Prospects of SuperKEKB and Belle-II

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"Jožef Stefan" Institute

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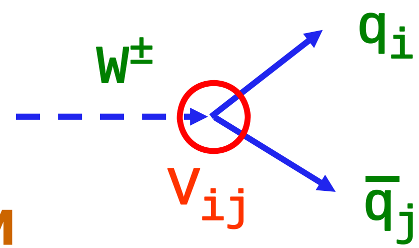
- Physics case for a Super B factory
- Accellerator upgrade → SuperKEKB
- Detector upgrade → Belle-II
- Summary

B factory physics program

B factory main task: measure CP violation in the system of B mesons

specifically: various measurements of complex elements of Cabbibo-Kobayashi-Maskawa matrix

CKM matrix is unitary

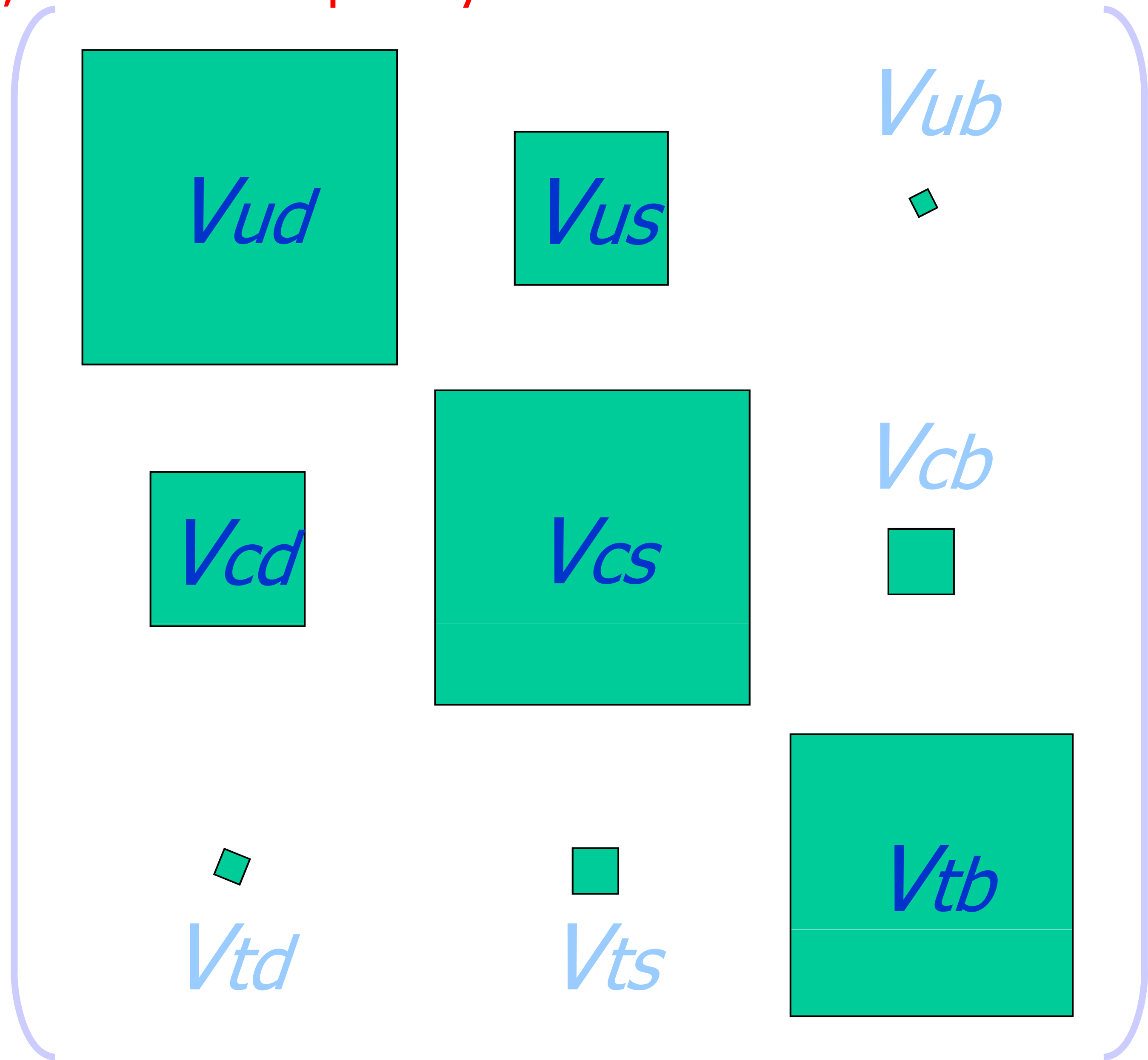


deviations could signal processes not included in SM

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta}) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$

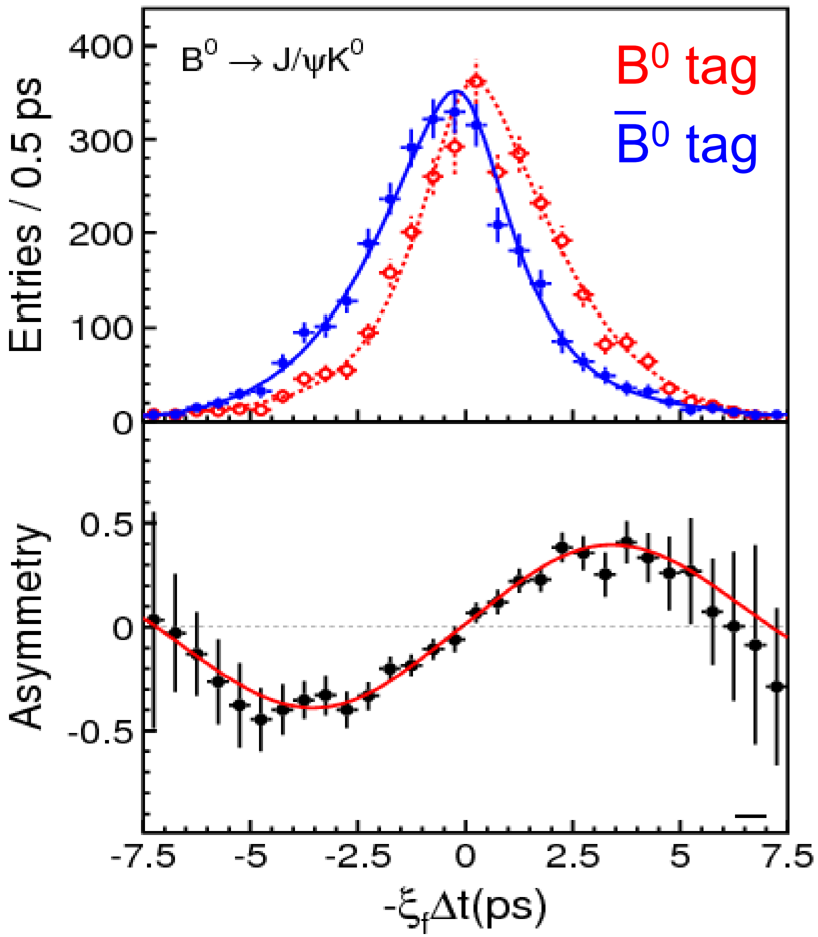
CKM: almost a diagonal matrix, but not completely

CKM: almost real, but not completely!



CP violation in the B system

CP violation in B system: from the discovery (2001) to a precision measurement (2006)

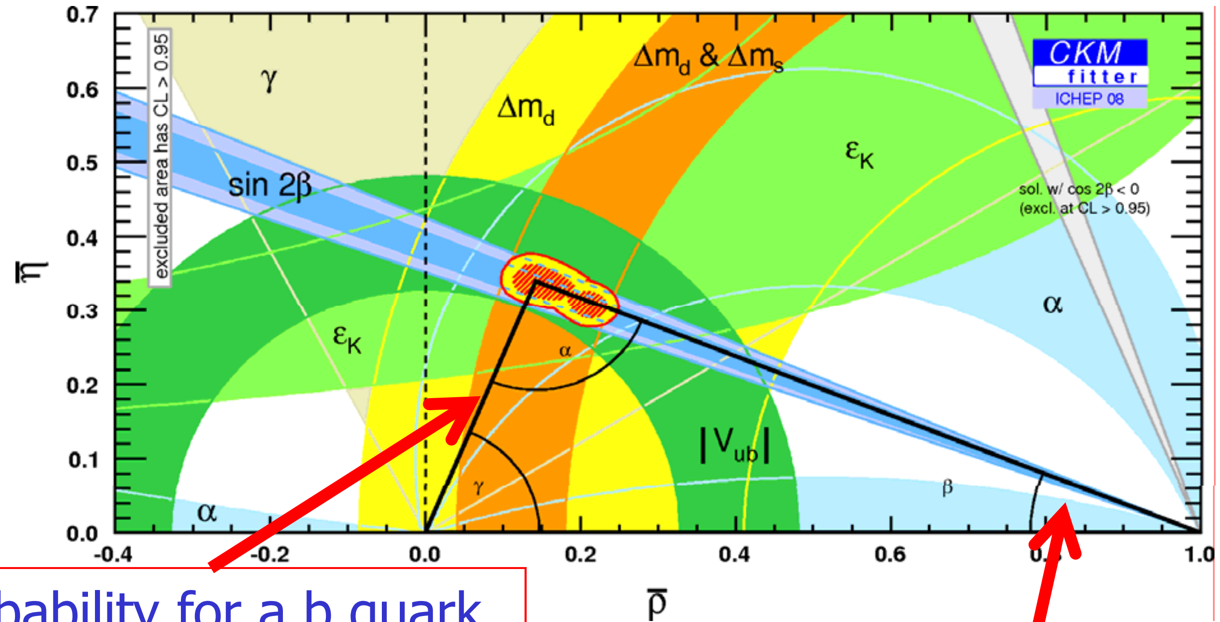


$\sin 2\phi_1 = \sin 2\beta$ from $b \to c\bar{c}s$

535 M $B\overline{B}$ pairs

$\sin 2\phi_1 = 0.642 \pm 0.031$ (stat) ± 0.017 (syst)

All measurements combined...



Probability for a b quark to turn into a u quark → determines the length of the side **V_{ub}**

CP asymmetry oscilation
amplitude

Constraints from measurements of angles a
unitarity triangle

➡ Nobel prize 2008 → Remark

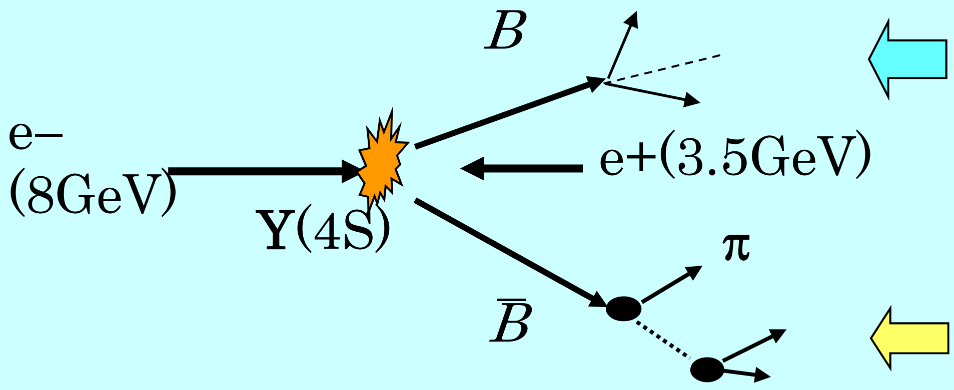
Also for us a good reason to celebrate...

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., $B \rightarrow \tau\nu$, $D\tau\nu$) by fully reconstructing the other B meson
- Observation of D mixing
- CP violation in $b \rightarrow s$ transitions: probe for new sources if CPV
- Forward-backward asymmetry (A_{FB}) in $b \rightarrow sl^+l^-$ has become a powerfull tool to search for physics beyond SM.
- Observation of new hadrons

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



Decays of interest
$B \to X_u\, l\, \nu$,
$B \to K\, \nu\, \nu$
$B \to D \tau \nu$, $\tau \nu$

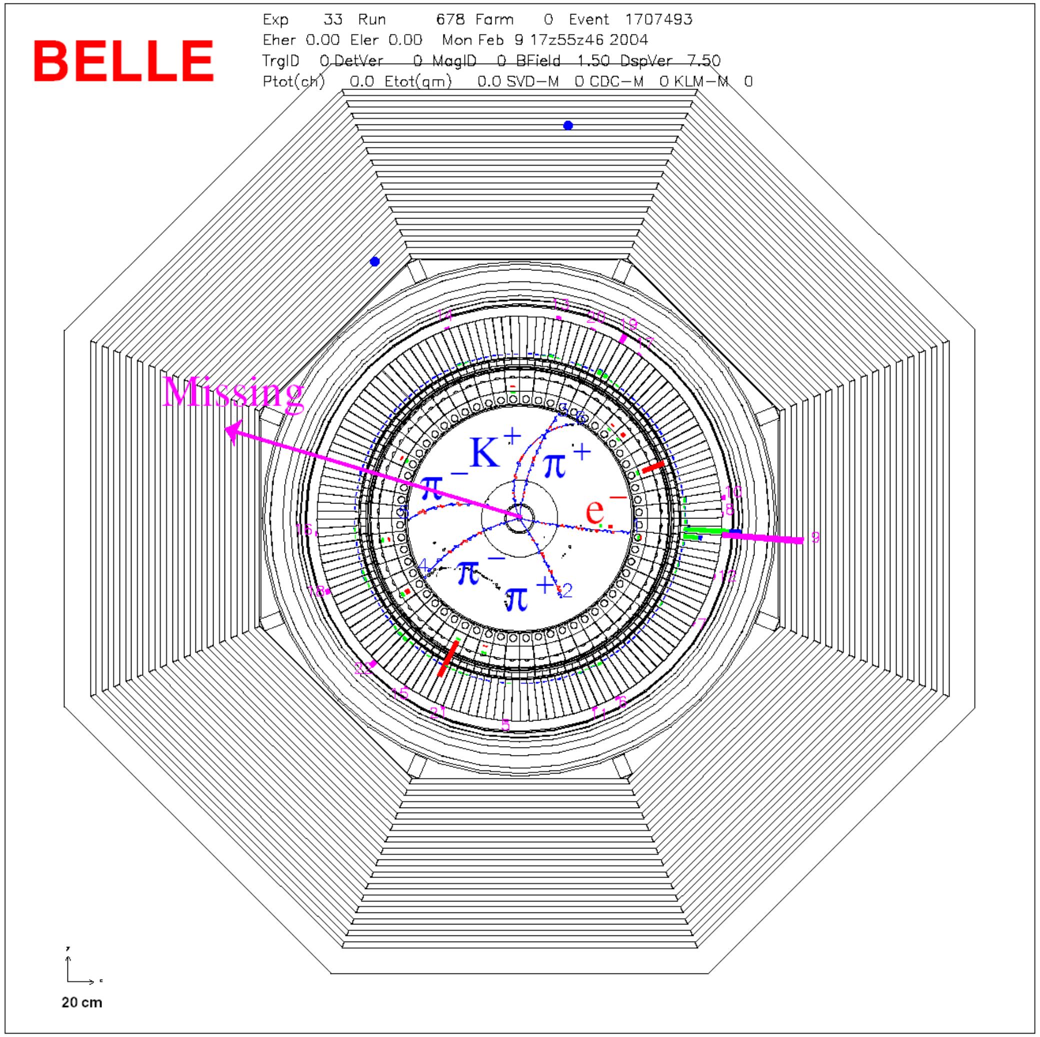
full reconstruction
$B \to D\pi$ etc. (0.1~0.3%)

→ Offline B meson beam!

Powerful tool for B decays with neutrinos

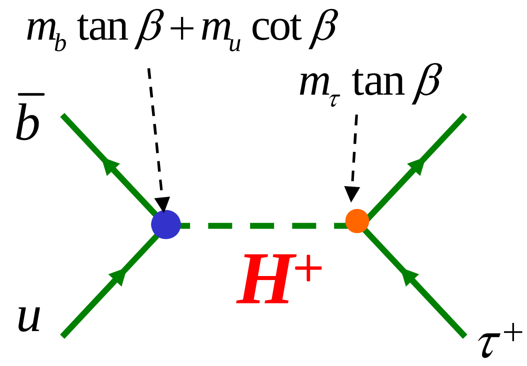
Event candidate $B^- \to \tau^- \nu_\tau$

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

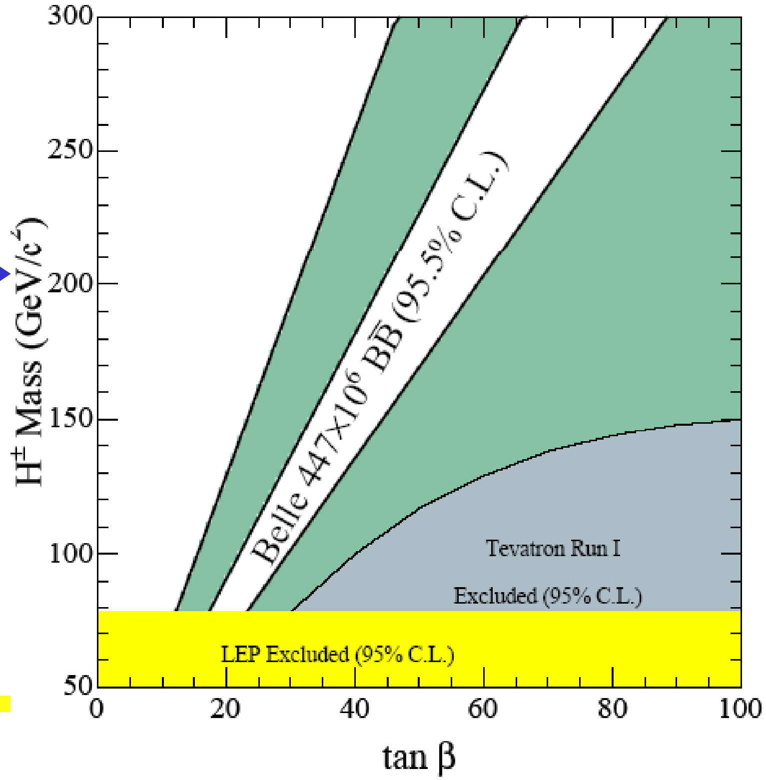


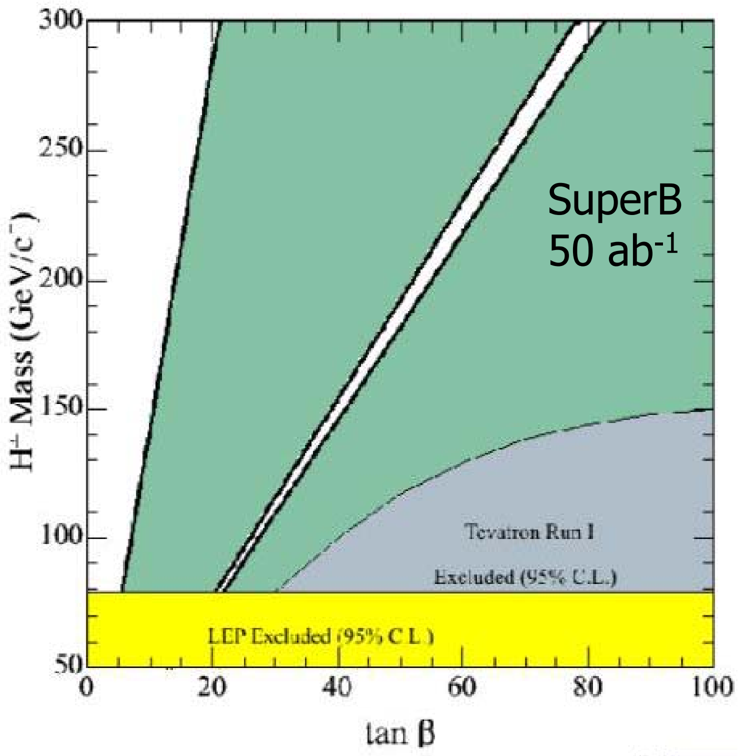
Charged Higgs limits from $B^- \to \tau^- \nu_\tau$

$$r_H = \frac{BF(B \to \tau\nu)}{BF(B \to \tau\nu)_{SM}} = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$



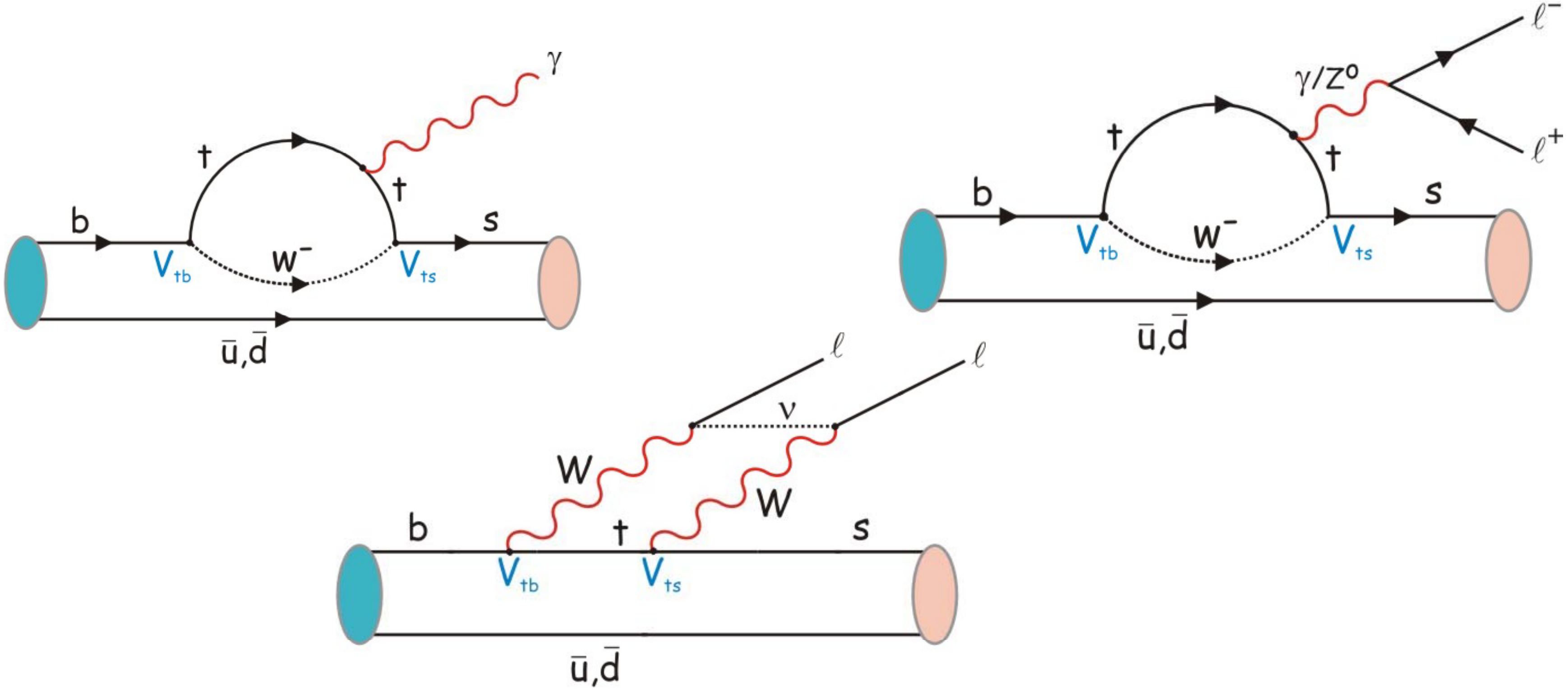
→ limit on charged Higgs mass vs. tanβ





Why FCNC decays?

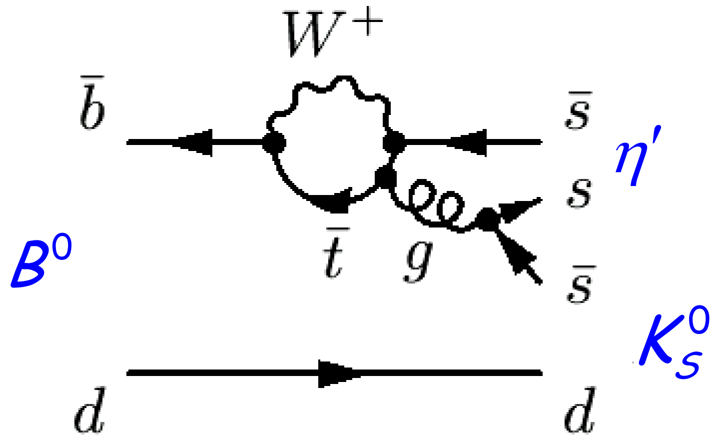
Flavour changing neutral current (FCNC) processes (like b→s, b→d) are fobidden at the tree level in the Standard Model. Proceed only at low rate via higher-order loop diagrams. Ideal place to search for new physics.



How can New Physics contribute to b→s?

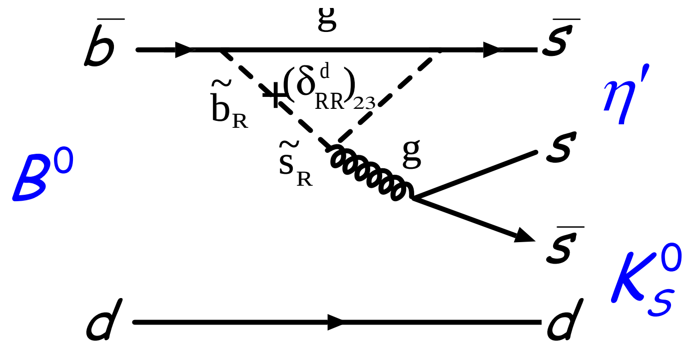
For example in the process:

$$B^0 \to \eta' K^0$$



Ordinary penguin diagram with a t quark in the loop

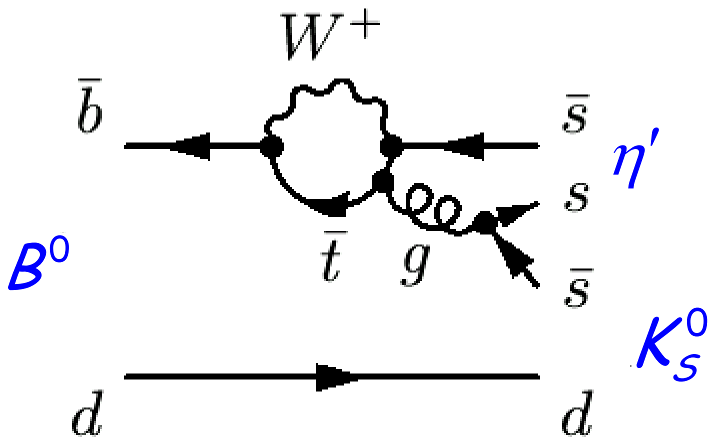
Diagram with supersymmetric particles



Searching for new physics phases in CP violation measurements in b→s decays

Prediction in SM: CP violation parameter

$B^0 \to \eta' K^0$



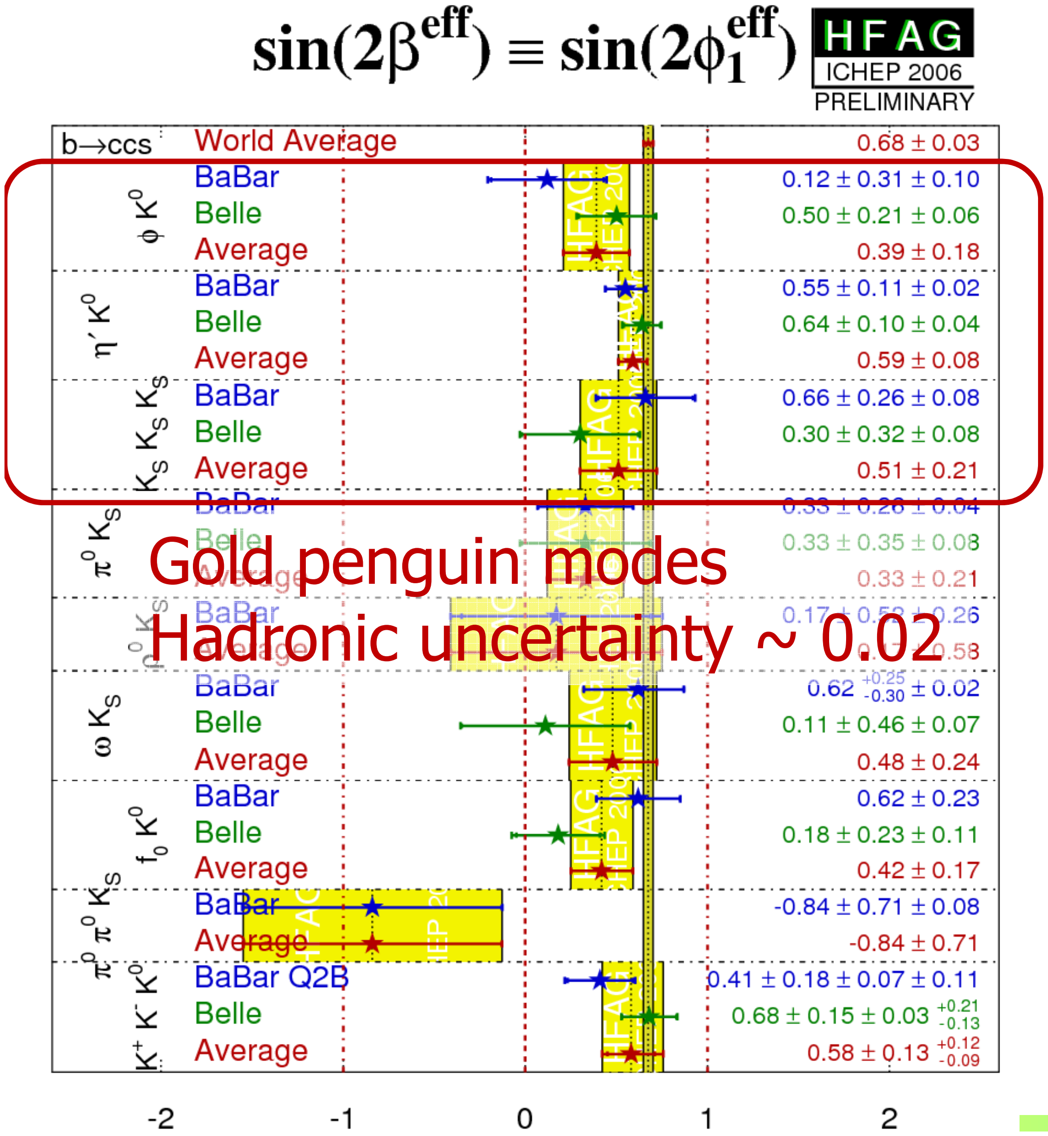
$$a_f = -\mathrm{Im}(\lambda_f)\sin(\Delta m t)$$

$$\mathrm{Im}(\lambda_f) = \xi_f \sin 2\phi_1$$

The same value as in the decay $B^0 \to J/\psi\ K_S$!

This is only true if there are no other particles in the loop! In general the parameter can assume a different value $\sin 2\phi_1^{eff}$

Search for NP: $b \to s\bar{q}q$



ICHEP08

BaBar
Belle
Naïve average

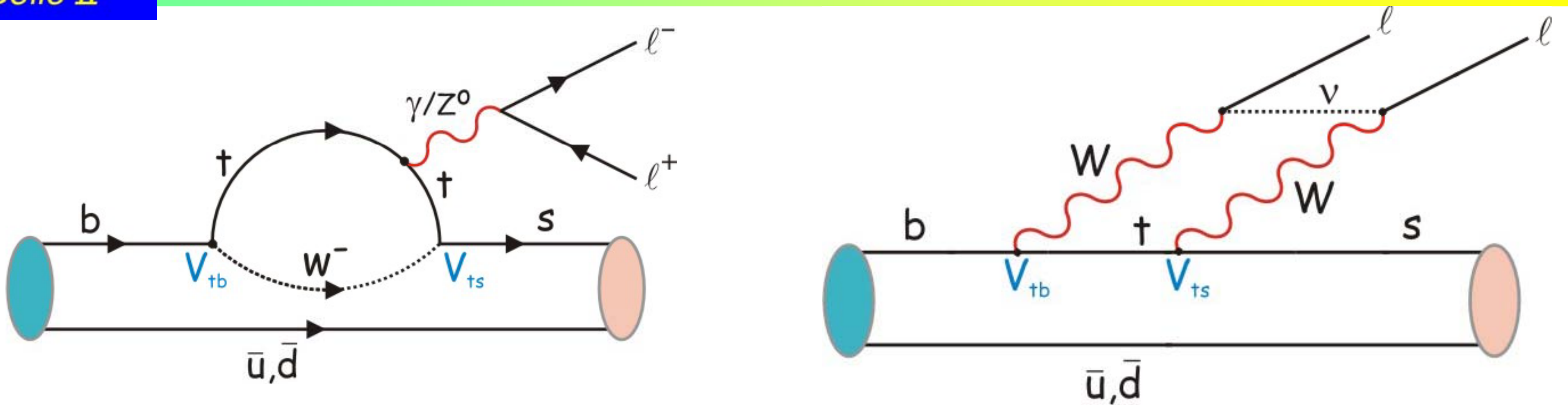
$0.26 \pm 0.25 \pm 0.04$
$0.67 \pm ^{0.25}_{0.27} \pm 0.07$
0.45 ± 0.18

$0.57 \pm 0.08 \pm 0.02$
$0.64 \pm 0.10 \pm 0.04$
0.60 ± 0.07

$0.71 \pm 0.24 \pm 0.04$
$0.30 \pm 0.32 \pm 0.08$
0.57 ± 0.20

Need much more data to clarify the issue

Another FCNC decay: B → $K^* l^+ l^-$



b → s l^+l^- was first measured in B → K l^+l^- by Belle (2001).

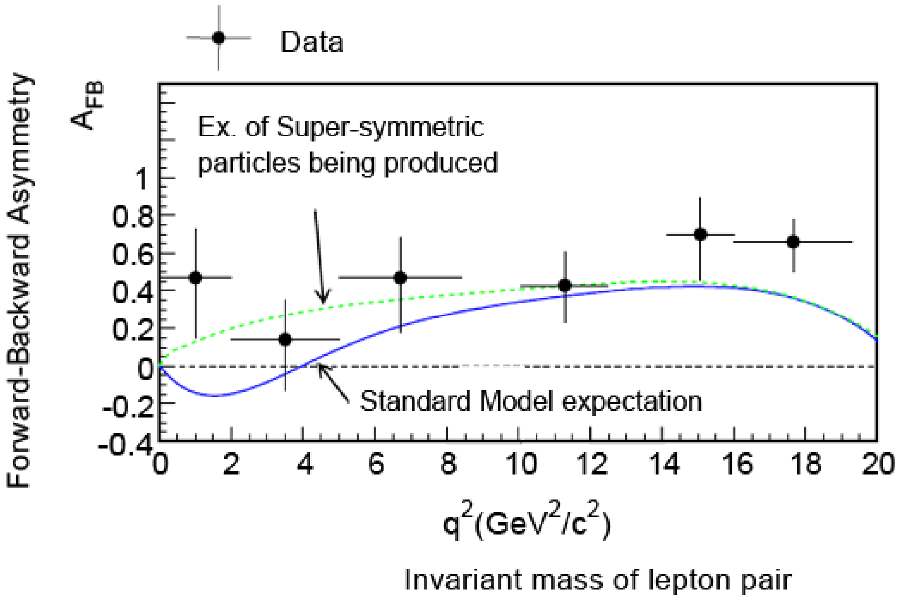
Important for further searches for the physics beyond SM

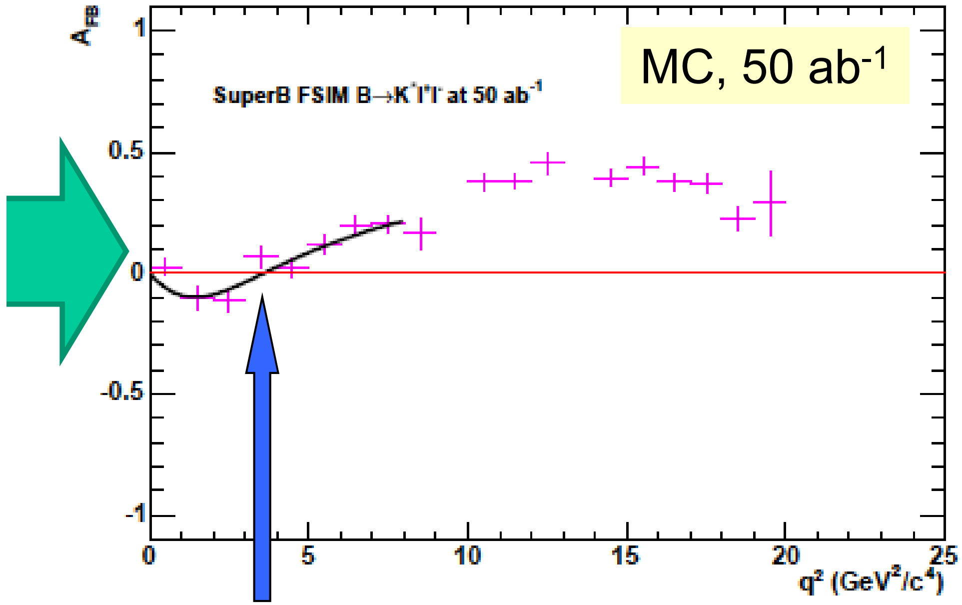
Particularly sensitive: backward-forward asymmetry in $K^* l^+l$

$$A_{FB} \propto \Re\left[C_{10}^{*}\left(sC_9^{eff}(s)+r(s)C_7\right)\right]$$

C_i : Wilson coefficients, abs. value of C_7 from b→sγ
s=lepton pair mass squared

$A_{FB}(B \rightarrow K^* l^+ l^-)[q^2]$ at a Super B Factory



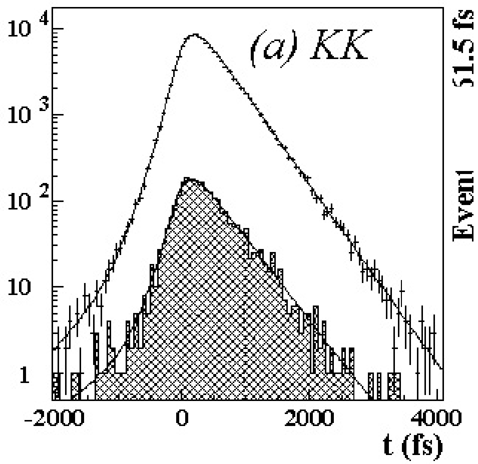


- Zero-crossing q^2 for A_{FB} will be determined with a 5% error with $50ab^{-1}$.

Strong competition from LHCb and ATLAS/CMS

D^0 mixing in K^+K^-, $\pi^+\pi^-$

Decay time distributions for KK, ππ, Kπ



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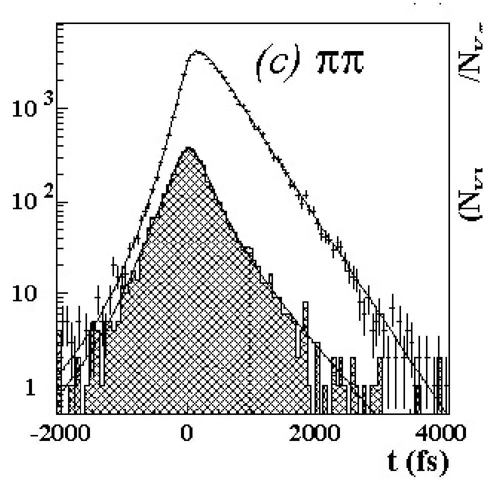
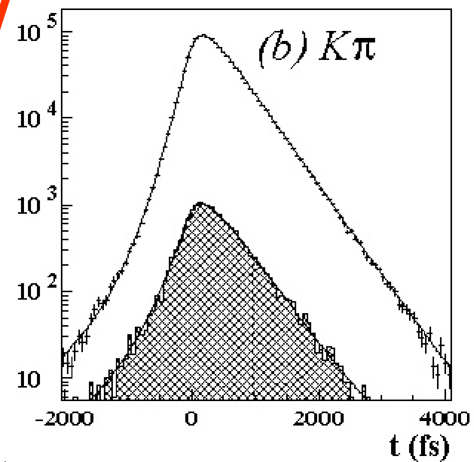
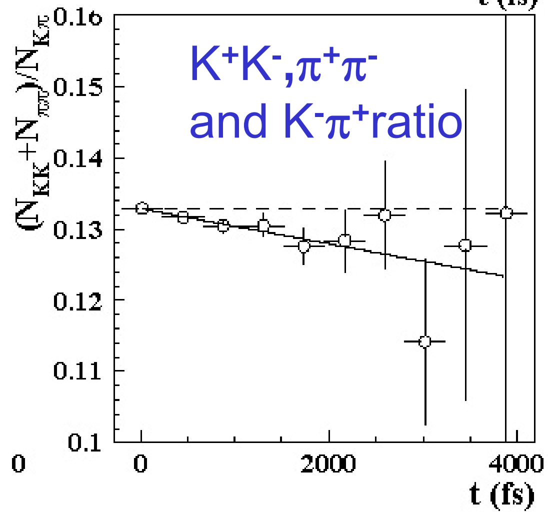




Difference of lifetimes visually observable

in the ratio of the distributions →

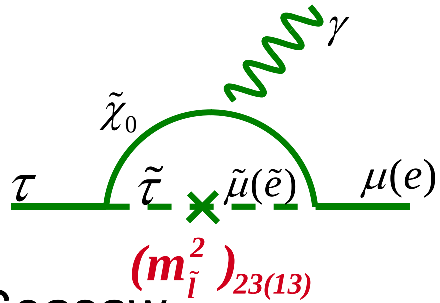
Real fit: $y_{CP} = (1.31 \pm 0.32 \pm 0.25)\ \%$



An observation of CP violations would be a clear sign of new physics

LFV and New Physics

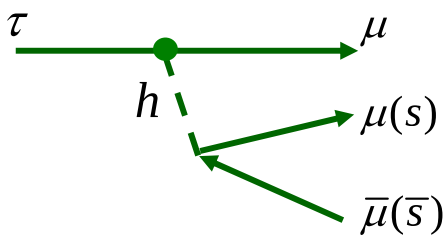
τ→lγ



- SUSY + Seasaw
- Large LFV Br(τ→μγ)=O(10^-7~9)

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

τ→3l,lη



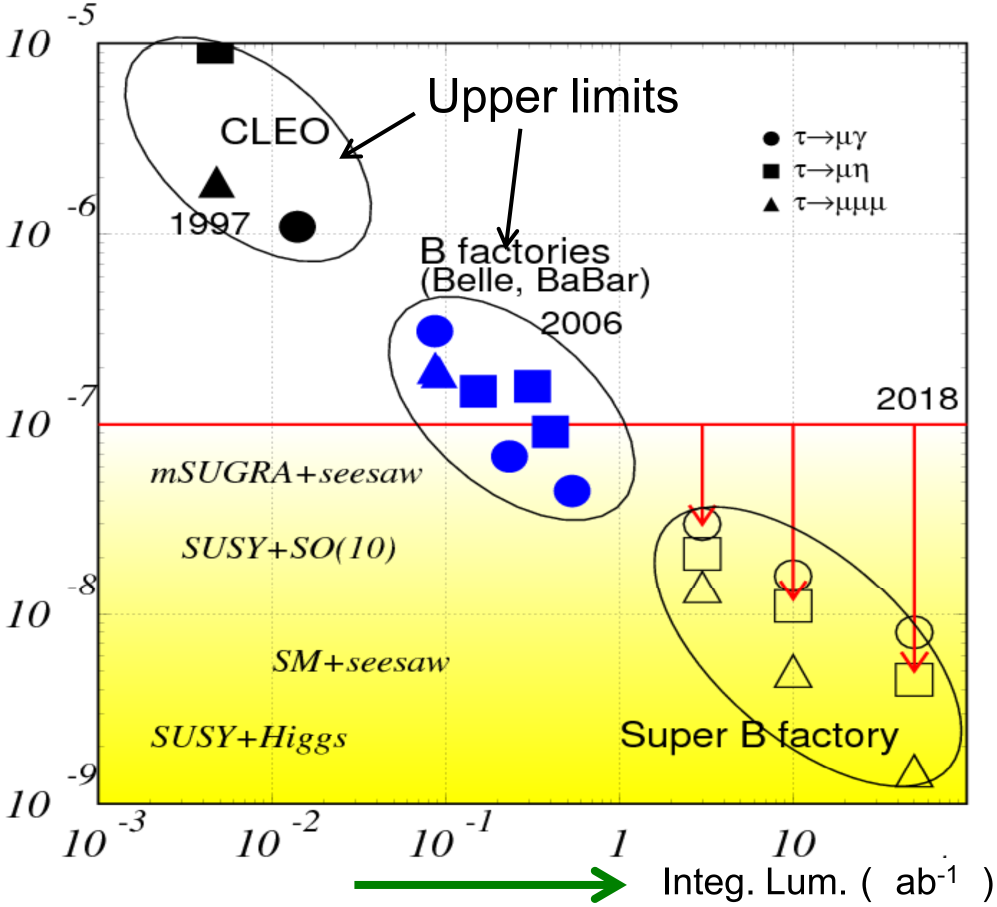
- Neutral Higgs mediated decay.
- Important when MSUSY >> EW scale.

$$Br(\tau \to 3\mu) = 4 \times 10^{-7} \times \left(\frac{(m^2_{\tilde{L}})_{32}}{\bar{m}^2_{\tilde{L}}} \right) \left(\frac{\tan \beta}{60} \right)^6 \left(\frac{100GeV}{m_A} \right)^4$$

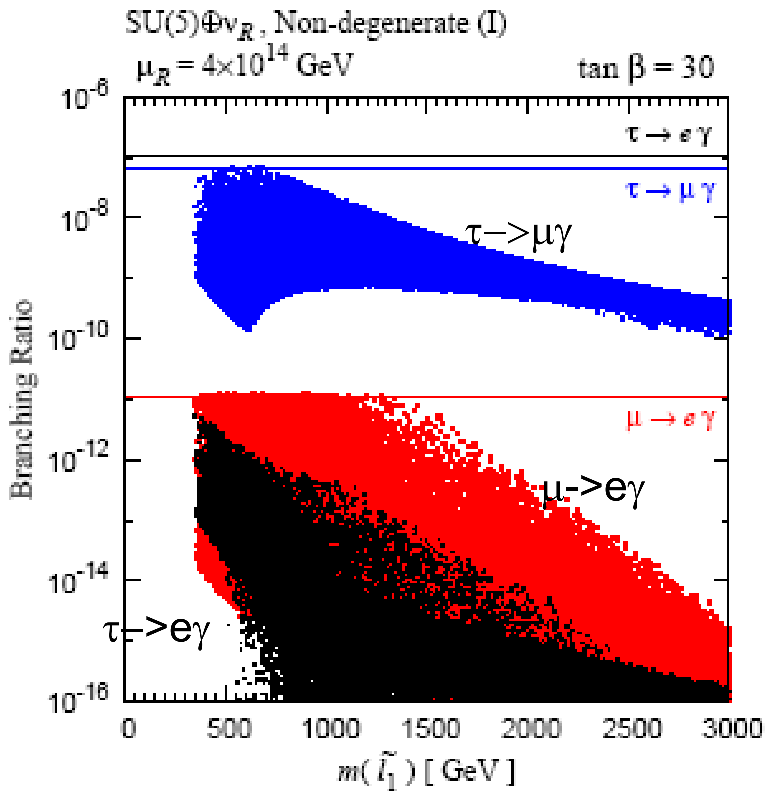
model	Br(τ→μγ)	Br(τ→lll)
mSUGRA+seesaw	10^{-7}	10^{-9}
SUSY+SO(10)	10^{-8}	10^{-10}
SM+seesaw	10^{-9}	10^{-10}
Non-Universal Z’	10^{-9}	10^{-8}
SUSY+Higgs	10^{-10}	10^{-7}

Precision measurements of τ decays

LF violating τ decay?



Theoretical predictions compared to present experimental limits



T.Goto et al., 2007

Physics at a Super B Factory

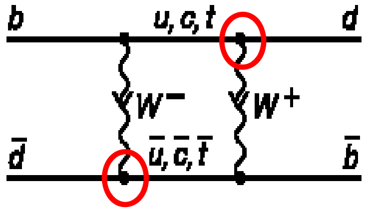
- There is a good chance to see new phenomena;
  - **CPV in B decays from the new physics (non KM).**
  - **Lepton flavor violations in τ decays.**
- They will help to diagnose (if found) or constraint (if not found) new physics models.
- Even in the worst case scenario (such as MFV), $B \rightarrow \tau\nu$, $D\tau\nu$ 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.

Super B Factory Motivation 2

- There are many more topics: CPV in charm, new hadrons, …

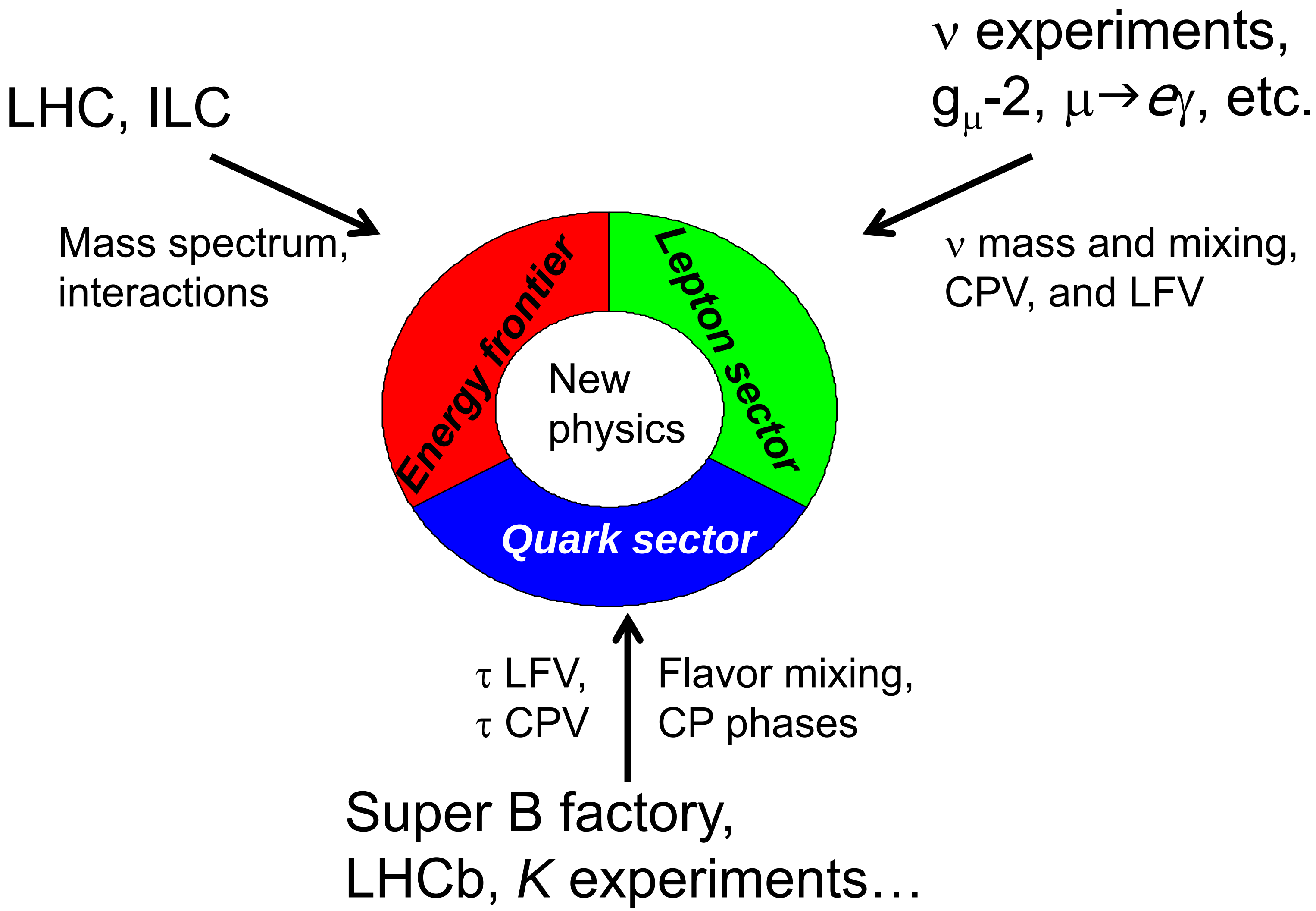
- Lessons from history: the top quark

<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

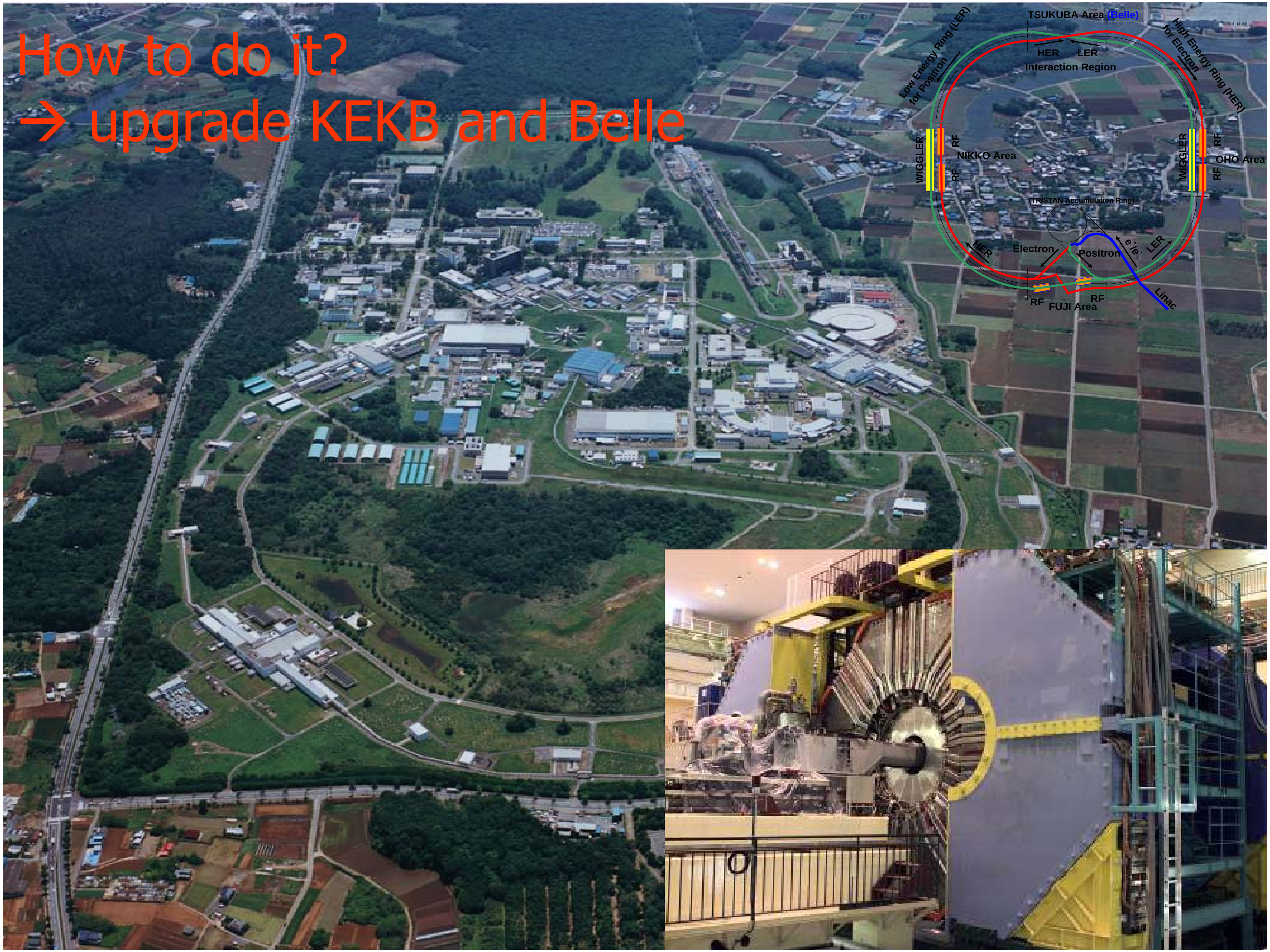


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Super B factory: an important part of a broad unbiased approach to New Physics



How to do it?
→ upgrade KEKB and Belle

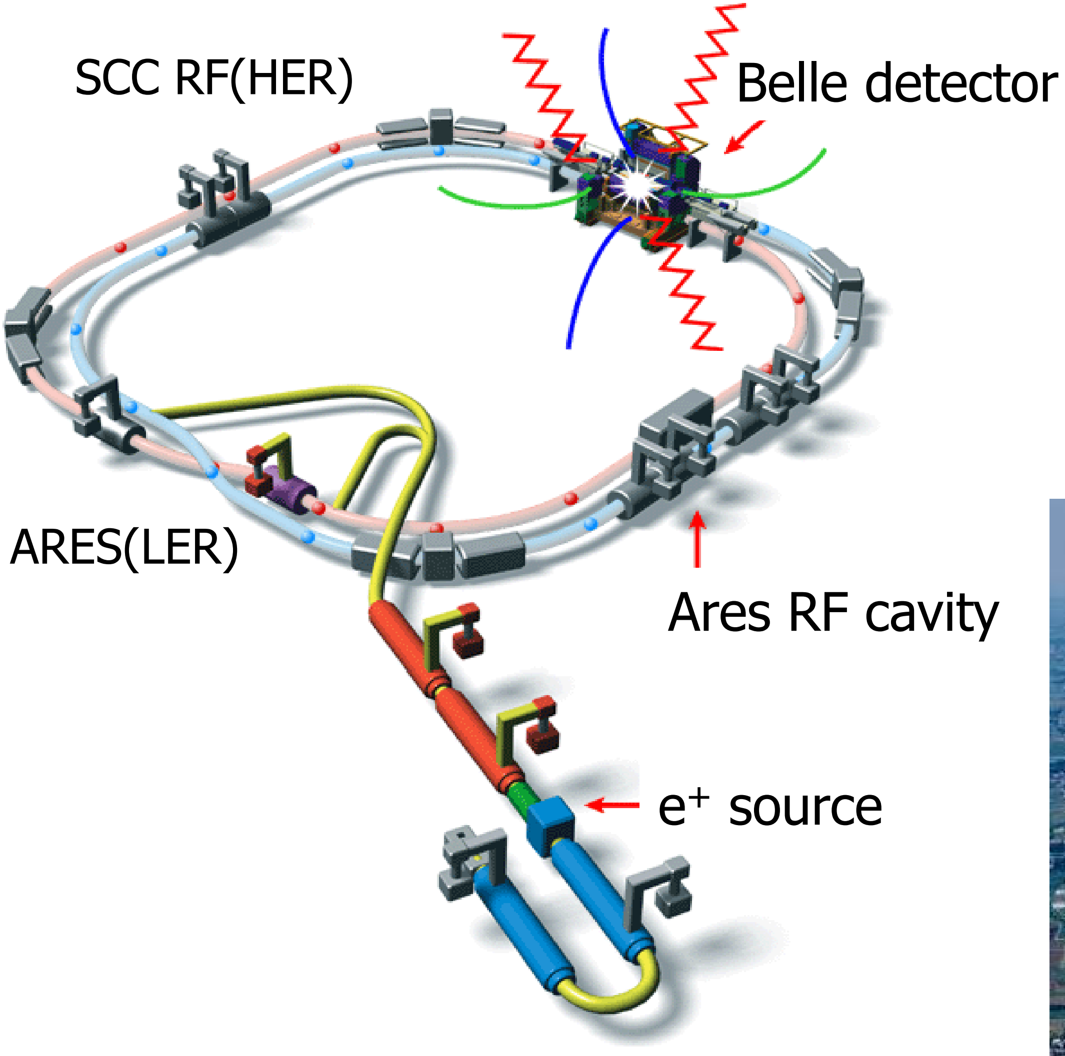


The KEKB Collider & Belle Detector

- e^- (8 GeV) on e^+(3.5 GeV)
  - $\sqrt{s} \approx m_{\Upsilon(4S)}$
  - Lorentz boost: $\beta\gamma$=0.425
- 22 mrad crossing angle
- Operating since 1999

Peak luminosity (WR!) :

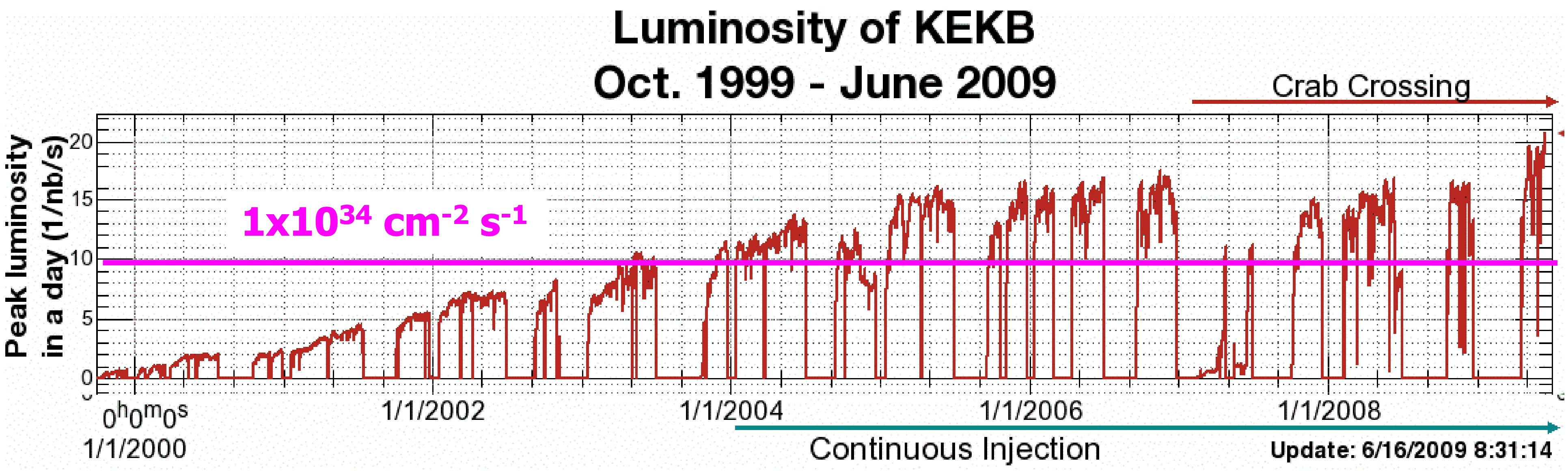
2. 1 x 10^{34} $cm^{-2}s^{-1}$



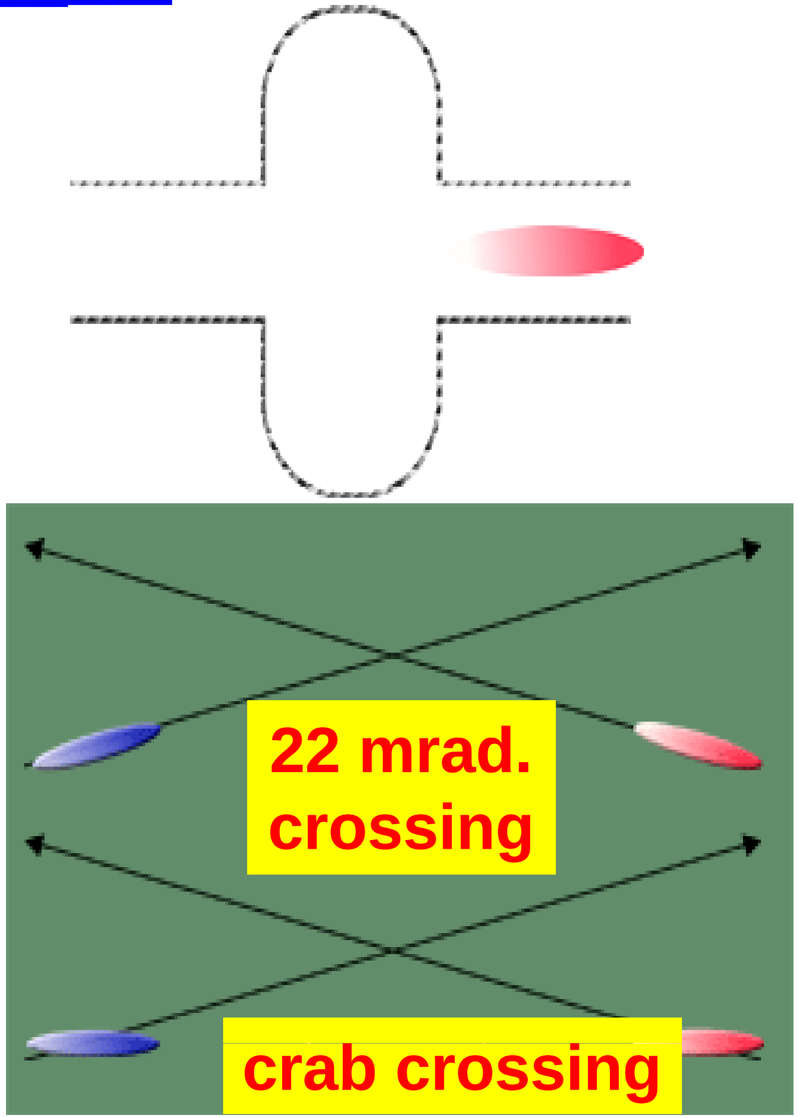
The KEKB Performance

Luminosity Records:

- **Peak L = 2.1x10^{34} cm^{-2} s^{-1}** (2x the design value)
- **Daily ∫Ldt = 1.5 fb^{-1}** (2.5 x the design value)
- **Total ∫Ldt ~ 950 fb^{-1}** (as of July 2009)



The latest improvements in KEKB performance: crab cavity



Installed in the KEKB tunnel (February 2007)

Strategies for Increasing Luminosity

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

Lorentz factor

Beam current

Beam-beam parameter

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

High-Current Option

(1) Smaller β_y^*
(2) Increase beam currents
(3) Increase ξ_y

Nano-Beam Option

Accelerator upgrade strategy

Why did we give up the "high current scheme"?

- To achive the required luminosity, we had to assume a beam-beam parameter of 0.3 while with Belle we achieved 0.09
- Bunch length could not be reduced to 3mm because of the coherent synchrotron radiation.
- No solution was found for IR design to realize β^*_x=20cm.
- Higher operating costs.

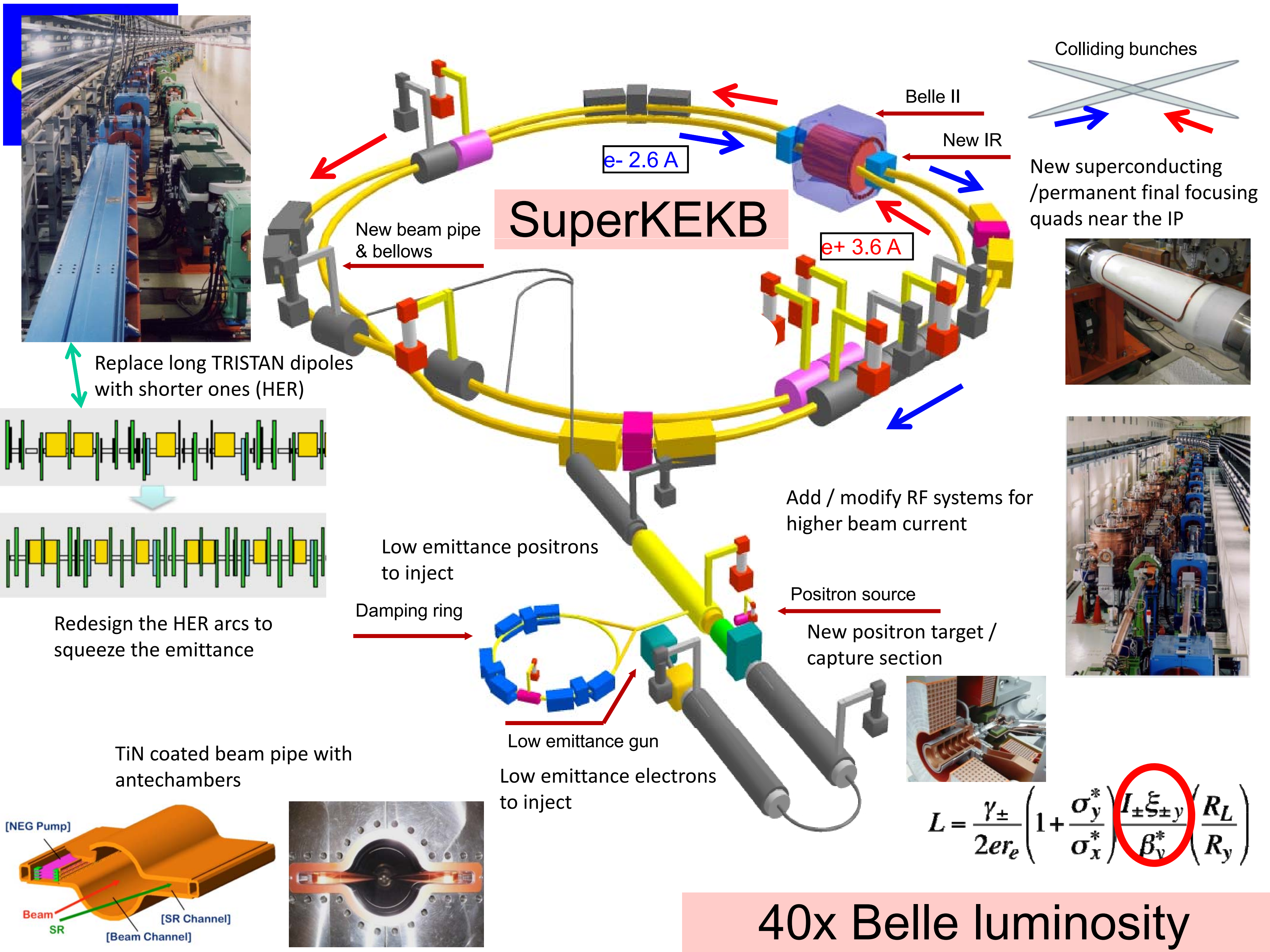
→Adopted the "Nano-beam scheme" as proposed by P. Raimondi and the SuperB group → design is on-going - no showstopper up to now.

To achieve a luminosity of $8.0 \times 10^{35} cm^{-2}s^{-1}$ (x40 of peak KEKB value),

- Beam current 1.7/1.4 → 3.6/2.6 A (x2)
- Beam-beam parameter 0.09 → 0.09 (x1)
- Small beta function at IP (x 1/20): horiz.: 1200→ 32/25mm / vert.: 5.9→0.27/0.42mm; beam size 100μm(H) x 2μm(V) → 10μm(H) x 59nm(V)
- Crab waist is considered as an option

Design parameters

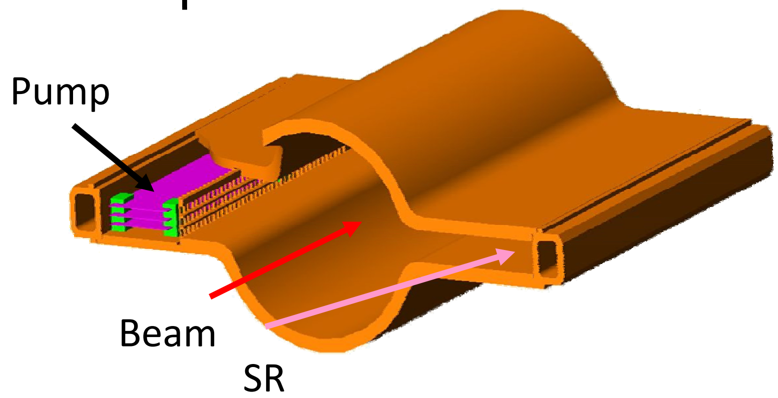
	KEKB Design	KEKB Achieved : with crab	SuperKEKB High-Current	SuperKEKB Nano-Beam
Energy (GeV) (LER/HER)	3.5/8.0	3.5/8.0	3.5/8.0	4.0/7.0
β_x^* (cm)	100/100	120/120	20/20	3.2/2.5
β_y^* (mm)	10/10	5.9/5.9	3/6	0.27/0.42
ε_x (nm)	18/18	18/24	24/18	3.2/1.7
σ_y (μm)	1.9	0.94	0.85/0.73	0.059
ξ_y	0.052	0.129/0.090	0.3/0.51	0.09/0.09
σ_z (mm)	4	~ 6	5/3	6/5
I_{beam} (A)	2.6/1.1	1.64/1.19	9.4/4.1	3.6/2.6
$N_{bunches}$	5000	1584	5000	2500
Luminosity (10^{34} cm^{-2} s^{-1})	1	2.11	53	80


SuperKEKB
Colliding bunches
Belle II
New IR
e- 2.6 A
e+ 3.6 A
New superconducting /permanent final focusing quads near the IP
New beam pipe & bellows
Replace long TRISTAN dipoles with shorter ones (HER)
Redesign the HER arcs to squeeze the emittance
Add / modify RF systems for higher beam current
Low emittance positrons to inject
Damping ring
Positron source
New positron target / capture section
Low emittance gun
Low emittance electrons to inject
TiN coated beam pipe with antechambers
[NEG Pump]
Beam
SR
[SR Channel]
[Beam Channel]
$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$
40x Belle luminosity

Beam duct for SuperKEKB

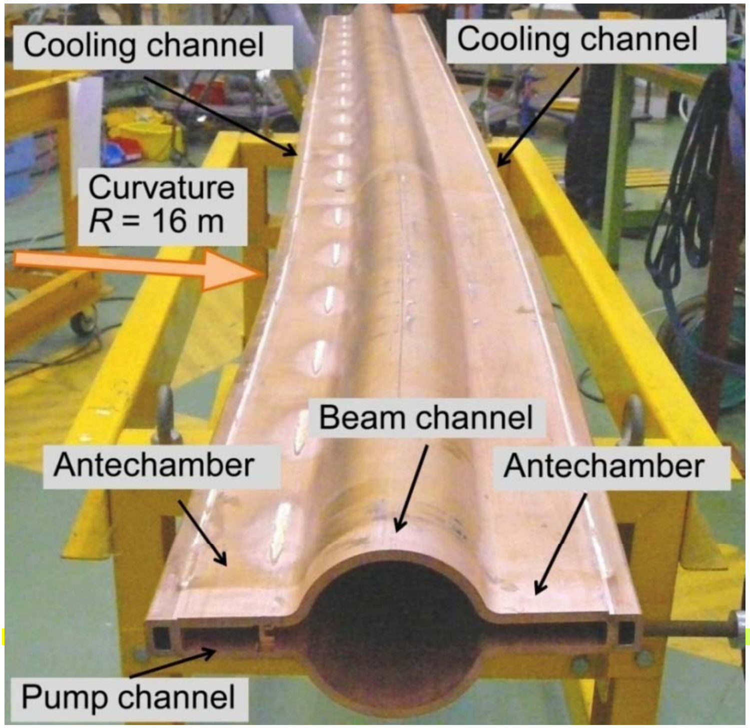
Copper beam duct with ante-chambers

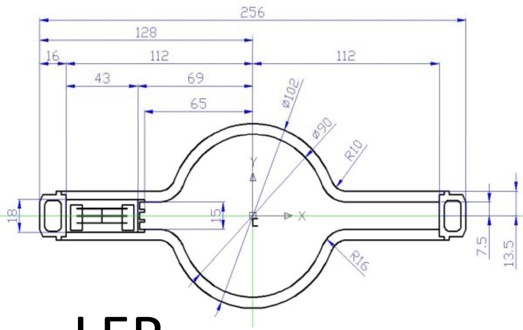
- Copper is required to withstand intense SR power



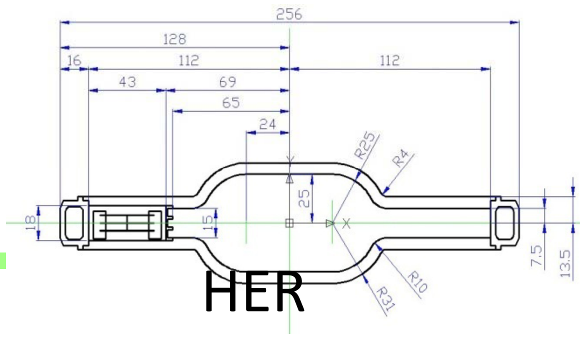
Features (compared to simple pipe):

- Low SR power density
- Less photoelectrons in beam pipe
- Low beam impedance



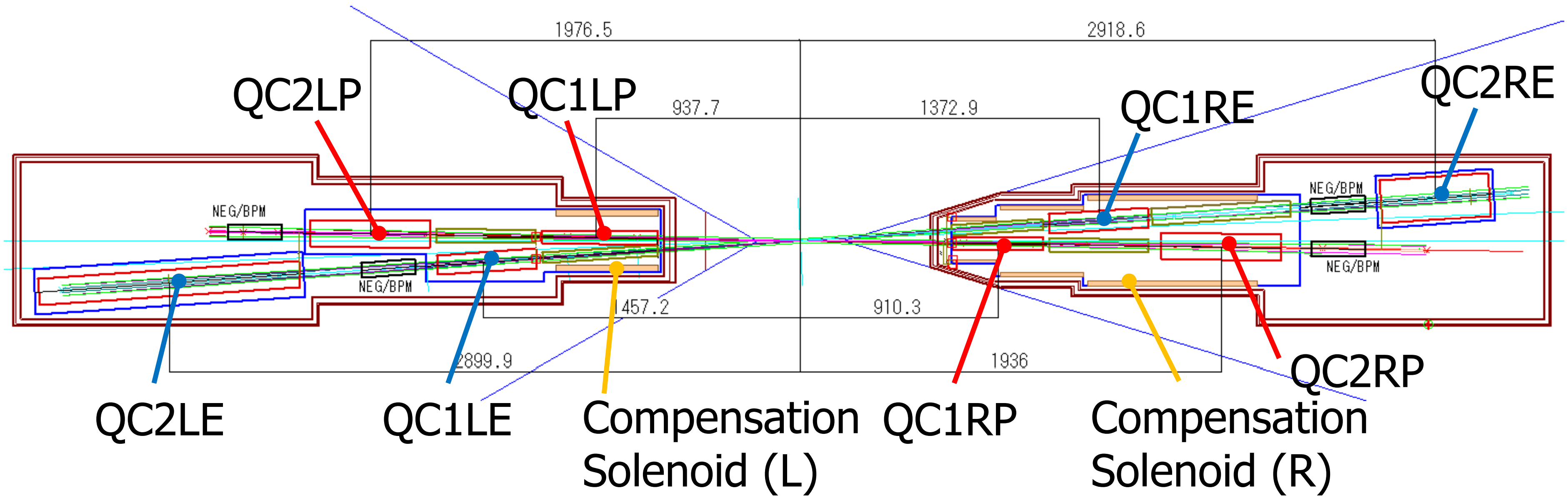


LER



HER

IR Superconducting Magnets



IR Superconducting magnets: main quads(8), corrector solenoids(2), corrector coils(43)

Preliminary! Under optimisation

Accelerator design → detector design

- For the nano-beam option
  → There are two final-Q magnets in both L / R sides

- 7x4GeV beam energies
  To solve the problem of dynamic aperture.

.
- Crossing angle becomes 83 mrad
  to put the final-Q magnets closer to the IP

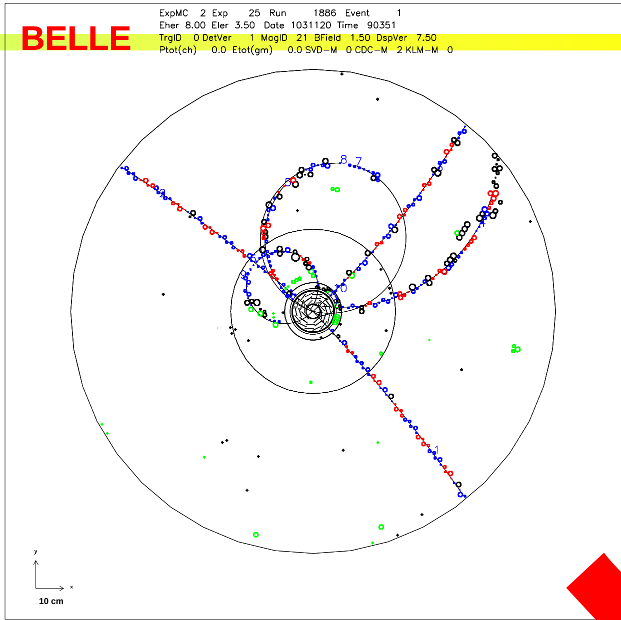
- The QCS chamber radius is 1cm
  → to avoid the resonant cavity structure
  →IP beam-pipe radius should be 1cm

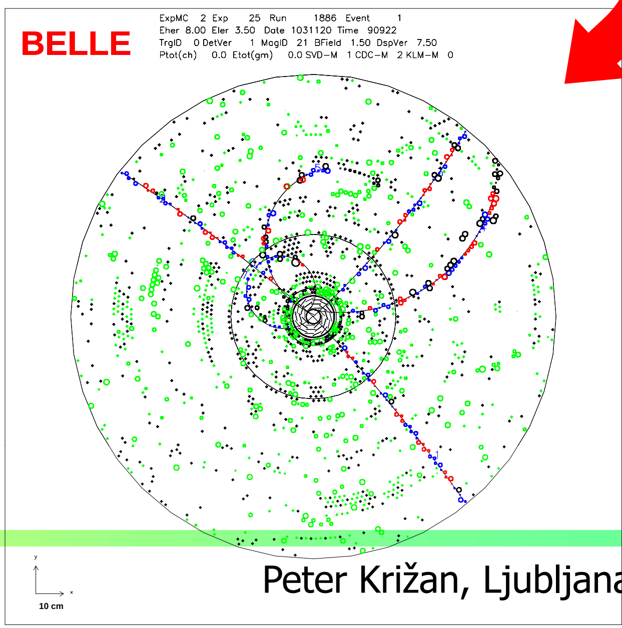
Detector backgrounds are under study – depend on the new machine parameters. Different in the nano-beam option than for the high current version

Requirements for the Belle II detector

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

- **Higher background (×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 ← $s\mu\mu$ recon. eff.
  - hermeticity ← ν “reconstruction”

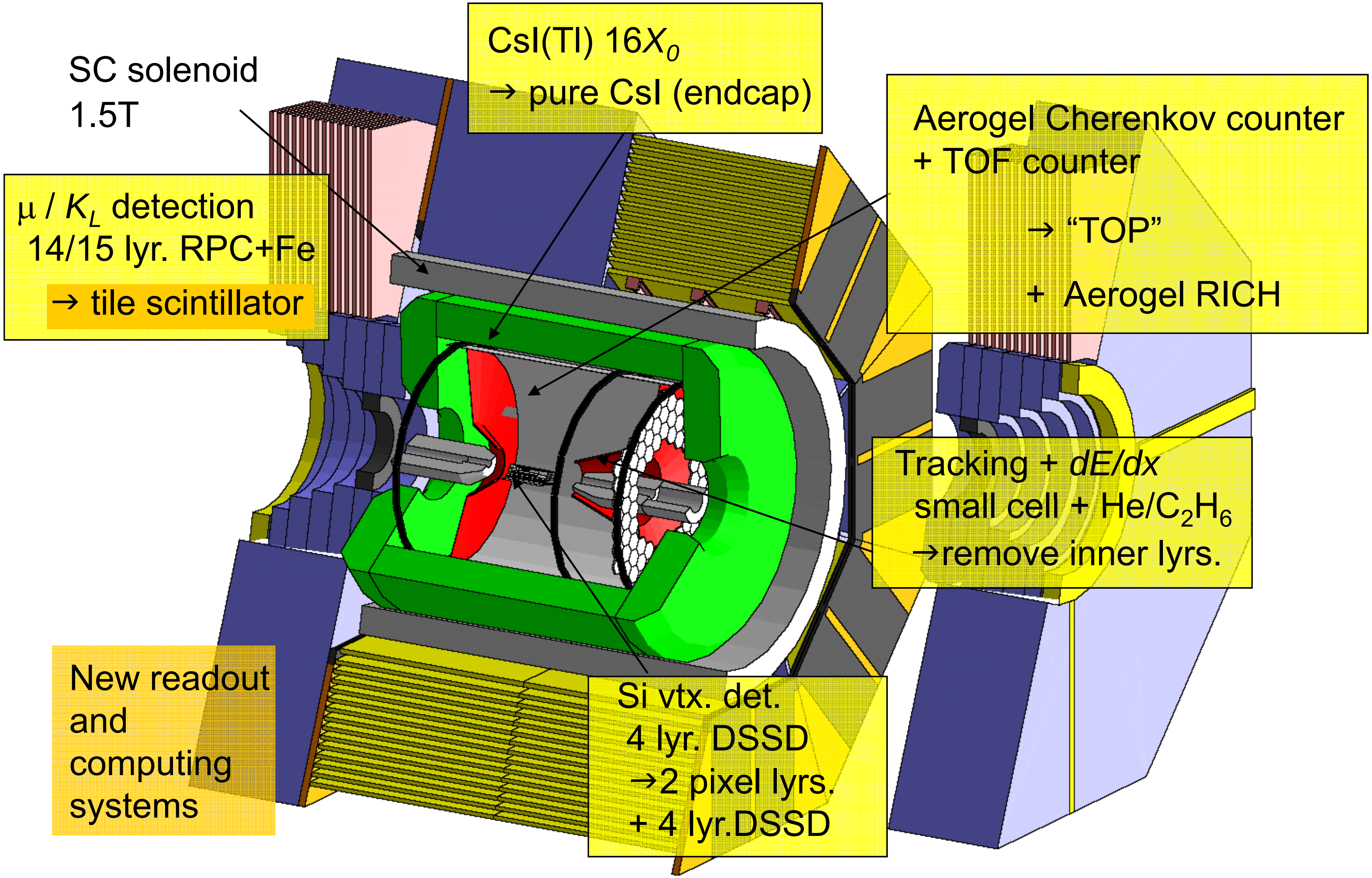




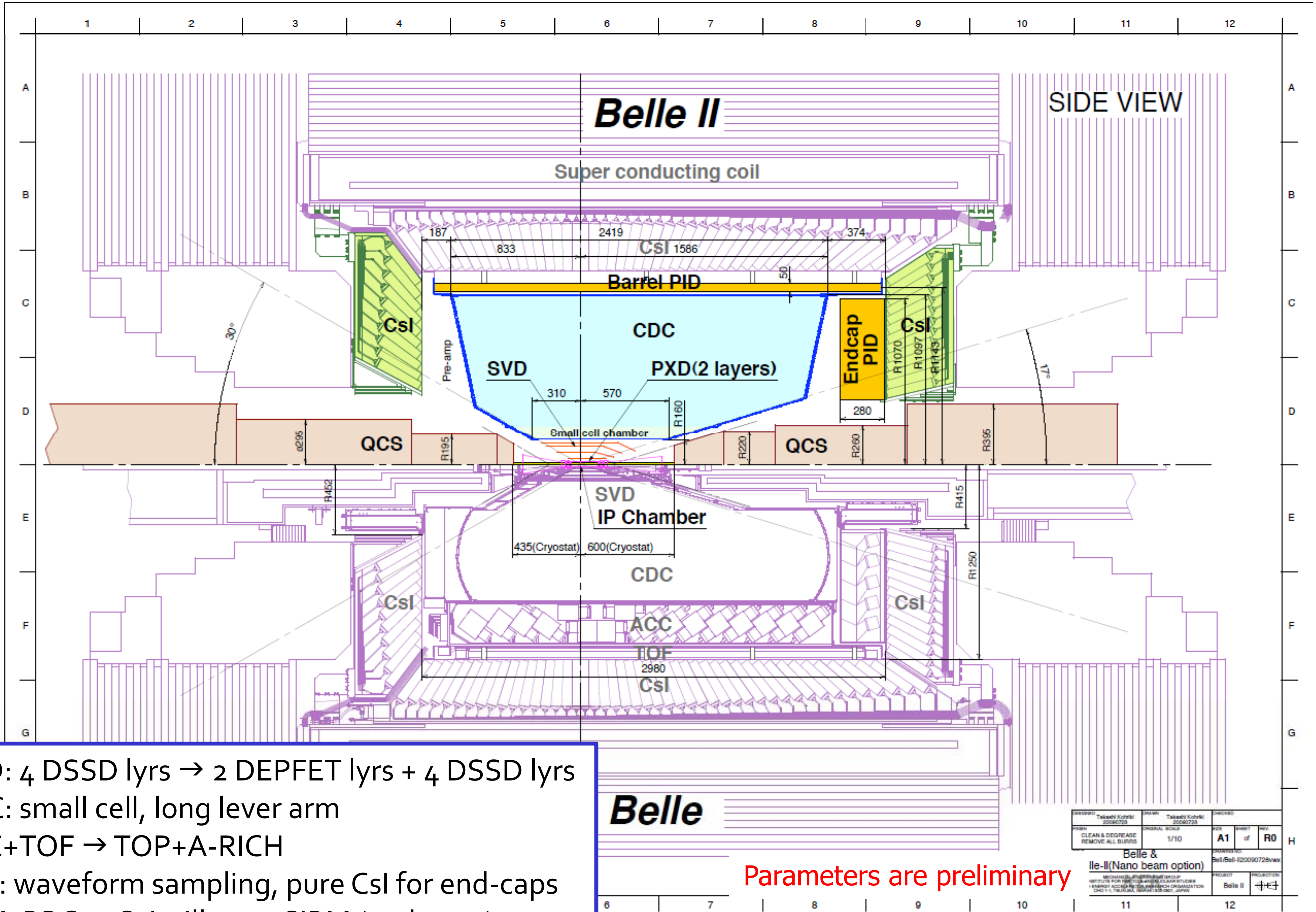
Possible solution:

- Replace inner layers of the vertex detector with a pixel detector.
- Replace inner part of the central tracker with a silicon strip detector.
- Better particle identification device
- Replace endcap calorimeter crystals
- Faster readout electronics and computing system.

Belle Upgrade for Super-B



Belle II in comparison with Belle

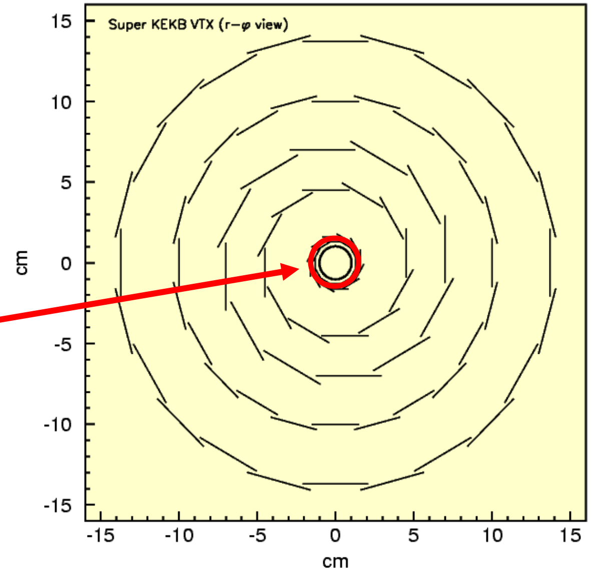


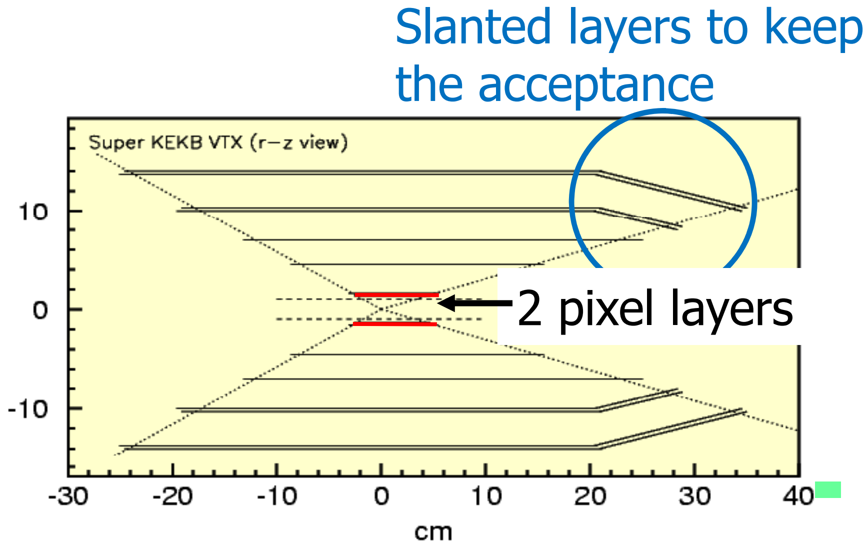
SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling, pure CsI for end-caps
KLM: RPC → Scintillator +SiPM (end-caps)

Parameters are preliminary

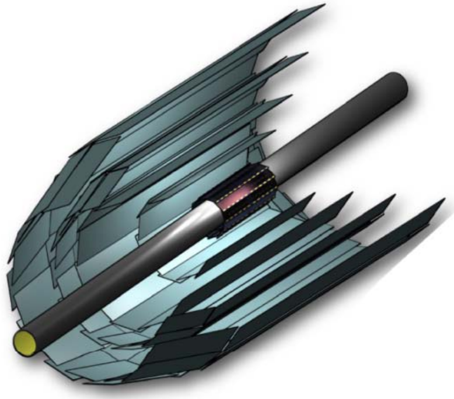
Vertex detector upgrade: PXD+SVD

- Configuration: 4 layers → 6 layers (outer radius = 8cm→14cm)
  - More robust tracking
  - Higher Ks vertex reconstr. efficiency
- Inner radius: 1.5cm → 1.3cm
  - Better vertex resolution
- Sensors of the two innermost layers L1+L2: DEPFET Pixel sensors →PXD
- Layers 3-6: normal double sided Si detector (DSSD) →SVD
- Strip readout chip: VA1TA → APV25
  - Reduction of occupancy coming from beam background.
  - Pipeline readout to reduce dead time.





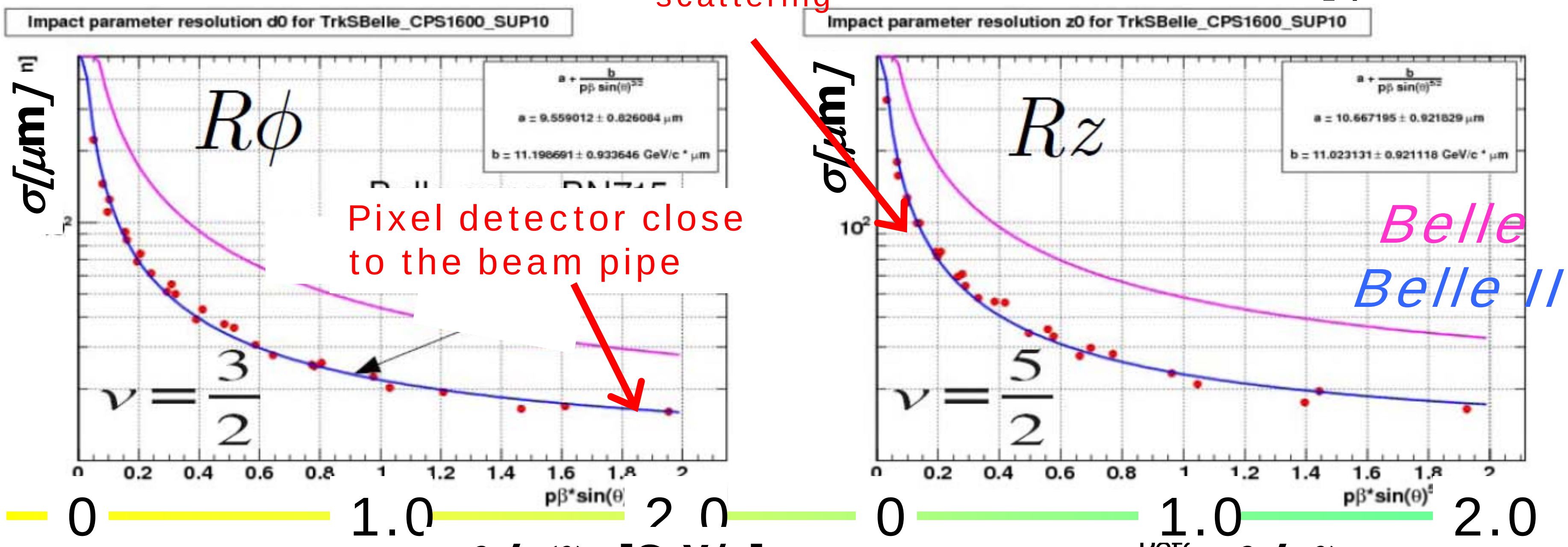
Vertex Detector



Beam Pipe		**r = 1cm**
DEPFET		
	Layer 1	**r = 1.3cm**
	Layer 2	**r = 2.2cm**
DSSD		
	Layer 3	**r = 3.8cm**
	Layer 4	**r = 8.0cm**
	Layer 5	**r = 11.5cm**
	Layer 6	**r = 14.0cm**

Significant improvement in IP resolution!

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



Current system

- Barrel: TOF + ACC
- End cap: ACC

(ACC: Threshold type Aerogel Cherenkov Counter)

Upgrade

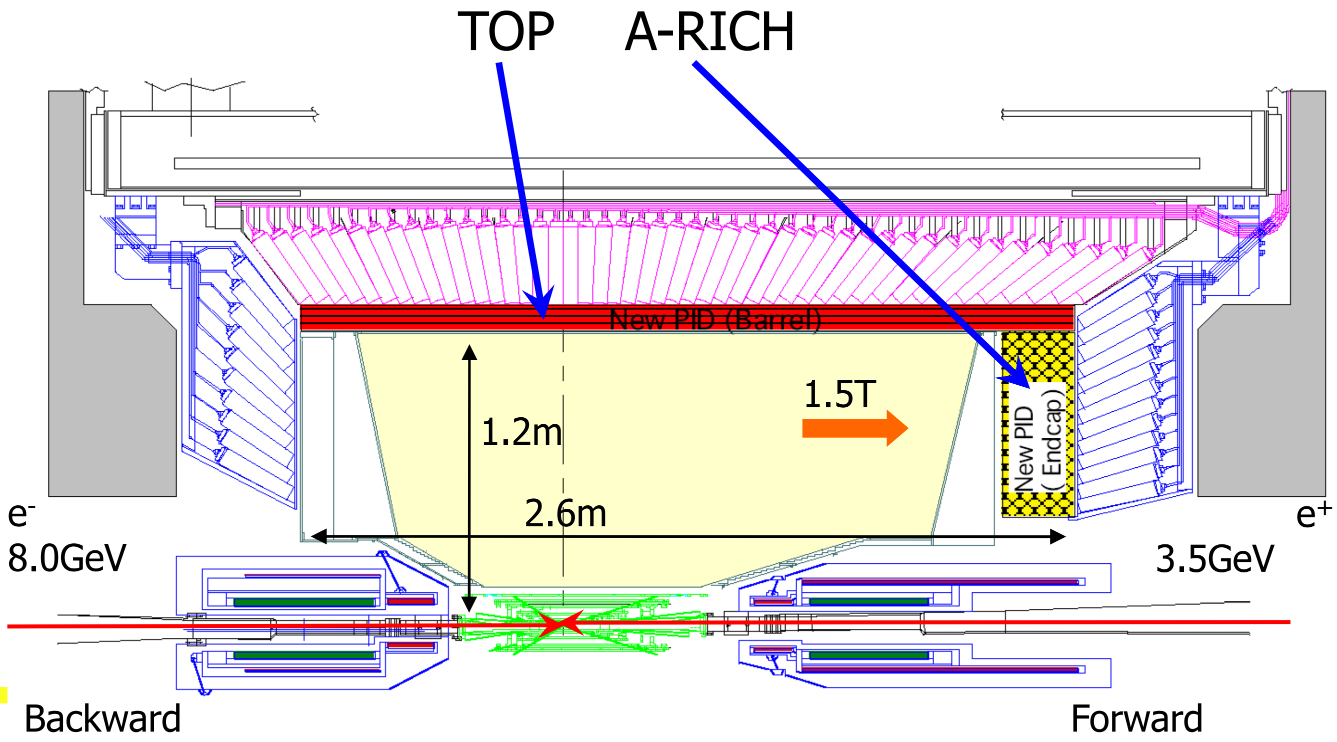
Belle-II

- Barrel: TOP counter
- End cap: Aerogel RICH

(TOP: Time-of-Propagation)

3σ K/pi separation

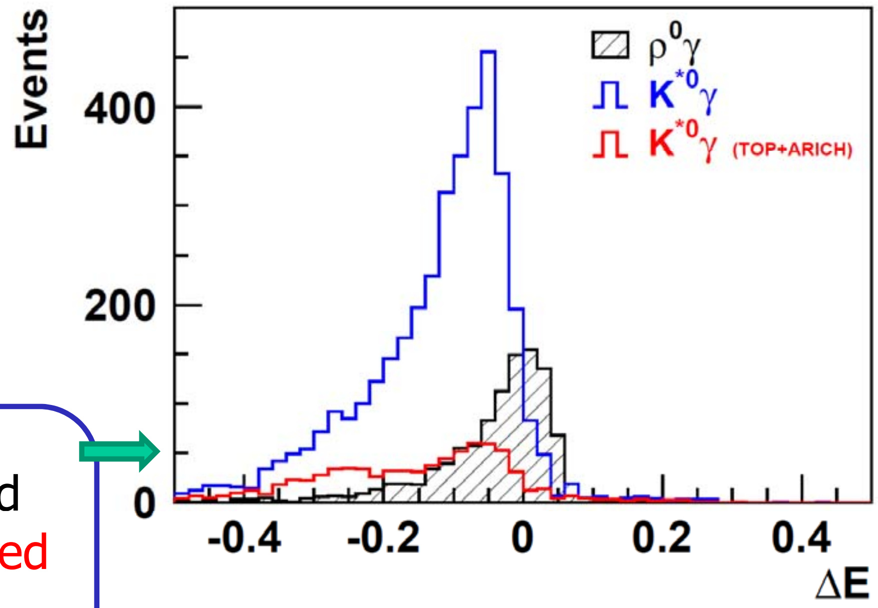
4σK/pi separation up to 4GeV

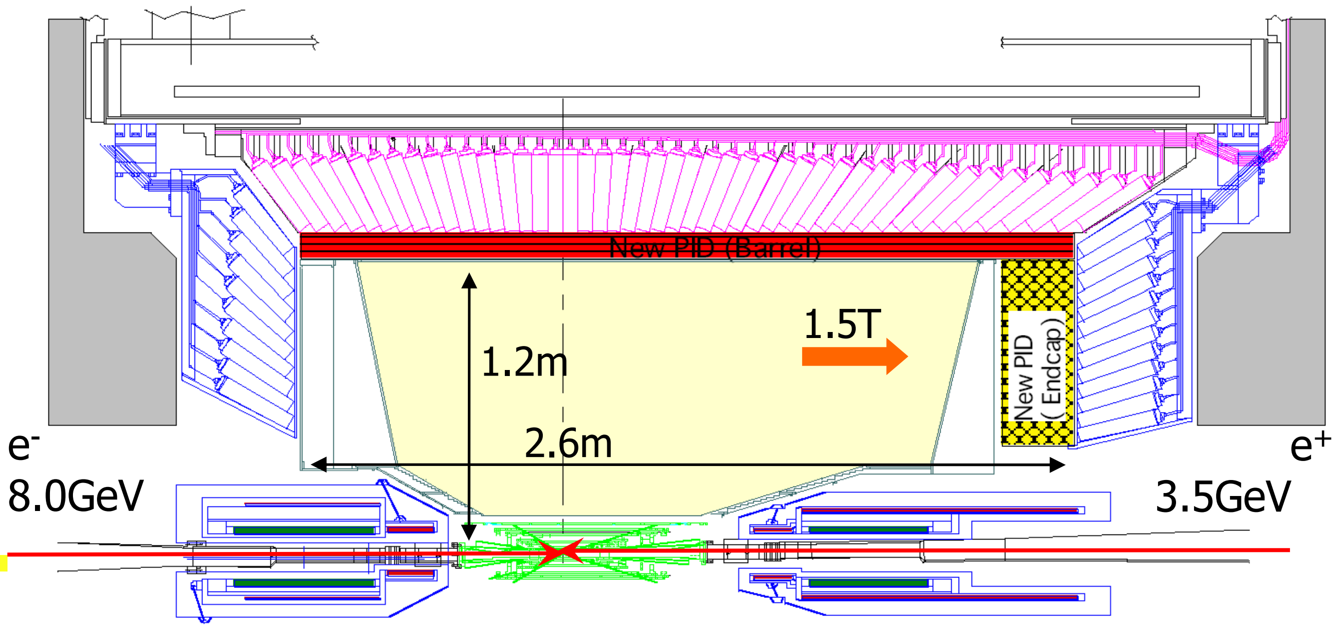


- Barrel: TOP counter
- End cap: Aerogel RICH

Expected impact, example $B \rightarrow K^*\gamma$: background reduced from blue (present Belle) to red

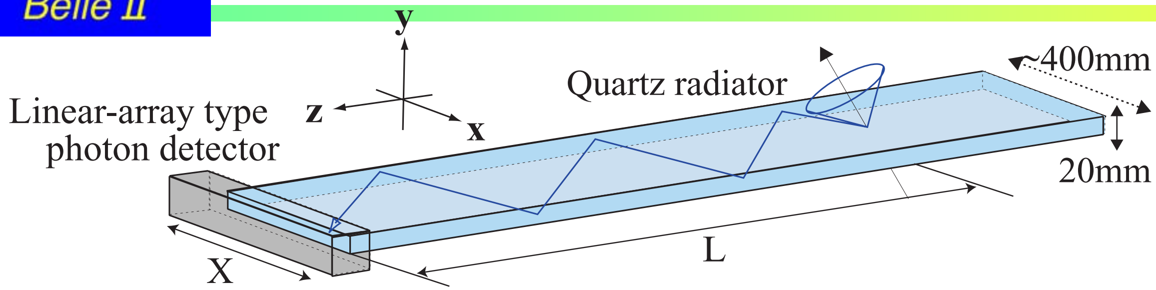
→Up to 80% gain in sensitivity

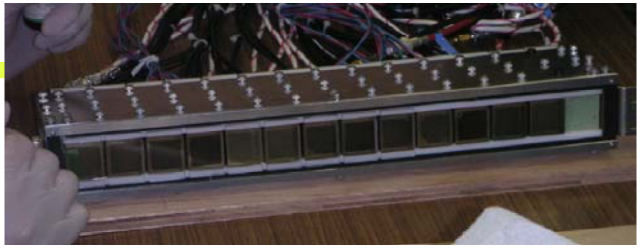




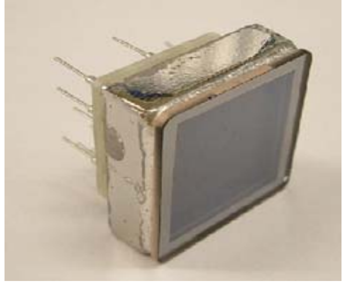
Ljubljana

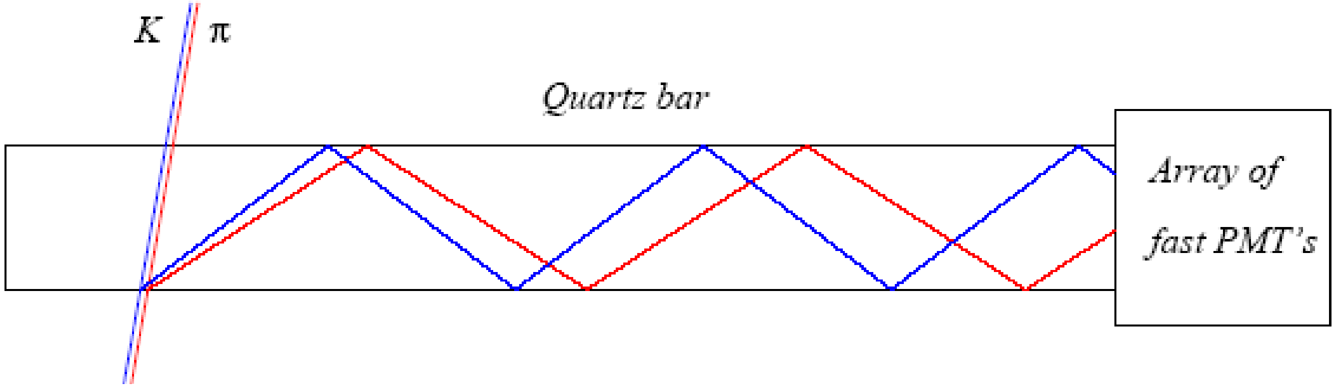
Barrel PID: Time of propagation (TOP) counter

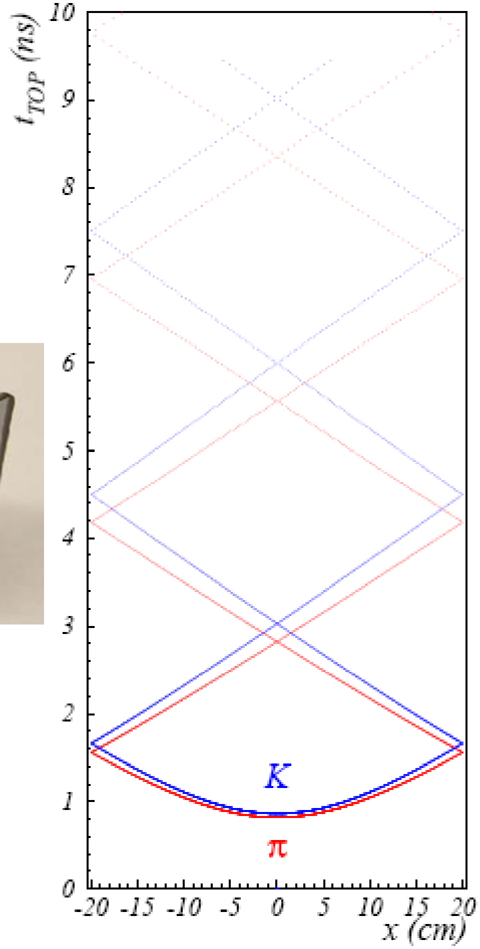




- Cherenkov ring imaging with precise time measurement.
- Reconstruct angle from two coordinates and the time of propagation of the photon
  - Quartz radiator (2cm)
  - Photon detector (MCP-PMT)
    - Good time resolution < ~ 40 ps
    - Single photon sensitive in 1.5 T

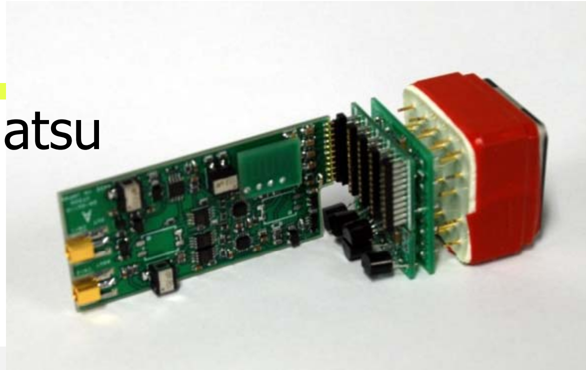




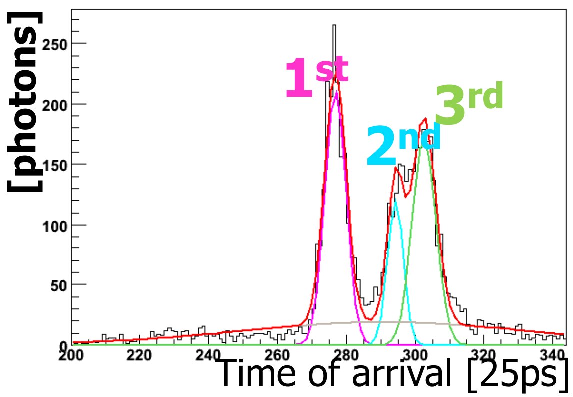


TOP test beam performance: proof-of-principle

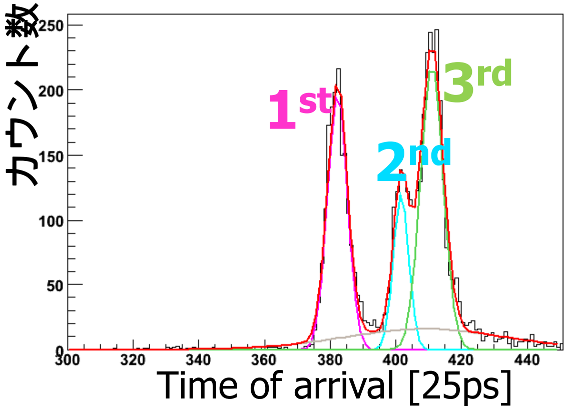
Photon detector: Hamamatsu MCP-PMT 27.5x27.5 mm²

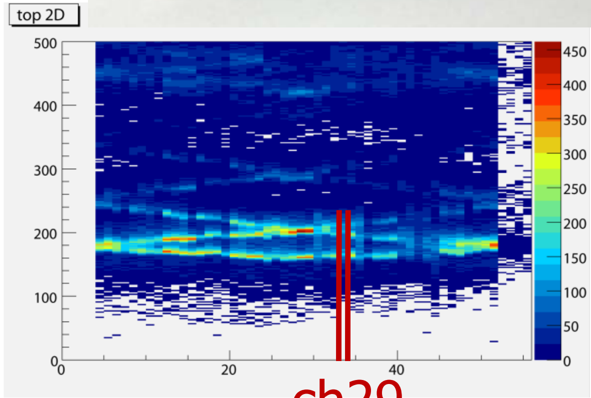


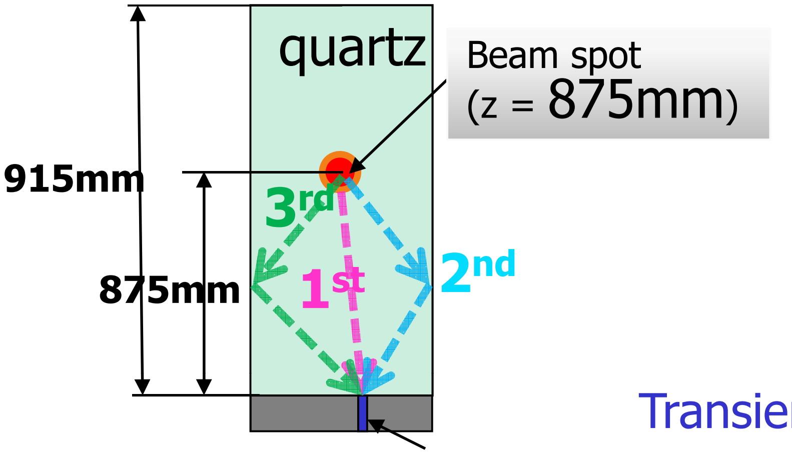
Test beam (2008)



simulation







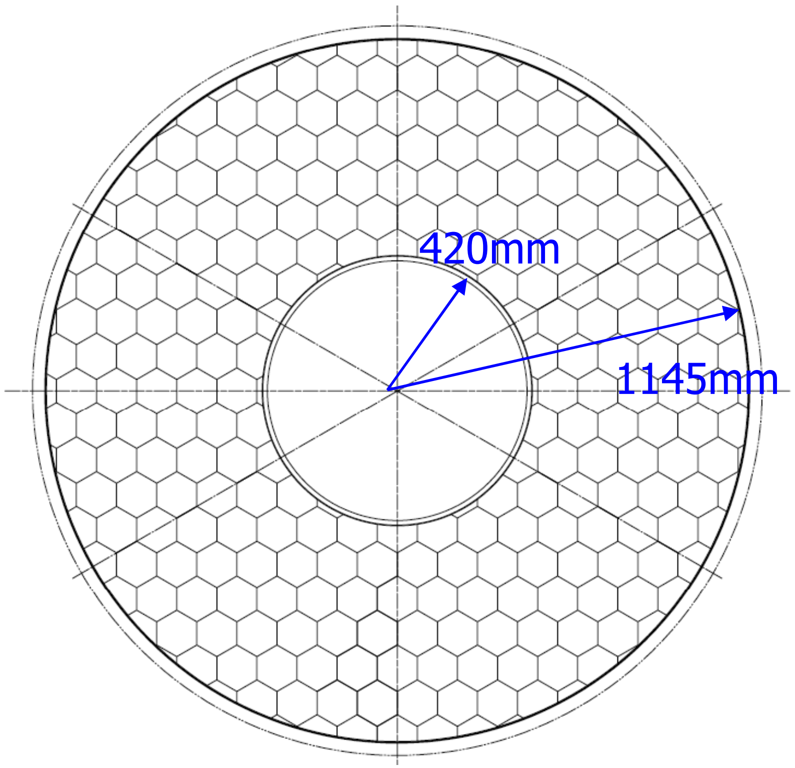
$$\sigma_{top} = \sqrt{\sigma^2_{MCP\text{-}PMT} + \sigma^2_{chromatic}}$$

	TTS (1st peak)
Data	**76.0±2.0 [ps]**
Simulation	**77.7±2.3 [ps]**

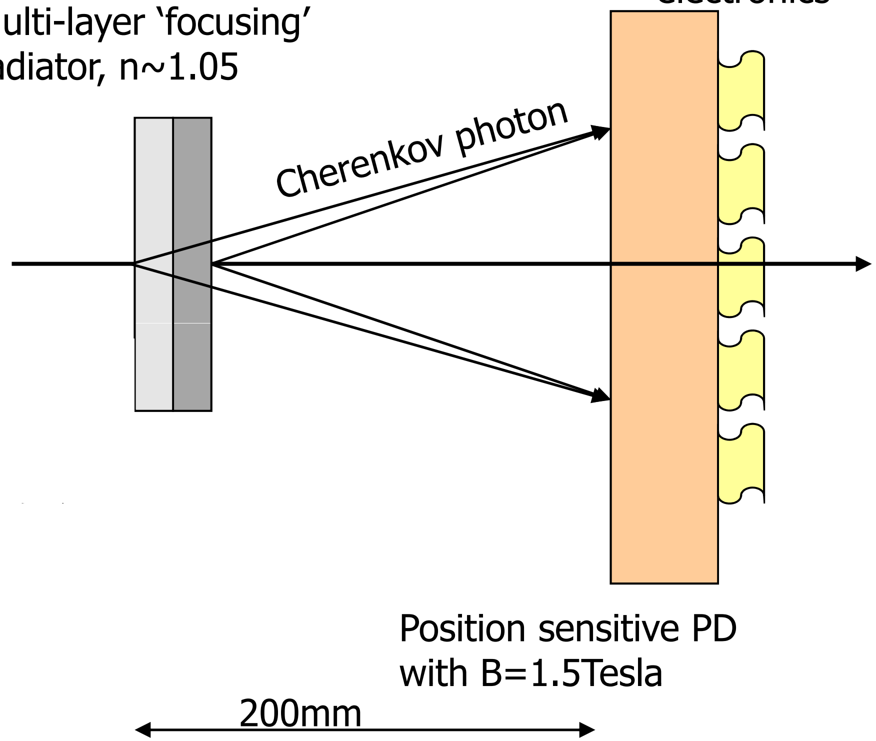
Transient time spread determined from the data

End-cap PID

Proximity focusing RICH with silica aerogel as Cherenkov radiator in a 'focusing' configuration

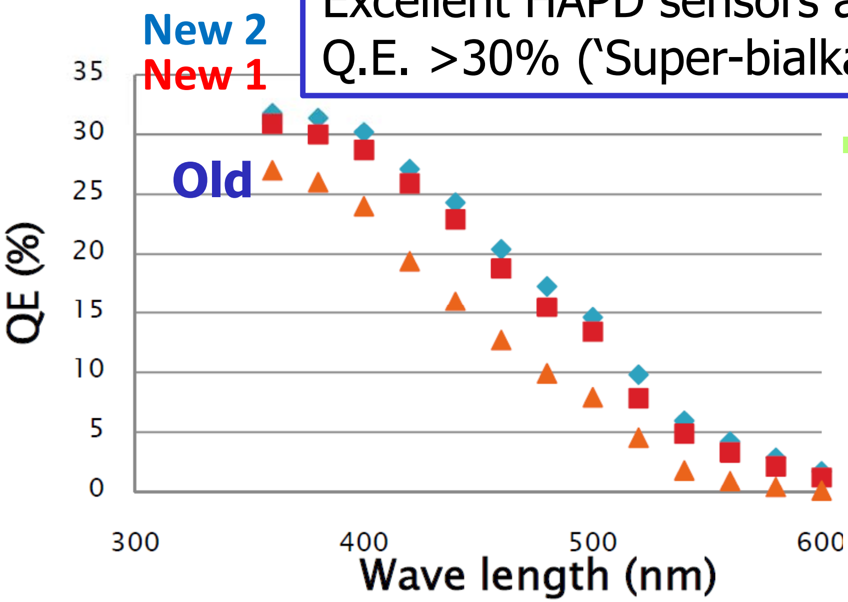


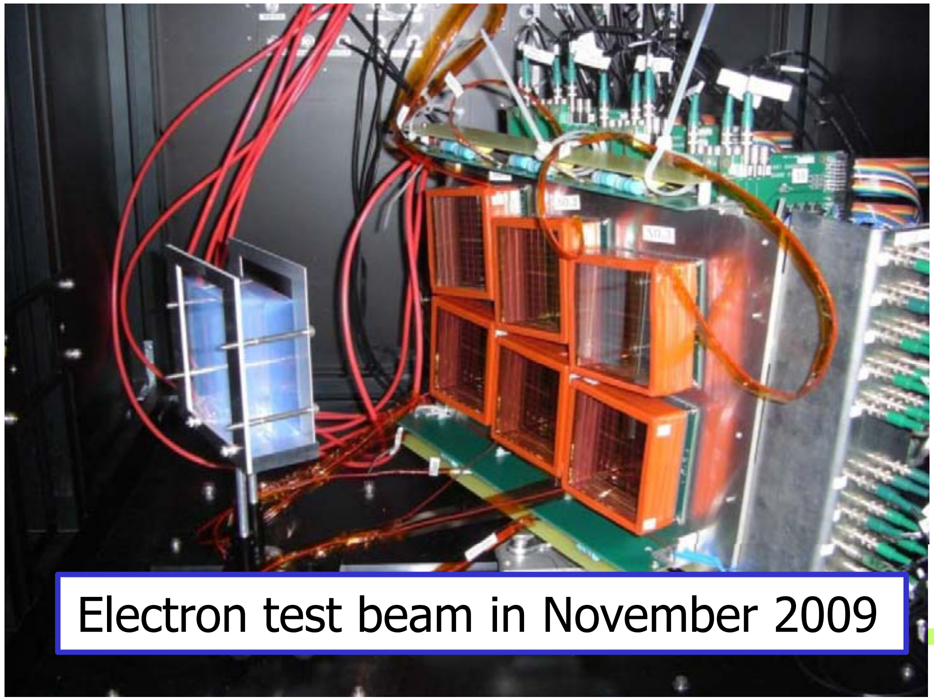
x-y view of forward end-cap



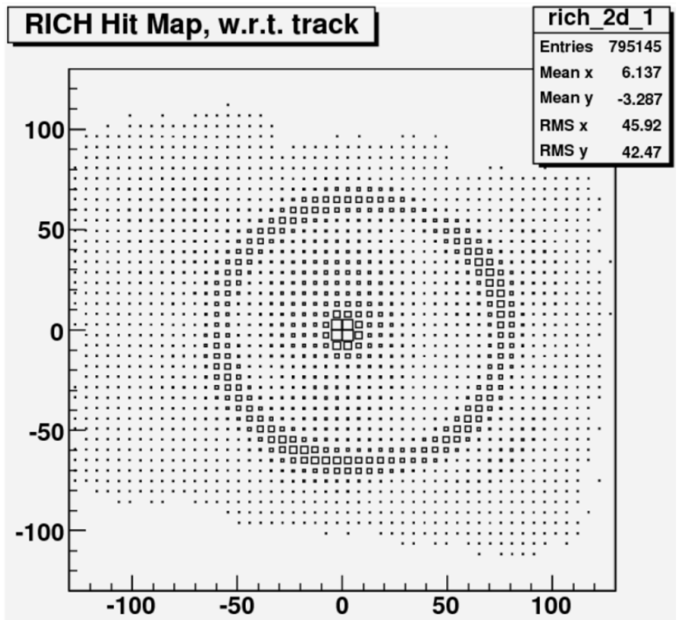
Proximity focusing RICH: Beam test performance

Excellent HAPD sensors at hand
Q.E. >30% ('Super-bialkali')



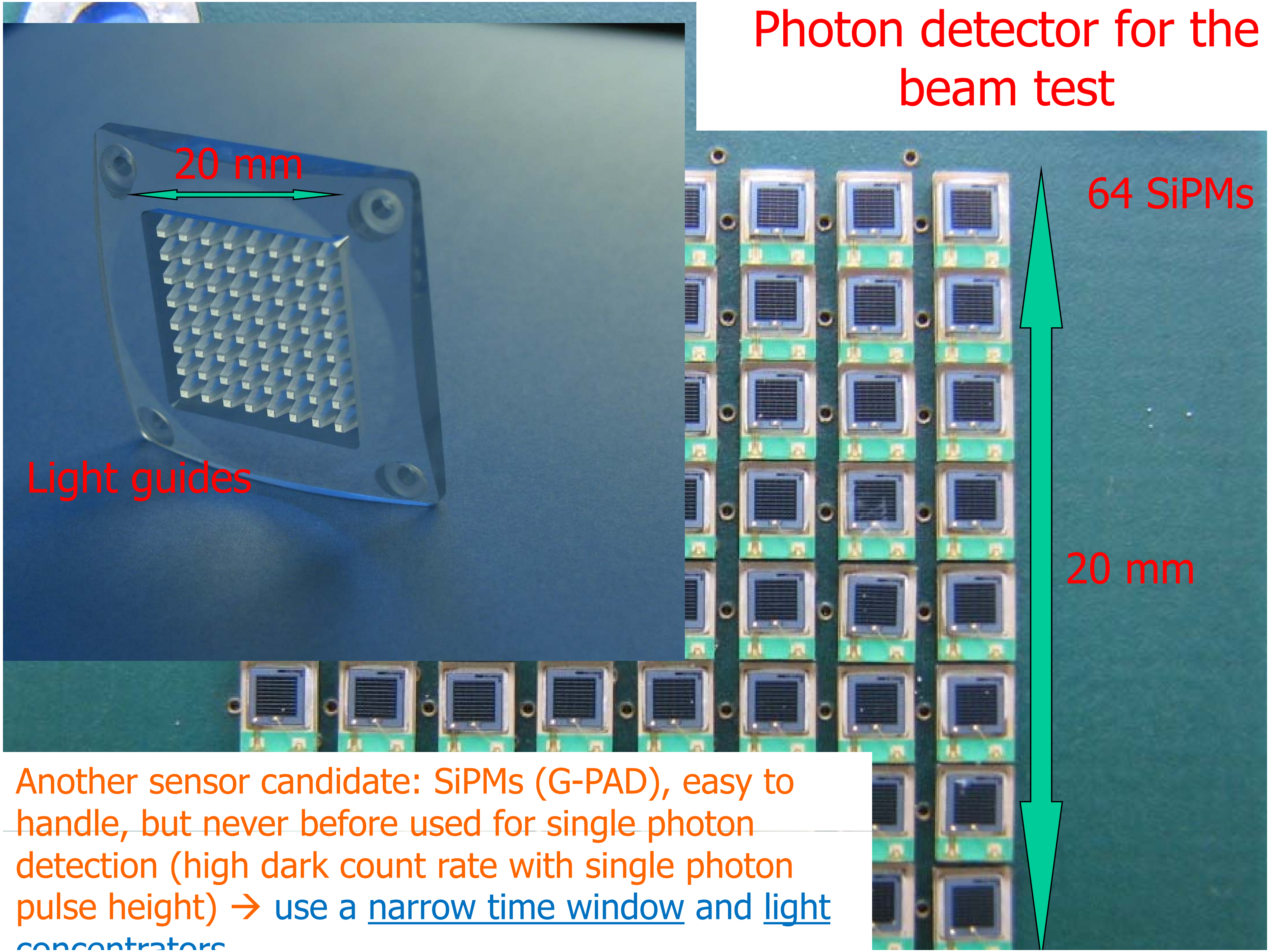


Electron test beam in November 2009



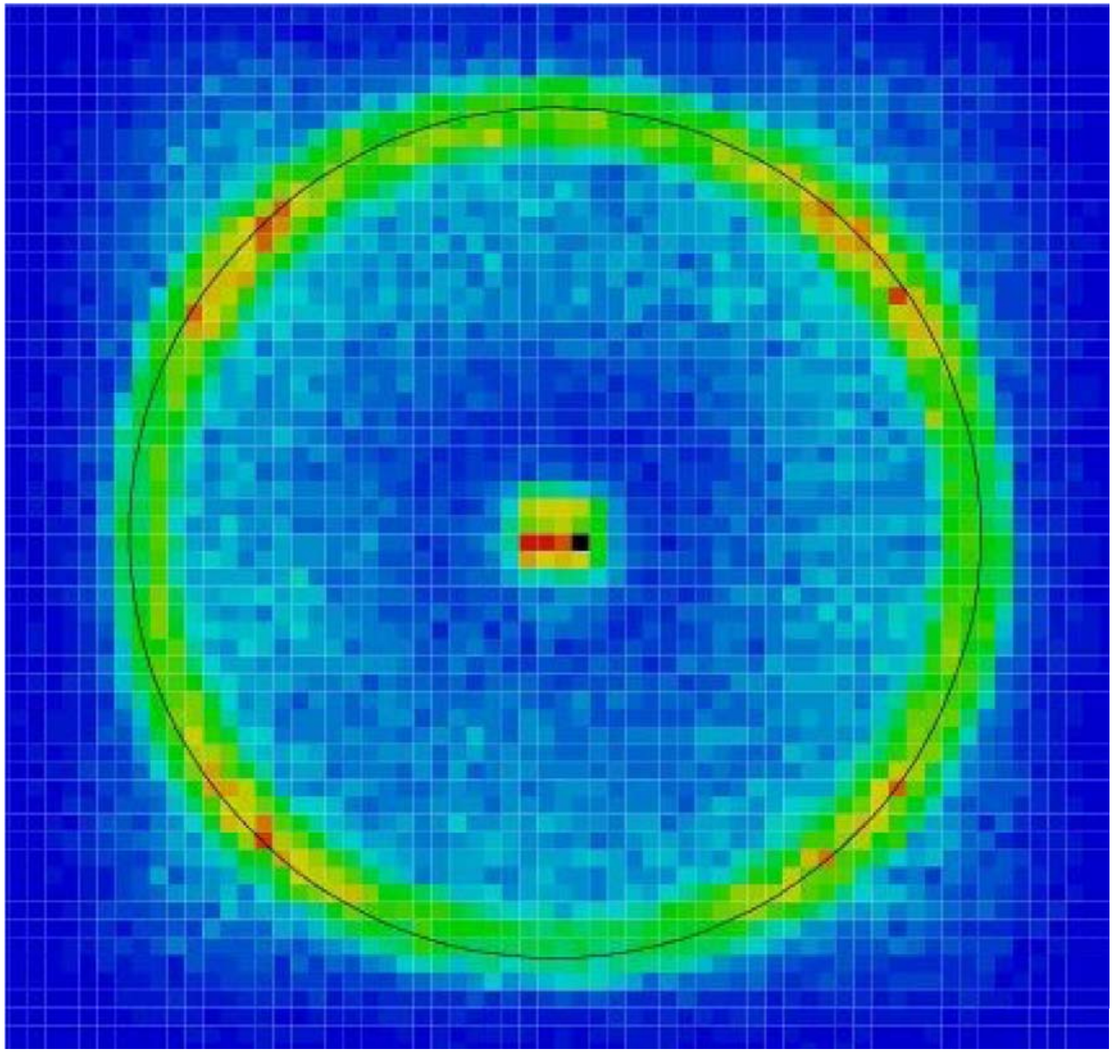
Number of photons / track = 14.3
Resolution / photon = 15.2 mrad
Resolution / track = 4.0 mrad

Photon detector for the beam test



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



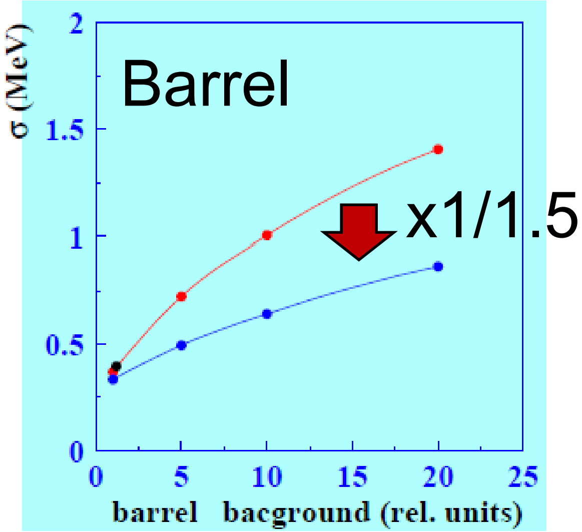
First successful use of SiPMs as single photon detectors in a RICH counter!

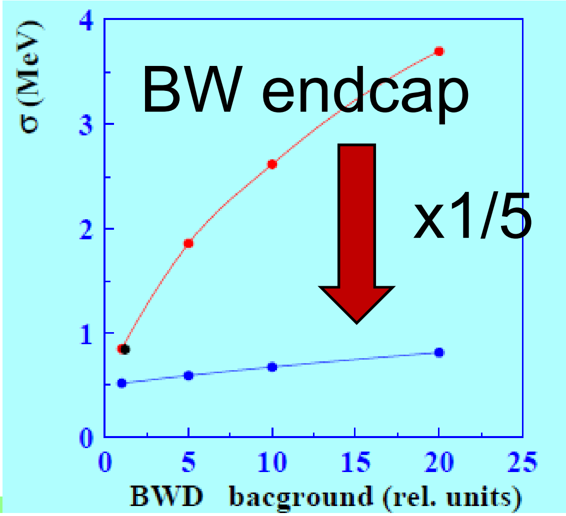
NIM A594 (2008) 13

Calorimeter (ECL) Upgrade

- Increase of dark current due to neutron flux
- Fake clusters & pile-up noise

- Barrel:
  0.5μs shaping + 2MHz w.f. sampling.
- Endcap:
  rad. hard crystals with short decay time (e.g. pure CsI) + photopentodes
  30ns shaping + 43MHz w.f. sampling



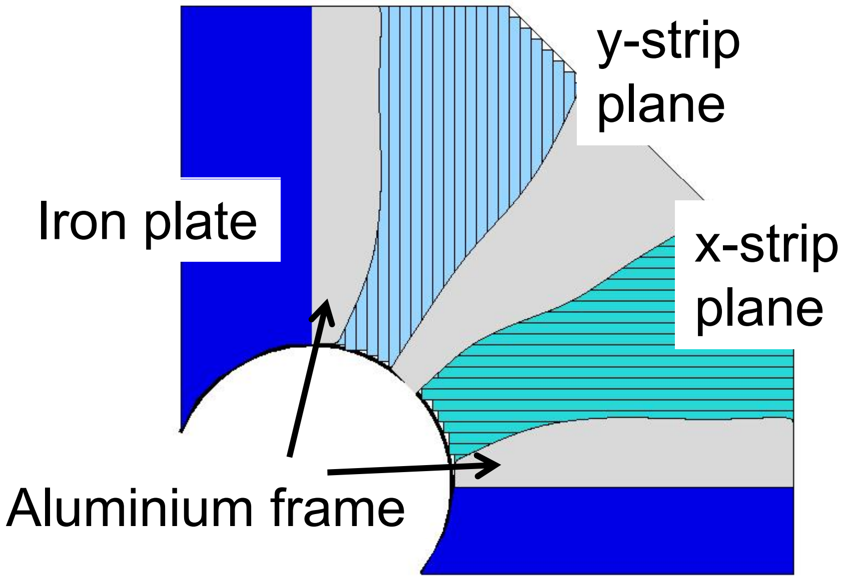


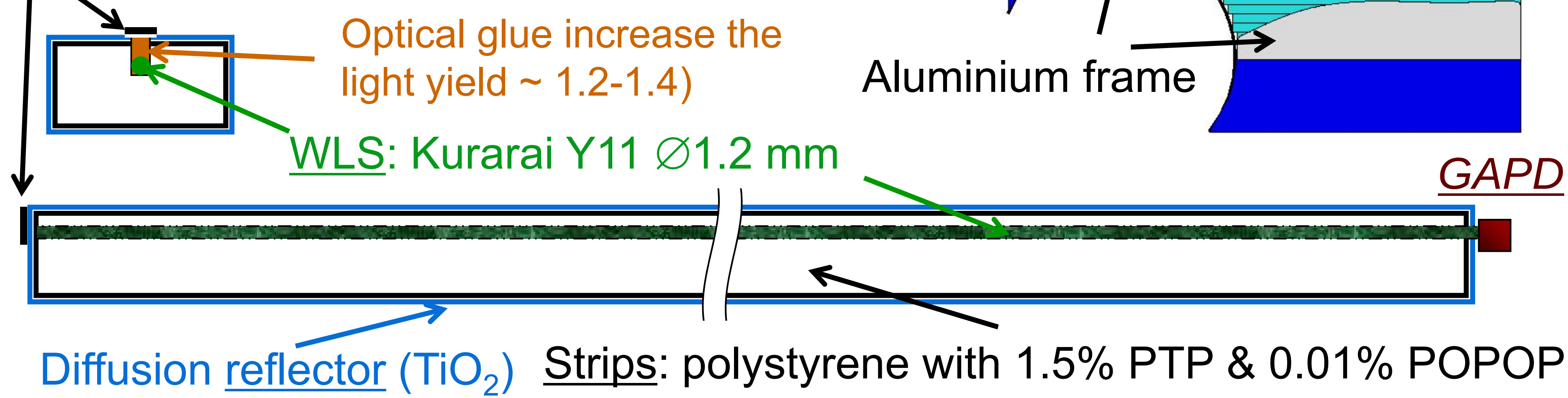
Pure CsI & photopentodes

KLM upgrade in the endcaps

Scintillator-based KLM (endcap)

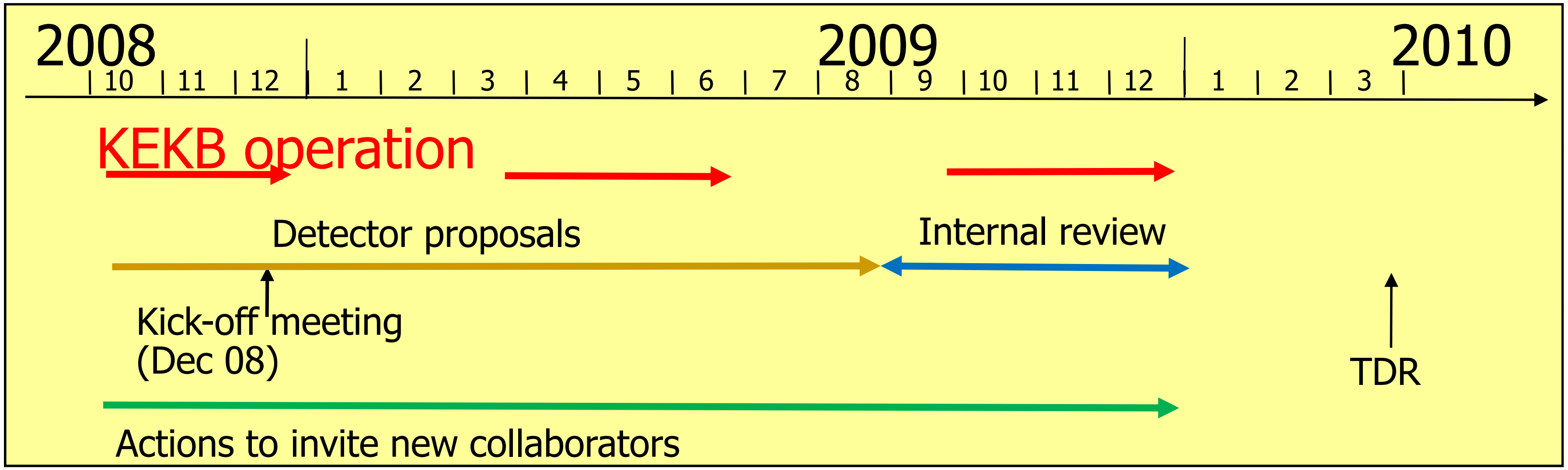
- Two independent (x and y) layers in one superlayer made of orthogonal strips with WLS read out
- Photo-detector = avalanche photodiode in Geiger mode (SiPM)
- ~120 strips in one 90º sector (max L=280cm, w=25mm)
- ~30000 read out channels
- Geometrical acceptance > 99%





Project timetable

- Near-term plan
  - Detector proposals (by Dec. 2009)
  - Decisions on technology choices (Barrel PID configuration/photon detector, ECL endcap crystalls and photosensors)
  - TDR by March 2010



Belle-II Collaboration

2004.06: LoI for SuperKEKB
2008.01: KEK Roadmap → identified as high priority project at KEK
2008.12: New collaboration (Belle-II) officially formed

❖ 13 countries/region, 43 institutes, ~300 members

Separate group/organization from Belle

Executive Board (Chair: H. Aihara)

Spokesperson: P. Križan
Project manager: M. Yamauchi

Institutional Board (Chair: L. Piilonen)

Physics coordinator: B. Golob

Technical coordinator: Y. Ushiroda

Software /computing coordinators: T. Hara / T. Kuhr

2009.11: 4th Open Collaboration Meeting

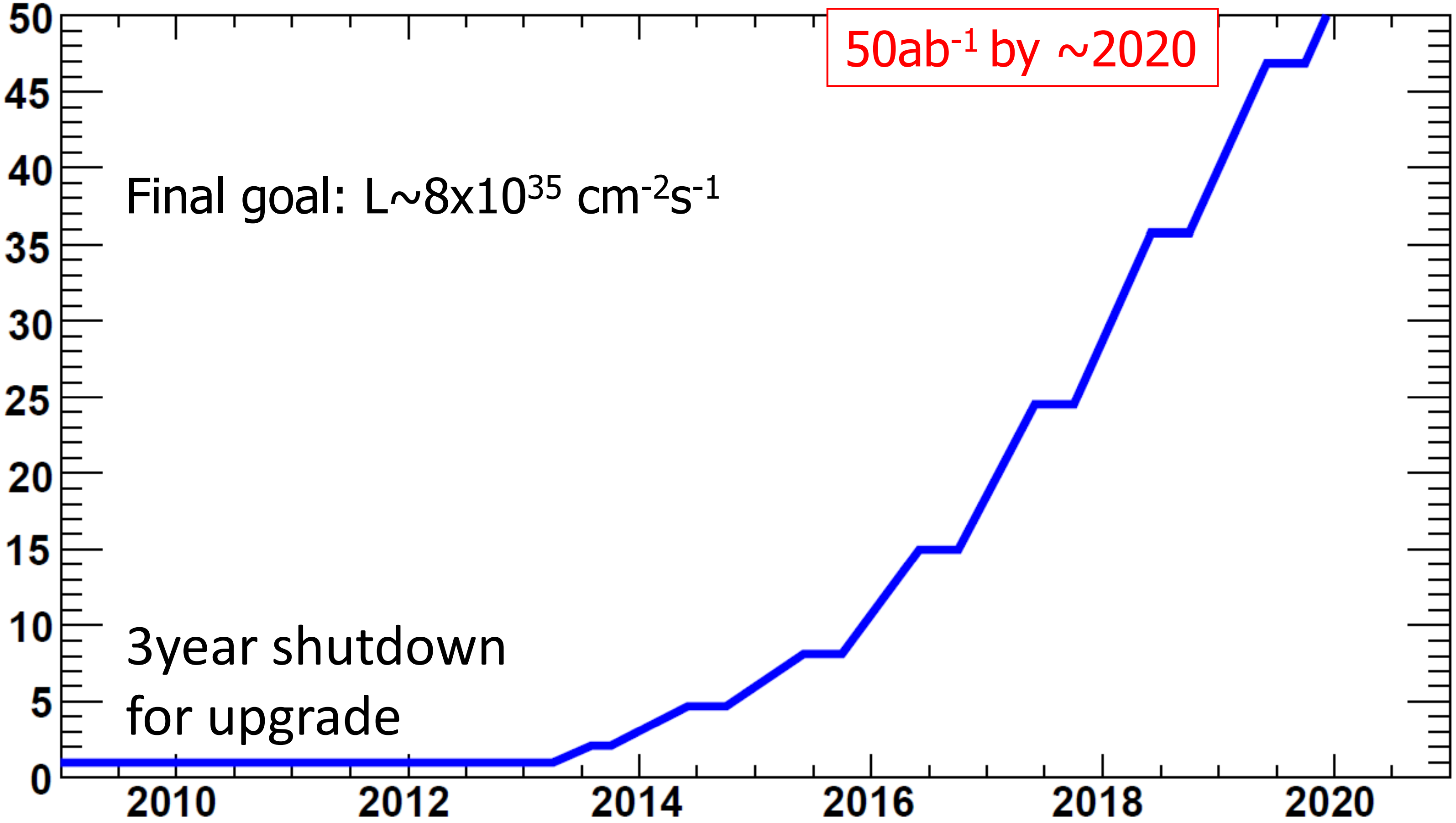
European groups of Belle-II

- Austria: HEPHY (Vienna)
- Czech republic: Charles University in Prague
- Germany: U. Bonn, KIT Karlsruhe, MPI Munich, U. Giessen
- Poland: INP Krakow
- Russia: ITEP (Moscow), BINP (Novosibirsk),
- Slovenia: J. Stefan Institute, U. Ljubljana, U. Maribor, U. Nova Gorica

Sizeable fraction of the collaboration: in total 100 collaborators out of 287!

Project plans

Long term plan:
•3 year shut-down for upgrade of the accelerator and detector
•Start machine operation in 2013



Project status

- SuperKEKB and Belle-II are priorities of KEK
- The Japanese government has allocated 32 oku-yen (32 M$) for upgrade R&D in FY 2009, as a part of its economic stimulus package. This is considered as a very important sign in Japan.
- KEK has submitted to the Ministry of education, science, and technology (MEXT) a budget request for FY 2010 and beyond for 350 M$ for the construction of SuperKEKB. MEXT submitted a request for the upgrade budget to the Ministry of finance.
- Japanese government is currently reviewing all major projects. The decision is expected by the end of this year.
- Several non-Japanese funding agencies have already allocated sizable funds for the upgrade.

Summary

- B factories have proven to be an excellent tool for flavour physics, with reliable long term operation, constant improvement of the performance.
- Major upgrade at KEK in 2010-13 → Super B factory, L x40
- Essentially a new project, all components have to be replaced, options to be frozen in the next few months
- The project has a strong European participation (about 1/3!)
- A physics reach update is being prepared – to be made public soon
- Expect a new, exciting era of discoveries, complementary to LHC