Medium response & hard-soft correlation

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UNIVERSITY OF JYVÄSKYLÄ

HELSINKI INSTITUTE OF PHYSICS

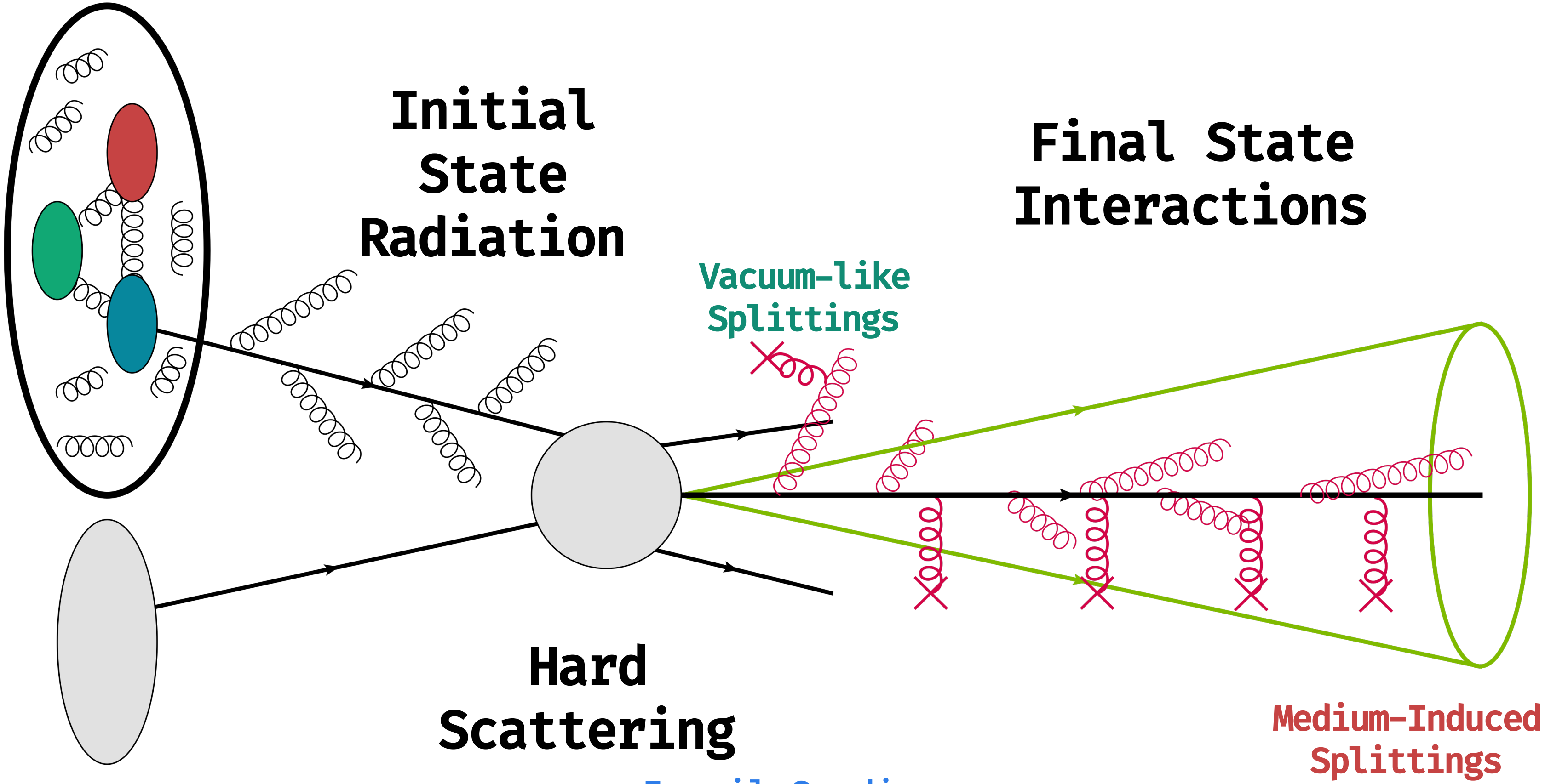
Centre of Excellence in Quark Matter

Yocto/LHC
Yoctosecond Imaging of QCD Collectivity Using Jet Observables
An ERC Advanced Grant 2019 - 2024

Funded by the European Union

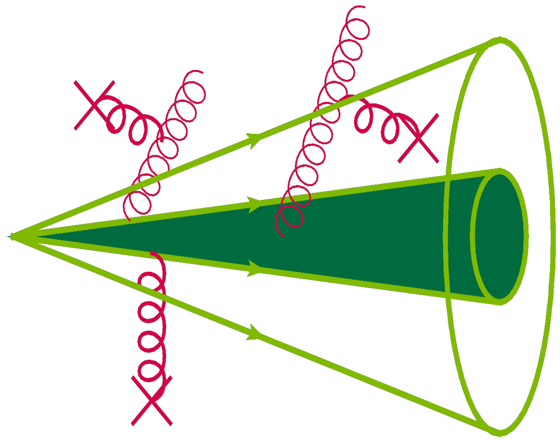
erc
European Research Council
Established by the European Commission

Hard-Soft Correlations



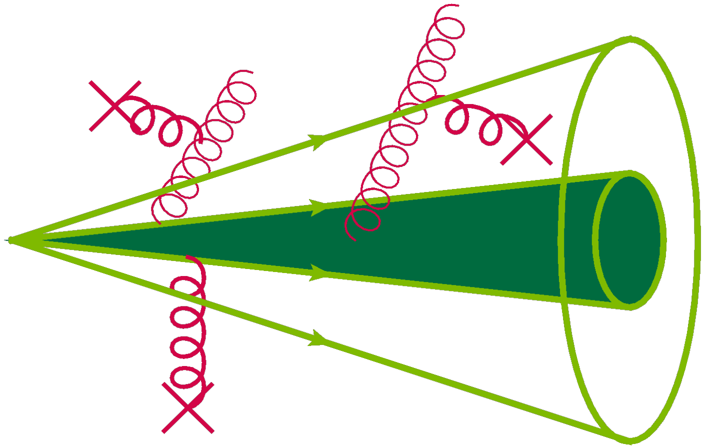
Vacuum-Like Physics

D. Pablos Tue 09:20
K. Zapp Wed 08:40
A. Cordeiro Wed 09:00
A. Takacs Wed 09:20
J. M. da Silva Thu 09:00
X. M. Lopez Thu 09:20
...



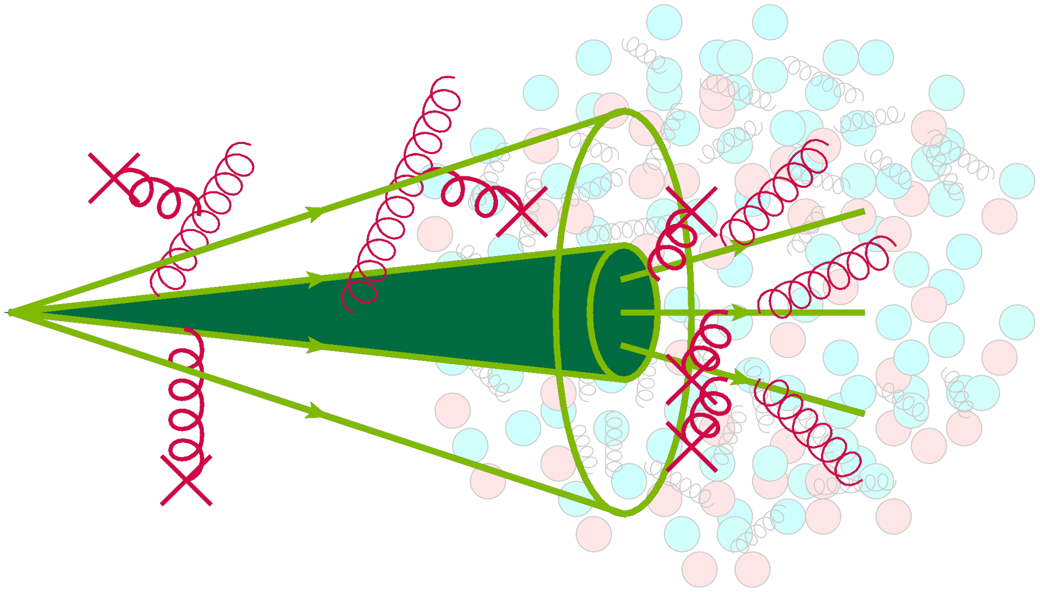
- Initial Coherent Scatterings
  - » Factorization: Coherent Radiation Not Resolved By QGP [Caucal, Iancu, Mueller, Soyez, PRL(2018)]
  - » Modified Vacuum Shower [Kumar, Majumder, Shen, PRC(2020)] [Kumar, Majumder, Sirimanna, Tachibana, 2501.07823]
  - » De-/coherent Energy Loss $\Rightarrow$ Jet v_2 and R_{AA} [Mehtar-Tani, Tywoniuk, JHEP(2013)] [Mehtar-Tani, Pablos, Tywoniuk, PRL(2021) PRD(2024)]
  - » Color Coherence on Recoils [Pablos, Sanjurjo, 2406.08550]
  - » Delayed Energy Loss (τ=0.6 fm/c) [Andres, Armesto, Niemi, Paatelainen, Salgado, PLB(2020)]
  - » ...

Decoherence

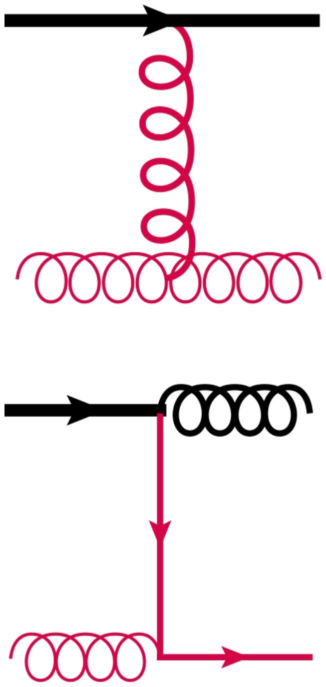


Decoherence

- Individual Antennas Resolved By QGP

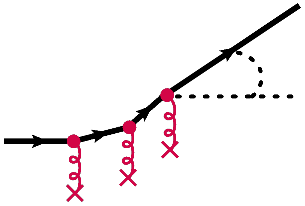


Jet-Medium Scattering



- Multiple Scattering:
  - » Momentum Broadening
  - » Drag
  - » Conversion

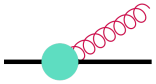
$$\left.\begin{array}{l}\text{Momentum Broadening}\\ \text{Drag}\end{array}\right\} \propto \hat{q} = \frac{\langle k_T^2 \rangle}{L}$$



Medium-Induced Radiation

[Baier, Dokshitzer, Mueller, Peigné, Schiff (1996)] [Zakharov (1996)] [Gyulassy, Levai, Vitev (1999)] [Wiedemann, Gyulassy (1999)]
[Arnold, Moore, Yaffe (2003)] [Caron-Huot, Gale (2010)]..

» BDMPS-Z Formalism: Resum Multiple-Scattering diagram



$$\underbrace{\frac{d\Gamma^a_{bc}}{dz}(P,z,t)}_{\text{Rate}} = \frac{\mathbf{d}}{\mathbf{dt}} \underbrace{\frac{dI^a_{bc}}{dz}(P,z,t)}_{\text{Spectrum}} = \frac{g^2 P^a_{bc}(z)}{4\pi P^2 z^2 (1-z)^2} \mathrm{Re} \int_0^t dt_1 \int_{\boldsymbol{p},\boldsymbol{q}} \frac{i\boldsymbol{q}.\boldsymbol{p}}{\delta E(\boldsymbol{q})} \underbrace{\Gamma_3(t)}_{\text{Medium}} \circ G(t,\boldsymbol{q};t_1,\boldsymbol{p}) \,.$$

$$\hat{q}(t) = \int d^2k_T \; k_T^2 \; \Gamma(t)$$

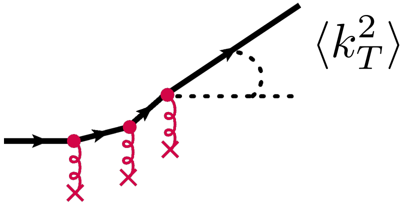
$\Gamma(t) \propto \frac{1}{q^2(q^2+m_D^2)}$ » HTL Potential

$\Gamma(t) \propto \frac{1}{(q^2+m_D^2)^2}$ » Static Screening

$\Gamma(t) \propto \hat{q}b^2$ » Harmonic Oscillator (HO)

$\Gamma(t) \propto C_{NP-QCD}(q)$ » Non-perturbative

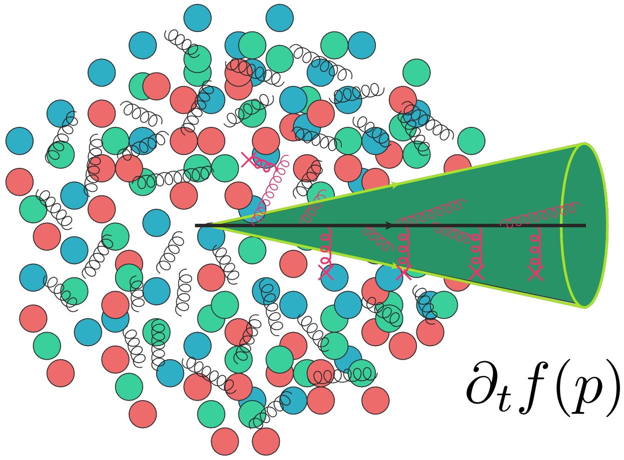
$\Gamma(t) \propto C_{Non-Eq}(q)$ » Non-Eq Extracted



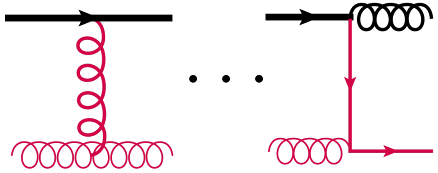
[Moore, Schlusser, PRD(2020)]
[Moore, Schlusser, Schlichting, IS, JHEP(2020)]

F. Lindenbauer Mon 17:55

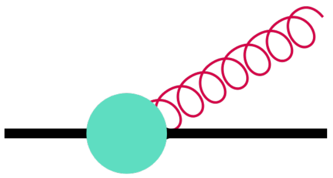
Effective Kinetic Theory



» Elastic Scattering



» Effective 1⟷2 Rate



$$\partial_t f(p) = \underline{\quad C^{2\leftrightarrow 2}[f] \quad} + C^{1\leftrightarrow 2}[f]$$

Static/Evolving

$$\boldsymbol{f(p) = f^{QGP}(p) + \delta f^{jet}(p)}$$

Includes Medium Recoil/Response

$$\boldsymbol{\delta f^{jet}(p) = f(p) - f^{QGP}(p) \lesseqgtr 0}$$

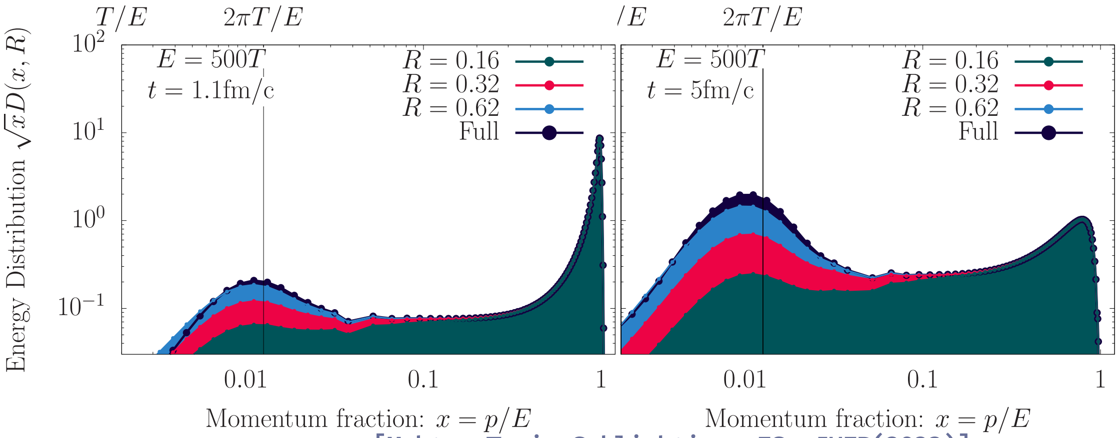
Energy Distribution

$$\boldsymbol{D(x) = \delta(xE_0 - p)p^3 \delta f^{jet}(p)}$$

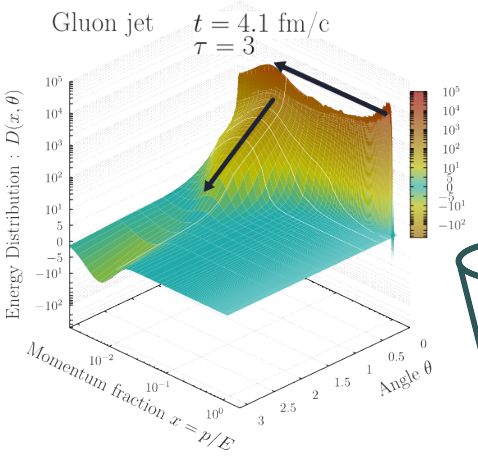
[Arnold, Moore, Yaffe]

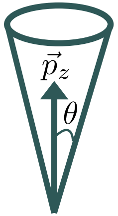
AMY Kinetic Theory

AMY Kinetic Theory



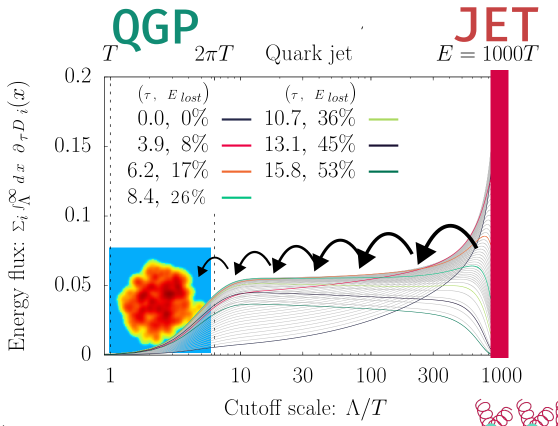
[Mehtar-Tani, Schlichting, IS, JHEP(2023)]





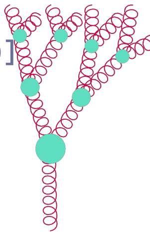
AMY Kinetic Theory

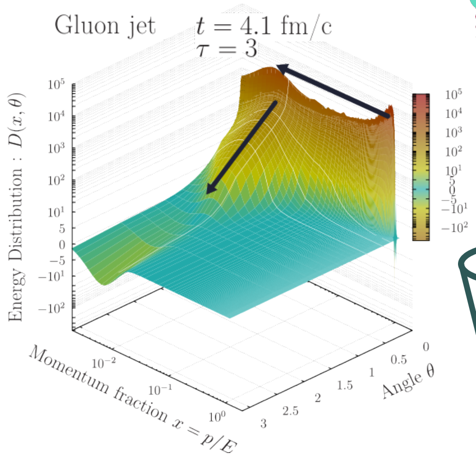
»K-Z Turbulent Cascade ⇒ Stationary Solution

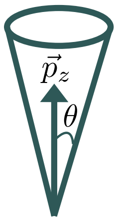


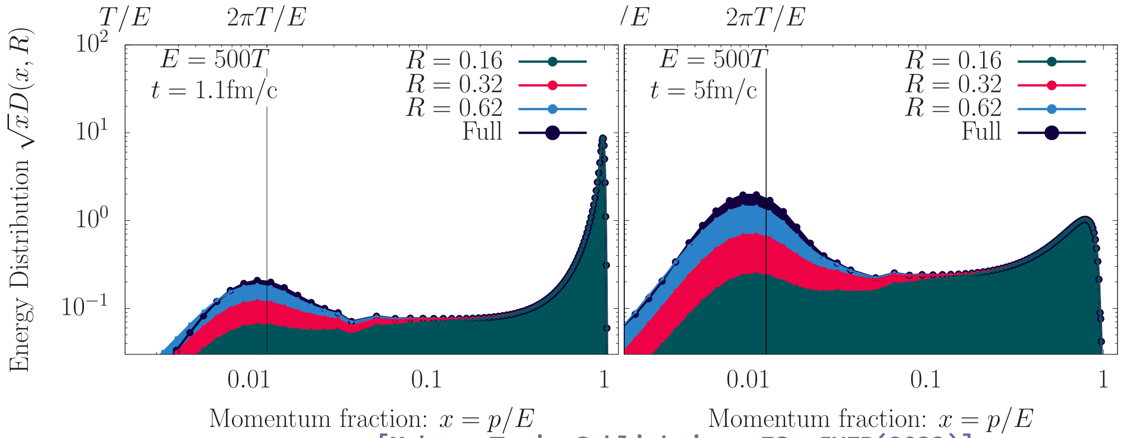
$$D(x) \propto \frac{1}{\sqrt{x}}$$

[Schlichting, IS, JHEP(2021)]









[Mehtar-Tani, Schlichting, IS, JHEP(2023)]

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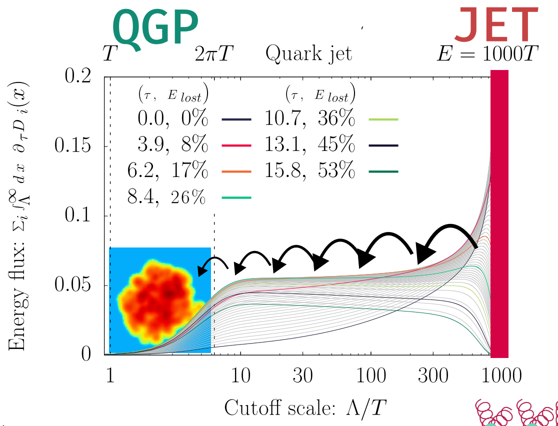
AMY Kinetic Theory



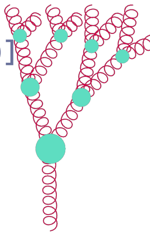
» K-Z Turbulent Cascade ⇒ Stationary Solution

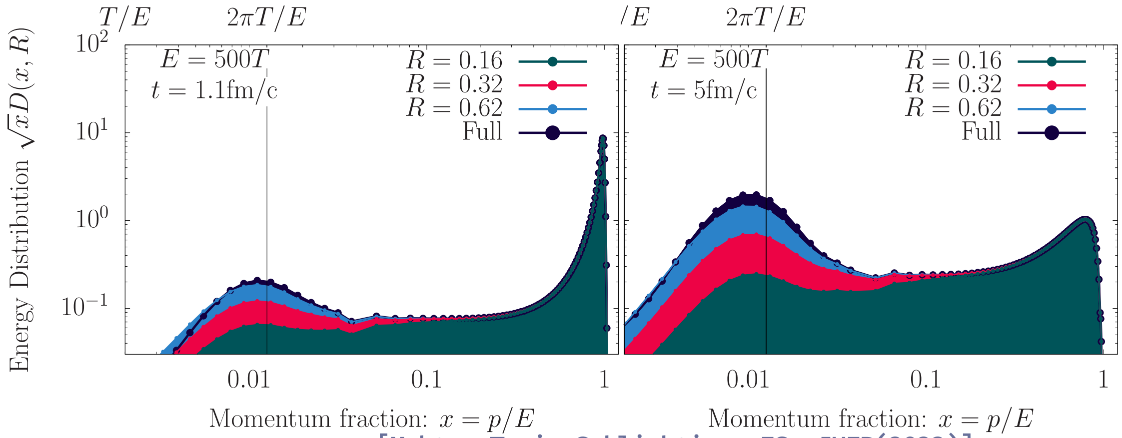
» Due to the Rate Momentum Dependence

$$\partial_t D(x) = \int_0^1 dz\ \mathcal{K}(z) \frac{1}{\sqrt{x}} \left[\sqrt{z} D\left(\frac{x}{z}\right) - z D(x)\right]$$

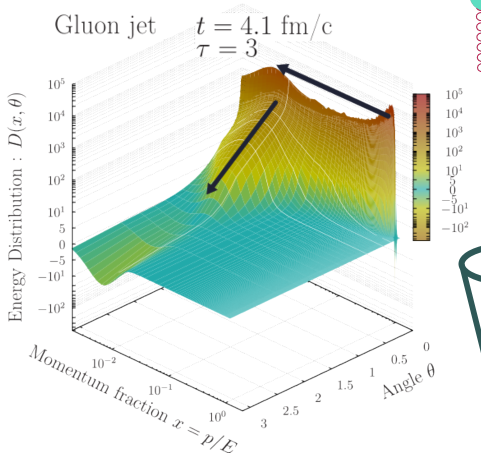
$$D(x) \propto \frac{1}{\sqrt{x}}$$

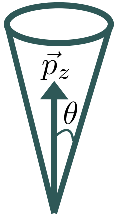
[Schlichting, IS, JHEP(2021)]





[Mehtar-Tani, Schlichting, IS, JHEP(2023)]





[Blaizot, Iancu, Mehtar-Tani, PRL(2013)]
[Blaizot, Mehtar-Tani, AOP(2016)]

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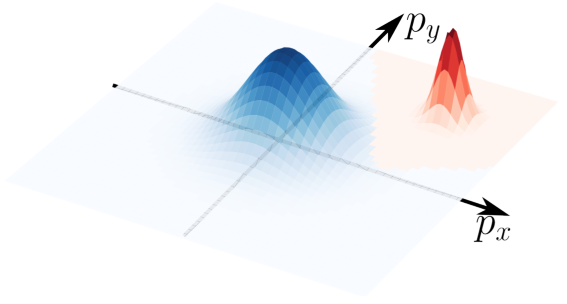
Evolving Background

[Zhou, Brewer, Mazeliauskas, JHEP(2024)]



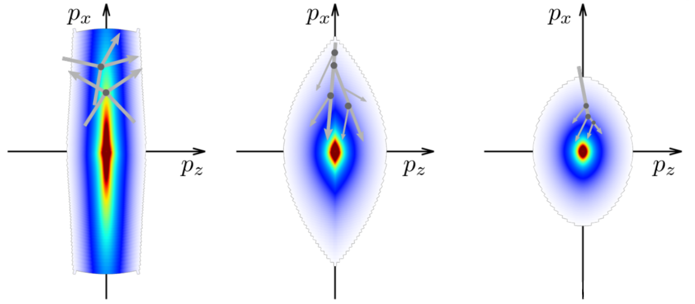
- Evolving Medium

$$\left(\partial_\tau + \frac{p_z}{\tau}\partial_{p_z}\right) f^{QGP}(p,t) = C[f^{QGP}]$$

$$\left(\partial_\tau + \frac{p_z}{\tau}\partial_{p_z}\right) \delta f^{jet}(p,t) = C[f^{QGP}, \delta f^{jet}]$$

- CGC Initial Condition:

$$f^{QGP}(p,t=0) = \frac{2A}{\lambda}\frac{Q_0 \exp[-\frac{2}{3}(p_T^2+\xi^2 p_z^2)/Q_0^2]}{\sqrt{p_T^2+\xi^2 p_z^2}}$$

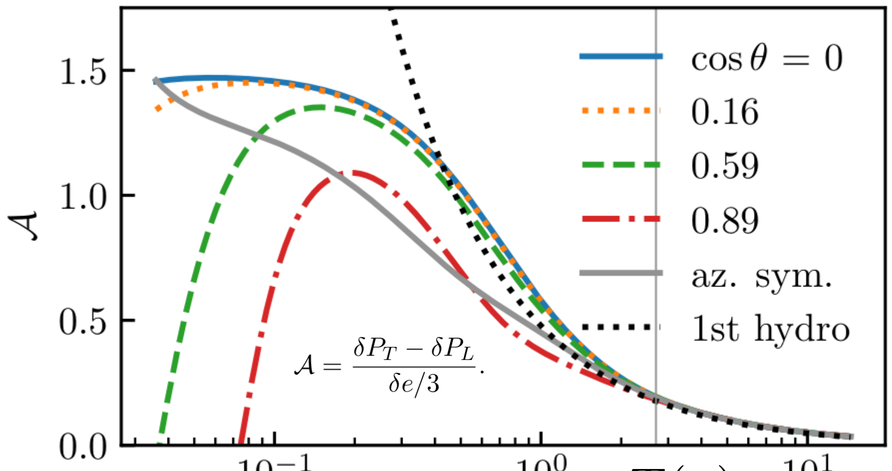


Evolving

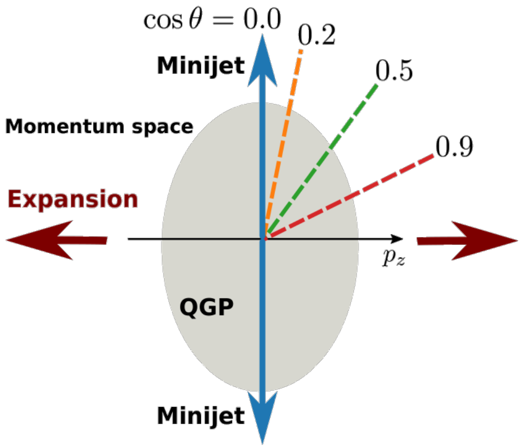
$$f(p, \boxed{t}) = f^{QGP}(p, \boxed{t}) + \delta f^{jet}(p, \boxed{t})$$

AMY Kinetic Theory

» "Hydrodynamisation" Of Jets: Indistinguishable From Soft Background Perturbations $\tilde{\omega}_{mjh} = 2.7$



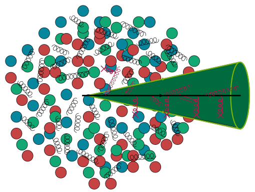
$$\tilde{w} = \frac{\tau T(\tau)}{4\pi\eta/s}$$



[Zhou, Brewer, Mazeliauskas, JHEP(2024)]

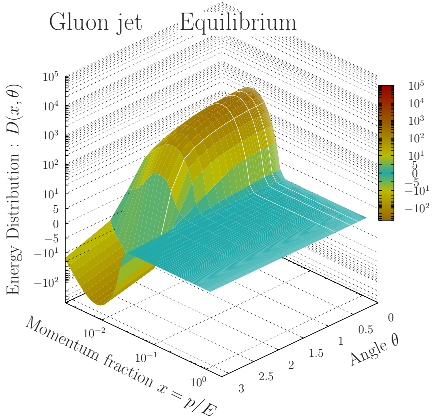
Medium Response

- Thermalized Jet Distribution



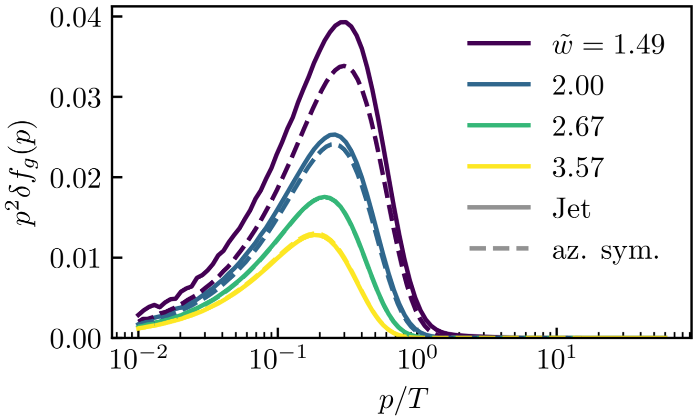
»Static Medium:

$$\delta \bar{f}_a^{(eq)}(\mathbf{p}) = V\left[\boldsymbol{\delta T}\partial_T + \boldsymbol{\delta u^z}\partial_{u^z} + \boldsymbol{\delta\mu_f}\partial_{\mu_f}\right] n_a(\mathbf{p})$$



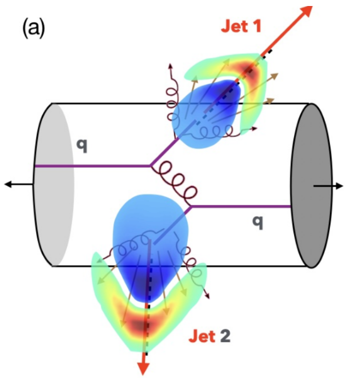
»Evolving Medium:

$$\delta f_{\mathrm{visc}} = \frac{\eta/s}{\tau\overline{T}(\tau)}(1-3\cos^2\theta)F\left(p/\overline{T}(\tau)\right)$$

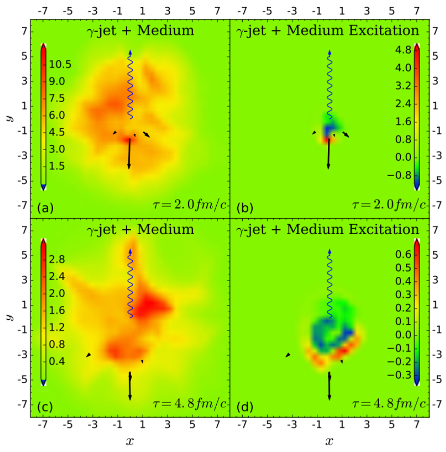


[Zhou, Brewer, Mazeliauskas, JHEP(2024)]

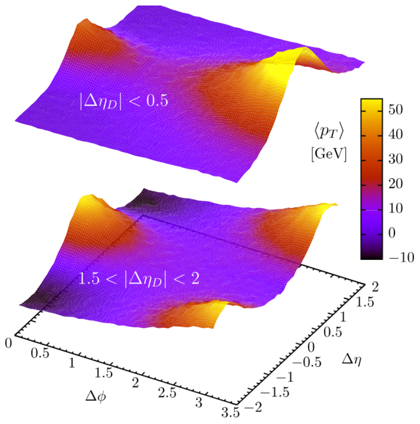
Diffusion Wake



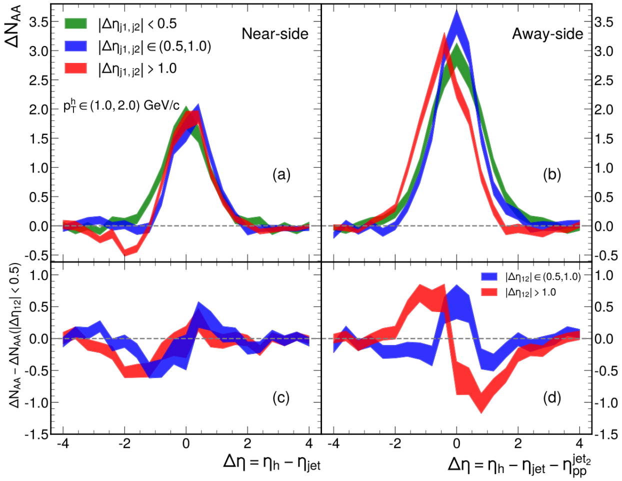
- Spatial Evolution of Response
  - »Boson-jet⇒ Wake in Boson direction
  - »Di-jet observables using rapidity gap



[Chen et al., PLB (2018)]

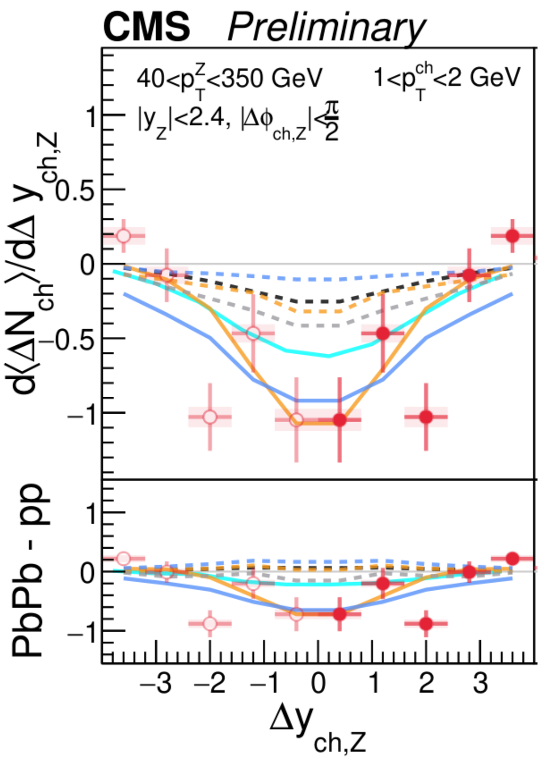


[Pablos, PRL (2020)]



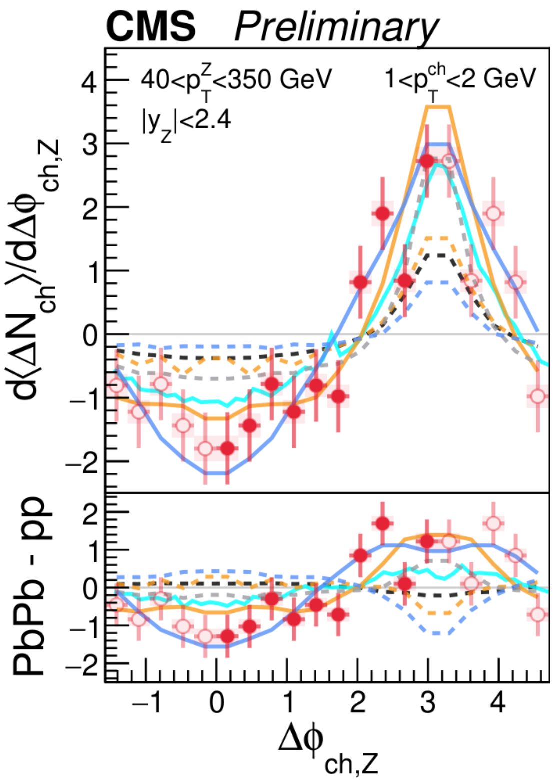
[Yang, Wang, 2501.03419]

Evidence Of Medium Response



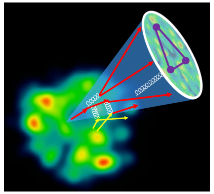
- Z-hadron correlation
  - »Depletion Z-direction $\Delta\phi=0$ & $\Delta y=0$
  - »Enhancement hadron-side $\Delta\phi=\pi$
  - »Captured by Medium Response Models

PbPb 0-30%
Hybrid
Hybrid No wake
PYQUEN
Jewel v2.2.0
Jewel No recoil
CoLBT
PYTHIA8 p_T^Z>20 GeV

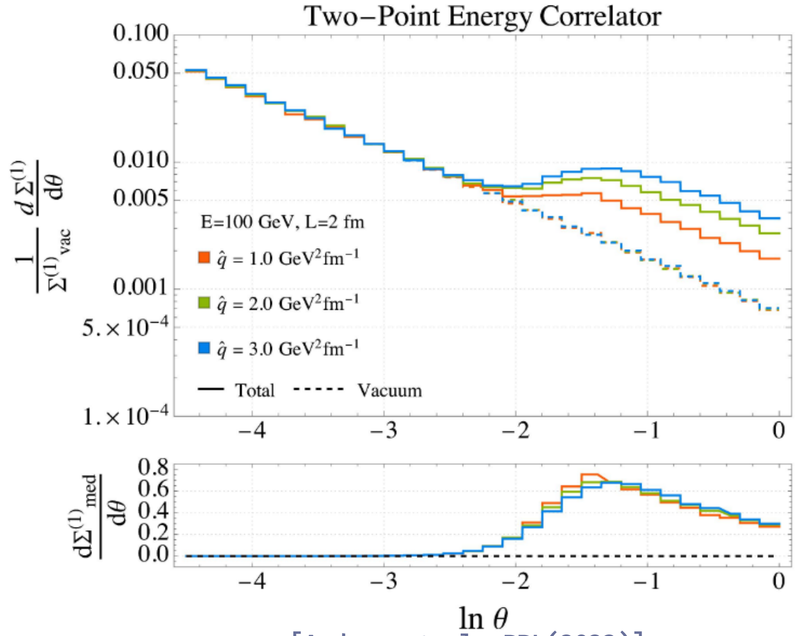


[CMS-PAS-HIN-23-006]

Energy-Energy Correlators



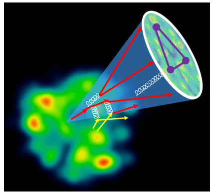
- Jet substructure from EEC in Medium



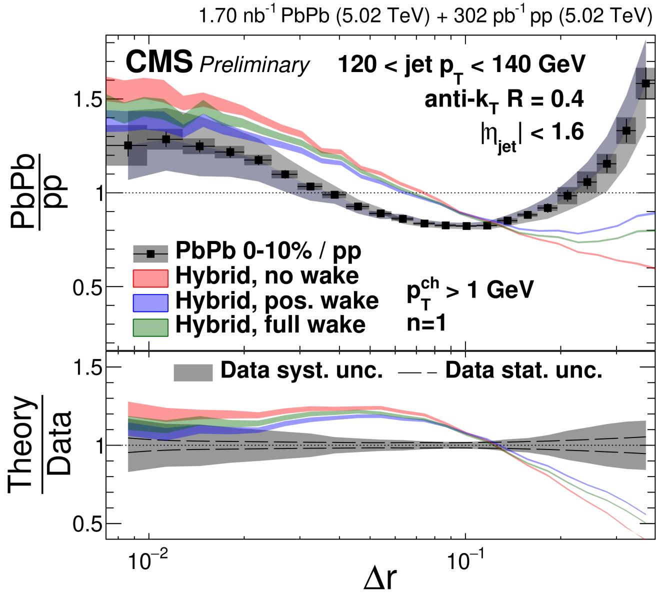
[Andres et al. PRL(2023)]

The new kid in town
Everybody loves you
So don't let them down...

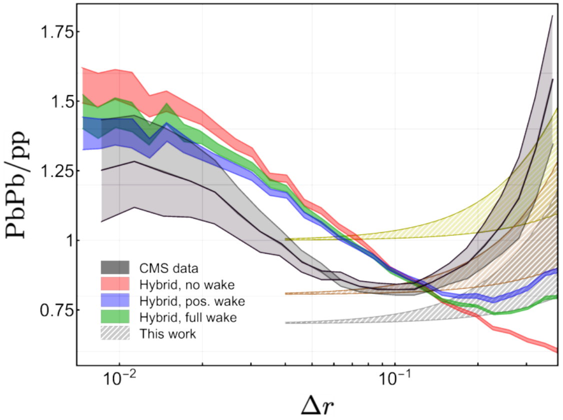
Energy-Energy Correlators



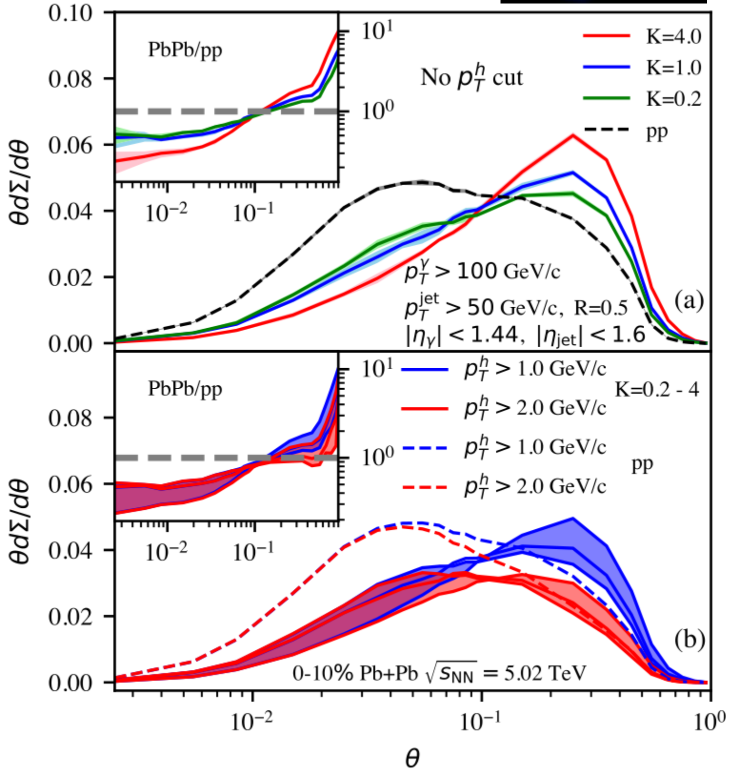
» Medium Response ⇒ Large angle enhancement



[CMS-PAS-HIN-23-004]



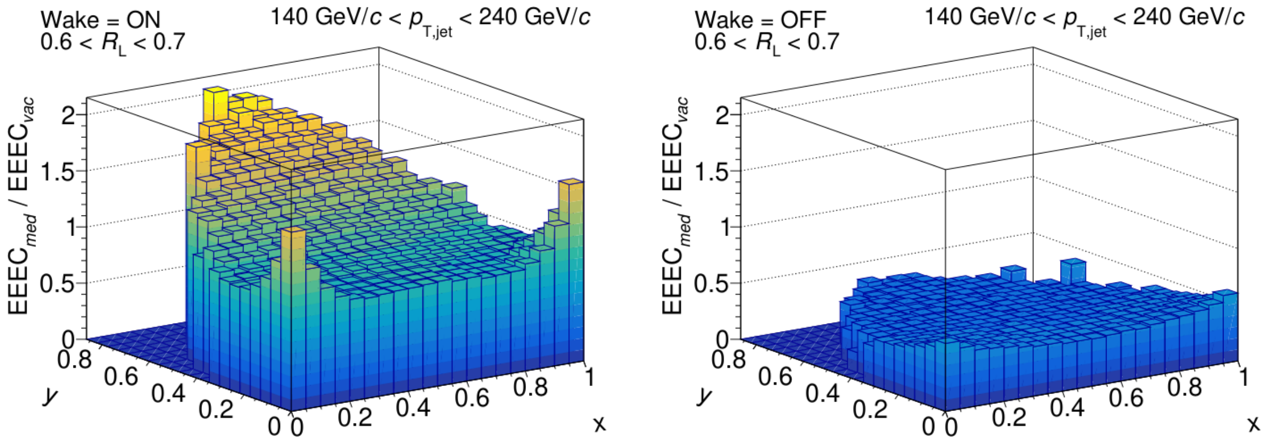
[Barata et al. arXiv:2412.03616]



[Yang, He, Moult, Wang, PRL(2024)]

Energy-Energy Correlators

- Imaging the Wake with 3-point energy correlator
  » Large enhancement in equilateral region (Jet-Wake-Wake)



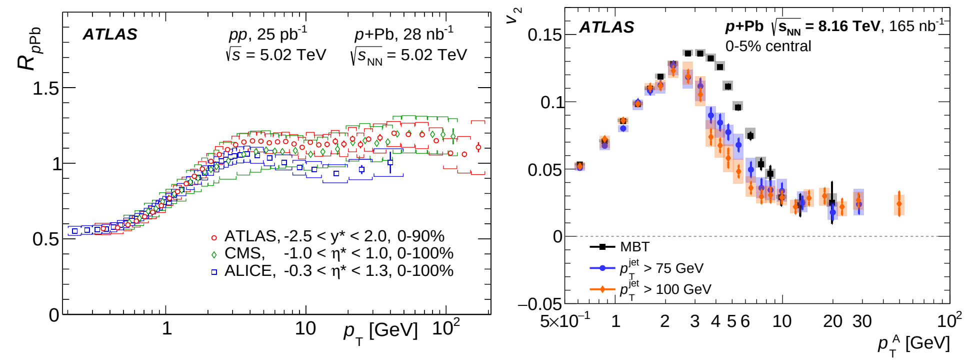
(a) [Bossi et al. JHEP(2024)] (b)

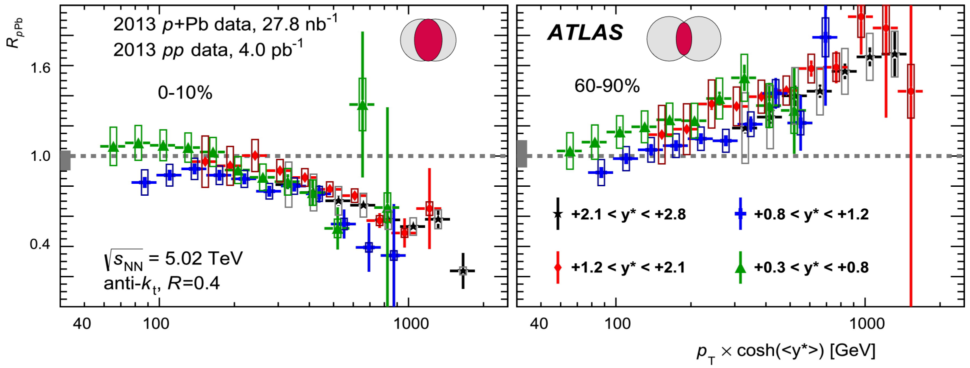
Small Systems

Small Systems: v_2 vs R_{AA}

[ATLAS JHEP. 07, 074 (2023)]
[CMS JHEP. 04, 039 (2017)]
[ALICE JHEP. 11, 013 (2018)]

- High-p_T v_2 in pp and pPb
- Centrality Dependence R_{pPb}
  - » Initial State Correlations?
  - » Initial State Energy loss?
- Exciting Lab For Hard/Soft Correlations





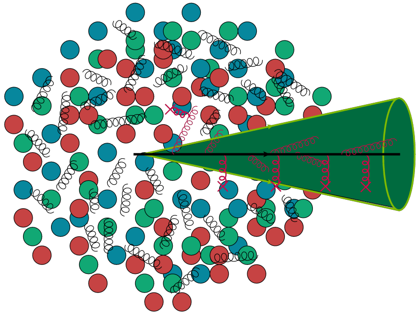
[ATLAS Phys. Lett. B. 748, 392–413 (2015)]

Jet No Longer A Perturbation

- Jets No Longer A Perturbation On Top Of Bulk
  - » Jet Carry Substantial Amount Of Energy
  - » Jet Modifies The Bulk
  - » Bulk Extent is Small $\Rightarrow$ Finite Size Effects Important
  - » Energy Loss Negligible?
  - » Vacuum-like Physics Important: Higher-Twist, GLV...

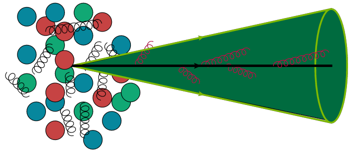
Heavy-Ion

$$f(p) = f^{QGP}(p) + \delta f^{jet}(p)$$



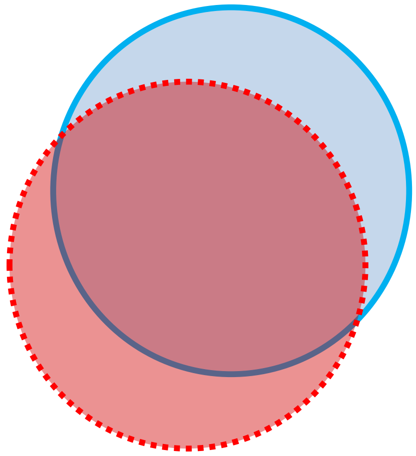
Small Systems

$$f(p) = f^{jet}(p) + \delta f^{Bulk}(p)$$



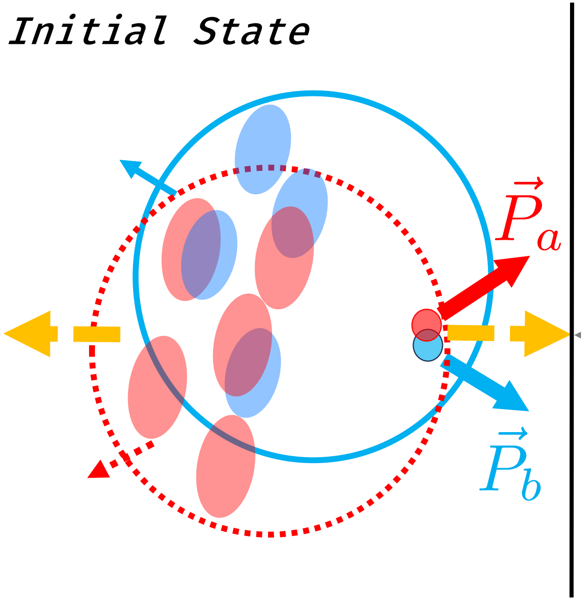
Transverse Correlation

Initial State

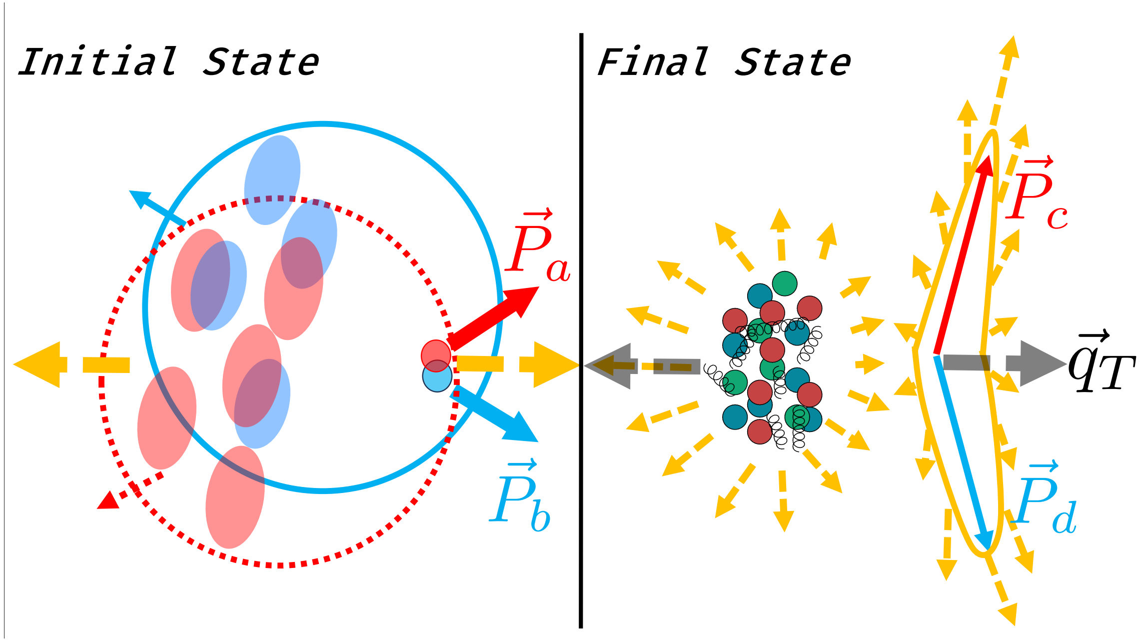


Transverse Correlation

Initial State



Transverse Correlation

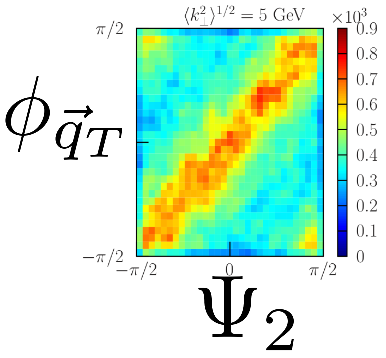


- Balanced Transverse Momentum $\vec{q}_T = \vec{p}_{aT} + \vec{p}_{bT}$ b/w Hard/Soft Particles

Transverse Correlation

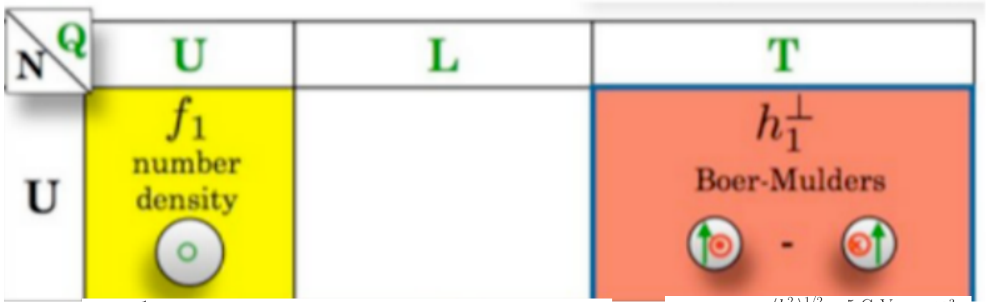
Transverse Correlation

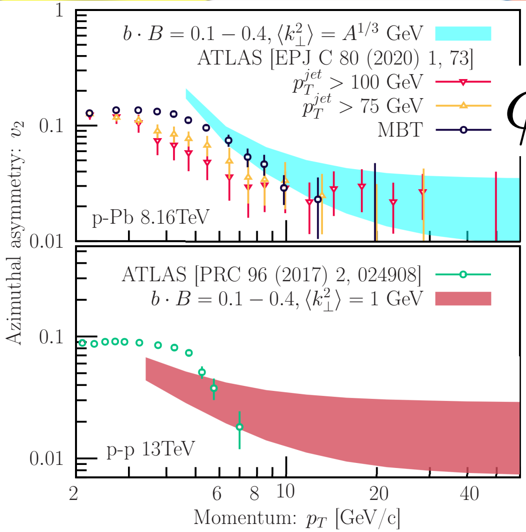
- Conservation Of Momentum $\Rightarrow$ Hard/Soft Correlation
  - » Corroborated By Simple PYTHIA simulation

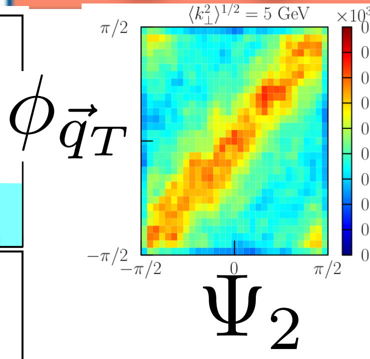


Transverse Correlation

- Conservation Of Momentum ⇒ Hard/Soft Correlation
  - » Corroborated By Simple PYTHIA simulation
- TMD-PDFs and FFs:
  - » Azimuthal Correlations Due Initial k_T
  - » Boer-Mulders'/Collins Effects

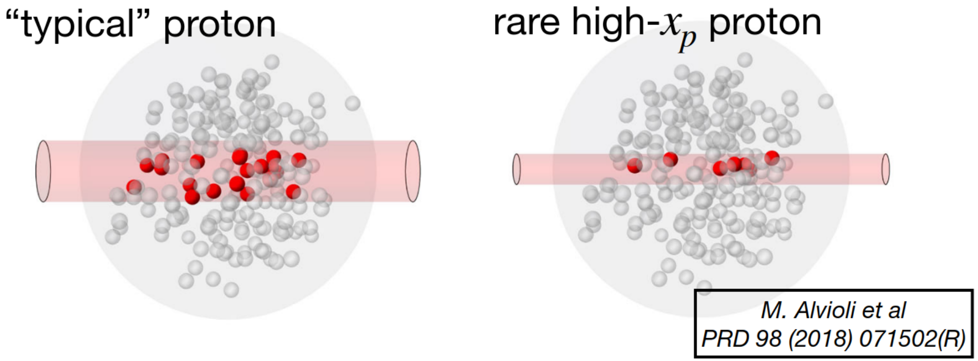


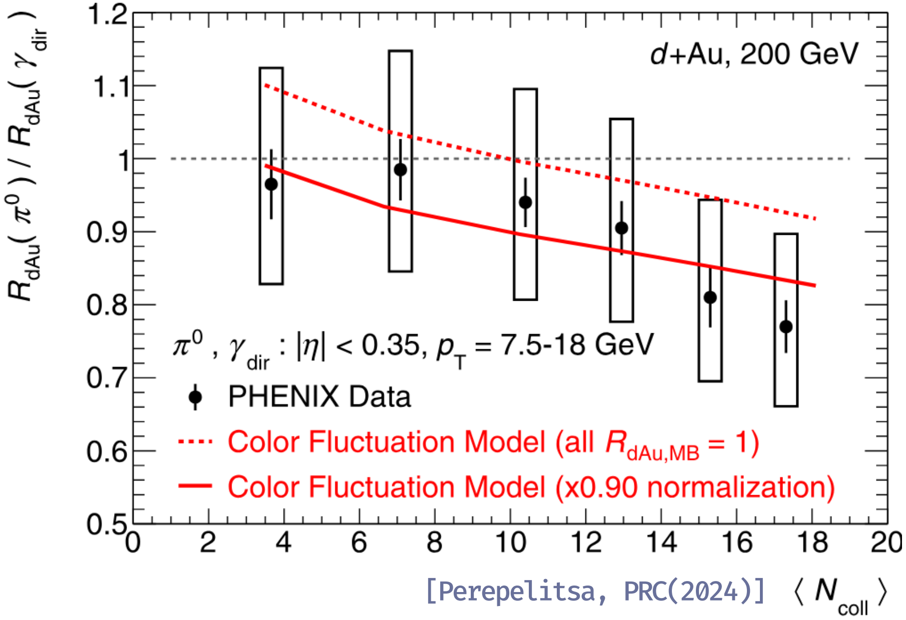




[IS, Majumder, PLB(2024)]
[IS, Majumder, PRC(2025)]

Bjorken-x



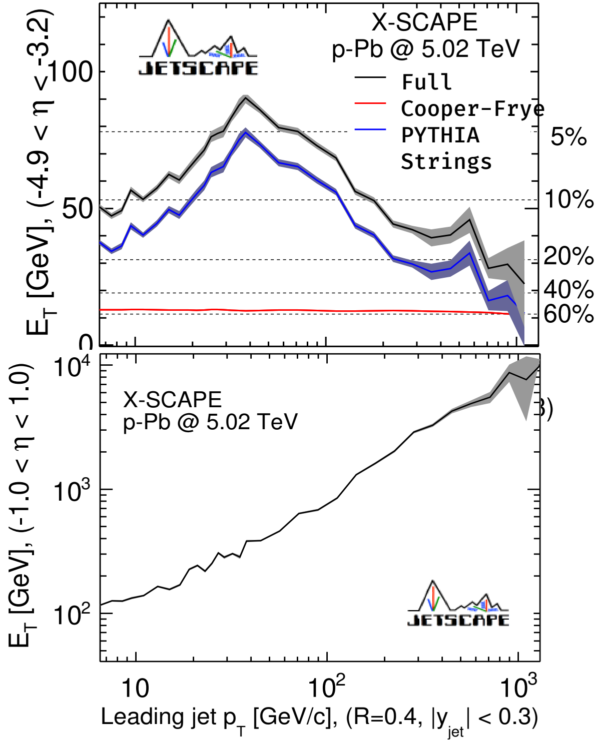


[Perepelitsa, PRC(2024)]

- Presence of Hard Partons ⇒ Significant Difference Bjorken-x Distribution Than Average Protons

Energy Conservation

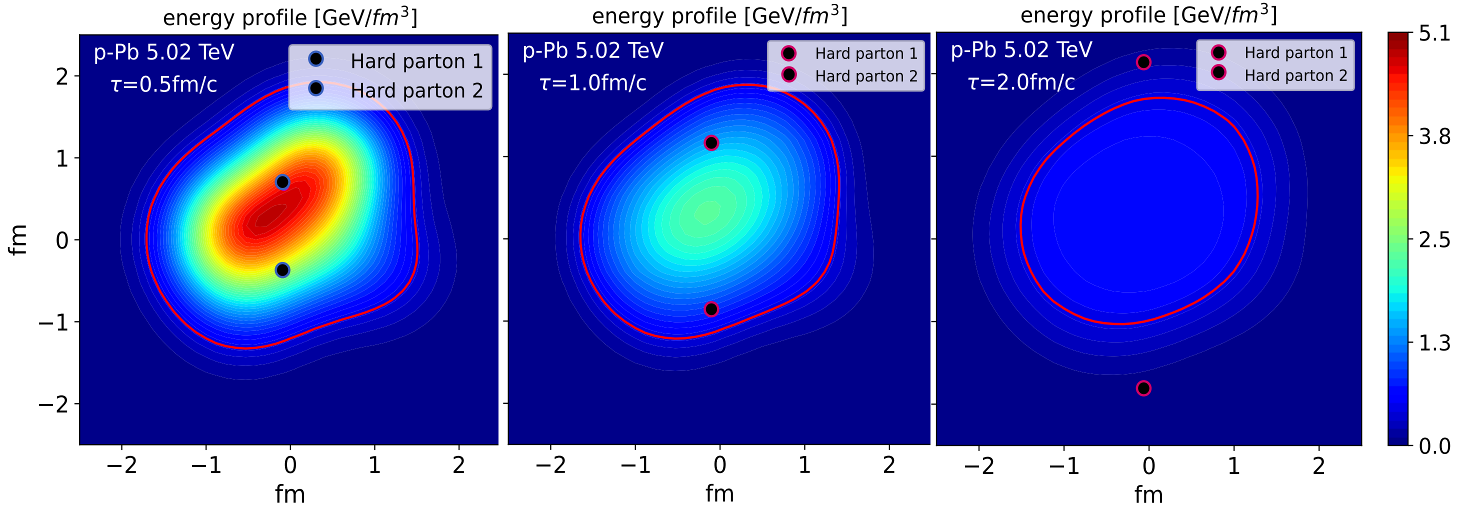
- Multi-stage Framework For Small Systems
  - » Correlations b/w Soft/Hard Particle Production
  - » Competition b/w Jet p_T and Partonic remnants
  - » Hard Scattering Increasing E_T until Momentum Conservation Limits

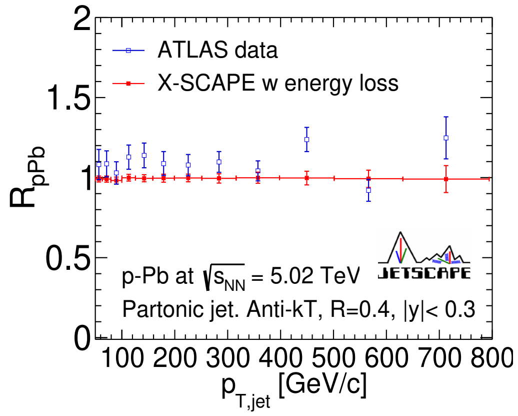


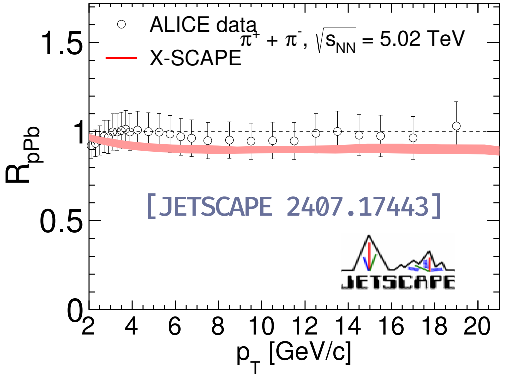
[JETSCAPE 2407.17443]

Energy Loss?

- Short Bulk Extent
  - » Energy Loss Negligible
  - » Finite Size Effect/Vacuum-like Physics More Important

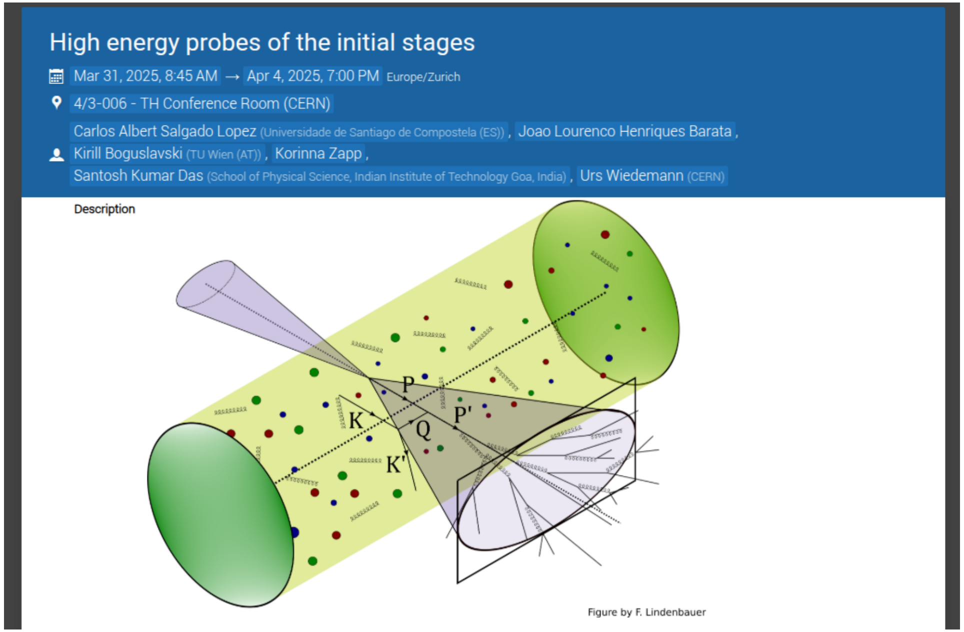






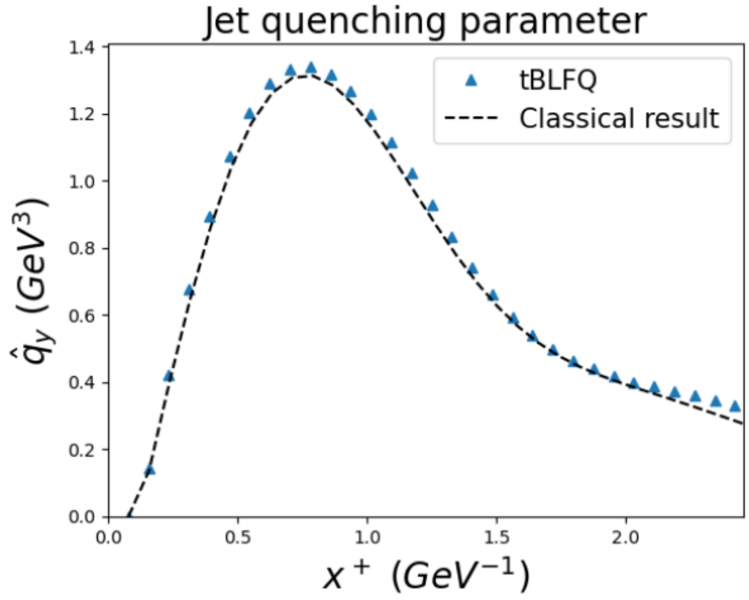
Initial Stages

- [High Energy Probes of the Initial Stages]



Early Stages

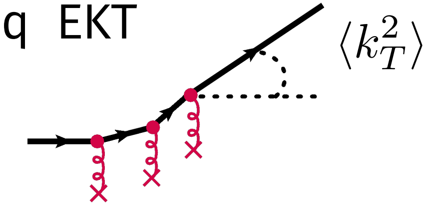
- Broadening In Glasma

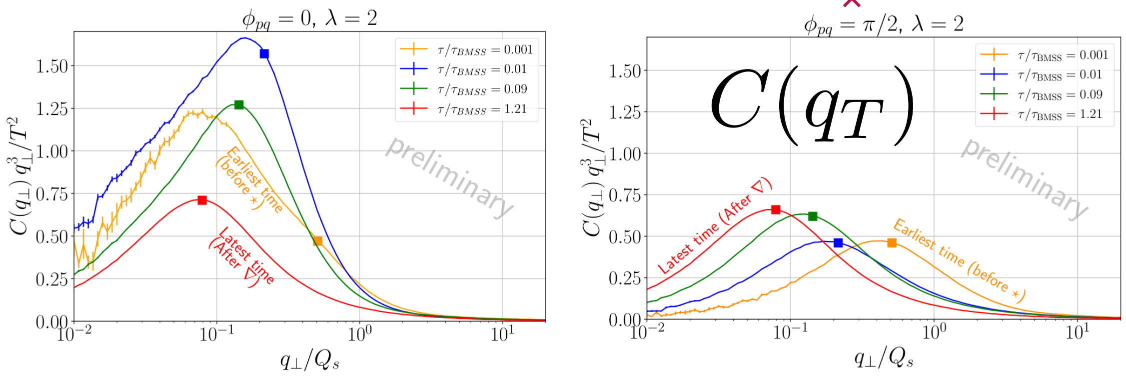


C. Lamas Mon. 17:40

- Broadening In Non-Eq EKT

$C(q_\perp) \simeq \Gamma(t)$

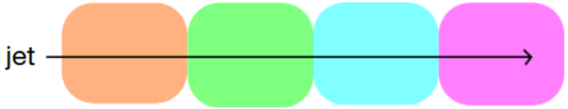




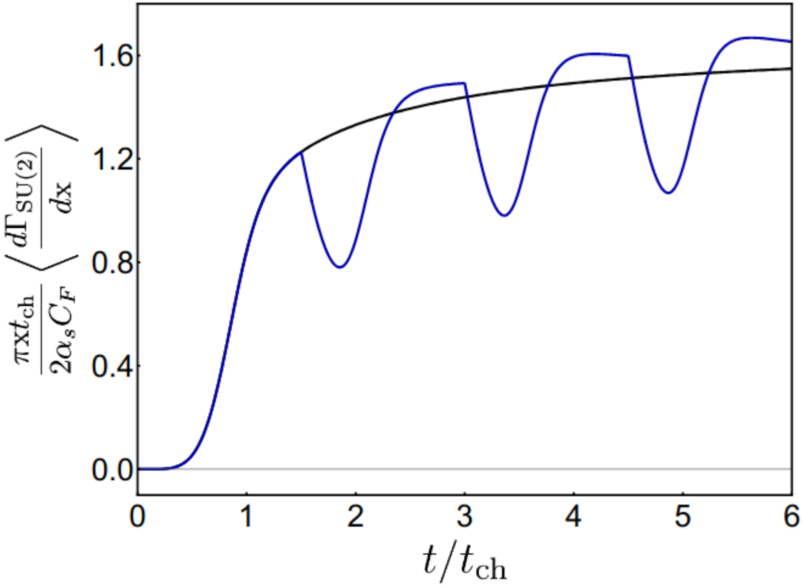
[Boguslavski et al. PLB (2024) PRD (2024)]

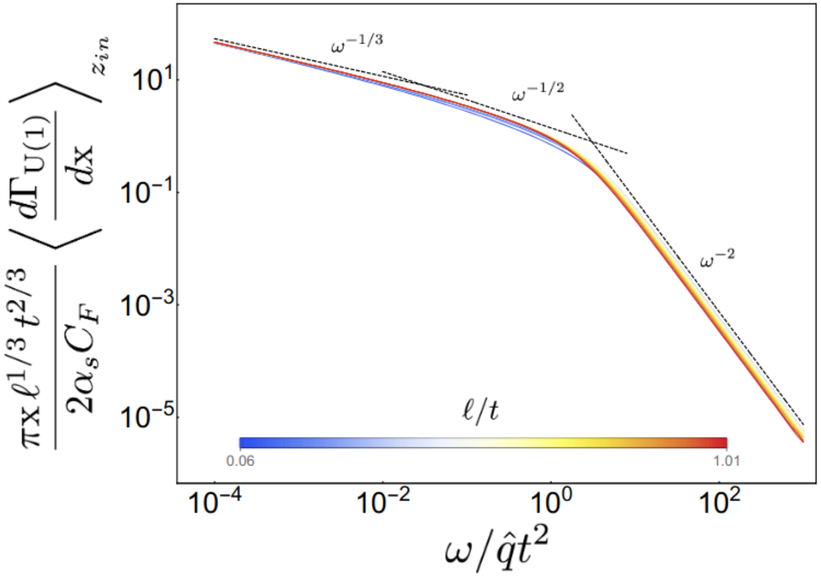
F. Lindenbauer Mon. 17:55

Early Stages



- Radiation in Gluon Flux Tubes





[Barata, Hauksson, Lopez, Sadofyev 2406.07615]

Conclusion

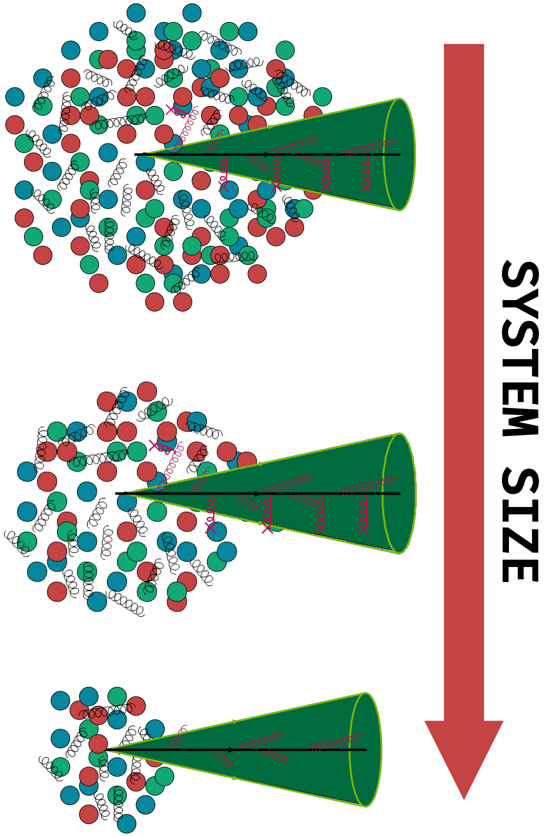
Contrast b/w Heavy Ion & Small Systems:

- Heavy-Ion ⇒ Jet Perturbation On Top Of The QGP
- Small Systems ⇒ Bulk Dynamics Influenced By presence of Jets

» Medium Response ⇒ Understand Equilibration Of Jets

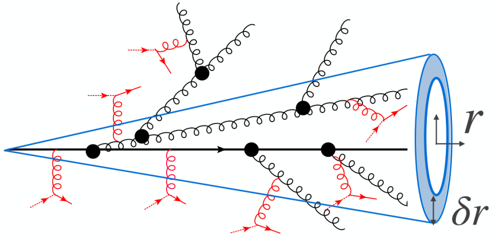
» Small Systems ⇒ A Laboratory to Understand Int. St. Correlations? Int. St. Energy Loss?

W. Ke Tue. 17:50

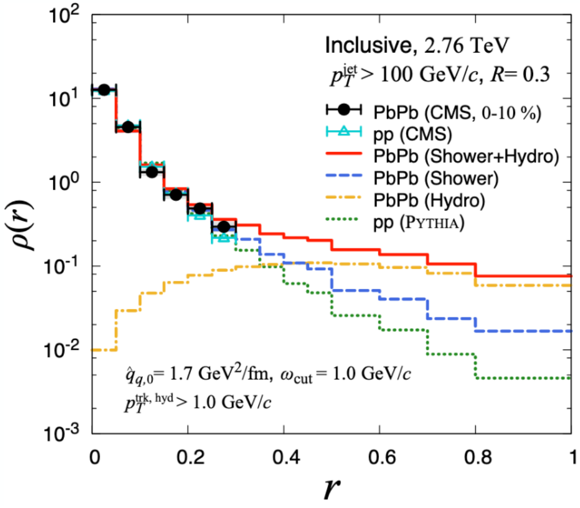


Backup

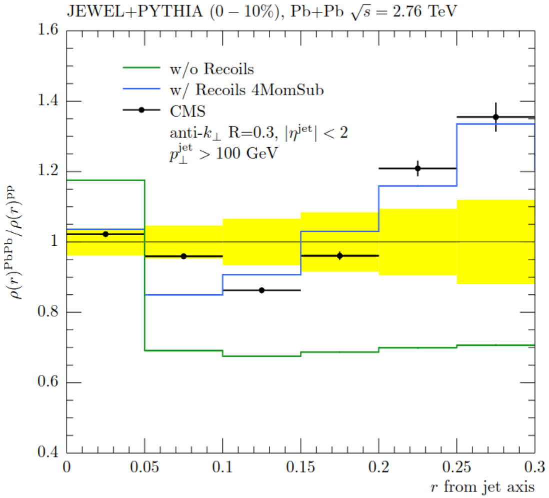
Medium Response



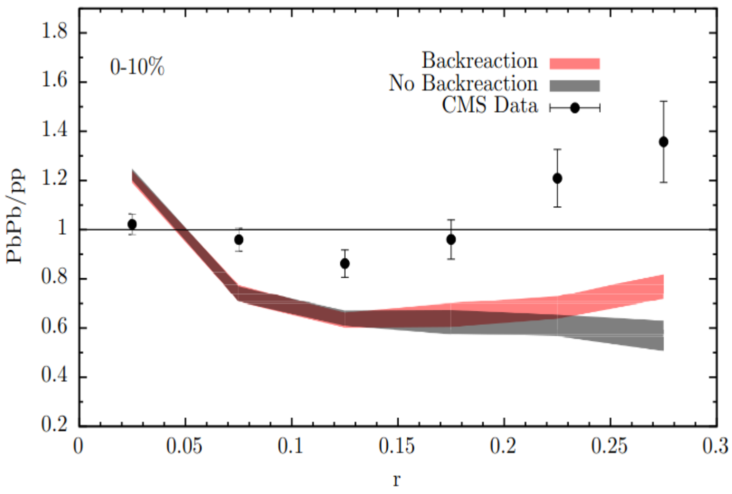
- Large Angle Enhancement Jet Shape



[Tachibana, Chang, Qin, PRC(2017)]



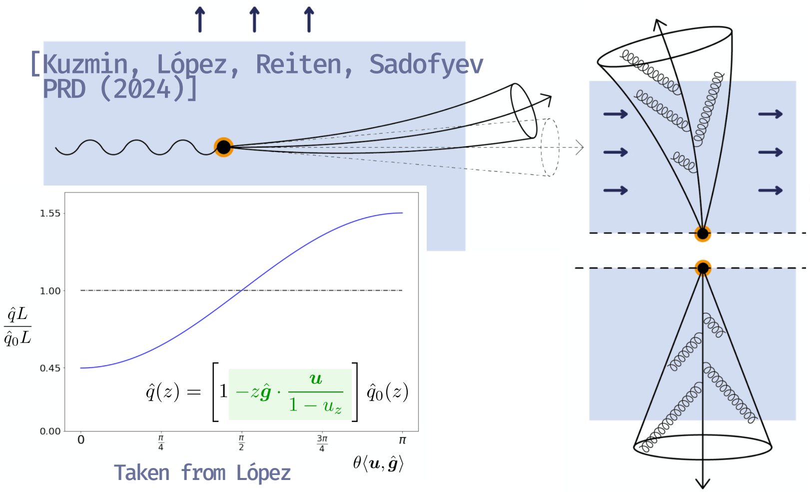
[Elayavalli, Zapp, JHEP(2017)]



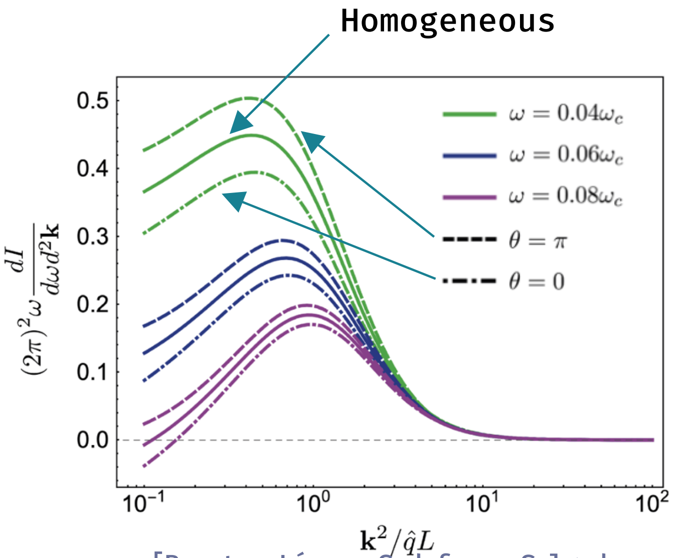
[Casalderrey-Solana, Gulhan, Pablos, Rajagopal, JHEP(2017)]

Gradient effects

Broadening



Radiation



[Barata, López, Sadofyev, Salgado
PRD (2023)]

» Suppressed Brodening/Radiation Along Gradient

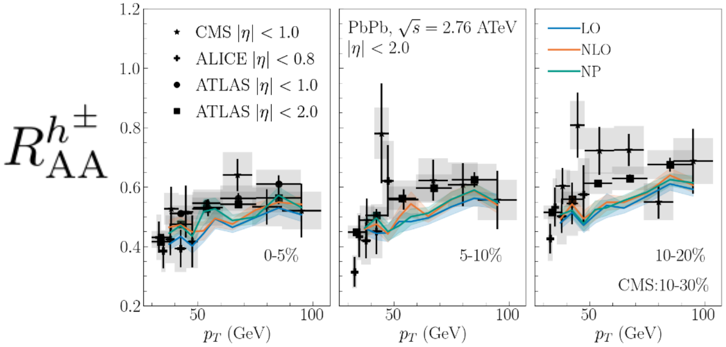
» Enhanced Broadening/Radiation Opposite To Gradient

Formation Time

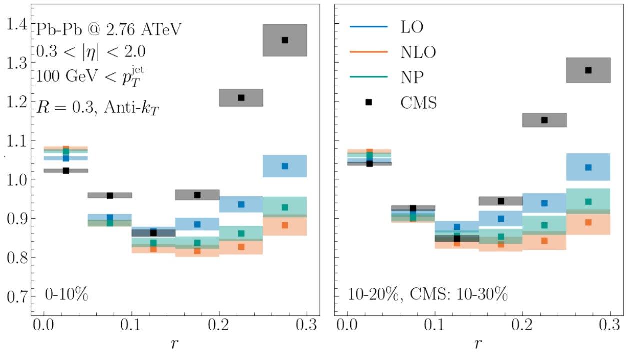
» Formation Time ⇒ Simultaneous Desc. Charged Hadron And Jet R_{AA}

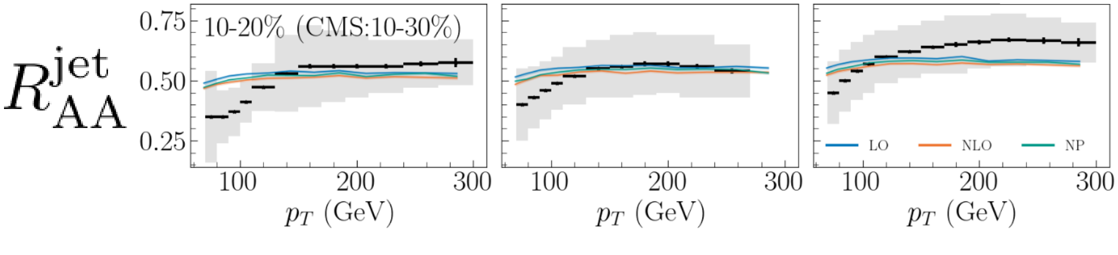
» Limitation: Jet Substructure Observables

» LO/NLO/NP Potential ⇒ Similar Ratios, ≠ Substructure



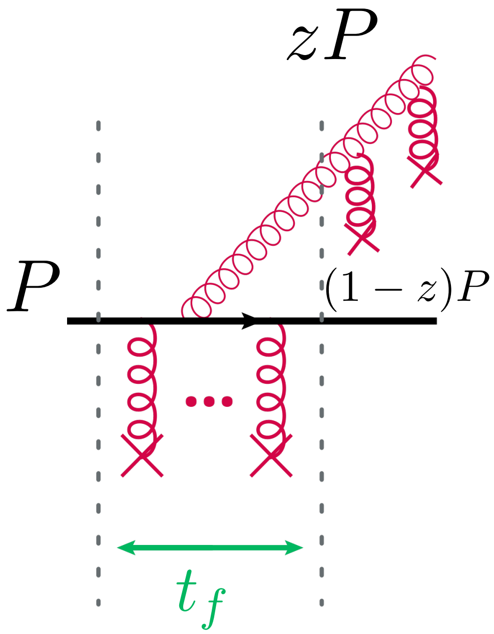
$$R^{\rho}_{\rm AA} = \frac{\rho_{\rm AA}(r)}{\rho_{\rm pp}(r)}$$





[Modarresi-Yazdi, Shi, Gale, Jeon ArXiv:2407.19966]

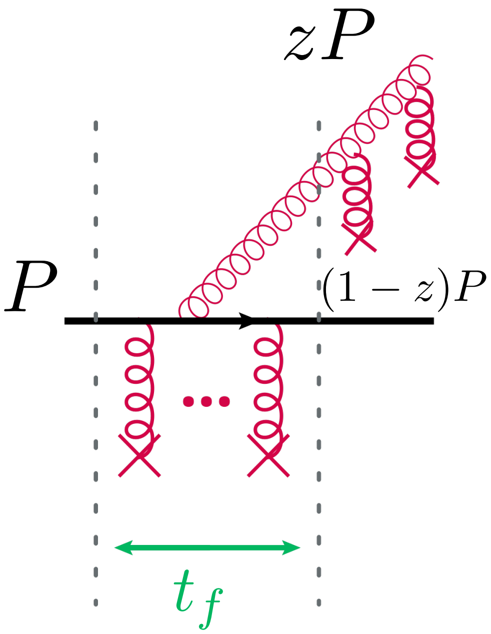
Medium-Induced Radiation



- Multiple Scattering $\Rightarrow$ Induce Radiation
- Interplay form-time $\Longleftrightarrow$ λ_{mfp}

$$\boldsymbol{t_{form}} \sim \frac{z(1-z)P}{k_T^2}\ , \quad \langle k_T^2 \rangle \simeq \hat{q}\, t_{form} \quad \Rightarrow \quad \boldsymbol{t_{form}} \sim \sqrt{\frac{z(1-z)P}{\hat{q}}}$$

Medium-Induced Radiation



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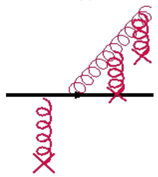
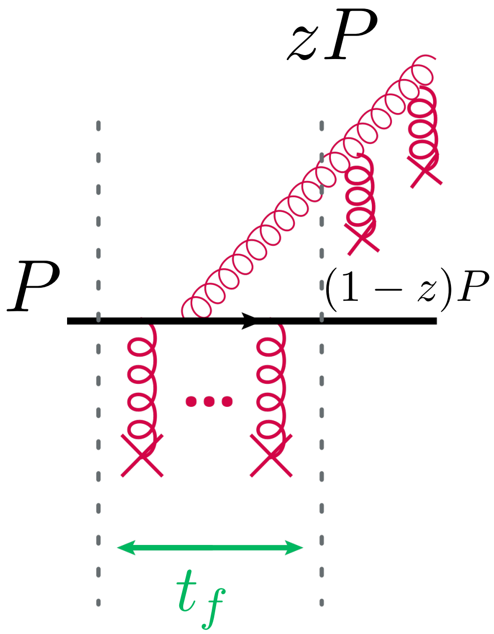
» $\boldsymbol{t_{form}} \ll \lambda_{mfp}$: Finite Number Of Scatterings



Medium-Induced Radiation



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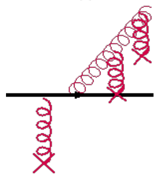
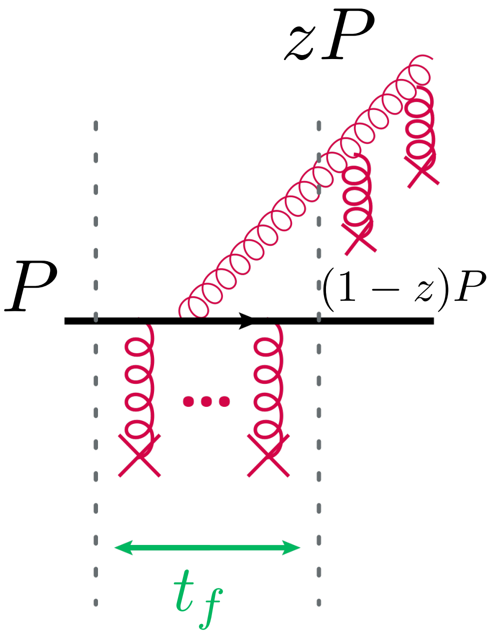


» $\boldsymbol{t_{form}} \ll \lambda_{mfp}$: Finite Number Of Scatterings

» $\boldsymbol{t_{form}} \gg \lambda_{mfp}$: Interference b/w Multiple Scatterings

Medium-Induced Radiation



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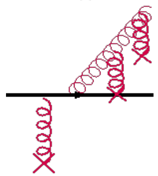

» $\boldsymbol{t_{form}} \ll \lambda_{mfp}$: Finite Number Of Scatterings

» $\boldsymbol{t_{form}} \gg \lambda_{mfp}$: Interference b/w Multiple Scatterings

- Interference Effects $\Rightarrow$ LPM Suppression for $zP \gg T$

Acknowledgment

Thanks to Kari Eskola, Abhijit Majumder, Harri Niemi, Chun Shen, Wenbin Zhao and the JYU physics department for fruitful discussions and valuable input.

UNIVERSITY OF JYVÄSKYLÄ

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