

Hard probes in heavy-ion collisions (theory)

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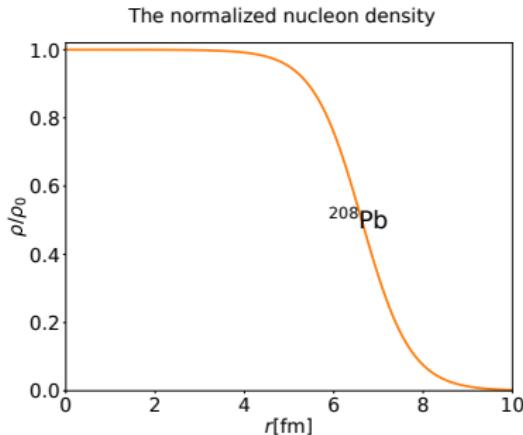
European Nuclear Physics Conference 2022



An Overview

Heavy nuclei at rest

* As seen by an electron with a resolution $\sim 1 \text{ fm}$:



C. W. De Jager, H. De Vries and C. De Vries, Atom. Data Nucl. Data Tabl. **14** (1974), 479-508.

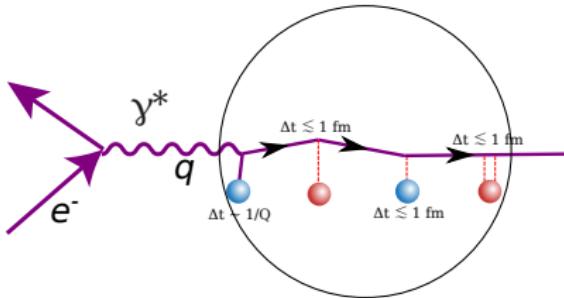
* The density of nuclear matter ρ_0 : $\Rightarrow \epsilon_0 \approx 0.17 \text{ GeV}/\text{fm}^3$

* The binding energy/nucleon (E_{bind}): $\Rightarrow t_{\text{bind}} \sim \hbar/E_{\text{bind}} \approx 25 \text{ fm}/c$

Interactions between nucleons are negligible for $t \ll t_{\text{bind}}$.

Deep Inelastic Scattering (DIS) on Heavy nuclei

- * As seen by an electron with a resolution $1/Q = 1/\sqrt{|q^2|} \ll 1 \text{ fm}$:



- * Nuclear wave functions of multi-partons/nucleons are not known?

- * Note that all the time scales involve are much shorter than t_{bind} :

As a first approximation, heavy nuclei are treated as "free" nucleons distributed as seen by low-energy electrons.

Parton saturation: A. H. Mueller, Nucl. Phys. B 335, 115-137 (1990);

The Glauber model: Miller, Reygers, Sanders and Steinberg, Ann. Rev. Nucl. Part. Sci. 57, 205-243 (2007).

Heavy-Ion Collisions (HIC) in the lab frame

- * At design energy of the LHC: lead ions with energy/nucleon = 2.76 TeV

$$\gamma \approx 2.9 \times 10^3 \Rightarrow \epsilon_0 \rightarrow 1.5 \text{ PeV/fm}^3, \quad t_{\text{bind}} \rightarrow 7.3 \times 10^4 \text{ fm/c.}$$

L. Evans and P. Bryant, JINST 3, S08001 (2008).

- * For particles with p_T or $m \gtrsim 1 \text{ GeV}$ produced in heavy-ion collisions

1. the spatial resolution involved $\lesssim 1 \text{ fm} \Rightarrow$ partonic substructure

Nuclear PDFs: nCTEQ collaboration: Phys. Rev. D 93, no.8, 085037 (2016) [arXiv:1509.00792 [hep-ph]];

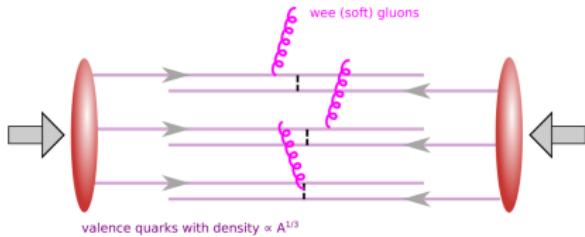
Eskola, Paakkinen, Paukkunen and Salgado, Eur. Phys. J. C 82, no.5, 413 (2022) [arXiv:2112.12462 [hep-ph]]. . . .

2. the typical time involved $\ll t_{\text{bind}} \rightarrow$ the Glauber modelling of nuclei

Can one obtain a consistent picture of HIC in perturbative QCD?

Soft (semi-hard) partons: bulk matter

- * Hard probes: high- p_T jets, heavy quarkonia etc.
- * Hard initial partons are mostly not hard probes.



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

1. They mostly pass through each other, carrying away most of energy.
2. **Bulk**: produced soft partons with $\epsilon \sim 10 \text{ GeV/fm}^3$ at $\tau \sim 1 \text{ fm/c}$
3. Parton saturation (CGC): $k \sim Q_s > \Lambda_{QCD}$ (semi-hard)

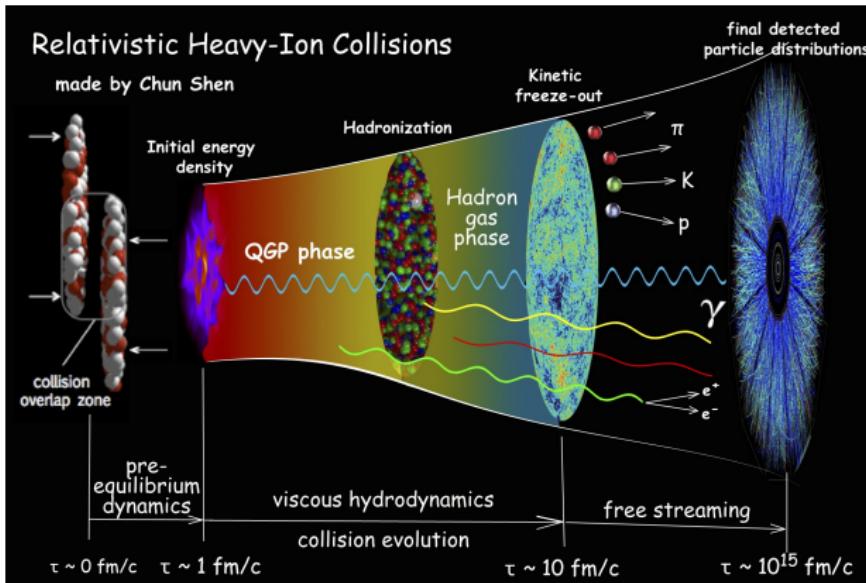
A comprehensive review: Kovchegov and Levin, Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol. 33, 1 (2012). .

Real-time dynamics of bulk matter

* A converging picture for $\tau \lesssim 1 \text{ fm}/c$: the bottom-up thermalization.

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

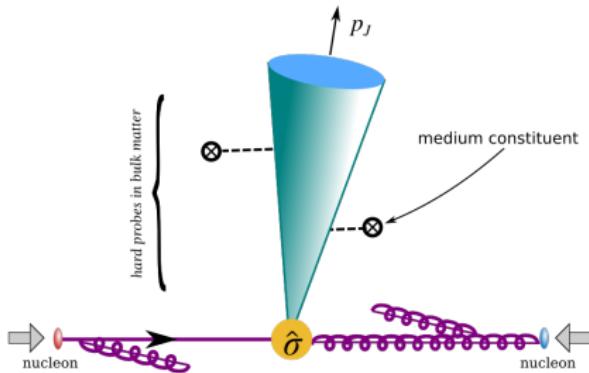
* The standard model of HIC



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

Factorization formula for hard probes in HIC

* The (conjectured) factorization formula



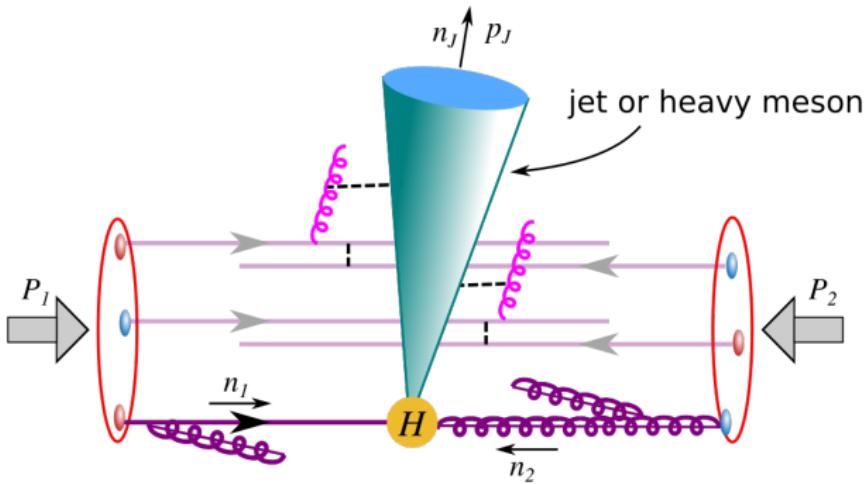
Assumed in (almost) all the studies of hard probes

1. Suppression of heavy quarkonia: Rothkopf, Phys. Rept. **858**, 1-117 (2020) [arXiv:1912.02253 [hep-ph]].
2. Jet quenching: Cao and Wang, Rept. Prog. Phys. **84**, no.2, 024301 (2021) [arXiv:2002.04028 [hep-ph]].

* **A main issue:** hard probes (e.g., jets) could include soft partons, which can not be distinguished from bulk matter.

Factorization formula for hard probes in HIC

* Our ultimate goal:

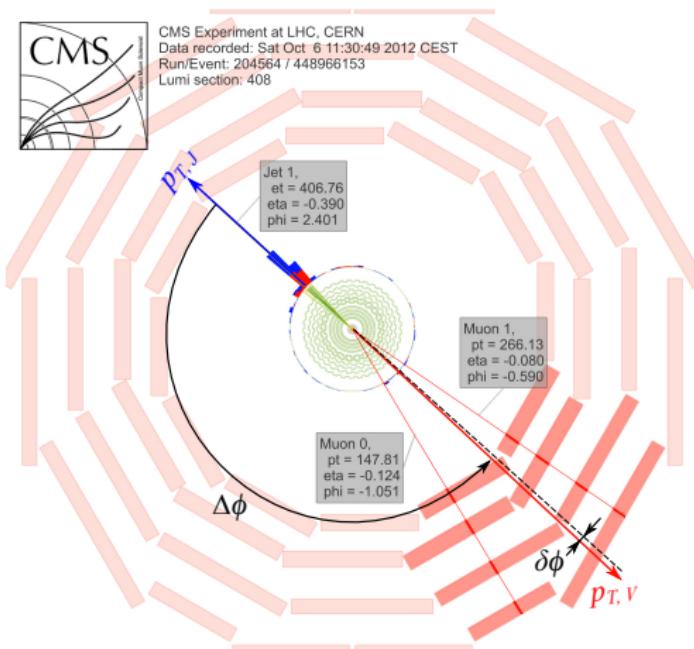


1. Will it reduce to the conjecture factorization formula?
2. Will soft partons be the same as bulk matter without hard probes?

Far from being done, the following ingredients have been accomplished!

Factorization formula for hard probes in HIC

- * Take $\Delta\phi \equiv |\phi_v - \phi_J|$ ($\delta\phi \equiv \pi - \Delta\phi$) as an example:



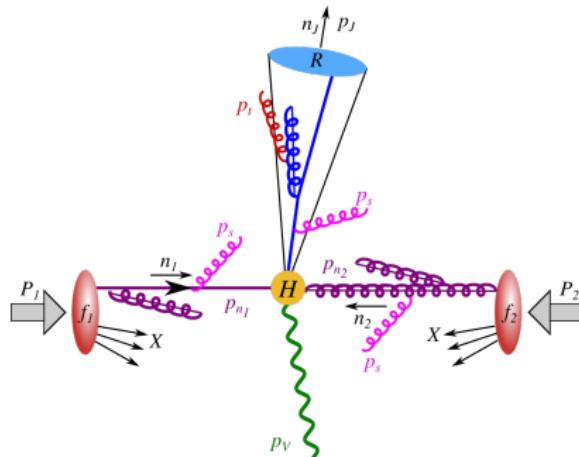
At three level, $\delta\phi = 0$.

Factorization and resummation in pp

Resummation using standard jet axis

* Resummation of Sudakov logarithms: $\underbrace{\alpha_s \ln^2 \delta\phi}_{LL} + \underbrace{\alpha_s \ln \delta\phi}_{NLL} + \underbrace{\alpha_s^2 \ln \delta\phi}_{NNLL} + \dots$

* Factorization formula using soft-collinear effective theory:



Hard function: $\mathcal{H}_{ij \rightarrow V k}$

Beam functions: $\mathcal{B}_{i/N_1}, \mathcal{B}_{j/N_2}$

Soft function: $\mathcal{S}_{ij \rightarrow V k}$

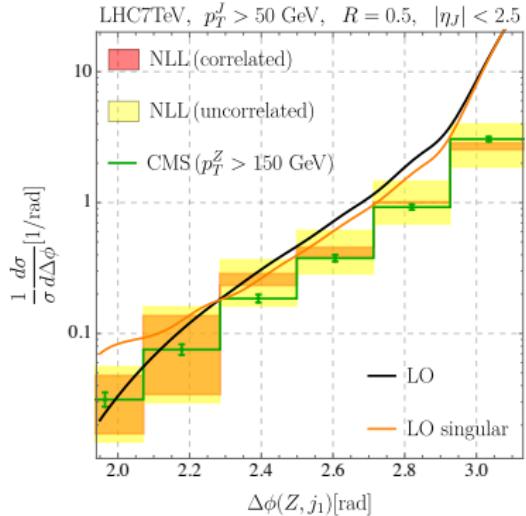
Jet function: \mathcal{J}^k contains NGLs!

$$\frac{d\sigma}{d^2 p_T^J d^2 p_T^V d\eta_J dy_V} = \sum_{ijk} \int \frac{d^2 x_T}{(2\pi)^2} e^{i\vec{q}_T \cdot \vec{x}_T} \mathcal{S}_{ij \rightarrow V k}(\vec{x}_T, \epsilon) \mathcal{B}_{i/N_1}(\xi_1, x_T, \epsilon) \mathcal{B}_{j/N_2}(\xi_2, x_T, \epsilon) \\ \times \mathcal{H}_{ij \rightarrow V k}(\hat{s}, \hat{t}, m_V, \epsilon) \mathcal{J}^k(p_J^2, \vec{x}_T, \epsilon)$$

Chien, Shao and BW, JHEP 11, 025 (2019) [arXiv:1905.01335 [hep-ph]].

NLL resummation

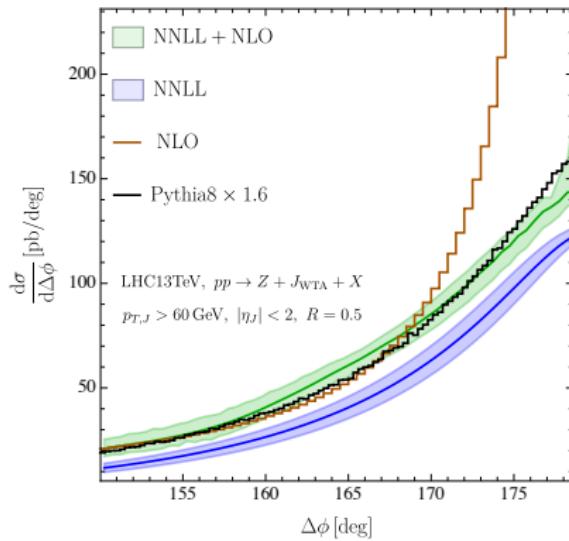
NLL resummed results using standard jet axis



Chien, Shao and BW, JHEP 11, 025 (2019) [arXiv:1905.01335 [hep-ph]].

large uncertainties \Rightarrow going beyond NLL

NNLL resummation in $\delta\phi$



The most precise (NNLL) results using Winner-Take-All (WTA) axis

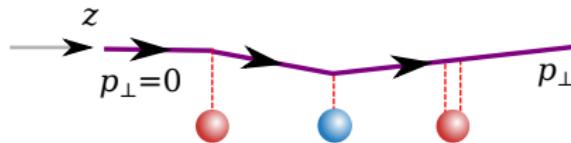
Chien, Rahn, Schrijnder van Velzen, Shao, Waalewijn and BW, Phys. Lett. B **815**, 136124 (2021) [arXiv:2005.12279 [hep-ph]].

Chien, Rahn, Shao, Waalewijn and BW, [arXiv:2205.05104 [hep-ph]].

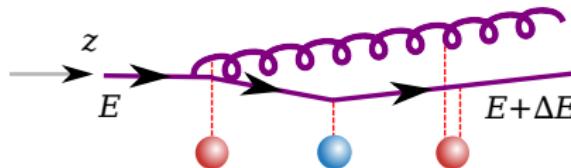
Jet quenching parameter \hat{q}

Medium effects on partons at leading order

* **p_\perp -broadening:** $\frac{d}{dz} \langle p_\perp^2 \rangle = \hat{q}$



* **Medium-induced energy loss:** $\frac{d}{dz} \Delta E = -\frac{\alpha_s N_c}{12} \langle p_\perp^2 \rangle$.



Baier, Dokshitzer, Mueller, Peigne and Schiff, Nucl. Phys. B 484, 265-282 (1997) [arXiv:hep-ph/9608322 [hep-ph]].

Jet quenching parameter \hat{q}

* Physical meaning: p_\perp -broadening per unit path length!

$$\hat{q}(\mu^2) \equiv \rho_0 \int_{p_\perp^2 < \mu^2} d^2 p_\perp \frac{d\sigma_{qN}}{d^2 p_\perp} p_\perp^2 = \frac{1}{\lambda} \int_{p_\perp^2 < \mu^2} d^2 p_\perp \frac{1}{\sigma_{qN}} \frac{d\sigma_{qN}}{d^2 p_\perp} p_\perp^2 = \frac{d}{dz} \langle p_\perp^2(z) \rangle$$

* Definition:

$$\boxed{\hat{q}(\mu^2) = \frac{4\pi^2 \alpha_s C_F}{N_c^2 - 1} \rho_0 x G(x, \mu^2)}$$

Baier, Dokshitzer, Mueller, Peigne and Schiff, Nucl. Phys. B 484, 265 (1997).

* \hat{q} in HIC is mostly measured via jet quenching phenomena.

$$\hat{q} = (2 - 4) T^3$$

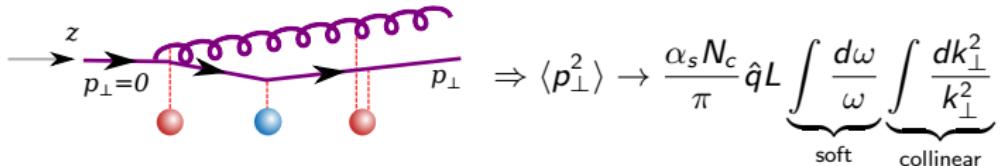
S. Cao et al. [JETSCAPE], Phys. Rev. C 104, 024905 (2021) [arXiv:2102.11337 [nucl-th]].

* \hat{q} could also be measured via suppression of heavy quarkonia.

Dominguez and BW, Nucl. Phys. A 818, 246-263 (2009) [arXiv:0811.1058 [hep-ph]]; Dominguez, Marquet and BW, Nucl. Phys. A 823, 99-119 (2009) [arXiv:0812.3878 [nucl-th]]; BW and Ma, Nucl. Phys. A 848, 230-244 (2010) [arXiv:1003.1692 [hep-ph]].

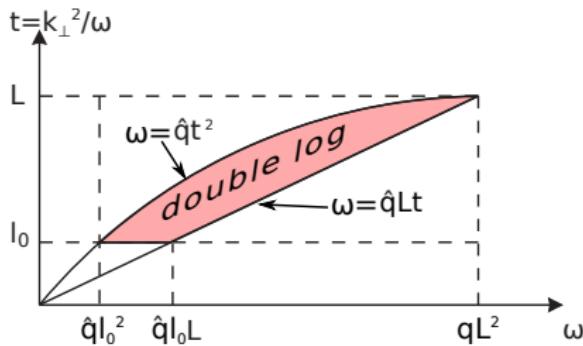
\hat{q} beyond leading order

* Contributions to $\langle p_{\perp}^2 \rangle$ from one gluon radiation in medium of length L



BW, JHEP 10, 029 (2011) [arXiv:1102.0388 [hep-ph]].

* Leading log at $O(\alpha_s)$: $\langle p_{\perp}^2 \rangle_{rad} = \frac{\alpha_s N_c}{2\pi} \hat{q} L \ln^2 \frac{L}{l_0}$ with l_0 nucleon size or $1/T$



Liou, Mueller and BW, Nucl. Phys. A 916, 102-125 (2013) [arXiv:1304.7677 [hep-ph]].

See, for a refined discussion near l_0 in QGP, Ghiglieri and Weitz, [arXiv:2207.08842 [hep-ph]].

\hat{q} beyond leading order

* Leading log resummation (all orders in α_s)

$$\langle p_\perp^2 \rangle_t = \hat{q} L \frac{l_1(2\sqrt{\alpha} \ln \frac{L}{l_0})}{(\sqrt{\alpha} \ln \frac{L}{l_0})} \quad \text{with } \alpha = \frac{\alpha_s N_c}{\pi}$$

Liou, Mueller and BW, Nucl. Phys. A 916, 102-125 (2013) [arXiv:1304.7677 [hep-ph]].

* Leading log result of radiative energy loss

$$\Delta E_t = \frac{\alpha_s N_c}{12} \langle p_\perp^2 \rangle_t L$$

BW, JHEP 12, 081 (2014) [arXiv:1408.5459 [hep-ph]]

* \hat{q} renormalization: $\hat{q}_t = \langle p_\perp^2 \rangle_t / L$.

Blaizot and Mehtar-Tani, Nucl.Phys. A929 (2014) 202–229, arXiv:1403.2323 [hep-ph];

Iancu, JHEP 1410 (2014) 95, arXiv:1403.1996 [hep-ph].

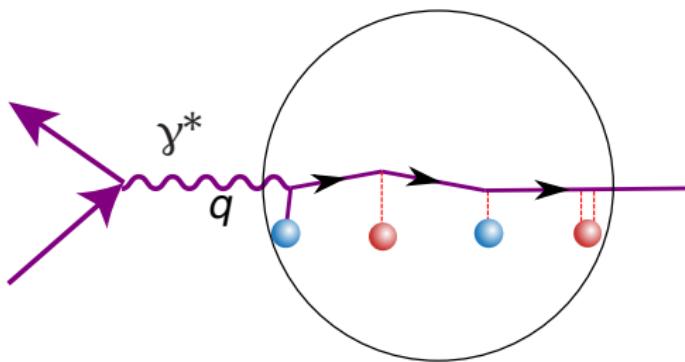
* \hat{q} renormalization in longitudinal expanding QGP: $L \rightarrow t$.

Iancu, Taels and BW, Phys. Lett. B 786, 288-295 (2018) [arXiv:1806.07177 [hep-ph]].

Factorization and resummation in DIS

Quark production at LO

When $\frac{1}{q^-} \ll L$:

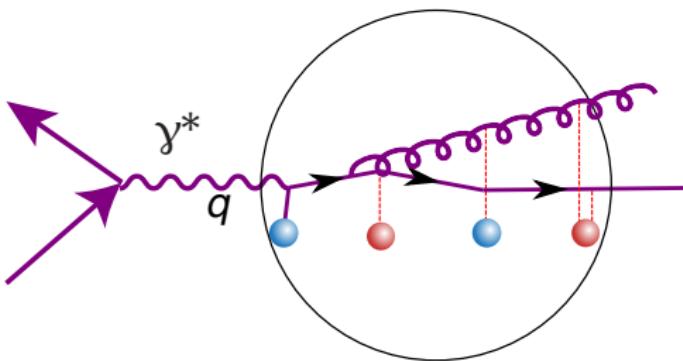


$$\frac{dN}{d^2b d^2k_\perp} = \int \frac{d^2x_\perp}{(2\pi)^2} e^{-ik_\perp \cdot x_\perp} \rho_0(x) q_N(x) \int_0^L dz \underbrace{e^{-\frac{1}{4}\hat{q}x_\perp^2 z}}_{S(x_\perp, z)}$$

Kovchegov and Mueller, Nucl. Phys. B 529, 451 (1998).

Quark production at NLO

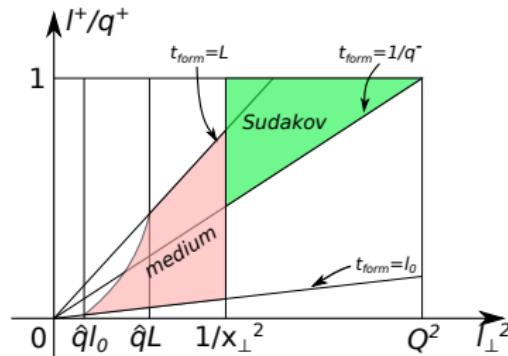
One gluon emission with multiple scatterings



There are both Sudakov and medium-dependent double logarithms!

Mueller, BW, Xiao and Yuan, Phys. Rev. D 95, no.3, 034007 (2017) [arXiv:1608.07339 [hep-ph]].

LL resummation and factorization



$$\frac{dN}{d^2b d^2k_\perp} = \int \frac{d^2x_\perp}{(2\pi)^2} e^{-ik_\perp \cdot x_\perp} \rho(x) q_N \left(x, \frac{1}{x_\perp^2 + 1/Q^2} \right)$$

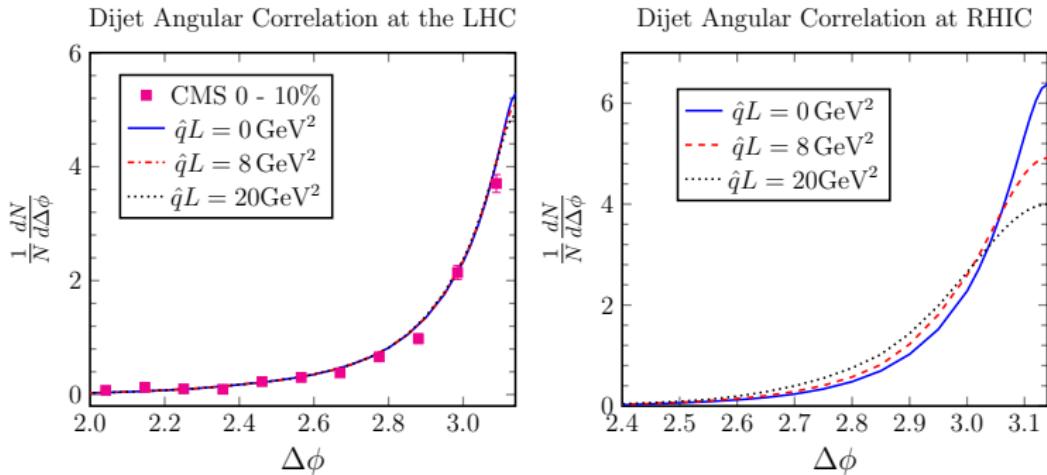
$$\times \int_0^L dz \exp \left[\underbrace{-\frac{1}{4} \hat{q}_t x_\perp^2 z}_{\text{medium-induced}} - \underbrace{\frac{\alpha_s C_F}{2\pi} \ln^2(Q^2 x_\perp^2)}_{\text{vacuum radiation}} \right]$$

where medium-induced double logs are included in \hat{q}_t .

Phenomenological studies

Measurement of \hat{q} via $\Delta\phi$

* Using dijets: NLL resummation of Sudakov logs + tree-level medium effects



Mueller, BW, Xiao and Yuan, Phys. Lett. B **763**, 208-212 (2016) [arXiv:1604.04250 [hep-ph]]. .

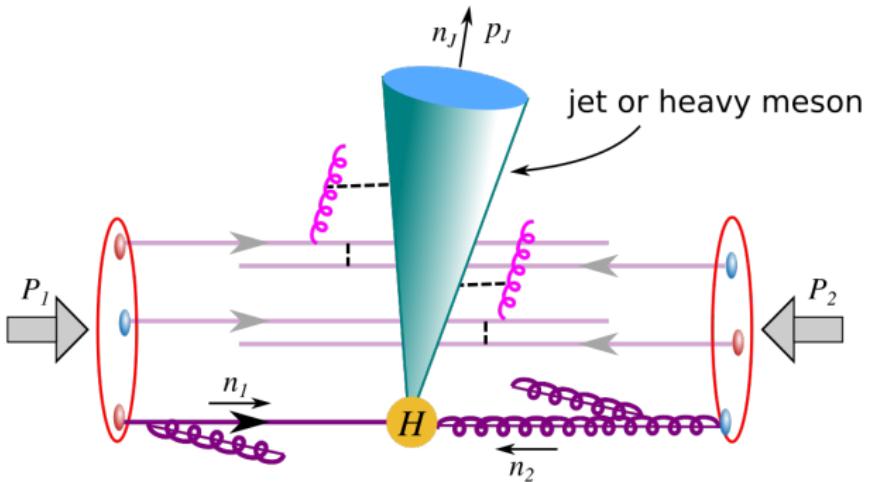
* Using boson-jet:

$$\hat{q}_0 = (4 - 8) \text{ GeV}^2/\text{fm} \text{ for } T_0 = 509 \text{ MeV at } \sqrt{s_{NN}} = 5.02 \text{ TeV.}$$

Chen, Wei and Zhang, PoS HardProbes2020, 031 (2021).

Summary and Perspective

* En route to a perturbative discription of



* Some ongoing projects:

1. **Bulk matter:** with Barrera & Salgado; Li, Qian & Zhang (Shandong U)
2. **Boson-jet correlation:** with Chien(Georgia S.), Rahn(Manchester), Shao(Fudan), Waalewijn(Nikhef)
3. **Dijet correlation at LO:** with Armesto, Cougoulic & Salgado