Heavy Ion Phenomenology - selected topics

29.11.2019

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The Large Heavy ion Collider

LHC runs 4wks/yr in pA- or AA-mode

$$\sqrt{s_{\rm NN}} = \sqrt{s_{\rm pp}}\sqrt{\frac{Z_1 Z_2}{A_1 A_2}}$$

$$\mathcal{L}^{\rm peak}_{\rm PbPb} = 3 \times 10^{27} {\rm cm}^{-2} s^{-1}$$

- ALICE
- ATLAS
- CMS
- LHCb (up to 50 % centrality).

participate

Ultra-relativistic heavy ion physics is QCD physics

- **How do collective phenomena and macroscopic properties of matter emerge from fundamental interactions in QCD?**

addressed in ultra-relativistic nucleus-nucleus collisions at the highest parton densities.

Perspectives today

(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales.

(2) Map the phase diagram of QCD with experiments planned at RHIC.

NSAC Long Range Plan 2015

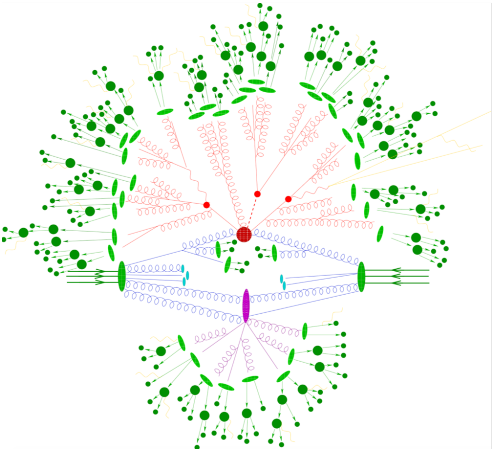
European Strategy Update

HL-LHC WG5 report, arXiv:1812.06772

- Characterizing long-wavelength QGP properties
- Probing the inner workings of QGP
- System size dependence
- Exploring nuclear pdfs

$\Longrightarrow$ This talk: how do these aims relate to current & future data from LHC?

Standard picture of proton-proton collisions



Included:

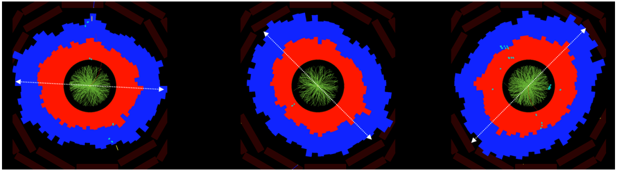
- Multiple Parton Interactions
- Hard Processes
- Parton Showers
- Elmag. Radiation
- Hadronization

Not included:

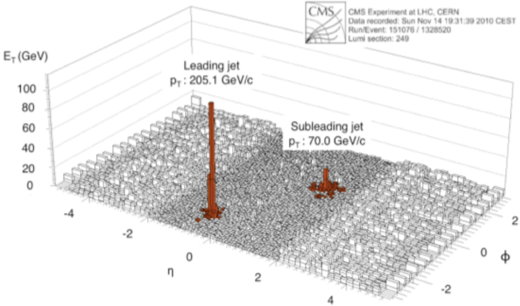
- Final State rescattering

Default: free streaming supplemented by fragmentation.

Observations in PbPb collisions at the LHC



Flow in low-$p_\perp$ particle production.



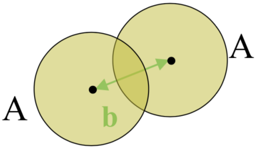
Jet quenching in high-$p_\perp$ particle production.

Not accounted for in standard picture of pp collisions.

Controlling the Cauldron

Examples of how controlled experimentation of signatures of collectivity is possible

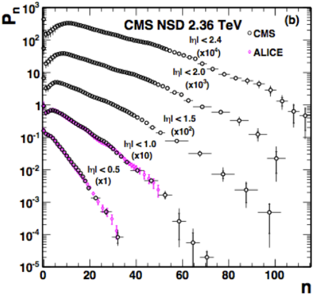
From multiplicity to centrality



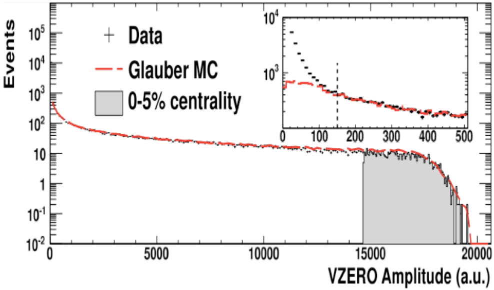
Unlike pp, multiplicity distribution in AA is dominated by geometry.
Cuts in multiplicity select centrality.

Bialas & Czyz, NPB111 (1976) 461

CMS, JHEP 1101 (2011) 079 LHC **pp**



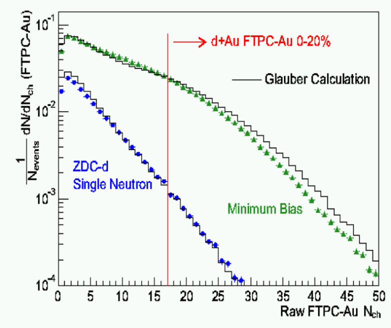
ALICE, PRL 105 (2010) 25230 LHC **PbPb**

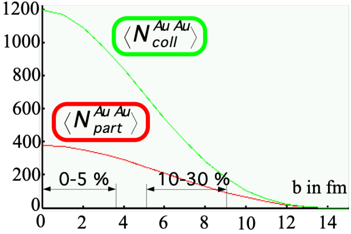


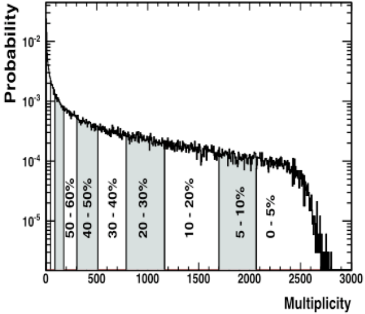
From multiplicity to centrality (cont'd)

- Glauber theory relates multiplicity to centrality.
- Many experimental tests, e.g.

STAR

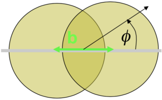






How to measure "flow" v_m?

- Measure particle production as function of angle ϕ w.r.t. reaction plane (RP).



$$v_n \equiv \langle e^{in\phi} \rangle$$

- But RP is unknown $\Longrightarrow$ measure particle correlations instead

$$\langle e^{in(\phi_1-\phi_2)} \rangle = v_n\{2\} v_n\{2\} + \langle e^{in(\phi_1-\phi_2)} \rangle^{\rm corr}, \mathcal{O}\left(\frac{1}{N}\right) \text{ −non-flow effect}$$

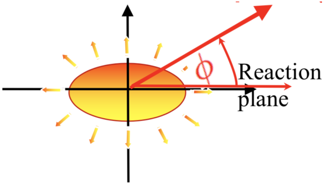
- Higher order cumulants $v_n\{2s\}$ Borghini, Dinh, Ollitrault, PRC 2001

$$\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \rangle - \langle e^{in(\phi_1-\phi_3)} \rangle \langle e^{in(\phi_2-\phi_4)} \rangle - \langle e^{in(\phi_1-\phi_4)} \rangle \langle e^{in(\phi_2-\phi_3)} \rangle$$
$$= -v_n\{4\} + \mathcal{O}\left(\frac{1}{N^3}\right)$$

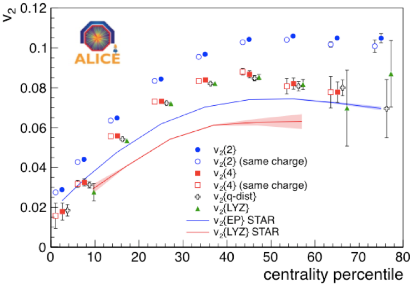
- To distinguish collective from microscopic correlations, require

$$v_n\{2\} \gtrsim 1/N^{1/2} \qquad \text{but} \qquad v_n\{4\} \gtrsim 1/N^{3/4}$$

Quantifying flow



$$\frac{dN}{d\eta\, d\phi} \propto \left[1 + 2\sum_m v_m \cos\left(m(\phi - \psi_{\mathrm{RP}})\right)\right]$$

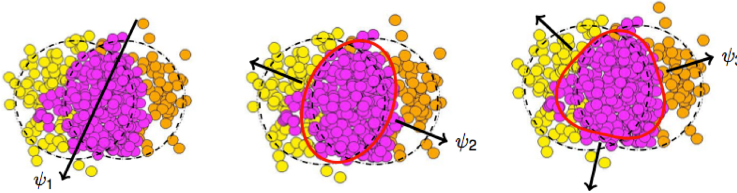


- Event multiplicity
  $N \sim 10^2 - 10^3$
  $\Longrightarrow 1/\sqrt{N} \sim \mathcal{O}(v_2)$
  $\Longrightarrow v_2\{2\}$ contaminated
  . by non-flow effects.

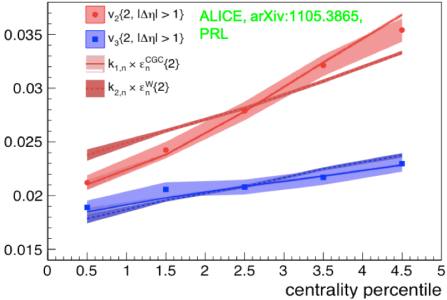
- $N \sim 10^2 - 10^3$
  $\Longrightarrow 1/N^{3/4} \lesssim 0.03 \ll v_2\{4\}$
  $\Longrightarrow v_2\{4\} \simeq v_2\{6\} \simeq v_2\{8\} \ldots$
  . free of non-flow effects.
  $\Longrightarrow$ **Signature of collectivity.**

Flow v_m as a response to spatial eccentricities δ_m

- Event-by-event fluctuations in the spatial nuclear overlap



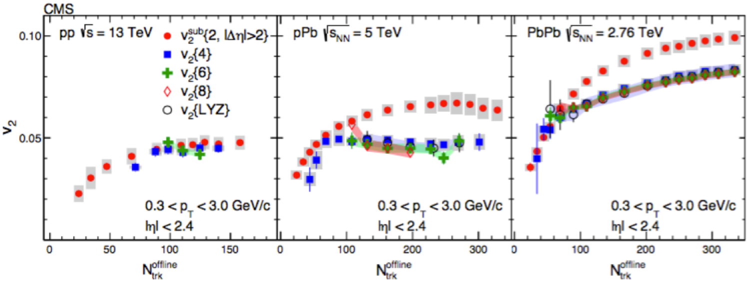
- $v_m \propto \left(\delta_m + \# \underbrace{\delta_{m_1}\delta_{m_2}}_{m_1 \pm m_2 \equiv m} \right)$
  - · linear response
  - · non-linear mode-mode coupling
- ...



System size dependence of collectivity

- Why does v_m in pp and pA show heavy-ion like behavior?

(CMS, Phys. Lett. B 765 (2017) 193)



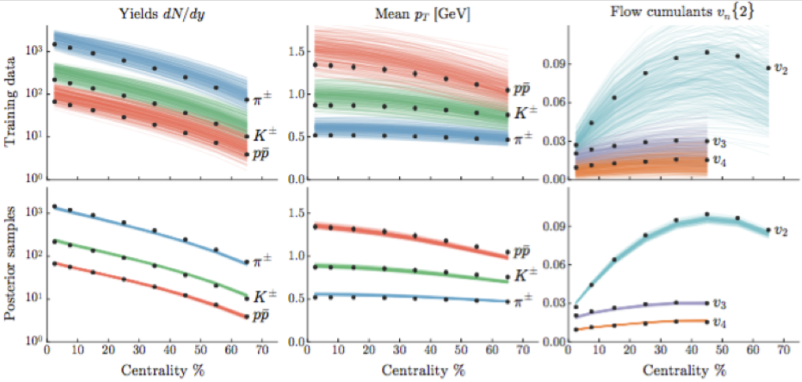
- "The observation of heavy-ion like behavior in pp collisions at the LHC suggests that more physics mechanisms are at play than traditionally assumed " Fisher & Sjøstrand, JHEP 01 (2017) 140

Models of collectivity

Several "full" multi-stage models of A+A collisions

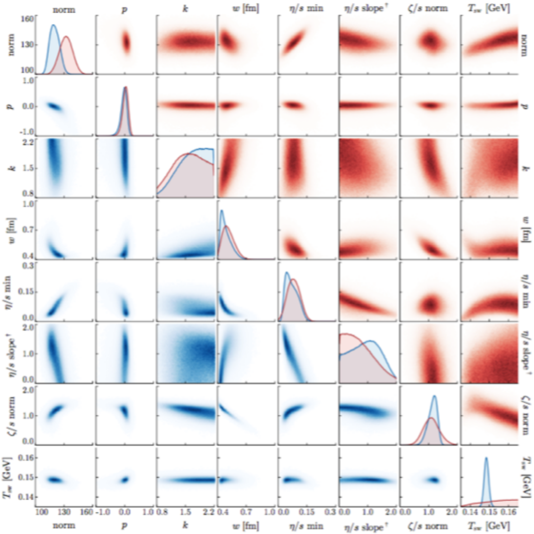
aim to extract QCD properties of matter, e.g. with Bayesian fits

(Bernhard et al., PRC94 (2016) 024907)



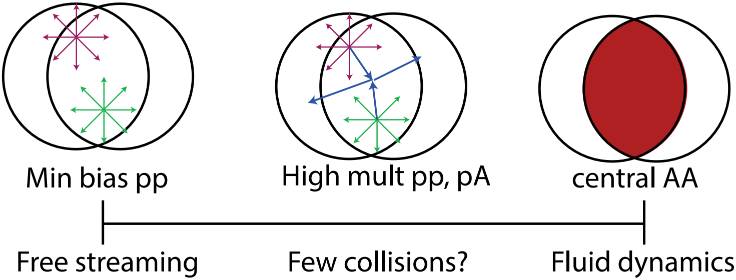
… (cont'd) (important, but not the focus of this talk)

(Bernhard et al., PRC94 (2016) 024907)



Simple questions about the nature of collectivity

- What are the mechanisms / the degrees of freedom relevant for collectivity?
- Is that the dynamical picture of collectivity?



How do we probe the QGP? (One schematic strategy)

- **Inject** perturbations $\delta h^{\mu\nu}$ (energy) or δA^{μ} (charge)
  - in form of spatial eccentricities
  - as jets
  - as electric charge, baryon number, heavy flavor
- **Measure** their propagation

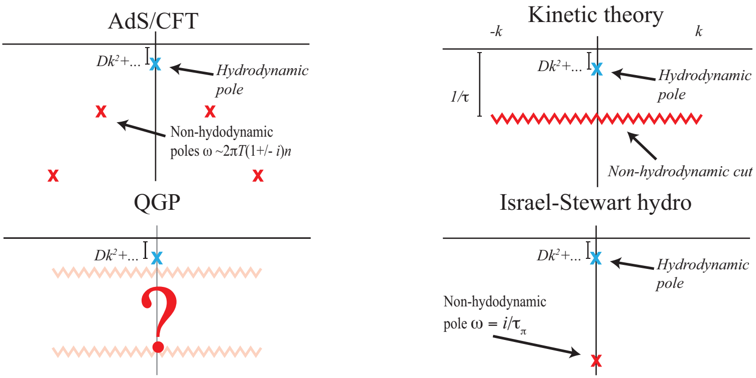
$$\delta T^{\mu\nu}(t,x) = \int_{t_i,x_i} G_R^{\mu\nu,\alpha\beta}(t-t_i, x-x_i)\delta h_{\alpha\beta}(t_i,x_i)$$

- **Conclude** about matter properties by analyzing $G_R(\omega, k)$.

$$G_R^{\alpha\beta,\gamma\delta}(t,k) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} e^{-i\omega t} G_R^{\alpha\beta,\gamma\delta}(\omega,k)$$

How?

Non-analytic structures in $G(\omega, k)$ - what we know



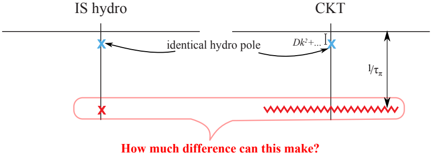
- Different QFTs have different collective dynamics

$$G_T^{0x,0x}(t,k) = \mathrm{Res}(\omega_{\mathrm{hydro}})e^{-i\omega_{\mathrm{hydro}}t} + \sum_n \mathrm{Res}(\omega_n)e^{-i\omega_n t}$$

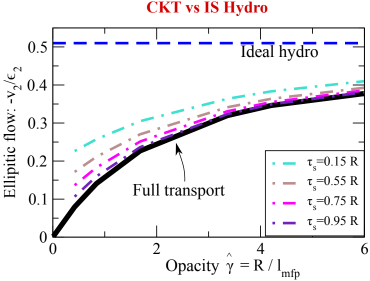
Is there sensitivity to the nature of collectivity? Yes

- Keep hydrodynamic excitations fixed throughout evolution.
- Switch non-hydro structure at time τ_s.
- Measured flow v_m sensitive to differences between fluid and non-fluid degrees of freedom.

$\Longrightarrow$ **Much more in talk by A. Kurkela.**



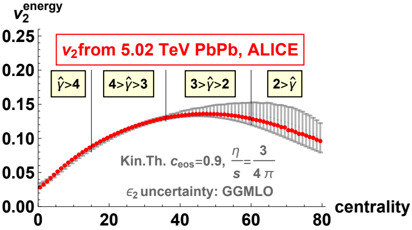
(Kurkela, Wiedemann, Wu, EPJC79 (2019) 759)

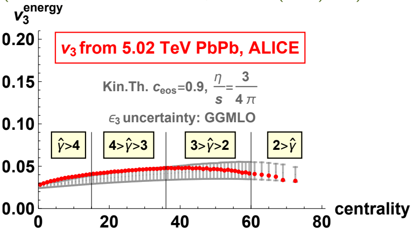


$\frac{v_m}{\epsilon_m}(\hat{\gamma})$ to data

Fair agreement of one-parameter RTA with centrality dependence

(Kurkela, Wiedemann & Wu, EPJC79 (2019) 965)





Small systems as test of inner workings

Decreasing the transverse system size R

- increases the smallest wavenumber $k \propto 1/R$
- time $t \sim R$ of in-medium propagation decreases
- ε decreases $\Longrightarrow \tau_R = \frac{1}{\gamma \varepsilon^{1/4}}$ increases

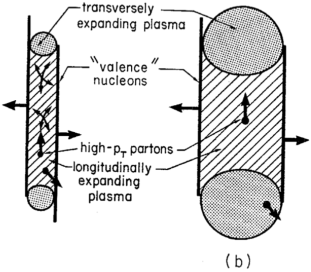
$$G_R(t,k) = \underbrace{c_{\mathrm{hyd}} \exp\left[-D\,k^2\,t\right]}_{\text{reduced for smaller R}} + \underbrace{c_{\mathrm{non-hyd}} \exp\left[-t/\tau_R\right]}_{\text{enhanced for smaller R}}$$

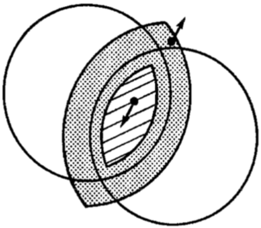
Reducing system size is one tool to enhance and characterize non-hydrodynamic modes.

Hard Probes, Jet Quenching, etc.

Bjorken conjectured monojet phenomena in 1982

He considered elastic rescattering in pp. (Fermilab-Pub-82/59-THY)



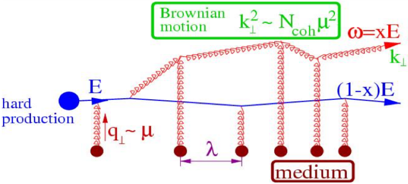


Based on calculation of collisional energy loss $\frac{dE_{2\leftrightarrow 2}}{dL} \approx 10\frac{\mathrm{GeV}}{\mathrm{fm}}$ which had to be revised to $\frac{dE_{2\leftrightarrow 2}}{dL} \ll 1\frac{\mathrm{GeV}}{\mathrm{fm}}$.

Radiative parton energy loss (BDMPS-Z)

- Baier, Dokshitzer, Mueller, Peigné, Schiff; Zakharov; Wiedemann; Gyulassy; Wang, ...

  Medium characterized by $\hat{q} \equiv \frac{\mu^2}{\lambda} \propto n_{\text{density}}$.



- phase accumulated in medium: $\left\langle \frac{k_\perp^2 \Delta z}{2\omega} \right\rangle \approx \frac{\hat{q}\, L^2}{2\omega} \equiv \frac{\omega_c}{\omega}$
- No. of coh. scatterings: $N_{\text{coh}} \approx \frac{t_{\text{coh}}}{\lambda}$, $t_{\text{coh}} \approx \frac{2\omega}{k_\perp^2}\Big|_{k_\perp^2 \approx \hat{q} t_{\text{coh}}} \approx \sqrt{\frac{\omega}{\hat{q}}}$.
- Gluon energy distribution: $\omega \frac{dI_{\text{med}}}{d\omega dz} \approx \frac{1}{N_{\text{coh}}} \omega \frac{dI_1}{d\omega dz} \approx \alpha_s \sqrt{\frac{\hat{q}}{\omega}}$ **(LPM effect in QCD)**.
- **BDMPS energy loss**:

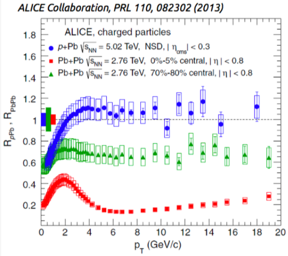
  $$\Delta E_{1\to 2} = \int_0^L dz \int_0^{\omega_c} d\omega \omega \frac{dI_{\text{med}}}{d\omega dz} \sim \alpha_s \omega_c \sim \alpha_s \hat{q} L^2.$$

Jet quenching is only seen in AA (so far)

Nuclear modification factor

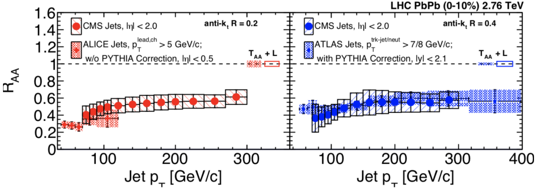
$$R_{AA}(p_\perp,\eta) = \frac{dN^{(\mathrm{AA})/\mathrm{dp}_\perp \mathrm{d}\eta}}{n_{\mathrm{coll}} dN^{(\mathrm{AA})/\mathrm{dp}_\perp \mathrm{d}\eta}}$$

for hadrons



for jets

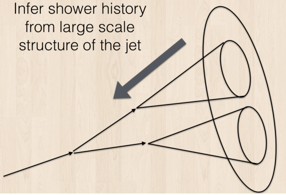
CMS PRC96 (2017) 015202

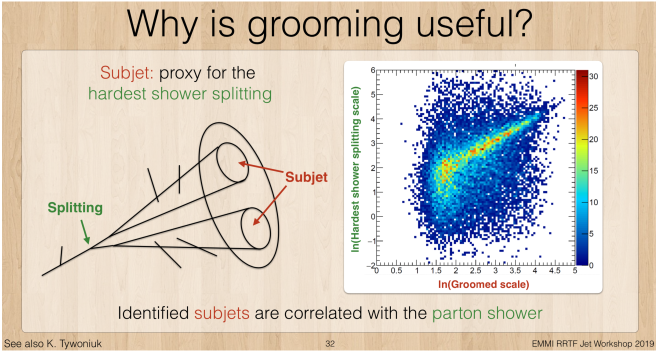


No evidence (yet?) for final state rescattering in pPb or pp.

Testing jet quenching with jet substructure

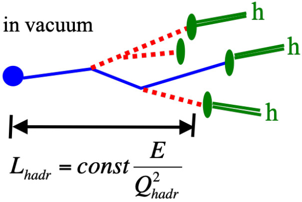
- Working hypothesis of all jet quenching models: spatio-temporal ordering of parton shower **slides Yi Chen, QM19**
- Can we test this?



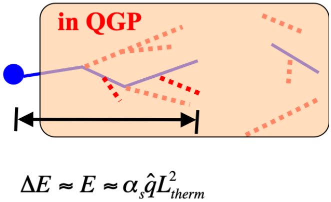


Jet thermalization

In QCD vacuum, jets hadronize.



In QCD plasma, jets thermalize.



Take home messages

- AA @ LHC = controlled experimentation in the smallest and hottest cauldrons: $|\vec{b}|$, $\vec{b}$, v_m, $\langle v_{m_1} v_{m_2} \rangle$, $\frac{dE_{\rm parton}}{dL}$ ...
- **Collectivity**
  - seen across system size in pp, pA and AA.
  - sensitive to fluid and non-fluid dynamic matter properties.
- **Jet Quenching** $\Longrightarrow$ equilibration of far-out-of equilibrium probes.
- **Future** @ HL-LHC, HE-LHC, FCC: $\mathcal{L}_{\rm int}$, pPb, FT, ...

European Strategy Update

CERN Yellow Report arXiv:1812.0672