Cone-size dependence of jet suppression in heavy-ion collisions

Daniel Pablos - INFN Torino

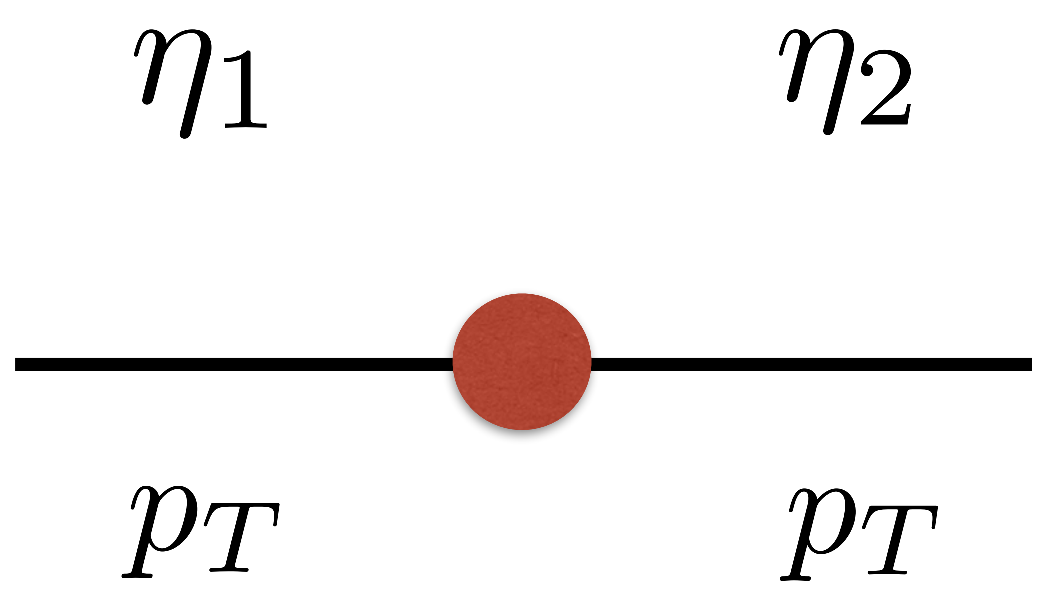
Fellini
Fellowship for Innovation at INFN

INFN
Istituto Nazionale di Fisica Nucleare

ECT* - Jet Quenching in the Quark-Gluon Plasma
15th June 2022

Jets in pp

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



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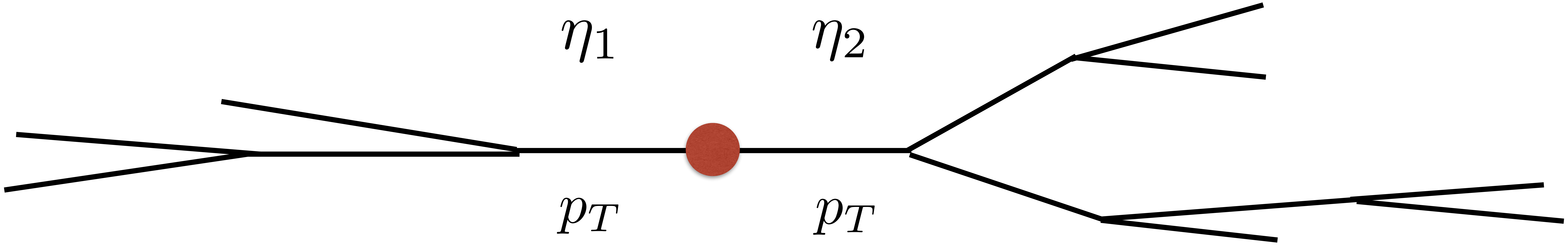
- Parton density evolution described via DGLAP:

$$t\frac{\partial}{\partial t}f(x,t) \quad = \quad \int \frac{dz}{z}\frac{\alpha_s}{2\pi}P_+(z)\,f\left(\frac{x}{z},t\right)$$



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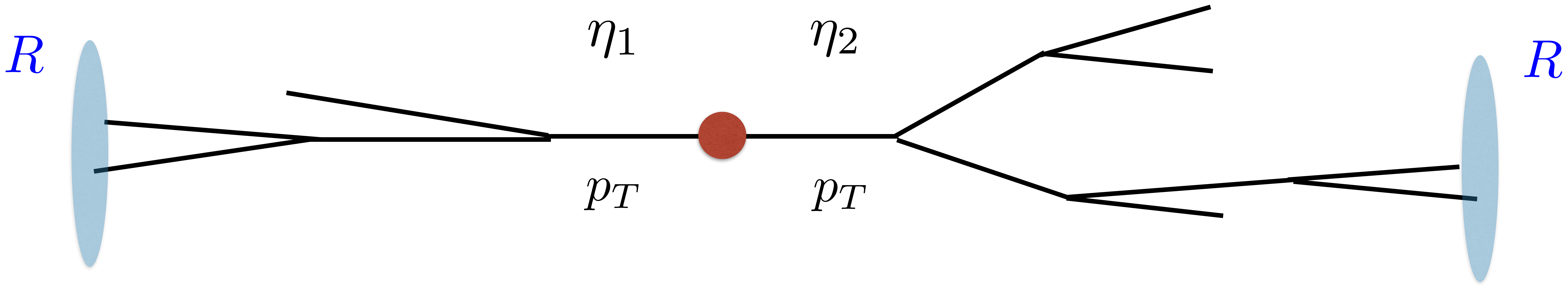

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- Jets are defined with clustering algorithm, reconstruction radius R.

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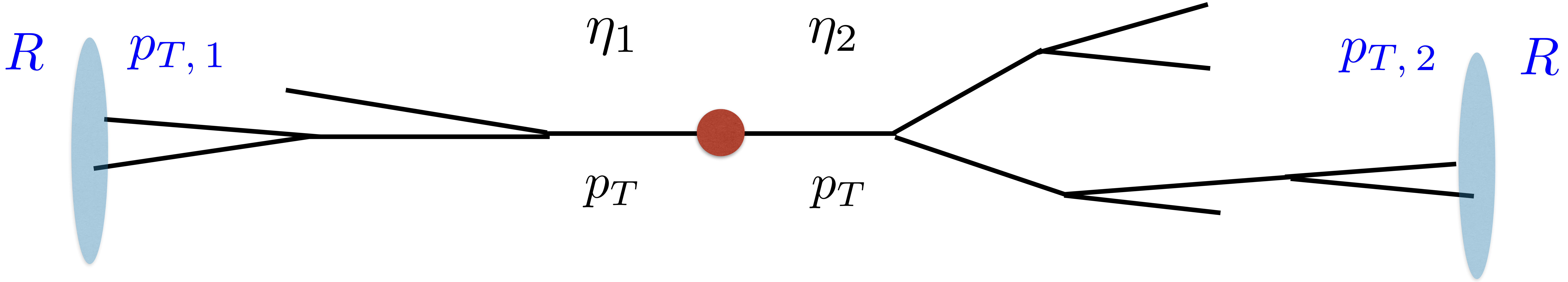


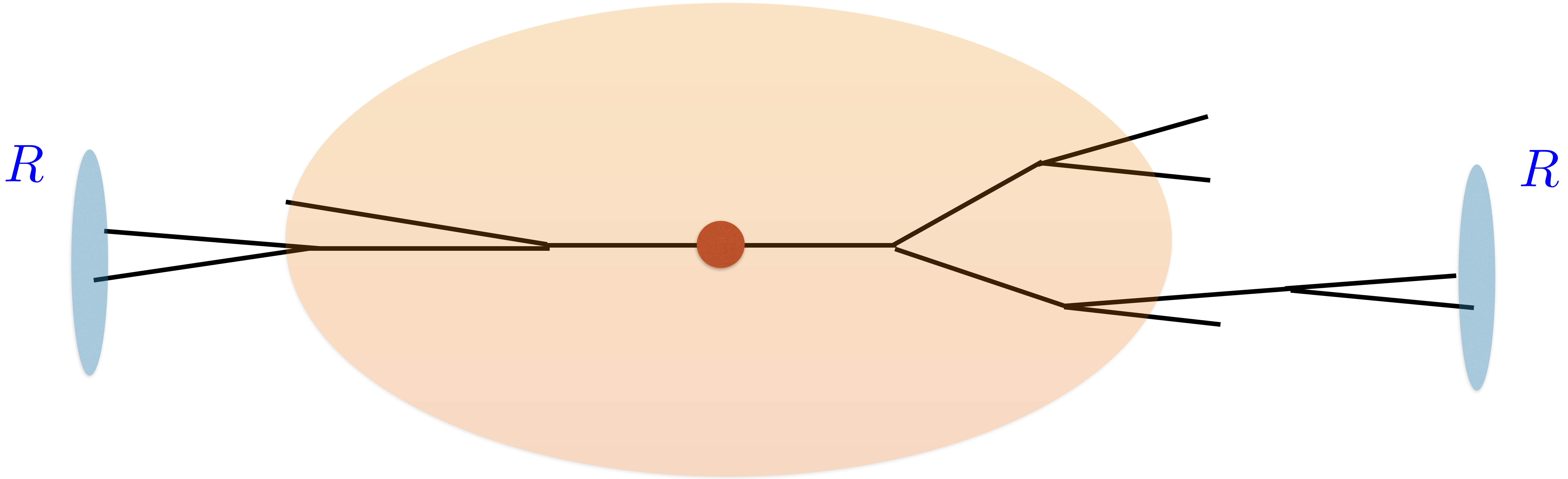
- Collimated structure enforced through collinear divergences & color coherence.
- Jets are defined with clustering algorithm, reconstruction radius R.

➔ 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.

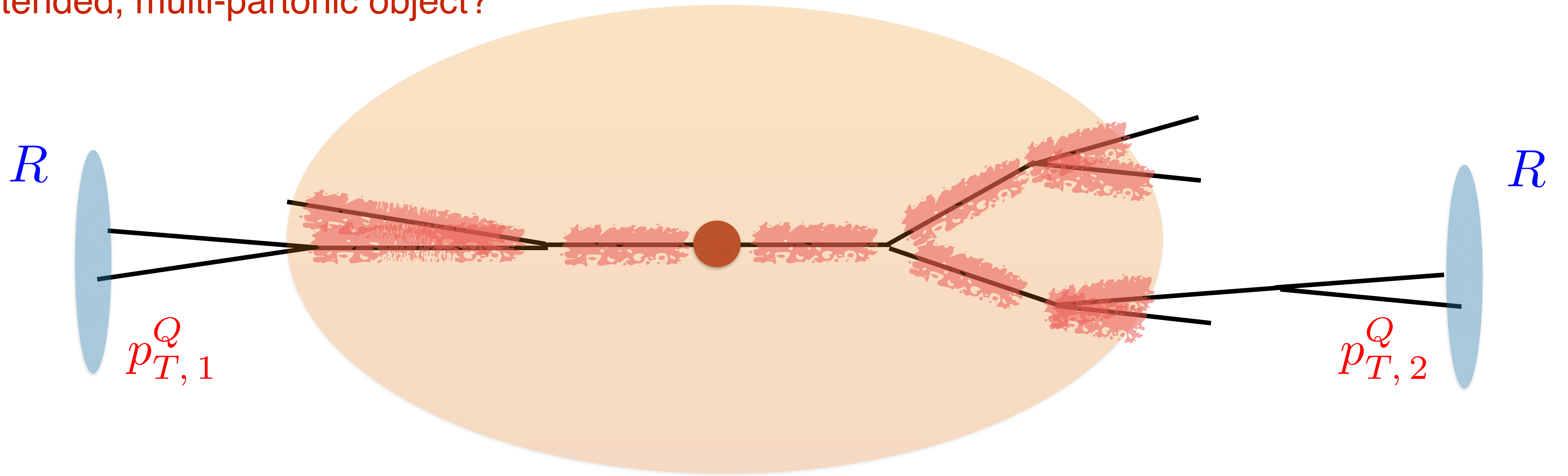


- Lesson example: total energy loss proportional to jet activity (more energy loss sources):
  - ➜ Causes dijet asymmetry in AA (for same traversed length). Milhano & Zapp - EPJ ‘16
  - ➜ Causes selection bias towards narrower jets.

Hadron vs. Jet Suppression
Casalderrey, Hulcher, Milhano, DP, Rajagopal - PRC ‘19

- Jet suppression beyond MC:

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



Outline

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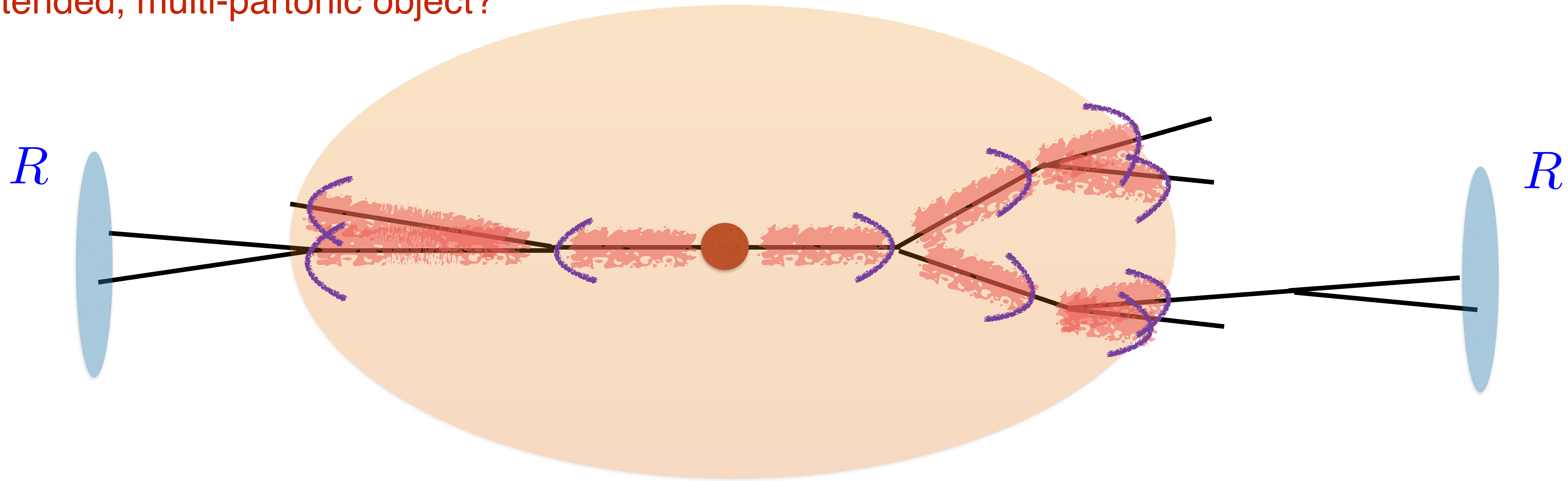


Outline

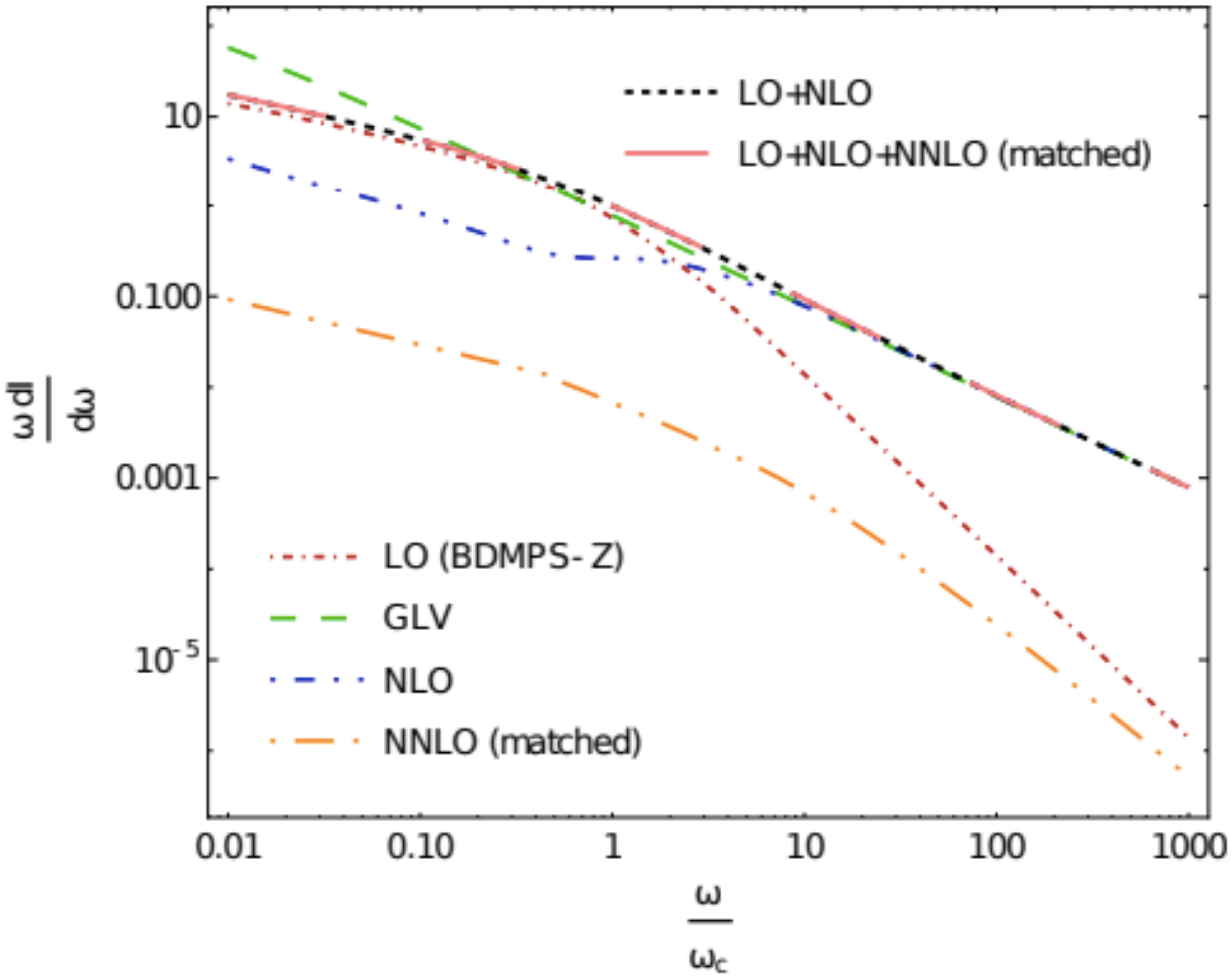
- Non-perturbative modelling of long wavelength jet modes:

  Where does "lost" energy go to?

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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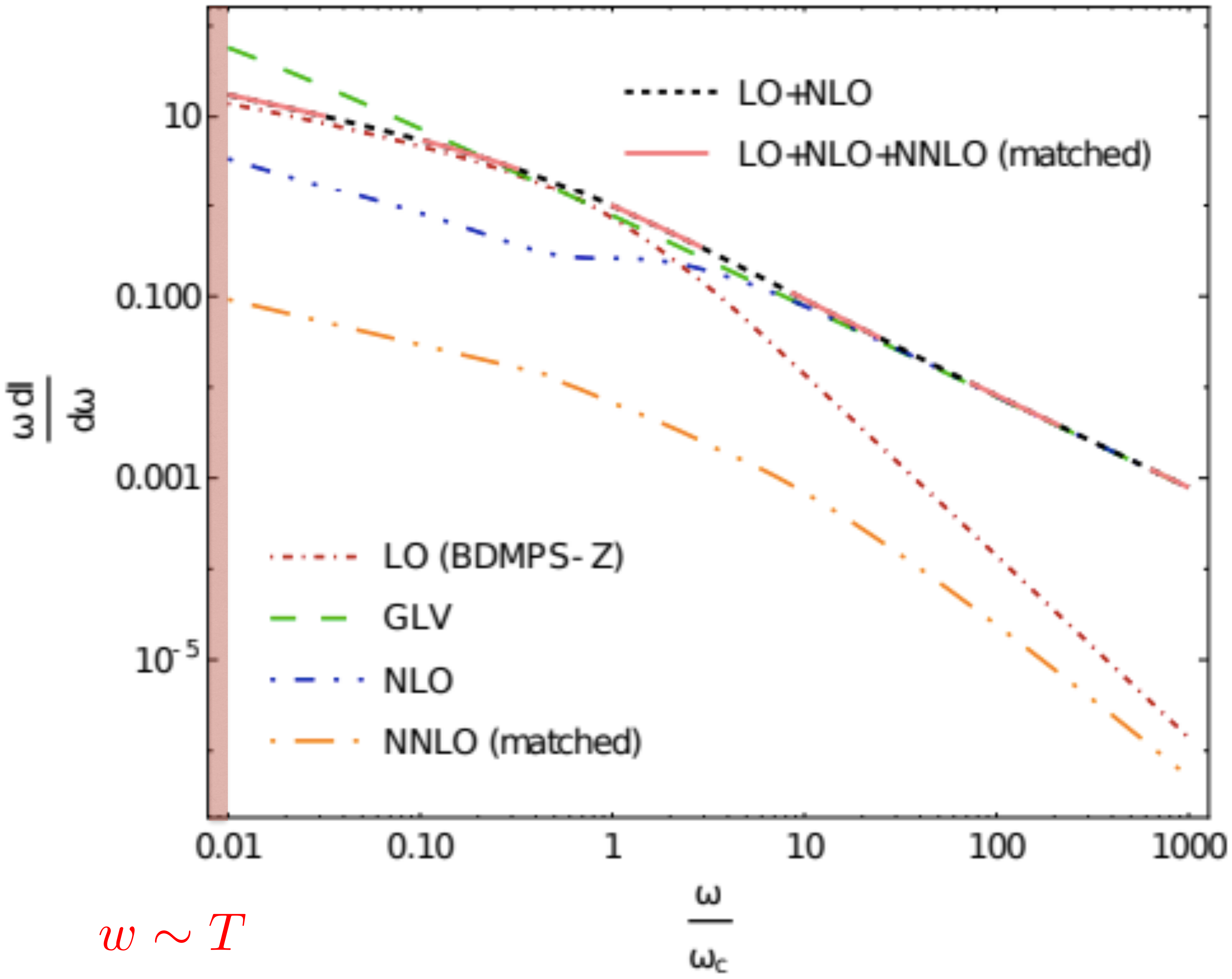

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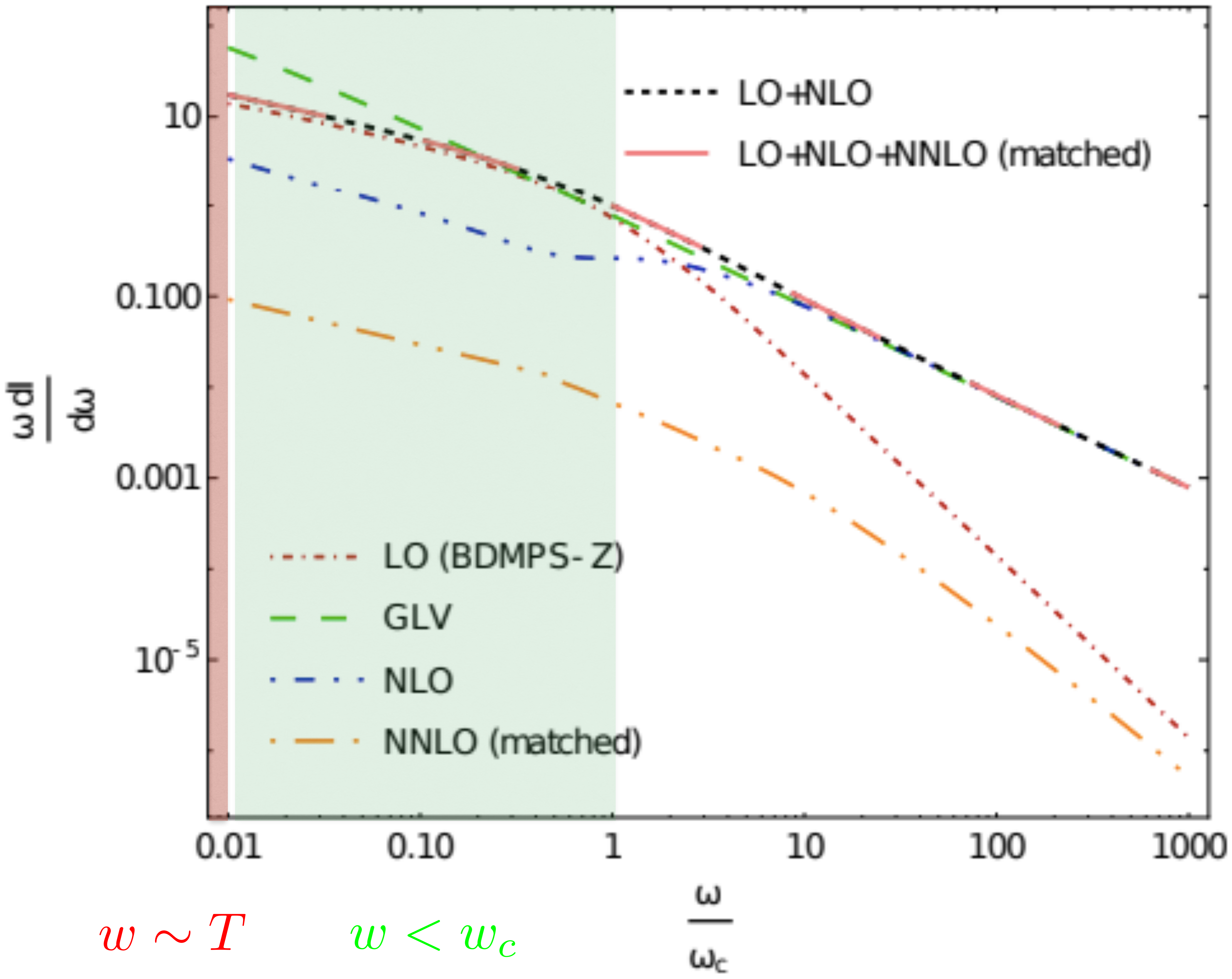

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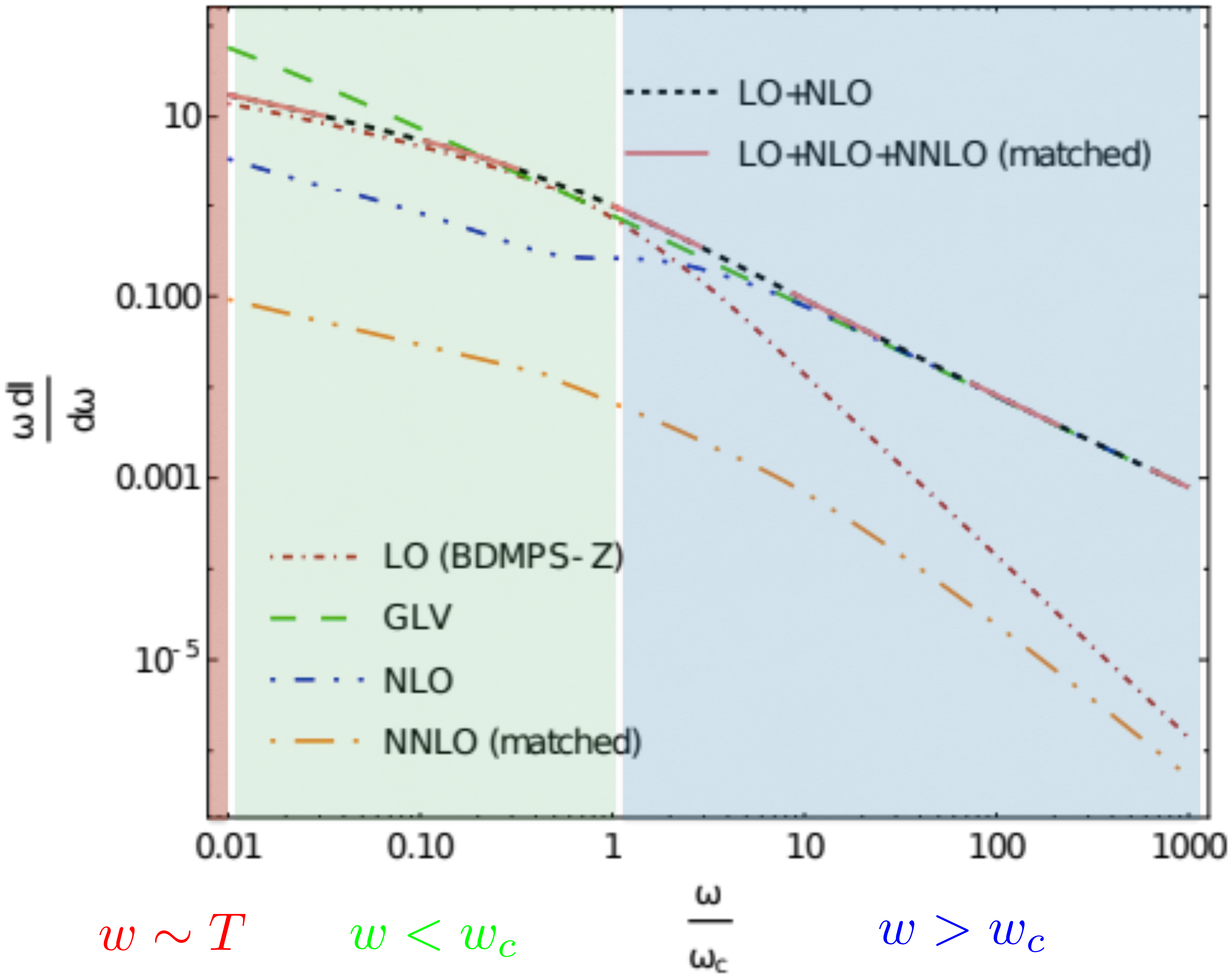

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- GLV regime $k_\perp^2 \gg Q_s^2 \equiv \hat{q} L$

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

Out of Cone Radiation

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

Multiplicative Ansatz:

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

Mehtar-Tani, DP, Tywoniuk - PRL '21

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

Broadening dist.

Characteristic broadening scale

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

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

- Use Molière expansion around multiple soft scatterings (a.k.a. IOE). Barata et al. - PRD '21

- Can be improved with fully differential spectrum. Barata et al. - JHEP '21

Further Improvements on Single Charge Energy Loss

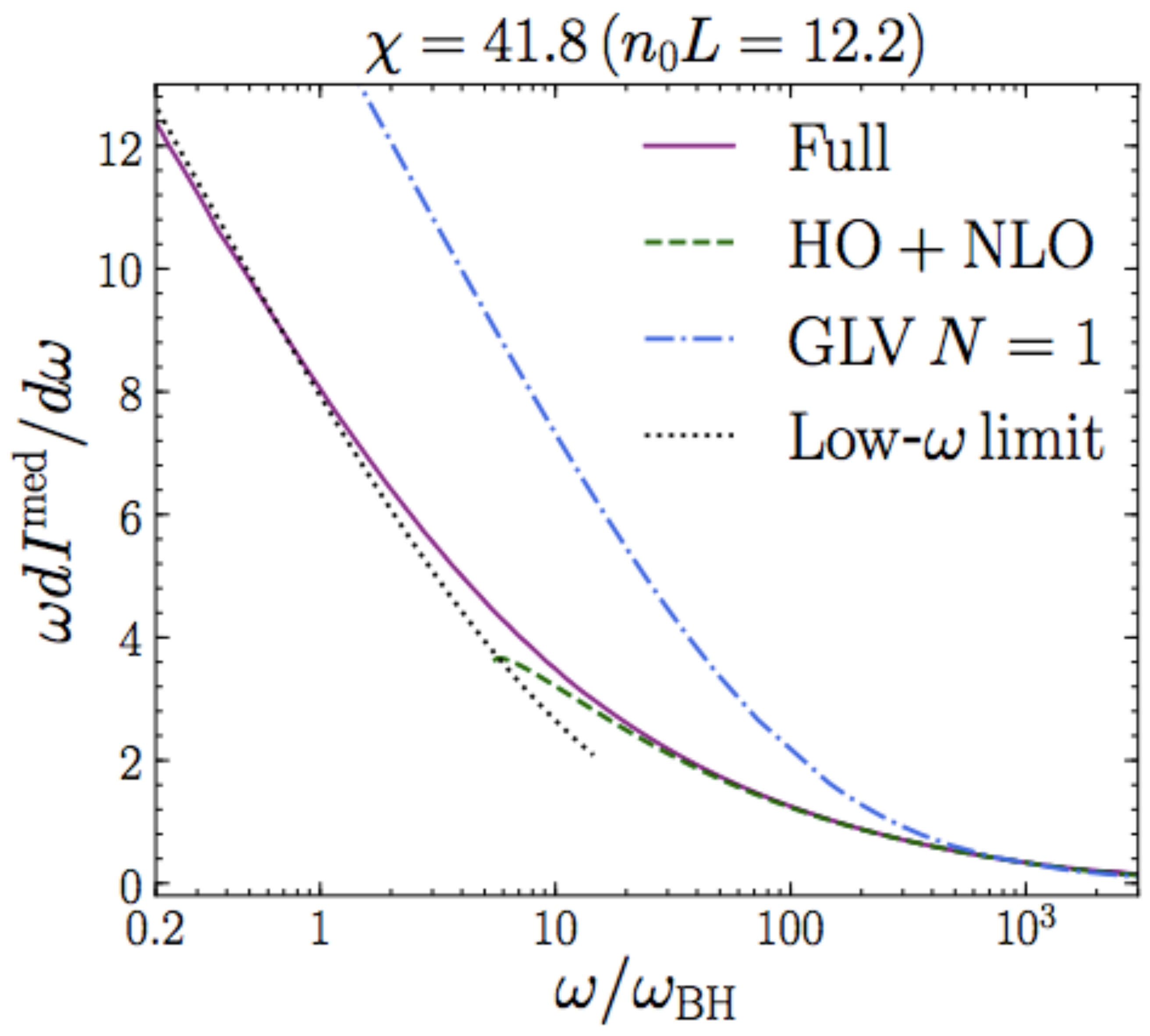
- All order resummation of medium induced radiation spectrum.

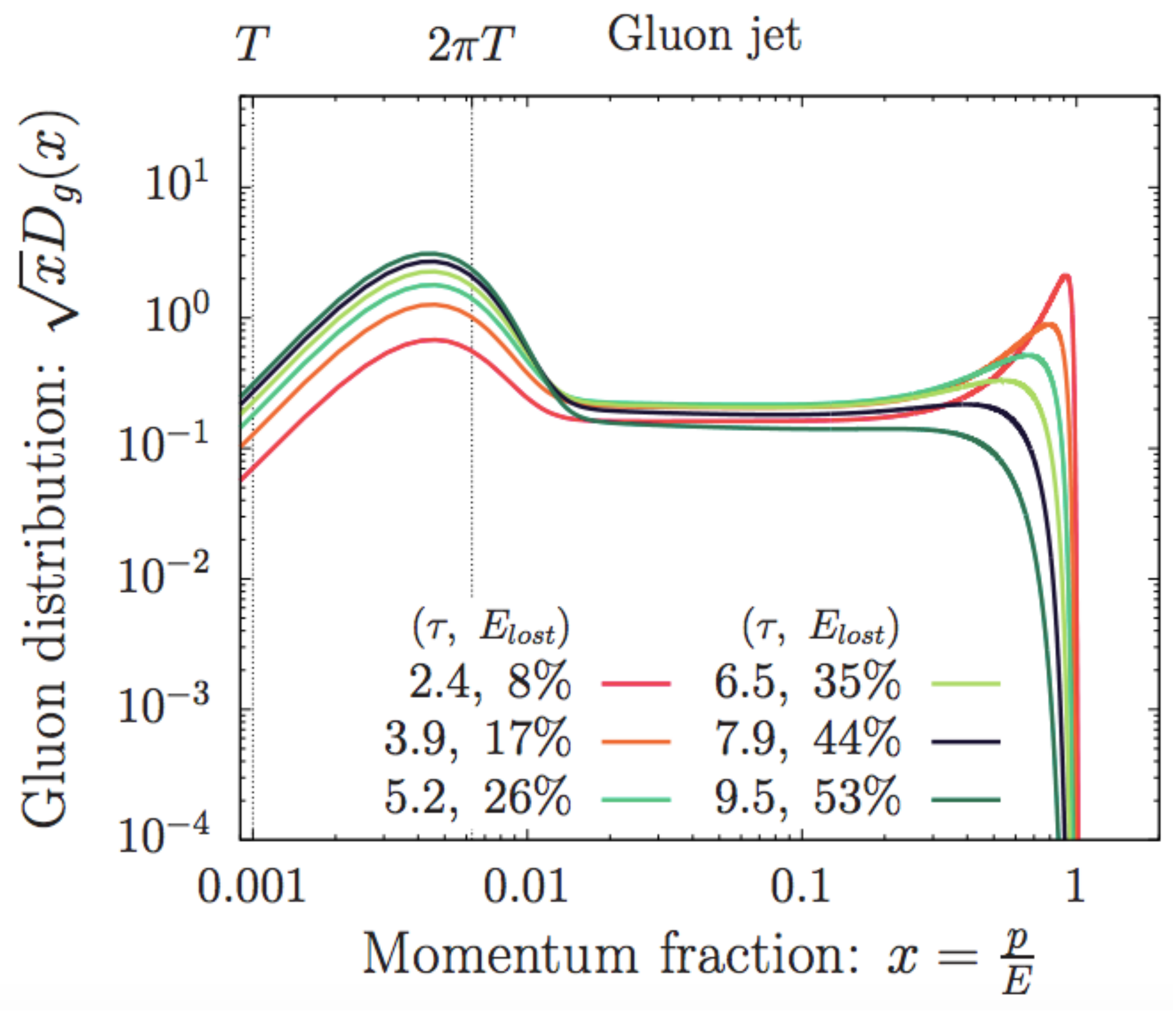
Feal et al. - PRD ‘18 & ‘19

Andrés et al. - JHEP ‘20 & ‘21

- Resummed Opacity Expansion (ROE) to cover Bethe-Heitler regime.

Isaksen et al. - arXiv:2206.02811





Schlichting & Soudi - JHEP ‘20

- In-medium fragmentation of hard parton in QGP through effective kinetic theory.
  - Includes $1\leftrightarrow 2$ and $2\leftrightarrow 2$ processes.
  - Features turbulent cascade, modified chemistry around the jet.

Detailed analysis of dynamics, can account for medium response.

Bare Quenching Factor

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

- For steeply falling spectrum and small energy loss:

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

Mehtar-Tani, DP, Tywoniuk - PRL '21

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

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

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

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

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

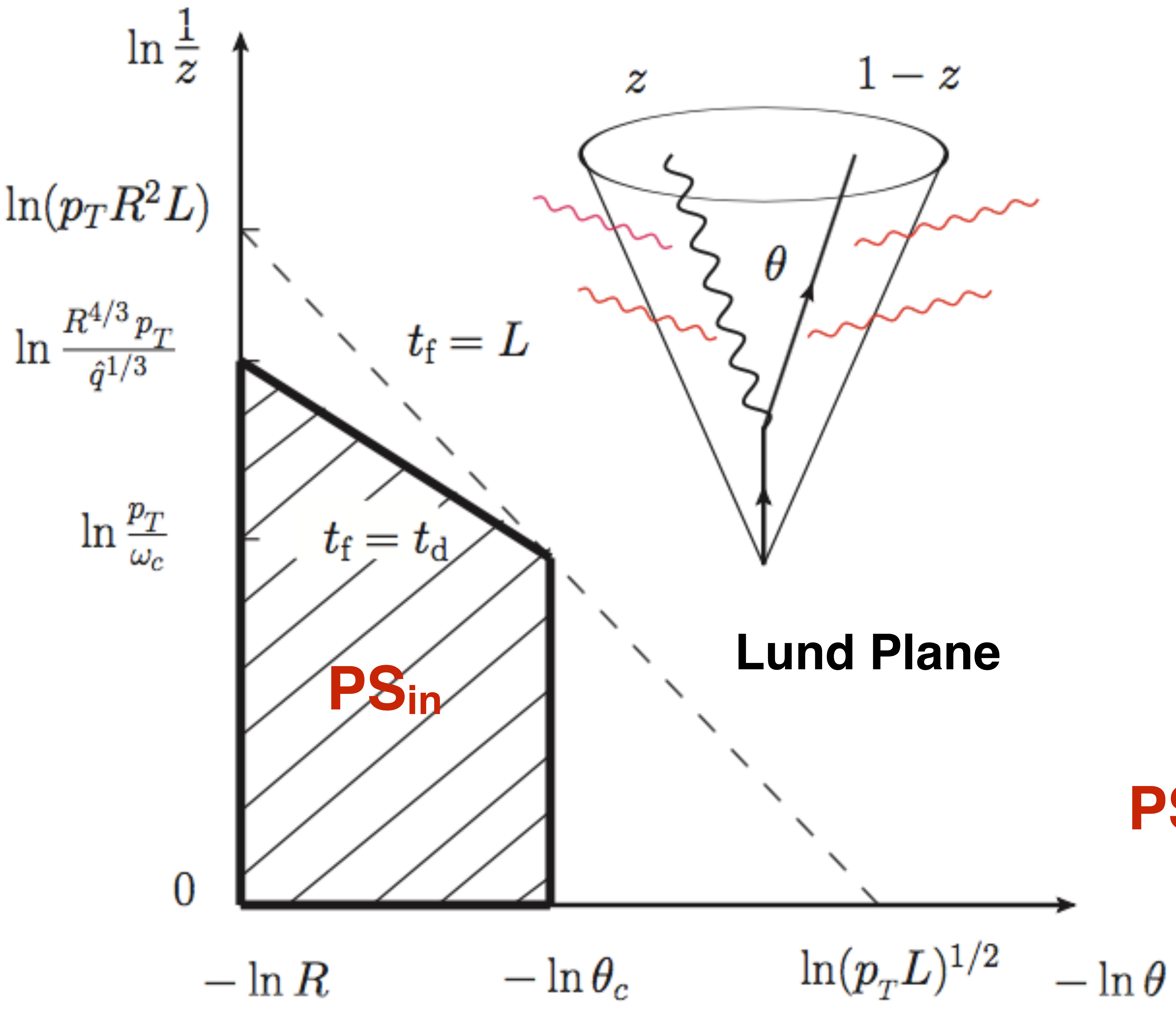
- O(1) emission probability
- undergo turbulent cascade, thermalise
- if uniformly distributed in jet hemisphere

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

Note that:

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

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:

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

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:

Dasgupta et al. - JHEP '14

Vacuum evol. obeys DGLAP:

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

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

PS_{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:

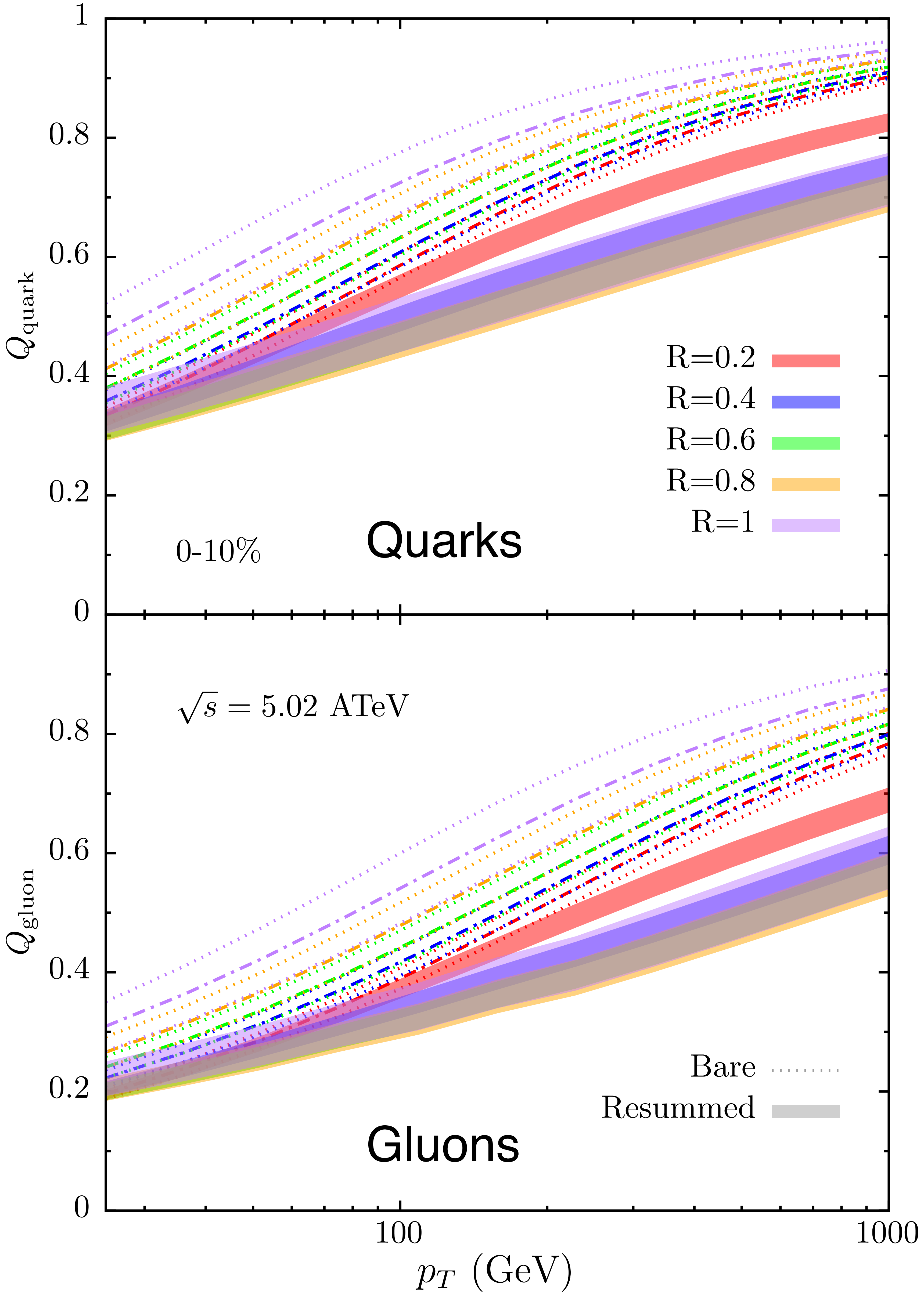
$$Q_i(p,0) = Q^{(0)}_{{\rm rad},i}(p_T)\, Q^{(0)}_{{\rm el},i}(p_T)$$

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 - PRL '21

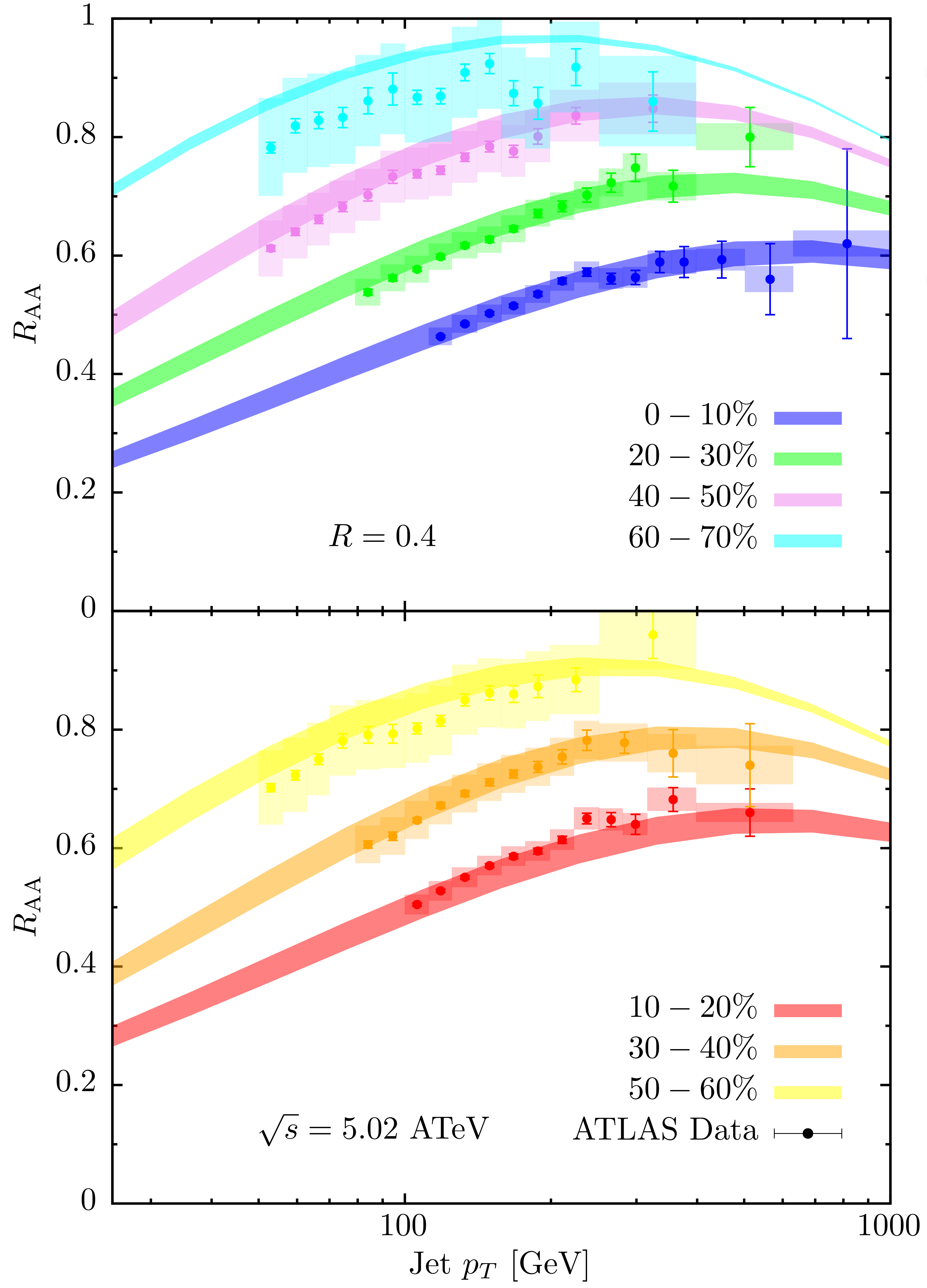
Resummed Quenching Factor



- 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.

Mehtar-Tani, DP, Tywoniuk - PRL '21

Jet Suppression



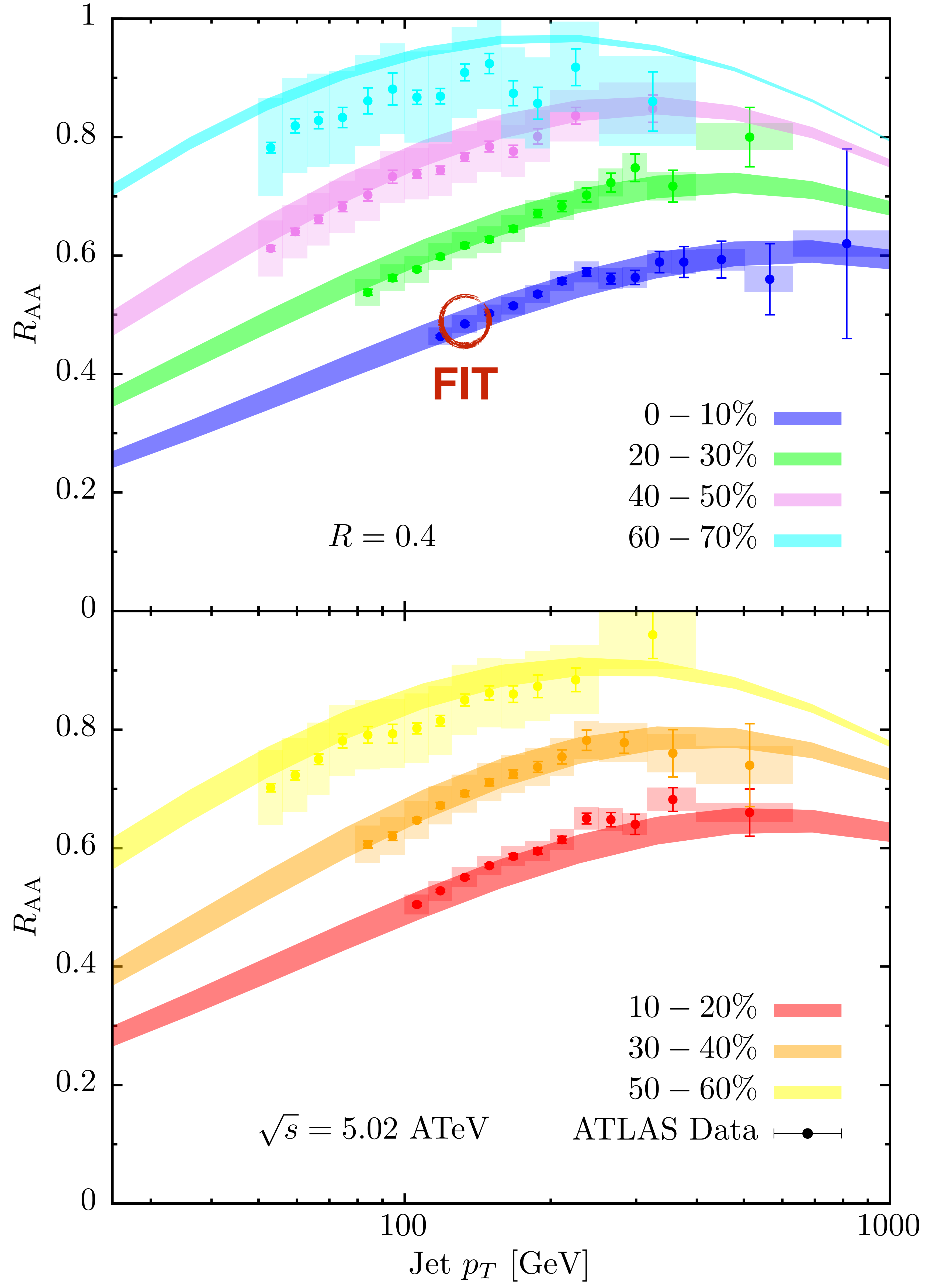
Mehtar-Tani, DP, Tywoniuk - PRL '21

- 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 - PRL '21

- 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 - JHEP '21

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

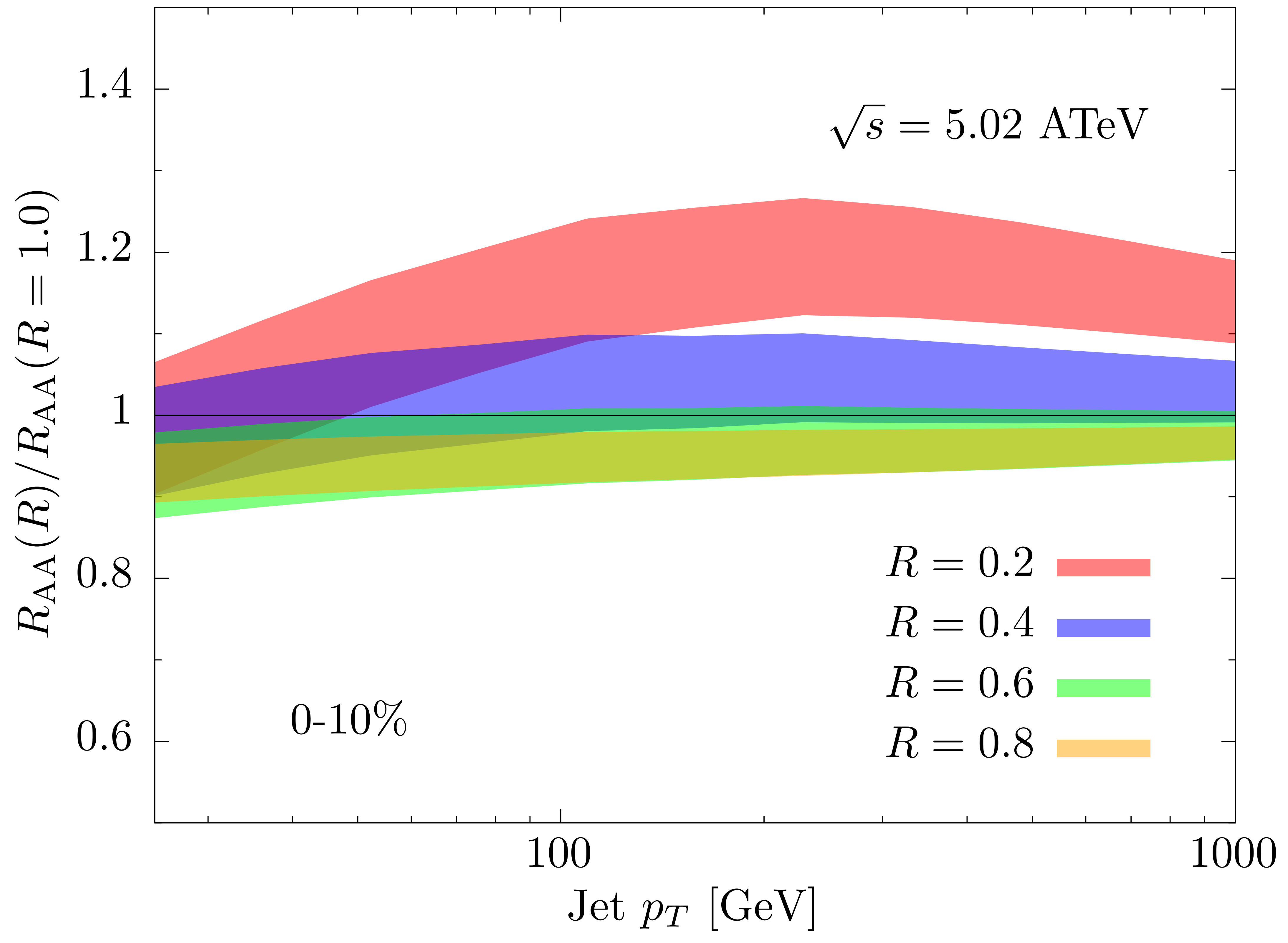
- $g_{\rm med} \in \{2.2,\ 2.3\}$

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

➔ $\hat{q} = 2.46\ {\rm GeV}^2/{\rm fm}$ $\omega_c \approx 65$ 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).

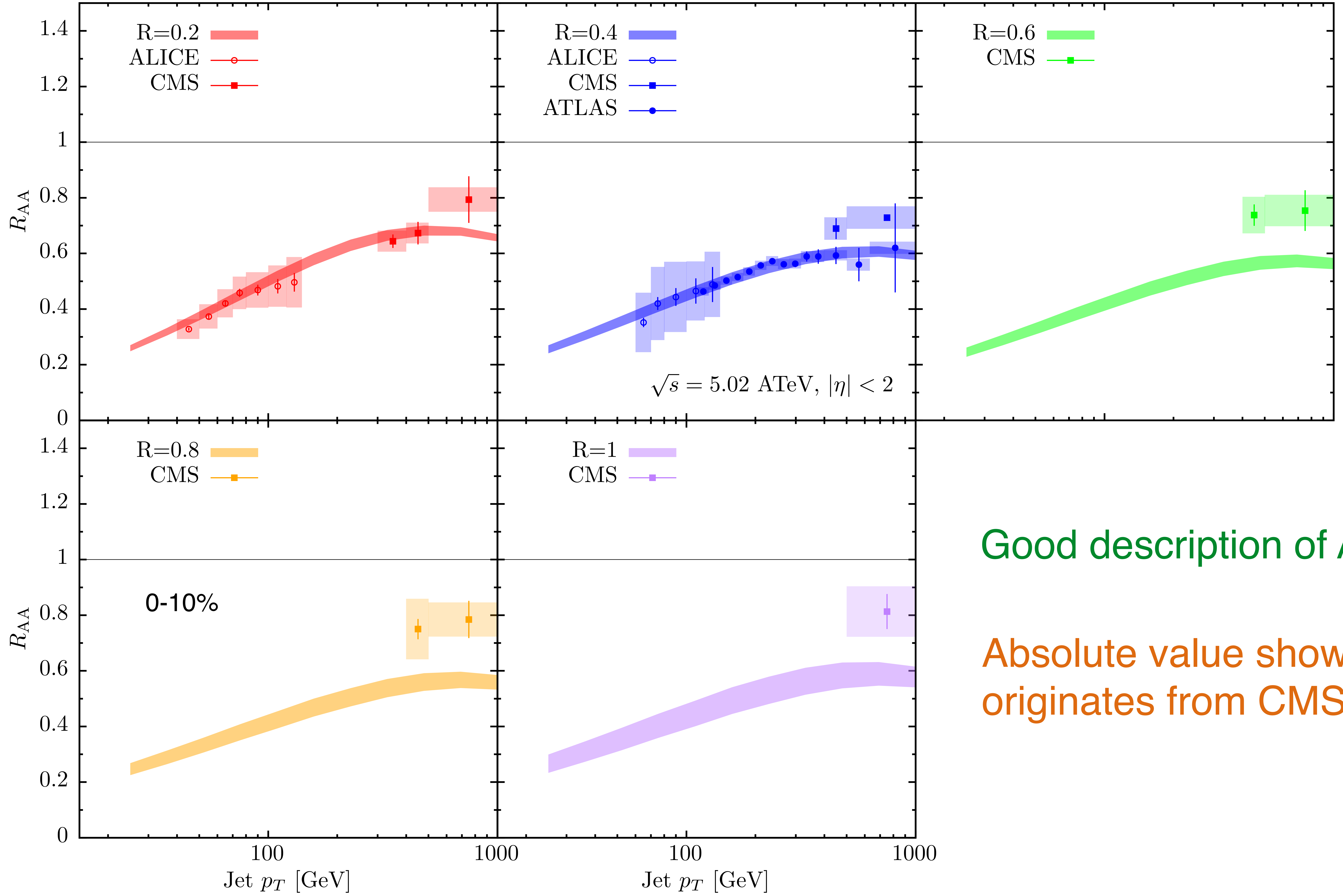
→ Modelling of fate of lost energy relatively small.

→ Determination of quenched phase space relatively large. Improvable in pQCD.

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

Mehtar-Tani, DP, Tywoniuk - PRL ‘21

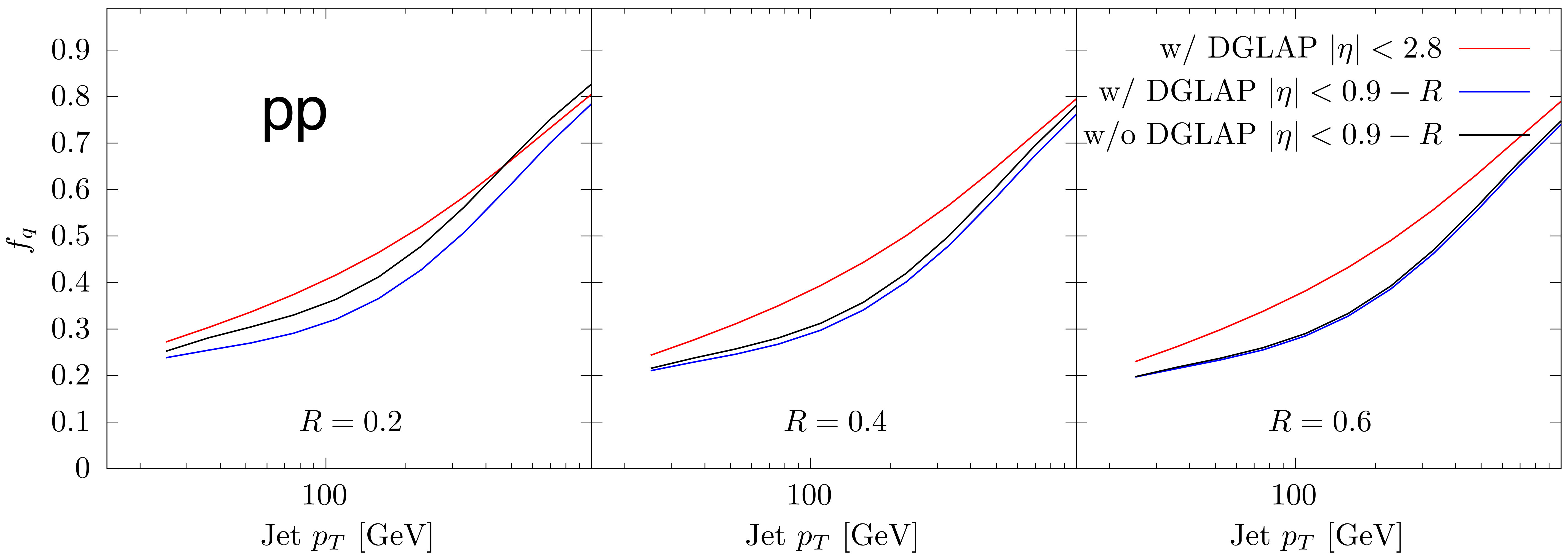
More Data Comparison

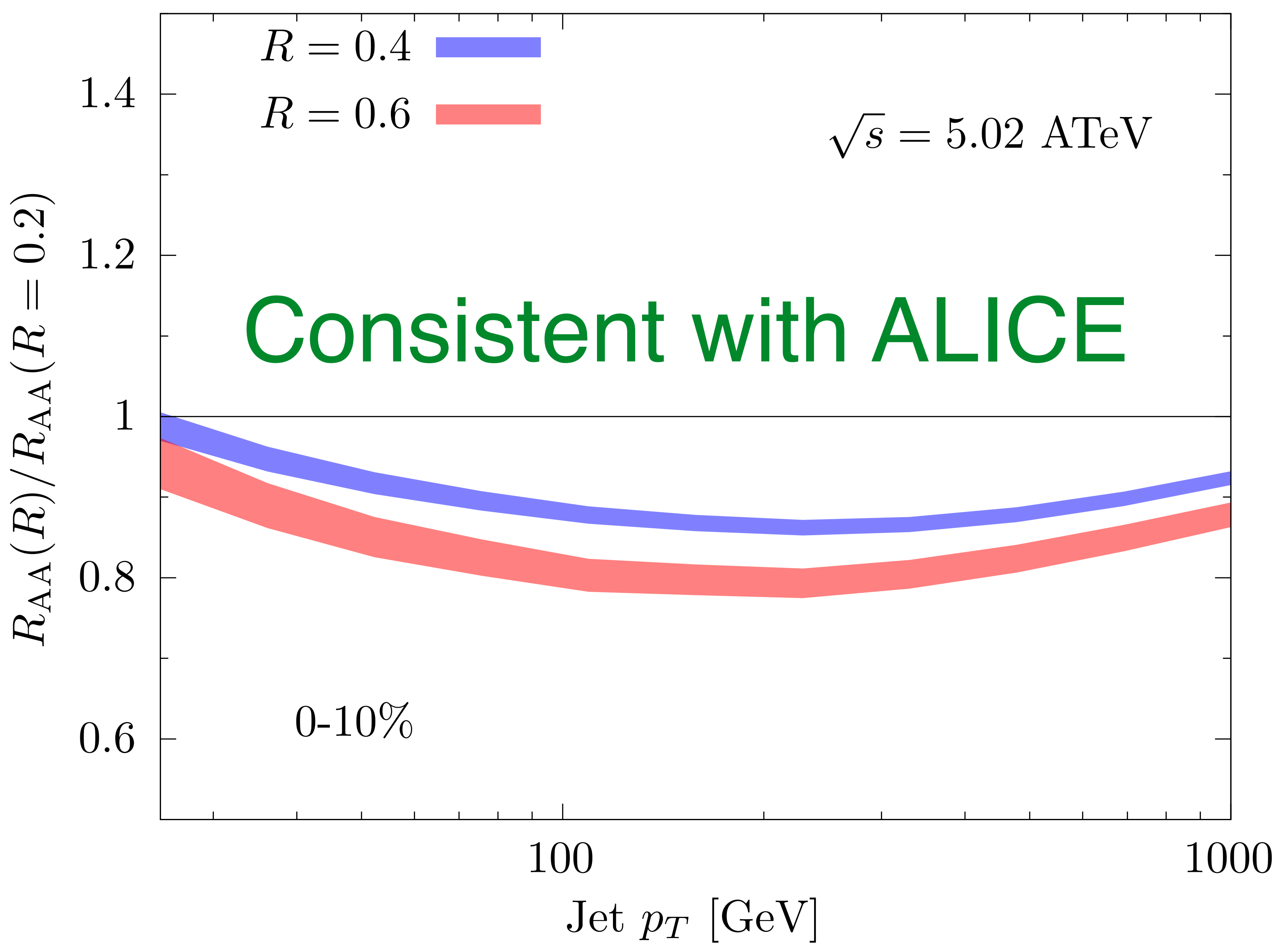


Good description of ALICE at lower p_T.

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

Accounting for rapidity cuts





w/ DGLAP: fit pp spectrum at R_0=1, evolve down to R.

w/o DGLAP: fit pp spectrum directly at η = 0.9 - R.

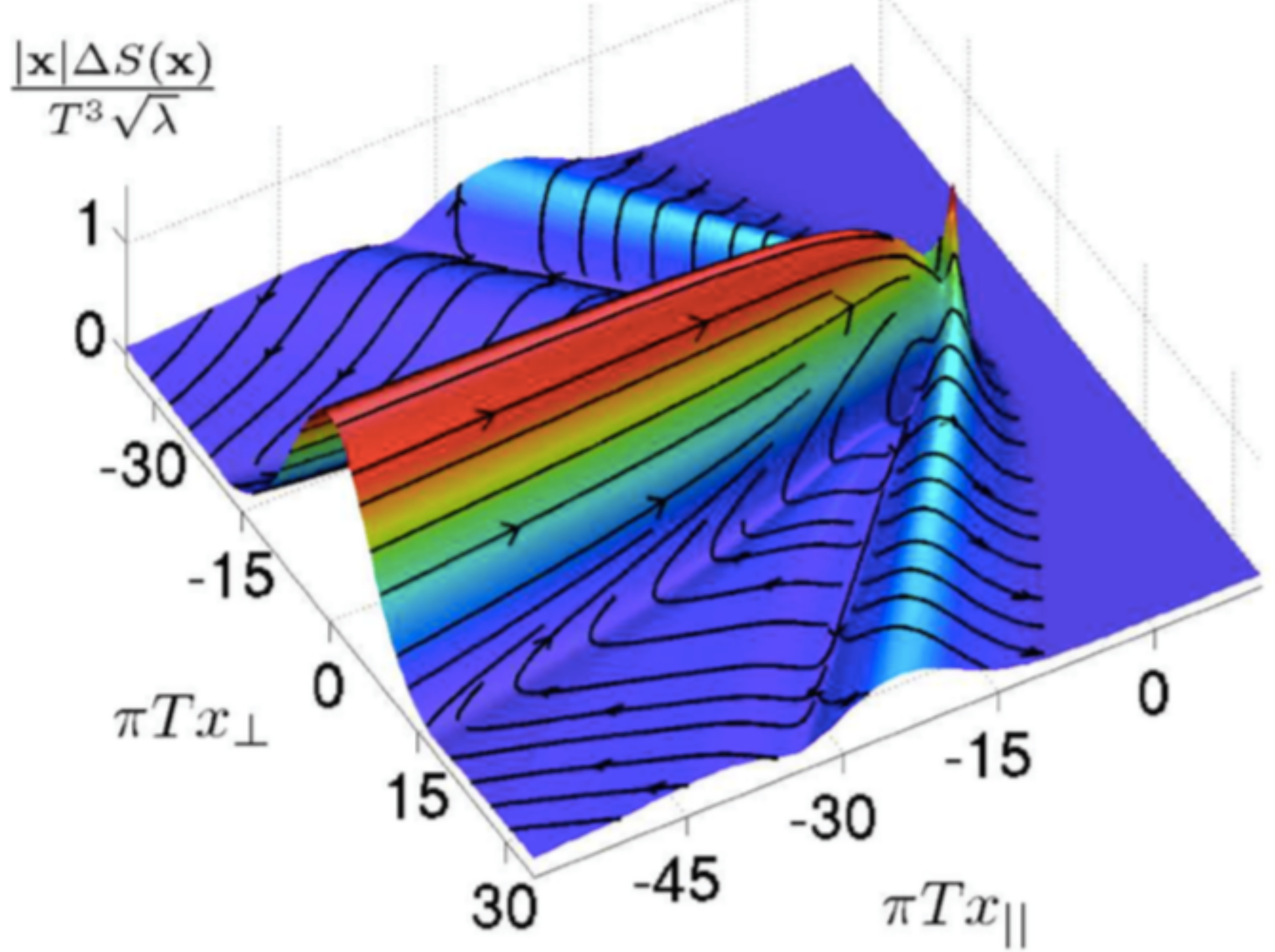
- Quark fraction depends on:
  - Rapidity, via PDF.
  - Cone R, via microjet evolution.

- Redoing calculation with ALICE rapidity cuts makes no difference.
  - Quark fraction change small in ratio.
  - Effect of spectral index change negligible.

The Wake of a Quark

- At strong coupling:
  - Modification of stress-energy tensor due to supersonic quark contains sound and diffusive modes.
  - Effective source for hydro corresponds to drag force on the quark.
  - Agreement between hydrodynamics & wake of a quark even for small distances ~ 1/T.

Energy flux



Fulfils Energy-Momentum Conservation in the Jet+Plasma Interplay.

Chesler & Yaffe - PRD '07

Estimation of the Hadrons from the Wake

- Assuming:
  - small perturbations on top of Bjorken flow.
  - perturbation stays localised near jet's rapidity.

Expand Cooper-Frye spectrum to first order in perturbations:

$$E\frac{d\Delta N}{d^3p} = \frac{1}{32\pi}\frac{m_T}{T^5}\cosh(y-y_j)\exp\left[-\frac{m_T}{T}\cosh(y-y_j)\right]$$

$$\left\{p_T\Delta P_T\cos(\phi-\phi_j)+\frac{1}{3}m_T\,\Delta M_T\,\cosh(y-y_j)\right\}$$

$$\Delta P^i_\perp = w\,\tau\int d^2x_\perp\,d\eta\,\delta u^i_\perp \qquad \Delta S = \frac{s\,\tau}{c_s^2}\int d\eta\,d^2x_\perp\,\frac{\delta T}{T}$$

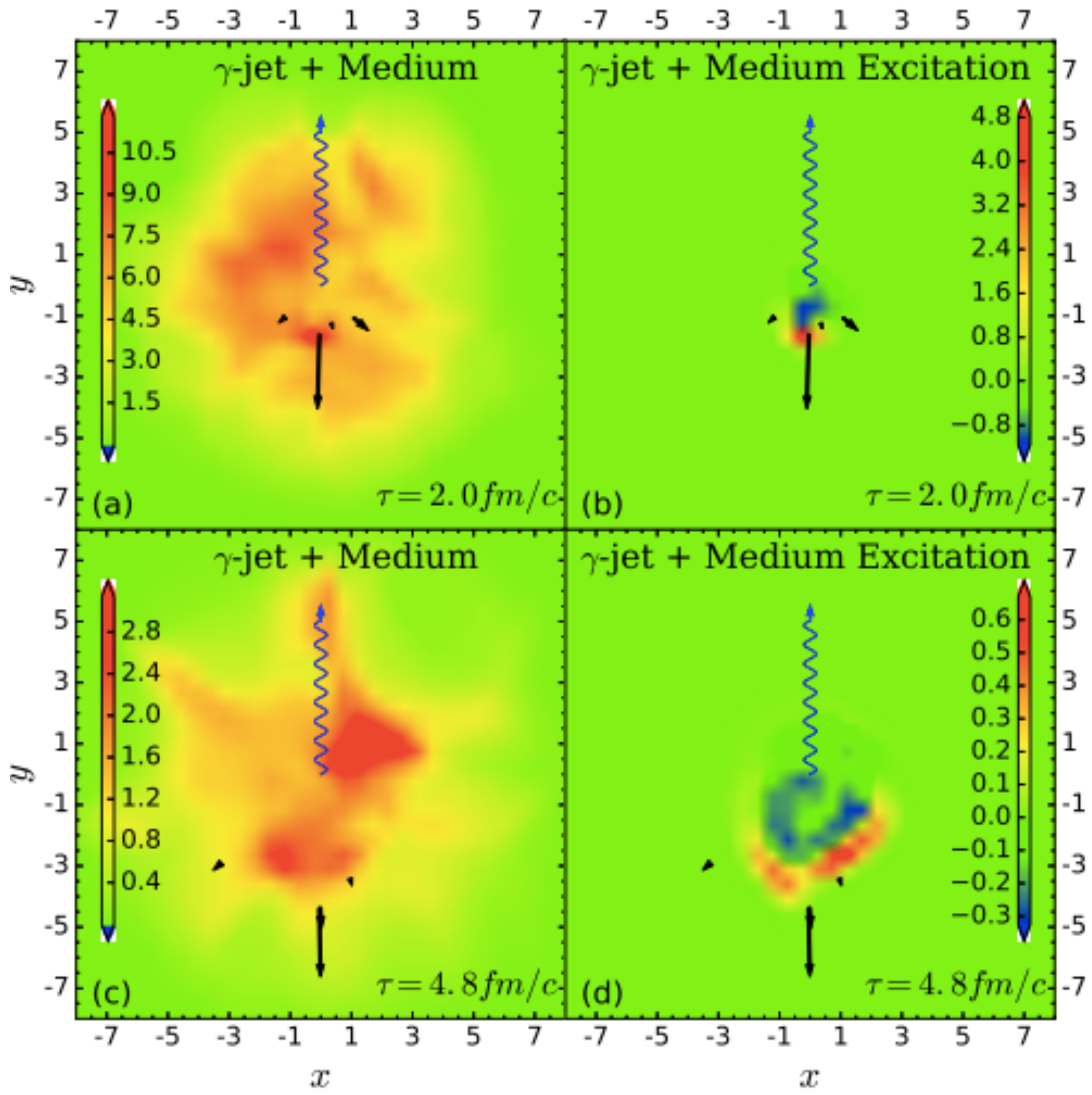
Velocity pert. Temperature pert.

✓ Fully constrained by energy-momentum conservation.

✓ Computationally efficient.

✗ Neglects important effects from local flow.

The Diffusion Wake

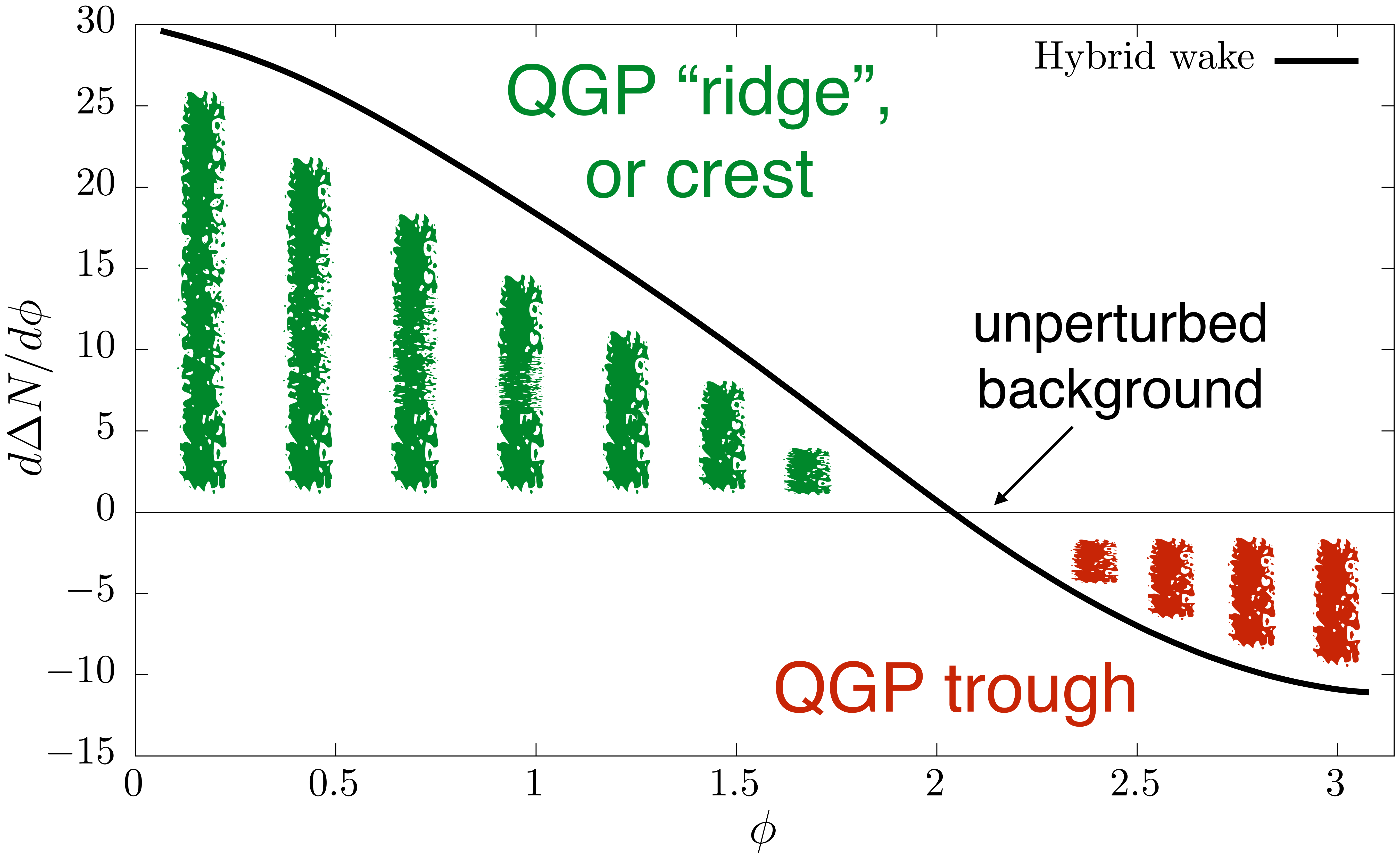


Chen et al. - PLB ‘18

Effect observed also in non-linear hydro. + source from jet.

QGP trough arises due to 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).



Jet R_{AA} at LHC with Hybrid Model

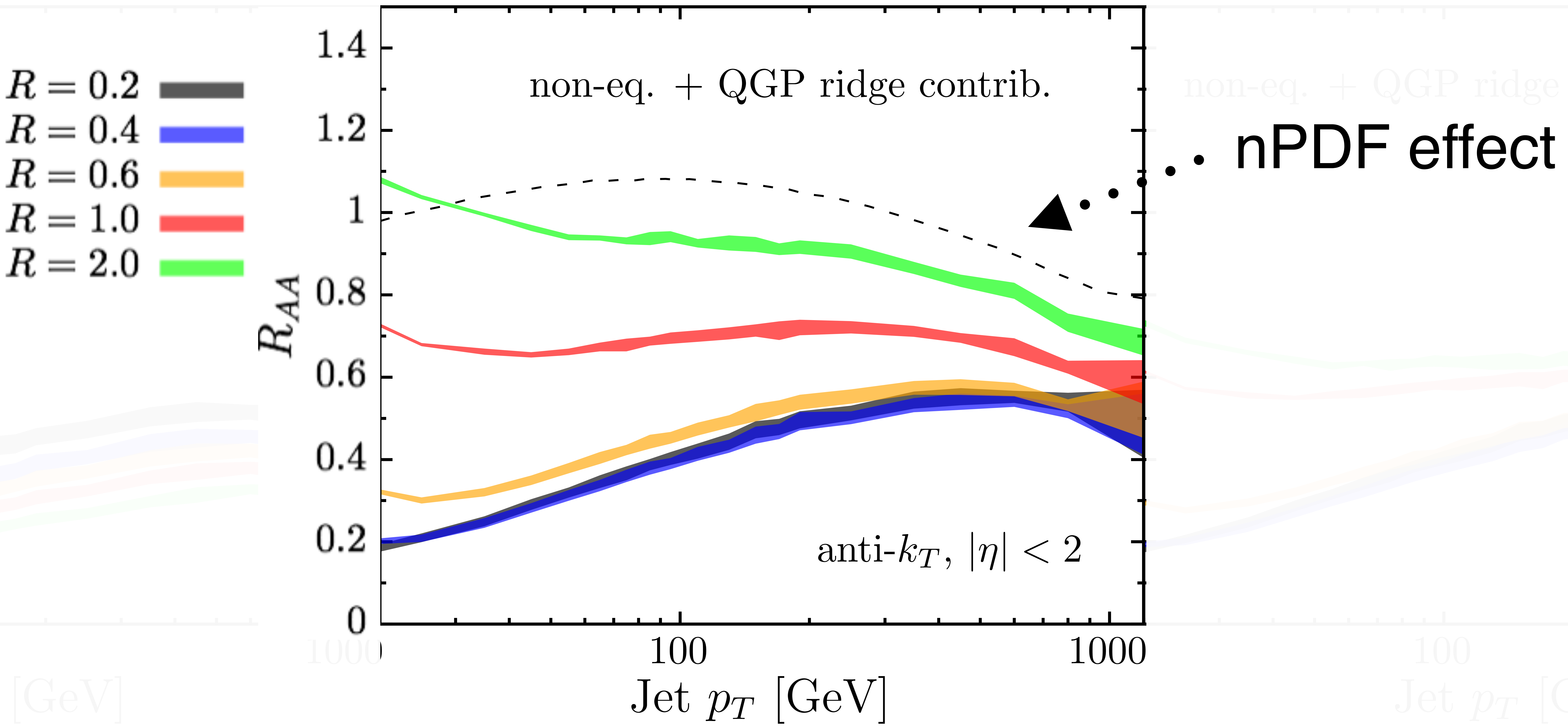
Include non-eq. contribution only, i.e. jet particles that did not hydrodynamize:

- Jet suppression increases with increasing R.

→ Wider jets “lose” more energy, more energy loss sources.

DP - PRL ‘20

Jet R_{AA} at LHC with Hybrid Model



Include both non-eq. and QGP "ridge" contributions:

- Energy is progressively recovered with increasing R.

! nPDF effect sets an upper limit on R_{AA} at very high p_T.

DP - PRL '20

Jet R_{AA} at LHC with Hybrid Model

Include non-eq., QGP "ridge" and QGP trough contribution:

- QGP trough amounts to jet suppression; over-subtraction effect.
- Effect increases with increasing R.

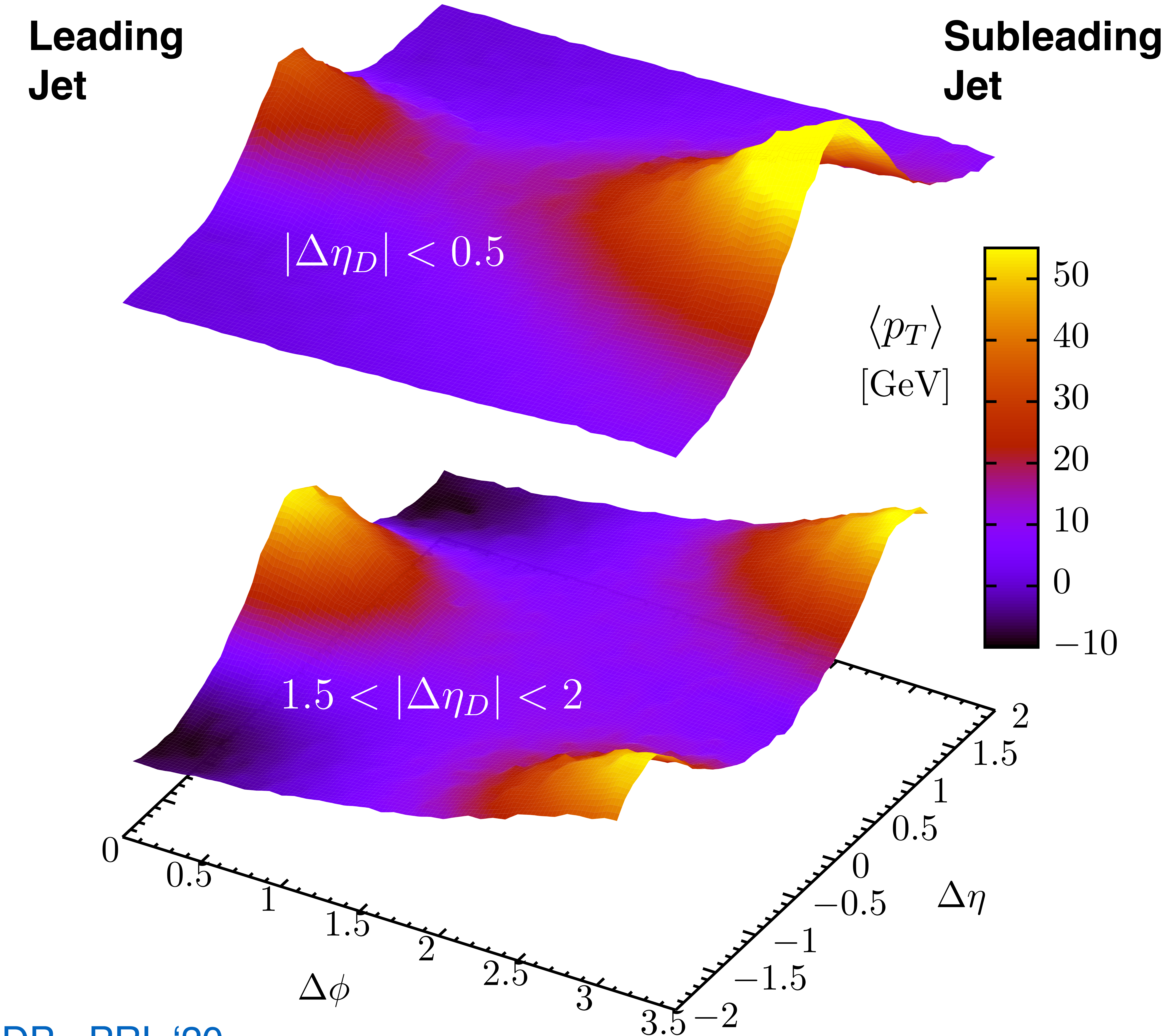
DP - PRL '20

Jet R_{AA} at LHC with Hybrid Model

Competition of effects that yield, overall,
a very mild evolution from small to large R.

DP - PRL '20

The Effect of the Recoiling Jet



DP - PRL '20

$\langle p_T \rangle$ density of wake hadrons w.r.t leading jet axis.

Aligned in rapidity

Subleading jet's QGP trough hits leading jet.

Separated in rapidity

Subleading jet's QGP trough misses leading jet.

$p_T^L > 250$ GeV

$p_T^S > 80$ GeV

$\Delta\phi_D > 2\pi/3$

differential in

$|\eta_D| \equiv |\eta_L - \eta_S|$

Leading Jet Suppression vs. |η_D|

DP - PRL '20

A new observable.

R = 0.4

leading jet area easy to miss;
small effect from QGP trough.

R = 1.0

strong dependence on |η_D|;
knee visible when |η_D|~R.

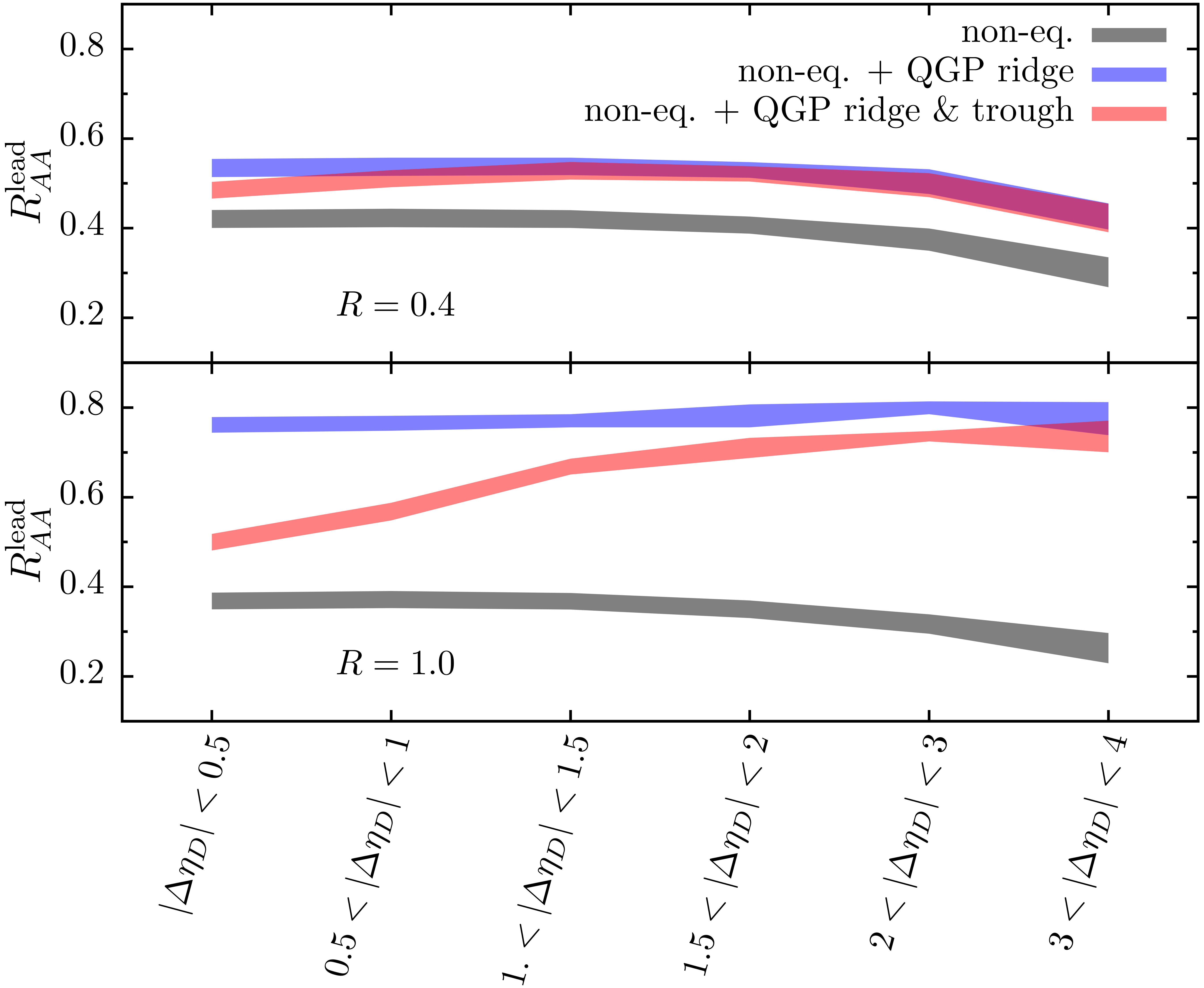
$p_T^L > 250$ GeV

$p_T^S > 80$ GeV

$\Delta\phi_D > 2\pi/3$

differential in

$|\eta_D| \equiv |\eta_L - \eta_S|$

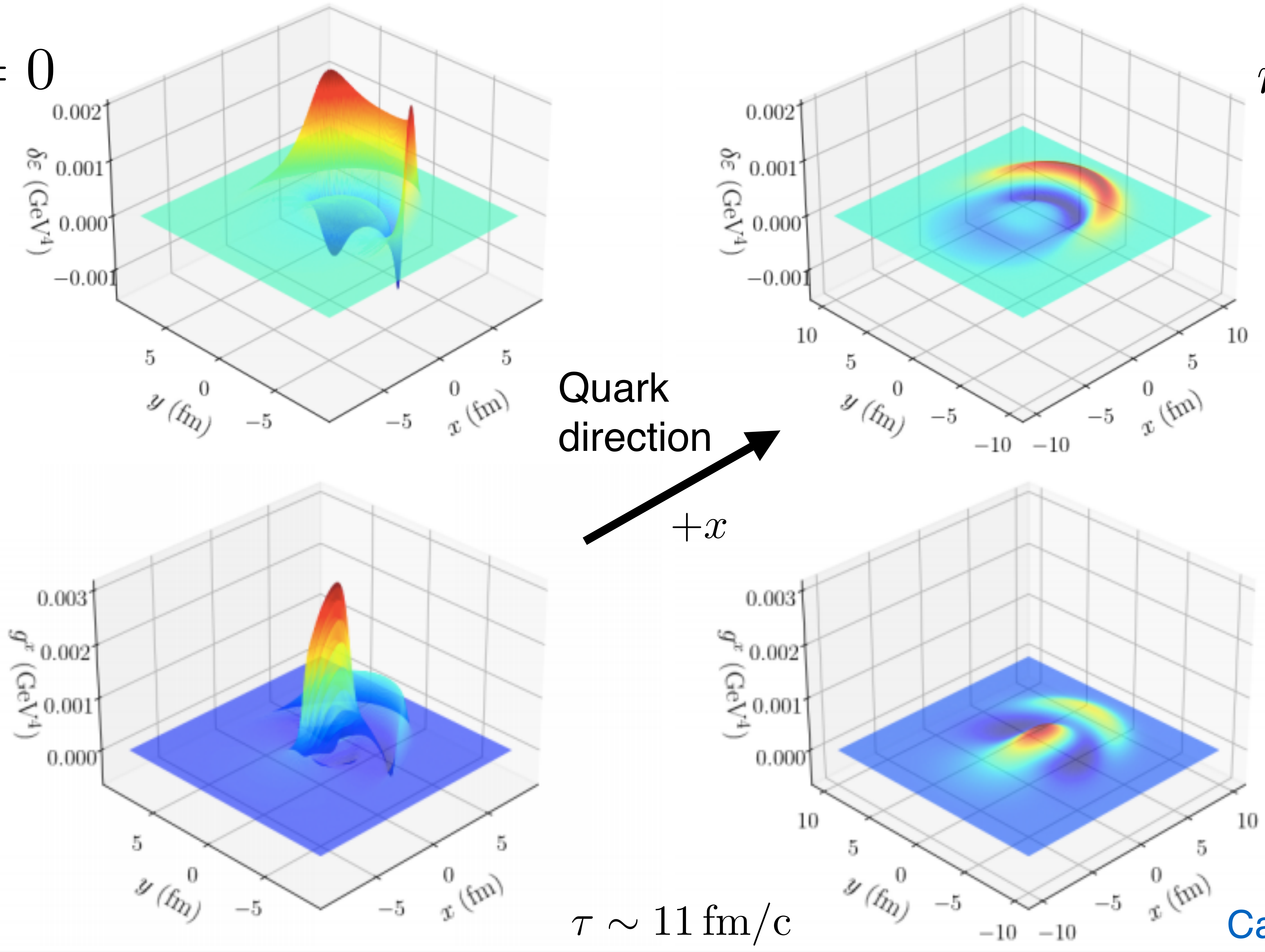


Linearized Hydrodynamics

- Analytic, but over-simplified medium response needs to be improved:
  - ➜ Starting point: linearised hydro eqs. for perturbations on top of viscous Bjorken flow.

$\eta = 0$

$\eta = \frac{s}{4\pi}$



- $\delta\epsilon$: energy density pert.

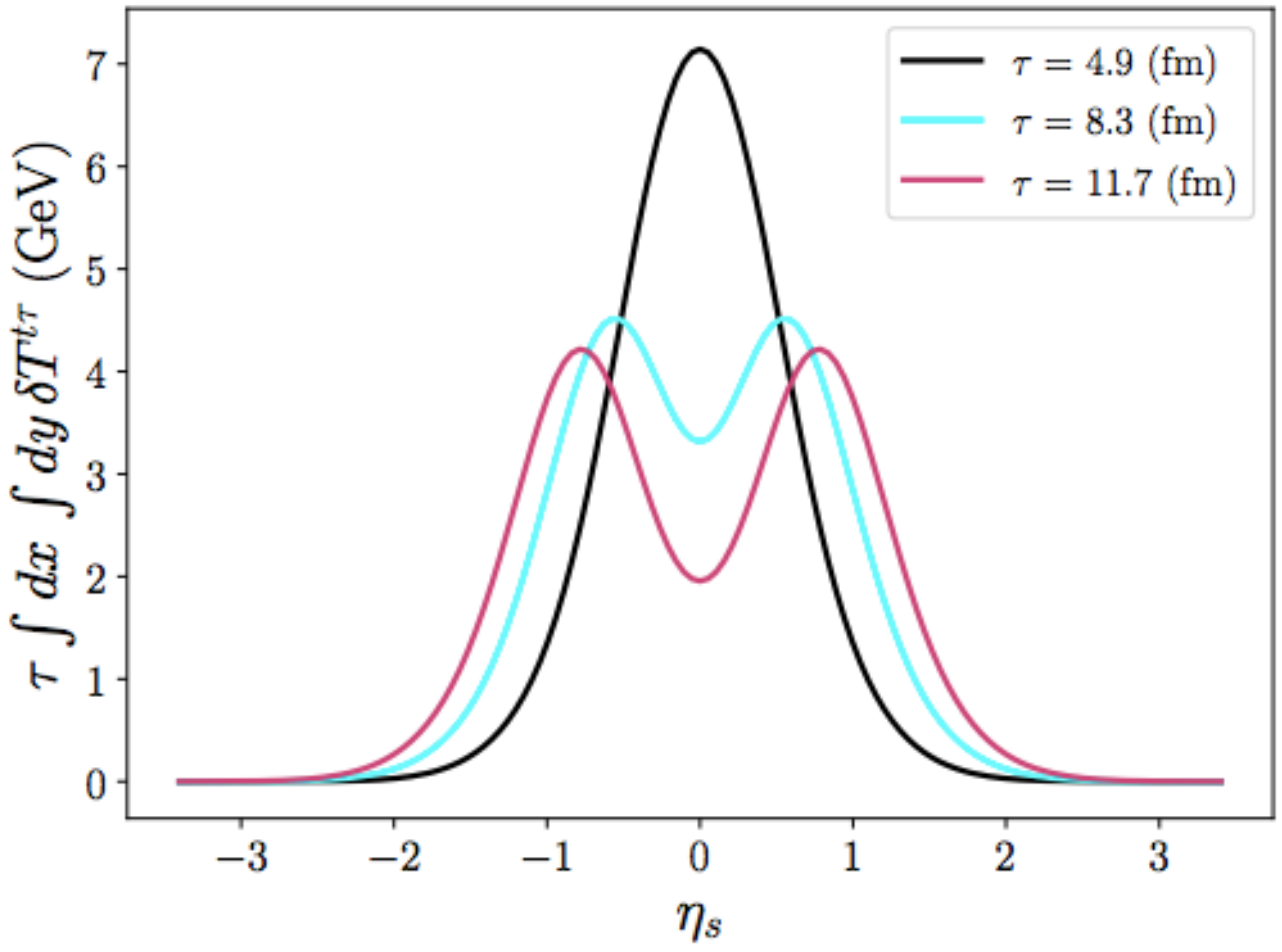
  Wavefront structure (Mach cone) diffuses due to viscosity.

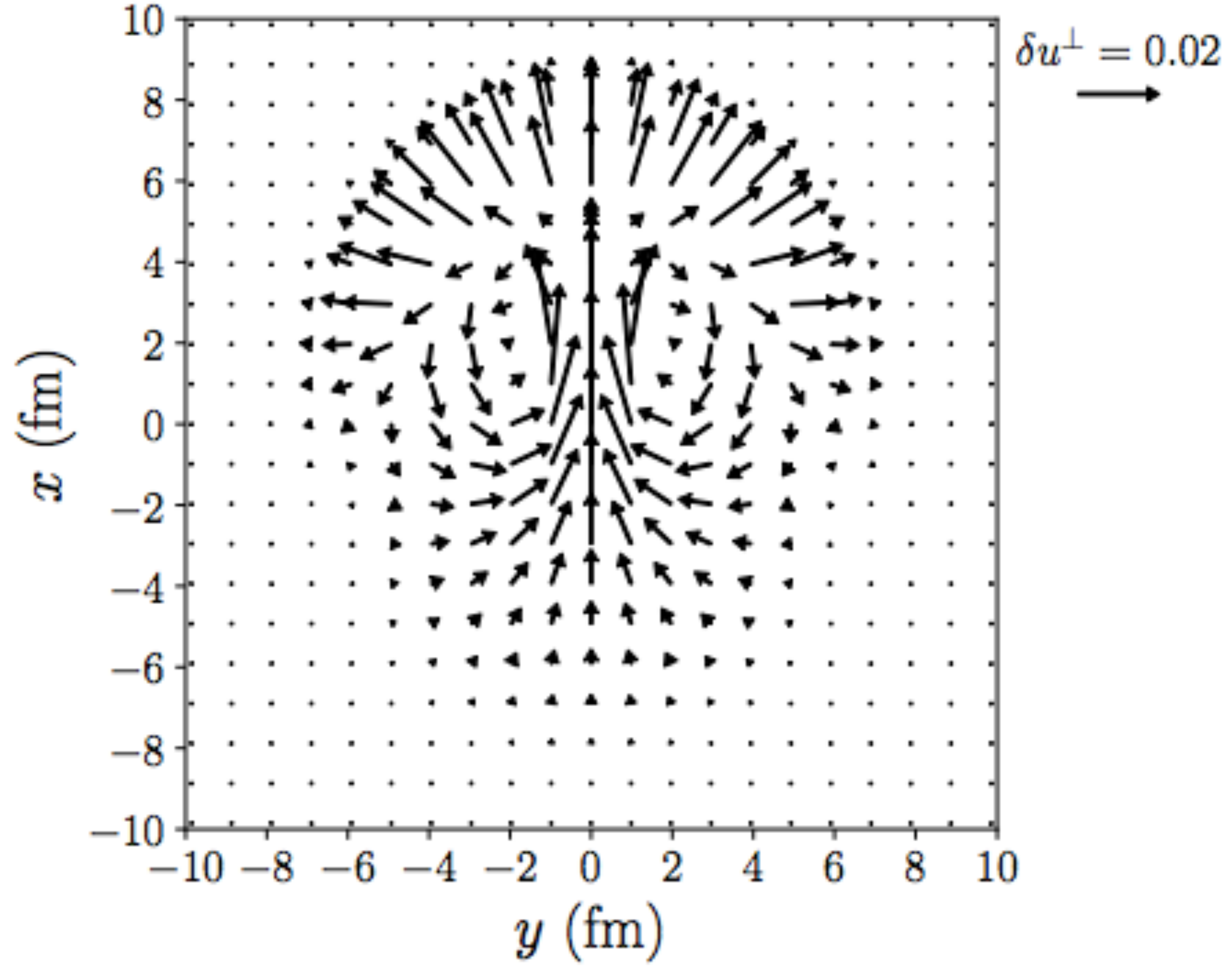
- g_x : momentum pert.

  Wing shaped structure diffuses due to viscosity (diffusion wake).

Casalderrey, Milhano, DP, Rajagopal, Yao - JHEP '21

Linearized Hydrodynamics





- Sound modes make wake energy spread in rapidity with time.
- Jet breaks long. boost invariance.

- Vortex ring around jet direction.

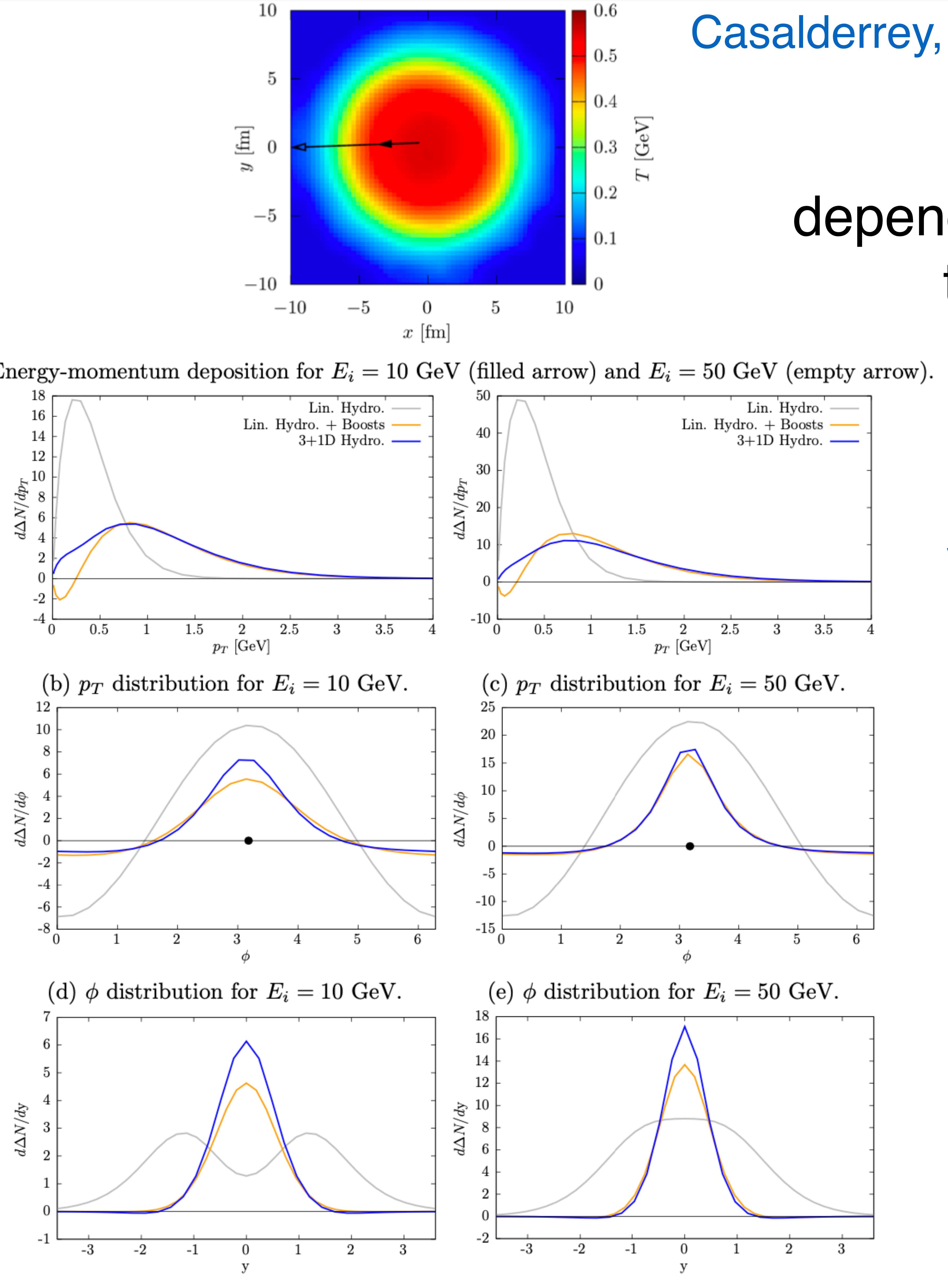
→ Imprints on Λ polarisation?

Serenone et al. - PLB ‘21

Casalderrey, Milhano, DP, Rajagopal, Yao - JHEP ‘21

Efficient Computations of the Wake

Casalderrey, Milhano, DP, Rajagopal, Yao - in preparation

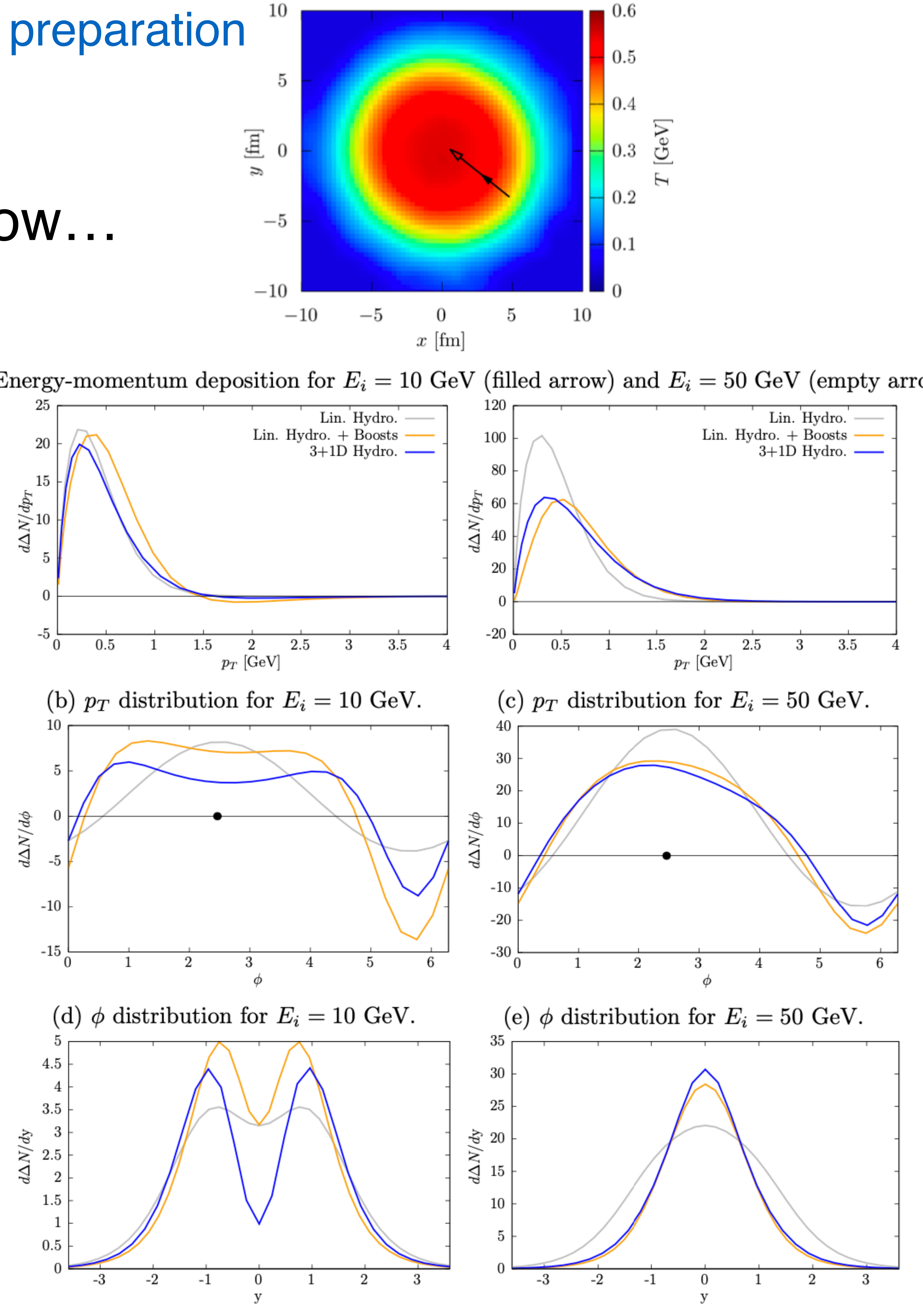


(a) Energy-momentum deposition for $E_i = 10$ GeV (filled arrow) and $E_i = 50$ GeV (empty arrow).
(b) p_T distribution for $E_i = 10$ GeV.
(c) p_T distribution for $E_i = 50$ GeV.
(d) ϕ distribution for $E_i = 10$ GeV.
(e) ϕ distribution for $E_i = 50$ GeV.
(f) y distribution for $E_i = 10$ GeV.
(g) y distribution for $E_i = 50$ GeV.

Hadrons from the wake
depend on evolution time, local flow…
thousands of possibilities.

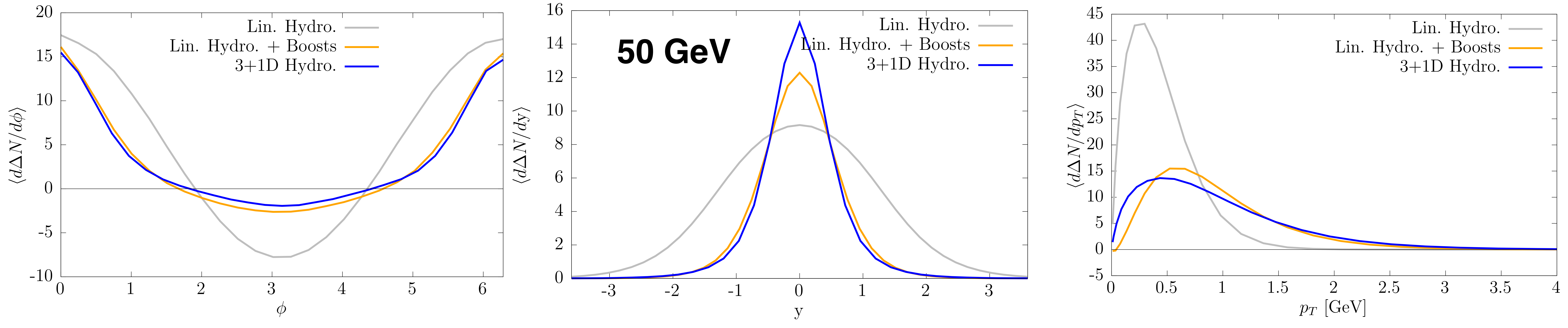
3+1D
Viscous Hydrodynamics
~ 2 hours

Superposition of
Bjorken flow solutions
+
Trans., Rot., & Boosts
~ 3 seconds

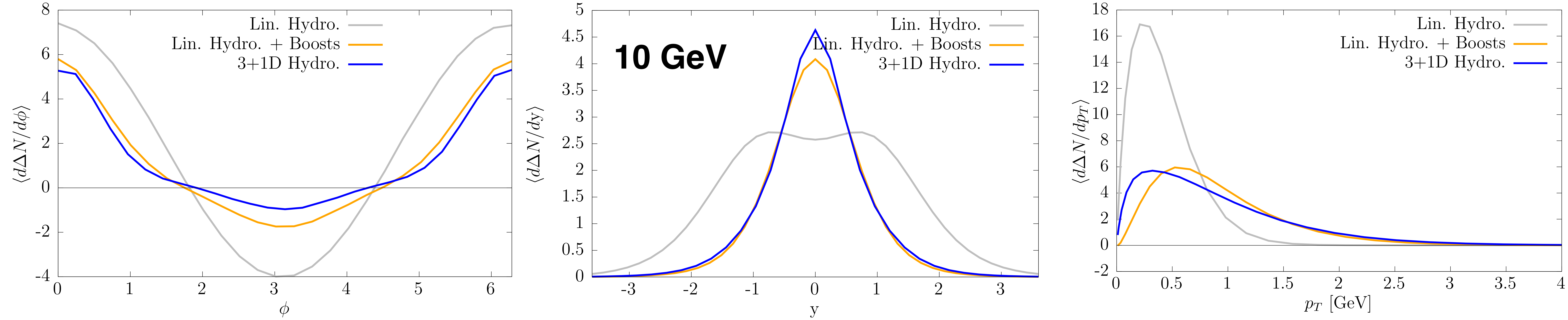


(a) Energy-momentum deposition for $E_i = 10$ GeV (filled arrow) and $E_i = 50$ GeV (empty arrow
(b) p_T distribution for $E_i = 10$ GeV.
(c) p_T distribution for $E_i = 50$ GeV.
(d) ϕ distribution for $E_i = 10$ GeV.
(e) ϕ distribution for $E_i = 50$ GeV.
(f) y distribution for $E_i = 10$ GeV.
(g) y distribution for $E_i = 50$ GeV.

Efficient Computations of the Wake



Average distribution (~ 50 events) becomes *harder* and more *collimated* than without transverse flow.



Conclusions & Outlook

- Jet energy loss requires accounting for several effects:
  - ➔ Resummation of multi-particle energy loss inside R from high-virtuality shower.
  - ➔ Determination of the resolved phase-space. Improvable in pQCD.
  - ➔ Modelling of hydrodynamized component. Important for larger R.

- Cone-size dependence of jet suppression:
  - ➔ Competing effects between larger phase-space and energy recovery.

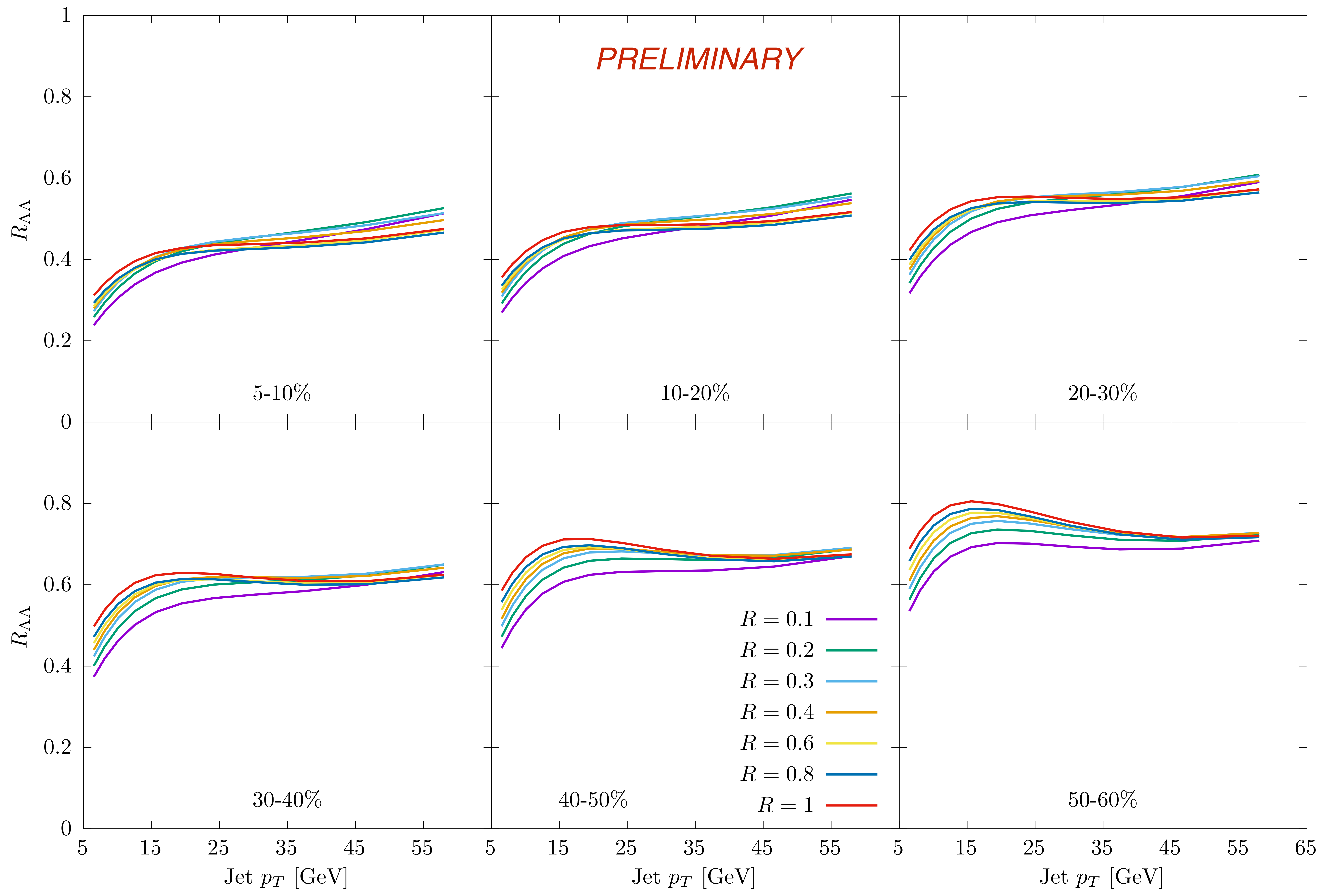
- Computationally efficient jet-by-jet, flow-dependent wakes:
  - ➔ Insights into devising tailored observables to reveal wake signatures.
  - ➔ Useful for massive medium response Monte Carlo simulations.
  - ➔ Can be supplemented as non-perturbative component to analytical computations.

- Recent impressive theory advances in many crucial ingredients:
  - ➔ Reliable predictions to confront experiments and test very exciting physics (color coherence, jet thermalization…).

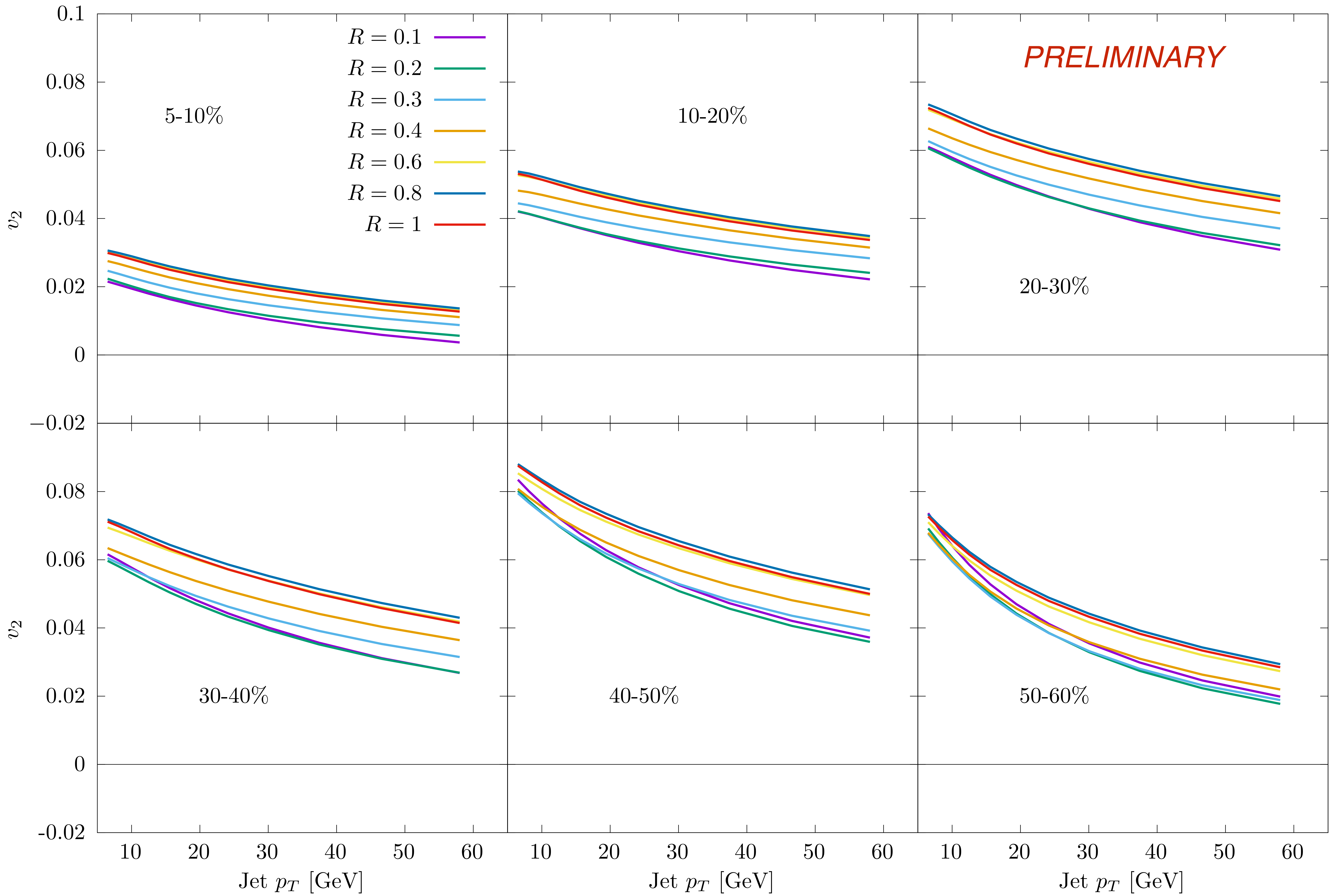
Thanks for your attention!

Backup Slides

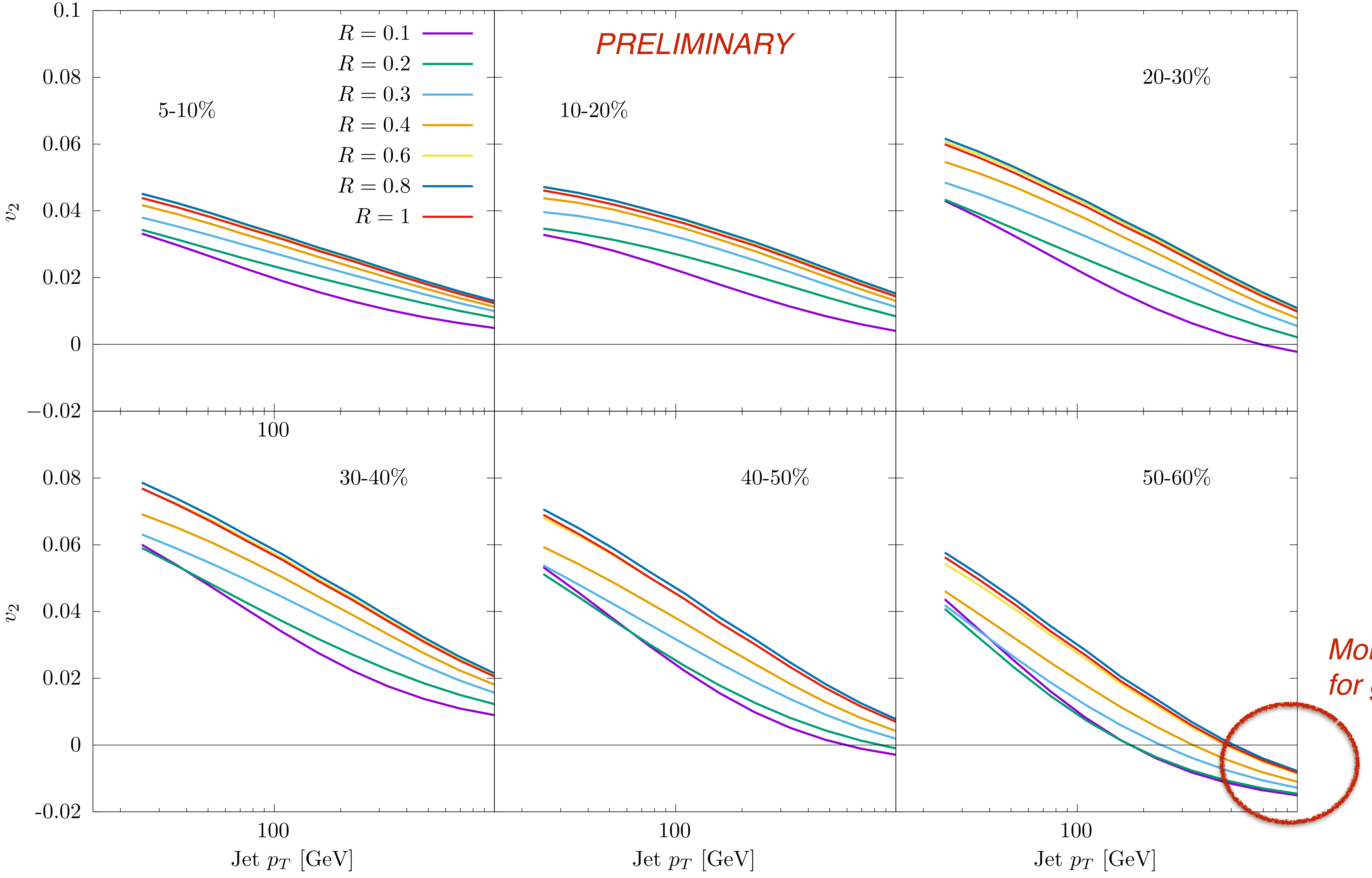
Jet R_{AA} at RHIC



Jet v_2 at RHIC

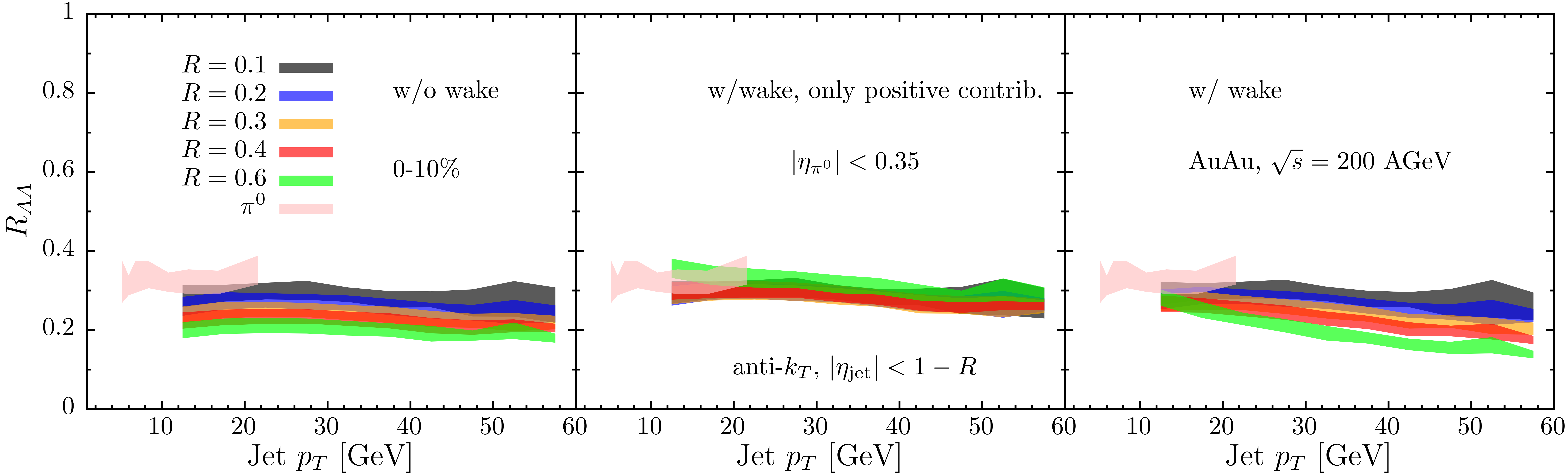


Jet v_2 at LHC



More stats. needed for good baseline

Jet R_{AA} at RHIC with Hybrid Model



DP - *PoS* HardProbes2020

Hybrid Strong/Weak Coupling Model

$$\frac{1}{E_{\rm in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{\rm stop}^2}\frac{1}{\sqrt{x_{\rm stop}^2 - x^2}}$$

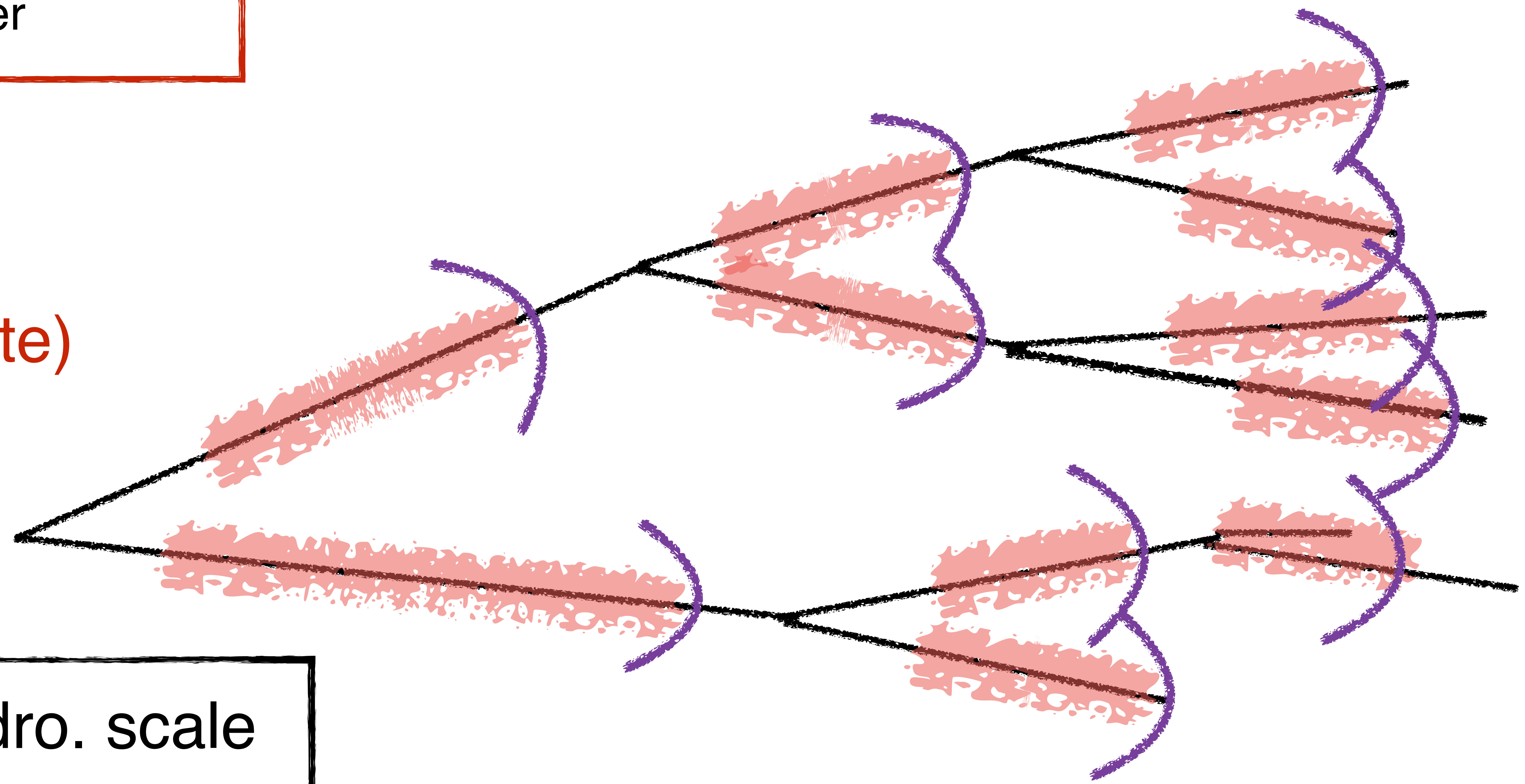
$$x_{\rm stop} = \frac{1}{2\kappa_{\rm sc}}\frac{E_{\rm in}^{1/3}}{T^{4/3}}$$

$\mathcal{O}(1)$ free parameter

Strongly coupled energy loss (hydrodynamization rate)

$$E\frac{d\Delta N}{d^3p} = \frac{1}{32\pi}\frac{m_T}{T^5}\cosh(y-y_j)\exp\left[-\frac{m_T}{T}\cosh(y-y_j)\right]$$
$$\left\{p_T\Delta P_T\cos(\phi-\phi_j)+\frac{1}{3}m_T\,\Delta M_T\,\cosh(y-y_j)\right\}$$

Hadrons from the hydro. wake (medium response)



PYTHIA8 down to hadro. scale (formation time argument for spacetime picture)

Casalderrey-Solana, Gulhan, Milhano, DP, Rajagopal JHEP ‘15,‘16,‘17

Accounting for Radial Flow

Casalderrey, Milhano, DP, Rajagopal, Yao - JHEP '21

- Modified spectra after Cooper-Frye:

$$\frac{\mathrm{d}\Delta N}{p_T\,\mathrm{d}p_T\,\mathrm{d}\phi\,\mathrm{dy}} = \frac{1}{(2\pi)^3}\int \tau\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\eta_s\, m_T \cosh(\mathrm{y}-\eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f+\delta T}\right) - f\left(\frac{u_0^\mu p_\mu}{T_f}\right)\right]$$

With wake ↗ ↖ No wake

- Ansatz to account for radial flow:

→ Boost particle momentum to frame in which fluid cell moves with $u^\mu = \gamma_\perp(\cosh\eta,\, v_x,\, v_y, \sinh\eta)$.

$$p^\mu_{\mathrm{cell}} = \Lambda^\mu{}_\nu(\boldsymbol{v}_{\mathrm{cell}})p^\nu_{\mathrm{lab}}$$

Use flow profile at freeze out from 2+1D hydro. simulations such as VISHNU.