# Jet Modification & Medium Response

**Daniel Pablos**




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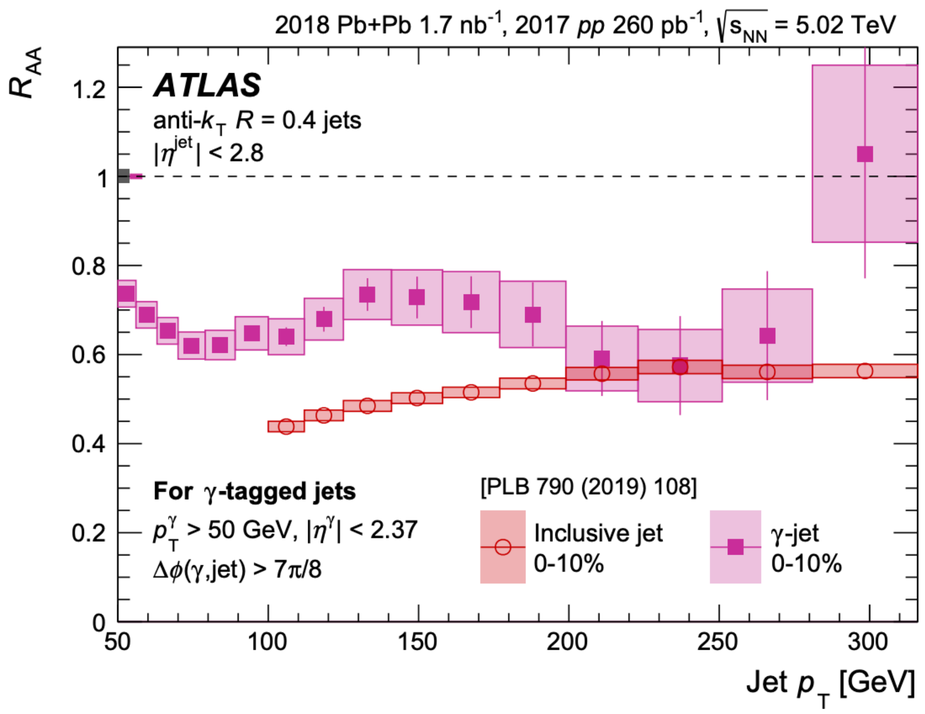
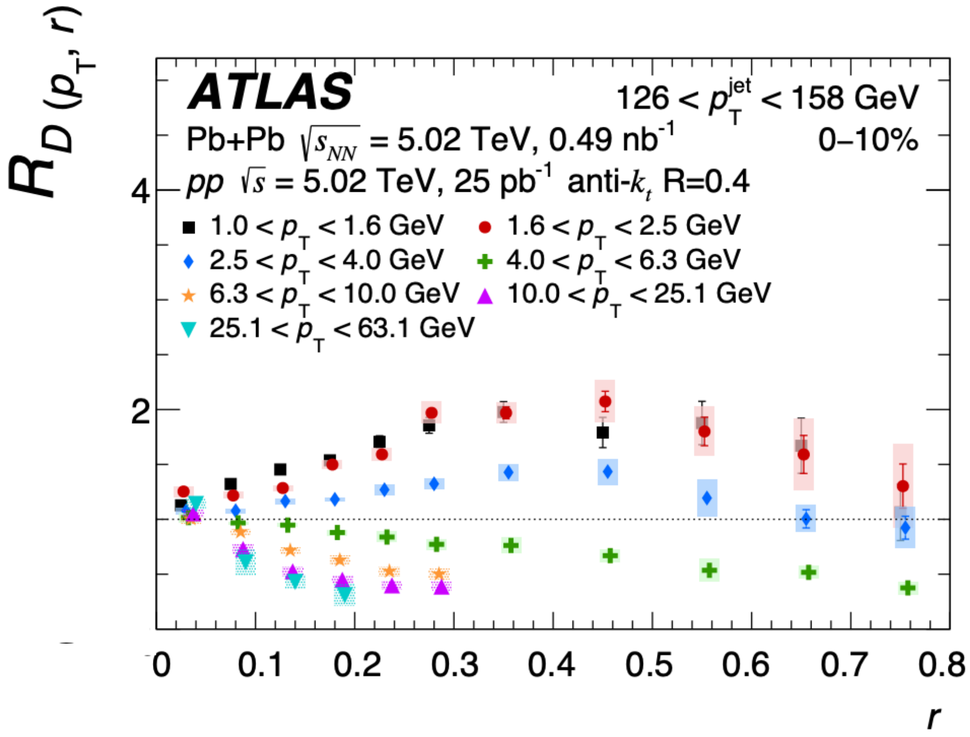
26th Sept. 2024
Hard Probes ‘24 - Nagasaki, Japan

# Jet Quenching

Evidence of high-$p_T$ yield reductions, together with excess of soft particles up to large angles.




Inclusive jet and boson-jet suppression.




Angular distribution of particles around the jet.

ATLAS - 2303.10090

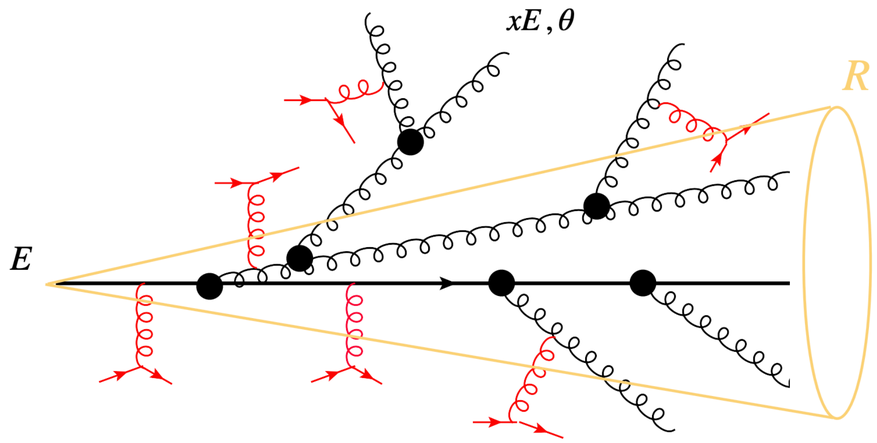
ATLAS - 1908.05264

# Jet Quenching

Transfer from high-energy to low-energy modes.

**pQCD:**

Medium induced radiation,
develops turbulent cascade.

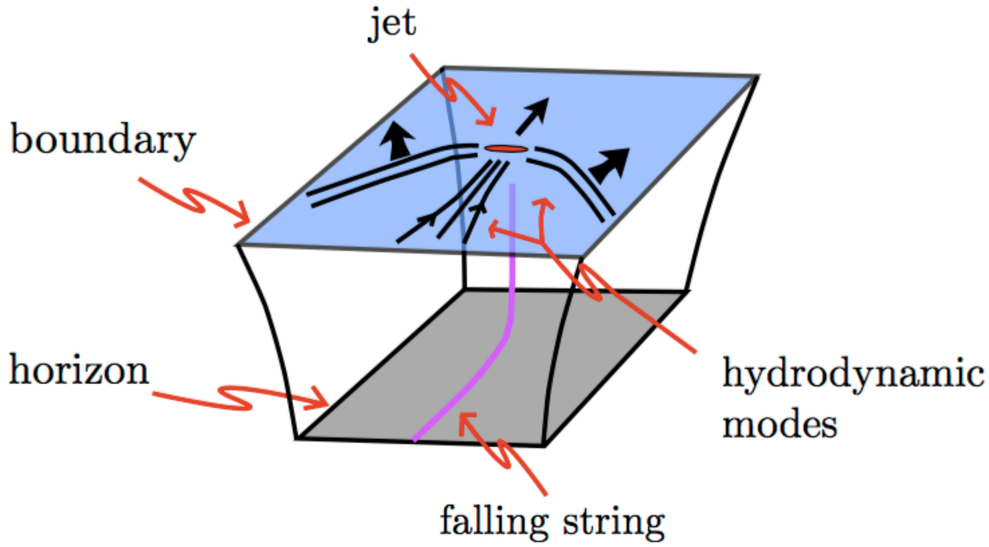



Mehtar-Tani et al. - 2209.10569

Blaizot et al. - 1209.4585, 1301.6102, 1311.5823

**npSYM:**

Falling string into black hole,
excitation of hydro modes.




Chesler & Rajagopal - 1402.6756, 1511.07567

*Jet quenching phenomena are evidence of the creation of deconfined QCD matter.*

# Jet Quenching

**Modified *Jet***  **Modified QGP**

**Energy-momentum conservation**

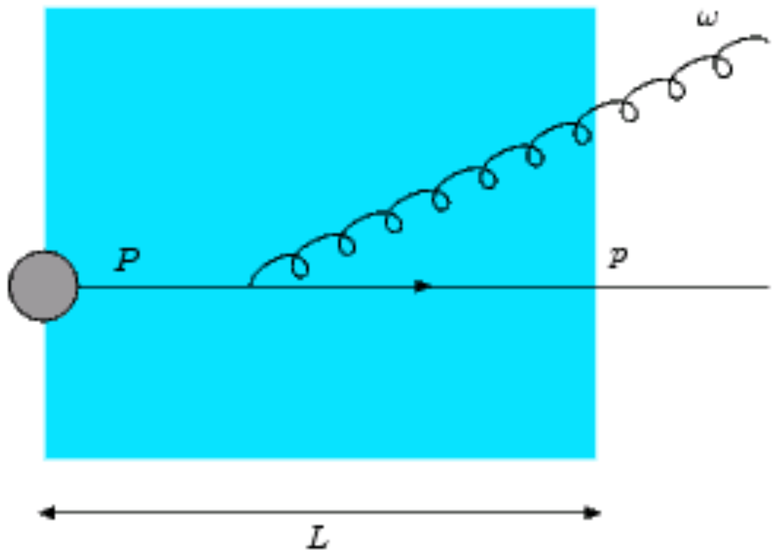
Manifestations of medium response:

→ Semi-hard perturbative recoils (probe short-length structure of QGP),
due to the elastic scatterings which trigger induced radiation.

→ Non-perturbative hydrodynamic wakes (probe long wavelength features of QGP),
due to thermalized partons, non-perturbative energy loss.

# Beyond the Static Brick

The paradigm of a flowing QGP requires that jet quenching calculations go beyond static brick setup.



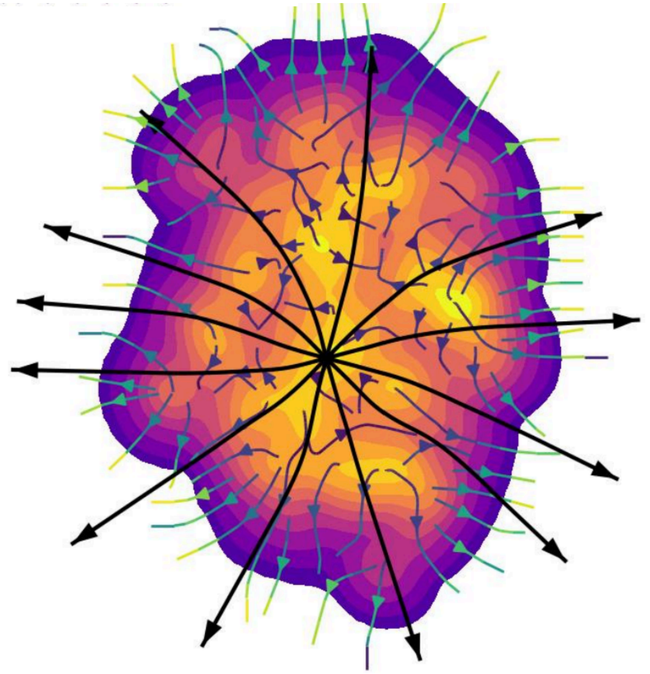



Fig. from J. Bahder's talk

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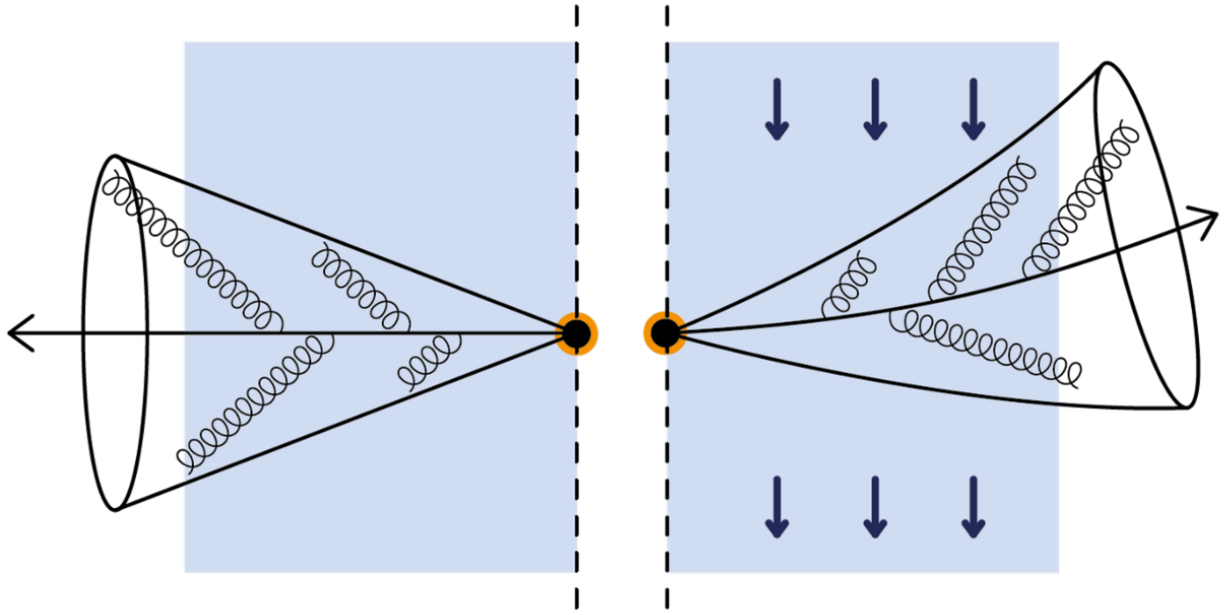
  - → Radiation

Fig. from X. Mayo's talk



See X. Mayo's talk

See J. Silva's talk

See C. Salgado's talk

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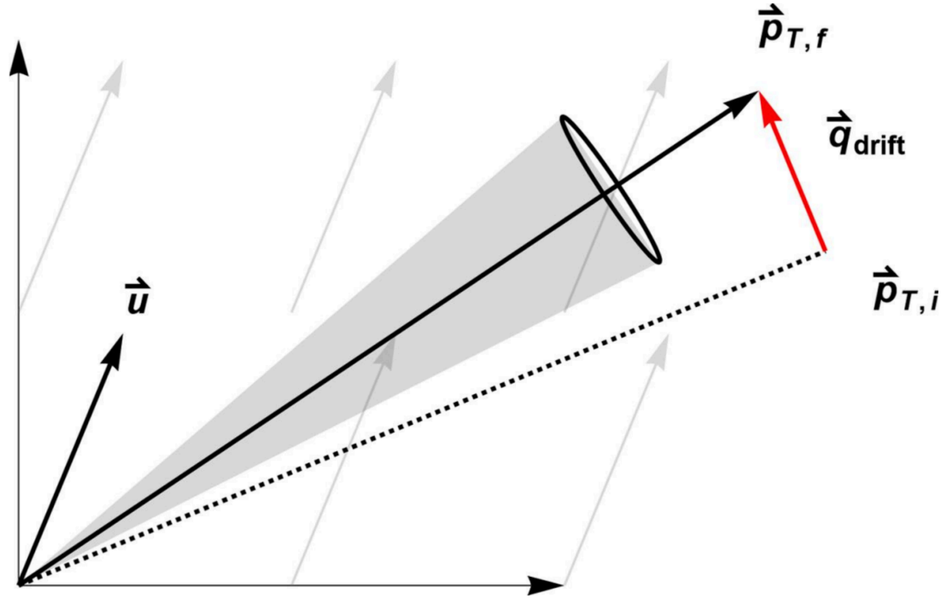
Fig. from J. Bahder's talk




See J. Bahder's talk
See R. Fries' talk
See T. Luo's talk

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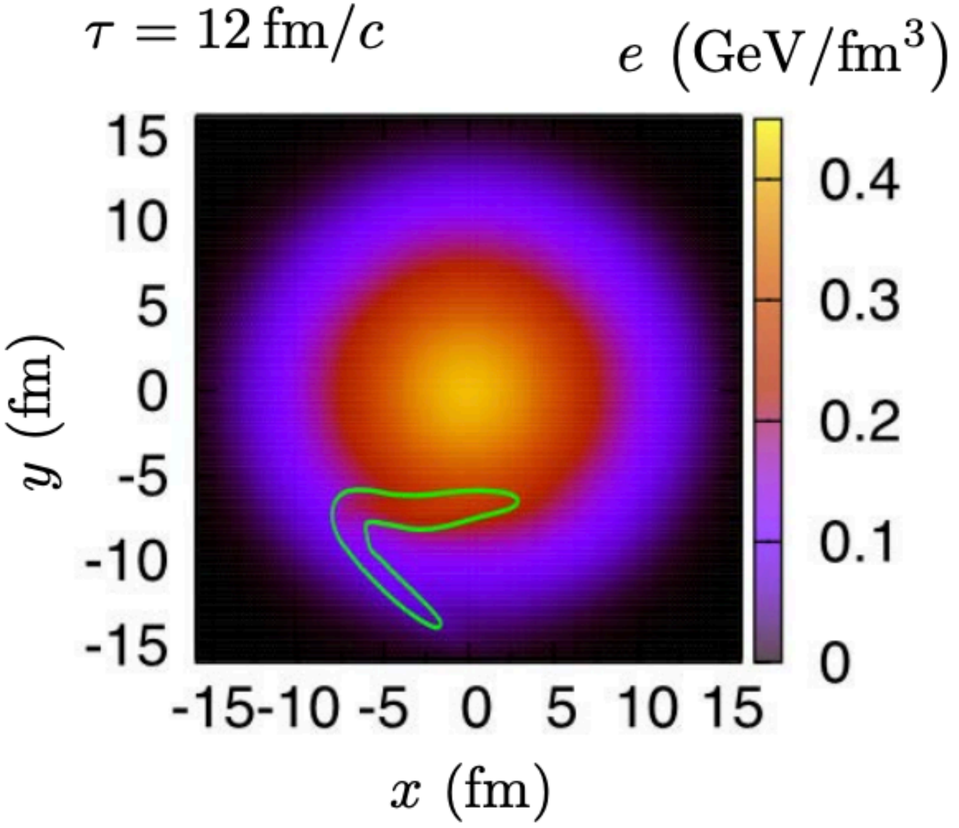
  - Broadening
  - Wake evolution




Tachibana & Hirano - 1510.06966

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*Finding experimental evidence*
*of spatiotemporal medium evolution*
*on jet observables should be*
*a key goal in jet quenching physics.*

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*Finding experimental evidence*
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*on jet observables should be*
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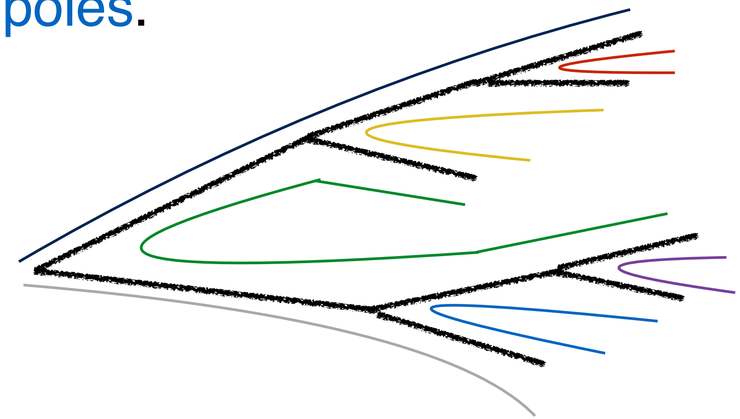
*On the right track!*

# Jets

A jet is not simply a set of on-shell charges.

- We know from vacuum physics that jets are better understood as a collection of color correlated dipoles.

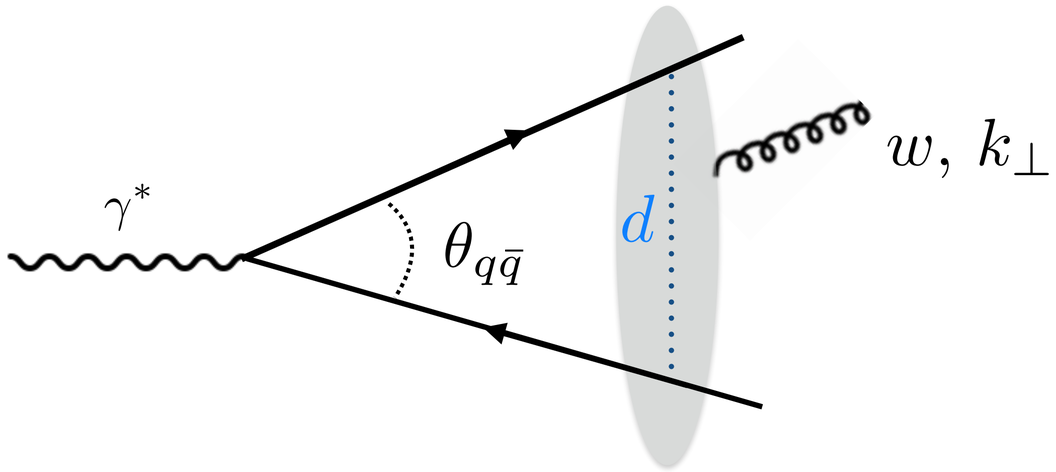


In the medium, energetic jets develop a high-virtuality, vacuum-like evolution that interacts with the medium.

- Interplay between vacuum and medium scales is a great theoretical challenge.
- Affected by color coherence physics.

# Color Coherence in Vacuum

Ex: consider gluon emission off a color singlet “jet”.




Wavelength of emission only resolves individual charges if

$$\lambda < d \sim \tau_f \theta_{q\bar{q}}$$

$$\rightarrow \theta < \theta_{q\bar{q}}$$

$\tau_f \sim w/k_\perp^2$

Formation time

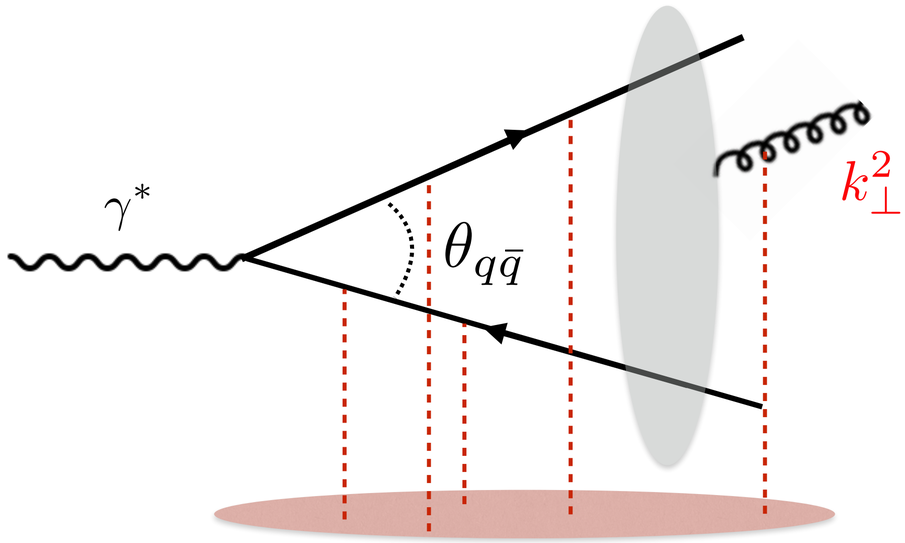
$\lambda \sim 1/k_\perp$

Effectively: radiation either from quark *or* anti-quark, provided angular restriction respected.

→ Leads to angular ordering; basis for probabilistic Monte Carlo approach to jet evolution.

# Color Coherence in Medium

Ex: consider stimulated gluon emission off a color singlet dipole in the medium.




Soft scatterings

$k_\perp^2 \sim \hat{q}\, L \equiv Q_{\rm med}^2$

Wavelength of stimulated emission within the medium L, only resolves individual charges if

$$\lambda < d \sim L\,\theta_{q\bar{q}}$$

$$\rightarrow \theta_{q\bar{q}} > 1/\sqrt{\hat{q}\,L^3} \sim \theta_c$$

Critical coherence angle

A dipole with an angle smaller than critical coherence angle only radiates off its total charge.

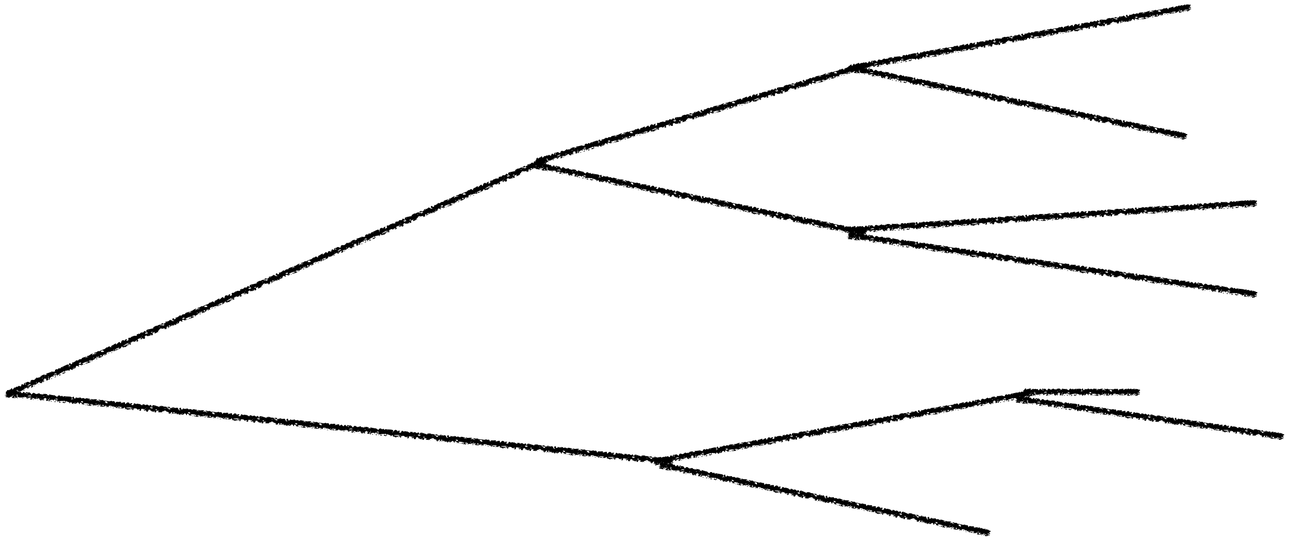
(In this example, no radiation at all.)

Also, minimum angle of medium-induced emission is $\theta_c$ .

# Interplay of Vacuum-Like and Medium Evolutions

Need a more precise understanding of color coherence in the medium,

And this needs to be put in models.





Vacuum-Like
Emission

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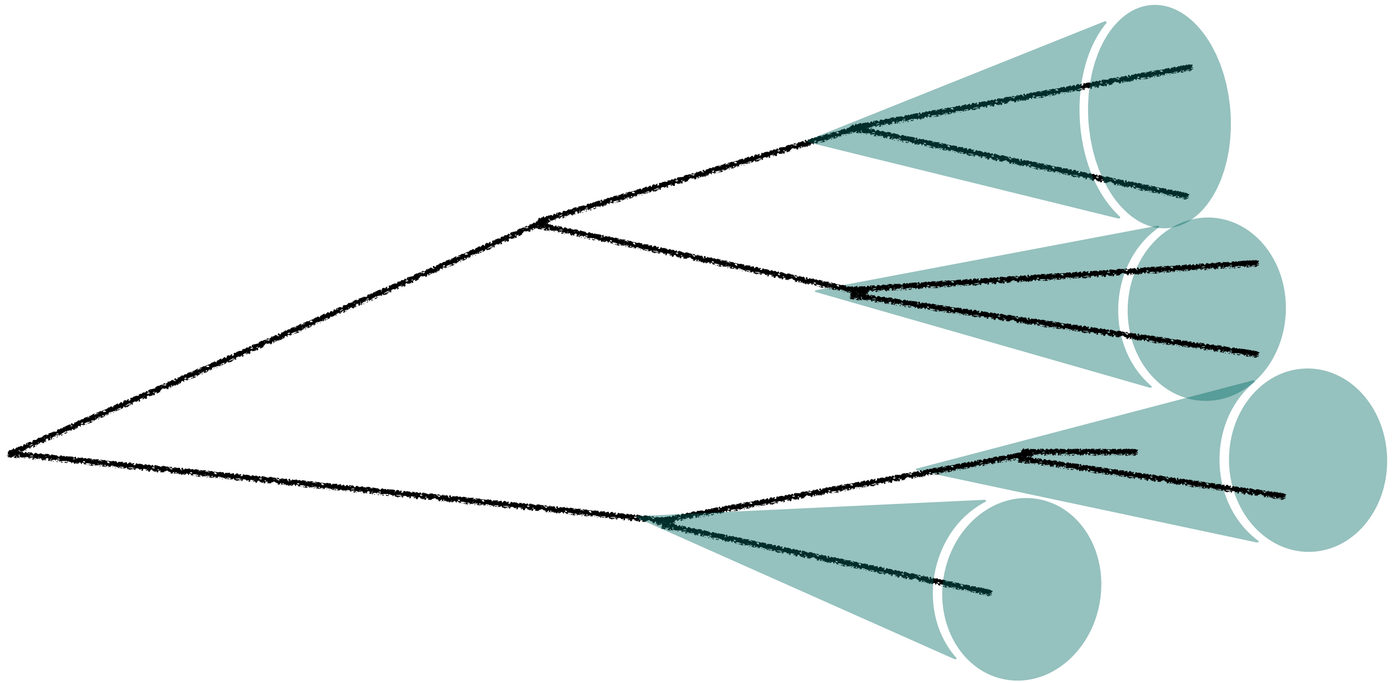


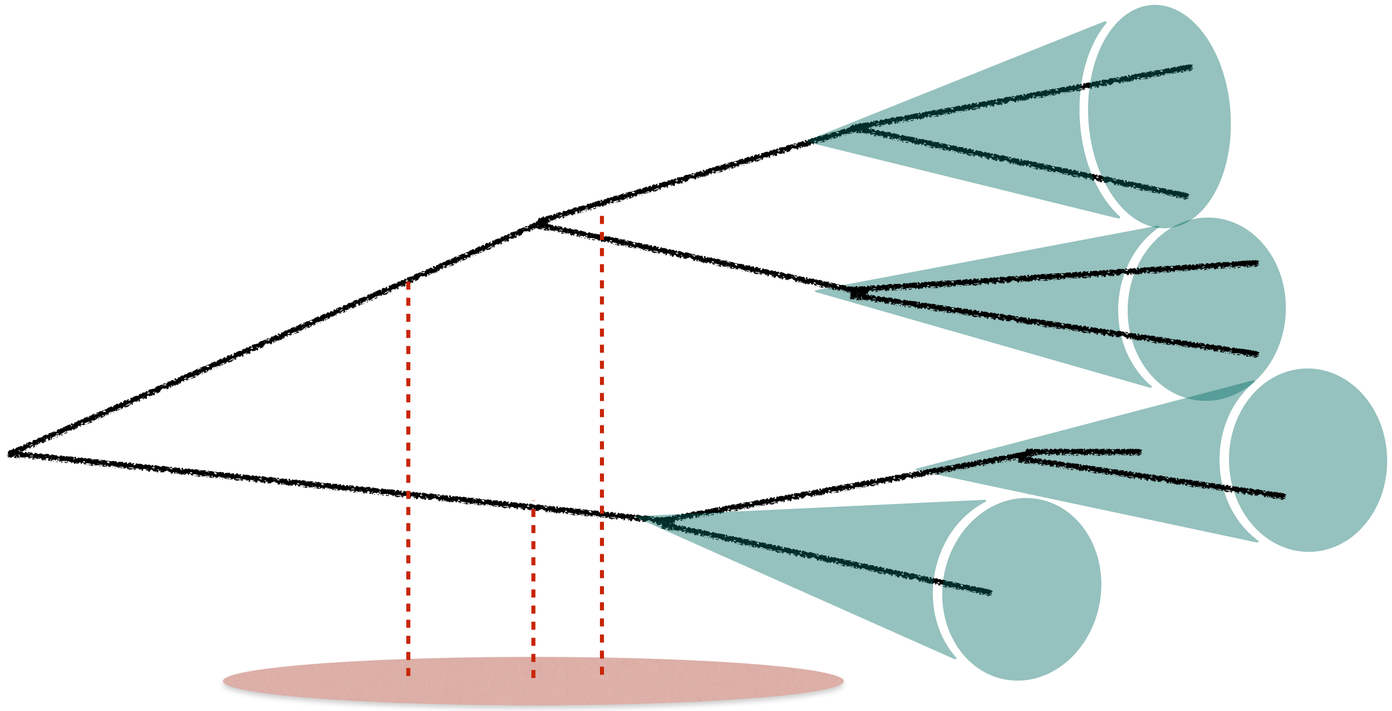
Effective emitter

Leading effect already implemented in JetMed, Hybrid, Collimator Evolution.

Caucal et al. - 1907.04866 Hulcher et al. - 1707.05245 Mehtar-Tani et al. - 2402.07869

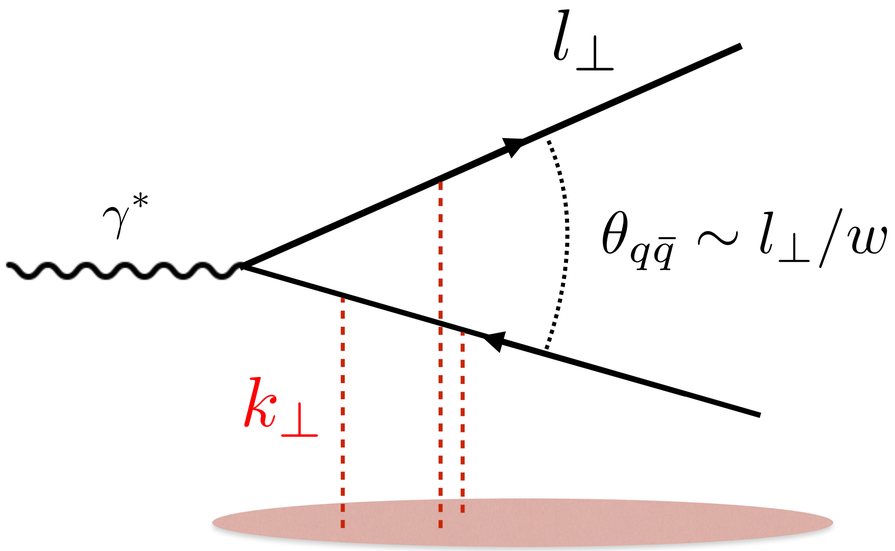
# Interplay of Vacuum-Like and Medium Evolutions

How can we account for potential modifications of the high-virtuality stage?



# Corrections to Vacuum-Like Shower

MATTER, incorporated in JETSCAPE, recently included *modified coherence* effects.




Wavelength of exchanged gluon only resolves dipole if

$$\lambda < d \sim \tau_f \, \theta_{q\bar{q}} \sim 1/l_\perp$$

$$\rightarrow k_\perp > l_\perp$$

Kumar et al. - 1909.03178

Only a hard enough momentum kick (rare), can resolve short-lived high-virtuality dipole.

→ Decrease of effective $\widehat{q}$ with increasing virtuality.

→ Mitigates impact of medium-modified splitting functions during vacuum-like evolution.

# Jet vs Hadron Suppression

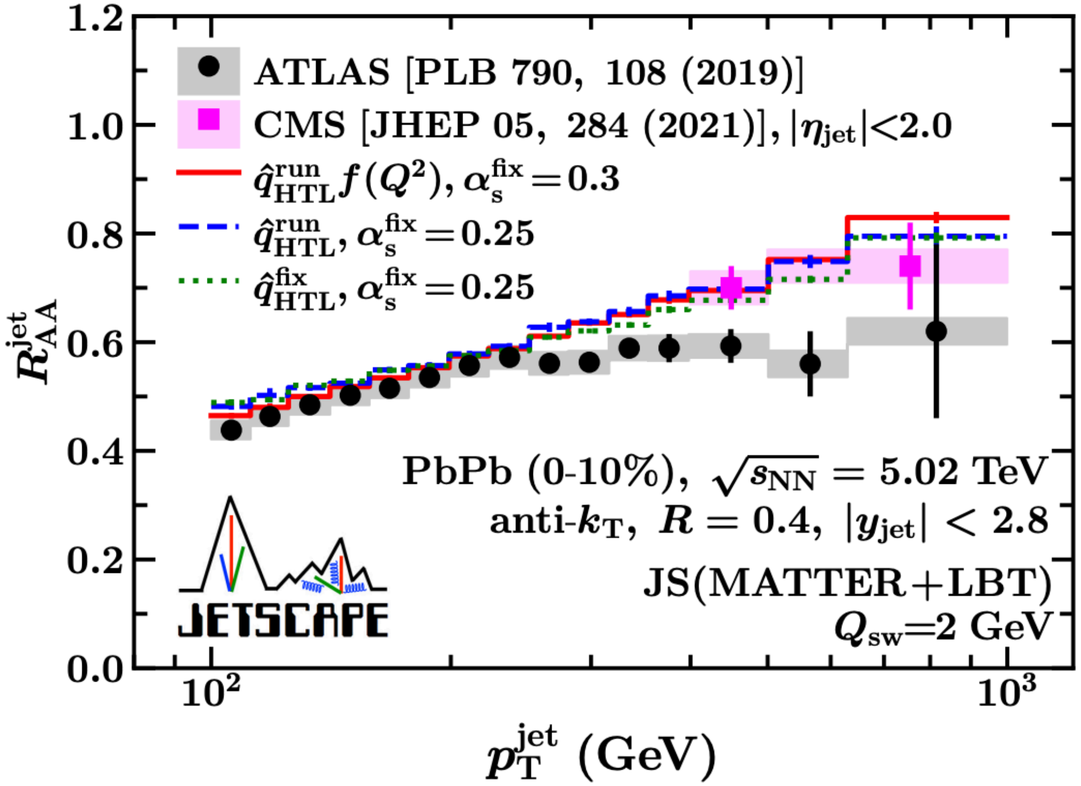
Modified coherence effects improve relation between single hadron and jet suppression.

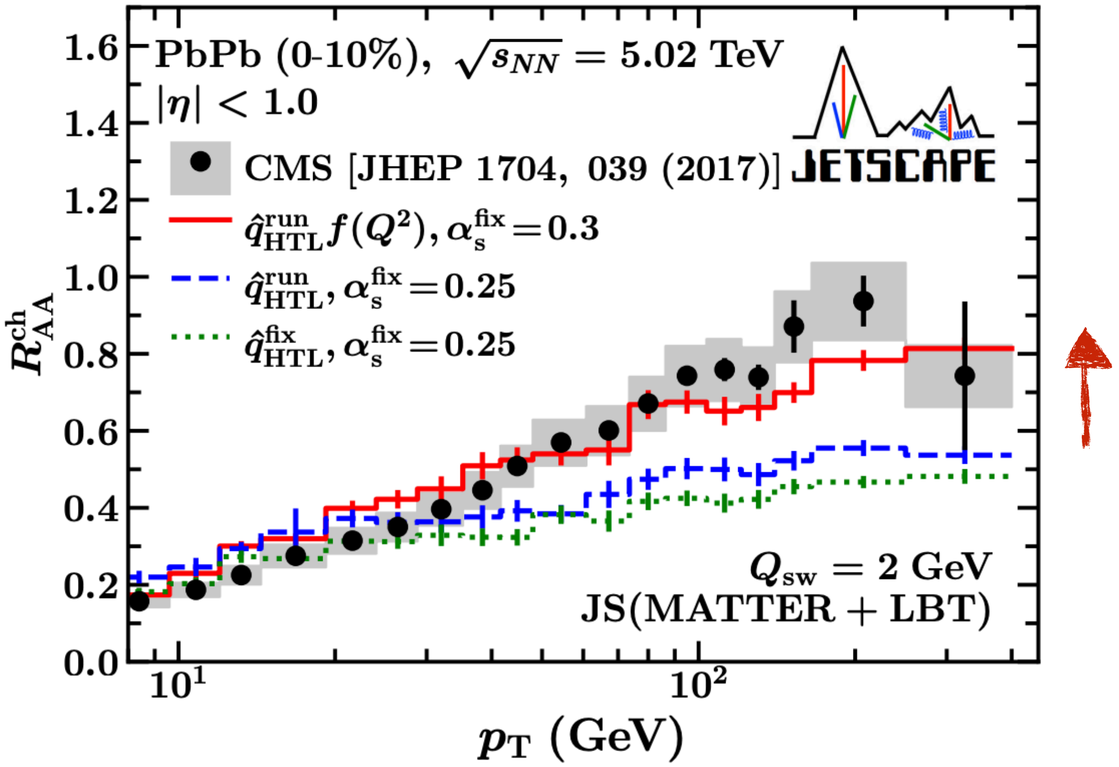
JETSCAPE - 2204.01163

$f(Q^2)$ is virtuality-dependent correction to $\widehat{q}$

See Y. Tachibana's talk

See P. Jacob's talk




Finite formation time of vacuum-like evolution greatly improves description in MARTINI.

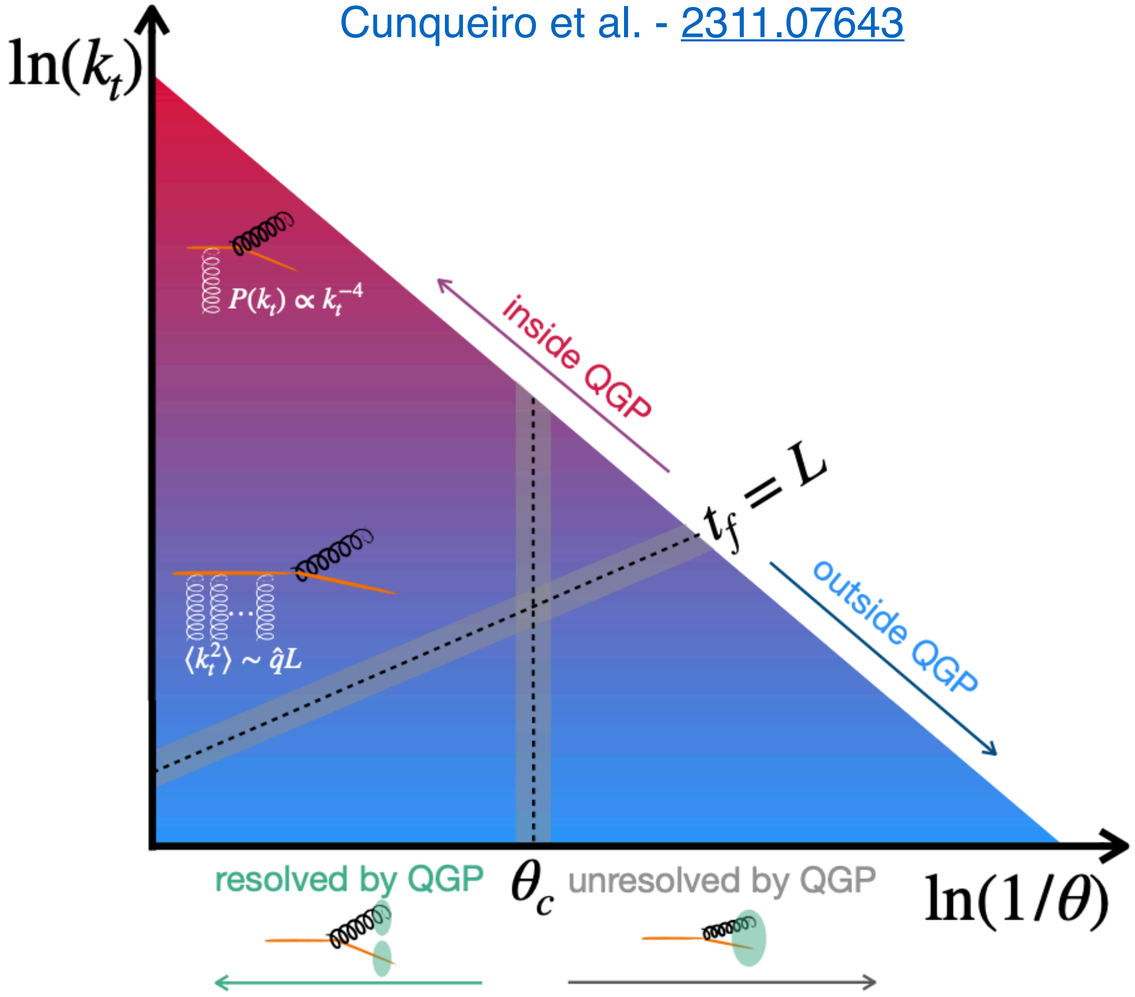
See S. Shi's talk

Modarresi-Yazdi et al. - 2407.19966

# Scanning the Lund Plane

Use Lund plane scan to determine degree of shower modification at different scales.

Cunqueiro et al. - 2311.07643




See A. Takacs' talk

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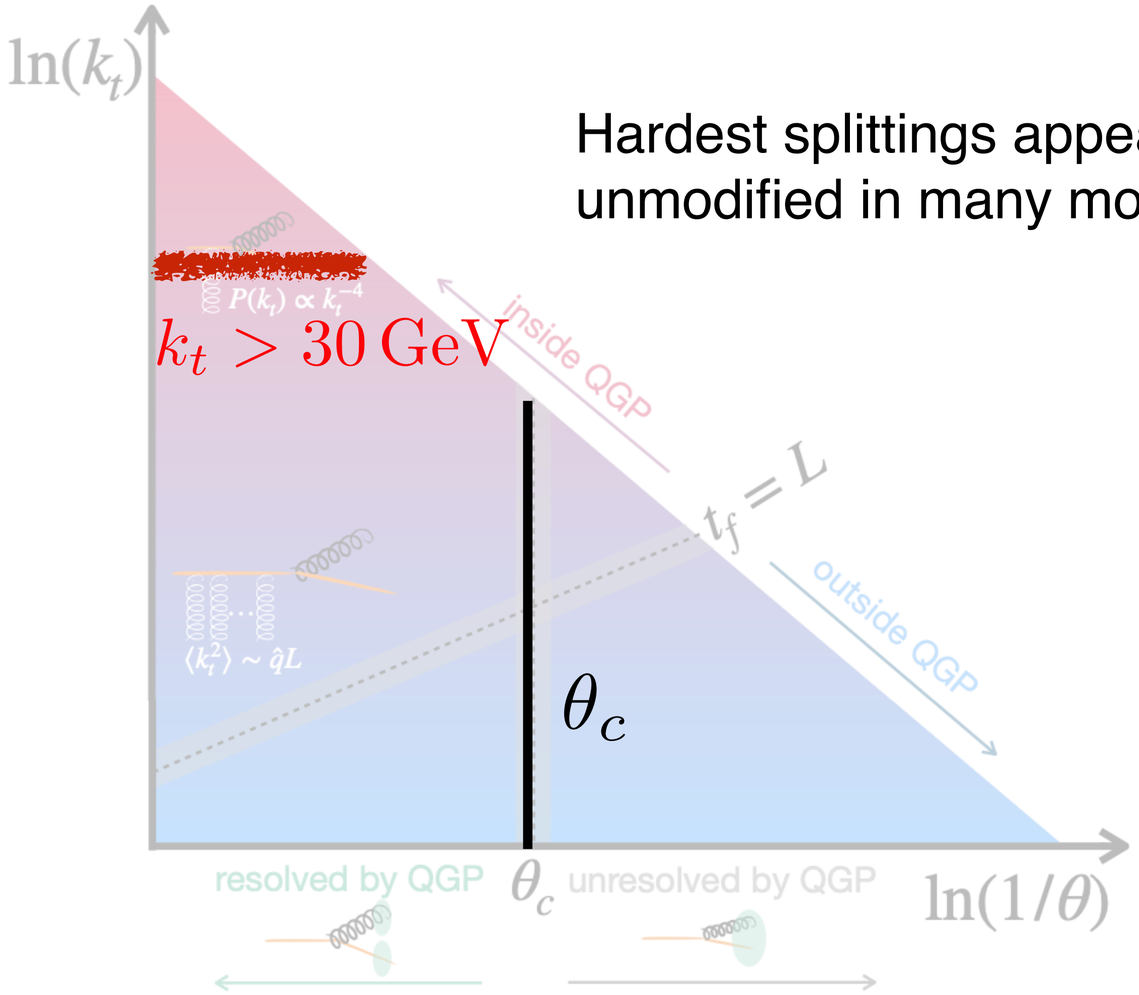
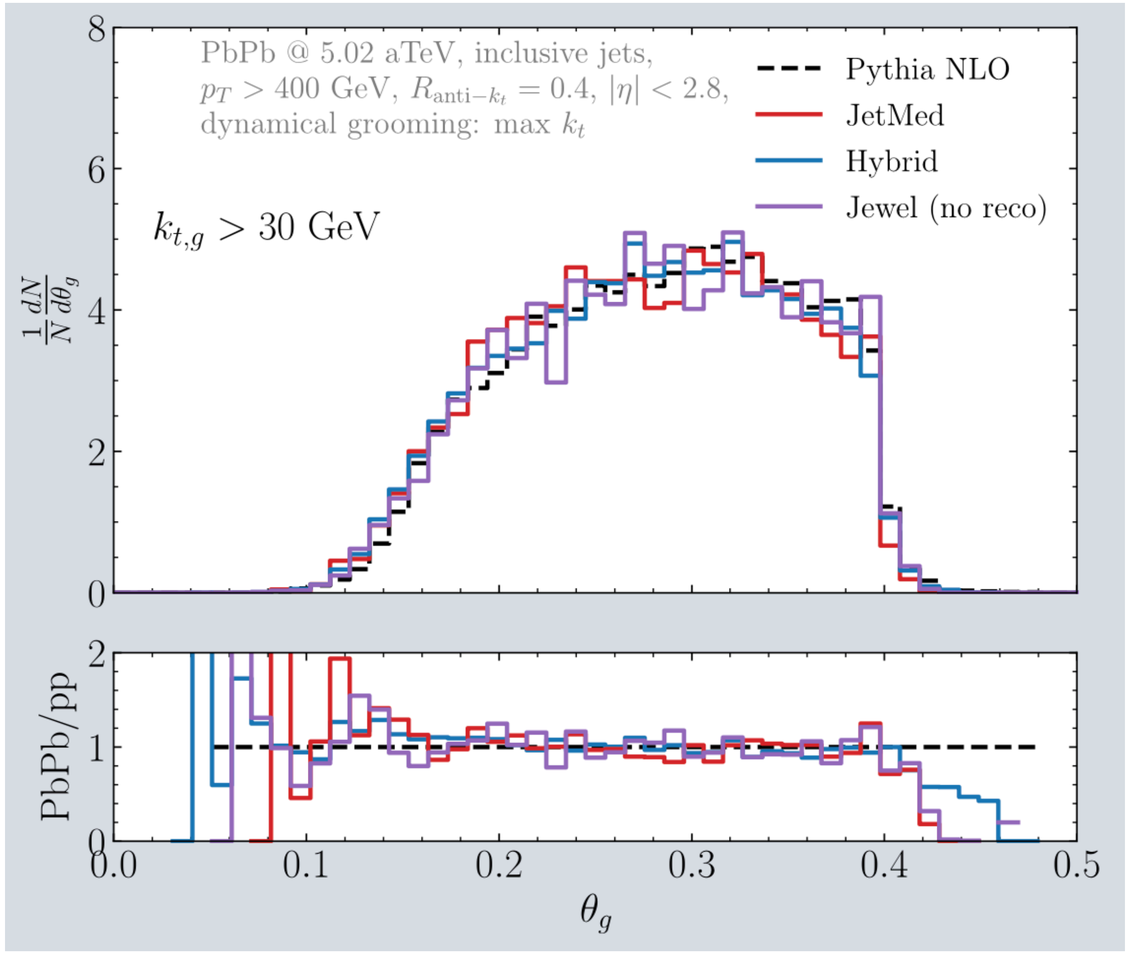



Hardest splittings appear unmodified in many models.

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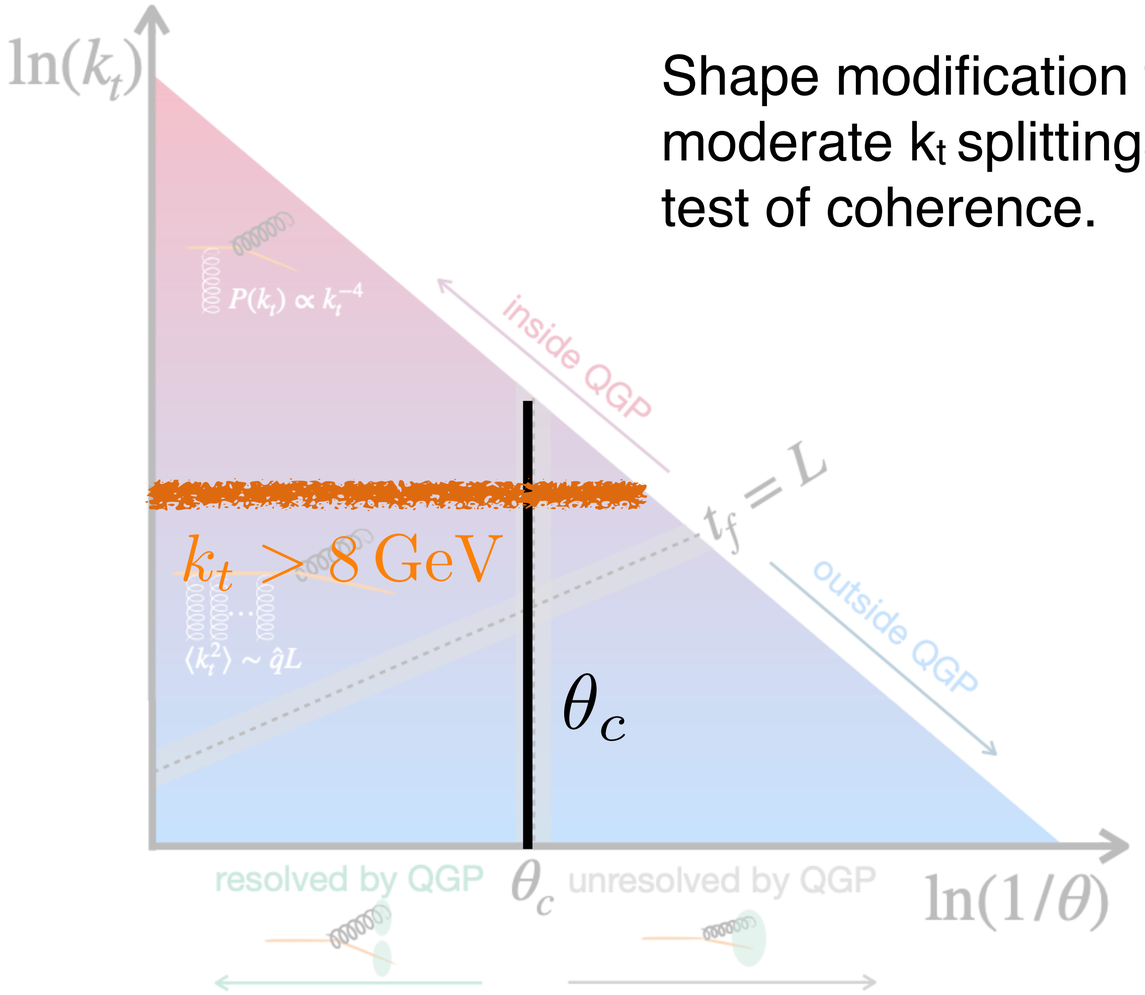
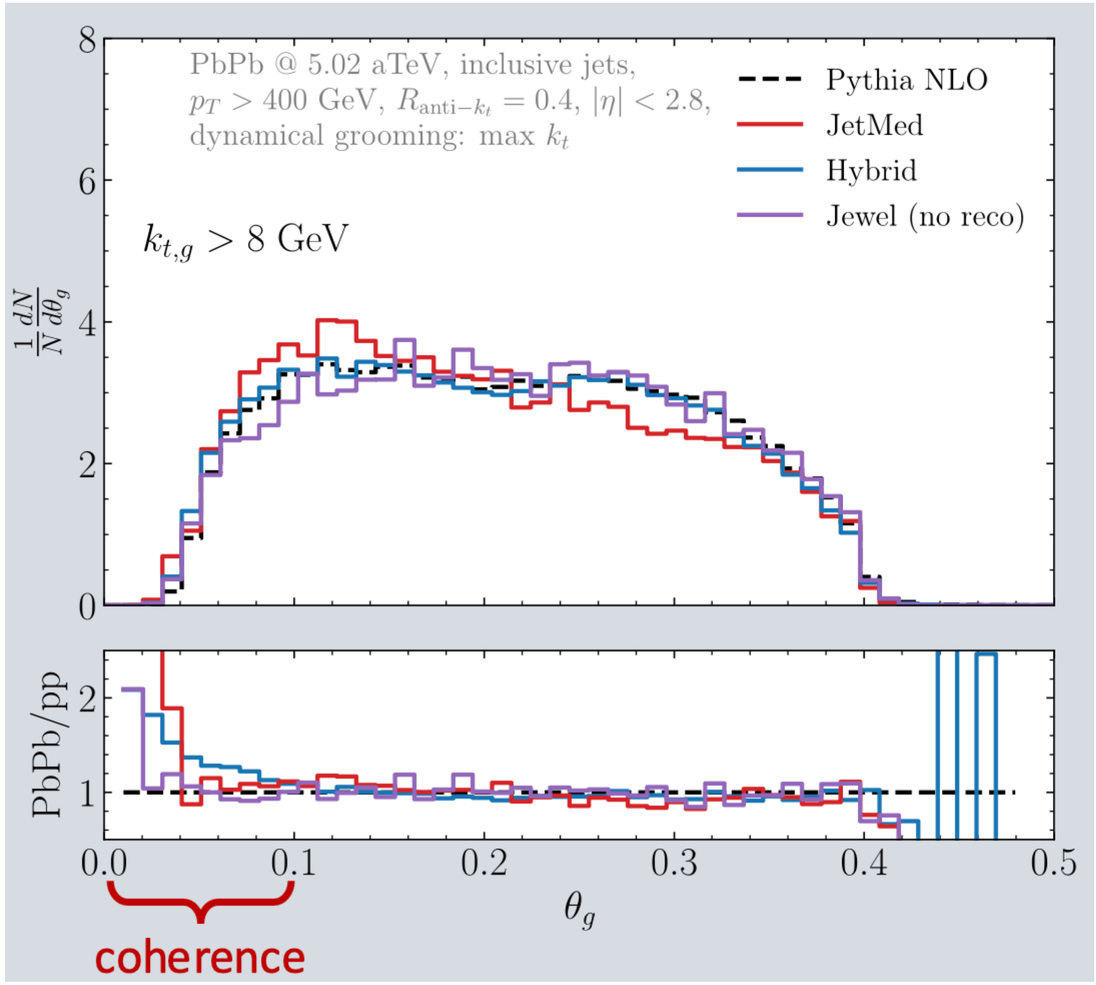



Shape modification for moderate $k_t$ splittings, test of coherence.

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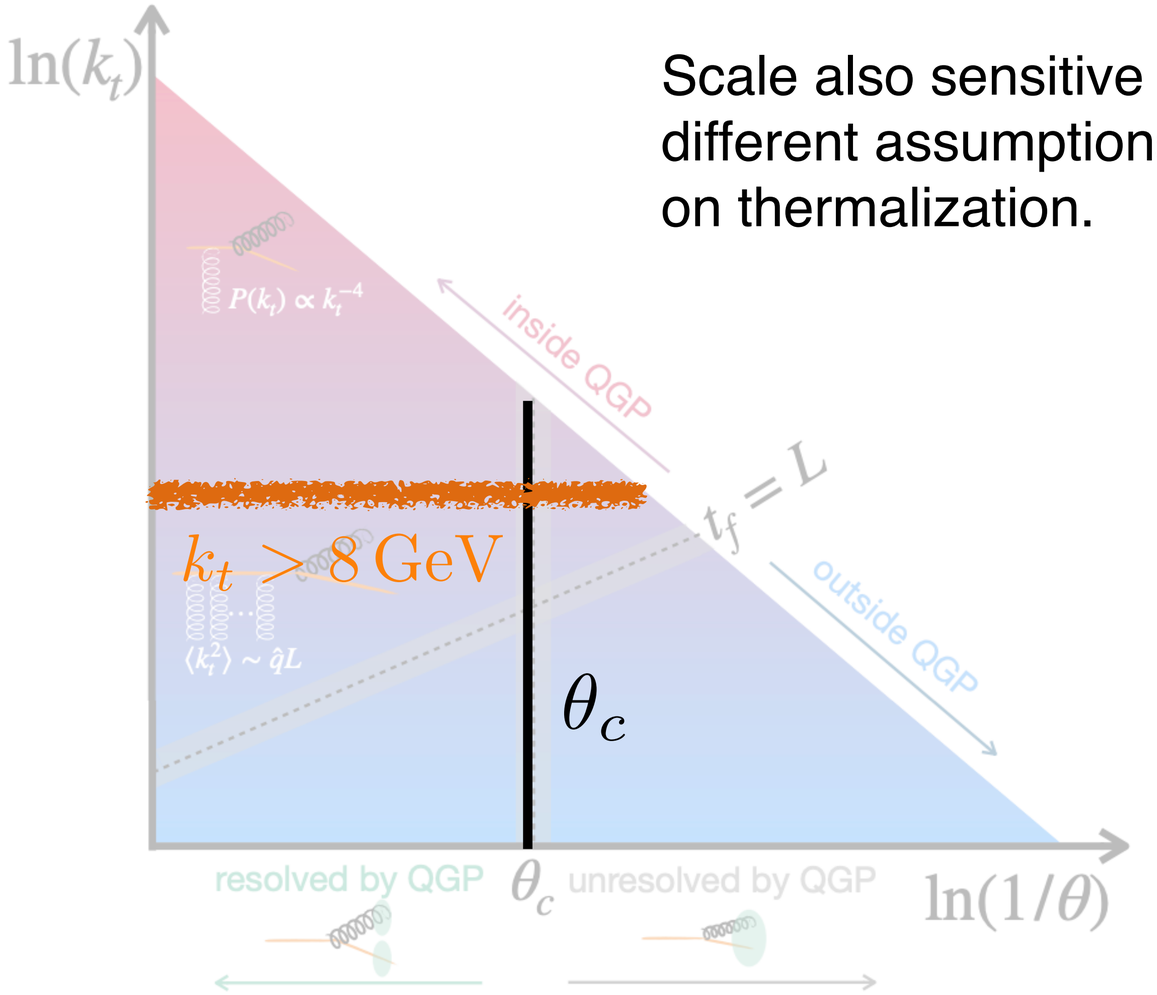
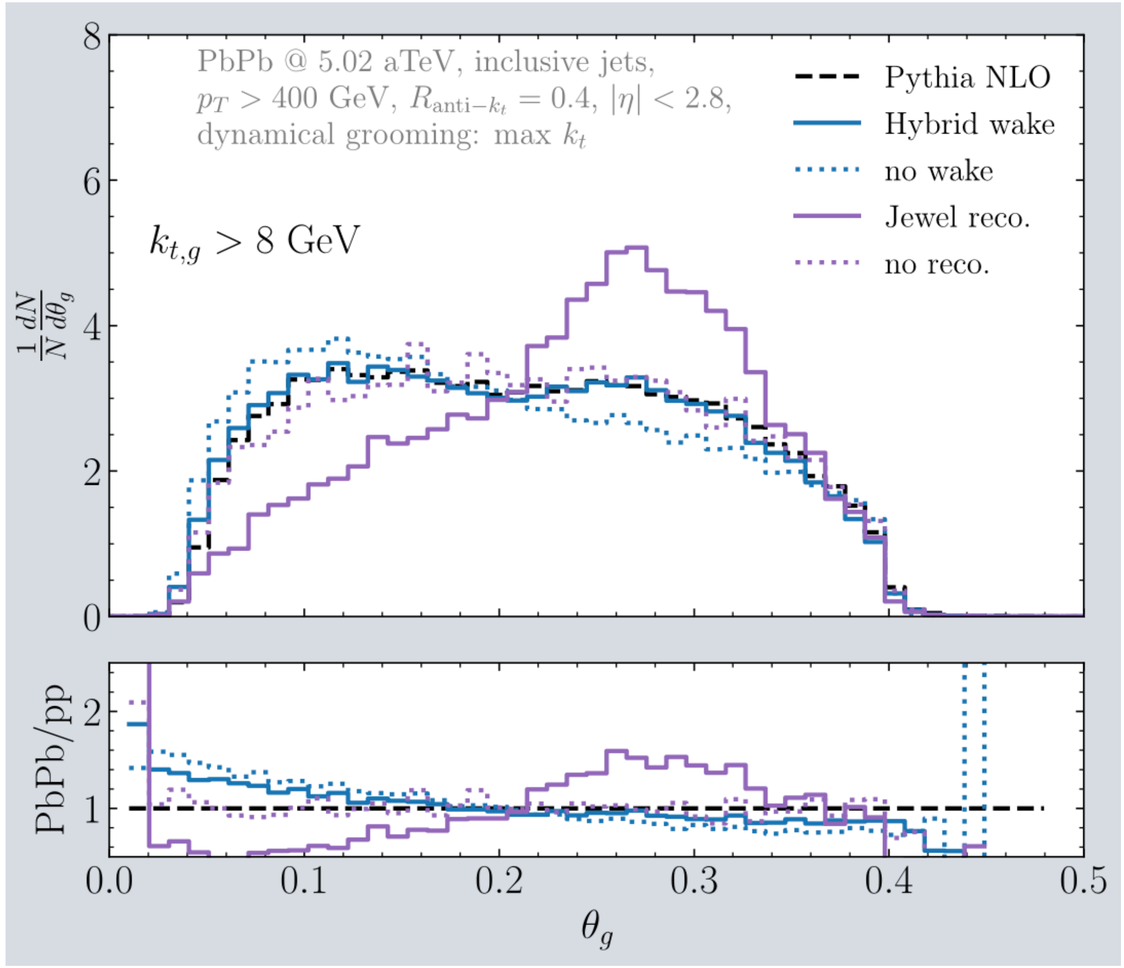



Scale also sensitive to different assumptions on thermalization.

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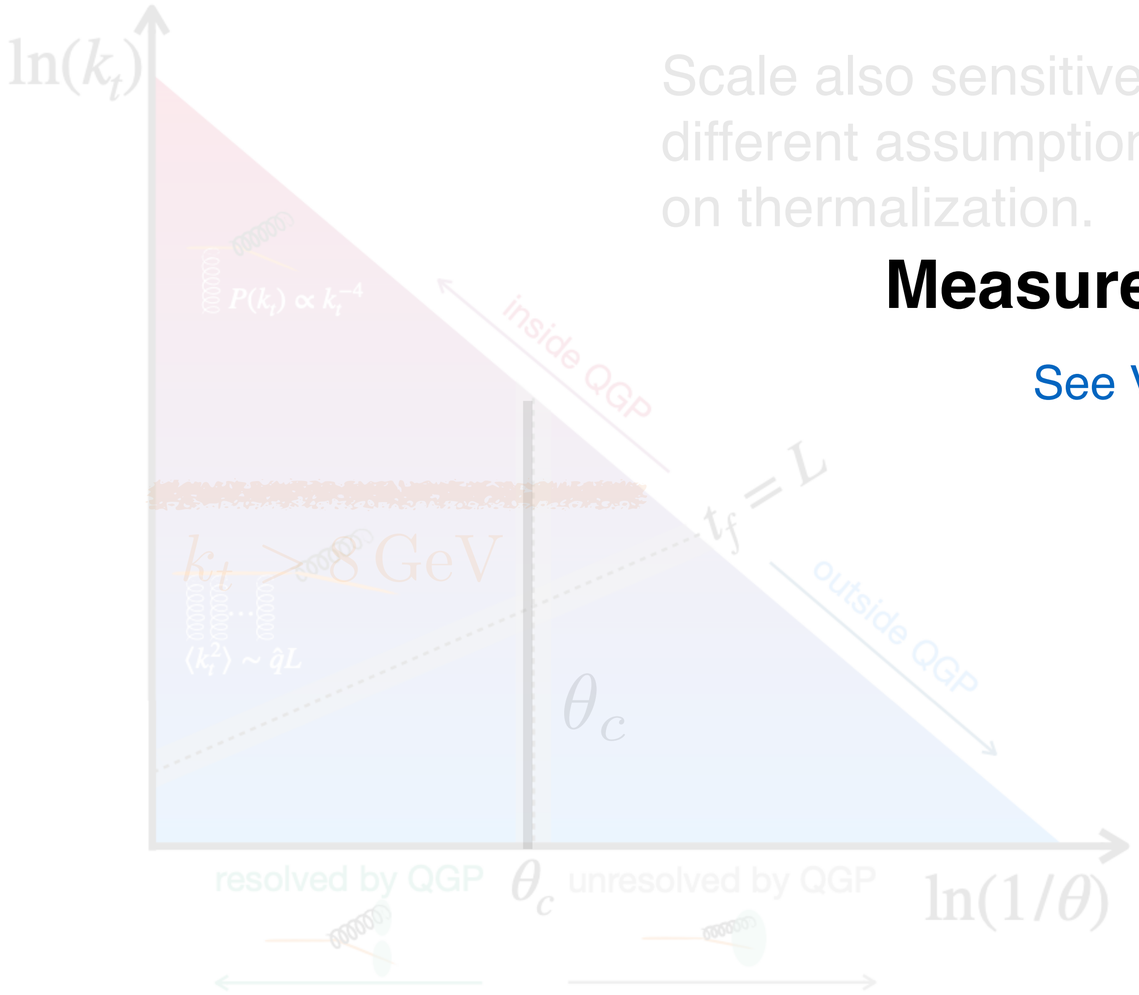
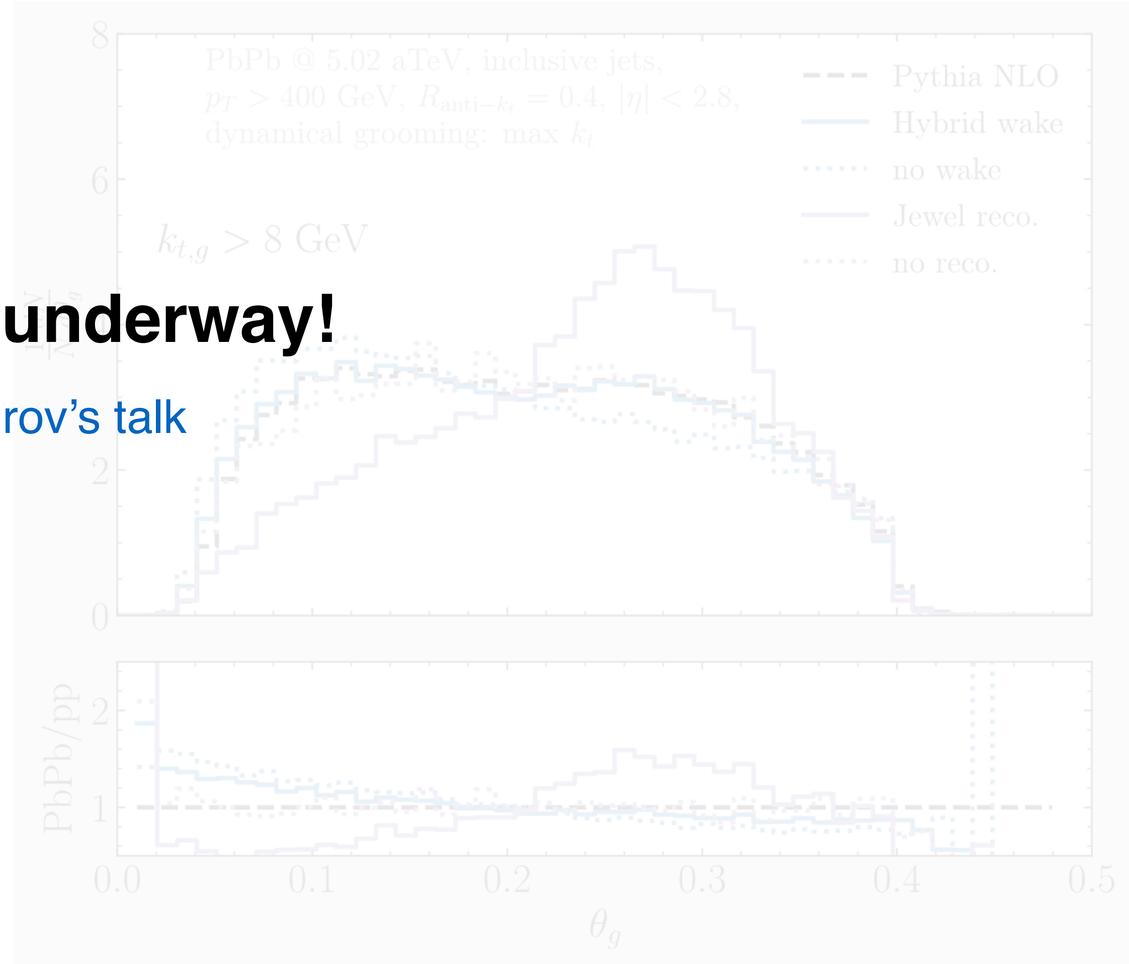



Scale also sensitive to different assumptions on thermalization.

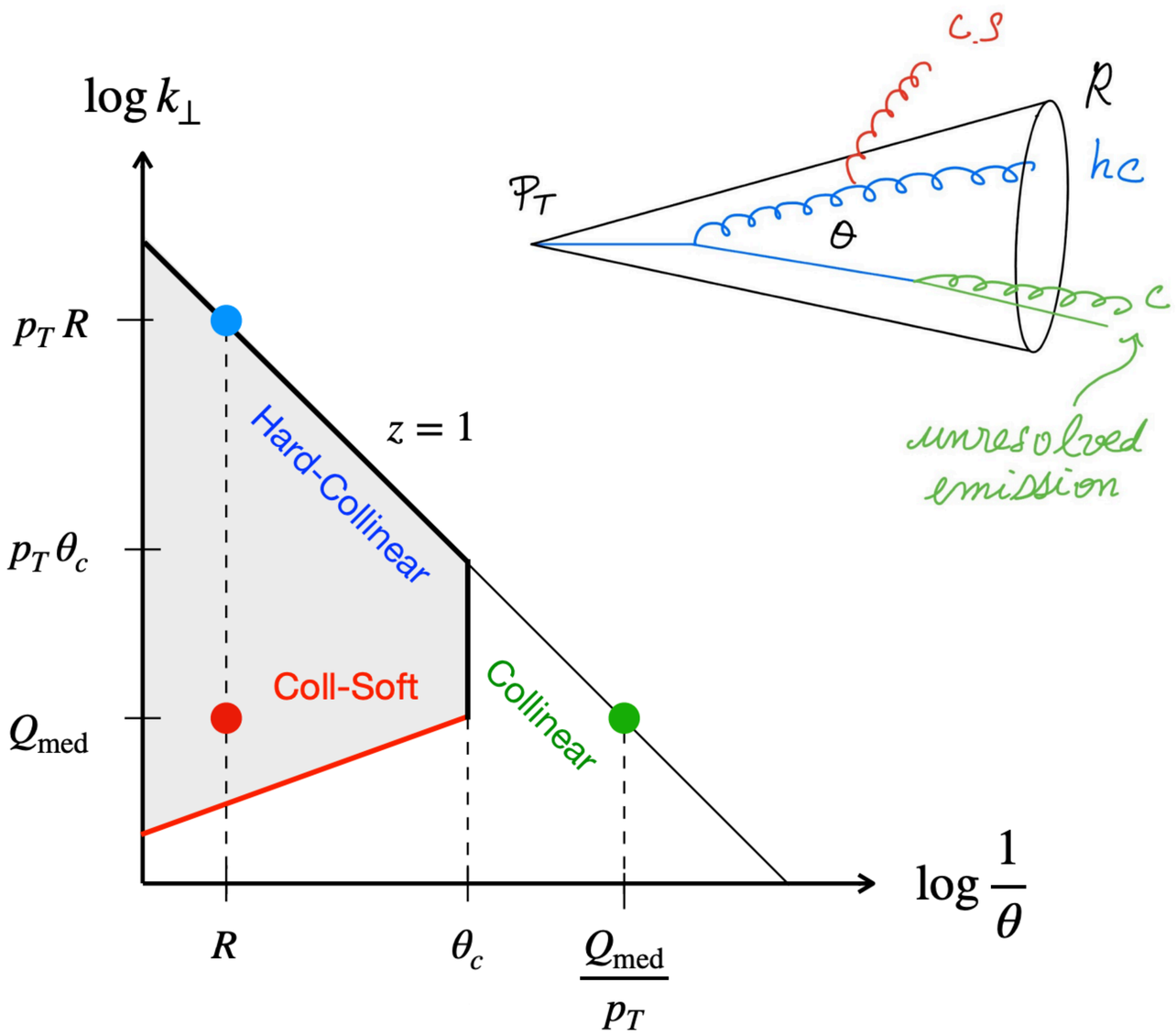
**Measurement underway!**

See V. Vladimirov's talk




See A. Takacs' talk

# Towards a Factorized Picture







*Goal*: **Factorization approach** for jet quenching to all orders in perturbation theory via EFT.

Resolved subjets (hard-collinear) convoluted with energy loss function (collinear-soft) made of Wilson line correlators.

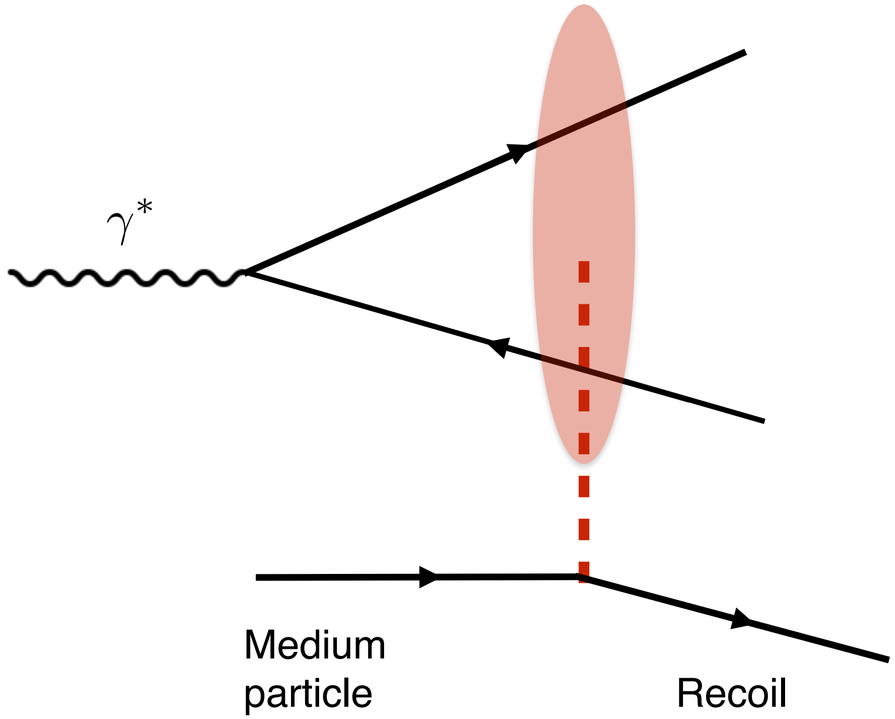
→ Better theoretical control on the interplay between vacuum and medium scales in computation of jet observables.

Mehtar-Tani et al. - 2409.05957

See Y. Mehtar-Tani's talk

# Color Coherence on Recoils

Which are the color coherence effects on recoiling particles?




Or, can we tell which leg of a dipole scattered with the medium constituent?

DP & Sanjurjo - 2406.08550

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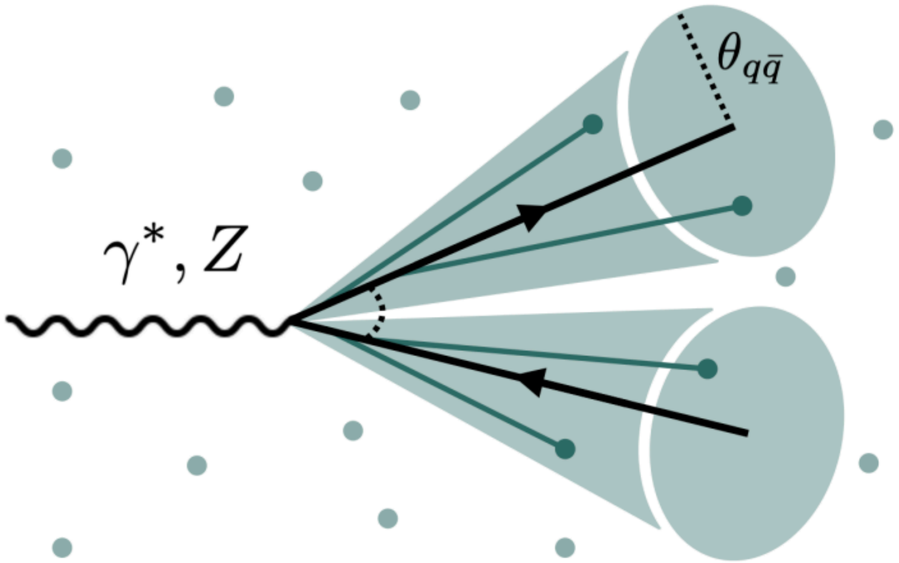



In the soft recoil limit, same result as gluon emission in vacuum:

$$\theta_{\text{recoil}} < \theta_{q\bar{q}}$$

If dipole in color coherent state:

→ Successive recoils draw the shape of the antenna.

→ Coll. energy loss of an antenna depends on its angle.

$$dE/dx \propto \log \theta_{q\bar{q}}$$

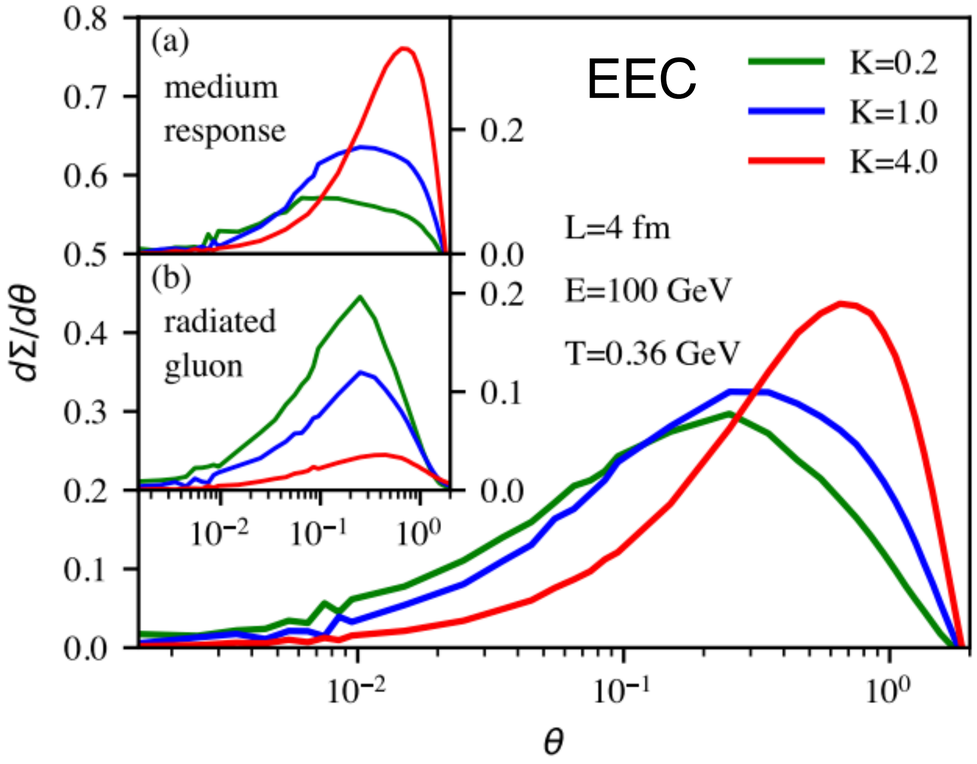
*To be implemented in models.*

DP & Sanjurjo - 2406.08550

# Recoils on the EEC

Models that include both medium induced radiation and recoiling particles (here LBT) observe largest contribution at large angles is from medium response.

Single quark



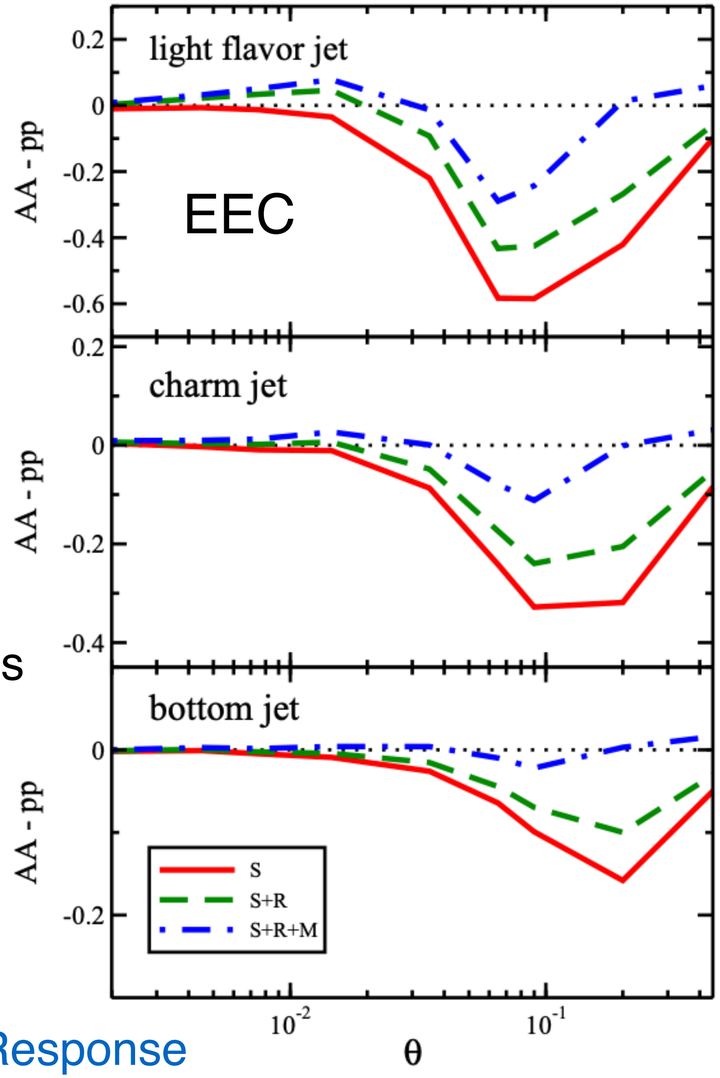

Debye mass

$$\mu_D^2 = \frac{3}{2} K g^2 T^2$$

See Z. Yang's talk

Yang et al. - 2310.01500

Xing et al. - 2409.12843

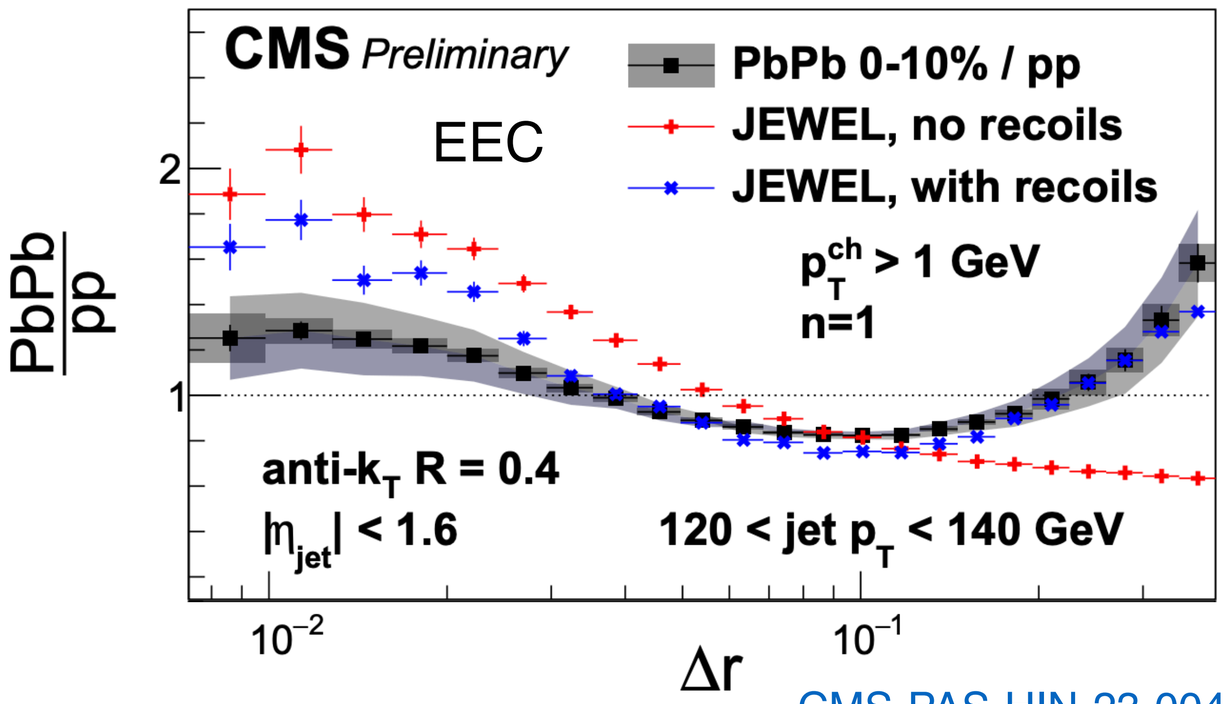



Flavored jets

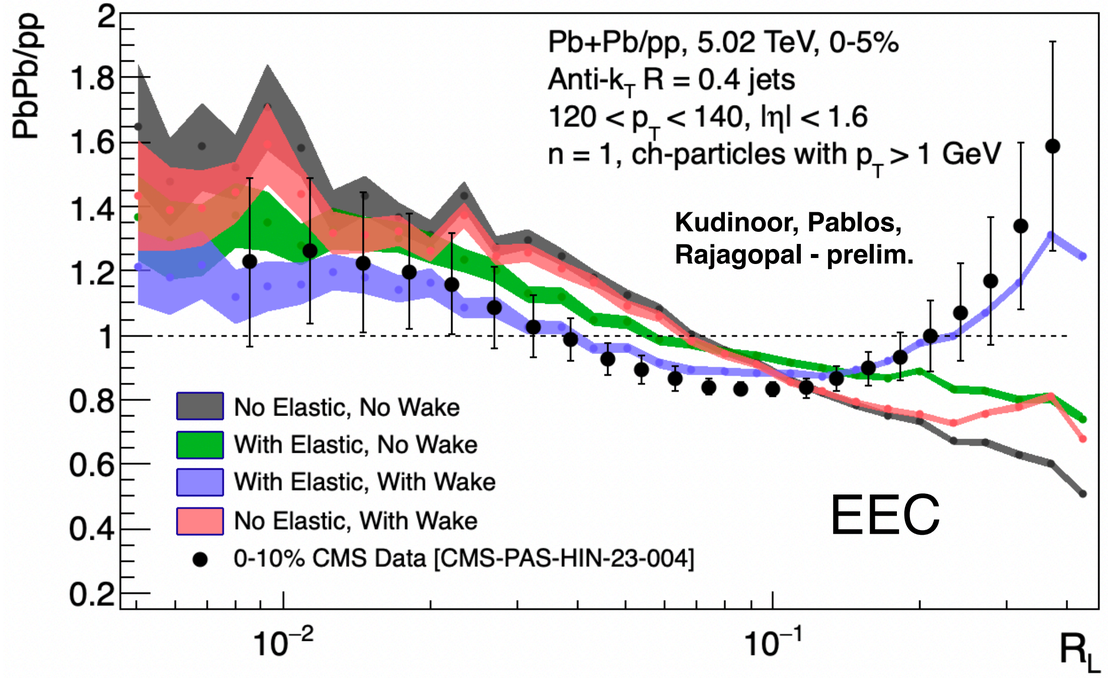
Shower
+Radiation
+Medium Response

See W. Xing's talk

# Recoils on the EEC



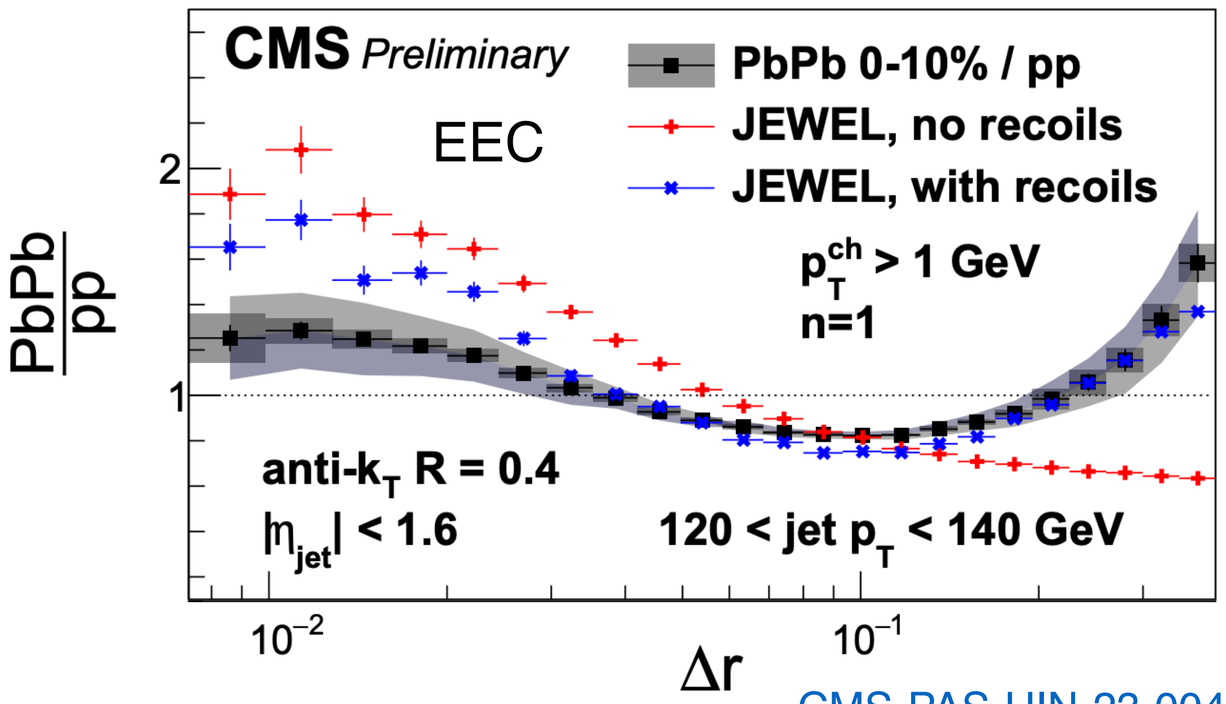

CMS-PAS-HIN-23-004

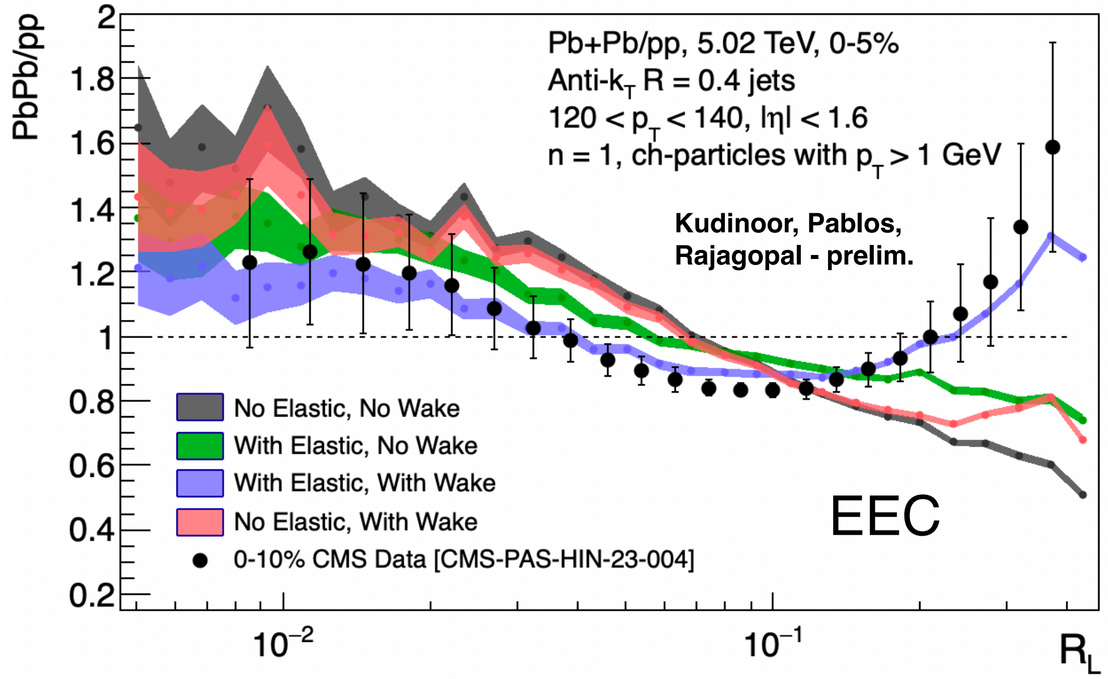



JEWEL + Recoils describes large angle enhancement

HYBRID + Recoils + Wake describes large angle enhancement

# Recoils on the EEC




CMS-PAS-HIN-23-004


JEWEL + Recoils describes large angle enhancement

HYBRID + Recoils + Wake describes large angle enhancement

*Work is ongoing to exploit full potential of energy correlators!*

See C. Andrés' talk  Holguin et al. - 2409.07514

# The Wake

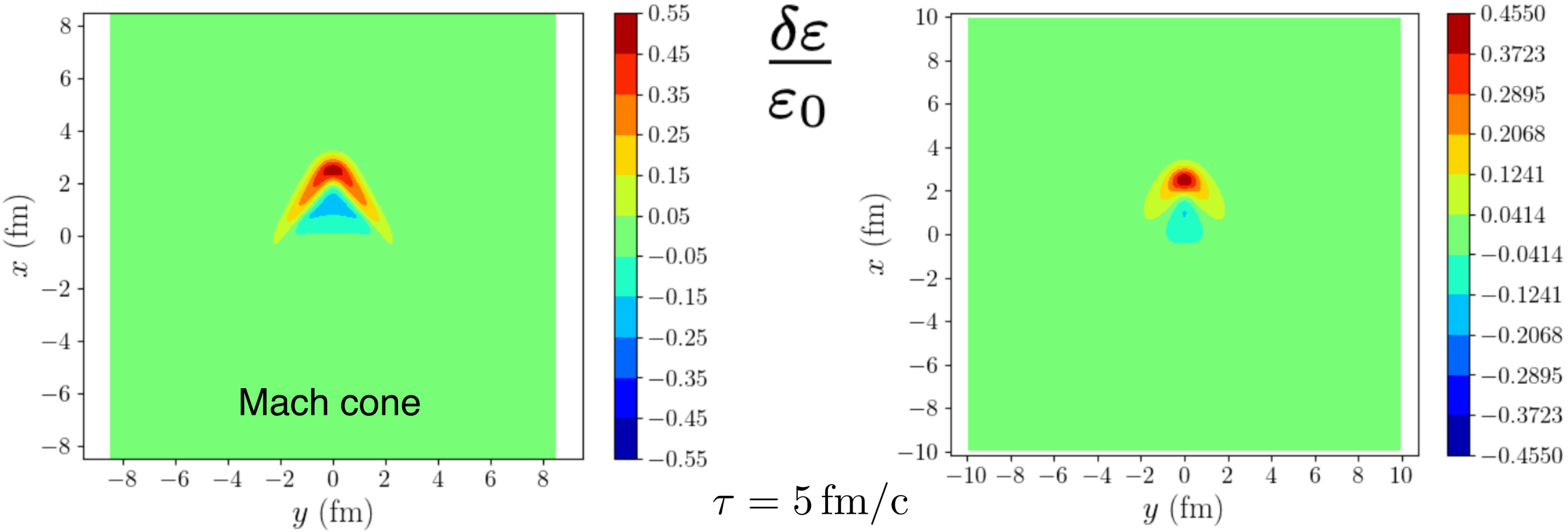
Casalderrey-Solana et al. - 2010.01140

Bjorken flow background

$$\nabla_\mu T^{\mu\nu} = J^\nu$$

Ideal

Viscous




$\tau = 5\,\mathrm{fm/c}$

Energy perturbation: **sound waves** carrying little momentum.

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Casalderrey-Solana et al. - 2010.01140

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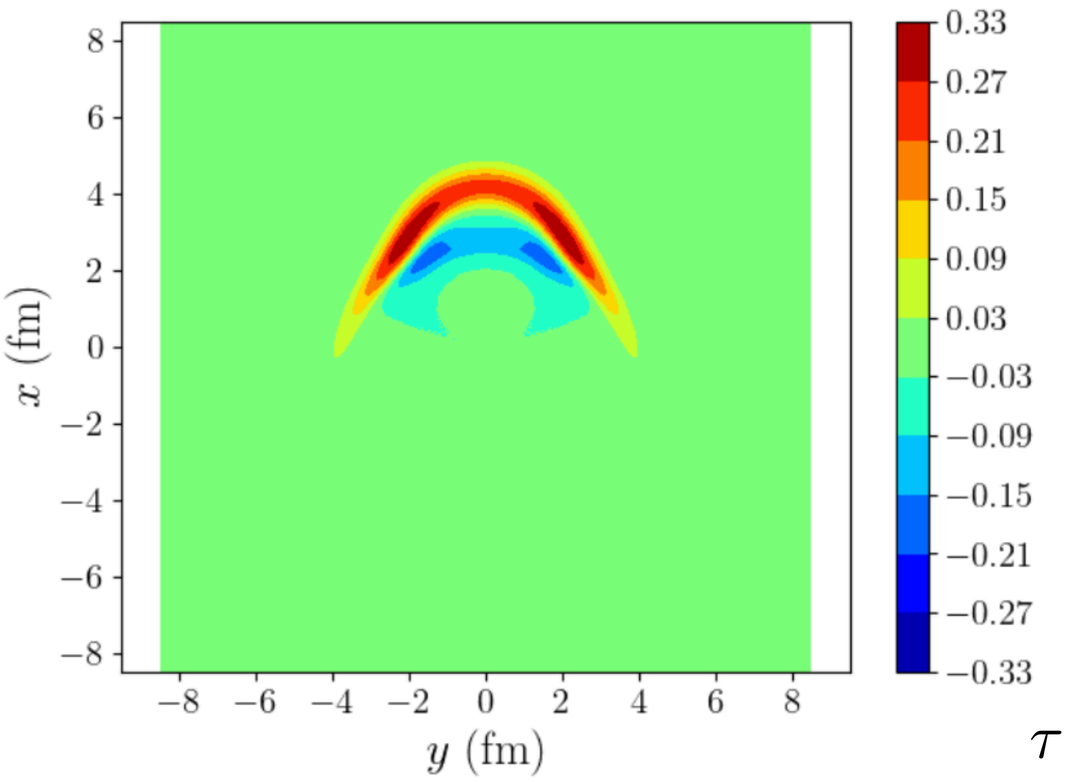
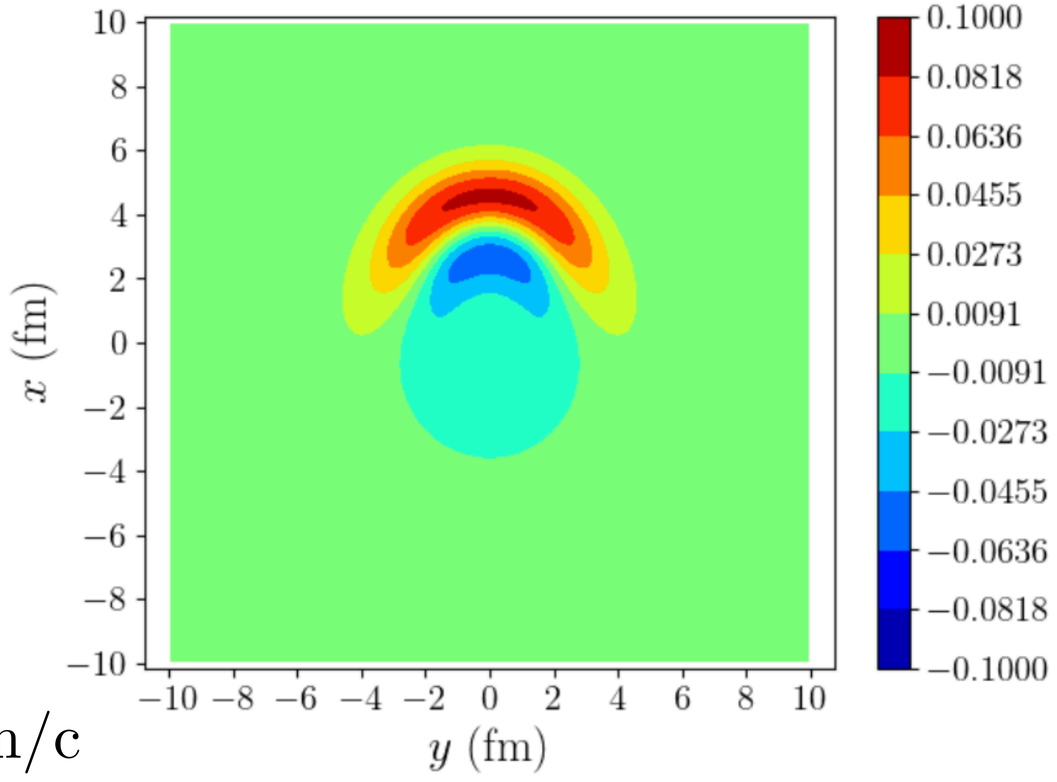



$$\frac{\delta\varepsilon}{\varepsilon_0}$$

Viscous




$$\tau = 8\,\mathrm{fm/c}$$

Energy perturbation: **sound waves** carrying little momentum.

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Casalderrey-Solana et al. - 2010.01140

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$$\nabla_\mu T^{\mu\nu} = J^\nu$$

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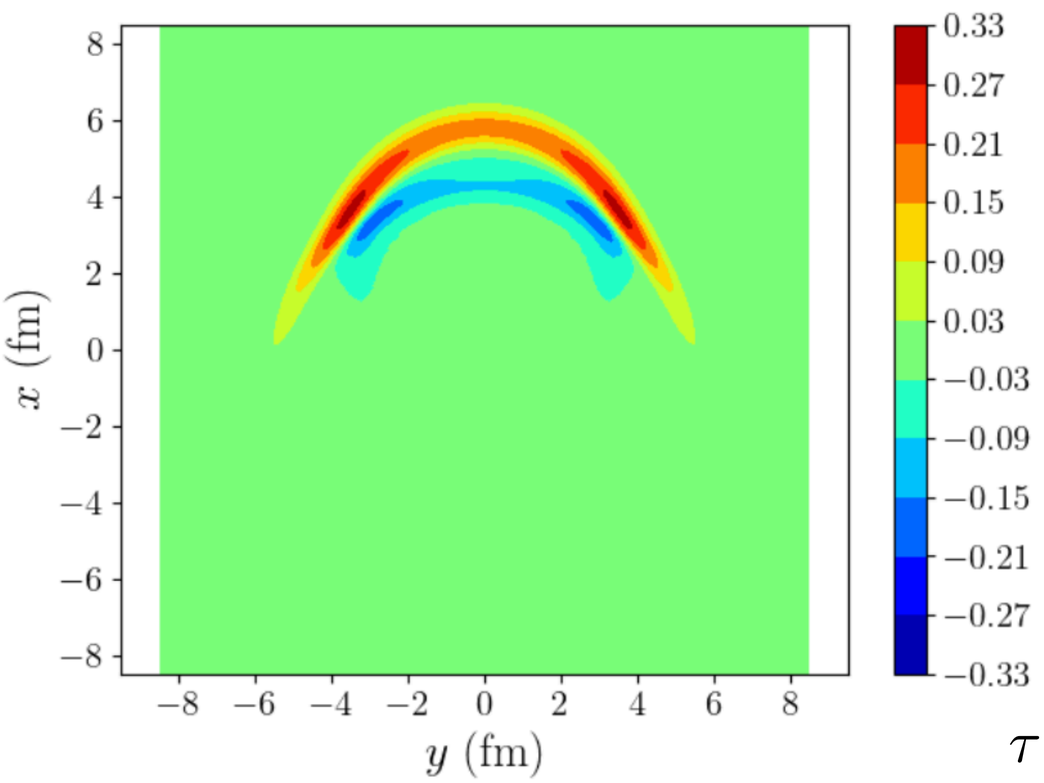
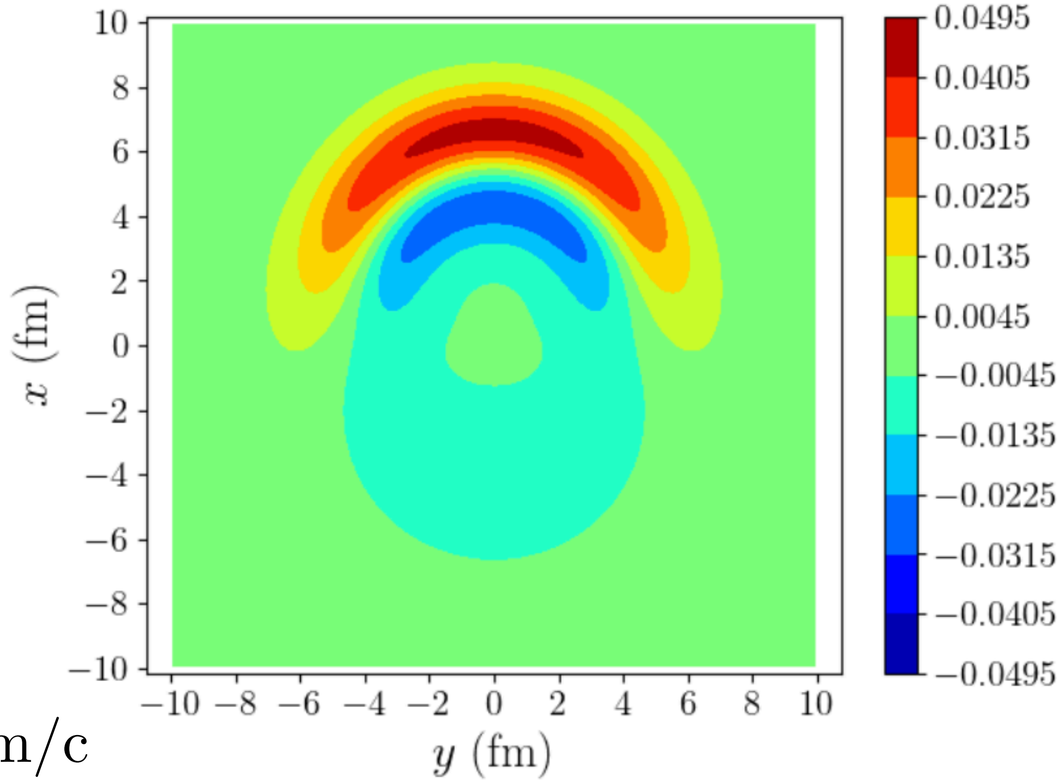



$$\frac{\delta\varepsilon}{\varepsilon_0}$$

Viscous




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

2010.01140

Energy perturbation: **sound waves** carrying little momentum.

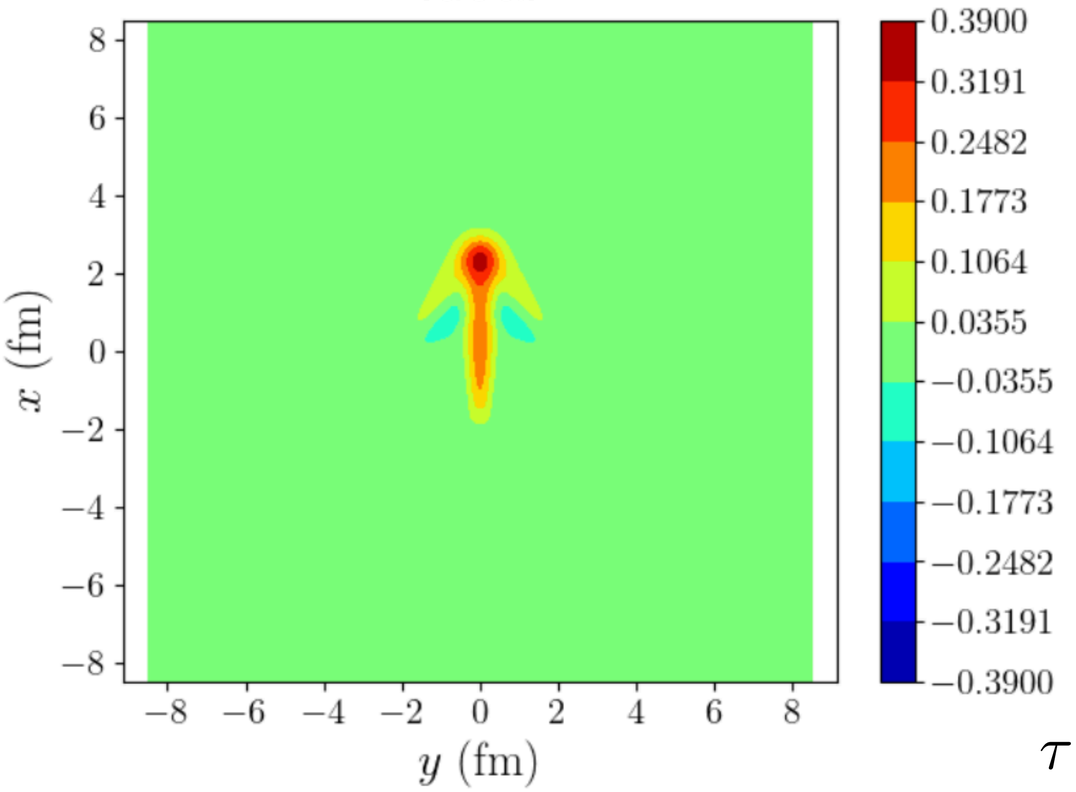
# The Wake

Casalderrey-Solana et al. - 2010.01140

Bjorken flow background

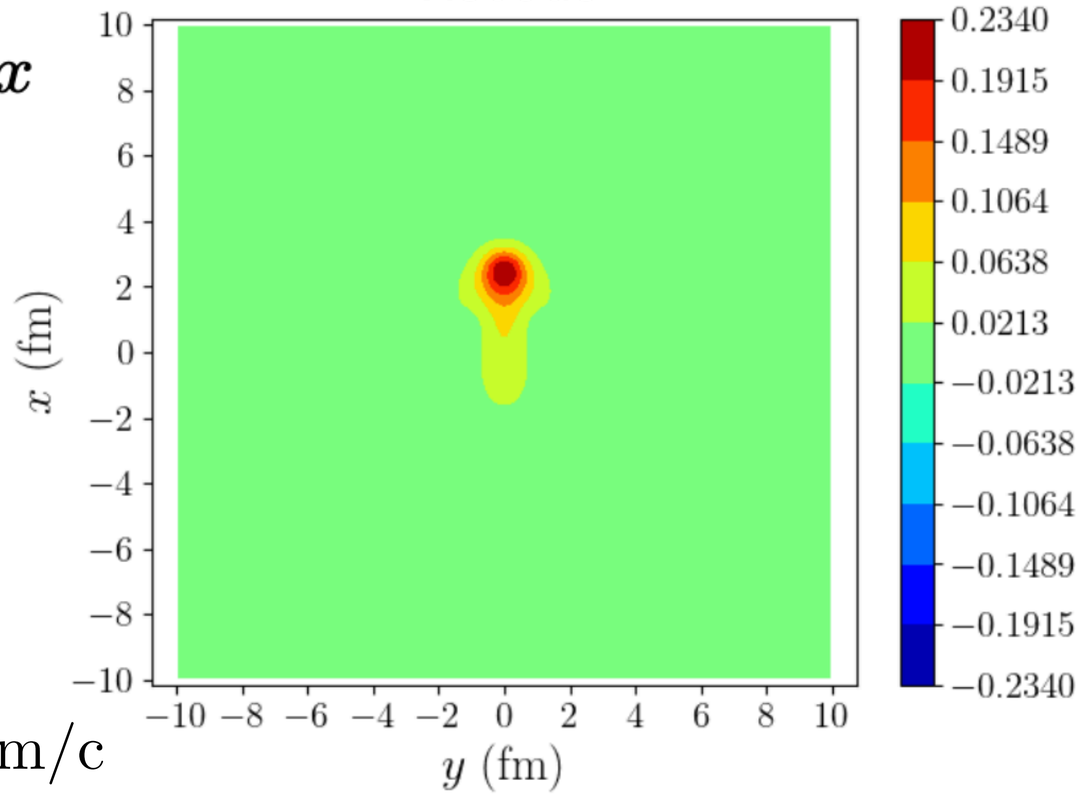
$$\nabla_\mu T^{\mu\nu} = J^\nu$$

Ideal




$\delta u^x$

Viscous




$\tau = 5\,\mathrm{fm/c}$

Momentum perturbation: **moving fluid** behind the jet carrying most momentum.

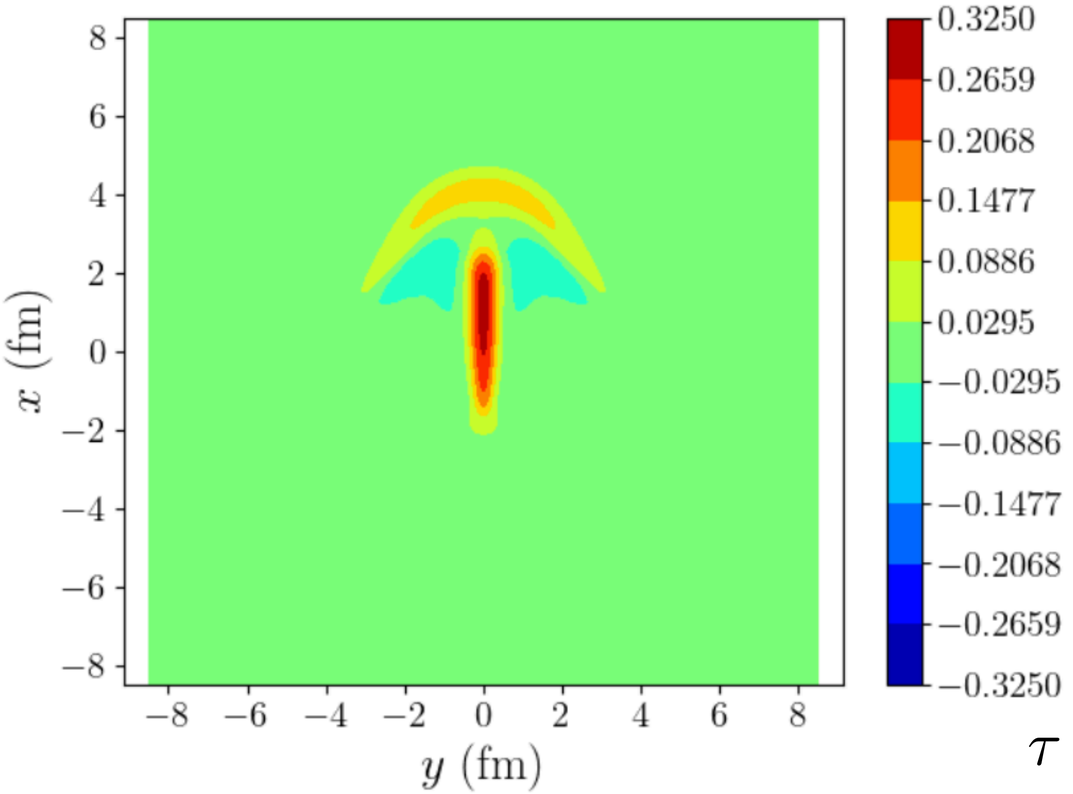
# The Wake

Casalderrey-Solana et al. - 2010.01140

Bjorken flow background

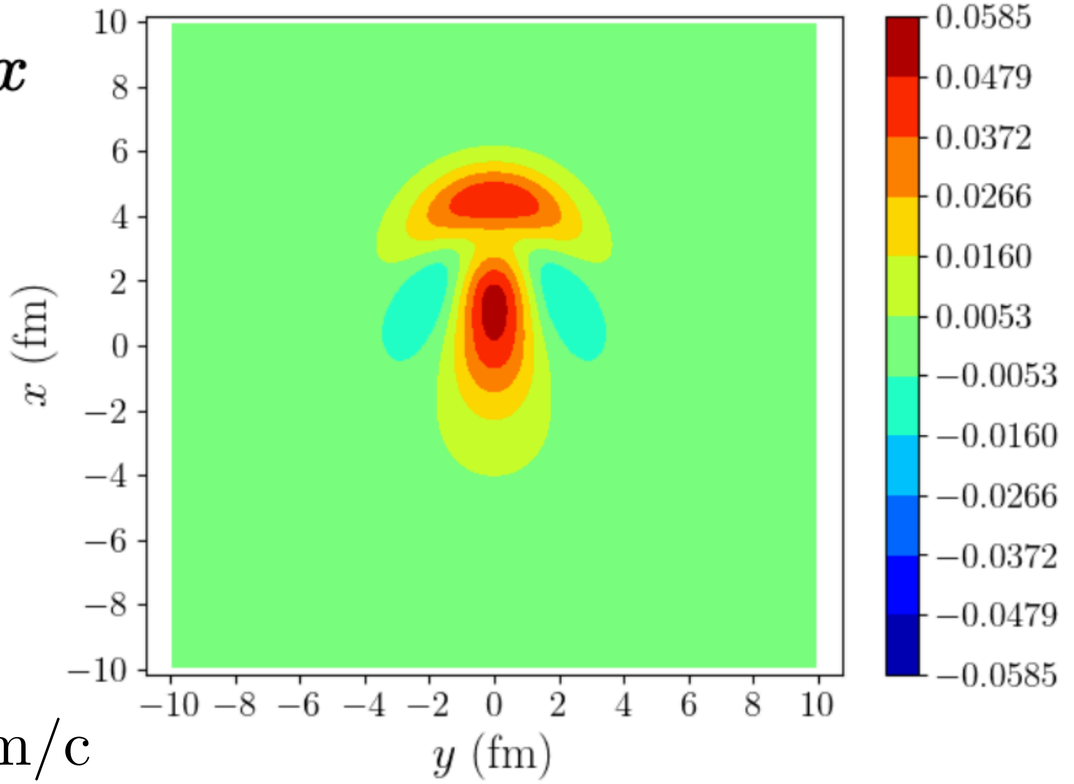
$$\nabla_\mu T^{\mu\nu} = J^\nu$$

Ideal




$\delta u^x$

Viscous




$\tau = 8\,\mathrm{fm/c}$

Momentum perturbation: **moving fluid** behind the jet carrying most momentum.

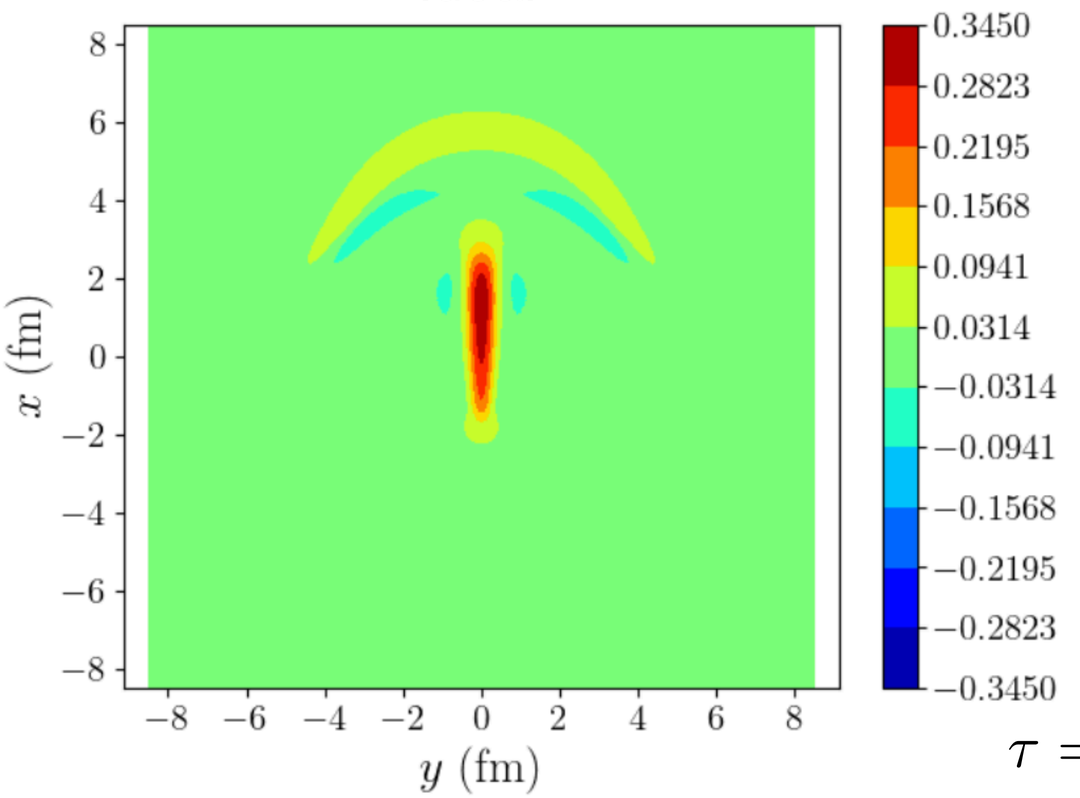
# The Wake

Casalderrey-Solana et al. - 2010.01140

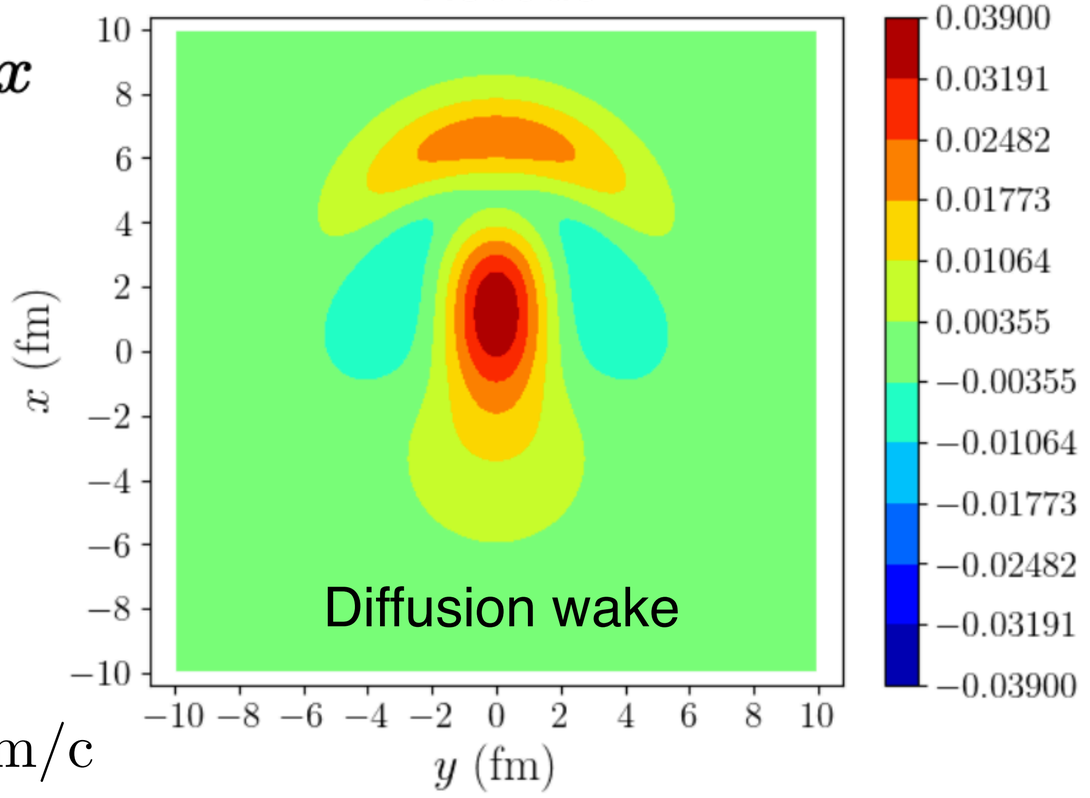
Bjorken flow background

$$\nabla_\mu T^{\mu\nu} = J^\nu$$

Ideal




Viscous

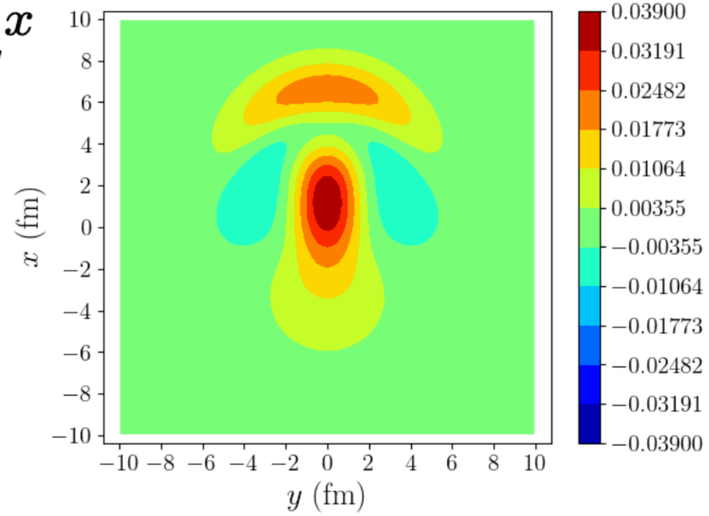



$\tau = 11\,\mathrm{fm/c}$

Momentum perturbation: **moving fluid** behind the jet carrying most momentum.

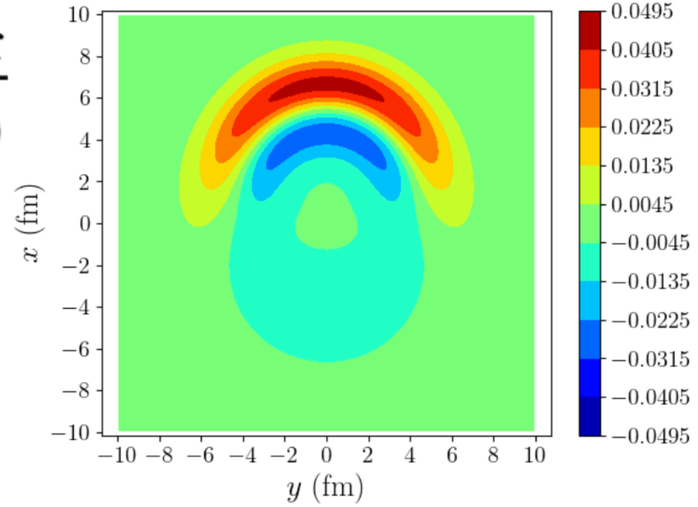
# Dragging the QGP

$\delta u^x$



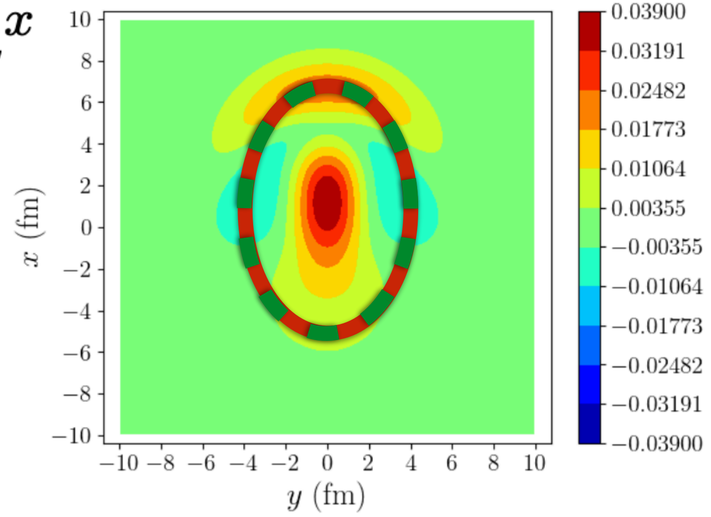

Cooper-Frye

$\frac{\delta\varepsilon}{\varepsilon_0}$



# Dragging the QGP

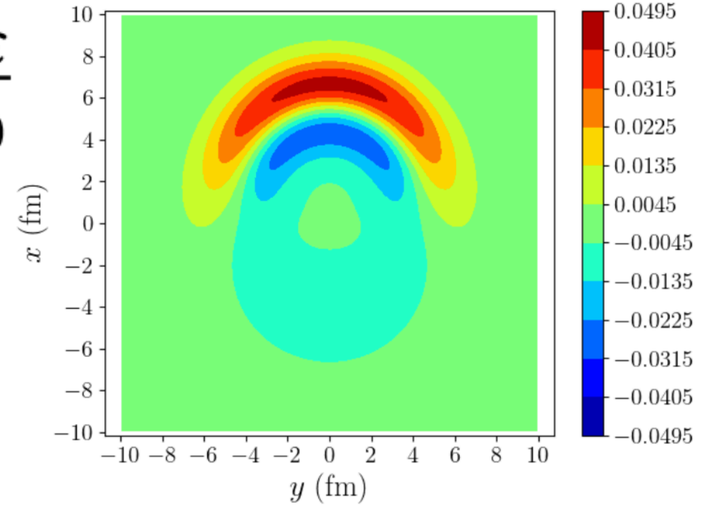
$\delta u^x$




**Increase** particle production in jet direction, **decrease** in opposite direction (boosted fluid cells).

Cooper-Frye

$\frac{\delta\varepsilon}{\varepsilon_0}$




Increase particle production isotropically.

With respect to unperturbed background

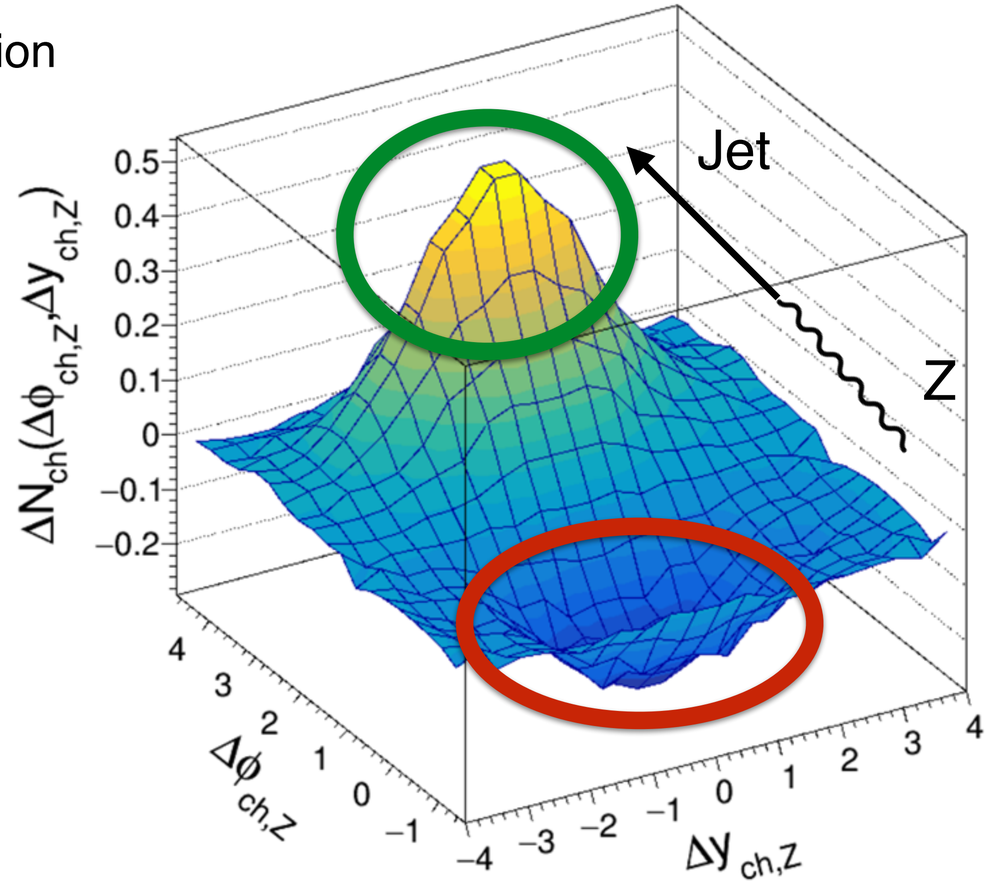


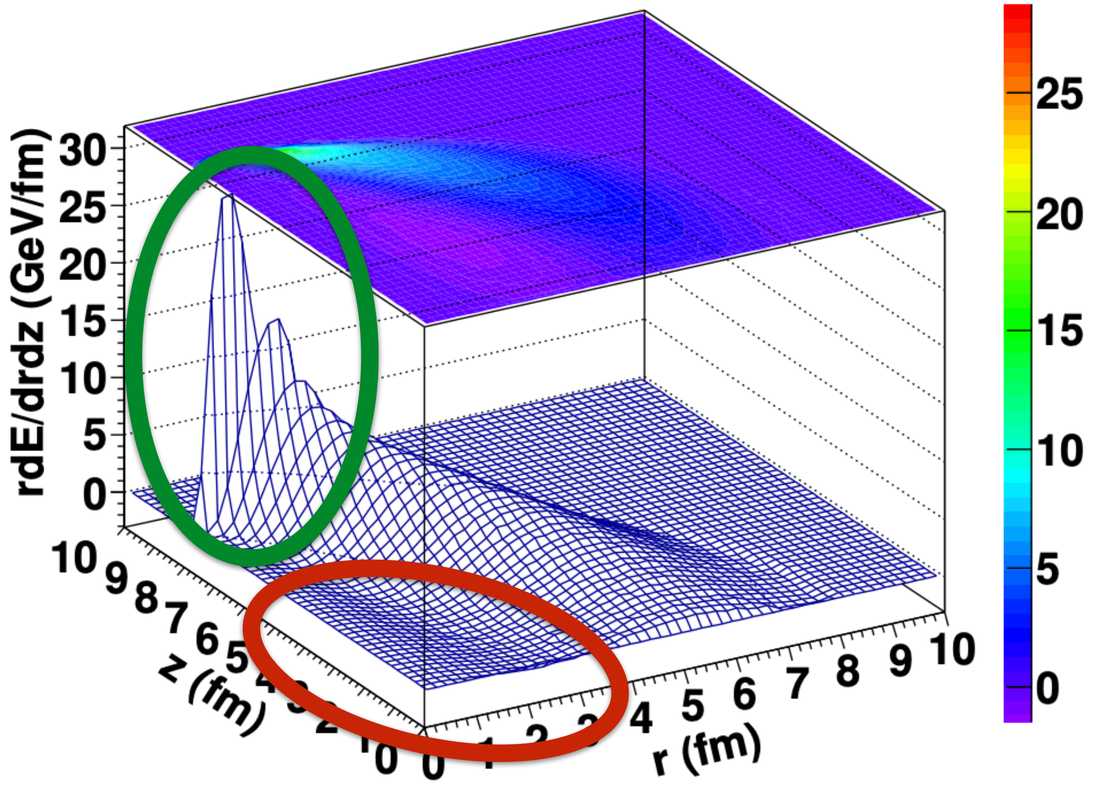

Fig. from Y.-J. Lee's talk

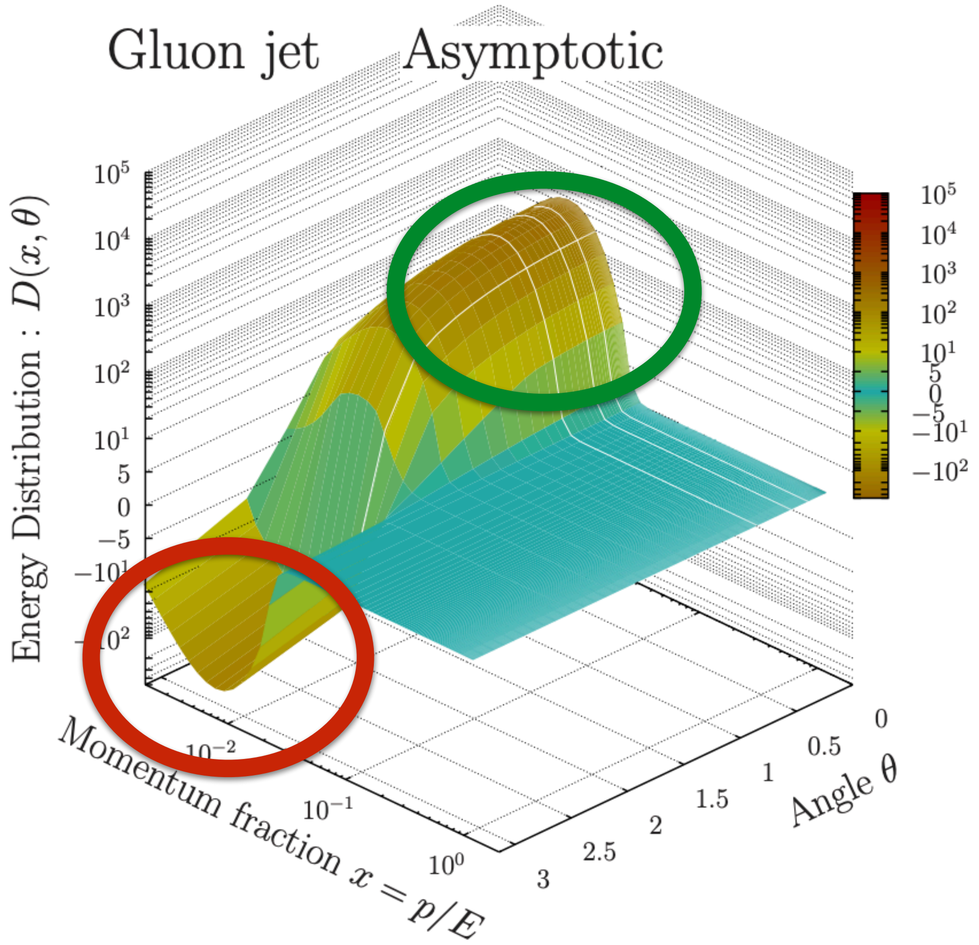
# Dragging the QGP

He et al. - 1503.03313

With respect to unperturbed background

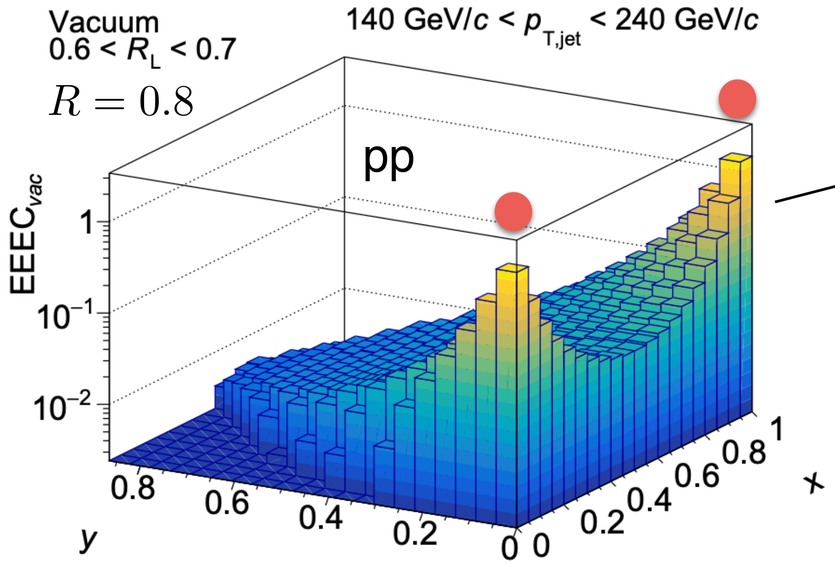
Mehtar-Tani et al. - 2209.10569



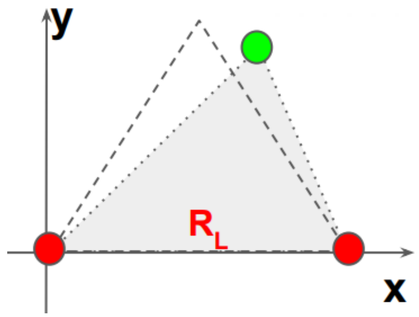




Naturally, excess + depletion is also observed in Effective Kinetic Theory implementations that account for energy-momentum conservation.

# The Wake on the EEEC




Collinear singularity in QCD (squeezed triangles).



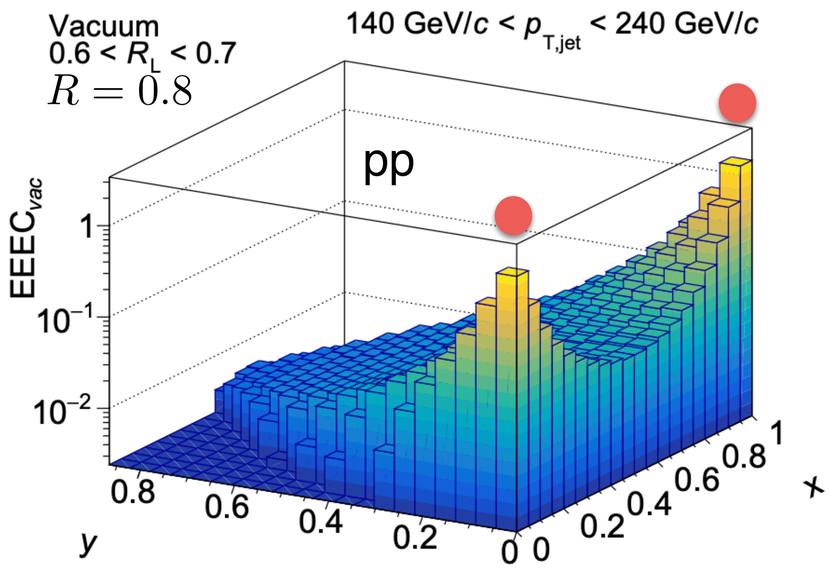

$0.6 < R_L < 0.7$

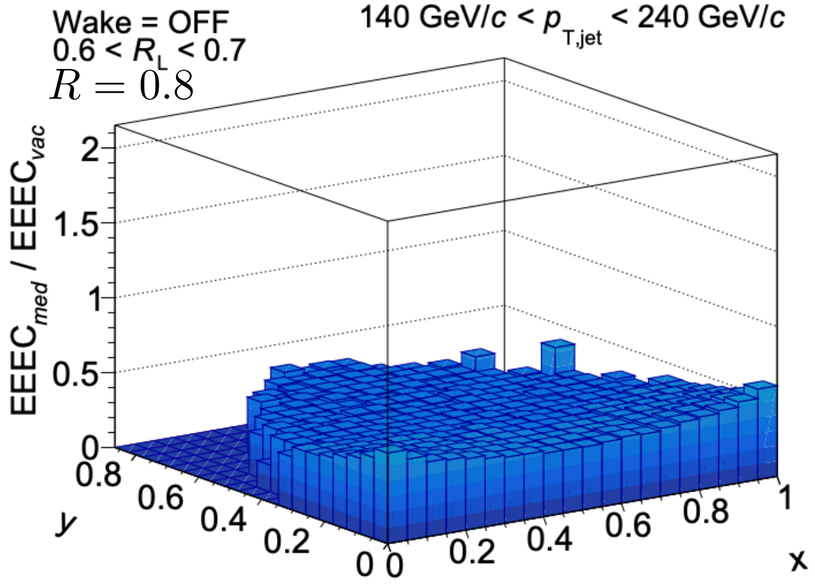
then rescaled to 1

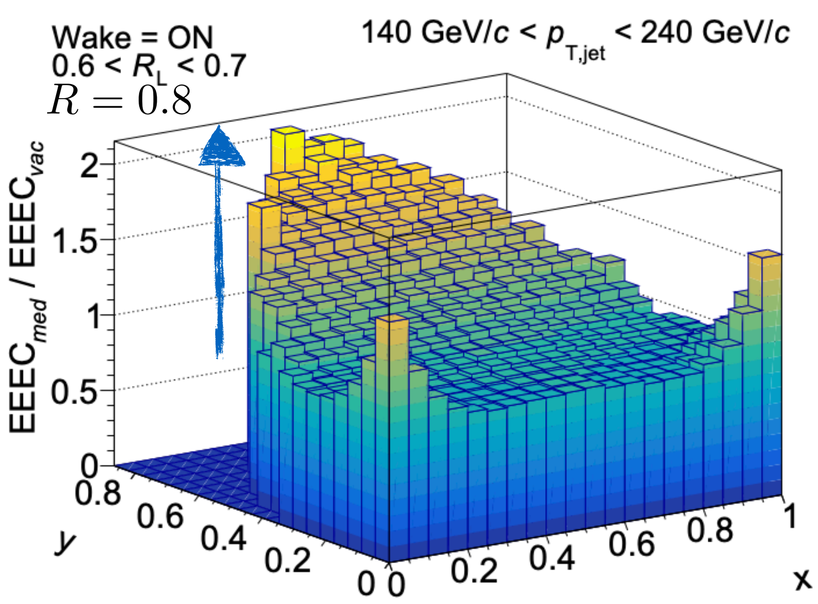
See A. Rai's poster

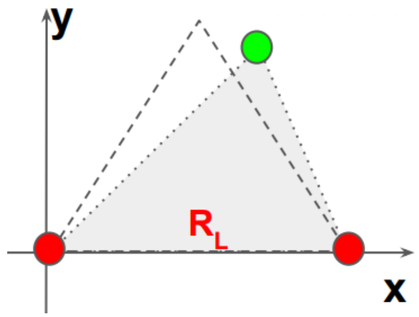
Bossi et al. - 2407.13818

# The Wake on the EEEC




$0.6 < R_L < 0.7$

then rescaled to 1

3-point energy correlator (EEEC) in PbPb:

- Striking dependence on the wake.
- Specially manifest in the *equilateral region*.
- Dominated by jet-wake-wake correlations.

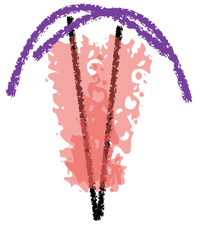
See A. Rai's poster

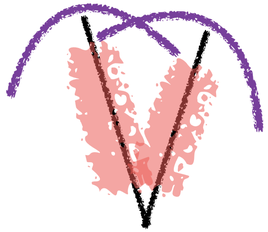
Bossi et al. - 2407.13818

# Multiple Wakes

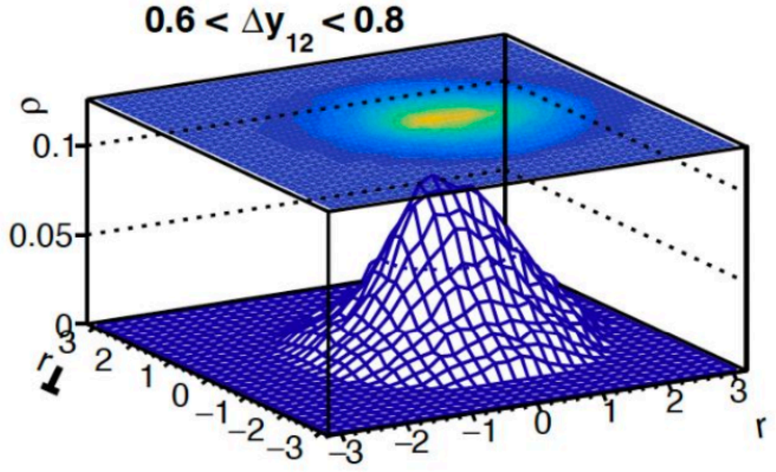
We have learned that wider structures tend to be more suppressed, but can we analyze the medium response to these multiple structures?

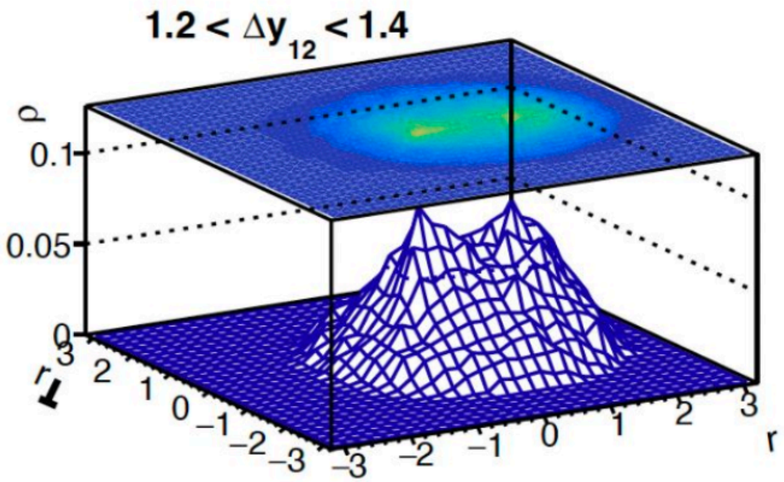
See M. Park's talk
See M. Nguyen's talk
See B. Hofman's talk

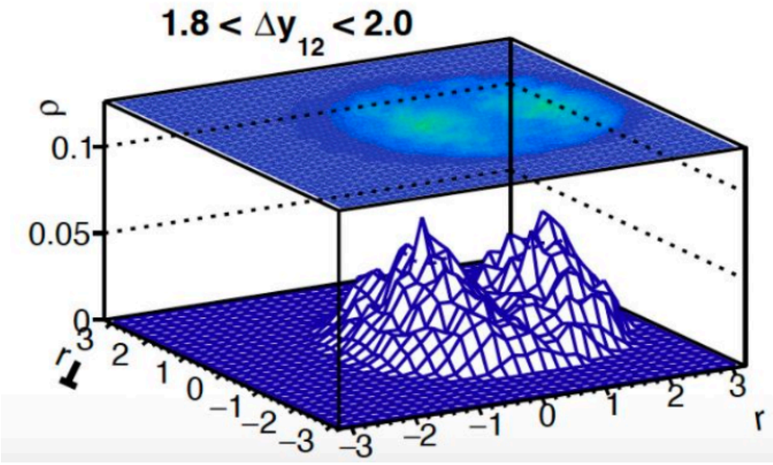




See A. Kudinoor's talk




Just wake particles

Exploit ATLAS' reconstruction of large R jets via hard small R jets.

See M. Rybar's talk

# Multiple Wakes

We have learned that wider structures tend to be more suppressed, but can we analyze the medium response to these multiple structures?

See M. Park's talk
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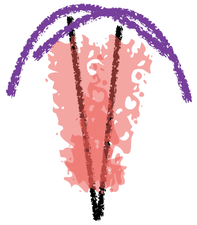
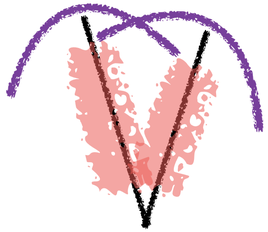
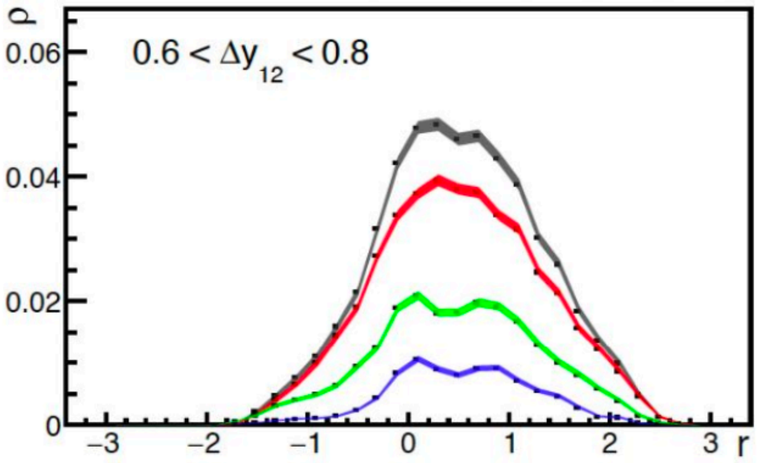
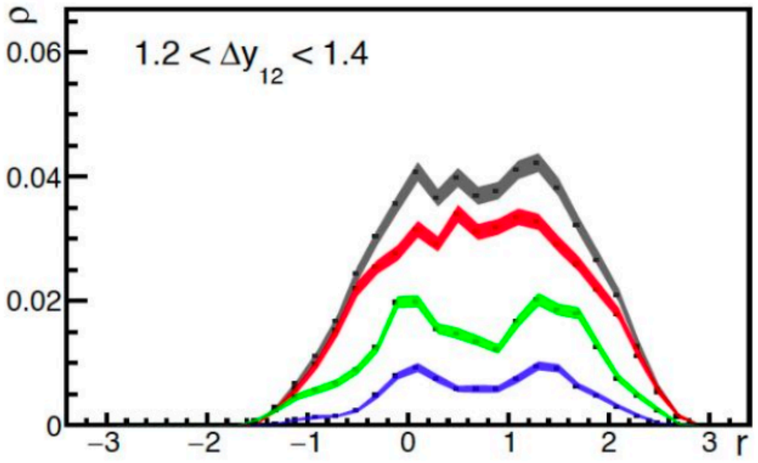
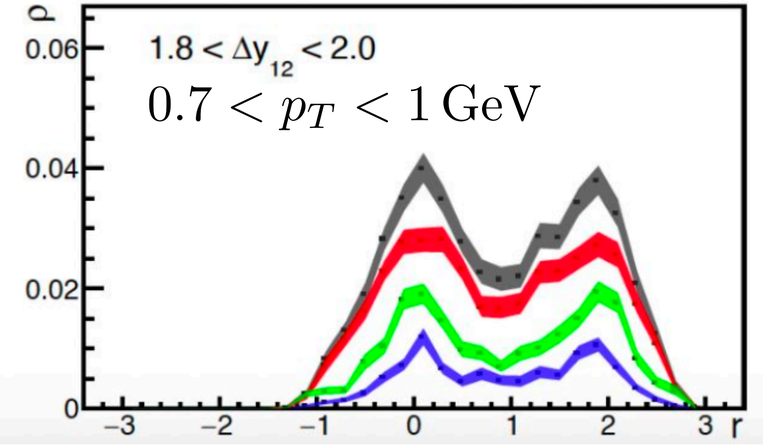
See B. Hofman's talk








Wake + Nonwake (Pb+Pb)
Wake (Pb+Pb)
Non-Wake (Pb+Pb)
Vacuum (pp)

Soft particles contribution dominated by wake(s).

See A. Kudinoor's talk

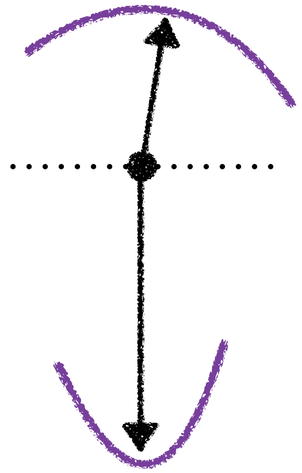
Outlook: Non-trivial interference patterns? Event plane correlations?

# Parton Cascade vs Medium Response

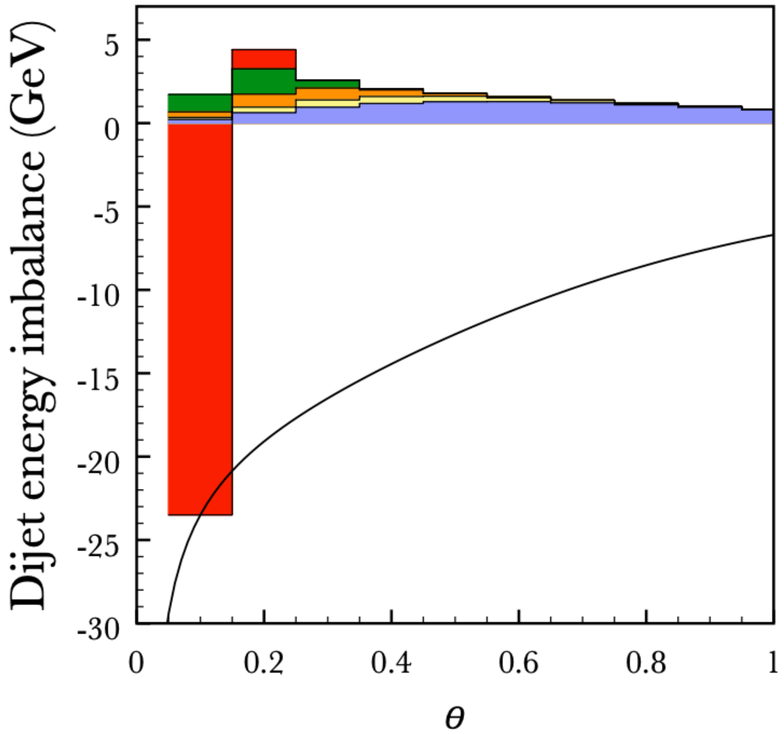
Turbulent cascade of soft quanta also extends rapidly to large angles.

→ Evidence of medium response not unambiguous.

Subleading jet

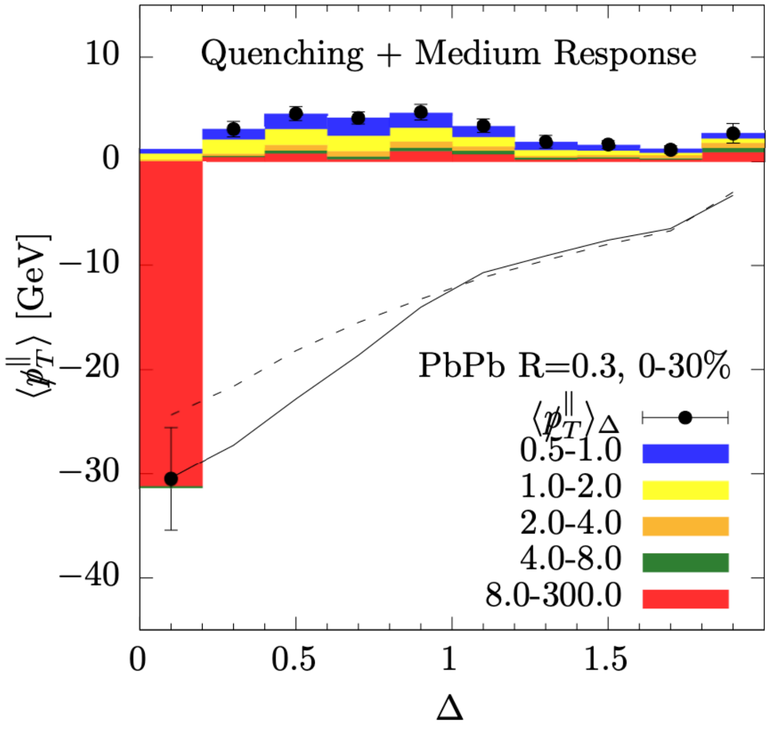


Leading jet




Medium-induced parton cascade

Blaizot & Mehtar-Tani - 1503.05958




Hydrodynamic wake

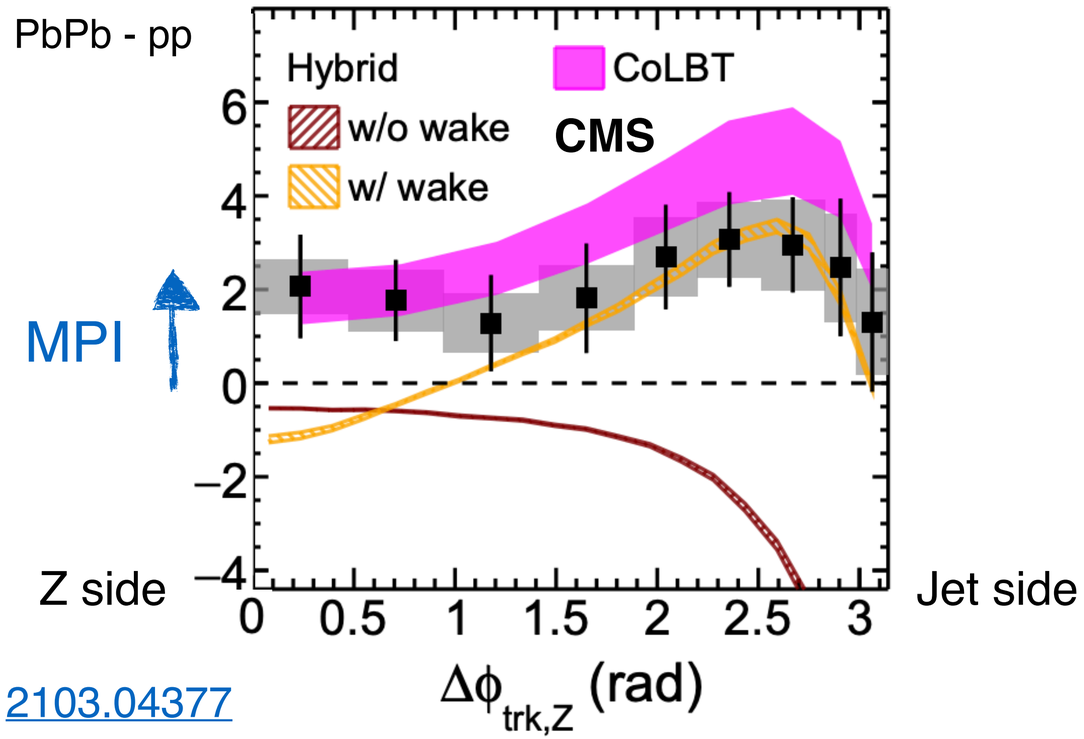
Casalderrey-Solana et al. - 1609.05842

# Looking for the Smoking Gun

What is truly unique about medium response, i.e. absent in other mechanisms, is the depletion in the direction opposite to the drag experienced by the fluid.

Look at **boson-jet** systems to avoid dealing with two wakes!

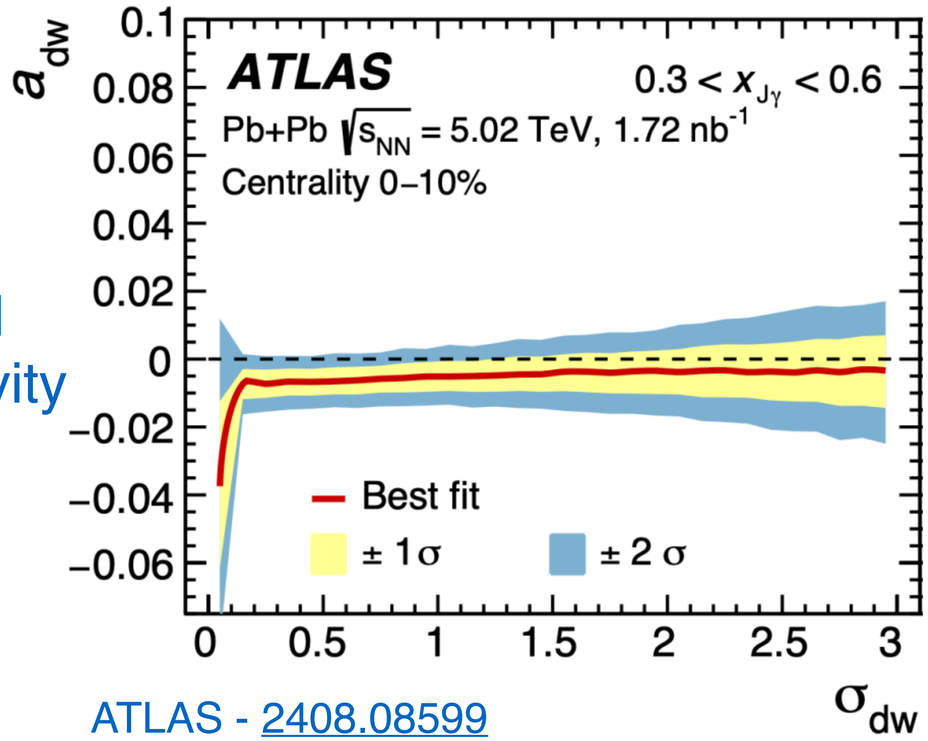
Searches have been ongoing:




CMS - 2103.04377

See Y. Go's talk

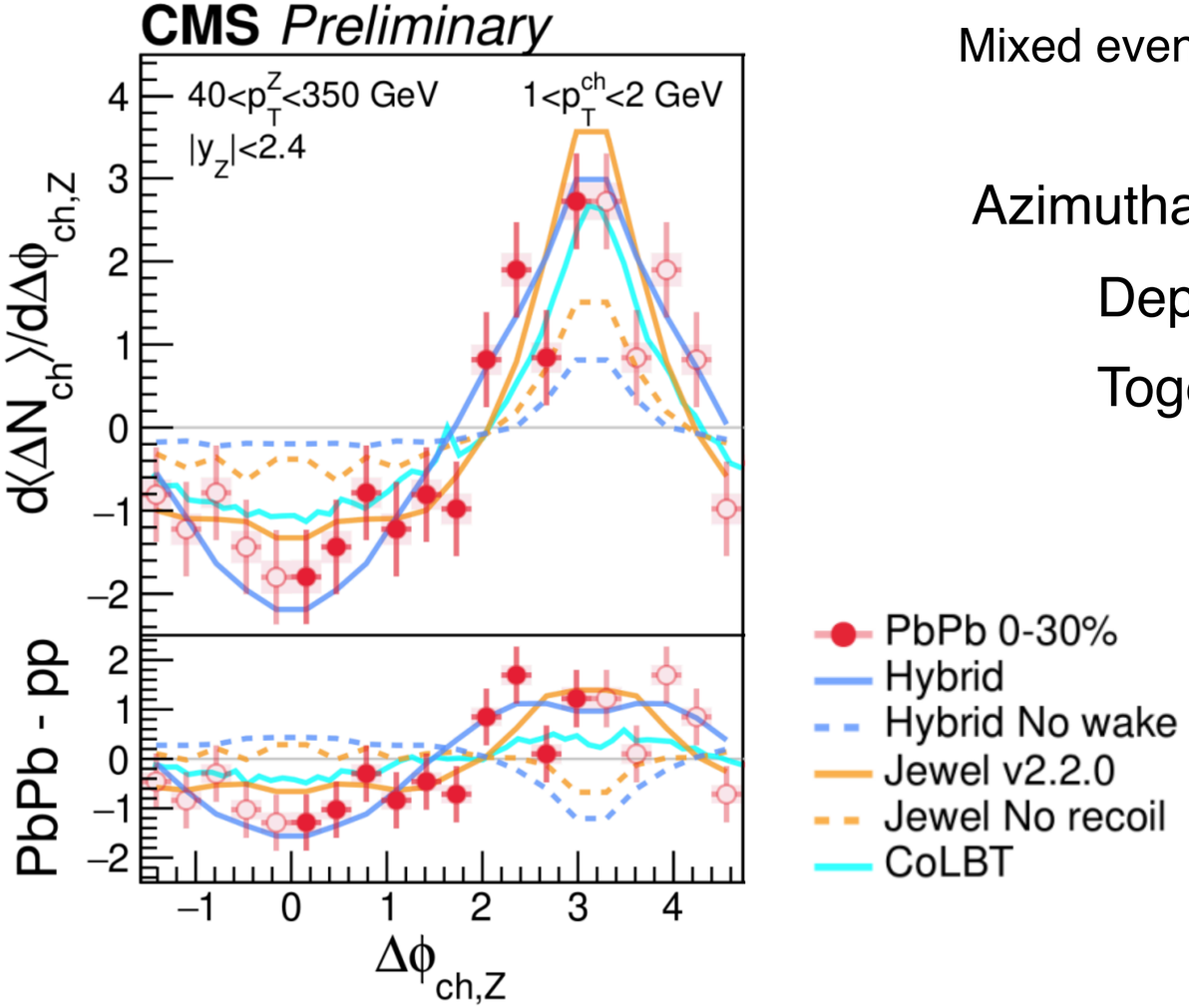
Limited sensitivity




ATLAS - 2408.08599

# Direct Evidence of Diffusion Wake

**New** at this conference: **first**, **unambiguous**, **evidence** of medium response of the QGP to the *jet* !!!




Mixed event background subtraction.

See Y.-J. Lee's talk

Azimuthal distance wrt Z boson.

Depletion around $\Delta\phi \sim 0$.

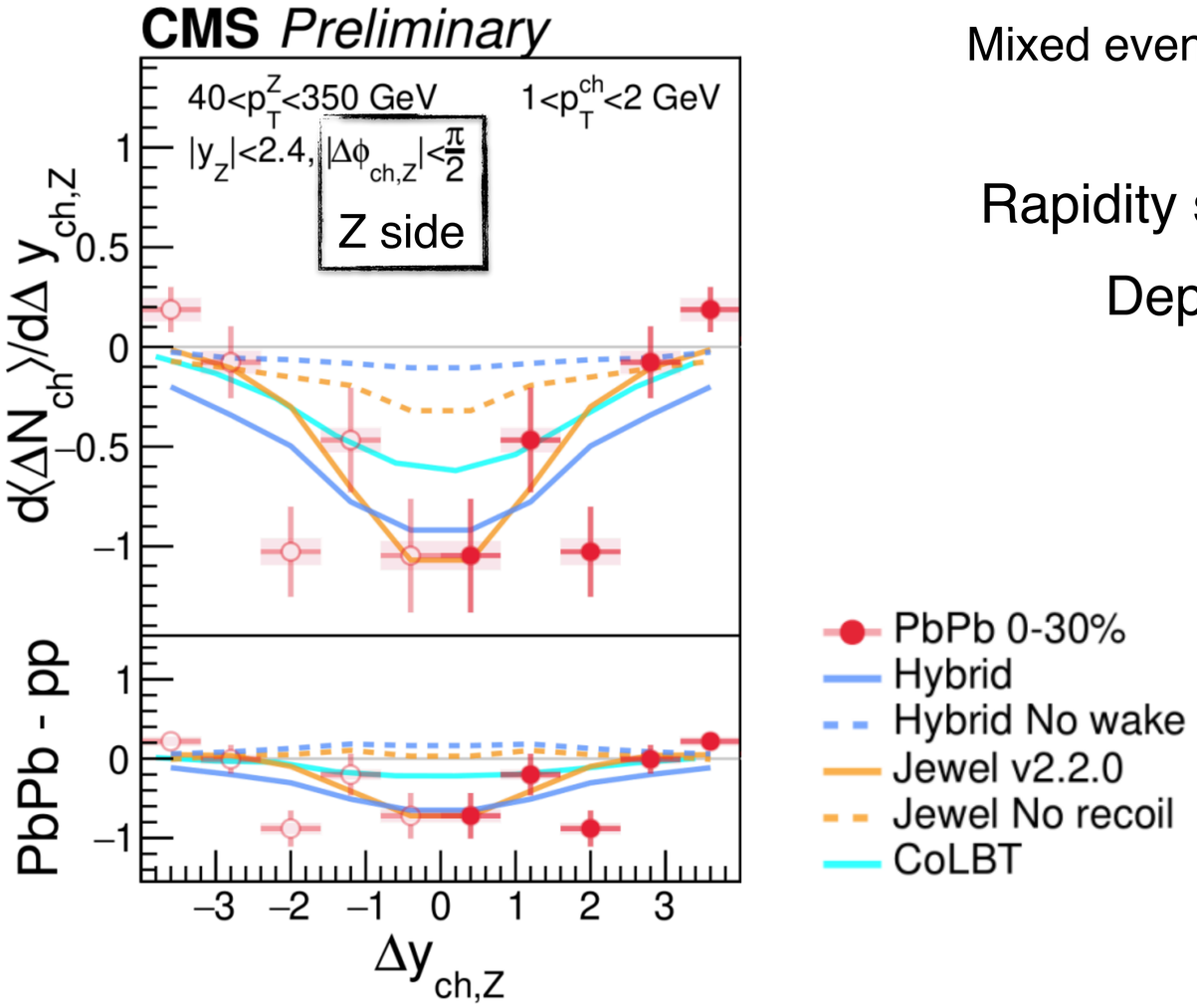
Together with excess at $\Delta\phi \sim \pi$.

Models without medium response fail.

Models with medium response have good agreement with data.

# Direct Evidence of Diffusion Wake

**New** at this conference: **first**, **unambiguous**, **evidence** of medium response of the QGP to the *jet* !!!




Mixed event background subtraction.

See Y.-J. Lee's talk

Rapidity separation wrt Z boson.

Depletion around $\Delta y \sim 0$ .

Models without medium response fail.

Models with medium response have good agreement with data.

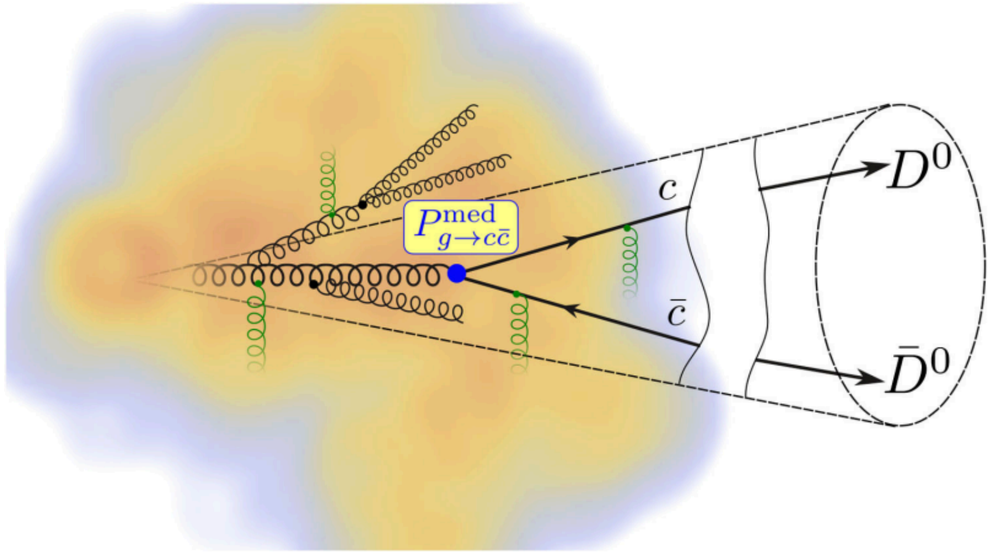
# Medium Induced Radiation

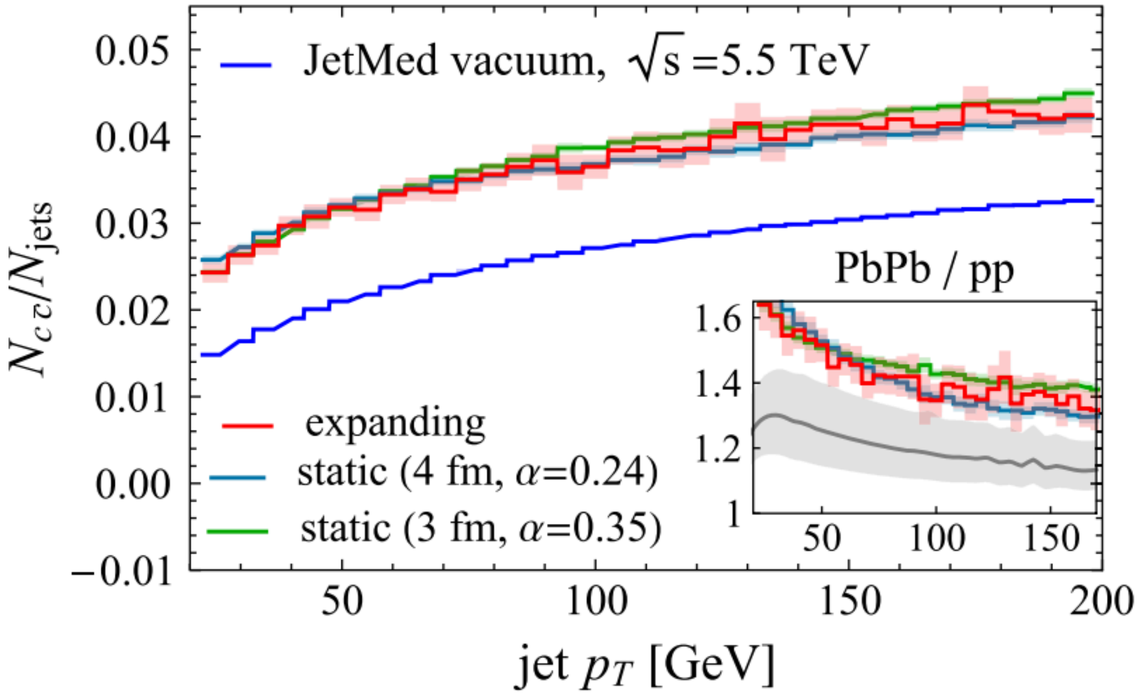
Genuine evidence of medium induced radiation is still lacking.

See U. Wiedemann's talk

Study of the medium-stimulated production of charm pairs within jets.

*Sizeable effect in realistic Monte Carlo can be measured with upcoming LHC data!*




Attems et al. - 2209.13600

# Conclusions & Outlook

The era of jet tomography has truly arrived.

→ Imprints of flowing QGP properties on jet radiation and broadening thanks to new calculations.

Interplay of vacuum and medium scales during jet evolution still in development.

→ Medium modification of early and not so early vacuum-like splittings.

→ Color coherence effects.

Milestone in jet quenching physics: direct evidence of the diffusion wake.

→ Medium response now of proven importance for phenomenology.

→ Can we consistently describe recoils & wake?

Need state-of-the-art implementations of medium induced radiation and medium response.

→ For a meaningful interpretation of observables.

→ To make robust statements about the nature of the QGP via jet quenching.


Thanks!


# Acknowledgements


*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement n. 101155036.*