Compton Polarimetry @ Storage Rings

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ELectron Stretcher Accelerator

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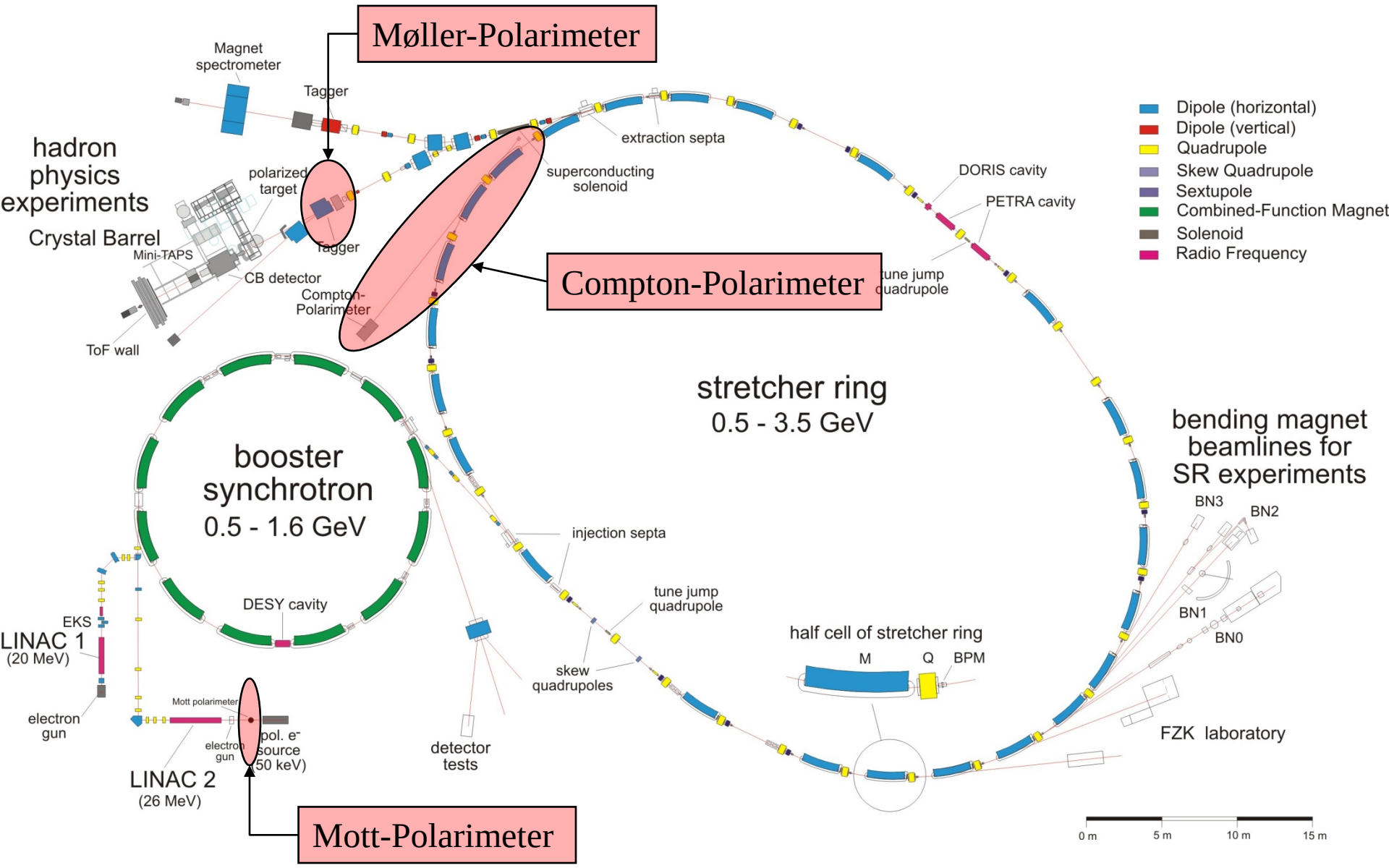
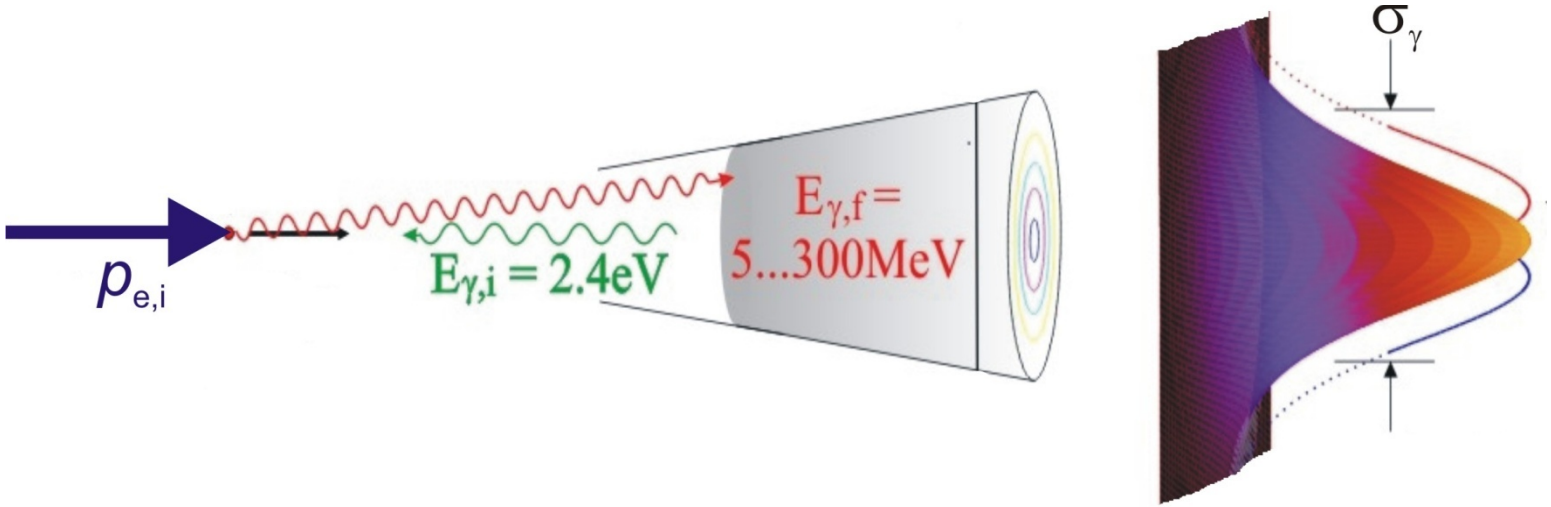
Here:

Concentrating on backscattered photons only!

Electron Stretcher Accelerator (ELSA)



Compton Scattering



Differential cross section:

$$\frac{d\sigma}{d\Omega^*}\left(\vec{S},\vec{P}\right) = \Sigma_0 + \Sigma_1\left(S_1\right) + \Sigma_2\left(S_3,\vec{P}\right)$$

Compton kinematics:

$$K_f^* = \frac{K_i^*}{1 + K_i^* \cdot \left(1 - \cos\vartheta^*\right)}$$

Polarised electrons:

$$\Sigma_2\left(S_3,\vec{P}\right) = -S_3P_z \cdot \underbrace{CK_f^* \sin\vartheta^*\left(1-\cos\vartheta^*\right)\sin\varphi^*}_{\Sigma_{2Z}} - S_3P_s \cdot \underbrace{CK_f^*\left(1-\cos\vartheta^*\right)\left(K_f^* + K_i^*\right)\cos\vartheta^*}_{\Sigma_{2S}}$$

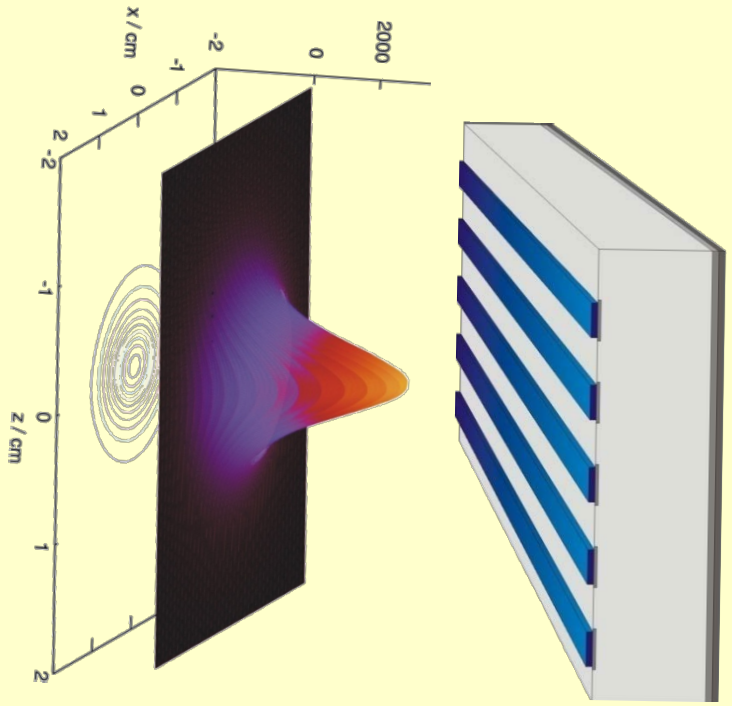
$$C = \frac{r_e^2}{2} \cdot \left(\frac{K_f^*}{K_i^*}\right)^2$$

spatial asymmetry

counting rate asymmetry

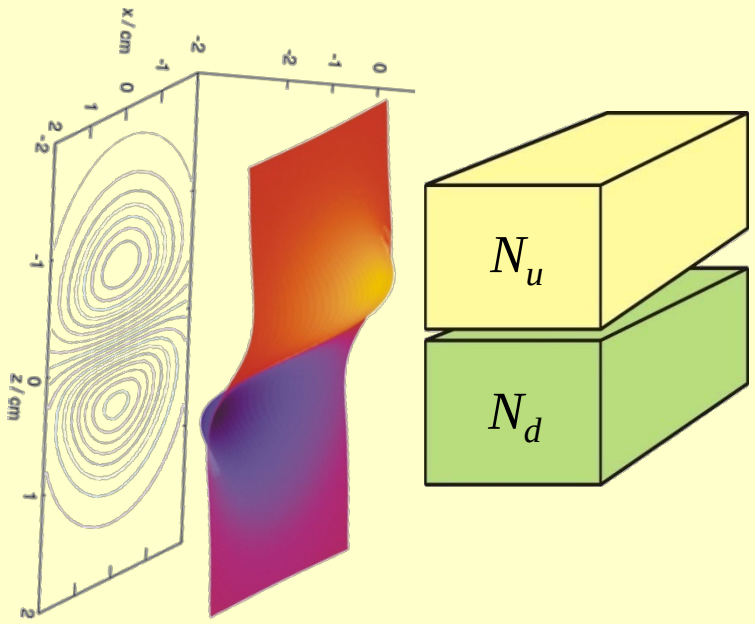
Measuring Principle

shift of the centre of the photon spatial distribution



silicon strip detector and
pair conversion required:
rather complicated

integral up-down counting rate asymmetry

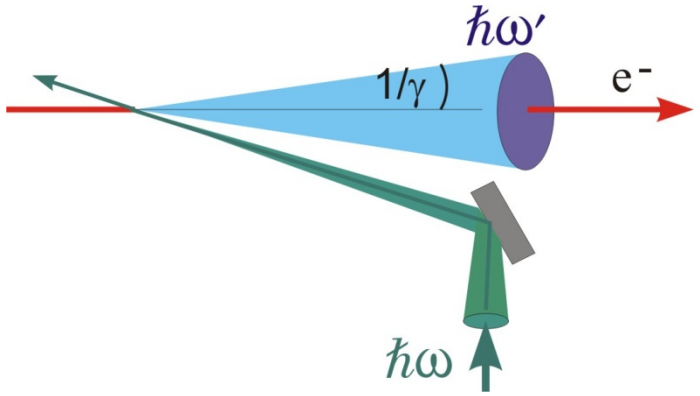


at least 2 crystal detectors and
no conversion required:
rather simple

Design Criteria

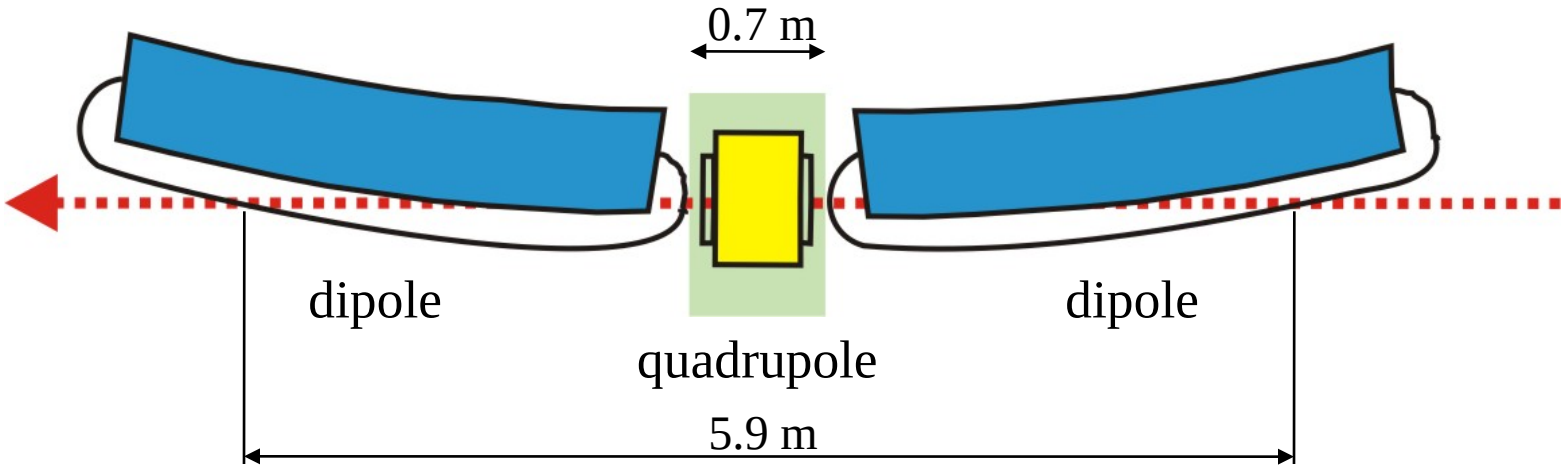
Basic Parameters:

- crossing angle: $\delta \approx 3\text{mrad}$
- electron beam width: $\sigma \approx 1\text{mm}$
- ➢ interaction region: $l \approx 0.7\text{m}$



Background due to Beam-Gas Radiation:

➢ straight section should be considerably short!



Numerical Simulations

1. Ideal beams ($\sigma_x=\sigma_z=0$) and infinite detector (simple):

– **integral asymmetry**:

$$A_{\text{int}} = \frac{\sqrt{N_u^+ N_d^-} - \sqrt{N_u^- N_d^+}}{\sqrt{N_u^+ N_d^-} + \sqrt{N_u^- N_d^+}} = \frac{\int_0^{\pi} d\varphi^* \int_0^{\pi} \sin\vartheta^* d\vartheta^* \cdot \Sigma_{2Z}}{\int_0^{\pi} d\varphi^* \int_0^{\pi} \sin\vartheta^* d\vartheta^* \cdot \Sigma_0} \cdot P_\gamma \cdot P_e$$

– **shift of center of spatial distribution**:

$$\Delta\overline{z} = \overline{z}_+ - \overline{z}_- = \frac{\int_0^{2\pi} d\varphi^* \int_0^{\pi} \sin\vartheta^* d\vartheta^* \cdot z(\vartheta^*,\varphi^*) \cdot \Sigma_{2Z}}{\int_0^{2\pi} d\varphi^* \int_0^{\pi} \sin\vartheta^* d\vartheta^* \cdot \Sigma_0} \cdot P_\gamma \cdot P_e$$

$$\left(\text{with } z(\vartheta^*,\varphi^*) = \frac{D}{\gamma} \cdot \frac{\sin\vartheta^* \left(\beta - \cos\vartheta^*\right)}{\left(1-\beta\cos\vartheta^*\right)^2} \cos\varphi^* \right)$$

1-dim integration: 

Numerical Simulations

2. Ideal beams (σ_x=σ_z=0) and finite detector (moderate):

– **integral asymmetry**:

$$A_{\text{int}} = \frac{\int_{-X_{\text{det}}/2}^{X_{\text{det}}/2} dx \int_{0}^{Z_{det}/2} dz \cdot \frac{\partial(\vartheta^*, \varphi^*)}{\partial(x,z)} \cdot \Sigma_{2Z}\left(\vartheta^*(x,z), \varphi^*(x,z)\right)}{\int_{-X_{\text{det}}/2}^{X_{\text{det}}/2} dx \int_{0}^{Z_{det}/2} dz \cdot \frac{\partial(\vartheta^*, \varphi^*)}{\partial(x,z)} \cdot \Sigma_{0}\left(\vartheta^*(x,z), \varphi^*(x,z)\right)} \cdot P_\gamma \cdot P_e$$

– **shift of center of spatial distribution**:

$$\Delta\overline{z} = \frac{\int_{-X_{\text{det}}/2}^{X_{\text{det}}/2} dx \int_{-Z_{det}/2}^{Z_{det}/2} dz \cdot \frac{\partial(\vartheta^*, \varphi^*)}{\partial(x,z)} \cdot z \cdot \Sigma_{2Z}\left(\vartheta^*(x,z), \varphi^*(x,z)\right)}{\int_{-X_{\text{det}}/2}^{X_{\text{det}}/2} dx \int_{-Z_{det}/2}^{Z_{det}/2} dz \cdot \frac{\partial(\vartheta^*, \varphi^*)}{\partial(x,z)} \cdot \Sigma_{0}\left(\vartheta^*(x,z), \varphi^*(x,z)\right)} \cdot P_\gamma \cdot P_e$$

(with: $\frac{\partial(\vartheta^*, \varphi^*)}{\partial(x,z)} = \left(\frac{\gamma}{D}\right)^2 \cdot \frac{\left(1-\beta\cos\vartheta^*\right)^3}{\beta-\cos\vartheta^*}$)

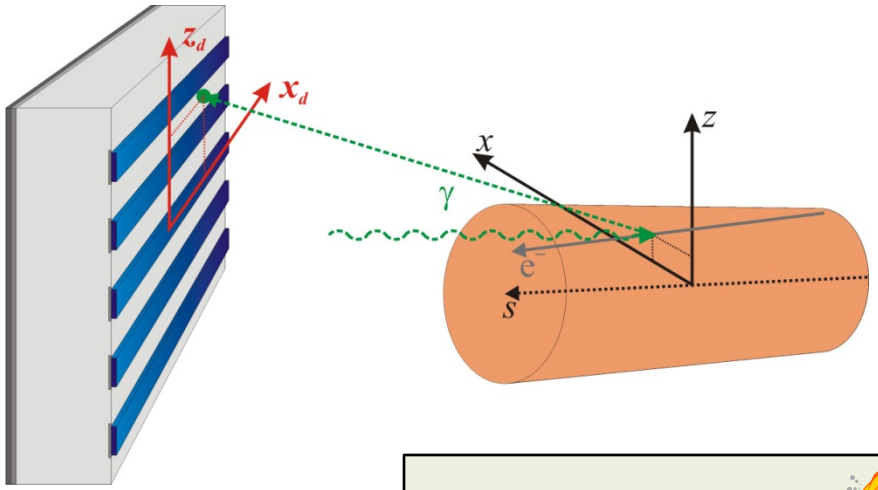
2-dim integration: 

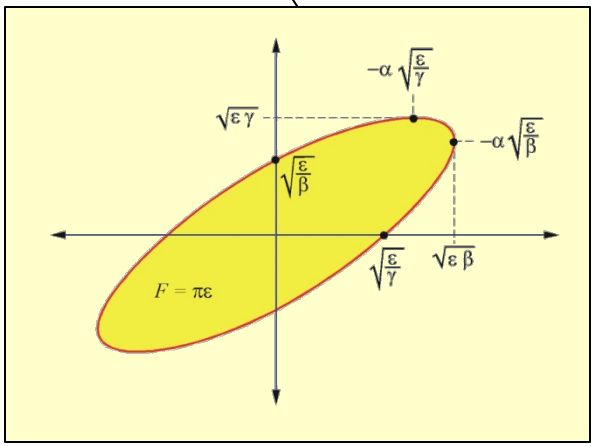
Numerical Simulations

3. Real beams ($\sigma_x, \sigma_z, \sigma_{x'}, \sigma_{z'} \neq 0$) and finite detector (!!!):

a) 2-D intensity profile of backscattered photons:

$$\dot{N}(x_d, z_d) = \int_{S_0}^{S_1} ds \int_{Z_{min}}^{Z_{max}} dz \int_{X_{min}}^{X_{max}} dx \int_{Z'_{min}}^{Z'_{max}} dz' \int_{X'_{min}}^{X'_{max}} dx' \frac{\partial(\vartheta^*, \varphi^*)}{\partial(x, z)} \cdot \rho_e(s, x, z, x', z') \cdot \rho_\gamma(s, x, z) \cdot \frac{d\sigma}{d\Omega^*}$$





5-dim integration: 

Numerical Simulations

3. Real beams ($\sigma_x, \sigma_z, \sigma_{x'}, \sigma_{z'} \neq 0$) and finite detector (!!!):

b) Asymmetry and shift from mean values:

- integral asymmetry:

$$\left.\begin{aligned} \dot{N}_u^{+,-} &= \sum_{i,j}^{\forall z_j \geq 0} \dot{N}^{+,-}(x_i, z_j) \\ \dot{N}_d^{+,-} &= \sum_{i,j}^{\forall z_j \leq 0} \dot{N}^{+,-}(x_i, z_j) \end{aligned}\right\} \quad A_{\text{int}} = \frac{\sqrt{\dot{N}_u^+ \dot{N}_d^-} - \sqrt{\dot{N}_u^- \dot{N}_d^+}}{\sqrt{\dot{N}_u^+ \dot{N}_d^-} + \sqrt{\dot{N}_u^- \dot{N}_d^+}}$$

- shift of center of spatial distribution:

$$\Delta\bar{z} = \sum_{i,j} z_j \dot{N}^+(x_i, z_j) - \sum_{i,j} z_j \dot{N}^-(x_i, z_j)$$

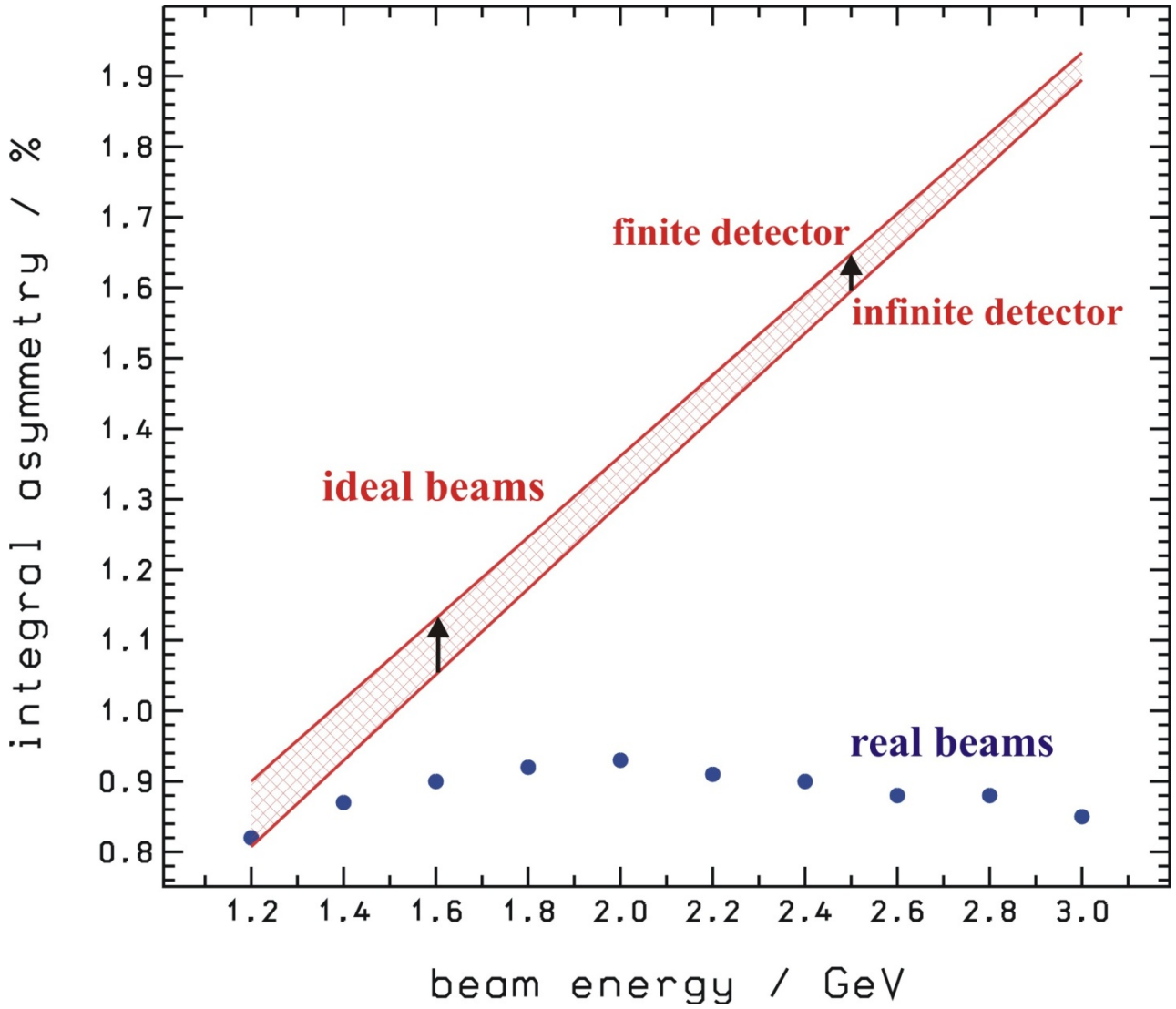
#15744 5-dim integrations: 

5-dim integration for each point:

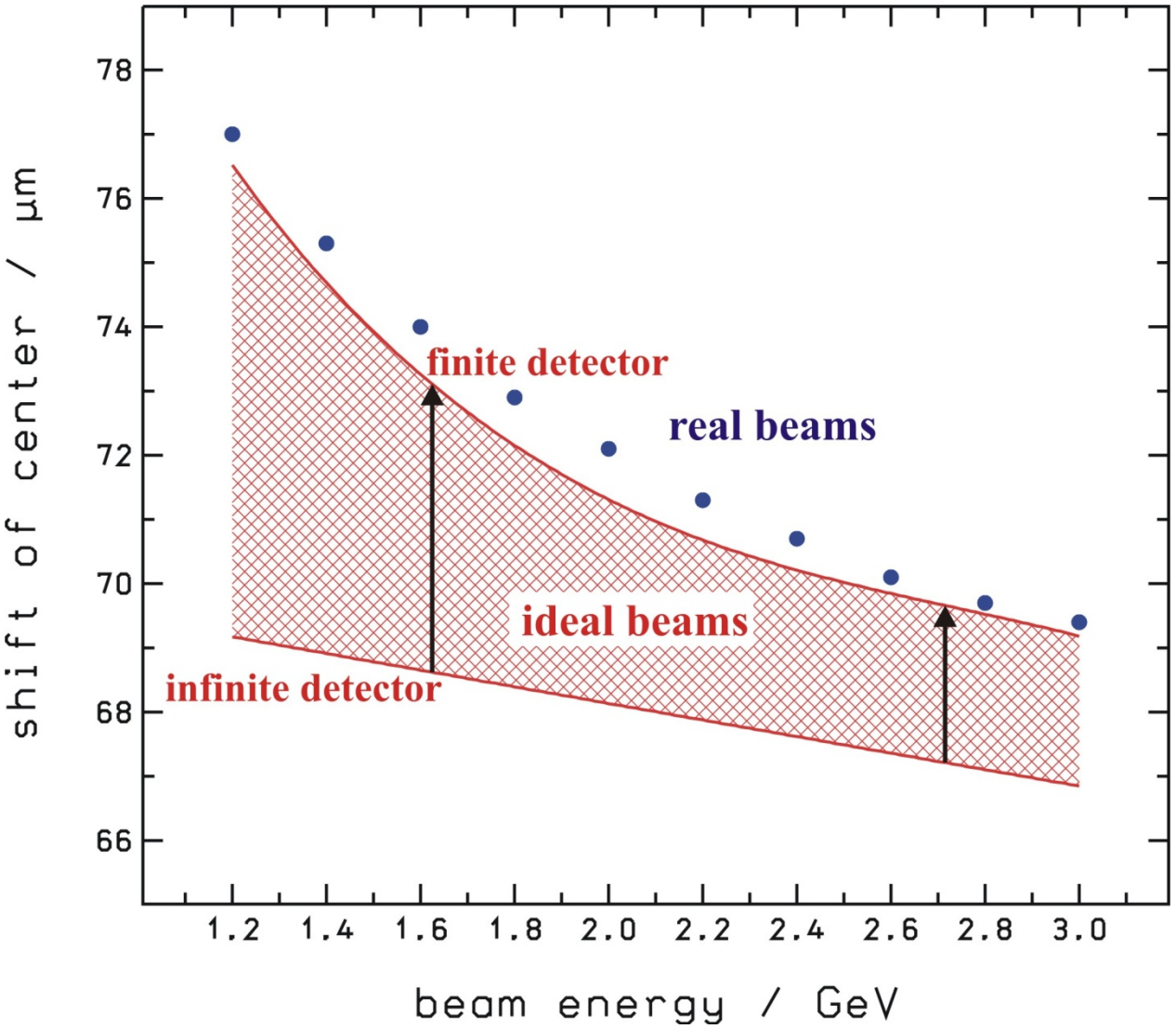
- detector size = 4.0 x 3.84 cm^2
- detector pitch = 100μm

➢ in total 41 x 384 points

Counting Rate Asymmetry

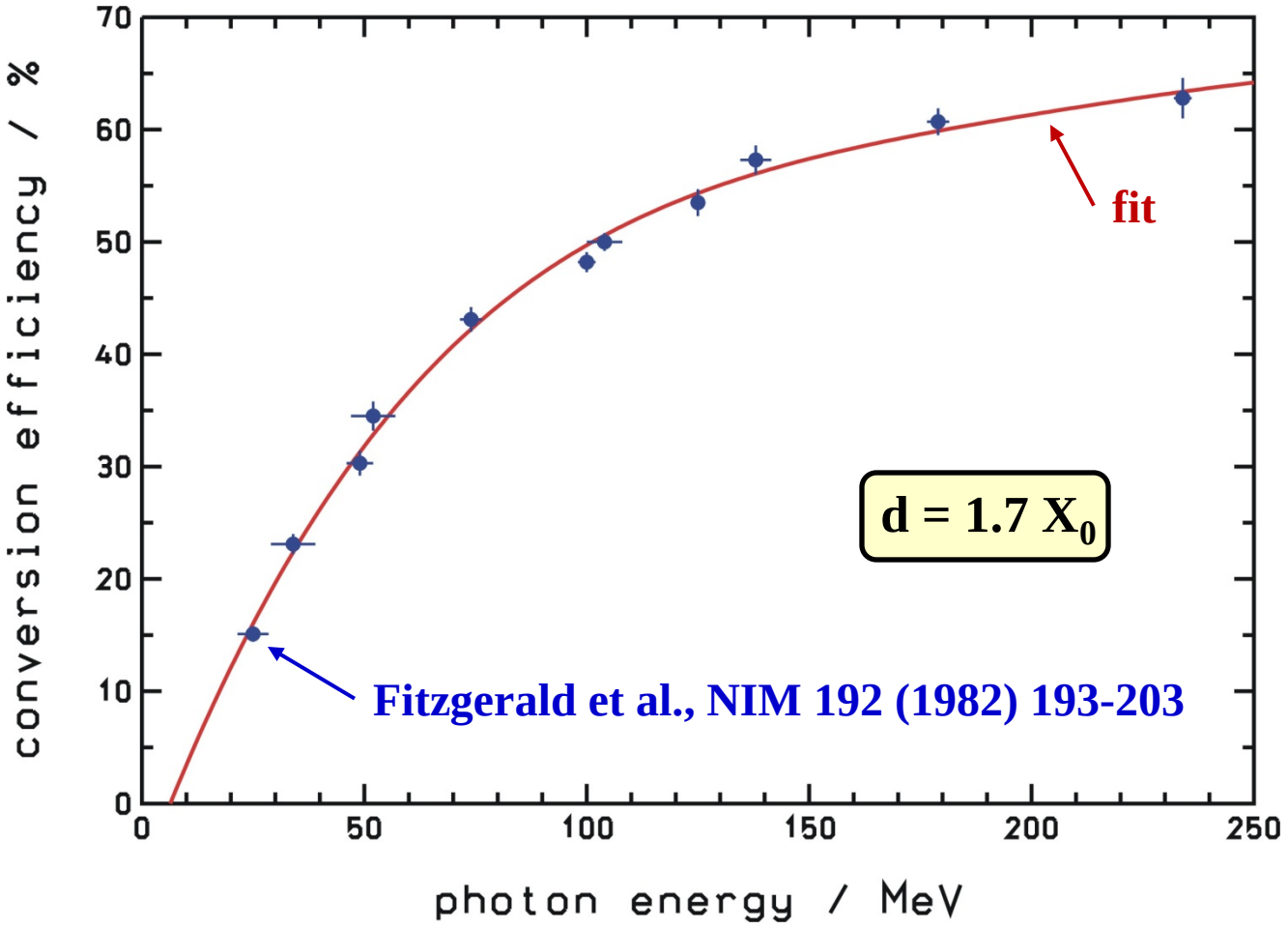


Shift of Spatial Distribution

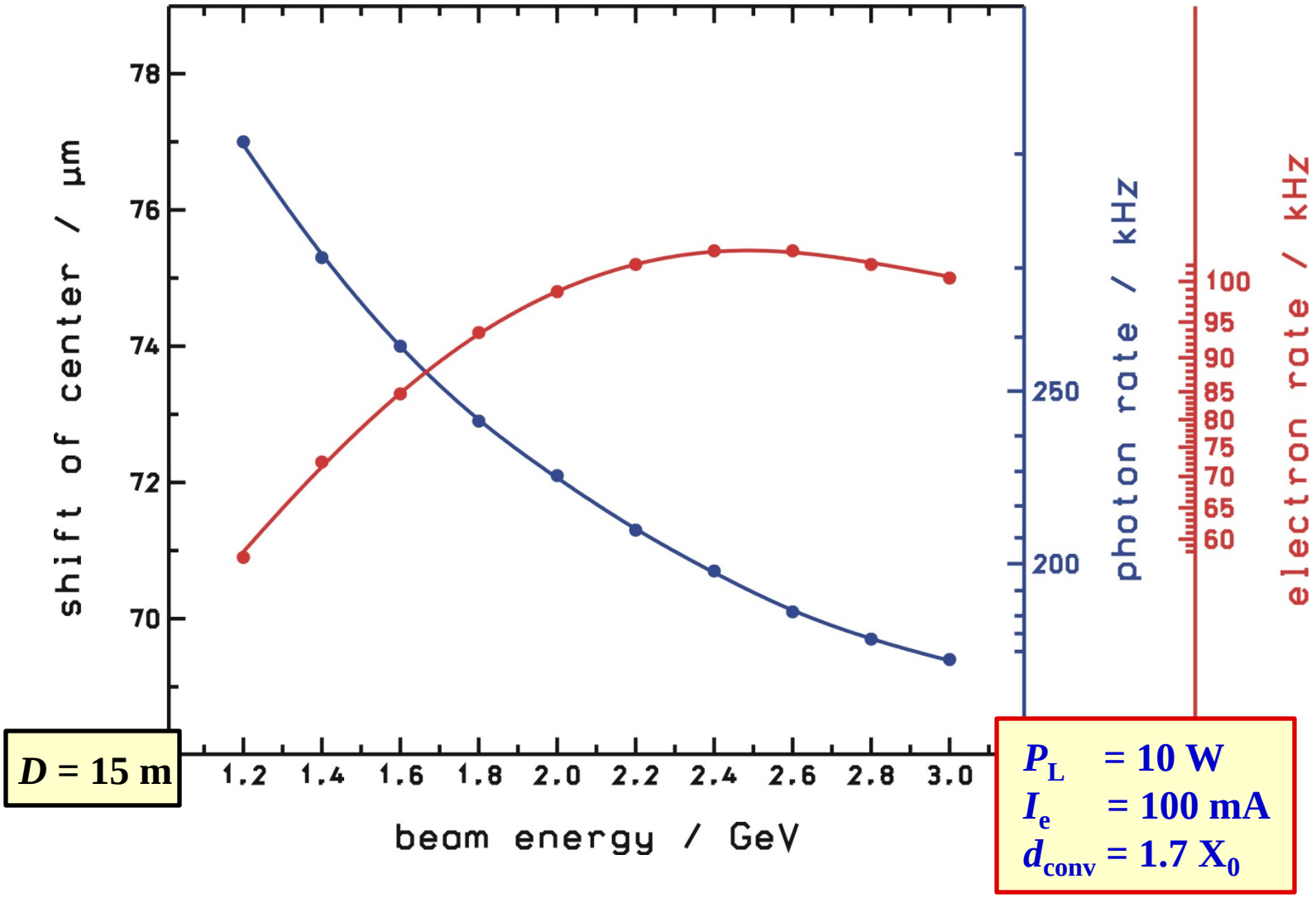


Numerical Simulations

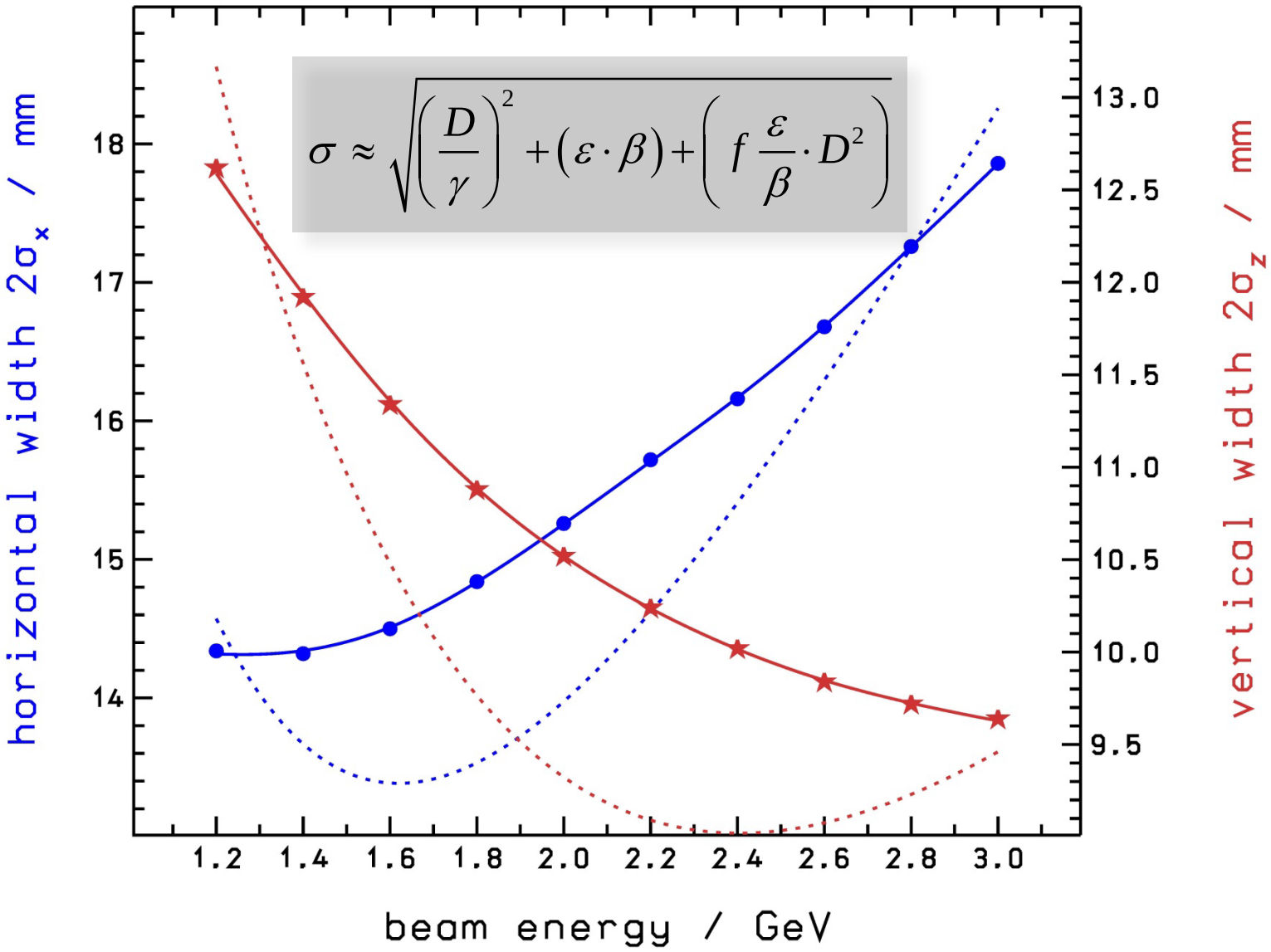
4. Pair conversion (e^+/e^-):



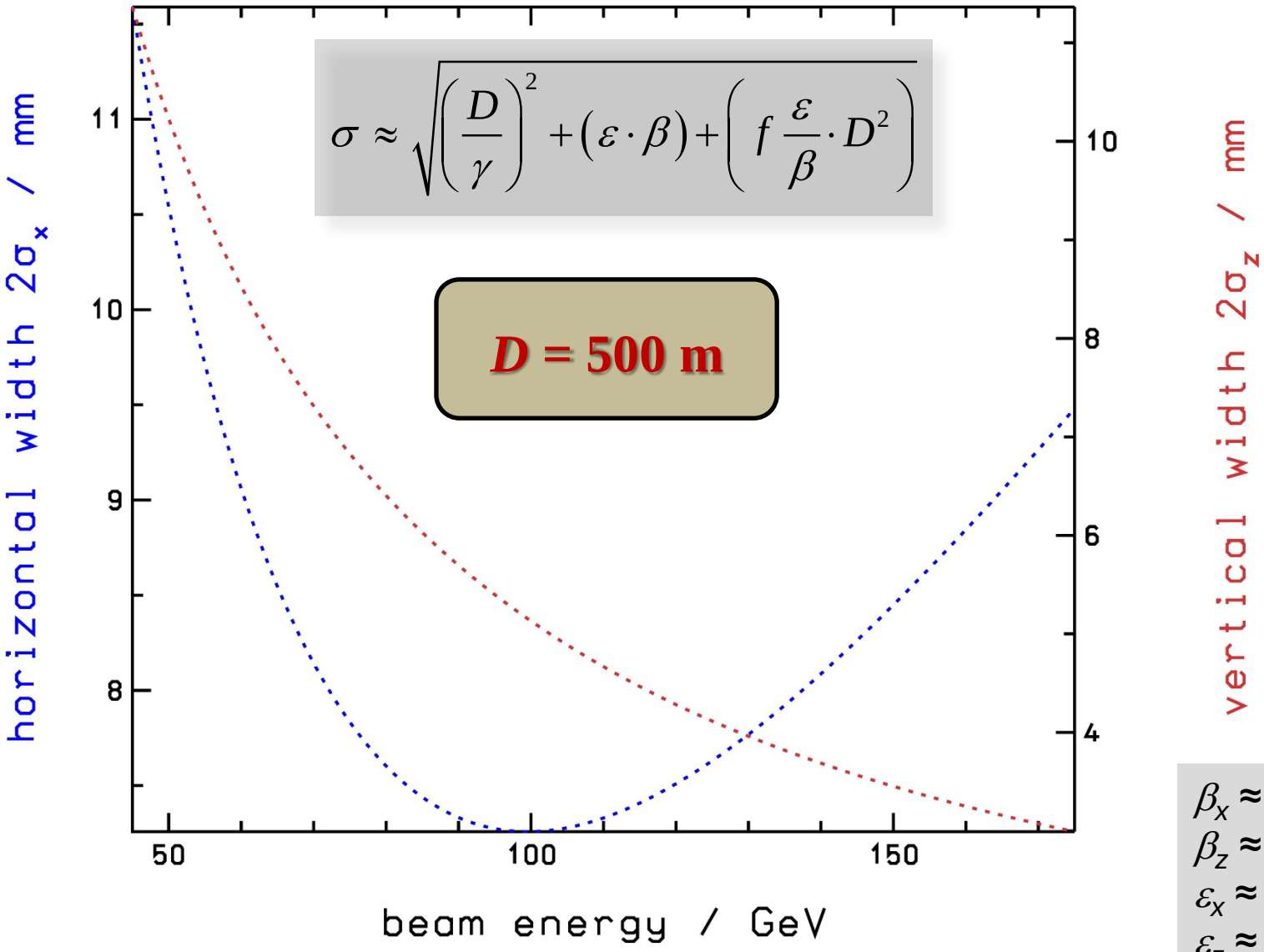
Analysing Power



Beam Parameters



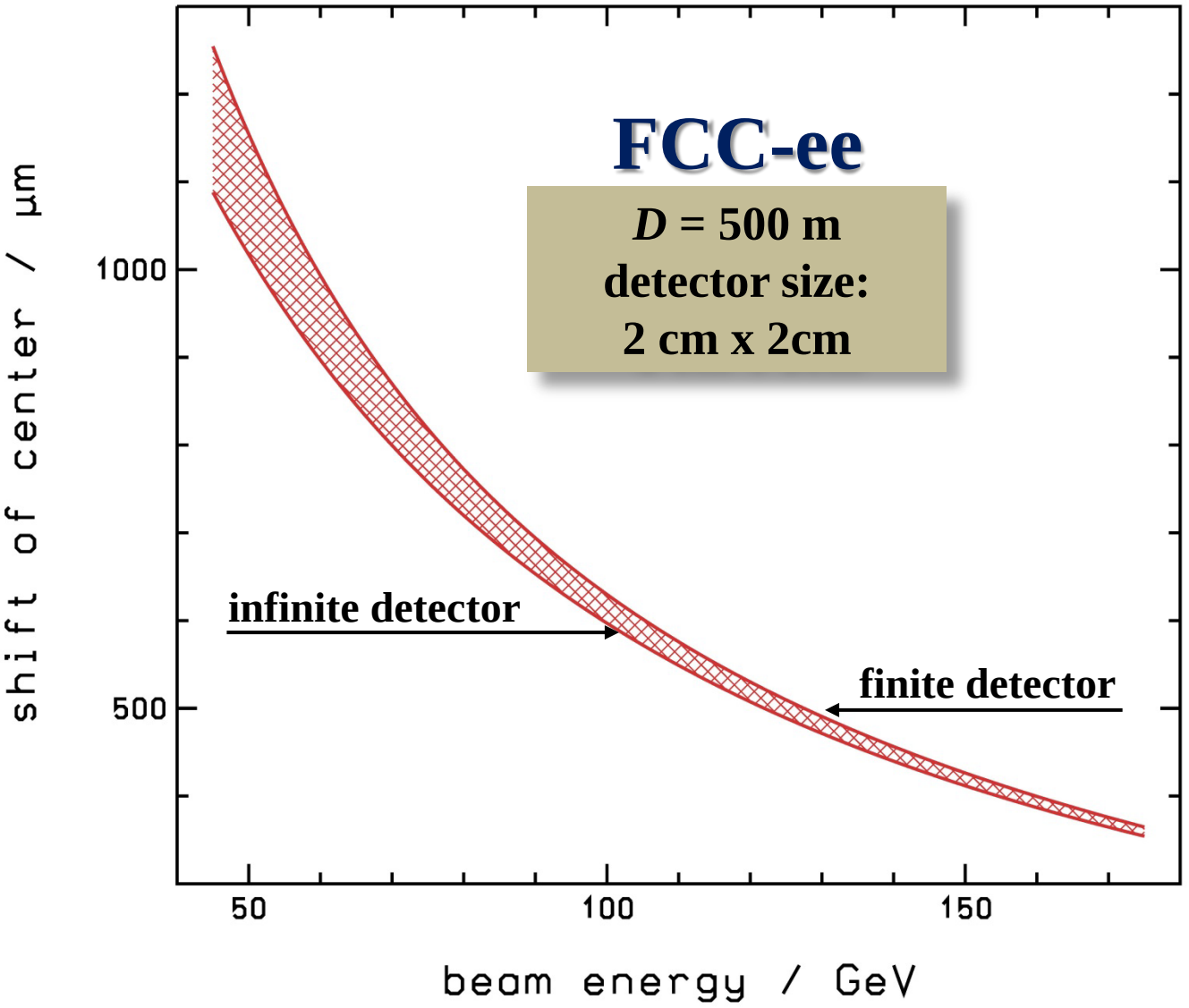
Beam Parameters FCC



@ Z:

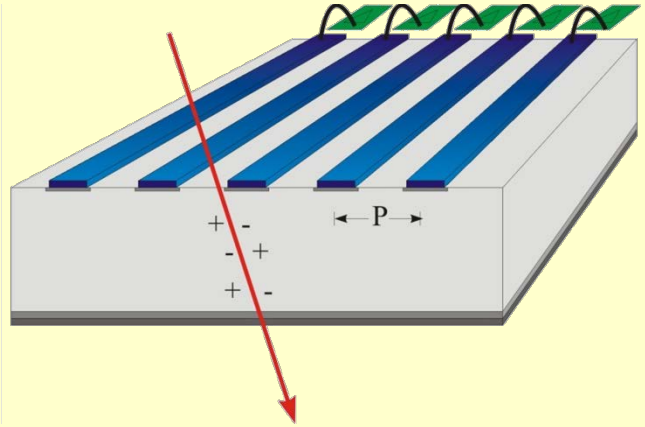
$\beta_x \approx$ 16m
$\beta_z \approx$ 100m
$\varepsilon_x \approx$ 90pm
$\varepsilon_z \approx$ 1pm

Shift of Spatial Distribution



Required Pitch

Strip detector with pitch *p*:

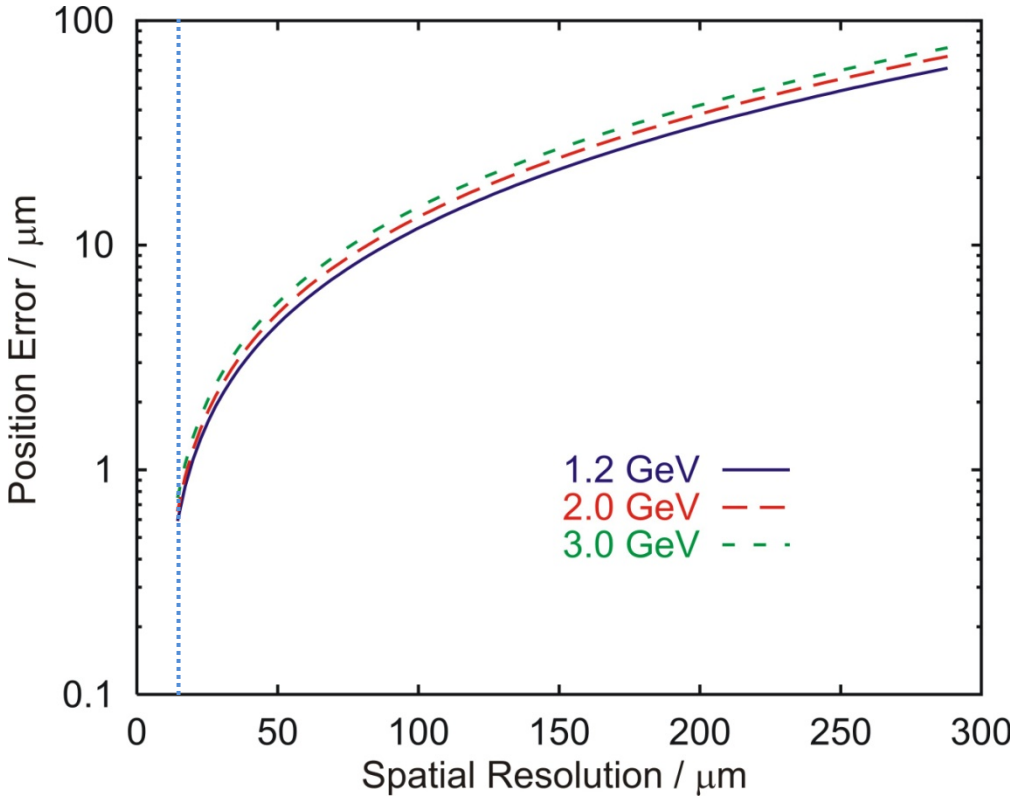


- **spatial resolution:**

$$\Delta z_{\mathrm{det}} = \frac{p}{\sqrt{12}}$$

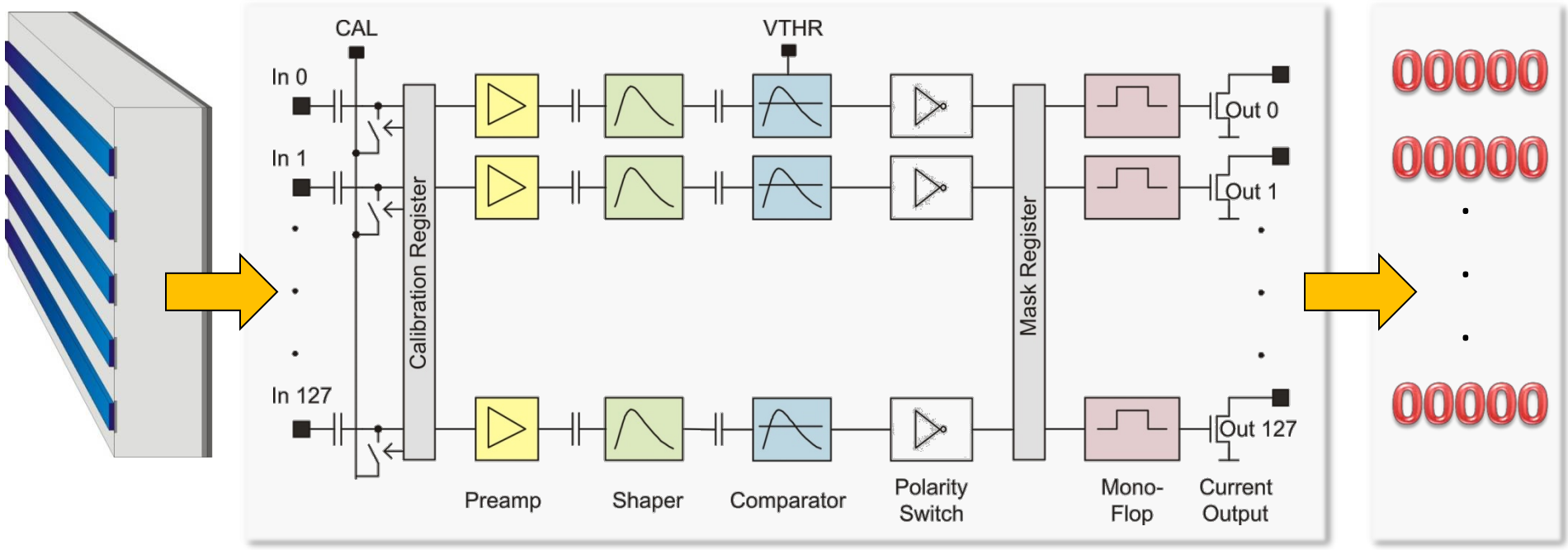
- **achievable position error:**

$$\Delta \bar{z} = \sqrt{\frac{\sigma_z^2}{N^2} + \frac{\sum_i n_i^2}{N^2} \cdot \Delta z_{\mathrm{det}}^2} \overset{N\to\infty}{\rightarrow} \Delta z_{\infty}$$



$\Delta P \leq 1\% \leftrightarrow \Delta z \leq 0.7\mu\mathrm{m} \leftrightarrow p \approx 50\mu\mathrm{m}$

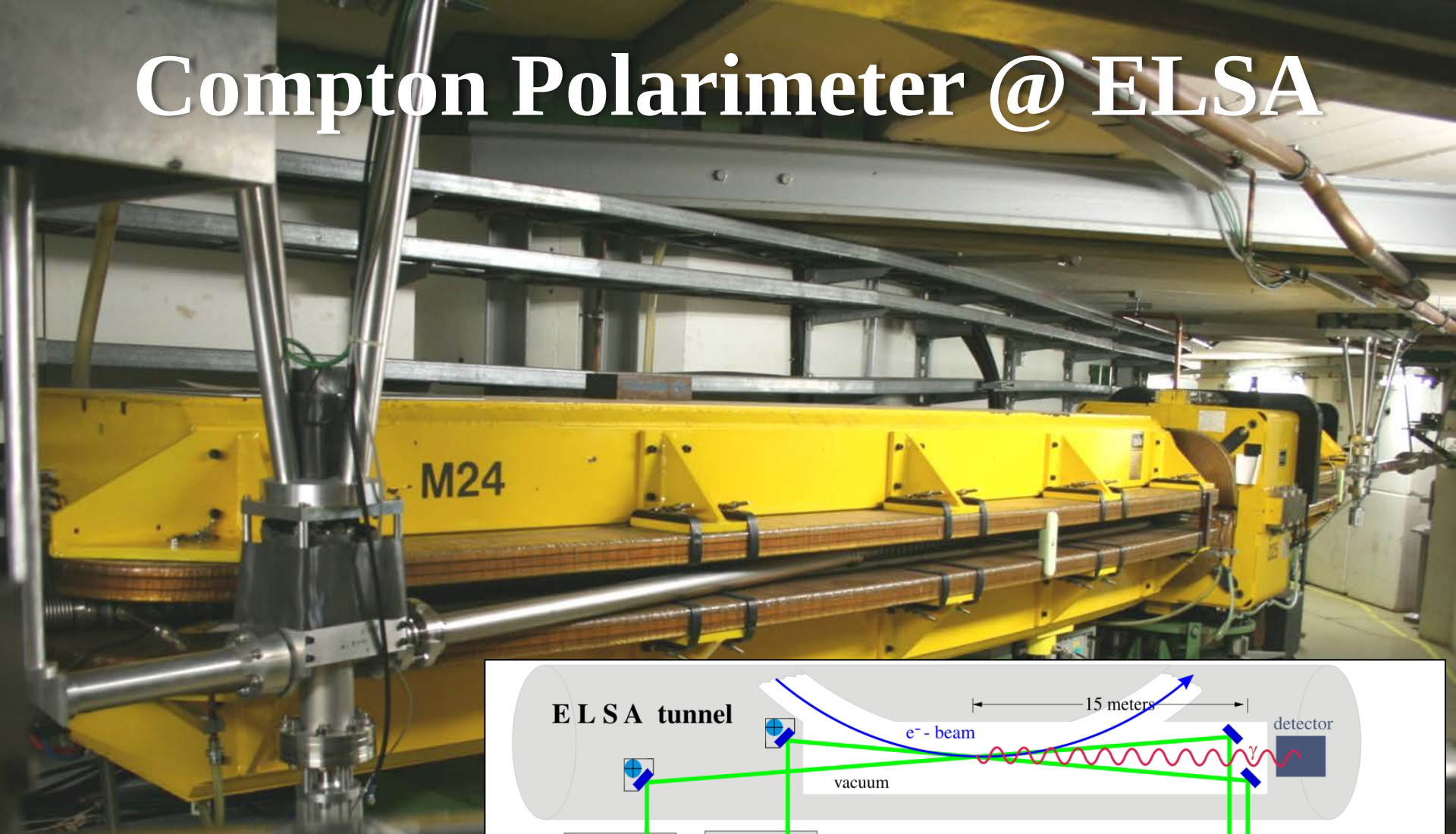
Counting Microstrip Detector



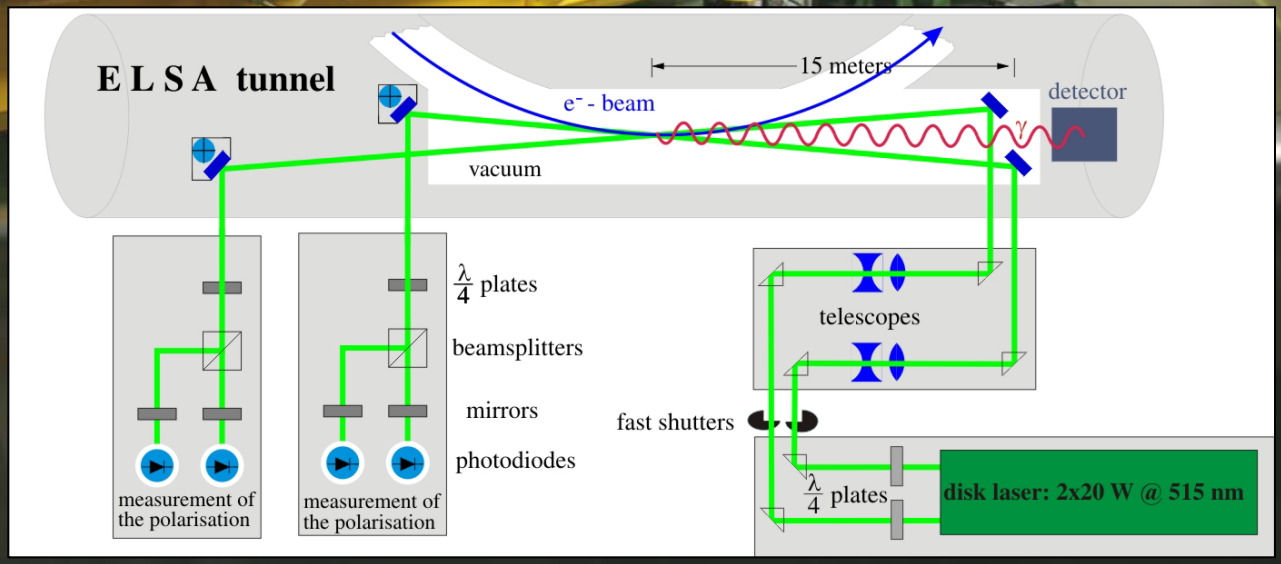
detector amplifier, shaper, discriminator counter

Developed in close collaboration with ATLAS pixel-detector group of N. Wermes, PI Bonn

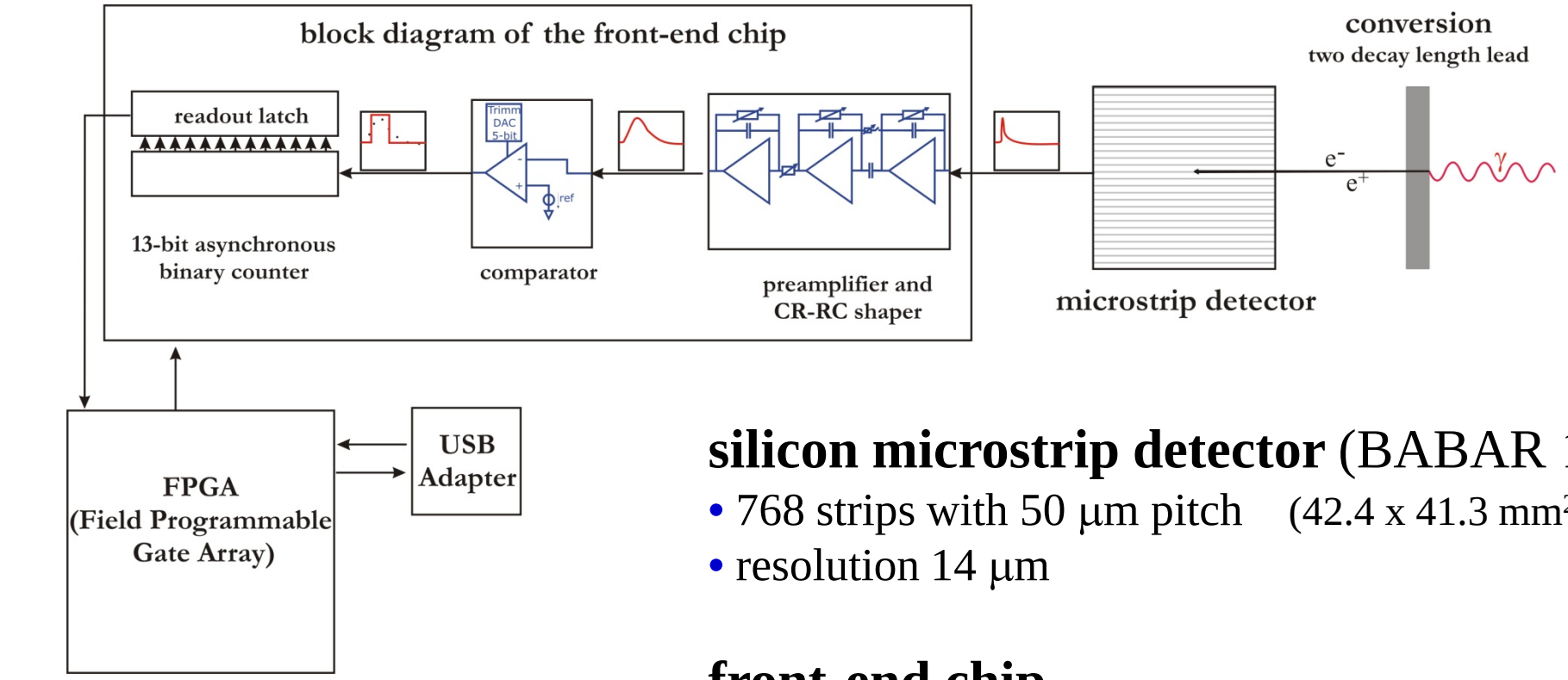
Compton Polarimeter @ ELSA

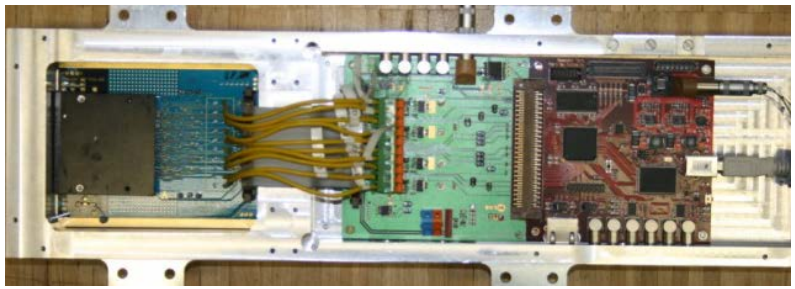


Si microstrip detector
768 channels, 50 µm pitch



Detector Design





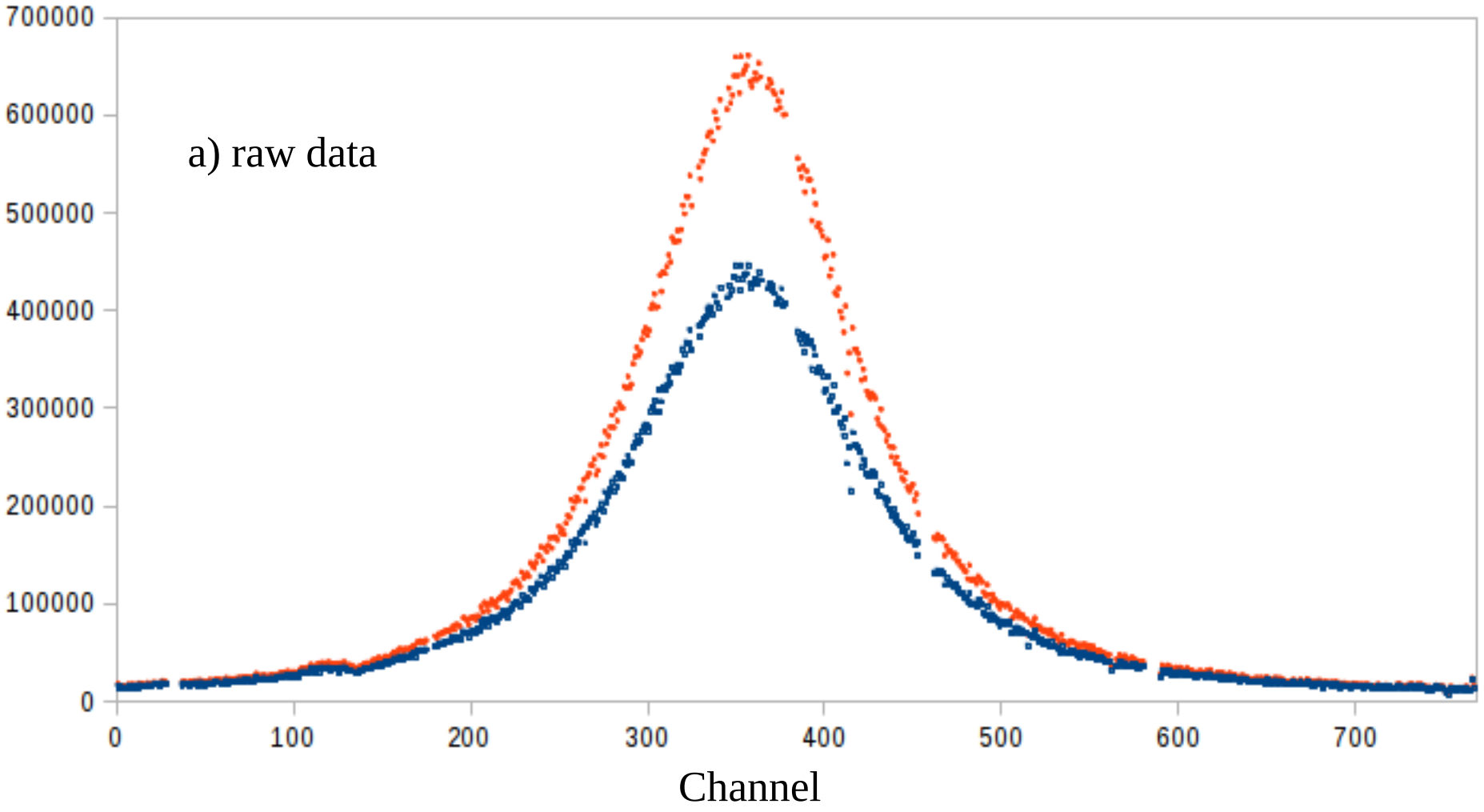
silicon microstrip detector (BABAR 1)

- 768 strips with 50 μm pitch (42.4 x 41.3 mm^2)
- resolution 14 μm

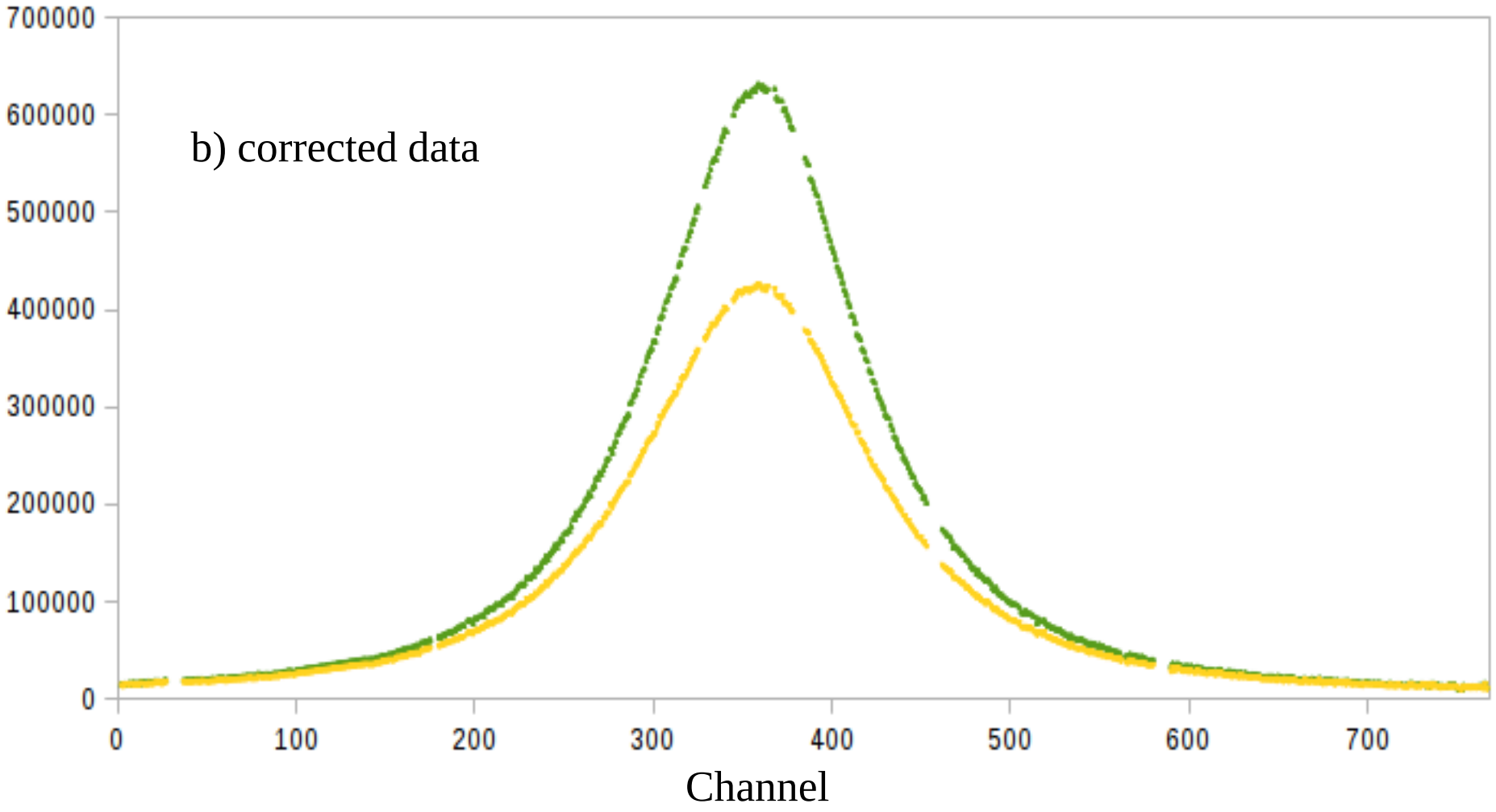
front-end chip

- high rate acceptance (10 - 150 MHz)
- digital part built in LVDS technology
- FPGA controlled

Detector Performance



Detector Performance



Summary and Outlook

Precise Compton Polarimetry:

- Compton backscattering of ~515 nm photons
- circularly polarized photons ↔ transverse polarized e-beam
- measurement of shift of photon intensity distribution
- counting silicon microstrip detector with p = 50 μm

Achievable precision:

- ELSA (3.5 GeV, distance 15 m): $\Delta P \approx 1\%$
- FCC-ee (< 90 GeV, distance 500 m): $\Delta P < 0.1\%$
- FCC-ee (175 GeV, distance 500 m): $\Delta P \approx 0.2\%$