Jet Modifications & Medium Response - Theoretical Overview

Daniel Pablos

INFN Torino - U. Oviedo

Fellowship for Innovation at INFN

Istituto Nazionale di Fisica Nucleare

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8th Sept. 2023

Quark Matter 2023 - Houston, Texas, USA

Outline

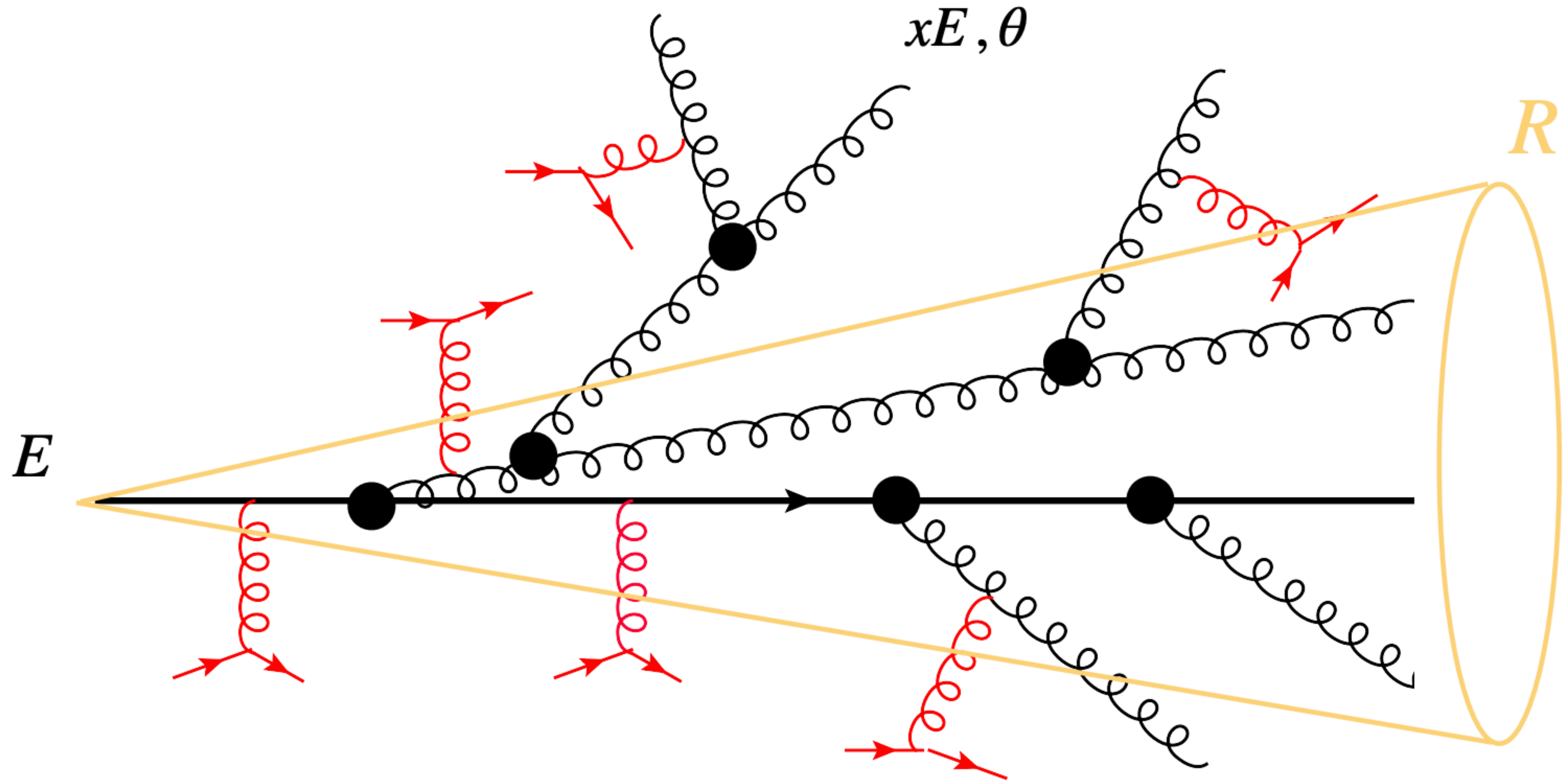
$$E^{\mathrm{jet}} \gg T$$

Energy loss with deconfined QCD matter, degrade energy down to medium scale.

pQCD:

Energetic parton emits quanta, which in turn emit more quanta.

Turbulent cascade with sink at E ~ T.



Mehtar-Tani et al. - 2209.10569

Blaizot et al. - 1209.4585, 1301.6102, 1311.5823

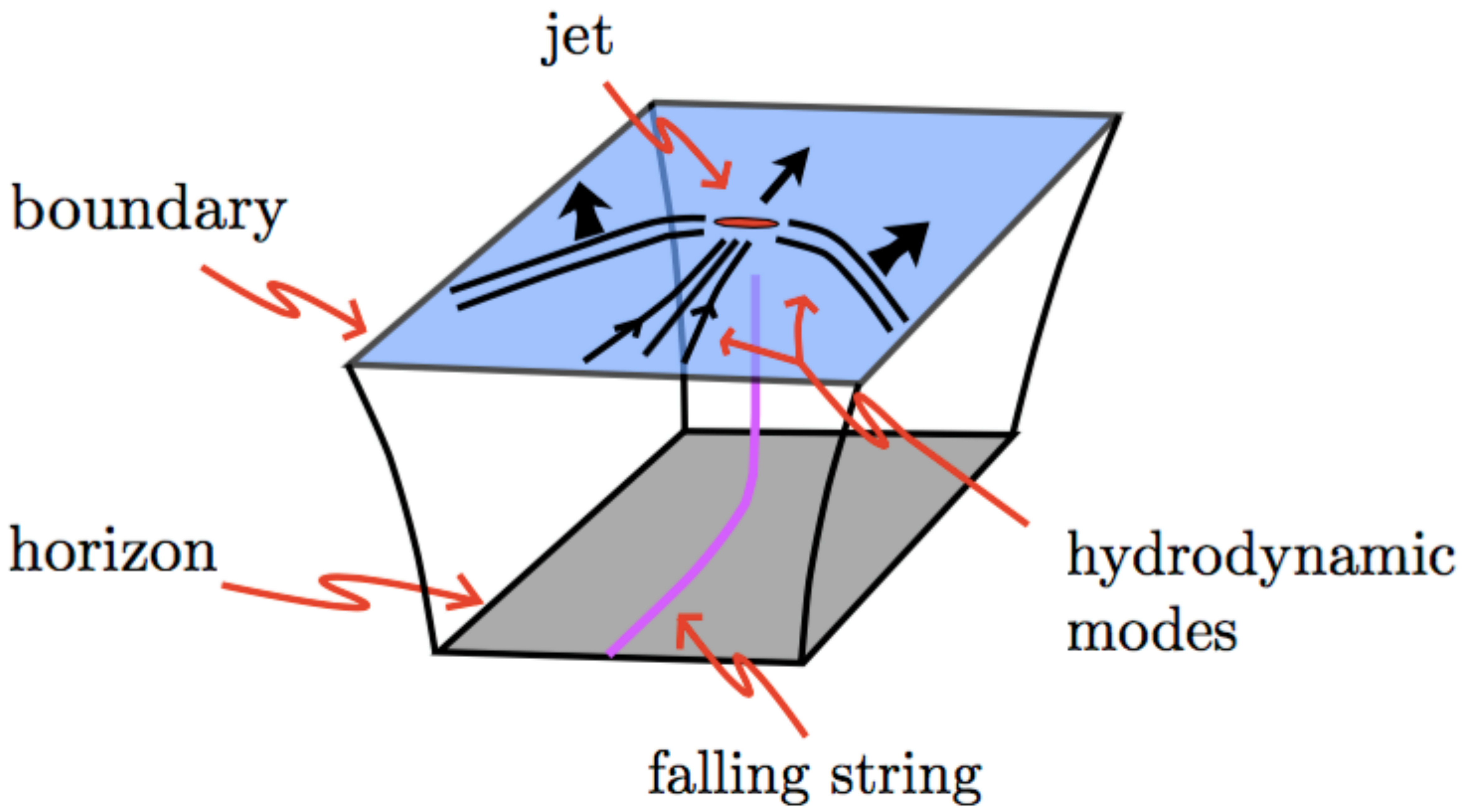
$$E^{\rm jet} \gg T$$

Energy loss with deconfined QCD matter, degrade energy down to medium scale.

npSYM:

Energetic parton dual to string falling into a black hole.

Excites hydro modes at distances ~ 1/T.



Chesler & Rajagopal - 1402.6756, 1511.07567

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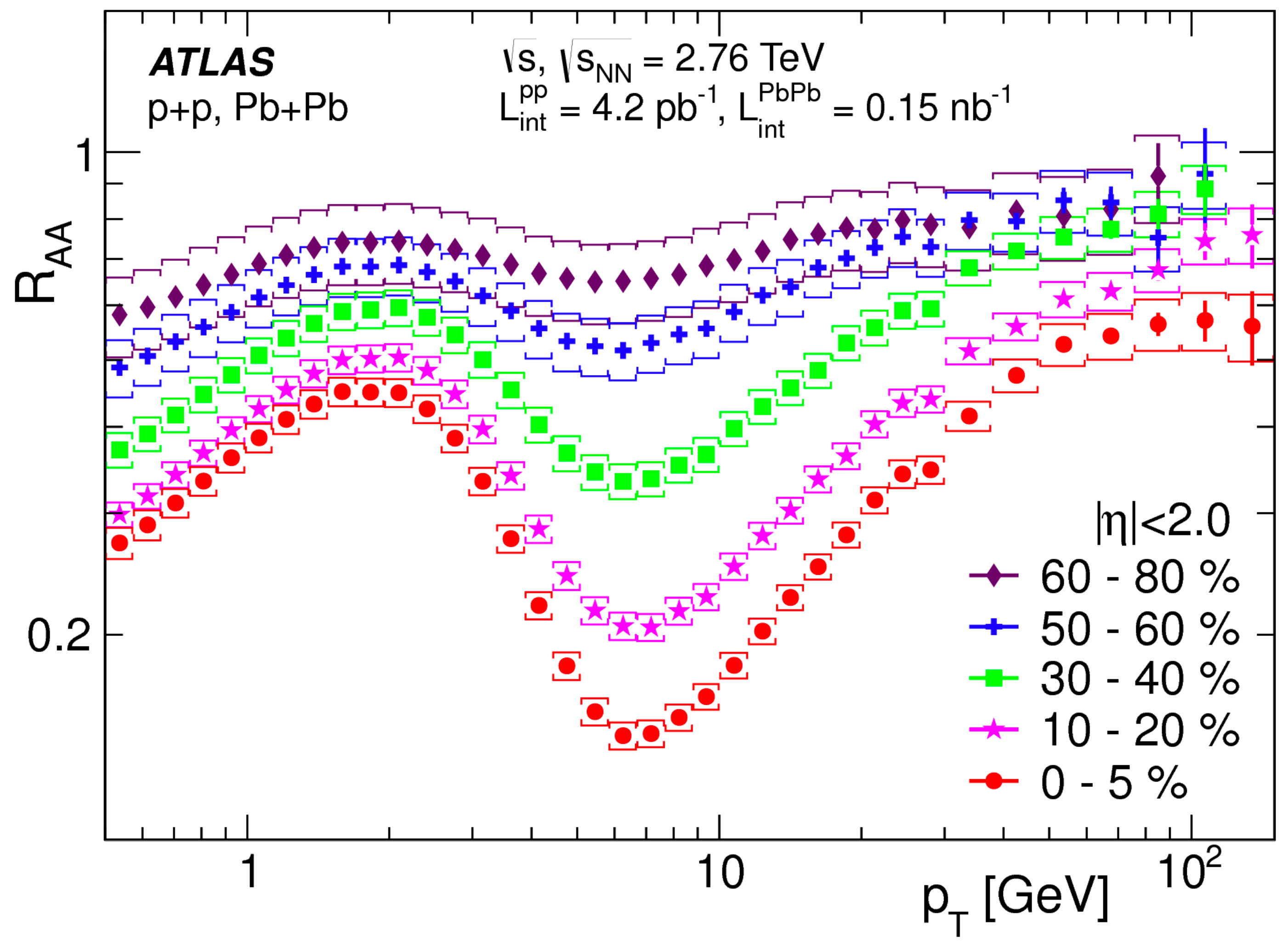
Energy loss with deconfined QCD matter, degrade energy down to medium scale.

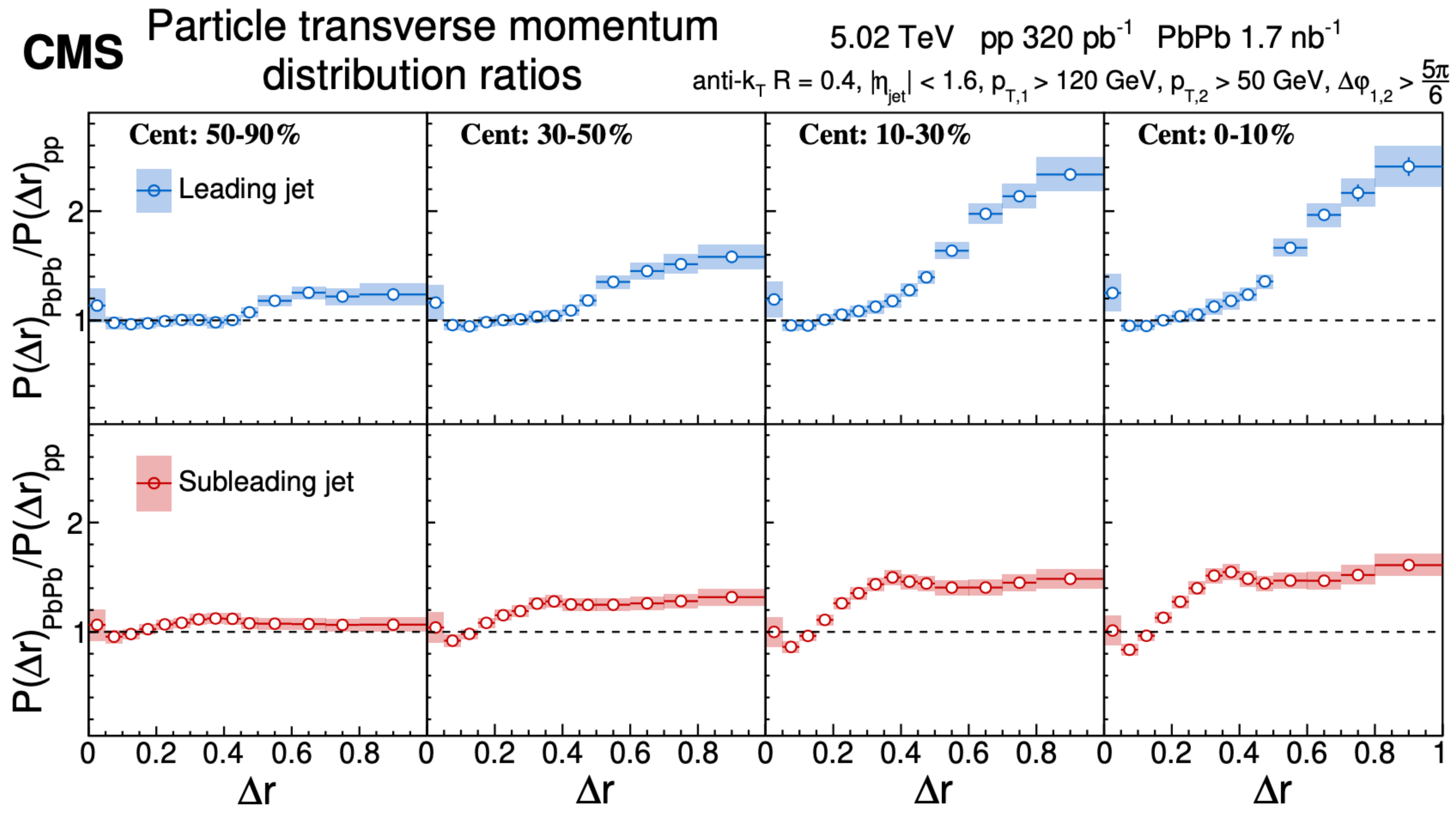
Experimental evidence:

Inclusive yields reduction.



ATLAS - 1504.04337

Excess of soft particles around the jet.



CMS - 2101.04720

Outline

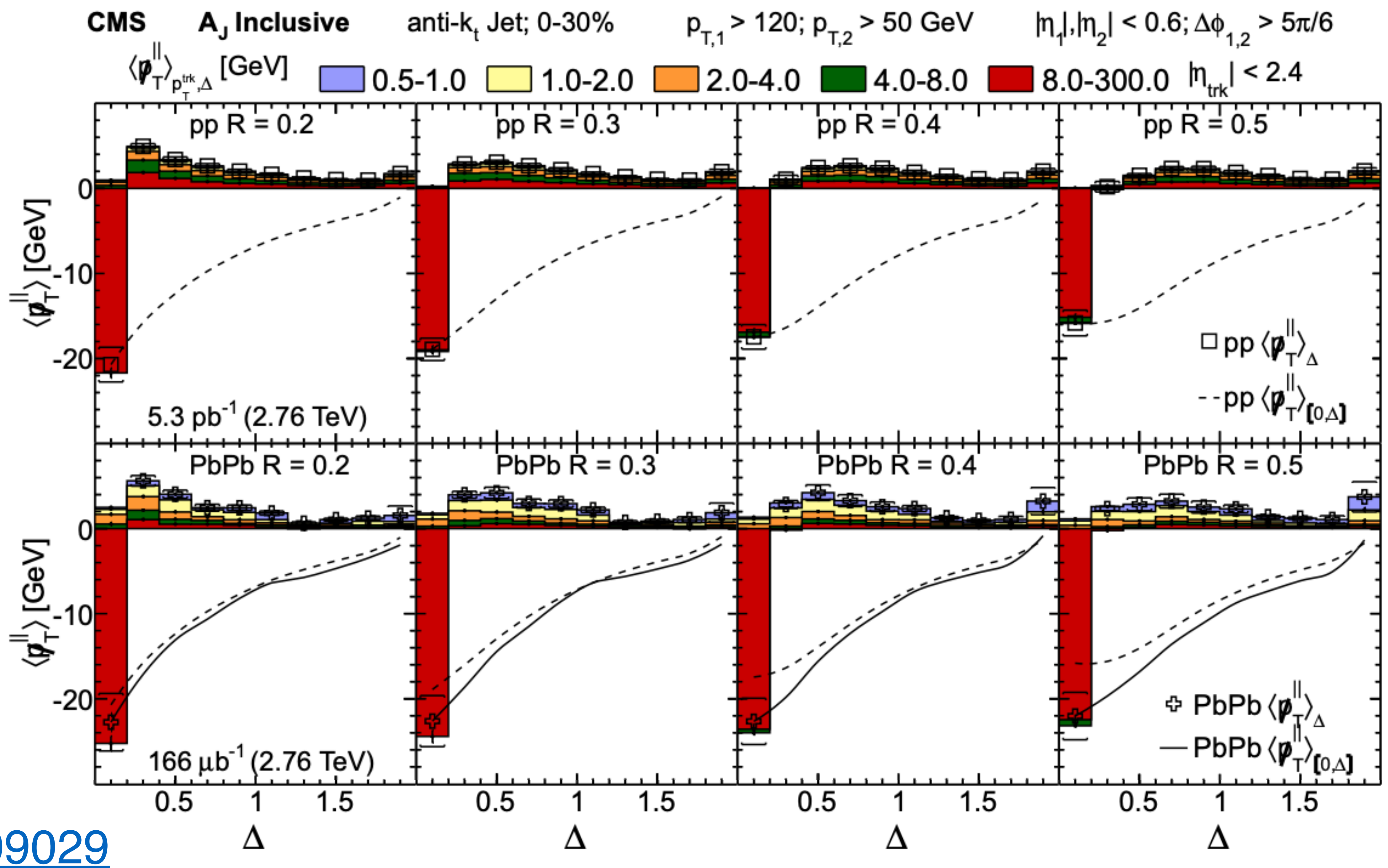
$$E^{\text{jet}} \gg T$$

Energy loss with deconfined QCD matter, degrade energy down to medium scale.

Experimental evidence:

Inclusive yields reduction. ⟷ Excess of soft particles around the jet.

Lost energy is recovered in the form of soft particles at large angles.



CMS - 1509.09029

Outline

If the medium experiences an hydrodynamic evolution:

- Jet modification knows about local properties of the fluid (broadening, radiation).
- Excitation of recoils, hydro modes correlated with jet direction (wake in the fluid).

Can completely hydrodynamize (all jet becomes part of the medium).

Challenge to use hydrodynamics in small systems (are opacities large enough?).

However, flow-like signatures are there.

See S. Schlichting's talk

If it was not hydro in small systems, was it hydro in large systems only?

Jets are crucial, complementary evidence tool to assess the dynamics of a liquid QGP.

*Can we find evidence of jet modifications due to a **flowing** medium?*

Outline

Medium behaves like a fluid at scales ~ 1/T, but:

Asymptotic freedom → Quark and gluon d.o.f. when probed at small enough lengths.

Jets can trigger high-momentum exchanges q:

- → Can be perturbative.
- → Can resolve short-length structure of QGP.

$$q < \sqrt{E^{\rm jet} T}$$

Can we find evidence that the QGP is not best described as a liquid at all length scales?

Can we use this to understand how a strongly coupled liquid emerges as one zooms out?

Outline

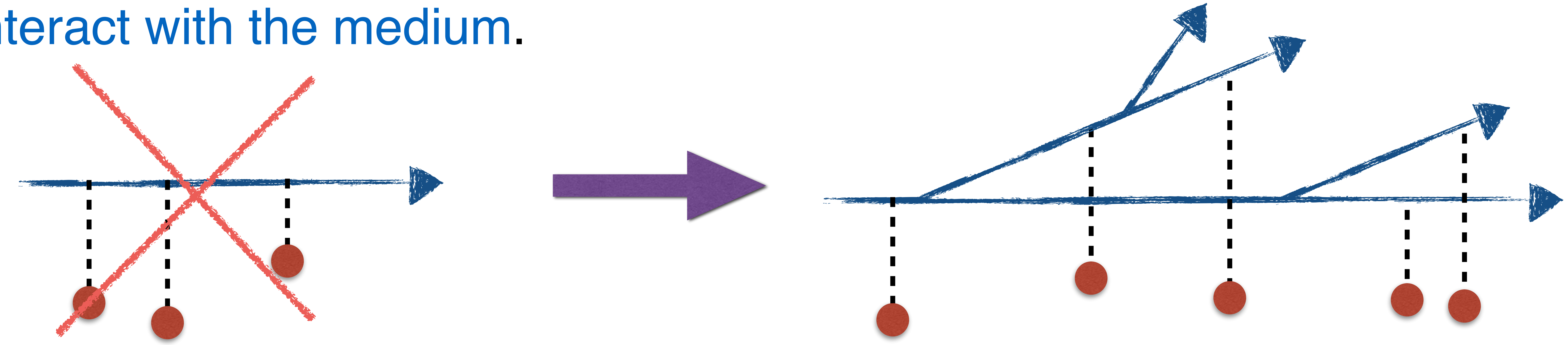
$$E^{\mathrm{jet}} \sim Q \gg \Lambda_{\mathrm{QCD}}$$

Multiple parton emission suppressed by α_s,
but enhanced by large logarithms due to large scale separation.

Momentum fraction distribution of produced partons will depend on the scale it is probed at.

Evolution with scale determined by DGLAP equations,
conveniently rewritten in terms of Sudakov form factor (no-splitting probability) for MC.

Jets typically present a multi-parton structure, triggered by production scale Q,
as they interact with the medium.



Challenge!
& Opportunity

Need to understand this interplay before more subtle effects can be assessed.

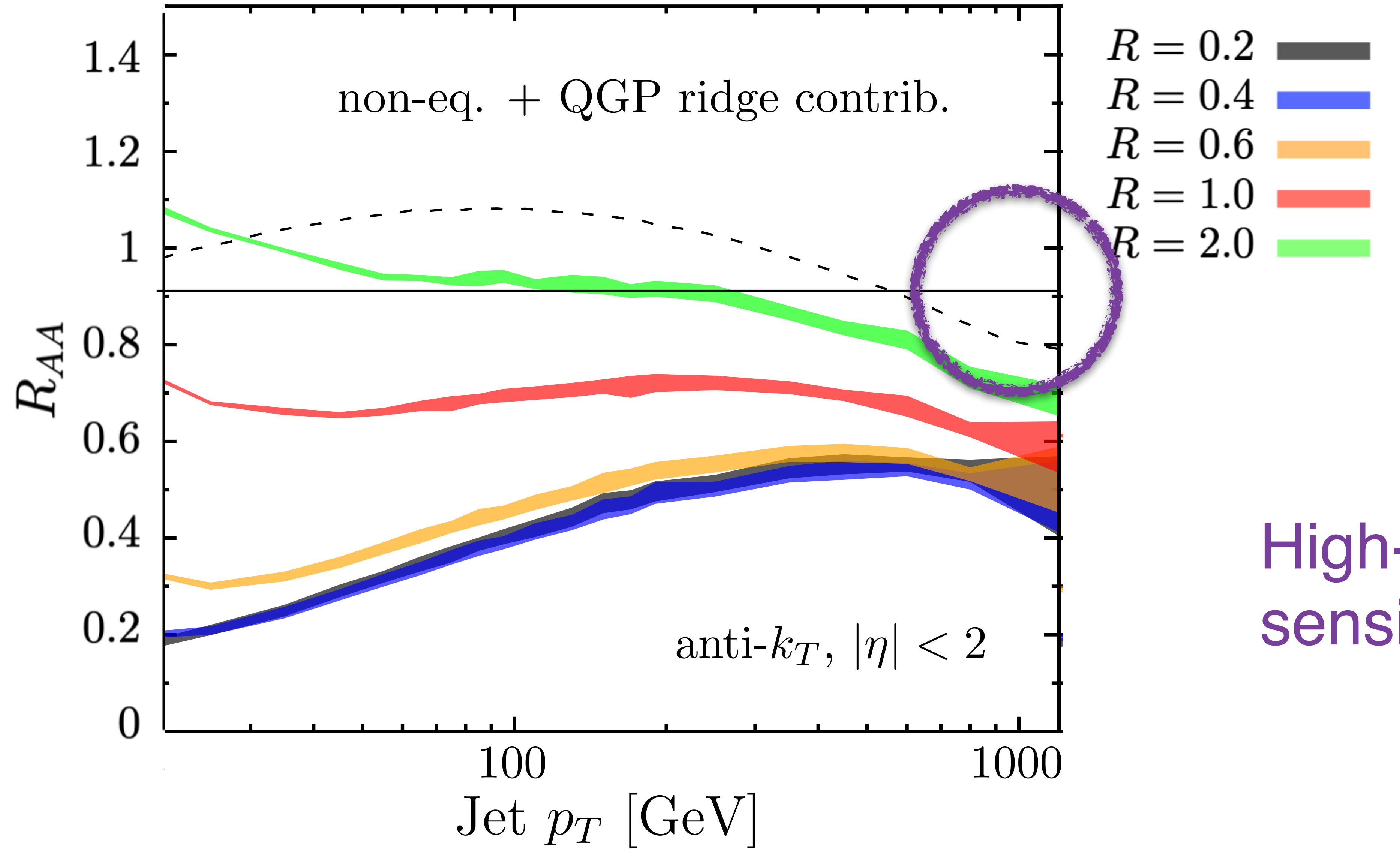
Jet Production

High p_T production at very early times described with pQCD.

Nuclear wave function is modified with increasing atomic number.

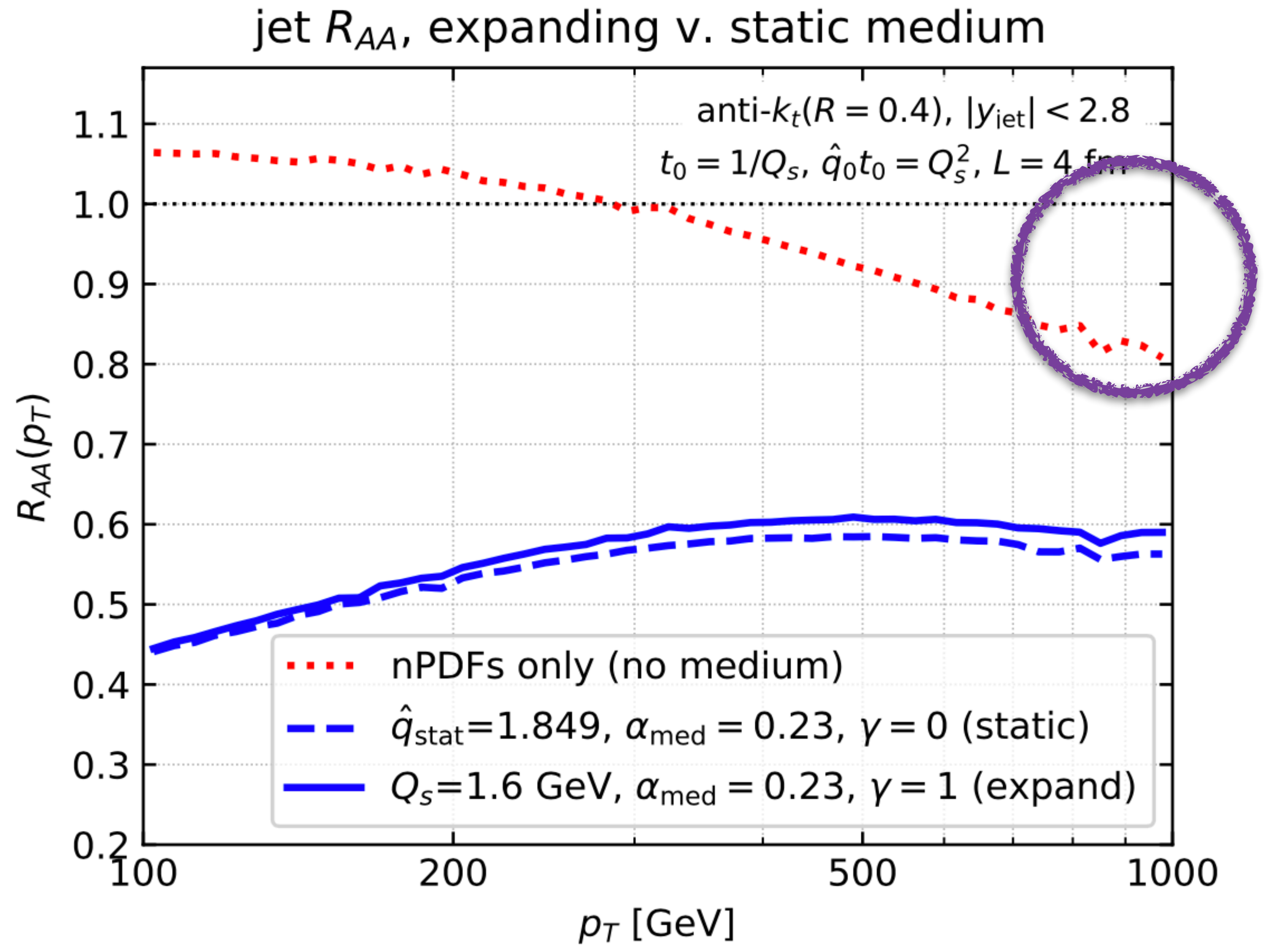
Low x described by shadowing/saturation physics.

Initial-state effects leave an imprint on jet observables, specially at large x (valence quarks), for any Q^2.



DP - 1907.12301

High-p_T jet suppression sensitive to initial-state effects.



Caucal et al. - 2012.01457

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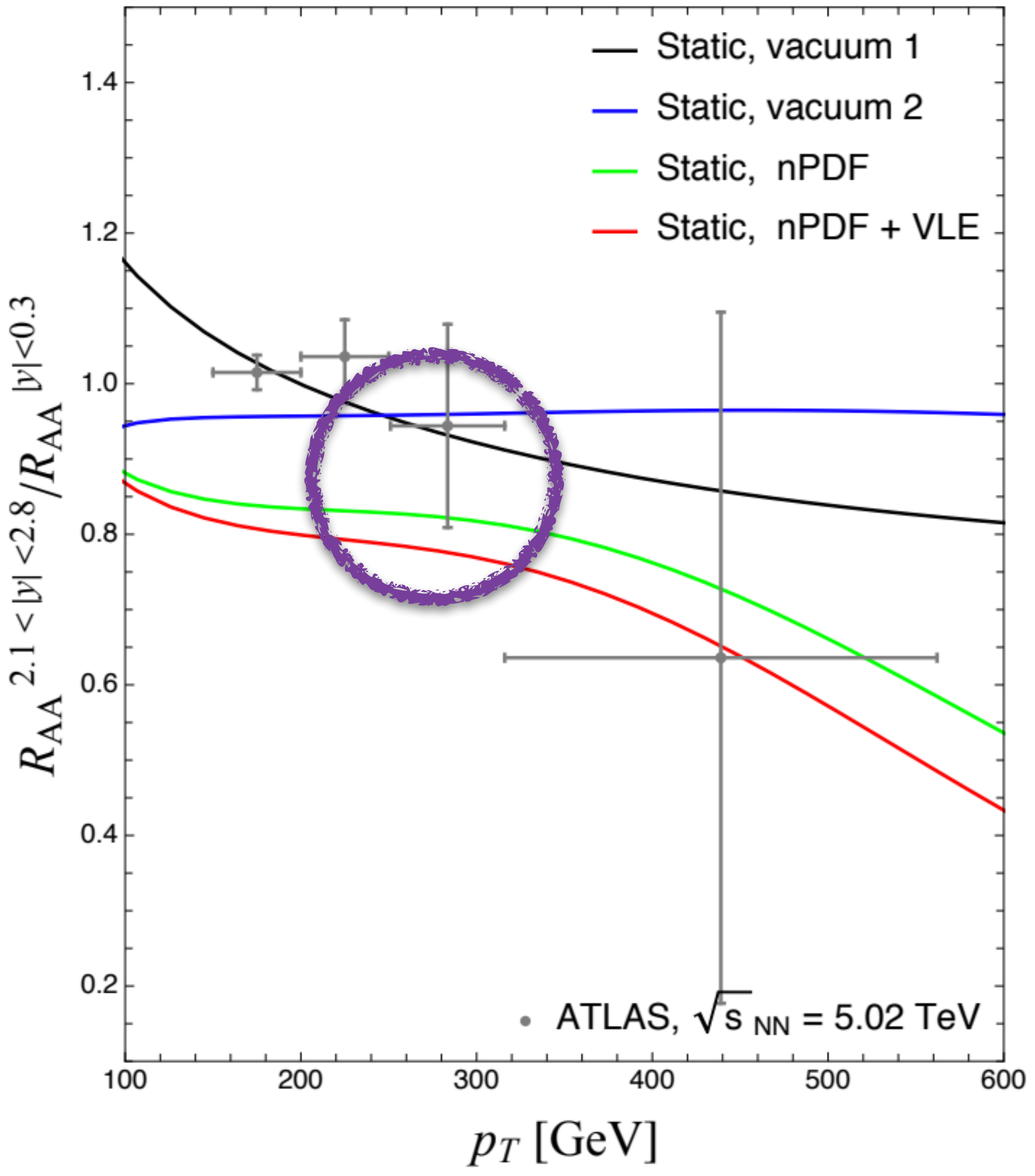
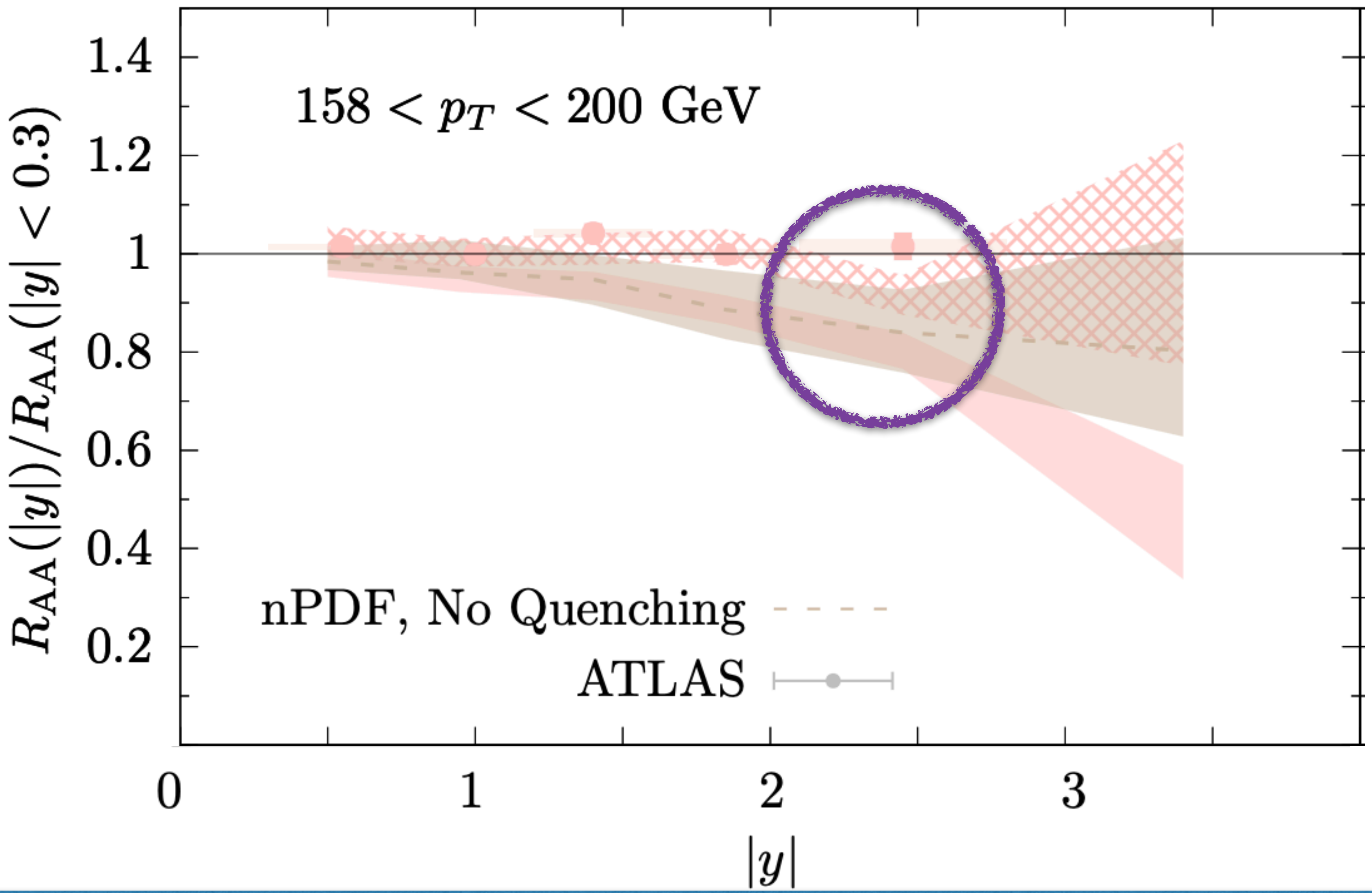
DP & A. Soto-Ontoso - 2210.07901



Adhya et al. - 2106.02592

Rapidity dependence of jet suppression sensitive to initial-state effects.



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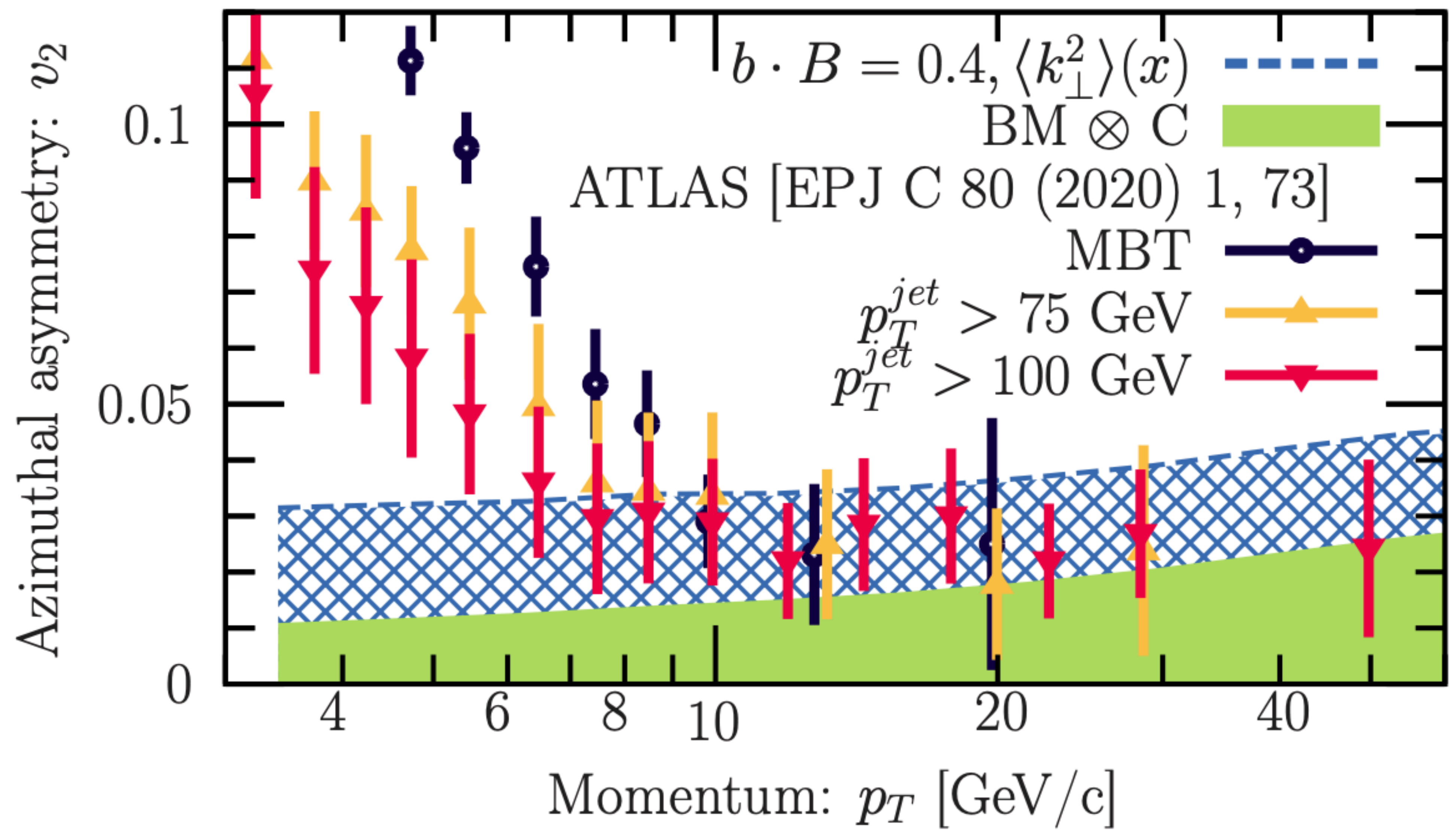
Soudi & Majumder - 2308.14702

Jet v_2 in nucleon-nucleus (*without quenching*) if intrinsic k_T large enough.

See I. Soudi's talk



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Initial-state effects on jet quenching observables need to be included and quantified for a correct interpretation of results.

Vacuum-like Jets in the Medium

Jets experience part of their evolution as if they were in vacuum, *formation times arguments*.

Formation time τ_f : when wavelength of emitted gluon resolves transverse separation.

A given emission is vacuum-like (VLE) if:

$$\tau_f \ll \tau_{\rm med}$$

Implies separation of momenta.

$k_\perp$
- med: From multiple soft scatterings. ($\hat{q}$)
- vac: From DGLAP evolution.

A given dipole is resolved (both legs lose energy) if:

$$\tau_{\rm coh} < L \quad \longrightarrow \quad \theta > \theta_c \sim 1/\sqrt{\hat{q}L^3}$$

Time it takes a dipole to decohere via multiple color rotations.

All VLE are angular ordered, since $\tau_v < \tau_{\rm coh}$. Caucal et al. - 1801.09703

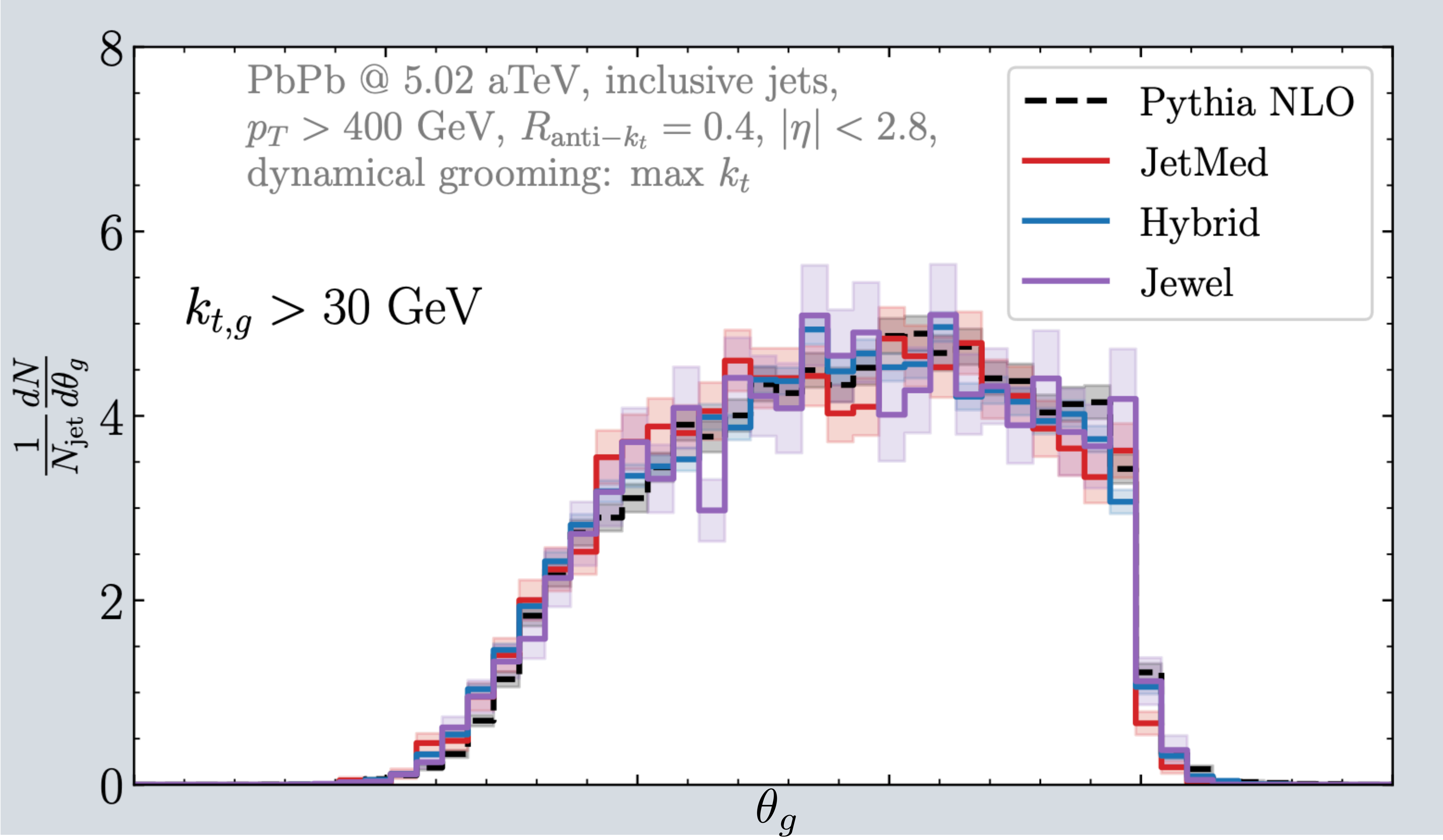
VLEs included in MC, either full factorization, or allowing corrections from rare kicks (JEWEL, MATTER).

Evidence for VLEs

Exploit jet clustering techniques to scan energy scales of parton splittings.

See A. Takacs' talk

Models indeed show dominance of vacuum physics at large k_T.



Accessing energetic resolved prongs, formed within QGP, possible with high p_T jets.

See also z_g measurement by ALICE.
2107.12984

What would we see in data? At which scale does the medium actually contribute?

Wide vs Narrow, Gluon vs Quark

The presence of the initial partonic distribution coming from vacuum physics, heavily affects total energy loss of jet.

Medium sensitive to vacuum-set scales, and so to jet substructure fluctuations.

Selection bias towards jet who experienced a narrower fragmentation (if steeply falling spectrum).

Depends on whether vacuum-like sources are resolved, i.e. if $\theta > \theta_c$.

However, a gluon-initiated jet:

Wider fragmentation in vacuum, $\propto C_A$ (this we know)

Interact more strongly with the medium, also $\propto C_A$ (this we would like to measure)

Species dependence can lead to jet narrowing without having to resolve jet substructure.

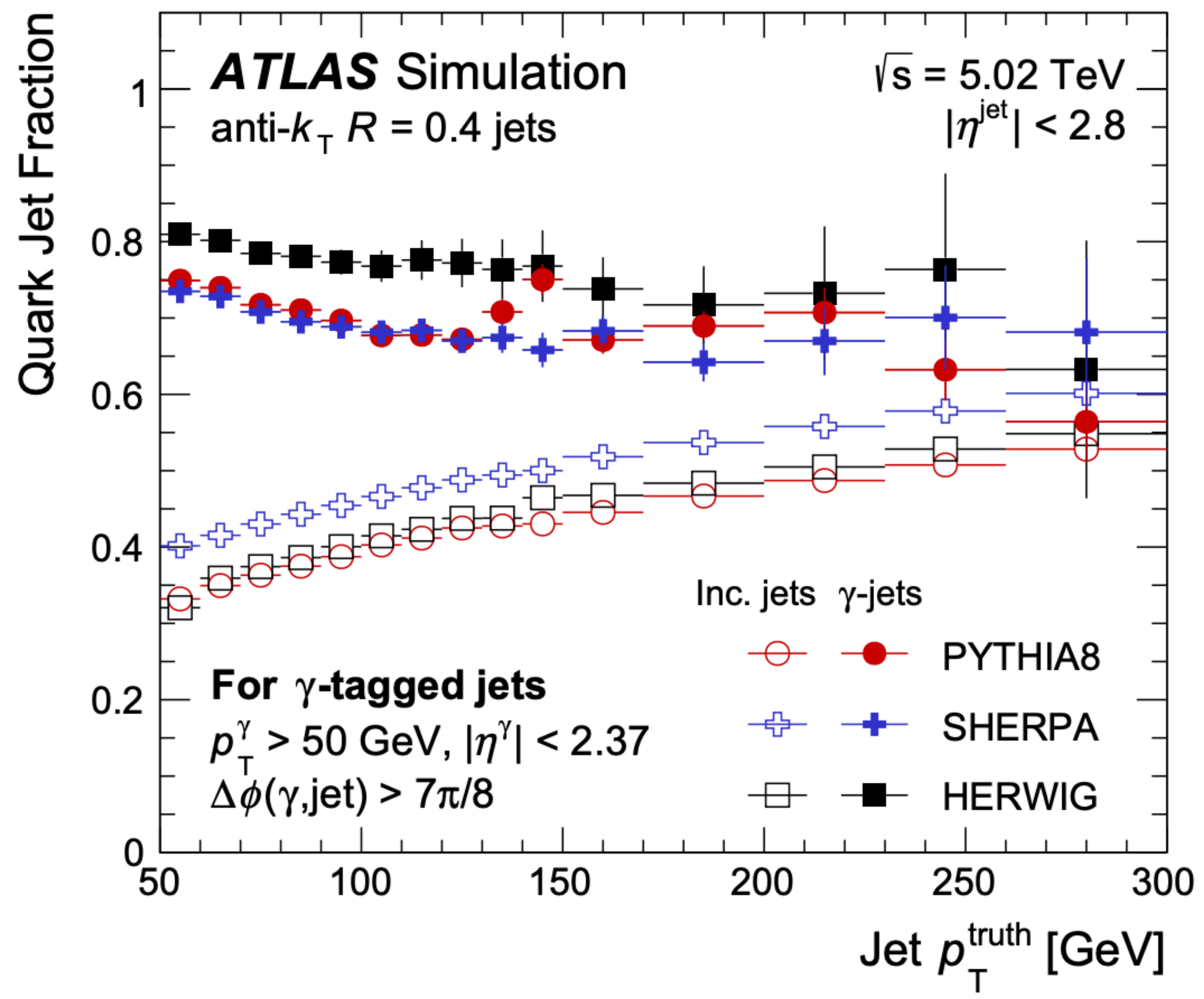
Confounding factors.

Get access to quark-enriched samples.

More direct access to the physics of the interplay between medium and vacuum scales, coherence.

Via, e.g.:

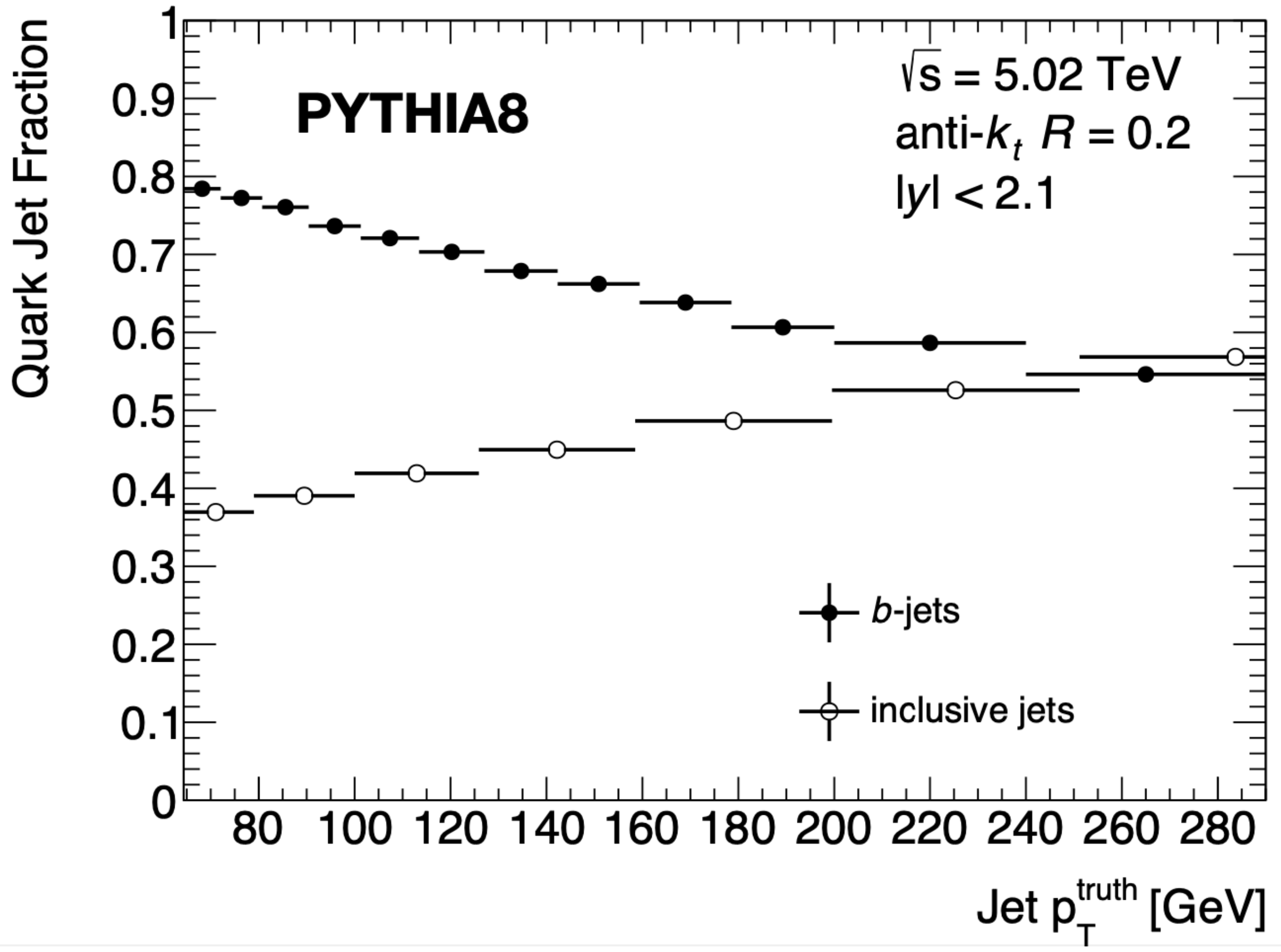
Boson-jet samples



See C. McGinn's talk
See M. Park's talk
See C. Sirimanna's talk

ATLAS - 2303.10090 CMS - PAS-HIN-23-001

Heavy flavour-tagged jets

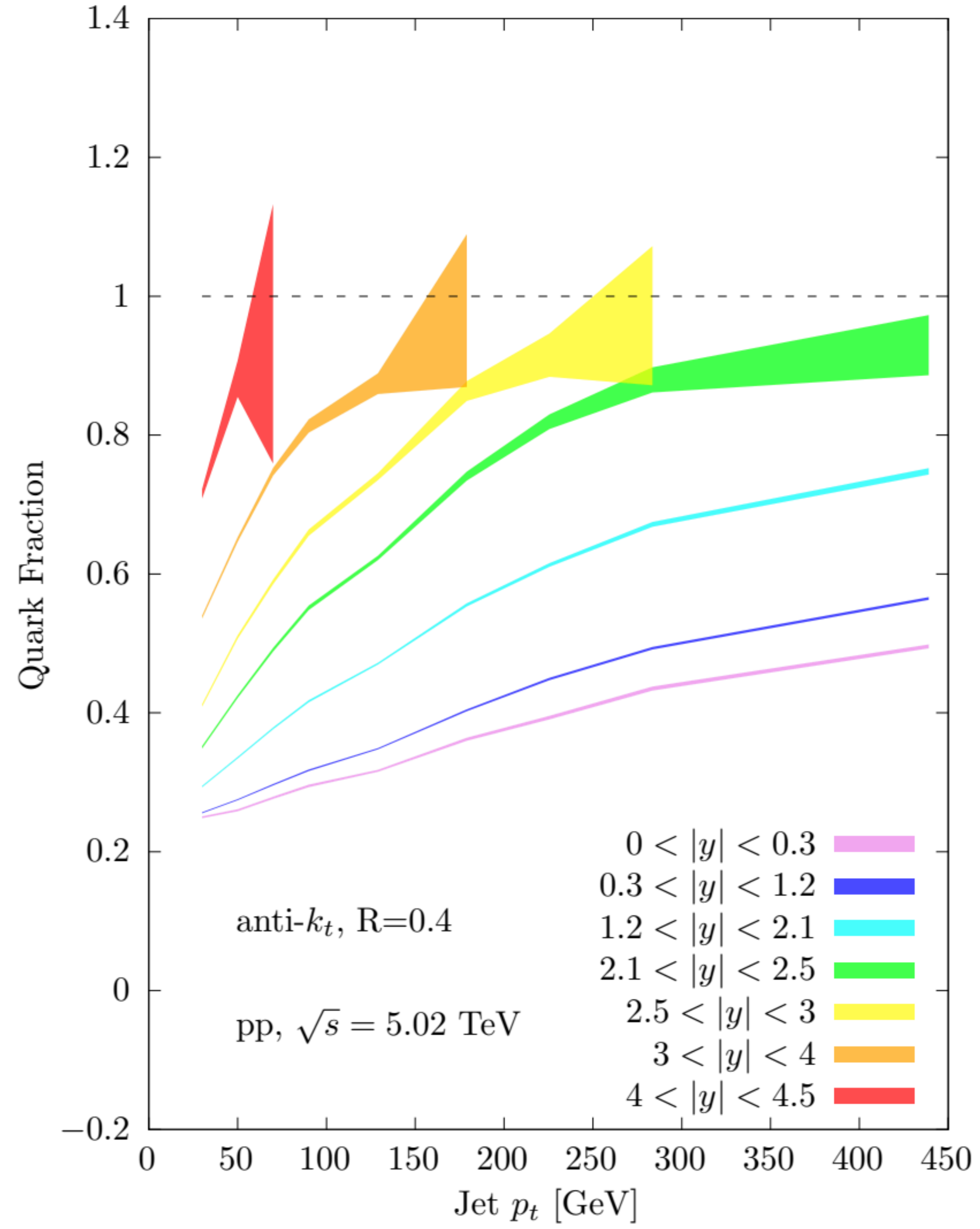


See A. Sickles talk

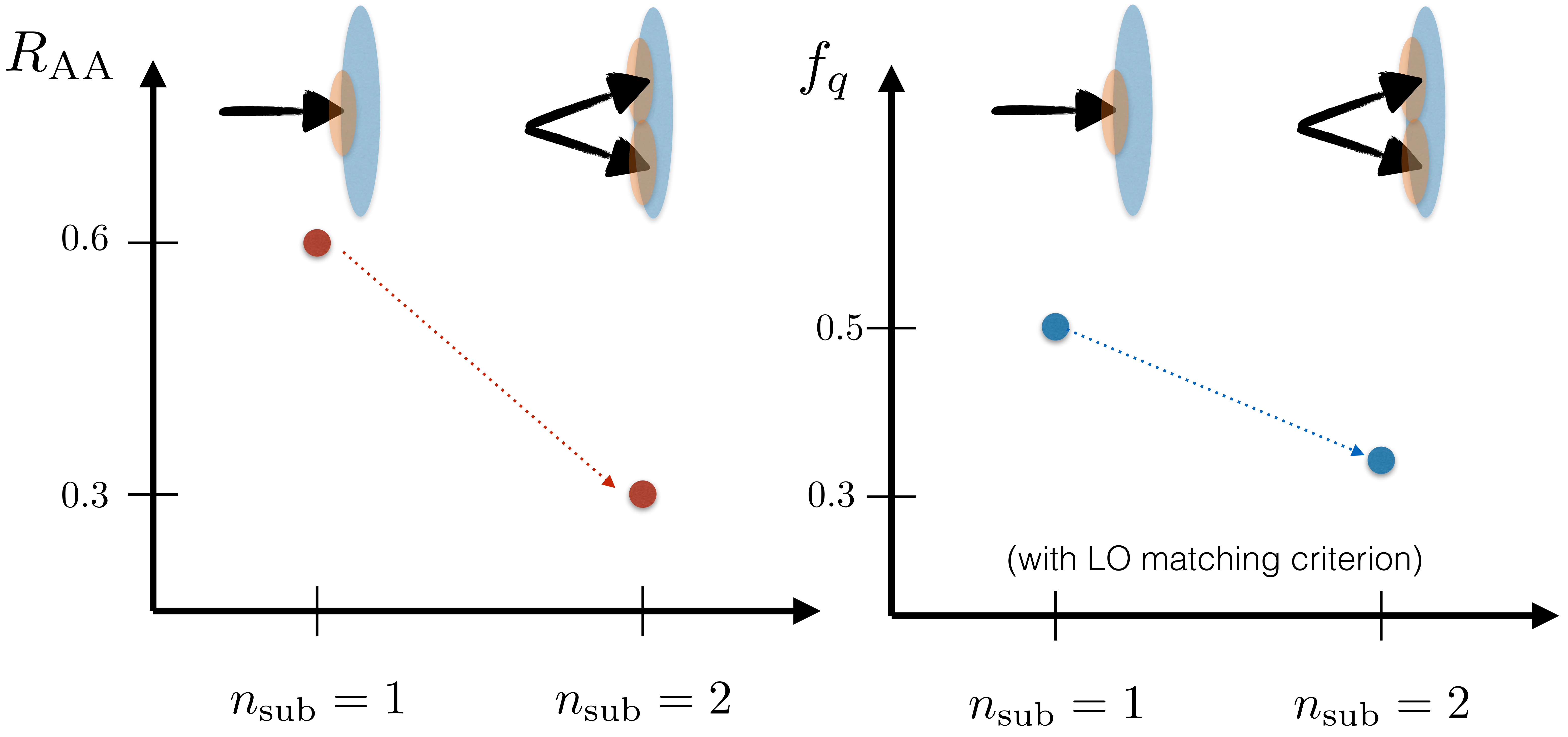
ATLAS - 2308.16652

Rapidity scans

DP & A. Soto-Ontoso - 2210.07901



ATLAS’ Jets from Jets & Coherence



See D. Hangal’s talk   ATLAS - [2301.05606](2301.05606)

If single resolved subjet:

$$f_q Q_q + (1 - f_q) Q_g = R_{\rm AA}$$

If two resolved subjets:

$$f_q Q_q Q_g + (1 - f_q) Q_g^2 = R_{\rm AA}$$

Physical solution only when assuming two *resolved* subjets, with

$$\frac{\log Q_g}{\log Q_q} \sim 2 \sim C_A / C_F$$

Reconstruct R=1 jets from R=0.2 jets:

If 2 or more subjets, more suppressed than single subjet.

If 2 or more subjets, quark-fraction decreases.

Illustration (with many caveats) that structures *form within*, and *interact with*, the medium independently.

EEC Species Dependence

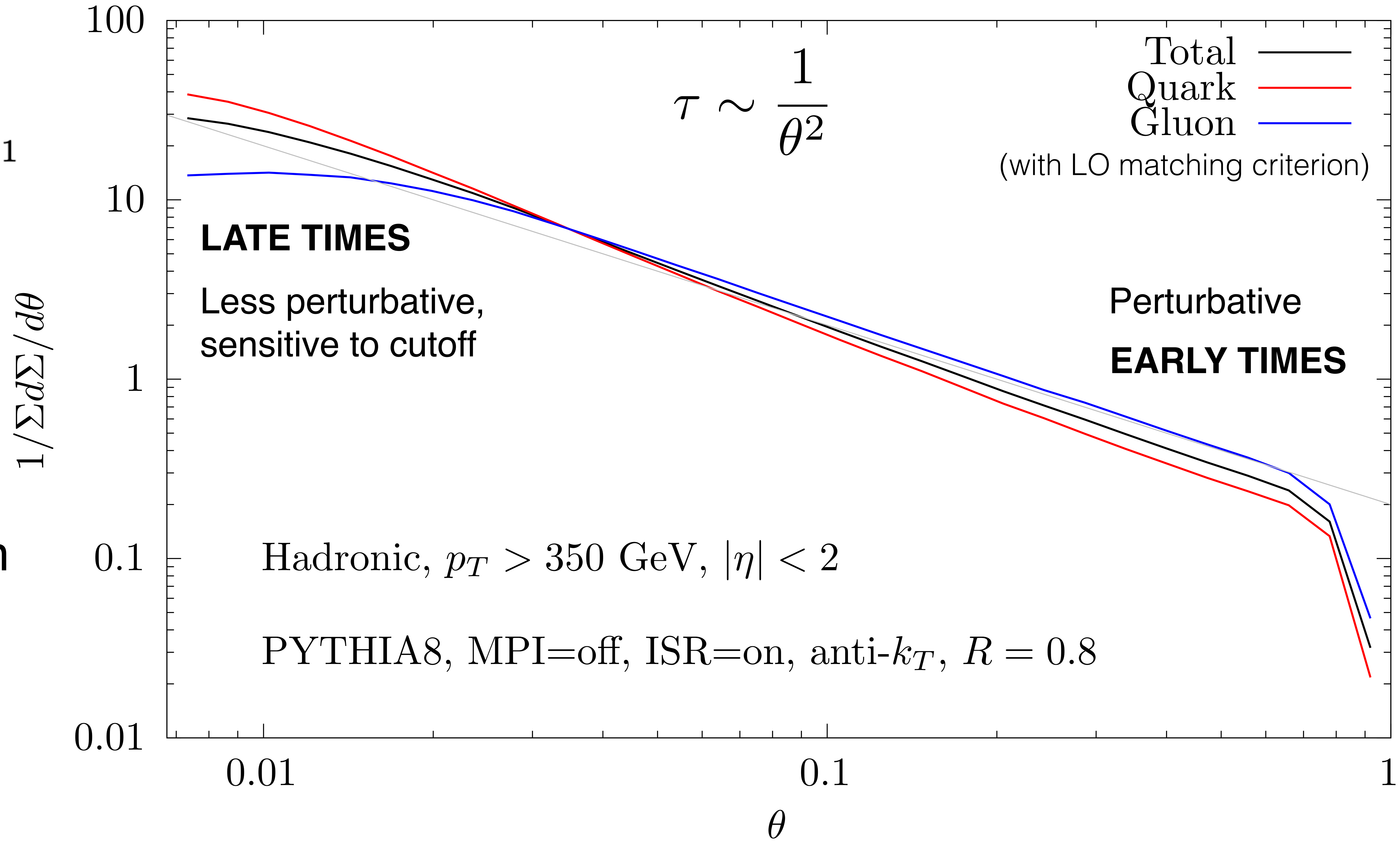
$$\frac{1}{\sigma}\sum_{ij\in\{g,q,\bar{q}\}}\int \mathrm{d}E_{i,j}\,\frac{\mathrm{d}\hat{\sigma}_{ij}^{\mathrm{vac}}}{\mathrm{d}\theta\,\mathrm{d}E_i\,\mathrm{d}E_j}\,\frac{E_i^n E_j^n}{Q^{2n}}\bigg|_{n=1}$$

$$\equiv J_{\mathrm{EEC}}^{(1)} = C\,\frac{1}{\theta^{1-\gamma(3)}} + \mathcal{O}(\theta^0)$$

Hofman & Maldacena - 0803.1467

EECs display different quark vs gluon slope due to anomalous dimension:

$$\gamma_{gg}(3) > \gamma_{qq}(3)$$



Quark jets present less structure at wider angles.

EECs & Coherence

C. Andrés et al. - 2209.11236, 2303.03413

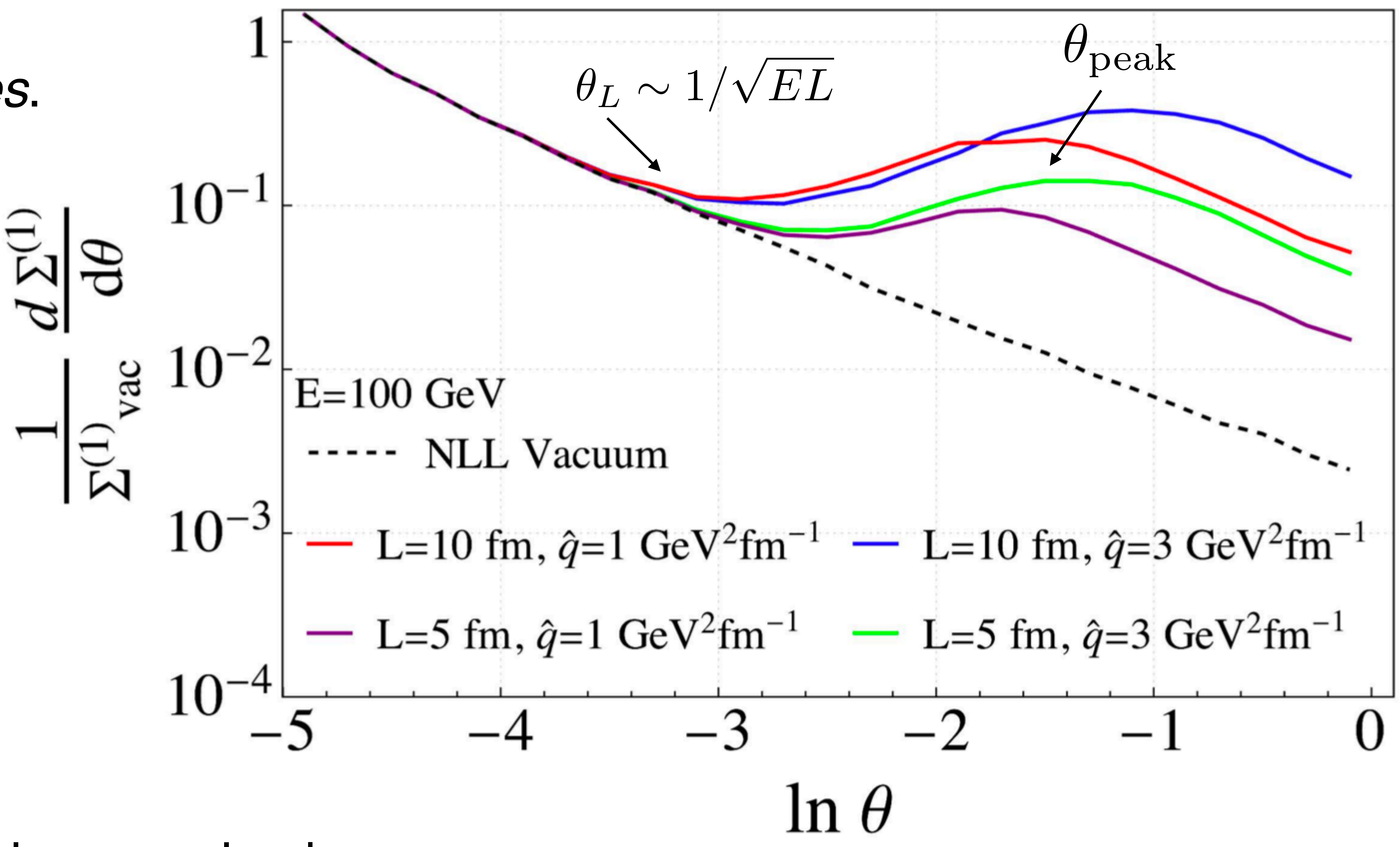
EEC in the medium expected to have *little sensitivity to initiator species*.

Onset of medium-induced radiation at θ_L ($\tau_f < L$ condition).

Peak position of EEC more sensitive to coherence, distinguish between:

$\theta_L \gg \theta_c$ Decoherent, all emissions resolved.

$\theta_c \ll \theta_L$ Partially coherent, some emissions resolved.



See C. Andrés' talk

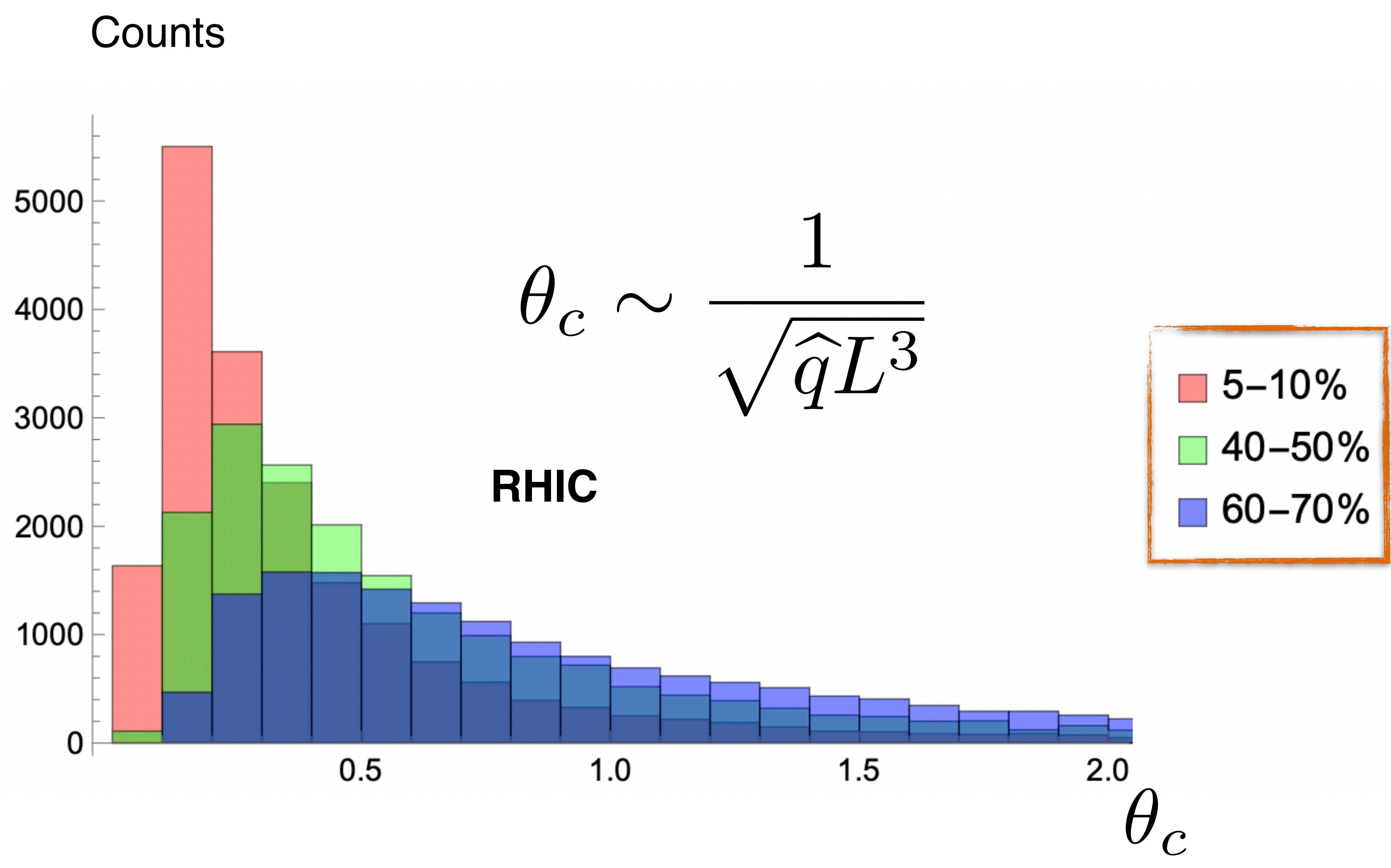
Jet v_2 & Coherence

Jet suppression depends on the size of the resolved phase-space.

- Shorter L, smaller resolved phase-space.
- Longer L, larger resolved phase-space.

Important contribution to **jet v_2**, unless

$$R < \theta_c(L_{\rm in}, L_{\rm out})$$



Can use centrality classes to target different values of L, different values of $\mathrm{Med}(\theta_c)$.

Study evolution of $v_2(R)$ vs centrality to explore the effect.

See Y. Mehtar-Tani's talk

Cascading down to T

While semi-hard VLE do not in general emit soft gluons independently (coherence),

Soft induced radiation experience successive independent democratic branchings.

One-gluon distribution admits description in terms of rate equation,
turbulent cascade result within multiple soft scattering approx.

Main thermalization mechanism in pQCD.

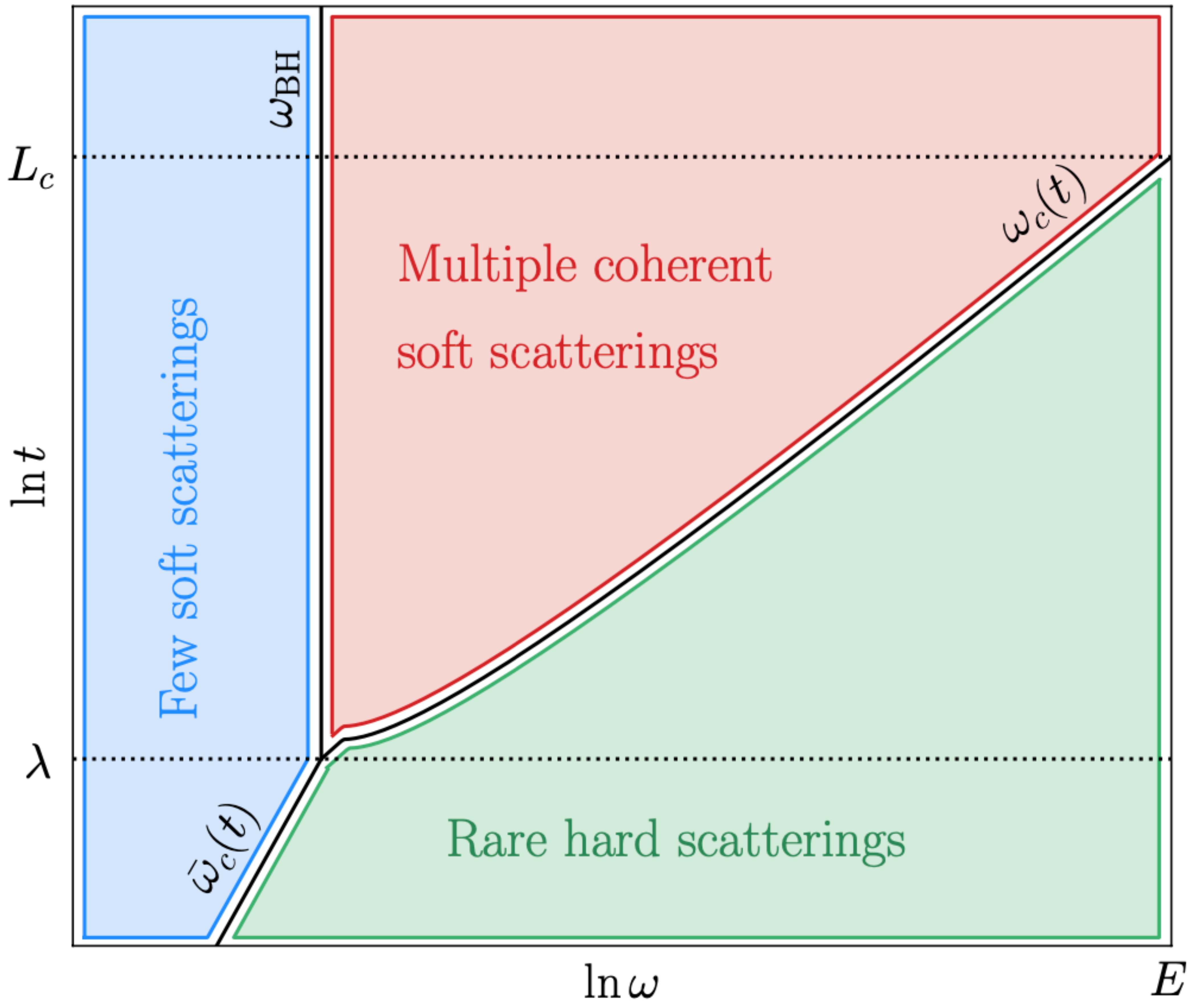
Very recently it has been shown that **hard** induced emissions can **also** be assumed to happen independently.

P. Arnold et al. - [2212.08086](), many more

Role of Single Scatterings

Recent developments highlight the role of single scatterings
(**BH** at small energy, **GLV** at high energy).

Isaksen et al. - 2206.02811



Analytical results for all the different regimes, including Bethe-Heitler.

Can account for their relative contribution, at each emitted energy, at each time step in the evolution.

Cascade picture is modified by single scatterings:

Rare hard scatterings (**GLV**) modify distribution of initiator (extra source).

Common soft scatterings (**BH**) modify soft tail, break turbulent flow.

Important to understand jet thermalization in pQCD when path-lengths are not too large (realistic geometries, smaller systems).

EKT Jet Thermalization

However, where Bethe-Heitler becomes important, also 2↔2 scatterings are important

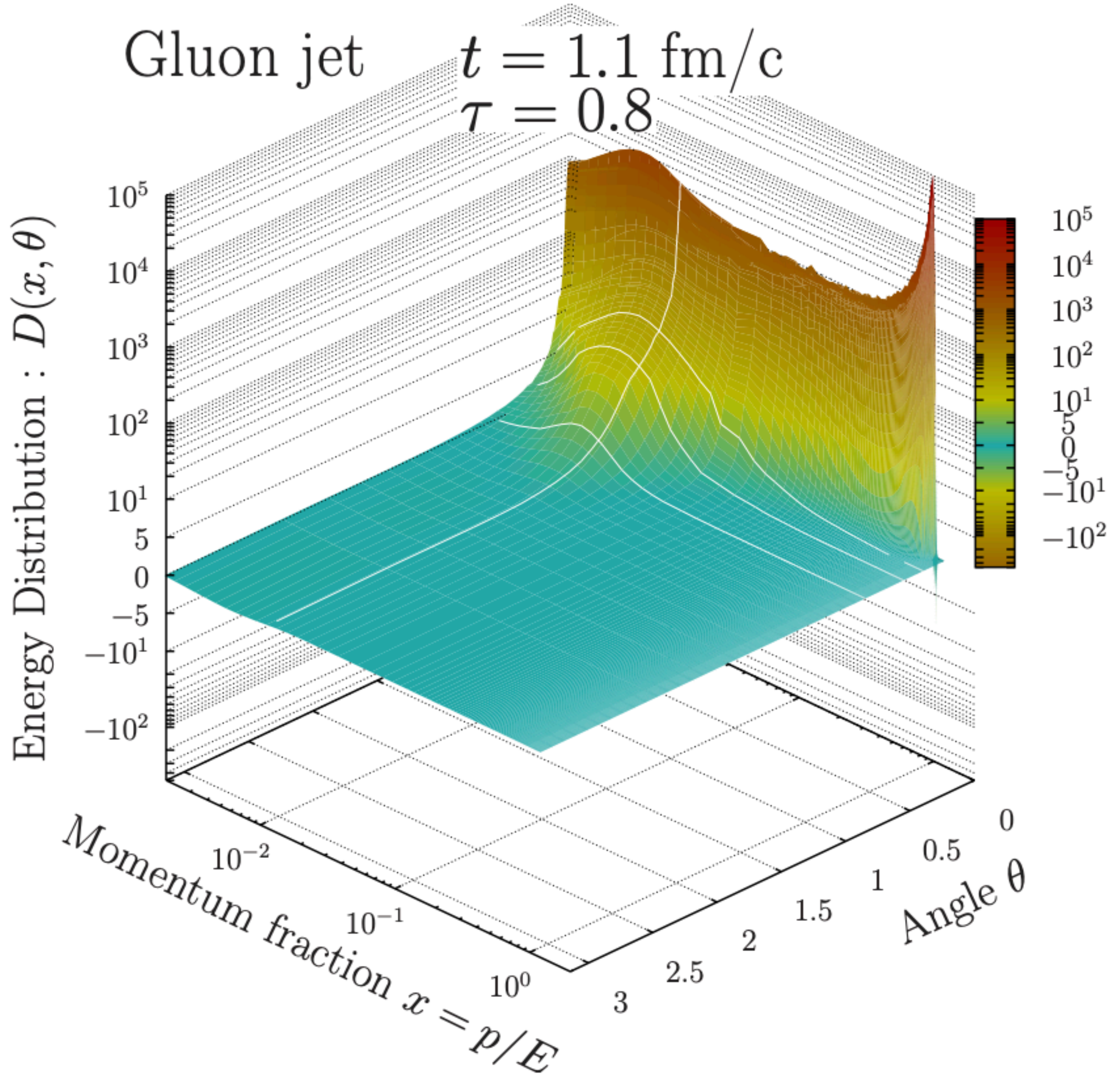
- Recoils needs to be taken into account.
- Thermal masses.

In-medium fragmentation of hard parton in QGP through effective kinetic theory (EKT):

Includes 1↔2 and 2↔2 processes.

Features cascade, modified chemistry around the jet.

Detailed analysis of dynamics,
can account for *medium response*.



Mehtar-Tani et al. - 2209.10569

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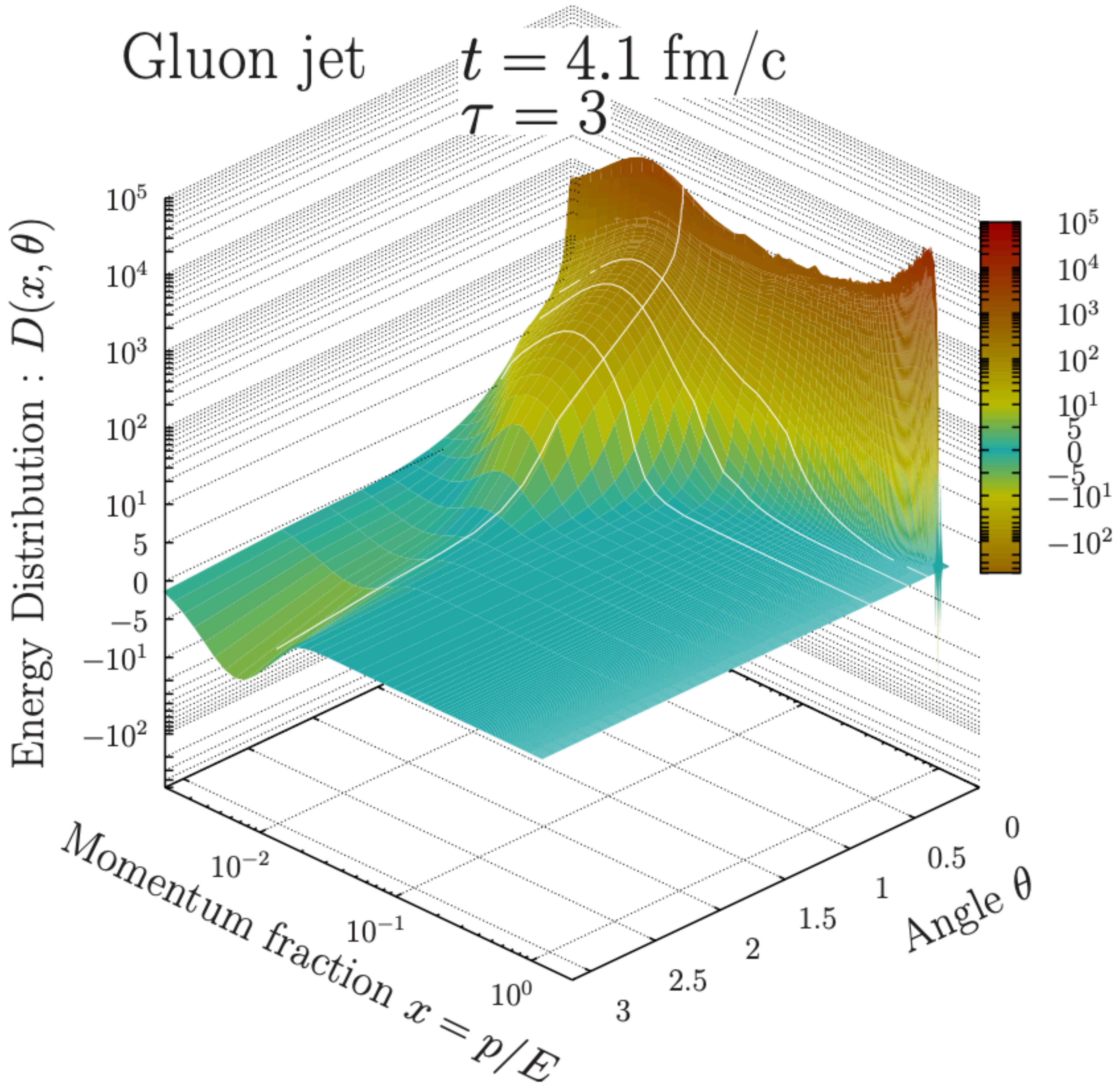

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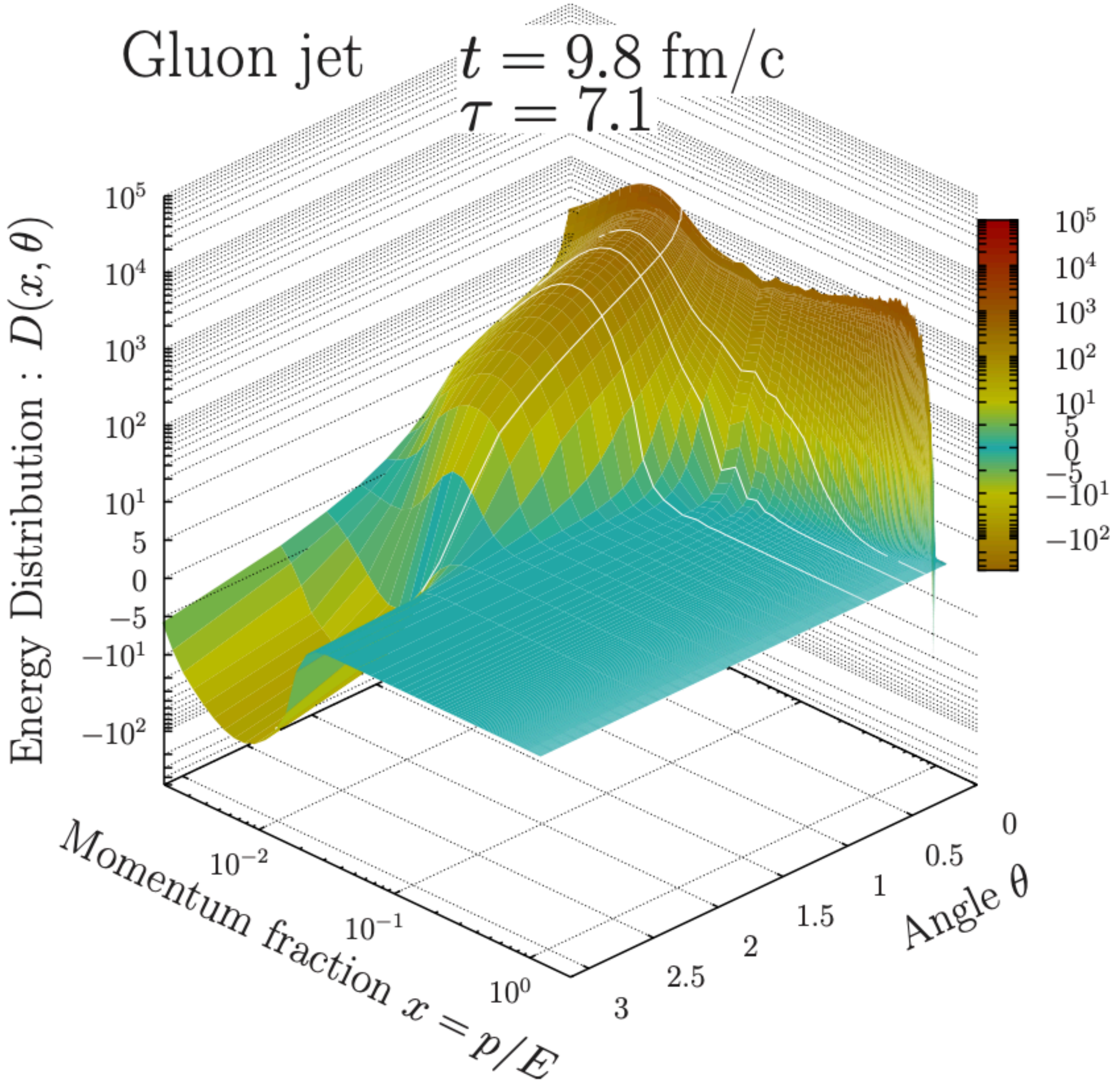

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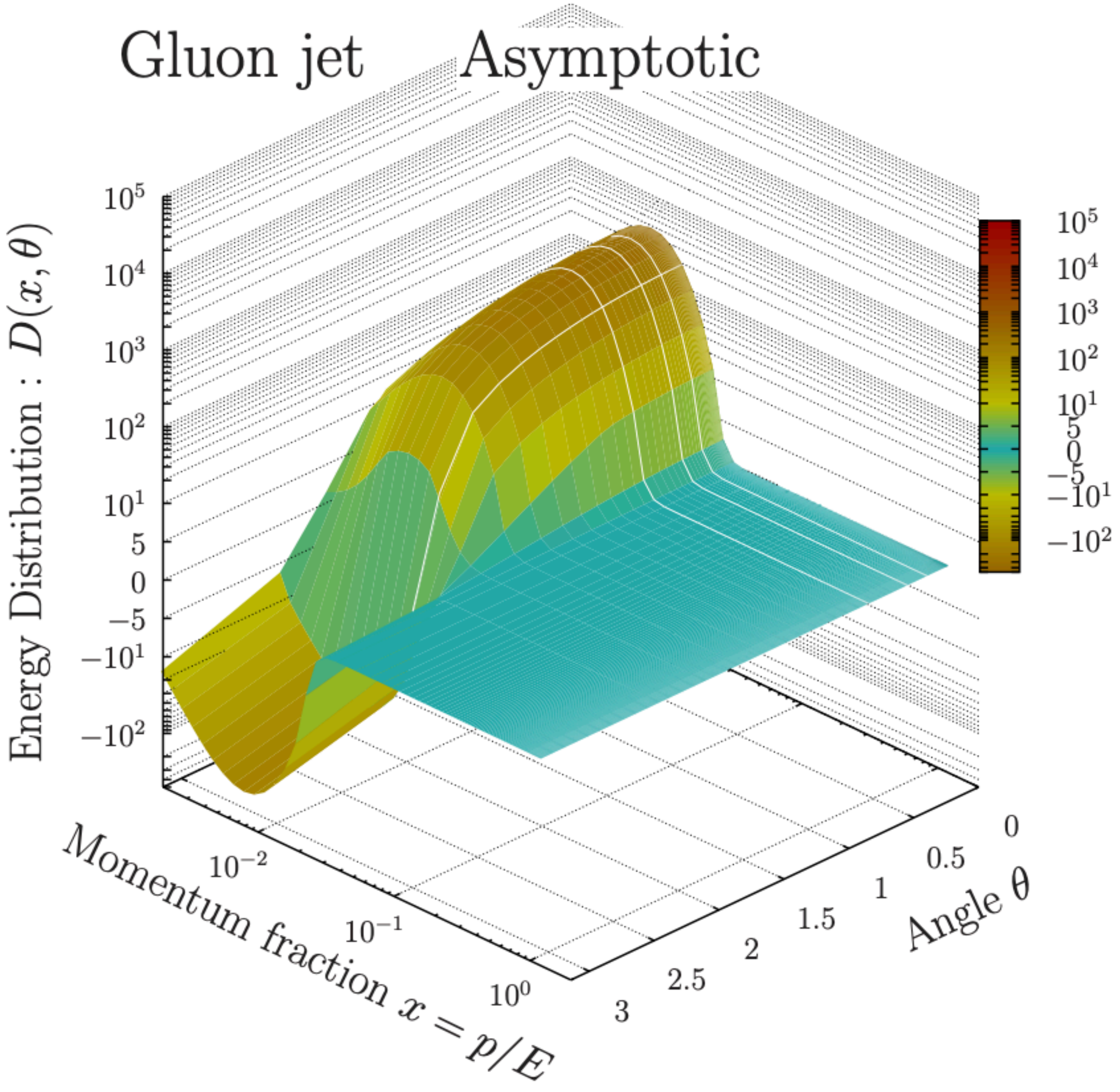


Mehtar-Tani et al. - 2209.10569

Flow and Gradient Effects

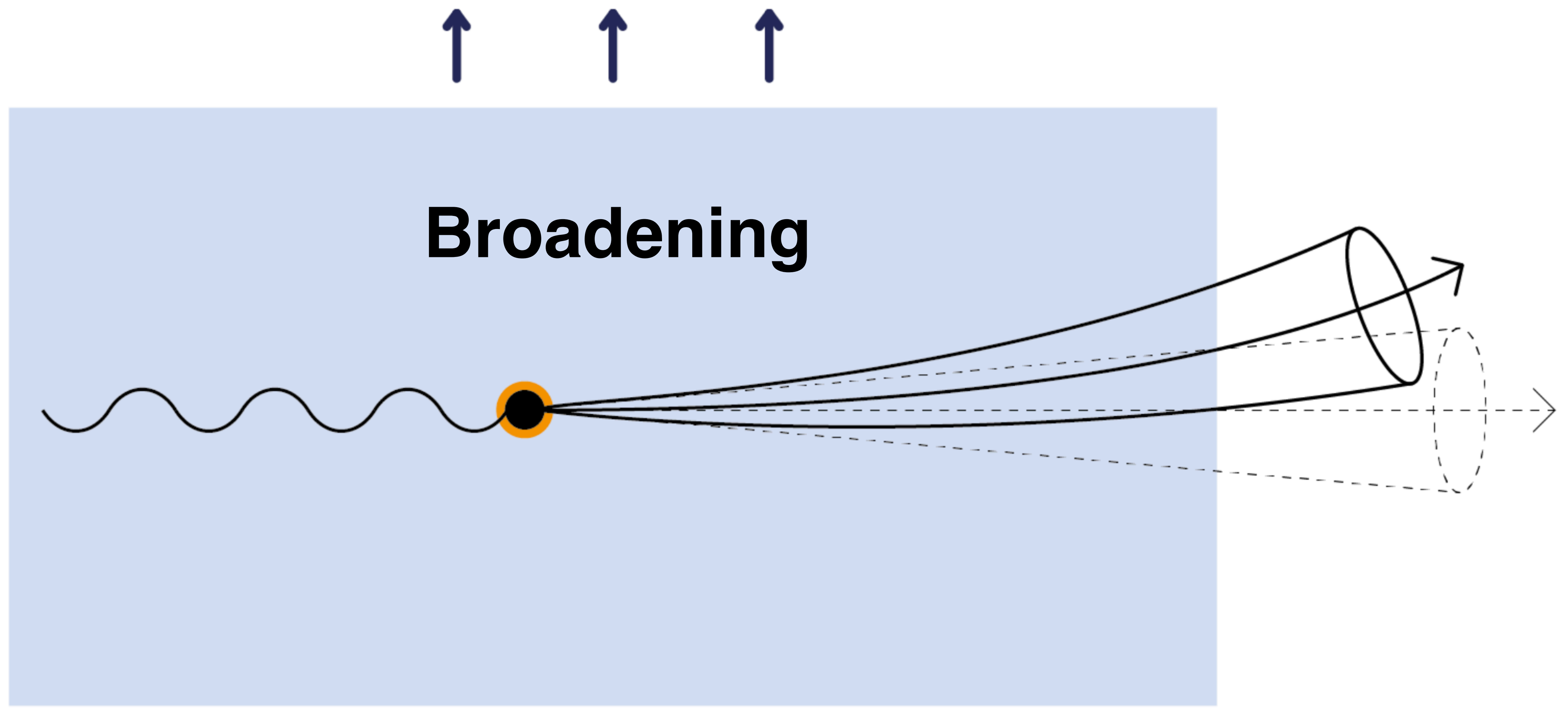
Up to very recently, most first-principle calculations assumed *static QGP brick*.

Accessing imprints of spacetime evolution of fluid QGP have required new theoretical results.

New calculations of *single and multiple scatterings* regimes using scattering potential with:

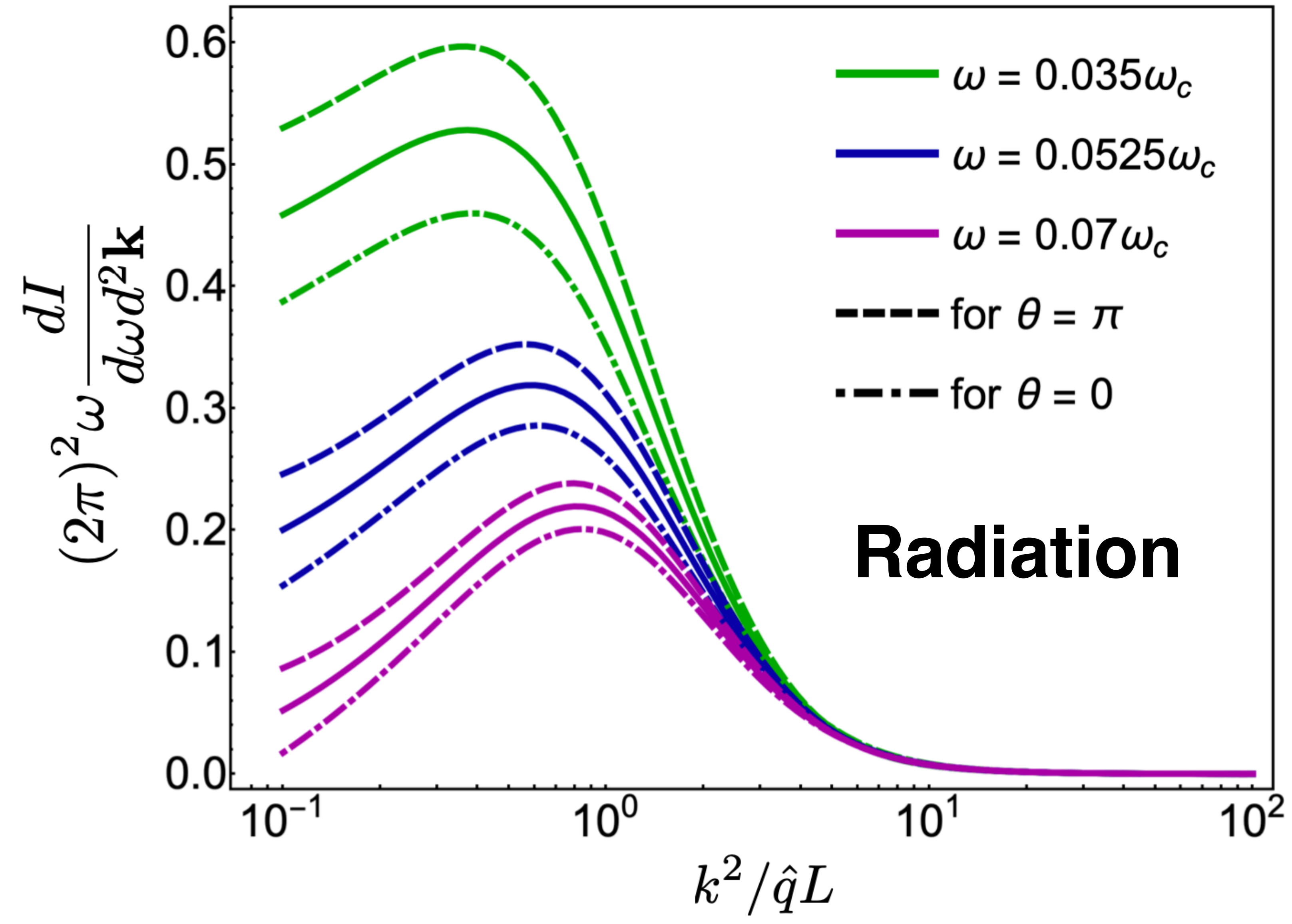
Gradients in temperature, density (not uniform): *broadening* & *radiation*. A. Sadofyev et al. - 2021-2023

Flowing matter (not static): *broadening*.



$$\langle \mathbf{p}\, p_\perp^2 \rangle \simeq \chi^2 \frac{L\nabla T}{2T} \frac{\mu^4}{E} \left(\log \frac{E}{\mu}\right)^2 \qquad \langle \mathbf{p} \rangle \simeq 3\,\chi\, \mathbf{u} \frac{\mu^2}{E} \log \frac{E}{\mu}$$

Primarily affects soft radiation.

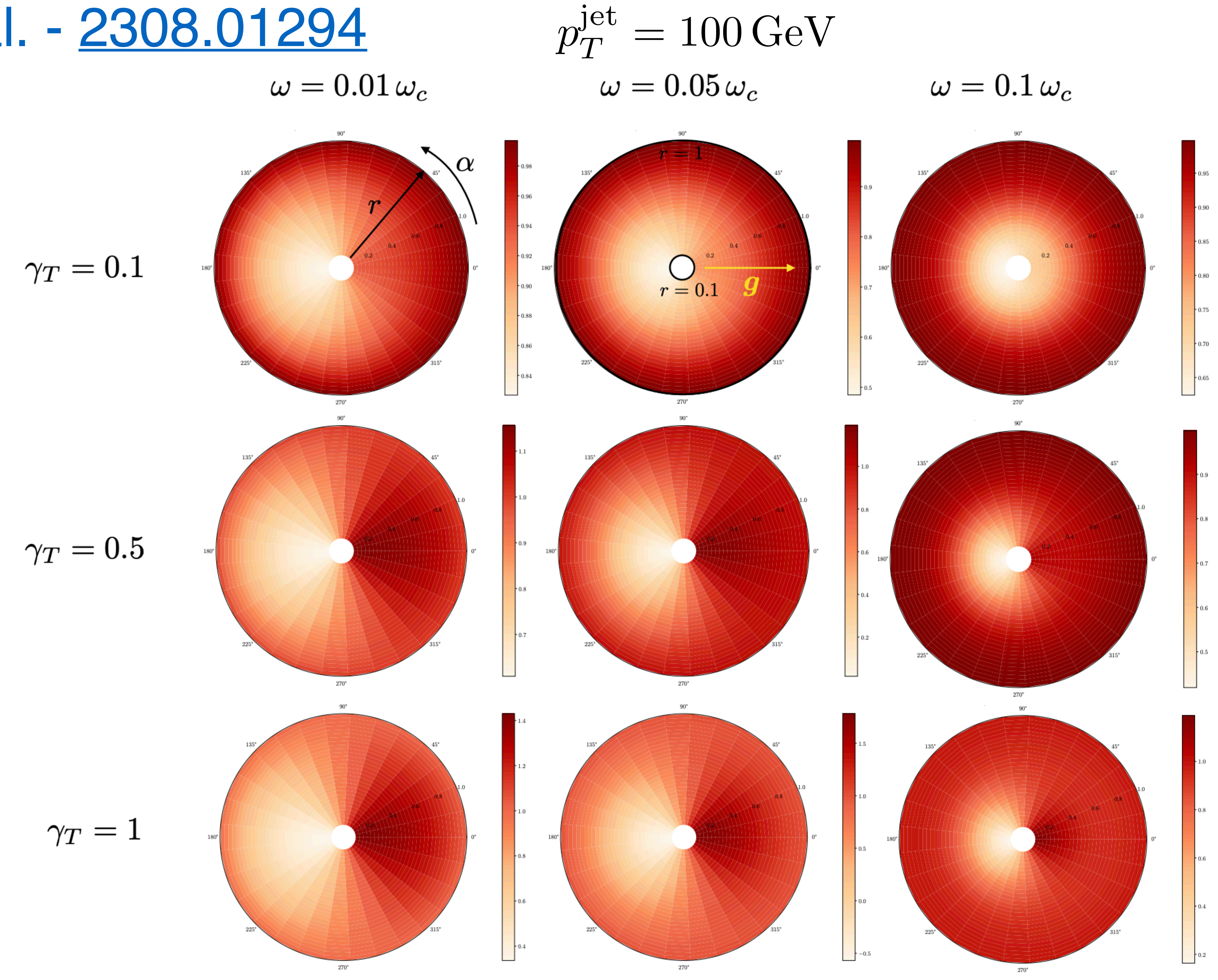


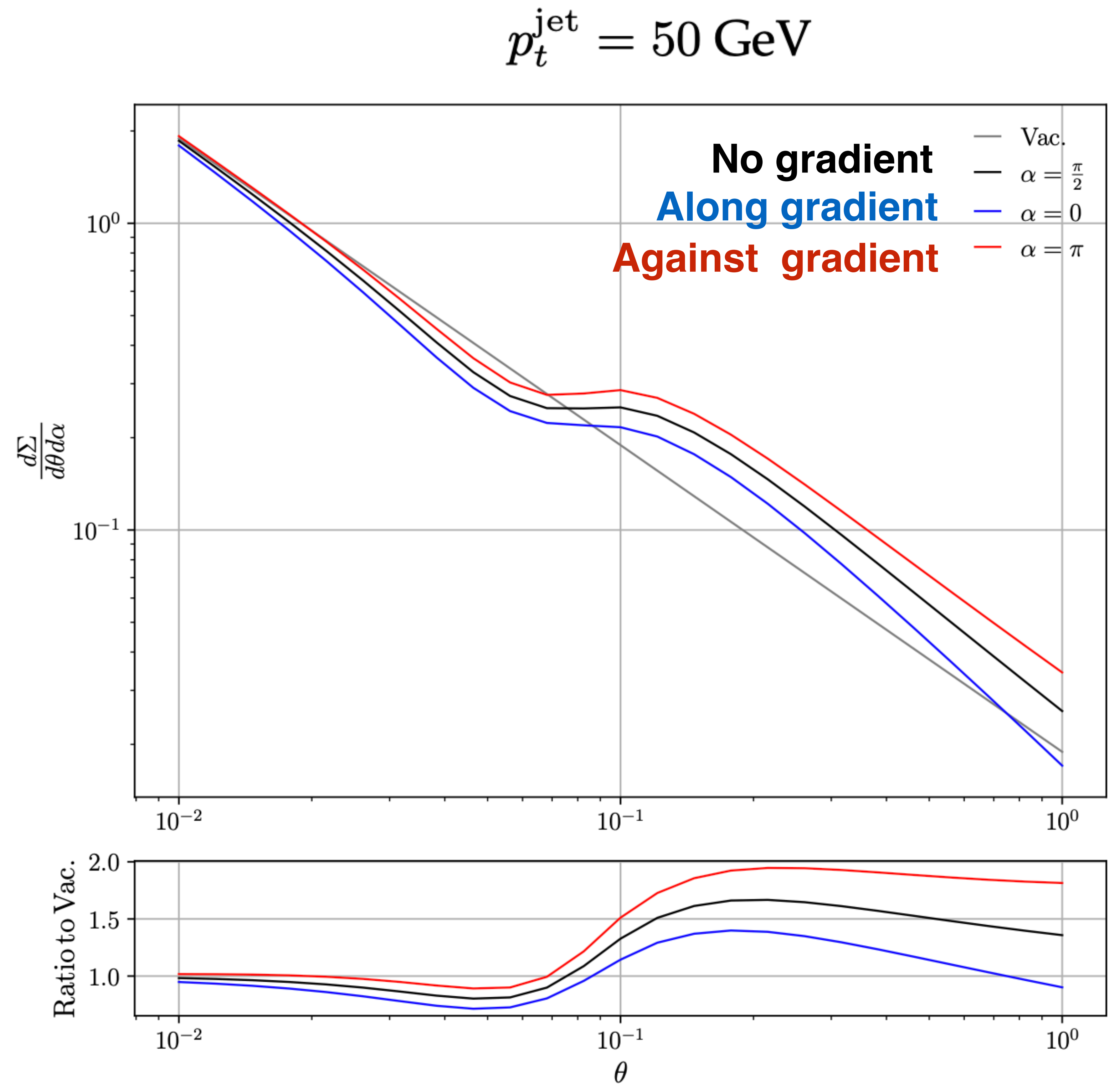
$$\left|\frac{\nabla T}{T^2}\right| = 0.05$$

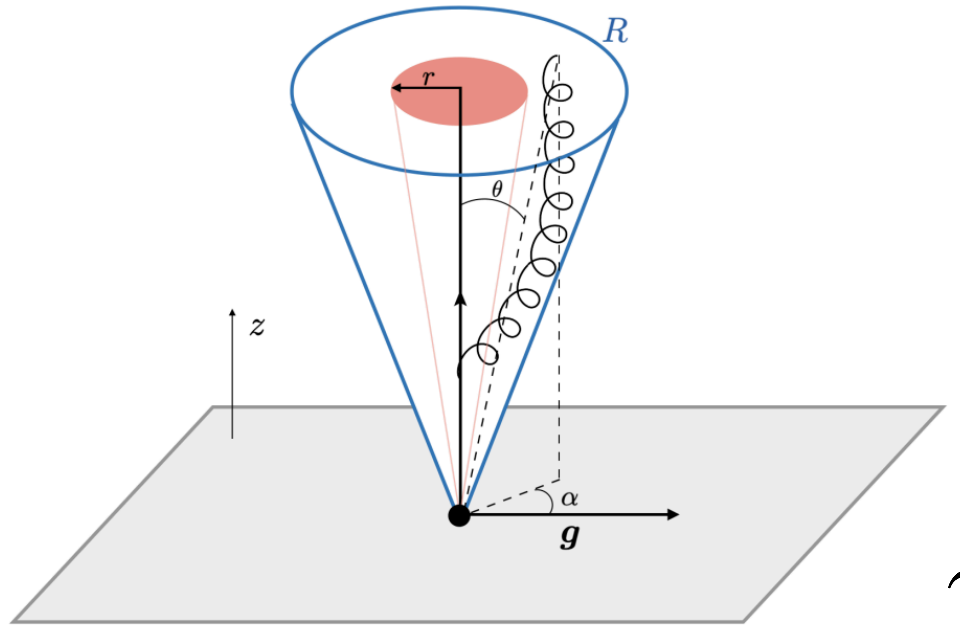
See also S. Hauksson et al. - PRC '21, '22

Anisotropic Jet Shapes & EEC

Barata et al. - [2308.01294]







$$\rho(r) = \int_0^r dr' \, \frac{p_t(r')}{p_t^{\rm jet}}$$

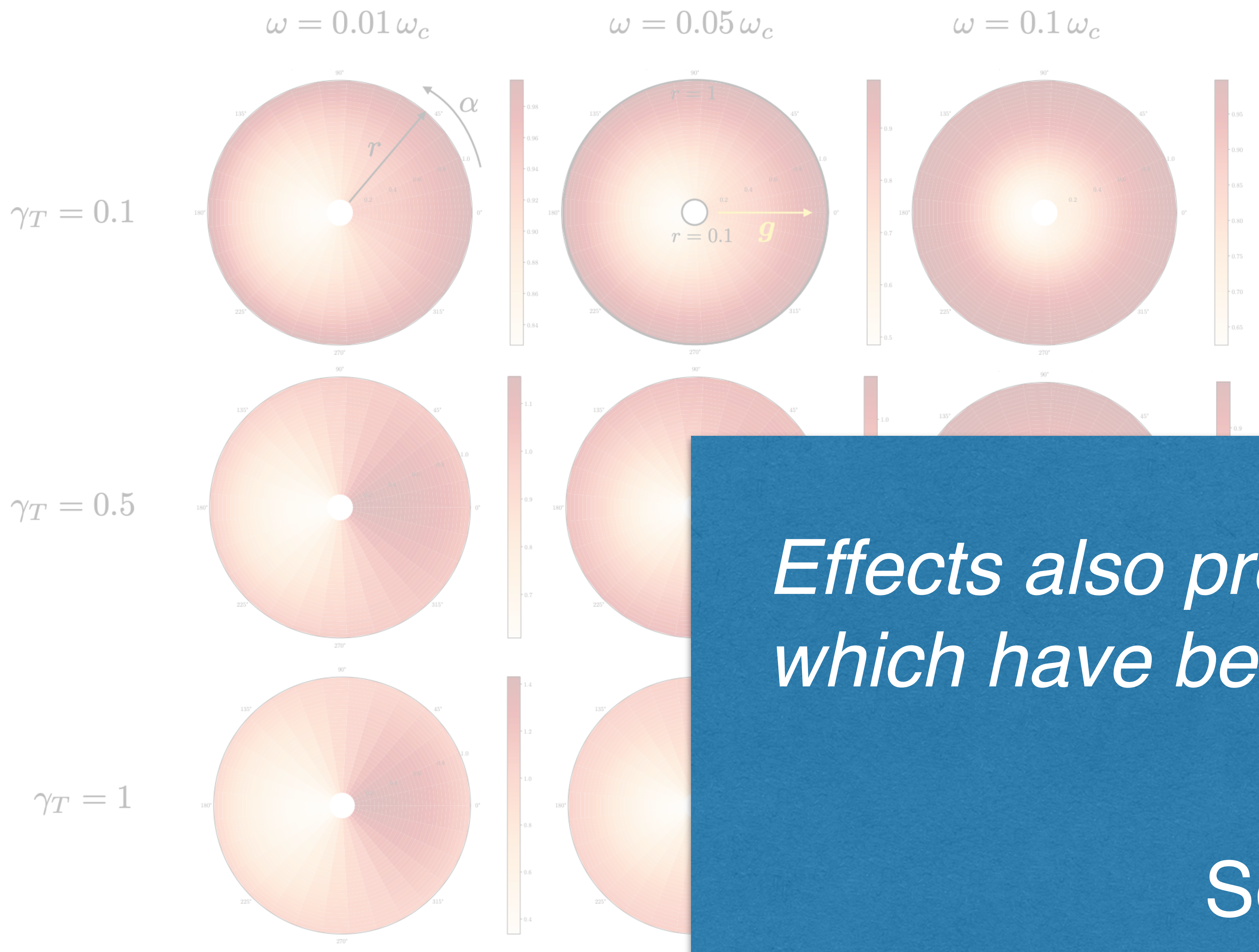
γ_T is gradient strength

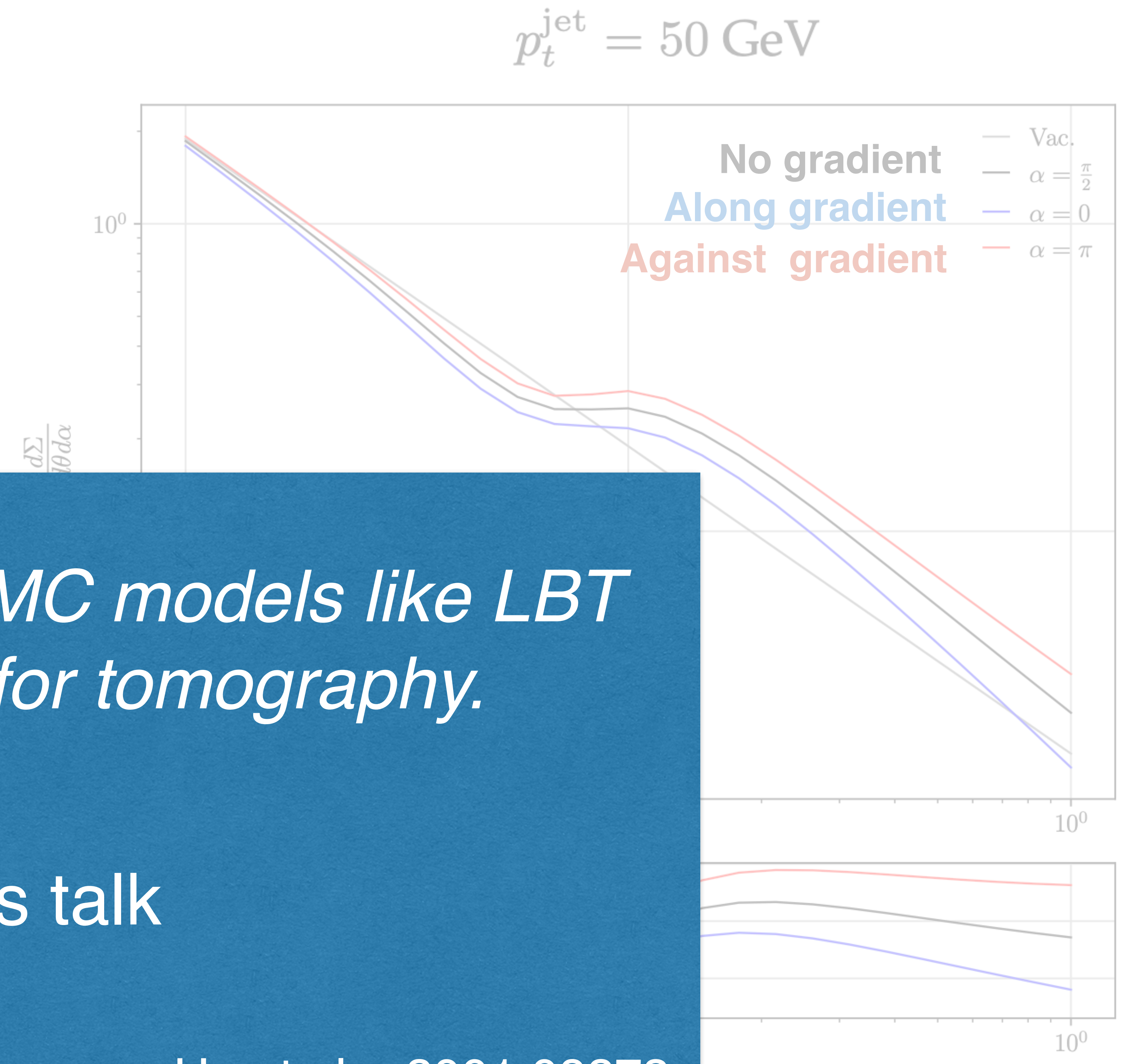
Transverse energy profile (jet shape) shows that gluons slightly pushed along gradients direction.

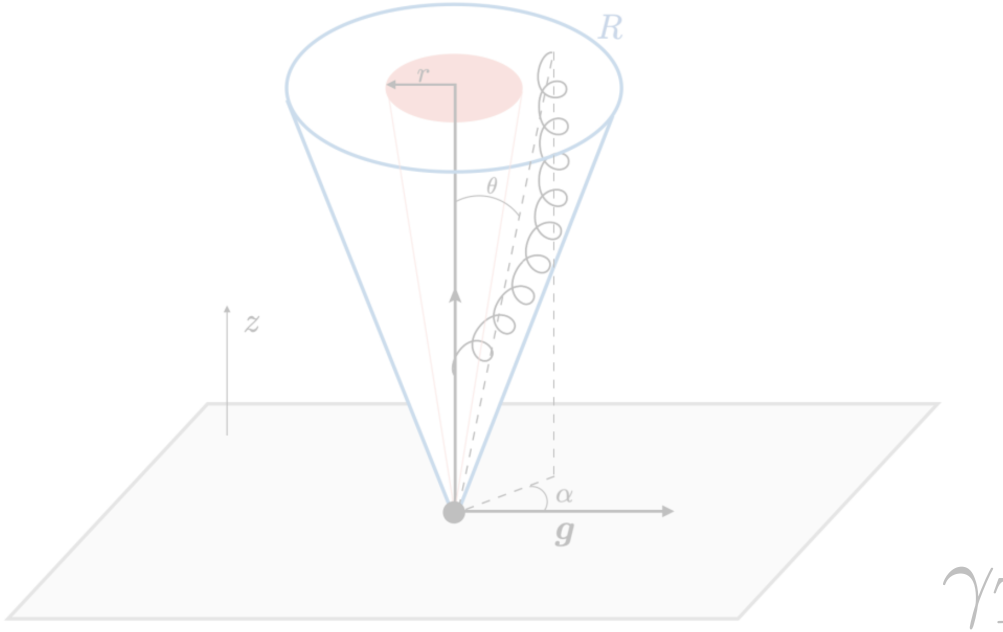
EEC's sensibility to gradient effects relatively robust under VLEs over a larger phase-space.

Anisotropic Jet Shapes & EEC

Barata et al - 2308.01294







$\rho(r) = \int_0^r$ ... $p_t^{\rm jet}$

Effects also present in MC models like LBT which have been used for tomography.

See Y. He's talk

He et al. - 2001.08273

Transverse energy profile (jet shape) shows that gluons slightly pushed along gradients direction.

γ_T is gradient strength

EEC's sensibility to gradient effects relatively robust under VLEs over a larger phase-space.

Sourcing Hydro with Jets

Adding gradient and flow effects in broadening and radiation provides key information about fluid QGP.

But when quanta reach thermal scale (?), they become part of the medium.

Treat them as source of energy and momentum into the hydro e.o.m.

$$\partial_\mu T^{\mu\nu}_{\text{hydro}} = J^\nu$$

Common approach: Gaussian functional form for the source term.

However, need better motivated form. Causal diffusion eq. used in Y. Tachibana et al. - 2001.08321.

Detailed studies of equilibration using EKT can provide answers.

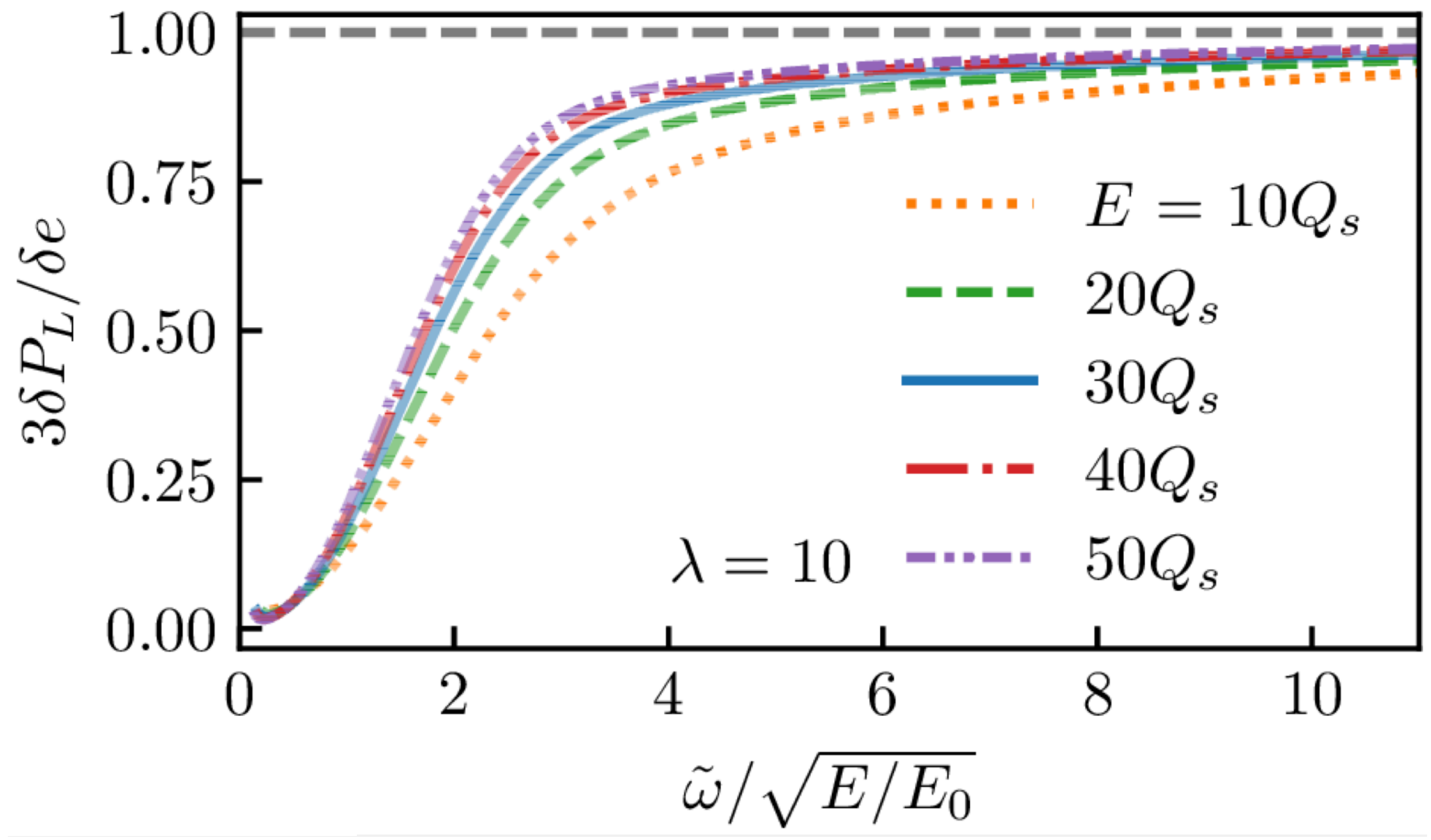
J_ν?

Mini-jet in an expanding background:

Hydrodynamizes slower than bkgd.

Hydro. times scales with $\sqrt{E}$.

See A. Mazeliauskas' talk



Green's functions à la KøMPøST?

See S. Ochsenfeld's talk

The Jet Wake

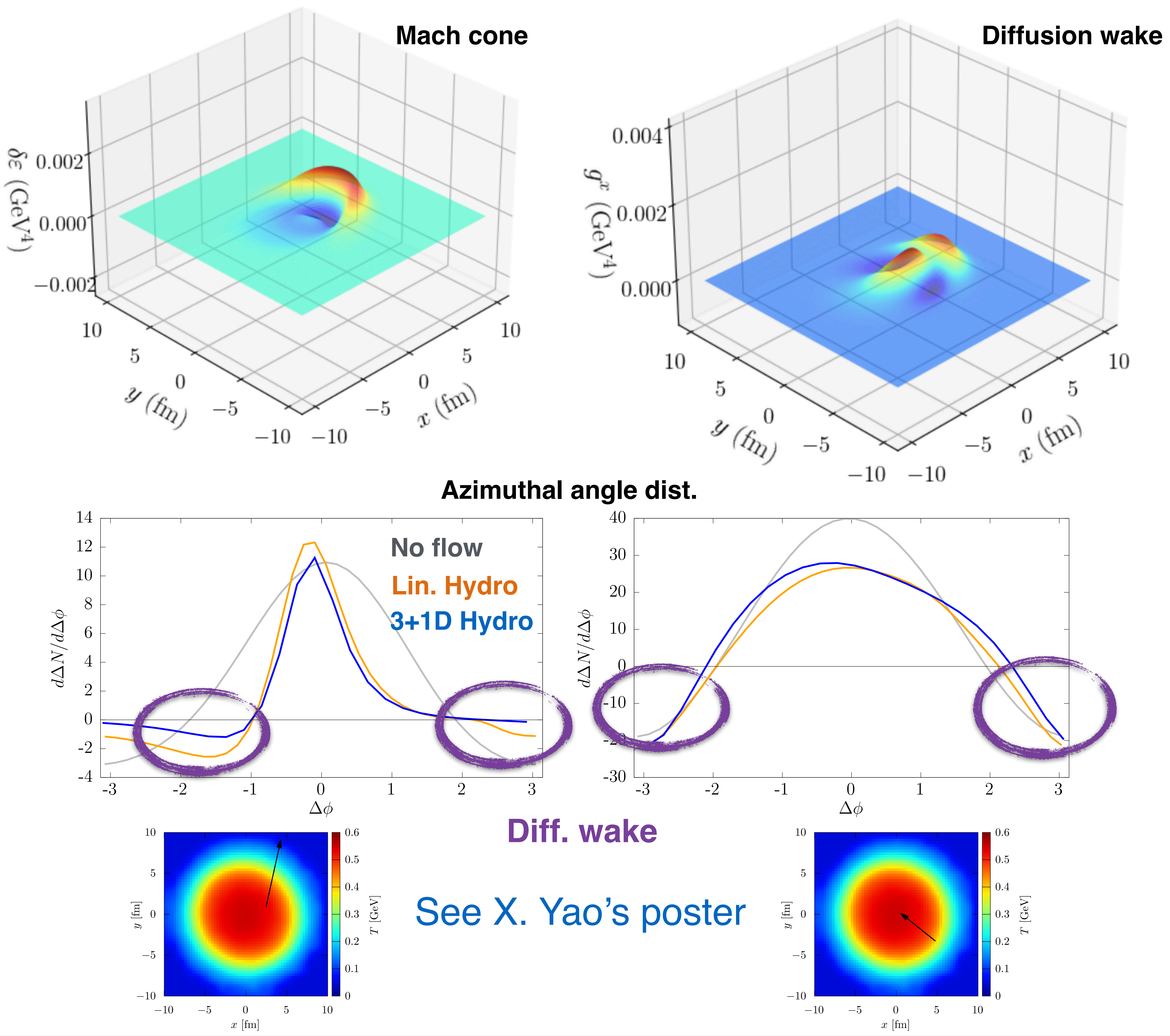
Jet-induced perturbation excites sound and diffusive modes.

Sensitive to fluid viscosity.

Sound modes spread energy in rapidity; break long. boost invariance.

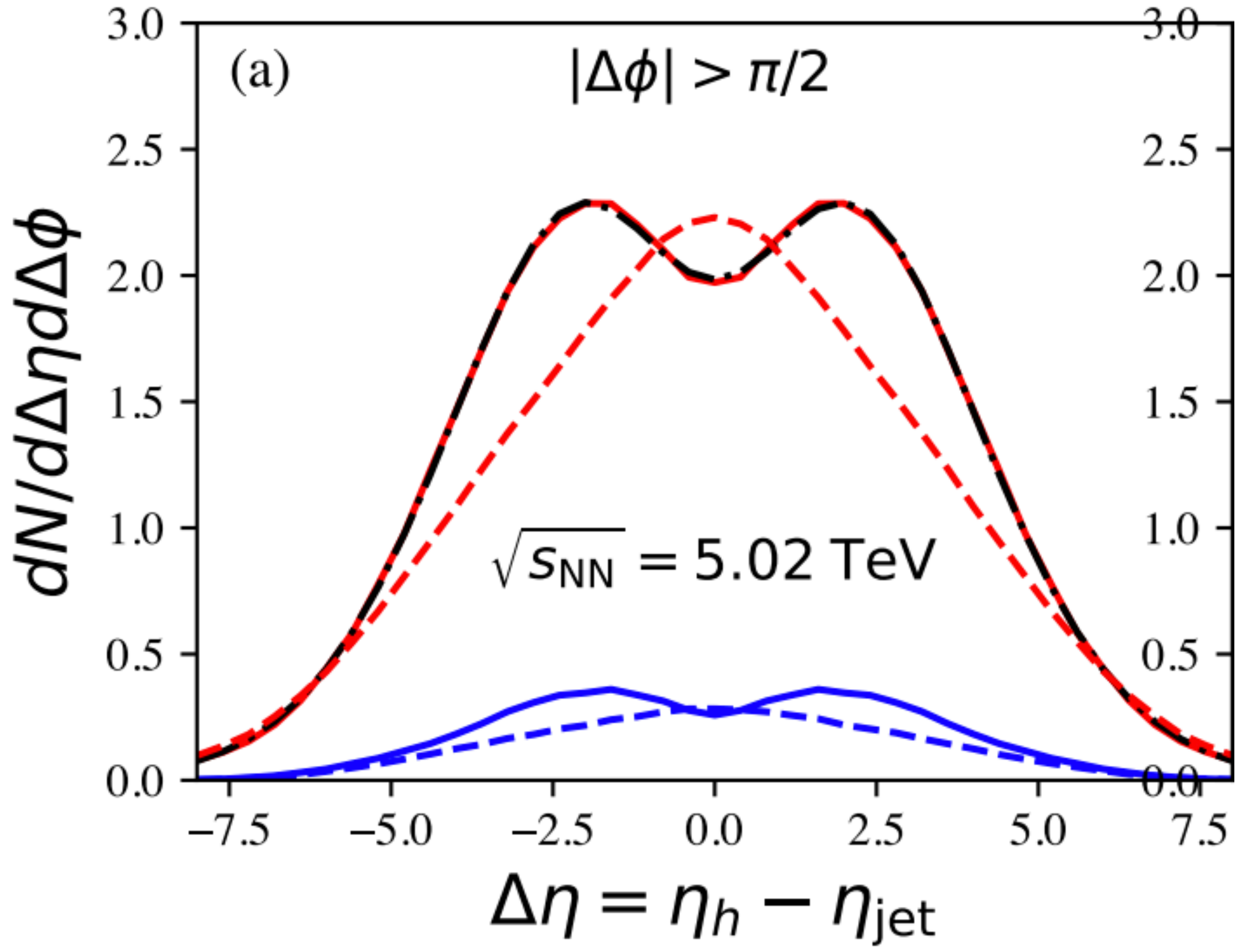
Final hadron distribution result of interplay of evolution time and flow at freezeout.

Lin. hydro speeds up by factor ~ 10.000.



Looking for Smoking Guns

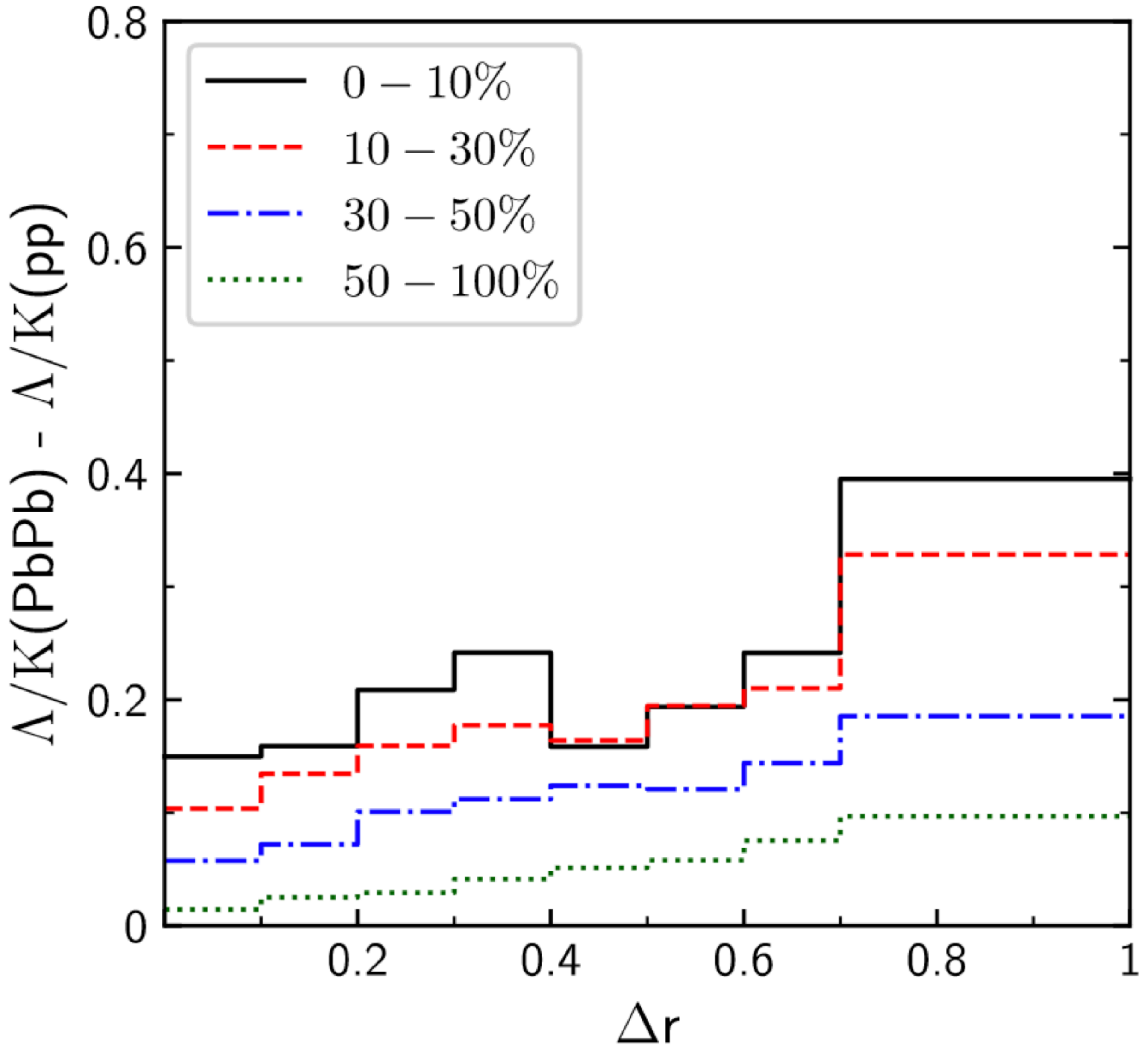
Boson-Jet Yang et al. - 2203.03683



Depletion on top
of multi-parton interactions
(double peak in rapidity).

See Z. Yang's talk

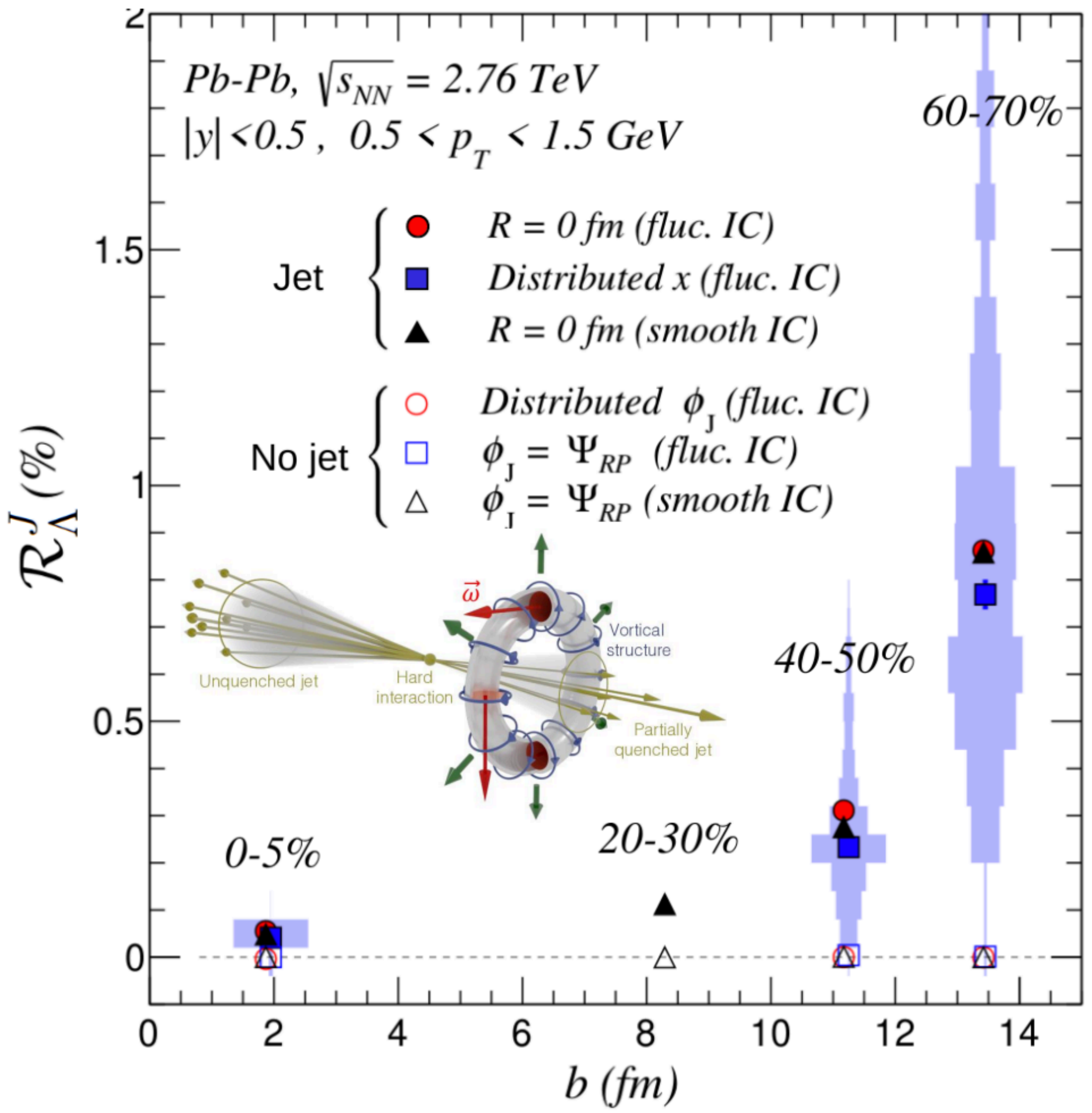
Inclusive Jets Luo et al. - 2109.14314



Baryon to meson enhancement
around the jet axis.

See G. Qin's talk

Λ Ribeiro et al. - 2305.02428



See W. Serenone's talk

Diffusion wake causes depletion of soft particles:

Opposite to the jet in φ.

Close to jet in η.

Medium recoils coalesce at intermediate p_T.

See Y. Go's talk for more

Λ hyperons polarize due to jet-induced vortex ring:

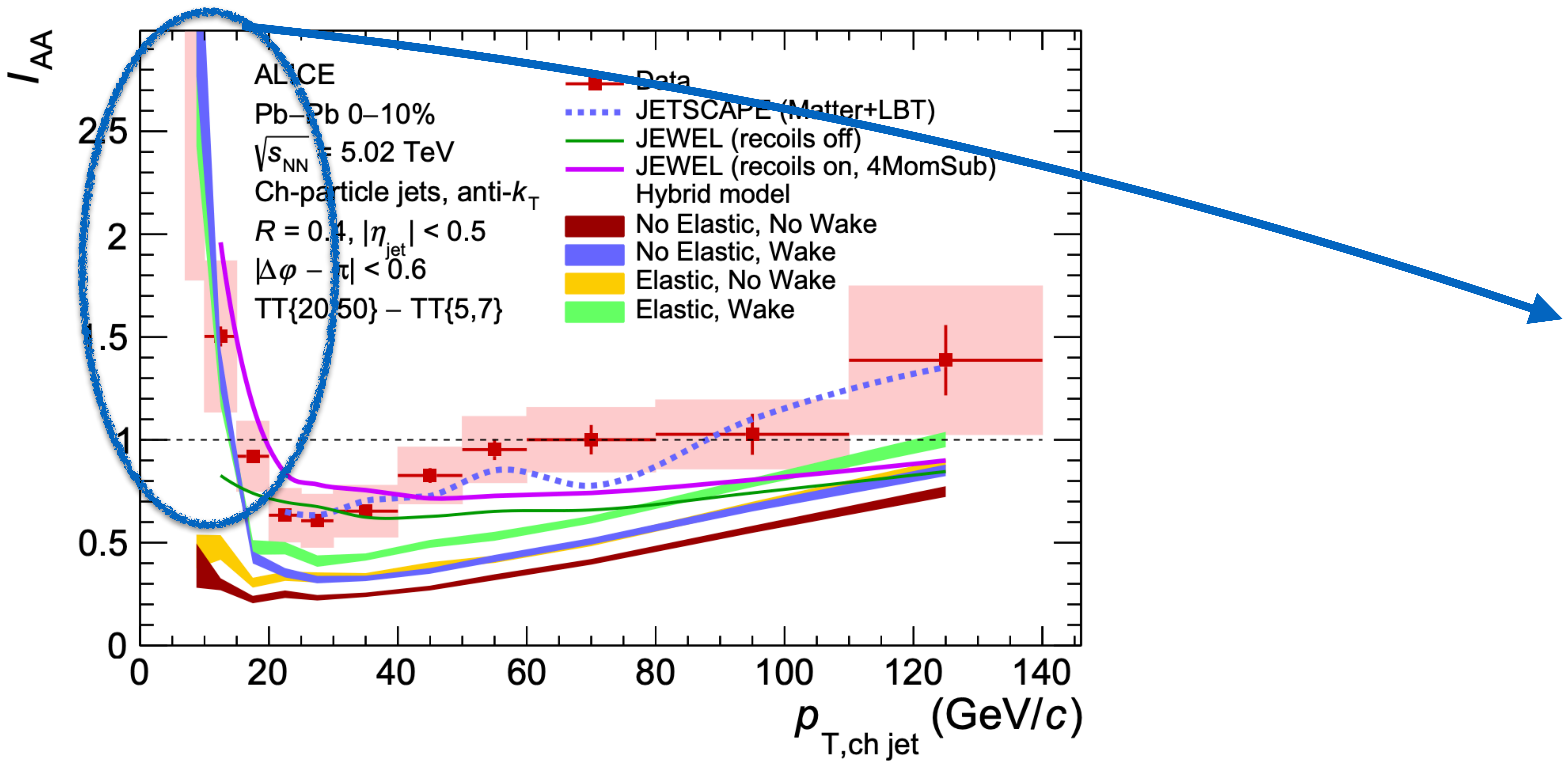
Decouple from system expansion vortices.

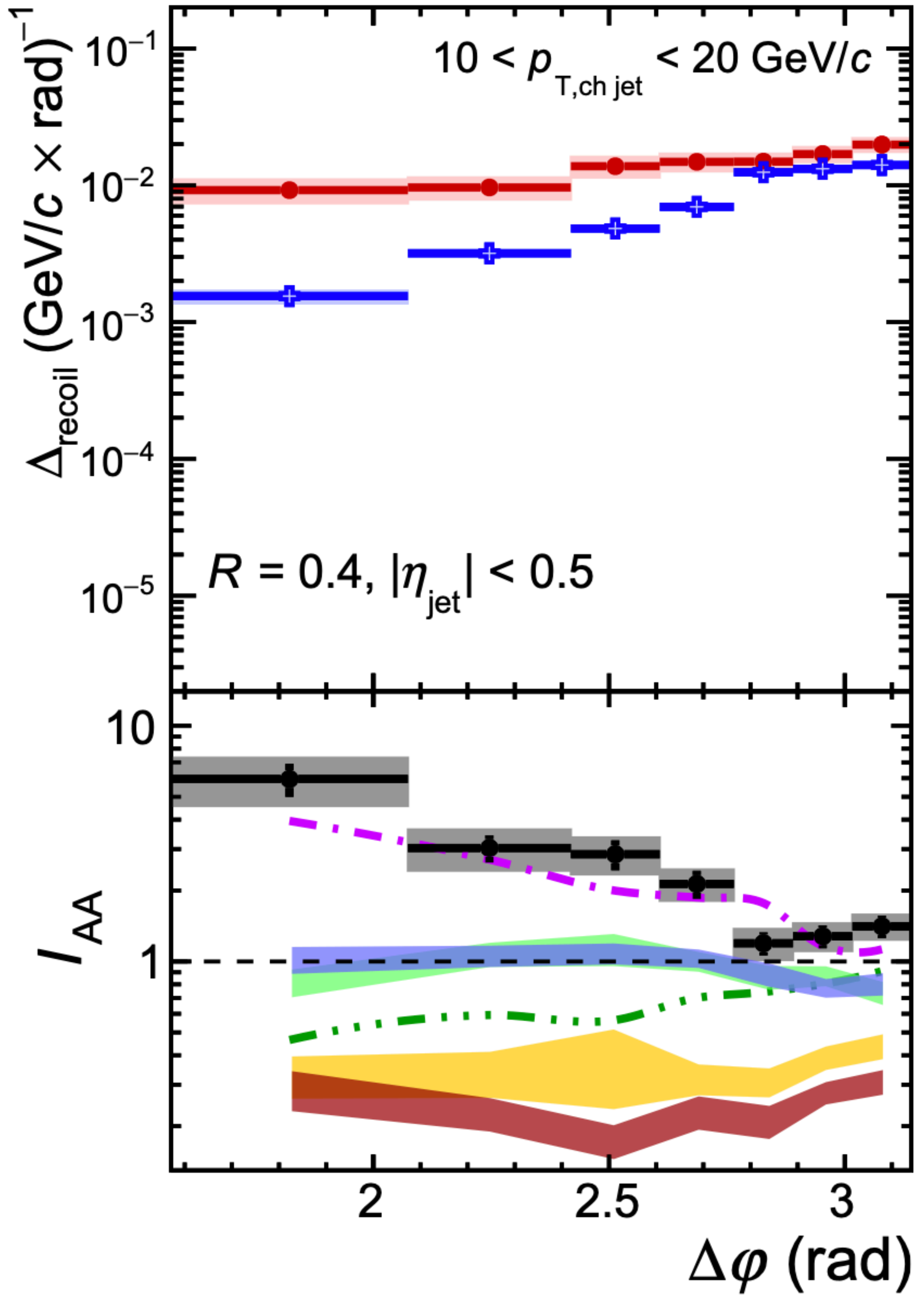
Promising tomographic tool.

As Low as It Jets

ALICE - 2308.16131, 2308.16128

See talk by J. Norman





Study of very low p_T semi-inclusive jets:

Overcomes survival bias.

Completely thermalized jets?

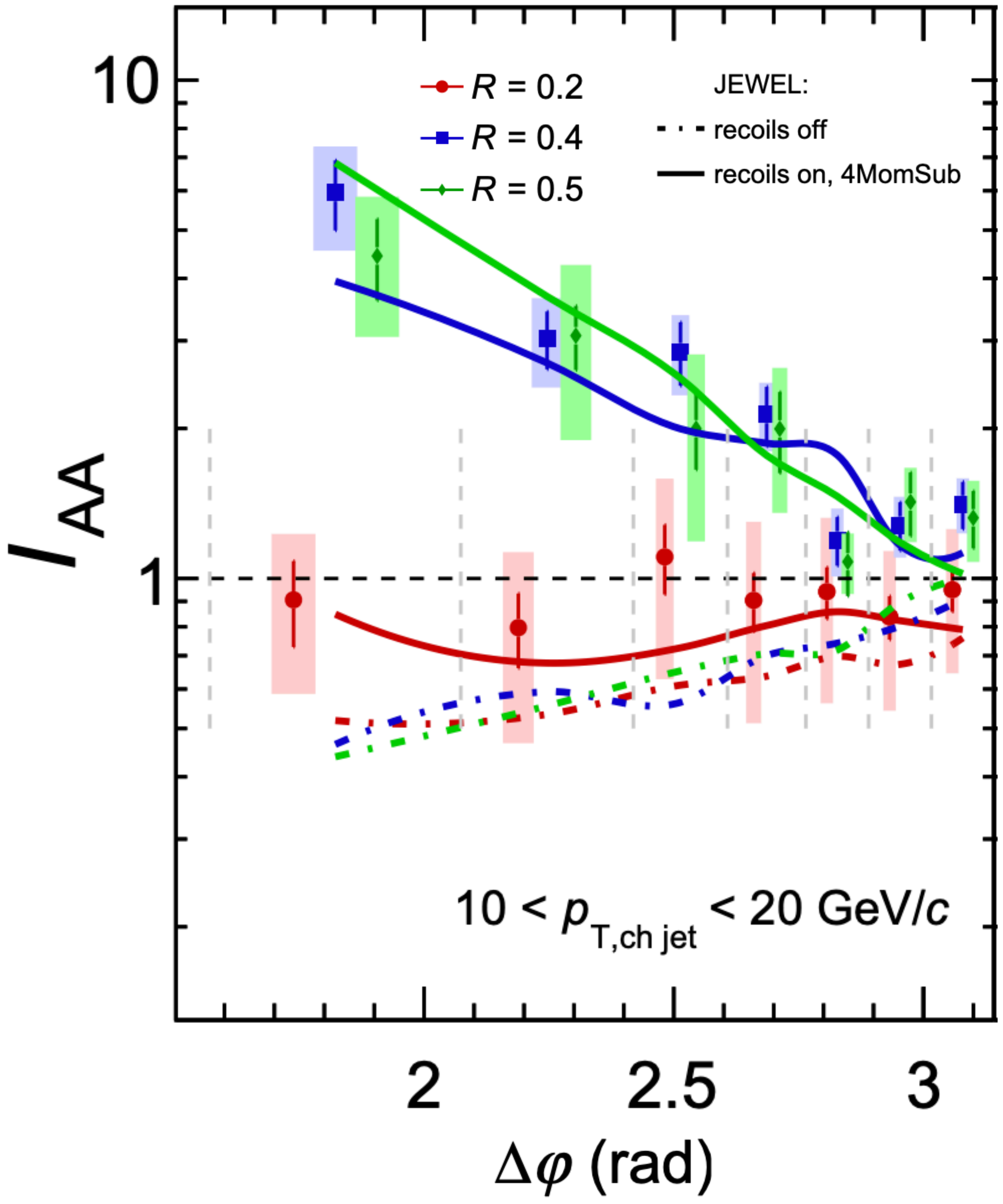
Look at the angular distribution of low p_T jets:

Huge effect! Challenge for models.

As Low as It Jets

ALICE - 2308.16131, 2308.16128

See talk by J. Norman



Acoplanarity not present in R=0.2 jets:

Disfavours explanation based on Molière scatterings.

Could point to strong broadening / diffusion causing uncertainty on reconstruction of jet direction.

Substructure of these jets?

Wake Effects on EEC

Hadrons from the wake have sizeable effect at large angles

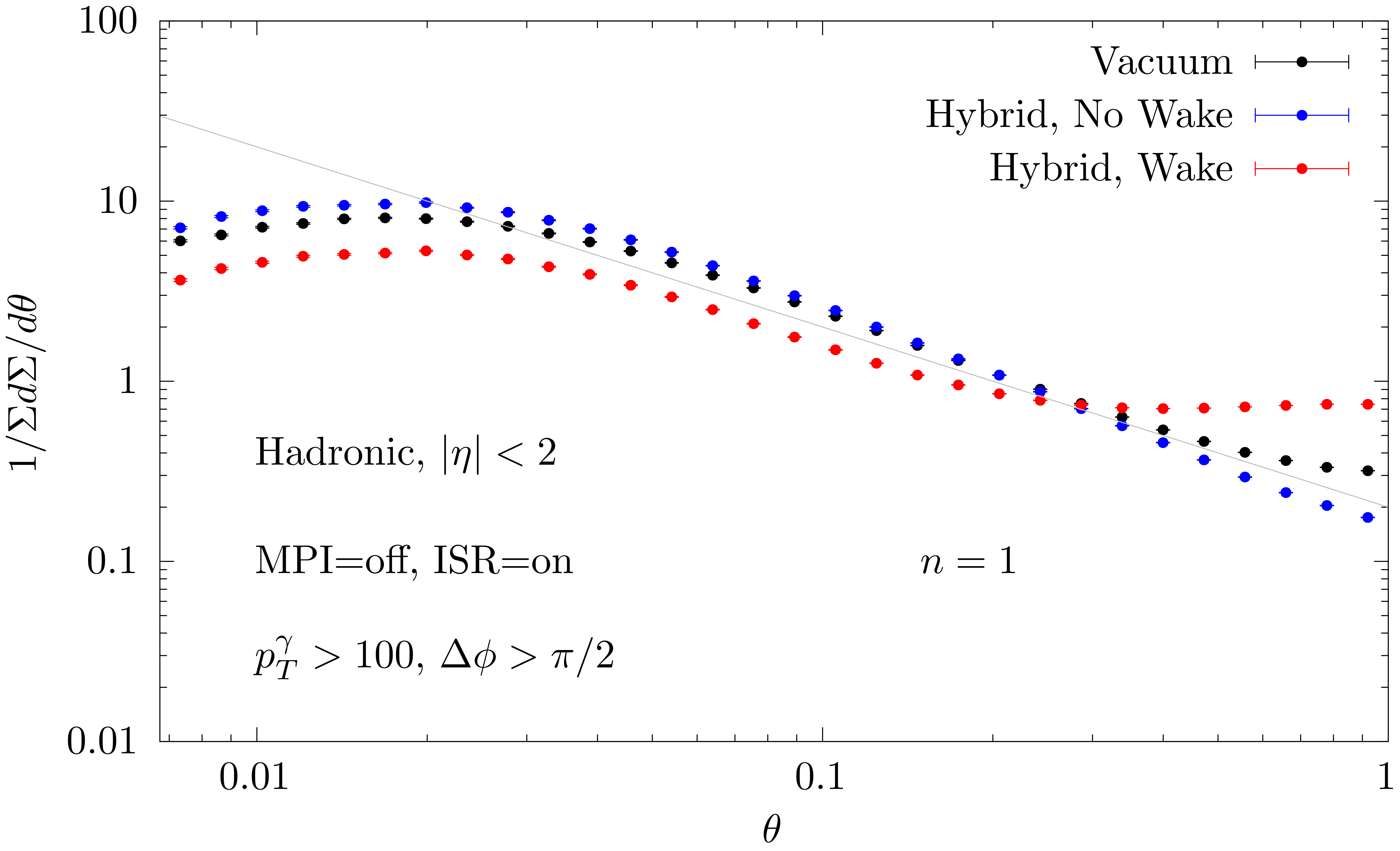
Soft, but numerous

Can mitigate with n=2.

Large angle, but non-perturbative!

Different angular structure than medium induced emissions.

Interesting to study 3-point correlator (shape of the wake?).



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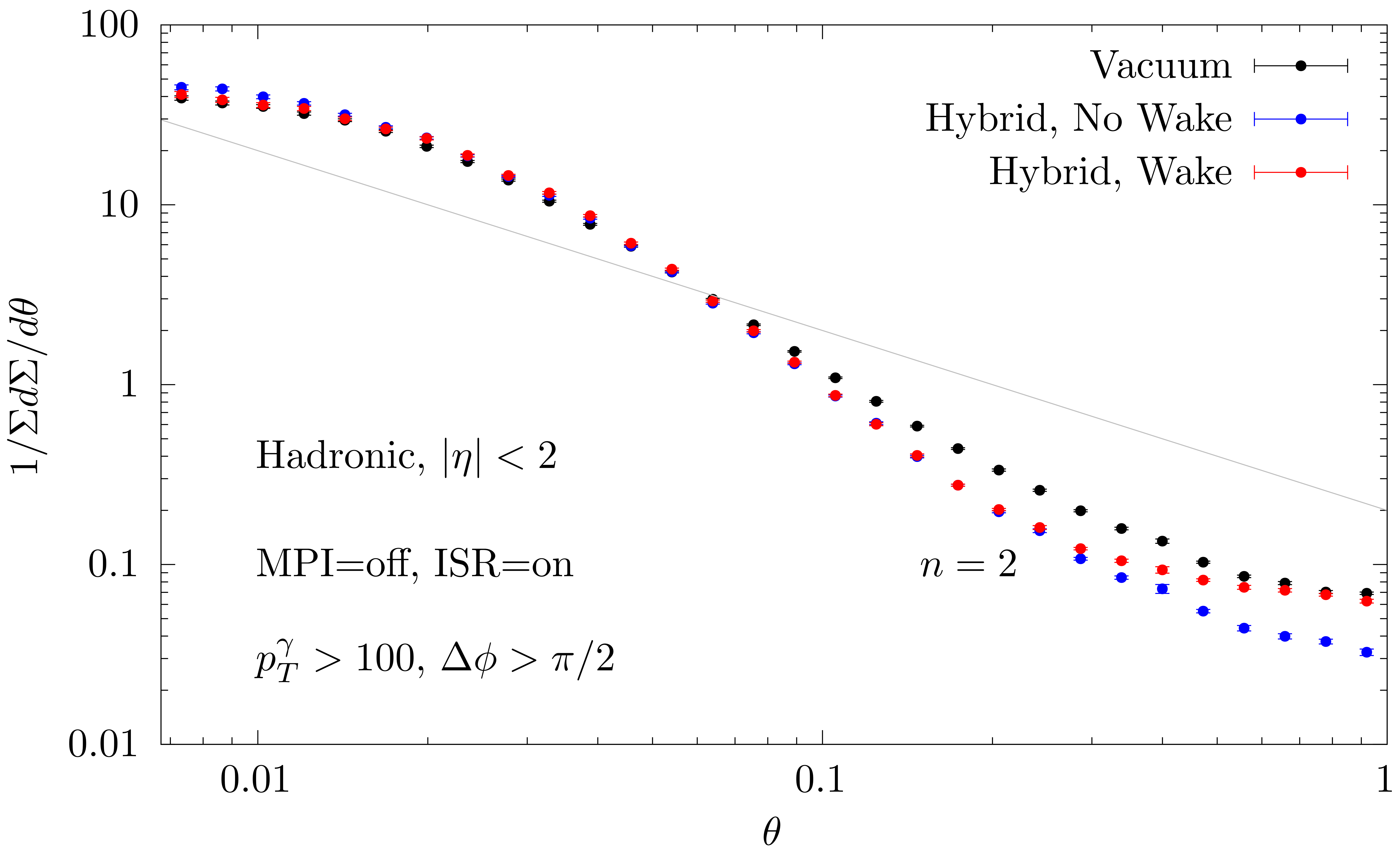

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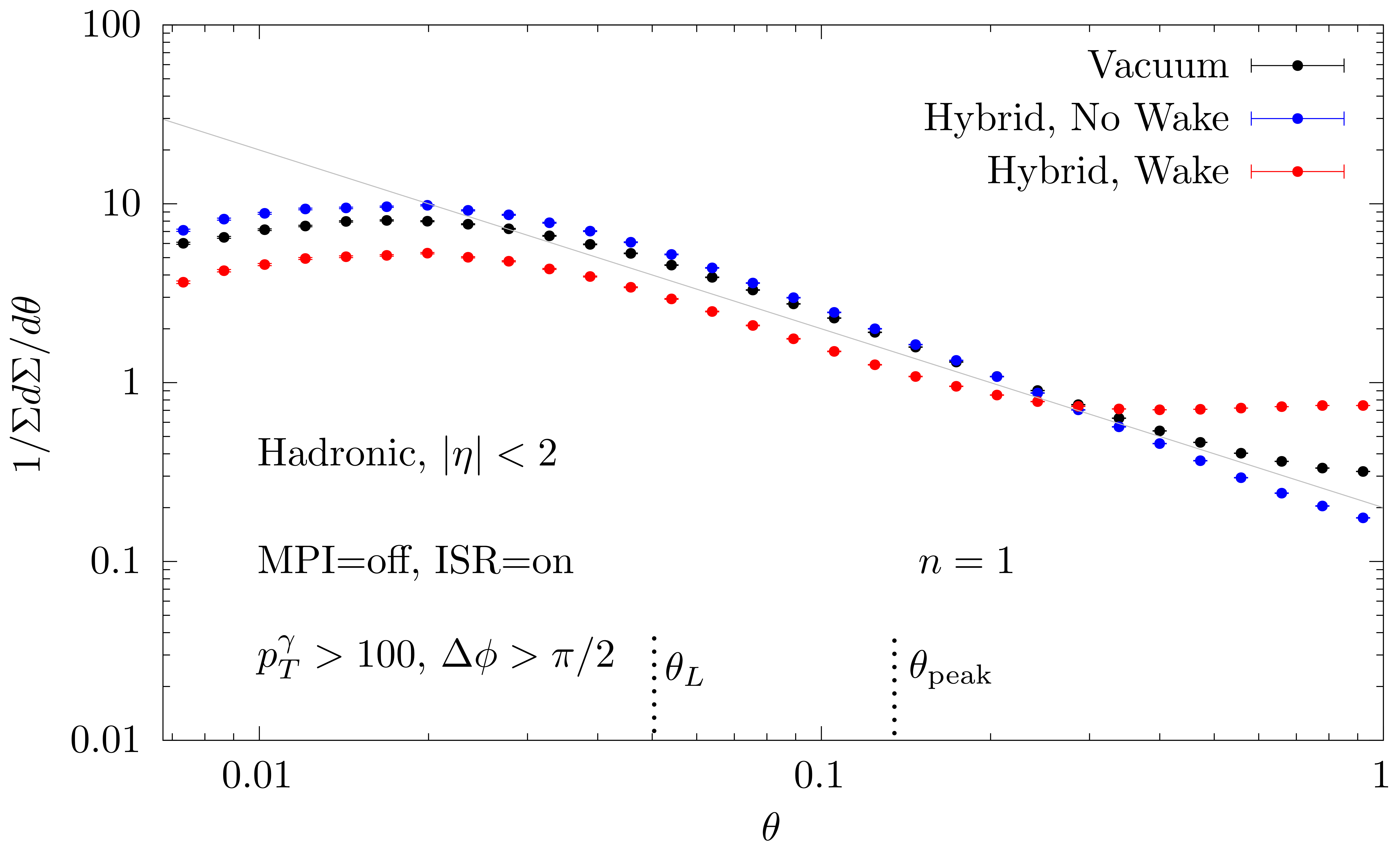


Jets as Part of the Medium

See also M. Kuha's poster

Jets no longer a perturbation when represent a sizeable part of multiplicity (mini-jets).

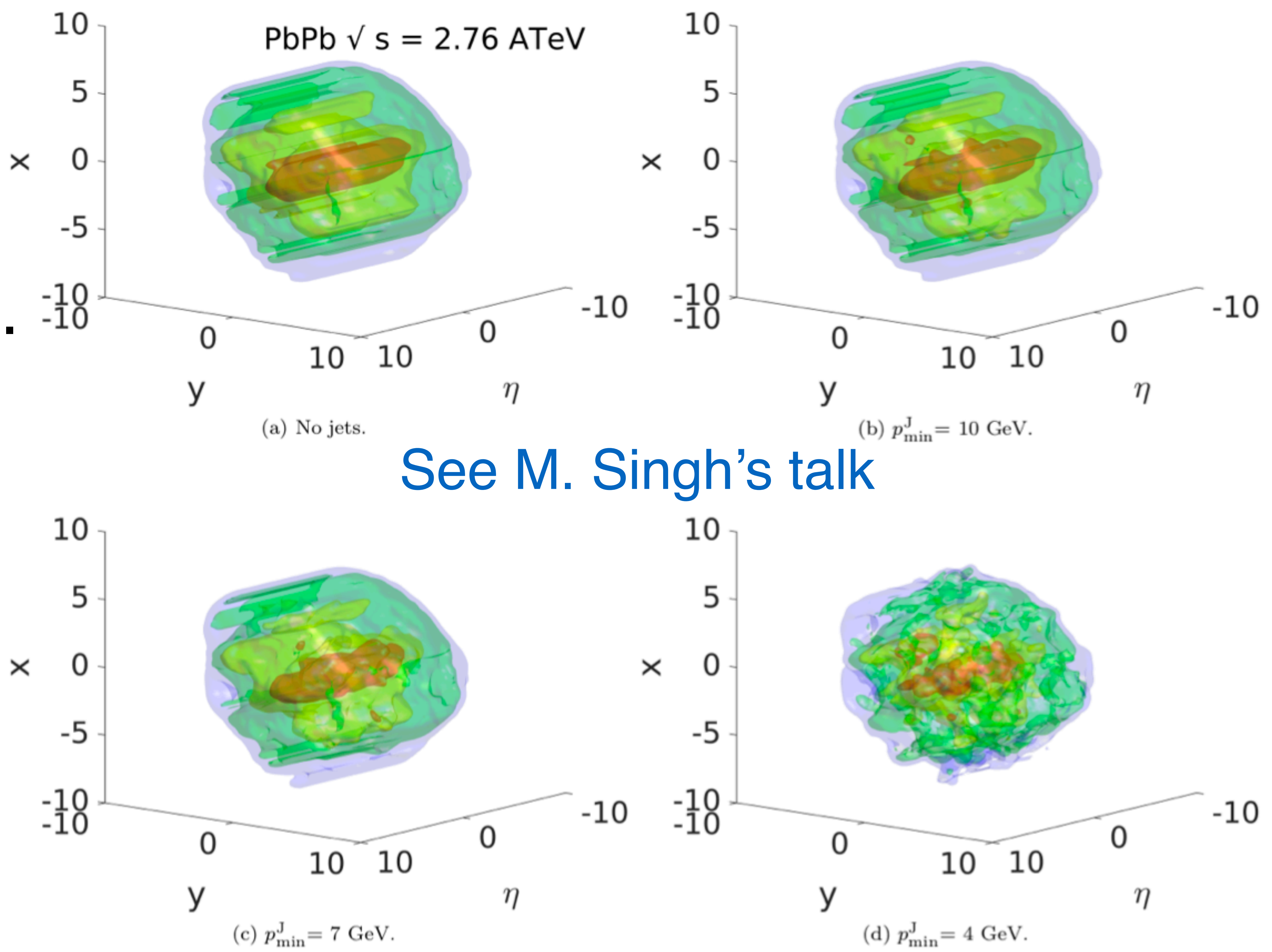
Stopping time ~ 2-3 fm > hydro. time: concurrent evolution.

Deposit energy and momentum in random orientations (mini-wakes).

New source of fluctuations that affect extraction of η/s .

Desirable to include in global Bayesian fits of Heavy-Ion Standard Model parameters.

See C. Shen's talk
See U. Heinz's talk
See A. Mankolli's talk



(a) No jets. (b) p^{J}_{min}= 10 GeV. (c) p^{J}_{min}= 7 GeV. (d) p^{J}_{min}= 4 GeV.

See M. Singh's talk

Modified hydro evolution can affect electromagnetic probes, jet quenching.

However, hard+soft studies do suffer important theoretical uncertainties.

Quenching in non-eq. phase.

Separation scale w.r.t saturation physics.

EKT: See J. Peuron's talk See F. Lindenbauer's poster

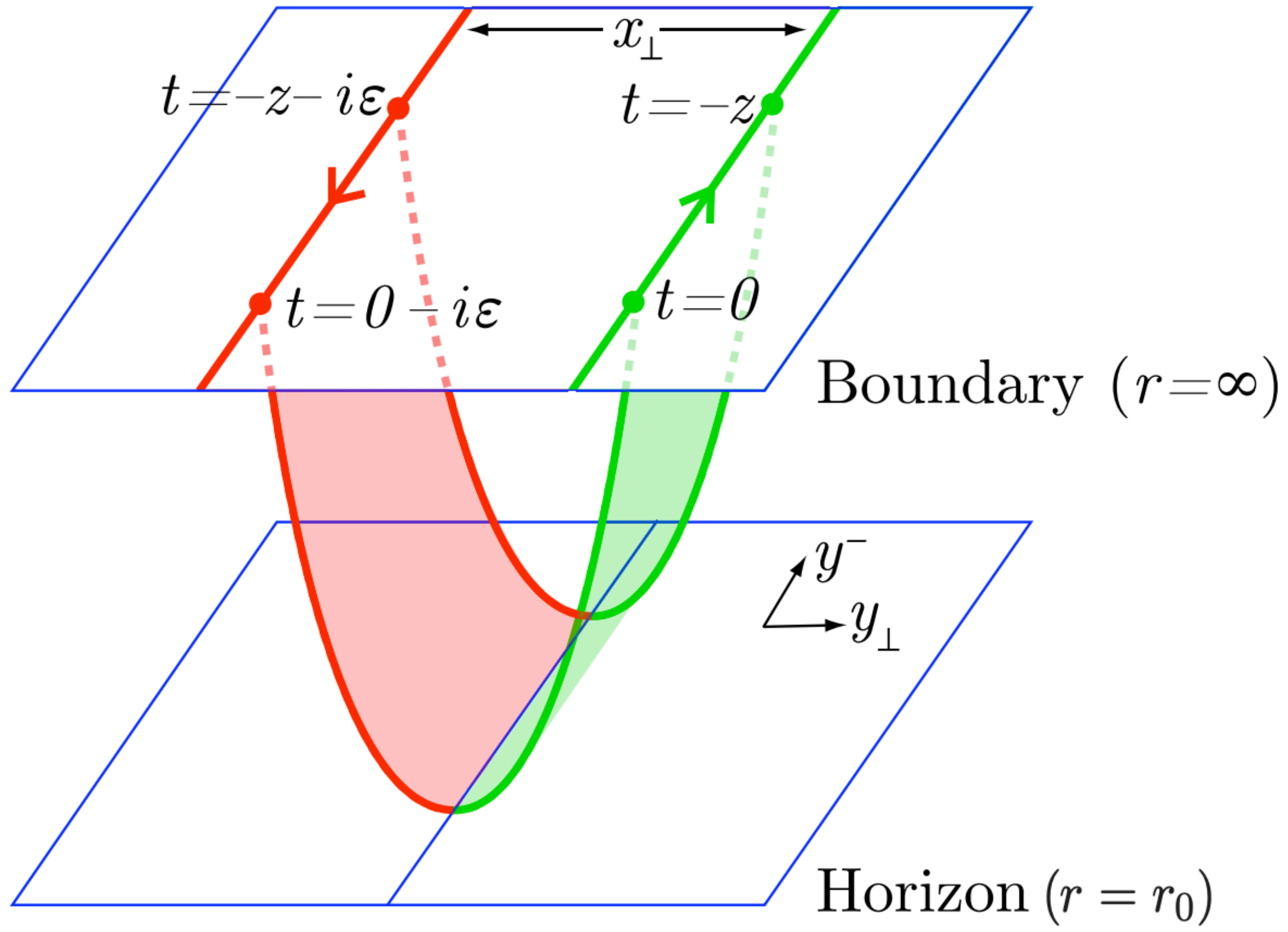
Glasma: M. Carrington et al. - 2112.06812 D. Avramescu et al. - 2303.05599

Looking for Point-Like Scatterers

Transverse momentum broadening dist. dominated by *soft scatterings*, leading to Gaussian broadening, diffusion.

However, there is also broadening in strongly coupled plasma:

See J. Grefa's talk



Computation of Wilson loops in AdS-Schwarzschild background, yield Gaussian broadening with jet quenching parameter

$$\hat{q} = \frac{\pi^{3/2}\Gamma(\frac{3}{4})}{\Gamma(\frac{5}{4})}\sqrt{\lambda}T^3$$

Liu et al. - hep-ph/0605178

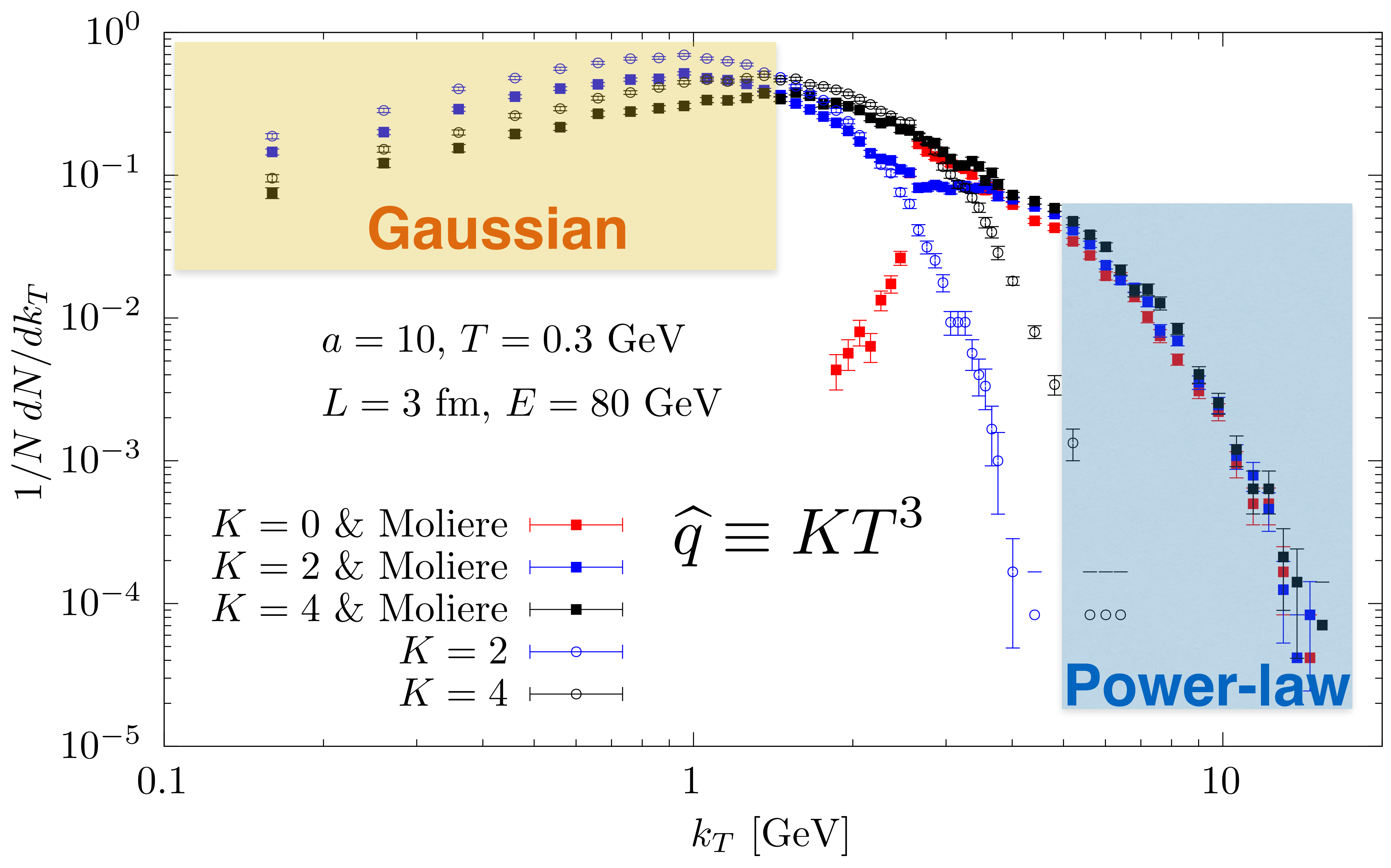
(not proportional to number density of scatterers)

Therefore, Gaussian broadening is not evidence for probing individual quark and gluon d.o.f.

As it also arises in a fluid with no quasiparticles.

Look for scatterings with large momentum transfers.

Looking for Point-Like Scatterers



See also Barata et al. - [2009.13667](2009.13667), [2106.07402](2106.07402)

Hybrid Strong/Weak Coupling Model:

Perturbative DGLAP (vacuum-like splittings)

Non-perturbative energy loss (feeding the wake).

Gaussian broadening.

Perturbative elastic scatterings. $t, u > a\, m_D^2$

(Naturally present in other MC, where
elastic scatterings down to arbitrarily low momentum exchange)

See K. Rajagopal's talk

Elastic scatterings:

Produce semi-hard recoils boosted along jet direction (in contrast to large angle soft wake).

Increase number of subjets inside the jet (competes with selection bias).

Enhance probability of finding large angle / k_T prong inside jet (competes with selection bias).

Non-Linear Radiative $\hat{q}$ Corrections

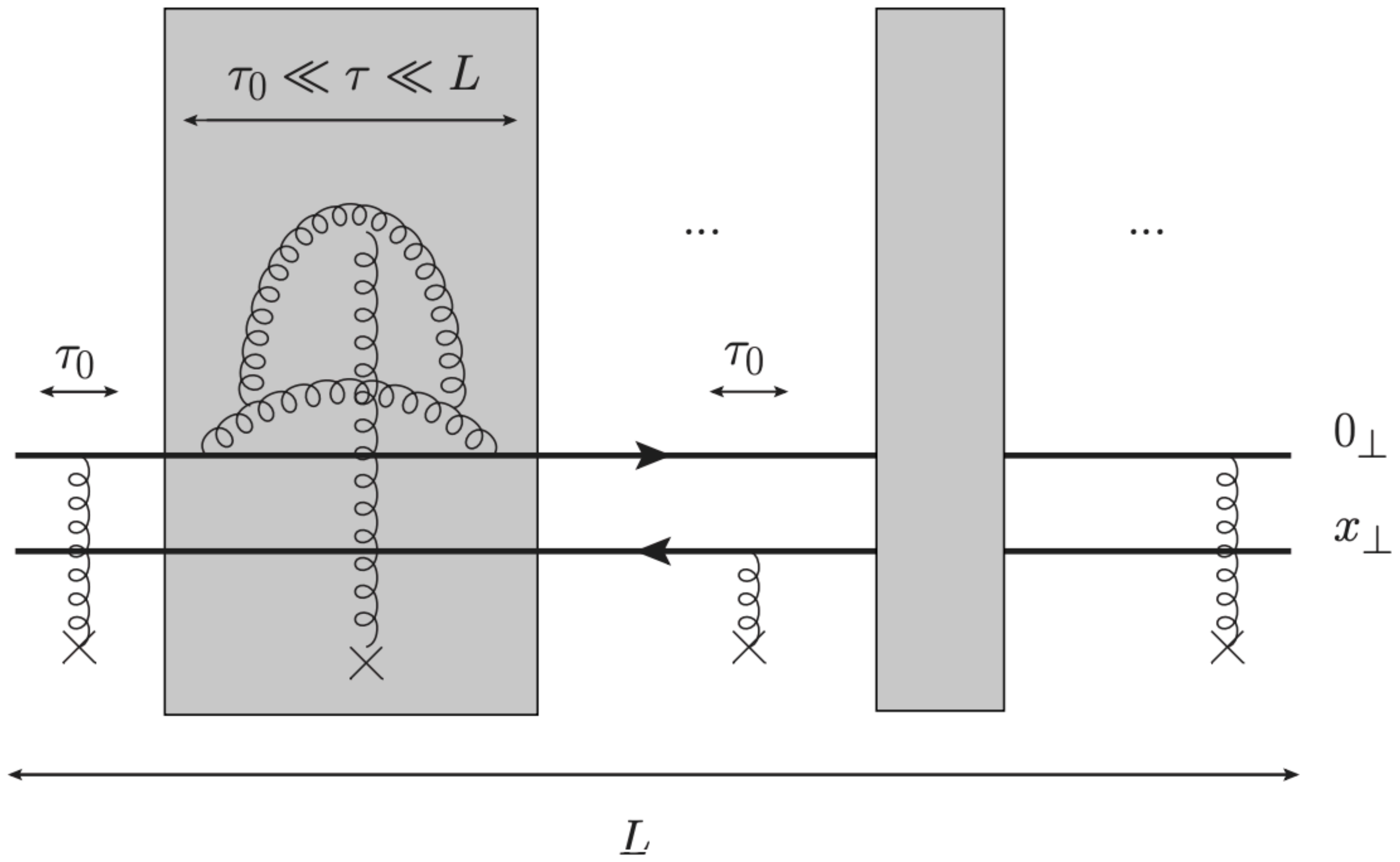
Radiative corrections due to soft emissions contribute to broadening as recoils.

Suppressed by α_s, but enhanced by double medium length logs (non-local). Liou et al. - 1304.7677

New analytic solution for the fully non-linear tower of fluctuations for $\hat{q}$.

Typical transverse momentum transferred $\sim L^{1/2+\sqrt{\bar{\alpha}_s}}$ (vs $\sim L^{1/2}$) (super-diffusive)

Harder large k_T tail $\sim 1/k_T^{4-2\sqrt{\bar{\alpha}_s}}$ (vs Rutherford-type $\sim 1/k_T^4$) (heavy-tailed dist.)

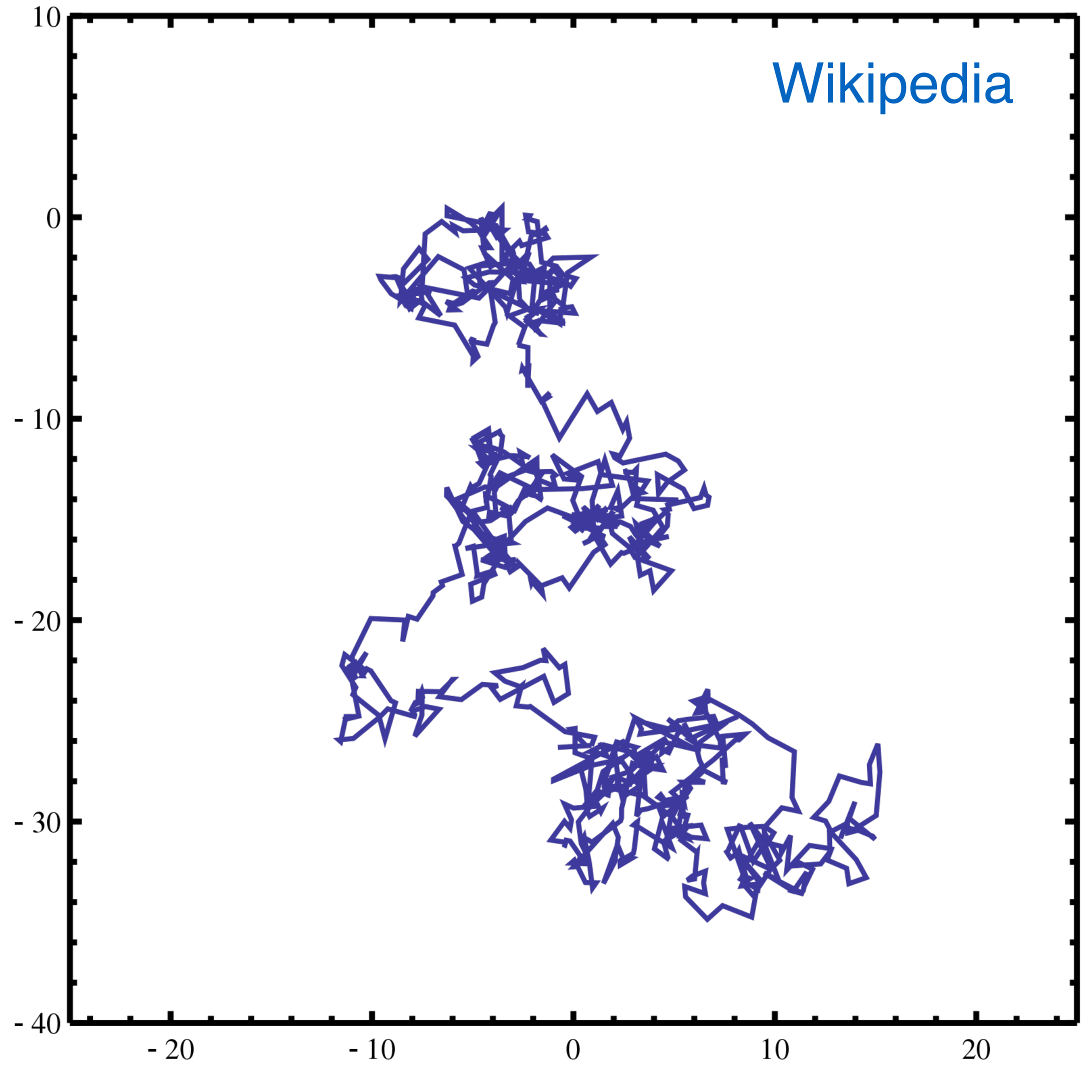


Lévy flights:

Self-similar gluon fluctuations.

Non-local jet-medium interactions.

Caucal & Mehtar-Tani - 2109.12041, 2203.09407



Harder tail increases probability to observe large momentum exchanges.

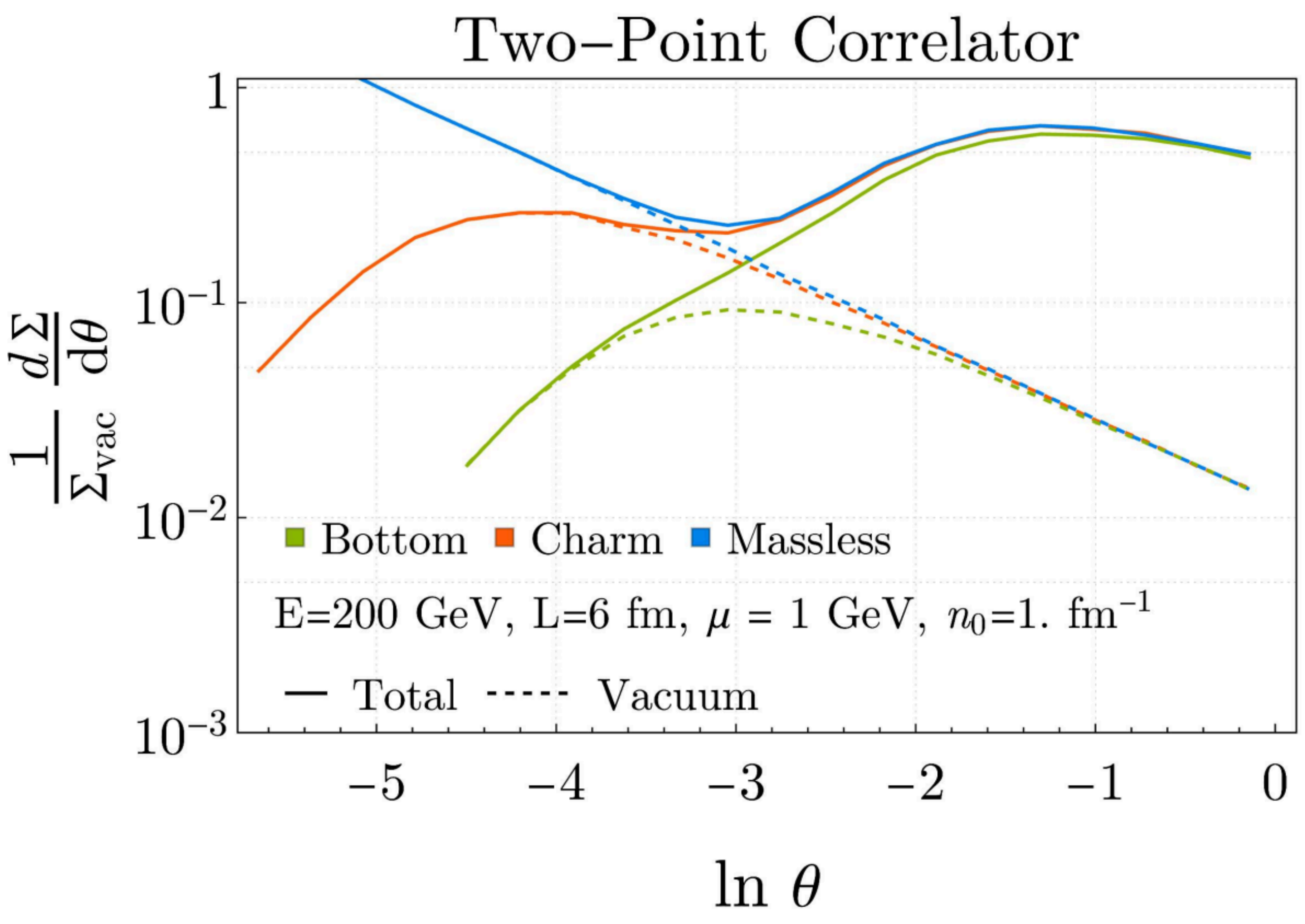
Singling Out Medium-Induced Radiation (MIR)

Soft cloud of particles around the jet cannot be unambiguously attributed to MIR (wake?)

Want to gain detailed access to the physics of pQCD energy loss.

Exploit special setups.

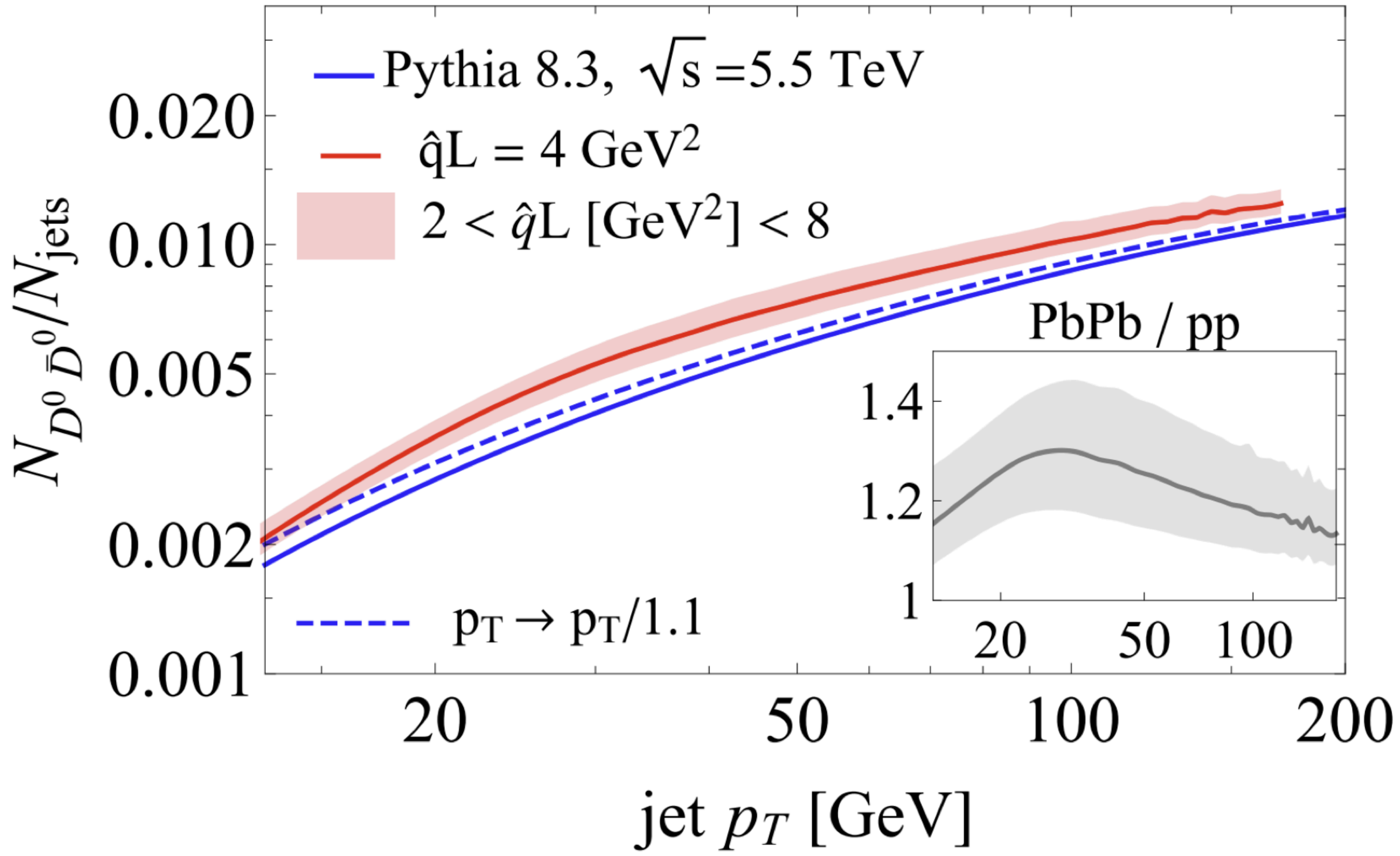
Dead cone region of charm & beauty.



See I. Moult’s talk

also L. Cunqueiro et al. - 2211.11789

Enhanced $g \to c\bar{c}$ radiation.



See W. van der Schee’s talk

Conclusions

If the medium possesses an hydrodynamic spacetime evolution, jets will see it:

- Preferred orientations of broadening and radiation depending on thermodynamic gradients and flow.
- Ripples on the fluid due to hydrodynamized energy and momentum.

Crucial piece of evidence in the fluid QGP paradigm.

Many pieces falling into place to develop more accurate jet quenching models. Main obstacles:

- Interplay between vacuum-like evolution and medium-induced radiation.
- Functional forms for sources of energy and momentum from jets into hydro.
- Quenching in the initial stages.

Quasi-particle nature of the QGP at short length scales can be revealed with jets:

- Look for large momentum transfers from the scattering of a parton within the jet, that modifies the jet substructure.
- Begun to identify specific observables, selection criteria, and kinematic regimes where hard scattering off medium partons are important. More and better ways to see this physics still to be found.

Remarkable new advances in theory need to be put together to honour the upcoming data from RHIC and LHC.

Thank You!


For ages 8 and up
WARNING:
QUENCHING HAZARD.
Hot QGP.
Not for jets under 10 GeV.
LET'S JET
SimplyFun
Learning & Connecting Through Play