Recent Developments on Jet Suppression

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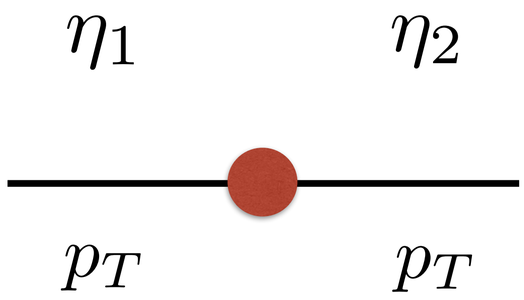
Jets in pp

- Hard parton pairs produced back-to-back in transverse plane, misaligned in rapidity.



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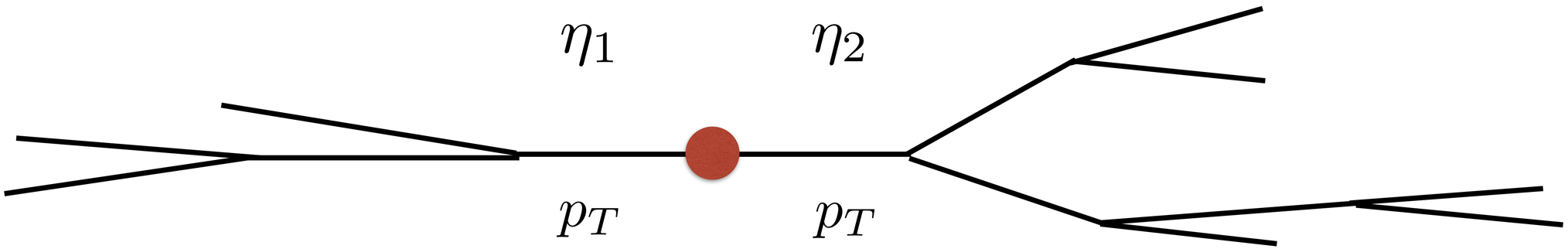

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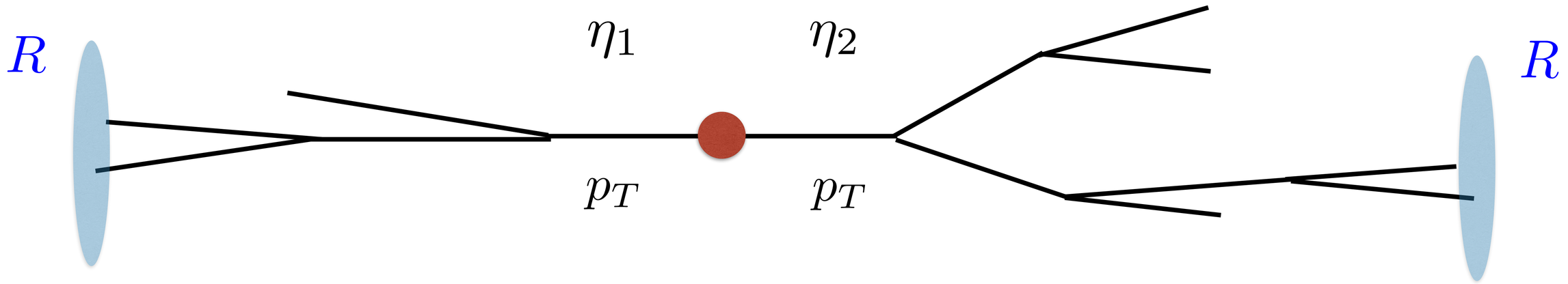

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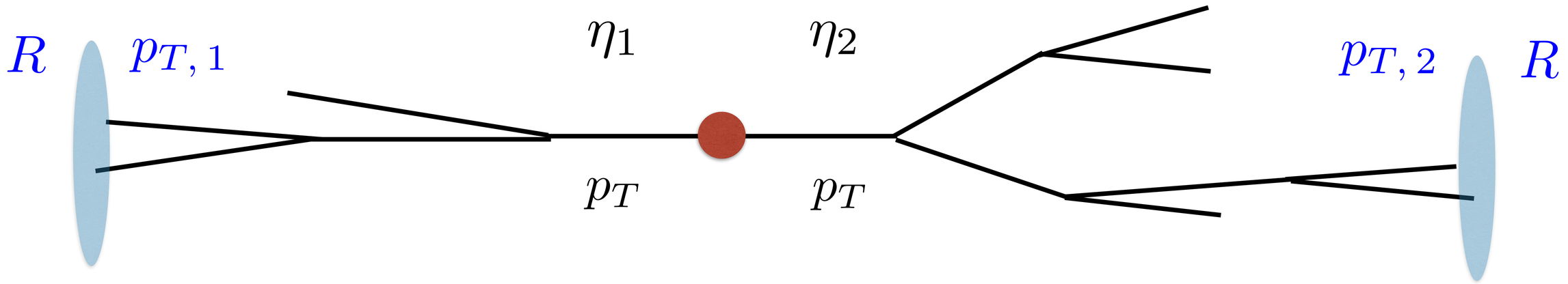


- Collimated structure enforced through collinear divergences & color coherence.

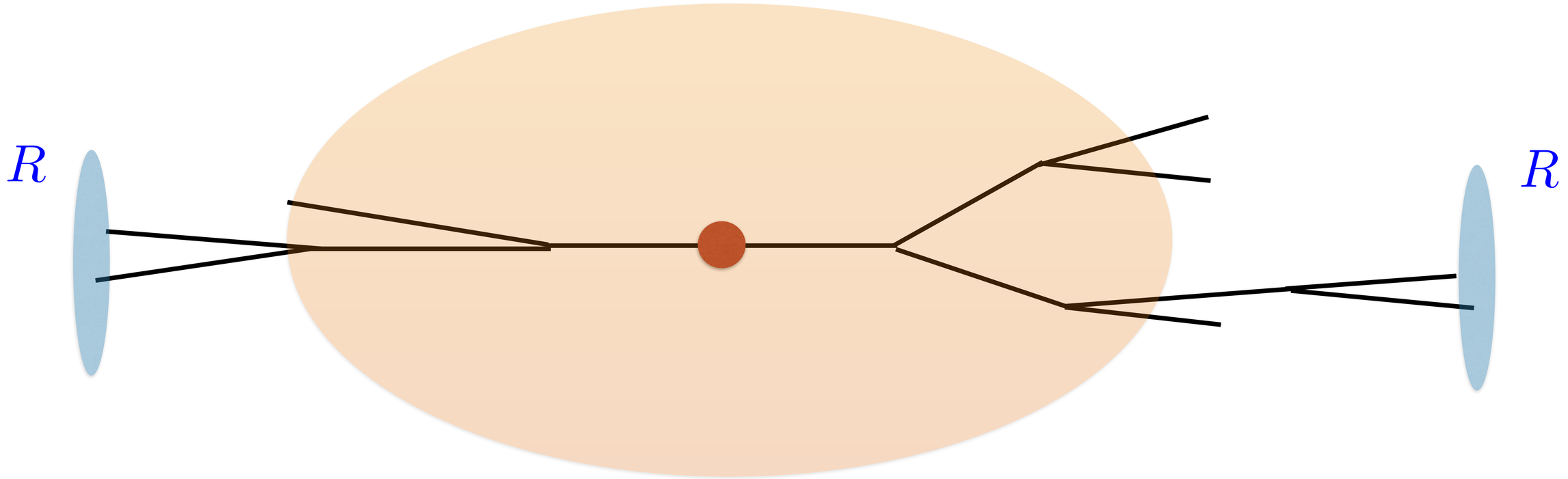
- Jets are defined with clustering algorithm, reconstruction radius R.

→ Degree of jet activity determines, e.g., out-of-cone radiation (causes dijet asymmetry in pp).

$$p_{T,1} > p_{T,2}$$

Jets in AA

- Jet partons interact with QGP and experience energy loss.
- Crucial insights obtained with jet quenching MCs.



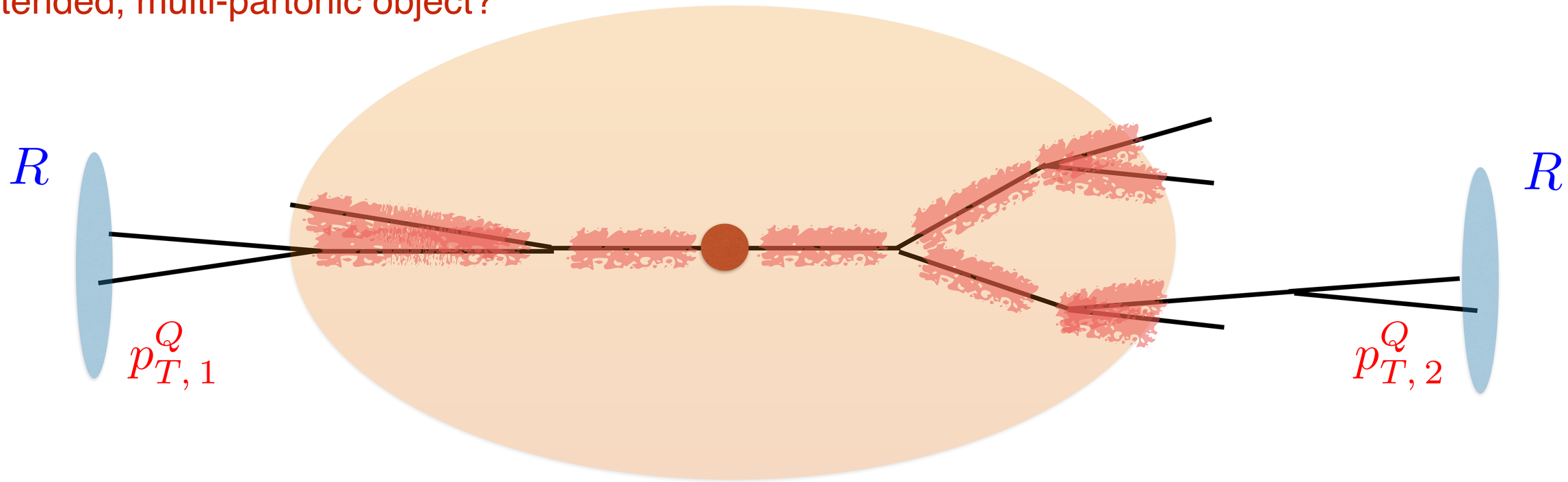
- Lesson example: total energy loss proportional to jet activity (more energy loss sources):
  - → Causes dijet asymmetry in AA (for same traversed length). Milhano & Zapp - EPJ '16
  - → Causes selection bias towards narrower jets. Hadron vs. Jet Suppression Casalderrey, Hulcher, Milhano, DP, Rajagopal - PRC '19

Recent Developments on Jet Suppression

- Jet suppression beyond MC:

  How to describe energy loss off an extended, multi-partonic object?

Outline



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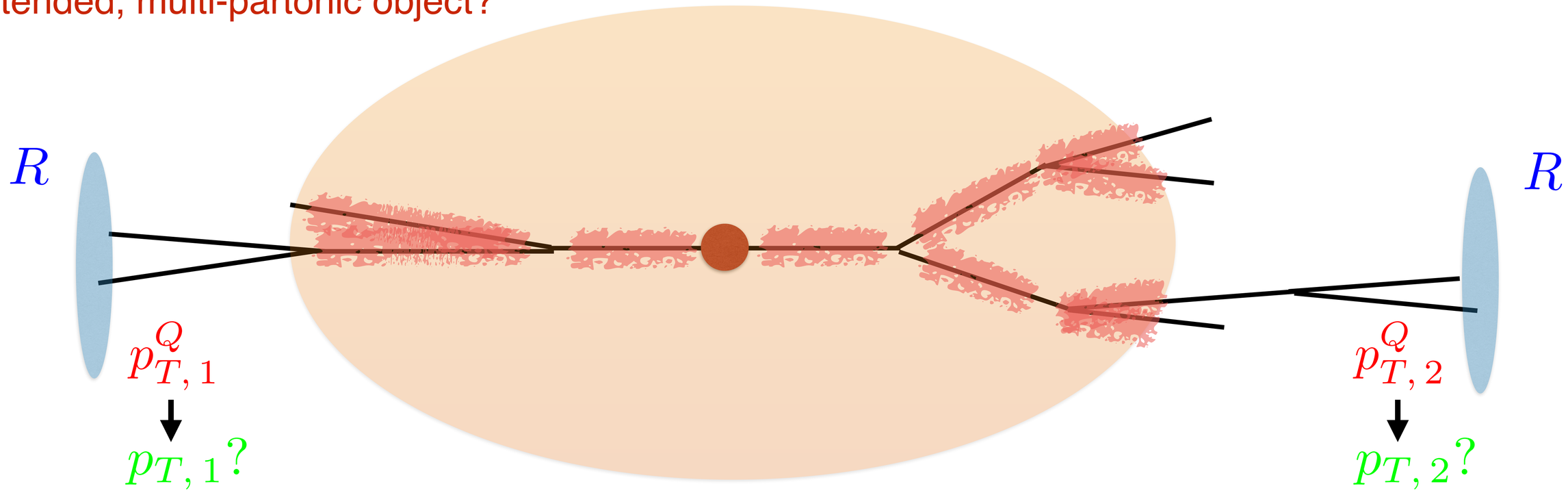

- Mitigating selection bias:

  What can we learn by knowing how much energy a given jet has lost?

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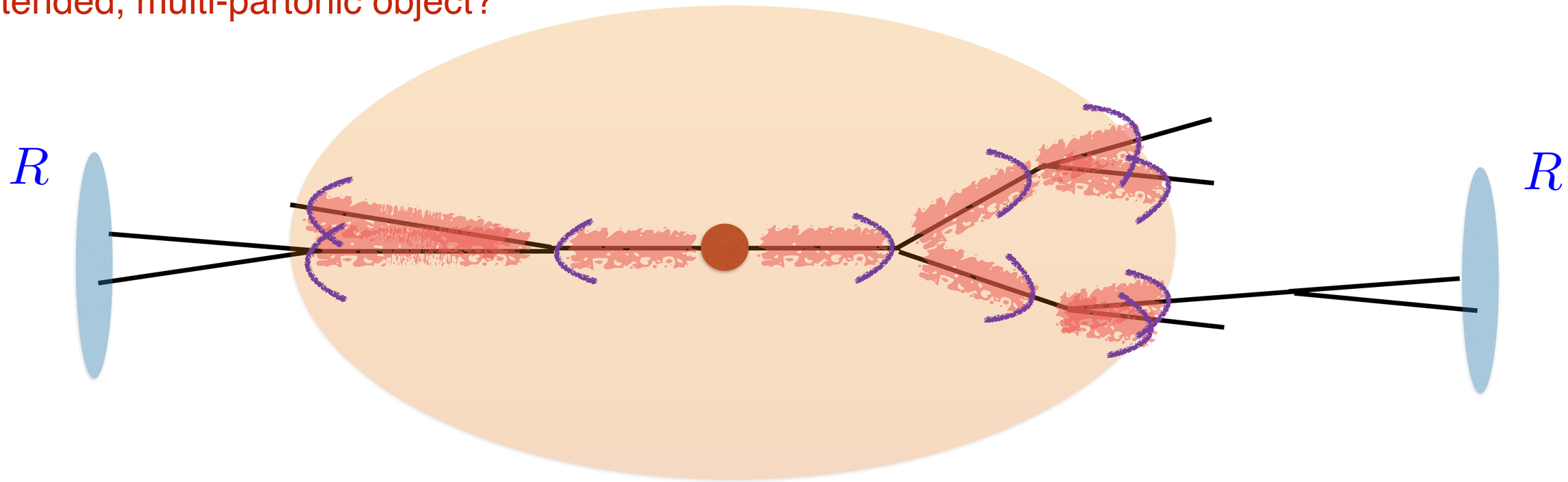


- Mitigating selection bias:

  What can we learn by knowing how much energy a given jet has lost?

- Non-perturbative modelling of long wavelength jet modes:

  Where does “lost” energy go to?

Radiative Energy Loss

- Framework: Light-Cone Perturbation Theory.

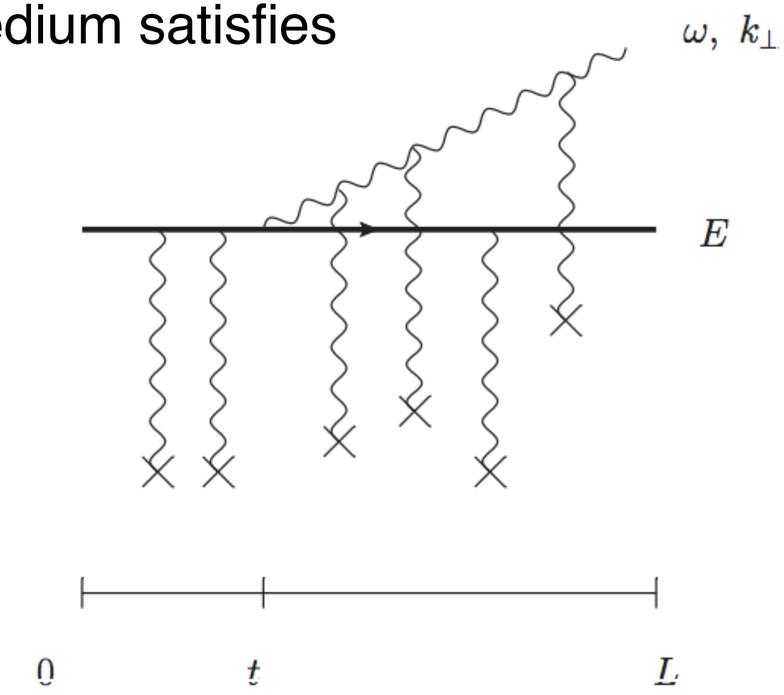
Baier, Dokshitzer, Mueller, Peigne, Schiff - NPB '97
Zakharov - JETP Lett. '96
Arnold, Moore, Yaffe - JHEP '03

  - Integrated medium induced spectrum:

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} = \frac{\alpha_s C_R}{\omega^2} \int_0^\infty dt_2 \int_0^{t_2} dt_1 \; \boldsymbol{\partial_x} \cdot \boldsymbol{\partial_y} \left[\mathcal{K}(\boldsymbol{x}, t_2 | \boldsymbol{y}, t_1) - \mathcal{K}_0(\boldsymbol{x}, t_2 | \boldsymbol{y}, t_1) \right]_{\boldsymbol{x}=\boldsymbol{y}=0}$$

  - Resummed propagator due to multiple interactions with the medium satisfies 2D Schrödinger-like equation:

$$\left[i\partial_t + \frac{\boldsymbol{\partial}^2}{2\omega^2} + iv(\boldsymbol{x}) \right] \mathcal{K}(\boldsymbol{x}, t_2 | \boldsymbol{y}, t_1) = i\delta(\boldsymbol{x} - \boldsymbol{y})\delta(t_2 - t_1)$$



  - With potential: $v(\boldsymbol{x}, t) = C_A \int_{\boldsymbol{k}} \frac{d^2\sigma}{d^2\boldsymbol{k}} (1 - e^{i\boldsymbol{k}\cdot\boldsymbol{x}})$

    and scattering cross-section:

Hard Thermal Loop:

$$\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}^2\boldsymbol{q}} \right)^{\mathrm{HTL}} = \frac{g^2 m_{\mathrm{D}}^2 T}{\boldsymbol{q}^2(\boldsymbol{q}^2 + m_{\mathrm{D}}^2)}$$

Gyulassy-Wang:

$$\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}^2\boldsymbol{q}} \right)^{\mathrm{GW}} = \frac{g^4 n(t)}{(\boldsymbol{q}^2 + \mu^2)^2}$$

Mehtar-Tani - JHEP '19

Usual Approximations of the Spectrum

- Dilute medium: expand to leading order in $v(\boldsymbol{x})$ (N=1 opacity expansion):

$$\omega \frac{\mathrm{d}I_{\mathrm{GLV}}}{\mathrm{d}\omega} = 32\pi\, \alpha_s\, C_R\, \hat{q}_0 \int_0^L \mathrm{d}s \int_{\boldsymbol{p},\boldsymbol{q}} \frac{\boldsymbol{p}\cdot\boldsymbol{q}}{\boldsymbol{p}^2(\boldsymbol{p}-\boldsymbol{q})^2(\boldsymbol{q}^2+\mu^2)^2} \left\{1 - \cos\left[\frac{(\boldsymbol{p}-\boldsymbol{q})^2}{2\omega} s\right]\right\}$$

Gyulassy-Levai-Vitev spectrum

Single hard scattering, preserves full form of potential.

Wiedemann - NPB '00
Gyulassy, Levai, Vitev - NPB '00
Wang, Guo - NPA '01
Majumder - PRD '12
Sievert, Vitev, Yoon - PLB '19

- Harmonic oscillator (diffusion) approximation:

$$v(\boldsymbol{x},t) = C_A \int_{\boldsymbol{k}} \frac{d^2\sigma}{d^2\boldsymbol{k}}(1 - e^{i\boldsymbol{k}\cdot\boldsymbol{x}}) \equiv \frac{1}{4}\hat{q}(\boldsymbol{x}^2,t)\boldsymbol{x}^2 = \frac{1}{4}\hat{q}_0\boldsymbol{x}^2 \log\left(\frac{1}{\mu^{\star 2}\boldsymbol{x}^2}\right)$$

neglect logarithmic dependence

$$\mu^{*2} \sim 1/\mathbf{x}^2$$

$$\omega \frac{\mathrm{d}I_{\mathrm{HO}}}{\mathrm{d}\omega} = 2\bar{\alpha} \ln|\cos(\Omega L)| \qquad \Omega(t) = \frac{1-i}{2}\sqrt{\frac{\hat{q}(t)}{\omega}}$$

BDMPS - ASW spectrum

Large medium, resums multiple soft interactions.

BDMPS-Z
Salgado, Wiedemann - PRD '03
Armesto, Salgado, Wiedemann - PRD '04

Improved Opacity Expansion (IOE)

- Perform "opacity" expansion on top of harmonic oscillator solution:

$$v(\boldsymbol{x},t) = \frac{1}{4}\boldsymbol{x}^2 \log\left(\frac{1}{\mu^{\star 2}\boldsymbol{x}^2}\right) = \frac{1}{4}\boldsymbol{x}^2\left(\log\left(\frac{Q^2}{\mu^{\star 2}}\right) + \log\left(\frac{1}{Q^2\boldsymbol{x}^2}\right)\right) \equiv v_{\rm HO}(\boldsymbol{x},t) + \delta v(\boldsymbol{x},t)$$

$$\mathcal{K}(\boldsymbol{x},t,\boldsymbol{y},s) = -\int_{\boldsymbol{z}}\int_s^t du\, \mathcal{K}_{\rm HO}(\boldsymbol{x},t|\boldsymbol{z},u)\delta v(\boldsymbol{z},u)\mathcal{K}(\boldsymbol{z},u|\boldsymbol{y},s)$$

Mehtar-Tani - JHEP '19
Mehtar-Tani, Tywoniuk - JHEP '19
Barata, Mehtar-Tani - JHEP '20

- Can systematically compute corrections up to arbitrary order in $\delta v(\boldsymbol{x},t)$:

$$\omega\frac{{\rm d}I}{{\rm d}\omega} = \omega\frac{{\rm d}I^{\rm HO=LO}}{{\rm d}\omega} + \omega\frac{{\rm d}I^{\rm NLO}}{{\rm d}\omega} + \cdots = \omega\frac{{\rm d}I^{\rm LO}}{{\rm d}\omega} + \sum_{m=1}^{\infty}\omega\frac{{\rm d}I^{{\rm N}^m{\rm LO}}}{{\rm d}\omega}$$

- Spectrum should be independent of Q^2 scale when all orders are included:

→ This leads to $Q^4 = \hat{q}_0\omega\,\ln Q^2/\mu_*^2$ (trans. mom. acquired by radiated gluon — natural scale)

Spectrum @ NLO in the soft limit in IOE:

$$\frac{{\rm d}I^{(0)}}{{\rm d}\omega} = \frac{2\alpha_s C_R}{\pi\omega}\ln|\cos\Omega L|\,,$$

$$\frac{{\rm d}I^{(1)}}{{\rm d}\omega} = \frac{\alpha_s C_R\hat{q}_0}{2\pi}{\rm Re}\int_0^L {\rm d}s\,\frac{-1}{k^2(s)}\ln\frac{-k^2(s)}{Q^2\,{\rm e}^{-\gamma_E}}$$

$$\hat{q} = \hat{q}_0\ln\frac{Q^2}{\mu_*^2}$$

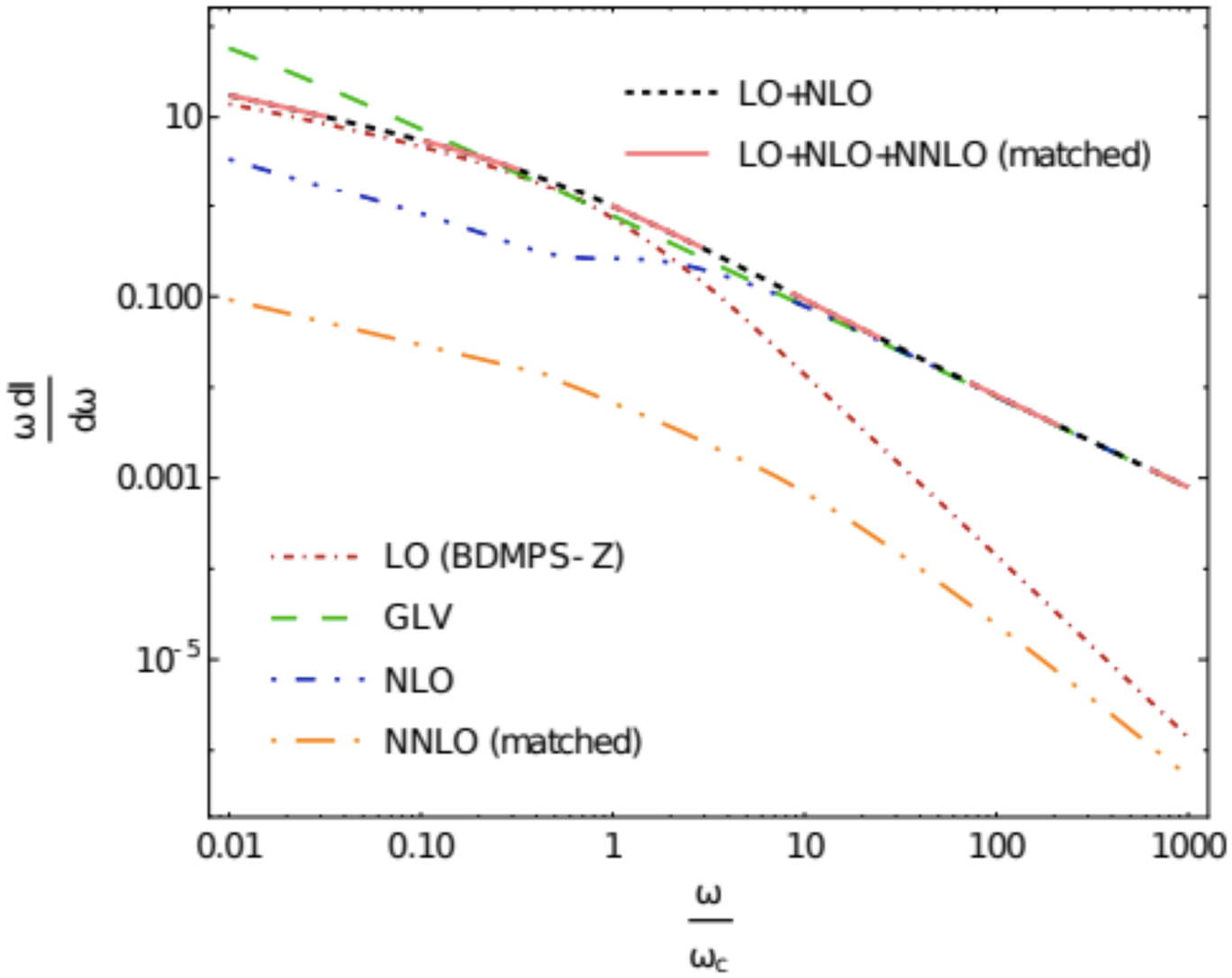
$$\Omega = (1-i)\sqrt{\hat{q}/(4\omega)}$$

$$k^2(s) = i\frac{\omega\Omega}{2}[\cot\Omega s - \tan\Omega(L-s)]$$

Improved Opacity Expansion (IOE)

Barata, Mehtar-Tani - JHEP '20

$$t_{\rm coh} = \omega/k_\perp^2 \qquad k_\perp^2 \sim \hat{q}\, t_{\rm coh} \qquad t_{\rm coh} \equiv \sqrt{\frac{\omega}{\hat{q}}}$$



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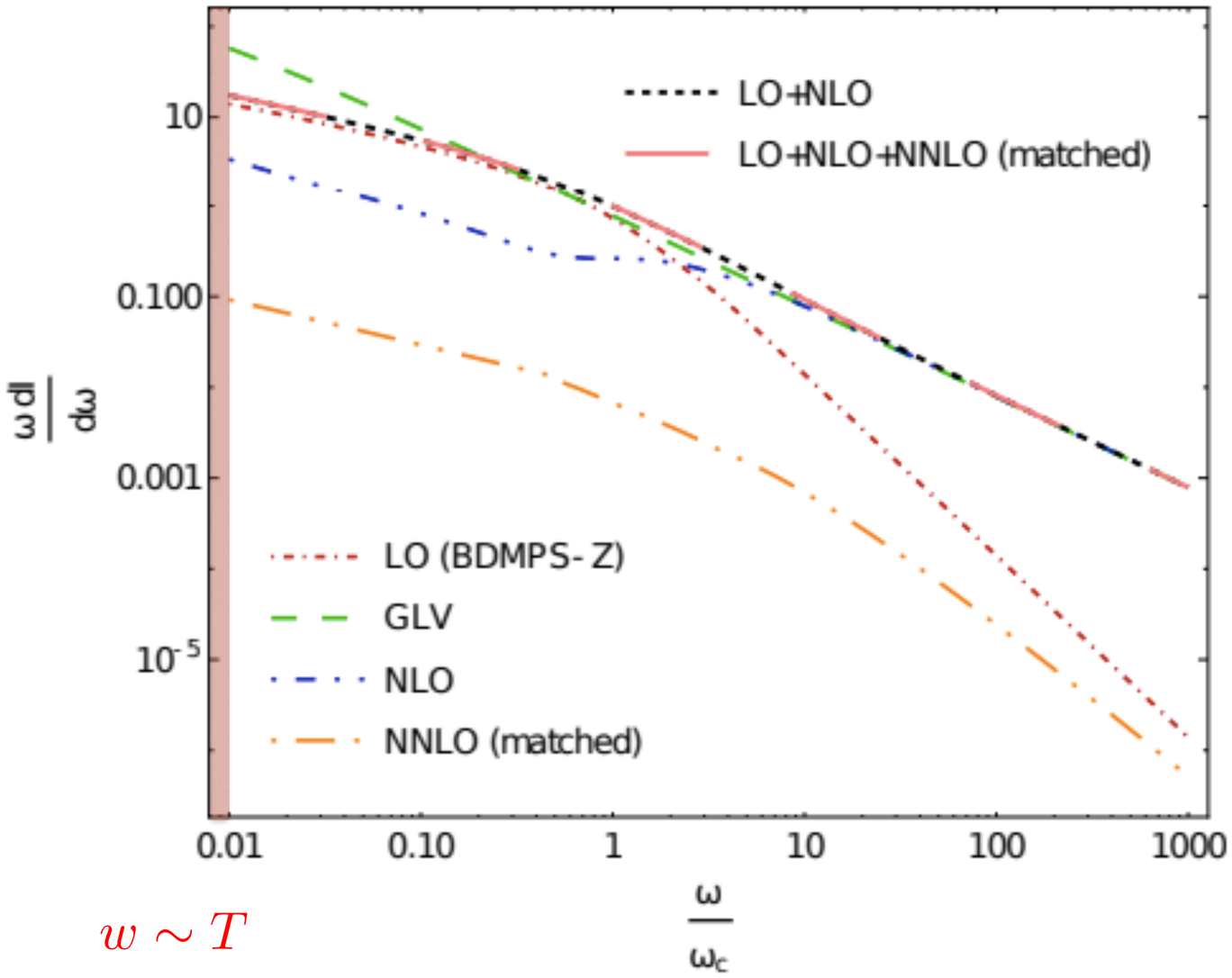

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- Bethe-Heitler regime $t_{\rm coh} \sim \ell_{\rm mfp}$

$$\omega \frac{{\rm d}I_{\rm BH}}{{\rm d}\omega} \simeq \alpha_s \frac{L}{\ell_{\rm mfp}} = \alpha_s N_{\rm scatt}$$

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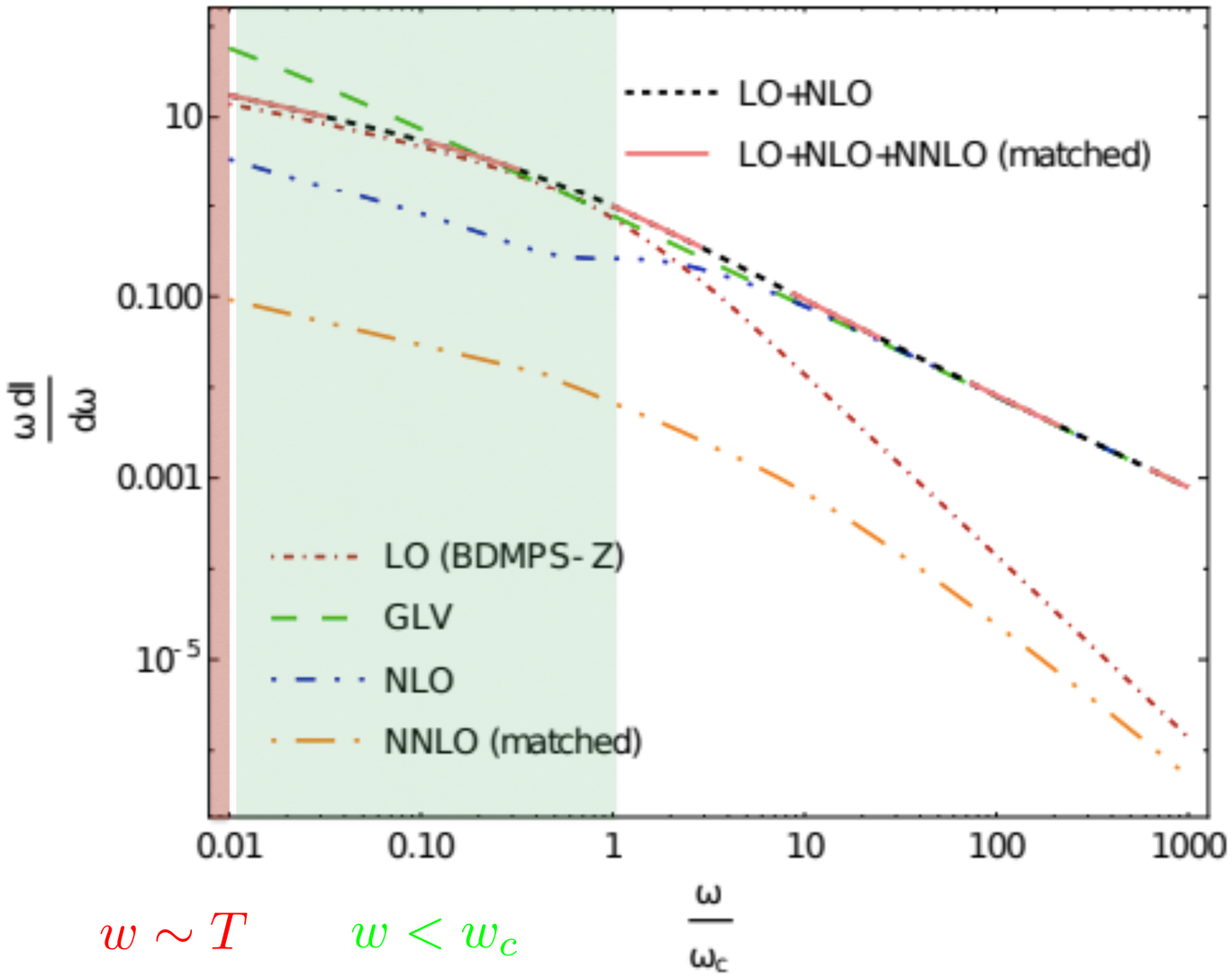

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- BDMPS-Z regime $\ell_{\rm mfp} \ll t_{\rm coh} \ll L$

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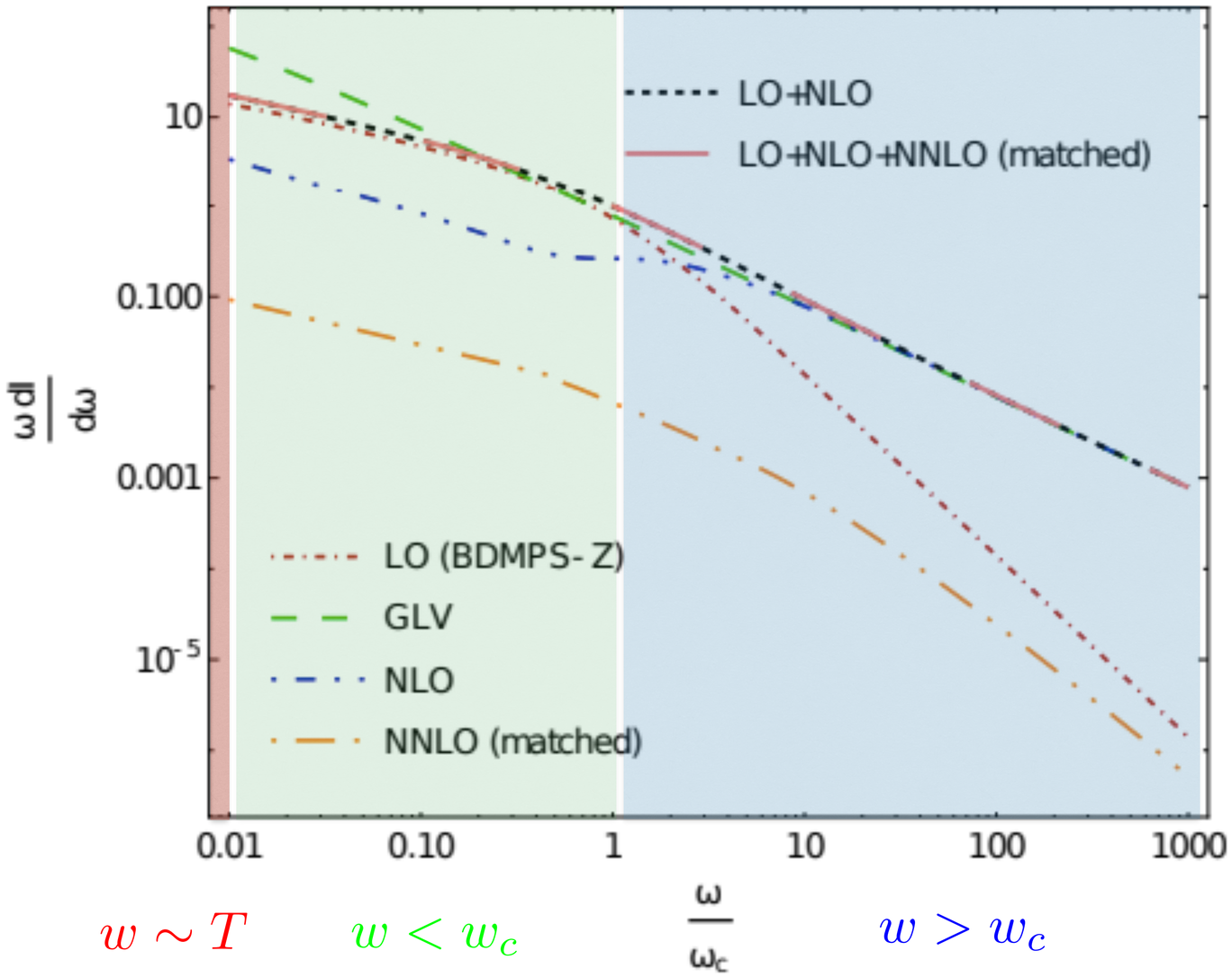
Barata, Mehtar-Tani - JHEP '20



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- GLV regime $k_\perp^2 \gg Q_s^2 \equiv \hat{q}L$

$$\omega \frac{{\rm d}I}{{\rm d}\omega} \sim \alpha_s^3 n L \int_{\omega/L}^{\infty} \frac{{\rm d}k_\perp^2}{k_\perp^4} \simeq \alpha_s \frac{\omega_c}{\omega}$$

Bare Quenching Factor

Baier, Dokshitzer, Mueller - JHEP '01
Salgado, Wiedemann - PRD '03

- For steeply falling spectrum and small energy loss:

$$\frac{\mathrm{d}\sigma_{\mathrm{med}}}{\mathrm{d}p_T} = \int_0^\infty \mathrm{d}\epsilon\, \mathcal{P}(\epsilon)\, \frac{\mathrm{d}\sigma_{\mathrm{vac}}}{\mathrm{d}p'_T}\bigg|_{p'_T = p_T+\epsilon} \approx \frac{\mathrm{d}\sigma_{\mathrm{vac}}}{\mathrm{d}p_T} \underbrace{\int_0^\infty \mathrm{d}\epsilon\, \mathcal{P}(\epsilon) \mathrm{e}^{-\epsilon \frac{n}{p_T}}}_{Q(p_T)}$$

Mehtar-Tani, DP, Tywoniuk - 2101.01742

- Quenching factor of a single parton for multiple independent emissions (R dependent):

$$Q^{(0)}_{\mathrm{rad}}(p_T) = \exp\left[-\int_{\omega_s}^\infty \mathrm{d}\omega\, \frac{\mathrm{d}I_>}{\mathrm{d}\omega}\left(1-\mathrm{e}^{-\nu\omega}\right) - \int_T^{\omega_s} \mathrm{d}\omega\, \frac{\mathrm{d}I^{(0)}}{\mathrm{d}\omega}\left(1-\mathrm{e}^{-\nu\omega(1-(\frac{R}{R_{\mathrm{rec}}})^2)}\right)\right]$$

$$\nu \equiv \frac{n}{p_T}$$

Full out-of-cone spectrum
for semi-hard emissions

$$\omega_s \equiv (g^2_{\mathrm{med}} N_c/(2\pi)^2)^2 \pi \hat{q}_0 L^2$$

→ O(1) emission probability

→ undergo turbulent cascade, thermalise

→ if uniformly distributed in jet hemisphere

$$R_{\mathrm{rec}} \sim \pi$$

Note that:

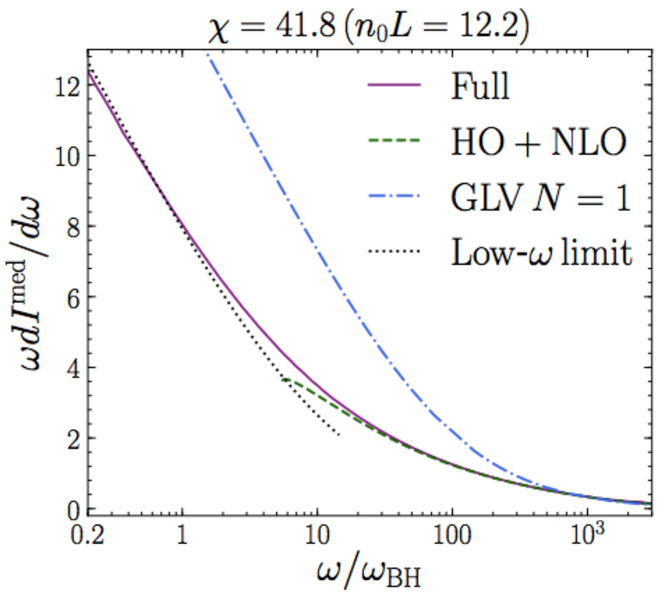
$$\Delta E = (1-(\frac{R}{R_{\mathrm{rec}}})^2) \int_T^{w_s} dw\, w \frac{dI^{(0)}}{dw} = -\frac{d}{d\nu} Q^{(0),\mathrm{turb}}_{\mathrm{rad}}(p_T)\bigg|_{\nu=0}$$

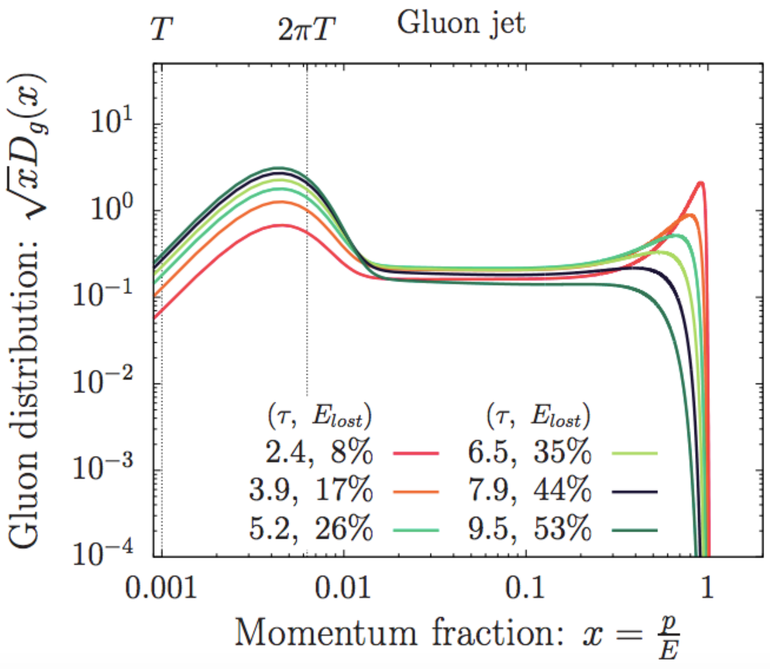
Further Improvements on Single Charge Energy Loss

- All order resummation of medium induced radiation spectrum.

Andrés et al. - JHEP '20 & '21

→ HO+NLO (IOE) agrees over a wide energy range.





Schlichting & Soudi - 2008.04028

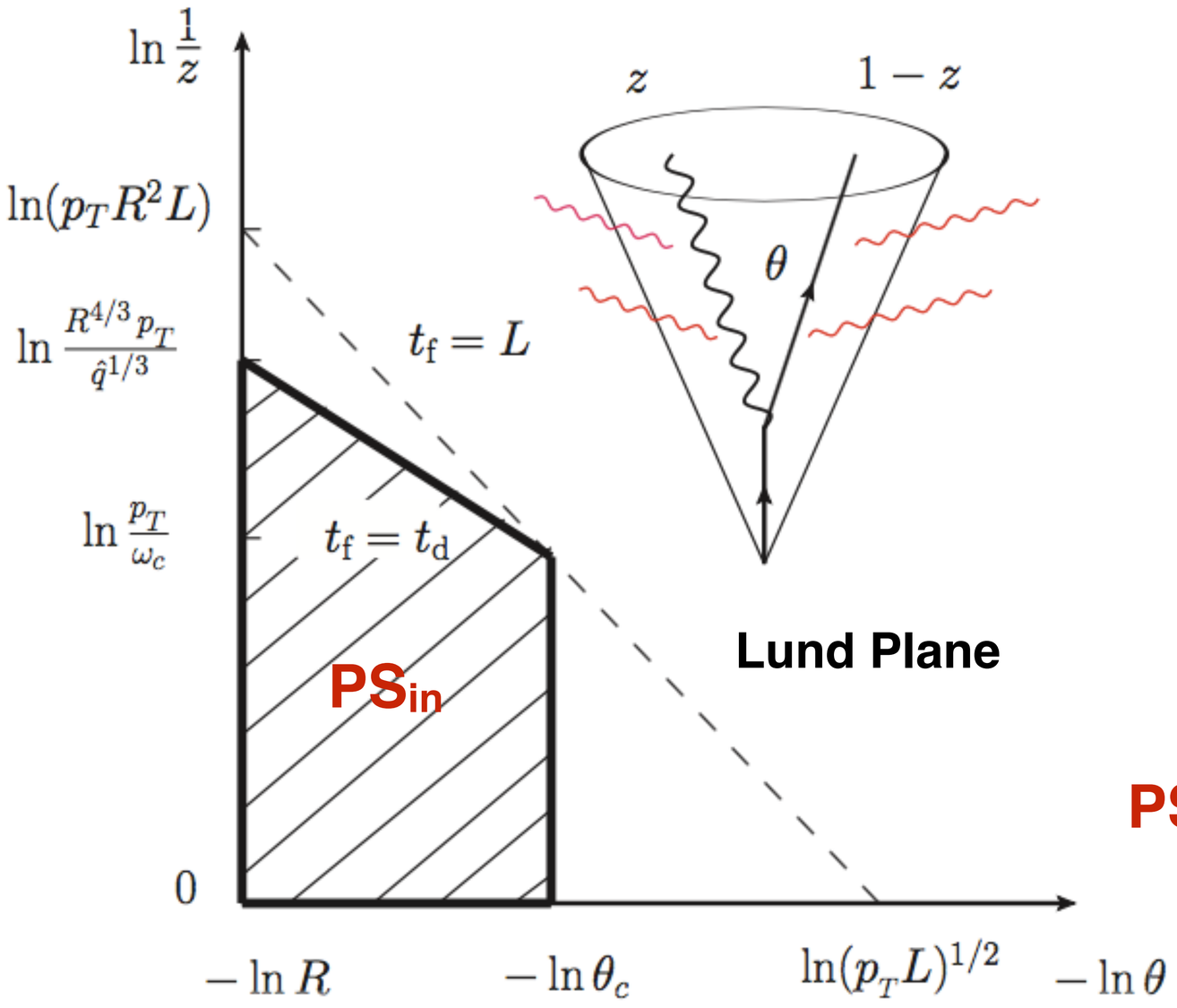
- In-medium fragmentation of hard parton in QGP through effective kinetic theory.

→ Includes 1↔2 and 2↔2 processes.

→ Features turbulent cascade, modified chemistry around the jet.

Detailed analysis of dynamics, can account for medium response.

Quenched Phase Space of a Jet



- Only those jet modes that:
  - → are formed inside the medium, and,

$$t_f < L$$

  - → are resolved by the medium,

$$t_f < t_d$$

contribute to double-logarithmic enhancement of quenched phase space:

$$\mathbf{PS_{in}} = \bar{\alpha} \int_{t_f < t_d < L} \frac{d\theta}{\theta} \int \frac{dz}{z} \equiv \bar{\alpha} \ln \frac{R}{\theta_c} \left(\ln \frac{p_T}{\omega_c} + \frac{2}{3} \ln \frac{R}{\theta_c} \right)$$

Mehtar-Tani, Tywoniuk - PRD ‘18

see also Caucal, Iancu, Mueller, Soyez - PRL ‘18

Jet Suppression: Framework

- Use microjet distributions derived using Generating Functional (GF) framework:

Vacuum evol. obeys DGLAP:

$$\frac{df^{\rm incl}_{j/i}(z,t)}{dt} = \sum_k \int_z^1 \frac{dz'}{z'} P_{jk}(z')\, f^{\rm incl}_{k/i}(z/z',t)$$

Dasgupta et al. - JHEP '14

- Extend GF in the medium to resum energy loss effects due to multi-particle nature of jet:

PS$_{\rm in}$ constraint

$$\frac{\partial Q_i(p,\theta)}{\partial \ln\theta} = \int_0^1 {\rm d}z\, \frac{\alpha_s(k_\perp)}{2\pi} p^{(k)}_{ji}(z)\, \boxed{\Theta_{\rm res}(z,\theta)} \times \left[Q_j(zp,\theta)Q_k((1-z)p,\theta) - Q_i(p,\theta)\right]$$

Initial condition at zero angle is single charge quenching factor:

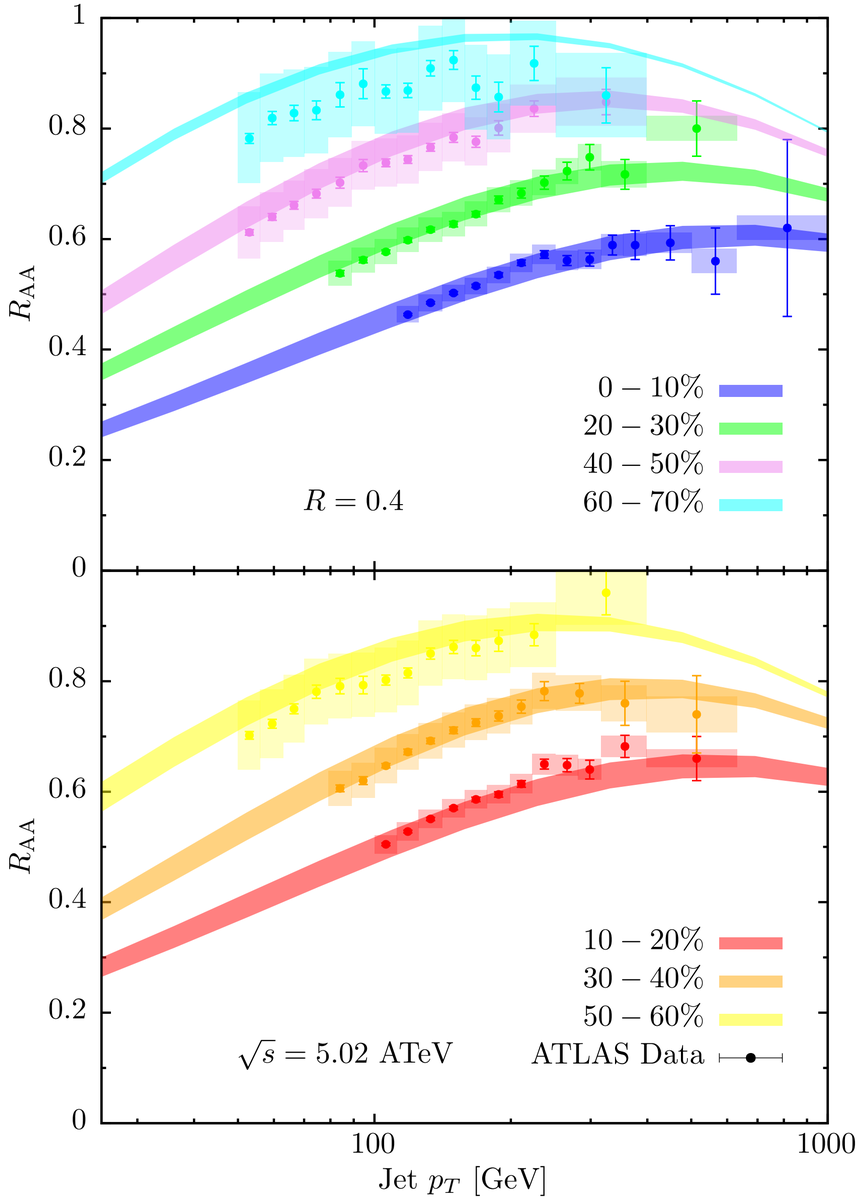
$$Q_i(p,0) = Q^{(0)}_{{\rm rad},i}(p_T)\, Q^{(0)}_{{\rm el},i}(p_T)$$

Radiative energy loss — Elastic energy loss

- Energy loss versus R displays non-monotonic behaviour. Competing effects:
  - → Increasing R means more likely to retain emitted (or thermalised) quanta: less quenching.
  - → Increasing R means larger quenched phase space: more quenching.

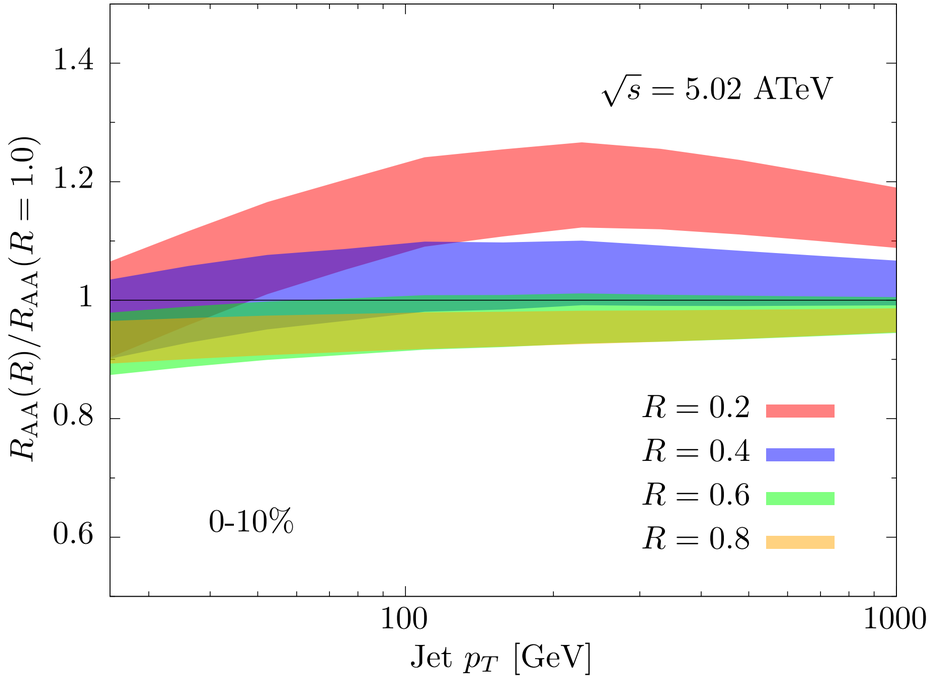
Mehtar-Tani, DP, Tywoniuk - 2101.01742

Jet Suppression: Results



Encouraging description of data across:

- Jet p_T.
- Centrality.
- Size R.



- Modelling uncertainties:
  - Non-perturbative sector relatively unimportant up to R<0.6
  - NLO contribution to radiative energy loss is very small.
  - Most important: Determination of quenched phase space. Can be systematically improved in pQCD.

Mehtar-Tani, DP, Tywoniuk - 2101.01742

Diagnosing Jet Energy Loss

- Experimentally, so far is impossible to know how much energy a given jet has lost.
- Moreover, due to steep falling jet spectrum, what we observe is jets that lost the least energy. → Selection (or survival) bias.

→ Hinders our ability to analyse true effects of energy loss. E.g.:

- Measure jets above $p_T > 100$ GeV.
- Observe that they are narrower in PbPb than in pp:
  - ★ Energy loss makes jets narrower?
  - ★ Observe the surviving (less quenched) jets, which are narrow?

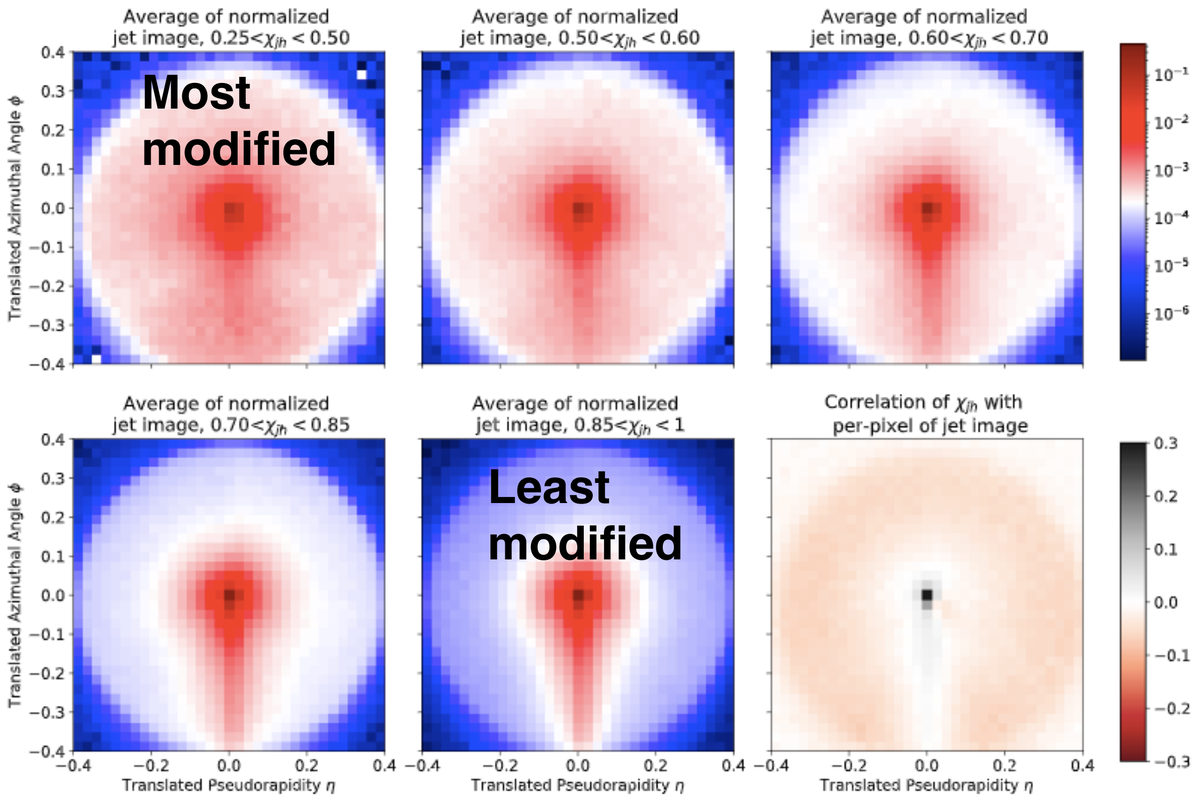
- Exploit deep learning techniques to extract energy loss jet-by-jet.

Energy loss ratio: $$\chi \equiv \frac{E_f}{E_i}$$

E_f: Final, measurable jet energy.

E_i: Vacuum energy (had there been no medium).

Deep Learning Jet Modifications

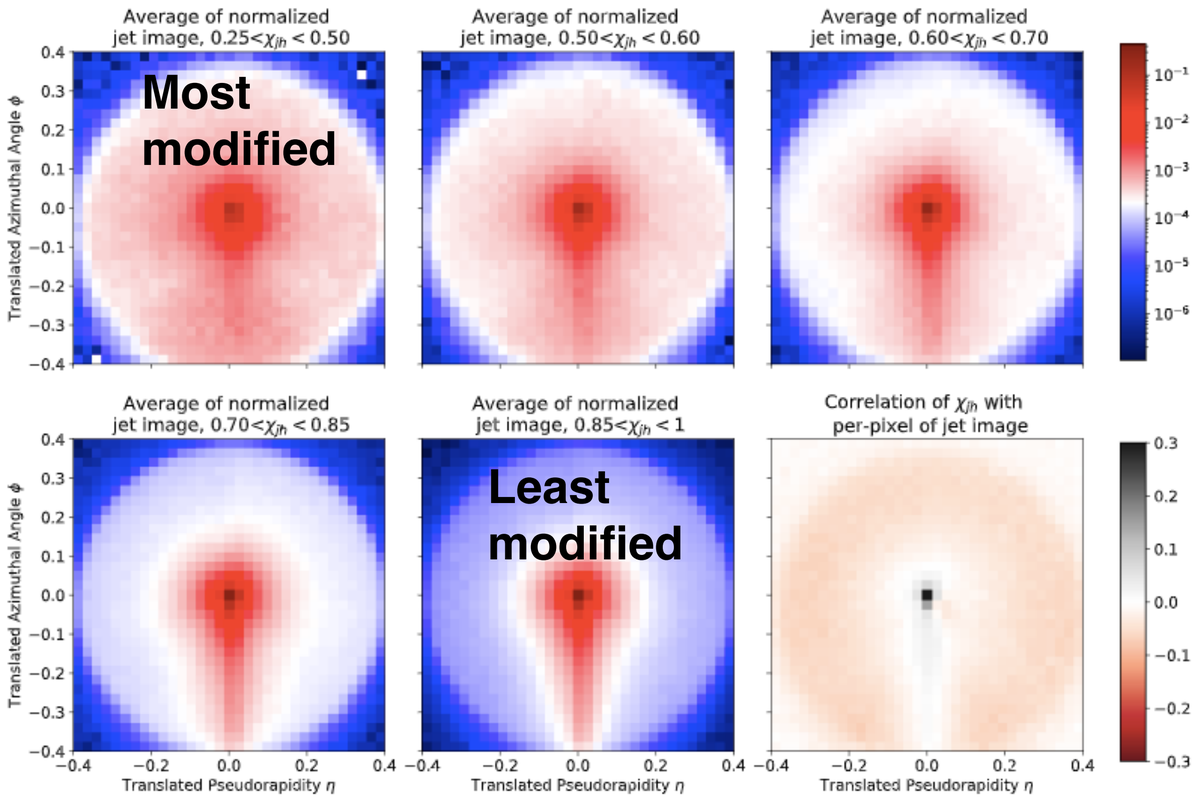


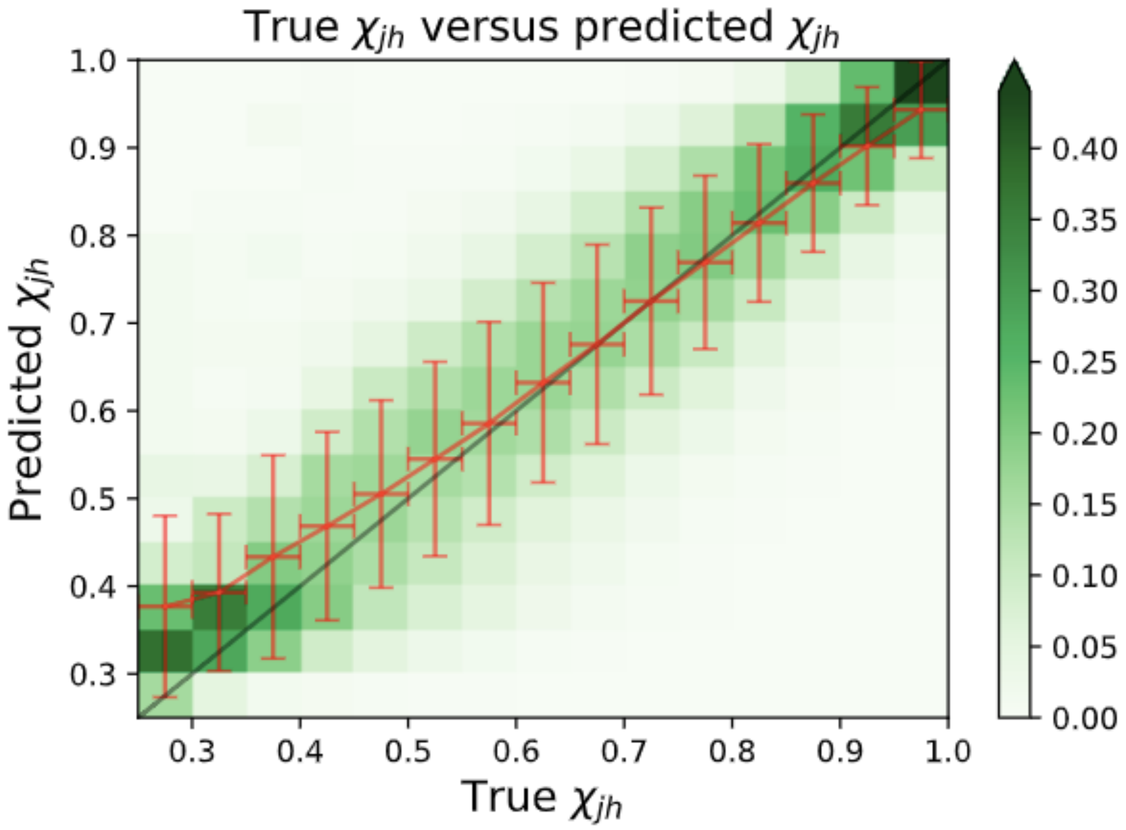
- Most models: Energy loss transfers jet energy to large angles in the form of soft particles.

- Use jet images as inputs for CNN. Main result.
- Use jet observables as inputs for FCNN. Mainly used for interpretability.

Du, DP, Tywoniuk - JHEP ‘21

Deep Learning Jet Modifications





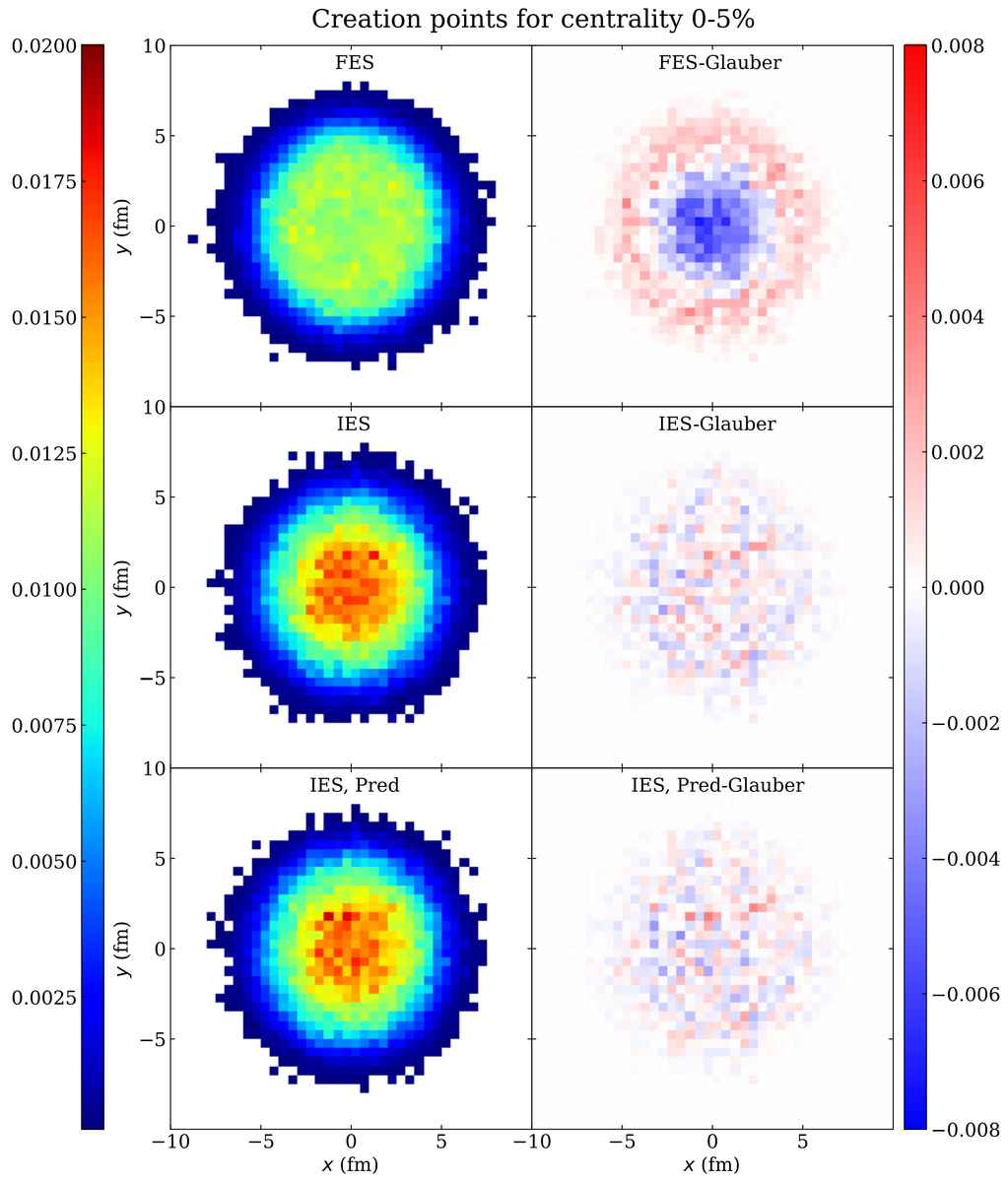
- Use jet images as inputs for CNN. Main result.
- Use jet observables as inputs for FCNN. Mainly used for interpretability.

Du, DP, Tywoniuk - JHEP '21

Good performance across a wide range in χ

- Consistency check: pp (vacuum) jets get $\chi \simeq 1$

Accessing True Path Length Distributions



- FES: Select jets according to final energy.

$$E_f > E_{\rm cut}$$

→ Surface bias compared to actual nuclear overlap density.

- IES: Select jets according to "initial" energy.

$$E_f/\chi > E_{\rm cut}$$

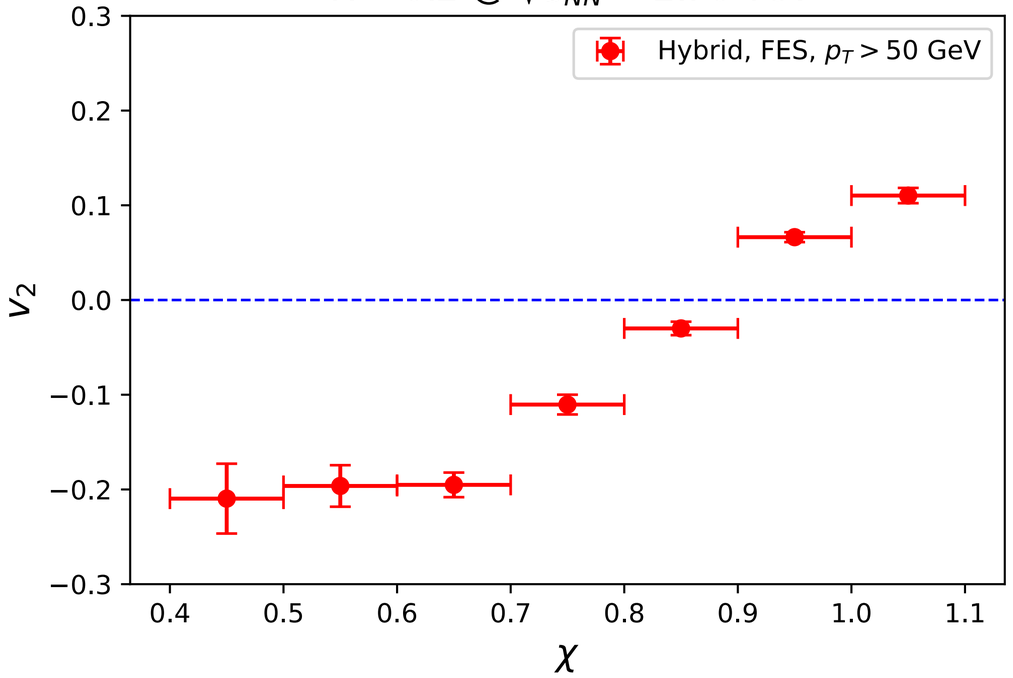
→ Production point density unbiased w.r.t. true underlying distribution.

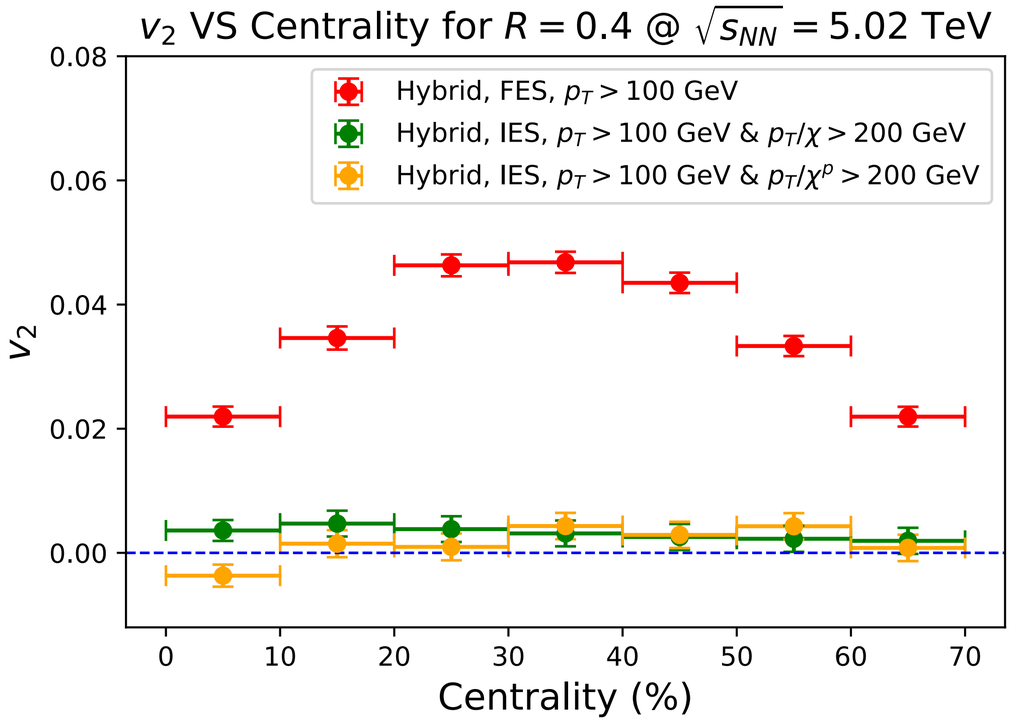
Du, DP, Tywoniuk - in preparation

Accessing Initial Jet Anisotropies

v_2 VS χ for centrality 30-40%, $R = 0.2$ @ $\sqrt{s_{NN}} = 2.76$ TeV

Du, DP, Tywoniuk - in preparation





- Intuitive origin of high-p_T jet anisotropies:

  Small χ (large energy loss):

  → longer path length;

  → $v_2 < 0$.

  and viceversa for large χ.

- However, if use IES:

  Reveals initial azimuthal anisotropies.

  In this model: none → $v_2 \sim 0$.

  And in experiments?

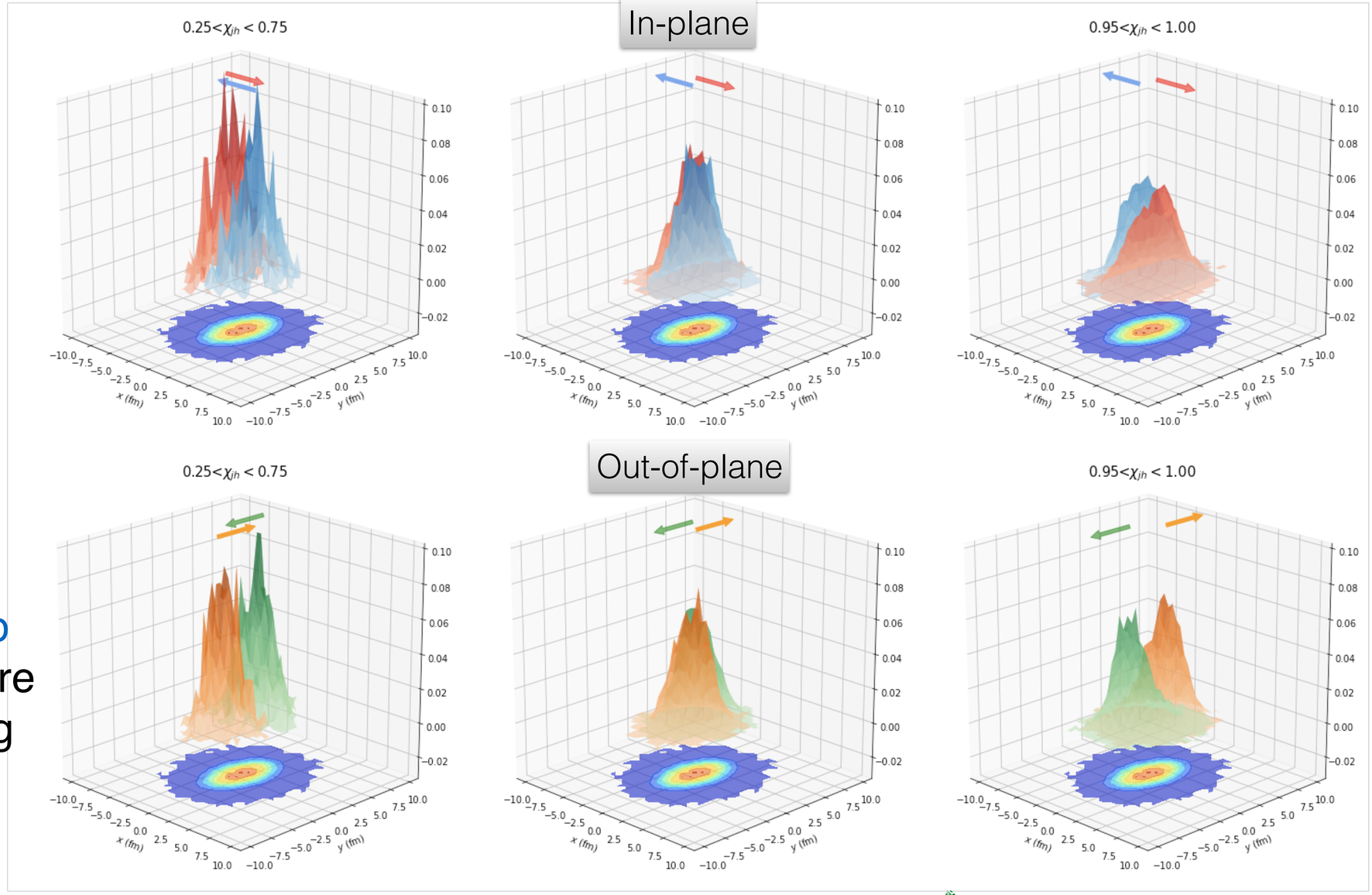
Tomography with Deep Learning

Determination of production point in transverse plane.

Differential in:

- Orientation w.r.t. event plane.
- Energy loss ratio χ .

Production points swap in order to traverse more medium with increasing energy loss.

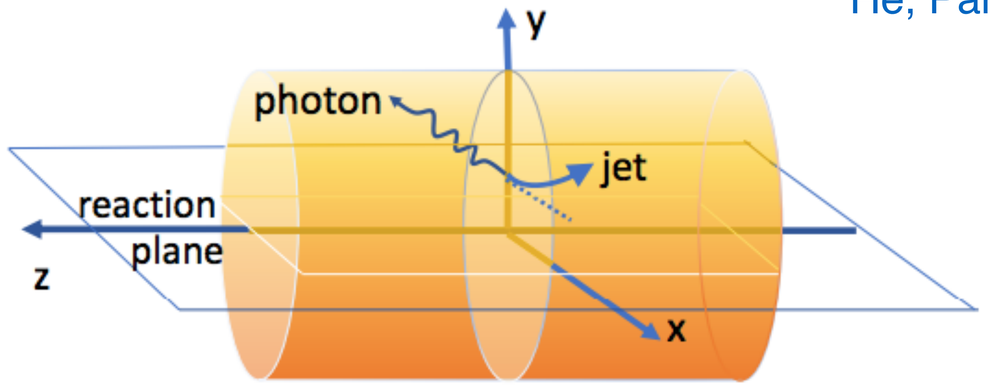


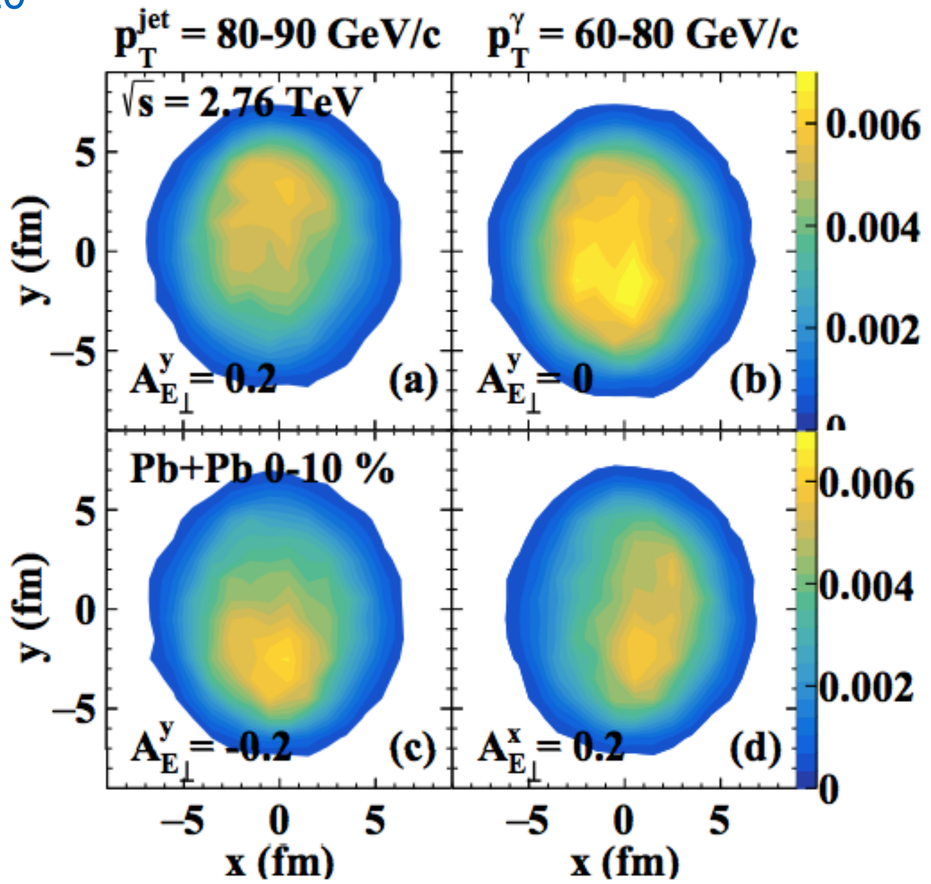
Du, DP, Tywoniuk - in preparation

more quenched χ less quenched

Gradient Jet Tomography

He, Pang, Wang - PRL '20





- Local gradient of $\widehat{q}$ leads to drift of parton distribution towards less dense region.

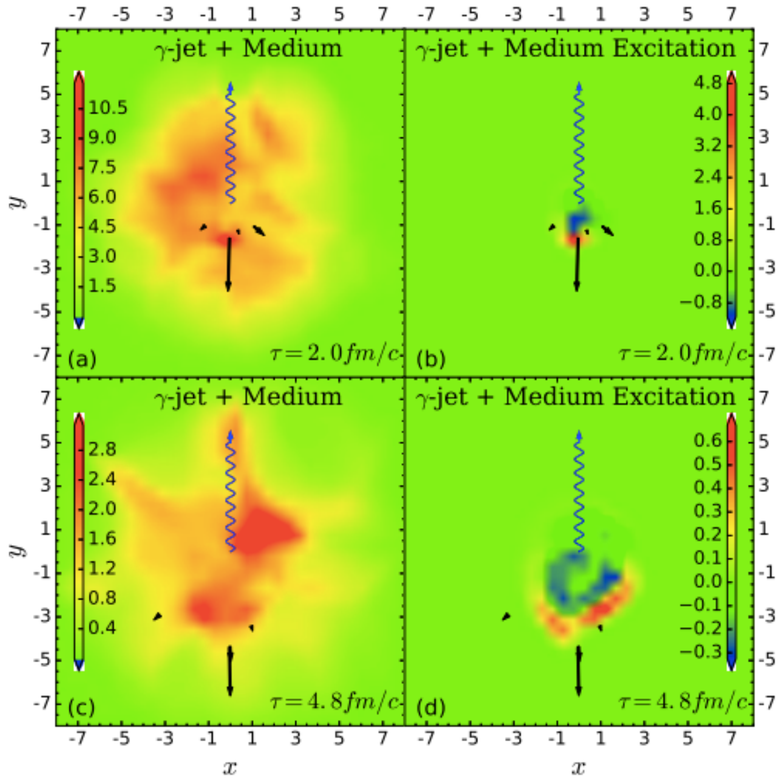
  → Momentum asymmetry w.r.t. plane defined between reaction plane and trigger particle (e.g. a photon).

$$A_N^{\vec{n}} = \frac{\int d^3r d^3k f_a(\vec{k},\vec{r}) \mathrm{Sign}(\vec{k}\cdot\vec{n})}{\int d^3r d^3k f_a(\vec{k},\vec{r})}$$

Value and sign of momentum asymmetry correlates strongly with production point.

The Fate of Hydrodynamized Energy

- Jet modes that reach thermal scale should evolve hydrodynamically.
  - Non-perturbative component of in-medium jet dynamics. Affects jet observables.
  - Crucial ingredient of the fluid QGP paradigm.
  - Need to find unequivocal signatures of jet modes hydrodynamization.



- A promising candidate:
  - The effect of the diffusion wake.

    Depletion of energy density behind the jet
    (the jet drags the fluid along its direction of propagation,
    reduces yield of particles in the opposite direction).

Chen et al. - PLB '18

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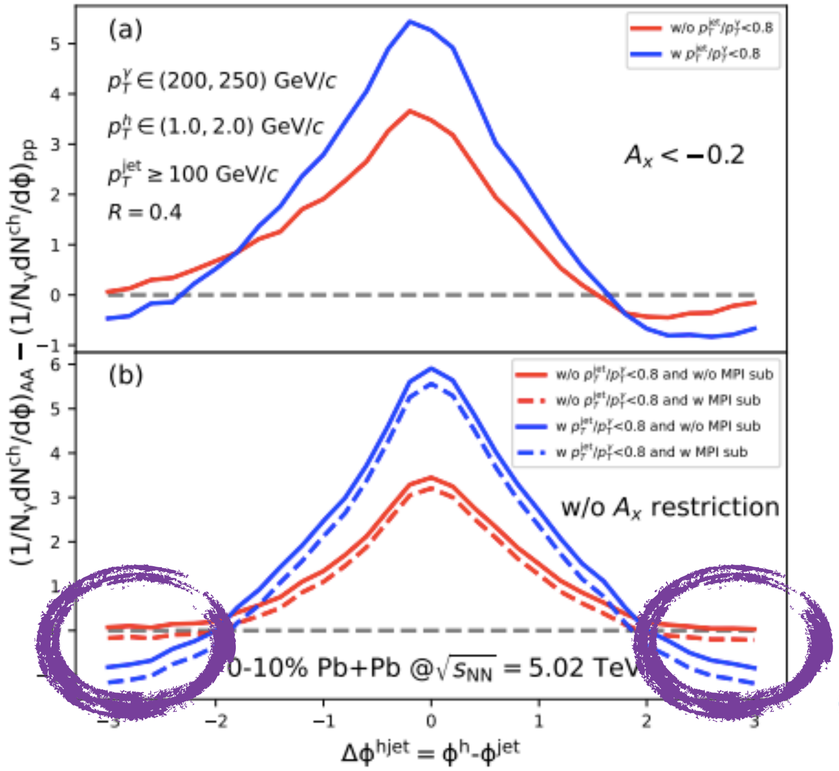
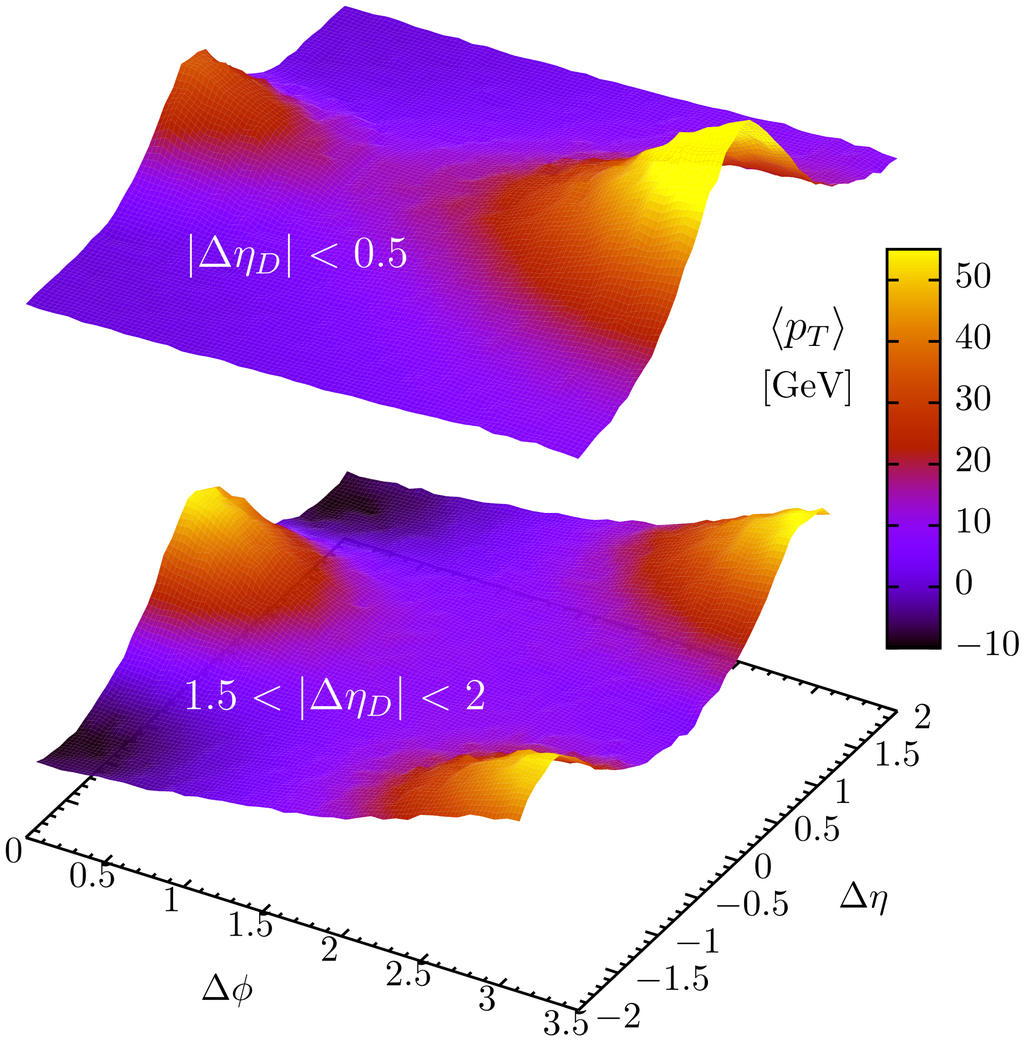


- Leads to depletion of soft particle yields opposite to the jet direction in the transverse plane.
- Effect can be modulated thanks to photon-jet momentum asymmetry & gradient jet tomography technique.

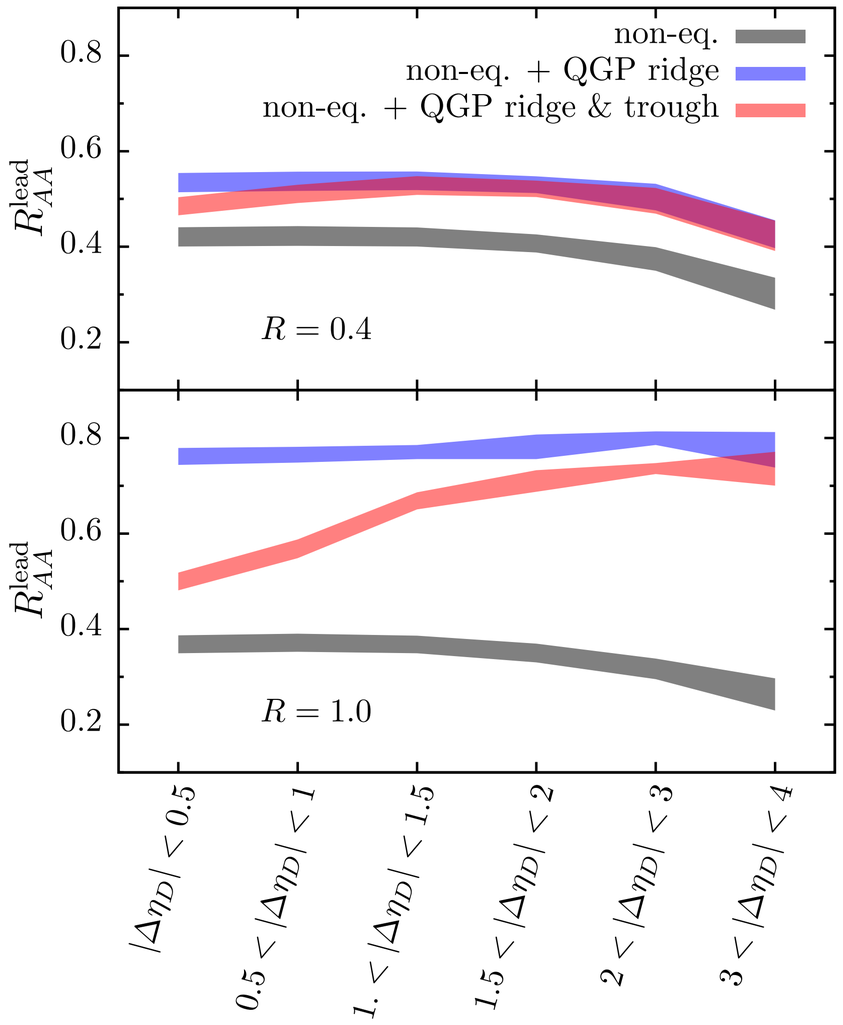
Chen et al. - 2101.05422

Dijets with Rapidity Gap



- Rapidity gap between dijet relatively wide.
- Rapidity extent of the wake relatively narrow.

Diffusion wake of more quenched subleading jet affects leading jet *when aligned in rapidity*.

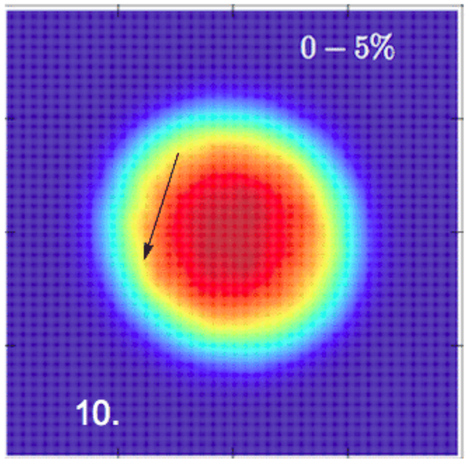


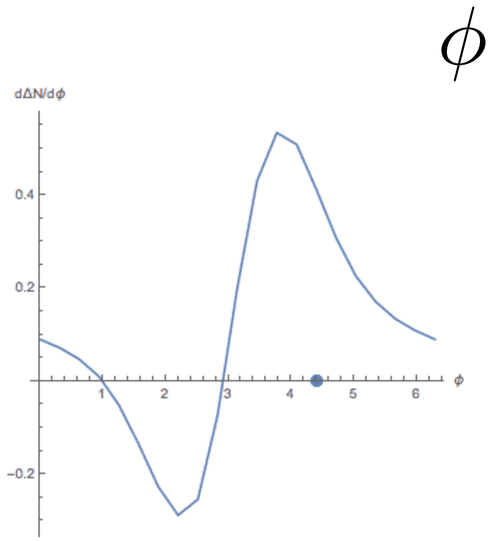
DP - PRL ‘20

Riders on the Flow

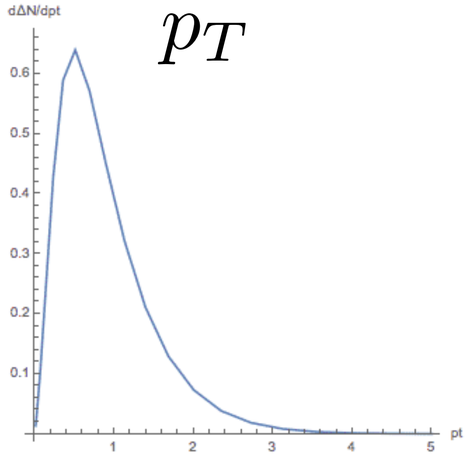
- Final distribution of hadrons from the wake is strongly affected by local QGP properties.

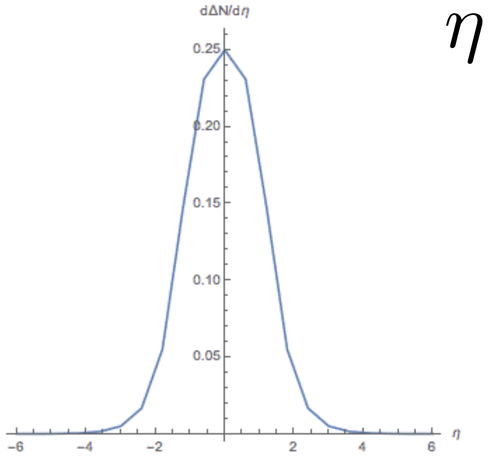
see, e.g., Tachibana et al. - 2001.08321





PRELIMINARY





- In particular:
  - Evolution time until freeze-out
  - Radial flow at freeze-out.

- Need to efficiently include in models:
  - Realistic jet quenching phenomenology.
  - More detailed tomography.

Linearised hydrodynamics + Local boost (very fast) can reproduce expected behaviour from 3+1D hydro.

Casalderrey, Milhano, DP, Rajagopal, Yao - JHEP ‘21 & in preparation

Outlook

- Multi-particle energy loss in jets can be accounted for analytically by resummation:

  Quenched phase space depends on jet p_T, size R and coherence effects.

  Further improvements for calculation of jet suppression:

  → More precise determination of quenched phase space (coherence physics).

  → Detailed dynamics and onset of wave turbulence.

  → Realistic modelling of hydrodynamized energy (specially for large R).

- Deep learning (DL) techniques can give access to energy lost jet-by-jet. Need to:

  → Extend framework to more models.

  → Generalize definition of energy loss ratio to “degree of modification”.

- New precision level in tomography with DL and gradient jet tomography.

- Look for signatures of hydrodynamic medium response to jet passage, such as diffusion wake.

  → To which degree parton cascades on top of a flowing medium can emulate such signatures?

Thanks for your attention!

Looking forward to meeting you in person again!

Backup Slides

Out of Cone Radiation

- Only emissions that end up out of the cone R should be accounted for:

Multiplicative Ansatz:

$$\omega \frac{\mathrm{d}I_>}{\mathrm{d}\omega} = \int_{(\omega R)^2}^{\infty} \mathrm{d}k_\perp^2 \, \omega \frac{\mathrm{d}I}{\mathrm{d}\omega \, \mathrm{d}k_\perp^2} \simeq B\left(\omega R; Q^2_{\mathrm{broad}}\right) \times \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}$$

Mehtar-Tani, DP, Tywoniuk - 2101.01742

$$B\left(\omega R; Q^2_{\mathrm{broad}}\right) = \frac{Q^2_{\mathrm{broad}}}{4\pi} \int_y^\infty \mathrm{d}x \, \boxed{\mathcal{P}(x)} \qquad y = (\omega R)^2 / \boxed{Q^2_{\mathrm{broad}}}$$

Broadening dist.

Characteristic broadening scale

$$\mathcal{P}(\boldsymbol{k}) \simeq \begin{cases} \frac{4\pi}{Q_s^2} \mathrm{e}^{-\boldsymbol{k}^2/Q_s^2} & k_\perp^2 \ll Q^2_{\mathrm{med}} \\ \frac{4\pi Q_s^2}{\boldsymbol{k}^4} & k_\perp^2 \gg Q^2_{\mathrm{med}} \end{cases}$$

$$\frac{\partial}{\partial L} \mathcal{P}(\boldsymbol{k}, L) = C_R \int_{\boldsymbol{q}} \gamma(\boldsymbol{q}) \left[\mathcal{P}(\boldsymbol{k} - \boldsymbol{q}, L) - \mathcal{P}(\boldsymbol{k}, L)\right]$$

- Using Molière expansion around multiple soft scatterings (a.k.a. IOE): Barata et al. - 2009.13667

$$B(y) = -\lambda + \mathrm{e}^{-y} \left\{1 + \lambda \left[1 + y\left(\mathrm{Ei}(y) - \log 4y\right)\right]\right\} \qquad y \equiv (\omega R)^2 / Q_s^2$$

$$\frac{\mathrm{d}I_>}{\mathrm{d}\omega} = B\left(\omega R; Q_s^2/2\right) \frac{\mathrm{d}I^{(0)}}{\mathrm{d}\omega} + B\left(\omega R; \max\left[Q_s^2, 16\omega/(\pi^2 L)\right]\right) \frac{\mathrm{d}I^{(1)}}{\mathrm{d}\omega}$$

Resummed Quenching Factor

- It can be shown through Generating Functional framework that quenching factor resums as:

$$\frac{\partial Q_i(p,\theta)}{\partial \ln\theta} = \int_0^1 \mathrm{d}z\, \frac{\alpha_s(k_\perp)}{2\pi} p_{ji}^{(k)}(z)\Theta_{\mathrm{res}}(z,\theta) \times \left[Q_j(zp,\theta)Q_k((1-z)p,\theta) - Q_i(p,\theta)\right]$$

$$k_\perp = z(1-z)p\theta$$

$p_{ji}^{(k)}(z)$ Unregularised Altarelli-Parisi splitting functions.

$$\Theta_{\mathrm{res}}(p,R) = \Theta(t_{\mathrm{f}} < t_{\mathrm{d}} < L)$$

(Quenched phase space).

Mehtar-Tani, Tywoniuk - PRD '18

- Initial condition at zero angle is bare quenching factor:

$$Q_i(p,0) = Q_{\mathrm{rad},i}^{(0)}(p_T)Q_{\mathrm{el},i}^{(0)}(p_T)$$

(Factorise in Laplace space).

→ Elastic energy loss:

$$Q_{\mathrm{el}}^{(0)}(p_T) = \exp\left[-\hat{e}L\nu\left(1-\left(\frac{R}{R_{\mathrm{rec}}}\right)^2\right)\right]$$

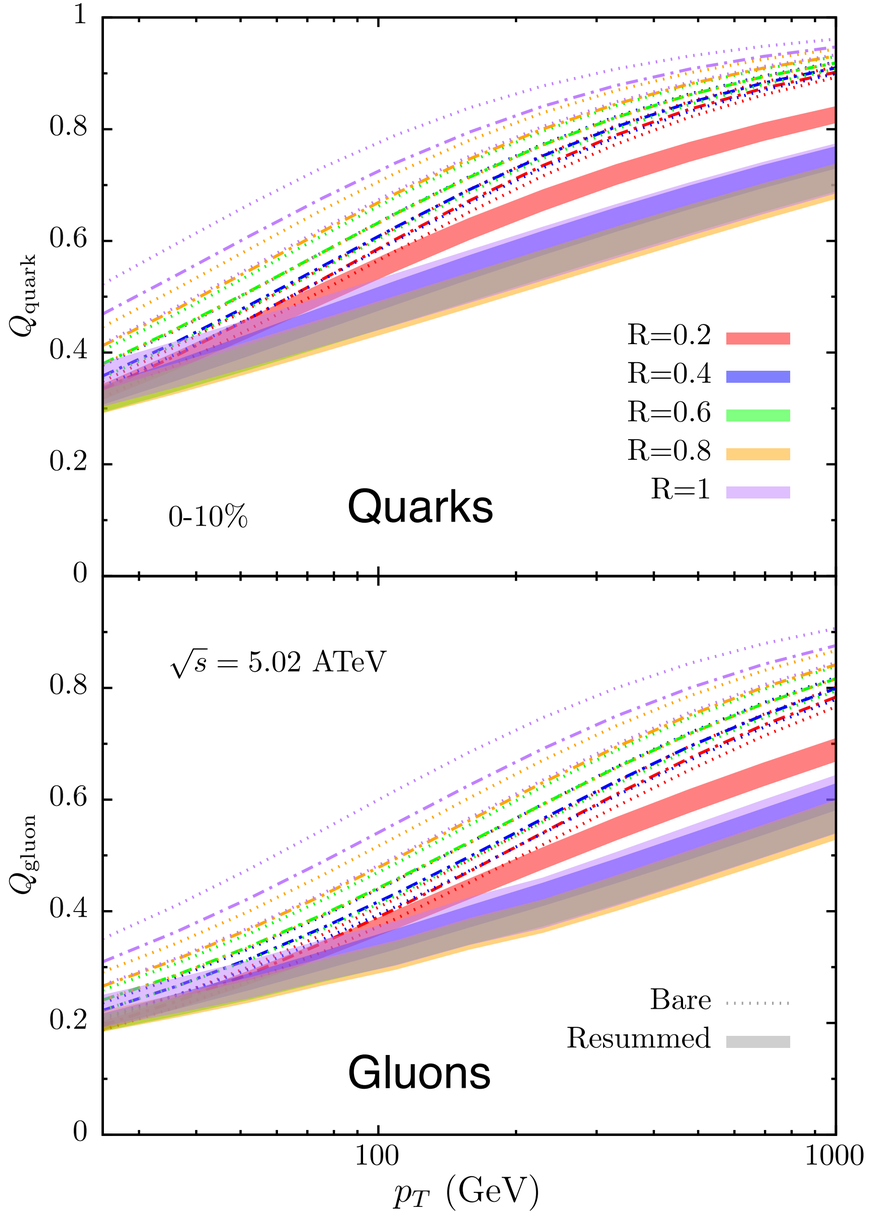
(R dependent recovery of thermalised modes).

$$\hat{e} = \hat{q}/(4T)$$

Fluc.-Diss. relation in weakly coupled plasma.

Mehtar-Tani, DP, Tywoniuk - 2101.01742

Resummed Quenching Factor



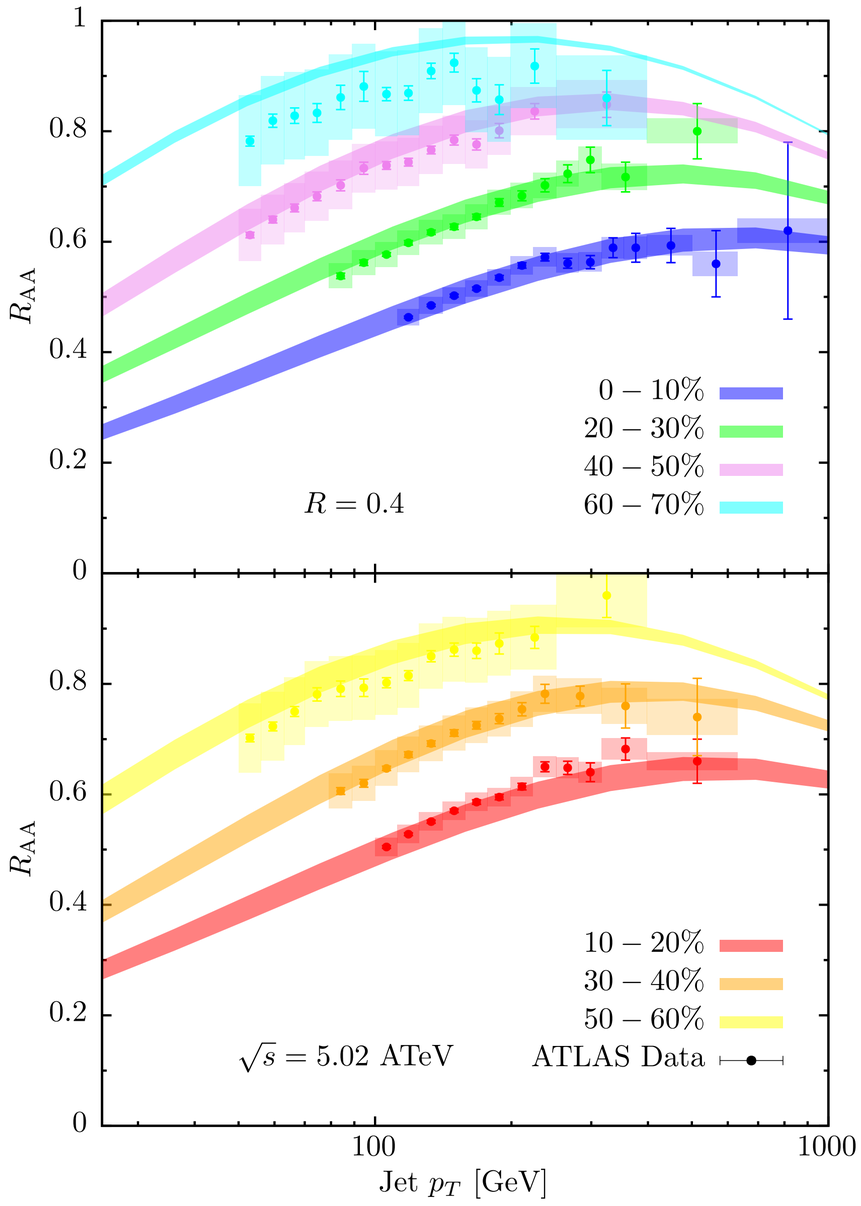
Mehtar-Tani, DP, Tywoniuk - 2101.01742

- Bare quenching factors (dashed):
  - less quenching for larger R.
    - Easier to keep (recover) the emitted (thermalised) modes.
- Resummed quenching factors (solid):
  - larger R can lead to more quenching.
    - Interplay between energy recovery and size of quenched phase space.

see also: DP - PRL '20

Jet Suppression

Mehtar-Tani, DP, Tywoniuk - 2101.01742

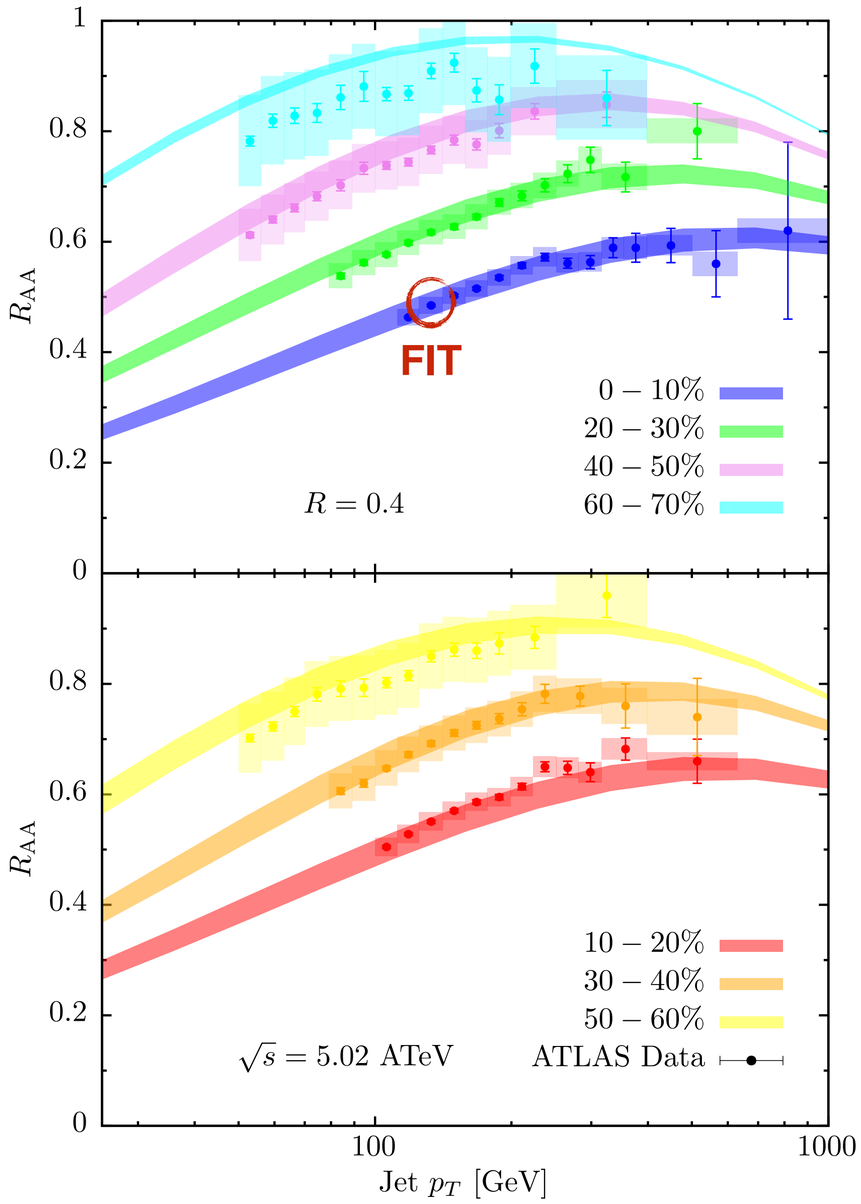


- Use PYTHIA8 to generate spectrum at initial angle R_0=1 (with nuclear PDFs EPS09 LO in medium case)
- Evolve microjets using DGLAP down to jet R.
- Compute resummed quenching factors for each jet p_T and R:
  - → Bare quenching factor requires knowledge of event-by-event, centrality dependent QGP properties:
    - → Embed framework into realistic heavy-ion environment:
      - Glauber sampling, random azimuthal orientation.
      - Compute event-by-event relevant quantities, e.g.: (in local fluid rest frame)

$$L = \int_{\Gamma(t)} dx_F \qquad \hat{q}_0 \propto \frac{1}{L}\int_{\Gamma(t)} dx_F\, T^3(x) \left(\frac{p\cdot u(x)}{p^0}\right)$$

Path of jet through hydro. profile (VISHNU) down to T_c

Jet Suppression



Mehtar-Tani, DP, Tywoniuk - 2101.01742

- Only two unconstrained parameters:

→ $R_{\rm rec}$ varied between $R_{\rm rec} = \pi/2$ (isotropic)
$R_{\rm rec} = (5/6)\,\pi/2$ (wake inspired)

Casalderrey, Milhano, DP, Rajagopal, Yao - 2010.01140

→ $g_{\rm med}$ fit to ATLAS R=0.4 around p_T~120 GeV at 0-10%

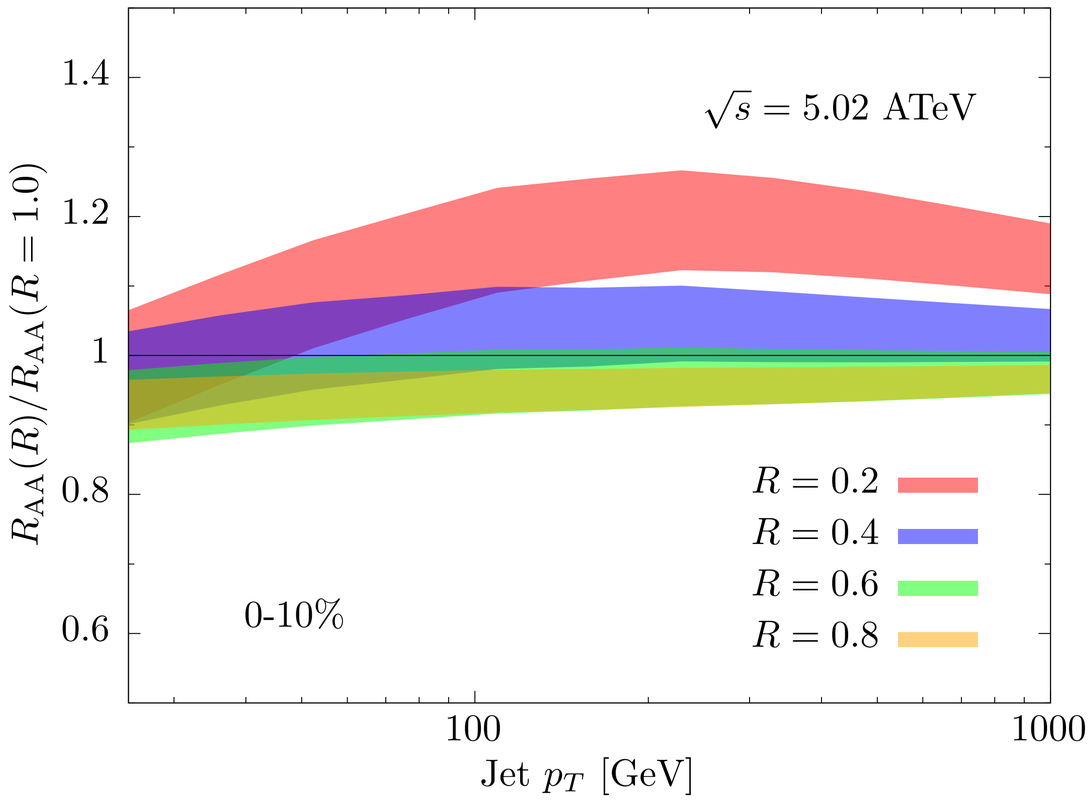
- $g_{\rm med} \in \{2.2,\ 2.3\}$

→ $\langle \hat{q}_0 \rangle \simeq 0.41\ \mathrm{GeV}^2/\mathrm{fm}$ in 0-10%

→ $\hat{q} = 2.46\ \mathrm{GeV}^2/\mathrm{fm}$ $\omega_c \approx 65$ GeV
due to logarithmic corrections.

Good description of both centrality and jet p_T suppression.

R Dependence & Modelling Uncertainties



Mild R dependence,
in agreement with CMS data.

- Modelling sensitivity for **R** between **0.2 and 0.6**:

Parameter	Variation	Effect
θ_c	$[\theta_c/2,\ 2\theta_c]$	$\lesssim 20\%$
IOE	LO/NLO	$\sim 2\%$
n	± 1	$\sim 10\%$
$R_{\rm rec}$	$[1,\ \infty]$	$\lesssim 10\%$
ω_s	$[\omega_s/2,\ 2\omega_s]$	$\lesssim 8\%$

→ NLO contribution very small
(hard emissions tend to be collinear).

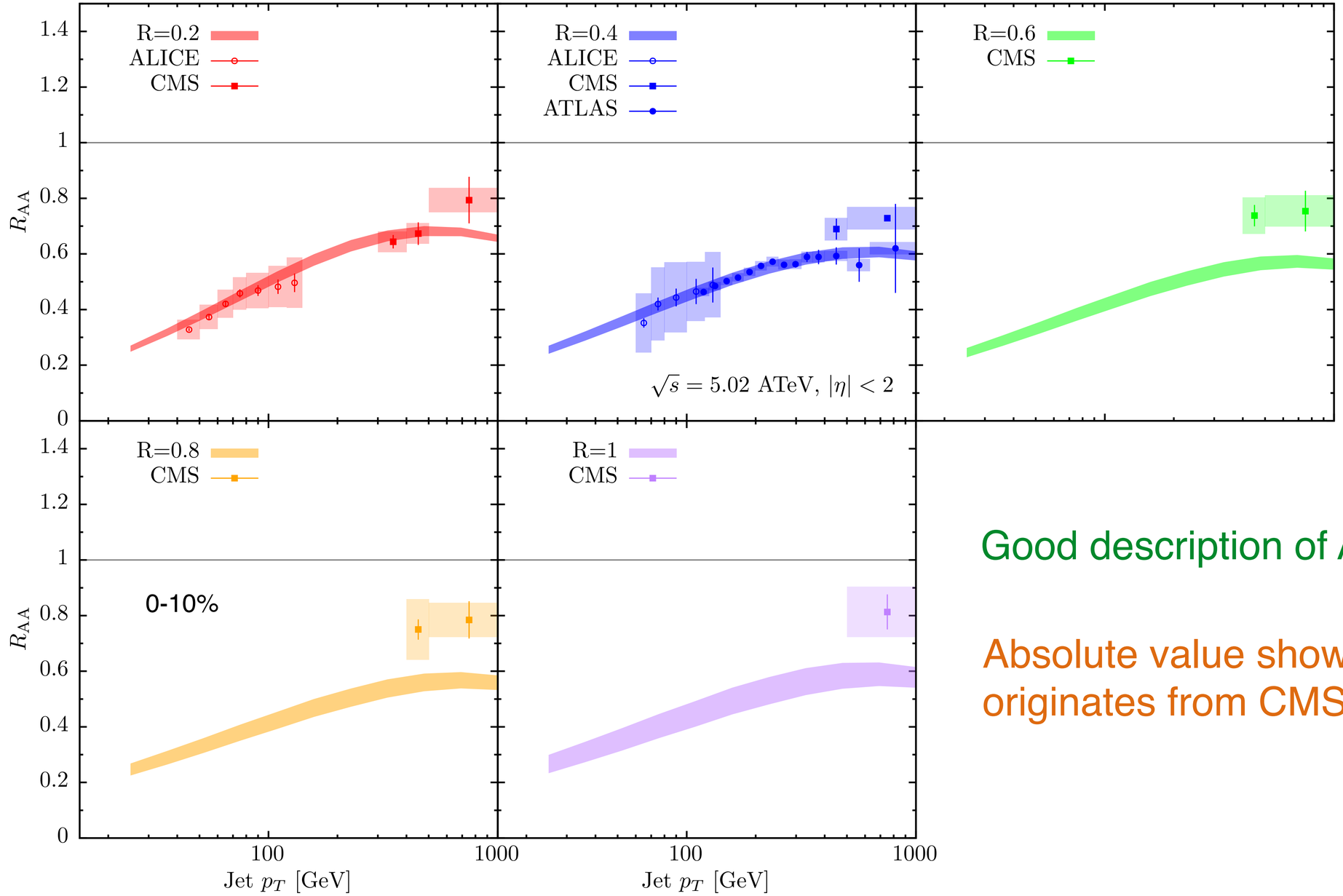
→ Modelling of fate of lost energy relatively small.

→ Determination of quenched phase space relatively large.

Need to improve perturbative sector before non-perturbative becomes relevant (for R<0.6!)

Mehtar-Tani, DP, Tywoniuk - 2101.01742

More Data Comparison



Good description of ALICE at lower p_T.

Absolute value shows some tension with CMS, originates from CMS/ATLAS tension.