Open HF, quarkonia, Z/W in PbPb

What’s the status at QCD@LHC 2022

G. K. Krintiras (cern.ch/gkrintir)
on behalf of the ALICE/ATLAS/LHCb & CMS collaborations
The University of Kansas
Pressing questions and open items

- What are the initial conditions of the collision?
- nPDF and initial EM field
- How does the system move toward hydrodynamization?
- What is the longitudinal structure of the QGP?
- What’s the hadronization mechanism with QGP?
- What are the transport properties of the QGP? How does QGP respond to hard probes? What are the inner workings of QGP at various length scales?

Input from
EF community workshop (Yen-Jie Lee)
What are the initial conditions of the collision?

nPDF and initial EM field
Polarization of quarkonia in PbPb

- Polarization ($\lambda_\theta$): degree to which the spin is aligned w.r.t. a chosen direction
- Evidence of $\lambda_\theta > 0$ (w.r.t the event plane) for inclusive J/$\psi$
  - vanishing $\lambda_\theta$ at larger $p_T$
  - significant effect up to semicentral events

**Evidence**

![Graphs showing polarization ($\lambda_\theta$) vs. centrality and $p_T$](image)

- **ArXiv: 2204.10171**

**Significant effect** up to semicentral events

Sensitivity to huge **magnetic field** and properties of a rotating fluid.
Nuclear PDFs: constraints **scarce** so far

- **State-of-the-art** nPDFs for perturbative QCD calculations
- **Strong constraints** on bound nucleon modifications from dijets and W’s
- **NNLO** nPDF analyses to include LHC data

![Graphs showing p-Pb and Pb-Pb data](arXiv: 2204.10640, arXiv: 2112.11904)

In preparation of EIC, HIC @ LHC provides the **best input to nPDFs**
State-of-the-art nPDFs for perturbative QCD calculations

- Strong constraints on bound nucleon modifications from dijets and W's
  - also possibly from top quark pair production
- NNLO nPDF analyses to include LHC data

**Probing the unknown very high-$x$ and $Q^2$ region**

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<table>
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<td>$l+$ jets</td>
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<tr>
<td>$\mu+$ jets</td>
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**CMS**

$p p$, 19.6 fb$^{-1}$, ($\sqrt{s}$=8 TeV)

$p P b$, 174 nb$^{-1}$, ($\sqrt{s_{\text{NN}}}$=8.16 TeV)

**Figure:**

- **CMS Projection**
- **arXiv:** 1812.06772
- **pp** (2 pb$^{-1}$, $\sqrt{s_{\text{NN}}}$=8.16 TeV)
- **pPb** (2 pb$^{-1}$, $\sqrt{s_{\text{NN}}}$=8.16 TeV)
- Pseudo-data
- $t\bar{t}$ Powheg (EPPS16)
- Reconstructed lepton $y$
- $\sigma$ [nb]
Nuclear PDFs: constraints **scarce** so far

- State-of-the-art nPDFs for perturbative QCD calculations
- Strong constraints on gluon modifications from dijets and W bosons
- NNLO nPDF analysis to include LHC data
- **Complementarity** at very **low-x** with \( \pi^0, \eta, \) and \( D^0 \) **mesons**
- **Bonus:** saturation models and energy loss constraints

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**arXiv: 2104.03116**

- Strong constraints on gluon modifications from dijets and W bosons.
- **NNLO nPDF analysis** to include LHC data.
- Complementarity at very **low-x** with \( \pi^0, \eta, \) and \( D^0 \) **mesons**.
- **Bonus:** saturation models and energy loss constraints.

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**arXiv: 2205.03936**

- **Most precise at LHC.**

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\( R_{pA} = \frac{p-Pb}{scaled \otimes pp} \)
Probing the initial state with DY: another standard candle

- Drell-Yan (DY) inclusive & differential pPb measurement in extended $15 < m_{\mu\mu} < 120$ GeV
- the most precise to date → constraints on the quark nPDFs
- High-precision in PbPb too
- Deviation from flat centrality dependence described by HG-PYTHIA (like ALICE, tension with ATLAS)
- Possibility to determine NN luminosity with # of Z boson counts

Z boson production could even provide a new normalization method!
**Charm quark dynamics** via (multi)particle correlations

**First** $\Delta v_2$ measurement for $D^0 \rightarrow$ sensitive to the strong created EM fields

- no EM induced charge-dependent splitting in $v_2$

**First** high-precision $v_2\{4\}/ v_2\{2\}$ also for $D^0 \rightarrow$ check whether fluctuations on $v_2$ are **universal**

- that’s the case modulo very central (peripheral) events

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**arXiv: 2112.12236**

**Calculation for prompt $D^0$**

- $v_2\{2\}$, Coll. E-loss (Langevin)
- $v_2\{4\}$, Coll. E-loss (Langevin)
- $v_2\{4\}$, Rad. E-loss

**Prompt $D^0 + \bar{D}^0$**

- $v_2\{2\}$, $|y| < 1$
- $v_2\{4\}$, $2 < p_T < 8$ GeV

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**Resolving $v_2$ event-by-event fluctuations with identified particle $v_2\{4\}$**
What are the transport properties of the QGP?
How does QGP respond to hard probes?
What are the inner workings of QGP at various length scales?
Comparing heavy flavor particle flow in all systems

- There is charm anisotropy... everywhere
  - ordering: $v_2$ (PbPb) ≥ $v_2$ (pPb) > $v_2$ (pp)
  - so system size should play a role?

- For open bottom hadrons: $v_2$ (PbPb) > 0 but $v_2$ (pPb) ~ $v_2$ (pp) ~ 0

- HF probes help to answer whether QGP is formed in high-multiplicity pPb/pp

Summary tool

**Novel input** to the description of heavy-quark transport and energy loss
There is finite charm anisotropy... **up to high** $p_T \rightarrow$ path length dependence

- $v_2$ of prompt $\psi(2S)$ larger than prompt $J/\psi$ $v_2$ up to high $p_T$
- so different levels of **recombination** for $J/\psi$ and $\psi(2S)$?

- The measured $v_3$ consistent with zero
- **not (yet?)** sensitive to event-by-event fluctuations

Azimuthal anisotropy for **prompt $\psi(2S)$** mesons is reported for the first time
Azimuthal correlations of muon pairs from HF decays can shed light on the HF energy-loss mechanism(s).

- Opposite- vs same-sign muons: (in principle) $c\bar{c}$ vs $b\bar{b}$
- Observables: HF yield and width of away-side correlation
- Yield suppression toward central collisions.
- Width quite independent of centrality and consistent with $p\bar{p}$

**ATLAS-CONF-2022-022**

![Graphs showing suppression vs centrality and width vs centrality](image)

An alternative method for probing HF interactions with QGP
Explore energy loss and QGP expansion at the same time

- Constraining the spatial diffusion coefficient via data-to-model comparisons
- different transport models for energy loss and hadronization ($T > T_c$)
- simultaneous description of $R_{AA}$ and $v_2 \rightarrow 1.5 < 2\pi D_s T_c < 4.5$ (best limits at LHC)
- Measurement of $R_{AA}$ and $v_2$ for charm and bottom
- mass splitting at low $p_T$ but converge at high $p_T$ ($\gg m_b$)
- $D_s$ in $R_{AA}$ & $v_2$ calculation in line with the extraction from $D^0$

HF probes start to become powerful tomography tools
Resolving the $p_T$ and $v_2$ puzzle of $D^0$

- Challenging to understand the $R_{pPb}$ and $v_2$ of $D^0$
- Models describe the HF $R_{pPb}$ but can't $v_2$ (POWLANG) or can predict only the $v_2$ (GCC)
- Recently a simultaneous description was provided in a modified AMPT version, key findings:
  - Parton interactions + Cronin effect important for $R_{pPb}$ while
  - Parton interactions are mostly responsible for the $v_2$

Cronin effect could also be important for HF in large systems
Observation of the **sequential melting** of $\Upsilon(nS)$ in PbPb and pPb first time including $\Upsilon(3S)$ in the picture

$$R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$$

**CMS-PAS-HIN-21-007**

Interplay of suppression-regeneration crucial to grasp data
Heavy quarkonia suppression

- Observation of the sequential melting of \( \Upsilon(ns) \) in PbPb and pPb
- first time including \( \Upsilon(3S) \) in the picture
- Similarly to the hierarchy suppression between \( J/\psi \) and \( \psi(2S) \)
- decreasing \( R_{AA} \) vs \( p_T \) connected with charm quark regeneration

CMS-PAS-HIN-21-007
PbPb 1.6 nb\(^{-1}\), pp 300 pb\(^{-1}\) (5.02 TeV)

CMS
Preliminary

Cent. 0-90 %

\( p_T < 30 \text{ GeV/c} \)
\( y_{l\bar{l}} < 2.4 \)

\( \Upsilon(1S) \) (2015 PbPb/pp)
\( \Upsilon(2S) \)
\( \Upsilon(3S) \)

Interplay of suppression-regeneration crucial to grasp data
The first measurement of prompt and nonprompt J/ψ at midrapidity in pPb 8.16 TeV thanks to the usage of electron triggers in TRD.

Theoretical models describing the forward, backward y results, also agree at midrapidity.

$R_{pPb}$ vs $p_T$ consistent with unity $\rightarrow$ CNM effects modest in the studied kinematic range.

Data can be described with no final-state effects.

*arXiv: 2211.14153*
For $B_s^0$ **low-pT enhancement** suggested by models

- current uncertainty **large** though

**First observation** of $B_c^+$

- unique state for enhancement (**low** $p_T$) and suppression (**high** $p_T$)

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**Novel probe for suppression-regeneration**
What's the hadronization mechanism with QGP?
Charmed baryon-to-meson ratio in all systems

- New measurements of $\Lambda_c^+/D^0$ down to $p_T=0$ and central PbPb
- difference wrt to $pp \rightarrow$ radial flow or multiplicity dependence of hadronization?
- challenging further the universality of hadronization process
- So far significant differences in mid vs forward $y$
- a systematic discrepancy in $y$ confirmed
- motivate improvements in model predictions in different phase-space regions

Data in tension with the Statistical Hadronization model
Production of exotic hadrons in HIC

- Exotic states test models in an expanded range of $n_{cq}$
- Effects are sensitive to size/binding energy of bound state and QGP density
- $\chi_{c1}(3872)/\psi(2S)$: something different for exotic vs conventional hadrons?
- Initial-state effects cancel in the ratio
- Enhancing effects start to outcompete breakup (at least at low $p_T$)

Machine learning techniques increases sensitivity to rare probes
Summary

- LHC nuclear data are a game changer
- Precise extractions of nPDFs crucial for modeling the initial state needed to characterize the QGP
- Comprehensive studies of heavy flavor collectivity in all systems
- Significant charm $v_2$, bottom flows (?) in PbPb
- Complementary measurements from $\Delta \phi$ correlations of HF decayed leptons
- Explore $v_2$ & $R_{AA,pA}$ at the same time
- Consistently extract $D_s$, understand $p_T$ broadening, and parton interactions
- A rich program on quarkonia suppression
  - $J/\psi$ in extended regions, $\psi(2S)$, $Y(ns)$, $B_s^0$, $B_c^+$
- Future data with improved precision will provide crucial insights
  - For example, $\Lambda_c^+/D^0$, exotic mesons, all above

Plot here
Key features of heavy flavor measurements

- Variety of meson/baryon states with different flavors in a broad kinematic range
- Techniques to separate heavy from light flavor decays
- We gain insight on whether heavy quarks flow with the bulk
- Parton interactions in the QGP (thermalization, energy loss,...)
- QGP properties (transport coeff)
- pQCD predictions, parton shower modeling, hadronization mechanisms
HL-LHC operational scenarios for pPb and PbPb

- Included in the YR and more recently refined (CERN-ACC-2020-0011, EPJ.Plus 136 (2021) 7)
- Scenarios are based on benchmarked models (agree remarkably well with Run 2 LHC data)
- ≈five one-month runs would be needed to reach 13 /nb of PbPb
- ≈two one-month runs would be needed to reach 1.2 /pb of pPb
- Projections could be improved, e.g., due to operational efficiency (>50%), etc

HL-LHC starts at Run 3 for heavy ions
Detailed flow measurements in \( pp/pPb \) indicate that:

- centrality/event activity and \( p_T \) dependence qualitatively similar to that in AA
- identified particle and multiparticle correlation techniques support a collective origin of \( v_n \)
- encompassed by hydrodynamical models, but not a unique description

We start answering whether a collective component in \( v_n \) exists by studying:

- the role of the initial conditions
- the impact of hard-scattering processes and energy loss
- alternative systems, e.g., ultraperipheral collisions (UPC)
Investigating the initial stages with **more elaborate** observables

- **Subtle** differences in $v_2\{2k\}(k \leq 5)$ fluctuation-driven **moments** of $v_2$
- Measured $v_2\{10\}$ measured for the first time!
- Constraints on hydro predictions
- High-precision for **sign changes** when correlating $v_n\{2k\}$ with $[p_T]$
- Very sensitive to gluon correlations (CGC): **not seen in data**

**Resolving $v_2$ event-by-event fluctuations with unprecedented precision**
## Key characteristics of the nPDF global fits

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<th>Feature</th>
<th>KSASG20</th>
<th>nCTEQ15WZSIH</th>
<th>TUJU21</th>
<th>EPPS21</th>
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P. Paakkinen (DIS22)
Key characteristics of the nPDF global fits

With input from Annu. Rev. Nucl. Part. Sci. 70 (2020)

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<th>Nuclear (most recent) PDFs</th>
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nPDFs from several groups but

- less available data sets compared to the free-nucleon cases
- different data sets (e.g., pPb LHC data), theoretical assumptions, and methodological settings
- not well understood aspects for bound nucleons, e.g.,
  - the nuclear modifications of the gluon distribution
  - Measurements at small-x test non-linear QCD evolution at small-x ("parton saturation")

In preparation of EIC, pPb @ HL-LHC provides the best input to nPDFs
Nuclear gluon PDFs: constraints scarce so far

- Stringent constraints with **dijet** production
- Enhanced **suppression** at forward \( y \)
- Significant reduction in EPPS16 uncertainties after reweighting already with Run 2 data (left plot)
- **Improved constraints** with HL-LHC data (right plot)
- Complementarity with W bosons and top quarks, and exclusive vector meson photoproduction
## HF transport models: ingredients

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But more importantly: different **implementations** and **input parameters**.

Input from

[QM22 conference (Luuk Vermunt)](https://example.com/qm22-conference)
Uncertainties in $B_s$ in PbPb

*arXiv: 2109.01908*

Table 2: Summary of systematic uncertainties in the $T_{AA}$-scaled yield measurements for $B^+$ and $B_s^0$ mesons, in three centrality ranges. The measurements are performed in the B meson kinematic region given by $10 < p_T < 50\text{GeV}/c$ and $|y| < 2.4$. The relative uncertainty values are shown in percentage.

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<th>$B^+$ 30–90%</th>
<th>$B^+$ 0–90%</th>
<th>$B_s^0$ 0–30%</th>
<th>$B_s^0$ 30–90%</th>
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<td>2.2</td>
<td>2.4</td>
<td>6.6</td>
<td>2.3</td>
<td>4.4</td>
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<tr>
<td>Fit modeling</td>
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<td>2.8</td>
<td>2.6</td>
<td>2.5</td>
<td>3.2</td>
<td>2.3</td>
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<tr>
<td>Tracking efficiency</td>
<td>5.0</td>
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<td>5.0</td>
<td>10</td>
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<tr>
<td>$T_{AA}$</td>
<td>2.0</td>
<td>3.6</td>
<td>2.2</td>
<td>2.0</td>
<td>3.6</td>
<td>2.2</td>
</tr>
<tr>
<td>$N_{MB}$</td>
<td>1.3</td>
<td></td>
<td></td>
<td>1.3</td>
<td></td>
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<tr>
<td>Branching fraction</td>
<td>2.9</td>
<td></td>
<td></td>
<td>7.5</td>
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<tr>
<td><strong>Total</strong></td>
<td>+16</td>
<td>+12</td>
<td>+15</td>
<td>+16</td>
<td>+15</td>
<td>+15</td>
</tr>
<tr>
<td></td>
<td>−15</td>
<td>−12</td>
<td>−15</td>
<td>−16</td>
<td>−15</td>
<td>−15</td>
</tr>
</tbody>
</table>
Measuring jet quenching

- Energy of partons is redistributed ('quenched') inside QGP
- Experimentally seen as $R_{AA}$ modifications of hadrons or jets
- dependent on centrality, $p_T$, parton mass
- Unprecedented access from low- to high-$p_T$

$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled} \times \text{pp}}$

---

**ATLAS** anti-$k_t$ $R = 0.4$ jets $|y| < 2.1$

- 0 - 10%, $\sqrt{s_{NN}} = 2.76$ TeV [PRL 114 (2015) 072302]
- 0 - 10%, $\sqrt{s_{NN}} = 5.02$ TeV
- 30 - 40%, $\sqrt{s_{NN}} = 2.76$ TeV [PRL 114 (2015) 072302]
- 30 - 40%, $\sqrt{s_{NN}} = 5.02$ TeV
- $\langle T_{AA} \rangle$ and luminosity uncer.

**Most central at 5.02 (2.76) TeV**

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**CMS Supplementary**

$R_{AA}$ and lumi. uncertainty

- $b \rightarrow J/\psi$
- $D^0$
- $h^\pm$
- $B^+$

Cent. 0-100%
First experimental evidence (4σ level) of the top quark in nucleus-nucleus collisions using leptons only and leptons+b jets.

It establishes a new tool for probing nPDFs as well as the QGP properties.

Evidence of $t\bar{t}$ cross section in PbPb

A nice heuristic idea for a yocto-chronometer!

ΔE/E = [(τ - t)/τ] * 0.1

Probe ~ [0.4; 1.2] fm

Depending on the chosen $p_T$, the antenna may still lose some energy. Knowing the energy loss, it is possible to build the density evolution profile of the medium!