Hadron-hadron correlations - A theory overview

Björn Schenke

Department of Physics, McGill University, Montreal, Canada

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h-h correlations

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Why correlation studies?

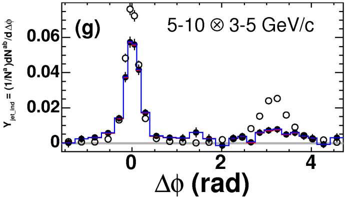
We want to learn about the medium produced in HICs:

- Interaction of hard partons with the medium, energy loss, $\hat{q}$
- Properties of the medium, like the equation of state
- Initial state properties (e.g. glasma?)

Azimuthal and rapidity correlations provide more detailed information than one-body observables and can be used to test theories.

High-p_T azimuthal correlations

High p_T is within the reach of perturbative QCD methods.
First correlation studies are being done with Monte-Carlo simulations like YaJEM, Q-PYTHIA, or MARTINI.
These are ideal tools because they provide a direct link between experiment and theory.



PHENIX, Phys.Rev.C78:014901, 2008

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Example 1: YaJEM

PYTHIA or HERWIG vacuum shower.

$\hat{q}(\eta, r, \phi, \tau)$ characterizes medium.

τ: Translate virtualities into formation times, distributed as

$$P(\tau) = \exp\left(-\frac{\tau}{\langle\tau\rangle}\right), \quad \text{with } \langle\tau\rangle = \frac{E_f}{Q_f^2} - \frac{E_f}{Q_i^2}$$

η, r, ϕ: Partons go along the eikonal trajectory of the initiating parton.

Medium induced virtuality leads to increased radiation

$$\Delta Q_a^2 = \int_{\tau_a^0}^{\tau_a^0+\tau_a} \hat{q}(\xi) d\xi\,, \quad (\tau_a^0 = \text{ endpoint of previous branching})$$

T. Renk, arXiv:0808.1803, Phys.Rev.C78:034908,2008.

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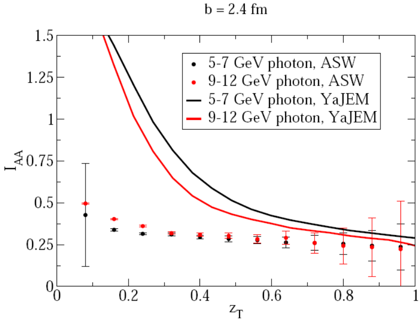
γ-h correlations in YaJEM: T. Renk, Phys.Rev.C80:014901,2009

Back-to-back γ-parton pair, evolve parton in 3+1D hydro medium.
Compare to simulation sampling energy loss probability from ASW.
I_{AA} for away-side hadrons with $p_T > 0.5\,\mathrm{GeV}$



Difference:

- YaJEM shower: sum rule: drop at high z_T increase at low z_T
- ASW calculation: energy is distributed to very low values and large angles

Data is always below 1: So is energy absorbed and redistributed in the medium? Is shower missing physics?

Correlation studies in Monte-Carlo simulations

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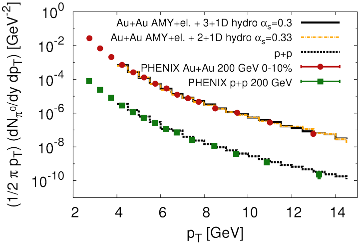
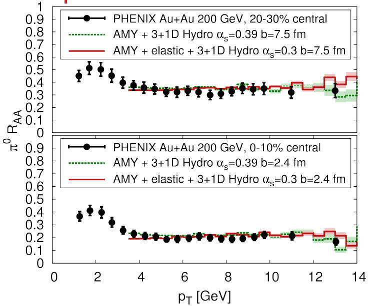
Example 2: MARTINI

- **PYTHIA 8.1** generates individual nucleon-nucleon collisions, vacuum shower
- Medium evolution in hydrodynamic background incl. elastic and inelastic (AMY) processes
- Hadronization using **PYTHIA 8.1**

Full microscopic information on the hard part of the event

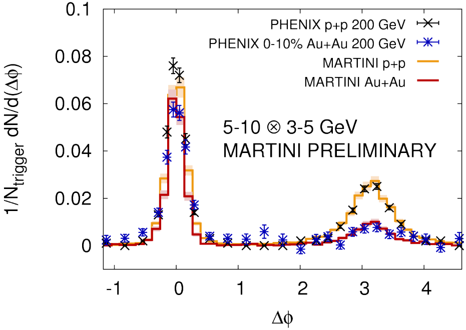




Correlation studies in Monte-Carlo simulations

MARTINI is well suited for correlation studies.
Can apply same methods as in experiment.

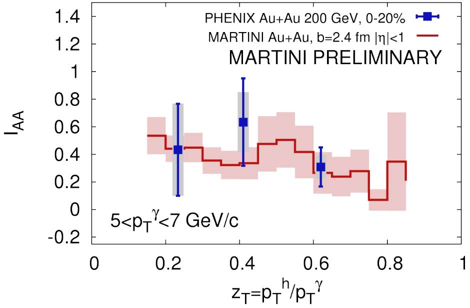
Charged hadron azimuthal correlations with MARTINI:



Works well for hard trigger and hard associated momenta.

Correlation studies in Monte-Carlo simulations

Also $\gamma - h$ correlations are being studied in MARTINI.



Low-p_T correlations

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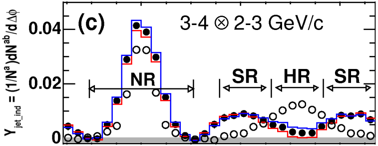
Possible explanations of the double peak structure:



- Cherenkov radiation
  Dremin, Nucl.Phys.A767:233 (2006)
  Majumder, Wang, Phys.Rev.C73:051901 (2006)
  ✗ predicts strong p_T dependence of angle
- Mach cones
  Stöcker, Nucl.Phys.A750:121 (2005)
  Casalderrey-Solana et al, Nucl.Phys.A774:577 (2006)
  Betz, Chaudhuri, Chesler, Neufeld, Noronha, Renk, Ruppert Torrieri, ...
- Deflected jets.
- Evolution of initial hot spots generates needed topology
  Takahashi et al, Phys.Rev.Lett.103:242301 (2009)

Recent studies:

- Energy deposition: Qin et al, Phys.Rev.Lett.103:152303 (2009), Neufeld, Renk, arXiv:1001.5068 (2010)
- Expanding medium Betz et al, Nucl.Phys.A830:777C-780C (2009)
- NeXSPheRIO fluctuating init. cond. Takahashi et al, Phys.Rev.Lett.103:242301 (2009)
- Parton Cascade BAMPS Bouras et al, arXiv:1004.4615 (2010)

Is it a Mach cone signal?

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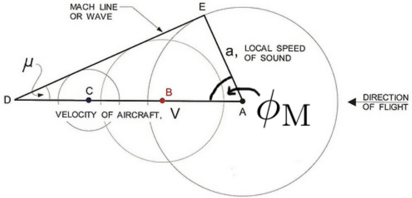
We hoped so, because

$$\cos\phi_\mathrm{M} = c_s/v_\mathrm{jet}$$



With $v_\mathrm{jet} \simeq 1$ for a light parton $\rightarrow c_s = \frac{dp}{de}$.
So we could learn about the equation of state fairly directly.

Mach cones form in hydro simulations
but they do not seem to survive the freeze-out.
see e.g. Betz et al, J.Phys.G35:104106 (2008)

Dependence on energy/momentum deposition by the hard parton/shower.

Energy deposition I

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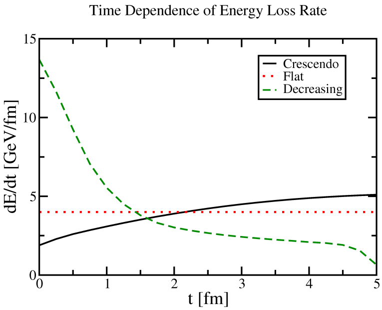
Three scenarios for energy deposition: Neufeld, Renk, arXiv:1001.5068 (2010)



- **Flat**: on-shell parton, elastic energy loss, $E_p \gg \Delta E_{\rm tot} \Rightarrow dE/dt \approx \text{const.}$
- **Crescendo**: increasing number of radiated gluons deposit energy $E_p \gg \Delta E_{\rm tot}$
- **Decreasing**: highly virtual parton evolving in shower motivated by YaJEM result.

Different $\frac{dE}{dt}$ enter the source term $J^\nu = \frac{dE}{dt}(U^\nu - \lambda\partial^\nu)\delta(\mathbf{x} - \mathbf{u}t)$
λ: local medium excitation parameter

Energy deposition I

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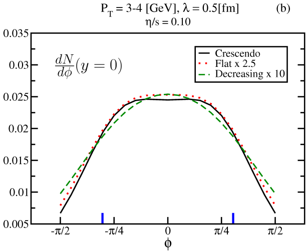
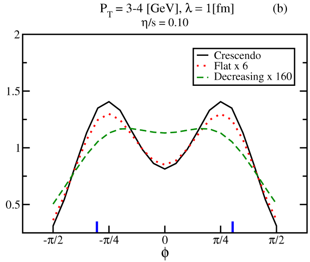
Use linearized hydrodynamics, static medium, isochronous freeze-out:

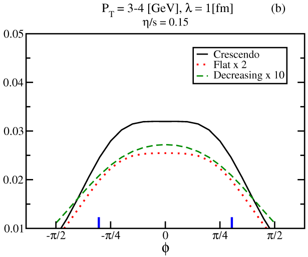
$$T^{\mu\nu} = T_0^{\mu\nu} + \delta T^{\mu\nu}$$

$$\partial_\mu \delta T^{\mu\nu} = J^\nu = \frac{dE}{dt}(t)(U^\nu - \lambda \partial^\nu)\delta(\mathbf{x} - \mathbf{u}t), \qquad \partial_\mu T_0^{\mu\nu} = 0$$

The results also depend on η/s.







Energy deposition II

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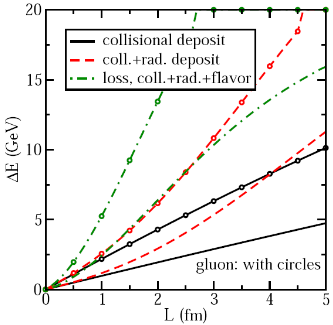
Mach cone formation depending on energy deposition
Qin et al, Phys.Rev.Lett.103:152303 (2009)

- Using in-medium splitting functions, solve coupled set of evolution equations for the deposited energy ΔE.
- Evolve from low to higher virtuality.



when including the in-medium shower (coll.+rad.), deposited energy increases

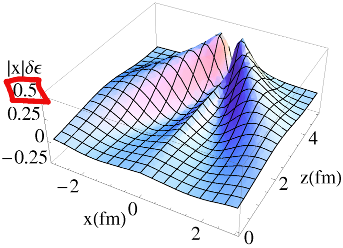
larger part of energy is deposited later

Energy deposition II

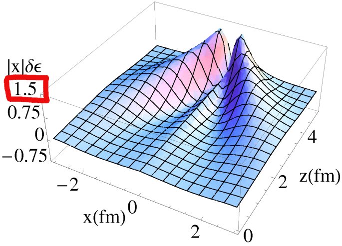
Mach cone formation depending on energy deposition

Qin et al, Phys.Rev.Lett.103:152303 (2009)

Solve lin. hydrodynamics with $J^\nu = \left[\frac{d\Delta E}{d\zeta}, 0, 0, \frac{d\Delta p_z}{d\zeta}\right] \delta^2(\vec{r}_T)\delta(t-z)$



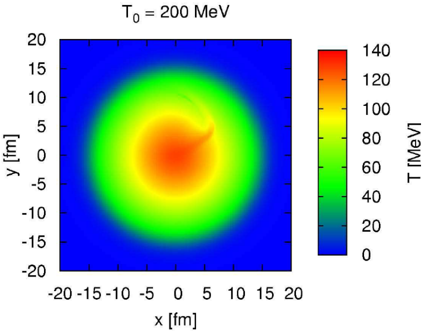
elastic energy loss

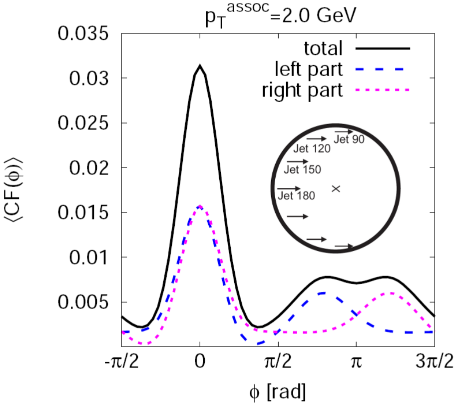


elastic+radiative
like crescendo

Expanding medium

Jets are tilted in the expanding medium.
Mach cones form but only after average over different paths double peak structure is observed.



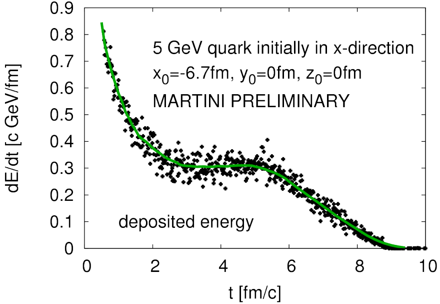


Betz et al, arXiv:1005.5461 and Nucl.Phys.A830:777C-780C (2009)

MARTINI → source term in expanding medium McGill

MARTINI provides source term in an expanding medium.

- Run MARTINI with high momentum parton traveling in x direction through hydro background.
- Take all energy and momentum lost to the medium (average over many runs):



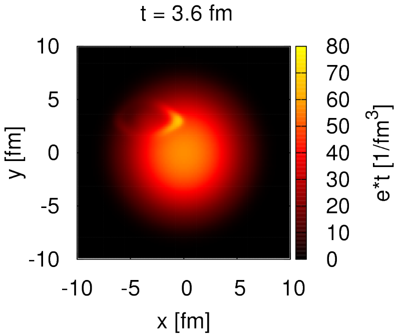
Includes full shower. Radiated partons deposit energy as well.

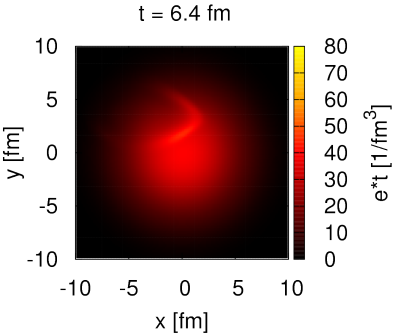
This determines the source term to enter the same hydro evolution.
Work in progress ...

MARTINI → source term in expanding medium

Take the MARTINI source term and incorporate it into 3+1d hydro evolution (e.g. MUSIC):

B. Schenke, C.Gale, S. Jeon, Phys.Rev.C80:054913,2009.
B. Schenke, S. Jeon, C. Gale, arXiv:1004.1408.



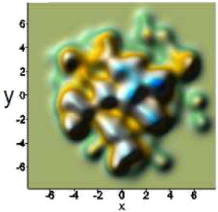


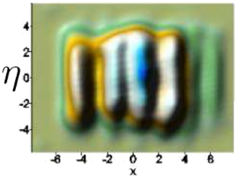
PRELIMINARY

Evolution of fluctuating initial conditions

No jets. Lumpy initial conditions from NEXUS.
SPheRIO hydro evolution.

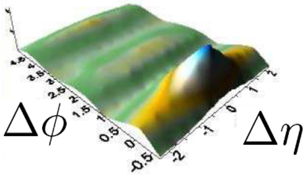
Initial energy density





$\eta = 0$ $\qquad$ y = 0

Final two-particle correlations using ZYAM



Tubes deflect the otherwise isotropic flow.
Takahashi et al, Phys.Rev.Lett.103:242301 (2009)
Andrade et al, arXiv:0912.0703 (2009)

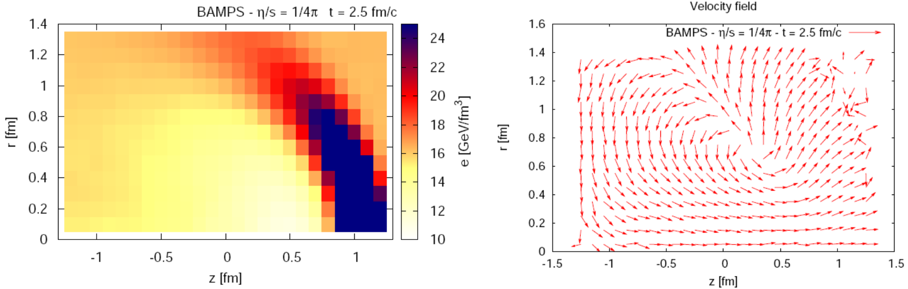
Three-particle correlations could reveal difference to Mach cone idea.

Also see Werner et al, 1004.0805 (2010)

Parton cascade BAMPS

Mach cone like structure forms in the BAMPS parton cascade model

Bouras et al, arXiv:1004.4615 (2010)



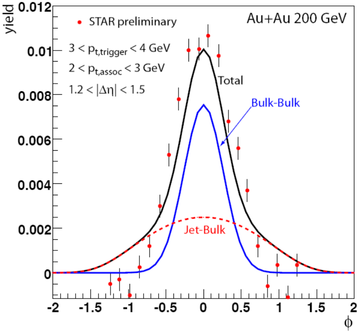
$20\,\mathrm{GeV}$ gluon traversing a $T = 400\,\mathrm{MeV}$ thermalized gluon plasma.
Larger $\eta/s \Rightarrow$ Mach cone disappears.

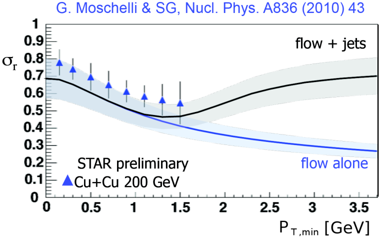
What about the ridge?

Soft ridge: best described by initial flux tubes (from glasma or other).
Dumitru et al, Nucl.Phys.A810:91 (2008)

- Correlations form early → wide correlations in η
- Radial flow focuses particles → narrow correlations in ϕ

Hard ridge: jets become important. Combined contributions from bulk-bulk and jet-bulk correlations can explain data:
Moschelli, Gavin, Nucl.Phys.A836:43-58 (2009); E. Shuryak, Phys.Rev.C76, 047901 (2007)





Summary

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- Monte-Carlo simulations for heavy-ion collisions provide link between theory and experiment to study hard parton-medium interactions e.g. using correlations in the high p_T regime.
- First results for h-h and $\gamma - h$ correlations are available.
- Away-side double peak is investigated mainly in hydro models. Medium response to energy deposition by hard partions? Result of initial fluctuations? Both?
- Near side ridge: Initial flux tubes best explanation. Combination of jets and soft contribution needed to describe hard ridge.