Looking for a unified description of pp, pA and AA collisions

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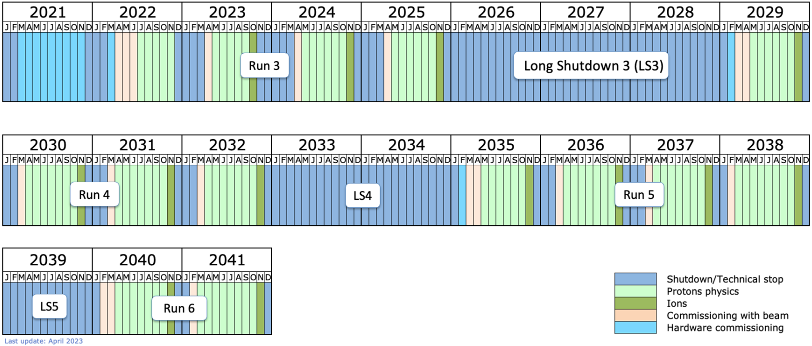
Overview on heavy-ion physics

1.1 Heavy-ion experiments

The LHC and HL-LHC:



https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

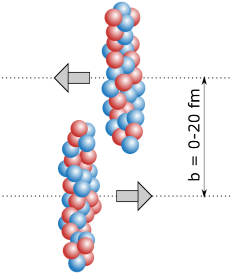
Guarantee experimental advances for two more decades!

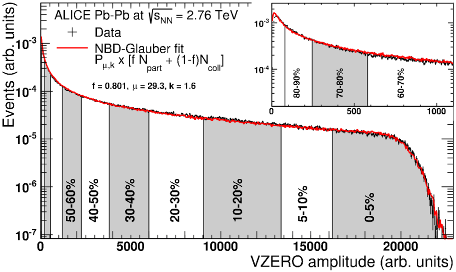
1.1 Heavy-ion experiments

Features:

1. **Beams:** p, Pb, Xe, O, Ne? $\cdots$

2. **"Measurement" of the impact parameter (centrality):**



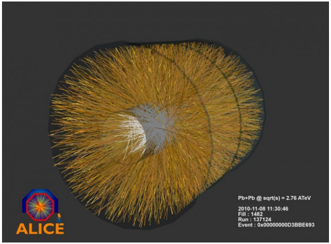


B. Abelev *et al.* [ALICE], Phys. Rev. C **88**, no.4, 044909 (2013) [arXiv:1301.4361 [nucl-ex]].

1.2 Bulk matter in AA collisons: QGP fluid

Bulk matter in central AA collisions:

a collection of produced soft particles



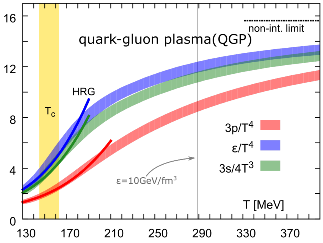
$$\varepsilon(t = 1\ fm/c) \sim 10 GeV/fm^3.$$

Tip: $\varepsilon = 0.16\ GeV/fm^3$ in nuclei.

CMS: Phys. Rev. Lett. **109**, 152303 (2012)

(Static) Quark-Gluon Plasma (QGP):

In thermal equilibrium:



Lattice QCD: Phys. Rev. D **90**, 094503 (2014).

Primodial matter in early universe at

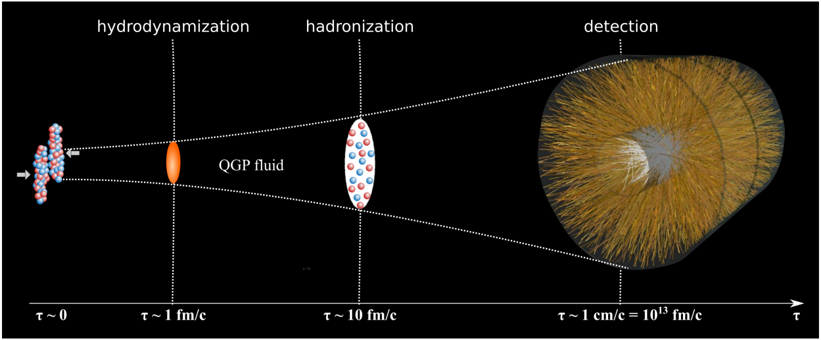
$$t \approx 1/T_{MeV}^2 \approx 10\mu s$$

1.2 Bulk matter in AA collisons: QGP fluid

1) Bulk matter is not a static QGP.

2) Bulk matter is mostly a strongly-coupled QGP fluid.

The entire history of AA collisions



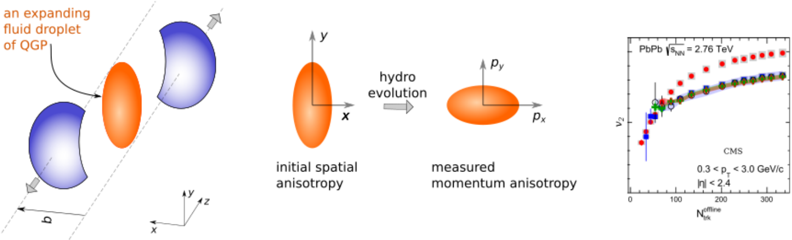
For a review: Heinz and Snellings, Ann. Rev. Nucl. Part. Sci. **63**, 123-151 (2013) [arXiv:1301.2826 [nucl-th]].

1.2 Bulk matter in AA collisons: QGP fluid

Evidence 1: collective flow

Definition of flow coefficients v_n:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2v_2\cos(2(\phi - \Psi_2)) + \cdots\right]$$

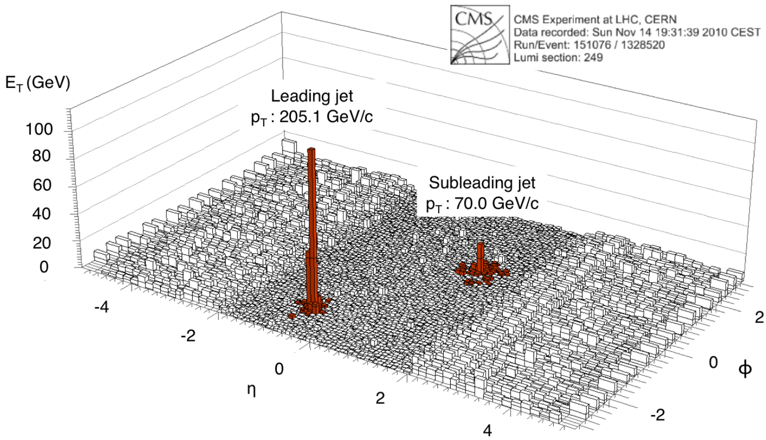


Hydro models fit successfully AA flow data!

For a review: Heinz and Snellings, Ann. Rev. Nucl. Part. Sci. **63**, 123-151 (2013) [arXiv:1301.2826 [nucl-th]].

1.2 Bulk matter in AA collisons: QGP fluid

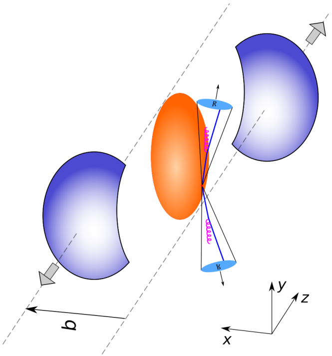
Evidence 2: jet quenching



One PbPb collision

1.2 Bulk matter in AA collisons: QGP fluid

Evidence 2: jet quenching

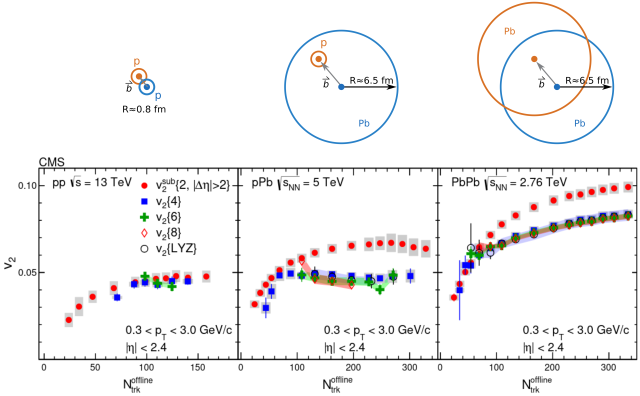


Jets lose energy to bulk matter!

First proposed in J. D. Bjorken, FERMILAB-PUB-82-059-THY.

1.3 A surprise in small systems

1. Collectivity in pp and pA collisions

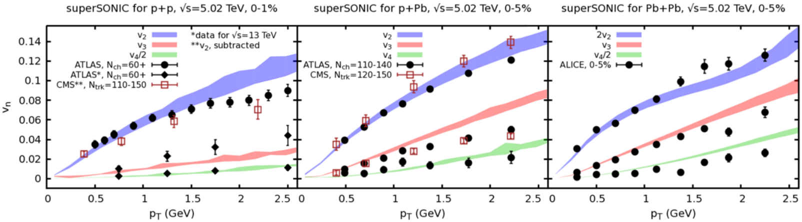


CMS collaboration, *Phys. Lett. B* **765** (2017) 193 [1606.06198].

2. No evidence of jet quenching in pp and pA so far!

1.3 Puzzles in small systems

Hydro models have some phenomenological success



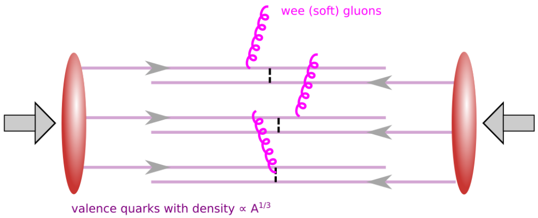
R. D. Weller and P. Romatschke, Phys. Lett. B **774**, 351-356 (2017) [arXiv:1701.07145 [nucl-th]].

One main open question:

QGP fluid forms in pp collisions?

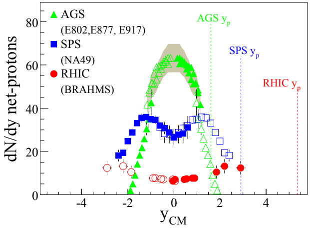
Bulk matter in parton picture

2.1 Parton Picture for bulk matter



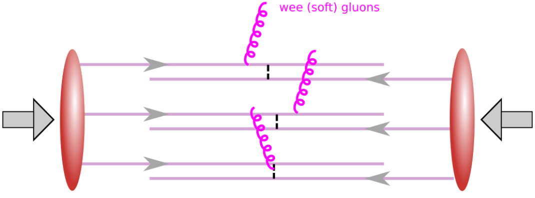
Bjorken, Lect. Notes Phys. **56**, 93 (1976).

1. At high energies, the valence quarks mostly pass through each other:



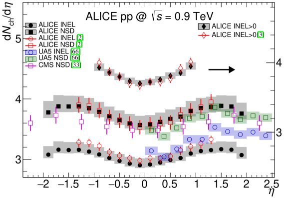
I. G. Bearden *et al.* [BRAHMS], Phys. Rev. Lett. **93**, 102301 (2004) [arXiv:nucl-ex/0312023 [nucl-ex]].

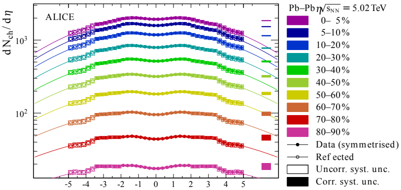
2.1 Parton Picture for bulk matter



Bjorken, Lect. Notes Phys. **56**, 93 (1976).

2 Longitudinal boost-invariance: "wee" partons fill a central plateau.





J. Adam *et al.* [ALICE], Eur. Phys. J. C **77**, no.1, 33 (2017) [arXiv:1509.07541 [nucl-ex]].

J. Adam *et al.* [ALICE], Phys. Lett. B **772**, 567-577 (2017) [arXiv:1612.08966 [nucl-ex]].

2.1 Parton picture for bulk matter

Bjorken, Lect. Notes Phys. **56**, 93 (1976).

1. The valence quarks pass through each other.
2. Produced "wee" partons fill a central plateau in rapidity.
3. The saturation model (CGC): $k \sim Q_s > \Lambda_{QCD}$

A comprehensive review: Kovchegov and Levin, Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol. **33**, 1 (2012). .

Let us see what follows from this picture.

2.2 v_2 from valence quark scattering

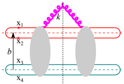
Keeping only the valence quark sector of hadrons:

$$\frac{d\sigma}{d^2\mathbf{b}d\eta d^2\mathbf{k}} = \prod_{i=A,B}\int d^2\mathbf{r}_i \sum_{s^i_q, s^i_{\bar{q}}} \frac{1}{4\pi}\int_0^1 d\xi_i |\psi_{s^i_q\, s^i_{\bar{q}}/\sigma}(\mathbf{r}_i,\xi_i)|^2 \frac{d\hat{\sigma}}{d^2\mathbf{b}d\eta d^2\mathbf{k}},$$

where the hadron wave function $\psi_{s^i_q\, s^i_{\bar{q}}/\sigma}$ can be wave function can be obtained numerically from the Basis Light- Front Quantization.

For pion-pion collisions:

$$\frac{d\hat{\sigma}}{d^2\mathbf{b}d\eta d^2\mathbf{k}} = \frac{1}{2(2\pi)^3}\frac{1}{N_c^2}\left(\quad \right)$$

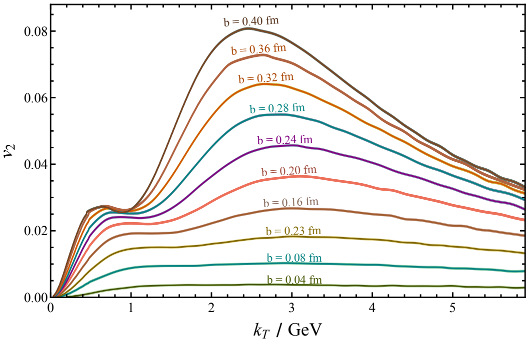


$$= \frac{2\alpha_s^2 C_F}{N_c}\int \frac{d^2\mathbf{l}}{(2\pi)^2}\frac{1}{|\mathbf{l}|^2}\frac{d^2\mathbf{l}'}{(2\pi)^2}\frac{1}{|\mathbf{l}'|^2}\left(e^{-i\mathbf{l}\cdot\mathbf{x}_3} - e^{-i\mathbf{l}\cdot\mathbf{x}_4}\right)\left(e^{i\mathbf{l}'\cdot\mathbf{x}_3} - e^{i\mathbf{l}'\cdot\mathbf{x}_4}\right)$$
$$\times 4\alpha_s N_c\left(\frac{\mathbf{k}}{|\mathbf{k}|^2} - \frac{\mathbf{k}-\mathbf{l}}{|\mathbf{k}-\mathbf{l}|^2}\right)\cdot\left(\frac{\mathbf{k}}{|\mathbf{k}|^2} - \frac{\mathbf{k}-\mathbf{l}'}{|\mathbf{k}-\mathbf{l}'|^2}\right)$$
$$\times\left[e^{i(\mathbf{l}-\mathbf{k})\cdot\mathbf{x}_1} - e^{i(\mathbf{l}-\mathbf{k})\cdot\mathbf{x}_2}\right]\left[e^{-i(\mathbf{l}'-\mathbf{k})\cdot\mathbf{x}_1} - e^{-i(\mathbf{l}'-\mathbf{k})\cdot\mathbf{x}_2}\right]$$

Just interference without final-state interactions!

2.2 v_2 from valence quark scattering

v_2 in pion-pion collisions:



Interference from gluon sources ($q\bar{q}$) separated by a distance $\sim$ the hadron size

Li, Qian, BW and Zhang, arXiv:2304.06557 [hep-ph].

Flow in CGC:

A review: T. Altinoluk and N. Armesto, Eur. Phys. J. A **56**, no.8, 215 (2020) [arXiv:2004.08185 [hep-ph]].

2.3 Collectivity from one scattering

Parametric estimates of final-state interactions:

In pp collisions at the LHC with $\langle p_T \rangle \sim 1$ GeV

$$\frac{dN_{pp}}{d\eta} \sim 10 \text{ at } \eta \sim 0$$

$$\Rightarrow \epsilon(t = 1\text{fm}/c) \sim \frac{dN_{pp}}{d\eta} \frac{\langle p_T \rangle}{1 \text{ fm}^3} \sim 10 \text{ GeV/fm}^3$$

Mean free path

$$\lambda \gtrsim 1/\epsilon^{\frac{1}{4}} \sim 0.4 \text{ fm}$$

It should be comparable to the proton size~ 0.8 fm!

2.3 Collectivity from one scattering

Kinetic theory in relaxation time approximation (RTA):

$$\partial_\tau F + \vec{v}_\perp \cdot \nabla_{\vec{x}_\perp} F - \frac{1}{\tau} v_z (1 - v_z^2) \partial_{v_z} F + \frac{4 v_z^2}{\tau} F = -C[F]$$

with $F(\Omega) = \int \frac{4\pi p^2 dp}{(2\pi)^3} p f$ and

$$C[F] = \qquad \gamma \varepsilon^{\frac{1}{4}} (-v \cdot u) F - \gamma \frac{\varepsilon^{\frac{5}{4}}}{(-v \cdot u)^3}.$$

Including one and only one final-state scattering

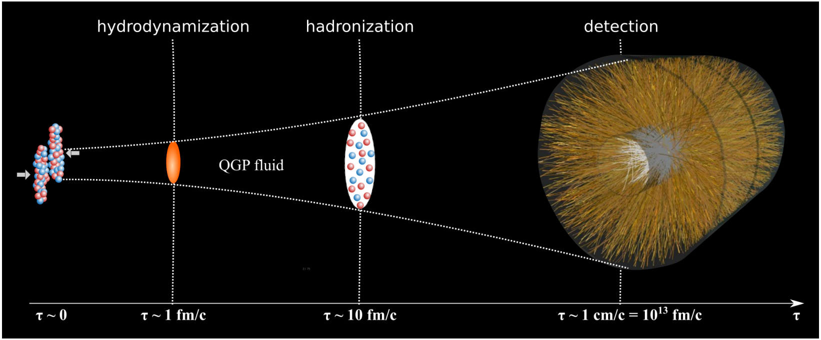
$$\frac{dE_\perp}{d\eta d\phi} = \frac{1}{2\pi} \frac{dE_\perp}{d\eta}\Big|_{\hat{\gamma}=0, \epsilon_n=0} \qquad \left\{ 1 - 0.210\, \hat{\gamma} - \underbrace{0.212\, \hat{\gamma} \epsilon_2}_{v_2} 2\cos(2\phi - 2\psi_2) \right\},$$

where ϵ_n: eccentricities; $\hat{\gamma} = R/l_{mfp}$; l_{mfp}: mean free path; R the systme size.

Kurkela, Wiedemann and BW, Phys. Lett. B **783**, 274 (2018), [arXiv:1803.02072].

2.4 Unified description of bulk matter

RTA does not capture all the physics



"bottom-up" thermalizaiton in AA collisions

R. Baier, A. H. Mueller, D. Schiff and D. T. Son, Phys. Lett. B **502**, 51-58 (2001) [arXiv:hep-ph/0009237 [hep-ph]].

Confirmed by simulations using Effective Kinetic Theory (EKT)!

2.4 Unified description of bulk matter

The BEDA for bulk matter in pp, pA and AA

(**BEDA**: Boltzmann Equation in Diffusion Approximation)

$$(\partial_t + \boldsymbol{v} \cdot \nabla_{\boldsymbol{x}})\, f^a = C^a_{2\leftrightarrow 2} + C^a_{1\leftrightarrow 2},$$

where $a = g, q, \bar{q}$ respectively for gluons, quarks and antiquarks and

$$C^a_{2\leftrightarrow 2} = \frac{1}{4}\hat{q}_a(t)\nabla_{\boldsymbol{p}} \cdot \left[\nabla_{\boldsymbol{p}} f^a + \frac{\boldsymbol{v}}{T^*(t)} f^a(1 + \epsilon_a f^a)\right] + \mathcal{S}_a,$$

where $\epsilon_a = 1$ for bosons and $\epsilon_a = -1$ for fermions.

1. Qualitatively agree with EKT but numerically cheaper

   S. Barrera Cabodevila, C. A. Salgado and BW, Phys. Lett. B **834**, 137491 (2022) [arXiv:2206.12376 [hep-ph]]; work in progress.

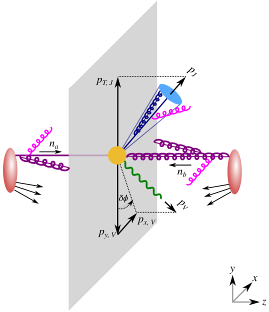
2. Sergio Barrera Cabodevila PhD project:

   Collectivity in small systems using the BEDA

Jet physics in pp, pA and AA

3.1 Factorization in pp collisions

Factorization formula, excluding Glauber modes, for recoil-free jets using SCET:



Hard function: $\mathcal{H}_{ij\to Vk} \leftarrow$ parton-level $\hat{\sigma}$

Beam functions: $\mathcal{B}_i, \mathcal{B}_j \leftarrow$ TMDs in hadrons

Soft function: $S_{ijk} \leftarrow$ soft radiation

Jet function: $\mathcal{J}_k$

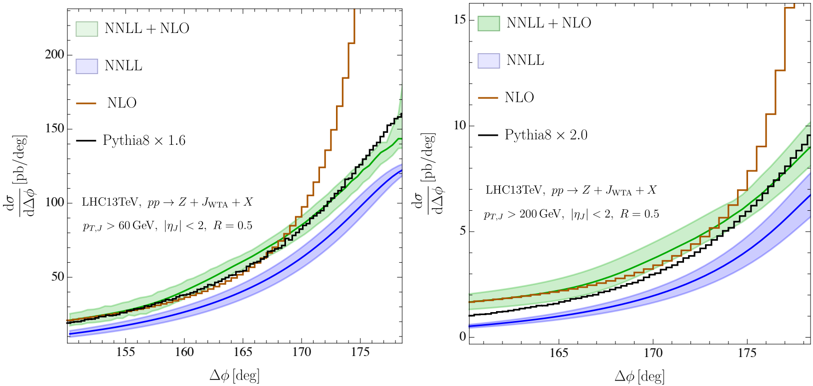
$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_x\,\mathrm{d}p_{T,V}\,\mathrm{d}y_V\,\mathrm{d}\eta_J} = \int \frac{\mathrm{d}b_x}{2\pi} e^{b_x q_x} \sum_{ijk} \mathcal{H}_{ij\to Vk}(p_{T,V}, y_V - \eta_J)\mathcal{B}_i(x_a, b_x)B_j(x_b, b_x)\mathcal{J}_k(b_x)S_{ijk}(b_x, \eta_J)$$

Resummation via the RG equation: for each function above denoted by F

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}F(\mu) = \gamma^F F(\mu) \text{ with } \gamma^F \text{ anomalous dimension of } F$$

3.1 Factorization in pp collisions

At next-to-next-to leading log (NNLL) + NLO (2→3) accuracy

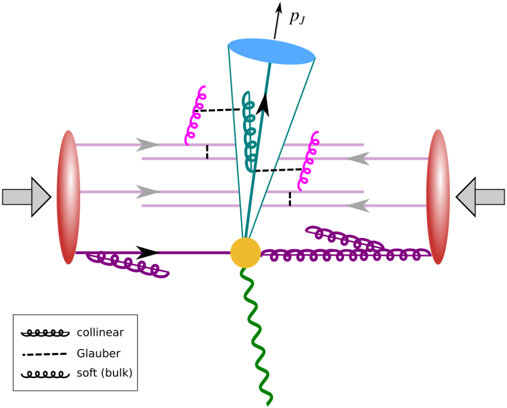


Note PYTHIA only has leading log (LL) accuracy!

Factorization provides a system way to deal with (vacuum) parton shower!

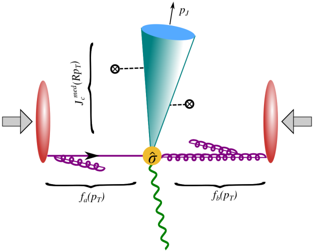
Chien, Rahn, Shao, Waalewijn and BW, JHEP **02**, 256 (2023) [arXiv:2205.05104 [hep-ph]].

3.2 Factorization from pp to AA



Couple jets to bulk matter!

3.2 Factorization from pp to AA



Is factorization so simple (even at LO order)?

$$\frac{d\sigma}{dp_T d\eta} = \sum_{abc} f_a \otimes f_b \otimes \hat{\sigma}_{ab\to c} \otimes \underbrace{J_c^{med}}_{\text{Bulk enters.}}$$

N. Armesto, C. A. Salgado, F. Cougoulic and BW, work in progress.

Note this has been assumed in all jet quenching studies!

Final step: to combine vacuum and medium showering (BEDA)

Summary

Aim: a unified QCD framework for pp, pA and AA at the LHC/HL-LHC

a unified framework for
high-energy nuclear collisions in the LHC/HL-LHC era

initial stages

Nuclear PDFs:

"*Distributions of hard partons in nulei*"

Prof. C. A. Salgado

Parton saturation: (CGC)

"*Distributions of semi-hard partons in nuclei*"

Prof. Nestor Armesto

↔ EIC Physics

2. hard probes

Ongoing Project:

"*exploring factorization of the dijet cross-section in heavy-ion collisions*"

with N. Armesto, C. A. Salgado & F. Cougoulic.

↔ YoctoLHC (ERC)

3. bulk matter

PhD Project:

"*flow in small systems*"

S. Barrera Cabodevila

(cosupervised with Prof. Salgado)

Ongoing Project:

"*Anisotropic flow & the valence quark skeleton of hadrons*"

with M. Li, W. Qian (IGFAE) & H. Zhang (Shandong U.)

pp ↔ pA ↔ AA

1. QCD factorization: "*high-precision calculations for QCD jets (boson-Jets, dijets, etc) in pp collisions*" **(ongoing)**

with Y.-T. Chien (Georgia State U.), R. Rahn(Nikhef), D. Shao(Fudan U.), W. J. Waalewijn (Nikhef)