# Monte-Carlo study of hard probes

Clint Young, with Charles Gale, Sangyong Jeon, and Björn Schenke

McGill

## High momentum partons at finite temperature

Elastic rates

$$\frac{d\Gamma}{d^3p'} = \frac{d_k}{16p^0(p^0-\omega)}\int\frac{d^3k}{(2\pi)^3k}\frac{d^3k'}{(2\pi)^3k'}|\mathcal{M}|^2(2\pi)^4\delta^4(k'-k-Q)n(k)[1\pm n(k')]$$

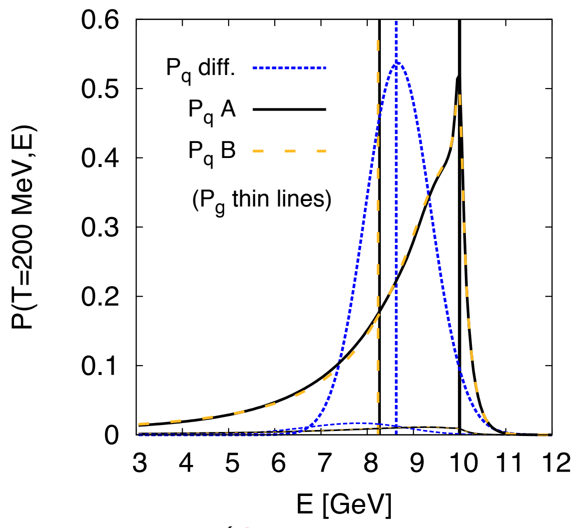
and radiative splittings

$$\frac{d\Gamma_{i\to j}}{dk} = \frac{C_s\alpha_s}{4p^7}\frac{1}{1\pm e^{-k/T}}\frac{1}{1\pm e^{-(p-k)/T}}P_{j\leftarrow i}(x)\int\frac{d^2\mathbf{h}}{(2\pi)^2}\,2\mathbf{h}\cdot\mathrm{Re}\mathbf{f}$$

contribute at the same order in $\alpha_s$. The rates determine integral parton evolution equations:

$$\begin{aligned}\frac{dP_{q\bar{q}}(p)}{dt} &= \int_k P_{q\bar{q}}(p+k)\frac{d\Gamma^q_{qg}(p+k,k)}{dkdt} - P_{q\bar{q}}(p)\frac{d\Gamma^q_{qg}(p,k)}{dkdt}\\ &\quad + P_g(p+k)\frac{d\Gamma^g_{q\bar{q}}(p+k,k)}{dkdt},\\ \frac{dP_g(p)}{dt} &= \int_k P_{q\bar{q}}(p+k)\frac{d\Gamma^q_{qg}(p+k,p)}{dkdt} + P_g(p+k)\frac{d\Gamma^g_{gg}(p+k,k)}{dkdt}\\ &\quad - P_g(p)\left(\frac{d\Gamma^g_{q\bar{q}}(p,k)}{dkdt} + \frac{d\Gamma^g_{gg}(p,k)}{dkdt}\Theta(2k-p)\right),\end{aligned}$$

The "diffusive approximation" fails to describe the small-z evolution of jets:

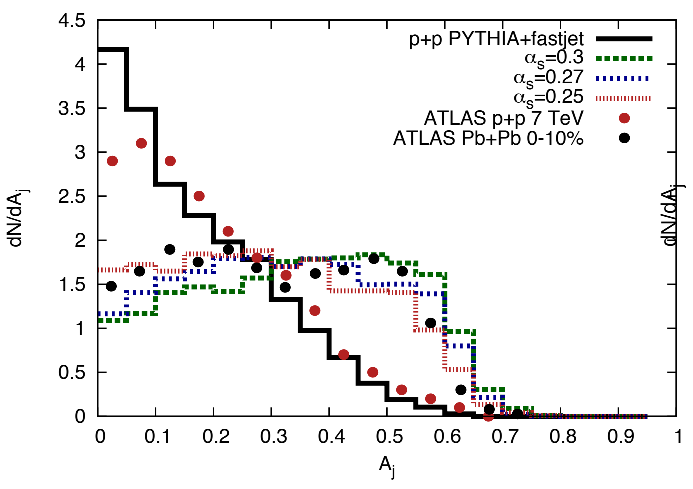


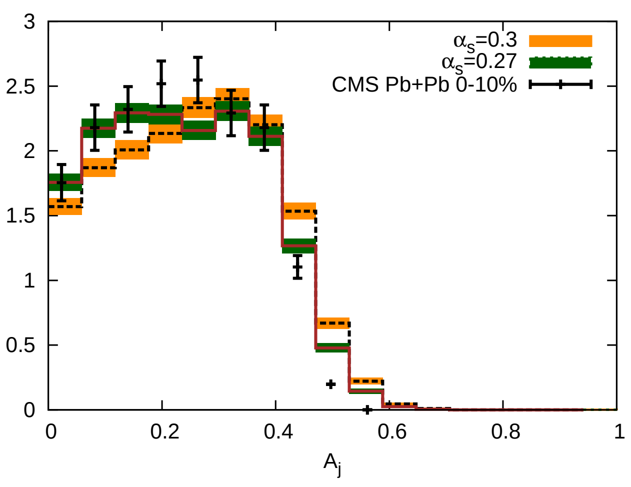

From Schenke and Qin (2009): the parton evolution of $P(E,t=0)=\delta(E-10\ \mathrm{GeV})$ to $t=5\ \mathrm{fm}/c$ at $T=200\ \mathrm{MeV}$

MARTINI (Schenke, Gale, and Jeon 2009) solves these integral equations using Monte Carlo. The space-time evolution in temperature and flow is determined using MUSIC (Schenke, Gale, and Jeon 2010), a 3+1-dimensional hydrodynamical simulation.

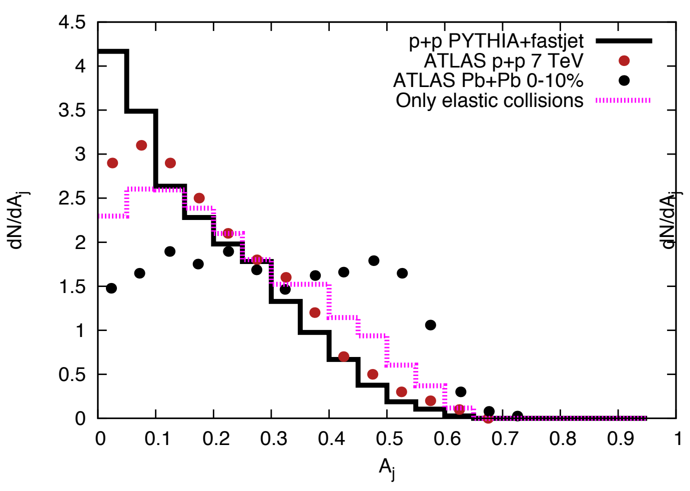
## Dijet asymmetry

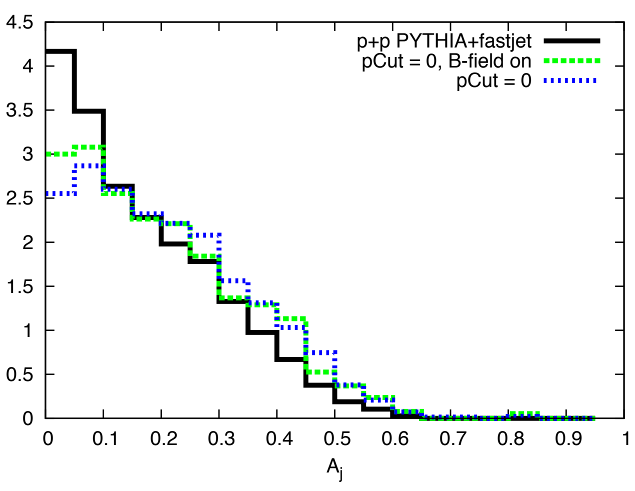
$2\to2$-scattering in QCD leads to dijets. In p+p collisions, $P_{tot\,1}\approx -P_{tot\,2}$. In Pb+Pb collisions, dijets develop significant asymmetry: for $A_j=(E_{T>}-E_{T<})/(E_{T>}+E_{T<})$, $dN/dA_j$ is no longer peaked at $A_j=0$:



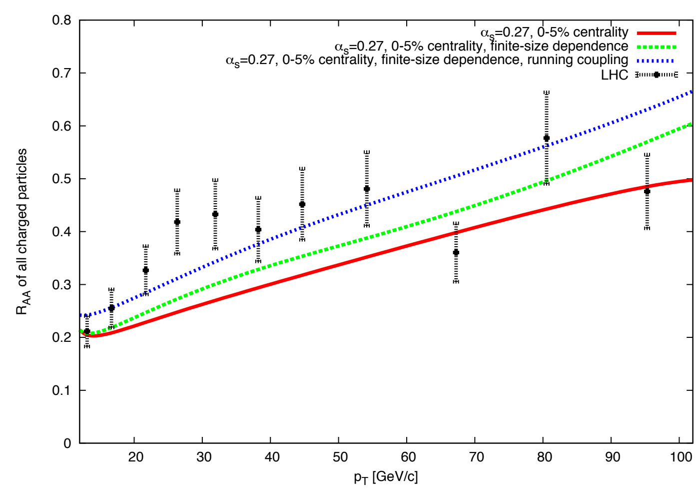

$\alpha_s=0.3$ is consistent with ATLAS' results, only when the evolution to small z is properly determined:




Elastic collisions alone require large $\alpha_s$ (or, large $\hat{q}$) to decollimate jets efficiently; radiative splittings alone lead to almost no dijet asymmetry because anti-$k_T$ algorithms are insensitive, by construction, to collinear processes.

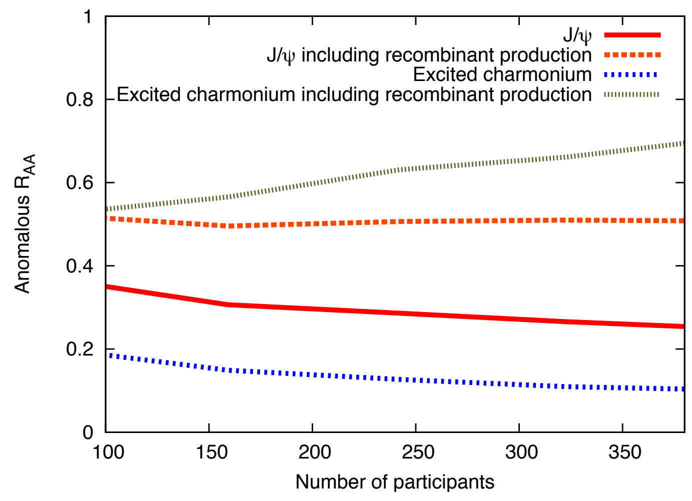
## Charged particle $R_{AA}$: the LPM effect, finite-size effects, and running coupling

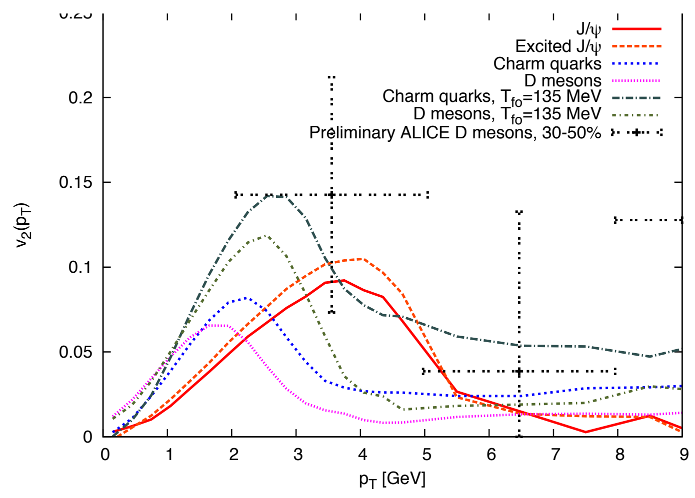



For a medium with finite size, the interference between vacuum and medium-induced splittings suppresses the radiative rates at early times (Caron-Huot and Gale, 2010).
The momentum scale of the splitting vertex is given by $\langle k_T^2\rangle=\hat{q}t_f=\hat{q}k/\langle k_T^2\rangle\to\langle|k_T|\rangle=(\hat{q}k)^{\frac{1}{4}}$.
Momentum transfers in elastic collisions are space-like and of order $gT$ and their running is ignored.

## MARTINI for heavy quarks: $v_2$ and $B_c$ mesons at the LHC

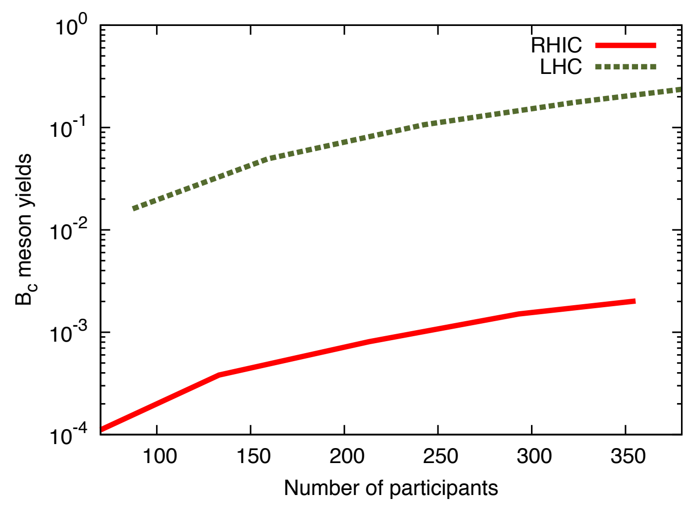
The convergence of HTL calculations for heavy quark properties is poor; however, the diffusive approximation is robust and allows the use of Langevin equations with rapidly decorrelating noise for describing the dynamics: $\frac{dp^i}{dt}=-\eta p^i+\xi^i$, $\langle\xi^i(t)\xi^j(t')\rangle=\kappa\delta^{ij}\delta(t-t')$ is reasonable when $M\gg T$.
Phenomenology of non-photonic electron elliptic flow at RHIC lead to the estimate $2\pi TD_c=3.0$, which is used in the following. It is consistent with AdS/CFT at finite temperature and lattice QCD estimates.
Quarkonium production in heavy-ion collisions is determined using a modified color evaporation model: the invariant mass $M=\sqrt{-p^2+V_{\mathrm{Cornell}}(r_{\mathrm{CM}})}$ is used to determine what final states are kinematically accessible.




Recombinant production of incompletely thermalized heavy quarks leads to production of excited charmonium, in greater yields than those for the $J/\Psi$ and increasing with $N_{\mathrm{part}}$.

The long lifetime of the QGP phase at the LHC compared with RHIC leads to comparatively large elliptic flows of the $J/\Psi$ yields.




$B_c$ mesons are produced recombinantly, with yields increasing in $N_{part}$.

## References

B. Schenke, C. Gale and G. -Y. Qin, Phys. Rev. C 79, 054908 (2009) [arXiv:0901.3498 [hep-ph]].
B. Schenke, C. Gale and S. Jeon, Phys. Rev. C 80, 054913 (2009) [arXiv:0909.2037 [hep-ph]].
B. Schenke, S. Jeon and C. Gale, Phys. Rev. C 82, 014903 (2010) [arXiv:1004.1408 [hep-ph]].
C. Young, B. Schenke, S. Jeon and C. Gale, Phys. Rev. C 84, 024907 (2011) [arXiv:1103.5769 [nucl-th]].
C. Young, B. Schenke, S. Jeon and C. Gale, arXiv:1111.0647 [nucl-th].
S. Caron-Huot and C. Gale, Phys. Rev. C 82, 064902 (2010) [arXiv:1006.2379 [hep-ph]].