The theory of jet modification and energy loss in the quark-gluon plasma

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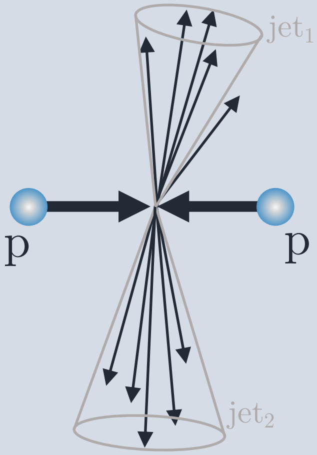
Introduction: why jets?

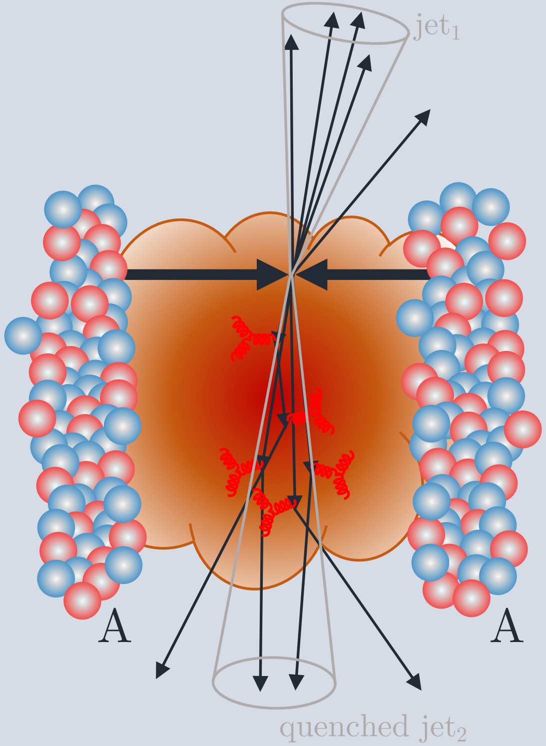
Jets until 2010s

- "Jet = hard parton"
- Measured in pp and AA

  → jets lose energy in QGP
- Jet quenching models:
  - scatterings ↔ energy loss
  - path length dependence
- Extracting QGP properties

  → jet tomography





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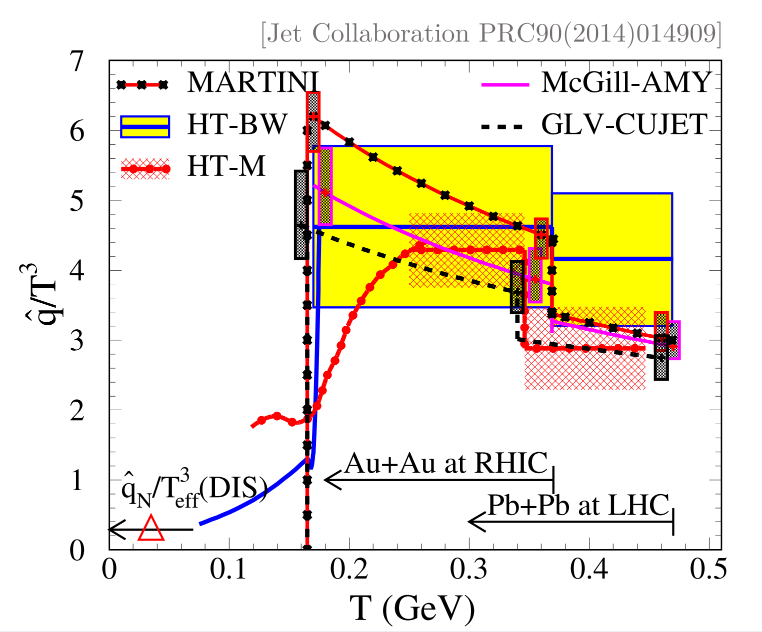


Small system collectivity

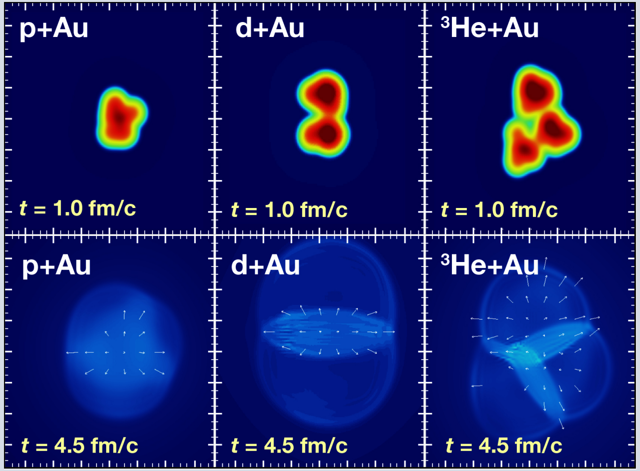
[review 2407.07484]
Raimond Snellings' plenary

- **flow**-like signals in: pA, pp, γA, jets
- **strangeness enhancement** in: pA, pp
- thermalization in small systems?

  microscopic interactions → macroscopic fields
- **no jet quenching** is observed

  More precision is needed!

hydro droplet seems to work!



[PHENIX: Nature Physics 15 (2019) 214]

Precision with jets

Precision with jets

- Separation of scales:

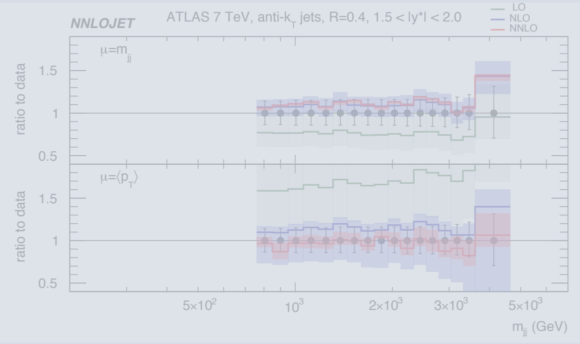
$$Q_{hard} > Q_{jet} \gg \Lambda_{QCD}$$

(~ TeV ~ $10^{1\text{-}3}$ GeV ~ 1 GeV)

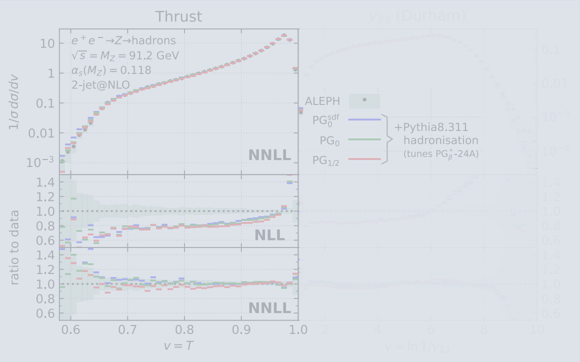
- Jet observables = scattering amplitudes

$$\frac{d\sigma}{d\mathcal{O}} = \int d\Phi_n \left|\mathcal{M}_{pp\to n}\right|^2 \delta\left(\mathcal{O} - \hat{\mathcal{O}}(p_1, \ldots, p_n)\right)$$

  - fixed order: NLO → N²LO → N³LO ~10% accurate
    (distribution of jets)
  - resummation: LL → NLL → N²LL ~10% accurate
    (substructure of jets)
  - matching, power corrections
    (event generation)



[NNLOJET 1807.06057]



[PanScales: 2406.02661]

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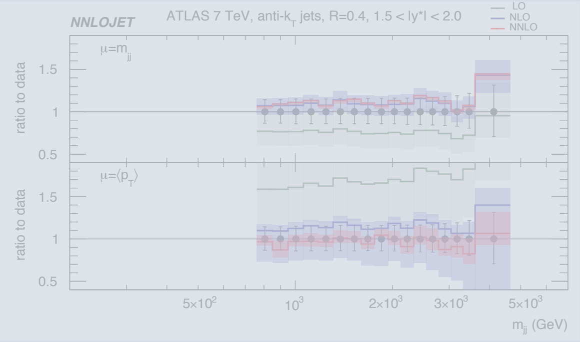

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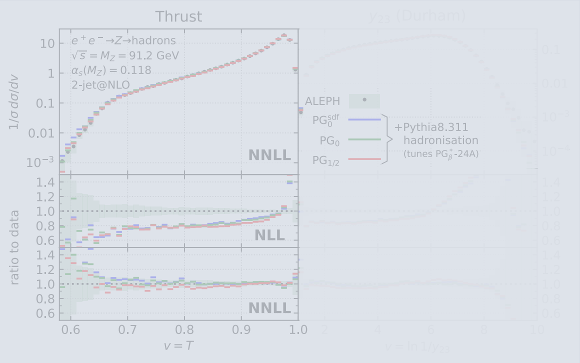

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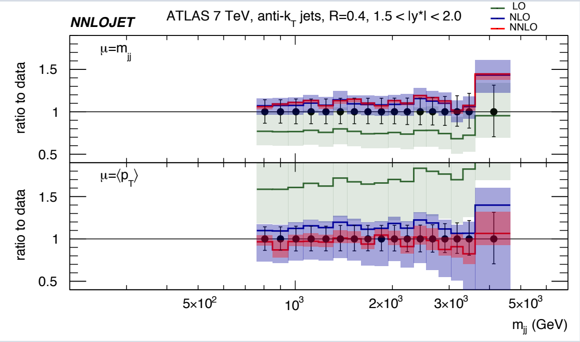

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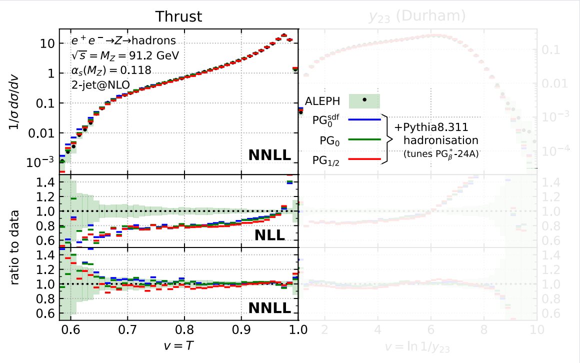

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Precision jet quenching

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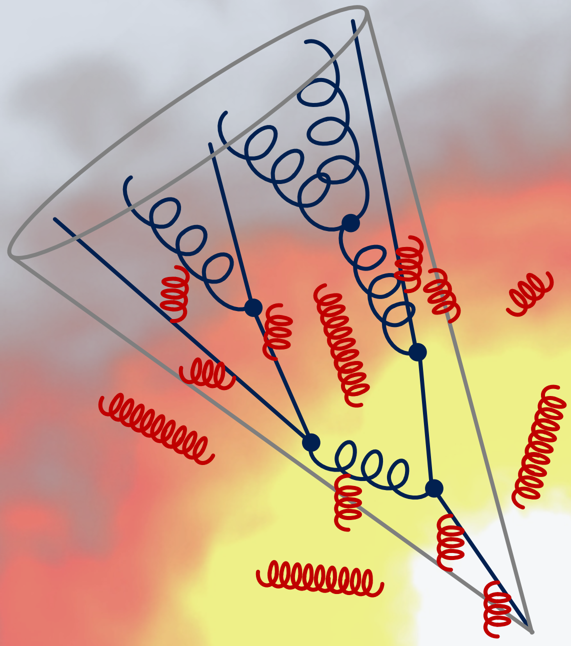
  - fixed order, resummation
  - Fluctuating paths
  - Medium response



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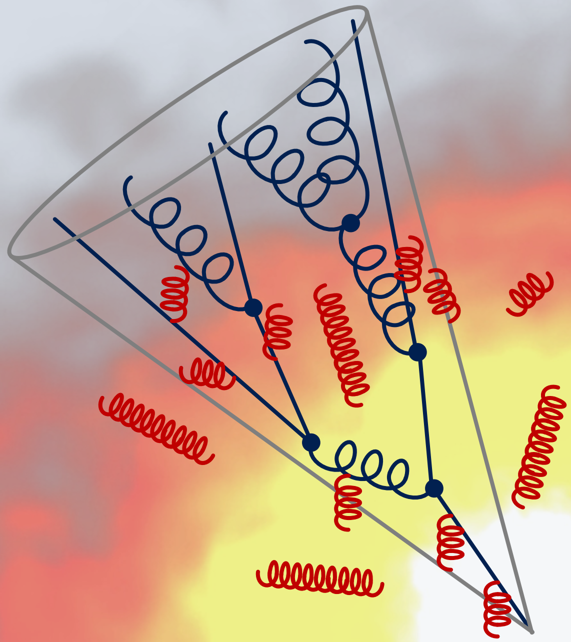
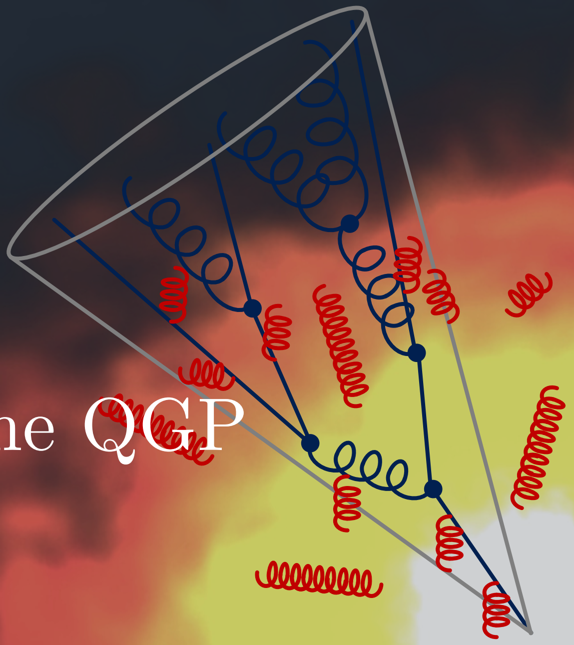


Jet modification in the QGP



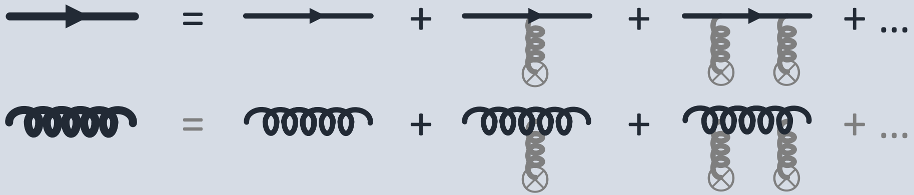
Introduction

- Separate hard and background fields $(q = q_h + q_0,\ A = A_h + A_0)$

$$\mathcal{L}_{QCD}(q, A) = \mathcal{L}(q_h, A_h) + \mathcal{L}(q_0, A_0) + \mathcal{L}_{int}(q_h, A_h, q_0, A_0)$$

$$\approx \mathcal{L}(q_h, A_h) + g\bar{q}_h\langle J\rangle q_h + gA_h\langle J\rangle A_h$$

- Dressed propagators (and vertices):



- Models for the background $\langle J(x^\mu)\rangle$:
    - High-temperature plasma $(T \gg \Lambda_{QCD})$
    - Color charge distribution
    - Non-perturbative "kernel"

← Coming back to this for medium response

Introduction

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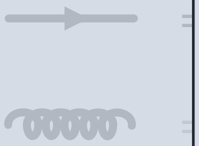

- Models for the backgro

  - High-te
  - Randon
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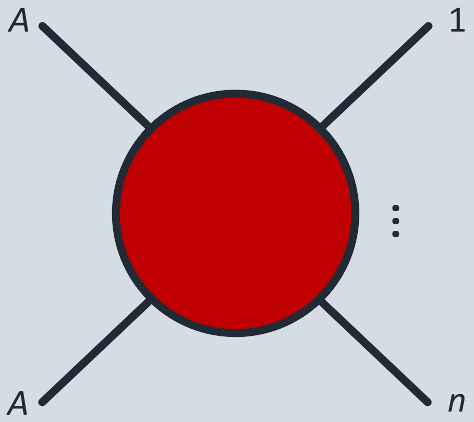
Goal: $\langle 1 \ldots n | AA \rangle$

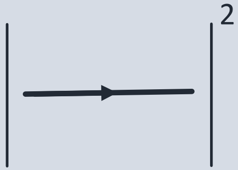


*This talk focuses on $i \to 1,\ldots,n$.

Broadening and decoherence

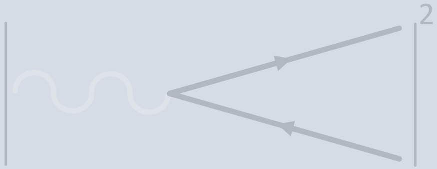
Vacuum

- Fixed path:



$$\approx \delta_{ij}\delta(p' - p)$$

- Color conservation:



Medium

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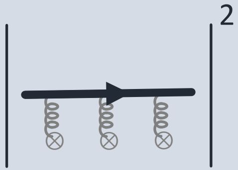
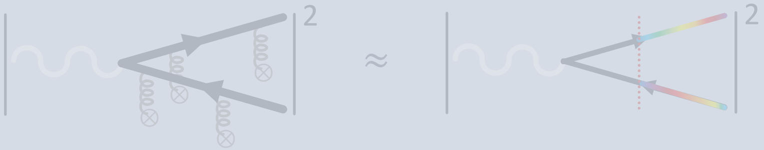


$$\approx \mathcal{G}_{ij}(p', p)$$

changing color and momentum

- Color decoherence:



color decoherence

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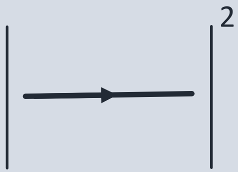

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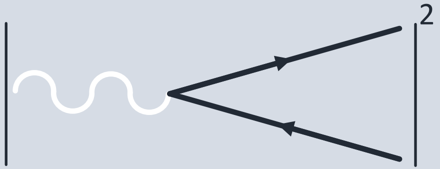

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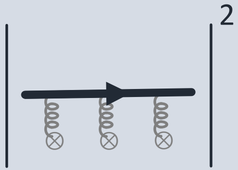

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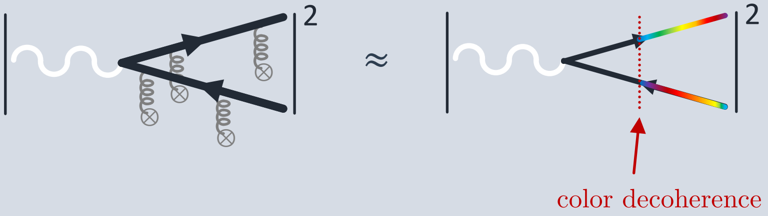
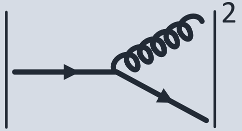


Medium-induced emissions

Vacuum

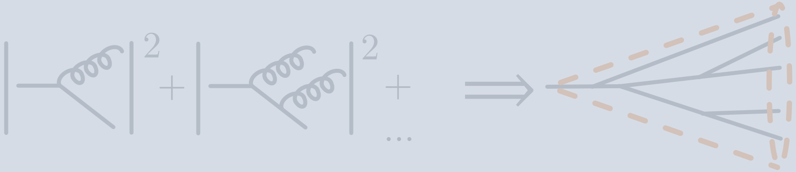
- Emission:



$$\Longrightarrow \quad \frac{dI_i^{vac}}{dz\,d\vartheta} \approx \frac{\alpha_s}{\pi}\frac{2C_i}{z}\frac{1}{\vartheta}$$

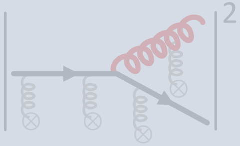
soft & collinear poles!

- Resumming emissions: collinear jet



Medium

- Vacuum + medium-induced emissions:



$$\Longrightarrow \quad \frac{dI_i^{med}}{dz} \approx \frac{\alpha_s}{\pi}\sqrt{\frac{Q_{med}}{E}}\frac{C_i}{\sqrt{z^3}}$$

$m < Q_{med}$

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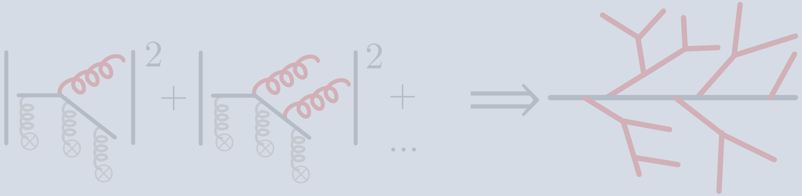
- Wide-angle medium-induced cascade:



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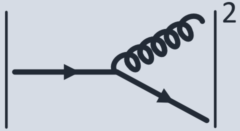

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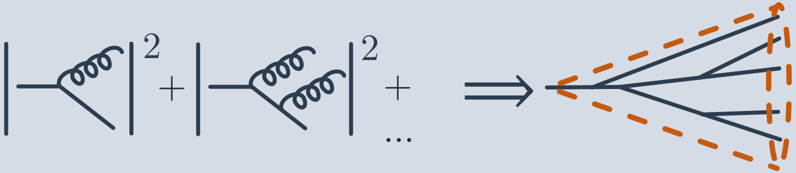

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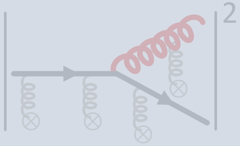

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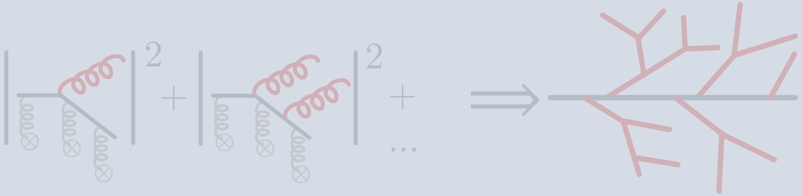

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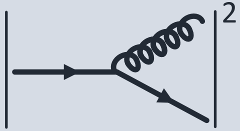

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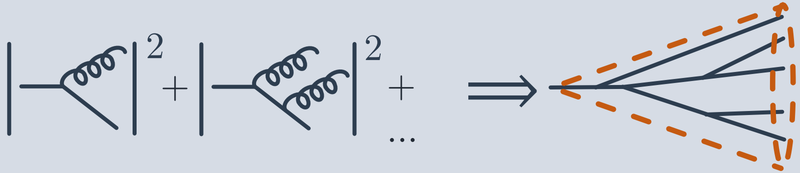

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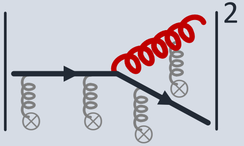

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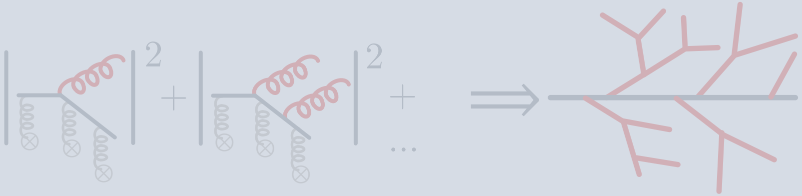

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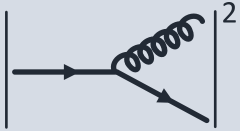

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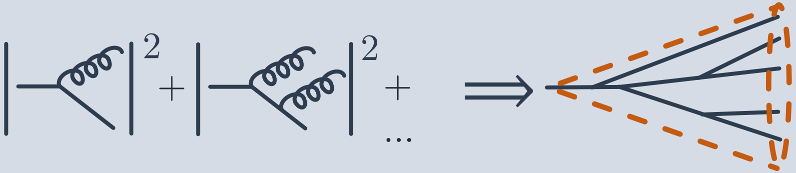

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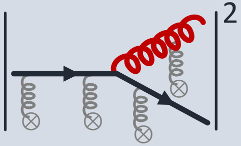

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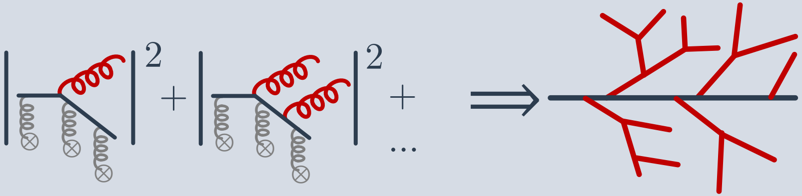

Jet evolution in QGP

[Mehtar-Tani, Tywoniuk, Salgado]
[Caucal, Iancu, Mueller, Soyez]

Factorized picture:

1. High virtuality:

   vacuum evolution → no modification*

2. Virtuality $\sim Q_{med}$:

   medium-induced cascade → energy loss

3. Out of medium:

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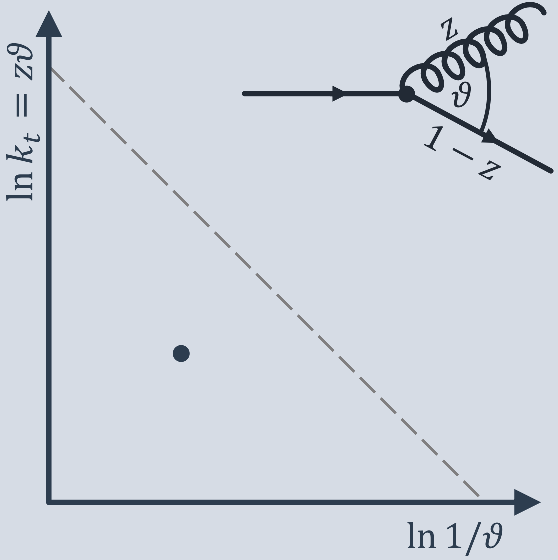

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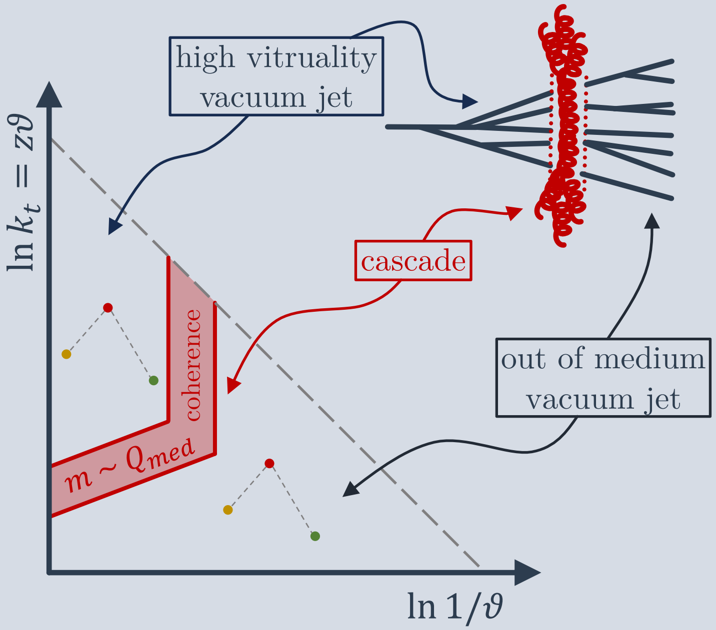

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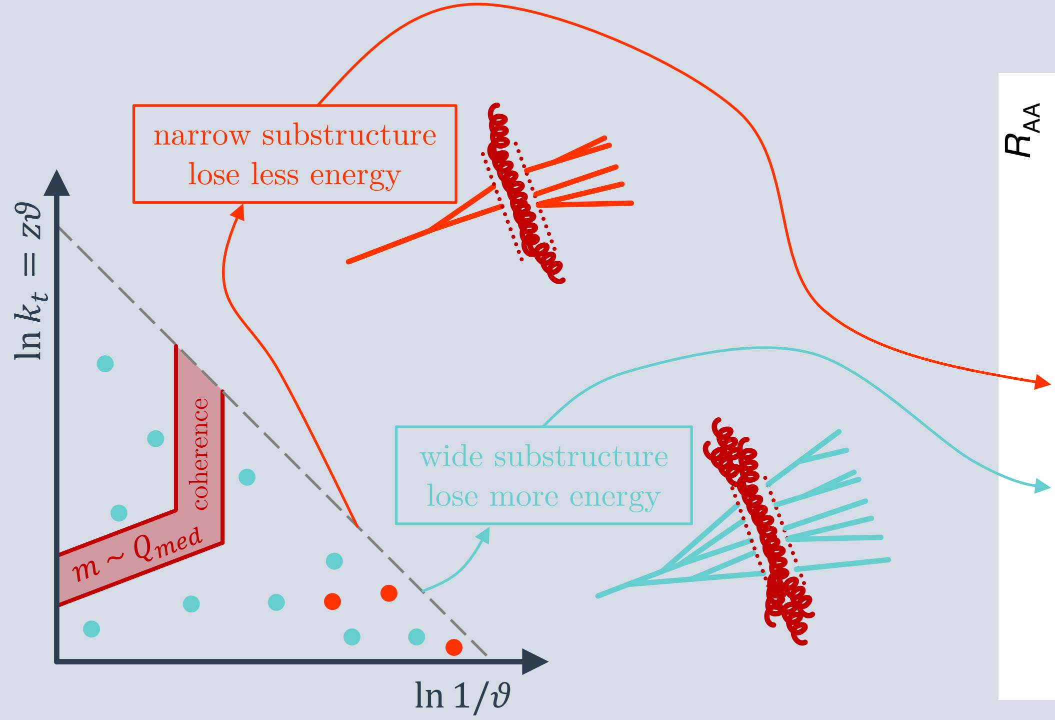
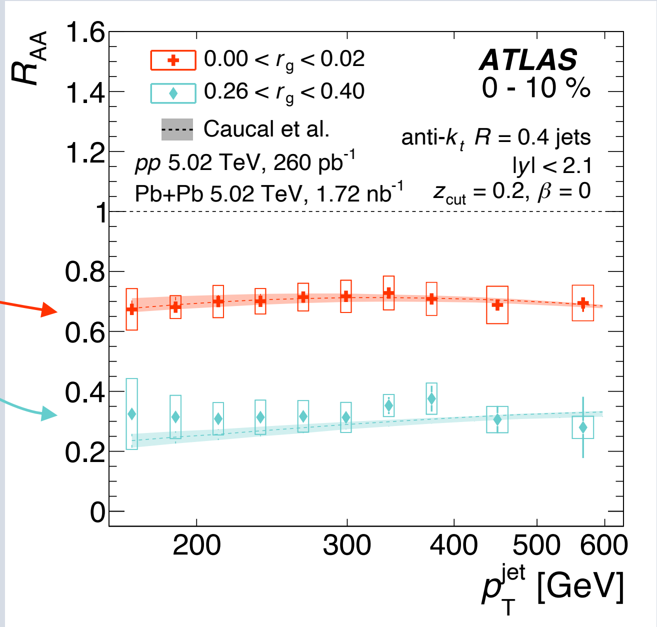
Experimental test of the factorized picture

Experimental tests

for more details, see
[Caucal, Soto-Ontoso, AT, PRD105(2022)114046]
[AT in PRD110(2024)014015]

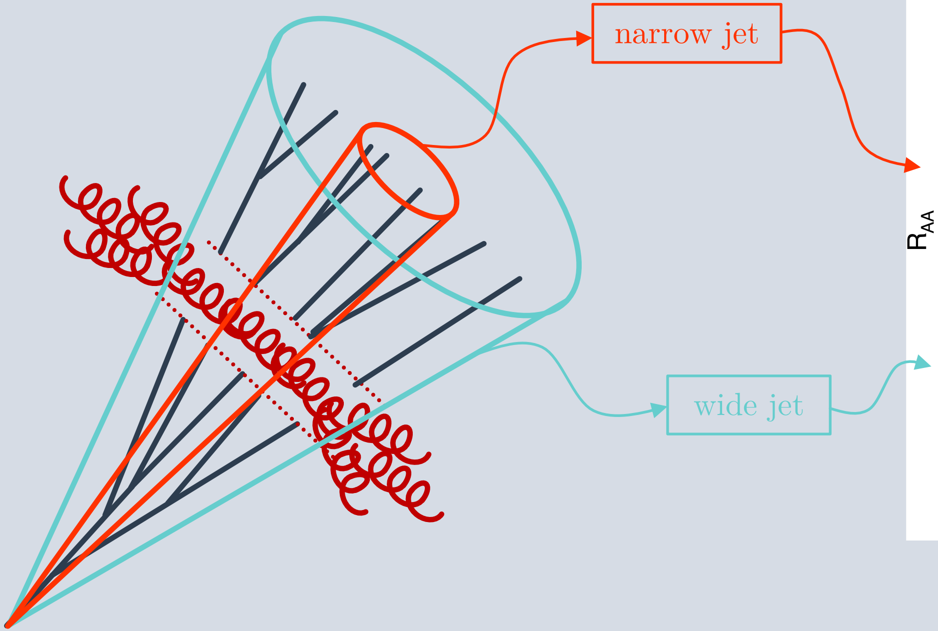


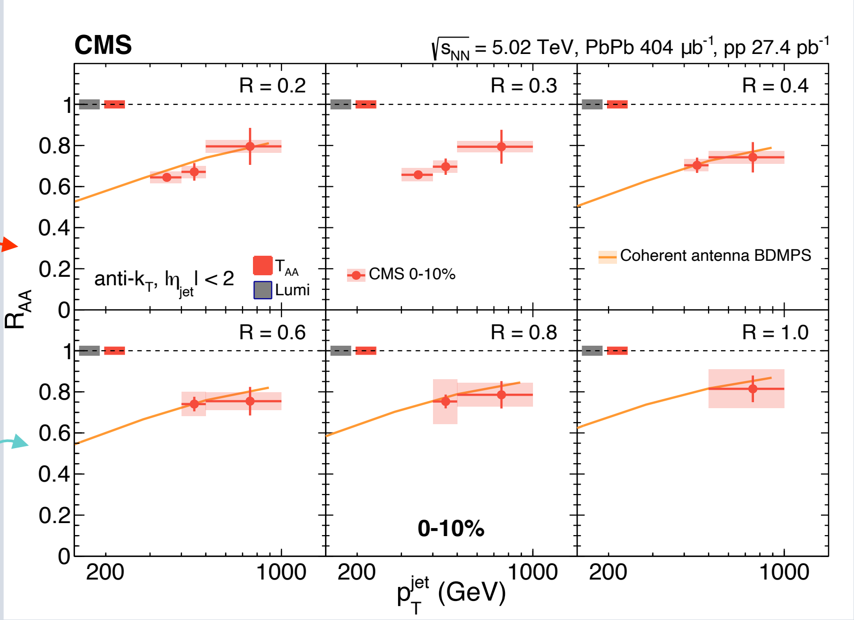


[ATLAS PRC107(2023)054909]

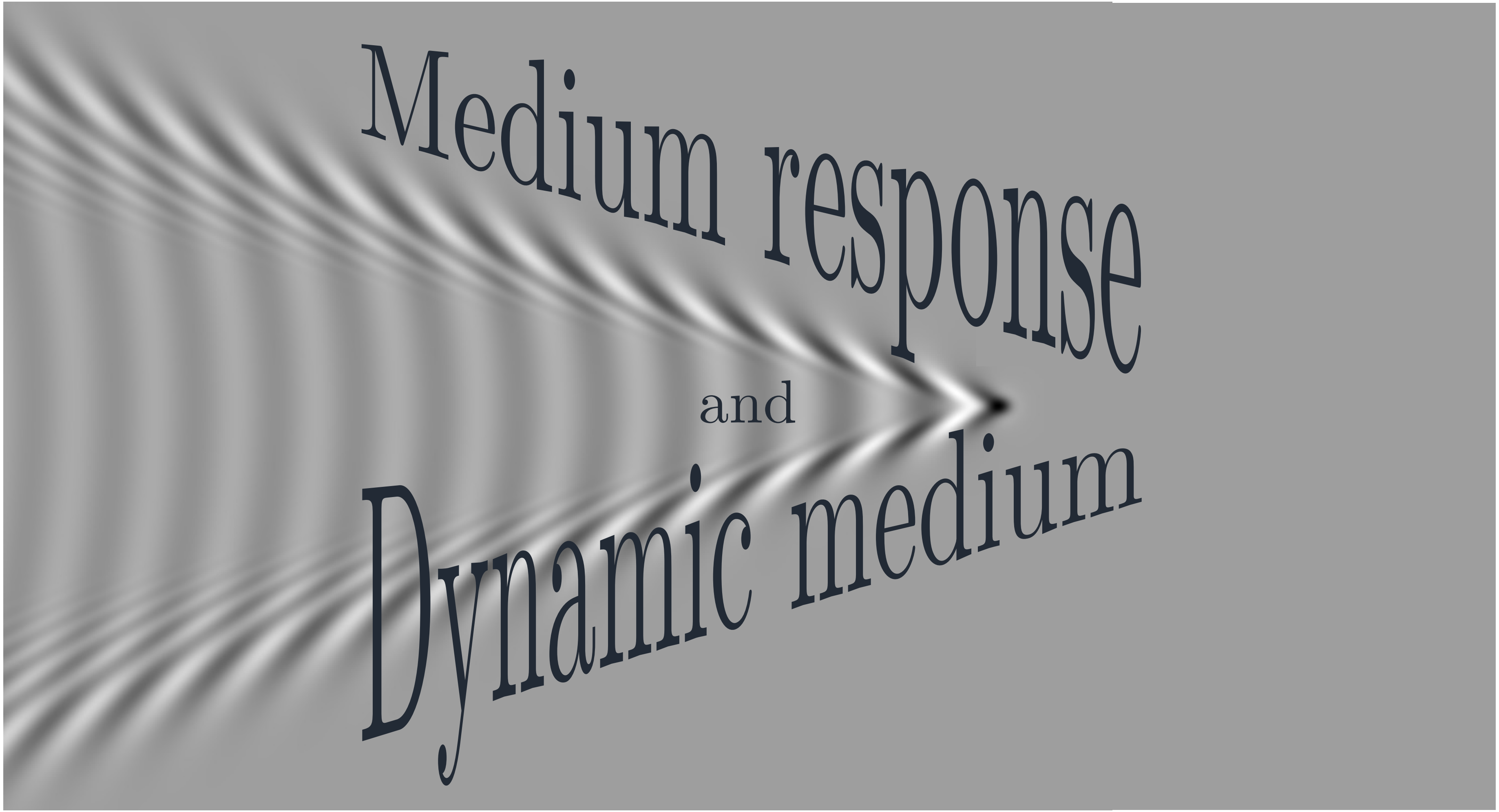
Experimental tests

[Mehtar-Tani, Pablos, Tywoniuk PRL127(2021)25]
[AT, Tywoniuk JHEP10(2021)038]
[CMS JHEP05(2021)284]



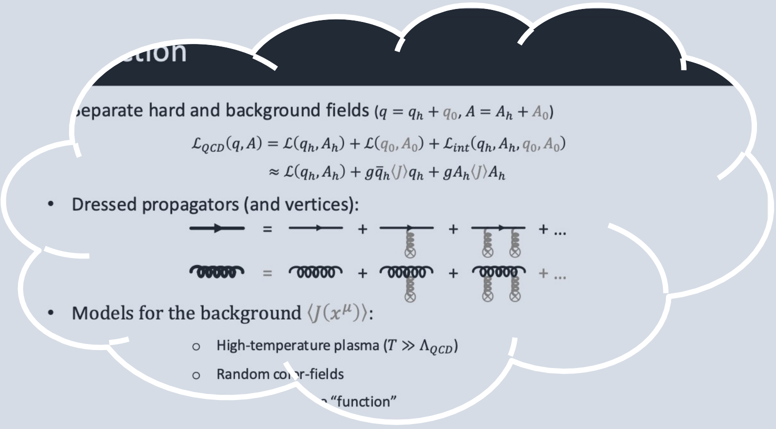


recovering lost energy ⚖ more eloss sources


Medium response
and
Dynamic medium

Dynamic medium and medium response

reminder from previous



1. solve for $q_0(t, \vec{x})$ and $A_0(t, \vec{x})$
   - high temperature, near equilibrium

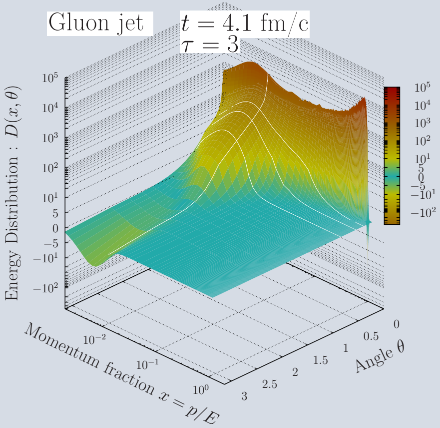
     (kinetic theory & Boltzmann equation)
   - high occupancy, far from equilibrium

     (classical statistical lattice, 2PI, CGC)
   - independent color charges + hydro
2. calculate $\langle J(t, \vec{x})\rangle$
3. evaluate $\langle|\mathcal{M}_{AA\to n}|^2\rangle_{med}$ for every path

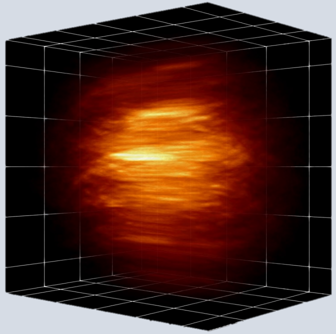
Dynamic medium and medium response

Talks by Markus Leuthner and Kayran Schmidt

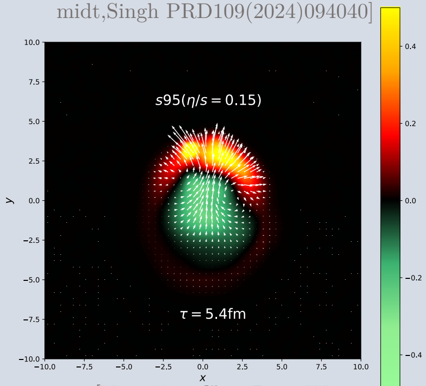
1. solve for $q_0(t,\vec{x})$ and $A_0(t,\vec{x})$
   - high temperature, near equilibrium (kinetic theory & Boltzmann equation)
   - high occupancy, far from equilibrium (classical statistical lattice, 2PI, CGC)
   - independent color charges + hydro
2. calculate $\langle J(t,\vec{x})\rangle$
3. evaluate $\langle|\mathcal{M}_{AA\to n}|^2\rangle_{med}$ for every path



[Mehtar-Tani,Schlichting, Soudi JHEP05(2023)091]



[Ipp,Leuthner,Muller,Schlichting,Schmidt,Singh PRD109(2024)094040]



[Yang,Luo,Chen,Pang,Wang PRL130(2023)052301]

Dynamic medium and medium response

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   - high temperature, near equilibrium
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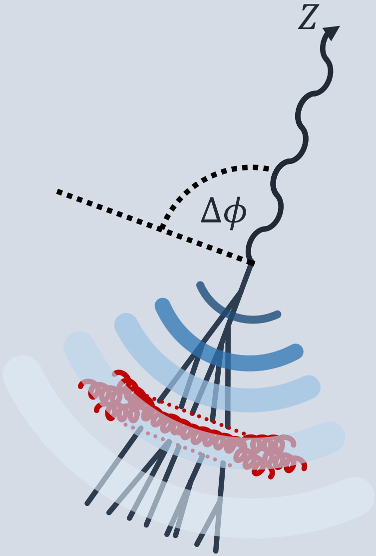

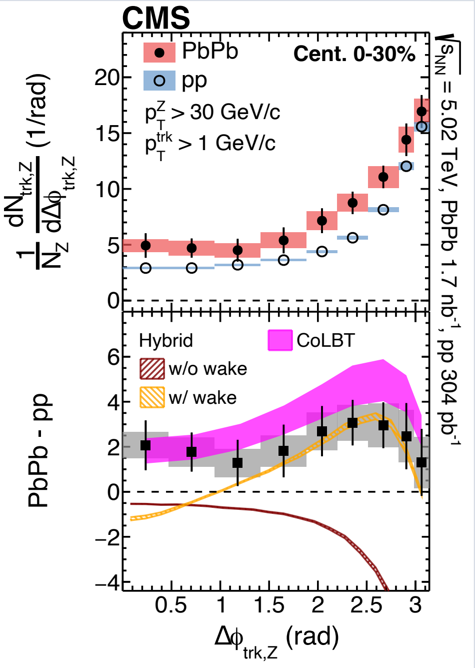

[CMS, PRL128(2022)122301]

Dynamic medium and medium response

1. solve for $q_0(t,\vec{x})$ and $A_0(t,\vec{x})$
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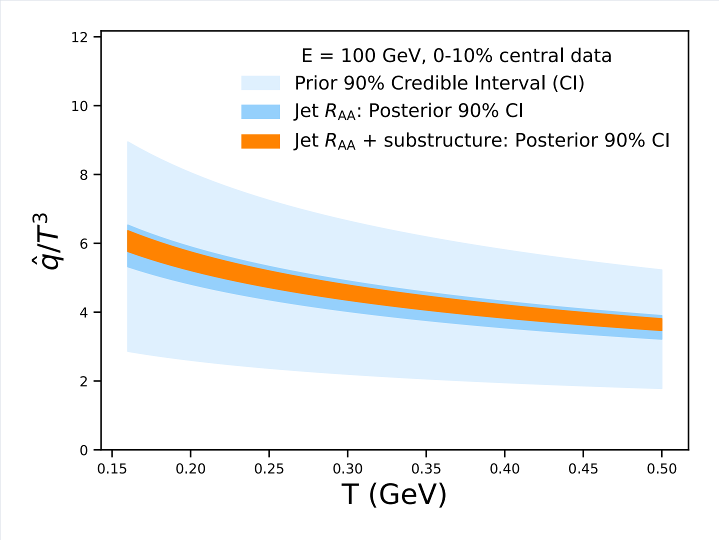


[JetScape 2401.04201]

Summary:

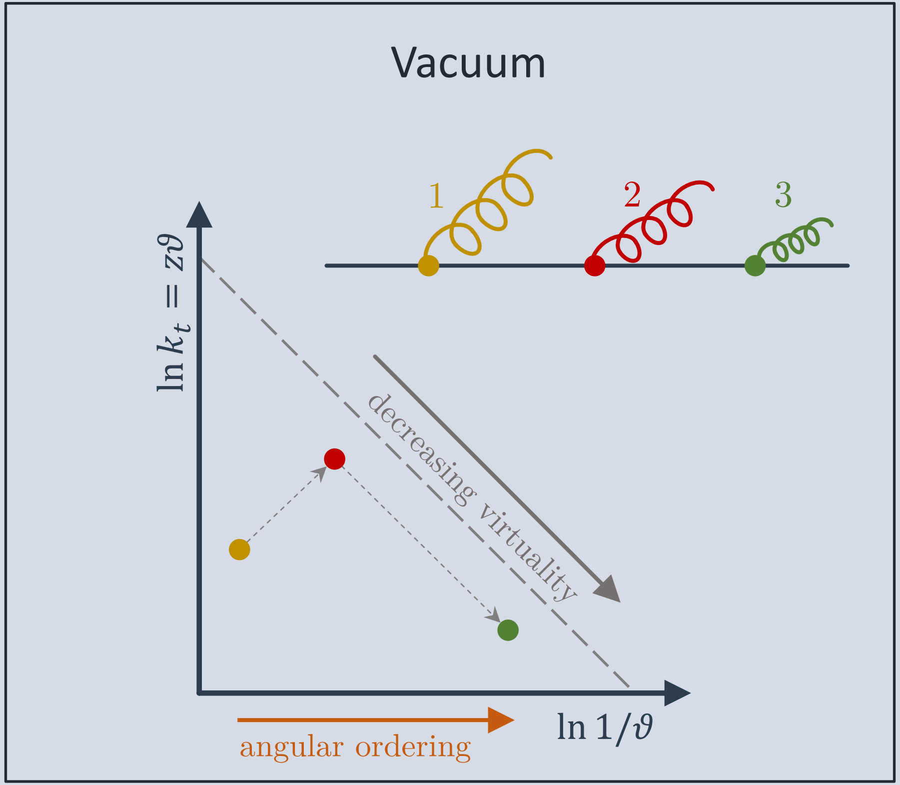
- Jets modify in the QGP → extract QGP features
- (Semi-) perturbative treatment
  - scattering amplitudes ↔ jet observables
- State of the art: factorized picture:
  - good agreement with data!
  - improvements in the doorstep!

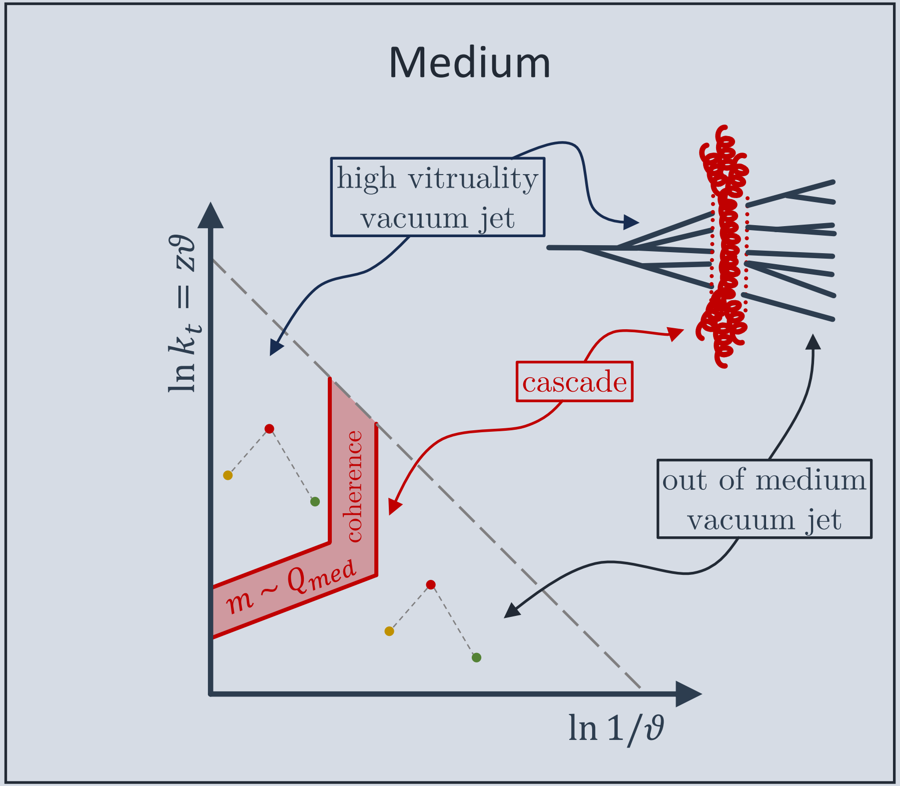
more it in the backup!

Thank you for your attention!

Jet evolution: factorized picture

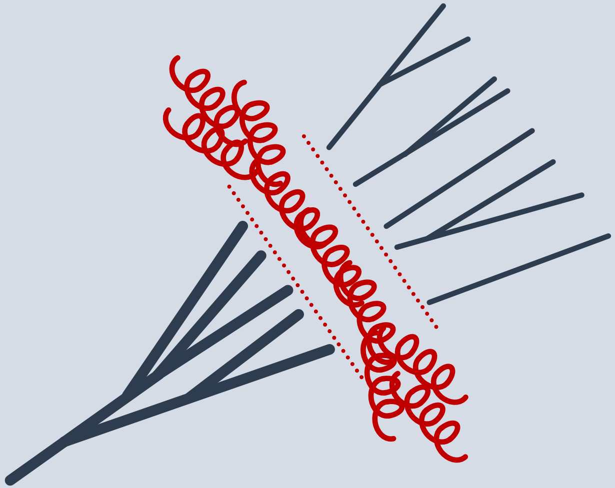
[Mehtar-Tani, Tywoniuk, Salgado]
[Caucal, Iancu, Mueller, Soyez]





Improvements

Factorized picture:



Ingredients:

- vacuum evolution:

  - jet creation (LO→NLO), jet evolution (LL →NLL)

  [Caucal,Soto-Ontoso,AT]
  [Gebhard,Mazeliauskas,AT]

- cascade evolution:

  - beyond soft&collinear limit (NLO_{med}, NLL_{med})

  - finite sized medium

  [Ghigliery, Teaney]
  [Caron-Huot, Gale]
  [Isaksen, AT, Tywoniuk]

- medium scales:

  - resolution, coherence, orderings

  [Arnold et al]

+1 medium modeling:

[Sadofyev et al]

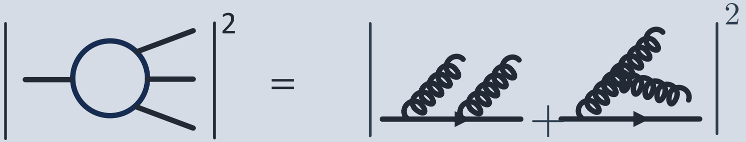
- homogeneous/static → dynamical medium

- medium response / jet thermalization

Jet modification: correlated emissions

Vacuum

- Two gluon emission (NLO rates):

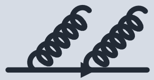


$$\approx \frac{dI_q^{vac}}{dz_1 d\vartheta_1} \frac{dI_g^{vac}}{dz_2 d\vartheta_2} \times \Theta(\vartheta_1 > \vartheta_2)$$

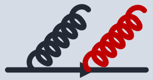
angular-ordering!

Medium

- Two gluon emission:
  - (anti-)Angular ordering:
    [Mehtar-Tani, Tywoniuk, Salgado]
    [Caucal, Iancu, Mueller, Soyez]



  - Medium coherence:
    [Mehtar-Tani, Tywoniuk, Salgado]
    [Casalderrey-Solana, Iancu]



  - In-medium ordering:
    [Blaizot, Dominguez, Mehtar-Tani]
    [Arnold 2015-]