The Light –Cone Plasma and the azimuthal Anisotropy

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Outline

- Maximum Entropy approach to a **nonthermal** plasma
- The eff. transverse temperature and softness in pp-Collisions
- Generalizing the universal distribution to Heavy-Ion Collisions
- Explaining momentum broadening from parton rescattering
- Analysing azimuthal anisotropy v_2

The Maximum Entropy Approach

- A method to handle the nonequilibrium situation of rapid high energy collisions
- A phenomenology based on the light cone dominance of high energy reactions
- Using as key variables transverse momentum and light cone fractions

Transverse Momentum and Light cone fractions

$$x = \frac{\epsilon + p_z}{E + P_z} = \frac{p_+}{P_+}.$$

of gluons-for simplification

The Maximum Entropy Approach

Each cell is labeled by impact parameter, transverse momentum, light cone momentum and longitudinal light cone coordinate. The number of quantum states in each cell is then given by the volume of the cell divided by h^3 and multiplied by the degeneracy factor for gluons g=2*8 :

$$\hat{G}_{b_\perp, p_\perp, p_+, x_-} = g \frac{d^2 b_\perp d^2 p_\perp dp_+ dx_-}{(2\pi)^3}$$
$$= g \frac{d^2 b_\perp d^2 p_\perp}{(2\pi)^2} dx \frac{d\rho}{2\pi}$$

$$x = dp_+ / P_+$$
$$\rho = dx_- P_+$$

Integrate out coordinate space:

Transverse space : $L_\perp^2$

Longitudinal space: $\int \frac{d\rho}{2\pi} \approx \frac{1}{x}$

homogeneously distributed

$$\int \frac{d\rho_{val}}{2\pi} \approx \frac{L_z}{\gamma}\frac{m\gamma}{2\pi} \approx 1$$

$$G_{x,p_\perp} = gL_\perp^2 \frac{d^2 p_\perp}{(2\pi)^2}\frac{dx}{x}.$$

$$\int \frac{d\rho_{sea}}{2\pi} \approx \frac{1}{xP}P \to \infty.$$

We want to maximize this entropy under the following two-constraints

$$\sum G_{x,p_\perp} |p_\perp| n_{x,p_\perp} = \langle E_\perp \rangle .$$

$$\sum G_{x,p_\perp} x n_{x,p_\perp} = 1$$

The total transverse energy is fixed

The light cone fractions of all partons (gluons) add up to unity

Search for extremum of S+ 1/λ E(transverse)+w unity :

The Lagrange parameters are the transverse temperature λ and the softness w

$$\frac{\delta\left(S + \frac{1}{\lambda}\sum |p_\perp| n_{x,p_\perp} + w\sum x n_{x,p_\perp}\right)}{\delta n_{x,p_\perp}} = 0.$$

Result: The Light Cone Plasma Distribution

$$n_{x,p_\perp} = \frac{1}{e^{\frac{|\vec{p}_\perp|}{\lambda} + xw} - 1}$$

We expect that with increasing cm energy the gluons on the light cone will get hotter and softer, i.e. their transverse temperature and softness will increase , i.e. their x-fractions will become smaller

Input parameters L,λ,w for pp-collisions

$\sqrt{s}$ (TeV)	$L_\perp$ (fm)	λ (GeV)	w	N	$\langle p_T \rangle$ (GeV)	dN/dy
0.2	0.726	0.269	2.76	33.6	0.38	4.0
1.0	0.745	0.308	3.96	59.2	0.43	5.5
2.0	0.753	0.331	4.70	75.8	0.46	6.5
7.0	0.792	0.383	7.03	126.6	0.54	9.6

We assume spatial transverse homogeneity and a collision area of size L^2. Input are the mean transverse momentum and the rapidity distribution at y=0. We use parton/hadron duality, then the double differential multiplicity distribution of charged particles comes out

Multiplicity distributions:

$$\frac{dN}{dyd^2p_\perp} = \frac{gL_\perp^2}{(2\pi)^2} \frac{1}{\exp\left[m_\perp\left(\frac{1}{\lambda} + \frac{we^{|y|}}{\sqrt{s}}\right)\right] - 1}$$

$$\frac{dN}{dy} \approx \frac{\pi g L_\perp^2 \lambda^2}{12\left(1 + w\lambda\frac{e^{|y|}}{\sqrt{s}}\right)^2}.$$

Parton-hadron duality pre-scription is to replace transverse momentum by transverse mass

$$m_\perp = \sqrt{m_\pi^2 + p_\perp^2}.$$

Corrections to the above formula are of order pion mass/effective transverse temperature

RHIC pp-Data at 200 GeV

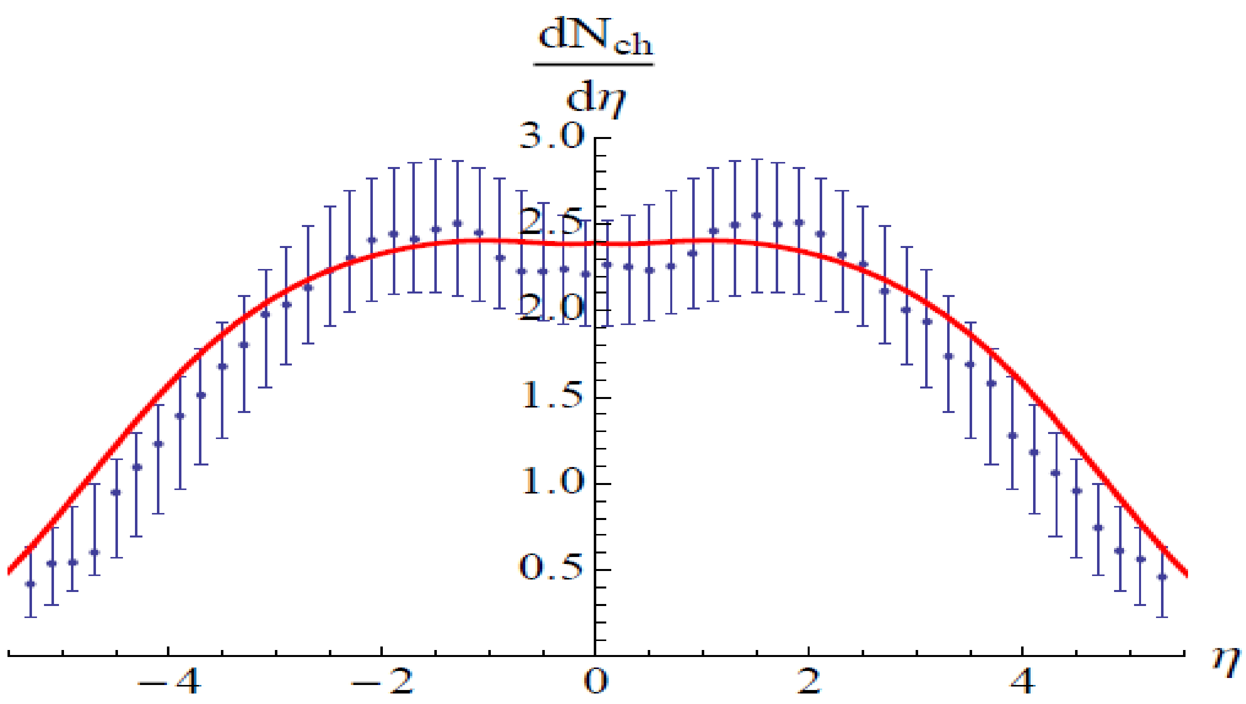


Figure 1: Data points show the charged-particle pseudo-rapidity distribution in p+p collisions at $\sqrt{s} = 200\,\text{GeV}$ from [11], the full drawn curve represents the result following from the light-cone plasma distribution.

LHC pp-data at 7000 GeV

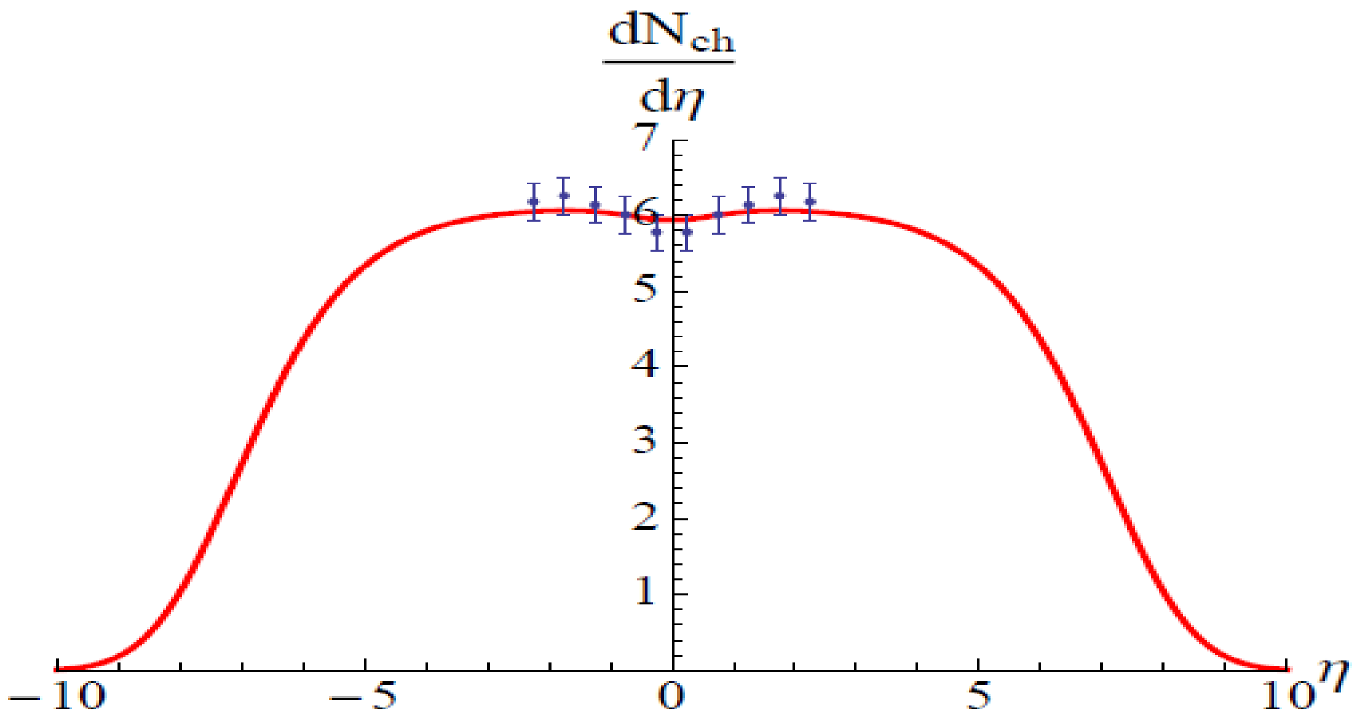


Figure 2: Data points show the charged-particle pseudorapidity distribution in p+p collisions at $\sqrt{s}$ = 7000 GeV from [7], the full drawn curve represents the result from the light-cone plasma distribution.

How to generalize this to AA-collisions?

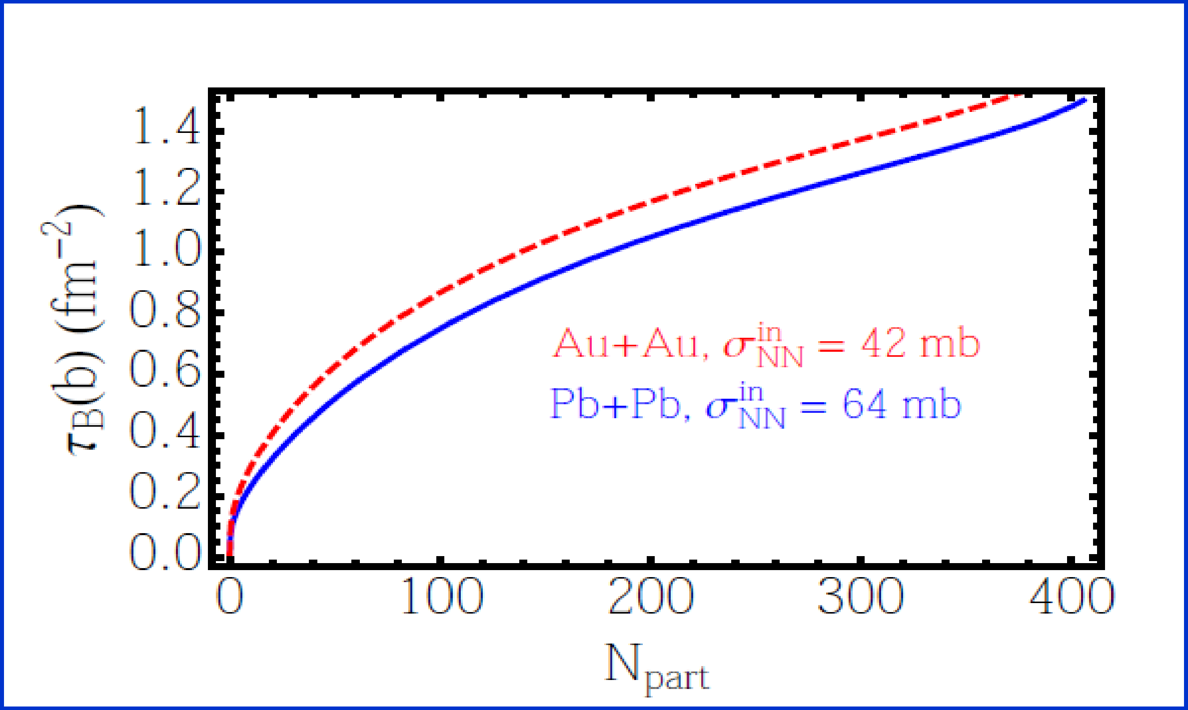
- Since we are dealing with soft collisions we rescale the pp-distribution with the number of participants- this is not sufficient
- We find that the mean transverse momentum of the partons, released by the wounded nucleons is broadened in the nucleus-nucleus collisions due to multiple collisions. So called radial flow arises naturally.

Multiplicity distribution in AA-collision

$$\frac{dN_{ch}^{AA}}{d\eta d^2 p_\perp} = \frac{N_{\text{part}}}{2}\frac{2}{3}\sqrt{1 - \frac{m_\pi^2}{m_\perp^2 \cosh^2 y}}\,\frac{dN(\langle p_\perp \rangle)}{dy d^2 p_\perp}.$$

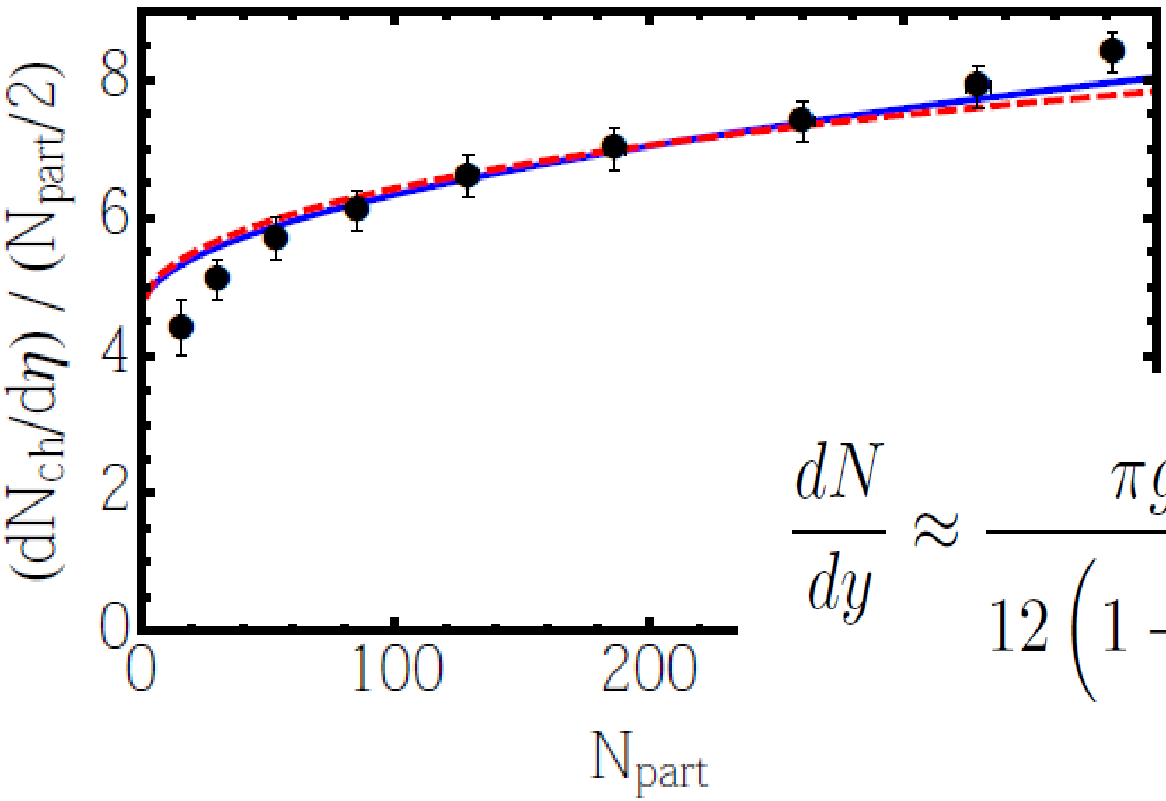
The pp-distribution in each hemisphere gets multiplied with the number of participants and its transverse temperature is increasing for central collisions to reproduce the measured mean transverse momentum.

λ increases with centrality because of multiple scattering:



$$\Delta p^2_{\perp,\pi} = \overline{\langle \sigma p^2_{\perp} \rangle}_g \tau_B(b) \langle z^2 \rangle_{\pi/g}.$$

Increase of dN/dη follows the effective transverse temperature



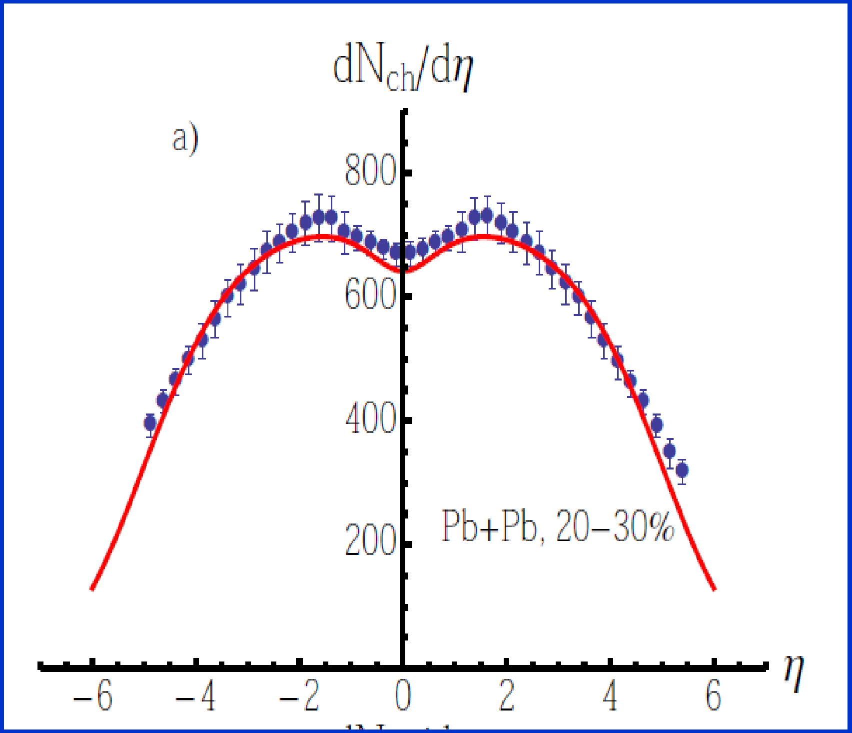
$$\frac{dN}{dy} \approx \frac{\pi g L_\perp^2 \lambda^2}{12\left(1 + w\lambda \frac{e^{|y|}}{\sqrt{s}}\right)^2}.$$

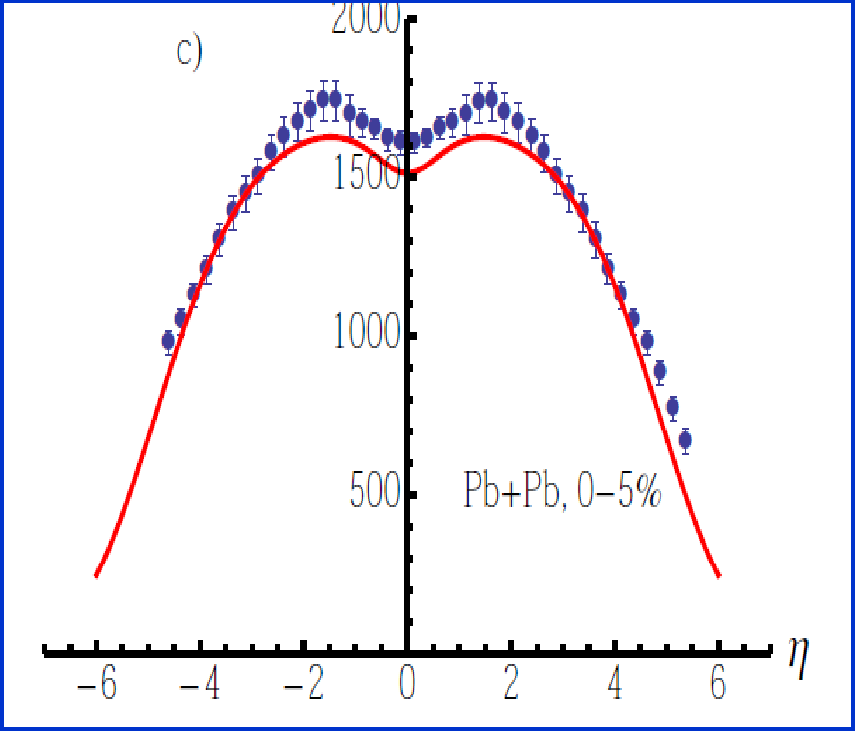
Light Cone distribution for Pb-Pb Collisions (2760 GeV) at different centralities

centr.	N_{part}	$L_\perp$ (fm)	λ_{AA} (GeV)	w_{AA}
20-30%	186	1.28	0.299	9.99
10-20%	260	1.28	0.306	10.55
0-5 %	383	1.28	0.316	11.30

Input parameters are Npart from geometry, L as in pp-collisions,
λ from mean transverse momentum , w- is obtained from the constraint

Pseudorapidity distributions for different centralities





Azimuthal anisotropy

$$v_2 = \frac{\int \frac{dN_{AA}}{dyp_\perp dp_\perp d\varphi}|_{y=0} p_\perp cos(2\varphi) d\varphi dp_\perp}{\int \frac{dN_{AA}}{dyp_\perp dp_\perp d\varphi}|_{y=0} p_\perp d\varphi dp_{bot}}$$

The azimuthal angle **φ** is the angle which the **transverse momentum forms with the scattering plane** created by impact parameter and beam axis

Generalization of light cone distribution

$$\frac{dN_{AA}}{dyp_\perp dp_\perp d\varphi} = g\frac{N_{part}}{2}\frac{L_x L_y}{(2\pi)^2}\frac{1}{e^{|\vec{p}_\perp|(\frac{1}{\lambda_0}+\frac{\cos[2\varphi]}{\lambda_2}+\frac{we^{|y|}}{\sqrt{s}})}-1}$$

Note: Anisotropy in momentum space $\lambda 2$ is necessarily connected with anisotropy in configuration space $Lx \neq Ly$. Calculation for gluons only!

Assumptions for flux tube deformation Lx≠Ly

(1) Flux tubes repel (type 2 superconductor)
(2) Their shape deformation is isomorphic to nucleus-nucleus overlap zone
Then the semi axis Lx and Ly of the cross section of the ellipsoids can be calculated Lx Ly=L^2

$$\delta(b) = \frac{L_x^2 - L_y^2}{L_x^2 + L_y^2}$$
$$= \frac{\int n_{part}(\rho cos(\varphi), \rho sin(\varphi), \vec{b})\, cos(2\varphi)\, \rho d\rho d\varphi}{\int n_{part}(\rho, \vec{b})\, \rho d\rho d\varphi}.$$

Schematic picture:

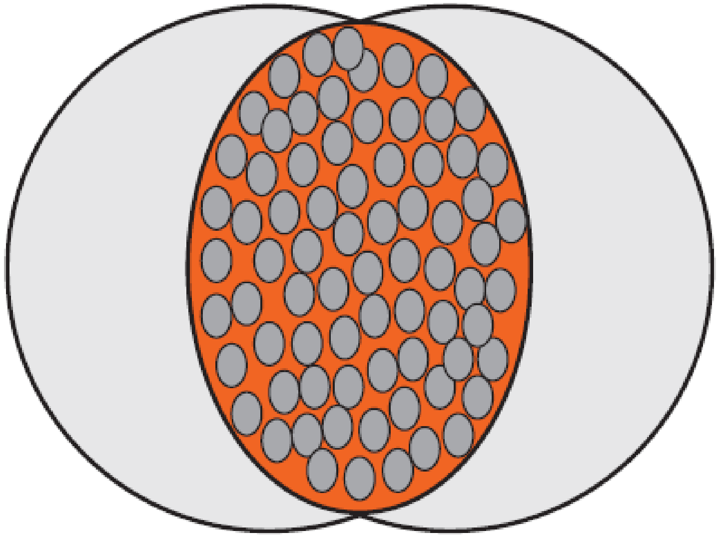


FIG. 1. Schematic picture of the overlap zone for a heavy-ion collision and flux tubes with equal deformation.

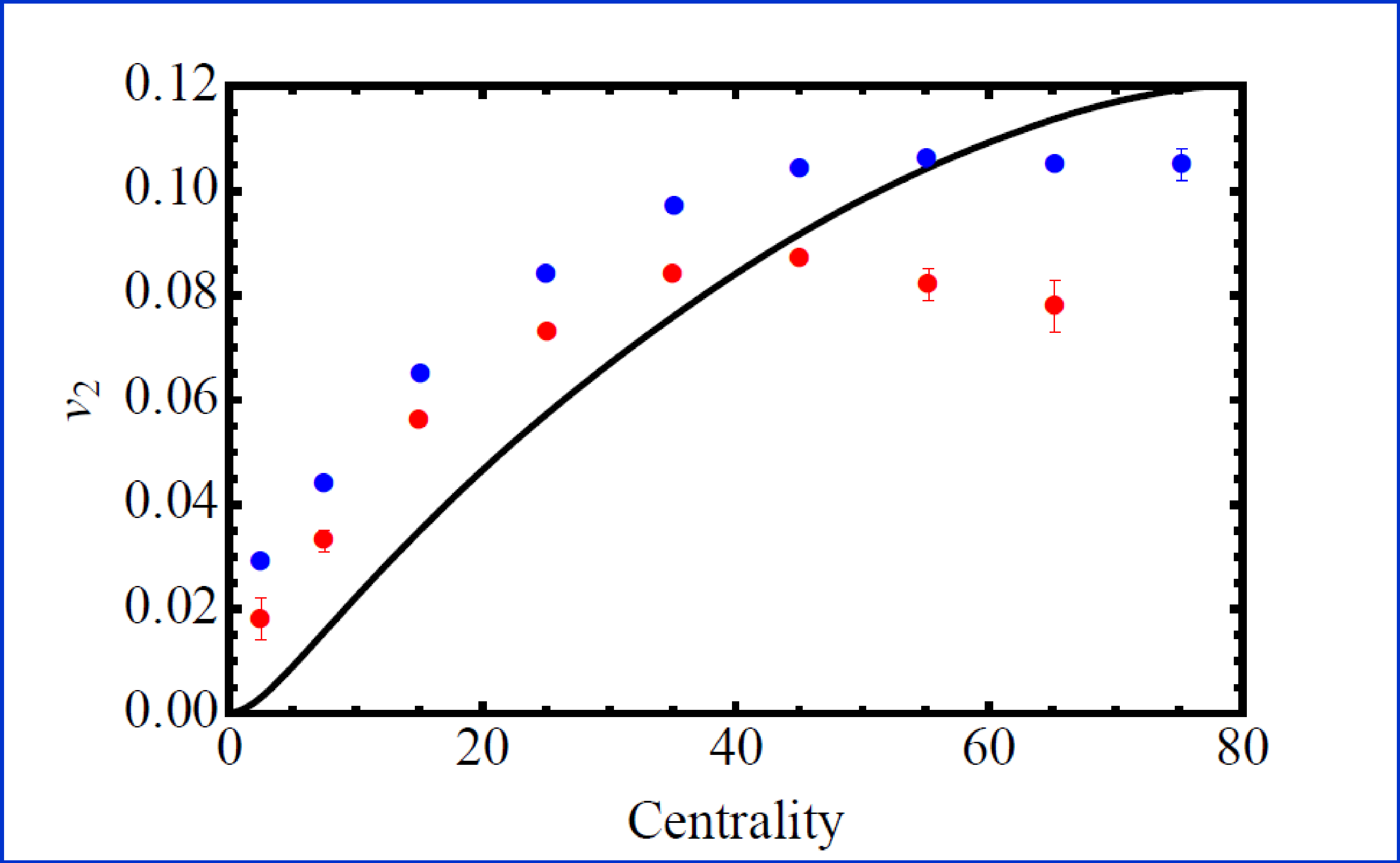
Momentum asymmetry follows from uncertainty relation

$$\frac{< p_x^2 - p_y^2 >}{< p_x^2 + p_y^2 >} = \frac{\frac{1}{L_x^2} - \frac{1}{L_y^2}}{\frac{1}{L_x^2} + \frac{1}{L_y^2}}$$

$$\lambda_2 = \frac{2\lambda_0}{\delta}.$$

The transverse asymmetry energy λ2 follows from the effective transverse temperature λ0 and the deformation of the fluxtube in configuration space δ. The azimuthal v2 = - δ/2

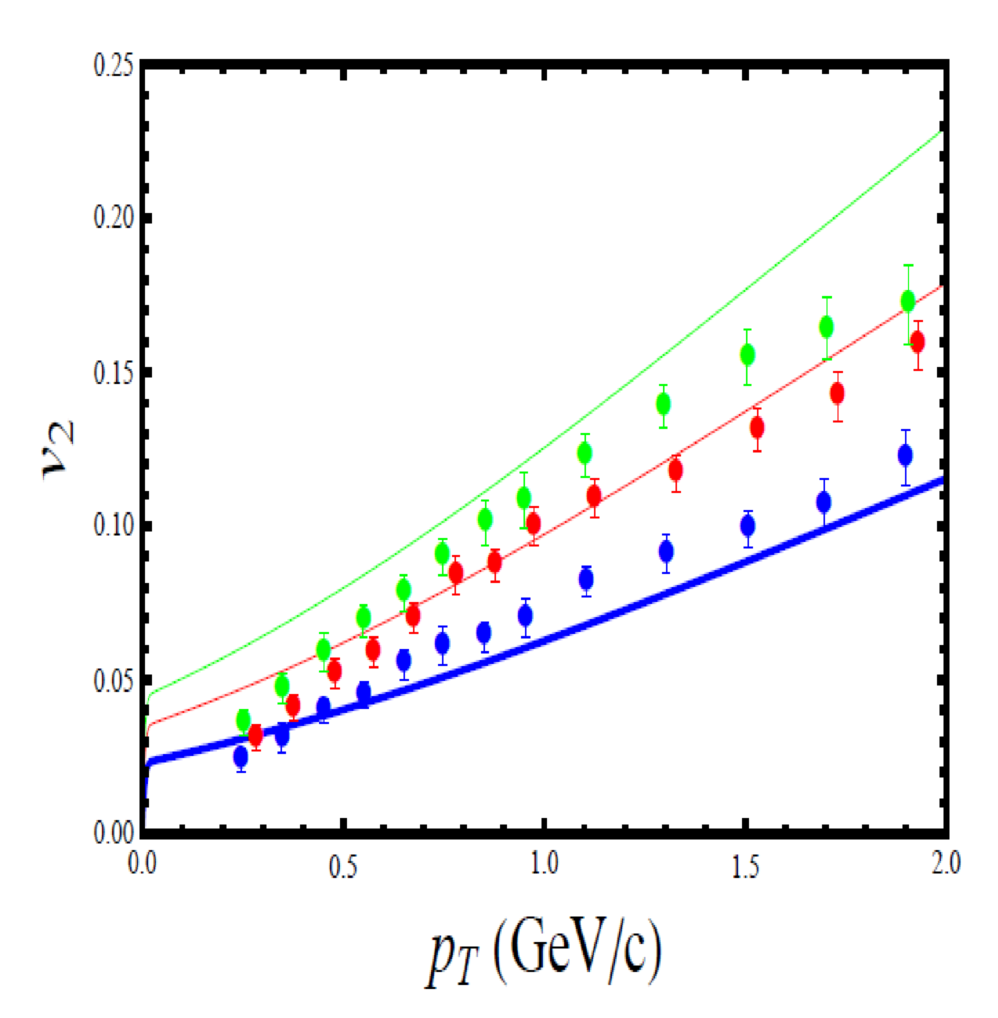
Azimuthal asymmetry



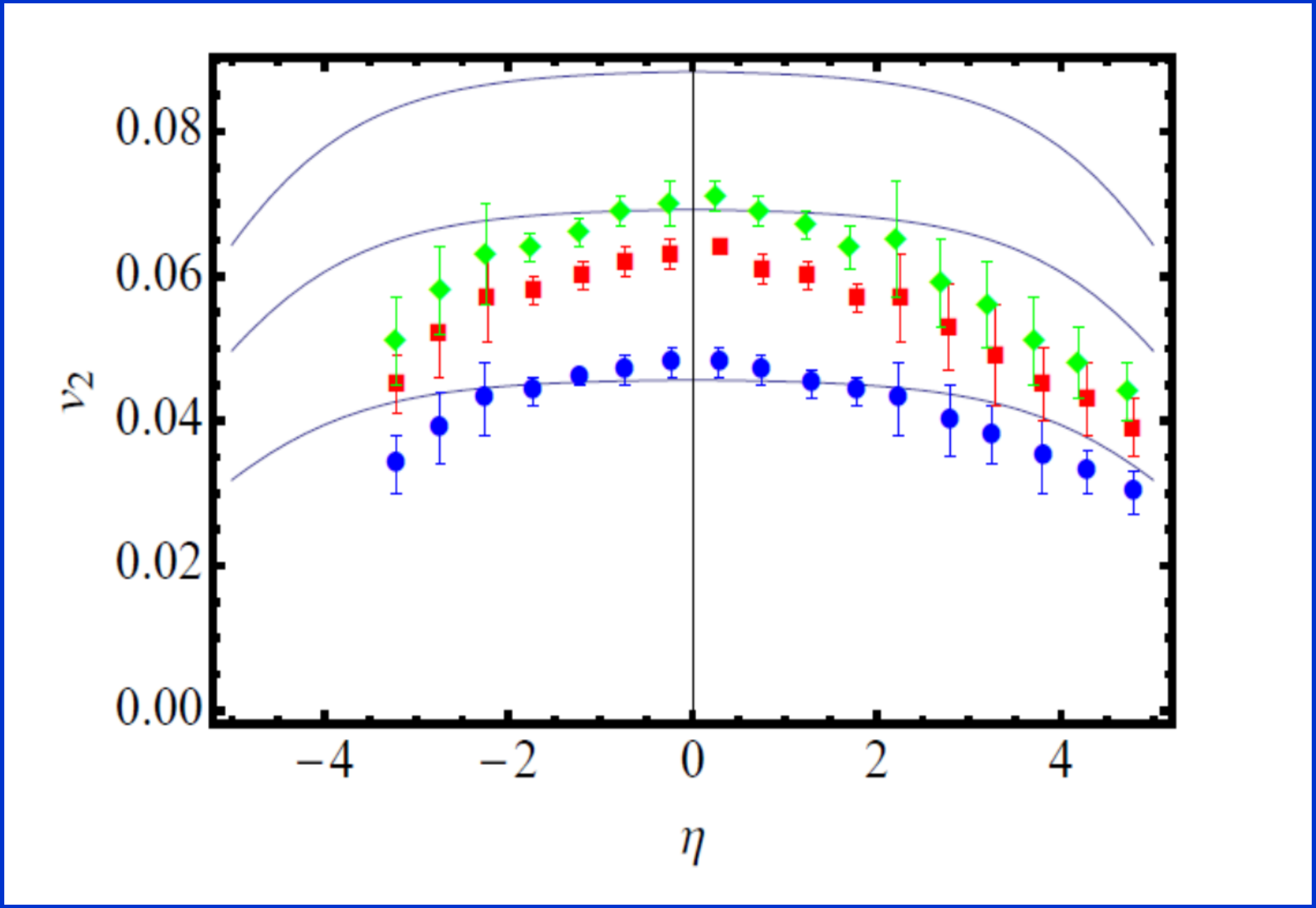
v2 as function of transverse momentum

v2 (Alice data) for different centralities:
Top 30%-40%
Middle 20%-30%
Bottom 10%-20%

Centrality	λ_0 (GeV)	λ_2 (GeV)	w
10-20%	0.396	-8.65	7.2
20-30%	0.383	-5.53	6.73
30-40%	0.376	-4.26	6.49



v2 as a function of rapidity



Preliminary data from A. Hansen (Alice)

Hadronization in vacuum and in thermal matter

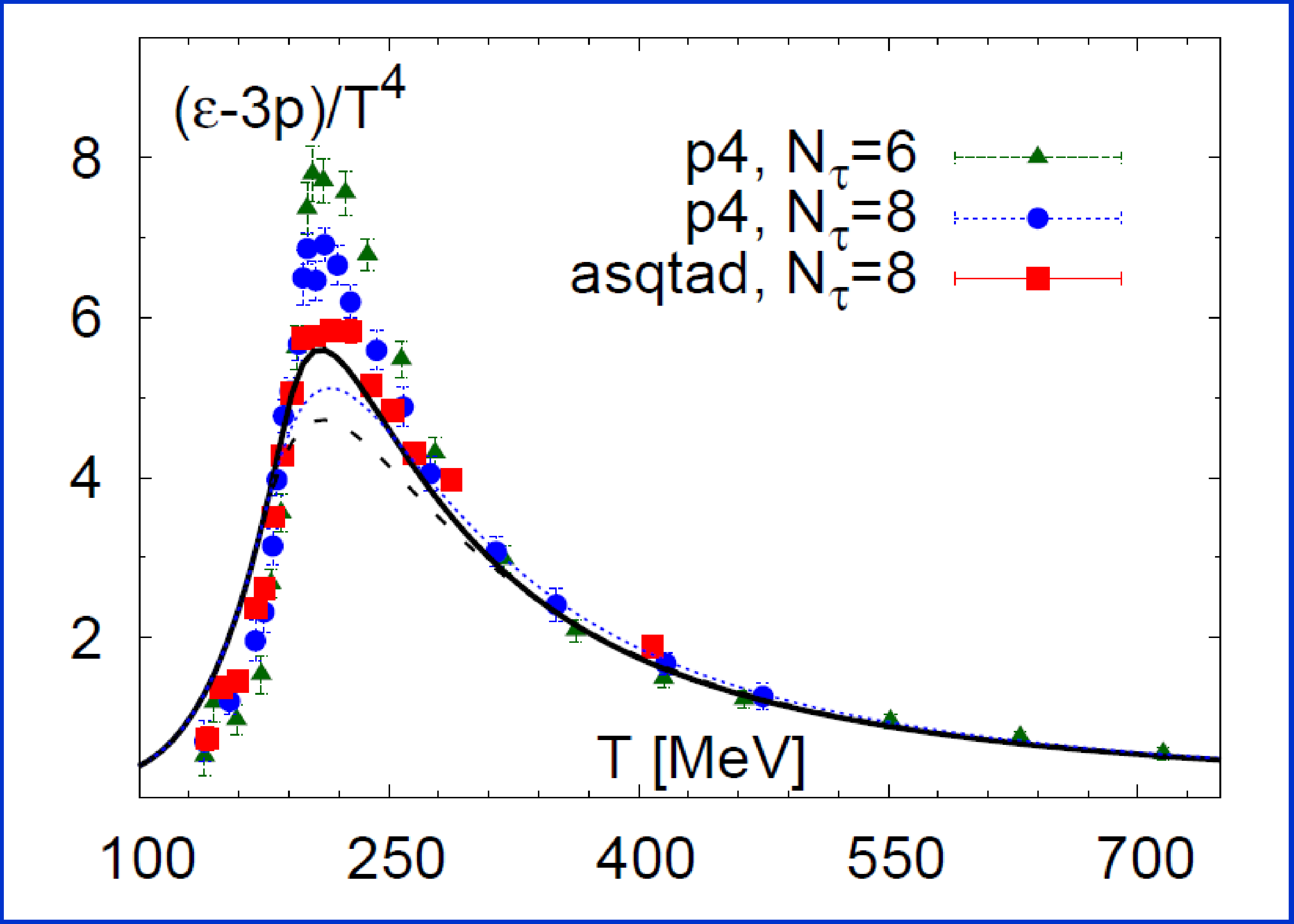
- Equation of state:
- Pressure $p(T)= f/3\ T^4 - B0 - B2\ T^2$
- Energy density $e(T)= f\ T^4 + B0 - B2\ T^2$

  This is consistent with thermodynamics

  and lattice simulations:

  $(e-3p)/T^4= 2\ B2/T^2 + 4\ B0/T^4$
- A simple constant Bag term B0 cannot explain lattice data

Trace anomaly (e-3p)/T^4 from lattice



Huovinen and Petreczky arxiv 0912.2541

How does the flux tube behave in the medium?

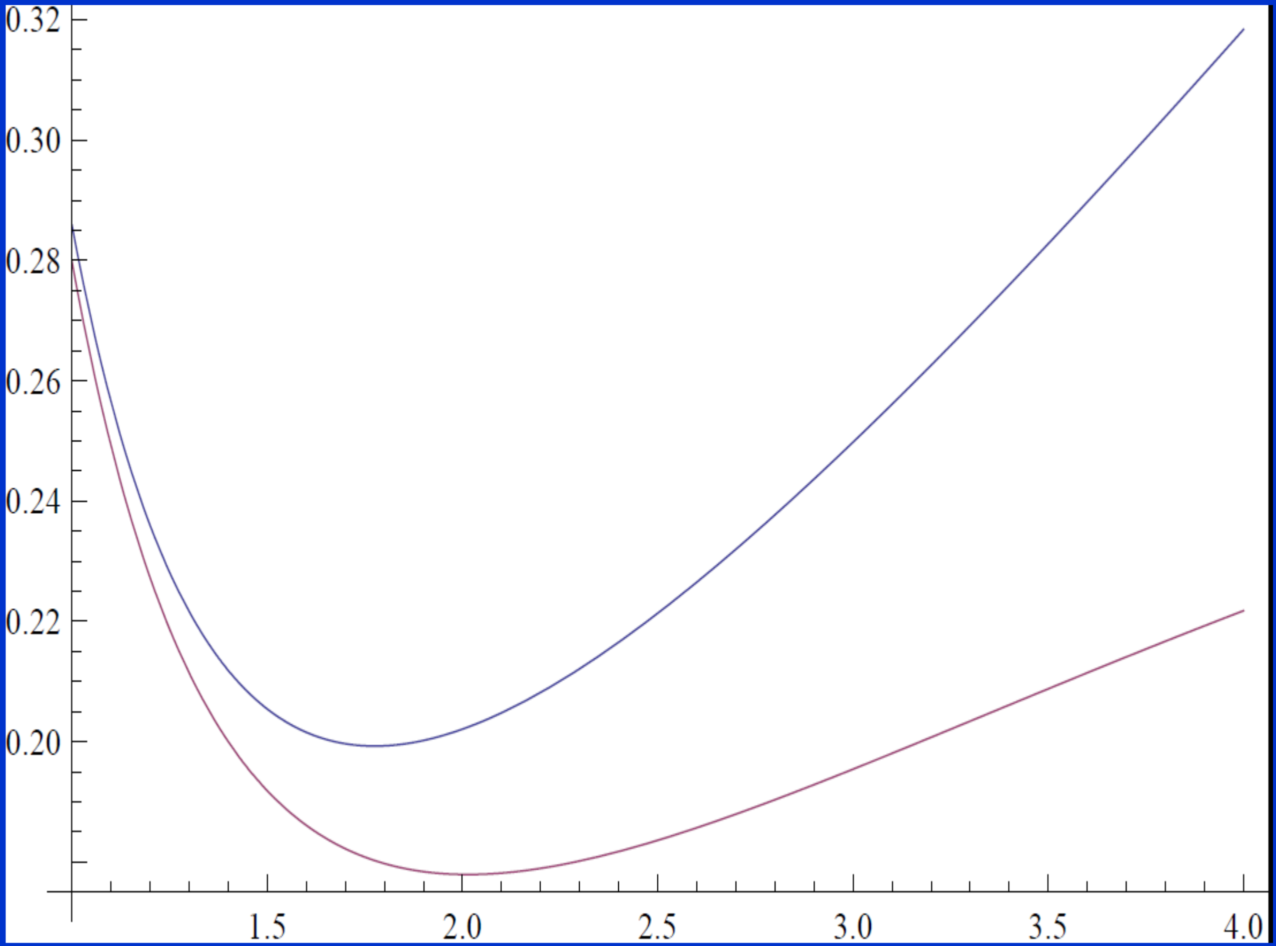
- In vacuum:
- Energy/Length of a flux tube=κ
- κ= (1/2 Electric field^2 + B) π r^2
- In „thermal“ matter:
- κ=volume term (π r^2 ×length)
- +surface term (2 π r ×length)=

(1/2 Electric field^2 + B0 –γ B2 T^2) π r^2 + α r

The parameters α=0.07 GeV^3 and γ=0.06 give:

String tension as a function of radius of fluxtube at T=0.2 GeV and T= 0.55 GeV

GeV^2



GeV^-1

Deformation due to temperature gradient

- In the heavy ion collision there is a stronger temperature (energy density) gradient along the x-direction than on the y direction.
- Therefore stronger

  bag pressure gradient along x direction
- And Lx<Ly

Conclusions:

- There is a universal maximum entropy distribution satisfying the constraints of a given transverse energy and unity-sum of parton light cone momentum fractions
- It is nonthermal and has two parameters: transverse temperature λ and softness w
- Direct calculation of the entropy and comparison with boosted thermal shows that light cone entropy is bigger (% effect)

Conclusions:

- Gluon dominance gives a good fit to the pp-data at RHIC and LHC with a reasonable overlap area L^2=(1 fm)^2 and the correct number of degrees of freedom
- Participant scaling and transverse momentum broadening explains the AA-multiplicity distributions as functions of centrality
- Deformed transverse flux tubes isomorphic to the overlap zone give azimuthal anisotropy
- Microscopic explanation of hydrodynamic flow

The Maximum Entropy Approach

We consider a fixed cell: Then to get to the entropy, we count the number of possibilities to distribute N particles on G quantum states , allowing multiple occupancy of each quantum state, because gluons are bosons.

Take e.g. N=11 and G=4 : o o o | o o o o o | o | o o

$$\Delta\Gamma_{x,p_\perp} = \frac{(G_{x,p_\perp} + N_{x,p_\perp} - 1)!}{(G_{x,p_\perp} - 1)!N_{x,p_\perp}!}$$

The entropy

The entropy is given by the log of the total phase space. Use Stirlings formula and factor out G:

$$S = \sum \ln(\Delta\Gamma_{x,p_\perp}) \tag{4}$$

$$= \sum G_{x,p_\perp}[(1+n_{x,p_\perp})\ln(1+n_{x,p_\perp}) - n_{x,p_\perp}\ln(n_{x,p_\perp})]. \tag{5}$$