Event by Event Analysis of the Anisotropy of the Low Energy Direct Photons in Relativistic Heavy Ion Collisions

Classical Bremsstrahlung Revisited

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Direct Photons in Heavy Ion Collisions

The electromagnetic probes carry the information from the early stage of the collision dynamics. Many theoretical Works since the very early stage of the heavy ion program.

J. Kapsta (1977); J. D. Bjorken and L. McLerran (1985); J. Thiel, T. Lippert, N. Grün (*1989);* V. Koch, B. Blättel, W. Cassing, U. Mosel (1990); P. A. Ruuskanen, (1992), A. Dumitru, L. McLerran, H.Stoecker (1993); D. Srivastava (1994); N. Arbex, U. Ornik, M. Plumer, R.Weiner (1995); A. Dumitru, J. A. Marhuhn, D. H. Rischke(1995), T. Hirano, S. Muroya, M. Namiki (1995); J. Alam, S. Raha and B. Sinha(1996). S. Jeon, A. Chikanian, J. Kapusta, S. M. H. Wong (1999); U. Eichmann, C. Ernst, L.M. Satarov. W. Greiner (2000); R. Chatterjee, H. Holopainen, T. Renk, K. J. Eskola (2011); A. K. Chaudhuri and B. Sinha (2011), T.S. Biro, M. Gyulassi, Z. Schram (2012); G. Basar, D. Kharzeev, V. Skokov,........

And more recently, using the state-of-art hydro or transport theories,

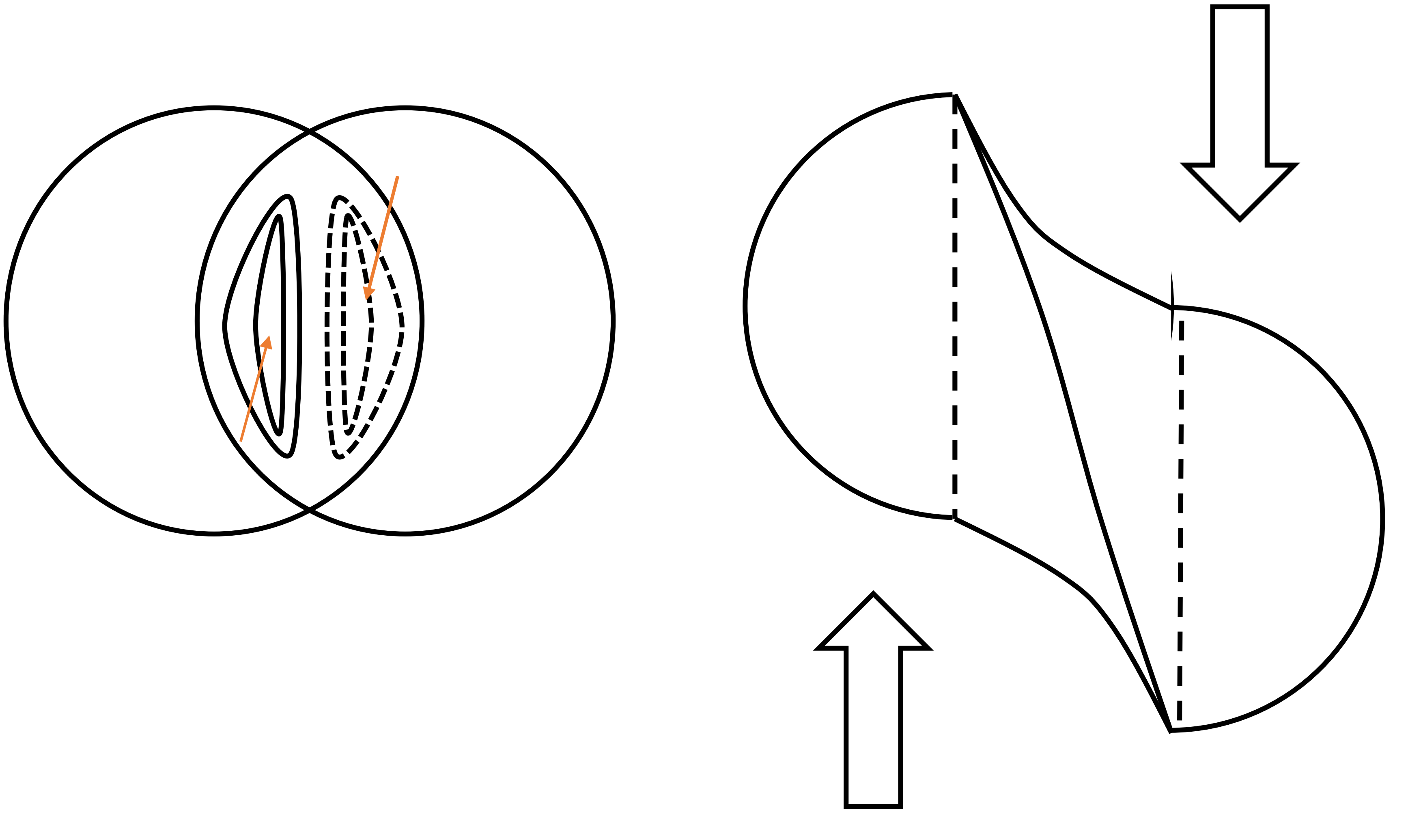
C. Shen, Ulrich Heinz, J-F. Paquet, I. Kozlov, C. Gale, C. Shen, G. S. Denicol, M. Luzum, B. Schenke, S. Jeon, Y. Hidaka, S. Lin, R. D. Pisarski, D. Satow, V. V. Skokov, G. Vujanovic, O. Linnyk, E. L. Bratkovskaya, W. Cassing, C. Greiner, M. Greif, S. Endres, H. v. Hess, J. Weil, M. Bleicher ....

Early days model of photon emission

Coherent Bremsstrahlung Emission due to Deceleration of Incident Nuclei

J. Kapsta, Phys. Rev. C15, 1580 (1977), J. D. Bjorken and L. McLerran, Phys. Rev. D31, 63 (1985), J. Thiel et. al., Nucl. Phys. A504, 864 (1989). V. Koch et. al., Phys. Lett. B236, 135 (1990), T. Lippert et. al., Int. J. Mod. Phys. A29, 5249 (1991), A. Dumitru et. al., Phys. Lett. B318, 583 (1993), U. Eichmann and W. Greiner, J. Phys. G23, L65 (1997), S. Jeon et. al., Phys. Rev. C58, 1666 (1998), J. Kapusta and S. M. H. Wong, Phys. Rev. C59, 3317 (1999), U. Eichmann, C. Ernst, L.M. Satarov and W. Greiner, Phys.Rev. C62, 044902 (2000) ..

Decelation of incidente nuclei



Classical Electromagnetic Radiation by an accelerated point charge is given by (Liénard-Wiechert Potential),

$$\vec{E}(\vec{x},t) = \frac{e}{4\pi}\frac{1}{\left|\vec{x}-\vec{\xi}(t')\right|}\frac{1}{1-\vec{\beta}(t')\bullet\vec{n}}\left(1-\vec{n}\vec{n}^T\right)\frac{d\vec{\beta}(t')}{dt'},$$

$$\vec{B}(\vec{x},t) = \vec{n}\times\vec{E}(\vec{x},t),$$

where $\vec{\xi}(t)$ is the trajectory of the point charge, and $\vec{\beta}(t) = d\vec{\xi}/dt$ is the velocity. *t'* is the emission time, defined by $t' = t - \left|\vec{x}-\vec{\xi}(t')\right|$

and $$\vec{n} = \frac{\vec{x}-\vec{\xi}(t')}{\left|\vec{x}-\vec{\xi}(t')\right|}.$$

Continuum Sources (Integrate over moving charges)

For $r = \left|\vec{x}\right| \gg \left|\vec{\xi}\right|$,

$$\vec{E}\left(\vec{x},t\right) = -\frac{e}{4\pi}\frac{1}{r}\left(1-\vec{n}\vec{n}^T\right)\int d^3\vec{\xi}\,\frac{\partial}{\partial\tau}\vec{J}\left(\vec{\xi},\tau\right)\Big|_{\tau=t-\left|\vec{x}-\vec{\xi}\right|},$$

$$\vec{B}\left(\vec{x},t\right) = \vec{n}\times\vec{E}\left(\vec{x},t\right),$$

with $\vec{n} = \frac{1}{r}\vec{x}$.

How to calculate the photon spectrum?

Equivalent Photon Method - Jackson´s book

How to calculate the photon spectrum?

Equivalent Photon Method - Jackson´s book

Or introduce the Wigner function,

$$f_W(\vec{x},\vec{p};t)=\int d^3\vec{u}\left\{e^{i\vec{p}\bullet\vec{u}/\hbar}\psi^\dagger(\vec{x}-\vec{u}/2,t)\psi(\vec{x}+\vec{u}/2,t)\right\}$$

where $\psi(\vec{x},t)$ is the wave function.

Identify the Classical Electromagnetic fields as the vector type wavefunction similar to the Dirac form*.

$$\vec{\psi}(\vec{x},t) \equiv \left(\vec{E} + i\vec{B}\right)/\sqrt{2},$$

then the Maxwell equations are equivalent to

$$i\left(\partial_t + \vec{\Sigma}\bullet\nabla\right)\vec{\psi} = \vec{j} \quad \text{and} \quad \nabla\bullet\vec{\psi} = \rho,$$

with $\vec{\Sigma} = \left\{ \frac{1}{i}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix}, \frac{1}{i}\begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix}, \frac{1}{i}\begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right\}$ generators of O(3) for spin 1

- ❖ L. Silberstein, Ann. d. Phys. 22, 579 (1907); 24, 783 (1907);
- ❖ H. Bateman, Cambridge 1915, Dover, New York,1955).
- ❖ I. Bialynicki-Birula, Act. Phys. Pol. A86 97 (1994).
- ❖ P. Holland, Proc. R. Soc. A461, 359 (2005).

The energy density and Poyinting Vector are expressed as

$$\varepsilon = \vec{\psi}^{\dagger}\vec{\psi},$$

$$\vec{P} = -i\left(\vec{\psi}^{\dagger} \bullet \vec{\Sigma}\right)\vec{\psi},$$

where the product $\left(\vec{\psi}^{\dagger} \bullet \vec{\Sigma}\right)$ is defined as $\left(\vec{\psi}^{\dagger} \bullet \vec{\Sigma}\right) = \sum_{i=x,y,z} \psi_i^{\dagger}\vec{\Sigma}_i$.

The time evolution after “freeze-out” ($\rho, \vec{j} = 0$) we need only

$$i\left(\partial_t + \vec{\Sigma} \bullet \nabla\right)\vec{\psi} = 0,$$

Then the corresponding Wigner function (scalar) decomposes into the electric and magnetic contributions,

$$f_W(\vec{x}, \vec{p}; t) = f_E(\vec{x}, \vec{p}; t) + f_B(\vec{x}, \vec{p}; t)$$

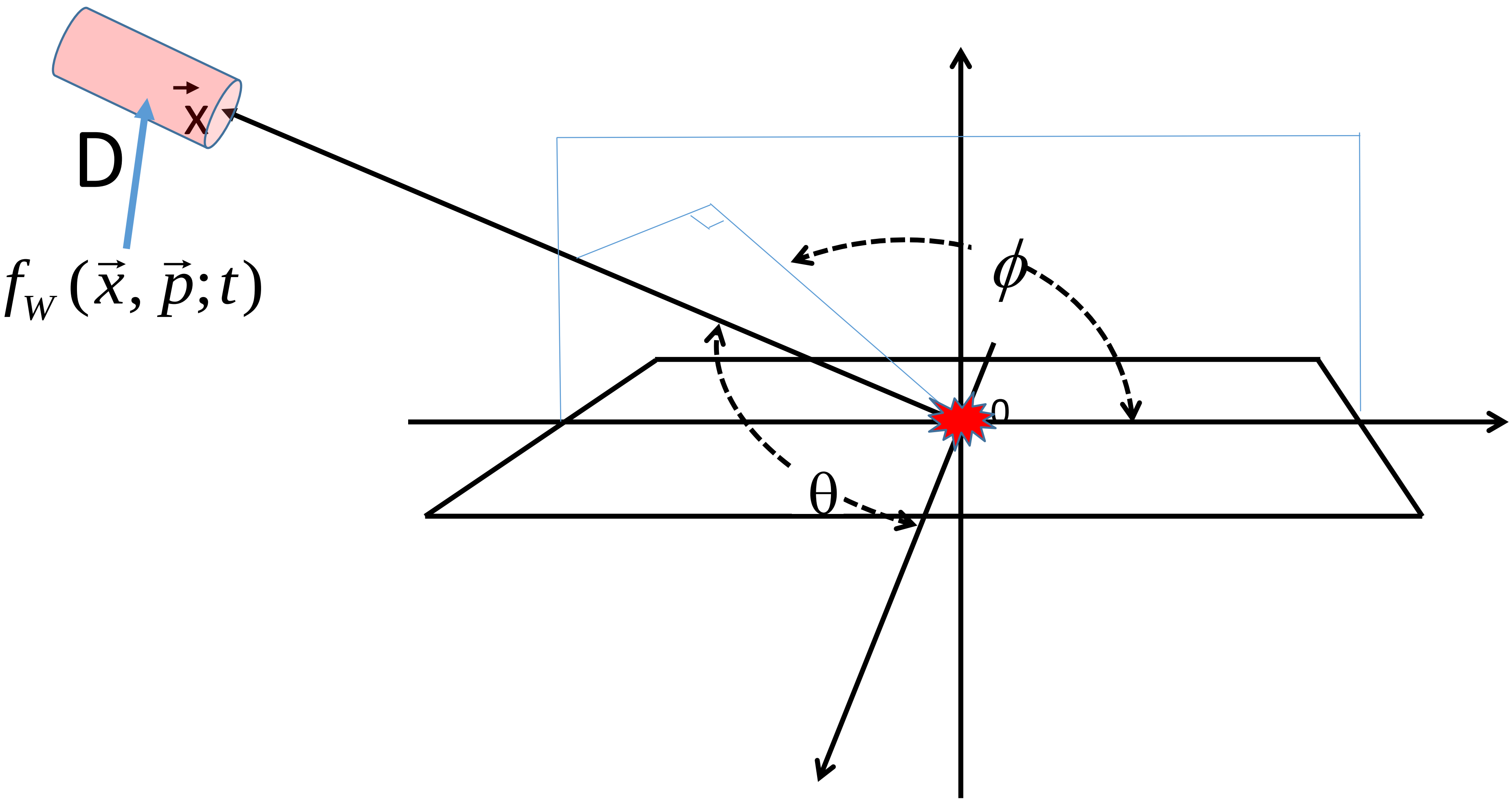
From the definition, we know that

$$\frac{d^3 n}{d^3 \vec{p}} = \int d^3\vec{r}\, f_W(\vec{x}, \vec{p}; t_{FO}) = \left|\psi(p)\right|^2,$$

where t_{FO} is the freezeout time. But it is instructive to calculate the spectrum as the energy that enters into the detector from the large distance behavior of the Wigner function as;

$$E_{Detector} = \int_{\vec{r}\in D} d^3\vec{r}\, f_W(\vec{x}, \vec{p}; t),$$

where D is the domain of the detector positioned at a solid angle $d^2\Omega$.



$\vec{x}$
D
$f_W(\vec{x}, \vec{p}; t)$
ϕ
θ
0

Minimal Model as Extreme Coherence

- Each set of participant protons of the two incidente nuclei are considered as point-like charges with the effective charge Z_{eff} .
- These two effective charges stop instantaneously as the two nuclei colide.

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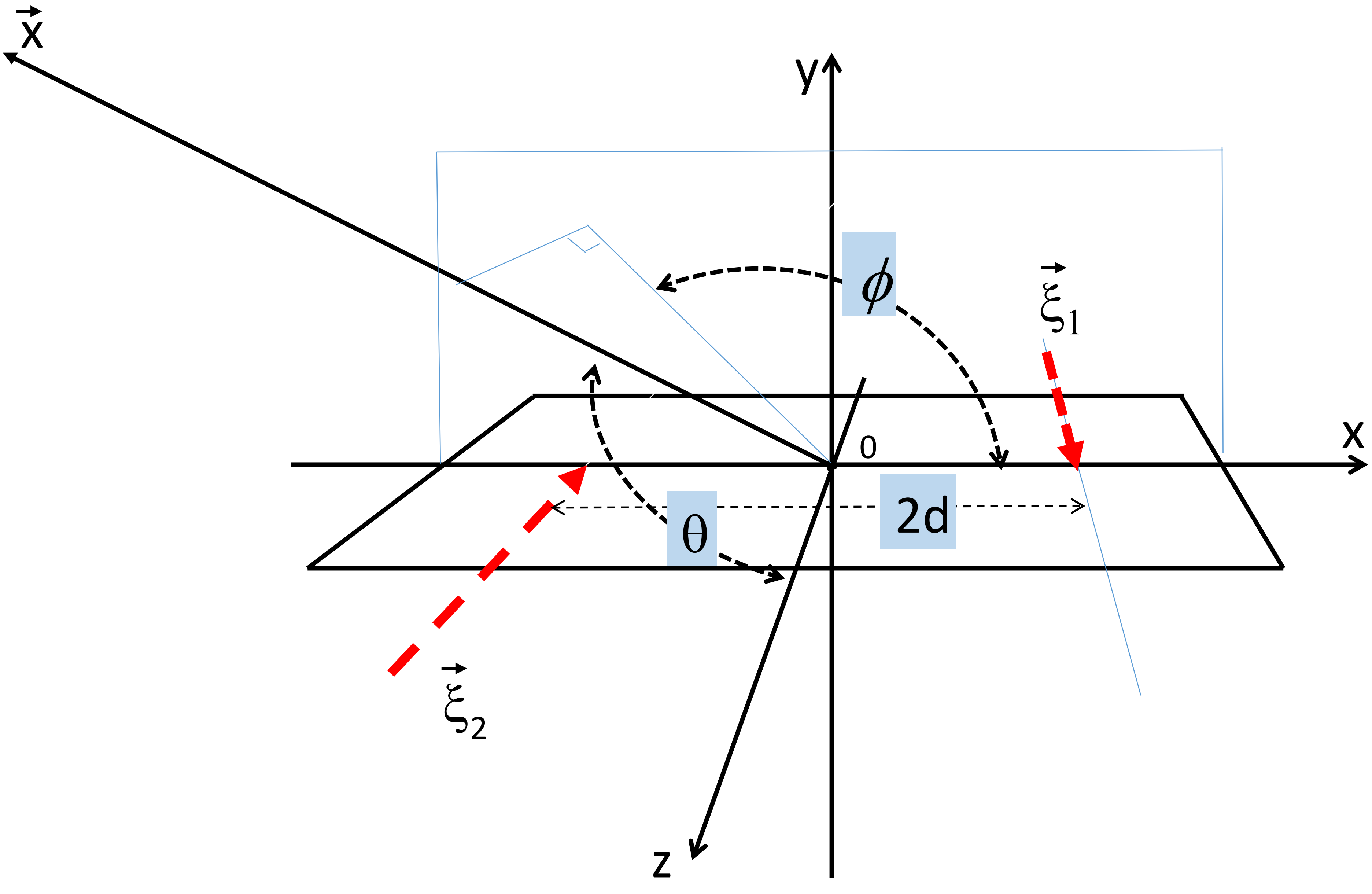


$\vec{x}$
y
ϕ
$\vec{\xi}_1$
x
0
2d
θ
$\vec{\xi}_2$
z

Taking the trajectories as $\vec{\xi}_1(t) = \begin{pmatrix} d \\ 0 \\ tV_0\theta(-t) \end{pmatrix}, \quad \vec{\xi}_2(t) = \begin{pmatrix} -d \\ 0 \\ -tV_0\theta(-t) \end{pmatrix}$

we get for the fields created by the trajectory-1 as

$$\vec{E}_1(\vec{x},t) = \frac{eV_0Z_{eff}}{4\pi}\frac{1}{r_-^{\,3}}\begin{pmatrix} -(x-d)z \\ -xy \\ (x-d)^2+y^2 \end{pmatrix}\delta(t-r_-), \qquad \vec{B}_1(\vec{x},t) = \frac{eV_0Z_{eff}}{4\pi}\frac{1}{r_-^{\,2}}\begin{pmatrix} y \\ -(x-d) \\ 0 \end{pmatrix}\delta(t-r_-),$$

where $r_- = \sqrt{(x-d)^2+y^2+z^2}$ and for the trajectory-2, we get simply by the following replacement,

$$\vec{E}_1(\vec{x},t),\ \vec{B}_1(\vec{x},t) \ \Rightarrow\ \vec{E}_2(\vec{x},t),\ \vec{B}_2(\vec{x},t)$$

$$\left(d, V_0\right) \ \Rightarrow\ \left(-d, -V_0\right)$$

From these, we have

$$f_{E,B}(\vec{x},\vec{p};t) = f^{(0)}{}_{E,B}(\vec{x}-\vec{d},\vec{p};t) + f^{(0)}{}_{E,B}(\vec{x}+\vec{d},\vec{p};t)$$
$$-2\cos(2\vec{p}\bullet\vec{d})\, f^{(0)}{}_{E,B}(\vec{x},\vec{p};t)$$

where $$f^{(0)}{}_{E,B}(\vec{x},\vec{p};t) = f_{E,B}(\vec{x},\vec{p};t)\Big|_{d=0}$$

and $$f_E(\vec{x},\vec{p};t) = \int d^3\vec{u}\left\{e^{i\vec{p}\bullet\vec{q}/\hbar}\vec{E}(\vec{x}-\vec{q}/2,t)\bullet\vec{E}(\vec{x}+\vec{q}/2,t)\right\},$$

and analogously for f_B .

These integrals contain the product of two delta functions

$$\delta\left(t-\sqrt{\left(\vec{x}+\vec{q}/2\right)^2}\right)\delta\left(t-\sqrt{\left(\vec{x}-\vec{q}/2\right)^2}\right)$$

which reduces for large distance (i.e., r,t >> 1/p, d) to

$$\delta\left(t-\sqrt{\left(\vec{x}+\vec{q}/2\right)^2}\right)\delta\left(t-\sqrt{\left(\vec{x}-\vec{q}/2\right)^2}\right)\simeq\delta(t-x)\delta(q_{//})$$

for arbitrary vector $\vec{q}$ with $\left|\vec{q}\right|\approx d$, and $q_{//}$ is the parallel component of $\vec{q}$ with respect to $\vec{\boldsymbol{x}}$

Finally we get

$$f_W(\vec{x}, \vec{p}; t) \cong 4\pi^2 \alpha_{EM} Z_{eff}{}^2 V_0{}^2 \frac{1}{p^2 r^2} \left\{ 1 - \cos\left(\vec{p} \bullet \vec{d} \right) \right\} \delta^2 \left(\vec{\Omega}_{\vec{p}} - \vec{\Omega}_{\vec{x}} \right)$$

The delta function (the last term) means that at a large (macroscopic) distance, the observational direction coincides with that of the momentum detected.

The energy spectrum is given by the integral within the volume of the detecter *D*, which is equivalente to

$$\frac{d^3\mathcal{E}}{d\vec{p}^3}=\frac{1}{(2\pi)^3}\int dt\int_{\Omega\in D} d^2\Omega_{\vec{x}} R_D{}^2 f_W(\vec{R}_D,\vec{p};t)$$

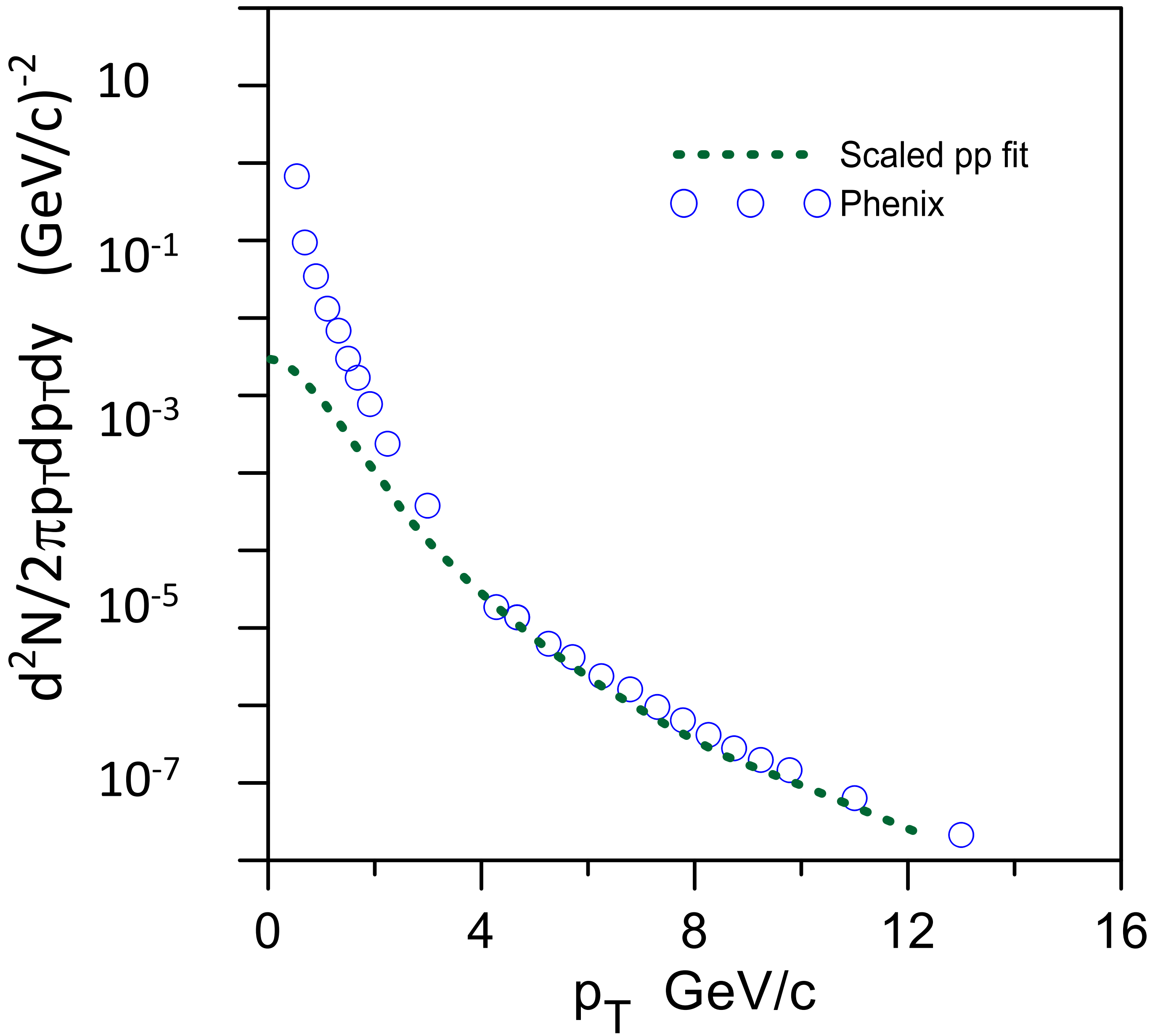
where R_D is the position of the detector D.
Photon number distribution is

$$\frac{d^3N}{d\vec{p}_T{}^2 dy}=\frac{1}{2\pi^2}\frac{\alpha_{EM} Z_{eff}{}^2 V_0{}^2}{p^2\cosh^2 y}\left\{1-\cos\left(2\vec{p}\bullet\vec{d}\right)\right\}$$

Angle integrated p_T spectrum is given by ($V_0 \sim 1$)

$$\left.\frac{d^3N}{2\pi p_T dp_T dy}\right|_{y=0}\simeq 0.37\times 10^{-3}\frac{Z_{eff}{}^2}{p_T{}^2}\left\{1-J_0\left(2pd\right)\right\}$$

p_T Spectrum

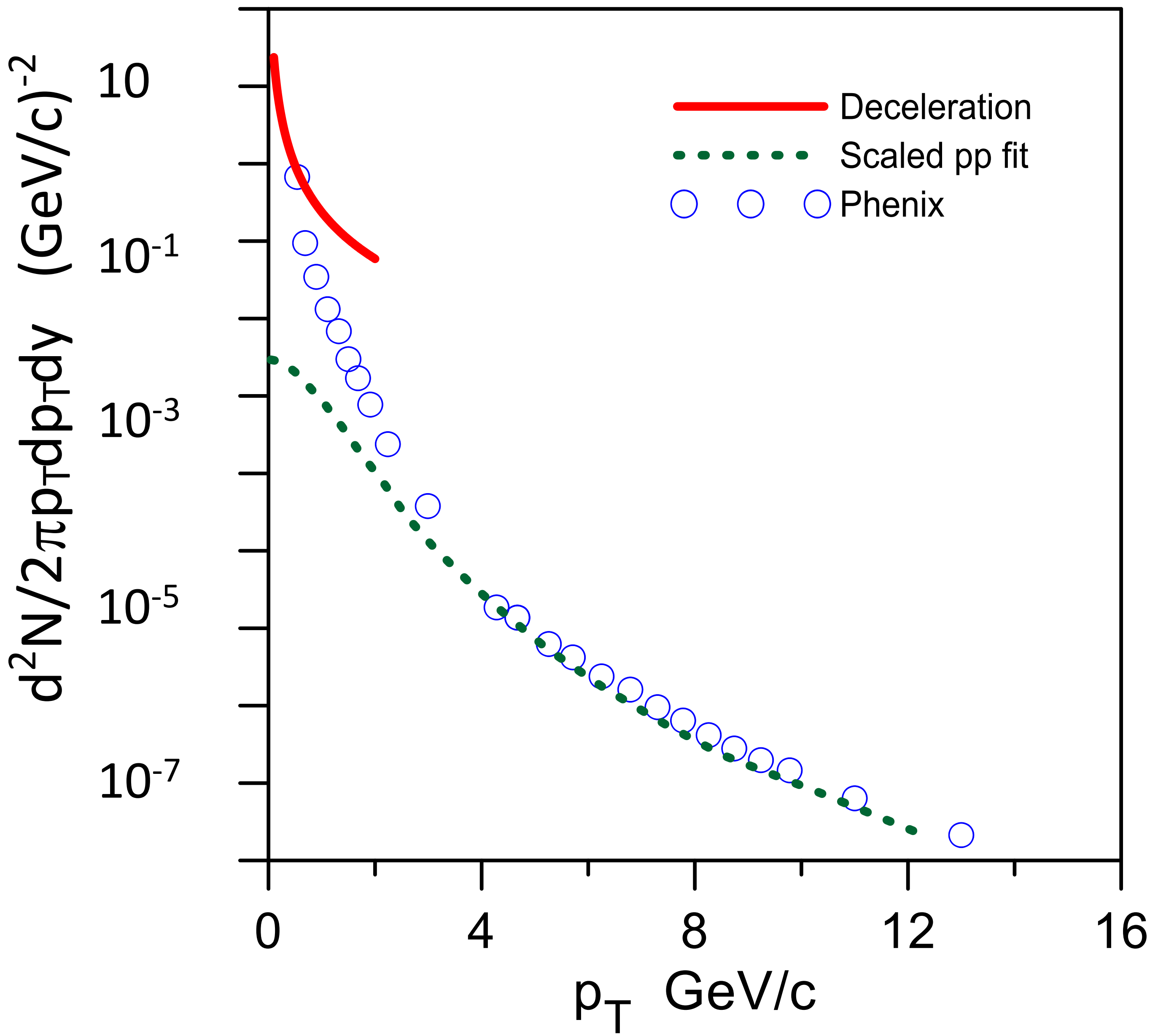


$V_0 \approx 1,$

$Z_{eff} \approx 80,$

$d \approx 1 fm$

p_T Spectrum



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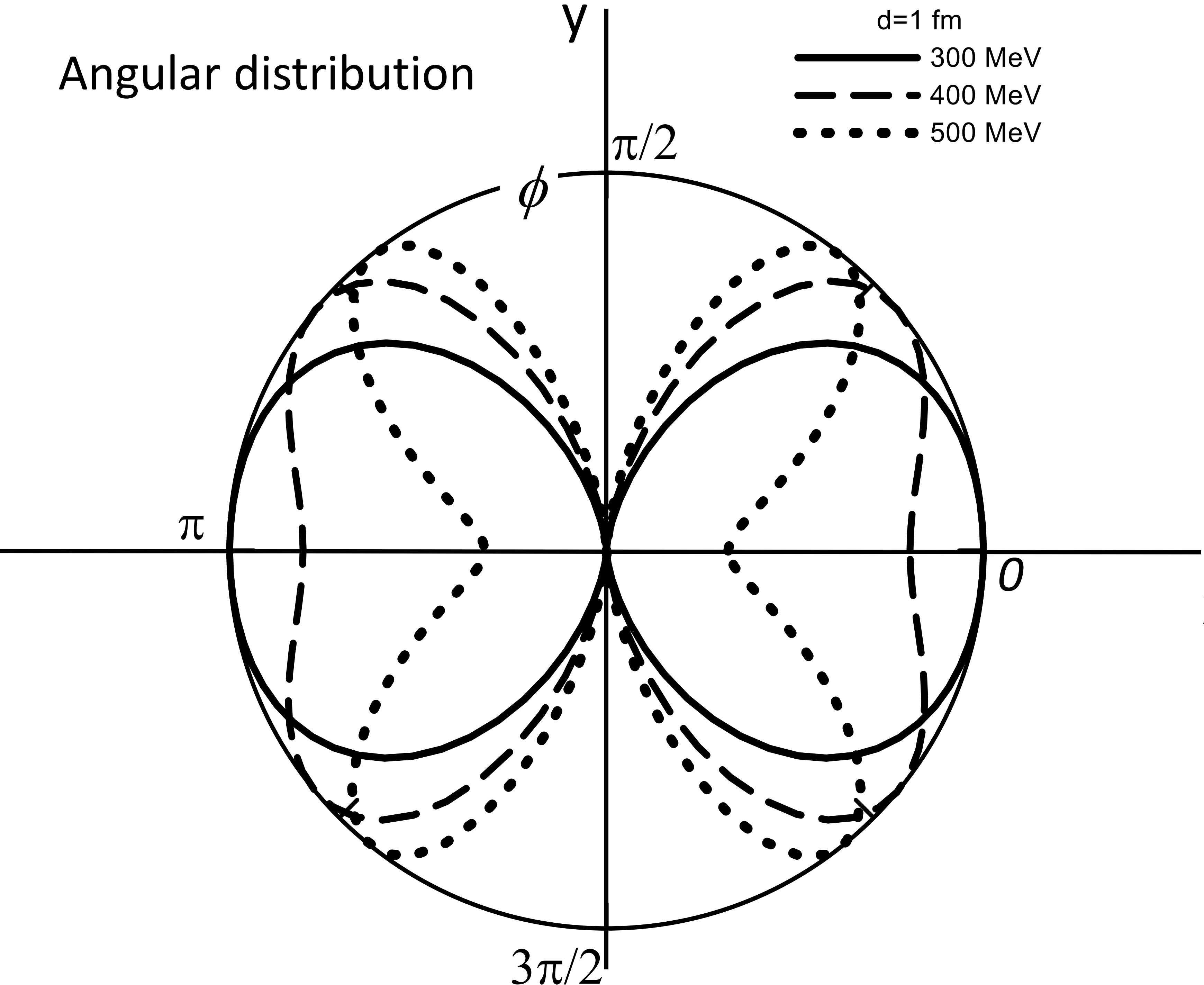
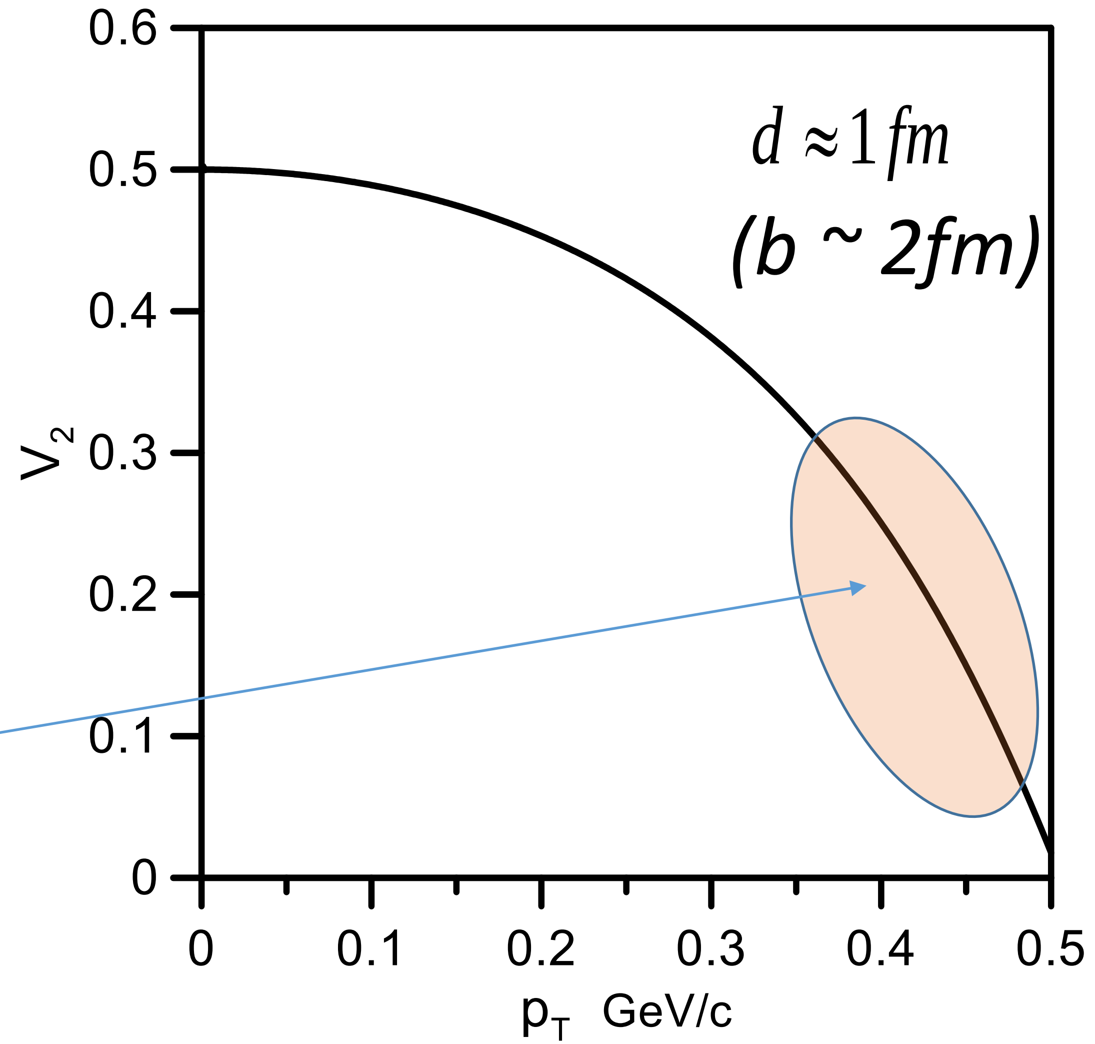

Angular distribution
d=1 fm
300 MeV
400 MeV
500 MeV
y
x
$\pi/2$
π
$3\pi/2$
0
ϕ

Anisotropy Parameter v_2

$$v_2 = \frac{J_2(2p_T d)}{1 - J_0(2p_T d)}$$



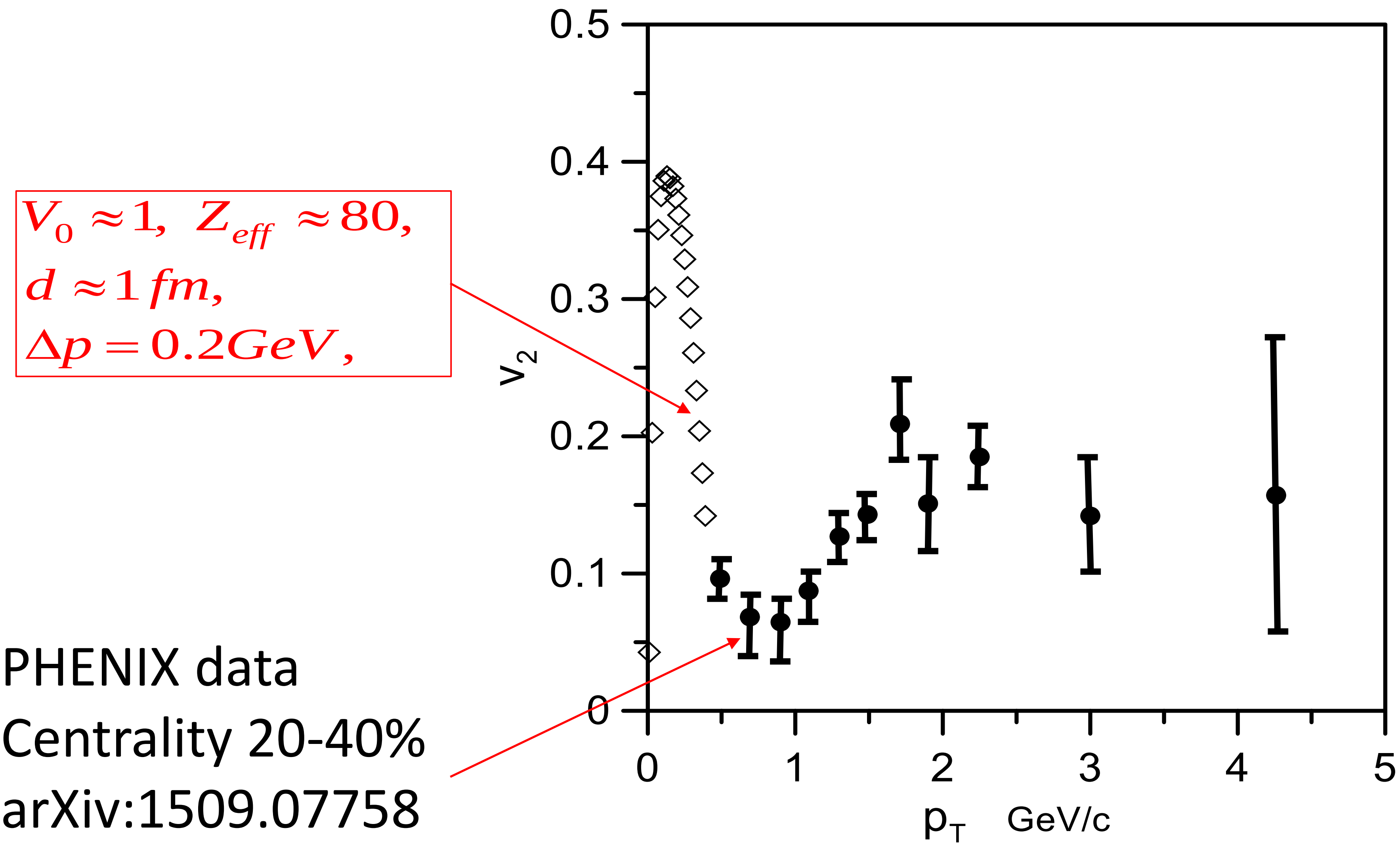
Large increase of v_2 for lower p_T !

If we suppose incoherence occurs between electro-magnetic fields generated by the incidente nuclei as exponetially with p_T, we may expect*

$$v_2 \approx \frac{J_2(2p_T d)}{1 + 2e^{2p_T/\Delta p}/Z_{eff} - J_0(2p_T d)}$$

* T.S. Biró, Z. Szendi and Z. Schram, Euro. Phys.J A50, 62 (2014)

Curiously,...



PHENIX data
Centrality 20-40%
arXiv:1509.07758

T. Koide and T. K, J. Phs. G 43 (2016) 095103.

Can the Classical Bremsstrahlung of Electromagnetic Fields be useful to understand

- Event by Event Initial Geometry
- Event by Event inhomogeneity and fluctuations
- Baryon Stopping

?

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?

More realistic simulations !

Can the C
Electromagneti

- Event by Event In
- Event by Event in
- Baryon Stopping

Can the Classical Bremsstrahlung of Electromagnetic Fields be useful to understand

June 30

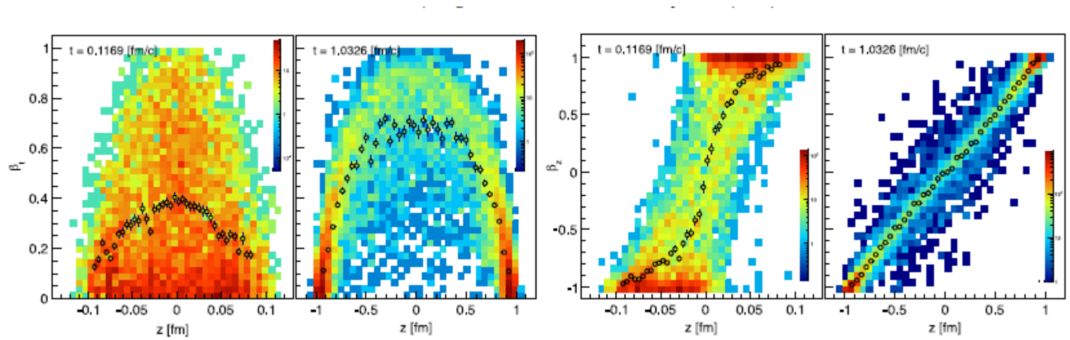


Fig. 12. Snapshots of the longitudinal profile of the particle velocity in PHSD for two different time-steps of the evolution for a central Au–Au collision at $\sqrt{s_{NN}} = 200$ GeV. The color scale in each panel represents the number of particles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

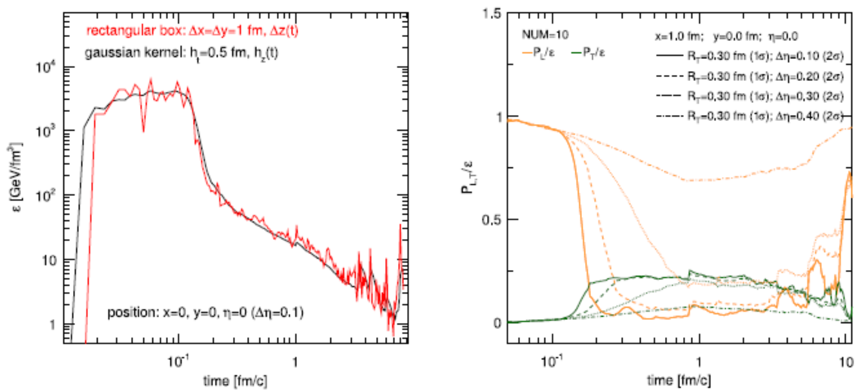


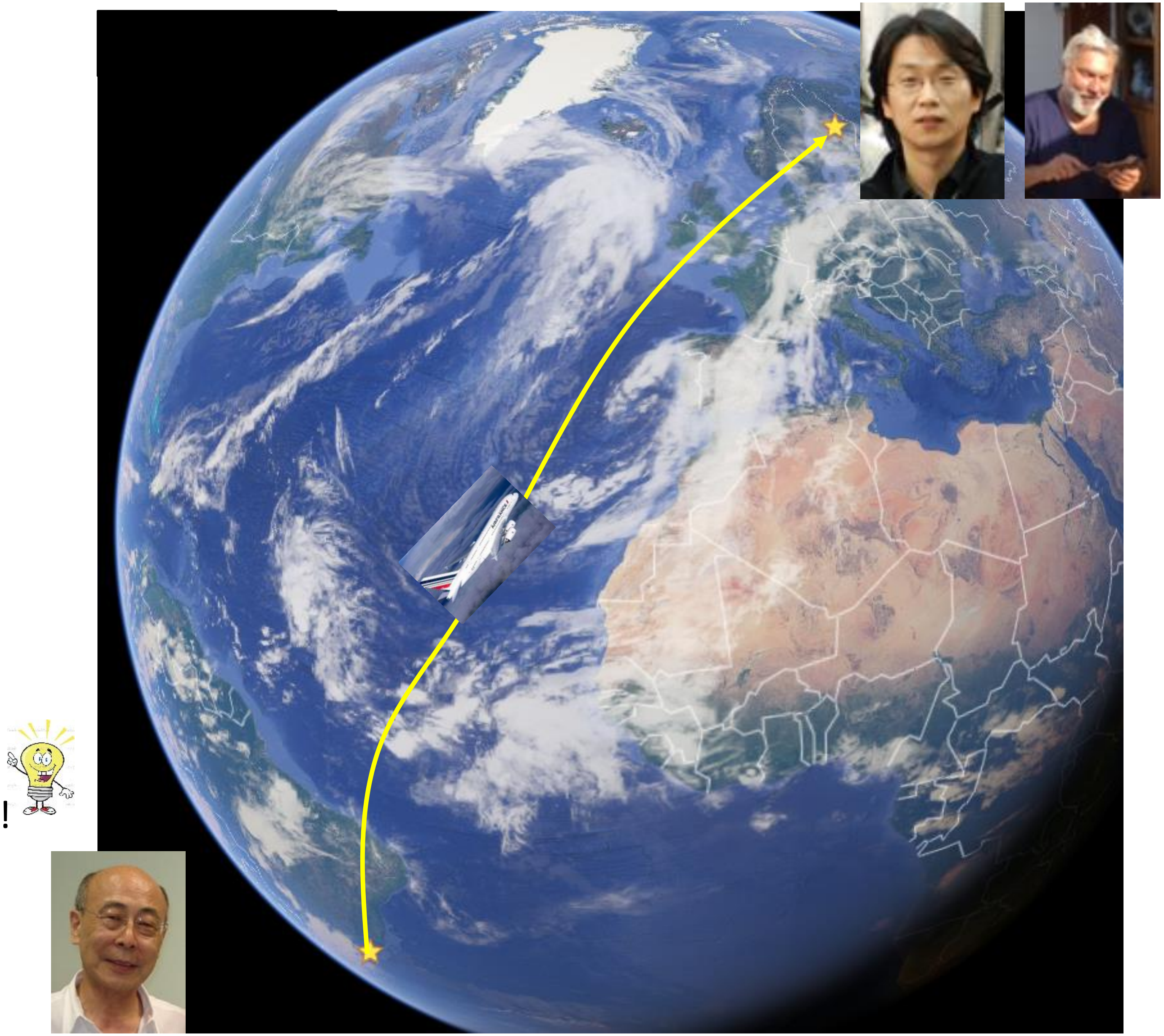
Fig. 13. Dependence of the local energy density ϵ with the time evolution for two different types of kernel functions (left plot); dependence of the longitudinal and transverse pressure components with the system evolution considering different characteristic lengths in the longitudinal direction (right plot). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

PHSD ! 

June 30, I fried to Frankfurt

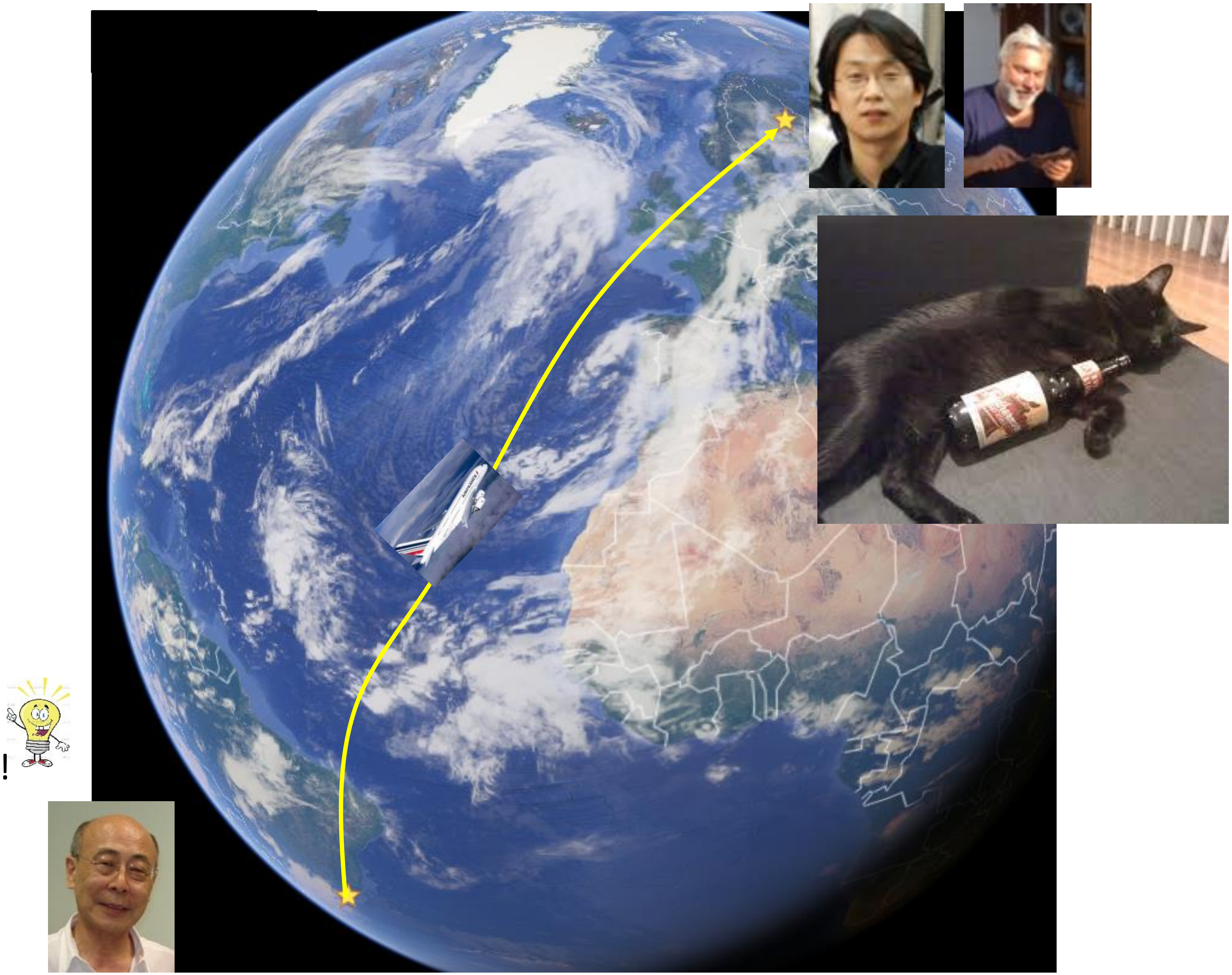
PHSD !

Yasushi Horst



PHSD !

Yasushi Horst



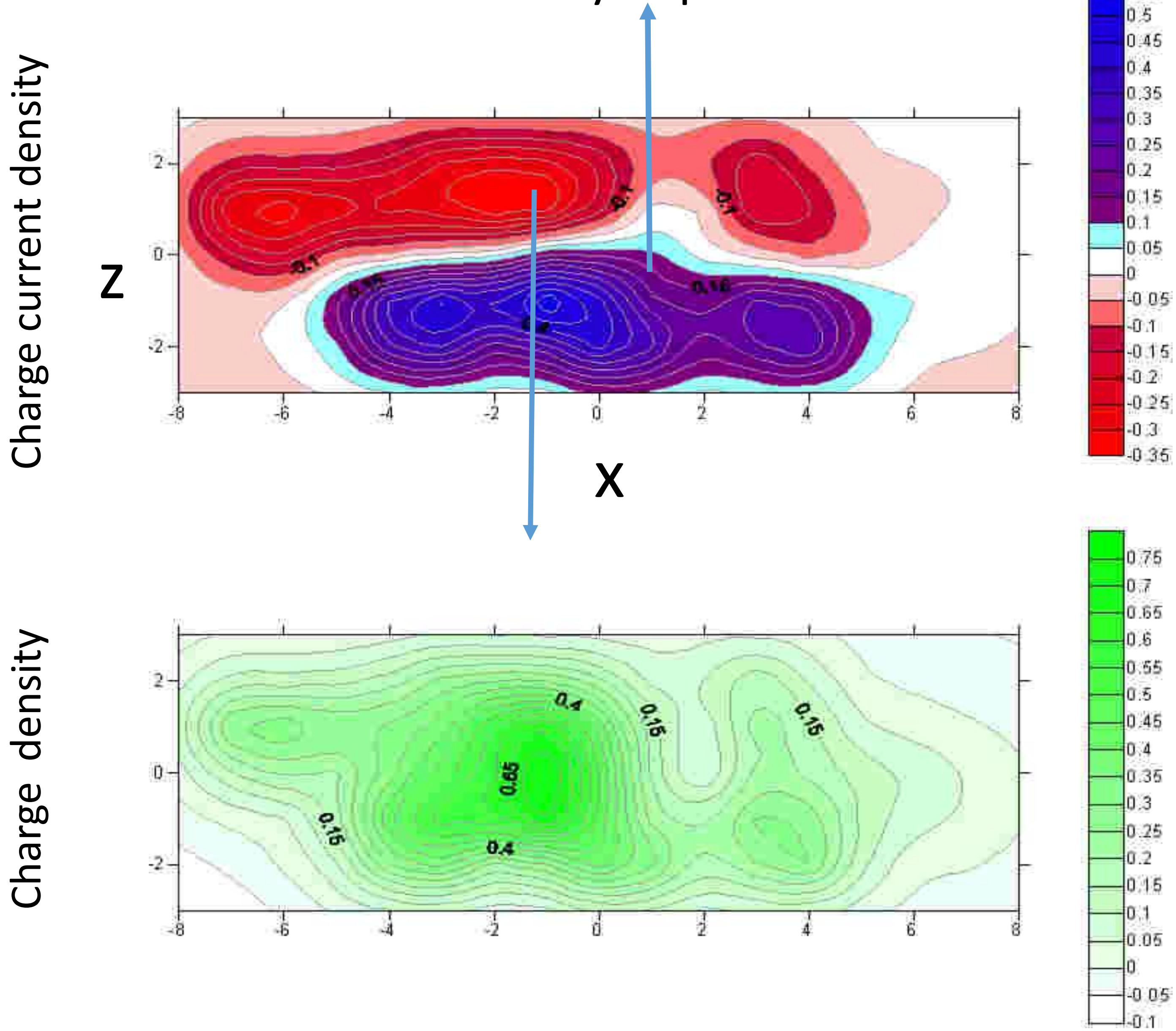
PHSD !

PHSD -> JAM

the time evolution of electric charge current density of a few events for

Au+Au b=2fm Sqs = 5GeV

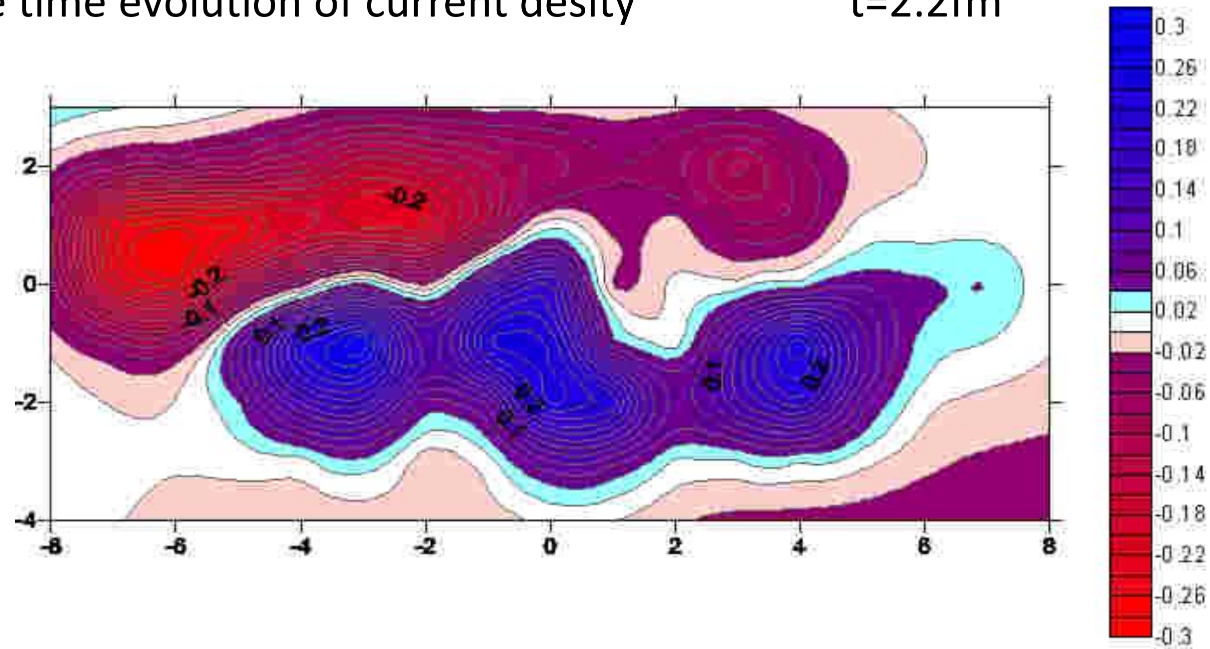
Example of the time evolution in y=0 plane t=1.8fm



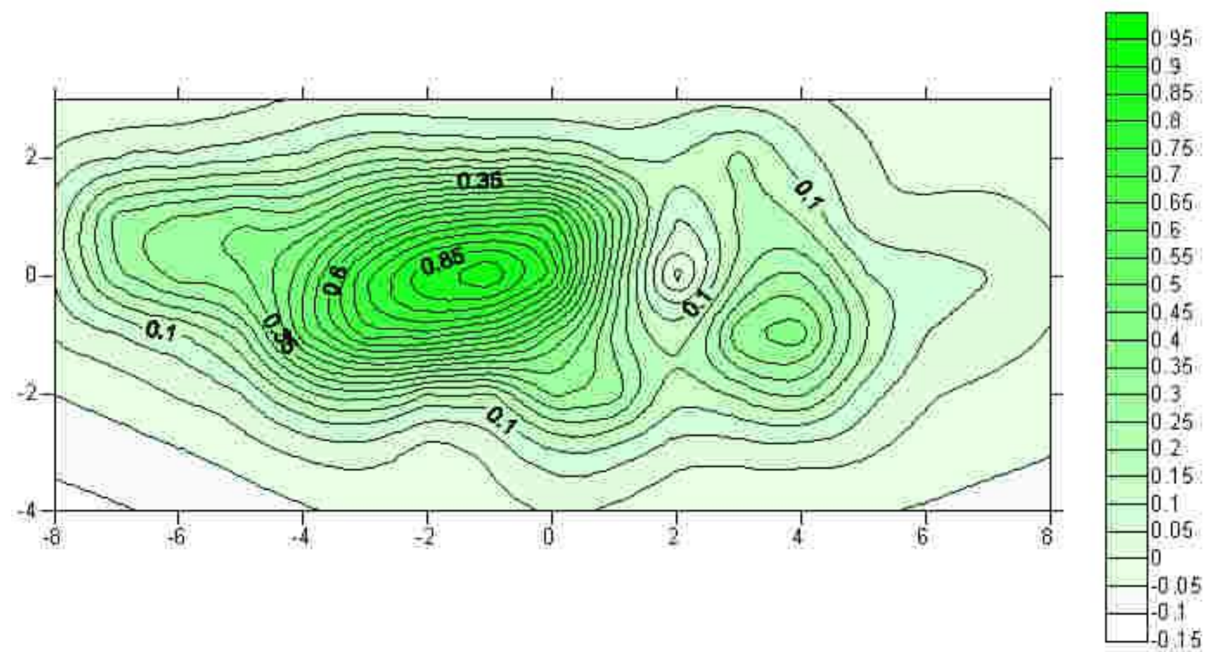
Au+Au, SQS=5GeV, b=2fm

Example of the time evolution of current desity t=2.2fm

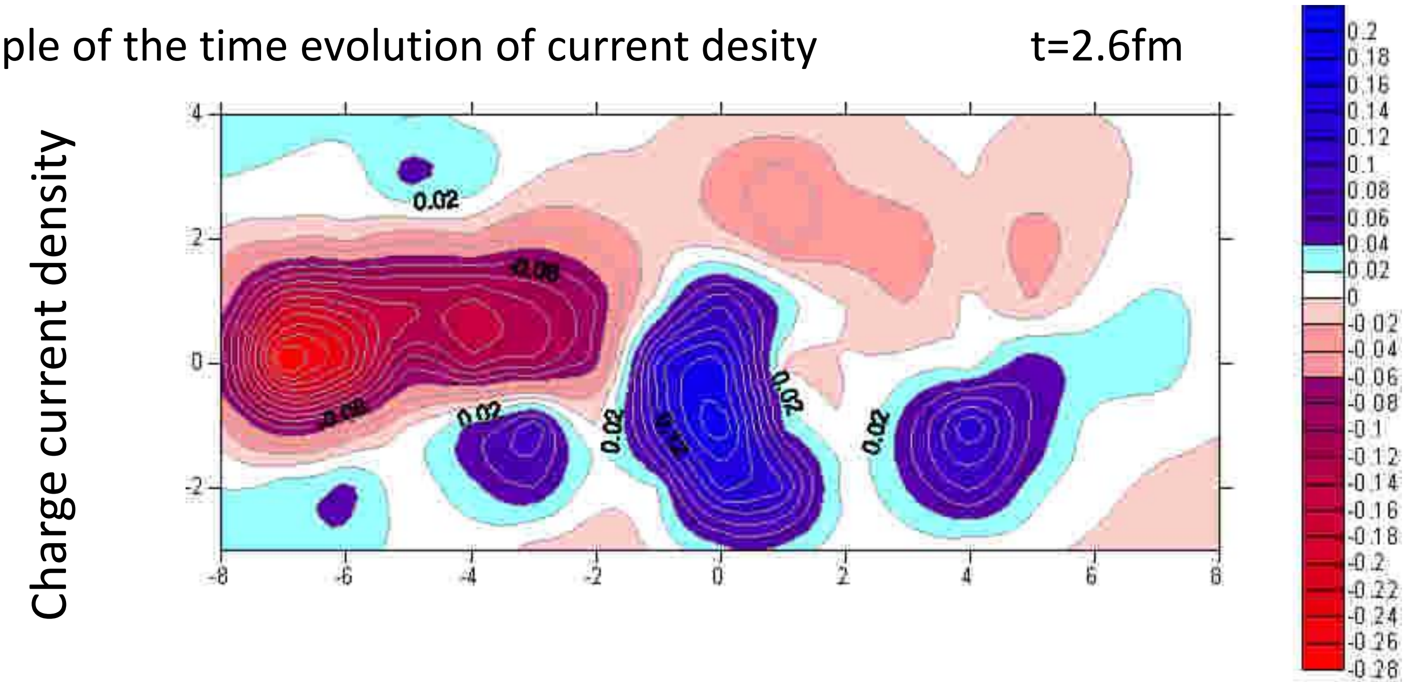
Charge current density

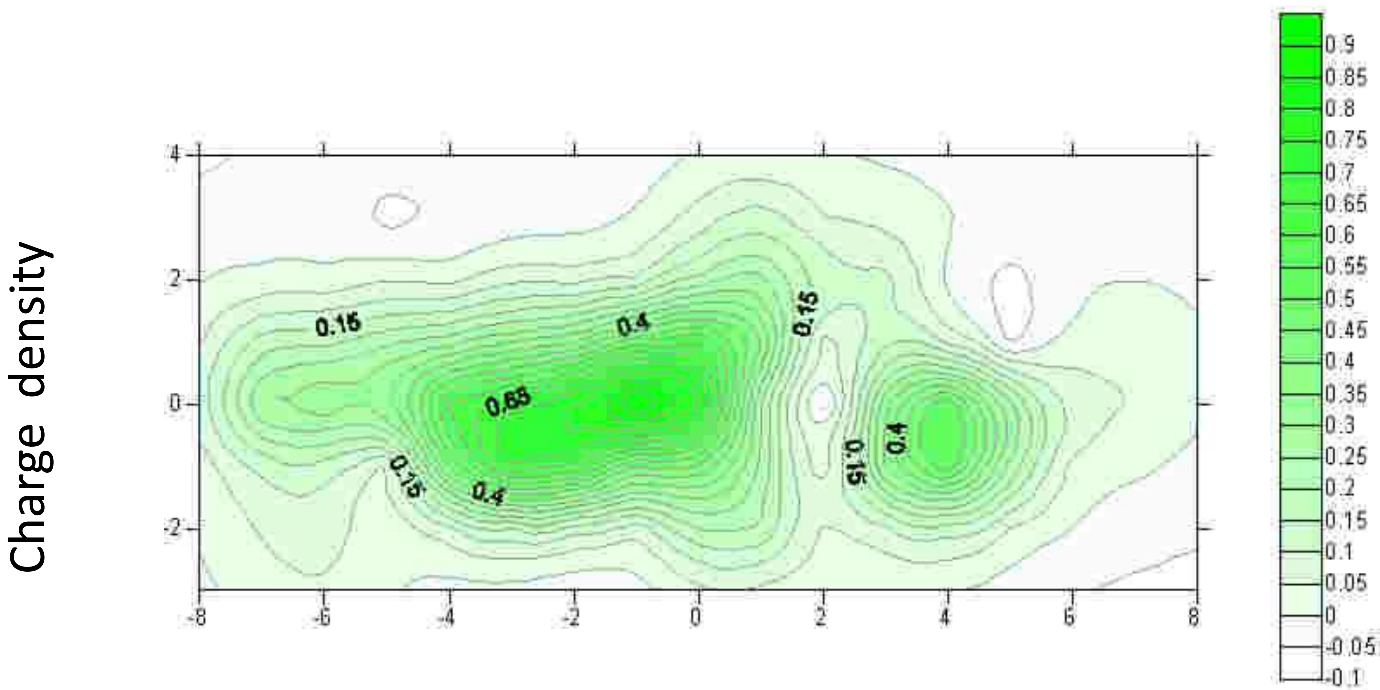


Charge density



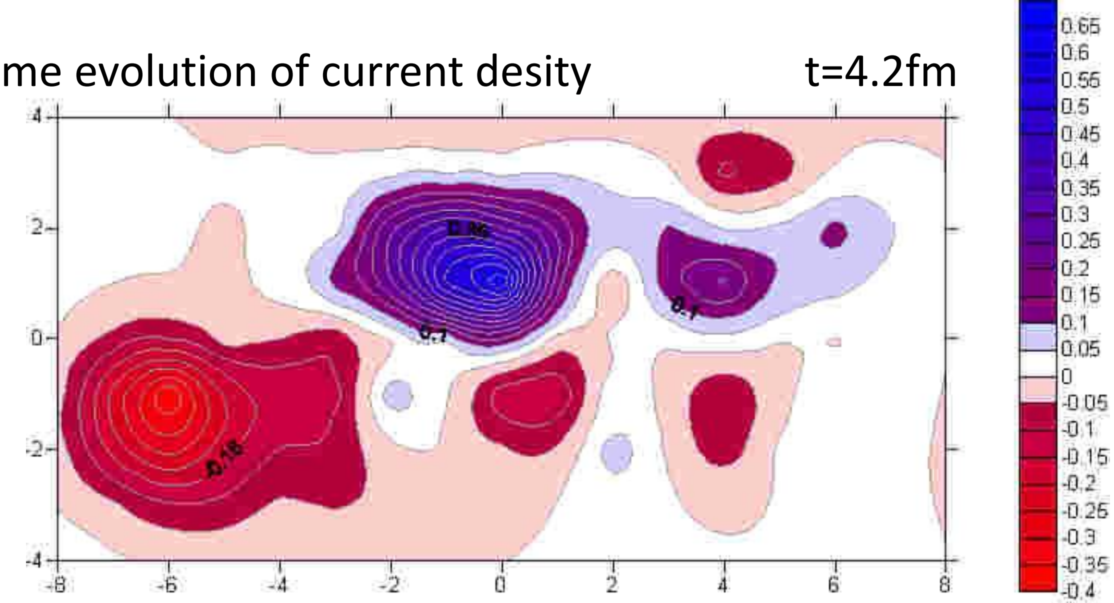
Example of the time evolution of current desity t=2.6fm



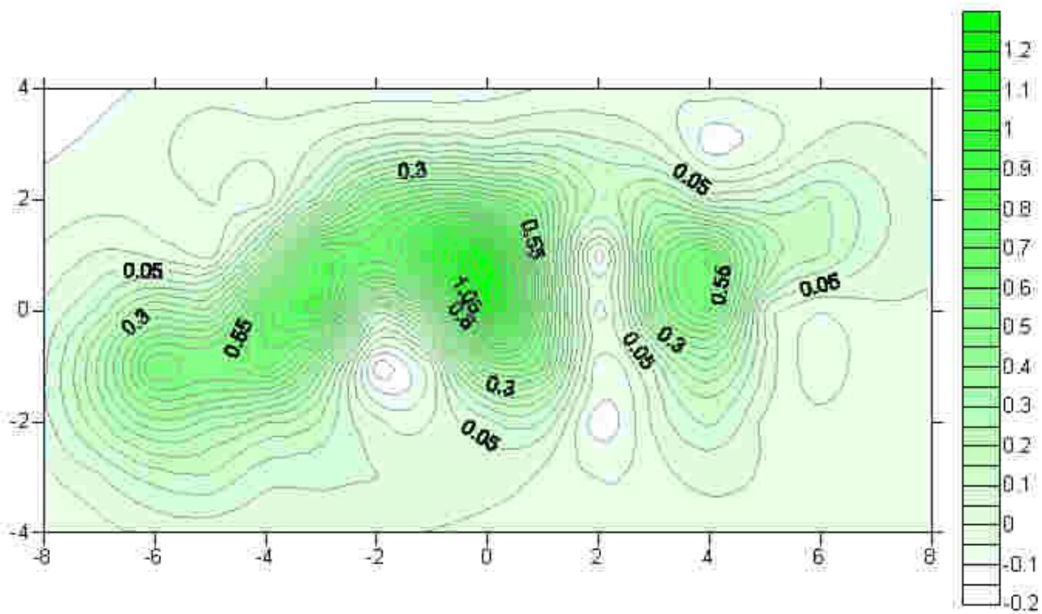


Example of the time evolution of current desity t=4.2fm

Charge current density

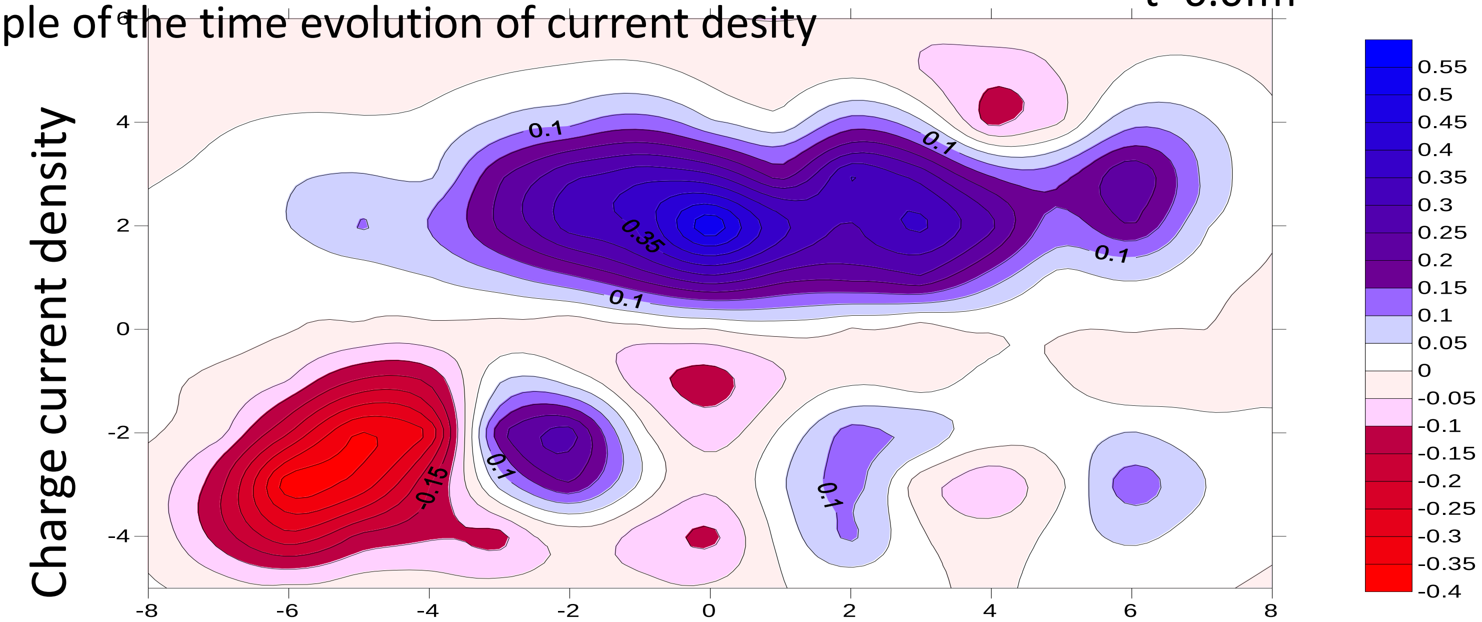


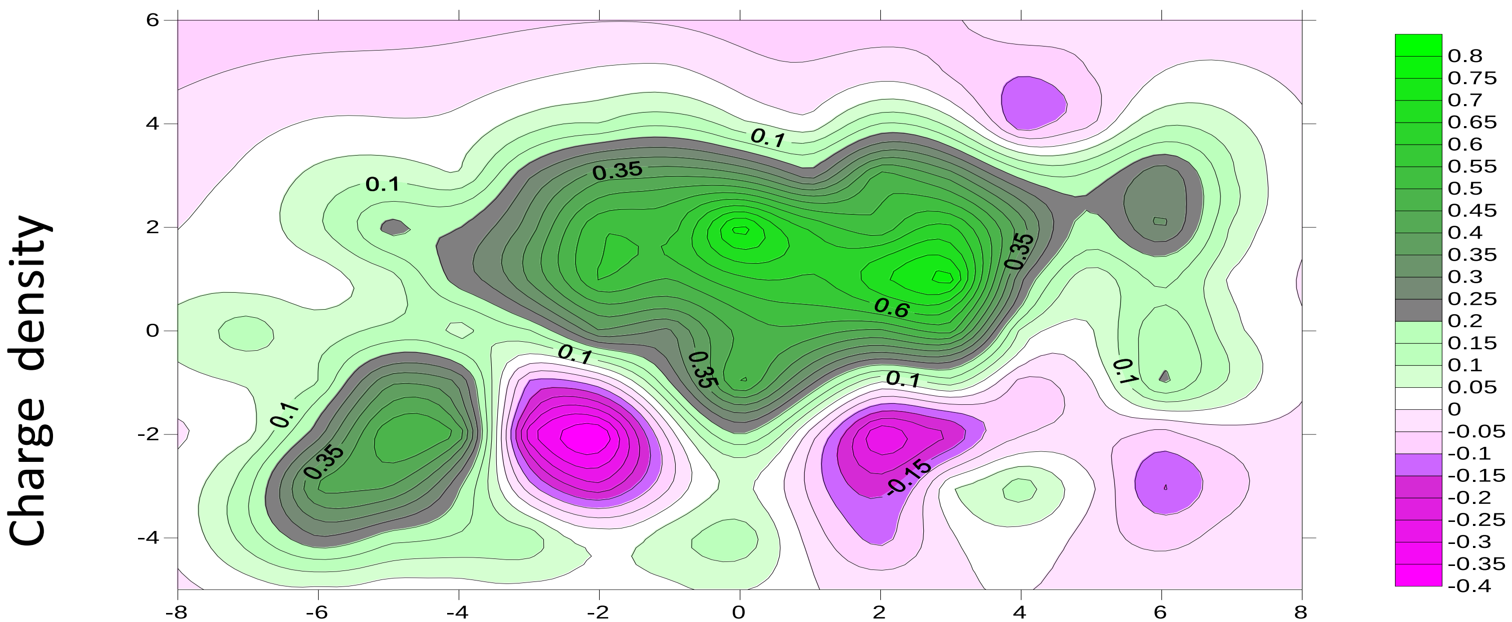
Charge density



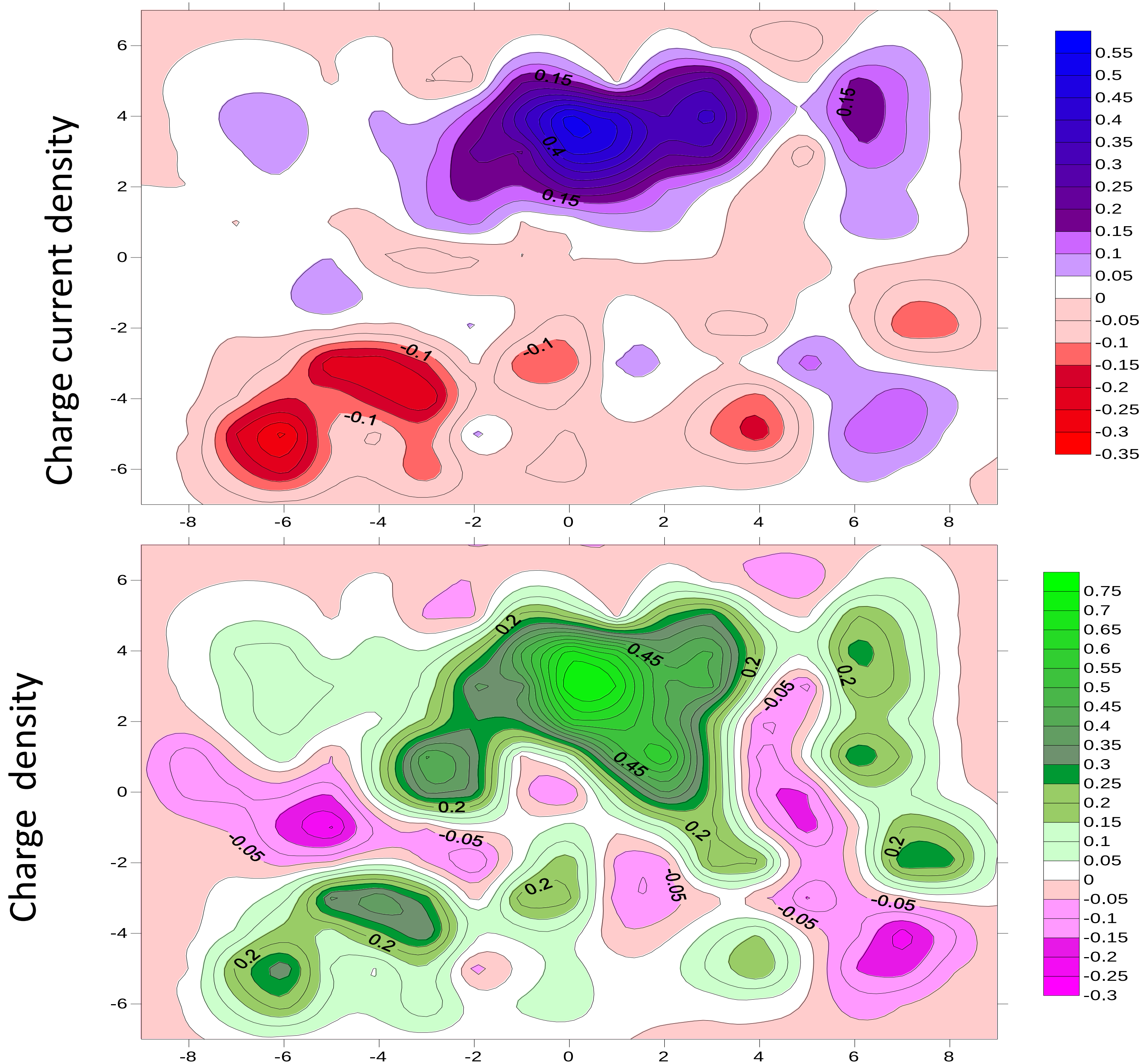
t=6.0fm

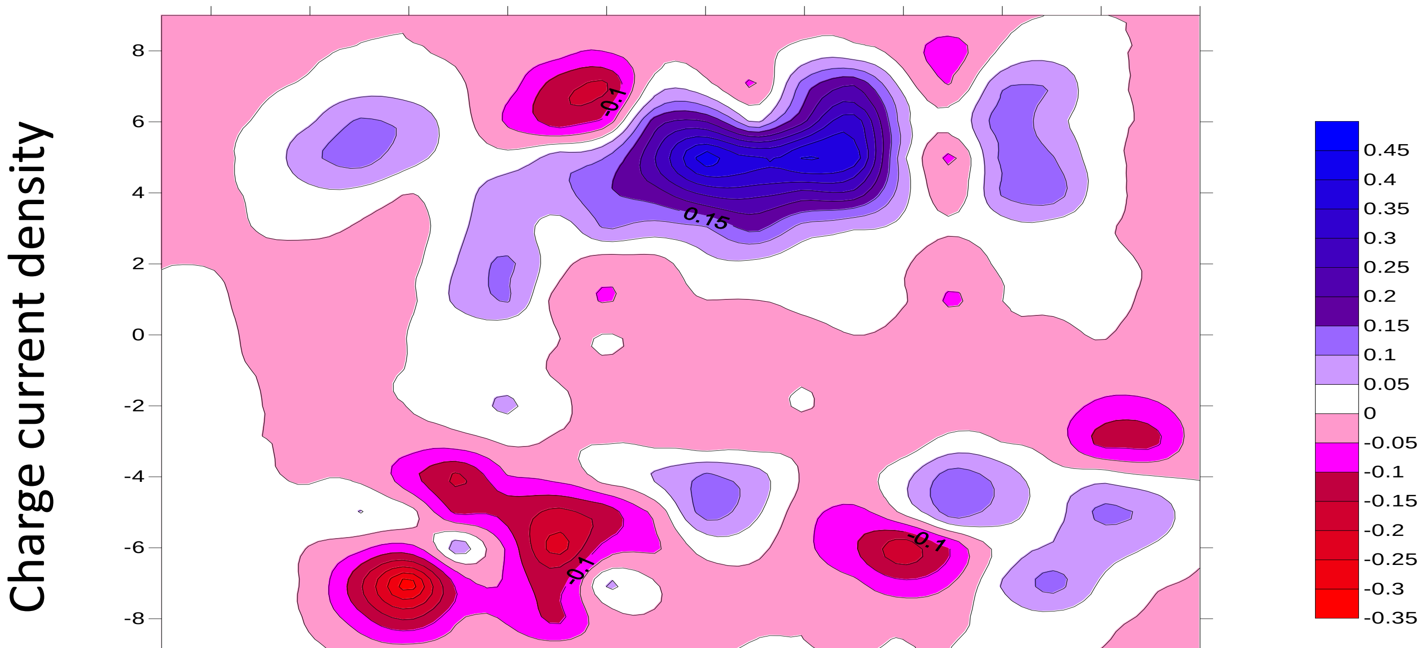
Example of the time evolution of current desity



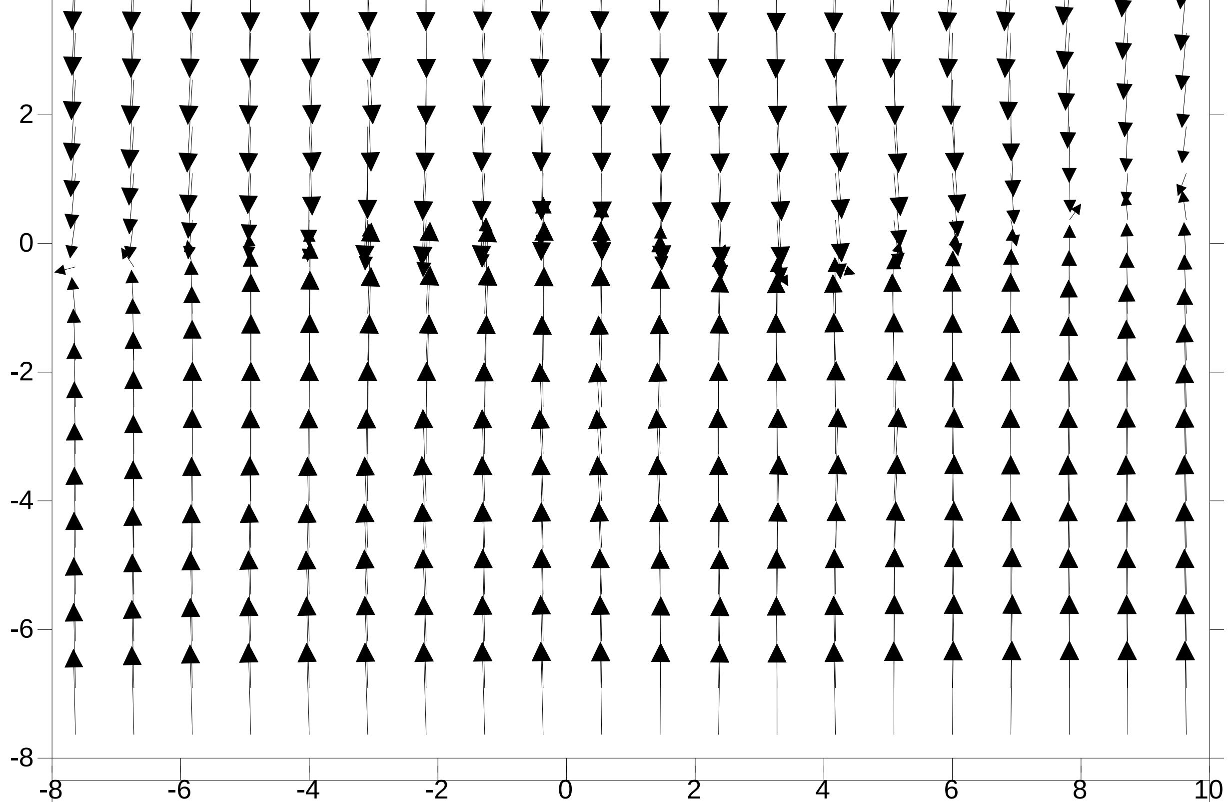


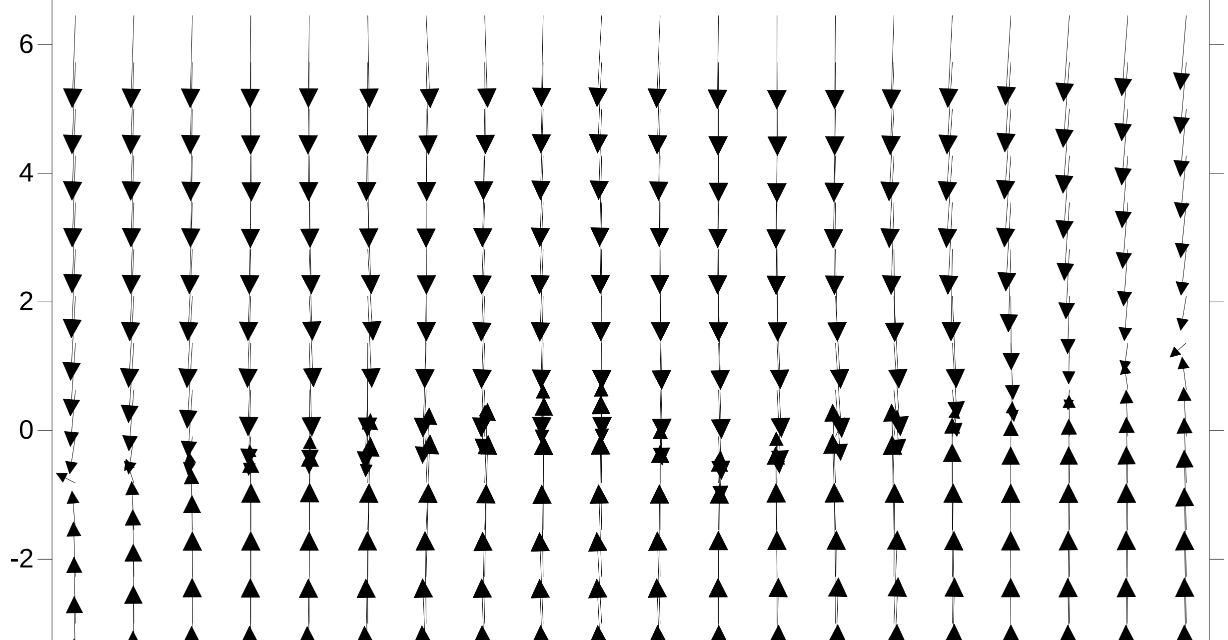
t=8.0fm

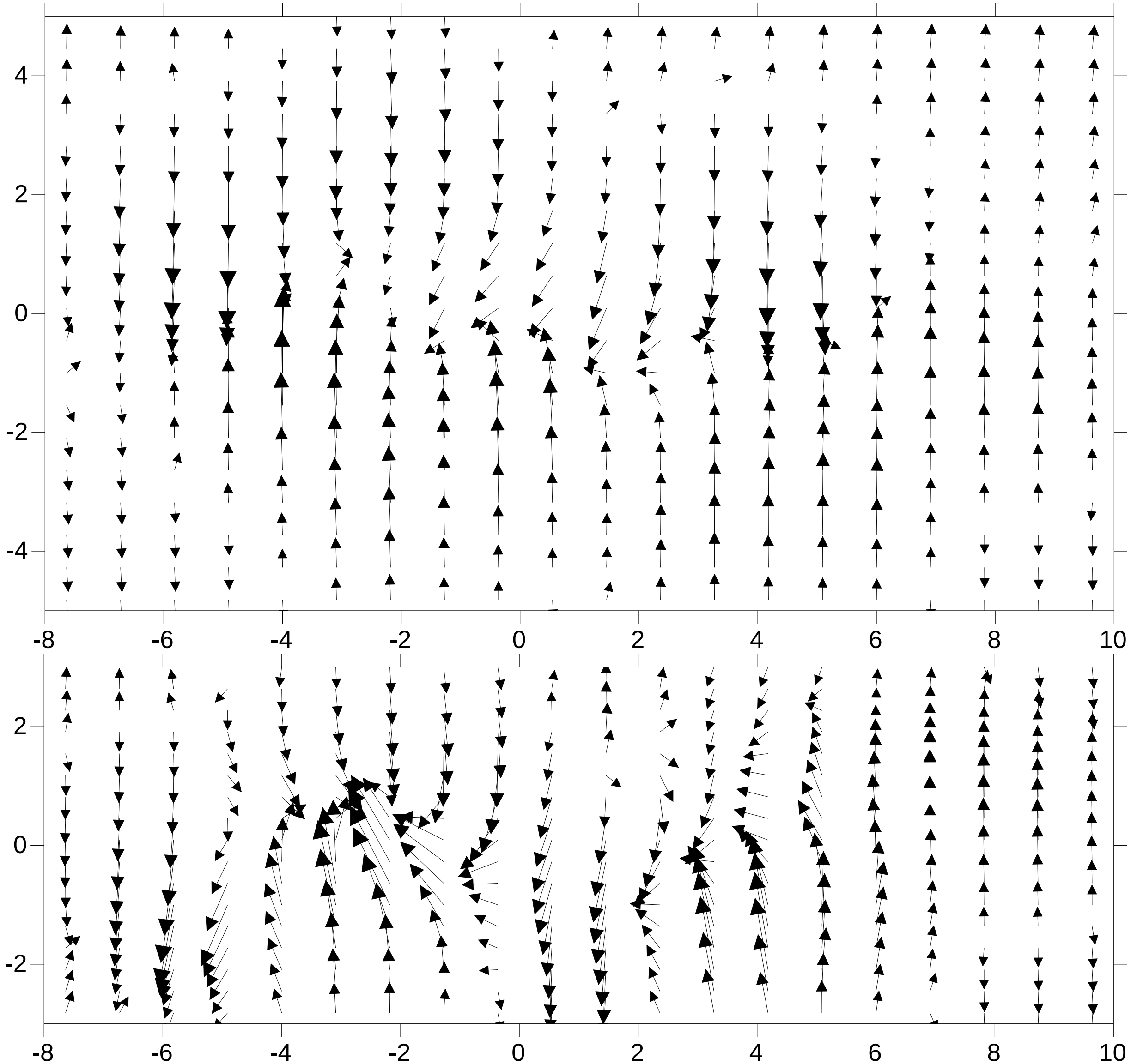



Charge current density
8
6
4
2
0
-2
-4
-6
-8
-0.1
0.15
-0.1
-0.1
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35


0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3

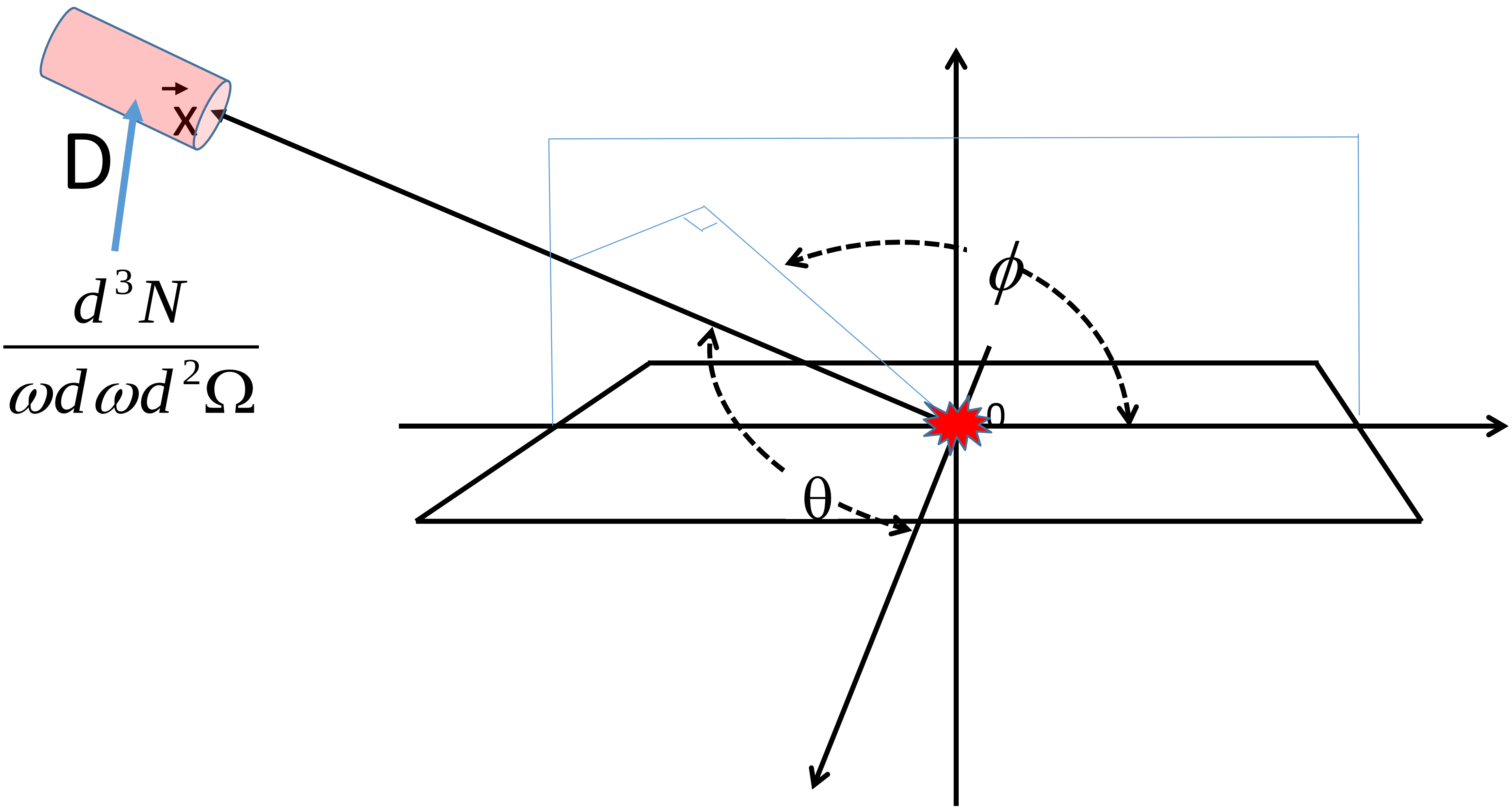

2
0
-2
-4
-6
-8
-8
-6
-4
-2
0
2
4
6
8
10


6
4
2
0
-2



4
2
0
-2
-4
-8
-6
-4
-2
0
2
4
6
8
10
2
0
-2
-8
-6
-4
-2
0
2
4
6
8
10

At large distance,

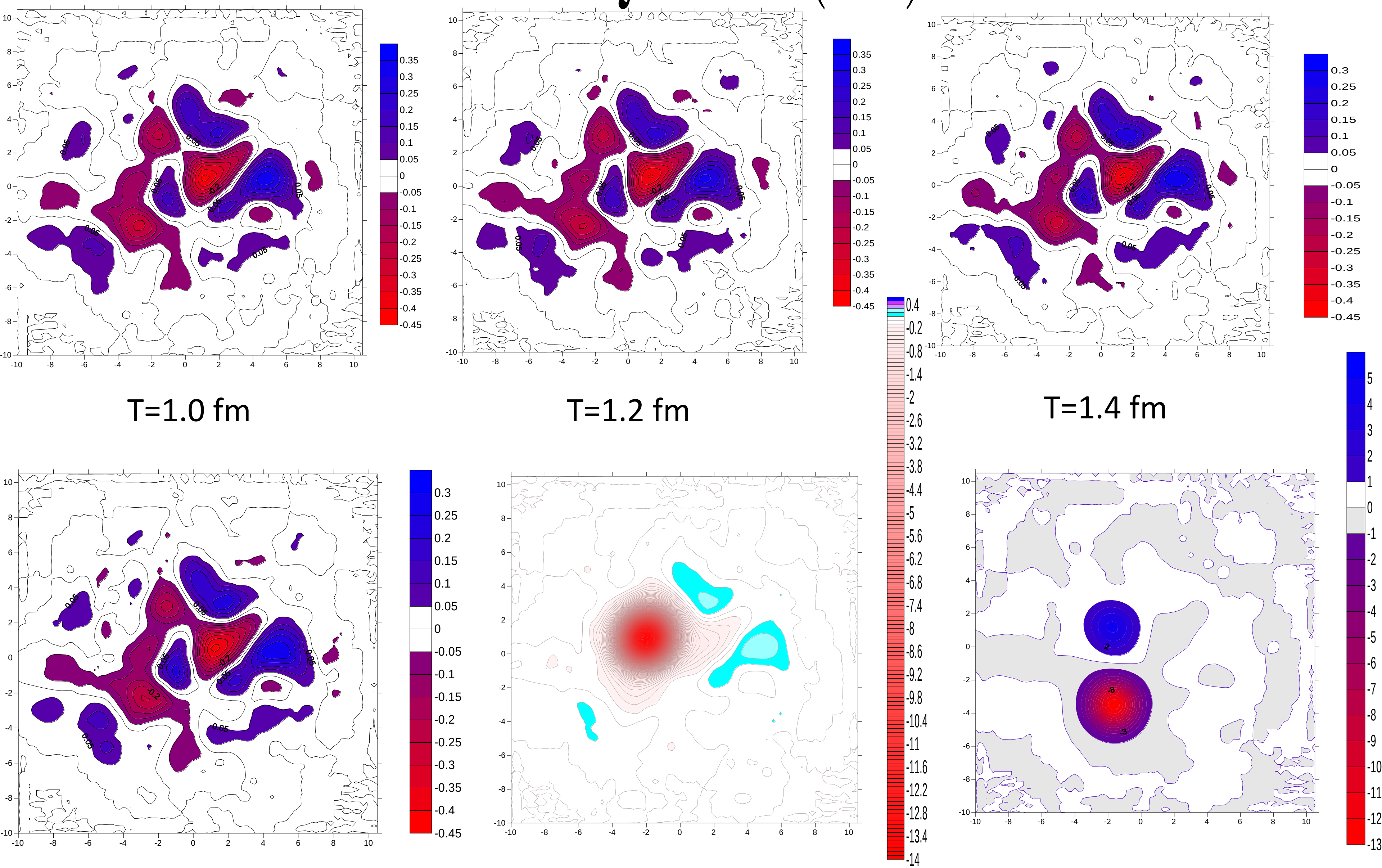


$$\frac{d^3N}{d^2\vec{p}_T dy} = \frac{d^3N}{\omega d\omega d^2\Omega} = \frac{1}{\pi}\left|\vec{A}\left(\omega,\vec{n}\right)\right|^2,$$

$$\vec{A}\left(\omega,\vec{n}\right) = -\frac{e}{4\pi}e^{i\omega r}\left(1-\vec{n}\vec{n}^T\right)\int d^3\vec{\xi}\int d\tau\, e^{i\omega\left(\tau-\vec{n}\cdot\vec{\xi}\right)}\frac{\partial\vec{J}}{\partial\tau}\left(\vec{\xi},\tau\right)$$

Mostly $J_z\left(\vec{\xi},\tau\right)$ is dominant.

x-y profile of $\int d\xi_z \, dJ_z\left(\vec{\xi},\tau\right)/dt$



T=1.0 fm

T=1.2 fm

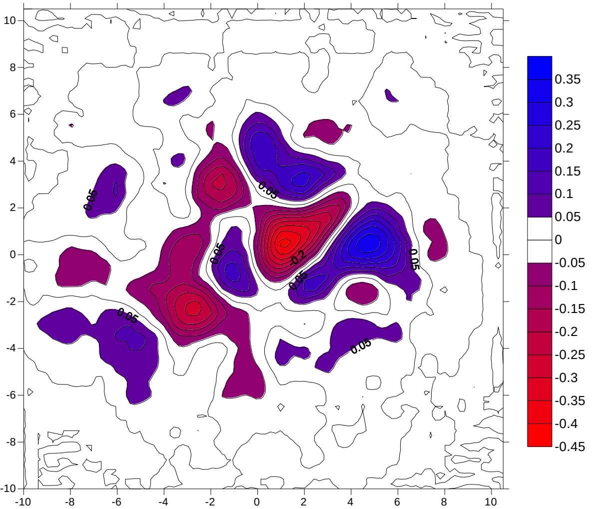
T=1.4 fm

T=1.6 fm

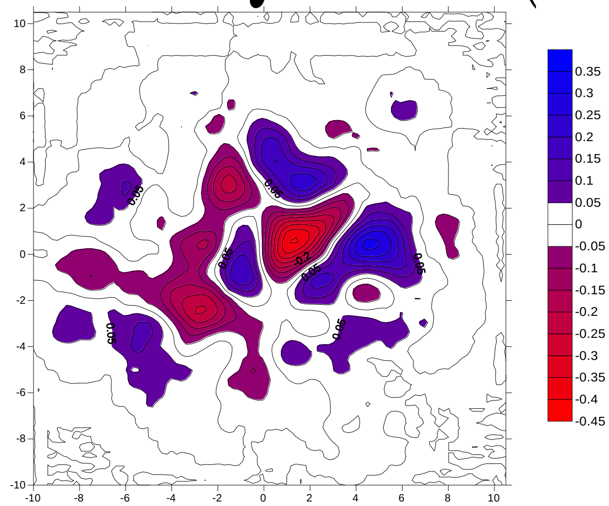
T=1.8 fm

T=2.0 fm

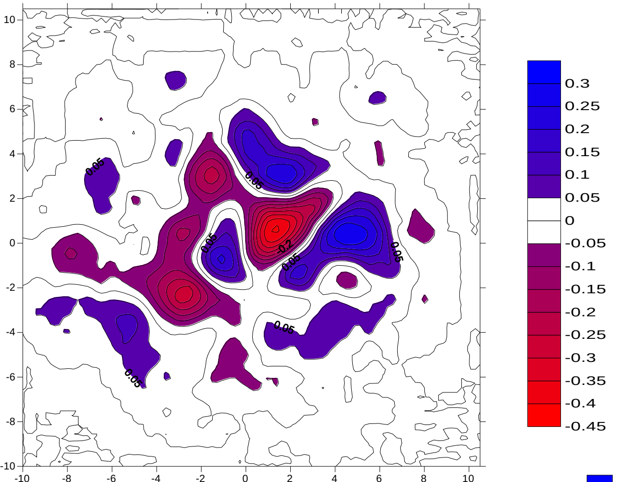
x-y profile of $\int d\xi_z \; dJ_z\left(\vec{\xi},\tau\right)/dt$



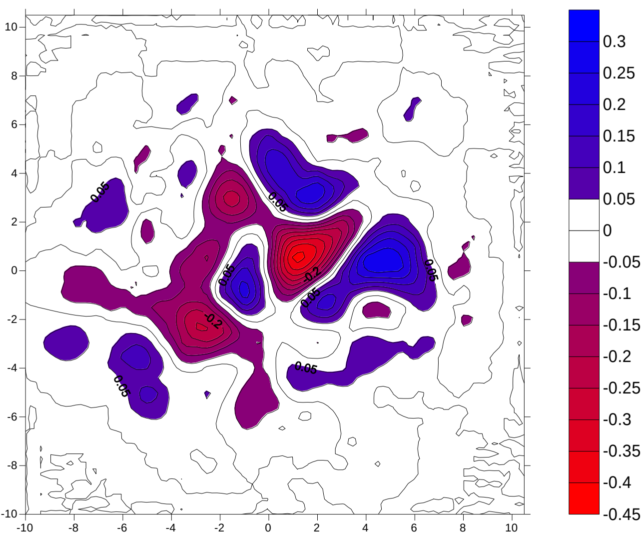
T=1.0 fm



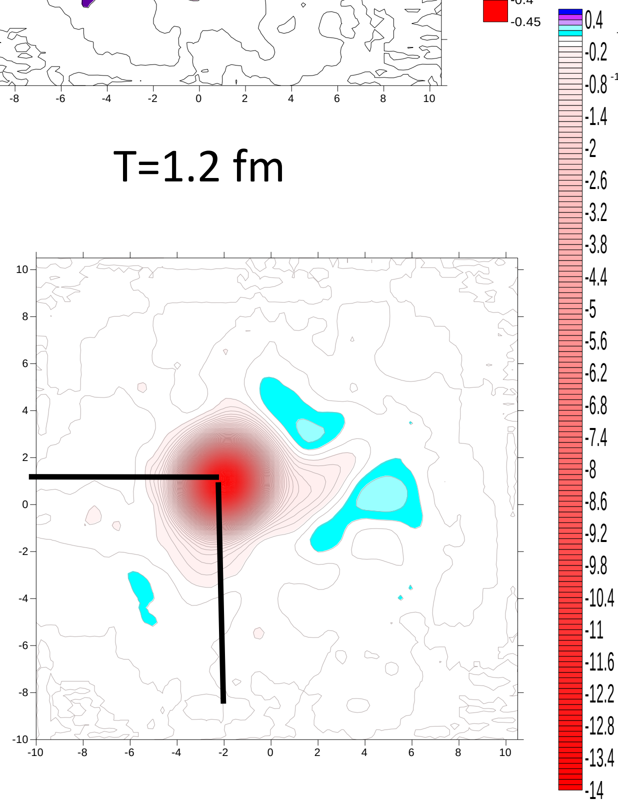
T=1.2 fm



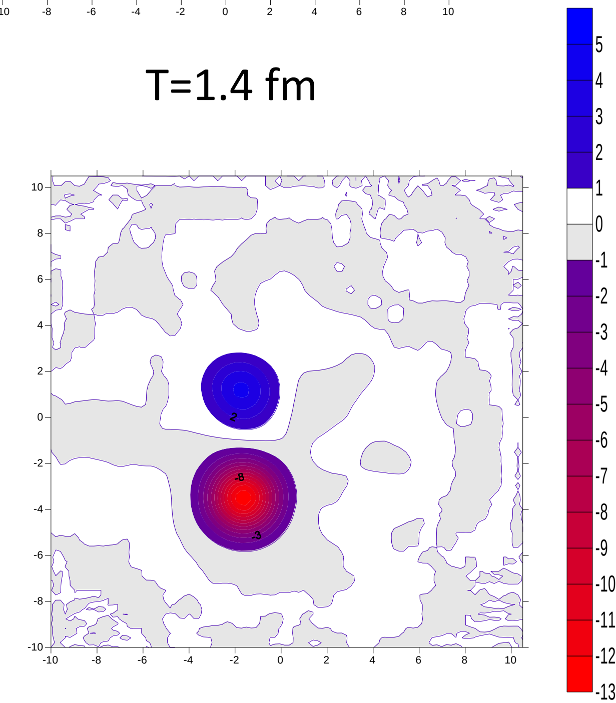
T=1.4 fm



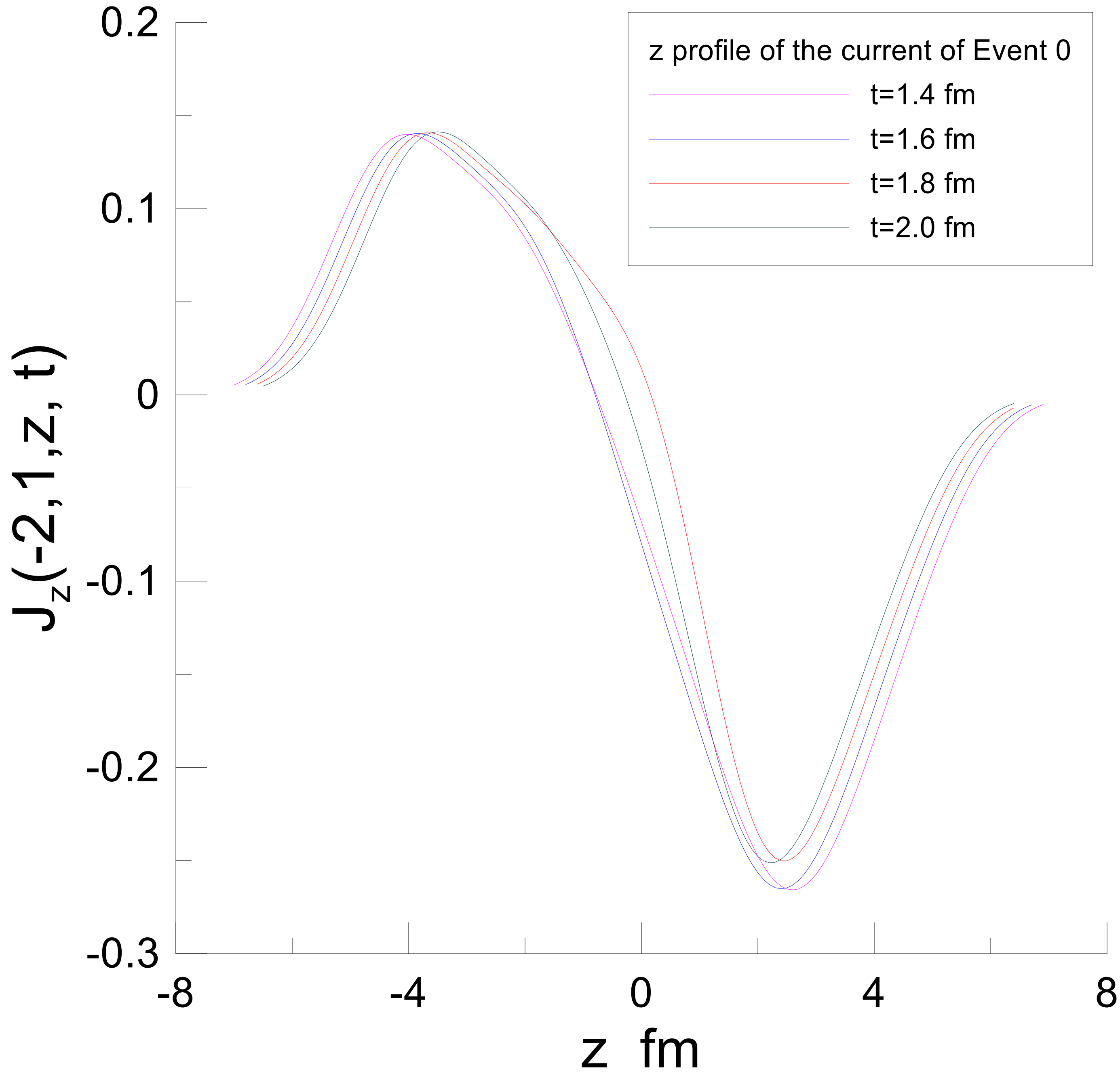
T=1.6 fm

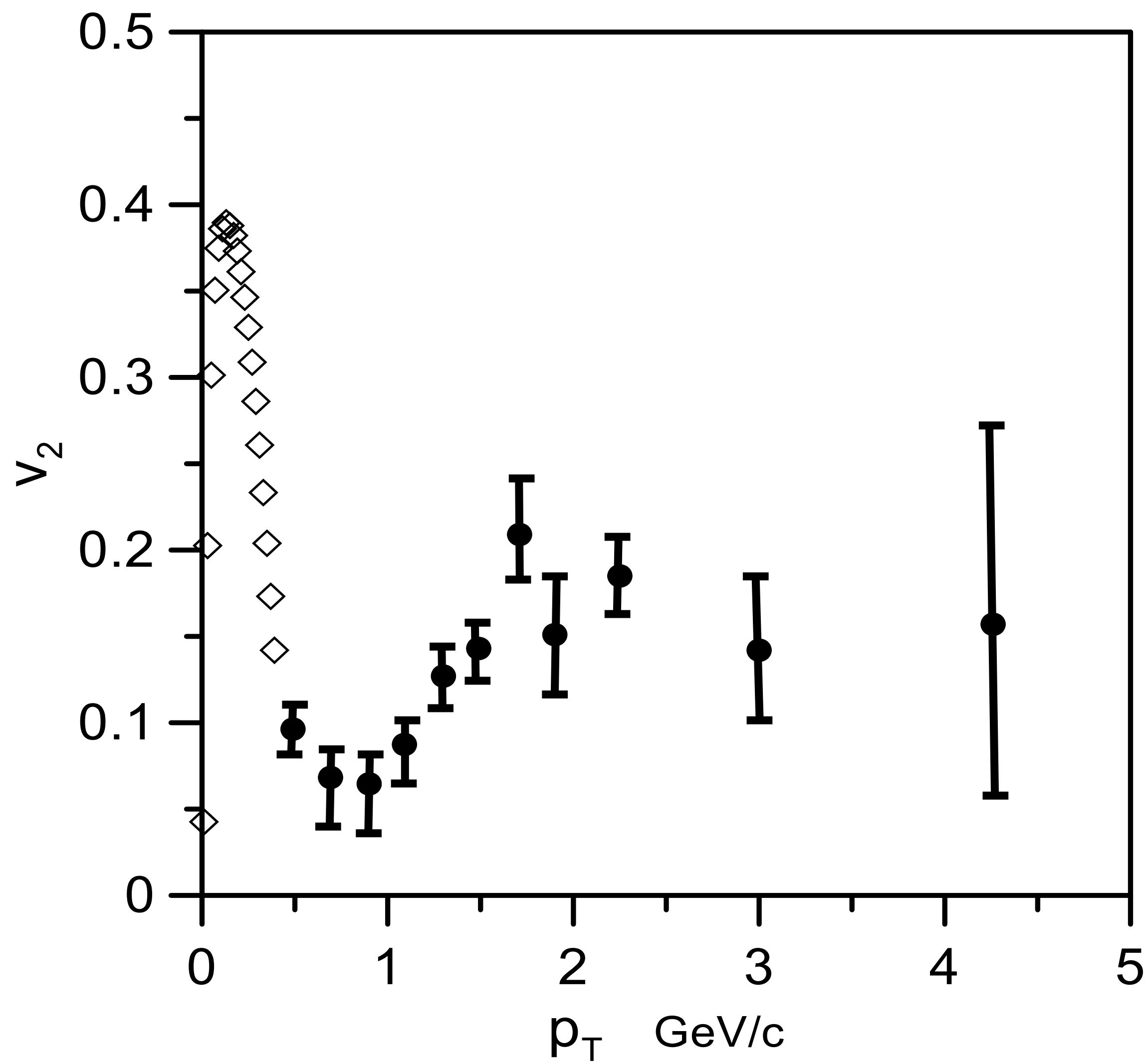


T=1.8 fm

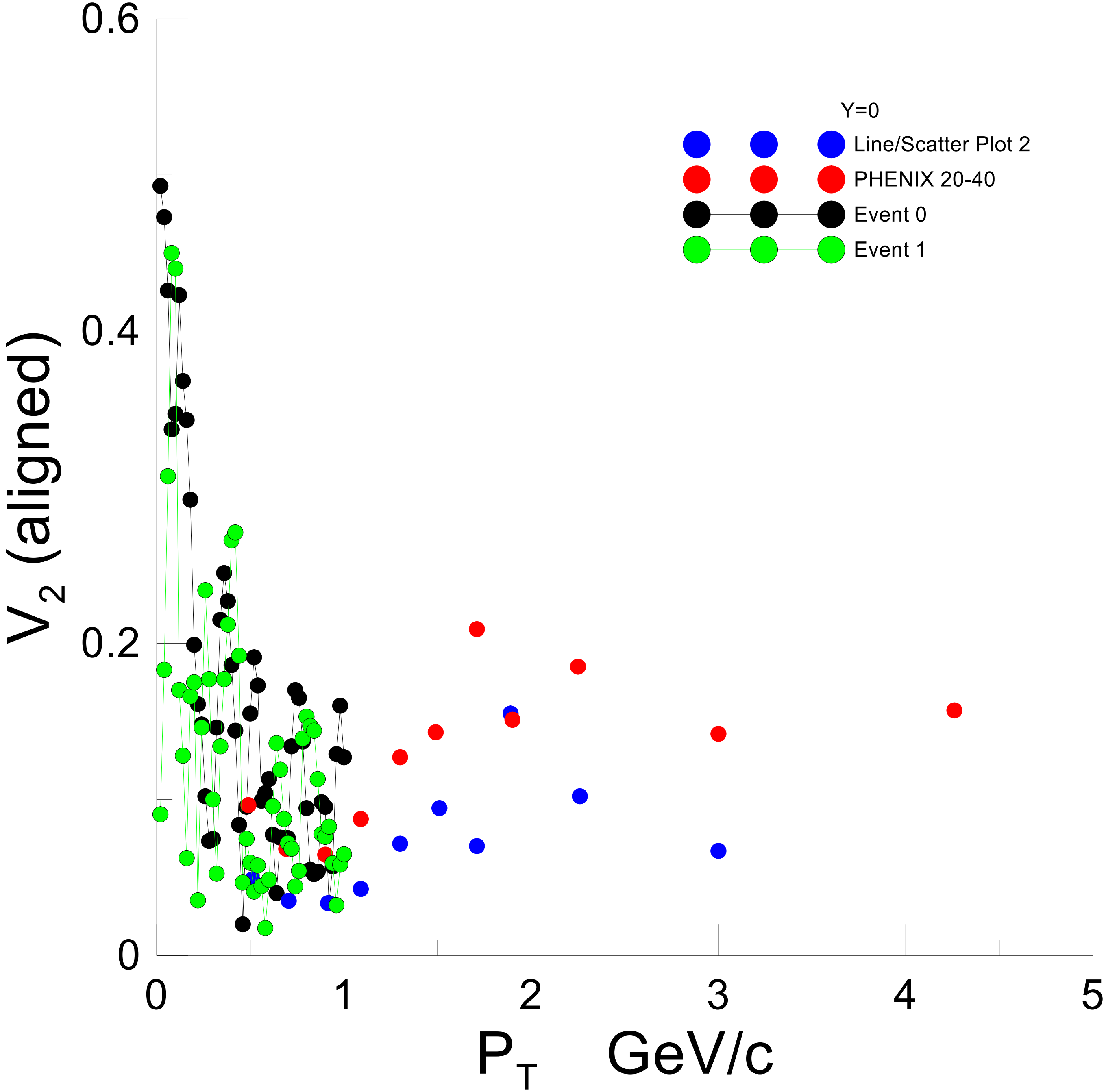


T=2.0 fm

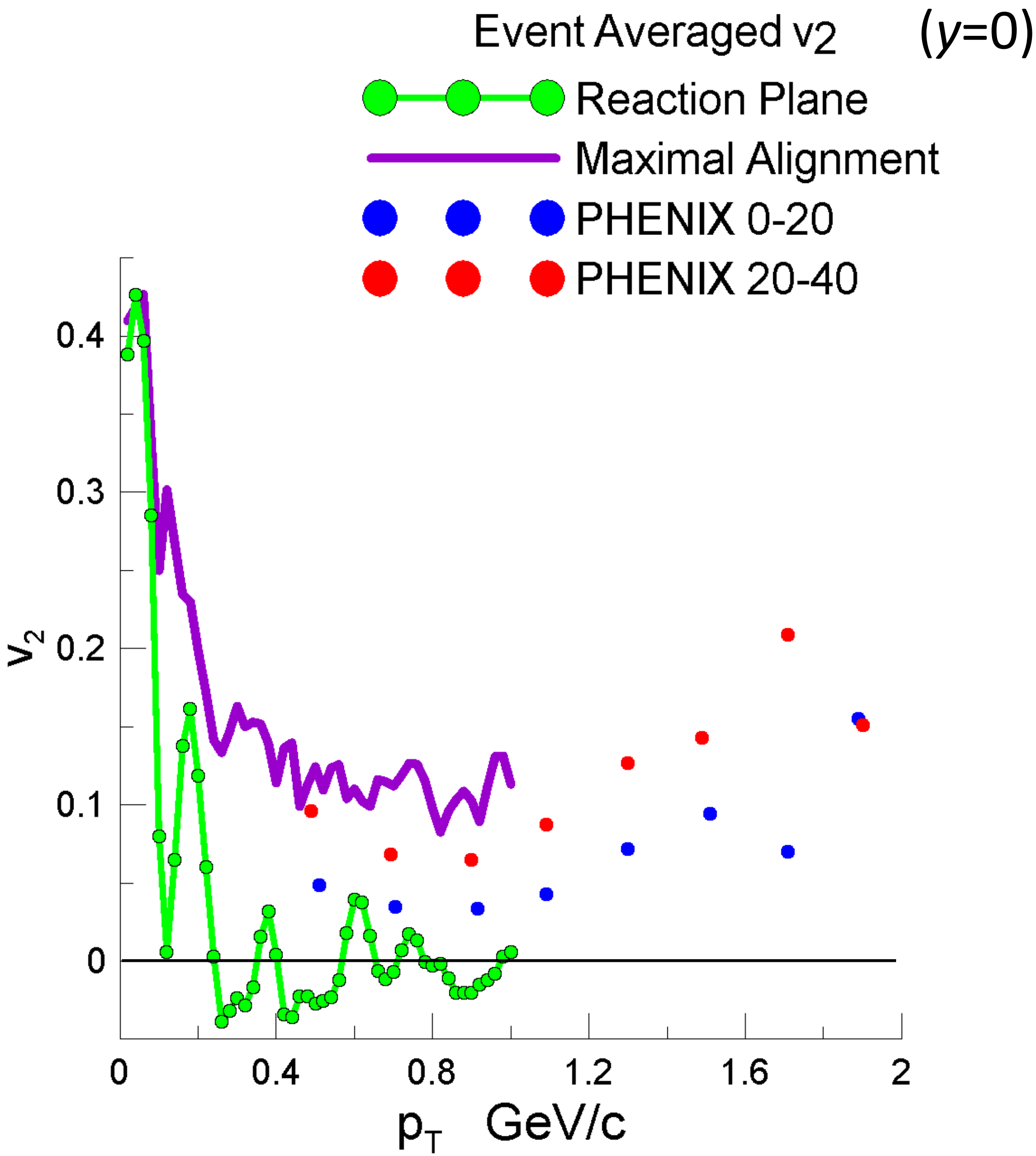

z profile of the current of Event 0
t=1.4 fm
t=1.6 fm
t=1.8 fm
t=2.0 fm
0.2
0.1
0
-0.1
-0.2
-0.3
-8
-4
0
4
8
$J_z(-2,1,z,t)$
z fm



0.5
0.4
0.3
0.2
0.1
0
v_2
0
1
2
3
4
5
p_T GeV/c



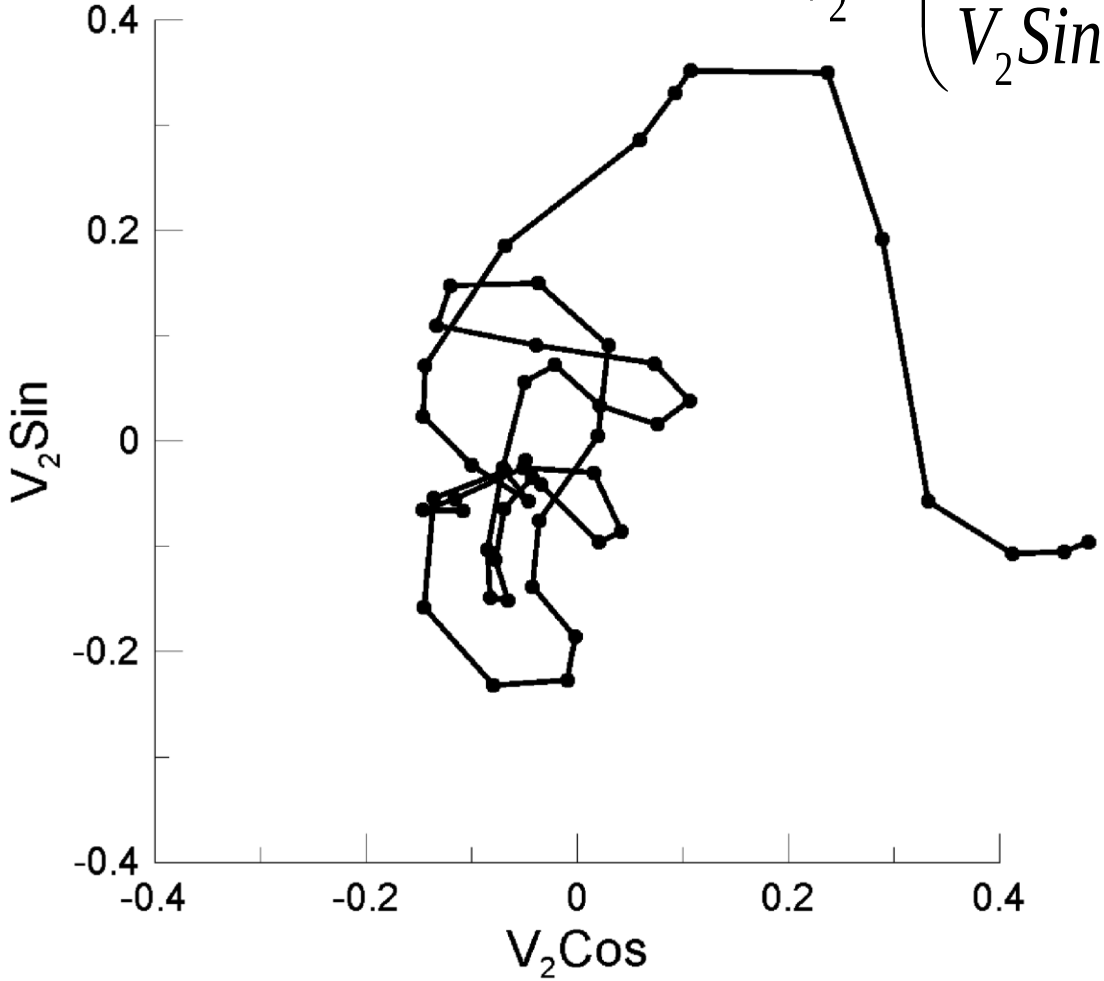
Y=0
Line/Scatter Plot 2
PHENIX 20-40
Event 0
Event 1
V2 (aligned)
PT GeV/c
0
0.2
0.4
0.6
0
1
2
3
4
5



Event Averaged v2 (y=0)
Reaction Plane
Maximal Alignment
PHENIX 0-20
PHENIX 20-40
v2
0.4
0.3
0.2
0.1
0
0
0.4
0.8
1.2
1.6
2
pT GeV/c

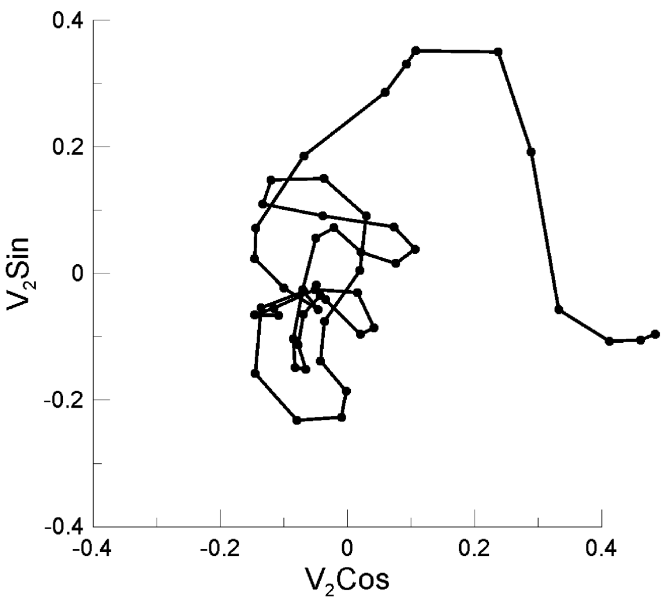
Change of $\mathbf{v}_2$ vector as function of energy

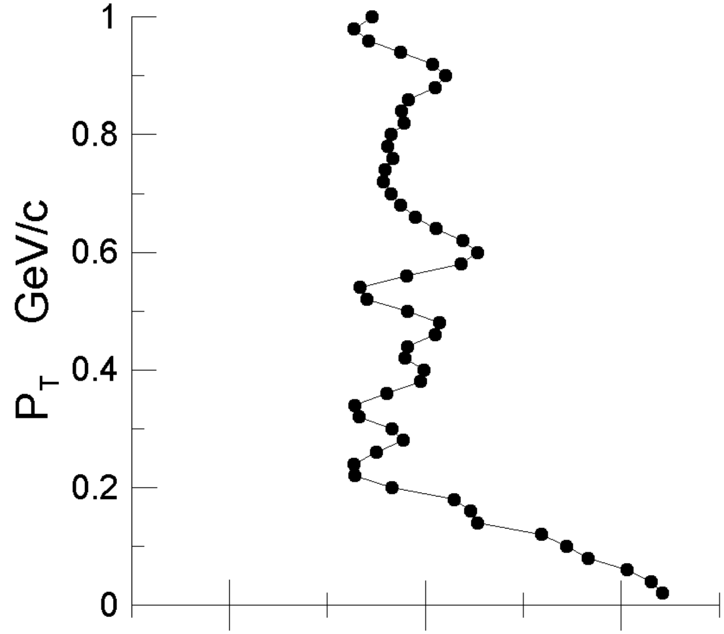
$$\vec{v}_2 = \begin{pmatrix} V_2Cos \\ V_2Sin \end{pmatrix} = \begin{pmatrix} \langle \cos(2\phi) \rangle \\ \langle \sin(2\phi) \rangle \end{pmatrix}$$



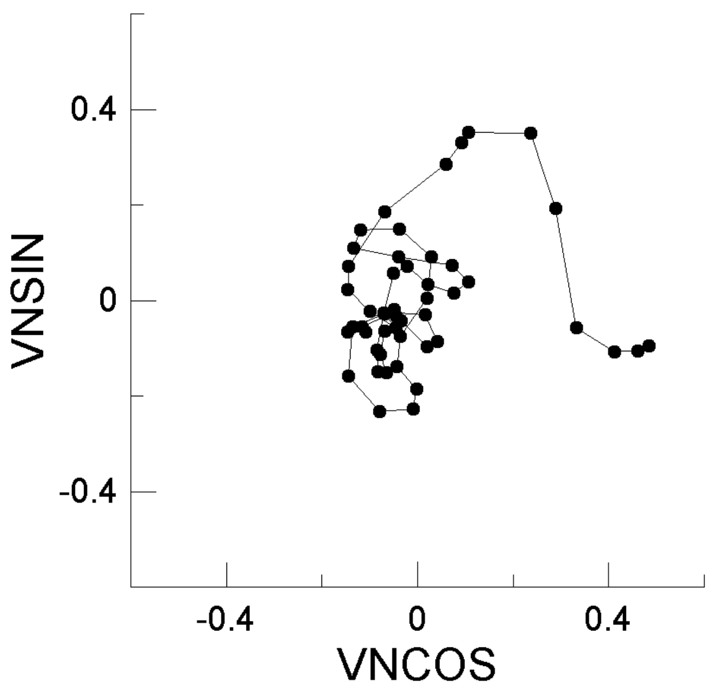
Change of $\mathbf{v}_2$ vector as function of energy

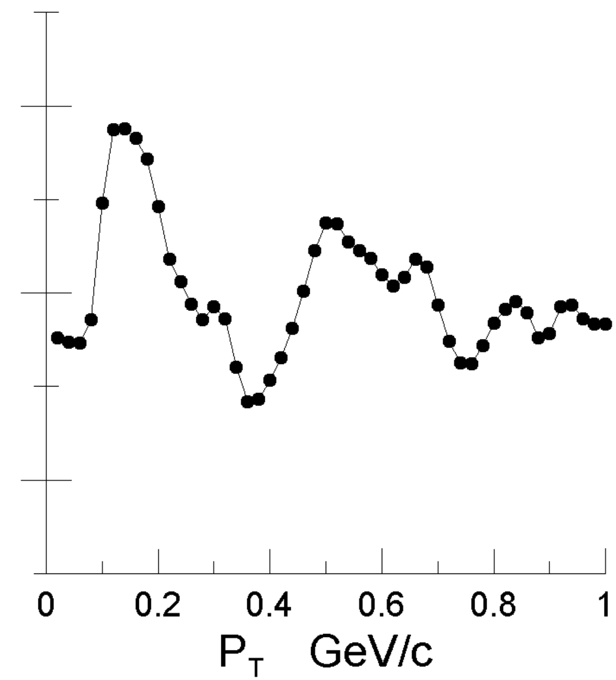
$$\vec{v}_2 = \begin{pmatrix} V_2 Cos \\ V_2 Sin \end{pmatrix} = \begin{pmatrix} \langle \cos(2\phi) \rangle \\ \langle \sin(2\phi) \rangle \end{pmatrix}$$



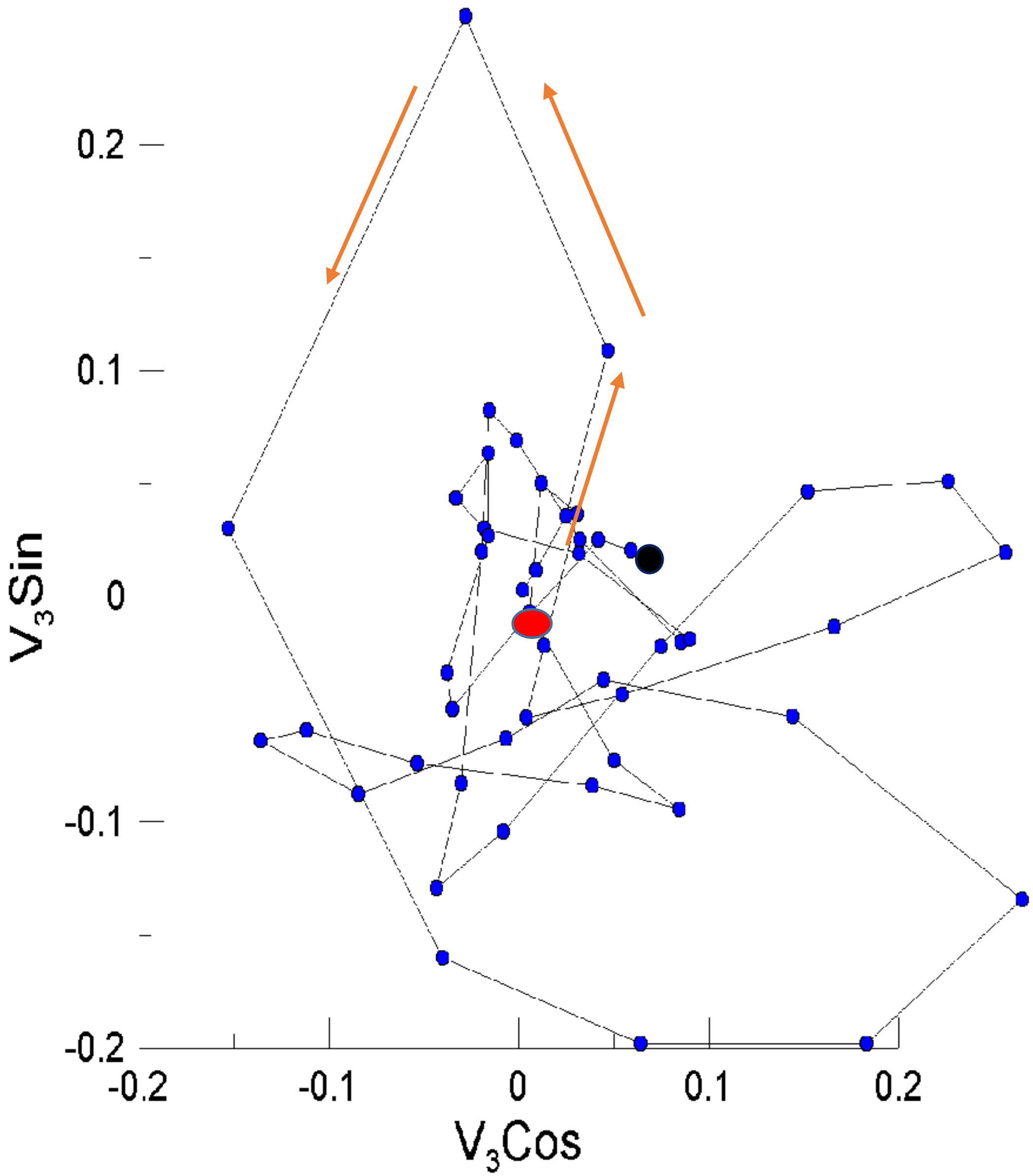


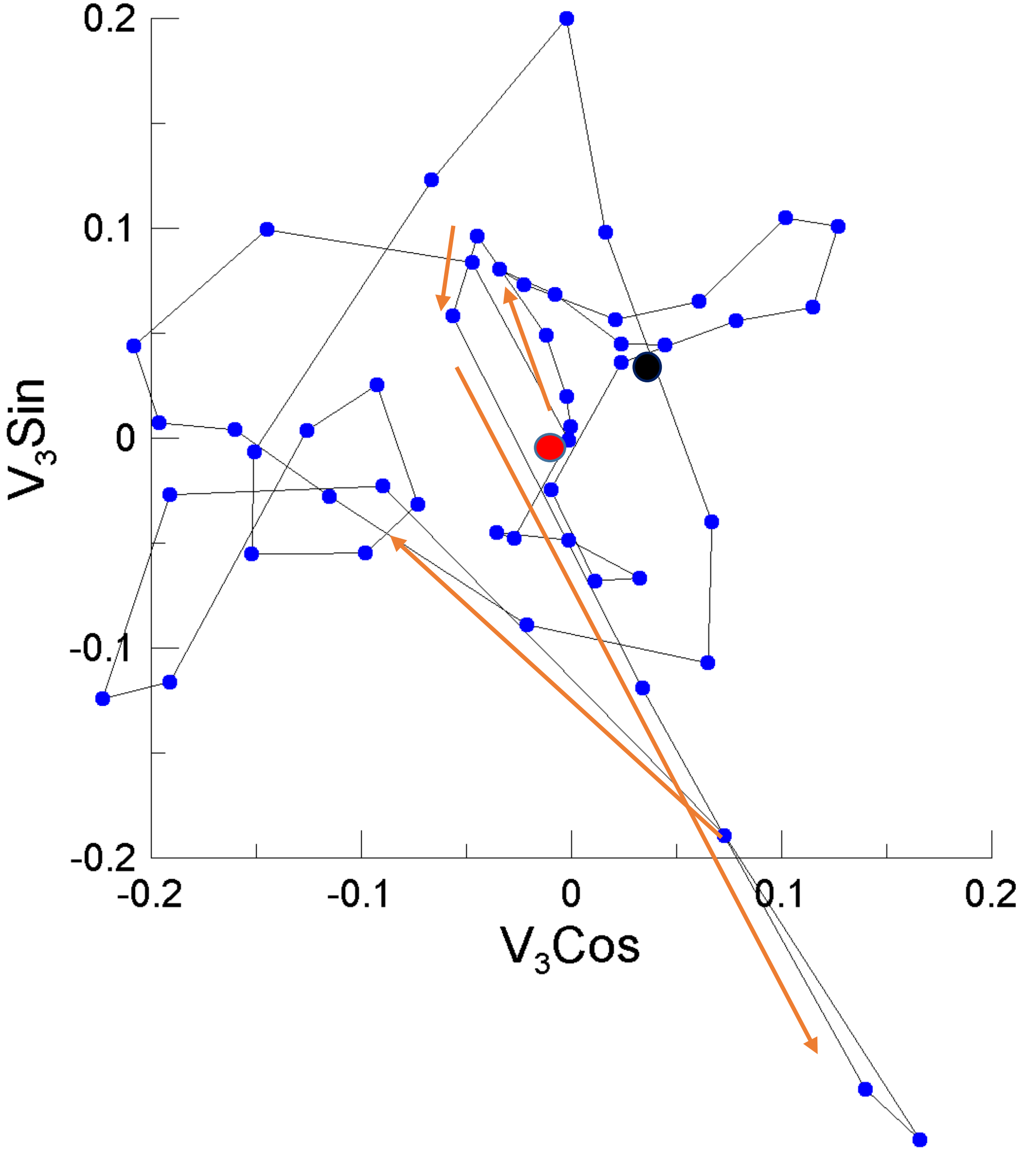
$$\vec{v}_2 = \begin{pmatrix} V_2 Cos \\ V_2 Sin \end{pmatrix} = \begin{pmatrix} \langle \cos(2\phi) \rangle \\ \langle \sin(2\phi) \rangle \end{pmatrix}$$



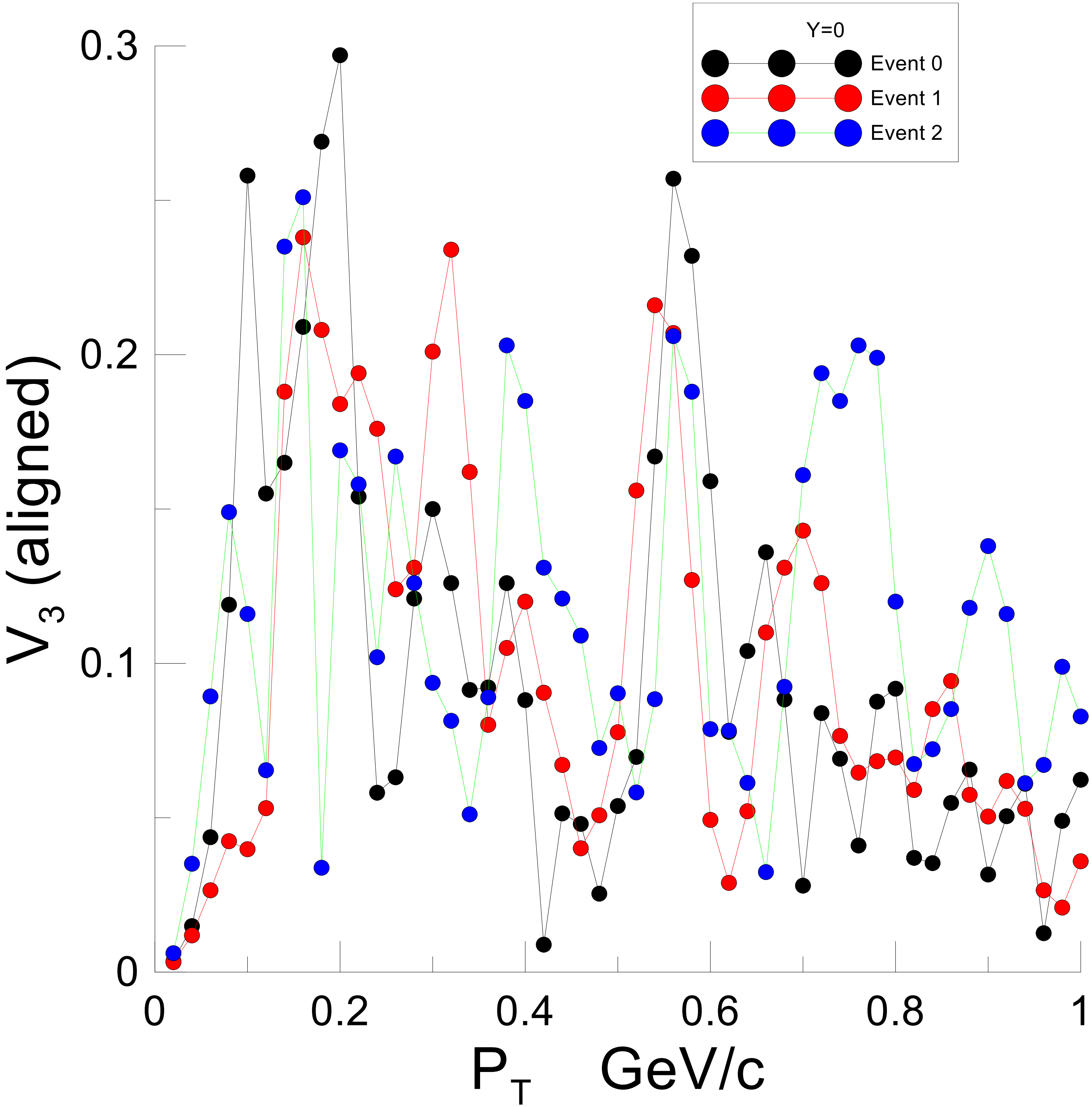


Similar behavior in V_3 …

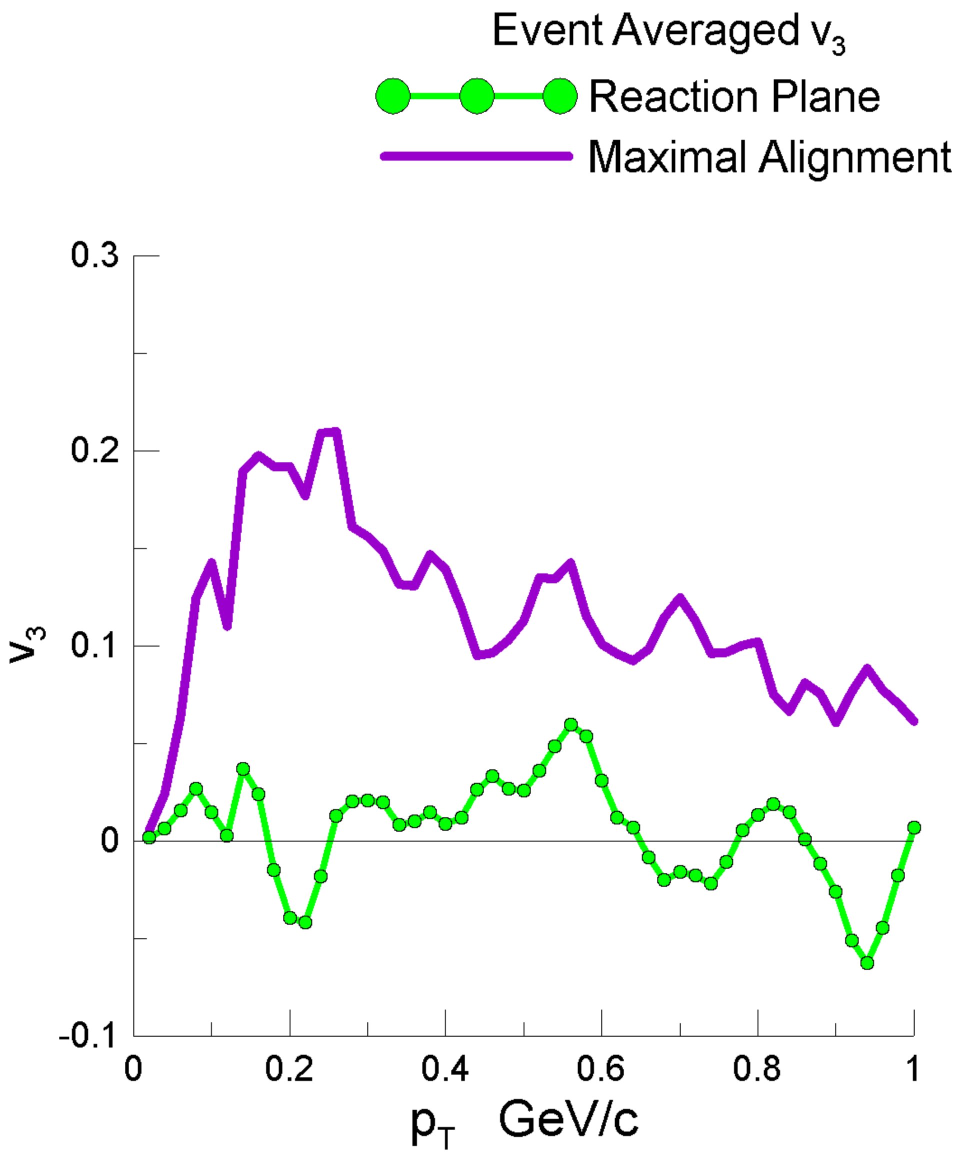

0.2
0.1
0
-0.1
-0.2
V_3Sin
-0.2
-0.1
0
0.1
0.2
V_3Cos



0.2
0.1
0
-0.1
-0.2
V3Sin
-0.2
-0.1
0
0.1
0.2
V3Cos

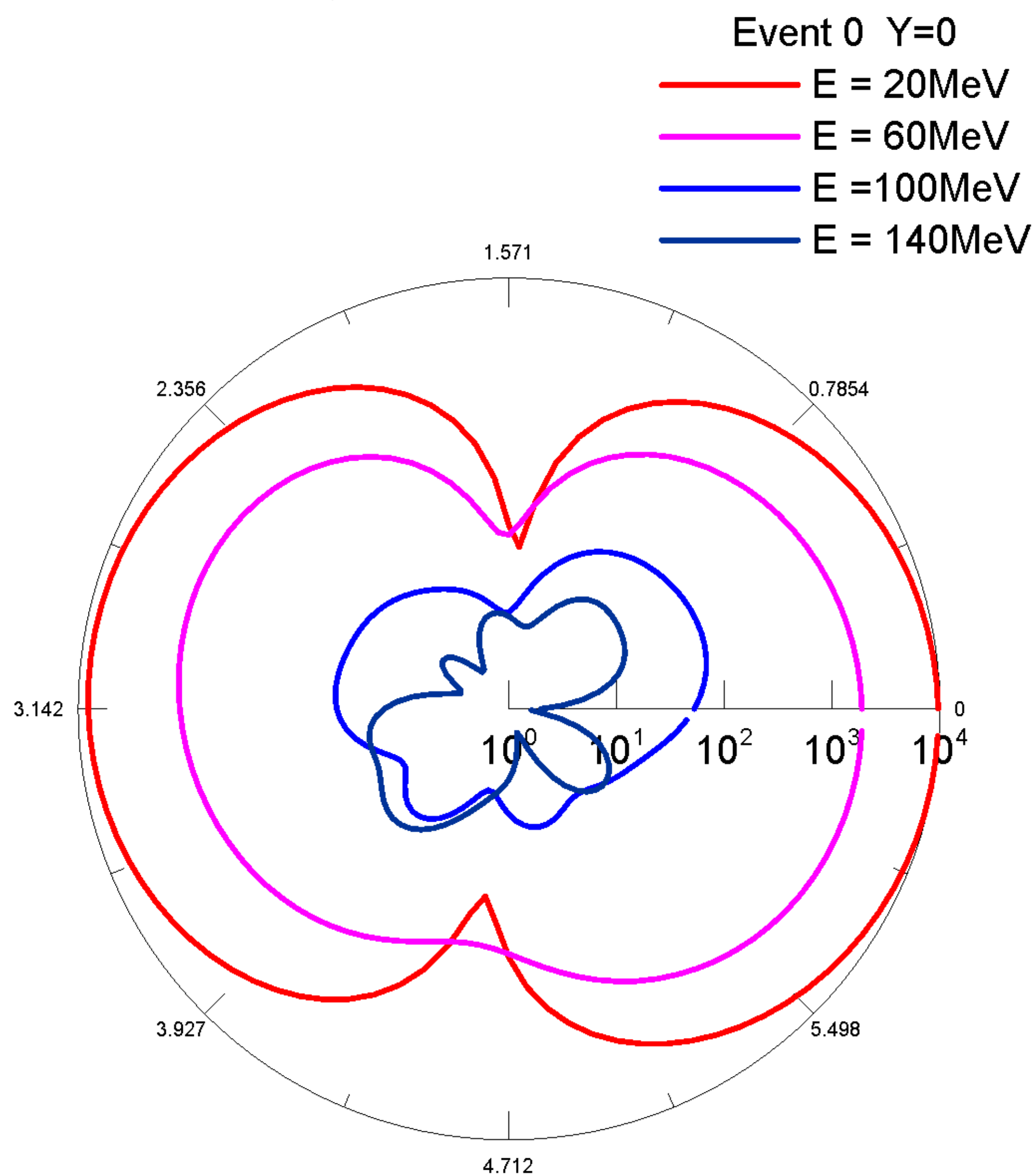


Y=0
Event 0
Event 1
Event 2
0.3
0.2
0.1
0
V_3 (aligned)
0
0.2
0.4
0.6
0.8
1
P_T GeV/c

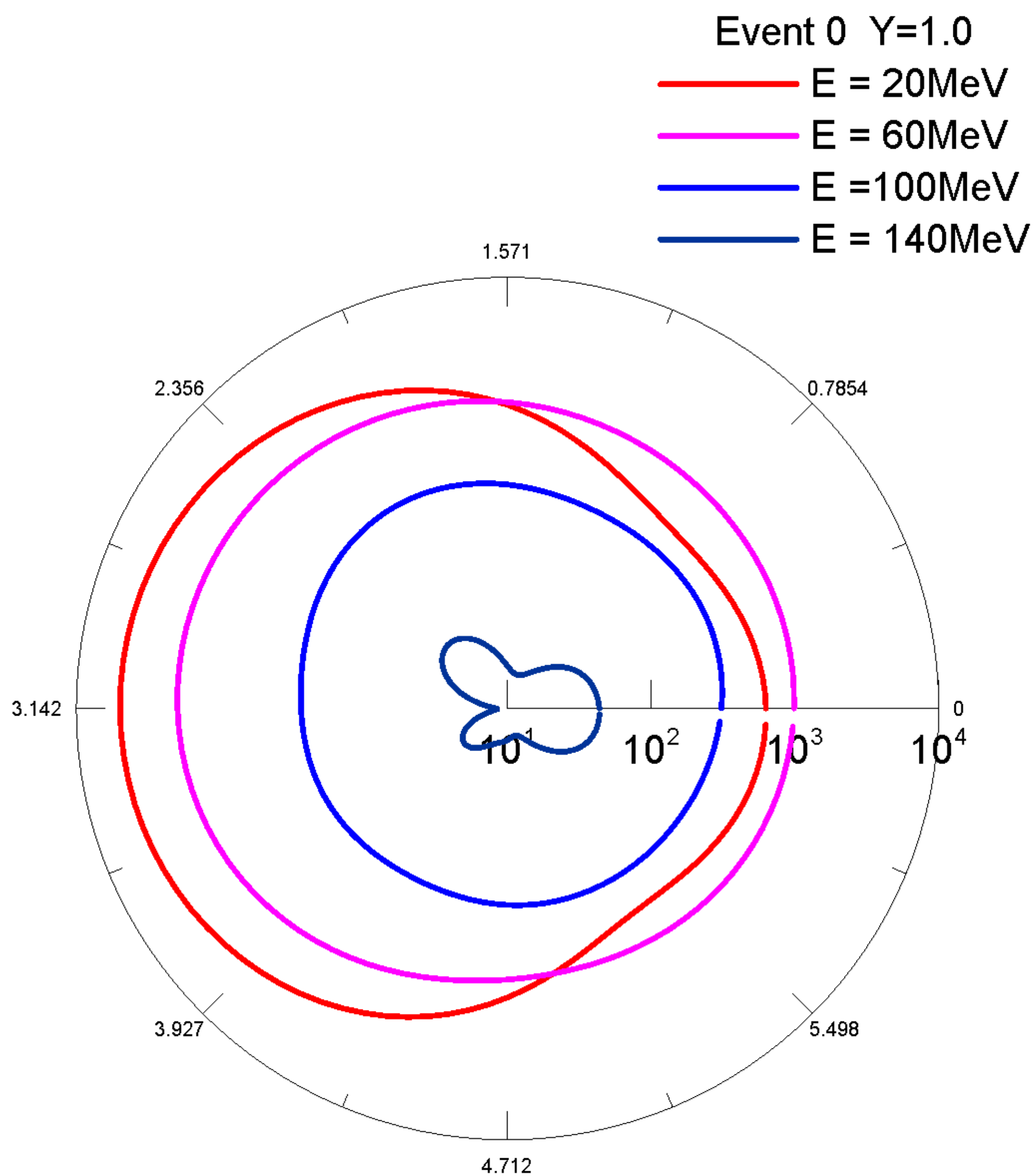


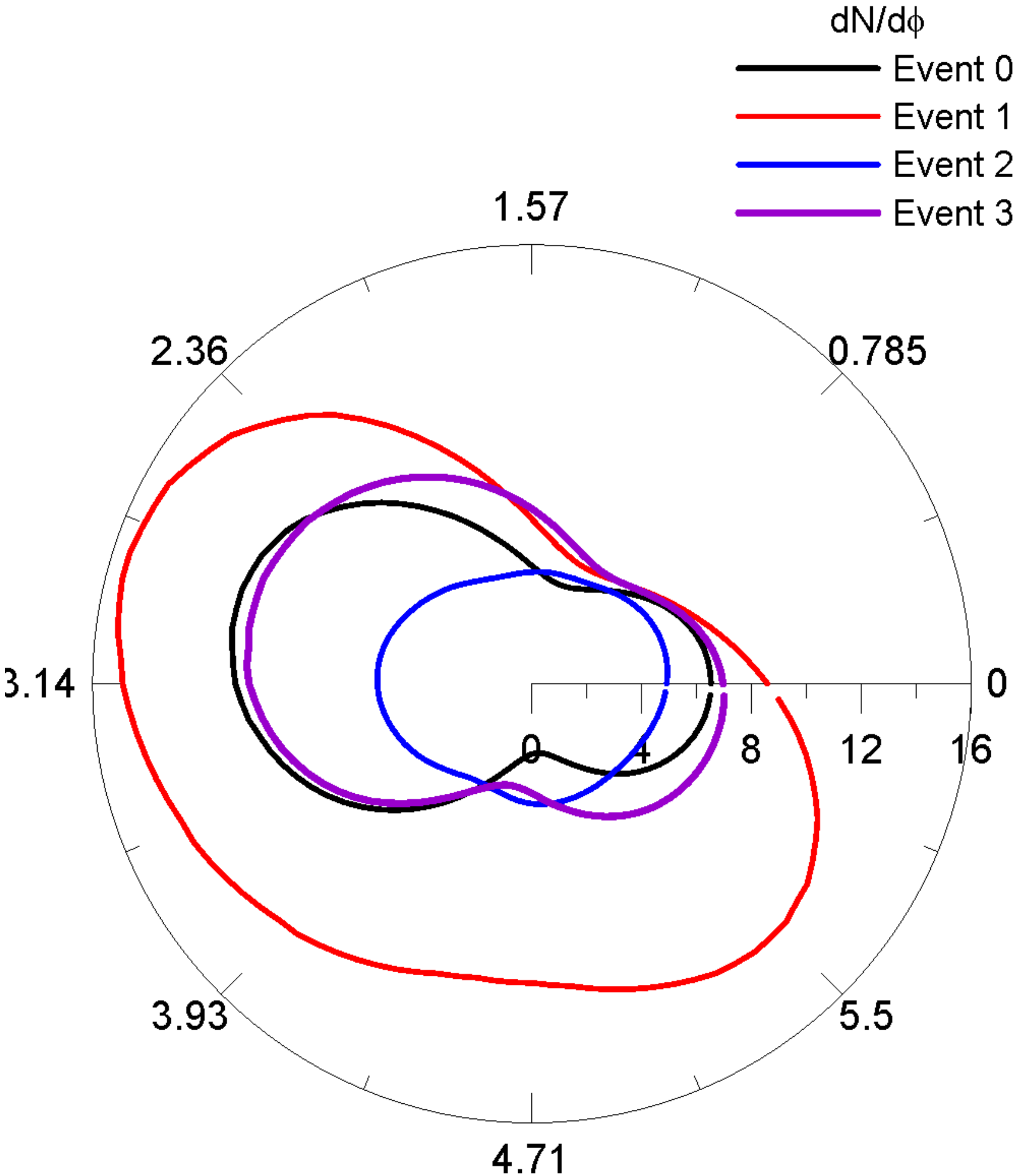
Event Averaged v_3
Reaction Plane
Maximal Alignment
0.3
0.2
0.1
0
-0.1
v_3
0
0.2
0.4
0.6
0.8
1
p_T GeV/c

Azimuthal Angular distribution at y=0

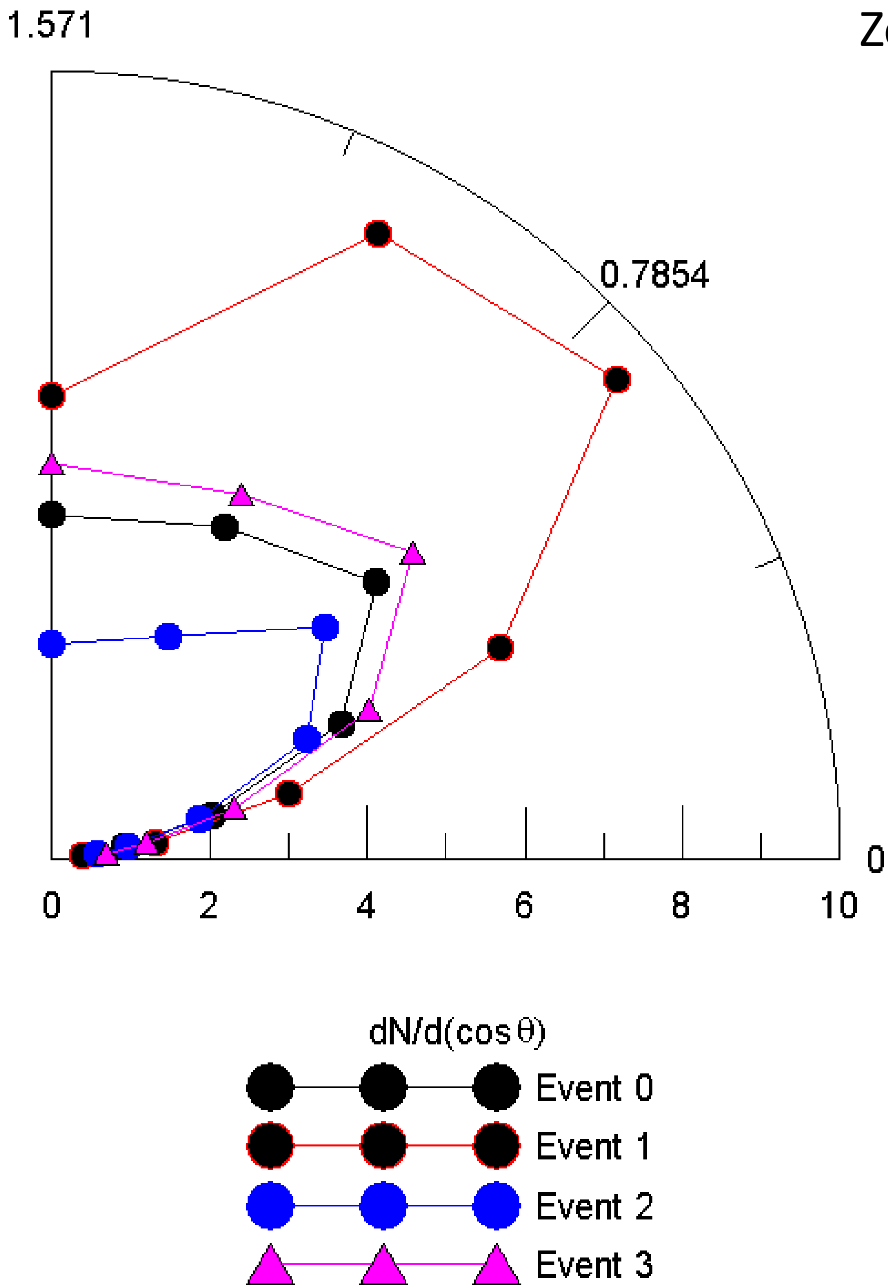


Azimuthal Angular distribution at y=1.0



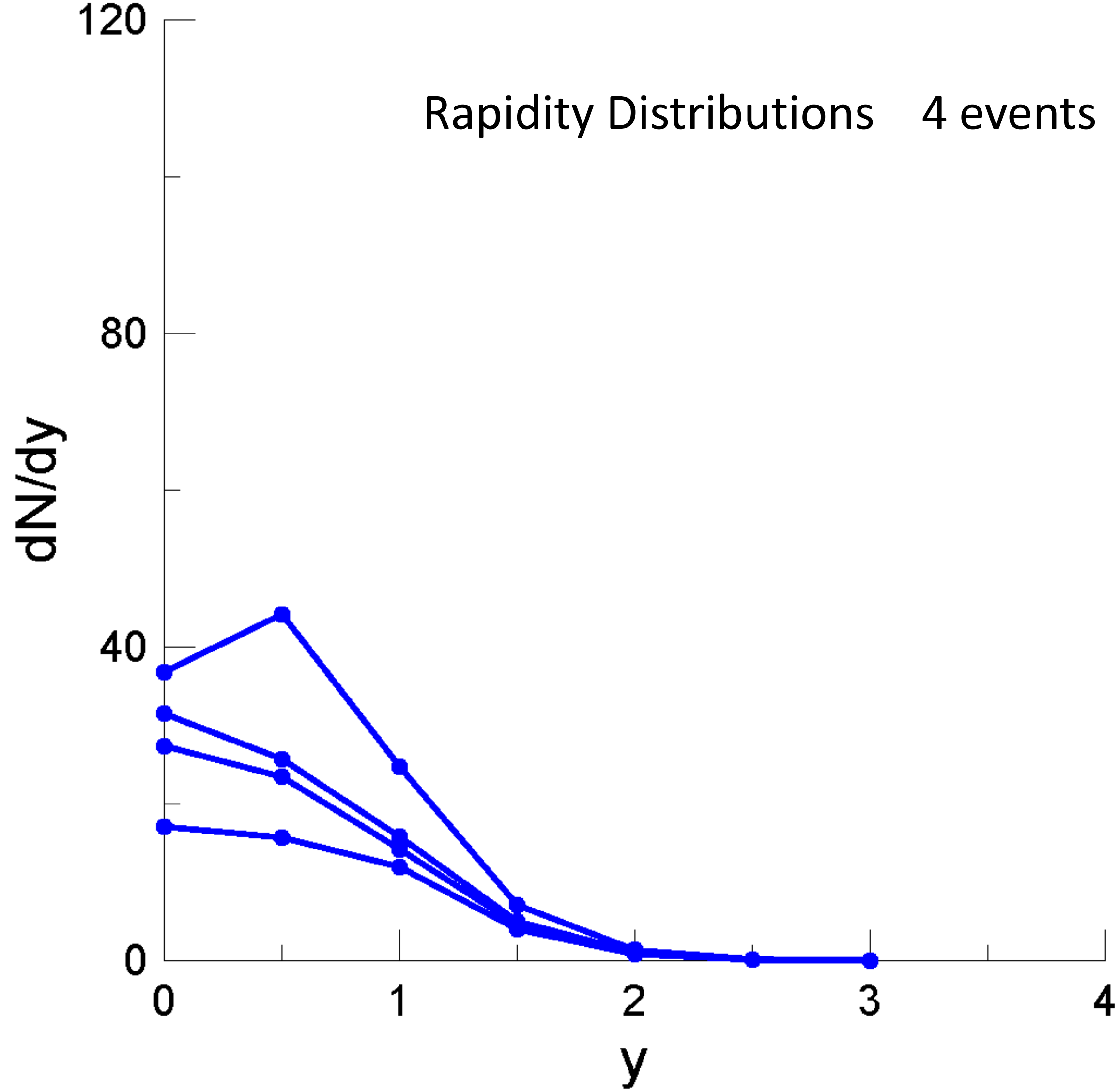

dN/dϕ
Event 0
Event 1
Event 2
Event 3
1.57
2.36
0.785
3.14
0
3.93
4.71
5.5
0
4
8
12
16

Zenith angle distribution (forward)

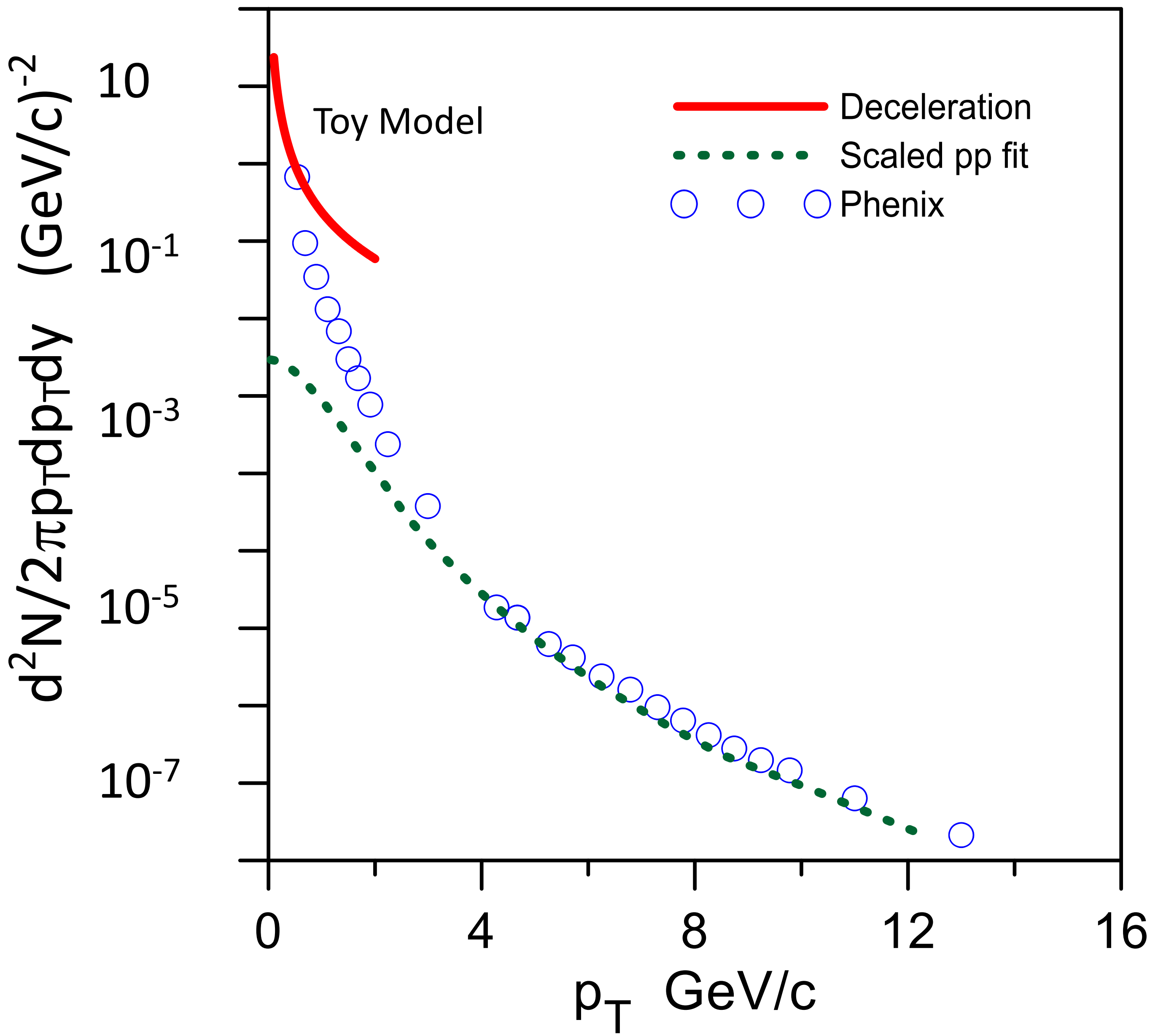


$$\sin\theta = \frac{1}{\cosh y},$$

$$\tan\theta = \sin y.$$


Rapidity Distributions 4 events
dN/dy
y
0
40
80
120
0
1
2
3
4

p_T Spectrum

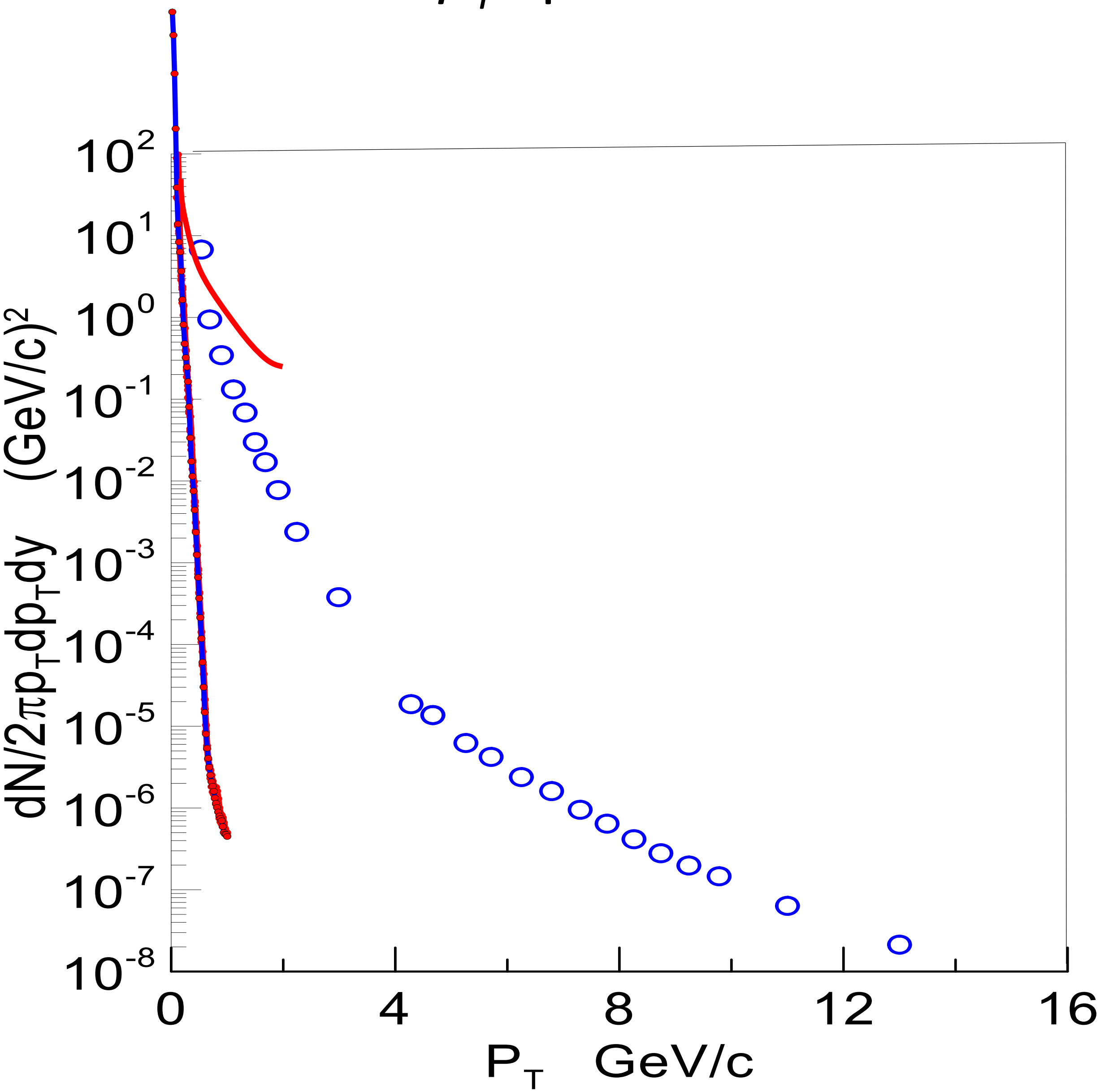


$$V_0 \approx 1,$$

$$Z_{eff} \approx 80,$$

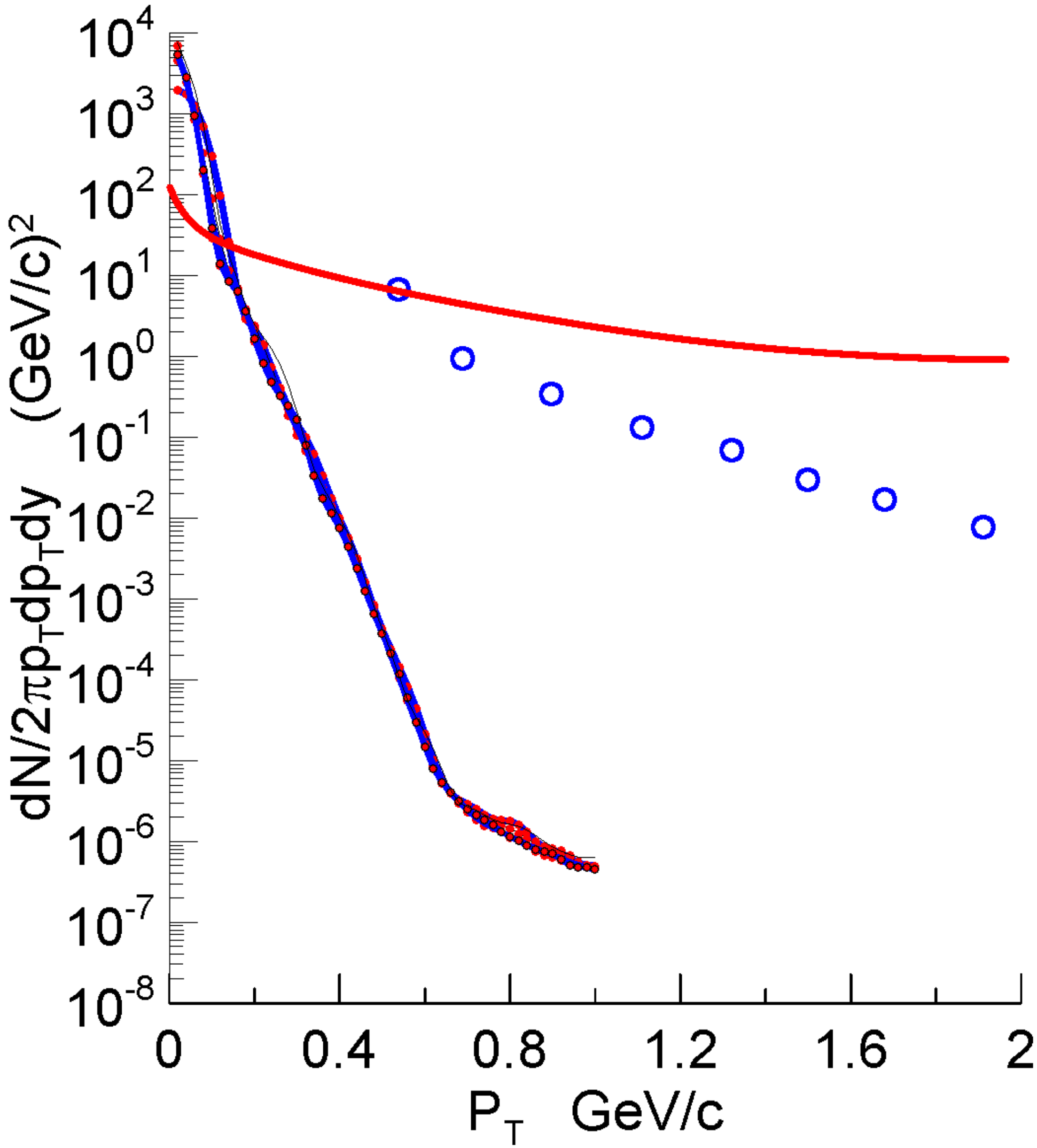
$$d \approx 1\,fm$$

p_T Spectrum

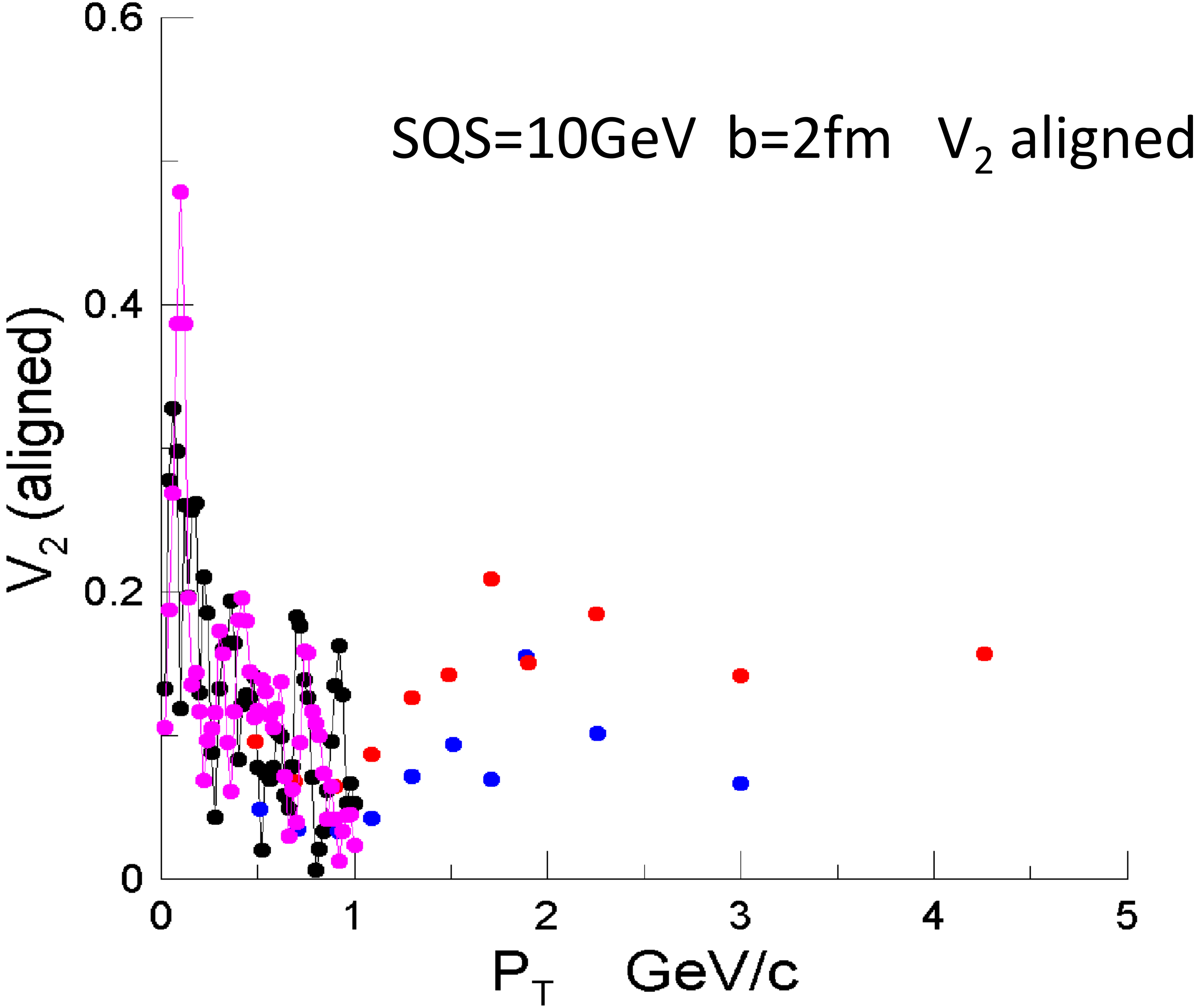


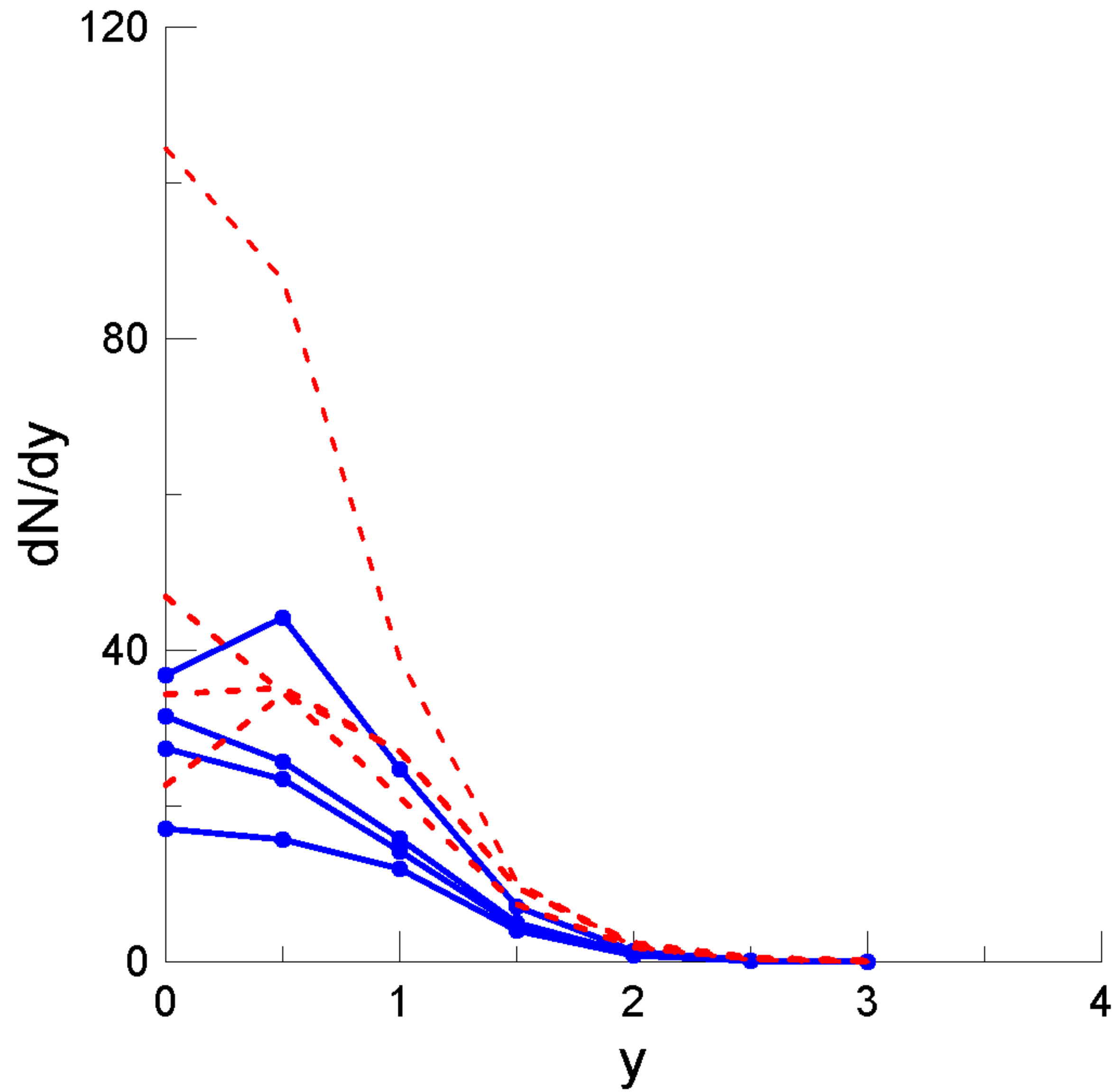
dN/2πp_Tdp_Tdy (GeV/c)^2
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
0
4
8
12
16
P_T GeV/c

p_T Spectrum

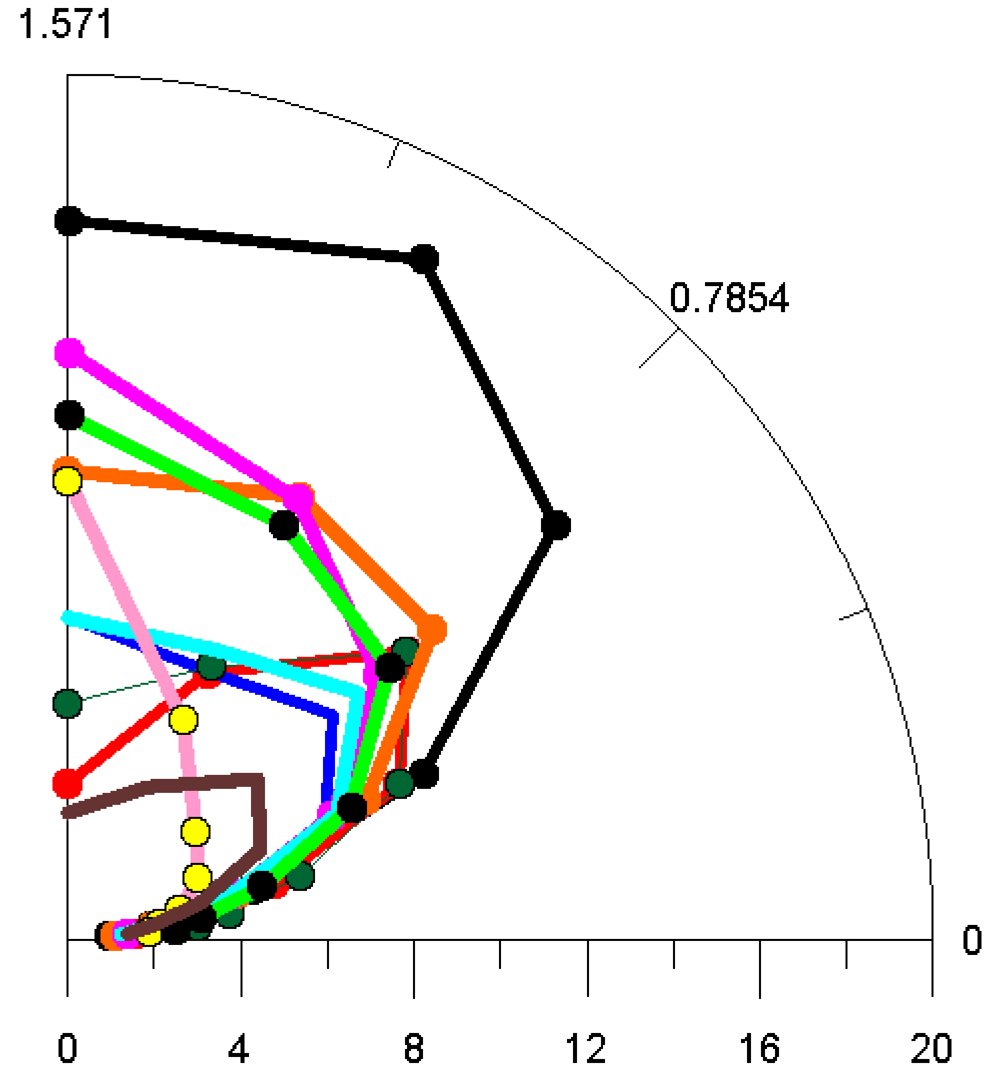


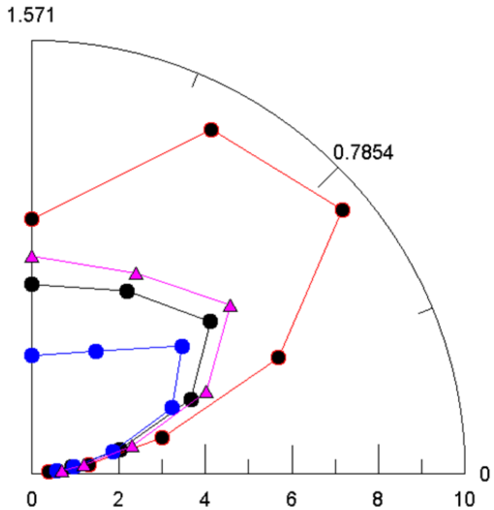
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
$dN/2\pi p_T dp_T dy \quad (GeV/c)^2$
0
0.4
0.8
1.2
1.6
2
P_T GeV/c


SQS=10GeV b=2fm V_2 aligned
V_2 (aligned)
0.6
0.4
0.2
0
0
1
2
3
4
5
P_T GeV/c

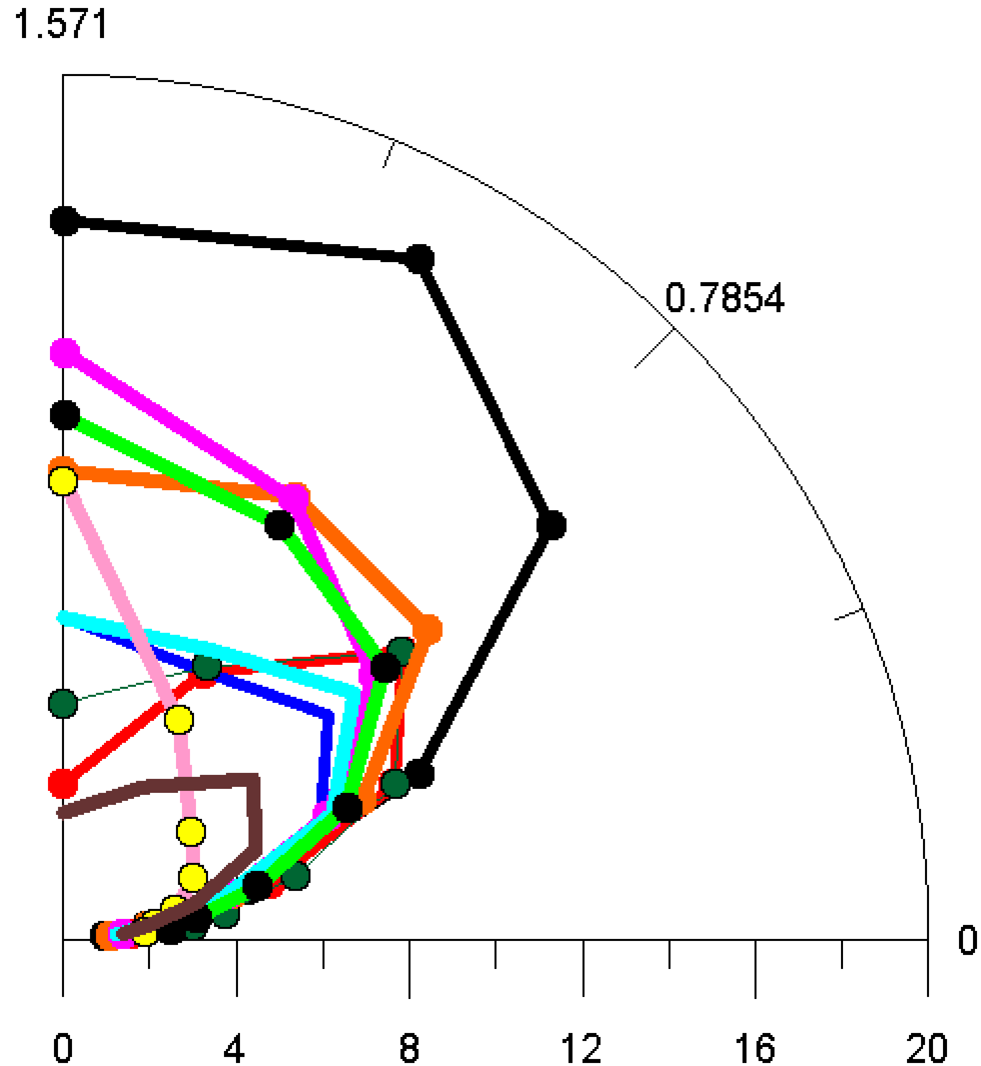


120
80
40
0
dN/dy
0
1
2
3
4
y


1.571
0.7854
0
0
4
8
12
16
20



1.571
0.7854
0
0
2
4
6
8
10



1.571
0.7854
0
0
4
8
12
16
20

Summary

- The classical electromagnetic fields radiated by the deceleration process of relativistic heavy ions were re-examined.
- A toy model and more sophisticated JAM simulations show a similar prediction for the v_2 anisotropy parameter, indicating that the photons from the charge decelation (or stopping) process reflects very well the initial state in the EbyE basis.
- If the increase of v_2 in PHENIX data for lower p_T really tells something, we may think of some coherent (collective) deceleration mechanism of the incident charges.
- Indication of large EbyE fluctuations and formation of hot spots in JAM simulation.
- If this this is the case, the classical EM radiation may offer a very interesting approach to determine the collision geometry, baryon stopping, etc..... But,
- Experimental difficulties due to critically low multiplicity (~ 10^2-10^3). A further study is necessary to examine more in detail using different models of the initial condition.

Some Basic Questions

- How to deal with the string dynamics and charge current ?

$$\frac{\partial \vec{J}}{\partial \tau}\left(\vec{\xi},\tau\right)=\frac{\partial}{\partial \tau}\left\langle \psi\left[Strings\right](\tau)\middle|\hat{J}\left(\vec{\xi}\right)\middle|\psi\left[Strings\right](\tau)\right\rangle$$

- How does the coarse-graining scale influence ?

ขอขอบคุณ !