Cone-size dependence of jet suppression from LHC to RHIC

Daniel Pablos - INFN Torino

Fellowship for Innovation at INFN

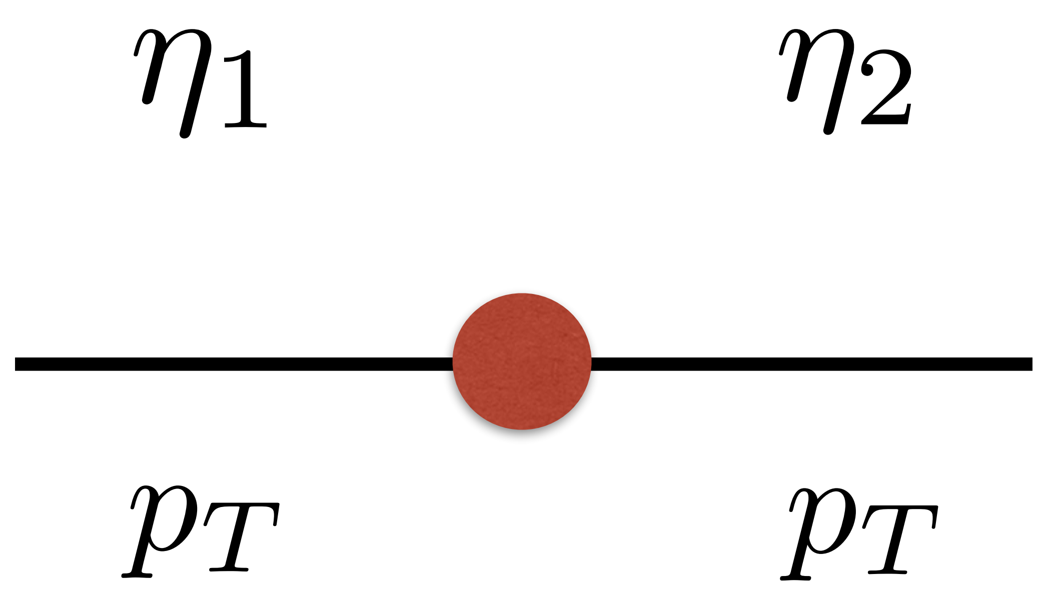
Istituto Nazionale di Fisica Nucleare

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement n. 754496.

RBRC Workshop: Predictions for sPHENIX
20th July 2022

Jets in pp

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

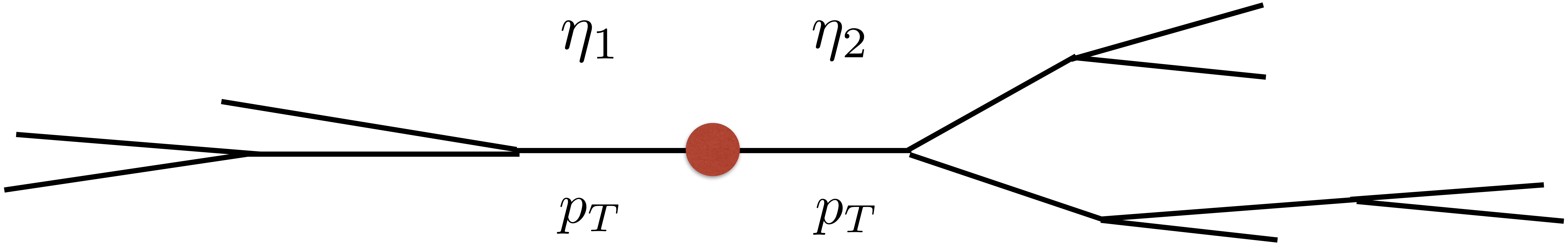


Jets in pp

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

- Parton density evolution described via DGLAP:

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



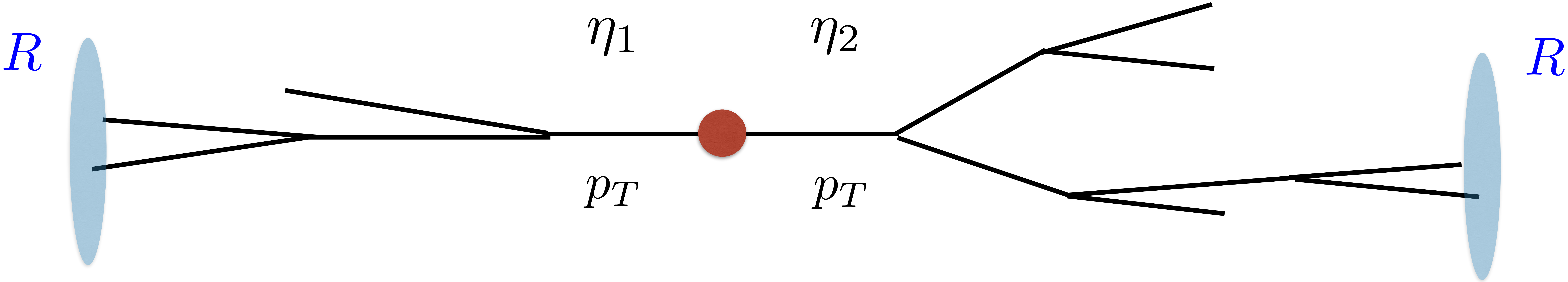
- Collimated structure enforced through collinear divergences & color coherence.

Jets in pp

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

- Parton density evolution described via DGLAP:

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



- Collimated structure enforced through collinear divergences & color coherence.

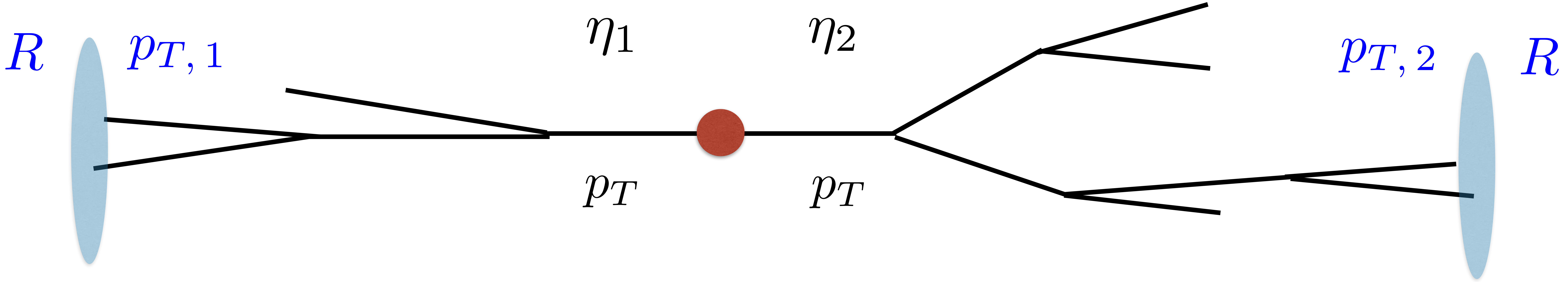
- Jets are defined with clustering algorithm, reconstruction radius R.

Jets in pp

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

- Parton density evolution described via DGLAP:

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



- Collimated structure enforced through collinear divergences & color coherence.

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

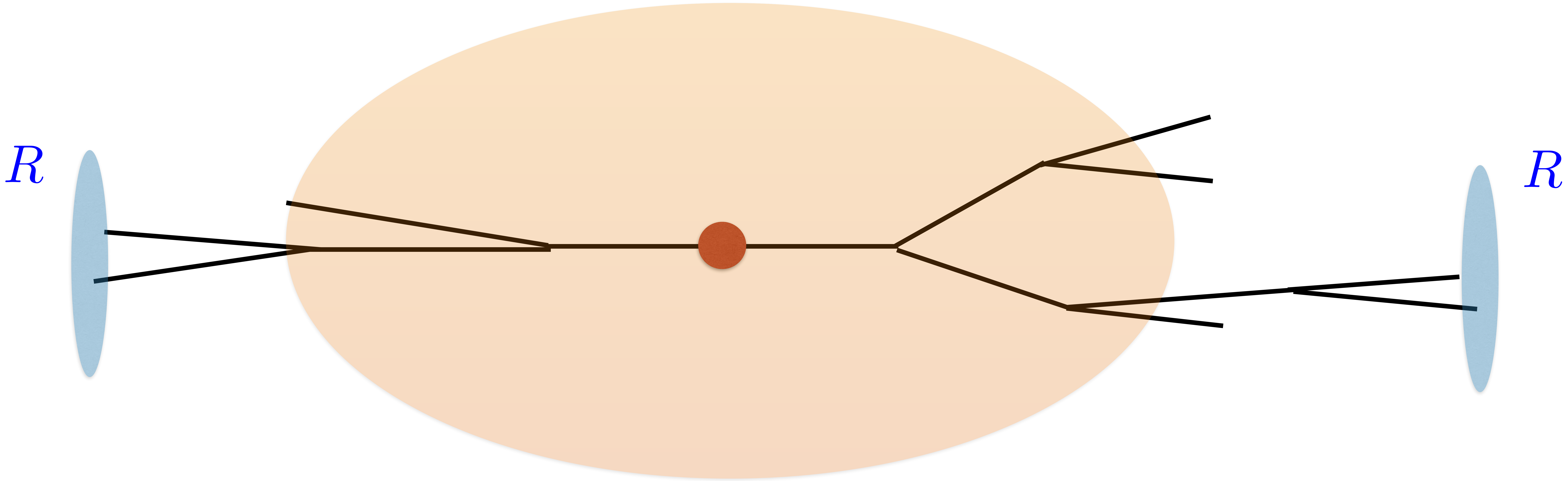
→ Degree of jet activity determines, e.g., out-of-cone radiation (causes dijet asymmetry in pp).

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

Jets in AA

- Jet partons interact with QGP and experience energy loss.

- Crucial insights obtained with jet quenching MCs.



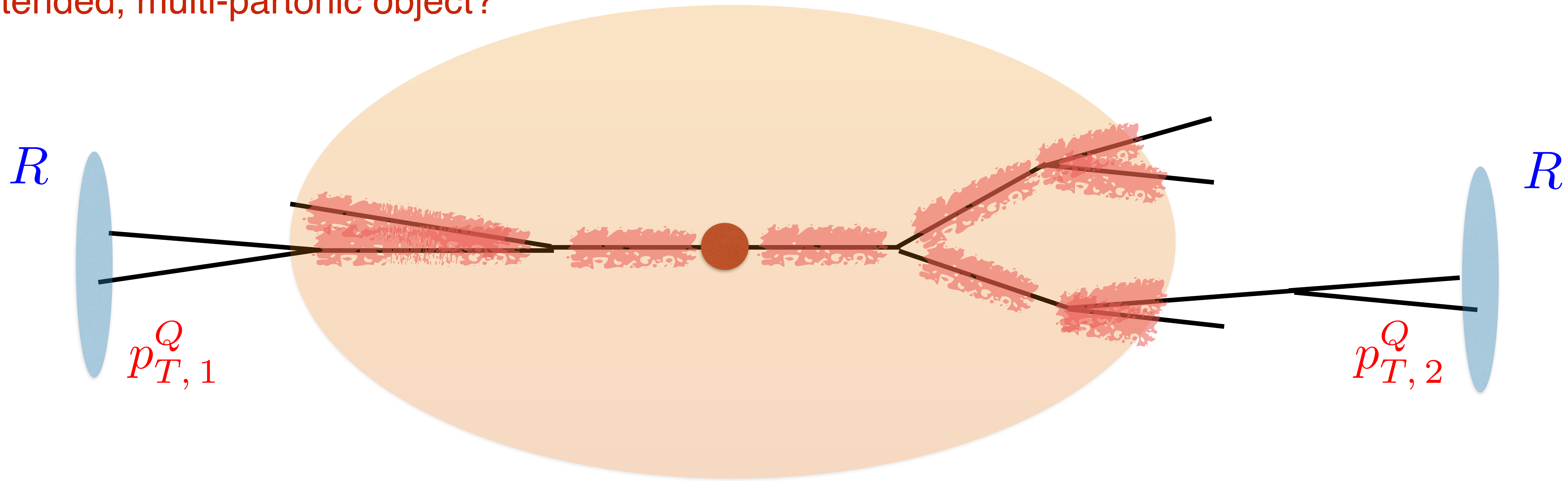
- Lesson example: total energy loss proportional to jet activity (more energy loss sources):
  - ➜ Causes dijet asymmetry in AA (for same traversed length). Milhano & Zapp - EPJ '16
  - ➜ Causes selection bias towards narrower jets. Hadron vs. Jet Suppression

Casalderrey, Hulcher, Milhano, DP, Rajagopal - PRC '19

Jets in AA

- Jet suppression beyond MC:

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

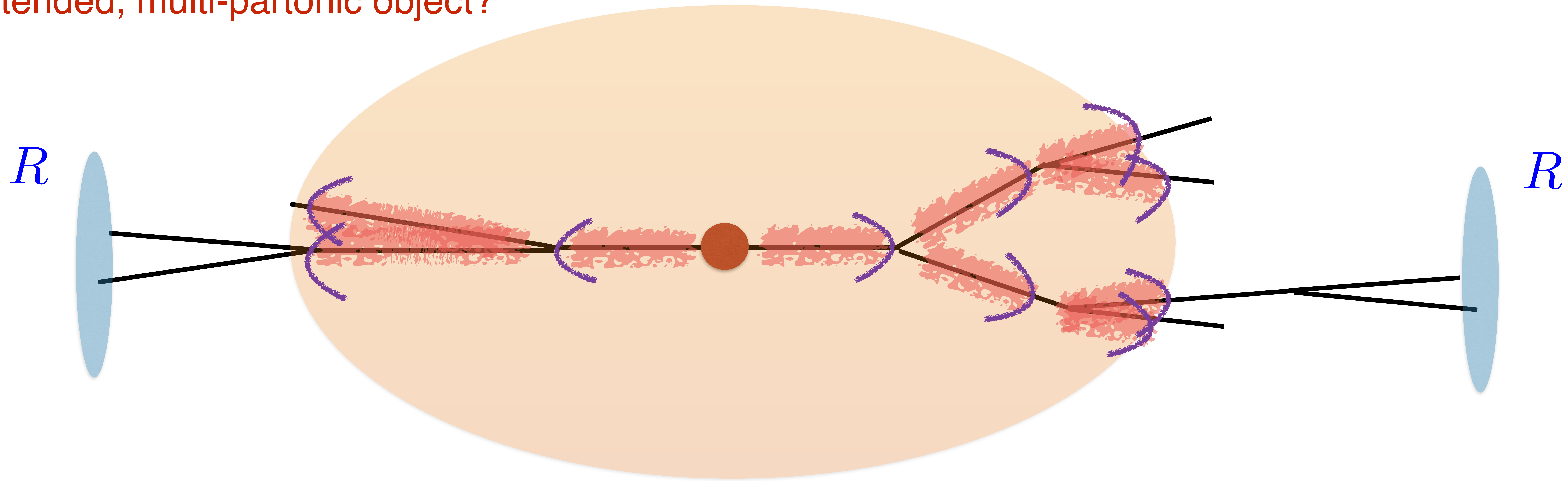


Outline

Jets in AA

- Jet suppression beyond MC:

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



Outline

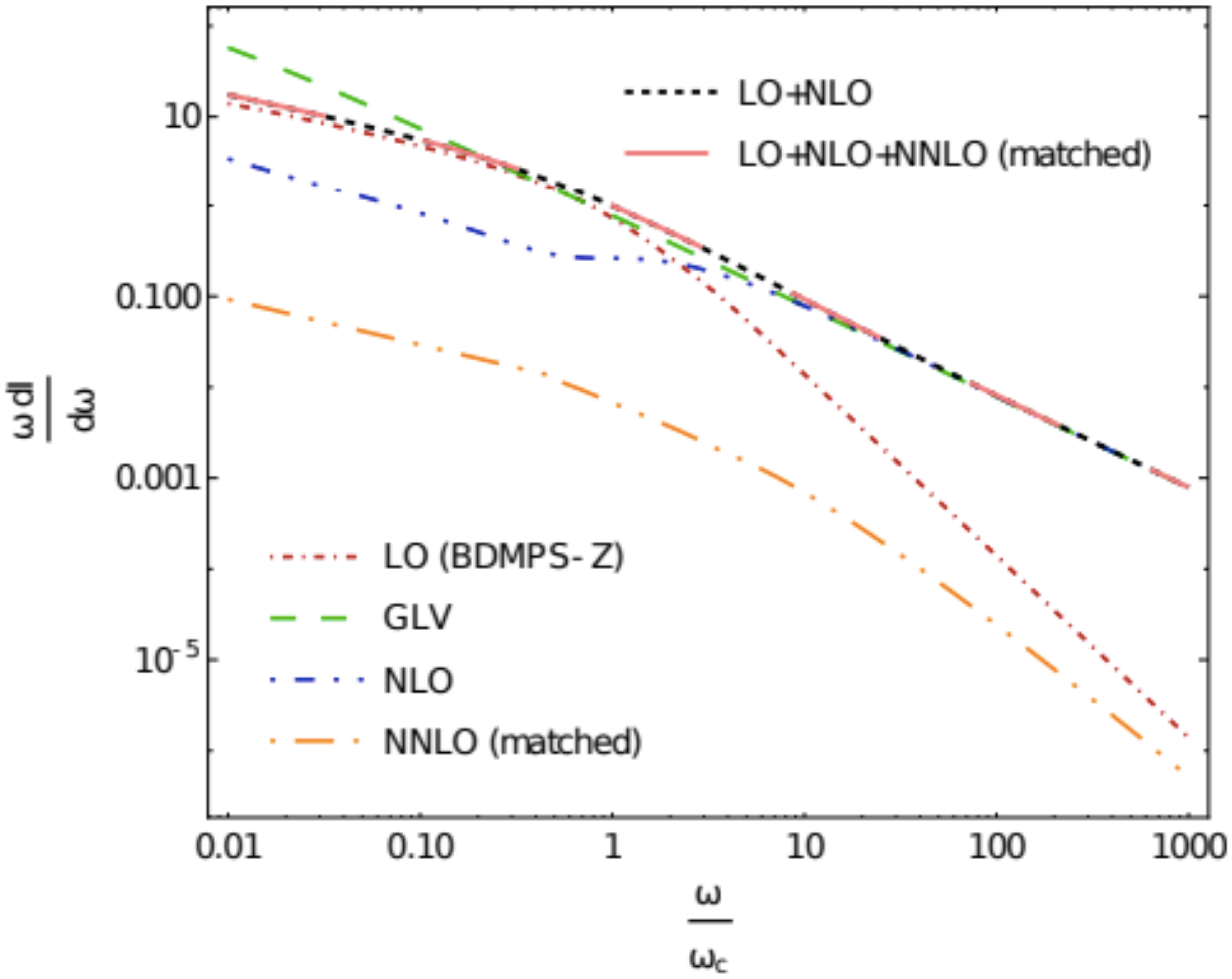
- Non-perturbative modelling of long wavelength jet modes:

  Where does “lost” energy go to?

Improved Opacity Expansion (IOE)

Barata, Mehtar-Tani - JHEP '20

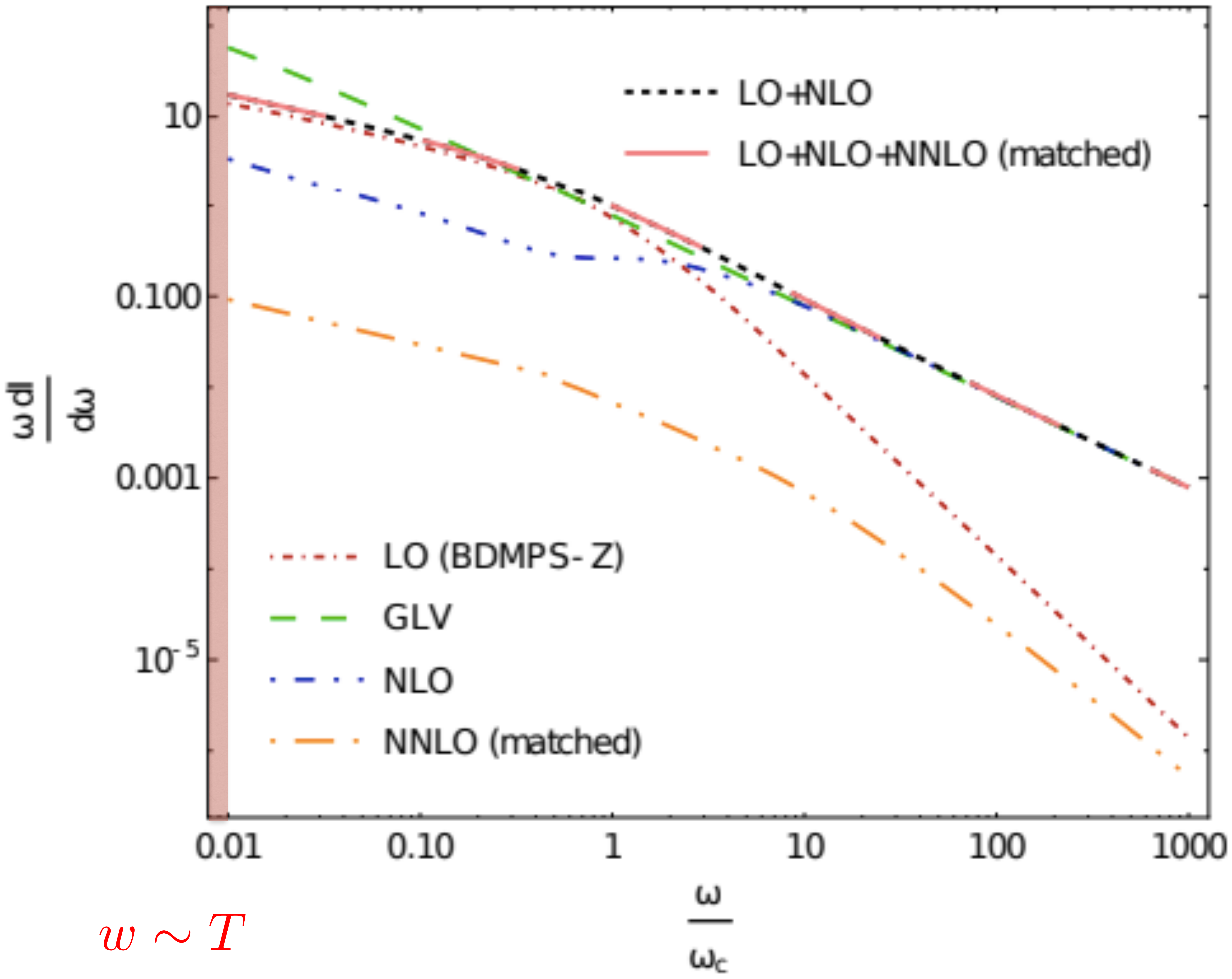
$$t_{\rm coh} = \omega/k_\perp^2 \qquad k_\perp^2 \sim \hat{q}\, t_{\rm coh} \qquad t_{\rm coh} \equiv \sqrt{\frac{\omega}{\hat{q}}}$$



Improved Opacity Expansion (IOE)

Barata, Mehtar-Tani - JHEP ‘20

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



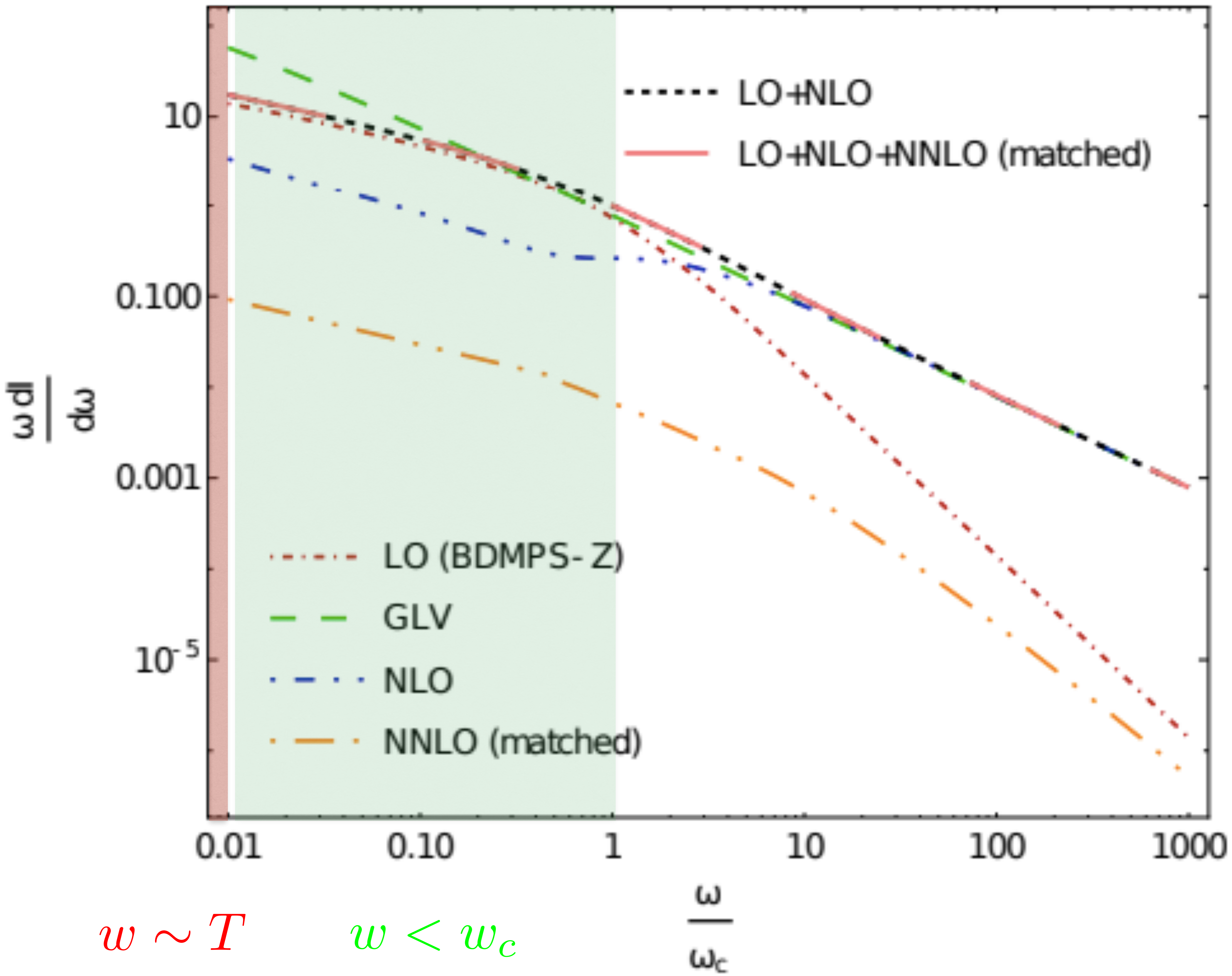
$w \sim T$

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

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

Improved Opacity Expansion (IOE)

Barata, Mehtar-Tani - JHEP '20



$w \sim T$ $w < w_c$

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

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

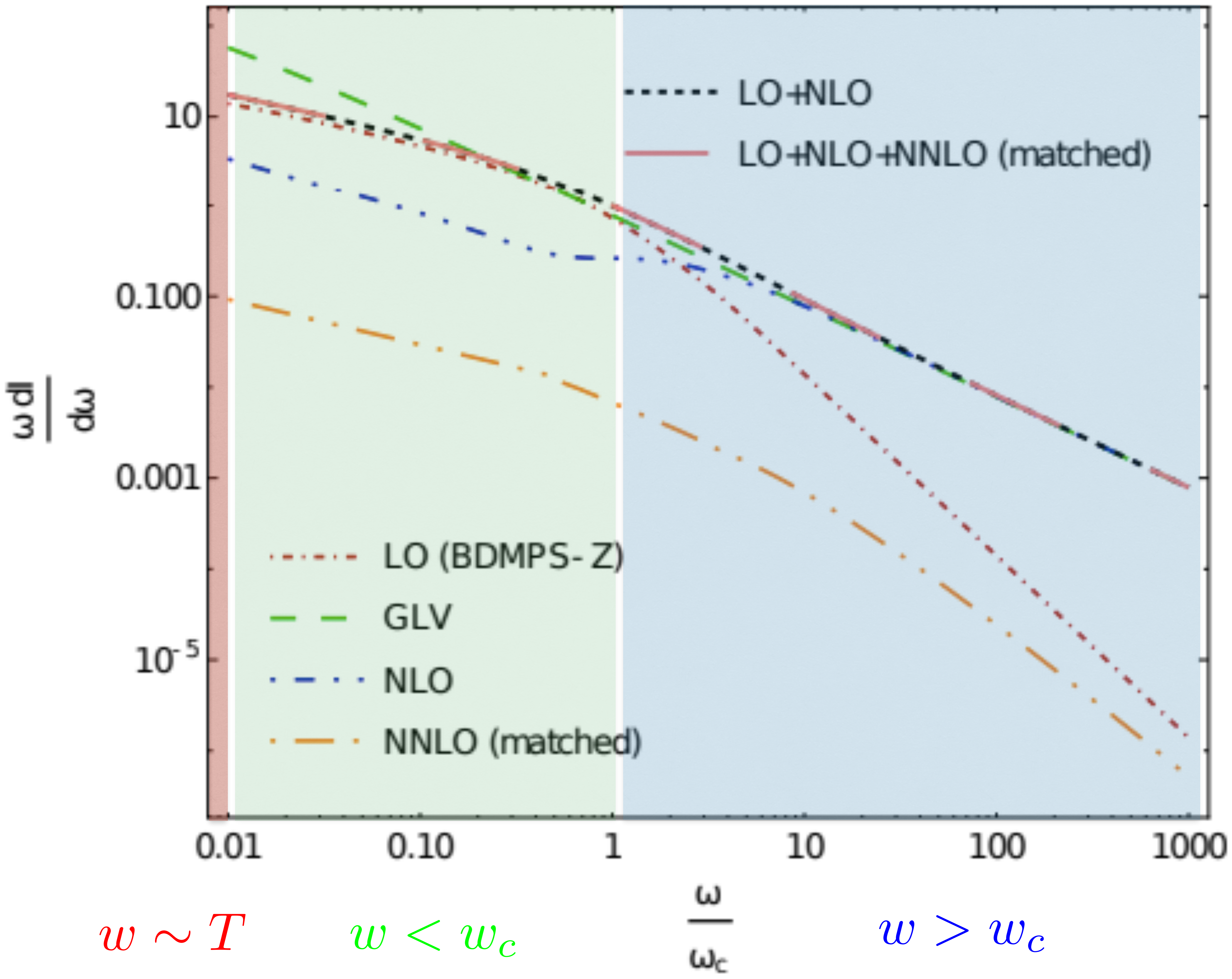
$$\omega \frac{{\rm d}I_{\rm BH}}{{\rm d}\omega} \simeq \alpha_s \frac{L}{\ell_{\rm mfp}} = \alpha_s N_{\rm scatt}$$

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

$$\omega \frac{{\rm d}I}{{\rm d}\omega} \simeq \alpha_s \frac{L}{t_{\rm coh}} = \alpha_s \sqrt{\frac{\omega_c}{\omega}}$$

Improved Opacity Expansion (IOE)

Barata, Mehtar-Tani - JHEP '20



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

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

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

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

$$\omega \frac{{\rm d}I}{{\rm d}\omega} \simeq \alpha_s \frac{L}{t_{\rm coh}} = \alpha_s \sqrt{\frac{\omega_c}{\omega}}$$

- 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

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

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

- 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

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 - PRL ‘21

- 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

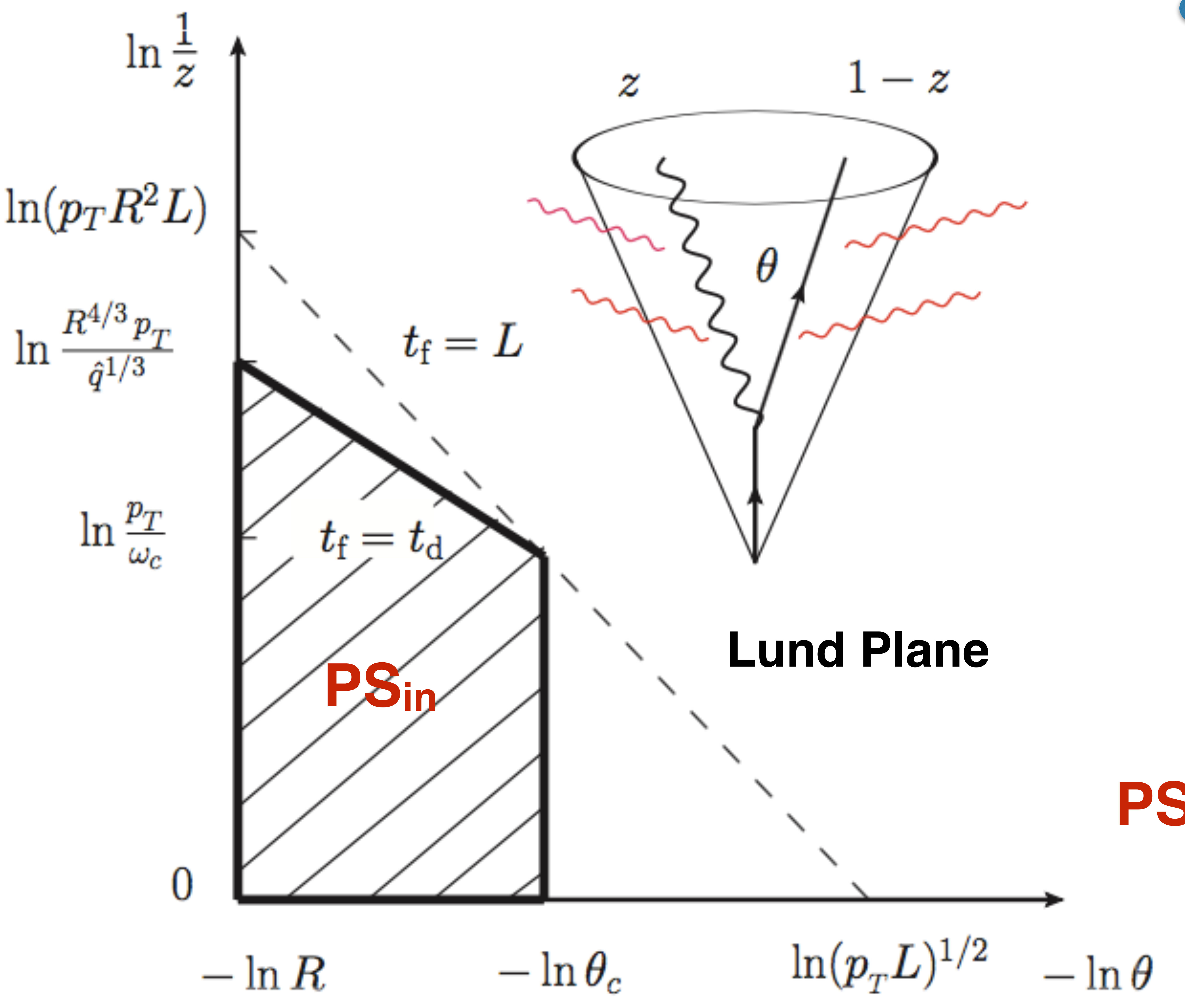
→ if uniformly distributed in jet hemisphere

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

Note that:

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

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:

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

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:

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

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

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

Initial condition at zero angle
is single charge quenching factor:

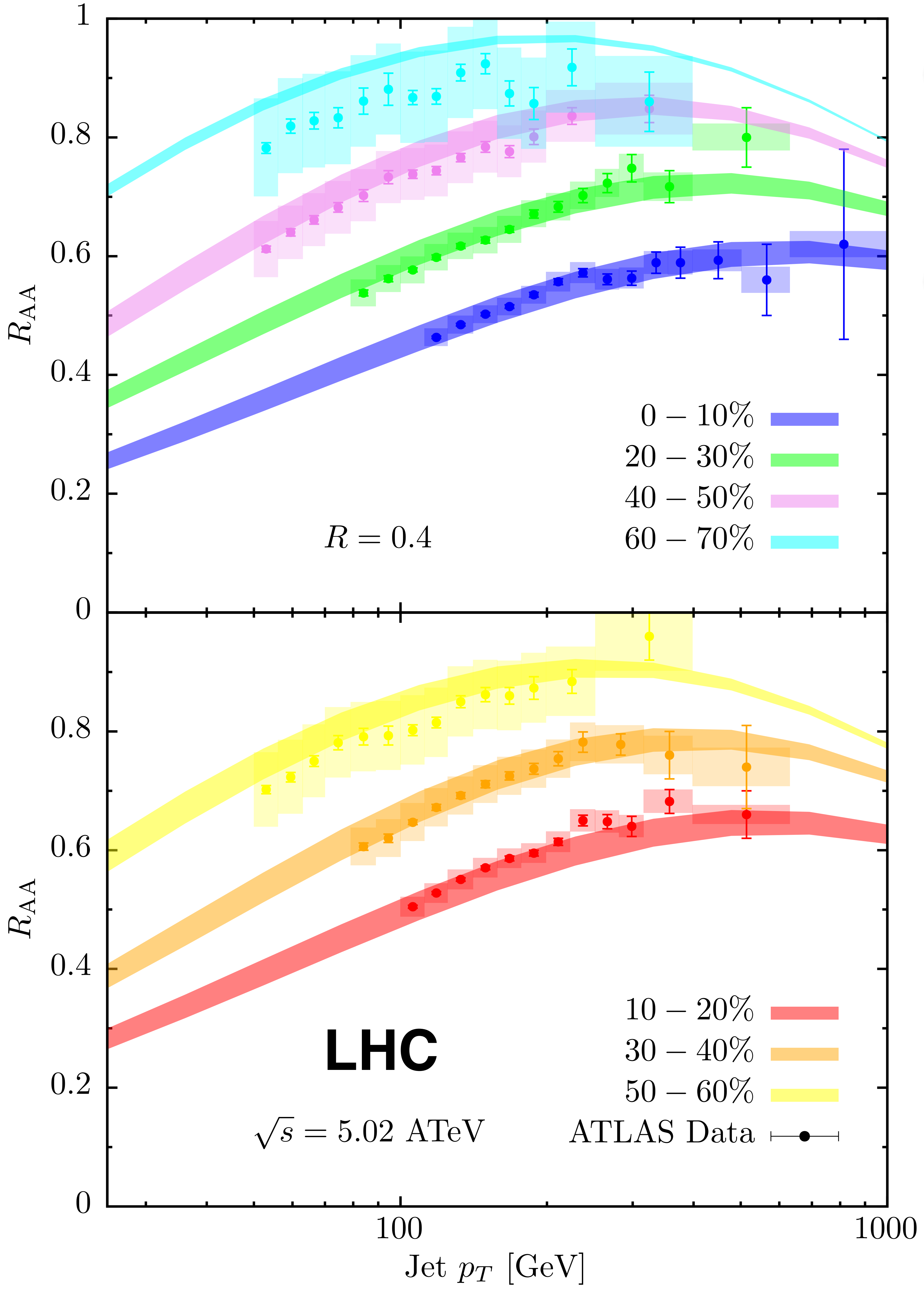
$$Q_i(p,0) = \underset{\text{Radiative energy loss}}{Q^{(0)}_{\text{rad},i}(p_T)}\,\underset{\text{Elastic energy loss}}{Q^{(0)}_{\text{el},i}(p_T)}$$

- 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

Jet Suppression at LHC

Mehtar-Tani, DP, Tywoniuk - PRL ‘21

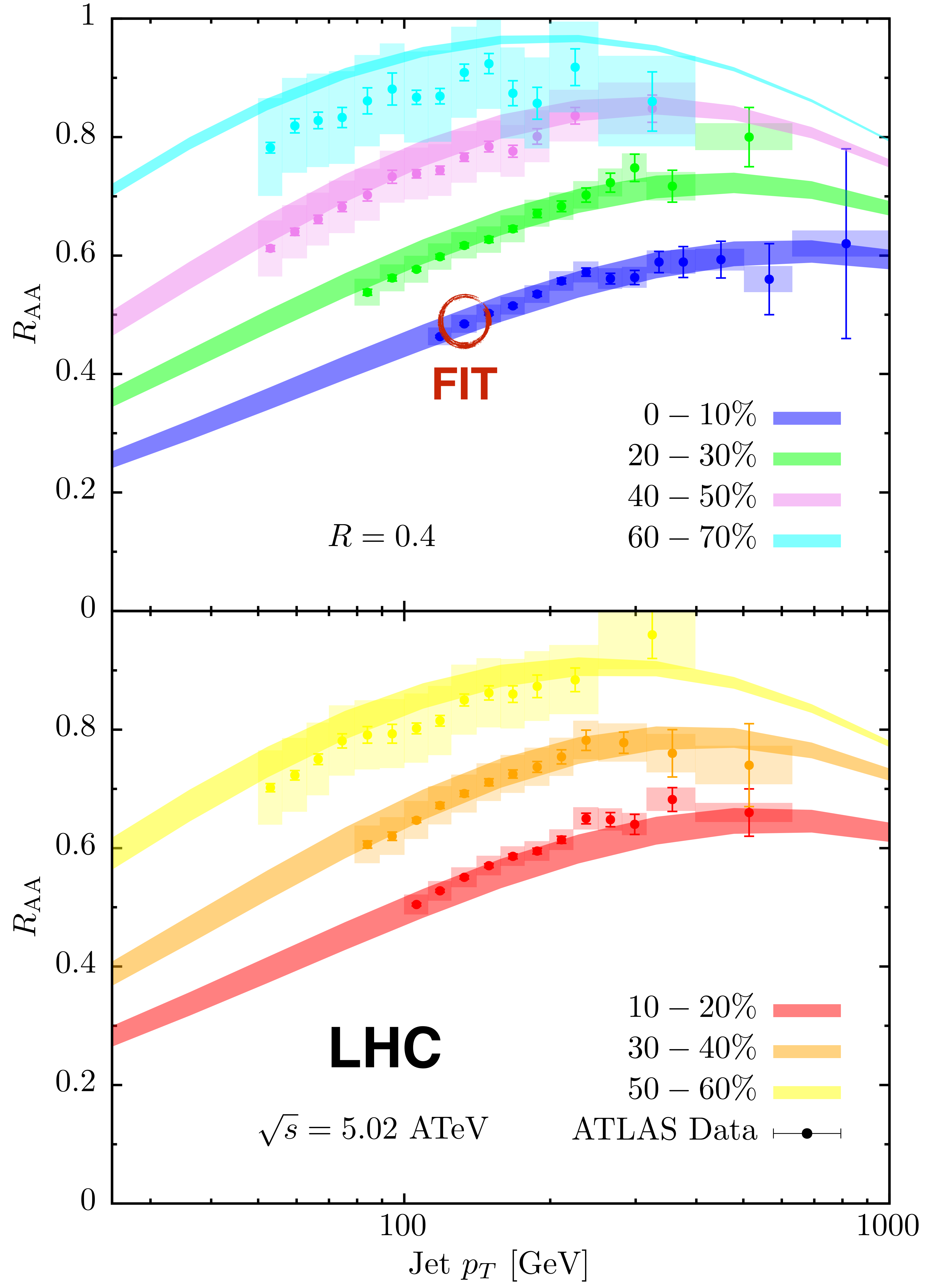


- Use PYTHIA8 to generate spectrum at initial angle R_0=1 (with nuclear PDFs EPS09 LO in medium case)
- Evolve microjets using DGLAP down to jet R.
- Compute resummed quenching factors for each jet p_T and R:
  - → Bare quenching factor requires knowledge of event-by-event, centrality dependent QGP properties:
    - → 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 at LHC



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%

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

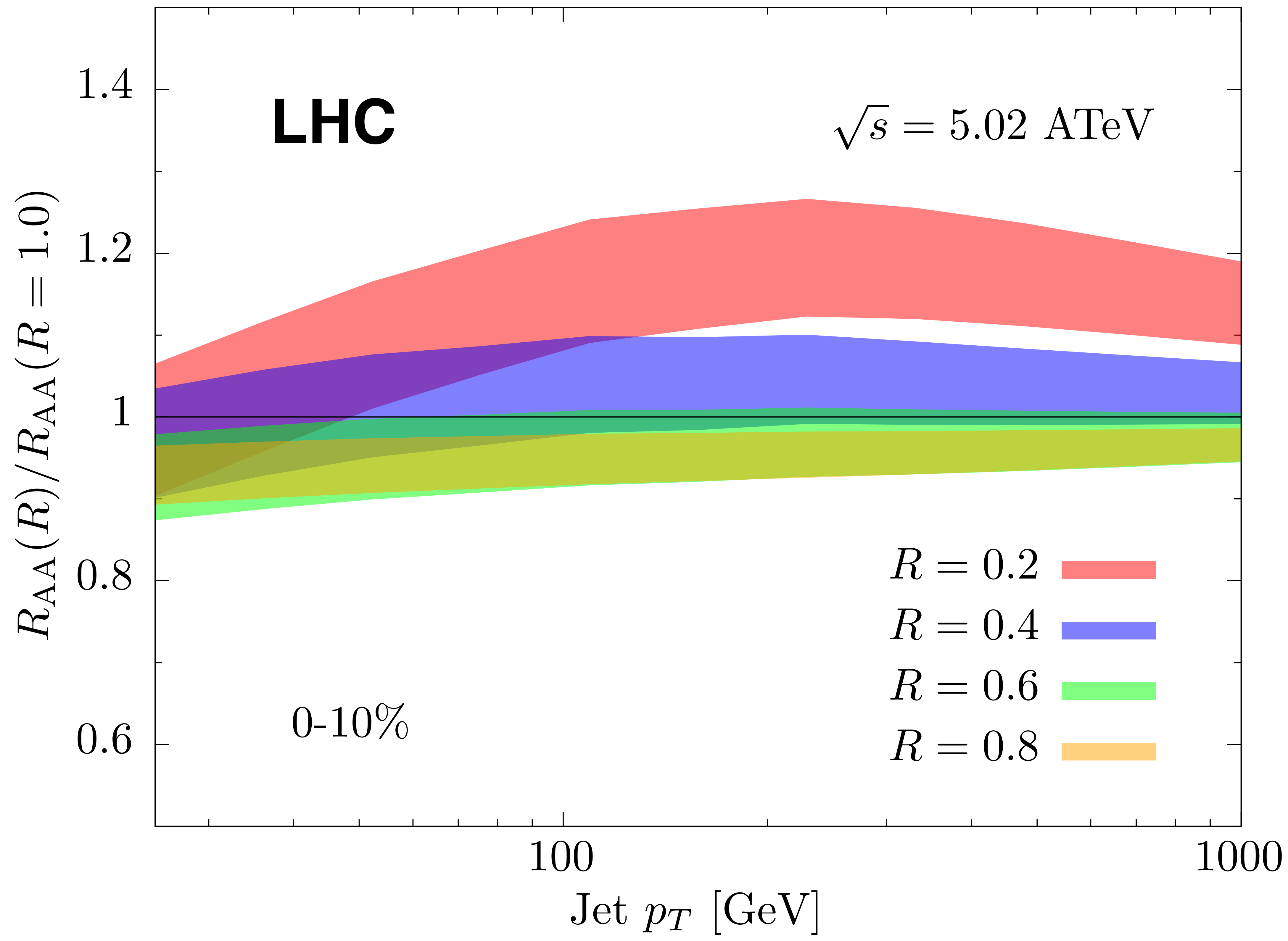
→ $\langle \hat{q}_0 \rangle \simeq 0.41\ \mathrm{GeV}^2/\mathrm{fm}$ in 0-10%

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

Mehtar-Tani, DP, Tywoniuk - PRL ‘21

- Modelling sensitivity at p_T=110 GeV 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	$[\omega_s/2,\ 2\omega_s]$	$\lesssim 8\%$

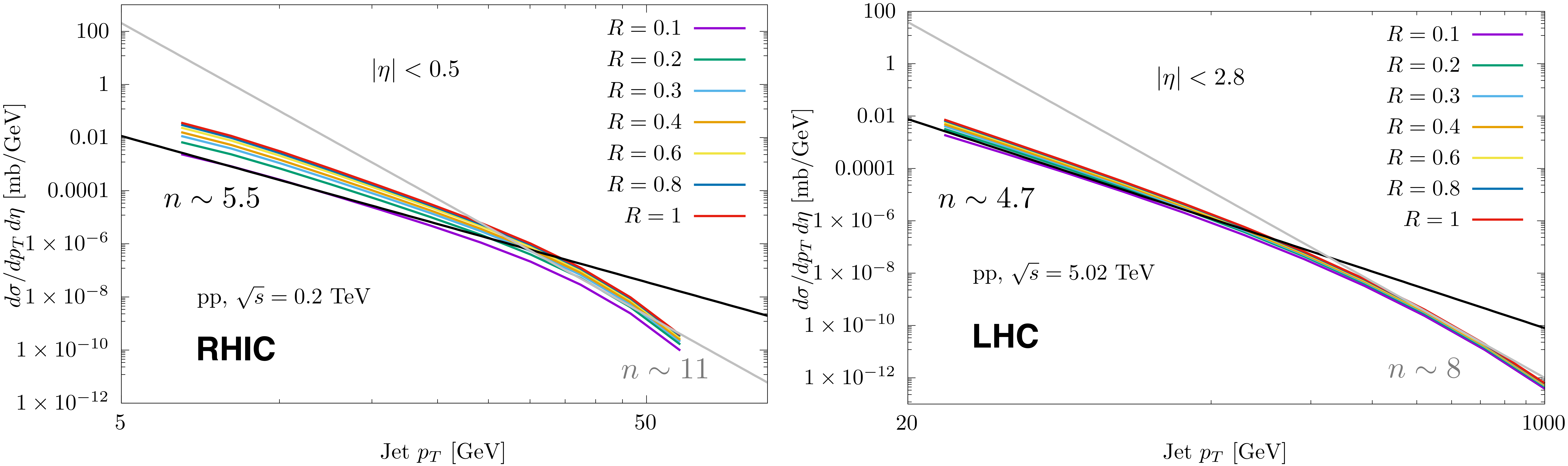
→ NLO contribution very small
(hard emissions tend to be collinear).

→ 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!)

RHIC vs LHC Vacuum Spectra

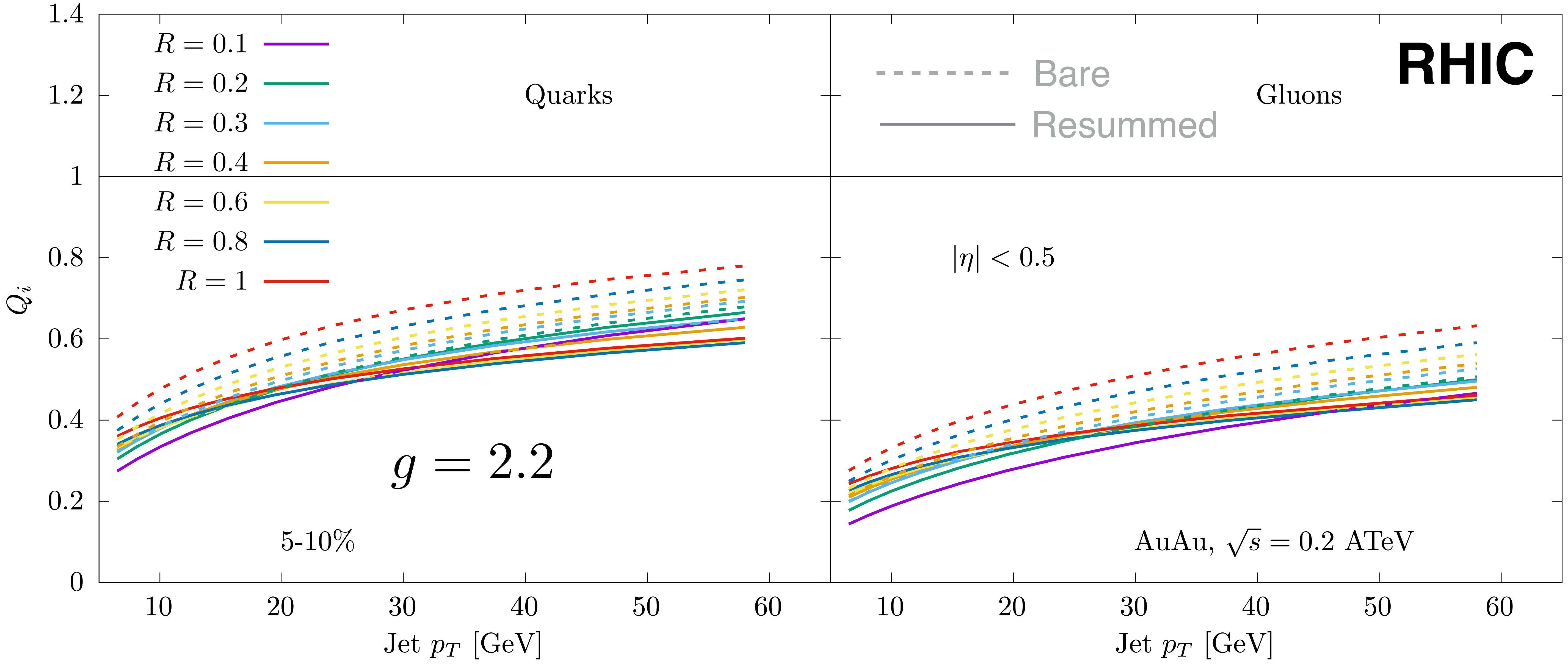


- Spectra increases with increasing R due to recapturing out-of-cone radiation.
- Steeper spectrum at RHIC energies, will push R_{AA} down.

RHIC vs LHC Vacuum Quark Fraction

- Quark-initiated jet fraction decreases with increasing R, as gluon-initiated jets are more active.
- Larger quark-initiated jet fraction at RHIC, should push total R_{AA} up.

RHIC vs LHC Quenching Factor

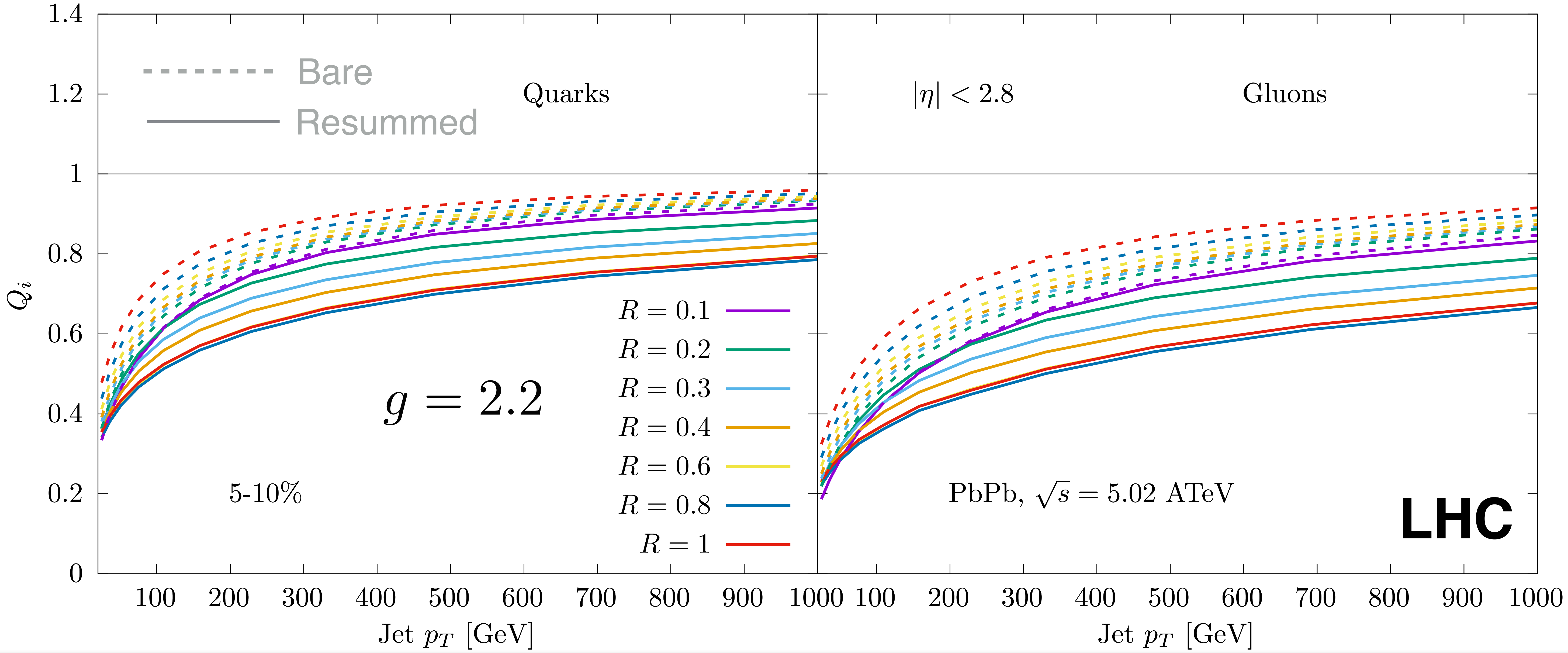


$$\langle \widehat{q}_0 \rangle^{\text{RHIC}} \simeq 0.25\,\text{GeV}^2/\text{fm}$$

$$\langle \widehat{q} \rangle^{\text{RHIC}} \simeq 1.22\,\text{GeV}^2/\text{fm}$$

$$\langle L \rangle^{\text{RHIC}} \simeq 4.5\,\text{fm}$$

- Similar quenching factors between LHC and RHIC (@ ~ p_T) when considering medium properties.
- Resummation more significant at LHC due to larger phase space.

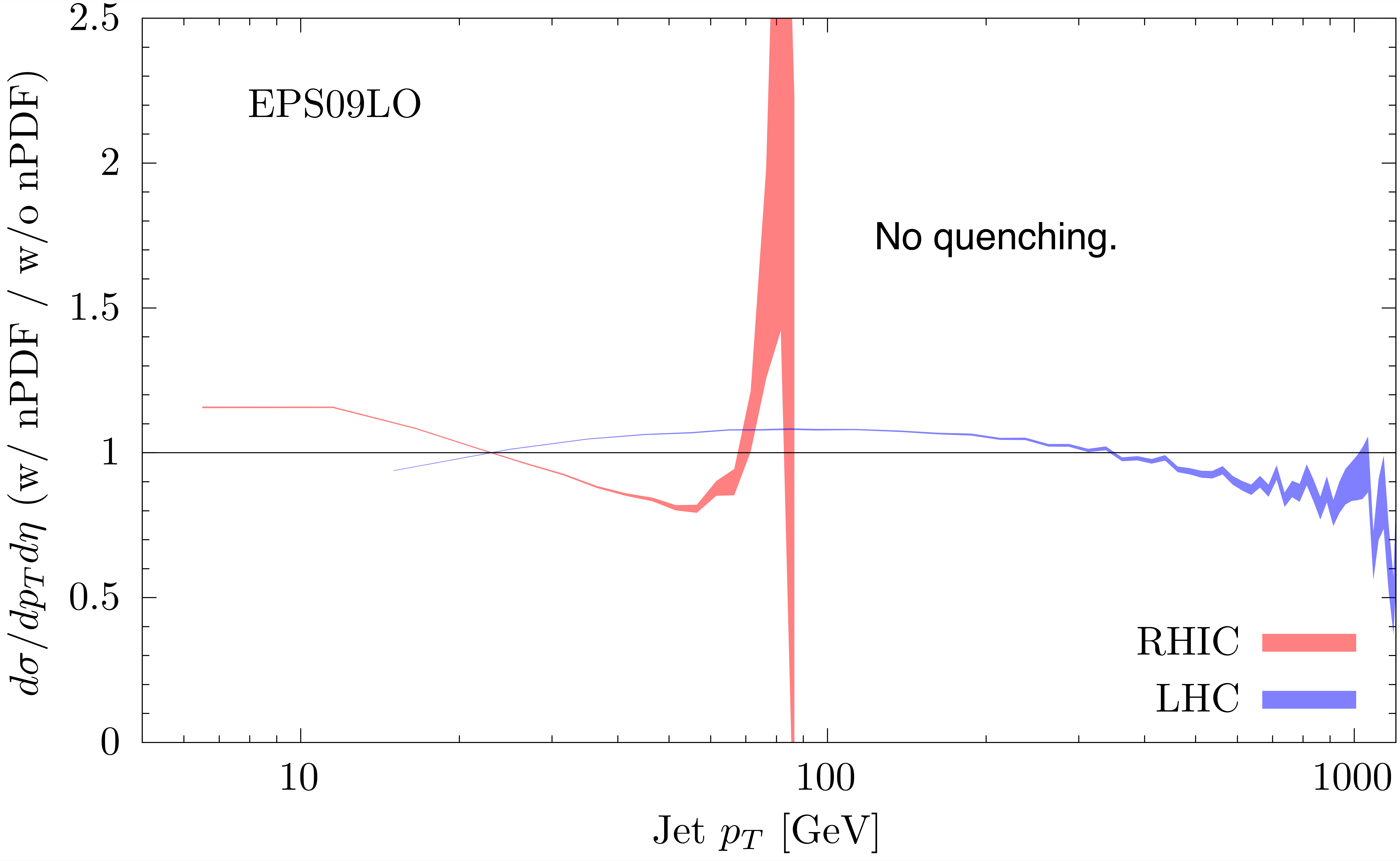


$$\langle \widehat{q}_0 \rangle^{\text{LHC}} \simeq 0.44\,\text{GeV}^2/\text{fm}$$

$$\langle \widehat{q} \rangle^{\text{LHC}} \simeq 2.34\,\text{GeV}^2/\text{fm}$$

$$\langle L \rangle^{\text{LHC}} \simeq 5.6\,\text{fm}$$

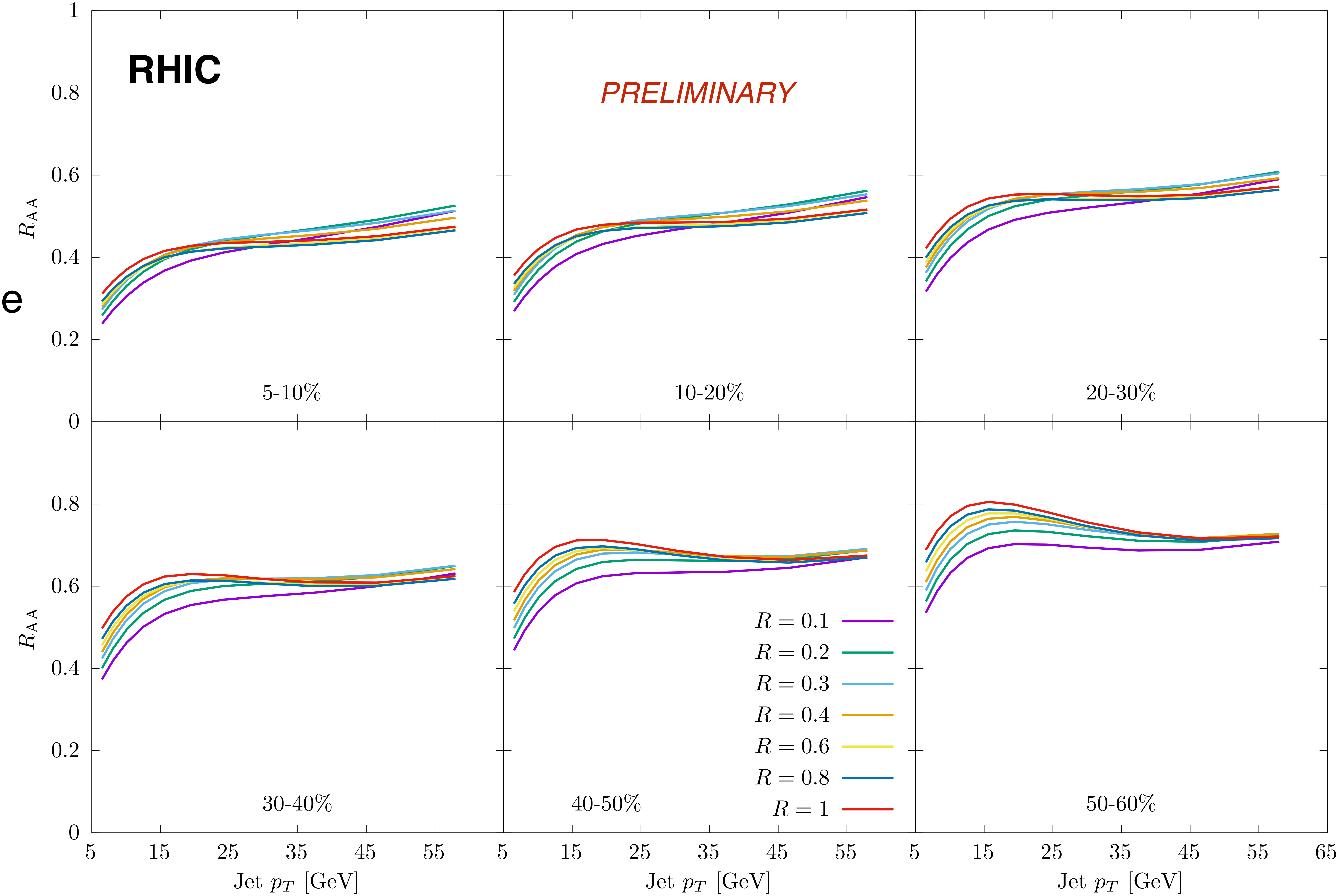
Effect of Nuclear PDF



Jet R_{AA} at RHIC

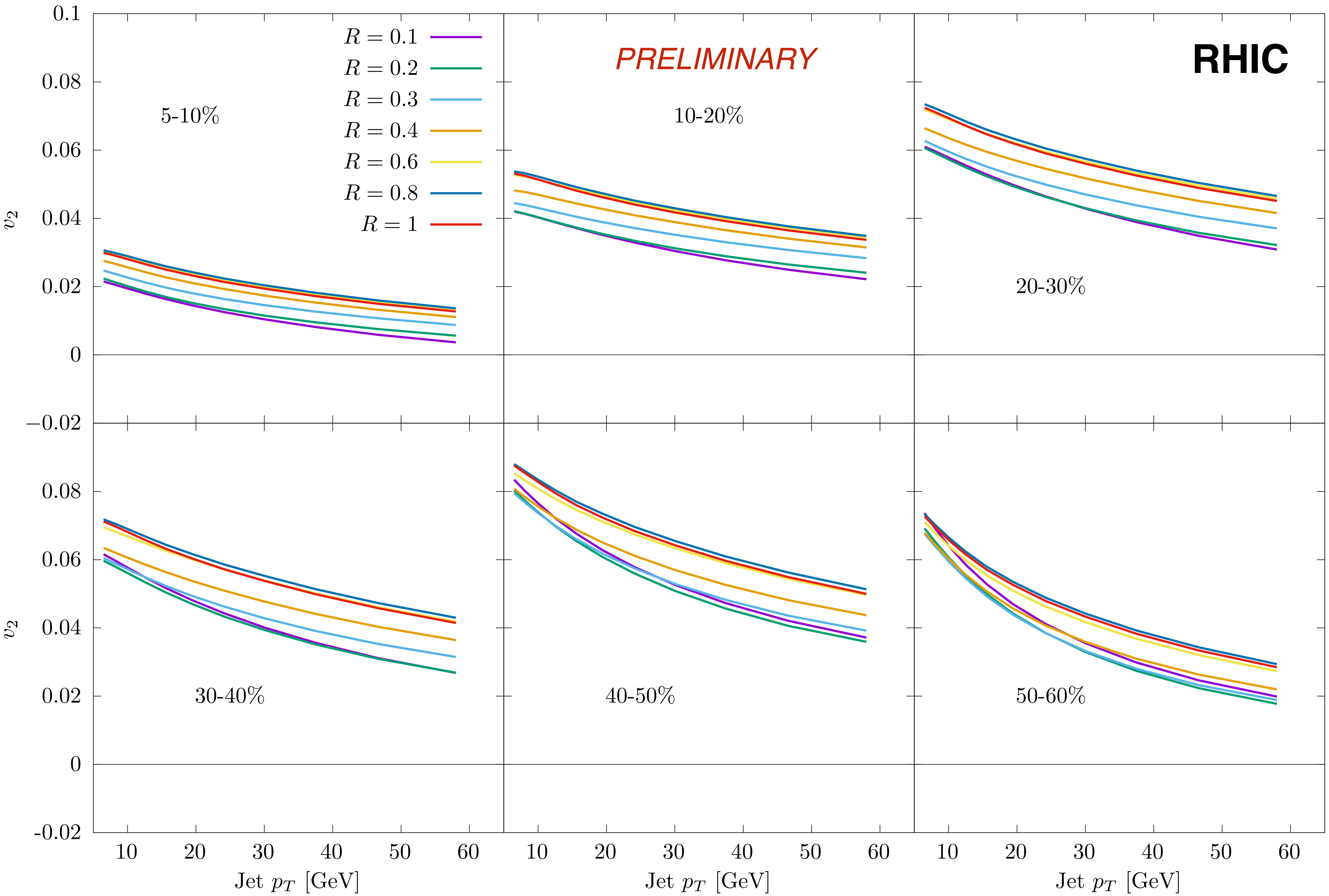
- Even milder R dependence than at LHC.

- In agreement with STAR data.



Jet v_2 at RHIC

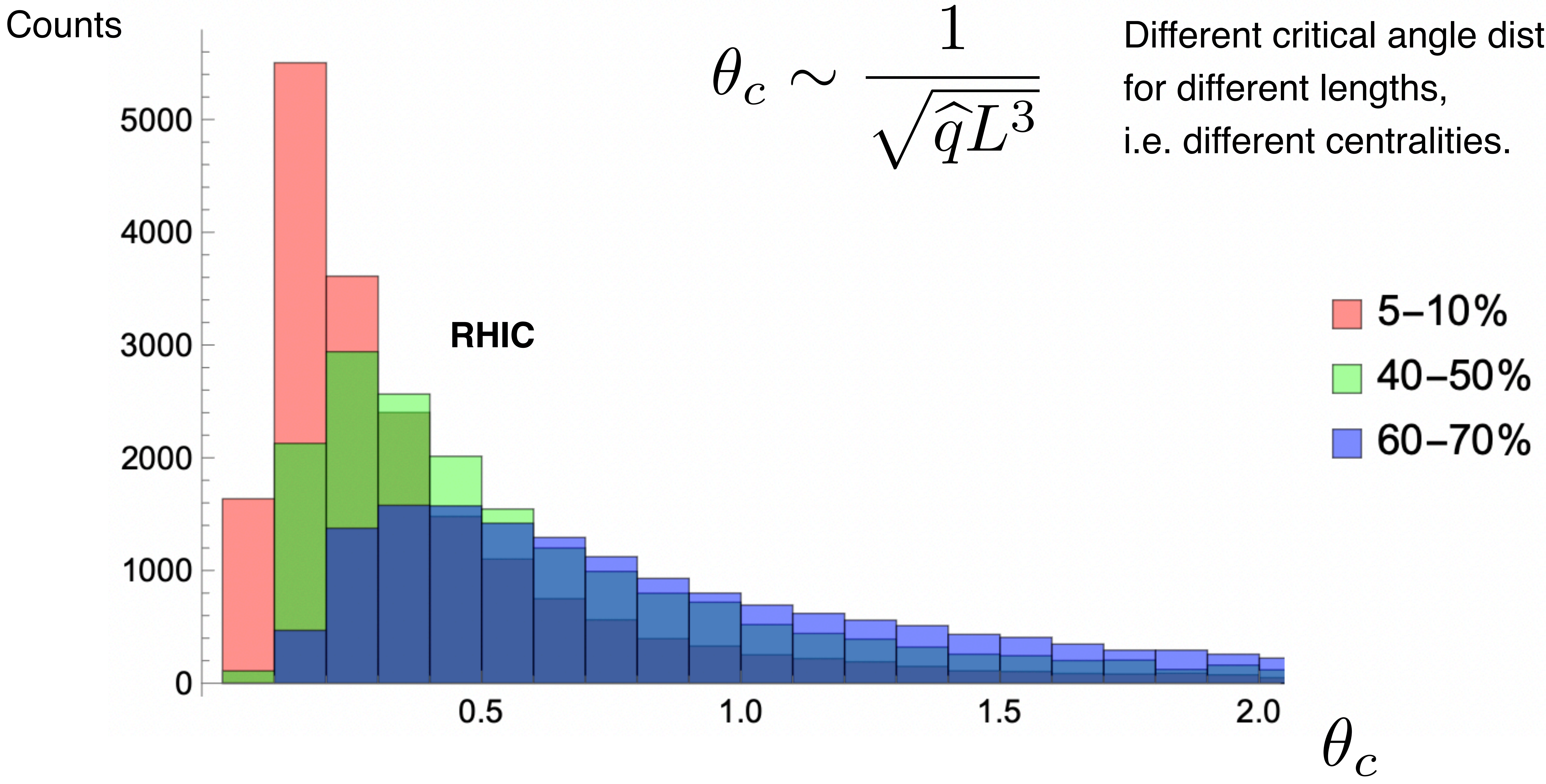
- Interesting grouping in v_2 for different R.
- R=0.3, and especially R=0.4, migrate as a function of centrality.



Coherence vs. Centrality

$$\theta_c \sim \frac{1}{\sqrt{\hat{q} L^3}}$$

Different critical angle dists.
for different lengths,
i.e. different centralities.

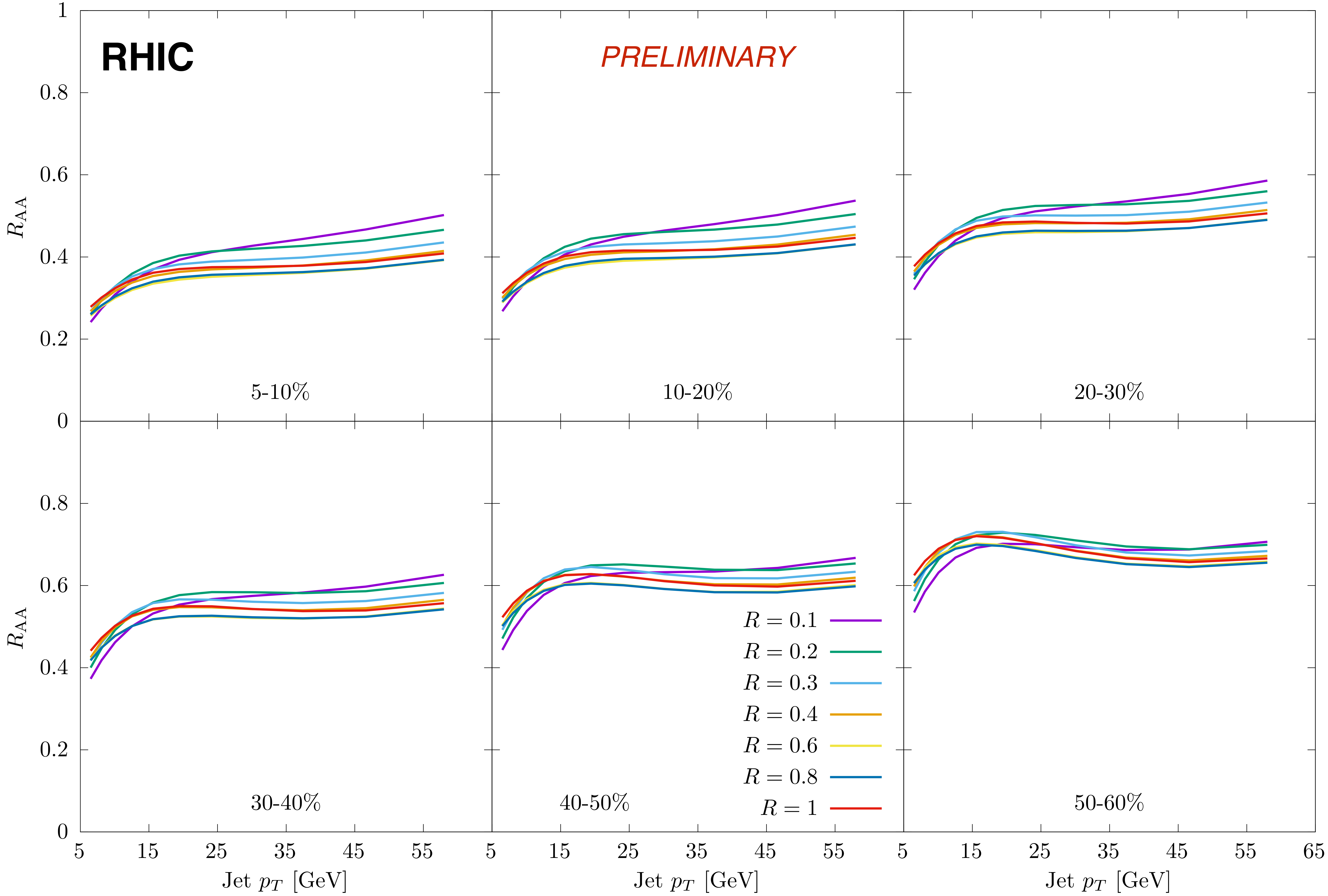


Jet R_{AA} at RHIC - No Coherence

$$\theta_c \to 0$$

- Remove effects of coherence.

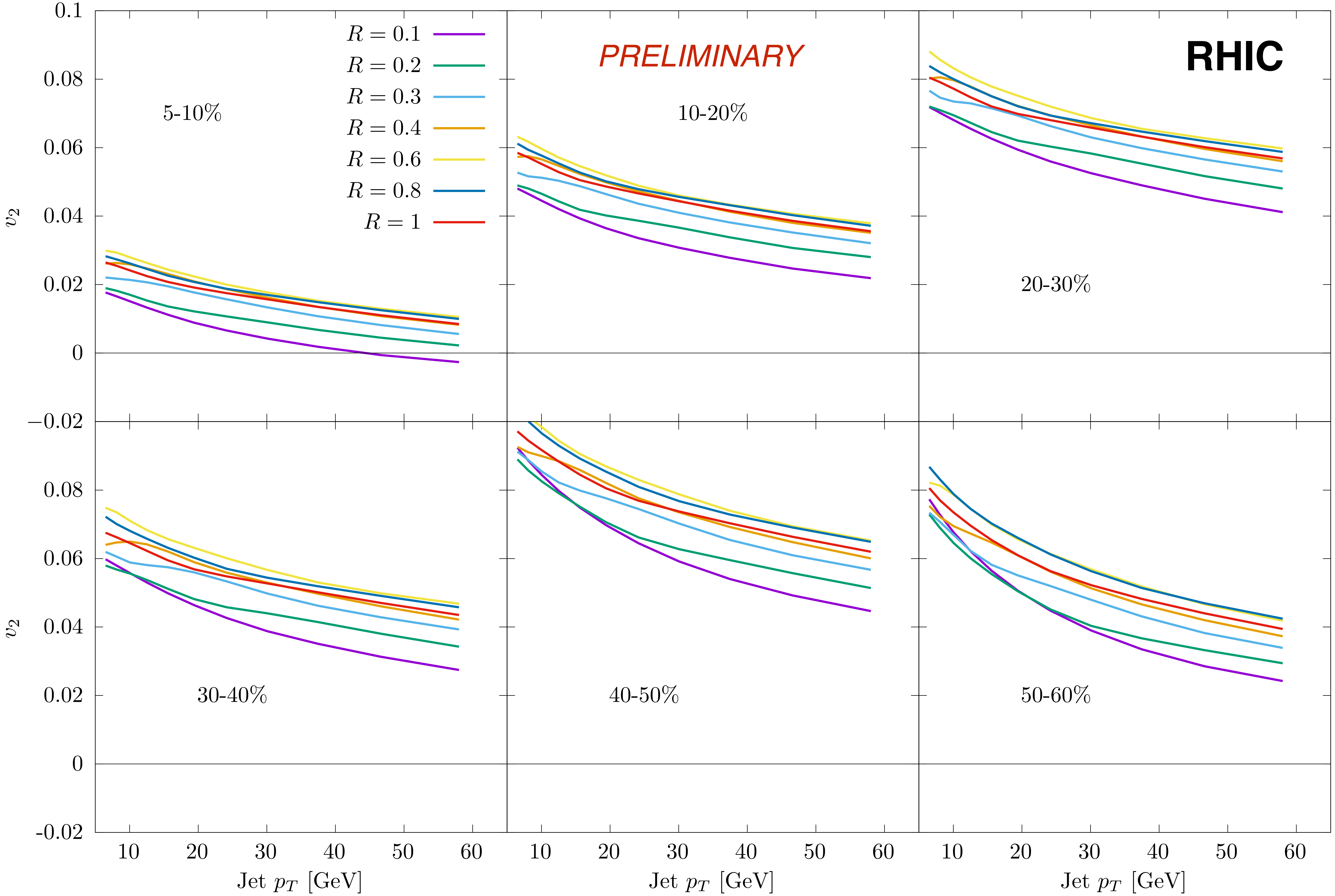
➔ Larger R tend to be more suppressed than w/ coherence.



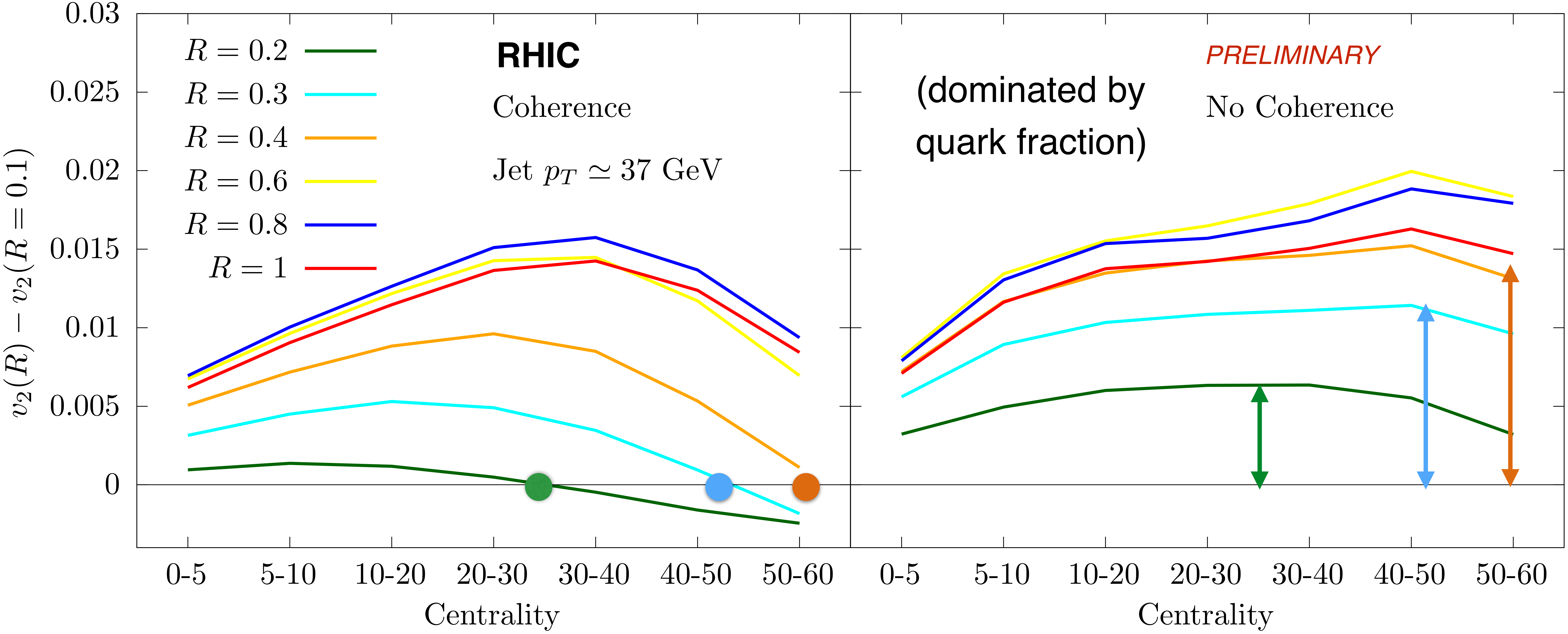
Jet v_2 at RHIC - No Coherence

$$\theta_c \to 0$$

- Less grouping, especially for smaller R.
- No migration of R=0.3 or R=0.4.

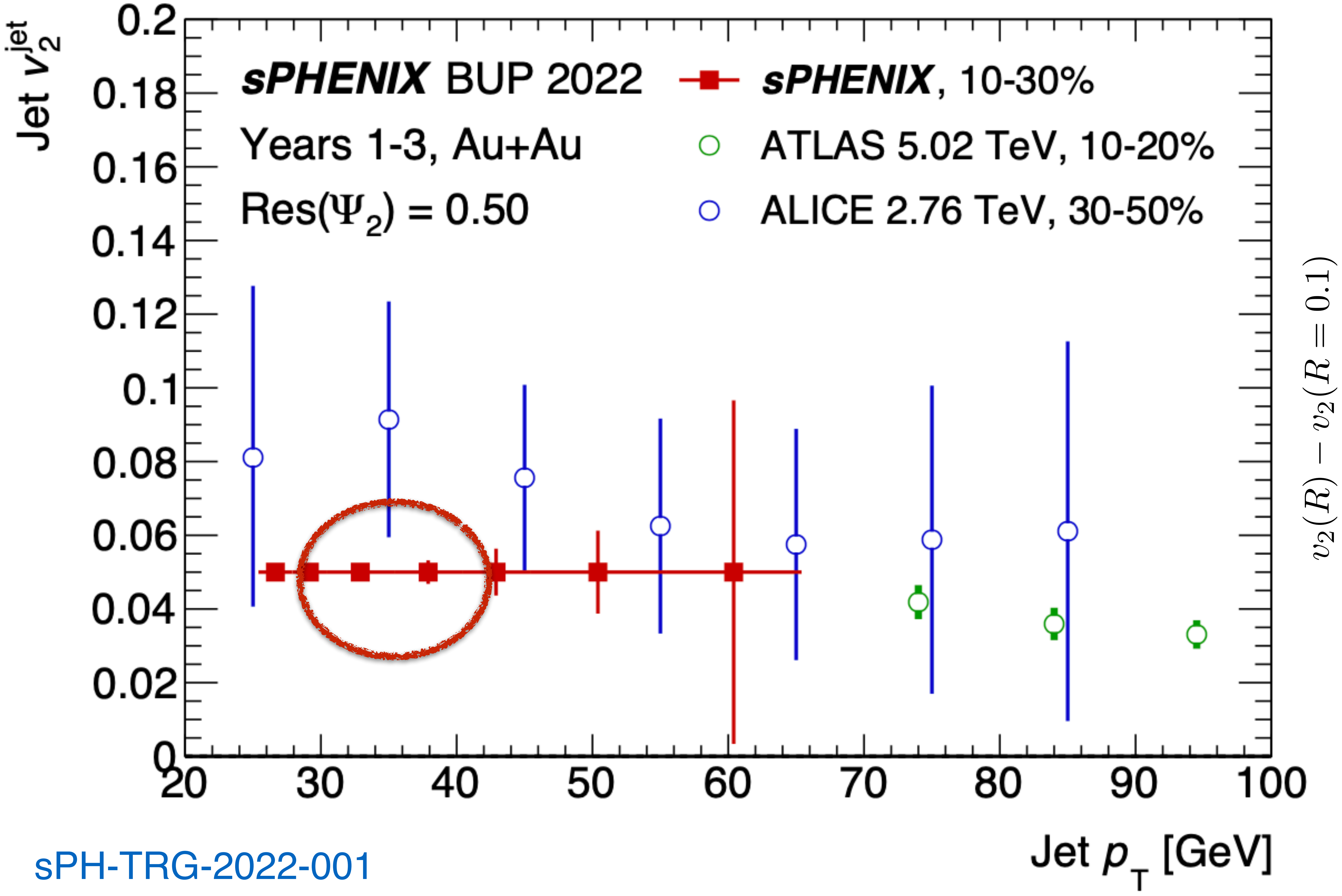


Jet v_2 & Coherence Effects



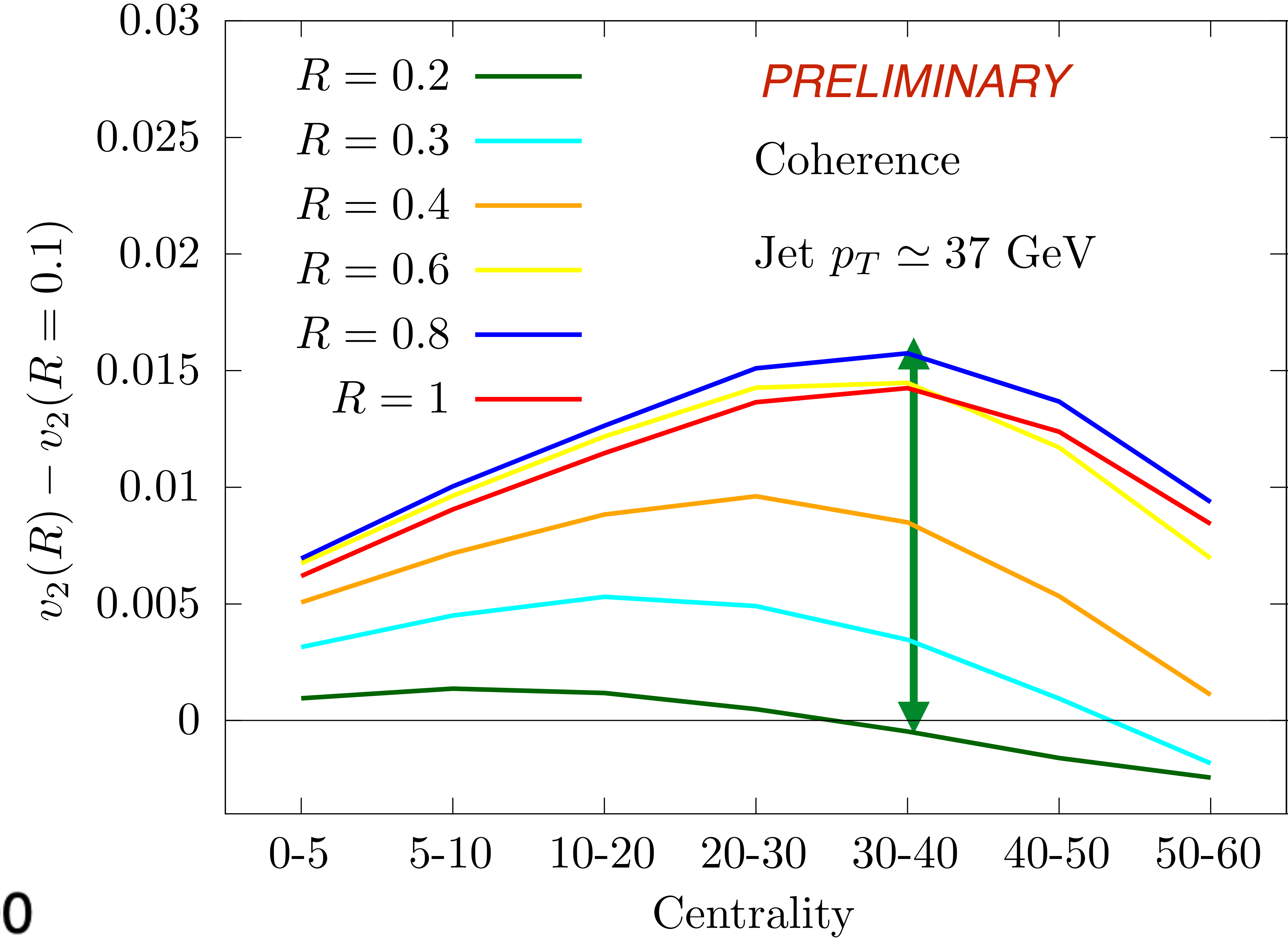
Effect up to differences in v_2 of 0.015.

Jet v_2 & Coherence Effects



sPH-TRG-2022-001

RHIC

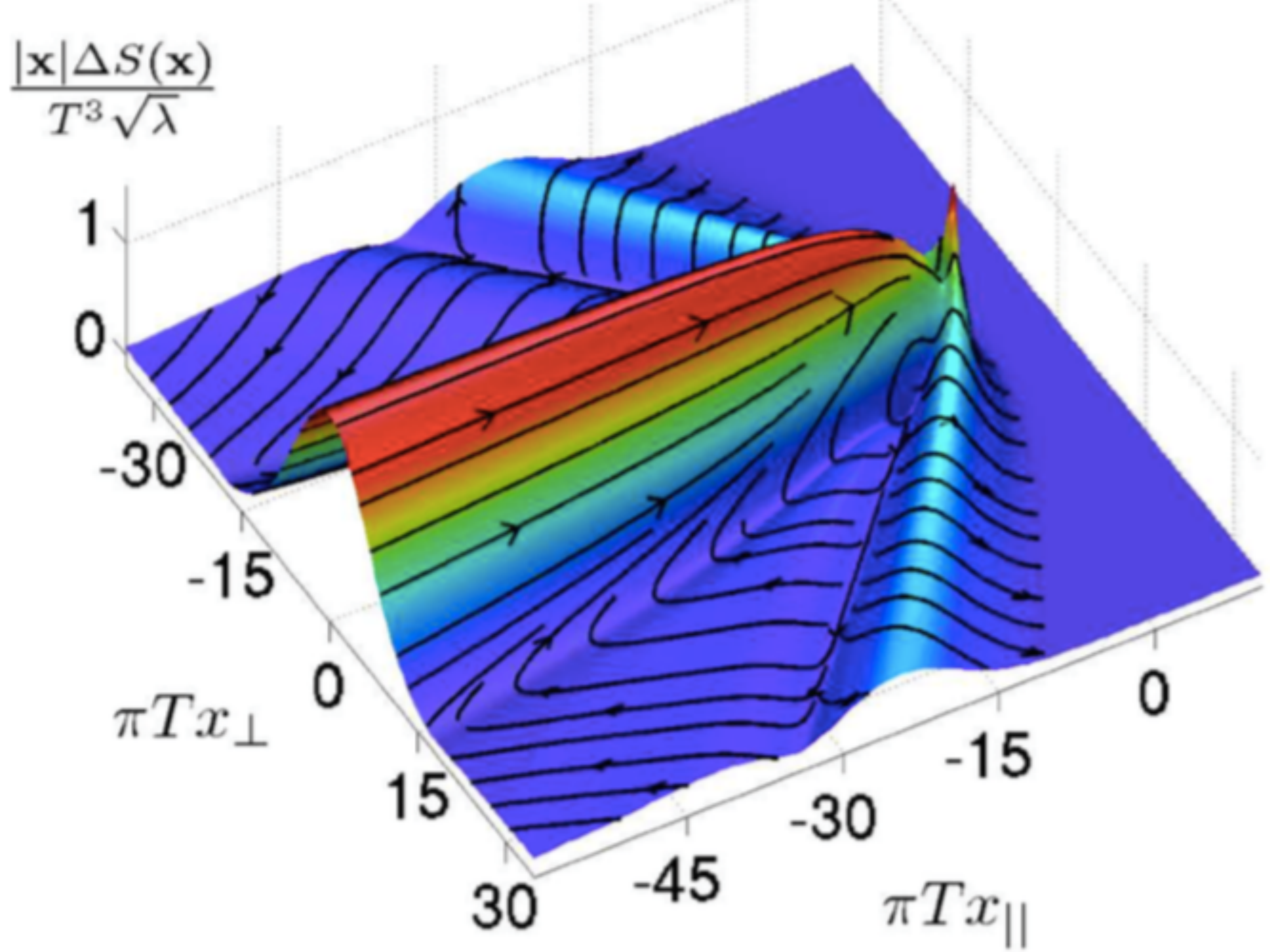


Effect up to differences in v_2 of 0.015.

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:

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

$$\Delta P^i_\perp = w\,\tau\int d^2x_\perp\,d\eta\,\delta u^i_\perp$$

Velocity pert.

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

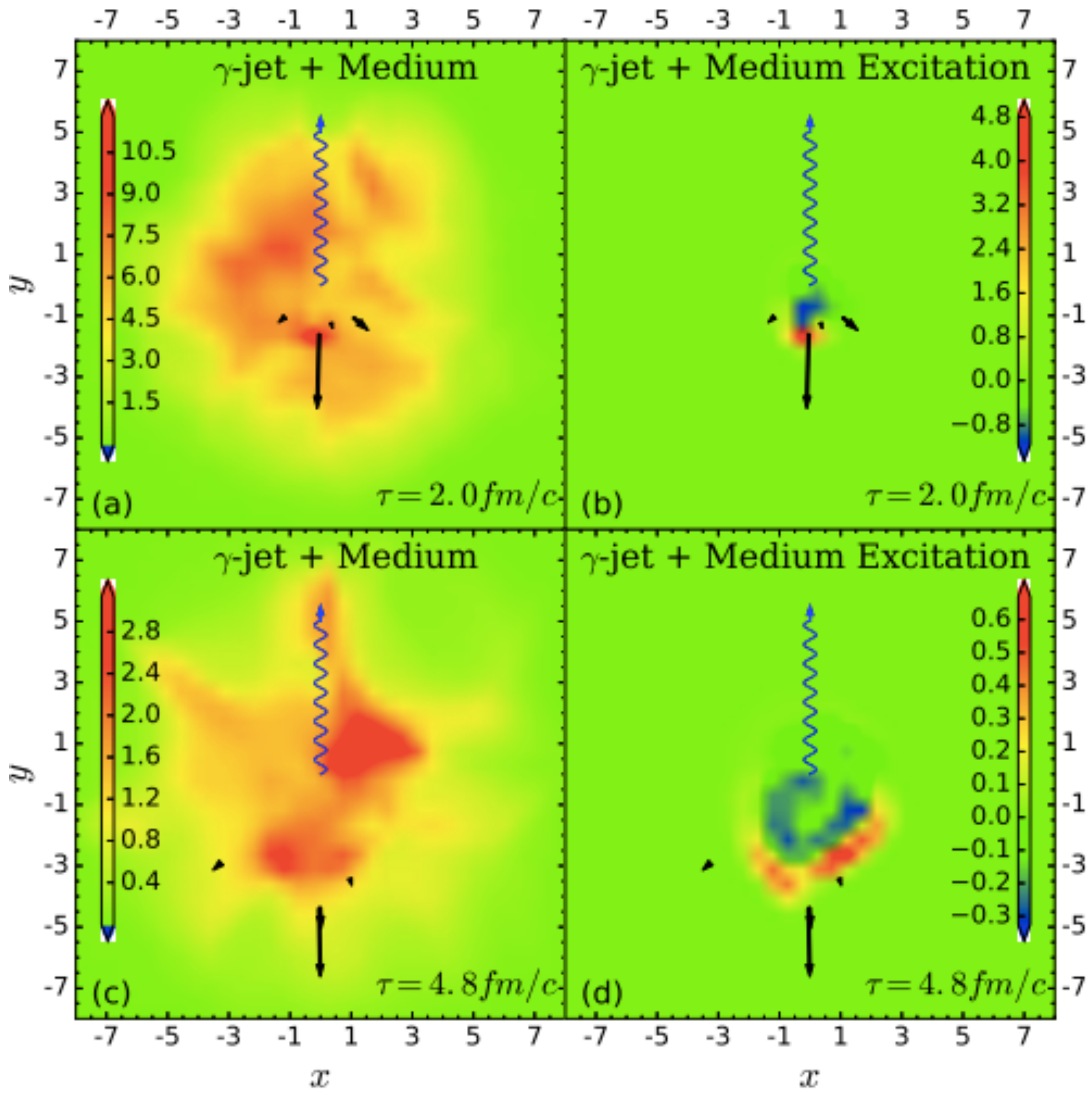
Temperature pert.

✓ Fully constrained by energy-momentum conservation.

✓ Computationally efficient.

✗ Neglects important effects from local flow.

The Diffusion Wake

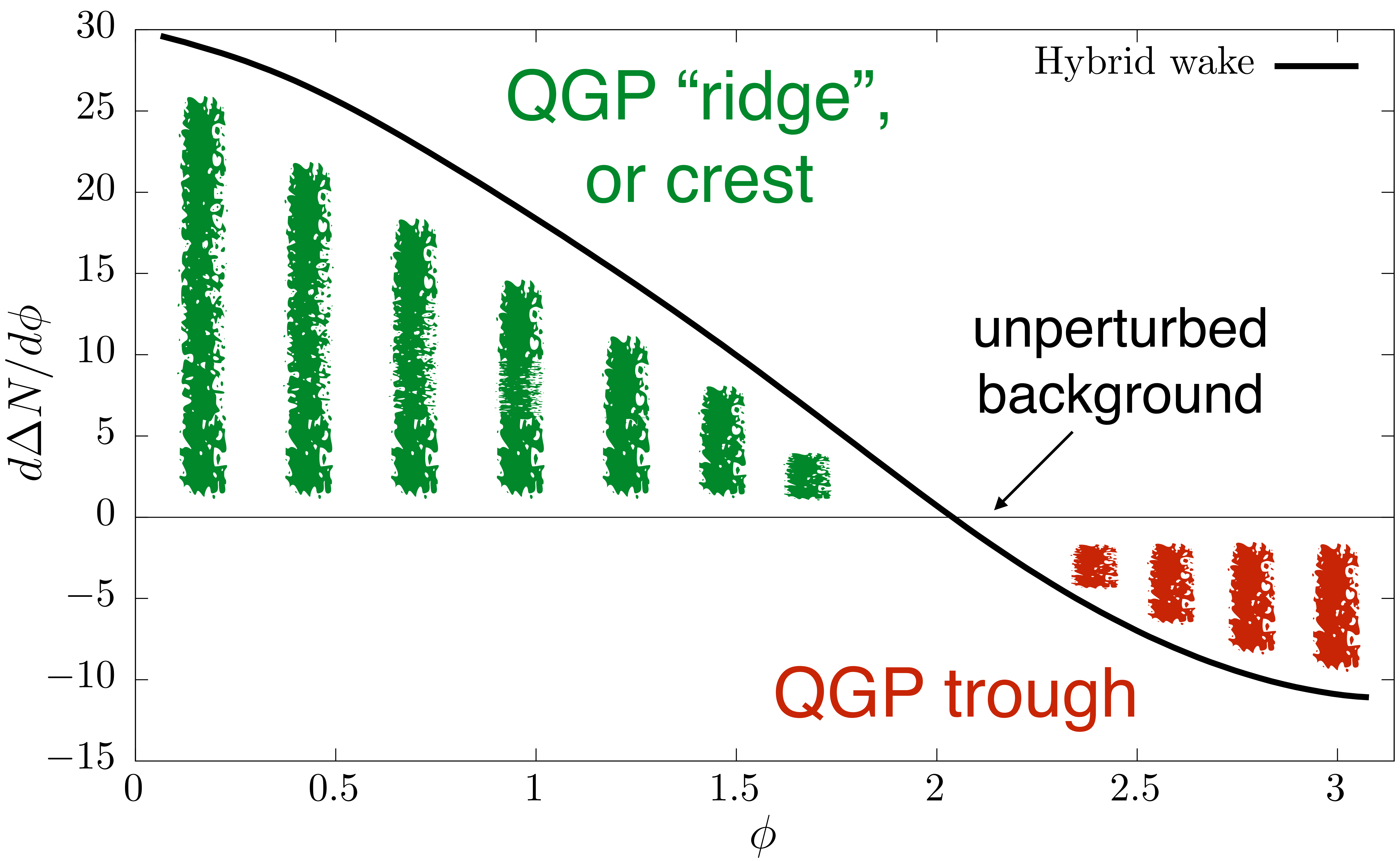


Chen et al. - PLB ‘18

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).

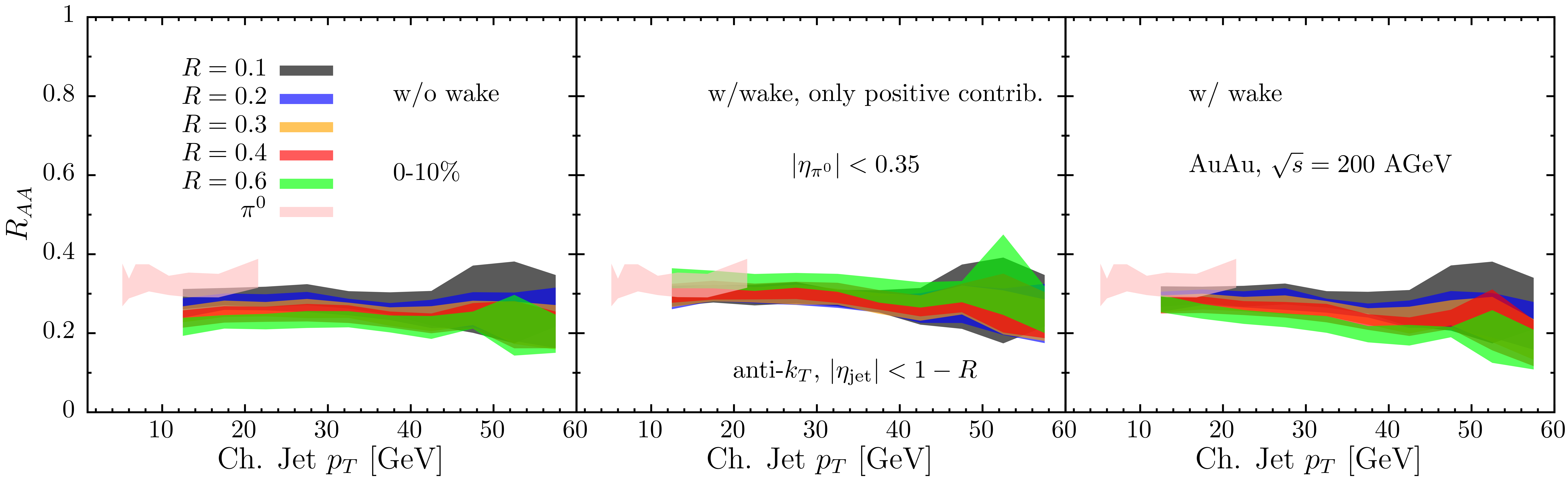


QGP “ridge”, or crest

unperturbed background

QGP trough

Jet R_{AA} at RHIC with Hybrid Model



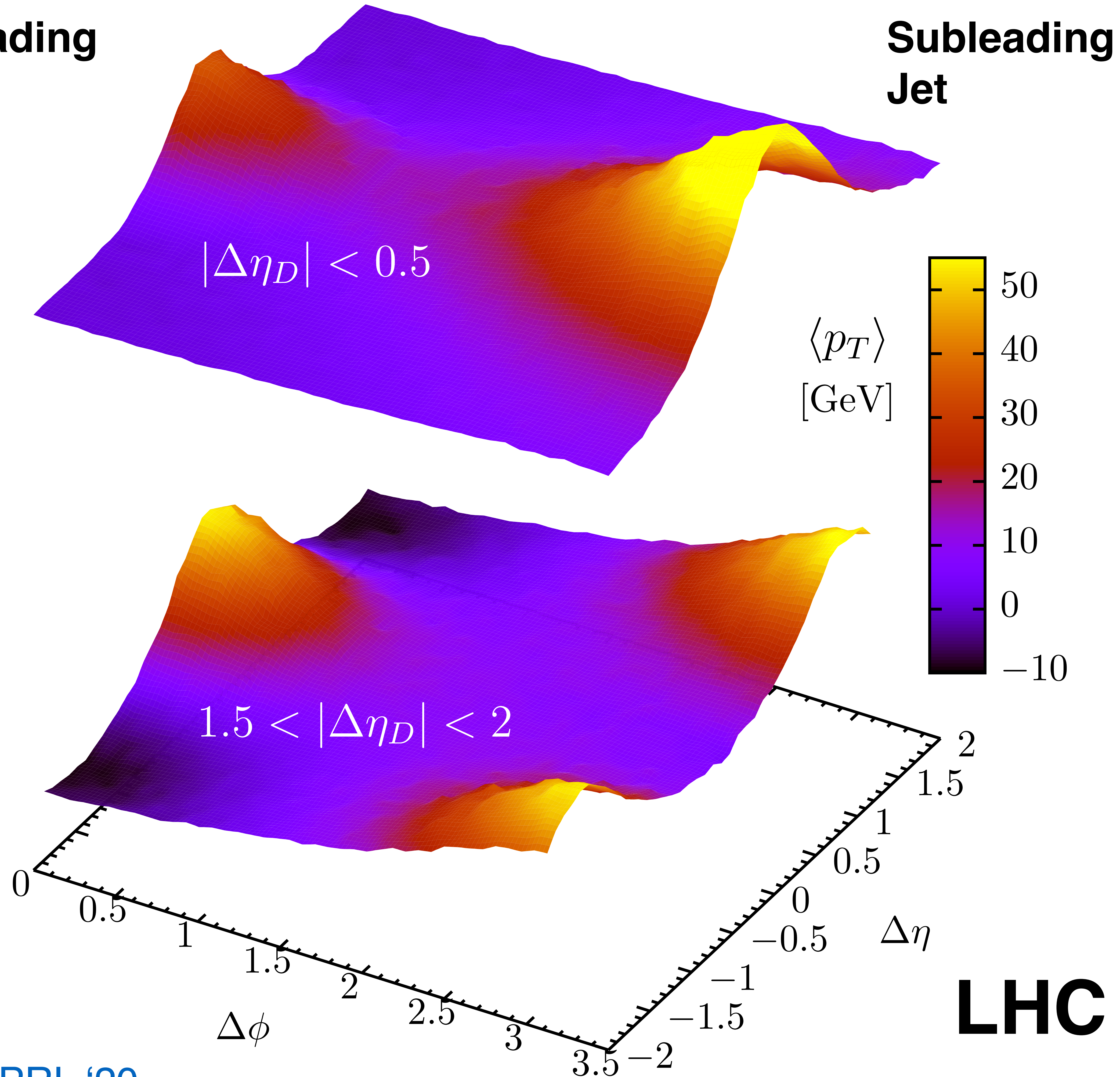
No wake:
Increasing R leads to more energy loss.

QGP ridge only:
Partial recovery of energy yields mild R dependence.

w/ QGP trough also:
extra suppression due to diffusion wake.

DP - HP '20

The Effect of the Recoiling Jet



LHC

$\langle p_T \rangle$ 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.

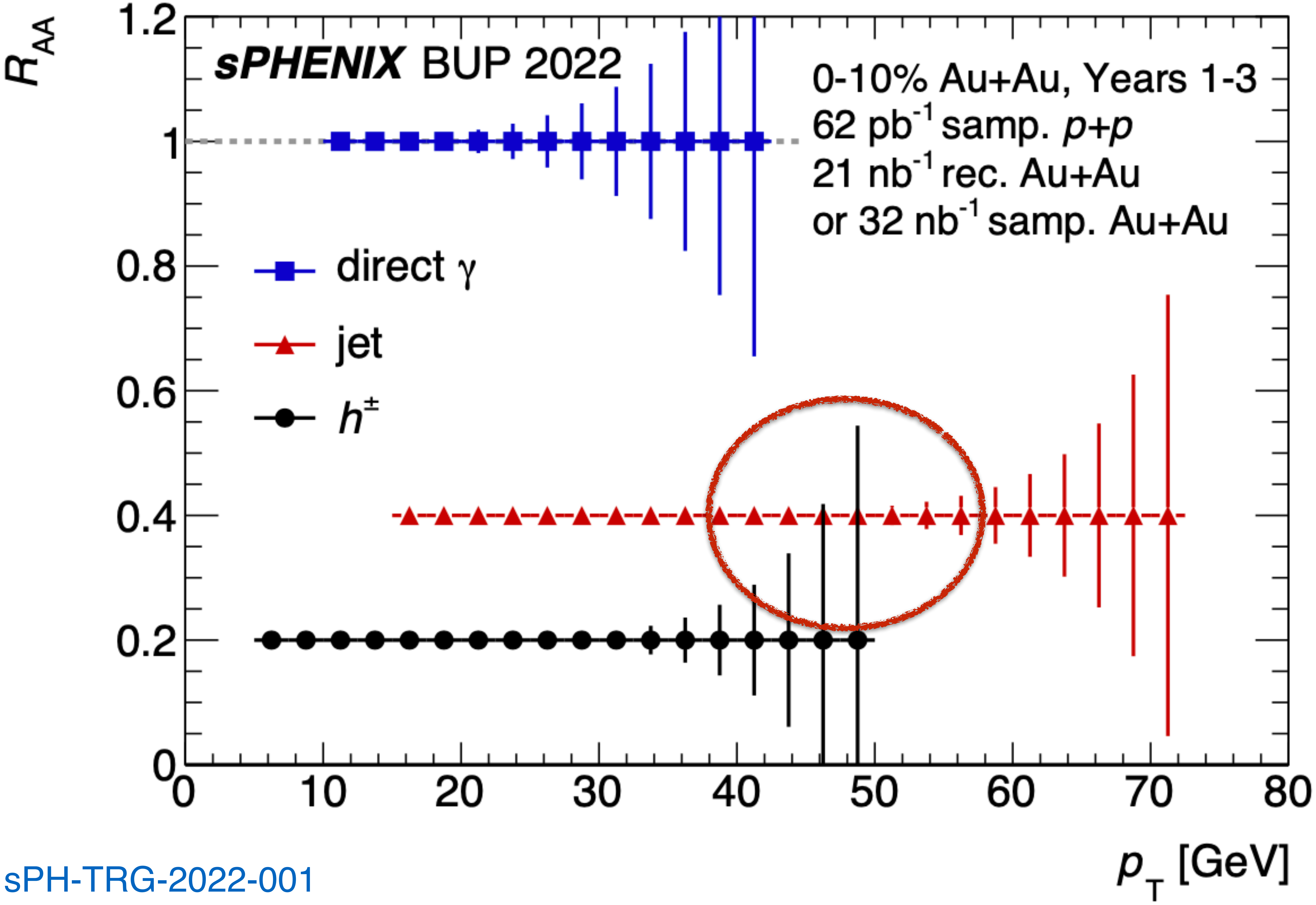
$$p_T^L > 250 \text{ GeV}$$
$$p_T^S > 80 \text{ GeV}$$
$$\Delta\phi_D > 2\pi/3$$

differential in

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

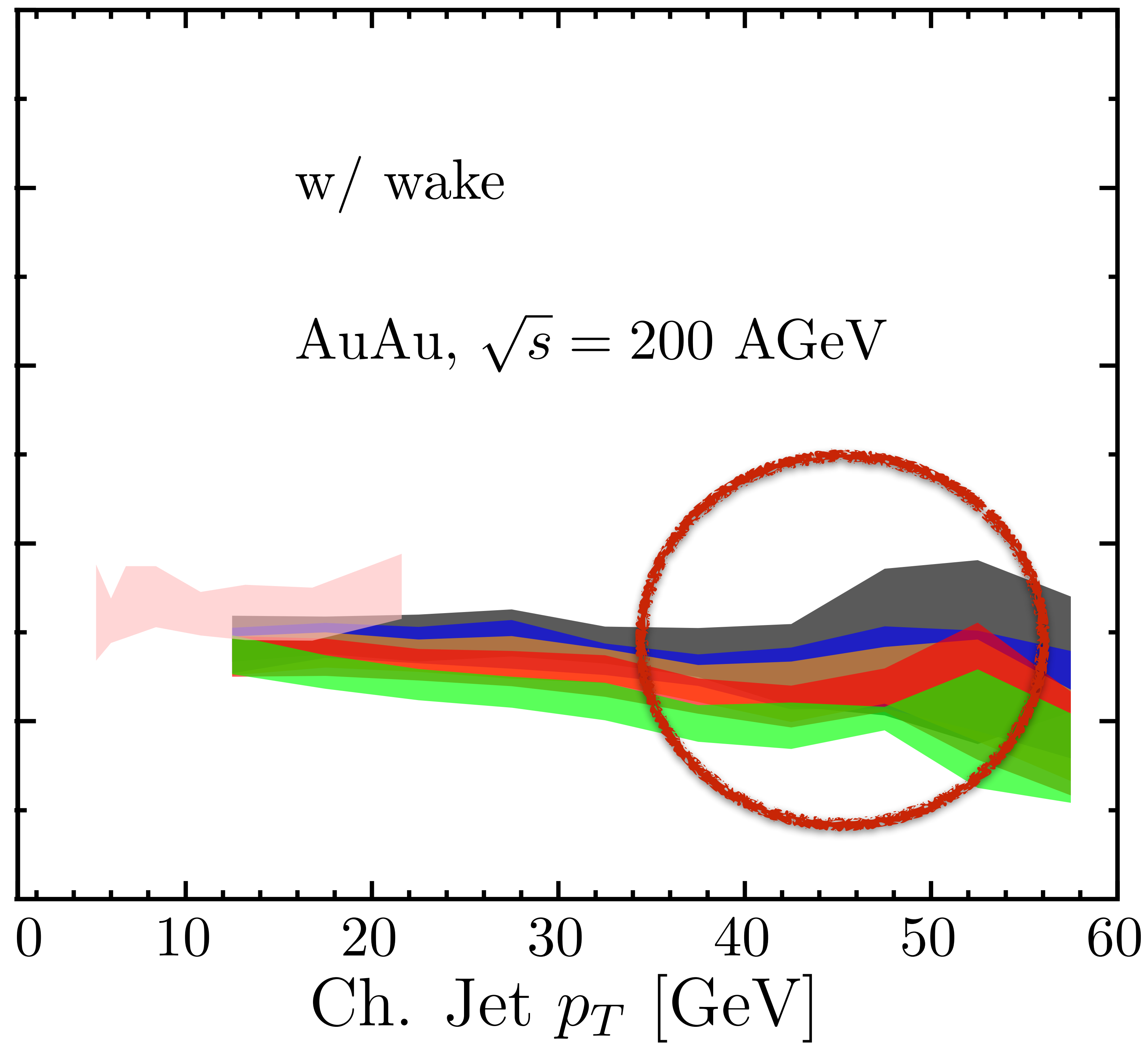
DP - PRL '20

Jet R_{AA} at sPHENIX



sPH-TRG-2022-001

DP - HP '20



Stronger effect of diffusion wake at RHIC than LHC:

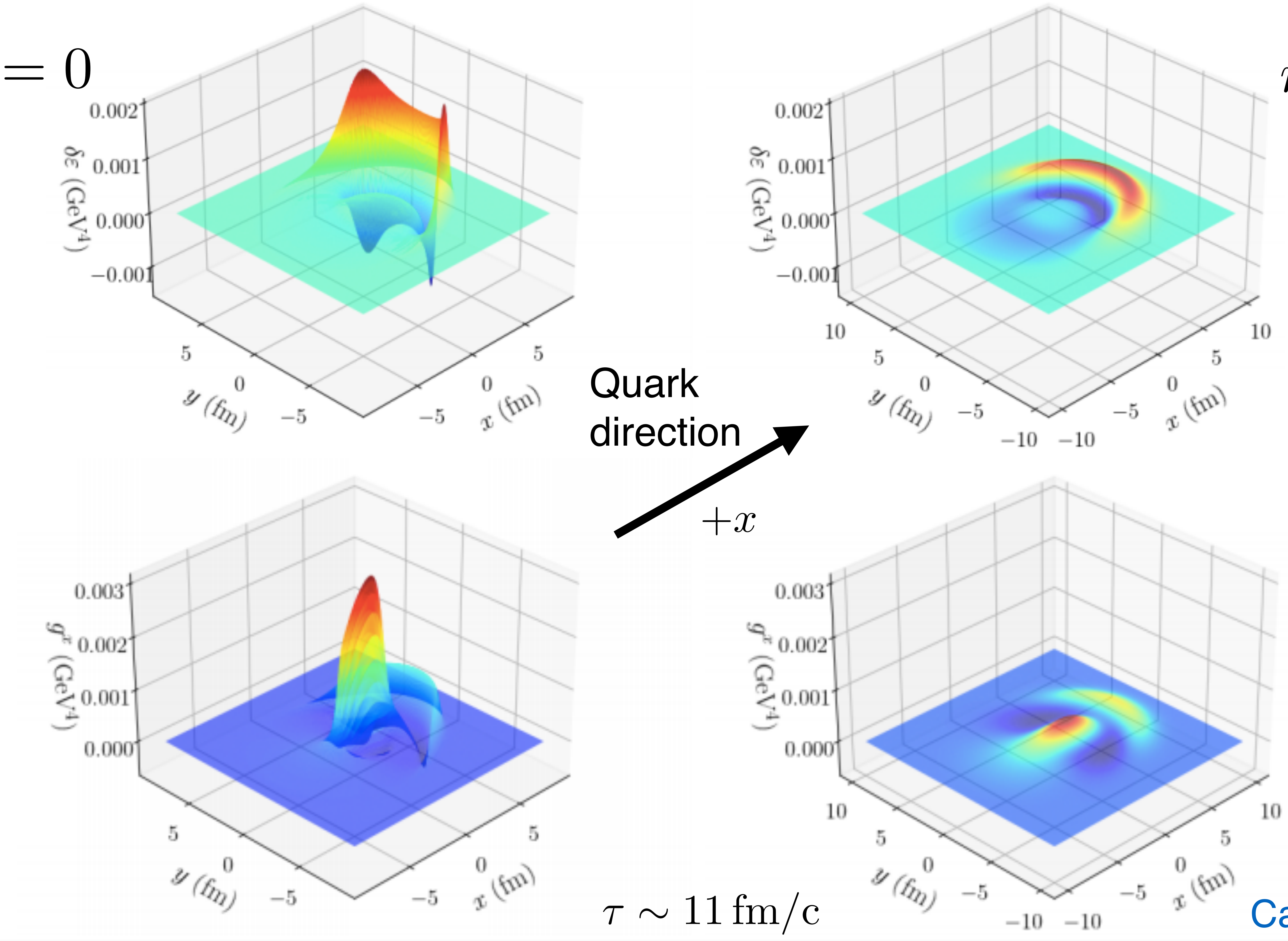
- Smaller rapidity gap.
- Steeper spectrum.
- Smaller p_T.

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.

$\eta = 0$

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



$\tau \sim 11\,\mathrm{fm}/c$

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

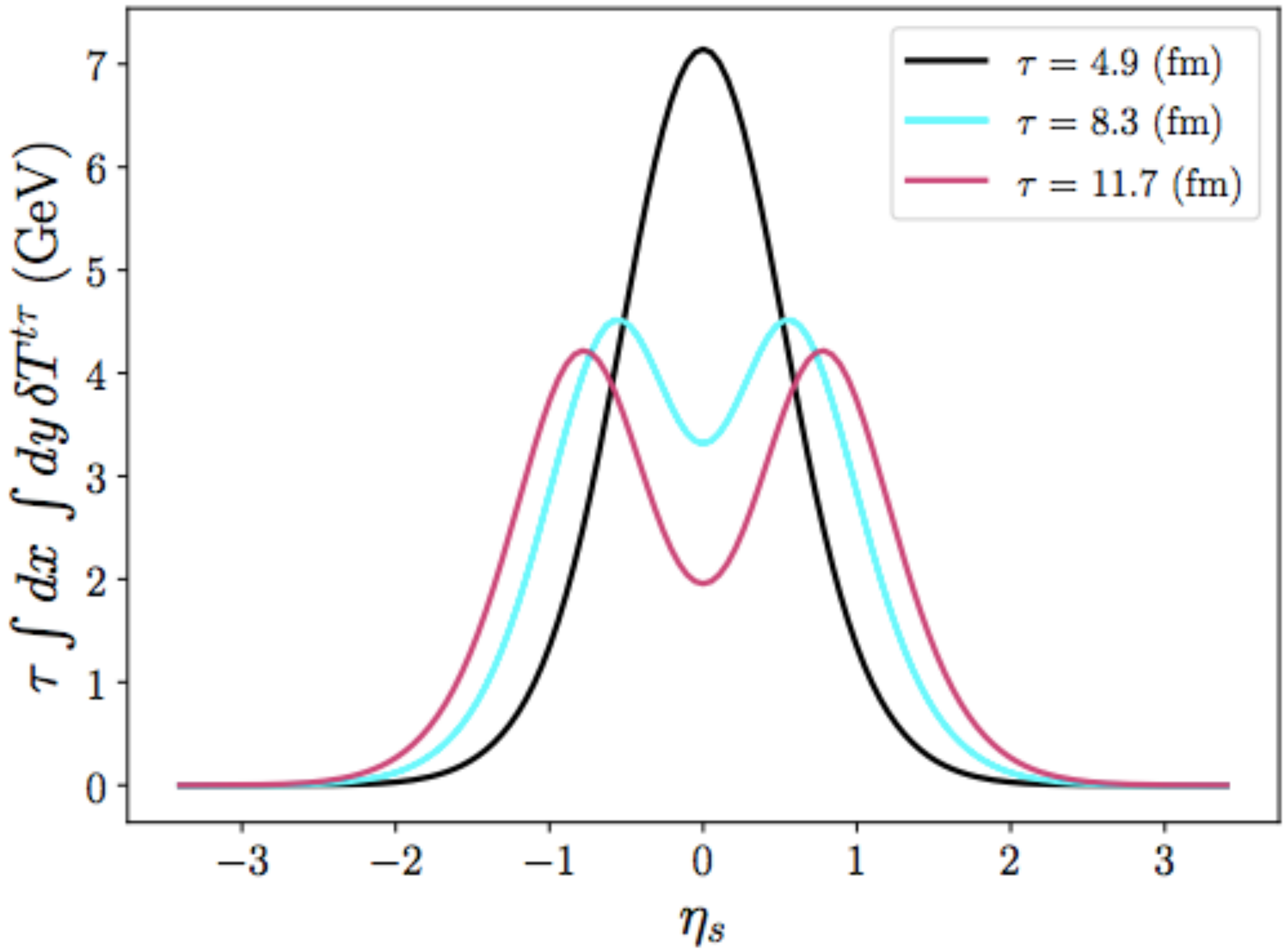
  Wavefront structure (Mach cone) diffuses due to viscosity.

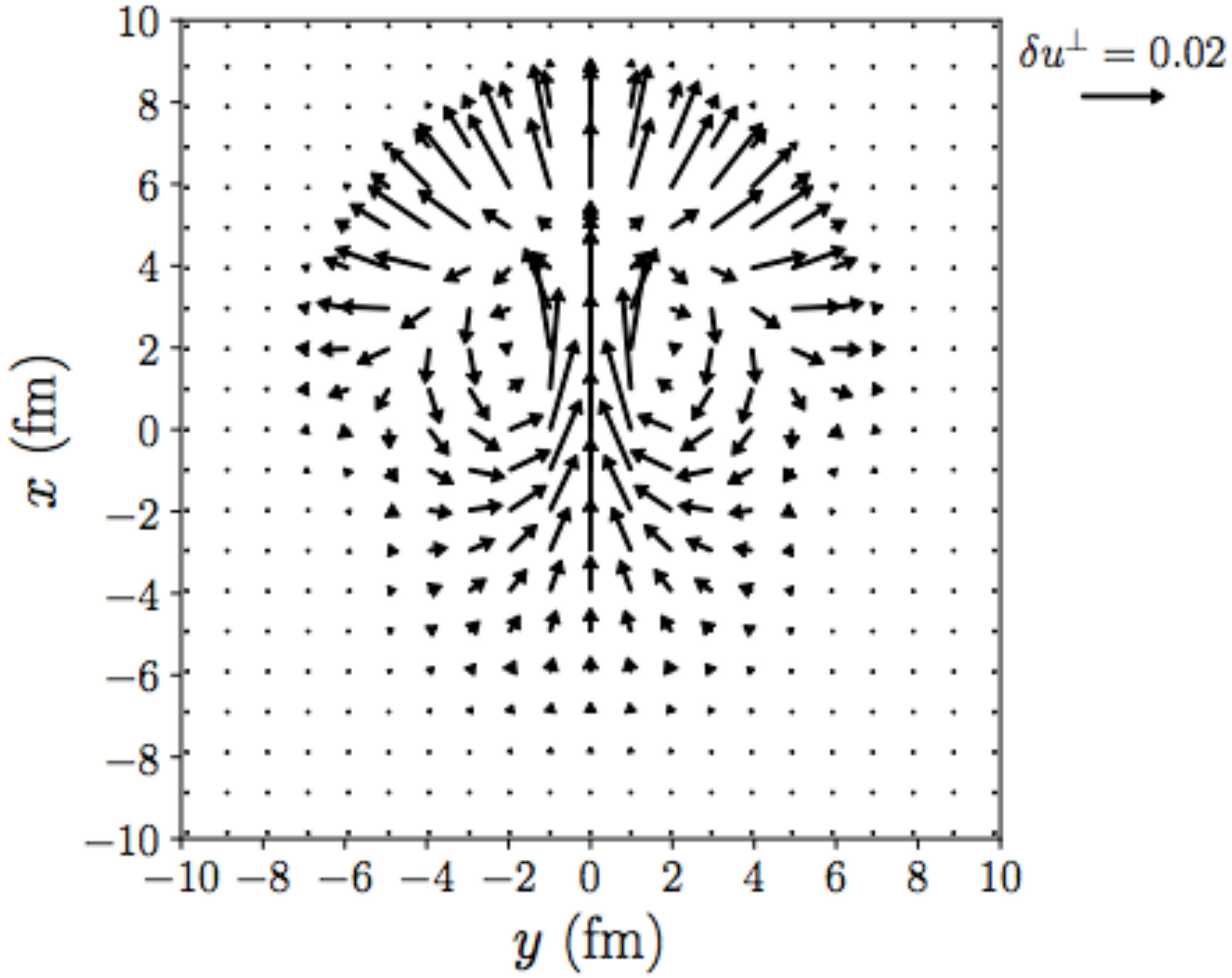
- g_x : momentum pert.

  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?

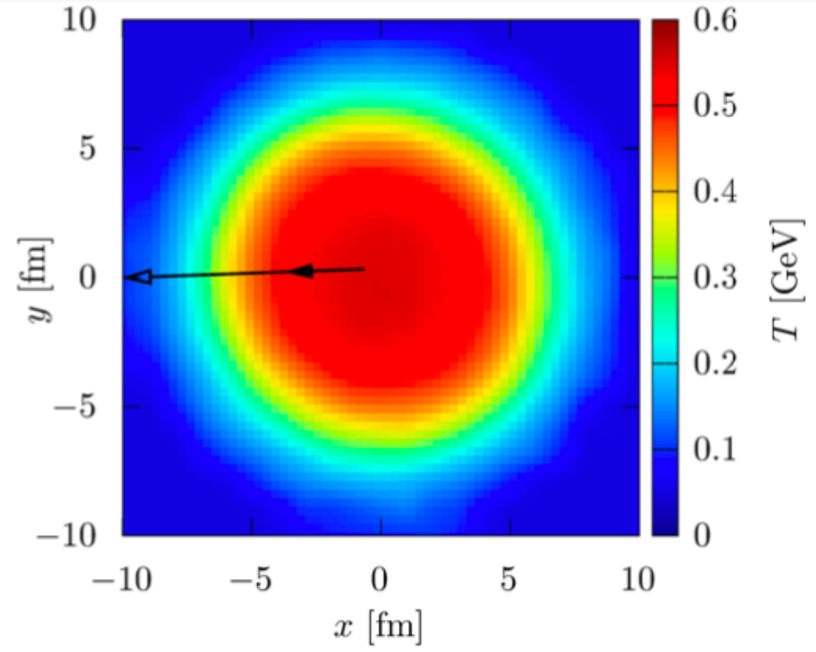
Serenone et al. - PLB ‘21

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

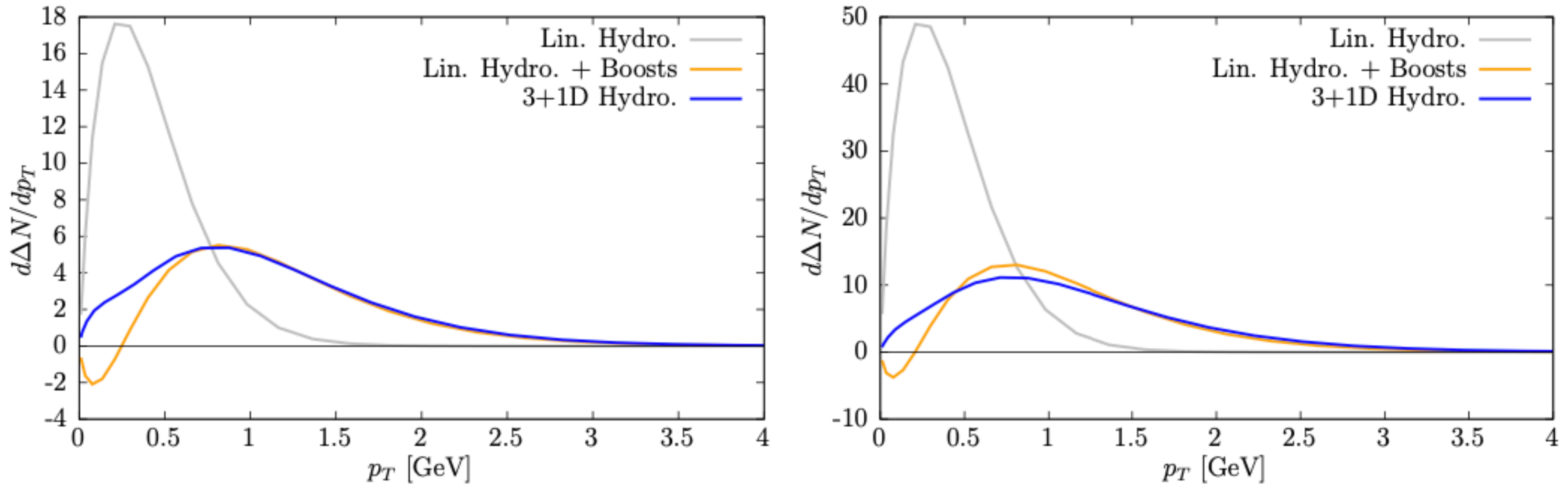
Efficient Computations of the Wake

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

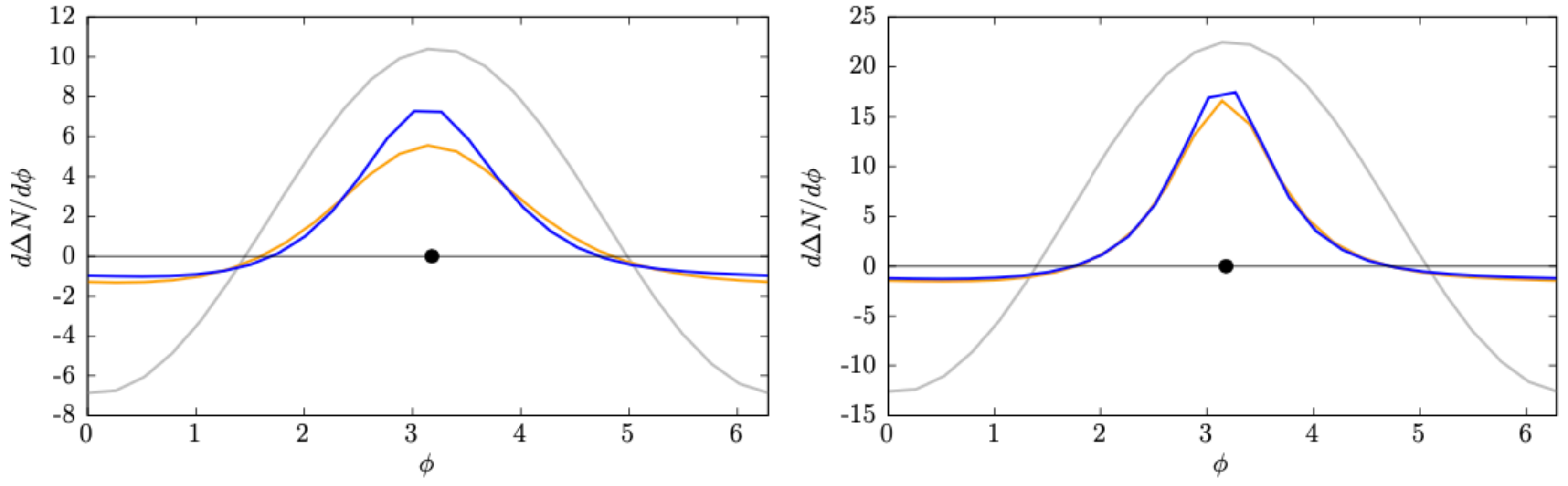
Hadrons from the wake
depend on evolution time, local flow…
thousands of possibilities.



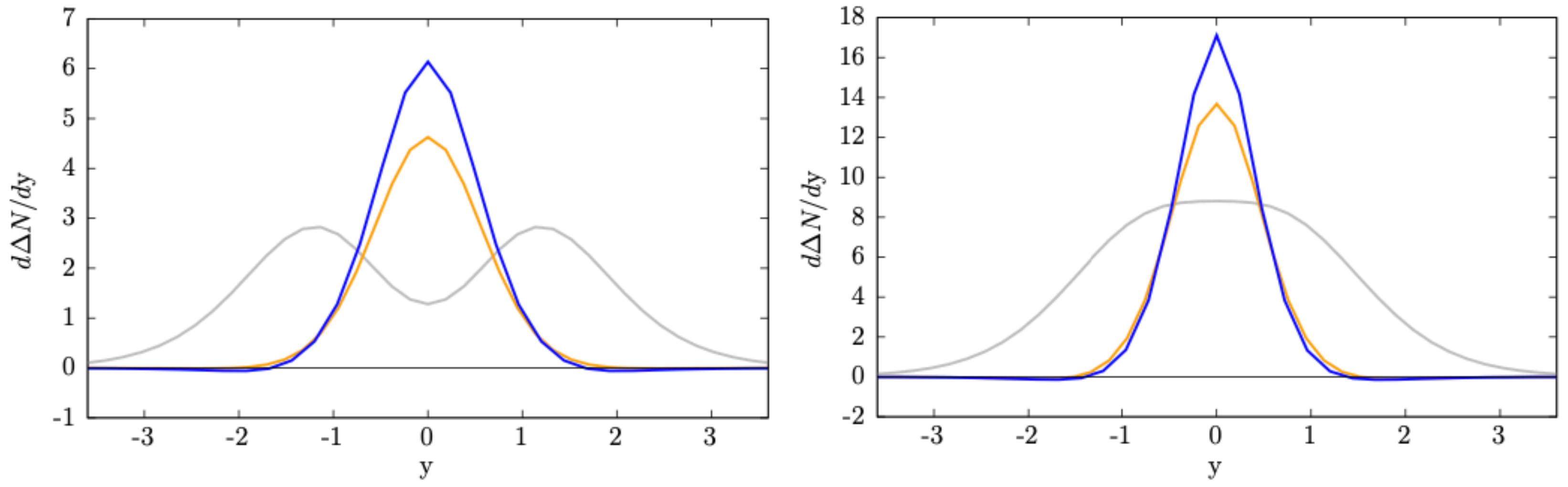
(a) Energy-momentum deposition for $E_i = 10$ GeV (filled arrow) and $E_i = 50$ GeV (empty arrow).



(b) p_T distribution for $E_i = 10$ GeV. (c) p_T distribution for $E_i = 50$ GeV.



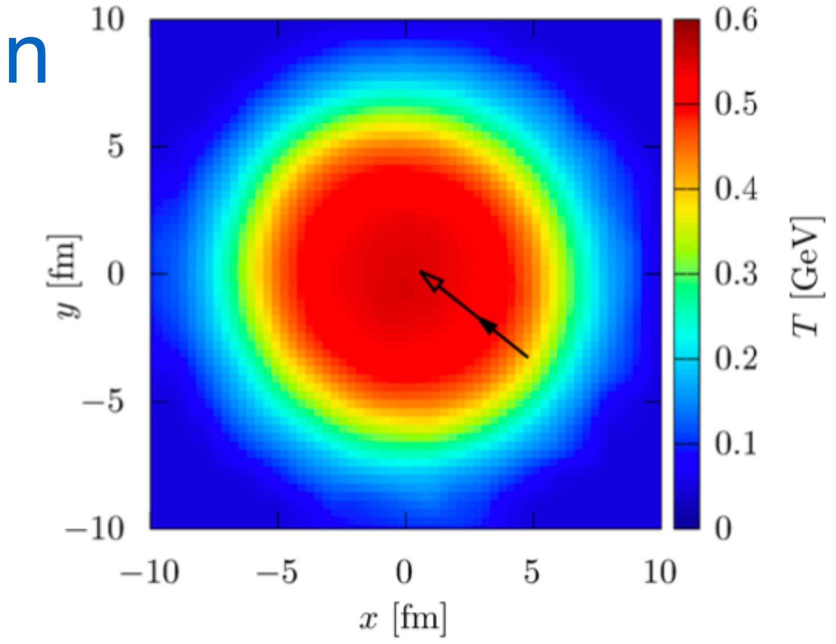
(d) ϕ distribution for $E_i = 10$ GeV. (e) ϕ distribution for $E_i = 50$ GeV.



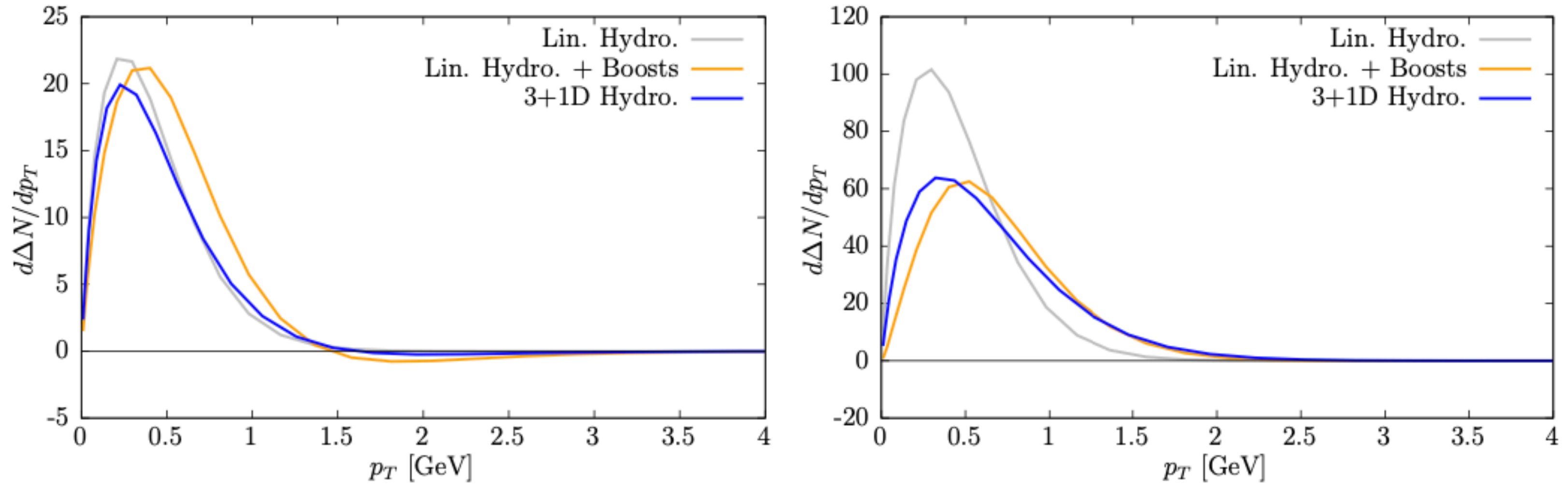
(f) y distribution for $E_i = 10$ GeV. (g) y distribution for $E_i = 50$ GeV.

3+1D
Viscous Hydrodynamics
~ 2 hours

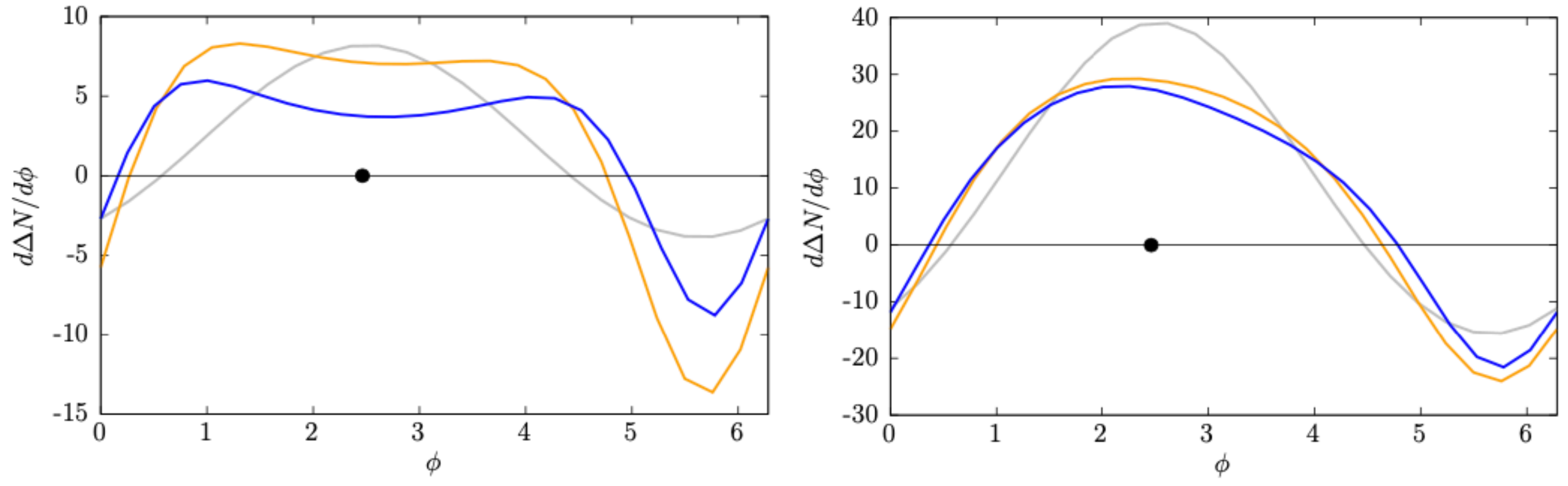
Superposition of
Bjorken flow solutions
+
Trans., Rot., & Boosts
~ 3 seconds



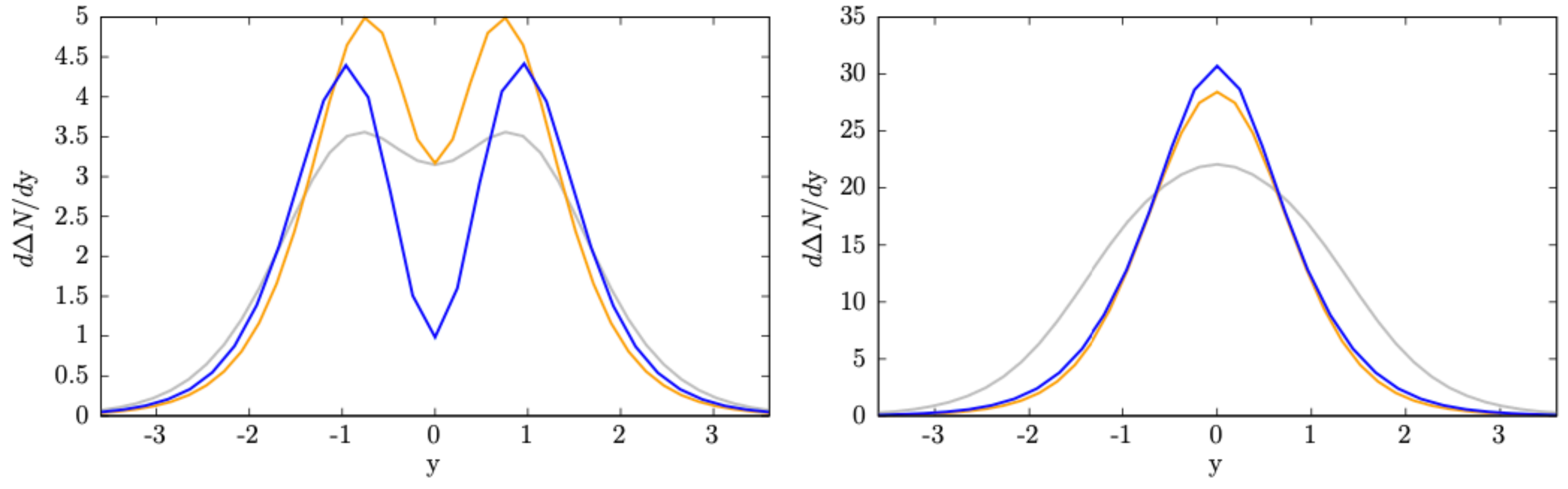
(a) Energy-momentum deposition for $E_i = 10$ GeV (filled arrow) and $E_i = 50$ GeV (empty arrow



(b) p_T distribution for $E_i = 10$ GeV. (c) p_T distribution for $E_i = 50$ GeV.

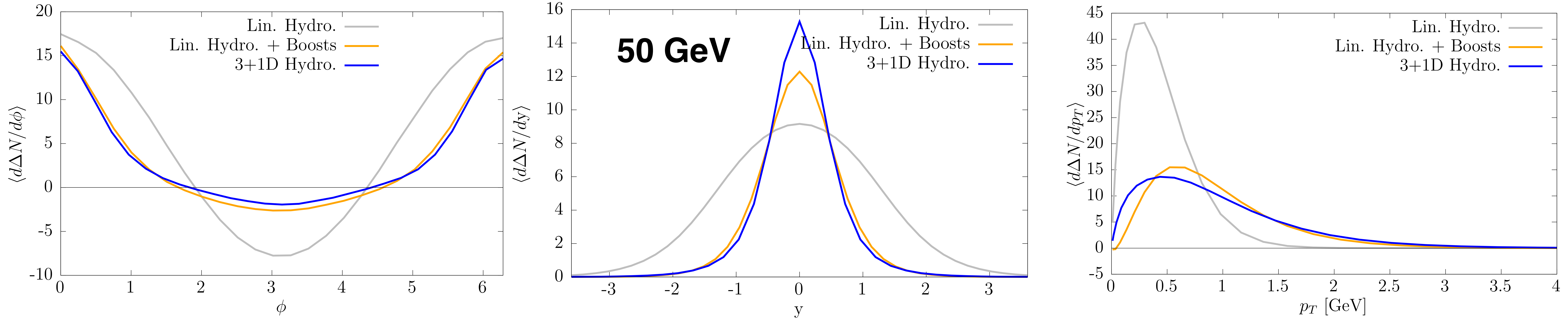


(d) ϕ distribution for $E_i = 10$ GeV. (e) ϕ distribution for $E_i = 50$ GeV.

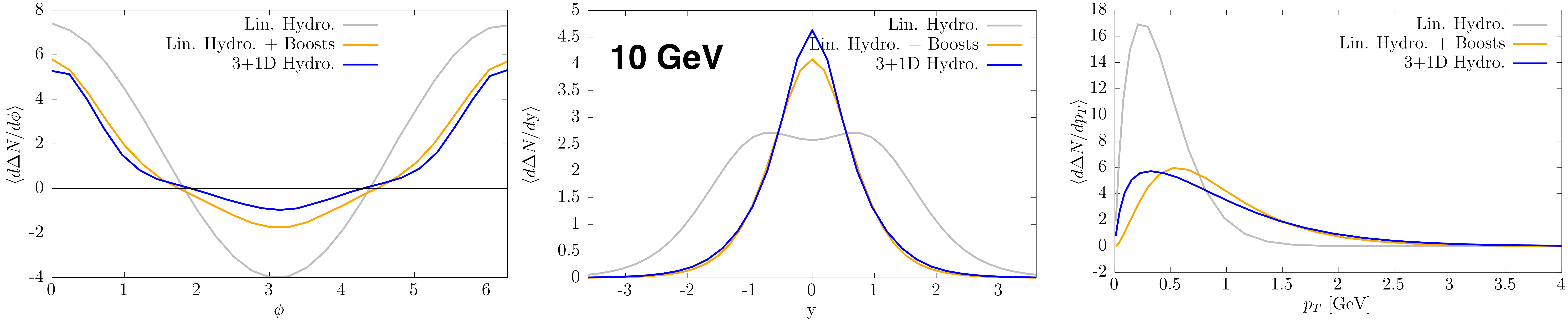


(f) y distribution for $E_i = 10$ GeV. (g) y distribution for $E_i = 50$ GeV.

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 and smaller p_T.

- Jet azimuthal anisotropy especially sensitive to coherence physics:
  - ➔ Effect measurable with sPHENIX.

- Higher p_T jets at RHIC kinematics with moderate R are sensitive to diffusion wake of recoiling jet:
  - ➔ Effect measurable with sPHENIX.

- 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.

Thanks for your attention!

Backup Slides

Further Improvements on Single Charge Energy Loss

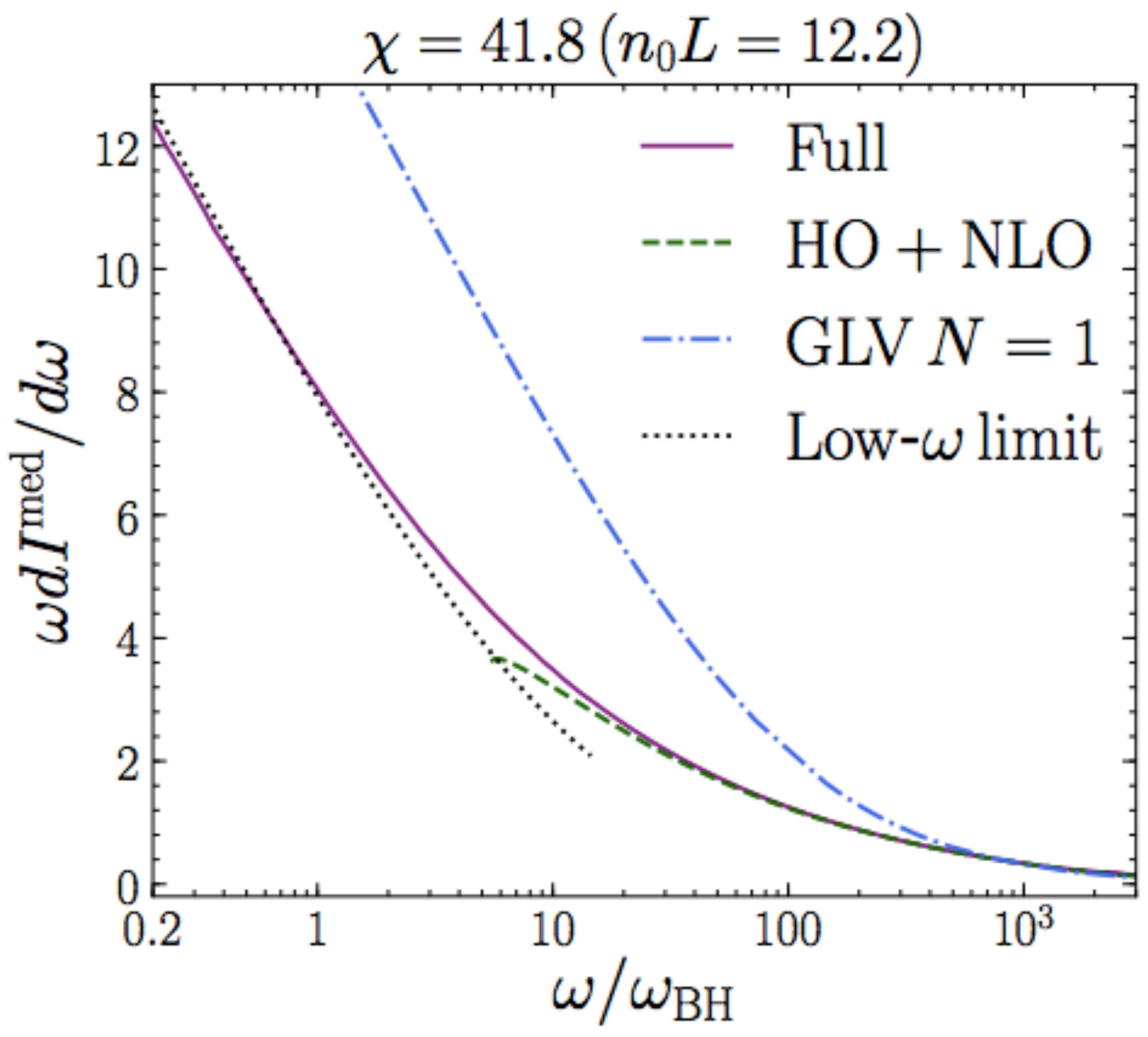
- All order resummation of medium induced radiation spectrum.

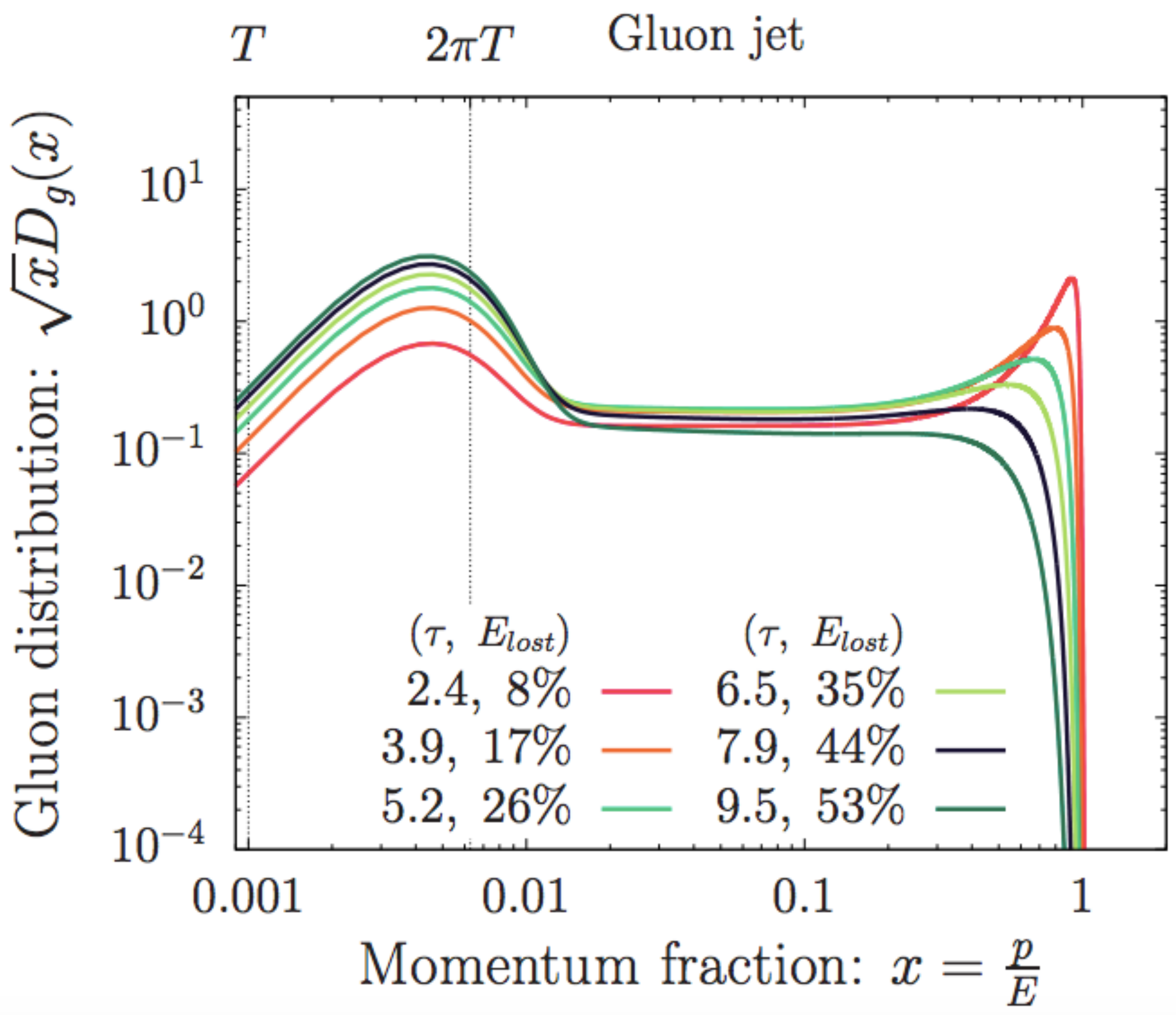
Feal et al. - PRD ‘18 & ‘19

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

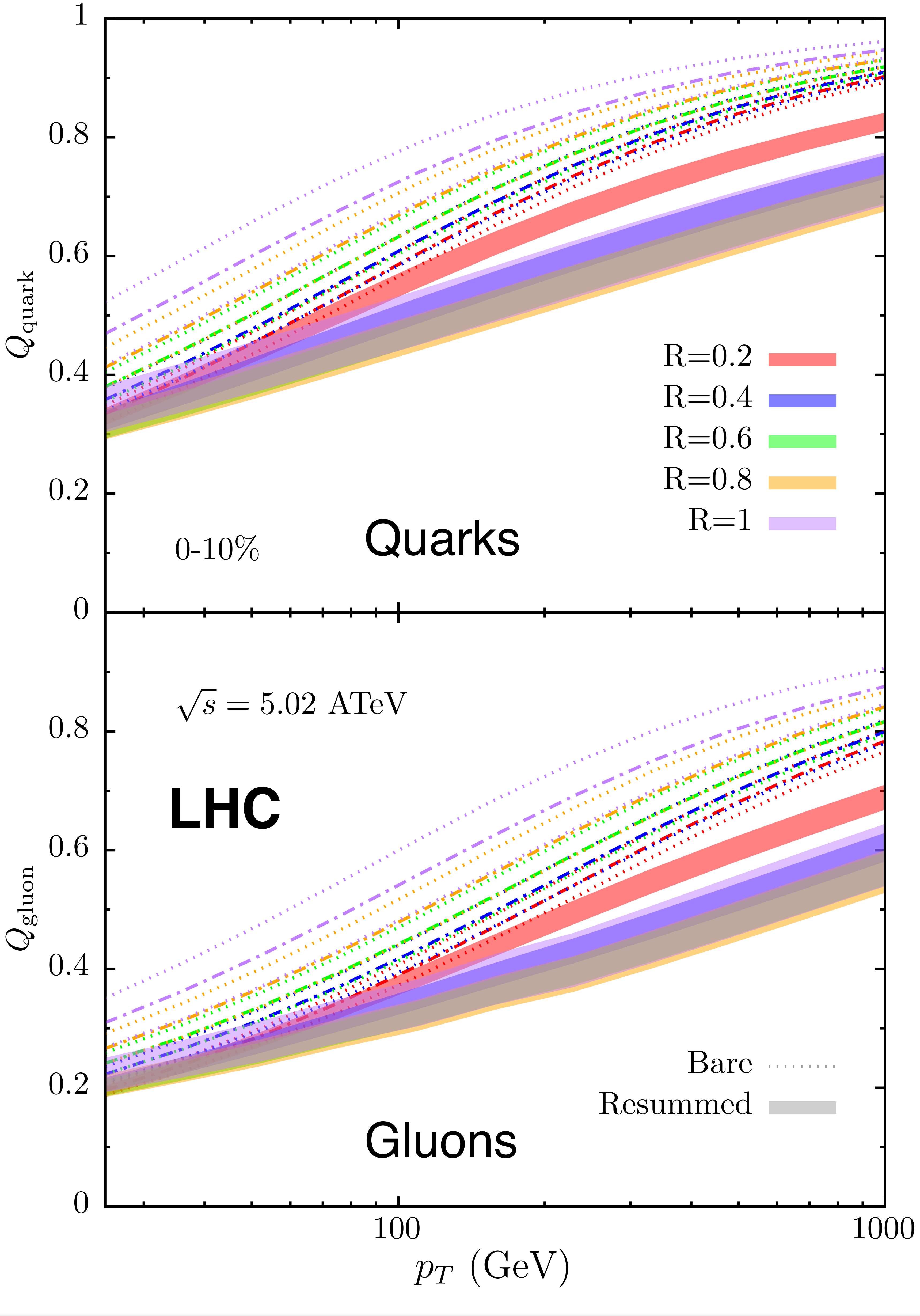
- In-medium fragmentation of hard parton in QGP through effective kinetic theory.

➡ Includes 1⟷2 and 2⟷2 processes.

➡ Features turbulent cascade, modified chemistry around the jet.

Detailed analysis of dynamics, can account for medium response.

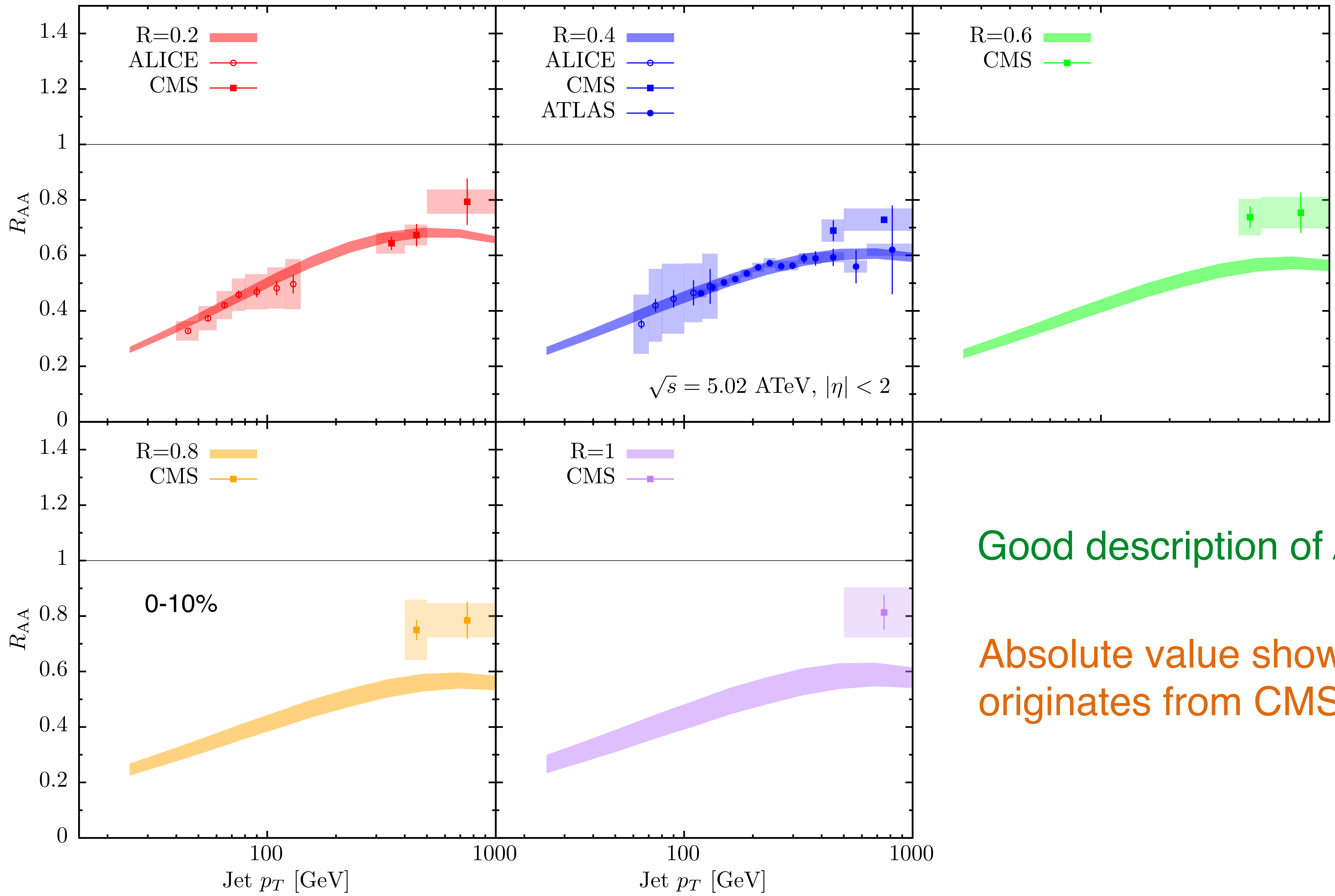
Resummed Quenching Factor



- 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

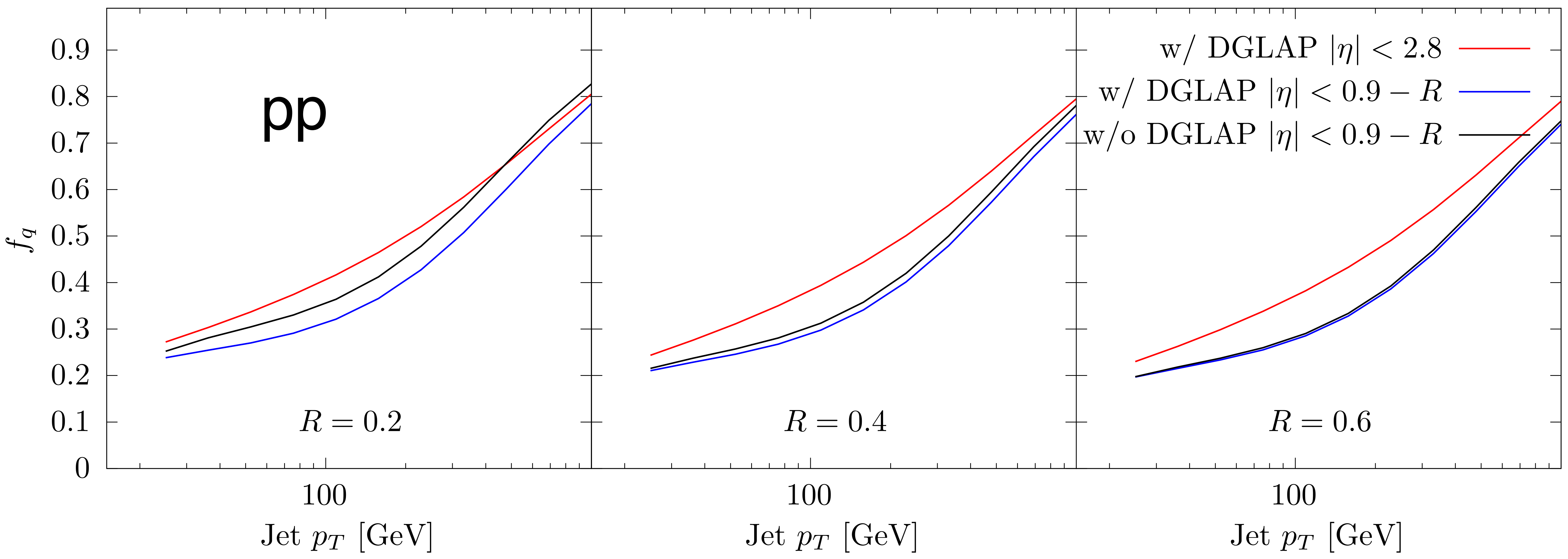
More Data Comparison

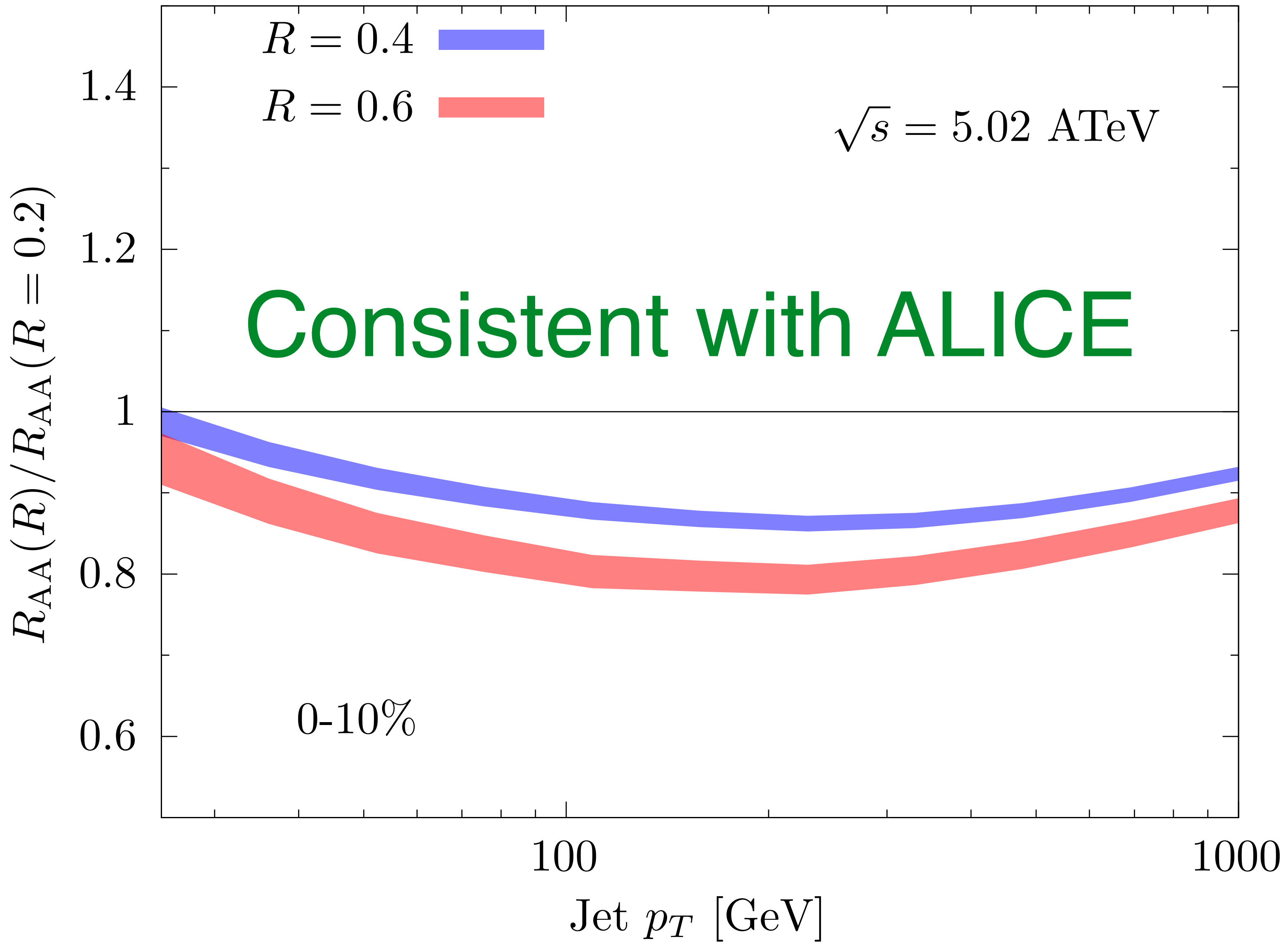


Good description of ALICE at lower p_T.

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

Accounting for rapidity cuts





Consistent with ALICE

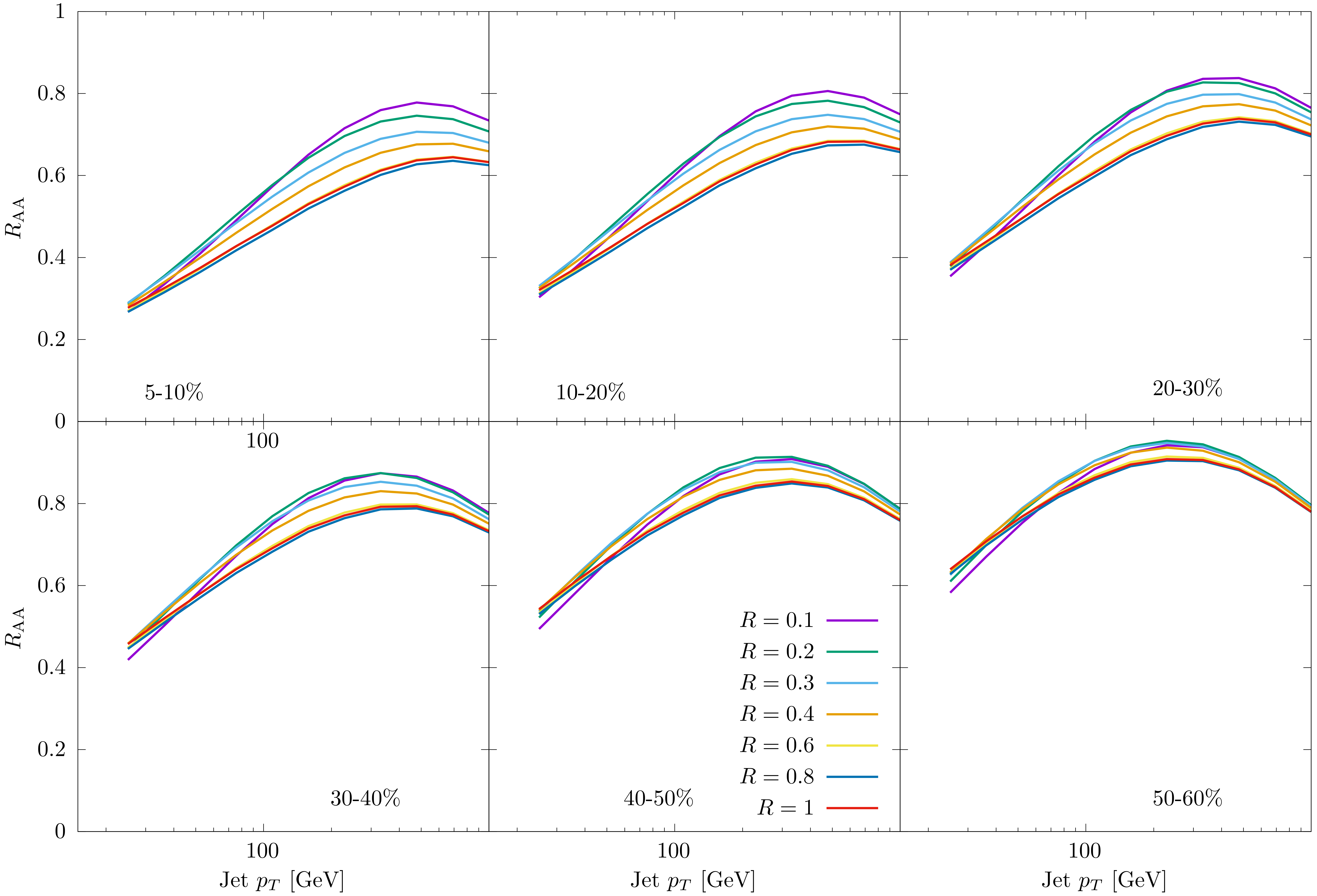
w/ DGLAP: fit pp spectrum at R_0=1, evolve down to R.

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

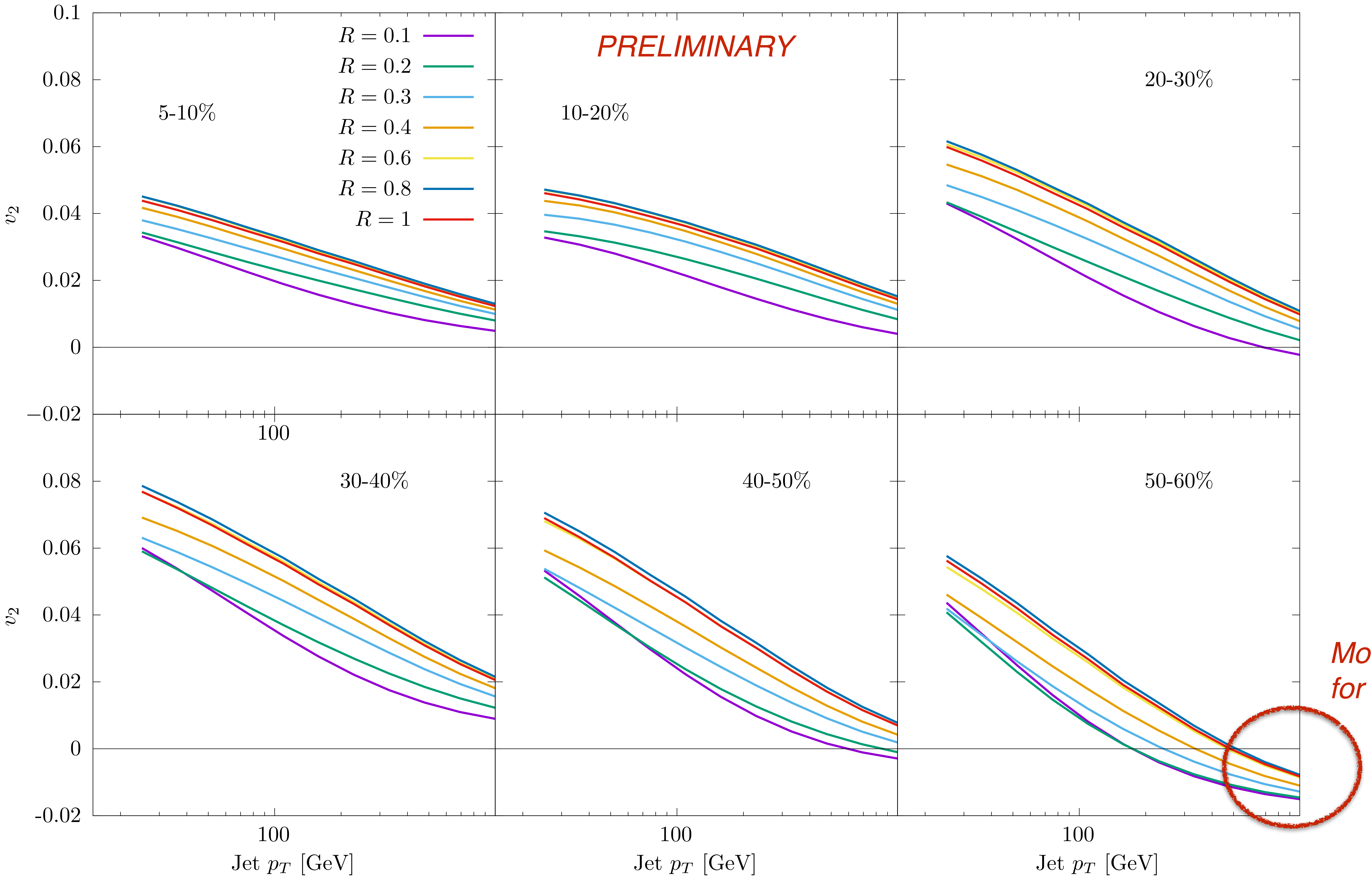
- Quark fraction depends on:
  - ➜ Rapidity, via PDF.
  - ➜ Cone R, via microjet evolution.

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

Jet R_{AA} at LHC



Jet v_2 at LHC



More stats. needed for good baseline

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

nPDF effect

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

Leading Jet Suppression vs. $|\eta_D|$

DP - PRL ‘20

A new observable.

R = 0.4

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

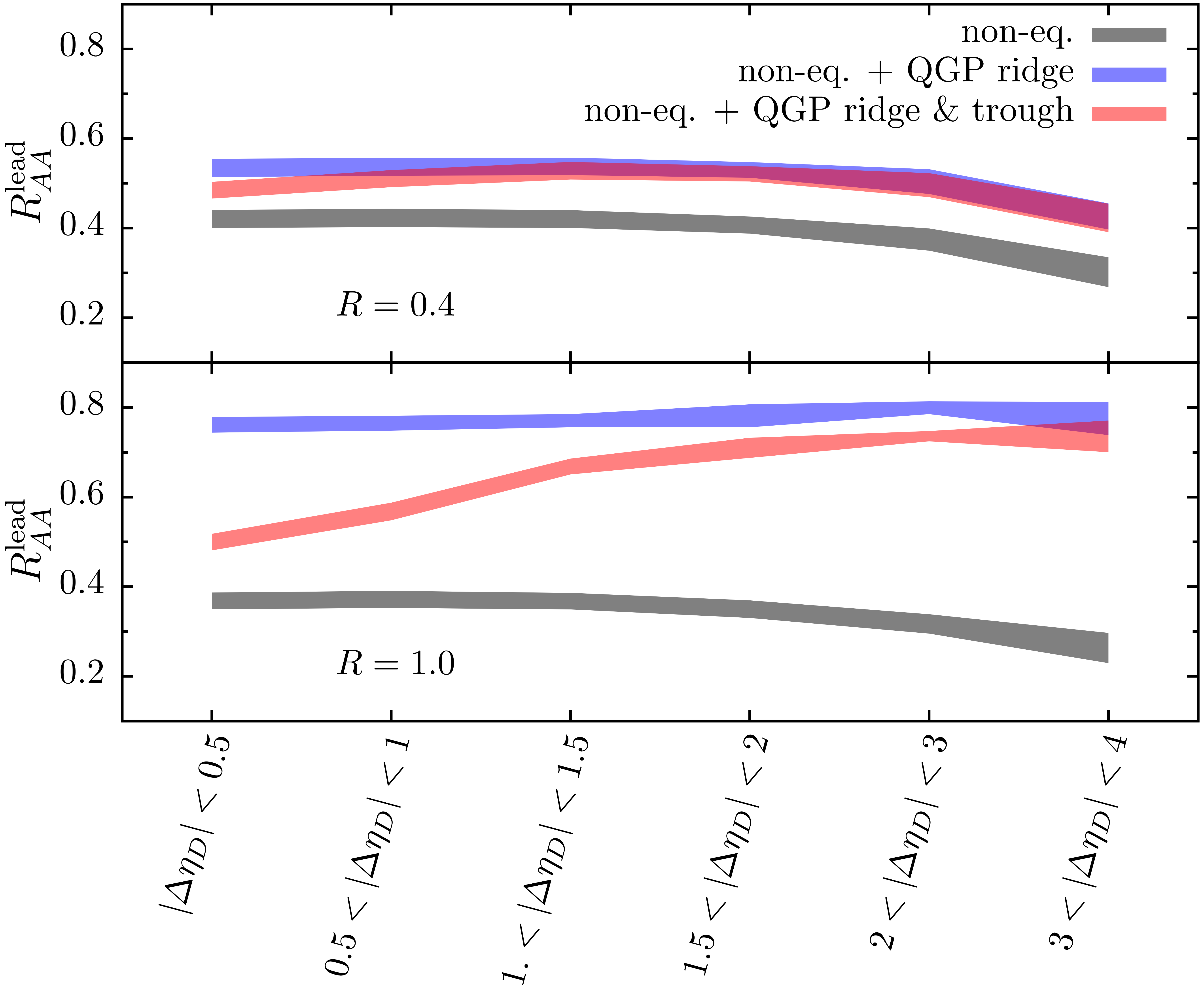
R = 1.0

strong dependence on $|\eta_D|$;
knee visible when $|\eta_D| \sim R$.

$$p_T^L > 250 \text{ GeV}$$
$$p_T^S > 80 \text{ GeV}$$
$$\Delta\phi_D > 2\pi/3$$

differential in

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



Hybrid Strong/Weak Coupling Model

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

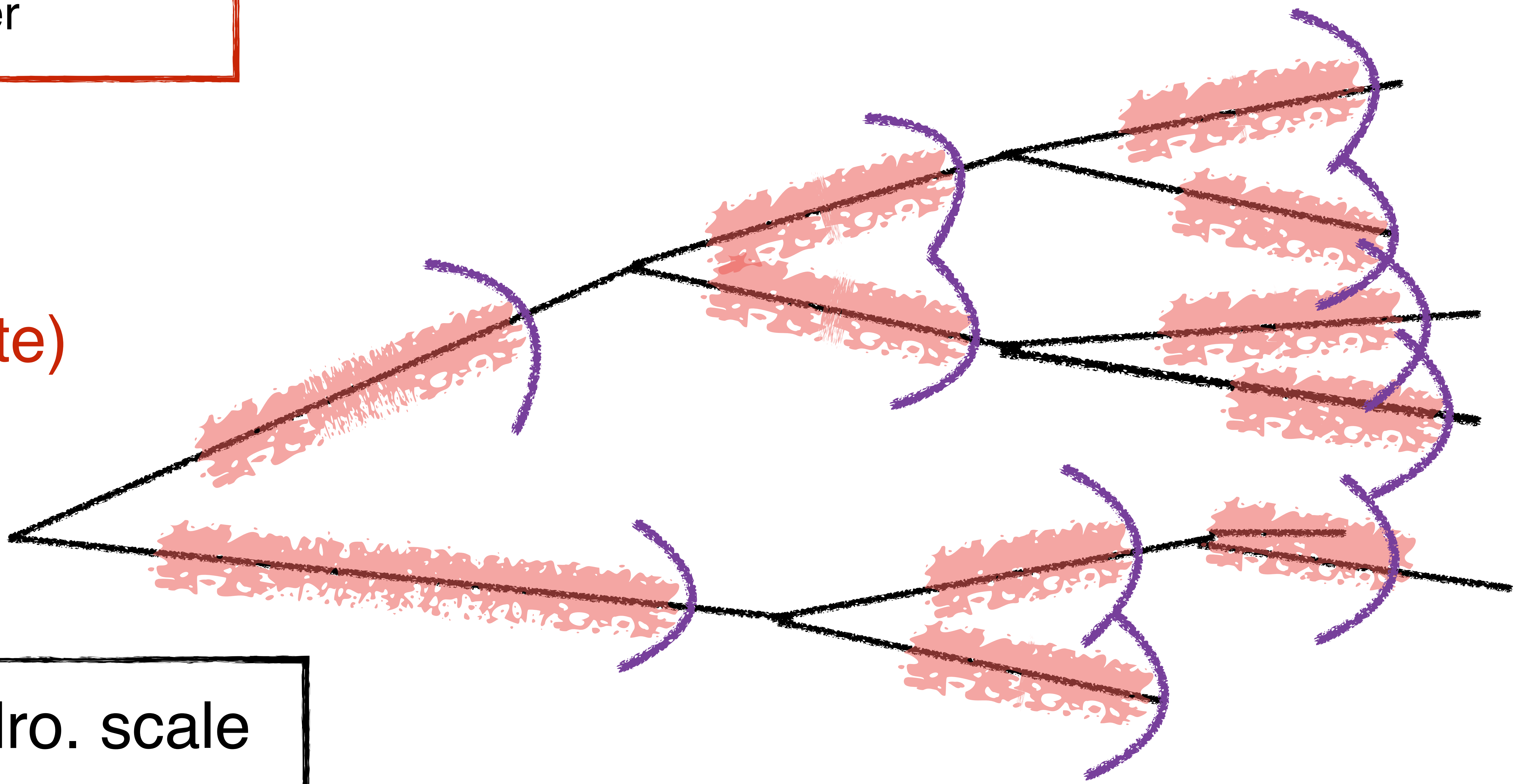
$$x_{\rm stop} = \frac{1}{2\boxed{\kappa_{\rm sc}}}\frac{E_{\rm in}^{1/3}}{T^{4/3}}$$

$\mathcal{O}(1)$ 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.