Head shock vs Mach cone: azimuthal correlations from 2 to 3 parton processes

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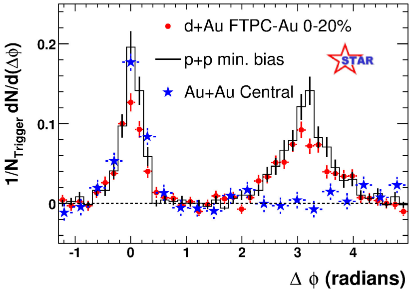
Outline

Azimuthal angular correlations from RHIC (STAR)

STAR NPA **757** (2005): Peak suppressed at $\Delta\phi = \pm\pi$ rad
Away-side parton absorbed by medium due to energy loss



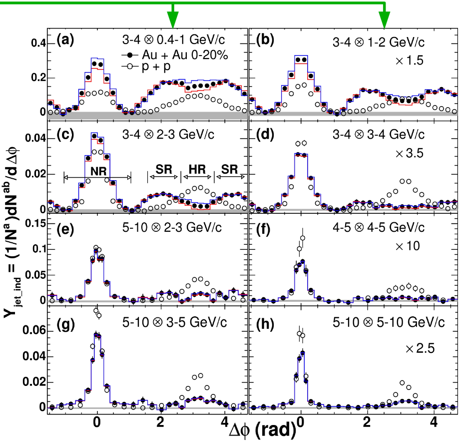
$$C(\Delta\phi) = \frac{1}{N_{\text{Trigger}}} \int d\Delta\eta \frac{dN}{d\Delta\phi d\Delta\eta}$$

Azimuthal angular correlations from RHIC (PHENIX)

The *ridge* and *broad away side*: excess yield of correlated particles at $\Delta\phi = 0$ and $\Delta\phi \approx \frac{2\pi}{3}, \frac{4\pi}{3}$ rad

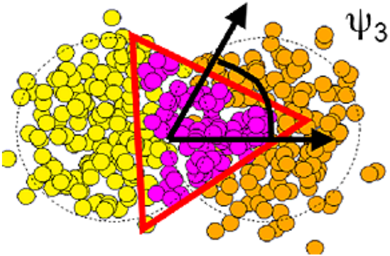
azimuthal correlations for large momentum difference, develop a "double hump" in the away side

PHENIX PRC78:014901,2008



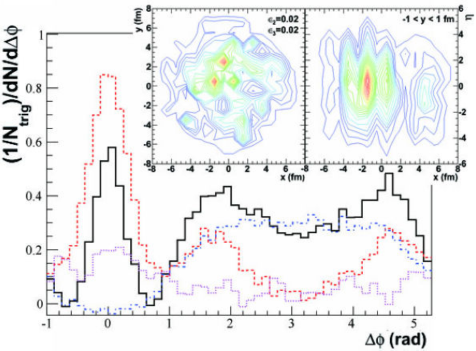
Fluctuations of matter density in colliding nuclei

...give rise to anisotropic flow of partially equilibrated matter



Fluctuations of matter density in colliding nuclei

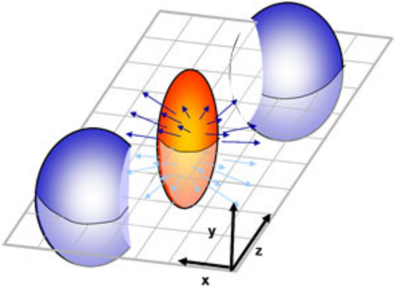
...hydrodynamic descriptions reproduced the double hump structure

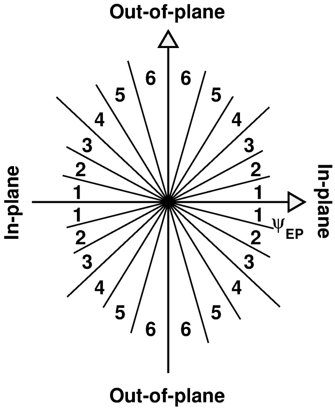


Guo-Liang Ma and Xin-Nian Wang, PRL 106 (2011)

Other observables

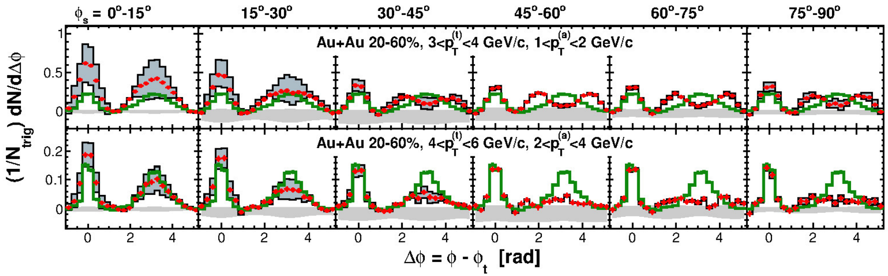
However other observables more consistent with final state effects:
In terms of angle with respect to event plane, more matter traversed for out-of-plane direction





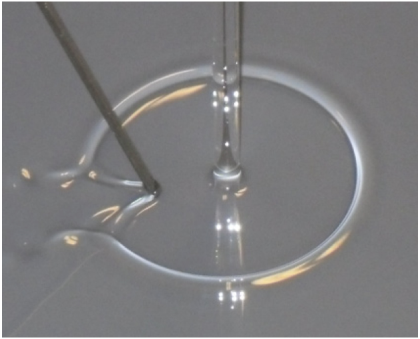
Other observables

Double hump appears for out-of-plane correlations (STAR)



STAR `arXiv:1010.0690 [nucl-ex]`

Head shock (wakes) vs Mach cones (shock waves)



white hole: Jannes et al. PRE 83 (2011)

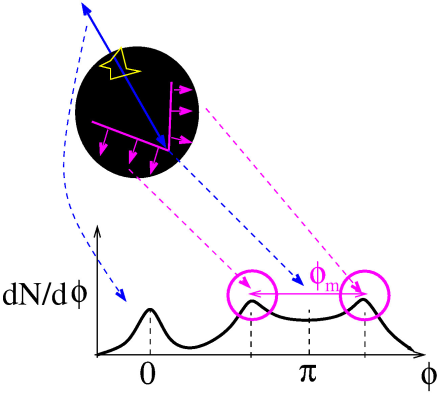


diagram: Torrieri et al. Acta Phys.Polon. B39 (2008)

Head shock (wakes) vs Mach cones (shock waves)

Recently

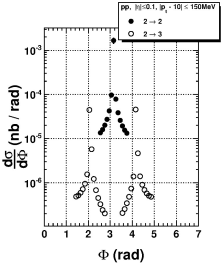
- interpretation is fragile, since jet-medium interaction produces also a wake whose contribution cannot be ignored [Casalderrey-Solana, Shuryak and Teaney, PoS CFRNC2006, (2006)]
- unlikely that fast moving parton under conditions in HIC (low viscosity, large parton velocity) generates double-hump via Mach cone since energy momentum deposition in the head shock region is strongly forward-peaked [Bouras, El, Fochler, Niemi, Xu and Greiner, PLB**710** (2012)]
- using a realistic multiple-gluon PS produced by in-medium moving parton, overlapping perturbations in very different spatial directions wipe out any distinct Mach cone structure [Neufeld and Vitev, PRC**86** (2012)]

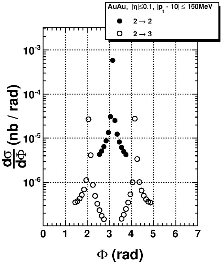
$\rightarrow$ A fast moving parton produces a wake rather than a shock wave for small $\frac{\eta}{s}$

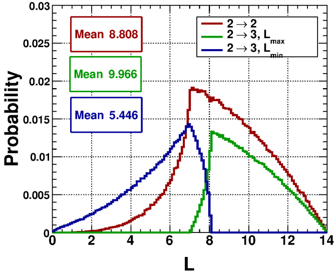
Path length and $2 \to 2$ vs $2 \to 3$

Three and two-hadron correlations in $\sqrt{s_{NN}} = 200$ *GeV*
proton-proton and nucleus-nucleus collisions
Ayala, Jalilian-Marian, Magnin, Ortiz, Paic, T-Y
PRL 104 (2010)

2010 Path length + scenario enhances 3 vs 2 particles: medium induced energy loss on LO $2 \to \{2,\ 3\}$ xsecs $\rightsquigarrow$ different geometry for trajectories of 3 as opposed to 2 particles in the final state of $A + A$ collisions, one particle absorbed by the medium, the other one punches through: *double hump*



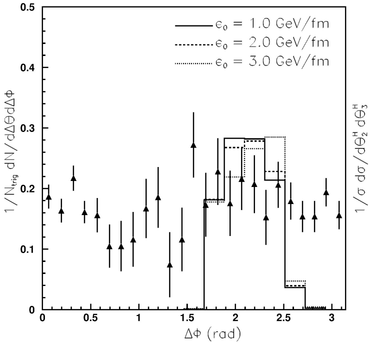




Hadron correlations from LO MEs + in-medium PFFs

Three-hadron angular correlations in high-energy proton-proton and nucleus-nucleus collisions from pQCD
Ayala, Jalilian-Marian, Magnin, Ortiz, Paic, T-Y, PRC 84 (2011)

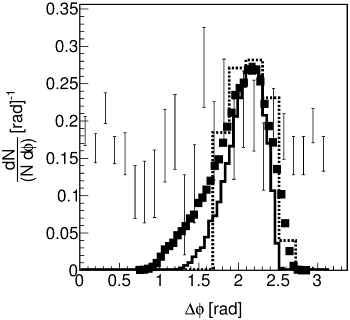
2011 Numerical study using LO parton matrix elements for $2 \to 3$ processes and including the effect of in-medium parton energy loss using modified fragmentation functions $\rightsquigarrow$ angular dependence of xsec vs PHENIX data.



Hadron correlations from Monte Carlo + in-medium PFFs

Monte Carlo approach for hadron azimuthal correlations in high energy proton and nuclear collisions
Ayala, Dominguez, Jalilian-Marian, Magnin, T-Y, PRC 86 (2012)

2012 Monte Carlo approach to study azimuthal correlations in $p + p$ and $A + A$ collisions at mid-rapidity: MadGraph event generator + modified fragmentation function + classification of events $\rightsquigarrow$ azimuthal correlations vs PHENIX data.



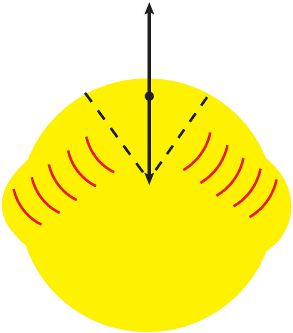
Hadron correlations from MC generator + linearized hydro

Head shock vs Mach cone: azimuthal correlations from 2 to 3 parton processes in relativistic heavy-ion collisions
Ayala, Dominguez, T-Y
PRC 88 (2013)

In a nutshell

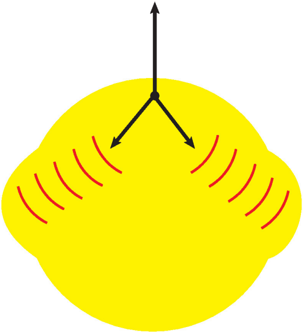
2013 Study hadron multiplicity produced by two partons in the away side coming from $2 \to 3$ processes for the case where their energy momentum is deposited into the medium, using linearized viscous hydrodynamics to compute the medium's response $\rightsquigarrow$ implement into Monte Carlo and generate azimuthal correlations vs PHENIX data.

$2 \to 2$: double hump only through shock waves



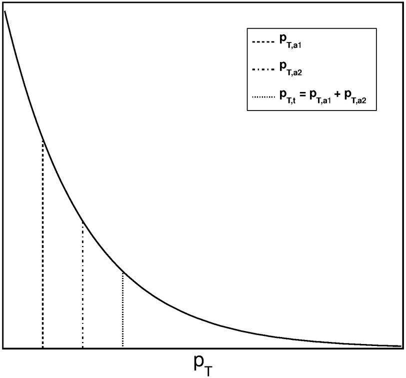
Single parton moving in plasma with momentum p_T deposits energy as a shock wave.

$2 \to 3$: double hump possible with wakes of two away-side partons



Two partons into the medium moving with momentum $p_{1T} + p_{2T} = p_T$ deposit energy, each as a wake (head shock), rather than a shock wave (Mach cone).

$2 \to 2$ vs $2 \to 3$



pQCD supression

$2 \to 3$ supressed by α_S wrt $2 \to 2$

p_T distribution enhancement

$2 \to 3$ enhanced wrt $2 \to 2$, on average (same deposited energy) two partons come with lower momentum than one in the away side

$2 \to 3$: double hump possible with wakes of two away-side partons

Mimic surface emission of the leading parton together with in-medium energy momentum deposited by the away side partons. Steps:

1 generate hard scattering partons: MadGraph $2 \to 3$ processes leading parton fragments in vacuum (KKP), away partons travel into medium (avg. 6 fm) with $dE/dx = 2$ GeV

2 study how the energy and momentum of hard scattering partons gets transferred to the medium: Linearized hydro

3 get the particle's multiplicity: Cooper-Frye away side partons that emerge, fragment in vacuum (KKP)

4 hadron momentum distribution for leading and associate

Linearized, small viscosity hydro

Medium total energy momentum $T^{\mu\nu}$

$$T^{\mu\nu} = T_0^{\mu\nu} + \delta T^{\mu\nu},$$

$\delta T^{\mu\nu}$ parton generated perturbation

$T_0^{\mu\nu}$ energy momentum for underlying medium in equilibrium

Small deviations from equilibrium hydro equations

$$\begin{aligned} \partial_\mu \delta T^{\mu\nu} &= J^\nu, \\ \partial_\mu T_0^{\mu\nu} &= 0 \end{aligned}$$

J^ν source of disturbance: fast moving parton.

Linearized, small viscosity hydro

Relativistic fluid energy momentum tensor components (small η, null ζ)

$$\begin{aligned}
\delta T^{00} &= \delta\epsilon \\
\delta T^{0i} &= \mathbf{g} \\
\delta T^{ij} &= \delta_{ij} c_s^2 \delta\epsilon - \frac{3}{4}\Gamma_s(\partial^i \mathbf{g}^j + \partial^j \mathbf{g}^i - \frac{2}{3}\delta_{ij}\nabla\cdot\mathbf{g})
\end{aligned}$$

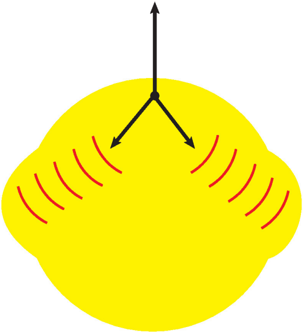
$\mathbf{g}$ fast parton momentum density $\rightarrow$ medium
$\delta\epsilon$ disturbance energy density
$\Gamma_s \equiv \frac{4\eta}{3\epsilon_0(1+c_s^2)}$ sound attenuation length
$c_s = \sqrt{1/3}$ speed of sound

Linearized, small viscosity hydro

Energy momentum equations are easier to be solved in Fourier space

$$
\begin{aligned}
\delta\epsilon &= \frac{i\mathbf{k}\cdot\mathbf{J} + J^0(i\omega - \Gamma_s k^2)}{\omega^2 - c_s^2 k^2 + i\Gamma_s \omega k^2} \\
\mathbf{g}_L &= \frac{i\left[\frac{\omega}{k^2}\mathbf{k}\cdot\mathbf{J} + c_s^2 J^0\right]\mathbf{k}}{\omega^2 - c_s^2 k^2 + i\Gamma_s \omega k^2} \\
\mathbf{g}_T &= \mathbf{g} - \mathbf{g}_L = \frac{i\mathbf{J}_T}{\omega + i\frac{3}{4}\Gamma_s k^2}
\end{aligned}
$$

Energy momentum in-medium deposition by partons



Two away-side partons in $2 \to 3$ processes deposit energy momentum into medium, so model the current they produce with localized disturbance:

$$J^\nu(\mathbf{x},t) = \left(\frac{dE}{dx}\right)\delta(\mathbf{x}-\mathbf{u}t)U^\nu$$

$\frac{dE}{dx}$ energy loss per unit length and $U^\nu \equiv \gamma(1,\mathbf{u})$ with $\mathbf{u}$ parton velocity

Neufeld and Renk, PRC **82** (2010)

Energy momentum deposition $\rightsquigarrow$ particle distribution

Particle yield at central rapidity (Cooper-Frye):

$$\frac{dN}{dyd\phi}(y=0) = \int_{p_T^{\min}}^{p_T^{\max}} \frac{dp_T\ p_T}{(2\pi)^3} \int d\Sigma_\mu p^\mu [f(p\cdot u) - f(p_0)]$$

angle between $\mathbf{g}$ and $\hat{\mathbf{z}}$: ϕ

constant freeze-out hyper surface $d\Sigma_\mu p^\mu = d^3r\ p_T$

equilibrium distribution (Boltzmann): $f(p_0) = \mathrm{e}^{-p_T/T_0}$

background medium's energy density and temperature: ϵ_0, T_0

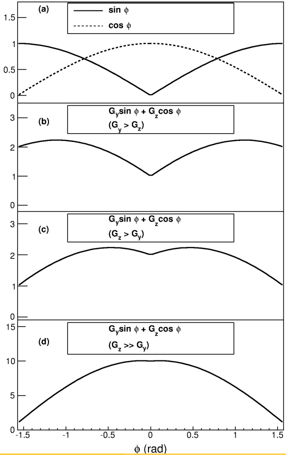
Take massless partons, so $v = 0.9995c$, $\Gamma_s = \frac{1}{3\pi T_0}$ $\eta = \frac{1}{4\pi}$ $T_0 = 350$ MeV and $c_s = \sqrt{1/3}$.

Energy momentum deposited by fast partons in medium

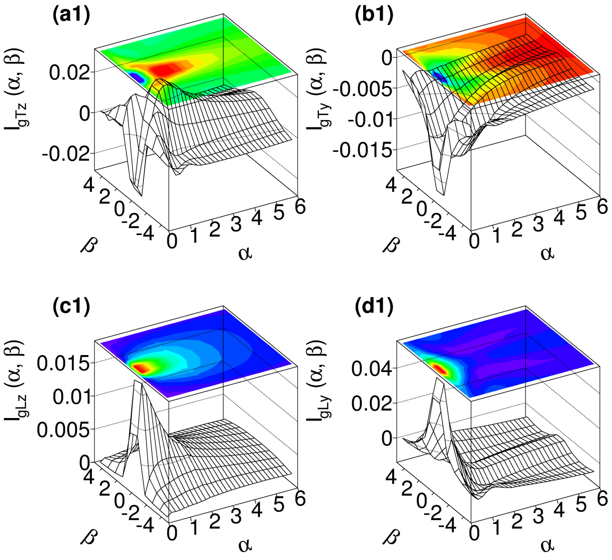
$$f(p\cdot u) - f(p_0) \quad \simeq \quad \left(\frac{p_T}{T_0}\right)\left(\frac{\delta\epsilon}{4\epsilon_0} + \frac{\mathbf{g}_y \sin\phi + \mathbf{g}_z \cos\phi}{\epsilon_0(1+c_s^2)}\right) \mathrm{e}^{-p_T/T_0}$$

Shape of distribution depends on $G_i \equiv \int d^2r \ \mathbf{g}_i$

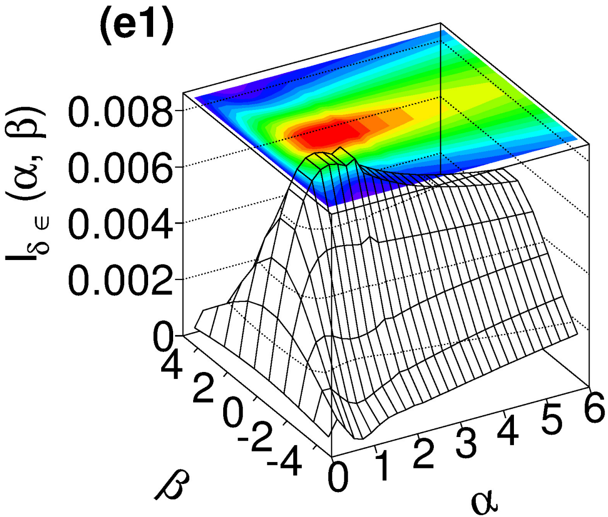
- $G_y > G_z$: $\sin\phi$ two peaks away from $\phi = 0$
- $G_z > G_y$: $\cos\phi$ two peaks close to $\phi = 0$
- $G_z \gg G_y$: peaks become one



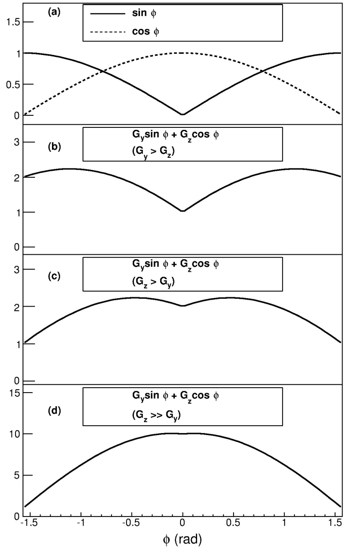
Energy momentum deposited by fast partons in medium



Energy momentum deposited by fast partons in medium



Energy momentum deposited by fast partons in medium



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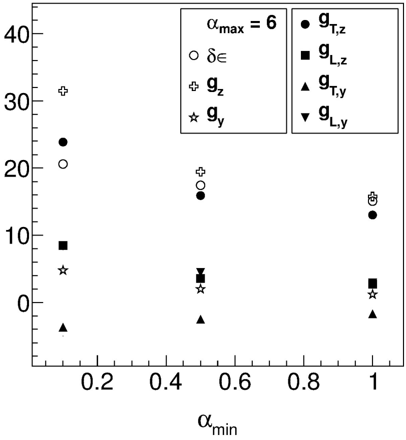
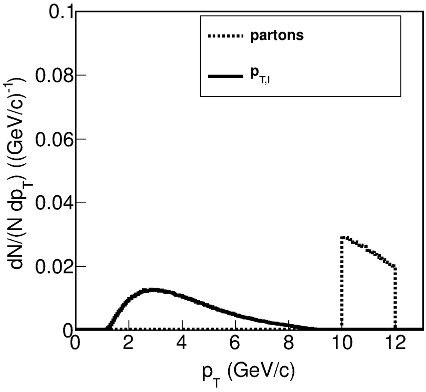
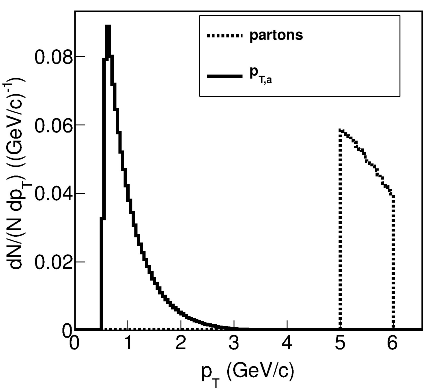


$2 \to 3$: two away-side + surface emission of leading



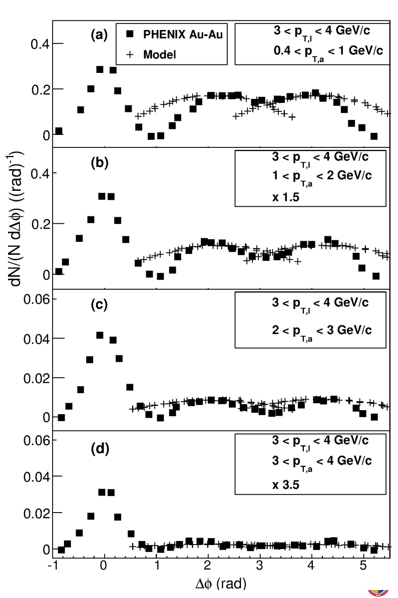


Surface emission of the leading parton together with in-medium energy momentum deposited by the away side one:

10 GeV $\leq p_{T,l} \leq 12$ GeV (LHS), 5 GeV $\leq p_{T,a} \leq 6$ GeV (RHS)

Azimuthal correlations: ADTY model vs PHENIX data

Per-trigger azimuthal angular correlations PHENIX 0-20% Au+Au @ 200 GeV vs ADTY Model PRC 88 (2013) arXiv: 1212.1127



Conclusion

- $2 \to 3$ vs $2 \to 2$ processes in-medium.
- Lower production rate compensated by higher momentum space population.
- Energy-momentum deposited in medium described by low viscosity hydro.
- Particles produced along direction of motion of partons (Wakes instead of Mach cones).
- Surface emission of leading particle together with away side partons depositing energy momentum within medium reproduce hadronization systematics of two hadron correlations.

Outlook

- realistic scenario: not only surface emmision but also partons traveling towards the fireball produced with larger and lower energies and different directions,
- some partons not depositing all of their energy within the medium and hadronizing outside,
- background is not static: dilution of the medium due to longitudinal expansion, decreasing energy density of the background fluid, resulting in a larger sound attenuation length and therefore a smaller energy momentum deposition within the medium
- not Cooper-Frye but rather a Bjorken-like scenario whereby freeze-out happens over a proper time period which can be related to a temperature interval