Jets and correlations in heavy-ion collisions

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Challenges of heavy-ion physics

Exploration of the QCD phase diagram:

- nature of the phase transition and search for the critical point
- properties of the quark-gluon plasma at high temperature (RHIC/LHC) and large density (GSI FAIR/NICA)

Complementarity of LHC, RHIC and future FAIR/NICA heavy-ion programs.

Note: lifetime of QGP is very short $\rightarrow$ we need in-situ probes

Center of mass energies ($\sqrt{s_{NN}}$) for different accelerators:

- **GSI**: 1-2 GeV
- **FAIR**: 2-6 (10 GeV)
- **NICA**: 4-11 GeV
- **RHIC**: 7-200 GeV
- **LHC**: 2.76, 5 TeV
Hard probes: tomography of nuclear matter

Jets, heavy quarks, quarkonia: originate from initial hard scattering of partons which carry a color charge interact with nuclear matter.

Photons, W and Z bosons: do not carry a color charge provide information about initial state nuclear parton distribution functions.

Jets: this talk c, b, γ, W and Z next HI talk

Goal: use in-medium parton energy loss to quantify medium properties

- energy loss different for gluons and light/heavy quarks (color factor, dead cone effect)
- parton interaction with medium not trivial: depends on strength of coupling, dynamics of fireball ...

... challenge for theorists
Dedicated heavy-ion experiments at RHIC

**STAR:**
- full azimuthal coverage
- excellent tracking and PID (TPC, TOF)
- electromagnetic calorimeter (BEMC)

**NEW:** Muon Telescope Detector, Heavy Flavor Tracker $\rightarrow$ precision measurements of heavy quarks

**PHENIX:**
- **central arms:** electrons ($|\eta| < 0.35$, $\Delta\varphi = \pi$)
  - tracking: DC, PC
  - PID: RICH, EMCal
- **forward arms:** muons ($-1.2 < |\eta| < 2.2$, $\Delta\varphi = 2\pi$)
  - tracking: wire chamber
ALICE: dedicated HI experiment at the LHC

Central Barrel ($|\eta|<0.9$)
- hadrons, $e$ and $\gamma$
- TPC: efficient tracking down to $\sim 100$ MeV/c
- ITS: excellent vertexing capability

Excellent particle identification capabilities!
Basically all known types.

Forward Detectors
Large $\eta$
Interaction trigger
Event characterization

Muon Spectrometer
$-4 < |\eta| < -2.5$
$p(\text{muons}) > 4\text{GeV/c}$

Calorimetry
- EMCAL + DCAL (Run2)
- PHOS
ALICE: dedicated HI experiment at the LHC

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Forward Detectors
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- Interaction trigger
- Event characterization

Muon Spectrometer

ATLAS and CMS deliver beautiful heavy-ion results as well!
Crucial: cross-check + complementarity!

Calorimetry
- EMCAL + DCAL (Run2)
- PHOS

Excellent particle identification capabilities!
Basically all known types.

J. Bielcikova (NPI ASCR)
Some basic heavy-ion physics terminology ...

- **A + A**: "hot/dense QCD matter" final state effects, thermal and collective particle production (flow)
- **p + A**: "cold nuclear matter" initial state effects, shadowing and gluon saturation
- **p + p**: "vacuum" reference

J. Bielcikova (NPI ASCR)
Some basic heavy-ion physics terminology ...

“hot/dense QCD matter”
final state effects
thermal and collective
particle production (flow)

“cold nuclear matter”
initial state effects
shadowing and gluon
saturation

“vacuum”
reference

Initial spatial anisotropy

Strong pressure gradients

Elliptical ($v_2$) azimuthal anisotropy

Sensitivity to early expansion

Fourier analysis of particle distribution relative to reaction plane

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Centrality and nuclear modification factor

Centrality in A+A:
- impact parameter cannot be directly measured and has to be estimated based on measured e.g. $N_{ch}$, $E_T$, ZDC...
- centrality is typically expressed as a % fraction of total geometric cross section
- **Glauber model**: connects centrality to a number of binary collisions ($N_{coll}$) and participants ($N_{part}$)

Nuclear modification factor:
...the way to compare an observable in A+A collisions to the reference ($p+p$ or peripheral A+A)

$$R_{AA}(p_T) = \frac{d^2 N_{AA}^{AA}}{dp_T d\eta} \frac{T_{AA} d^2 \sigma_{NN}^{NN}}{dp_T d\eta}$$

$N_{coll}/\sigma_{inel}^{NN}$
Particle production in central Pb+Pb collisions

- suppression of charged hadron production: $R_{AA}$(LHC) < $R_{AA}$(RHIC)
- minimum $R_{AA} \sim 0.14$ at $p_T = 6$-7 GeV/c
- increase of $R_{AA}$ with $p_T$ but even at $p_T \sim 100$ GeV/c $R_{AA} < 1$
- although $R_{AA}$ is known to be limited in sensitivity to models of quenching, these data excluded already some of them

Jet tomography in heavy-ion collisions

- Jet reconstruction is performed with a collinear and infrared safe anti-kt algorithm

**Challenge for experimentalists:**
- Large and fluctuating background: \( \langle \rho \rangle \approx 180 \text{ GeV/c} \)
  in central Pb-Pb collisions @ 2.76 TeV
  - limits jet resolution parameter \( R \) to modest values \( R \approx 0.2-0.4 \)
- Average background subtracted on jet-by-jet basis and fluctuations together with instrumental effects unfolded on statistical basis
How much are jets modified?

Inclusive jet production is suppressed in central Pb+Pb collisions...
How much are jets modified?

Inclusive jet production is suppressed in central Pb+Pb collisions ...

... and internal structure of jets is modified.
Dijet asymmetry observed in central Pb+Pb collisions, without angular decorrelation.

ATLAS: PRL 105 (2010) 252303

Where did the energy go? First studies in CMS paper: PRC 84 (2011) 024906
Where did the energy go?

Where did the energy go?

Missing $p_T$:

$$p_T^\parallel = \sum_i -p_T^i \cos (\phi_i - \phi_{\text{Dijet}})$$

- increases with $A_J$ and is balanced by:
  - 2-8 GeV/c particles in pp
  - $p_T < 2$ GeV/c particles in 0-10% Pb+Pb
- high $p_T$ imbalance at small $\Delta R$ compensated by low $p_T$ particles in subleading jet direction extending to large $\Delta R$.

Y.S. Lai (CMS) Thu 15:15

Y.S. Lai (CMS)

J. Bielcikova (NPI ASCR)
Path length effects on di-jet production

- earlier study of jet production vs. event plane showed modest path length dependence ($v_2^{jet} \sim 2-5\%$)

ATLAS: *PRL 111 (2013)*152301

**Study di-jet asymmetry $A_J$ vs. event plane, extract its elliptical modulation $c_2$.**

Calculate “elliptic” modulation $c_2$:

$$\langle A_J \rangle (\phi^{lead} - \psi_2) = A_{J,0} \left( 1 + 2c_{2,obs} \cos \left( 2(\phi^{lead} - \psi_2) \right) \right)$$
Path length effects on di-jet production

- Earlier study of jet production vs. event plane showed modest path length dependence ($v_{2}^{jet} \sim 2-5\%$)

ATLAS: *PRL* 111 (2013)152301

Study di-jet asymmetry $A_{J}$ vs. event plane, extract its elliptical modulation $c_{2}$.

$c_{2}$ is small (<2%) and negative!

Data indicate larger $A_{J}$ for leading jets oriented out-of-plane than for in-plane ones.
Neighbouring jet production in Pb-Pb collisions

Production of neighbouring jets quantified using a rate of jets accompanying a given test jet

\[ R_{\Delta R} = \frac{1}{dN_{\text{jet}}^{\text{test}}/dE_T^{\text{test}}} \sum_{i=1}^{N_{\text{jet}}^{\text{test}}} \frac{dN_{\text{jet},i}^{\text{nbr}}}{dE_T^{\text{test}}} (E_T^{\text{test}}, E_{T,\text{min}}^{\text{nbr}}, \Delta R) \]

Similarly as for inclusive jets introduce nuclear modification factor \( \rho_{R_{\Delta R}} \)

\[ \rho_{R_{\Delta R}} = R_{\Delta R} (\text{central})/R_{\Delta R} (\text{peripheral}) \]

Study its dependence on:
- \( E_T \) of test jet
- \( E_T \) of neighbouring jet
Neighbouring jet production in Pb-Pb collisions

ATLAS, arXiv:1506.08656

Suppression of neighbouring jet production in central Pb-Pb:

~ independent of test jet $E_T$
~ similar to inclusive jets

Nuclear modification factor for neighbouring jets approaches 1 when $E_{\text{test}} \approx E_{\text{nbr}}$.

Suggests similar quenching for jets with same observed $E_T$ and path length.
Semi-inclusive recoil jets in Pb-Pb

A unique observable:
enables study of intra and inter-jet angular broadening + is directly comparable to analytic pQCD.

Recoil jet yields are suppressed ($\Delta l_{AA}$):
suppression is independent of $R$ and slowly decreases with jet $p_T$

No evidence of intra-jet broadening:
$\Delta_{\text{recoil}}$ for $R=0.2/0.5$ similar in pp and central Pb-Pb collisions
Hadron-jet correlations at RHIC

Nuclear modification factor “I_\text{CP} “:
• close to 1 at low p_T
• large suppression at p_T > 10 GeV/c: I_\text{CP} \sim 0.2

A word of caution: different kinematic selections, Δϕ cut, ...

Larger suppression at RHIC compared to the LHC energy.
Acoplanarity?

Width ($\sigma$) consistent in Pb+Pb with PYTHIA embedded data.

No evidence of medium-induced acoplanarity of recoil jets at the LHC.

High-$p_T$ trigger: no broadening with centrality.
Acoplanarity?

ALICE@ LHC 2.76 TeV

**Width (σ) consistent in Pb+Pb with PYTHIA embedded data.**

No evidence of medium-induced acoplanarity of recoil jets at the LHC.

STAR@RHIC 0.2 TeV

Low-\(p_T\) trigger: broadening with centrality

J. Bielcikova (NPI ASCR)
Acoplanarity?

Future large-angle jet deflection studies may provide a direct probe of the nature of the quasi-particles in hot QCD matter.

Low-$p_T$ trigger: broadening with centrality
Strange particle production in jets
Baryon/meson enhancement in p-Pb and Pb-Pb relative to pp collisions

High multiplicity p–Pb and Pb–Pb collisions have many similarities (see later) including also an enhanced p/π and Λ/K^0_S ratio

What is physics origin of this enhancement?
• radial flow
• coalescence/recombination vs fragmentation

Measure B/M ratios in jets and compare to that in bulk ...

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Strange particle production in jets

\[ p_{T,jet} > 10 \text{ GeV/c} \]

\[ p_{T,jet} > 20 \text{ GeV/c} \]

\[ \Lambda/K_0^0 \text{ ratio in charged jets in p-Pb and Pb-Pb significantly lower than inclusive and pp} \]

Jet composition is not influenced by the enhanced baryon/meson production in the bulk.
Cold nuclear matter effects on particle and jet production
Modification of particle and jet production in p-Pb collisions?

- Single particle $R_{ppb}$: tension at high $p_T$ between ALICE and ATLAS/CMS
- Jet fragmentation: ATLAS observed modification in pPb

At the same time inclusive jet production is not modified in pPb, agreement across experiments.

[Graphs showing data from CMS, ATLAS, and ALICE for different variables, including charged hadrons and jets.]
Is it in the pp @ 5 TeV reference?

Note: no measured pp reference at 5 TeV exists, different interpolations used by individual experiments.

CMS does not observe modification of jet fragmentation in pPb collisions in contrast to ATLAS.
Is it in the pp @ 5 TeV reference?

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Revisited CMS p-Pb reference from *EPJC 75 (2015)* 237, which used previously published CMS + CDF data

The ratio of old/new reference resembles the “bump” in the charged particles $R_{pPb}$. 
Ridge
The ridge phenomenon ...

Many physics scenarios have been suggested. The near-side ridge probably originates from initial state fluctuations, which give a rise to a new "triangular flow" ($v_3$).
Collectivity in small systems: the LHC ridges

High multiplicity pp @ 7 TeV

CMS, JHEP09 (2010) 091

CMS, PLB 718 (2012) 795

pPb @ 5.02 TeV

CMS pPb $\sqrt{s} = 5.02$ TeV, $N \geq 110$

$1 < p_T^{\text{proj}} < 2$ GeV/c

$1 < p_T^{\text{assoc}} < 2$ GeV/c

ALICE, PLB 719 (2013) 29

ATLAS p+Pb, $\sqrt{s_{NN}} = 5.02$ TeV, $L_{\text{int}} = 28$ nb$^{-1}$

$1 < p_T^{a,b} < 3$ GeV

Similarity of the ridges in pp, pA and AA:
Common hydrodynamical origin?

But can hydrodynamical models be reliably applied in small systems?

Initial state effects (gluon saturation, extended color connections in longitudinal direction) or final-state parton-parton induced interactions?
Ridge persists in 13 TeV pp collisions

Very similar ridge properties at 7 and 13 TeV!
Looking forward to see the “$v_n$” study and more precision data!
p-Pb ridge present at forward rapidity

Correlations of charged particles in forward direction: $2 < \eta < 4.9$

M. Meissner (LHCb) 
Thu 11:50

Ridge observed in high multiplicity p+Pb collisions in forward direction as well!

Ridge more pronounced in Pb+p than p+Pb hemisphere ...

The near-side ridges in both hemispheres are the same when evaluated in same absolute activity bins.

LHCb-CONF-2015-004

NEW!
p-Pb ridges extend to large rapidities

ALICE, p-Pb $\sqrt{s_{NN}}$=5.02 TeV, muon-tracklet correlations with $0.5 < p_T < 1$ GeV/c

Double ridge extends over 10 units of rapidity.

central 0-20%

peripheral 60-100%

2 ridges

(project onto $\Delta \phi$, calculate "$v_2$"

J.F. Grosse-Oetringhaus (ALICE), Thu 16:50

ALICE, arXiv: 1506.08032

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Evidence for collectivity in p-Pb?

Mass ordering in $v_2$ resembling hydro picture observed earlier at low $p_T$ in $p$, $\pi$ and $K$ by ALICE.

\textit{ALICE: PLB 726 (2013) 164}

It is now confirmed by the CMS data for $\Lambda$ and $K^0_S$. 

\textit{CMS, PLB 742 (2015) 200}
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CMS, PLB 742 (2015) 200

Multiparticle correlations (4-8) as well as Lee-Yang-Zero studies give consistent “$v_2$” values. Proof of collectivity!

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Can data from RHIC bring further insights?

RHIC has unique capabilities to study variations in the initial state.

Evidence for ridge in d+Au and $^3$He+Au collisions at 0.2 TeV at RHIC: non-zero $v_2$, particle mass ordering
Can data from RHIC bring further insights?

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Evidence for ridge in d+Au and $^3$He+Au collisions at 0.2 TeV at RHIC: non-zero $v_2$, particle mass ordering
Summary

- wealth of new data on jets and correlations from Run 1 at the LHC as well as from RHIC experiments came since EPS-HEP 2013

  (my apologies, it was not possible to show all of them today)

jets in A+A collisions: measurements of inclusive jet production are now accompanied with important information on several jet structure observables which should improve our understanding of the hot and dense matter

high-multiplicity p+p and p+Pb collisions: ridge phenomenon quantified in a great detail, but satisfactory theoretical understanding across collision systems and energies missing

for the EPS-HEP conference: ridge measurements extended to pp @ 13 TeV and forward rapidities in p+Pb

- looking forward to Run2 data at the LHC as well as high statistics runs at RHIC to pin down medium properties and possible collective effects in small collision systems!

THANK YOU!
BACKUP slides
RHIC BES: charged particle $R_{CP}$

around $\sqrt{s_{NN}} = 27\text{-}39$ GeV turning point:
unquenched $\rightarrow$ quenched particle production
$^3\text{He}+\text{Au}$ vs models

J. Bielcikova (NPI ASCR)
well-established models: realistic collision geometry, initial state conditions, hadronization
both use a fit to hadron $R_{AA}$ to tune the free parameters within the model

Both models agree well with data, but YaJEM shows a slightly steeper increase with $p_T$

$→$ Jet $R_{AA}$ vs event plane to pin down the path-length dependence of jet quenching and to differentiate models
No indication of cold nuclear matter modification of jet production in MB data.
Multiplicity dependence of charged jets in p-Pb

- centrality dependent charged jet $Q_{pPb}$ measured up to 100 GeV/c: consistent with binary scaling
- no modification of jet radial structure

No significant multiplicity dependence or CNM effects observed.
Nuclear modification factor: RHIC vs LHC

ALICE: arXiV-1506.07287

\[ p_T (\text{GeV}/c) \]

- $\pi^\pm$, ALICE 0-5% Pb-Pb
- $\pi^0$, PHENIX 0-5% Au-Au

$S_{NN} = 2.76 \text{ TeV}$

$S_{NN} = 200 \text{ GeV}$
Path length effects on jet production

0-5%, Pb-Pb, R=0.2

30-50%, Pb-Pb, R=0.2

ALICE Preliminary
Pb-Pb √s_{NN} = 2.76 TeV
R = 0.2 anti-k_{T}, \mid \eta_{jet} \mid < 0.7

\[ p_{T, track} > 0.15 \text{ GeV/c}, \; p_{T, lead} > 3 \text{ GeV/c} \]

Pb+Pb √s_{NN} = 2.76 TeV
R = 0.2 anti-k_{T}, \mid \eta_{jet} \mid < 0.7

\[ p_{T, track} > 0.15 \text{ GeV/c}, \; p_{T, lead} > 3 \text{ GeV/c} \]
Sensitivity of different observables

Surface bias dependence:
- single hadron and jet-hadron observables: strong surface bias
- di-hadron correlations: show less bias
- $\gamma$, $Z$-triggered: offer unbiased measurement

FINISH
Jet-track correlations in Pb+Pb

anti-kt R=0.3: $p_{T,1}>120$, $p_{T,2}>50$ GeV/c,

$|\eta_{jet}|<1.6$, $\Delta\phi_{1,2}>5\pi/6$
Hunting the collectivity in pPb ...

Non-zero Fourier coefficients $v_1$-$v_4$ measured in p-Pb collisions.

What is their relation to those measured in Pb-Pb?

Apply a scale factor $K = 1.25$ to account for the $<p_T>$ difference in both systems

**Basar, Teaney, arXiv:1312.6770**

Similarity of the scaled $v_n(p_T/K)$ in p-Pb and $v_n$ in Pb-Pb indicates a similar origin of the anisotropy in both systems.
The recoil jet is modified:

- **softening of recoil jet in central Au+Au collisions at RHIC.**

- **γ-jet** a “golden probe” of parton energy loss in the medium

- produced in Compton scattering

  \[ q+g \rightarrow q+\gamma \]

- photons do not interact strongly

- precise measurement of the in-medium modification of fragmentation function

\[
I_{AA} = \frac{\text{Yield}(A+A)}{\text{Yield}(p+p)}
\]

The recoil jet is modified:

softening of recoil jet in central Au+Au collisions at RHIC.
Where did the energy go?

Look into different cones away from the trigger photon!

Lost high-\(p_T\) hadrons emerge as multiple soft hadrons at large angles.

\[
\xi = -\ln \left( \frac{p_T^h}{p_T^\gamma} \right)
\]
Modification of jet fragmentation in Pb-Pb


enhancement for $z<0.04 \rightarrow$ suppression at $z = 0.04-0.2 \rightarrow$ enhancement for $z>0.2$

- most pronounced in central Pb-Pb collisions
Where did the energy go?

Jet asymmetry is balanced by soft particles at large angles.

Leading jet ($p_T > 120 \text{GeV/c}$)

Subleading jet ($p_T > 30 \text{GeV/c}$)

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Does the picture change at RHIC energy?

2. Rerun jet-finding algorithm with low constituent $p_T$ cut

Constituent $p_T > 2$ GeV/c

Constituent $p_T > 0.2$ GeV/c

1. Run jet-finding algorithm and find di-jets

Anti-kt $R=0.4$

$p_T^{\text{leading}} > 20$ GeV/c, $p_T^{\text{subleading}} > 10$ GeV/c

$|\Delta \phi \pi| < 0.4$

3. Do jet matching and calculate “matched” $|A_J|$ with constituent $p_T, \text{cut} > 0.2$ GeV/c

$|\Delta \phi \pi| < 0.4$

$|A_J|$
A_{J} \text{ measurement at RHIC energy}

1. Run jet-finding algorithm and find di-jets

Anti-kt \ R=0.4
\ p_T^{\text{leading}}>20 \ \text{GeV/c}, \ p_T^{\text{subleading}}>10 \ \text{GeV/c}
\ |\Delta \phi-\pi|<0.4

2. Rerun jet-finding algorithm with low constituent p_T cut

Constituent p_T > 2 \ \text{GeV/c}

Constituent p_T > 0.2 \ \text{GeV/c}

3. Do jet matching and calculate “matched” |A_{J}| with constituent p_T, cut > 0.2 \ \text{GeV/c}
Lost energy remerges in low $p_T$ particles
- Decreasing $p_T = 2 \rightarrow 1 \rightarrow 0.2$ GeV/$c$
  - The dijet is regaining balance
- For the same $R=0.4$ and jet $p_T$ selection, balance cannot be restored within $R=0.2$
  → broadening
- $p_T^{\text{cut}} = 1$ GeV/$c$ not sufficient to restore balance
  → signs of jet softening between 1 and 2 GeV/$c$
How many particles carry the missing energy?

- $\Delta_{\text{mult}}$ increases with centrality
- for large $A_J$ and central Pb-Pb collisions there are about 14 extra particles with $p_T > 0.5$ GeV/c in the subleading jet hemisphere

hemi$N_{\text{ch}}$ difference:

$$\Delta_{\text{mult}} = N_{\text{ch}}^{\text{subleading}} - N_{\text{ch}}^{\text{leading}}$$

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