Emergent QCD phenomena at the LHC and connections to EIC physics

Wei Li
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QCD: a fundamental theory of strong force

*Quarks (and Glue) at the Frontiers of Knowledge*

The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

– Frank Wilczek, Quark Matter 2014
QCD: a fundamental theory of strong force

Quarks (and Glue) at the Frontiers of Knowledge

The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

– Frank Wilczek, Quark Matter 2014

Perturbative

Lattice calculations
Emergent phenomena

“More is different” – P. W. Anderson
Emergent phenomena

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Emergent phenomena

“More is different” – P. W. Anderson

\[ x \times 1,000,000,000,000,000,000,000 = \]
Emergent phenomena

“More is different” – P. W. Anderson
Emergent phenomena

“More is different” – P. W. Anderson

Search for and study new emergent phenomena of many-body QCD system are just as fundamental!
Phases of many-body QCD systems

$T_C \sim 154$ MeV

(Lattice QCD)
Phases of many-body QCD systems

$T_c \sim 154$ MeV
(Lattice QCD)

Is there a critical point?
Phases of many-body QCD systems

Properties of hot QCD matter?

Is there a critical point?

$T_c \sim 154$ MeV
(Lattice QCD)
Creating the hot QCD matter

“Large” systems

Hot QCD Matter – QGP

“Small” systems

also ep, eA, e^+e^-

Cold QCD – reference boring …
Discovery of strongly coupled QGP

- QGP flows frictionless, as a nearly perfect liquid
- QGP is very opaque to color-charged particles

![Diagram showing fluid imperfection vs. temperature for different substances like Ultra-Cold Atoms, Helium, Water, Quark-Gluon Plasma.](image1)

![Diagram illustrating PbPb collision with particle trajectories.](image2)
Off-center AA collision

Perfect QGP fluid Paradigm

Geometry! Geometry! Geometry!
Perfect QGP fluid Paradigm

Off-center AA collision

Geometry! Geometry! Geometry!
Perfect QGP fluid Paradigm

Off-center AA collision

\[ \sim 1 + 2 v_2 \cos[2(\phi - \Psi_R)] \]

- “elliptic flow”
Perfect QGP fluid Paradigm

Off-center AA collision

Geography! Geography! Geography!

CMS event display

Hydrodynamic expansion

Momentum anisotropy

\[ \frac{dN}{d\phi} \sim 1 + 2 v_2 \cos[2(\phi - \Psi_R)] \]

“elliptic flow”
Perfect QGP fluid Paradigm

Off-center AA collision

Reaction plane

Geometric! Geometry! Geometry!

 CMS event display

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\[ \frac{dN}{d\phi} \]

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- "elliptic flow"

Two-particle angular correlations

PbPb 35-40%

\[ 1 < p_t < 3 \text{ GeV/c} \]
Perfect QGP fluid Paradigm

Off-center AA collision

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Perfect QGP fluid Paradigm

Off-center AA collision

Geometry! Geometry! Geometry!

Reaction plane

(z)

(x)

- defines $\psi_R$.

(denom of the impac parameter)

Hydrodynamic expansion

Momentum anisotropy

$dN/d\phi$

$-\pi$ $-\pi/2$ $0$ $\pi/2$ $\pi$

$\sim 1 + 2 v_2 \cos[2(\phi - \psi_R)]$

- "elliptic flow"

Two-particle angular correlations

PbPb 35-40%

$1 < p_t < 3$ GeV/c

Jets

$\cos(2\Delta \Phi)$

1 d$^2N_{\text{pair}}$/d$\Delta \eta$ d$\Delta \phi$

1.8

1.6

1.4

1.2

1.0

0.8

0.6

0.4

0.2

0

-4 -2 0 2

$\Delta \eta$

-4 -2 0 2

$\Delta \phi$

CMS event display
Perfect QGP fluid Paradigm

Geometry! Geometry! Geometry!

Well described by nearly ideal hydrodynamics with minimal fluid imperfection ($\eta/s \sim 0.2$)
Revenge of small systems (2010)

(b) CMS MinBias, $1.0\text{GeV/c} < p_T < 3.0\text{GeV/c}$

Minimum bias pp

JHEP 09 (2010) 091

I $< p_T < 3$ GeV/c

(d) CMS $N \geq 110$, $1.0\text{GeV/c} < p_T < 3.0\text{GeV/c}$

High multiplicity pp ($N_{trk} > 110$)
Revenge of small systems (2010)

Minimum bias pp

JHEP 09 (2010) 091

$|p_T|<3 \text{ GeV/c}$

High multiplicity pp ($N_{\text{trk}}>110$)

Ridge

QGP droplet in pp?
Revenge of small systems (2010)

JHEP 09 (2010) 091

Not reproduced by pp MC

$|p_T| < 3$ GeV/c

Ridge

PYTHIA 8

QGP droplet in pp?
Revenge of small systems (2010)

Not reproduced by pp MC

JHEP 09 (2010) 091

Be prepared for surprises at EIC!

QGP droplet in pp?
Universal collective effects in high-density QCD final states?
Universal collective effects in high-density QCD final states?
Strangeness enhancement

– as a QGP signature


Not described by the Lund string model (PYTHIA)

Captured by models w/ dense color environment
Quarkonia suppression – as a QGP signature

Suppression of Upsilon states in pPb

Stronger suppression for excited states, esp. at backward rapidity

Medium effect needed?!
Elliptic flow of heavy flavor hadrons!

CMS Preliminary  
pPb 186 nb\(^{-1}\) (8.16 TeV)

- \(|y_{lab}| < 1\)
- \(1.2 < |y_{lab}| < 2.4\)
- \(185 \leq N_{\text{trk}}^{\text{offline}} < 250\)

**New at QM2019!**

Strong flow of **charm**, not beauty hadrons

Latest results at Quark Matter 2019: https://indico.cern.ch/event/792436/

Many dozens of papers on “small” (used to be cold) systems at the LHC
Proton as an emergent QCD many-body phenomenon

Role of initial proton “geometry”
Proton as an emergent QCD many-body phenomenon

Role of initial proton “geometry”

Proton “geometry” fluctuation?
Proton as an emergent QCD many-body phenomenon

Role of initial proton “geometry”

Hydrodynamics in pA

Proton “geometry” fluctuation?

Mäntysaari, Schenke, PLB 772 (2017) 681
Proton as an emergent QCD many-body phenomenon

Role of initial proton “geometry”

Hydrodynamics in pA

Proton “geometry” fluctuation?

Opportunity of probing quantum fluctuations at sub-fermi and yoctosec scales!

Mäntysaari, Schenke, PLB 772 (2017) 681
Proton “geometry” fluctuations?

J/ψ production in e+p

H. Mäntysaari, B. Schenke, PRL 117 (2016) 052301
PRD 94 (2016) 034042
Hot QCD matter at EIC?

Ultraperipheral AA
Hot QCD matter at EIC?

Ultraperipheral AA
Hot QCD matter at EIC?

Ultraperipheral AA

High-multiplicity e+A = (q\bar{q})+A (small Q^2, large W)

Collectivity should be observable!
Future

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<th>2021</th>
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Run 3

2021-2022: x8-10 L_{int} for pPb, PbPb

OO, pO
Future

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- Run 3
- Run 4

OO, pO

x8-10 L_{int} for pPb, PbPb

EIC
Future

ALICE upgrades
• High readout rate
• New inner tracking

CMS, ATLAS Phase-2 upgrades

x8-10 $L_{\text{int}}$ for pPb, PbPb

EIC
Future

ALICE upgrades
• High readout rate
• New inner tracking

CMS, ATLAS
Phase-2 upgrades

CMS Time-Of-Flight: $|\eta|<3$

EIC

Particle identification!

x8-10 $L_{int}$ for pPb, PbPb

OO, pO

Run 3
Run 4

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CMS

PbPb (5.5 TeV)

Phase-2 Simulation
Hydjet
$|\eta| > 1.6$

$1/\beta$

$K$

$\pi$

$p$
CMS Mip Timing Detector

CERN-LHCC-2017-027
CMS Mip Timing Detector

Barrel Timing Layer:

- L(Y)SO:Ce crystal bars + SiPM
- Coverage: $|\eta|<1.5$
- Material: $< 0.4 \ X_0$
- Time resolution: $\sim 30\text{ps}$
CMS Mip Timing Detector

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- Time resolution: $\sim 30\text{ps}$

**Endcap Timing Layer:**
- Ultra-fast silicon detectors
- Coverage: $1.6<|\eta|<3.0$
- Material: $<0.2 \ X_0$
- Time resolution: $\sim 30\text{ps}$ with two layers

Gain: 10-30
CMS Mip Timing Detector

**Barrel Timing Layer:**
- L(Y)SO:Ce crystal bars + SiPM
- Coverage: \(|\eta|<1.5\)
- Material: < 0.4 \(X_0\)
- Time resolution: \(\sim 30\text{ps}\)

**Endcap Timing Layer:**
- Ultra-fast silicon detectors
- Coverage: 1.6\(<|\eta|<3.0\)
- Material: < 0.2 \(X_0\)
- Time resolution: \(\sim 30\text{ps with two layers}\)

Technology for future precision tracker!
Summary

Remarkable collective phenomena observed across all high-density QCD systems (pp/pA/AA)

- Perfect QGP fluid paradigm in AA

In small systems,

- Origin still under debate in small systems
- New window to probe subnucleonic fluctuations!

Hot QCD physics at EIC? Be prepared for surprises!
Summary

Remarkable collective phenomena observed across all high-density QCD systems (pp/pA/AA)

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Hot QCD physics at EIC? Be prepared for surprises!

Strong synergy among hot QCD, cold QCD and HEP communities in terms of physics interests and detector innovations
Backups
Endcap Timing Layer (ETL)

**Design:**

- 2 disks covering a surface of $\sim 14 \, \text{m}^2$
- Material budget: $< 0.2 \, \text{X}_0$
- Rapidity coverage: $1.6 < |\eta| < 3.0$
- $x10$ higher radiation level than BTL
- Timing resolution: $\sim 30-50 \, \text{ps}$

**Sensors:**

- **Ultra fast silicon detectors:**
  - Low gain avalanche diodes optimised for precision timing.
Barrel Timing Layer (BTL)

Design:
- 72 trays covering a surface of ~38 m²
- Material budget: < 0.4 $X_0$
- Rapidity coverage: |$\eta$| < 1.5
- Timing resolution: ~ 30 ps

Sensors:
- L(Y)SO:Ce crystal bars as scintillator:
  - Excellent radiation tolerance, high signal and fast response time.
- Silicon Photomultipliers as detectors:
  - Compact, fast and insensitive to magnetic fields.
TOF-PID comparison with ALICE and STAR

**STAR (RHIC)**

- 200 GeV d+Au
- Counts
  - $1.2 < p_\text{T} < 1.4$ GeV/c

**ALICE (LHC)**

- TOF $\beta$
- e, $\pi$, K, d

| Experiment | $|\eta|$ coverage | $L$ at $\eta = 0$ (m) | $\sigma_T$ (ps) | $L/\sigma_T \times 100$ |
|------------|-------------------|------------------------|-----------------|------------------------|
| CMS        | $|\eta| < 3.0$      | 1.16                   | 30              | 3.9                    |
| ALICE      | $|\eta| < 0.9$      | 3.7                    | 56              | 6.6                    |
| STAR       | $|\eta| < 0.9$      | 2.2                    | 80              | 2.2                    |

- Competitive momentum coverage compared to ALICE and STAR
- Unique wider rapidity coverage
“Hot QCD matter” at EIC?

Experimental requirements

- Wide $\eta$ coverage (> 5-6 units)
- Good $p_T$ resolution (forward tracking)
- PID up to high momentum (RICH)
- Fast online trigger (w/ tracking)
Hot QCD matter at EIC?

$\pi^+(30\text{GeV})+A\text{u}(100\text{GeV})$ from AMPT

Multiplicty distribution

$N_{\text{trk}}>90$  
$1<p_T<3\text{ GeV}$

A long-range ridge can be observed at EIC in high-multiplicity $e^+\text{Au}$ events!
Hot QCD matter at EIC?

Comparing $v_n$ in (qqq)+A vs (q$q$)+A

- Disentangle “hydro” vs CGC?
- Insight on subnucleonic fluctuations?