FUNDAMENTAL SHORT TIME-SCALE RELATIVISTIC PHYSICS: COLLECTIVE PHENOMENA. PARTICLE ACCELERATION AND PRODUCTION IN FEMTOSECOND LASER-MATTER INTERACTION

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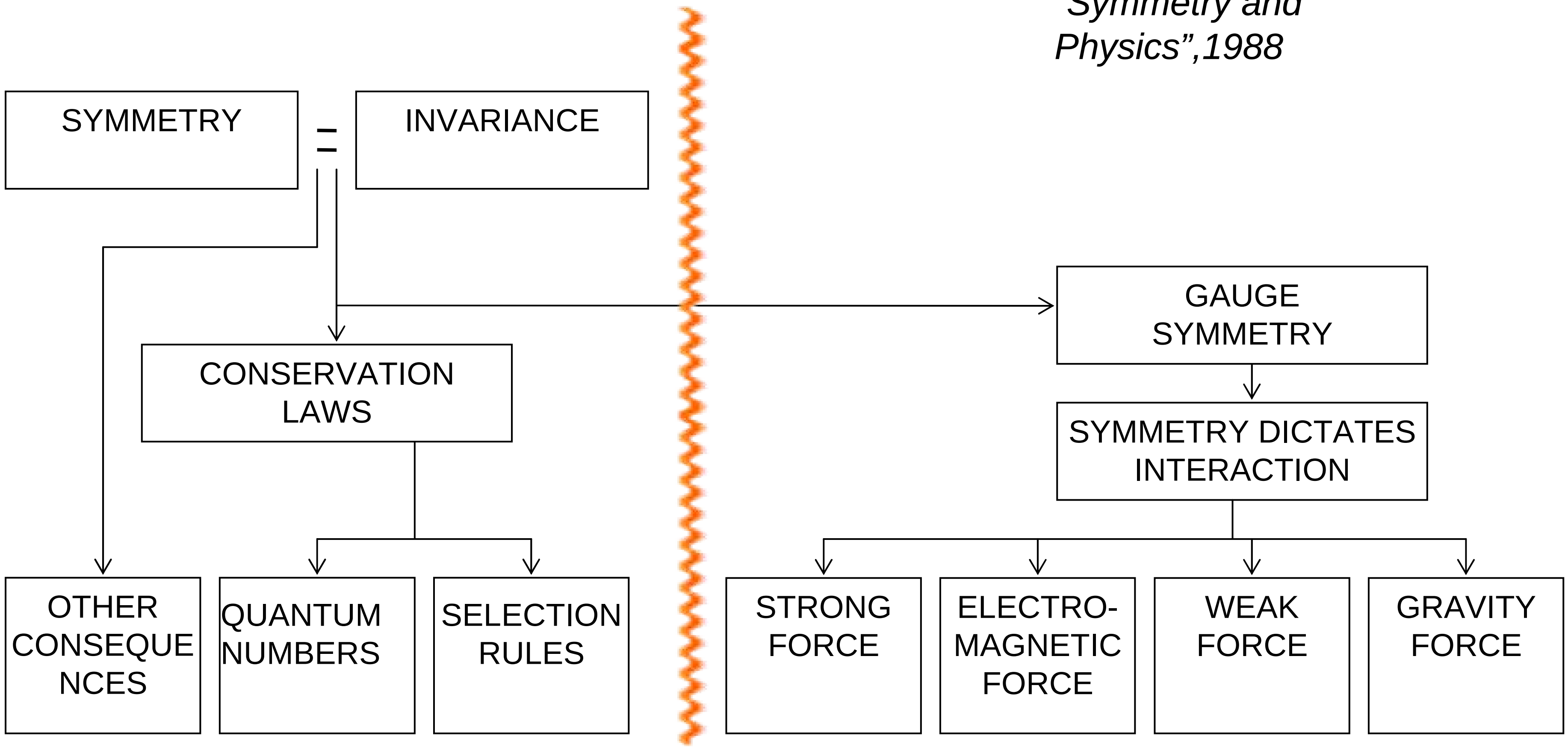
Outlook

- Relativistically invariant self-similarity approach in nuclear physics.
- Similarity of extreme states of nuclear matter and ultrashort laser-matter interaction.
- Correlation between geometric characteristics in Lobachevsky space and measurable parameters.

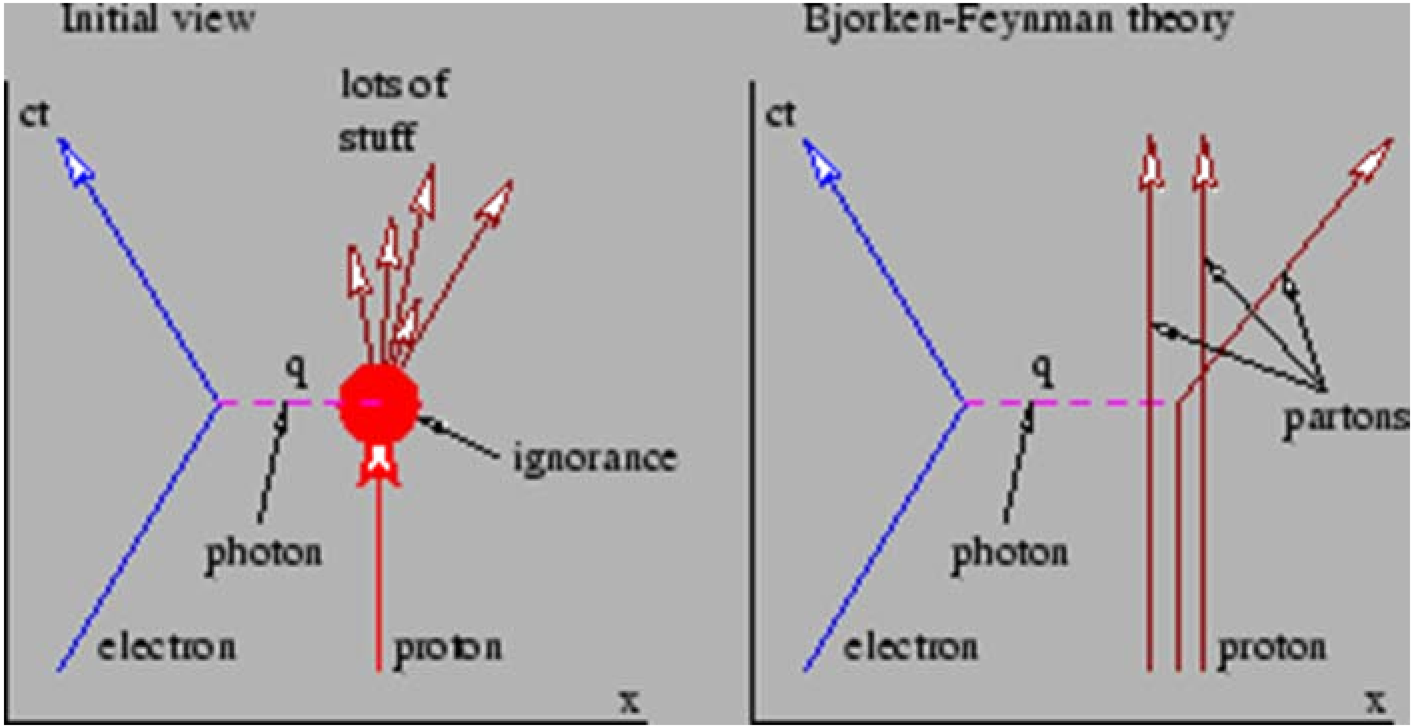
Chen Ning Yang
“Symmetry and Physics”,1988



Schematic diagram illustrating the role of symmetry in fundamental physics.

Self-similarity is a special symmetry of solutions which consists in that the change in scales of independent variables can be compensated by the self-similarity transformation of other dynamical variables.

This results in a reduction of the number of the variables which any physical law depends upon.



$$x = -\frac{q^2}{2P_2 q}$$

This is the way in which the self-similarity laws following from dimensionality considerations in the region

$P^2 >> M^2$ are extensively applied

$$P_1 + xP_2 = P_1' + \sum P_i'$$

$$\left(P_1 + xP_2 - P_1' \right)^2 = \left(\sum P_i' \right)^2$$

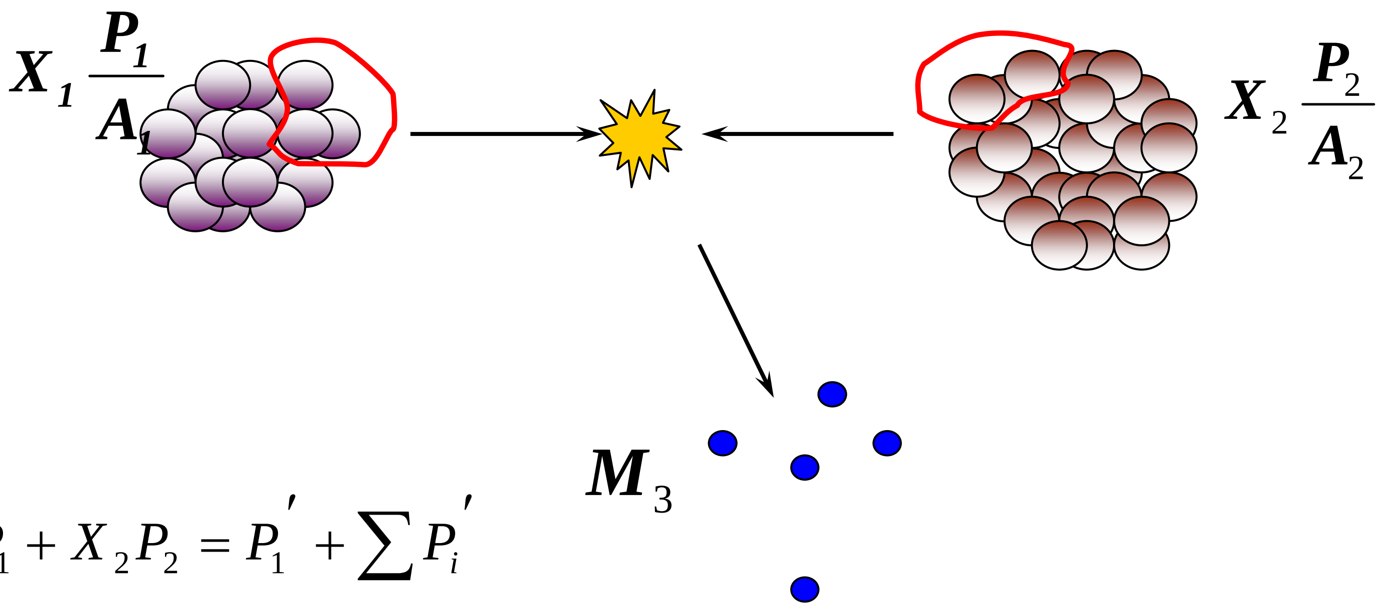
$$P_1 - P_1' = q$$

$$\left(q + xP_2 \right)^2 = \left(\sum P_i' \right)^2$$

$$2\sum_{k>1} \left(\gamma_{kl} - 1 \right) M_k M_l$$

$$q^2 + 2xP_2q + x^2 P_2^{\,2} = M^2$$

$$x = -\frac{q^2}{2P_2q}$$



$$X_1 P_1 + X_2 P_2 = P_1' + \sum P_i'$$

The relationship between X_1 and X_2 is described by the conservation laws written in the form

$$\left(X_1 M_1 u_1 + X_2 M_2 u_2 - M_3 u_3\right)^2 = \left(M_n X_1 u_1' + M_n X_2 u_2' + \sum_{k=4} M_k u_k\right)^2$$

Essentially, we are using the correlation depletion principle in the relative four-velocity space which enables us to neglect the relative motion of not detected particles, namely the quantity $2\sum_{k>1}\left(\gamma_{kl} - 1\right) M_k M_l$ in the right-hand part of the above equation.

$$X_1 X_2(\gamma_{12}-1) - X_1\left(\frac{M_3}{M_p}\gamma_{13}+\frac{M_4}{M_p}\right) - X_2\left(\frac{M_3}{M_p}\gamma_{23}+\frac{M_4}{M_p}\right) = \frac{M_4^2 - M_3^2}{2M_p}$$

In the case of production of antiparticle with mass M_3, the mass M_4 is equal to M_3 as a consequence of conservation of quantum numbers. In studying the production of protons and nuclear fragments

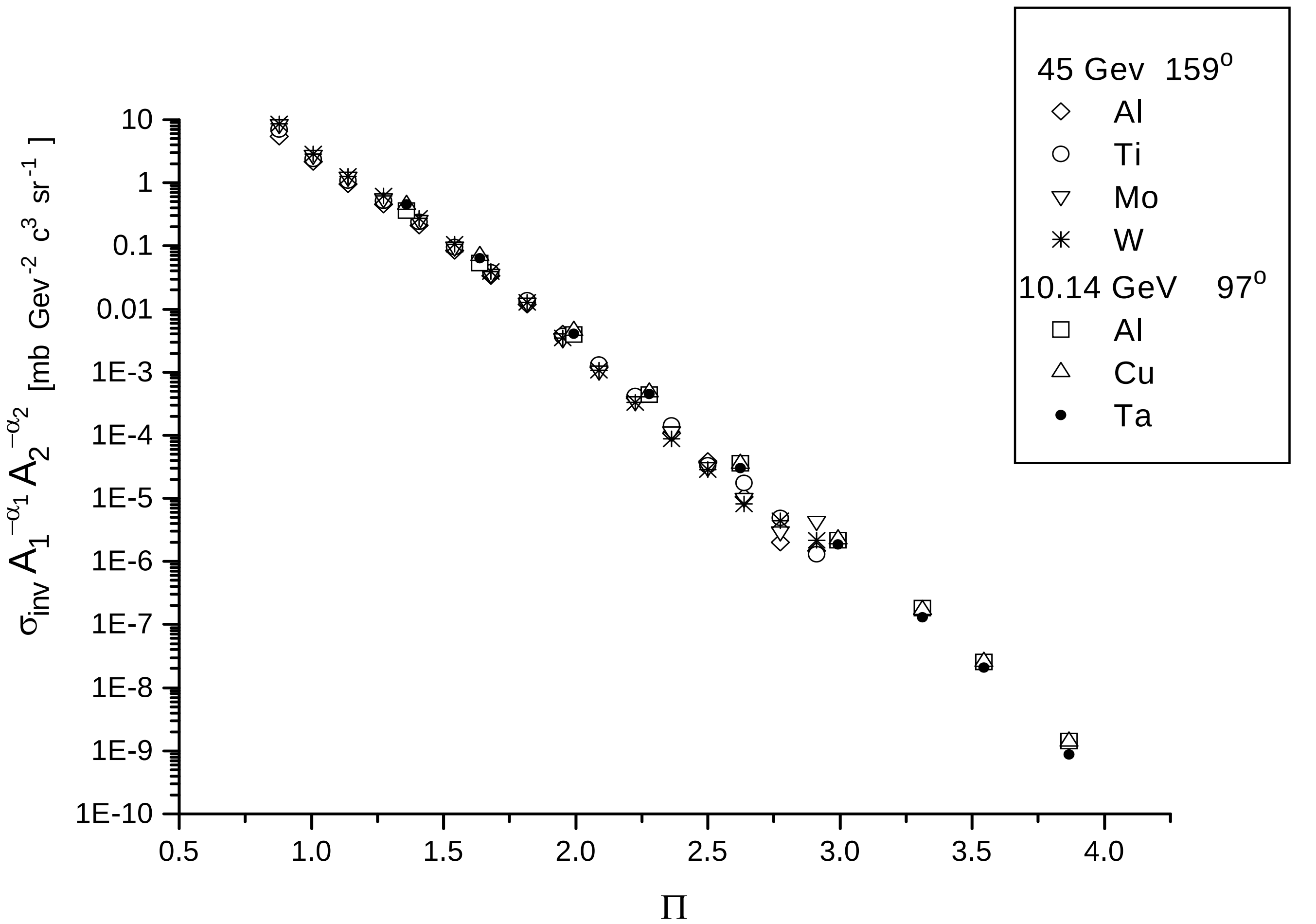
$M_4 = -M_3$ as far as the minimum value of Π corresponds to the case that no other additional particles are produced. The values X_1 and X_2 obtained from the minimum Π are used to construct a universal description of the A-dependencies.

$$S = (P_1 + P_2)^2$$

$$\Pi = \frac{1}{2}\left(X_1^2 + X_2^2 + 2X_1 X_2 \gamma_{12}\right)^{1/2}$$

$$E\frac{d^3\sigma}{d^3p} = C_1 A_1^{\alpha(X_1)} A_2^{\alpha(X_2)} f(\Pi)$$

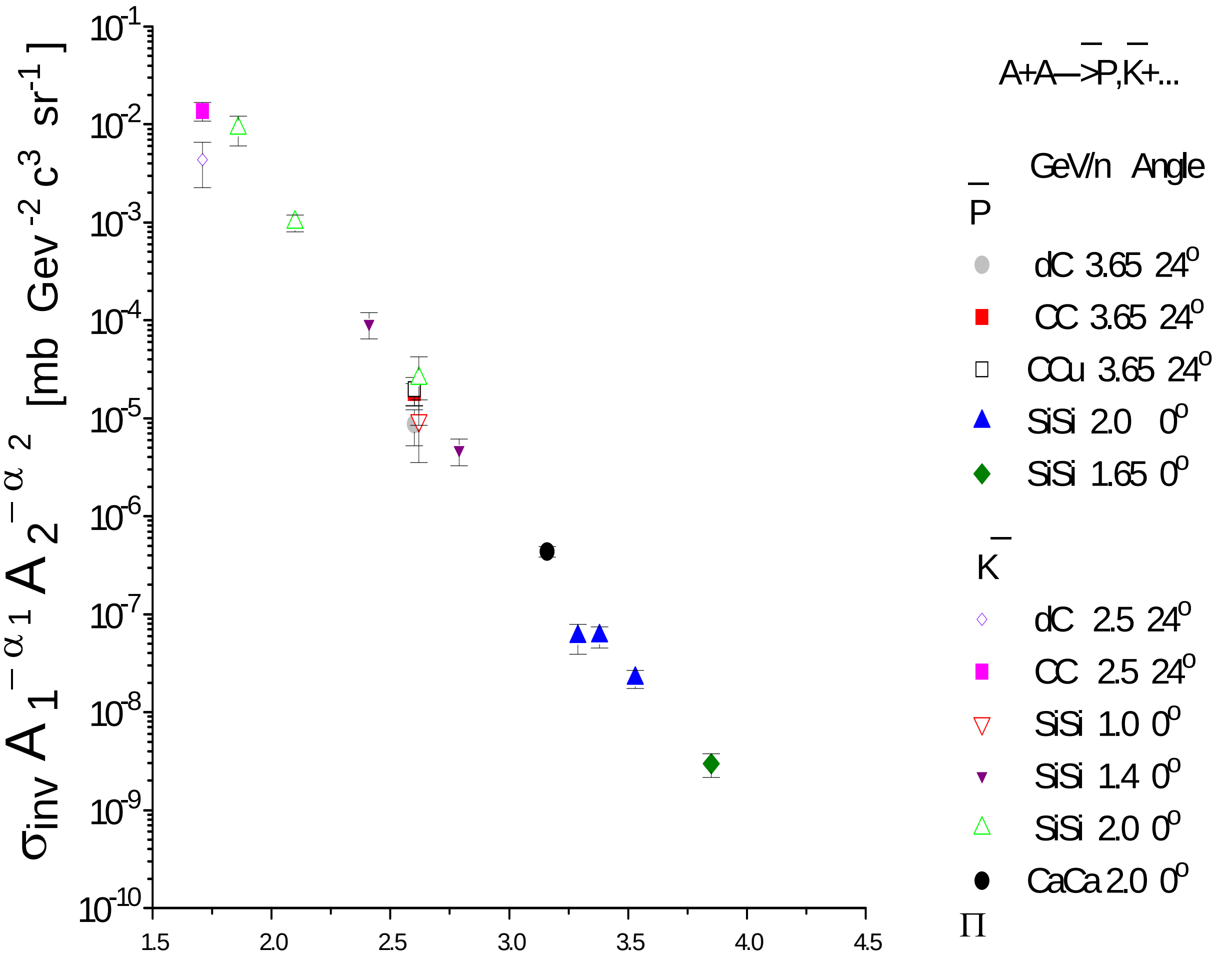
Cumulative processes



S.V.Boyarinov, et al. Yad. Fis. , v.57, N8, (1994) ,1452-1461.

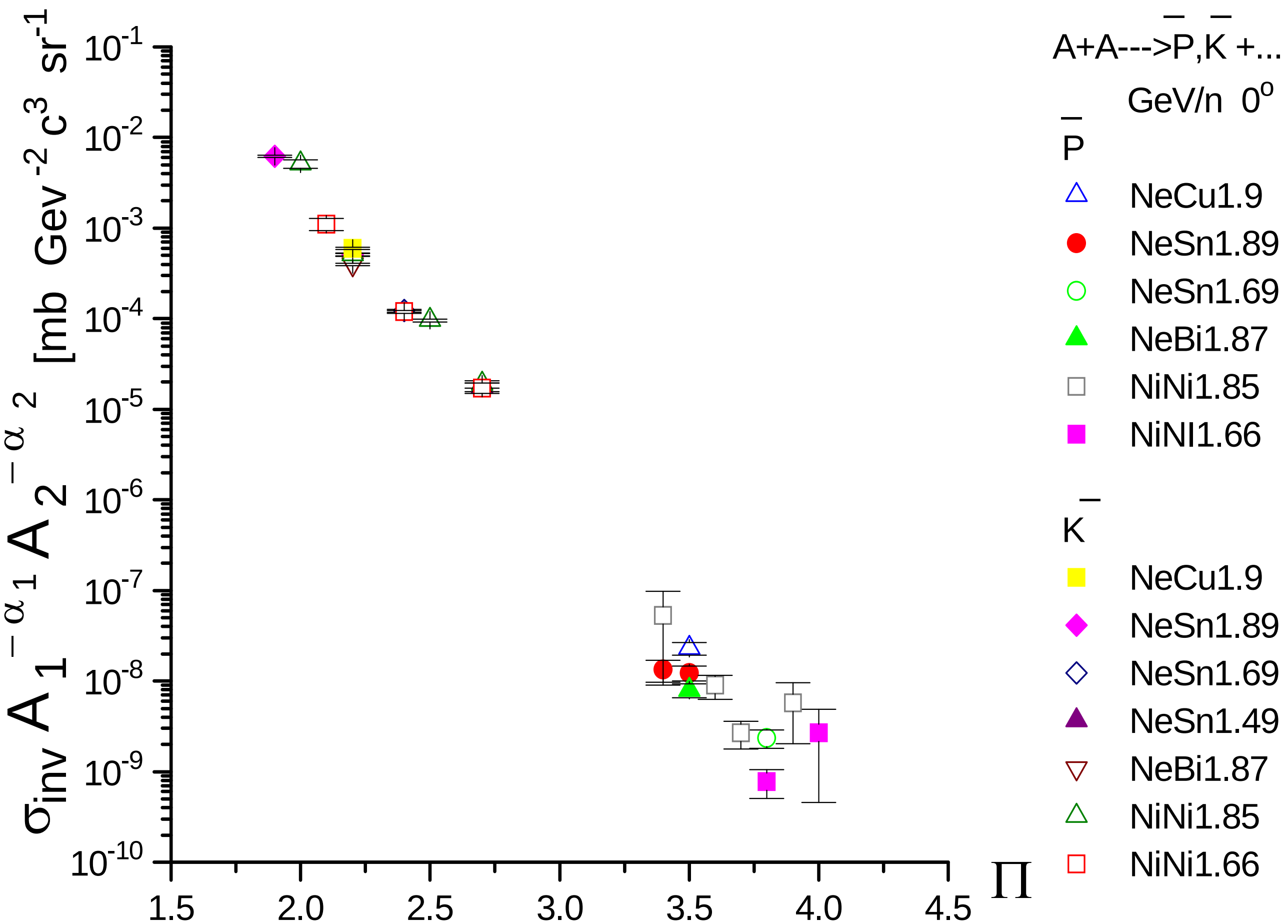
O.P.Gavrishchuk et al. Nucl. Phys., A523 (1991) 589.

Twice cumulative



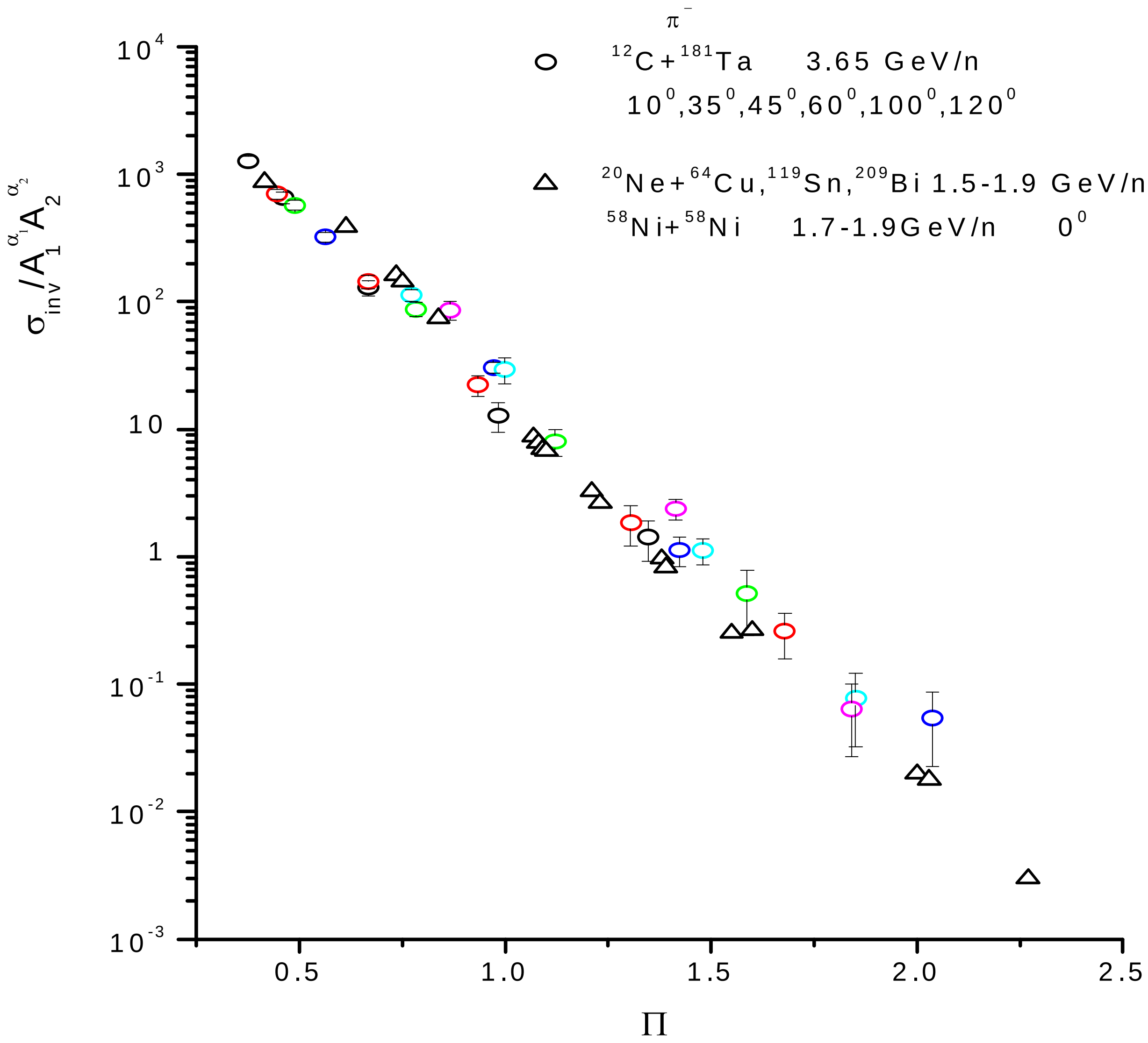
Jim Carroll Nucl. Phys. A488 (1989) 2192.
A.Shor et al. Phys. Rev. Lett. 62 (1989) 2192.
A.A.Baldin et al. Nucl. Phys., A519 (1990) 407.
A.A.Baldin et al. Rapid Communications JINR, 3-92 (1992) 20.

Twice cumulative

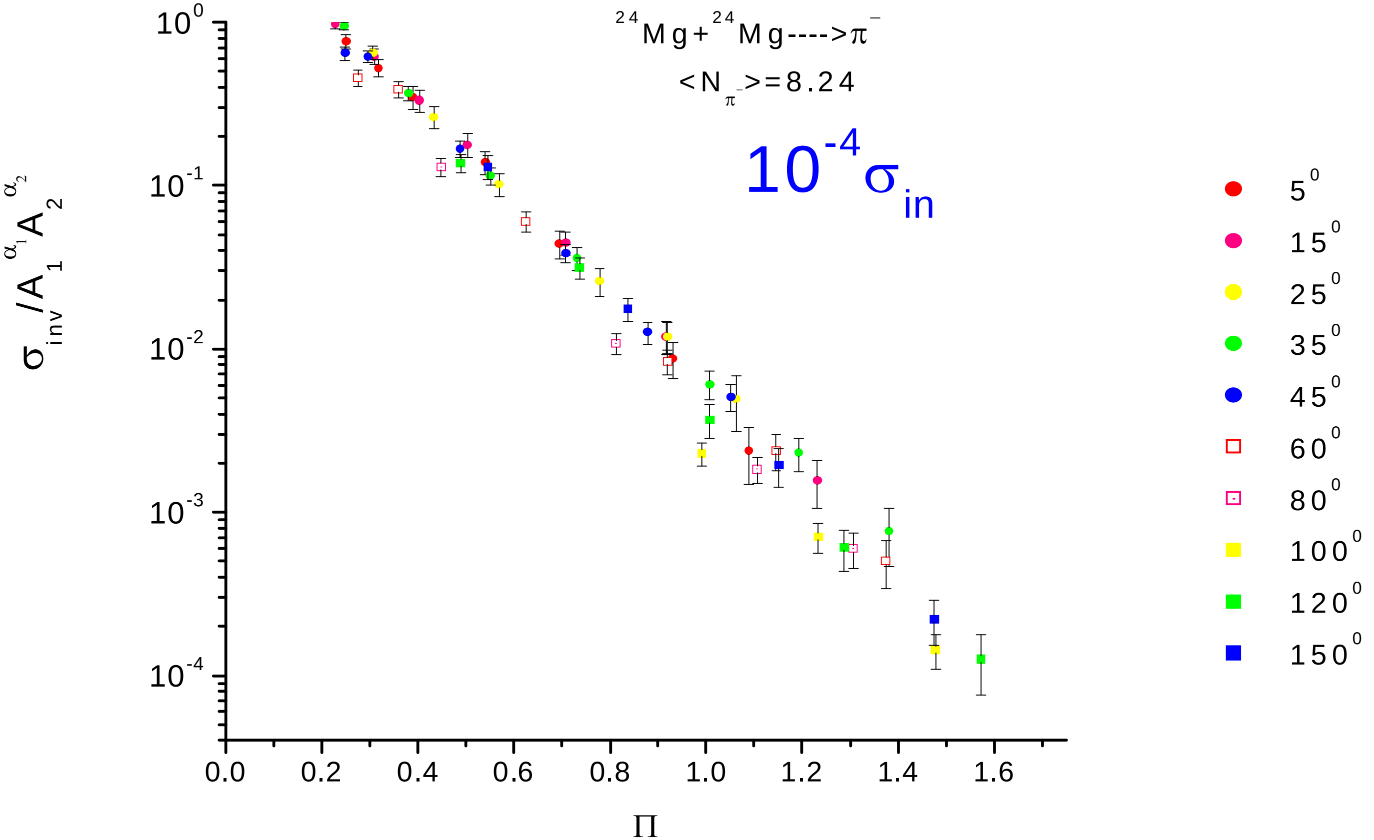


A.Schroter et al. Z.Phys. A350, (1994), 101-113.

Inclusive pion spectra
(various experiment types)

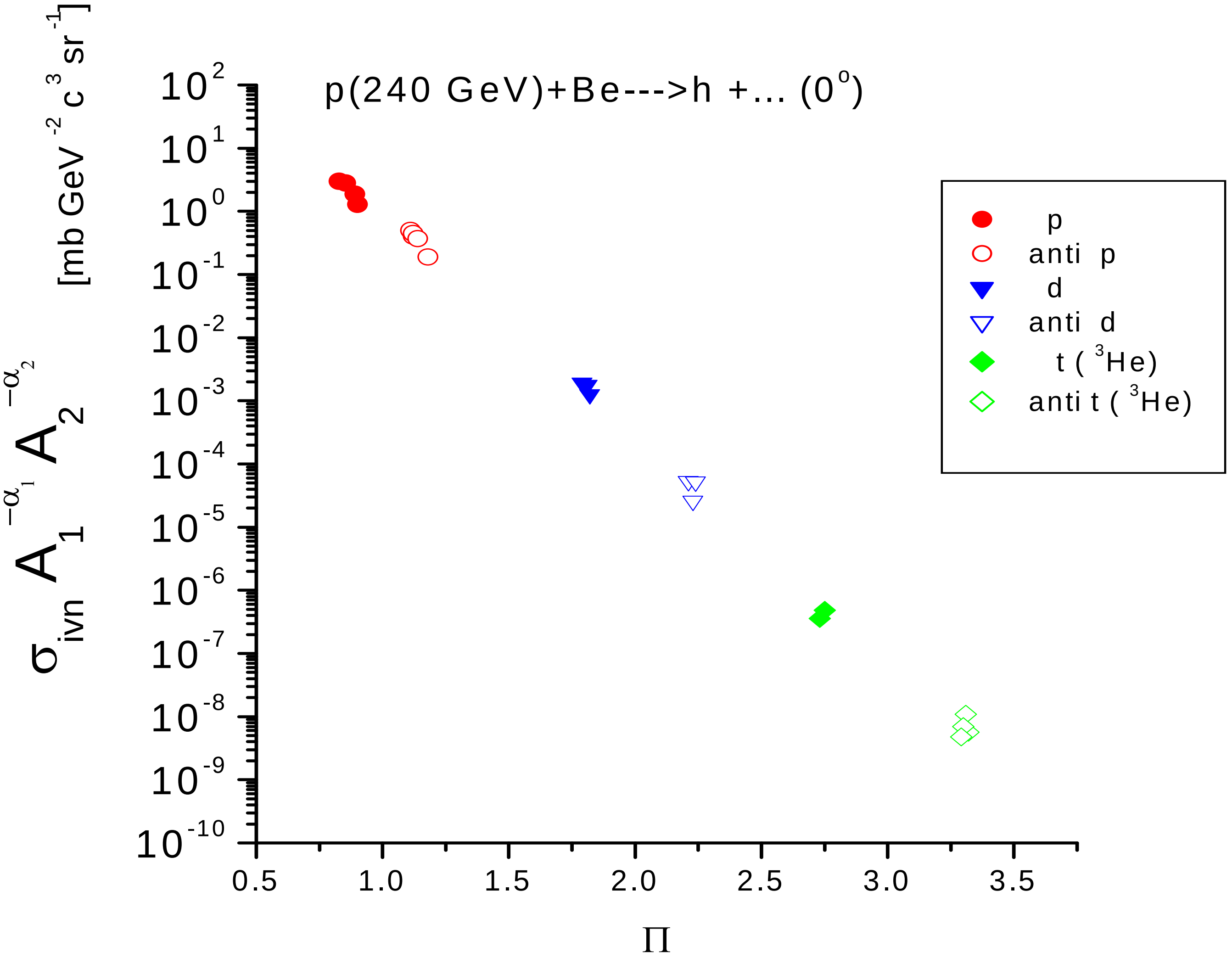


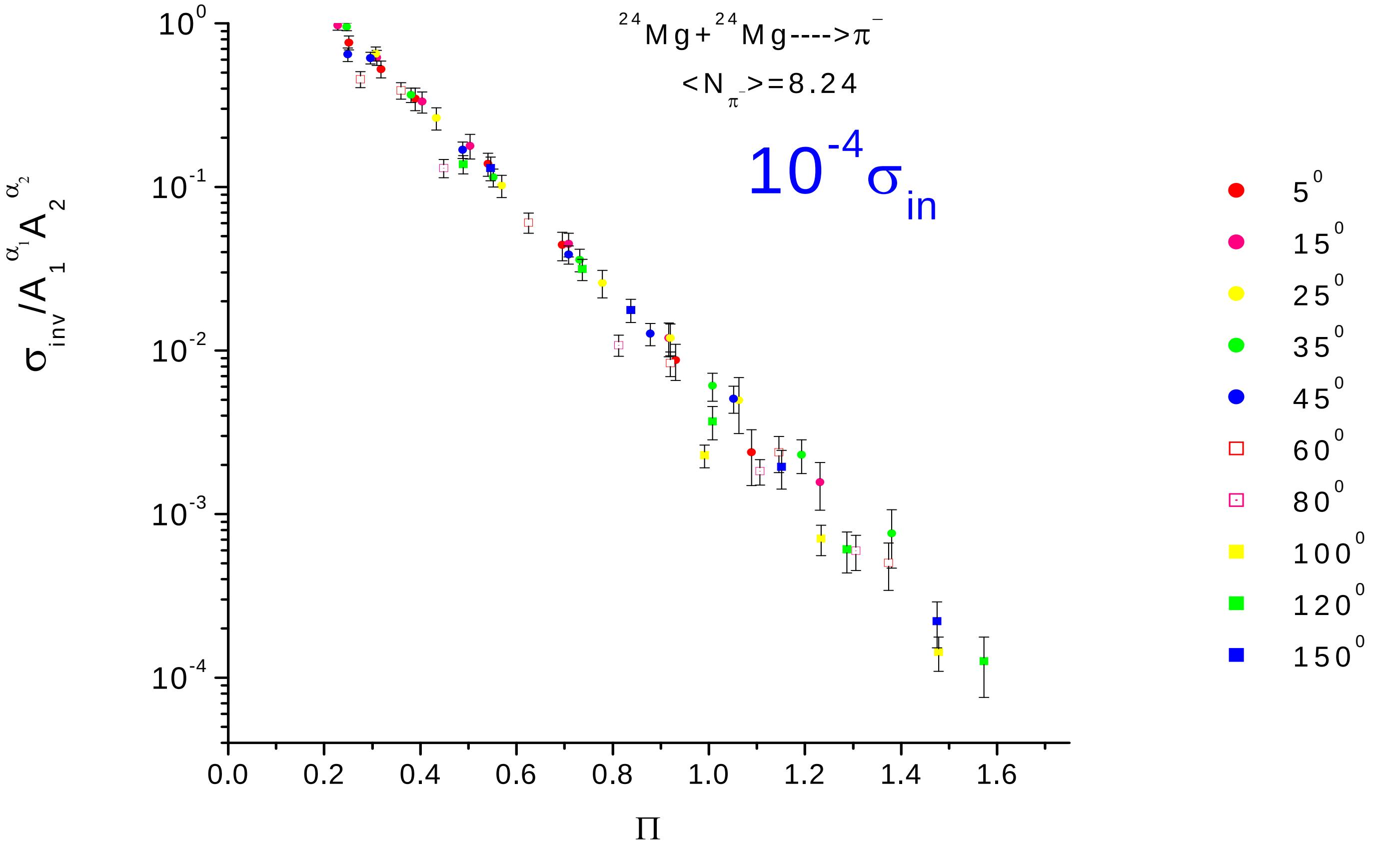
Inclusive pion spectra in selected high-multiplicity events



A.A.Baldin, E.N.Kladnitskaya, O.V. Rogachevsky, JINR Rapid Comm., (1999), N.2 [94]-99, p.20.
M.Kh.Anikina, et al., Phys. Lett. B., (1997), v.397, p.30.

Antimatter production

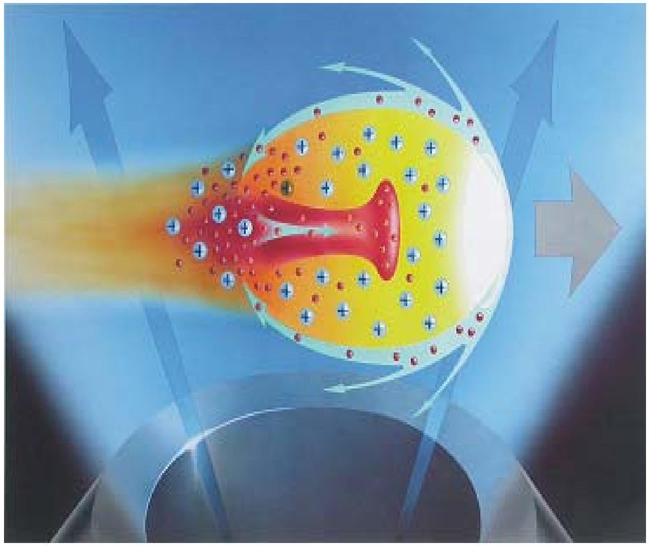




A.A.Baldin, E.N.Kladnitskaya, O.V. Rogachevsky, JINR Rapid Comm., (1999), N.2 [94]-99, p.20.
M.Kh.Anikina, et al., Phys. Lett. B., (1997), v.397, p.30.

Fundamental short time-scale relativistic physics: new collective phenomena

Laser powers $>10^{19}$-10^{20} W/cm^2;
Times <100 fs;
Electron densities $>10^{20}$ cm^{-1};



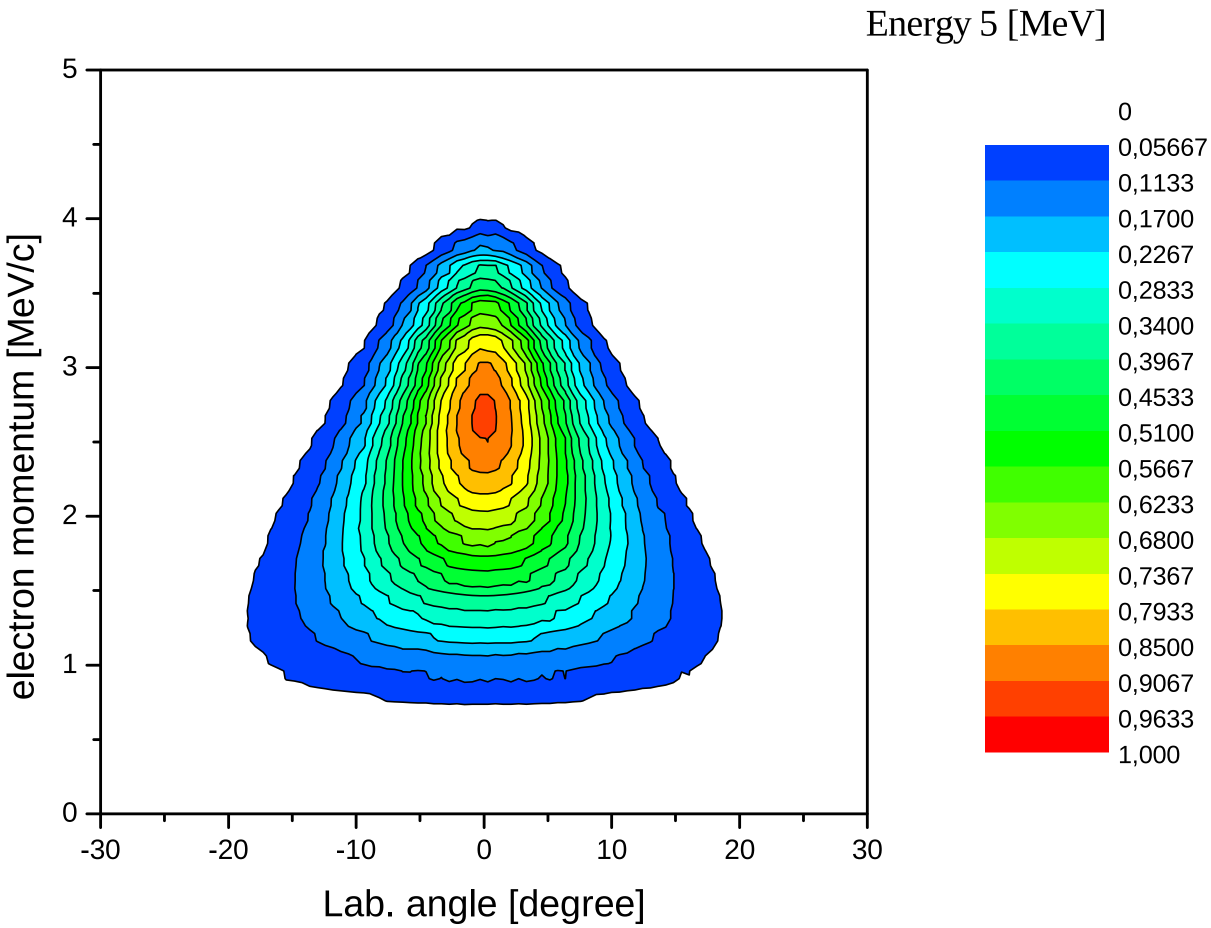
High efficiency (~20%)
Quasi-monochromatic electron spectrum
Low emittance
Very short acceleration distance (100μm – 1mm)

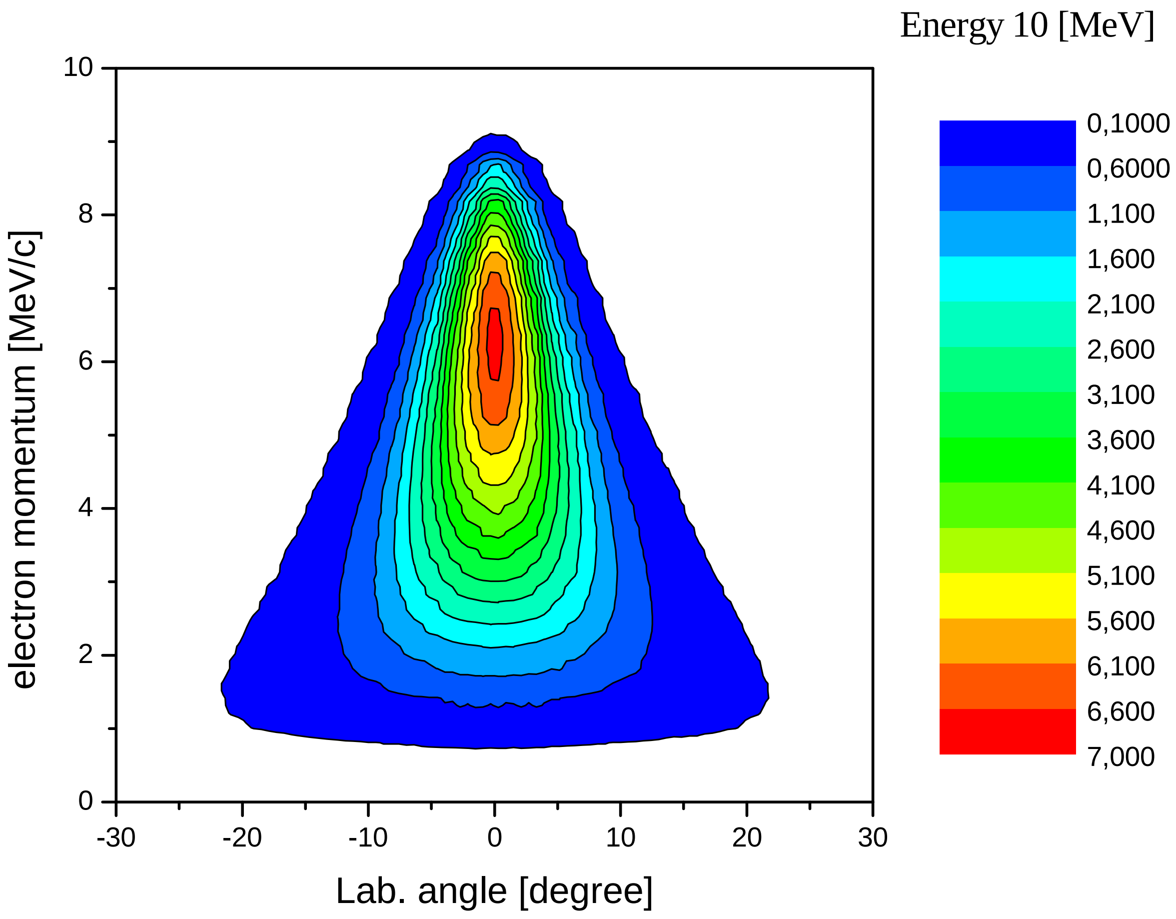
1. Mangles et al Nature vol.43 30 September 2004 pp.535-538
2. Geddes, Esarey et al Nature vol.43 30 September 2004 pp.538-541
3. Pukhov, Malka et al Nature vol.43 30 September 2004 pp.541-544

$$E_\gamma + xP_1 = xP_1' + P_3 + P_4$$

$$x = \frac{E_\gamma (E_3 - P_3 \cos\alpha_3)}{M_1 (E_\gamma - E_3 - M_4)}$$

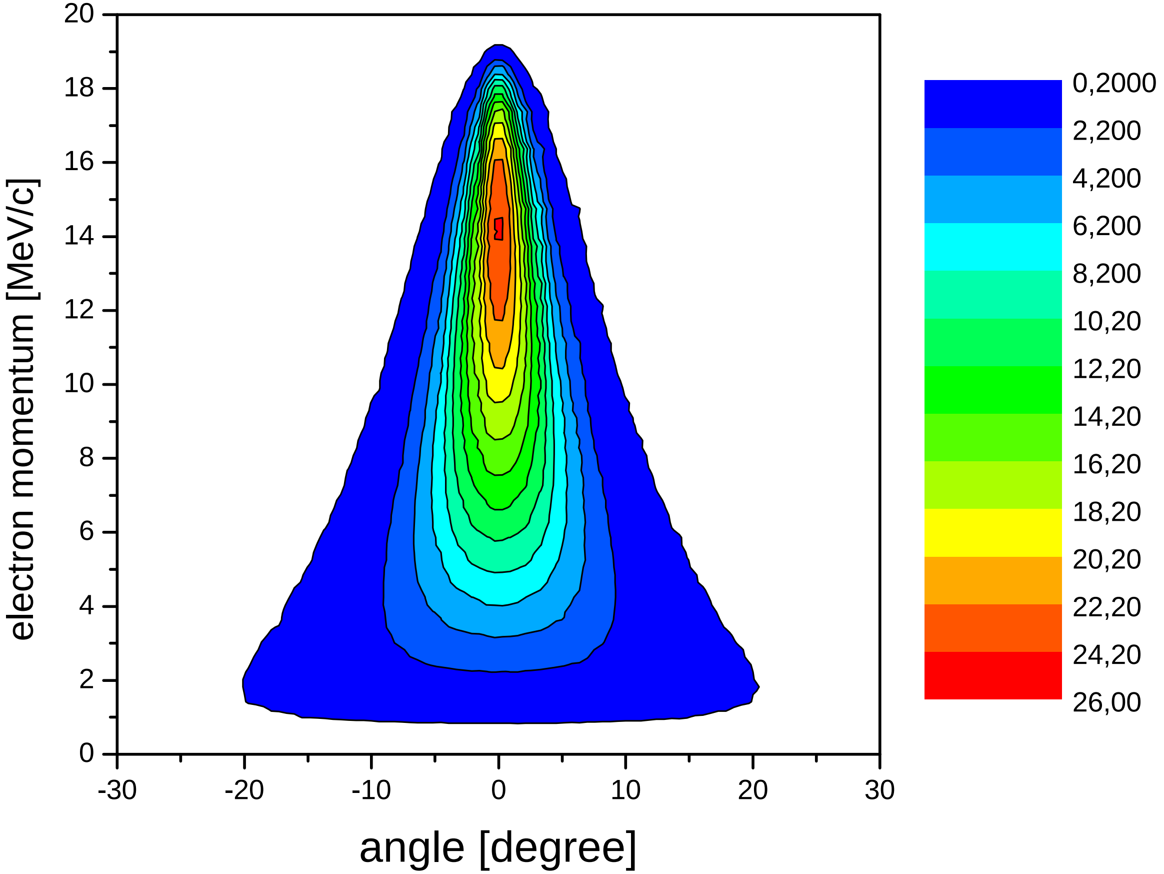
$$\sigma_{inv} = C_1 \exp\left(-\frac{X}{C_2}\right) \qquad \sigma_{inv} = C_1 \exp\left(-\frac{\Pi}{C_2}\right)$$

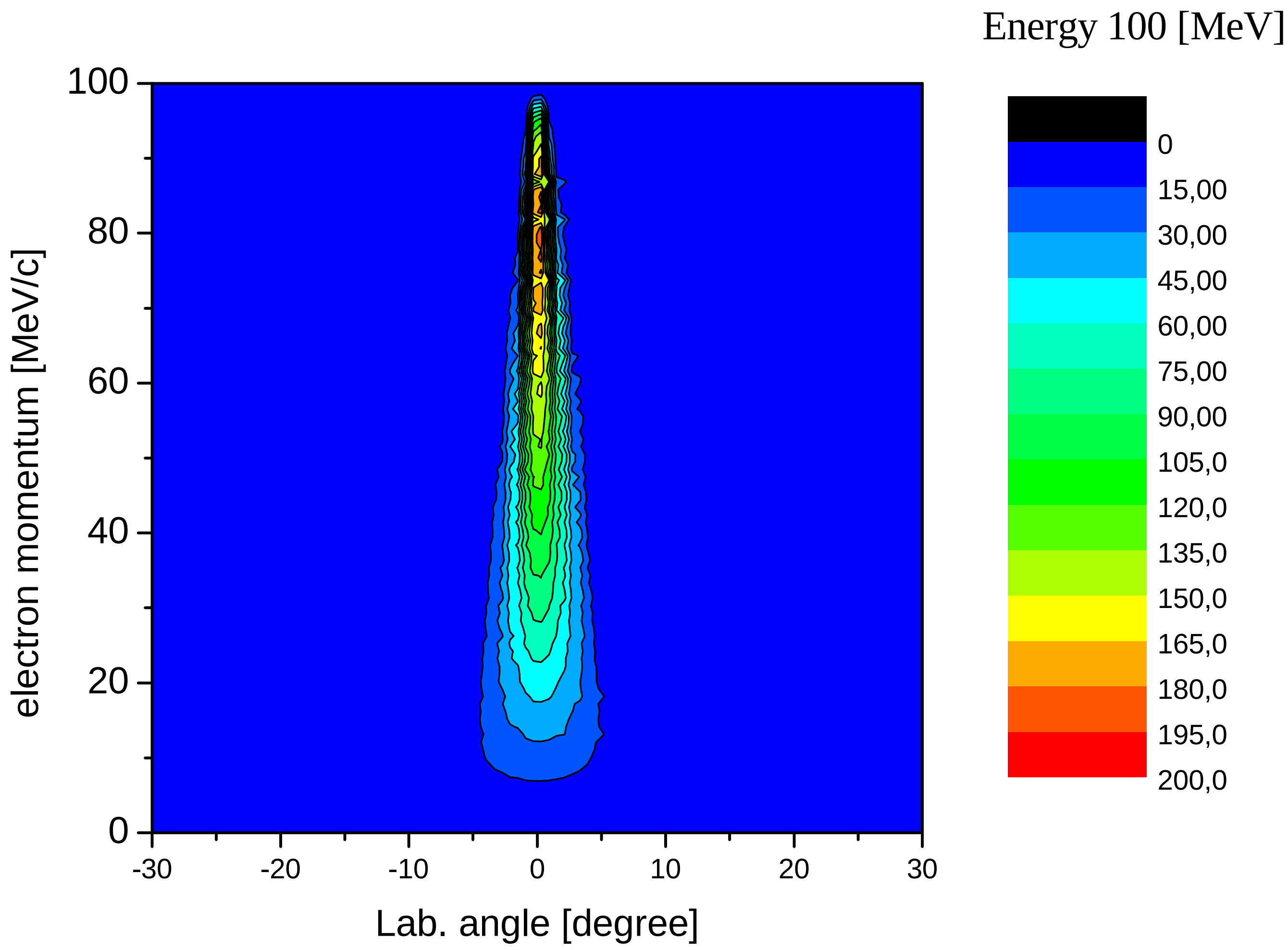

Energy 5 [MeV]
electron momentum [MeV/c]
5
4
3
2
1
0
-30
-20
-10
0
10
20
30
Lab. angle [degree]
0
0,05667
0,1133
0,1700
0,2267
0,2833
0,3400
0,3967
0,4533
0,5100
0,5667
0,6233
0,6800
0,7367
0,7933
0,8500
0,9067
0,9633
1,000



Energy 10 [MeV]
electron momentum [MeV/c]
Lab. angle [degree]
0
2
4
6
8
10
-30
-20
-10
0
10
20
30
0,1000
0,6000
1,100
1,600
2,100
2,600
3,100
3,600
4,100
4,600
5,100
5,600
6,100
6,600
7,000

Energy 20 [MeV]





Energy 100 [MeV]
100
80
60
40
20
0
electron momentum [MeV/c]
-30
-20
-10
0
10
20
30
Lab. angle [degree]
0
15,00
30,00
45,00
60,00
75,00
90,00
105,0
120,0
135,0
150,0
165,0
180,0
195,0
200,0

Relativistic pair production: three steps

- Generation of MeV electrons in subcritical laser plasma

10^{18} W/cm^2; $n_e = n_c \exp(-x/\Delta)$; $n_c = 10^{21} 1/cm^3$; $\Delta = 30\, mkm$

$$\frac{dN_e}{dE} \approx 3 \cdot 10^{10} \cdot E \cdot \exp(-1.2 \cdot E)$$

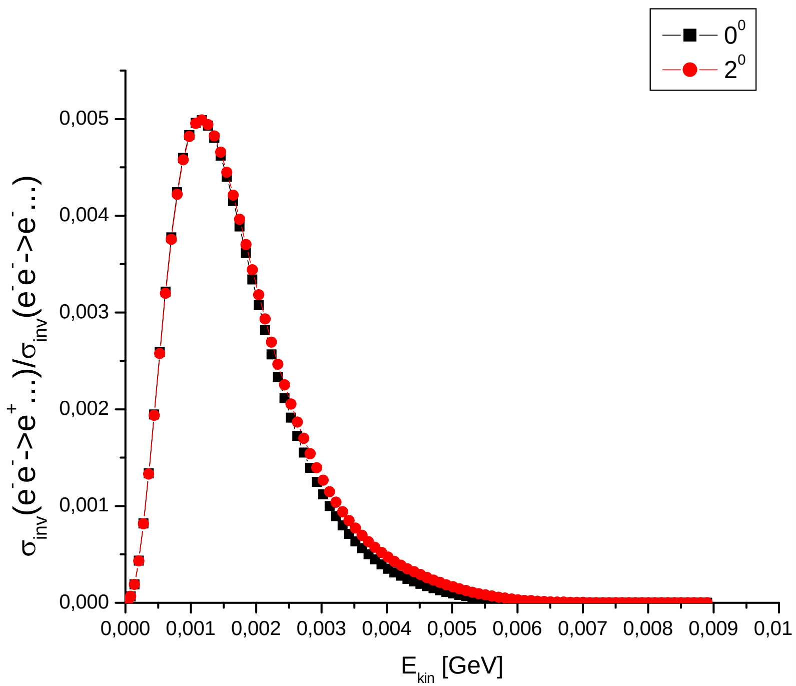
- Bremsstrahlung conversion of MeV electron energy into MeV photons in a high-Z solid target

$8 \cdot 10^7$ photons with the energy higher than 1 MeV

- e+e- pair production (photonuclear reactions)

e+e- pairs

$$10\ MeV \quad e^- + e^- \rightarrow e^+ + 3e^-$$



Appl. Phys. Lett., Vol. 77, No. 17, 23 October 2000

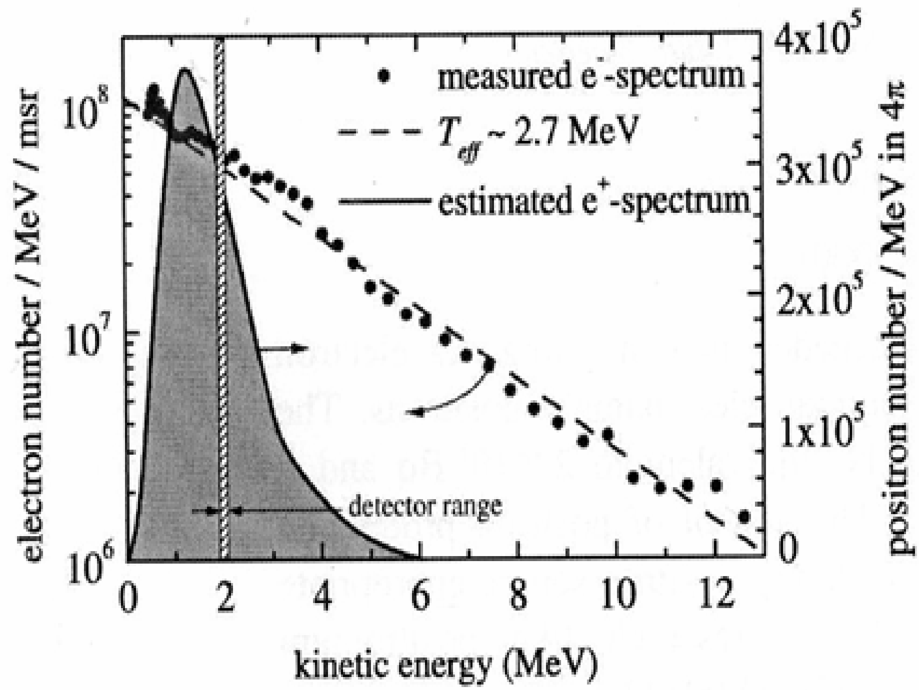
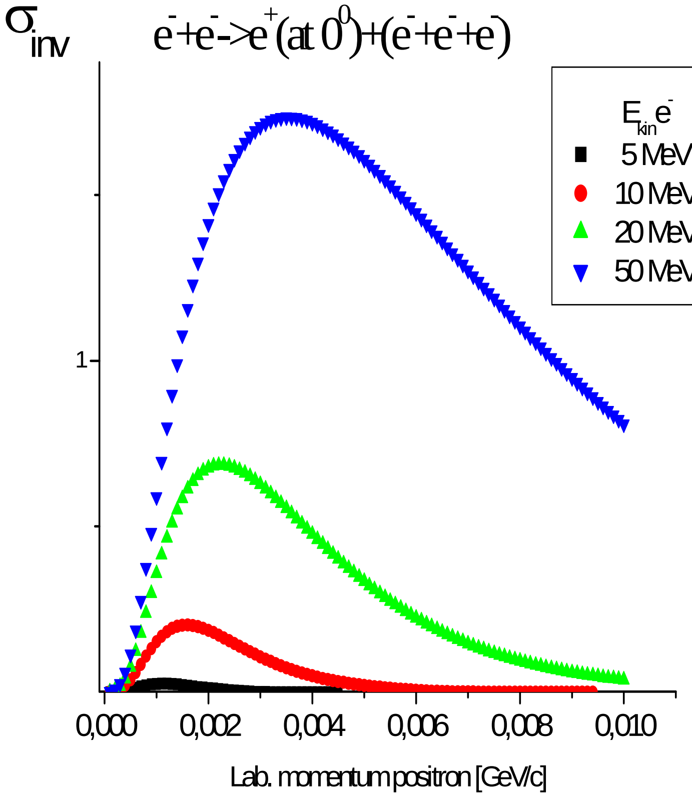
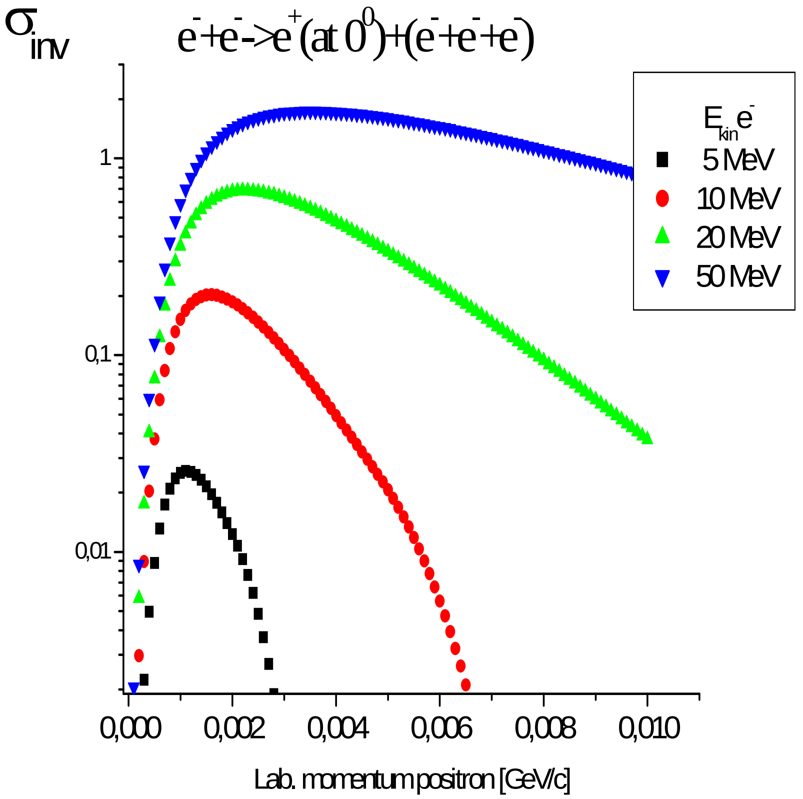


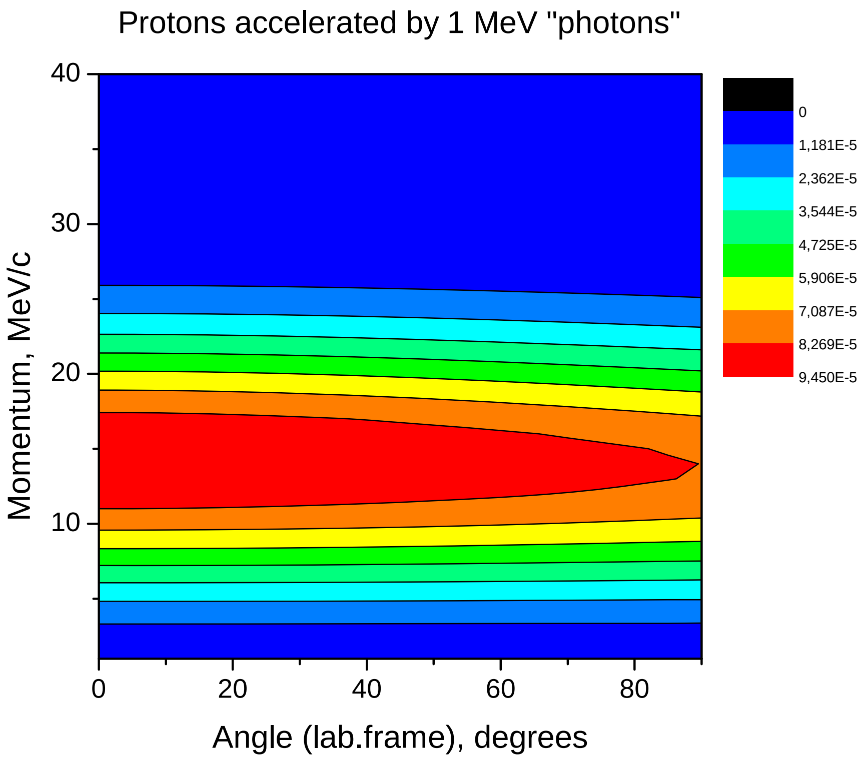
FIG. 1. Measured energy distribution of the primary electrons (closed-circles, exponential fit as dashed line) used to produce positrons (expected spectrum as solid line). The line-shaded stripe gives the energy range covered by the detector. It encompasses ~5% of the total number of positrons.

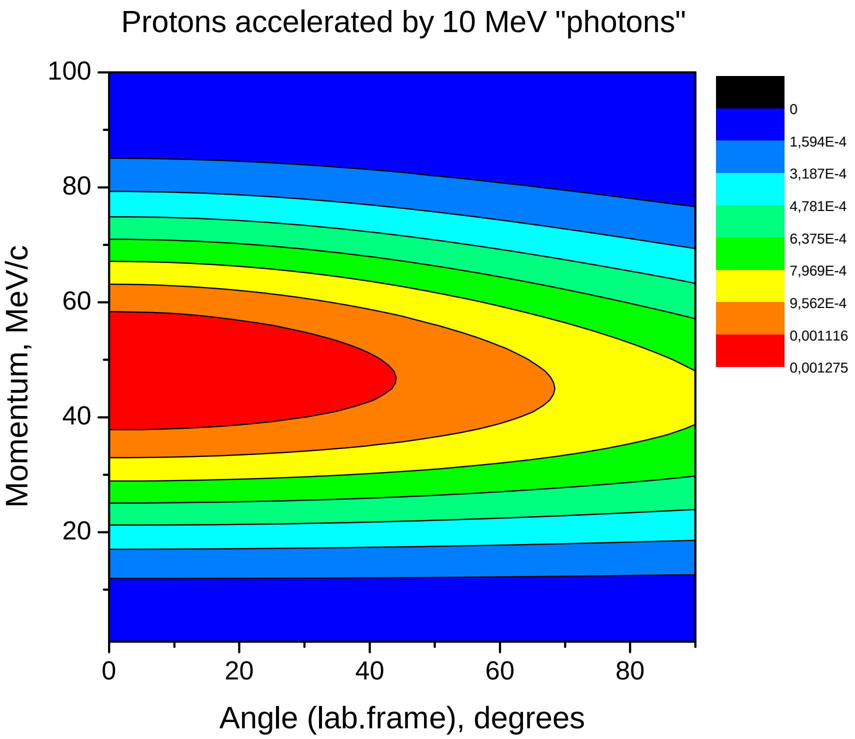
$$\sigma_{inv} = C_1 \exp\left(-\frac{\Pi}{C_2}\right)$$





protons


Protons accelerated by 1 MeV "photons"
40
30
20
10
0
20
40
60
80
Momentum, MeV/c
Angle (lab.frame), degrees
0
1,181E-5
2,362E-5
3,544E-5
4,725E-5
5,906E-5
7,087E-5
8,269E-5
9,450E-5

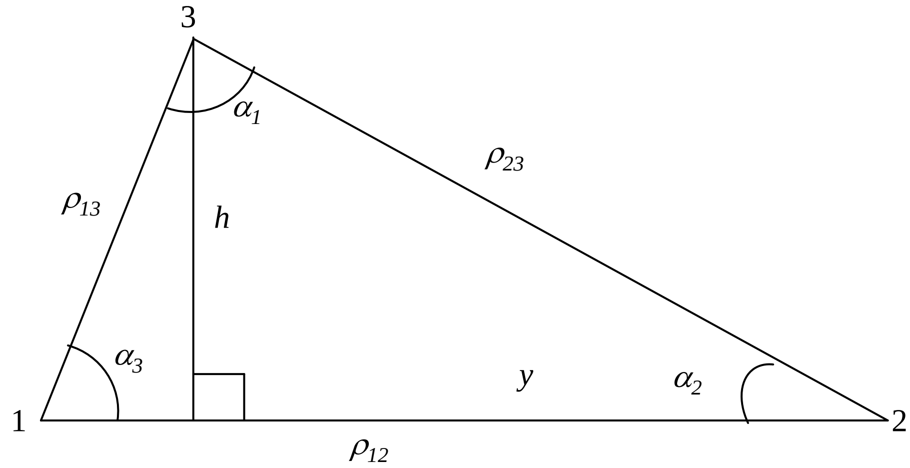

Protons accelerated by 10 MeV "photons"
100
80
60
40
20
0
20
40
60
80
Momentum, MeV/c
Angle (lab.frame), degrees
0
1,594E-4
3,187E-4
4,781E-4
6,375E-4
7,969E-4
9,562E-4
0,001116
0,001275

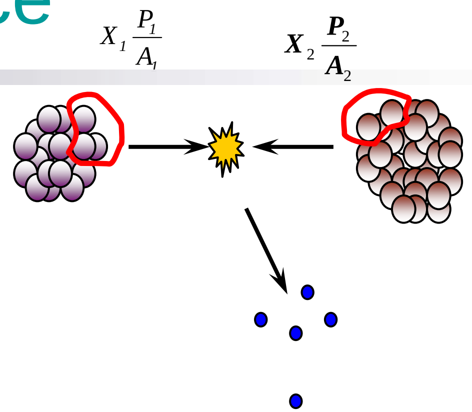
Self-similar solution connects the initial and final states.

Initial state:
intensity (energy);
frequency; phase;
duration;
geometric dimensions of acting volume;
target density, Z, A, temperature
Prepulse (dynamic target preparation).
Final state:
fraction of four-momentum transferred;
angular, energy spectra of registered radiations;
time characteristics of final state.

The goal of the self-similarity approach is to reduce the number of variables = find a symmetry in the phenomenon of transition from initial to final state.

Lobachevsky Space





Longitudinal rapidity $$y = \frac{1}{2} \ln \frac{E + p_{\parallel}}{E - p_{\parallel}}$$

$$defect = \pi - \alpha_1 - \alpha_2 - \alpha_3$$

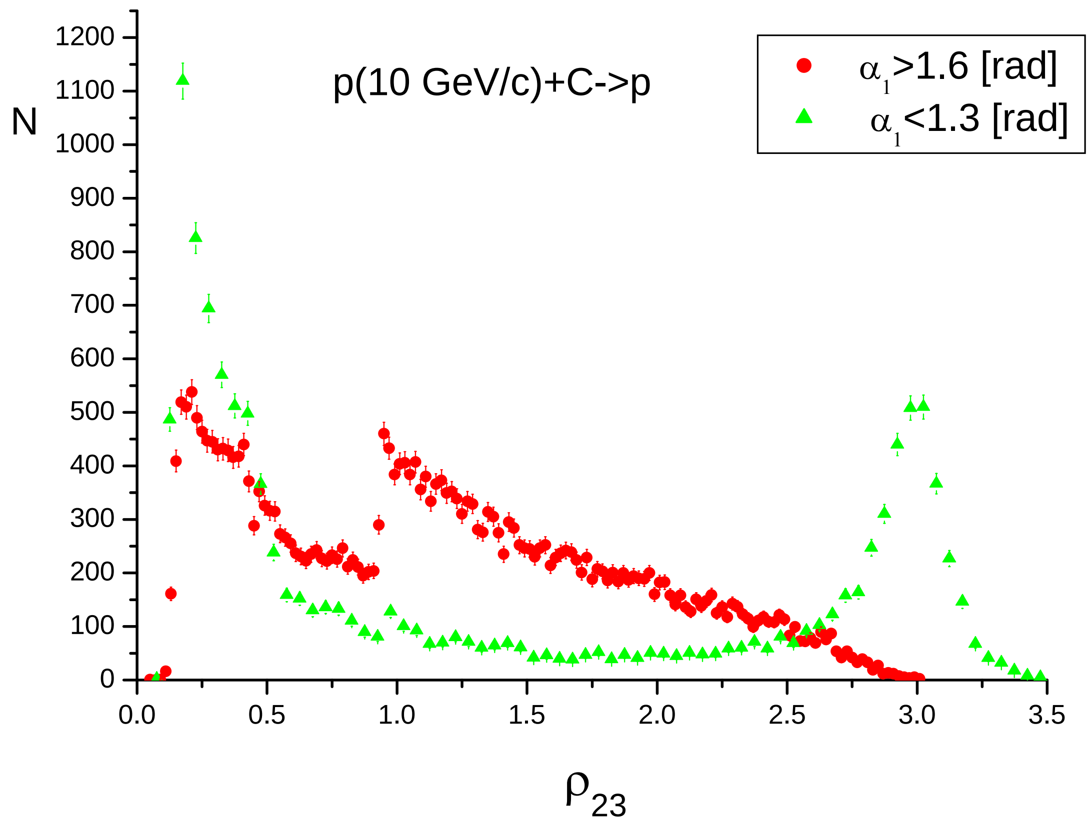
Transverse mass $$m_T = \sqrt{m^2 + p_T{}^2}$$

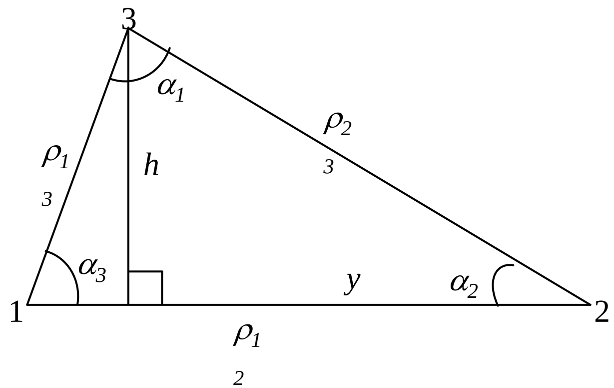
$$perimeter = \rho_1 + \rho_2 + \rho_3$$

Transverse rapidity $$\mathrm{ch}\, h = \frac{m_T}{m}$$

Angle of Parallelism $$\Pi_L(h) = 2 \cdot arctg\left(e^{-h}\right)$$

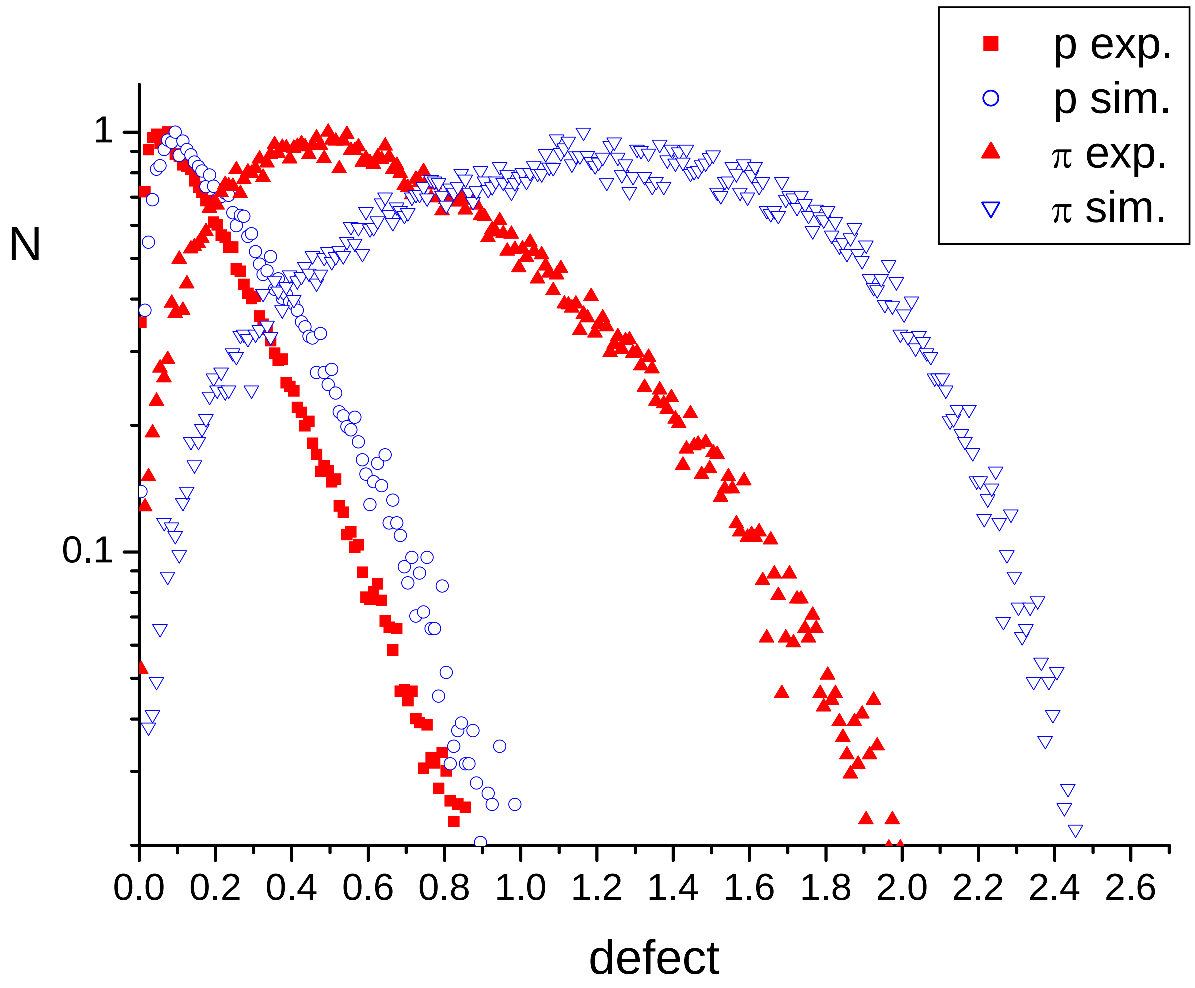
Proton distribution for two angular intervals in p(10GeV/c)+C





A. A. Baldin, E. G. Baldina, E. N. Kladnitskaya, O. V. Rogachevskii, Phys.Part.Nucl.Lett., vol. 1, no. 4, 7-16 (2004).

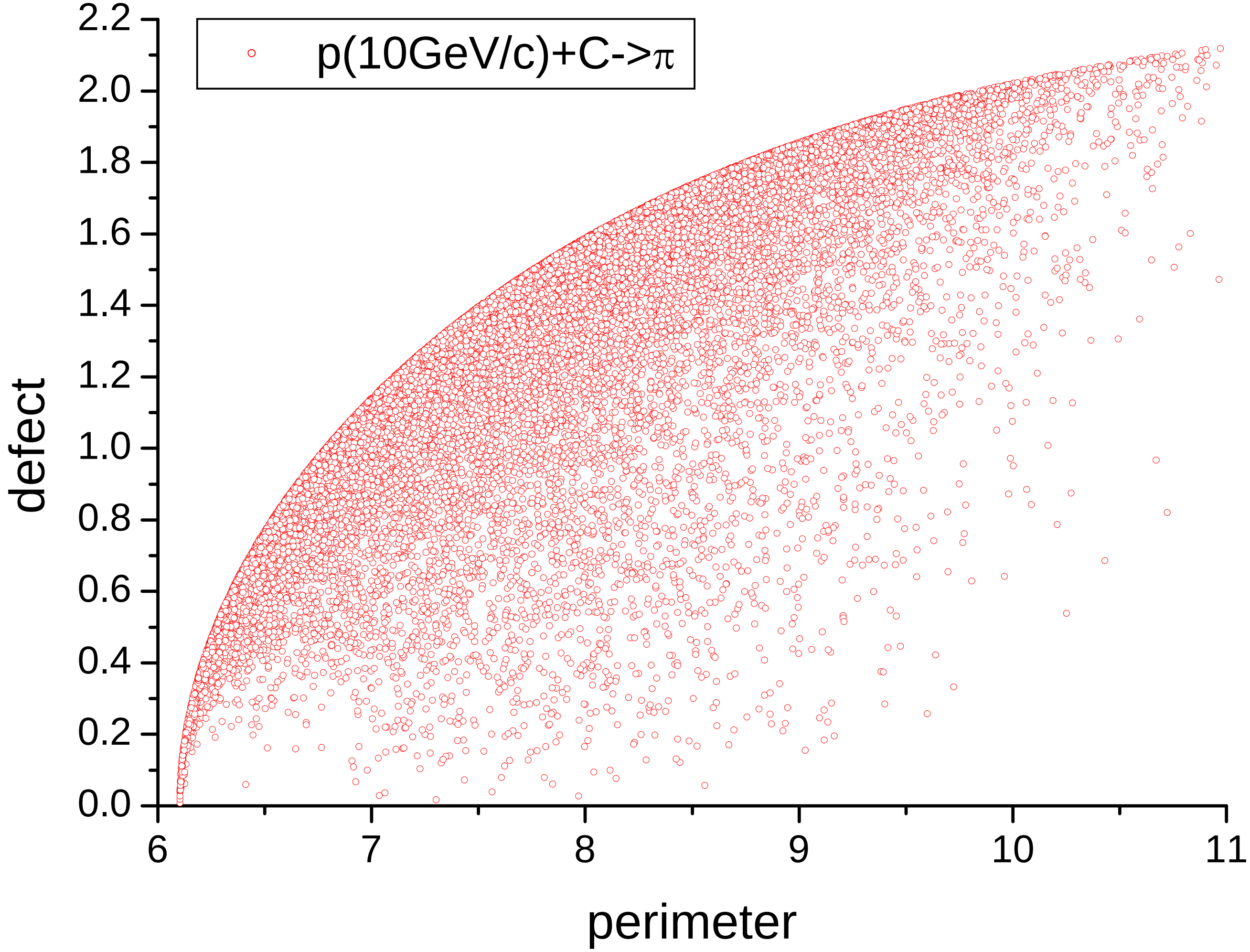
Normalized distributions of defects of triangles formed by all combinations of protons and all combinations of mesons registered in p(10GeV/c)+C



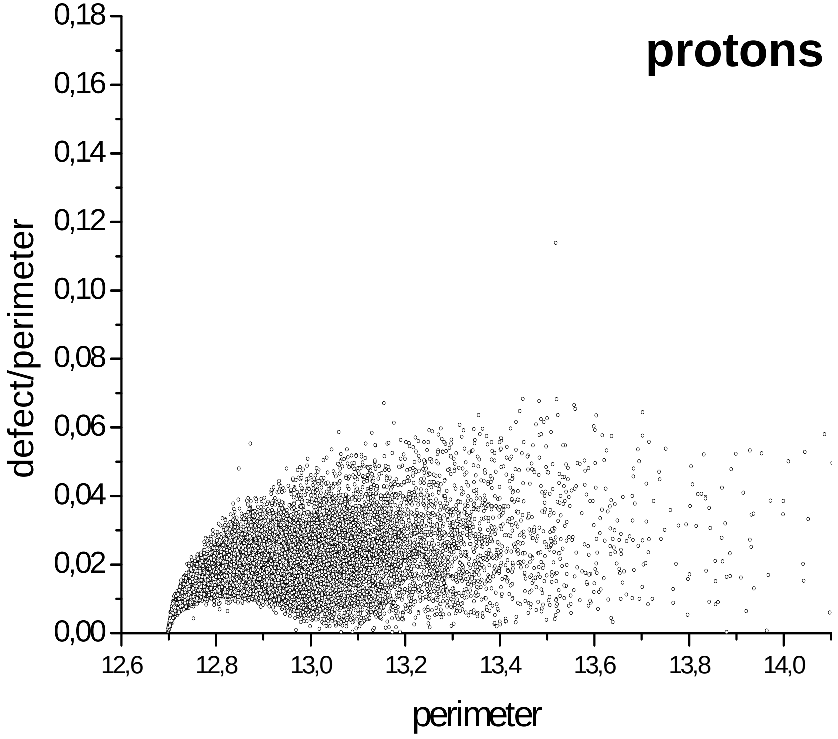
Note, that the model adequately reproduces inclusive spectra of both protons and π - mesons.
The distribution of trios of π-mesons, however, differs noticeably from experimental data.

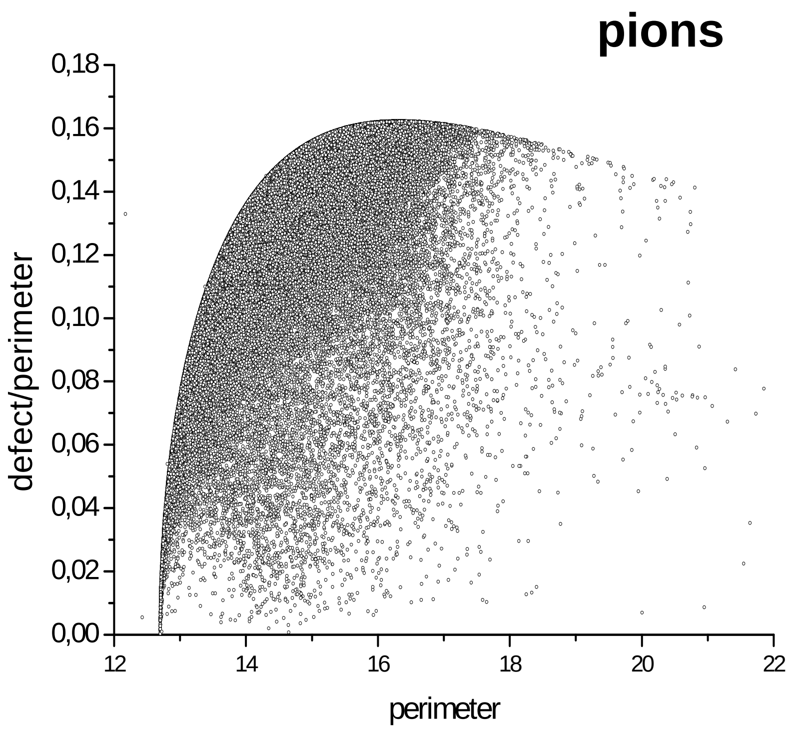
$$defect = \pi - \alpha_1 - \alpha_2 - \alpha_3$$

$$perimeter = \rho_1 + \rho_2 + \rho_3$$



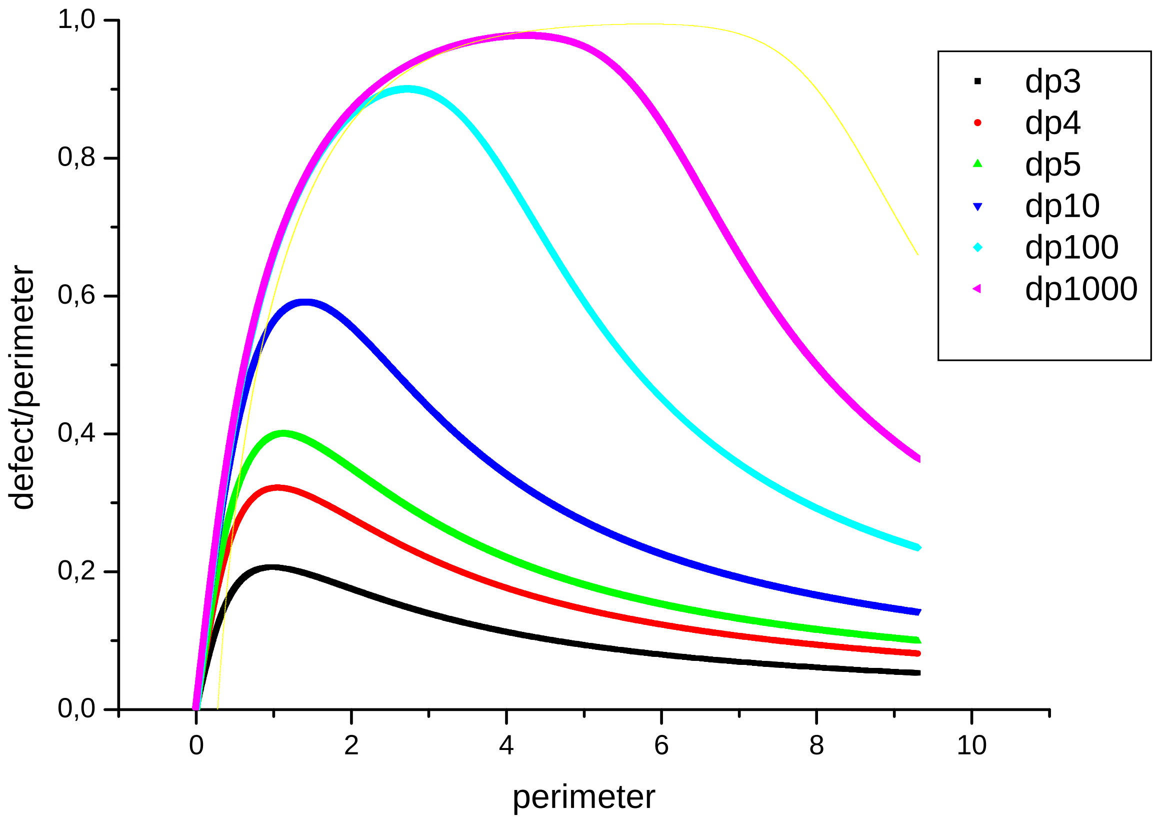
It is important to underline that, unlike the Euclidean space, the area-to-perimeter ratio for triangles in the Lobachevski space is limited.

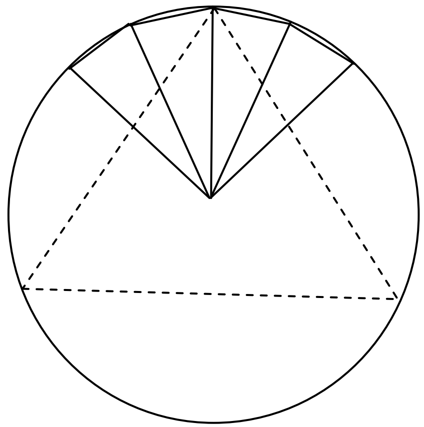




$\pi^{-}C$ (40 GeV)

Analysis of Lobachevsky geometry

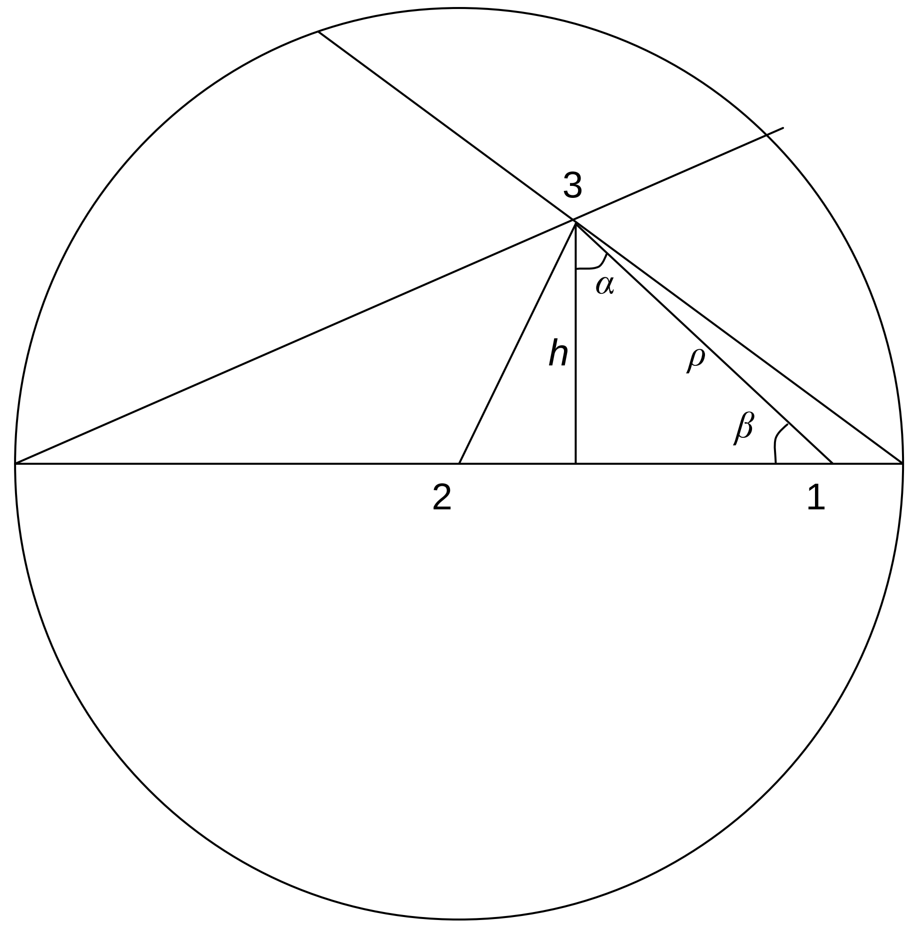




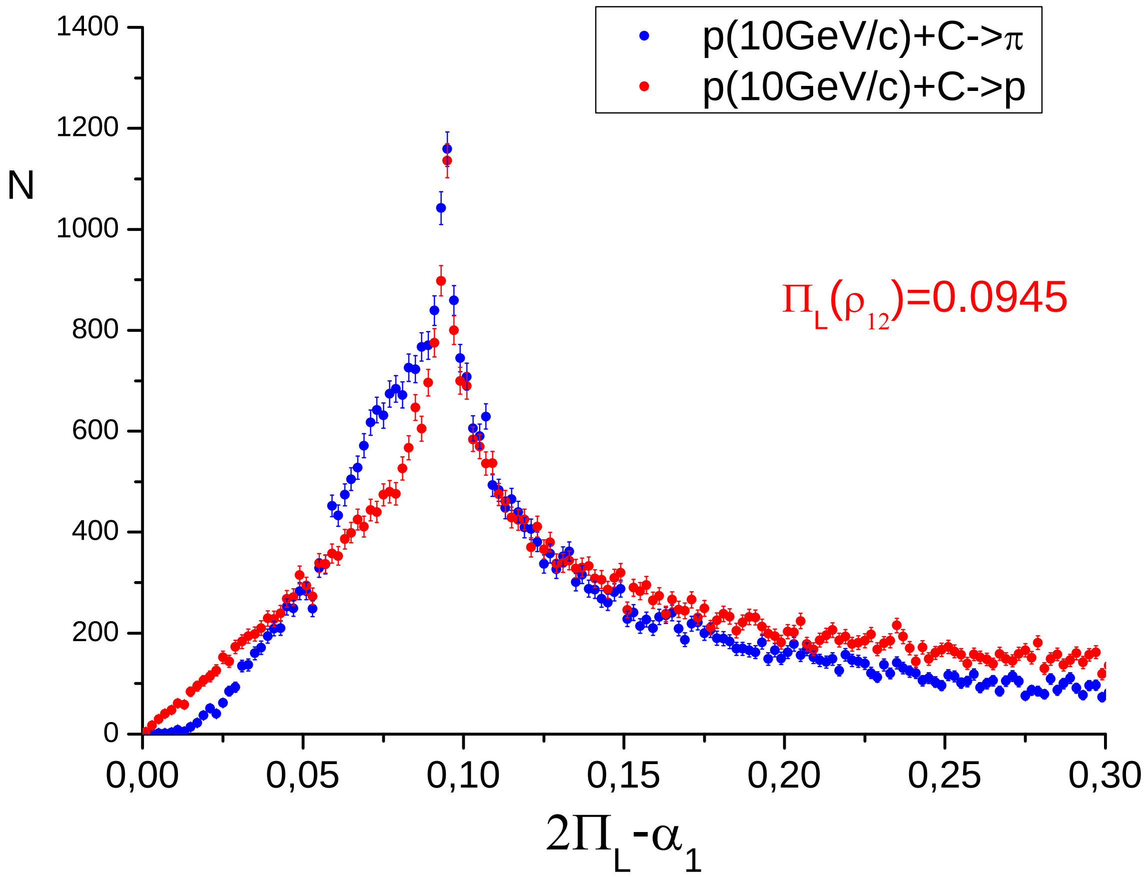
Regular polyhedrons with n=3, 4, 5, 10, 100, and 1000 inscribed in a circle with an increasing radius

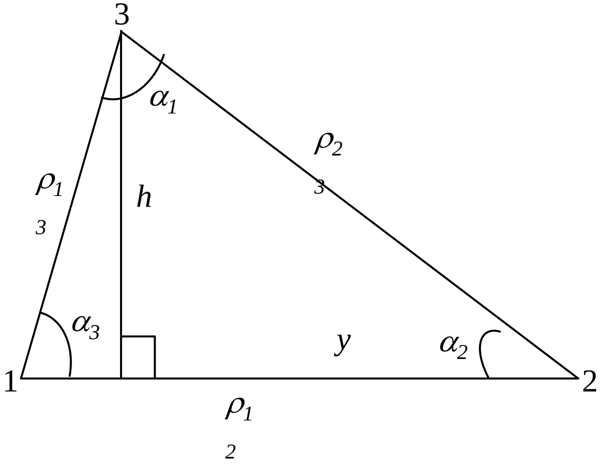
$$tg\,\frac{\Pi_L(h)}{2} = e^{-h}$$

$$\Pi_L(h) = 2\cdot arctg\left(e^{-h}\right)$$



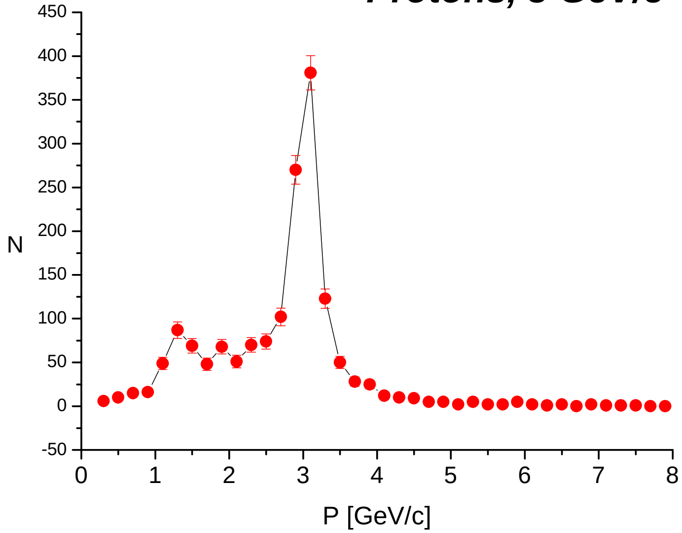
$$\Delta_{12}^{3} = 2\Pi_L\left(h_3\right) - \alpha_3$$


p(10GeV/c)+C->π
p(10GeV/c)+C->p
Π_L(ρ_12)=0.0945
N
2Π_L-α_1
0,00
0,05
0,10
0,15
0,20
0,25
0,30
0
200
400
600
800
1000
1200
1400

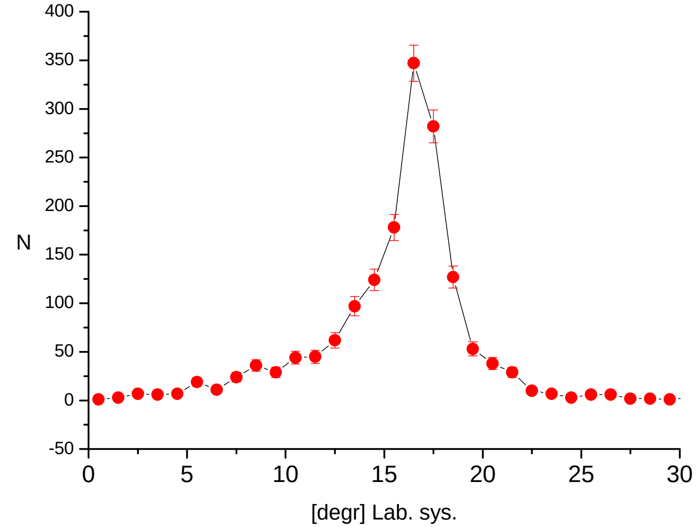

3
1
2
α1
α2
α3
ρ2 3
ρ1 3
ρ1 2
h
y

pC (10 GeV)

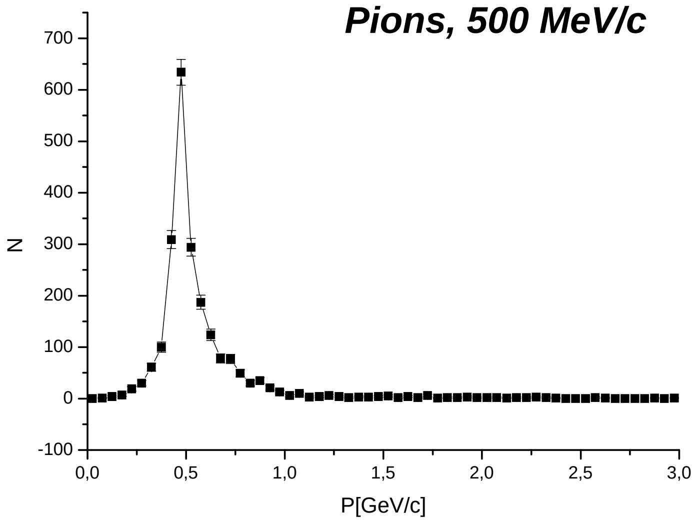
Protons, 3 GeV/c



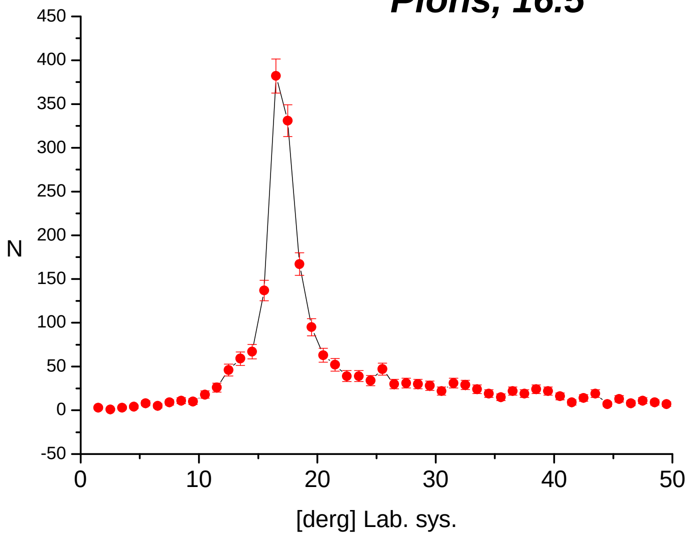
Protons, 16.5 º

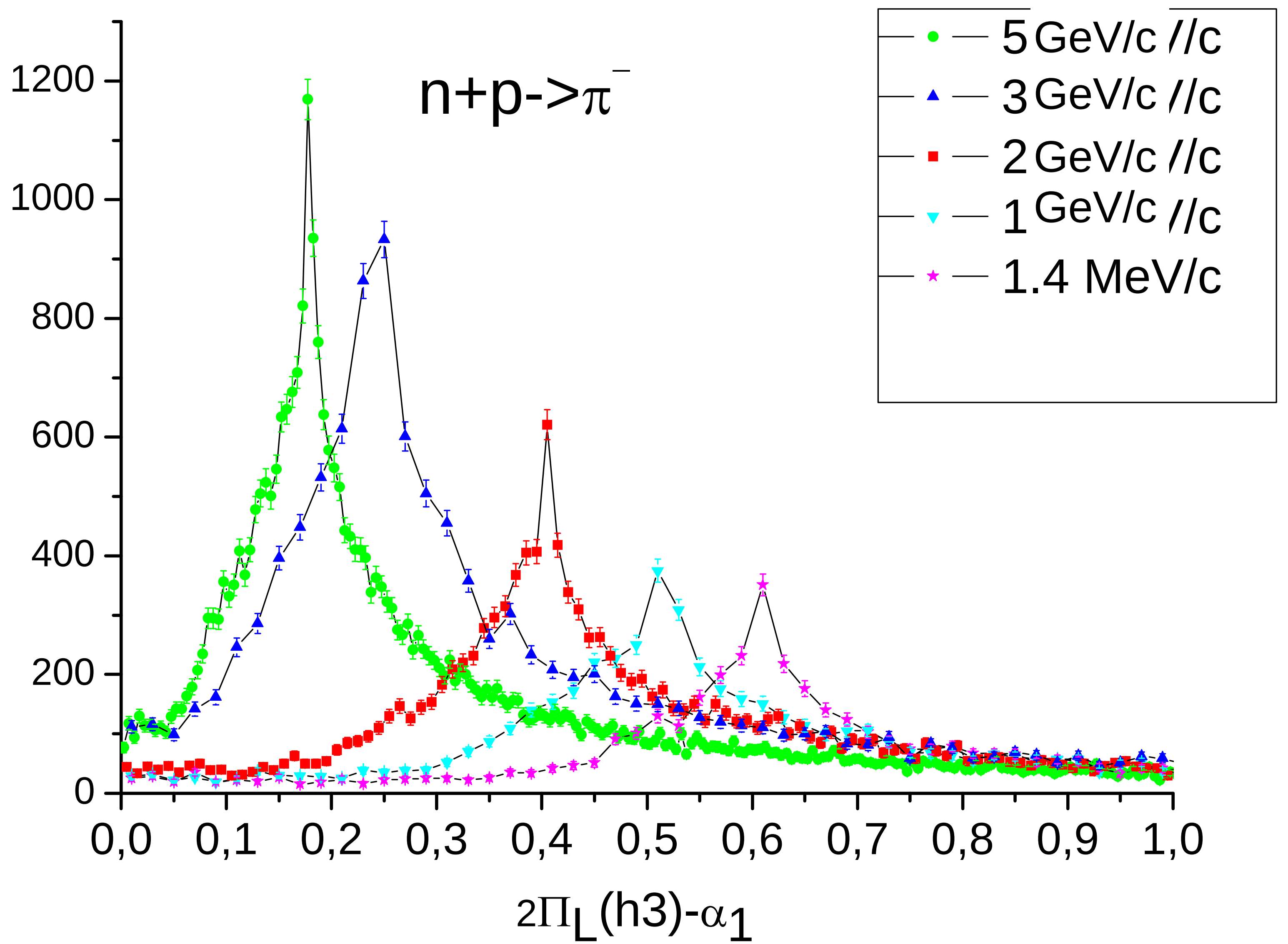


Pions, 500 MeV/c



Pions, 16.5 º

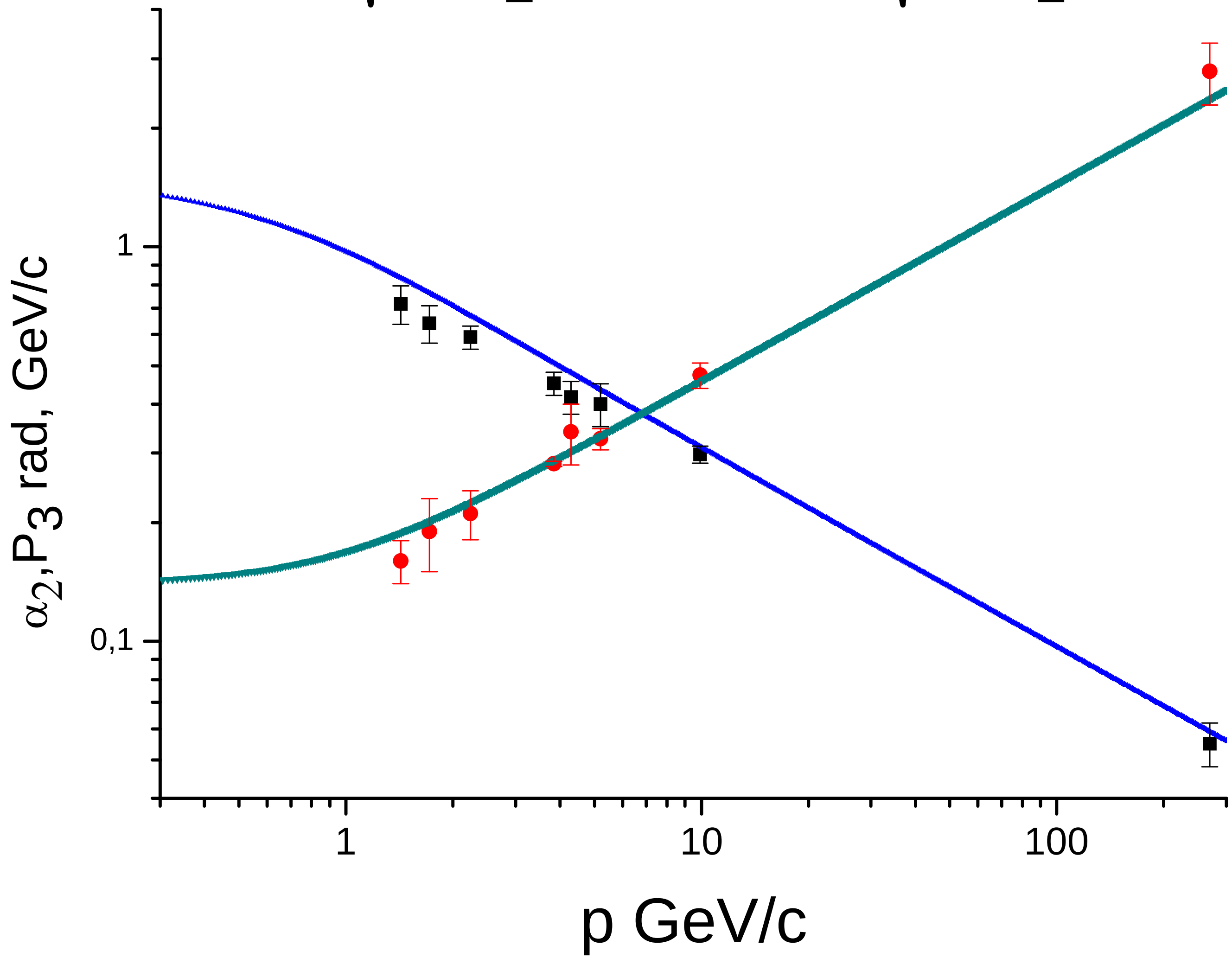




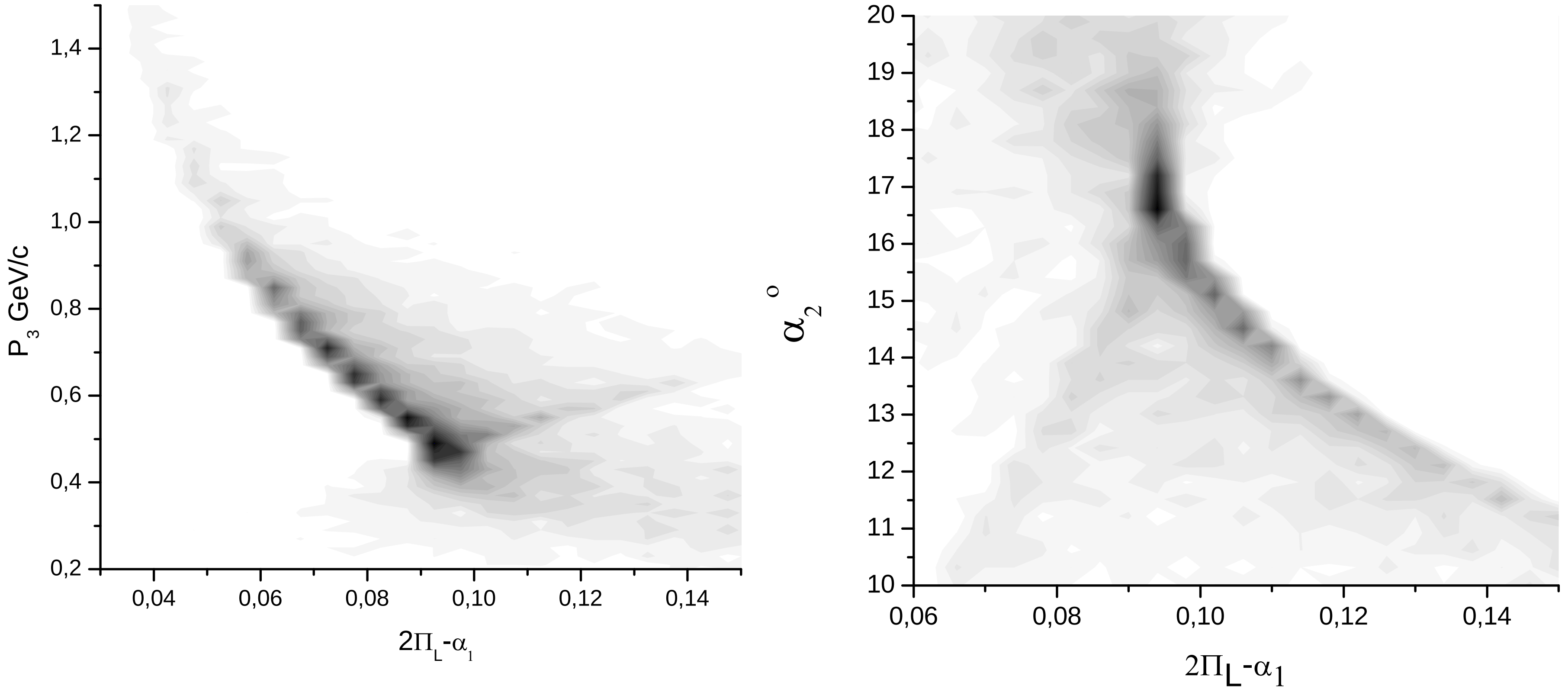
n+p->π⁻
5 GeV/c //c
3 GeV/c //c
2 GeV/c //c
1 GeV/c //c
1.4 MeV/c
0
200
400
600
800
1000
1200
0,0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
2Π L(h3)-α 1

Directed Nuclear Radiation

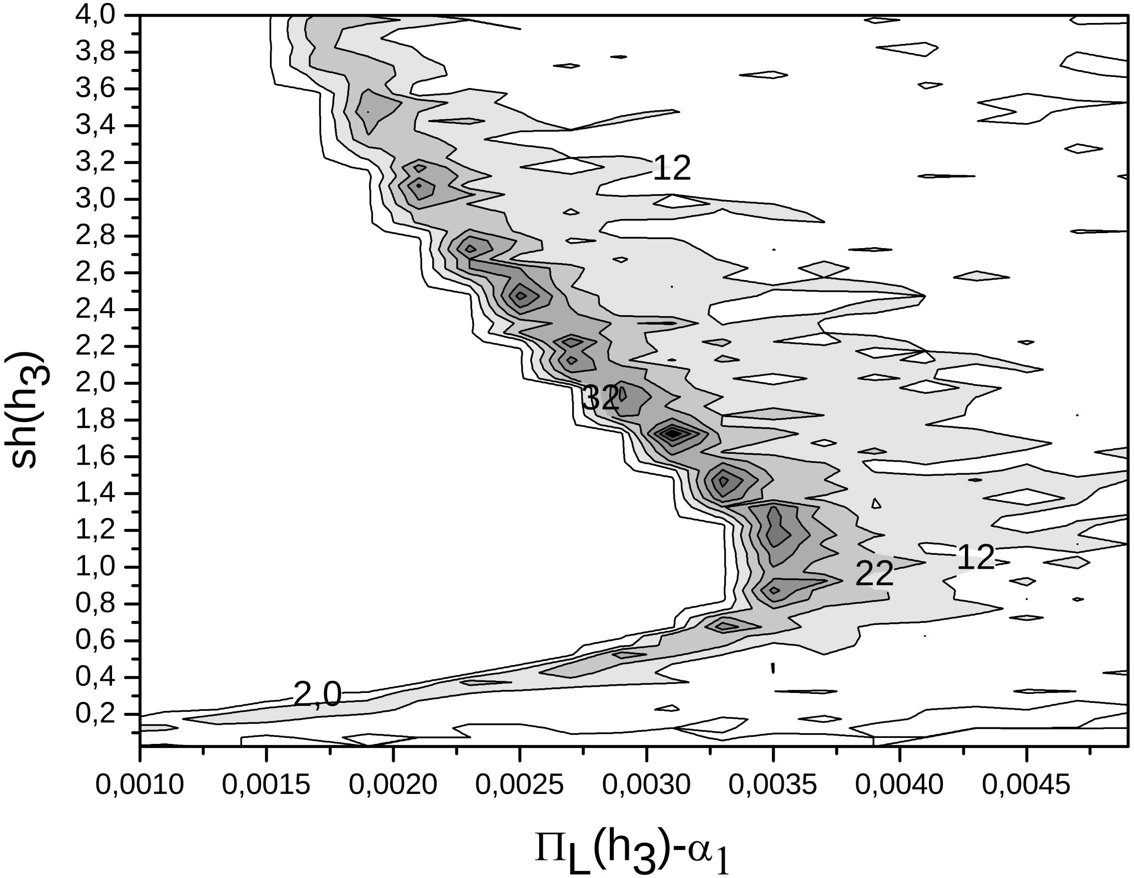
$$\cos\alpha_2 = \sqrt{\frac{1+th(\rho_1)}{2}} - sh(h_3)\sqrt{\frac{1-th(\rho_1)}{2}}$$



Directed Nuclear Radiation
P+C->pions at 10GeV



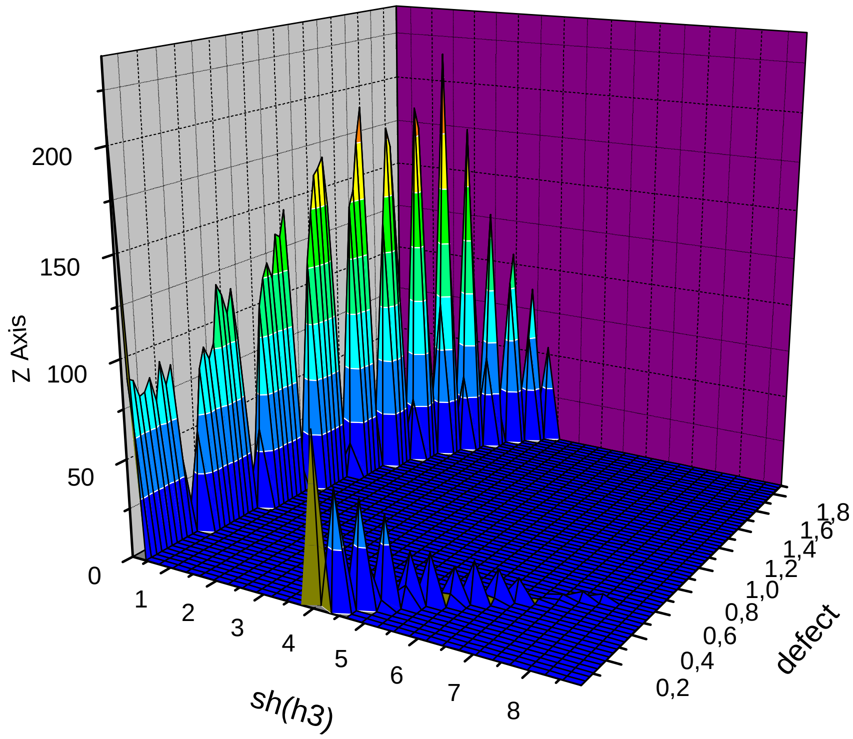
π-C (40 GeV)

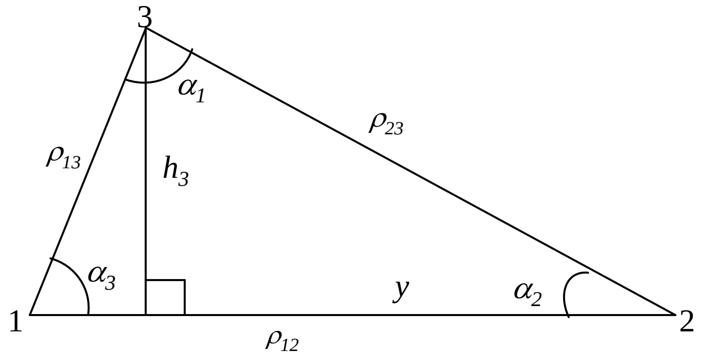


$$f(h) = 2\left(\Pi_L(h) - arctg\frac{th\left(\frac{\rho_1}{2}\right)}{sh(h)}\right) = 2arctg\left(\frac{\left(1 - th\left(\frac{\rho_1}{2}\right)\right)\cdot sh(h)}{sh^2(h) + th\left(\frac{\rho_1}{2}\right)}\right)$$

Lobachevsky Space

$n+p \rightarrow \pi^-$ 5GeV





$$defect = \pi - \alpha_1 - \alpha_2 - \alpha_3$$

Common features of relativistic nuclear physics and ultrashort laser-matter interaction:

Extreme states of matter;

Relativism;

Collective phenomena;

Multiparticle interactions.

- The XX International Seminar on High Energy Physics Problems "*Relativistic Nuclear Physics and Quantum Chromodynamics*", organized by the Joint Institute for Nuclear Research will be held October 4-9, 2010 in Dubna, Russia.

Important Deadlines

- Abstracts submission before **August 31, 2010**. Abstracts should be sent to ishepp@theor.jinr.ru