Sensitivity Study for $\mathrm{B}^0 \to \pi^0\pi^0$

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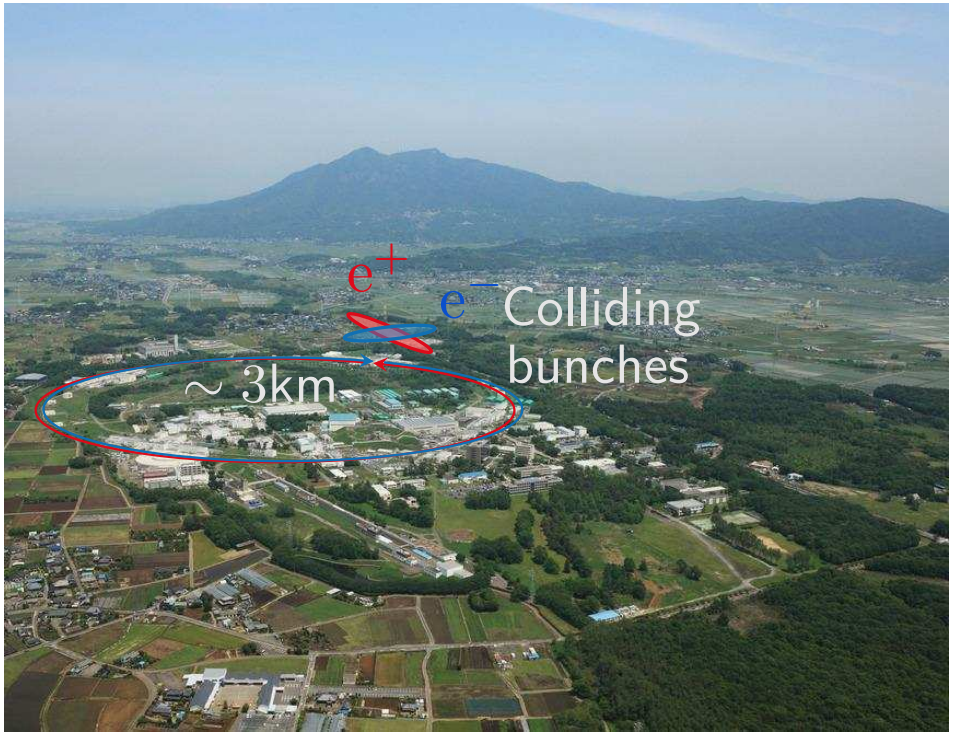
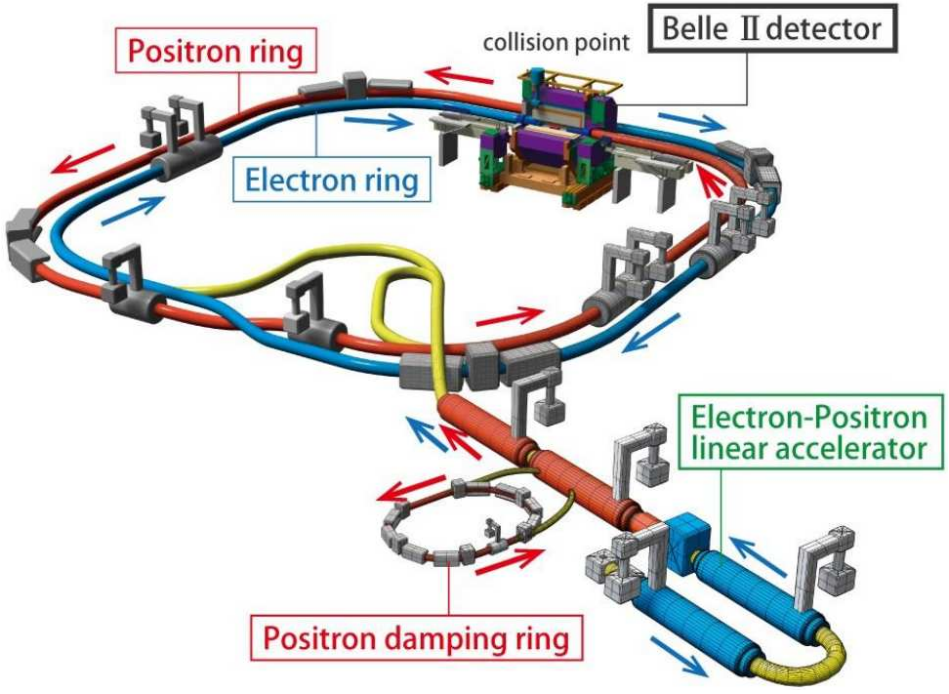
June 7, 2016

KEKB/SuperKEKB Collider

Upgrade: KEKB $\Rightarrow$ SuperKEKB

Belle $\Rightarrow$ Belle II



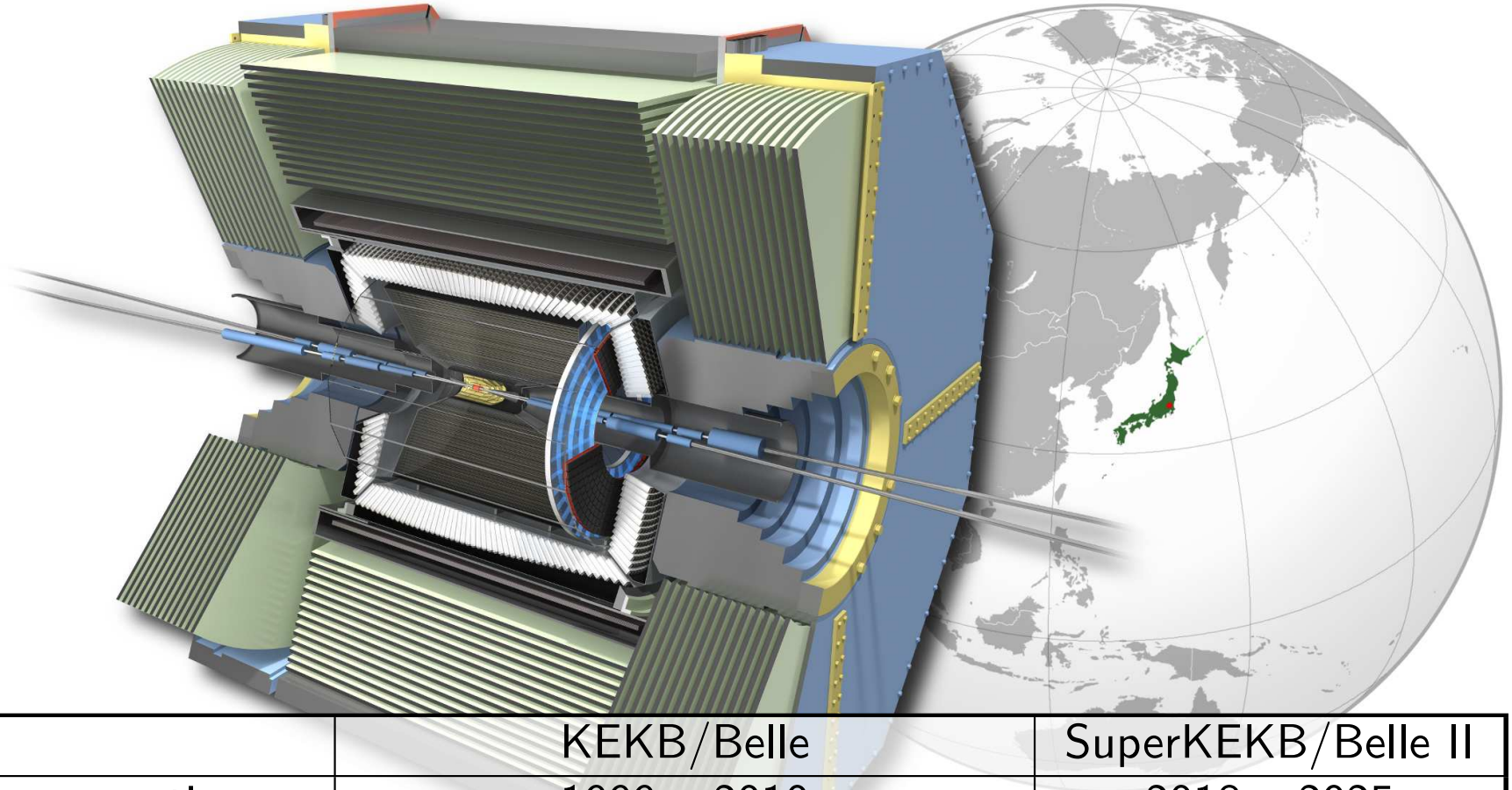


KEK = kō enerugī kasokuki kenkyū kikō

high energy collider research organization

At: Tsukuba, Ibaraki Prefecture, Japan

Belle/Belle II Experiment



	KEKB/Belle	SuperKEKB/Belle II
operation	1999 – 2010	2018 – 2025
e^-/e^+ beam E	$8/3.5$ GeV	$7/4$ GeV
e^-/e^+ beam I	$1.2/1.6$ A	$2.6/3.6$ A
Inst. Lumi. $\mathcal{L}$	$2.11 \cdot 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$	$8 \cdot 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
$\int \mathcal{L} \cdot dt$	$1023\,\mathrm{fb}^{-1}$ ($772 \cdot 10^6$ B $\overline{\mathrm{B}}$ pairs)	$50\,\mathrm{ab}^{-1}$

Nano Beam Scheme

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

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

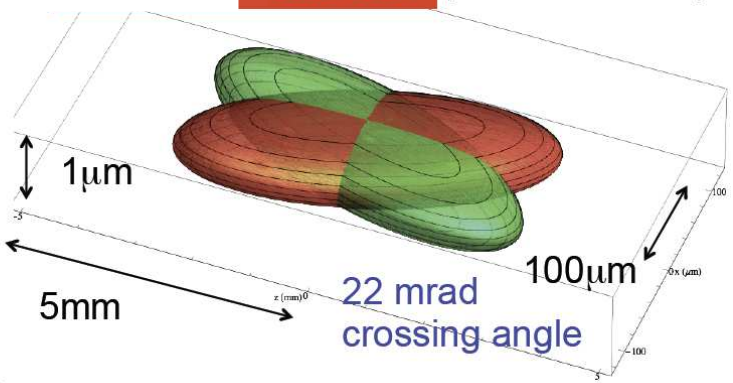
Geometric factors ↑ R_{ξ_y}

beam size ↓ $\sigma_{x,y}$

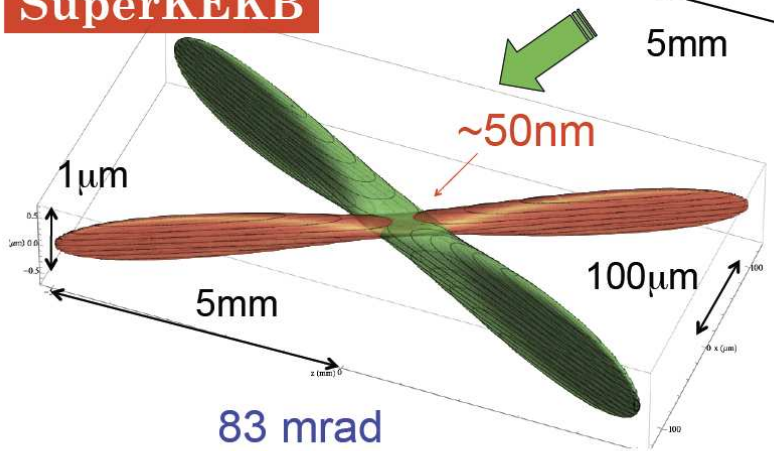
$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y} \beta_{x,y}}$$

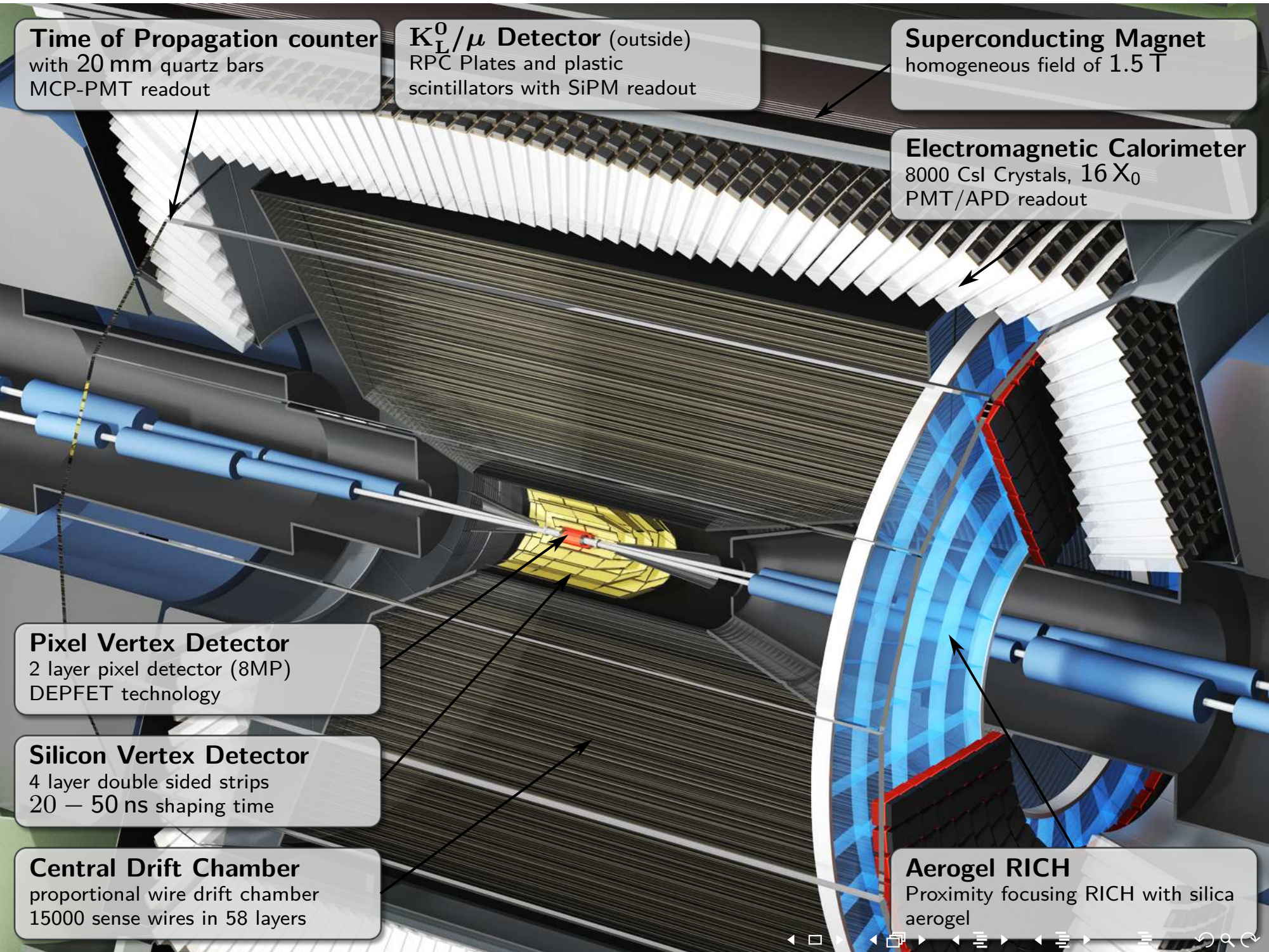
emittance ↑ $\varepsilon_{x,y}$

KEKB *(without crab)*



SuperKEKB




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

Our Contributions

PXD development:

- Sensor design, prod. and testing

$\Rightarrow$ Analysis of testbeam data

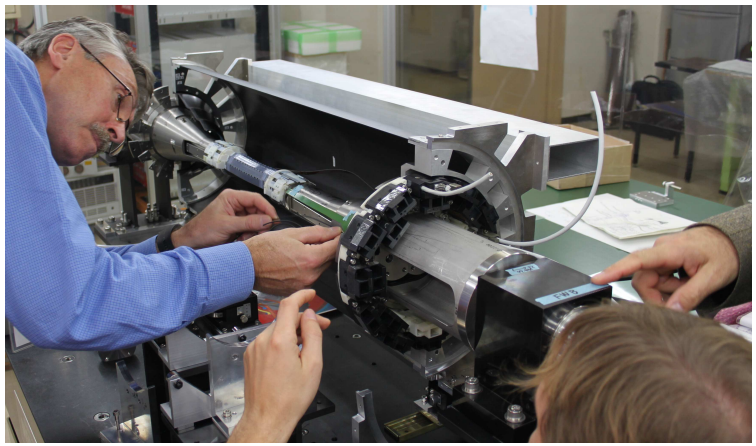
- Mechanical design, final assembly
- Cooling system (IBBelle)

Software development:

- Belle II framework development
- PXD and SVD simulation

$\Rightarrow$ w/o machine background

- Tracking, Vertexing and Flavor Tagging
- Neural z-vertex trigger



Machine commissioning:

- Design, prod. and operation of CLAWS detector

Belle CP-Analysis:

- $\mathrm{B}^0 \to \pi^+\pi^-$, $\pi^-\mathrm{K}^+$, $\mathrm{K}^-\mathrm{K}^+$ $\rho\rho$, $\omega\mathrm{K}^0_\mathrm{S}$

Belle II sensitivity studies:

- $\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^0_\mathrm{S}$, $\pi^0\pi^0$

CP-Violation in the SM

- Why CP-Violation? $\Rightarrow$ Matter-Antimatter-Asymm. in the universe larger than in SM. Sakharov's 2nd cond.: C-V, CP-V.
- Why in the B^0-system? $\Rightarrow$ largest CP-V. within the SM.
- CP-V. in the SM $\Rightarrow$ Weak Interaction $\Rightarrow$ $\mathbf{V}_{CKM}$

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

- Wolfenstein-Parameters: $\lambda = \sin\theta_C \approx 0.2, A, \rho, \eta$

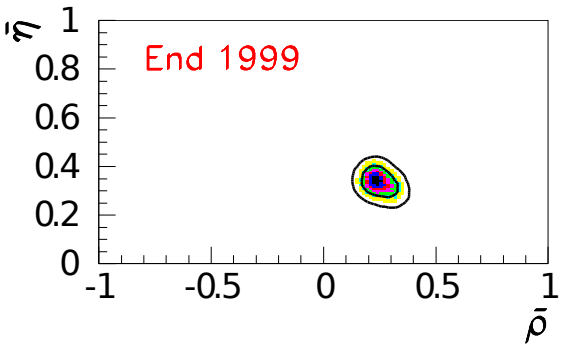
$$\mathbf{V}_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta)] & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

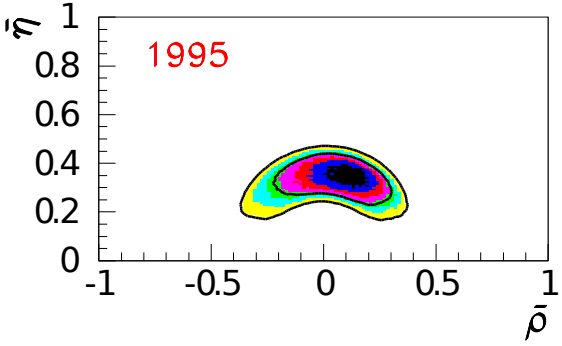
$$\Rightarrow \mathcal{L}^{\text{Yuk}} \propto igW^\mu J^{cc}_\mu \Rightarrow J^{cc}_\mu \xrightarrow{CP} J^{cc\,\prime}_\mu \neq J^{cc}_\mu$$

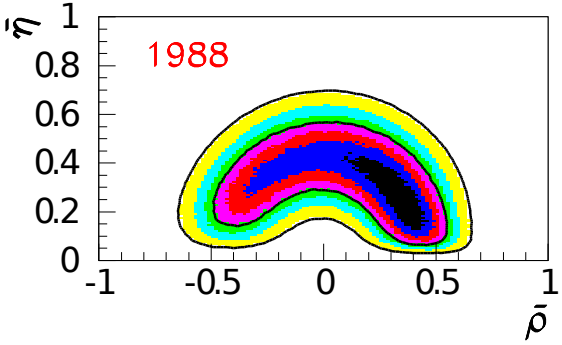
- Unitarity: $\sum_k V_{ik}V^*_{jk} = 0 \Rightarrow V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$

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

CKM-Triangle

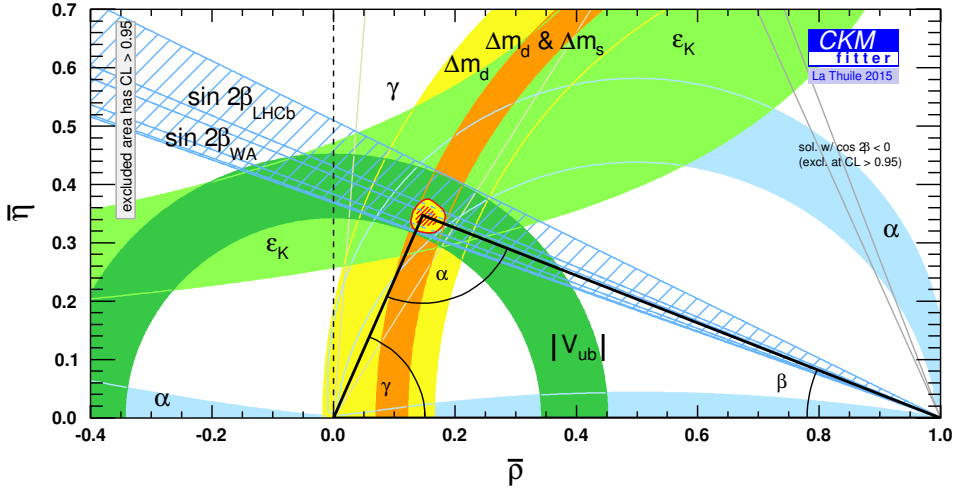




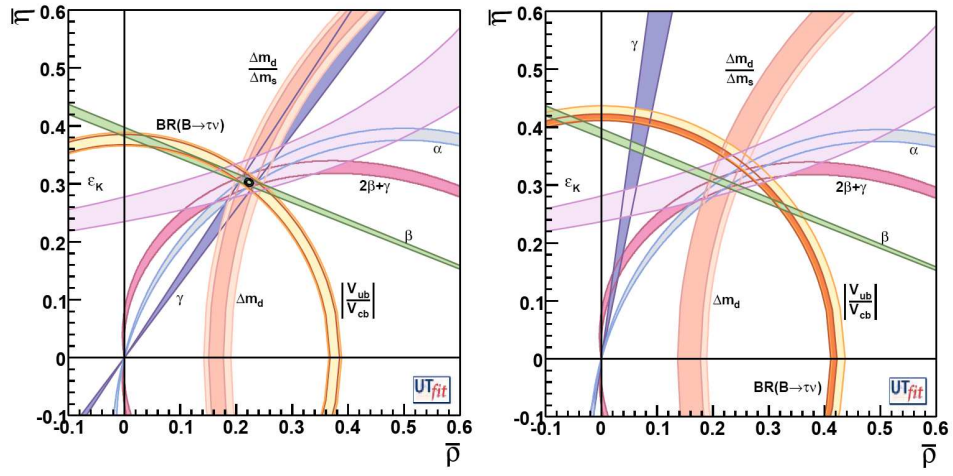


hep-ph/0002171

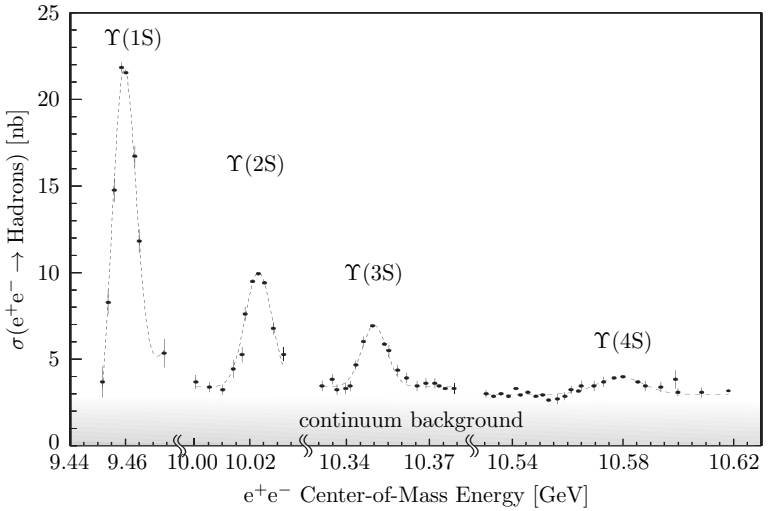
$$\bar{\rho} = \left(1 - \frac{\lambda^2}{2}\right)\rho \qquad \bar{\eta} = \left(1 - \frac{\lambda^2}{2}\right)\eta$$



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



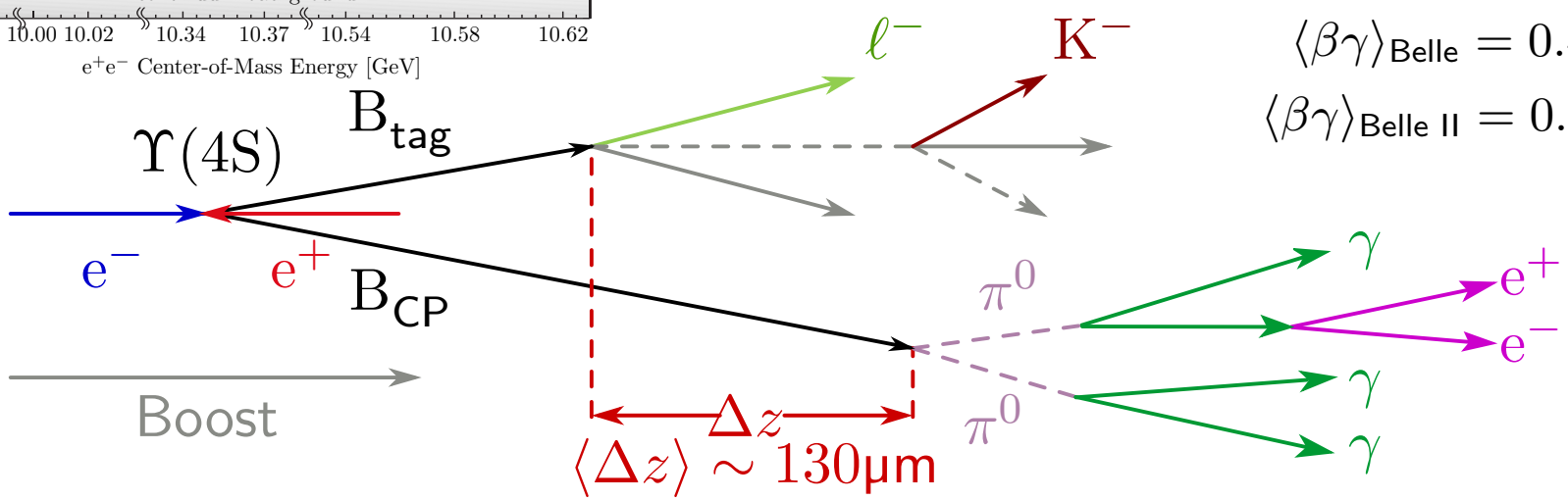
Time-dep. CP-Analysis at B-Factories



- $\Upsilon(4S)$ above $B\overline{B}$ prod. threshold

$\Rightarrow$ B-Factory

- $\sim 51\ \%$ are B^+B^-
- $\sim 48\ \%$ are $B^0\overline{B}^0$ $\quad q_{B^0,\overline{B}^0} = 1, -1$



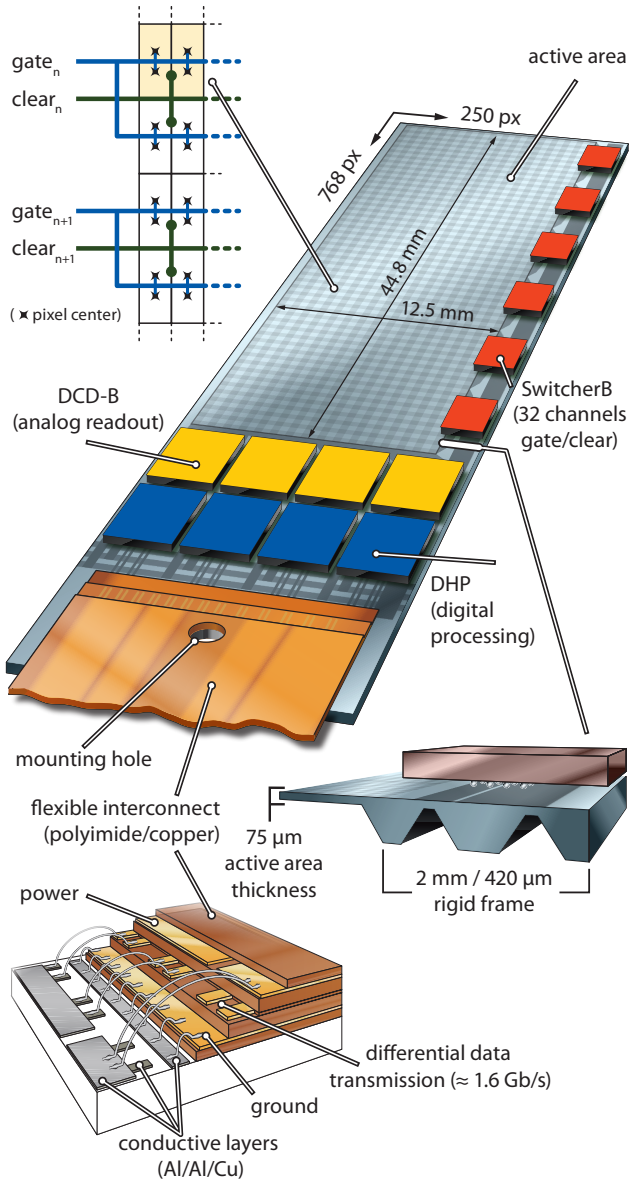
$\langle\beta\gamma\rangle_{\text{Belle}} = 0.425$

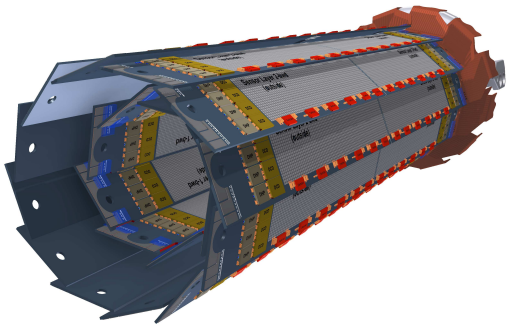
$\langle\beta\gamma\rangle_{\text{Belle II}} = 0.284$

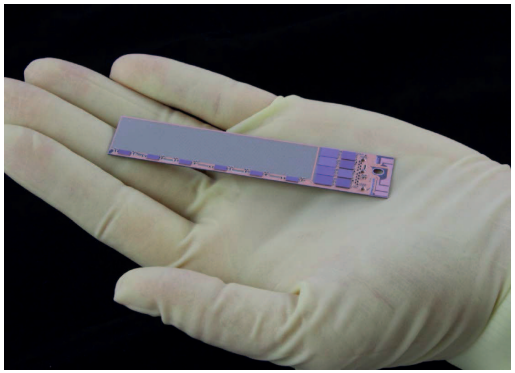
- $B^0\overline{B}^0$ at rest in CMS $\Delta t = \frac{\Delta z}{\langle\beta\gamma\rangle c} \Rightarrow$

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

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

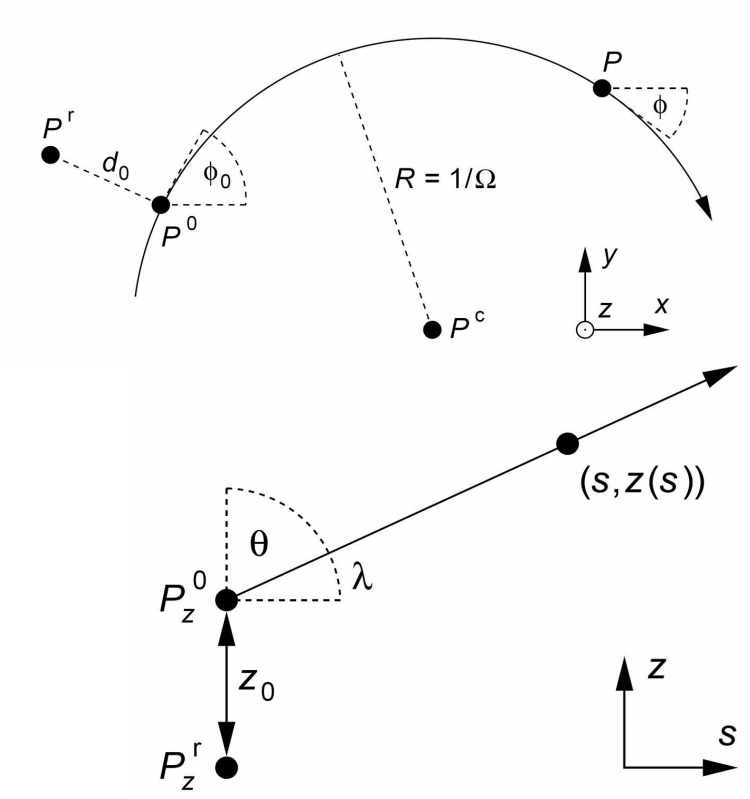
Depleted Field Effect Transistor

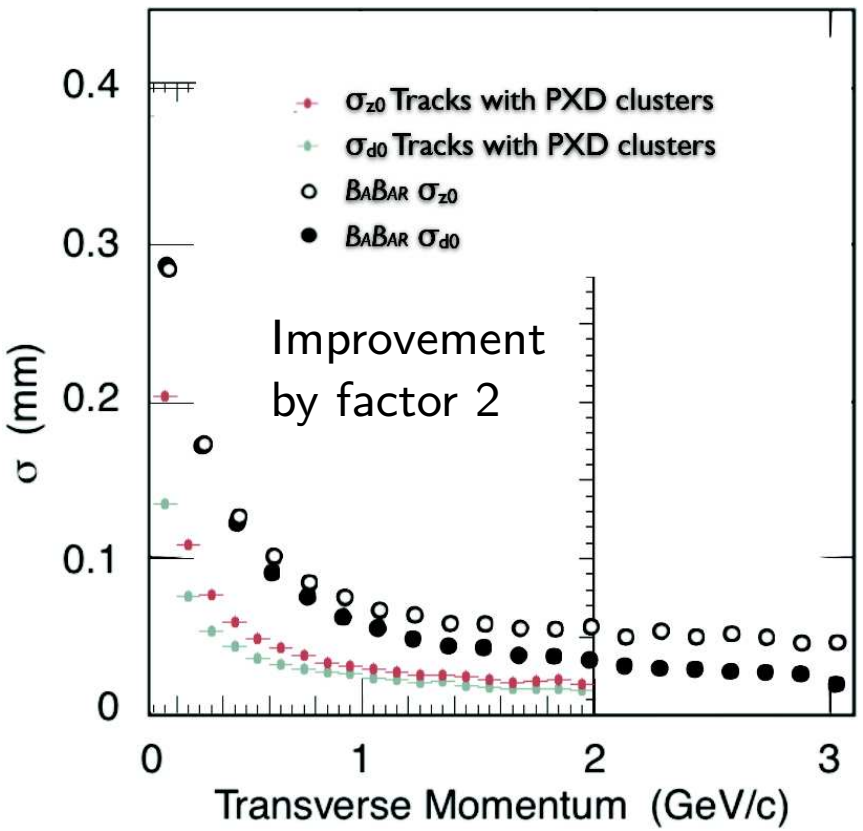
The Impact Parameter

Particle track parametrization:

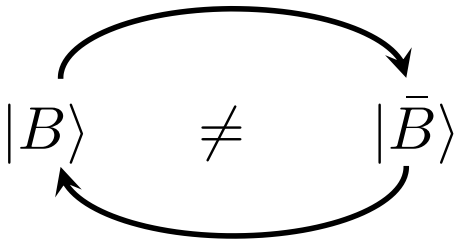
$\Rightarrow \vec{t}(d_0,\ \phi_0,\ \Omega = \frac{q}{p_t},\ z_0,\ \tan(\lambda))$

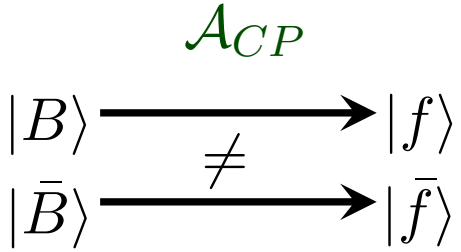
- $d_0(z_0)$: distance from point of closest approach to origin.

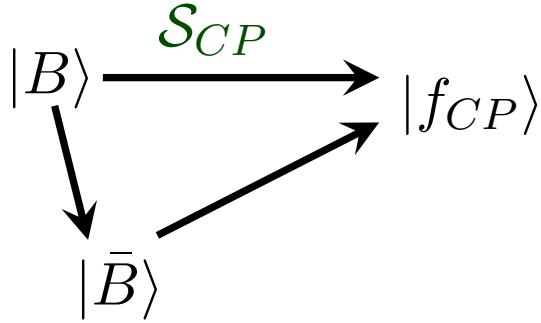




Time-dependent CP-Analysis



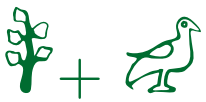




For $B \to \pi\pi$: tree and penguin diags. contribute!

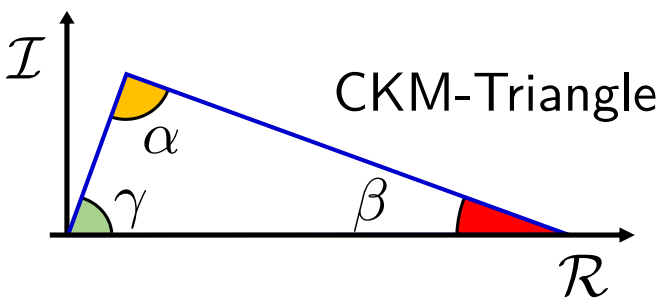
 : $\mathcal{A}_{CP} = 0$

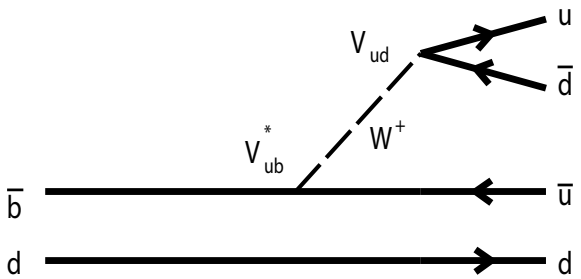
$\mathcal{S}_{CP} = \sin(2\alpha)$

 : $\mathcal{A}_{CP} \neq 0$

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

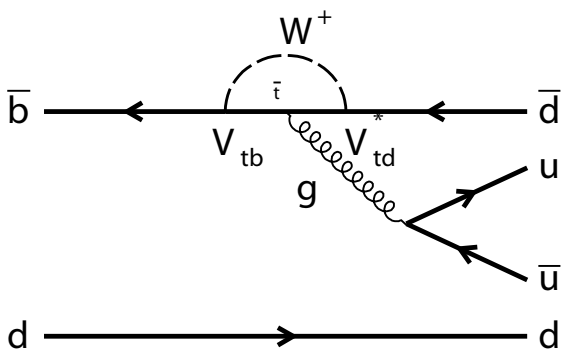
$\Rightarrow \alpha^{\text{eff}} = \alpha - \Delta\alpha$





Isospin

$I = 0, 2$



$I = 0$

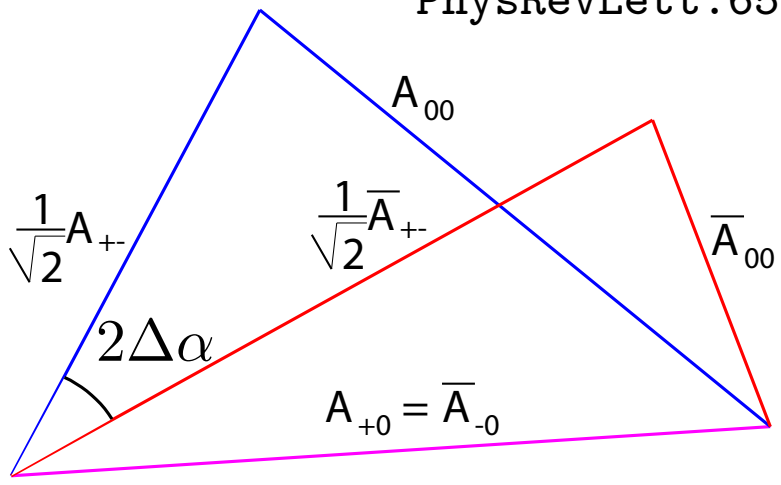
Extraction of α angle from $B \to \pi\pi$

PhysRevLett.65.3381

- Extr. $\Delta\alpha$ through isospin analysis:

$$A^{+-} = A(B \to \pi^+\pi^-)$$

- $\frac{1}{\sqrt{2}}A^{+-} + A^{00} = A^{+0}$
- $\frac{1}{\sqrt{2}}\bar{A}^{+-} + \bar{A}^{00} = \bar{A}^{-0}$



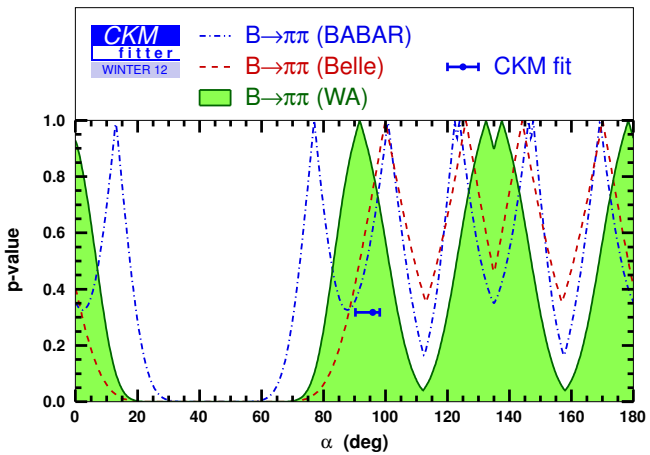
Pure Tree: $A^{+0} = \bar{A}^{-0}$

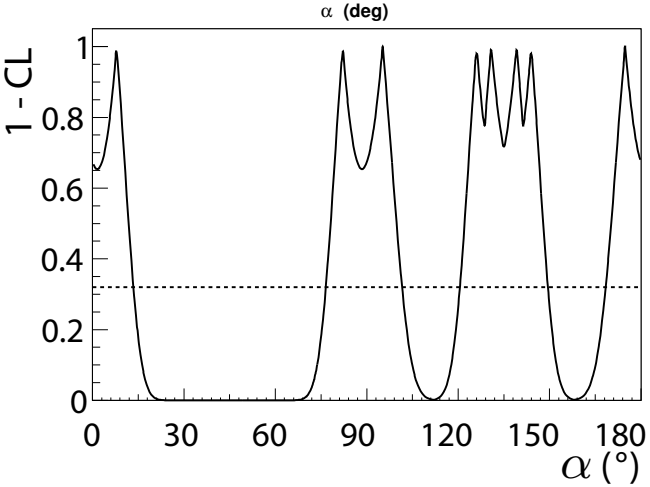
- Isospin analysis requires also $\mathcal{S}_{\pi^+\pi^-}$ and $\mathcal{S}_{\pi^0\pi^0}$.
- $\mathcal{S}_{\pi^0\pi^0}$ needs $\langle\Delta z\rangle \sim 130\mu m$ of $B \to \pi^0\pi^0$ where $\pi^0 \to \gamma\gamma$

$\Rightarrow$ Challenge!

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

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

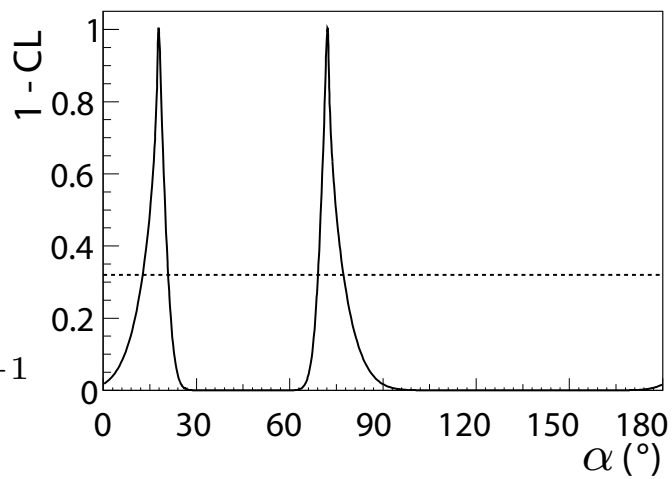




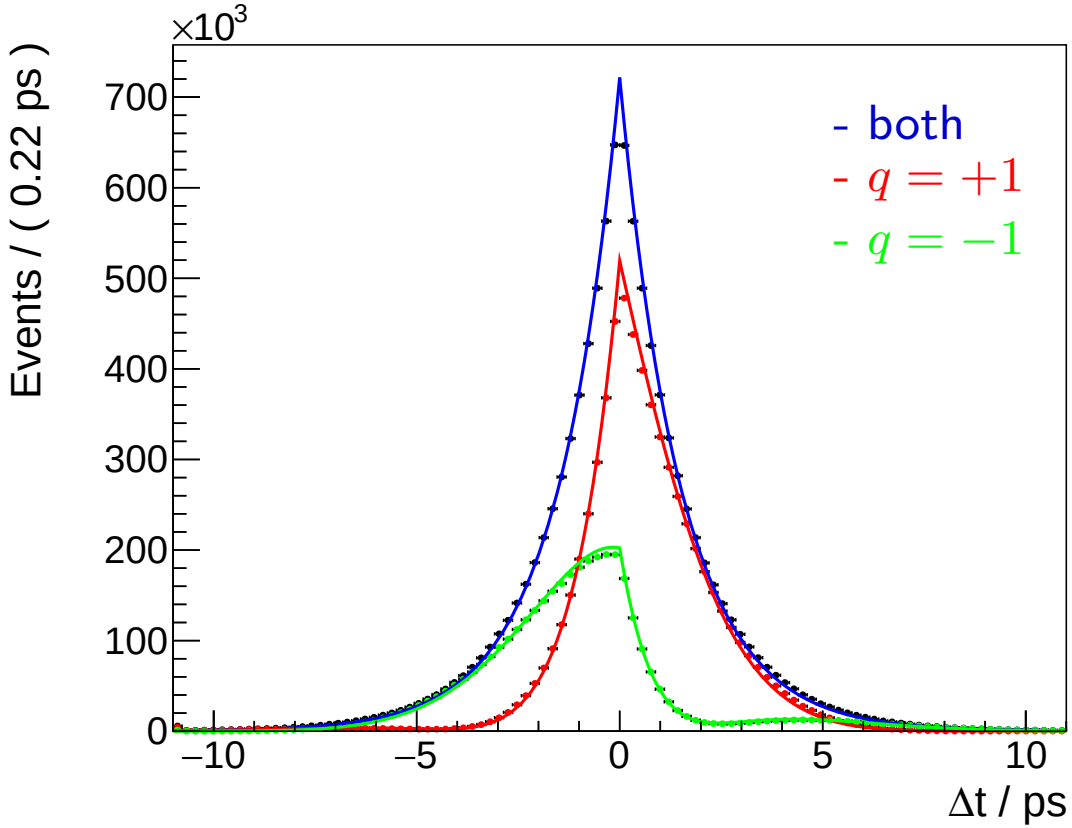
- with $\mathcal{S}_{\pi^0\pi^0} \Rightarrow$ 2 fold ambiguity on α
- Converted $\gamma \to e^+e^-$ and $\pi^0 \to e^+e^-\gamma$ req. for $\langle \Delta z \rangle$
- Possible with $\mathcal{L}_{\text{Belle II}} = 50 \cdot \mathcal{L}_{\text{Belle}}$ and Belle II PXD?

Extrapolated to $\mathcal{L}_{\text{Belle II}} = 50\text{ab}^{-1}$

arXiv:hep-ex/0703029



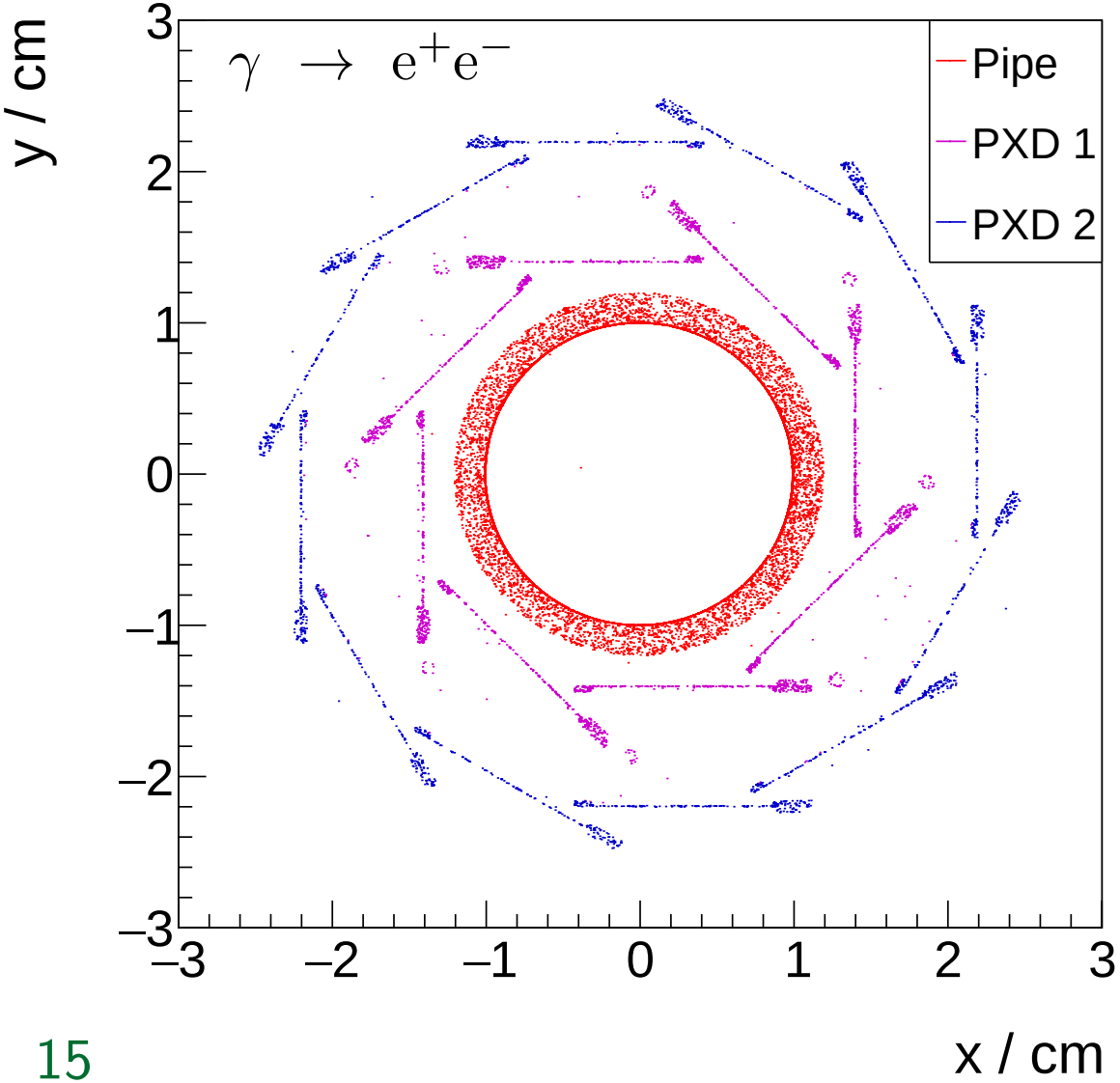
Expected Asymmetry



- $\mathcal{A}_{CP}{}^{\pi^0\pi^0} = 0.43$ (PDG)
- $\mathcal{S}_{CP}{}^{\pi^0\pi^0} = \sqrt{1-\mathcal{A}_{CP}}\sin 2\cdot(\alpha - \Delta\alpha^*) \approx 0.76$

*hep-ex/0703039

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
  $B_2 \to \pi^0\pi^0$
- $\pi^0 \to \gamma\gamma \quad (\mathcal{B} = 98.82\%)$
- $\pi^0 \to e^+e^-\gamma \ (\mathcal{B} = 1.17\%)$
- $N_{\text{Belle II}} =$

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

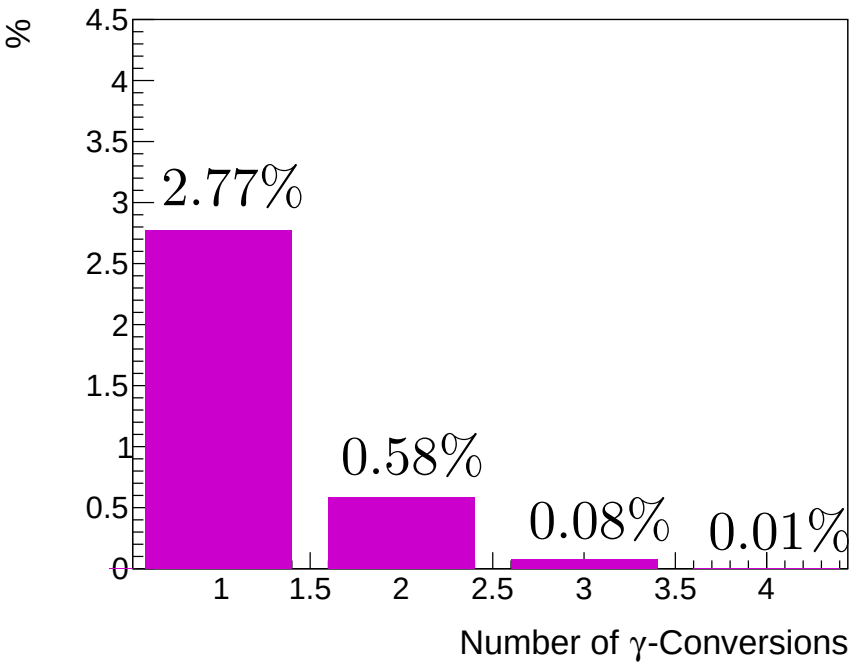
~ 100k events.

- 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

B^0 Vertex Reconstruction

Algorithm: Kinematic Vertex Fit

Access: RAVE (Reconstruction in a Abstract, Versatile Environment) TNS.2011.2119492

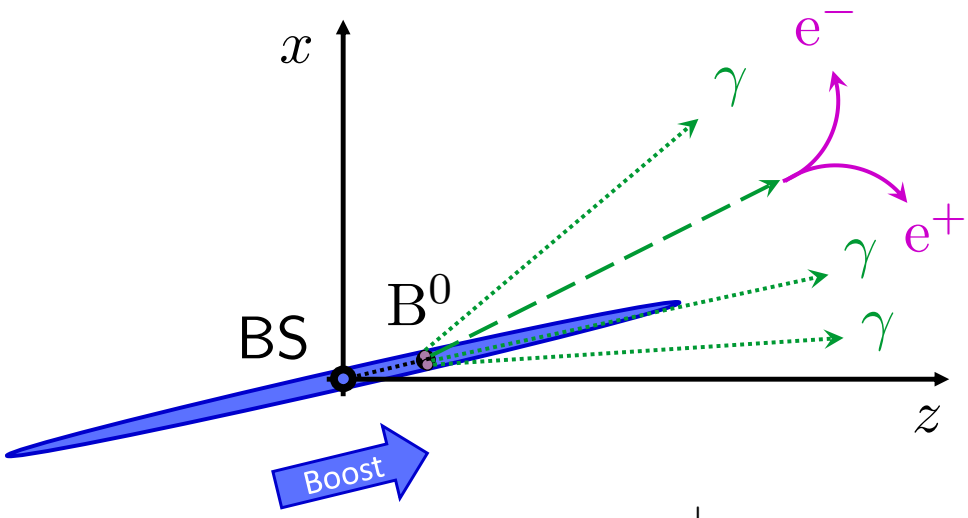
- Vertex Reconstruction with spatial constraint centered at the Beam Spot.

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

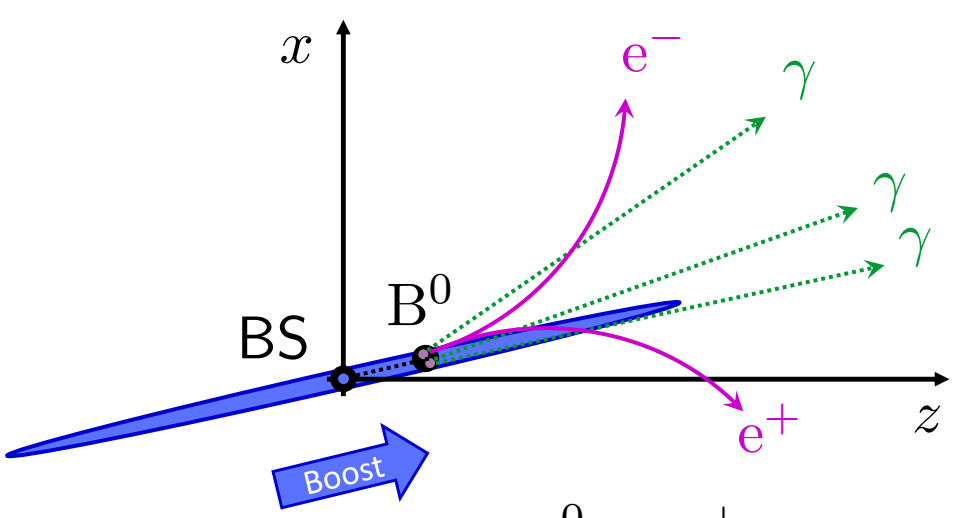
$\Rightarrow$ π^0 Vertex $\hat{=}$ B^0 Vertex.

- ✂ on $e^{\pm}$ Tracks: At least one PXD hit.

- Check with MC truth.



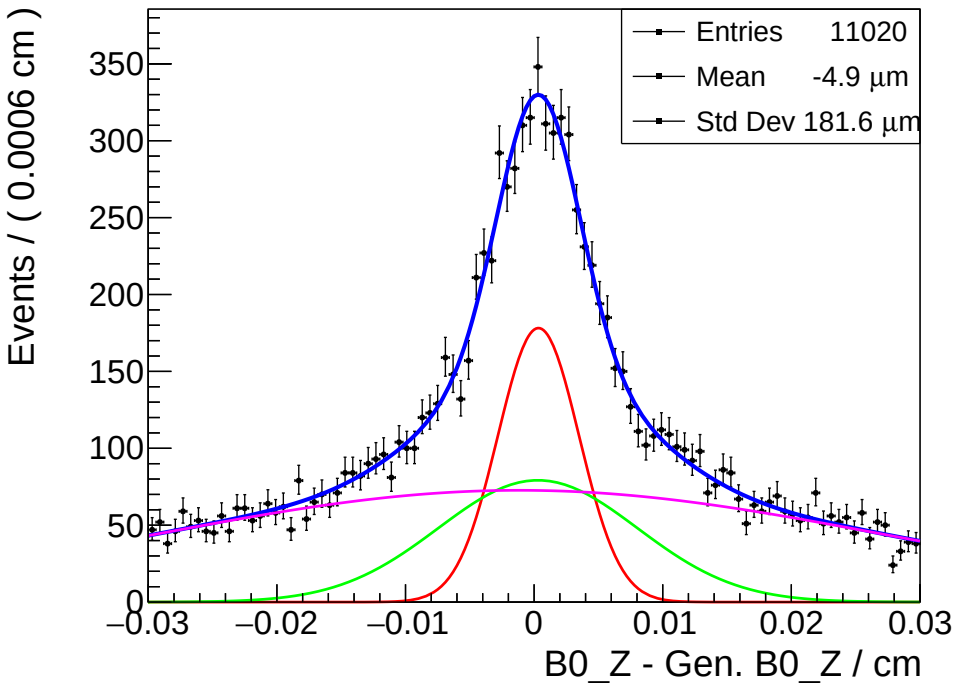
$\gamma \to e^+e^-$



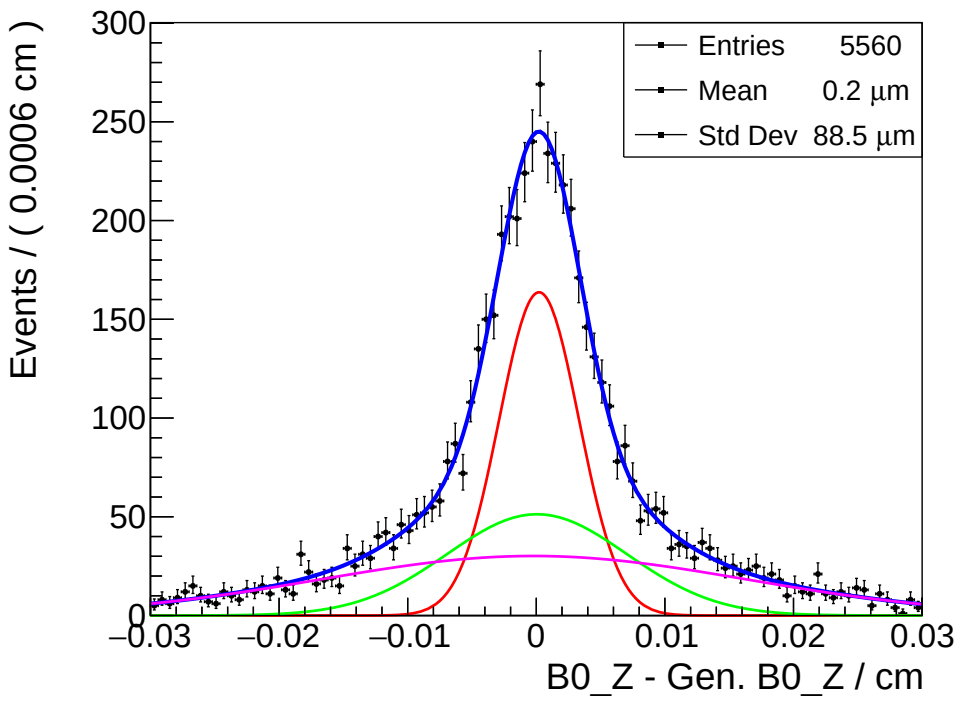
$\pi^0 \to e^+e^-\gamma$

B^0 z-Vertex Resolution

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



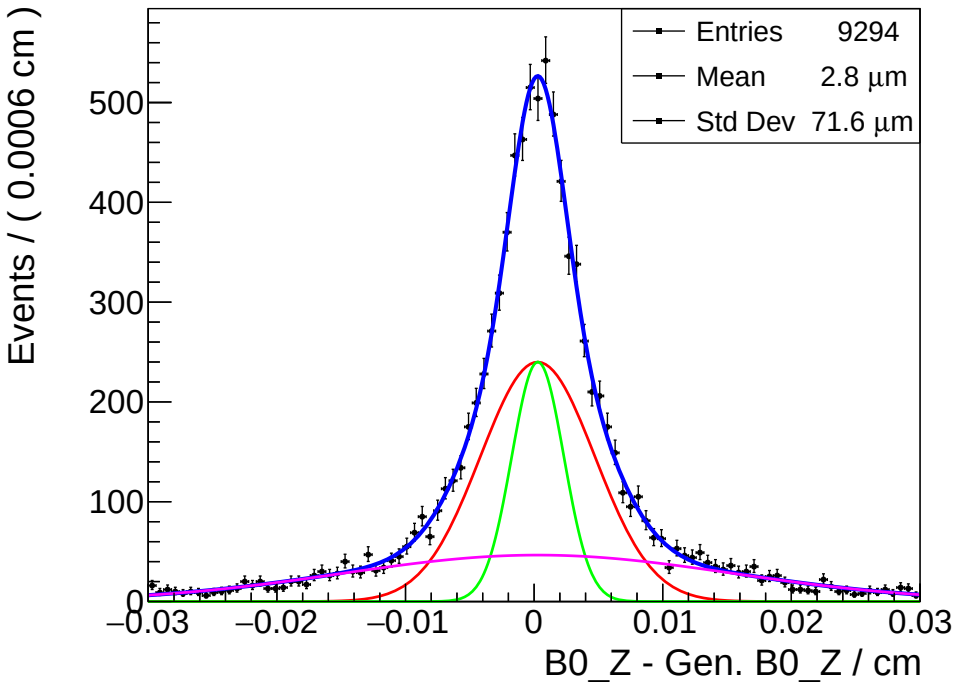
No PXD Hit required



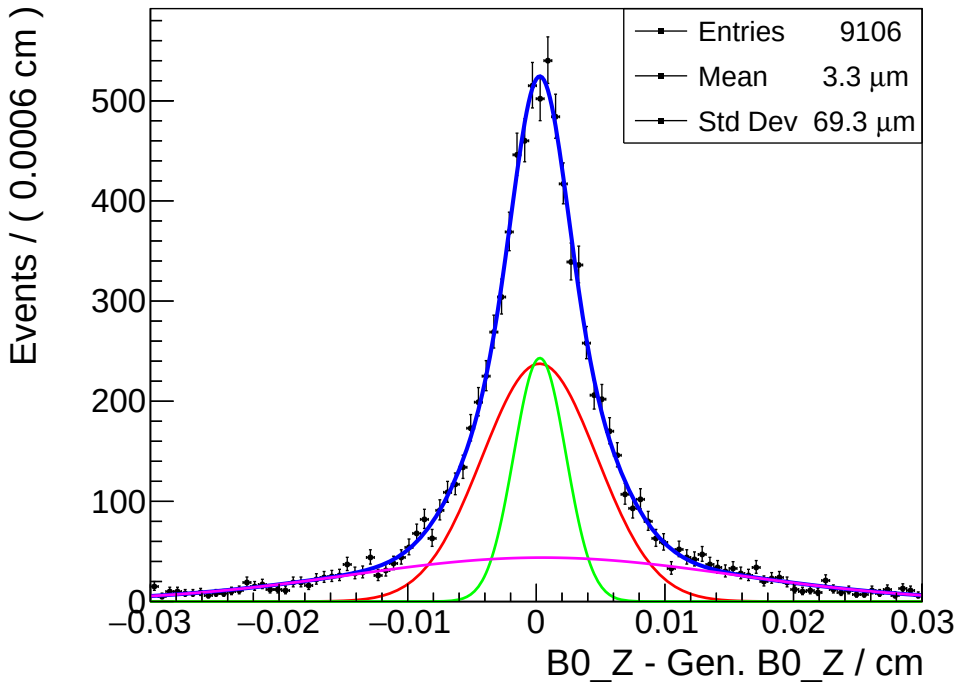
At least one track (e^+ or e^-) has one PXD Hit

B^0 z-Vertex Resolution

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



No PXD Hit required

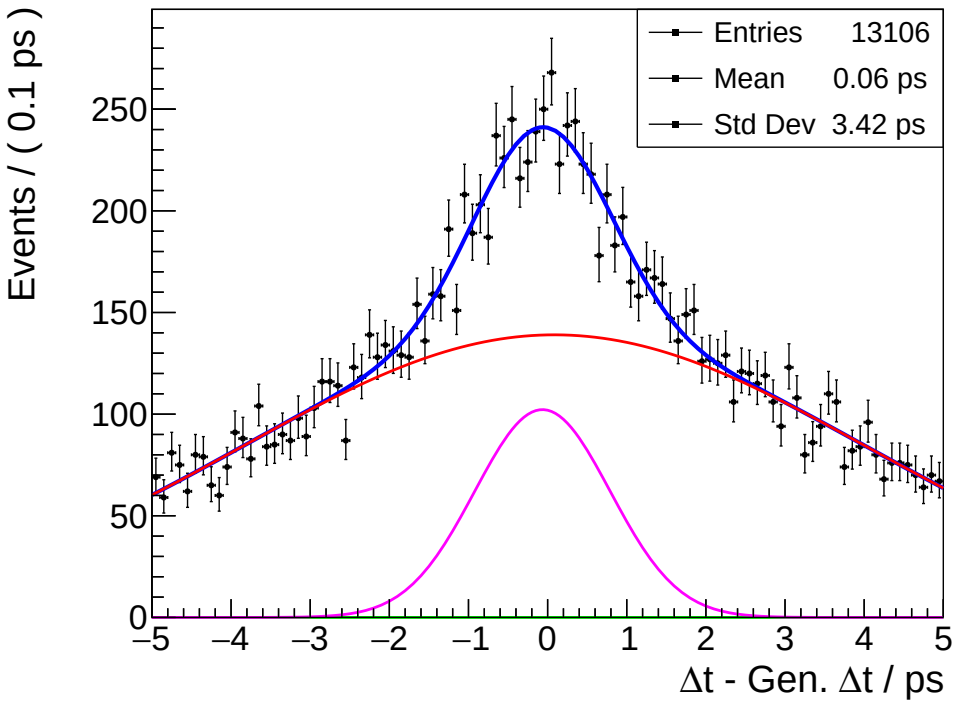


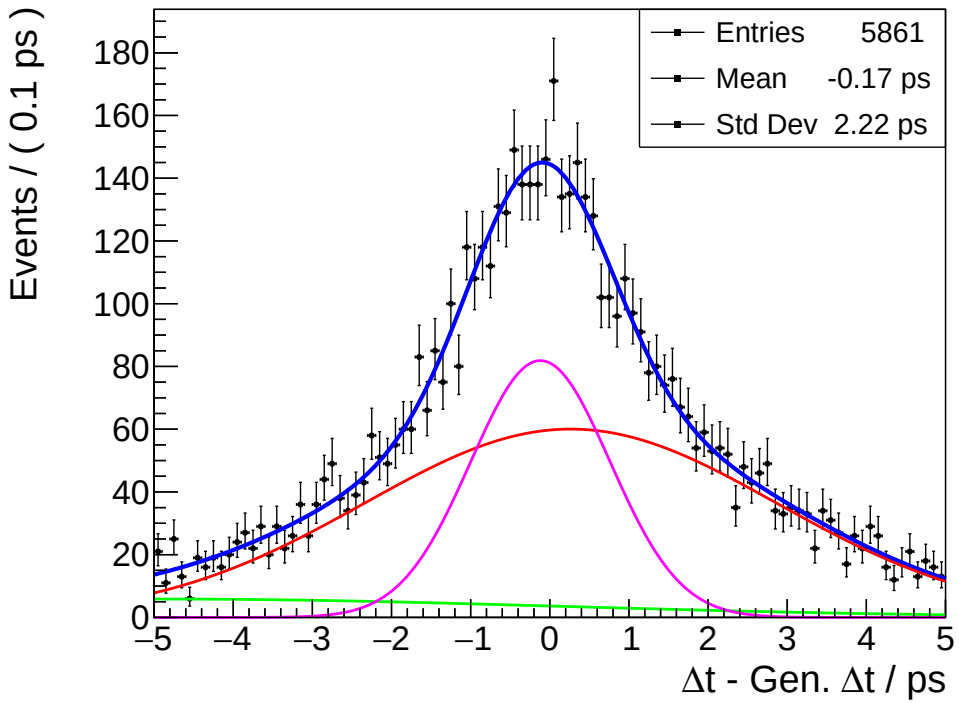
At least one track (e^+ or e^-) has one PXD Hit

Δt Resolution

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

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





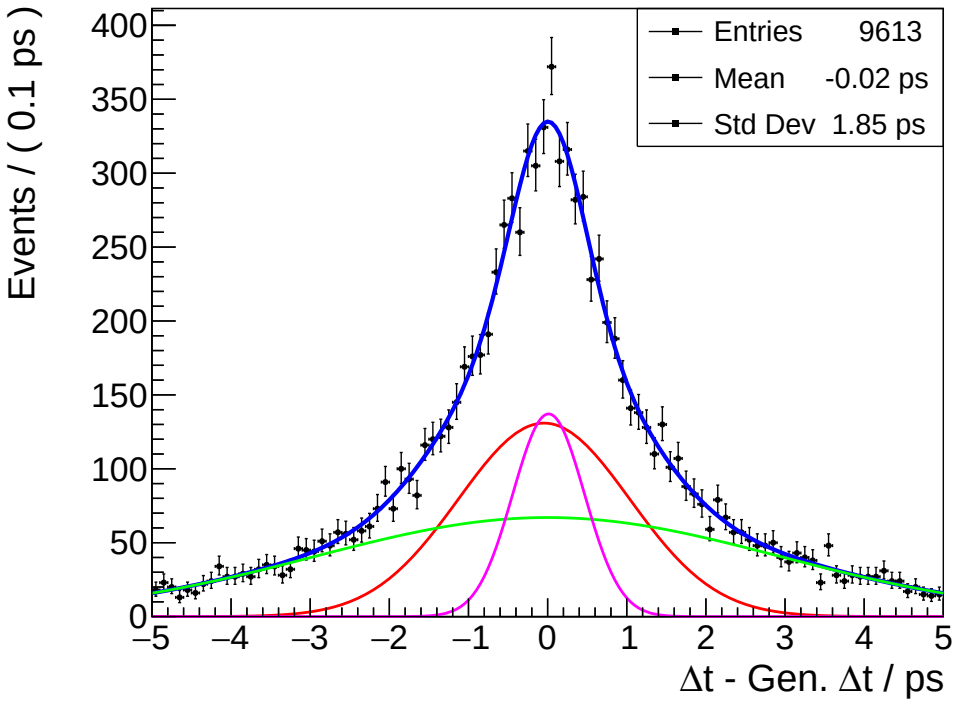
No PXD Hit required

At least one track ($\mathrm{e^+}$ or $\mathrm{e^-}$) has one PXD Hit

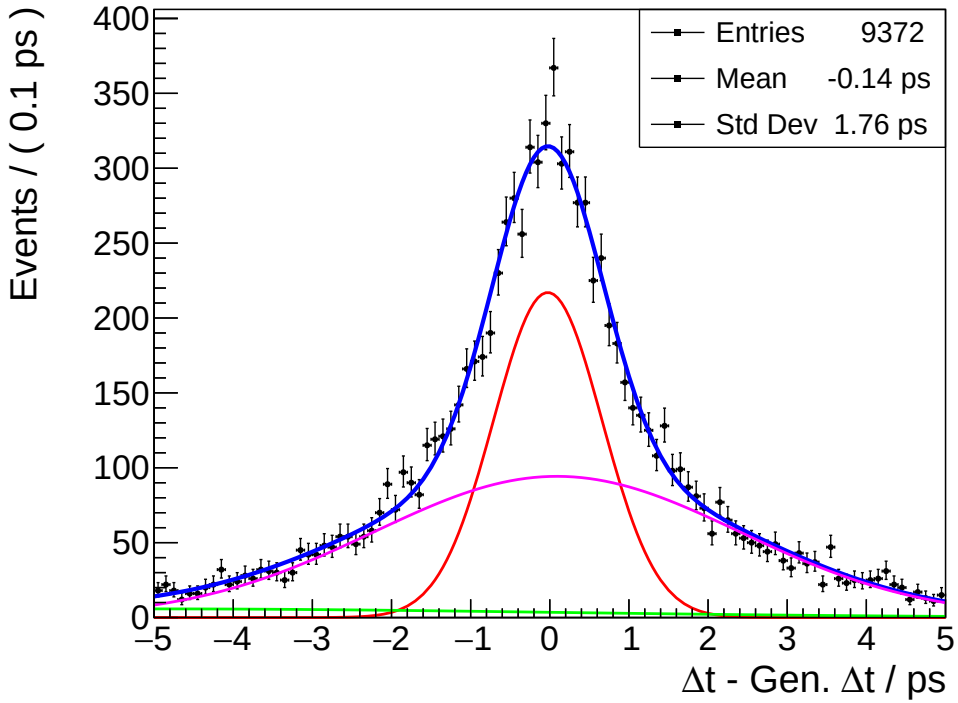
Δt Resolution

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

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



No PXD Hit required



At least one track ($\mathrm{e^+}$ or $\mathrm{e^-}$) has one PXD Hit

Summary and Outlook

- Beam Spot constrained kinematic vertex fit reaches higher resolution with PXD Information.

$\Rightarrow$ Higher Δt resolution.

- Next: Continuum suppression and MC Campaign.
- "New Physics" needed to explain observed matter-antimatter asymmetry

$\Rightarrow$ New Sources of CP-Violation needed.

- Search at next generation B-Factory SuperKEKB with $50\,\mathrm{ab}^{-1}$ complementary to LHC.
- Machine commissioning started! Begin of data taking planned for 2018! Strong contribution from our institute!

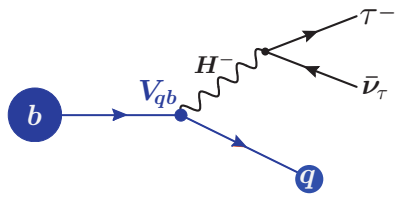
NP in Semileptonic Decays

Semi-leptonic

Semi-tauonic decay modes are highly sensitive to new physics

Clean measurement is a major Belle II goal

Can target inclusive and light meson modes; target higher excited states and carry out differential measurements



$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\,\tau\,\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\,\ell\,\bar{\nu}_\ell)}$$

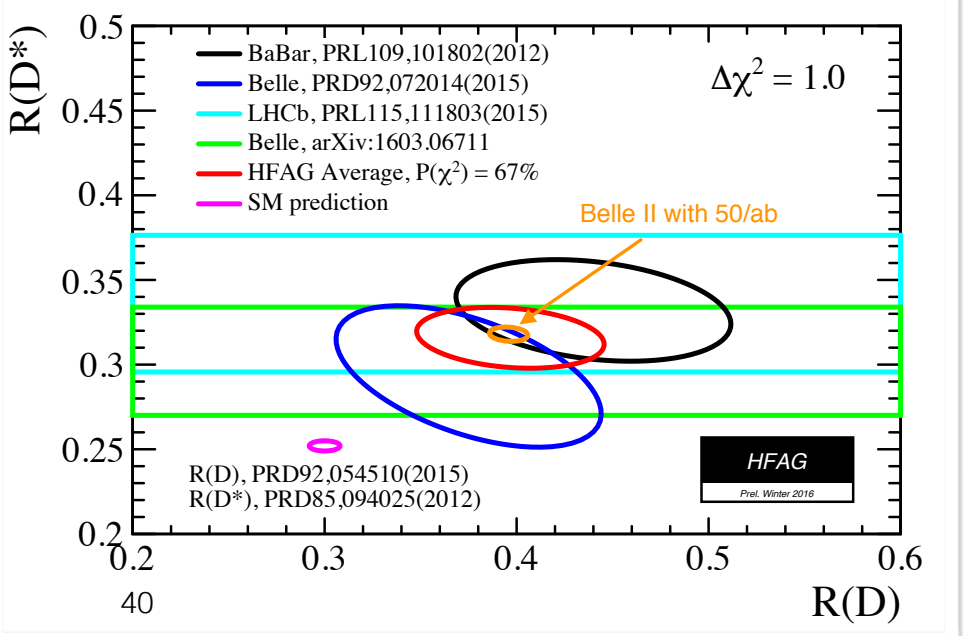
$R(X)$ $R(\pi)$ $R(D^{**})$

$R(D)$

Error	stat.	tot.
B-Factories	13%	16.2%
Belle II 5/ab	3.8%	5.6%
Belle II 50/ab	1.2%	**3.4%**

$R(D^*)$

Error	stat.	tot.
B-Factories	7.1%	9.0%
Belle II 5/ab	2.1%	3.2%
Belle II 50/ab	0.7%	**2.1%**



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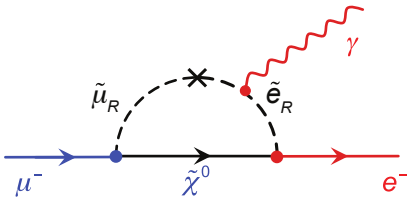
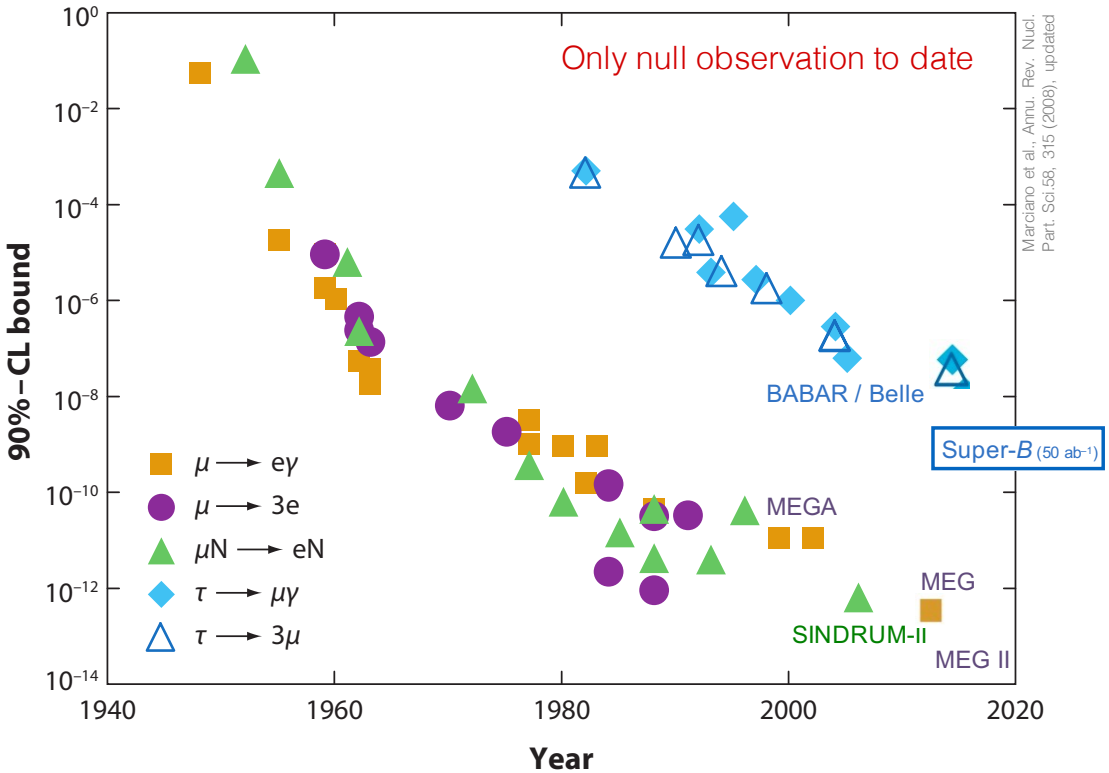
LFV

Charged lepton flavour violation:
SM-free signals!



LFV signals are expected in many BSM scenarios, such as the MSSM or as a consequence of Seesaw models



Spectacular perspectives: Mu2e / COMET
PRISM / PRIME

B^0 Reconstruction

1 Select single ECL clusters: γ_{s}

Inputs: E9E25, LAT, NHits, R, E, σ_E, t, σ_t,

2 Rec. and sel. $\gamma_{\mathsf{c}} \to \mathrm{e}^+\mathrm{e}^-$

Inputs: m, p, E, p_{highest}, $\theta_{\mathrm{e}^+,\mathrm{e}^-}$

3 Rec. and sel.: $\pi^0{}_{\mathsf{ss}} \to \gamma_{\mathsf{s}}\gamma_{\mathsf{s}}$
$\pi^0{}_{\mathsf{sc}} \to \gamma_{\mathsf{s}}\gamma_{\mathsf{c}}$
$\pi^0{}_{\mathsf{dal}} \to \mathrm{e}^+\mathrm{e}^-\gamma_{\mathsf{s}}$

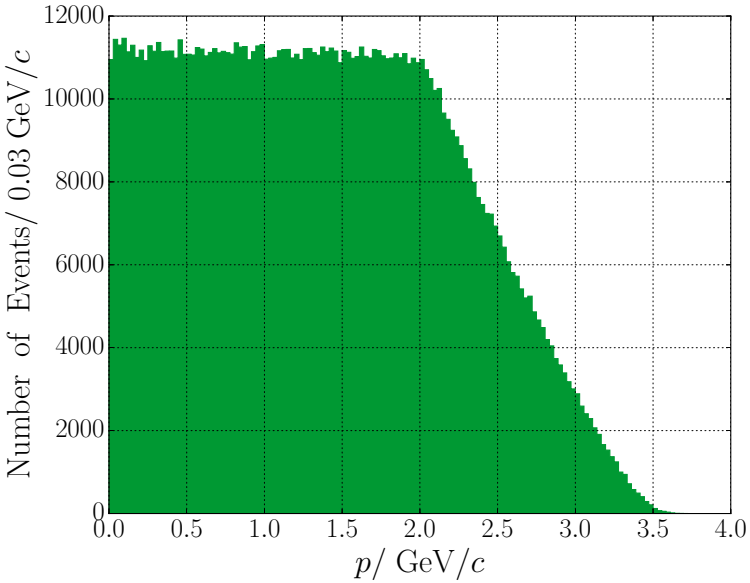
Inputs: m, p, E, p_{lowest}, $\theta_{\mathrm{e}^+,\mathrm{e}^-}$, $\theta_{\gamma,\mathrm{e}^+\mathrm{e}^-}$

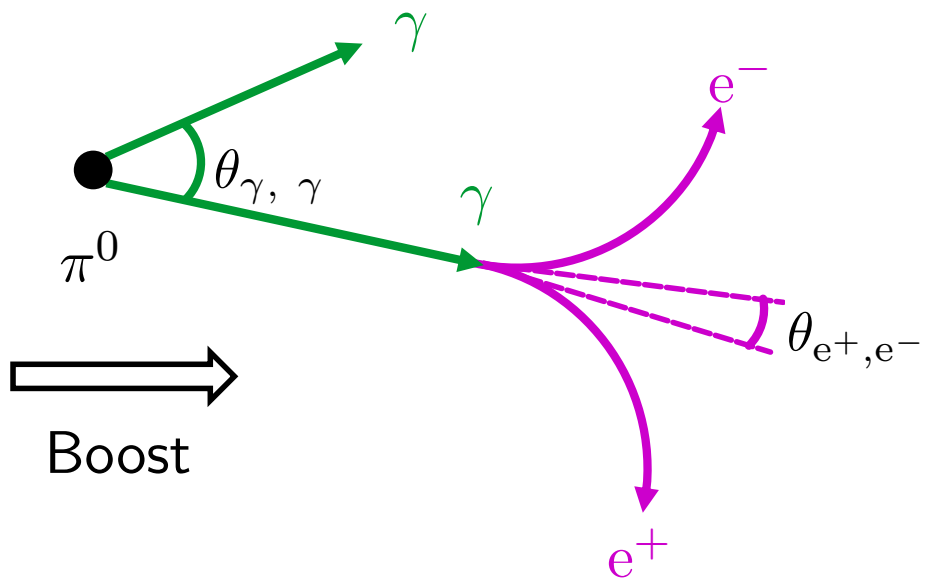
4 Rec. and sel.: $\mathrm{B}^0{}_{\mathsf{ss}} \to \pi^0{}_{\mathsf{ss}}\pi^0{}_{\mathsf{ss}}$
$\mathrm{B}^0{}_{\mathsf{sc}} \to \pi^0{}_{\mathsf{sc}}\pi^0{}_{\mathsf{ss}}$
$\mathrm{B}^0{}_{\mathsf{dal}} \to \pi^0{}_{\mathsf{dal}}\pi^0{}_{\mathsf{ss}}$

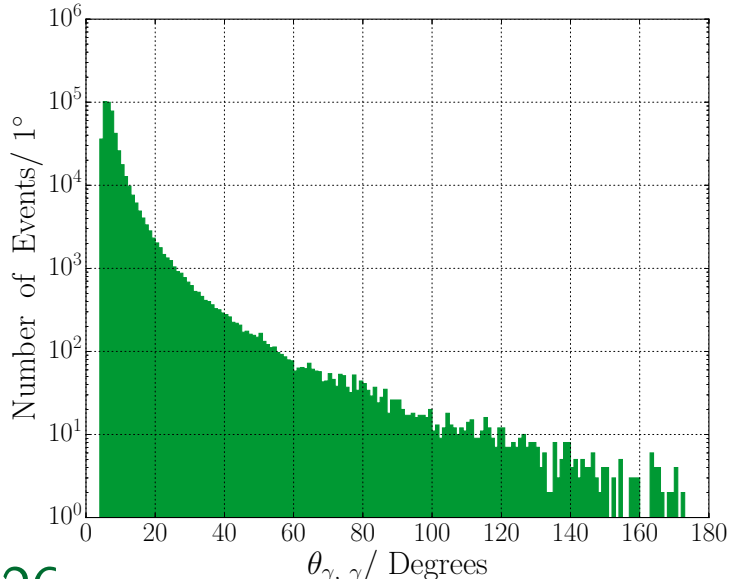
Inputs: m_{bc}, ΔE, σ_m, $\theta_{\pi^0{}_1,\pi^0{}_2}$

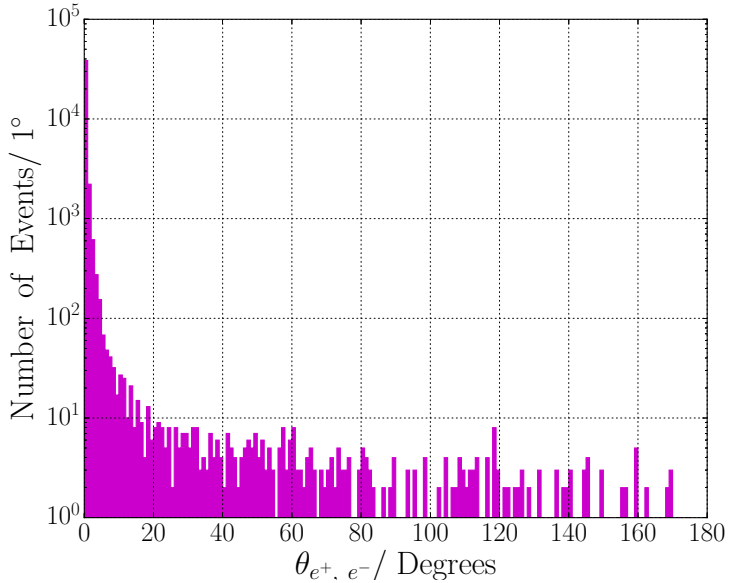
- Selection with FBDTS.

$\pi^0 \to \gamma\gamma$ Kinematics

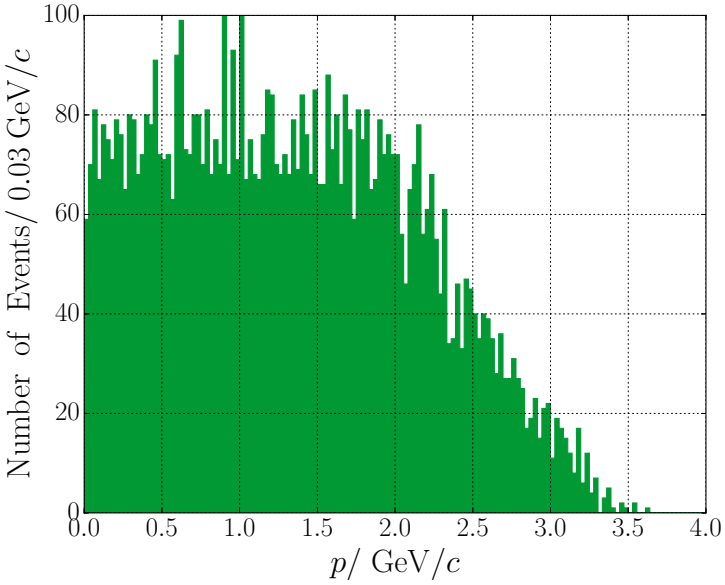


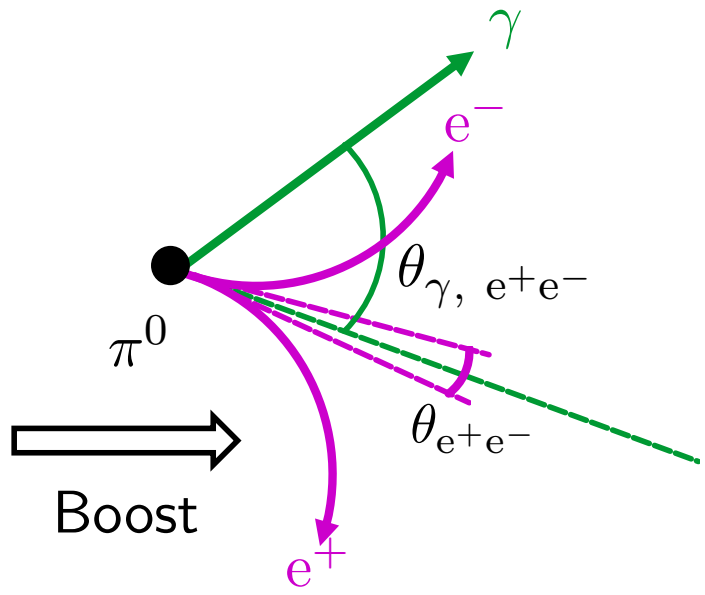


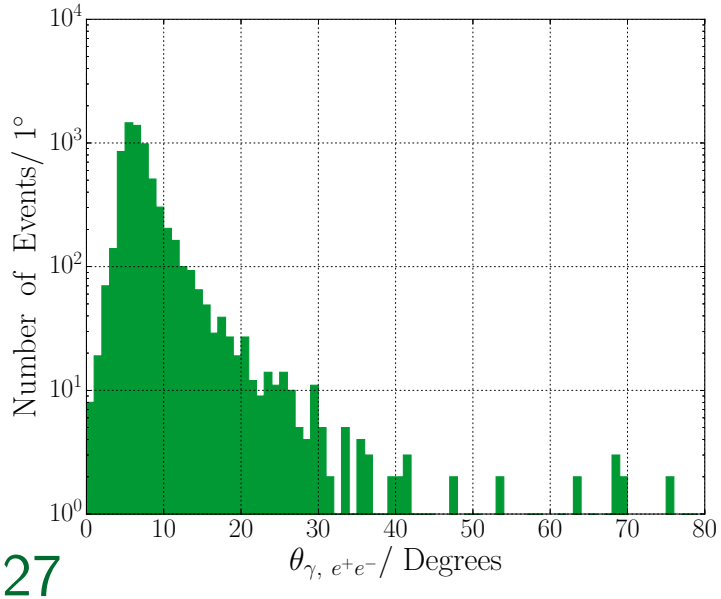


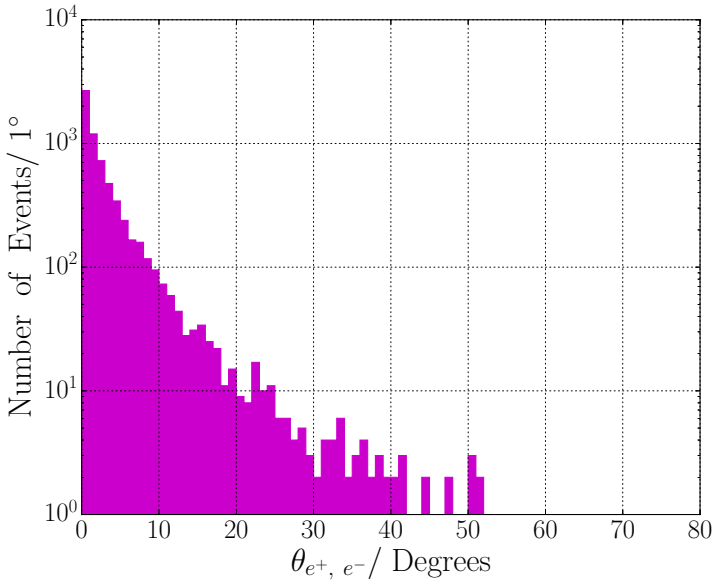


$\pi^0 \to e^+e^-\gamma$ Kinematics

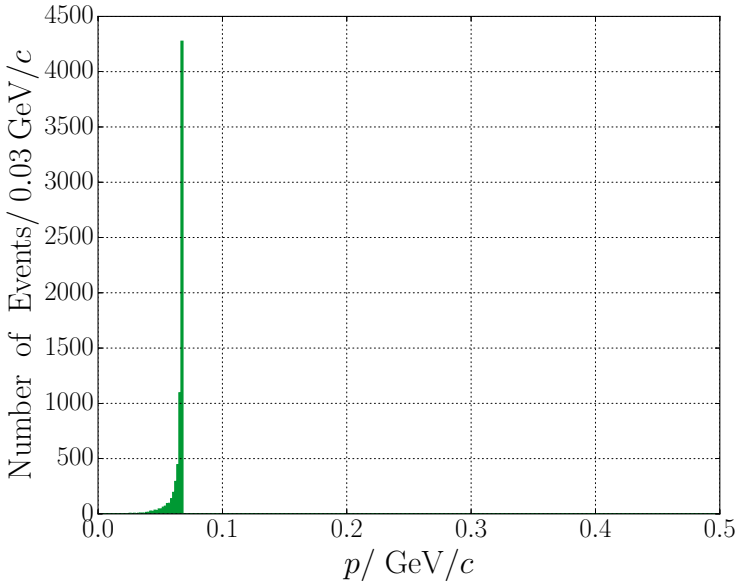


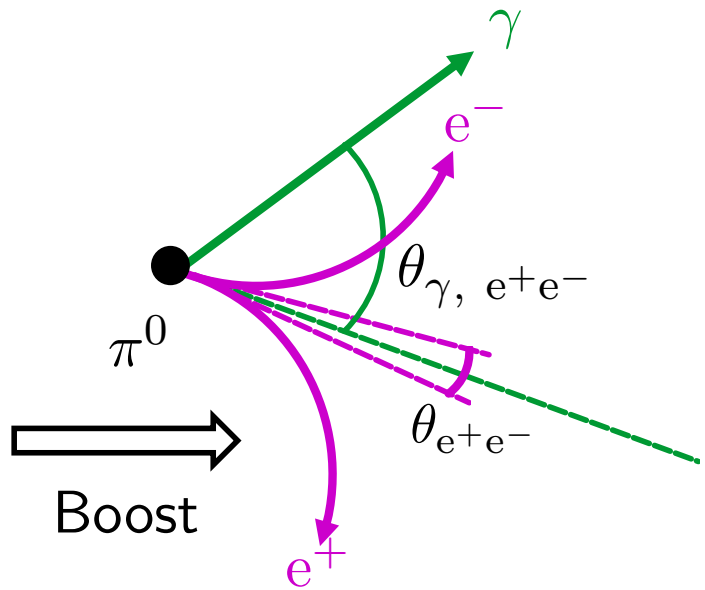


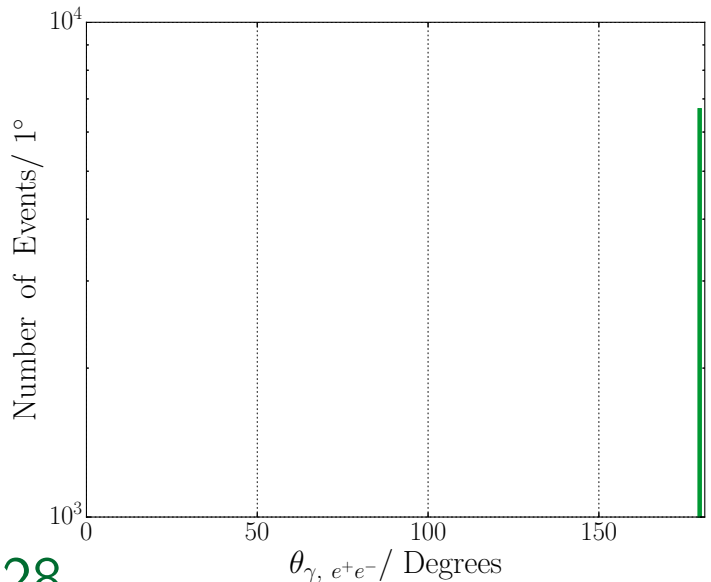


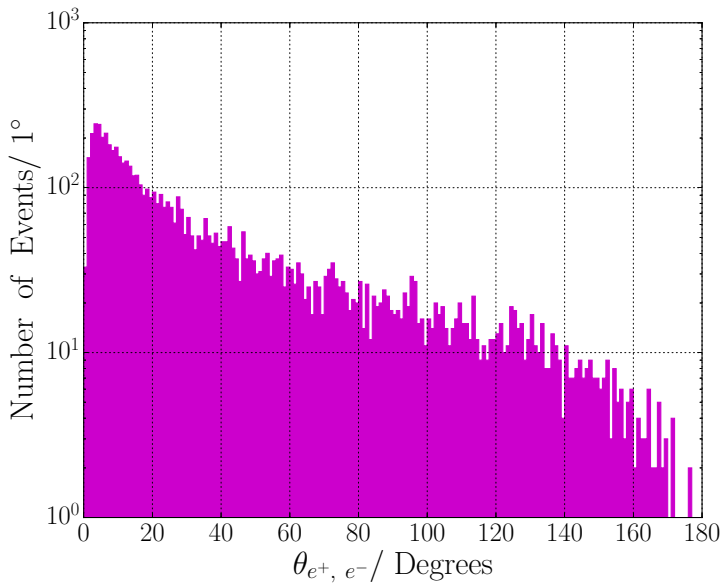


$\pi^0 \to e^+e^-\gamma$ CMS Kinematics









e^+, e^- Track Reconstruction

- e^+, e^-