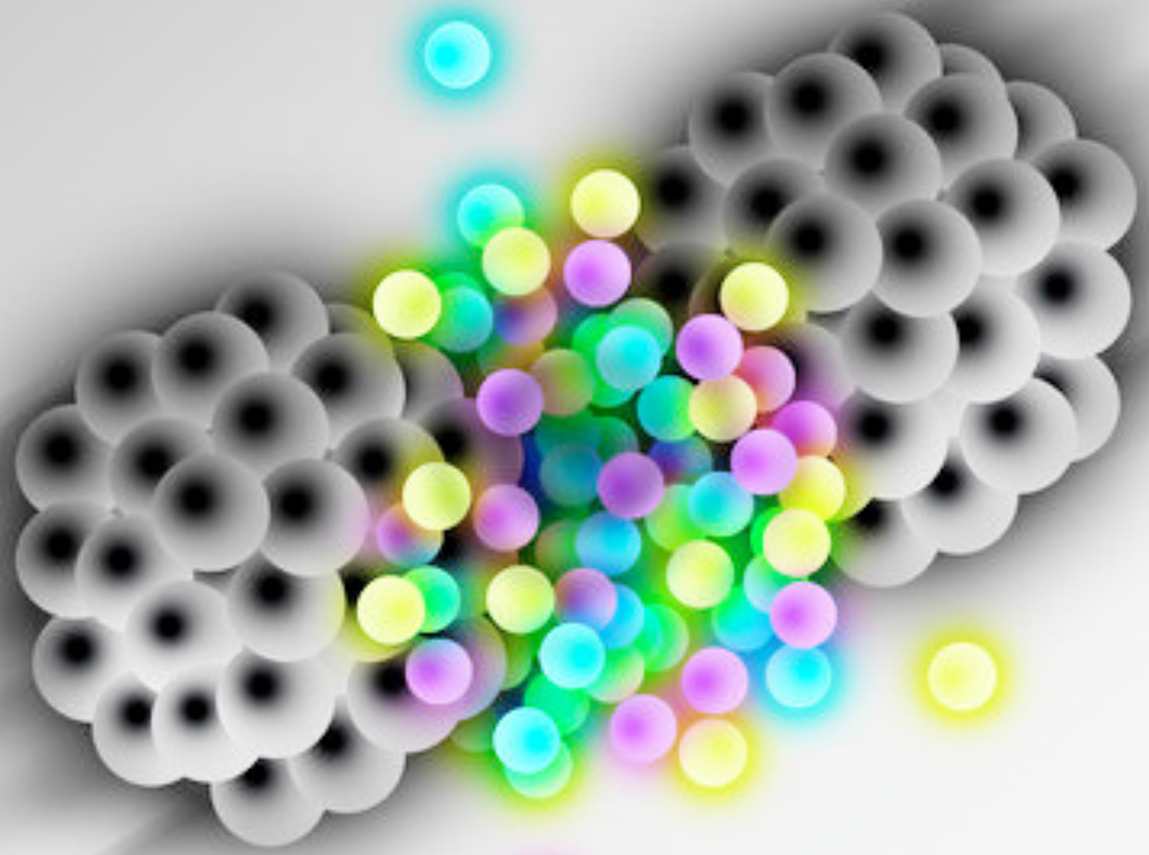
New winds in heavy-ion physics



Liliana Apolinário

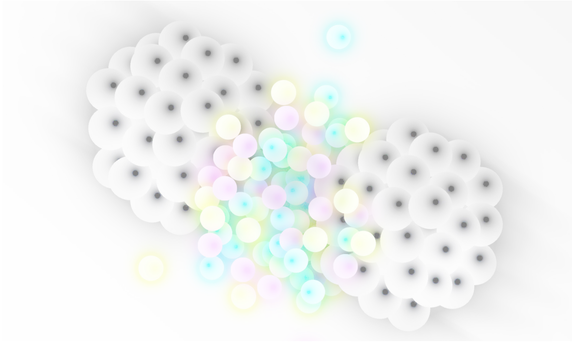
LIP

TÉCNICO LISBOA

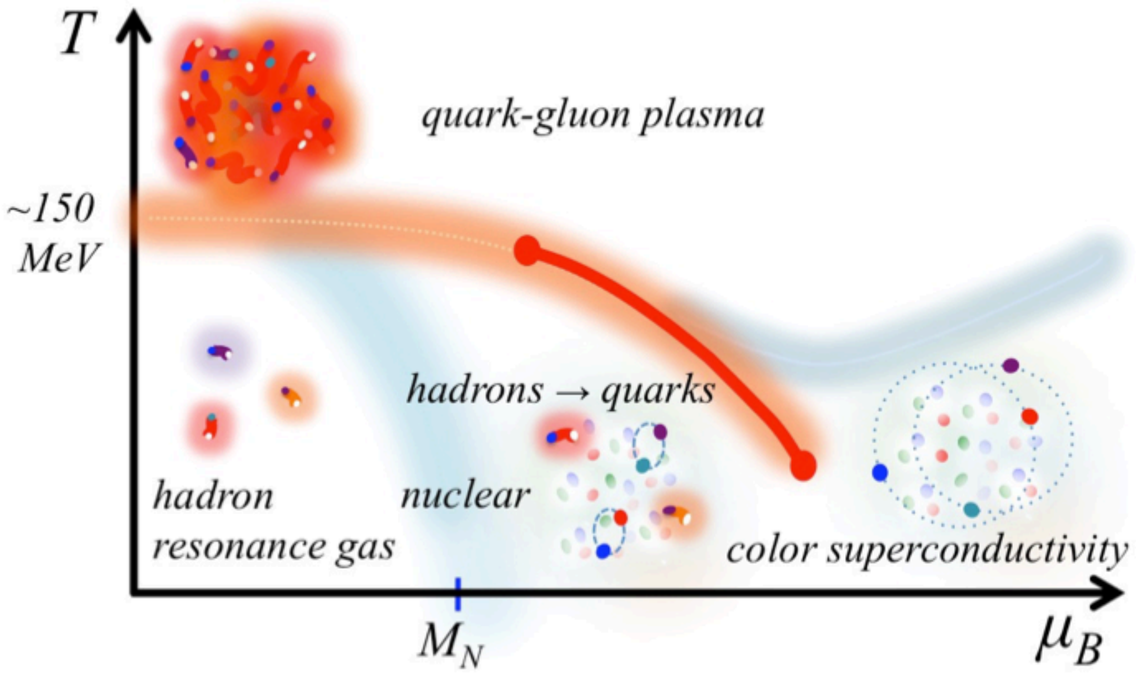
DIS2022

Monday, May 2nd

Heavy-Ion Collisions



- Heavy-ion collision:
  - Probe the QCD phase diagram
  - Understand the QCD fundamental interactions
    - Collectivity from a gauge-field theory?
  - Tools used to study created matter shared with nearby physics fields research
    - QGP vs colliding nuclei?



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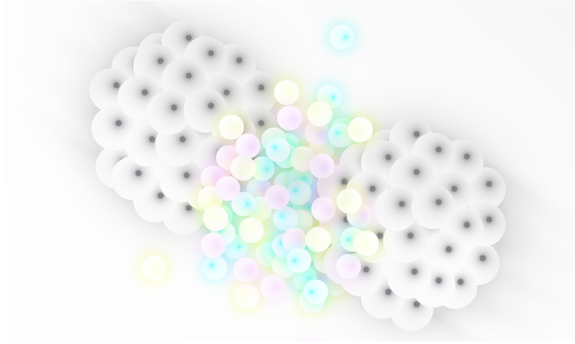
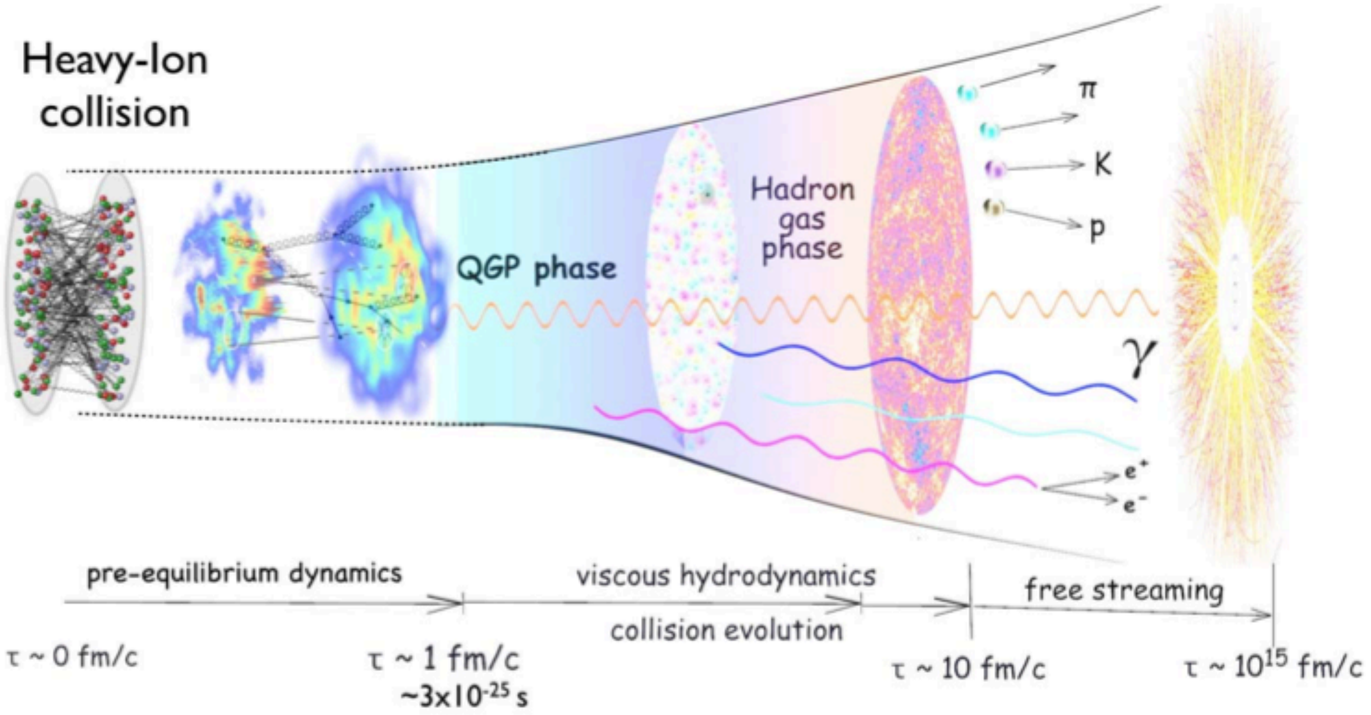


- Different QGP probes will access different wavelengths:



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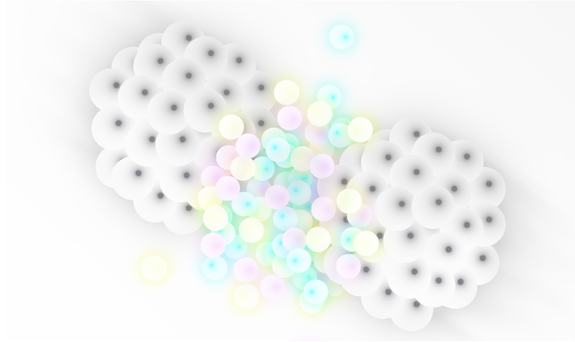

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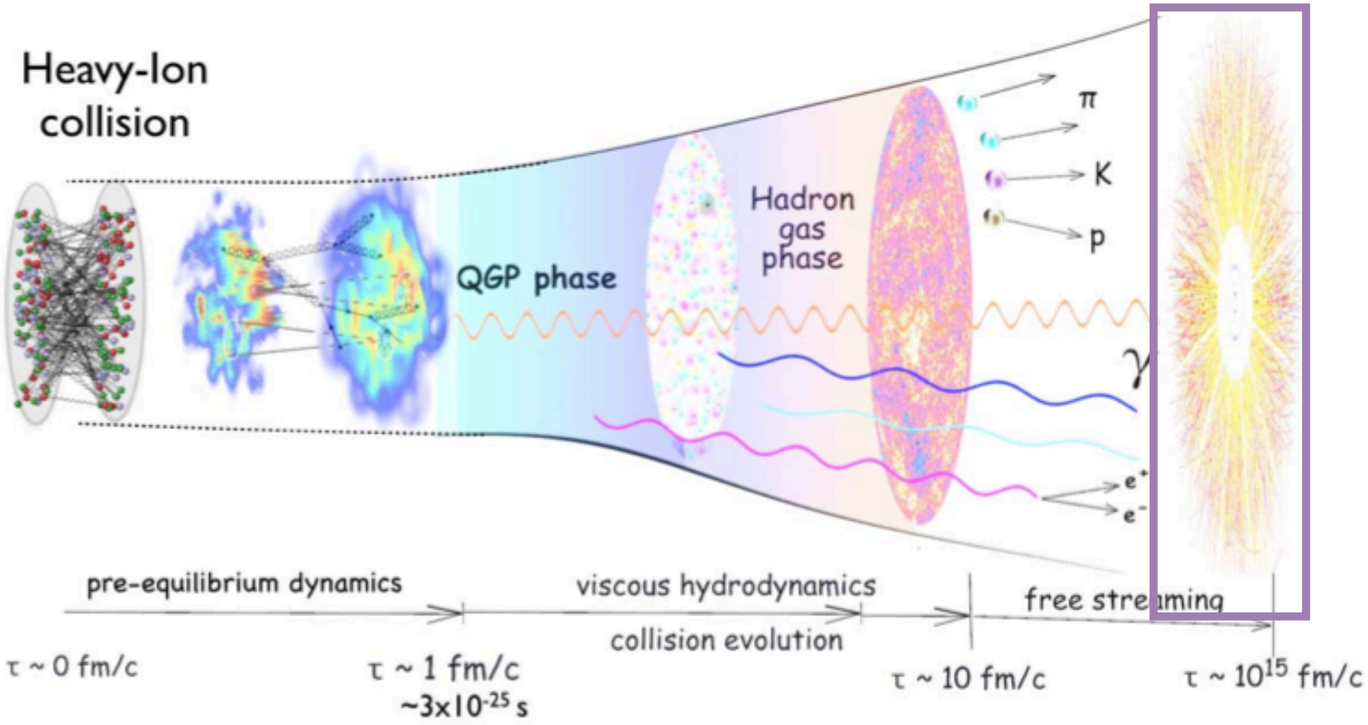
  - Soft probes (bulk of the collision): low momentum particles - hydrodynamic based description



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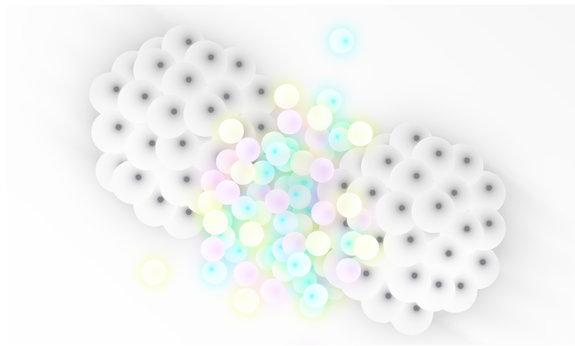
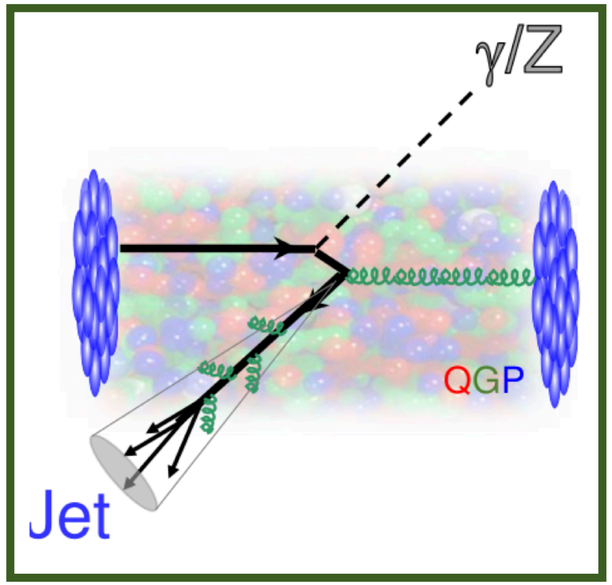
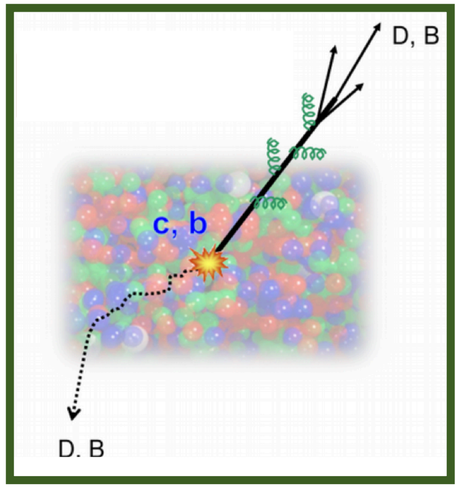
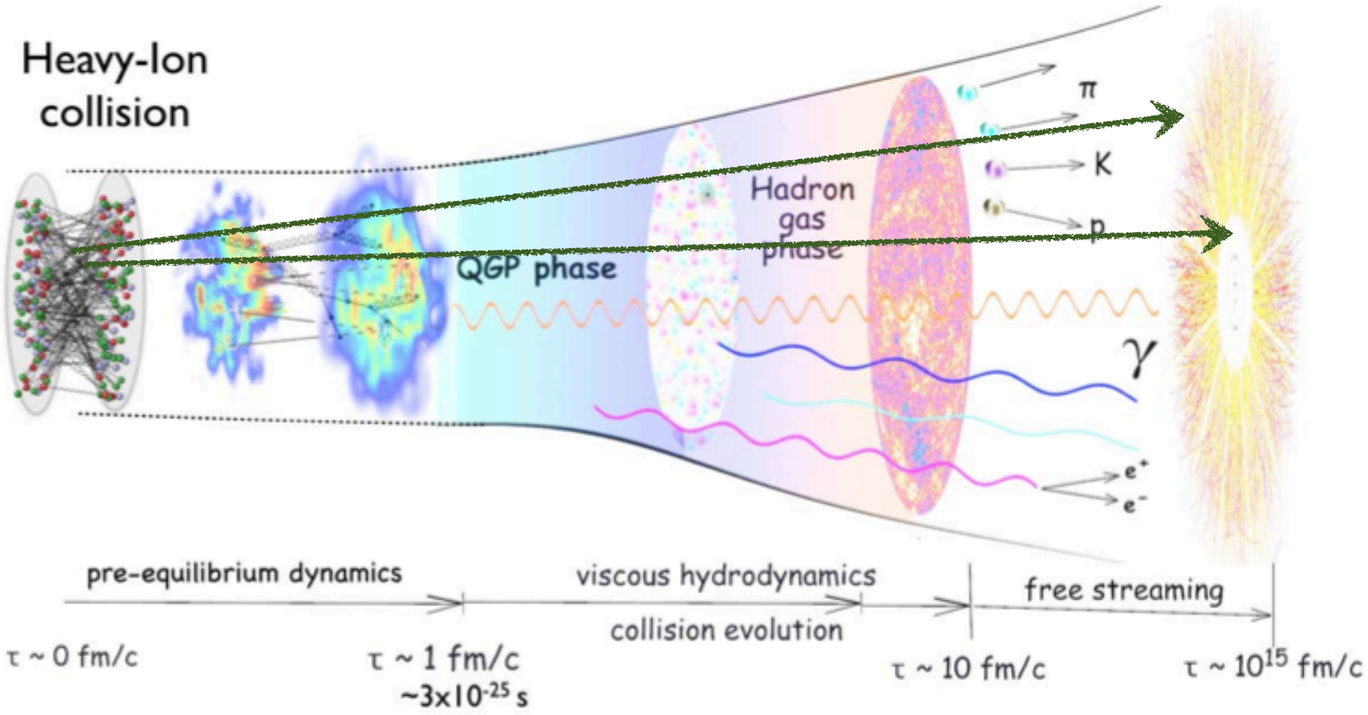


- Different QGP probes will access different wavelengths:
  - Soft probes (bulk of the collision): low momentum particles - hydrodynamic based description
  - **Hard probes** (large-Q^2 process): high-momentum particles - pQCD based description **Focus of this talk**







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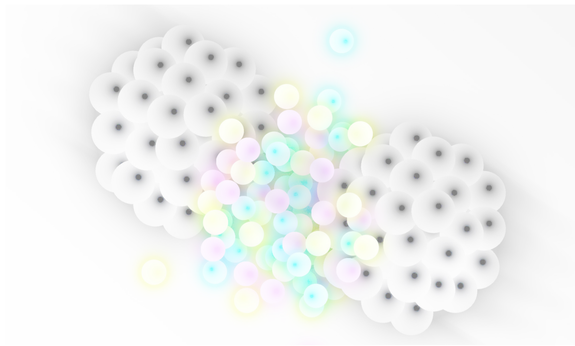

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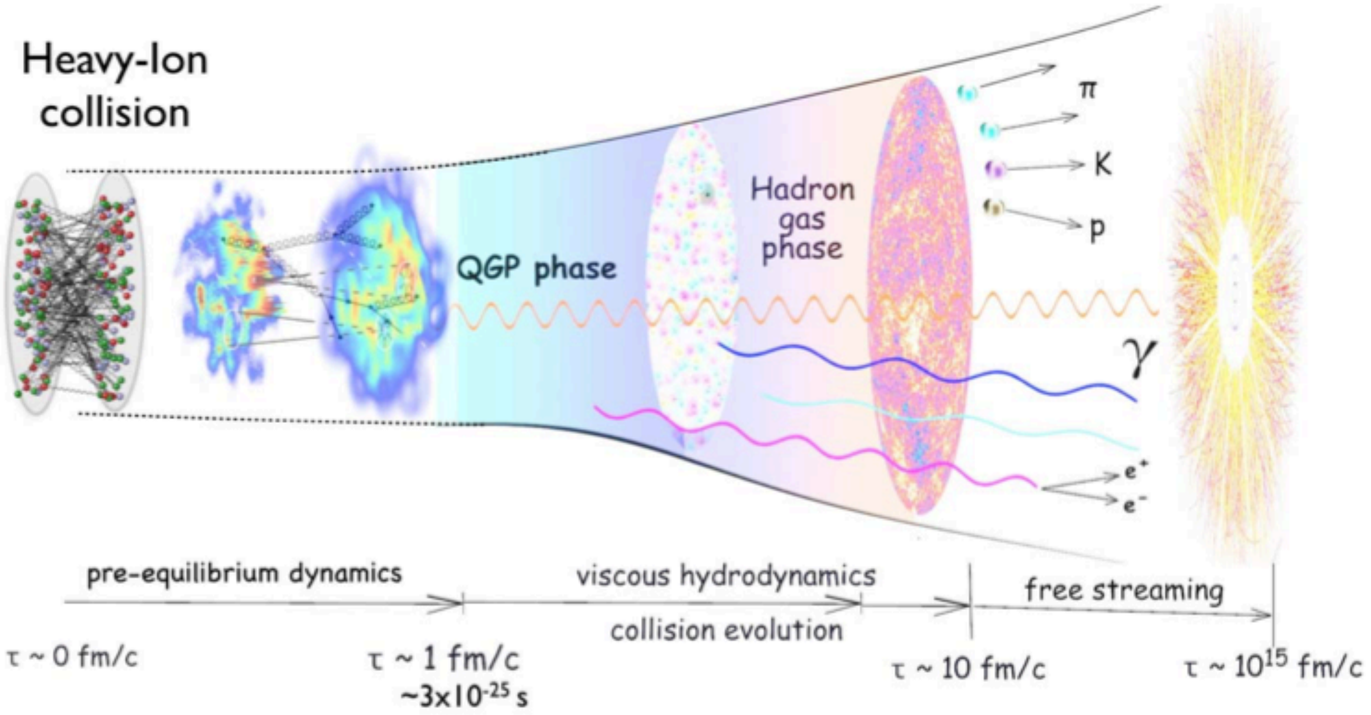
Common difficulty: QGP is dynamically evolving system

All observables require interpretation in the framework of transport models



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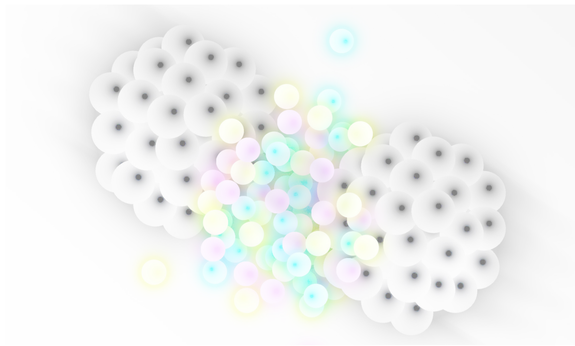

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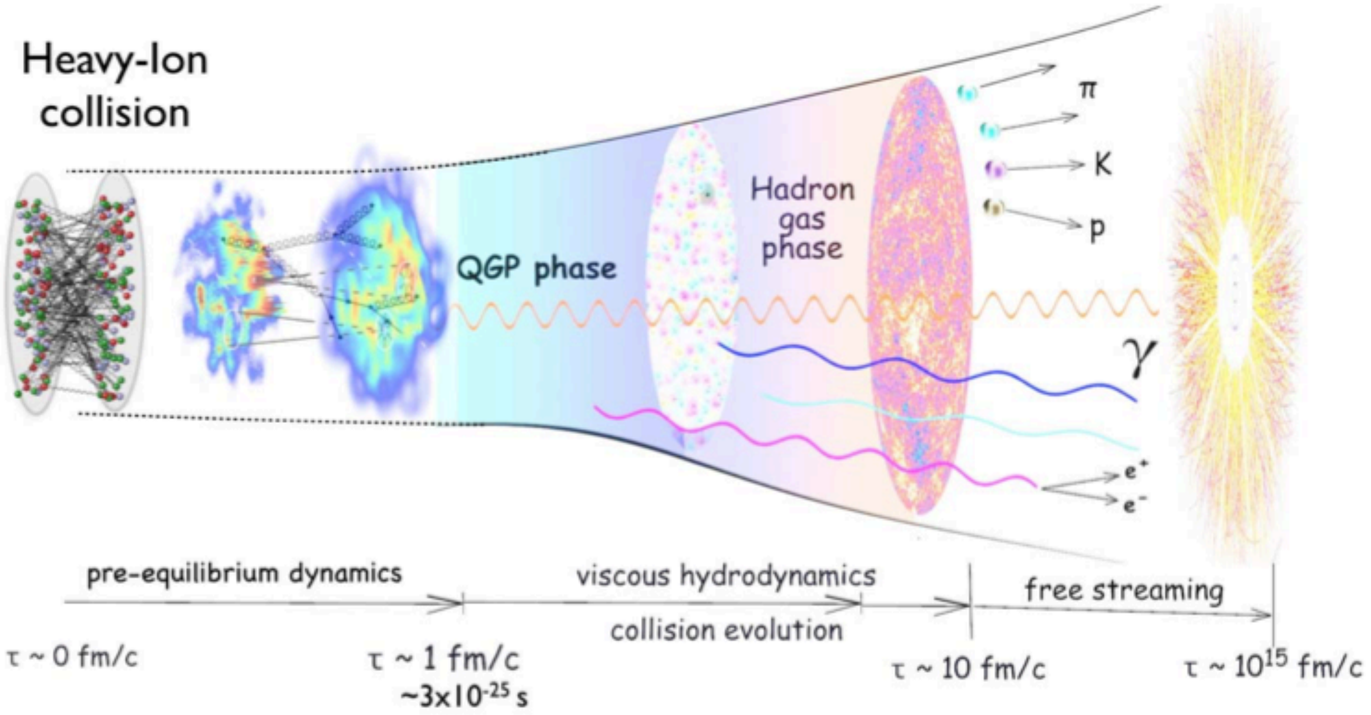
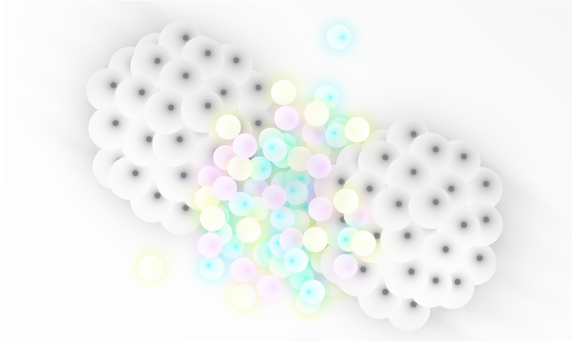
Heavy-ion collision characterisation:

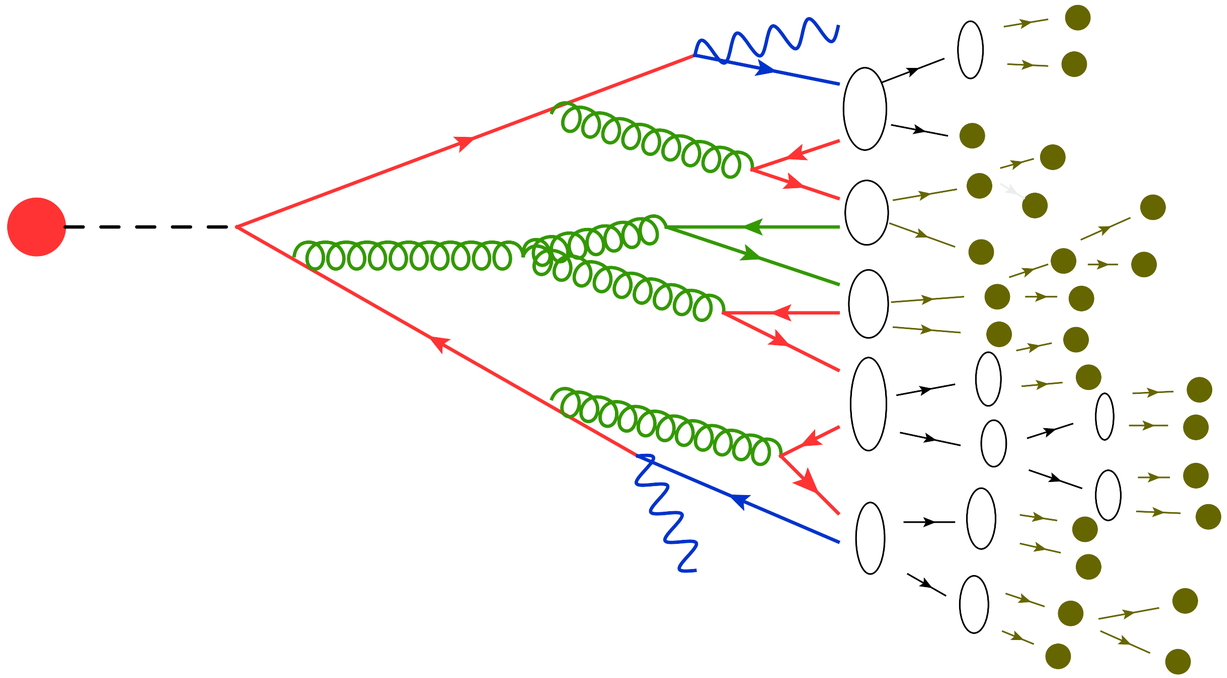
A multi-scale problem!



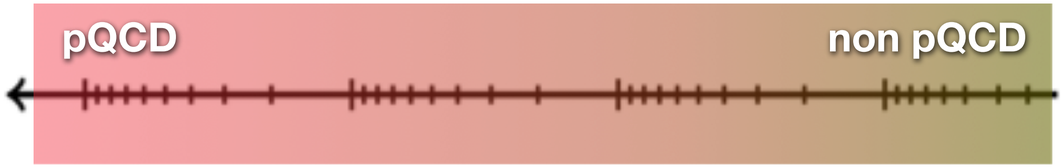
Jets in heavy-ions



- Also a multi-scale problem:



$Q^2 \equiv \mathcal{O}(100^2\mathrm{GeV}^2 \sim 1\mathrm{TeV}^2)$



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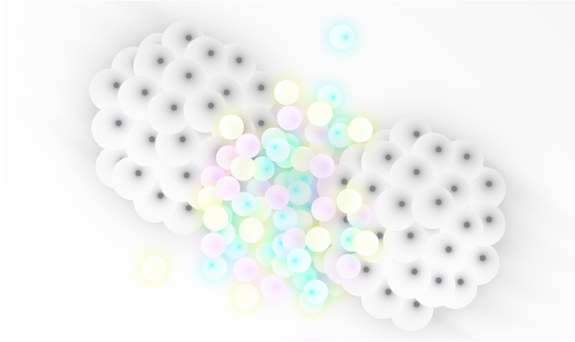

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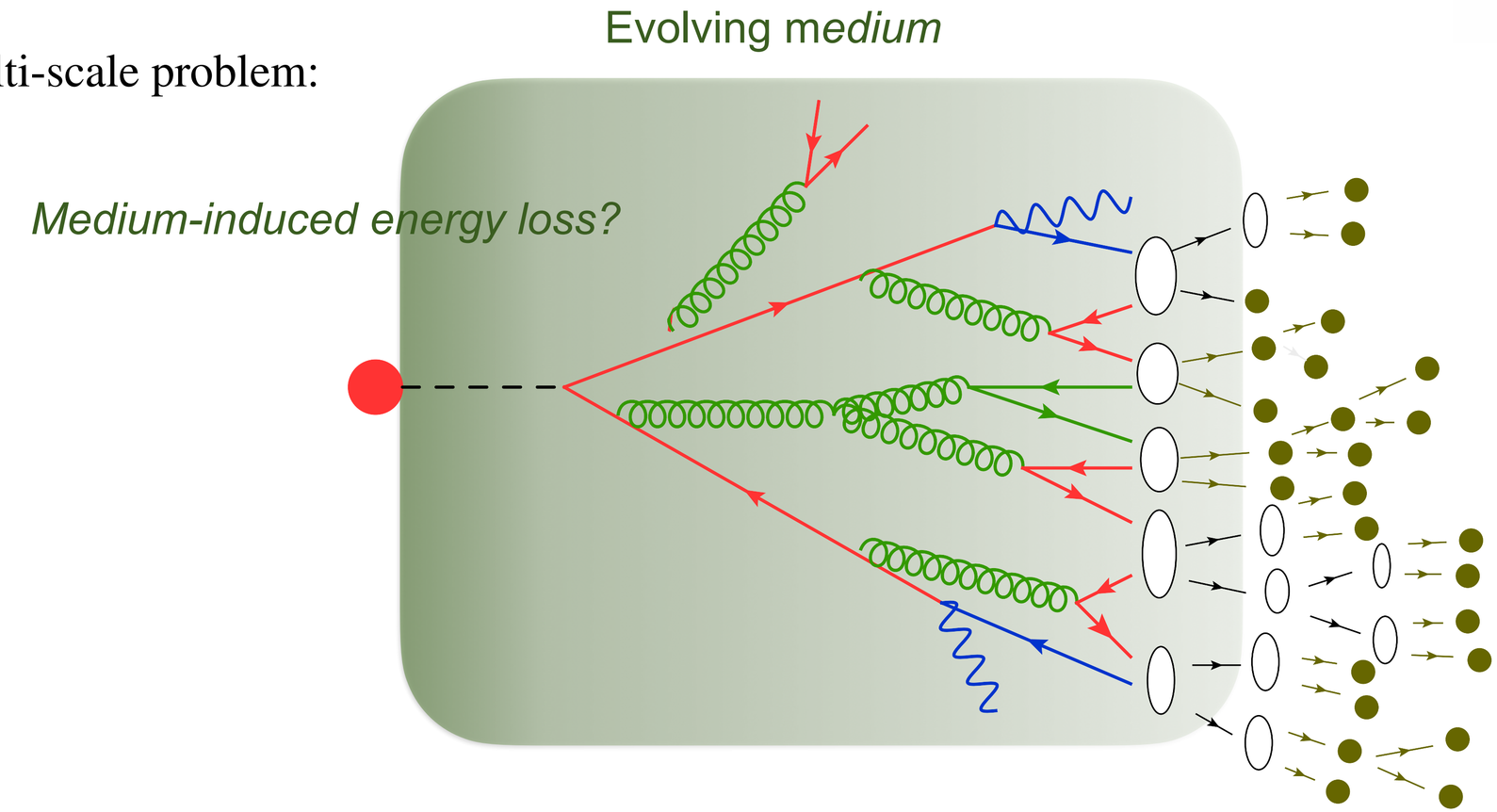

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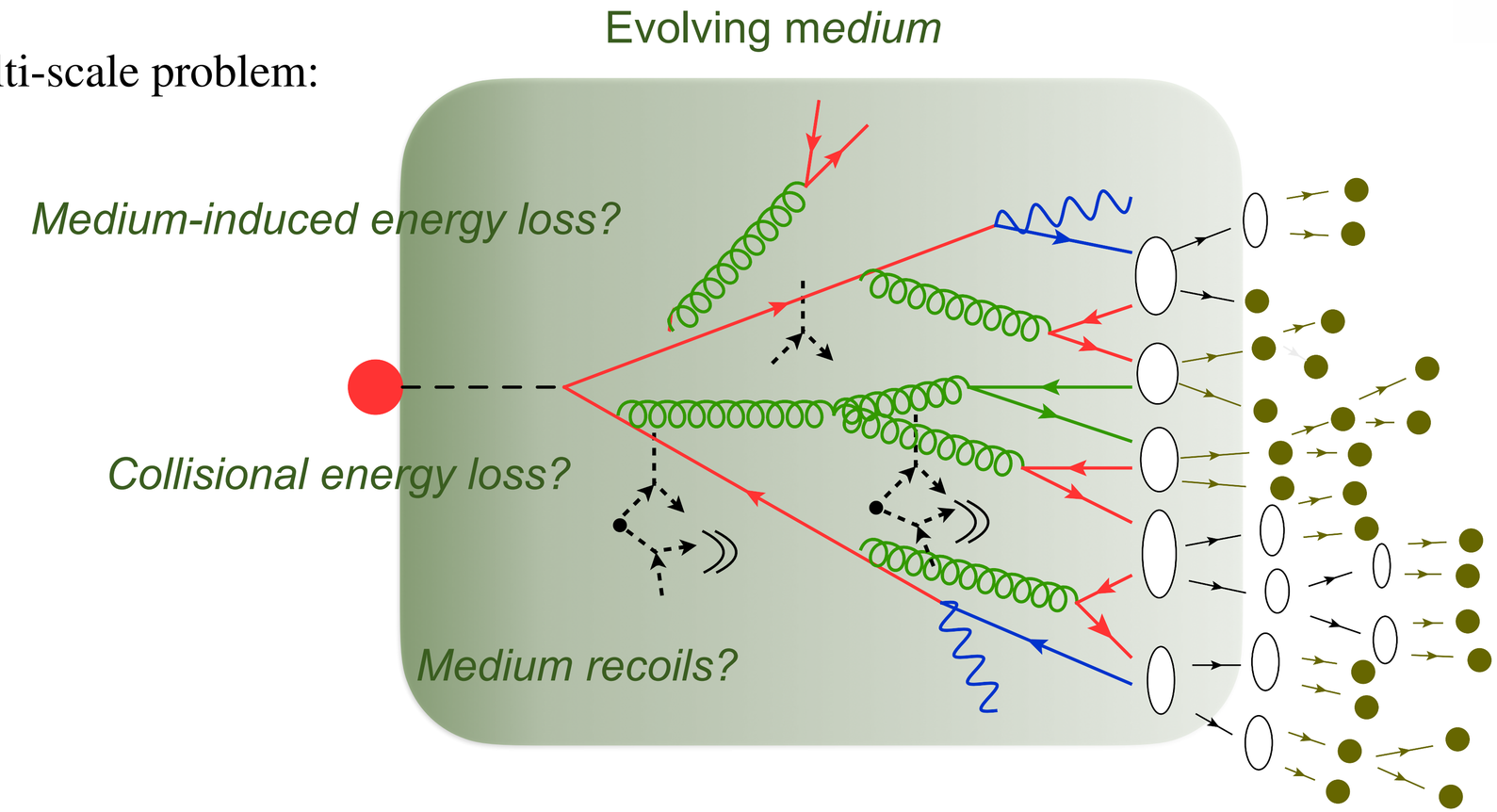

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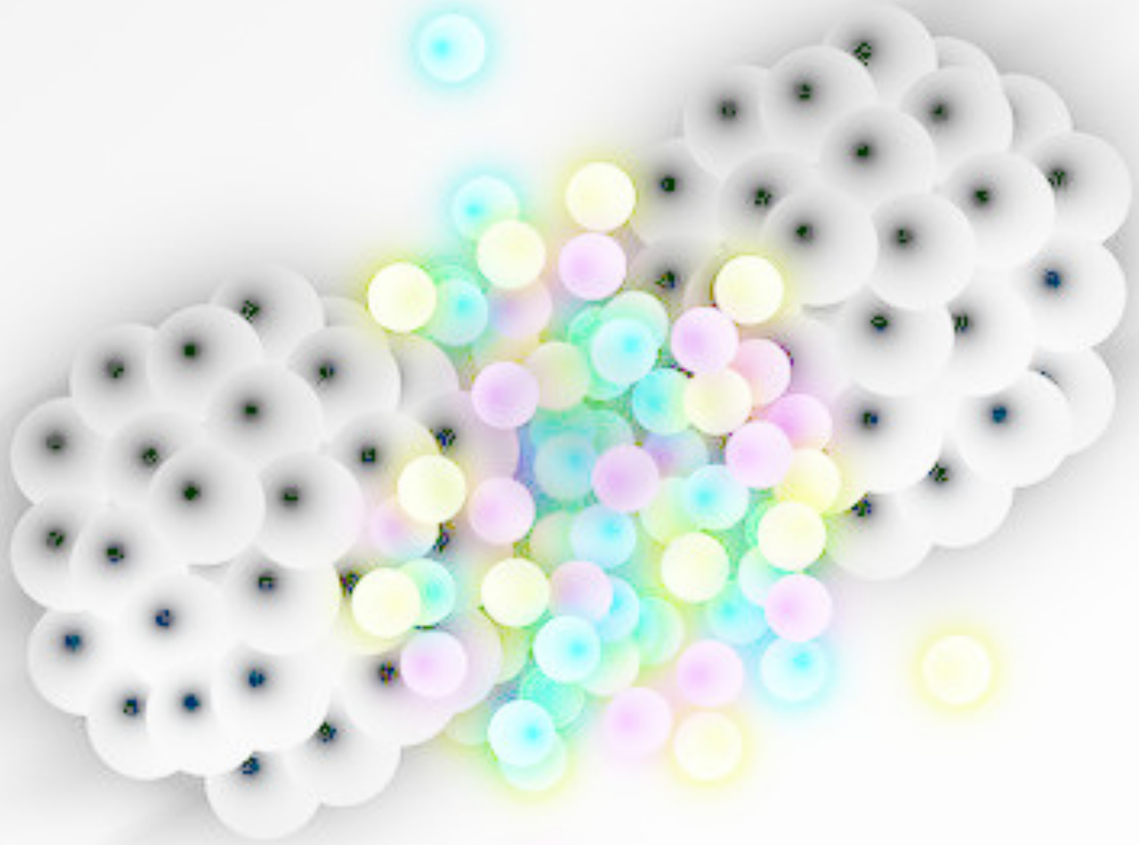
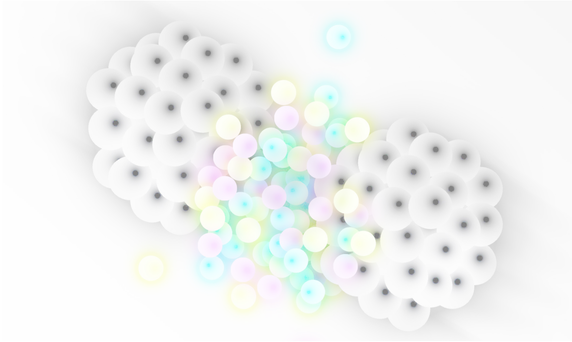
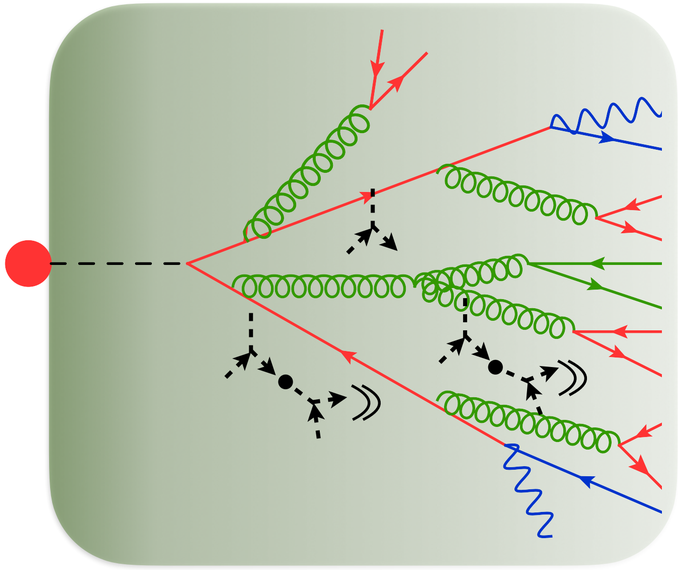
Improving theoretical control



In-medium processes



- Amount of energy loss measures transparency to the passage of a high momentum particle:
    - Towards higher accuracy in elementary building blocks of the parton shower



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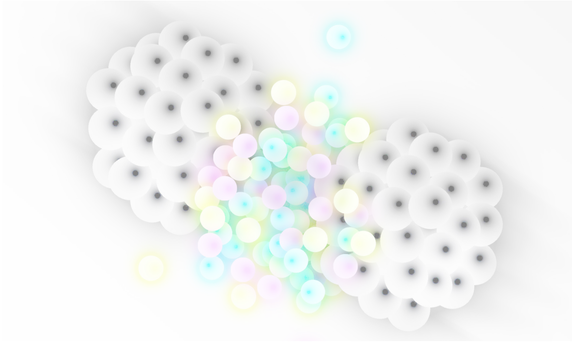

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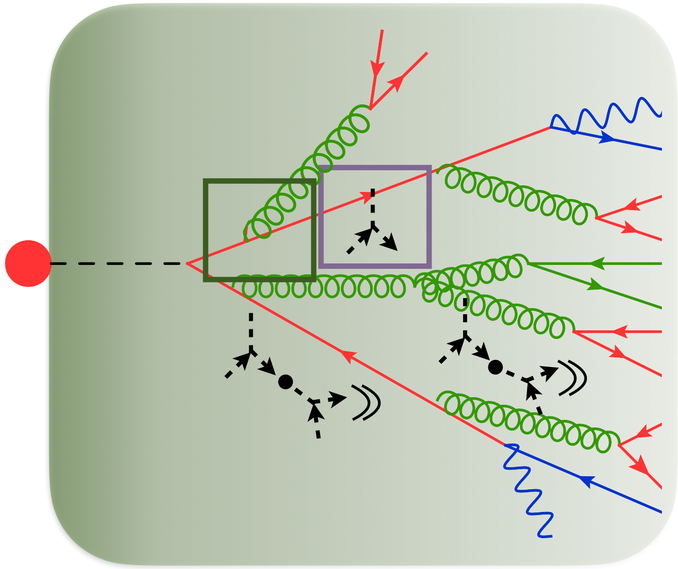
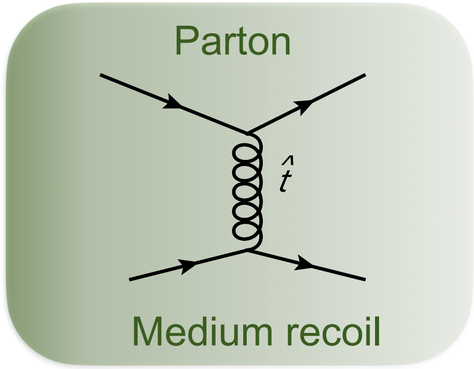


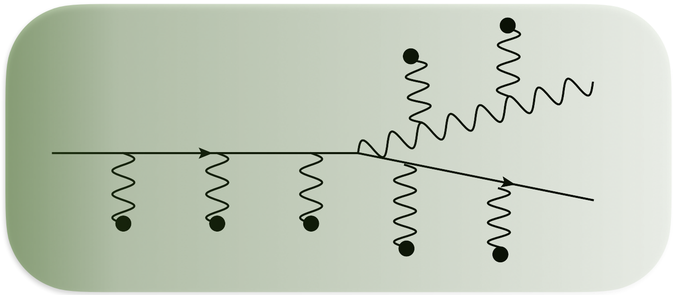
Elastic scattering processes:



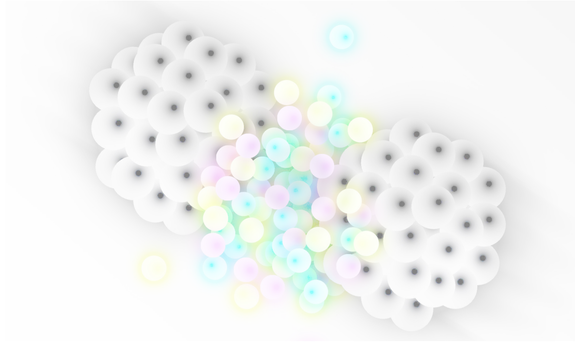
Relevant for heavy (low-energy) partons

Dominant for light (high-energy) partons

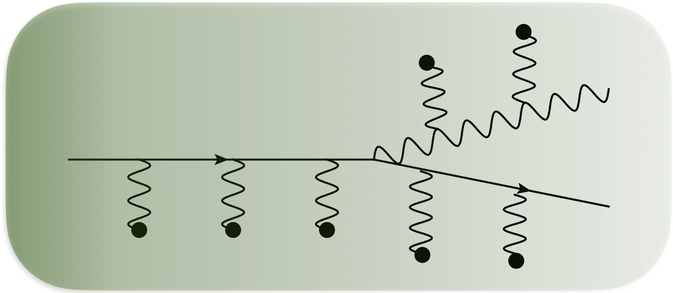
Inelastic scattering processes:



Medium-induced radiation



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



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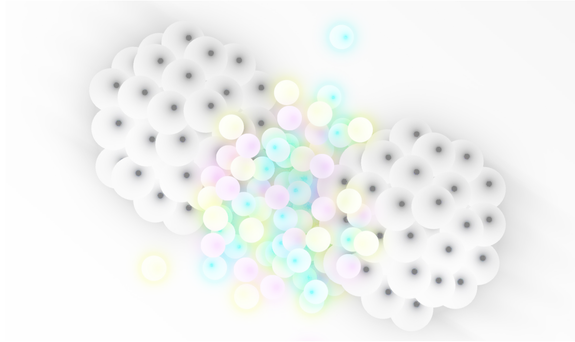

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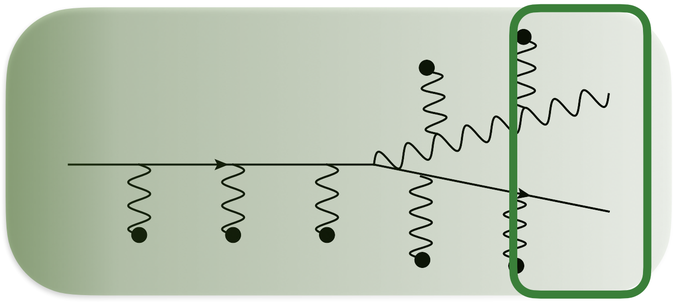

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$$\mathcal{P}(t'',\boldsymbol{k};t',\boldsymbol{q}) \equiv \int d^2\boldsymbol{z}\, e^{-i(\boldsymbol{k}-\boldsymbol{q})\cdot\boldsymbol{z}}\ \exp\left\{-\frac{1}{2}\int_{t'}^{t''} ds\, n(s)\,\sigma(\boldsymbol{z})\right\}$$

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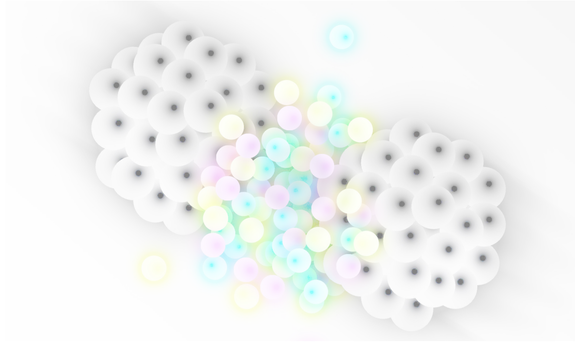

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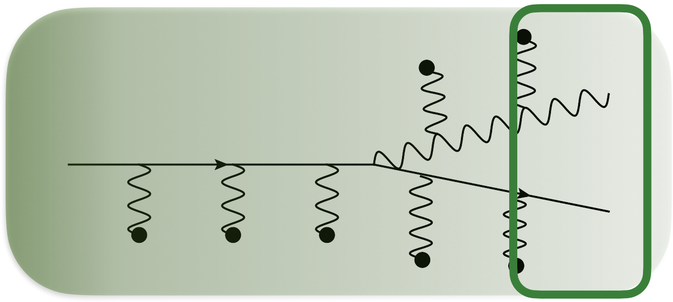

Density of scattering centres:

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

Dipole cross-section (collision rate):

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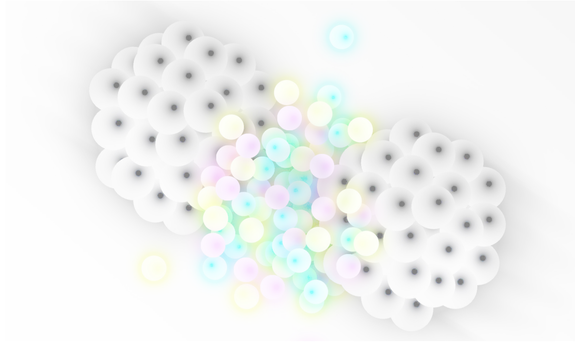

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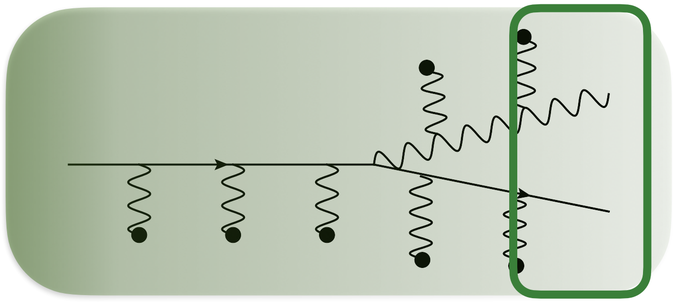

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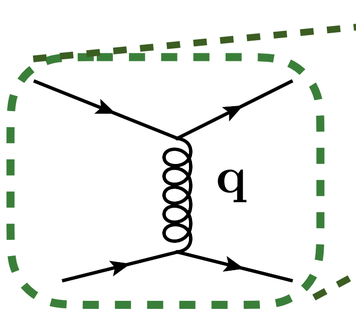

Parton-medium interaction

Medium-induced radiation

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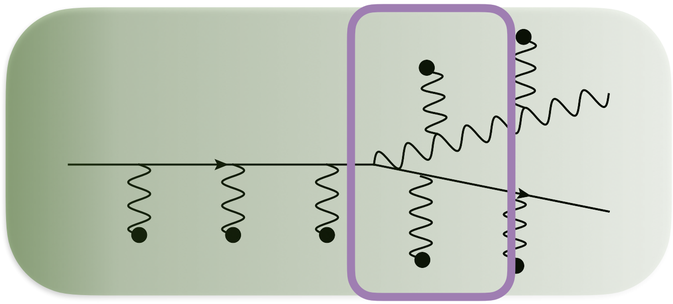

Emission Kernel:

$$\mathcal{K}(t',\boldsymbol{z};t,\boldsymbol{y}) \equiv \int_{\boldsymbol{pq}} e^{i(\boldsymbol{q}\cdot\boldsymbol{z}-\boldsymbol{p}\cdot\boldsymbol{y})}\,\widetilde{\mathcal{K}}(t',\boldsymbol{q};t,\boldsymbol{p})$$
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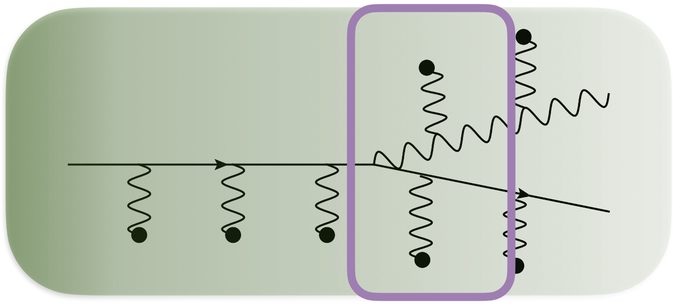

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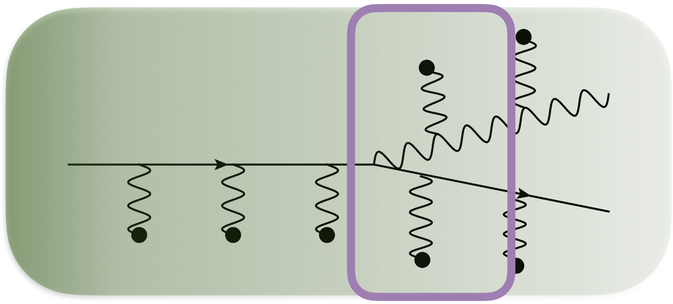
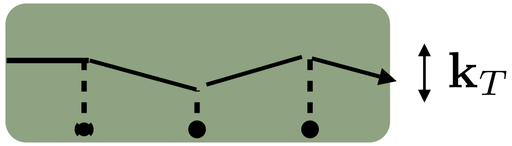
Solution to the path integral (for an arbitrary potential) poses significant technical challenges…

Medium-induced radiation

- Accumulation of momenta enhances gluon radiation:
  - In addition to energy loss, parton also undergoes transverse momentum diffusion **See also Sievert talk (Tue)**
    - Medium-induced transverse momentum broadening





Transport coefficient:

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

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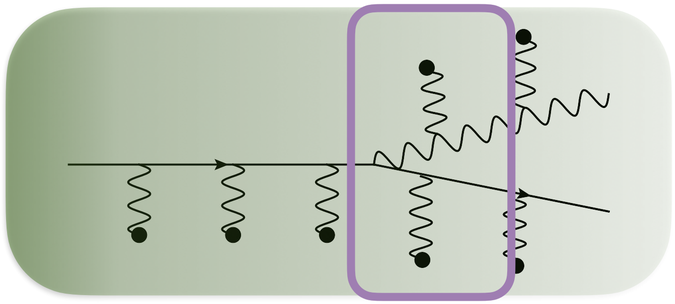
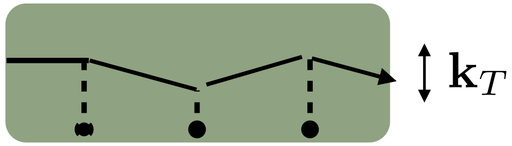




Transport coefficient:

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

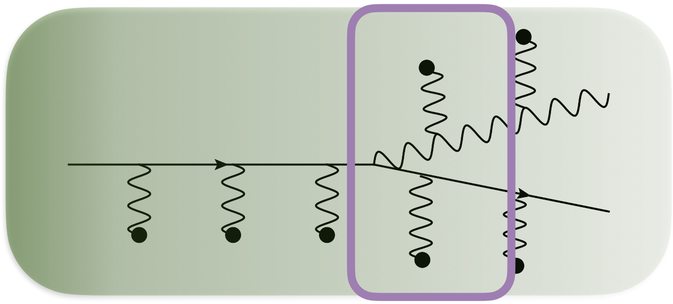
Dipole cross-section (collision rate):

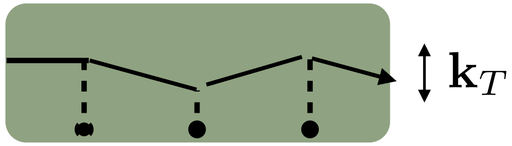
$$\sigma(\boldsymbol{r}) = \int_{\boldsymbol{q}} V(\boldsymbol{q}) \left(1 - e^{i\boldsymbol{q}\boldsymbol{r}}\right)$$

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

Medium-induced radiation

- Accumulation of momenta enhances gluon radiation:
  - In addition to energy loss, parton also undergoes transverse momentum diffusion See also Sievert talk (Tue)
    - Medium-induced transverse momentum broadening





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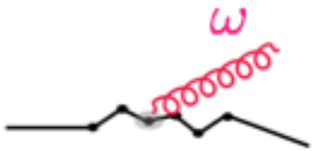
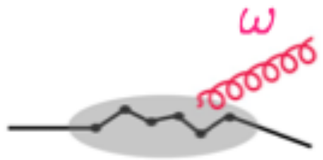
Medium-interactions per emission?

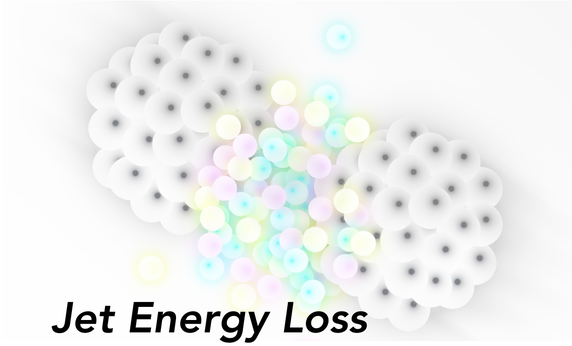


Multiple-soft scattering



Single-hard emission

Current landscape

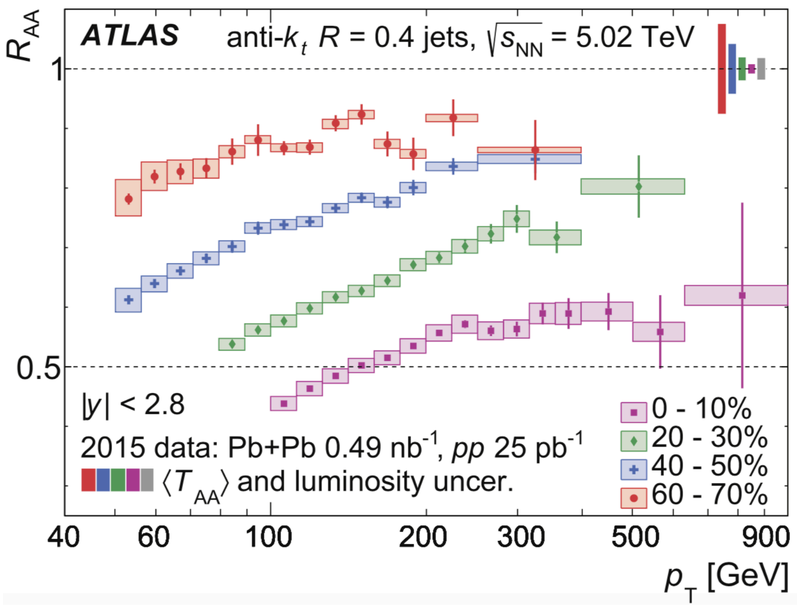


- Medium-induced energy loss and momentum broadening closely connected
  - From single-particle or jet suppression, recover $\hat{q}$

$$R_{AA} = \frac{Y^X_{AA}}{\langle T_{AA} \rangle \cdot \sigma^X_{pp}}$$

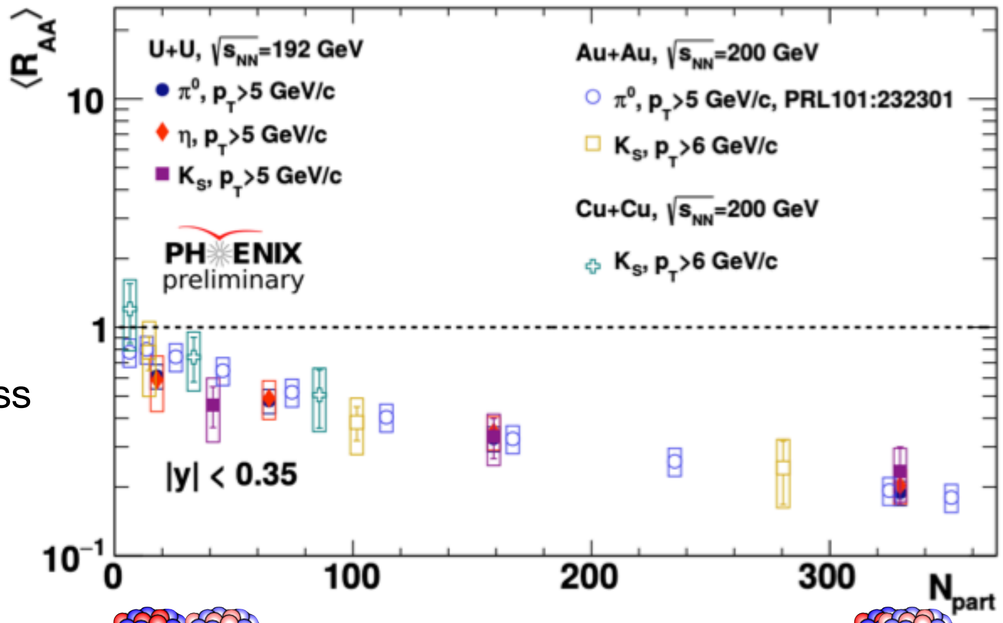
Jet Energy Loss

ATLAS [1805.05635]



Particle Energy Loss

PHENIX [2002.11156]



$$R_{AA} = 1$$

No energy loss

$$R_{AA} < 1$$

Energy loss

Current landscape

- Medium-induced energy loss and momentum broadening closely connected
  - From single-particle or jet suppression, recover $\hat{q}$

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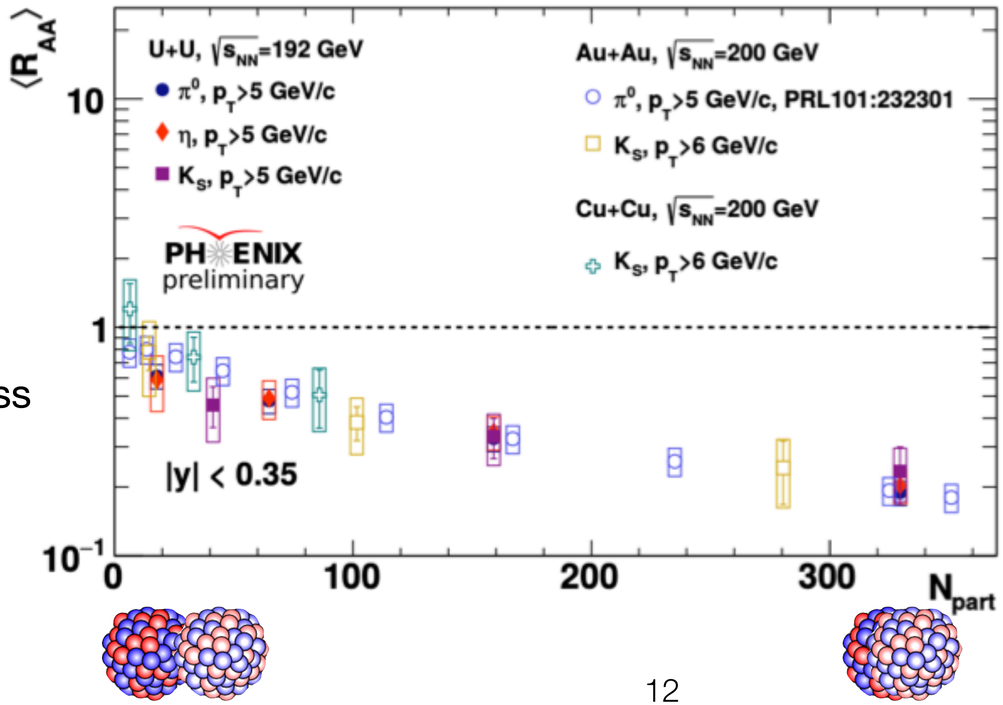
RHIC (AuAu 200 GeV)

Particle Energy Loss

PHENIX [2002.11156]



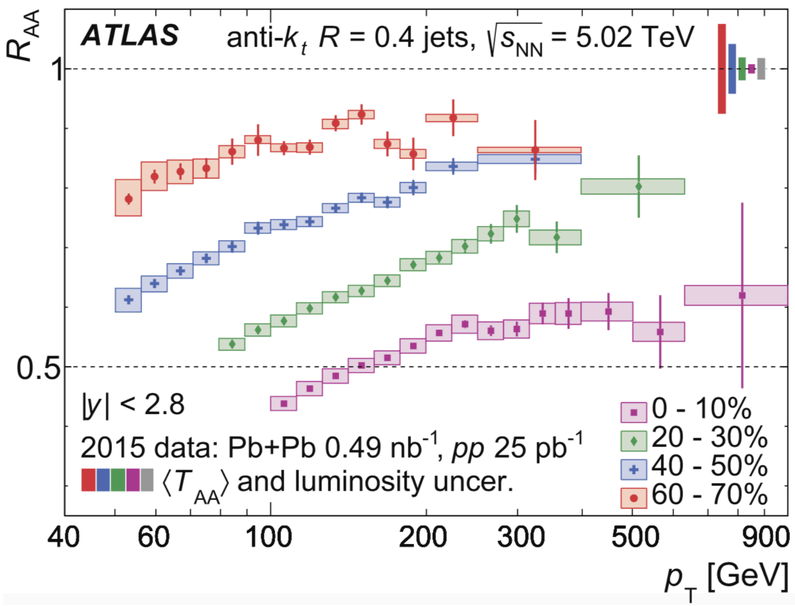
$R_{AA} = 1$

No energy loss

LHC (PbPB 5.02 TeV)

Jet Energy Loss

ATLAS [1805.05635]



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Energy loss

Current landscape

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

See also Escobedo (Quarkonia - Th) and Ru (CNM - Th) talks

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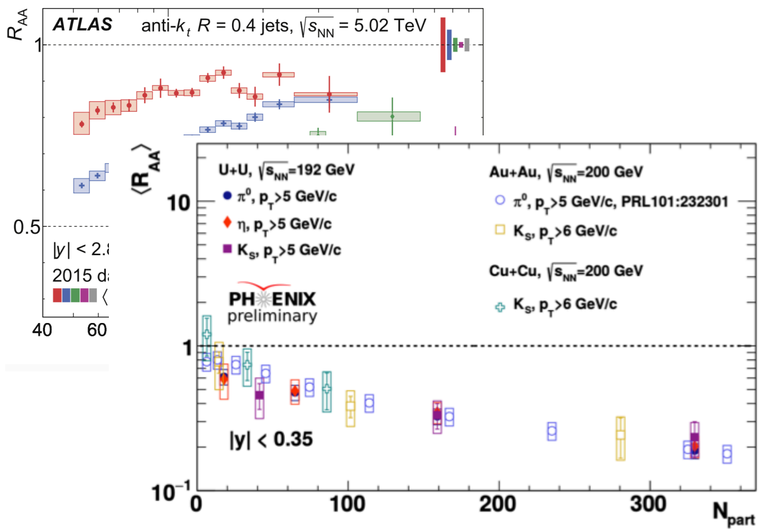
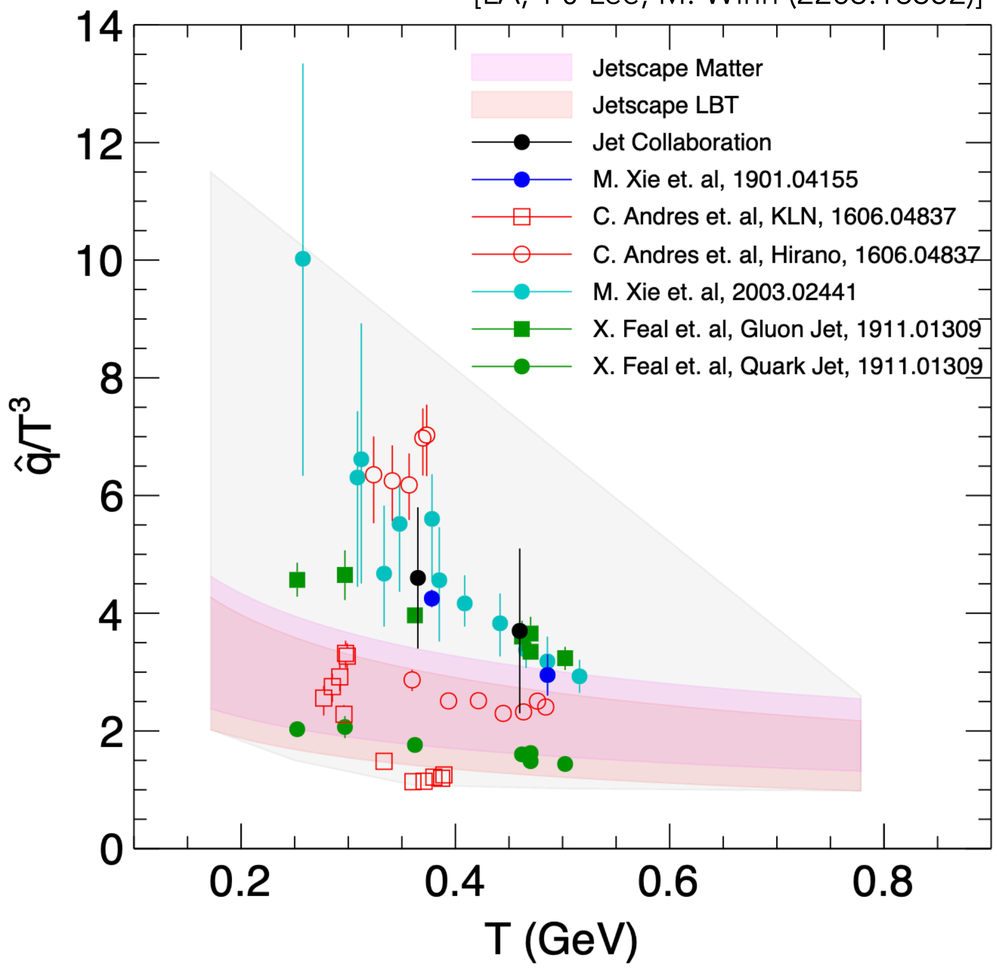


[LA, Y-J Lee, M. Winn (2203.16352)]



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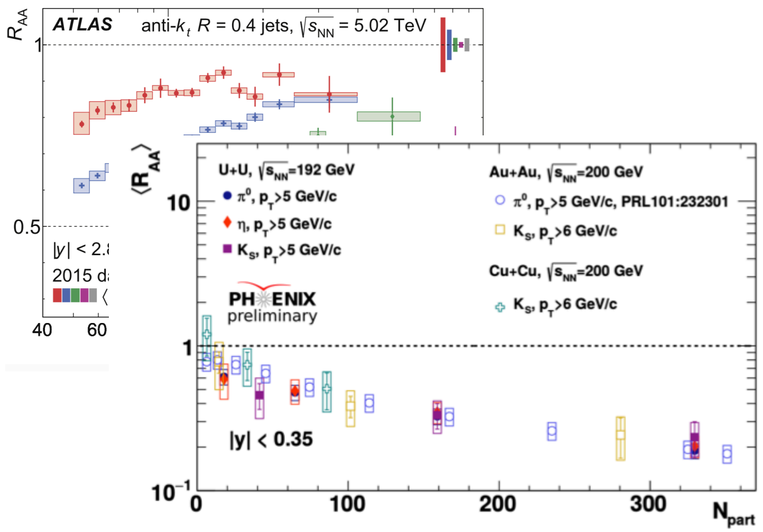
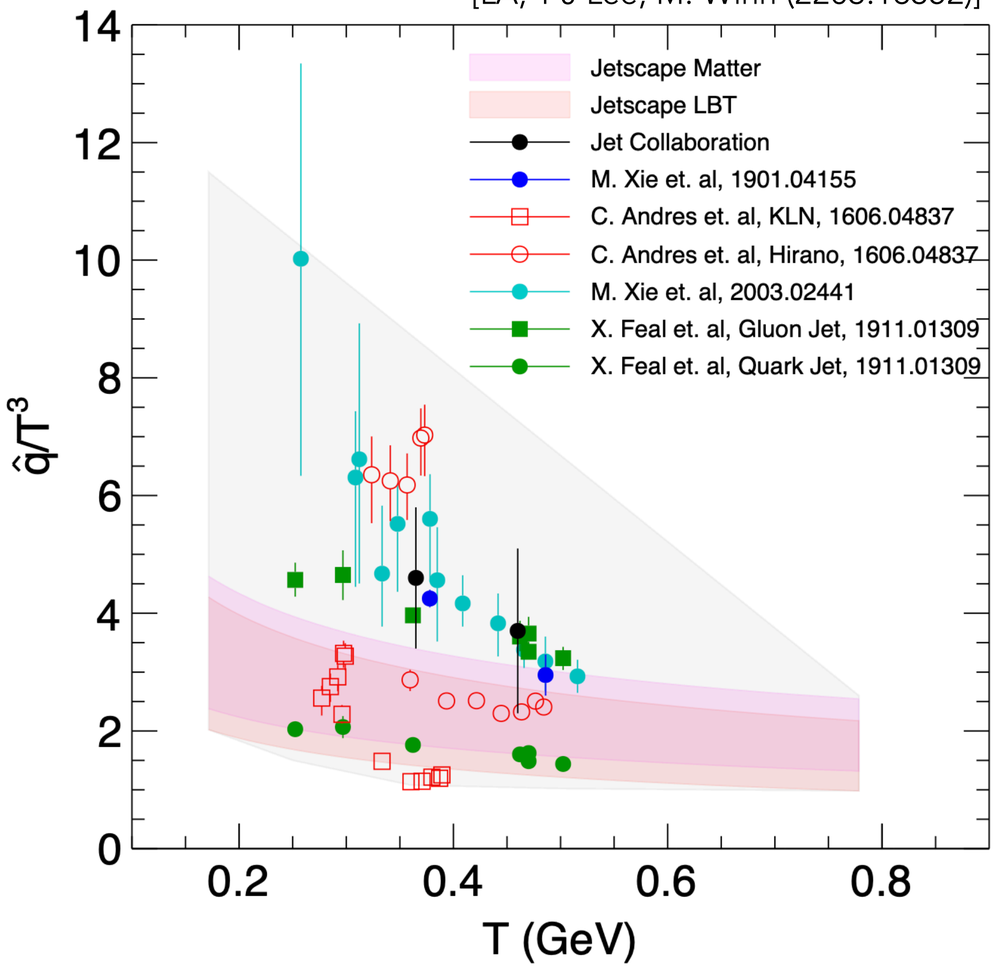


Several ansatz:

- 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?
- …

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



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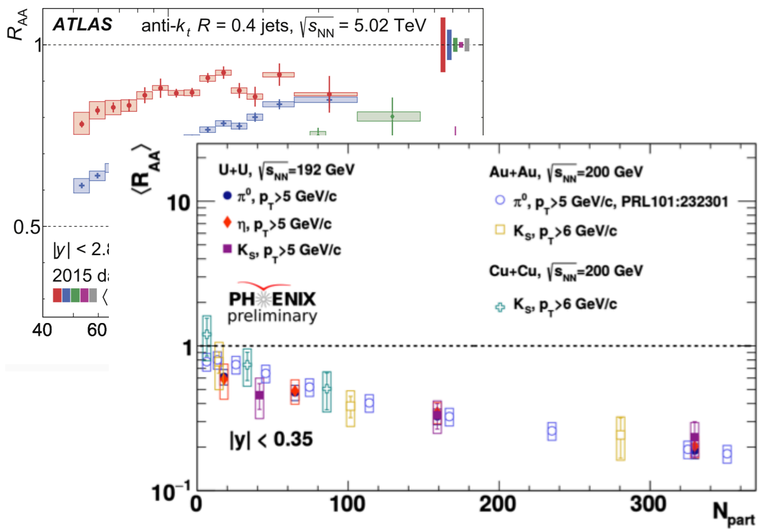

How can we improve it?

Several ansatz:

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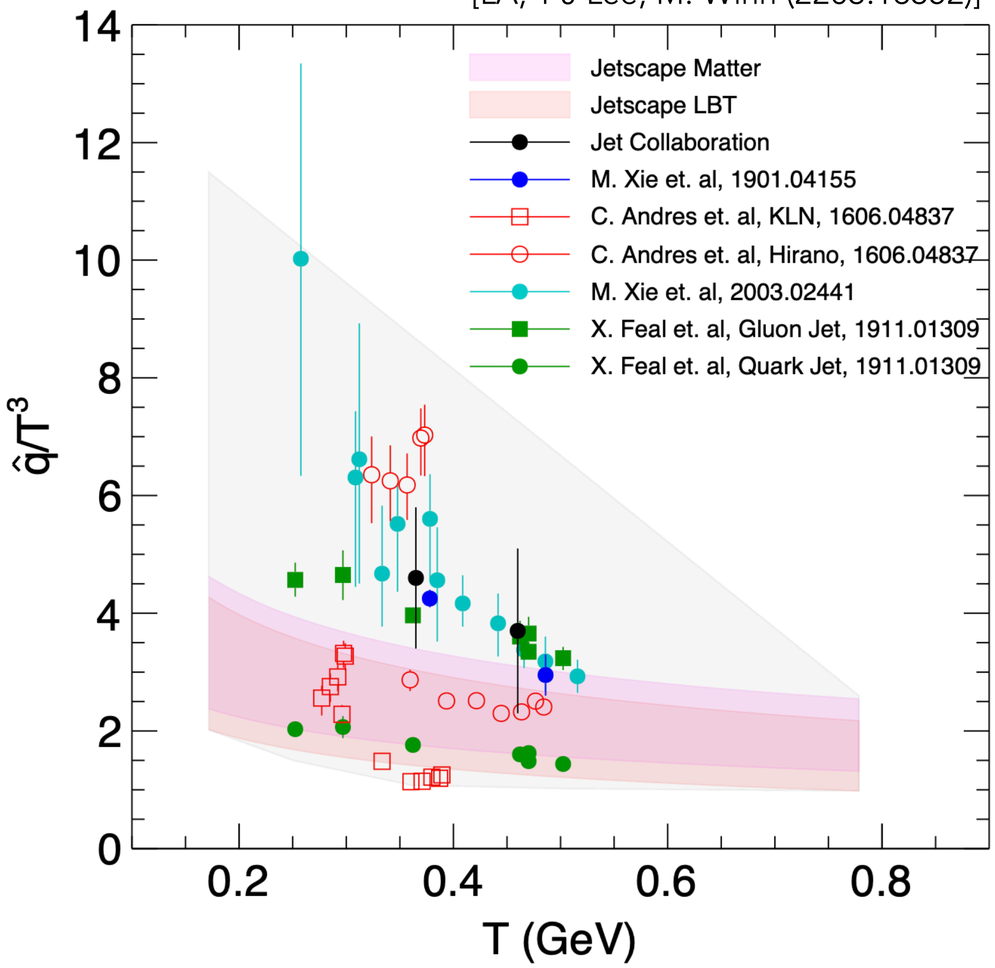
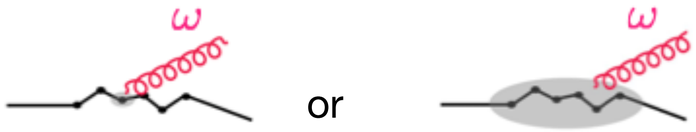


Improving medium-induced radiation

- **Accuracy** of radiation spectrum: 

  - Improved analytic opacity expansion (expand multiple soft interaction)

[Barata, Mehtar-Tani, Soto-Ontoso, Tywoniuk (1910.02032, 2106.07402)]

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

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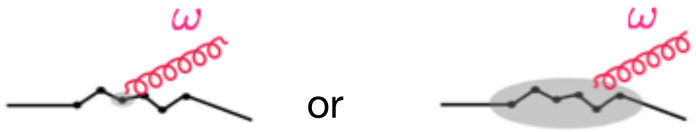
- **Accuracy** of radiation spectrum: 

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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, Dominguez, Gonzales (2011.06522)]

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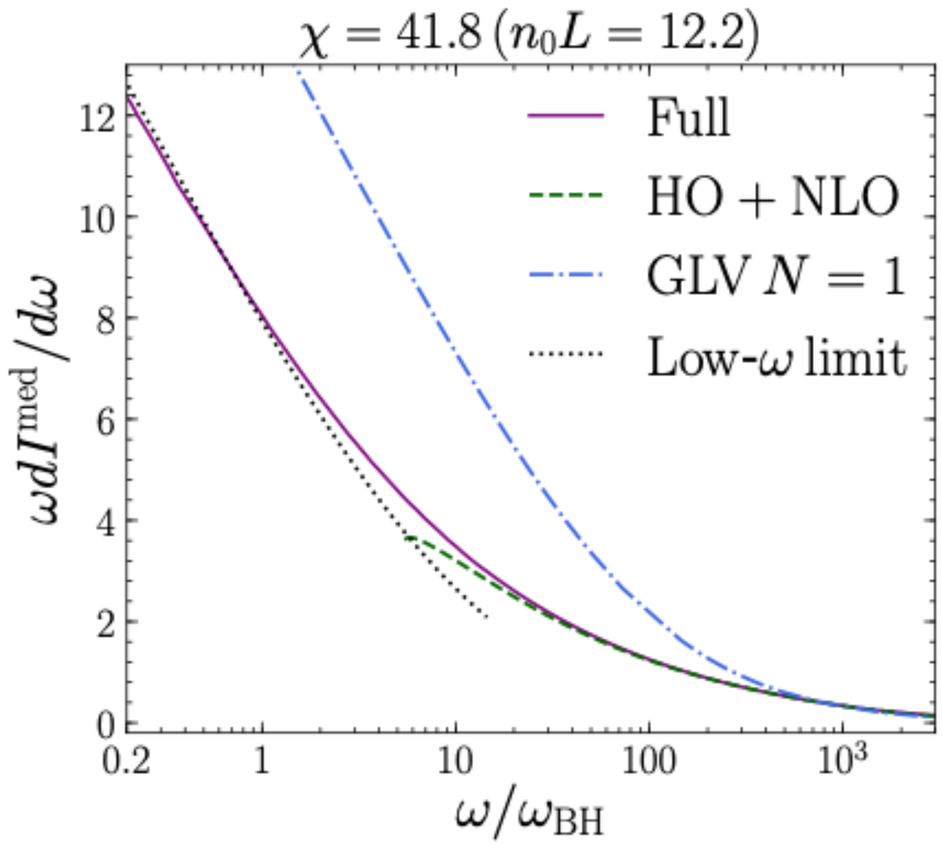


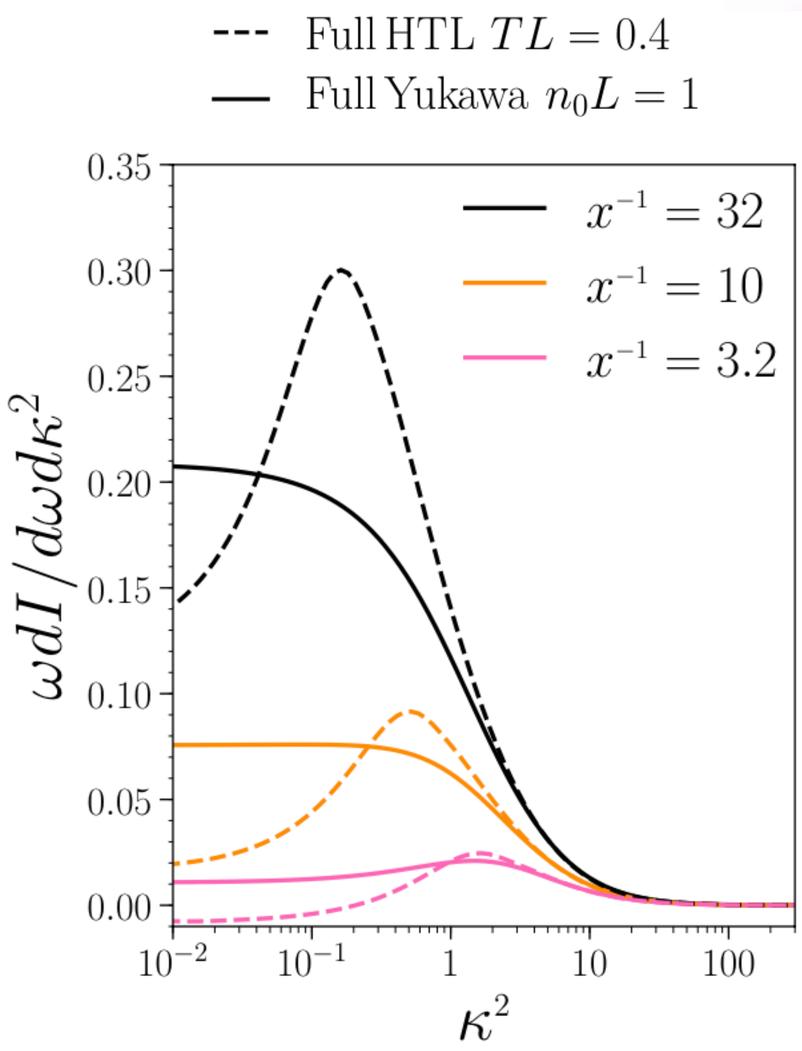
Improving medium-induced radiation

[Andrés, LA, Dominguez, (2002.01517)]

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

Yukawa potential: $V(\boldsymbol{q}) = \dfrac{8\pi\mu^2}{(\boldsymbol{q}^2+\mu^2)^2}$

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



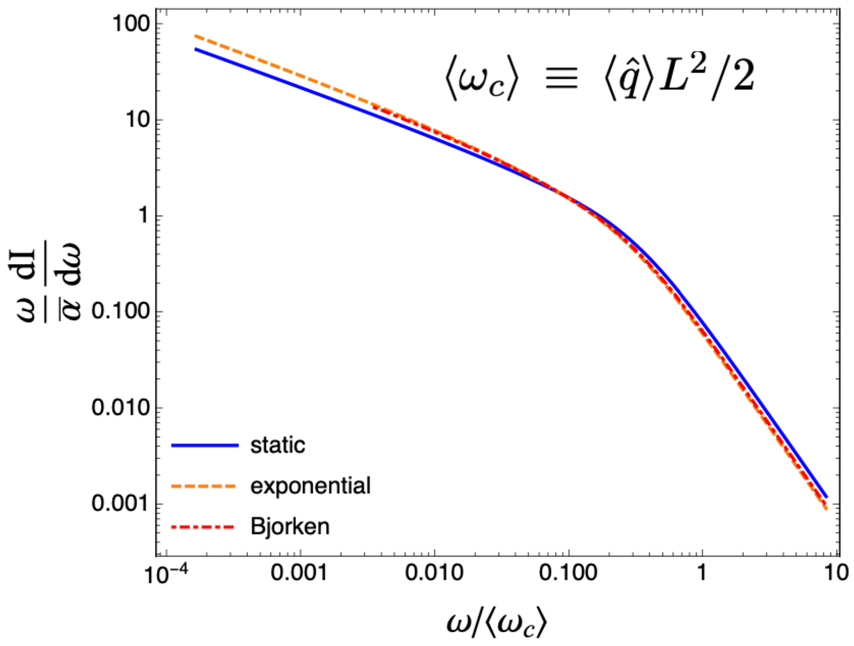
Also: [Barata, Sadofyev, Salgado (2202.08847)]

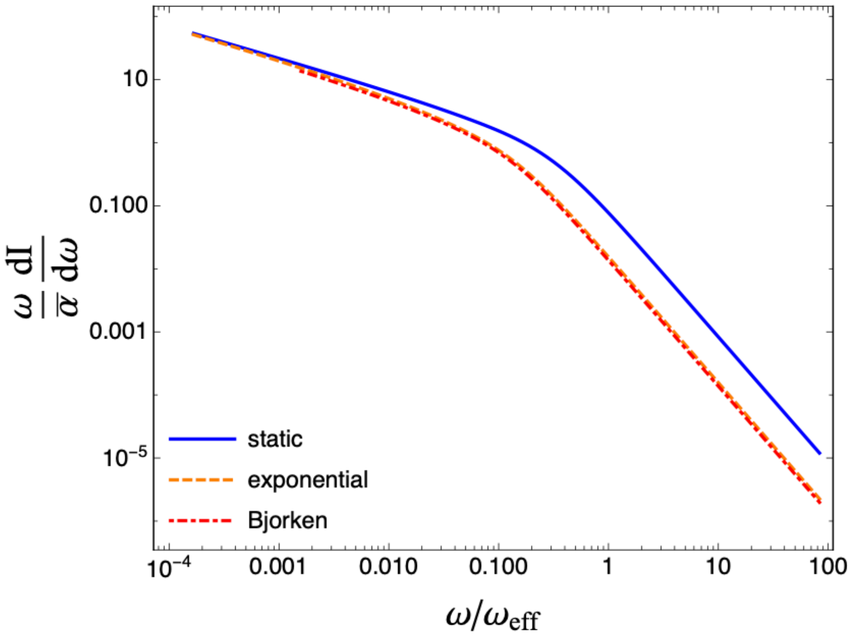
Improving medium-induced radiation

- Effects of **medium expansion** on energy loss (HO): $\hat{q} = \hat{q}(t)$
  - Static equivalent of an expanding medium obtained by scaling laws:

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

[Adhya, Salgado, Spousta, Tywoniuk, (1911.12193)]





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

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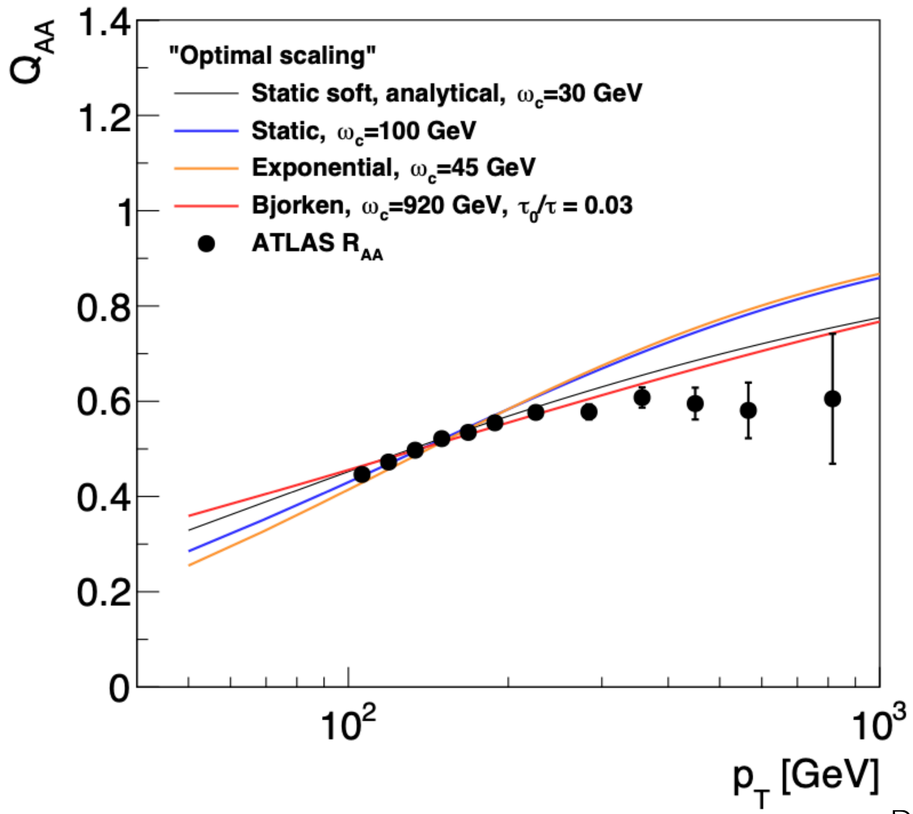
$\hat{q}_0$ [GeV^3]	static	exponential	Bjorken
no scaling	0.2	0.2	0.2
soft scaling	0.2	0.05	1.66
optimal scaling	0.2	0.09	1.84
scaling by $\langle \omega_c \rangle$	0.2	0.1	3.33

[Adhya, Salgado, Spousta, Tywoniuk, (1911.12193)]



Also: [Barata, Sadofyev, Salgado (2202.08847)]

Improving medium-induced radiation

[Andrés, LA, Dominguez, Gonzalez, Salgado (on-going)]

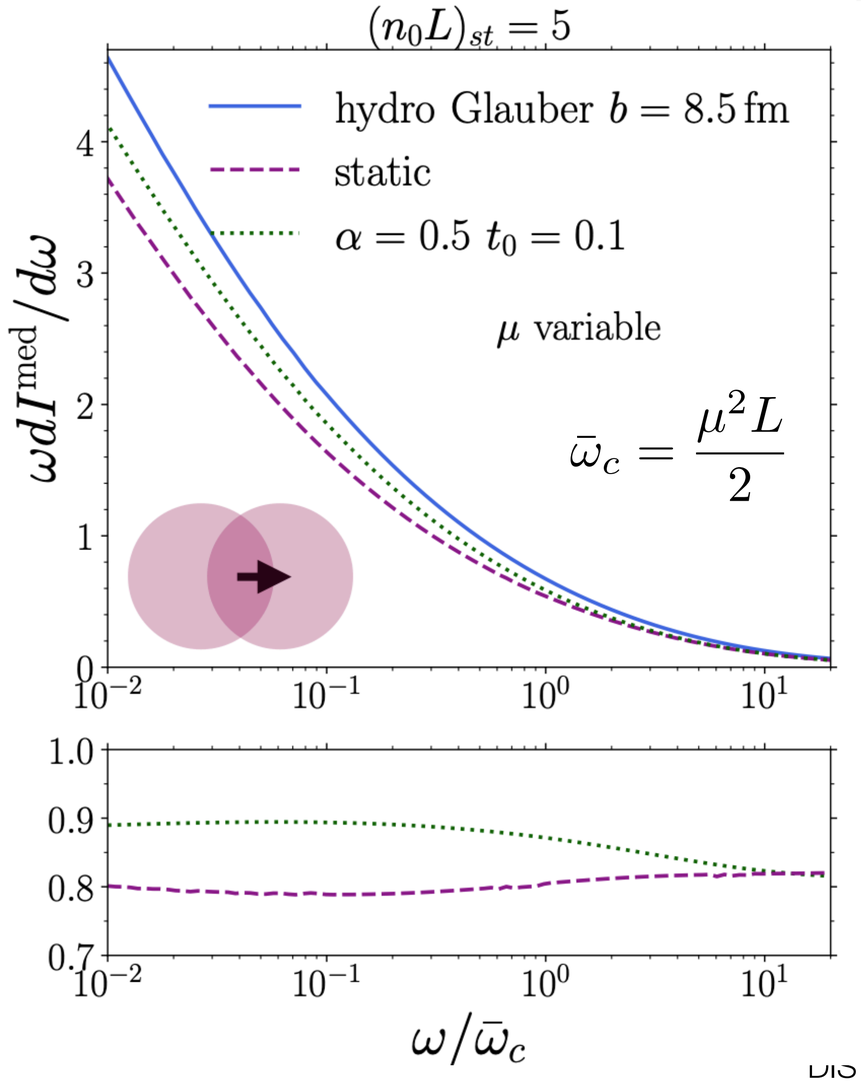
- Effects of **medium expansion** on energy loss (full solution):
  - Static equivalent of an expanding medium obtained by scaling laws:

$$n_0 L = \int_0^{L'} dt\, n(t) \qquad \frac{n_0 \mu^2 L^2}{2} = \int_0^{L'} dt\, t\, n(t)\, \mu^2(t)$$

  - For a hydrodynamic medium, use instead a power-law equivalent to improve accuracy

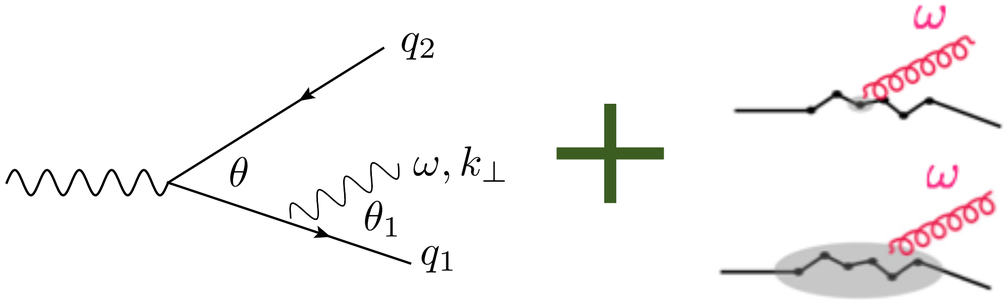
$$n_{hydro}(t) = k_1 T(t) \qquad n(t) = \frac{n_0'}{(t+t_0)^\alpha} \qquad \mu^2(t) = \frac{\mu'^2}{(t+t_0)^{2\alpha}}$$

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



Improving "medium" parton showers

- Multiple emitters:
  - Interference effects suppressed (+ anti-angular ordering)

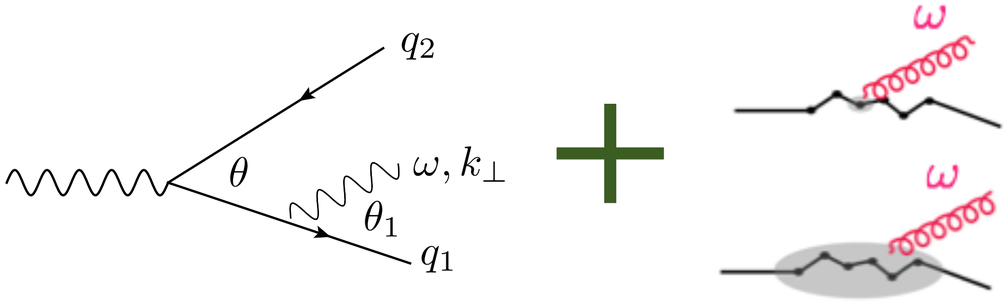


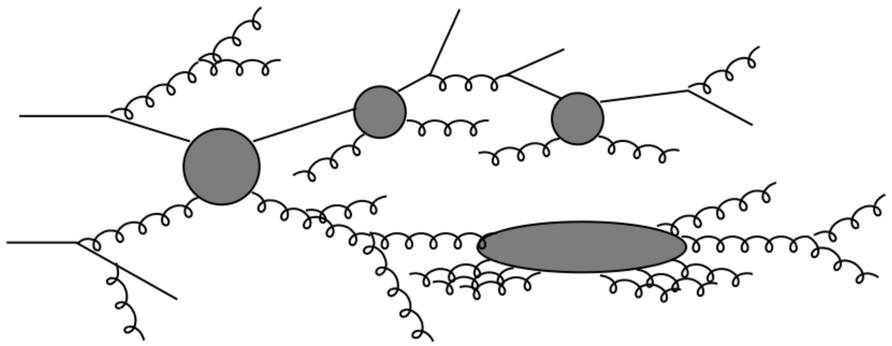
$$dN_q^{\omega\to 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin\theta d\theta}{1-\cos\theta} \left[\Theta(\cos\theta_1 - \cos\theta) + \Delta_{med}\Theta(\cos\theta - \cos\theta_1)\right]$$

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

Improving "medium" parton showers

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





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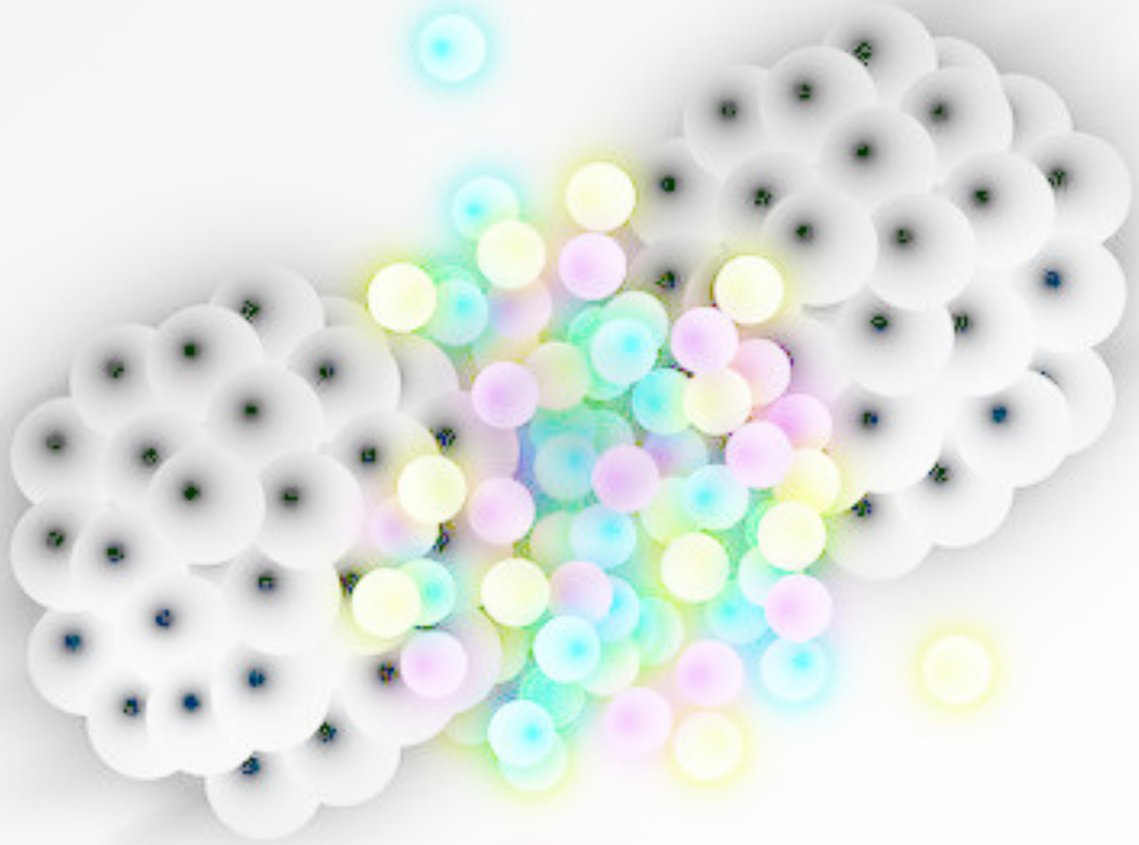
Monte Carlo: [Q-PYTHIA, JEWEL] [Armesto, Cunqueiro, Salgado (0907.1014), Zapp (1311.0048)]

New experimental handles



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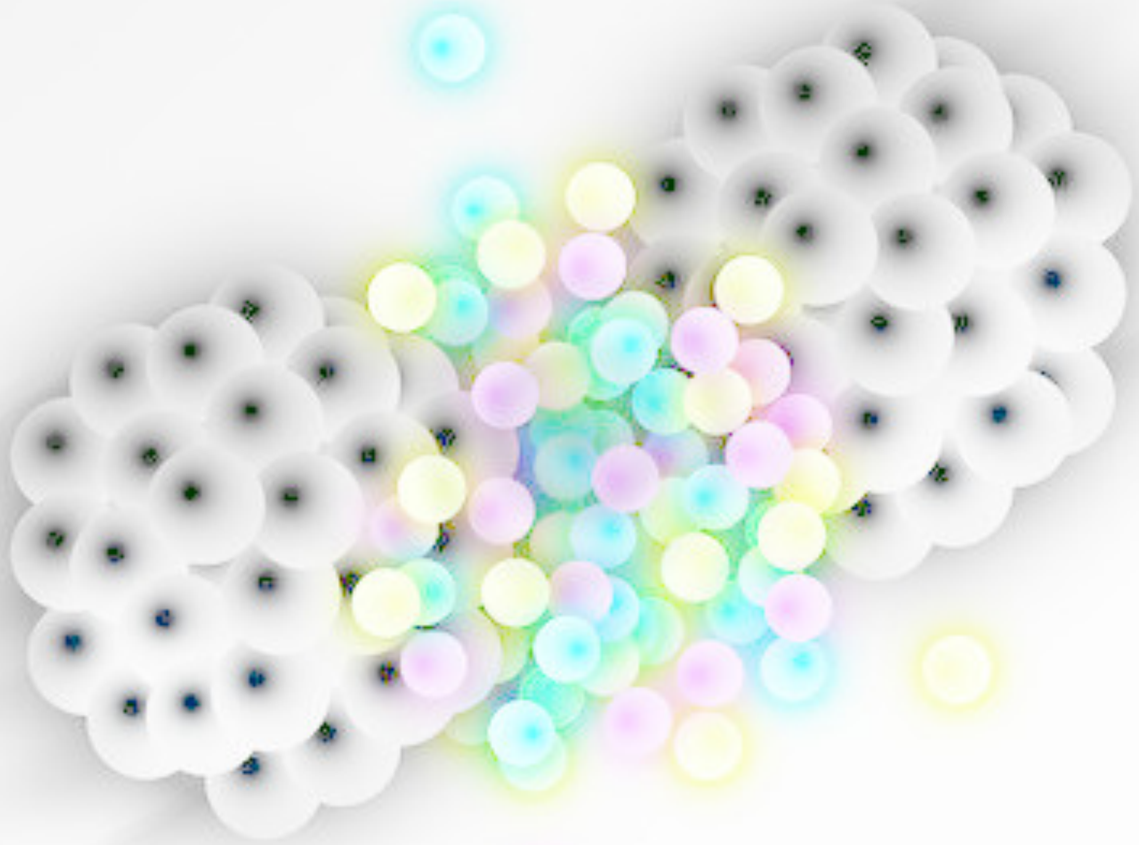
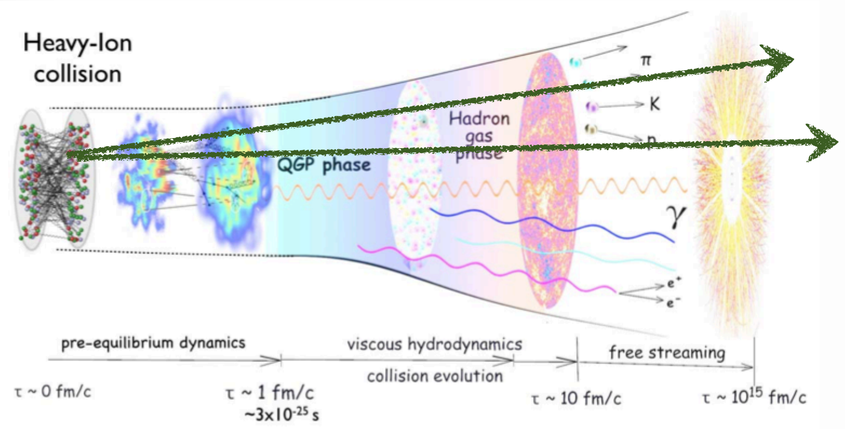
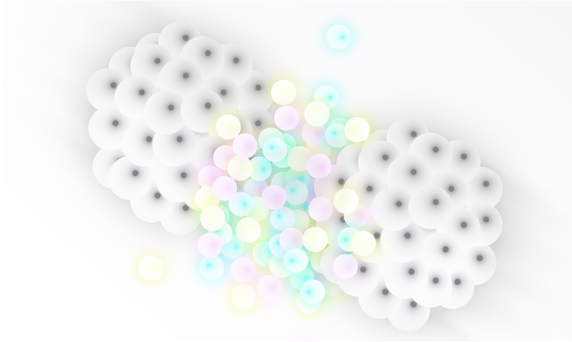


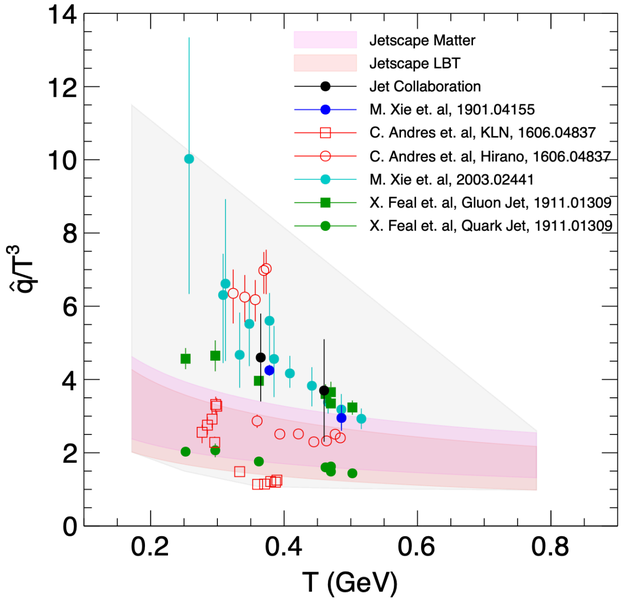


From particles to jets



- How can we access QGP-related information?

[Adapted from Yi Chen (QM2019)



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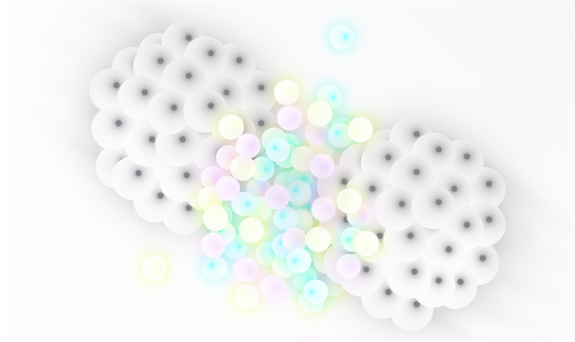

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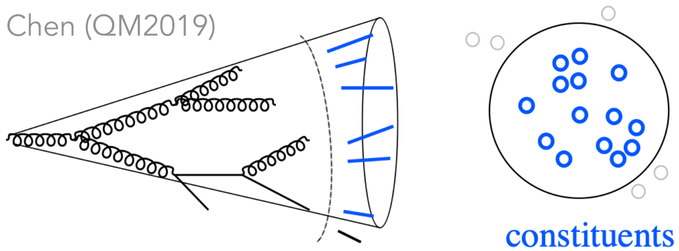
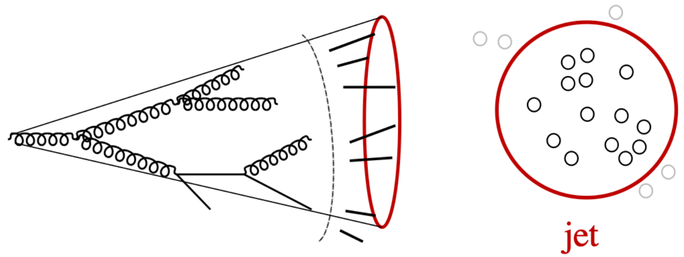
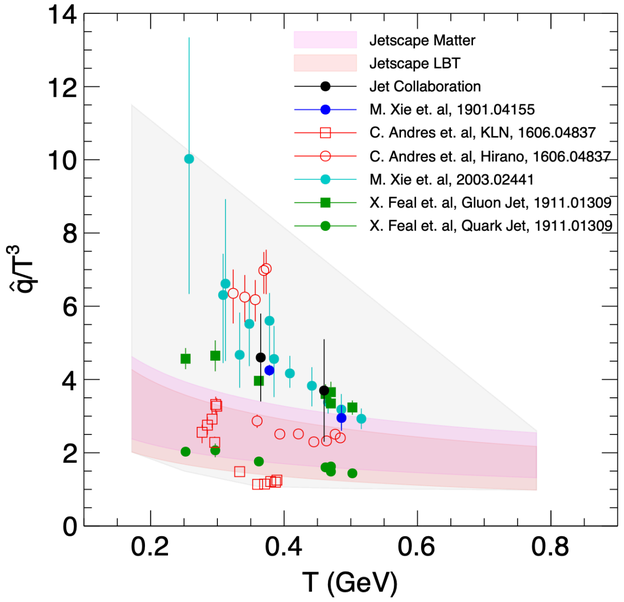


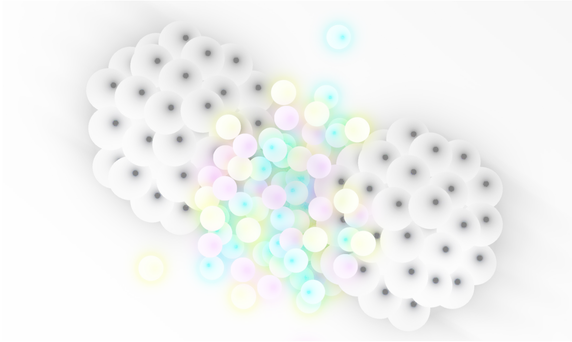


However:
- Susceptible to hadronization effects…



However:
- Sensitive to average quantities…

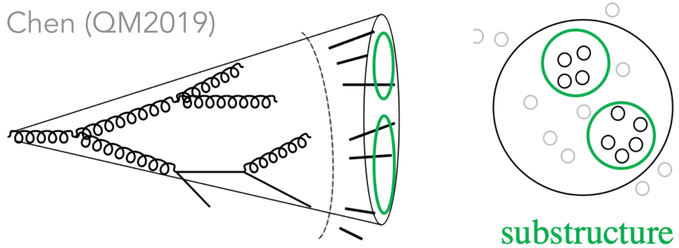
From jets to jet substructure



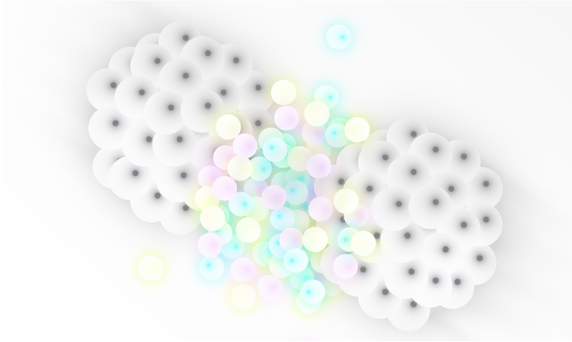
- How can we access QGP-related information?

What more information can they provide?

[Adapted from Yi Chen (QM2019)



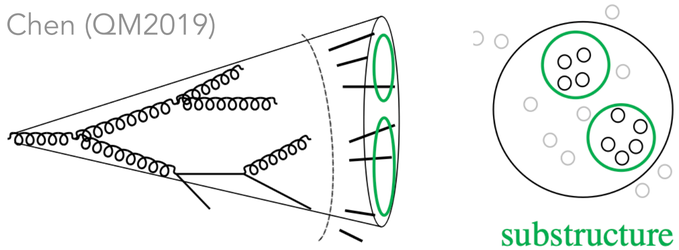
From jets to jet substructure



- How can we access QGP-related information?

What more information can they provide?

[Adapted from Yi Chen (QM2019)



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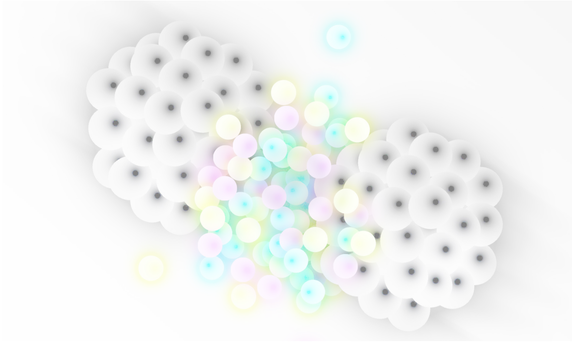

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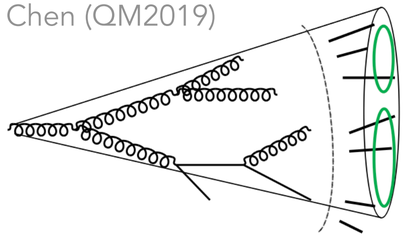
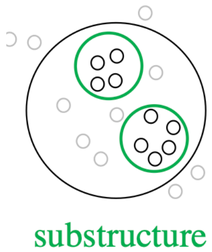
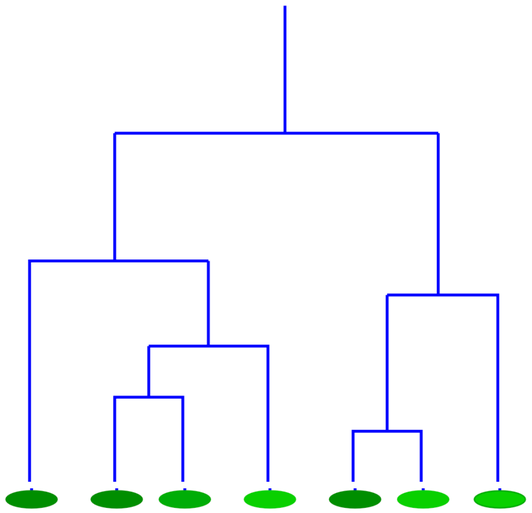
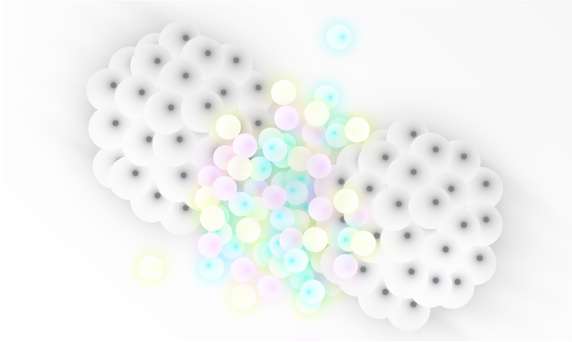






From jets to jet substructure



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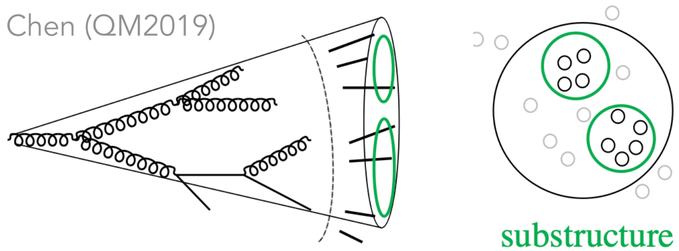
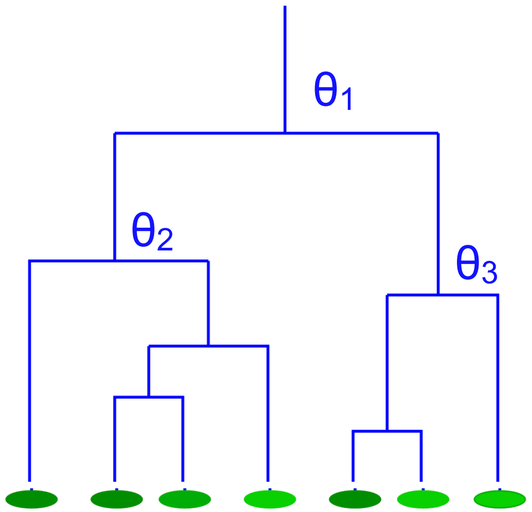
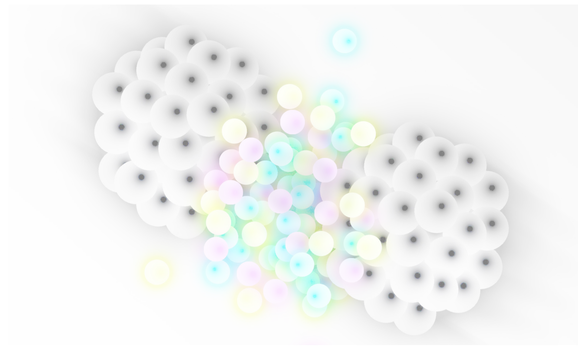




Angular ordered tree

From jets to jet substructure



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What more information can they provide?

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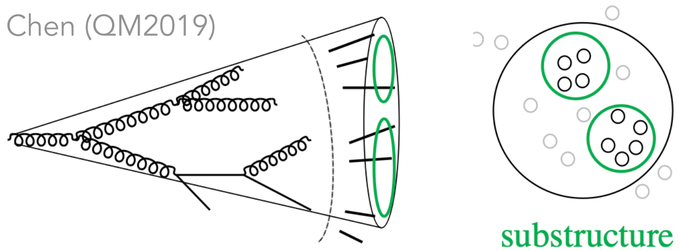
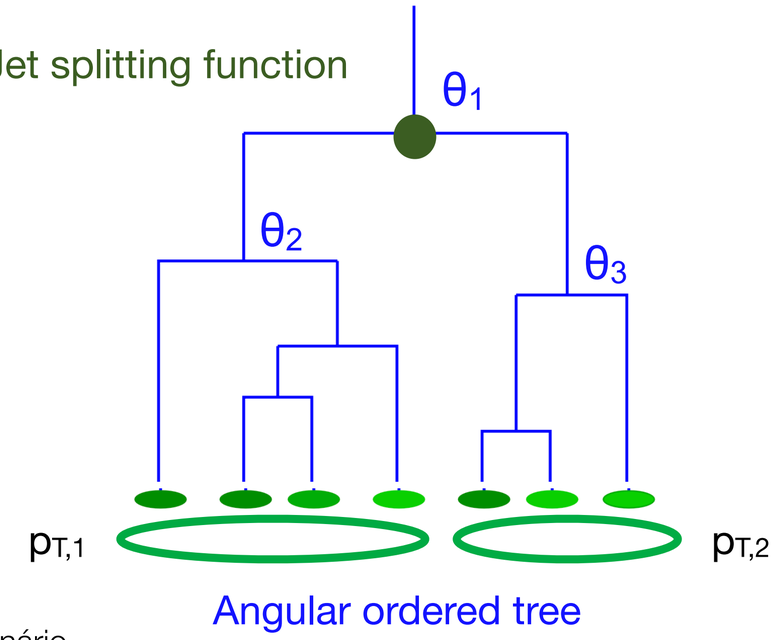


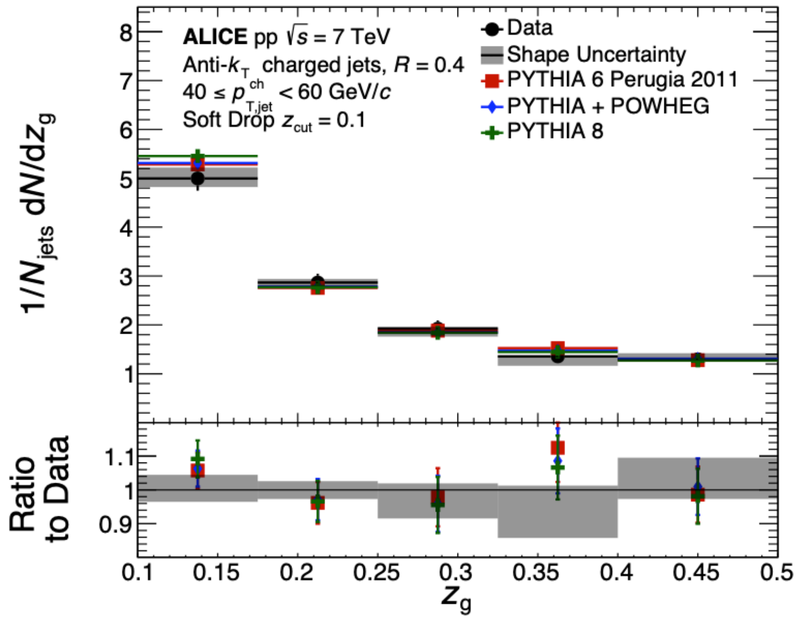
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

Jet splitting function



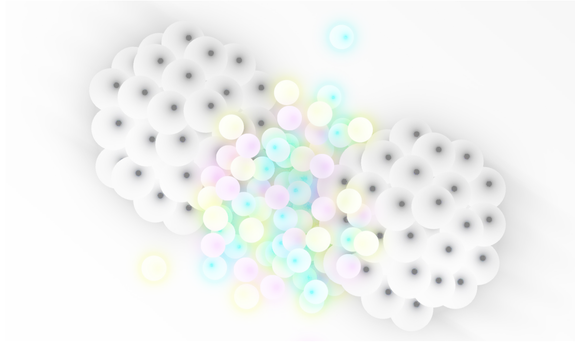
$$\text{when} \quad \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{R_{12}}{R_0}\right)^{\beta}$$

[Larkoski, Marzani, Soyez, Thaler (1402.2657)]
[Dasgupta, Fregoso, Marzani, Salam (1307.0007)]



[ALICE PLB 802 (2020) 135227]

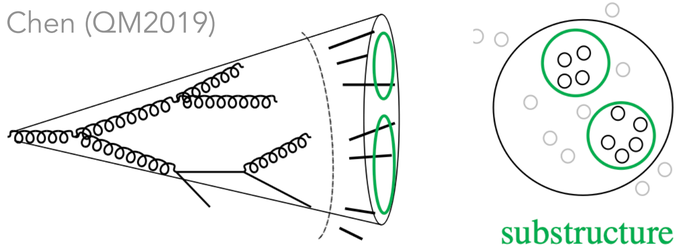
From jets to jet substructure



- *How can we access QGP-related information?*

What more information can they provide?

[Adapted from Yi Chen (QM2019)]

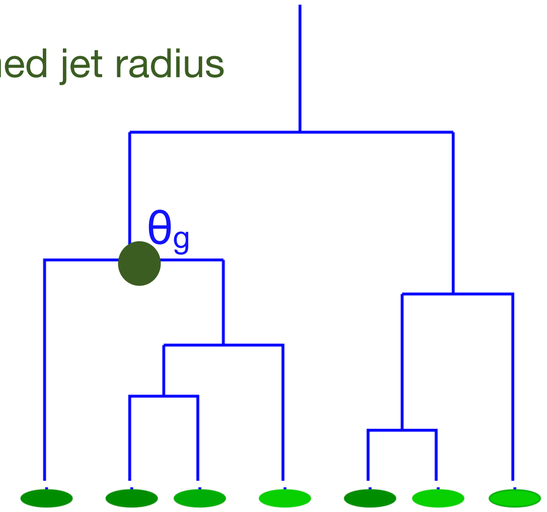


$$\kappa^{(a)} = \frac{1}{p_{t,\mathrm{jet}}} z(1-z) p_t \left(\frac{\theta}{R}\right)^a$$

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

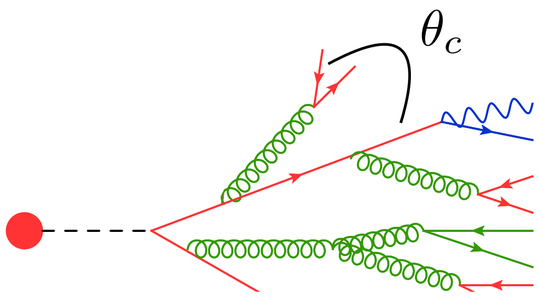
[Caucal, Soto-Ontoso, Takacs (2111.14768)]

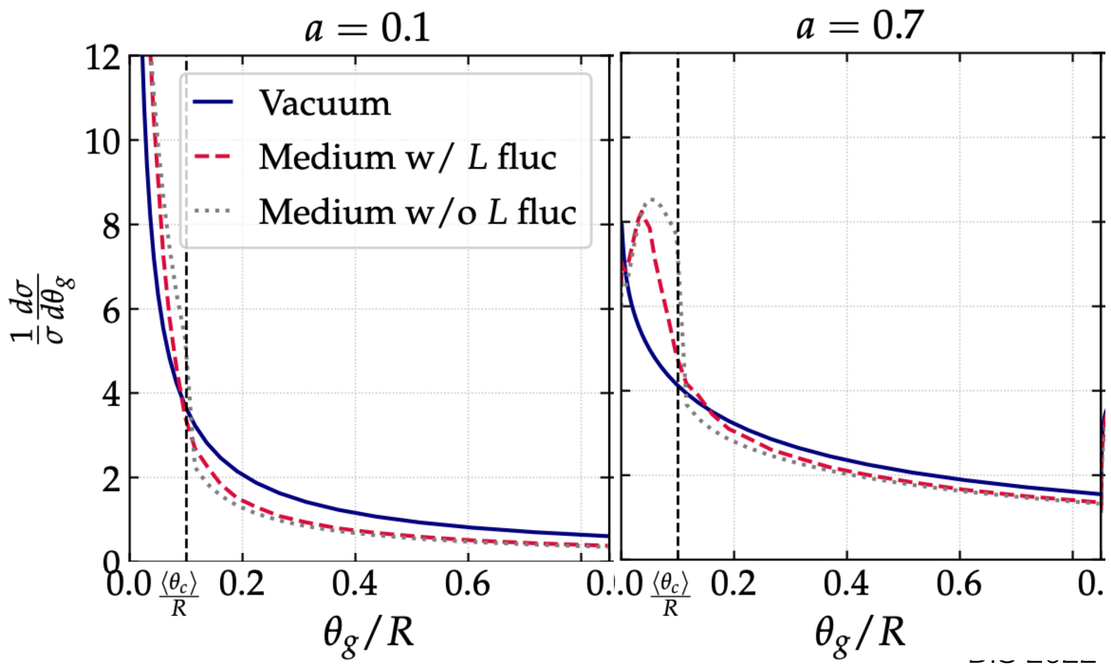
Groomed jet radius



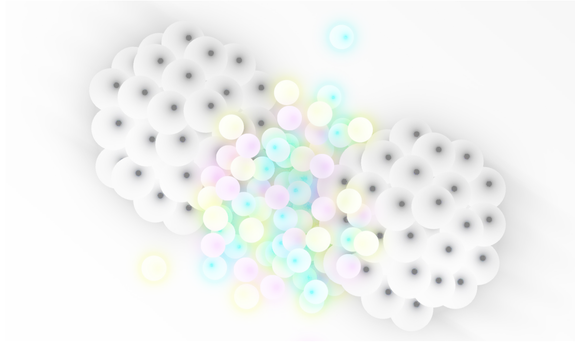
Angular ordered tree

Sensitive to decoherence angle?

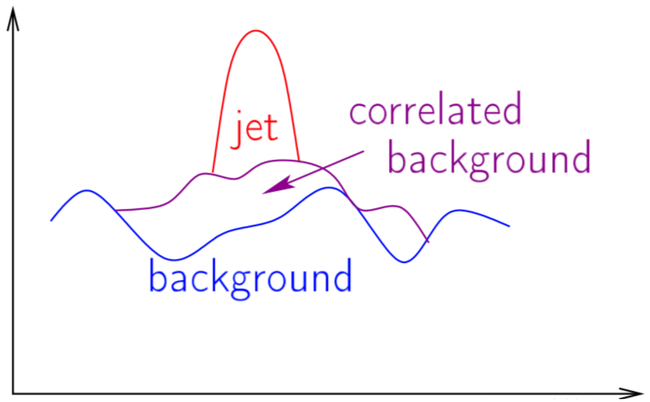




From jets to jet substructure



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



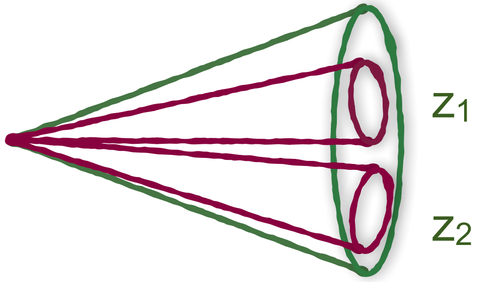
[Zapp QM (17)]

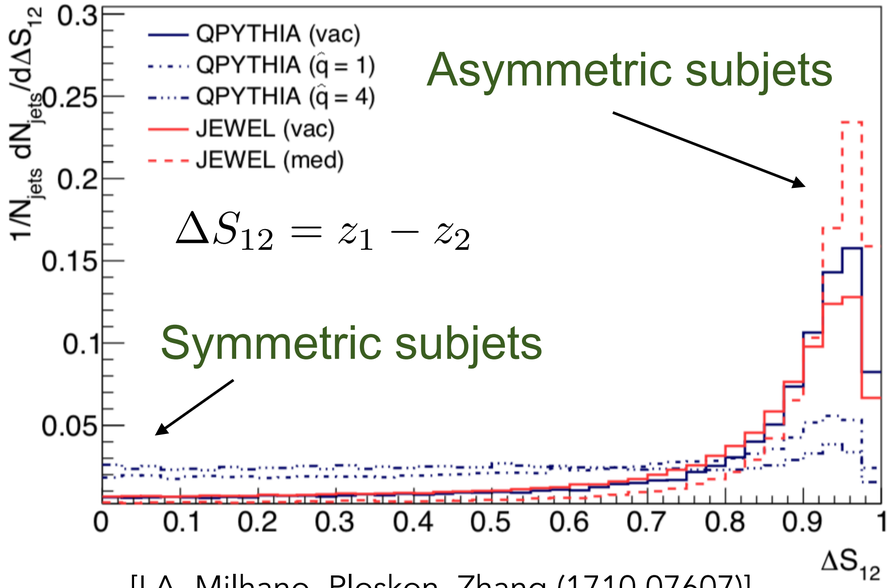
From jets to jet substructure

Fully reclustered anti-kt subjets

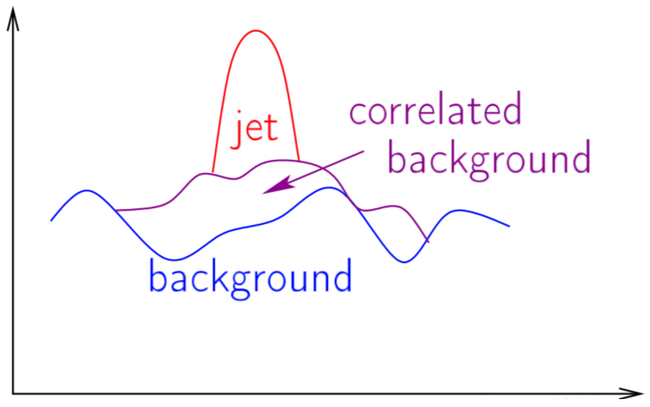
- How can we access QGP-related information?
  - Jets in PbPb ≠ Jets in pp + Background

    - Background-resilient to distinguish quenching models





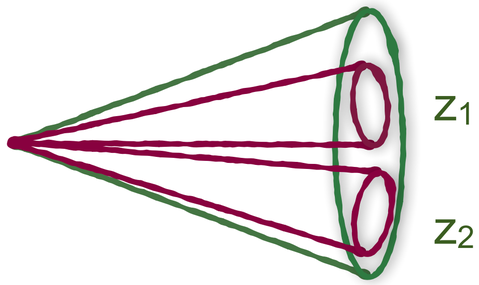
[LA, Milhano, Ploskon, Zhang (1710.07607)]



[Zapp QM (17)]

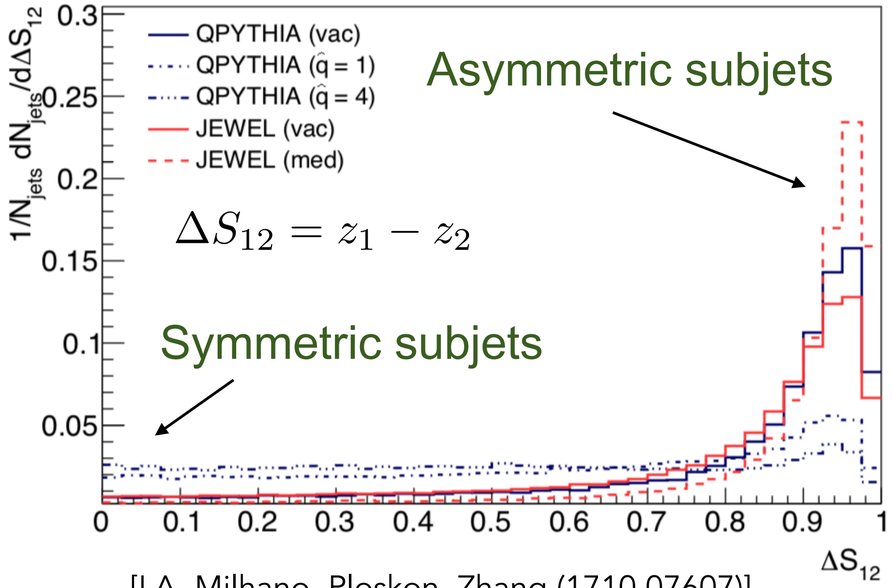
From jets to jet substructure

- How can we access QGP-related information?
  - Jets in PbPb ≠ Jets in pp + Background



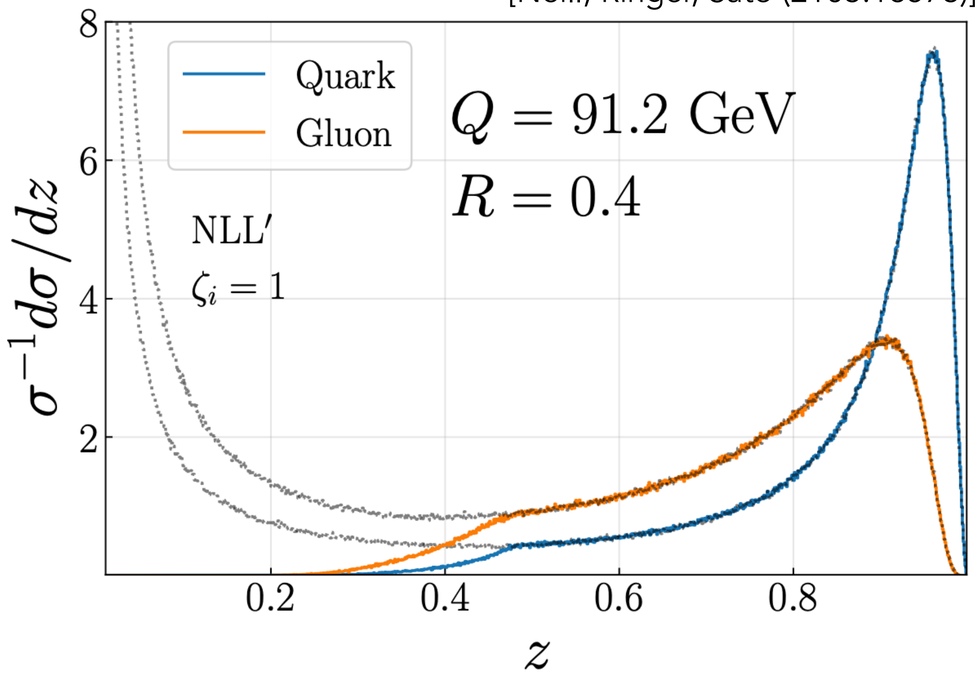
Fully reclustered anti-kt subjets

- Background-resilient to distinguish quenching models
- Leading jet: quantifies quark vs gluon in-medium energy loss

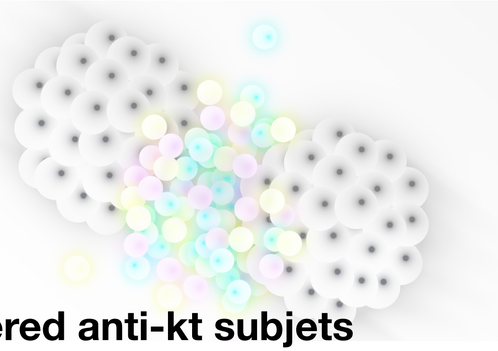


[LA, Milhano, Ploskon, Zhang (1710.07607)]

[Neill, Ringer, Sato (2103.16573)]



From jets to jet substructure



- How can we access QGP-related information?
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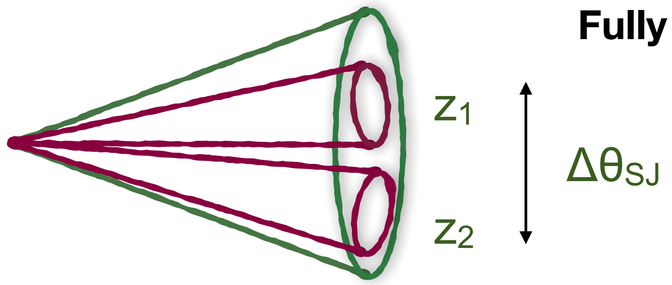
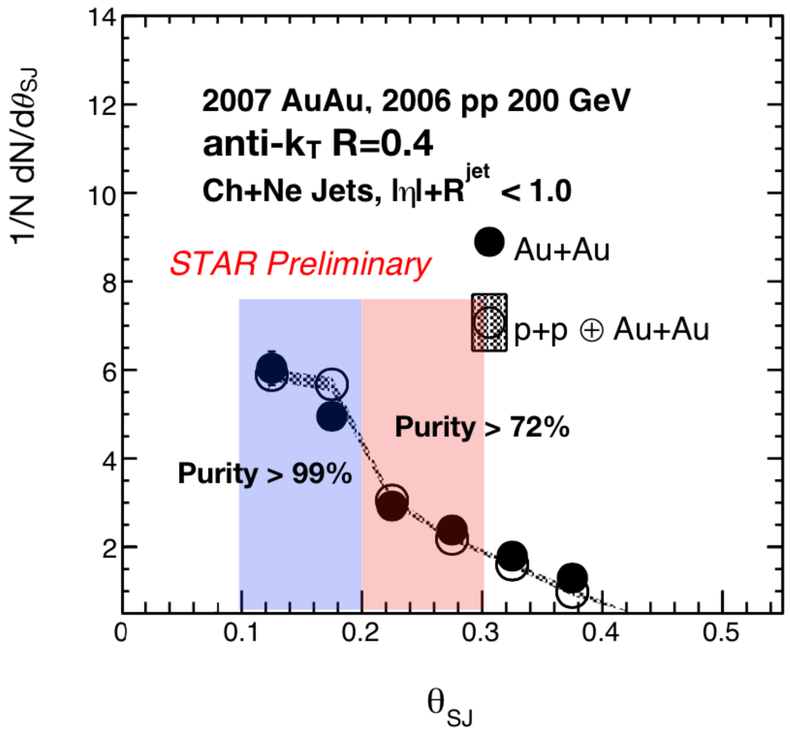


- Background-resilient to distinguish quenching models
- Leading jet: quantifies quark vs gluon in-medium energy loss
- Allows to create samples that are the same in pp and in PbPb

[STAR (QM2019)]

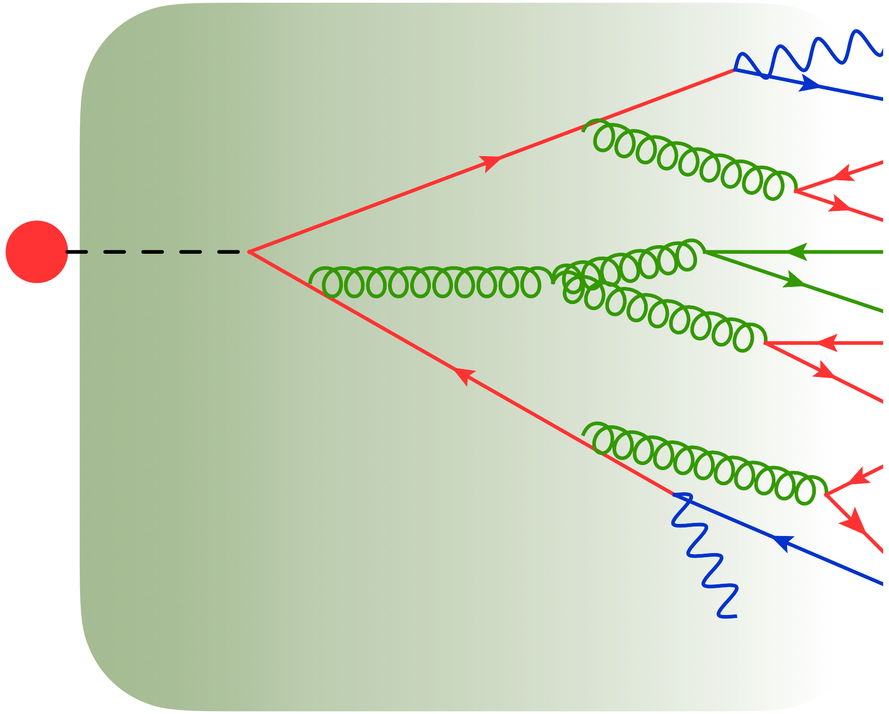


From jets to jet substructure

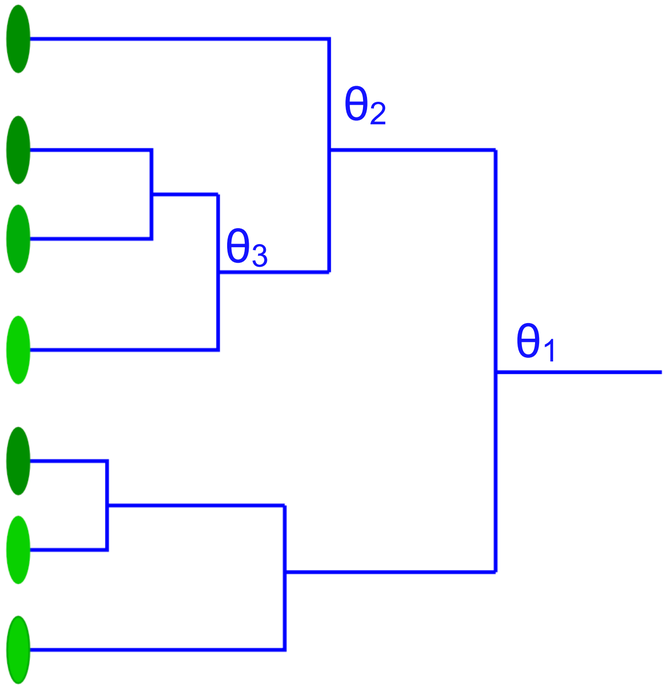
See also:
Barrera, Basyak, Szczurek, Singh, Mondal, + CMS/ATLAS (Tue)

- Jets propagate on a fast evolving medium:

Parton Shower



Jet



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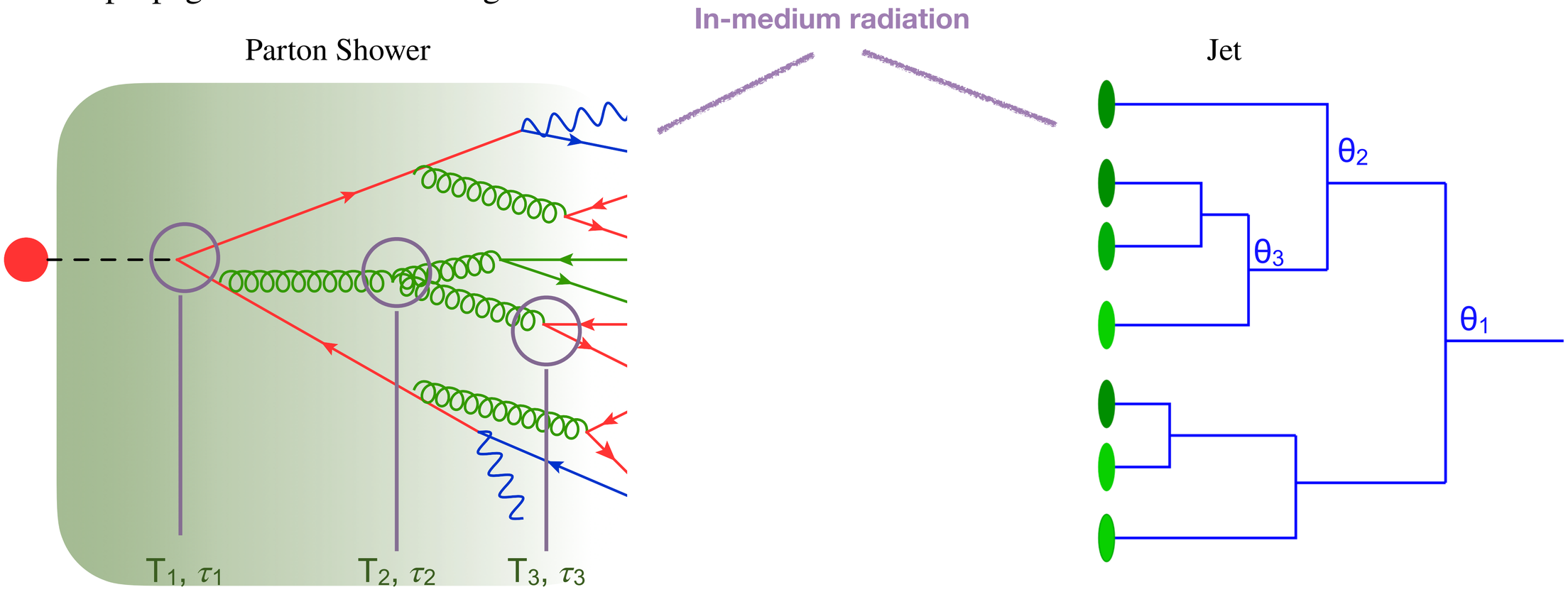

$\theta_1 >> \theta_2 >> \theta_3 \ldots \mapsto \tau_1 >> \tau_2 >> \tau_3 \ldots$

(Vacuum) $\mapsto$ (QGP)

From jets to jet substructure

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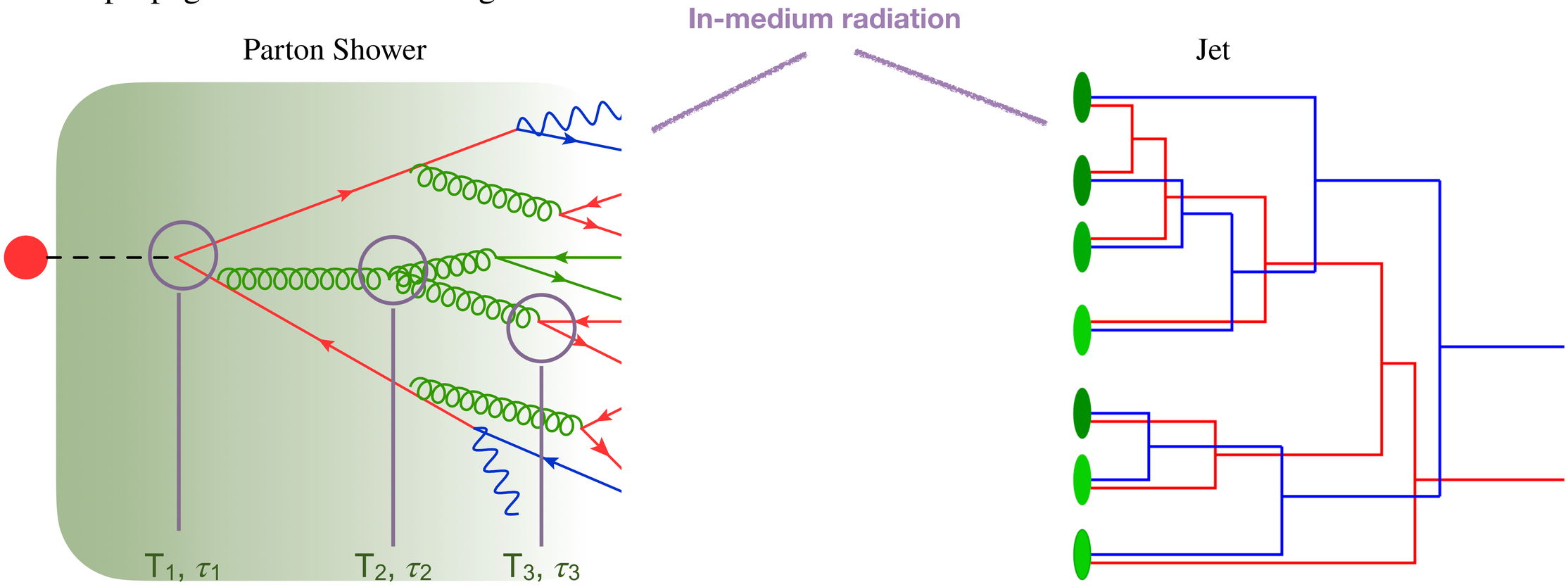

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From jets to jet substructure

See also:
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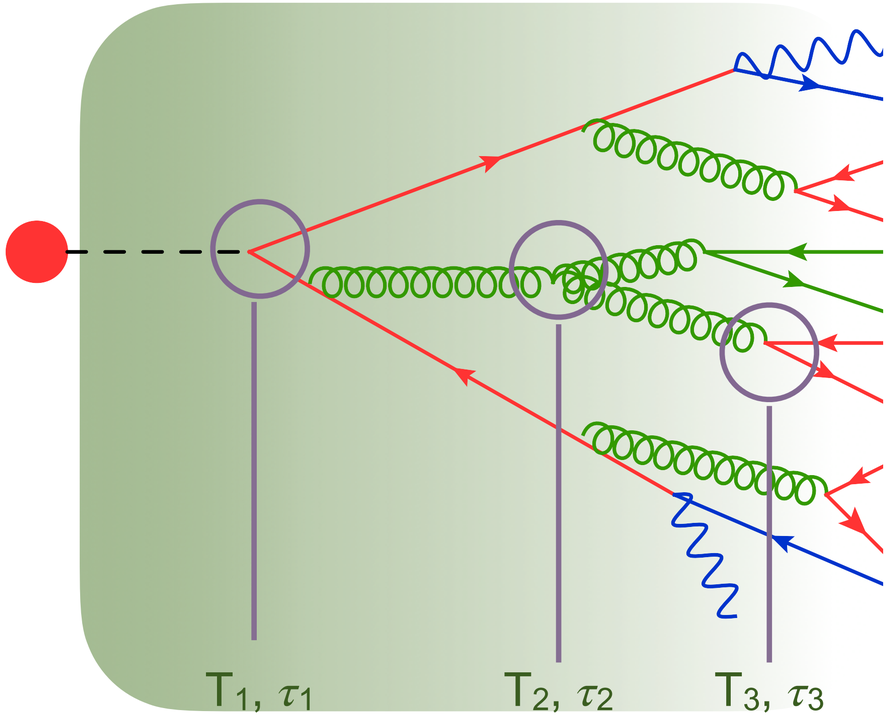
- Jets propagate on a fast evolving medium:

In-medium radiation

Parton Shower



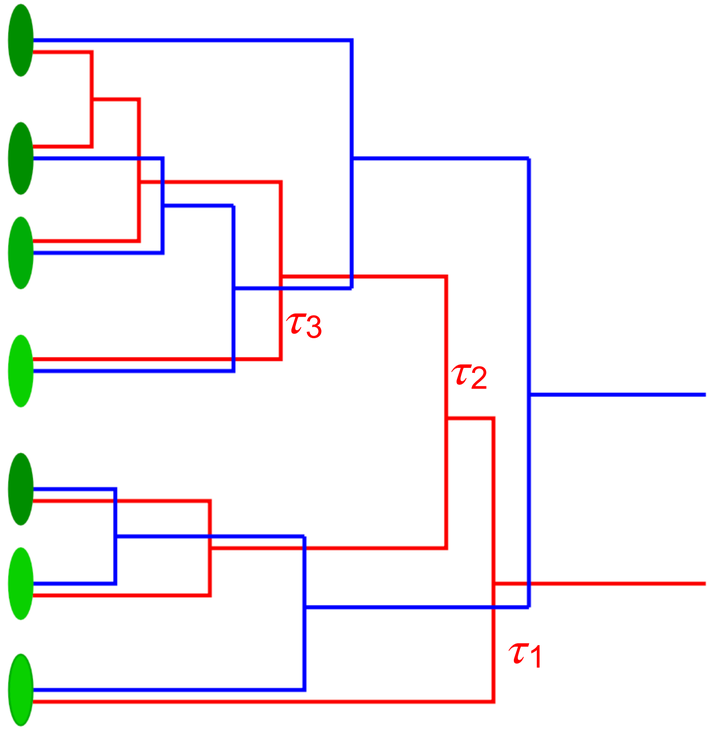
$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{t,i}^{2p}$$

p = 0.5

$$d_{ij} \sim p_T \theta^2 \sim \frac{1}{\tau_{form}}$$

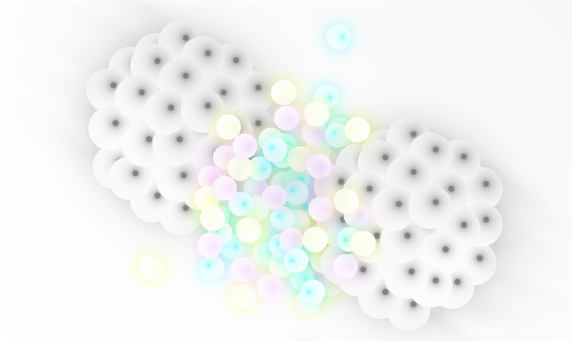
Jet



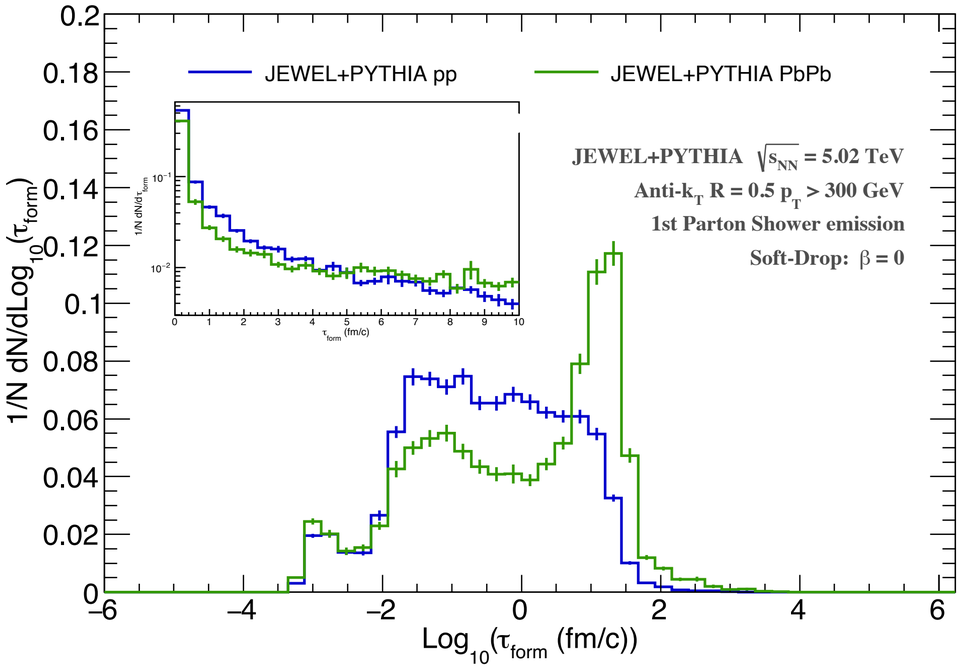
$\theta_1 >> \theta_2 >> \theta_3 \ldots \mapsto \tau_1 >> \tau_2 >> \tau_3 \ldots$

(Vacuum) $\mapsto$ (QGP)

Novel jet reclustering tools

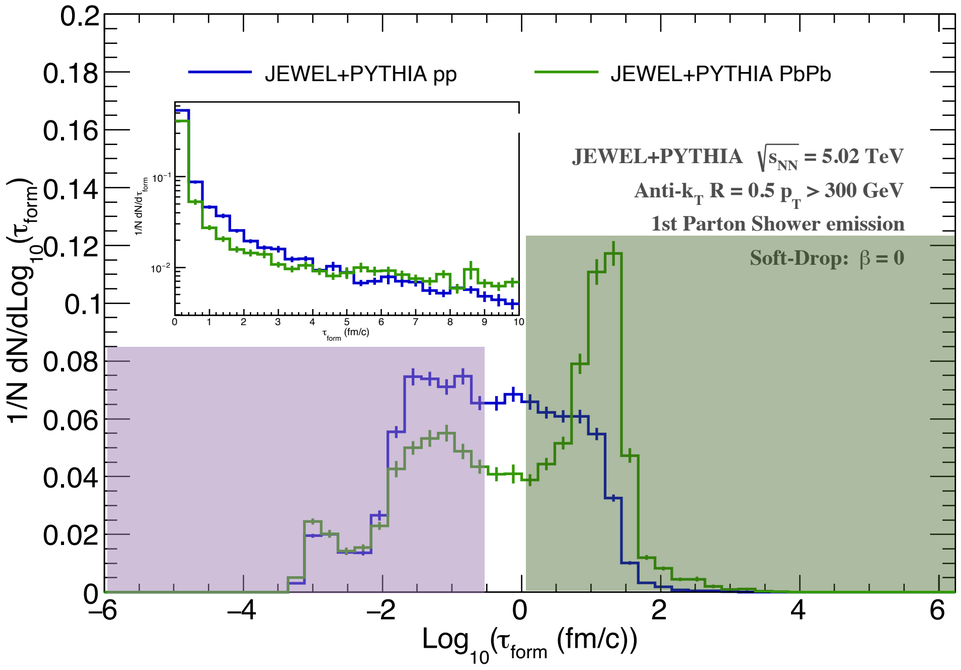


- Easily select two classes of jets:

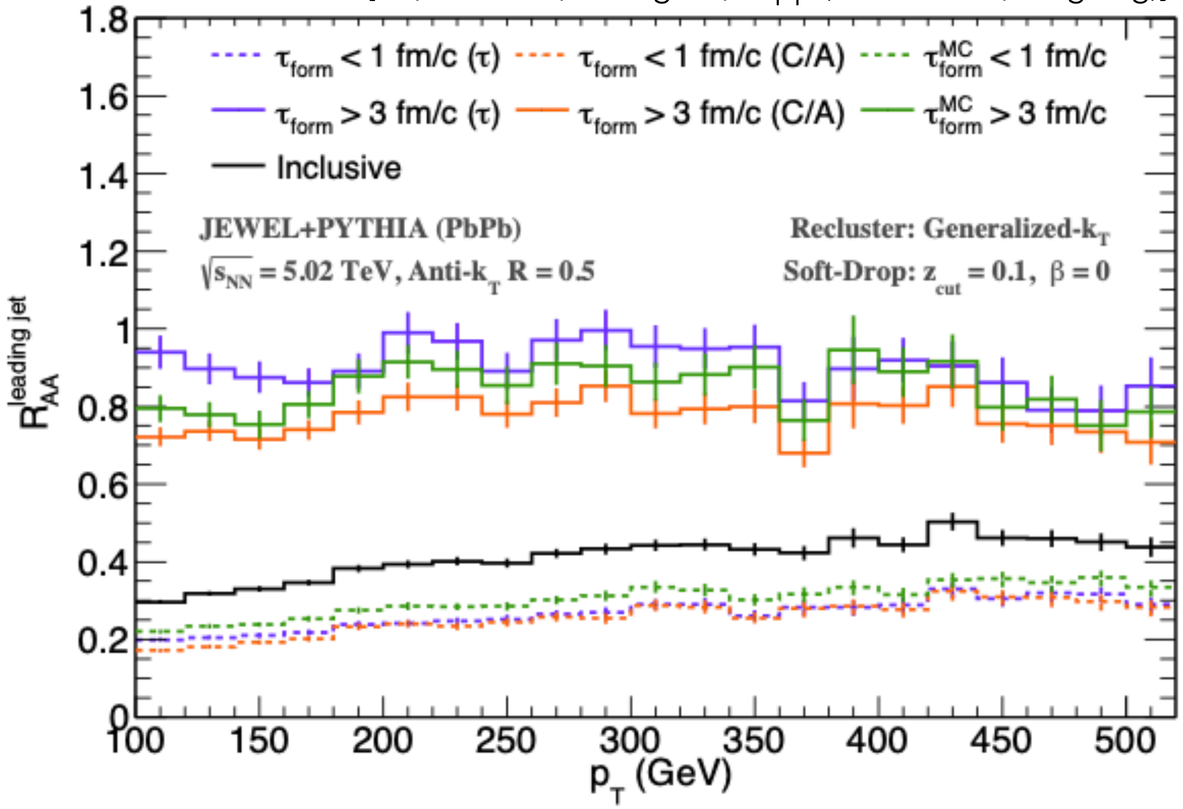


Novel jet reclustering tools

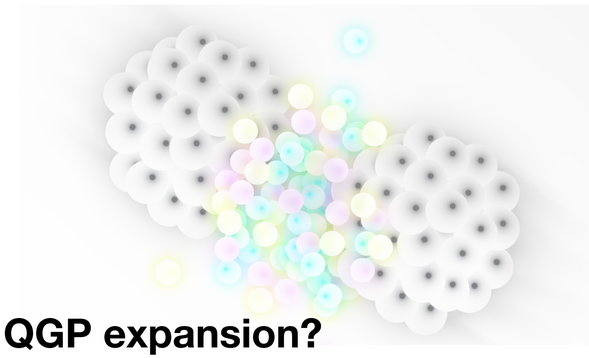
- Easily select two classes of jets:
  - "early" jets: $\tau_1 < 1$ fm/c (strongly modified)
  - "late" jets: $\tau_1 > 3$ fm/c (weakly modified)



[LA, Cordeiro, Rodriguez, Zapp (2012.02199, on-going)]



Novel jet reclustering tools



How can it be related to the QGP expansion?

- Easily select two classes of jets:
  - "early" jets: $\tau_1 < 1$ fm/c (strongly modified)
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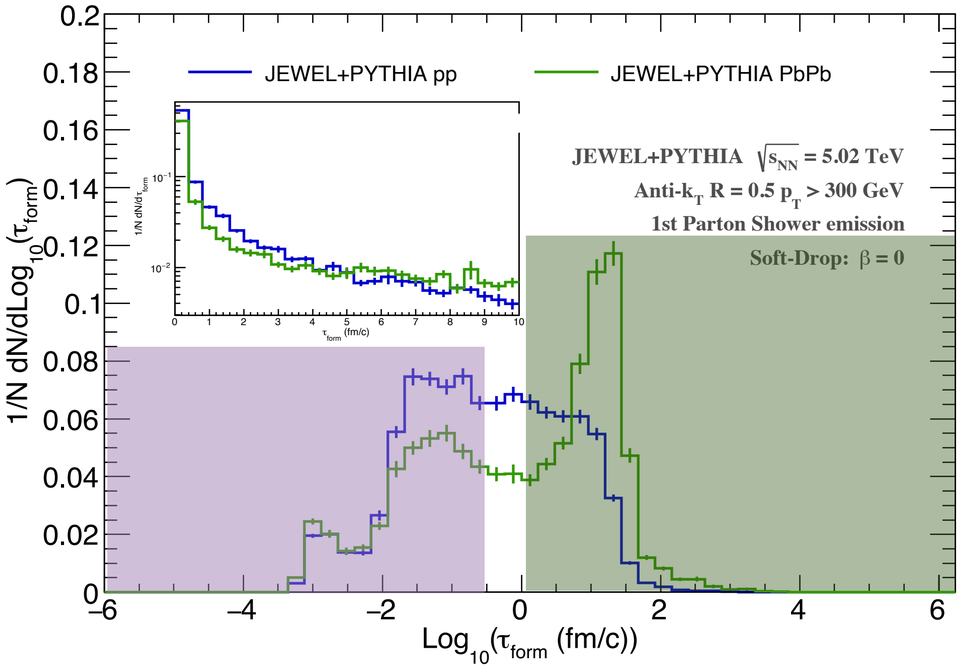

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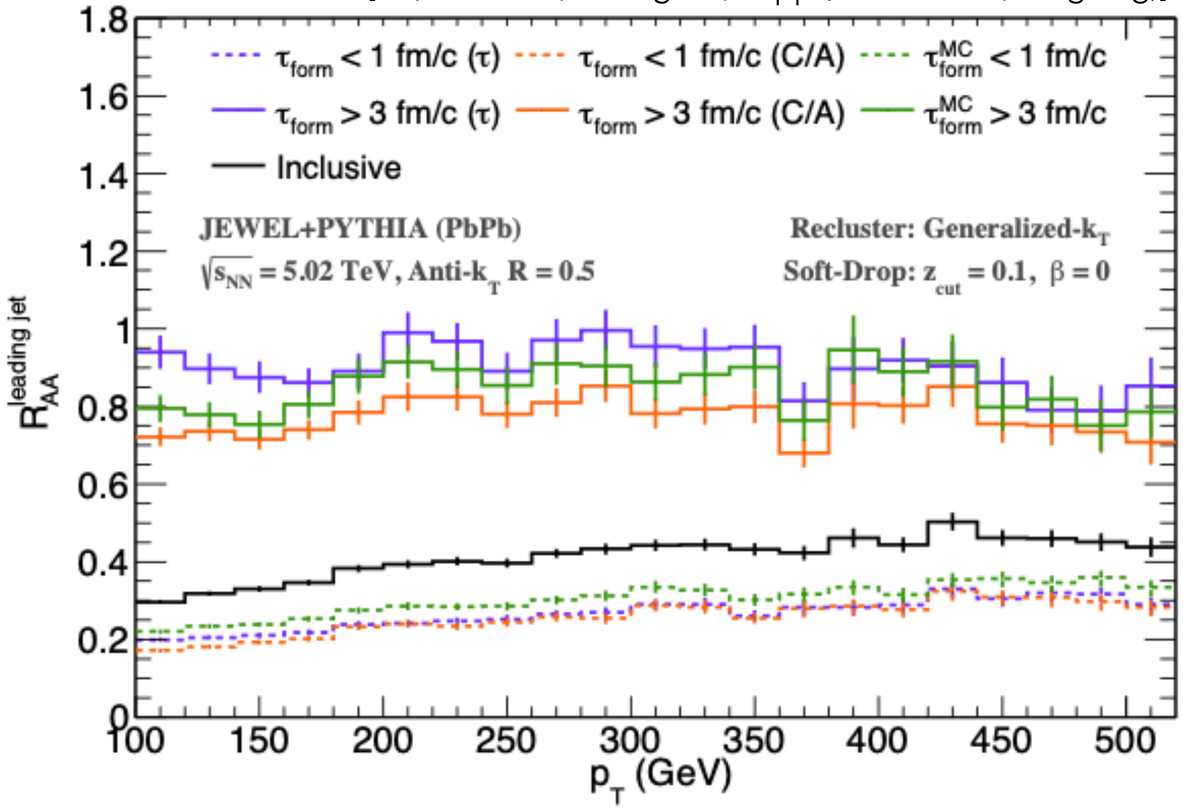
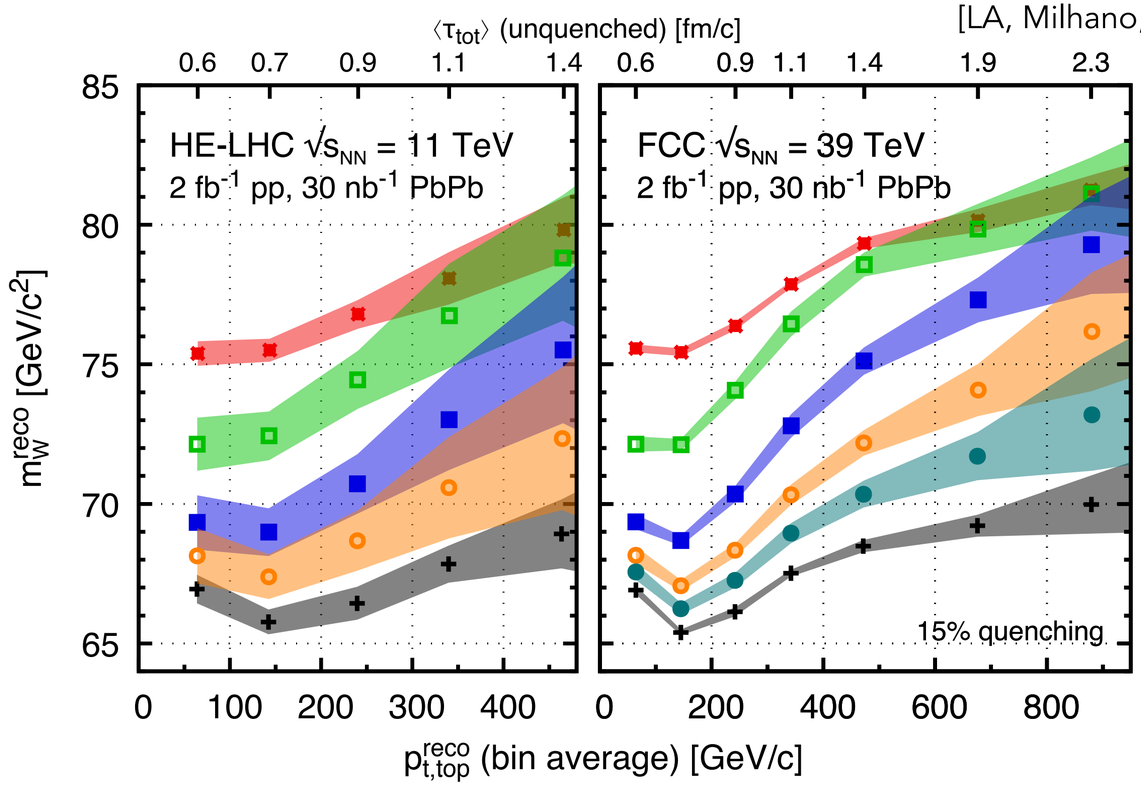
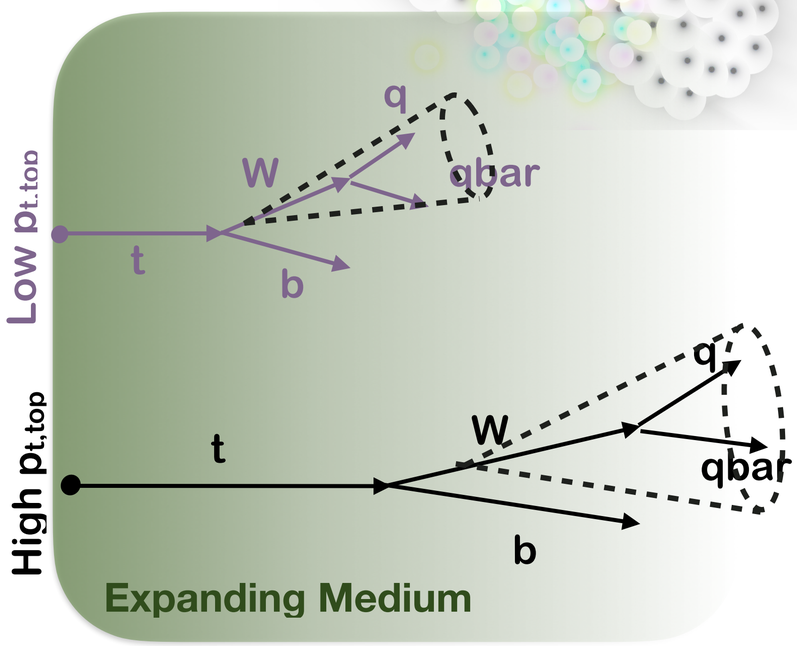


Novel heavy-flavour observables

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

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





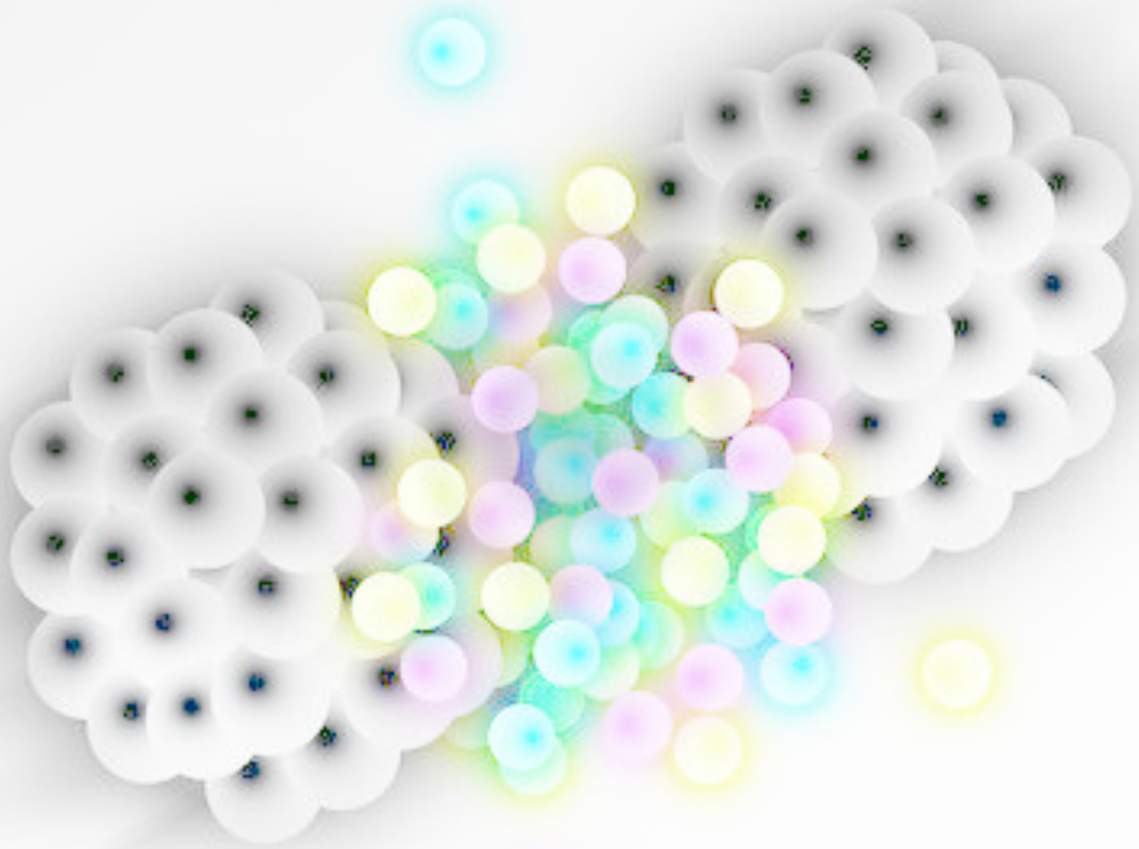
unquenched
quenched
τ_m= 1.0 fm/c
τ_m= 2.5 fm/c
τ_m= 5 fm/c
τ_m= 10 fm/c

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

First tops measured in PbPb (CMS - 2006.11110)

See also: Ye, Tork, Kalteyer, Antonioli, Seidel (Wed)

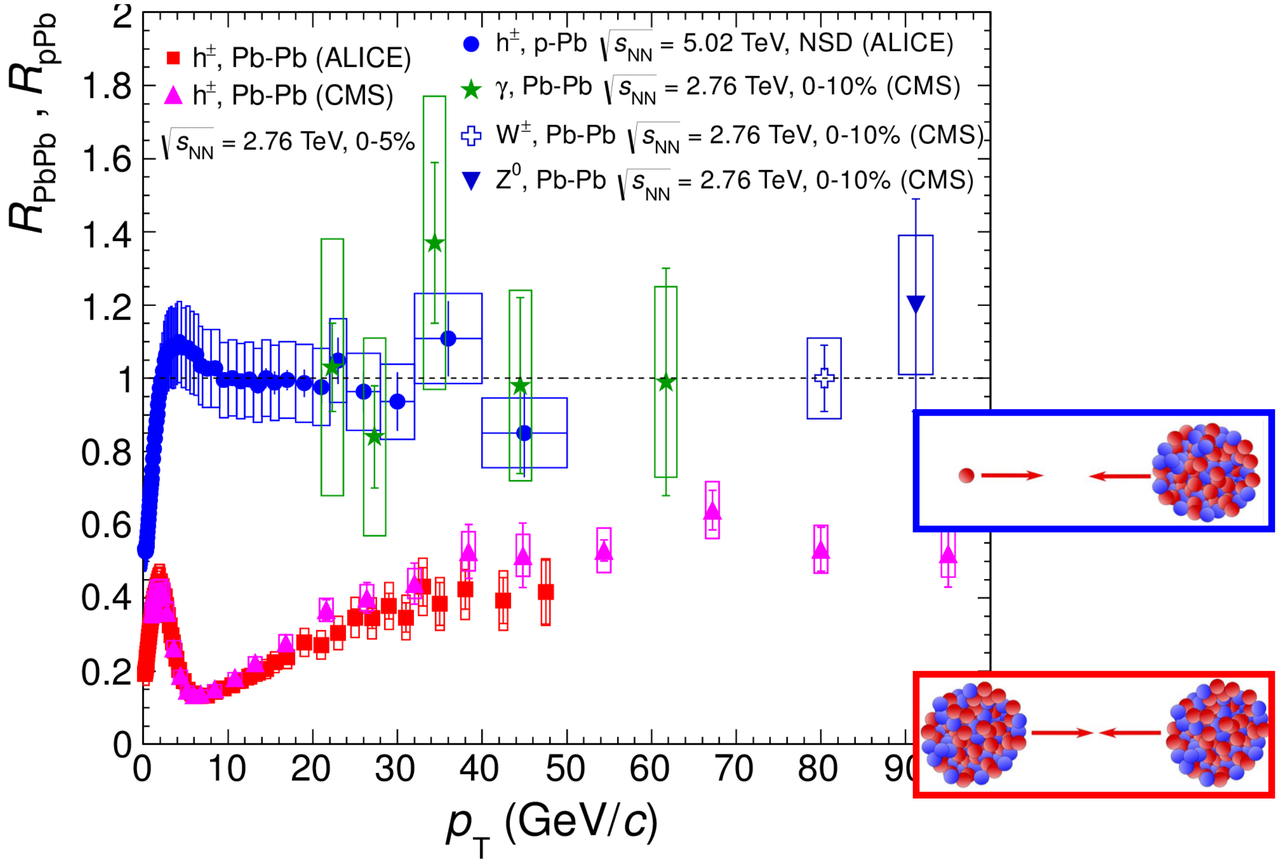
From dense to light



QGP onset

See also P. Steinberg (today)

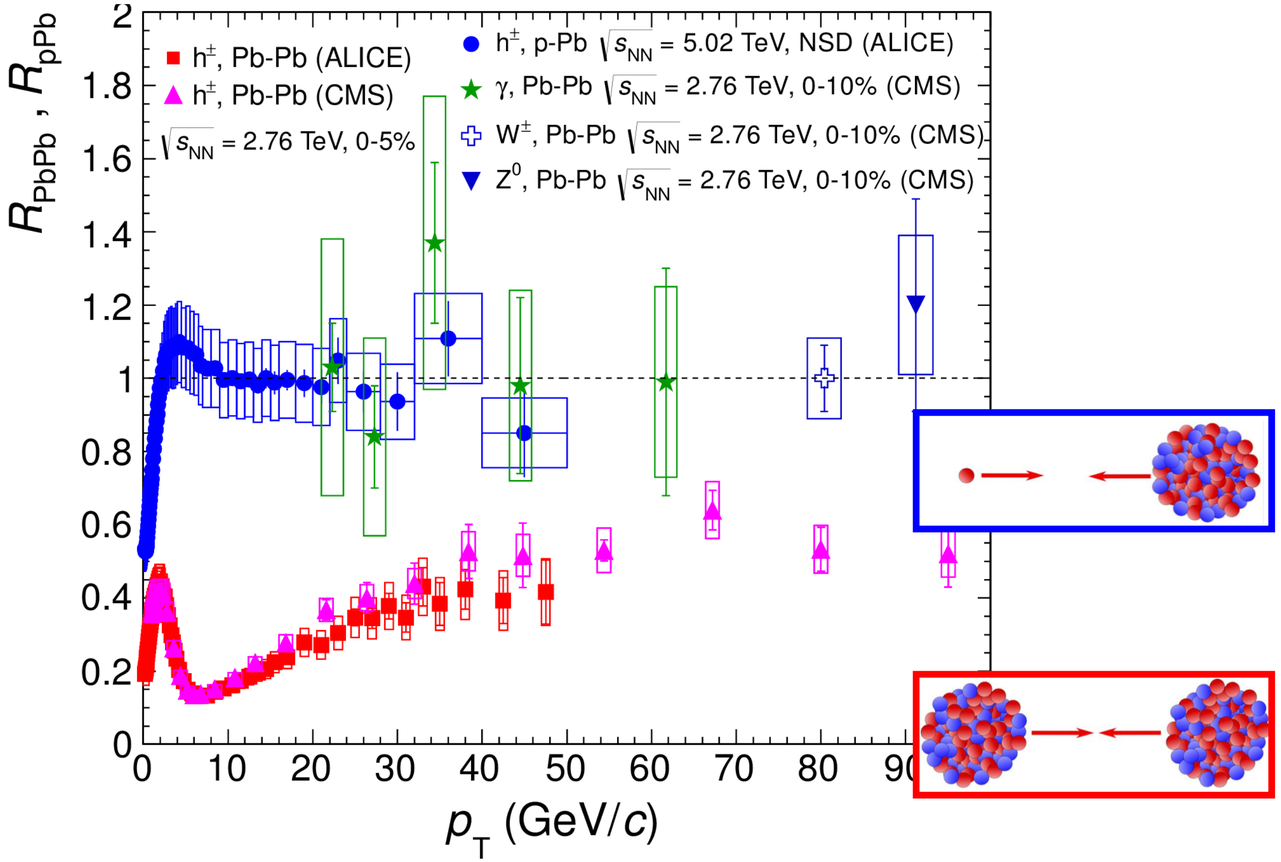
- No energy loss in pA…



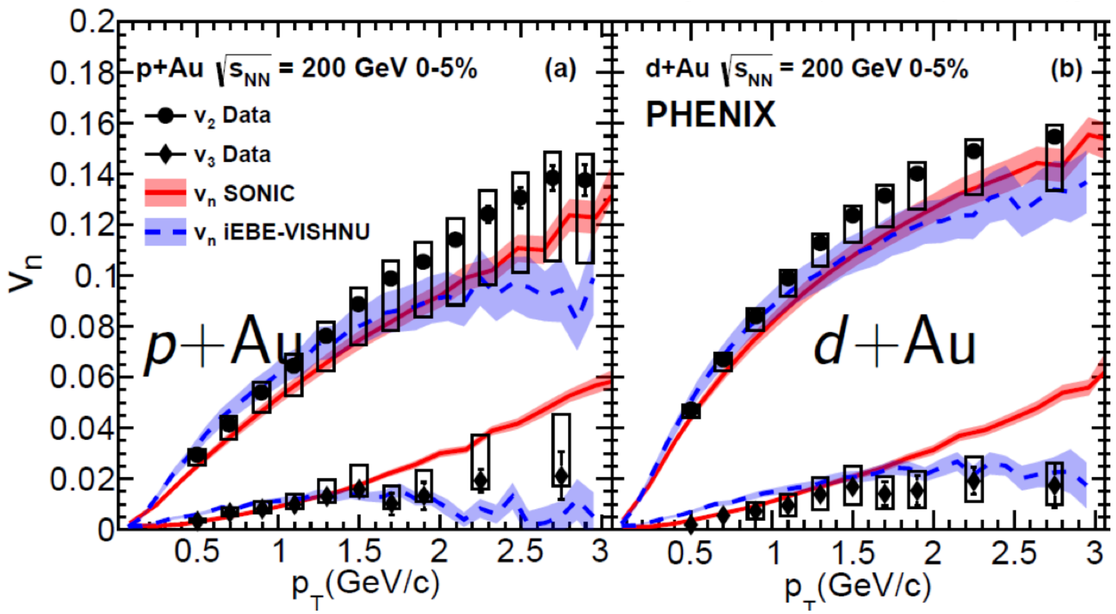
QGP onset

See also P. Steinberg (today)

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



[PHENIX (PRL 123, 039901)]

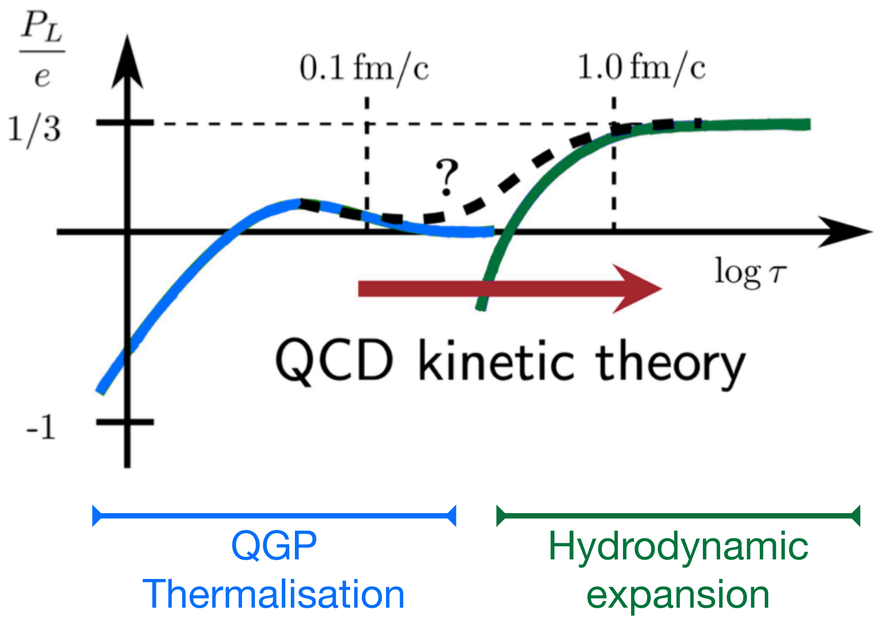


Flow coefficients well reproduced by hydro predictions, but not by initial state effects only

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

From dense to light systems

- Extrapolation from dense to light needs further understanding…



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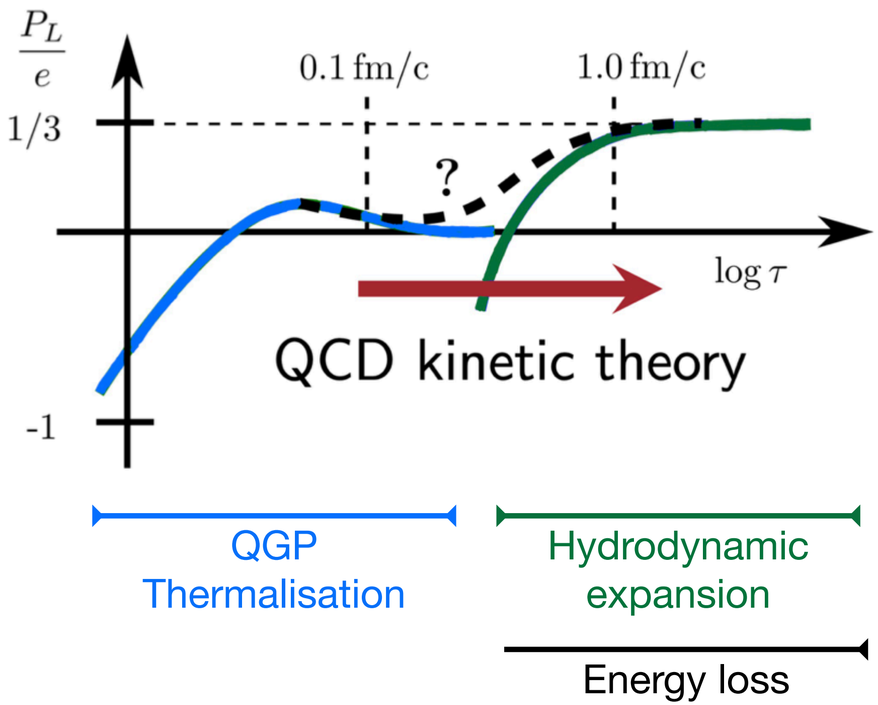

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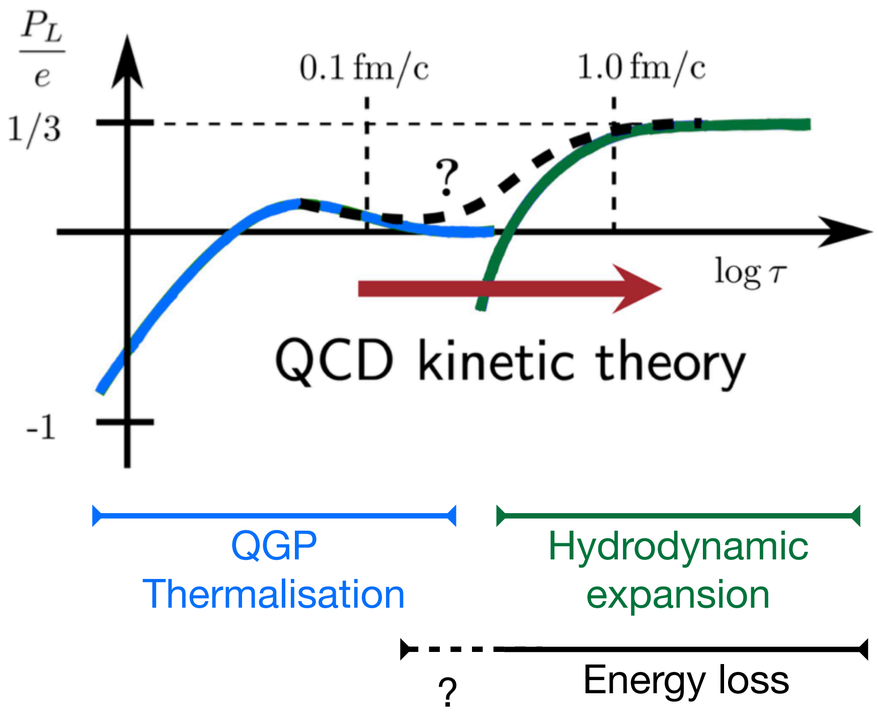

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From dense to light systems

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

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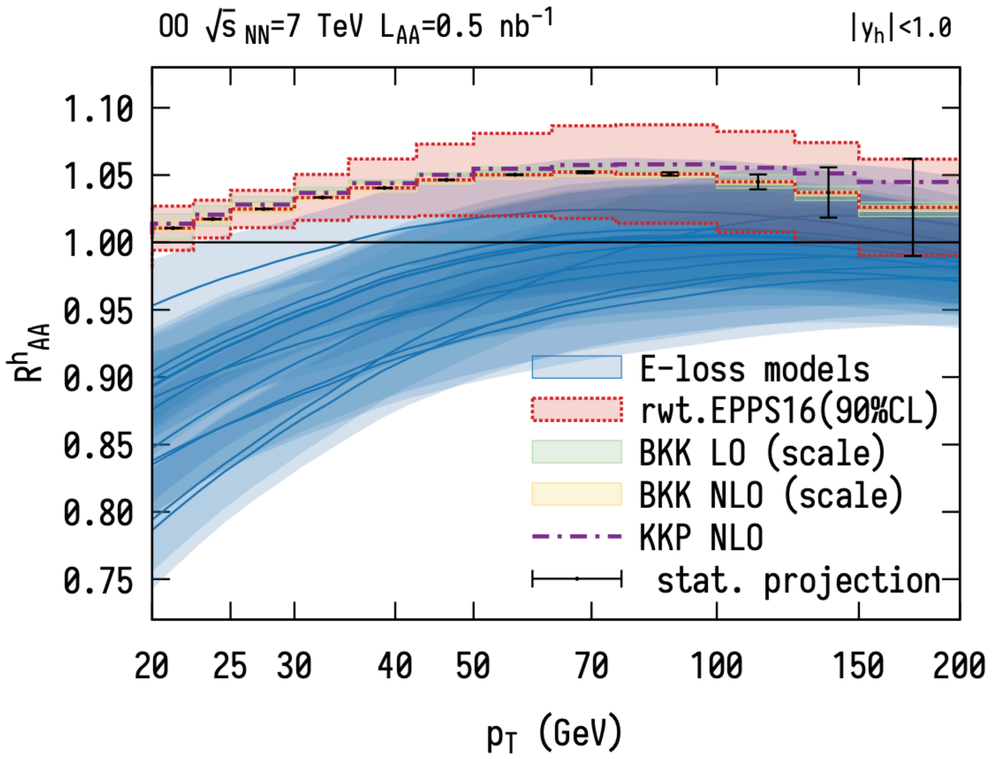

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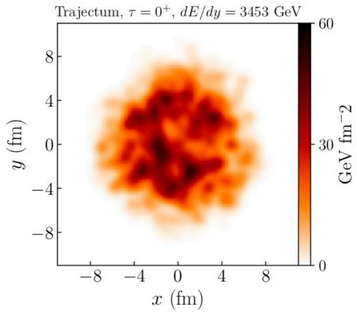
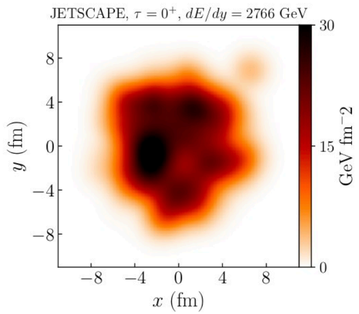
Cold or Hot nuclear matter effects?

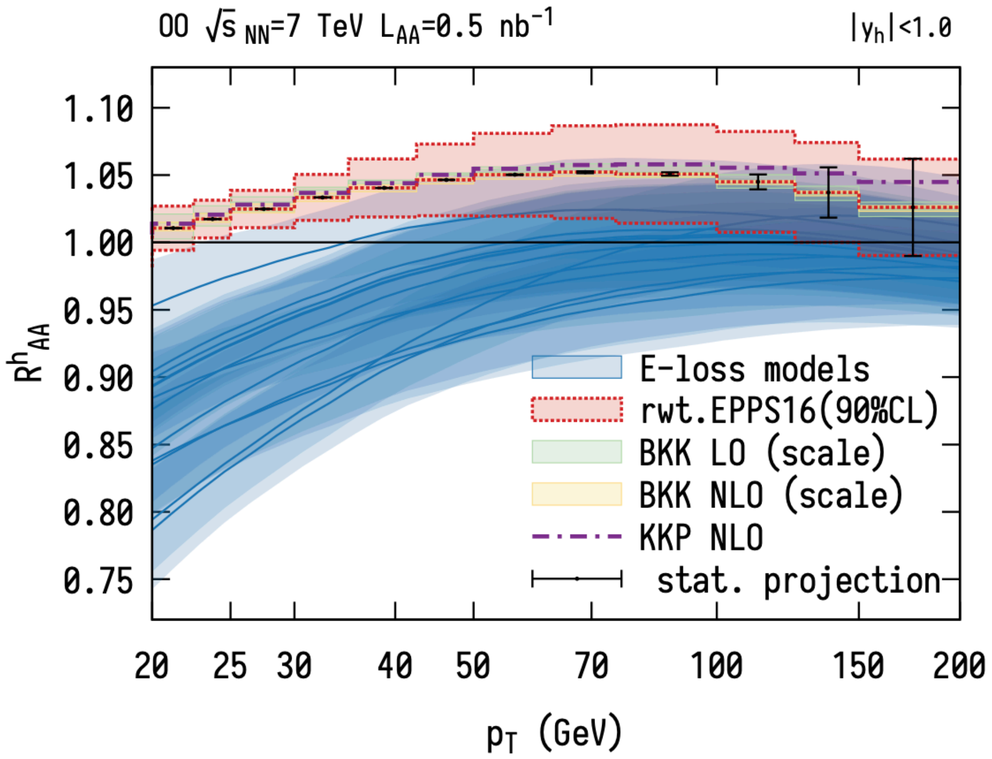
Nucleon structure at high energy:



or



?



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From dense to light systems

See also Mikuni, Klest (Tue), Lim, Radhakrishnan, Morales, Vitev (Th)

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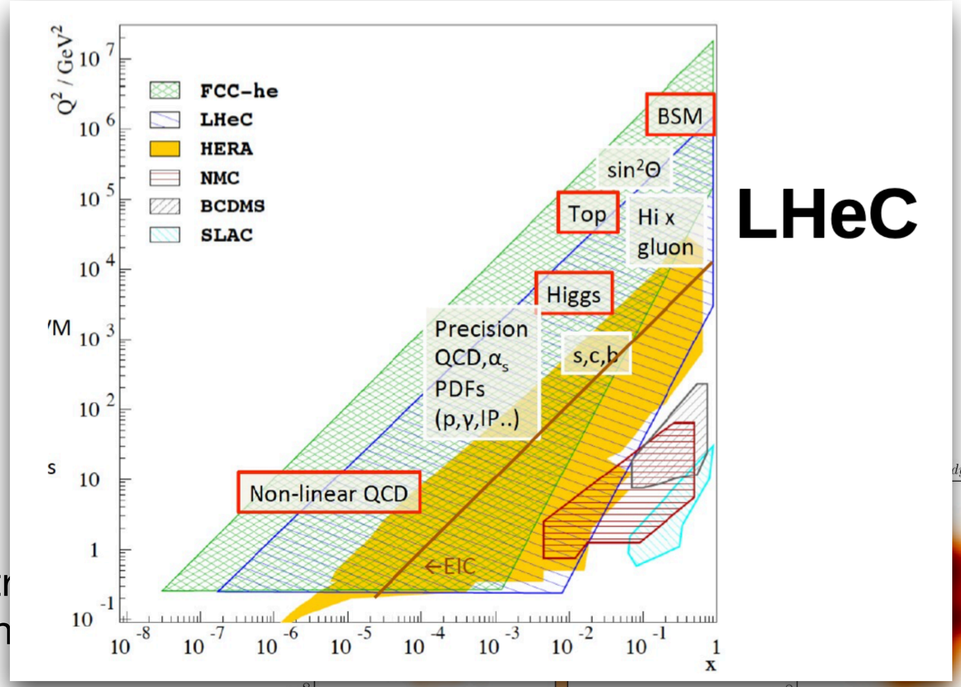
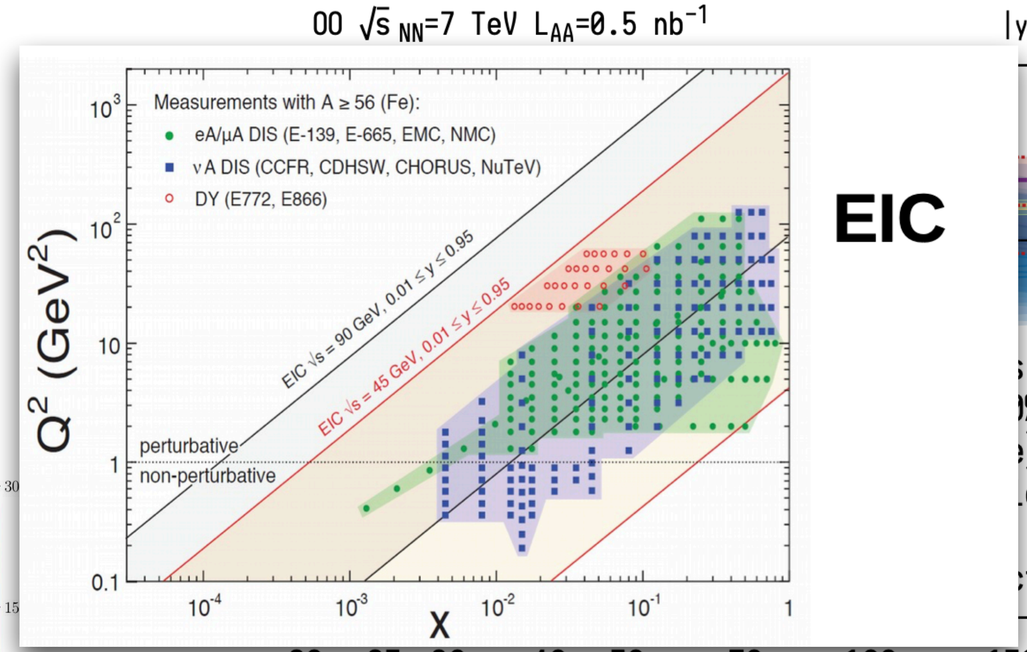


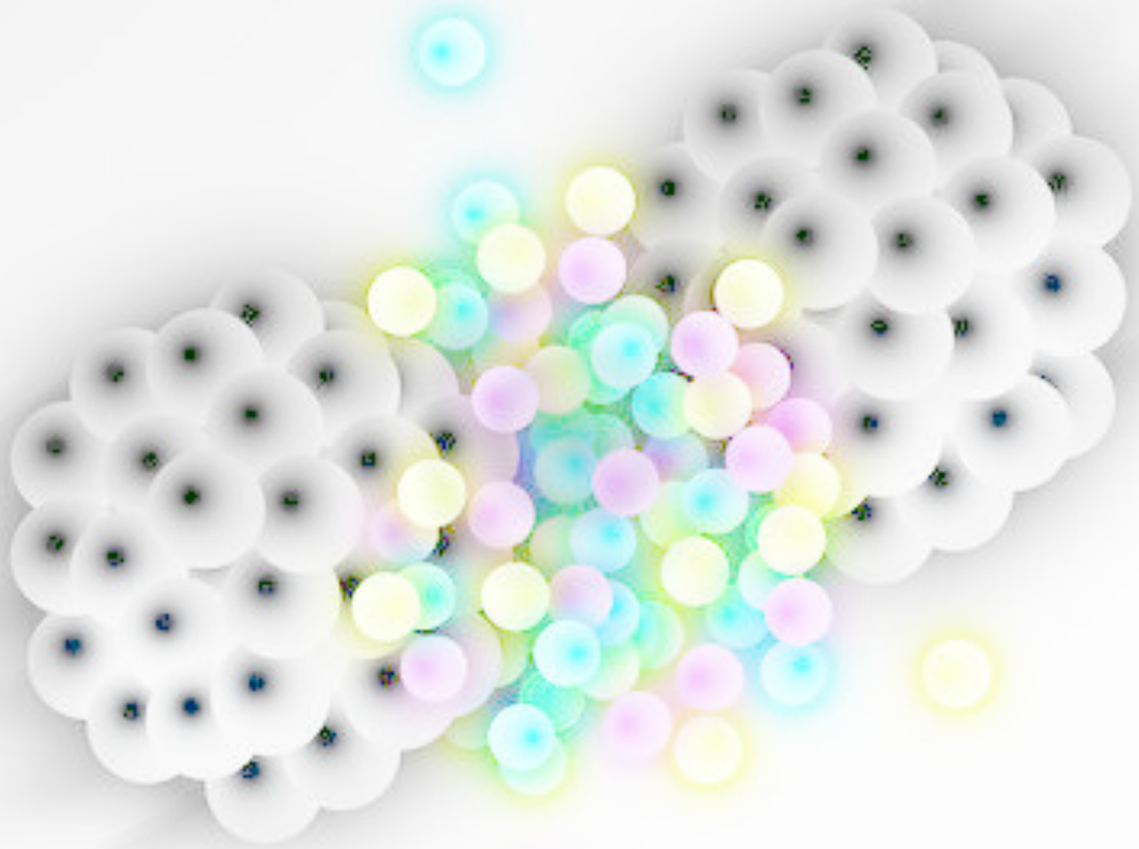
LHeC



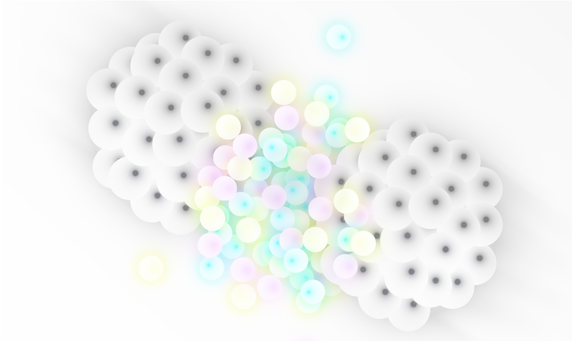
EIC

Nucleon str
high en

Wrapping up



Summary



- **Heavy-ions** are a vibrant field full of **activity**
  - From far-from-equillibrium QCD to a fully thermalised medium
- **Quark-Gluon Plasma** studies have entered **precision** physics era
  - Determination of energy loss, momentum broadening and structure of a medium-modified parton showers
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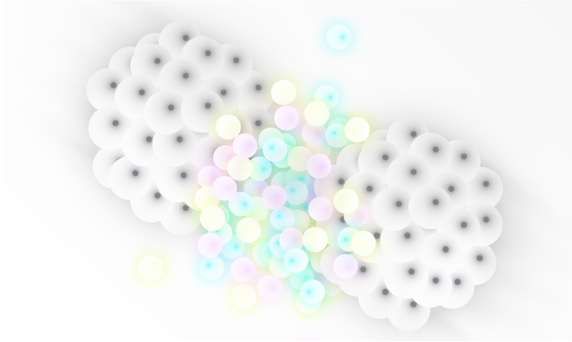

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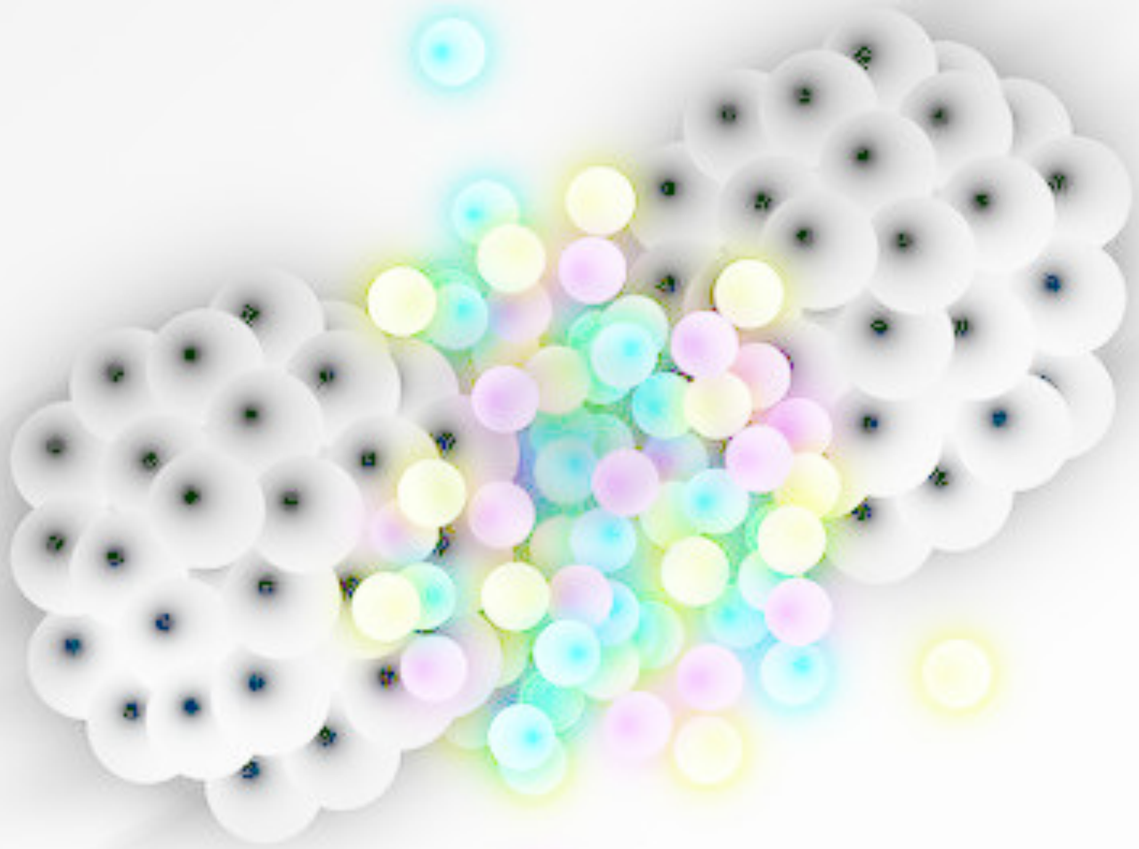
Thank you!

Backup Slides



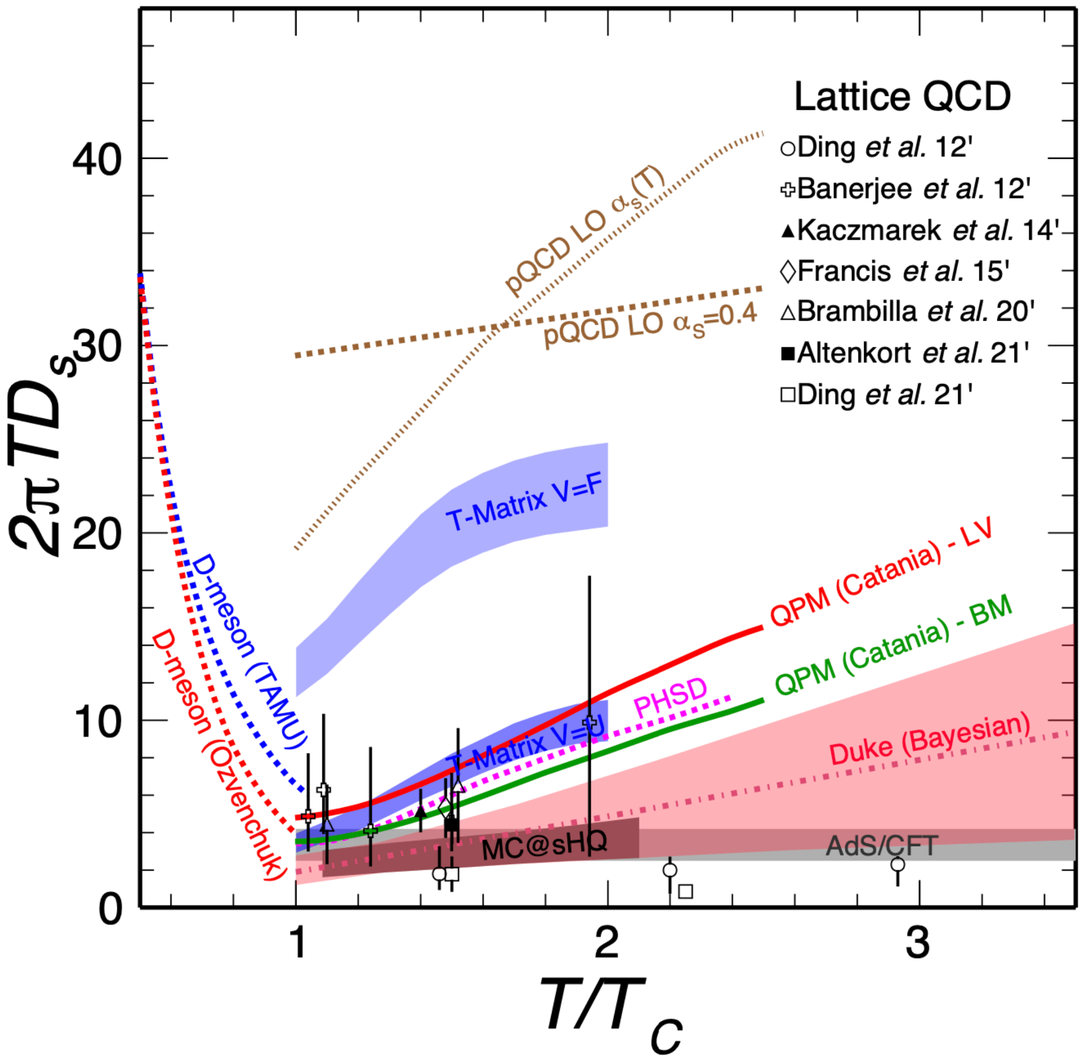
Heavy-Quark transport coefficients

- Heavy-quark transport coefficients

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

$$\hat{e} = \frac{dE}{dt}$$

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



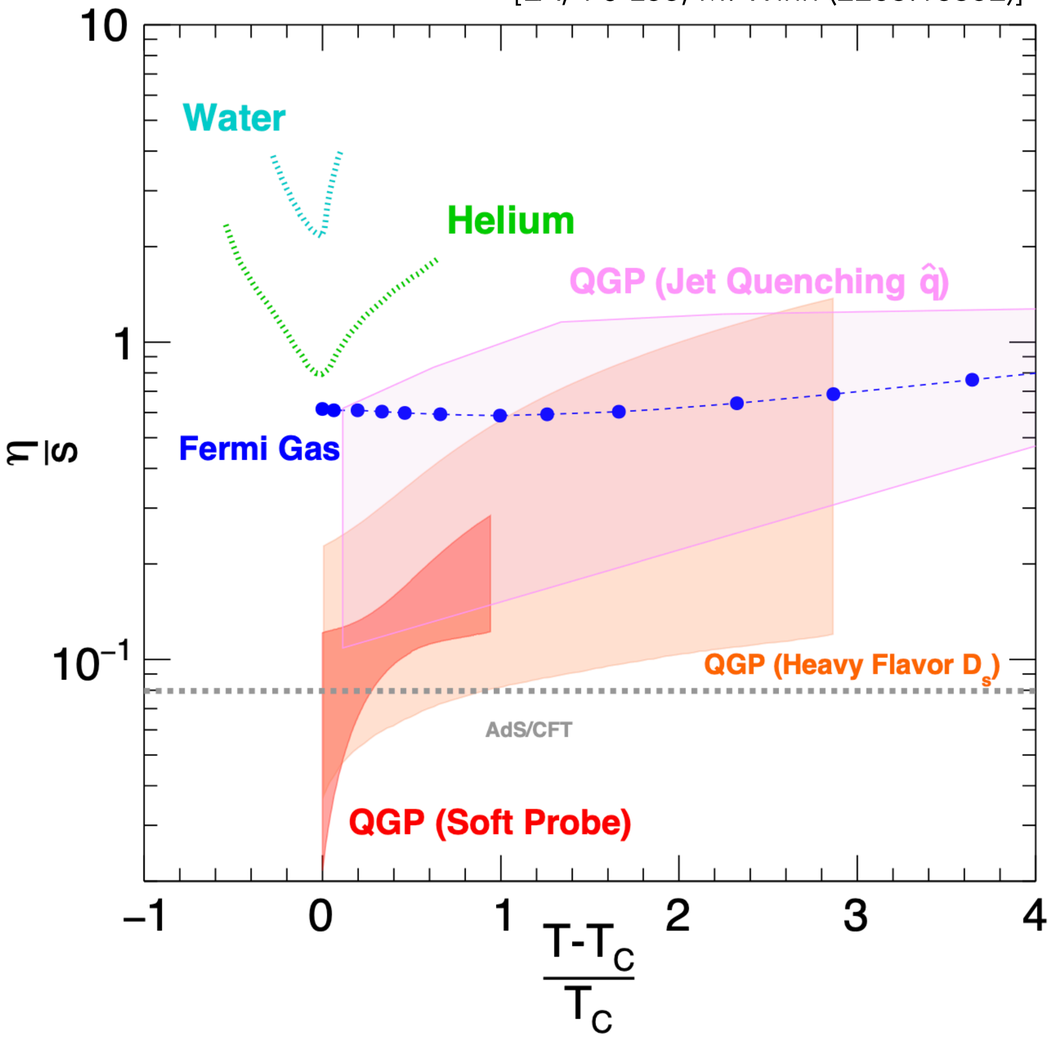
Soft vs Hard

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

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

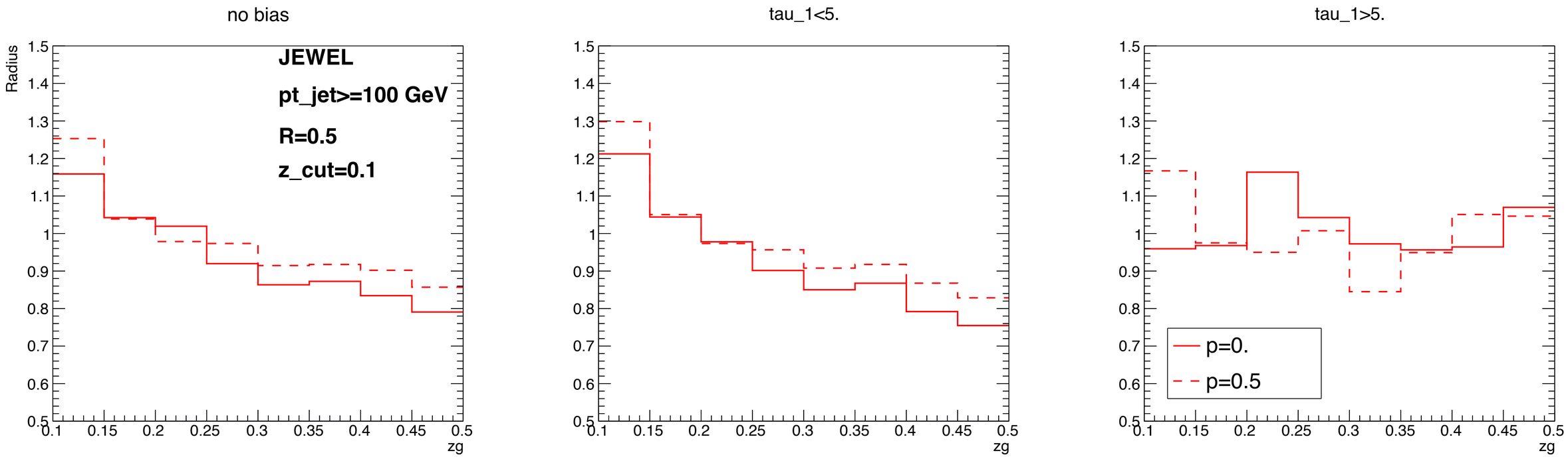
$$\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}$$

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

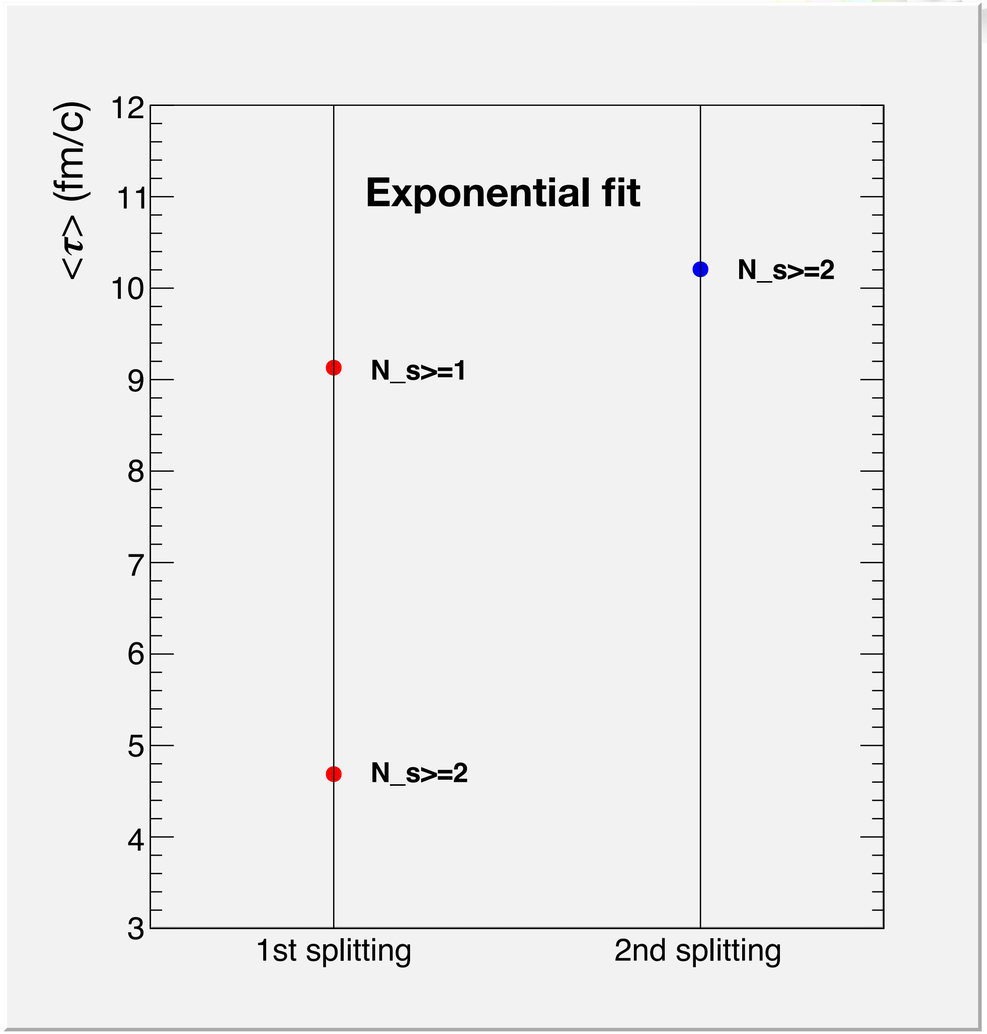


Zg 1st SD

- Ratio of zg JEWEL (PbPb/pp):



1st and 2nd Emissions



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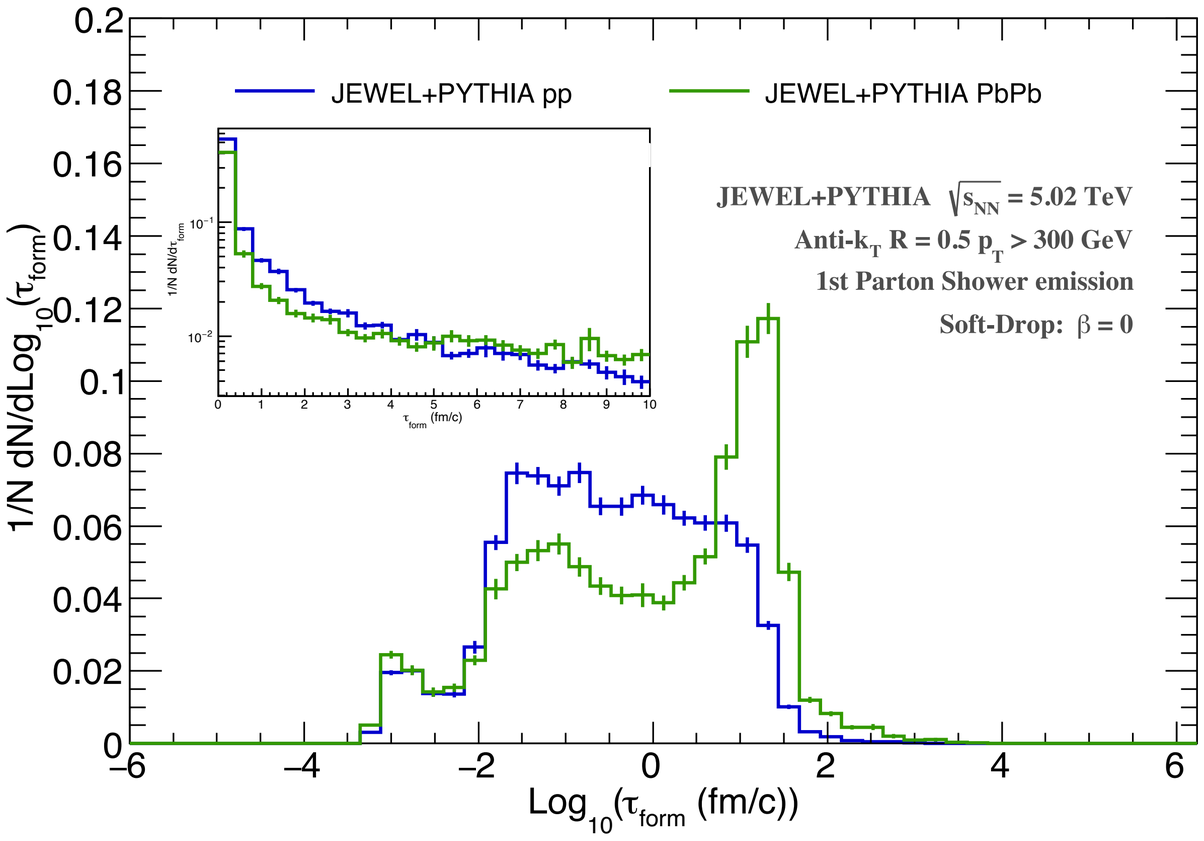
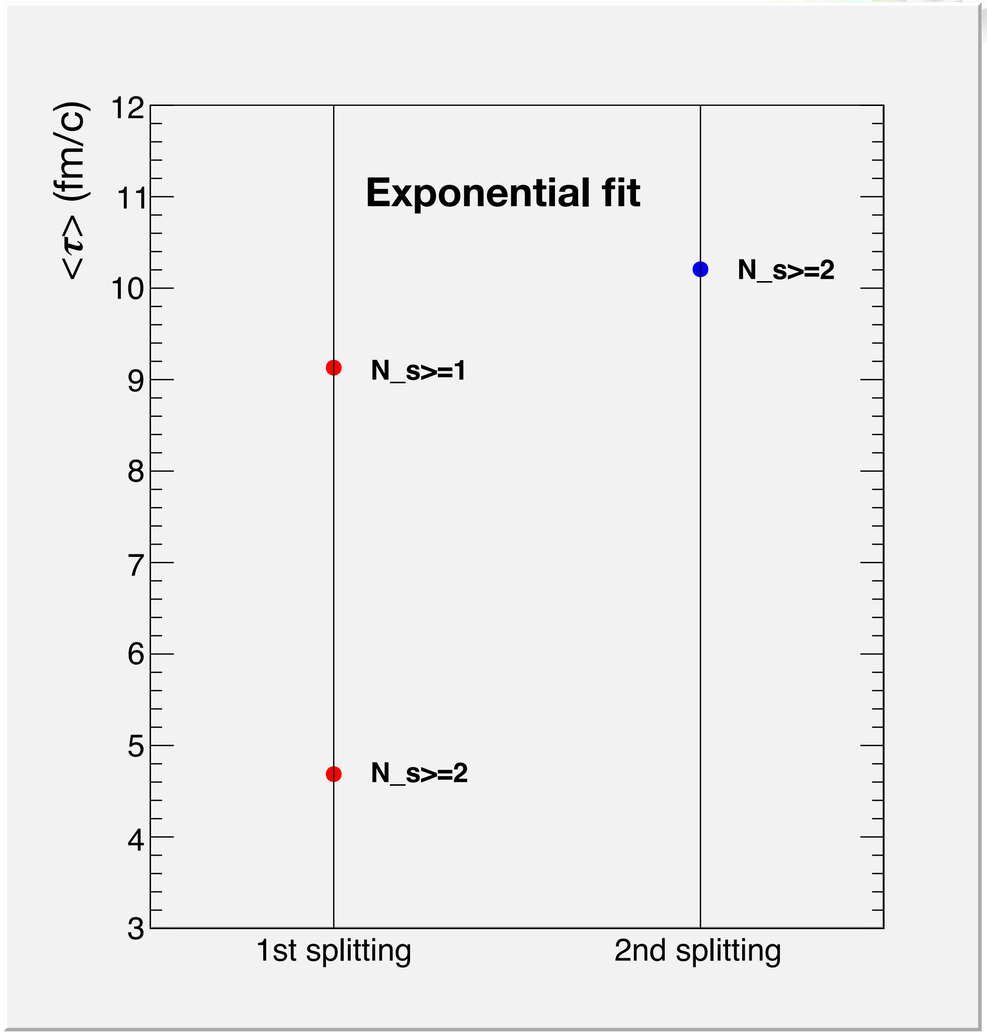


Harder fragmentation ⇔ Longer τ



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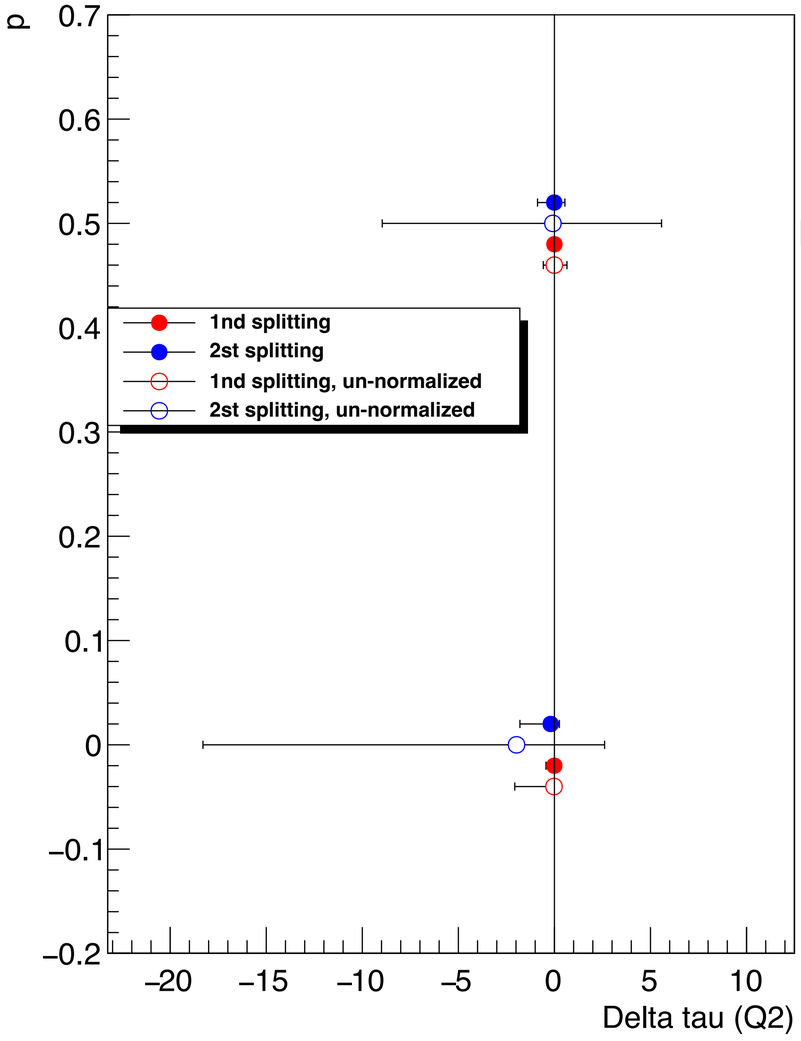
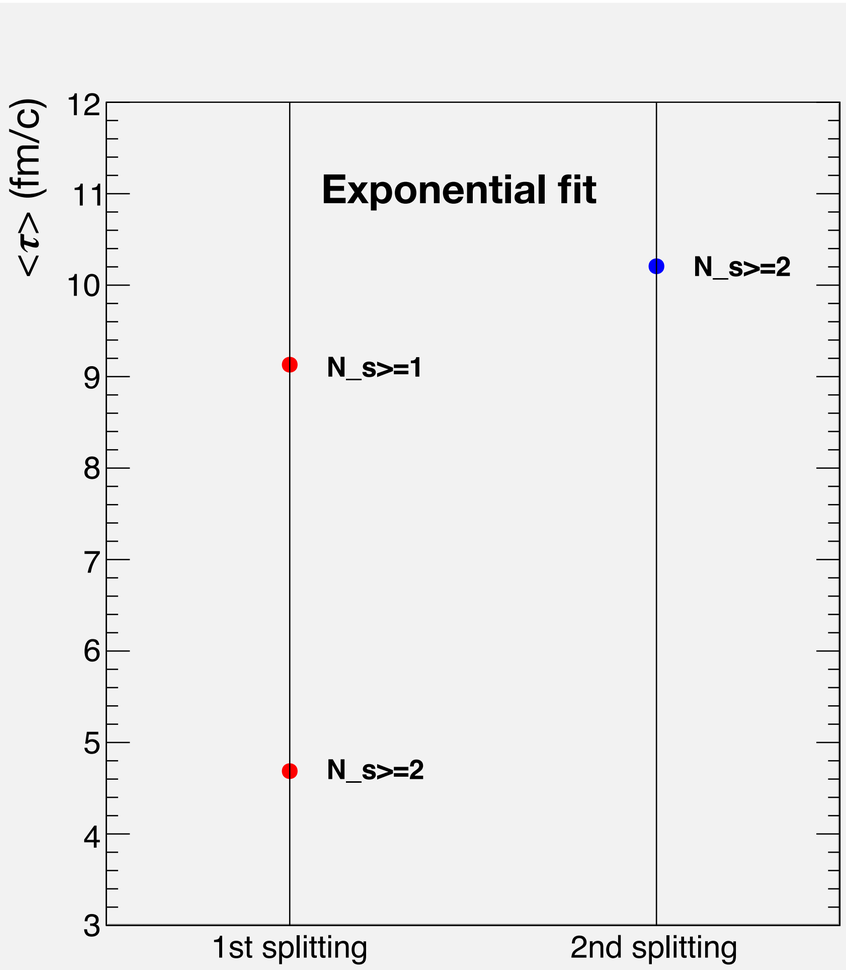


Select jets that fragment more will increase τ window

Can we use two SD handles per jet?



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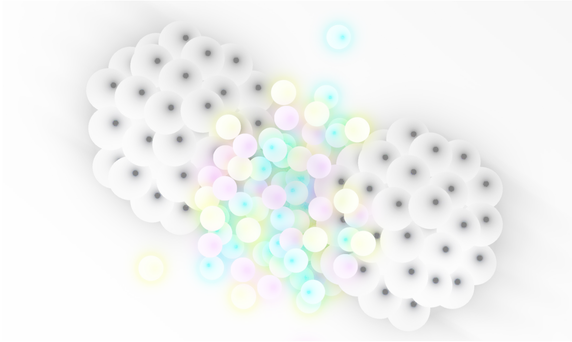

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