Jets in evolving anisotropic QCD matter

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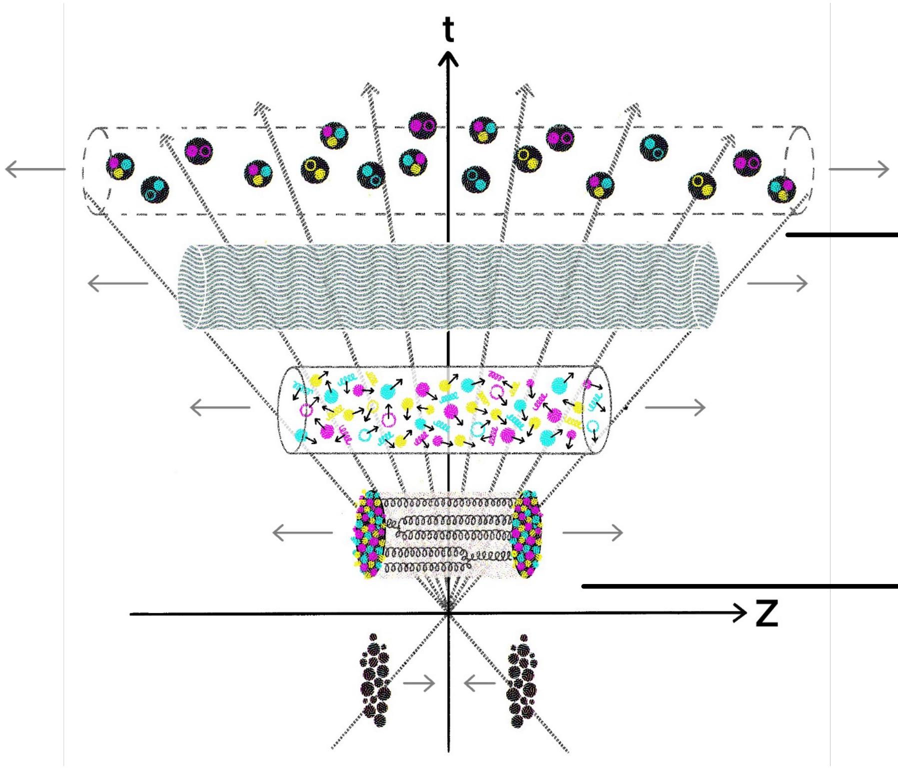
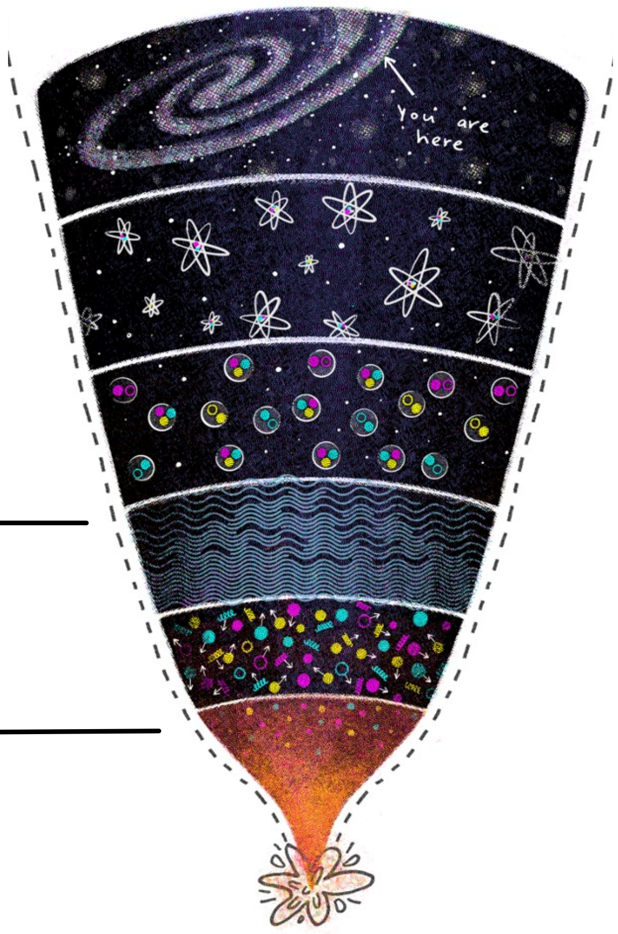
Heavy-ion collisions



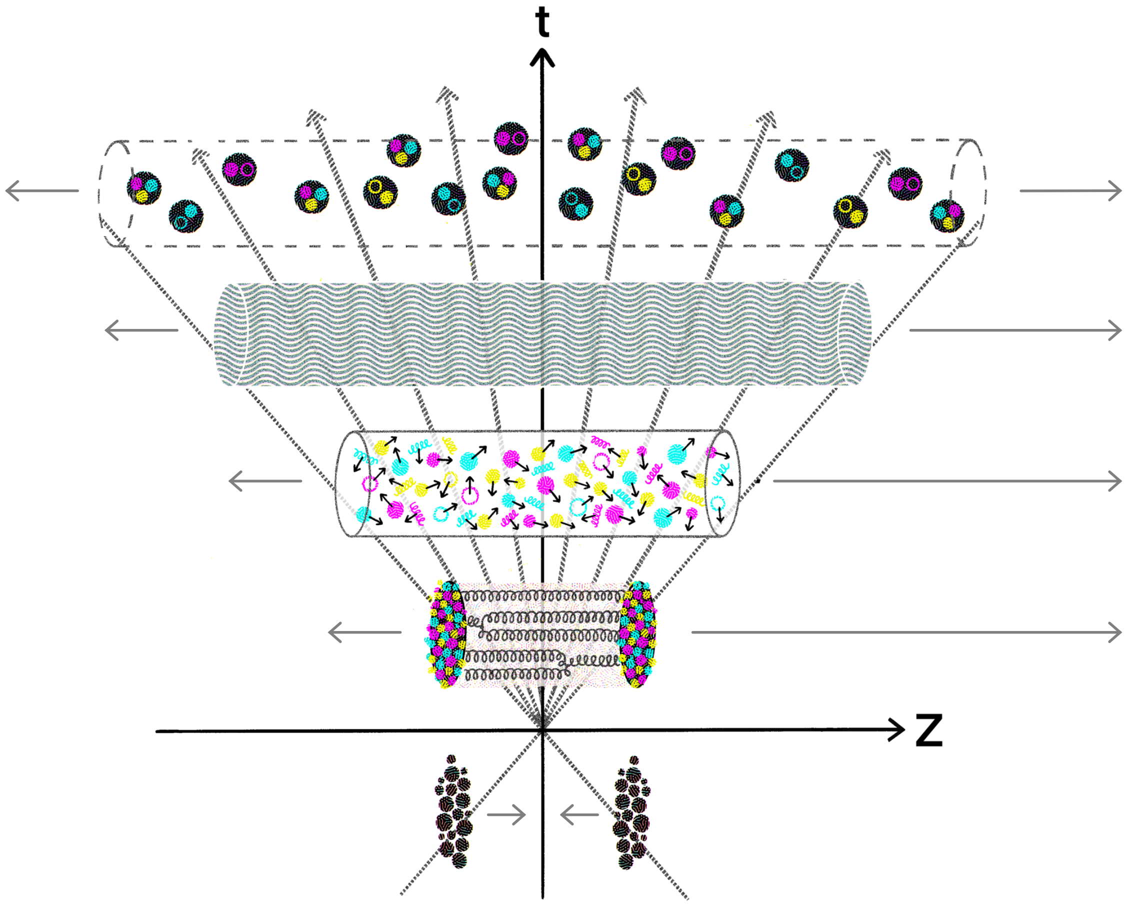
Little Bang

emergence of complex matter can be probed in heavy-ion collisions (HIC)



Big Bang

Heavy-ion collisions



Phases of QCD matter in HIC:

hadron gas

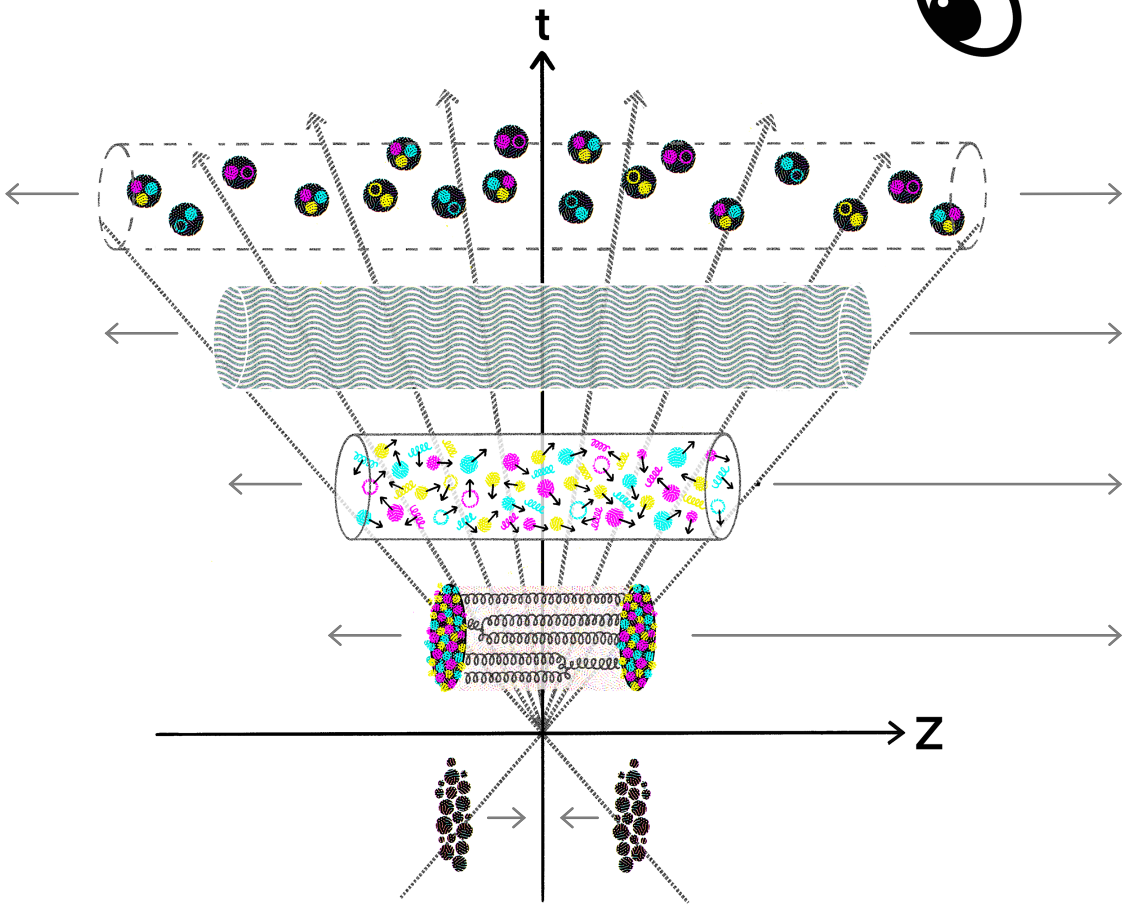
hydrodynamic Quark-Gluon Plasma (QGP)

non-equilibrium matter

glasma (strong color fields)

Matter produced in HIC undergoes multiphase evolution

Heavy-ion collisions



before the collision

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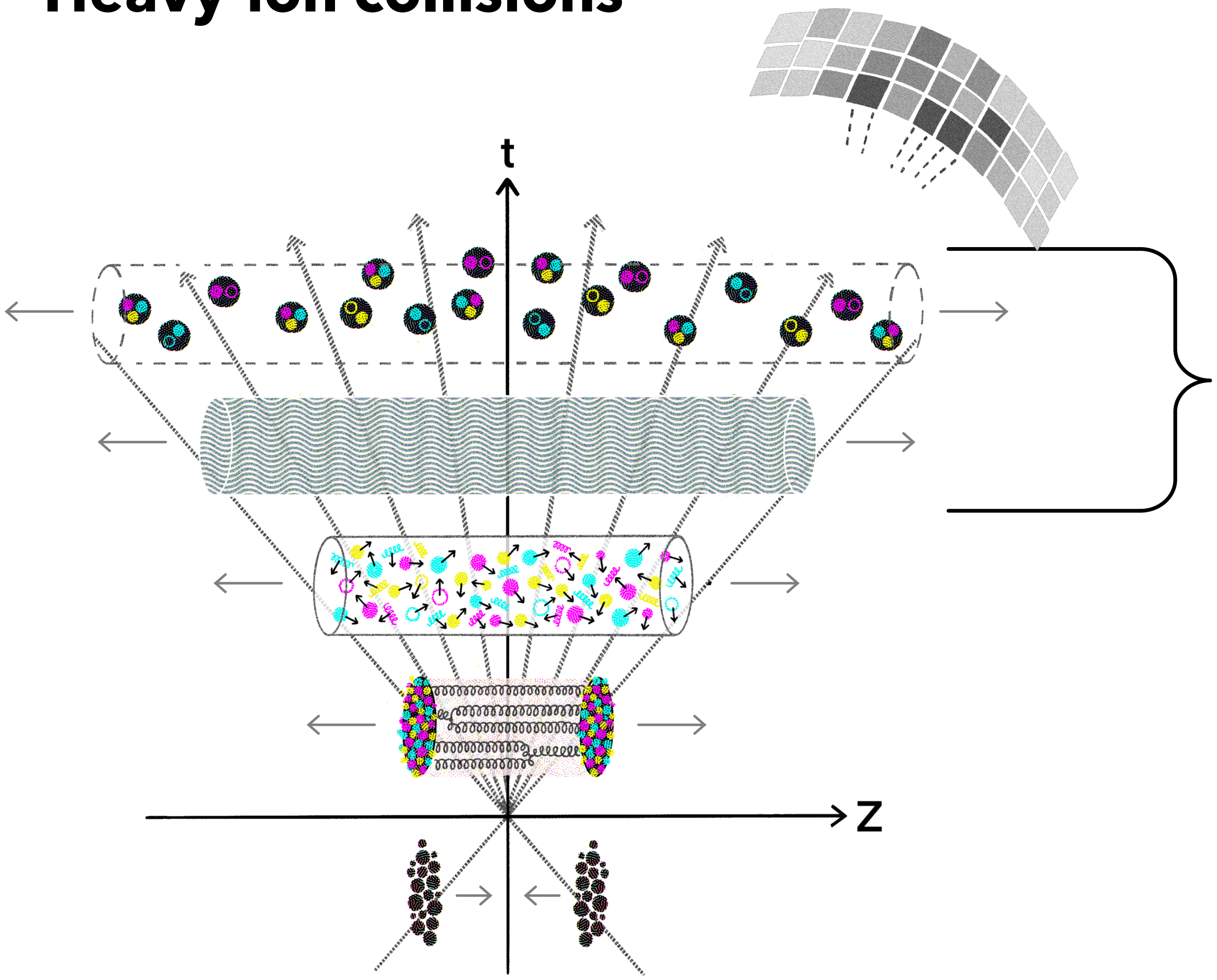
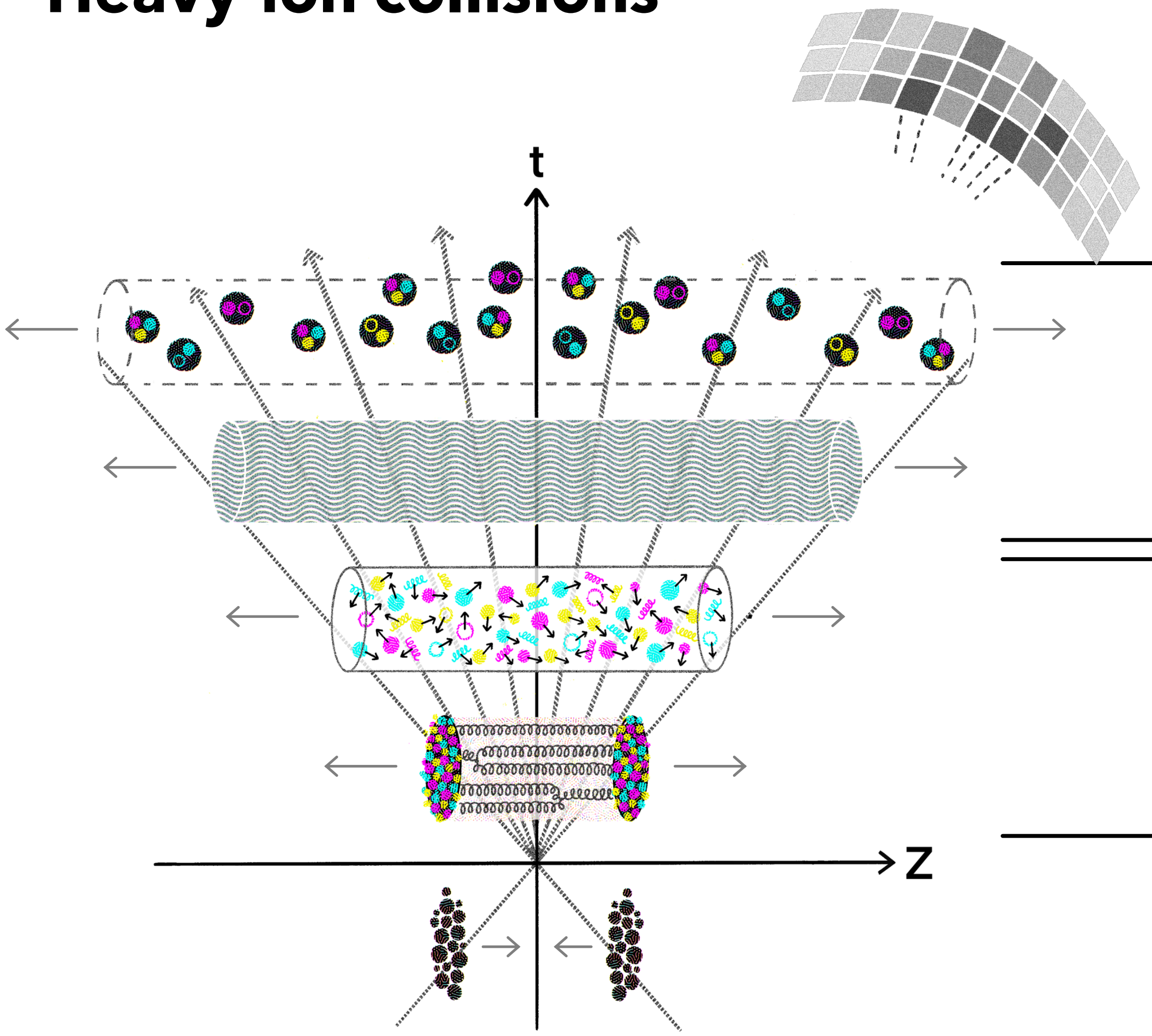
Heavy-ion collisions



Final state dynamics and the hydrodynamic QGP phase

accessible

Heavy-ion collisions

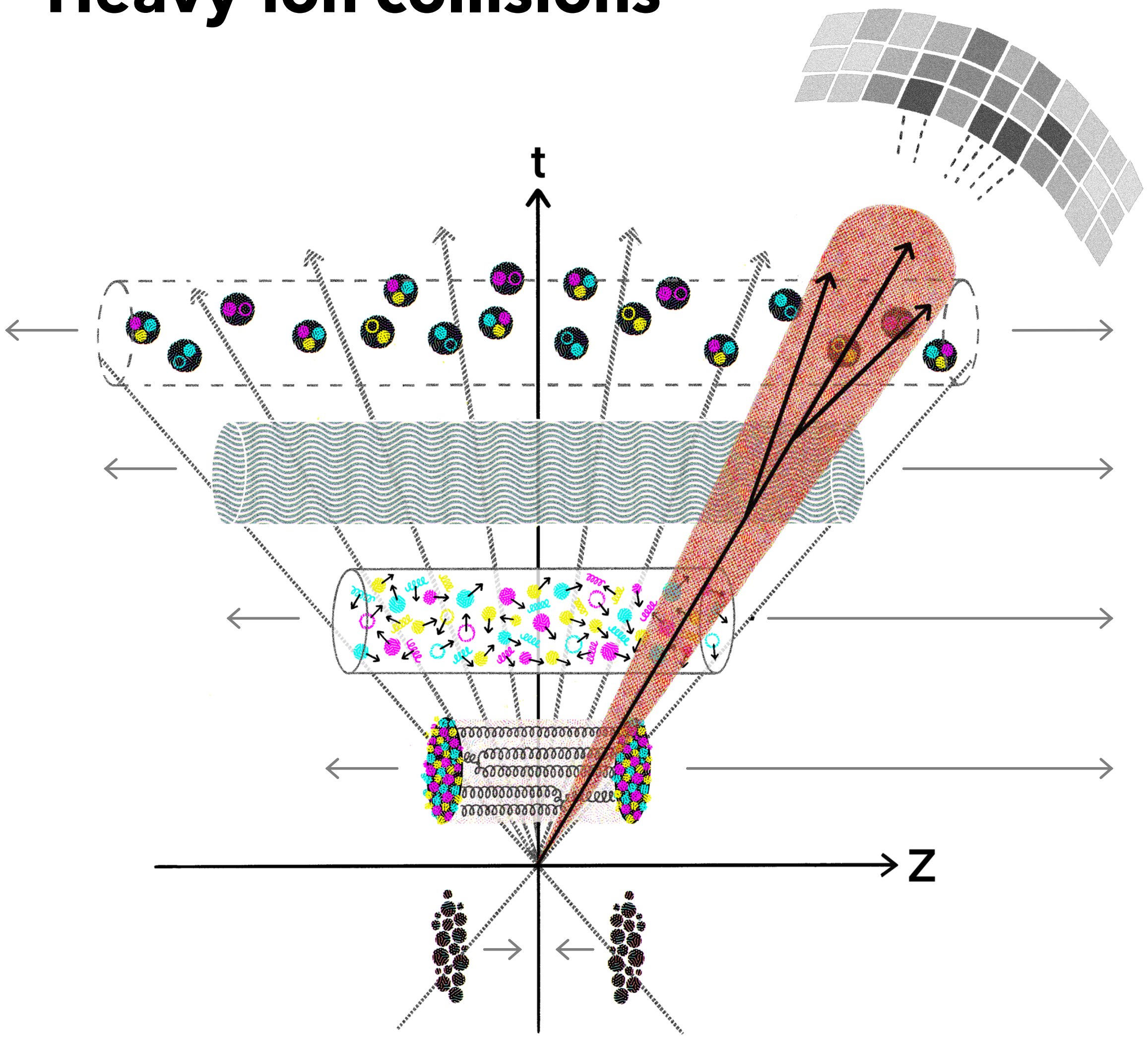


Final state dynamics and the hydrodynamic QGP phase — accessible

Formation of complex nuclear matter — non-accessible

The primary goal of HIC programs worldwide

Heavy-ion collisions



Phases of QCD matter in HIC:

hadron gas

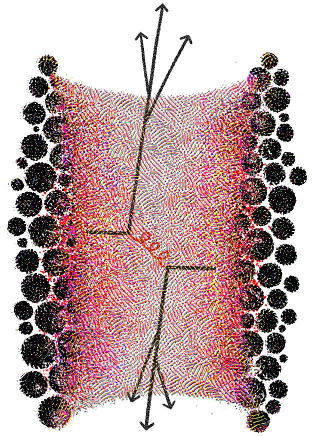
hydrodynamic QGP

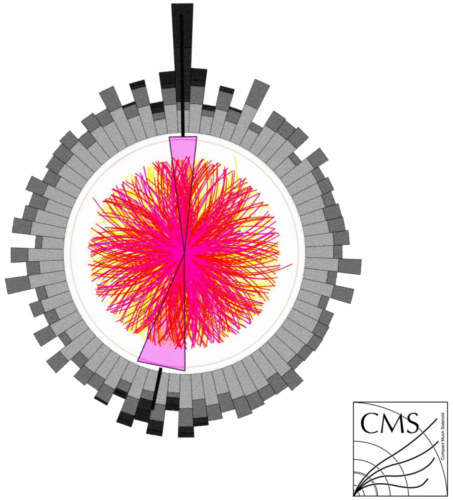
non-equilibrium matter

glasma (strong color fields)

Jets are a tool to probe
the early evolution of matter

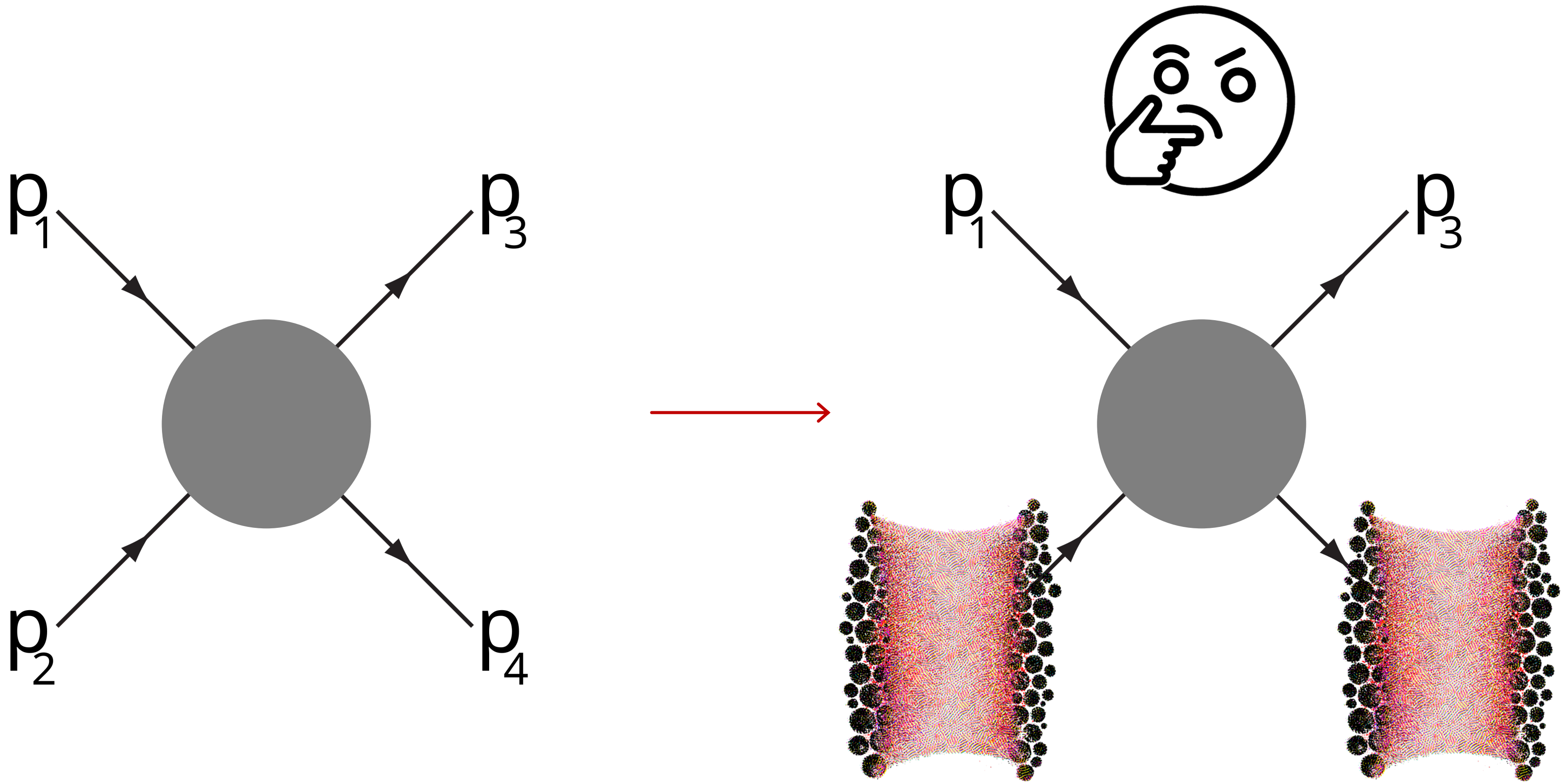
jet quenching





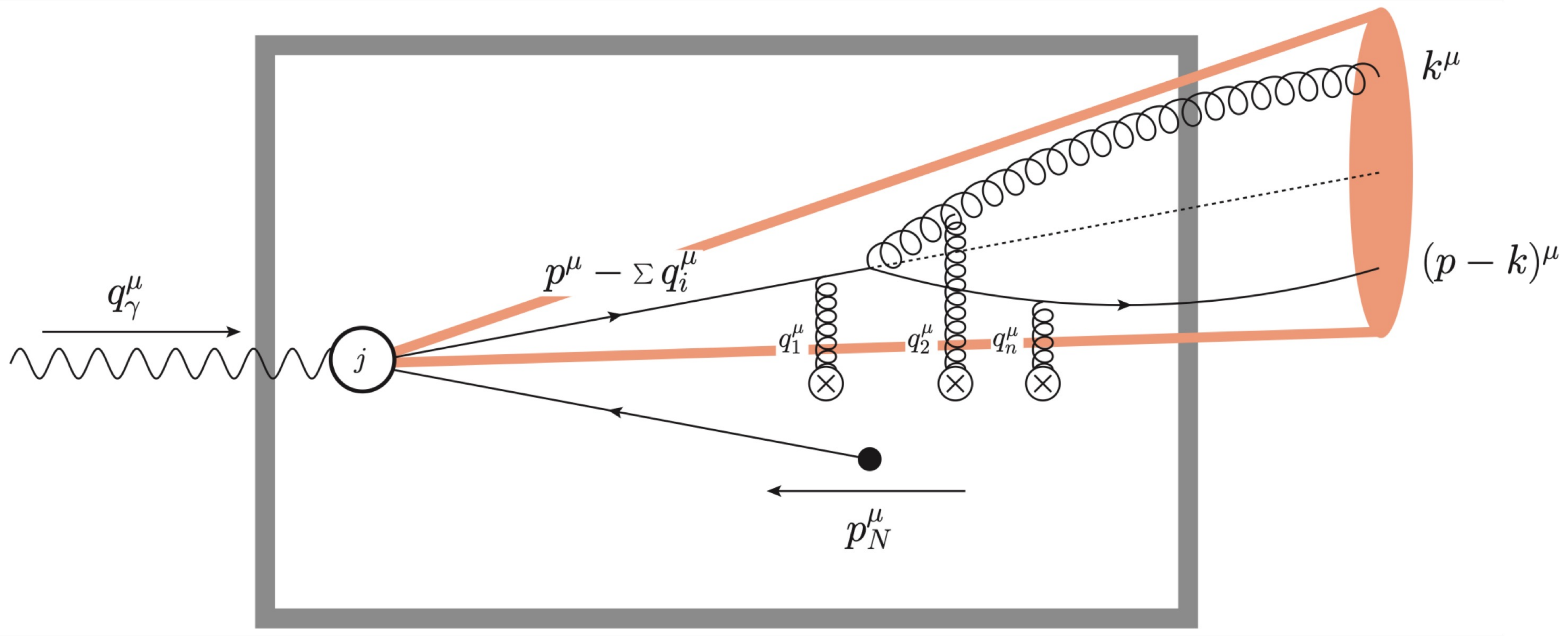
jets lose energy propagating
through nuclear matter

Jet quenching formalisms

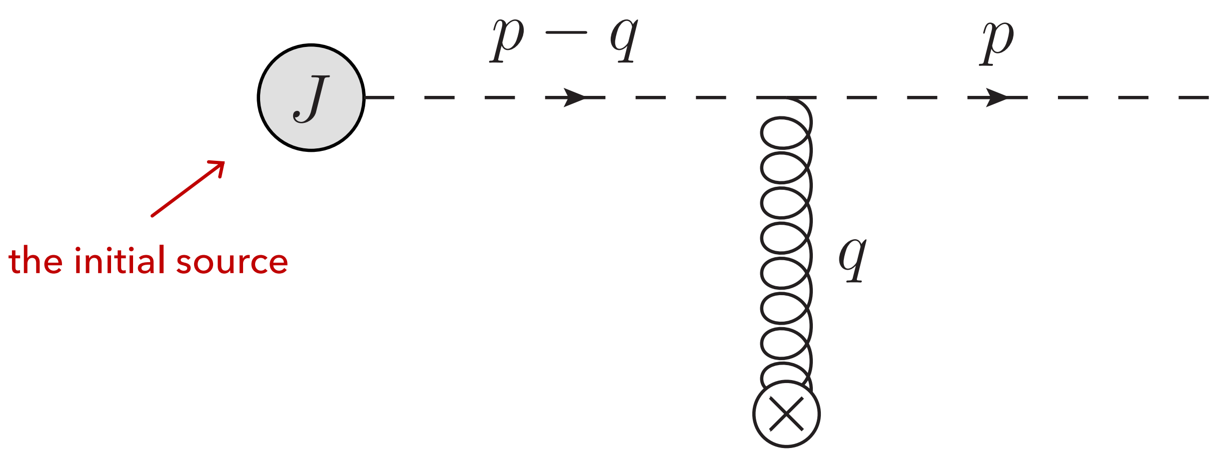


Jet quenching formalisms

R. Baier et al., NPB, 1997
B. G. Zakharov, JETP, 1997
R. Baier et al., NPB, 1998
M. Gyulassy et al., NPB, 2000
X.-F. Guo, X.-N. Wang, PRL, 2000
U. Wiedemann, NPB, 2000
M. Gyulassy et al., NPB, 2001
P. Arnold, G. Moore, L. Yaffe, JHEP, 2002
C. Salgado, U. Wiedemann, PRD, 2003



Jet quenching formalisms



the initial source

$$iM_1(p) = \int \frac{d^4q}{(2\pi)^4} \left[ig\, t^a_{\text{proj}} A^{\mu a}_{\text{ext}}(q)\ (2p-q)_\mu \right] \left[\frac{i}{(p-q)^2 + i\epsilon} \right] J(p-q)$$

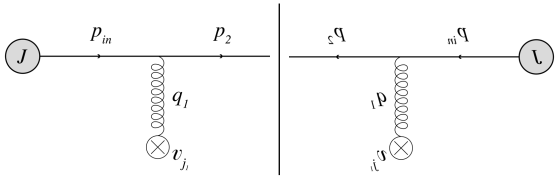
$$gA^{\mu a}_{ext}(q) = \sum_i e^{iq\cdot x_i}\, t^a_i\, u^\mu_i\, v_i(q)\ (2\pi)\, \delta\left(q^0\right)$$

(1,0,0,0)

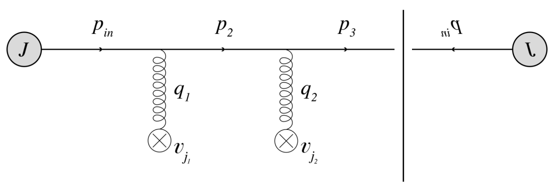
color sources

Jet quenching formalisms

$$E\frac{d\mathcal{N}}{d^3p} \simeq f(E)\delta^{(2)}(\mathbf{p}) + \Big\langle$$



$$\Big\rangle + \Big\langle$$



$$\Big\rangle$$

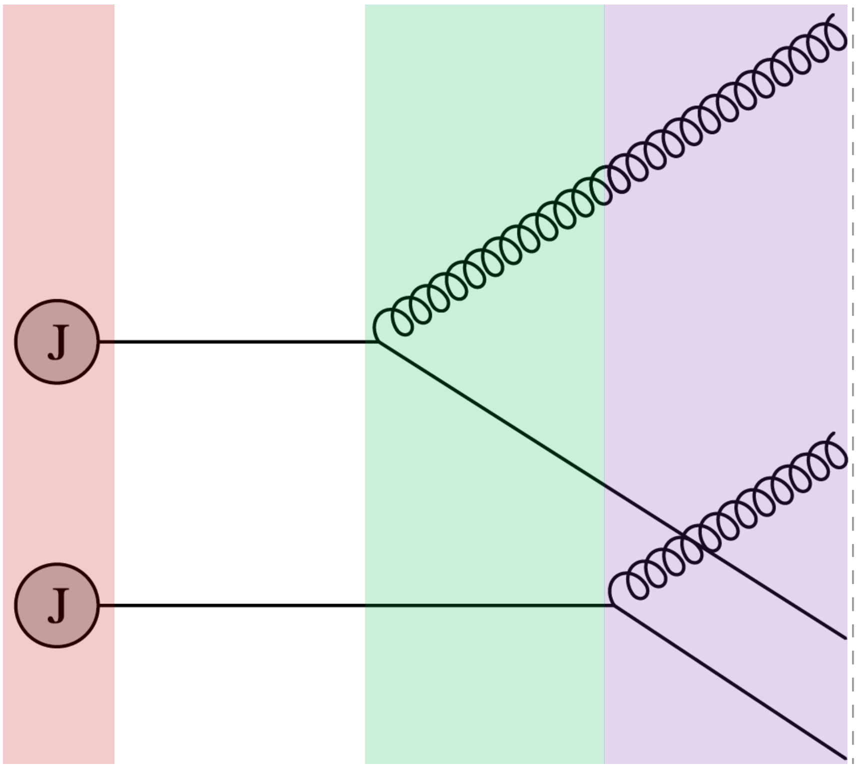
$$\mathcal{V}(\mathbf{q}) = -\mathcal{C}\rho\left(|v(\mathbf{q})|^2 - \delta^{(2)}(\mathbf{q})\int_l |v(\mathbf{l})|^2\right)$$

$$E\frac{d\mathcal{N}^{(1)}}{d^3p} = \int_0^L dz \int_q \mathcal{V}(\mathbf{q})\, f(E)\delta^{(2)}(\mathbf{p}-\mathbf{q})$$

$$\hat{q} = \frac{\partial}{\partial L}\langle p_\perp^2\rangle = \frac{\mathcal{C}g^4\rho}{4\pi\mu^2}L\,\frac{\mu^2}{L}\log\frac{E}{\mu}$$

opacity χ

Jet quenching formalisms



$$(2\pi)^2 \omega \frac{d\mathcal{N}}{d\omega d^2\mathbf{k}} = \frac{\alpha_s}{N_c\,\omega^2} \mathrm{Re} \int_0^L d\bar{z} \int_0^{\bar{z}} dz \int_{\mathbf{x}_0,\mathbf{y}} |J(\mathbf{x}_0)|^2 \Big[(\nabla_{\mathbf{x}} \cdot \nabla_{\bar{\mathbf{x}}}) \times \left\langle \mathcal{G}^{bc}(\mathbf{k}, L; \mathbf{y}, \bar{z})\, \mathcal{G}^{\dagger\, \bar{a}b}(\mathbf{k}, L; \bar{\mathbf{x}}, \bar{z}) \right\rangle \left\langle \mathcal{G}^{ca}(\mathbf{y}, \bar{z}; \mathbf{x}, z)\, \mathcal{W}_A^{\dagger\, a\bar{a}}(\mathbf{x}_0; \bar{z}, z) \right\rangle \Big]\Big|_{\mathbf{x}=\bar{\mathbf{x}}=\mathbf{x}_0}$$

broadening of the gluon

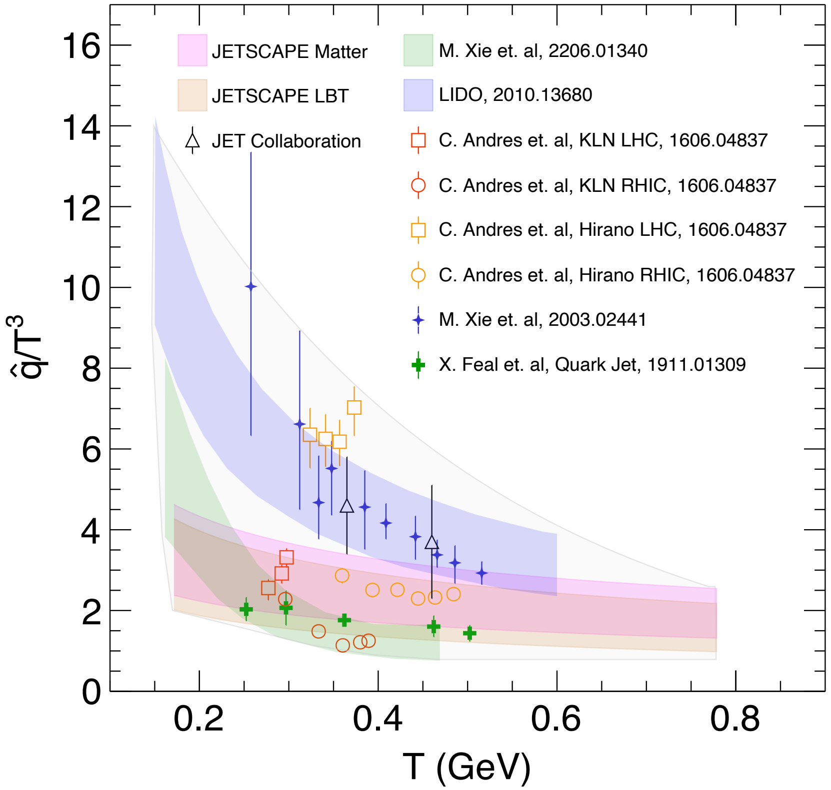
emission kernel

$$\mathcal{K}(\mathbf{x}, t; \mathbf{y}, s) = \frac{1}{N_c^2 - 1} \int_{\mathbf{r}(s)=\mathbf{y}}^{\mathbf{r}(t)=\mathbf{x}} \mathcal{D}\mathbf{r}\, \exp\left[i\frac{\omega}{2} \int_s^t d\tau\, \dot{\mathbf{r}}^2 \right] \times \mathrm{Tr}\, \mathcal{P} \exp\left[iT^c \int_s^t d\tau\, \mathcal{V}(\mathbf{r}(\tau) - \mathbf{x}_{in}) \right]$$

$$\mathcal{V} \propto \hat{q}_0\, x^2 \log \frac{1}{\mu^2 x^2} + \mathcal{O}(\mu^4 x^4)$$

Jet quenching formalisms

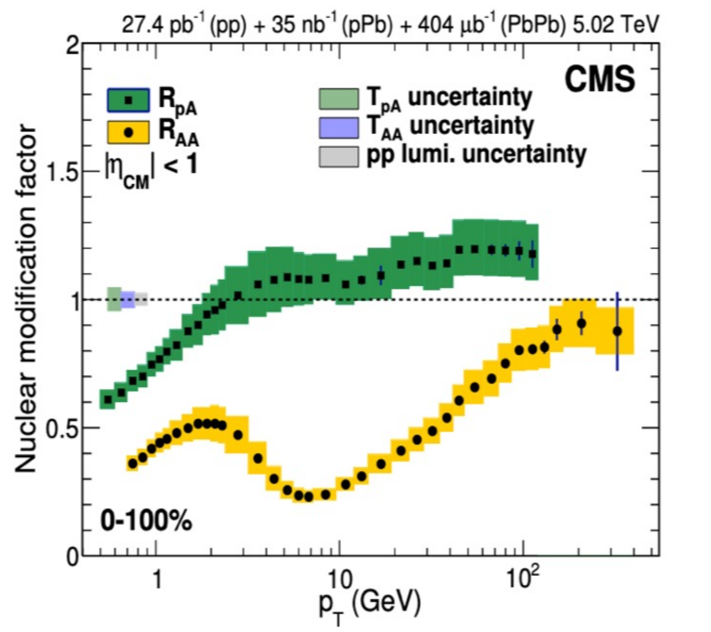
- Jets are observed only in the final state, yet they carry imprints of the matter phases throughout its evolution.
- Describing the scattering off matter requires an effective QCD framework with background stochastic fields.
- $\hat{q}$ is the first object to appear in jet quenching calculations and remains central to most phenomenological considerations.
- $\hat{q}$ is hard to measure or estimate in simulations

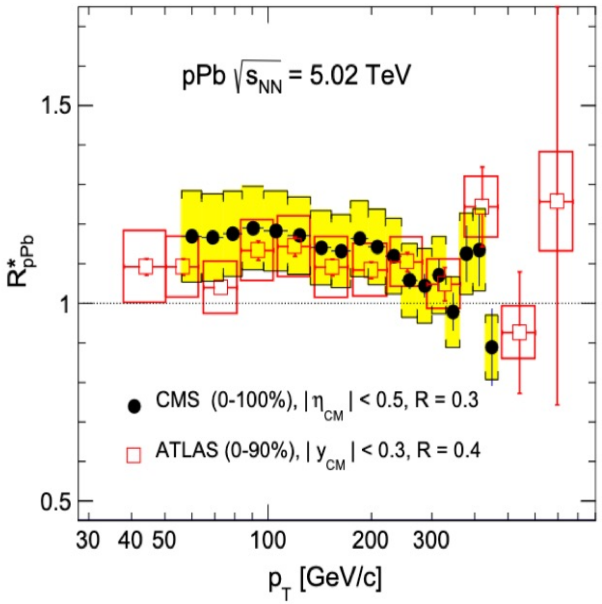


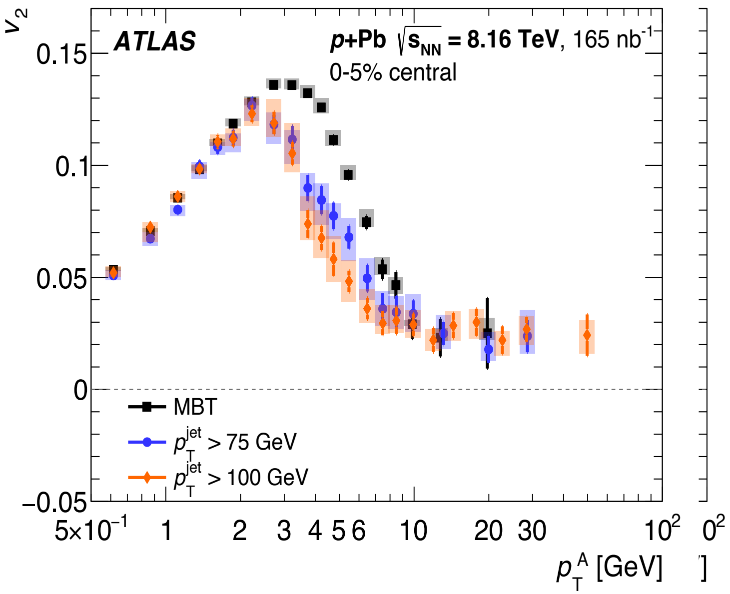
Theoretical uncertainties in $\hat{q}$ extracted in different works

Hot QCD White Paper, arxiv: 2023.17254

Heavy-ion collisions



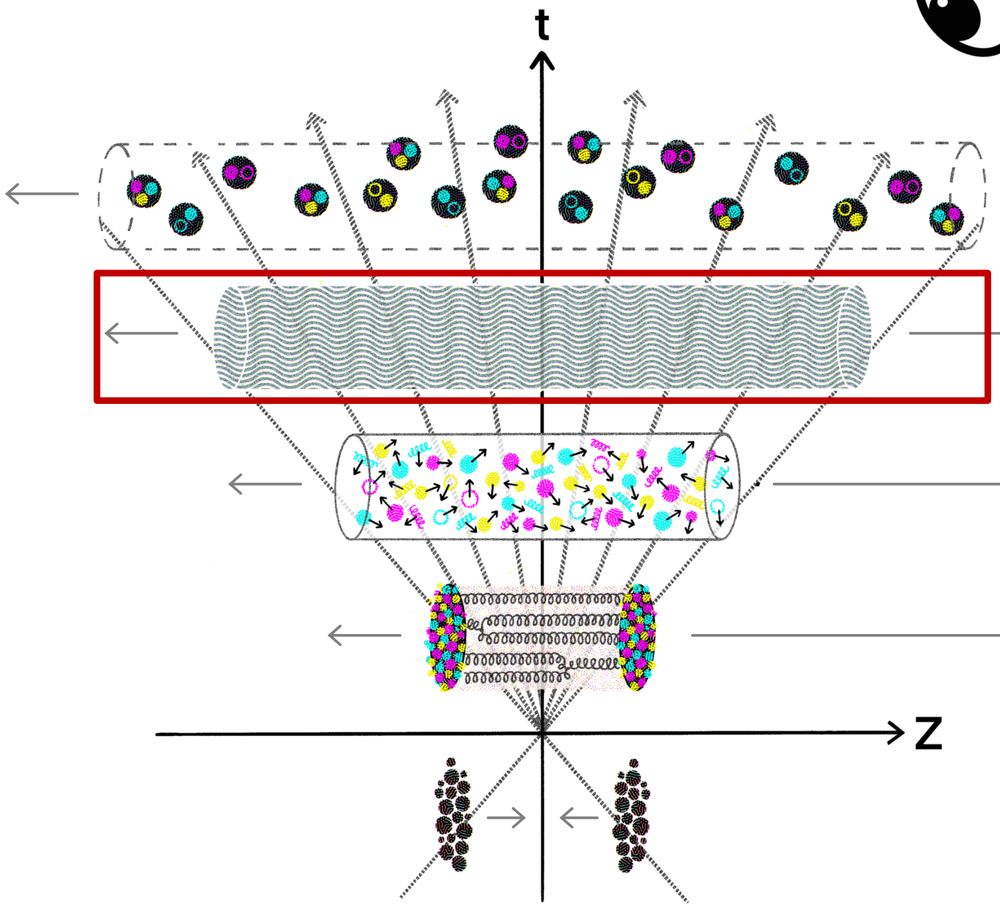




Notable tension in observations:

- Small systems seem to flow
- No clear signal for jet quenching

Heavy-ion collisions



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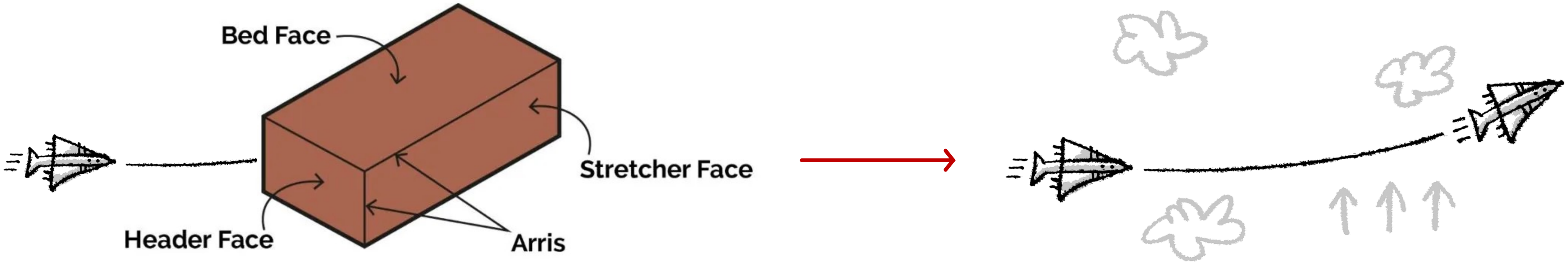
N. Armesto, C. Salgado, U. Wiedemann, PRC, 2005
R. Baier, A. H. Mueller, D. Schiff, PLB, 2007
H. Liu, K. Rajagopal, U. A. Wiedemann, JHEP, 2007
T. Renk, J. Ruppert, C. Nonaka, S. Bass, PRC, 2007

Jets in evolving matter



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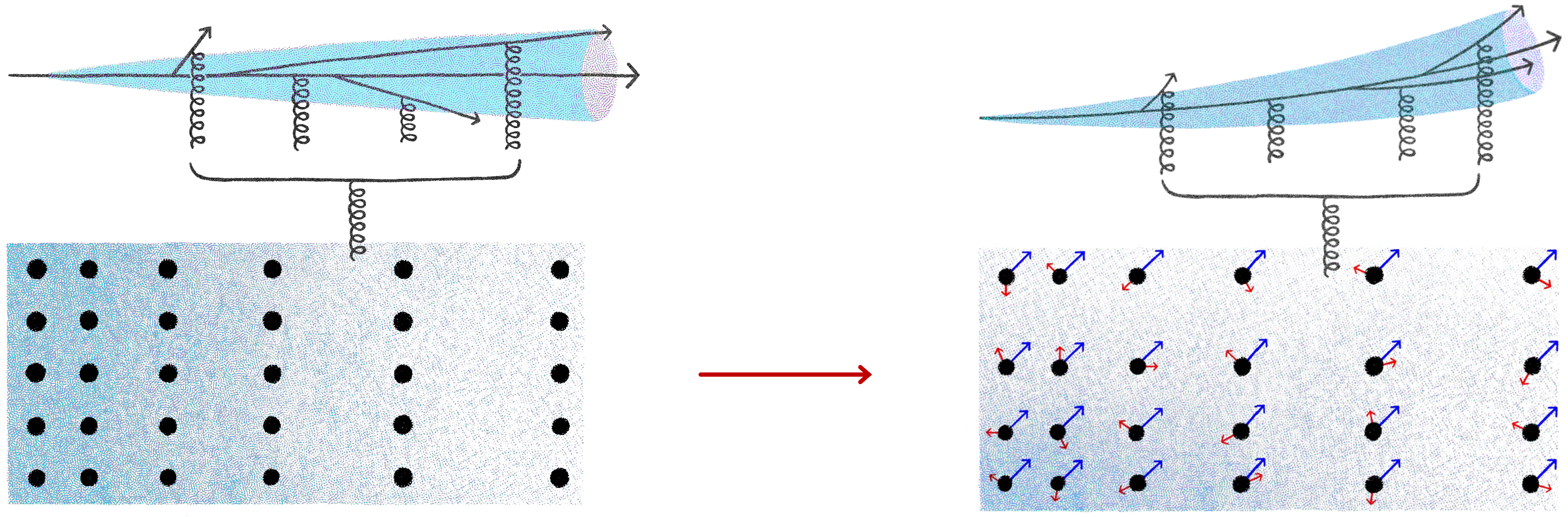

Y. He, L.-G. Pang, X.-N. Wang, PRL, 2020
AS, M. Sievert, I. Vitev, PRD, 2021
J. Barata, AS, C. Salgado, PRD, 2022
C. Andres, F. Dominguez, AS, C. Salgado, PRD, 2022
L. Antiporda, J. Bahder, H. Rahman, M. Sievert, PRD, 2022
Y. Fu, J. Casalderrey-Solana, X.-N. Wang, PRD, 2023
J. Barata, AS, X.-N. Wang, PRD, 2023
J. Barata, X. Mayo Lopez, AS, C. Salgado, PRD, 2023
M. Kuzmin, X. Mayo Lopez, J. Reiten , AS, PRD, 2024
J. Barata, G. Milhano, AS, EPJC, 2024
M. Kuzmin, X. Mayo Lopez, arxiv, 2024
J. Barata, C. Salgado, J. Silva, JHEP, 2024
J. Bahder, H. Rahman, M. Sievert, I. Vitev, arxiv, 2024
J. Barata, S. Hauksson, X. Mayo Lopez, AS, PRD, 2024
W. Ke, J. Terry, I. Vitev, JHEP, 2025
J. Barata, X. Du, AS, PRD, 2025
A. Sengupta, R. Fries, HP2024 proceeding, 2025
J. Barata, X. Mayo Lopez, M. Kuzmin, AS, C. Salgado, arxiv, 2025
Erik Carrió , Daniel Pablos, arxiv, 2026

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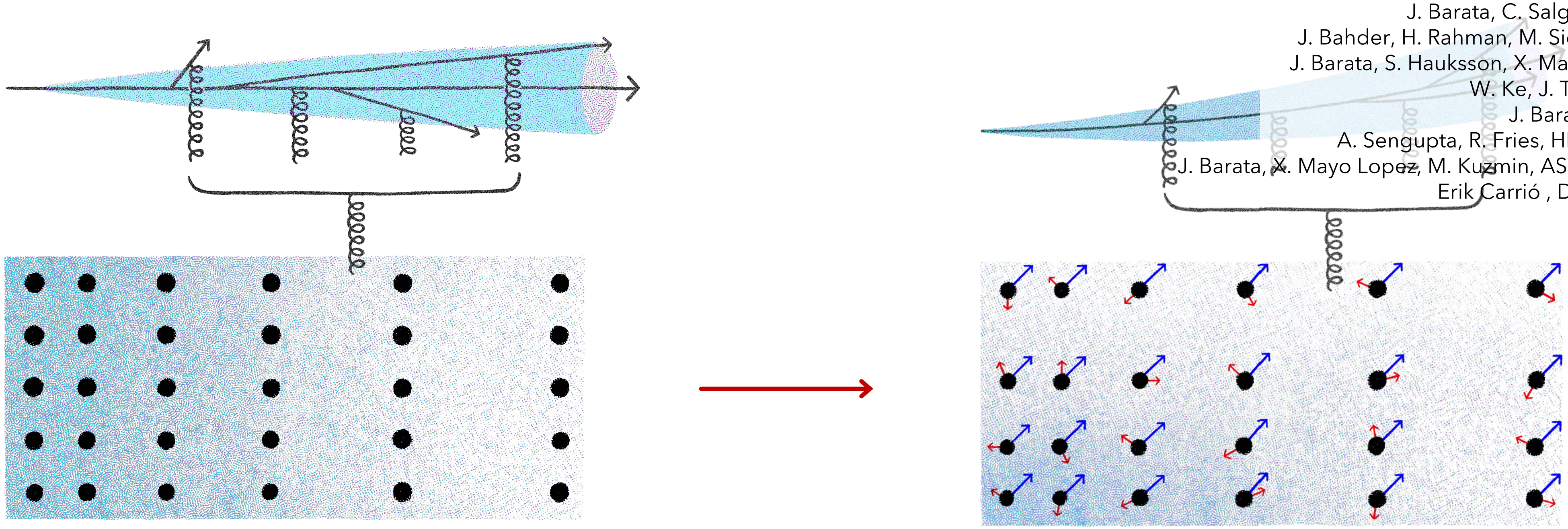

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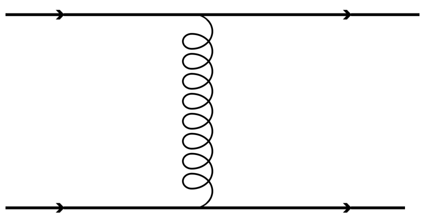
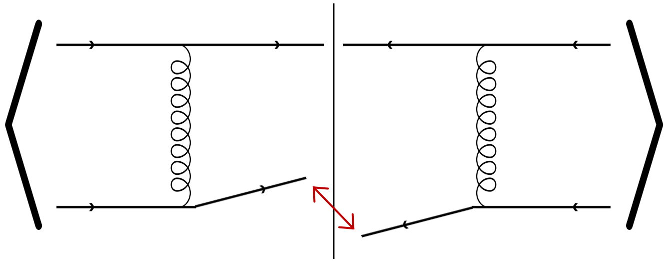
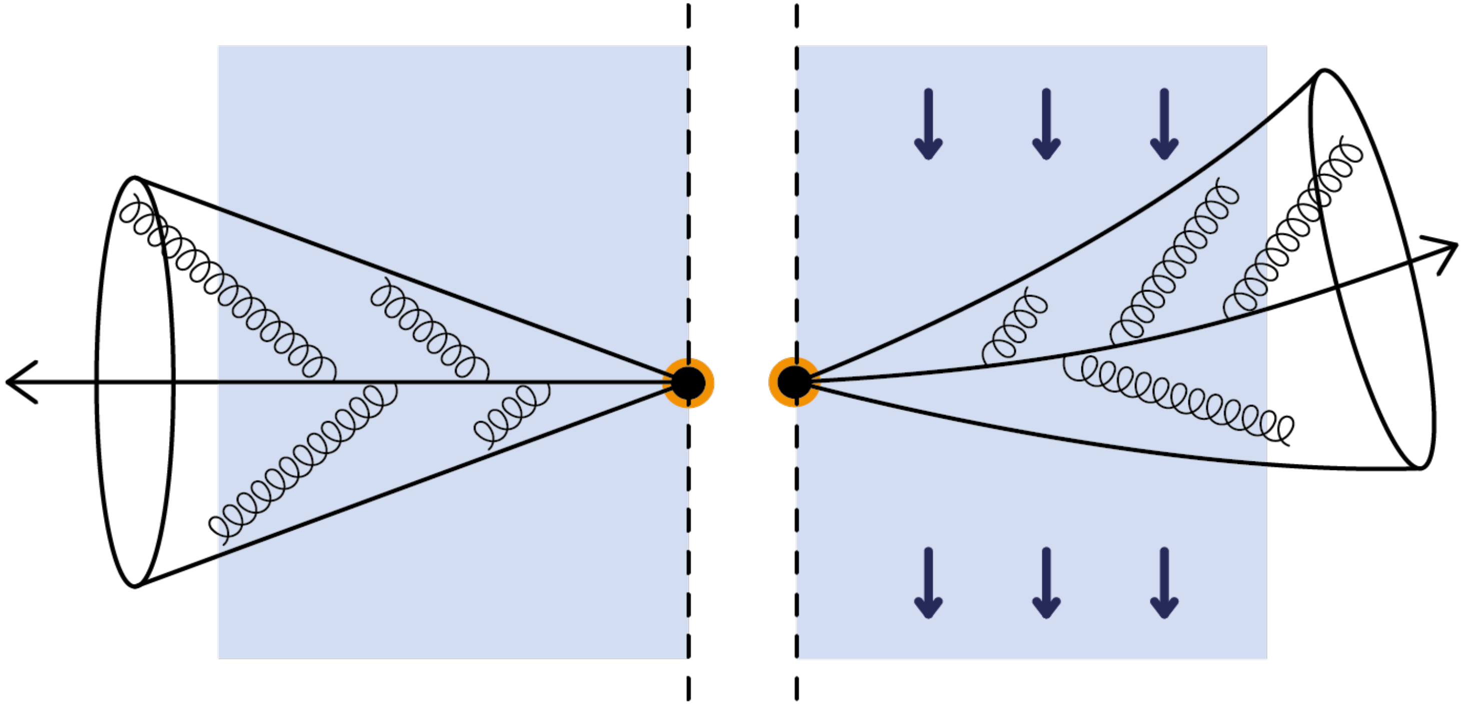


$$\mathbf{p}' \to \gamma(\mathbf{p} - \mathbf{u}E)$$

$$\mathcal{O}\big((p_\perp/E)^n\big) \to \mathcal{O}\big((\gamma u_\perp)^n\big)$$



$$\int_{\mathbf{x}} \rho(\mathbf{x}) e^{-i(\mathbf{q}\pm\bar{\mathbf{q}})\cdot\mathbf{x}} \neq (2\pi)^2 \delta^{(2)}(\mathbf{q} \pm \bar{\mathbf{q}})$$

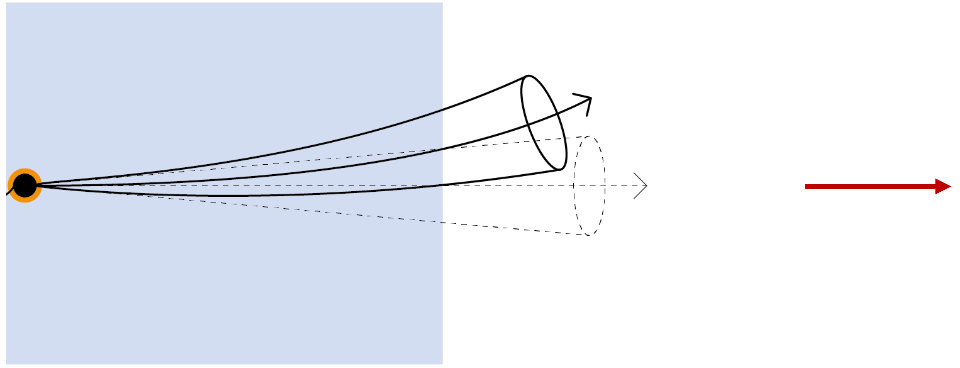


- Modified jet substructure
- Modified distribution of jets/energetic partons

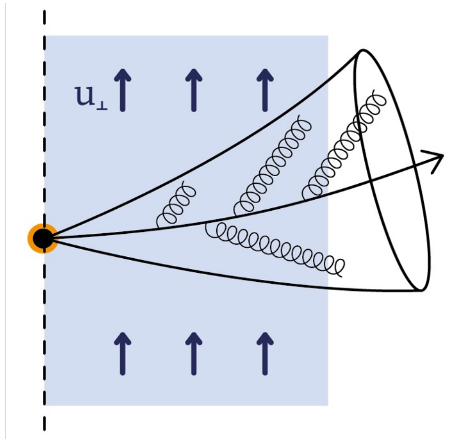
Jets in evolving matter

- Opacity $\chi \approx 4$
- $u \approx 0.7$ (about $\pi/4$ to z-axis)
- $\mu = gT$ with $g \approx 2$ and $T \approx 500\ MeV$

$$\left\langle \frac{p_\perp}{E} \right\rangle \simeq 3\,\chi\,\frac{u_\perp}{1-u_z}\,\frac{\mu^2}{E^2}\,\log\frac{E}{\mu}$$

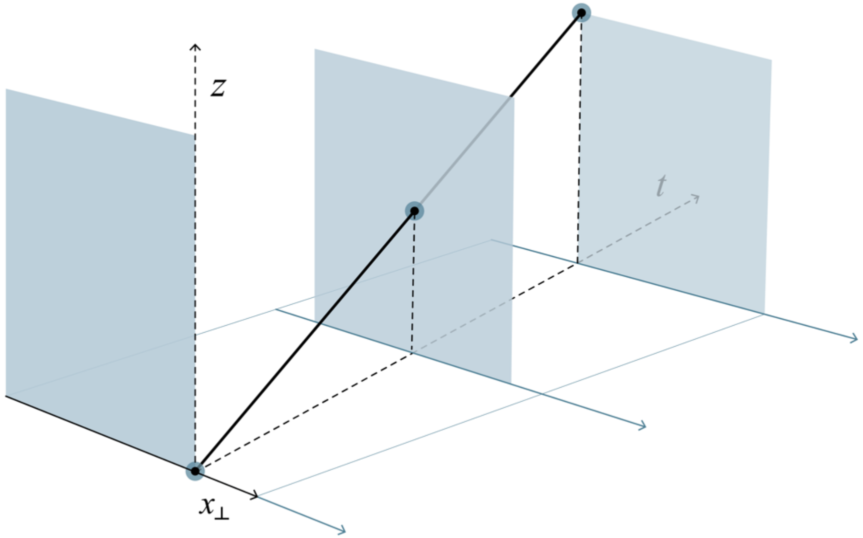


$E \sim 50$ GeV and $\langle\theta\rangle \sim 1^o$

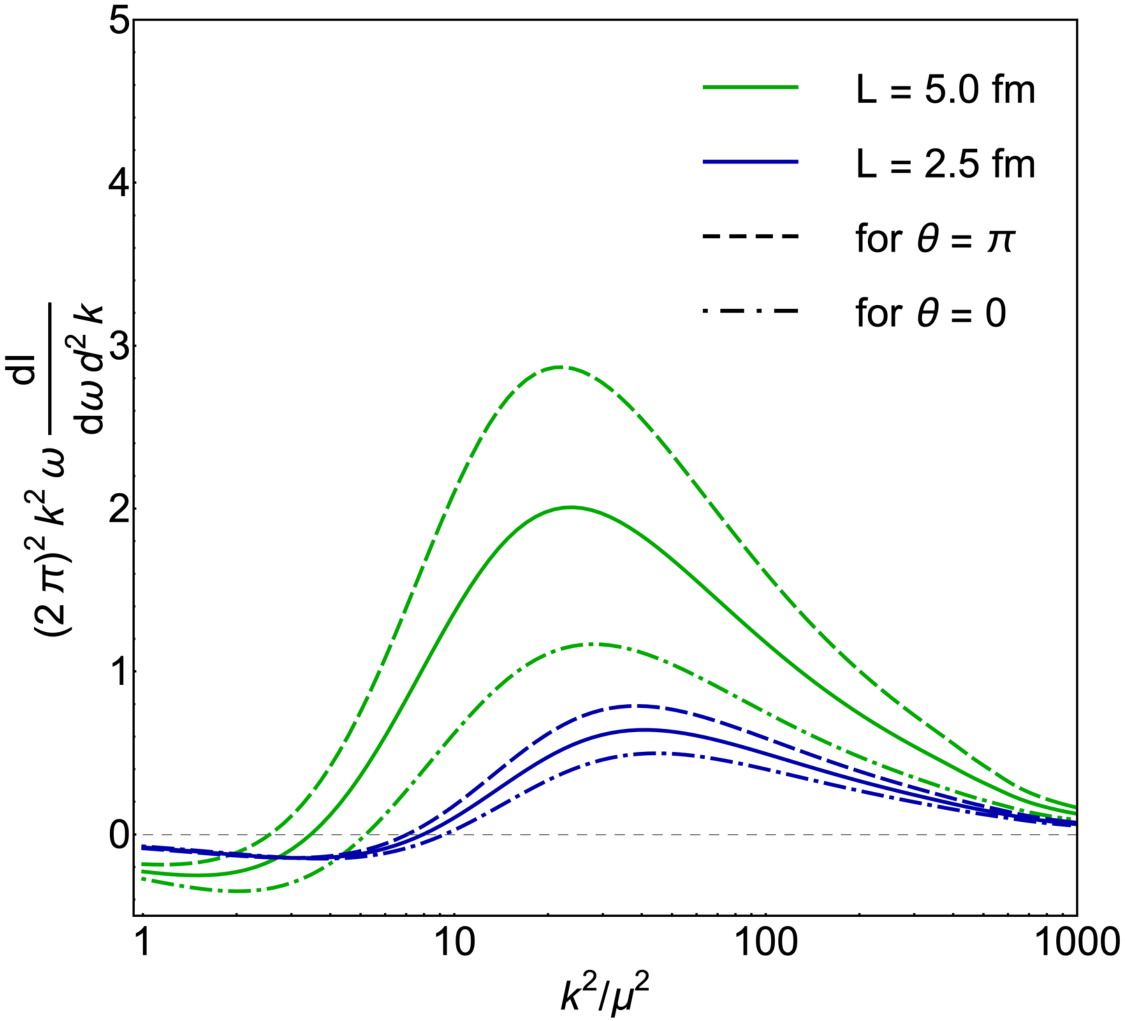


$E \sim 10$ GeV and $\langle\theta\rangle \sim 15^o$

Jets in evolving matter



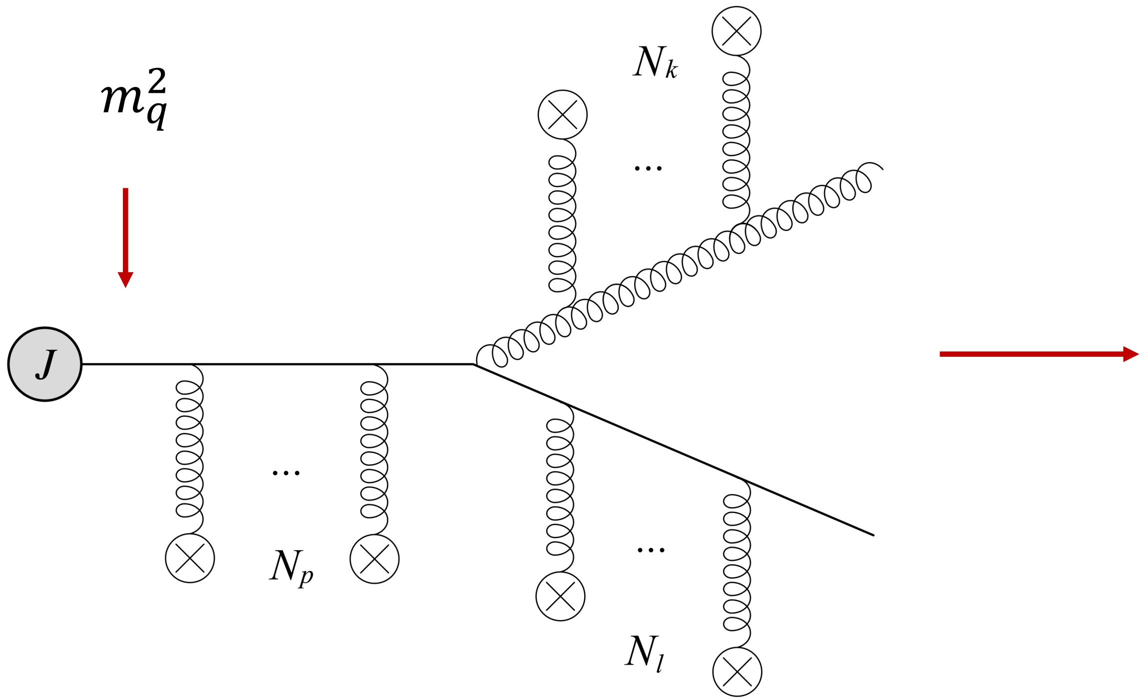
$$\hat{q} = \left(1 - z\,\boldsymbol{\nabla}_\perp \frac{\mathbf{u}_\perp}{1-u_z}\right)\hat{q}_0$$

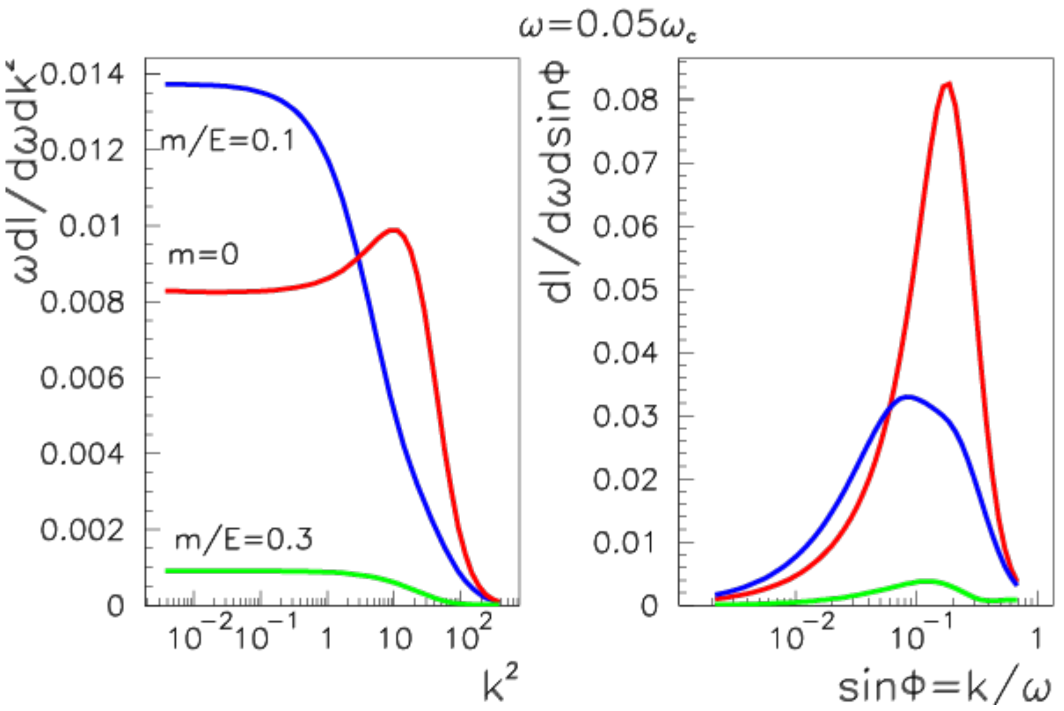


$E = 100\,\mathrm{GeV} \quad L = 5\,\mathrm{fm} \quad |\nabla T|/T^2 = 0.1 \quad \chi = 3 \quad x = 0.1$

Y. Dokshitzer, V. Khoze, S. Troian, JPG, 1991
N. Armesto, C. Salgado, U. Wiedemann, PRD, 2004
M. Djordjevic, M. Gyulassy, NPA, 2004
B.-W. Zhang, E. Wang, X.-N. Wang,PRL, 2004
P. Aurenche, B. G. Zakharov, JETP Lett., 2009

Directional dead-cone effect





$$(2\pi)^2\omega\frac{dI}{d\omega d^2\mathbf{k}} \sim \mathrm{Re}\int_0^\infty d\bar{x}_s^+ \int_0^{\bar{x}_s^+} dx_s^+ \int_{\mathbf{y}} e^{-i\frac{m_q^2 x^2}{2\omega}(\bar{x}_s^+ - x_s^+)}\, S_2(\mathbf{k},\mathbf{k},x_f^+;\mathbf{y},\mathbf{r},\bar{x}_s^+)\boldsymbol{\nabla}_{\mathbf{y}}\cdot\boldsymbol{\nabla}_{\mathbf{x}}\mathcal{K}(\mathbf{y},\bar{x}_s^+;\mathbf{x},x_s^+)\Big|_{\mathbf{r}=\mathbf{x}=\mathbf{0}}$$

J. Barata, X. Mayo Lopez, M. Kuzmin, AS, C. Salgado, arxiv, 2025

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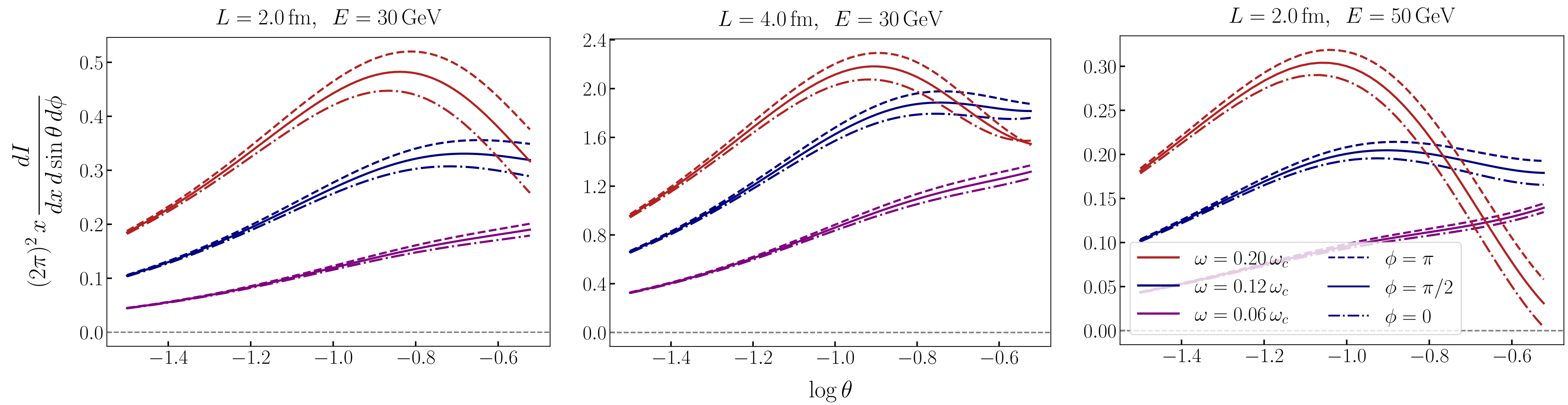

$$(2\pi)^2\omega\frac{dI}{d\omega d^2\mathbf{k}} = \lim_{x_f^+\to\infty}\frac{\alpha_s}{N_c\,\omega^2}\mathrm{Re}\int_0^\infty d\bar{x}_s^+\int_0^{\bar{x}_s^+} dx_s^+ \int_{\mathbf{y}} e^{-i\frac{m_q^2x^2}{2\omega}\left(1-\frac{\mathbf{k}\cdot\mathbf{u}}{u^-\omega}-\frac{m_q^2}{E^2}\frac{\mathbf{u}^2}{4u^{-2}}\right)(\bar{x}_s^+-x_s^+)}$$

$$\times\, e^{-i\frac{m_q^2}{E^2}\omega\frac{\mathbf{y}\cdot\mathbf{u}}{2u^-}}\, S_2(\mathbf{k},\mathbf{k},x_f^+;\mathbf{y},\mathbf{r},\bar{x}_s^+)\,\boldsymbol{\nabla}_{\mathbf{y}}\cdot\boldsymbol{\nabla}_{\mathbf{x}}\,\mathcal{K}(\mathbf{y},\bar{x}_s^+;\mathbf{x},x_s^+)\Big|_{\mathbf{r}=\mathbf{x}=\mathbf{0}}$$

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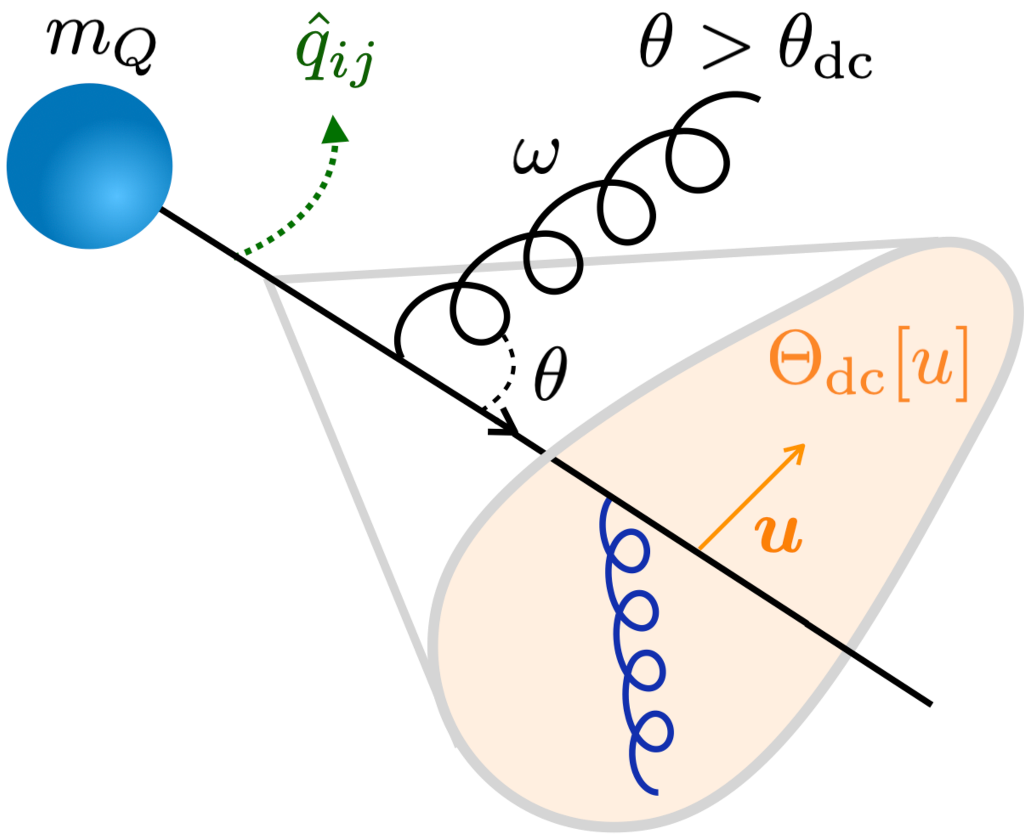

$$\Theta^2_{\rm dc}(\mathbf{k}\cdot\mathbf{u}) = \theta^2_{\rm dc}\left(1 - \frac{\mathbf{k}\cdot\mathbf{u}}{u^-\omega}\right)$$

AS, M. Sievert, I. Vitev, PRD, 2021
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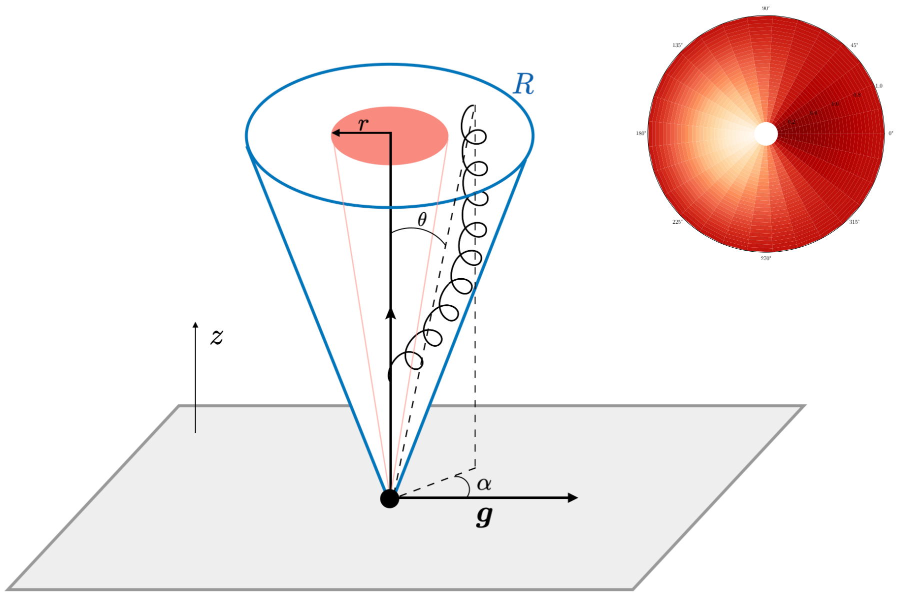
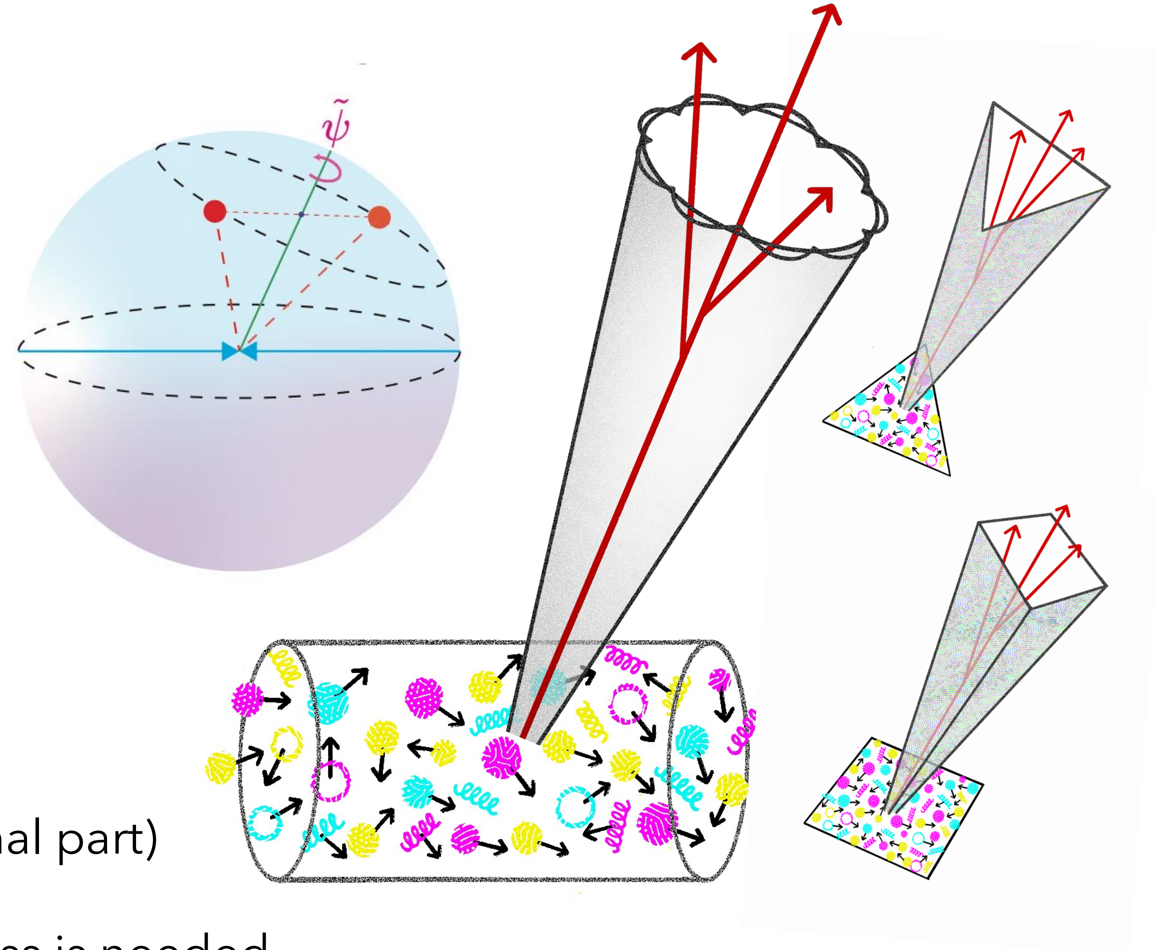
Differential observables





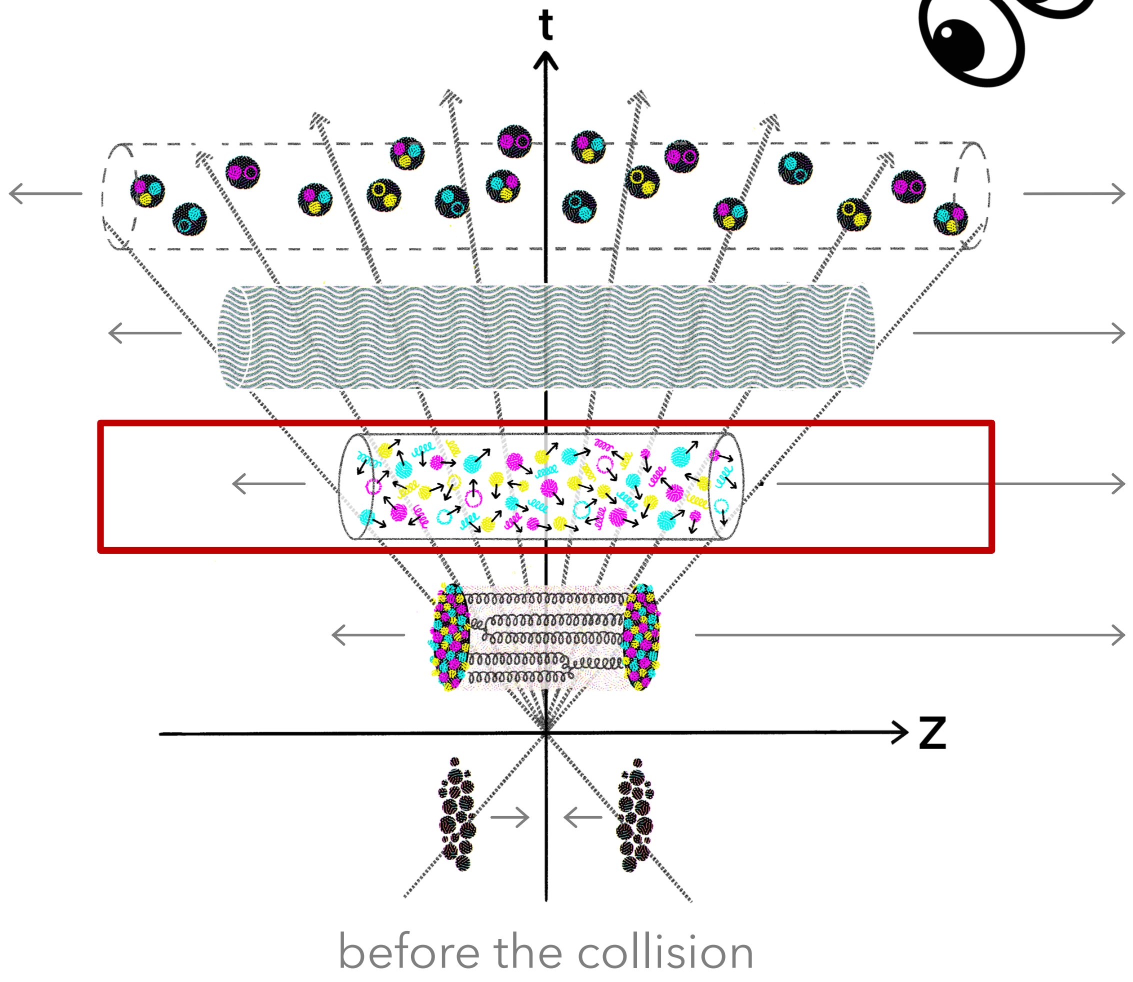
- The matter evolution affects the softer part of the jet
- It is imprinted in substructure (especially in its azimuthal part)
- Only very early estimates are out there -- more progress is needed

Jet quenching during initial stages

- $\hat{q}$ is extremely hard to access experimentally, but it provides an important measure for phenomenological estimates
- Large scale simulations, see e.g. JETSCAPE (PRC, 2021), suggest that a typical value for the QGP at $\mathrm{T} \sim 200\ \mathrm{MeV}$ is $\hat{\mathrm{q}} \sim 0.12\ \mathrm{GeV}^2/\mathrm{fm}$
- Historically, the glasma phase was assumed less relevant, but a series of recent works indicate that $\hat{\mathrm{q}} \geq 5\ \mathrm{GeV}^2/\mathrm{fm}$ during the first $0.3\ \mathrm{fm/c}$
- The simulations of the non-equilibrium dynamics within kinetic theory show **continuity of** $\hat{\mathrm{q}}$ consistent with these glasma phase values
- Similarly strong effects are also observed for heavy quarks

see e.g. P. Aurenche, B. G. Zakharov, PLB, 2012
A. Ipp, D. I. Müller, D. Schuh, PRD, 2020
A. Ipp, D. I. Müller, D. Schuh, PLB, 2020
M. Carrington, A. Czajka, S. Mrowczynski, PLB, 2022
M. Carrington, A. Czajka, S. Mrowczynski, PRC, 2022
D. Avramescu et al., PRD, 2023
J. Barata, S. Hauksson, X. Mayo López, AS, PRD, 2024
S. Hauksson, S. Jeon, C. Gale, PRC, 2022
K. Boguslavski et al., PRD, 2024
K. Boguslavski et al., PLB, 2024
K. Boguslavski, J. Barata, F. Lindenbauer, AS, 2025
M. Carrington, A. Czajka, S. Mrowczynski, NPA, 2020
K. Boguslavski et al., PRD, 2024
C. Gale et al., SQM2024
X. Du, PRC, 2024
D. Avramescu et al., PRD, 2025
D. Avramescu et al., PRL, 2025

Jet quenching during initial stages



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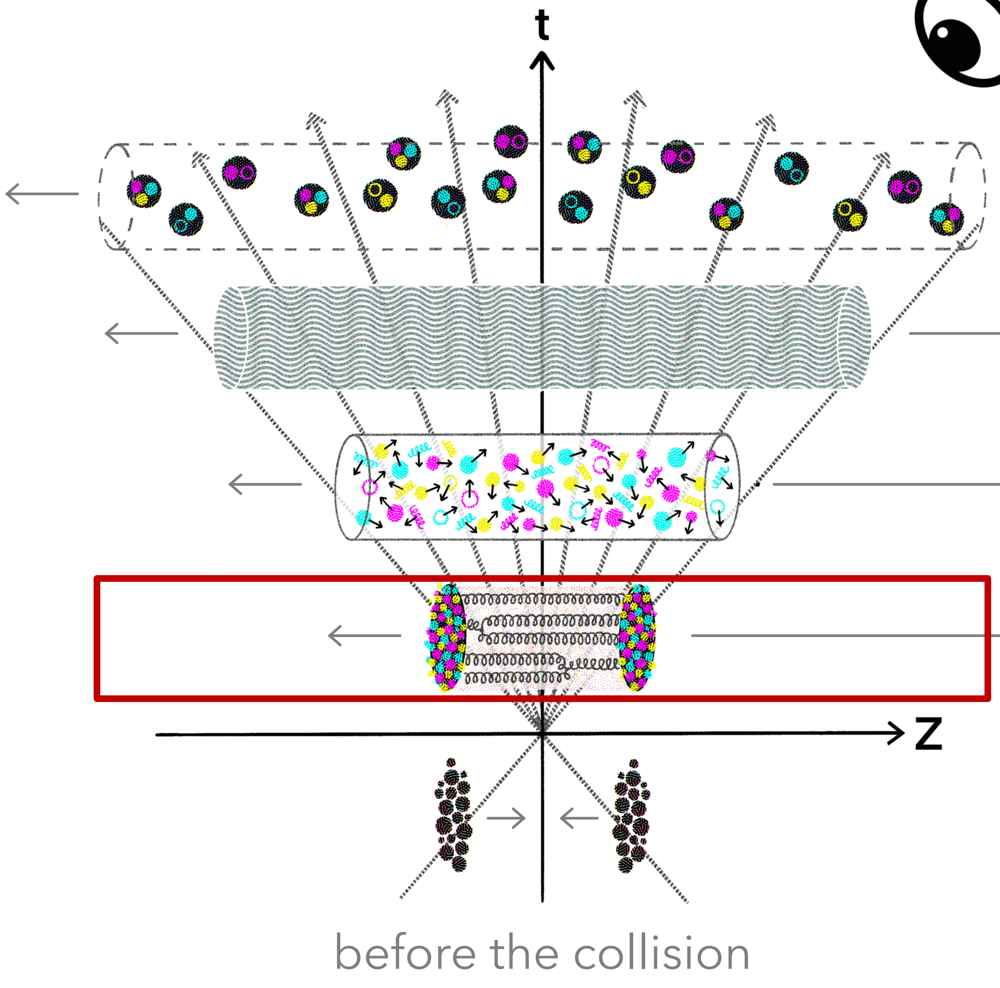


Phases of QCD matter in HIC:

hadron gas

hydrodynamic Quark-Gluon Plasma (QGP)

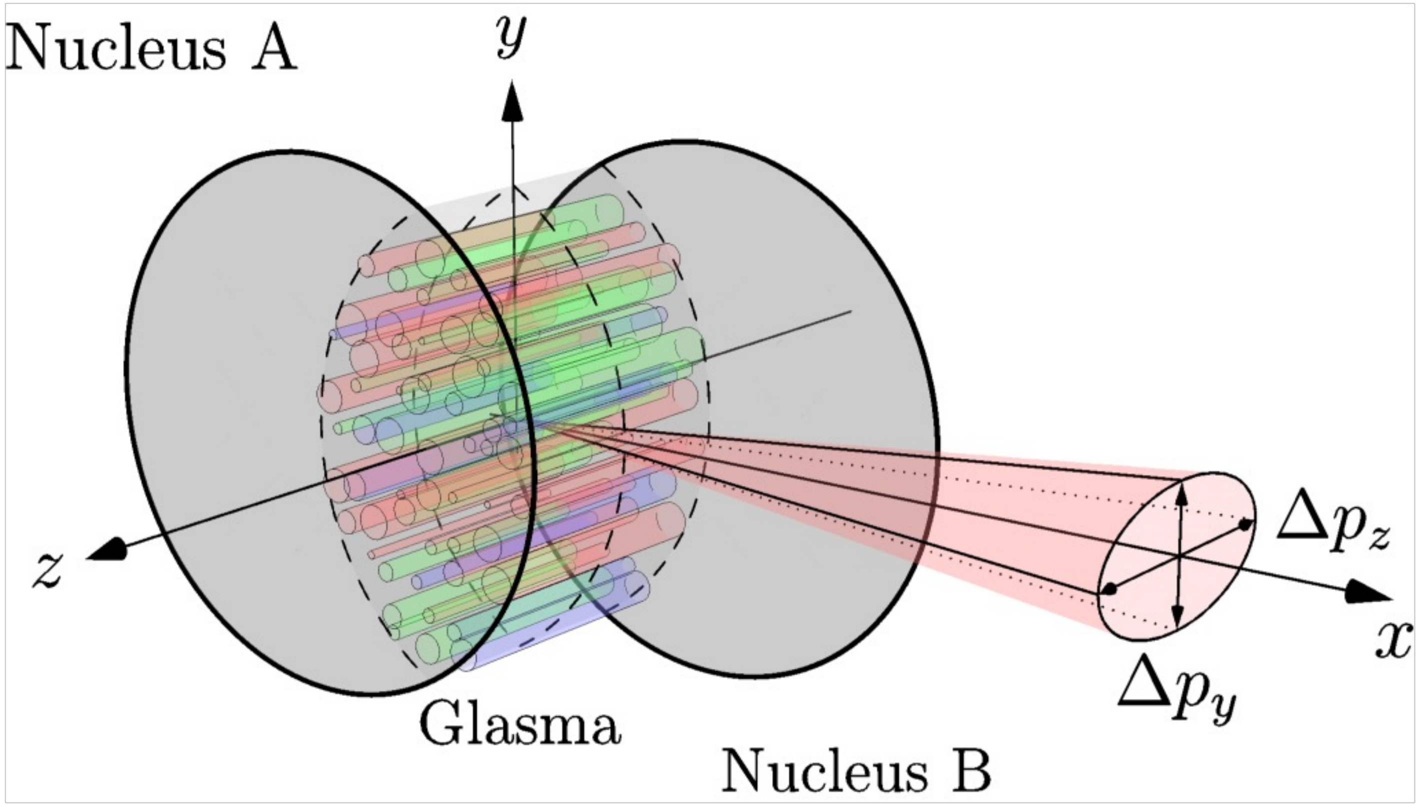
non-equilibrium matter

glasma (strong color fields)

Matter produced in HIC undergoes multiphase evolution

A. Ipp, D. I. Müller, D. Schuh, PRD, 2020
A. Ipp, D. I. Müller, D. Schuh, PLB, 2020
M. Carrington, A. Czajka, S. Mrowczynski, PLB, 2022
M. Carrington, A. Czajka, S. Mrowczynski, PRC, 2022
D. Avramescu et al., PRD, 2023

Jets in the glasma



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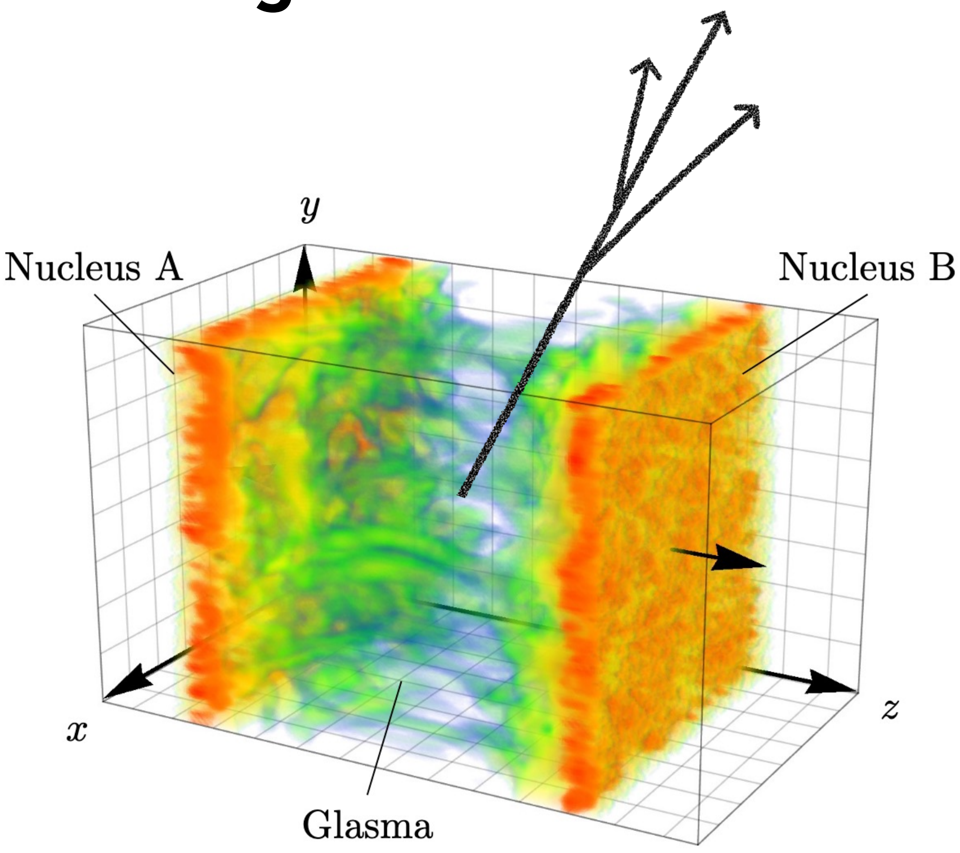
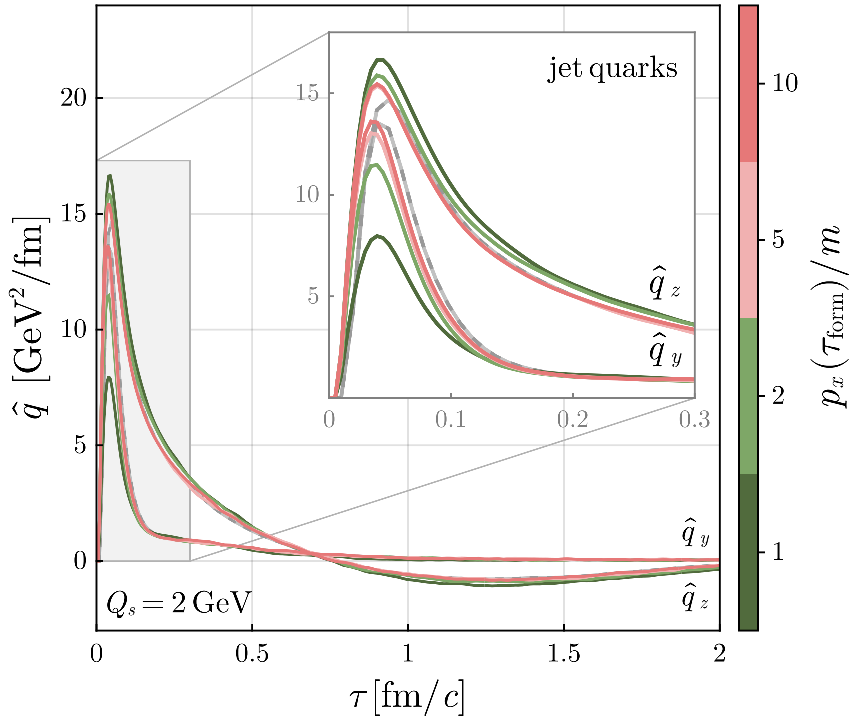
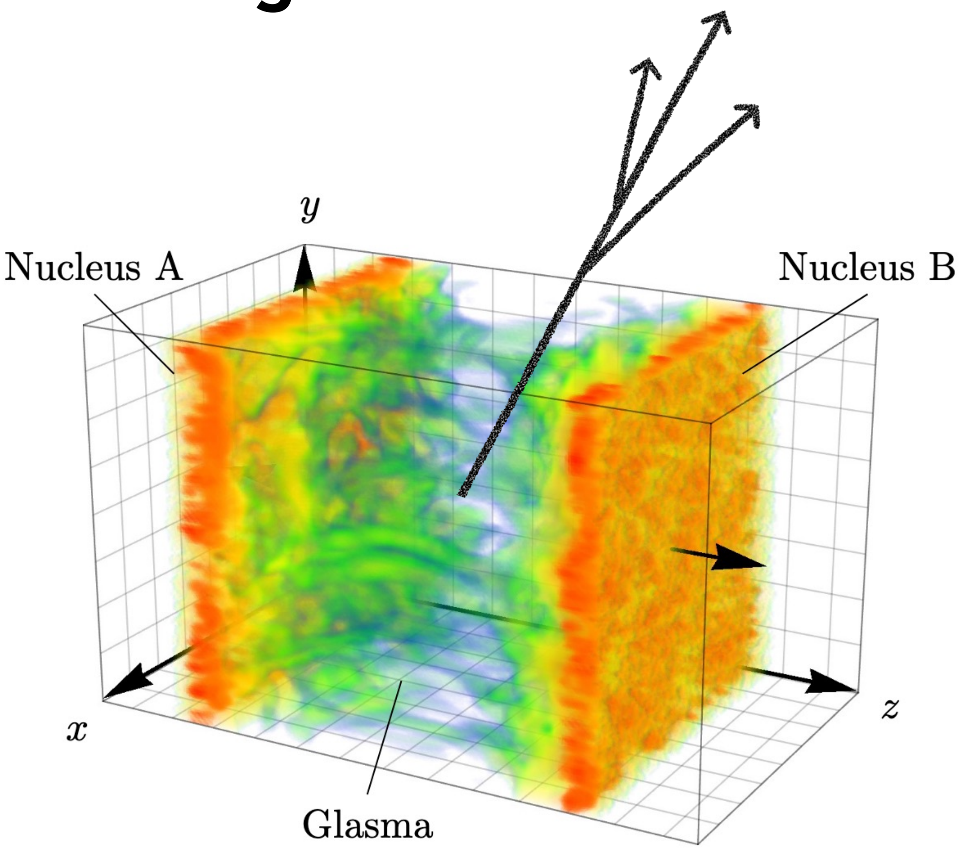
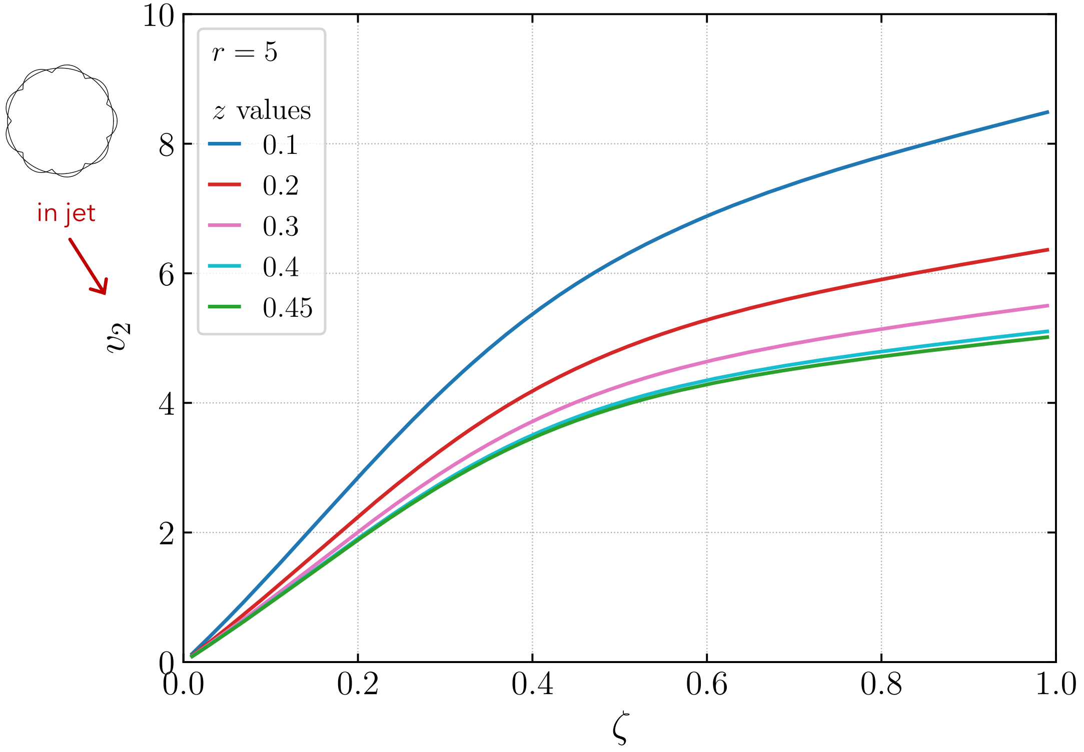




Does that $\hat{q}$ lead to a substantial energy loss and anisotropy?

Jets in the glasma

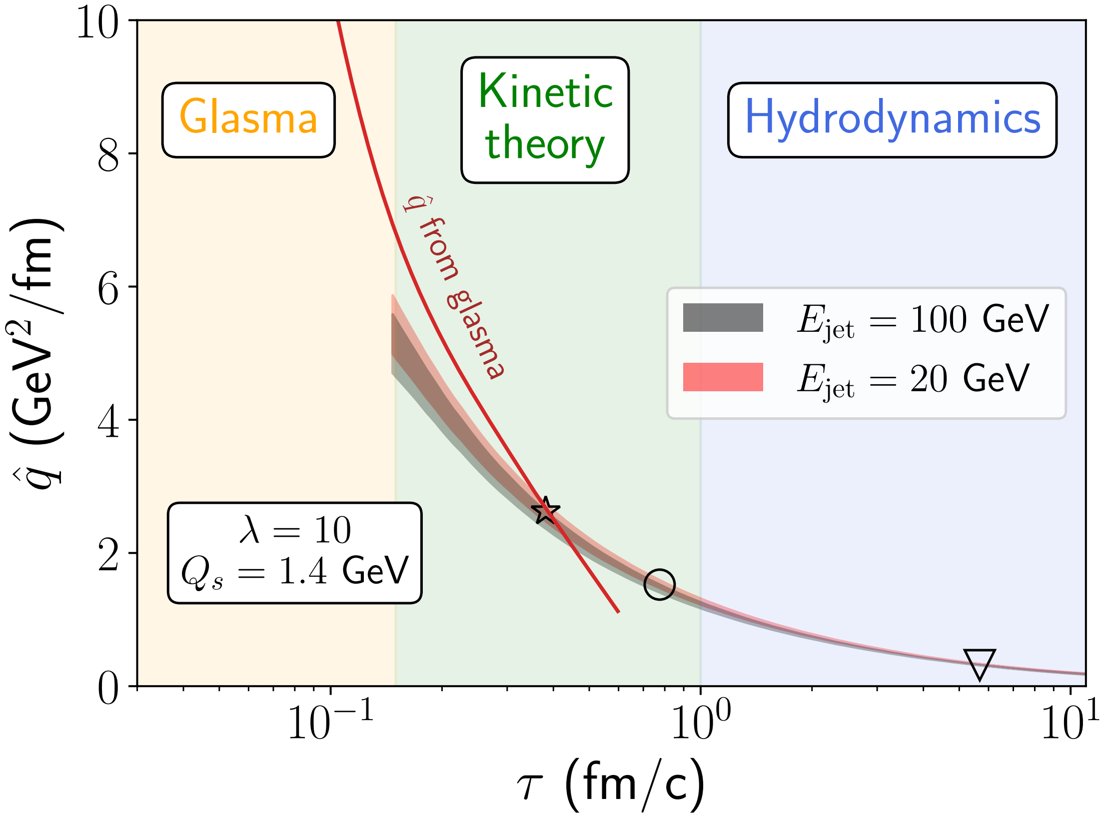


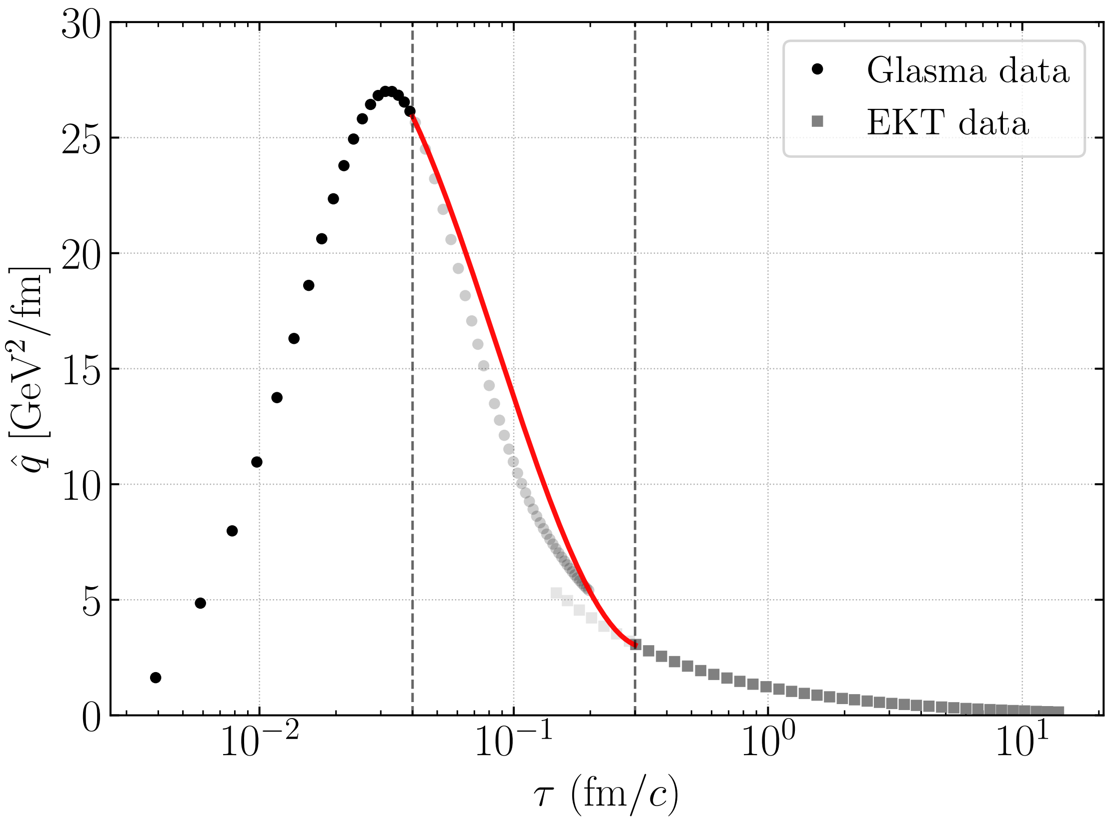


Does that $\hat{q}$ lead to a substantial energy loss and anisotropy?

D. Avramescu et al., PRD, 2023
K. Boguslavski et al., PLB, 2024
J. Barata, G. Milhano, AS, J. Silva, arxiv, 2025

Jet quenching during initial stages





Do the glasma and pre-equilibrium broadening patterns fit together?

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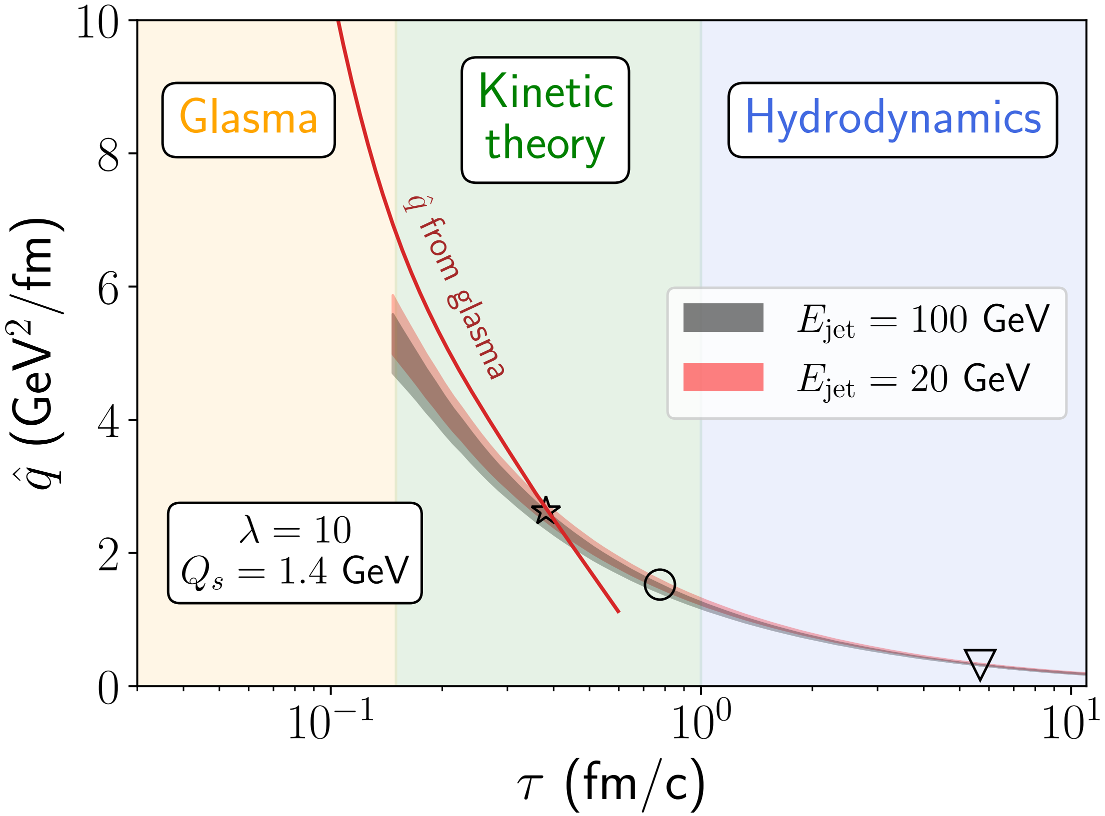

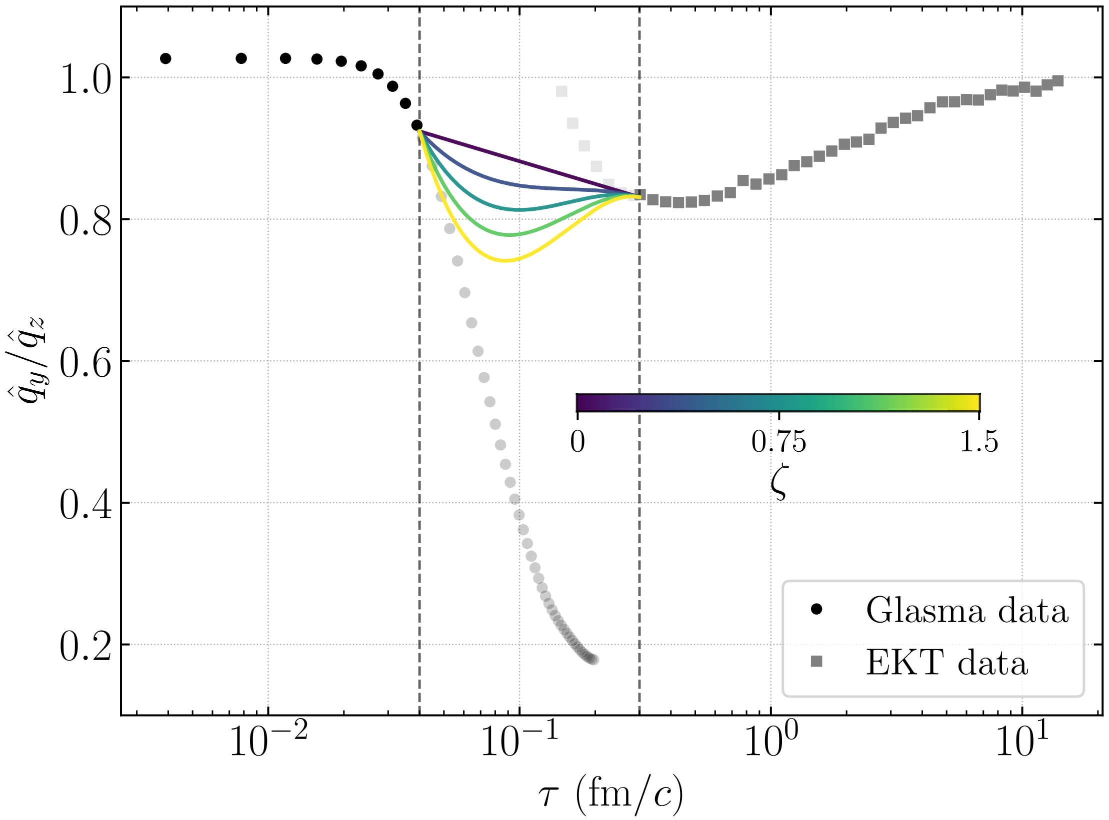

Do the glasma and pre-equilibrium broadening patterns fit together?

Energy correlators

Energy Correlations in Electron-Positron Annihilation: Testing Quantum Chromodynamics

C. Louis Basham, Lowell S. Brown, Stephen D. Ellis, and Sherwin T. Love
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 21 August 1978)

An experimental measure is presented for a precise test of quantum chromodynamics. This measure involves the asymmetry in the energy-weighted opening angles of the jets of hadrons produced in the process $e^+e^- \to$ hadrons at energy W. It is special for several reasons: It is reliably calculable in asymptotically free perturbation theory; it has rapidly vanishing (order $1/W^2$) corrections due to nonperturbative confinement effects; and it is straightforward to determine experimentally.

$$\frac{d\Sigma}{d\Omega} = \sum_{N=2}^{\infty} \int \sum_{a=1} E_a^{-1} d^3p_a \; \frac{d^N\sigma}{E_1^{-1}d^3p_1 \cdots E_N^{-1} d^3p_N} S_N\left[\sum_{b=1}^{N} \frac{E_b}{W} \delta(\Omega_b - \Omega)\right].$$

$$\frac{d^2\Sigma}{d\Omega\, d\Omega'} = \sum_{N=2}^{\infty} \int \prod_{a=1}^{N} E_a^{-1} d^3p_a \; \frac{d^N\sigma}{E_1^{-1}d^3p_1 \cdots E_N^{-1} d^3p_N} S_N\left[\sum_{b,c=1}^{N} \frac{E_b E_c}{W^2} \delta(\Omega_b - \Omega)\delta(\Omega_c - \Omega')\right].$$

Energy correlators

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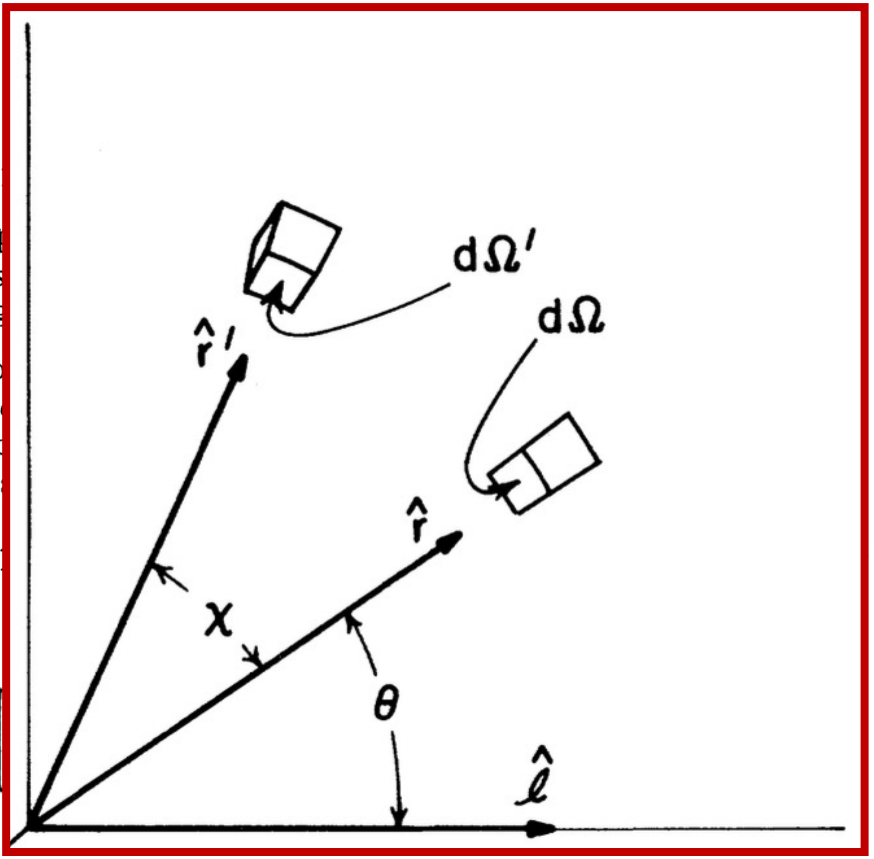

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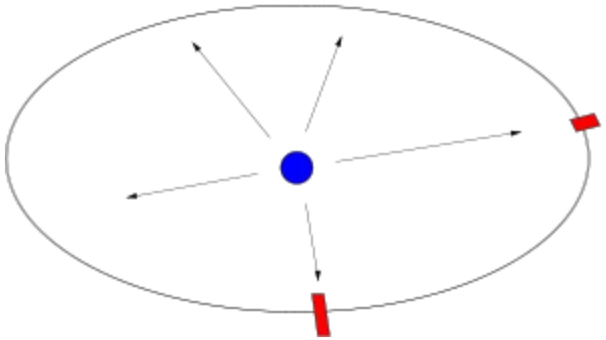
Energy correlators



Basham et al, 70s; Sveshnikov&Tkachov, 90s;

$$\frac{d\Sigma}{d\Omega} = \sum_{N=2}^{\infty} \int \sum_{a=1} E_a{}^{-1} d^3p_a \; \frac{d^N\sigma}{E_1{}^{-1} d^3p_1 \cdots E_N{}^{-1} d^3p_N} S_N \left[\sum_{b=1}^{N} \frac{E_b}{W} \delta(\Omega_b - \Omega) \right].$$

Sterman, 70s

$$\frac{d\Sigma}{d^2n} = \frac{1}{p_t} \langle \Psi | \mathcal{E}(n) | \Psi \rangle \;, \longleftarrow \; \mathcal{E}(n) = \lim_{R\to\infty} R^2 \int_0^\infty dt\, n_i T^{0i}(t, R\,\mathbf{n})$$

Maldacena&Hofman, 2008

$$\langle \Psi | \mathcal{E}(n_1) \mathcal{E}(n_2) ... | \Psi \rangle \sim \sum_n |\theta_{12}|^{\tau_n - 4} \langle \Psi | \mathcal{U}_{2,n}(n_1) ... | \Psi \rangle$$

Energy correlators

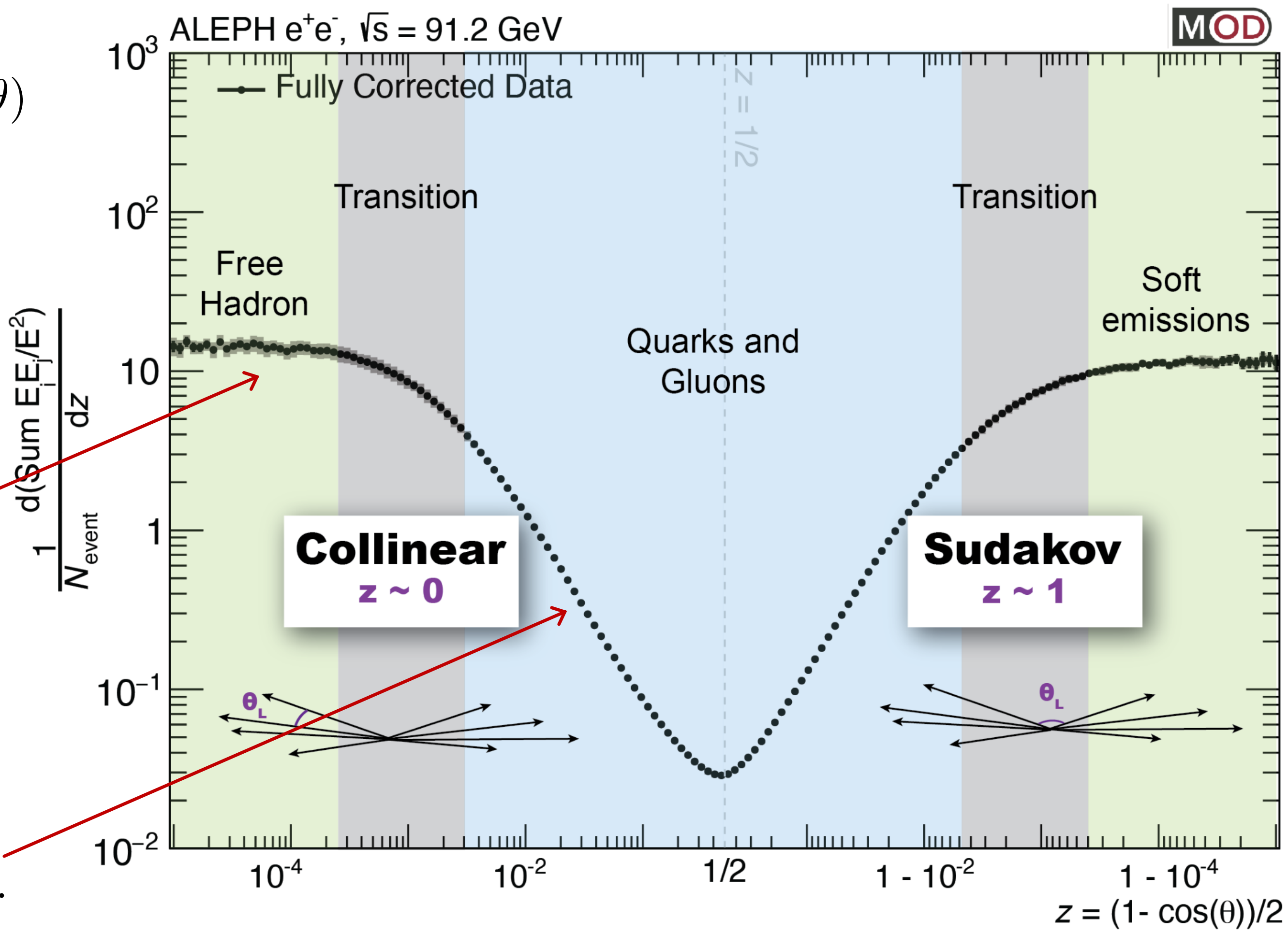
$$\frac{d\Sigma}{d\cos\theta} = \frac{1}{p_t^2}\int_{n_1,n_2} \langle \mathcal{E}(n_1)\mathcal{E}(n_2)\rangle\, \delta(n_1\cdot n_2 - \cos\theta)$$

$\updownarrow$

$$\frac{d\Sigma}{d\cos\theta} = \sum_{i\neq j} \frac{E_i E_j}{p_t^2}\delta(\mathbf{n}_1\cdot\mathbf{n}_2 - \cos\theta)$$

$$\frac{d\Sigma}{d\theta} \sim \theta + \ldots$$

$$\frac{d\Sigma}{d\theta} = \frac{1}{\theta^{1-\gamma(3)}} + \ldots$$



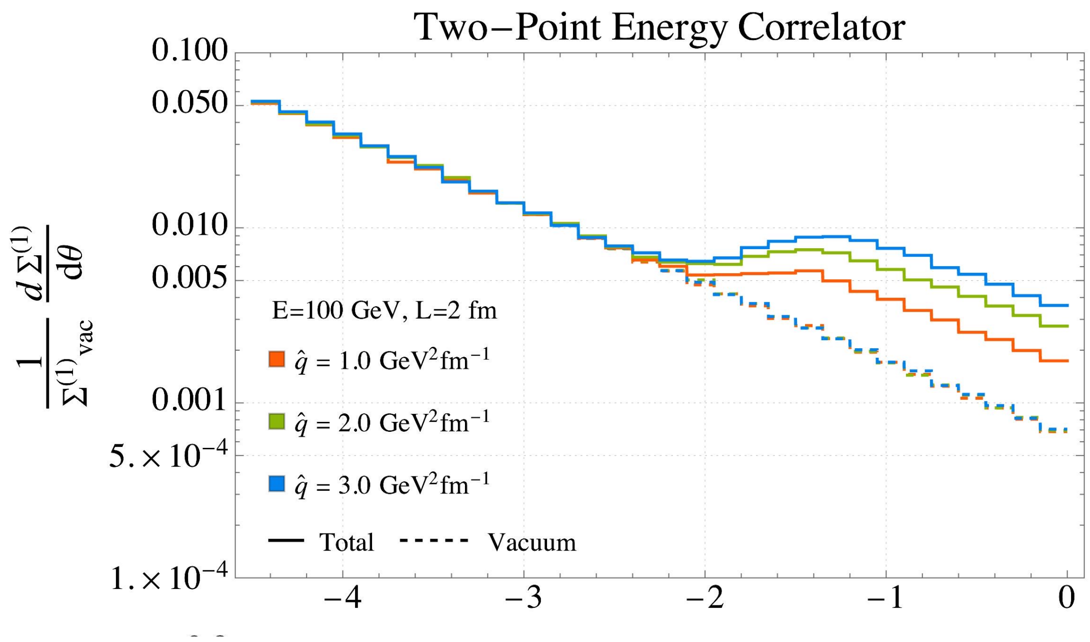
C. Andres et al., PRL, 2023
J. Barata et al., JHEP, 2024

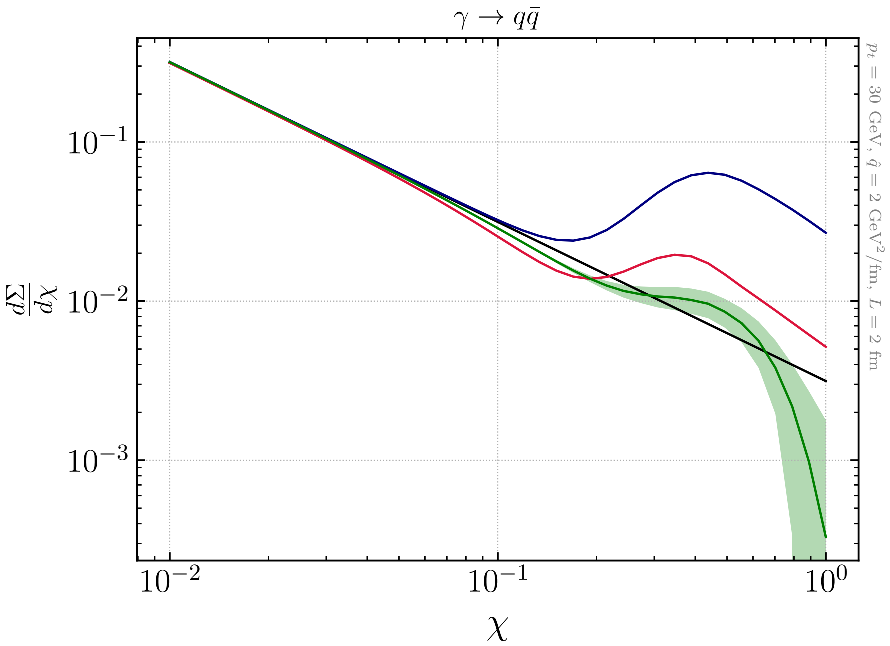
Energy correlators

$$\langle \mathrm{HIC}|\mathcal{E}(n_1)\mathcal{E}(n_2)|\mathrm{HIC}\rangle$$

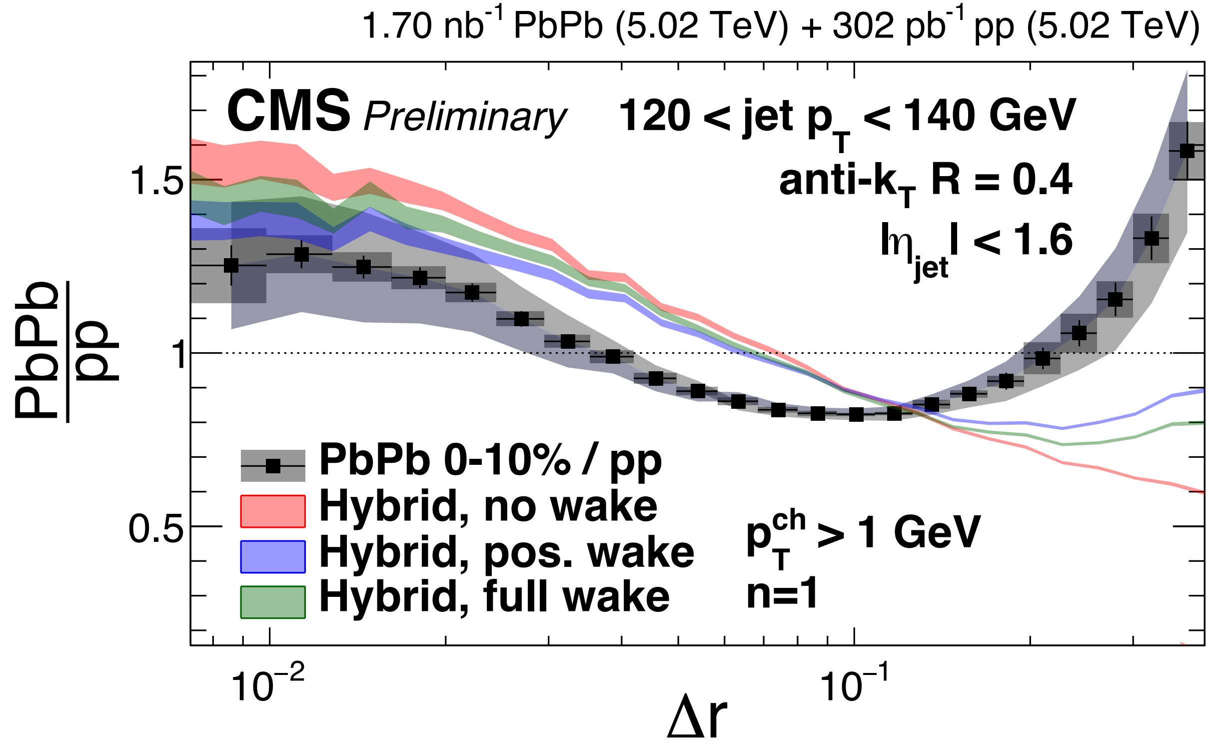
$$\downarrow$$

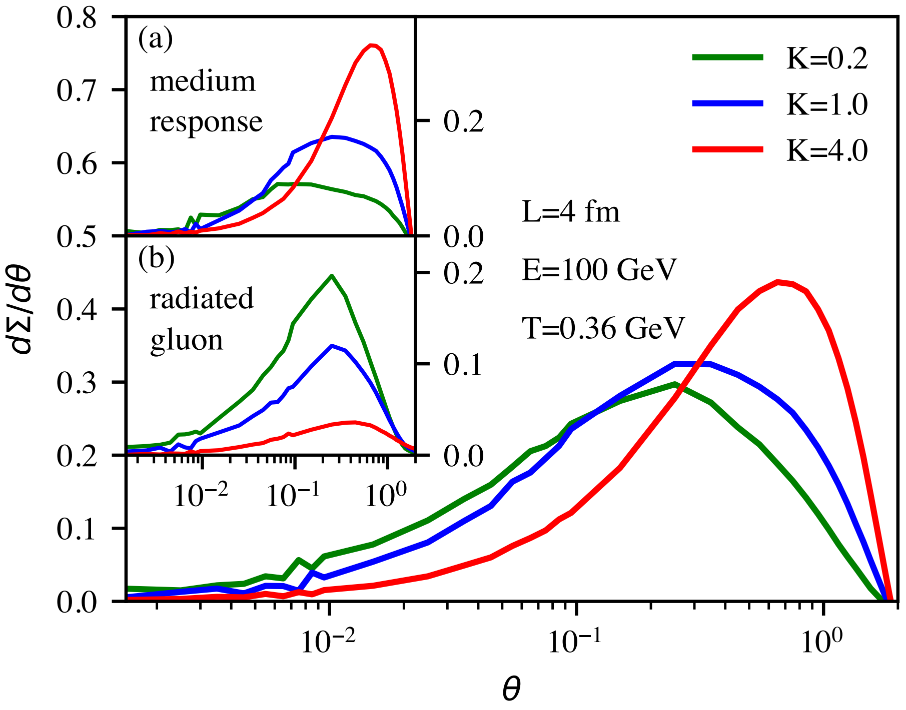
$$\frac{d\Sigma}{d\cos\theta} = \frac{1}{p_t^2}\int_{n_1,n_2} \langle \mathcal{E}(n_1)\mathcal{E}(n_2)\rangle\, \delta(n_1\cdot n_2 - \cos\theta)$$





Energy correlators





Energy correlators

- The vac. PENC in the OPE limit:

$$\frac{d\Sigma^{(N)}_{\mathrm{P,vac}}}{dR_L} = \sum_{k=1} a^{\mathrm{P}(N)}_{\tau,0} R_L^{\tau-3}\Big|_{\tau=2k}$$

- The medium-induced part of PENC: (for a static and homogeneous matter)

$$\frac{d\Sigma^{(N)}_{\mathrm{P,\,med\,(no\,vac)}}}{dR_L} = \sum_{k=2} b^{\mathrm{P}(N)}_{\tau,0}(\omega_c/p_t, \theta_c) R_L^{\tau-3}\Big|_{\tau=2k}$$

- The medium response contribution: (no azimuthal structure, leading terms)

$$\frac{d\Sigma^{(N)}_{\mathrm{P,\,response}}}{dR_L} = \sum_{k=2} c^{\mathrm{P}(N)}_{\tau}\Big[\mathcal{E}_c\Big] R_L^{\tau-3}\Big|_{\tau=2k}$$

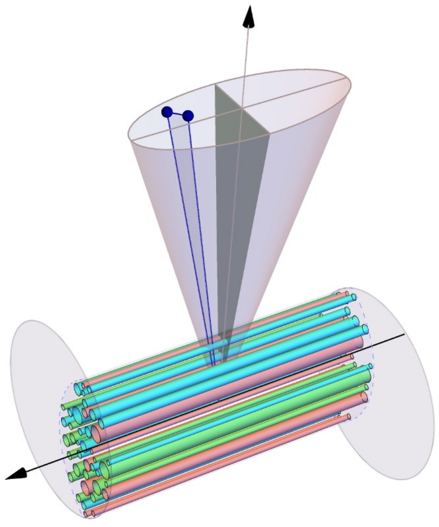
Jet quenching during initial stages

$$\frac{1}{\sin\chi\sin\Psi}\frac{d\Sigma}{d\chi d\Psi}\bigg|_{\eta=0} = \int_{n_1,n_2} \frac{\langle\mathcal{E}(n_1)\mathcal{E}(n_2)\rangle}{p_t^2}\,\delta(n_1\cdot n_2-\cos\chi)\,\delta\left(\frac{n_1-n_2}{|n_1-n_2|}\cdot b-\cos\Psi\right),$$

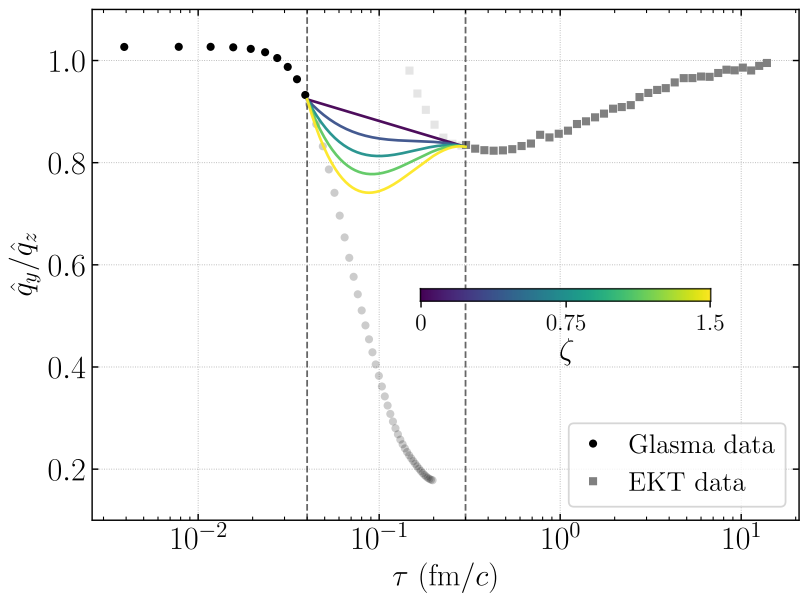
$$\langle\mathcal{E}(n_1)\mathcal{E}(n_2)\rangle = \frac{2p_t^2}{(1-n_1\cdot n_2)^3}\sum_{\delta,j}\int_\gamma \frac{c_{\delta,j,\gamma}}{2\pi i} w^\gamma G_{\delta,j,\gamma}(z,\bar{z})$$

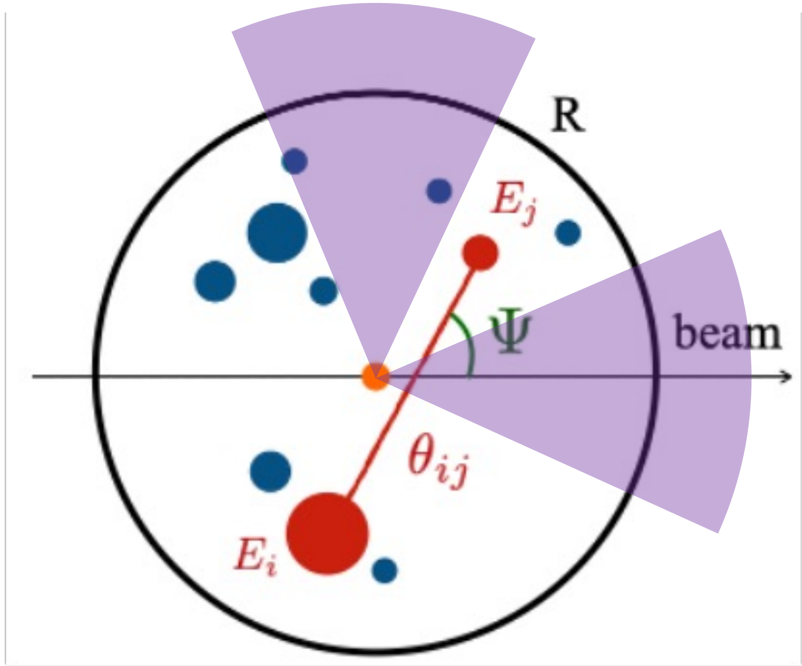
$$\frac{d\Sigma}{d\chi d\Psi} = \sum_{k=1}(c_{\tau,0}+b_{\tau>2,0}+a_{\tau>2,0})\,\chi^{\tau-3} + \sum_{k=2}(c_{\tau,2}+b_{\tau>4,2}+a_{\tau>4,2})\,\chi^{\tau-3}\cos(2\Psi) + \sum_{k=3}(c_{\tau,4}+b_{\tau>6,4}+a_{\tau>6,4})\chi^{\tau-3}\cos(4\Psi) + \ldots$$

- vacuum
- medium-induced
- response



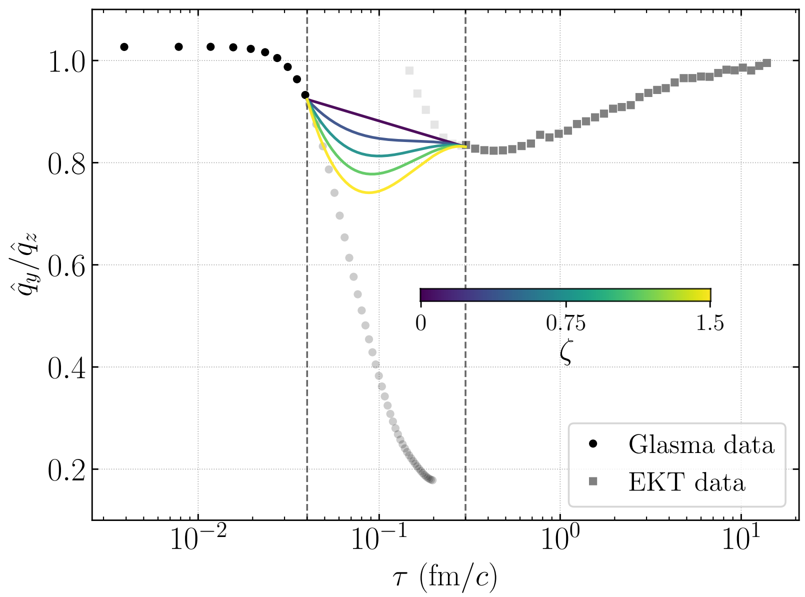
Clover EEC



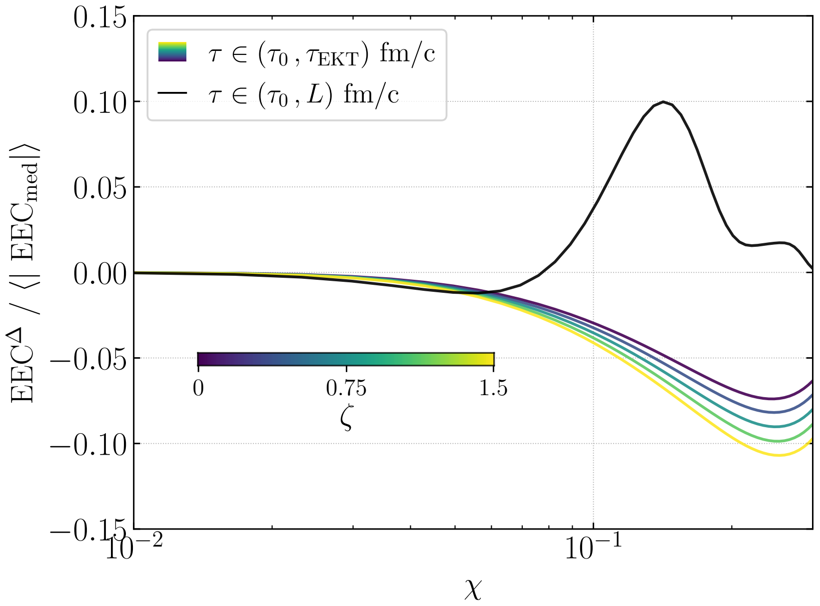


$$\frac{d\Sigma^{\Omega}}{d\chi} = \int_{\Omega} d\Psi \frac{d\Sigma}{d\chi d\Psi}$$

Clover EEC



$\hat{q}_y/\hat{q}_z$
1.0
0.8
0.6
0.4
0.2
10^{-2}
10^{-1}
10^{0}
10^{1}
τ (fm/c)
0
0.75
1.5
ζ
Glasma data
EKT data



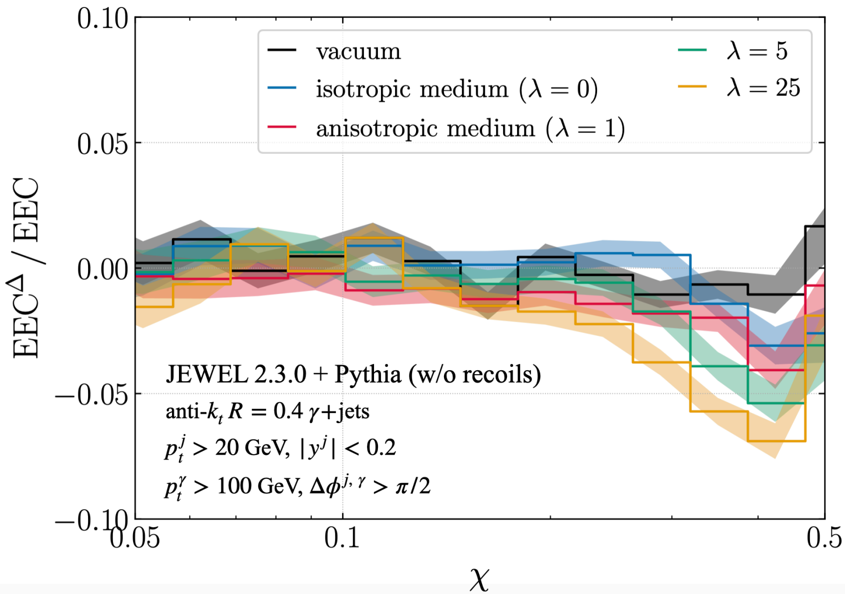
EEC^{Δ} / $\langle|\,\mathrm{EEC}_{\mathrm{med}}|\rangle$
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
$\tau \in (\tau_0\,,\tau_{\mathrm{EKT}})$ fm/c
$\tau \in (\tau_0\,,L)$ fm/c
0
0.75
1.5
ζ
10^{-2}
10^{-1}
χ

Clover EEC

JEWEL (no recoils)

$$T(\eta_s) = (1 + \lambda\eta_s^2)T_{\text{default}}$$

$$\left.\frac{\partial^2 T}{T^3 \partial z^2}\right|_{z=0} = \frac{1}{3}\frac{1+6\lambda}{f^2 T_i^2 (\tau_i t^2)^{2/3}}$$



Summary and outlook

- Many recent advances in describing probe–matter interactions across different phases of the nuclear matter created in HIC
- Improved sensitivity of hard-probe theory to differential structures and details of matter evolution, giving access to the initial stages and opening the way to explore small systems
- These jet modifications can be probed experimentally, moving us closer to true jet tomography, more differential observables would further enhance this (and there are some suggestions out there)
- Theoretical uncertainties remain large – missing theoretical ingredients already available should be incorporated into simulation frameworks
- The picture gets more ~~complicated~~ interesting, but that also calls for stronger cross-talk between theory and experiment