High-density QCD:
Exploring high-density effects in pp and p-Pb collisions

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Disclaimers/apologies:
- Focus on highlighting important concepts; not on showing the latest results
- Results shows are biased towards ALICE for practical reasons

CERN-Fermilab Hadron Collider Physics Summer School
28 Aug - 6 Sep 2019
Single particle $R_{AA}$ revisited: particle type dependence

Low $p_T$: increase of baryon production
Mass dependence of radial flow

$p_T > 8$ GeV: baryon, meson $R_{AA}$ similar
as expected from parton energy loss
Jets and parton energy loss

Two new aspects to pursue

Jets: parton showers + hadronisation

Explore energy loss of multi-parton states:
Interference effects, distance dependence?

Angular distribution of photon radiation:
1) In-cone radiation: $R_{AA} = 1$, change of fragmentation
2) Out-of-cone radiation: $R_{AA} < 1$
Nuclear modification factor for jets

$R_{AA} < 1$ out to high $p_T \approx 800$ GeV

No strong $p_T$-dependence: suggests increase of $\Delta E$ vs $E$

Note: 10% energy loss for a 800 GeV jet is 80 GeV!
Where is the ‘lost energy’: Looking outside the jet cone

Momentum balance variable:

\[ p_{T,\text{miss}}^{\parallel} = \sum_{\text{tracks}} p_T \cos(\varphi - \varphi_{\text{jet}}) \]

Momentum imbalance restored by hadrons at:
- large angle \( R > 0.8 \)
- small \( p_T \) < 2 GeV/c

Jet energy loss is a dramatic effect, not a minor reshuffling of particles
Gamma-jet vs jet-jet

Di-jet

Both jets can lose energy
Initial kinematics not well controlled
Asymmetry due to energy loss differences

γ-jet

Photon does not lose energy
Clean selection of initial $p_T$
(same can be done with Z-jet)
Gamma-jet momentum balance

60 GeV trigger photon

100 GeV trigger photon

Also allows to explore energy dependence of lost energy
Looking inside jets: recoil fragment distributions

Recoil fragment distributions: $\gamma$-jet and di-jet

Low-z: enhancement of soft fragments
High-z: di-jets: increase of hard fragments
$\gamma$-jet: suppression of hard fragments

Different energy loss bias; selection quark vs gluon jets

CMS, arXiv:1801.04895
Looking inside jets: recoil fragment distributions

Recoil fragment distributions: $\gamma$-jet and di-jet

$\gamma$-jet, $p_{T\gamma} > 60$ GeV

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**High-z**:
- di-jets: increase of hard fragments
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$\xi_\gamma = \ln \left( \frac{p_{T,\gamma}}{p_{T,h}} \right)$

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ATLAS-CONF-2017-074
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ATLAS Preliminary

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Models capture trends when soft fragments are included

CMS, arXiv:1801.04895

ATLAS-CONF-2017-074
Jet substructure: Exploring the parton shower

Jet structure studied by declustering:

Momentum fraction

\[ z = \frac{\text{min}(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} \]

\[ z > z_{\text{cut}} \]

Larkoski et al, PRD 91, 111501

Re-wind clustering;
- remove soft splittings ‘grooming’
- select (semi-)hard splittings

Softdrop momentum fraction

\( n_{SD} \): number of splittings

\( n_{SD} \) similar in pp and PbPb

No extra splittings visible

Symmetric splittings reduced:
Formation time effect?

\( \Delta R_{\text{rec}} > 0.1 \)

\( R=0.4, p_{T_{\text{jet}}} = 80 - 120 \)

\( n_{SD} \) cut = 0.1

\( 1/N_{\text{jets}} \frac{dN}{dz} \)

ALICE, arXiv:1905.02512
Production mechanism: Heavy flavour in jets

Initial expectation: color-singlet $J/\psi$ could be produced without accompanying fragments
New insight: high-$p_T$ $J/\psi$ produced in jets

Similar studies ongoing with open heavy flavour
Small systems: pp and p-Pb

Exploring the limits of fluid/collective behaviour
Multiplicity production in pp

Multiplicity distribution is very broad:
- Average multiplicity small: 5-10 particles at mid rap
- Some events have > 100 particles

Very large densities also in pp!

What is the mechanism?

Single hard scattering + underlying event?
- Multiple parton interactions?
- Underlying even fluctuations?
Physics of small and large colliding systems

“pp” models
Vacuum processes amended by MPI, CR, ropes

“AA” models
Hydrodynamic models
Statistical models

“pp” models
p-Pb
Pb-Pb
Physics of small and large colliding systems

pp

p-Pb

Pb-Pb

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“single process limit”

“thermal limit”
Physics of small and large colliding systems

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Degree of complexity

“thermal limit”
Physics of small and large colliding systems

Underlying QCD is the same – different limits
Opportunity: stress test models/understanding

"AA" models
Hydrodynamic models
Statistical models

..."p-Pb
Pb-Pb

"pp" models
Vacuum processes amended by MPI, CR, ropes

"single process limit"

Degree of complexity

"thermal limit"
Example: strangeness enhancement

pp, p-Pb:
strong dependence of
strange baryon content
on multiplicity
What is the mechanism?

Baseline Pythia: no change in strange baryon content
Driven by hadronisation probability/string breaking
No final state interactions

Large systems:
Yields described by thermal model
‘phase space dominance’

Color Ropes, EPOS LHC:
Increasing density leads to larger strangeness content
Strangeness production vs multiplicity

Is the increase driven by strangeness or baryon content?

Effect increases with strangeness content: \( \Omega > \Xi > \phi \)

Very weak/no effect for single strange particles \( K, \Lambda \)

No increase of \( p/\pi \): not a pure ‘baryon effect’
Strangeness production vs multiplicity

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Puzzling situation: a new insight in baryon and strangeness production/hadronisation may emerge!
Reminder: Radial flow

Spectra change from pp to Pb+Pb:
• Increase in mean $p_T$
• Larger effect for larger mass

First indication of collective behaviour
Pressure leads to radial flow
Same Lorentz boost ($\beta$) gives larger momentum for heavier particles
($m_p > m_K > m_\pi$)
Multiplicity dependence of spectra

Shapes of the spectra change!

Selection of larger multiplicity (mostly low $p_T$)
Gives strong increase at high $p_T$

**Correlation** between **soft processes**: multiplicity and **hard processes**: high $p_T$

Ratio to MB spectra: ‘modulation of $p_T$ spectra’
Mean $p_T$ vs multiplicity — mass dependence

Increase of the mean $p_T$ depends on mass — suggests radial flow?

Trends similar to Pb-Pb, but do not match smoothly…

Different mechanism?
Baryon to meson ratios vs $p_T$

pp, p-Pb:

baryon/meson ratio at intermediate $p_T$ depends on multiplicity

Pb-Pb: increase driven by radial flow
Baryon to meson ratios vs $p_T$

**pp**

- ALICE Preliminary pp $\sqrt{s} = 7$ TeV
  - V0M Class I, $\langle dN_{ch}/d\eta \rangle = 21.3$
  - V0M Class X, $\langle dN_{ch}/d\eta \rangle = 2.3$

(V0M Multiplicity Classes)

- ALICE p-Pb $\sqrt{s_{NN}} = 5.02$ TeV
  - 0-5%, $\langle dN_{ch}/d\eta \rangle = 45.1$
  - 60-80%, $\langle dN_{ch}/d\eta \rangle = 9.8$

(V0A Mult. Classes - Pb side)

- ALICE Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
  - 0-5%, $\langle dN_{ch}/d\eta \rangle = 1601.0$
  - 60-80%, $\langle dN_{ch}/d\eta \rangle = 55.5$

**p-Pb**

**Pb-Pb**

Pb-Pb: increase driven by radial flow

pp, p-Pb:
baryon/meson ratio at intermediate $p_T$ depends on multiplicity

Are these effects related?
Try a different ordering: spectra ratios by particle type

Interesting pattern: baryon-meson difference. No mass dependence?

NB: this divides out the mass dependence of mean-p$_T$ in minbias spectra

ALICE, PRC 99, 024906
A propos baryon production: $\Lambda_c$ also?

$\Lambda_c/D$ in pp much larger than expected from fragmentation, $e^+e^-$

$\Lambda_c/D$ similar to $\Lambda/K$:
Specific mechanism for low $p_T$ baryon production in pp?
Charm production and Multiple Parton Interactions


Multiple parton interactions produce multiple c-cbar pairs
$J/\psi$ vs multiplicity — recent results

Multiple parton interactions in Pythia

Comparison to data

Forward vs mid-rapidity

Models with MPIs reproduce the observed trends
Two-particle correlations in pp and Pb+Pb

Near-side long range correlation: indicates early time origin
Two-particle correlations in pp and Pb+Pb

Near-side long range correlation: indicates early time origin
Seen in high-multiplicity pp and p+Pb events
Two-particle correlations

High-multiplicity p+p

Clear change in shape from low multiplicity to high multiplicity:
no near-side peak in low multiplicity events
Away-side also affected: well described by dipole term (cos (2 $\Delta \phi$))
Smooth evolution from pp to p+Pb: effect stronger in p+Pb

High-multiplicity p+Pb

ATLAS-CONF-2016-026
Extracting the double-ridge/flow

Central - Peripheral = Double ridge

Use peripheral to subtract jet contribution from central

Remaining signal almost symmetric between near- and away-side: looks like $v_2$ (+ smaller contributions from higher harmonics)
$v_2$ from di-hadron correlations in p+Pb

Similar ‘mass ordering’ observed for $v_2$ from two-particle correlations in p+Pb

Is this also pressure-driven?
Elliptic flow in p-Pb: heavy flavours

Charmed particle also carry azimuthal asymmetries: not a soft underlying event effect

No $v_2$ for beauty?

Heavy flavour decay muons: charm and beauty

ATLAS, arXiv:1909.01650
Limits on hydrodynamic behaviour

Naive expectation: need at least a few collisions for each parton to reach thermal equilibrium and apply hydrodynamic

1) System size: \( R > \lambda \)

Would not expect azimuthal asymmetries in pp and p-Pb

2) Thermalisation time: \( \tau > \frac{\lambda}{v} \)

Fits to data: thermalisation times \( \tau \approx 0.1-1 \text{ fm/c} \)

pQCD calculation: \( \tau \approx 6.9 \text{ fm/c} \)

Heiselberg and Levy, nucl-th/9812034,
W Lin et al,

Baier et al, PLB 502, 51, PLB 539, 46
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Density tomography

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Naive expectations can be bypassed in nature…
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Density tomography \( \tau \gtrsim 6.9 \text{ fm/c} \)

Density fits to data: thermalisation times \( \tau \approx 0.1-1 \text{ fm/c} \)

**Closely related**, since \( v \approx c = 1 \)

Heiselberg and Levy, nucl-th/9812034, W Lin et al,

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Naive expectations can be bypassed in nature...

Active field of research — brings together foundations of hydrodynamics, transport theory, and even string theory
Flow without a liquid

Can you have flow with a few scatterings?
‘anisotropic escape’ mechanism

Initially isotropic
momentum distribution

More particles moving in $\pm x$-direction

Scattering randomises directions; more scatterings to ‘out-of-plane’

Anisotropic density converted
into anisotropic momentum distribution by few scatterings

Kurkela, Wiedemann, Wu, arXiv:1805.04031

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Small systems: kinetic transport, equal to viscous hydro

Transverse size: \( \gamma = \frac{R}{l_{\text{mfp}}} \)

Viscous hydro \( \eta/s=0.8 \)

Ideal hydro

Full transport

Single hit

\( -\frac{\gamma}{\delta^2} \)}
Flow without a liquid

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Kurkela, Wiedemann, Wu, arXiv:1803.02072

Two parallel strings in AMPT

Formation time is important

Two-particle correlations

Shows a clear signal in a transport calculation

Other mechanisms/pictures being discussed: string shoving, CGC
⇒ more field-based; to some extent just a different language?
Deriving proton substructure

Flow-like effects in pp require substructure
‘constituents’, strings, etc

J.S. Moreland, N Phys. A982, 503
Deriving proton substructure

Flow-like effects in pp require substructure: ‘constituents’, strings, etc.

Bayesian fit + gaussian emulator: probe large parameter space
Output: full covariance matrix 15 parameters

Input: multiplicity, mean $p_T$, $v_n$ in PbPb and p-Pb
Deriving proton substructure

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Number of constituents

Constituent width, radius

input: multiplicity, mean \( p_T \), \( v_n \) in PbPb and p-Pb

No strong preference for a specific constituent number

J. S. Moreland, N Phys. A982, 503
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Shows that we are sensitive to nucleon substructure ‘configuration space picture of the proton’

J.S. Moreland, N Phys. A982, 503
Proton substructure from UPCs

Coherent and incoherent exclusive J/ψ in ep

\[ \gamma p \rightarrow J/\psi p, Q^2 = 0 \text{ GeV}^2 \]

Coherent: average

\[ \frac{d\sigma^{\gamma p \rightarrow Vp}}{dt} \sim |\langle A^{\gamma p \rightarrow Vp} \rangle|^2 \]

Incoherent: RMS

\[ \frac{d\sigma^{\gamma p \rightarrow Vp^*}}{dt} \sim \langle |A^{\gamma p \rightarrow Vp}|^2 \rangle - \langle A^{\gamma p \rightarrow Vp} \rangle^2 \]

Dissociative increase more slowly than elastic consistent with HERA data

Different angle: Spatial size, fluctuations measured by coherent/incoherent interactions

Should compare and contrast conclusions from flow/final state and EM interactions
Final state interactions, but no energy loss?

For all particle types: $R_{pPb} = 1$, no (large) energy loss

Model curves: effect of parton energy loss

However: spectra shapes change at low to intermediate $p_T$ in high multiplicity collisions
Summary/conclusions

• Jets: tool to study angular distributions of radiated energy
  • Access to underlying dynamics

• High-multiplicity pp and p-Pb show features similar to Pb-Pb collisions:
  • Elliptic flow
  • Increased strange baryon production

• Mechanisms:
  • Multiple parton interactions
  • Final state effects in pp: approach QGP formation?
  • Flow generation more effective than expected with $R \sim \lambda$
Switching off the flow: $e^+e^-$

High-multiplicity events

Low $T$; ‘multi-jet’

High $T$; ‘di-jet’

No evidence of long-range correlations beyond Pythia expectation

10 < $N$ < 20

ALEPH $e^+e^-$ thrust axis

$10 < N_{\text{thr}} < 20$

$|\eta| < 5.0$

$0.0 < p_T < 100.0 \text{ GeV}$

Thrust Axis

N ≥ 35

ALEPH $e^+e^-$ thrust axis

$35 < N_{\text{thr}} < 999$

$|\eta| < 5.0$

$0.0 < p_T < 100.0 \text{ GeV}$

Thrust Axis

J-Y Lee

ALEPH e$^+$e$^-$, $\sqrt{s}=91\text{ GeV}$

10 < $N_{\text{thr}}$ < 20

$|\eta| < 5.0$

$0.0 < p_T < 100.0 \text{ GeV}$

Thrust Axis

1.6 < $\Delta \eta$ < 3.0

No evidence of long-range correlations beyond Pythia expectation