Impact of the Belle II Pixel Detector on CP-Violation Measurements

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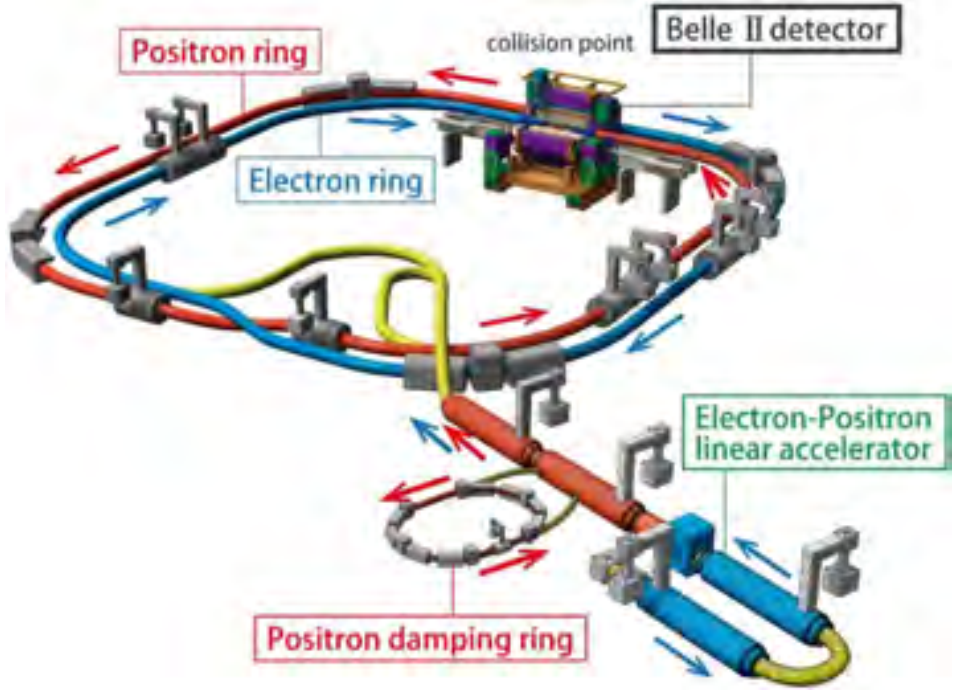
KEKB/SuperKEKB Collider

Upgrade: KEKB $\Rightarrow$ SuperKEKB

Belle $\Rightarrow$ Belle II

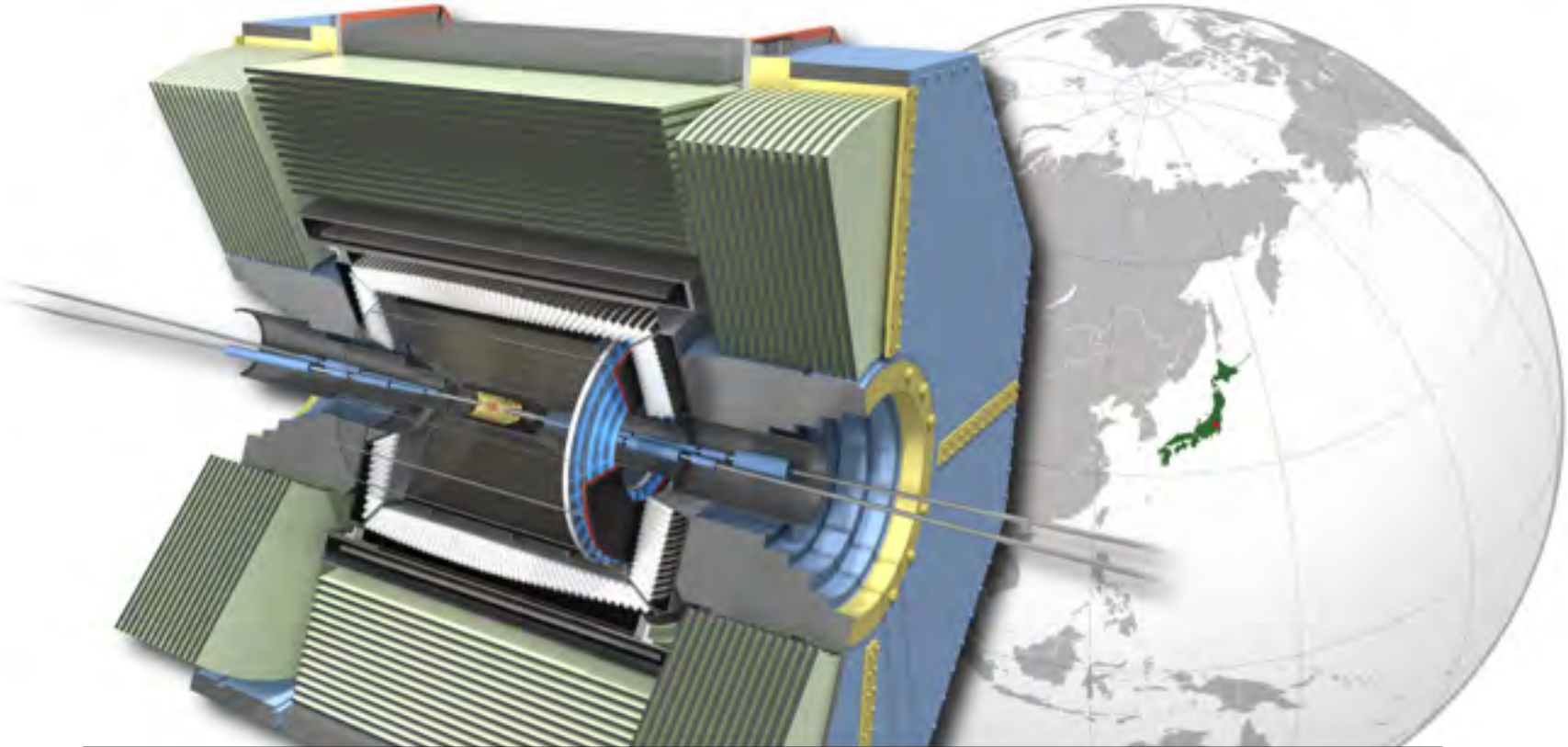


KEK = kō enerugī kasokuki kenkyū kikō

high energy collider research organization

At: Tsukuba, Ibaraki Prefecture, Japan

Belle/Belle II Experiment



	KEKB/Belle	SuperKEKB/Belle II
operation	1999 – 2010	2018 – 2025
Inst. Lumi. $\mathcal{L}$	$2.11 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$	$8 \cdot 10^{35}\text{cm}^{-2}\text{s}^{-1}$
e^-/e^+ beam E	$8/3.5$ GeV	$7/4$ GeV
Boost $\langle\beta\gamma\rangle$	0.425	0.284
e^-/e^+ beam I	$1.2/1.6$ A	$2.6/3.6$ A

Nano Beam Scheme

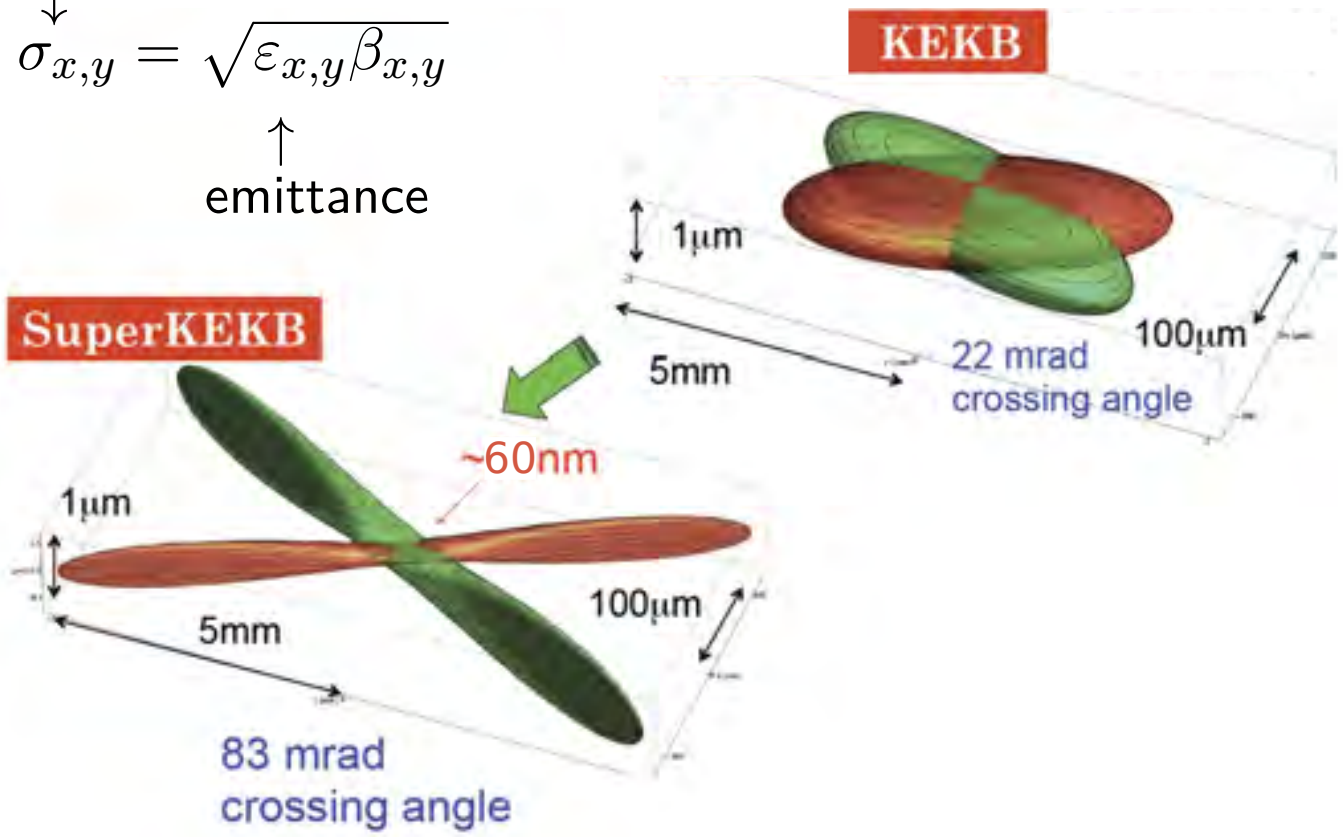
Lorentz factor ↓ $\gamma_\pm$ — beam-beam parameters ↓ $I_\pm \xi_\pm$

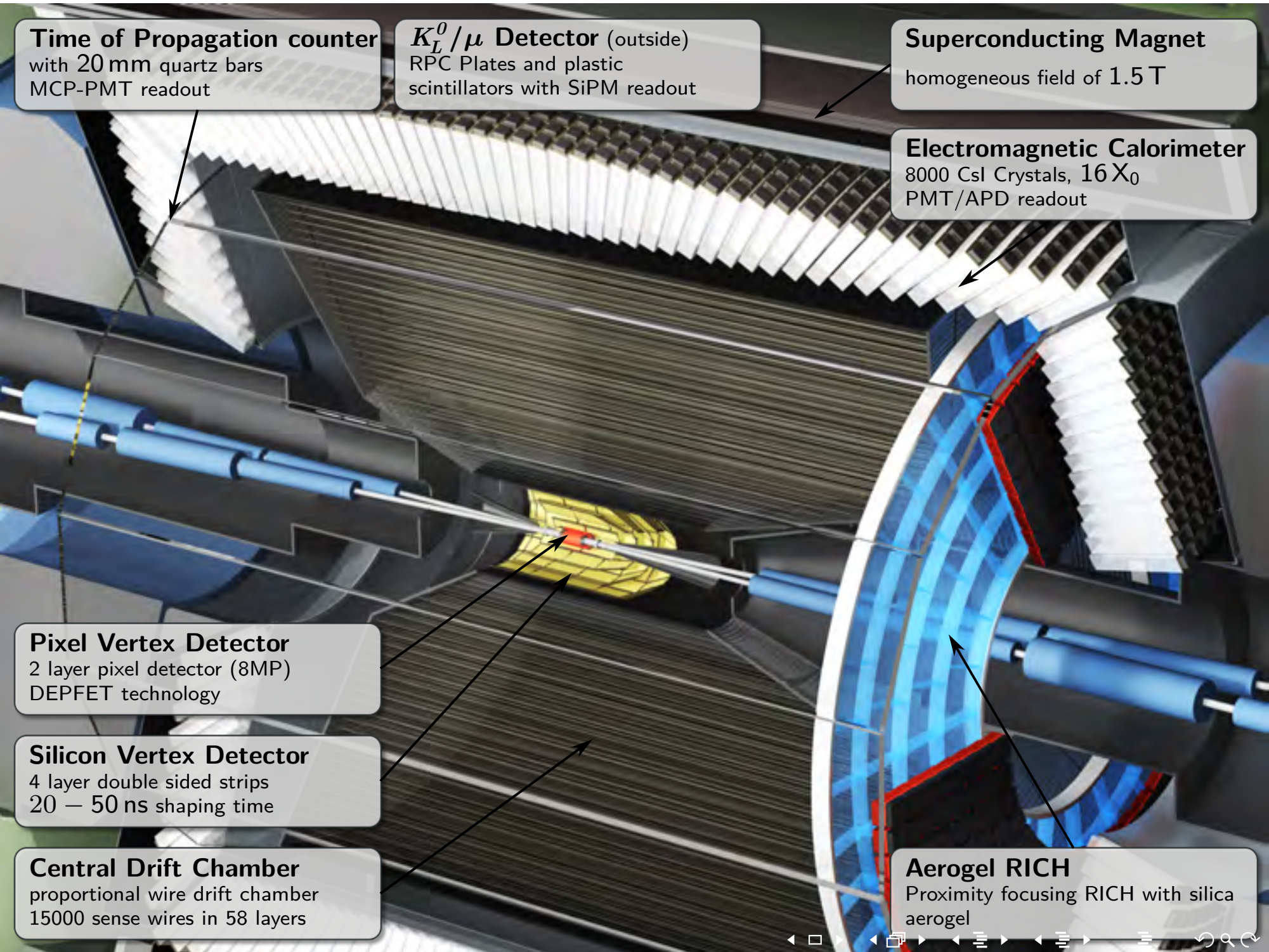
$$\mathcal{L} = \frac{\gamma_\pm}{2 e r_e} \left(1 + \frac{\sigma_y}{\sigma_x}\right) \left(\frac{I_\pm \xi_\pm}{\beta_y}\right) \left(\frac{R_L}{R_{\xi_y}}\right)$$

↑ Geometric factors

beam size ↓ $\sigma_{x,y}$ — emittance ↑ $\varepsilon_{x,y}$

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




Time of Propagation counter
with 20 mm quartz bars
MCP-PMT readout
K_L^0/μ **Detector** (outside)
RPC Plates and plastic
scintillators with SiPM readout
Superconducting Magnet
homogeneous field of 1.5 T
Electromagnetic Calorimeter
8000 CsI Crystals, $16\,X_0$
PMT/APD readout
Pixel Vertex Detector
2 layer pixel detector (8MP)
DEPFET technology
Silicon Vertex Detector
4 layer double sided strips
$20 - 50$ ns shaping time
Central Drift Chamber
proportional wire drift chamber
15000 sense wires in 58 layers
Aerogel RICH
Proximity focusing RICH with silica
aerogel

CP-Violation in the SM

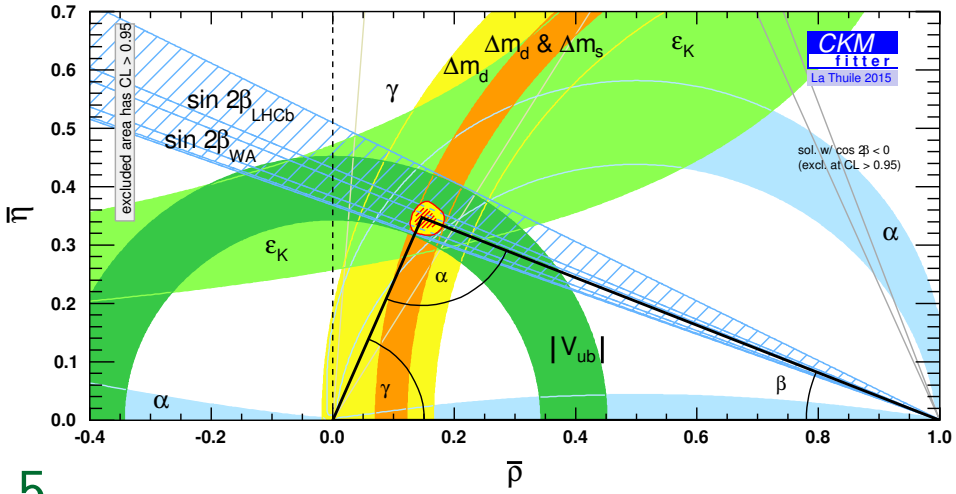
- CP-V. in the SM $\Rightarrow$ Weak Interaction $\Rightarrow$ $\mathbf{V}_{CKM}$

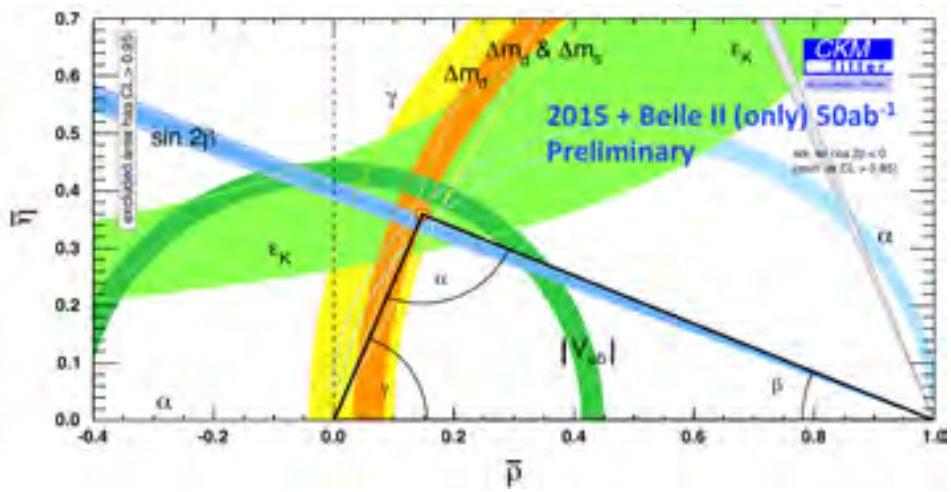
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Params: 3 Real, 1 Im.: $\lambda = \sin\theta_C \approx 0.2, A, \rho, \eta$
- Unitarity: $\sum_k V_{ki}^* V_{kj} = 0 \Rightarrow V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

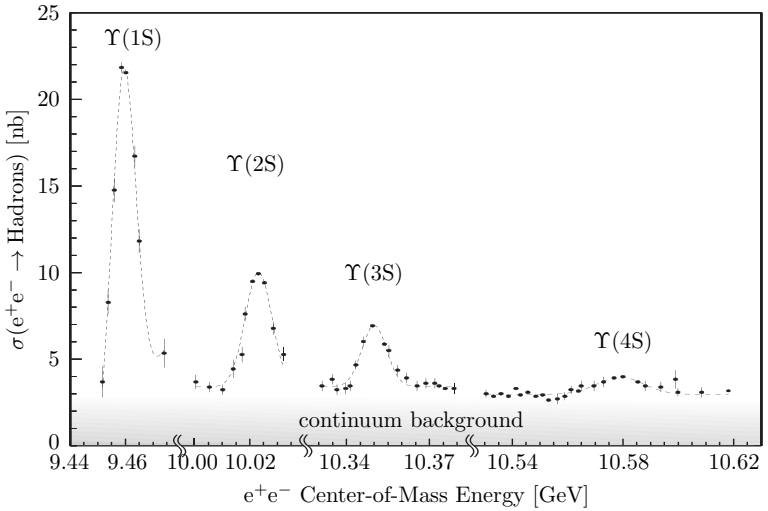
$$\mathcal{O}(\lambda^3) \quad \mathcal{O}(\lambda^3) \quad \mathcal{O}(\lambda^3)$$

$\Rightarrow$ Largest CP-V. within the SM in the B-system.



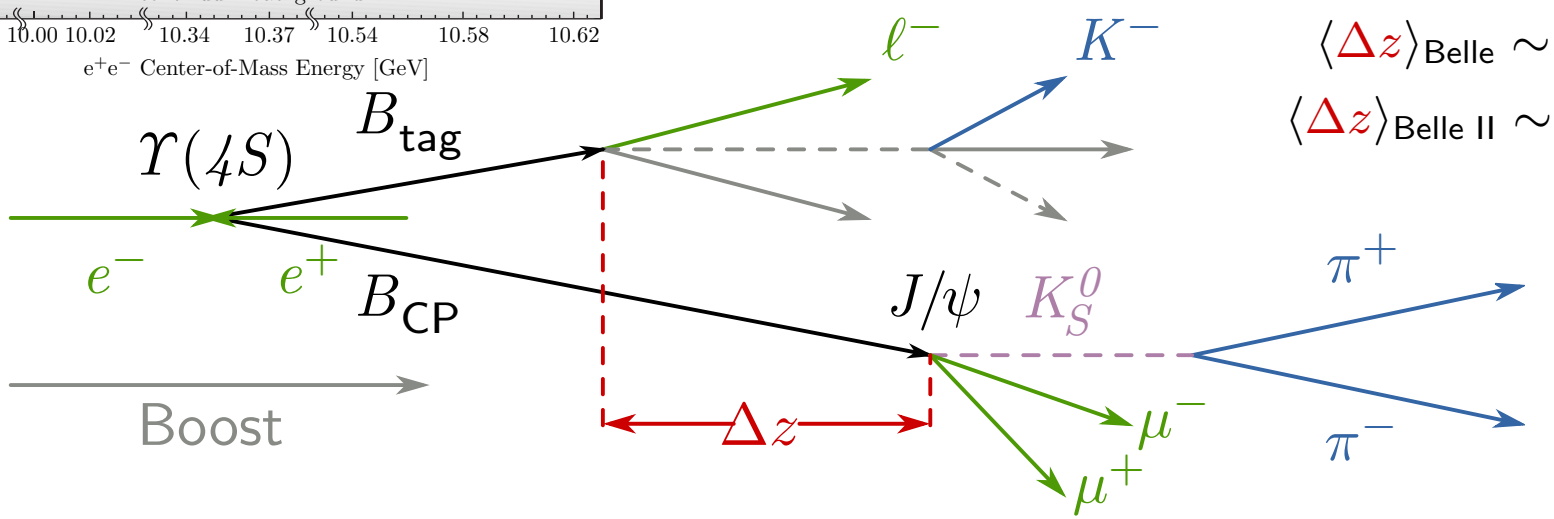


Time-dep. CP-Analysis at B-Factories



- $\Upsilon(4S)$ above $B\overline{B}$ prod. threshold
- $\Upsilon(4S) \to B\overline{B} > 96\ \%$
- $\frac{\Gamma(B^+B^-)}{\Gamma(B^0\overline{B}^0)} \sim 1.06$

$\Rightarrow$ B-Factory



$\langle \Delta z \rangle_{\text{Belle}} \sim 200\ \mu\text{m}$

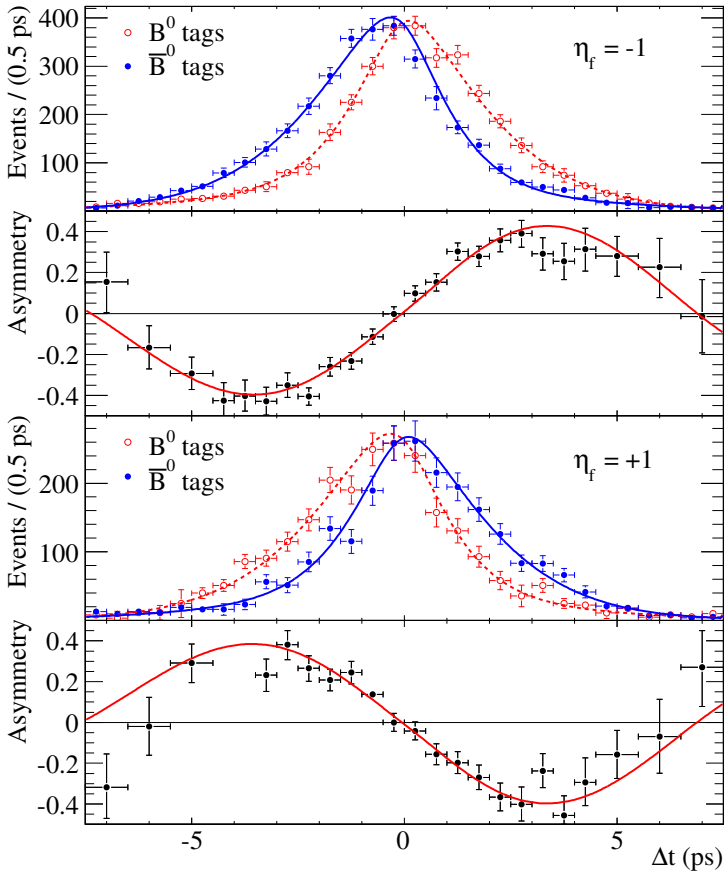
$\langle \Delta z \rangle_{\text{Belle II}} \sim 130\ \mu\text{m}$

$\Rightarrow$ $\Delta t = \frac{\Delta z}{\langle \beta\gamma \rangle c}$ since $B^0\overline{B}^0$ at rest in $\Upsilon(4S)$ frame

$q_{B^0,\overline{B}^0} = 1, -1$

$$\mathcal{P}^{\text{Sig}}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[1 + q\left(\mathcal{A}_{CP}\cos(\Delta m \Delta t) + \mathcal{S}_{CP}\sin(\Delta m \Delta t)\right)\right]$$

Time-dependent CP-Asymmetry



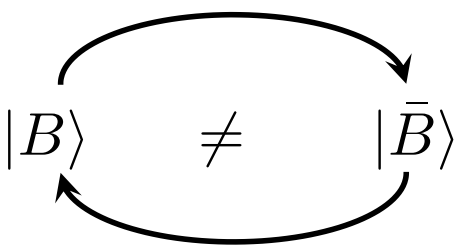
$$a_{\mathrm{CP}} = \frac{N\left(B^0,\ \Delta t\right) - N\left(\overline{B}^0,\ \Delta t\right)}{N\left(B^0,\ \Delta t\right) + N\left(\overline{B}^0,\ \Delta t\right)}$$
$$= \mathcal{A}_{CP}\cos(\Delta m \Delta t) + \mathcal{S}_{CP}\sin(\Delta m \Delta t)$$

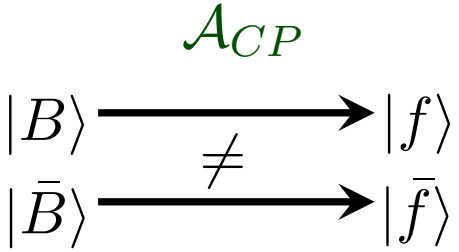
$\mathcal{A}_{CP}$: Direct CP Violation:

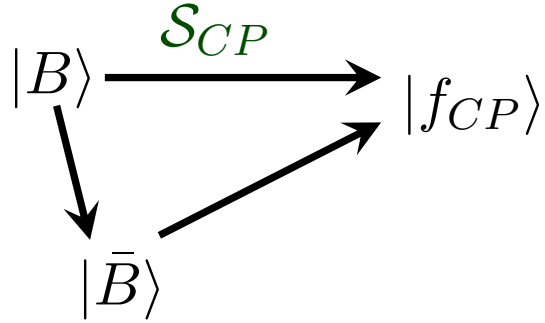
$$A = \langle f|B^0\rangle \neq \langle \bar{f}|\overline{B}^0\rangle = \bar{A}$$

$\mathcal{S}_{CP}$: Mixing-induced CP Violation:

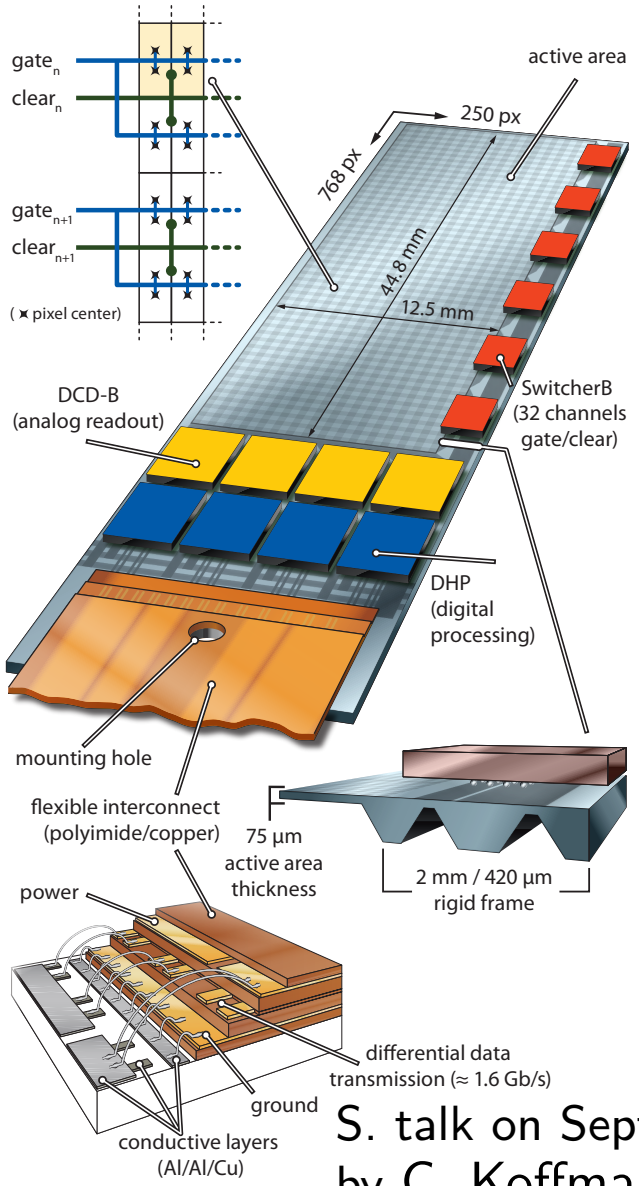
$$J/\psi\ K_S^0 \Rightarrow\ \mathcal{A}_{CP} = 0$$
$$\mathcal{S}_{CP} = \sin(2\beta)$$

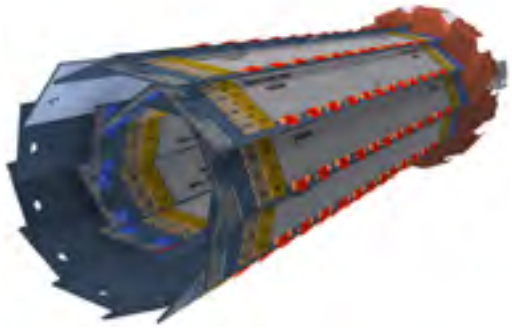


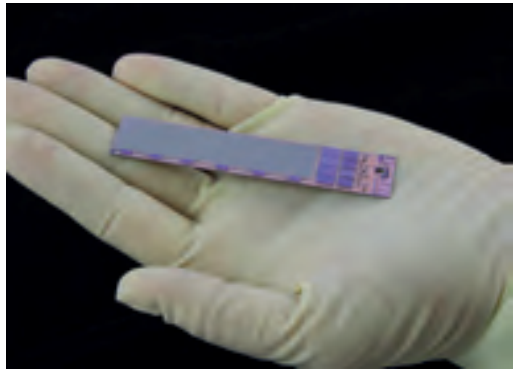




DEPFET Pixel Vertex Detector







- Inst. Lumi.: $\mathcal{L}_{\text{Belle II}} \sim 40 \cdot \mathcal{L}_{\text{Belle}}$

$\Rightarrow$ Background $\uparrow\uparrow\uparrow$

- Closest to IP

$\Rightarrow$ Occupancy $(\sim r^{-2})$ $\uparrow\uparrow\uparrow$

- $\langle\beta\gamma\rangle_{\text{Belle II}} < \langle\beta\gamma\rangle_{\text{Belle}}$

$\Rightarrow$ smaller Δz

$\Rightarrow$ Pixel Detector needed !

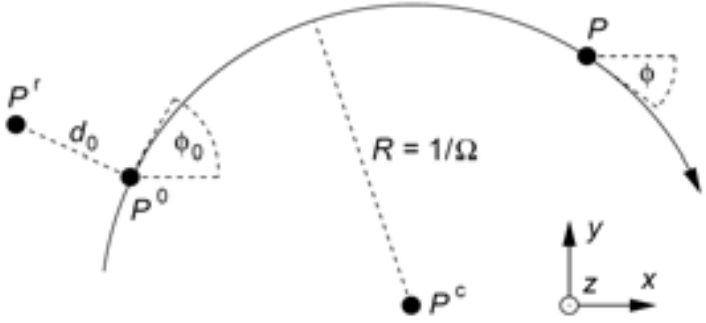
$\Rightarrow$ DEPFET Technology most suited
DEPleted Field Effect Transistor

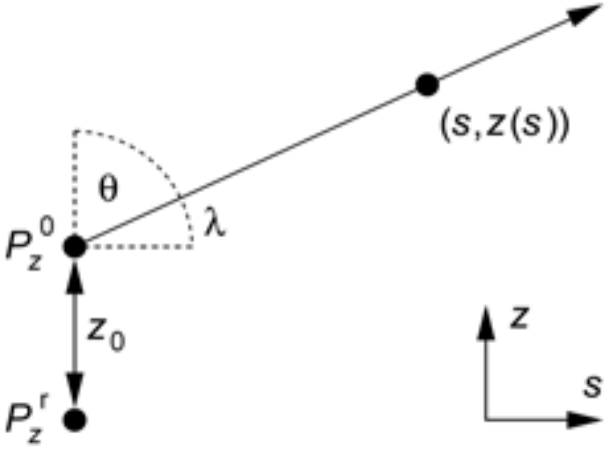
S. talk on Sept 5
by C. Koffmane

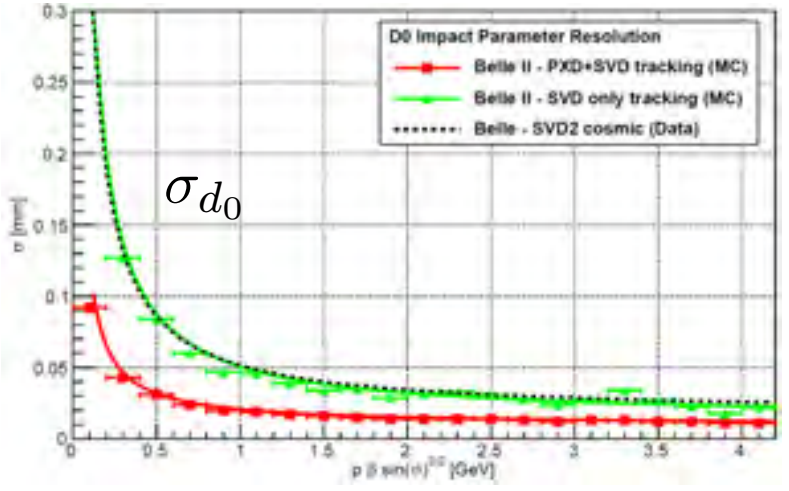
The Impact Parameter

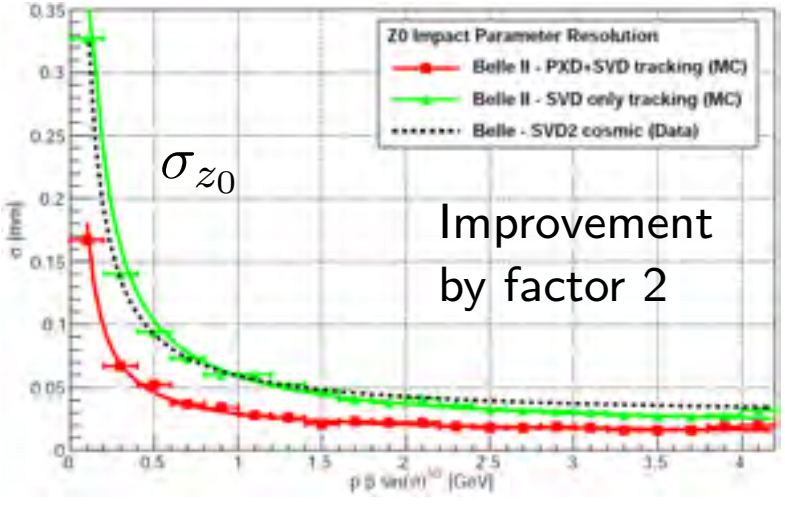
Particle track parametrization $\Rightarrow \vec{t}(d_0,\ \phi_0,\ \Omega = \frac{q}{p_t},\ z_0,\ \tan(\lambda))$

- $d_0(z_0)$: distance between point of closest approach and IP.

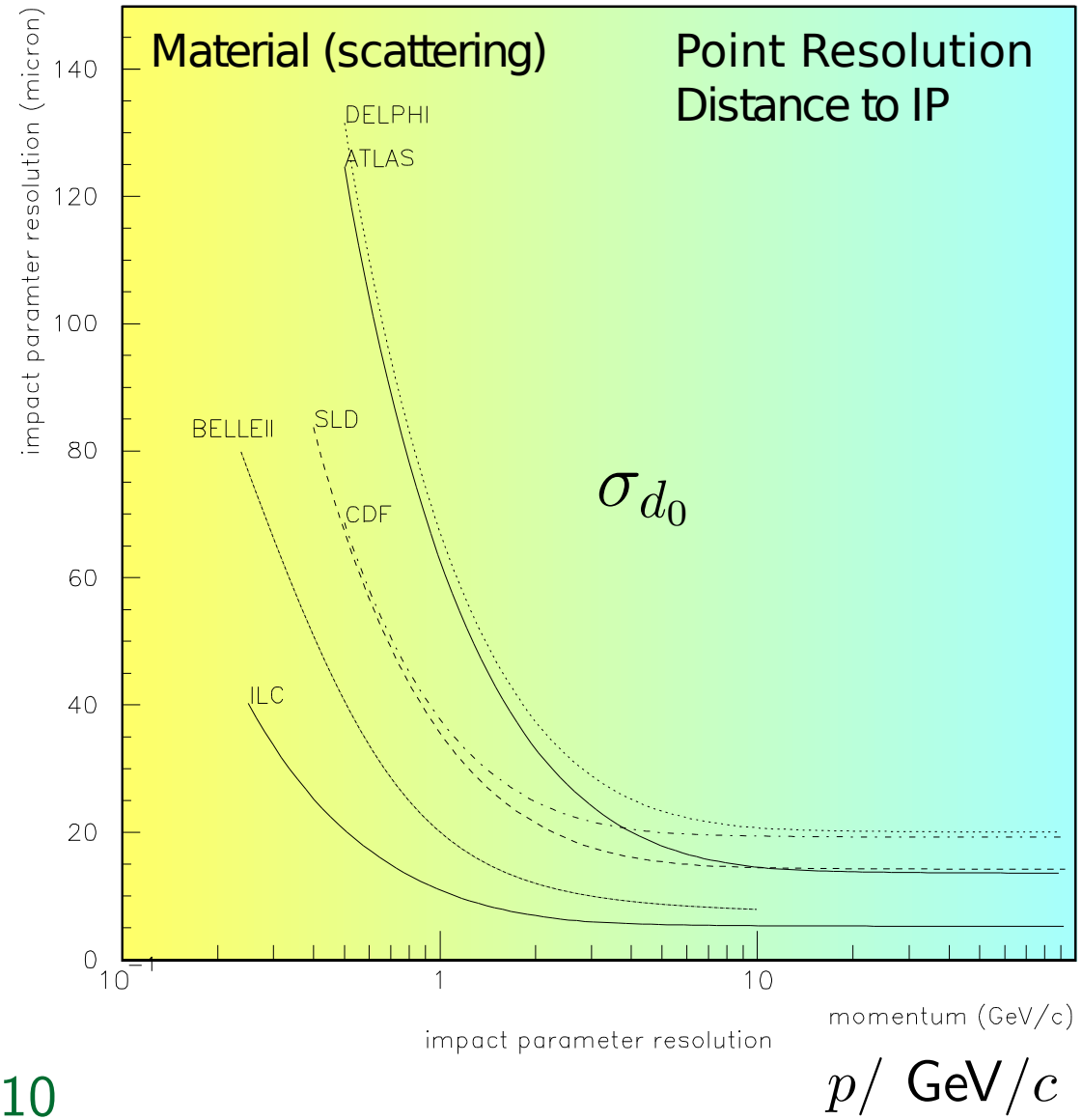








DEPFET Pixel Vertex Detector



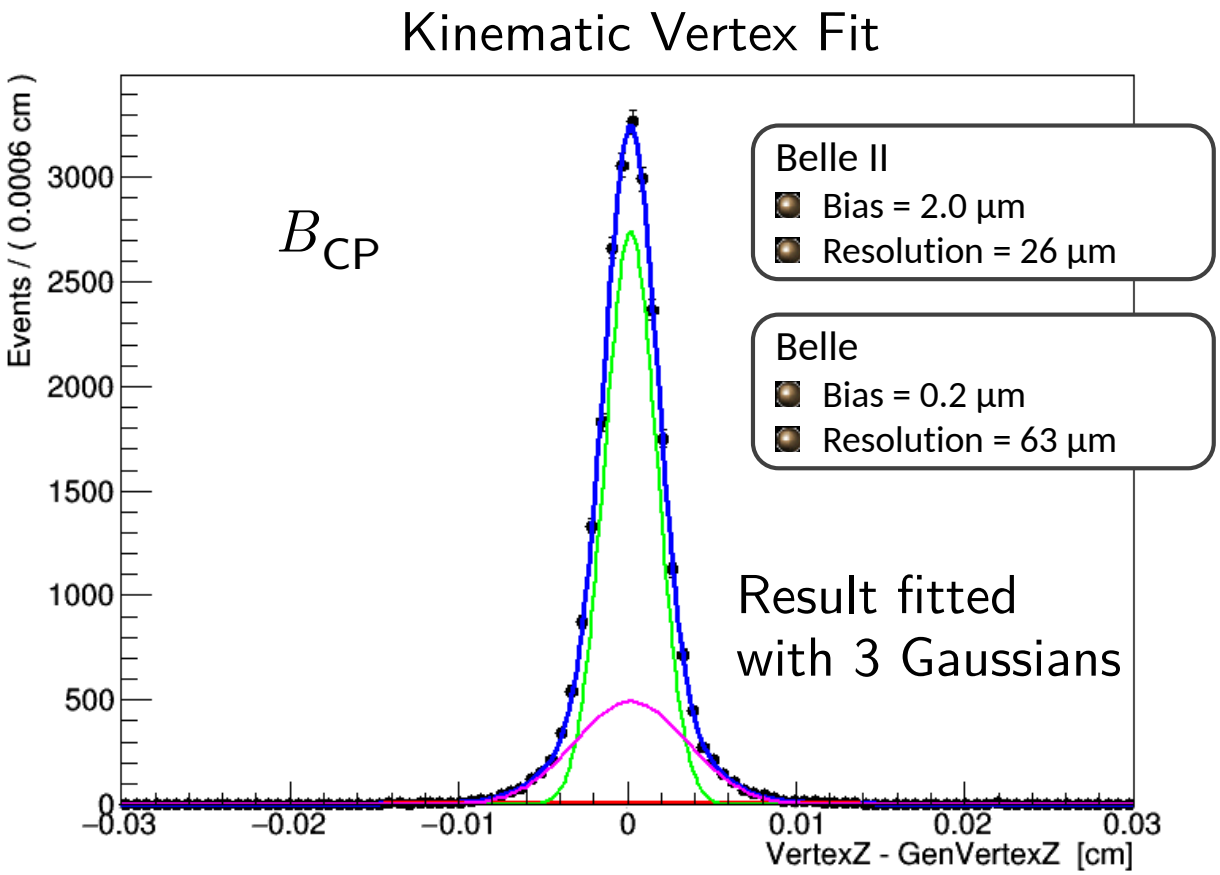
- Mult. Scattering:

$$\Delta\phi \sim \sqrt{\frac{X}{X_0}}$$

$\Rightarrow$ Low material budget required!

B_{CP} Vertex

- $B_{\mathrm{CP}} \to J/\psi\ K_S^0$
- $K_S^0 \to \pi^+\pi^-,\ \pi^0\pi^0$: Decay outside of PXD. ✗
- $J/\psi \to \mu^+\mu^-$: Both muons have at least on PXD hit. ✓

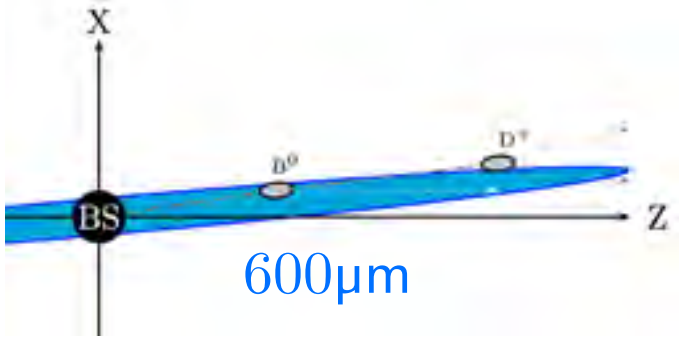


B_{tag} Vertex Resolution

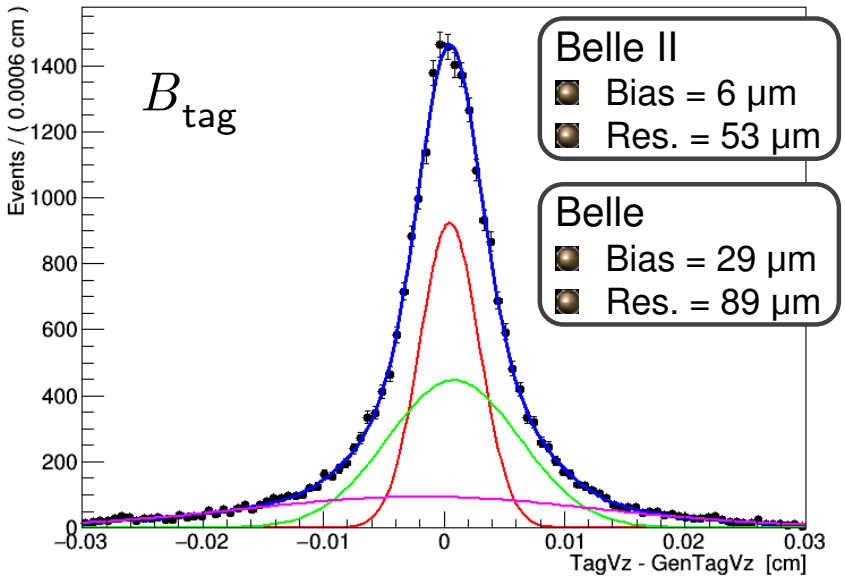
Algorithm: Adaptive Vertex Fit (AVF)
CMS NOTE 2008/033

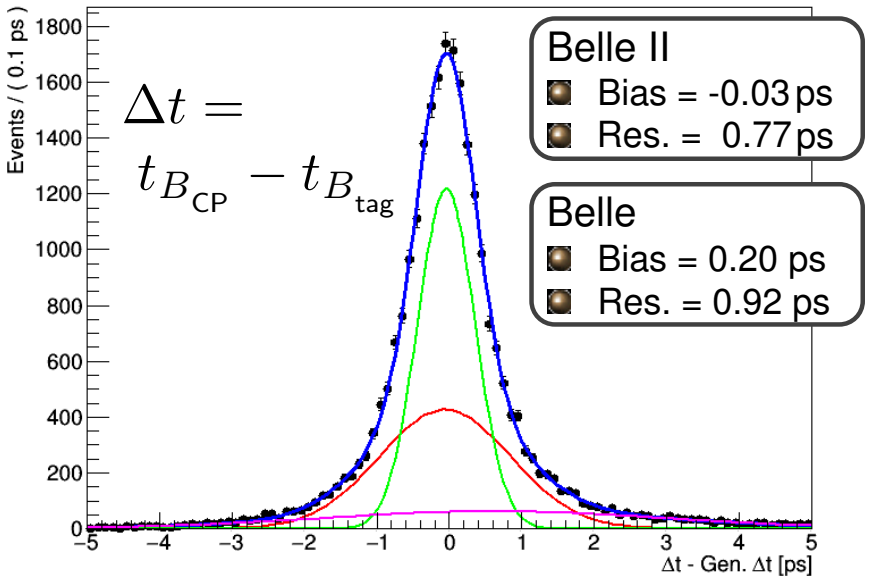
Access: RAVE (Reconstruction in a Abstract, Versatile Environment)

- Track weighting according to proximity to other tracks and spatial constraint.



- ✂ on K_S^0 Tracks.



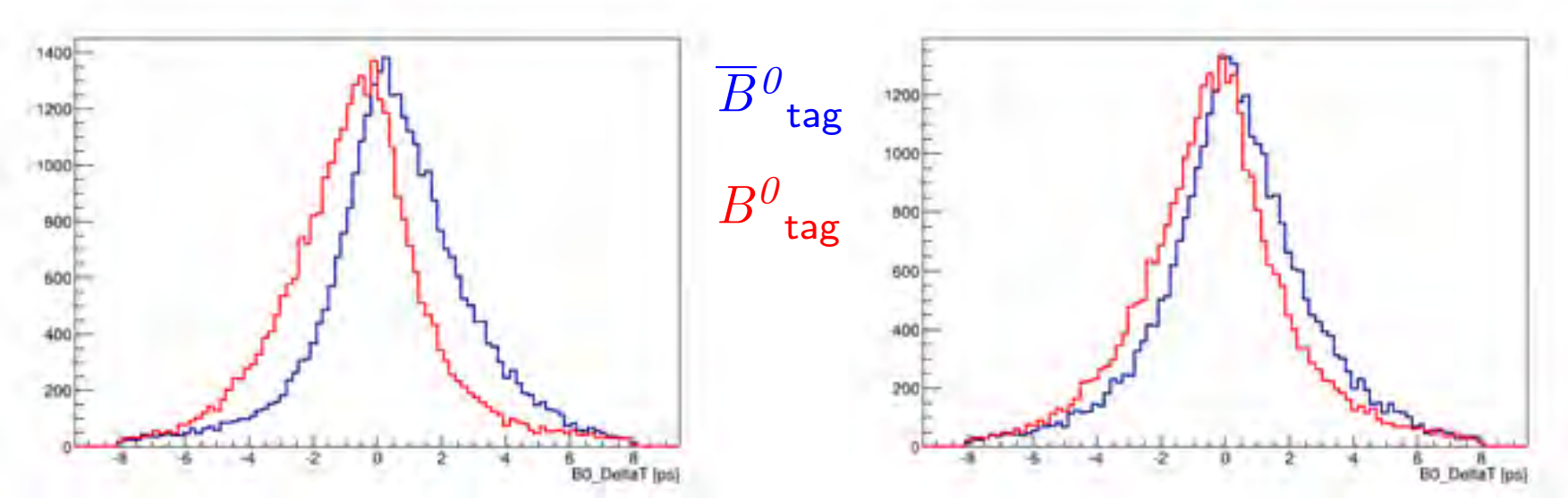


Δt Distribution

MC Analysis $B_{\text{CP}} \to J/\psi K_S^0$

a) q_{MC} truth, $\varepsilon_{\text{Eff}} = 100\ \%$

b) q tagged, $\varepsilon_{\text{Eff}} = 35.5\ \%$



Impact on $\mathcal{P}(\Delta t, q, r)$:

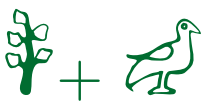
$$\mathcal{P}^{\text{Obs}}(\Delta t, q) = \frac{e^{-|\Delta t|\tau_{B^0}}}{4\tau_{B^0}} \left[1 + q \cdot r \left(\mathcal{A}_{CP} \cos(\Delta m \Delta t) + \mathcal{S}_{CP} \sin(\Delta m \Delta t)\right)\right]$$

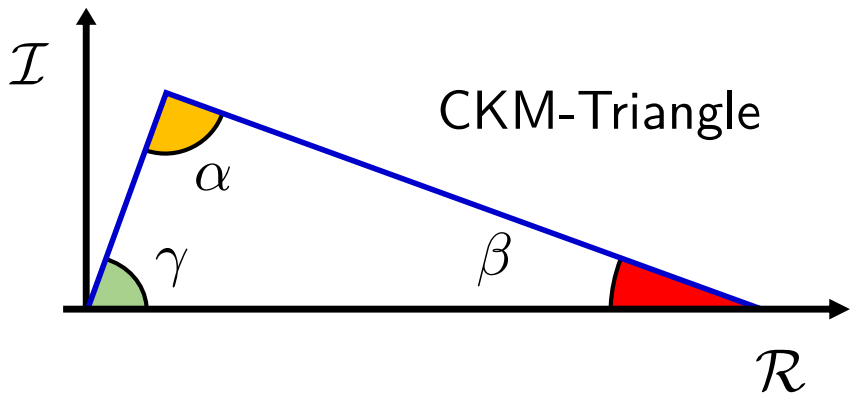
$\varepsilon_{\text{Eff}}(\text{Belle}) = 29\ \%$

Time-dependent CP-Analysis

- For $B \to \pi\pi$: tree and penguin diags. contribute!

 : $\mathcal{A}_{CP} = 0$
$\mathcal{S}_{CP} = \sin(2\alpha)$

 : $\mathcal{A}_{CP} \neq 0$
$\mathcal{S}_{CP} = \sqrt{1 - \mathcal{A}_{CP}}\sin(2\alpha^{\text{eff}})$
$\Rightarrow \alpha^{\text{eff}} = \alpha - \Delta\alpha$

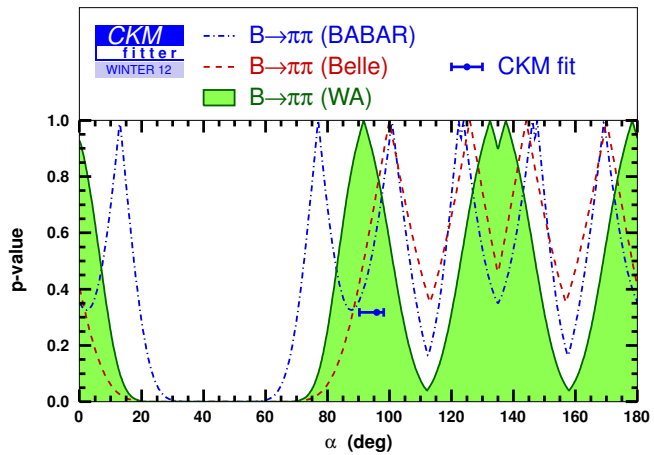


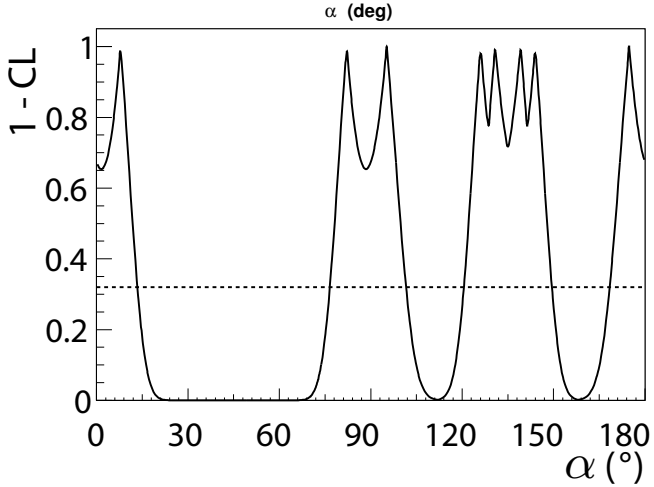
- Extr. of $\Delta\alpha$ through isospin $\mathcal{S}_{\pi^0\pi^0}$.
- $\mathcal{S}_{\pi^0\pi^0}$ needs $\langle\Delta z\rangle \sim 130\mu\text{m}$ of $B \to \pi^0\pi^0$ where $\pi^0 \to \gamma\gamma$

$\Rightarrow$ Challenge!

Extraction of α angle from $B \to \pi\pi$

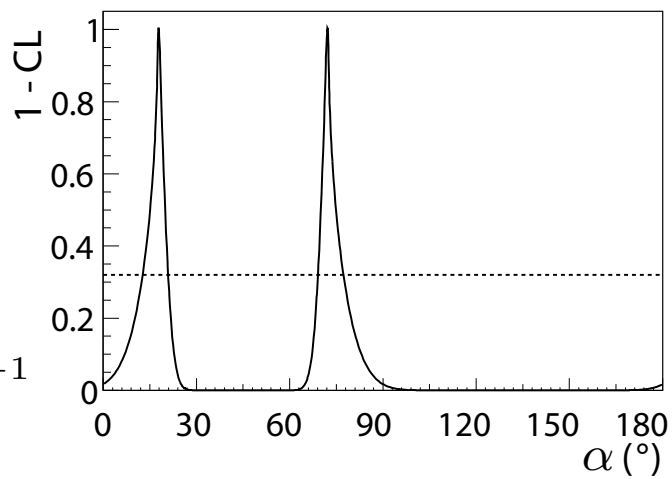
- w/out $\mathcal{S}_{\pi^0\pi^0} \Rightarrow$
  8 fold ambiguity on α



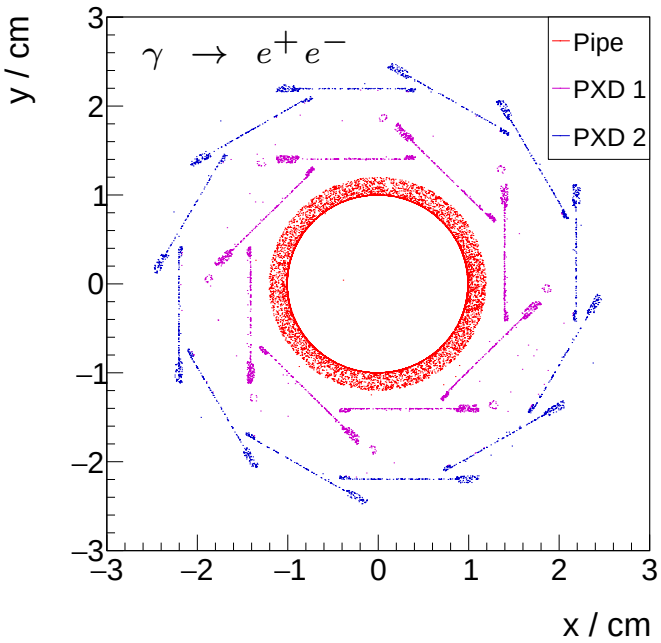


- with $\mathcal{S}_{\pi^0\pi^0} \Rightarrow$
  2 fold ambiguity on α
- Converted $\gamma \to e^+e^-$ and $\pi^0 \to e^+e^-\gamma$ req. for $\langle \Delta z \rangle$
- Possible with
  $\mathcal{L}_{\text{Belle II}} = 50 \cdot \mathcal{L}_{\text{Belle}}$ and
  Belle II PXD?

Extrapolated to
$\mathcal{L}_{\text{Belle II}} = 50\text{ab}^{-1}$
arXiv:hep-ex/0703029



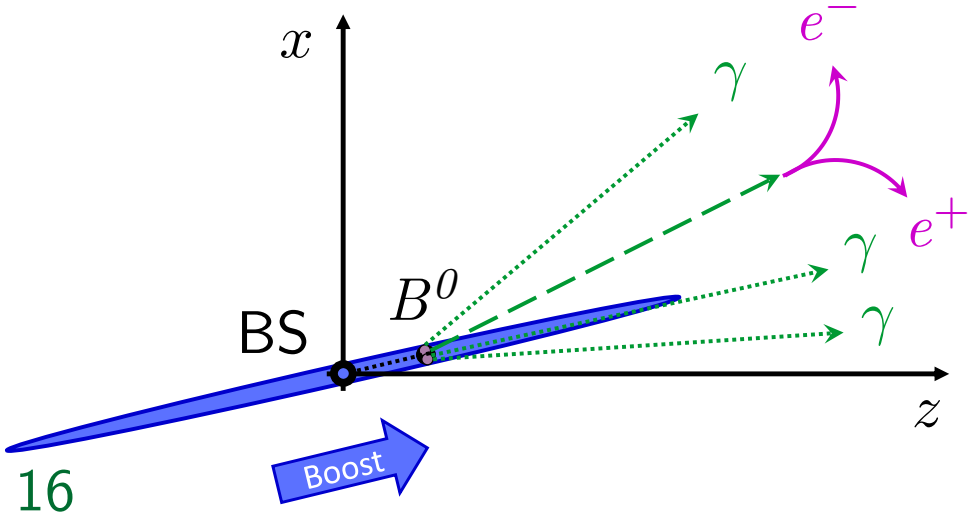
$B^0{}_{\mathrm{CP}}$ Vertex Reconstruction



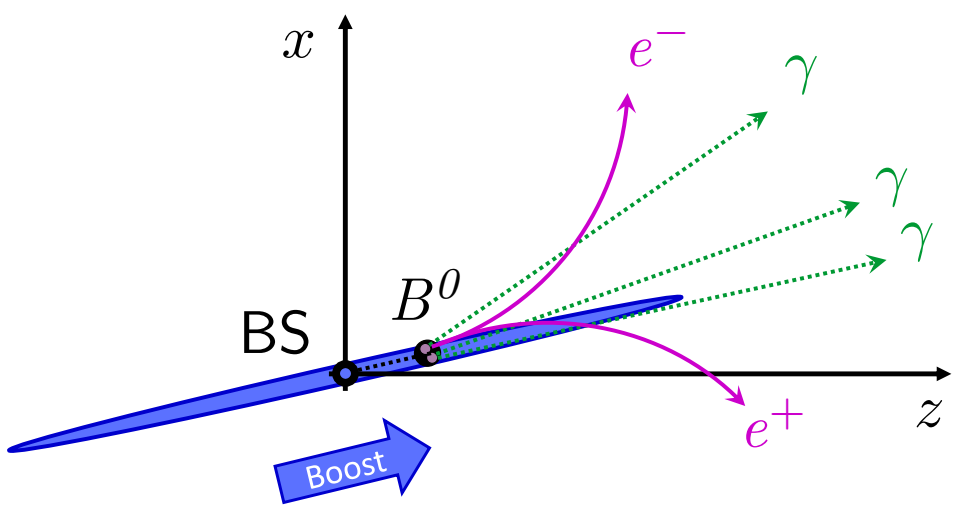
- $\tau_{\pi^0} \sim 0.9$ as $\cong$ 0.1 nm

$\Rightarrow$ π^0 Vertex $\hat{=}$ B^0 Vertex.

- Kinematic Vertex Fit with spatial constraint centered at the Beam Spot.

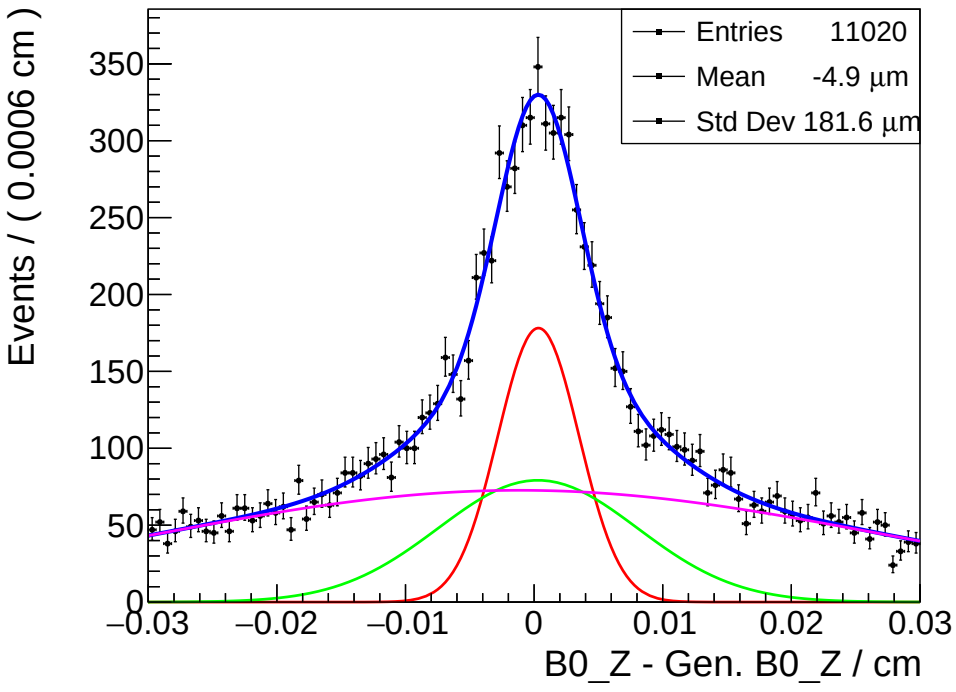


$\pi^0 \rightarrow e^+e^-\gamma$

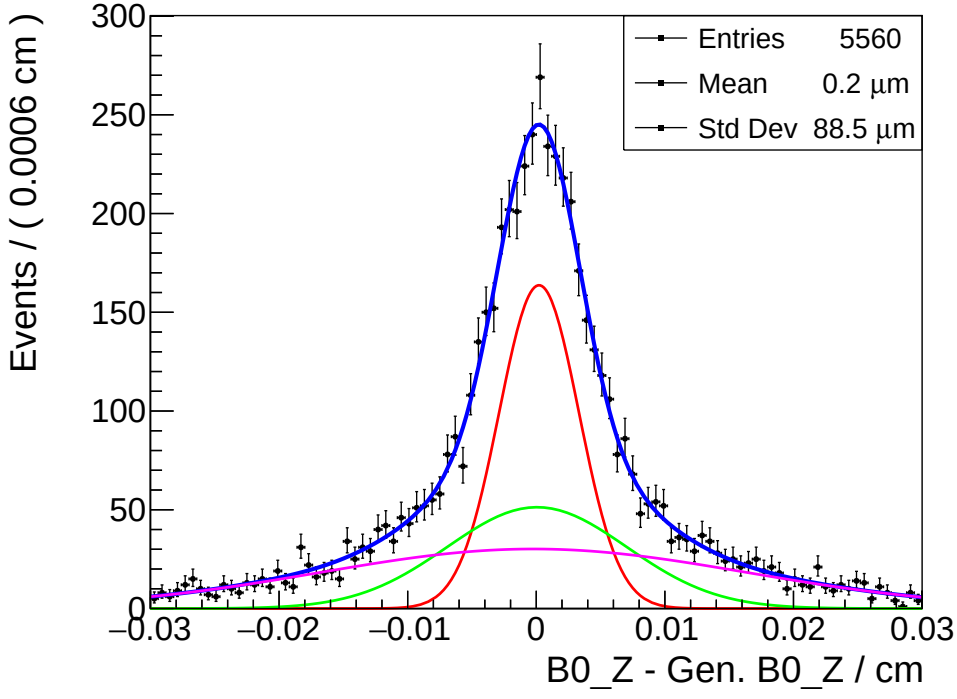


B^0 z-Vertex Resolution

$$B^0 \rightarrow \pi^0 \pi^0$$
$$\hookrightarrow \gamma \gamma$$
$$\hookrightarrow e^+ e^-$$



No PXD Hit required

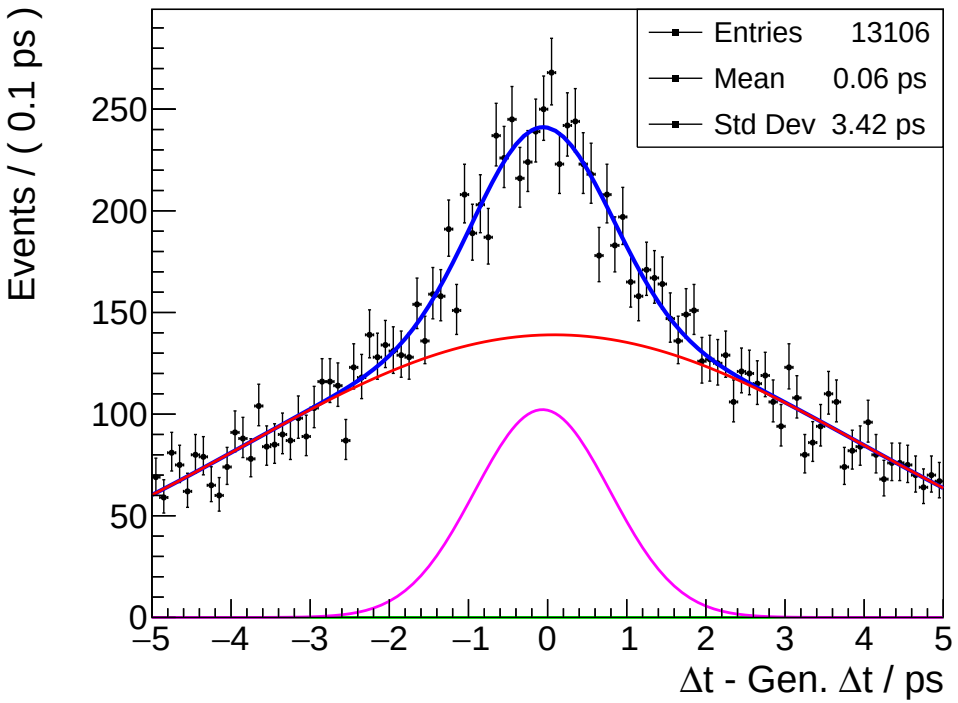


At least one track (e^+ or e^-) has one PXD Hit

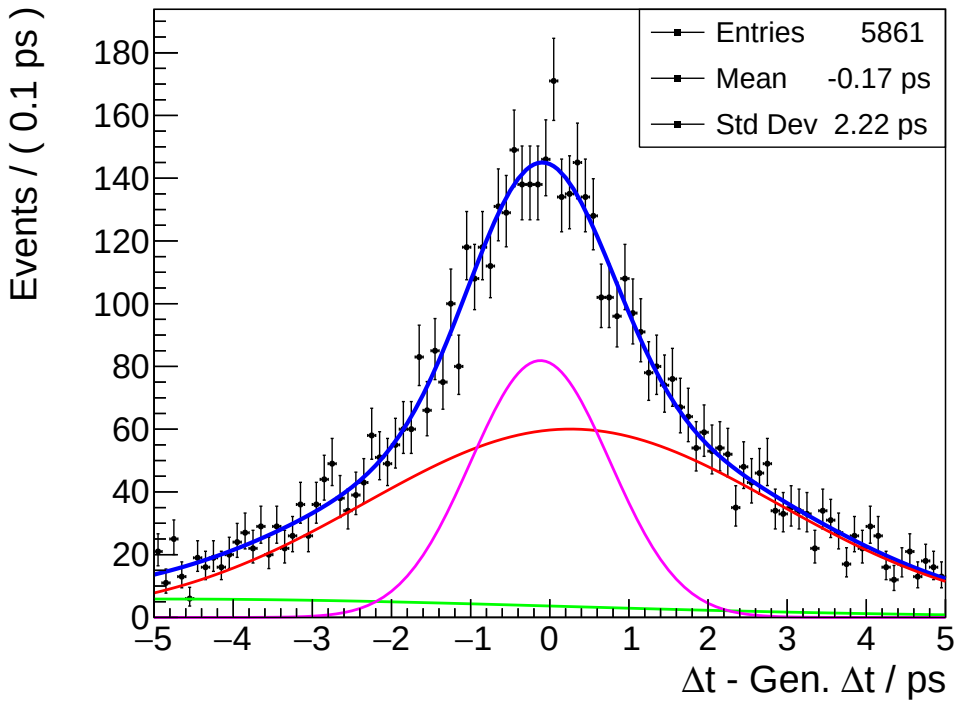
Δt Resolution

$$\Delta t = t_{B^0\,\text{CP}} - t_{B^0\,\text{tag}}$$

$$B^0{}_{\text{CP}} \to \pi^0\ \pi^0$$
$$\hookrightarrow \gamma\ \gamma$$
$$\hookrightarrow e^+ e^-$$



No PXD Hit required

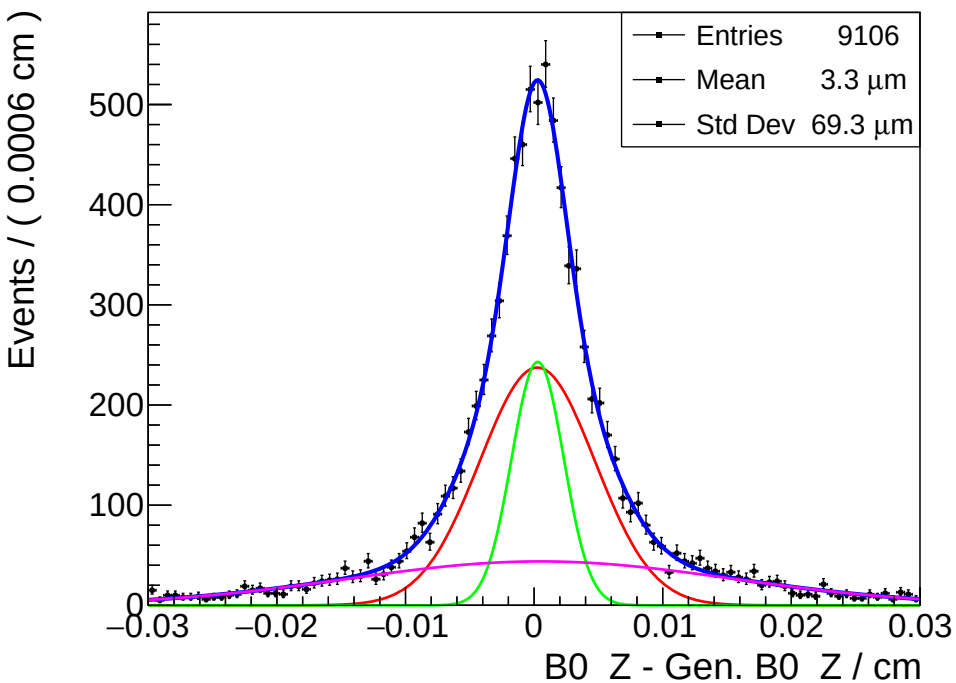


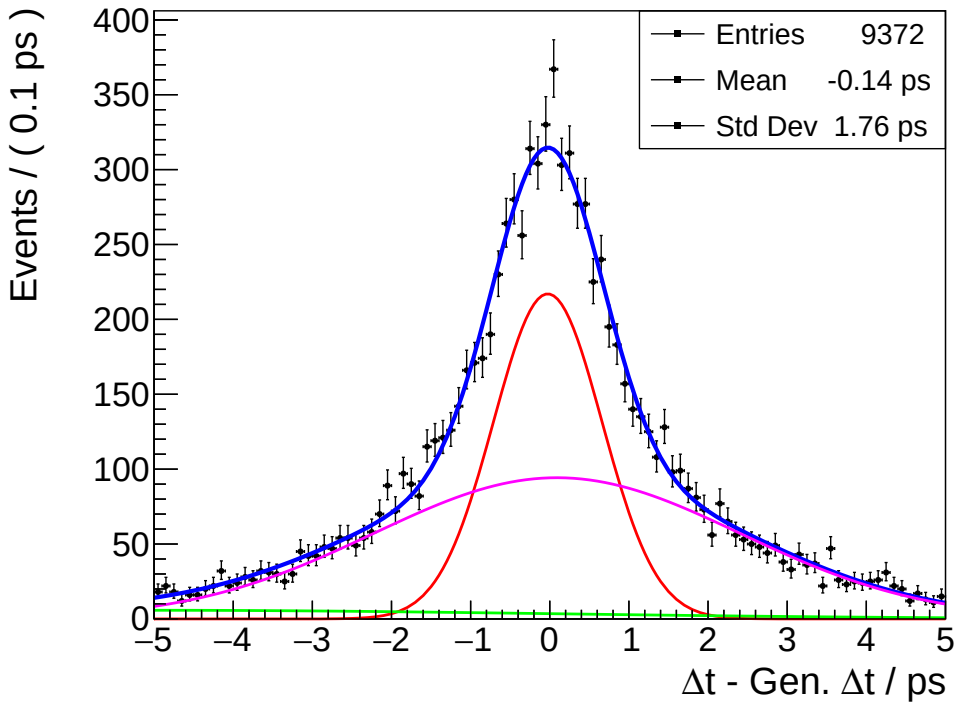
At least one track (e^+ or e^-) has one PXD Hit

Δt Resolution

$$B^0{}_{\mathrm{CP}} \to \pi^0 \pi^0$$
$$\hookrightarrow e^+ e^- \gamma$$

$$\Delta t = t_{B^0{}_{\mathrm{CP}}} - t_{B^0{}_{\mathrm{tag}}}$$





Summary and Outlook

- Upgrade of KEK to SuperKEKB:
  Boost reduction, Background increase,
  required maintenance of vertex resolution.

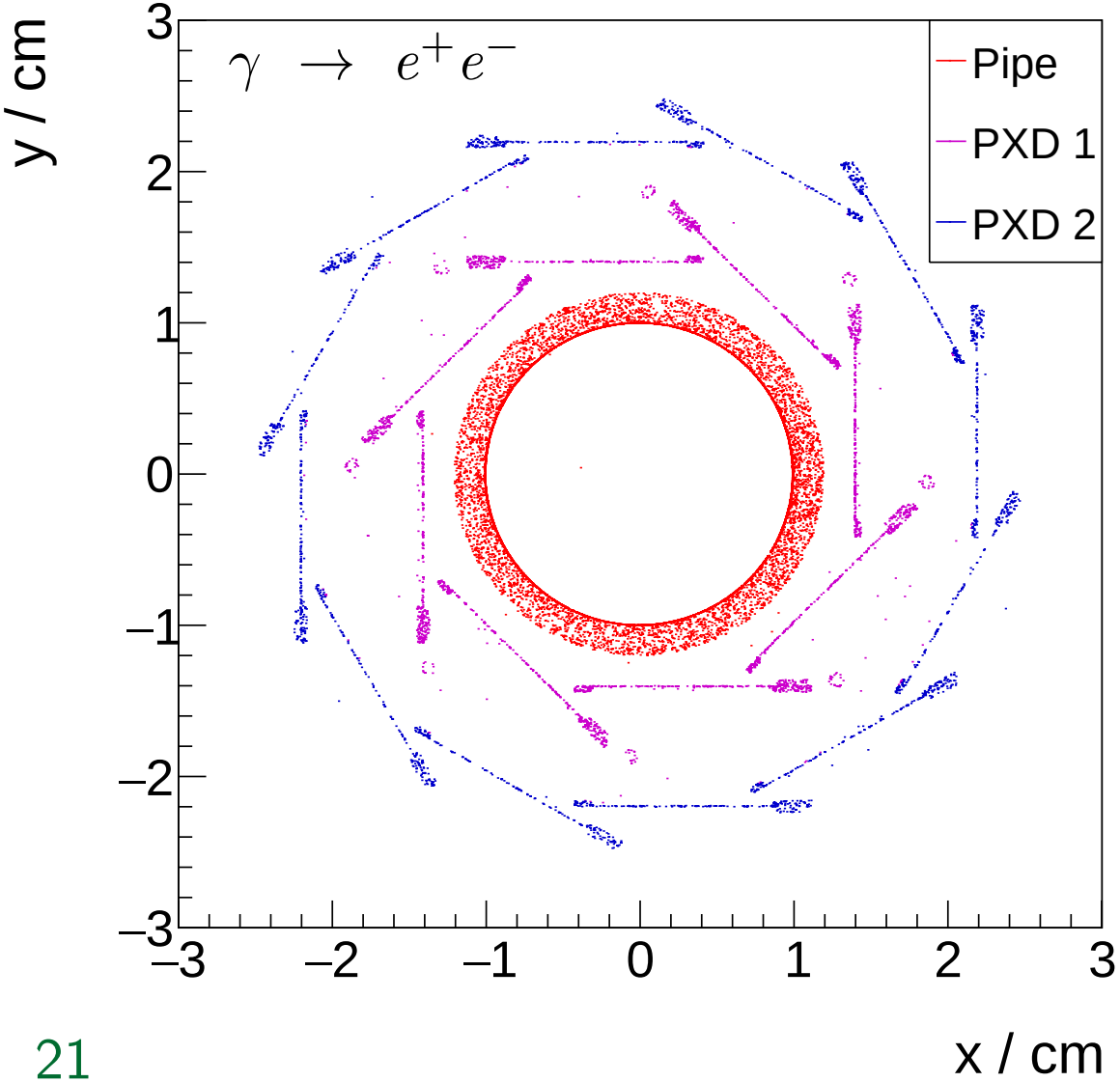
$\Rightarrow$ New DEPFET Pixel Vertex Detector (PXD) for Belle II.

- PXD is crucial for the Belle II physics programm.
- Impact of the PXD is studied with Monte Carlo Simulations:

$\Rightarrow$ Belle II Δt resolution is higher although $\langle \beta\gamma \rangle$ has been decreased!

- Machine commissioning started! Begin of data taking planned for 2018!

Vertex of γ-Conversions in $B^0 \to \pi^0\pi^0$



- $\Upsilon(4S) \to B^0{}_1 B^0{}_2 \to$
  $B_1 \to$ generic
  $B_2 \to \pi^0\pi^0$
- $\pi^0 \to \gamma\gamma \quad (\mathcal{B} = 98.82\%)$
- $\pi^0 \to e^+e^-\gamma \ (\mathcal{B} = 1.17\%)$
- $N_{\text{Belle II}} =$

$$\begin{aligned} \mathcal{L}_{\text{Belle II}} &\cdot \mathcal{B}(\Upsilon(4S) \to B^0\overline{B}^0) \\ &\cdot 2 \cdot \mathcal{B}(B^0 \to \pi^0\pi^0) \sim \\ 50\text{ab}^{-1} &\cdot 1.1\text{nb} \cdot 0.49 \\ &\cdot 2 \cdot 1.91 \cdot 10^{-6} \end{aligned}$$

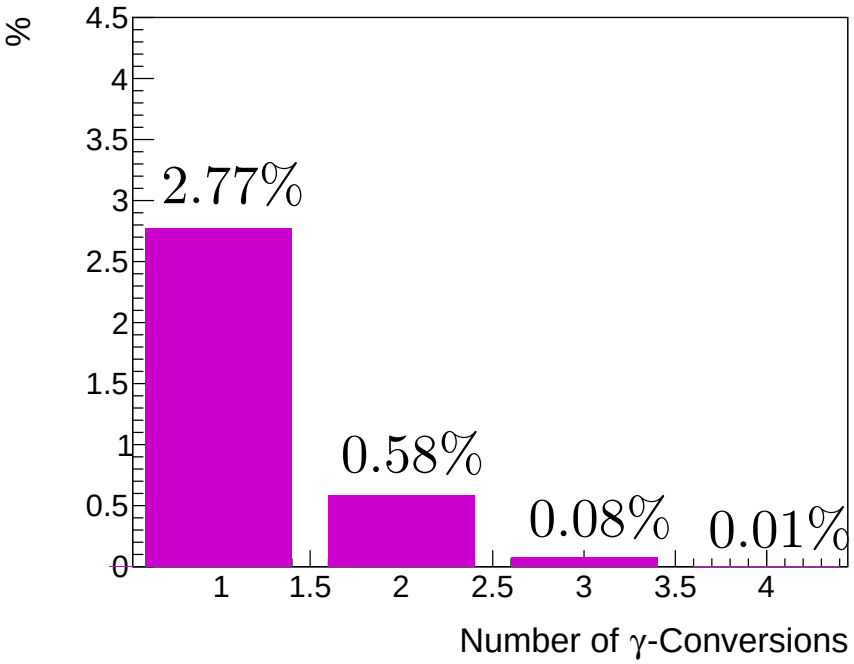
~ 100k events.

- Accept.: $\theta \in [17, 150]^\circ$
- ECL: $\theta \in [12.4, 155.1]^\circ$

Events with γ-Conversions

a) If there is an event with γ-conversions

$\Rightarrow$ How Many?



b) How many Events have at least one γ-conversion?

Vertex in	Events %
Beam Pipe	2.00 %
1st. PXD Layer	0.60 %
2nd. PXD Layer	0.50 %
Total inside PXD	3.10 %

c) ... and at least one γ-conversion or one $\pi^0 \to e^+e^-\gamma$ decay?

$\pi^0 \to e^+e^-\gamma$	2.00 %
Total $\pi^0 \cup \gamma$	5.05 %

Requirement: All converted γ in accept. and not converted in ECL

e^+, e^- Track Reconstruction

- e^+, e^-