Exploring perturbative QCD splittings in heavy-ion collisions

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Probing QCD at High Energy and Density with Jets 2023, Seattle
Introduction

theory

observation

[S, Catani’s lectures on yt]
Introduction

How is it done in pp collisions?
Hardest splitting in jets

1. Find a jet
2. Recluster with C/A
3. Find branching with hardest $k_t$

$k_{t,g} = z_g \cdot \theta_g \cdot p_T$

$1/\theta_g$

$z$

$\theta$

non-perturbative

[Mehtar-Tani, Soto-Ontoso, Tywoniuk]
[Caucal, Soto-Ontoso, Takacs]
[ALICE, JHEP 05 (2023) 244]
[ATLAS, PRC 107 (2023) 054909]
Hardest splitting in jets

- Higher energy = more perturbative

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Hardest splitting in jets

- Higher energy = more perturbative
- Low $k_t$ = non-pert. corrections
- Cut on $k_t$ to reduce corrections
- ($p_T > 400$ GeV to enhance stat.)
Hardest splitting in jets

Pythia8 hadrons:
pp @ 5.02 TeV, inclusive jets,
$p_T = 1$ TeV, $R_{\text{anti-}k_t} = 0.4$, $|\eta| < 2.8$,
dynamical grooming: max $k_t$

$k_{t,g} > 30$ GeV

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Hardest splitting in jets

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Hardest splitting in jets

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$k_{t,g} > 0$ GeV

pp @ 5.02 aTeV, inclusive jets,
$p_T > 400$ GeV, $R_{\text{anti-}k_t} = 0.4$, $|\eta| < 2.8$,
dynamical grooming: max $k_t$
Hardest splitting in jets

- Higher energy = more perturbative
- Low $k_t$ = non-pert. corrections
- Cut on $k_t$ to reduce corrections
- $(p_T > 400$ GeV to enhance stat.)
- Controlled pp baseline!
How to do it in AA collisions?
Hardest splitting in quenched jets

- Medium scales
Hardest splitting in quenched jets

JetMed partons:
AA @ 5.02 aTeV, inclusive jets,
$\rho_T = 400$ GeV, $R_{\text{anti}-k_t} = 0.4$, $|\eta| < 2.8$

dynamical grooming: max $k_t$

- Medium scales

JetMed: Causal, Iancu, Mueller, Soyez
Hardest splitting in quenched jets

JetMed partons:
pp, AA @ 5.02 aTeV, inclusive jets,
$p_T = 400$ GeV, $R_{\text{anti-$k_t$}} = 0.4$, $|\eta| < 2.8$,
dynamical grooming: max $k_t$

• Medium scales

JetMed: Caucl, Iancu, Mueller, Soyez
Hardest splitting in quenched jets

Quick reminder of JetMed

- Multiple soft scattering approximation in infinite plasma
- Vacuum-like emissions undisturbed: $t_f < t_d < L$
- Wide angle energy loss of resolved emissions

JetMed: Caucl, Iancu, Mueller, Soyez

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Hardest splitting in quenched jets

- Medium scales
I. Test of vacuum-like factorization
Hardest splitting in quenched jets (high-$k_t$)

- Medium scales
- $k_{t,\text{cut}}$ for very hard emissions
- very early emissions!

JetMed partons: pp, AA @ 5.02 aTeV, inclusive jets, $p_T = 400$ GeV, $R_{\text{anti}-k_t} = 0.4$, $|\eta| < 2.8$, dynamical grooming: max $k_t$

JetMed: Cauca, Iancu, Mueller, Soyez
Hardest splitting in quenched jets

- less jets = $R_{AA}$, self-normalize!

[JetMed: CaucaI, Iancu, Mueller, Soyez]
[Hybrid: Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal]
[Jewel: Zapp, Krauss, Stachel, Wiedemann]
Hardest splitting in quenched jets

- less jets = $R_{AA}$, self-normalize!
- no modification:
  pp = AA = most models

[PbPb @ 5.02 aTeV, inclusive jets, \( p_T > 400 \) GeV, \( R_{\text{anti-}k_t} = 0.4, |\eta| < 2.8 \), dynamical grooming: max \( k_t \)]

\[ k_{t,g} > 30 \text{ GeV} \]

JetMed: CaucaI, Iancu, Mueller, Soyez
Hybrid: Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal
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Hardest splitting in quenched jets

- less jets = $R_{AA}$, self-normalize!
- no modification:
  pp = AA = most models
- vacuum-like baseline in AA!

[JetMed: CaucaL, Iancu, Mueller, Soyez]
[Hybrid: Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal]
[Jewel: Zapp, Krauss, Stachel, Wiedemann]
II. Test of color resolution
Hardest splitting in quenched jets

- Medium scales
- $k_{t,\text{cut}}$ for perturbative emissions
- not so early emissions!
Hardest splitting in quenched jets (coherence)

- less jets = $R_{AA}$, self-normalize!

[JetMed: CaucaI, Iancu, Mueller, Soyez]
[Hybrid: Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal]
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Hardest splitting in quenched jets (coherence)

- less jets $= R_{AA}$, self-normalize!
- modification in shape!

$PbPb @ 5.02 \text{ aTeV}, \text{inclusive jets, } p_T > 400 \text{ GeV, } R_{\text{anti-}k_t} = 0.4, |\eta| < 2.8$, dynamical grooming: max $k_t$

$k_{t,g} > 8 \text{ GeV}$

$[\text{JetMed: Caucal, Iancu, Mueller, Soyez}]$
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Hardest splitting in quenched jets

Quick reminder of Hybrid

• less jets, $R_{AA}$, self-normalize!

• modification in shape:
  - coherent resolution!

• vacuum emissions are undisturbed:

• energy loss of resolved emissions:

$$r_d = (L - t_f) \theta > L_{res}$$

• 2+1D hydro

Much more in the backup!
Hardest splitting in quenched jets (coherence)

- less jets = $R_{AA}$, self-normalize!
- modification in shape!
- test of color resolution!

- PbPb @ 5.02 aTeV, inclusive jets, $p_T > 400$ GeV, $R_{\text{anti-}k_t} = 0.4$, $|\eta| < 2.8$, dynamical grooming: max $k_t$

$\frac{1}{N_{\frac{dN}{d\eta}}} > 8$ GeV

[JetMed: Cauca, Iancu, Mueller, Soyez]
[Hybrid: Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal]
[Jewel: Zapp, Krauss, Stachel, Wiedemann]
III. Test of medium response
Hardest splitting in quenched jets

- Medium scales
- $k_{t,cut}$ for perturbative emissions
- Not so early emissions!
Hardest splitting in quenched jets (medium resp)

- less jets = $R_{AA}$, self-normalize!
- modification in shape!
- test of color resolution!
- test of thermalization!

$PbPb \oplus 5.02 \text{ aTeV}$, inclusive jets, $p_T > 400$ GeV, $R_{\text{anti-}k_t} = 0.4$, $|\eta| < 2.8$,
dynamical grooming: max $k_t$

$\mu g$

$PbPb/pp$

$•$ less jets = $R_{AA}$, self-normalize!
$•$ modification in shape!
$•$ test of color resolution!
$•$ test of thermalization!

[JetMed: CaucaL, IanCU, Mueller, Soyez]
[Hybrid: Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal]
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Quick reminder of medium response

- less jets = $R_{AA}$, self-normalize!
- modification in shape!
- test of color resolution!
- test of thermalization!

**Hybrid**

- lost jet energy sources hydro
- instant thermalization
- soft response

**Jewel**

- recoilers from elastic scatterings
- free streaming recoilers
- hard response

Much more in the backup!
Hardest splitting in quenched jets (medium resp)

- less jets = $R_{AA}$, self-normalize!
- modification in shape!
- test of color resolution!
- test of thermalization!

PbPb @ 5.02 aTeV, inclusive jets, $p_T > 400$ GeV, $R_{\text{anti-}k_t} = 0.4$, $|\eta| < 2.8$, dynamical grooming: max $k_t$

$\frac{dN}{dp_T} > 8$ GeV

JetMed: Cauca1, Iancu, Mueller, Soyez
Hybrid: Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal
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IV. Experimental aspects
Reconstructing the hardest splitting

- Expected luminosity $\sim 13 \text{ nb}^{-1}$
  (15k jets above 400 GeV)
- Small angles: $\theta_g \sim 0.01$
Reconstructing the hardest splitting

- Expected luminosity $\sim 13$ nb$^{-1}$
  (15k jets above 400 GeV)
- Small angles: $\theta_g \sim 0.01$
- Unfolding is stable (fakes $< 5\%$):
  
  \[
  R = 0.4, k_t > 7 \text{ GeV} \\
  R = 0.2, k_t > 2.8 \text{ GeV}
  \]
Summary: perturbative splittings in AA

1. high kt:
   - test of mode separation
   - vacuum-like baseline in AA collisions

2. moderate kt:
   - test of color resolution
   - test of jet thermalization
   - new baseline for AA collisions
Thank you for your attention!
The Hybrid model

1. Generate Pythia8 event with nPDFs
2. Space-time structure using formation time
3. Remove energy according to holography: \( \frac{dE}{dx} (E, T) \)
4. Energy only lost for resolved partons
   \[ r_d = \theta (L - t_f) > L_{res} \]
5. The lost energy sources additional freeze out.
Hybrid model: primary Lund plane (from shower history)

\[ r_d = \theta(L - t_f) > L_{\text{res}} \]
The Jewel model

1. Generate Pythia6 event with nPDFs without FSR
2. Time and formation time are the same
3. Vacuum radiation or elastic scattering every timestep
   \[-\ln S_{rad}(t, t_0) = \int_{t_0}^{t} \frac{dt}{t} \int dz \frac{\alpha_s}{\pi} P(z)\]
   \[-\ln S_{el}(t, t_0) = \frac{t - t_0}{\lambda_{mfP}}\]
4. Elastic scatterings reset the shower scale, multiple scatterings are suppressed ("LPM")
5. The recoiler from 2-2 scatterings freestream

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Jewel model: Lund plane