Brick Problem:
Jet Quenching and Mach Cone

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With B. Mueller and S. Bass

Short introduction to PARTON CASCADE

1. We have N classical particles (partons on mass shell) in phase space (position and momentum)
2. They will evolve under the influence of nearby particles (or internal forces) and/or external field
3. Occasionally they will come close to each other and make scatterings (phase space and number of particles changing)
4. They move on with new momentum after collision

-> NOTHING NEW BUT PUT SOMETHINGS TOGETHER TO UNDERSTAND PHYSICS

1. BRICK problem

- HOW DO WE KNOW THE PROPERTIES of QGP? (Temperature, Volume, Entropy, …)
  → Well controlled experiments or simulations to setup standards
  → Strongly pushed by Berndt Mueller

- QGP at temp T in a BOX and Pass a JET (high energy parton) through the QGP – JET Quenching
- Investigate the JET and response of the QGP: Ideal tool for this study is HYDRODYNAMICS with JET (DUKE GROUP works on the problem)
- But let us try with PCS(Parton Cascade Simulation)

2. Initial STATE: Gluon Plasma

- Phase Space Distribution: Bose-Einstein

$$f(\vec{r}, \vec{p}) = C \frac{1}{e^{\beta E} - 1}$$

- Box Size: $V = L_x L_y L_z$

a. Number Density: $$n(T) = \frac{16}{\pi^2} \varsigma(3) T^3$$

b. Energy Density: $$\varepsilon(T) = \frac{48}{\pi^2} \varsigma(4) T^4$$

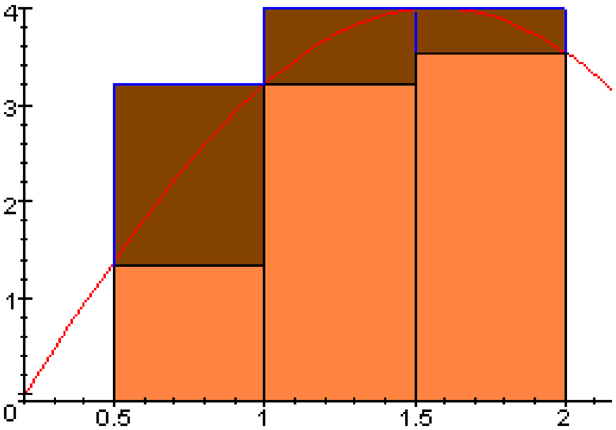
c. Debye Mass: $$\mu_D{}^2 = \frac{24}{\pi} \alpha_s T^2 \varsigma(2)$$

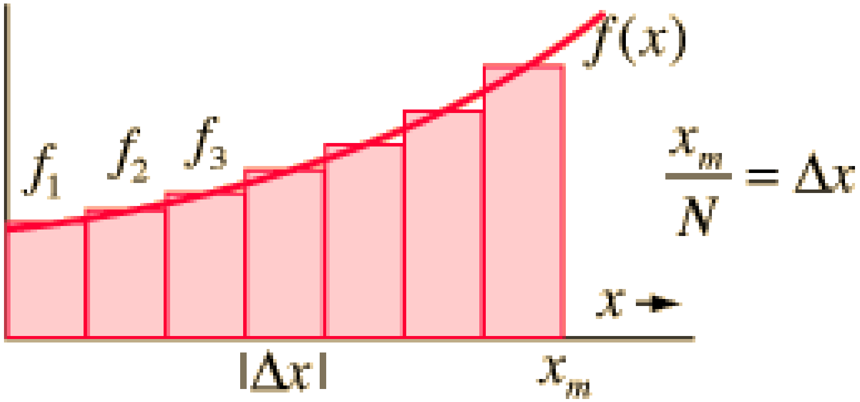
(Monte Carlo Sampling)

- Integral Method:

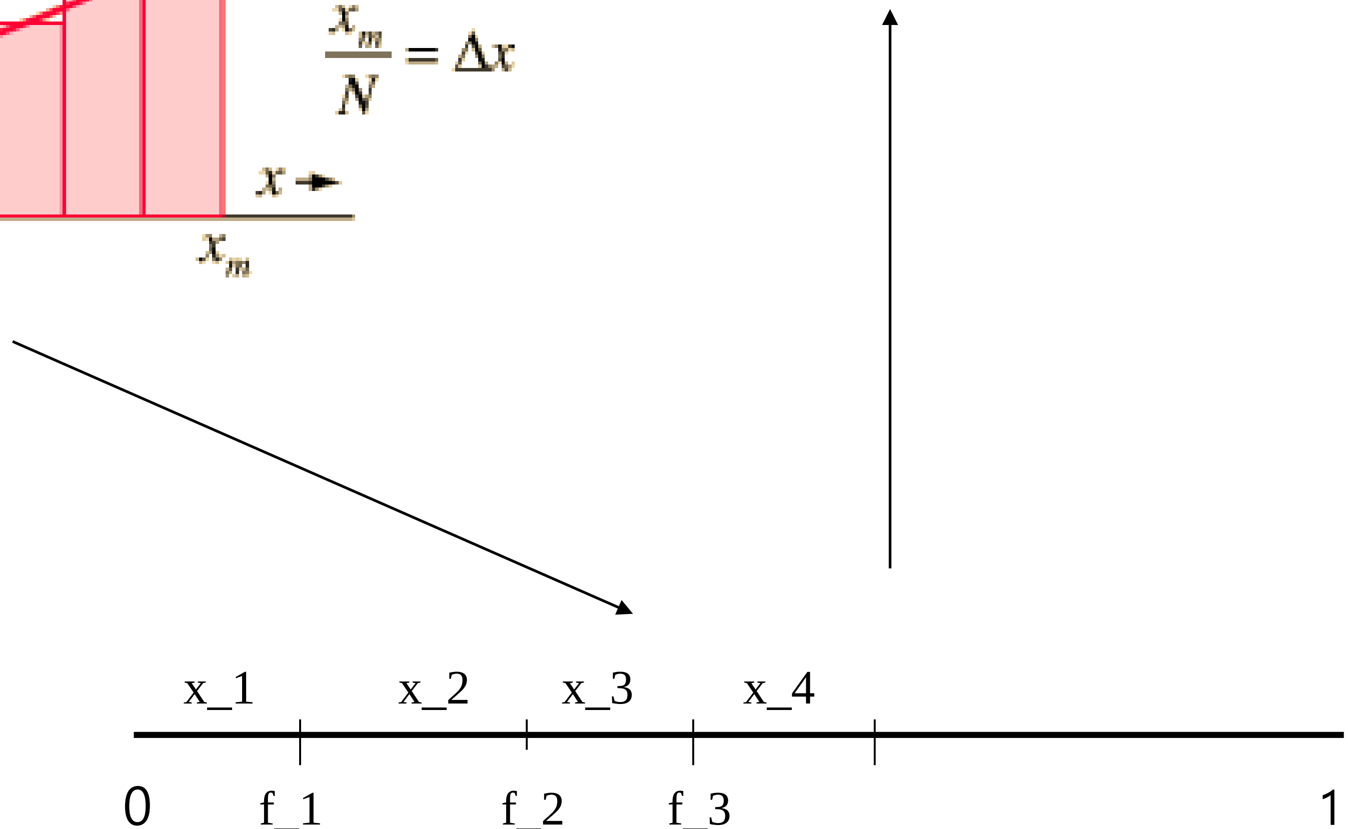
$$r = \int_{x_0}^{x} f(x')dx'$$

- Dart Method:





$$r = \int_{x_0}^{x} f(x')dx'$$



3. Cross Section

We consider only gg ←→ gg, gg → ggg

- 2->2:

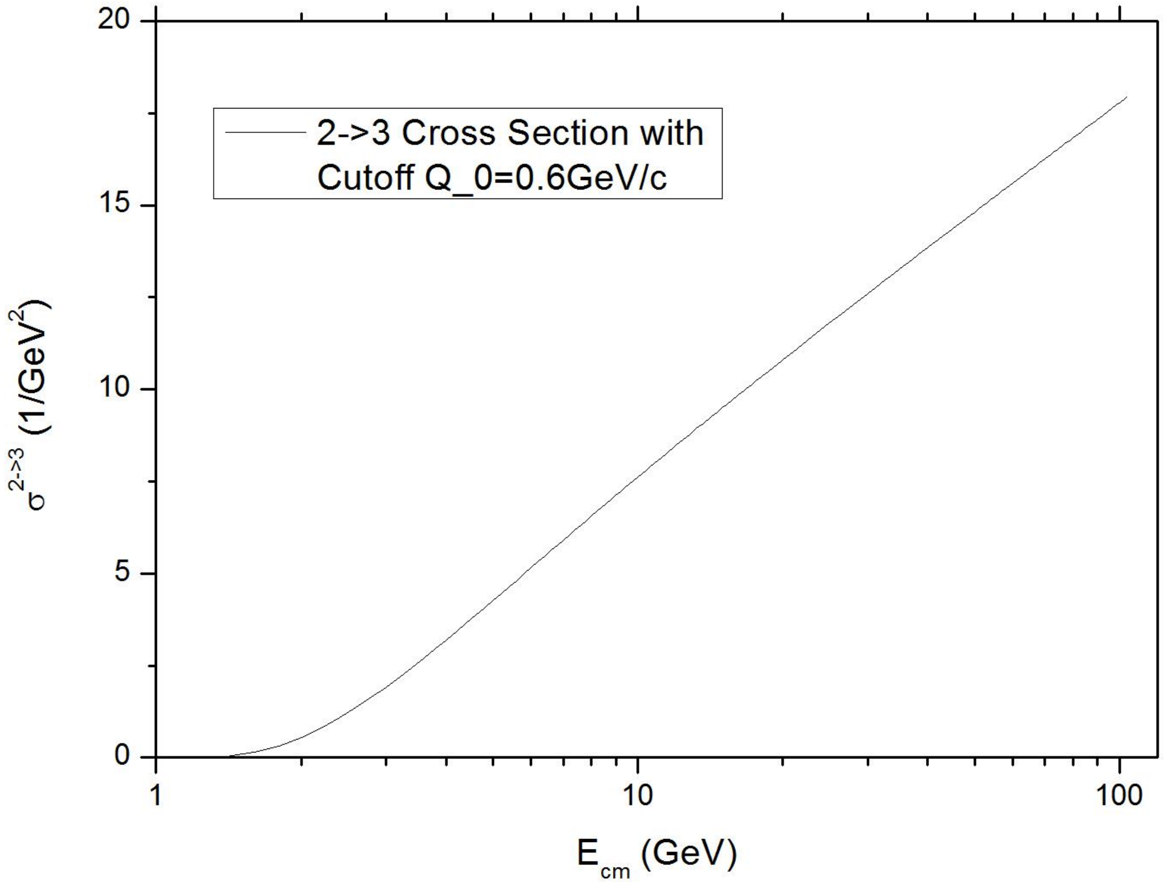
$$\frac{d\sigma}{dq_\perp^2} = \frac{9\pi\alpha^2}{2}\frac{1}{(q_\perp^2 + \mu_D^2)^2}$$

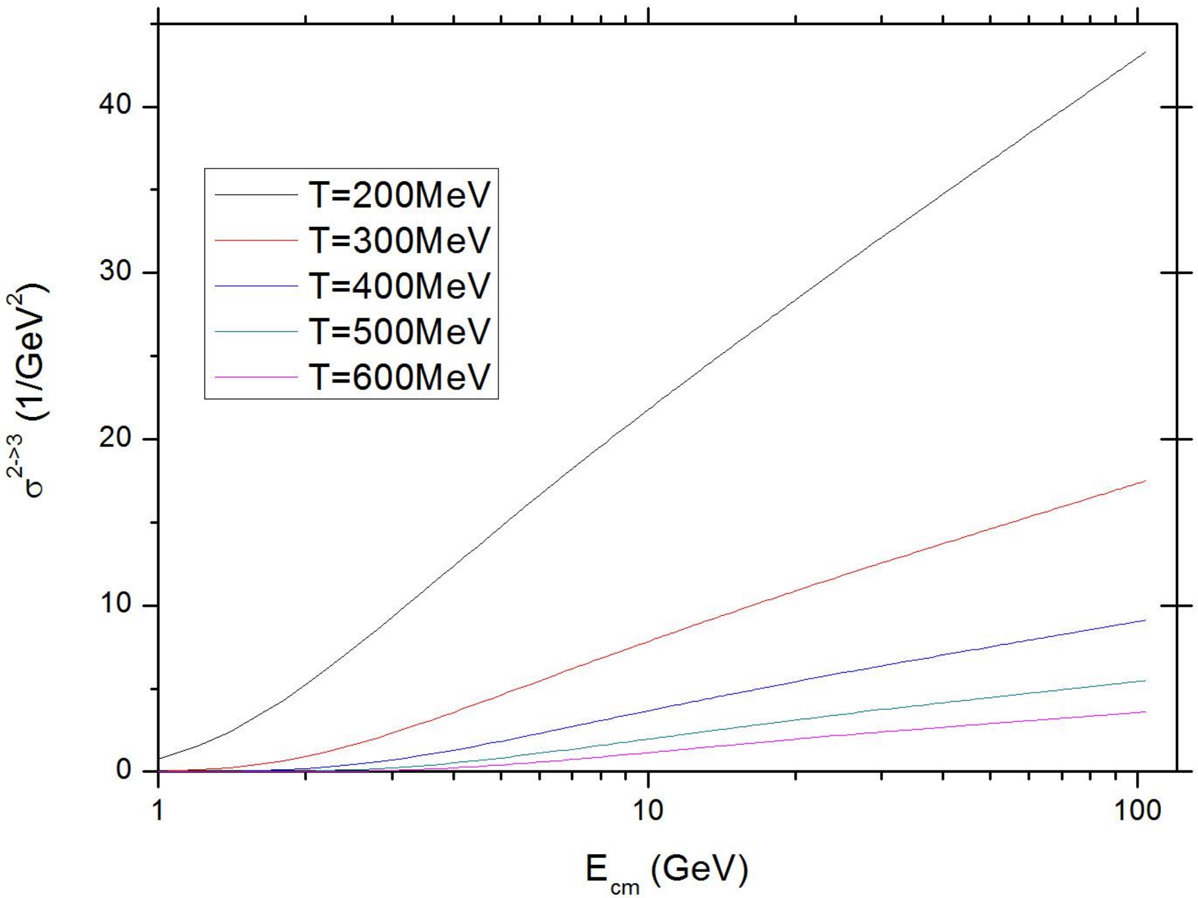
$$\frac{d\sigma}{dt} = \frac{9\pi\alpha^2}{2s^2}\left(3 - \frac{tu}{s^2} - \frac{us}{t^2} - \frac{st}{u^2}\right)$$

- 2->3:

$$\frac{d\sigma}{d^2q_\perp dy d^2k_\perp} = \frac{9N_c\alpha^3}{2\pi}\frac{q_\perp^2}{(q_\perp^2 + \mu_D^2)^2}\frac{1}{k_\perp^2(\vec{q}_\perp - \vec{k}_\perp)^2}\Theta\left(\frac{E_{cm}}{2} - k_\perp \cosh y\right)$$

NOTE: 10/GeV^2=4mb




T=200MeV
T=300MeV
T=400MeV
T=500MeV
T=600MeV
$\sigma^{2\to3}$ (1/GeV^2)
E_{cm} (GeV)
0
10
20
30
40
1
10
100

4. The Properties of JET

A. Only ELASTIC SCATTERING:

1. Energy Loss:

- Impressive Calculation by Duke Group, including medium response to the fast parton based on Kinetic Theory by Asakawa, Bass and Mueller and by Neufeld and Mueller:

- Collisional Dynamics Calculation:

$$\frac{dE}{dx} = [\text{Incident Flux}][\text{Target Density}][\text{Cross Section}][\Delta E]$$

$$= 3\pi\alpha^2 T^2 \ln\frac{\nu_{\max}}{\nu_{\min}}, \quad \text{or } = 3\pi\alpha^2 T^2 \ln\frac{E_{cm}{}^2}{2\mu^2}$$

= 1.42 GeV/fm, or 3.32 GeV/fm, E=100GeV and T=400MeV
= 1.25 GeV/fm, or 2.98 GeV/fm, E= 60GeV and T=400MeV

Note the average CM energy between Jet and a medium particle:

$$E_{cm} = \frac{1}{\rho} \int \frac{d^3k}{(2\pi)^3} (2EE_k - 2\vec{p} \cdot \vec{k})^{1/2} f_{Bose}(\vec{k}, T)$$
$$= \frac{5\varsigma(3.5)}{4\varsigma(3)} (\pi E T)^{1/2}$$

For example,

E_cm = 7.2 GeV, E= 30GeV on T=0.4GeV
= 10.2 GeV, E= 60GeV on T=0.4GeV
= 13.1 GeV, E=100GeV on T=0.4GeV

- Momentum Transfer squared & Transport Coefficient

$$\hat{q} = \rho \int dq_\perp{}^2 q_\perp{}^2 \frac{d\sigma}{dq_\perp{}^2} = \frac{9}{2}\pi\alpha^2\rho\left[\ln\left(\frac{E_{cm}{}^2 + 4\mu^2}{4\mu^2}\right) - \frac{E_{cm}{}^2}{E_{cm}{}^2 + 4\mu^2}\right]$$

= 2.55 GeV^2/fm, E=100GeV & T=400MeV

= 2.15 GeV^2/fm, E= 60GeV & T=400MeV

Measurement: $\hat{q} = \dfrac{d < p_T{}^2 >}{dl}$

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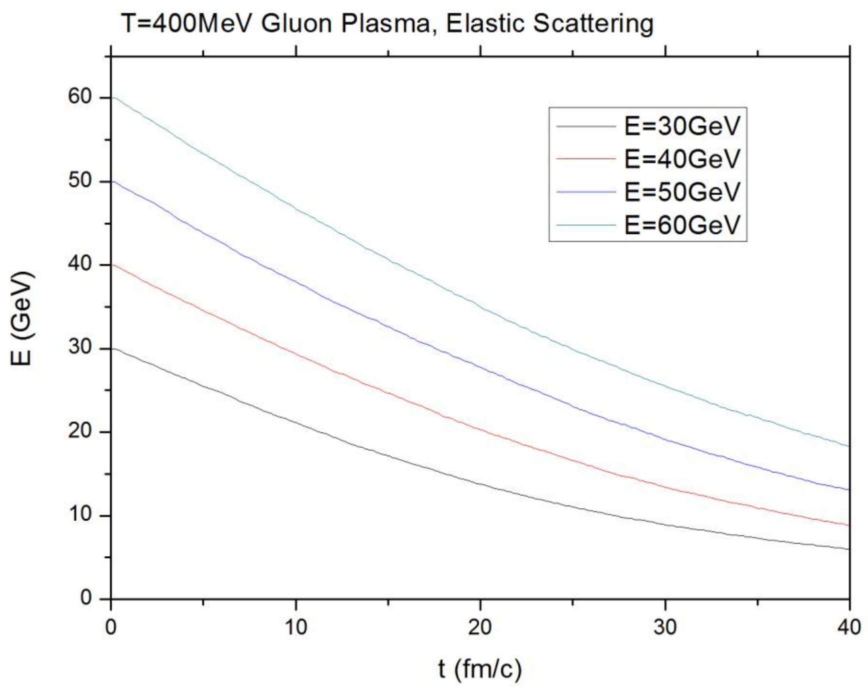
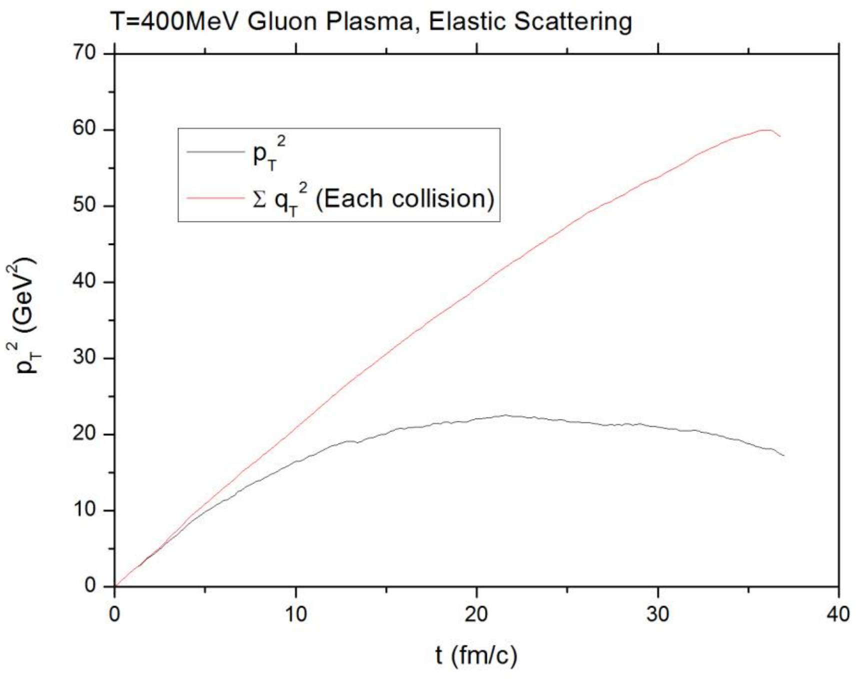
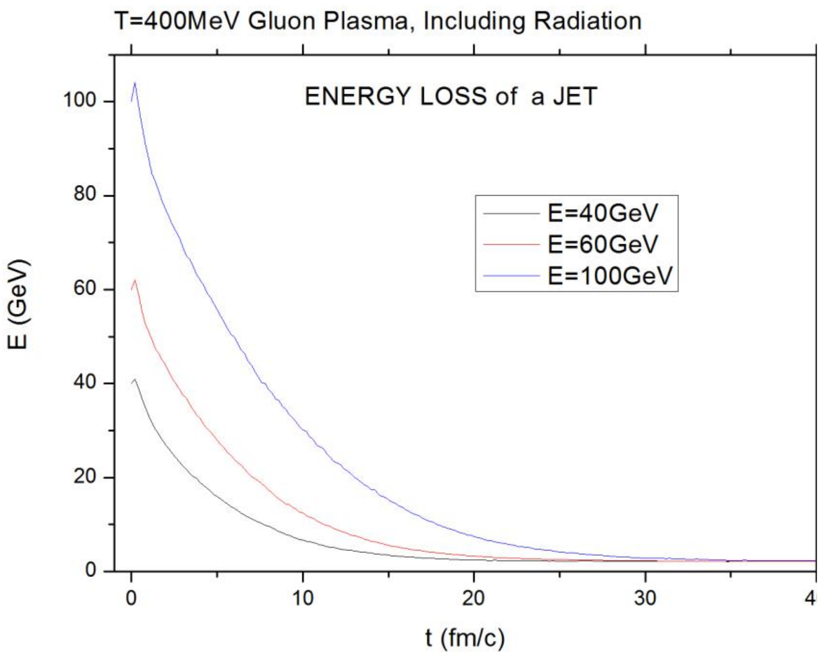


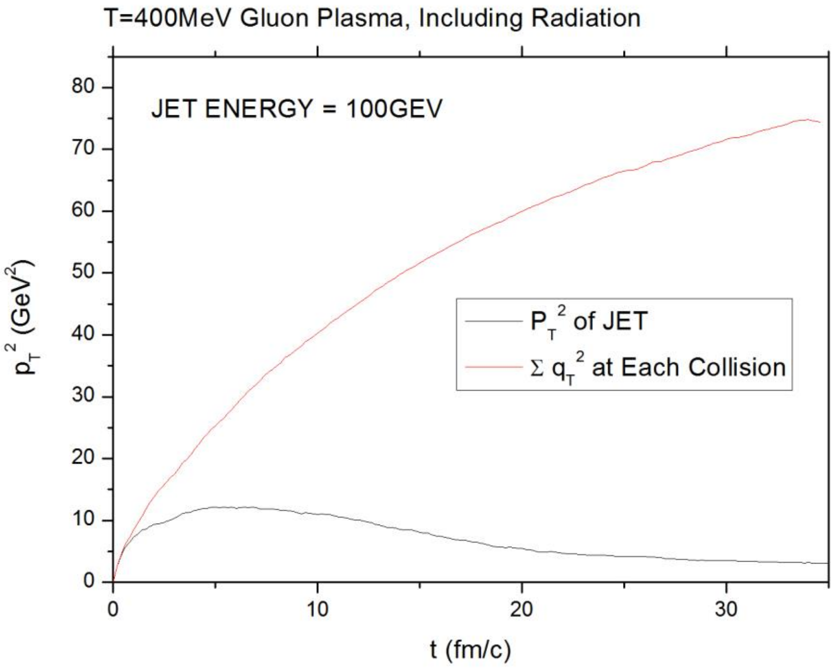
T=400MeV Gluon Plasma, Elastic Scattering
E=30GeV
E=40GeV
E=50GeV
E=60GeV
E (GeV)
t (fm/c)



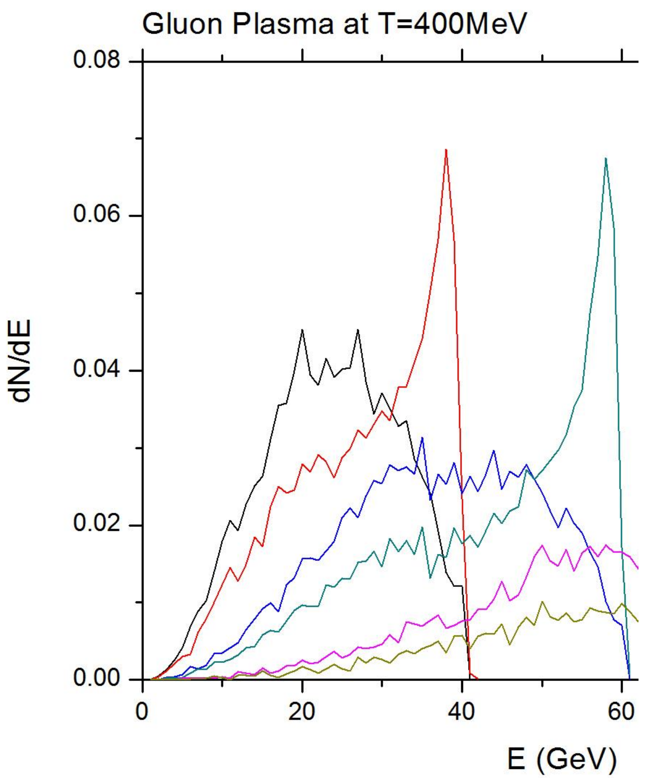
T=400MeV Gluon Plasma, Elastic Scattering
p_T^2
$\Sigma\ q_T^2$ (Each collision)
p_T^2 (GeV^2)
t (fm/c)

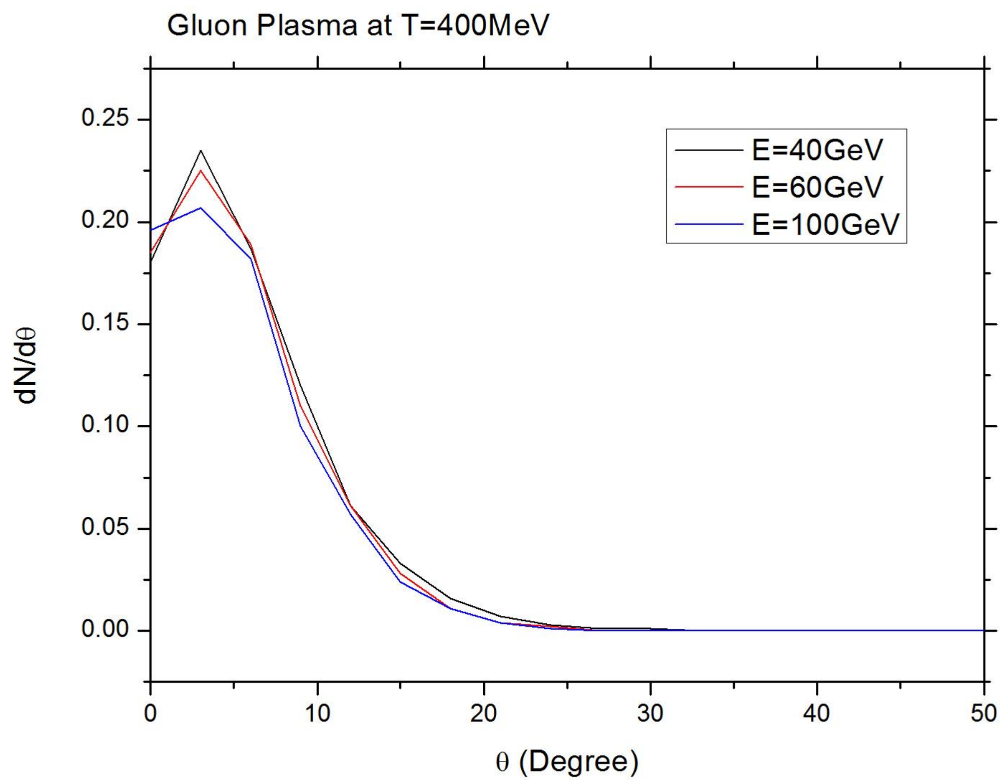
B. Including INELASTIC SCATTERING:





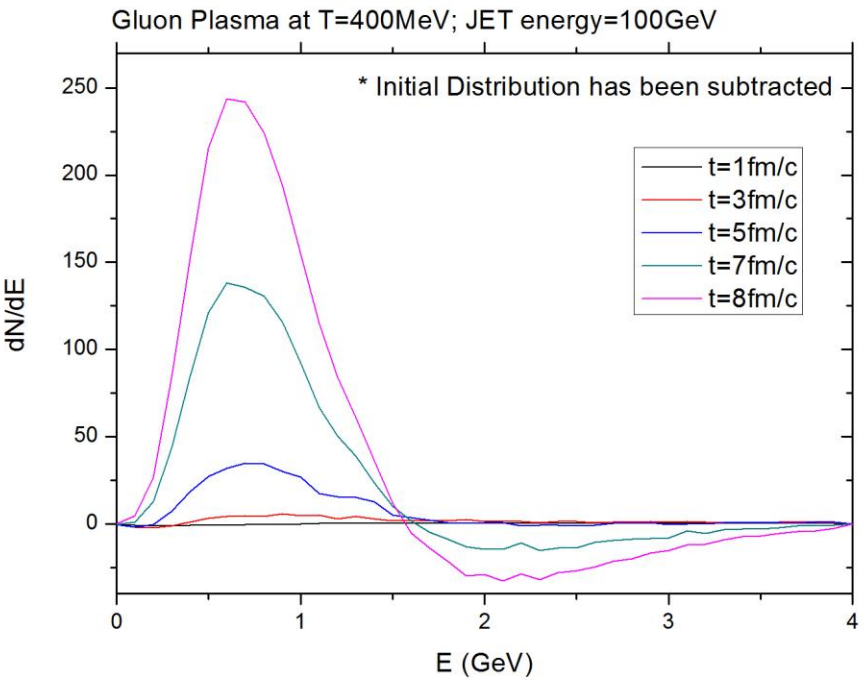
C. Energy Spectrum: after D

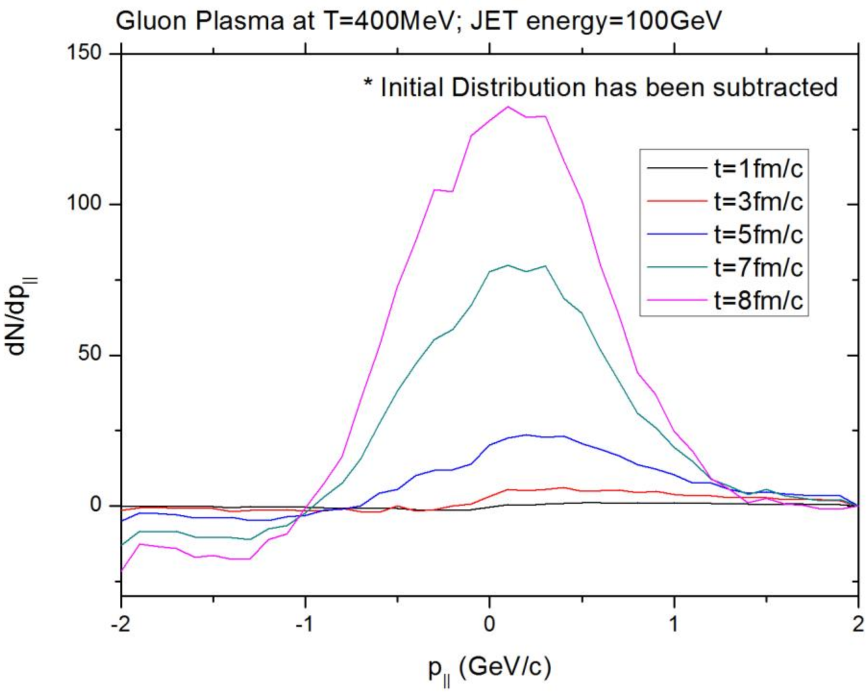


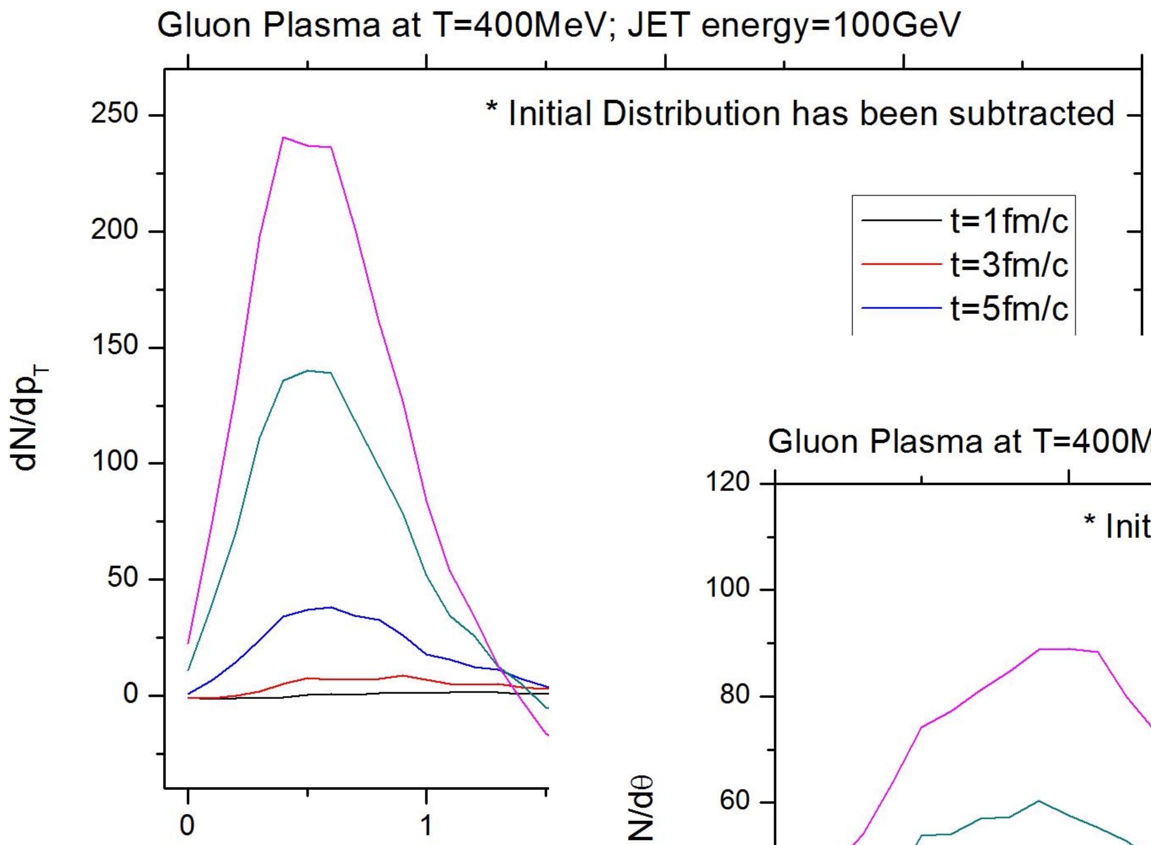


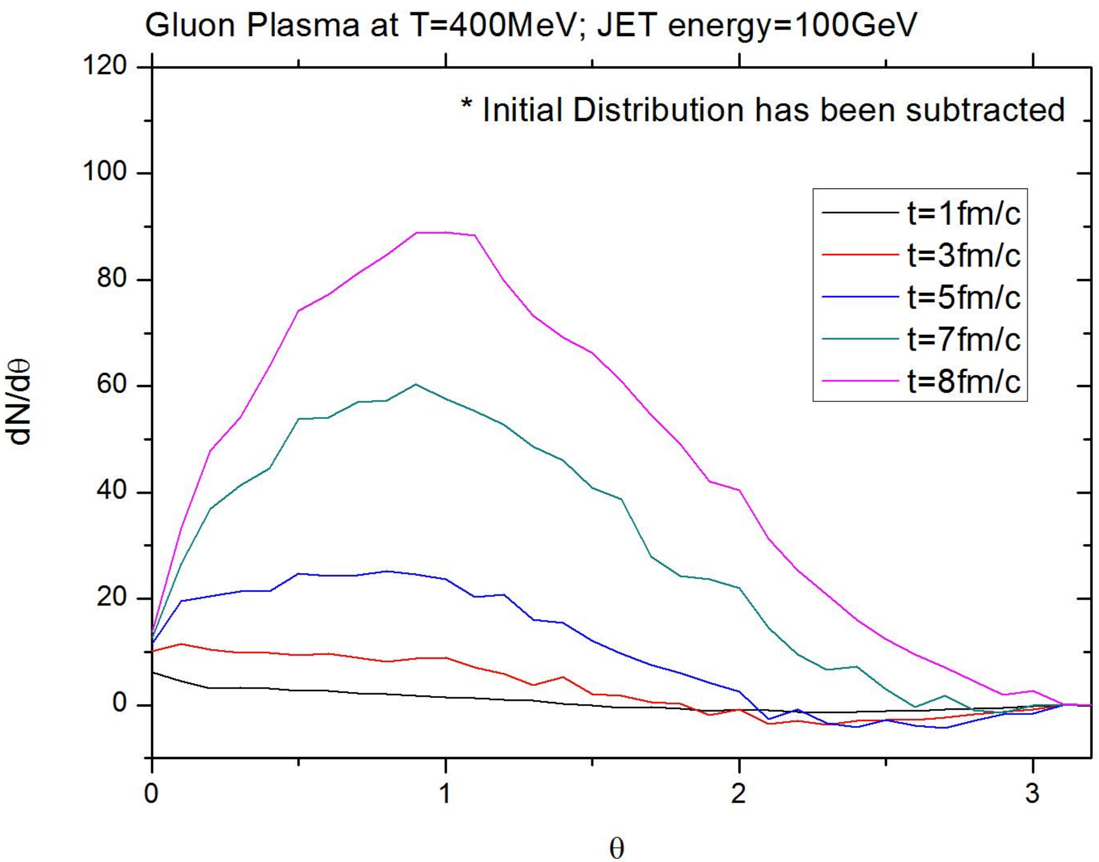
5. Medium Properties

A. Number Density:






Gluon Plasma at T=400MeV; JET energy=100GeV
* Initial Distribution has been subtracted
t=1fm/c
t=3fm/c
t=5fm/c
dN/dp_T
250
200
150
100
50
0
0
1


Gluon Plasma at T=400MeV; JET energy=100GeV
* Initial Distribution has been subtracted
t=1fm/c
t=3fm/c
t=5fm/c
t=7fm/c
t=8fm/c
dN/dθ
120
100
80
60
40
20
0
0
1
2
3
θ

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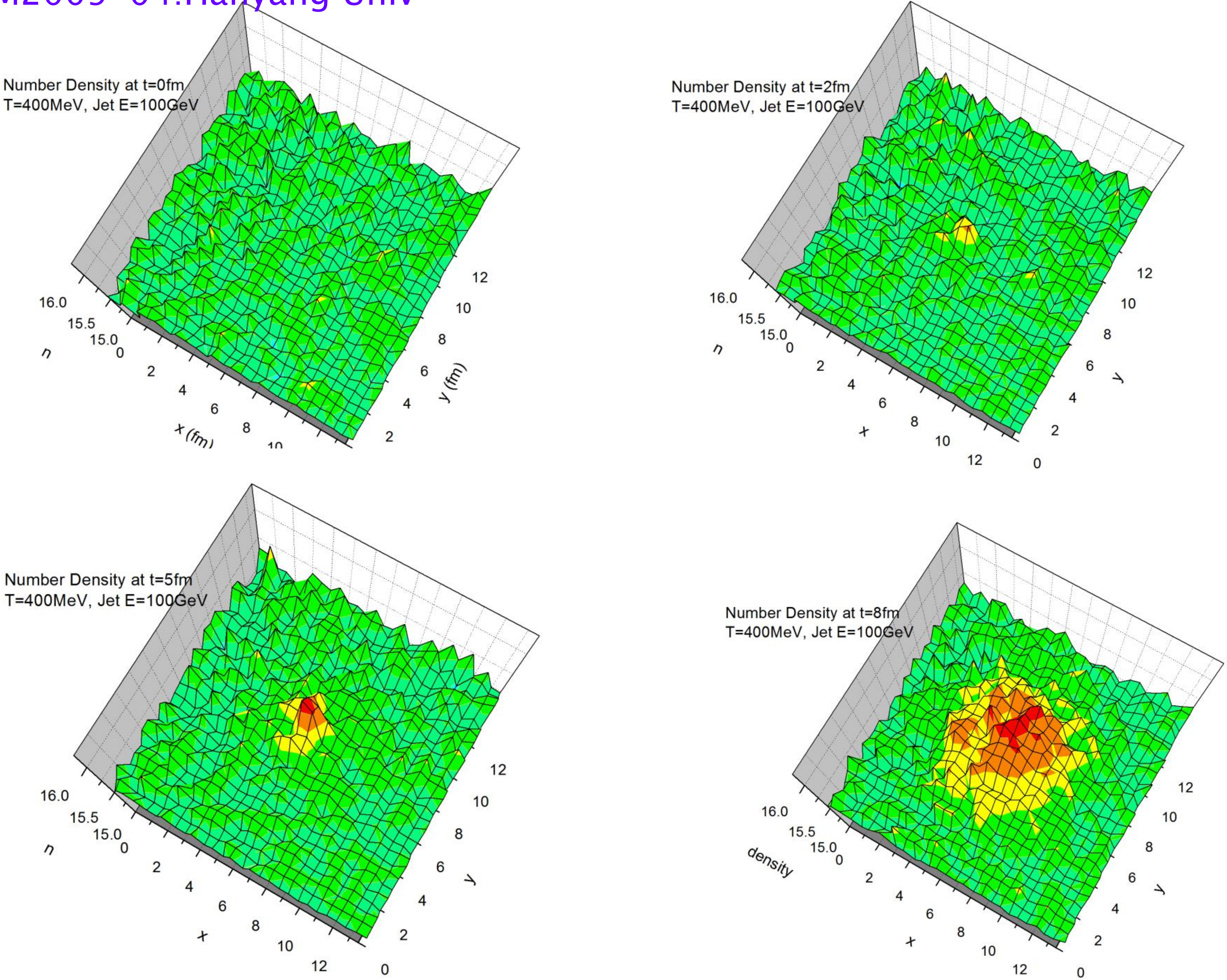

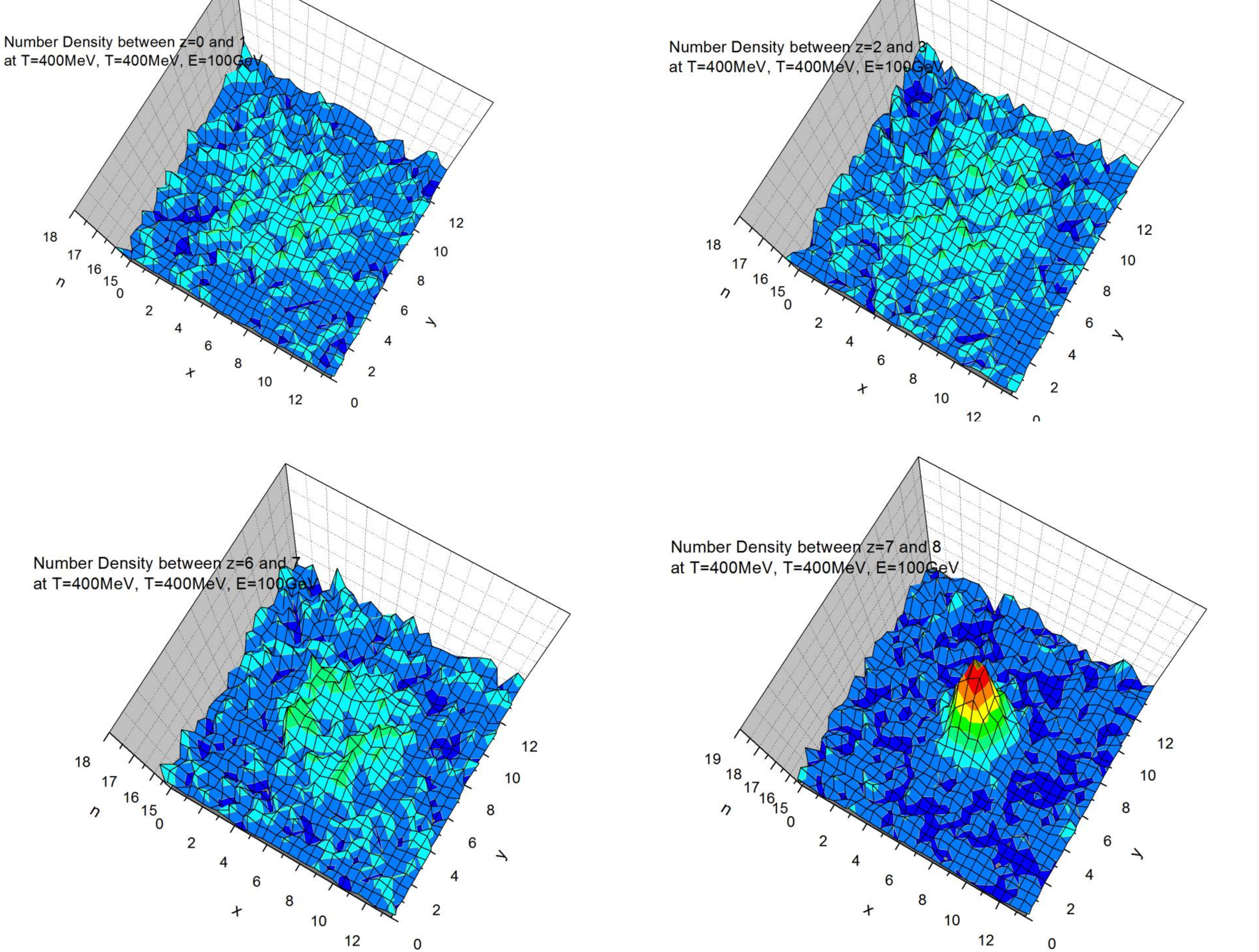
Number Density between z=0 and 1
at T=400MeV, T=400MeV, E=100GeV
n
x
y
Number Density between z=2 and 3
at T=400MeV, T=400MeV, E=100GeV
n
x
y
Number Density between z=6 and 7
at T=400MeV, T=400MeV, E=100GeV
n
x
y
Number Density between z=7 and 8
at T=400MeV, T=400MeV, E=100GeV
n
x
y

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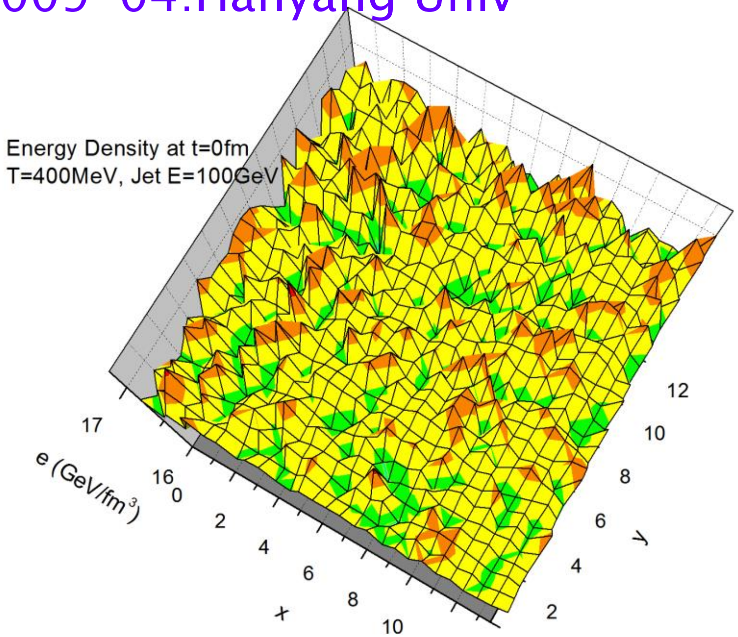

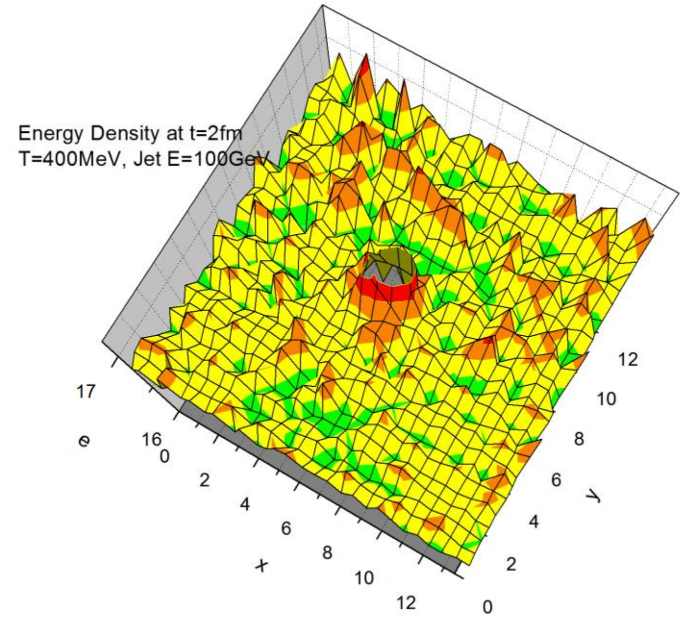

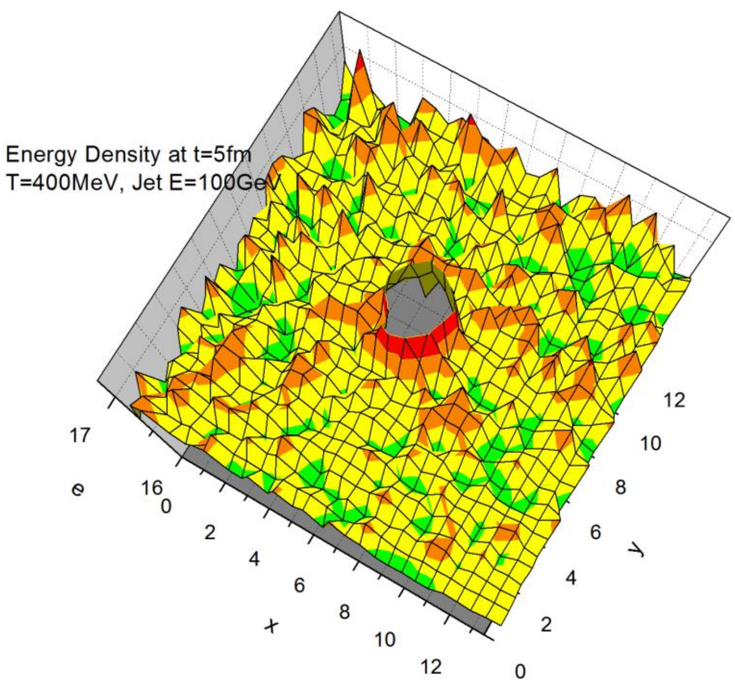

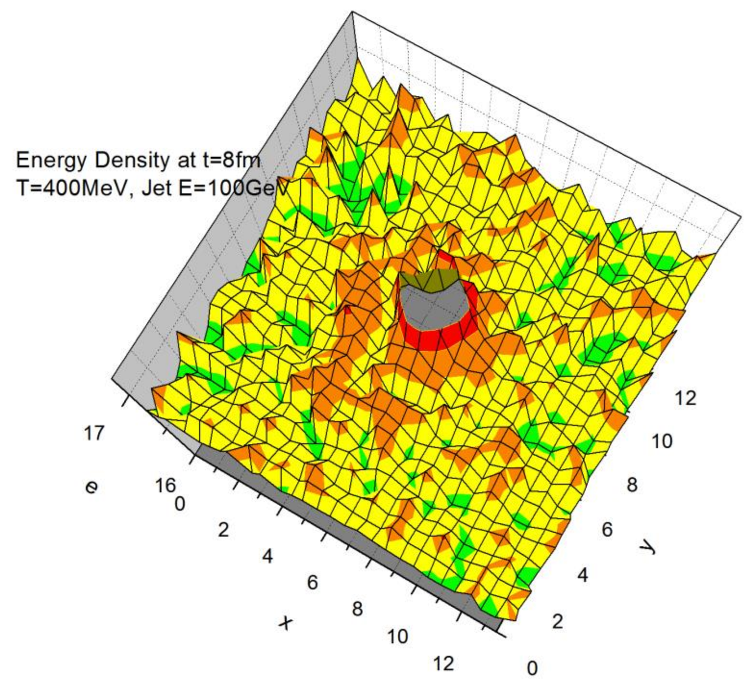

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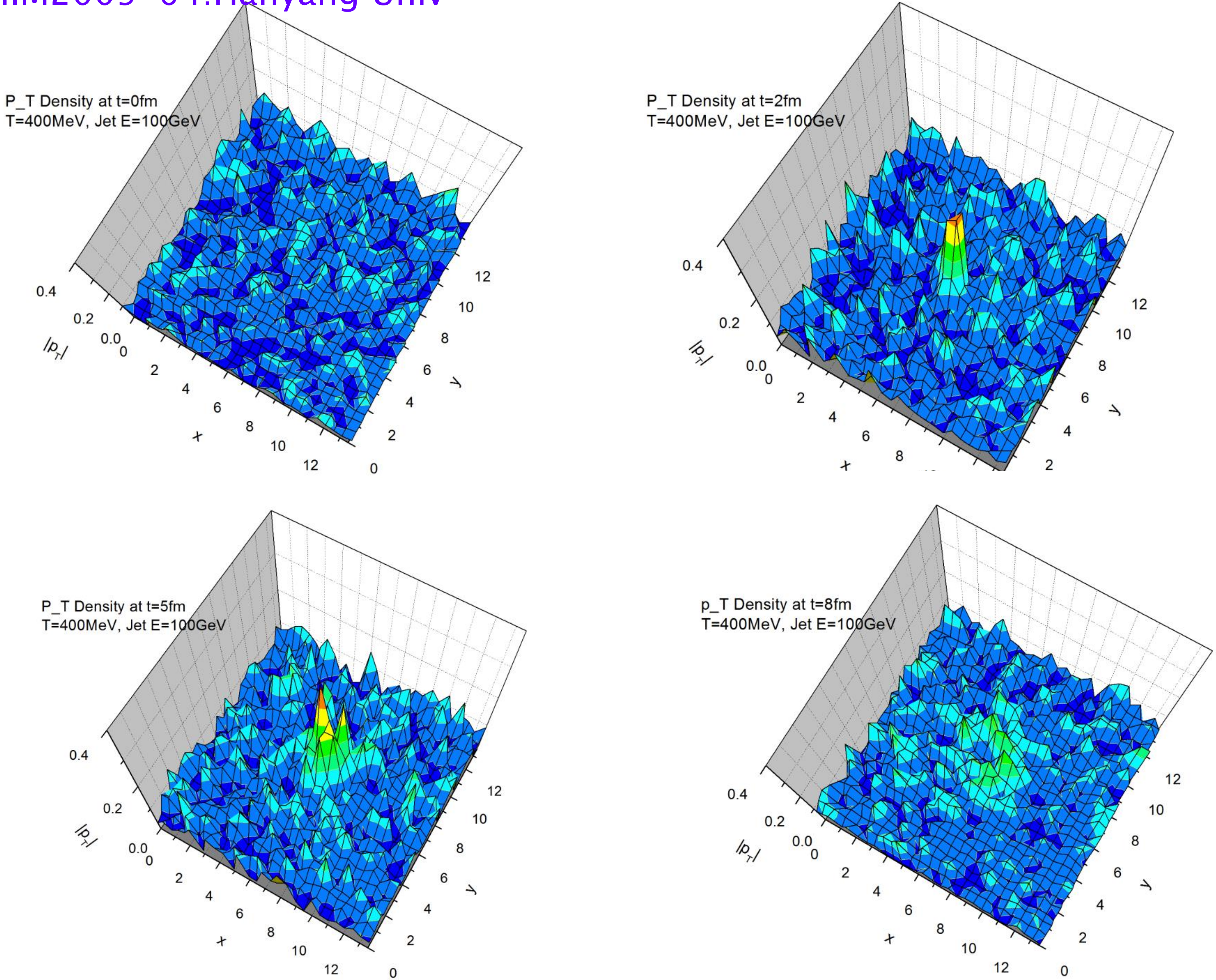

6. Discussions and Conclusions

- Energy Loss to Elastic scattering has been calculated to the theoretical value
- Radiation energy loss is far greater than elastic collisions
- Mach cone like structure has been seen but not conclusive