Monte Carlo modeling of jets

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LIP

TÉCNICO LISBOA

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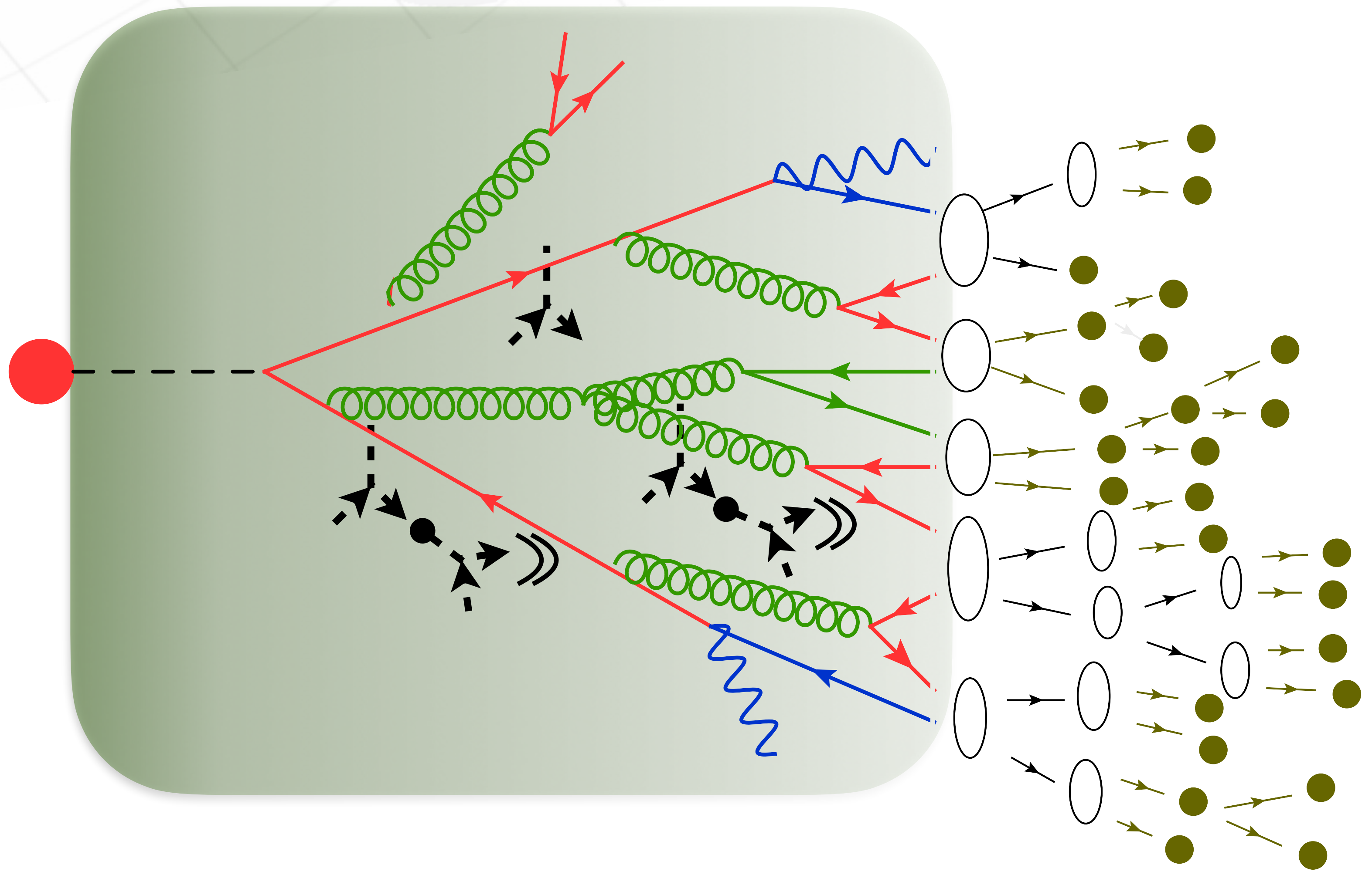
Hard Probes 2023, Aschaffenburg, Germany

Jets in Heavy-Ion Collisions

Analytical results

Several developments over the last years

[see C. Andrés' talk (today)]



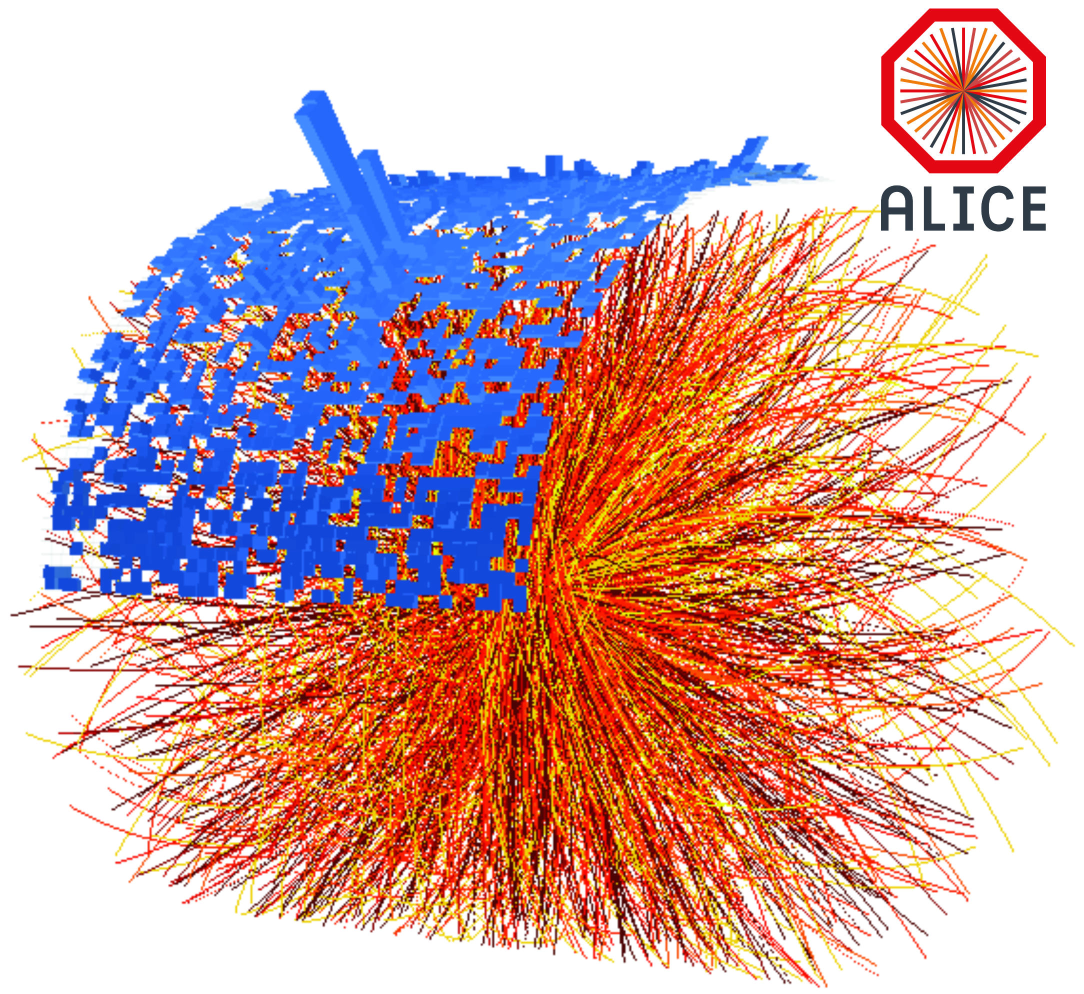
Direct comparison

possible

Experiment

More background-free observables

[see LHC/RHIC talks (today)]



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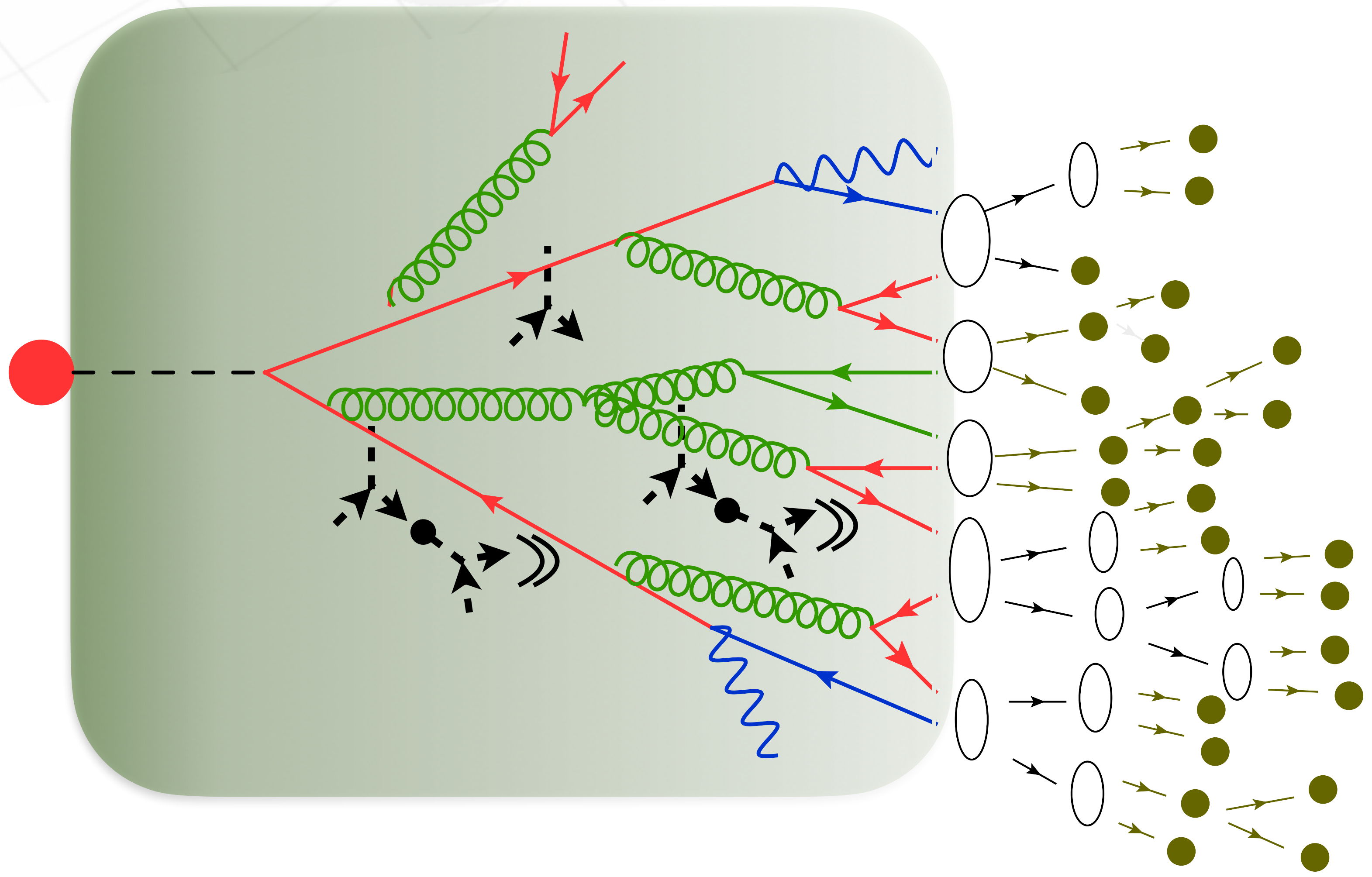

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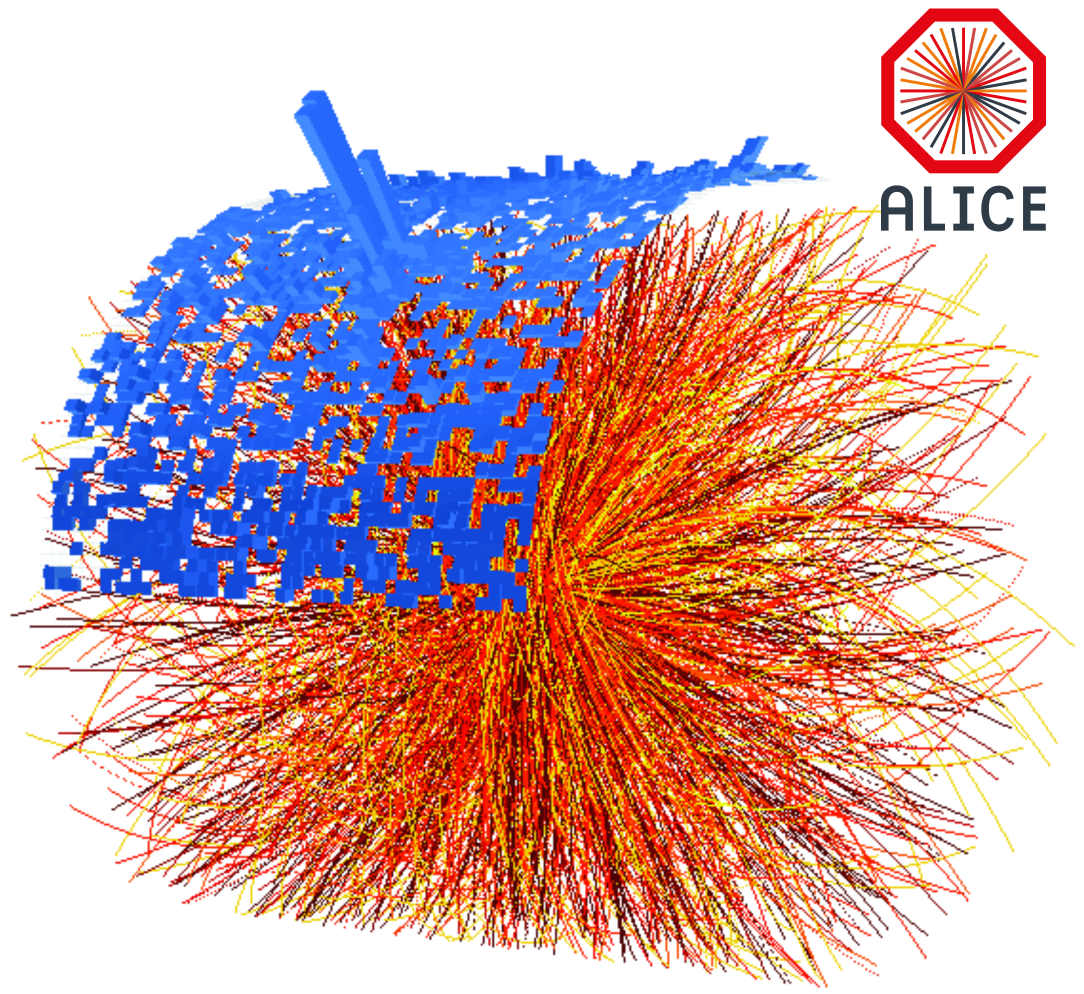

Why do we need Monte Carlo event generators?

Analytic vs MC approaches

Analytical approaches

Based on first principle calculations that address elementary jet processes

Analytic vs MC approaches

Analytical approaches

Based on first principle calculations that address elementary jet processes

✓ Improvements beyond:
- static medium
- limited kinematic approximations
- …

⚠ Limited understanding for:
- lower momentum scales
- interplay between “vacuum” and “medium”-induced shower

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Monte Carlo approaches

Can consider the full jet shower evolution and evolving medium

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Monte Carlo approaches

Can consider the full jet shower evolution and evolving medium

✓ Rely on analytical results

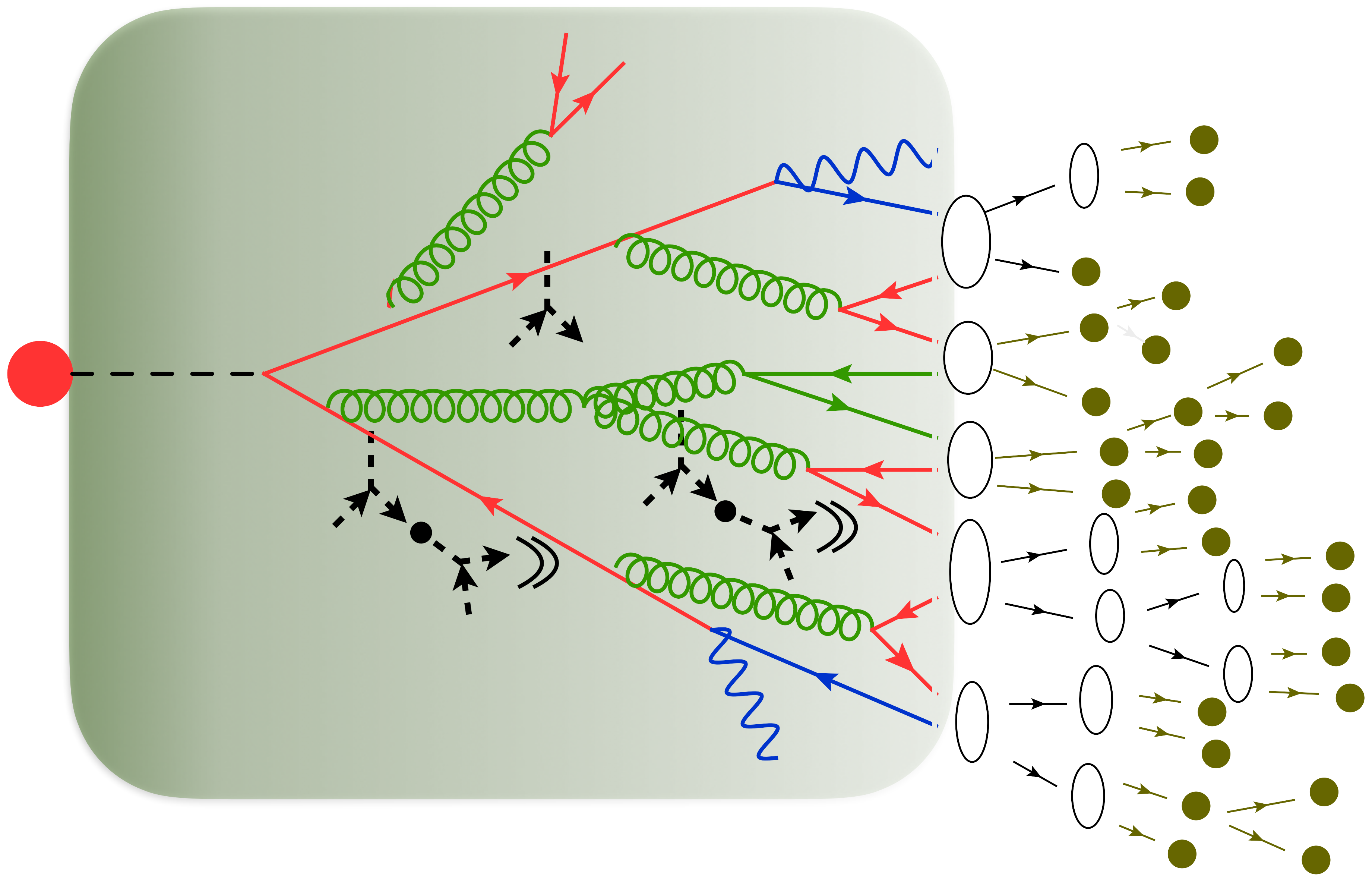
⚠ … But lacking most recent analytical developments

⚠ ✓ Require further modelling beyond analytically-controlled phase-space regions

What is a jet quenching Monte Carlo?

Jet quenching Monte Carlo models

- N-particle system originated through a parton shower
  - Vacuum radiation
  - Medium-induced effects
    - Medium-induced radiation
    - Jet-induced medium response
    - Medium response re-scattering



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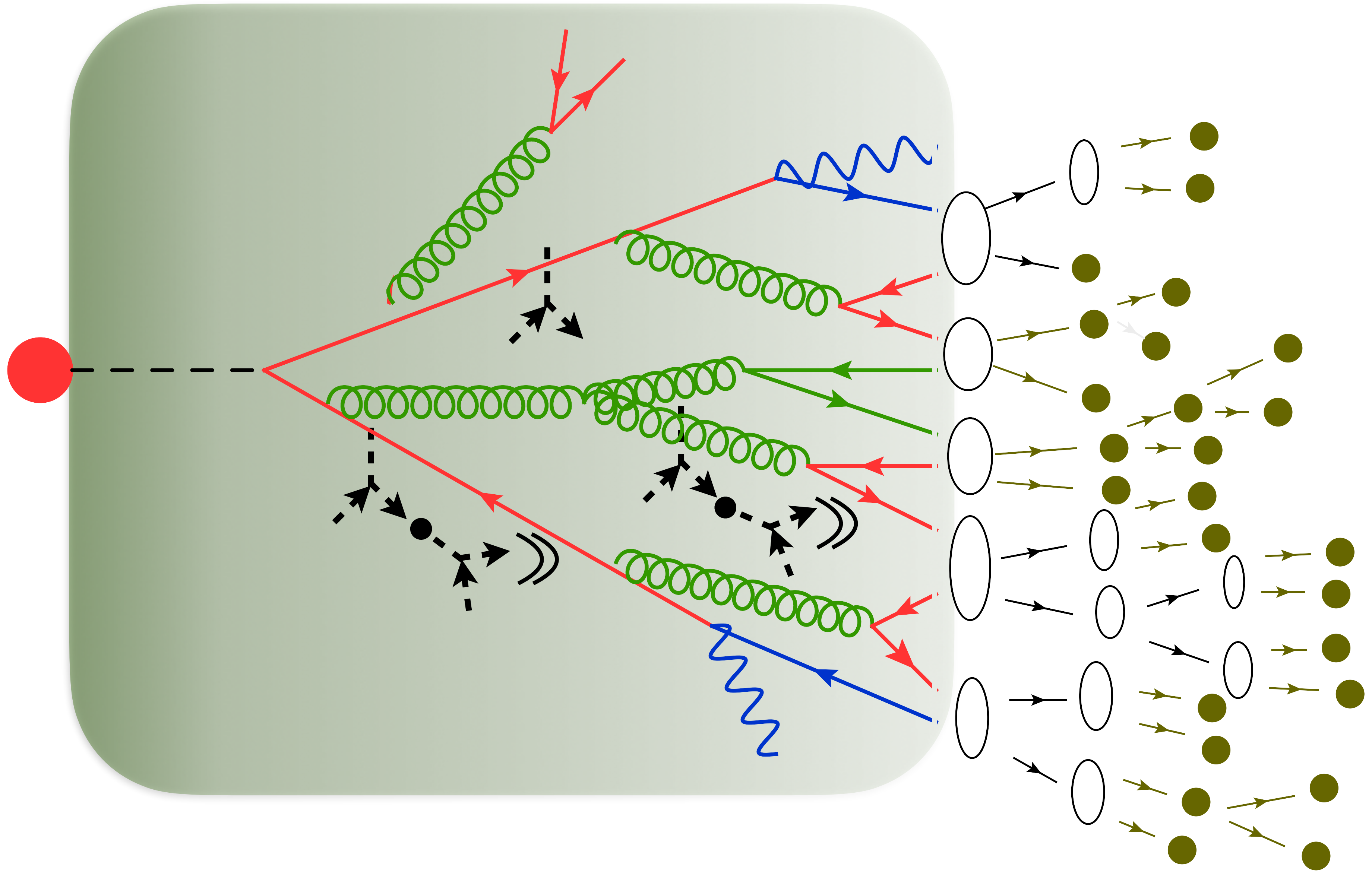

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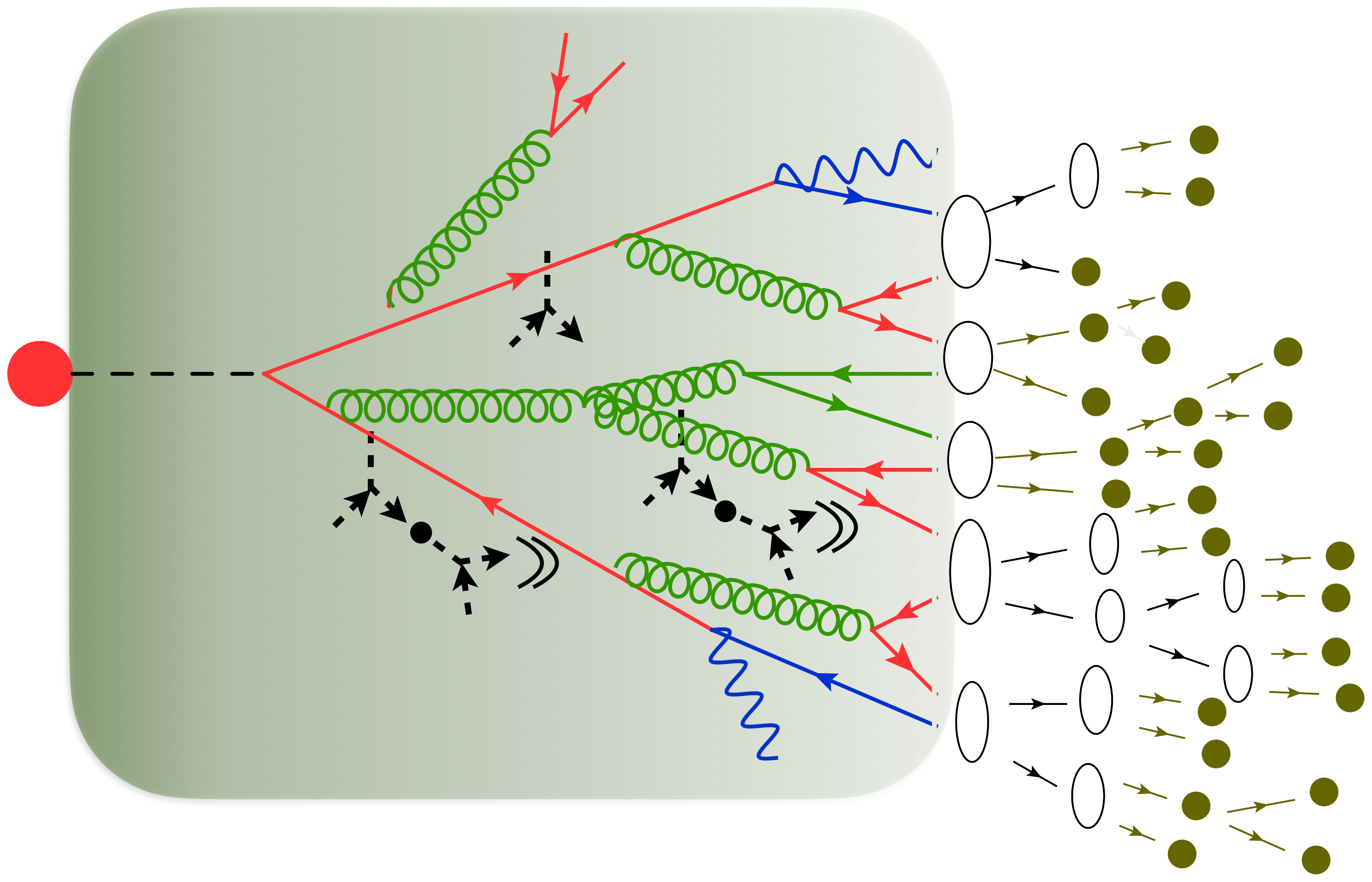
Evolving medium

Hadronization



Medium-modified jet in all momentum scales?

Jet quenching Monte Carlo models

- Two different approaches:

Change in the jet evolution:

Modifications on a developed shower

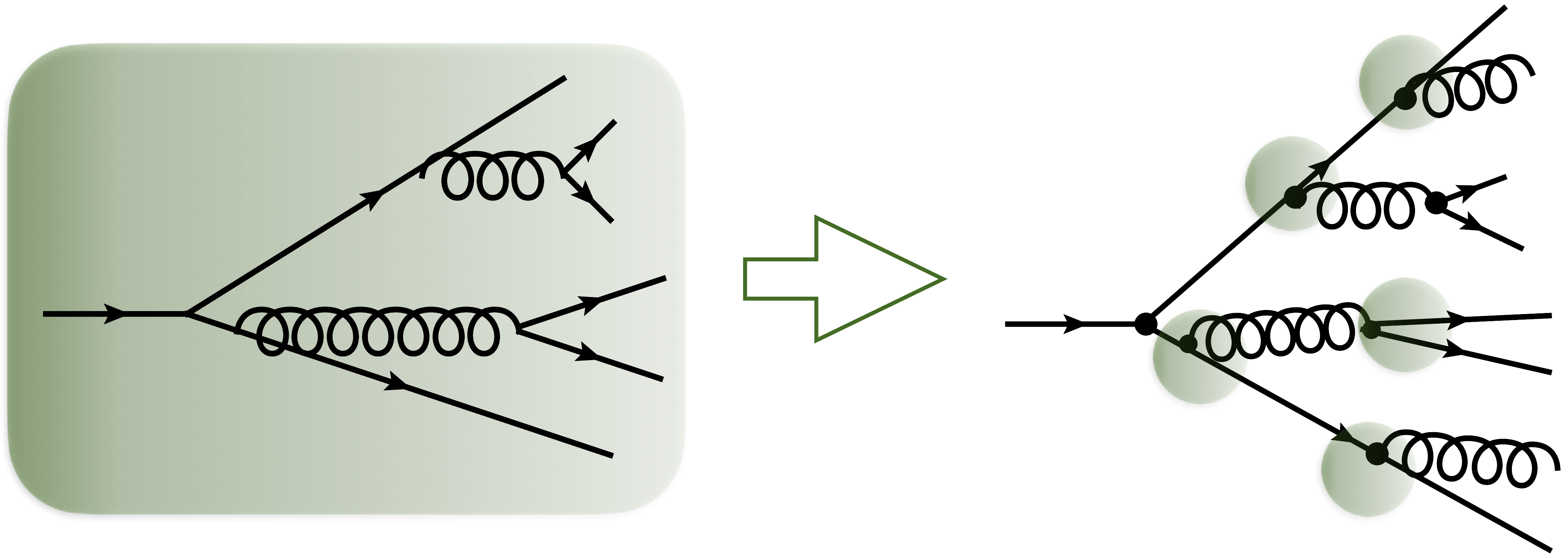
Jet quenching Monte Carlo models

- Two different approaches:

Change in the jet evolution:

Medium-induced modifications can take place throughout the parton evolution

Medium-modifications at all momentum scales



E.g: JETSCAPE, JEWEL, MATTER, Q-PYTHIA,…

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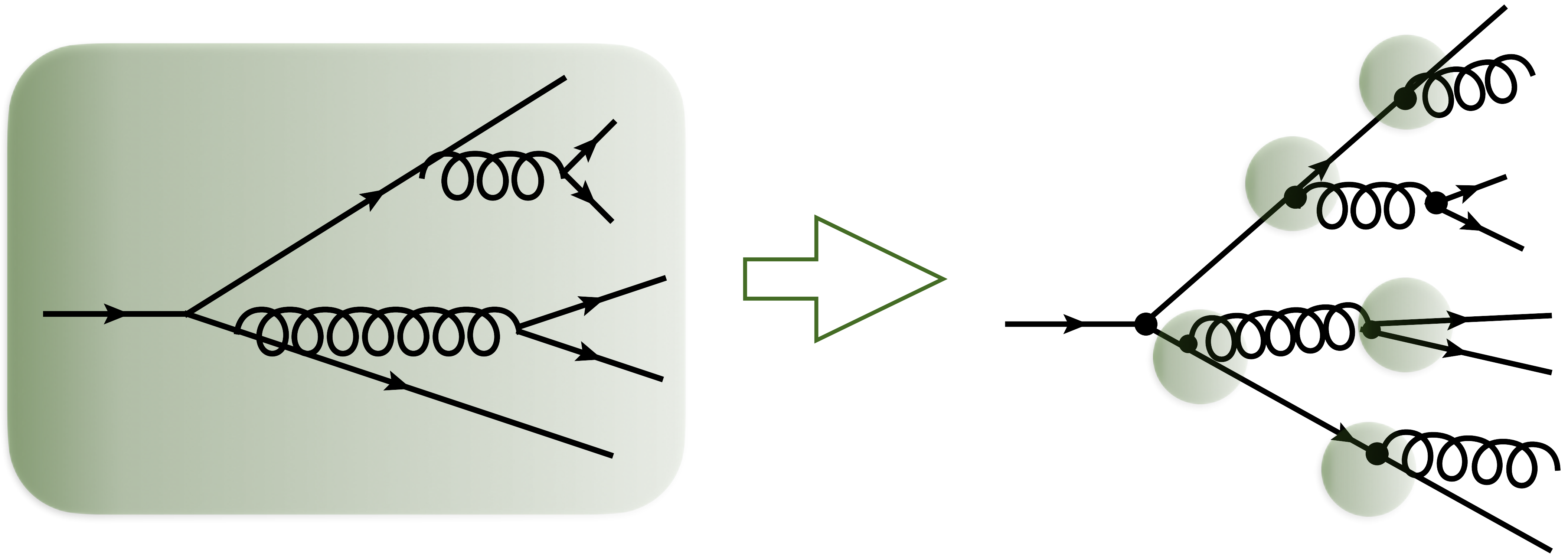
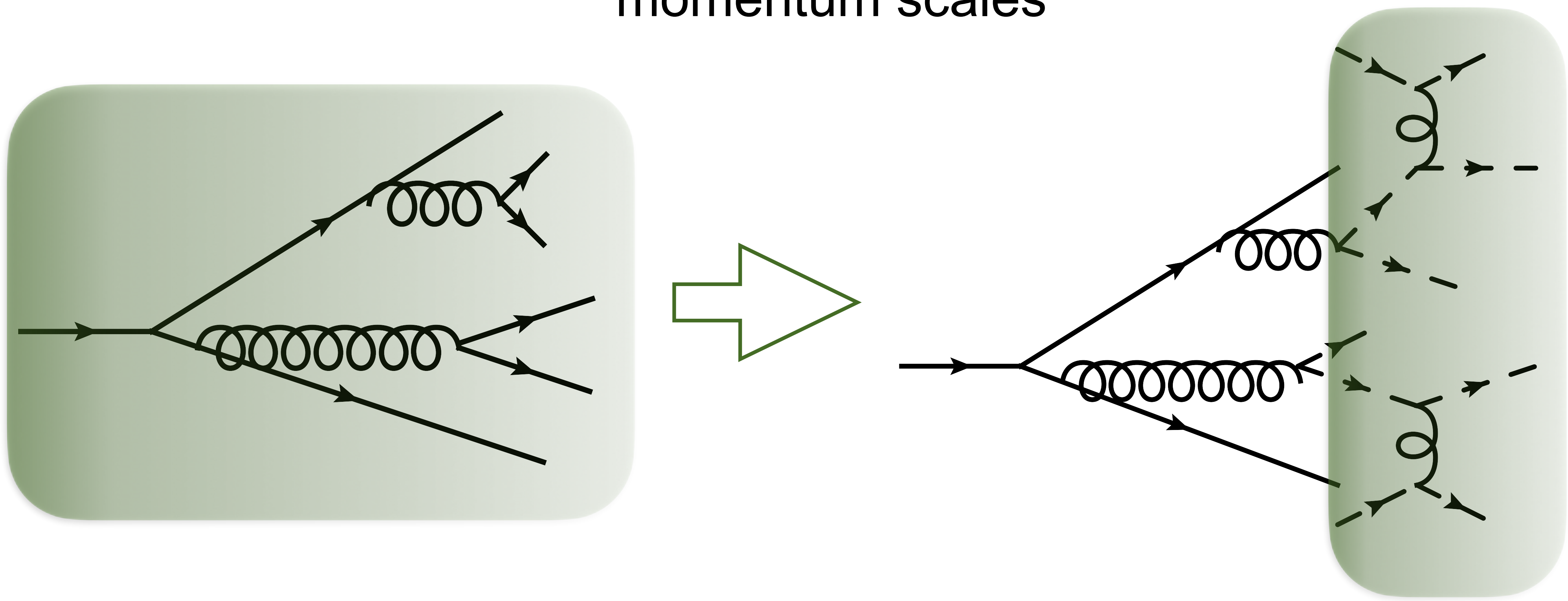


E.g: JETSCAPE, JEWEL, MATTER, Q-PYTHIA,…

Modifications on a developed shower

Vacuum (hard and collinear) parton structure unmodified

Medium-modifications dominate low momentum scales



E.g:(Co-)LBT, Hybrid, MARTINI, PyQUEN..

Jet quenching Monte Carlo models

- Comparison between the two:

Change in the jet evolution:

Choose (or develop) a given vacuum parton shower
(Fixed to the ordering variable and parton shower accuracy)

Modifications on a developed shower

Minimal changes to the vacuum parton shower
(Easier to develop alongside vacuum physics)

Jet quenching Monte Carlo models

- Comparison between the two:

Change in the jet evolution:

Choose (or develop) a given vacuum parton shower
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Medium-induced effects from in-medium radiation spectrum (inheriting kinematical restrictions)

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Medium-induced effects from transport equations (inheriting kinematical restrictions)

Jet quenching Monte Carlo models

- Comparison between the two:

Change in the jet evolution:	Modifications on a developed shower
Choose (or develop) a given vacuum parton shower (Fixed to the ordering variable and parton shower accuracy)	Minimal changes to the vacuum parton shower (Easier to develop alongside vacuum physics)
Medium-induced effects from in-medium radiation spectrum (inheriting kinematical restrictions)	Medium-induced effects from transport equations (inheriting kinematical restrictions)
Modifications done in momentum scales relatively above the non-perturbative region	Modifications in the low-momentum particle distribution (close to non-perturbative region)

Jet quenching Monte Carlo models

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Choose (or develop) a given vacuum parton shower (Fixed to the ordering variable and parton shower accuracy)	Minimal changes to the vacuum parton shower (Easier to develop alongside vacuum physics)
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Modifications done in momentum scales relatively above the non-perturbative region	Modifications in the low-momentum particle distribution (close to non-perturbative region)

No “correct” answer… All with their pros and cons…

Jet quenching Monte Carlo models

- Comparison between the two:

Change in the jet evolution:

Choose (or develop) a given vacuum parton shower (Fixed to the ordering variable and parton shower accuracy)

Interplay between vacuum and medium shower

Modifications on a developed shower

Modifications in the low-momentum particle distribution (close to non-perturbative region)

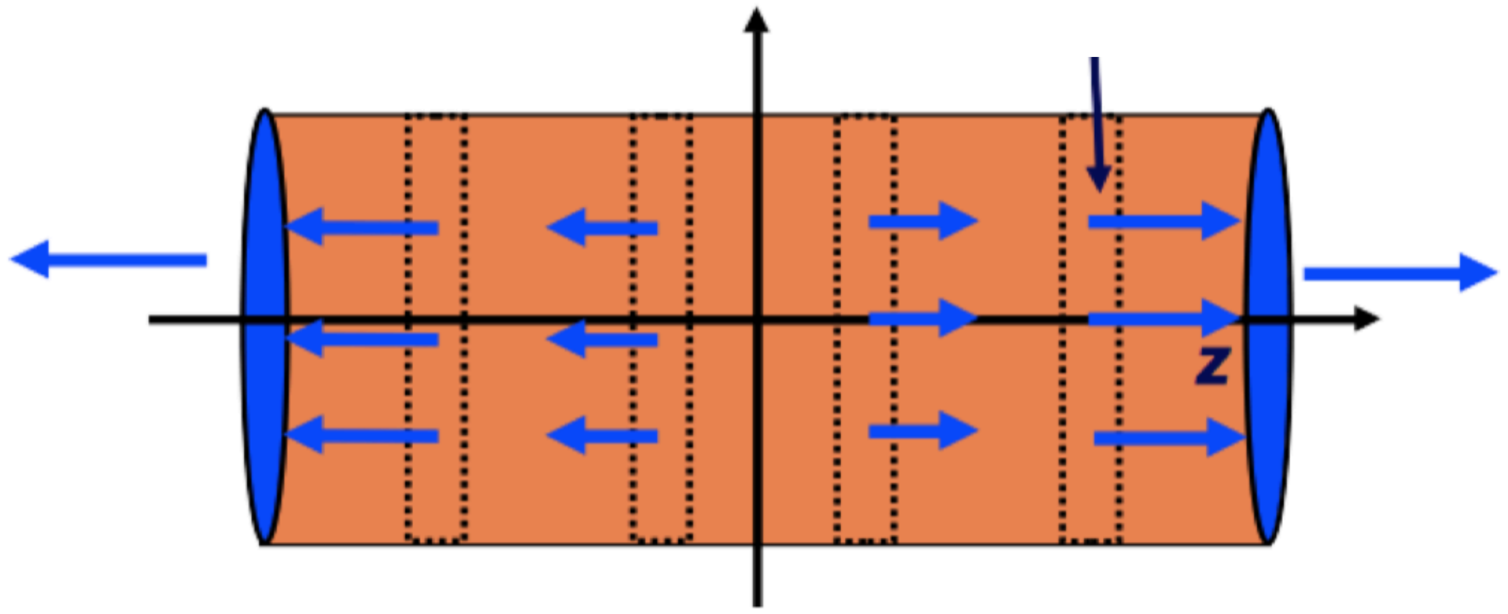
QCD processes at lower momentum scales

Medium Evolution modelling

- Medium evolution model

Bjorken 1D expansion

[Bjorken (1983)]



$$T = T_0 \left(\frac{\tau_0}{\tau}\right)^{v_s^2}$$

Longitudinal (1D) expansion
(Energy density characterised by a power-law evolution)

Medium Evolution modelling

- Medium evolution model

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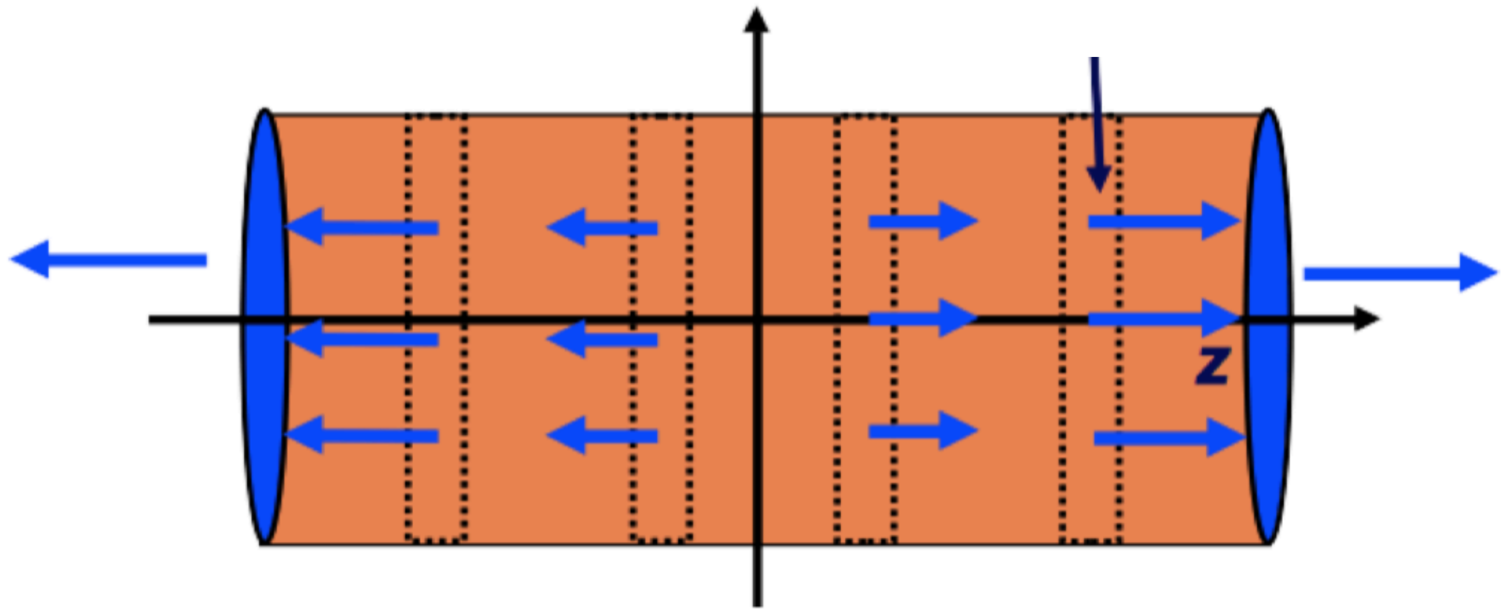

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Longitudinal (1D) expansion
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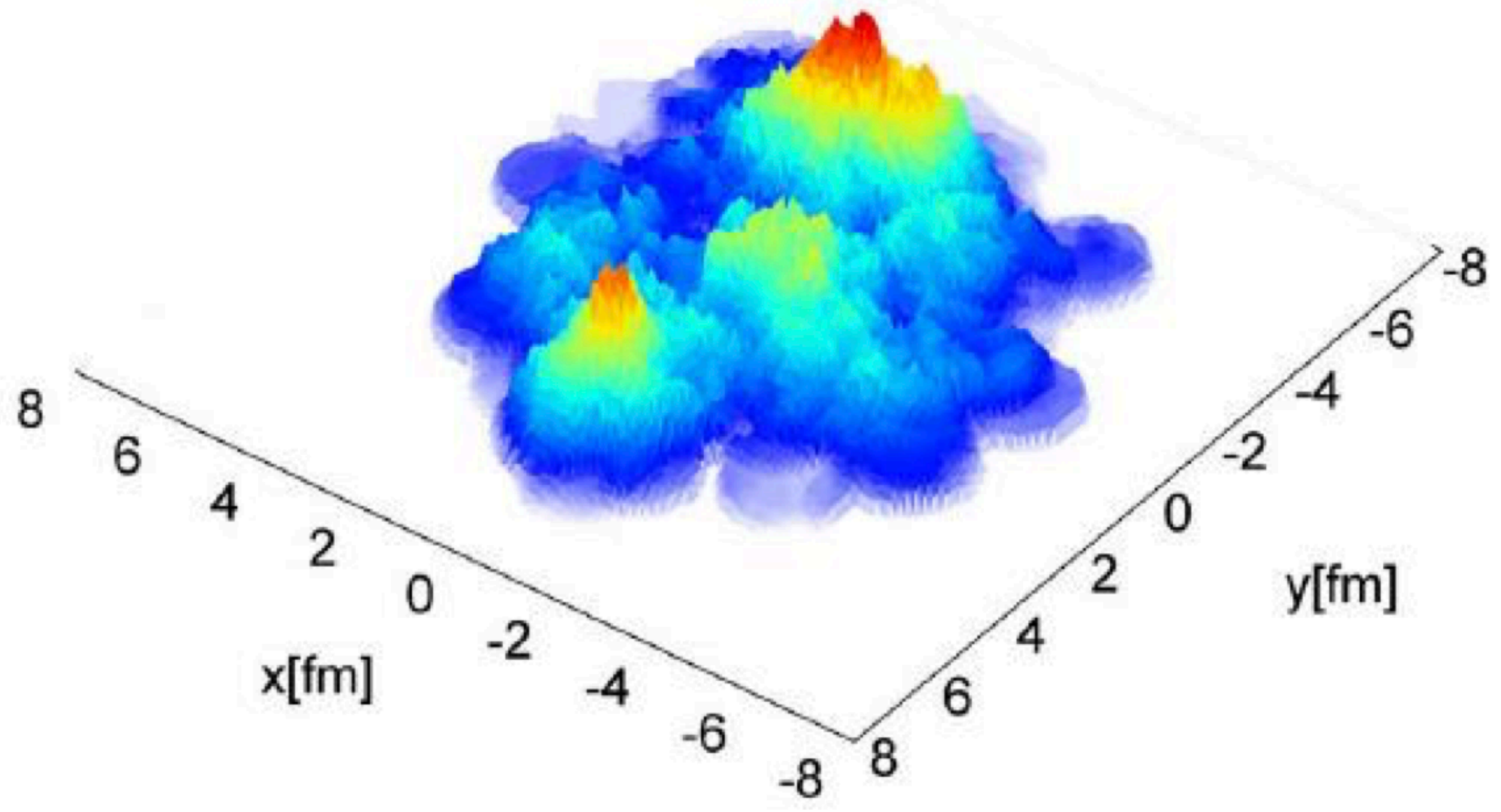
Event-by-event non-ideal hydrodynamics

[Molner et al(1407.8152), Shen et al (1409.8164),…]



$$\partial_\mu T^{\mu\nu} = j^\nu$$

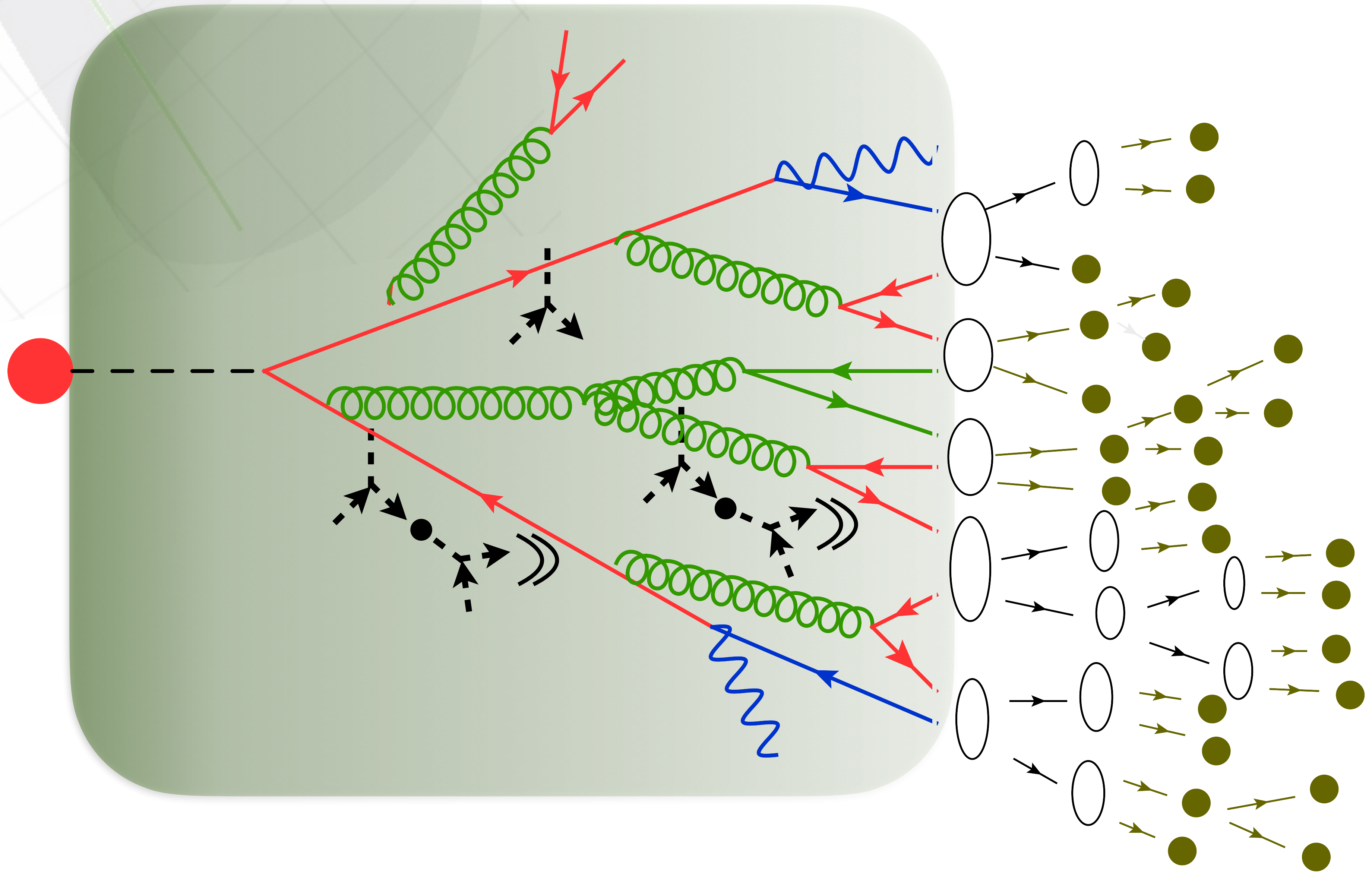
3D expansion
(Energy density characterised by relativistic hydrodynamic evolution)

Medium Evolution modelling

[see K. Boguslavski' talk (today)]

[Andrés, et al (1902.03231), Stojku et al (2008.08987), JETSCAPE (2102.11337), Adhya et al (2211.15803)]

- Uncertainty driven by the onset of medium-jet interactions…



See also: D. Avramescu (Tue), M. Gonzalez (Wed)

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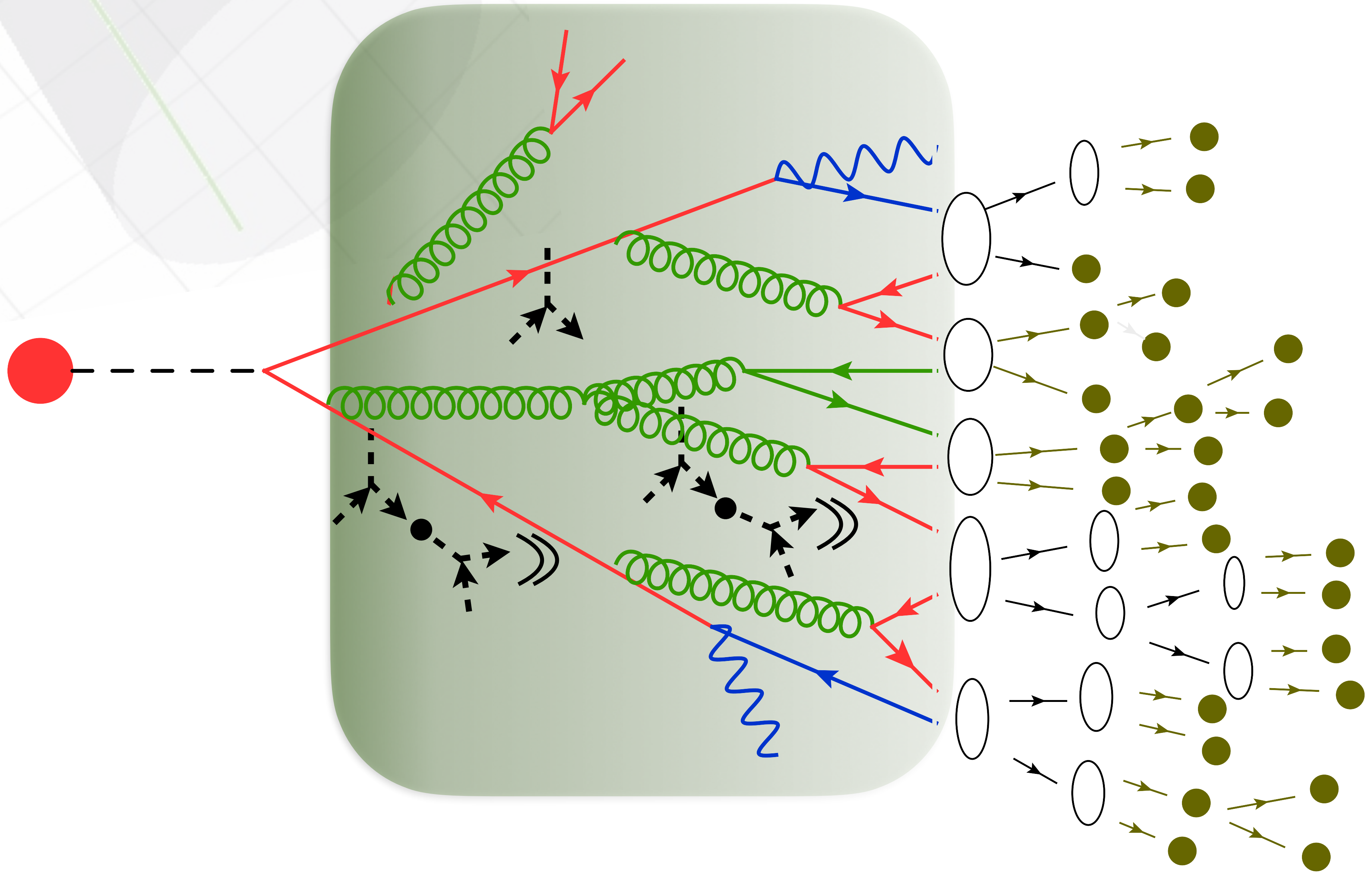
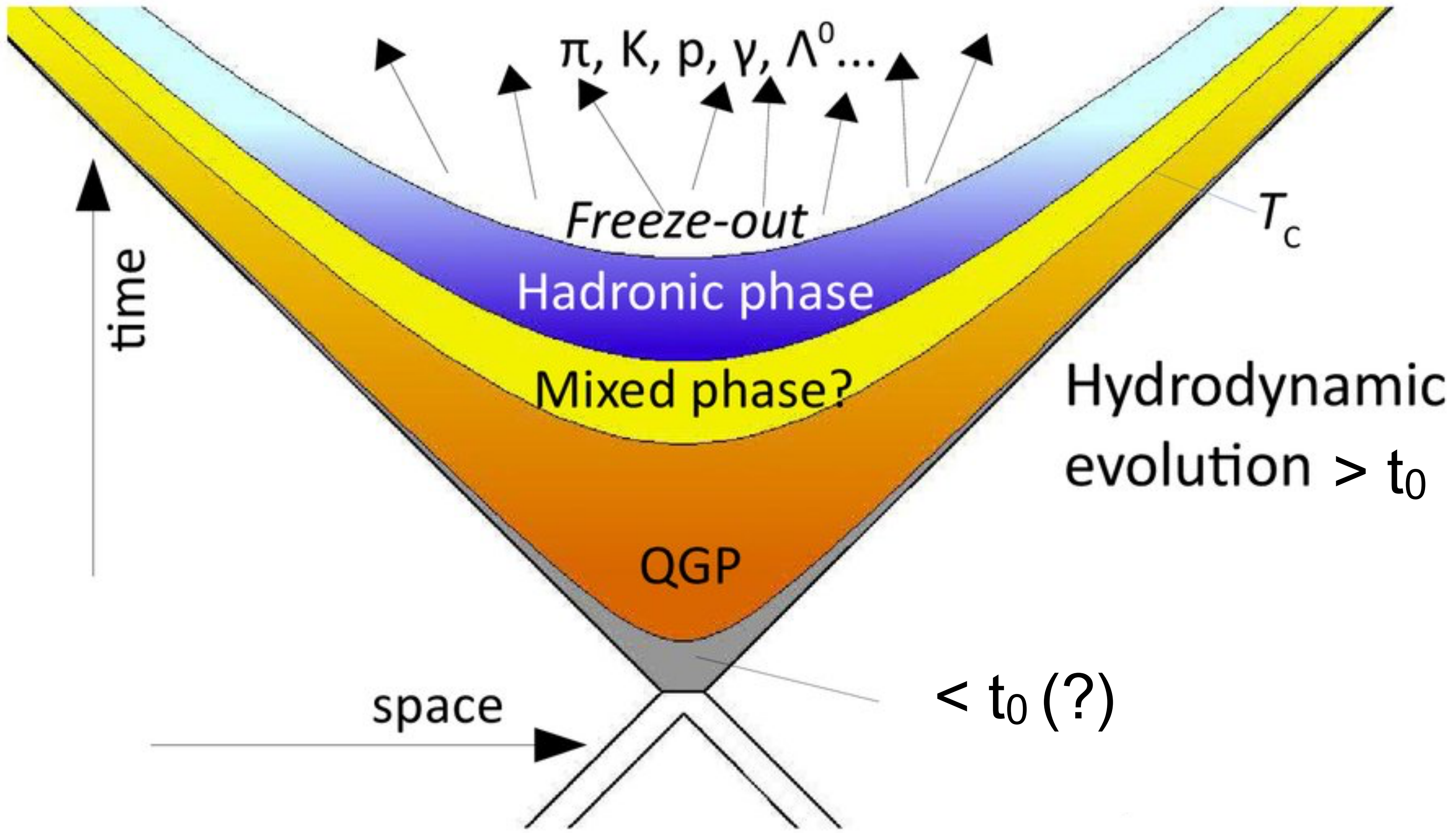




Jet-medium interactions start at t_0? What happens before?

See also: L. Campos, J. Casalderrey-Solana, M. Djordjevic, E. Iancu, Y. He, R. Modarresi-Yazdi (Tue), W. Qian (Wed), C. Parker (Thu)

State-of-the-art models

- Several jet quenching Monte Carlo models: See references in the backup slides

Q-PYTHIA

PYQUEN

Jetmed(Saclay)

JEWEL

Co-LBT

DREENA-A

MARTINI

MATTER

CUJET

JETSCAPE

Hybrid strong/weak coupling

LBT

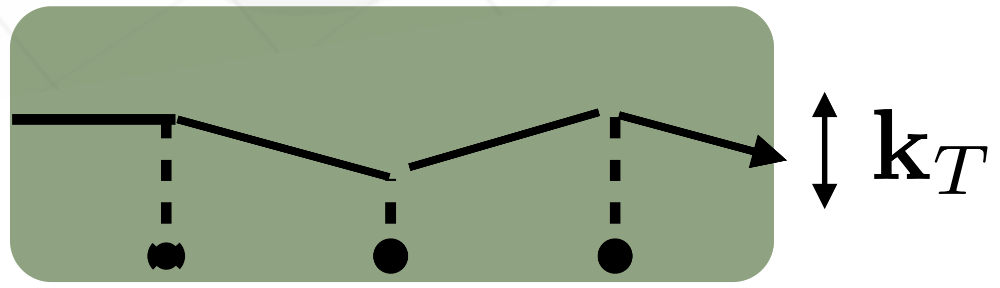
...

The successes of Monte Carlo approaches

From the jet to the medium

- Medium-induced radiation and momentum broadening closely connected (multiple soft-scattering approximation)

  - Accumulation of momenta enhances gluon radiation and partons undergo transverse momentum broadening



Transport coefficient:

$$\hat{q} = \frac{\langle k_T \rangle}{\lambda}$$

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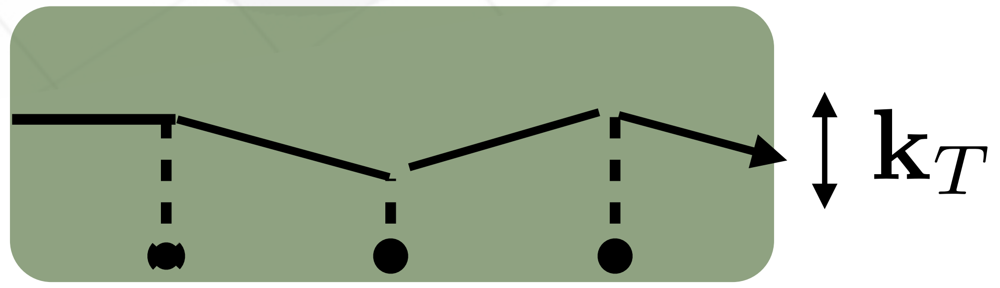

Dipole cross-section (collision rate):

$$\sigma(\boldsymbol{r}) = \int_{\boldsymbol{q}} V(\boldsymbol{q}) \left(1 - e^{i\boldsymbol{q}\boldsymbol{r}}\right)$$

Transport coefficient:

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$$\hat{q} \propto \int d^2\mathbf{q}^2 q^2 \frac{d\sigma(\mathbf{q})}{d^2\mathbf{q}}$$

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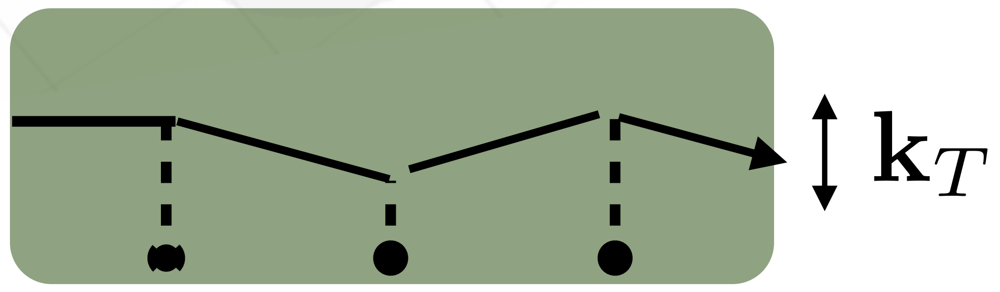

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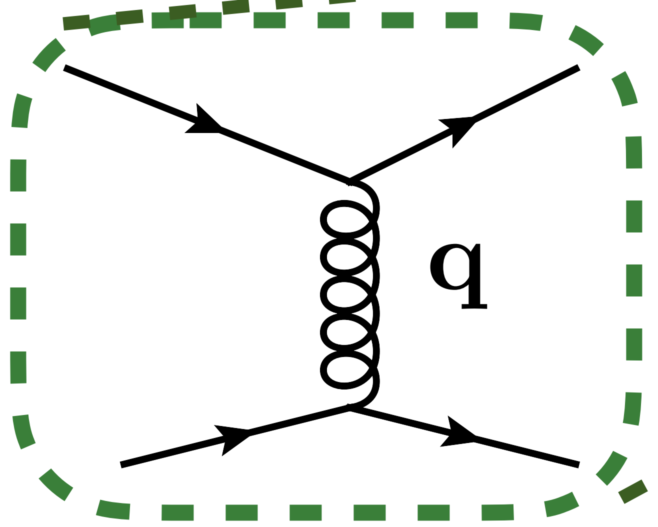


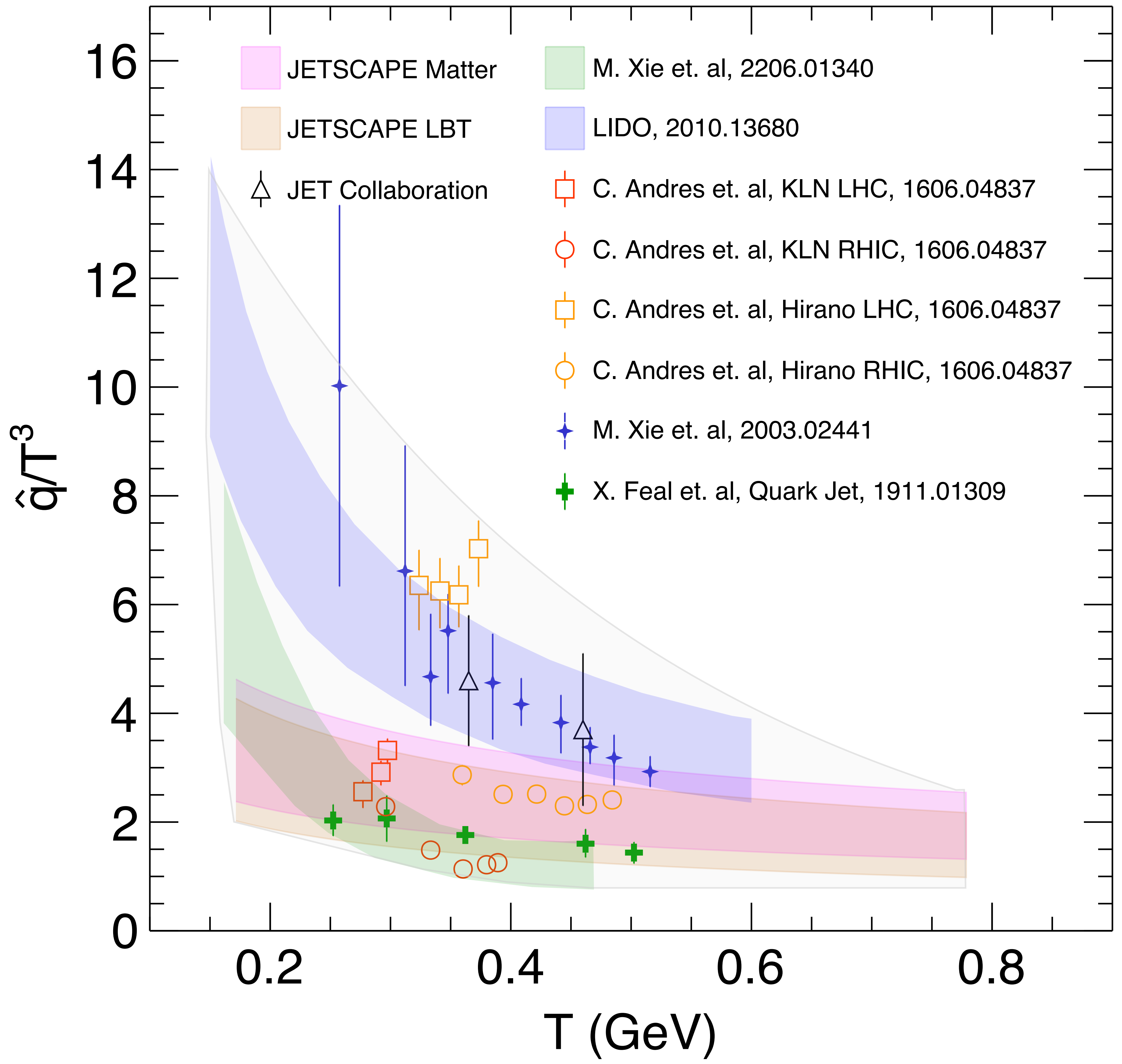
Parton-medium interaction

Medium transport coefficients

JETSCAPE & Analytics

- From single-particle or jet suppression recover $\hat{q}$

[LA, Y-J Lee, M. Winn (2203.16352)]



See also: I. Grishmanovski, M. Tie, J. Weber, M. Xie (Tue) S. Bass (Eed)

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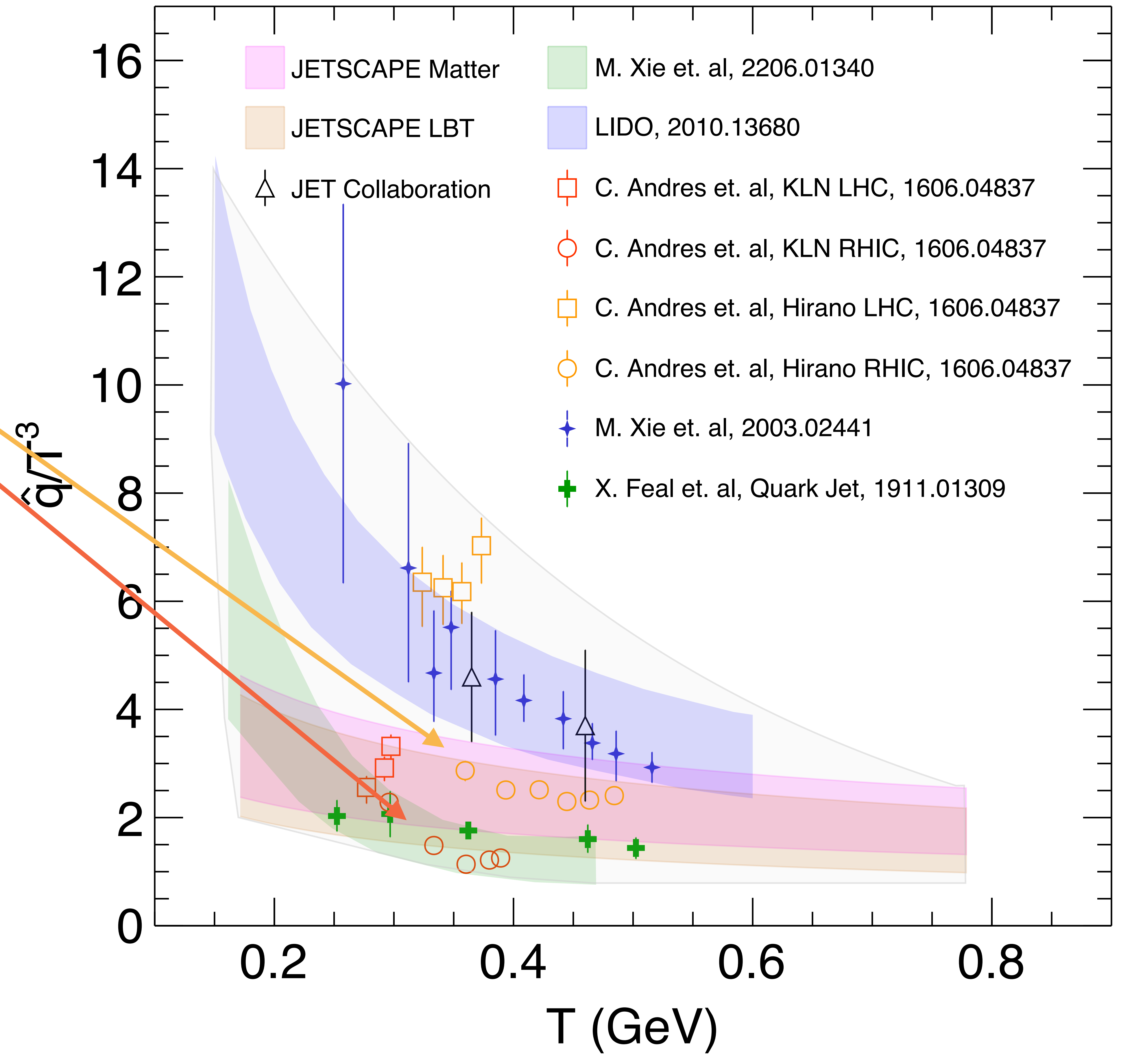

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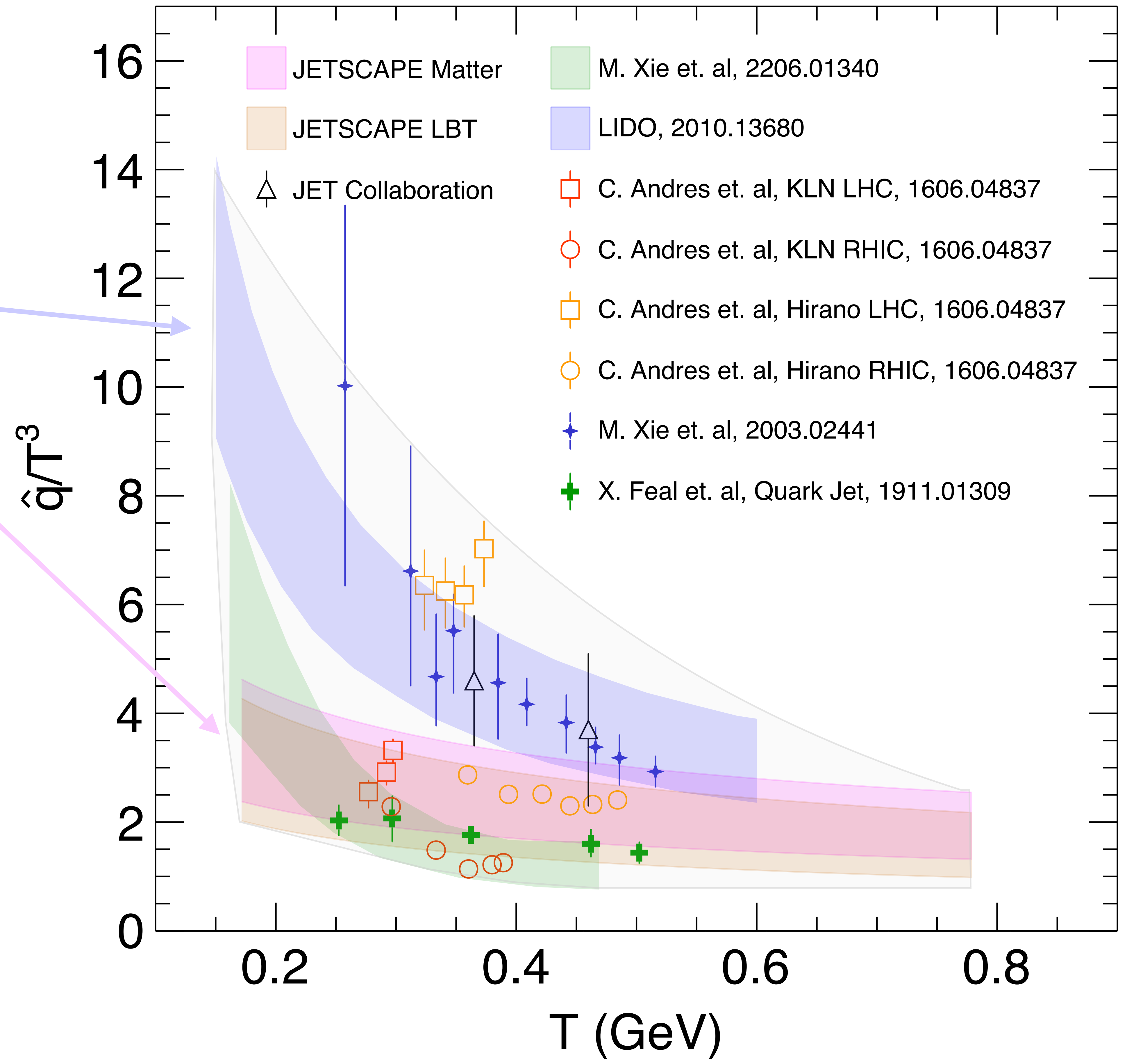

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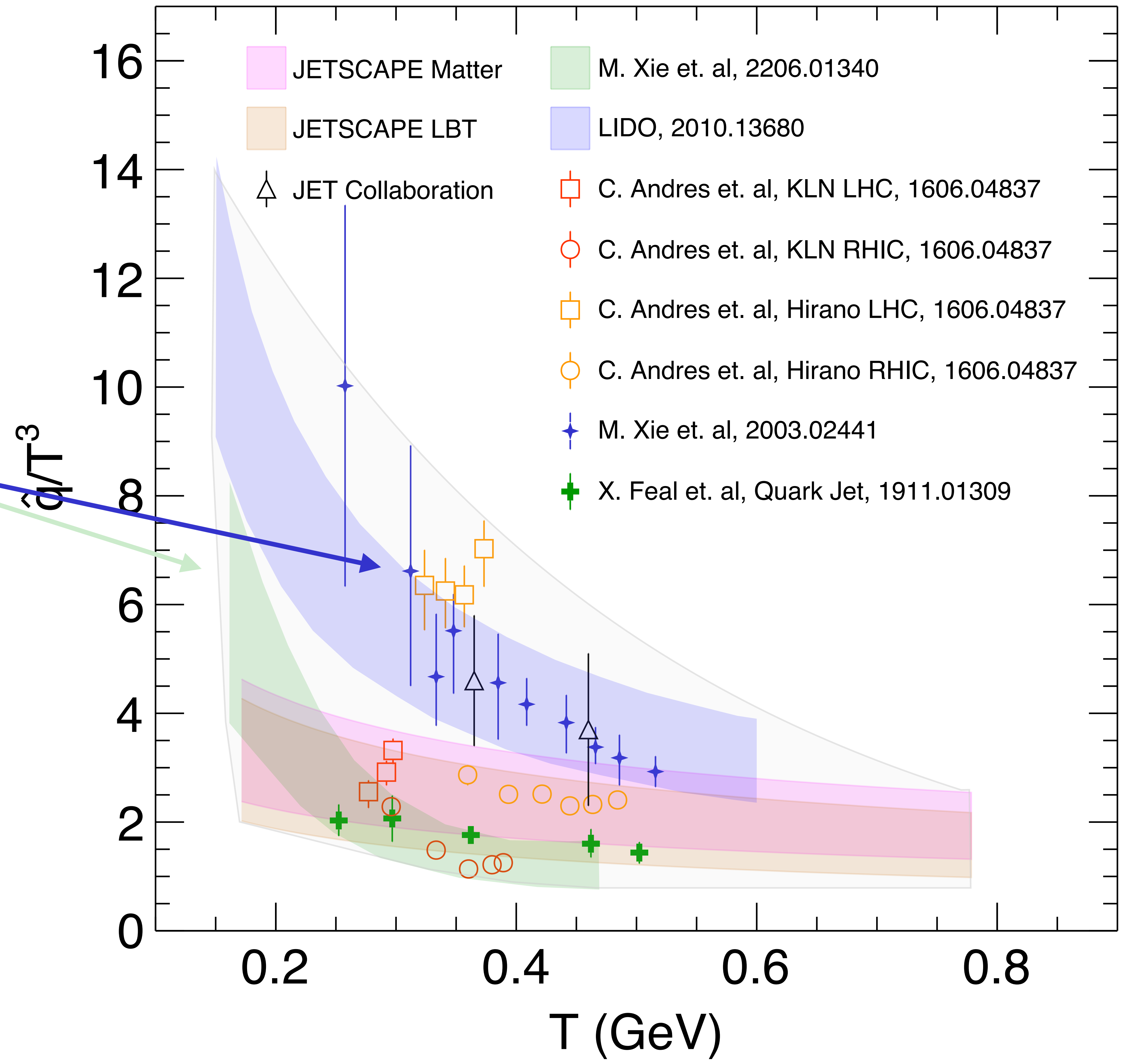

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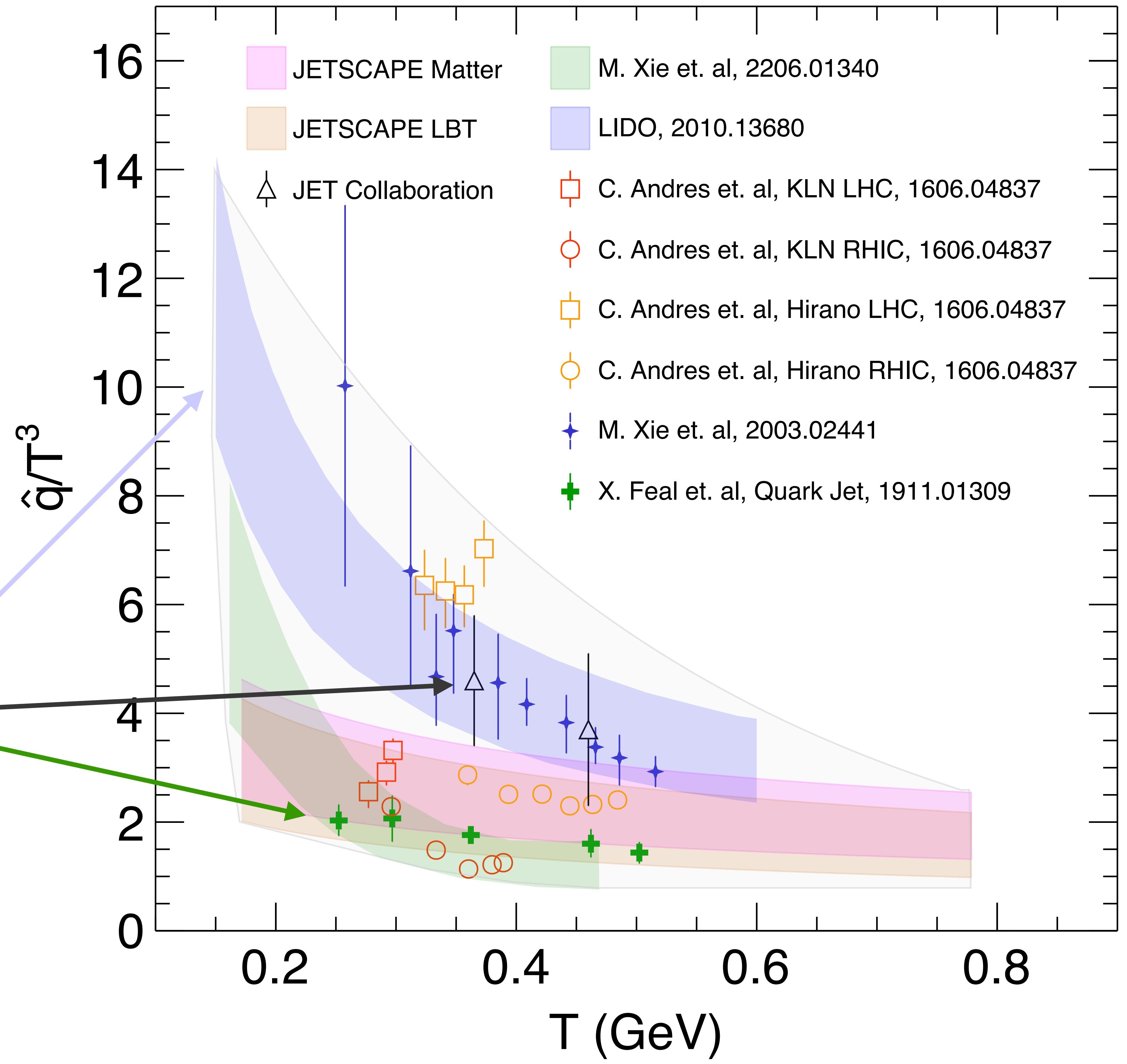
Include different data sets
(boson-hadron correlations dominated by quark, inclusive particle spectra contains a mixture of the two)

Hadron vs Jet measurements
(model-dependent description of medium response on jets)



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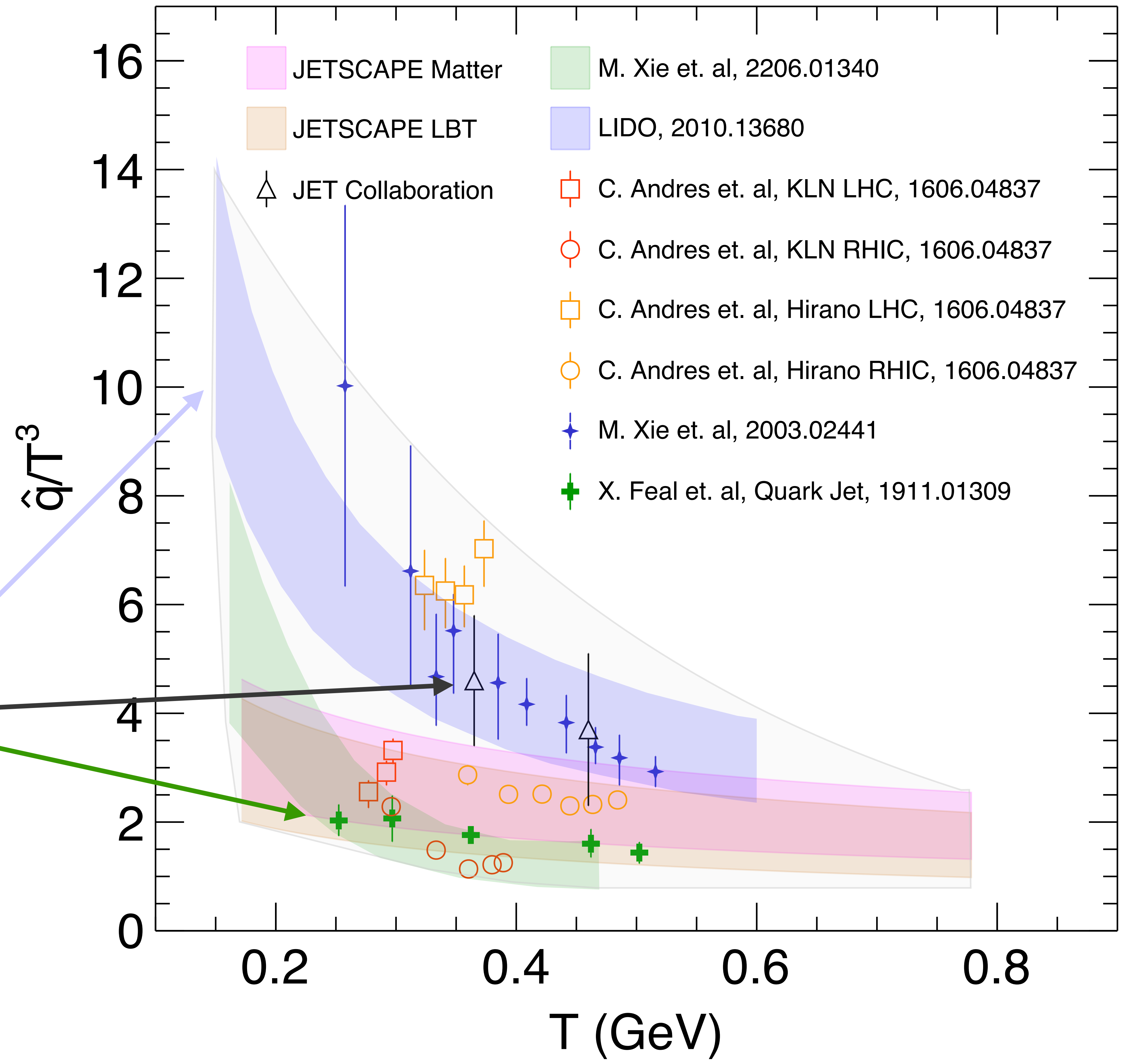


Towards quantitative assessment of QGP characteristics using hard probes

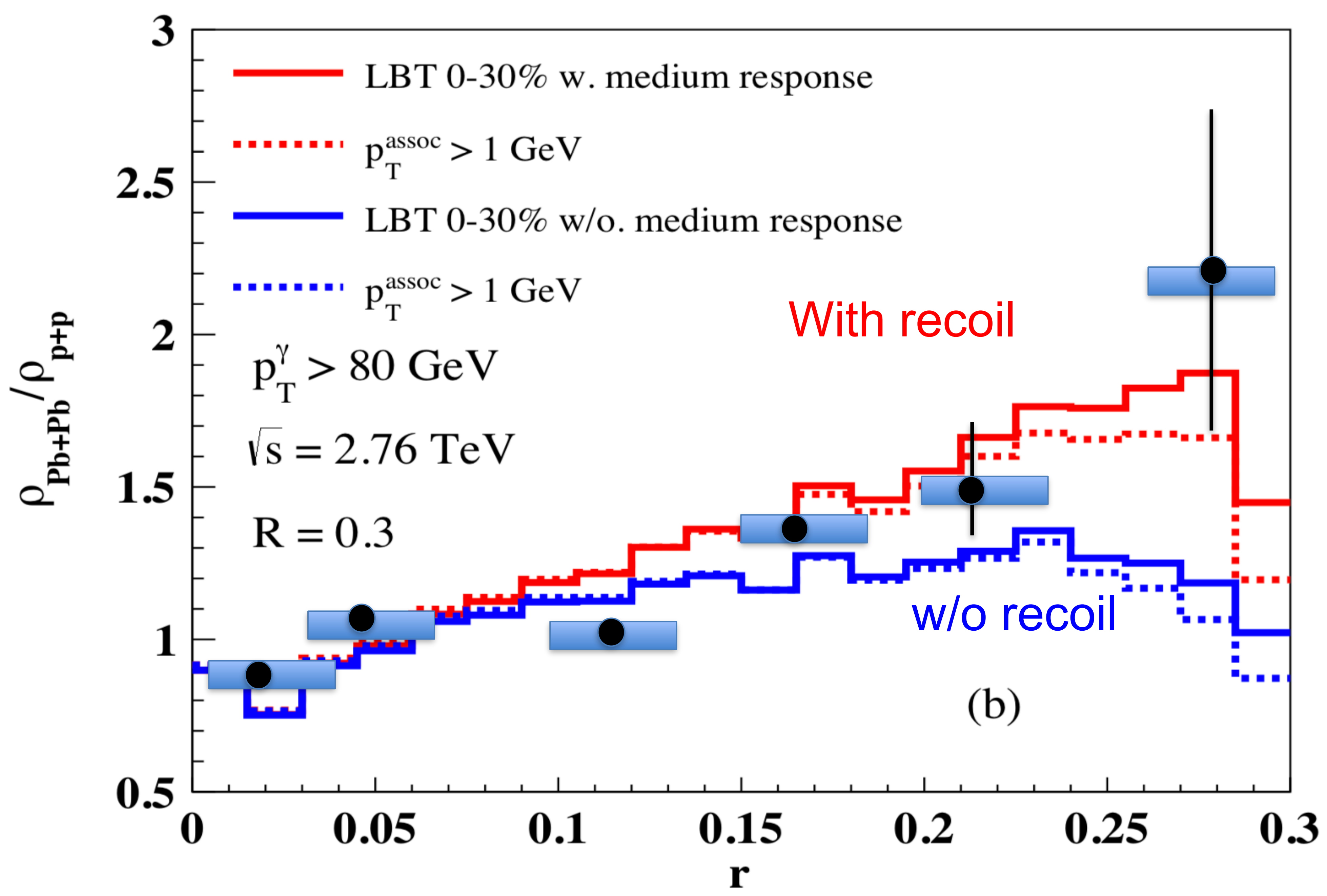
See also: L. Campos (Tue), Y. Tachibana (Wed), S. Cao, H-Z. Zhang(Th)

The elusive medium response

[see Y. Go' talk (today)]

- Soft components seem necessary for a better description of the jet radial profile and/or jet mass:

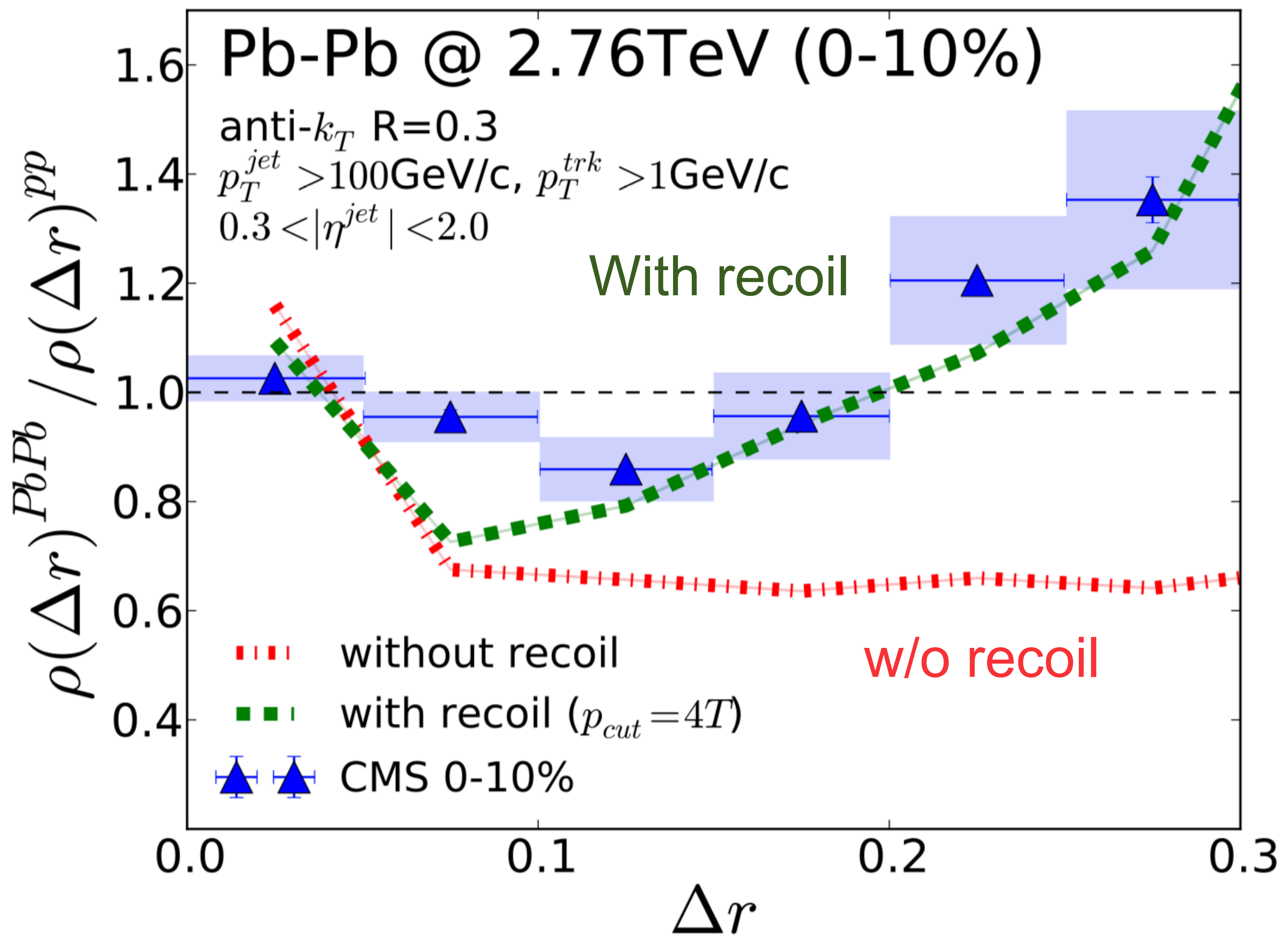
LBT



[Luo, Cao, He, Wang, (1803.06785)]

MARTINI

[Park, Jeon, Gale (1807.06550)]



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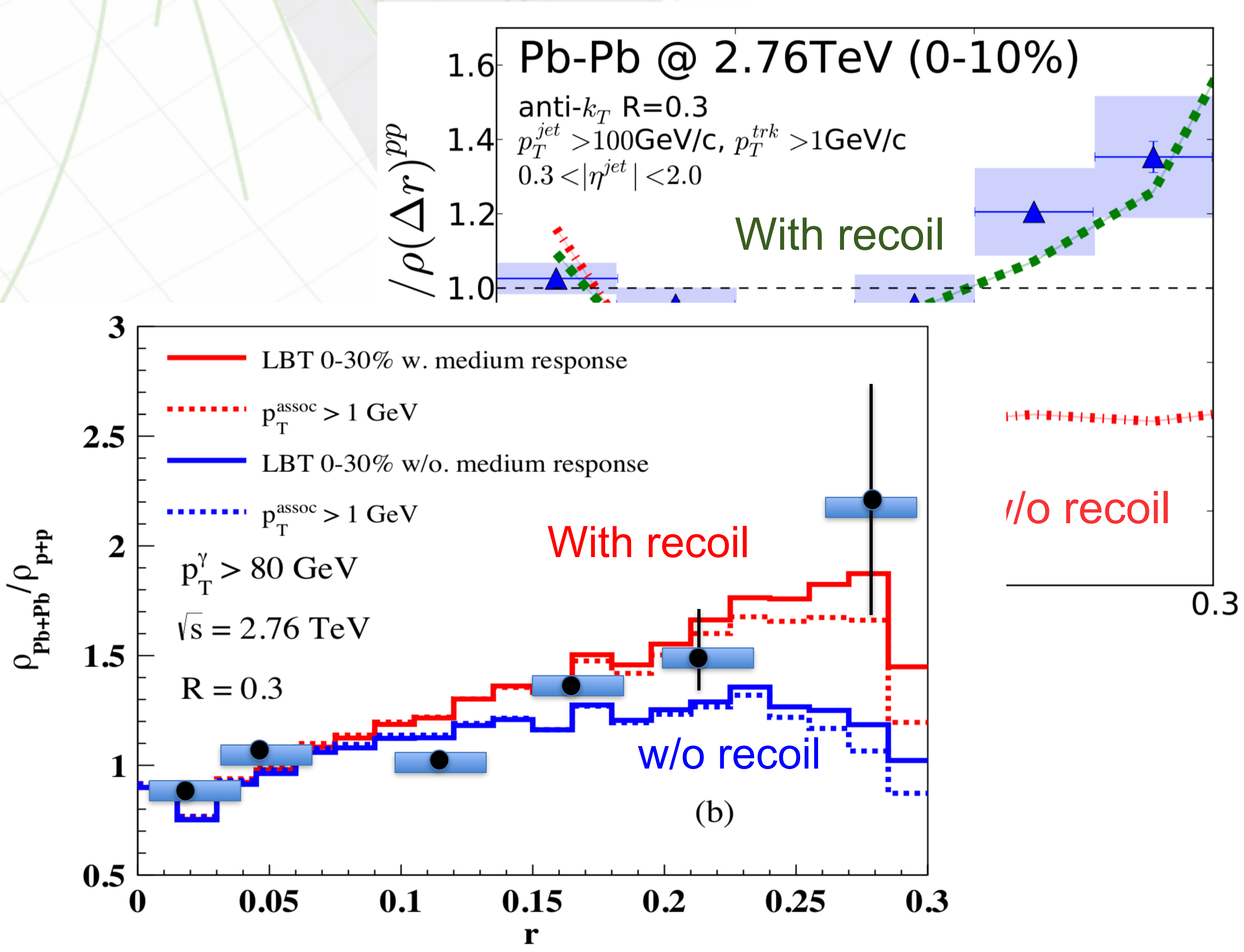

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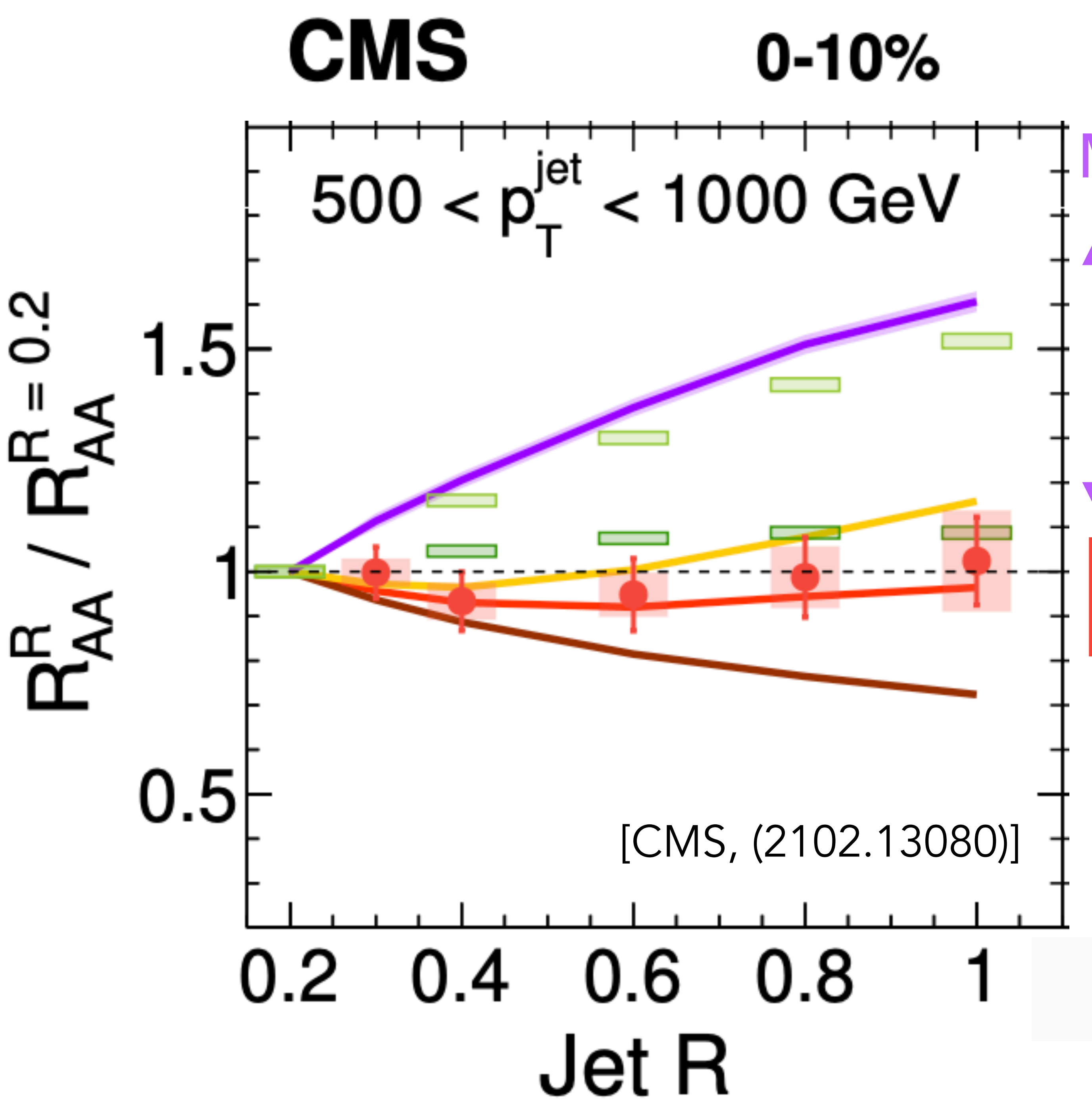


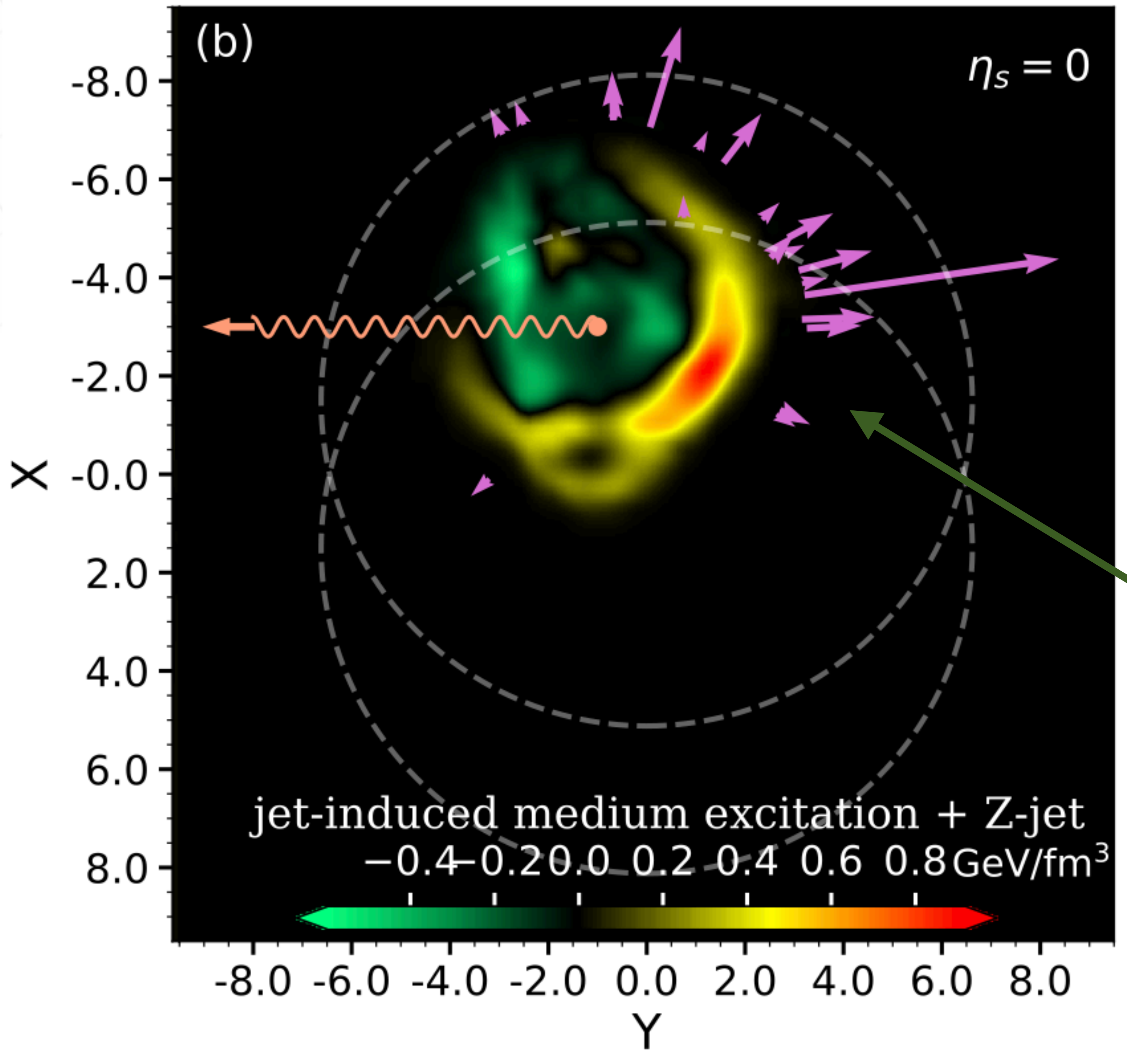
But might result into additional energy at larger angles…

Is the enhancement due to medium-response or to poorly known non-perturbative physics?

QGP-wake signal

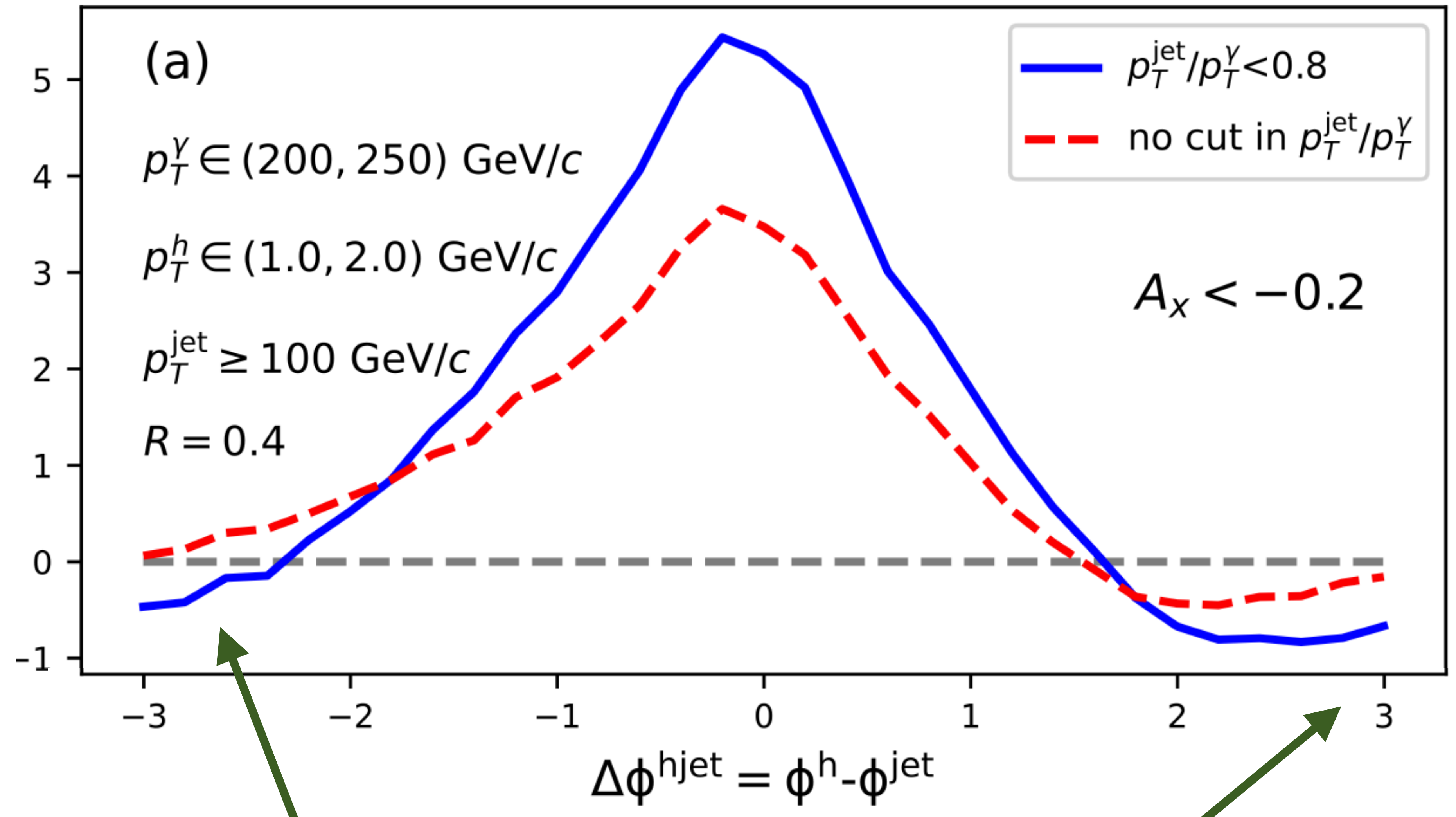
- Jet-induced medium exceptions in Z+jet events:

Co-LBT



ɣ+hadron yield (PbPb-pp)

[Chen, Cao, Luo, Pang, Wang (1704.03648)]



Soft-hadron depletion in ɣ direction

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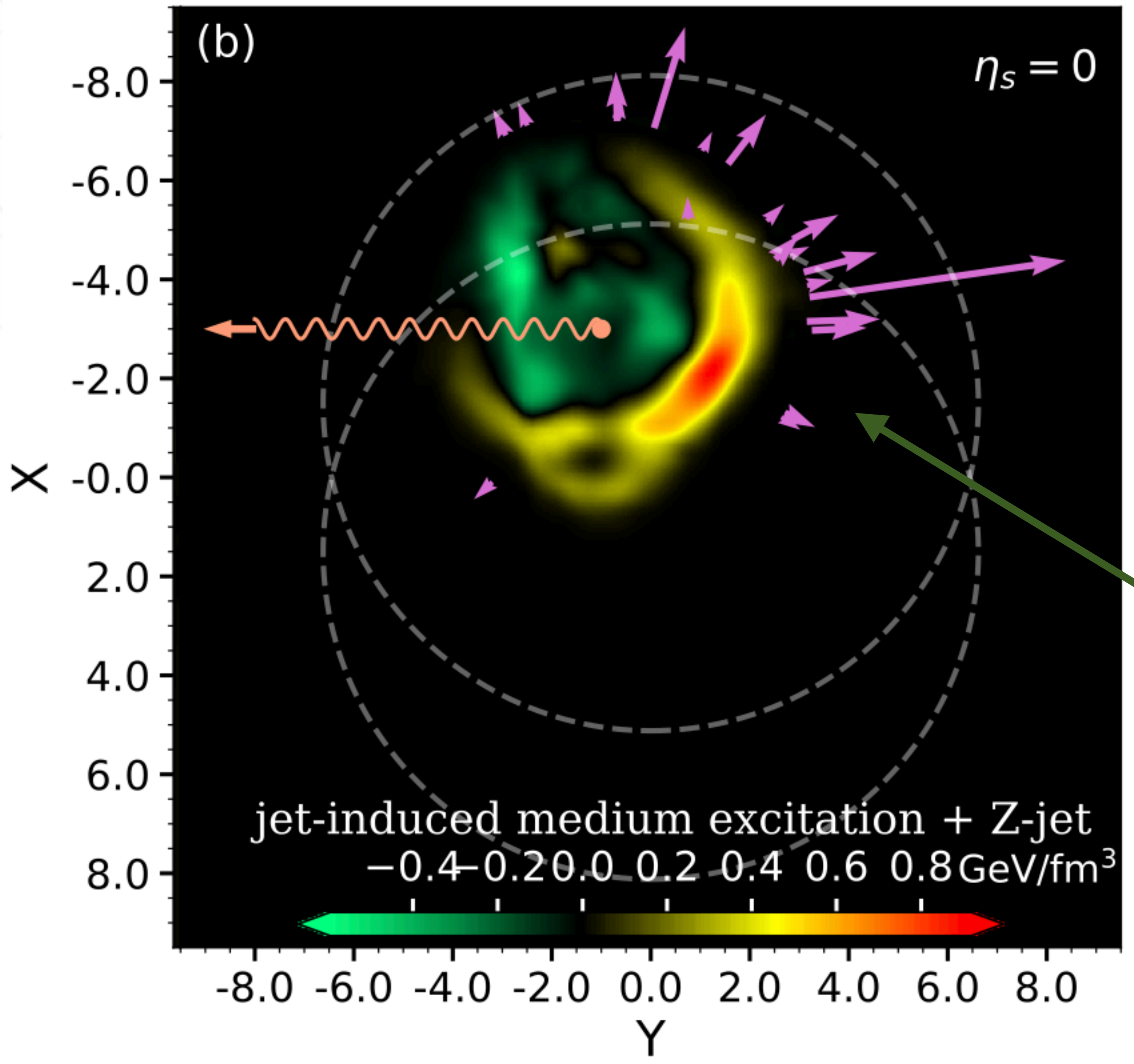

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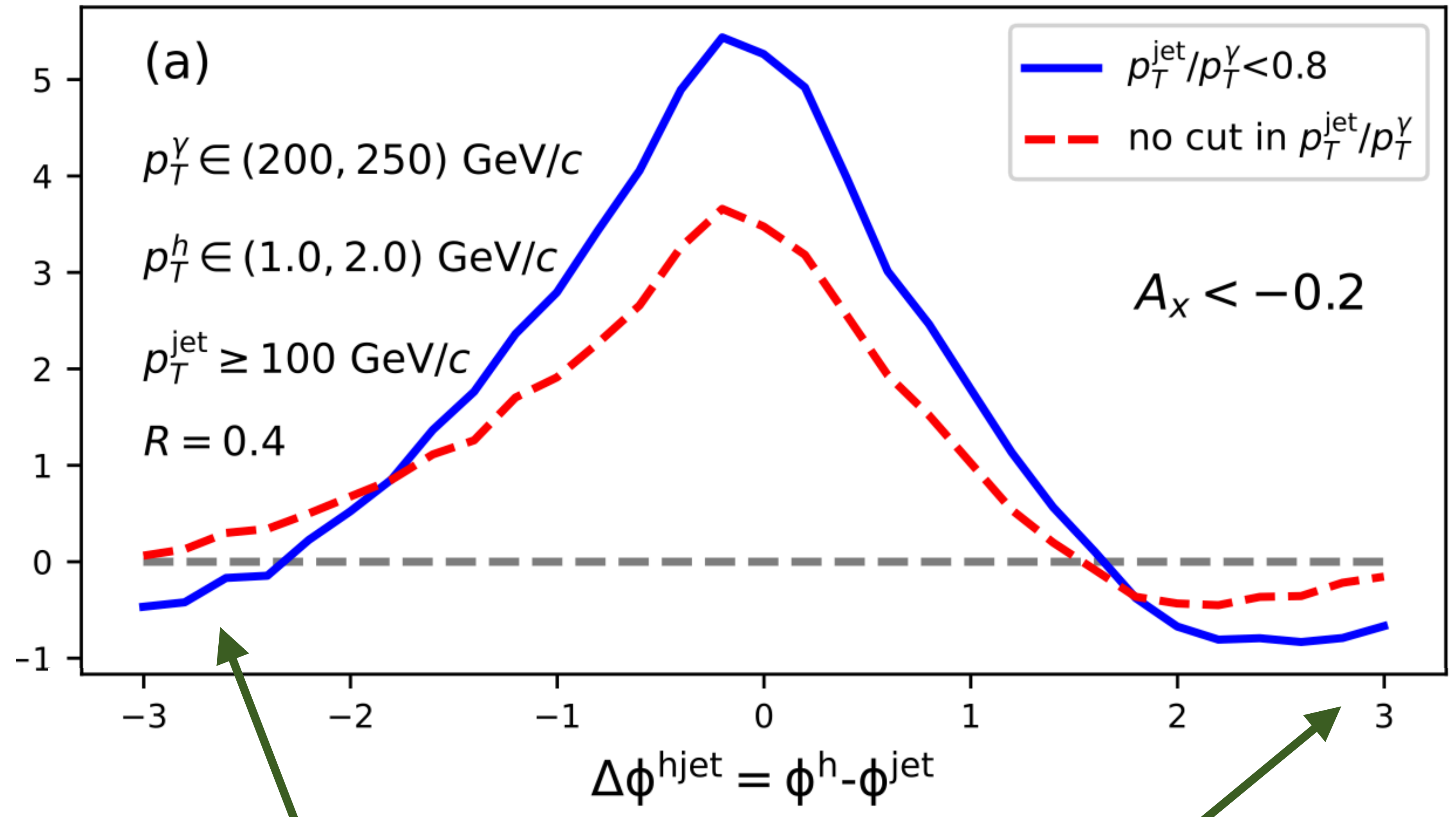


Soft-hadron depletion in γ direction

Introduction of viscous hydro in MC ⇒ 3D wake that depend on EoS

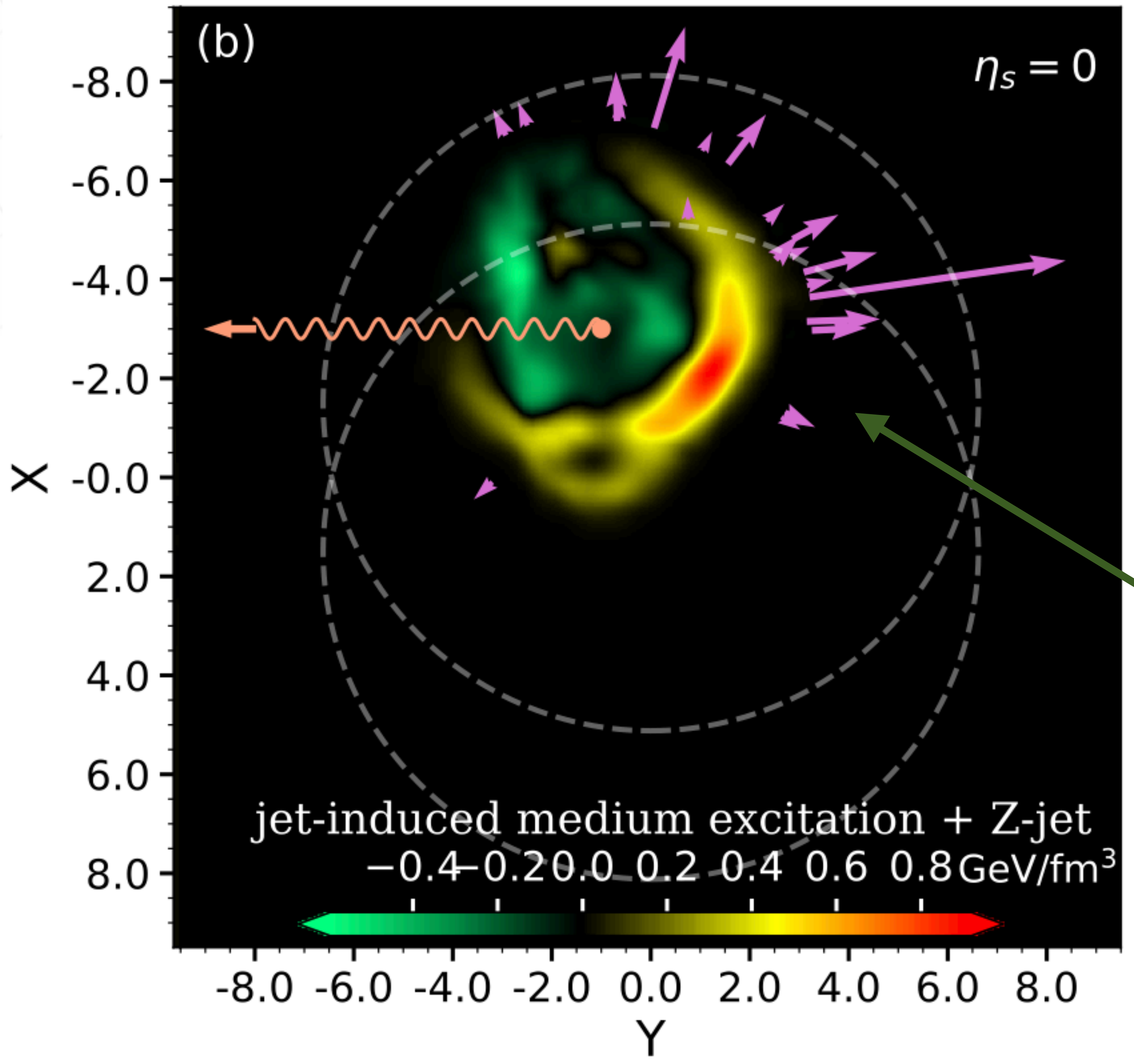
See also: Y. He, M. Ploskon (Tue)

QGP-wake signal

Jet tomographic analysis via ML
[ML@jets: see Y. Du's talk (Friday)]

- Jet-induced medium exceptions in Z+jet events:

Co-LBT



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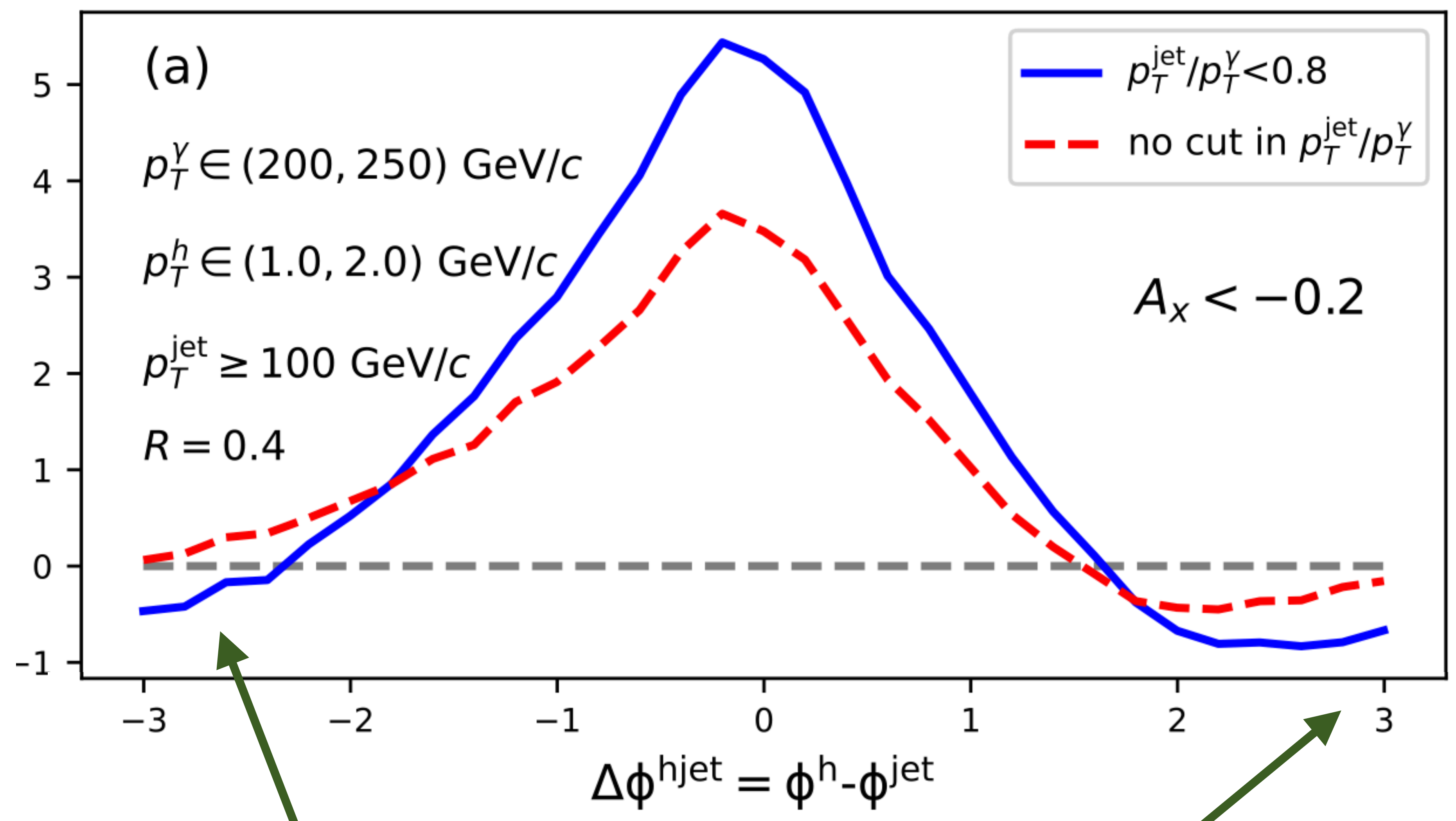

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Understanding biases

- Comparison between quenched and unquenched made through some jet selection:
  - Impact of jet selection biases on jet substructure observables?

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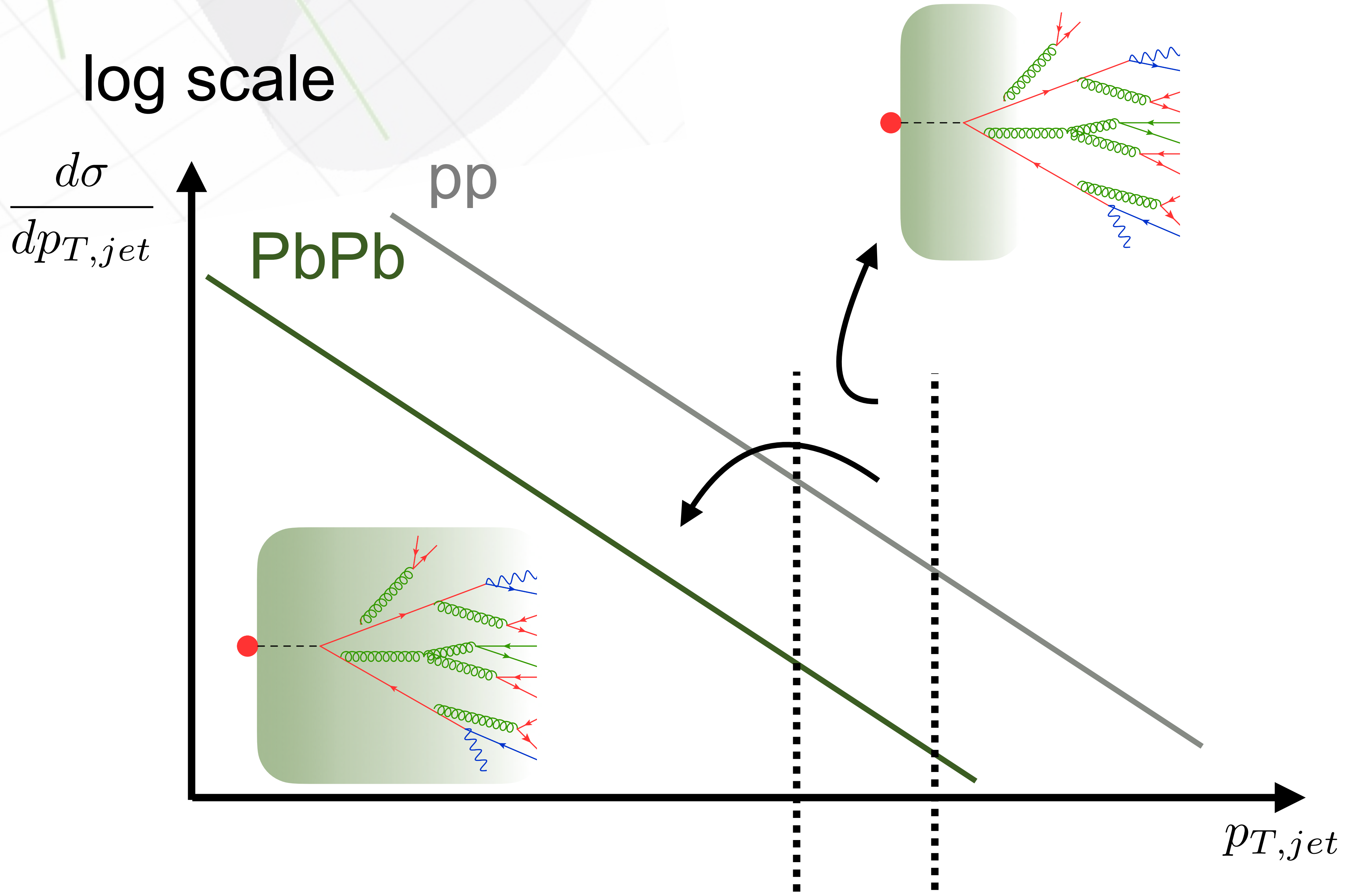

How to compare unmodified with modified jets?

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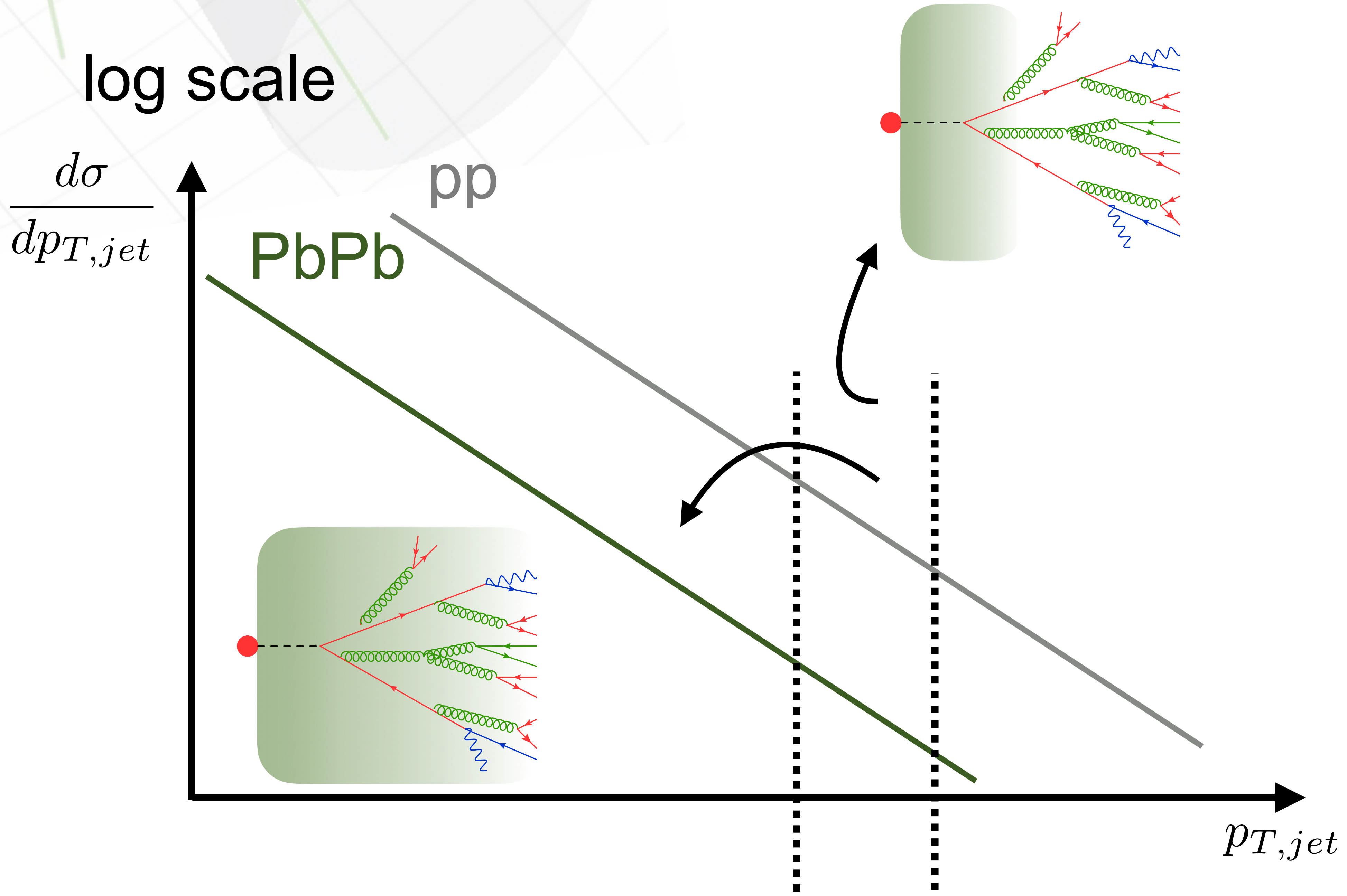
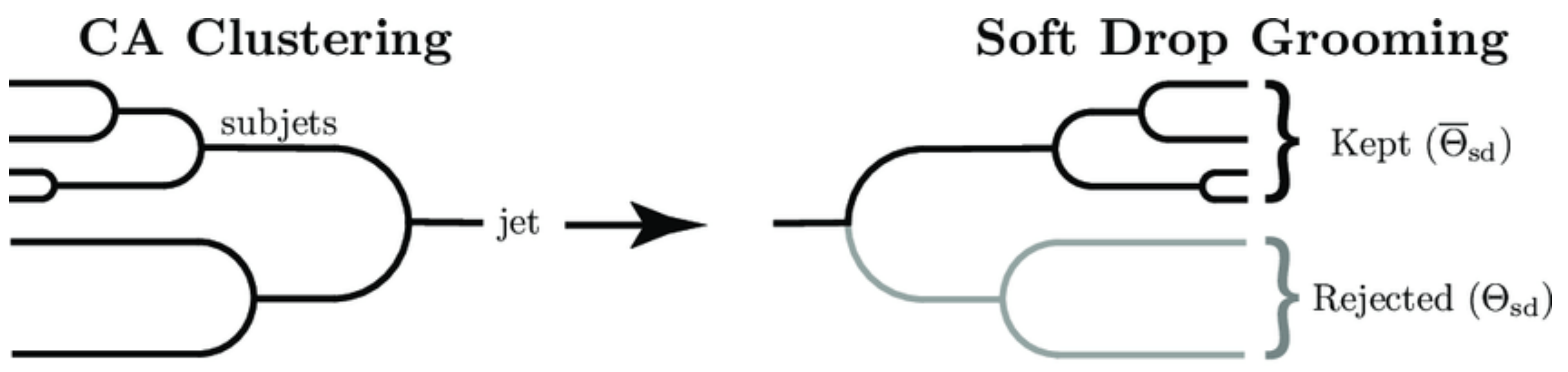


How to compare unmodified with modified jets?

Which jet selection results from applying grooming?



$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

Understanding biases

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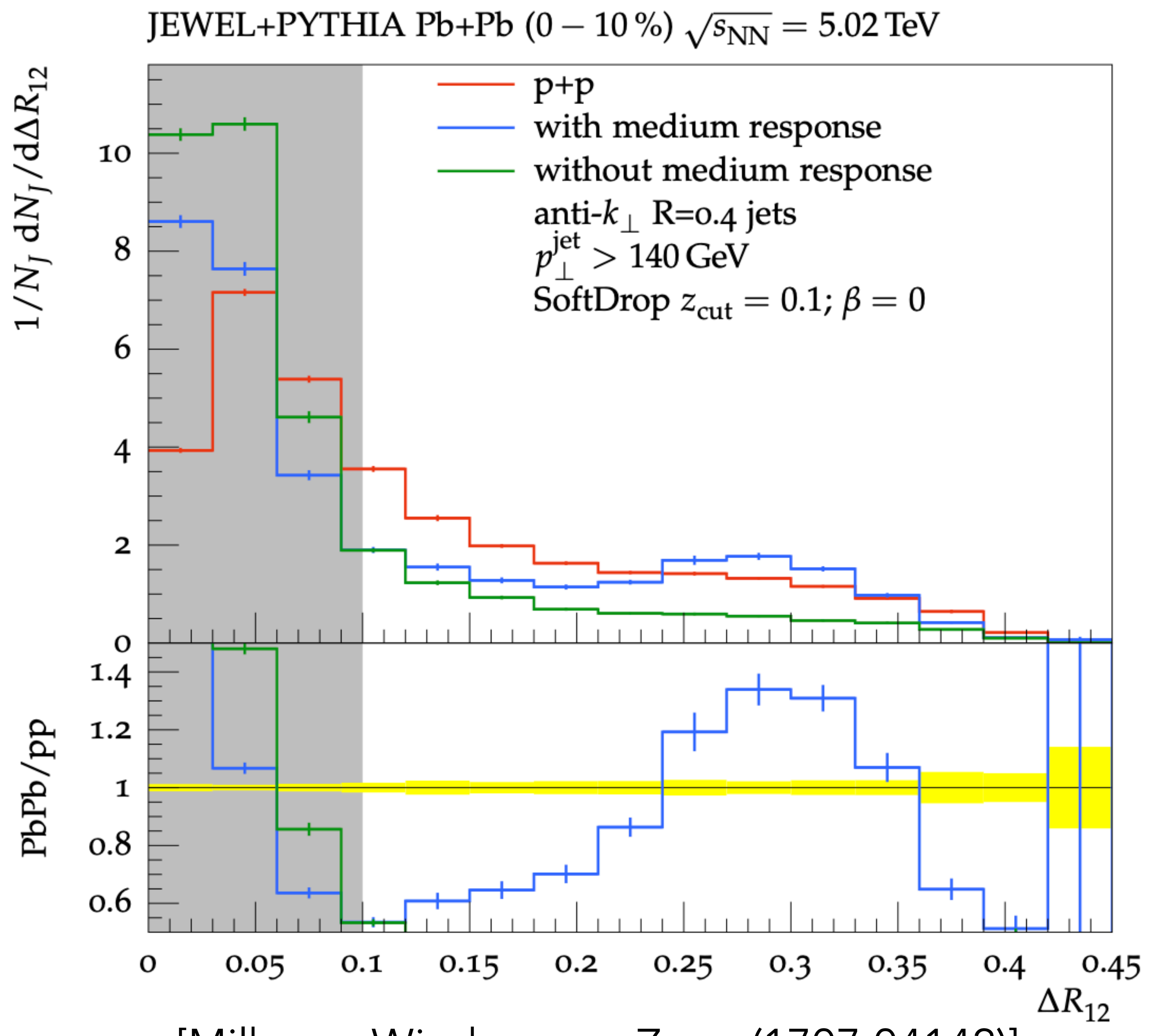
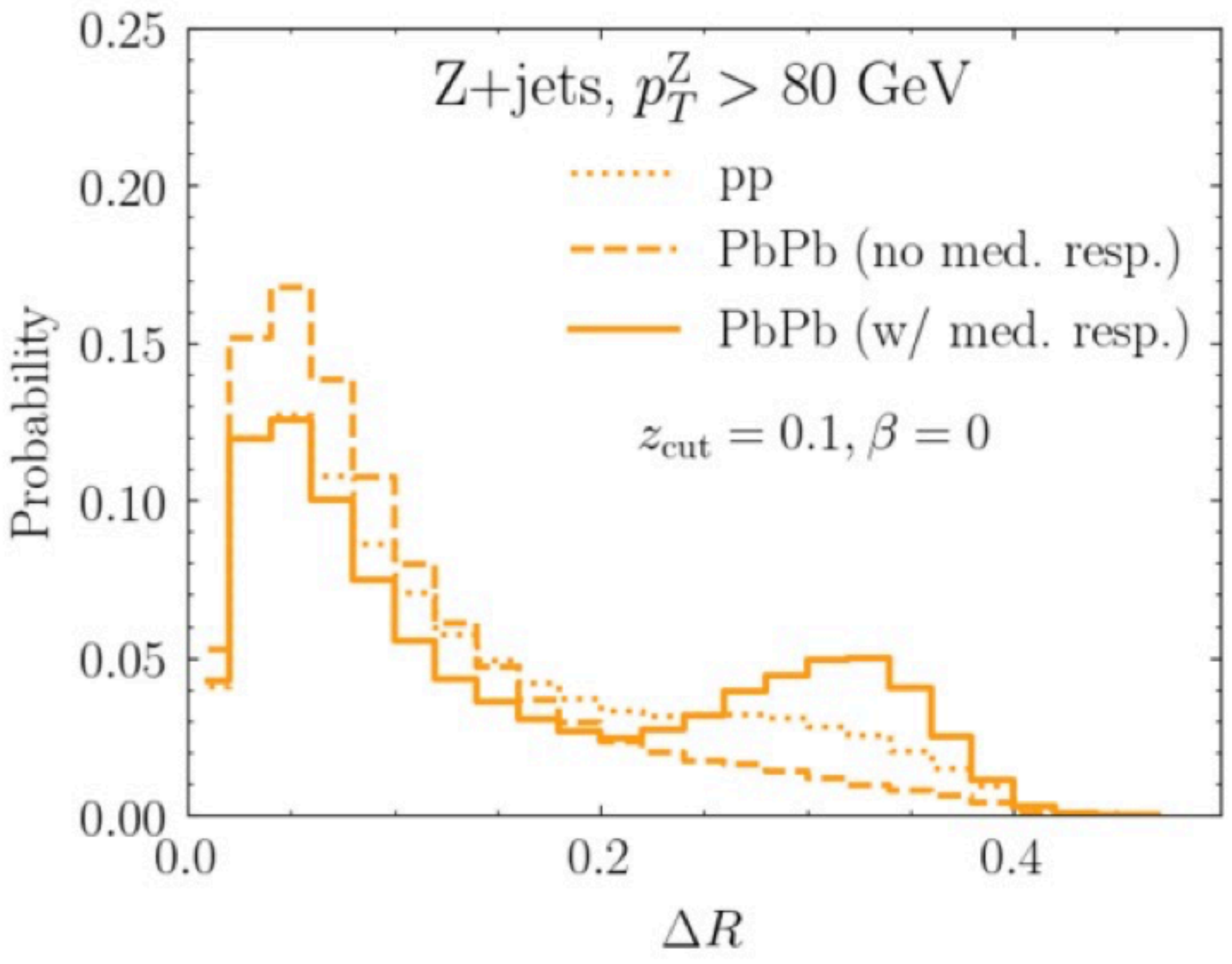
  - Impact of jet selection biases on jet substructure observables?

JEWEL



[Milhano, Wiedemann, Zapp (1707.04142)]

Hybrid



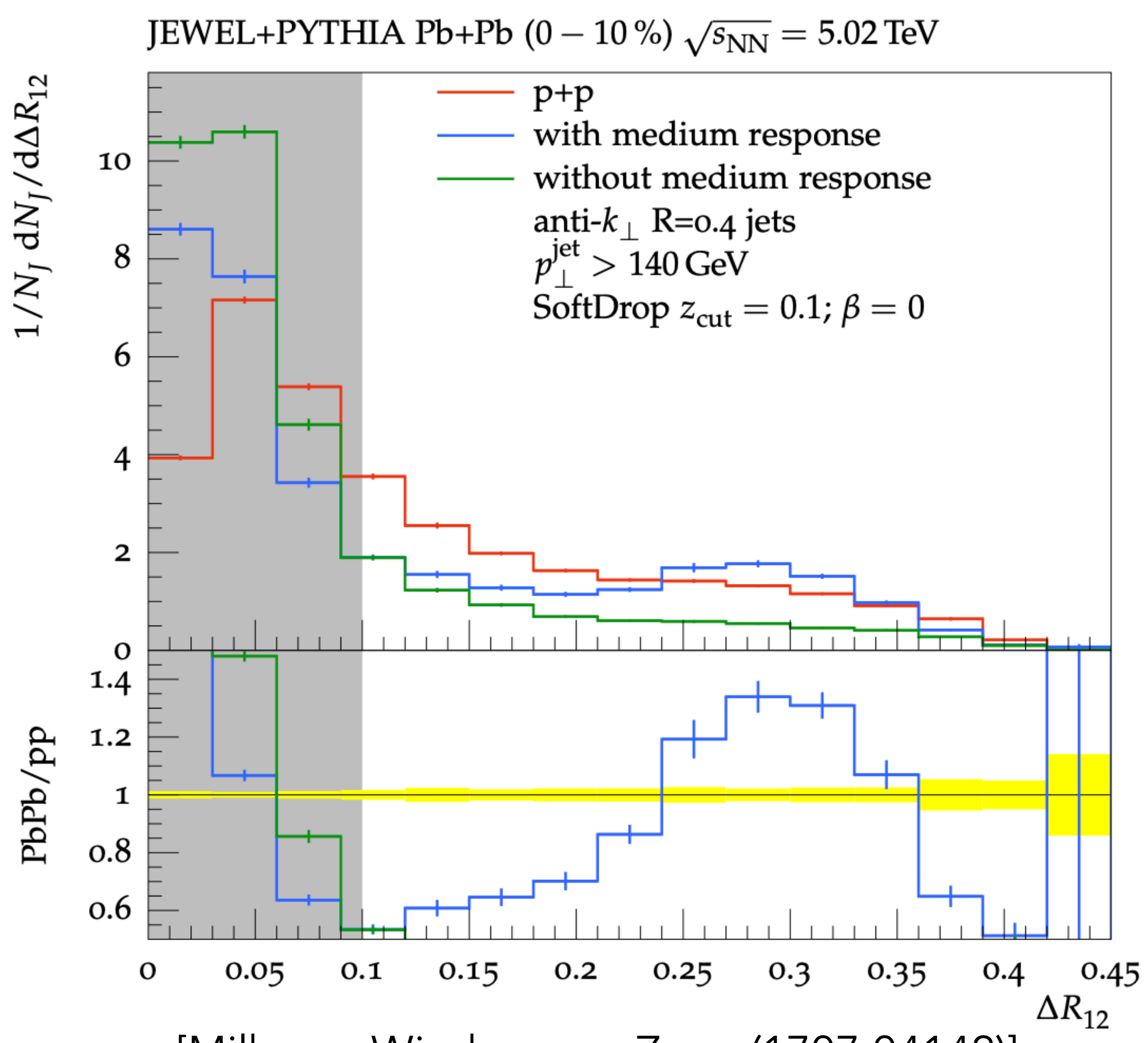
[Brewer, Brodsky, Rajagopal (2110.13159)]

Jets passing the Soft Drop condition are more likely to have medium-induced/recoil effects

Understanding biases

- Comparison between quenched and unquenched made through some jet selection:
  - Impact of jet selection biases on jet substructure observables?

JEWEL



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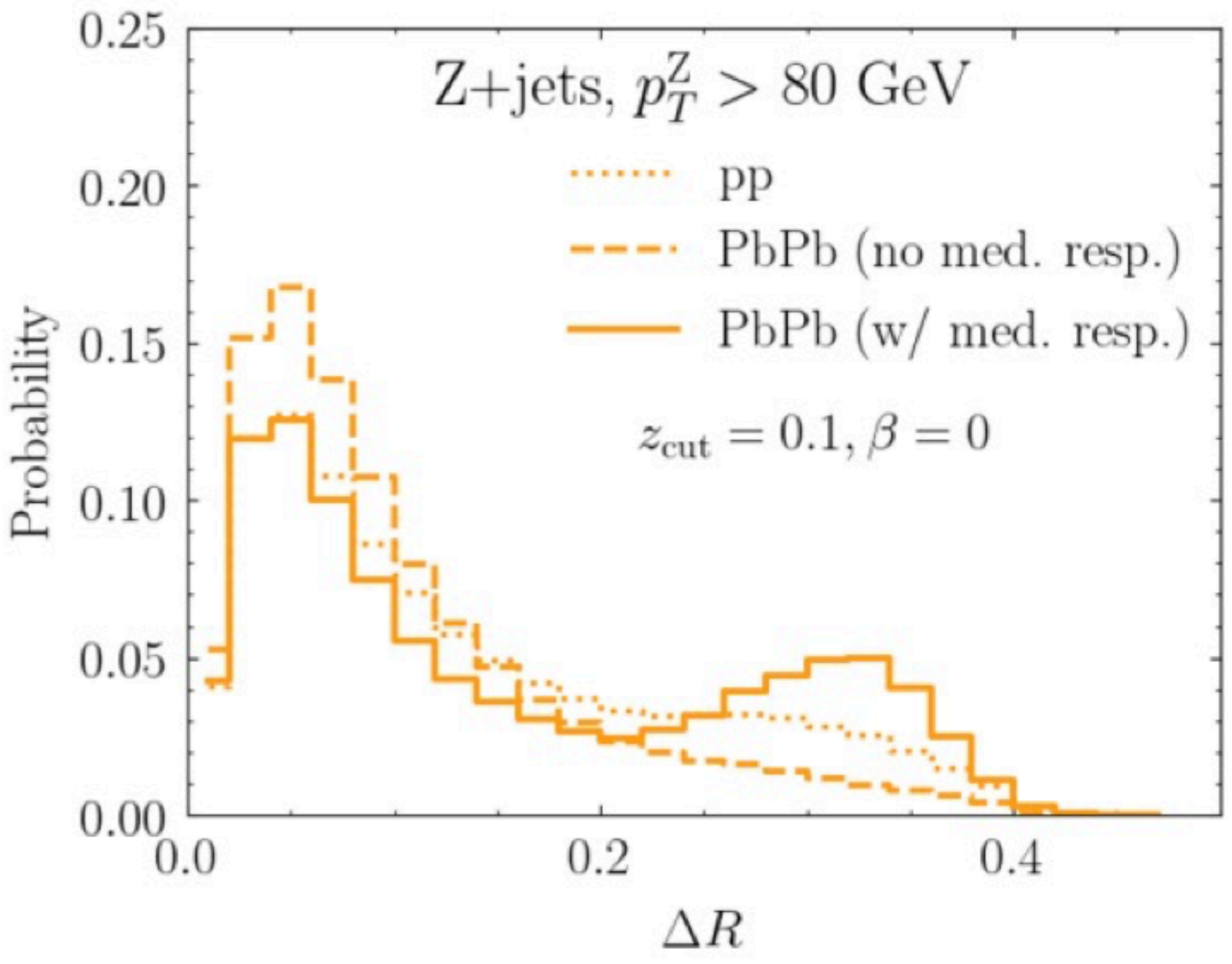

[Brewer, Brodsky, Rajagopal (2110.13159)]

Jets passing the Soft Drop condition are more likely to have medium-induced/recoil effects

Grooming can be used to select different contributions of medium response

New opportunities

Towards the Future

- Jet quenching Monte Carlo are still limited on their treatment of:
  - Medium-modified parton showers
  - Low momentum scales

⇨ Jet substructure description

[see A. Soto-Ontoso's talk (today)]

Towards the Future

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[see A. Soto-Ontoso's talk (today)]
→ Still incomplete…

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  - Medium-modified parton showers
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⇨ Jet substructure description → Still incomplete…

[see A. Soto-Ontoso's talk (today)]

- What are we missing in our tools?
  - Continuous improvement with most recent analytical results to address medium-induced effects
  - Early-stages dynamics
  - Improved parton showers?

Proton-proton vs PbPb

- Our accuracy is bounded by our reference (pp)
  - Based on leading logarithmic (LL) order
    - But new PanScales parton showers: next-to-leading logarithmic accuracy (NLL) [Dasgupta et al, (2002.11114), Beekveld et al (2205.02237)]

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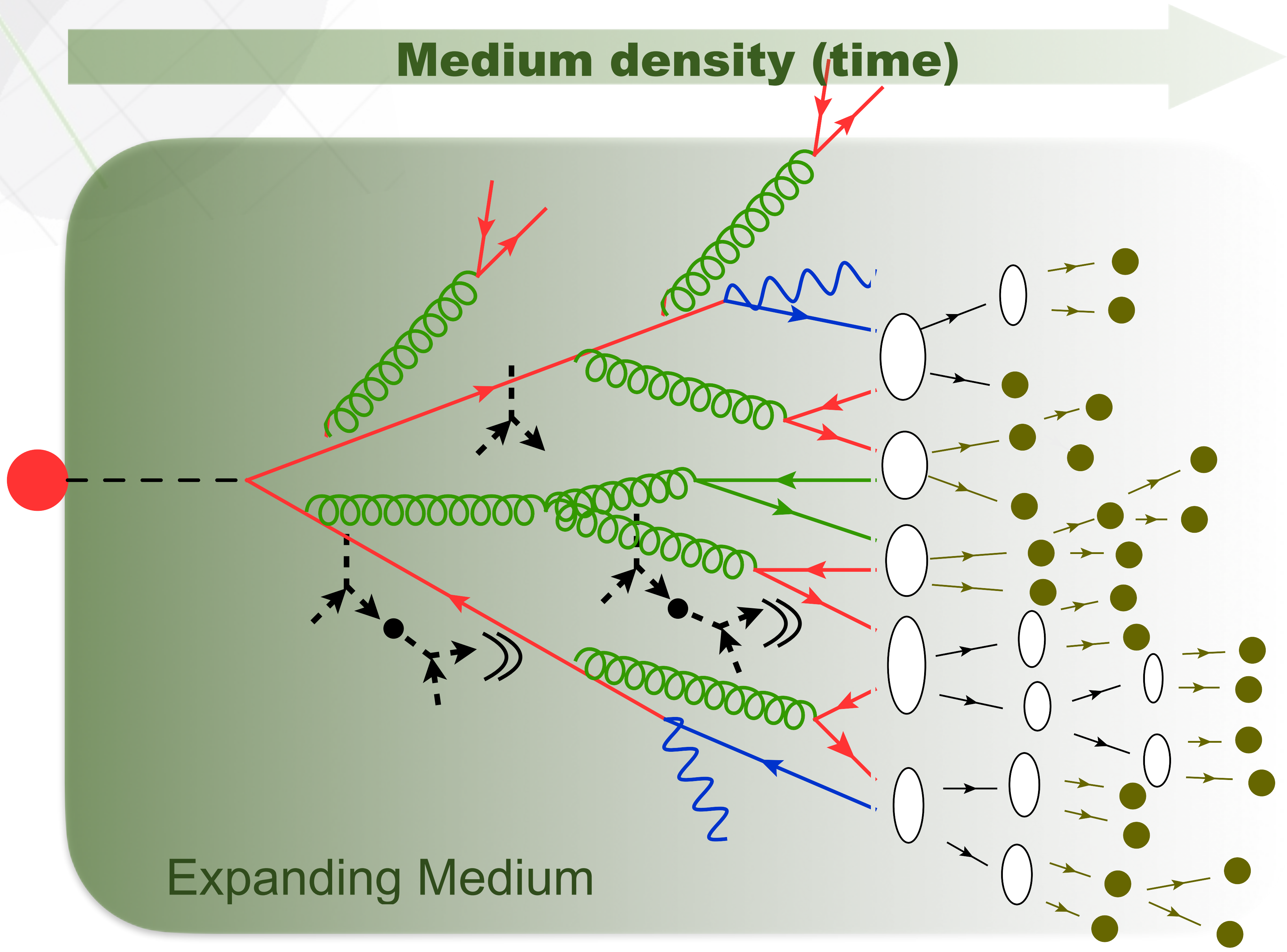
[Dasgupta et al, (2002.11114), Beekveld et al (2205.02237)]

- But also due jet quenching:
  - Analytical results
  - Needed extrapolations beyond analytical validity region
  - Phenomenological extensions to include medium-effects from all momentum scales

Parton Showers in heavy-ions

- Cannot compete with proton-proton accuracy…
  - But have a qualitatively different problem: quantum system developing on top of an evolving medium



$Q^2 \equiv \mathcal{O}(100^2\mathrm{GeV}^2 \sim 1\mathrm{TeV}^2)$ ⟶ $Q^2 \equiv \mathcal{O}(1\mathrm{GeV}^2)$

pQCD — non pQCD

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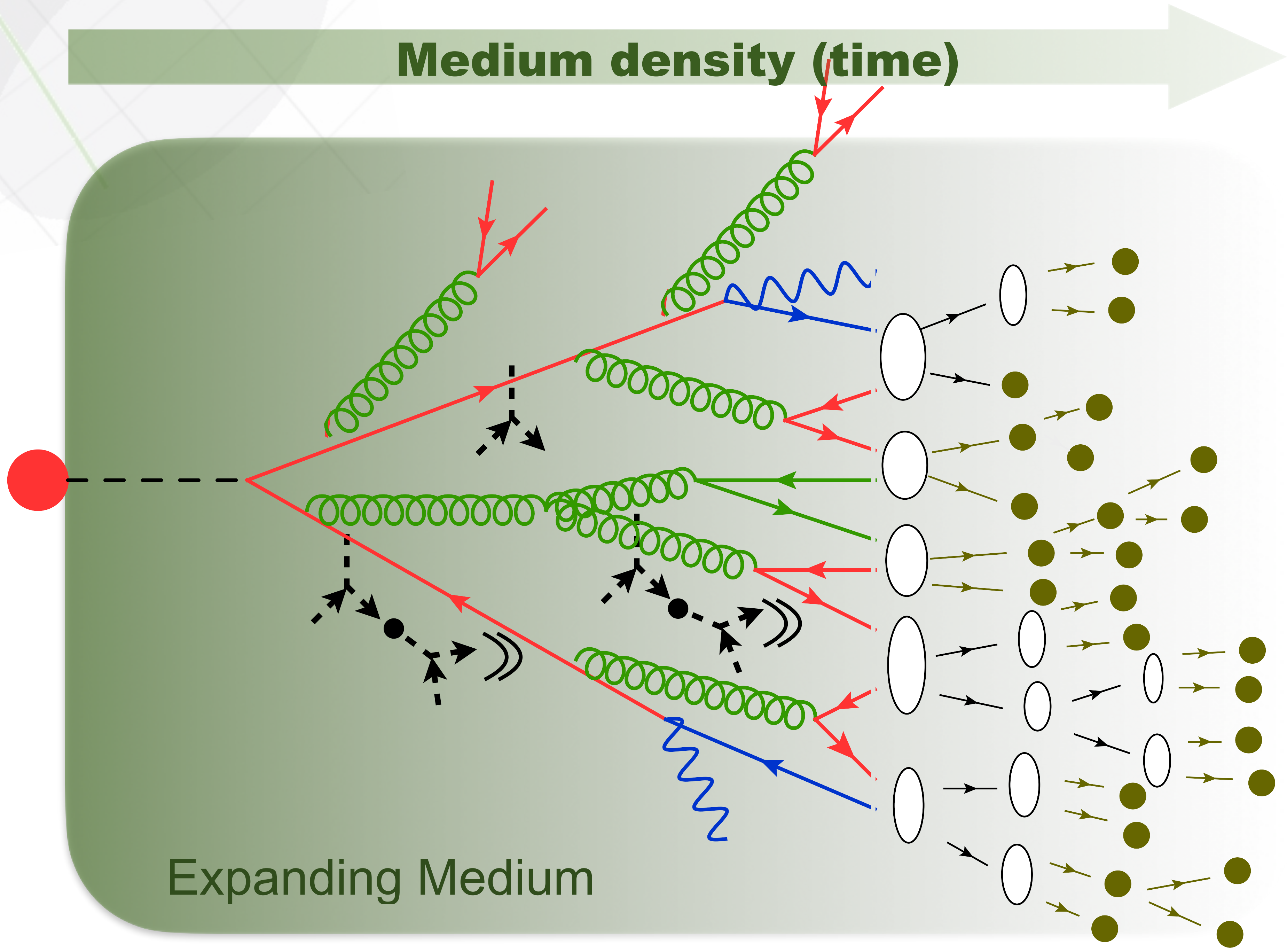

$Q^2 \equiv \mathcal{O}(100^2\mathrm{GeV}^2 \sim 1\mathrm{TeV}^2)$ $\dashrightarrow$ $Q^2 \equiv \mathcal{O}(1\mathrm{GeV}^2)$

pQCD — non pQCD

Heavy-ions are unique laboratory for:

- QGP tomography
- Interplay of parton showers with evolving medium (role of the parton shower ordering variable?)
- Transition from perturbative to non-perturbative

Summary

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- Monte Carlo event generators widely used tools to probe QGP physics
  - Require phenomenological extensions that need to be constantly tested and refined by analytical input
  - Ideal framework to probe novel QCD-related phenomena

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- Monte Carlo event generators widely used tools to probe QGP physics
  - Require phenomenological extensions that need to be constantly tested and refined by analytical input
  - Ideal framework to probe novel QCD-related phenomena
  - Invaluable instruments for:
    - Testing new observables in more “realistic” conditions as compared to analytical approaches
    - Understanding biases in our experimental results

Thank you!

Acknowledgments

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MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

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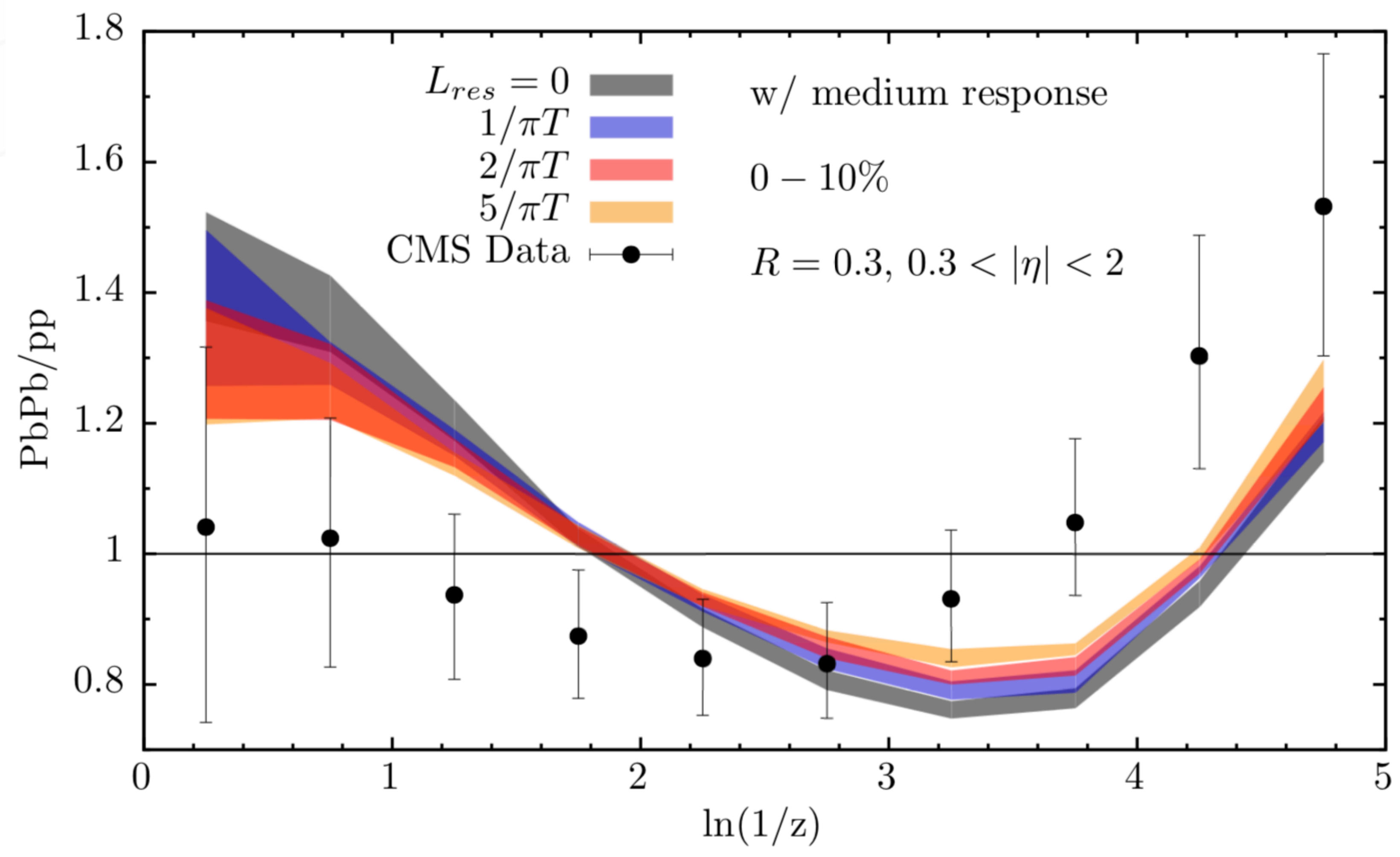
TÉCNICO LISBOA

Backup Slides

Bibliography

- Monte Carlo models for jet quenching:
  - CUJET: [Buzzatti, Liao, Gyulassy, Shi (14, 16, 18)]
  - Dreena: [Zigic, Salom, Auvinen, Djordjevic, M. Djordjevic (19, 22)]
  - Hybrid Strong/Weak coupling: [Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal (14;17); Helcher, Pablos, Rajagopal (18)]
  - JETSCAPE: [JETSCAPE Collab. (17)]
  - JEWEL: [Krauss, Wiedemann, Zapp(13); Zapp (14); Elayavalli, Zapp (16;17)]
  - LBT/Co-LBT: [Wang and Y. Zhu (16); Cao, Luo, Qin, Wang (15); He, Luo, Wang, Zhu (17);]
  - MARTINI: [Schenke, Gale, Jeon (09); Park, Jeon, Gale (18)]
  - MATTER: [Majumder (13); Kordell, Majumder (17); Cao, Majumder (18)]
  - PYQUEN: [Lokhtin, Snigirev (06)]
  - Q-PYTHIA: [Armesto, Cunquero, Salgado (09)]
  - Jetmed(Saclay): [Caucal, Iancu, Mueller, Soyez (18)]

Color (de)coherence



JETSCAPE

[Tachibana et al (2301.02485)]