58th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e^+e^- Colliders

24 - 27 October 2016, Cockcroft Institute at Daresbury Laboratory, UK

Measurement of beam polarisation and beam energy in one device

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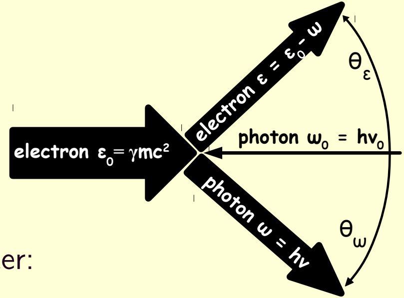
26 Oct 2016

Inverse Compton Scattering (ICS)



Scattering parameter: $\varepsilon_0, \varepsilon, \omega \gg \omega_0$

$$u = \frac{\omega}{\varepsilon} = \frac{\theta_\varepsilon}{\theta_\omega} = \frac{\omega}{\varepsilon_0 - \omega} = \frac{\varepsilon_0 - \varepsilon}{\varepsilon}; \quad u \in [0, \kappa]\text{, where } \kappa = \frac{4\omega_0\varepsilon_0}{m^2}.$$

Scattering angles: $\eta_\omega \equiv \gamma\theta_\omega = \sqrt{\frac{\kappa}{u} - 1}; \quad \eta_\varepsilon \equiv \gamma\theta_\varepsilon = u\sqrt{\frac{\kappa}{u} - 1}.$

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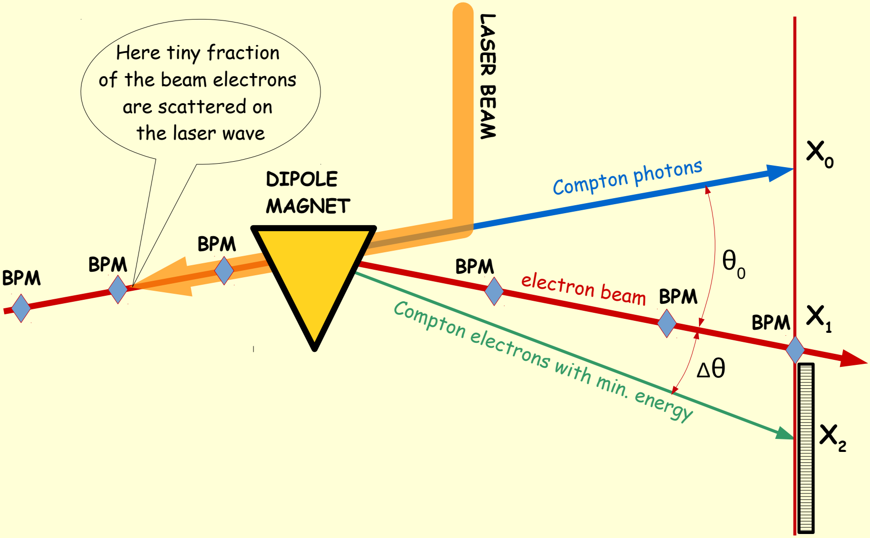
note that $\kappa \simeq 1.53$ for $\varepsilon_0 = 100$ GeV and $\omega_0 = 1$ eV.

The concept of laser - ICS experiments



ICS cross section is sensitive to polarisation

$$d\sigma = \left\{ \frac{1}{\kappa(1+u)^2} \left(2 + \frac{u^2}{1+u} + 4\frac{u}{\kappa}\left[\frac{u}{\kappa} - 1\right]\left[1 - \xi_\perp \cos(2(\varphi - \varphi_\perp))\right] \right) + \right.$$

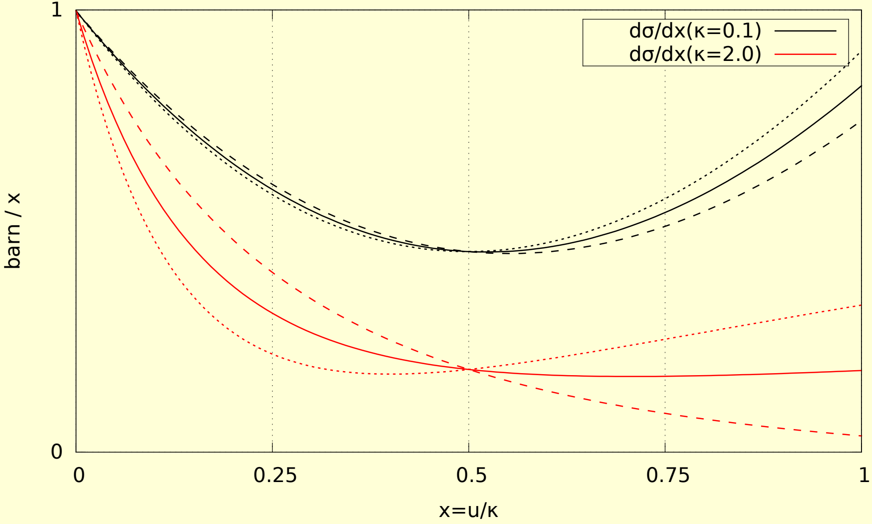
$$\left. + \xi_\circlearrowleft \left(\zeta_\parallel \frac{u(u+2)(\kappa - 2u)}{\kappa^2(1+u)^3} - \zeta_\perp \frac{2u^2\sqrt{\kappa/u - 1}}{\kappa^2(1+u)^3} \sin\varphi \right) \right\} r_e^2 d\varphi\, du,$$

Modified Stokes parameters:

$\xi_\perp$ and $\varphi_\perp$ – degree and direction of laser linear polarisation,
$\xi_\circlearrowleft$ – degree of laser circular polarisation,
$\zeta_\parallel$ and $\zeta_\perp$ – longitudinal and transverse electron beam polarisation.

Laser beam: $\sqrt{\xi_\perp^2 + \xi_\circlearrowleft^2} = 1$, $\xi_\perp \in [0, 1]$, $\xi_\circlearrowleft \in [-1, 1]$.
Electron beam: $\sqrt{\zeta_\perp^2 + \zeta_\parallel^2} < 1$, $\zeta_\perp \in [-1, 1]$, $\zeta_\parallel \in [-1, 1]$.

ICS cross section is sensitive to polarisation



Dashed lines illustrate the influence of $\xi_{\circlearrowright}\zeta_{\parallel}$

Experiments with polarised $e^{\pm}$ beams

ACO, VEPP-2, SPEAR, DORIS, TRISTAN, VEPP-4, CESR, LEP, HERA...

- Compton polarimeters usually dealt with scattered photons.
- At higher electron energies the divergence of γ-beam is small, high energy SR photons appear, etc. ...
- ... it is reasonable (like ILC) to look at the scattered electrons.
- Maximum electron scattering angle: $\max(\theta_\varepsilon) = 2\omega_0/m$. If ω_0 =2.33 eV one has $\max(\theta_\varepsilon) \simeq 10$ μrad.
- Beam angular spread: $\sigma'_y = \sqrt{\epsilon_y/\beta_y} \ll \max(\theta_\varepsilon)$. An example: ϵ_y=100 pm and β_y=100 m gives $\sigma'_y = 1$ μrad.
- The dimension of scattered electrons angular distribution does not depend on beam energy.

Scattered electrons after a bending dipole

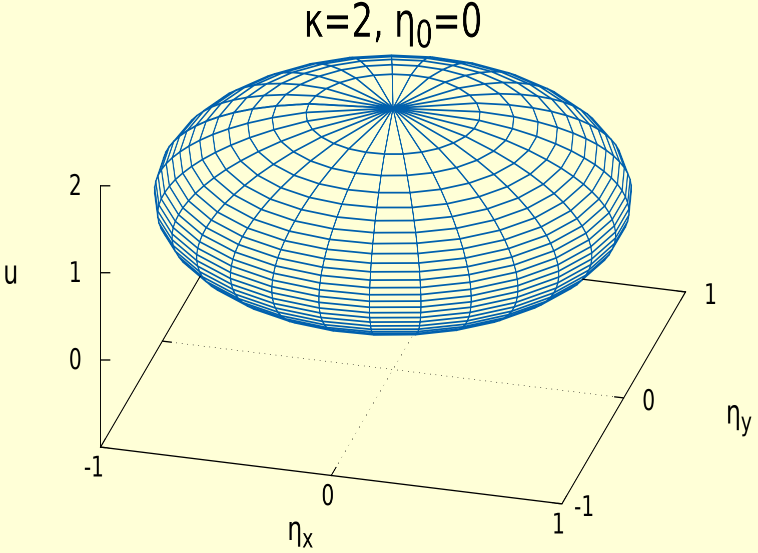
- An energy of a scattered electron: $\varepsilon(u) = \varepsilon_0/(1+u)$.
- This electron will be bent to the angle $\theta_s = c\int Bdl \cdot \dfrac{(1+u)}{\varepsilon_0}$.
- Let $\boxed{\eta_s \equiv \gamma\theta_s = \eta_0 + u\eta_0}$, where

  η_s and η_0 are the <u>bending angles in units of $1/\gamma$</u>
- Note $\eta_0 = \int Bdl/B_c\lambdabar_c$, where $B_c\lambdabar_c = \dfrac{mc}{e} \simeq 1.7\times 10^{-3}$ [T m].
- With scattered electron angles defined as

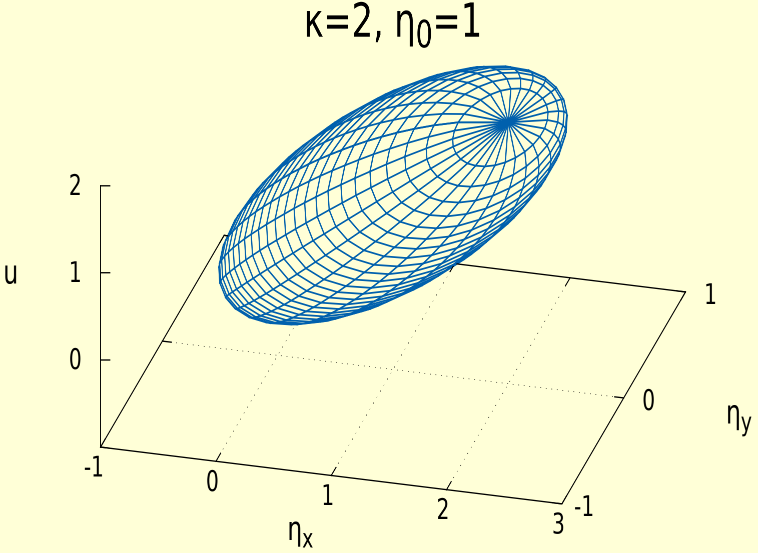
$$\begin{cases} \eta_x \equiv (\eta_s - \eta_0) = u\eta_0 + \quad u\sqrt{\kappa/u - 1}\cos\varphi \\ \eta_y = \qquad\qquad\qquad\qquad u\sqrt{\kappa/u - 1}\sin\varphi \end{cases}$$

one gets the equation: $\boxed{(\eta_x - u\eta_0)^2 + \eta_y^2 = u(\kappa - u).}$

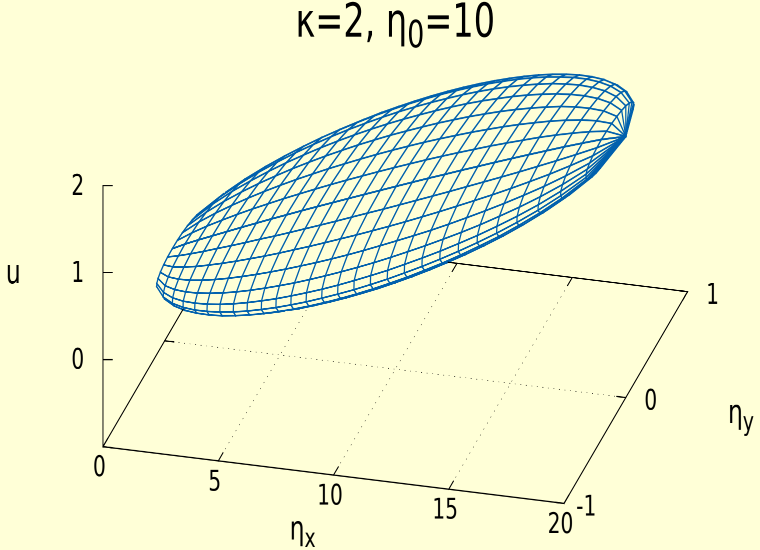
Scattering surface in (η_x, η_y, u) space, no bend



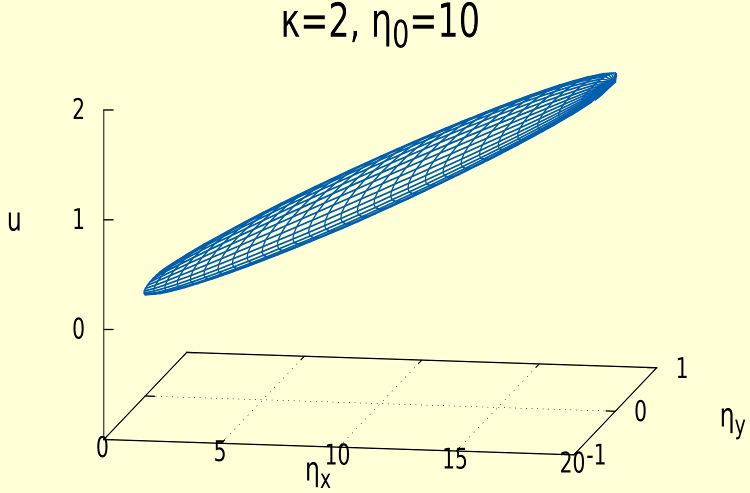
Scattering surface in (η_x, η_y, u) space, $1/\gamma$ bend



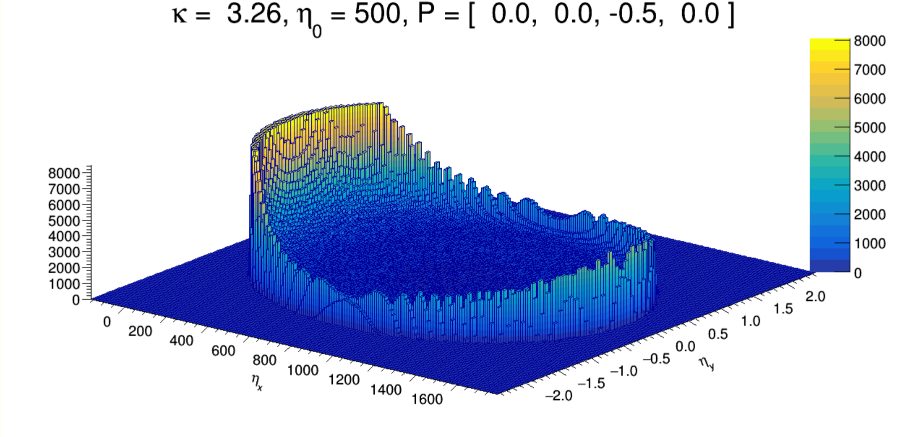
Scattering surface in (η_x, η_y, u) space, $10/\gamma$ bend



Scattering surface in (η_x, η_y, u) space, $10/\gamma$ bend



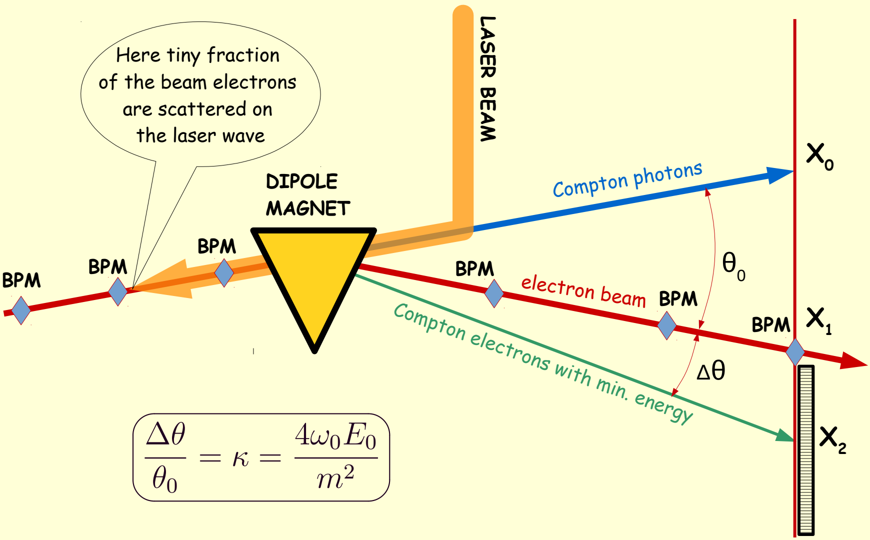
Scattered electrons distribution in η_x, η_y plane



The sizes of ellipse [rad] are: $O_y = \frac{4\omega_0}{m}$, $O_x = \frac{4\omega_0}{m}\sqrt{1+\eta_0^2} = \Delta\theta$.

O_x measurement can be used for calibration of $\eta_0 = \int Bdl/B_c\lambda_c$.

Reminder: the scheme of experiment



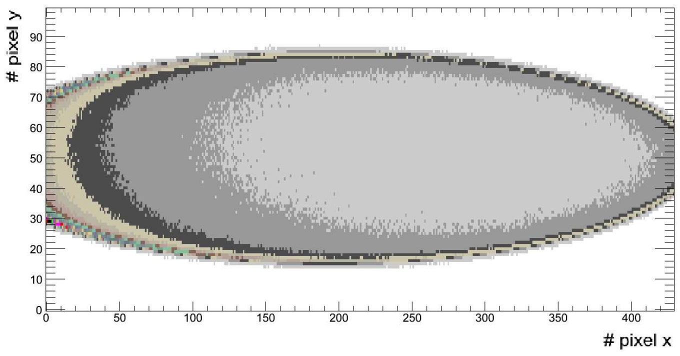
$$\frac{\Delta\theta}{\theta_0} = \kappa = \frac{4\omega_0 E_0}{m^2}$$

ILC note LC-M-2012-001

A Transverse Polarimeter for a Linear Collider of 250 GeV e Beam Energy

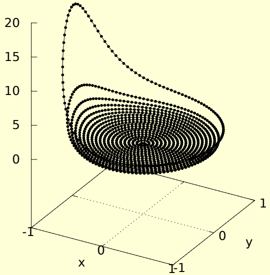
Itai Ben Mordechai and Gideon Alexander

"For the detection of the scattered electrons we consider only a position measurement using a Silicon pixel detector placed at a distance of 37.95 m from the Compton IP. The active dimension of the detector is 2×200 mm^2. The size of the pixels cell taken is 50×400 μm^2 similar to the one used in the ATLAS detector [9]. This scheme yields an approximate two dimensional resolution of 14.4×115.5 μm^2 [10] with a data read-out rate of 160 Mb/sec."

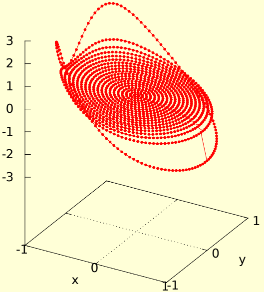


Fitting the distribution of scattered electrons

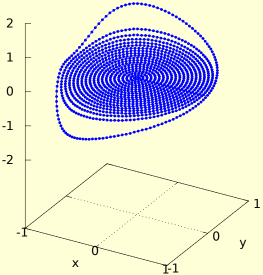
$\mathcal{U}$ - unpolarised cross section



$\mathcal{L}$ - longitudinal electron polarisation



$\mathcal{T}$ - transverse electron polarisation

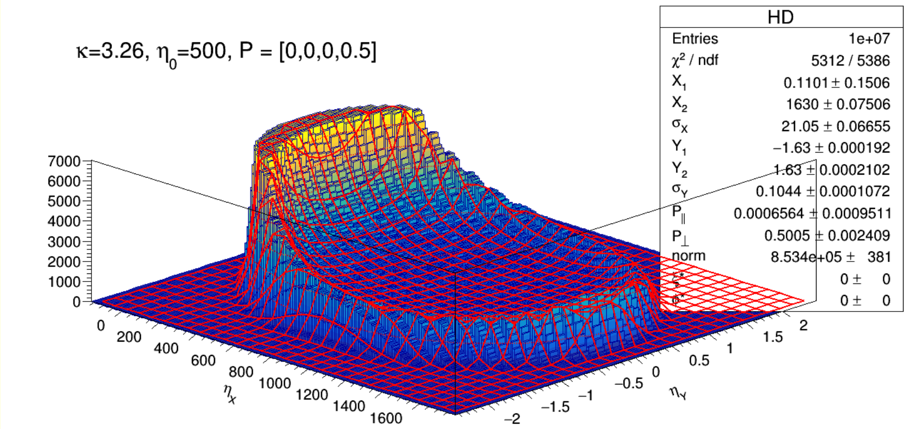


The x, y distribution of scattered electrons is the convolution of

a) cross section $\boxed{f(x,y) = \mathcal{U} + \xi_{\circlearrowleft}(\zeta_{\parallel}\mathcal{L} + \zeta_{\perp}\mathcal{T})}$ and

b) transverse distributions (σ_x, σ_y) of electrons in the beam.

Fitting the distribution of scattered electrons

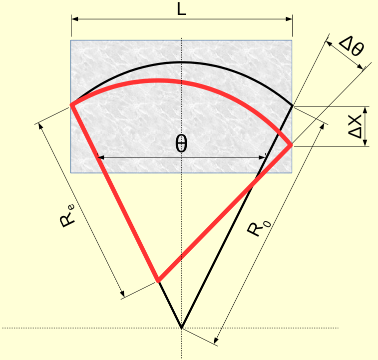


100 x-bins $[0:2000]$ 50 y-bins $[-2:2]$

Fit range $\eta_x = [200, 2000]$. MC: $\gamma\Delta\theta = 3.26 \times 500 = 1630$.

Fit result: $\Delta\theta = X_2 - X_1 = (1630.02 \pm 0.08) - (0.110 \pm 0.151)$

Two arcs in a dipole of length L



Note that $R_{min} = R_0/(1+\kappa)$.

S_0, R_0 – black arc length & radius,

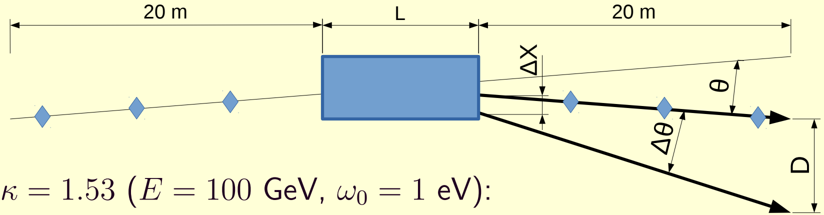
S, R_{min} – red arc length & radius.

$$S_0 = 2R_0 \arcsin\left[\frac{L}{2R_0}\right]$$ and

$$S = 2R_{min} \arcsin\left[\frac{\sqrt{L^2+\Delta X^2}}{2R_{min}}\right],$$

where $\Delta X = \sqrt{R_{min}^2 - \left[\frac{LR_{min}}{2R_0}\right]^2} - \sqrt{R_{min}^2 - \left[L - \frac{LR_{min}}{2R_0}\right]^2}$.

Spectrometer: general consideration



Let $\kappa = 1.53$ ($E = 100$ GeV, $\omega_0 = 1$ eV):

θ mrad	$\Delta\theta$ mrad	L m	ΔX mm	$\Delta S/S$	D mm
1	1.53	10	3.83	$2.59 \cdot 10^{-7}$	46
2	3.06	10	7.65	$1.04 \cdot 10^{-6}$	92
1	1.53	5	1.91	$2.59 \cdot 10^{-7}$	46
2	3.06	5	3.83	$1.04 \cdot 10^{-6}$	92

Therefore:

a) $\Delta S/S \propto \kappa\theta$

b) $\Delta X \propto \kappa\theta \cdot L$

c) $D \propto \kappa\theta \cdot L_{arm}$

The best case: a) small $\kappa\theta$; b) short dipole; c) long arm.

The penultimate slide

Initial conditions:

1. Inverse Compton scattering of laser radiation is a currently available reliable method for beam polarisation and energy determination.
2. The future high energy lepton colliders require polarised beams and polarimetry, inter alia for application of resonant depolarisation technique for precise beam energy calibration at circular machines.

Conclusions:

1. Analysis of 2D-distribution of ICS electrons allows to measure beam polarisation degree and direction as well as to provide a unique way for accurate calibration of the $\int Bdl$ exactly along a beam trajectory in a conventional magnetic spectrometer. Such a spectrometer was installed at LEP and no doubt it should be implemented at future high-energy colliders, either linear or circular.
2. The proposed approach has no limitations in beam energy, the only thing it requires is a small value of vertical emittance of the electron beam. So now it's a good time to start the proof-of-principle project at one of the existing low-emittance facilities.
3. Another subject for further studies should be a possibility to measure the position of backscattered photons with high accuracy. This seems to be not an easy task, but it allows to build the completely independent beam energy measurement approach for arbitrary beam energies.

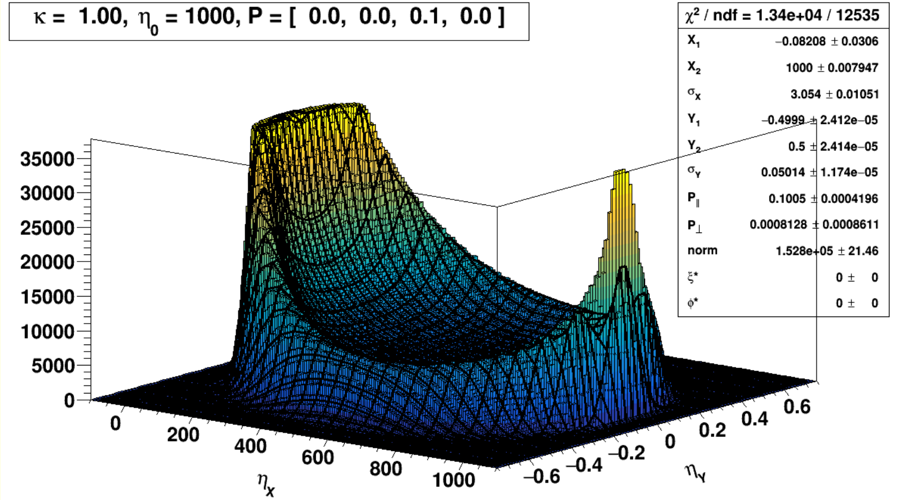
The End

THANK YOU!

Special thanks to the conference organizers for the invitation and warm welcome!

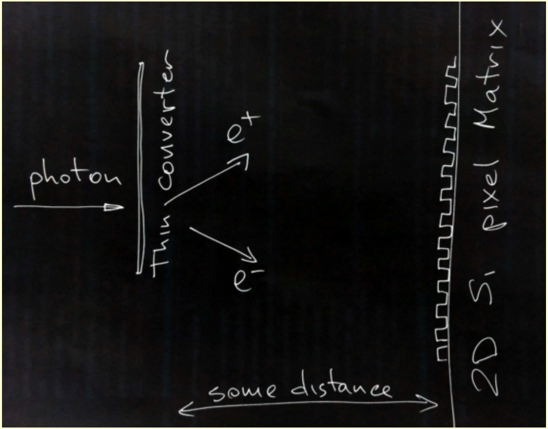
Another example

More statistics, another κ, longitudinal polarization 10%, $\lesssim 10^{-5}$ "accuracy" in X_2 measurement, etc.



Photon detector?

The task is to measure accurately the centre of gravity in a narrow spatial distribution of high energy photons.



Can have up to ≃100 photons/bunch with some simple laser source