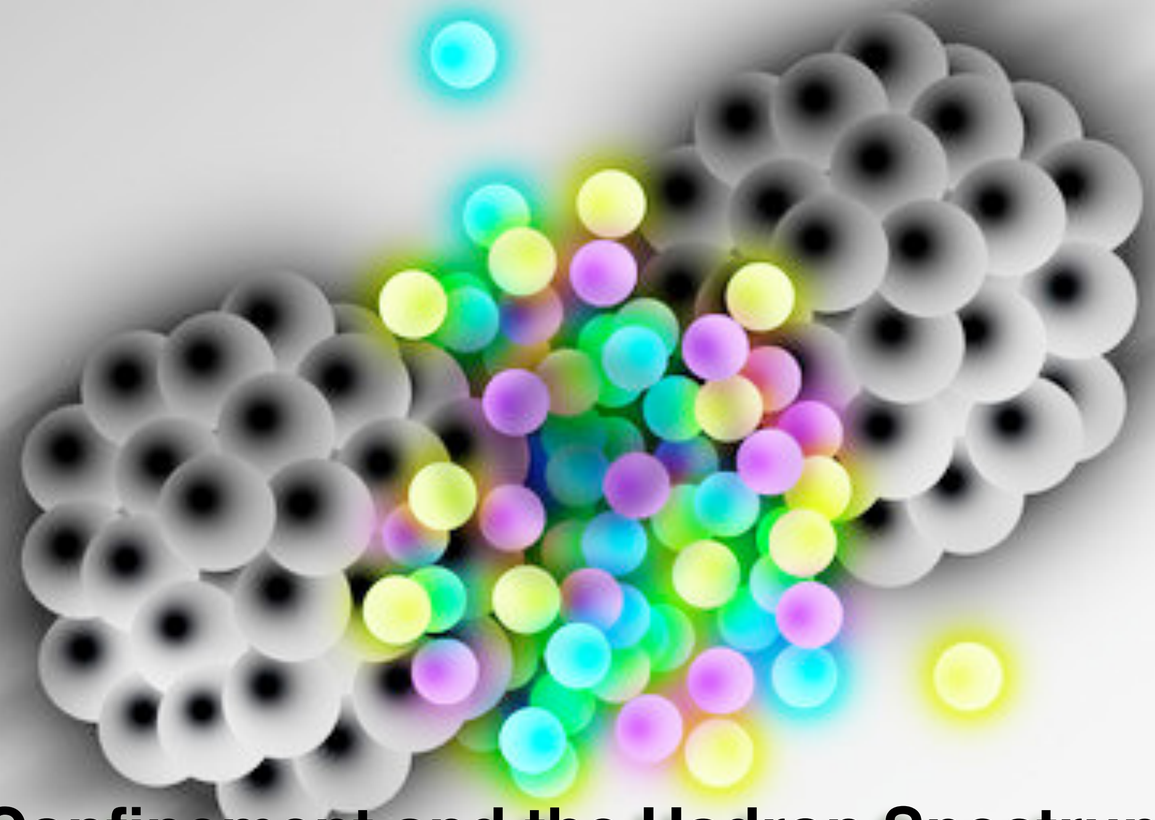
Overview of jet quenching theory



Liliana Apolinário

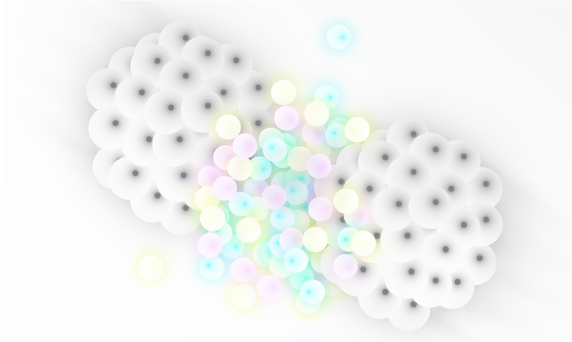
LIP

TÉCNICO LISBOA

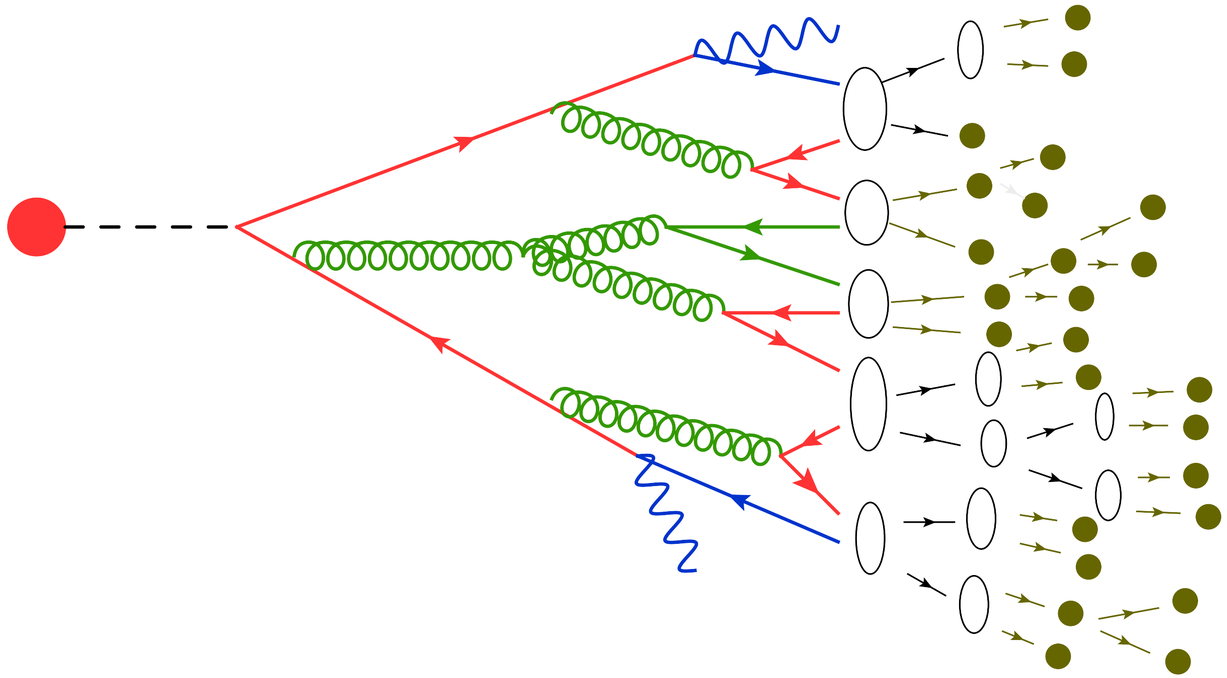
XVth Quark Confinement and the Hadron Spectrum

Tuesday, August 2nd

Jets in heavy-ions



- A multi-scale problem:



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Jets in heavy-ions

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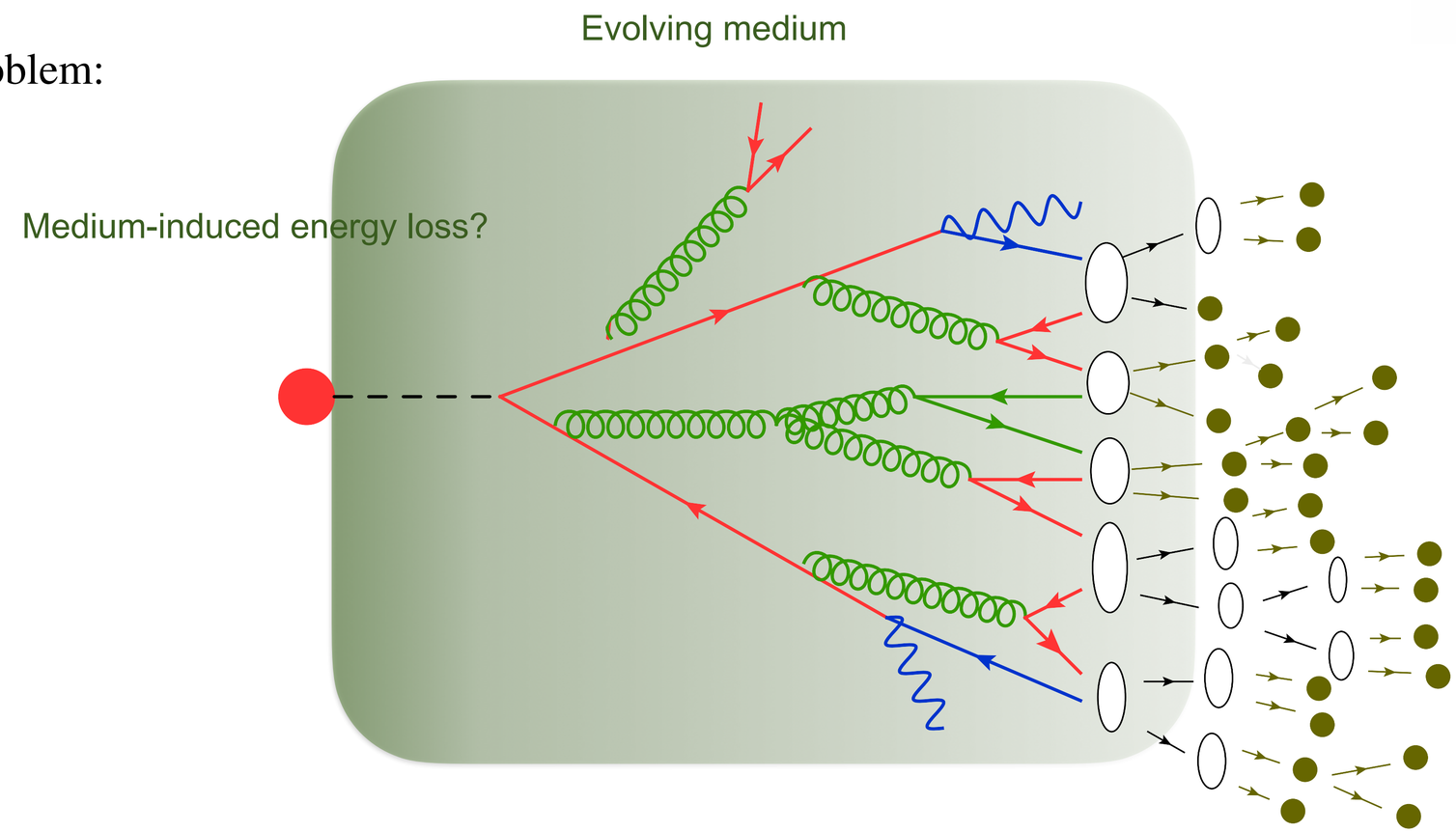

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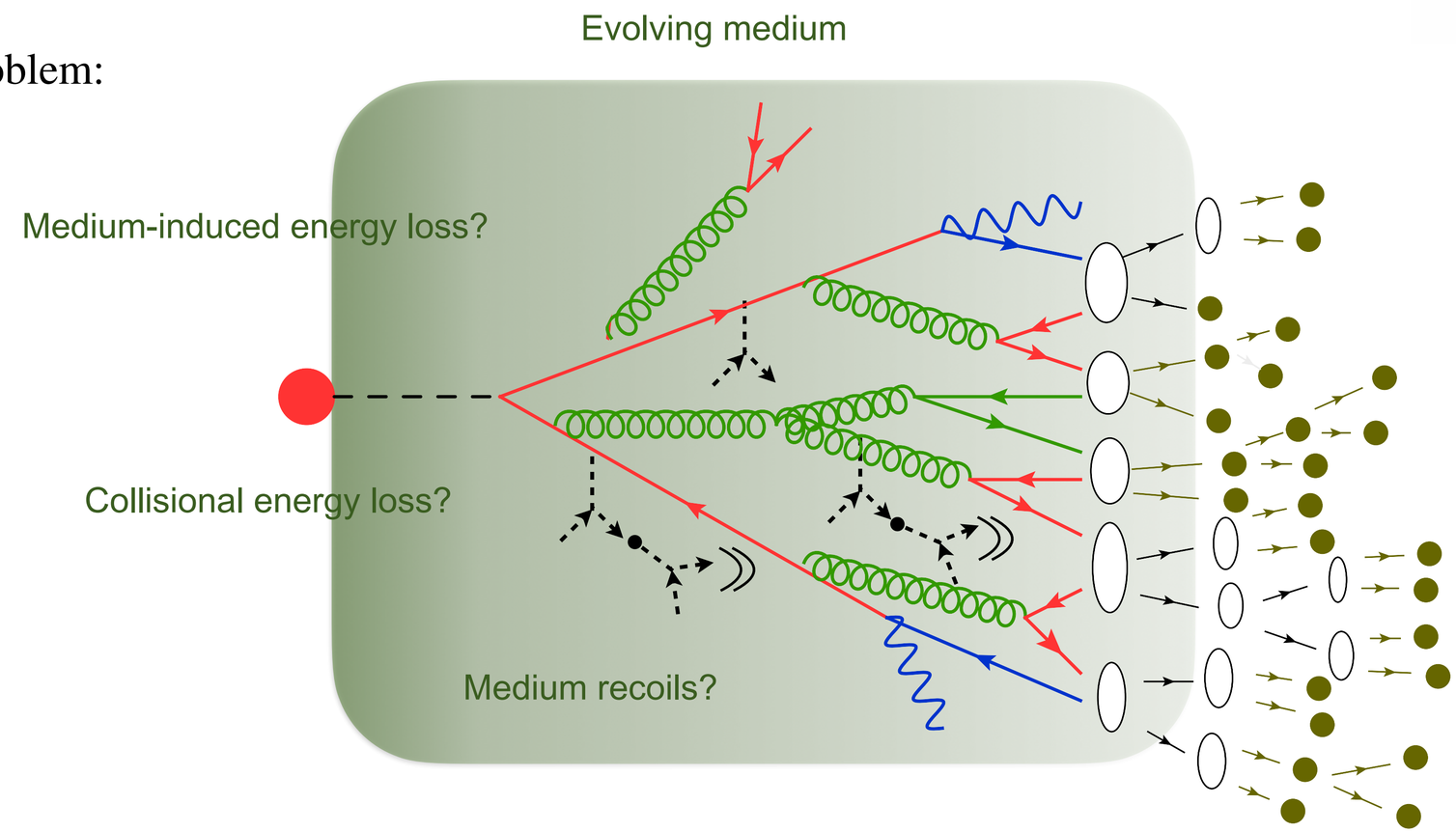

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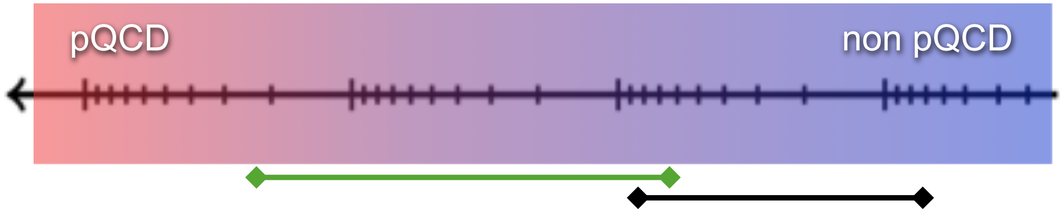

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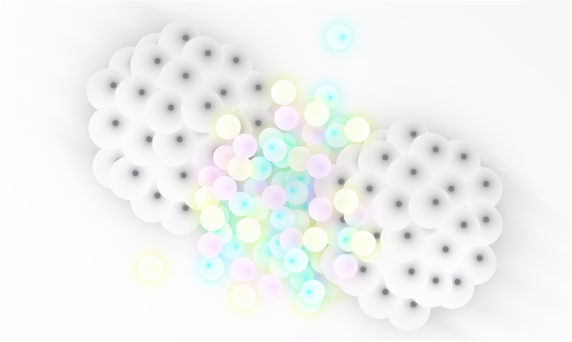
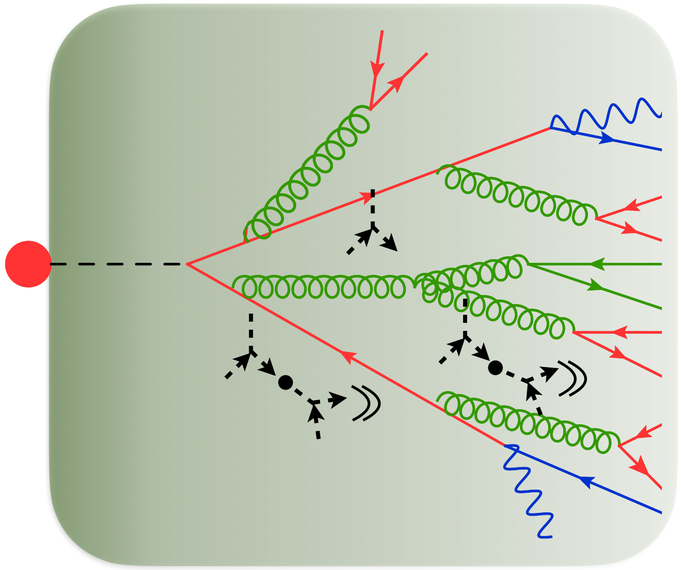
In-medium processes



- Amount of energy loss measures transparency to the passage of a high momentum particle:



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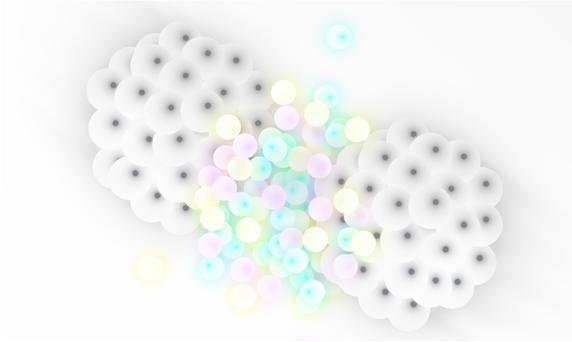

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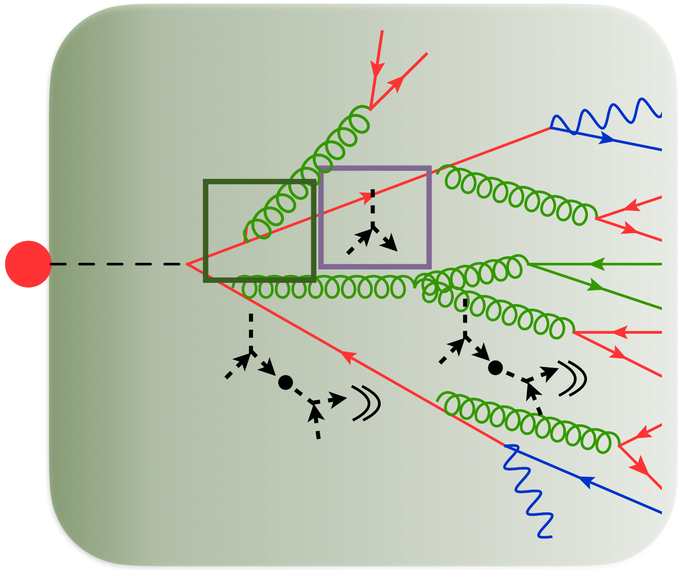
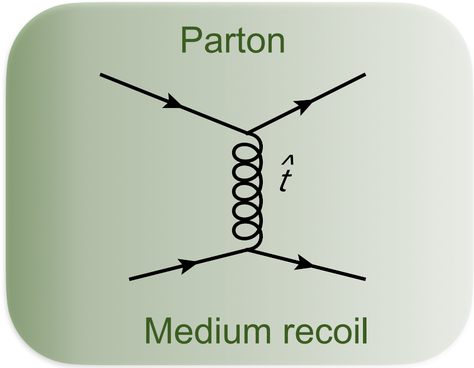


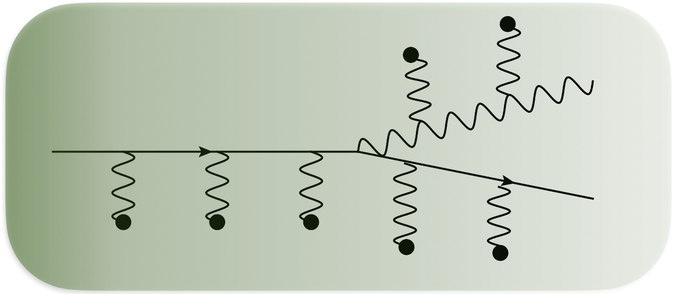
Elastic scattering processes:



Relevant for heavy (low-energy) partons

Dominant for light (high-energy) partons

Inelastic scattering processes:



Medium-induced radiation

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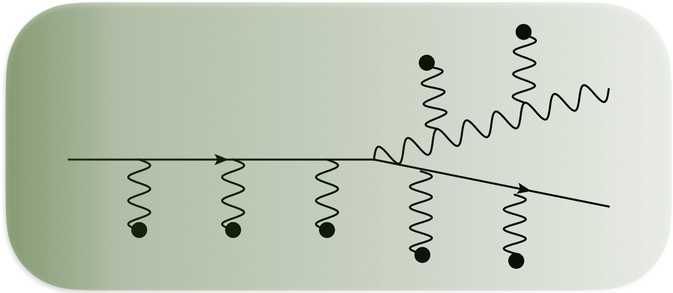

- Accumulation of momenta enhances gluon radiation:
  - Single-gluon emission spectrum:

$$\omega \frac{dI}{d\omega d^2\mathbf{k}} = \frac{2\alpha_s C_R}{(2\pi)^2\omega^2} \mathrm{Re} \int_0^\infty dt' \int_0^{t'} dt \int_{\mathbf{p},\mathbf{q}} \mathbf{p}\cdot\mathbf{q}\ \tilde{\mathcal{K}}(t',\mathbf{q};t,\mathbf{p})\ P(\infty,\mathbf{k};t',\mathbf{q})$$

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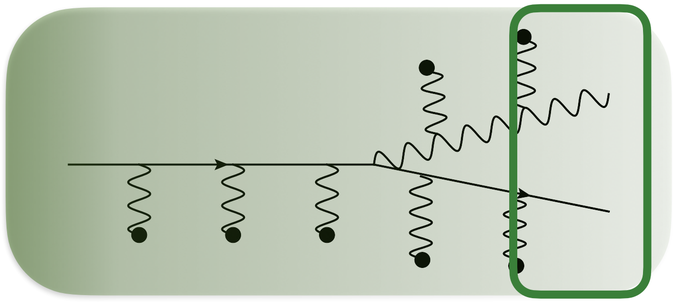

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Momentum Broadening:

$$\mathcal{P}(t'',\boldsymbol{k};t',\boldsymbol{q}) \equiv \int d^2\boldsymbol{z}\, e^{-i(\boldsymbol{k}-\boldsymbol{q})\cdot\boldsymbol{z}}\ \exp\left\{-\frac{1}{2}\int_{t'}^{t''} ds\, n(s)\,\sigma(\boldsymbol{z})\right\}$$

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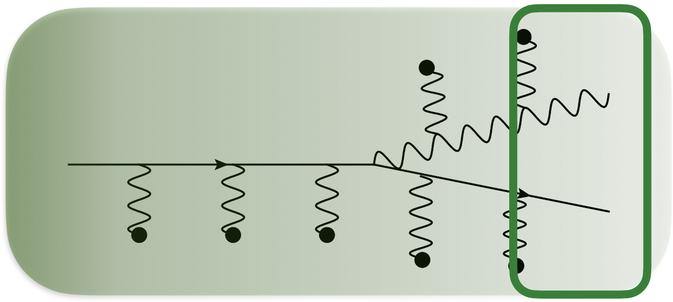

Density of scattering centres:

$$n(x_+) = \int dx_{i+}\delta(x_+ - x_{i+}).$$

Dipole cross-section (collision rate):

$$\sigma(\boldsymbol{r}) = \int_{\boldsymbol{q}} V(\boldsymbol{q})\left(1 - e^{i\boldsymbol{q}\boldsymbol{r}}\right)$$

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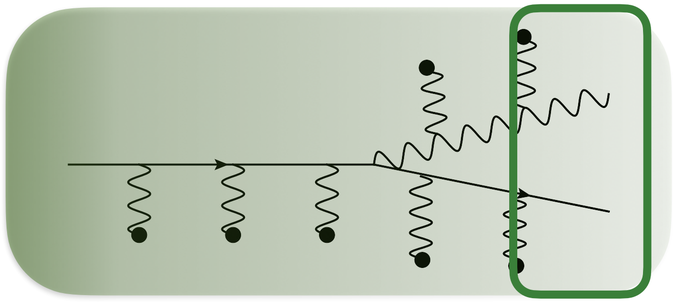

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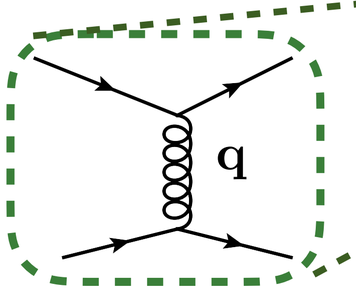

Parton-medium interaction

Medium-induced radiation

- Accumulation of momenta enhances gluon radiation:
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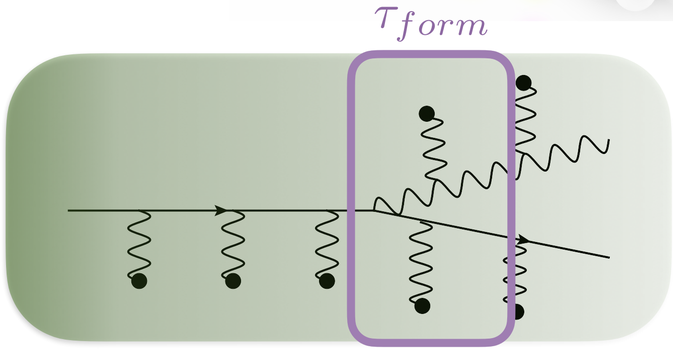
Emission Kernel:

$$\mathcal{K}(t',\boldsymbol{z};t,\boldsymbol{y}) \equiv \int_{\boldsymbol{pq}} e^{i(\boldsymbol{q}\cdot\boldsymbol{z}-\boldsymbol{p}\cdot\boldsymbol{y})}\,\widetilde{\mathcal{K}}(t',\boldsymbol{q};t,\boldsymbol{p})$$
$$= \int_{\boldsymbol{r}(t)=\boldsymbol{y}}^{\boldsymbol{r}(t')=\boldsymbol{z}} \mathcal{D}\boldsymbol{r} \exp\left[\int_t^{t'} ds \left(\frac{i\omega}{2}\dot{\boldsymbol{r}}^2 - \frac{1}{2}n(s)\sigma(\boldsymbol{r})\right)\right]$$

Inelastic scattering processes:



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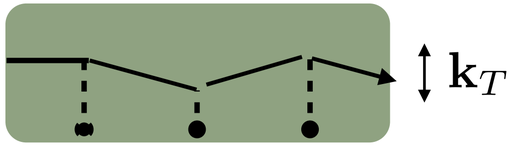
Solution to the path integral (for an arbitrary potential) poses significant technical challenges…

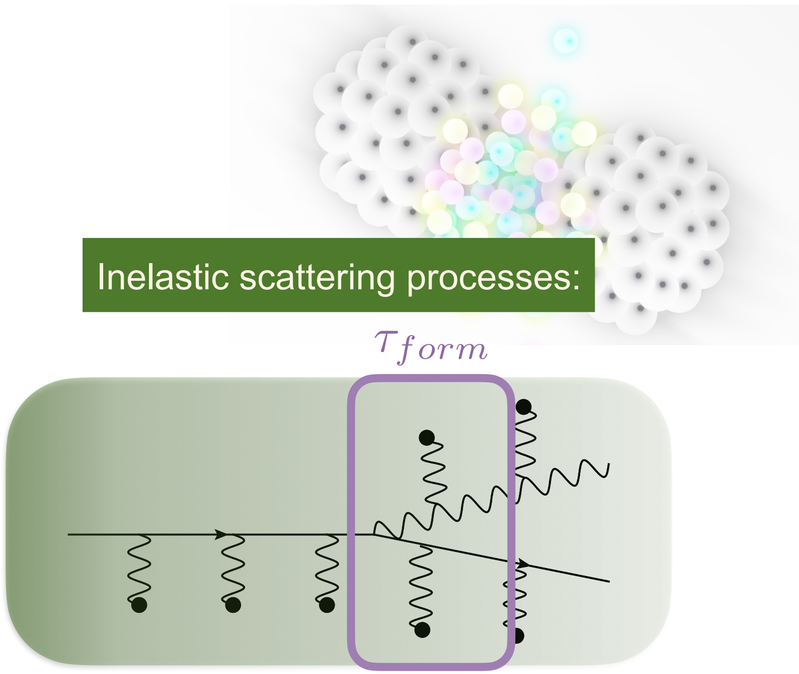
Medium-induced radiation

- Accumulation of momenta enhances gluon radiation:
  - In addition to energy loss, parton also undergoes transverse momentum diffusion
    - Medium-induced transverse momentum broadening



Transport coefficient:

$$\hat{q} = \frac{\langle k_T \rangle}{\lambda}$$



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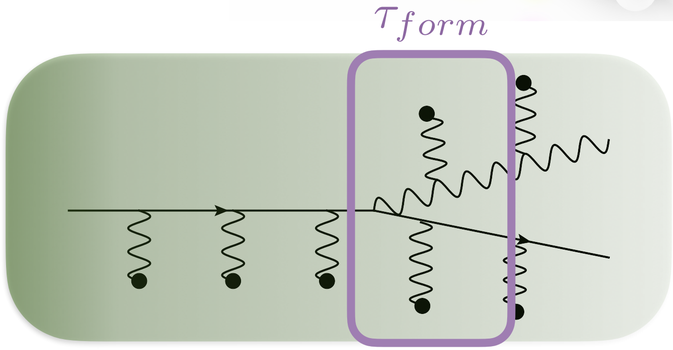

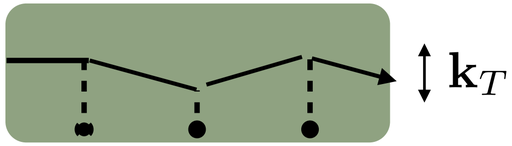

Transport coefficient:

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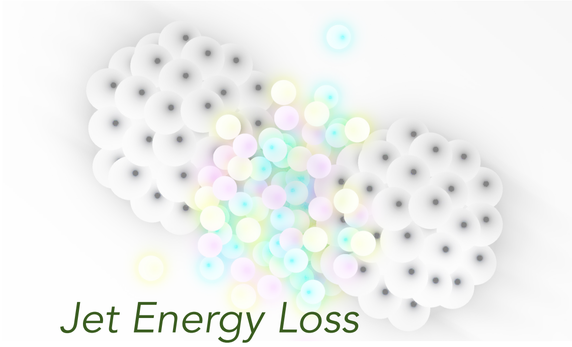
Medium-induced energy loss and momentum broadening closely connected!

Current landscape



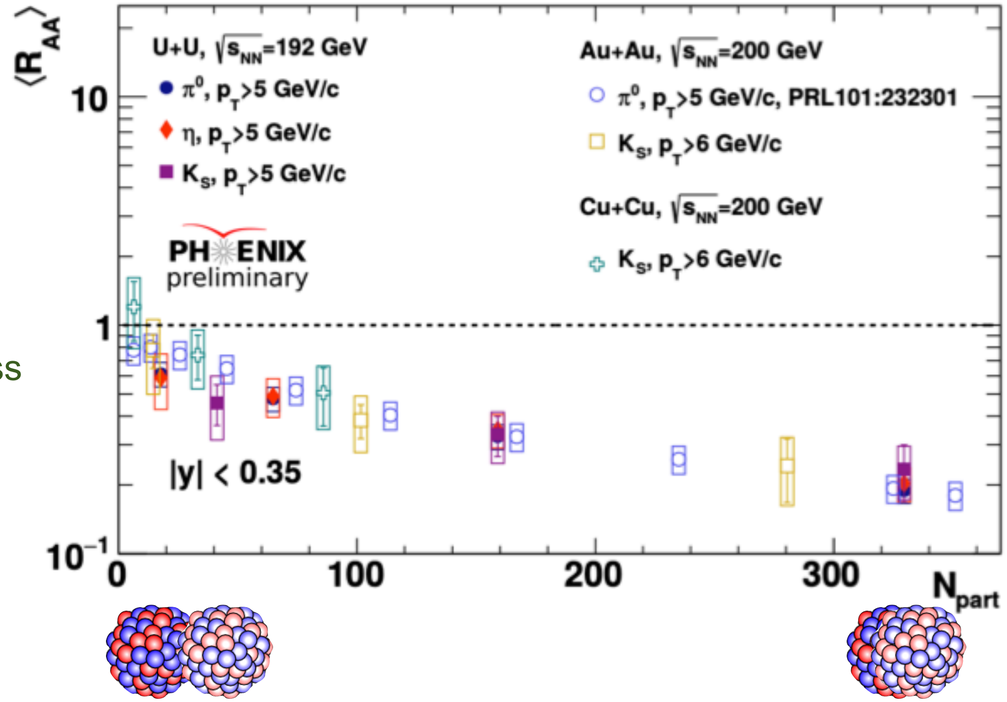
Jet Energy Loss

- From single-particle or jet suppression, recover $\hat{q}$

$$R_{AA} = \frac{Y_{AA}^{X}}{\langle T_{AA} \rangle \cdot \sigma_{pp}^{X}}$$

Particle Energy Loss

PHENIX [2002.11156]



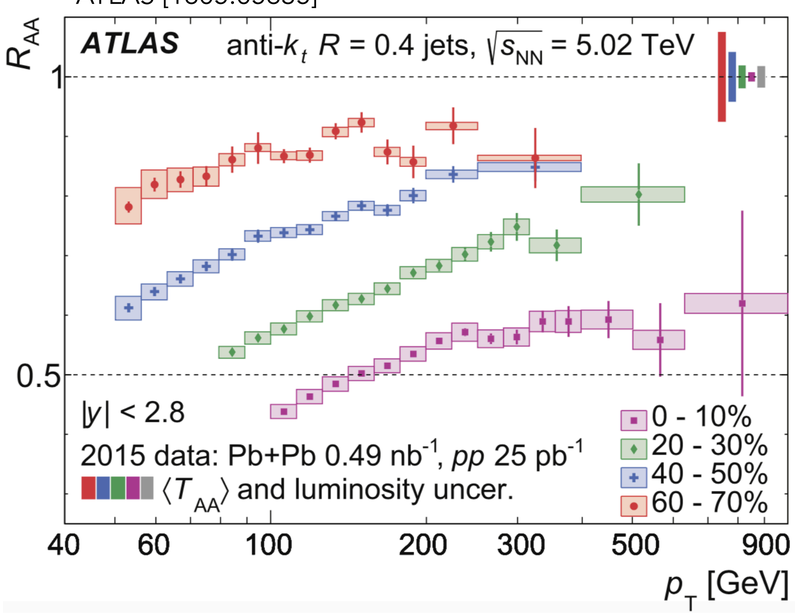
$R_{AA} = 1$

No energy loss

$R_{AA} < 1$

Energy loss

ATLAS [1805.05635]



Current landscape

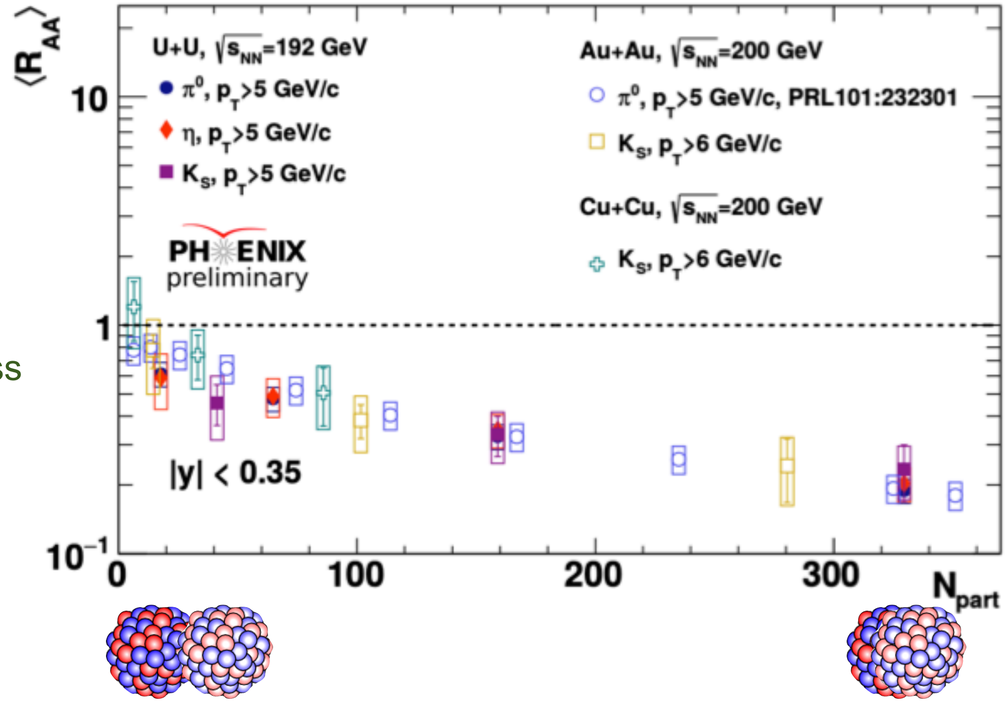
- From single-particle or jet suppression, recover $\hat{q}$

$$R_{AA} = \frac{Y_{AA}^{X}}{\langle T_{AA} \rangle \cdot \sigma_{pp}^{X}}$$

RHIC (AuAu 200 GeV)

Particle Energy Loss

PHENIX [2002.11156]



$R_{AA} = 1$

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Energy loss

LHC (PbPb 5.02 TeV)

Jet Energy Loss

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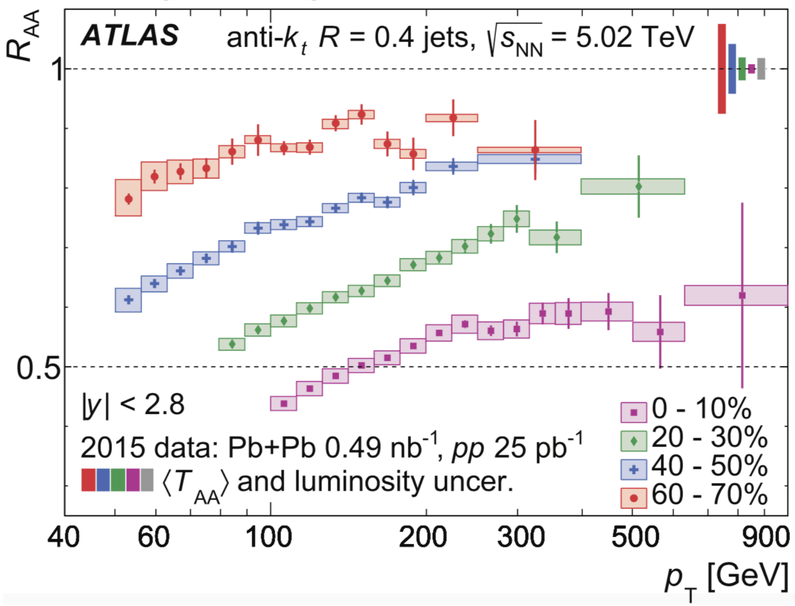

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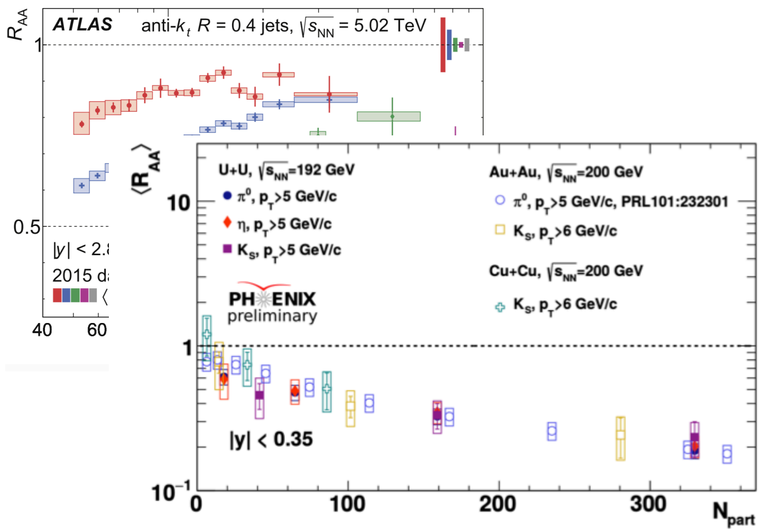
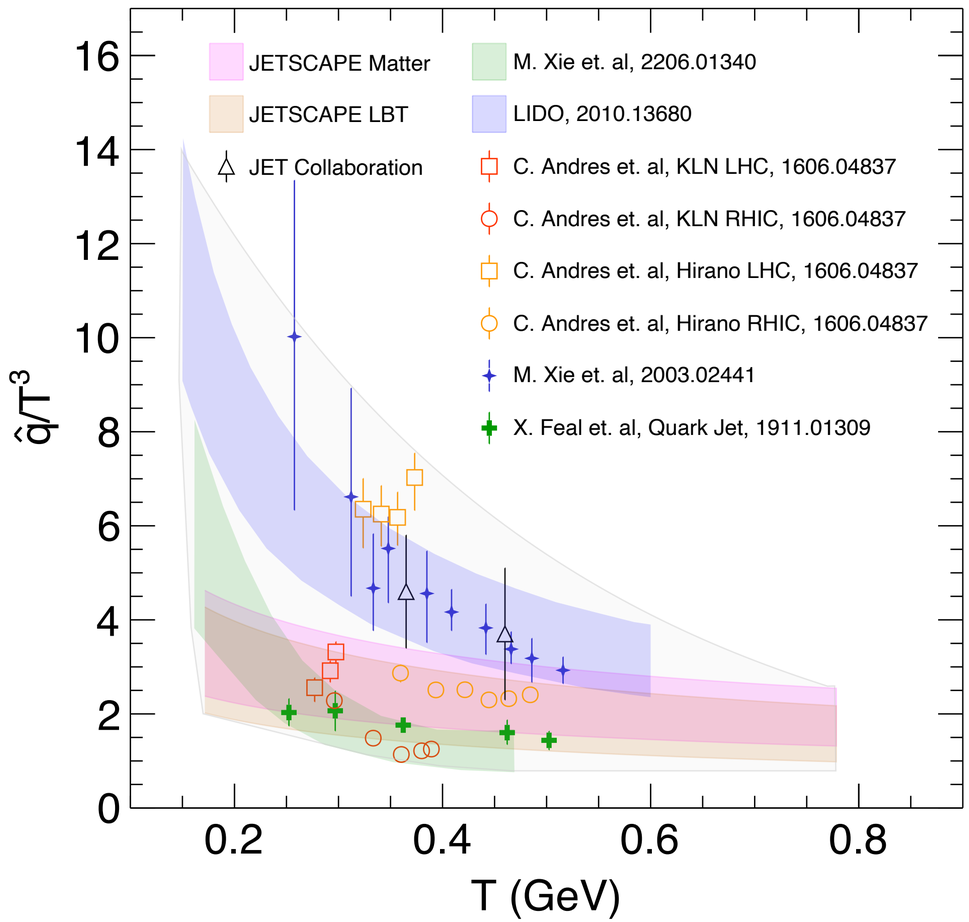


[LA, Y-J Lee, M. Winn (2203.16352)]



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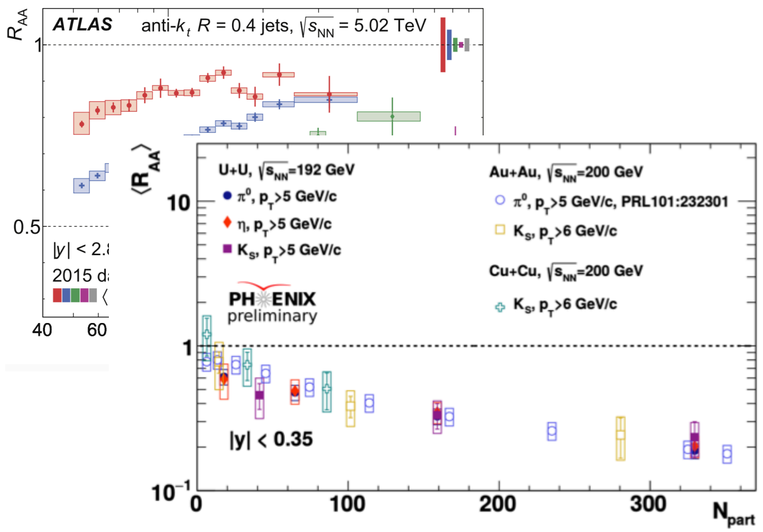
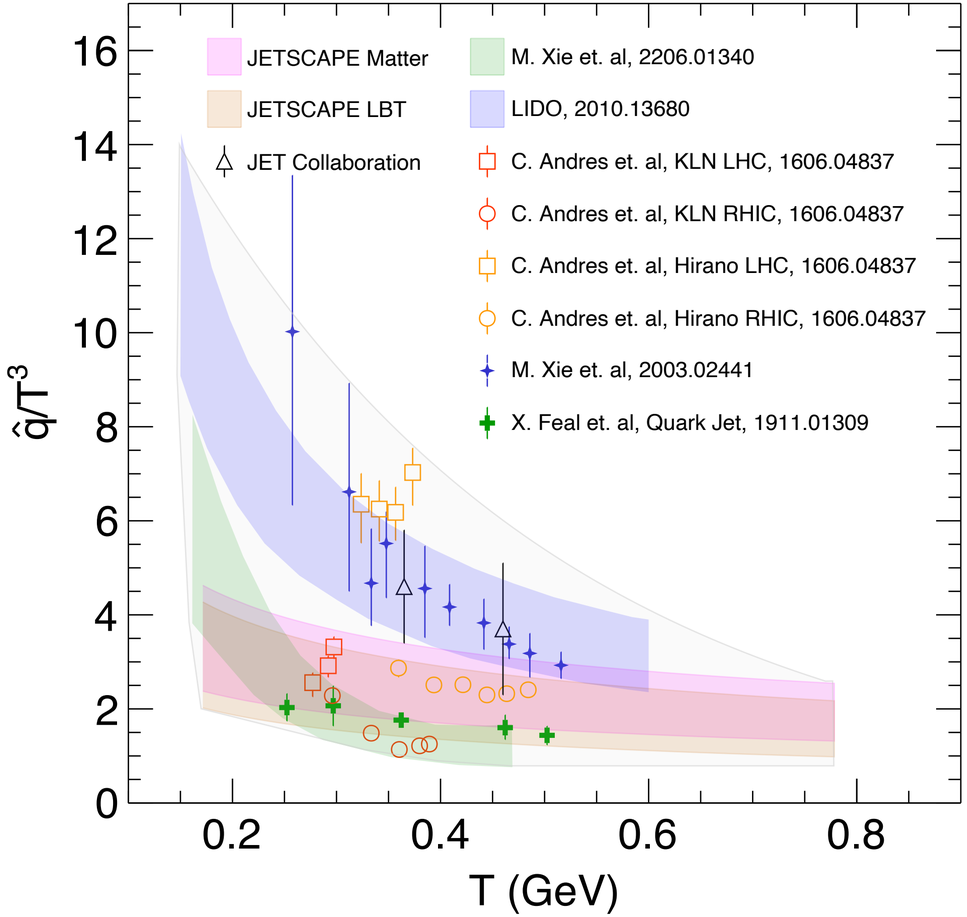


Several ansatz:

- Initial state (factorisation to final-state effects)?
- Medium temperature and energy-density time-evolution profiles?
- QGP phase initialisation time?
- Energy loss during partonic and hadronic phases?
- QGP EoS and degrees of freedom?
- Data sets used?

...

[LA, Y-J Lee, M. Winn (2203.16352)]

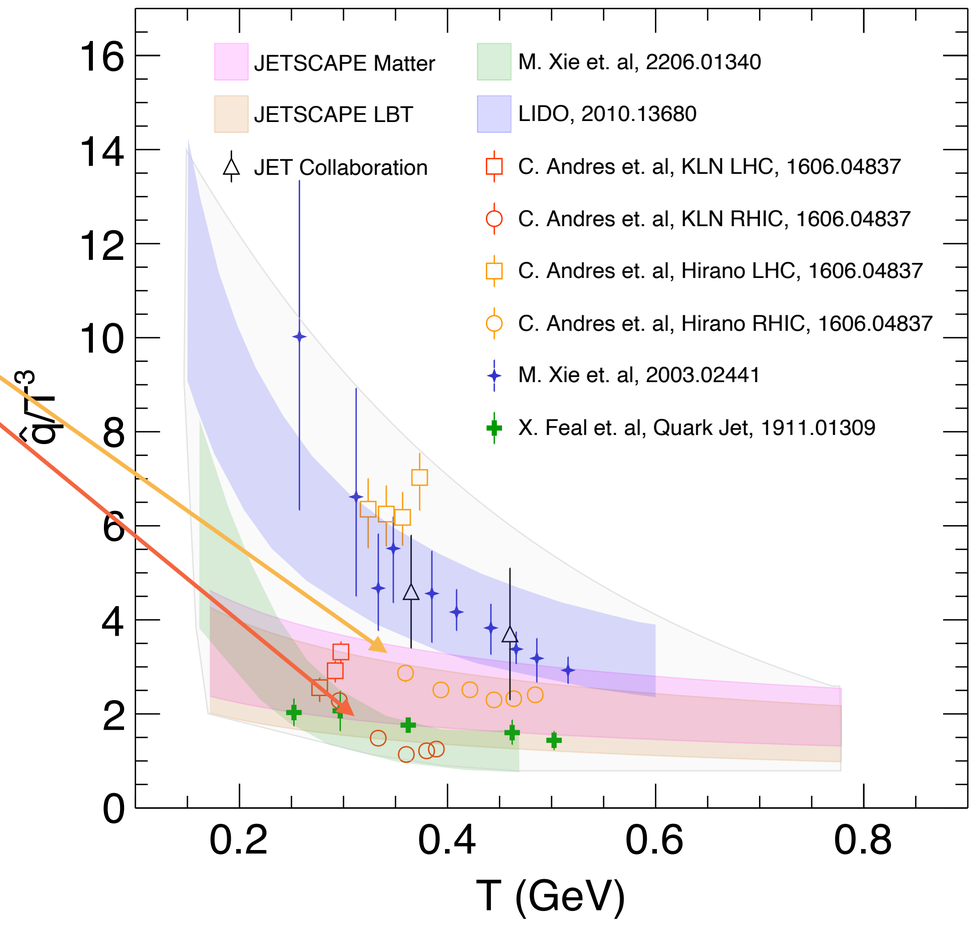


Current landscape

- From single-particle or jet suppression, recover $\hat{q}$

Changing QGP initialisation conditions

[LA, Y-J Lee, M. Winn (2203.16352)]



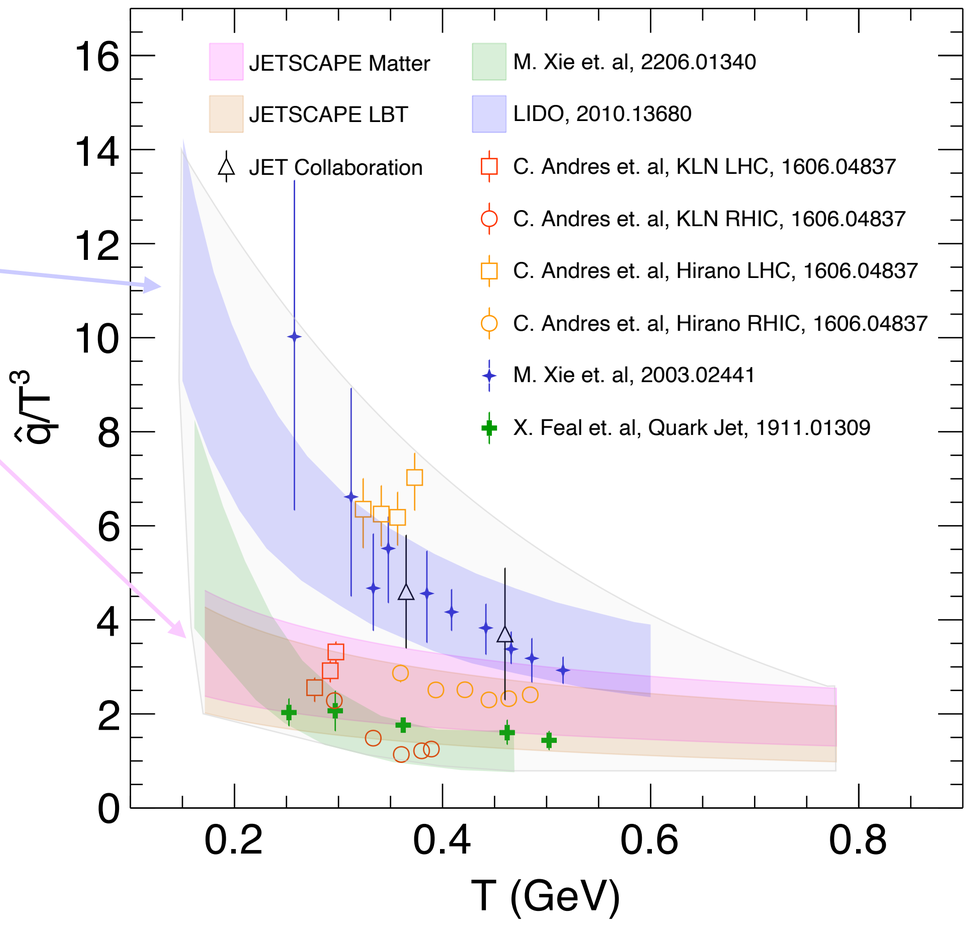
Current landscape

- From single-particle or jet suppression, recover $\hat{q}$

Changing QGP initialisation conditions

Energy loss during all parton shower evolution vs energy loss during final stage
(Compensation of effects with higher transport coefficient)

[LA, Y-J Lee, M. Winn (2203.16352)]



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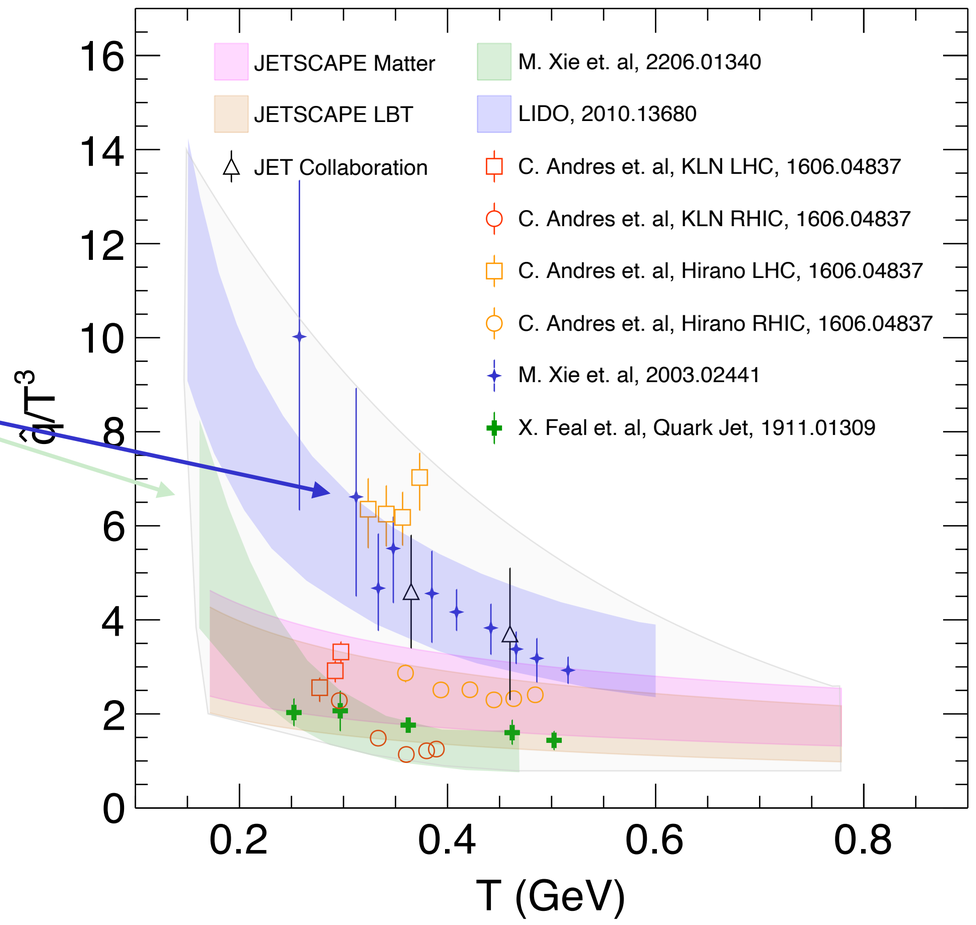
Improved Baysian analysis gives a stronger Temperature dependence

[LA, Y-J Lee, M. Winn (2203.16352)]



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Changing QGP initialisation conditions

Energy loss during all parton shower evolution vs energy loss during final stage
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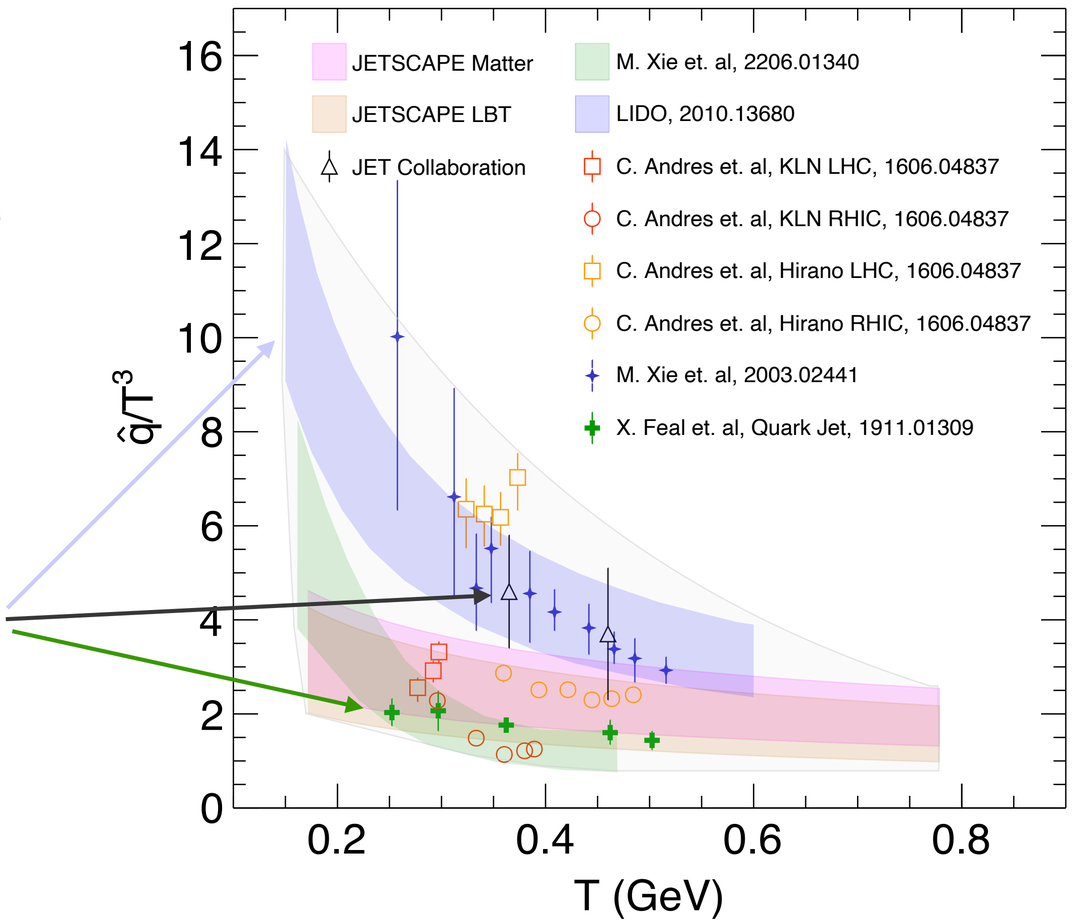
Improved Baysian analysis gives a stronger Temperature dependence

Include different data sets
(boson-hadron correlations dominated by quark, inclusive particle spectra contains a mixture of the two)

Hadron vs Jet measurements
(model-dependent description of medium response on jets)

[LA, Y-J Lee, M. Winn (2203.16352)]



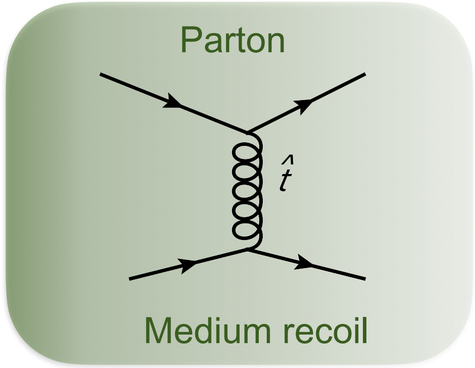
Current landscape

[HQ: Beraudo et al (1803.0382), Cao et al (1809.07894)]

See also:
Hai-Tao Shu's talk [Thursday]

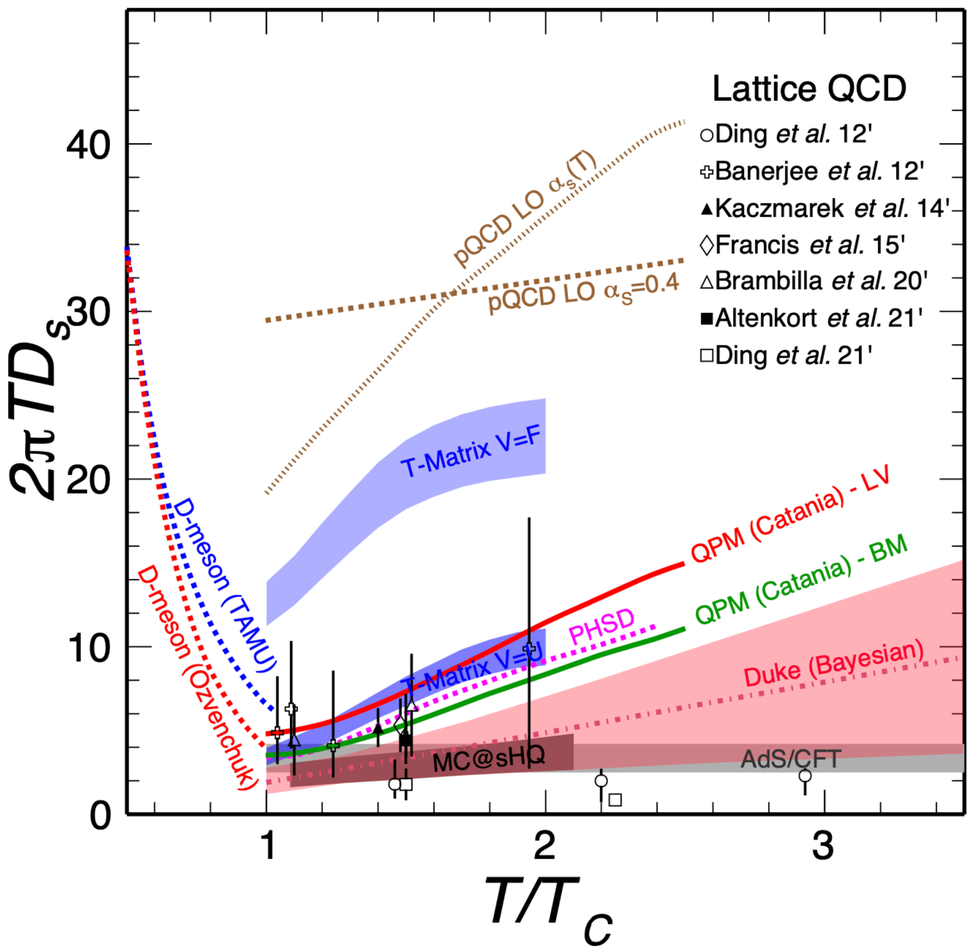
- Propagation of low-momentum heavy quarks:
  - Brownian motion with many small momentum transfer elastic collisions with the medium.
    - Heavy-quarks transport coefficients can also be retrieved from experimental data:

Elastic scattering processes:



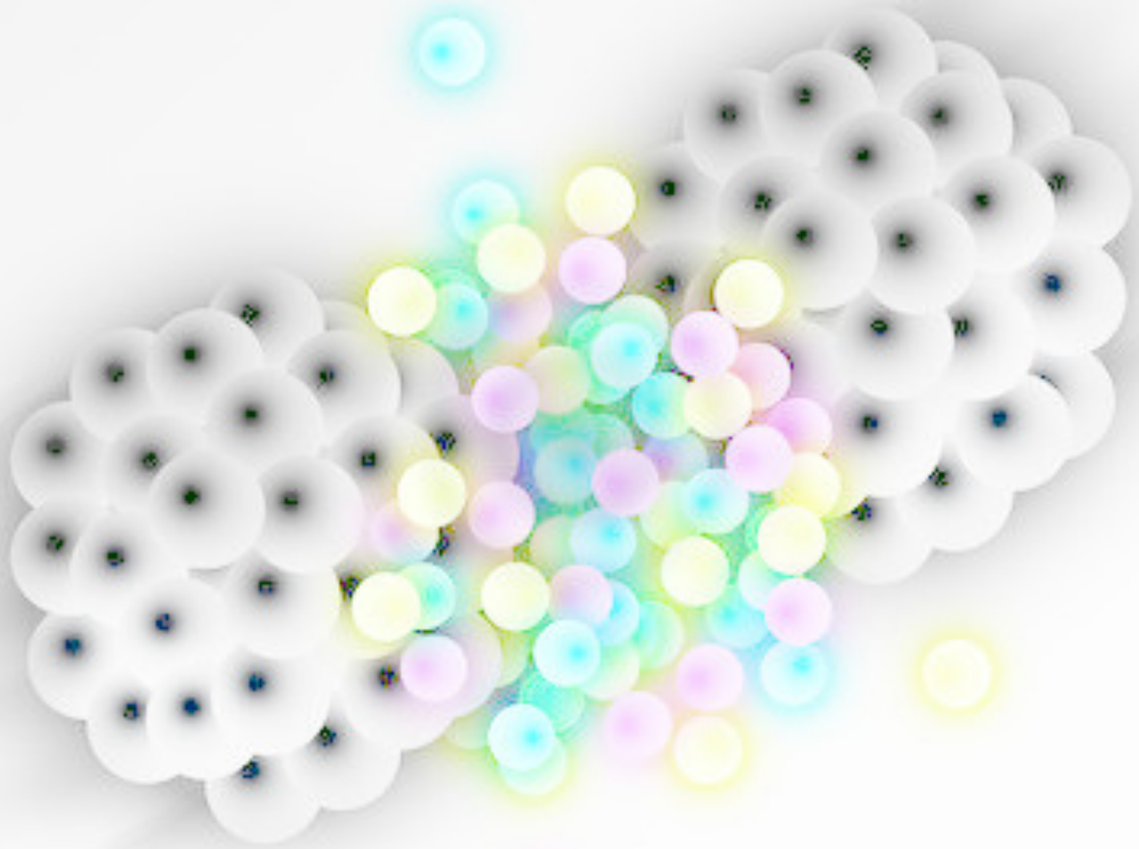
Elastic diffusion: $D_s = \frac{d(\Delta E)^2}{dt}$

[LA, Y-J Lee, M. Winn (2203.16352)]

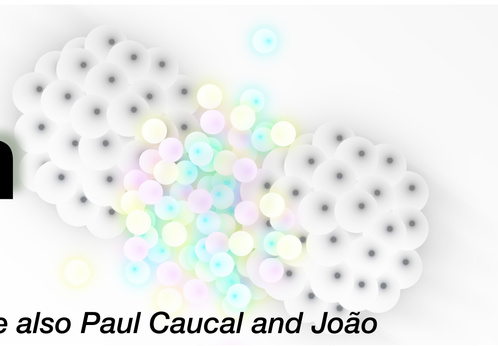


How can we improve it?

Improving theoretical control

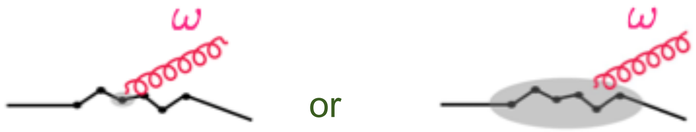


Improving medium-induced radiation



See also Paul Caucal and João Barata's talks [Thursday]

- Accuracy of radiation spectrum:



  - Improved analytic opacity expansion (expand multiple soft interaction)

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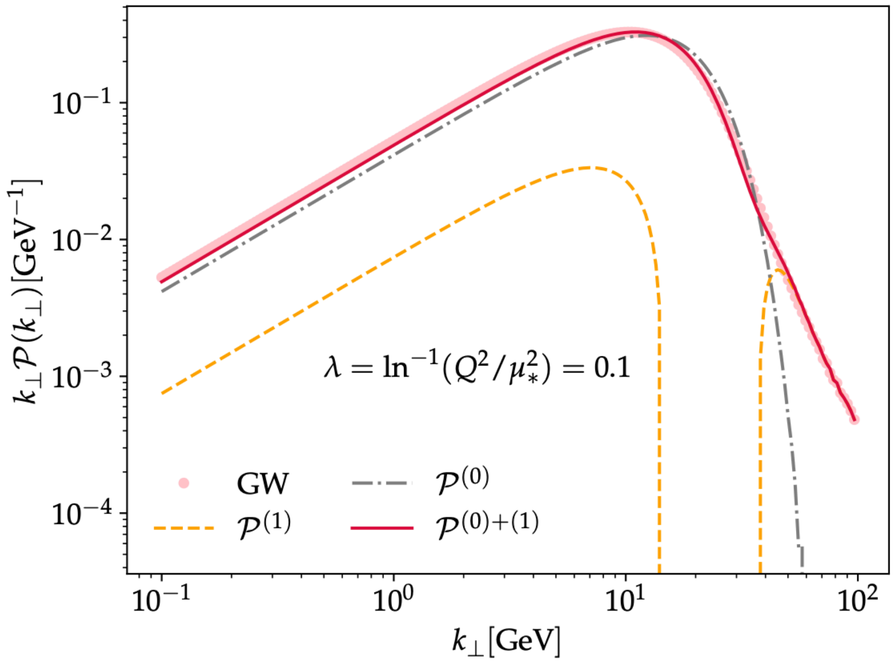
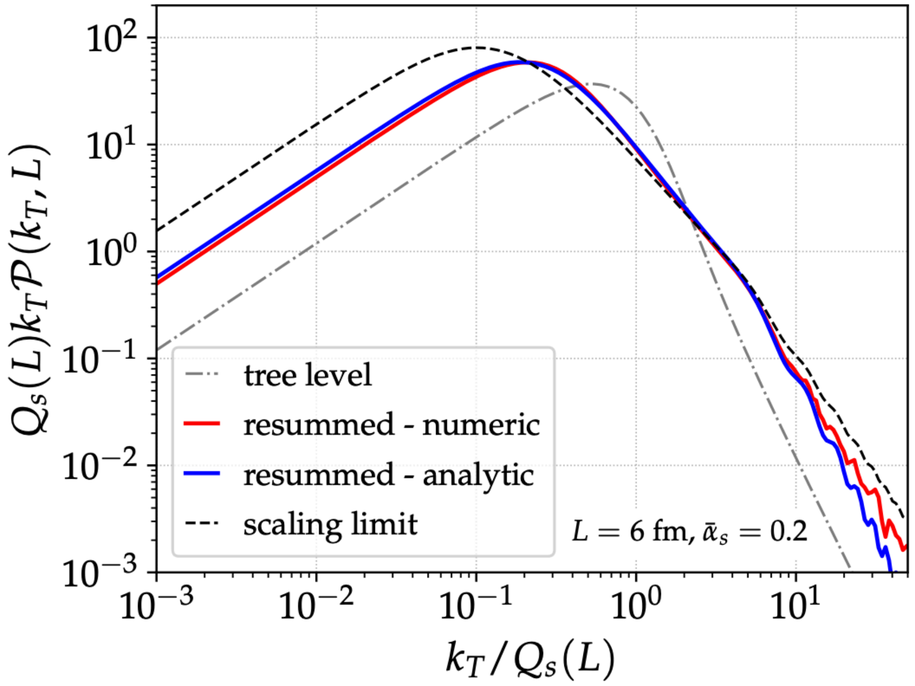
$$n(s)\sigma(\mathbf{r}) \simeq \frac{1}{2}\hat{q}\mathbf{r}^2 + \mathcal{O}(r^2 \ln r^2) \Rightarrow v(r,s)_{HO} + \delta v(r,s)$$

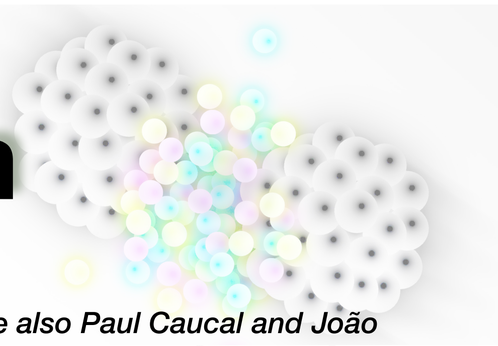
[Barata, Mehtar-Tani, Soto-Ontoso, Tywoniuk, (2009.13667)]



[Caucal, Mehtar-Tani 2109.12041)]



Improving medium-induced radiation



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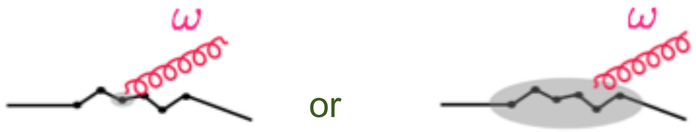

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  - Full numerical solution:

[Andrés, LA, Dominguez, Gonzales (2002.01517,2011.06522)]

    - Solve the spectrum by using Schwinger-Dyson type equations (in momentum space):

$$\partial_\tau \mathcal{P}(\tau, \boldsymbol{k}; s, \boldsymbol{l}) = -\frac{1}{2} n(\tau) \int_{\boldsymbol{k}'} \sigma(\boldsymbol{k} - \boldsymbol{k}') \mathcal{P}(\tau, \boldsymbol{k}'; s, \boldsymbol{l})$$

$$\partial_t \widetilde{\mathcal{K}}(s, \boldsymbol{q}; t, \boldsymbol{p}) = \frac{i\boldsymbol{p}^2}{2\omega} \widetilde{\mathcal{K}}(s, \boldsymbol{q}; t, \boldsymbol{p}) + \frac{1}{2} n(t) \int_{\boldsymbol{k}'} \sigma(\boldsymbol{k}' - \boldsymbol{p}) \widetilde{\mathcal{K}}(s, \boldsymbol{q}; t, \boldsymbol{k}')$$

Set of integro-partial differential equations that can be numerically solved to any (realistic) potential

Also: [Feal, Salgado, Vasquez (1911.01309)]

Improving medium-induced radiation

[Andrés, LA, Dominguez, (2002.01517)]

- Accuracy of radiation spectrum:
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  - Full numerical solution:
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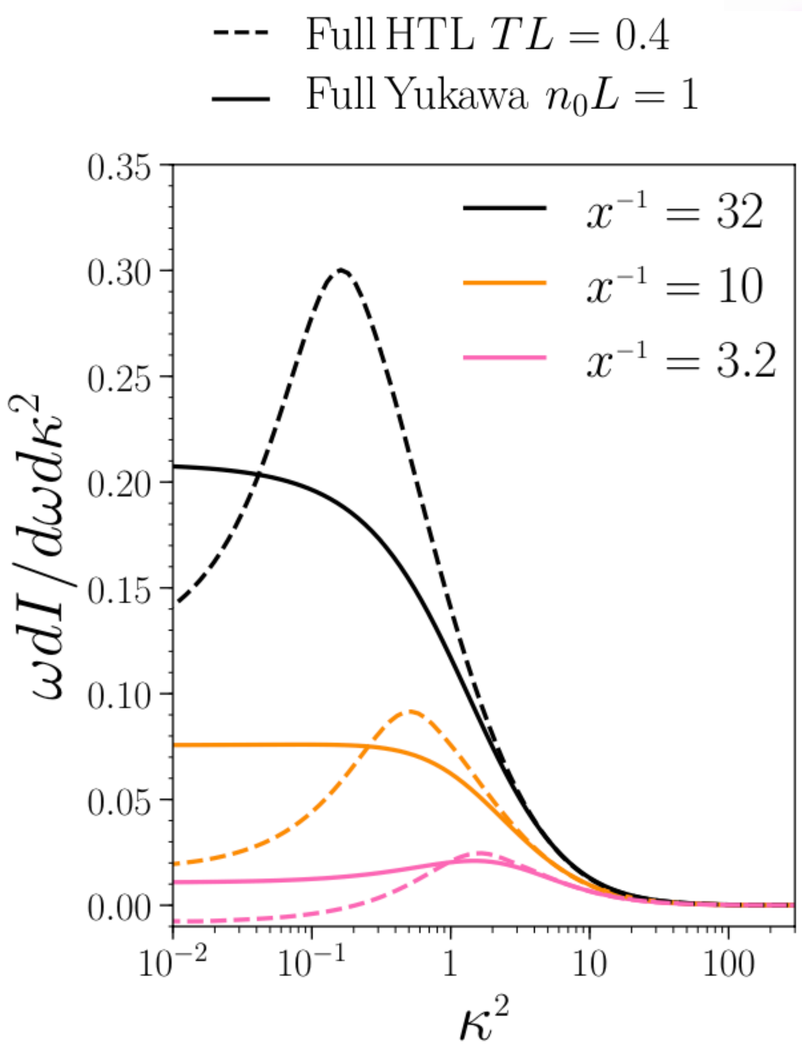
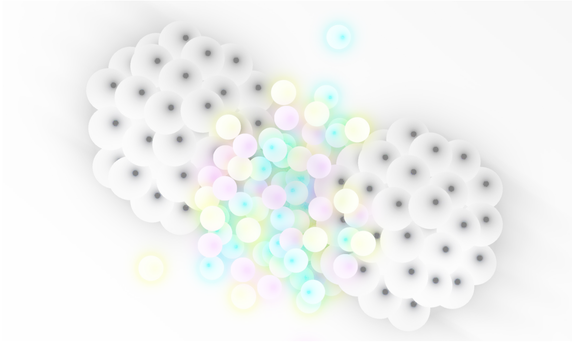
Yukawa potential: $V(\boldsymbol{q}) = \dfrac{8\pi\mu^2}{(\boldsymbol{q}^2+\mu^2)^2}$

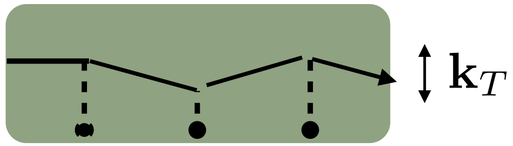
HTL potential: $\dfrac{1}{2}n\,V(\boldsymbol{q}) = \dfrac{g_s^2 N_c m_D^2 T}{\boldsymbol{q}^2(\boldsymbol{q}^2+m_D^2)}$



Non-perturbative corrections



- Corrections to $\hat{q}$ by higher-order effects due to the presence of a thermalised medium



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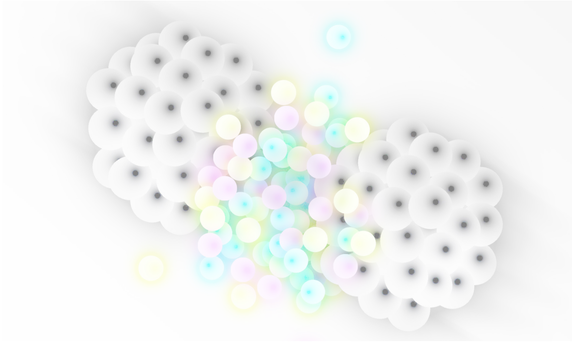

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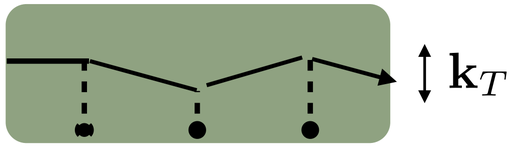

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Broadening Kernel: $C(q_\perp) \equiv (2\pi)^2 \dfrac{d\sigma(q_\perp)}{d^2 q_\perp} \equiv (2\pi)^2 \dfrac{d\Gamma(q_\perp)}{d^2 q_\perp}$

Also: [Ghiglieri, Laine (2112.01407)]
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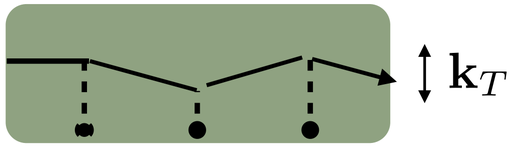

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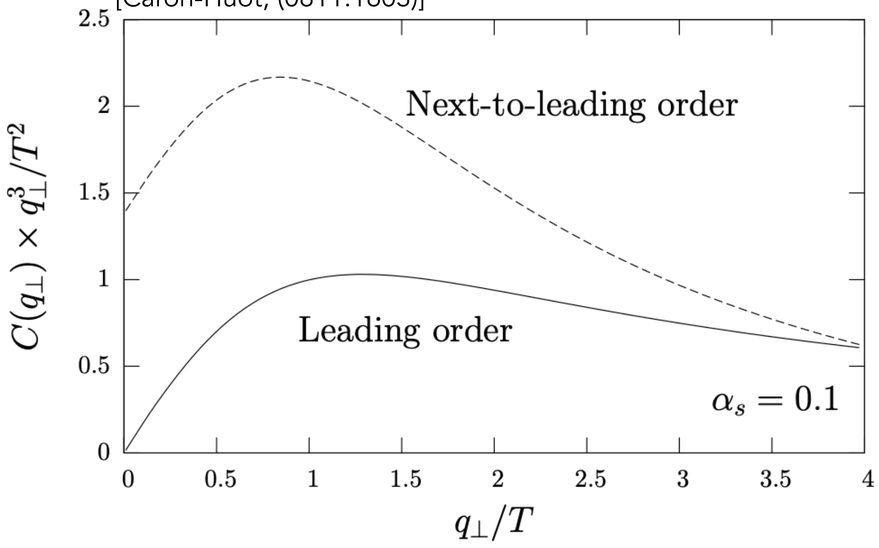
Perturbative determination of the O(g) NLO corrections

[Caron-Huot, (0811.1603)]



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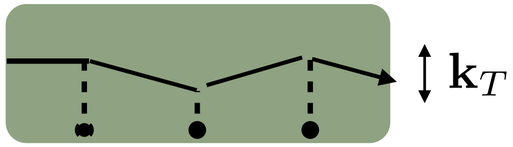

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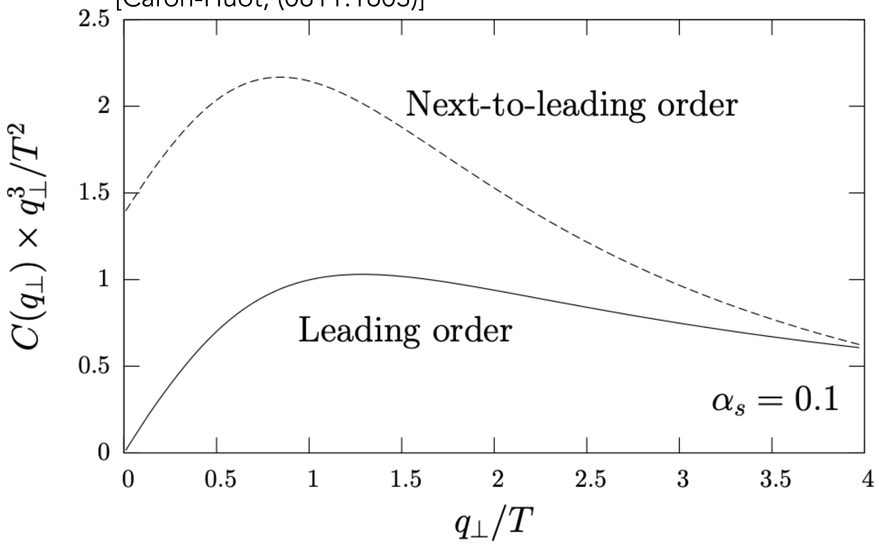
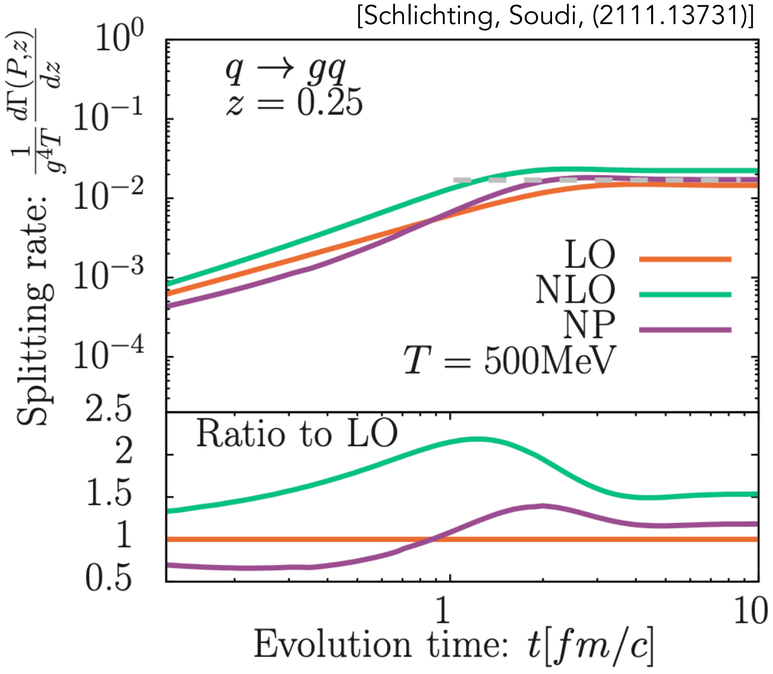


Non-perturbative determination of momentum broadening

$$C_{\rm QCD}(b_\perp) = (C_{\rm QCD}(b_\perp) - C_{\rm EQCD}(b_\perp)) \cdot + C_{\rm EQCD}(b_\perp)$$

[Moore, Schlichting, Schlusser, Soudi, (2105.01679)]

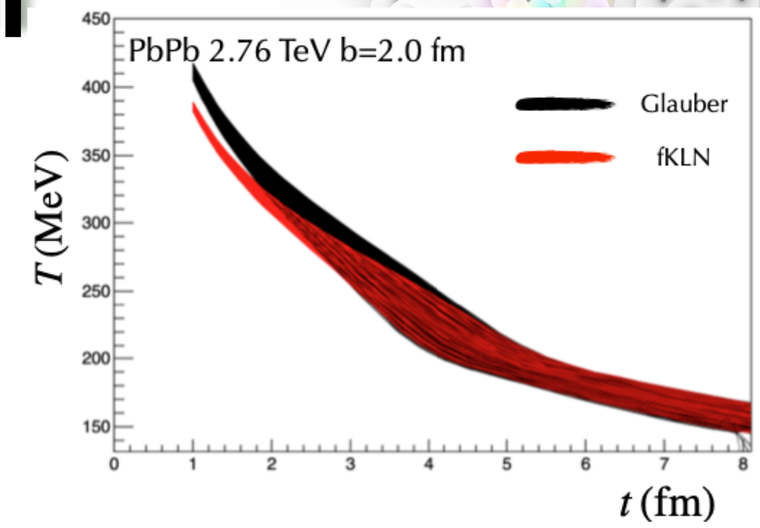
[Schlichting, Soudi, (2111.13731)]



Effects of an evolving medium

- Input parameters for radiation spectrum will depend on time:
  - T = T(t) and will differ depending on the medium parameterization

Central production points (|x|,|y| < 0.1 fm)



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  - Possible solution: identify static equivalent of an expanding medium (scaling laws)

For the harmonic oscillator: $\langle \hat{q} \rangle = \frac{2}{L^2} \int_{t_0}^{L+t_0} \mathrm{d}t\, (t - t_0) \hat{q}(t)$

Energy loss in a static equivalent of an expanding medium?

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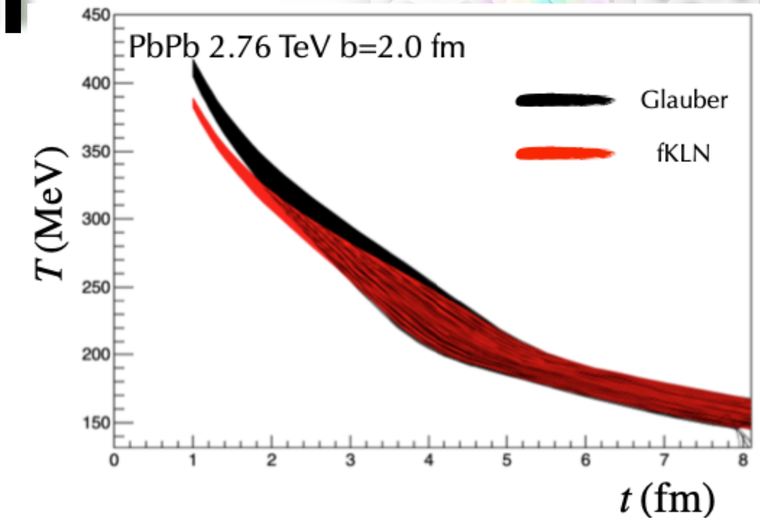

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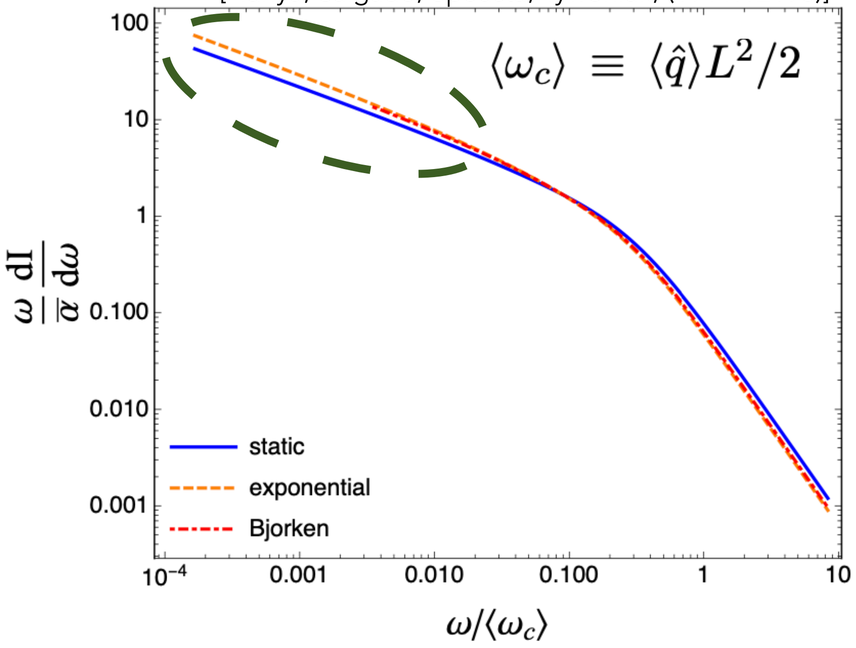

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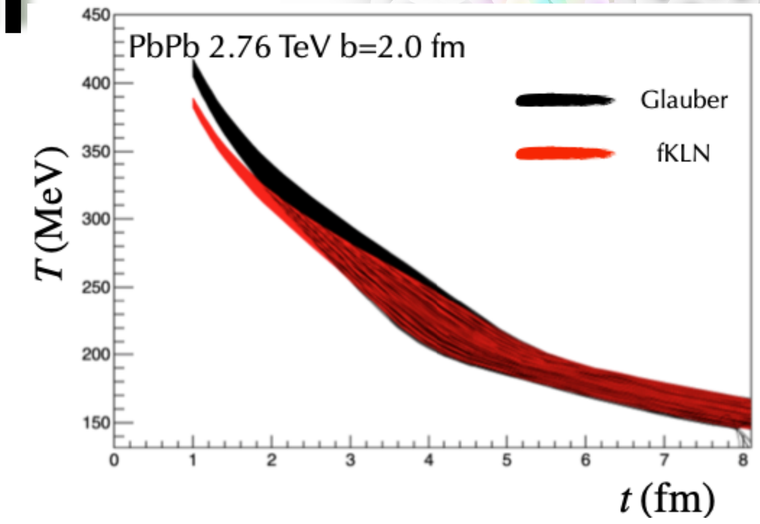
$$\omega_{\text{eff}} = \begin{cases} \frac{1}{2}\hat{q}_0 L^2 & \text{static medium} \\ 2\hat{q}_0 L^2 & \text{exponentially expansion} \\ 2\hat{q}_0 t_0 L & \text{Bjorken expansion} \end{cases}$$

Scaling laws don't work well over all energy range…

Central production points (|x|,|y| < 0.1 fm)



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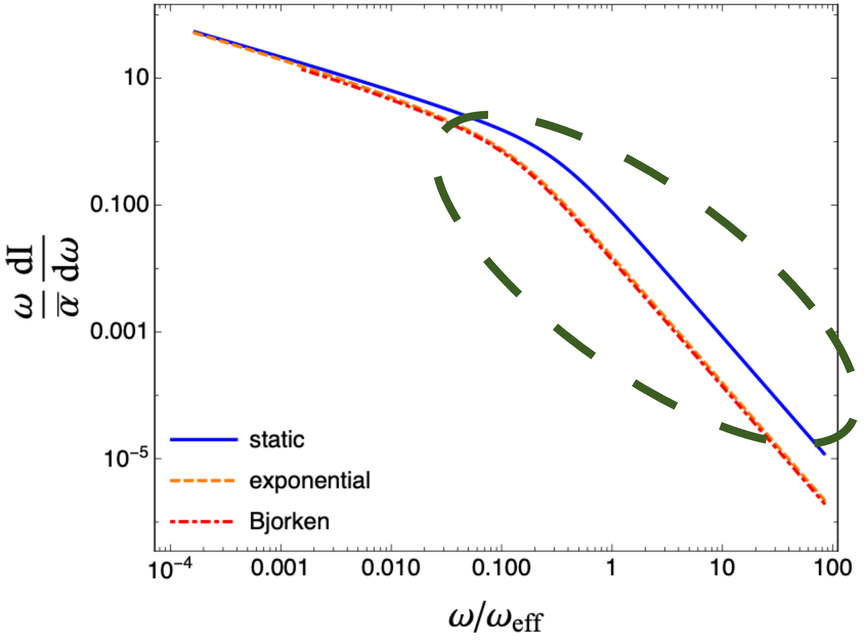

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$\hat{q}_0$ [GeV^3]	static	exponential	Bjorken
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optimal scaling	0.2	0.09	1.84
scaling by $\langle \omega_c \rangle$	0.2	0.1	3.33

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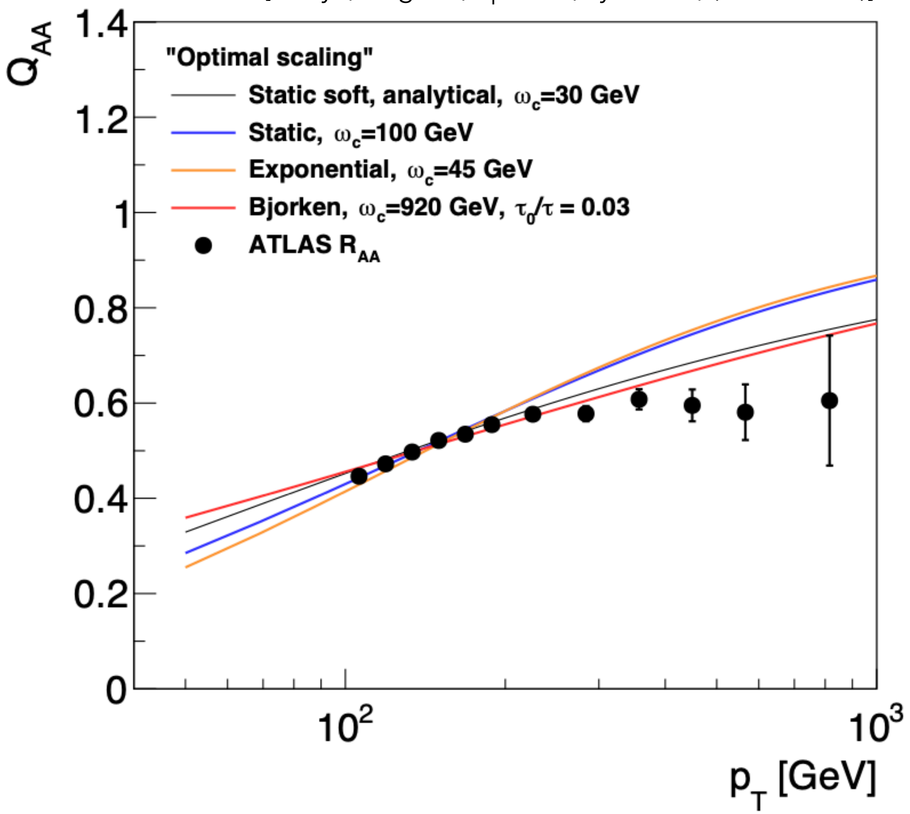

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Qualitative agreement with ATLAS R_{AA}.

Different transport coefficient values…

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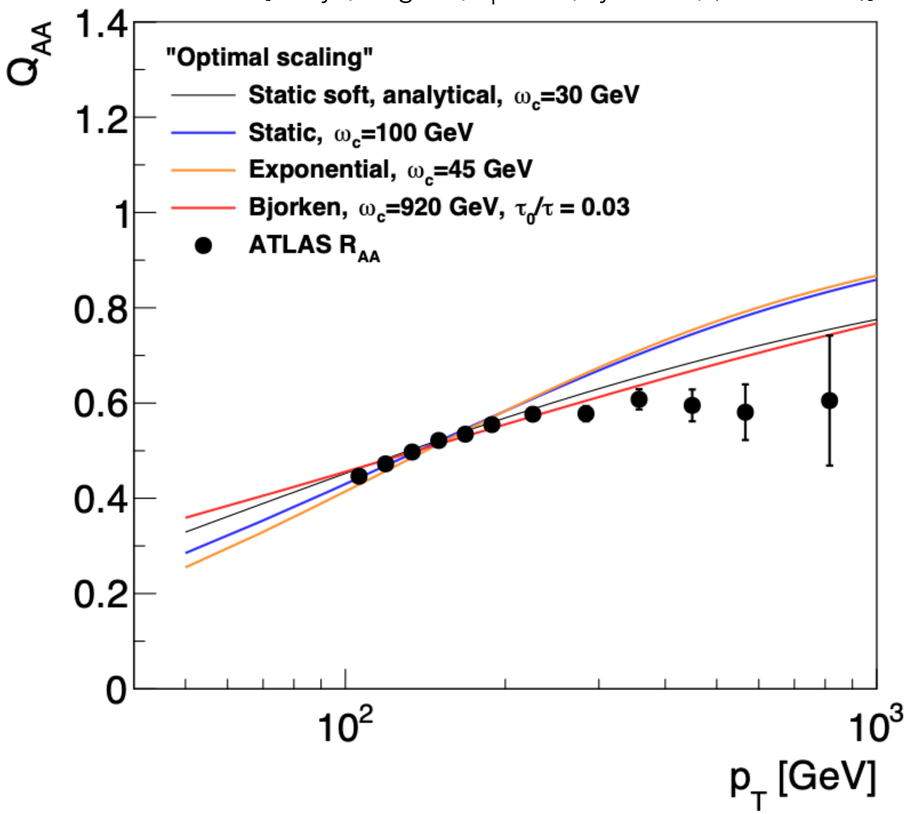

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[Andrés, LA, Dominguez, Gonzalez, Salgado (in preparation)]

- How about using a power-law equivalent medium evolution profile instead?
  - Medium density and Debye from hydro profile:

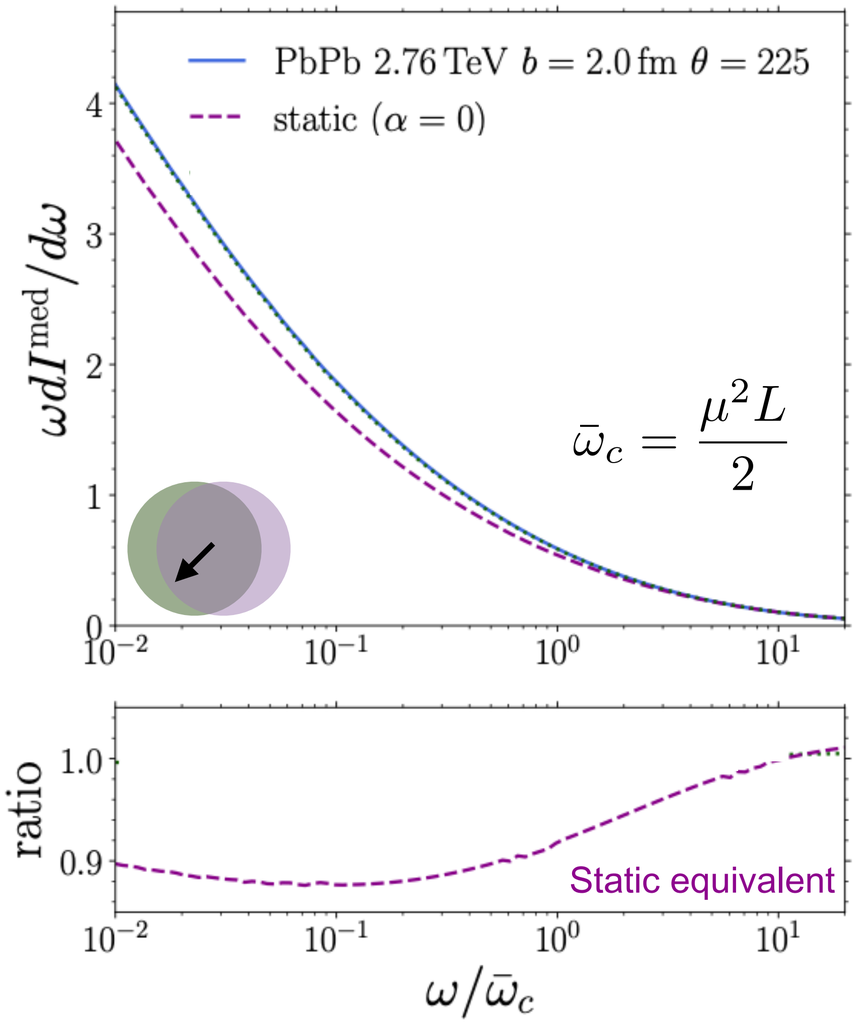
$$\mu^2_{hydro}(t) = k_2 T^2(t) \qquad n_{hydro}(t) = k_1 T(t)$$

  - Power-law spectrum equivalent of a medium profile:

$$\mu^2(t) = \frac{\mu'^2}{(t+t_0)^{2\alpha}} \qquad n(t) = \frac{n'_0}{(t+t_0)^{\alpha}}$$

  - Constants obtained from a new "scaling-law":

$$\int_0^{L_1} dt\, n(t) = \int_0^{L_2} dt\, n_{hydro}(t) \qquad \int_0^{L_1} dt\, t\, n(t)\, \mu^2(t) = \int_0^{L_2} dt\, t\, n_{hydro}(t)\, \mu^2_{hydro}(t)$$



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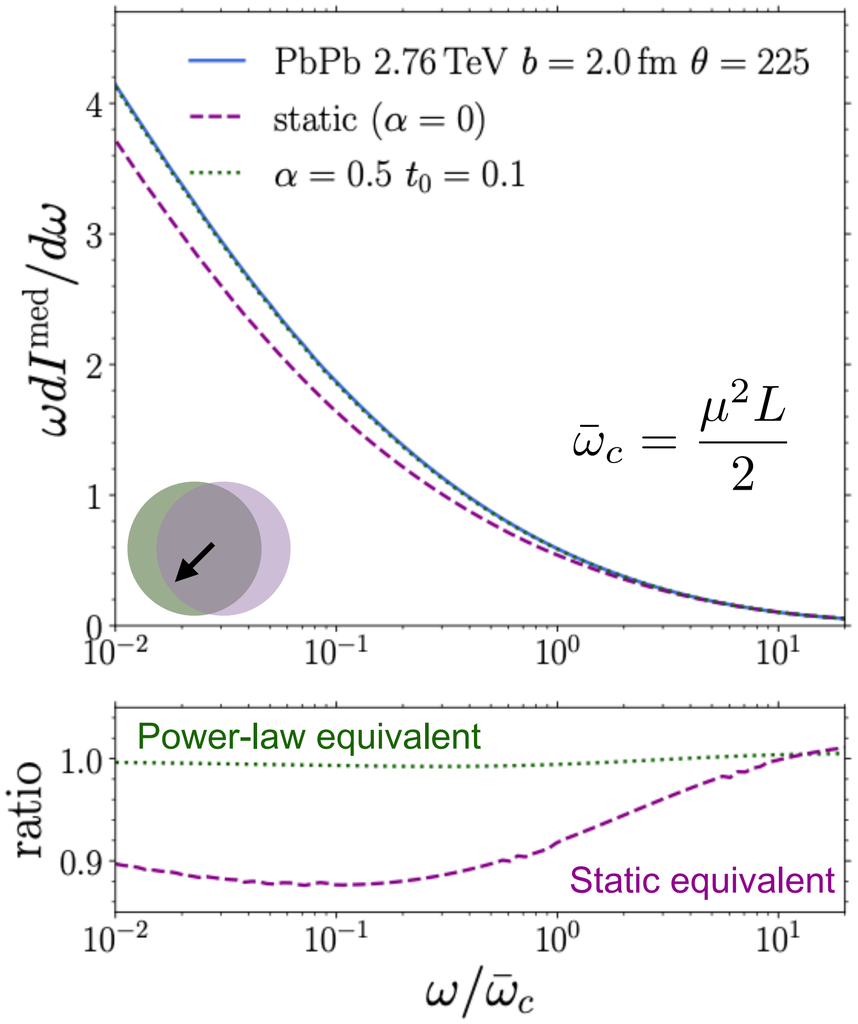

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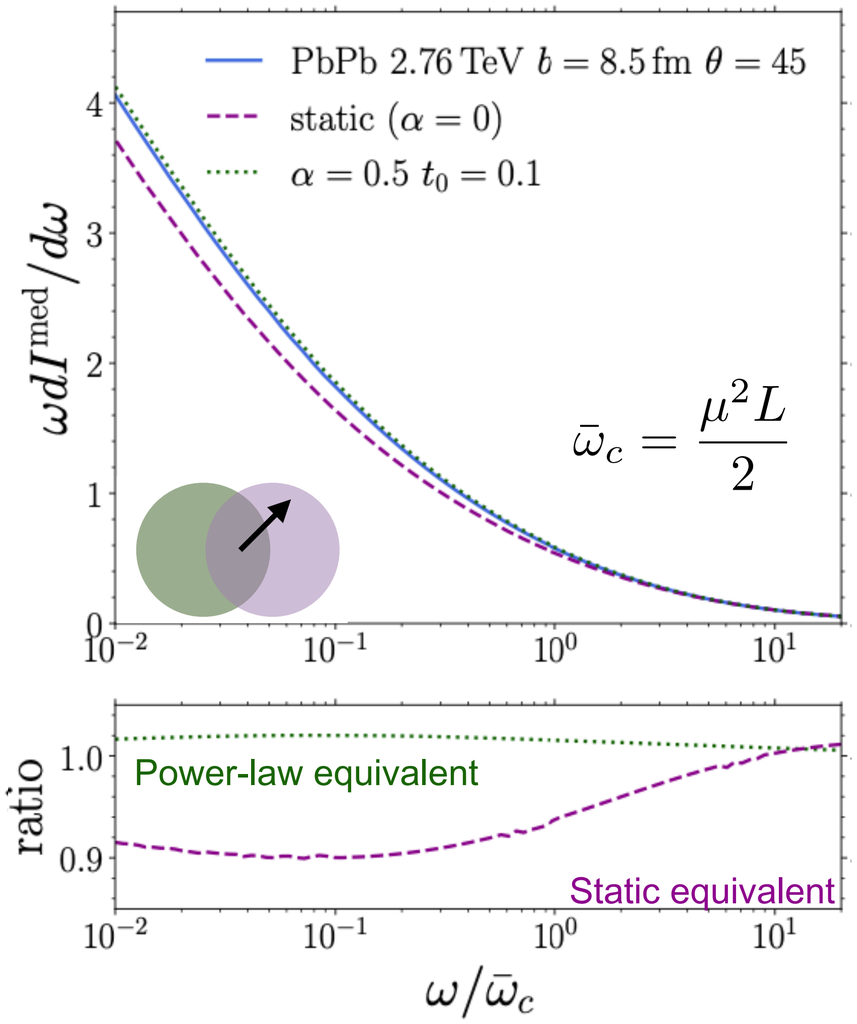

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Effects of an evolving medium

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- Equivalent evolving-medium works from better than static:
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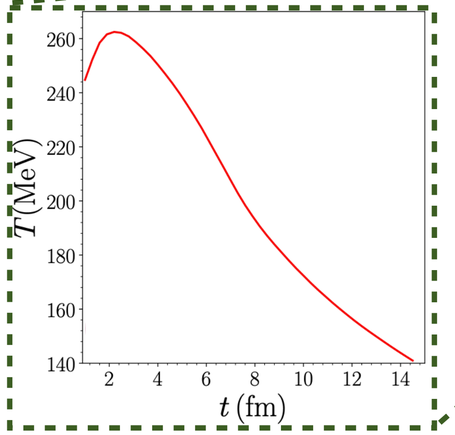
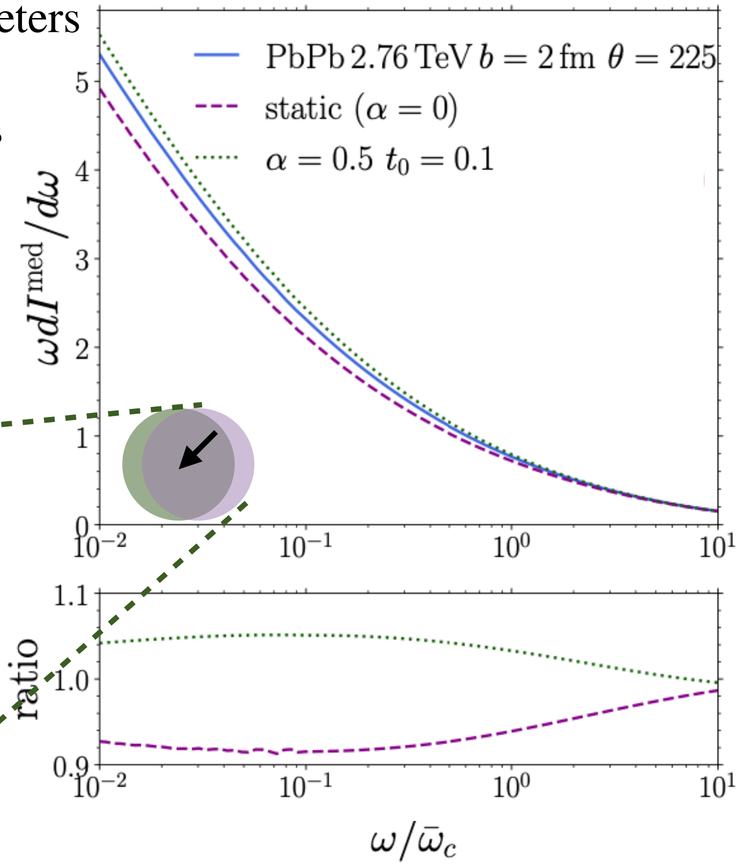
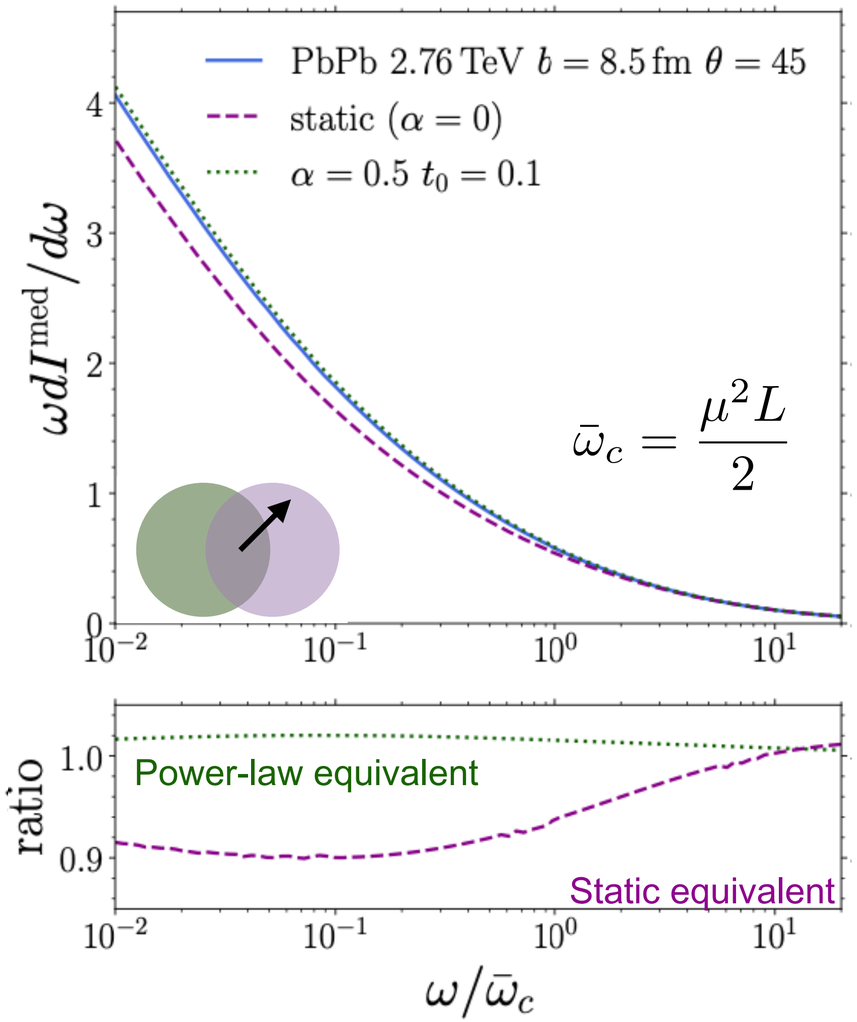
  - For different production points

See also Andrey Sadofyev's talk [later today]

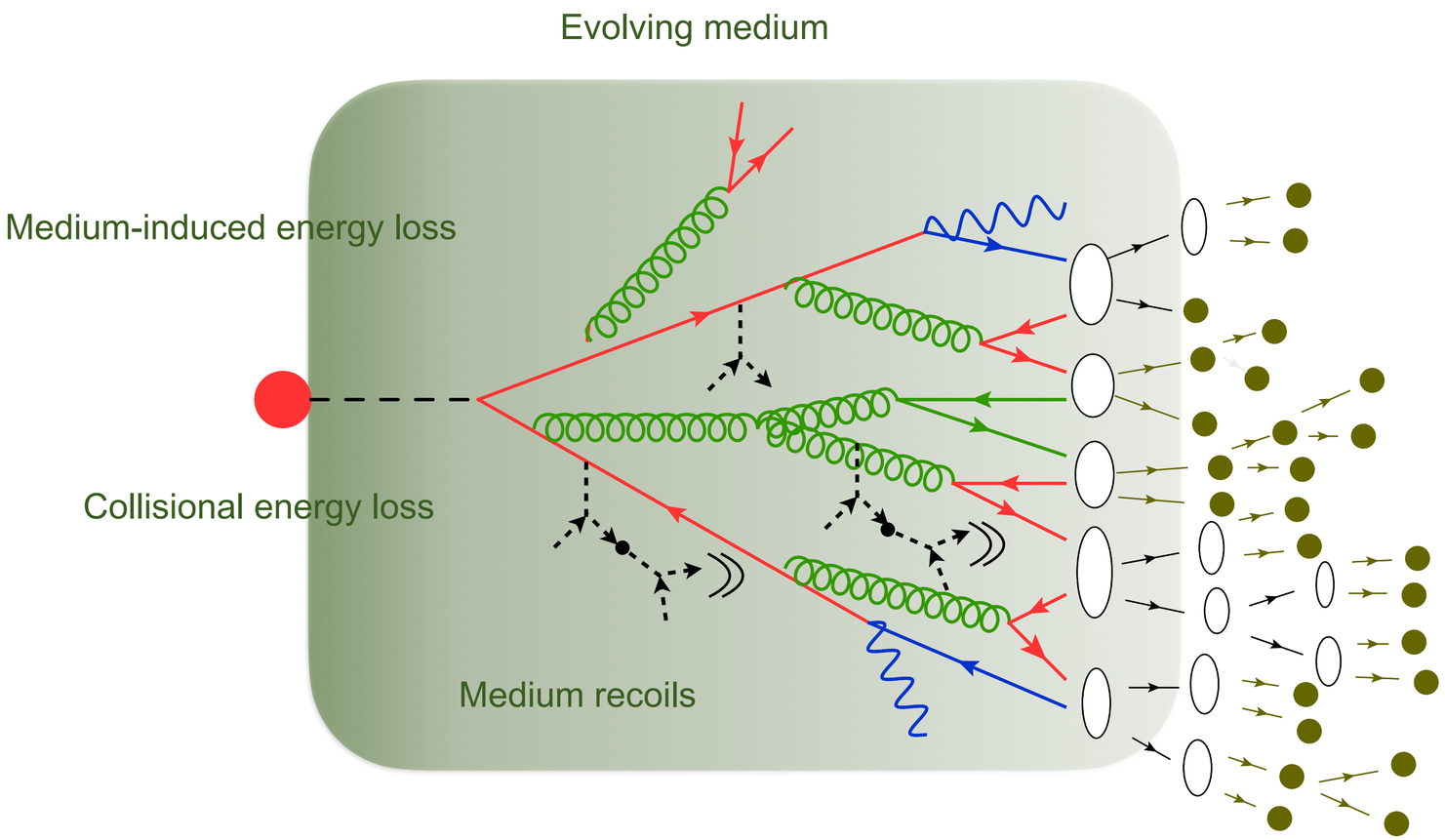






Parton showers: from high to low-energy

- Need to describe low-energy fragments and how do they thermalise with the medium



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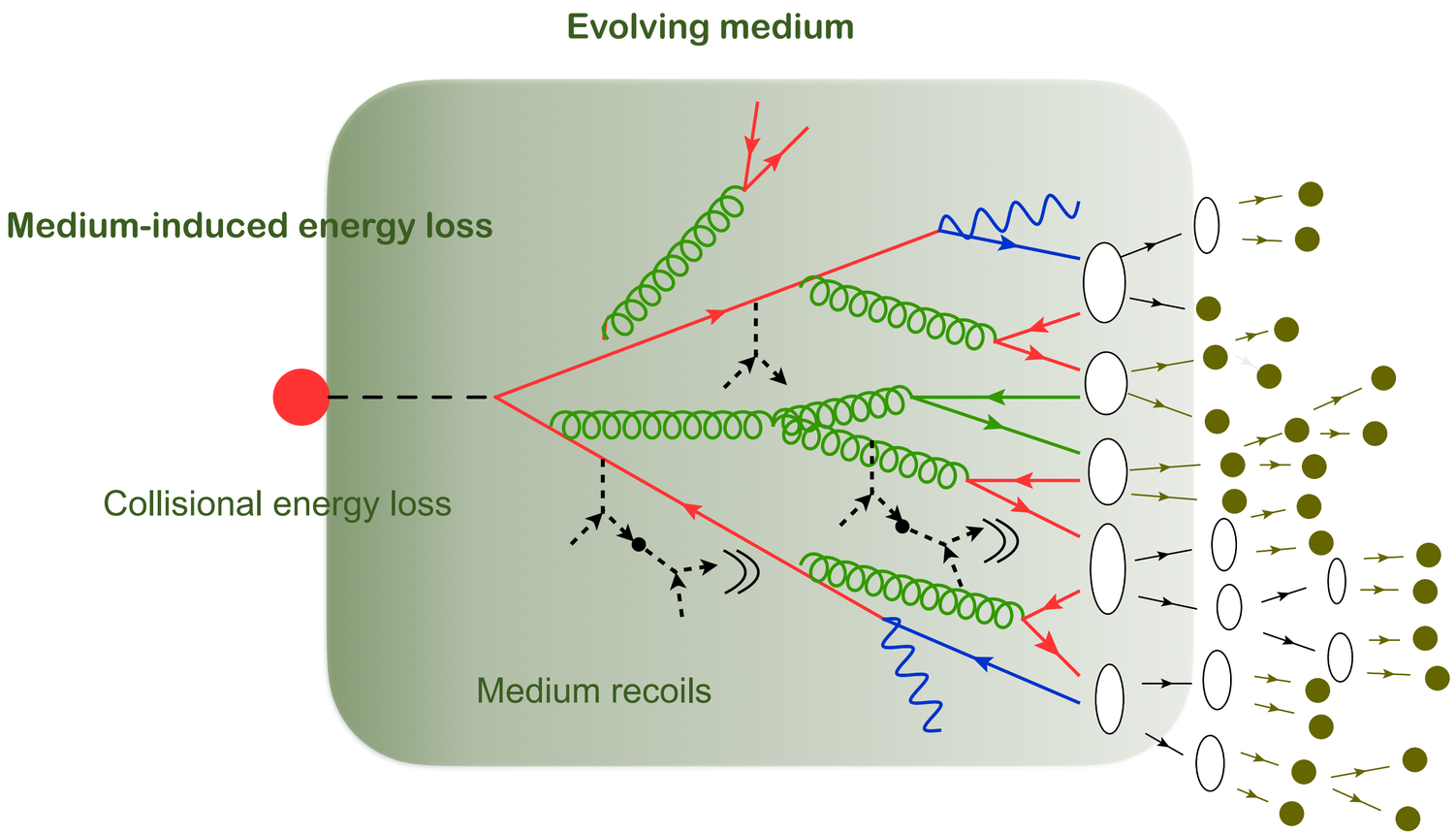

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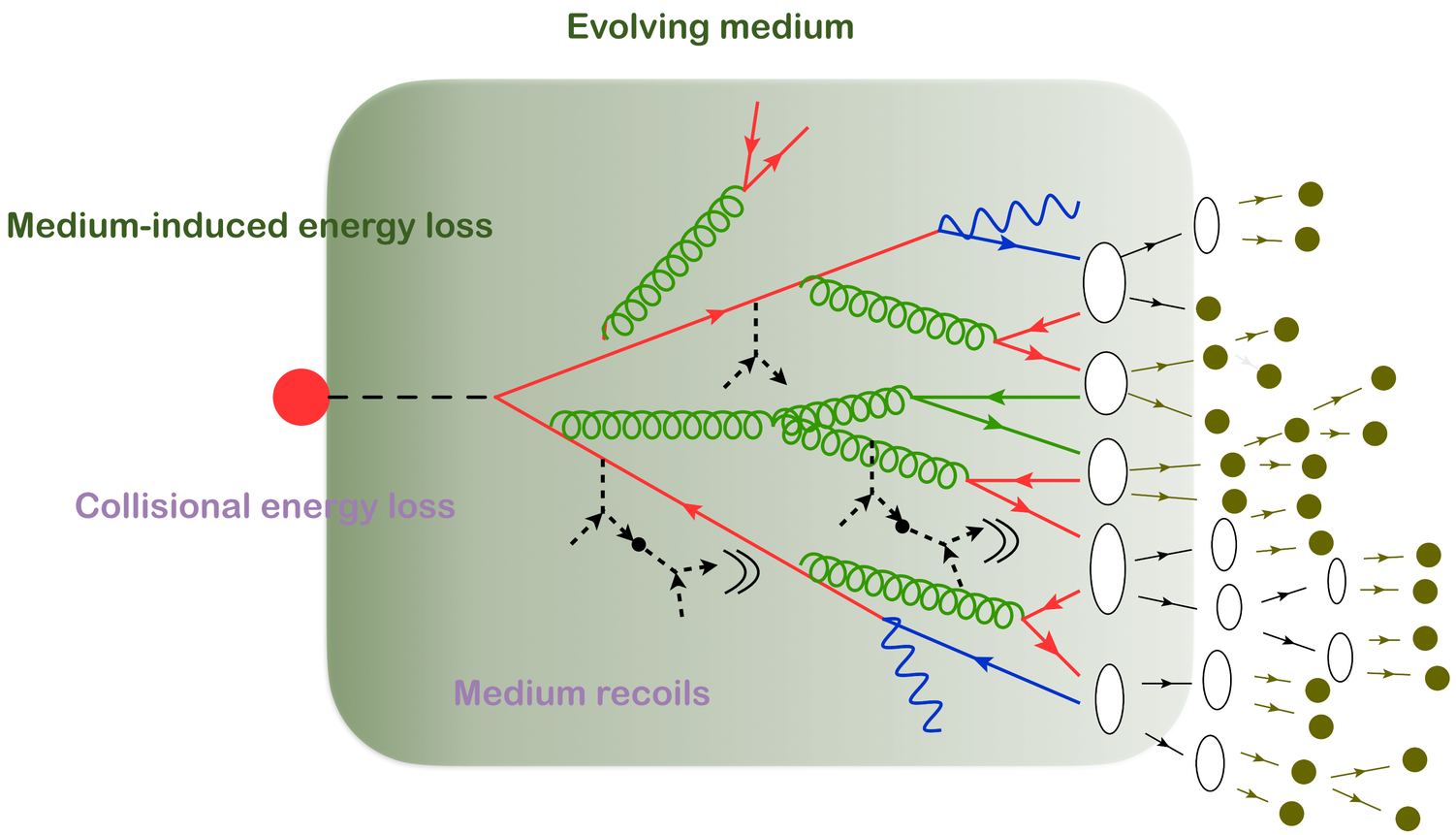

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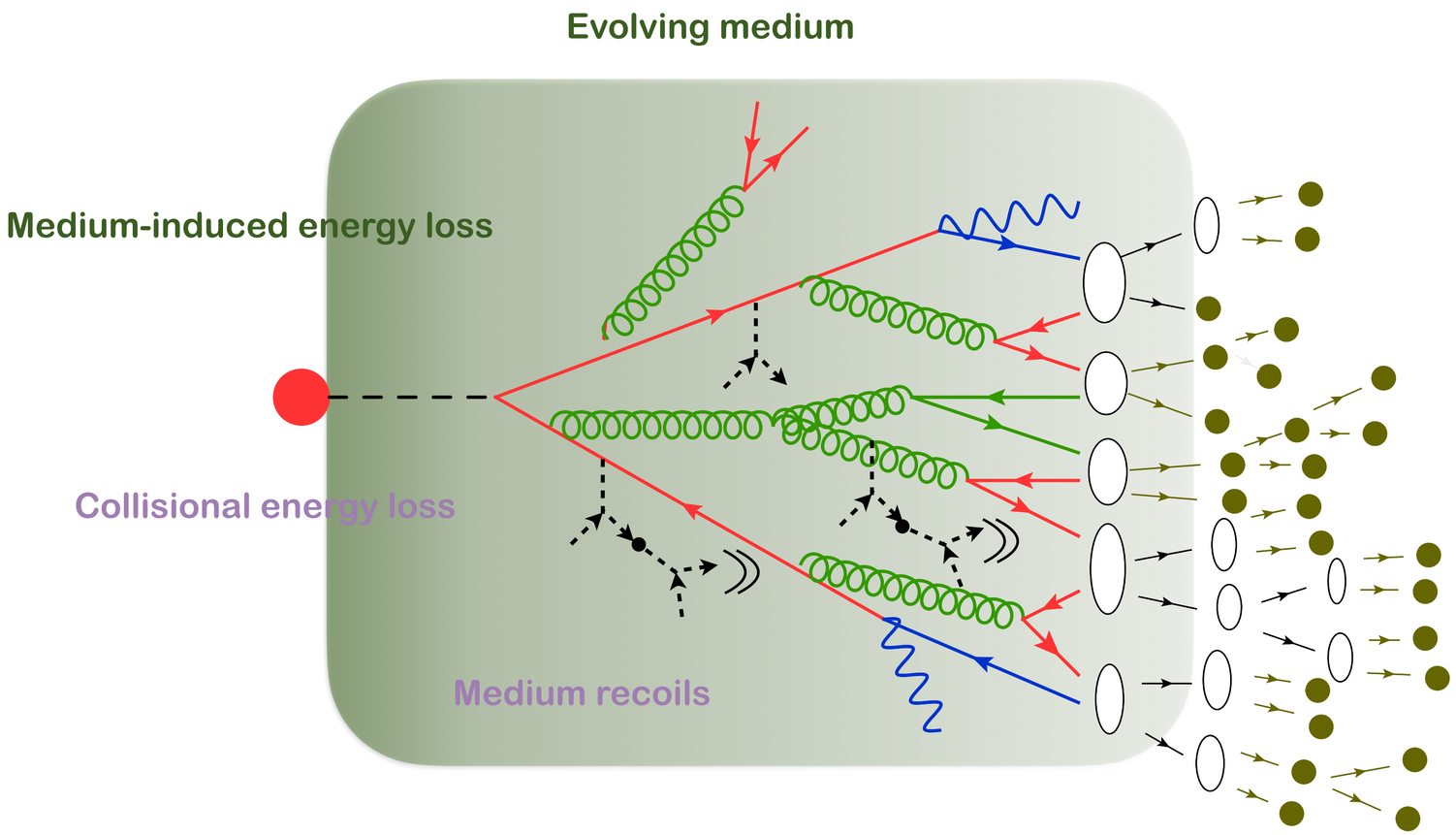

Transport models:

[He,Luo, Wang, Zhu, (1503.03313)]

E.g: Linear Boltzmann Model (LBT)

$$p \cdot \partial f_a(x,p) = \mathcal{C}_{\rm el}$$

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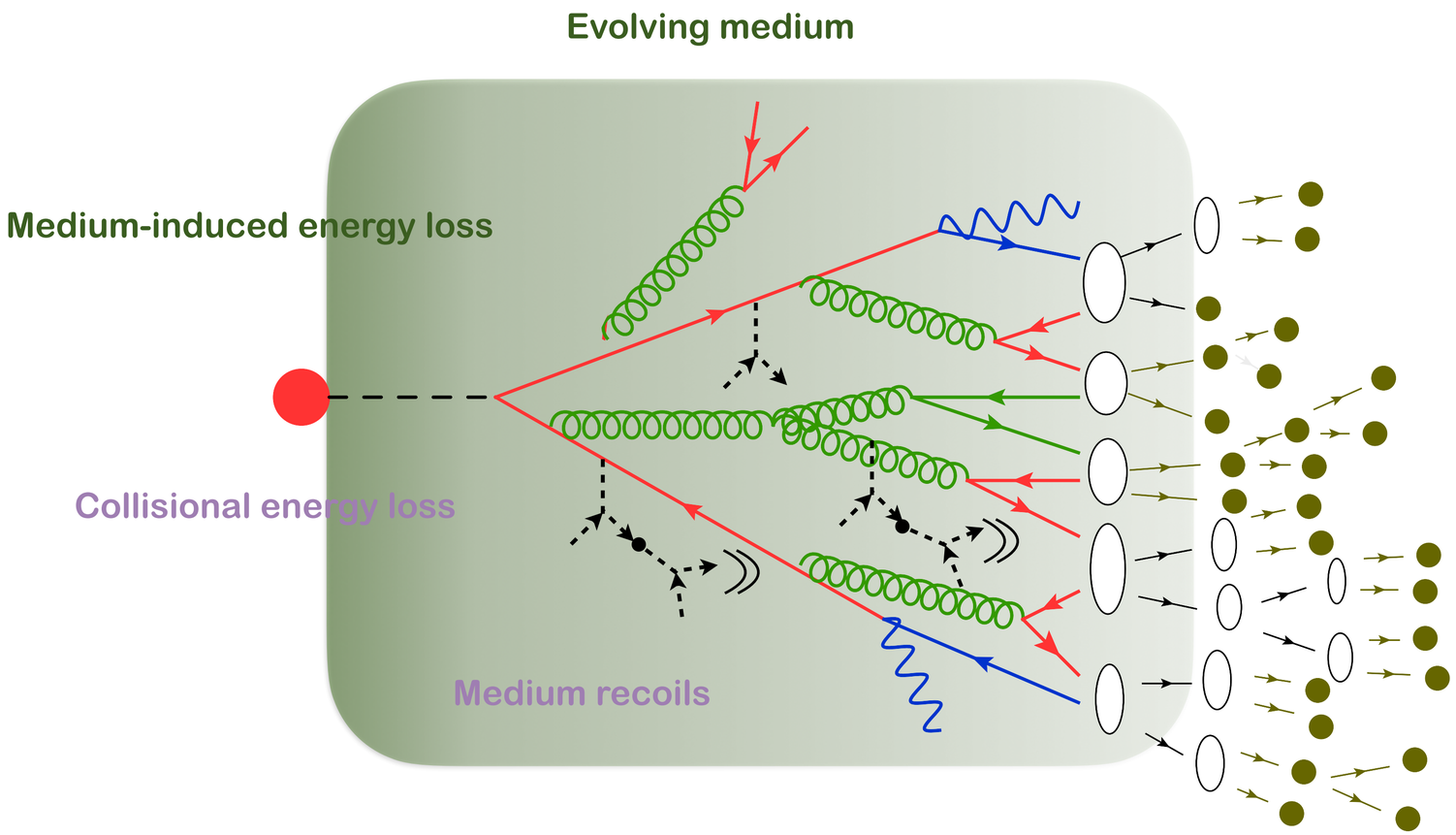

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[Wang, Zhu (1302.5874)]

+ Radiative Energy-loss (Higher-twist)

$$p \cdot \partial f_a(x,p) = E(\mathcal{C}_{\rm el} + \mathcal{C}_{\rm inel})$$

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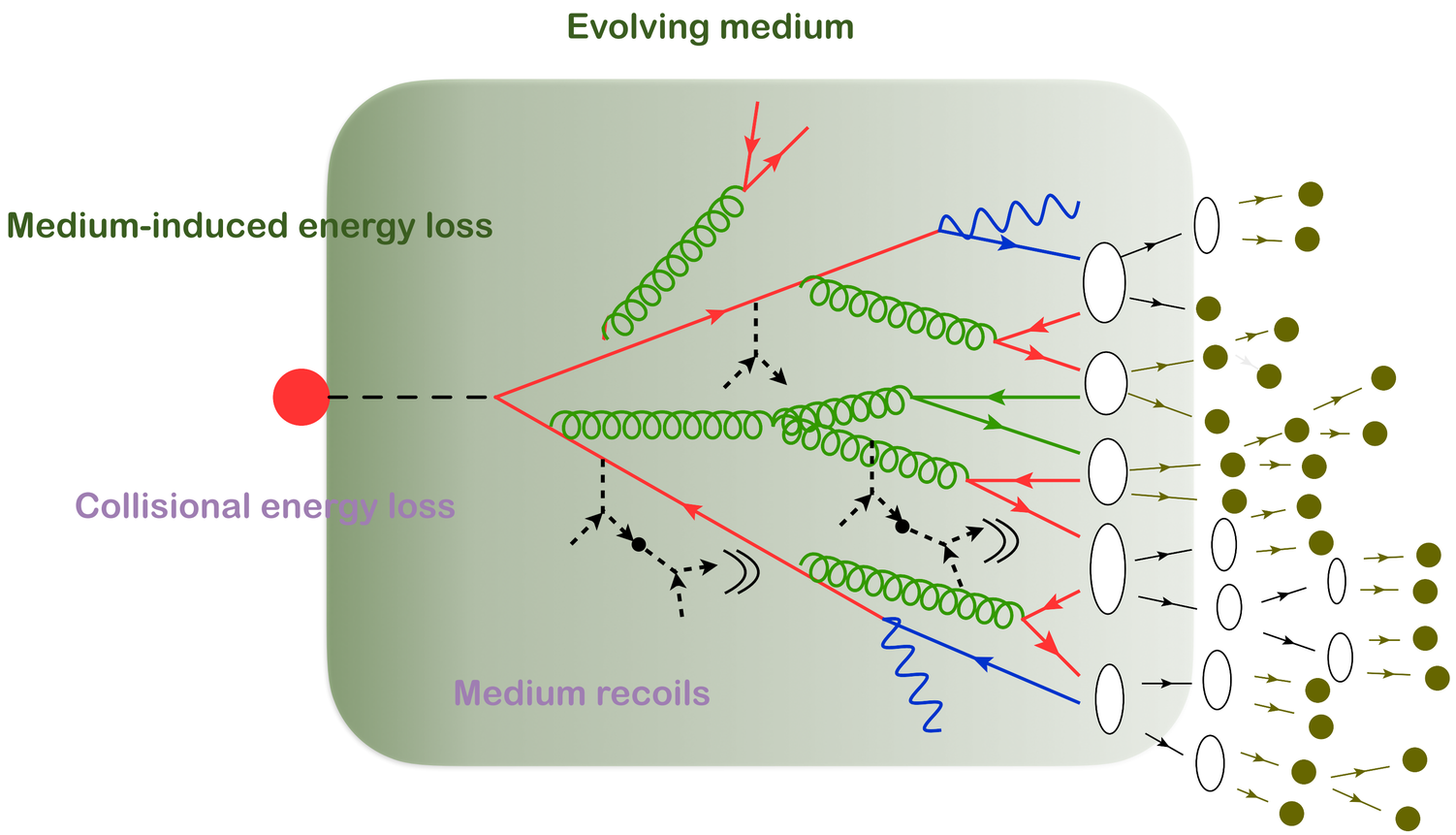


Transport models:

[He,Luo, Wang, Zhu, (1503.03313)]

E.g: Linear Boltzmann Model (LBT)

$$p \cdot \partial f_a(x,p) = \mathcal{C}_{\rm el}$$

[Wang, Zhu (1302.5874)]

+ Radiative Energy-loss (Higher-twist)

$$p \cdot \partial f_a(x,p) = E(\mathcal{C}_{\rm el} + \mathcal{C}_{\rm inel})$$

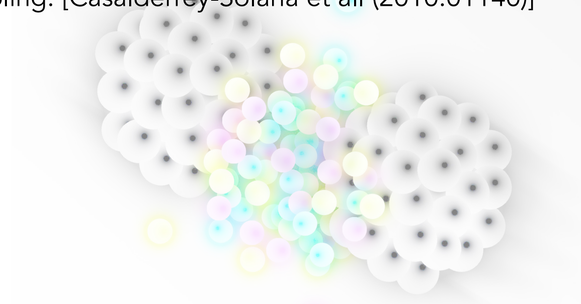
[Chen, Cao, Luo, Pang, Wang (2005.09678)]

+ (3+1)D viscous hydrodynamical model

$$\partial_\mu T^{\mu\nu} = J^\nu$$

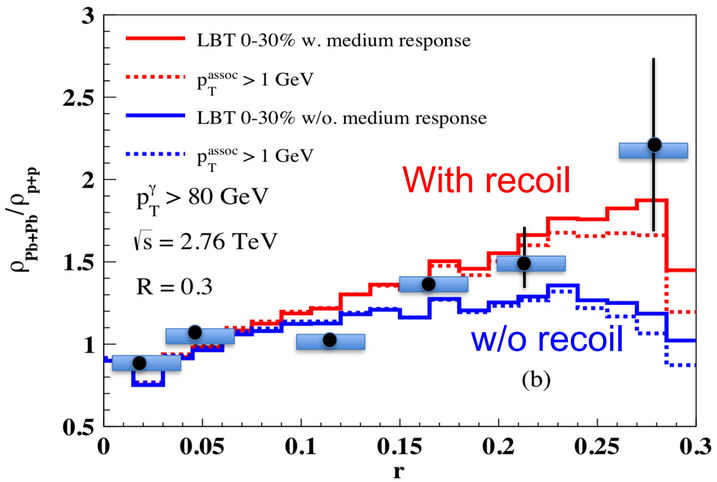
CoLBT-hydro model
(simultaneous simulations of jet propagation
and jet-induced medium excitations)

Also within strong-coupling: [Casalderrey-Solana et all (2010.01140)]



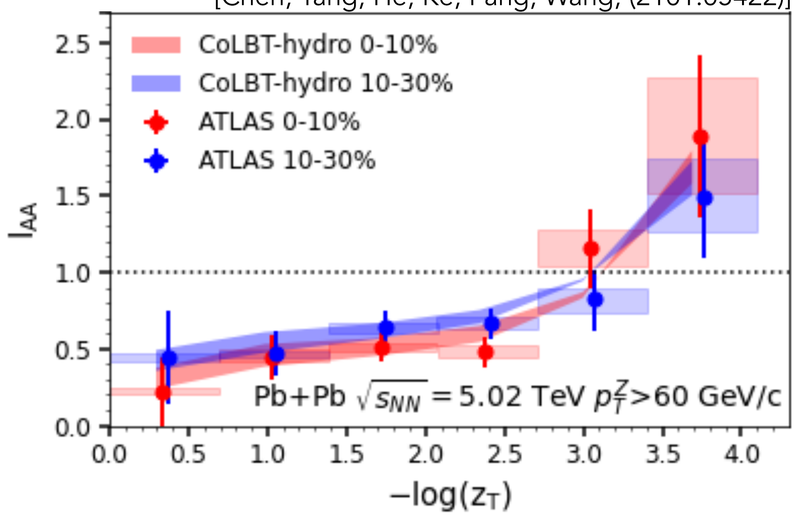
Medium response effects

- Soft fragments originated from the jet-induced medium excitations compatible with enhancement of soft fragments at large distances from the jet axis (jet radial profile & jet fragmentation function)



[Luo, Cao, He, Wang, (1803.06785)]

[Chen, Yang, He, Ke, Pang, Wang, (2101.05422)]



How to identify medium-response from effects from medium-induced radiation?

Also within strong-coupling: [Casalderrey-Solana et all (2010.01140)]

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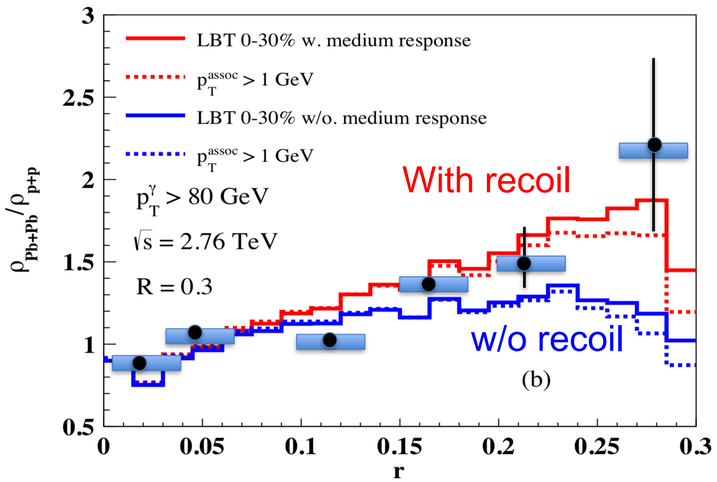

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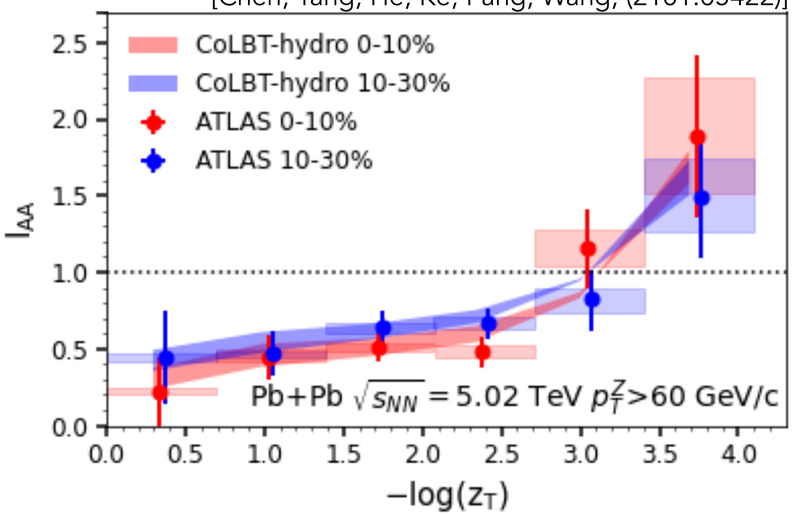
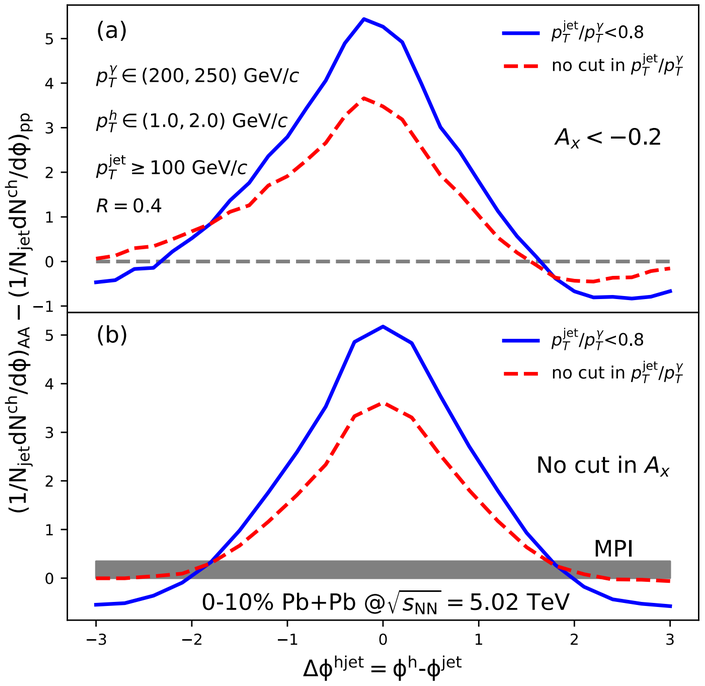


[Chen, Cao, Luo, Pang, Wang (1704.03648)]



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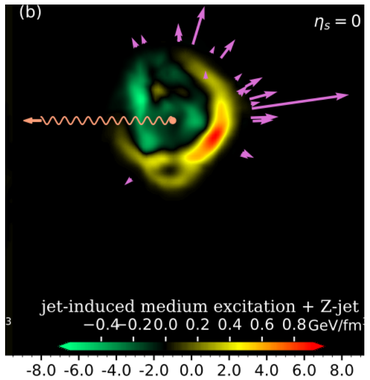
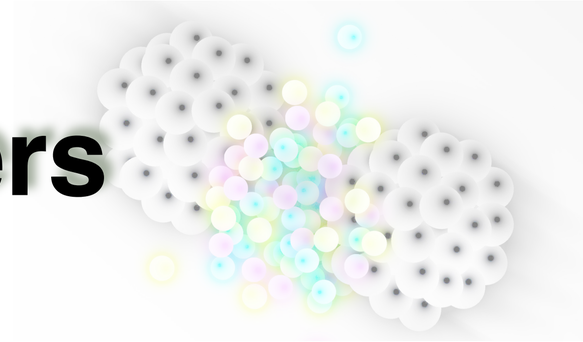
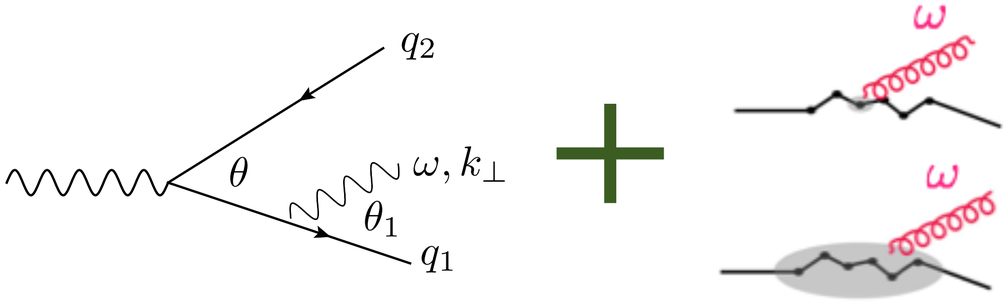
Signal of diffusion wake?

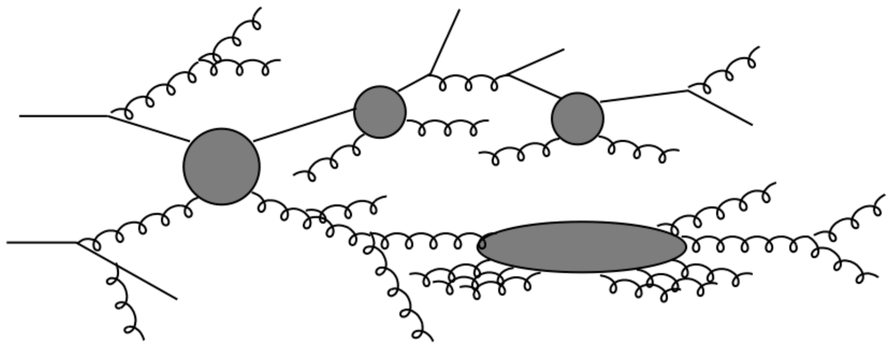


Improving "medium" parton showers



- Multiple emitters:
  - Interference effects suppressed (+ anti-angular ordering)
  - Non-instantaneous emissions will induce modifications to the vacuum parton shower structure:





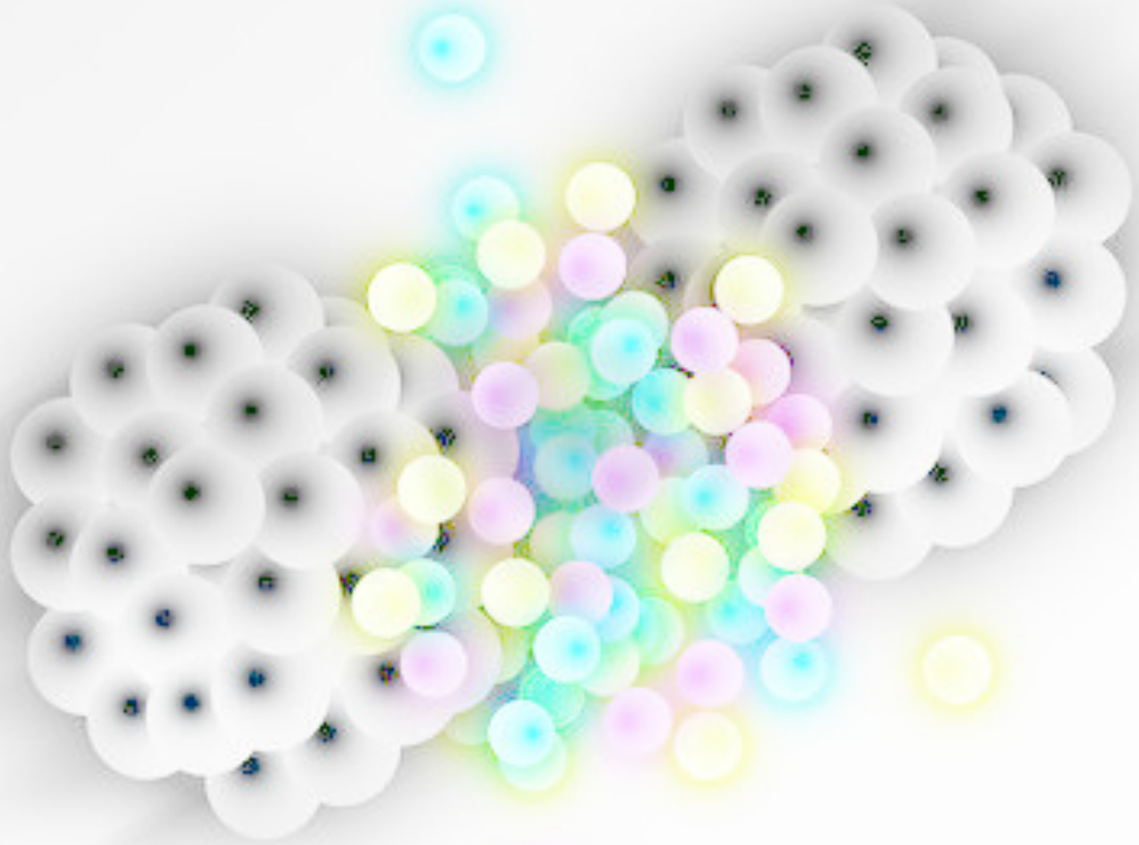
$$dN_q^{\omega\to 0} \sim \alpha_s C_R \frac{d\omega}{\omega}\frac{\sin\theta d\theta}{1-\cos\theta}\left[\Theta(\cos\theta_1-\cos\theta)+\Delta_{med}\Theta(\cos\theta-\cos\theta_1)\right]$$

Analytic: [Casalderrey-Solana, Iancu, Mehtar-Tani, Salgado, Tywoniuk (1105.1760, 1210.7765)]

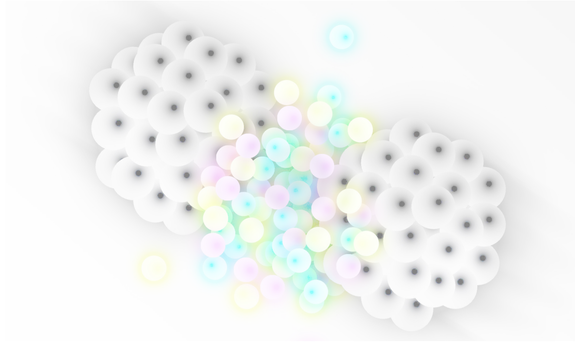
Monte Carlo: [Q-PYTHIA, JEWEL] [Armesto, Cunqueiro, Salgado (0907.1014), Zapp (1311.0048)]

See also Miguel Escobedo's talk [Thursday]

New experimental handles

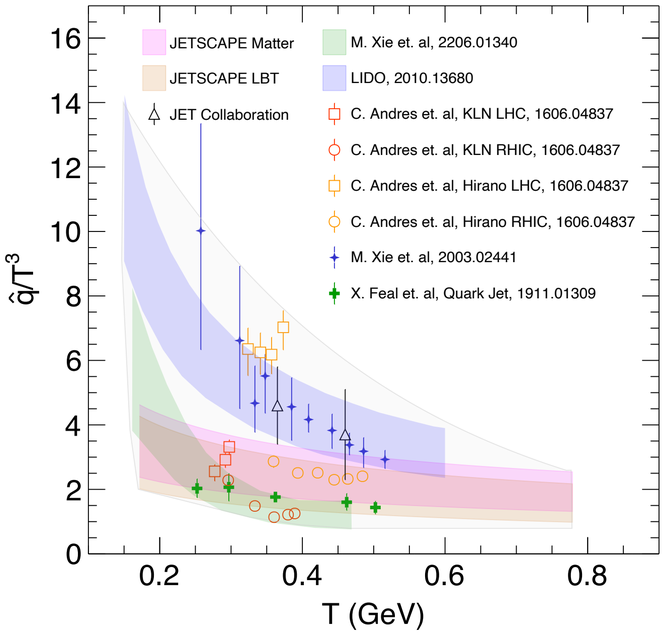


From particles to jets



- How can we access QGP-related information?

[Adapted from Yi Chen (QM2019)



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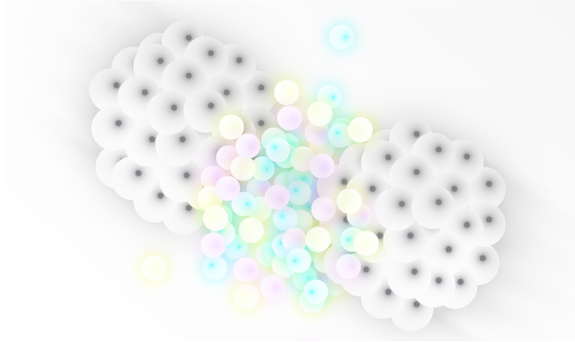

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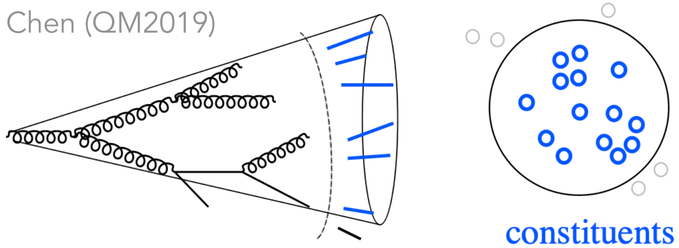
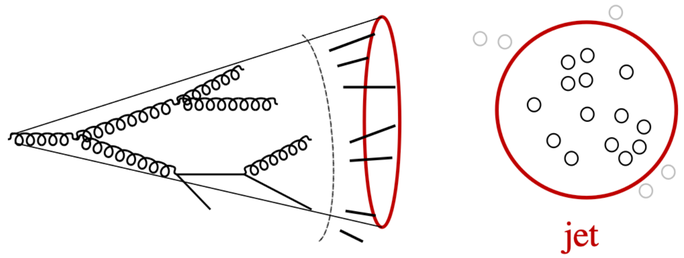
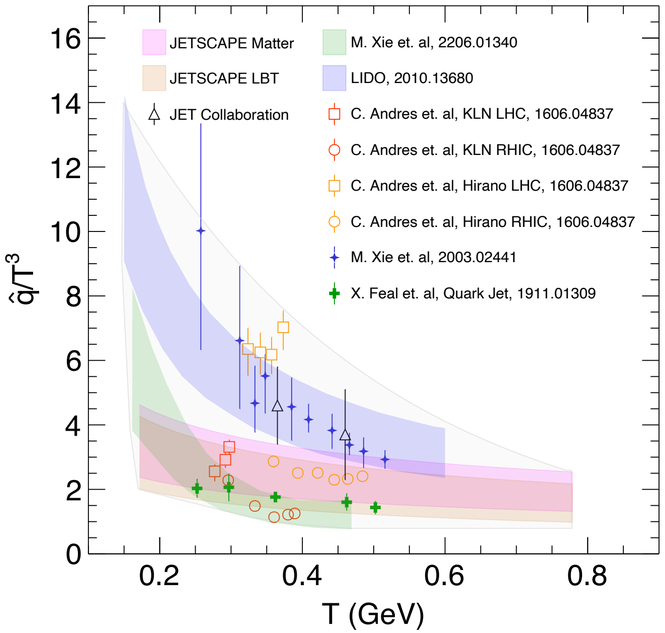


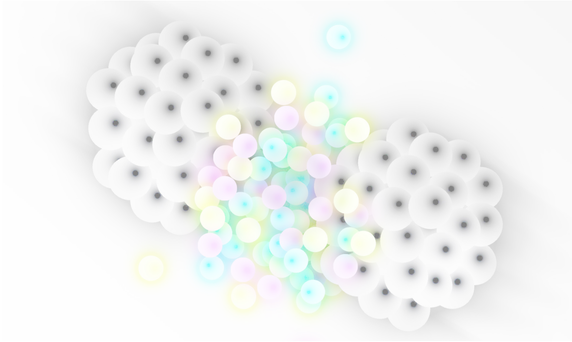


However:
- Susceptible to hadronization effects…



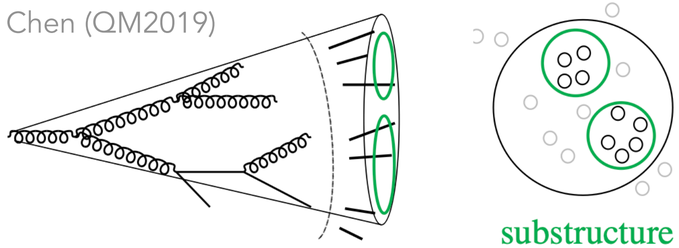
However:
- Sensitive to average quantities…

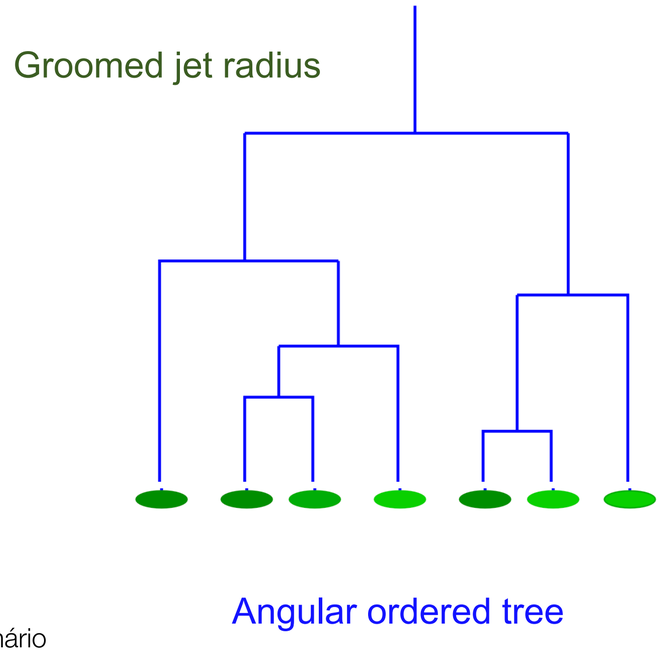
From jets to jet substructure

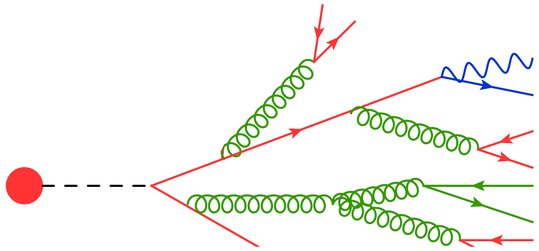


- Jet substructure: tool to understand novel in-medium QCD features

[Adapted from Yi Chen (QM2019)







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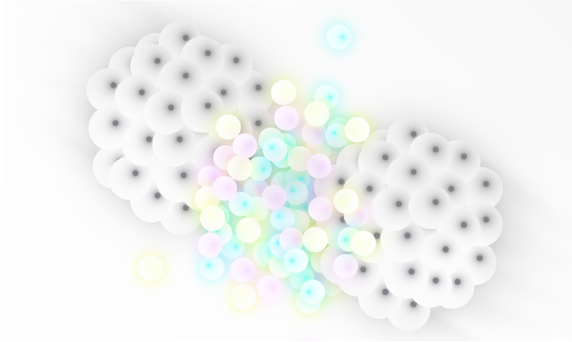

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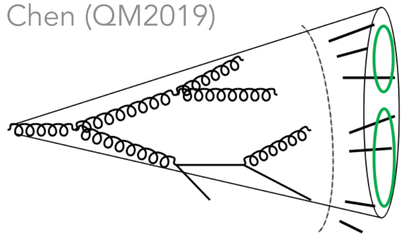
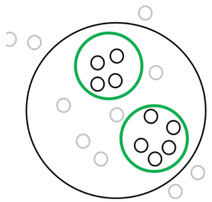
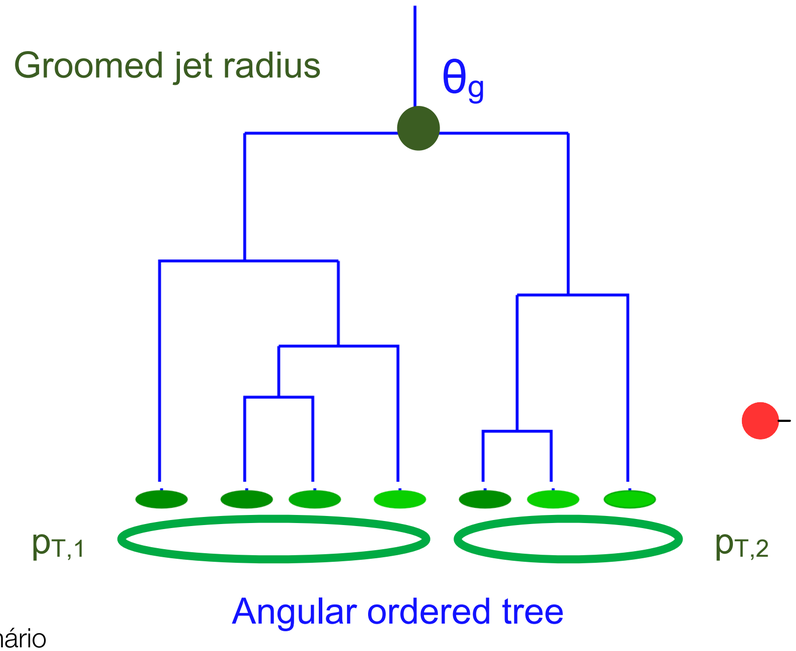
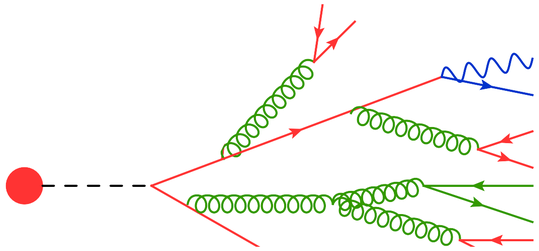




$$\kappa^{(a)} = \frac{1}{p_{t,\mathrm{jet}}} z(1-z) p_t \left(\frac{\theta}{R}\right)^a$$

[Mehtar-Tani, Soto-Ontoso, K. Tywoniuk (1911.00375)]





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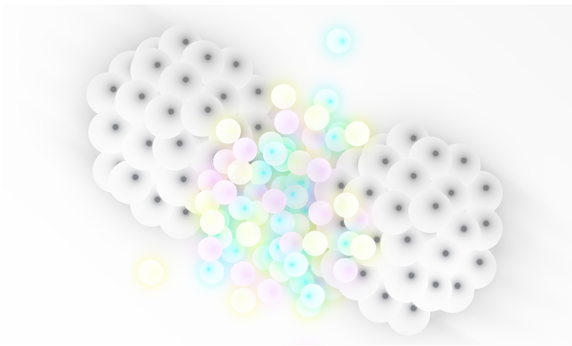

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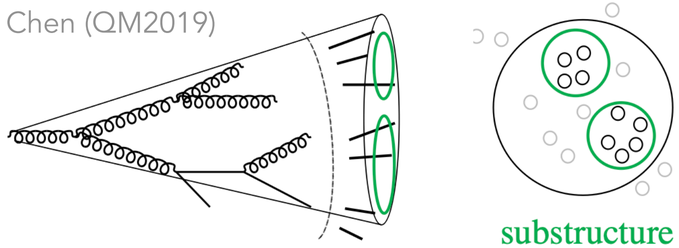

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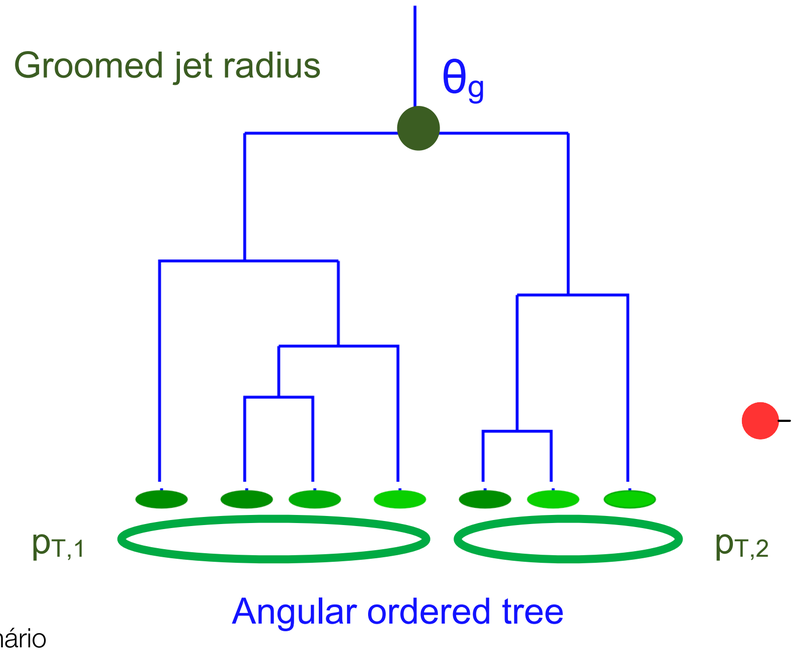
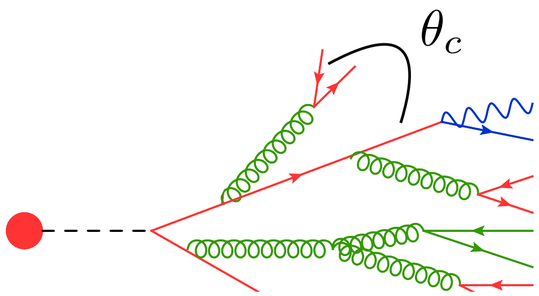
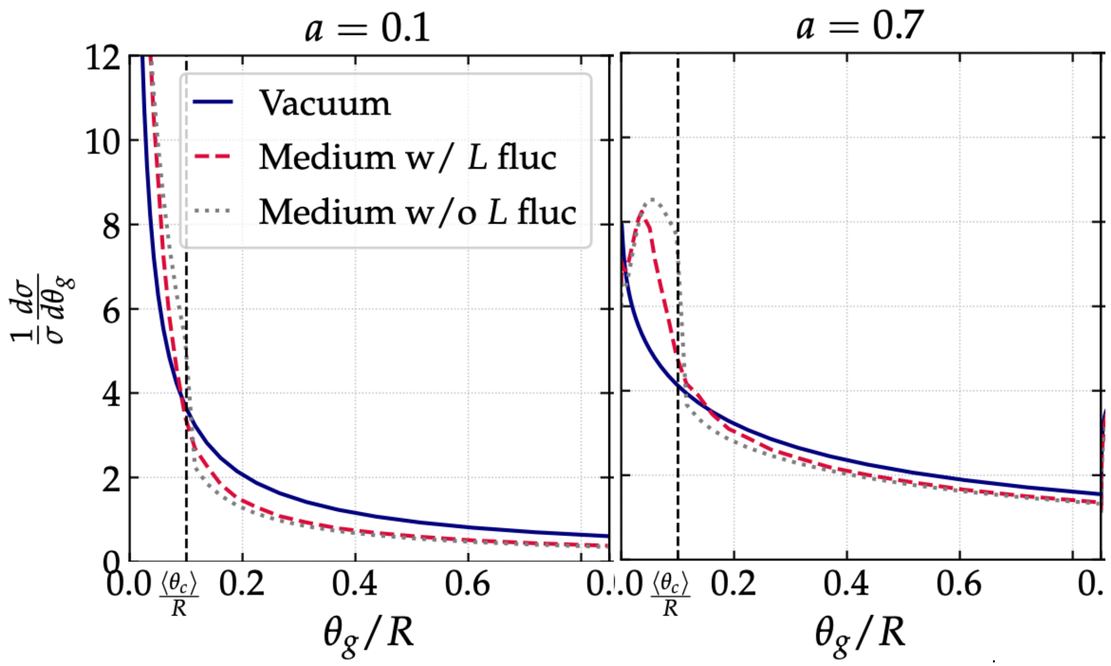
[Caucal, Soto-Ontoso, Takacs (2111.14768)]

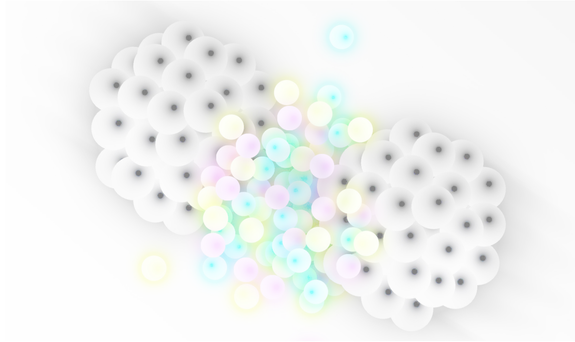


Sensitive to decoherence angle?





From jets to jet substructure

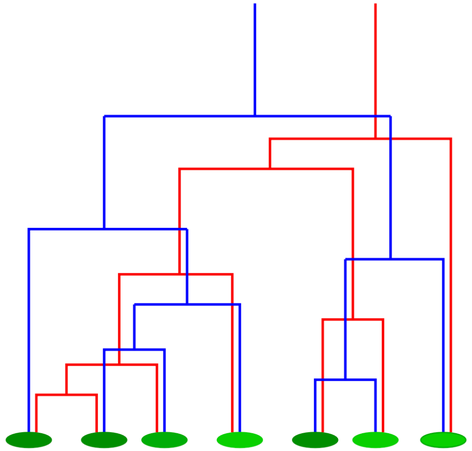


- Jet substructure: tool to understand novel in-medium QCD features

[LA, Cordeiro, Zapp (2012.02199)]

Recluster jets with generalised-k_T (p = 0.5)

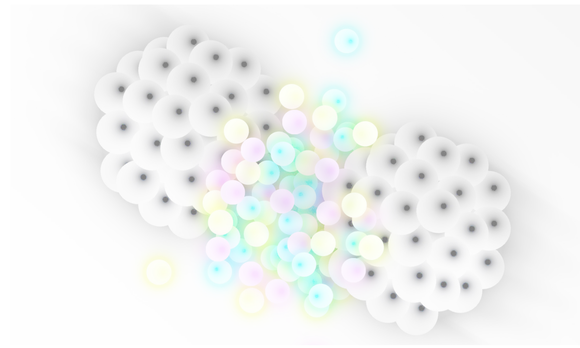
$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \xrightarrow{p = 0.5} d_{ij} \sim p_T \theta^2 \sim \frac{1}{\tau_{form}}$$



Angular-ordered tree

Time-ordered tree

From jets to jet substructure



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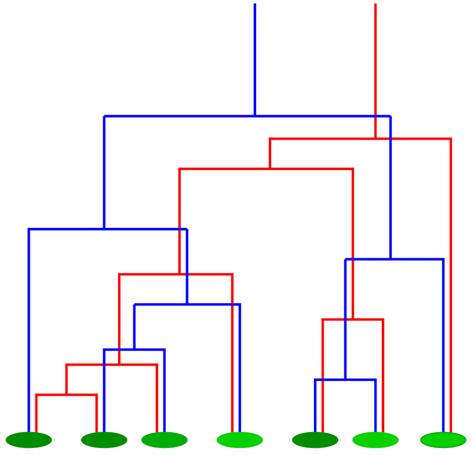
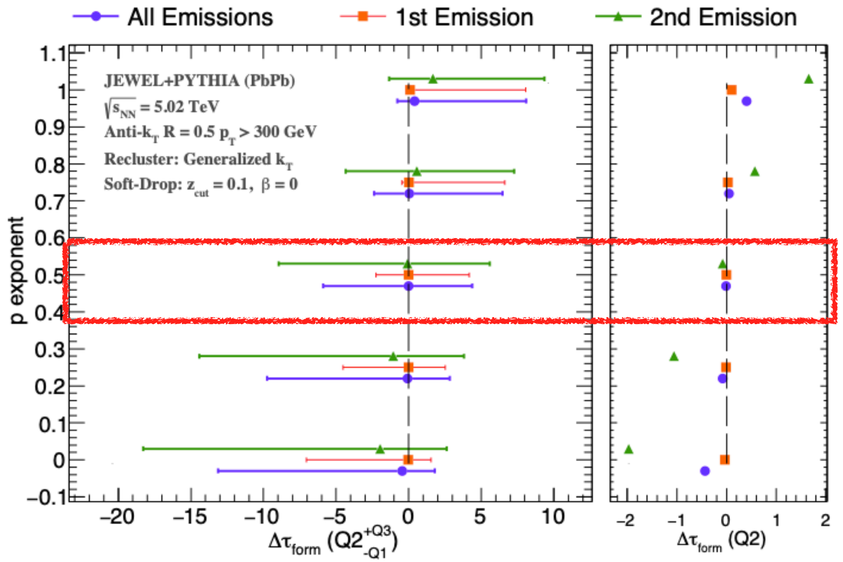
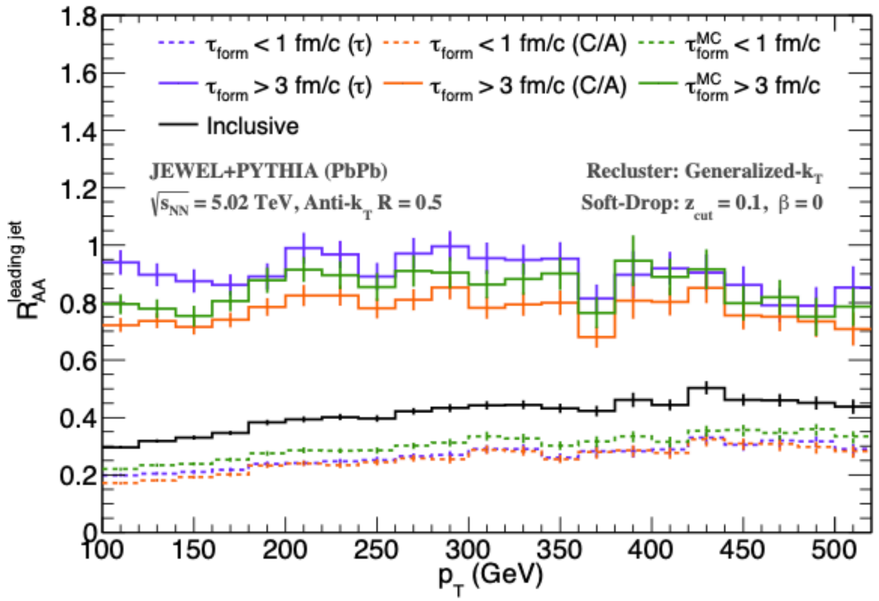


Angular-ordered tree

Time-ordered tree



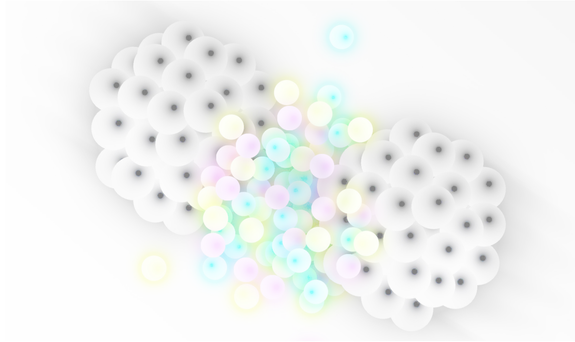
$$\Delta\tau_{\rm form} = \tau_{\rm form}^{\rm Parton\ Shower} - \tau_{\rm form}^{\rm Unclustering}$$



Maximizes correlation between Monte Carlo truth and jet re-clustering

"Late" jets experience less energy loss

From jets to jet substructure



- Jet substructure: tool to understand novel in-medium QCD features

[LA, Rodriguez, Zapp (in preparation)]

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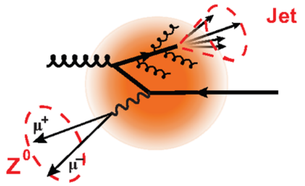
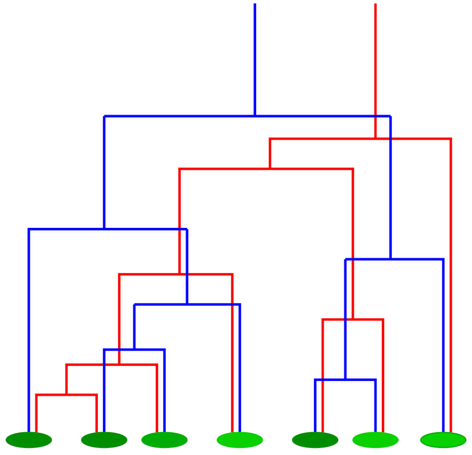
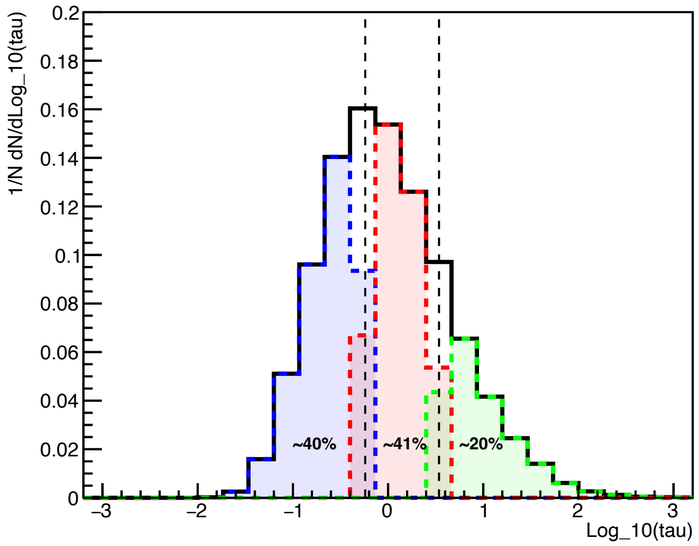




Angular-ordered tree

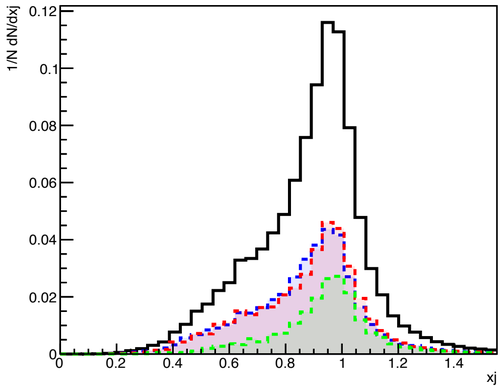
Time-ordered tree

Log(τ_1) distribution

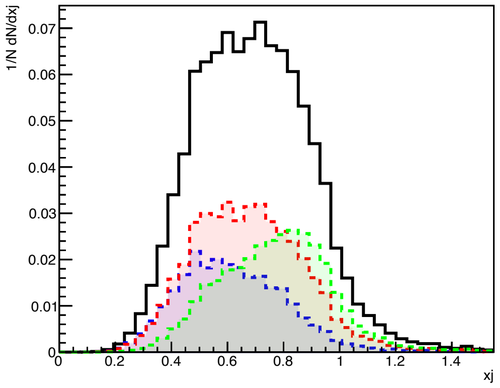


Boson-Jet Momentum imbalance

pp Z+jet jewel+pythia



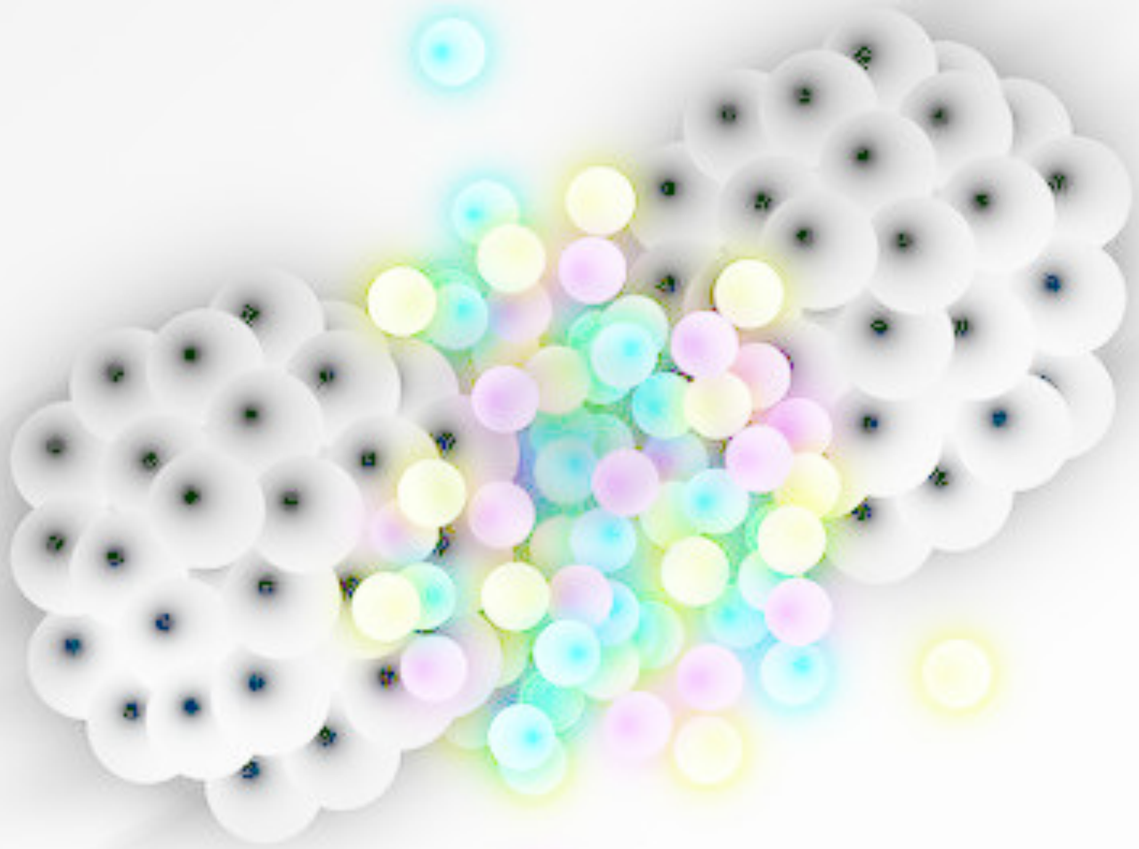
PbPb Z+jet jewel+pythia



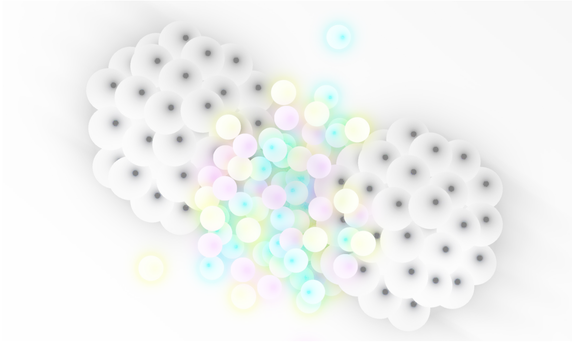
Formation time classes ⇔ In-medium energy loss classes

Time-differential measurements with jets?

Wrapping up

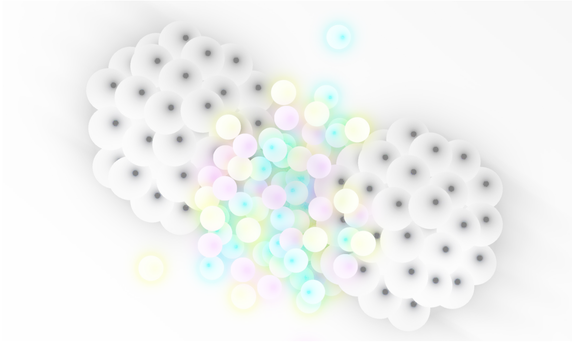


Summary



- **Jet Quenching description:**
  - Improving theory **accuracy** in the description of single-gluon radiative energy loss
  - Description beyond single-gluon emission to **full parton showers** by combining theoretical results and Monte Carlo modelling
  - **Jet-medium response** addressed by transport models providing a unique framework to address both elastic and inelastic processes
- **Jet Quenching phenomenology:**
  - Novel jet observables that identify in-medium QCD processes and address the effects of a **fast evolving medium**
  - Still missing a MC implementation of most recent theory results on jet observables…

Summary



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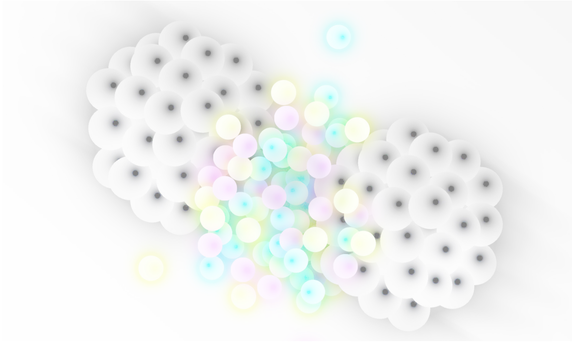
Thank you!

Acknowledgments



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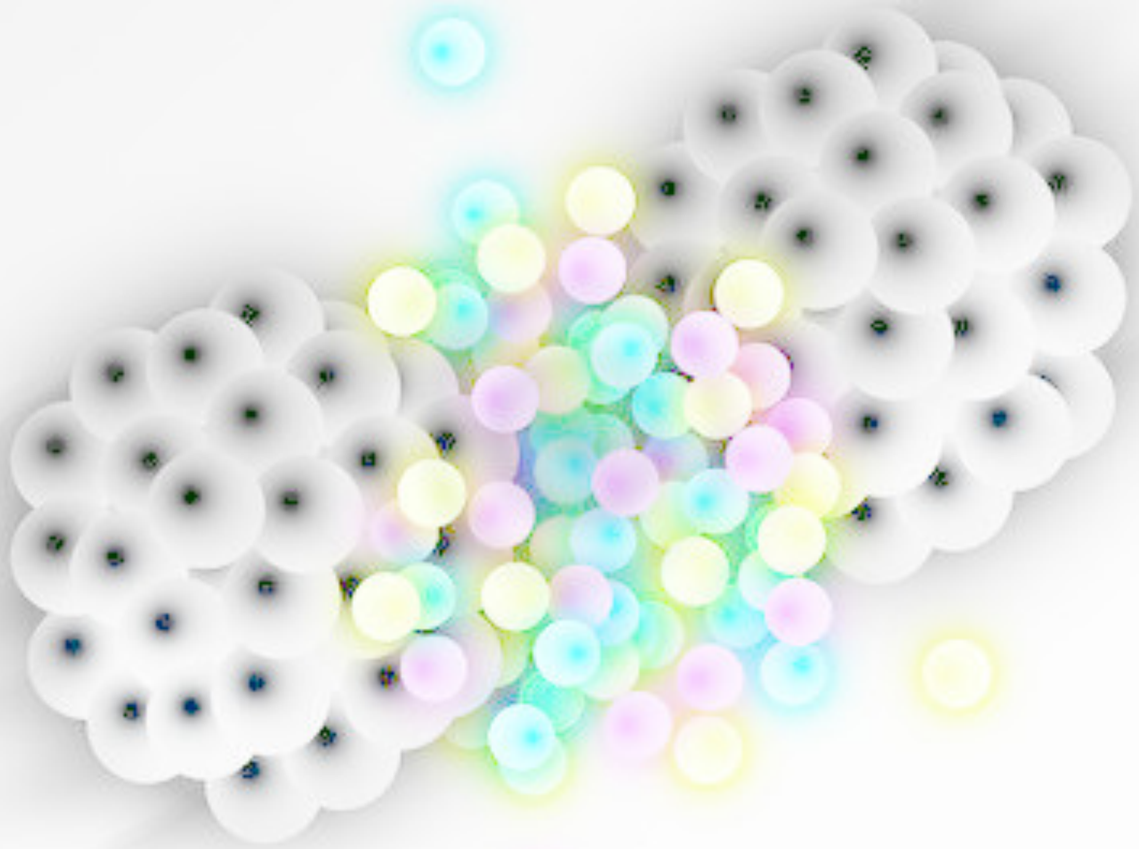
TÉCNICO LISBOA

Backup Slides

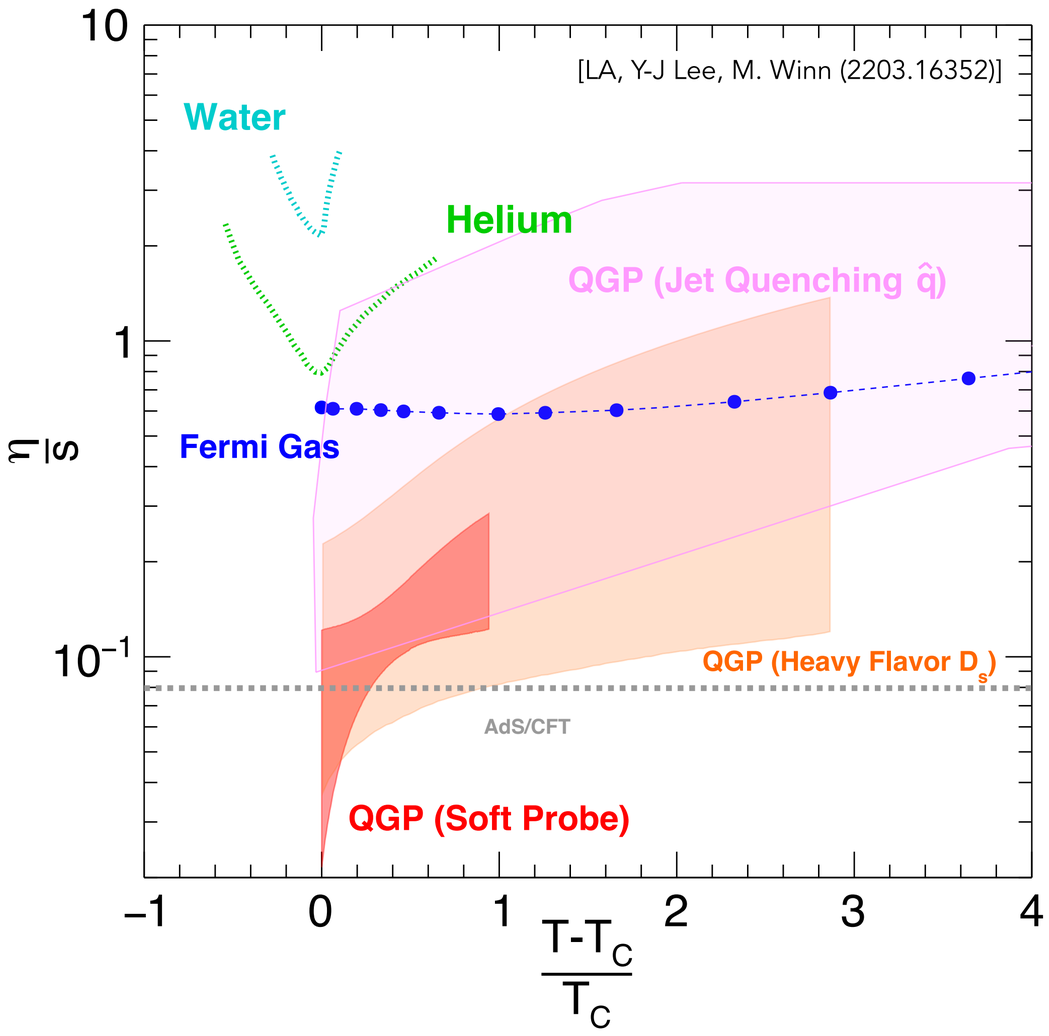


Soft vs Hard

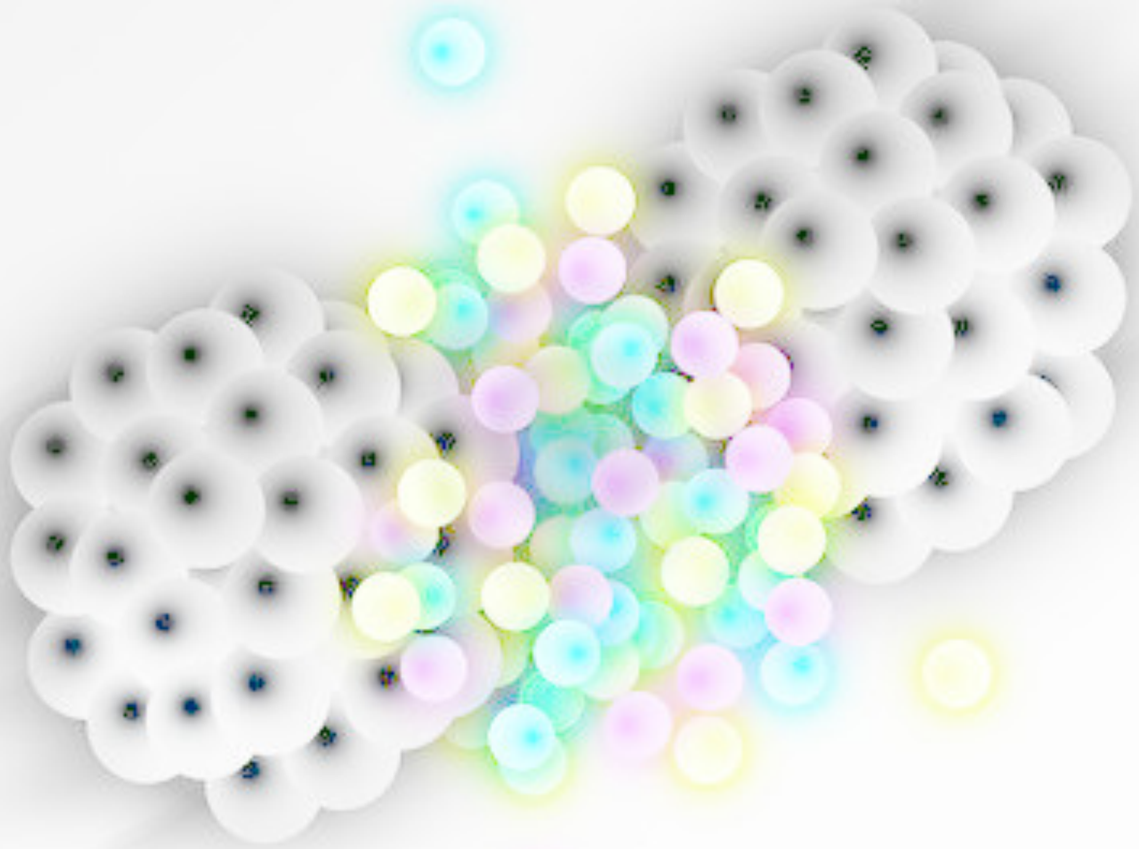
- Compilation of the specific shear viscosity as a function of temperature of the medium.

$$\frac{\eta}{s} = \frac{Ds(2\pi T)}{4\pi k}$$

$$\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}$$

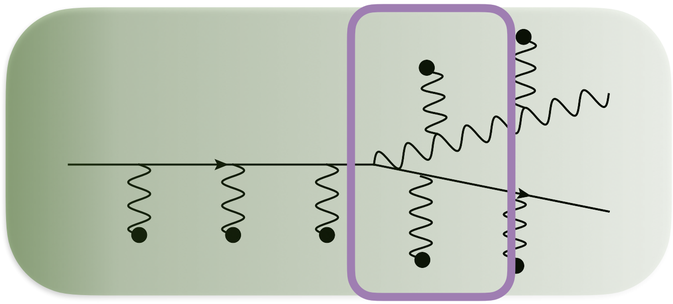


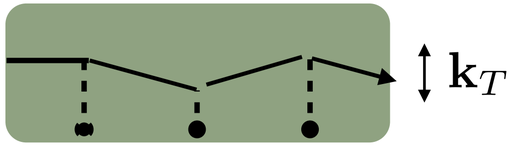
Improving theoretical control



Medium-induced radiation

- Accumulation of momenta enhances gluon radiation:
  - In addition to energy loss, parton also undergoes transverse momentum diffusion
    - Medium-induced transverse momentum broadening





Transport coefficient:

$$\hat{q} = \frac{\langle k_T \rangle}{\lambda}$$

Dipole cross-section (collision rate):

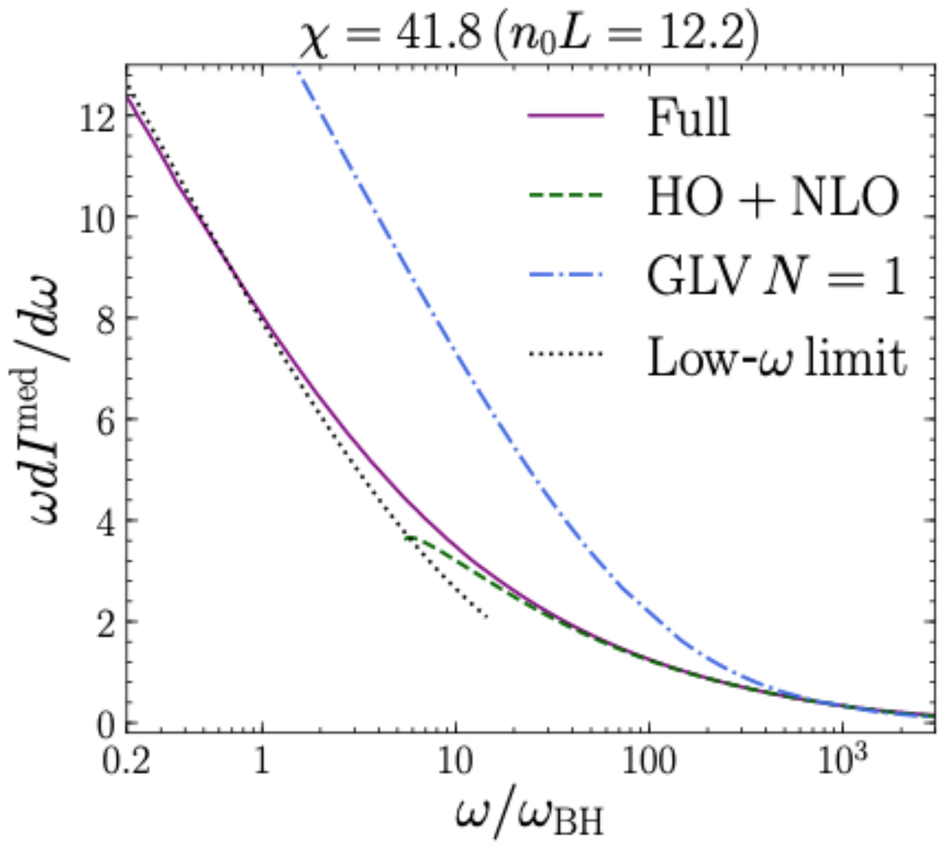
$$\sigma(\boldsymbol{r}) = \int_{\boldsymbol{q}} V(\boldsymbol{q}) \left(1 - e^{i\boldsymbol{q}\boldsymbol{r}}\right)$$

$$\hat{q} \propto \int d^2\mathbf{q}^2 q^2 \frac{d\sigma(\mathbf{q})}{d^2\mathbf{q}}$$

Improving medium-induced radiation

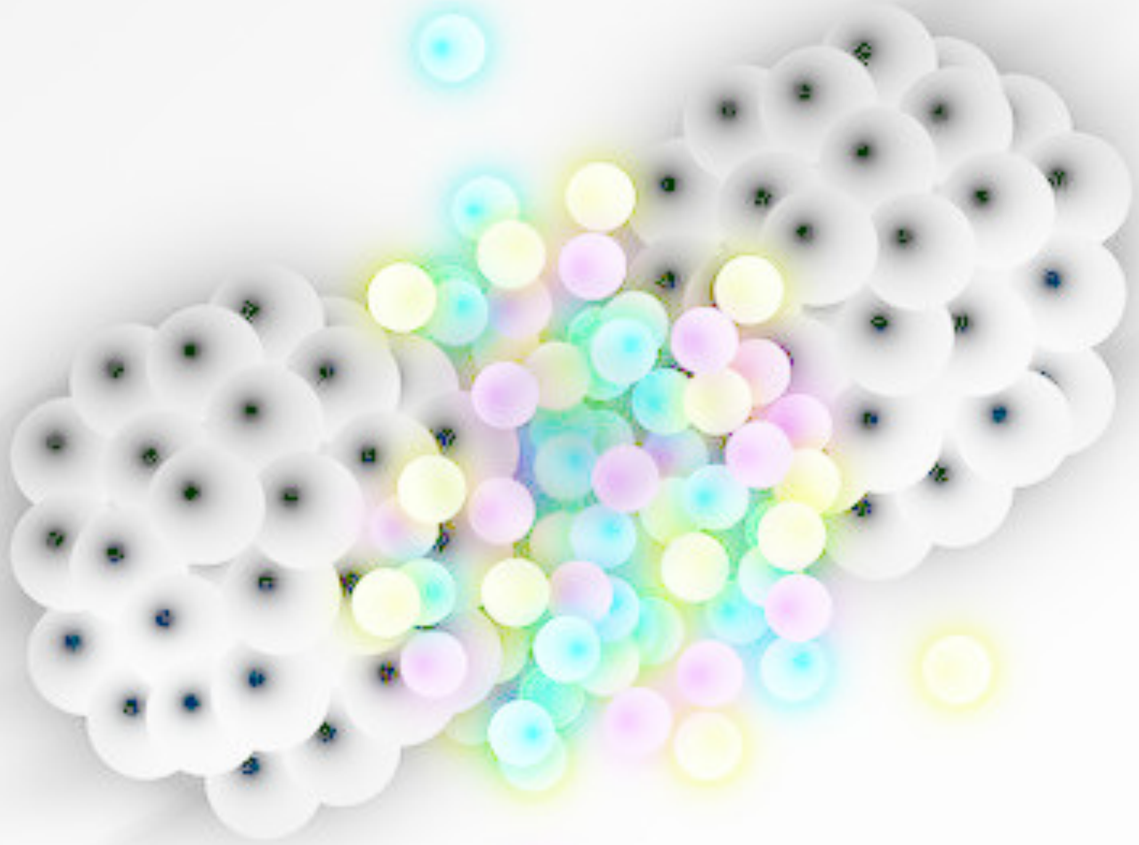
[Andrés, Dominguez, Gonzales (2011.06522)]

- Accuracy of radiation spectrum:
  - Improved analytic opacity expansion
  - Full numerical solution:
    - Solve the spectrum by using Schwinger-Dyson type equations (in momentum space):



See also:

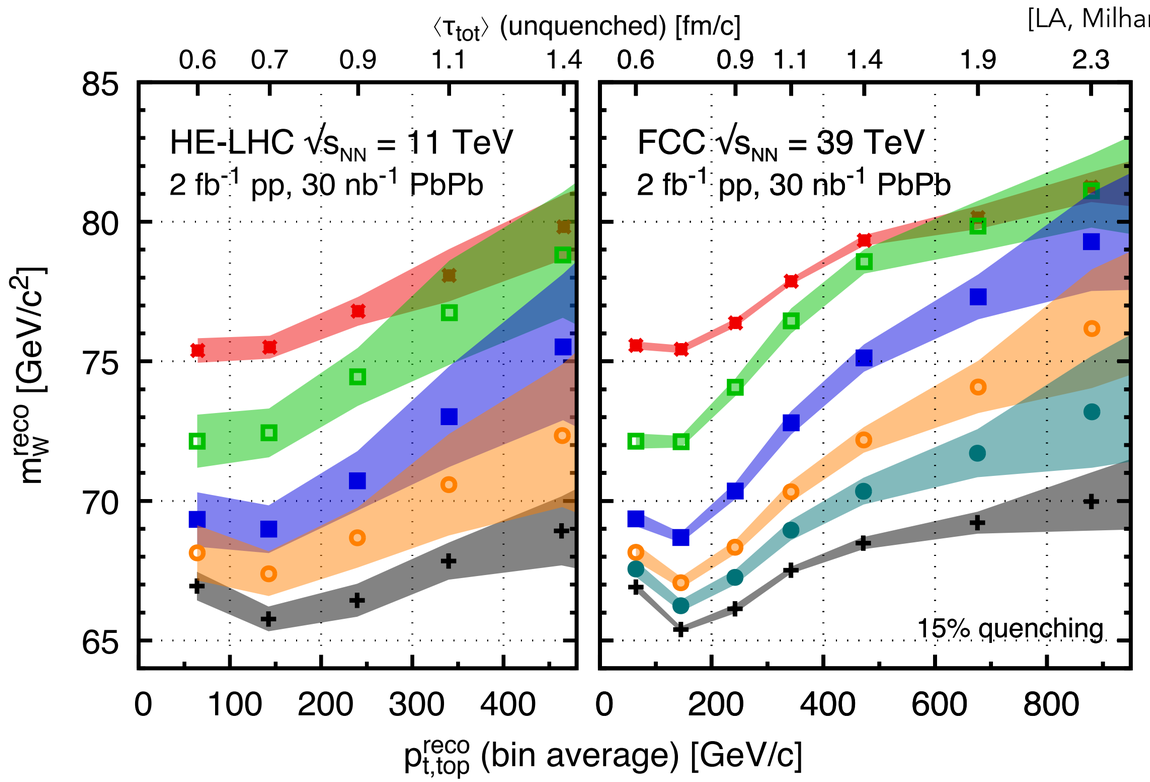
New experimental handles

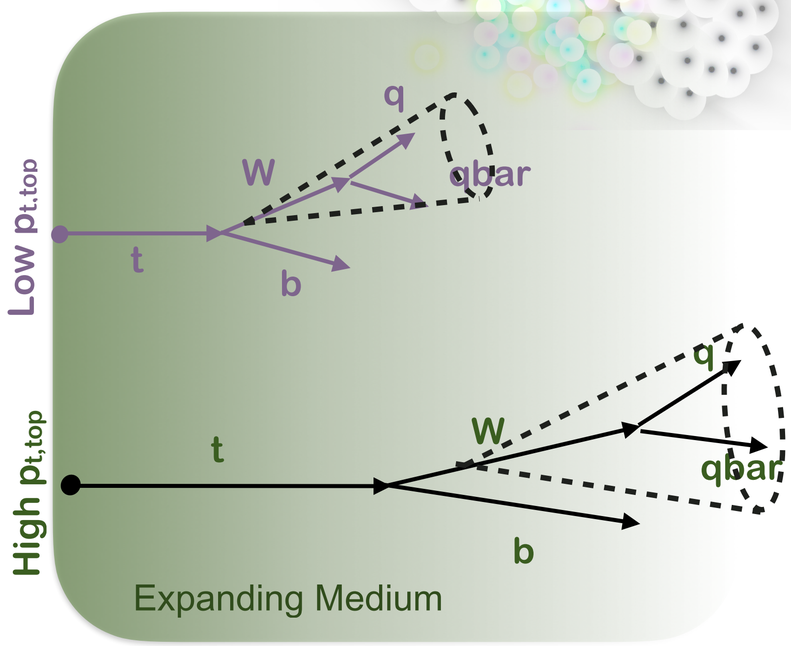


Time-differential measurements

- Hard probes: result of the full integrated medium evolution
  - Time-differential measurements might be possible with tops

[LA, Milhano, Salgado, Salam (1711.03105)]



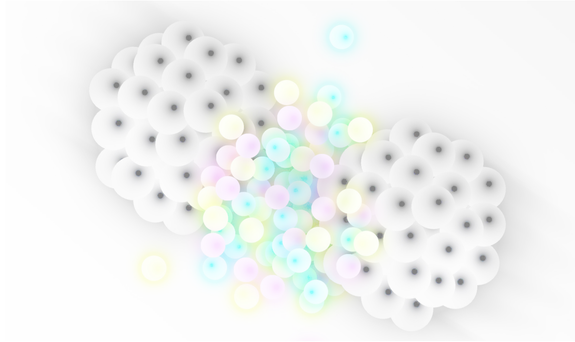


unquenched
quenched
τ_m= 1.0 fm/c
τ_m= 2.5 fm/c
τ_m= 5 fm/c
τ_m= 10 fm/c

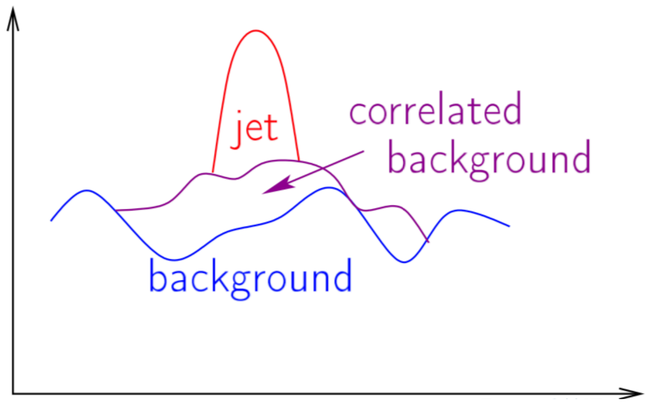
Tops as time-delayed probes of the QGP
(QGP tomography)

First tops measured in PbPb (CMS - 2006.11110)

From jets to jet substructure

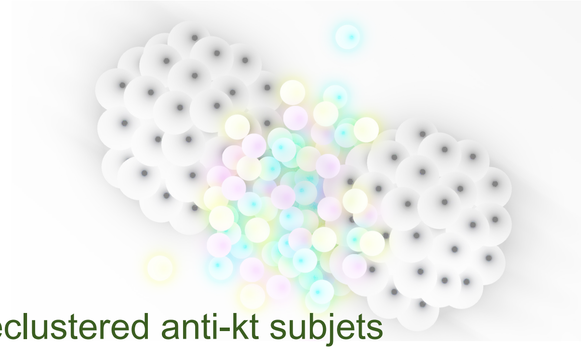


- How can we access QGP-related information?
  - Jets in PbPb $\neq$ Jets in pp + Background



[Zapp QM (17)]

From jets to jet substructure



Fully reclustered anti-kt subjets

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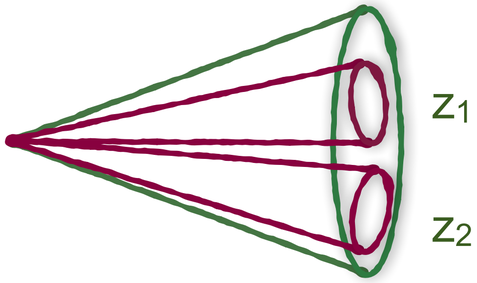
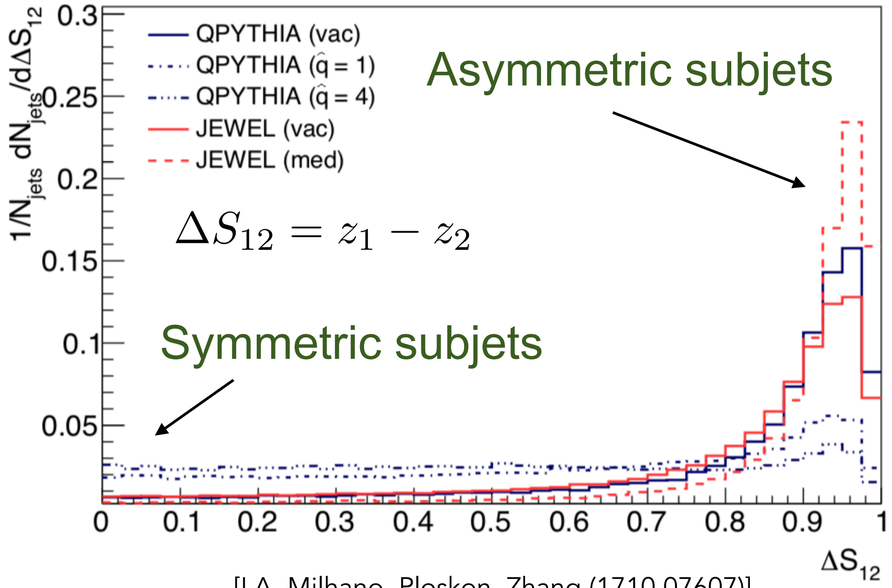
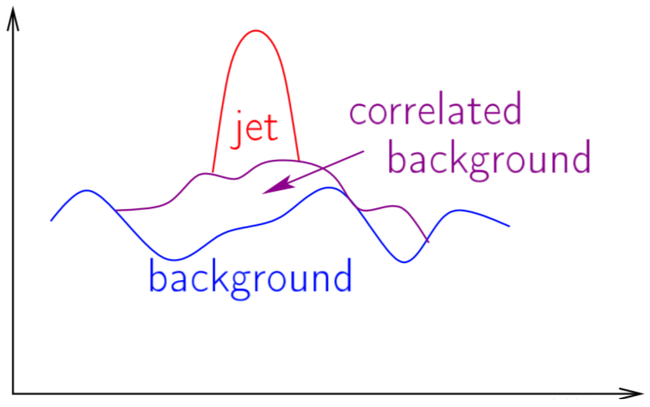


- Background-resilient to distinguish quenching models



[LA, Milhano, Ploskon, Zhang (1710.07607)]



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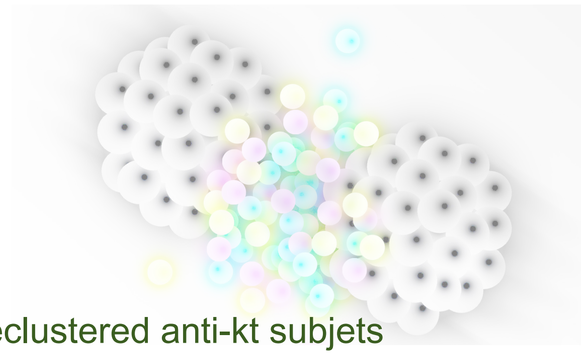

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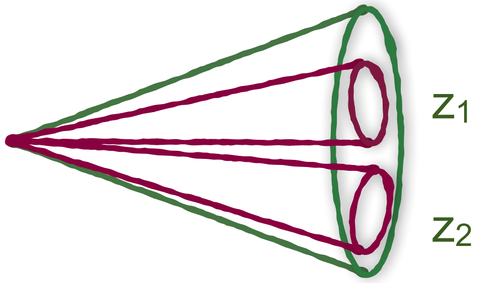

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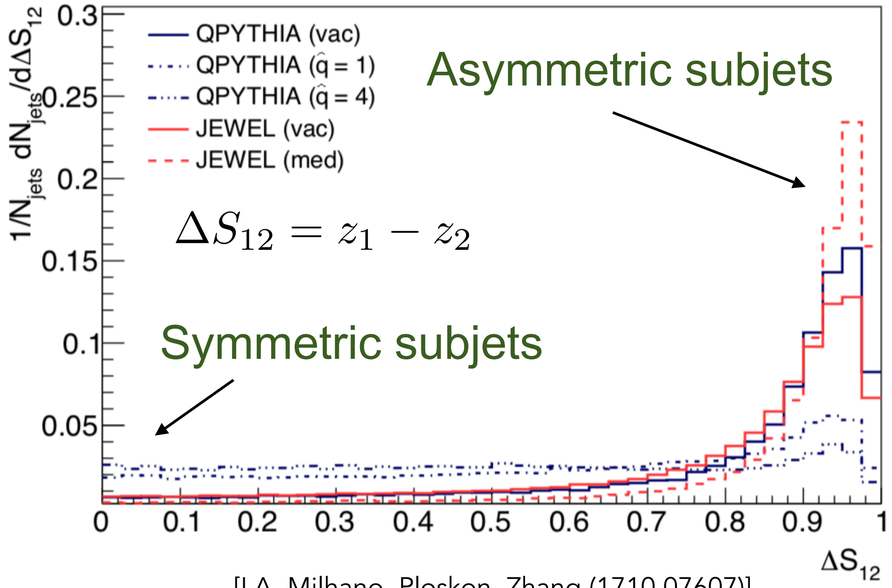
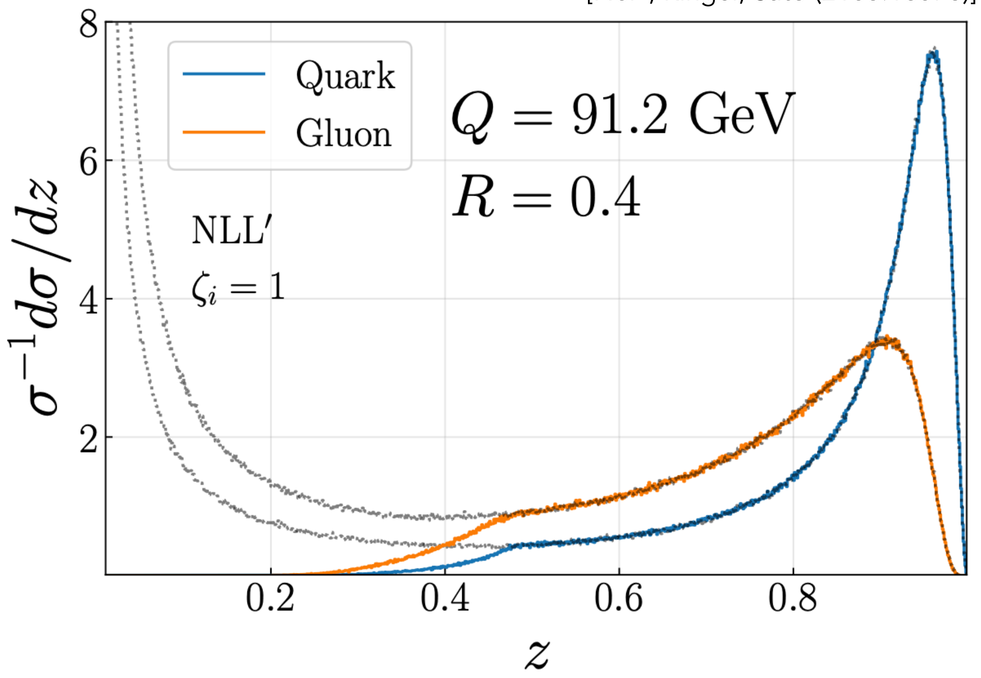
- Leading jet: quantifies quark vs gluon in-medium energy loss



[LA, Milhano, Ploskon, Zhang (1710.07607)]

[Neill, Ringer, Sato (2103.16573)]



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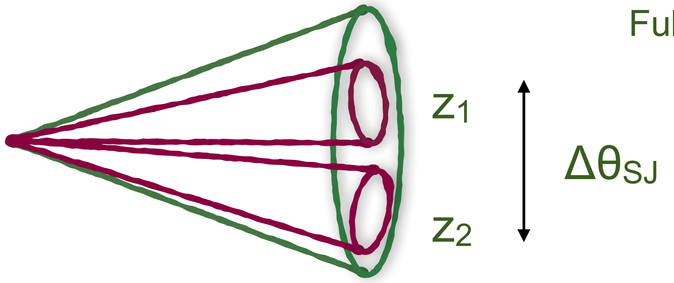
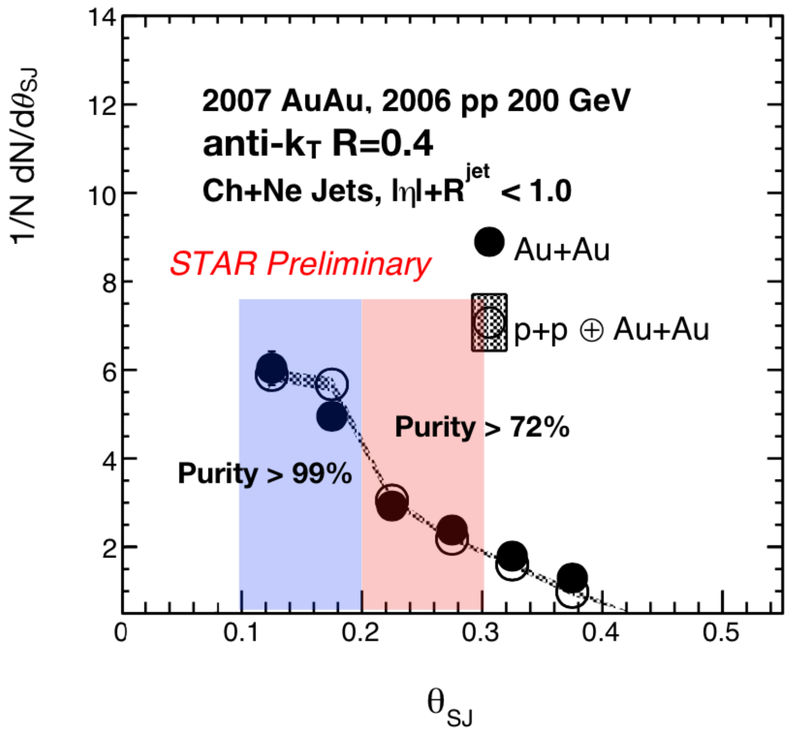
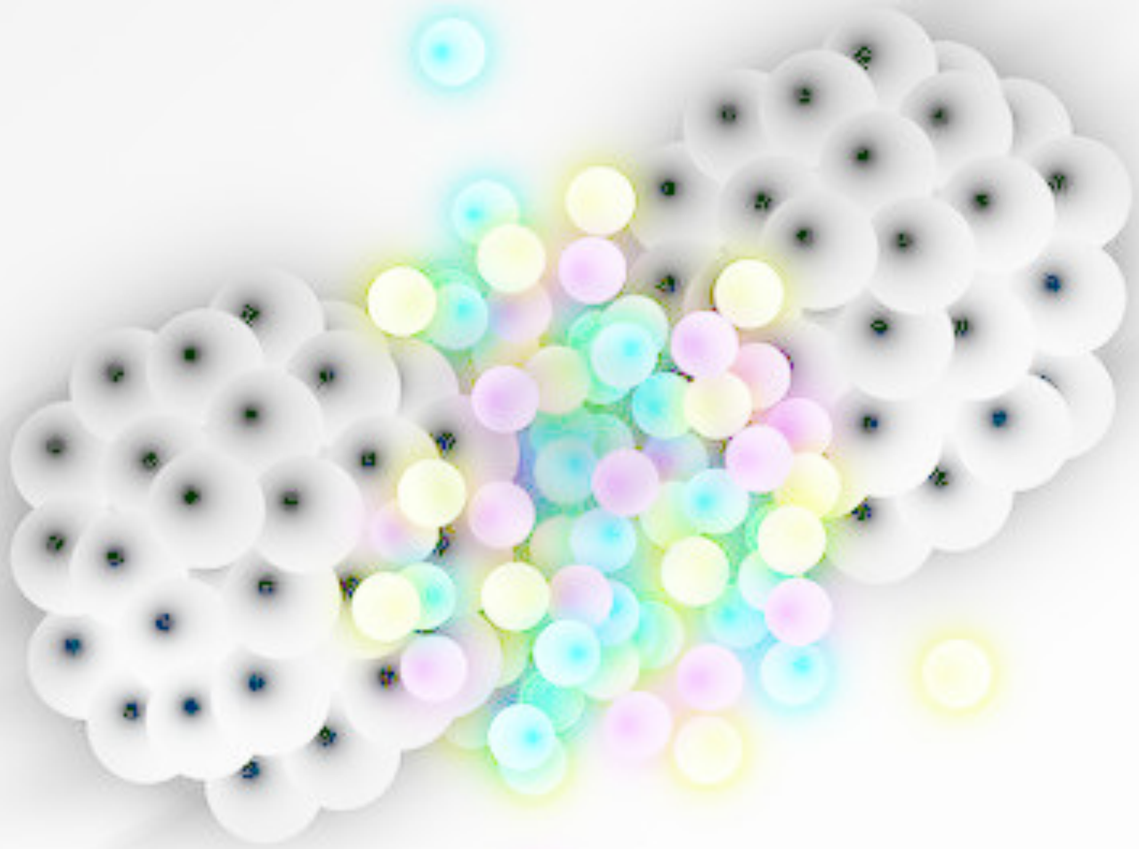


- Background-resilient to distinguish quenching models
- Leading jet: quantifies quark vs gluon in-medium energy loss
- Allows to create samples that are the same in pp and in PbPb

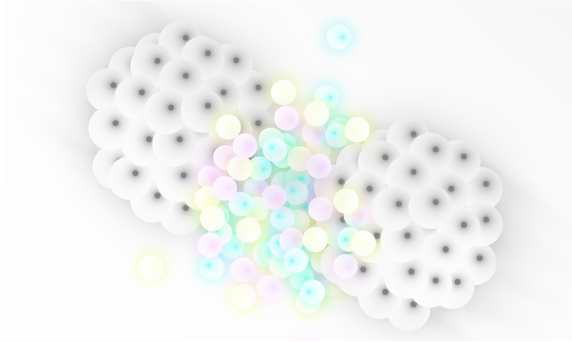
[STAR (QM2019)]



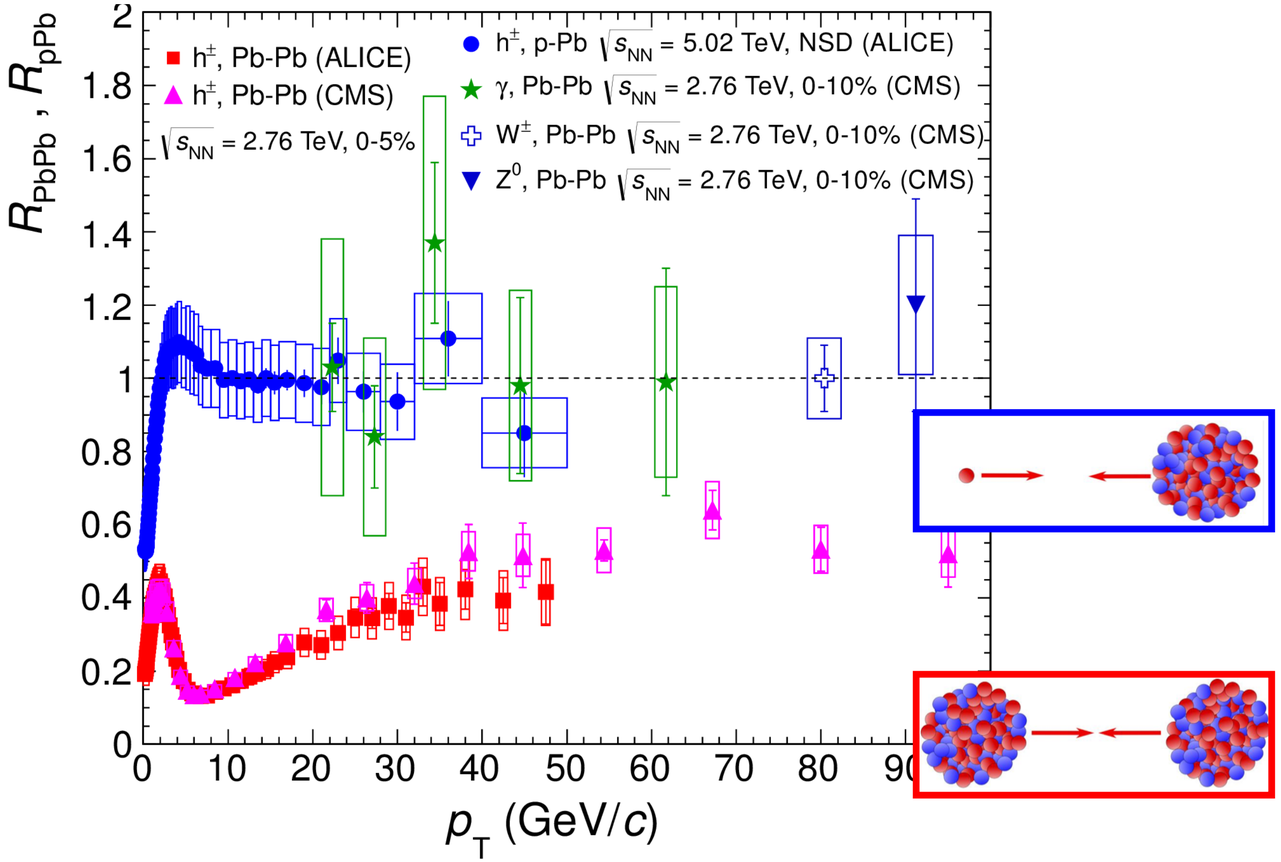
From dense to light



QGP onset



- No energy loss in pA…



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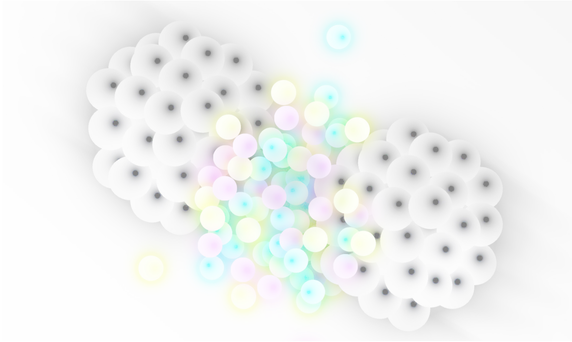
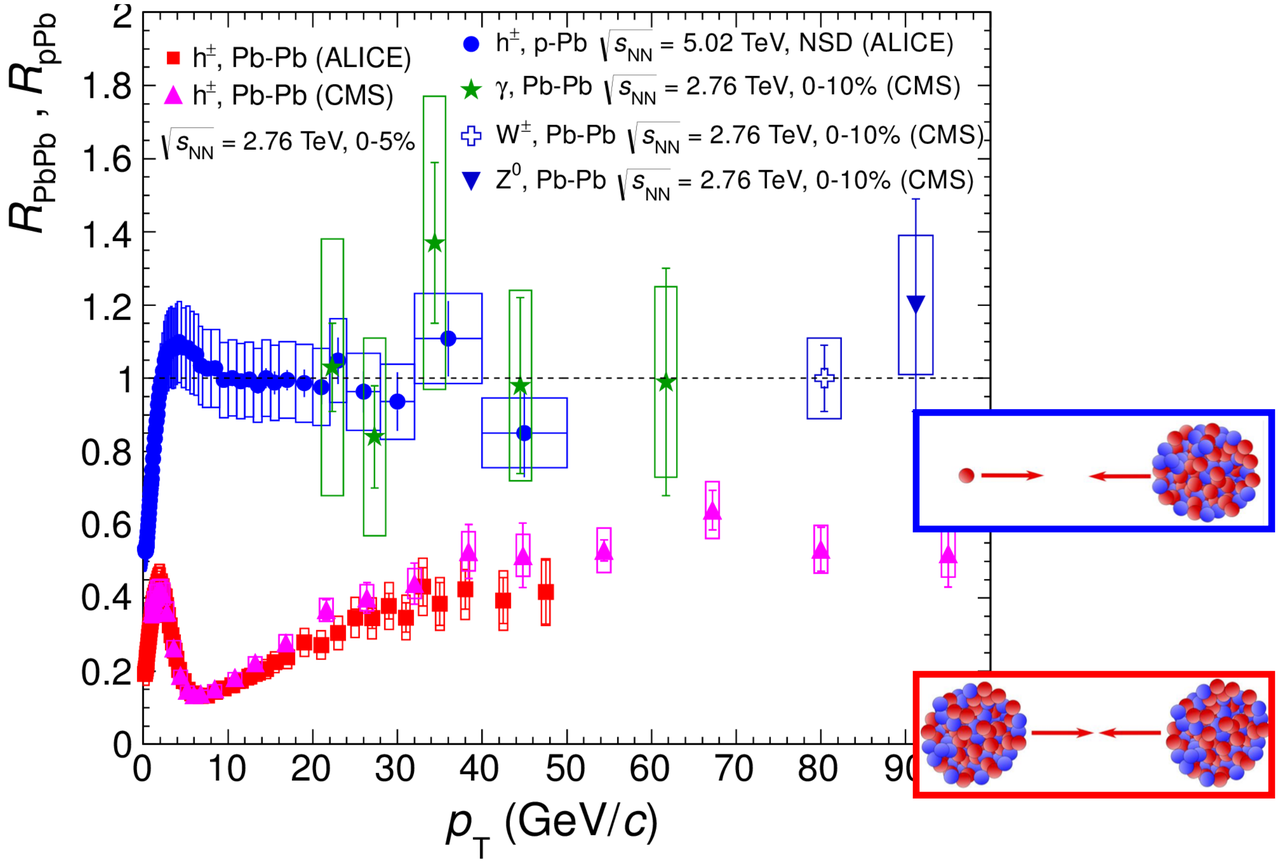
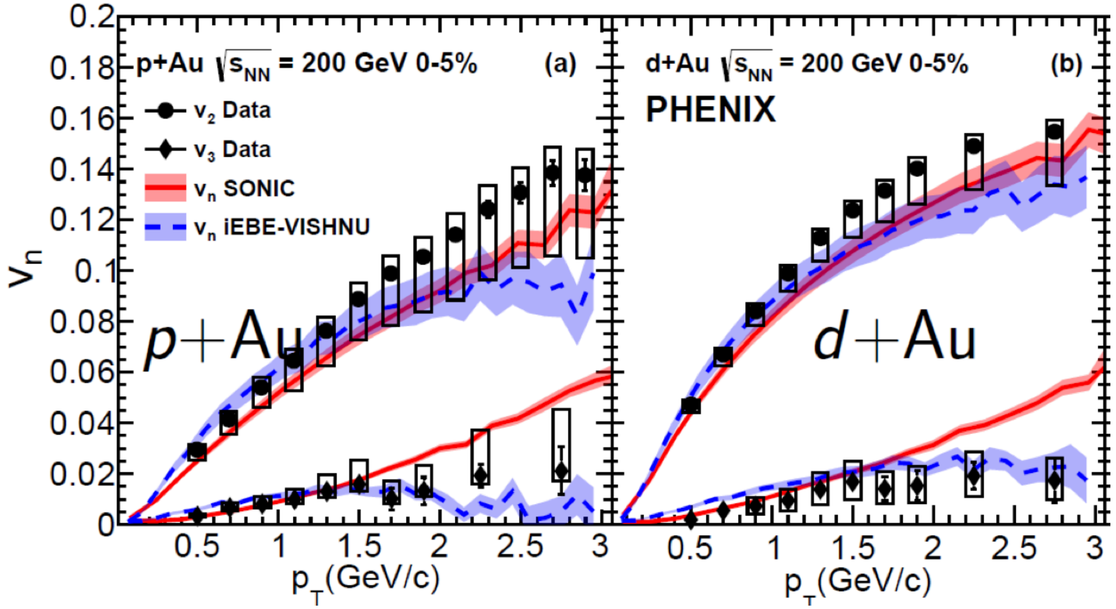


- No energy loss in pA… but strong evidence in support of hydrodynamic behavior



[PHENIX (PRL 123, 039901)]

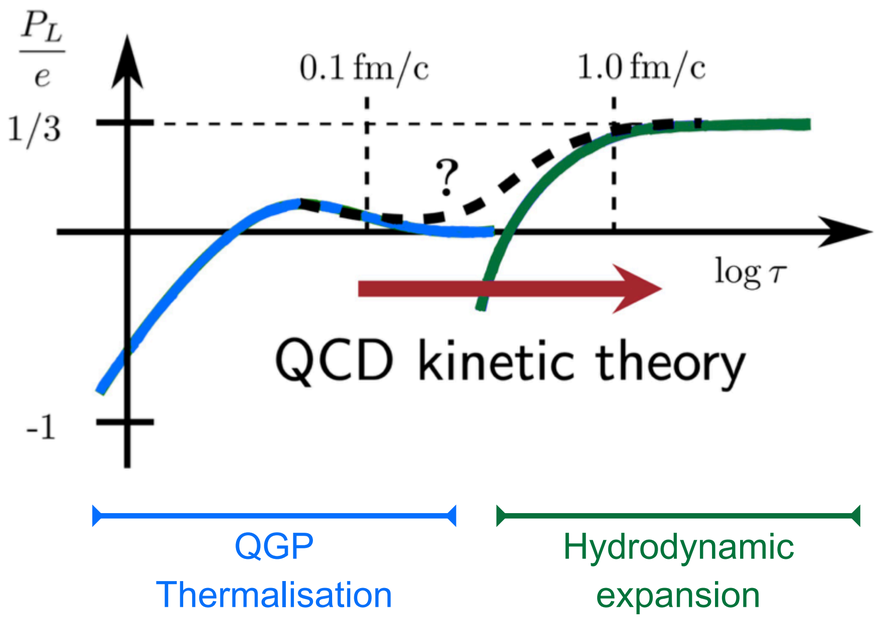


Flow coefficients well reproduced by hydro predictions, but not by initial state effects only

From dense to light systems

[Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney (1601.03283, 1805.00961)]
[Schlichting, Soudi (2008.04928)]

- Extrapolation from dense to light needs further understanding…



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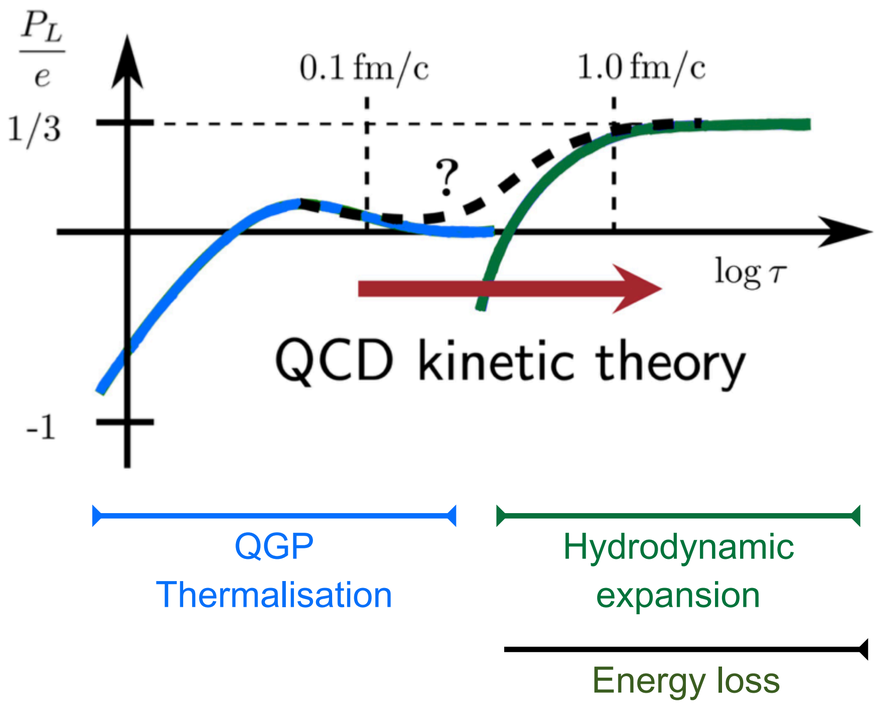

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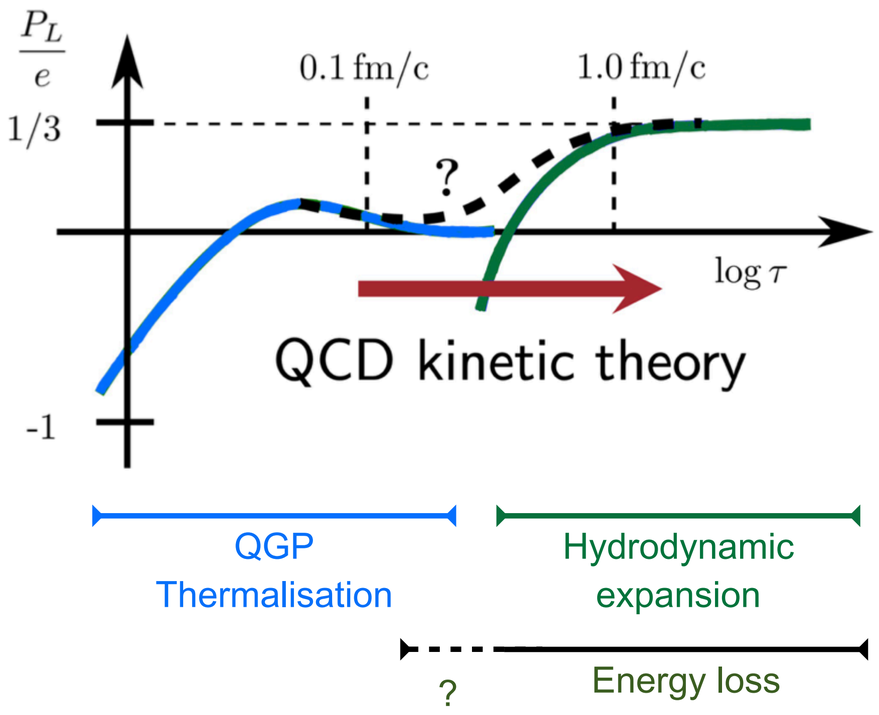

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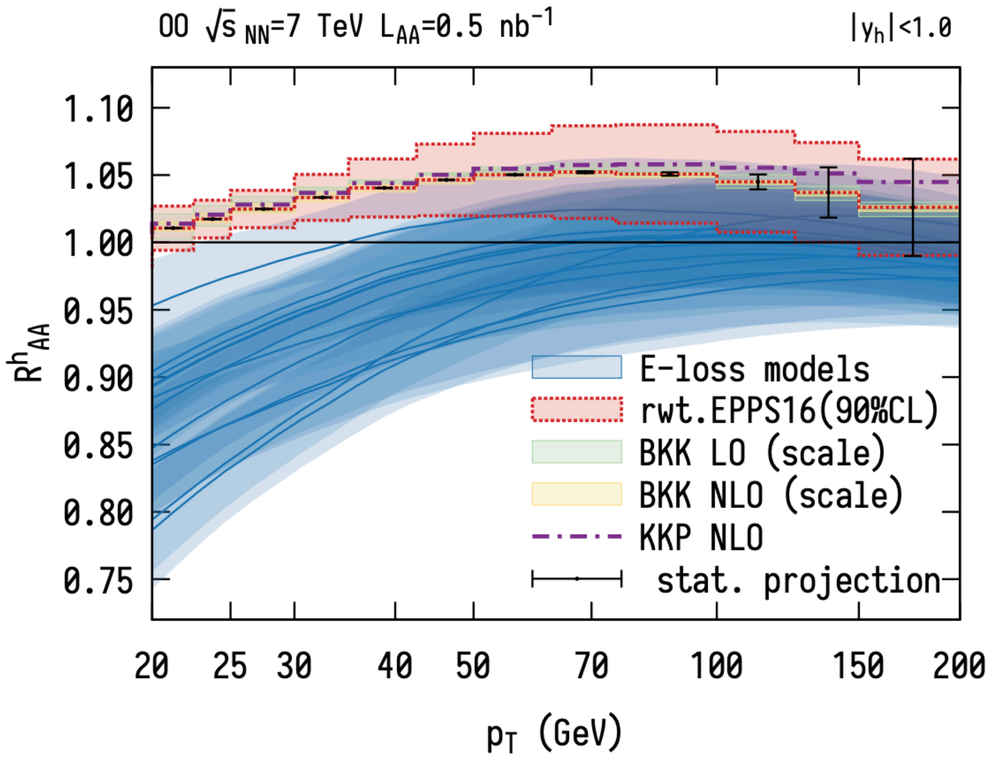
- Future oxygen runs can help us to determine the smallest amount of energy loss, provided that we control the initial state

[Huss, et al (2007.13754)]

Future OO run similar to PbPb peripheral (better suited to system-size dependence)

Future pO run crucial do reduce nPDF uncertainties



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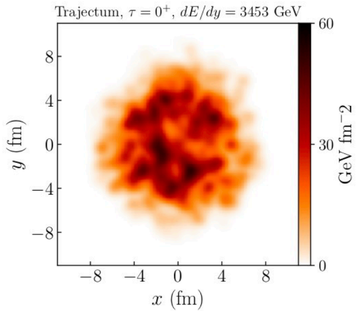
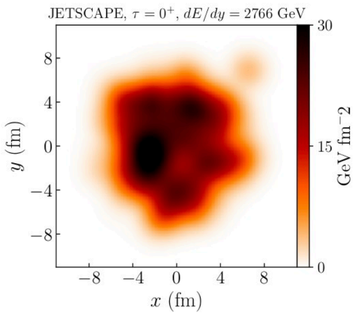
Cold or Hot nuclear matter effects?

Nucleon structure at high energy:



or



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