Sensitivity Study of $B^0 \to \pi^0\pi^0$ for the Belle II Experiment

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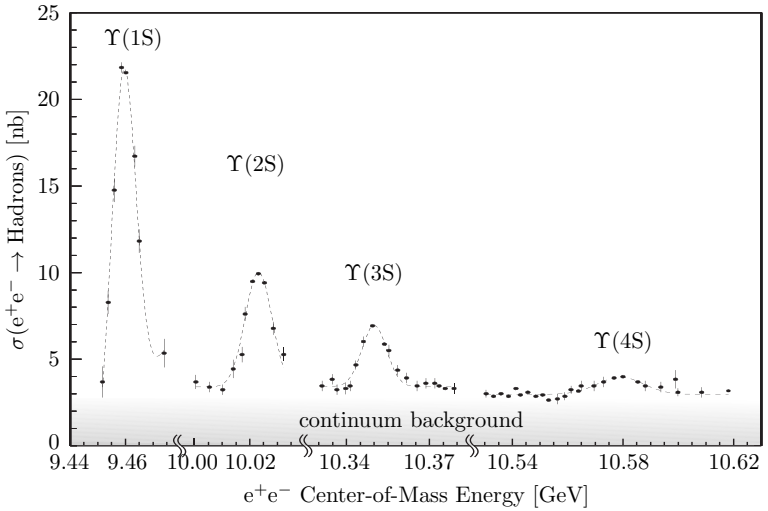
1. Why CP-V. Sensitivity to $B^0 \to \pi^0\pi^0$?
2. γ-Conversions and $\pi^0 \to e^+e^-\gamma$
3. Summary and Outlook

Max-Planck-Institut
für Physik

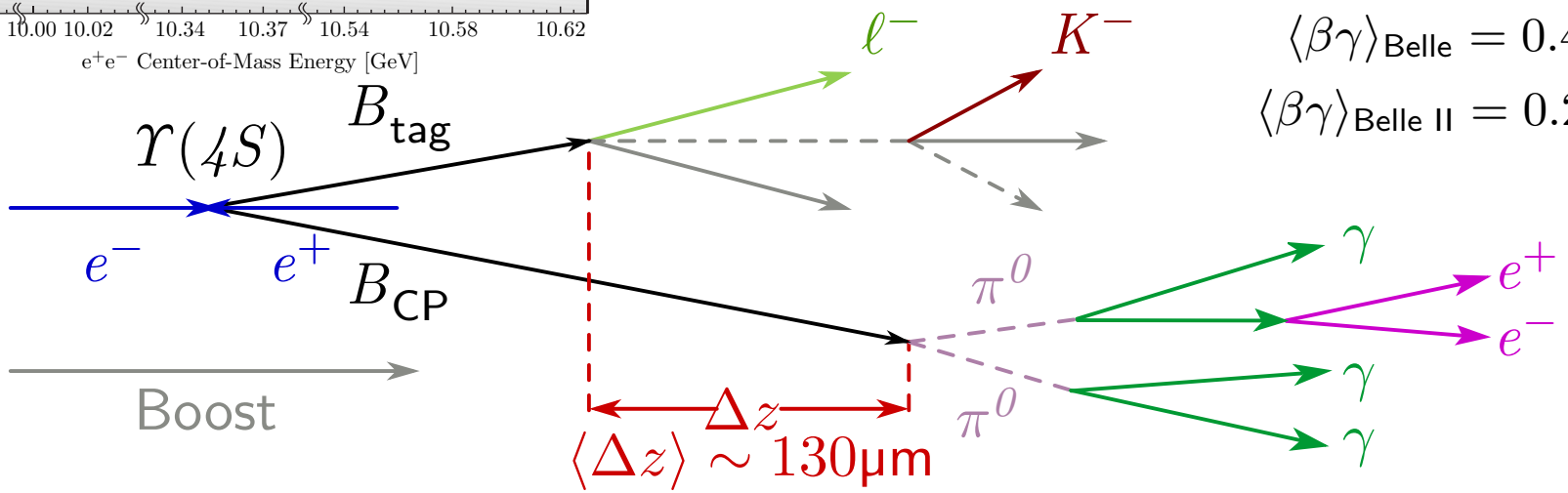
Time-dep. CP-Analysis at B-Factories



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

$\Rightarrow$ B-Factory

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



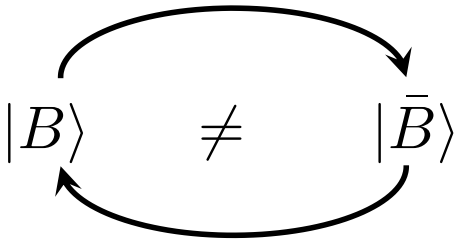
$\langle\beta\gamma\rangle_{\text{Belle}} = 0.425$

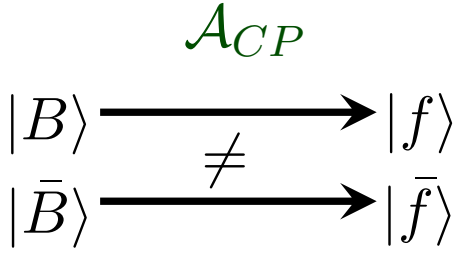
$\langle\beta\gamma\rangle_{\text{Belle II}} = 0.284$

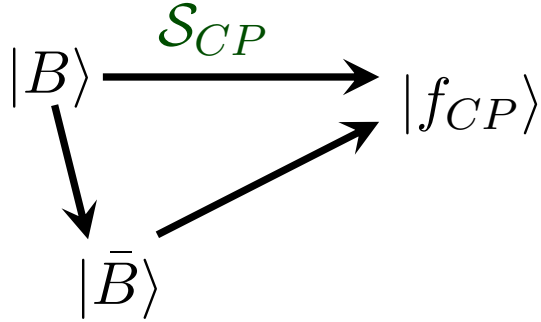
- $B^0\overline{B}^0$ at rest in CMS $\Delta t = \frac{\Delta z}{\langle\beta\gamma\rangle c} \Rightarrow$

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

Time-dependent CP-Analysis



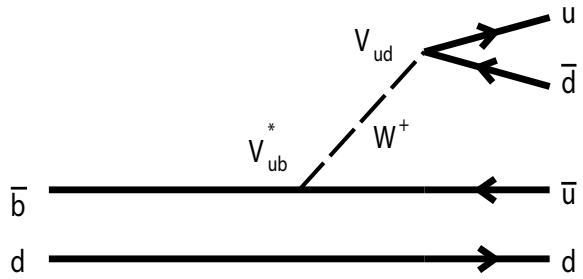




For $B \to \pi\pi$:

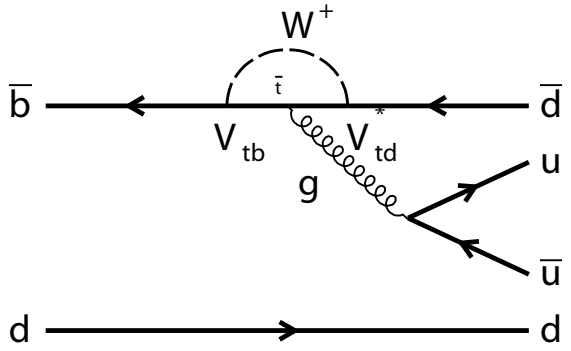
- Penguin and tree diagrams contribute!
- Only tree diagram: $\mathcal{A}_{CP} = 0$
  $\mathcal{S}_{CP} = \sin(2\alpha)$
- Penguin + tree diags.: $\mathcal{A}_{CP} \neq 0$
  $\mathcal{S}_{CP} = \sqrt{1 - \mathcal{A}_{CP}} \sin(2\alpha^{\text{eff}})$

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



Isospin

$I = 0, 2$



$I = 0$

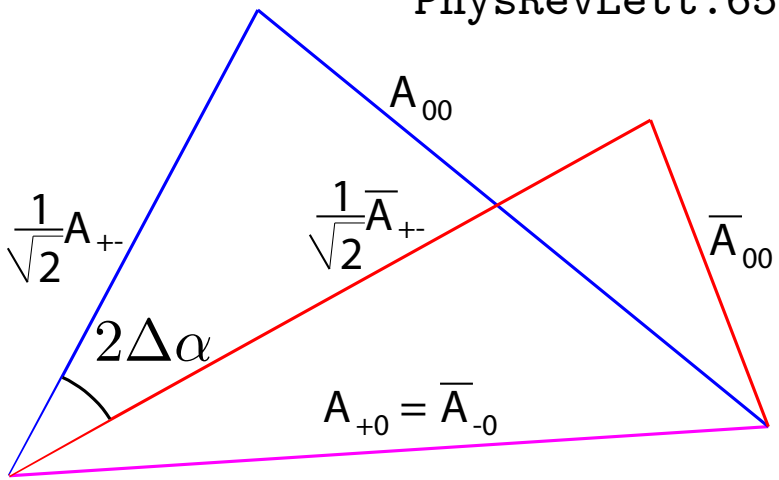
Extraction of α angle from $B \to \pi\pi$

PhysRevLett.65.3381

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

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

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



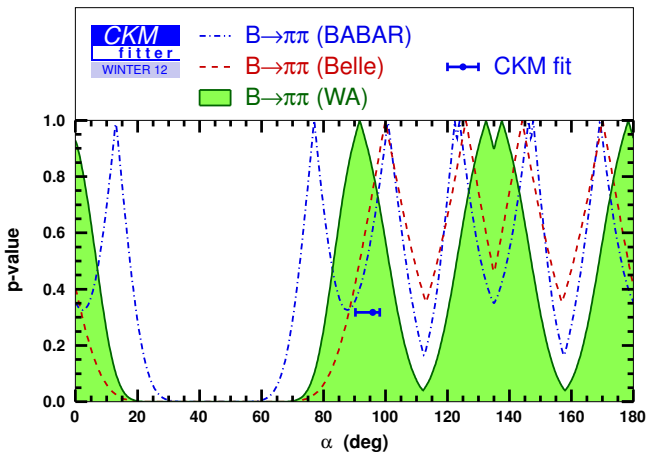
Pure Tree: $A^{+0} = \bar{A}^{-0}$

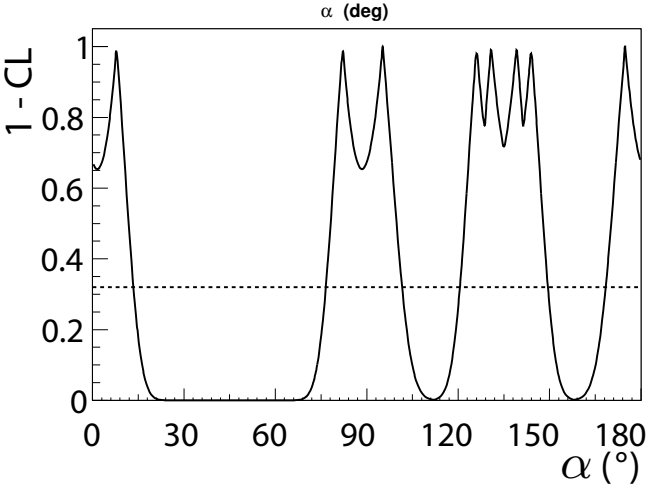
- Isospin analysis requires also $\mathcal{S}_{\pi^+\pi^-}$ and $\mathcal{S}_{\pi^0\pi^0}$.
- $\mathcal{S}_{\pi^0\pi^0}$ needs $\langle\Delta z\rangle \sim 130\mu m$ of $B \to \pi^0\pi^0$ where $\pi^0 \to \gamma\gamma$

$\Rightarrow$ Challenge!

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

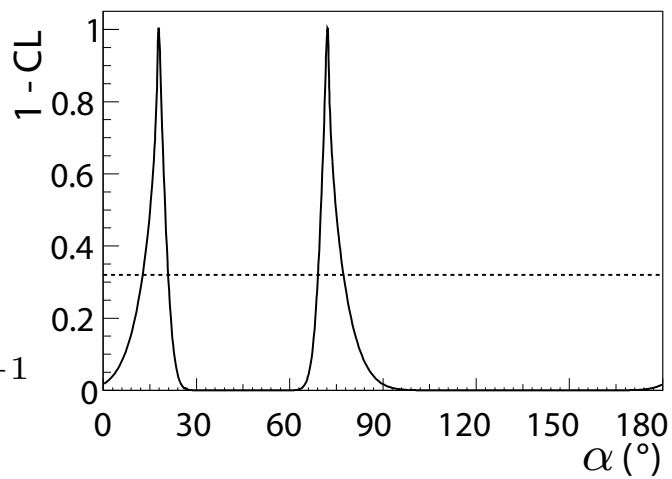
- w/out $\mathcal{S}_{\pi^0\pi^0} \Rightarrow$
  8 fold ambiguity on α



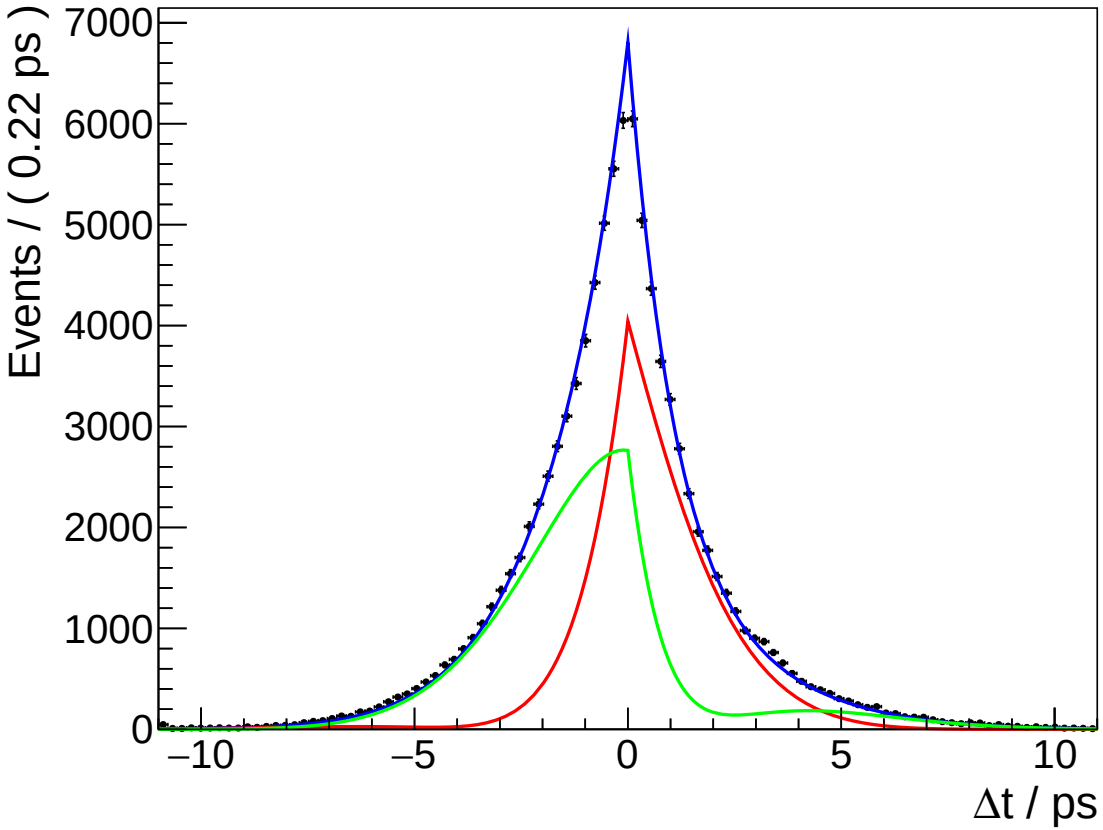


- with $\mathcal{S}_{\pi^0\pi^0} \Rightarrow$
  2 fold ambiguity on α
- Converted $\gamma \to e^+e^-$ and $\pi^0 \to e^+e^-\gamma$ req. for $\langle \Delta z \rangle$
- Possible with
  $\mathcal{L}_{\text{Belle II}} = 50 \cdot \mathcal{L}_{\text{Belle}}$ and
  Belle II PXD?

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



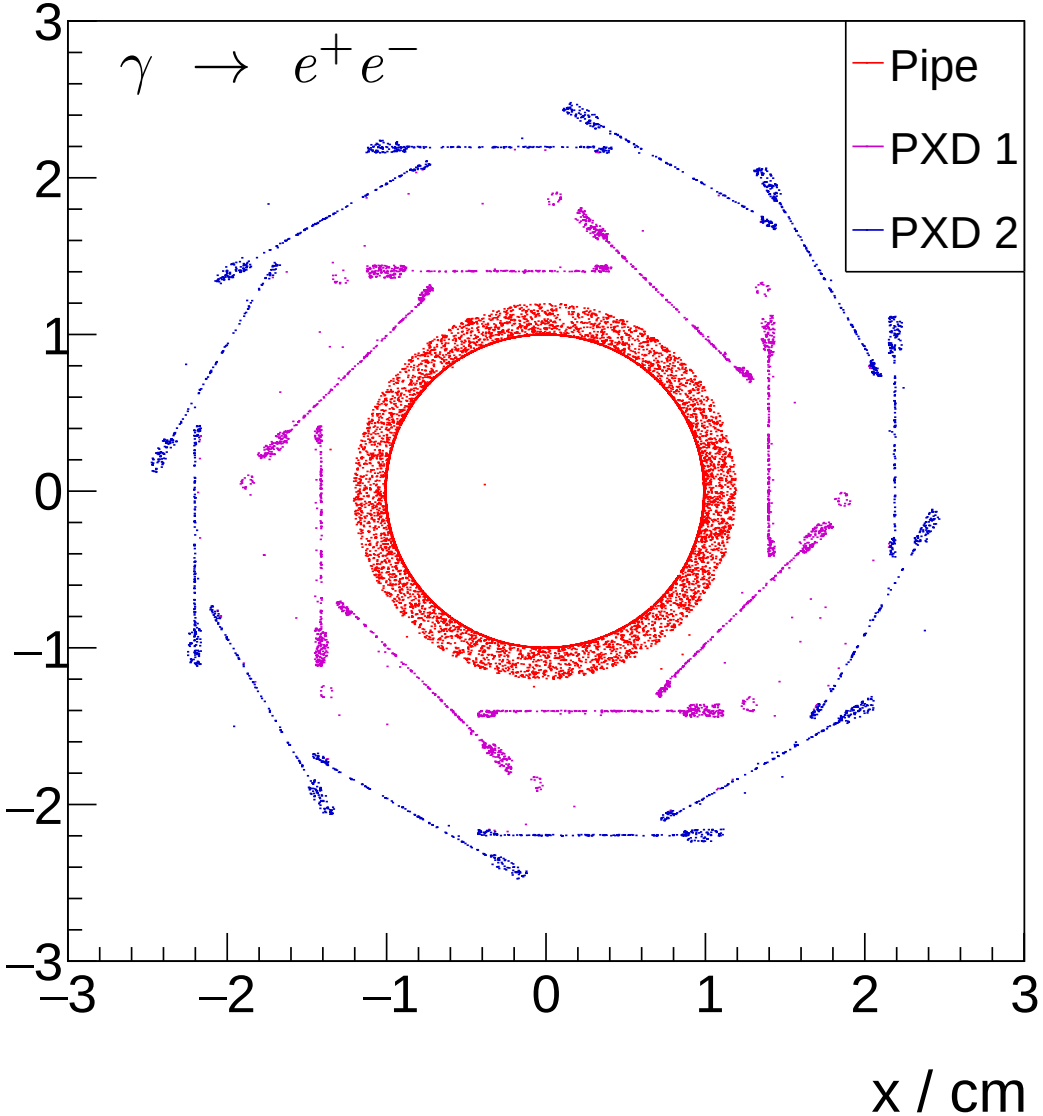
Expected Asymmetry



- $\mathcal{A}_{CP}{}^{\pi^0\pi^0} = 0.43$ (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 $B^0 \to \pi^0\pi^0$



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

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

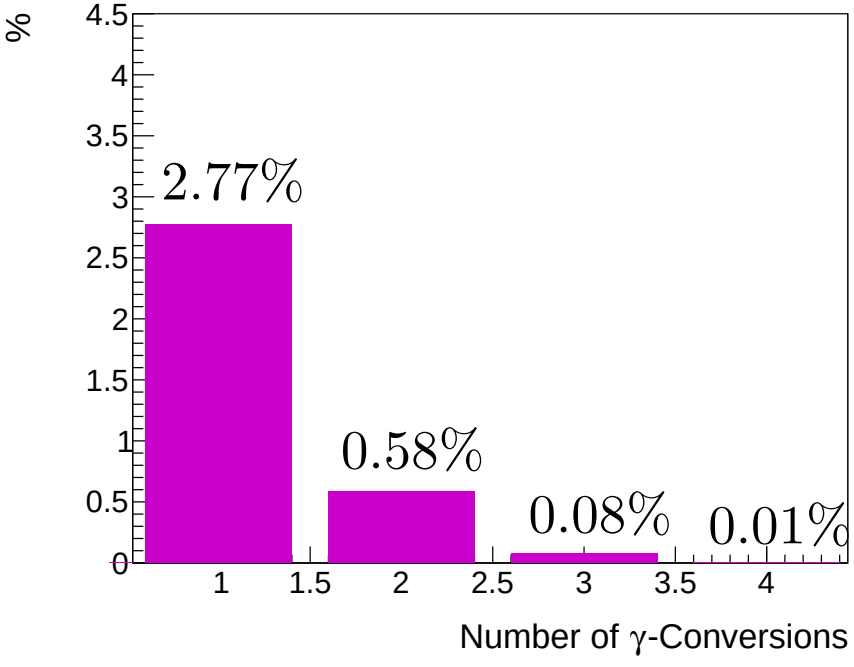
~ 100k events.

- 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?

Total inside PXD	3.10 %

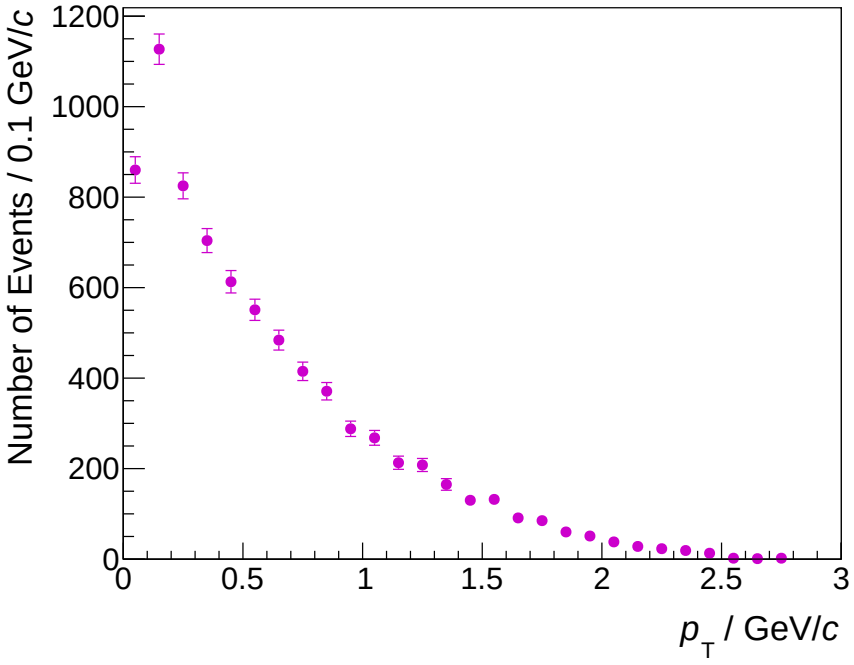
c) ... and at least one γ-conversion or one $\pi^0 \to e^+e^-\gamma$ decay?

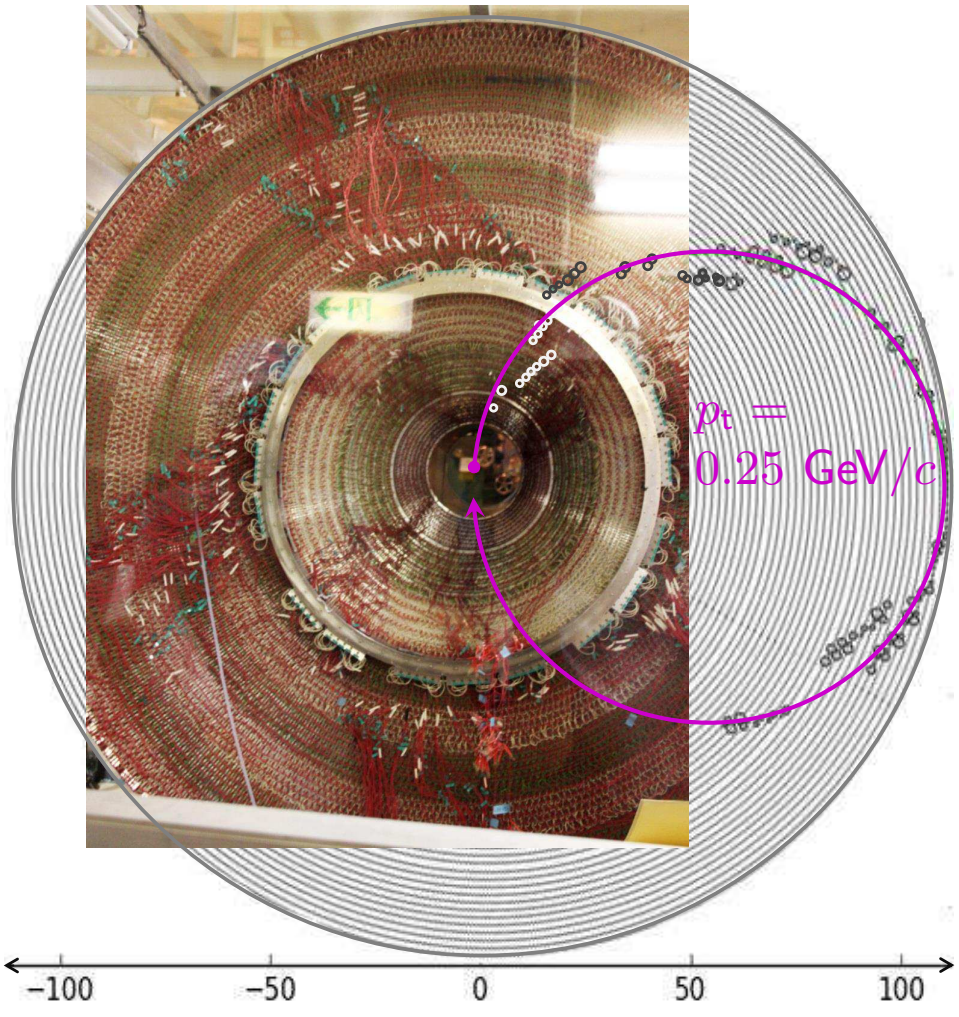
$\pi^0 \to e^+e^-\gamma$	2.00 %
Total $\pi^0 \cup \gamma$	5.05 %

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

p_t-Distribution of γ-Daughters

- e^+ and e^- from γ



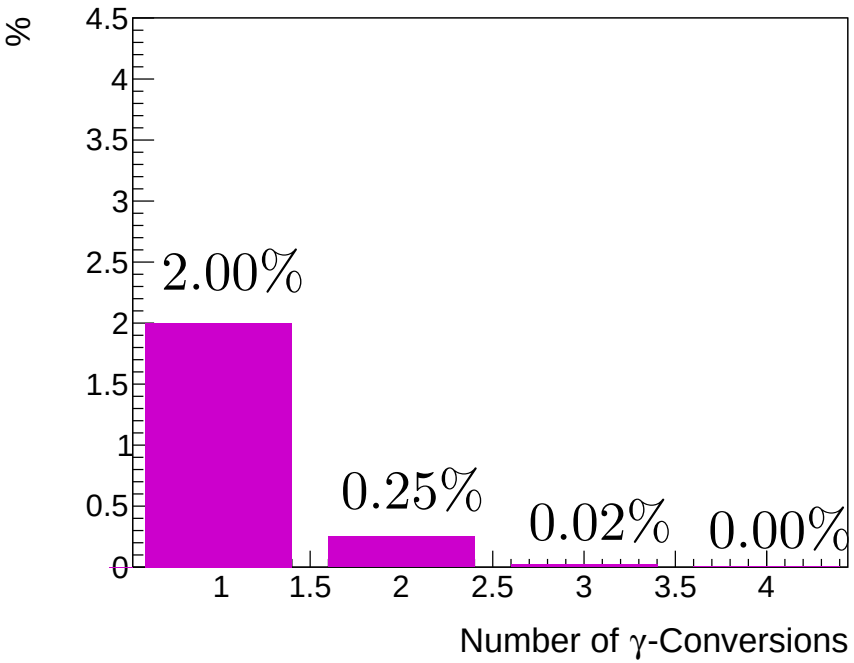


Events with γ-Convs. after p_t cut

✂ One of the γ- or π^0-daughters (e^+ or e^-) has $p_t > 250$ MeV/c.

a) If there is an event with γ-conversions

⇒ How Many?



b) ... at least one γ-conversion?

Total inside PXD	2.82 %

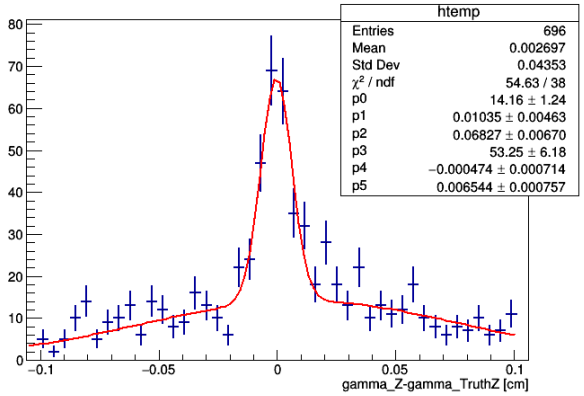
c) ... and at least one γ-conversion or one $\pi^0 \to e^+e^-\gamma$ decay?

$\pi^0 \to e^+e^-\gamma$	1.72 %
Total $\pi^0 \cup \gamma$	4.50 %

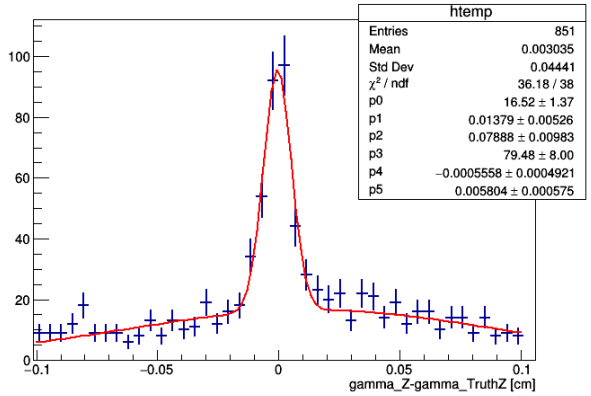
Requirement: All converted γ in accept. and not converted in ECL

π^0 and B^0 Vertex Resolution

$\pi^0 \rightarrow \gamma\ \gamma$

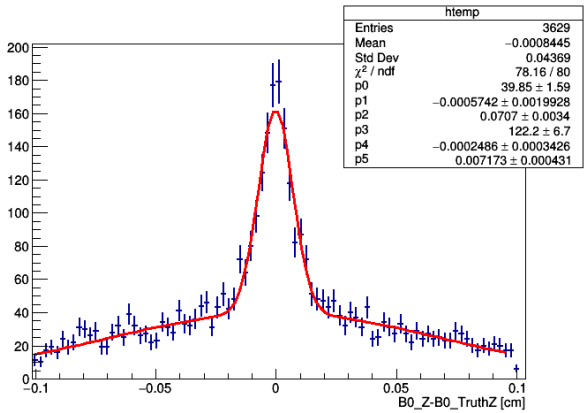


- Bias = -4.7 μm
- Resolution = 65.4 μm

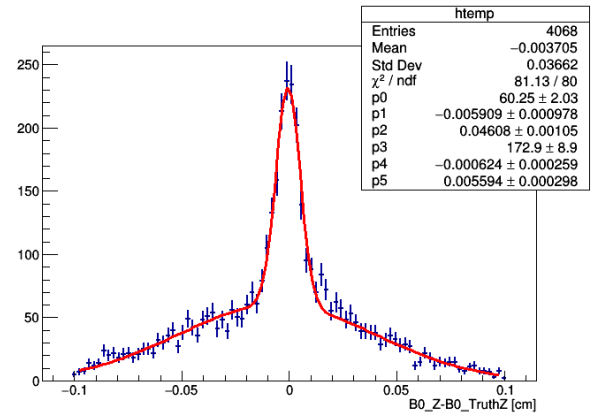


- Bias = -5.6 μm
- Resolution = 58.0 μm

$B^0 \rightarrow \pi^0\ \pi^0$



- Bias = 2.5 μm
- Resolution = 71.7 μm



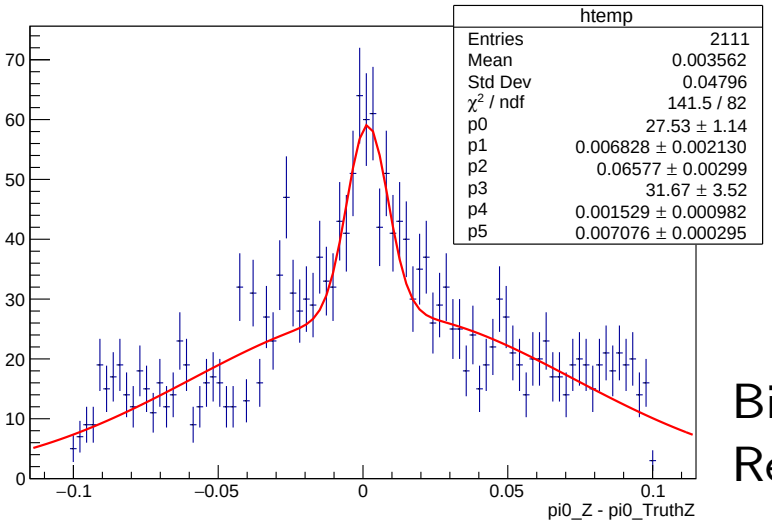
- Bias = 6.2 μm
- Resolution = 55.9 μm

V0 Finder

e^+, e^- Lists

π^0 and B^0 Vertex Resolution

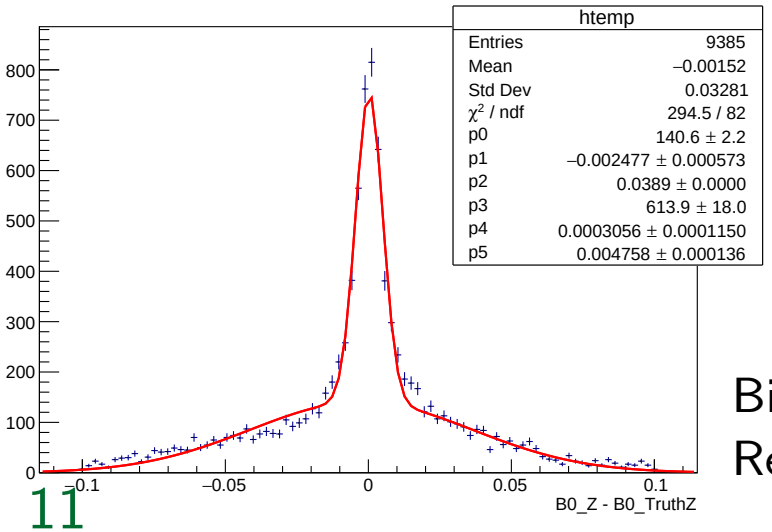
$\pi^0 \rightarrow e^+e^-\gamma$



Bias $= 1.5$ µm

Resolution $= 70.8$ µm

$B^0 \rightarrow \pi^0\,\pi^0$



Bias $= 3.1$ µm

Resolution $= 47.6$ µm

- Total amount of events with 4γ in ECL: 64.15%
- Events available for $\mathcal{S}_{CP}$: $N_{\mathcal{S}_{CP}} = N_{\text{Conv}} + N_{\text{Dalitz}}$
- Events available for $\mathcal{A}_{CP}$: $N_{\mathcal{A}_{CP}} = N_{\text{Conv}} + N_{\text{Dalitz}} + N_{4\gamma}$

$\Rightarrow \frac{N_{\mathcal{S}_{CP}}}{N_{\mathcal{A}_{CP}}} = 7.3\%$

$\Rightarrow$ After $\asymp p_t$: $\frac{N_{\mathcal{S}_{CP}}}{N_{\mathcal{A}_{CP}}} = 6.6\%$

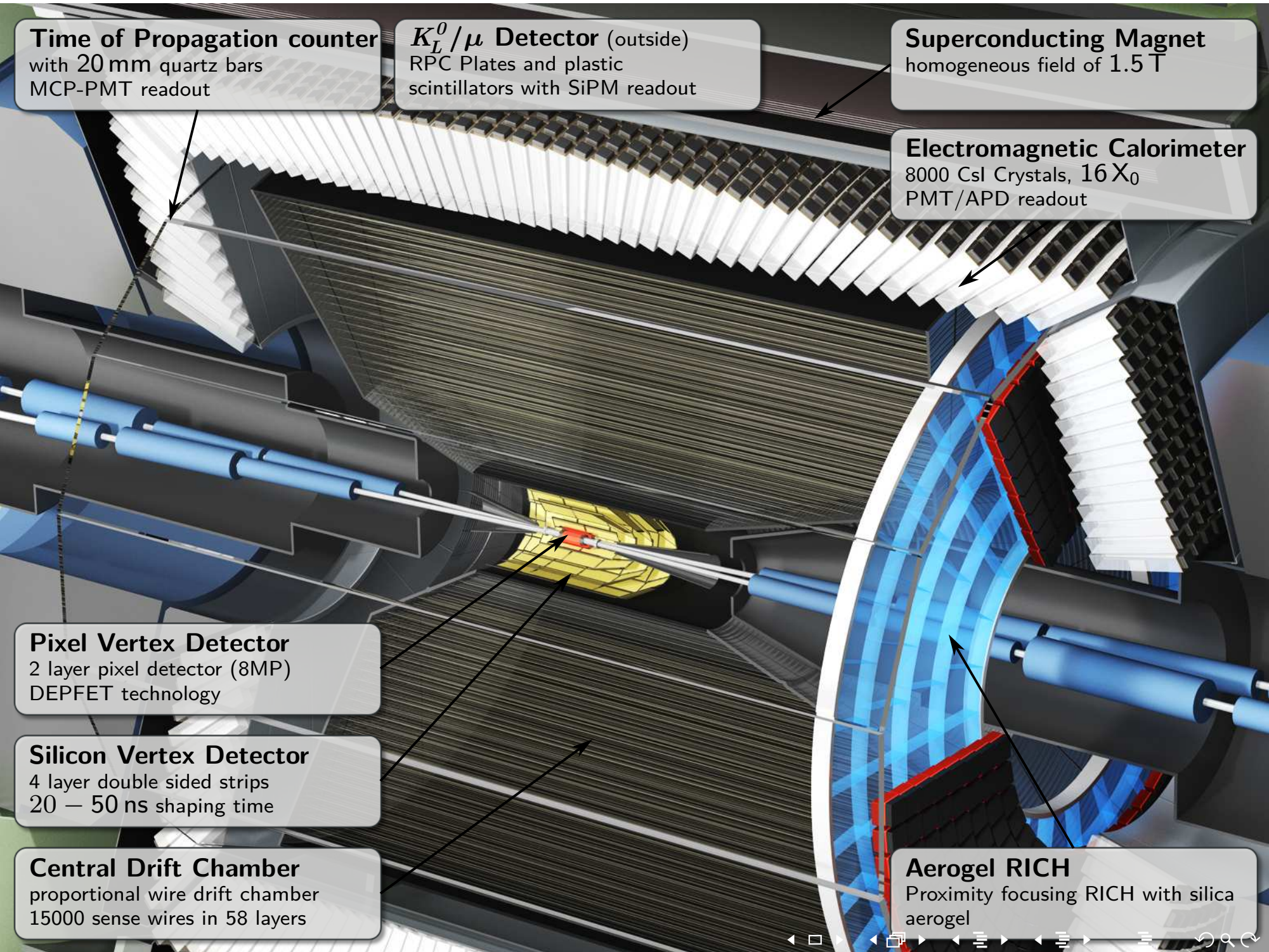
J/ψ Resolutions:

Belle II $= 22$µm

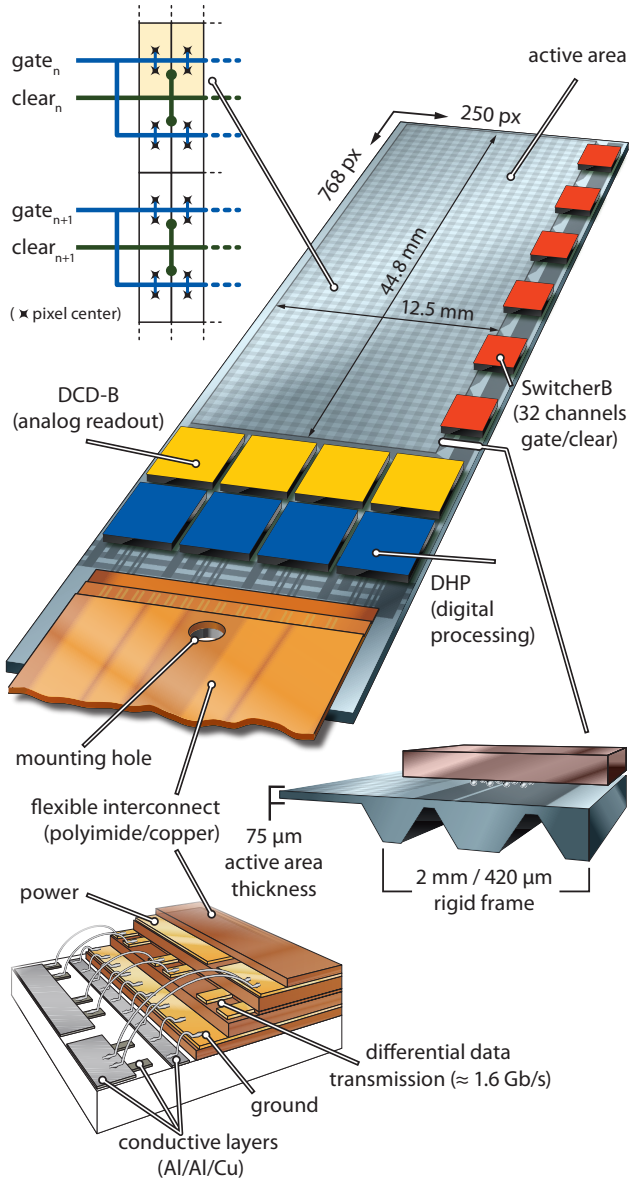
Belle $= 63$µm

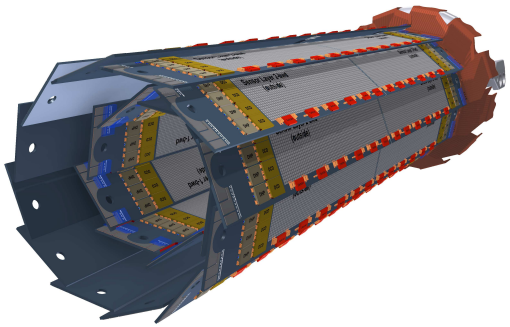
Summary and Outlook

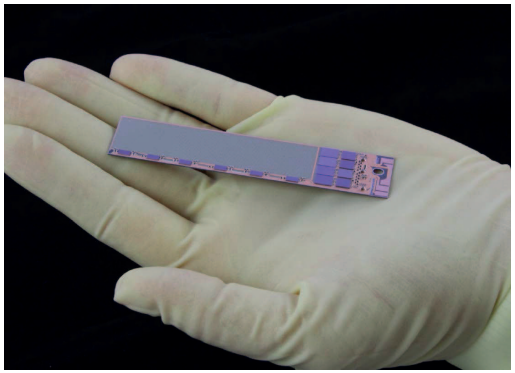
- Resolution of $B \to \pi^0\pi^0$ Vertex within Belle J/ψ accuracy but: How many can we reconstruct?
- Δt resolution?
- How much can we improve of $e^{\pm}$ reconstruction?
- What to do when only one $e^{\pm}$ from conversion?


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

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

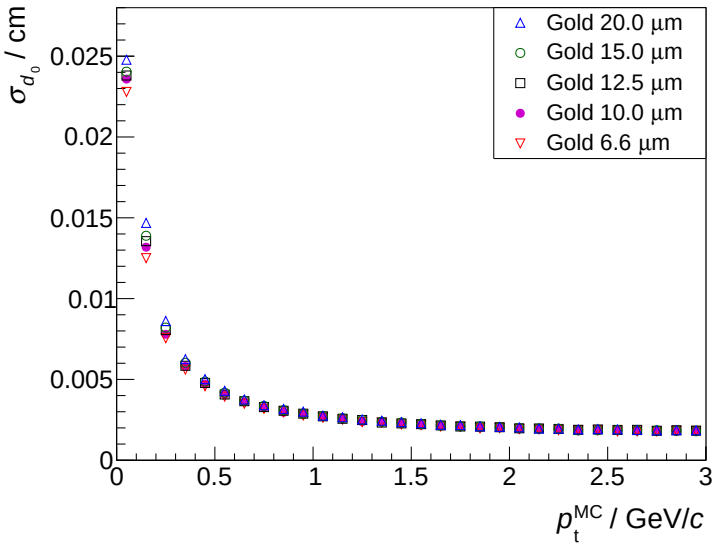
$\Rightarrow$ Pixel Detector needed !

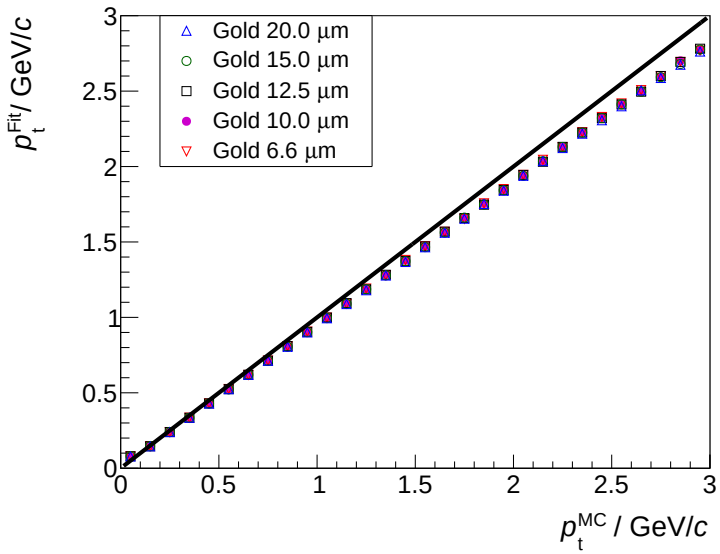
$\Rightarrow$ DEPFET Technology most suited

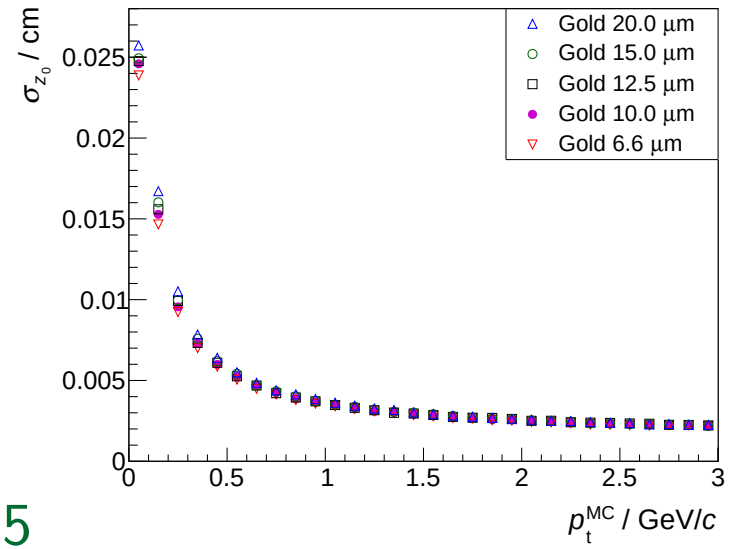
Depleted Field Effect Transistor

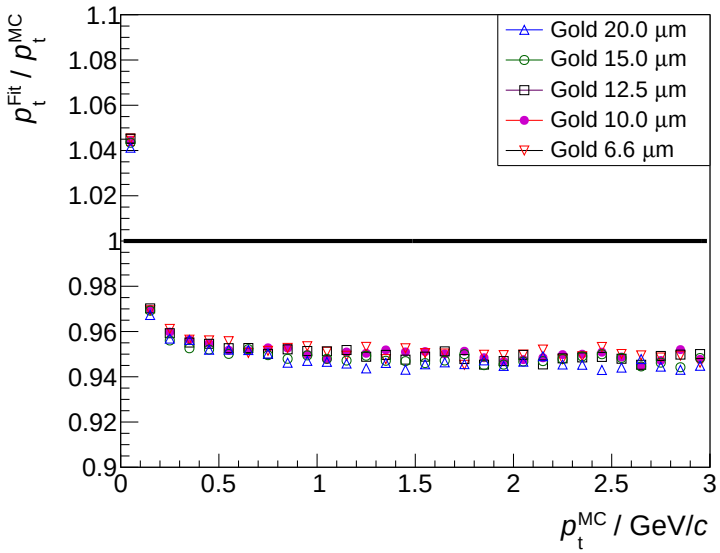
e^+, e^- Track Reconstruction

- e^+, e^-

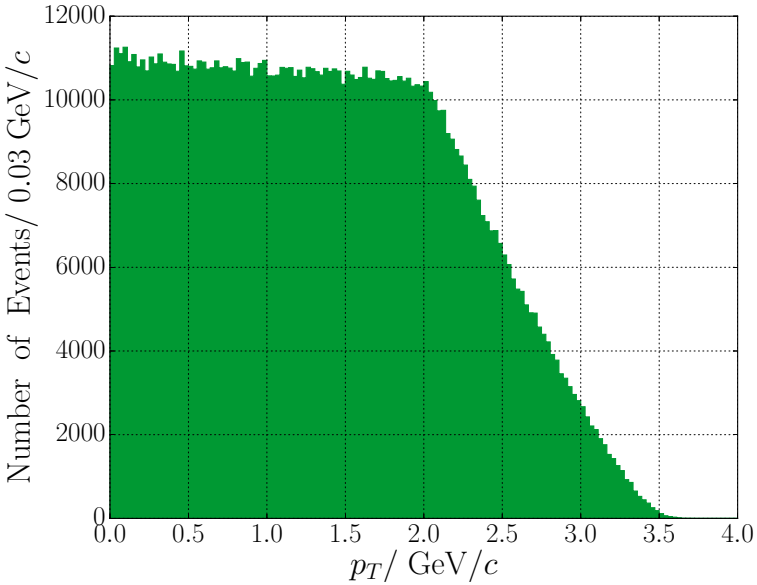


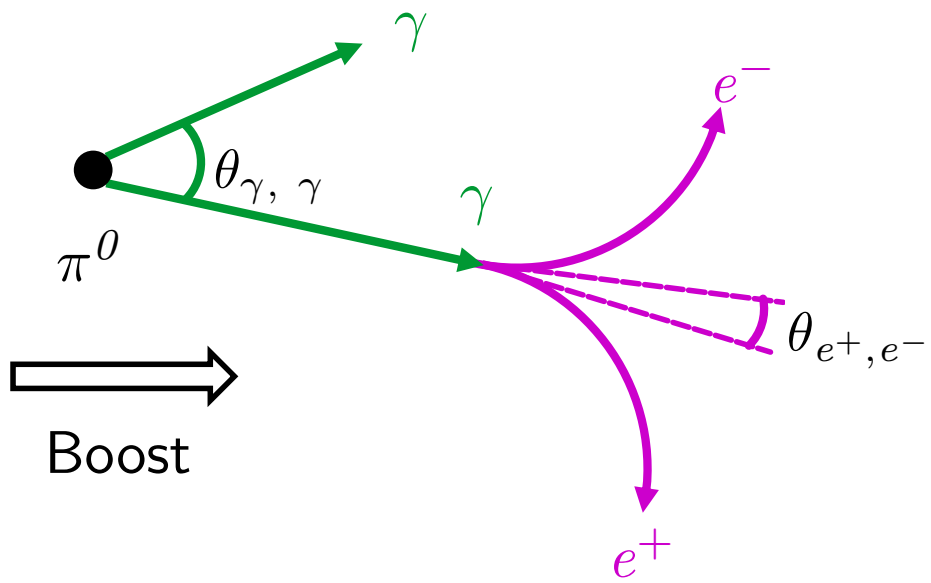


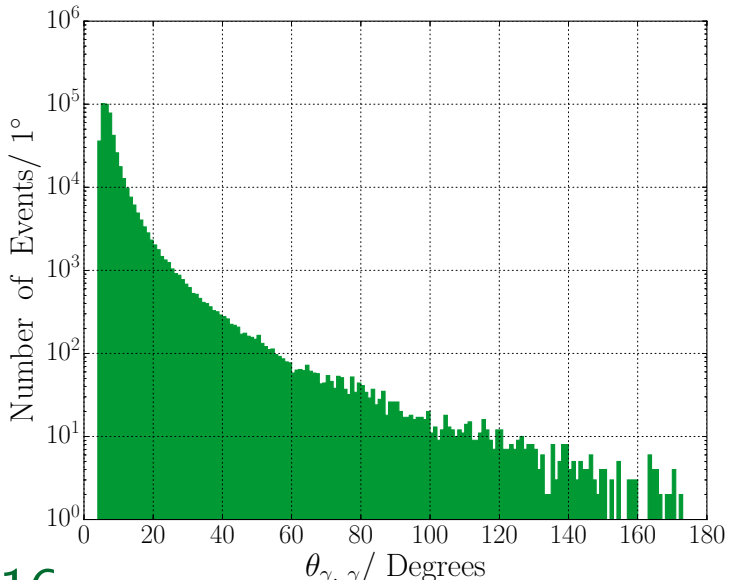


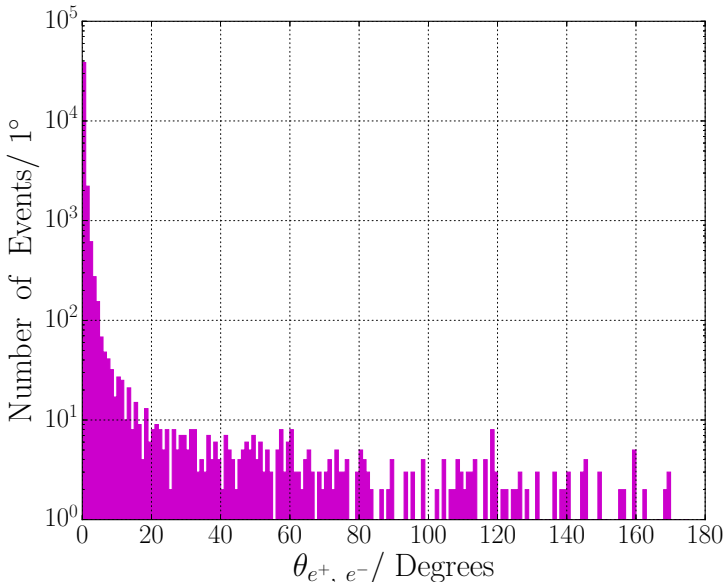


$\pi^0 \to \gamma\gamma$ Kinematics

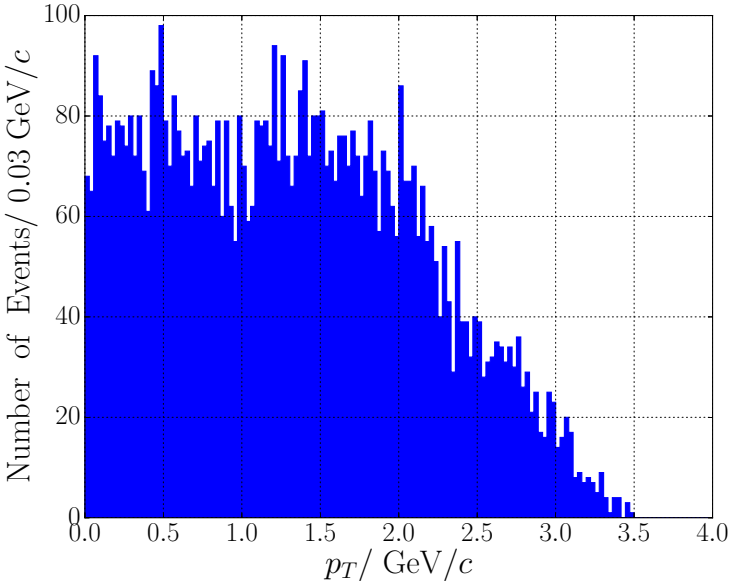


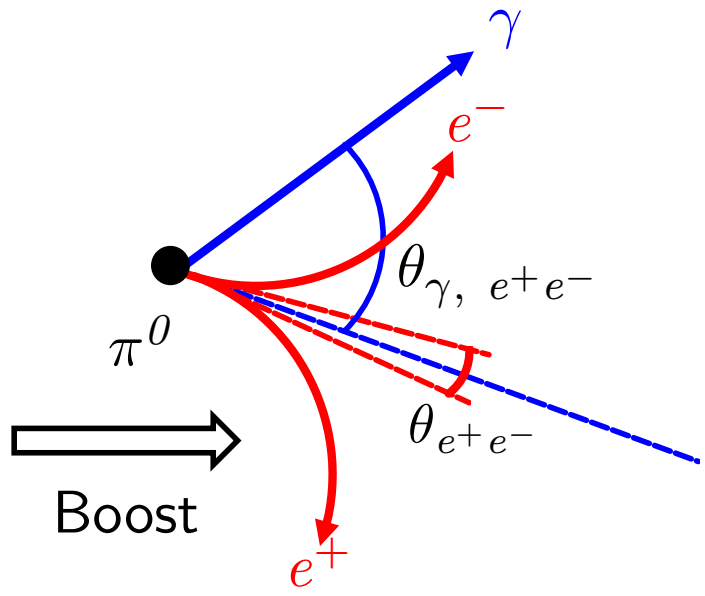


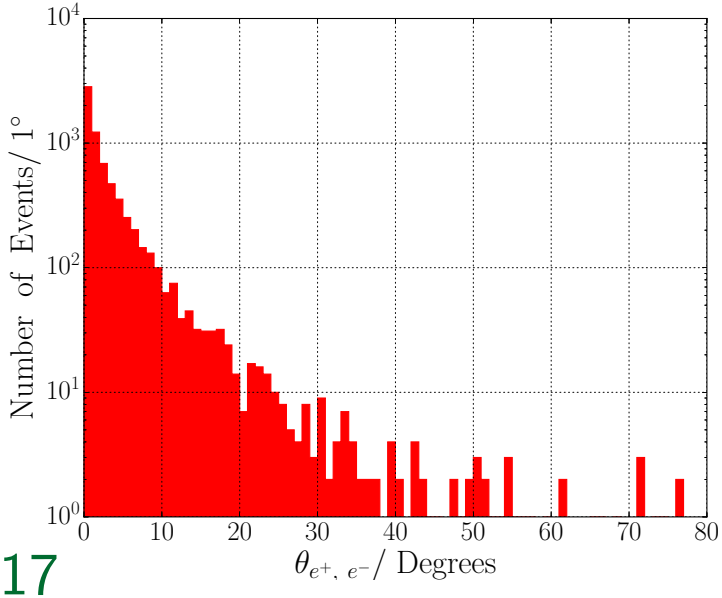


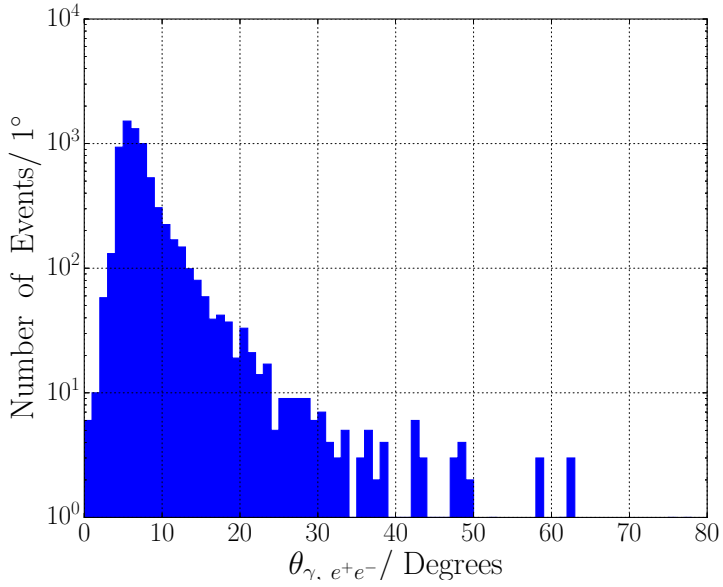


$\pi^0 \to e^+e^-\gamma$ Kinematics









CP-Violation in the SM

- Why CP-Violation? $\Rightarrow$ Matter-Antimatter-Asymm. in the universe larger than in SM. (Sakharov)
- Why in the B^0-system? $\Rightarrow$ largest CP-V. within the SM.
- CP-V. in the SM $\Rightarrow$ Weak Interaction $\Rightarrow$ $\mathbf{V}_{CKM}$

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

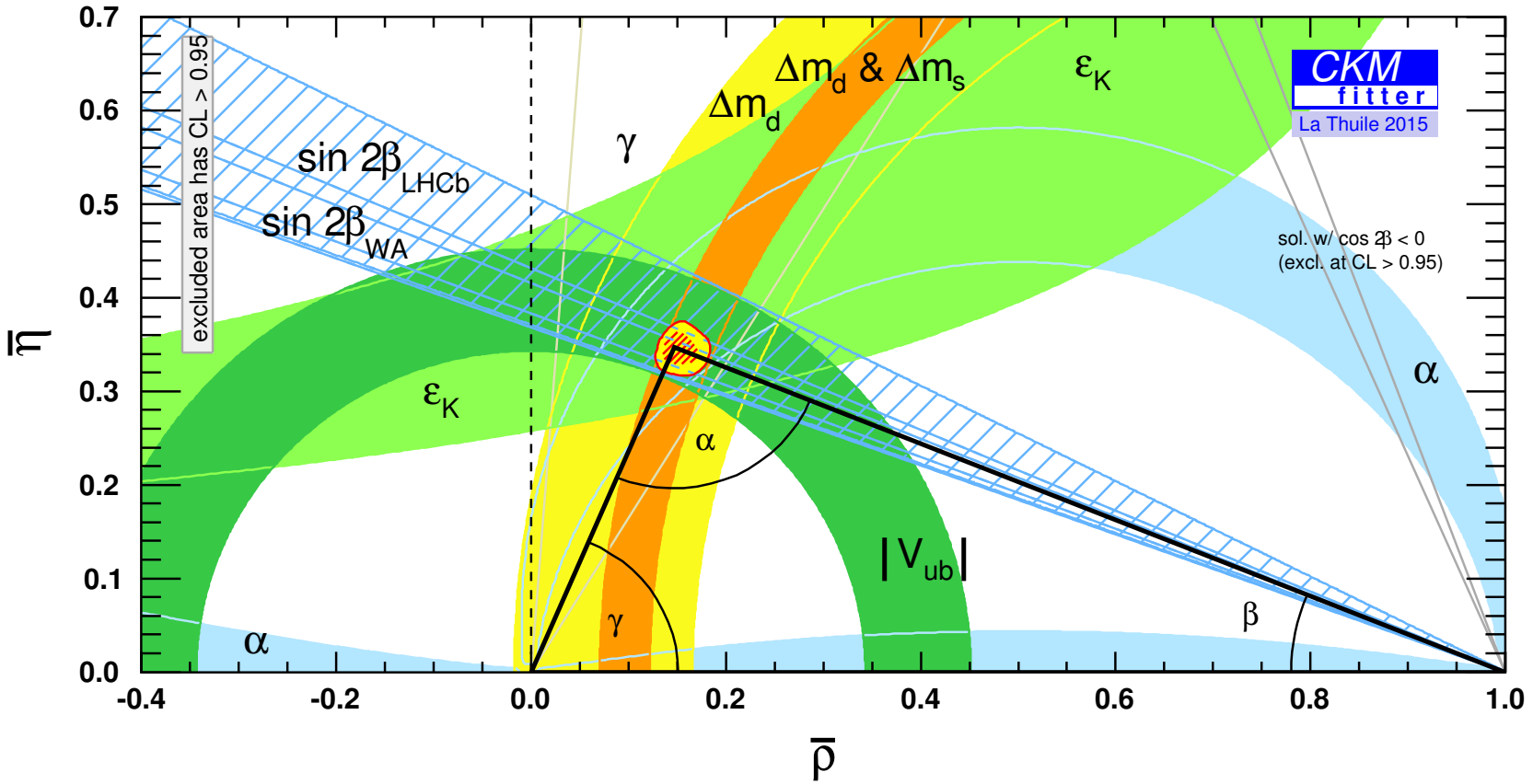
- Wolfenstein-Parameters: $\lambda = \sin\theta_C \approx 0.2, A, \rho, \eta$

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

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

- Unitarity: $\sum_k V_{ik}V^*_{jk} = 0 \Rightarrow \underbrace{V_{ud}V^*_{ub}}_{\mathcal{O}(\lambda^3)} + \underbrace{V_{cd}V^*_{cb}}_{\mathcal{O}(\lambda^3)} + \underbrace{V_{td}V^*_{tb}}_{\mathcal{O}(\lambda^3)} = 0$

CKM-Triangle



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