The “stopped jet” at RHIC and beyond

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What is a jet?
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- **LPHD**: Hadronization does not affect exclusive observables (jet shape, energy distribution etc..)
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• LPHD: Hadronization does not affect exclusive observables (jet shape, energy distribution etc..)
• medium is colored, deconfined
• study modifications to learn more about QGP
• learn about (p)QCD in dense environment
$4 < p_T(trig) < 6$ GeV

$\varphi = 0$

$2 < p_T(trig) < 4$ GeV

$\varphi = \pi$

**Baselines:** $p+p$ (vacuum) and $d+Au$ (cold nuclear matter)
Fragmentation process is well described by pQCD in vacuum!
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Is the jet completely stopped??
Jet tomography

Where does the emitted particles originate from?

\[ \sqrt{s_{NN}} = 62.4 \text{ GeV} \]

\[ \sqrt{s_{NN}} = 200 \text{ GeV} \]

\[ \sqrt{s_{NN}} = 5.5 \text{ TeV} \]

Jet tomography

Where does the emitted particles originate from?

→ surface bias!

Jet tomography

Where does the emitted particles originate from?

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Jet tomography

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\[
\begin{align*}
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\end{align*}
\]

\(\rightarrow\) surface bias!

Di-hadron correlations are better: 25 % of them originate from the center of the overlapping zone!

Can scan the geometry of the medium!

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Can scan the geometry of the medium!


Increasing the trigger $p_T$

- a fine-tuned signal
- background has a complicated structure: $v2$, $v3$, ...
- harder trigger means more collimated jet in vacuum - this part reappears
Increasing the associated $p_T$
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- When increasing the trigger $p_T$ we see the jet resurfacing?
- No broadening - just depletion?

Adams et al. PRL 97 (2006) 162301
Increasing the associated $p_T$

$z_T = \frac{p_T(assoc)}{p_T(trig)}$

$I_{AA} = \frac{D_{AA}}{D_{pp}}$

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- No broadening - just depletion?
Where does the missing energy go?

Higher $p_T \rightarrow$ Away-side suppression

$\langle p_T \rangle_{\text{assoc}} > 2$ GeV/c

- $4 < p_T^{\text{trig}} < 6$ GeV/c

Adams et al. PRL 90 (2005) 152301

- big excess in soft particle production
- spread out over large angles

Lower $p_T \rightarrow$ Away-side enhancement

$\langle p_T \rangle_{\text{assoc}} > 0.15$ GeV/c

Adams et al. PRL 91 (2003) 072304

- $\langle p_T \rangle_{\text{assoc}} > 0.15$ GeV/c
- spread out over large angles

Adams et al. PRL 95 (2005) 152301
Where does the missing energy go?

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- spread out over large angles

Is it the jet - or the response of the medium - or just the medium??
Theory of jet quenching


\[ \Delta E \sim \hat{q}L^2 \]

- \( \hat{q} \) is related to the medium density
- theory works fairly well for the hard part of the spectrum

\[ K = 4.1 \pm 0.6 \]

\[ \hat{q}(\xi) = K \hat{q}_{\text{QGP}}(\xi) \approx K \cdot 2\epsilon^{3/4}(\xi) \]

[disclaimer: cold lithium atoms]
A medium-modified shower

1) The probability of losing a fraction $\Delta E$ of the energy

$P(\Delta E)$
A medium-modified shower

I) The probability of loosing a fraction $\Delta E$ of the energy

$P(\Delta E)$

II) Medium-modified shower

**MC**: Can account for all emissions + energy momentum conservation!

Figure 5: Ratio of medium to vacuum fragmentation functions for $\pi^0$'s (left) and all hadrons (right), for different gluon energies $E_{\text{jet}}$, medium lengths $L$, transport coefficients $\hat{q}$ and maximum virtualities $t_{\text{max}}$, see the legends on the plots.

Jet quenching. In Fig. 6 we present results for the nuclear suppression factor for charged particles defined as

$$R_{\text{AA}}(\eta=0, p_T) = \left| \frac{dN_{\text{ch}}}{d\eta dp_T} \right|_{\text{quenched}} / \left| \frac{dN_{\text{ch}}}{d\eta dp_T} \right|_{\text{unquenched}}$$

for which we run $10^6$ pp events at $\sqrt{s_{\text{NN}}} = 200$ GeV both in the unquenched case ($\hat{q} = 0, L = 0$) and in the quenched case, requiring a minimum $p_{\text{T}}^{\text{min}} = 8$ GeV in PYTHIA

For the latter the geometry is that of a $0-10\%$ central PbPb collisions and the treatment of the product ion points and of the quenching parameters is done like in the PQM model [24]. In short, the production points of the hard scatterings are distributed in the nuclear overlapping area according to the probability of binary nucleon-nucleon collisions. Then, $\hat{q}$ and in-medium path length $L$ are computed locally through two integrals of the density of binary nucleon-nucleon collisions along parton trajectories isotropically distributed in azimuth, see the Appendix A. In this model the only free parameter is the scale of the transport coefficient $k$ (in fm). Using the value reported in Ref. [24] to reproduce single-inclusive RHIC $R_{\text{AA}}$, $k = 6 \cdot 10^6$ fm (which corresponds to an average $\langle \hat{q} \rangle = 14$ GeV$^2$/fm in this case) we get a suppression factor of order 5 at $p_T > 5$ GeV in semi-quantitative agreement with RHIC experimental data [1]. While no comparison to experimental data is aimed here, we note that these results are in good agreement with those from Ref. [24] in the PQM model which considers the energy loss of the leading parton through the simple ansatz [4] usually assumed in previous jet quenching phenomenology at RHIC. This implies that the introduction of evolution in...
A medium-modified shower

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$P(\Delta E)$

II) Medium-modified shower

MC: Can account for all emissions + energy momentum conservation!

Still missing piece: medium response!
Large phase space for perturbative QCD!

New paradigm at LHC...

Annual Yield ($E_T^\text{min}$ or $p_T^\text{min}$)

Pb+Pb minbias, 5.5 TeV
Binary scaling from p+p

$L=0.5 \text{ mb}^{-1}\text{s}^{-1}$; 1 year=$10^6 \text{s}$
Jet physics in heavy-ion collisions

Jet physics in heavy-ion collisions

Also new ideas about soft radiation at large angles from QCD coherence in medium! - see many talks at the conference

J. Casalderrey-Solana, Y. Mehtar-Tani, H. Ma, A. Beraudo, K. Zapp and many more...

Summary

- mix of both perturbative and soft physics!
- see strong depletion of away-side yield, no broadening
- soft particles are spread out at large distances
- mix of both fragmentation and medium physics
- jets at LHC (and RHIC too..)
Back-up slides
Jets in HIC

Pythia with Gaussian smearing

$1/N \frac{dN}{dA}$

Jet clustering has been performed with the anti-$k_t$ algorithm [fl] with $R=0.4$. Our analysis will differ in that we study HYyJET [ge] rather than HIJING and use a lower $p_t$ cut-off for the Pythia events. The tune we use for HYyJET 6 gives an average background level of $\Sigma_{e\gamma}$ GeV per unit area for $|\eta|<2.8$ and $|\Delta\phi|>\pi/2$. The results labelled "pp" reference always correspond to $p_{t,min}$ GeV with no smearing. Jet clustering has been performed with the anti-$k_t$ algorithm [fl] with $R_{re}$. Specific version of HIJING [fn]c Our analysis will differ in that we study HYyJET rather than HIJING and use a lower $p_t$ cut-off for the Pythia events. The tune we use for HYyJET gives an average background level of $\Sigma_{e\gamma}$ GeV per unit area for $|\eta|<2.8$ and $|\Delta\phi|>\pi/2$. Further comparisons are discussed in appendix vcg. HYyJET's simulation of quenching has been turned off to avoid the potential confusion that might arise from the quenching of hard jets associated with the PbPb simulation rather than with the embedded Pythia event. Quenching has only a modest effect on the HYyJET fluctuations. Since detectors can have an impact on fluctuations, we have also processed the events through a simplified calorimeter. The tuning parameters used to simulate LHC events at $\sqrt{s}=2.76$ TeV with HYDJET vur6 have been extrapolated between the vtt GeV iRHICl and yry TeV iLHC at designed energies used in [ut] ifootnote 7lo namely $n_{hsel}=u$, $y_{fl}=w$, $yt_{fl}=x$, and $p_{t,min}=y$. Quenching effects have been switched off by setting $n_{hsel}=ur$. The embedded events come from Pythia version 6rxvwo tune DWo run at $\sqrt{s}=v$. 76 TeV.

Further information can be found in Cacciari, Salam, Soyez arXiv:1101.2878 [hep-ph].
Soft associated production

Adams et al. PRL 95 (2005) 152301

near-side ridge!
Radiative energy loss in pQCD

- Projectile undergoes multiple scatterings in the medium
  - acquires a phase
  - induces radiation
  - loose energy to the medium [NEGLECTED]

- medium-induced one-gluon radiation spectrum

\[ k_\perp^2 = \sqrt{\frac{\omega \mu^2}{\lambda}} = \sqrt{\omega q} \]

\[ \Delta E \sim \hat{q} L^2 \]

[Baier, Dokshitzer, Mueller, Peigne, Schiff, Zakharov (1997-2001), Gyulassy, Levai, Vitev...]

\[ \omega \frac{dN}{d\omega d\theta} \]
Onset of decoherence in media

- a dense medium suppresses interferences
- angular ordering is relaxed