Energy loss in Monte-Carlo schemes with specific example of MARTINI

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McGill

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Brookhaven National Laboratory

Hadronic Jet Production

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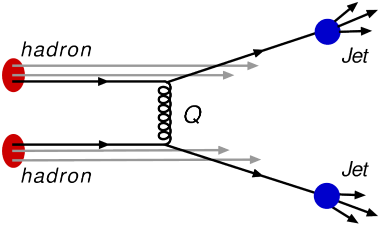
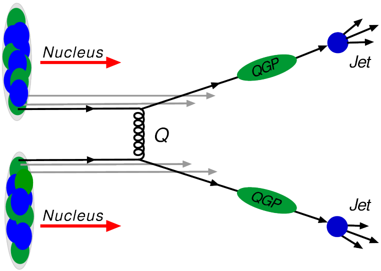
Vacuum: Monte-Carlo simulations are well established tools



Jet production scheme:

$$\frac{d\sigma}{dt} = \int_{abcd} f_{a/A}(x_a, Q)\, f_{b/B}(x_b, Q)\, \frac{d\sigma_{ab\to cd}}{dt}\, D_{\rm vac}(z_c, Q_{\rm frag})$$

Heavy-Ion Collision



How does the medium modify jet properties? Schematically:

$$\frac{d\sigma_{AB}}{dt} = \int_{\text{geometry}} \int_{abcd} f_{a/A}(x_a, Q) f_{b/B}(x_b, Q) \times \frac{d\sigma_{ab\to cd}}{dt} \mathcal{P}(x_c \to x'_c | T, u^\mu) D_{\text{vac}}(z'_c, Q_{\text{frag}})$$

$\mathcal{P}(x_c \to x'_c | T, u^\mu)$: Medium modification of hard parton properties

Implementation

How do we implement the modifications in MC simulations?

$$\frac{d\sigma_{AB}}{dt} = \int_{\text{geometry}} \int_{abcd} f_{a/A}(x_a, Q) f_{b/B}(x_b, Q) \times \frac{d\sigma_{ab\to cd}}{dt} \mathcal{P}(x_c \to x'_c | T, u^\mu) D_{\text{vac}}(z'_c, Q_{\text{frag}})$$

PYTHIA is often (not always) the vacuum MC shower algorithm of choice.
It takes care of $f_{a/A}(x_a, Q) f_{b/B}(x_b, Q)$ and $\frac{d\sigma_{ab\to cd}}{dt}$ and includes $D_{\text{vac}}(z'_c, Q_{\text{frag}})$.
How is it modified to include $\mathcal{P}(x_c \to x'_c | T, u^\mu)$?
Alternatively one can write the above expression in terms of a modified fragmentation function $D_{\text{med}}(z_c, Q_{\text{frag}})$.

Modifying vacuum showers

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One way: Modify the virtualities (example: YaJEM).
$\hat{q}(\eta, r, \phi, \tau)$ characterizes medium.
We need time and spatial information of the shower.
Translate virtualities into formation times, distributed as

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

Spatial information: assume that all partons go along the eikonal trajectory of the initiating parton.
Virtuality gain per unit path length of a parton traversing the medium:

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

Medium induced virtuality leads to increased radiation.

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

Modifying vacuum showers

McGill

YaJEM includes another implementation of energy loss, motivated by results from AdS/CFT correspondence:
Medium exerts a **drag force** on hard partons.

$$\Delta E_a = \int_{\tau_a^0}^{\tau_a^0+\tau_a} D(\xi) d\xi\,, \quad (\tau_a^0 = \text{endpoint of previous branching})\,,$$

where $D = D(\eta, r, \phi, \tau)$ is the drag coefficient.

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

Modifying vacuum showers

McGill

Or: Perfom interleaved splitting and **scattering** (any cross-section, momentum distribution, density) (example: JEWEL).
Again, translate virtuality into time and determine

$$S_{\text{no scattering}}(\tau) = \exp(-\sigma_{\text{el}} n \tau \beta)$$

for a constant density. Can be extended to more general case. If no scattering occurs during lifetime, perform splitting. Otherwise scatter.
For **radiative** processes, modify the splitting functions (early JEWEL versions, also in T. Renk, Phys.Rev.C79:054906, 2009.)

$$P_{a\to bc}(z) = \frac{4}{3}\frac{1+z^2}{1-z} \to \frac{4}{3}\left(\frac{2(1+f_{\text{med}})}{1-z} - (1+z)\right)$$

or simply

$$P_{a\to bc}(z) = (1+f_{\text{med}})P_{a\to bc}(z) \quad \text{(JEWEL)}$$

N. Borghini, U.A. Wiedemann, hep-ph/0506218

K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, U.A. Wiedemann, Eur.Phys.J.C60:617-632,2009

Modifying vacuum showers

McGill

Q-PYTHIA also modifies the splitting function:

$$P_{\text{tot}}(z) = P_{\text{vac}}(z) + \Delta P\,,$$

using

$$\Delta P = \Delta P(z,t,\hat{q},L,E) = \frac{2\pi k_T^2}{\alpha_s}\frac{dI^{\text{med}}}{dzdk_T^2}$$

where $\hat{q}$,L characterize the medium by entering in $dI^{\text{med}}/dzdk_T^2$.

Wang, Guo 2001; Borghini, Wiedemann 2005; Polosa, Salgado 2006; Armesto, Cunqueiro, Salgado, Xiang 2007; Majumder 2009

PYQUEN/HYDJET performs the complete PYTHIA vacuum shower and after that modifies the jets using elastic and radiative (BDMPS) processes.

I.P. Lokhtin, A.M. Snigirev, J.Phys.G34:S999-1004,2007

MARTINI

Now MARTINI.

An event: 1 - Initial jet distribution

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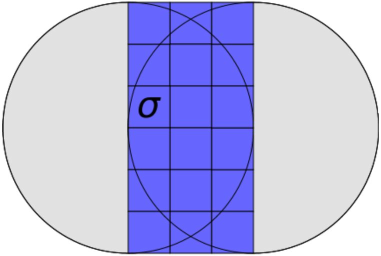
Let's follow a typical **MARTINI** event and point out difficulties.

- Determine transverse positions of initial hard processes: Sample initial positions of nucleons in nuclei A and B, using Woods-Saxon form of the nuclear density function. Superimpose the transverse areas, depending on the impact parameter. Determine number of jet events in patches of area $\sigma_{\rm inel}$, each having probability $\sigma_{\rm jet}(p_T^{\rm min})/\sigma_{\rm inel}$.



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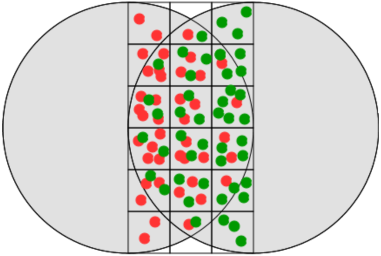

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Alternative: (e.g. to only study R_{AA}) Evolve jets from only one nucleon-nucleon collision in the medium. Then its initial position is sampled from the initial jet density distribution:

$$\mathcal{P}_{AB}(\mathbf{b},\mathbf{r}_T) = \frac{T_A(\mathbf{r}_T + \mathbf{b}/2)T_B(\mathbf{r}_T - \mathbf{b}/2)}{T_{AB}(b)}$$

2 - Perform hard scattering/vacuum shower

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PYTHIA 8.1 is used to generate the individual nucleon-nucleon collisions.

Initial parton distribution functions are selected using **LHAPDF**.
Nuclear effects can be included (**EKS98** or **EPS08**).
We modified PYTHIA slightly to allow for colliding neutrons, assuming isospin symmetry.
PYTHIA 8.1 performs the initial state shower.

Problem: PYTHIA 8.1 needs fine tuning.
We did a rough tune to match π^0 and photon spectra in pp.

2 - Perform hard scattering/vacuum shower

McGill

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Initial parton distribution functions are selected using **LHAPDF**.
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We modified PYTHIA slightly to allow for colliding neutrons, assuming isospin symmetry.
PYTHIA 8.1 performs the initial state shower.

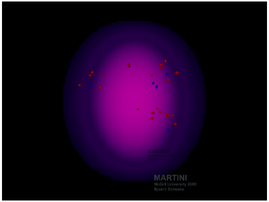
Problem: No interference between medium and vacuum shower.
Either let PYTHIA **do the whole final state shower** (as in PYQUEN), **or stop the shower** when medium evolution starts, i.e., only go down to the scale $Q_{\min} = \sqrt{\frac{p_T}{\tau_0}}$, where τ_0 is the time when the medium evolution begins. E.g. $\tau_0 = 0.6\,\mathrm{fm}$ for most of the hydro simulations.

3 - Medium evolution

Parton positions are evolved even for $\tau < \tau_0$.
Once $\tau > \tau_0$ the full medium evolution begins.
First, we need information on the soft background medium.
Currently, in MARTINI we included 4 different hydrodynamic calculations at different impact parameters.

Problem: Currently cannot use fluctuation of the impact parameter because hydro evolution is given for fixed average impact parameter in a given centrality bin.

Hydro provides temperature $T(\tau, x, y, \eta)$ and fluid velocities $u^\mu(\tau, x, y, \eta)$.
We perform Lorentz boosts to local fluid cells and then determine whether in-medium processes occur.



3 - Medium evolution

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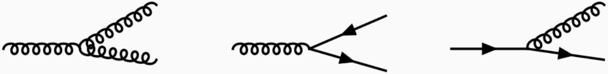
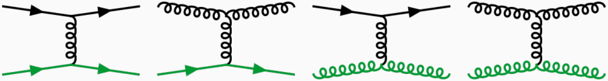
The possible processes, included in MARTINI:

Inelastic processes (AMY)

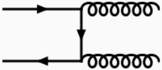


Elastic processes

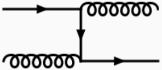


Conversion

annihilation



Compton



(both ways)

+photon emission/conversion

3 - Medium evolution

In the local fluid cell the medium is characterized by temperature T.

1 advance parton positions

according to their velocity $\mathbf{v}$

1. advance parton positions

3 - Medium evolution

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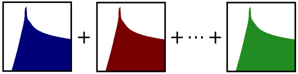
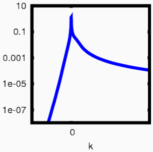
In the local fluid cell the medium is characterized by temperature T.

2 determine whether the parton undergoes **a** process

using the total probability

$P_{total} =$ 

1. advance parton positions
2. decide if a process occurs



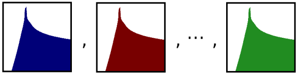
Cartoon of a typical rate

3 - Medium evolution

In the local fluid cell the medium is characterized by temperature T.

3 decide which process occurs

...according to relative weight:



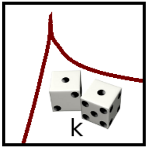
1. advance parton positions
2. decide if a process occurs
3. decide which process occurs

3 - Medium evolution

In the local fluid cell the medium is characterized by temperature T.

4 sample transferred energy/momentum

...using the rate



and perform process

1. advance parton positions
2. decide if a process occurs
3. decide which process occurs
4. sample k using the transition rate

3 - Medium evolution

McGill

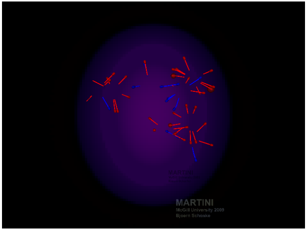
In the local fluid cell the medium is characterized by temperature T.

5 if emitted parton has energy above threshold

add emitted parton, e.g.

and evolve it in future steps

1. advance parton positions
2. decide if a process occurs
3. decide which process occurs
4. sample k using the transition rate
5. add emitted partons to shower



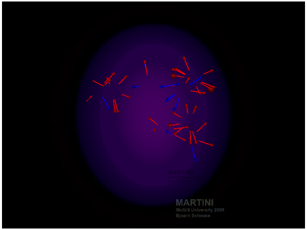
3 - Medium evolution

So, MARTINI solves Focker-Planck type rate equations

$$\frac{dP_j(E,t)}{dt} = \sum_{ab} \int d\omega \left(P_a(E+\omega,t) \frac{d\Gamma_{a\to j}}{d\omega}(E+\omega,\omega) - P_j(E,t) \frac{d\Gamma_{j\to b}}{d\omega}(E,\omega) \right)$$

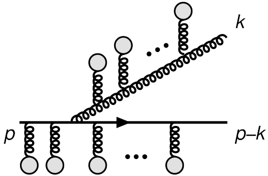
using Monte-Carlo methods, **in addition** keeping track of all the microscopic information in each event.

1. advance parton positions
2. decide if a process occurs
3. decide which process occurs
4. sample k using the transition rate
5. add emitted partons to shower



3 -Medium evolution - aside: LPM?

MARTINI employs AMY rates. The LPM effect is included in the rates.



To get the transition rates:
Resum all such diagrams and then square.

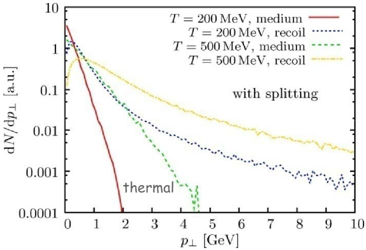
JEWEL (planned): microscopically, based on the formation time $t_f = 2\omega/k_T^2$:

1. create gluon in inelastic process with ω and k_T
2. check if scattering during t_f
   - no: gluon is formed, done
   - yes: scattering after $\Delta t < t_f$, re-evaluate formation time, back to 2

So far no description of interference with vacuum radiation.
Others implement LPM e.g. by parametrized modification of parton splittings (Q-PYTHIA,Q-HERWIG).

3 -Medium evolution - aside: recoil?

- At this point **MARTINI** does not include recoil of medium partons. The soft background stays thermal.
- **JEWEL** does include recoil of scattering centers:
  The initial thermal spectrum of scattering centers becomes a power law at intermediate and high p_T, with the recoil going predominantly in the jet direction.
  Problem: How to connect color strings between recoiled partons and leading jet partons? How will this affect hadronization?



from: presentation by Gunnar Ingelman (also see Eur.Phys.J.C60:617-632,2009)

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Outlook: MARTINI + real-time hydro evolution

Within **MARTINI**, we are working on interleaving hydrodynamic evolution for the soft part with the existing evolution of the hard part.
Jet partons can deposit energy/momentum, modifying $T^{\mu\nu}$ that will be further evolved in the hydrodynamic simulation, and reacting back on the hard part ...

4 - Hadronization

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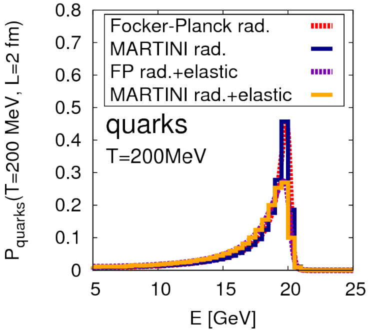
The medium evolution for a parton ends if

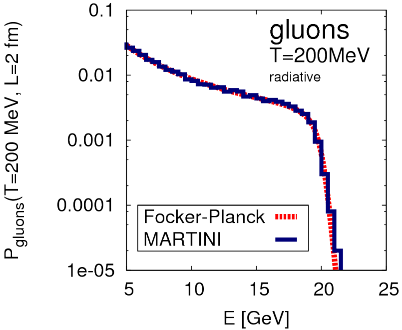
- its energy in a fluid cell's rest frame drops below $4T$ or
- it enters the hadronic phase (in a mixed phase, processes only occur for the QGP fraction)

Once all partons have left the QGP phase, hadronization is performed using PYTHIA's Lund fragmentation model.
Problem: Overall colorless system is mandatory. So we have to **keep track of all color strings in the evolution**.
If a parton is emitted, we have to connect string ends appropriately. If conversion occurs, we have to add a string end to a thermal parton that we sample from the medium distribution.
Problem: **Collisions randomize color structure of the shower**. So other fragmentation methods that include this should be studied.
Problem: We do a **pure vacuum fragmentation** - there should be modifications to that - pick-up of medium partons?

Brick in MARTINI

Some brick results from **MARTINI**:
Quark $E_{\mathrm{ini}} = 20\,\mathrm{GeV}$, $L = 2\,\mathrm{fm}$, $T = 200\,\mathrm{MeV}$





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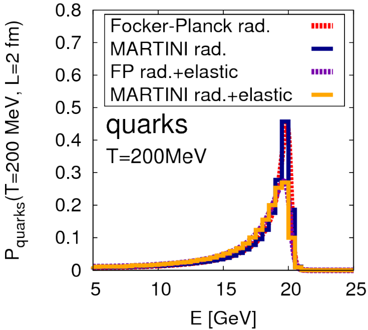

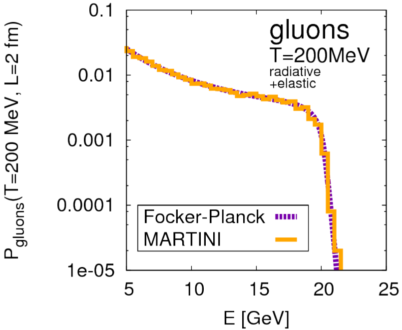

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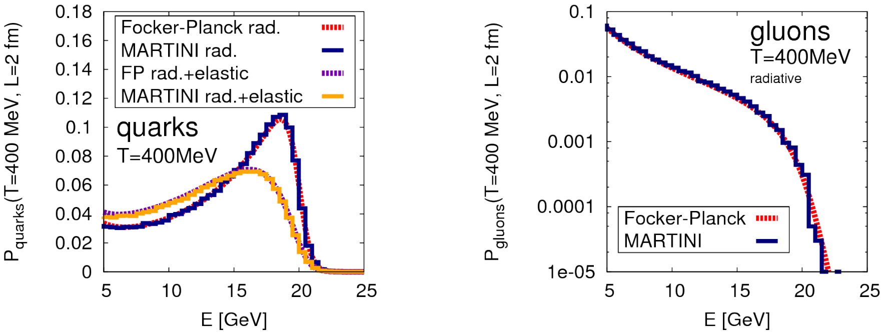

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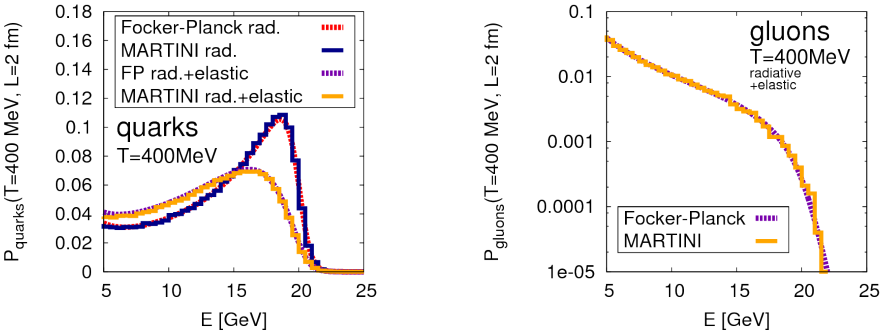

Brick in MARTINI

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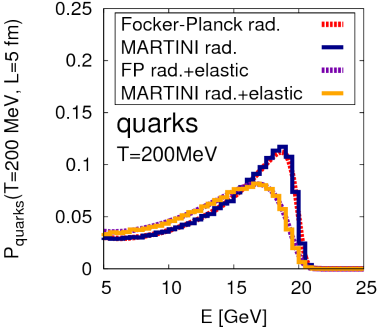

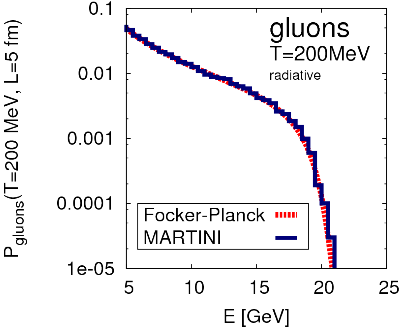

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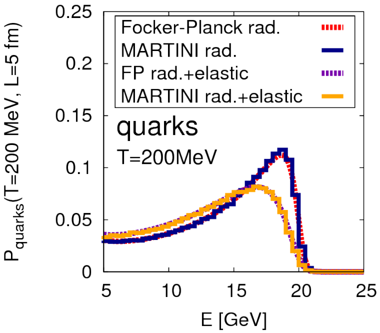

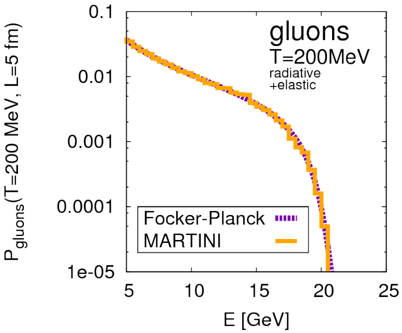

Brick in MARTINI

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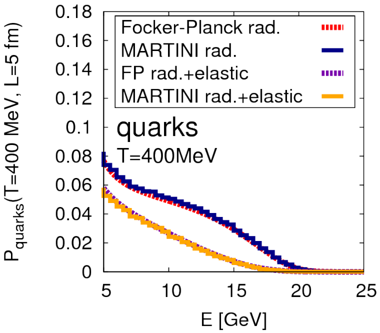

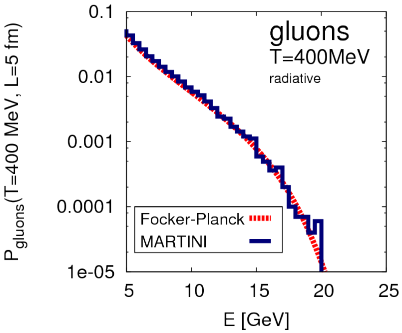

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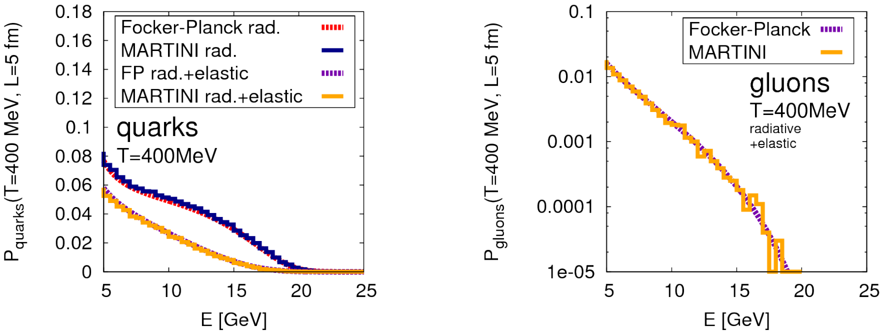


Brick conclusion

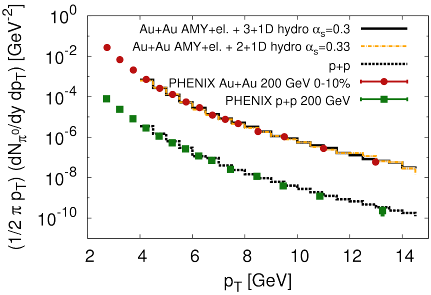
Brick results in **MARTINI** are the same as for McGill-AMY as we know it.
They have to be because that's what we put in.

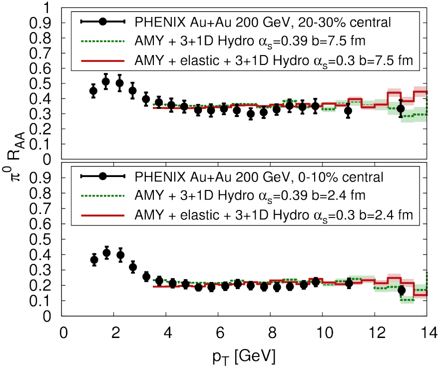
So nothing **new** to worry about here...

+

Results and comparison to exp. data

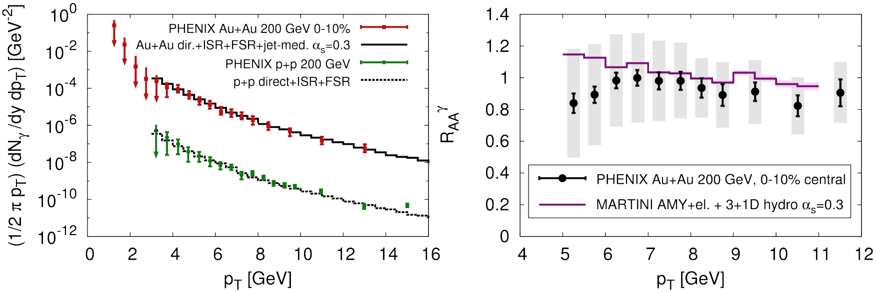
π^0 production





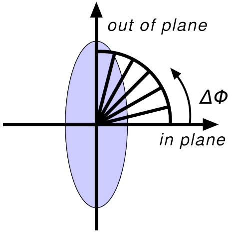
Results and comparison to exp. data

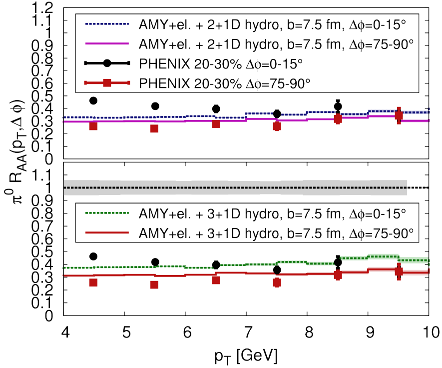
photon production



Results and comparison to exp. data

azimuthal dependence of R_{AA}





Summary

We are on the right track. Many MCs are being developed.
All of them are different. Good! We can learn a lot.

I tried to focus on problems. Here are some important ones:

- Different implemented energy loss formalisms. → The old problem of TECHQM. Even new concepts to include energy loss.
- Different vacuum MCs/versions/tunes used.
- Transition from vacuum shower to medium shower. Interference?
- Color structure in heavy-ion events unclear.
  Hadronization = model. Need to compare different ones.
- Medium response: The soft medium evolution should not be completely decoupled from the jet evolution. (working on it)
- Eventually comparisons between MCs will be needed. We need good documentations/simple user interfaces/clean codes.

Summary - MCs

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Alphabetically. Not necessarily complete.

- HIJING (Heavy Ion Jet INteraction Generator)
  X.-N. Wang, M. Gyulassy, Phys.Rev.D44:3501-3516,1991.
- JEWEL (Jet Evolution With Energy Loss)
  K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, U.A. Wiedemann, Eur.Phys.J.C60:617-632,2009.
  K. Zapp, J. Stachel, U.A. Wiedemann, Phys.Rev.Lett.103:152302,2009.
- MARTINI (Modular Algorithm for Relativistic Treatment of Heavy IoN Interactions)
  B. Schenke, C.Gale, S. Jeon, Phys.Rev.C80:054913,2009.
- PQM (Parton Quenching Model)
  A. Dainese, C. Loizides, G. Paic, Eur.Phys.J.C38:461-474,2005.
- PYQUEN/HYDJET/HYDJET++ (HYDrodynamics plus JETs)
  I.P. Lokhtin, A.M. Snigirev, J.Phys.G34:S999-1004,2007.
  I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, I. Arsene, K. Tywoniuk, Comput.Phys.Commun.180:779-799,2009.
- Q-PYTHIA / Q-HERWIG
  N. Armesto, L. Cunqueiro, C.A. Salgado, Eur.Phys.J.C63:679-690,2009.
  N. Armesto, G. Corcella, L. Cunqueiro, C.A. Salgado, JHEP 0911:122,2009.
- YaJEM (Yet another Jet Energy-Loss Model)
  T. Renk, arXiv:0808.1803, Phys.Rev.C78:034908,2008.

A MARTINI event

A MARTINI event

MARTINI

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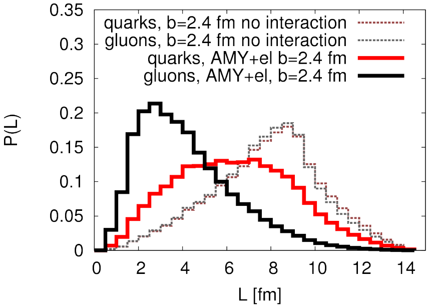
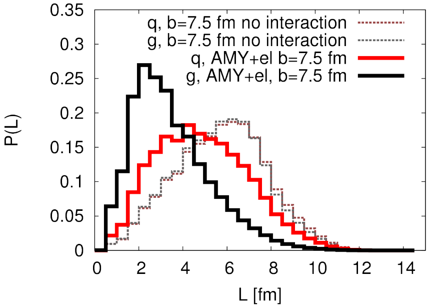
Backup.

Traveled distances

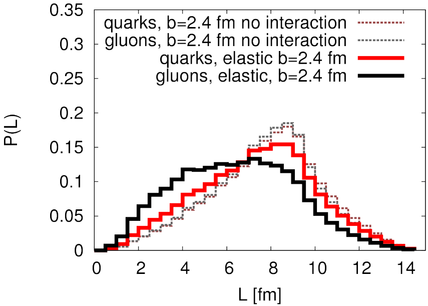
3+1D hydro, AMY+elastic, $\alpha_s = 0.3$

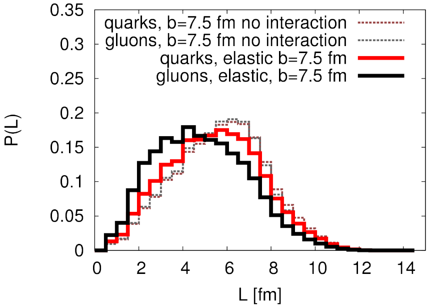




Traveled distances

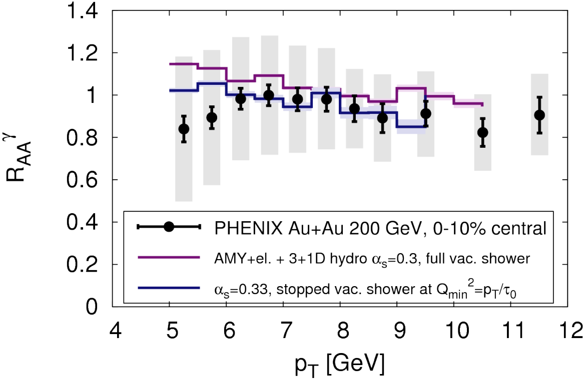
3+1D hydro, elastic only, $\alpha_s = 0.3$





Effect of different vacuum-medium transition

To fit π^0-R_{AA} we need a 10 % larger α_s when we end the vacuum shower at $Q_{\min} = \sqrt{p_T/\tau_0}$. This changes the photon production:



PRELIMINARY

Color structure - Conversion processes

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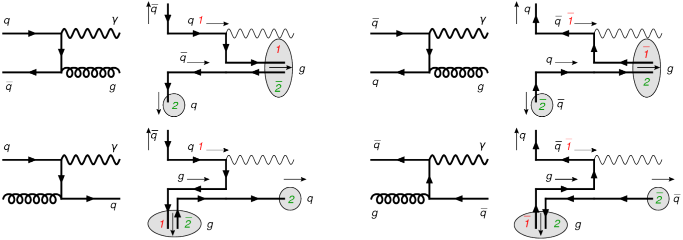
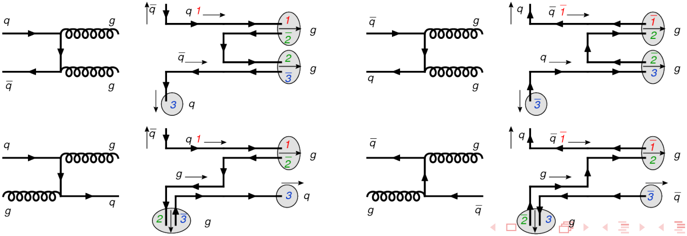
Photon conversion



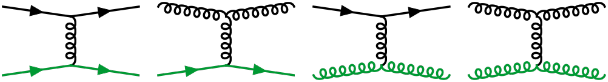
Quark to gluon conversion



Elastic processes - diffusion method

Previously, the "diffusion method" has been used to include elastic energy loss:
Approximate the transition rates by

- the mean energy loss dE/dt computed from these diagrams



- a diffusion term

The rate equation becomes

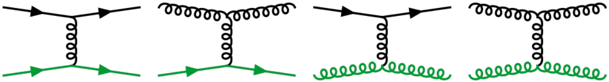
$$\frac{dP(E)}{dt} \approx \frac{d}{dE}(A\,P(E)) + \frac{d^2}{dE^2}(B\,P(E))$$

with the drag and diffusion coefficients $A = dE/dt$ and $B = T\,dE/dt$.

Elastic processes

Go beyond the approximation and compute the transition rate directly:

$$\frac{d\Gamma}{d\omega}(E,\omega,T) = d_k \int \frac{d^3k}{(2\pi)^3} \int \frac{d^3k'}{(2\pi)^3} \frac{2\pi}{16pp'kk'} \delta(p-p'-\omega)\delta(k'-k-\omega) \times |\mathcal{M}|^2 f(k,T)(1 \pm f(k',T))$$



- $\mathcal{M}$ is calculated from the diagrams above
- $f(k,T)(1 \pm f(k',T))$ contains the medium, characterized by the temperature T and the flow velocities of the local cells

Elastic processes

To compute the transition rate:

- Shift integration from $\mathbf{k}'$ to the exchanged momentum $\mathbf{q} = \mathbf{p} - \mathbf{p}'$

$$\frac{d\Gamma}{d\omega}(E,\omega,T) = \frac{d_k}{(2\pi)^3}\frac{1}{16\,E^2}\int_0^p dq \int_{\frac{q-\omega}{2}}^{\infty} dk\,\theta(q-|\omega|) \times \int_0^{2\pi}\frac{d\phi_{kq|pq}}{2\pi}|\mathcal{M}|^2 f(k,T)(1\pm f(k',T))$$

Cure the infrared divergence:

- introduce q^* to separate hard ($\sim \sqrt{ET}$) from soft ($\sim gT$) scale
- compute soft part using resummed (hard thermal loop) propagators

In the final result $q*$ will not drop out as it does in the calculation of dE/dt because some approximations cannot be done in this case.

Two methods

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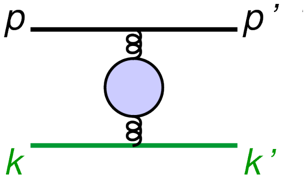
The soft part can be calculated from the diagram



The 'blob' indicates the resummed (screened) gluon propagator

Now we can

- A: fix q^*, compute hard and soft part and combine them
- B: extend the computation of the soft part to large q

Method B is a good approximation because elastic energy loss is dominated by small momentum transfers.

B. S., C. Gale, G.-Y. Qin, Phys. Rev. **C79**, 054908 (2009)

Results: Elastic energy loss only

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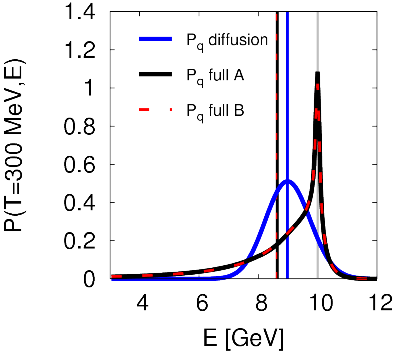
Quark jet, initial energy $E = 10\,\mathrm{GeV}$
going through brick of QGP with length $L = 2\,\mathrm{fm}$
at fixed temperature $T = 300\,\mathrm{MeV}$.



Diffusion method leads to significantly different results.

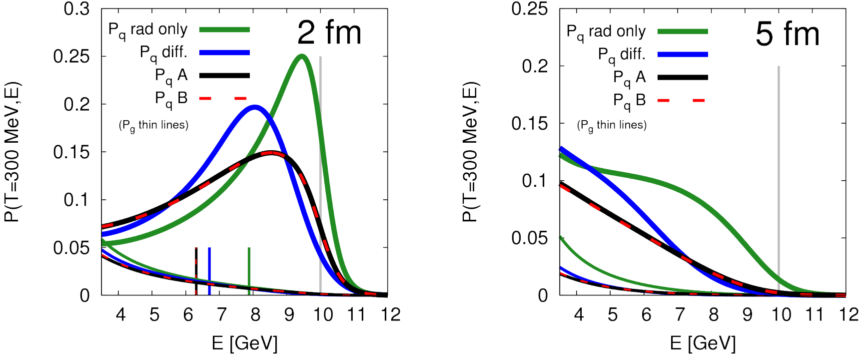
Method A and B lead to the same result as expected.

B. S., C. Gale, G.-Y. Qin, Phys. Rev. **C79**, 054908 (2009)

Results: Radiative + elastic energy loss

McGill

Quark jet, initial energy $E = 10\,\mathrm{GeV}$
going through brick of QGP with length $L = 2\,\mathrm{fm}$, and $L = 5\,\mathrm{fm}$
at fixed temperature $T = 300\,\mathrm{MeV}$.



B. S., C. Gale, G.-Y. Qin, Phys. Rev. **C79**, 054908 (2009)