Hard probes, finite temperatures, and Monte Carlo

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Jets at the LHC

- dN/dA_j
- Jets in a thermal medium
- The importance of full Monte Carlo
- MUSIC+MARTINI+fastjet
- Numerical calculation of dN/dA_j

Running coupling, finite-size effects, and Monte Carlo

Conclusions

Reconstructing jets

A definition insensitive to non-perturbative physics is needed.

The anti-k_T algorithm (Cacciari et al. 2008): The metric between hadrons 1 and 2 is

$$d_{12} = \underbrace{\min\left(\frac{1}{k_{1T}^2}, \frac{1}{k_{2T}^2}\right)}_{\text{infrared safe}} \times \underbrace{\frac{(y_1 - y_2)^2 + (\phi_1 - \phi_2)^2}{R^2}}_{\text{collinearly safe}} .$$

A list of distances between all hadrons is constructed and *ordered*. The momenta of the hadrons are summed and the list shortened until all distances exceed some R.

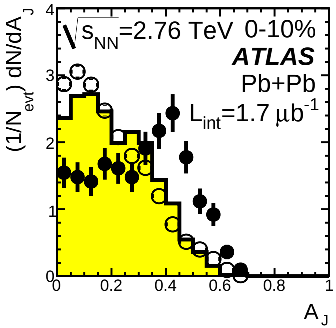
Dijets at the LHC

$A_j \equiv \frac{E_{T>} - E_{T<}}{E_{T>} + E_{T<}}$, dN/dA_j for dijets (like v_2 for bulk hadrons) a signal nearly absent in *pp*.

Also like v_2, no need for *pp* reference.

Possible sources of asymmetry:

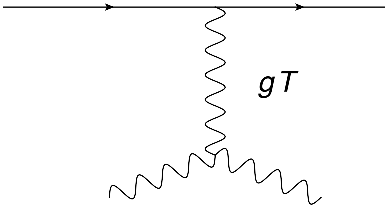
- The beginning: in-medium evolution to low Q^2 (Majumder and Shen 2011).
- The middle: thermally determined rates (CY, Schenke et al. 2011), $\hat{q}$ (Casalderrey et al. 2011).
- The end: color flow affecting hadronization (Beraudo eta al. 2011), problems with jet reconstruction in a fluctuating background (Cacciari et al. 2011).

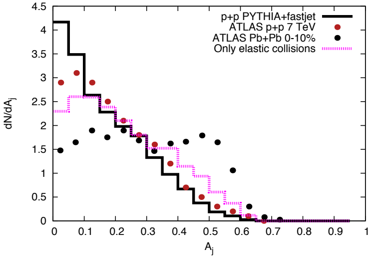


From ATLAS (2010).

Thermal processes modifying jets

HTL effective theory inspires the consideration of these processes:
First, collisions with HTL quasiparticles:

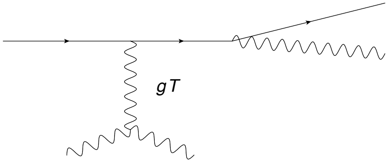


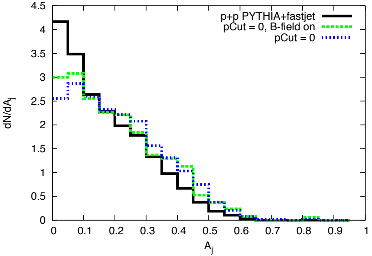


Effect on dijets: leads to *some* asymmetry.

Thermal processes modifying jets

HTL effective theory inspires the consideration of these processes:
Next, collinearly enhanced radiative splittings:

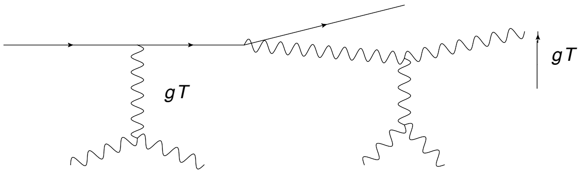




In HTL effective theory, radiative splittings are collinearly enhanced (contribute at leading order), but also affected by coherence effects (LPM effect) (Arnold, Moore, and Yaffe 2002).
Effect on dijets: leads to almost no asymmetry! Anti-k_T algorithms find split partons efficiently.

Thermal processes modifying jets

HTL effective theory inspires the consideration of these processes:
Finally, transverse momentum broadening of slowed and split partons:



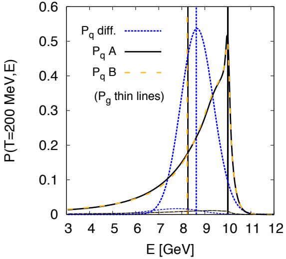
Effect on dijets: deflects partons by $\delta\theta \sim gT/p_T$, can be large for $p_T \sim gT$.

Full Monte Carlo for solving rate equations

The evolution of partons in-medium is determined by an *integral* equation:

$$\frac{dP(E)}{dt} = \int d\omega \left[P(E+\omega)\frac{d\Gamma(E+\omega, E)}{d\omega} - P(E)\frac{d\Gamma(E, E+\omega)}{d\omega} \right]$$

Diffusive approximations turn this into a differential equation but miss some of the physics! Specifically, the evolution of a jet to small z is underestimated:



Schenke and Qin (2009).

Full simulation of of a jet in medium

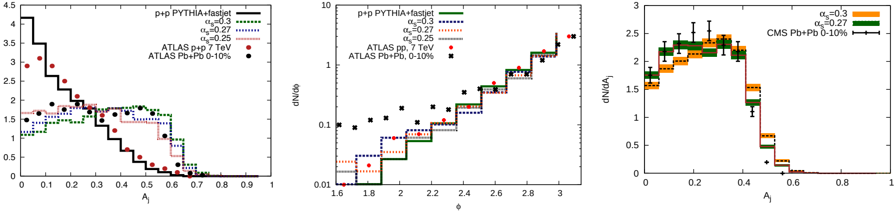
MARTINI (Schenke et al. 2009) solves for the inclusive

$$d\sigma_{AA\to h} = \sum_{i,j} \int d\mathbf{b}\, dx_1\, dx_2\, f^i_{A_1}(x_1, Q^2) f^j_{A_2}(x_2, Q^2) d\sigma_{ij\to kl} \times P(k, l|m, n; u^\mu, T) D_m D_n$$

using event generation and Monte Carlo:

- Shadowing and anti-shadowing of pdf's, averaging over isospin
- PYTHIA8 for multiple final states via parton showering
- Monte Carlo for solving the elastic and inelastic rate equations, informed by the 3+1-dimensional hydrodynamical evolution calculated by MUSIC (Schenke et al. 2009)
- Hadronization via the Lund string model, *including* color flow in splittings
- Jet reconstruction via FASTJET, an anti-k_T algorithm

Dijets with MARTINI: applying all perturbative processes



Physics conclusion: dN/dA_j can be explained with in-medium jet evolution to small z's, and collisions moving small-z partons out of the jet cone.

One practical issue: this calculation applied a p_{cut}, an assumption that all partons radiated with low enough energy are kicked out of the cone. Lowering this cut has little effect but *becomes computationally difficult*.

dN/dA_j at RHIC

At sPHENIX, full azimuthal coverage, pseudorapidity covered for $|\eta| < 2$.

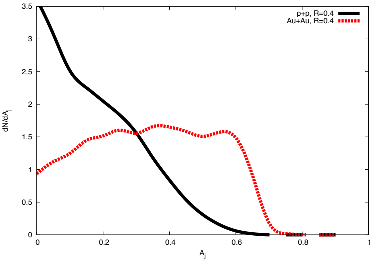
$\sqrt{s} = 200\mathrm{GeV}\ A$, $b = 4\ \mathrm{fm}$.

$R = 0.4$

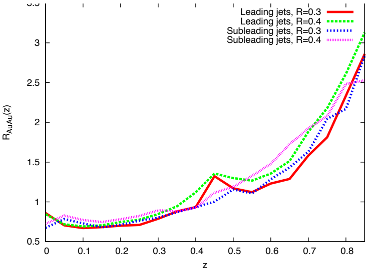
$p_T^{\mathrm{leading}} > 25\ \mathrm{GeV}/c$,

$p_T^{\mathrm{subleading}} > 5\ \mathrm{GeV}/c$.

$|\eta_{\mathrm{leading}}| < 1$.



AA fragmentation functions



- For PHENIX dijets in the same ranges as the asymmetry calculation above.
- Subleading jets a way to find jets strongly modified by the medium.
- Actually, after evolution, $R(z)$ large near $z = 1$ because small x partons are kicked out of the cone.
- Recoil from the medium needs to be included (in progress).

Running coupling, finite-size effects, and Monte Carlo

Arnold-Moore-Yaffe rates $\frac{d\Gamma_{a\to bc}}{dpdk}$ correct to order g and are suitable for Monte Carlo, however they:

- assume an infinite medium
- do not run couplings with momentum scale

At the LHC, jets consist of hadrons from 10 to 100 GeV. At both RHIC and the LHC, the medium exists for $\sim 10\ \mathrm{fm/c}$.
Can these effects be included, and easily applied to phenomenology with Monte Carlo?

Running coupling in $\frac{d\Gamma_{a\to bc}}{dpdk}$

Running coupling is easily included: $\frac{d\Gamma}{dk}(p/T, k/T, \alpha_s) \to \frac{d\Gamma}{dk}(p, k, \Lambda_{\mathrm{QCD}})$

- In the AMY integral equation, $S^0_\mu(p,k)$ should run with momentum scales while Debye masses should not.
- Rough estimate: all scatterings transfer $q \sim gT$ while the scale of the splitting vertex is $\left\langle k_T^2 \right\rangle = \hat{q} t_f = \hat{q} p / \left\langle k_T^2 \right\rangle \to \langle |k_T| \rangle = (\hat{q} p)^{\frac{1}{4}}$.

Finite-size effects on $\frac{d\Gamma_{a\to bc}}{dpdk}$

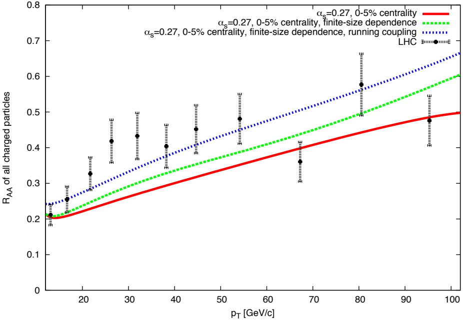
The emission rate of a hard parton can be reorganized as

$$\frac{d\Gamma_{a\to bc}(t)}{dk} = \frac{P_{bc}^{a\,(0)}(x)}{\pi p}\mathrm{Re}\int_0^t dt' \int_{\mathbf{q},\mathbf{p}} \frac{i\mathbf{q}\cdot p}{\delta E}\mathcal{C}(t)K(t,\mathbf{q};t',\mathbf{p})$$

(Caron-Huot and Gale, 2011).

Correct description of finite-size effects, that spans many formalisms, *however*, not easy to implement with Monte Carlo.

Parametrizing these effects for R_{AA} at the LHC



Preliminary results including the effect of running coupling and finite-size effects:
Total rates $\Gamma(\tau)$ rescaled with $\alpha_s(\mu)$ and a parametrization of finite-size effects

Conclusions

Dijet asymmetry can be explained by partonic evolution down to small z and transverse momentum broadening.
Determined with ease with MARTINI: Monte Carlo integration without diffusive approximations.

Challenges for Monte Carlo:
Recoiling partons
Running coupling
Media of finite-size

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