Trident Production Observed in Aligned Crystals

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Strong fields

Critical field

- Relativistic, quantum field for electrons?
- Combine c, ħ and e, m to get a field:

$$\mathcal{E}_0 = m^2c^3/e\hbar = 1.32 \times 10^{16}\ \mathrm{V/cm}$$

$$B_0 = 4.41 \times 10^9\ \mathrm{T}$$

Klein paradox

'The problem' in 1928

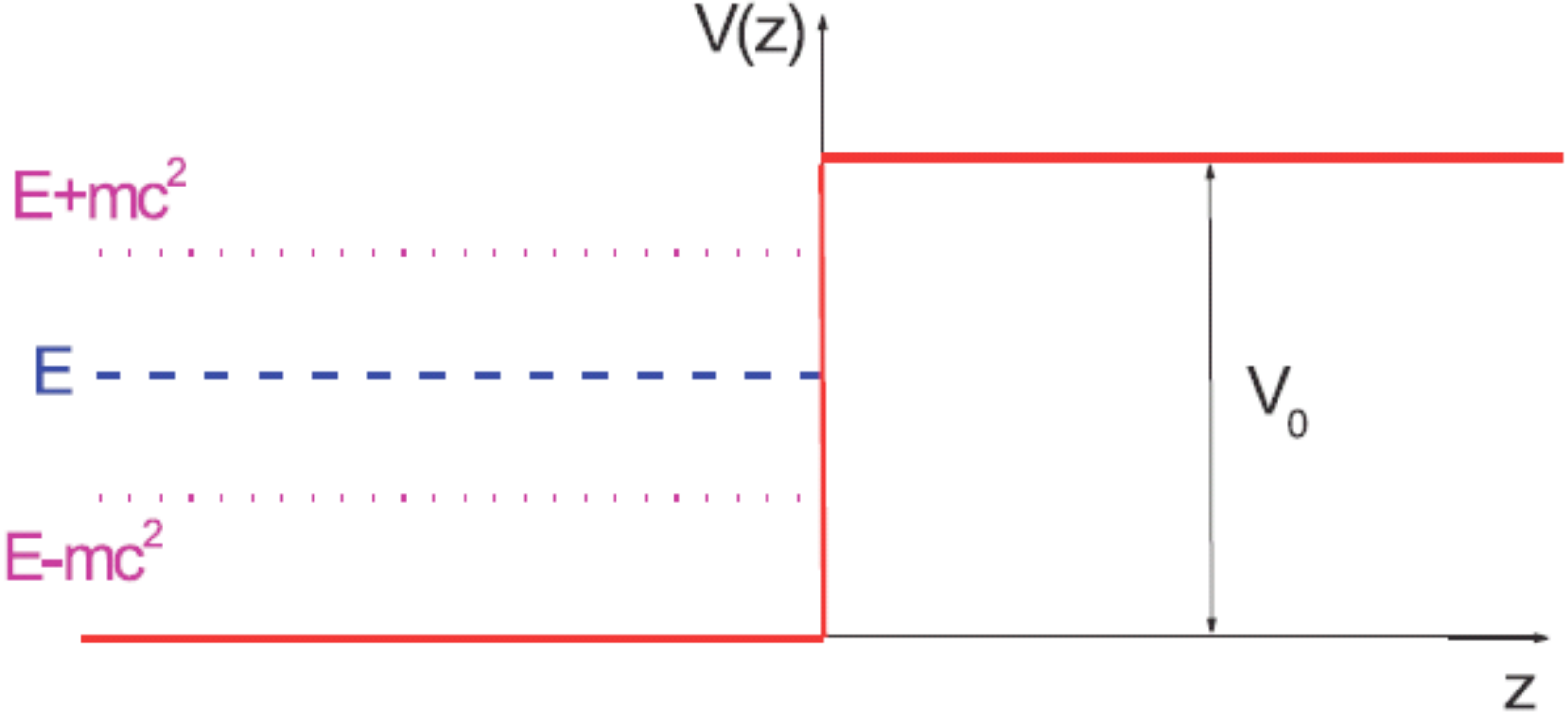
The Quantum Theory of the Electron.

By P. A. M. DIRAC, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received January 2, 1928.)

$$(p_0 + \alpha_1 p_1 + \alpha_2 p_2 + \alpha_3 p_3 + \beta)\,\psi = 0,$$

A 'Dirac electron' incident on a potential barrier



Die Reflexion von Elektronen an einem Potentialsprung nach der relativistischen Dynamik von Dirac.

Von **O. Klein** in Kopenhagen.

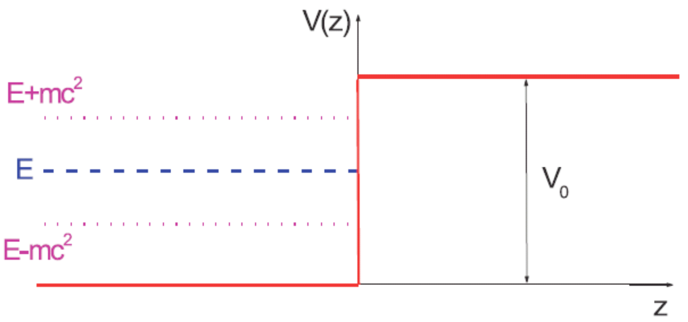
(Eingegangen am 24. Dezember 1928.)

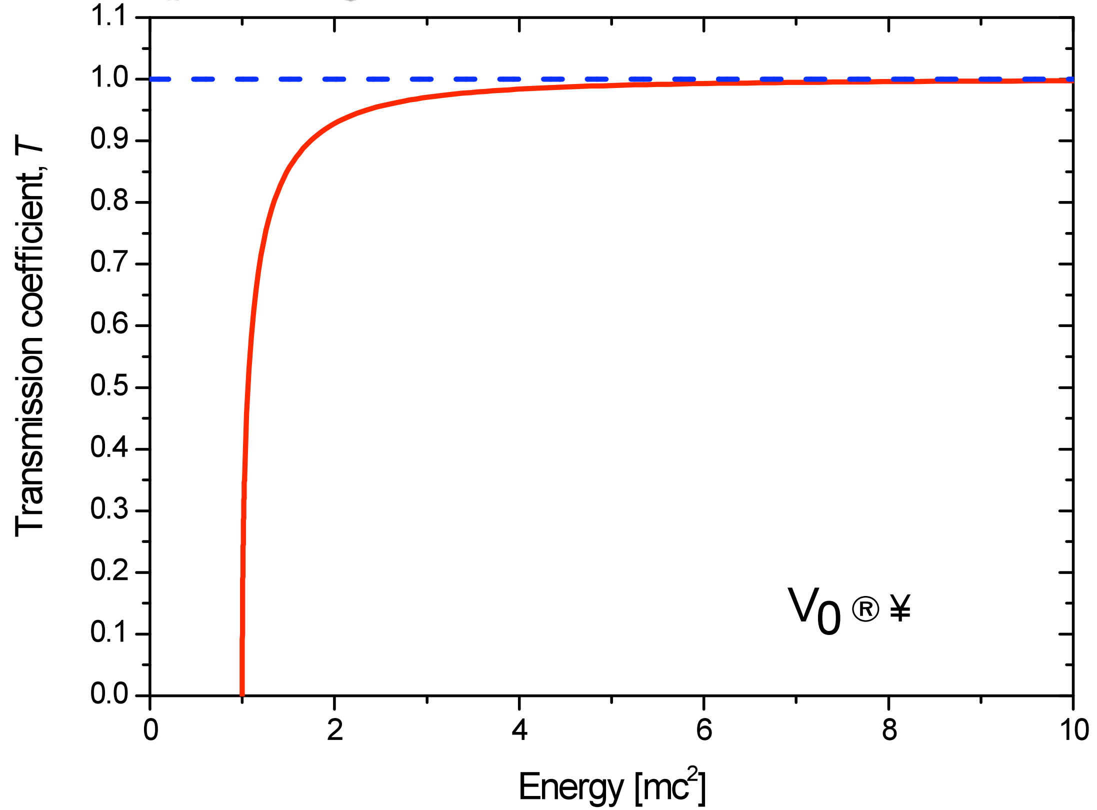
Grenzwert des Bruchteils der Elektronen, der durch die Grenzfläche dringt, ist also $\frac{2p}{E/c + p}$, d. h. von derselben Größenordnung wie das Ver-

Auch wenn die Sprungfläche durch ein kleines Gebiet ersetzt wird, wo das Potential rasch aber stetig anwächst, werden nach der Theorie, wie aus der ganzen Rechnungsweise hervorgeht, Elektronen in das verbotene Gebiet, wo sie negative kinetische Energie besitzen, eindringen, was eng

A bit of history on strong fields and the Klein paradox

'Electrons in the forbidden region penetrate into the region where they possess negative kinetic energy'





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Über das Verhalten eines Elektrons im homogenen elektrischen Feld nach der relativistischen Theorie Diracs.

Von **Fritz Sauter** in München.

Mit 6 Abbildungen. (Eingegangen am 21. April 1931.)

wahrscheinlichkeit erst dann endliche Werte annimmt, wenn die Größe des Potentialanstieges auf einer Strecke gleich der Comptonwellenlänge vergleichbar wird mit der Ruheenergie des Elektrons. Die von O. Klein berechneten großen

zum negativen Impuls gefunden hat. N. Bohr sprach die Vermutung aus, daß dieser hohe Wert nur durch die Annahme eines Potential*sprunges*, also eines unendlich steilen Potentialanstieges bedingt ist und daß überhaupt nur dann endliche Übergangswahrscheinlichkeiten zu erwarten sind, wenn der Anstieg so steil ist, daß das Potential auf einer Strecke von der Größe der Comptonwellenlänge h/mc um einen Betrag von der Größenordnung der Ruheenergie des Elektrons anwächst**.

Dies steht in Übereinstimmung mit der in der Einleitung angegebenen Vermutung von N. Bohr, daß man erst dann endliche Wahrscheinlichkeiten für den Übergang eines Elektrons in das Gebiet mit negativem Impuls erhält, wenn der Potentialanstieg $v \frac{h}{mc}$ auf einer Strecke von der Comptonwellenlänge h/mc von der Größenordnung der Ruheenergie wird.

Felder von dieser Stärke experimentell herzustellen, ist natürlich unmöglich. Man könnte jedoch eventuell daran denken, daß solche Felder

Potential over a Compton wavelength equals the rest energy of the electron

$$D = e^{-k^2 \pi}.$$

$$k = \sqrt{\frac{2\pi}{h c v}} \cdot m c^2,$$

$$1/k^2 = hEe/2\pi m^2 c^3$$

$$= \mathcal{E} / \mathcal{E}_0 2\pi$$

$$\mathcal{E}_0 = m^2 c^3 / e\hbar$$

'To produce fields of this strength experimentally, is naturally impossible.'

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PHYSICAL REVIEW VOLUME 82, NUMBER 5 JUNE 1, 1951

On Gauge Invariance and Vacuum Polarization

JULIAN SCHWINGER
Harvard University, Cambridge, Massachusetts
(Received December 22, 1950)

$$2\,\mathrm{Im}\mathfrak{L}=\frac{1}{4\pi}\sum_{n=1}^{\infty} s_n^{-2}\exp(-m^2 s_n)$$

$$=\frac{\alpha^2}{\pi^2}\mathcal{E}^2\sum_{n=1}^{\infty} n^{-2}\exp\left(\frac{-n\pi m^2}{e\mathcal{E}}\right). \qquad (6.41)$$

This is the probability, per unit time and per unit volume, that a pair is created by the constant electric field.

factor 2

Sauter:

$$D = e^{-k^2\pi}.$$

$$k = \sqrt{\frac{2\pi}{hcv}}\cdot m\,c^2,$$

PHYSICAL REVIEW VOLUME 75, NUMBER 12 JUNE 15, 1949

On the Classical Radiation of Accelerated Electrons

JULIAN SCHWINGER
Harvard University, Cambridge, Massachusetts
(Received March 8, 1949)

We shall conclude this section by briefly examining under what conditions quantum phenomena will invalidate the classical considerations we have presented. This will occur when the momentum of the emitted quantum is comparable with the electron momentum. Hence, for the validity of our classical treatment, it is required that

$$\frac{E}{mc^2}\ll\frac{mc^2}{(e\hbar/mc)H}, \qquad (\mathrm{II}.56)$$

$$\chi = \gamma\mathcal{E}/\mathcal{E}_0 \ll 1$$

Recent

H. Nitta and T. Kudo, H. Minowa, American Journal of Physics1999 **67**, pp. 966-971, *Motion of a wave packet in the Klein paradox*

VOLUME 92, NUMBER 4 PHYSICAL REVIEW LETTERS week ending 30 JANUARY 2004

Klein Paradox in Spatial and Temporal Resolution

P. Krekora, Q. Su, and R. Grobe

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(Received 20 August 2003; published 30 January 2004)

ARTICLES

Chiral tunnelling and the Klein paradox in graphene

M. I. KATSNELSON[1]*, K. S. NOVOSELOV[2] AND A. K. GEIM[2]*

Published online: 20 August 2006; doi:10.1038/nphys384

Invariants

The critical (Schwinger) field

- Schwinger, 1949

$$\mathcal{E}_0 = m^2c^3/e\hbar = 1.32 \times 10^{16}\ \mathrm{V/cm}$$

$$B_0 = 4.41 \times 10^9\ \mathrm{T}$$

Quantum corrections to synchrotron radiation emission

Relativistic invariant:

$$\chi = \gamma\mathcal{E}/\mathcal{E}_0$$

What are the invariants?

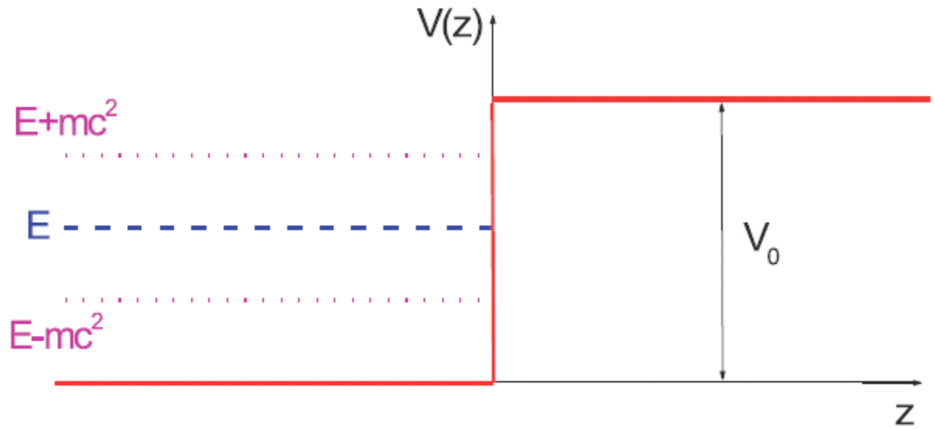
$$\chi^2 = \frac{(F_{\mu\nu}p^\nu)^2}{m^2c^2\mathcal{E}_0^2},$$

$$\Xi = \frac{F_{\mu\nu}^2}{\mathcal{E}_0^2} = \frac{2(\vec{B}^2 - \vec{\mathcal{E}}^2)}{\mathcal{E}_0^2},$$

$$\Gamma = \frac{e_{\lambda\mu\nu\rho}F^{\lambda\mu}F^{\nu\rho}}{\mathcal{E}_0^2} = \frac{8\vec{\mathcal{E}}\cdot\vec{B}}{\mathcal{E}_0^2},$$

Motion perpendicular to the electric field:

$$\chi = \frac{\gamma\mathcal{E}}{\mathcal{E}_0}$$



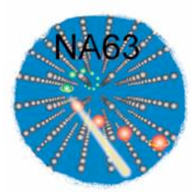
Beamstrahlung

Electric field from one bunch boosted by $2\gamma^2$ as seen by the other

SLC:
χ (or Υ) $\approx 10^{-3}$

NLC:
χ (or Υ) ≈ 1

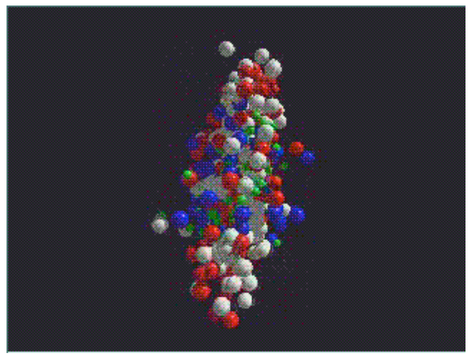
heavy ions



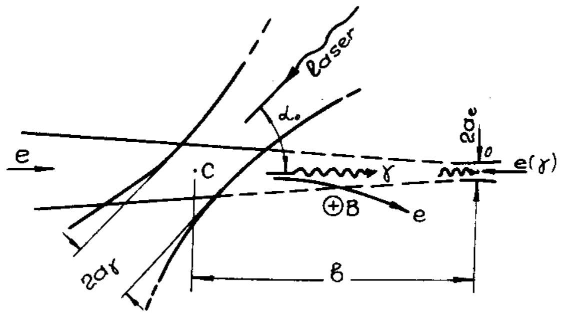
Superstrong field, but of short duration

$$E_{1s}/E_0 = \alpha^3 Z^3$$

Extended nucleus:
$Z \approx 172$



Strong lasers



γγ-collision scheme
(Telnov *et al.*)

Laser wavelength (and γ energy) limited by non-linear Compton scattering
χ (or Υ) ≈ 1

Trident production

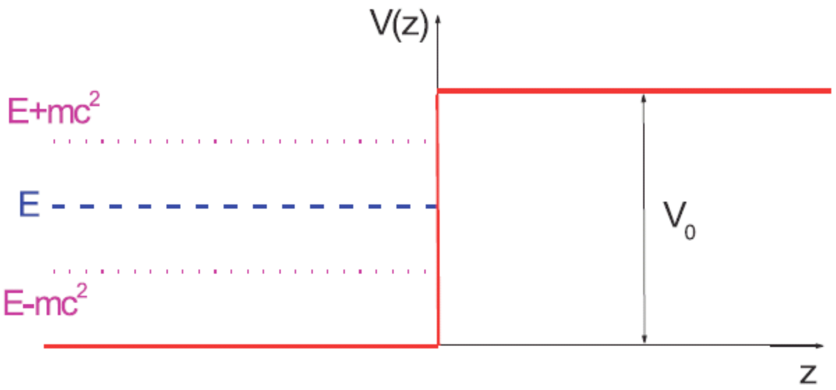
$$e^- \rightarrow e^- e^+ e^-$$

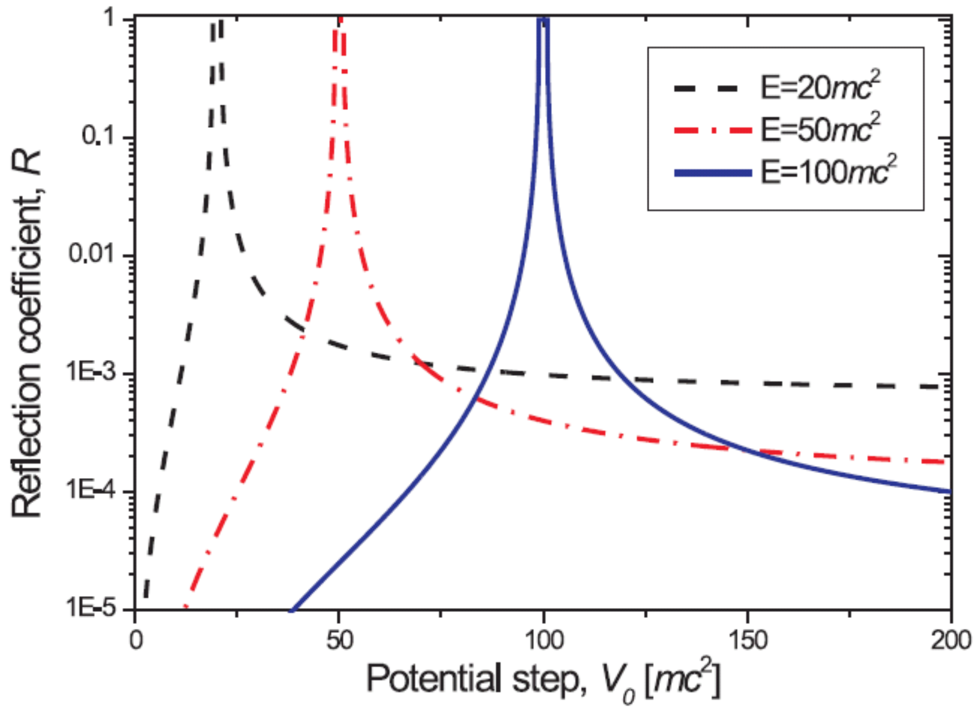
ARTICLES

Chiral tunnelling and the Klein paradox in graphene

M. I. KATSNELSON[1]*, K. S. NOVOSELOV[2] AND A. K. GEIM[2]*

- ***Nature Physics* 2**, 620 - 625 (2006)
  Chiral tunnelling and the Klein paradox in graphene
- M. I. Katsnelson1, K. S. Novoselov2 and A. K. Geim2
- **Abstract**
- The so-called Klein paradox—unimpeded penetration of relativistic particles through high and wide potential barriers—is one of the most exotic and counterintuitive consequences of quantum electrodynamics. The phenomenon is discussed in many contexts in particle, nuclear and astro-physics but direct tests of the Klein paradox using elementary particles have so far proved impossible….



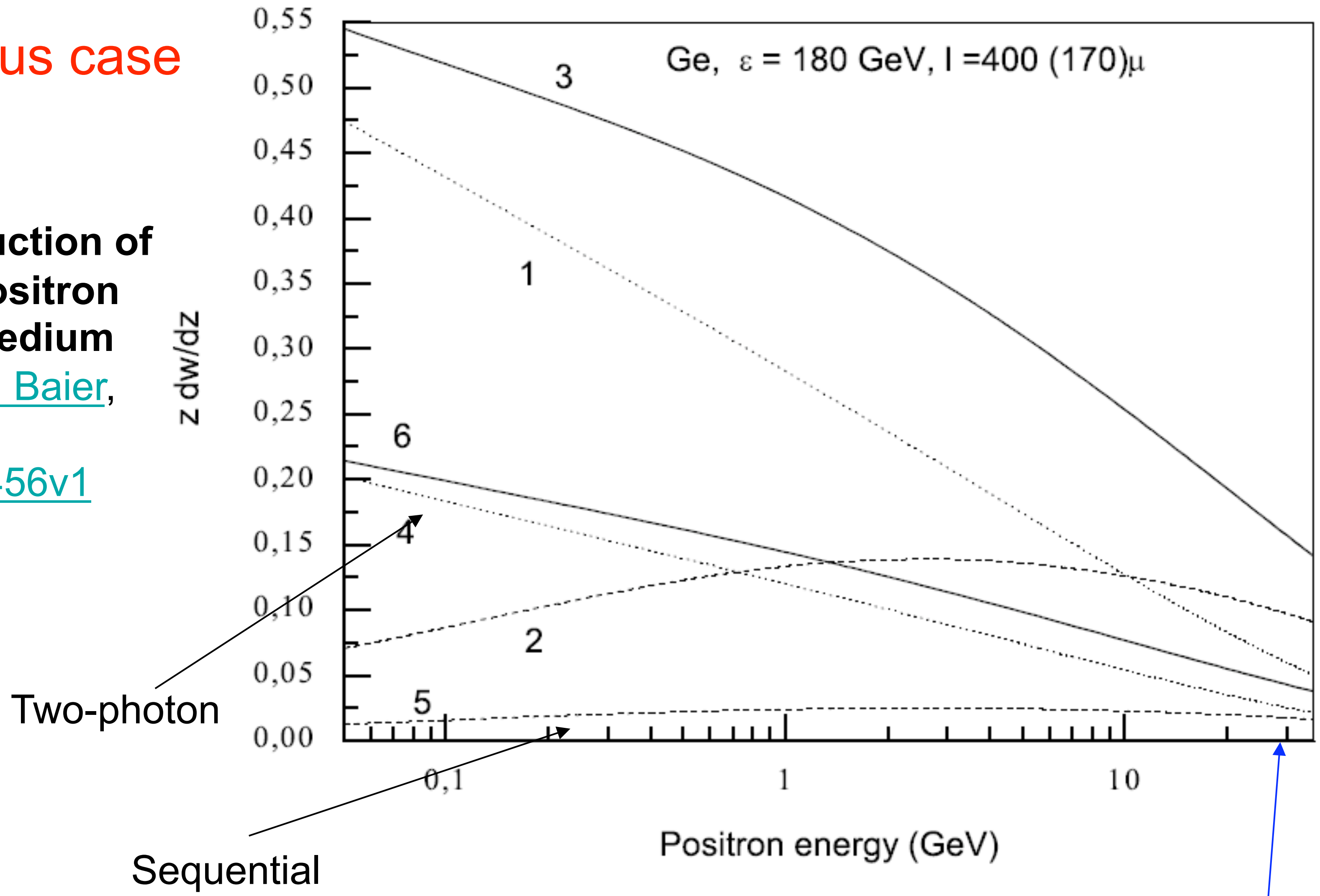


Amorphous case

Electroproduction of electron-positron pair in a medium

Authors: V. N. Baier, V. M. Katkov

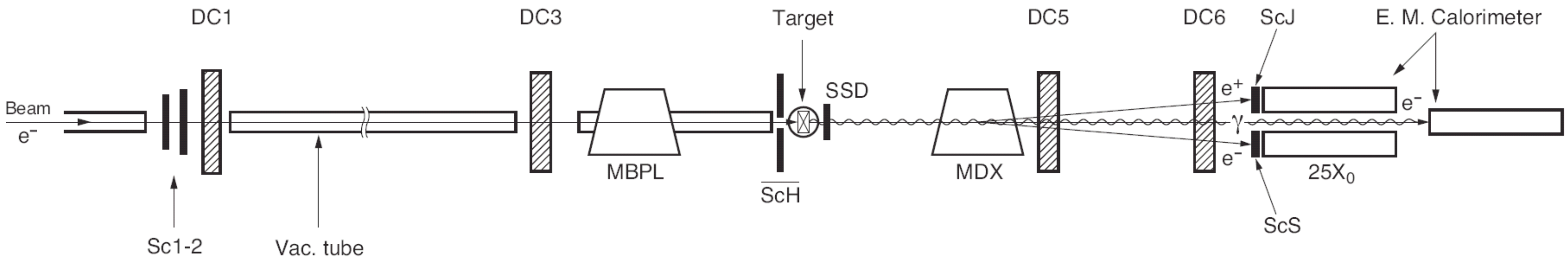
arXiv:0805.0456v1 [hep-ph]



Two-photon process dominates below 30 GeV

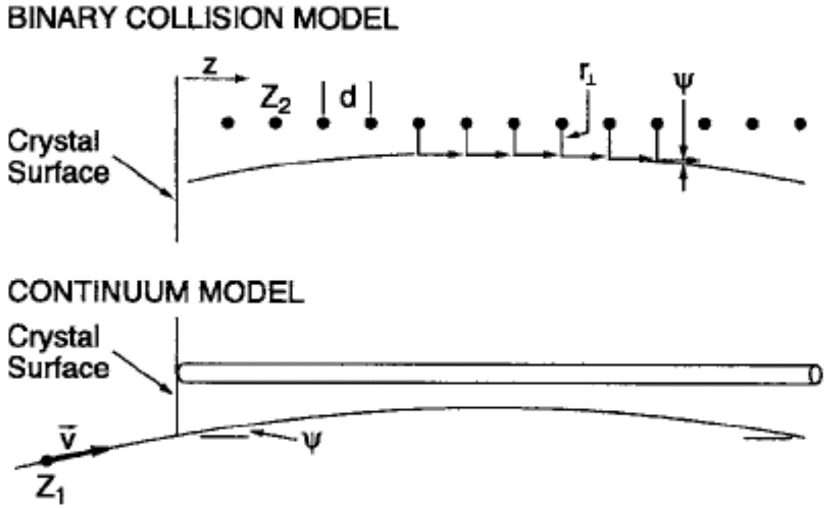
The combination zdw/dz for the pair electroproduction probability in amorphous Ge at the initial electron energy $\varepsilon = 180$ GeV. The dotted curves 1 and 4 are the contributions of two-photon diagrams Eq.(3), the dashed curves 2 and 5 are the contributions of cascade process Eq.(11), the solid curves 3 and 6 are the sum of two previous contributions for two thicknesses $l = 400\ \mu m$ and $l = 170\ \mu m$ respectively. For convenience the ordinate is multiplied by 10^3.

Trident production

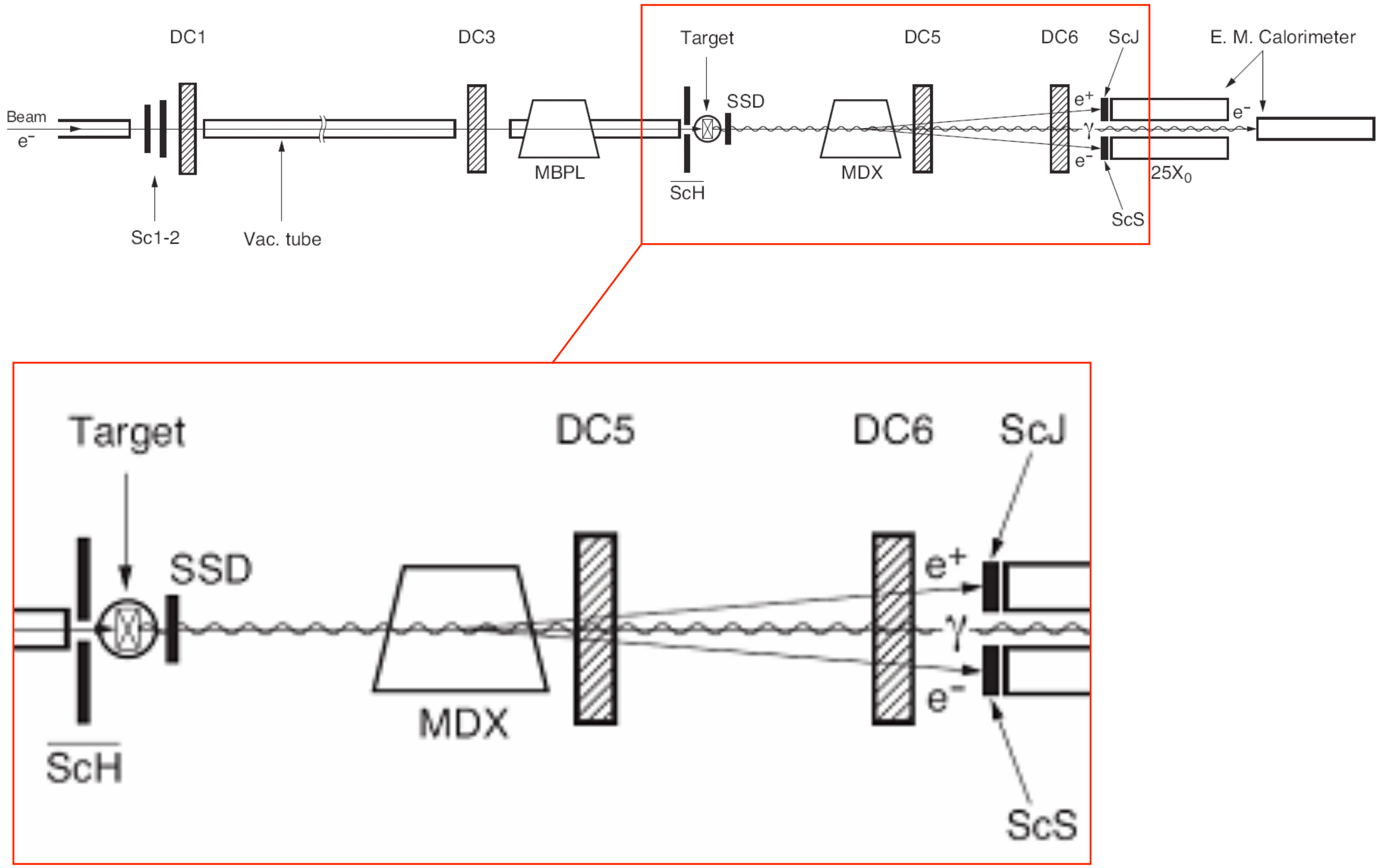


$$\chi = \gamma \mathcal{E} / \mathcal{E}_0$$

$$\mathcal{E}_0 = mc^2 / e\lambda_c = 1.32 \cdot 10^{16}\ \mathrm{V/cm}$$



$$10^{11} - 10^{12}\ \mathrm{V/cm}$$



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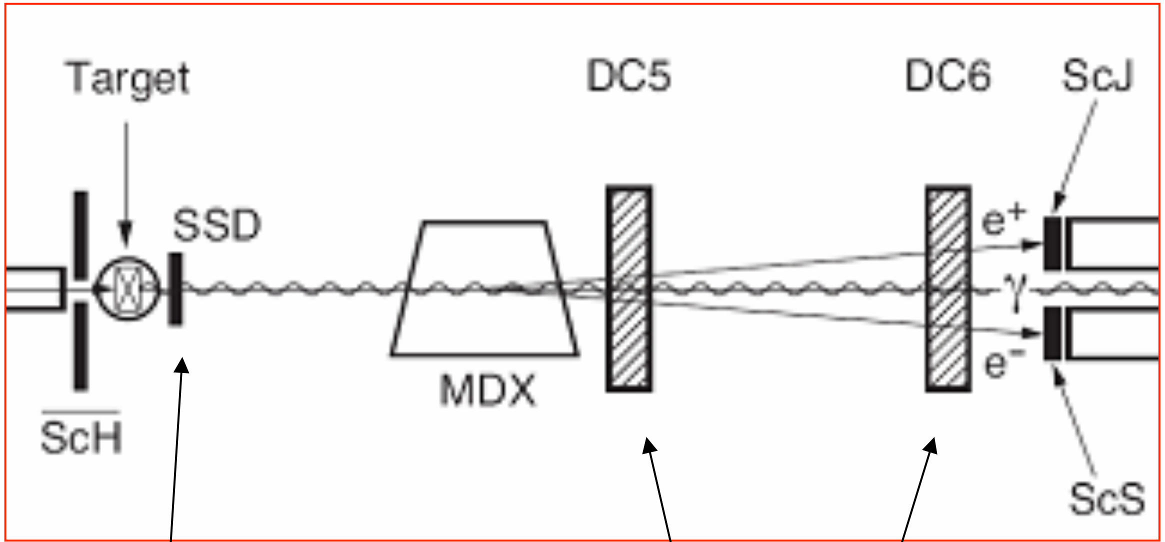
Primary particle:
Detected in the forward direction

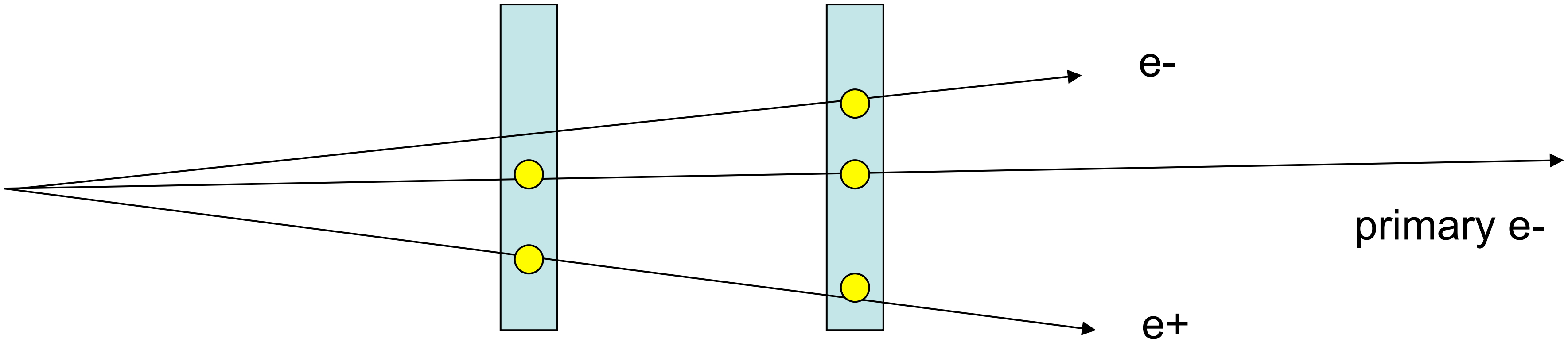
Produced particles:
Momentum analyzed (MDX,DC5,DC6) and energy analyzed (LGs)

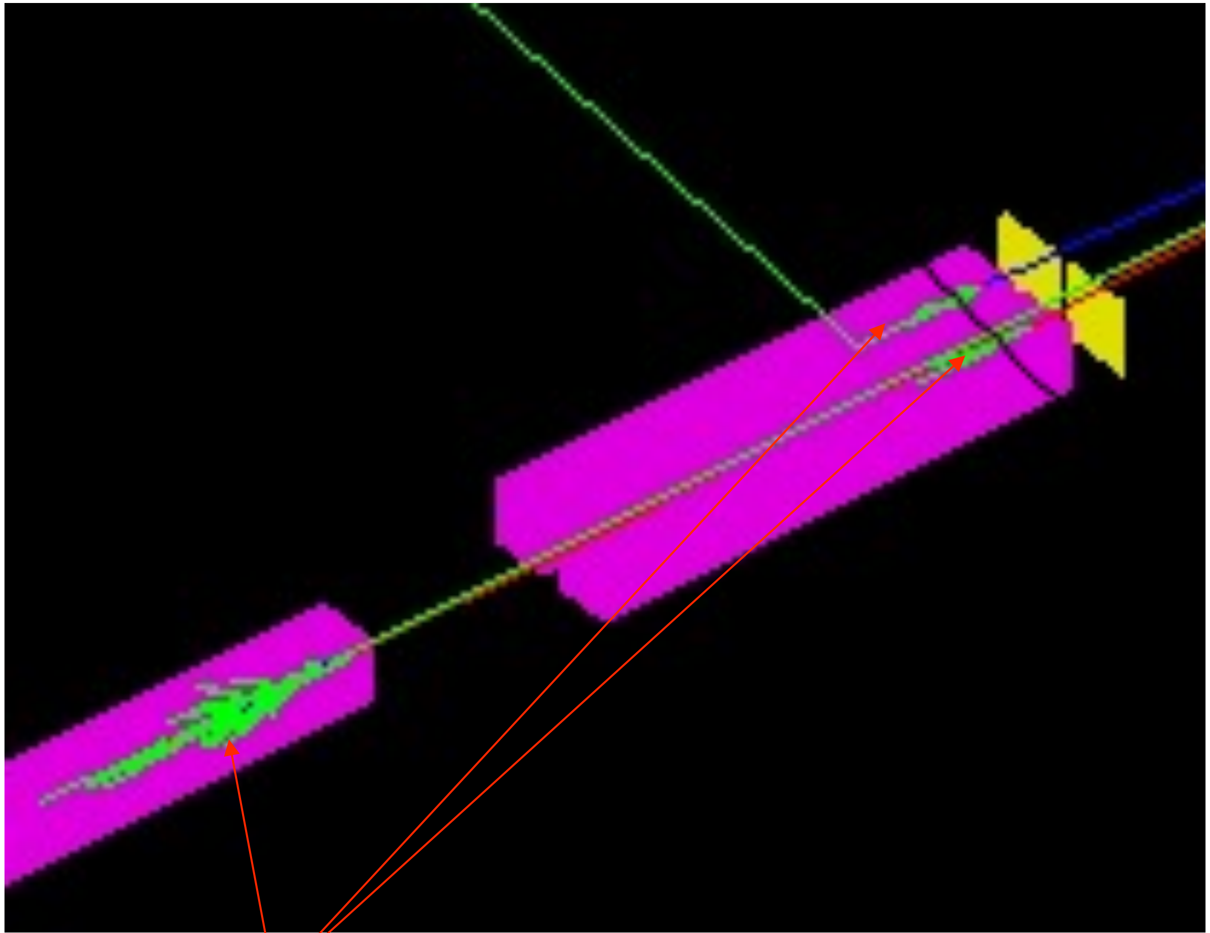


Count of number of charged particles

No true multihit capability, but produced particles incident in adjacent cells

'2+3 event'





Trident production:

Background (no target) in nearly complete agreement with GEANT simulation (= no big surprises)

Contributes about 20%

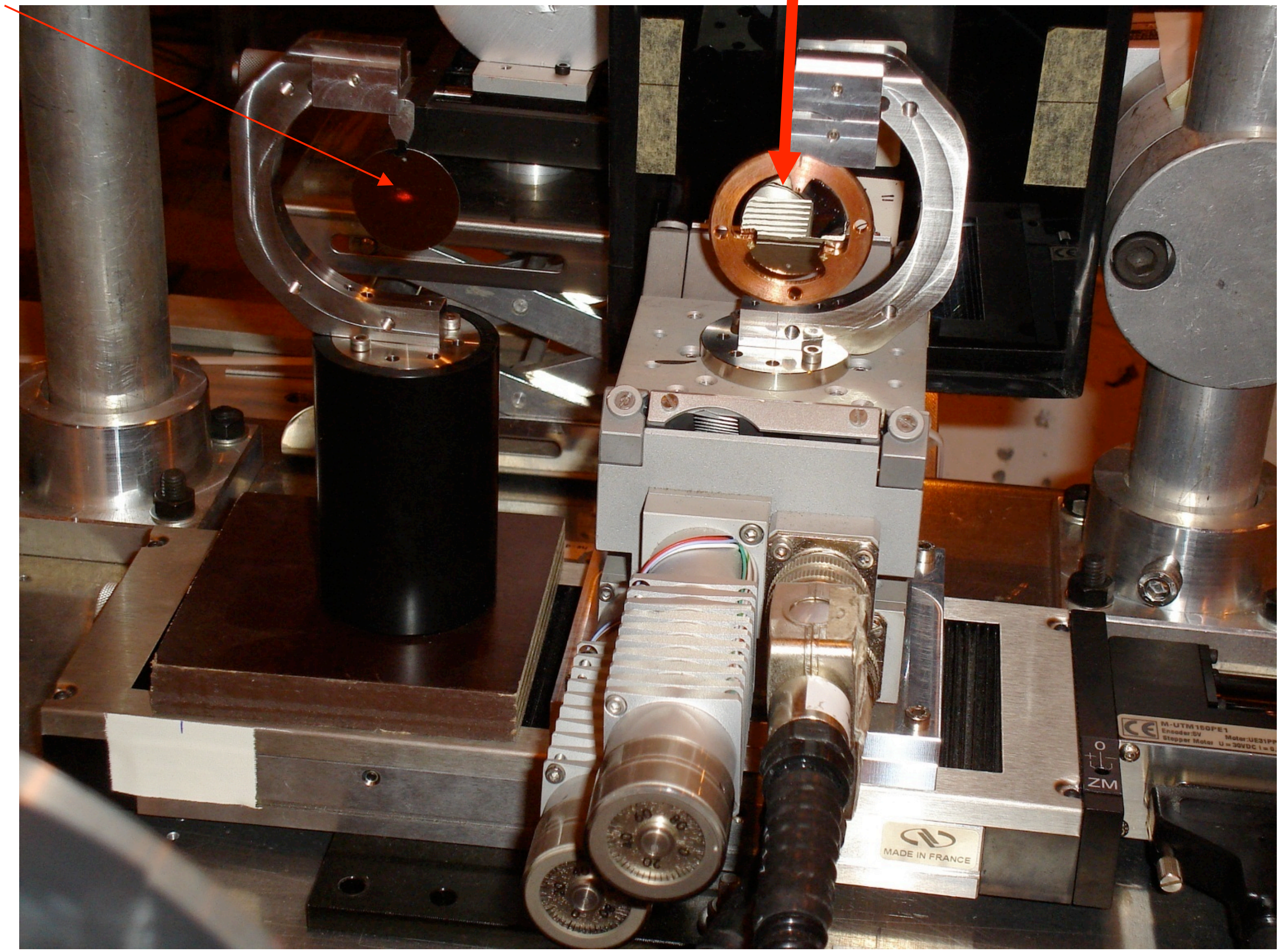
1. Formation length
2. Direct process

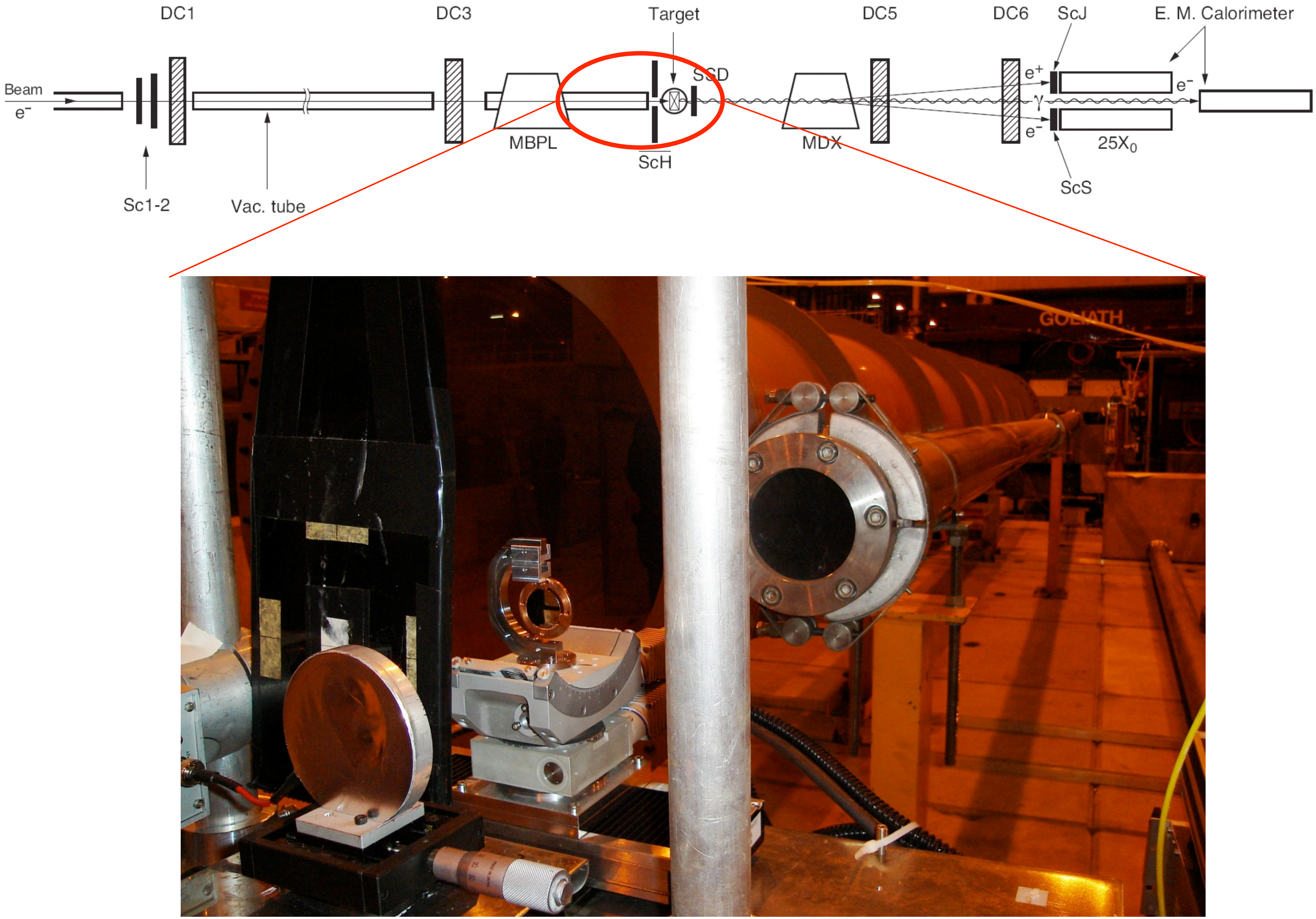
=>

Setup optimized for detection of 1-10 GeV pairs from 200 GeV electrons

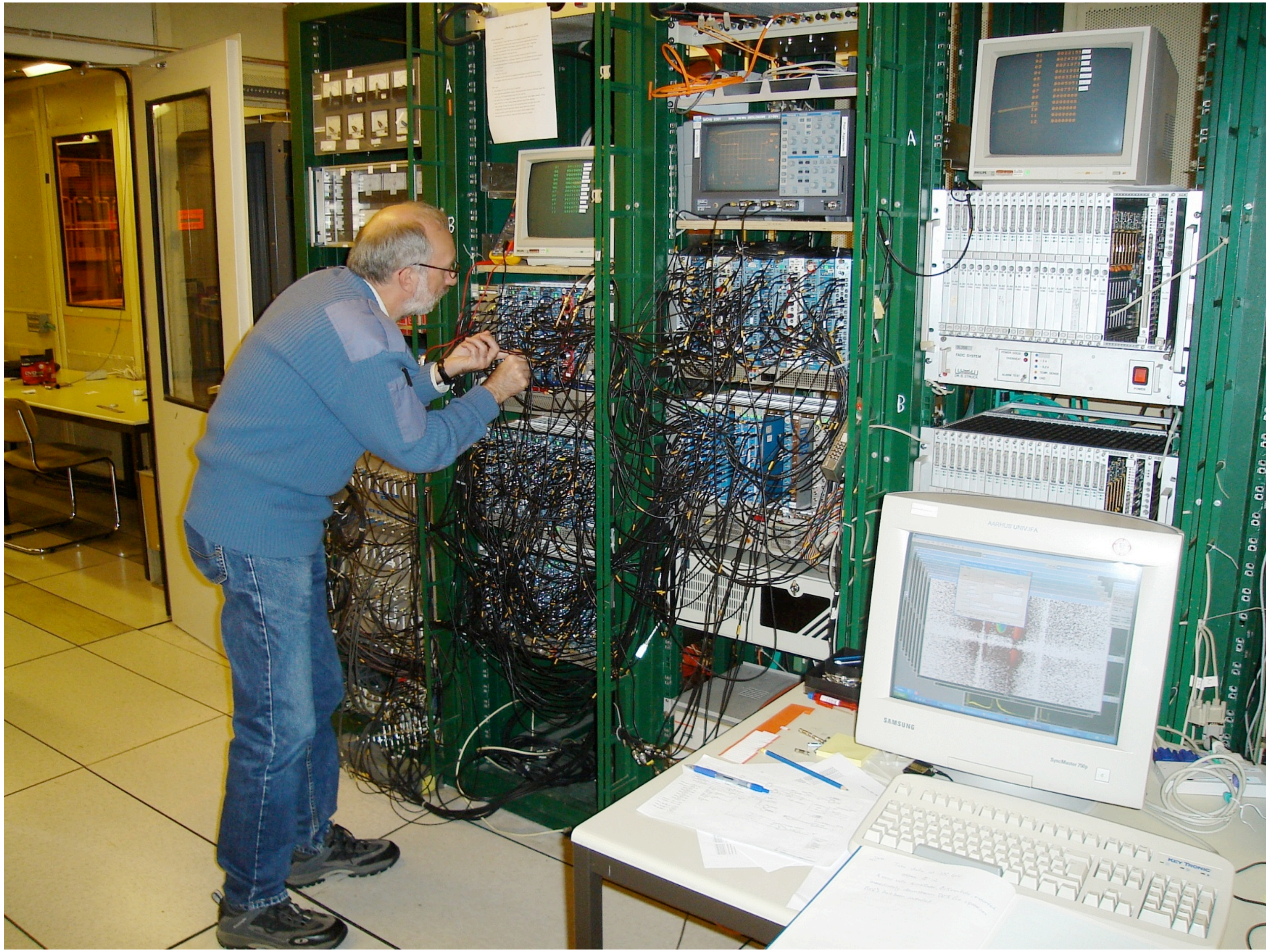
Germanium crystal

spare





Total length of setup: 65 m => good angular resolution



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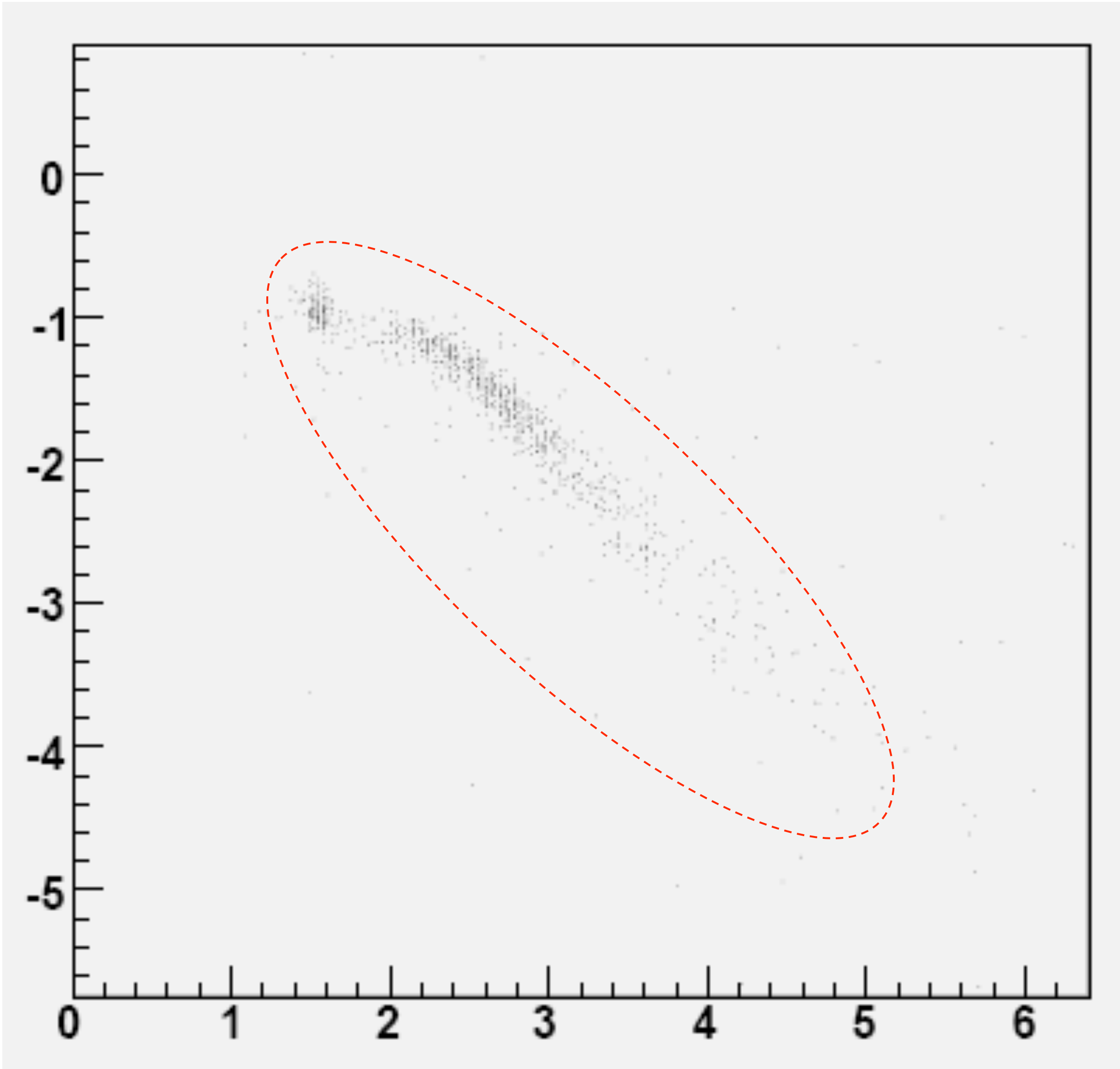
One of the complications -
Setting up within a few days: Electronics, hardware, crystal target….

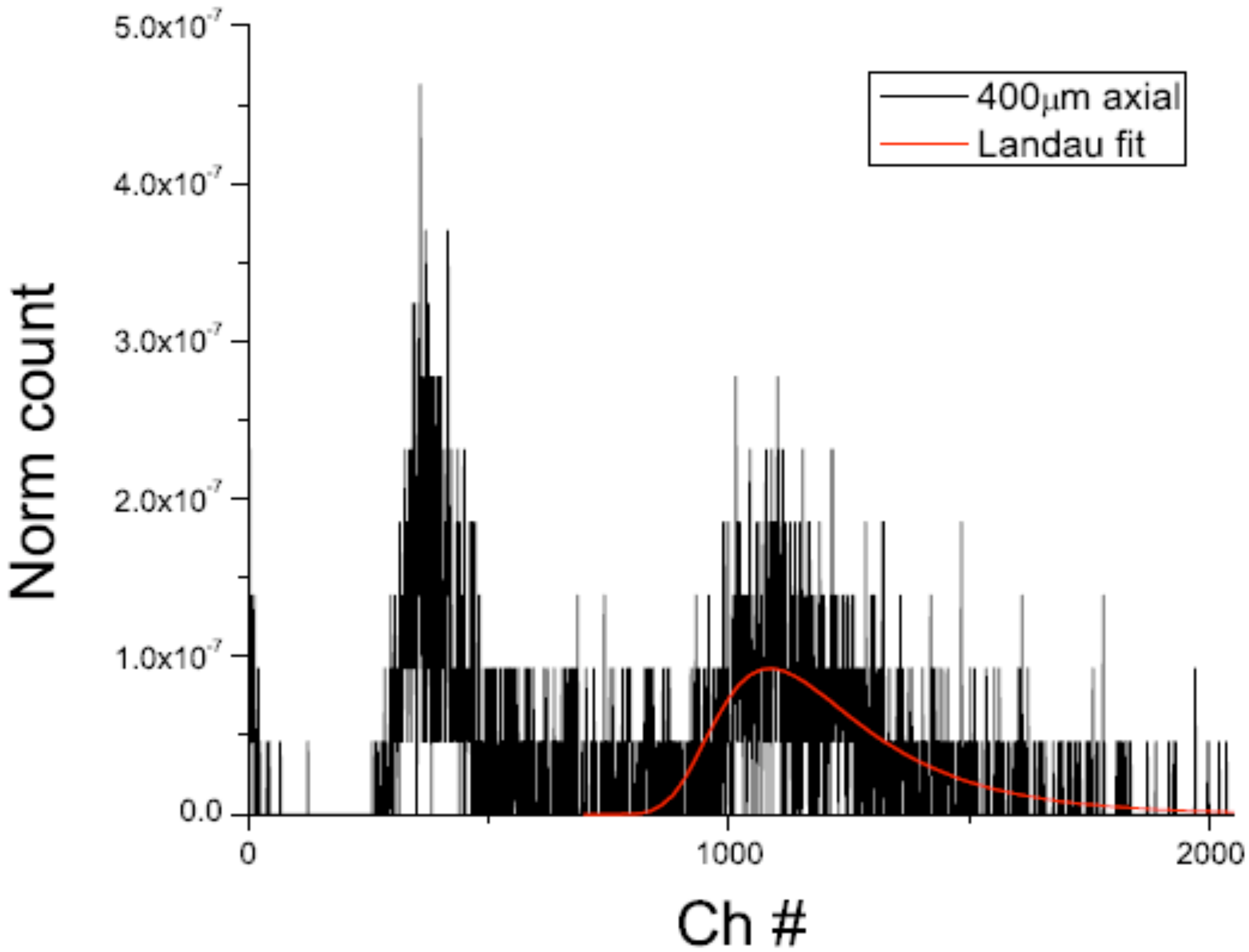
Analysis

- The momentum of the pair spectrometer trident events (vertical axis, [GeV/c]) compared to the signal in the LgJ detector (horizontal axis, [GeV]).

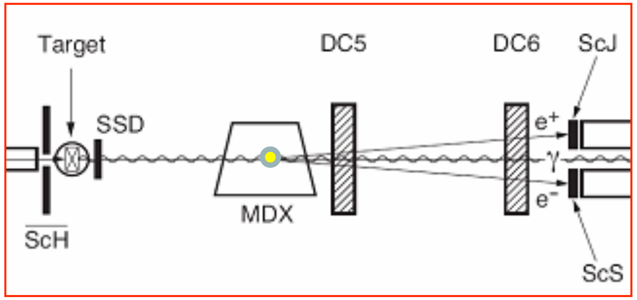


Analysis

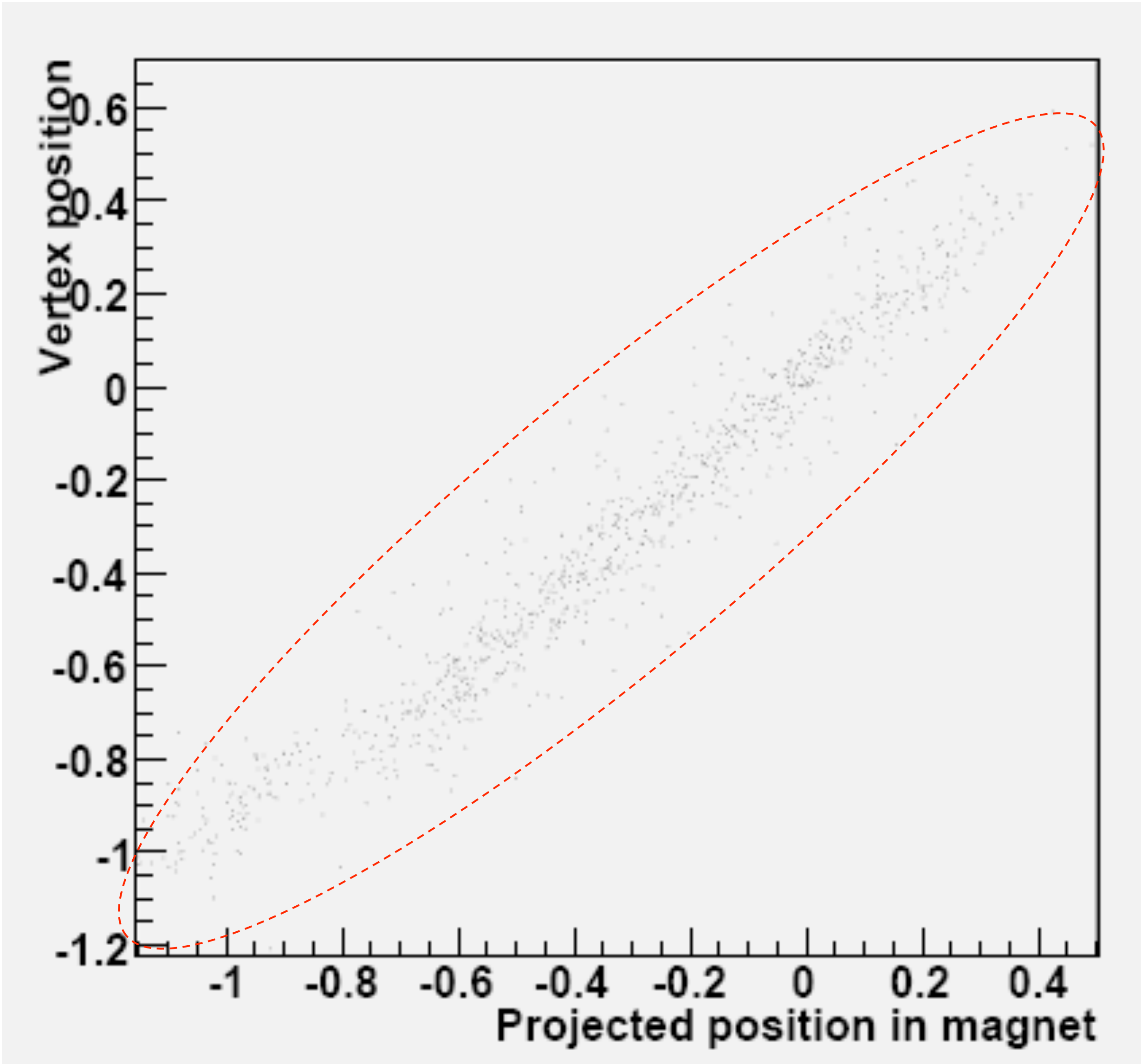
- The SSD spectrum after the trident algorithm event selection and with all cuts but the one in the SSD spectrum itself. Here, the three particles can clearly be seen.

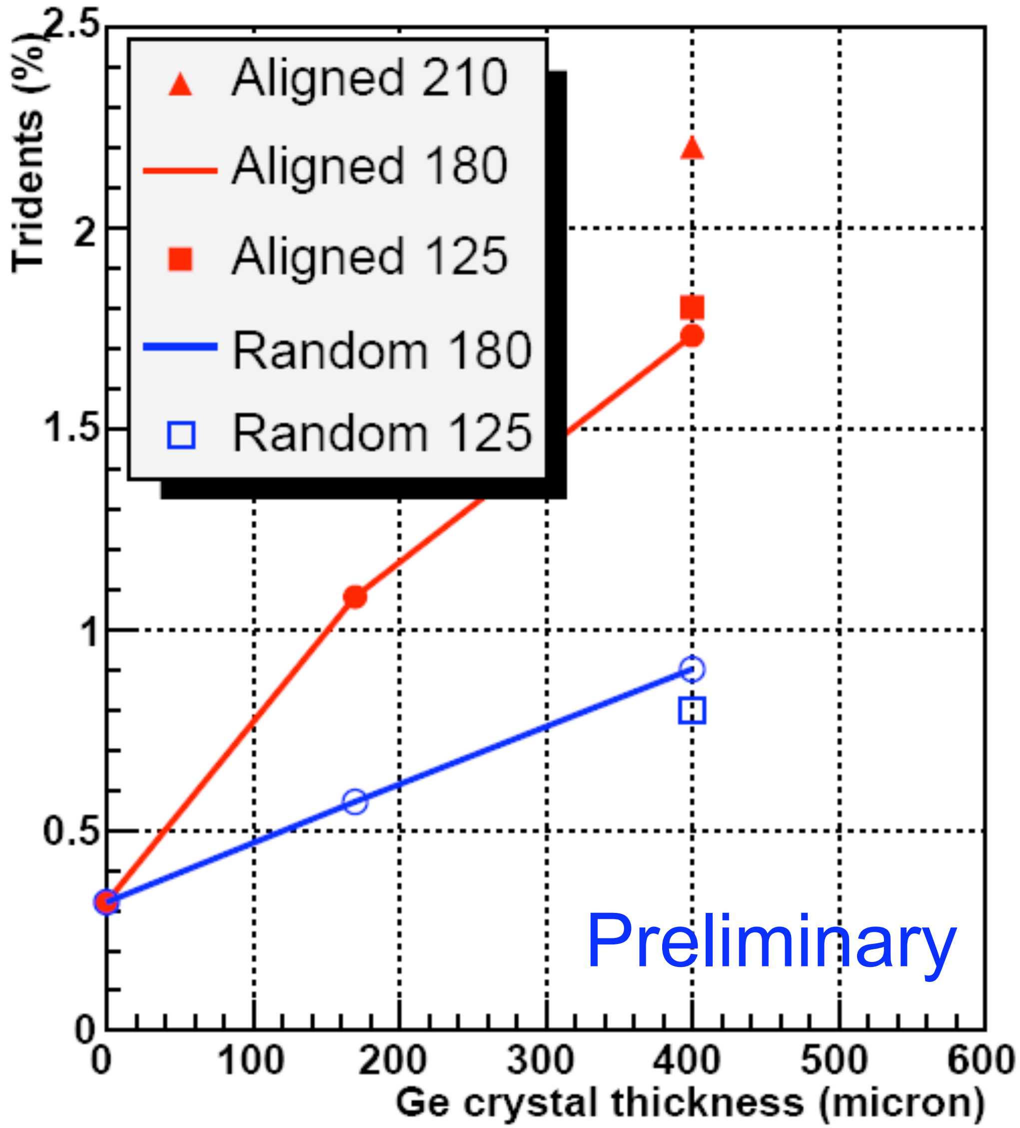


Analysis



- Comparison of the projection of the calculated vertex position and the projection into the center of the MDX magnet. The units of length are in cm.





Enhancement, 400 um Ge <110>, 180 GeV: ≈ (1.7-0.3)/(0.8-0.3) = **2.8**

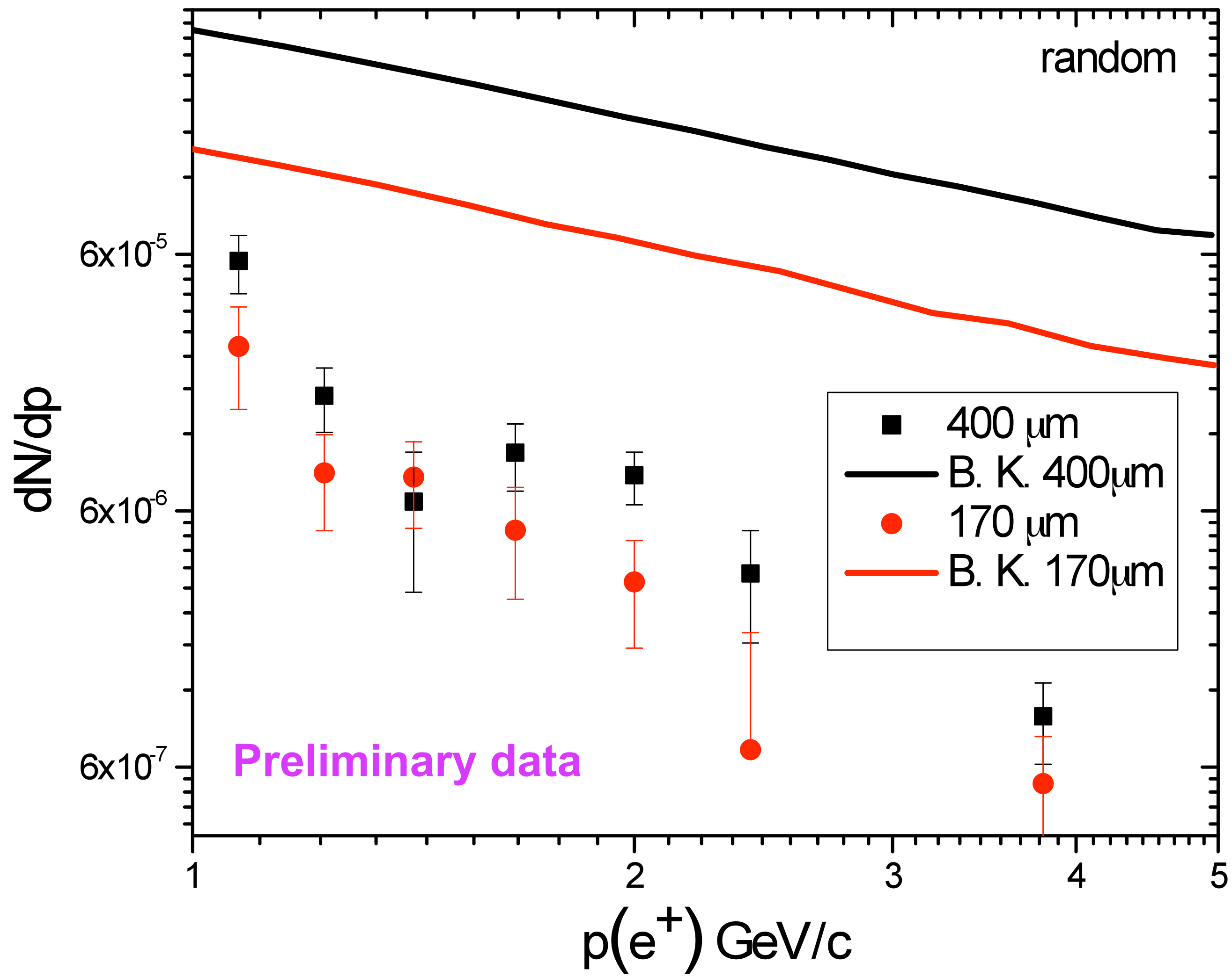
Enhancement, 170 um Ge <110>, 180 GeV: ≈ (1.1-0.3)/(0.6-0.3) = **2.7**

Different thicknesses – 'same' enhancement.

Sequential process (prop. to thickness *squared*) negligible (?)

Trident production in Ge crystals

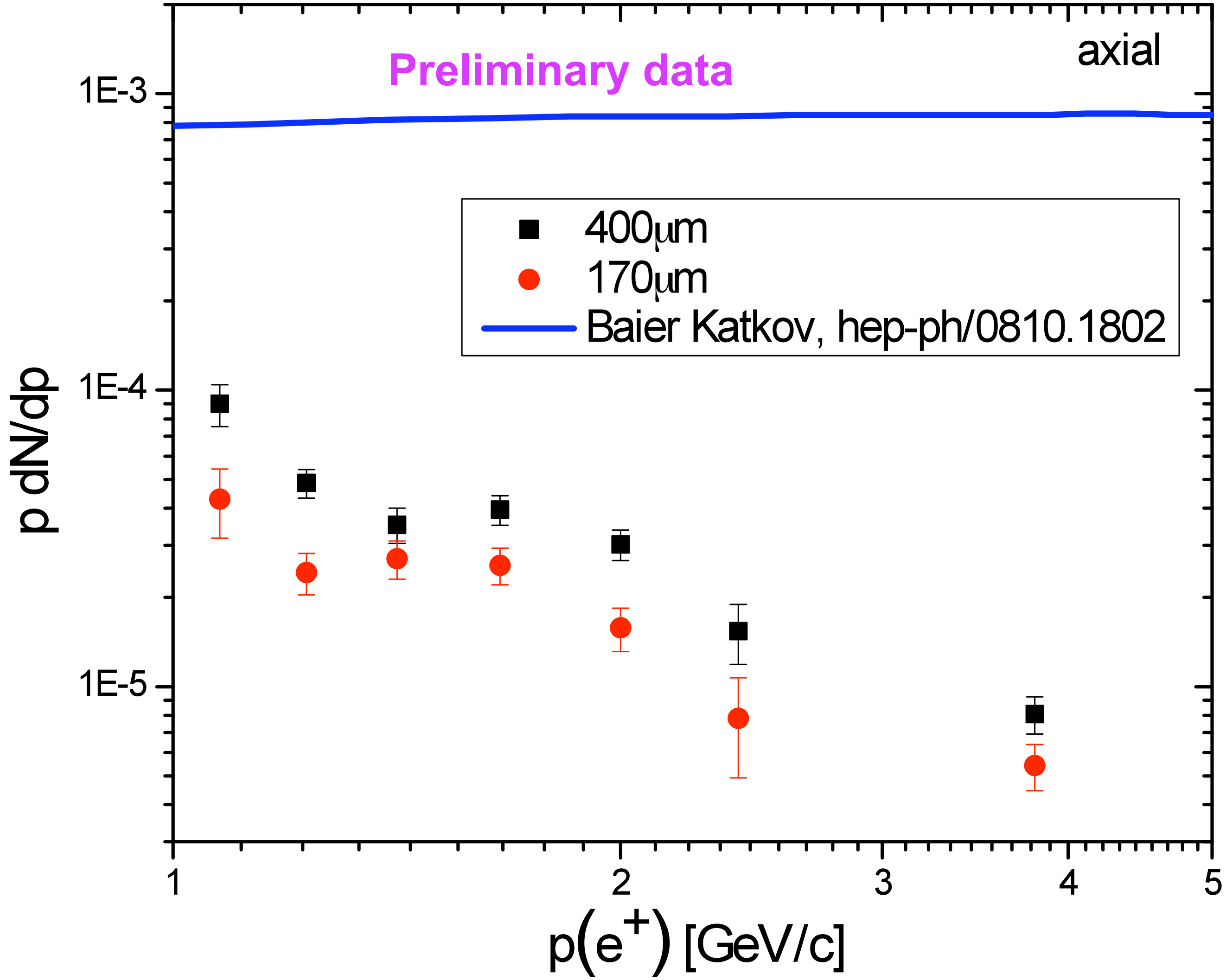
E = 180 GeV



Detection efficiency **not** included (presently being investigated)

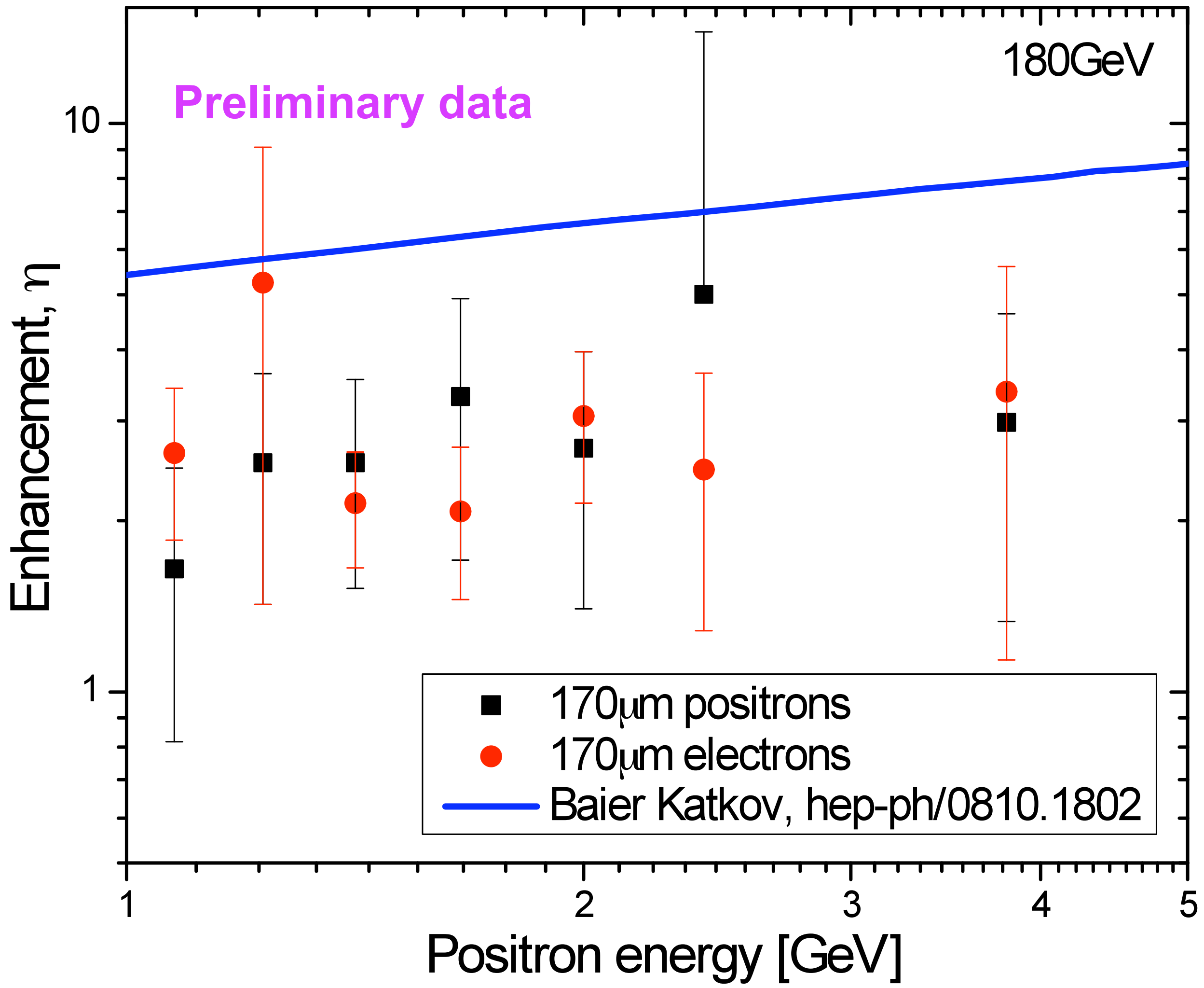
Trident production in Ge crystals

E = 180 GeV



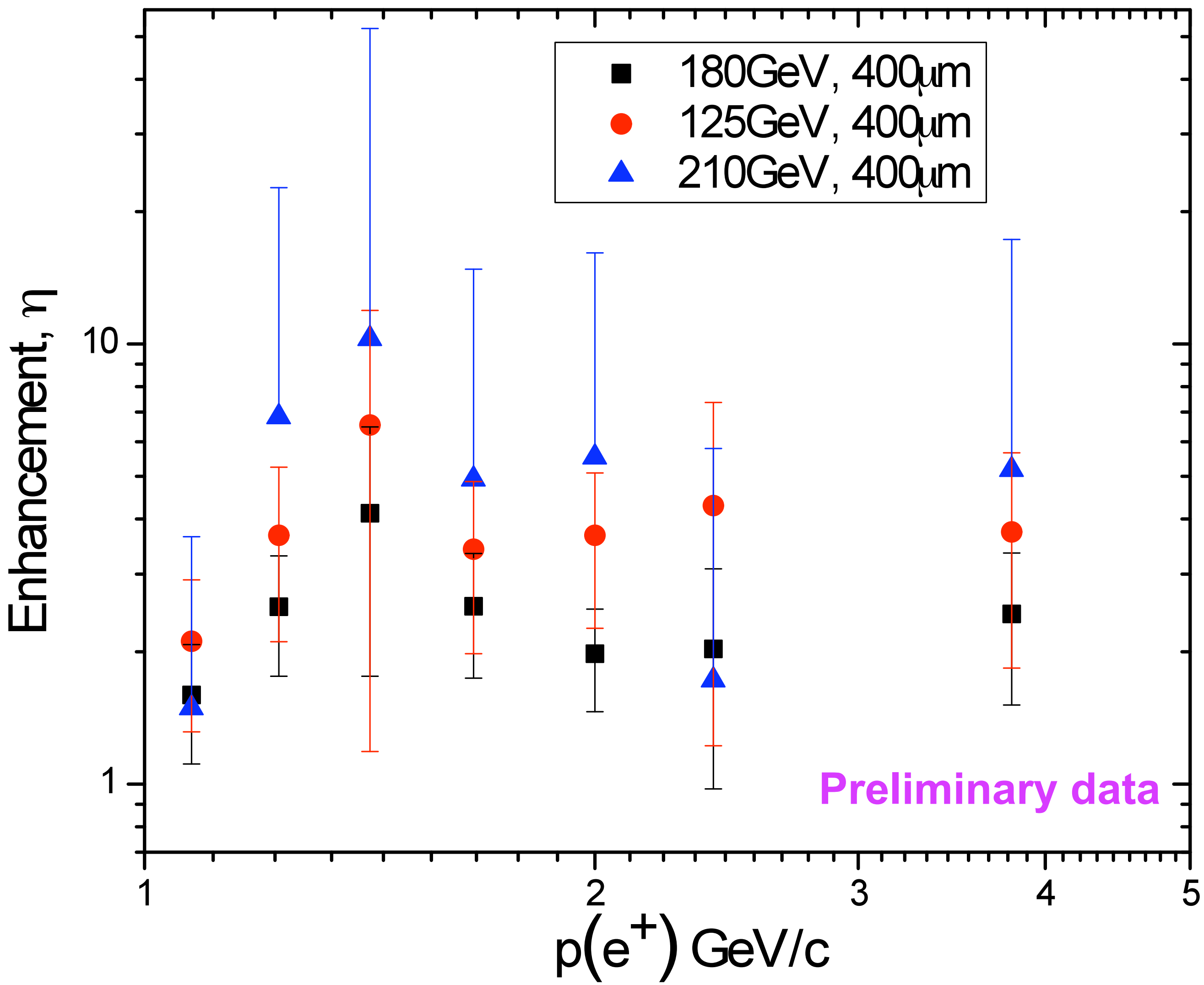
Detection efficiency **not** included (presently being investigated)

Trident production in Ge crystals



Detection efficiency not (as) relevant

Trident production in Ge crystals



On our theory 'wish-list':

Average enhancement (1 GeV < p(e^+) < 5 GeV) as a function of energy of the primary

Conclusions

- …direct tests of the Klein paradox using elementary particles ~~have so far proved impossible~~….

… are in fact possible (at least a close analogue)!