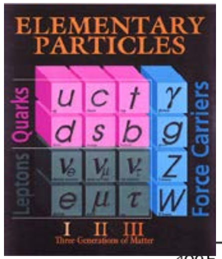
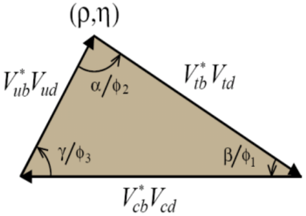
Challenging the Standard Model - Belle II and the SuperKEKB Project

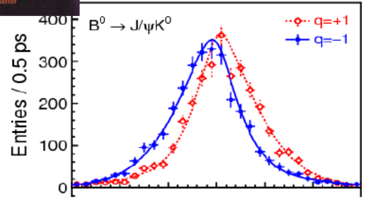
Christian Kiesling

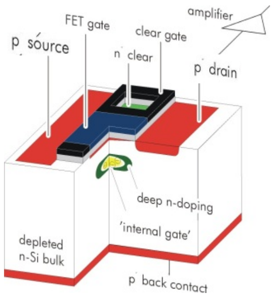
MPI for Physics und LMU München

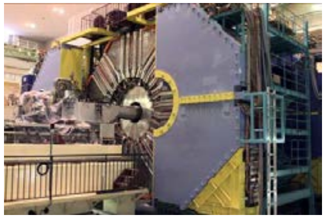
- Flavor Physics and the Standard Model
- Results of Present Experiments
- Why go beyond ?
- SuperKEKB and Belle II
- New Detector Components for Belle II





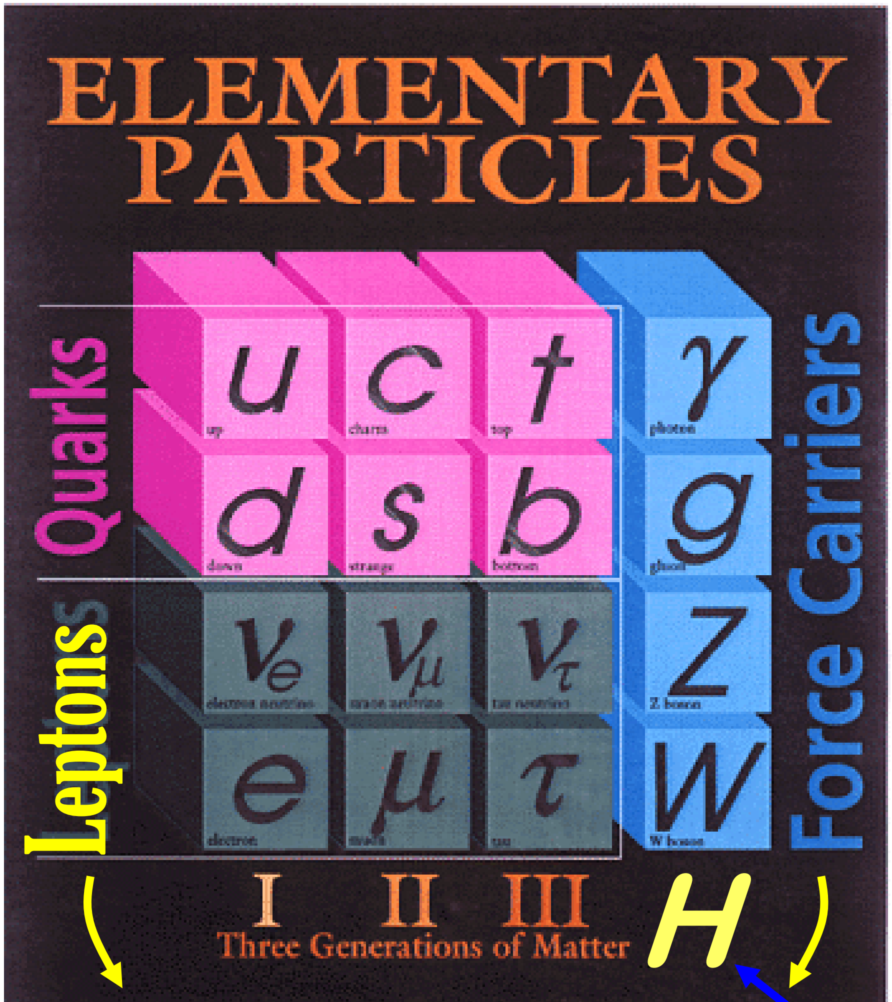






Particles in the Standard Model (SM)

uud … , or $u\bar{d}$ …



electr. charge		electr. charge	Mass of particles (in GeV):			
+2/3		0	0.005	1.4	175	0
-1/3		0	0.006	0.3	4.5	0
0		0	>0	>0	>0	91
-1		±1	0.0005	0.1	1.8	80

„particles“:
Spin 1/2
(fermions)

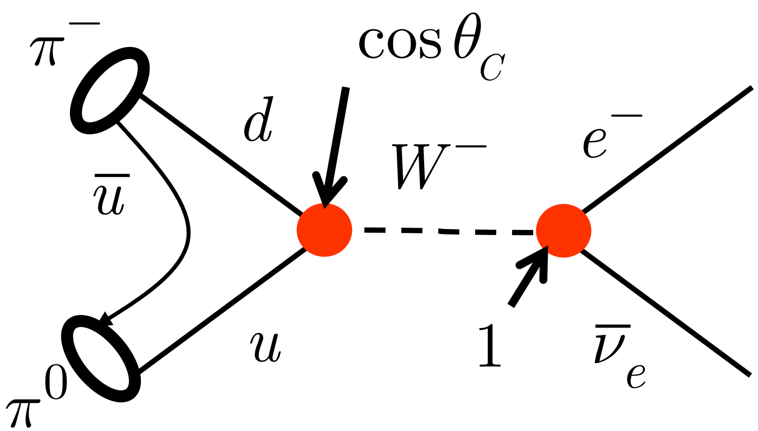
„fields“:
Spin 1(0)
(bosons)

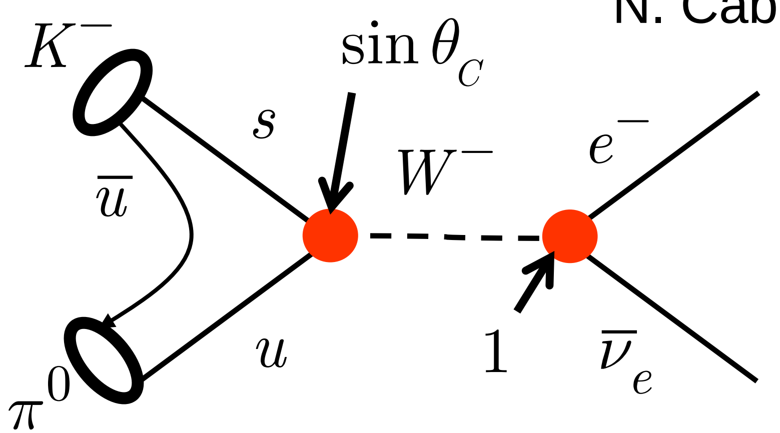
the Higgs

the last missing particle is found

Changing Flavor in the Standard Model

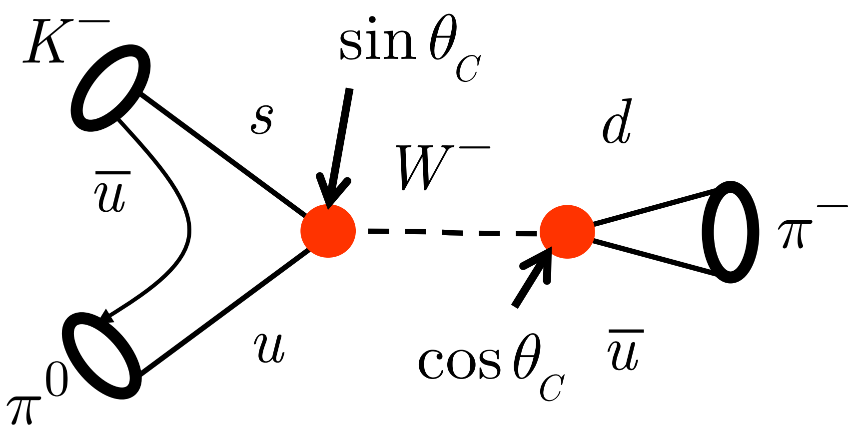
N. Cabibbo



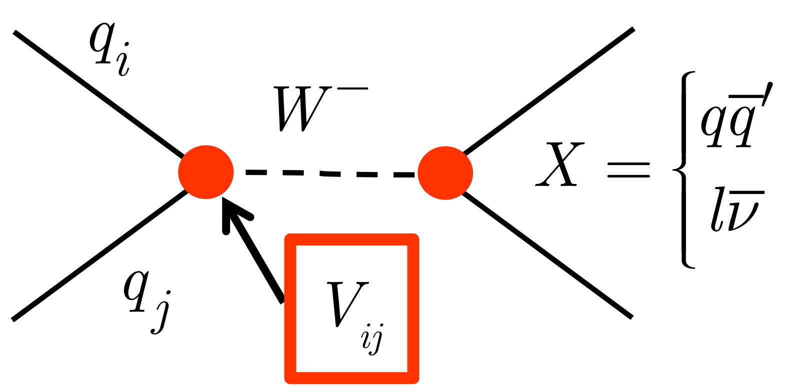


$\pi^- \to \pi^0 e^- \bar{\nu}_e$ semi-leptonic decays $K^- \to \pi^0 e^- \bar{\nu}_e$

purely hadronic decays, e.g.



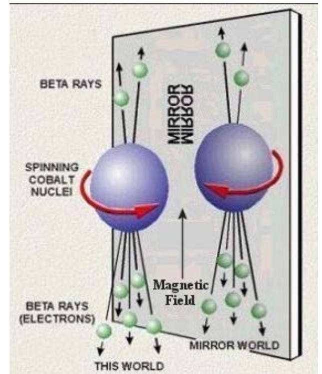
general flavor change:



Surprising Discoveries in Weak Interactions of Quarks

T.D. Lee

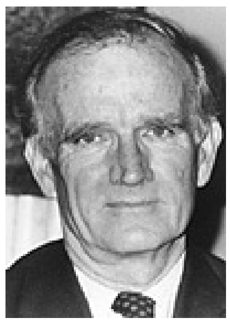
C.N. Yang



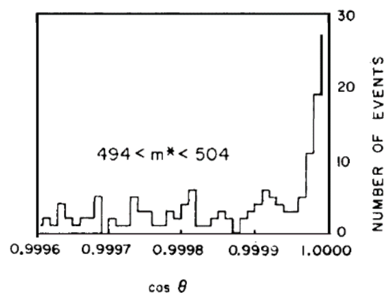
P violated maximally in weak interactions

1957

J. Cronin



V. Fitch

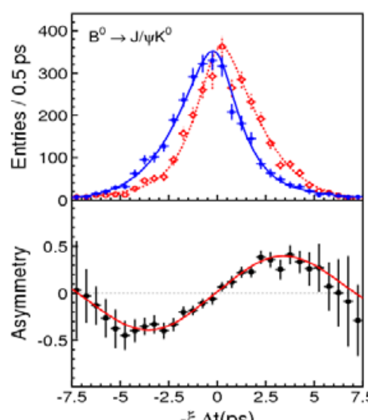


Small CP violation in neutral K system

1980

M. Kobayashi

T. Maskawa



O(1) CP violation and 3 generations of quarks

2008

Fundamental Discrete Symmetries

$\vec{p}$ $\vec{s}$

Spatial Inversion P:

ν_e | P $[\nu_e]$

Charge Conjugation C:

ν_e | C $[\bar{\nu}_e]$

Time reversal T:

ν_e | T ν_e

Spatial + Charge CP:

ν_e | CP $\bar{\nu}_e$

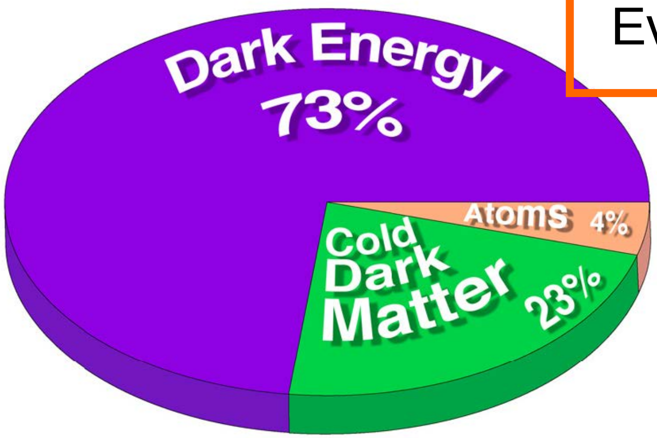
is CP, T conserved ??

ν_e | CPT $\bar{\nu}_e$

CPT: conserved in all local quantum theories exhibiting Lorentz-invariance

Why is CP Violation Interesting ?

The Standard Model $SU_3 \times SU_2 \times U_1$ (SM) describes all data so far
yet: cannot be the correct theory, SM only a „low energy“ approximation



Evidence for Physics beyond the Standard Model:

- Neutrinos have mass (Dirac, Majorana?)
- Dark Matter exists
  (only 4% of the Universe accounted for by SM)
- Baryon Asymmetry in the Universe is
  much too large (by 10 orders of magnitude)

need
very high energy
(LHC) or
v. high precision
(Super B factories)

At least two of them have to do with CP Violation

$\not{C}\not{P}$: One of the so-called Sakharov-conditions

The Origin of CP Violation in the SM

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

„flavor“ Matrix V: unitary „mass“

CP violation from Quark Mixing:

Extension of the Cabibbo-Matrix

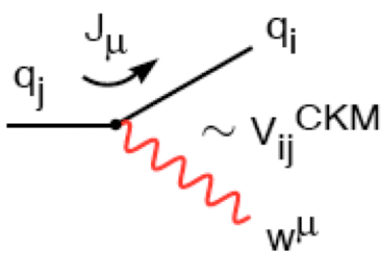
$$d' = \quad d \cos\theta_C + s \sin\theta_C$$
$$s' = -d \sin\theta_C + s \cos\theta_C$$

Condition for CPV: Matrix must have complex elements
only possible via n x n matrix with n > 2

Theory formulated in 1973 by Kobayashi & Maskawa
(Charm-, Bottom- and Top-Quark were not discovered yet!)

b-quark experiments have established the theory of K&M !

CKM Matrix and the Unitarity Triangle(s)



weak decays of hadrons (quarks change flavor)
are described in the SM by the (unitary) CKM matrix

Cabibbo, Kobayashi, Maskawa $\qquad \lambda = \sin\theta_C$

$$V^{\mathrm{CKM}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

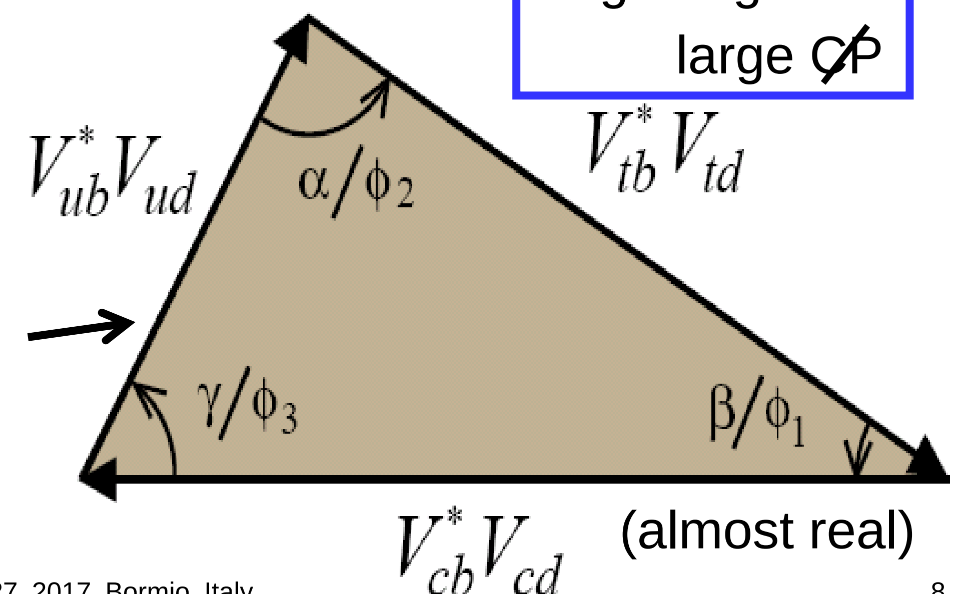
large angles = large ~~CP~~

$$\boxed{V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0}$$

Triangle for K mesons

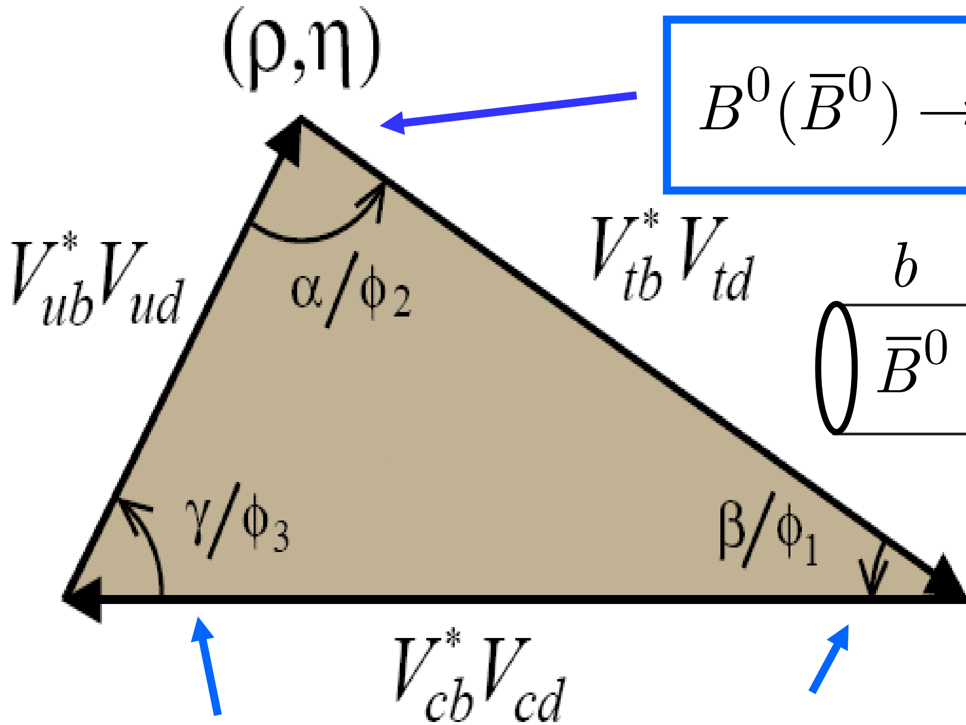
$$\boxed{V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0}$$

Triangle for B mesons



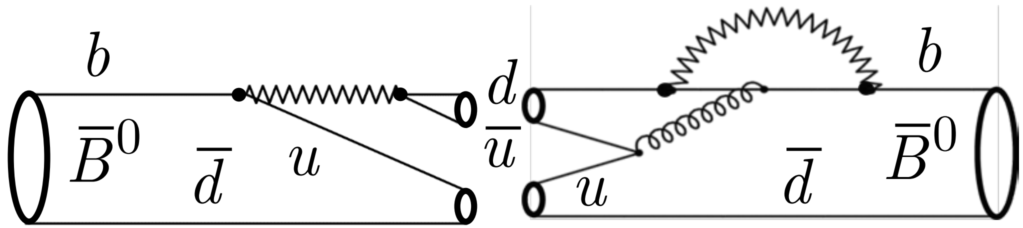
(almost real)

Measuring the Angles Φ_1,Φ_2,Φ_3 (β,α,γ)



$$B^0(\overline{B}^0) \to \pi\pi, \rho\rho, \rho\pi, a_1\pi$$

$Br \sim 10^{-6}$



T ~ P

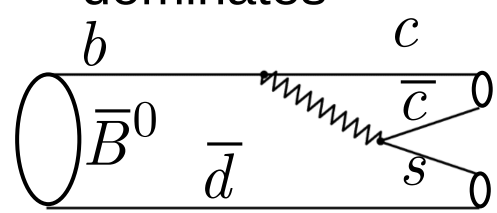
Tree (T) or Penguin (P) dominates

$Br \sim 10^{-4}$

$$B^+(B^-) \to D\,K, D^*\pi$$
$$B^0(\overline{B}^0) \to K\pi$$

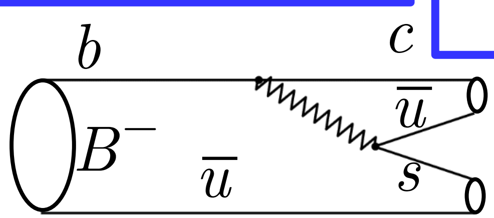
$$B^0(\overline{B}^0) \to J/\psi\, K_{S,L}$$
$$\to \phi\, K_{S,L}$$

....

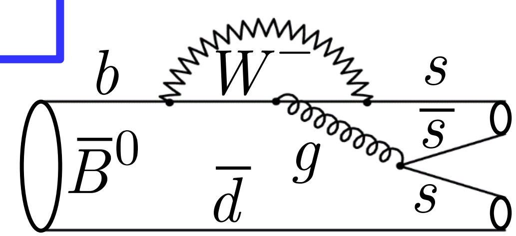


T

$Br \sim 10^{-5}$



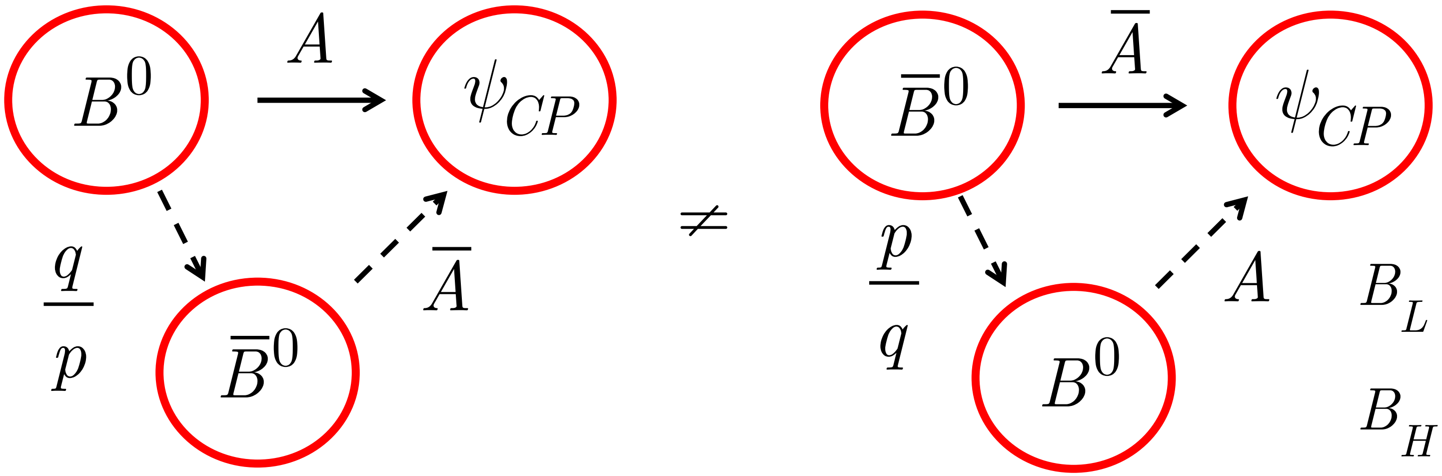
T (only)



P

What are the CP-Observables ?

$$A = \left\langle \psi_{CP} \mid B^0 \right\rangle; \qquad \bar{A} = \left\langle \psi_{CP} \mid \bar{B}^0 \right\rangle \qquad \psi_{CP} : \text{CP eigenstate}$$



$$\lambda_\psi = \frac{q}{p}\frac{\bar{A}}{A}$$

$$B_L = pB^0 + q\bar{B}^0$$

$$B_H = pB^0 - q\bar{B}^0$$

$$\mathcal{A}_{CP}(\psi, \Delta t) = \frac{\Gamma(\bar{B}^0 \to \psi; \Delta t) - \Gamma(B^0 \to \psi; \Delta t)}{\Gamma(\bar{B}^0 \to \psi; \Delta t) + \Gamma(B^0 \to \psi; \Delta t)}$$

„time-dependent CP asymmetry“

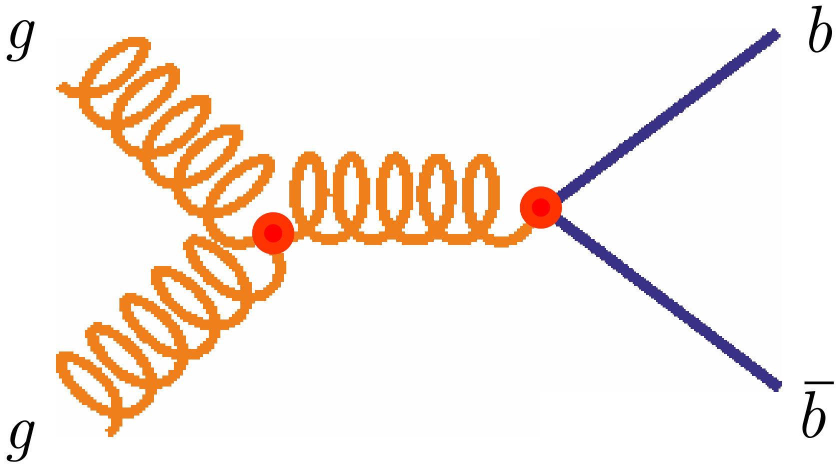
$$= \frac{1 - \left|\lambda_\psi\right|^2}{1 + \left|\lambda_\psi\right|^2} \cos \Delta m \Delta t + \frac{2\,\mathrm{Im}(\lambda_\psi)}{1 + \left|\lambda_\psi\right|^2} \sin \Delta m \Delta t$$

„direct“

„mixing-induced“

B-Mesons as Sensitive Probes

B-mesons can be (easily) produced in pairs via the Strong Interaction:



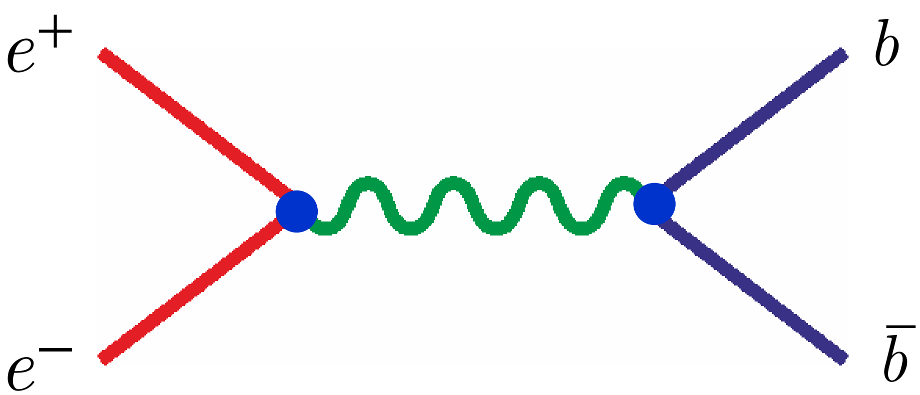
LHC:

ATLAS,
CMS,

LHCb

large
cross section

… or the Electromagnetic Interaction:



B Factories:

KEK (Belle)
PEP II (BaBar)

Belle II @ SuperKEKB

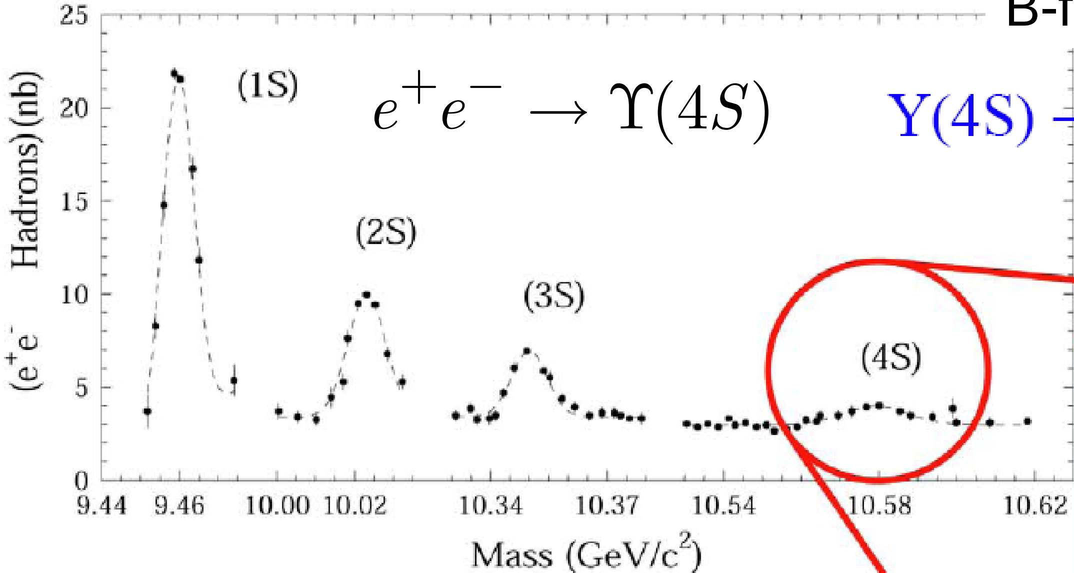
clean
events

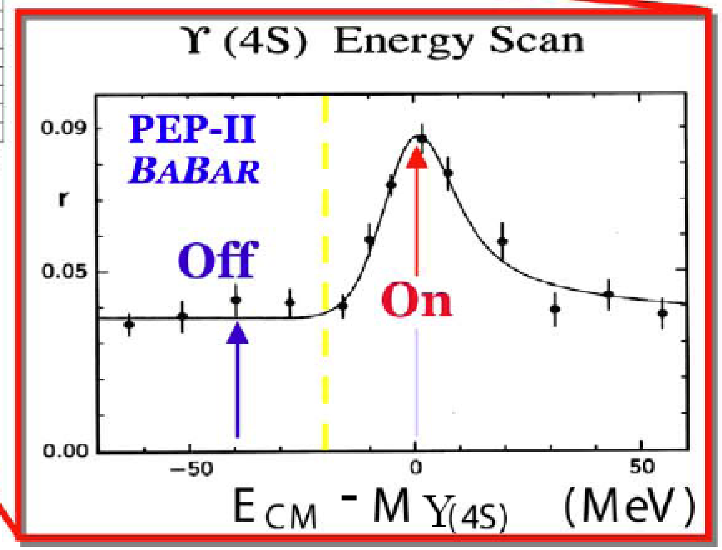
B-Factories: Where do we Measure?

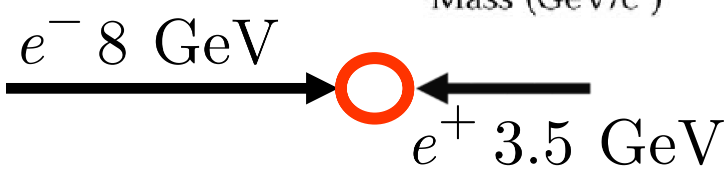
B-factories at KEK and SLAC

$$e^+e^- \rightarrow \Upsilon(4S)$$

Y(4S) -> $B^0\bar{B}^0$ (50%), B^+B^- (50%)







B-mesons are produced exclusively,
neutral B-mesons: quantum-entangled

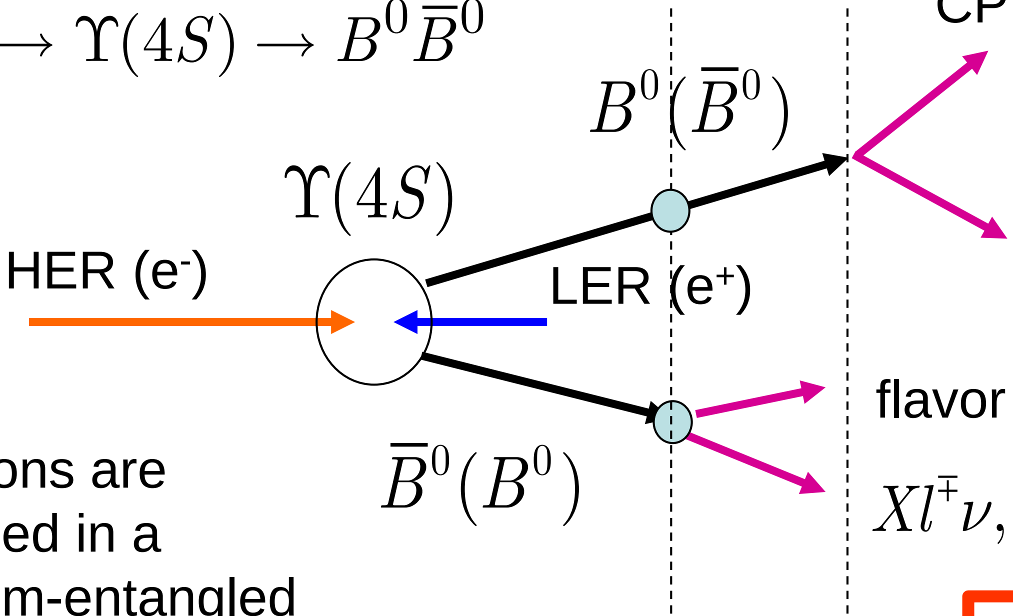
Beam energies are asymmetric:
both B's have the same Lorentz boost,
fly parallel in the lab system

background („continuum") below the resonance peak

The ~~CP~~ Observables: What do we measure?

B-Mesons: $\left|B^0\right\rangle = \left|\bar{b}d\right\rangle \quad \left|B^+\right\rangle = \left|\bar{b}u\right\rangle$

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0$$



some state $f(\bar{f})$ or CP eigenstate, e.g.

$J/\psi K_S$ the „Golden" channel

$CP = -1$

flavor eigenstate

$Xl^{\mp}\nu, D^{*\pm}X$ „flavor tagging"

B mesons are produced in a quantum-entangled state !

$$\Delta z = \beta\gamma c\Delta t$$

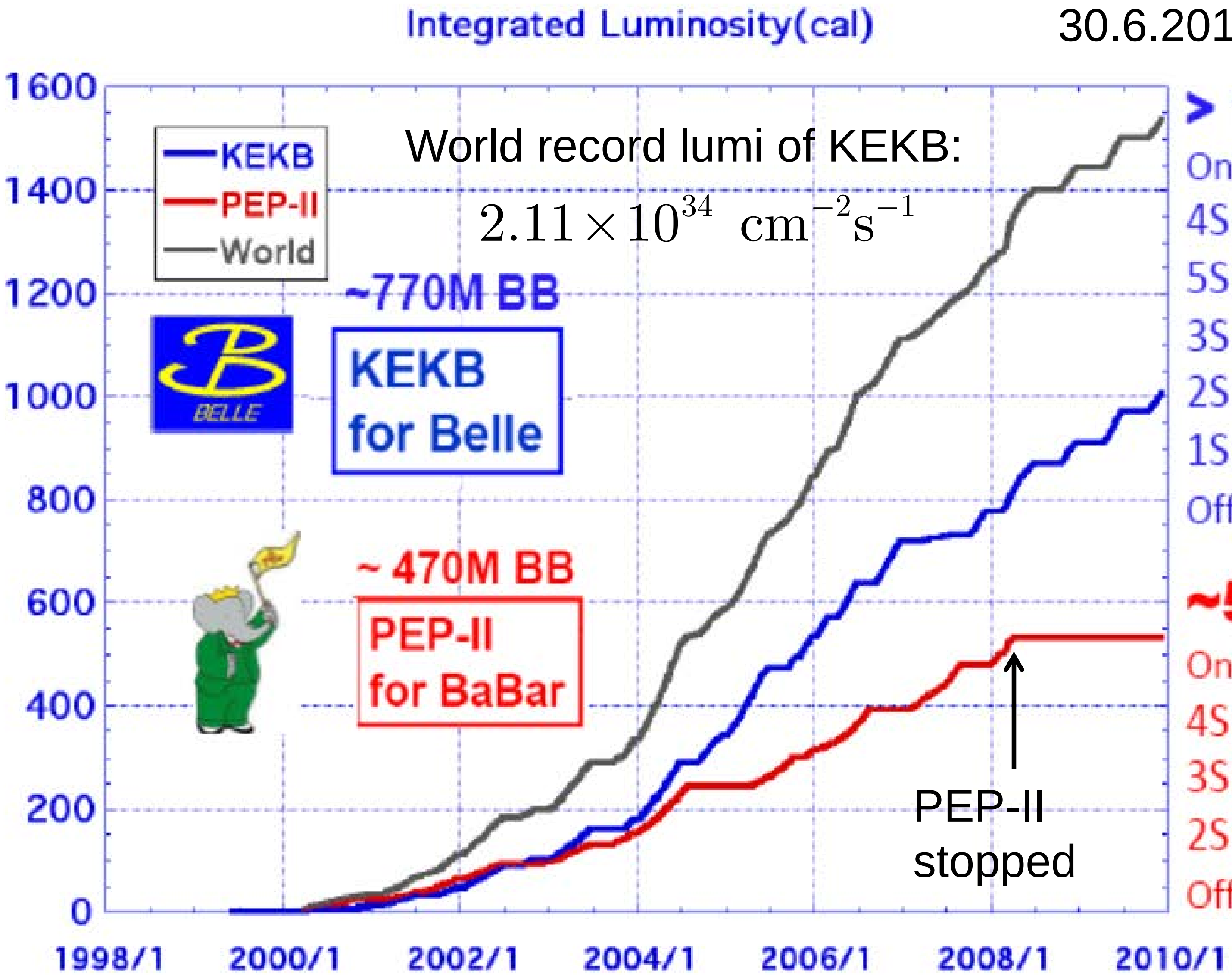
$$\boxed{\Delta t = t_{\mathrm{CP}} - t_{\mathrm{tag}}}$$

Asymmetric beam energies: translate decay time to decay length

Δz ~ 150 µm → need excellent vertex detection

Luminosity Accumulated at Past B-Factories

30.6.2010: KEKB stopped



> 1.0 ab^{-1}

On-resonance samples:

4S: 711 fb^{-1}

5S: 121 fb^{-1}

3S: 3.0 fb^{-1}

2S: 24 fb^{-1}

1S: 5.7 fb^{-1}

Off-resonance: 87 fb^{-1}

~553 fb^{-1}

On-resonance samples:

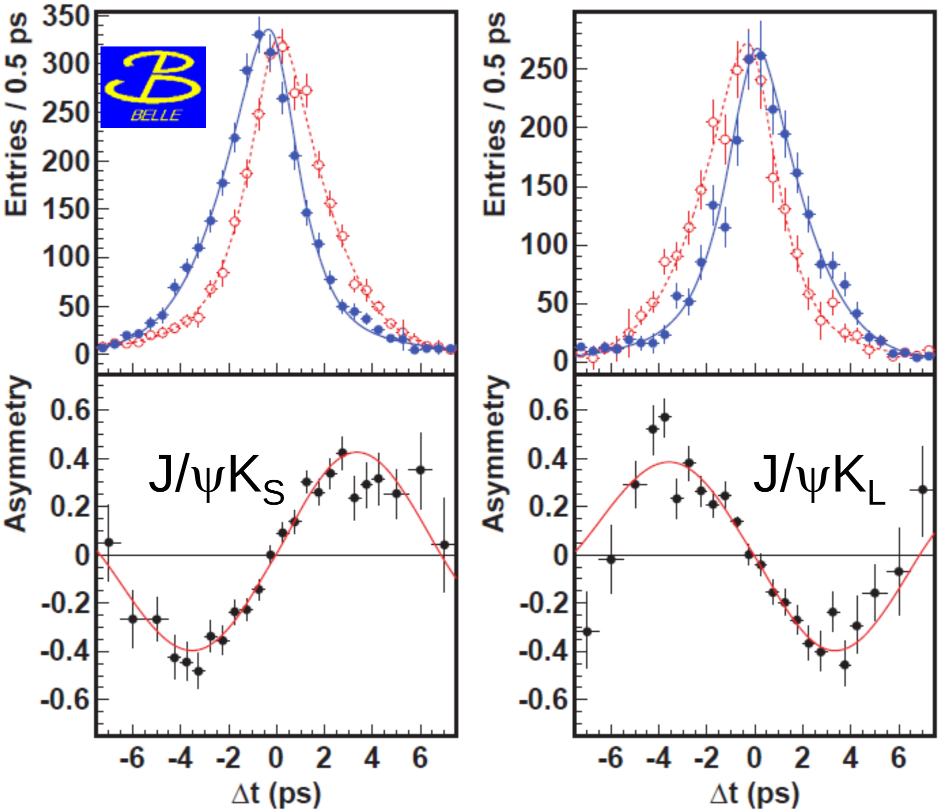
4S: 433 fb^{-1}

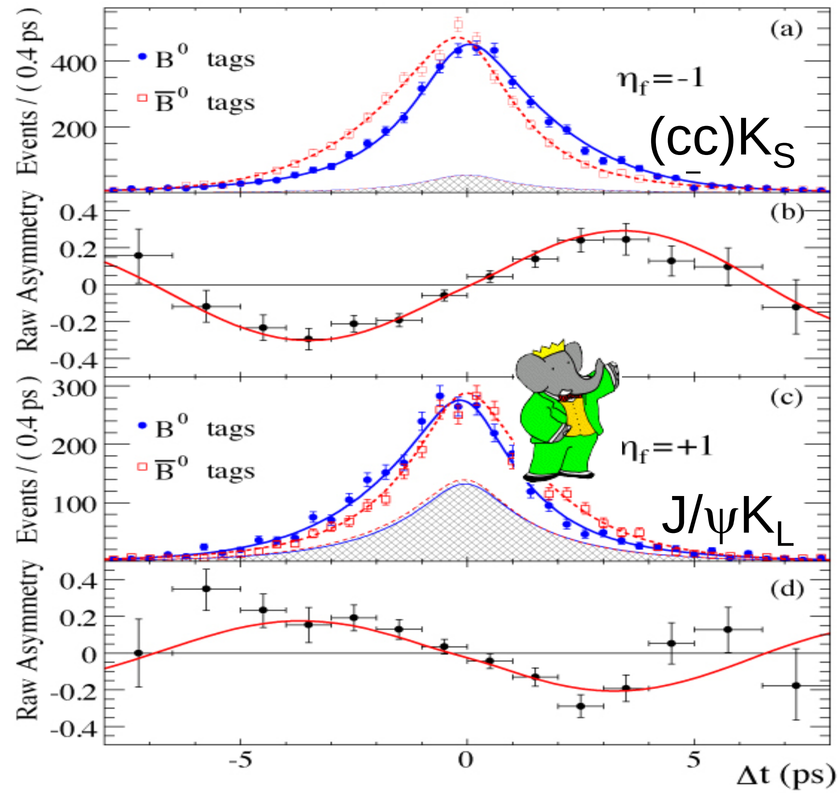
3S: 30 fb^{-1}

2S: 14 fb^{-1}

Off-resonance: 54 fb^{-1}

Measurement of Φ_1 (β) in Charmonium K^0 modes





$\sin2\phi_1=0.667\pm0.023\pm0.012$

$A_f=0.006\pm0.016\pm0.012$

PRL108,171802(2012)

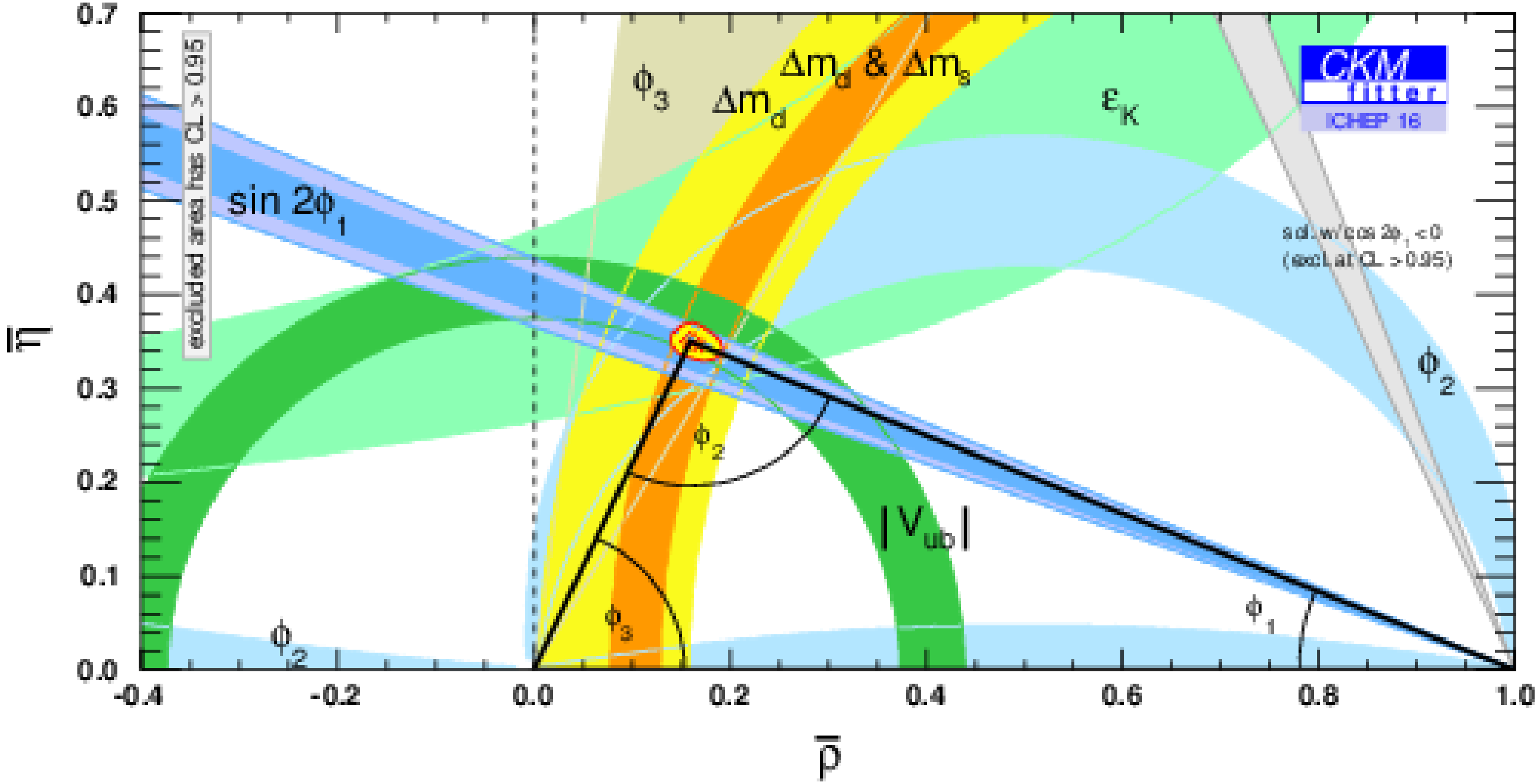
$\sin2\phi_1=0.687\pm0.028\pm0.012$

$A_f=-0.024\pm0.020\pm0.016$

PRD79,072009(2009)

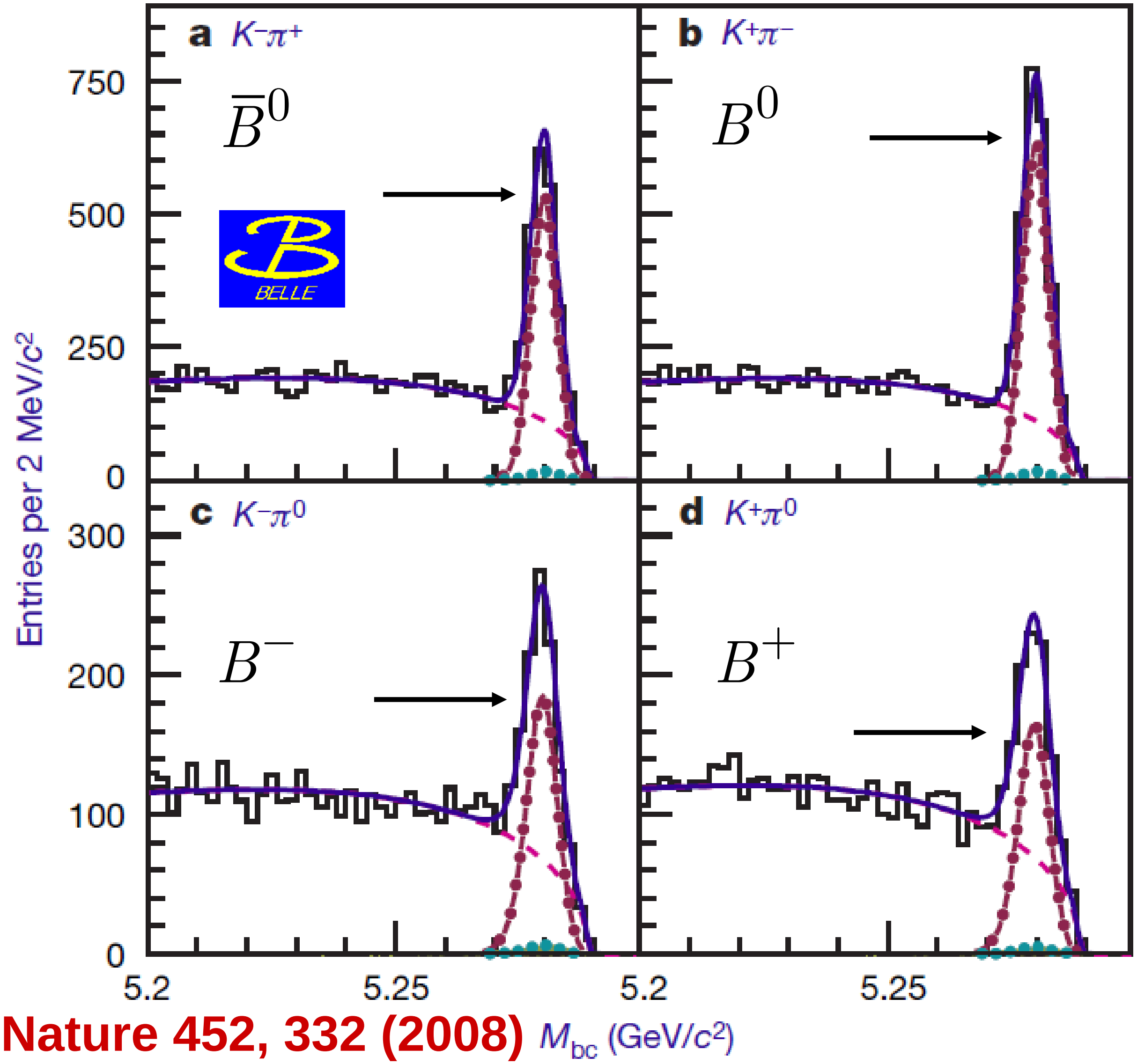
Excellent description by the Standard Model

The Unitarity Triangle in 2016



Generally consistent with SM, some „tensions“ exist …

Tensions in the SM: Direct CPV in $B \to K\pi$



Nature 452, 332 (2008)

$$A_{CP}(K^+\pi^-) < 0$$

WA: -0.098 ± 0.012

$$A_{CP}(K^+\pi^0) > 0$$

WA: $+0.050 \pm 0.025$

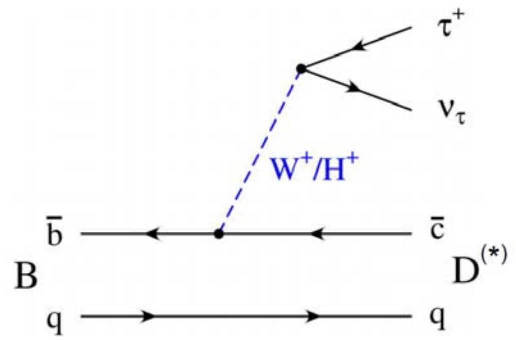
should be equal at the weak decay level

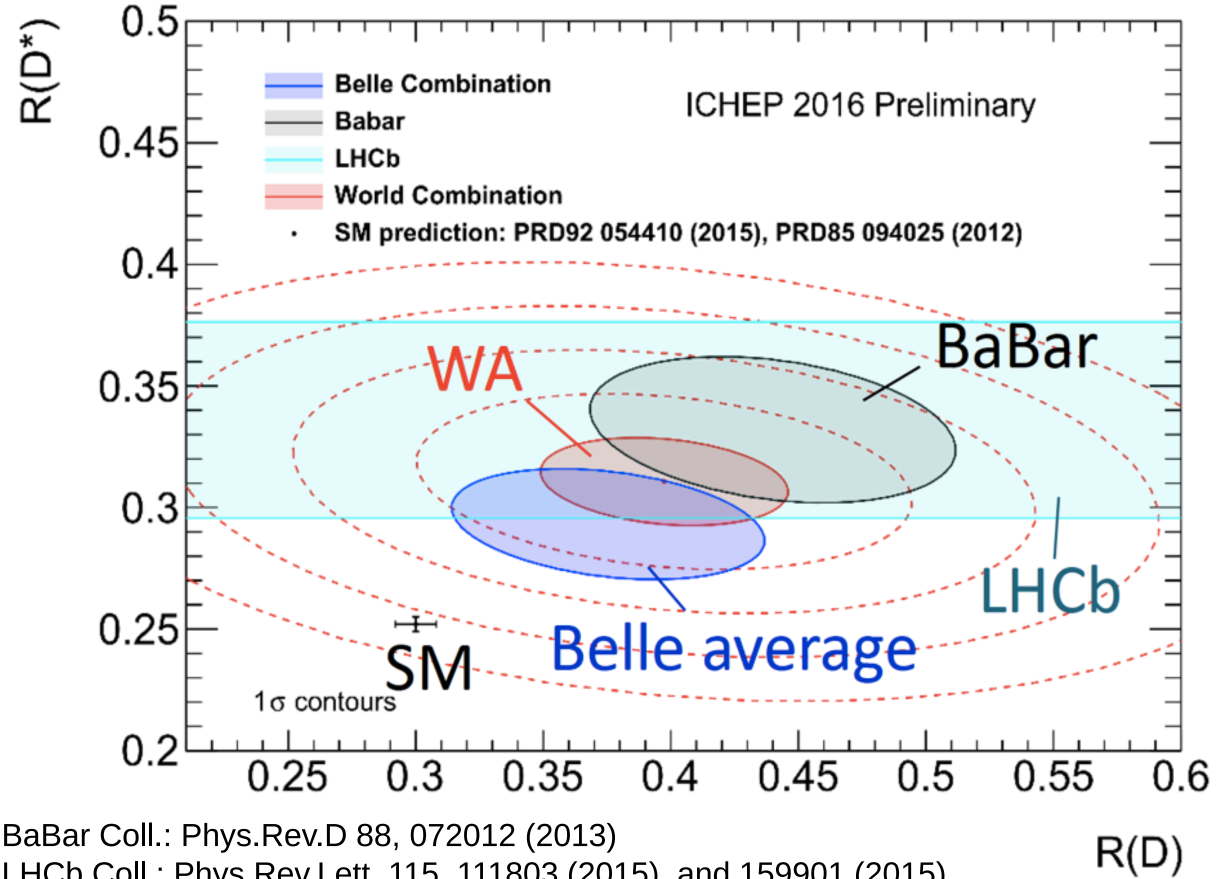
- QCD corrections?

- New Physics?

Tensions in the SM: Another Example

$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}l\bar{\nu}_l)} \text{ with } l = e, \mu$$





BaBar Coll.: Phys.Rev.D 88, 072012 (2013)
LHCb Coll.: Phys.Rev.Lett. 115, 111803 (2015), and 159901 (2015)
Belle Coll.: Phys.Rev. D94, 072007 (2016):

SM value:
lepton universality

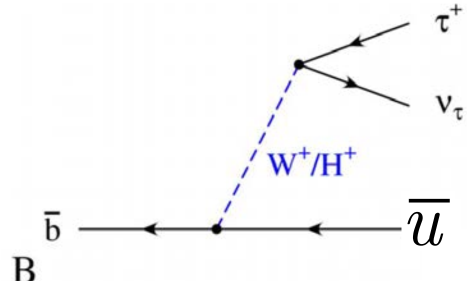
~ 4σ away from SM

New Physics (NP) could explain the discrepancy

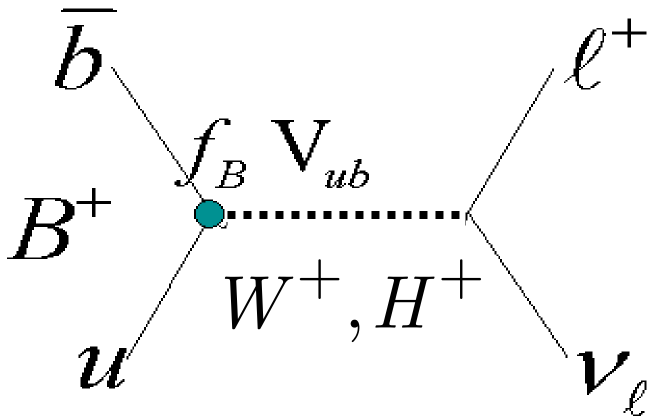
NP should appear at the same order as SM, but:
is dominated by SM

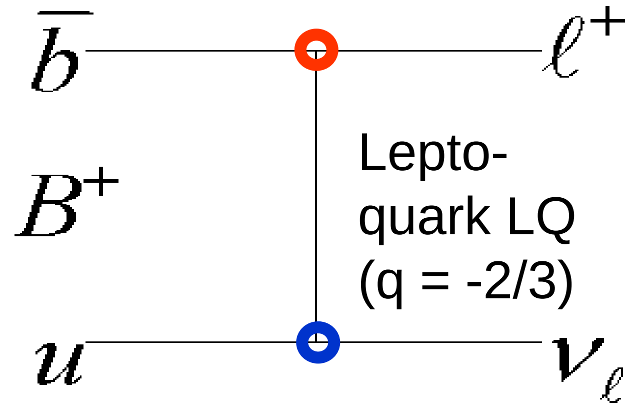
New Physics at the Tree Level

Another interesting process, with potential for New Physics:

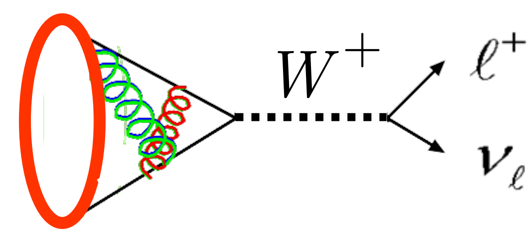


process dominated by SM





$$\boxed{\Gamma(B^+ \to \ell^+\nu) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1-\frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2}$$

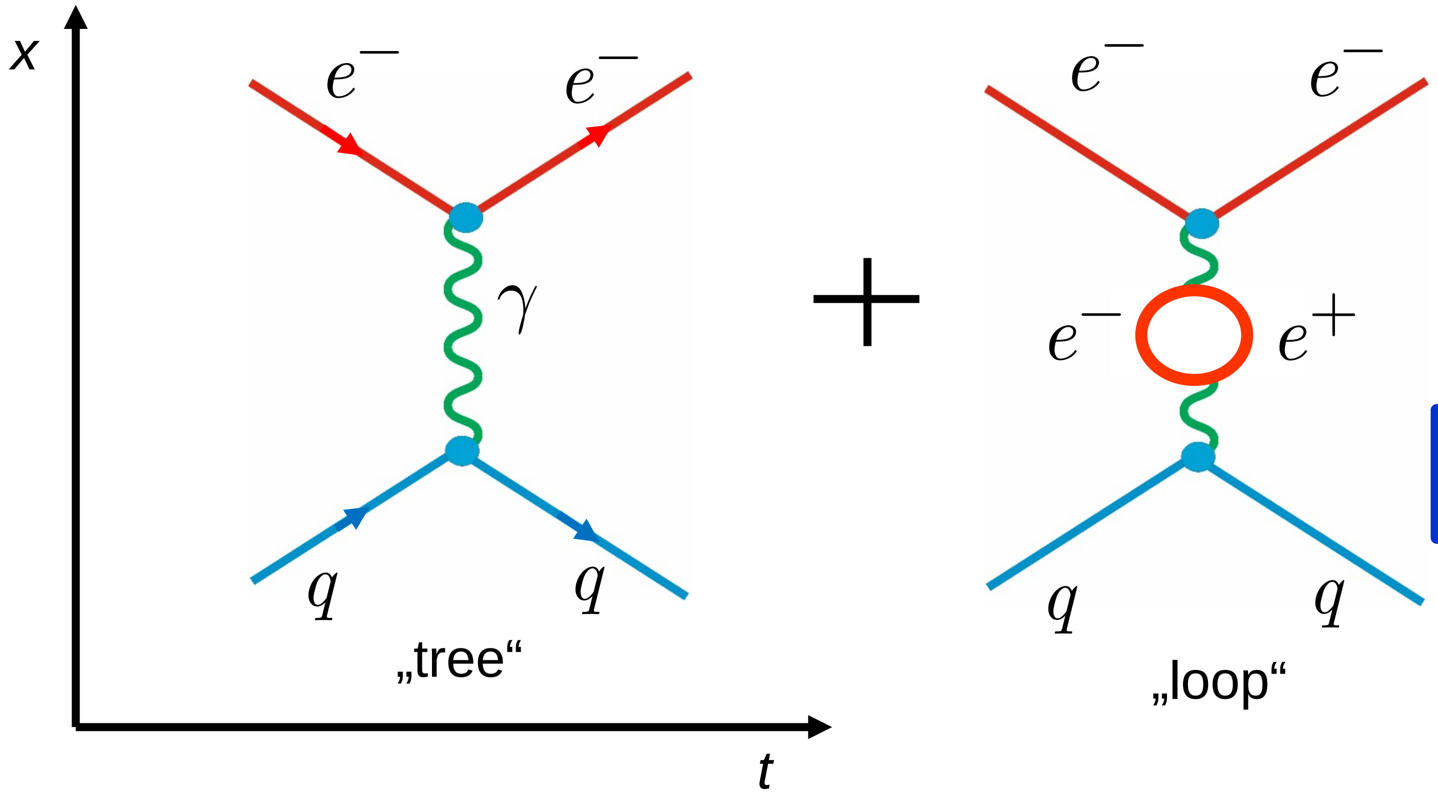


f_B <- Lattice QCD

seen at 4.6 σ level:
Belle Collaboration, PRD 92, 051102 (R) (2015)

Beyond the trees: Precision Physics

Feynman Diagrams at higher order: corrections to the SM observables:



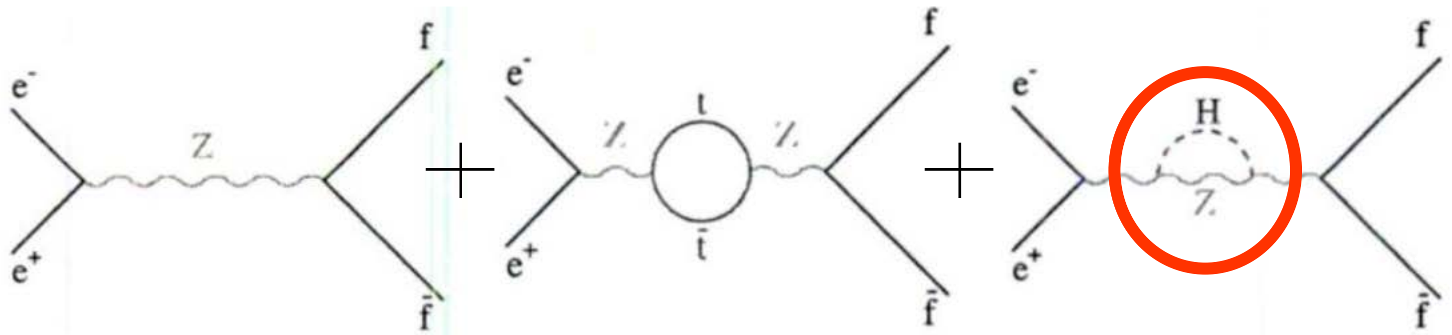
„Lamb shift“
in the H atom

+ . . .

$$\boxed{\Delta E \Delta t \geq \hbar}$$

Precision measurements of quantum loop effects open the window to large (~ unlimited) mass scales.

Example: Loops @ LEP „Finding“ the Higgs



$$M_W^2 = \frac{\pi\alpha}{G_F\sqrt{2}\sin^2\theta_W(1-\Delta r)}$$

$$\Delta r = \Delta r(\text{had}) + \underbrace{\Delta r(\text{top}) + \Delta r(\text{Higgs})}_{\text{loop corrections}}$$

„known“ from L.E.measurements

loop corrections

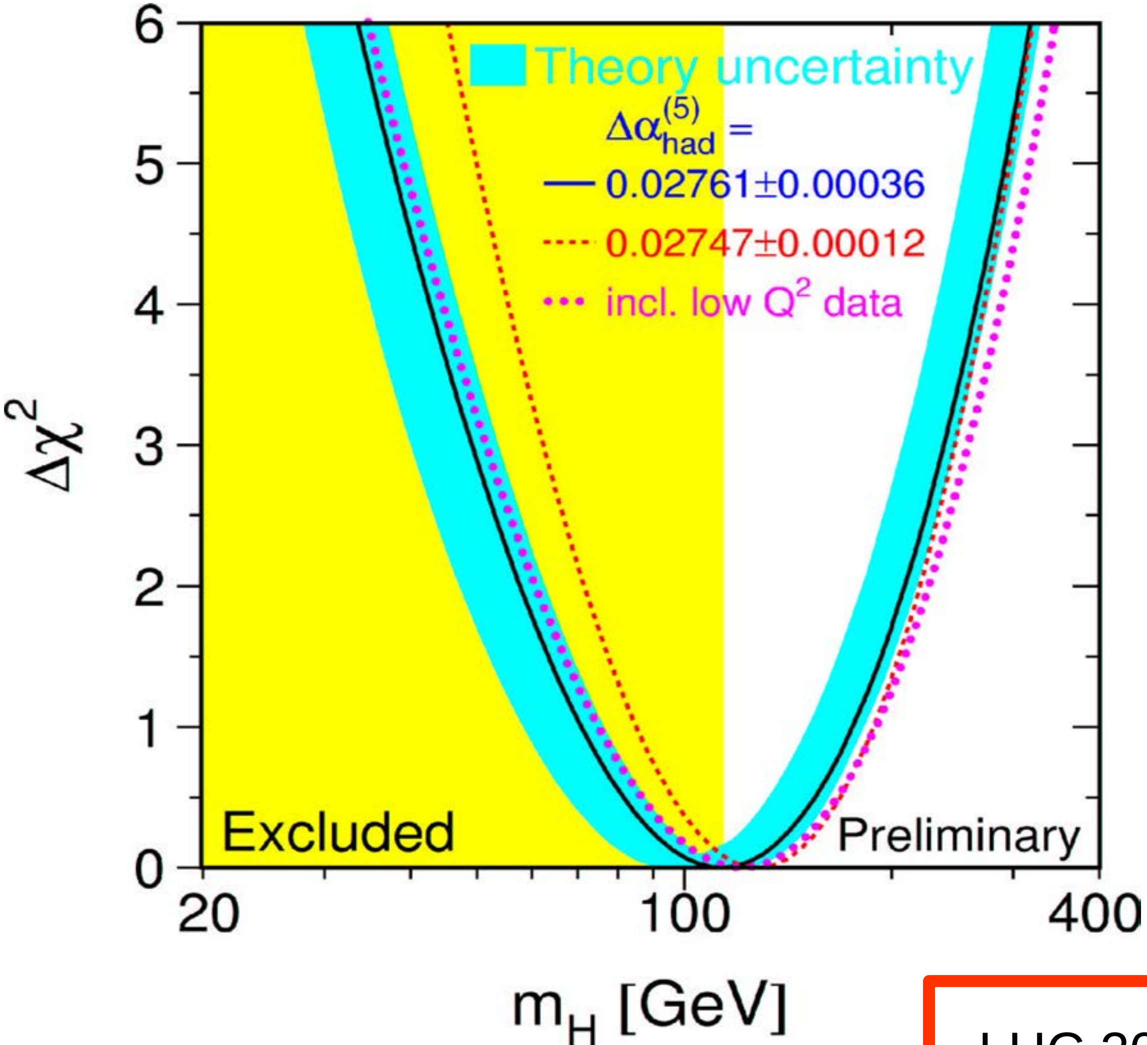
$$\Delta r(\text{top}) = \frac{3G_F}{8\sqrt{2}\tan^2\theta_W} m_t^2$$

Small, but very sensitive to the top mass

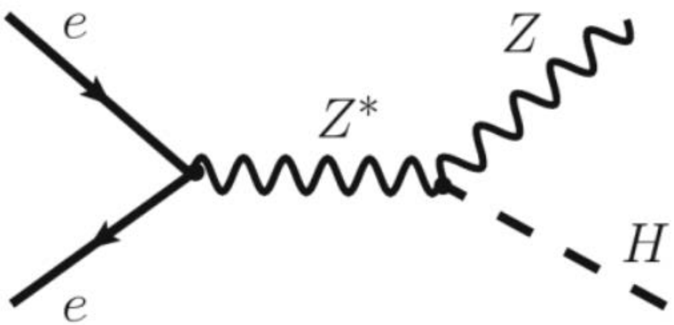
$$\Delta r(\text{Higgs}) = \frac{3G_F m_W^2}{8\sqrt{2}\pi^2}\left(\ln\frac{m_H^2}{m_Z^2} - \frac{5}{6}\right)$$

Small, logarithmic sensitivity, but “measurable“ after the top mass was known precisely

LEP: „Finding“ the Higgs



LEP fits suggested a very light Higgs



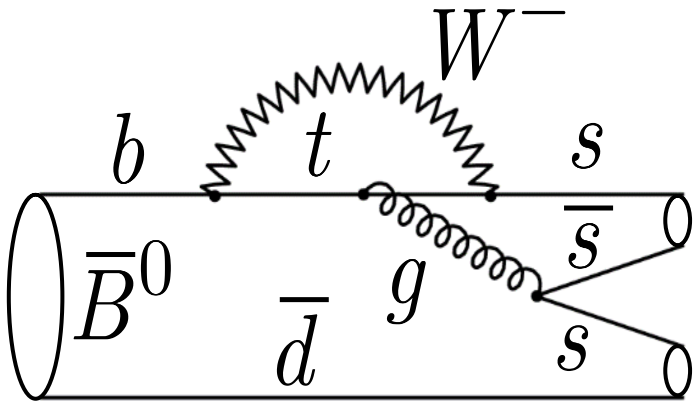
LEP 2 used to look for „Higgs-Strahlung“,

But no signal found …

$$m_H > 113 \text{ GeV}$$

LHC 2012: $m_H = 126 \text{ GeV}$

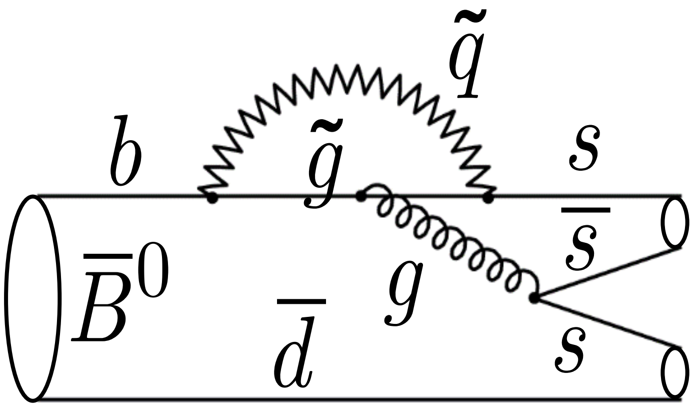
New Physics with Loop Diagrams



P

FCNC process loop-suppressed in SM

SM „penguin“



P

potentially large contribution from NP

NP „penguin“

Example: NP in the decay of *B* mesons

$$B^0(\overline{B}^0) \to \phi\, K_{S,L}$$

Principle:

Deviation of observables from the SM prediction signals NP

virtual particles in the loop reveal their existence

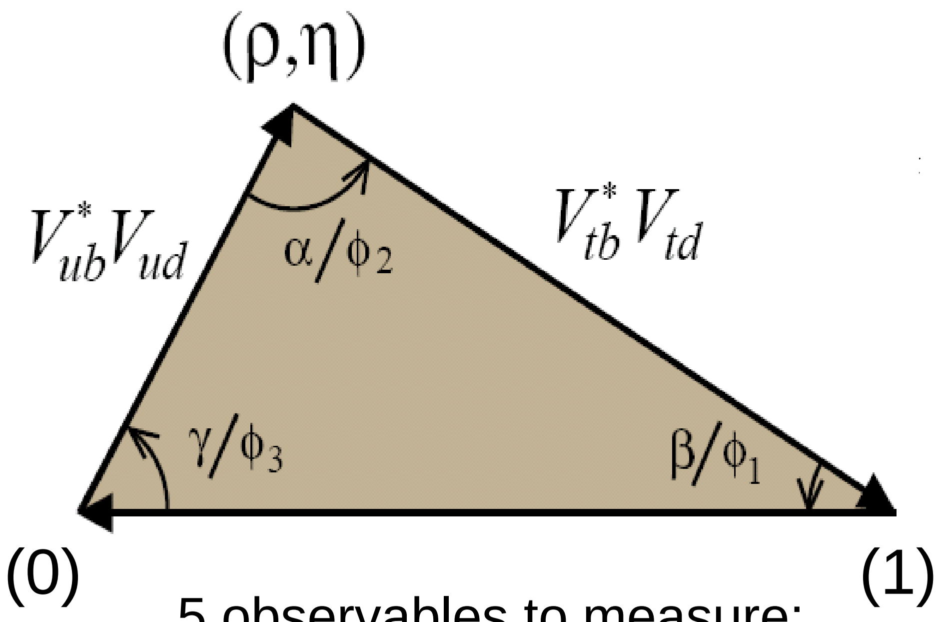
„Quantum Loop Effects“

e.g. NP=SUSY:

additional diagrams e.g. from gluino-squark contributions

$\longrightarrow \Lambda_{NP}$ no kinematic limit

New Physics at the Loop Level



5 observables to measure:
2 sides, 3 angles:
heavily over-determined

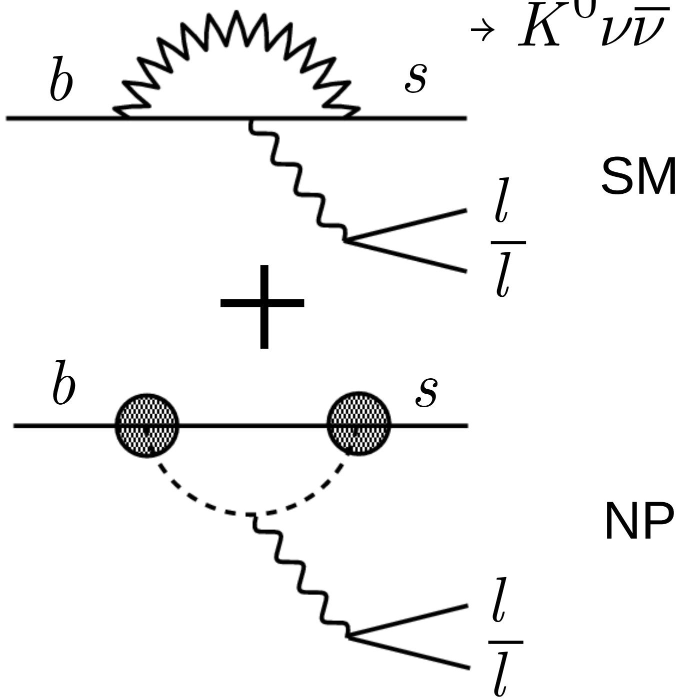
Standard Model: all 5 measurements must give consistency with the triangle

Rare decays, e.g.

$$\overline{B}^0 \rightarrow \overline{K}^0 l^+ l^-$$

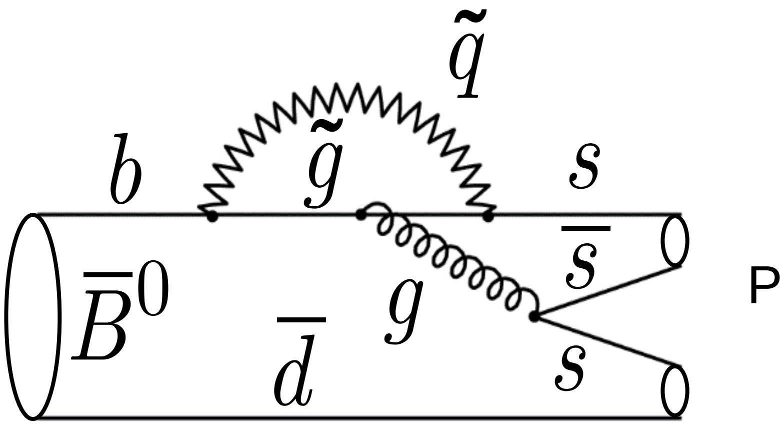
„Penguin“

$$\rightarrow \overline{K}^0 \nu\overline{\nu}$$



If triangle „does not close“ → **New Physics** ← unexpectedly „large“ branching fractions

New Physics at the Loop Level ....



NP „penguin“

Generic ansatz:

$$M = M_{SM} \times \left(1 + h_B e^{2i\xi_B}\right)$$

$$h_{(B)} \cong \left(\frac{|C_{ij}|}{|\lambda_{ij}^t|}\right)^2 \left(\frac{4.5\ \mathrm{TeV}}{\Lambda}\right)^2$$

$$\lambda_{ij}^t = V_{ti}^* V_{tj}$$

Rare Decays of *B* mesons:

	SM pred.
$B \to X_{s,d}\gamma$	$\mathcal{O}\left(10^{-4}\right)$
$B \to X_{s,d} l^+ l^-$	$\mathcal{O}\left(10^{-6}\right)$
$B \to X_d \nu\bar{\nu}$	$\mathcal{O}\left(10^{-6}\right)$
$B \to l^+ l^-$	$\mathcal{O}\left(10^{-10}\right)$
$B \to \nu\bar{\nu}$	$\mathcal{O}\left(10^{-54}\right)$

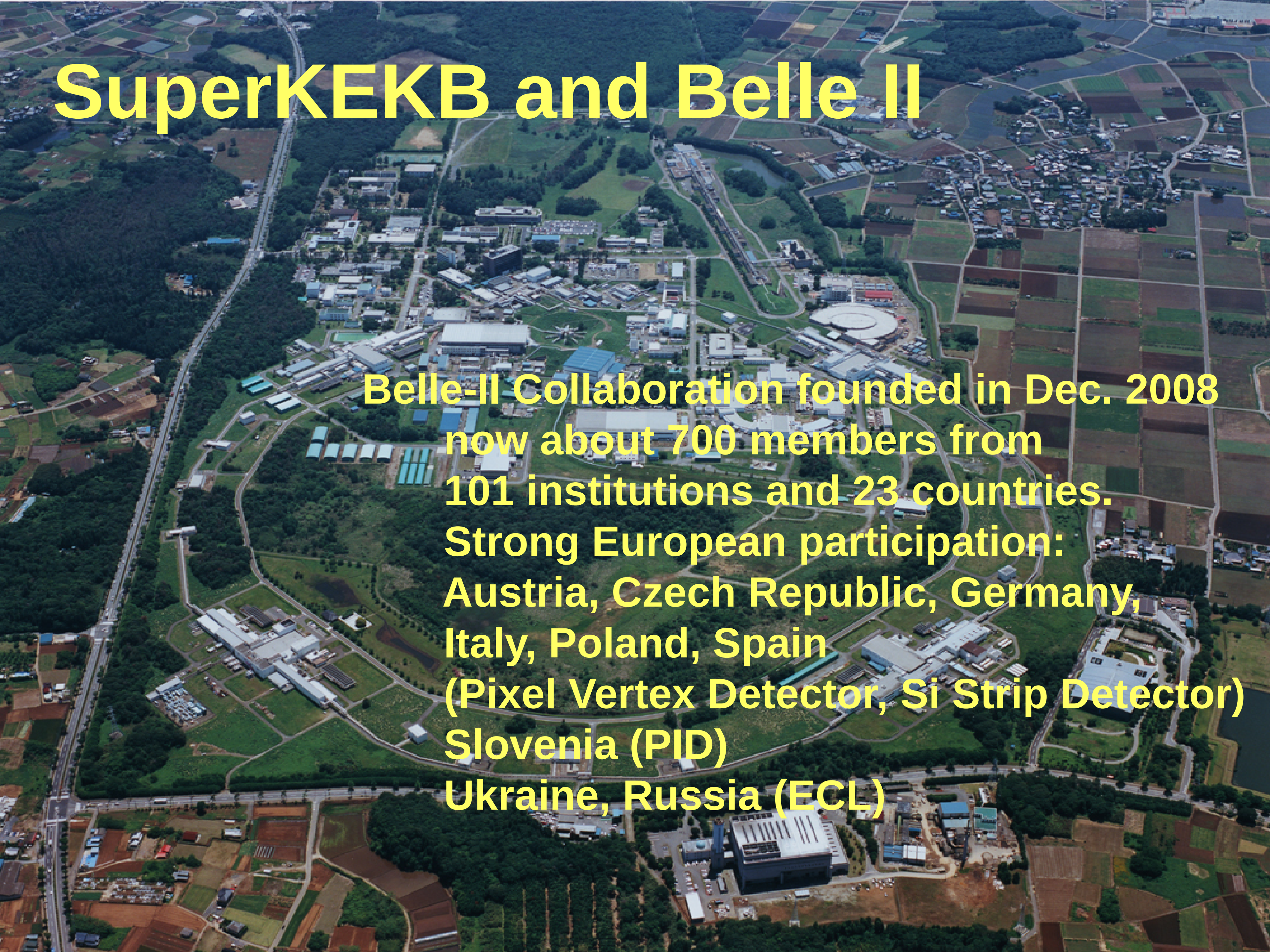
Lepton flavor violation:

$$\left.\begin{array}{l}\tau \to \mu\gamma \\ \tau \to \mu\mu\mu \\ \tau \to \mu\eta\end{array}\right\}$$

NP could make these decays possible

need precision (statistics) to challenge the SM

SuperKEKB and Belle II



Belle-II Collaboration founded in Dec. 2008

now about 700 members from
101 institutions and 23 countries.
Strong European participation:
Austria, Czech Republic, Germany,
Italy, Poland, Spain
(Pixel Vertex Detector, Si Strip Detector)
Slovenia (PID)
Ukraine, Russia (ECL)

Strategies for High Luminosity

$$\mathcal{L} = \frac{N_+ N_- f}{4\pi\sigma_x\sigma_y} R$$

basic formula for the (instantaneous) luminosity

Accelerator physicists usually like this one better:

stored current

tune shift

$$\mathcal{L} = \frac{\gamma_+}{2er_e}\left(1+\frac{\sigma_y}{\sigma_x}\right)\left(\frac{I_+\xi_{y,+}}{\beta_y}\right)\left(\frac{R}{R_{\xi_y}}\right)$$

vertical beta function at IP

$R_{,\xi}$: reduction factors (geometrical)

$\sigma_{x,y}$: beam spot size at IP

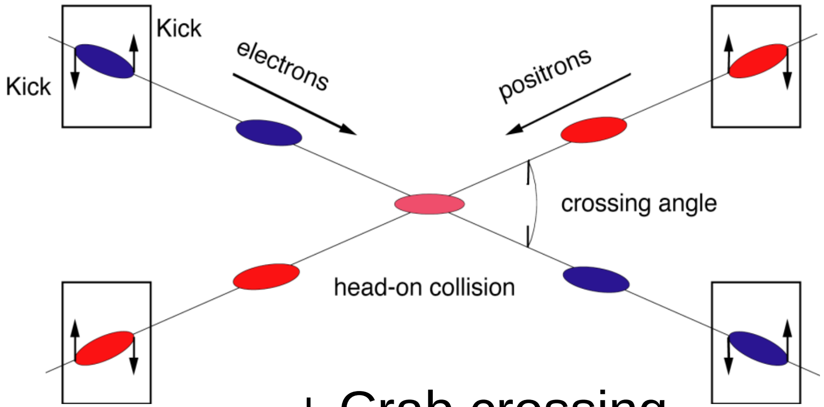
beam-beam parameter (or tune shift)

$$\xi_{y,+} = \frac{r_e}{2\pi\gamma_+}\left(\frac{\beta_y N_-}{\sigma_y(\sigma_x+\sigma_y)}\right)R_{\xi_y}$$

$$\boxed{\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\beta_{x,y}}}$$

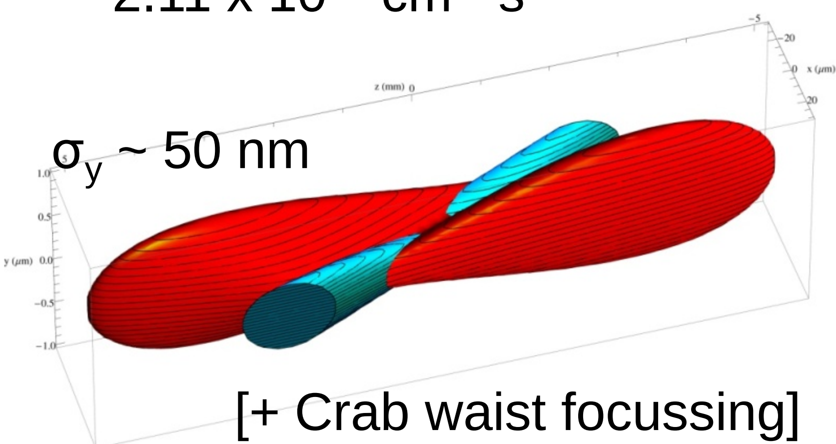
beam emittance (need damping ring(s))

Two Options for High Luminosity



+ Crab crossing

world record luminosity of
2.11 x 10^{34} cm^{-2} s^{-1}



σ_y ~ 50 nm

[+ Crab waist focussing]

High Current Option

Extension of current KEKB design, with much higher beam currents (9.4 A LER, 4.1 A HER), and crab crossing.

→ large tune shift and short bunches required -> CSR !

Nano Beam Option

Proposal by P. Raimondi *et al.* for the Italian Super B Factory: Primarily reduce beam size at the IP.

→ very low emittance beams required: damping ring

Nano-Beam Option for SuperKEKB

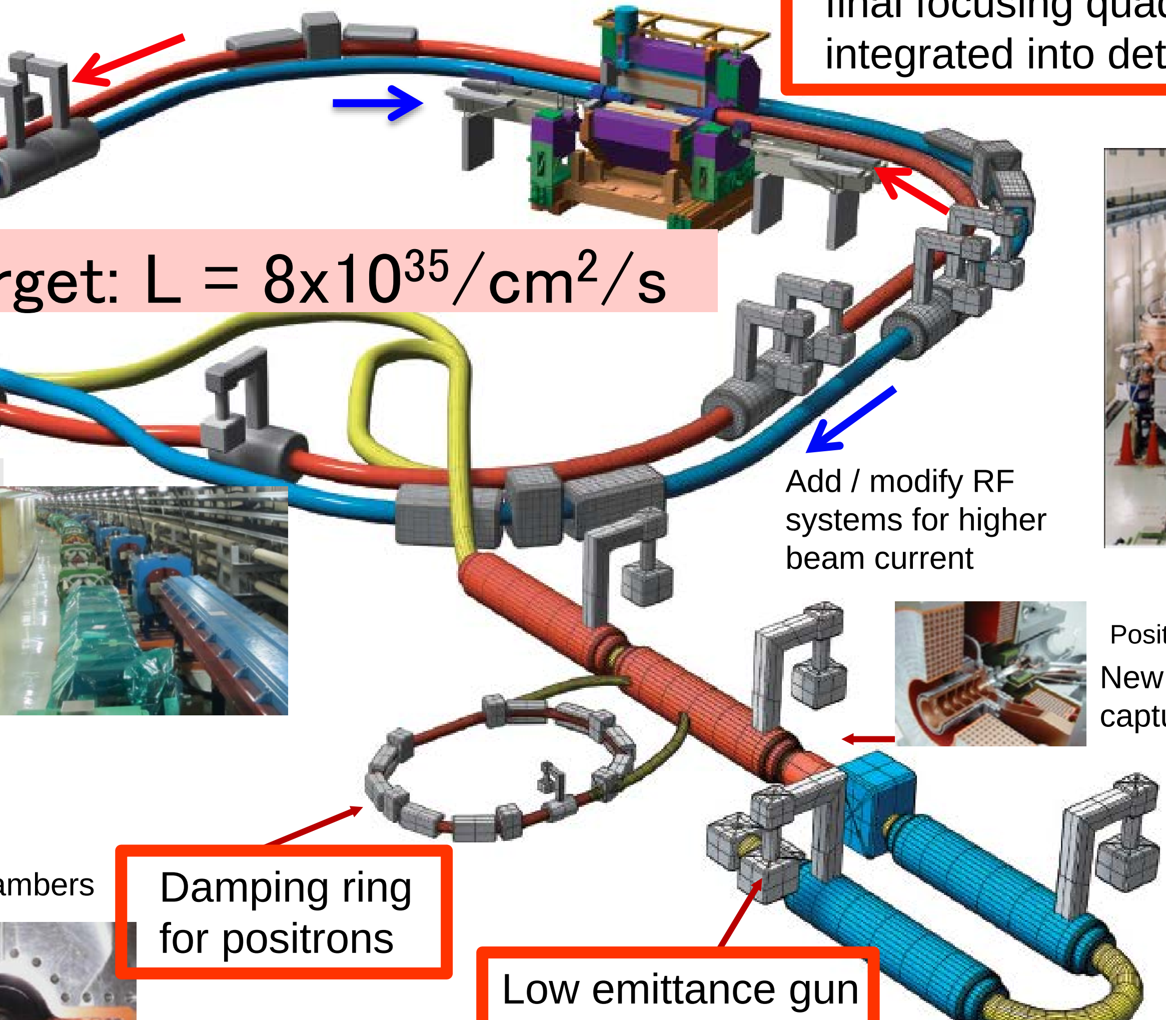
$\sigma_y \sim 50\ \mathrm{nm}$

e^+ 4GeV 3.6 A

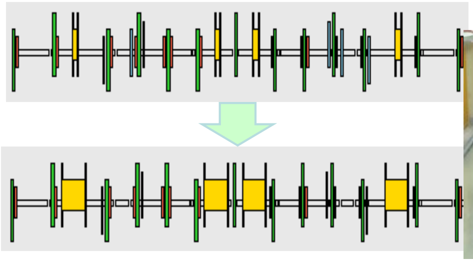
e^- 7GeV 2.6 A

New superconducting final focusing quads integrated into detector

Target: L = $8\mathrm{x}10^{35}/\mathrm{cm}^2/\mathrm{s}$



Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance

Add / modify RF systems for higher beam current

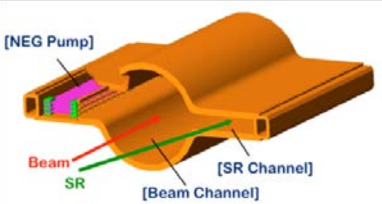
Positron source

New positron target / capture section

Damping ring for positrons

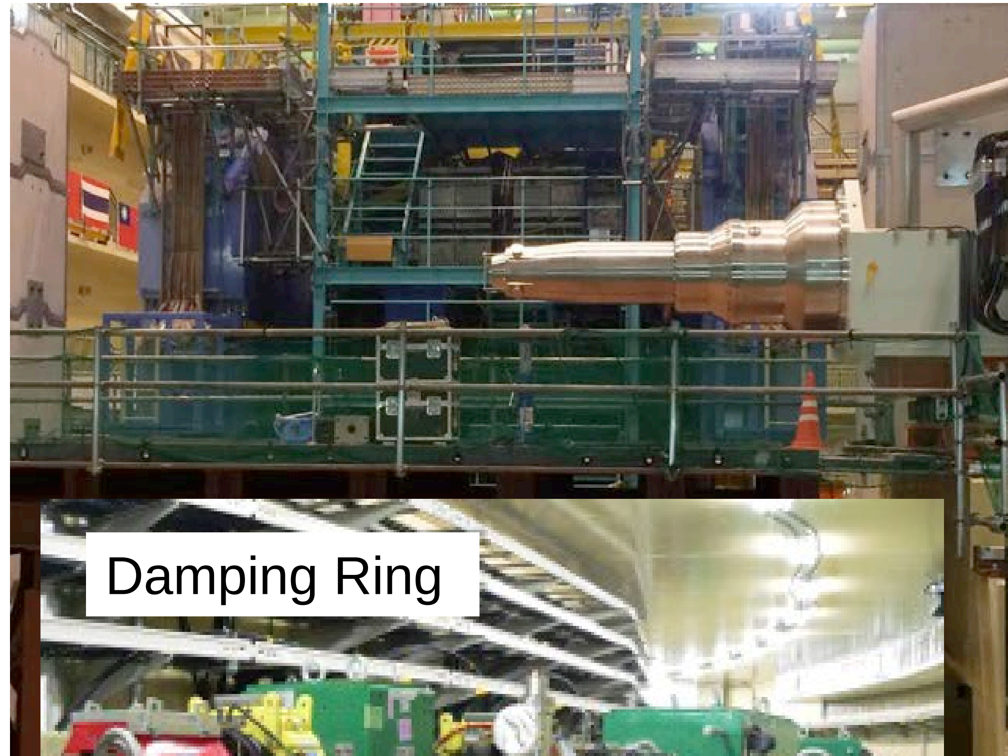
Low emittance gun for electrons

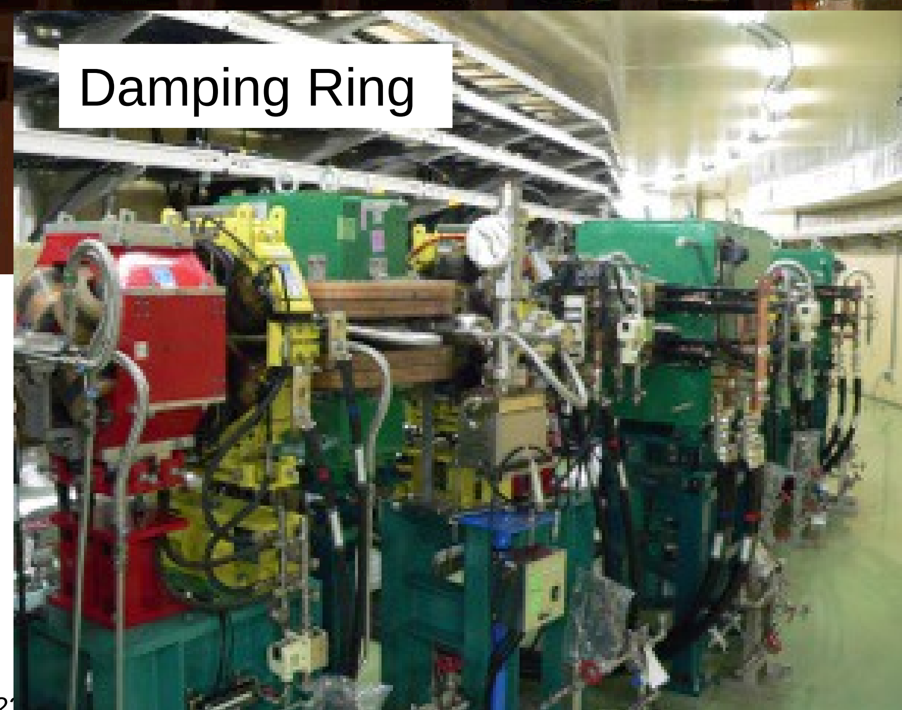
TiN-coated beam pipe with antechambers



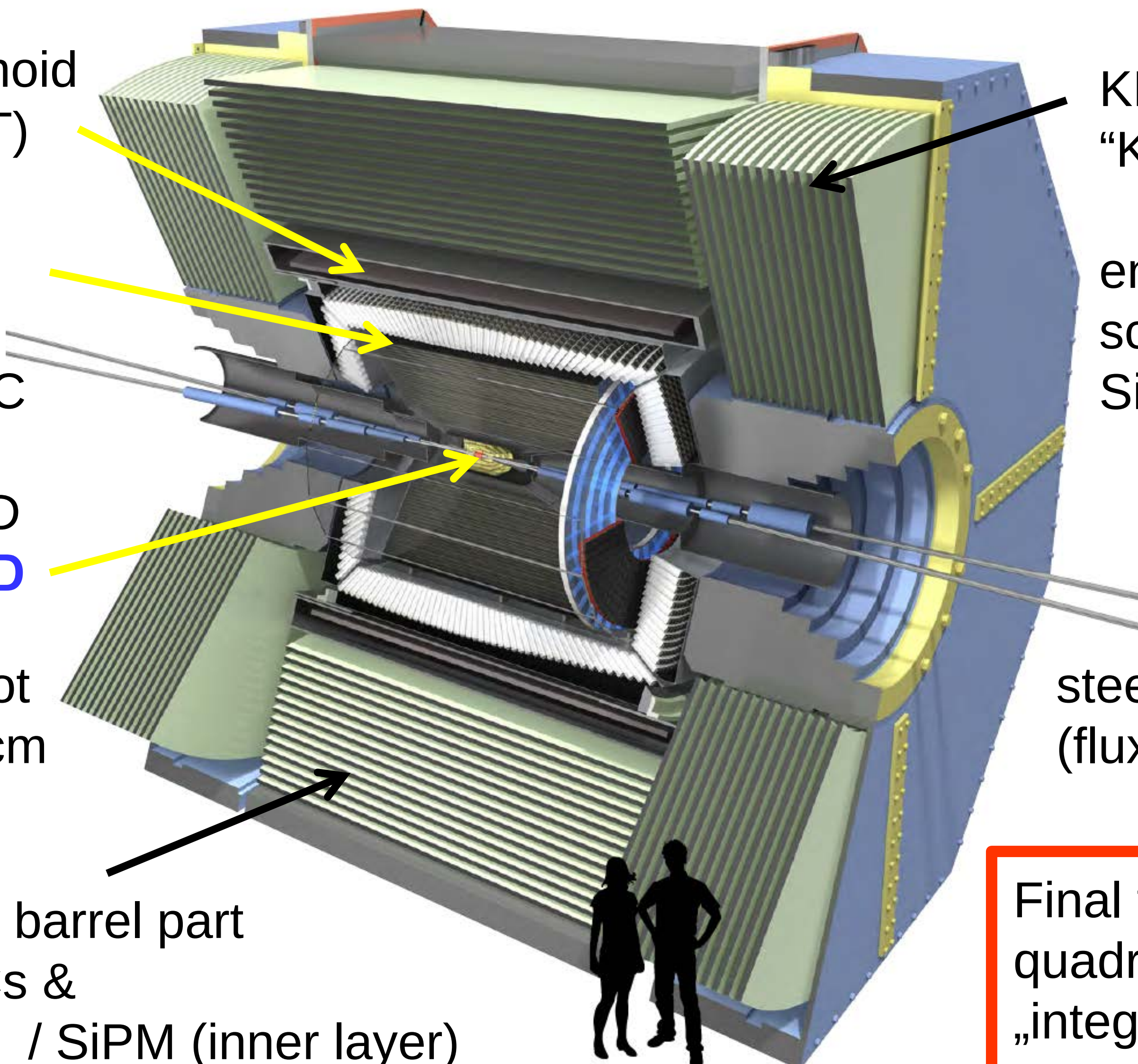
SuperKEKB Hardware almost ready ...

Both rings have been commissioned („Phase 1“), still to do:





The Belle II Detector



Solenoid
(1.5 T)

new PID

new CDC

new SVD
new PXD

(strips will not work @1.4 cm radius)

KLM barrel part
RPCs &
scint / SiPM (inner layer)

KLM
“K_L and muon”

end cap:
scinillator &
SiPM

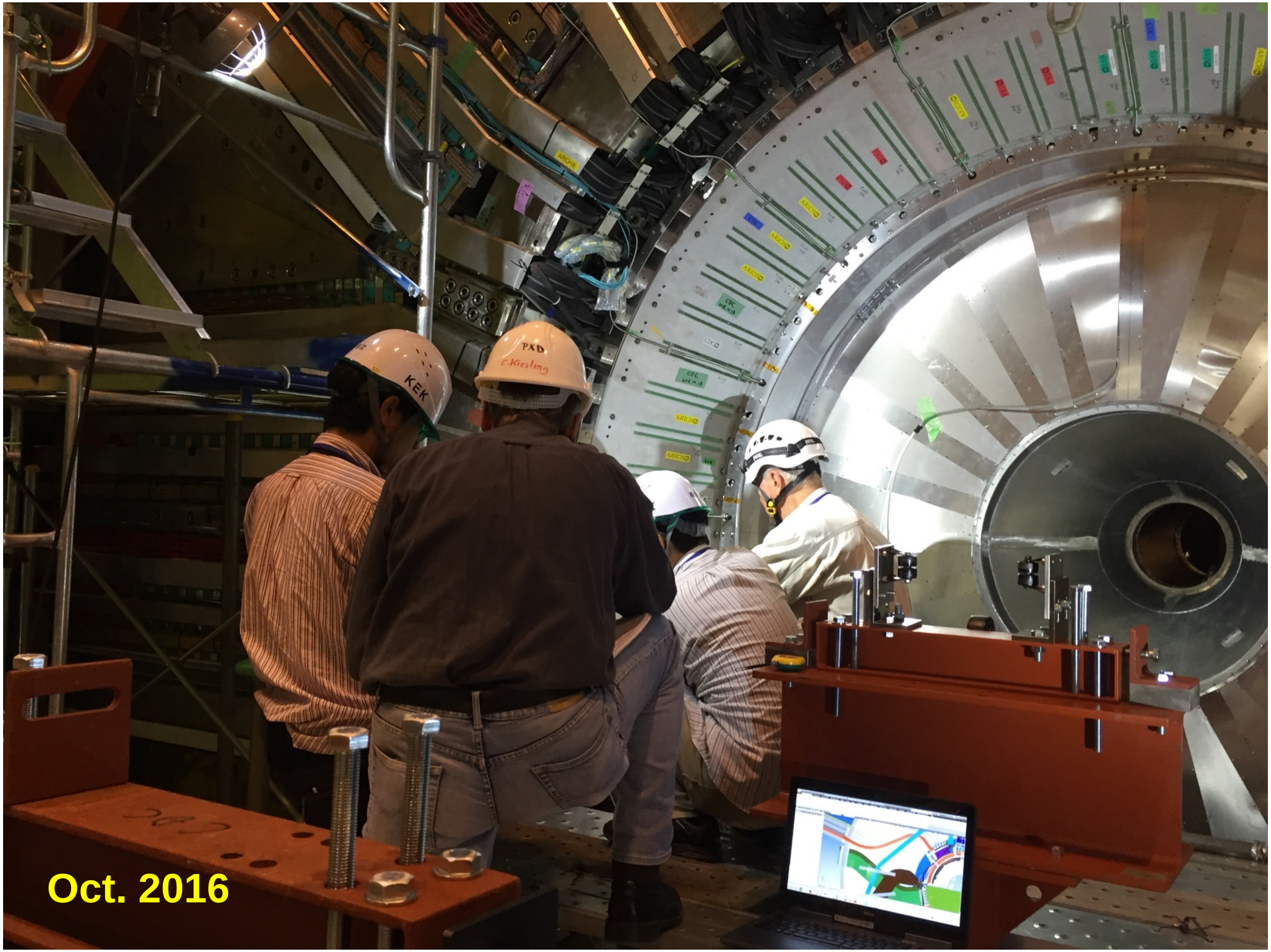
steel plates
(flux return yoke)

Final focus quadrupoles „integrated“ into vertex detector

Belle (II) in Tsukuba Hall

Installation of the Central Drift Chamber

… only the Vertex Detector is missing …



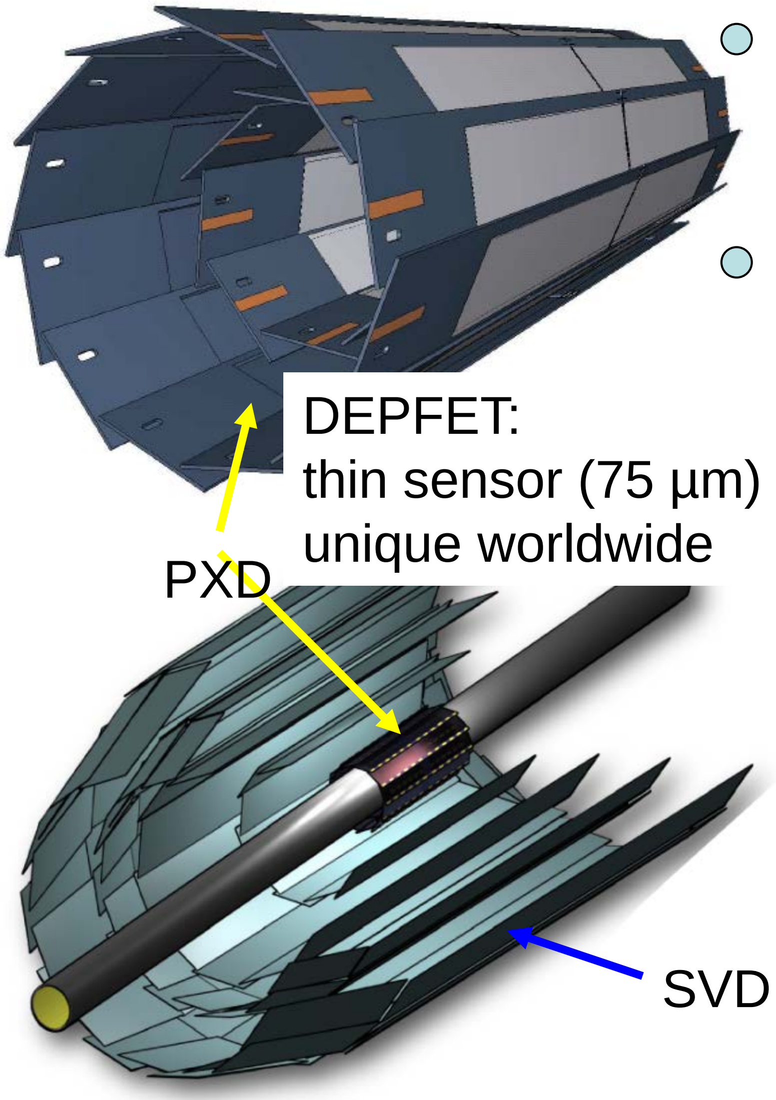
Vertexing: Silicon Tracking System @ Belle II

SuperKEKB: Nano beam option, 1 cm radius of beam pipe

„PXD“

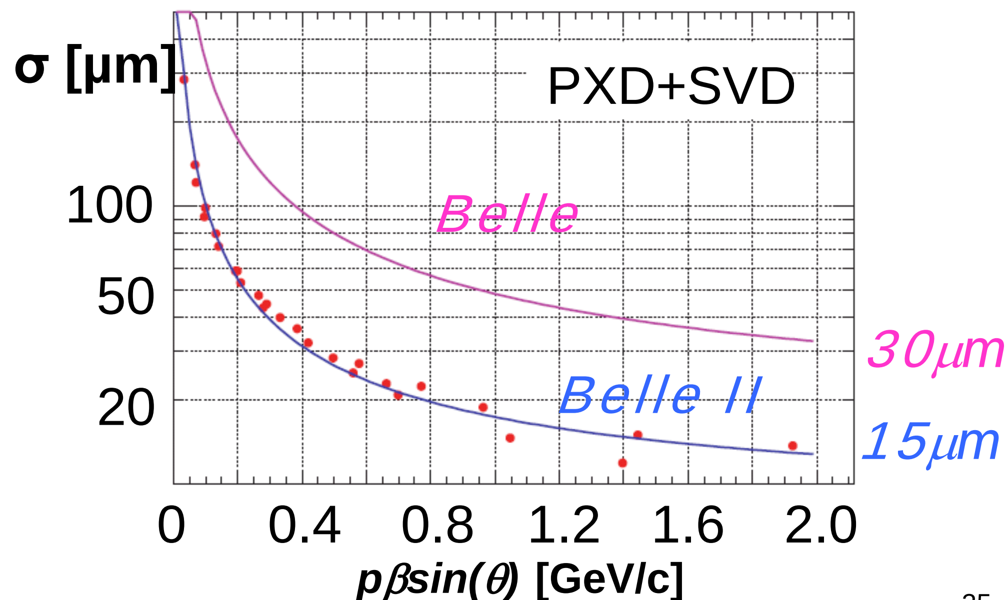
- 2 layer Si pixel detector (DEPFET technology)
  (R = 1.4, 2.2 cm) monolithic sensor
  thickness 75 µm (!), pixel size ~50 x 50 µm²
- 4 layer Si strip detector (DSSD)
  (R = 3.8, 8.0, 11.5, 14.0 cm)

„SVD“



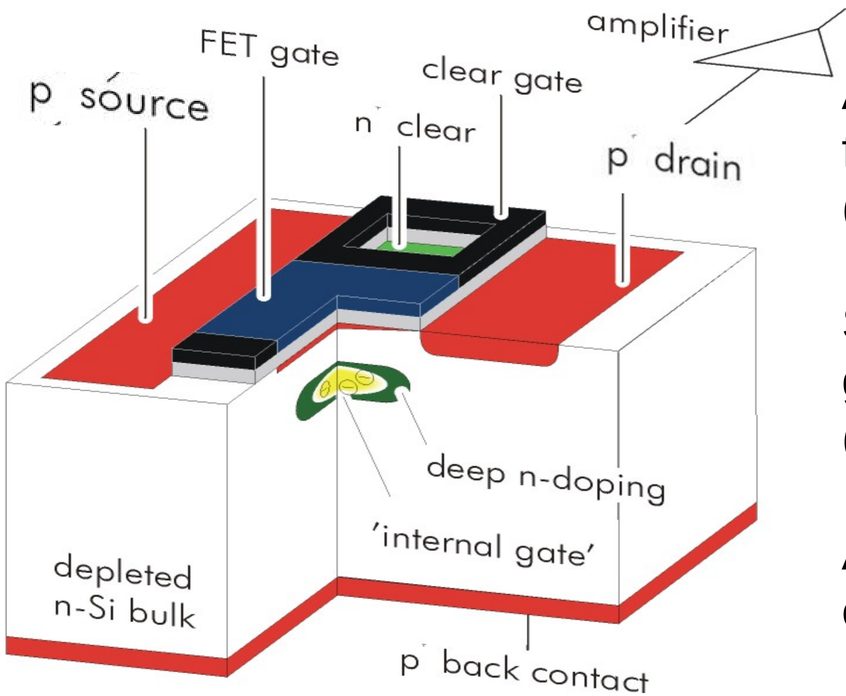
DEPFET:
thin sensor (75 µm)
unique worldwide

Significant improvement in z-vertex resolution



DEPFET Principle

Depleted p-channel FET



p-channel FET on a completely depleted bulk invented at MPI, produced at HLL

A deep n-implant creates a potential minimum for electrons under the gate
("internal gate")

Signal electrons accumulate in the internal gate and modulate the transistor current
(g_q ~ 400 pA/e^-)

Accumulated charge can be removed by a clear contact ("reset")

Fully depleted + FET → large signal, fast signal collection

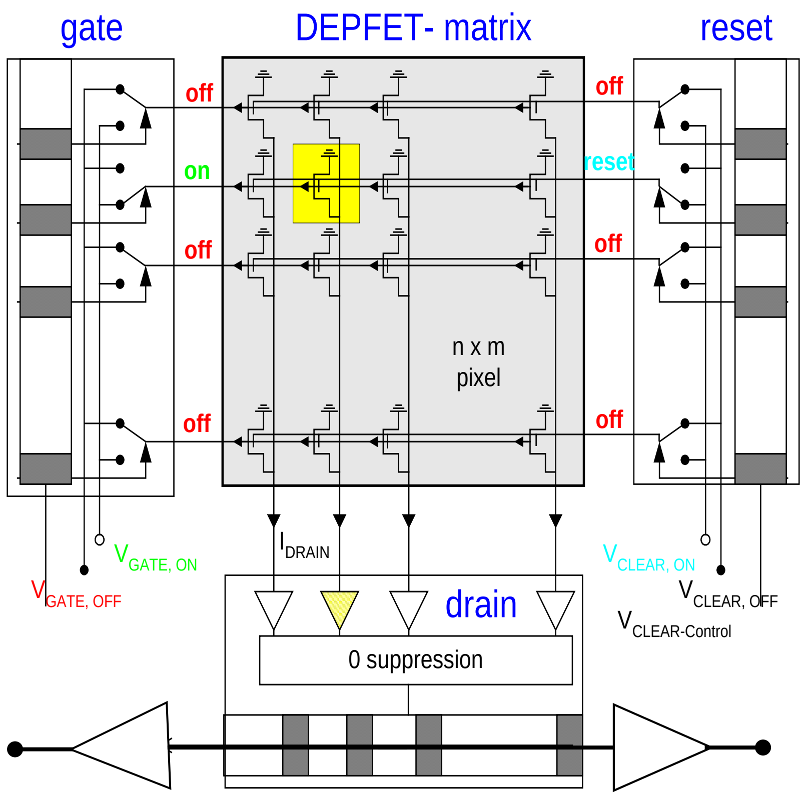
Low capacitance, internal amplification
→ low noise

Transistor on only during readout:
→ low power

Array of DEPFETs

Row wise read-out
("rolling shutter mode")

- select row with external gate
  read current,
  clear internal gate,
  read current again
  → the difference is the signal



- readout time of entire PXD
  in 20 µs

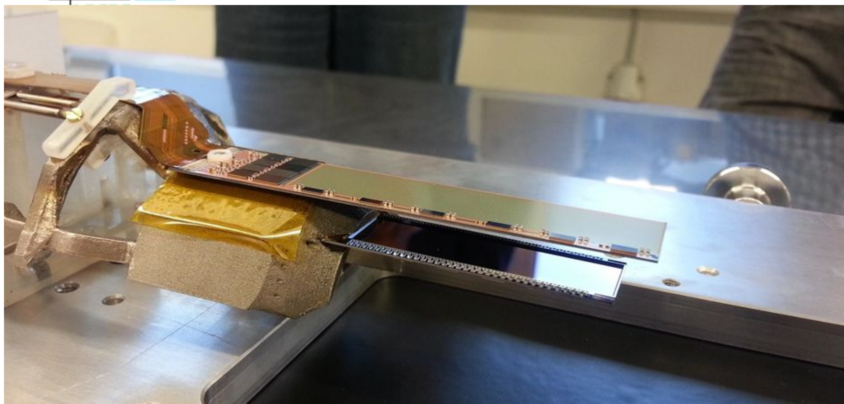
- three different auxiliary ASICs
  needed,
  DCD, DHP outside acceptance

→ Switcher

→ DCD (drain current digitizer)

→ DHP (data handling processor)

PXD Performance (Beam Test @ DESY, April 2016)

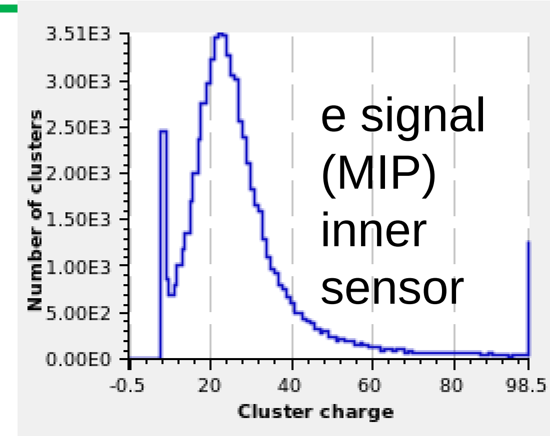


2 PXD modules with ASICs, SMDs and Kapton, fixed on SCB

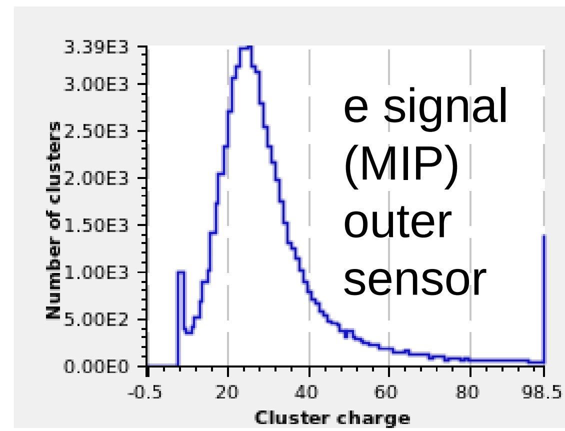
2-6 Gev electron beam

1T B-field

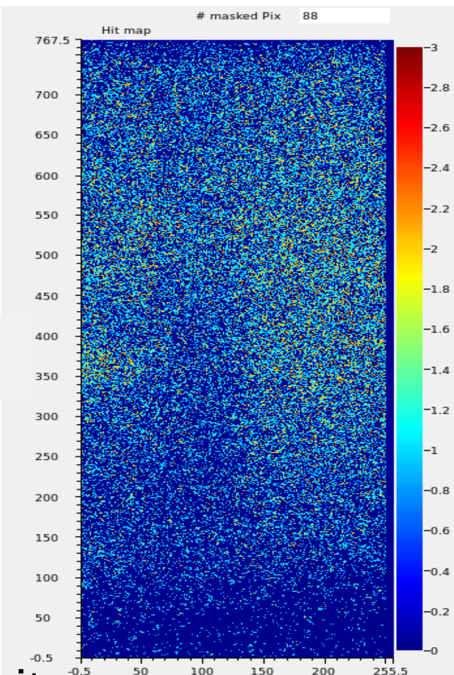
full DAQ (together with 4 SVD ladders)

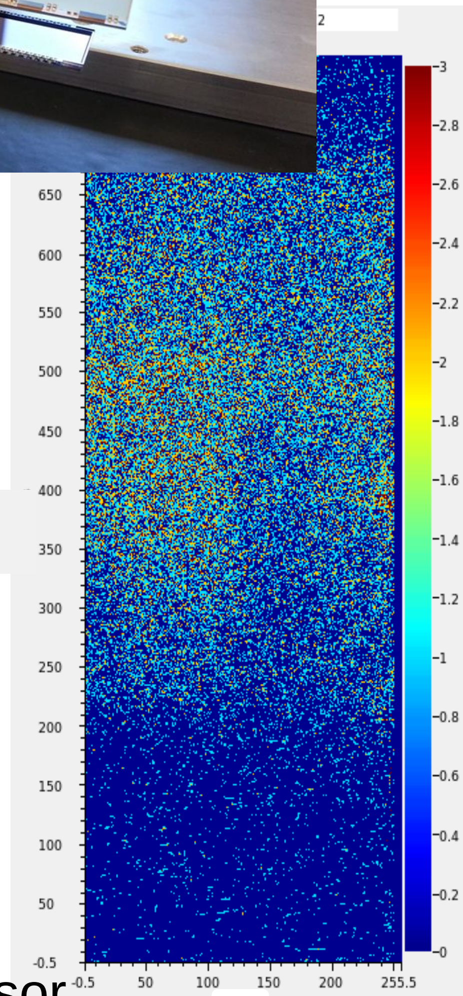


e signal (MIP) inner sensor



e signal (MIP) outer sensor

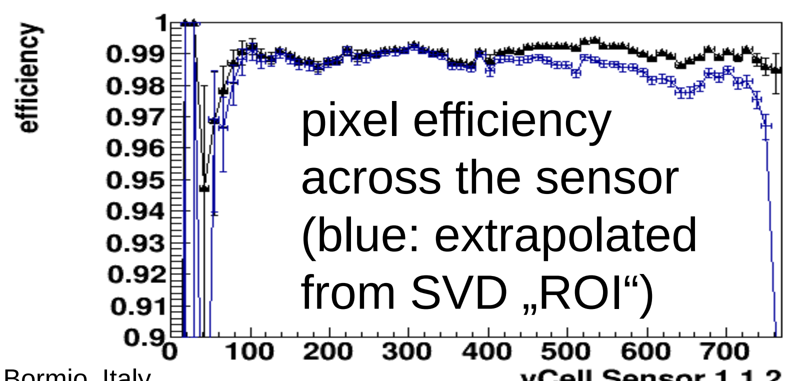




hit maps:

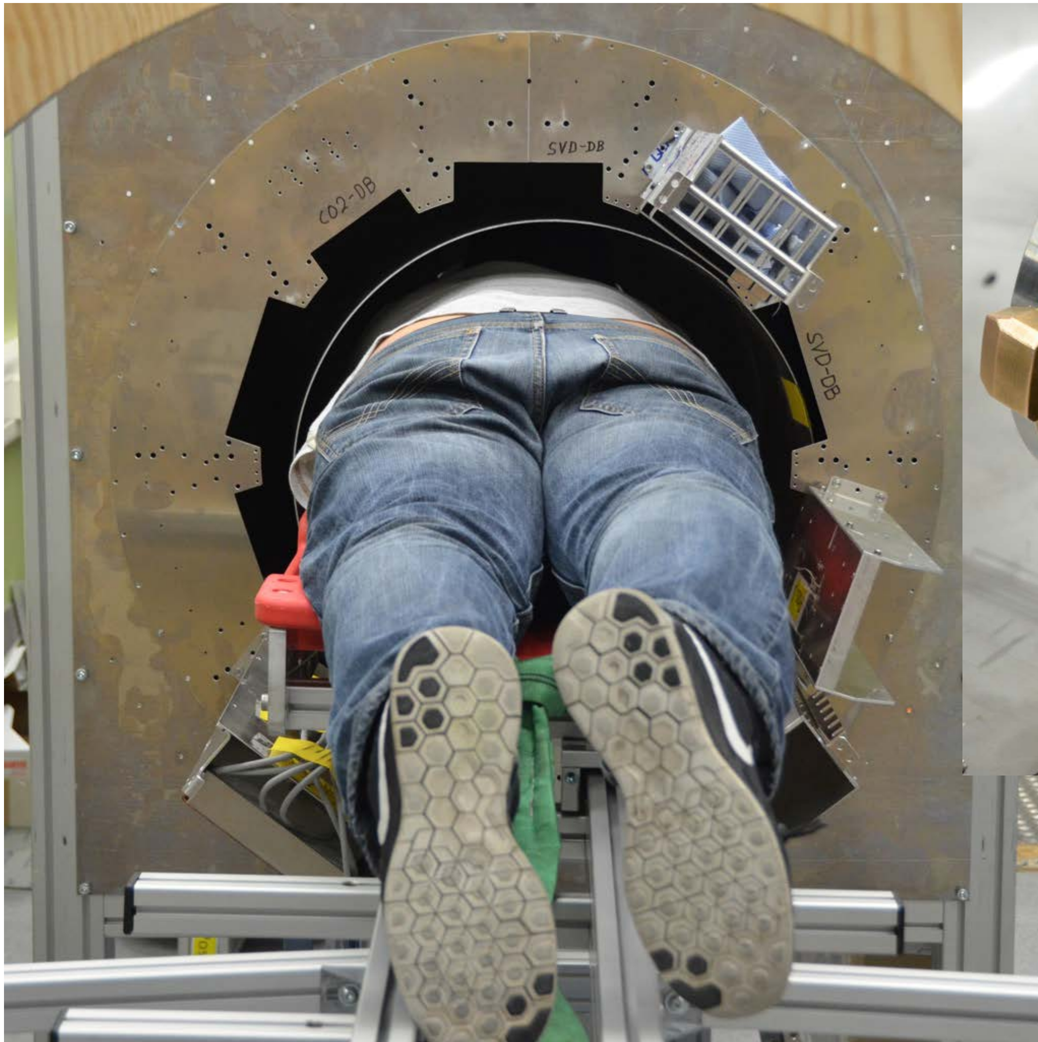
inner sensor

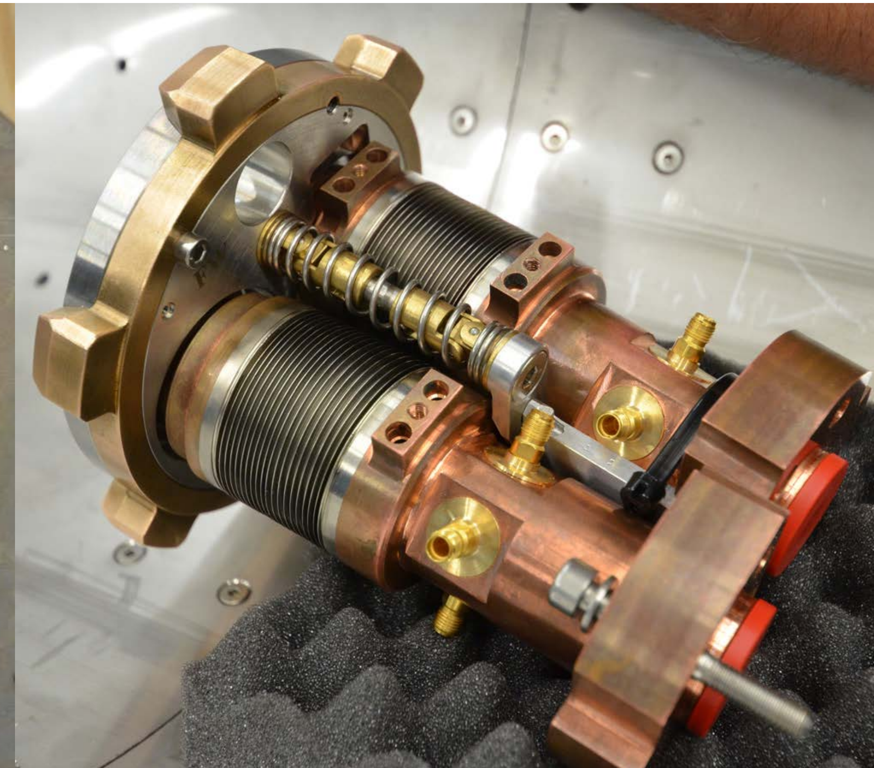
outer sensor



pixel efficiency across the sensor (blue: extrapolated from SVD „ROI“)

VXD Installation Test @ MPI



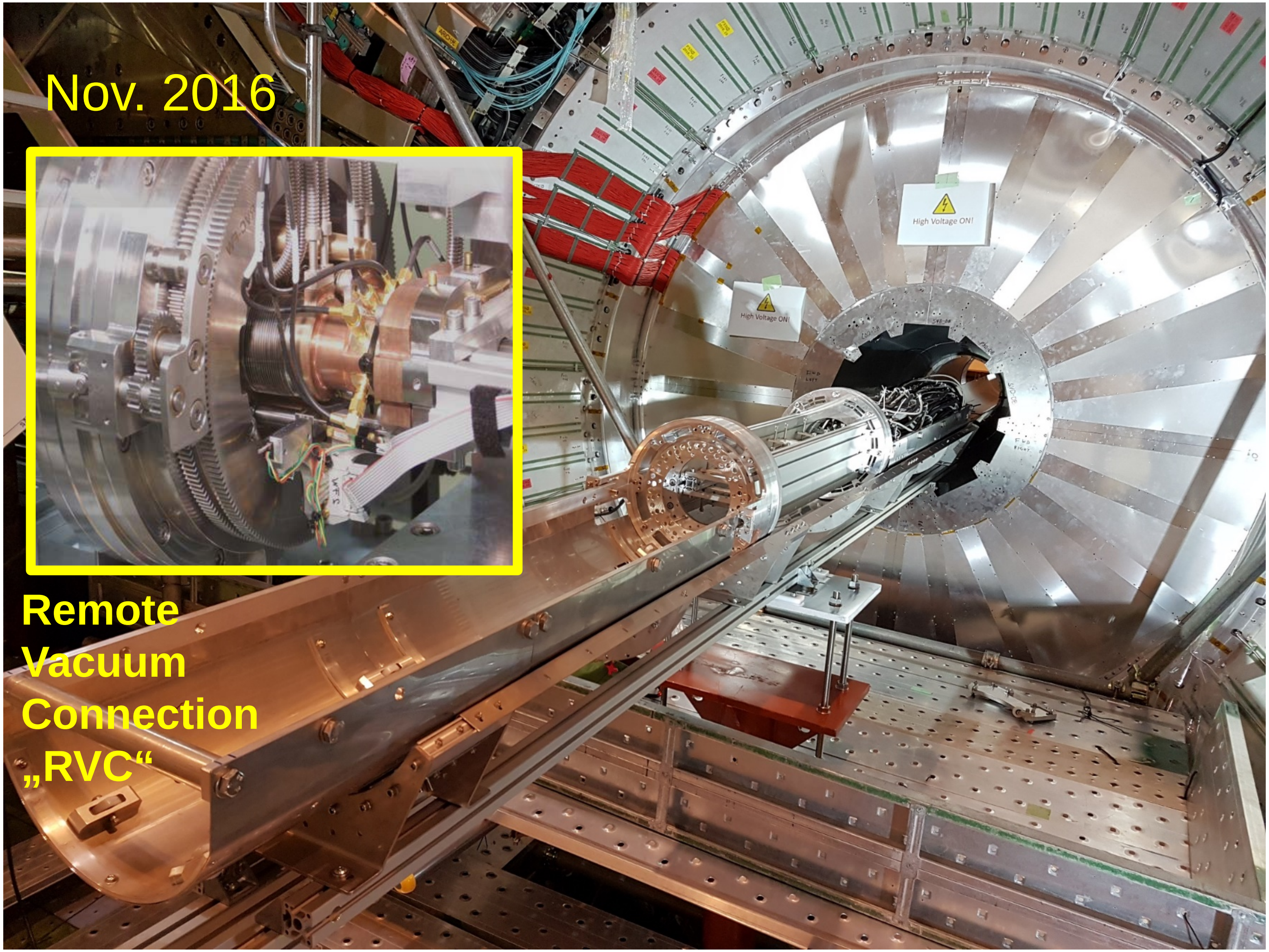


Installation of the bellows and connection of beam position monitors

Nothing for claustrophobics …

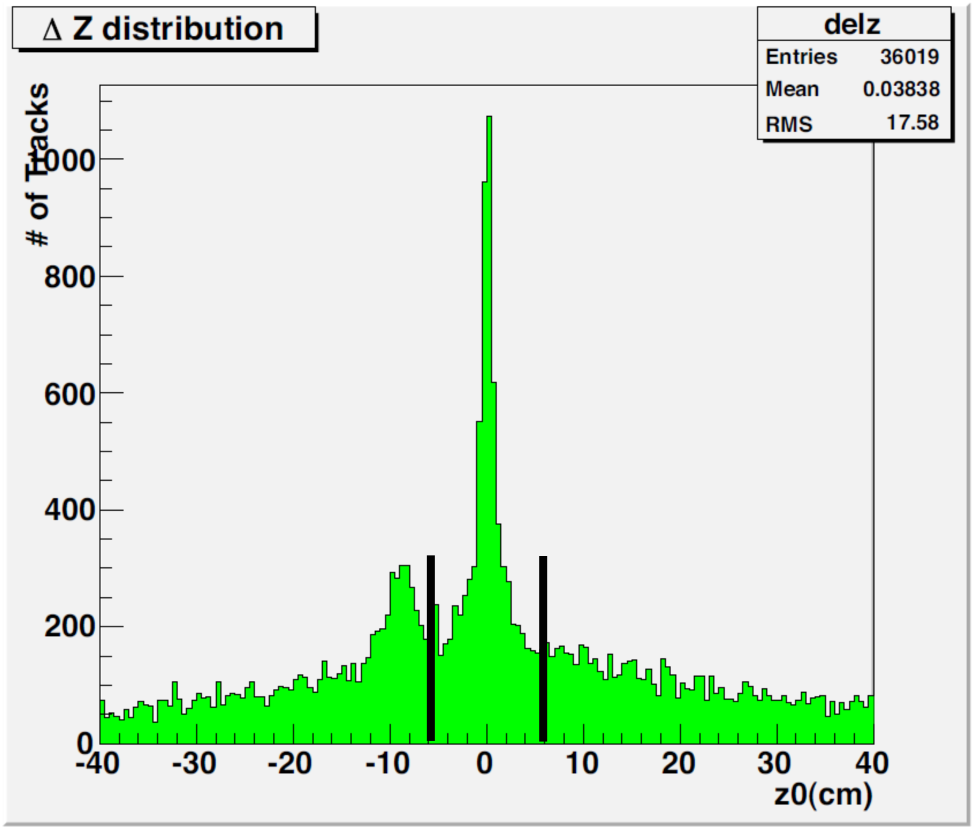
First real exercise with „dummy“ in Nov. 2016

VXD Test Installation into Belle



Track Triggers @ Belle II

The Background Problem:



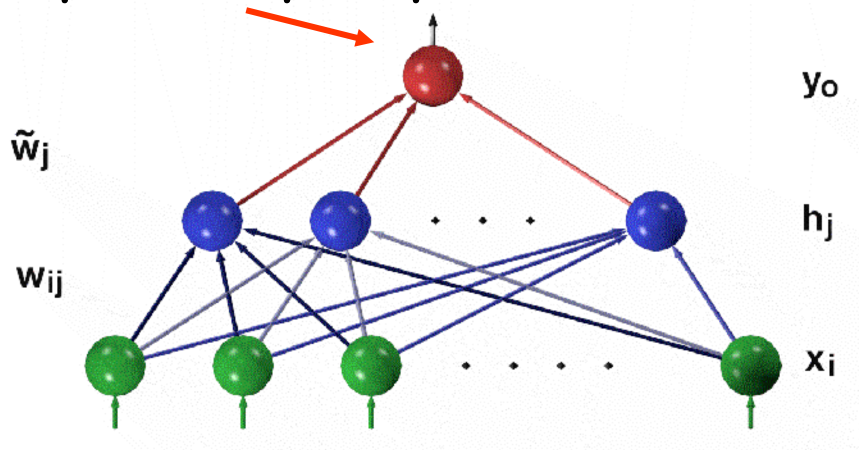
vertex distribution along beam axis (from Belle experiment)

- Majority of events are coming from outside the interaction region
- These events will increase at Belle II due to the much larger beam background (Touschek effect)
- Need to open trigger for NP, + need to reduce trigger rate (reduce dead time and data rate to DAQ systems)
- Build a level 1 „z-vertex“ trigger using the Belle II CDC:

→ need resolution O(2cm)

Neural Approach for a z-Vertex Trigger

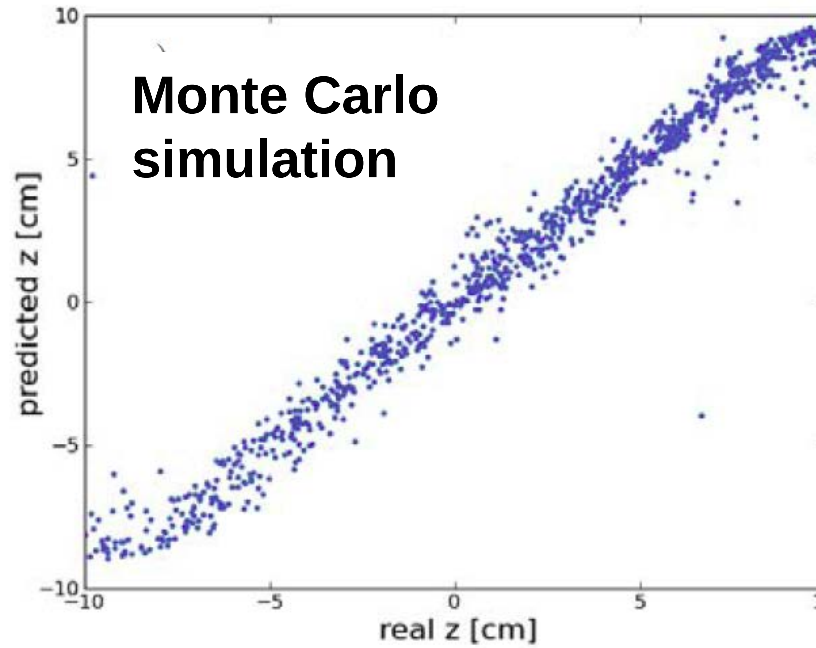
output: z-impact parameter of track

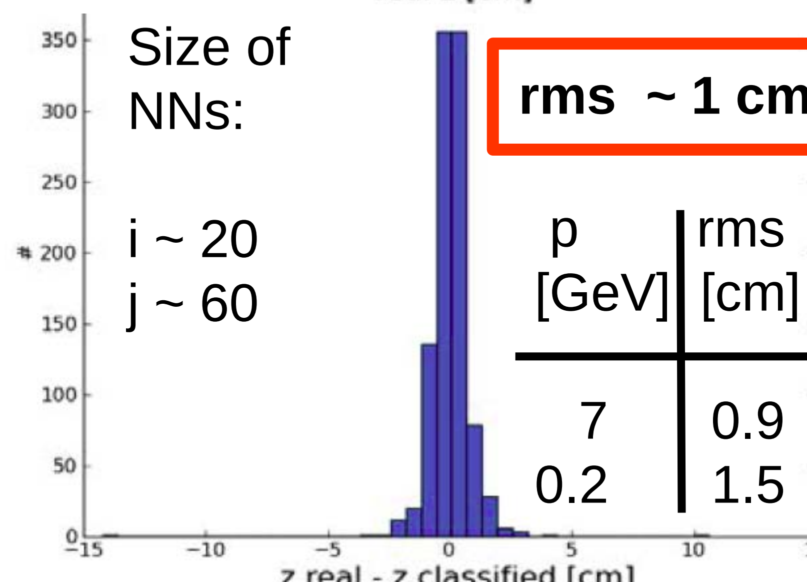


input: subset of axial/stereo CDC wires, suitably preprocessed, using also the drift time information

Data (pre)processing:
- sectorize phase space in **(θ,φ,p_T)**
- select network by coarse 3D track finder

Determine z-impact for track in given sector, using associated CDC wire set





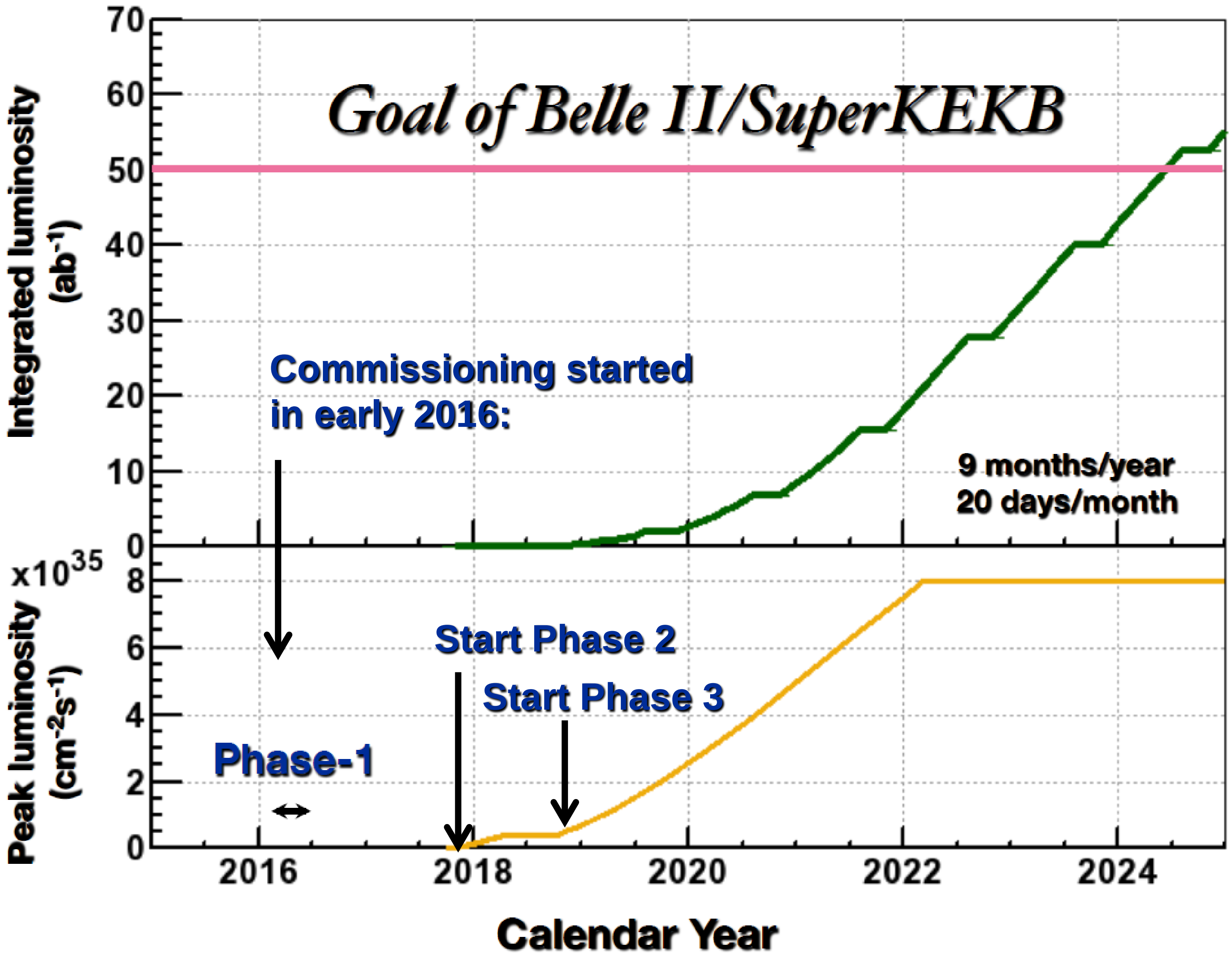
Size of NNs:

i ~ 20
j ~ 60

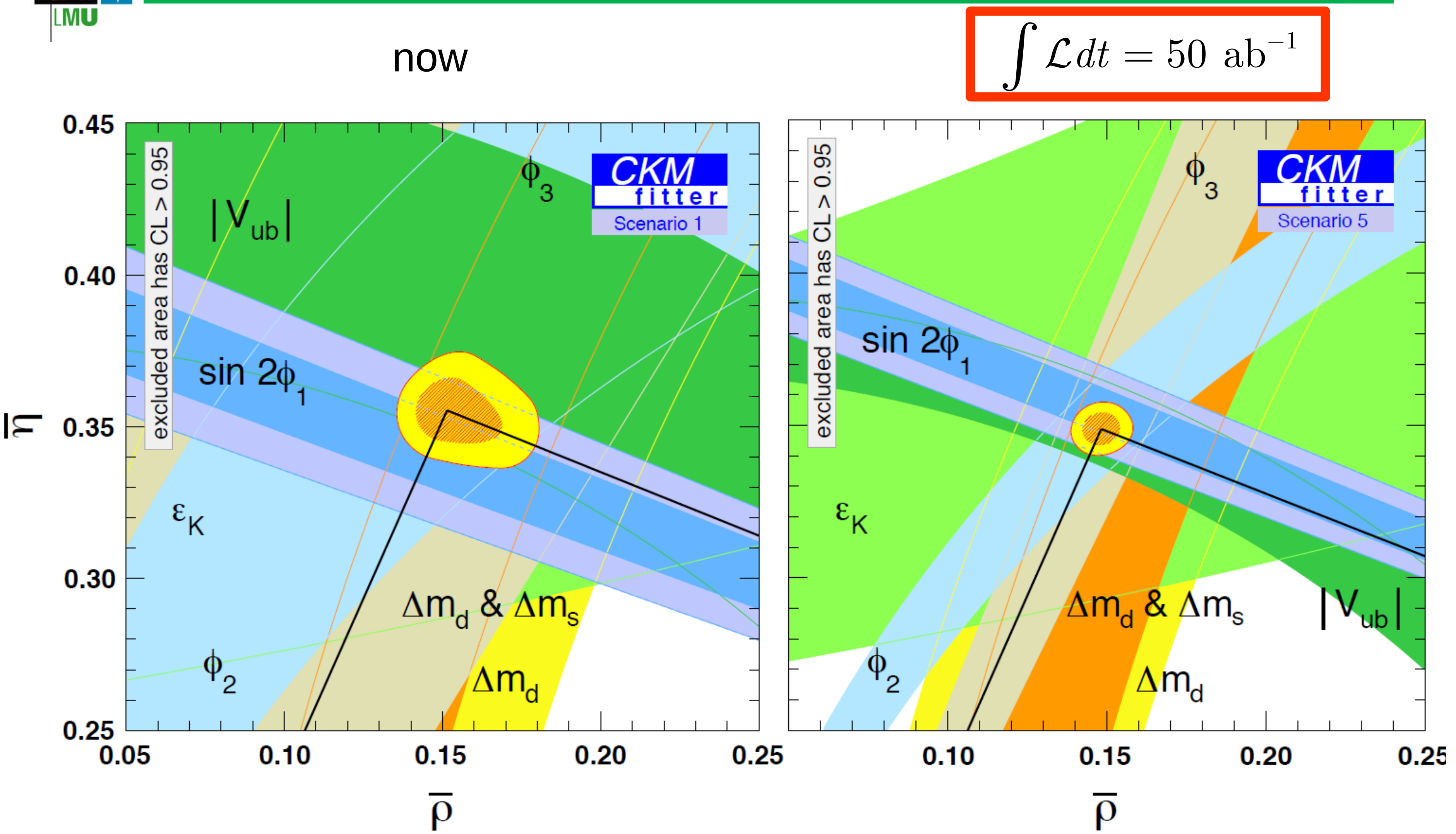
rms ~ 1 cm

p [GeV]	rms [cm]
7	0.9
0.2	1.5

Luminosity Development for SuperKEKB



The Unitarity Triangle in the year 2025

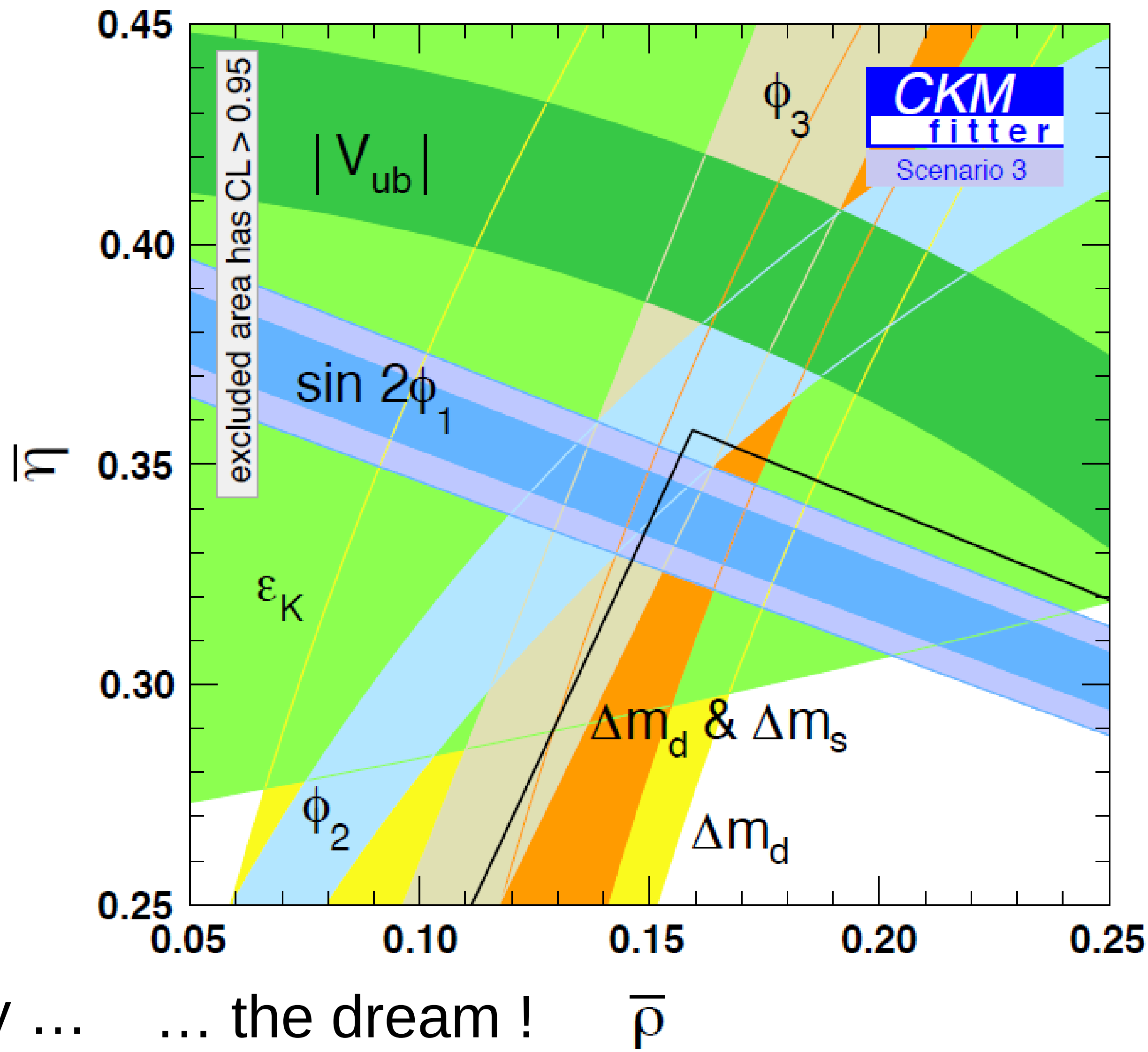


SM verified yet another time - a nightmare …

The Unitarity Triangle in the year 2025

$$\int \mathcal{L} dt = 50 \text{ ab}^{-1}$$

2025 @ World Average Values
p-value=10^{-5}



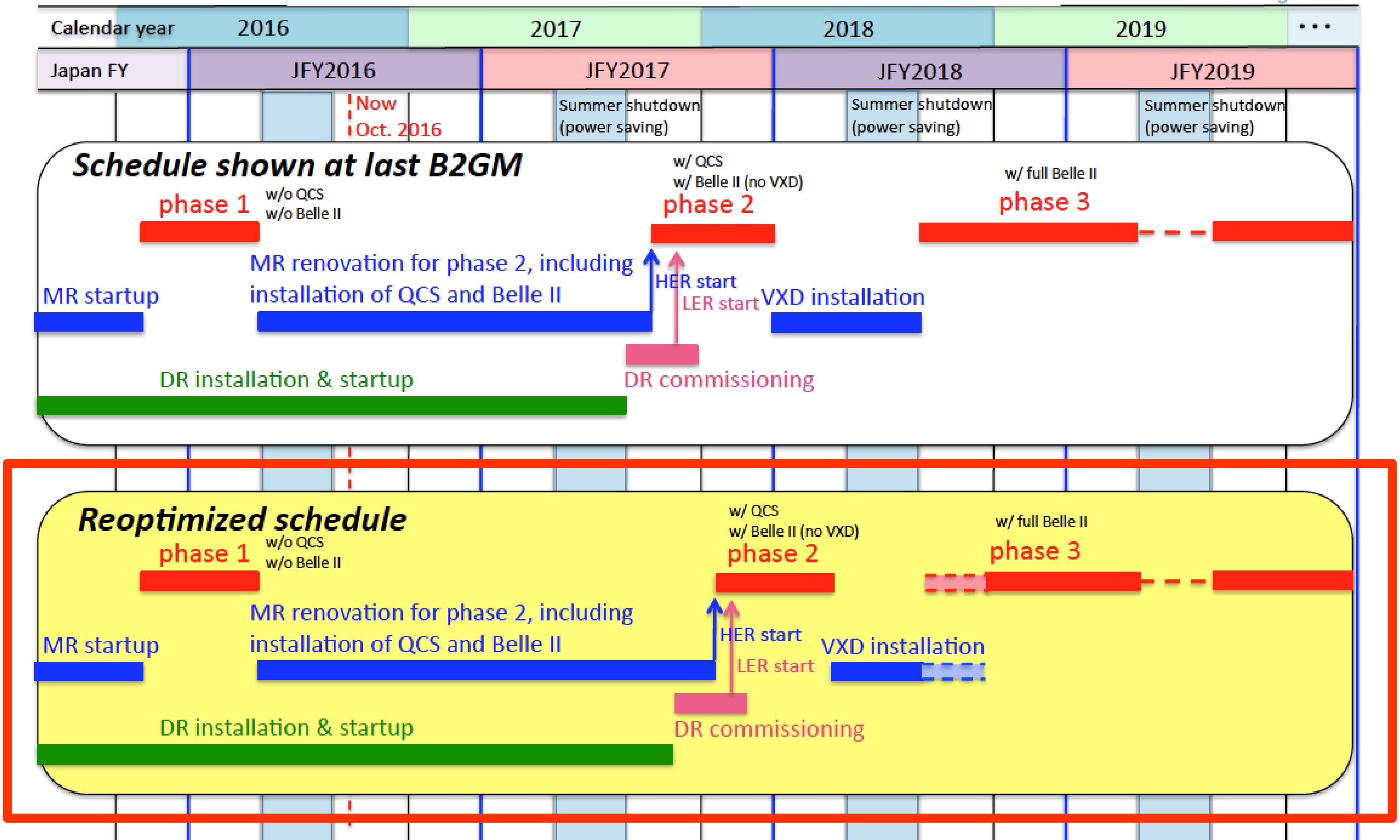
present tensions stay … … the dream !

Summary and Conclusions

- „New Physics“ needed to explain the observed matter-antimatter asymmetry → new sources of CP violation
- Present measurements of the fundamental parameters of the CKM matrix show some „tensions“
- A new generation B factory, „SuperKEKB“, with O(50) times the present luminosity and an upgraded detector „Belle II“ under construction, physics program complementary to the LHC
- European institutions contribute with a novel pixel vertex detector „PXD“, and the surrounding Silicon Strip Detector („SVD“), furthermore with an ambitious PID detector („ARICH“) and with fast electronics for the electromagnetic calorimenter („ECL“)
- Also strong (leading) involvement in software (Slow control, DQM, reconstruction and computing)
- Excellent prospects for high precision flavor physics (SM & NP, exotic hadrons, τ physics ….) from 2019 onwards

Backup

Schedule of SuperKEKB



K. AKAI, SuperKEKB schedule for phase 2, Oct. 17, 2016 @B2GM

8

LHCb vs SuperKEKB

+ LHCb

large samples (but low efficiencies)

exclusive decays

B_s oscillations

B_c, bottom baryons

$B^0_{s,d} \to \mu\mu$

$B \to J/\psi K_S$

$D^0 \to K^+\pi^-, K^+K^-$

+ SuperKEKB

all final states measurable,
esp. those with photons, neutrinos

+ inclusive decays

rare decays, such as

$B^+ \to l^+\nu, B^+ \to K^+\nu\overline{\nu}$

$b \to s\gamma, b \to sl^+l^-$

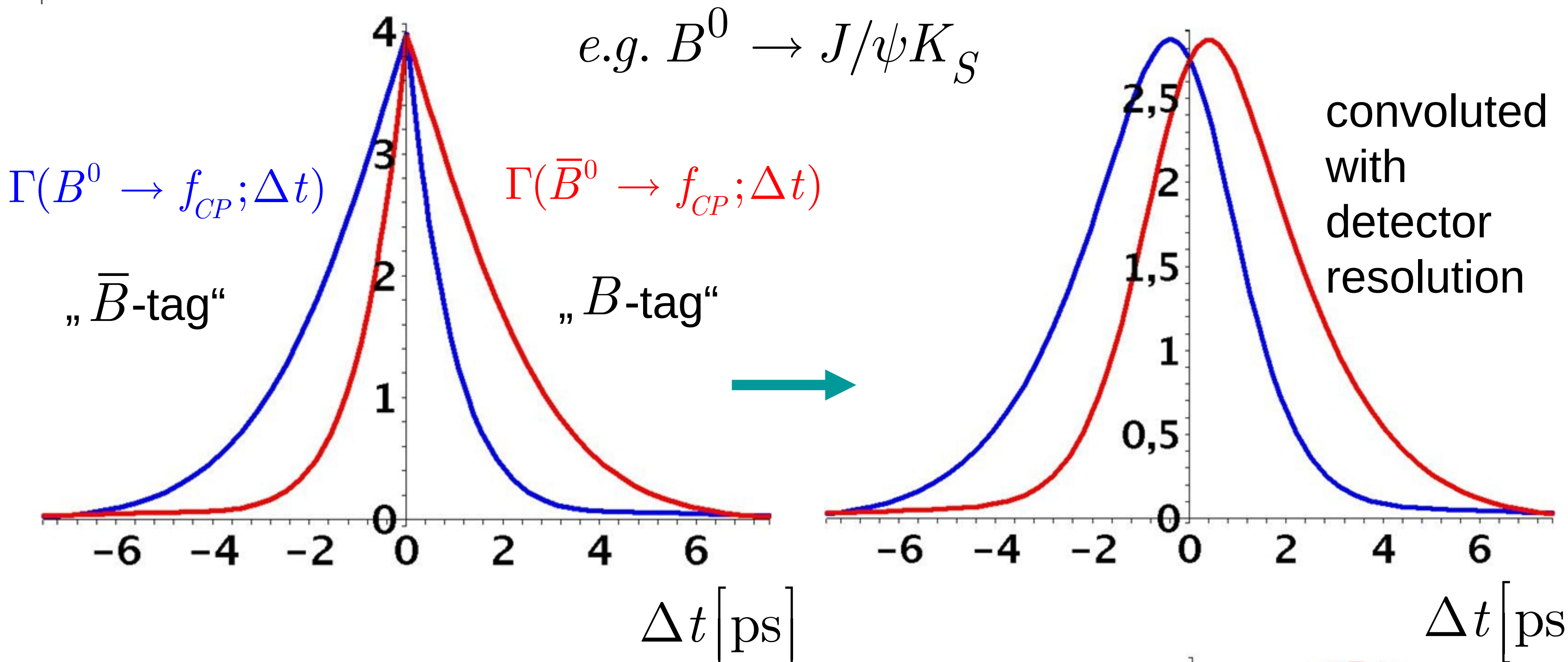
$B \to J/\psi\phi, \pi\pi, \rho\pi, \rho\rho, \pi\pi\pi$

$D^0\overline{D}^0$ mixing

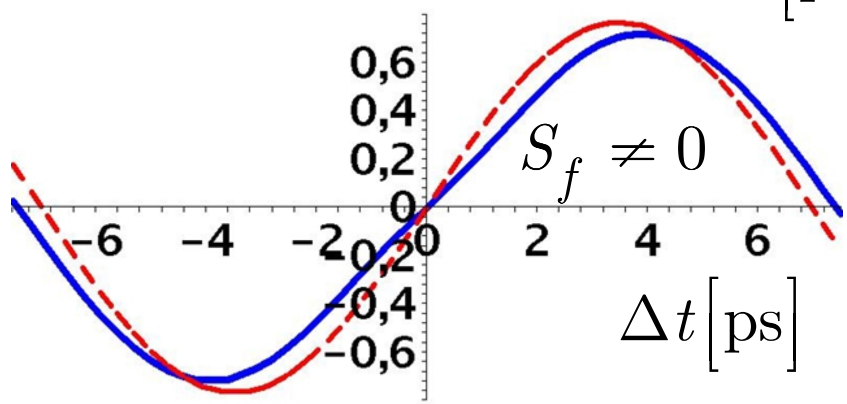
$e^+e^- \to \tau^+\tau^-$

LHCb and SuperKEKB will run concurrently. → largely complementary

Time-Dependent CP-Asymmetries



$$A_{CP}(\Delta t) = \frac{N(\overline{B}^0,t) - N(B^0,t')}{N(\overline{B}^0,t) + N(B^0,t')}$$
$$= A_f \cos \Delta m \Delta t + S_f \sin \Delta m \Delta t$$



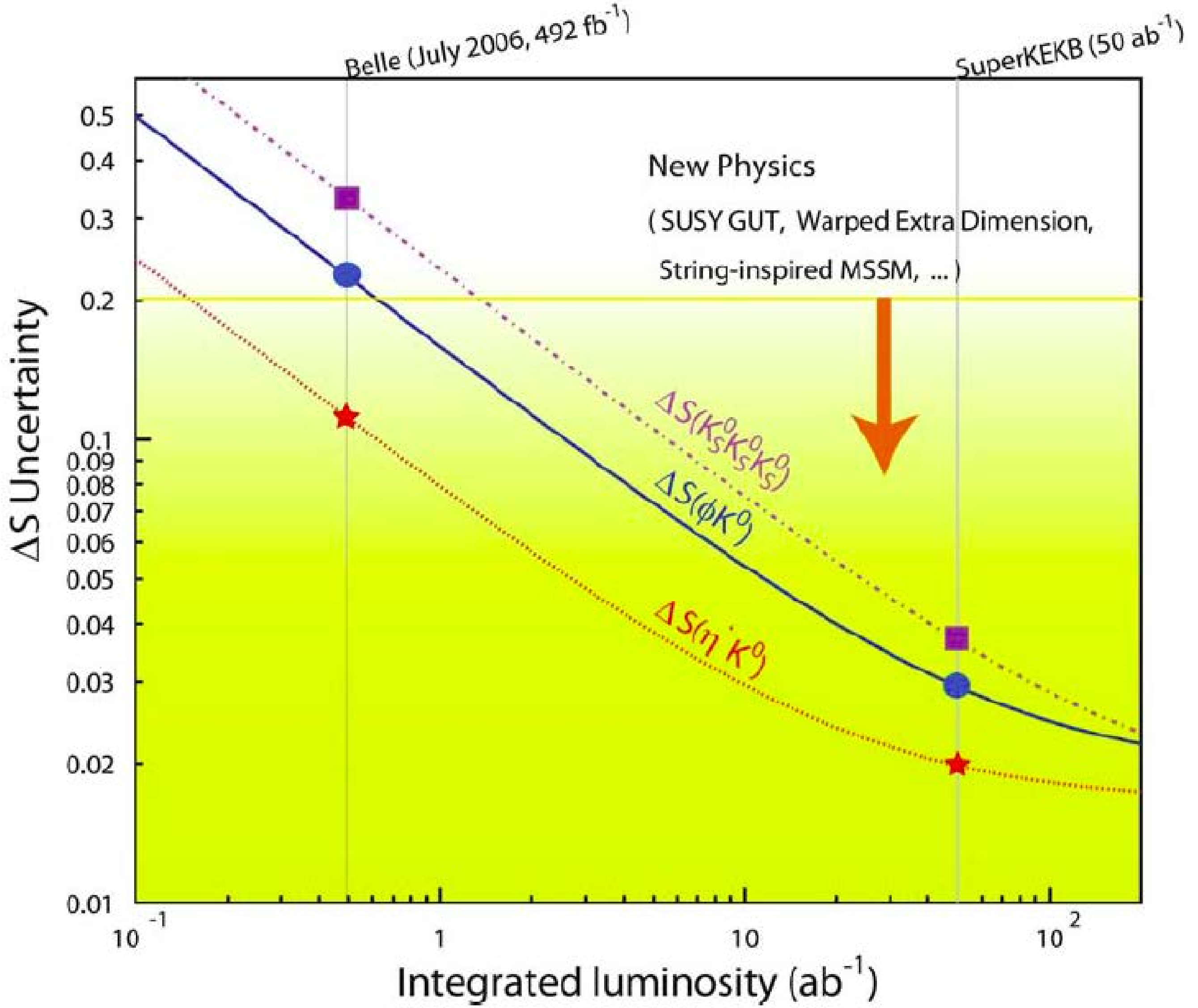
Here: no direct CP violation: $A_f = 0$

New Physics & CP Violation

$$\mathcal{A}_{CP}(\Delta t)$$
$$= S_f \sin \Delta m \Delta t$$

$$\Delta S = S_{SM} - S_{\exp}$$

Good chances to „see“ New Physics at SuperKEKB



New Physics and Rare Decays

B mesons:

$$B \to X_{s,d}\gamma \qquad \mathcal{O}\left(10^{-4}\right)$$
$$B \to X_{s,d}l^+l^- \qquad \mathcal{O}\left(10^{-6}\right)$$
$$B \to X_d\nu\overline{\nu} \qquad \mathcal{O}\left(10^{-6}\right)$$
$$B_s \to l^+l^- \qquad \mathcal{O}\left(10^{-9}\right)$$

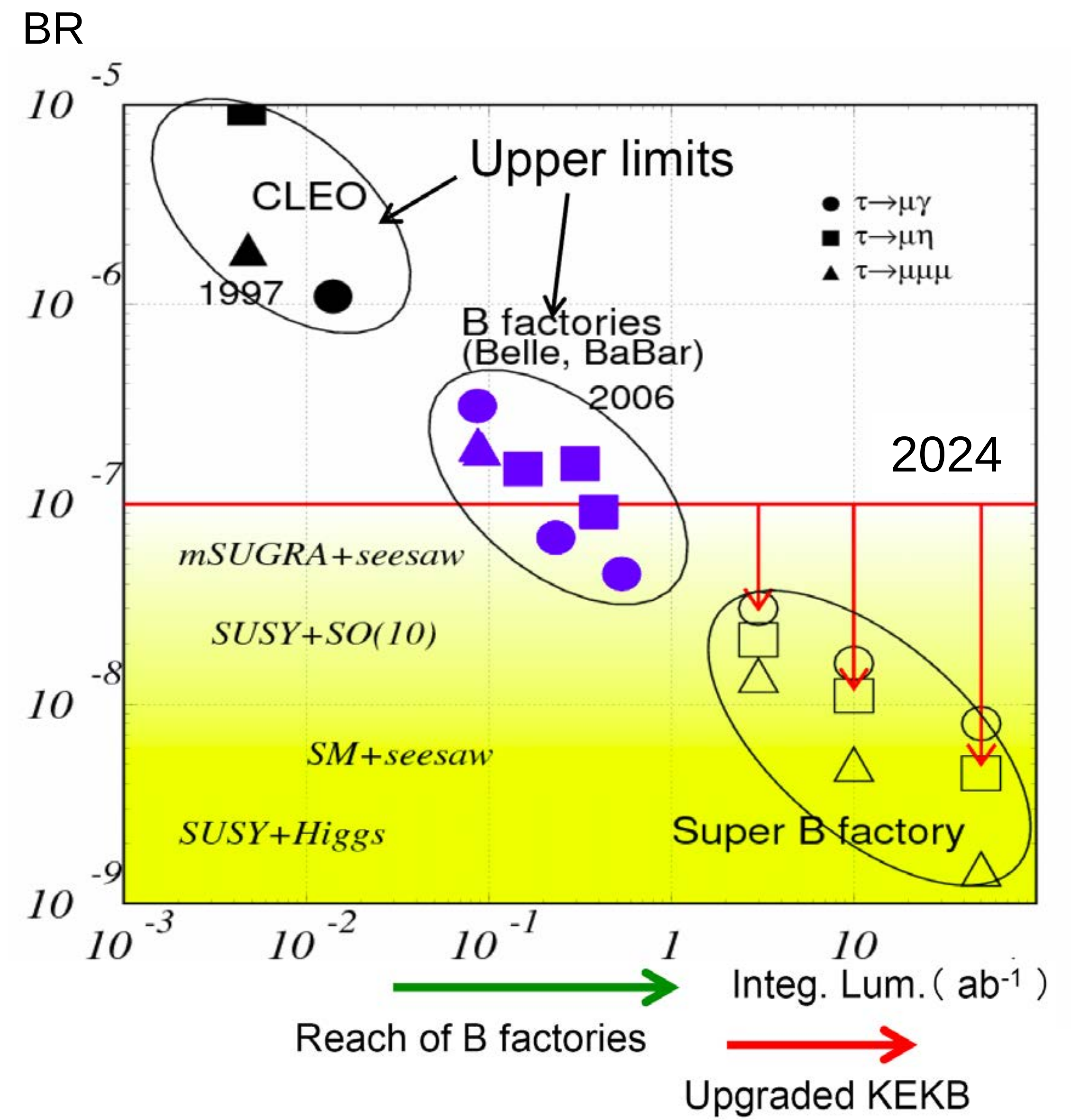
SM pred.

leptons:

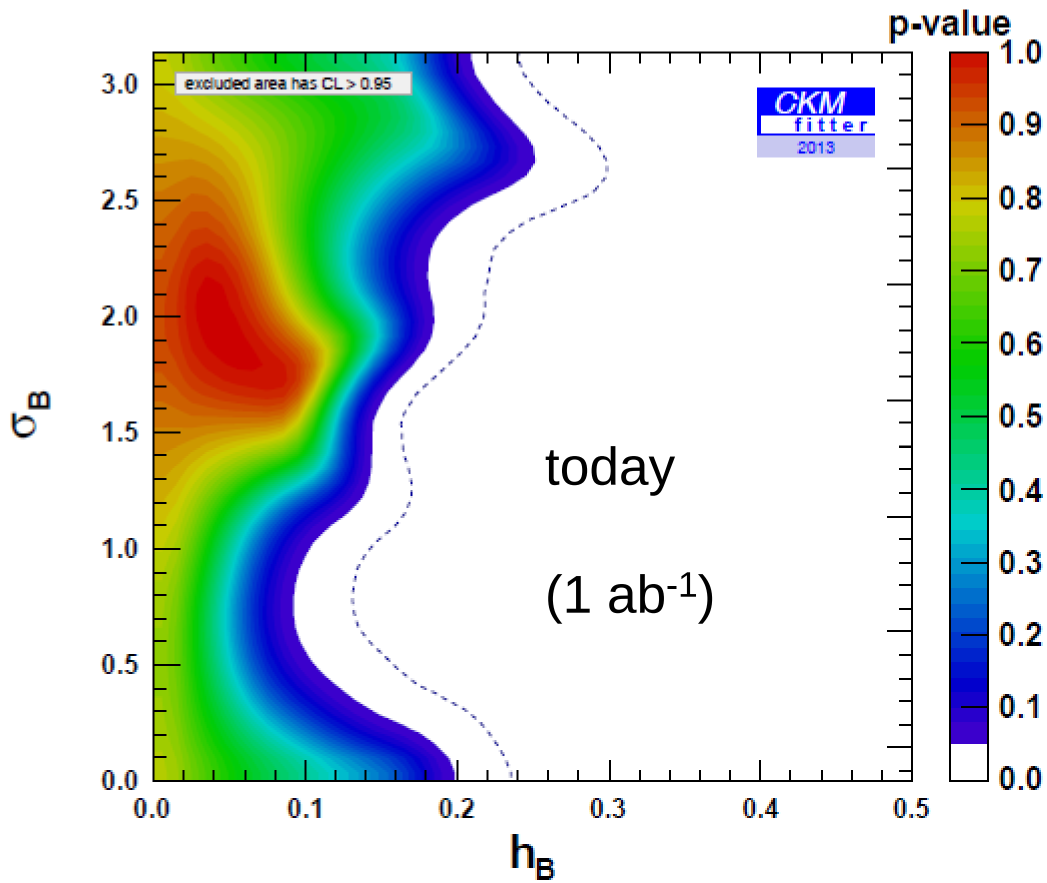
$$\left.\begin{array}{l}\tau \to \mu\gamma \\ \tau \to \mu\mu\mu \\ \tau \to \mu\eta\end{array}\right\}$$

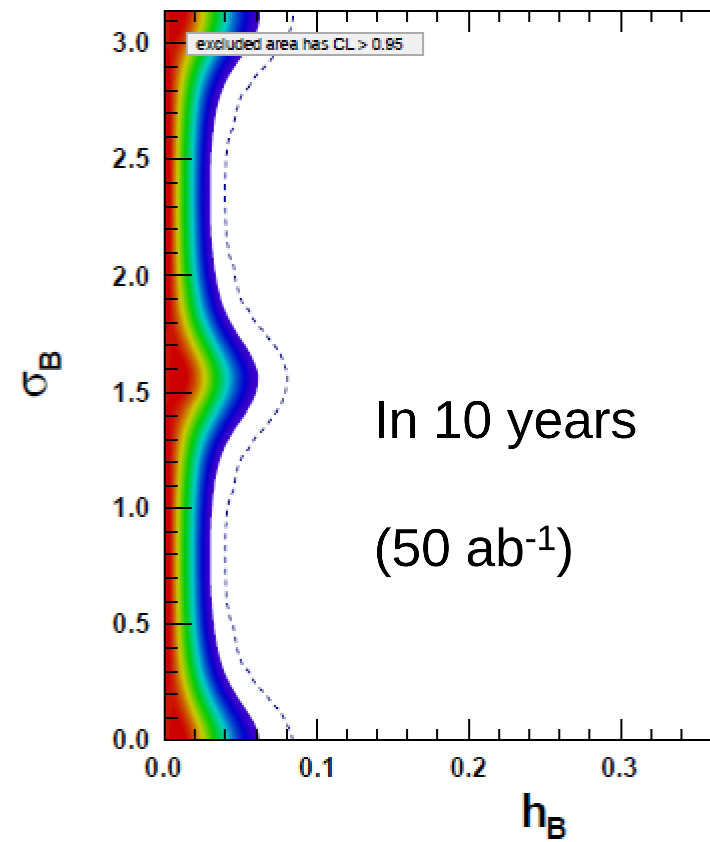
NP could make these decays possible

need precision (statistics) to challenge the SM



New Physics Amplitudes





$$h_{(B)} = 1.5 \frac{\left|C_{ij}\right|^2}{\left|\lambda_{ij}^t\right|^2} \left(\frac{4.5 \text{ TeV}}{\Lambda} \right)^2$$

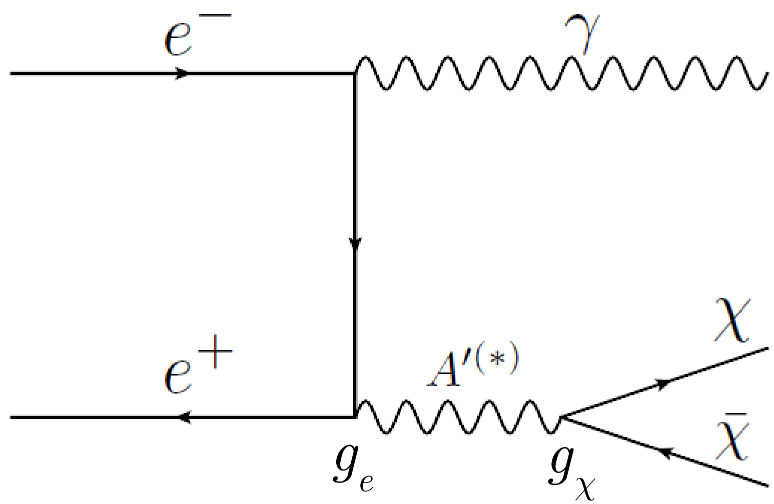
$$\lambda_{ij}^t = V_{ti}^* V_{tj}$$

CKM Fitter Group, arXiv:1309.2293

Search for Dark Matter

Model: Light Dark Matter, coupling to SM particles via light mediator A

(alternative to the standard WIMP paradigm)



mono-chromatic photon

„missing" energy:
Light Dark Matter particle χ
pair-produced via mediator A
(„hidden", or „dark" photon)

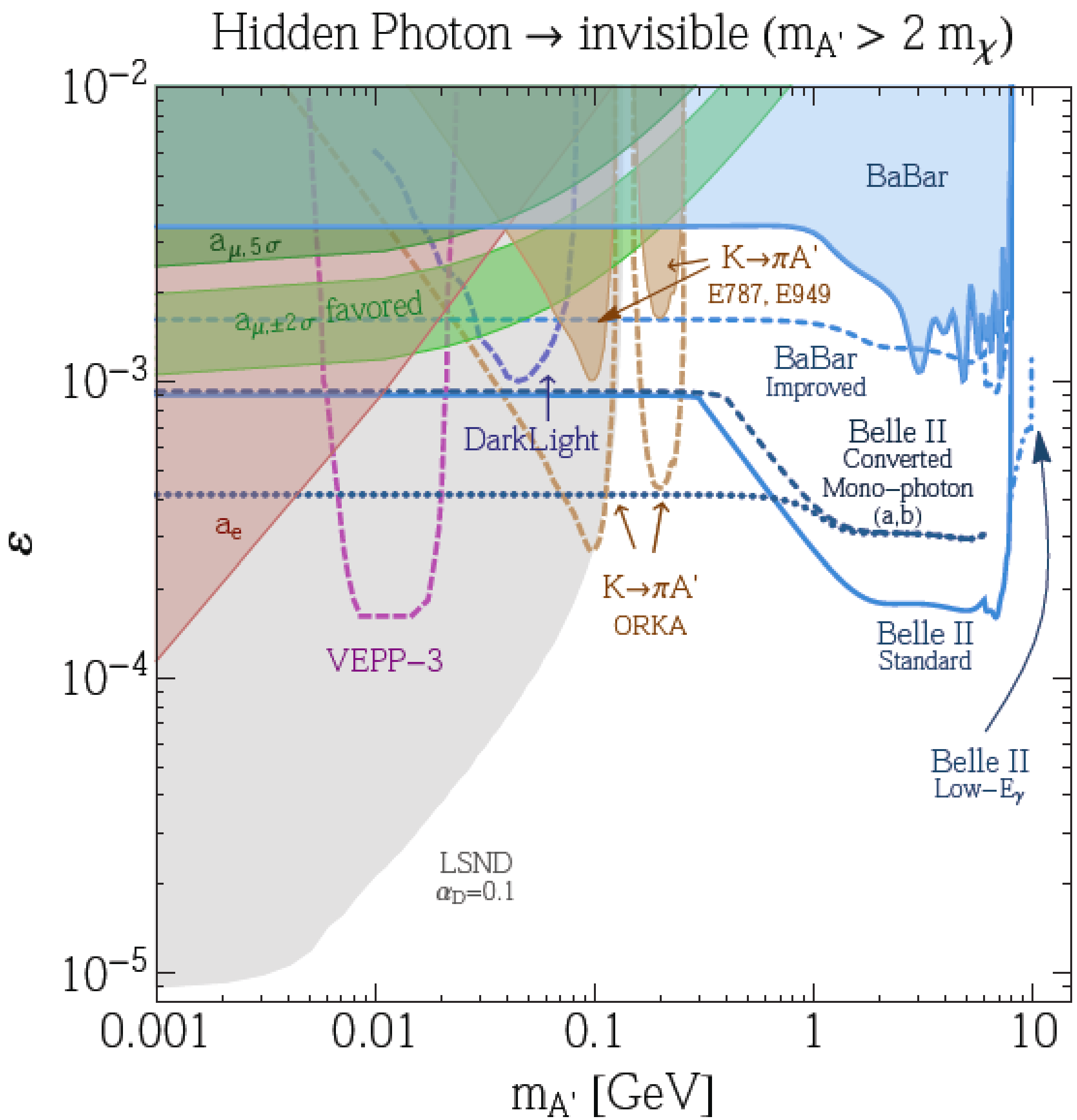
coupling of mediator to electrons

$$g_e = \varepsilon e q_i \qquad g_\chi < \sqrt{4\pi}$$

Experimental challenge:

Single photon trigger (E > 1 GeV)

Limits on Light Dark Matter

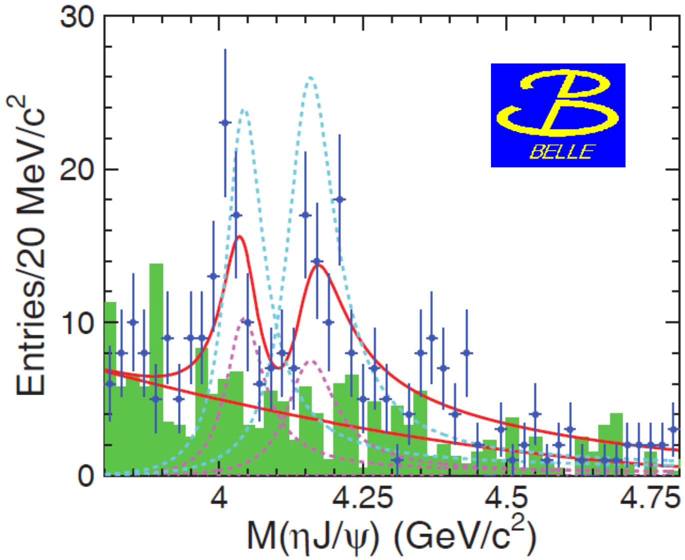


Potential for
Light Dark Matter search
with SuperKEKB

Parameter space for
masses > 100 MeV
largely unexplored

Single Photon Trigger is
now on the „menu“ for
the Belle II detector

Exotic Hadrons (some examples)



$$e^+e^- \rightarrow J/\psi\,\eta$$

$\psi(4040)$ and $\psi(4160)$ seen

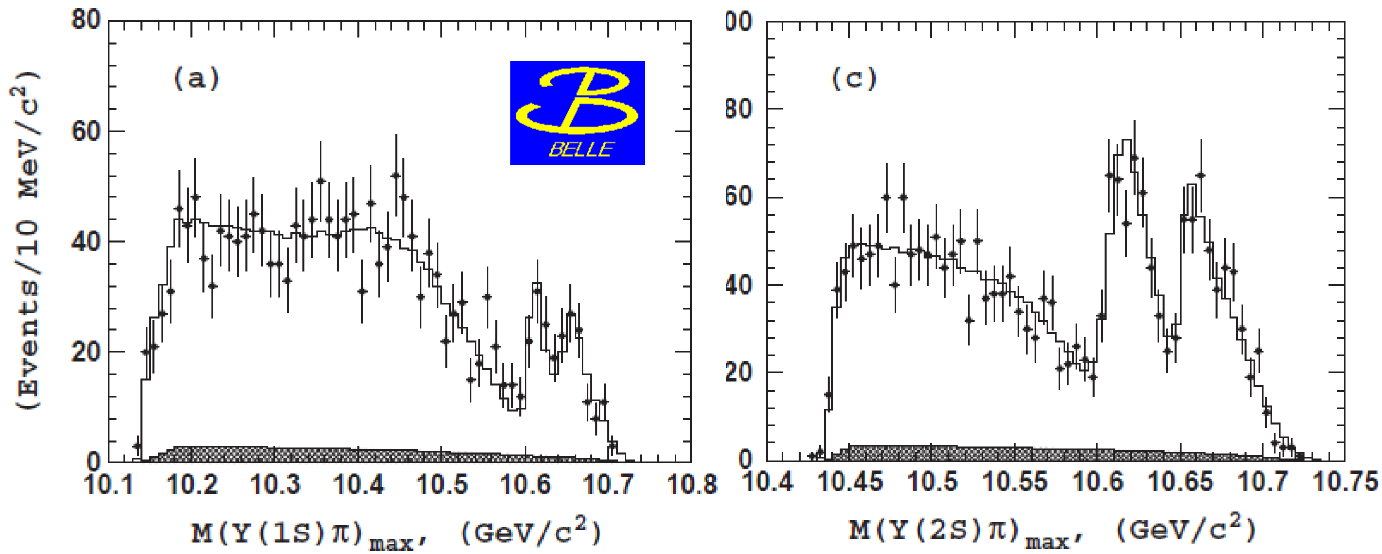
first time in channels without charmed meson pairs.

Bottonia with I=1

$$\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$$

$$\rightarrow Z_b(10610)\pi,$$

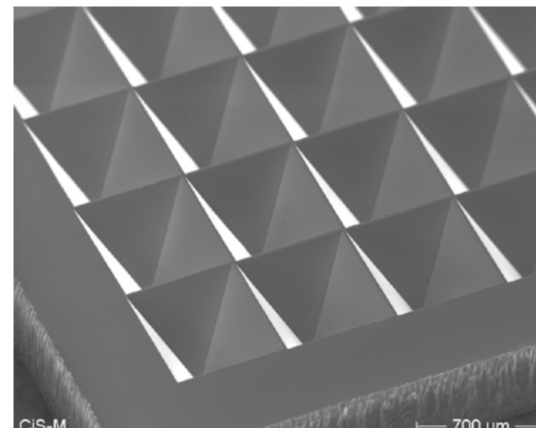
$$\rightarrow Z_b(10650)\pi$$



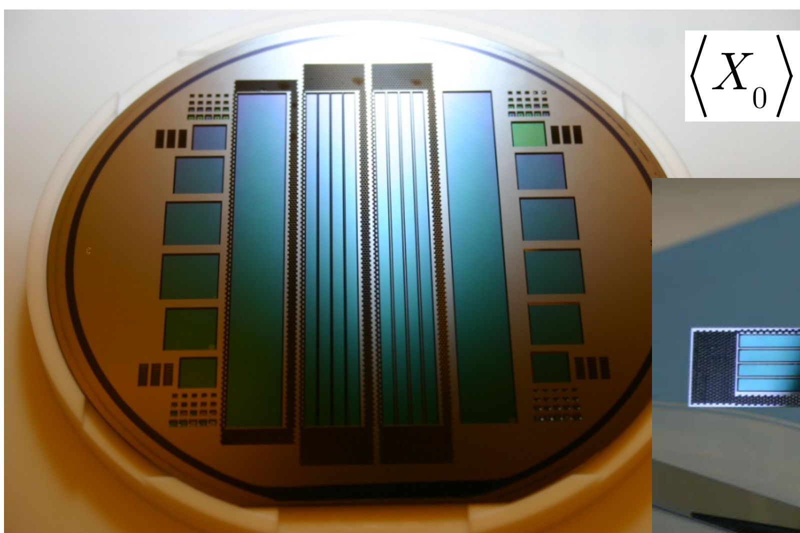
DEPFET Sensor Thinning Technology

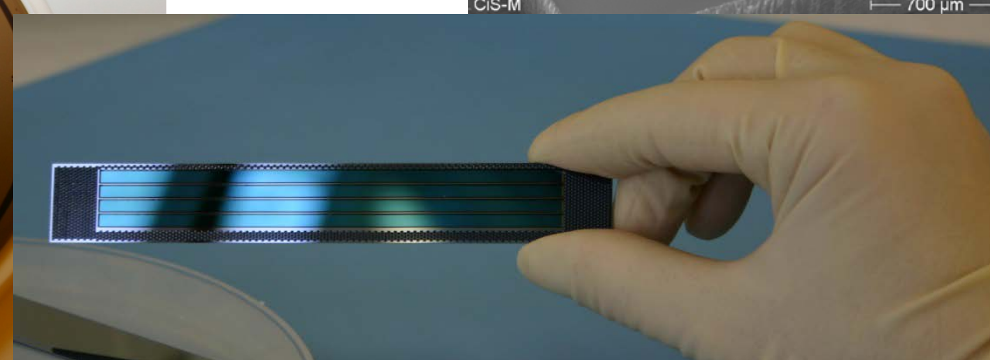
1. implant backside on sensor wafer
2. bond sensor wafer to handle wafer
3. thin sensor side to desired thickness
4. process DEPFETs on top
5. structure resist, etch backside up to oxide/implant

- Sensor wafer bonded on “handle” wafer.
- Rigid frame for handling and mechanical stiffness
- 50 μm thickness achieved
- Full-sized Belle II matrices produced
- Electrical properties tested successfully



$$\langle X_0 \rangle = 0.18\%$$





PXD System Overview

Total of 0.2% of X_0

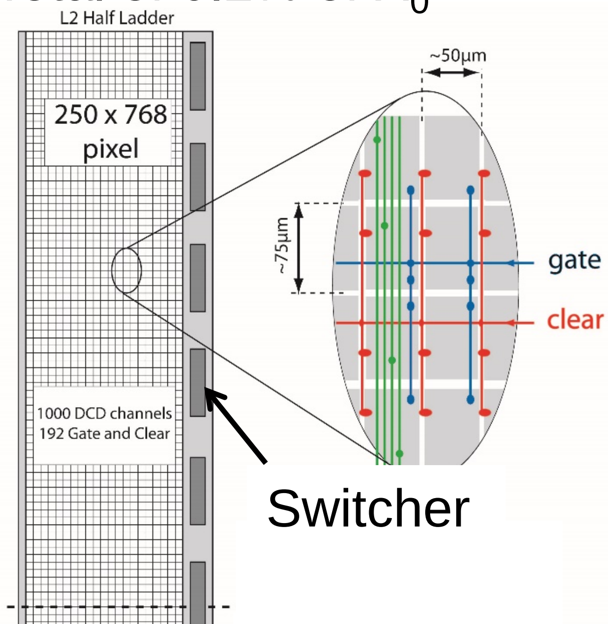
2 layers: @1.4(2.2) cm

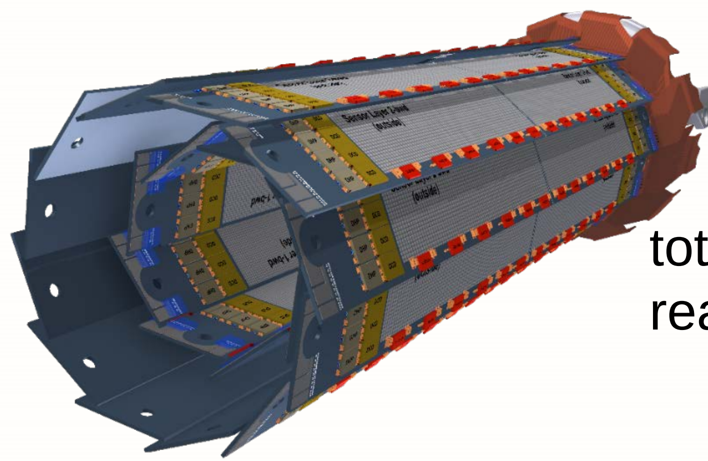
Pixels: 50 x 60(75) µm

half ladder: 768 rows

250 cols

15 x 70 (85) mm

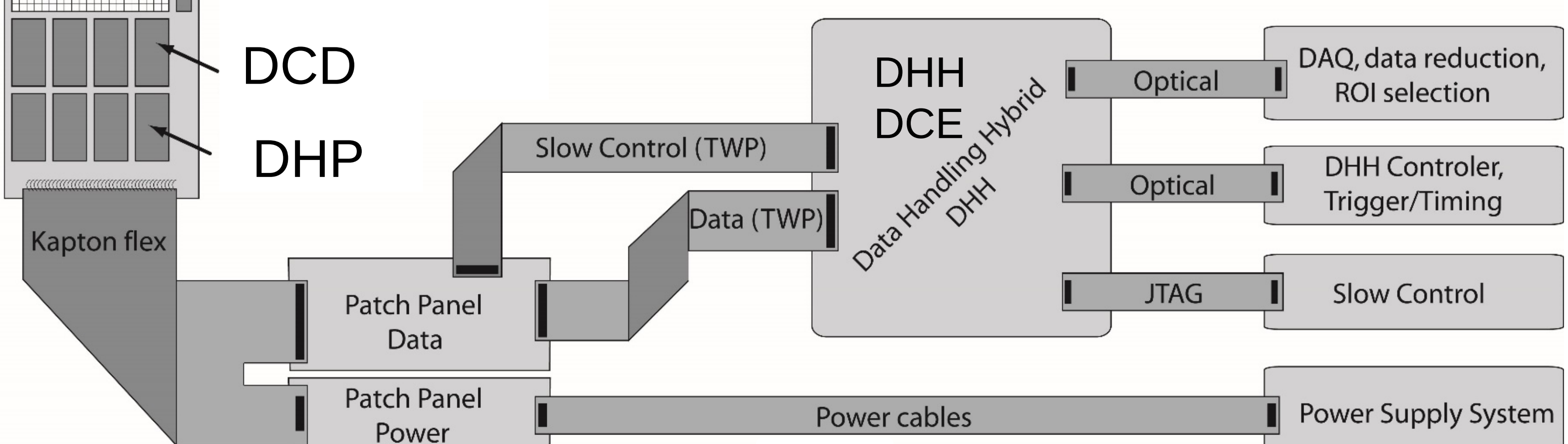




Thickness: 75 µm

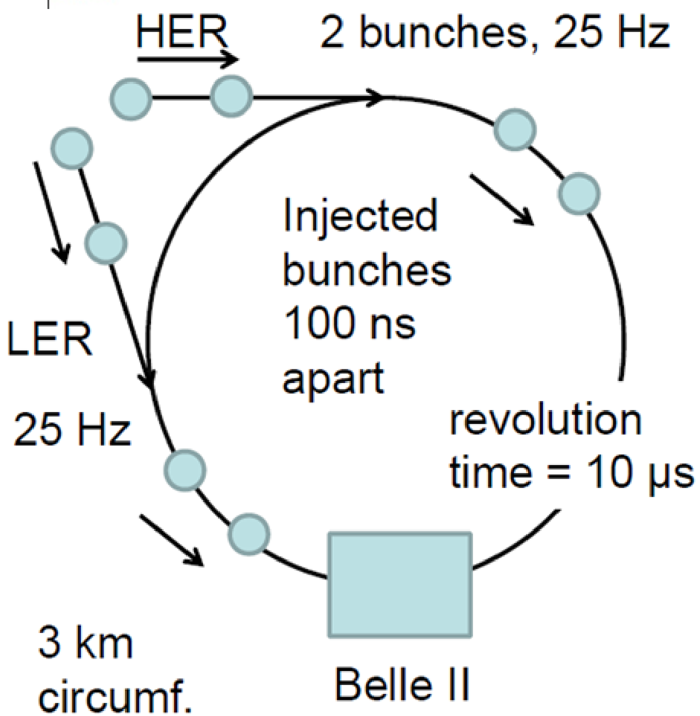
total of 8 Mpx

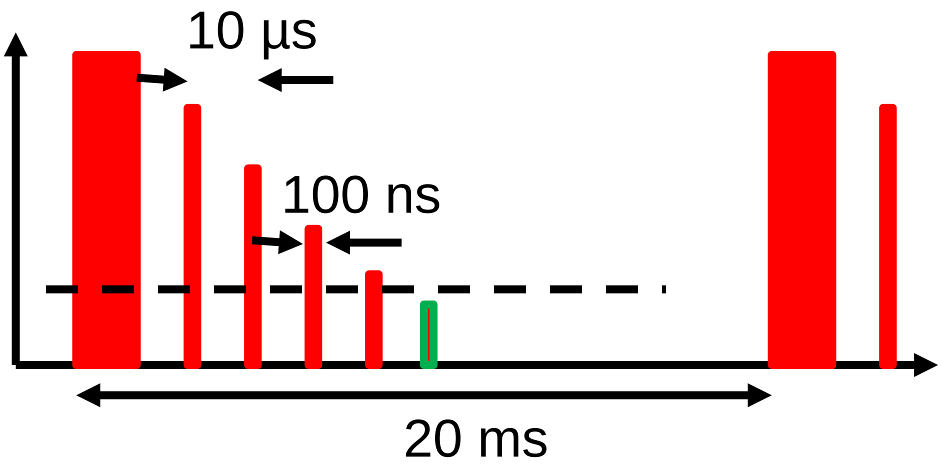
readout: 20 µs



total of 240 Gb/s !

Problem for the PXD: Injection "Noise"



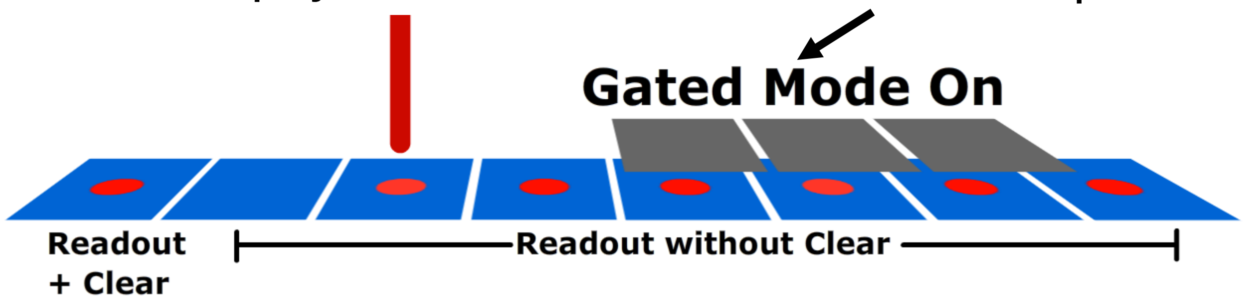


Important mode of operation for the PXD:
"Gated Mode" during 20µs readout

Continuous
injection
(ΔI/I very small)

Energy
deposition from
"physics"

switch on CLEAR
voltage
for ~ 500 ns - 1 µs



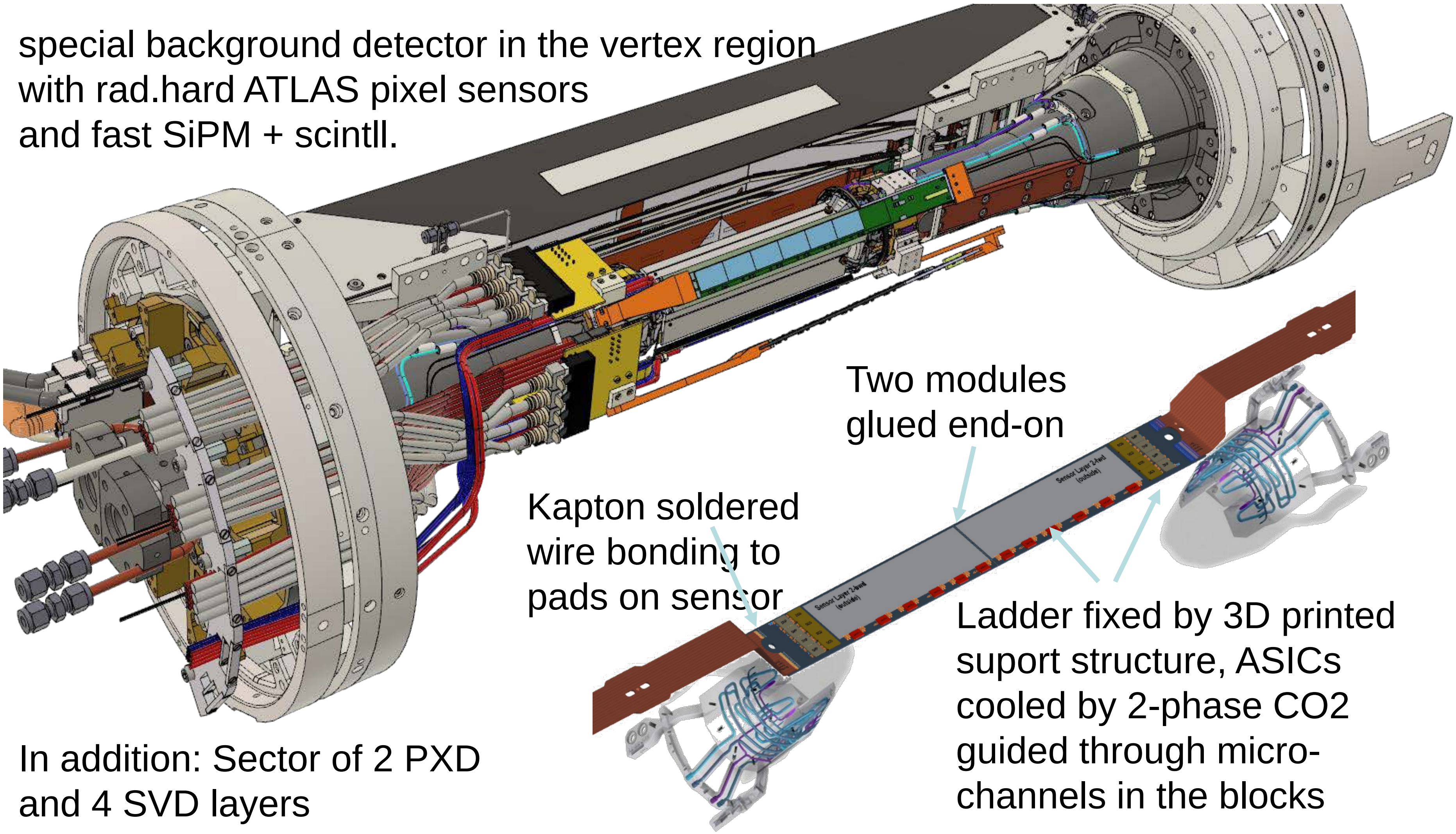
Noisy bunches pass PXD

Phase 2 Detector: BEAST

First nano-beam collisions during Phase 2

Vertex detector mounted on the beam pipe

special background detector in the vertex region
with rad.hard ATLAS pixel sensors
and fast SiPM + scintll.



Two modules glued end-on

Kapton soldered wire bonding to pads on sensor

Ladder fixed by 3D printed suport structure, ASICs cooled by 2-phase CO2 guided through micro-channels in the blocks

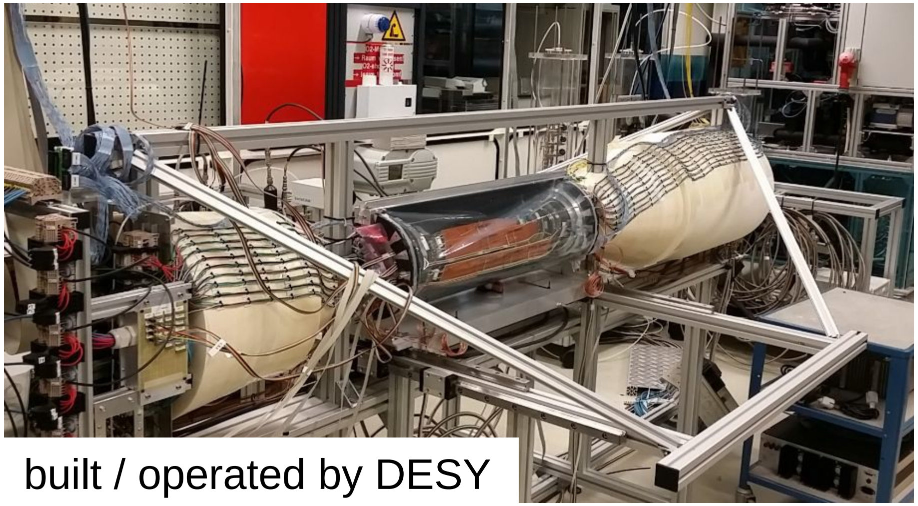
In addition: Sector of 2 PXD and 4 SVD layers

VXD (= PXD + SVD) Subprojects

2-phase CO2 cooling unit („IBBelle“)

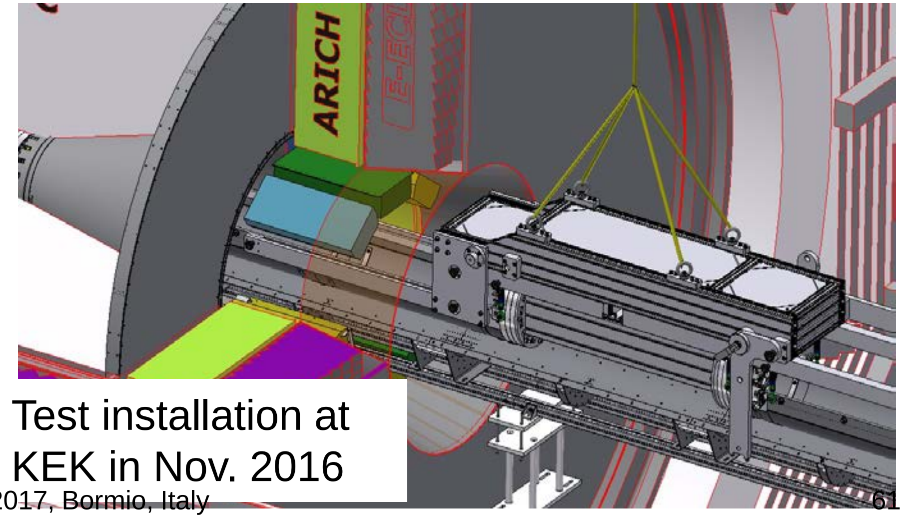
built at MPI in collaboration with CERN / Nikhef, being lowered into its final place in Tsukuba hall

VXD thermal management mockup for CO2 cooling studies: original sizes and materials



built / operated by DESY

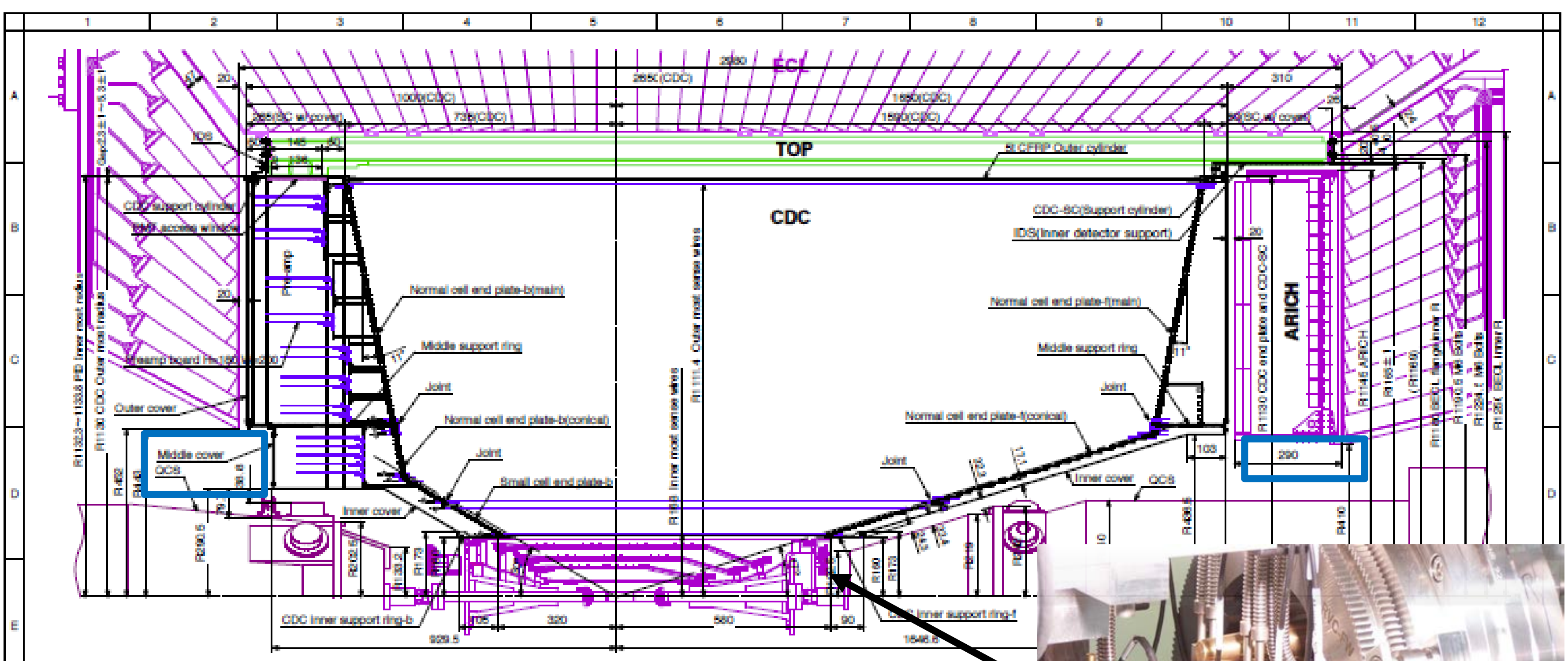
VXD installation into Belle (design by MPI)

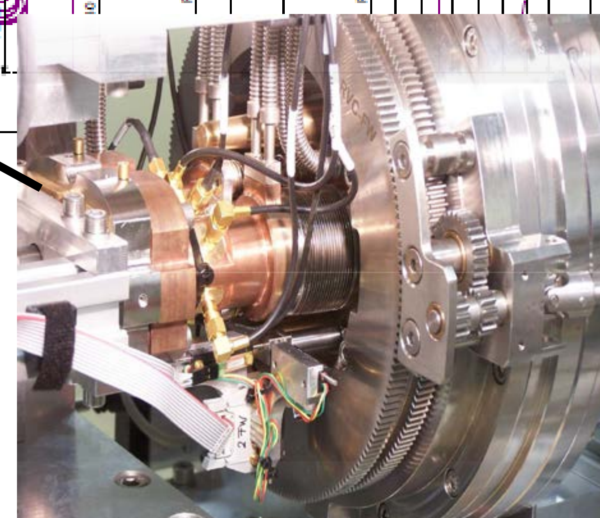


Test installation at KEK in Nov. 2016

VXD Installation Highly Non-Trivial

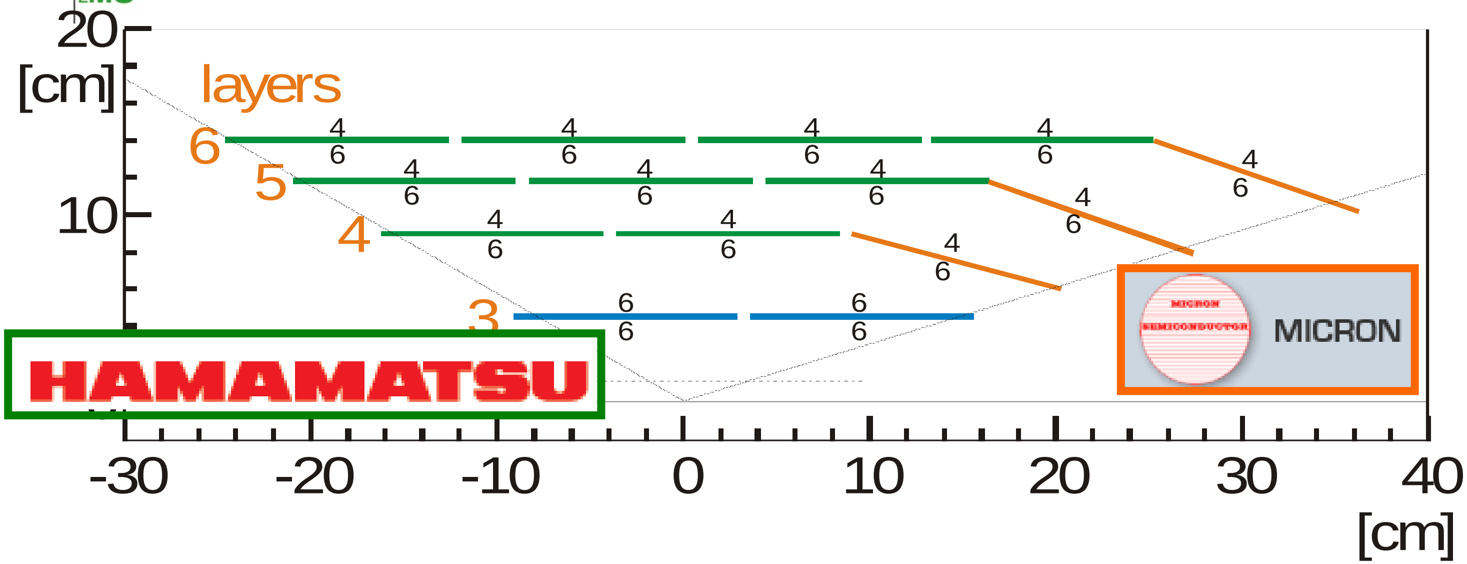
QCSR vacuum connection cannot be reached (no space)





- Solution: “Remote Vacuum Connection” (RVC), mounted on the tip of the QCSR(L)
  Inner bore of the QCS = beam pipe
- Closing mechanism operated by gear from outside

New Si System for Belle II : SuperSVD



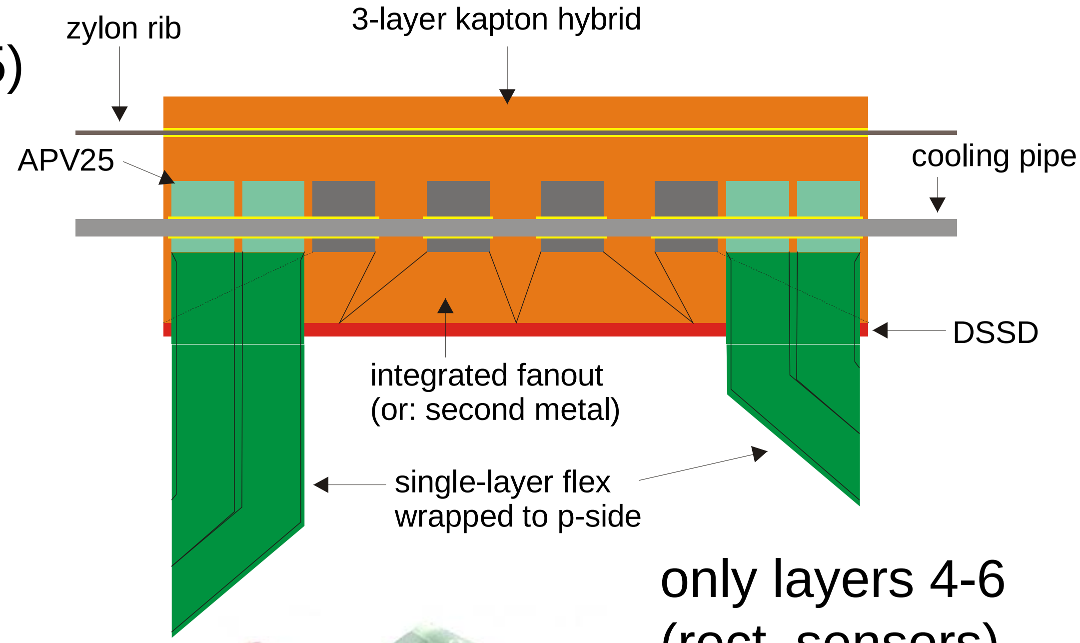
300 µm DSSD

Pitch:
50/160 µm (rect.)
50-75/160 µm (wedge)

Layer	# Ladders	Rect. Sensors [50µm]	Rect. Sensors [75µm]	Wedge Sensors	APVs
6	17	0	68	17	850
5	14	0	42	14	560
4	10	0	20	10	300
3	8	16	0	0	192
Sum:	**49**	**16**	**130**	**41**	**1902**

Chip on Sensor: The Origami Concept (SVD)

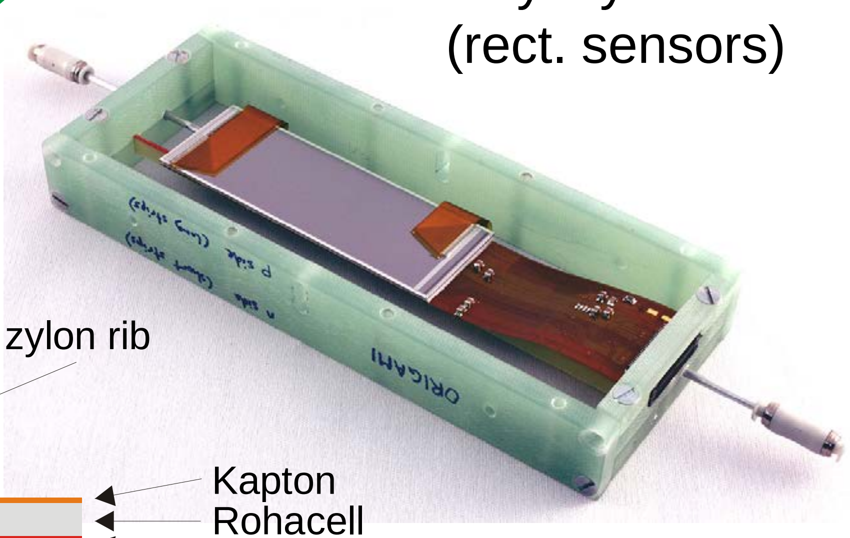
- Thinned readout chips (APV25) on sensor
- Strips of bottom side are connected by flex fanouts wrapped around the edge
- All readout chips are aligned → single cooling pipe
- Shortest possible connections → high signal-to-noise ratio

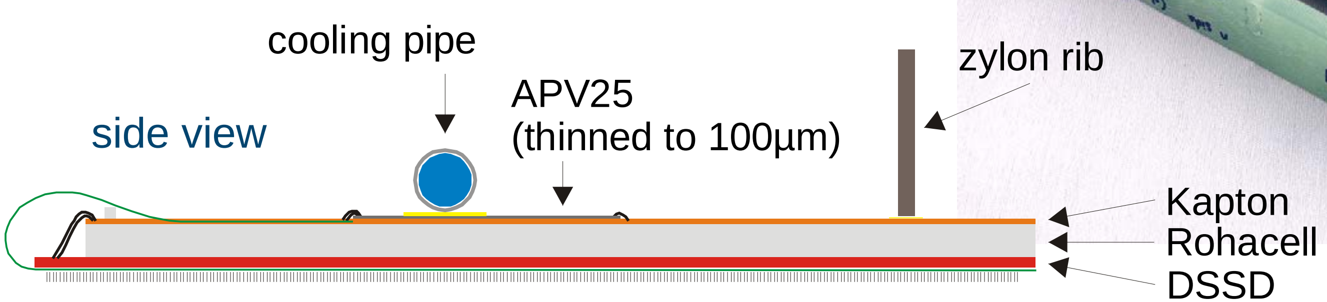


only layers 4-6
(rect. sensors)

Total material budget: 0.6% X_0

(cf. 0.48% for conventional readout)

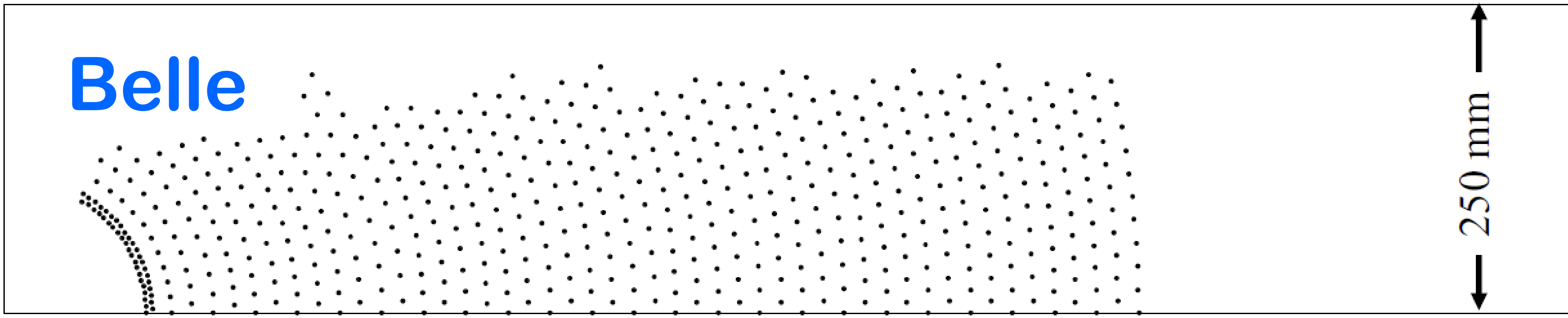




New Central Drift Chamber (CDC)

	Belle	Belle-II
Radius of inner boundary (mm)	77	160
Radius of outer boundary (mm)	880	1096
Radius of inner most sense wire (mm)	88	168
Radius of outer most sense wire (mm)	863	1082
Number of layers	50	58
Number of total sense wires	8400	15104
Effective radius of dE/dx measurement (mm)	752	928
Gas	He-C_2H_6	He-C_2H_6
Diameter of sense wire (μm)	30	30

New Central Drift Chamber (CDC)

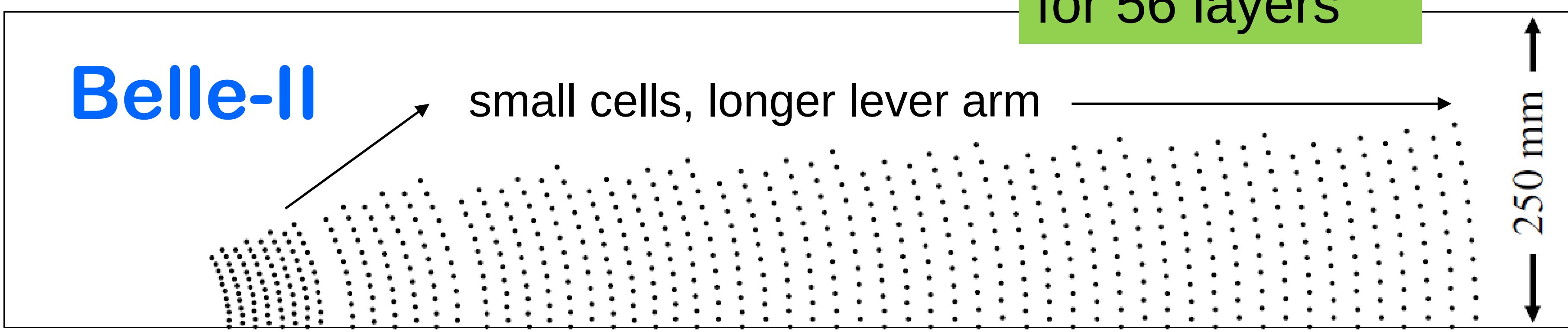


normal cell: 13.3 x 16 mm^2

small cell: 5.4 x 5.0 mm^2

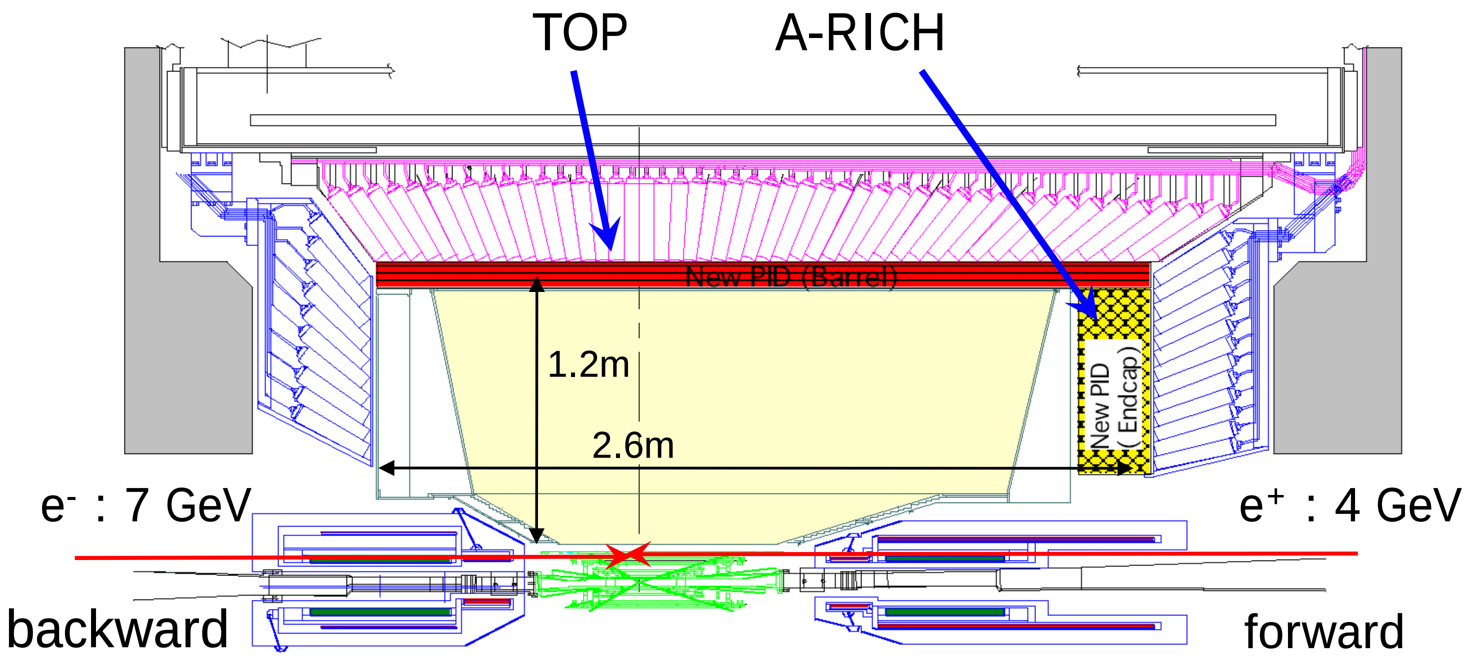
1200 mm

dE/dx: 4.8%
for 56 layers



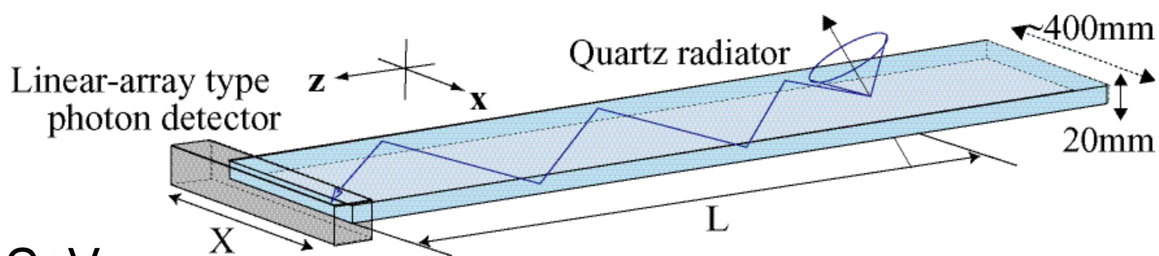
z-coordinate via standard stereo wire arrangement, charge division planned

Upgrade: Particle Identification



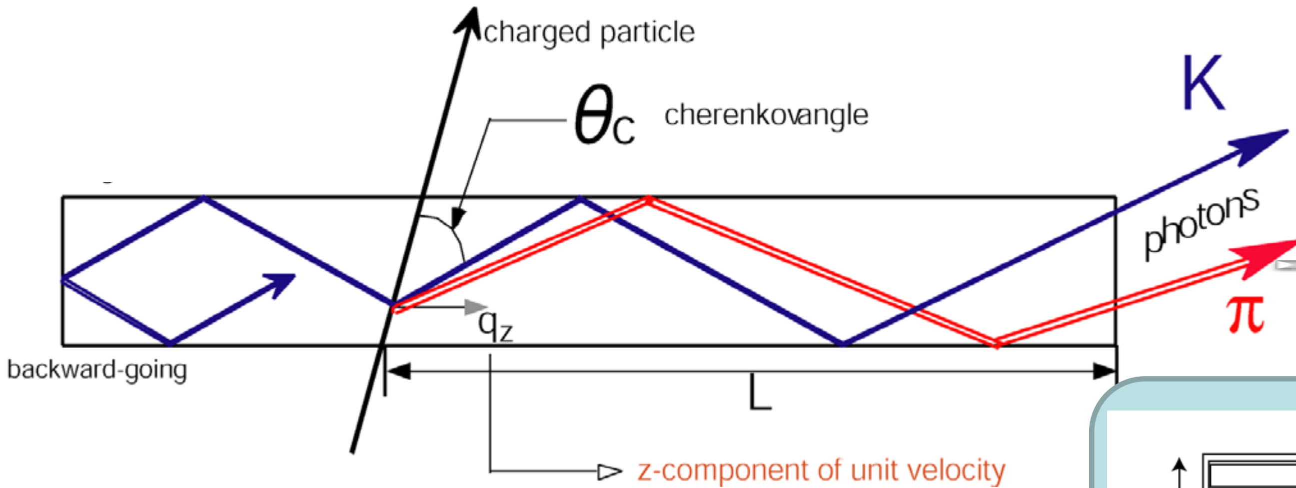
Goal:

3σ K/pi separation (barrel)
4σ K/pi separation up to 4 GeV
(end caps)

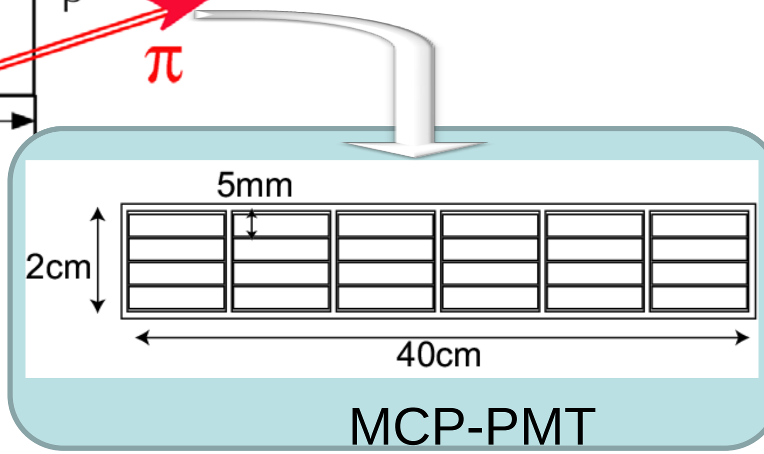


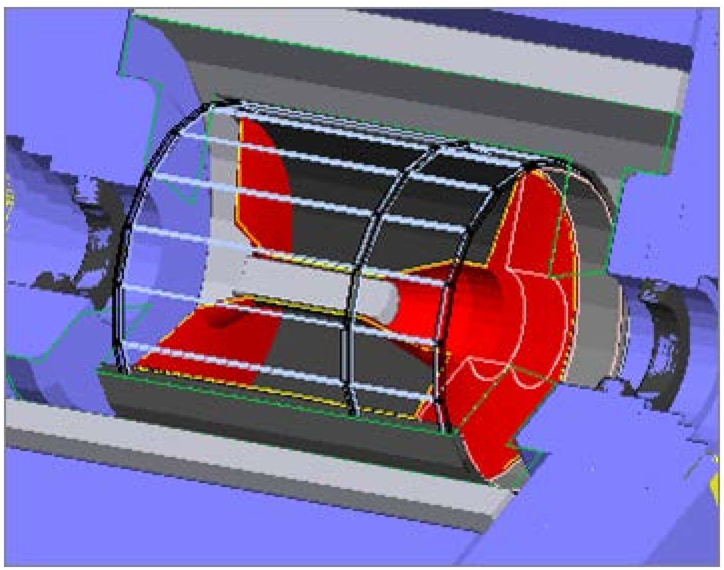
TOP: time of propagation

Baseline Design for Barrel PID (TOP)



TOP =
Time of Propagation





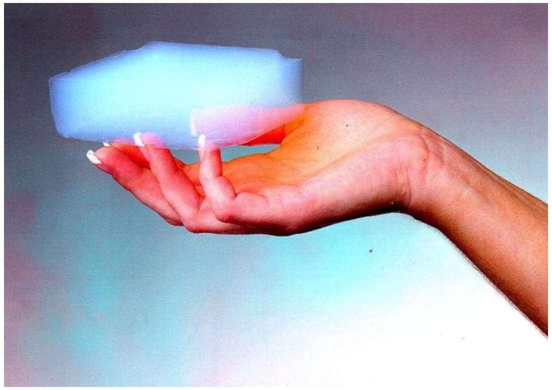
Ring imaging with :

– One coordinate with a few mm precision
– Time-of-arrival

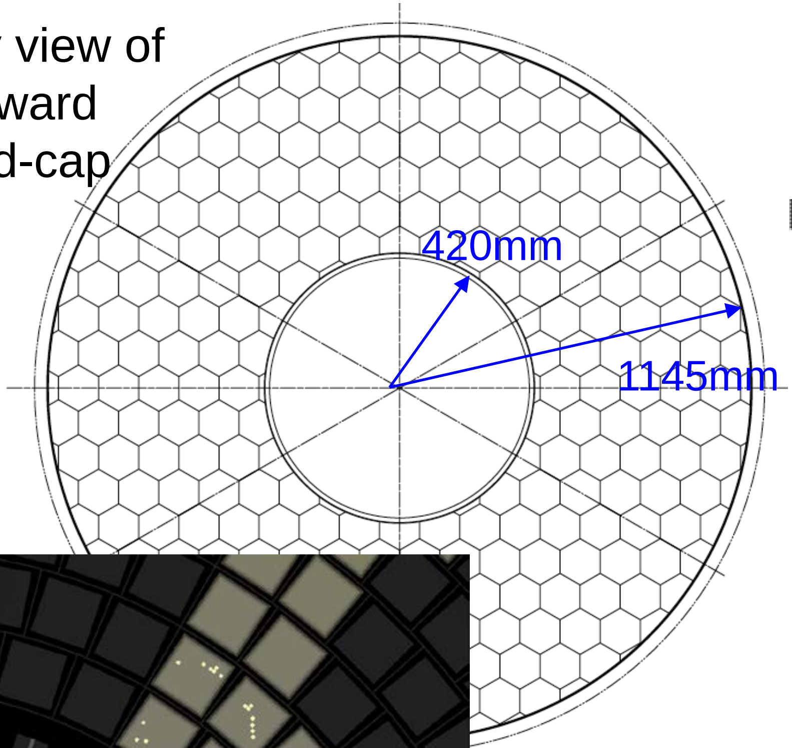
→ Excellent time resolution < ~40ps required for single photon in 1.5T B field

Baseline Design for Endcap PID (A-RICH)

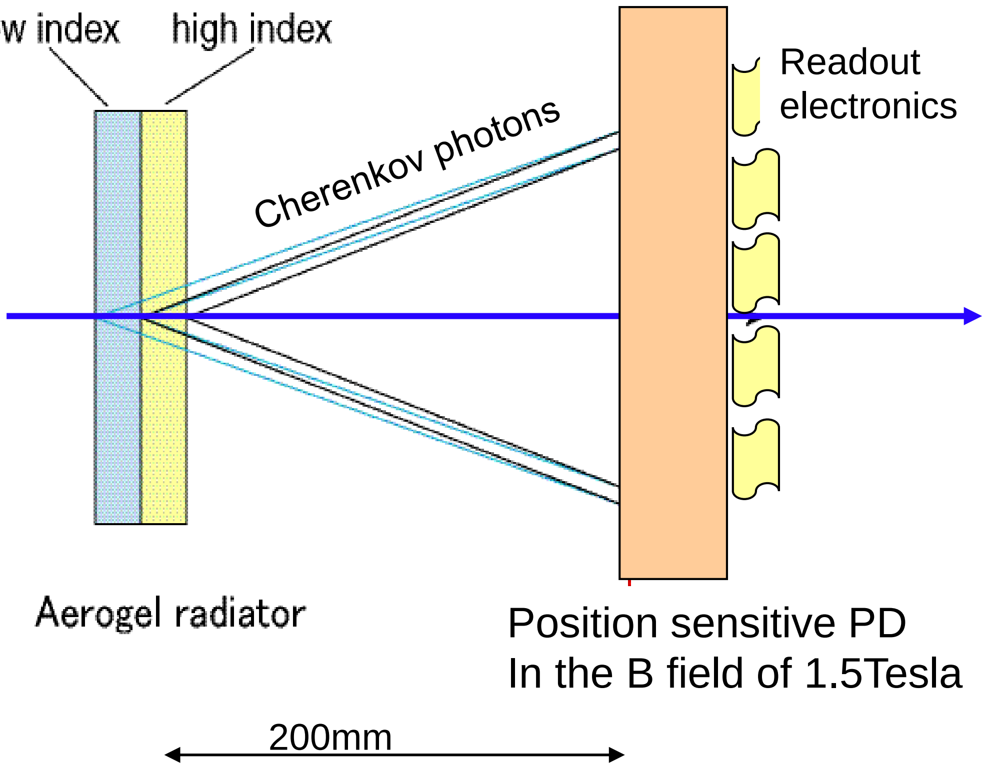
Proximity focusing RICH with silica aerogel as Cherenkov radiator for new Belle forward PID



x-y view of forward end-cap

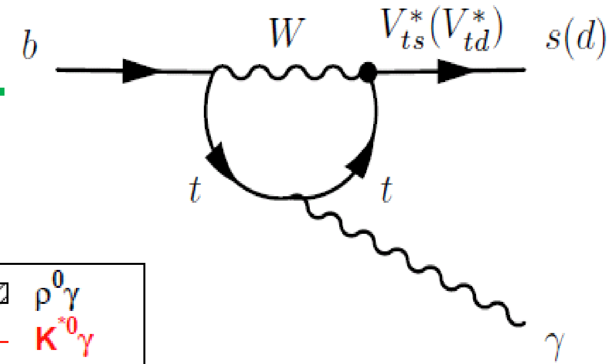


first C rings from cosmics



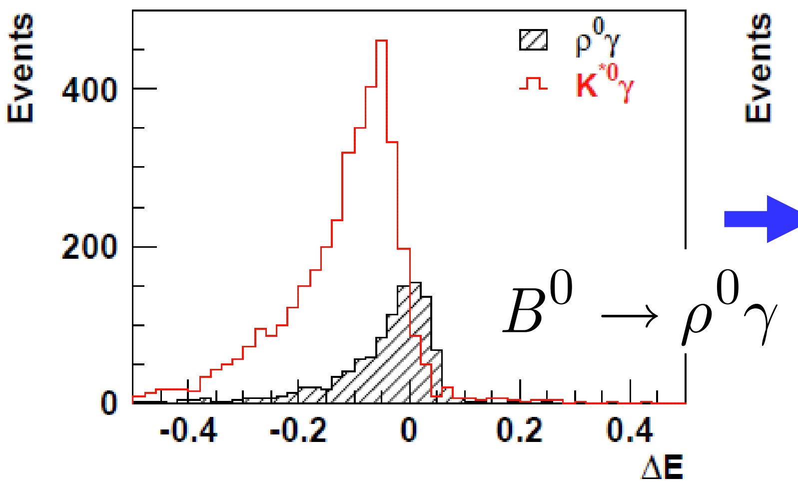
Position sensitive PD
In the B field of 1.5Tesla

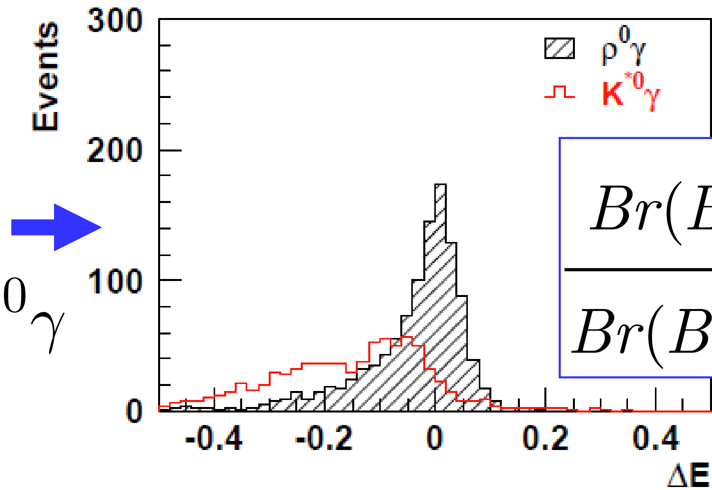
PID Improvement in Belle-II



Present Belle PID

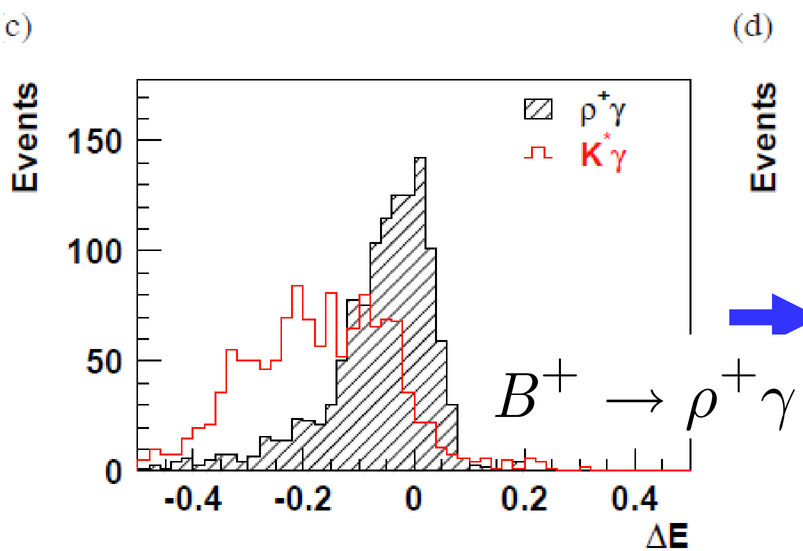
Belle II PID

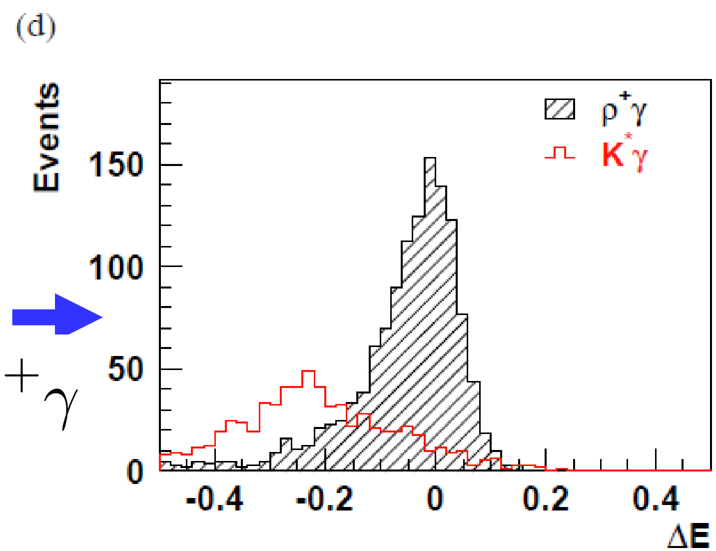




$$\frac{Br(B \rightarrow \rho\,\gamma)}{Br(B \rightarrow K^*\gamma)} \sim \left|\frac{V_{td}}{V_{ts}}\right|^2$$

$$(\sim 1/40)$$





$B \rightarrow \rho\gamma$

difficult because of dominating

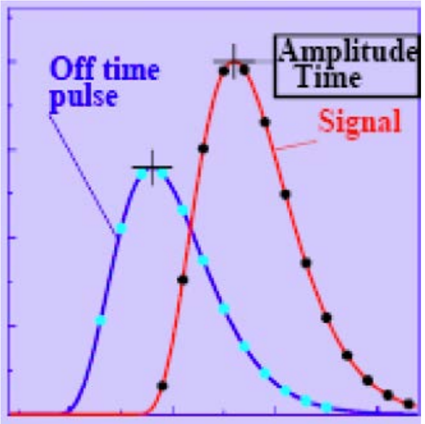
$K^*\gamma$

(Background from K's misident. as π's)

Calorimeter Upgrade (ECL)

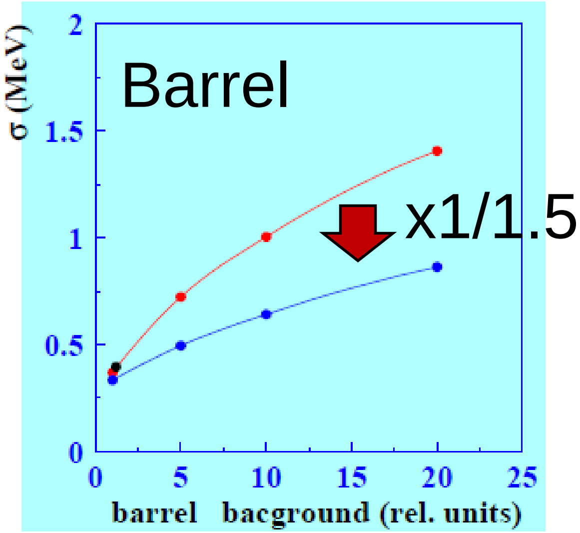
- Increase of dark current due to neutron flux
- Fake clusters & pile-up noise

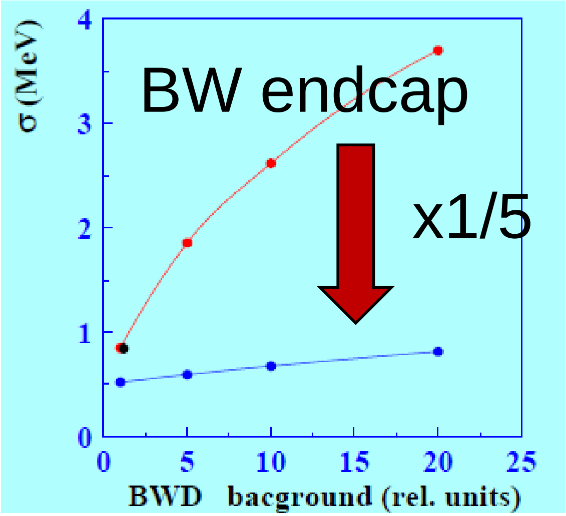
- Barrel:
  500 ns shaping + 2MHz w.f. sampling.
- Endcap:
  rad. hard crystals with short decay time (e.g. pure CsI) + photopentodes
  30ns shaping + 43MHz w.f. sampling



FADC: 16 samples

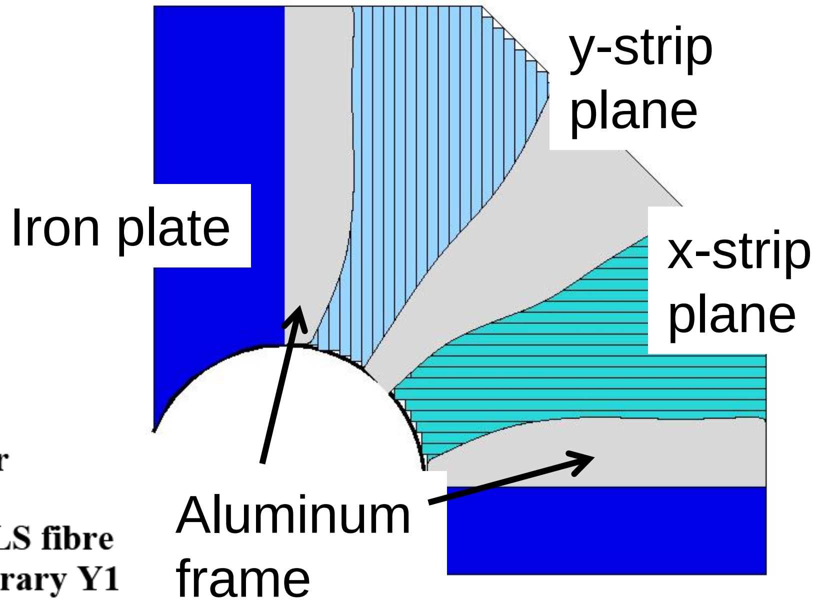
Pileup Reduction:

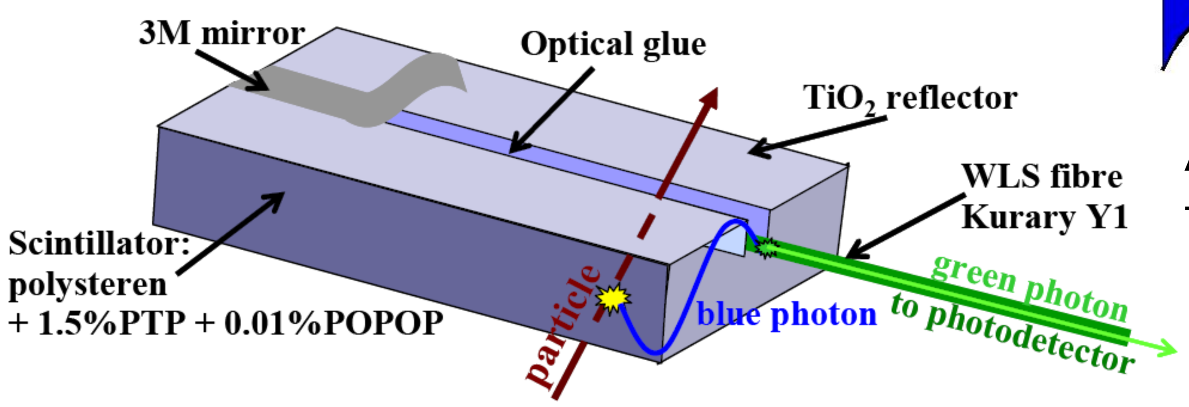




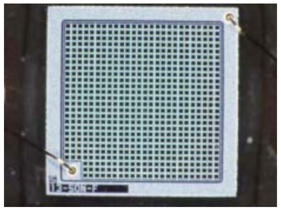
Upgrade of KLM (Endcaps)

- Two independent (x and y) layers in one superlayer made of orthogonal scintillator 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%





676 pixels (20x20μm^2)



SiPM, e.g. Hamamatsu 1.3x1.3 mm^2

DEPFET-Collab. @ Belle II

Original Collaboration: DEPFET pixel detector @ ILC (since 2002)
now: design, deliver and operate the PXD for Belle II

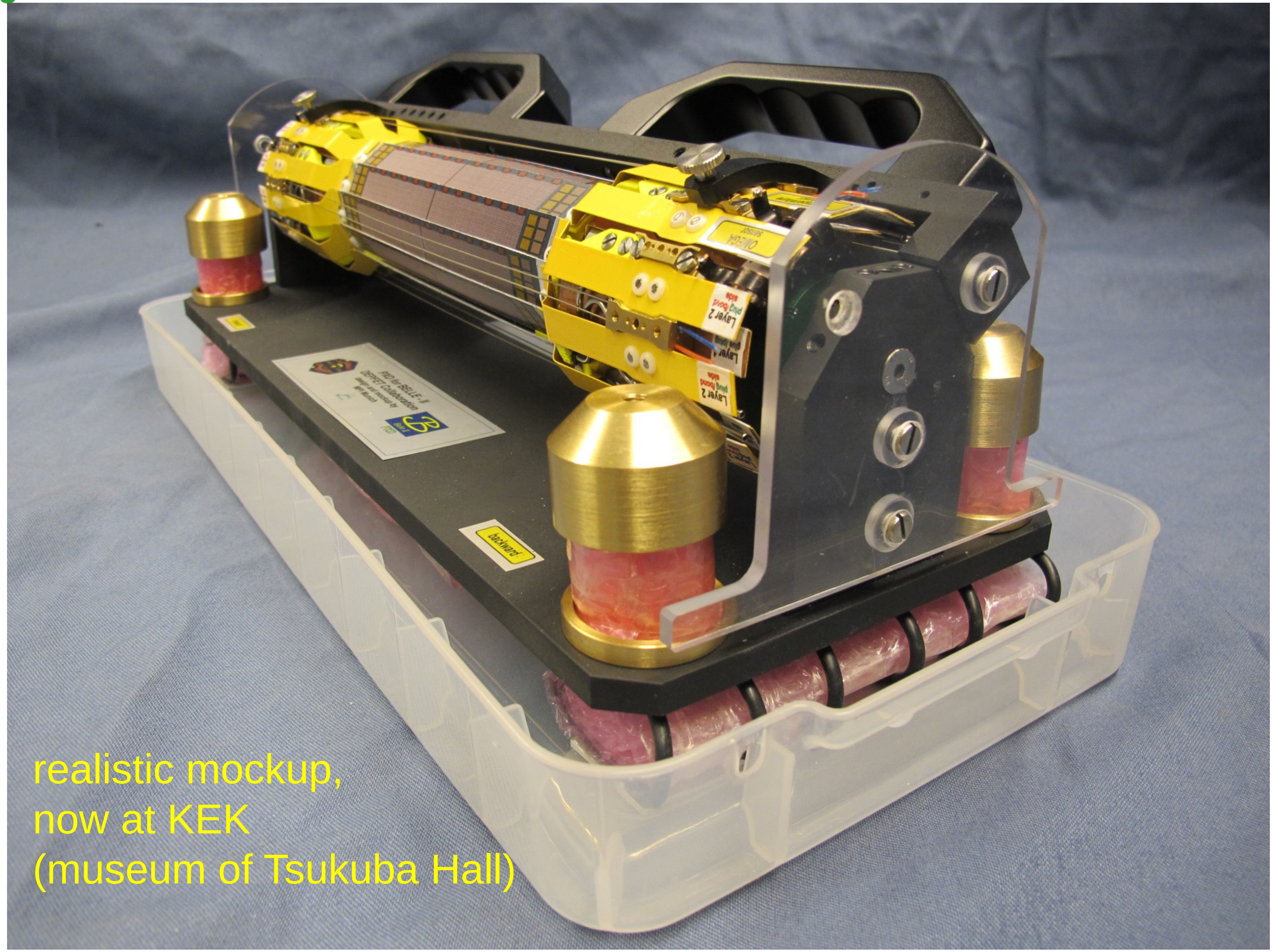
IHEP Beijing, China (Z.A. Liu)
Charles University, Prague, Czech Rep. (Z. Dolezal)
DESY Hamburg (C. Niebuhr)
University of Bonn (J. Dingfelder)
University of Hamburg (C. Hagner)
University of Heidelberg (P. Fischer)
University of Giessen (W. Kühn)
University of Göttingen (A. Frey)
KIT Karlsruhe (T. Müller, I. Peric)
University of Mainz (C. Sfienti)
MPG Semiconductor Laboratory, Munich (J. Ninkovic)
Ludw.-Max.-University, Munich (T. Kuhr)
MPI for Physics, Munich (H.-G. Moser)
Technical University, Munich (S. Paul, A.Knoll)
Struct. Biol.Research Center, KEK (S. Wakatsuki)
IFJ PAN, Krakow, Poland (M. Rozanska)
University of Barcelona, Spain (A. Dieguez)
CNM, Barcelona, Spain (E. Cabruja)
IFCA Santander, Spain (I. Vila)
IFIC, Valencia, Spain (J. Fuster)
University of Tabuk, Saudi Arabia (R. Ayad)

DEPFET@Belle II

Management:

- Project Leader
  C. Kiesling (MPI)
- Technical Coord.
  L. Andricek (HLL)
- IB- Board
  Chair: J. Dingfelder (Bonn)
- „Liaison“ with Belle II
  Shuji Tanaka (KEK)

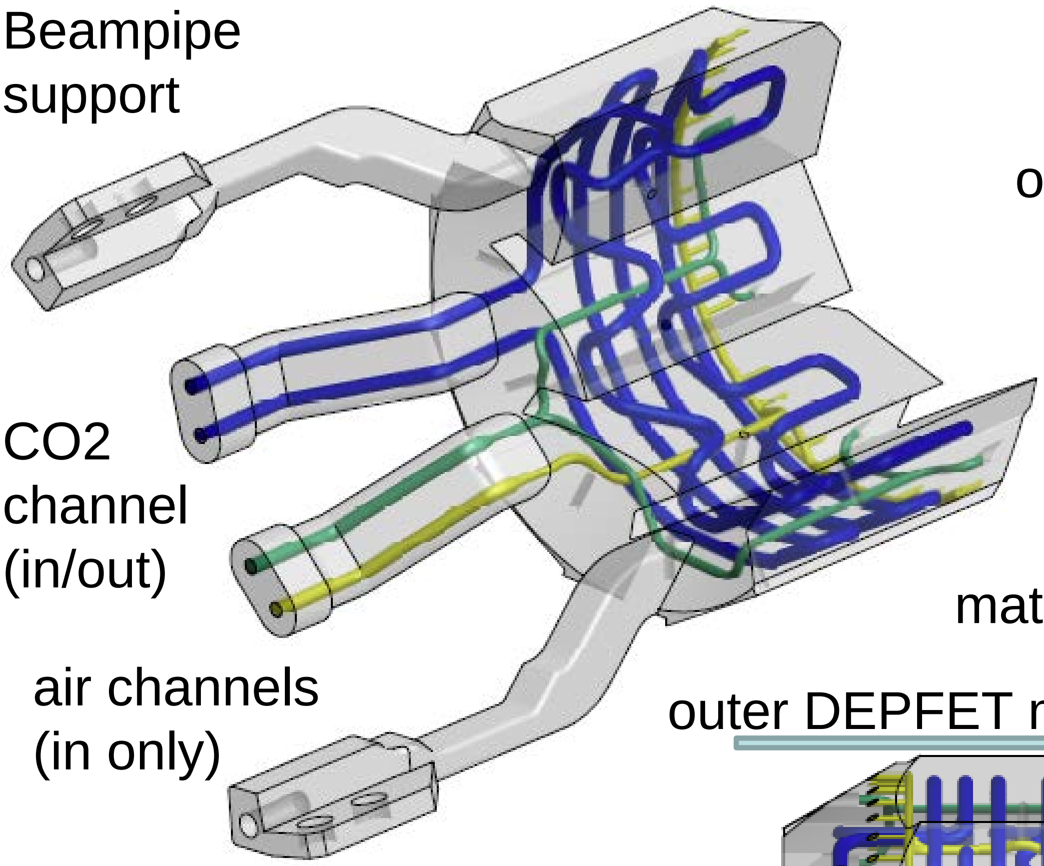
Full-Size Mockup of the PXD



realistic mockup,
now at KEK
(museum of Tsukuba Hall)

Mechanics and Cooling

Beampipe support



CO2 channel (in/out)

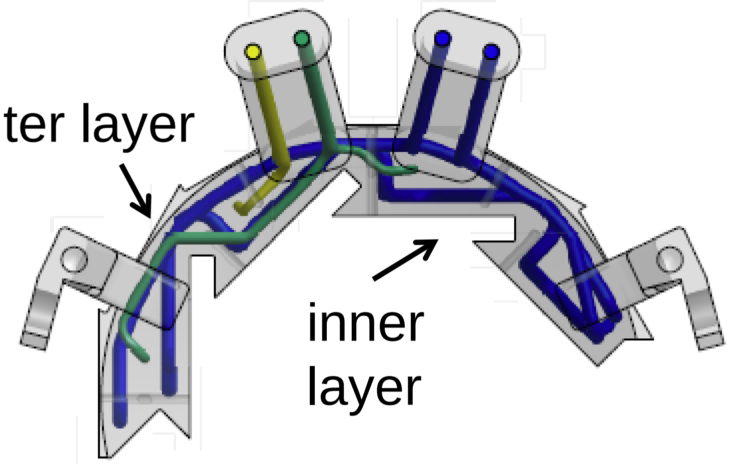
air channels (in only)

design: MPI
manufactured in Belgium

air

CO2

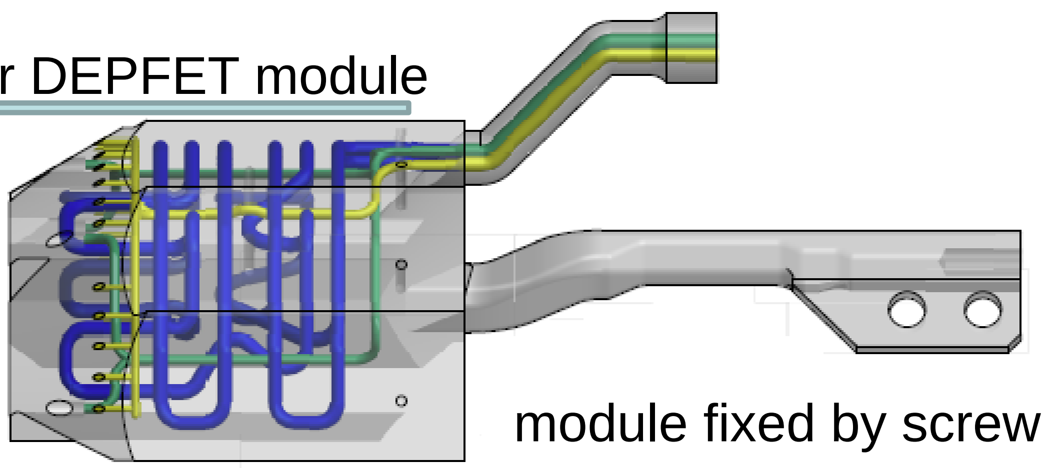
outer layer



inner layer

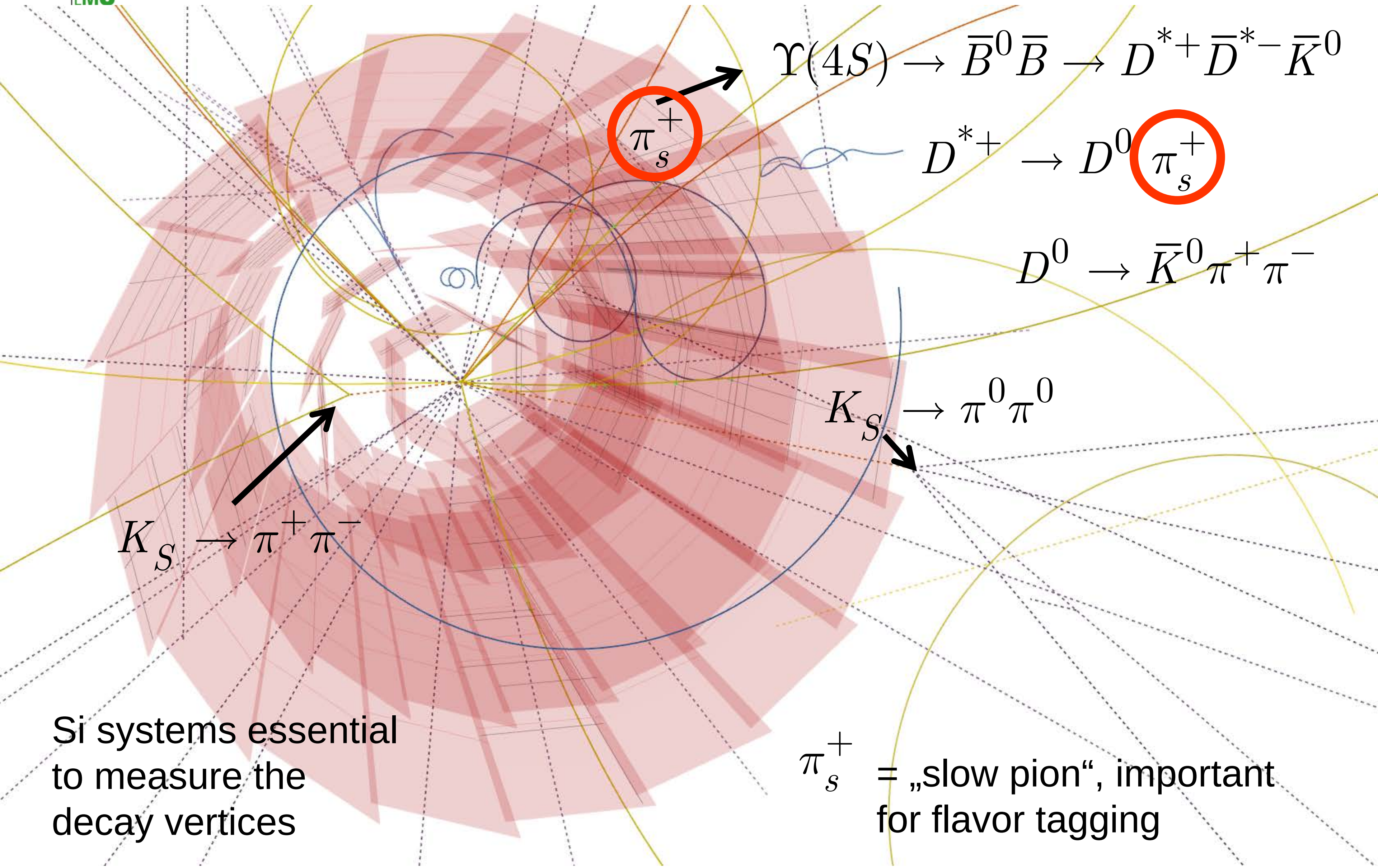
material INOX

outer DEPFET module



module fixed by screw

An Event in the Silicon Tracking System (Belle)



Si systems essential to measure the decay vertices

π_s^+ = „slow pion“, important for flavor tagging