Deriving a parton shower for jet thermalization in QCD plasmas

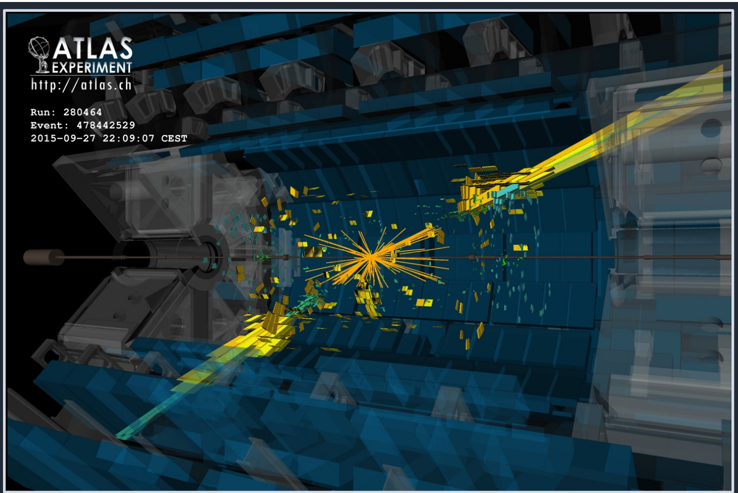
[I. Soudi, AT 2510.25837, 2607.xxxx]

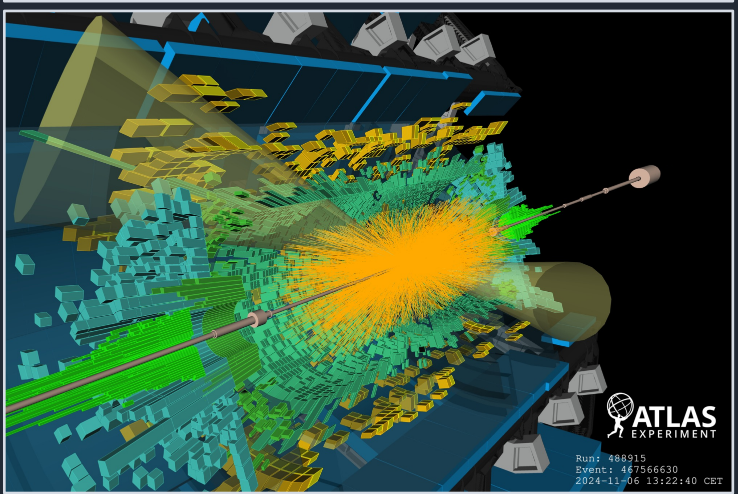
Adam Takacs

CERN TH,

University of Bergen

1. Jets in heavy-ion collisions





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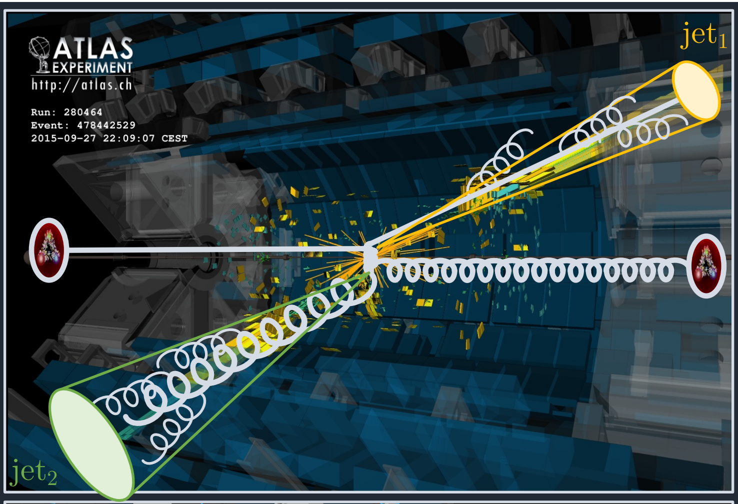
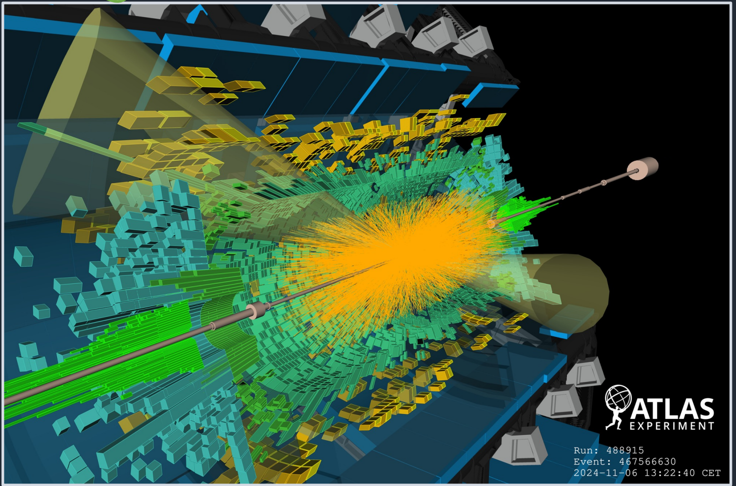




Scattering amplitudes in the QGP

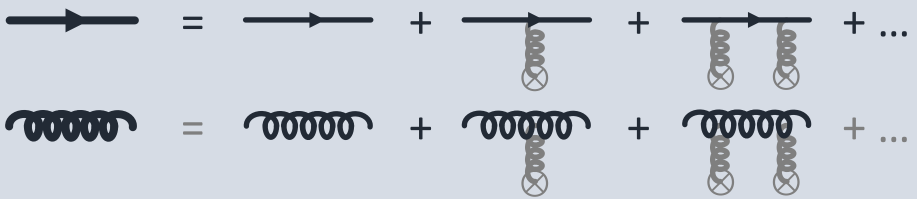
- Separate fields to hard and bkg. $(q = q_h + q_0,\ A = A_h + A_0)$

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

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

← integrating out soft degrees of freedom

- Dressed propagators (and vertices):



effective, in-medium Feynman rules

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

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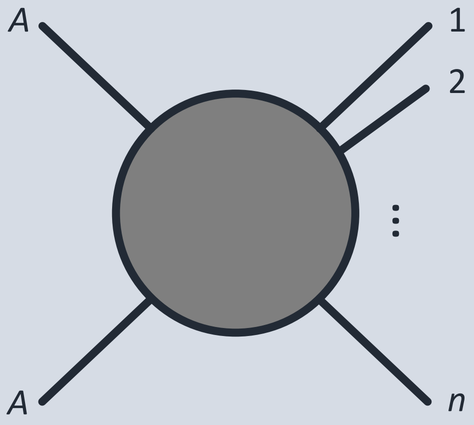
Goal: $\langle 1,2 \ldots n | AA \rangle$



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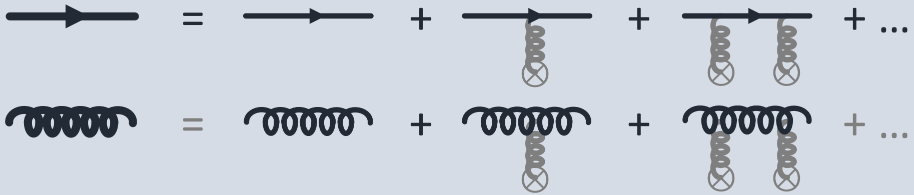

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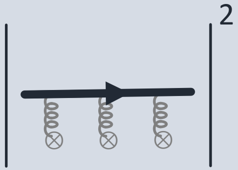
Example: jets in large medium

[Blaizot, Dominguez, Iancu, Mehtar-Tani]
[Casalderrey-Solana, Mehtar-Tani, Tywoniuk, Salgado]
[Caucal, Iancu, Mueller, Soyez]

- Broadening: (in vacuum straight line $\delta_{ij}\delta(p-p')$)



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

changing color and momentum

- Evolution equation for mom. distr:

$$\partial_t \mathcal{P}(\boldsymbol{p},t) = \int_{\boldsymbol{q}_\perp} [C(\boldsymbol{q}_\perp)\mathcal{P}(\boldsymbol{p}-\boldsymbol{q}_\perp,t) - \underbrace{C(\boldsymbol{q}_\perp)\mathcal{P}(\boldsymbol{p},t)}_{\text{virtual term}}]$$

"time"

mom. distribution

scattering rate

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diffusion approx. $q \ll p$

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$$\Longrightarrow \frac{d\sigma}{dz\,d\vartheta} \approx 2\bar{\alpha}_s \sqrt{\frac{Q_{med}}{z^3 E}}\, B(\vartheta)$$

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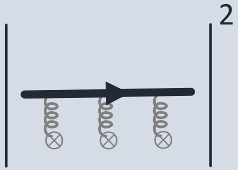

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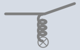

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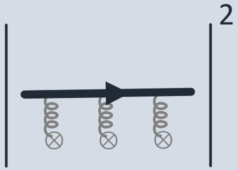

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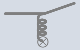

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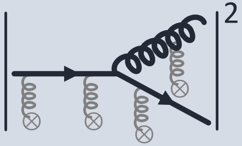

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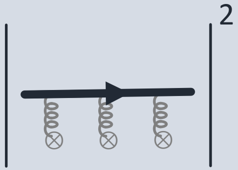

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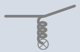

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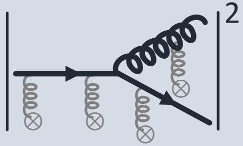

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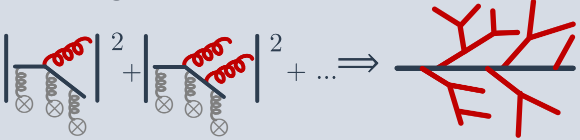

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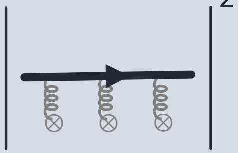

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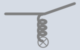

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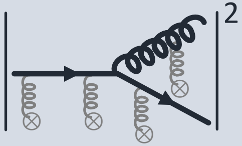

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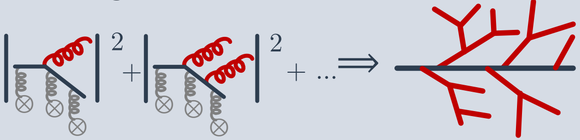

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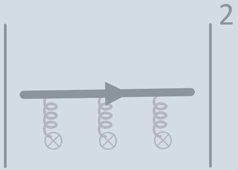

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"time" · mom. distribution · scattering · virtual term

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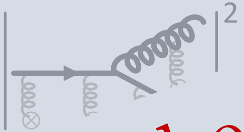

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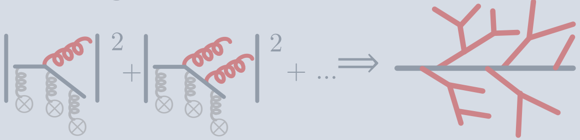


$\ldots(x,t)]$

term

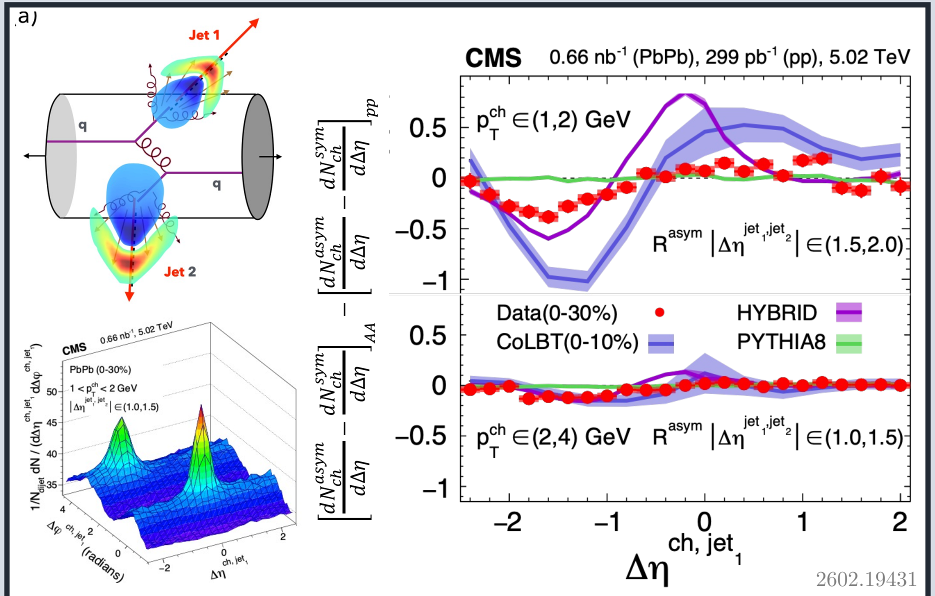
(+ mixing with jet evolution!)

Jet evolution in the QGP

- Successful in pheno (R_{AA}, jet substr)
- **Does not thermalize!**
- Not applicable for observables sensitive to med. resp.

2. Jet thermalization and Medium response

Recent experimental progression



- Precise measurements on medium response.
- There is room for improvement.

Medium response

In-medium jet evolution

Strongly coupled

Falling string + metric perturbation evolution in AdS/CFT

[Chesler, Yaffe]

In practice: instantaneous freeze-out/hydro

[Hybrid 2010.01140]

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

Weakly coupled

QCD-EKT: thermalization from first principles.

[Arnold,Morre,Yaffe]
[Baier,Mueller,Schiff,Son]

$$(\partial_t + v \cdot \nabla_x)\delta f(t,x,p) = \delta C^{2\leftrightarrow 2} + \delta C^{1\leftrightarrow 2}$$

How EKT is related to jet quenching?

Minijet quenching in AMY-EKT: [Mehtar-Tani,Schlichting,Soudi]
[Brewer,Mazeliauskas,Zhou]

In practice: few scatterings + hydro.

[JEWEL, LBT, Hybrid (w Moliere)]

Medium response

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∂_ν

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→2

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In this talk: ***(i)*** **AMY-EKT ↔ jet quenching,**

(ii) **EKT ↔ parton showers,**

(iii) **EKT parton shower → med. resp**

(i) Linearized kinetic theory

- lin. Boltzmann eq: $f(t,\boldsymbol{x},\boldsymbol{p}) = n(p) + \delta f(t,\boldsymbol{x},\boldsymbol{p})$

$$\left(\partial_t + \tfrac{\boldsymbol{p}}{p}\nabla_{\boldsymbol{x}}\right)\delta f(t,\boldsymbol{x},\boldsymbol{p}) = \delta C^{1\leftrightarrow 2}[n,\delta f] + \delta C^{2\leftrightarrow 2}[n,\delta f].$$

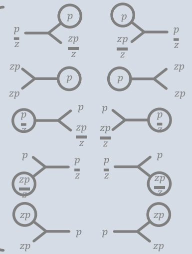
- $1 \leftrightarrow 2$ collisions:

$$\delta C^{1\leftrightarrow 2}[n,\delta f] = \int dz\,\left[\tfrac{1}{z^3}\Gamma\left(z,\tfrac{p}{z}\right)\delta\mathcal{F}\left(\tfrac{p}{z};p,\tfrac{zp}{z}\right) - \tfrac{1}{2}\Gamma(z,p)\delta\mathcal{F}(p;zp,\bar{z}p)\right]$$

splitting rate statistical factors (detailed balance)

$$\begin{aligned}\delta\mathcal{F}(p,k,p') = \delta f(p)&\left[(1+n(k))(1+n(p')) - n(k)n(p')\right]\\ -\,\delta f(k)&\left[n(p')\,(1+n(p)) - (1+n(p'))n(p)\right]\\ -\,\delta f(p')&\left[n(k)\,(1+n(p)) - (1+n(k))n(p)\right].\end{aligned}$$

- Two type of splitting
- Merging (holes)



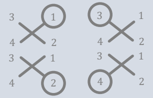
- $2 \leftrightarrow 2$ collisions:

$$\delta C^{2\leftrightarrow 2}[n,\delta f] = \int d\Omega\,|\mathcal{M}|^2\delta\mathcal{F}(p_1,p_2;p_3p_4)$$

scattering mx statistical factors (detailed balance)

$$\begin{aligned}\delta\mathcal{F} = \;&\delta f_3[n_4n_1n_2 \mp n_4n_1n_2]\\ &+\delta f_4[n_3n_1n_2 \mp n_3n_1n_2]\\ &-\delta f_2[n_1n_3n_4 \mp n_1n_3n_4]\\ &-\delta f_1[n_2n_3n_4 \mp n_2n_3n_4].\end{aligned}$$

- Single type of scatt.
- Recoils, holes.



(i) Linearized kinetic theory (high-energy limit $p \gg T$)

- lin. Boltzmann eq:

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- $1 \leftrightarrow 2$ collisions: (high energy limit of Γ = BDMPS-Z in the HO limit)

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Agrees with the BDMPS-Z medium-induced cascade!

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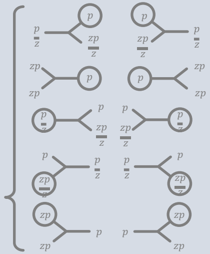

- $2 \leftrightarrow 2$ collisions: (high-energy + small angle limit of $C(q_\perp)$ = BDMPS-Z in the HO limit)

$$\delta C^{2\leftrightarrow 2}[n,\delta f] \approx \int_{q_\perp} dq_\perp\, C(q_\perp)[\delta f(p+q_\perp) - \delta f(p)]$$

Agrees with the BDMPS-Z broadening evolution!

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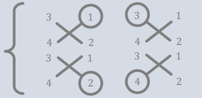
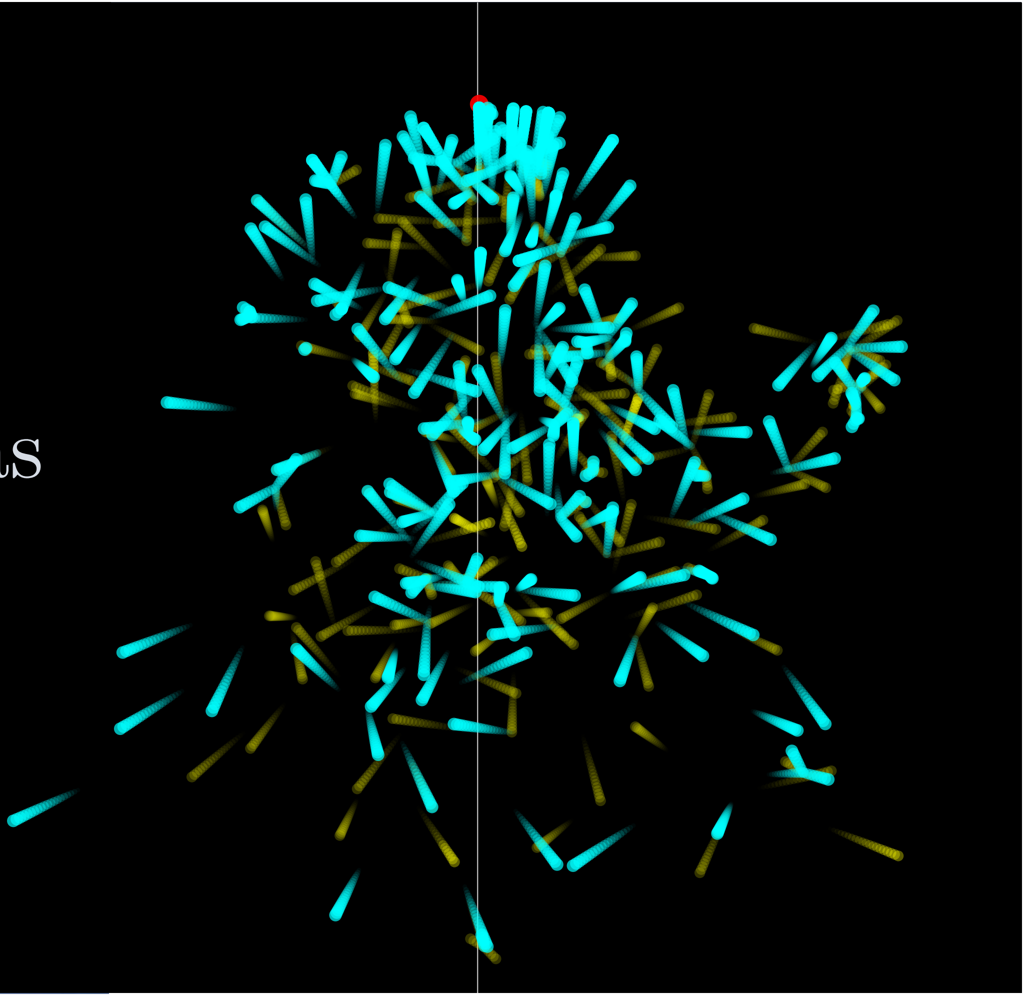


(i) AMY-EKT $\leftrightarrow$ jet quenching!

3. Kinetic theories as parton showers



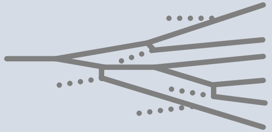
Linearized Boltzmann eq. as a parton shower

$$\left(\partial_t + \frac{\boldsymbol{p}}{p}\nabla_{\boldsymbol{x}}\right)\delta f(t,\boldsymbol{x},\boldsymbol{p}) = \delta C[n,\delta f].$$

- Homogeneous case:
    1. Separate “real” and “virtual” collisions: $\delta C = \delta C^{\mathrm{r}}[n,\delta f] - \delta C^{\mathrm{v}}[n]\,\delta f$.
    2. Integrate the Boltzmann eq: where $\Delta(t) = \exp\left[\int^t dt'\,\delta C^{\mathrm{v}}[n]\right]$

$$\delta f(t) = \Delta(t)\delta f_0 + \int^t dt'\,\frac{\Delta(t)}{\Delta(t')}\,\delta C^{\mathrm{r}}[n,\delta f].$$

4. Iterate: $\delta f_0 = \delta(p - p_0)$.
5. Histogram the particles: $\delta f(t,x,p) = \frac{1}{N_{\mathrm{ev}}}\frac{\mathrm{d}N}{\mathrm{d}\boldsymbol{p}\mathrm{d}\boldsymbol{x}}$



```
Initial condition:#[ID, p, x, weight]
  [21 (100,0,0,100) (0,0,0,0) 1]


Output:
   [[21 (1.5,0.0,00,1.5) (0.1,0.0,00,0.1) 1],
   [21 (2.8,0.0,0.0,2.8) (2.0,0.0,00,2.0) 1],
   [21 (5.0,0.0,0.0,5.0) (9.4,0.0,0.0,9.4) 1],
   [21 (1.7,1.1,0.6,1.1) (9.7,0.0,0.0,9.7) −1],
   [21 (82.,−0.9,−0.2,82) (9.7,0.0,0.0,9.7) 1],
   [21 (1.0,0.4,0.2,0.9) (12.0,1.4,0.5,12.0) 1],
   [21 (2.2,0.0,0.0,2.2) (15.0,0.0,0.0,15.0) 1],
   [21 (3.3,0.0,0.0,3.3) (15.0,0.0,0.0,15.0) 1],
   [21 (1.5,0.7,0.2,1.3) (15.5,2.6,1.0,14.8) 1],
   [21 (2.1,0.9,0.3,1.8) (15.5,2.6,1.0,14.8) 1]]
```

(ii) kinetic theories ↔ parton showers!

- Inhomogeneous case is trivial: free streaming between collisions.

(iii) inhomogeneous perturbations

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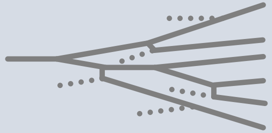

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```

(*ii*) kinetic theories ↔ parton showers!

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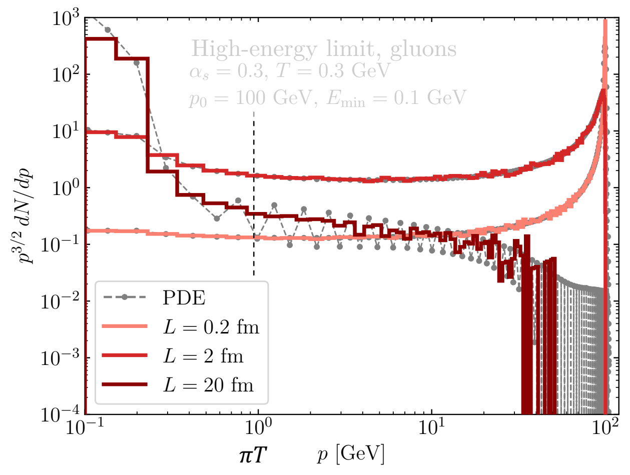
(*iii*) inhomogeneous perturbations

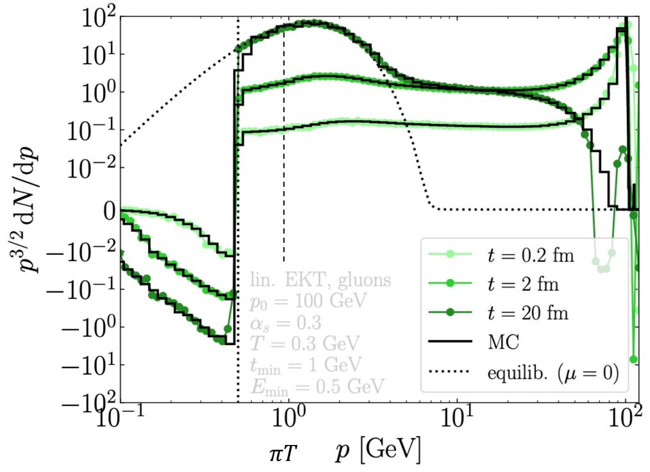
Numerical solution (gluons)

see also [Mehtar-Tani,Schlichting,Soudi]
[Brewer,Mazeliauskas,Zhou]

High-energy limit



Full EKT

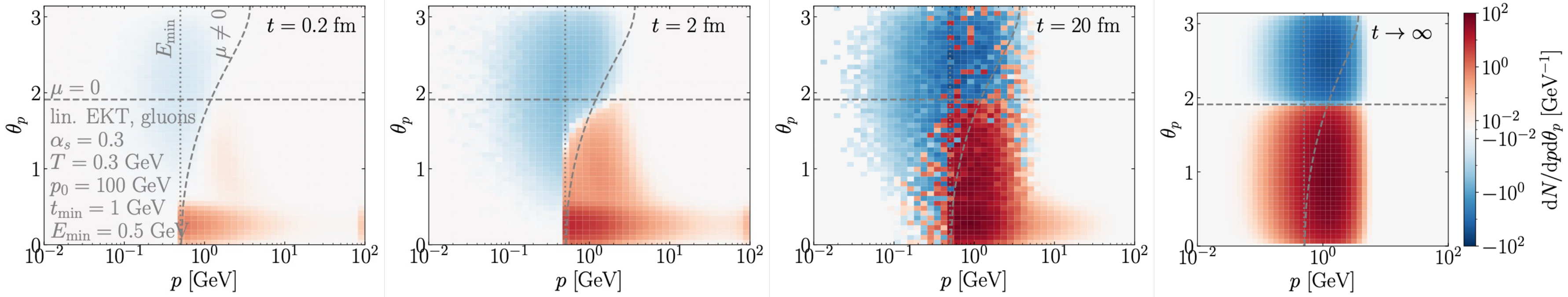


- Parton shower = diff. eq. solver
- Cascade doesn't thermalize!

- Parton shower = diff. eq. solver
- Thermalization!
- Mixture of $\mu = 0$ and $\mu = 0$ equilibrium.

Numerical solution(gluons)

see also [Mehtar-Tani,Schlichting,Soudi]
[Brewer,Mazeliauskas,Zhou]



1. Collinear radiation of soft gluons.
2. Broadening of soft fragments
3. $\mu \neq 0$ equilibrium $\to$ $\mu = 0$ equilibrium.

- (+) and (−) medium response.
- Soft and hard medium response.
- Boosted equilibrium only at very late times.

Outlook:
Why all the fuss?

Applications

lin. Boltzmann eq:

$$\left(\partial_t + \frac{\boldsymbol{p}}{p}\nabla_{\boldsymbol{x}}\right)\delta f(t,\boldsymbol{x},\boldsymbol{p}) = \delta C[n,\delta f].$$

1. **New phenomenological applications of EKT!**

   Interface with jets, hadronization, etc.

2. **Multi-particle correlations in EKT.**

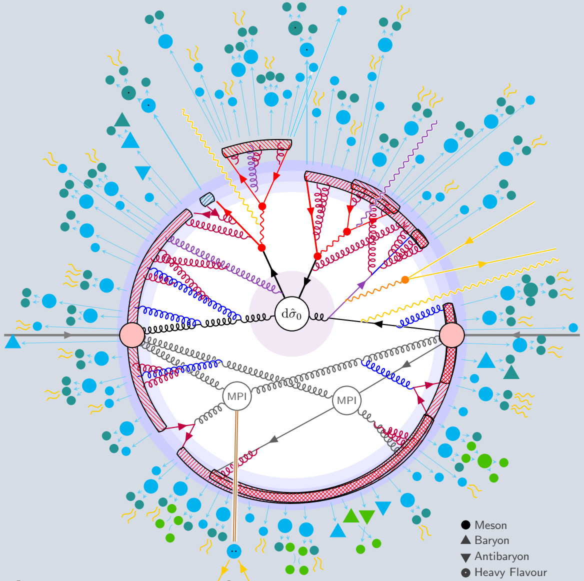
   Parton-shower is an n-particle cross-section generator:

   Unexplored topic in EKT, great relevance in EEC.

3. **Incorporate inhomogeneities.**

   Previously neglected! (parton shower speedup)

   Hydrodynamization: $\delta f(p,x) \to \delta f_{eq}(p,\delta T(t,x),\delta u(t,x))$



[Pythia 8.3 2203.11601]

Applications

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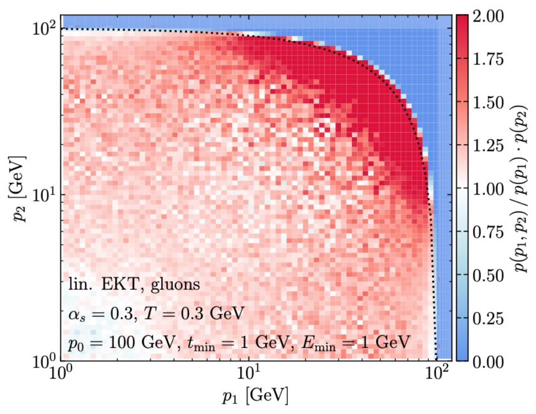

Correlations beyond molecular chaos!

Applications

lin. Boltzmann eq:

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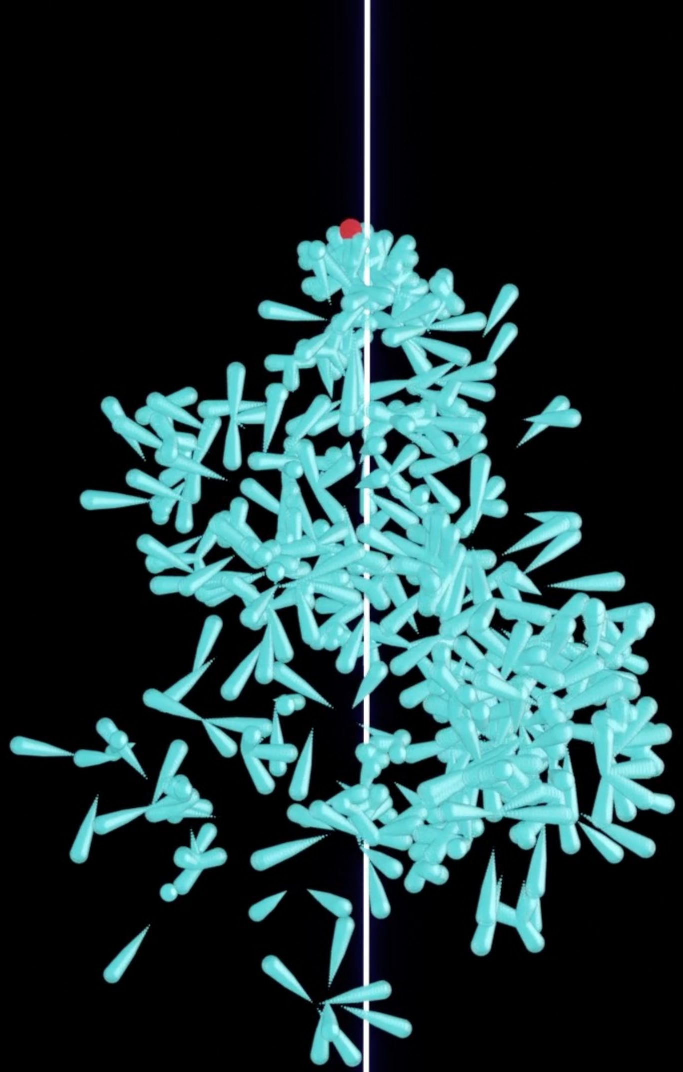
Adam Takacs



Summary:

A decade of jet substructure in heavy ion collisions

Dec 7 – 18, 2026
CERN

QCD@LHC 2026

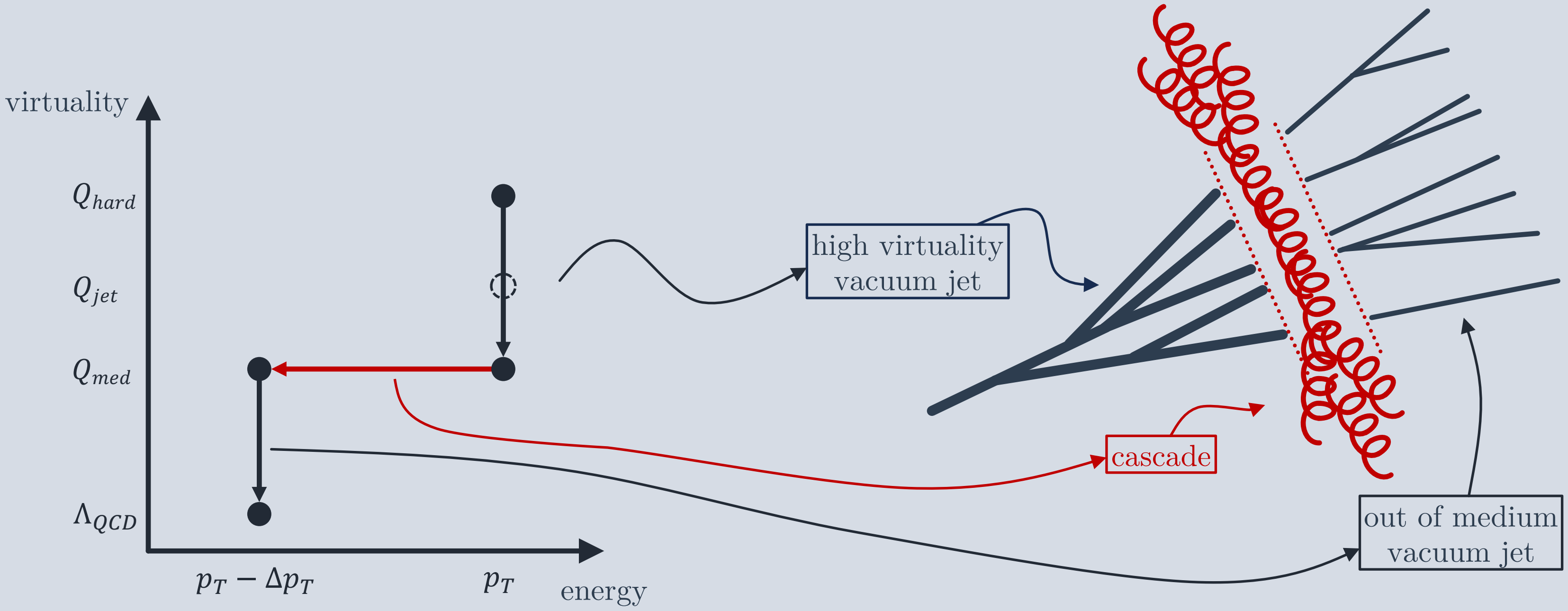
28 September 2026 to 2 October 2026
University of Oxford
Europe/London timezone

1. Perturbative grounds of jet quenching
2. AMY-EKT $\leftrightarrow$ parton energy loss and broadening
3. Lin. Boltzmann eq. $\leftrightarrow$ parton shower
4. New opportunities for EKT:
   - Jet thermalization,
   - Multi-particle correlations, hydrodynamization, fluctuations
   - Including in phenomenological workflows

Thank you for your attention!

Jet evolution in QGP

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

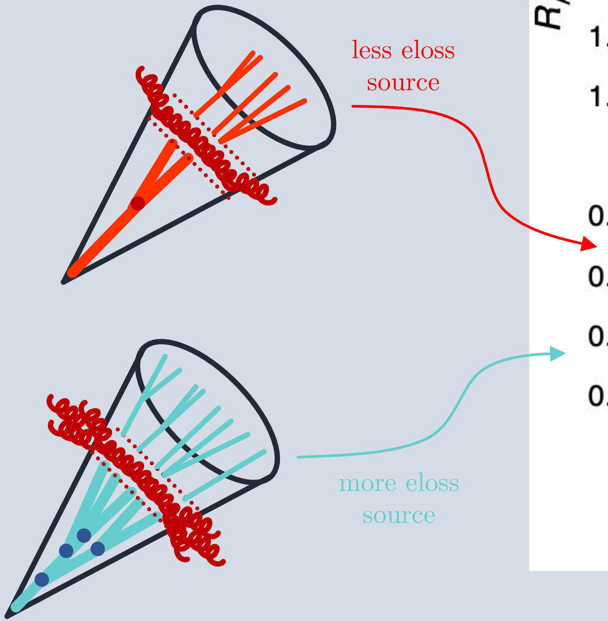


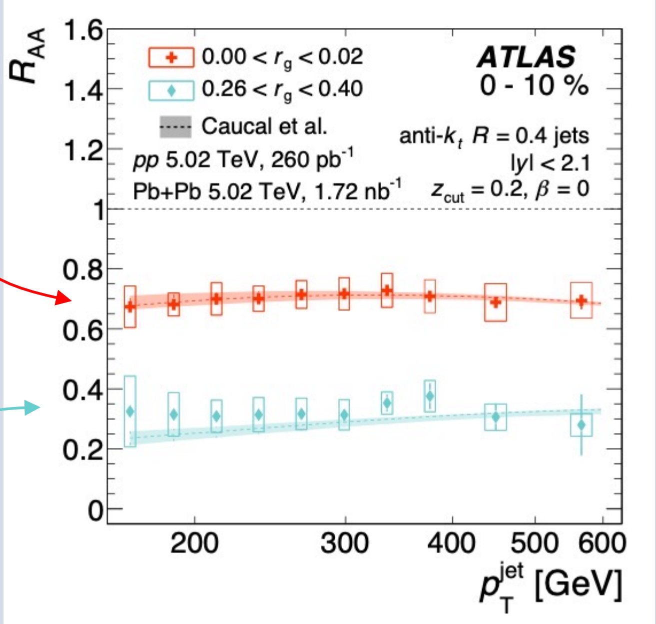
Experimental tests

[Caucal,Soto-Ontoso,AT, PRD105(2022)114046] → [ALICE PRL135(2025)031901]
[AT in PRD110(2024)014015] → [CMS 2602.09271]

Jet spectrum for different substructure

$$R_{AA} \sim \frac{d\sigma_{AA}^{jet}/dp_T}{d\sigma_{pp}^{jet}/dp_T}$$





[ATLAS PRC107(2023)054909]