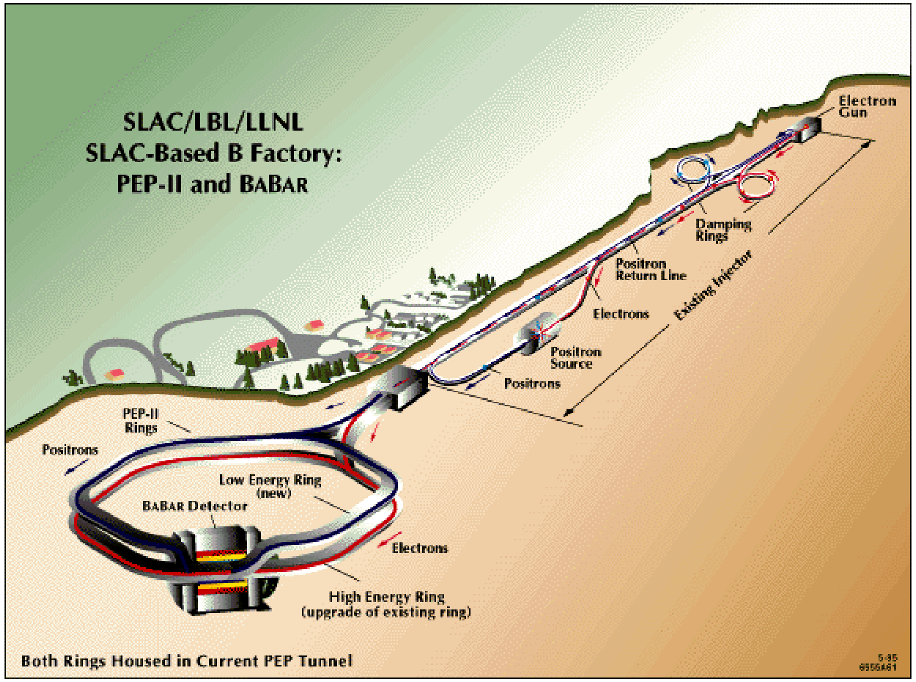
Unitarity condition:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Goal: measure sides and angles in several different ways, check consistency →

Asymmetric B factories





$\sqrt{s}$=10.58 GeV

$e^+ \rightarrow \Upsilon(4s) \leftarrow e^-$

$\Upsilon(4s)$ → B, $\bar{B}$

$\Delta z \sim c\beta\gamma\tau_B \sim 200\mu m$

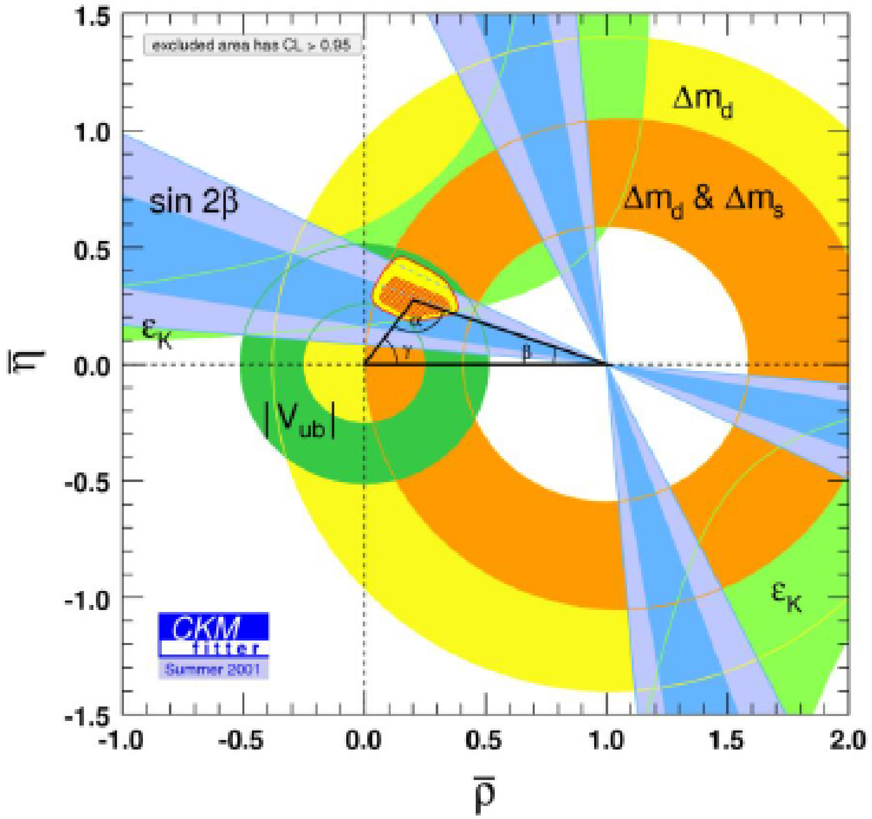
BaBar p(e^-)=9 GeV p(e^+)=3.1 GeV $\beta\gamma$=0.56

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

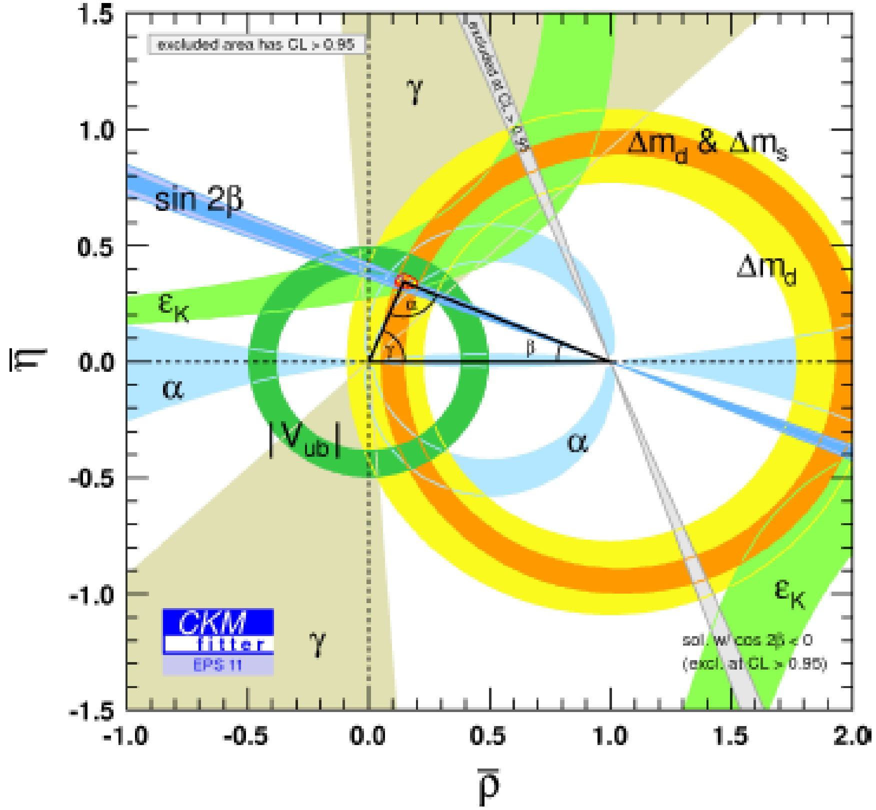
Unitarity triangle – 2011 vs 2001

CP violation in the B system: from the discovery (2001) to a precision measurement (2011).

EPS 2001

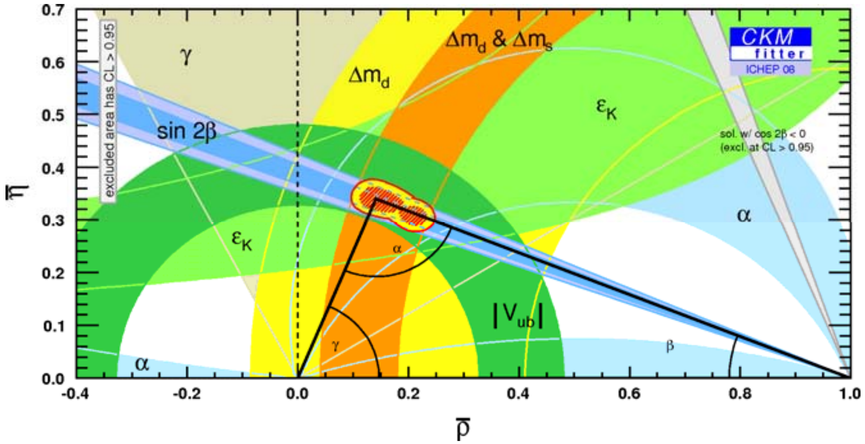


EPS 2011



KM's bold idea verified by experiment

Relations between parameters as expected in the Standard model →



Nobel prize 2008!

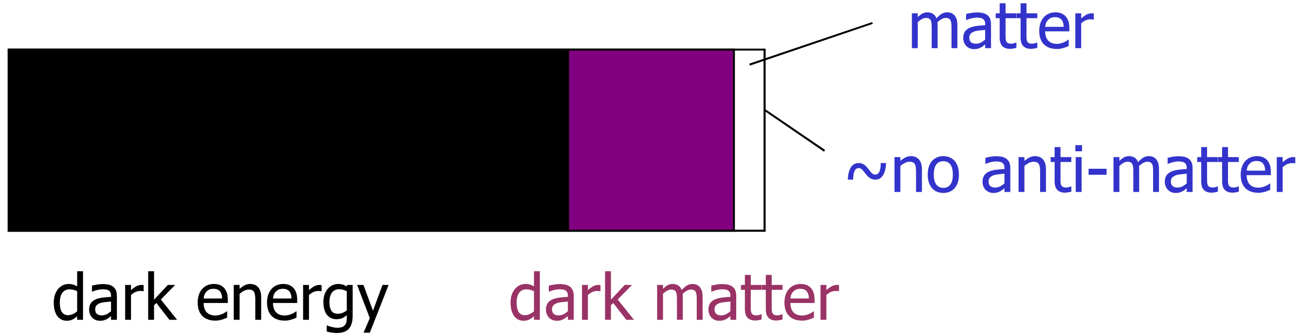
→ With essential experimental confirmations by BaBar and Belle! (explicitly noted in the Nobel Prize citation)

The KM scheme is now part of the Standard Model of Particle Physics

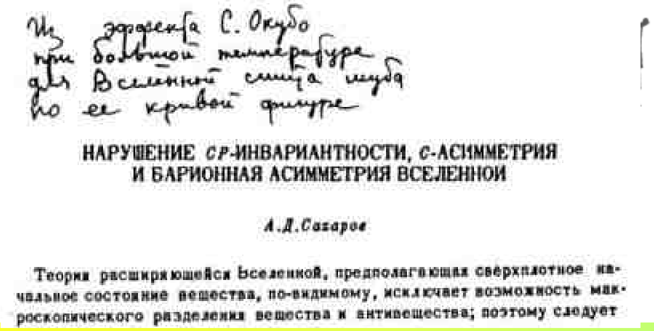
•However, the CP violation of the KM mechanism is too small to account for the asymmetry between matter and anti-matter in the Universe (falls short by 10 orders of magnitude !)

•SM does not contain the fourth fundamental interaction, gravitation

•Most of the Universe is made of stuff we do not understand...



Are we done ? (Didn't the B factories accomplish their mission, recognized by the 2008 Nobel Prize in Physics ?)



Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

НАРУШЕНИЕ CP-ИНВАРИАНТНОСТИ, C-АСИММЕТРИЯ И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сахаров

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует

Matter - anti-matter asymmetry of the Universe: KM (Kobayashi-Maskawa) mechanism still short by 10 orders of magnitude !!!

Two frontiers

Two complementary approaches to study shortcomings of the Standard Model and to search for the so far unobserved processes and particles (so called New Physics, NP). These are the **energy frontier** and the **intensity frontier** .

Energy frontier : direct search for production of unknown particles at the highest achievable energies.

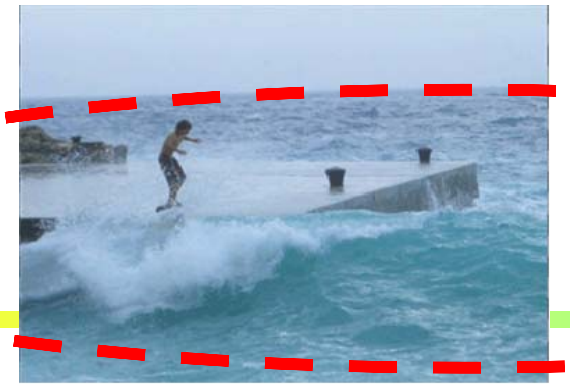
Intensity frontier : search for rare processes, deviations between theory predictions and experiments with the ultimate precision.

→for this kind of studies, one has to investigate a very large number of reactions events → need accelerators with ultimate **intensity** (= luminosity)

Comparison of **energy** /**intensity** frontiers

To observe a large ship far away one can either use **strong binoculars** or observe **carefully the direction and the speed of waves** produced by the vessel.

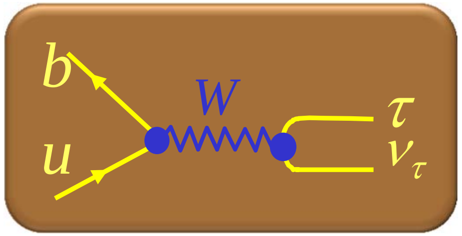
Energy frontier (LHC)



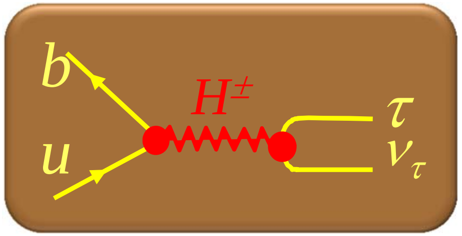
Luminosity frontier (Belle and Belle II)

An example: Hunting the charged Higgs in the decay $B^- \to \tau^- \nu_\tau$

In addition to the Standard Model Higgs – most probably just discovered at the LHC - in New Physics (e.g., in supersymmetric theories) there could also be a charged Higgs.



The rare decay $B^- \to \tau^- \nu_\tau$ is in SM mediated by the W boson

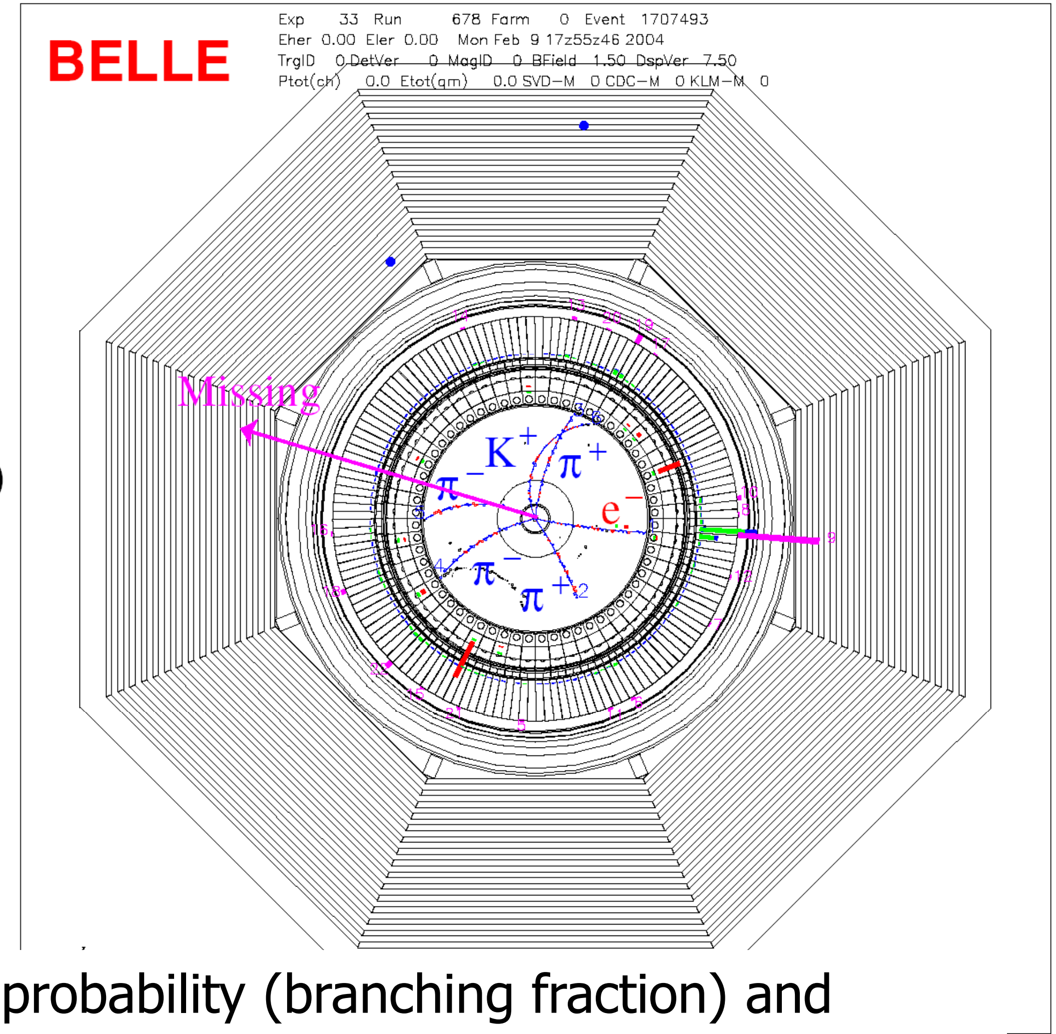


In some supersymmetric extensions it can also proceed via a charged Higgs

The charged Higgs would influence the decay of a B meson to a tau lepton and its neutrino, and modify the probability for this decay.

Missing Energy Decays: $B^{-} \rightarrow \tau^{-} \nu_{\tau}$

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



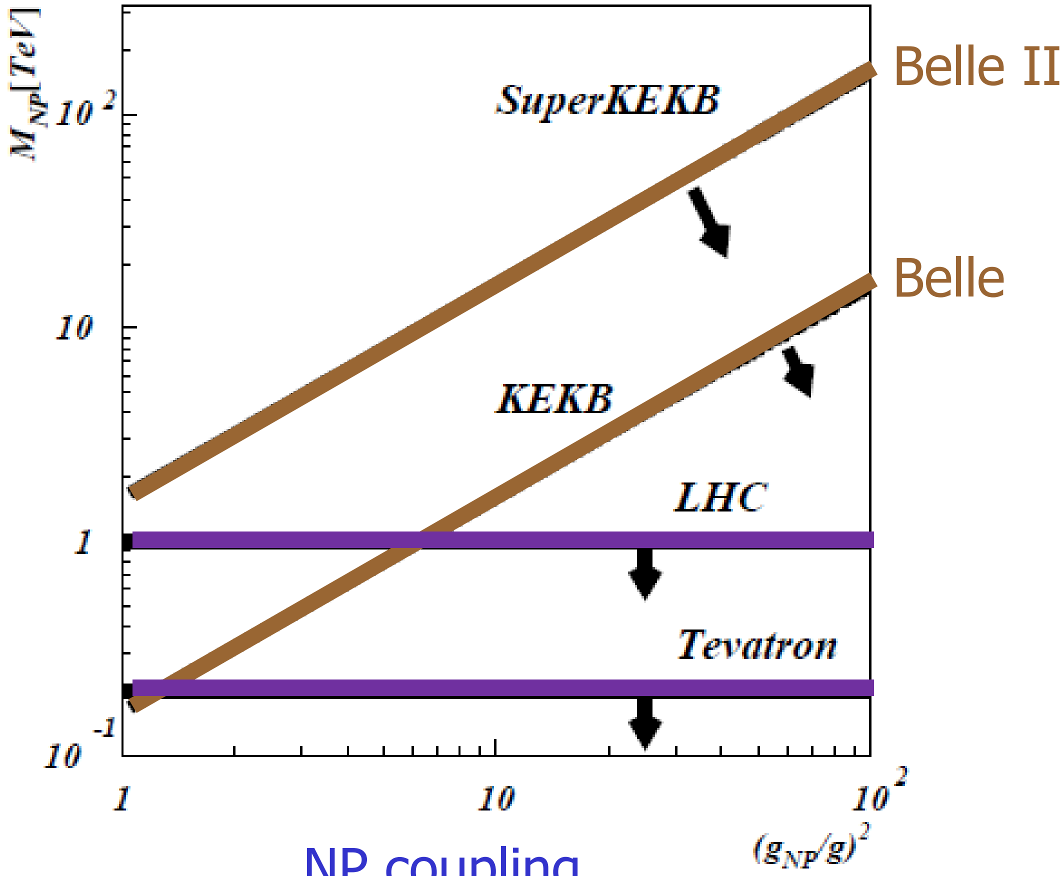
By measuring the decay probability (branching fraction) and comparing it to the SM expectation:

→ Properties of the charged Higgs (e.g. its mass)

New Physics reach

energy frontier vs. **intensity frontier**

NP mass scale (TeV)



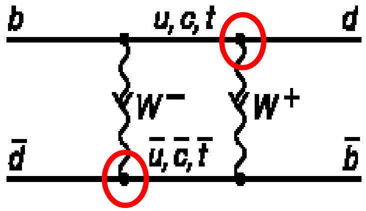
NP coupling

Super B Factory Motivation 2

- Lessons from history: the top quark

<u>Physics of top quark</u>

First estimate of mass: BB mixing	→ ARGUS
Direct production, Mass, width etc.	→ CDF/D0
Off-diagonal couplings, phase	→ BaBar/Belle



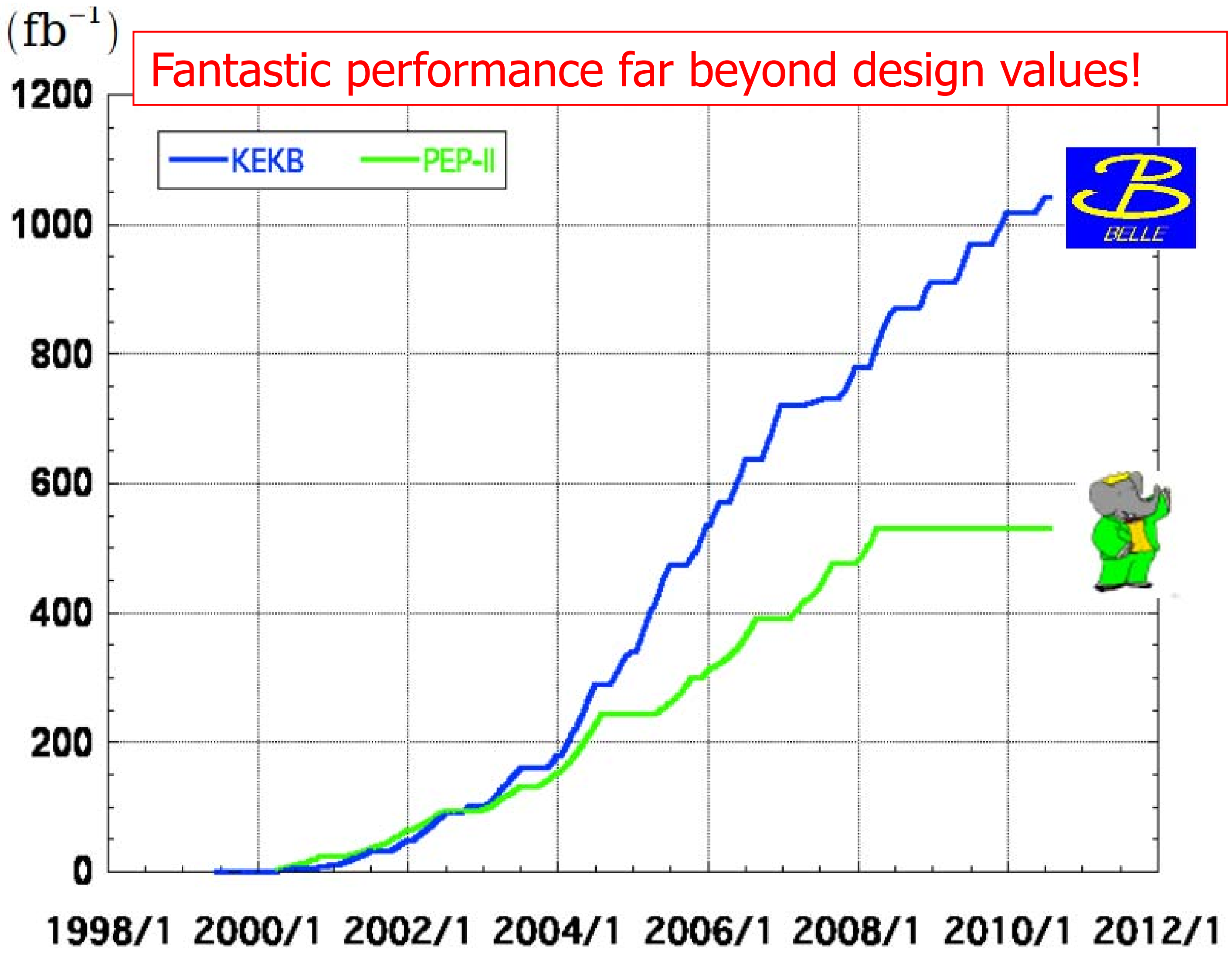
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Even before that: prediction of charm quark from the GIM mechanism, and its mass from K^0 mixing

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 $b \to s l^+ l^-$ has become a powerfull tool to search for physics beyond SM.
- Observation of D mixing
- Searches for rare τ decays
- Observation of new hadrons

Integrated luminosity at B factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

What next?

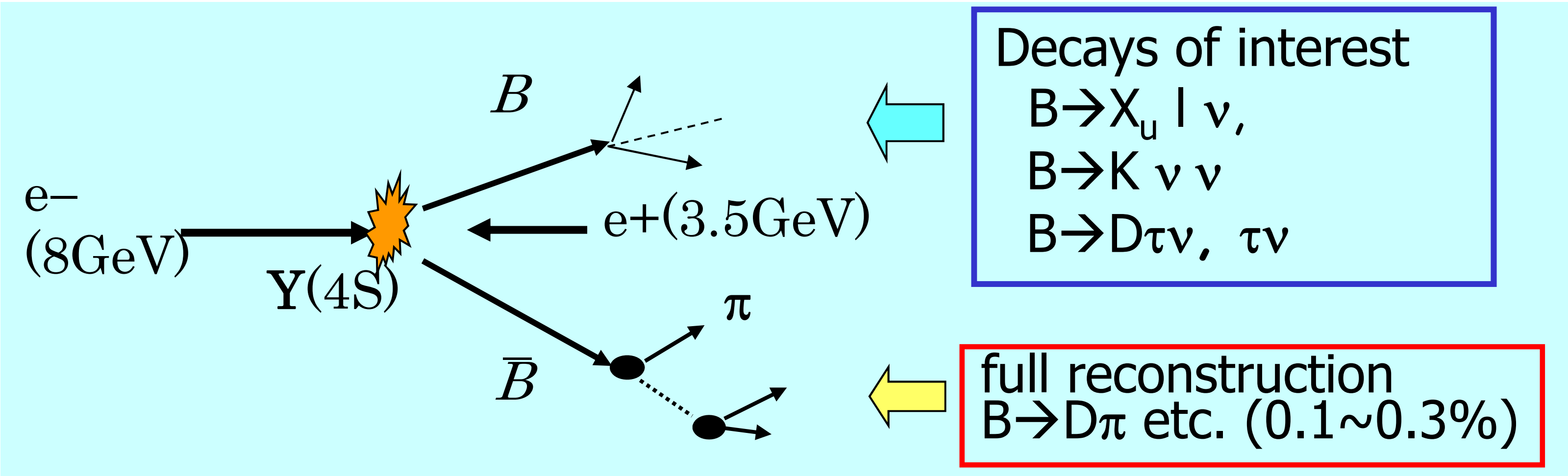
To search for NP effects, need much more data (two orders!) → Luminosity frontier experiment → Super B factory

However: it will be a different world in four years, there will be serious competition from LHCb and BESIII

Still, e^+e^- machines running at (or near) Y(4s) will have considerable advantages in several classes of measurements, and will be complementary in many more

Full Reconstruction Method

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

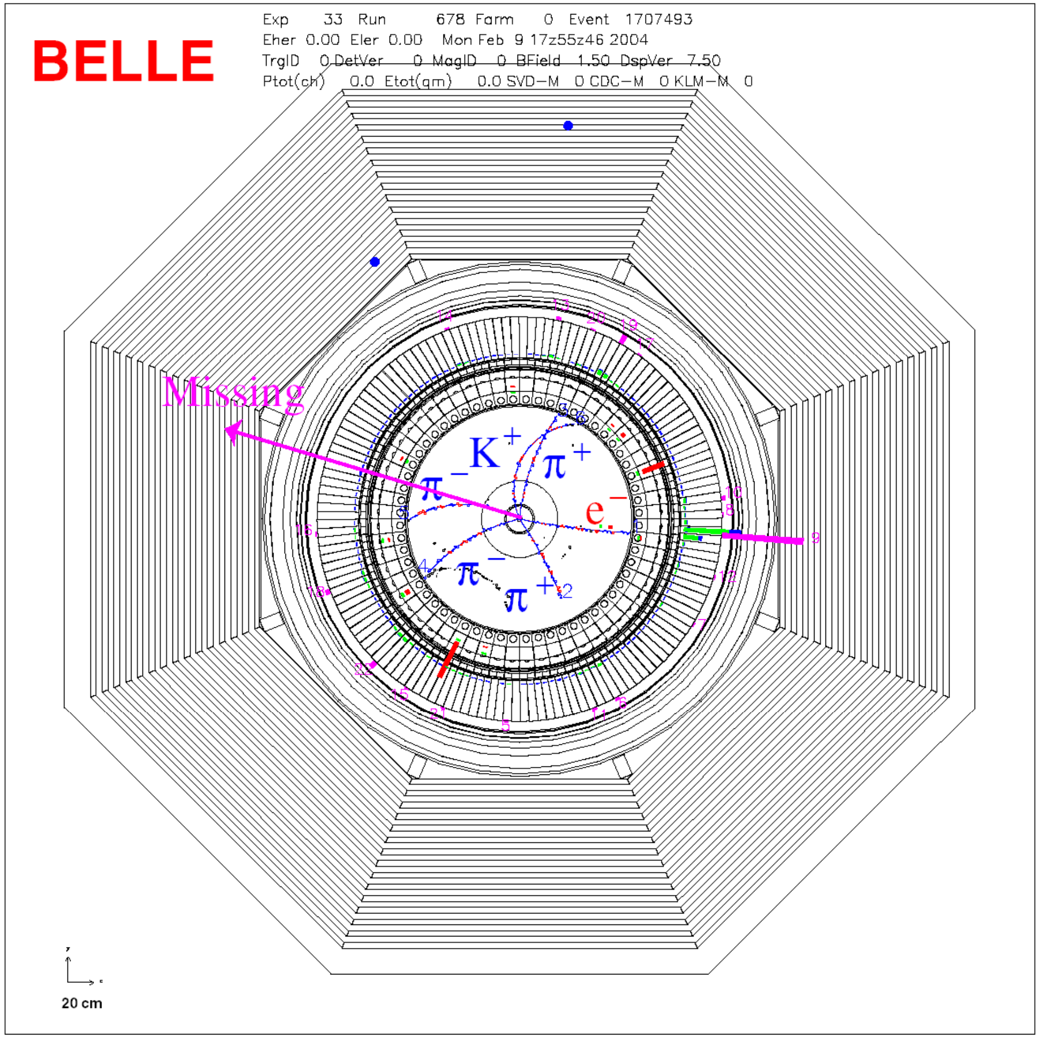


→ Offline B meson beam!

Powerful tool for B decays with neutrinos

Missing Energy Decays: $B^- \rightarrow \tau^- \nu_\tau$

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



$B \rightarrow \nu \nu$ decay

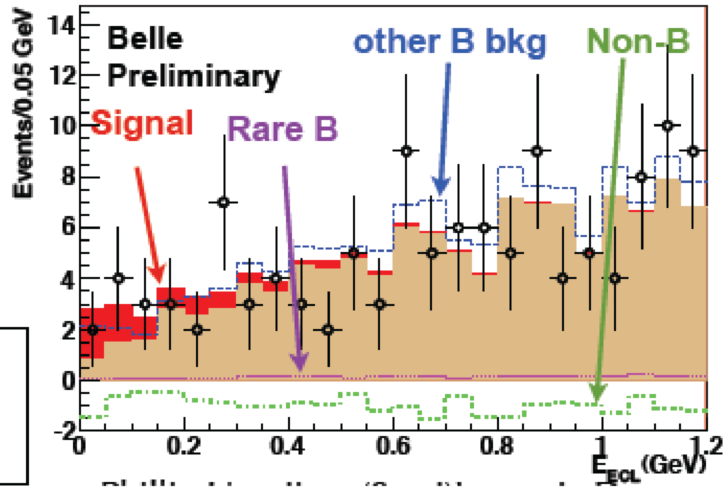
$B \rightarrow \nu \nu$ similar as $B \rightarrow \mu \mu$ a very sensitive channel to NP contributions

Even more strongly helicity suppressed by $\sim(m_\nu/m_B)^2$

$\rightarrow$ Any signal = NP

Unique feature at B factories: use tagged sample with fully reconstructed B decays on one side, require no signal from the other B.

Use rest energy in the calorimeter and angular distribution as the fit variables.



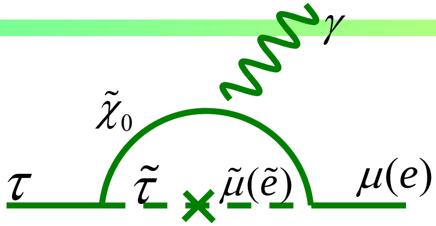
90% C.L. BR < 1.3 x 10^{-4}

Belle Preliminary 657M BBbar

c.f. (Babar) BR < 2.2 x 10^{-4}

LFV and New Physics

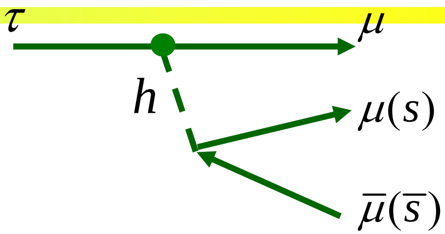
τ→lγ



- SUSY + Seasaw $(m^2_{\tilde{l}})_{23(13)}$
- Large LFV Br(τ→μγ)=O($10^{-7\sim9}$)

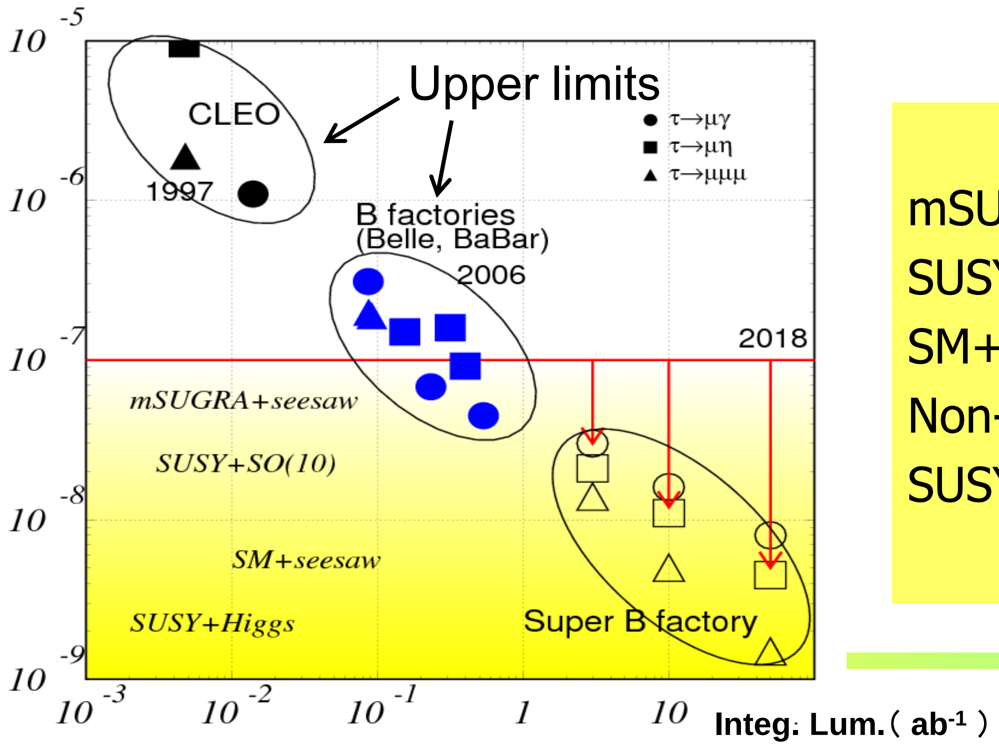
$$Br(\tau \to \mu\gamma) \simeq 10^{-6} \times \left(\frac{(m^2_{\tilde{L}})_{32}}{\bar{m}^2_{\tilde{L}}}\right)\left(\frac{1\,TeV}{m_{SUSY}}\right)^4 \tan^2\beta$$

τ→3l,lη



- Neutral Higgs mediated decay.
- Important when MSUSY >> EW scale.

$$Br(\tau \to 3\mu) = 4\times10^{-7} \times \left(\frac{(m^2_{\tilde{L}})_{32}}{\bar{m}^2_{\tilde{L}}}\right)\left(\frac{\tan\beta}{60}\right)^6\left(\frac{100GeV}{m_A}\right)^4$$



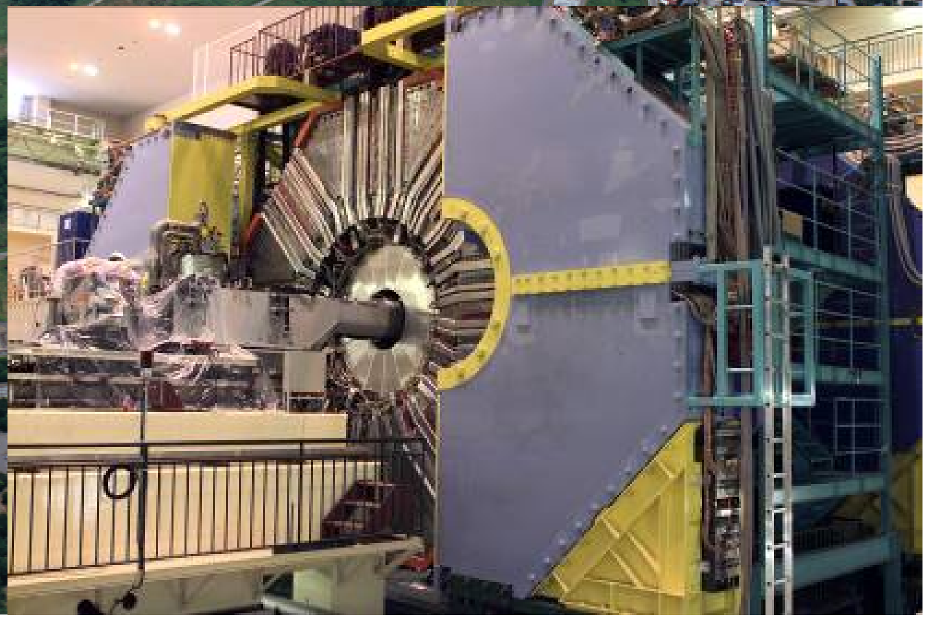
model	Br(τ→μγ)	Br(τ→lll)
mSUGRA+seesaw	10^{-7}	10^{-9}
SUSY+SO(10)	10^{-8}	10^{-10}
SM+seesaw	10^{-9}	10^{-10}
Non-Universal Z′	10^{-9}	10^{-8}
SUSY+Higgs	10^{-10}	10^{-7}

Physics at a Super B Factory

- There is a good chance to see new phenomena;
  - **CPV in B decays from the new physics (non KM).**
  - **Lepton flavor violations in τ decays.**
- They will help to diagnose (if found) or constrain (if not found) new physics models.
- $B \rightarrow \tau\nu$, $D\tau\nu$ can probe the charged Higgs in large tanβ region.
- **Physics motivation is independent of LHC**.
  - If LHC finds NP, precision flavour physics is compulsory.
  - If LHC finds no NP, high statistics B/τ decays would be a unique way to search for the >TeV scale physics (=TeV scale in case of MFV).

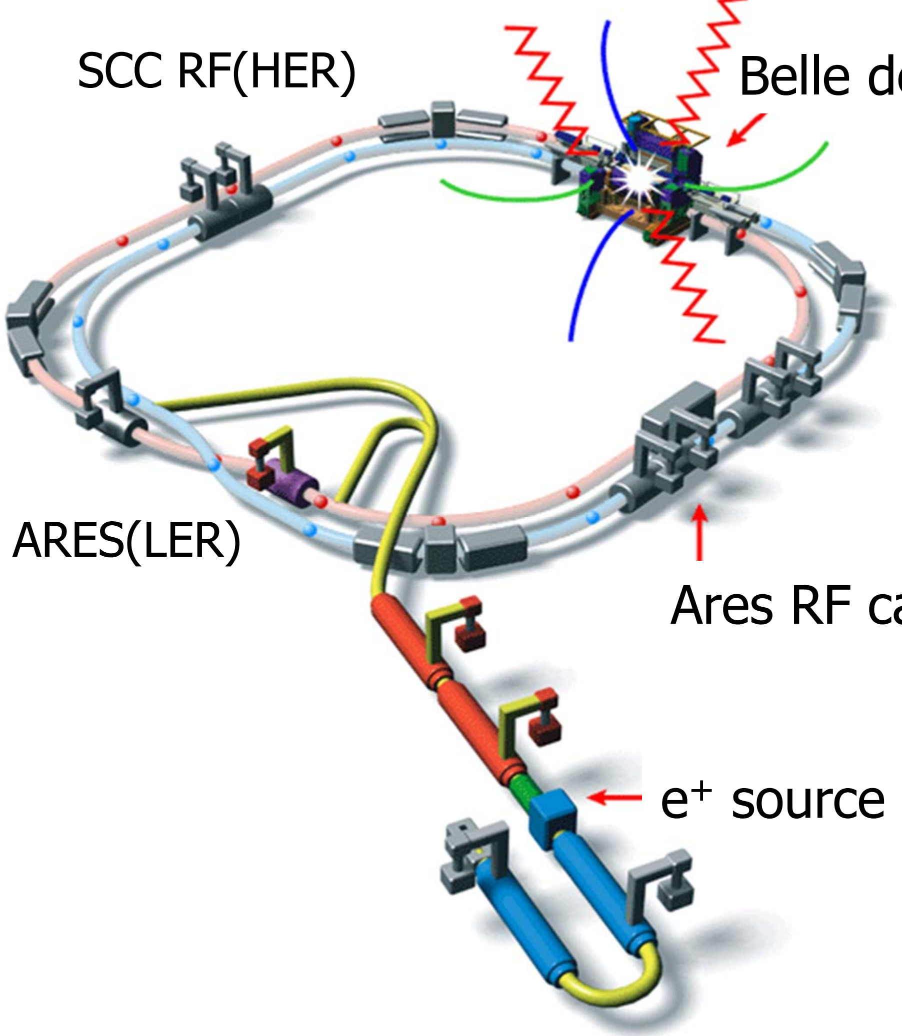
Physics reach with 50 ab^{-1}:
- Physics at Super B Factory (Belle II authors + guests) hep-ex arXiv:1002.5012

How to do it?
→ upgrade KEKB and Belle



The KEKB Collider

Fantastic performance far beyond design values!



- e^- (8 GeV) on e^+(3.5 GeV)
  - $\sqrt{s} \approx m_{\Upsilon(4S)}$
  - Lorentz boost: $\beta\gamma$=0.425
- 22 mrad crossing angle

Peak luminosity (WR!) :

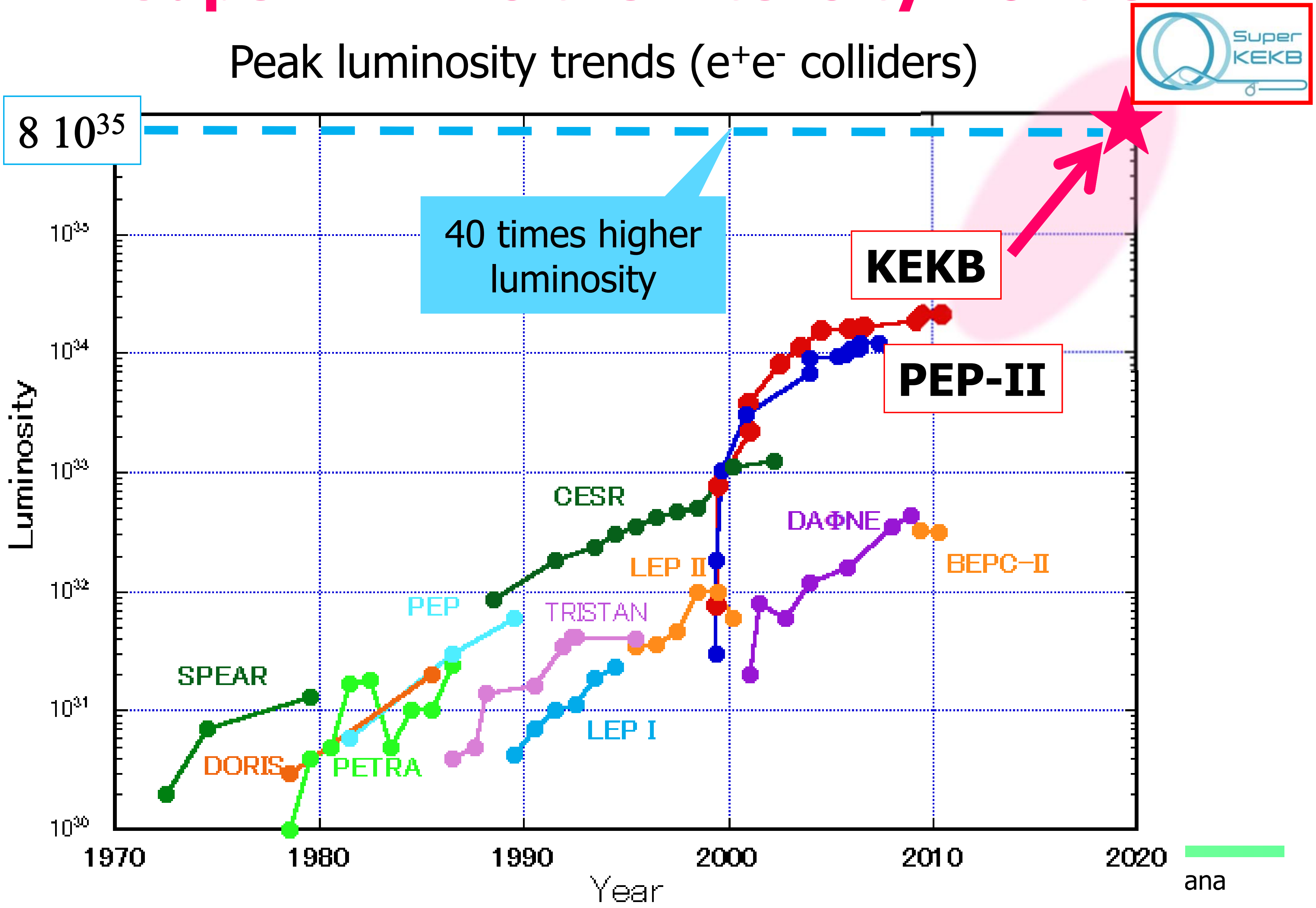
2. 1 x 10^{34} $cm^{-2}s^{-1}$

=2x design value

First physics run on June 2, 1999
Last physics run on June 30, 2010
L_{peak} = 2.1x10^{34}/cm^2/s
L > 1ab^{-1}

SuperKEKB is the intensity frontier

Peak luminosity trends (e^+e^- colliders)



How to increase the luminosity?

Lorentz factor

Beam current

Beam-beam parameter

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

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 β_y^*

(2) Increase beam currents

(3) Increase ξ_y

"Nano-Beam" scheme

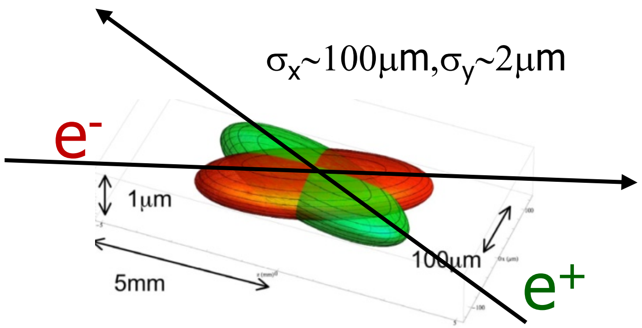
Collision with very small spot-size beams

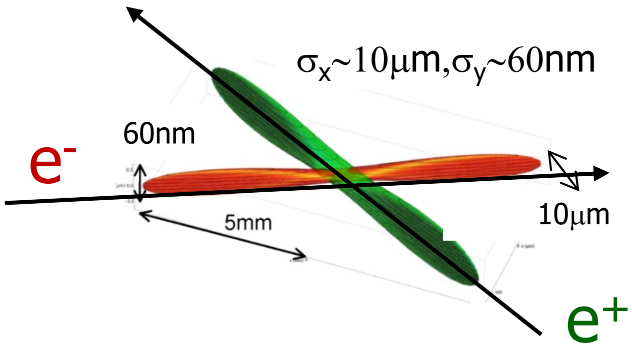
Invented by Pantaleo Raimondi for SuperB – 'spin-off' of linear collider studies

How big is a nano-beam ?

How to go from an excellent accelerator with world record performance – KEKB – to a 40x times better, more intense facility?

In KEKB, colliding electron and positron beams are much thinner than the human hair...





... For a 40x increase in intensity you have to make the beam as thin as a few 100 atomic layers!

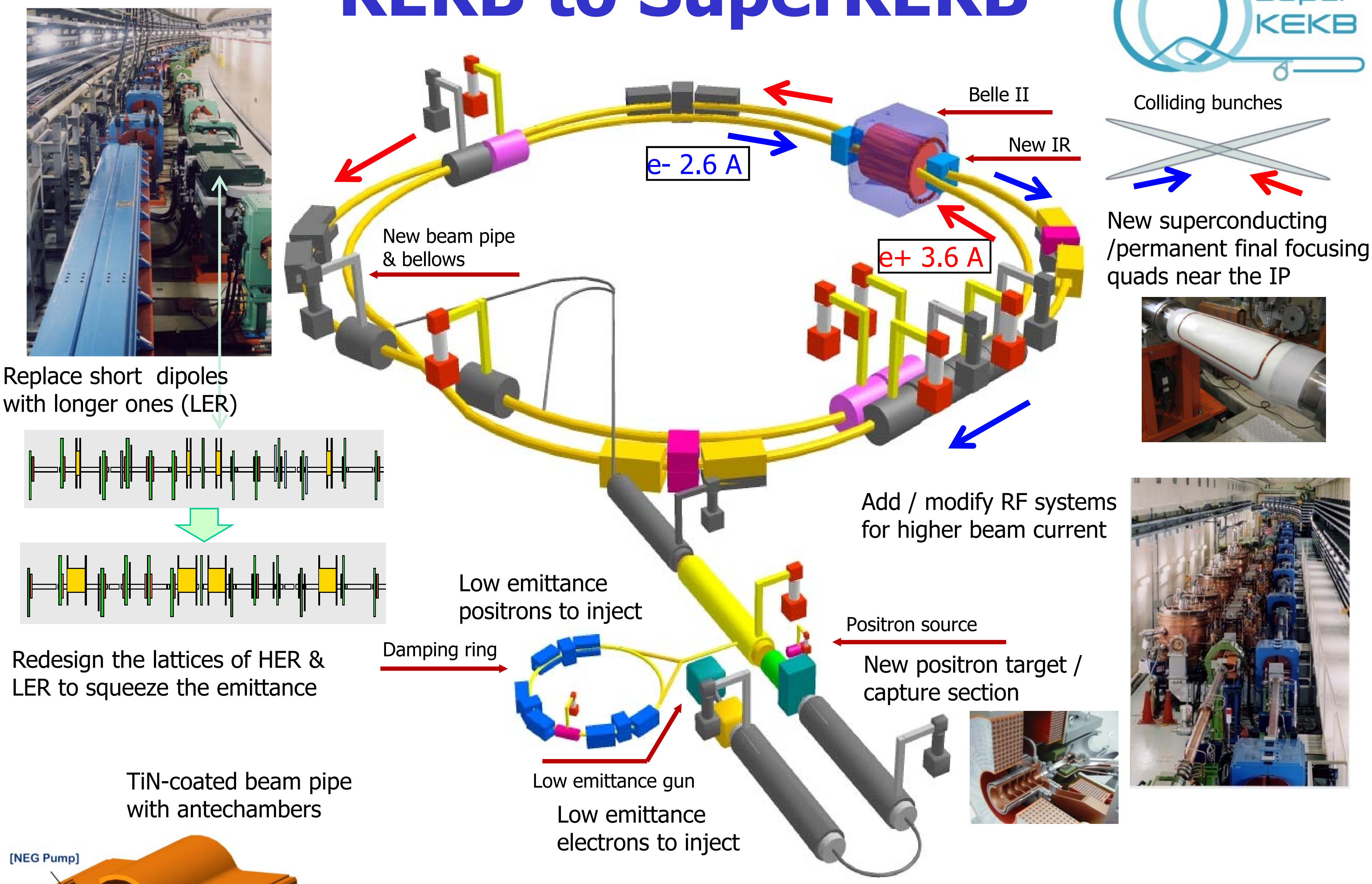
Machine design parameters

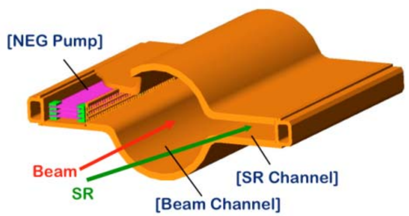
Super KEKB
Quest for BSM

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





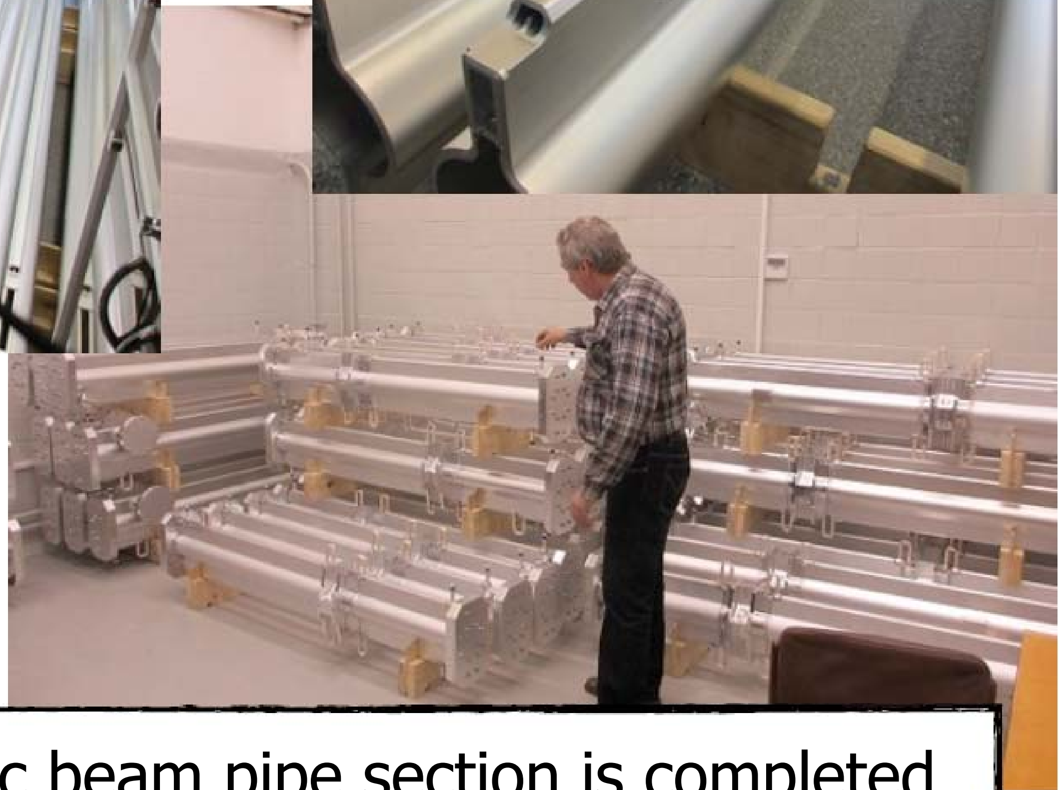
To obtain x40 higher luminosity

1/3 of new dipole magnets have been installed in LER. (July 9, 2012)

Three magnets per day ! Total ~100

- Installing the 4 m LER dipole over the 6 m HER dipole (remains in place).
- All LER dipoles are scheduled to be installed this year.

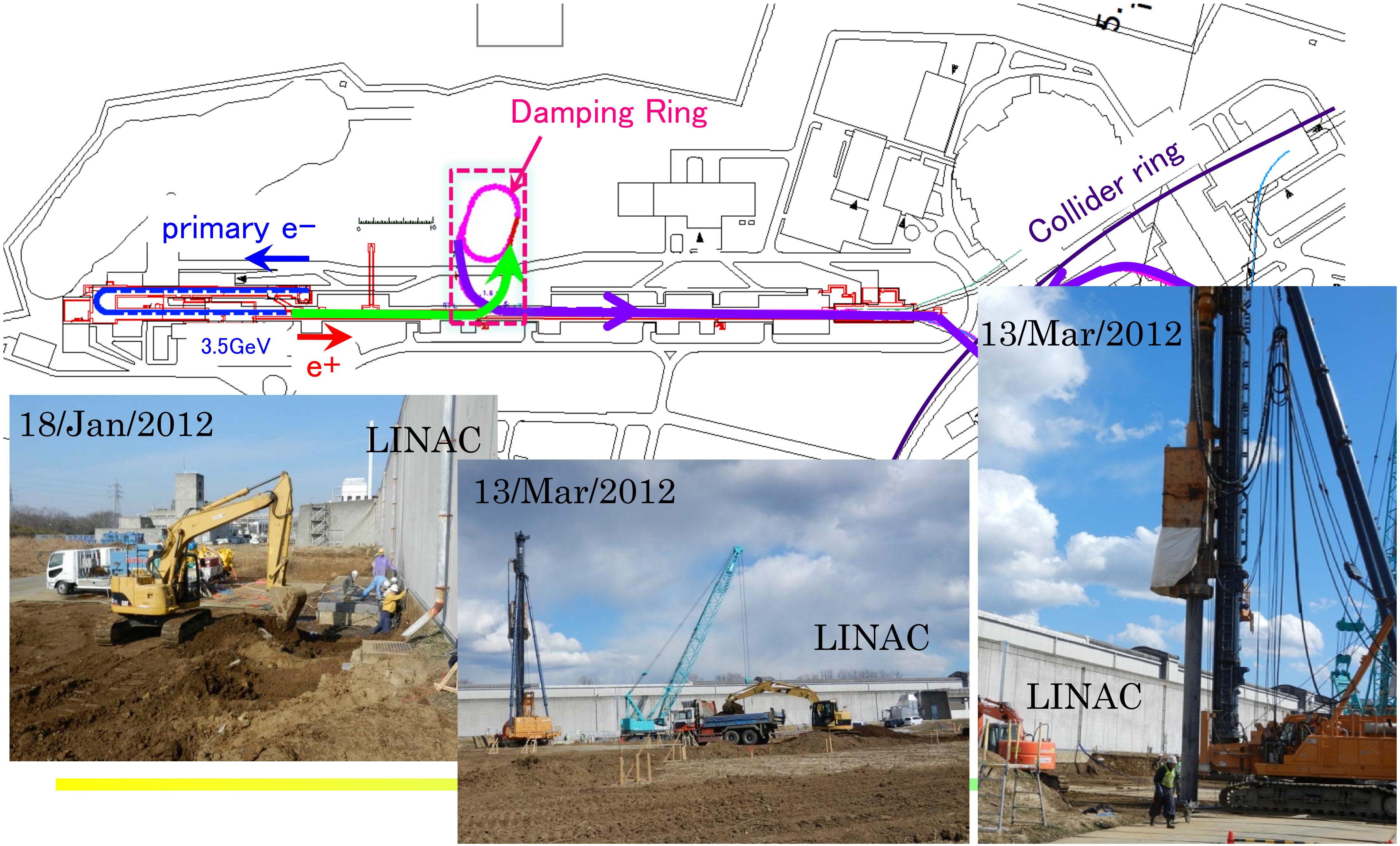
Entirely new LER beam pipe with ante-chamber and Ti-N coating



Beam pipe is made of aluminum.

Fabrication of the LER arc beam pipe section is completed

Damping ring construction started in Jan 2012



TiN Coating Machine

Beam pipe with TiN coating reduces emission of secondary photoelectrons.

TiN coating machine (1st vertical type) in Oho experimental hall

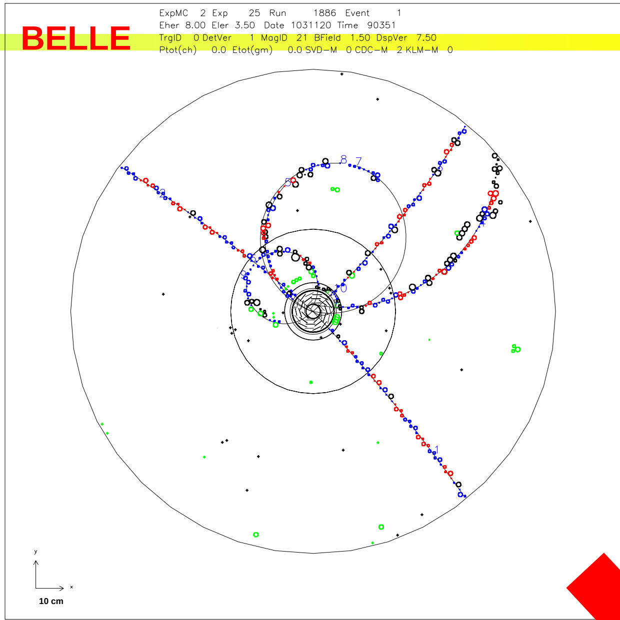
Now we have two coating machines.

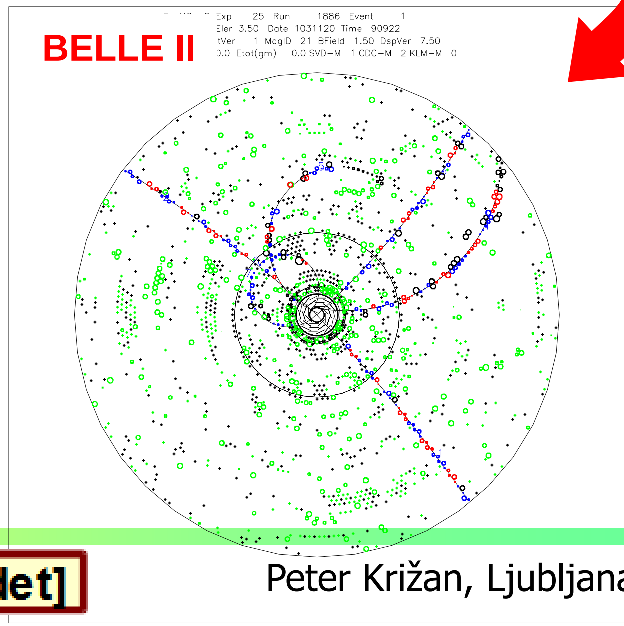
TiN coating has started – in a good shape

Need to build a new detector to handle higher backgrounds

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

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



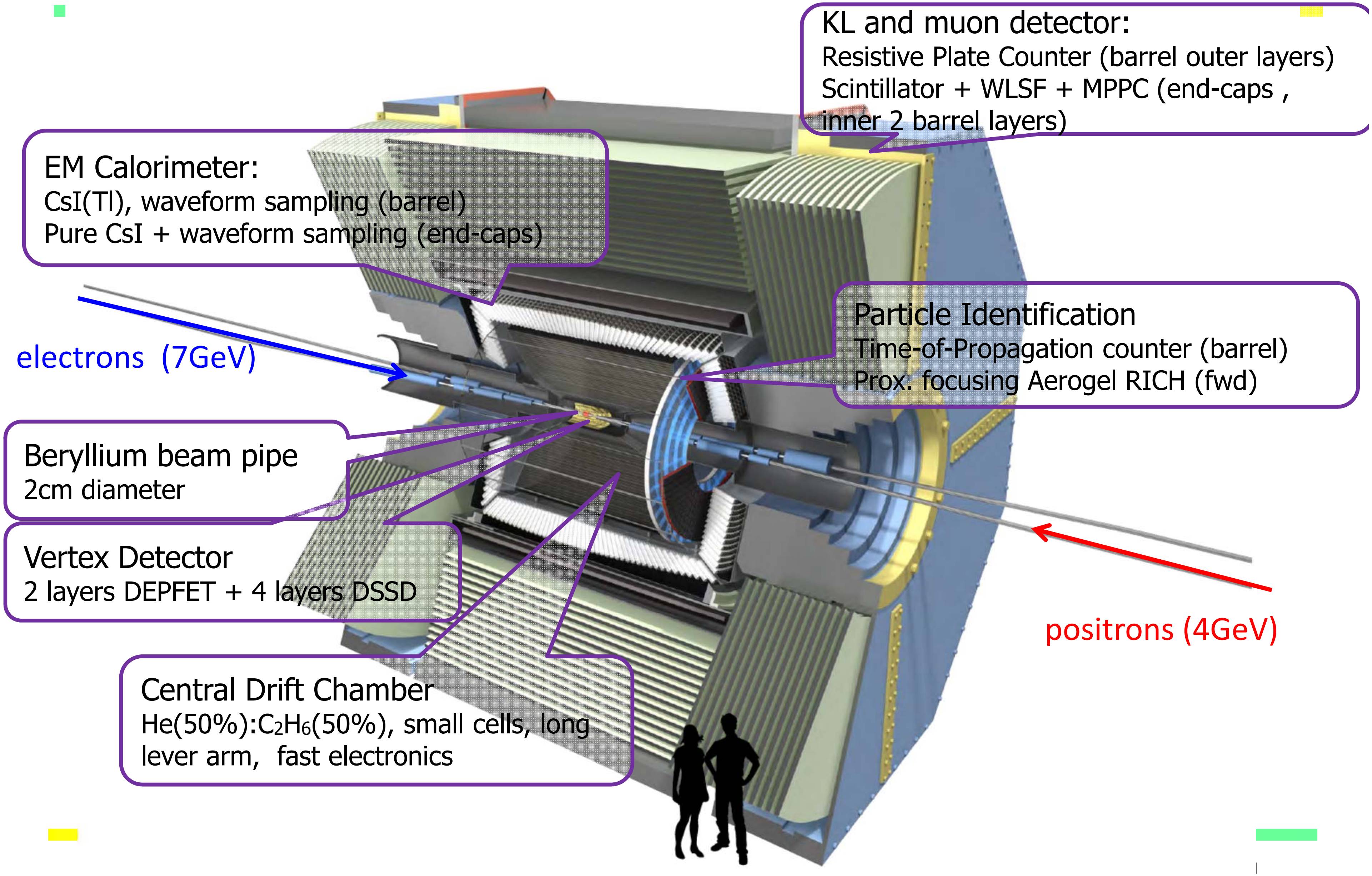


Have to employ and develop new technologies to make such an apparatus work!

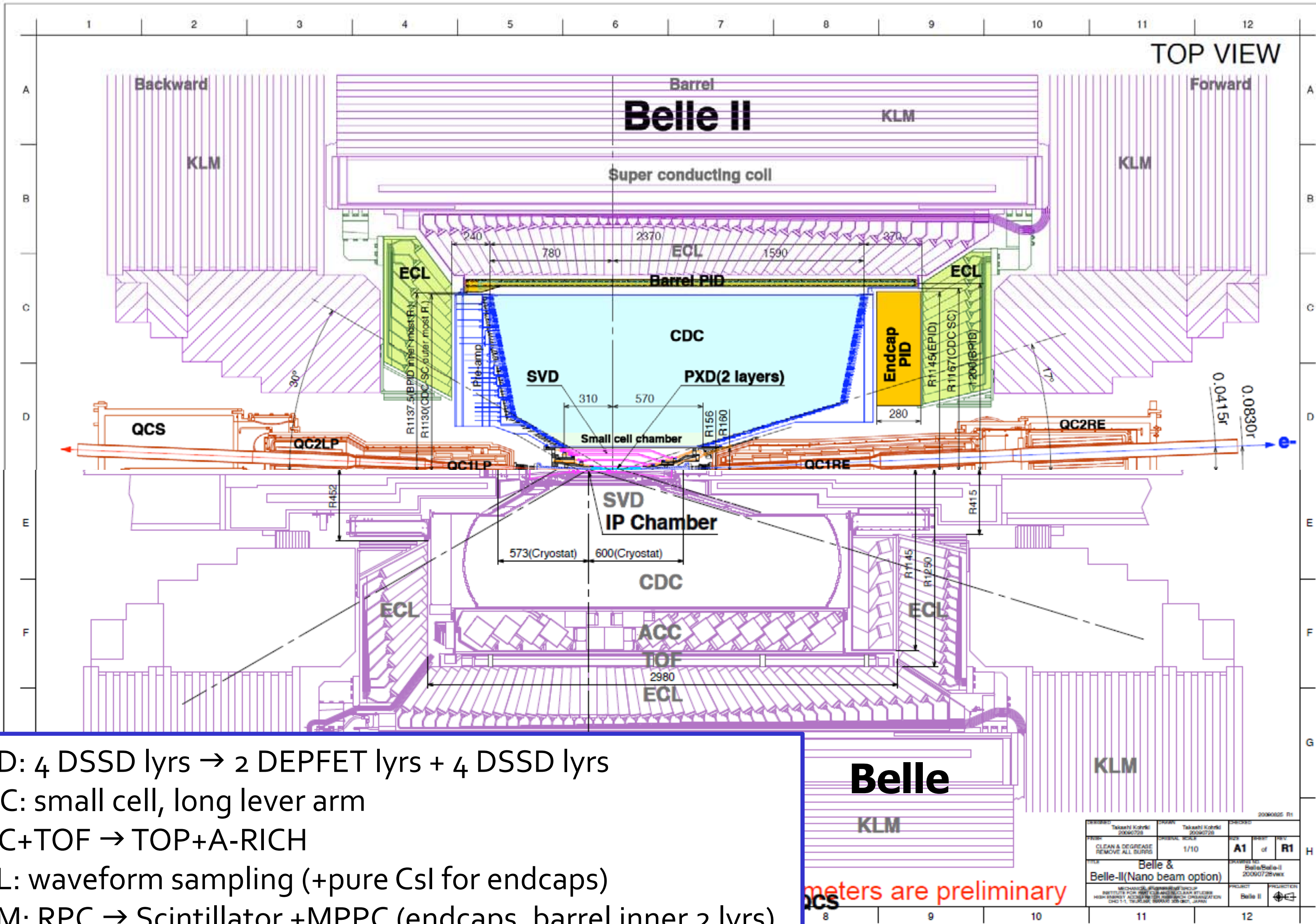
→

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

Belle II Detector



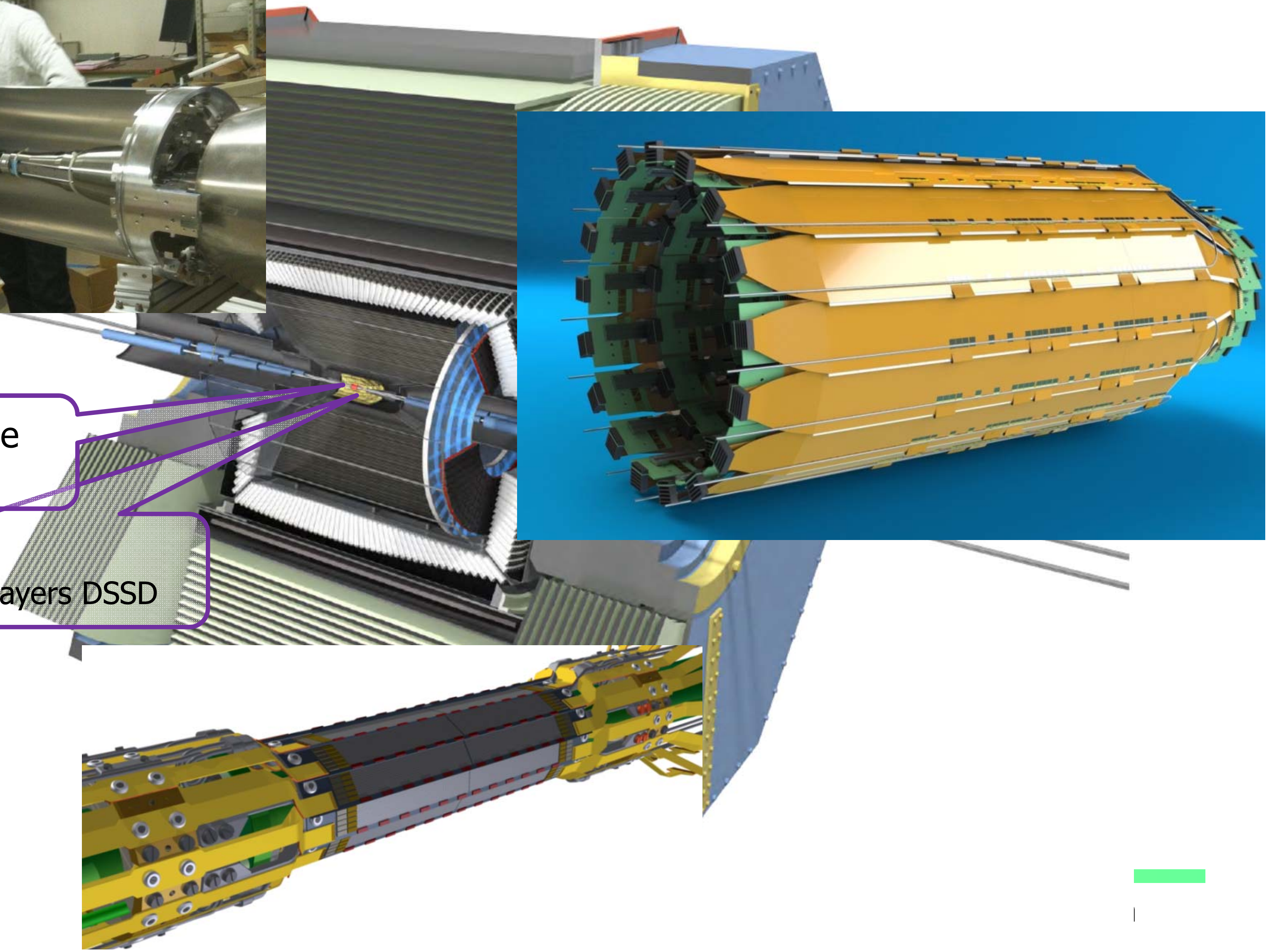
Belle II Detector (in comparison with Belle)



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)

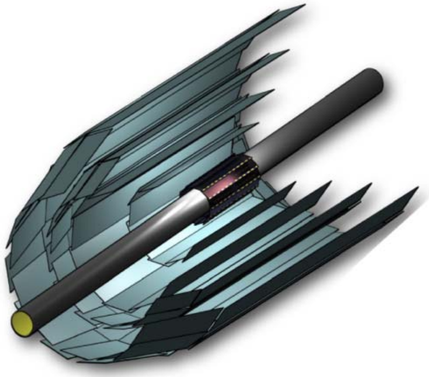
...meters are preliminary

Belle II Detector – vertex region



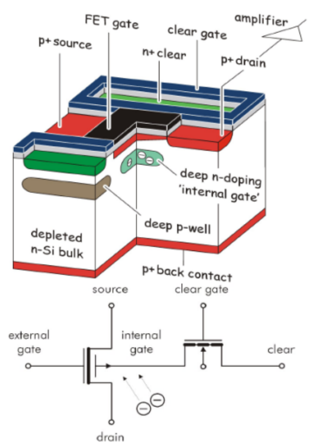
Vertex Detector

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

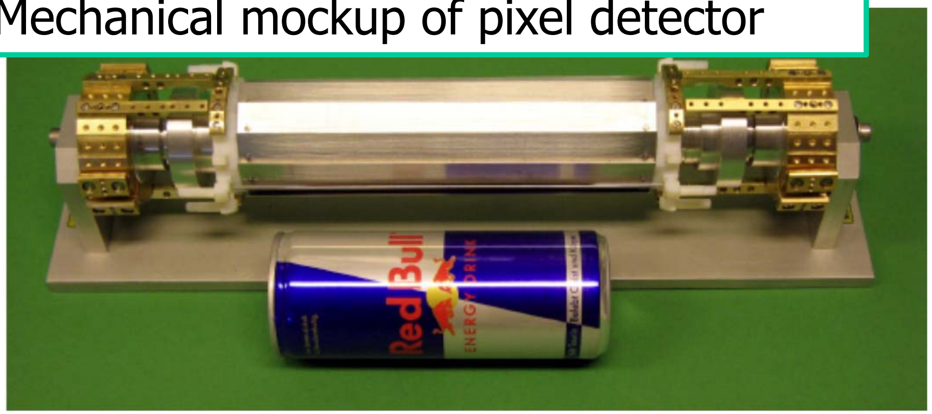


Beam Pipe		**r = 10mm**
DEPFET		
	Layer 1	**r = 14mm**
	Layer 2	**r = 22mm**
DSSD		
	Layer 3	**r = 38mm**
	Layer 4	**r = 80mm**
	Layer 5	**r = 115mm**
	Layer 6	**r = 140mm**

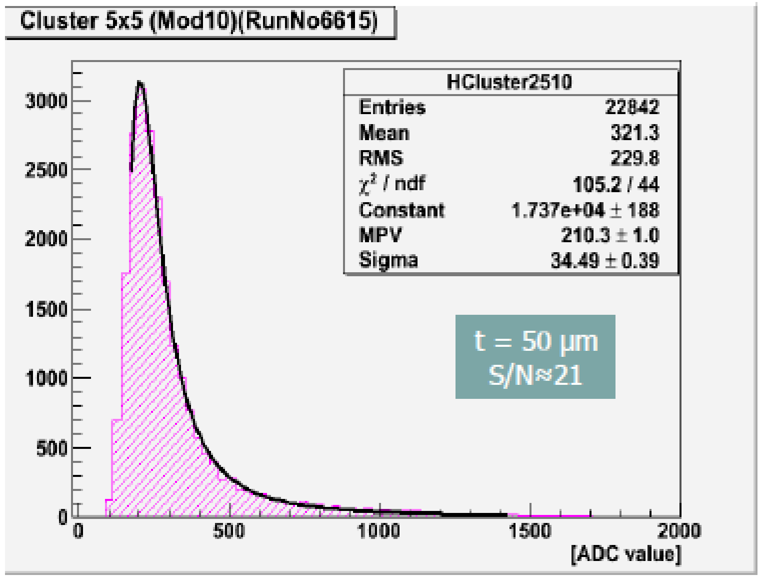
DEpleted P-channel FET



Mechanical mockup of pixel detector



DEPFET pixel sensor

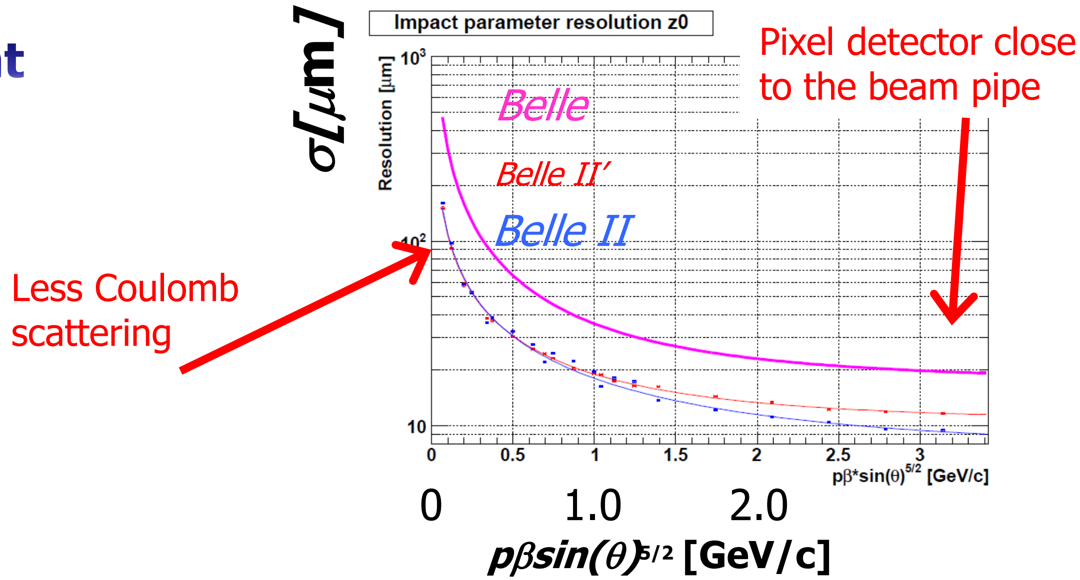


DEPFET sensor: very good S/N

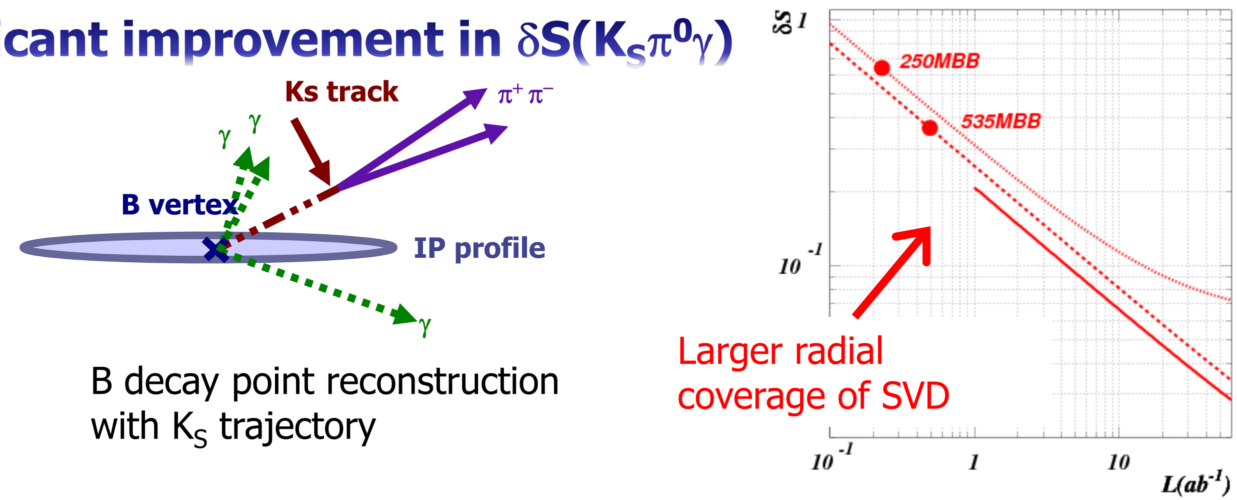
Expected performance

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

Significant improvement in vertex resolution!

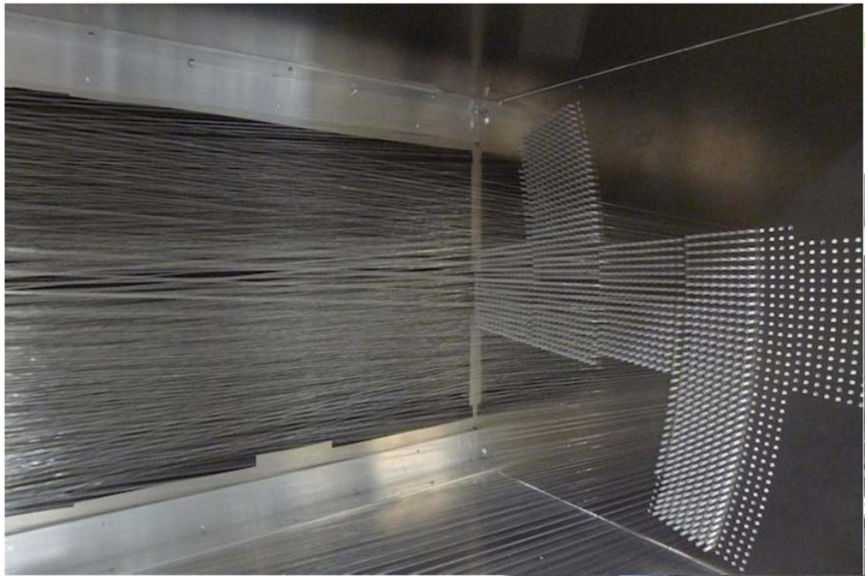


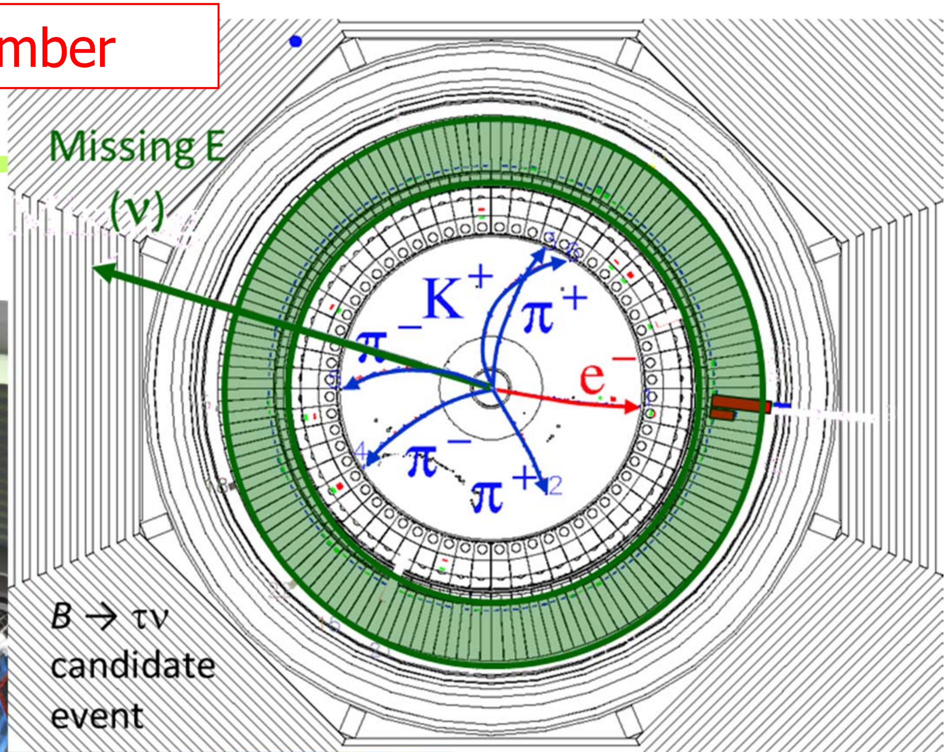
Significant improvement in $\delta S(K_S\pi^0\gamma)$

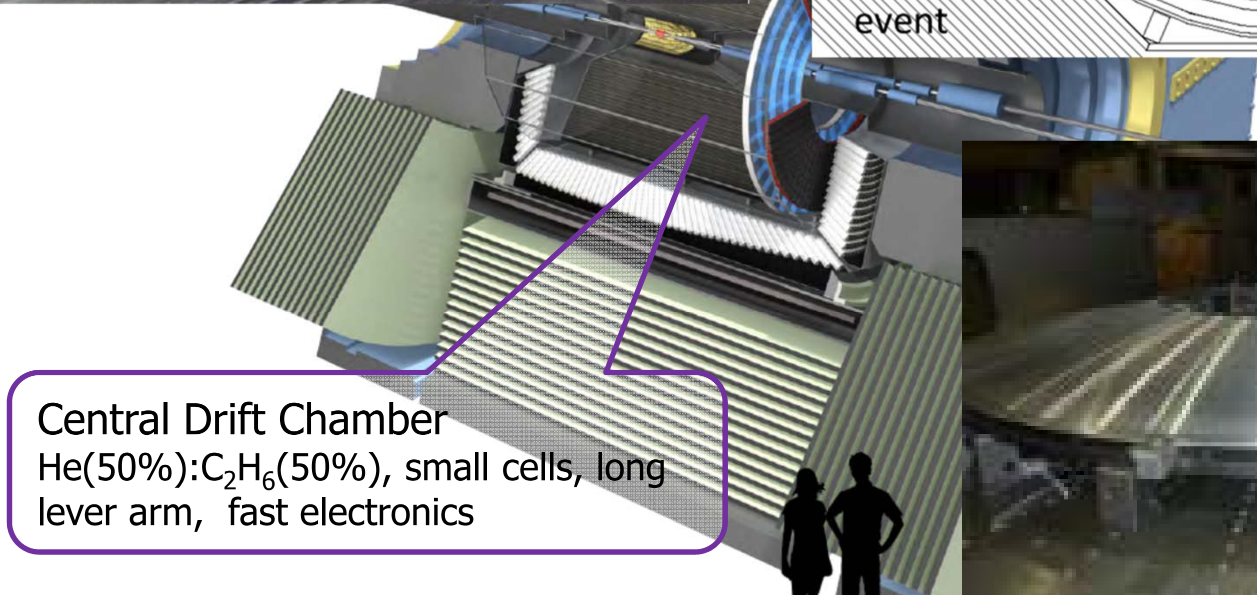


B decay point reconstruction with K_S trajectory

Main tracking device: small cell drift chamber



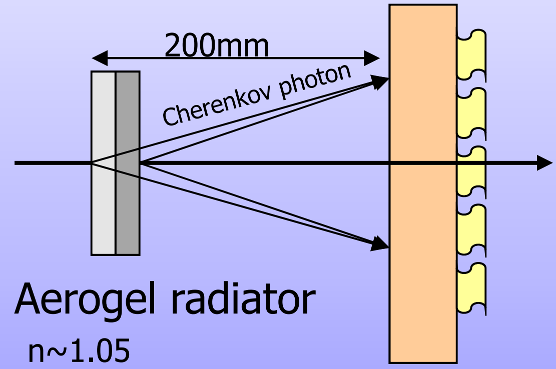




Endplates of the drift chamber have been fabricated

Particle Identification Devices

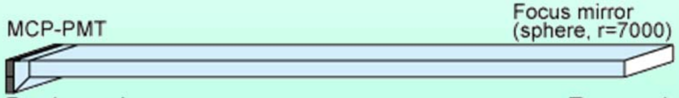
Endcap PID: Aerogel RICH (ARICH)



Aerogel radiator
n~1.05

Hamamatsu HAPD
+ new ASIC

Barrel PID: Time of Propagation Counter (TOP)

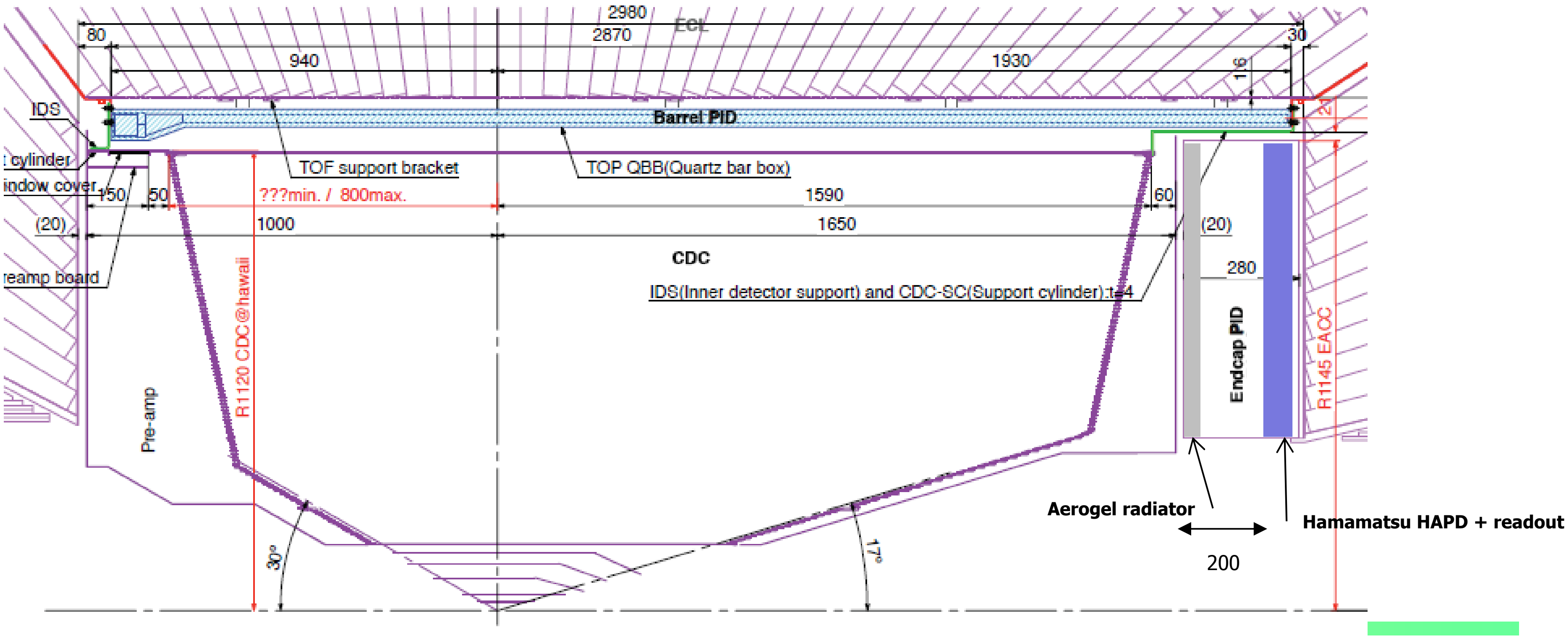


Quartz radiator

Focusing mirror

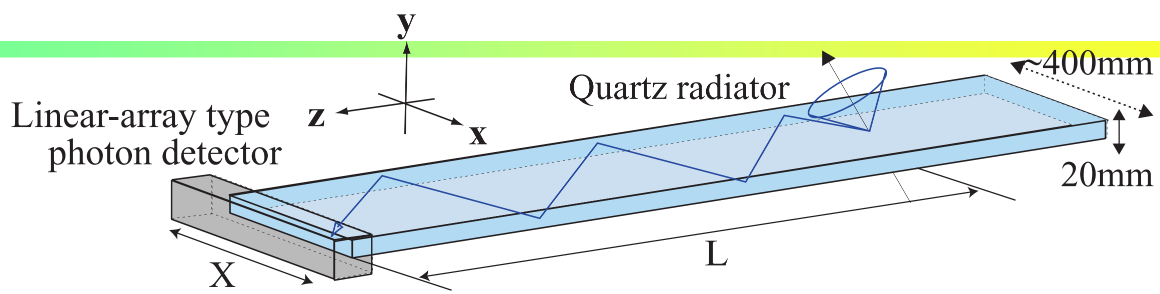
Small expansion block

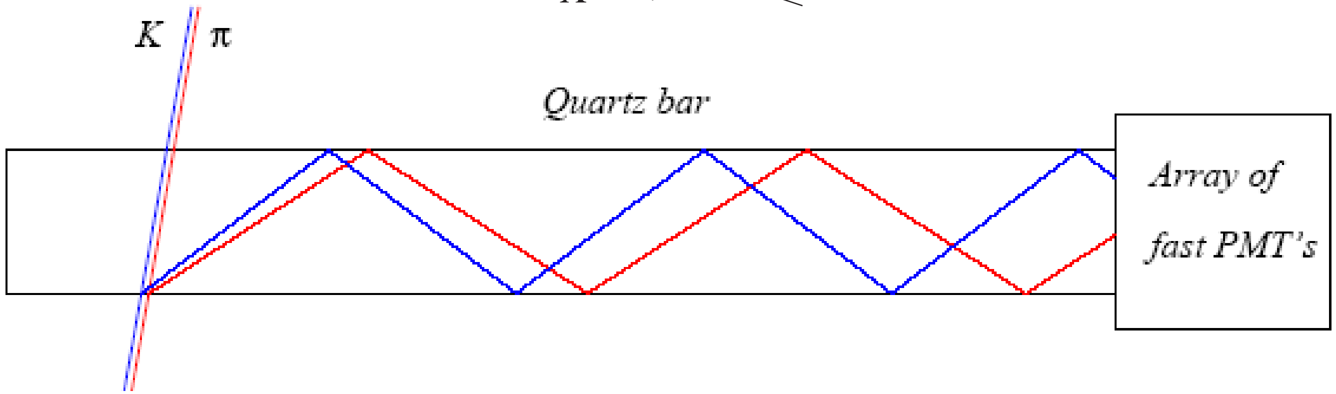
Hamamatsu MCP-PMT (measure t, x and y)

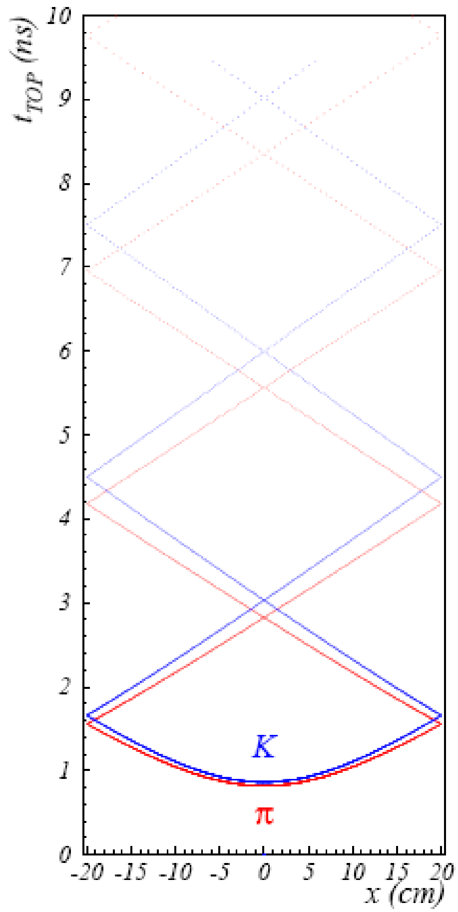


Peter Križan, Ljubljana

Barrel PID: Time of propagation (TOP) counter



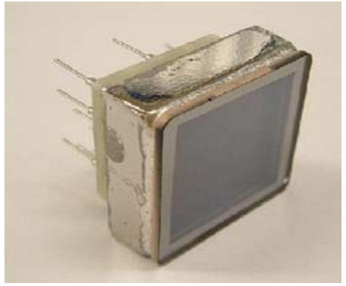




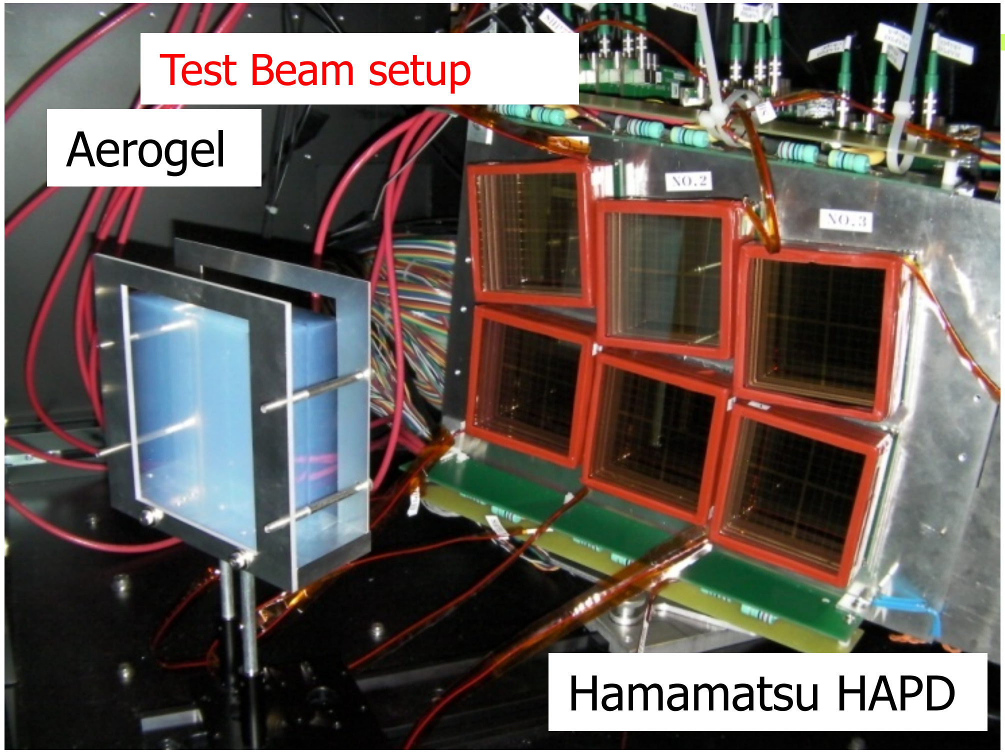
- Cherenkov ring imaging with precise time measurement.
- Device uses internal reflection of Cerenkov ring images from quartz like the BaBar DIRC.
- Reconstruct Cherenkov angle from two hit coordinates and

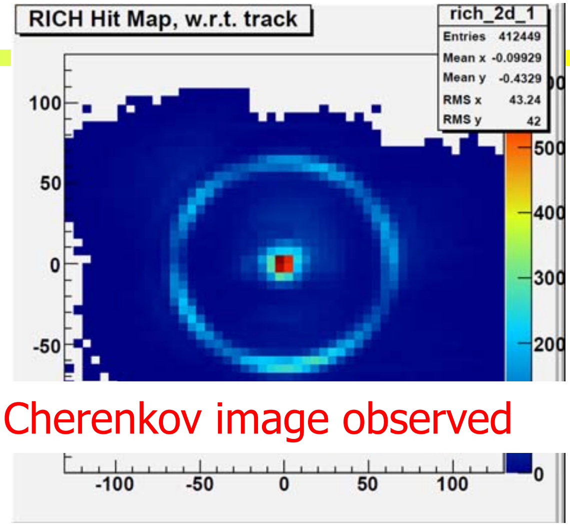
the time of propagation of the photon

  – Quartz radiator (2cm)
  – Photon detector (MCP-PMT)
    - Good time resolution ~ 40 ps
    - Single photon sensitivity in 1.5



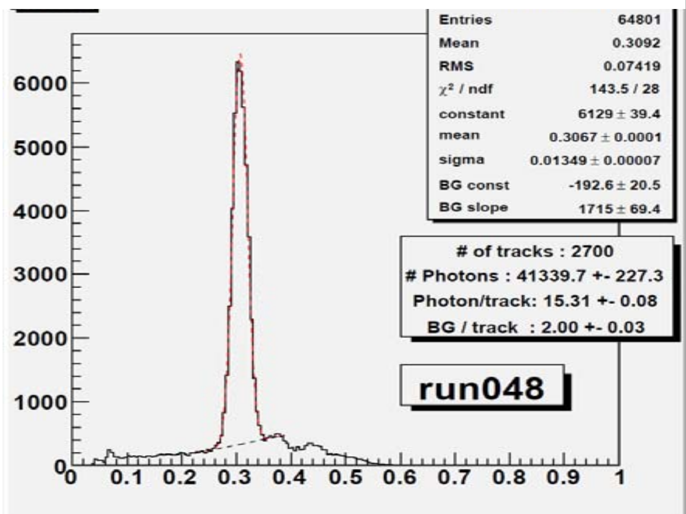
Aerogel RICH (endcap PID)





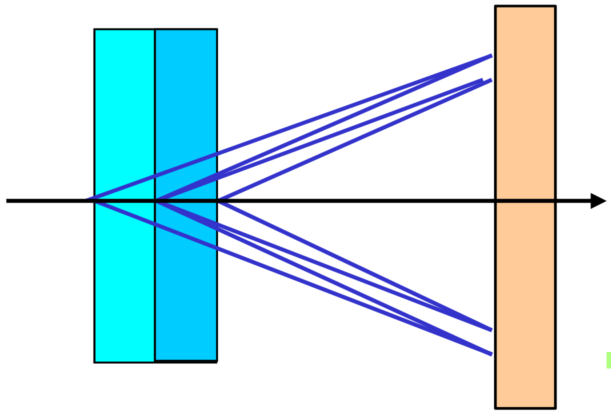
Clear Cherenkov image observed

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.



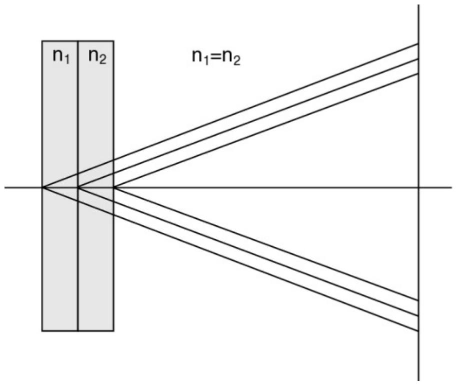
6.6 σ π/K at 4GeV/c !

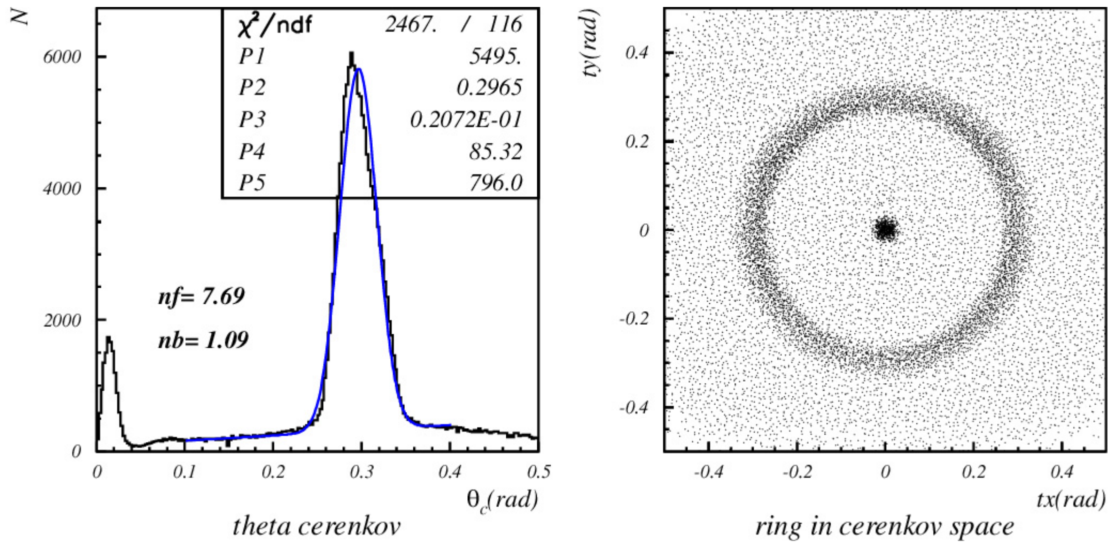
Peter Križan, Ljubljana

Focusing configuration – data

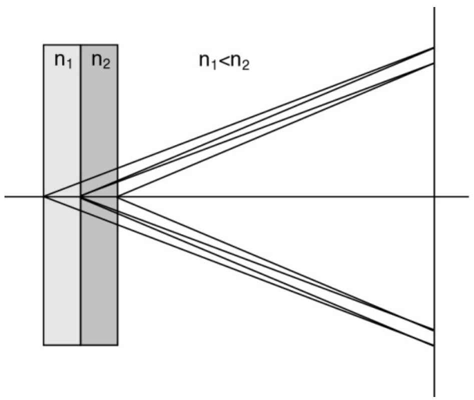
Increases the number of photons without degrading the resolution

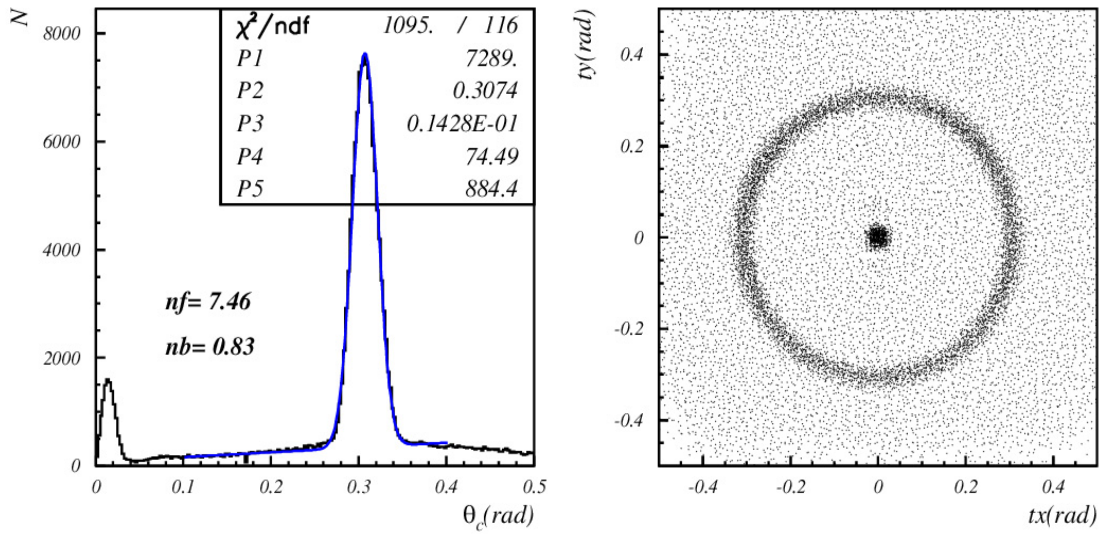
4cm aerogel single index





2+2cm aerogel



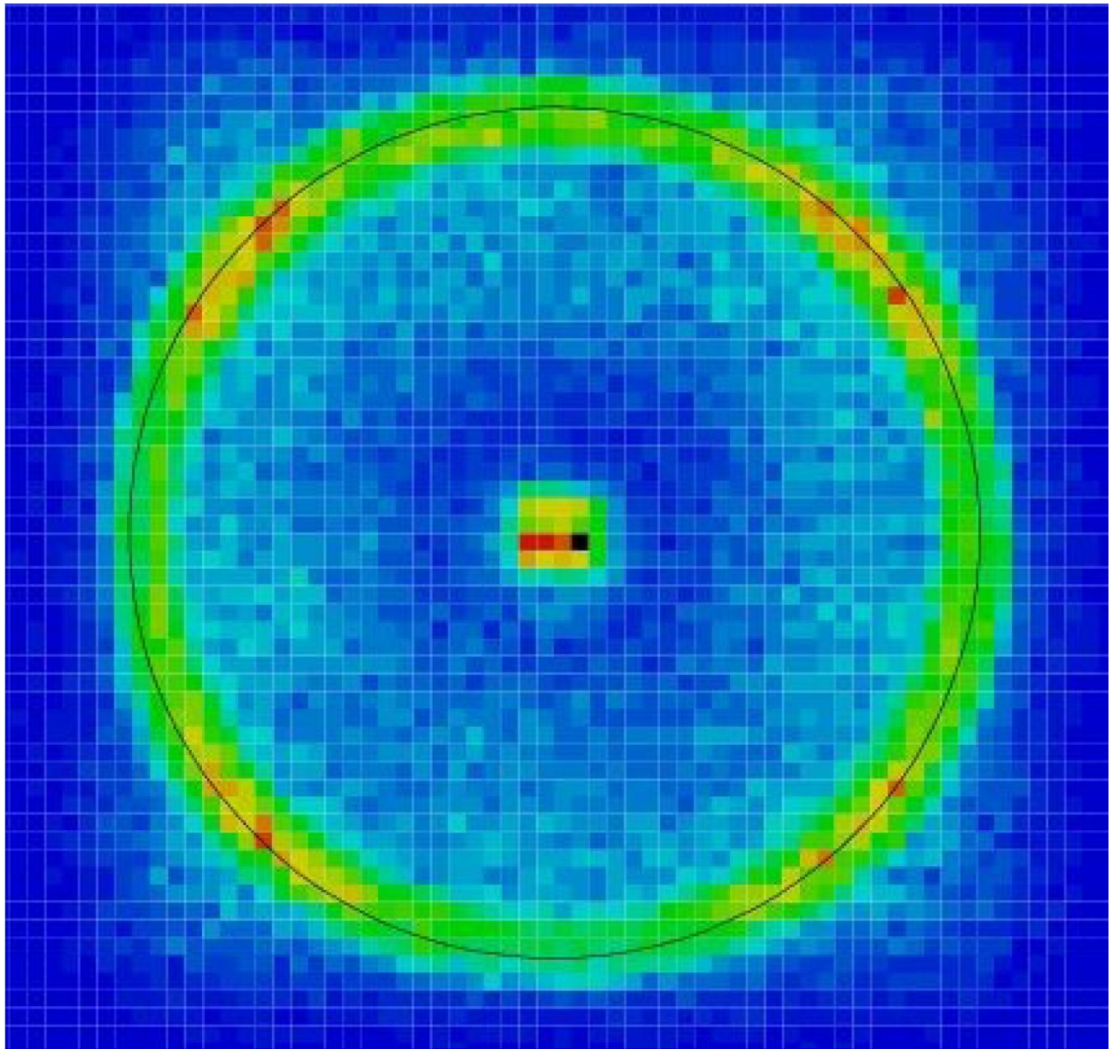


→NIM A548 (2005) 383

Another candidate: SiPM

Another sensor candidate: SiPMs (G-PAD), easy to handle, but never before used for single photon detection (high dark count rate with single photon pulse height) → use a narrow time window and light concentrators

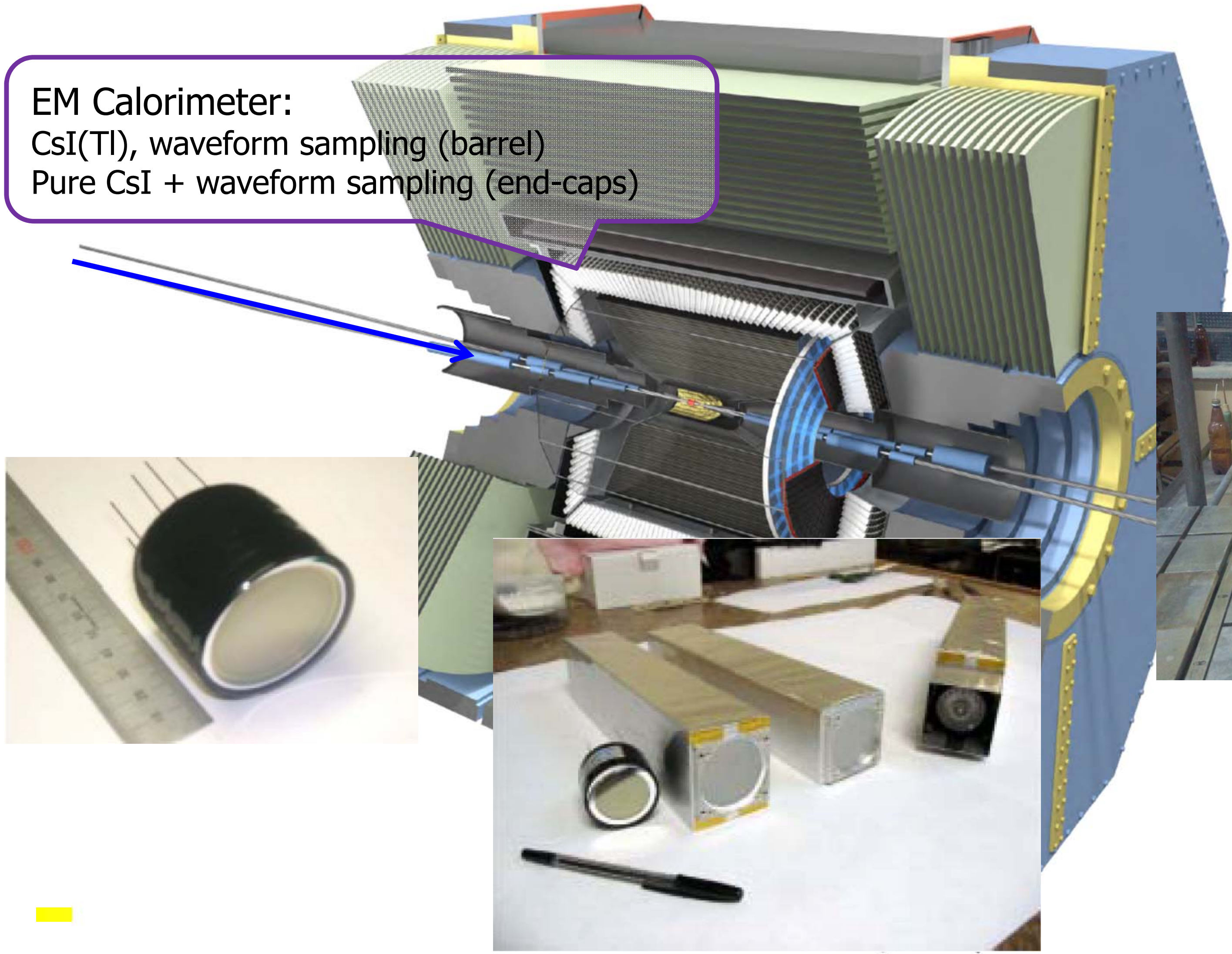
Cherenkov ring with SiPMs



First successful use of SiPMs as single photon detectors in a RICH counter!

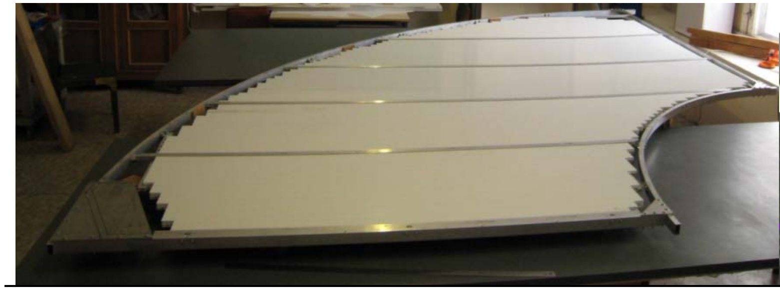
NIM A594 (2008) 13

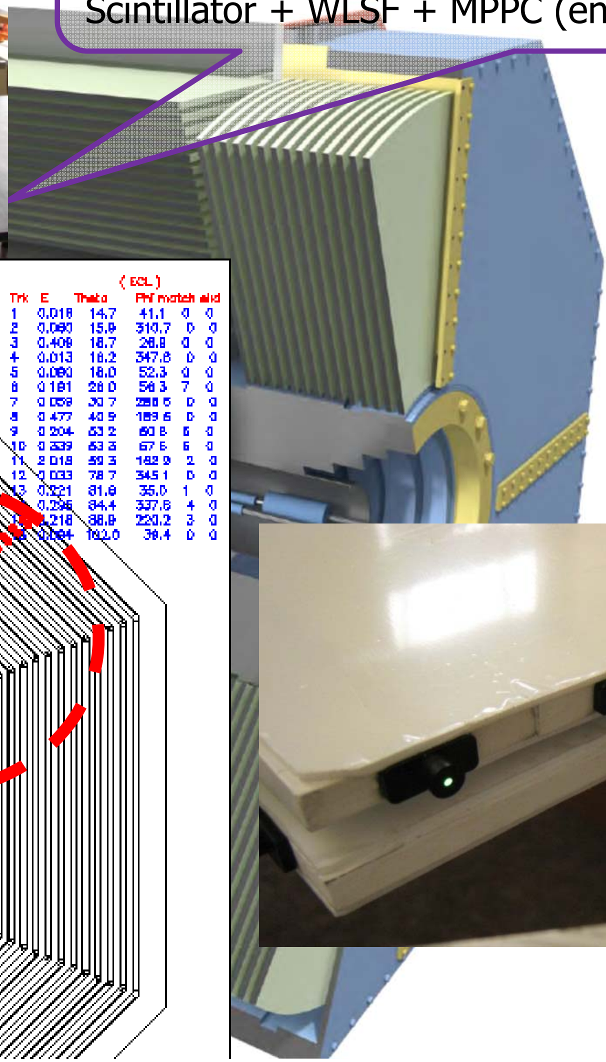
EM calorimeter: upgrade needed because of higher rates (barrel: electronics, endcap: electronics and CsI(Tl) → pure CsI), and radiation load (endcap: CsI(Tl) → pure CsI)

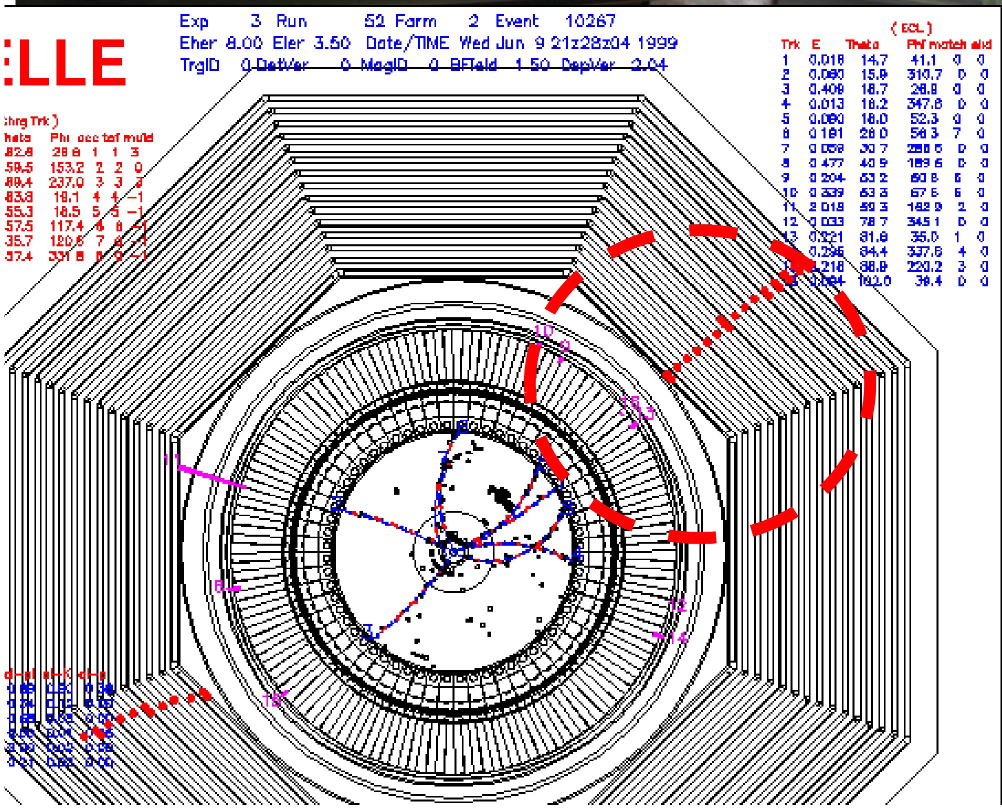


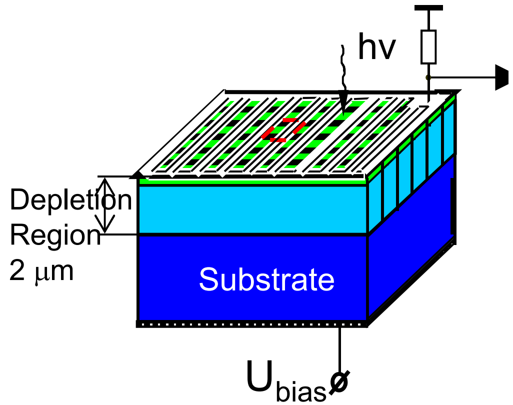
Detection of muons and K_Ls: Parts of the present RPC system have to be replaced to handle higher backgrounds (mainly from neutrons).

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







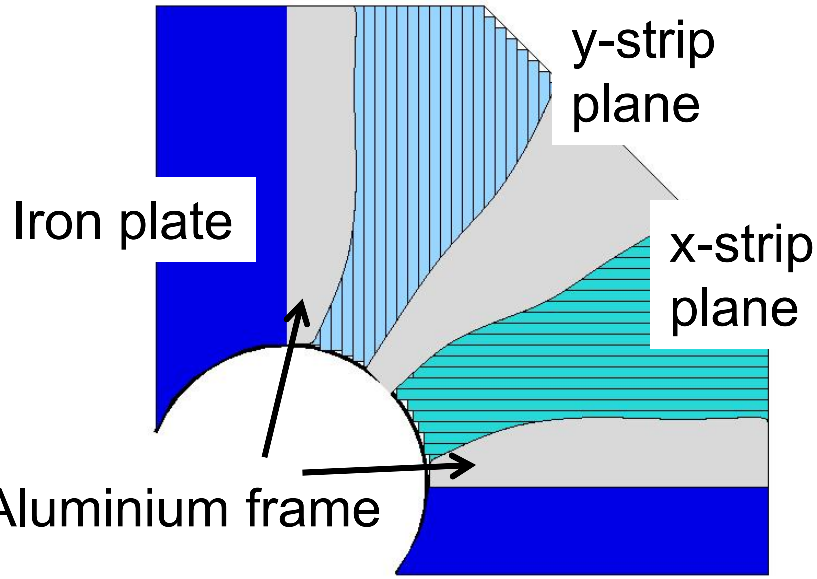


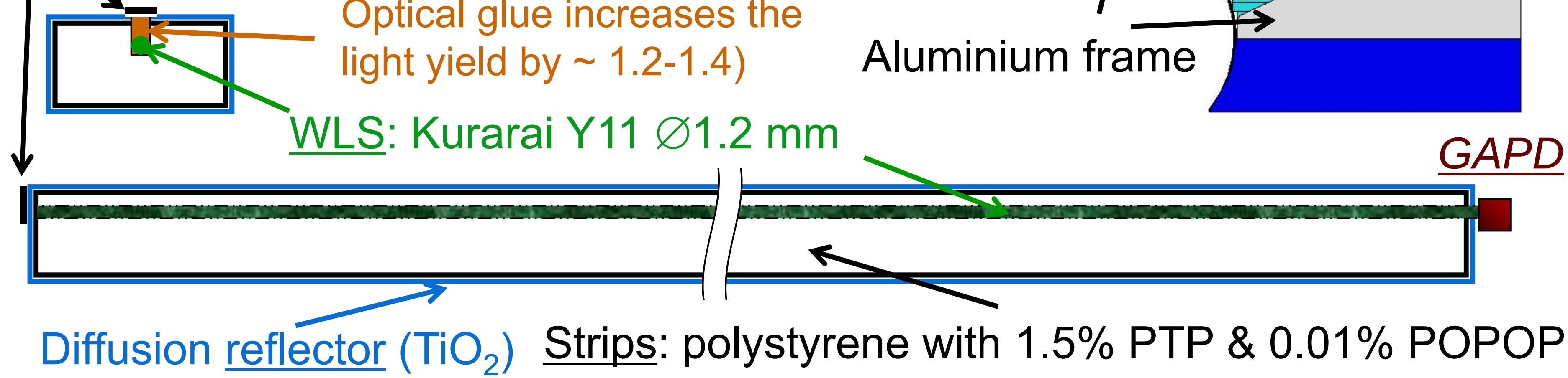
ljana

Muon detection system upgrade in the endcaps

Scintillator-based KLM (endcap and two layers in the barrel part)

- Two independent (x and y) layers in one superlayer made of orthogonal strips with WLS read out
- Photo-detector = avalanche photodiode in Geiger mode (SiPM)
- ~120 strips in one 90º sector (max L=280cm, w=25mm)
- ~30000 read out channels
- Geometrical acceptance > 99%





The Belle II Collaboration

A very strong group of ~400 highly motivated scientists!

European groups of Belle-II

- Austria: HEPHY (Vienna)
- Czech republic: Charles University (Prague)
- Germany: U. Bonn, U. Giessen, U. Goettingen, U. Heidelberg, KIT Karlsruhe, LMU Munich, MPI Munich, TU Munich
- Poland: INP Krakow
- Russia: ITEP (Moscow), BINP (Novosibirsk), IHEP (Protvino)
- Slovenia: J. Stefan Institute (Ljubljana), U. Ljubljana, U. Maribor and U. Nova Gorica
- Spain: U. Valencia
- Ukraine: ISMA (Kharkiv)

A sizeable fraction of the collaboration:

in total ~150 collaborators out of ~400!

SuperKEKB/Belle II Status

Funding

- ~100 MUS for machine approved in 2009 -- Very Advanced Research Support Program (FY2010-2012)
- Full approval by the Japanese government in December 2010; the project was finally in the JFY2011 budget as approved by the Japanese Diet end of March 2011
- Most of non-Japanese funding agencies have also already allocated sizable funds for the upgrade of the detector.

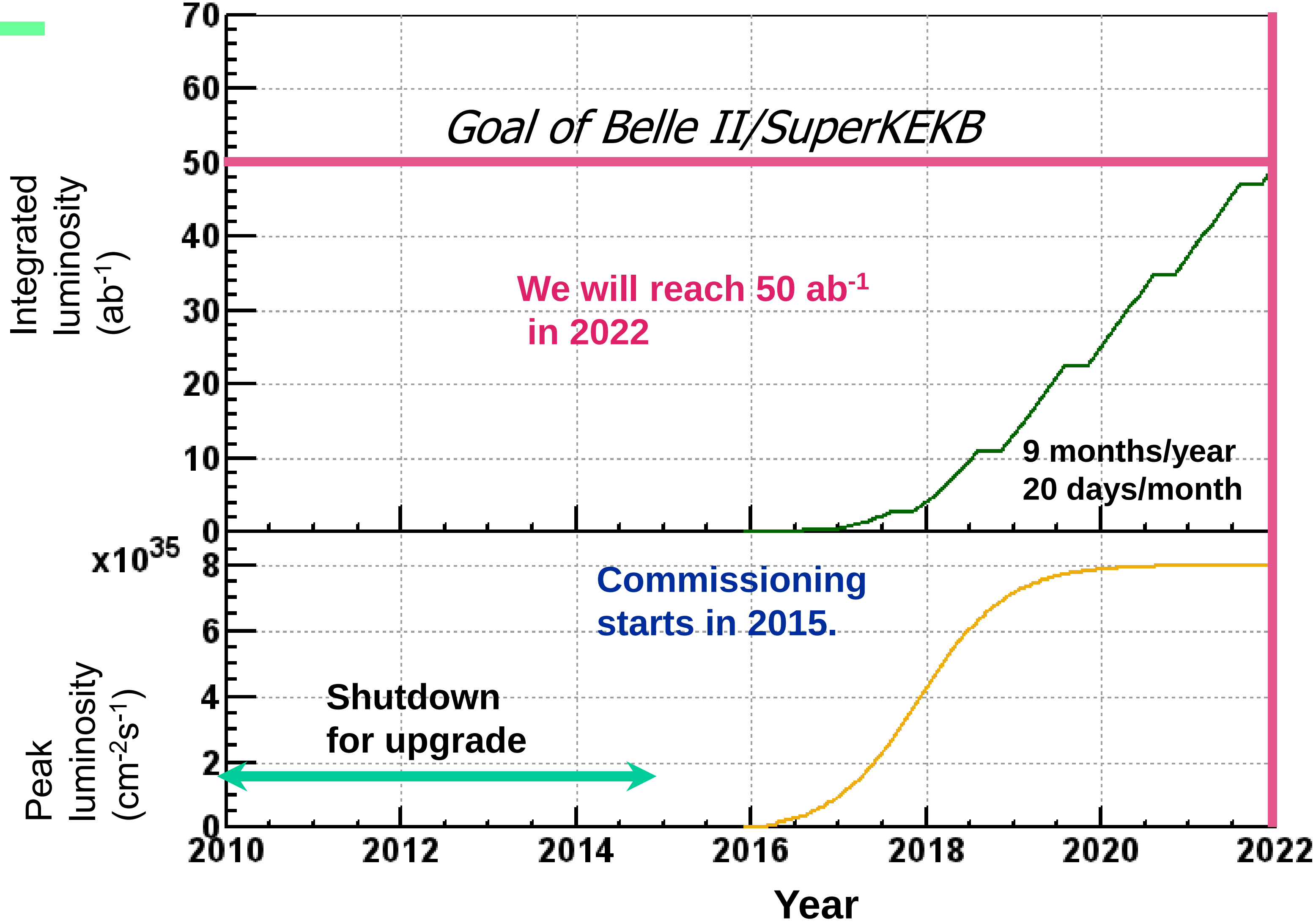
→construction started in 2010!

Fortunately little damage during the March 2011 earthquake → no delay

Ground breaking ceremony in November 2011

SuperKEKB and Belle II construction proceeds according to the schedule.

Schedule



The schedule is likely to shift by a few months because of a new construction/commissioning strategy for the final quads.

Conclusion

- KEKB has proven to be an excellent tool for flavour physics, with reliable long term operation, breaking world records, and surpassing its design perfomance by a factor of two.
- Major upgrade at KEK in 2010-15 → SuperKEKB+Belle II, with 40x larger event rates, construction well under way
- Expect a new, exciting era of discoveries, complementary to the LHC
- There is a lot of work to be done – if you are interested, join us – it is a good group with excellent working atmosphere!