

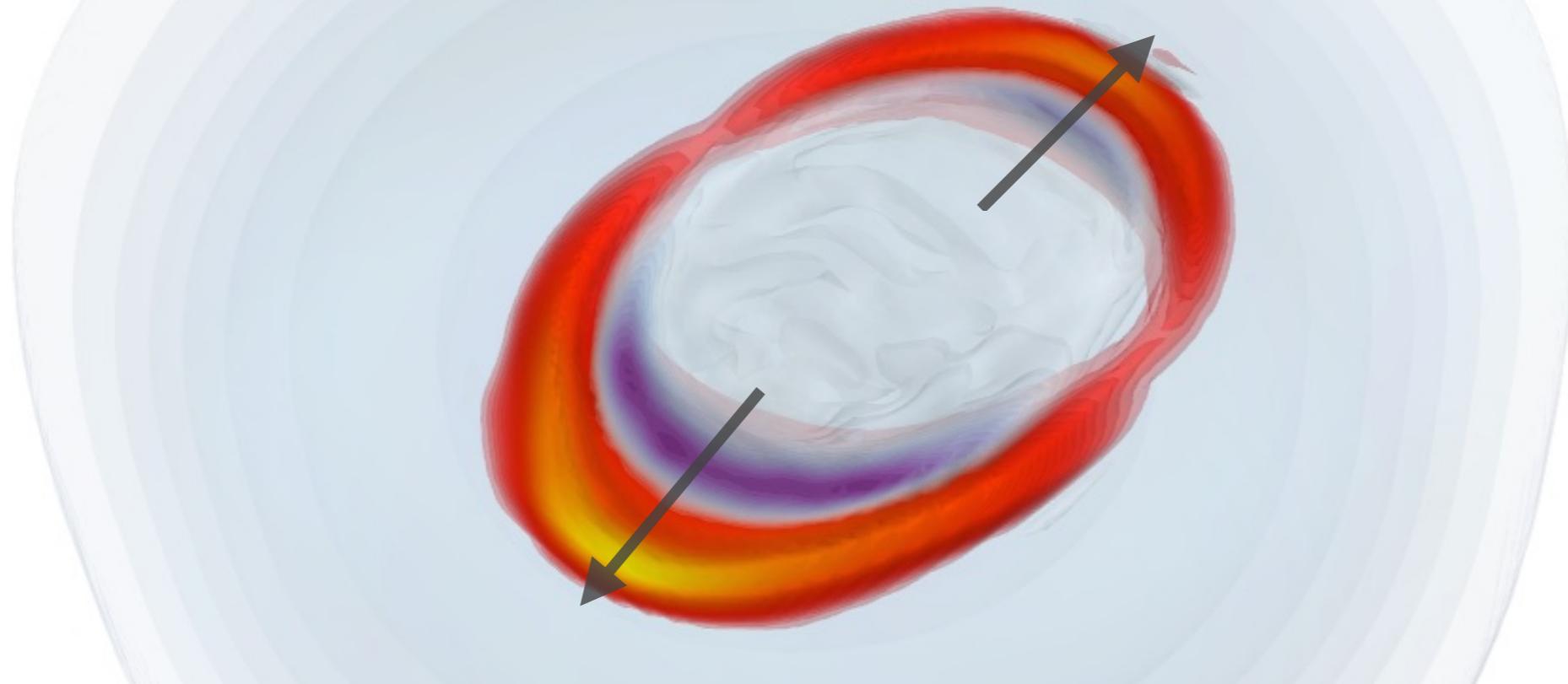


WAYNE STATE
UNIVERSITY



Medium response to jet-induced excitation: theory overview

Yasuki Tachibana



Related big problem in QGP physics

Thermalization

Related big problem in QGP physics

In-medium thermalization



Related big problem in QGP physics

In-medium thermalization

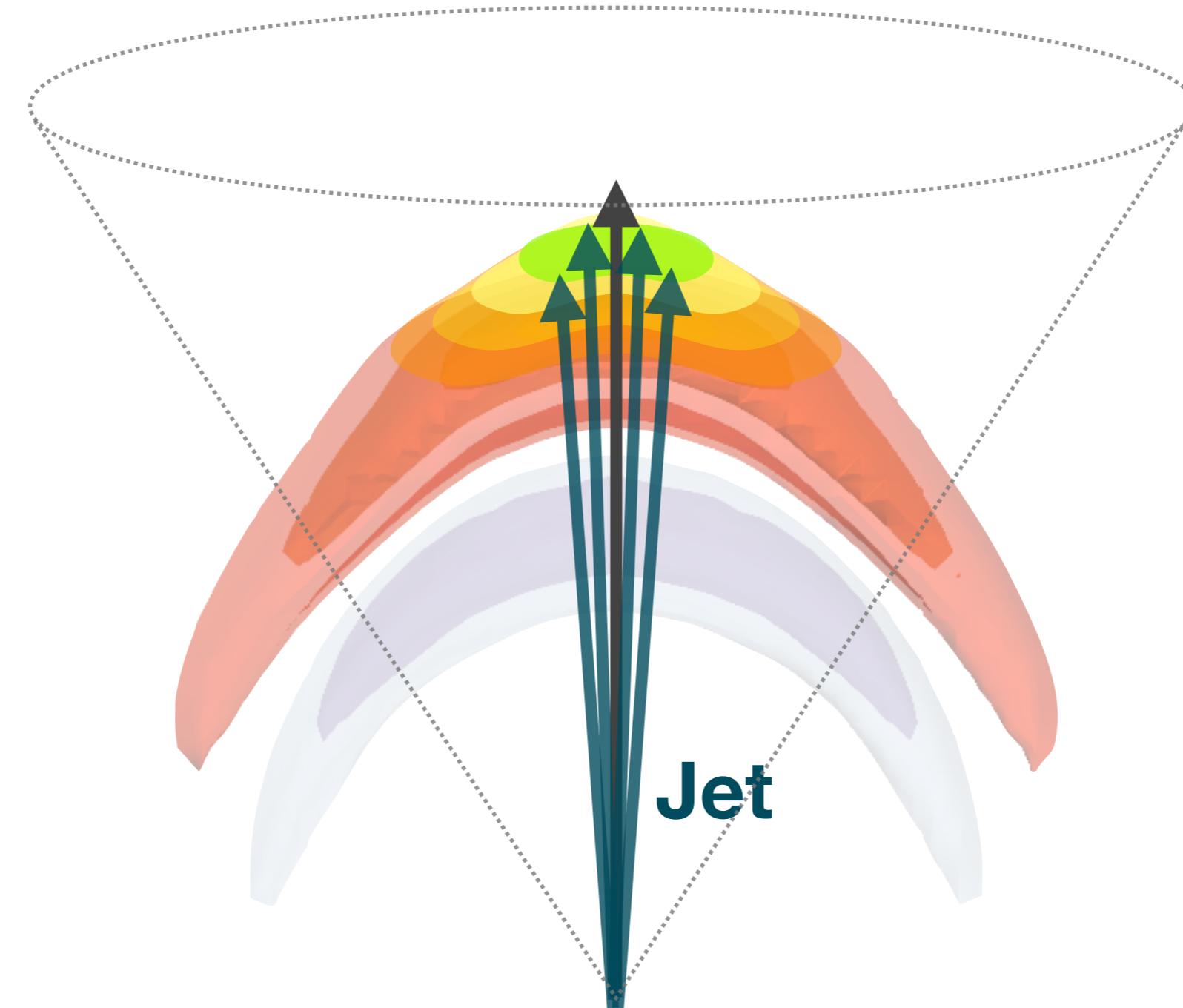
QGP

Hard Parton



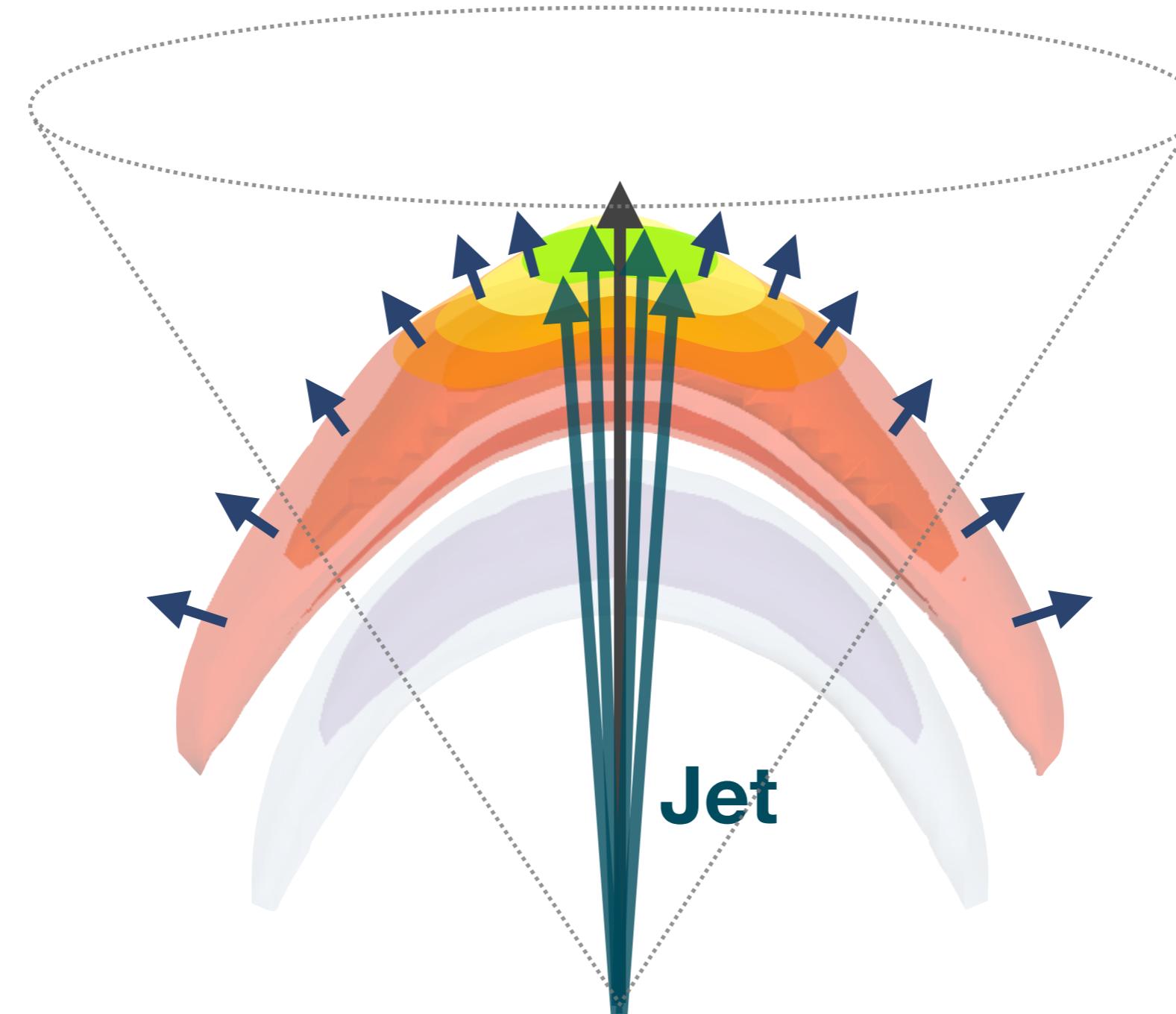
Affect jet observables

Energy and momentum transported by medium response



Affect jet observables

Energy and momentum transported by medium response



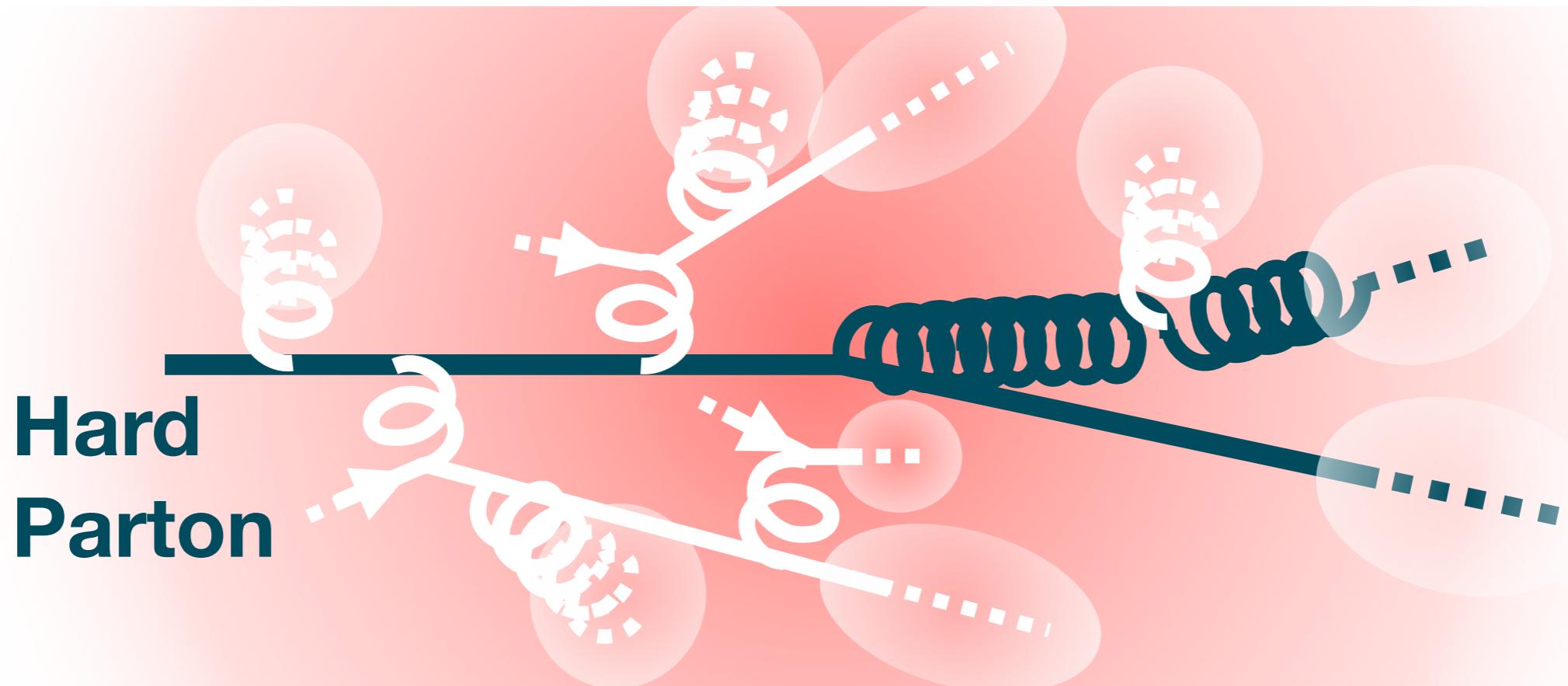
Modification of jet structure

Outline

- Introduction
- Models for medium response
- Results from recent theoretical studies
- Summary and outlook

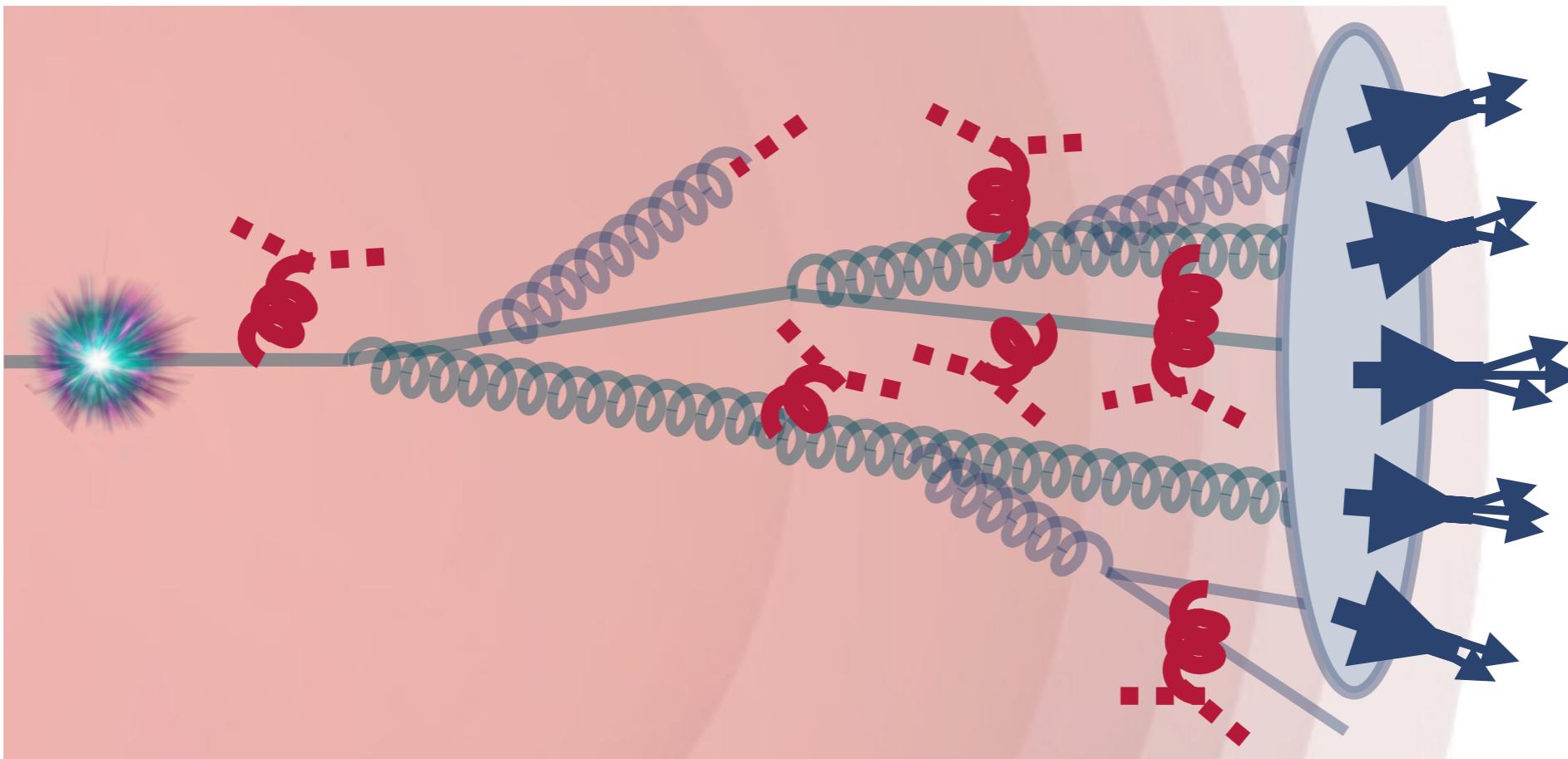
Introduction

Medium response to hard parton propagation



- **Interaction with hard parton**
 - Energy and momentum received by medium constituents
 - Lead nonequilibrium processes in medium
- **In-medium thermalization**
 - Relaxation into soft mode
 - Deposited energy carried by (locally) thermalized medium

Medium response in heavy ion collisions



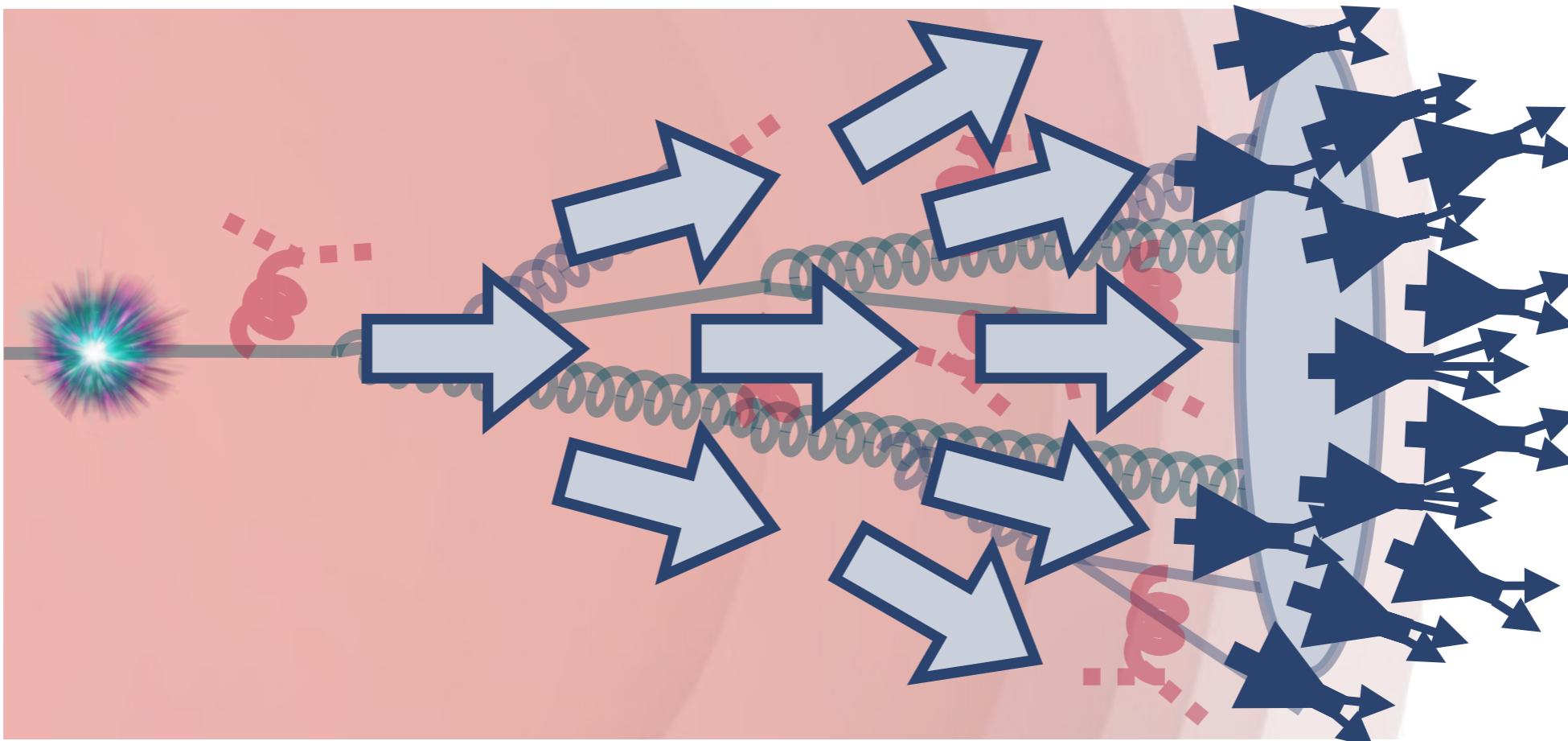
- **Medium response to jet**

- Carry energy and momentum received from jet
- Enhancement of particle emission around jet

- **Particles from medium response**

- Soft, spread out from jet
- Jet-correlated (cannot/should not be subtracted)

Medium response in heavy ion collisions



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Motivations

- **QGP properties for in-medium thermalization**

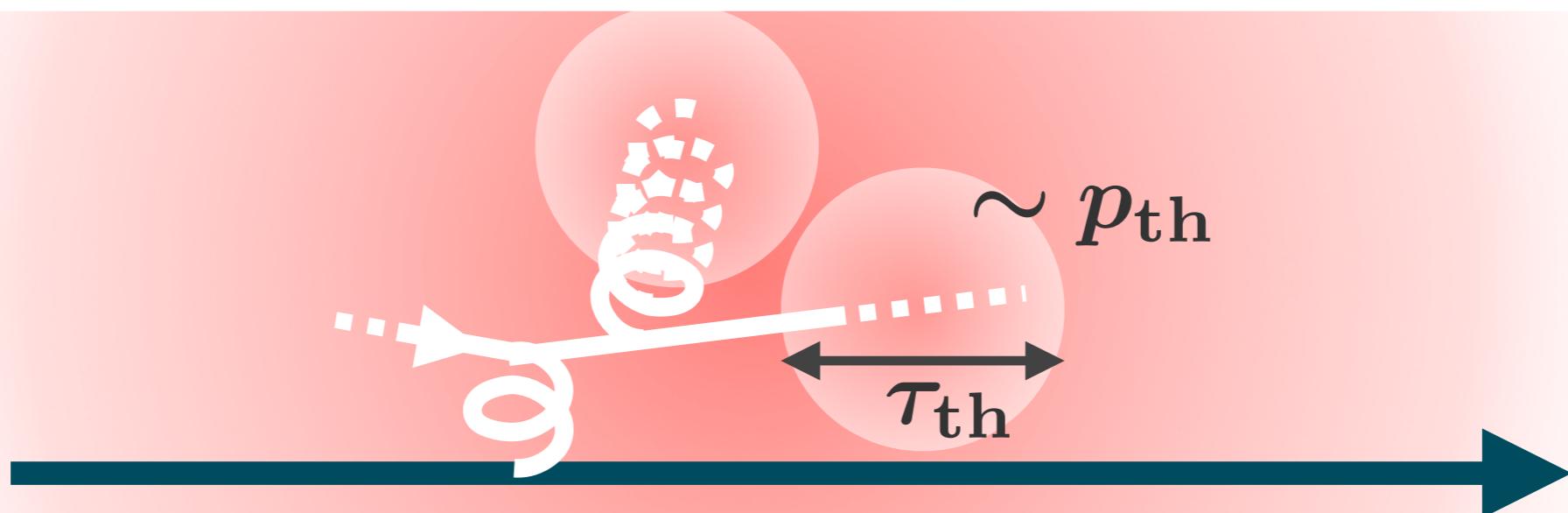
R. B. Neufeld ('09), R. B. Neufeld, I. Vitev ('12), E. Iancu, B. Wu ('15), A. Majumder ('16),...

- Partial thermalization of energy and momentum of jet
- Information of in-medium thermalization

Fraction of thermalized part contribution



Relaxation time τ_{th} , typical momentum scale p_{th} , etc.

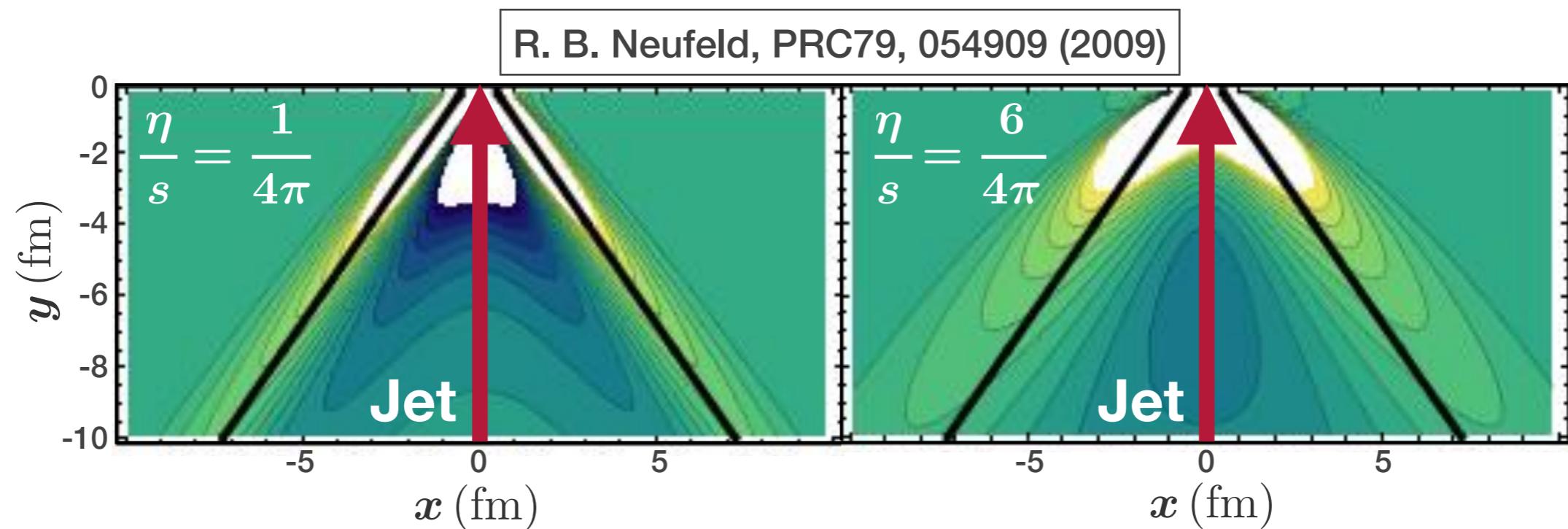


Motivations

● Shockwave (Mach cone) induced in fluid

H. Stöcker ('05), J. Casalderrey-Solana, E. V. Shuryak, D. Teaney ('05), J. Ruppert, B. Muller ('05), L. M. Satarov, H. Stoecker, I. N. Mishustin ('05)

- Structure characterized by fluid properties (shear viscosity, sound velocity, etc.)
R. B. Neufeld ('09), R. B. Neufeld, I. Vitev ('12), Alejandro Ayala et al. ('16), L. Yan, S. Jeon, C. Gale ('17)



- Transportation of thermalized part by Mach cone

Angular distribution of thermalized part contribution



Fluid property (Shear viscosity, sound velocity, etc.)

Motivations

- Full picture of jet quenching

Redistribution of the jet energy and momentum

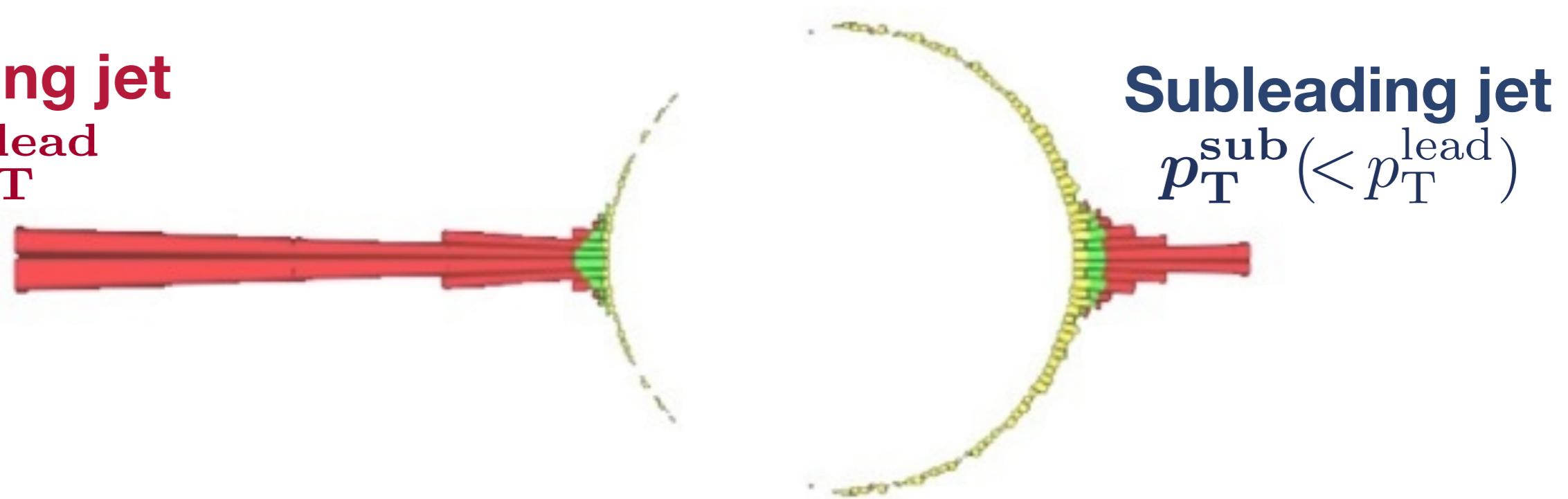
CMS (2011)

Adapted from C. Roland

 >8 GeV
 4-8 GeV
 1-4 GeV

Leading jet

p_T^{lead}



Motivations

- Full picture of jet quenching

Redistribution of the jet energy and momentum

CMS (2011)

Adapted from C. Roland

Balance

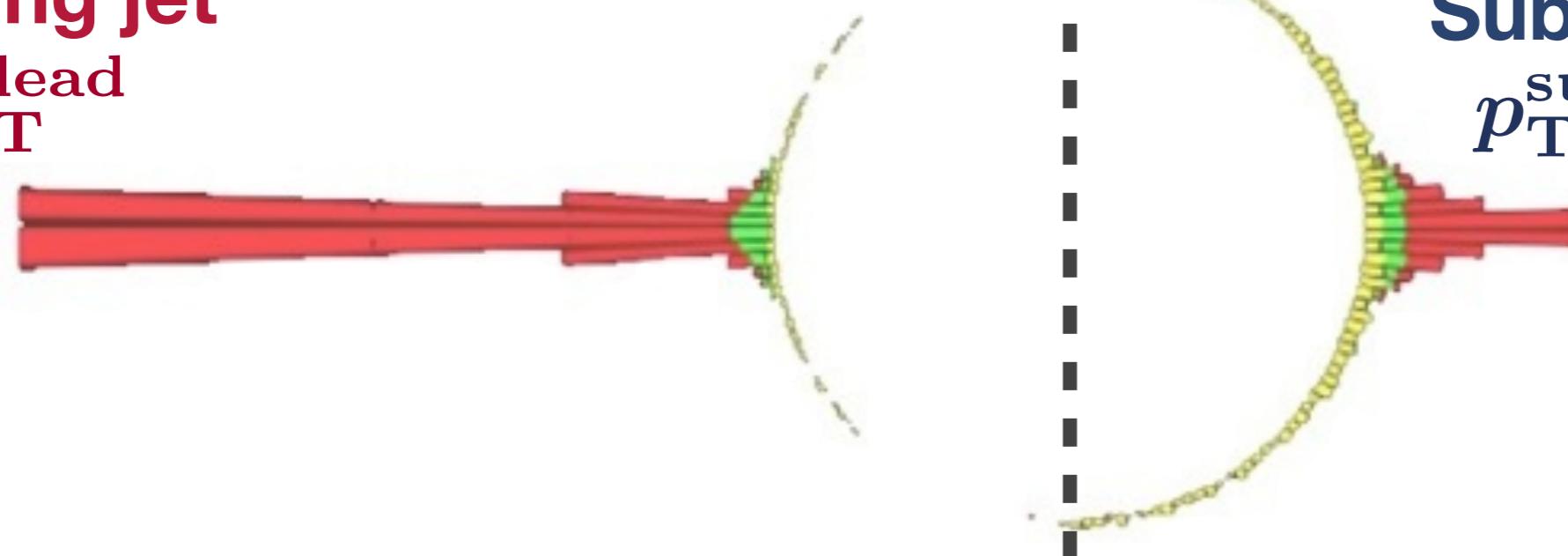
$$\sum_{i \in H_{\text{lead}}} \vec{p}_i \simeq - \sum_{i \in H_{\text{sub}}} \vec{p}_i$$



>8 GeV
4-8 GeV
1-4 GeV

Leading jet

p_T^{lead}



Subleading jet

$p_T^{\text{sub}} (< p_T^{\text{lead}})$

Motivations

- Full picture of jet quenching

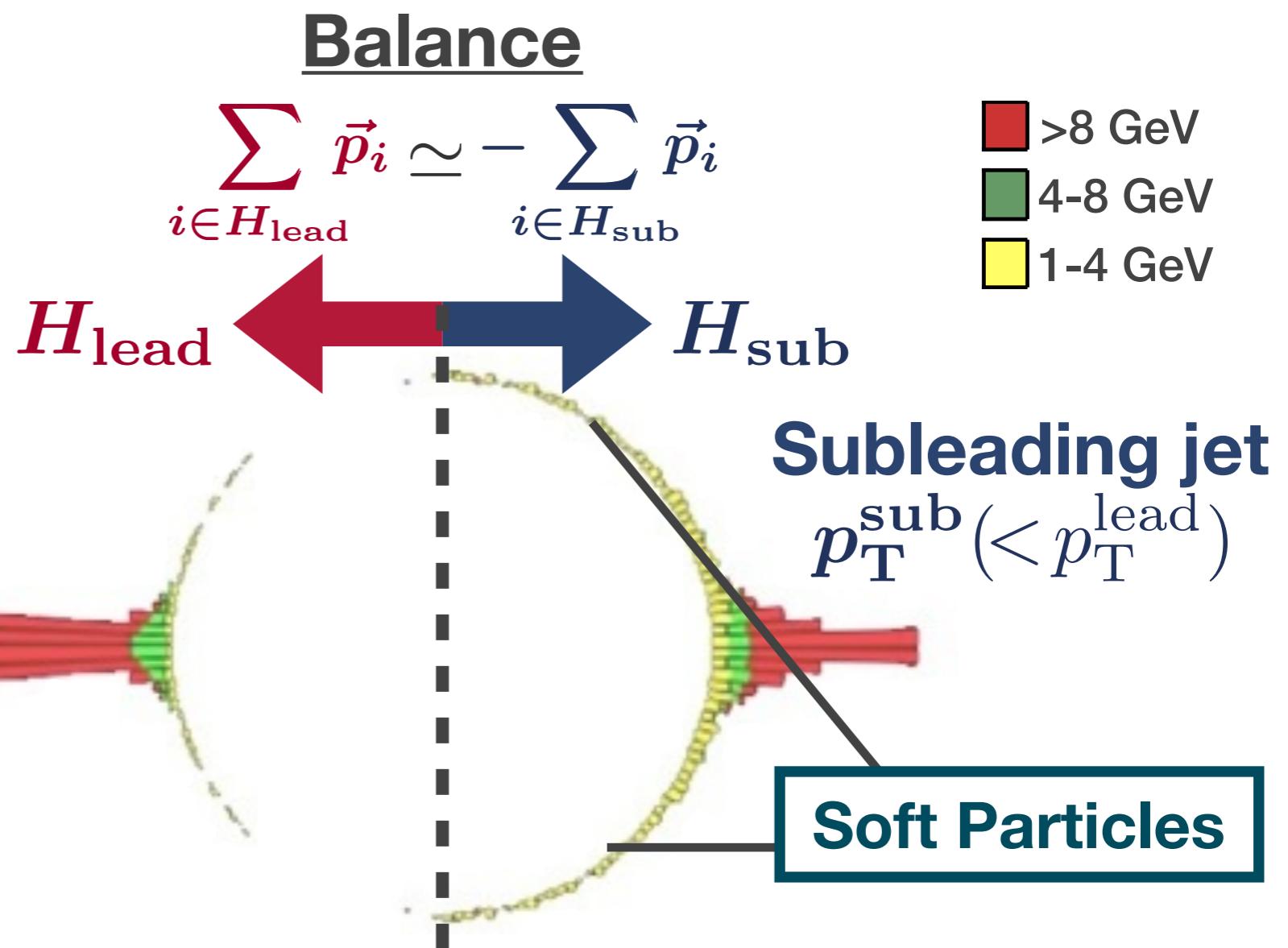
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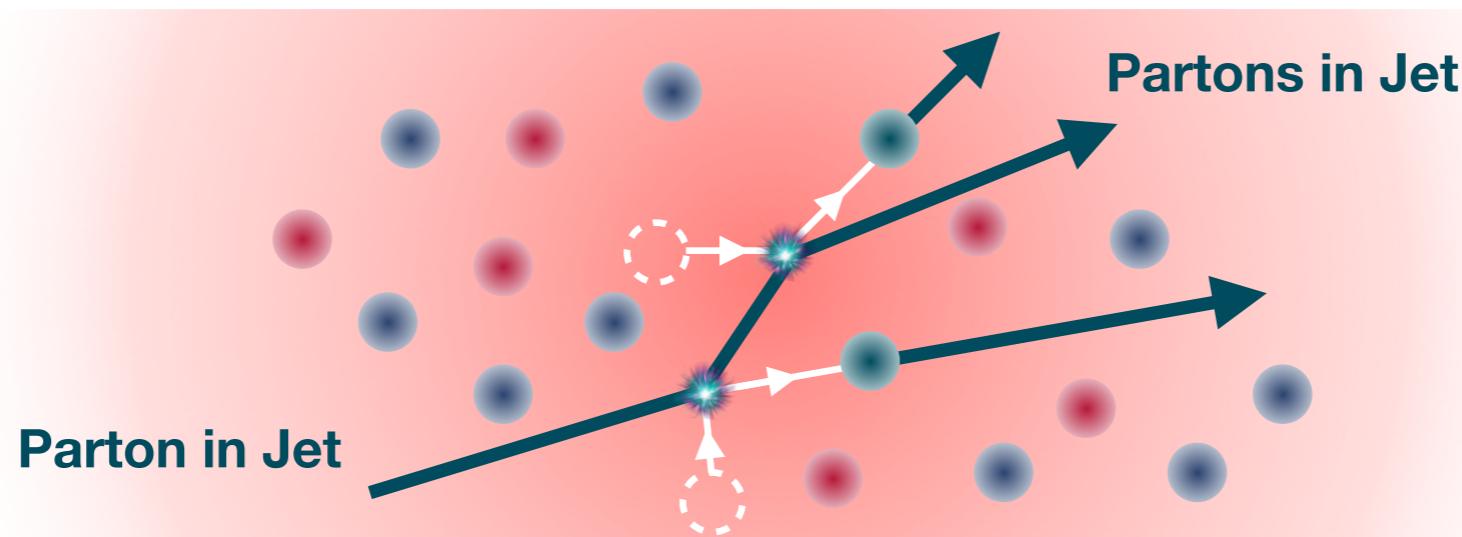
Result from entire processes in jet quenching

Models for medium response

Models: Recoil

- Monte-Carlo models for jet with recoil partons

- Far enough from thermalization in medium response (**hard**)
- Sampling of partons from thermalized medium for collisions
- Add the recoiled partons to the jet



JEWEL

K. C. Zapp, R. Kunnawalkam Elayavalli, J. G. Milhano, U. A. Wiedemann,...

Linearized Boltzmann Transport (LBT) Model

T. Luo, S. Cao, Y. He, X.-N. Wang, S.-L. Zhang, G.-Y. Qin, Y. Zhu,...

[Talk by X.-N. Wang and S.-L. Zhang]

[Poster by T. Luo and G.-Y. Qin]

MARTINI

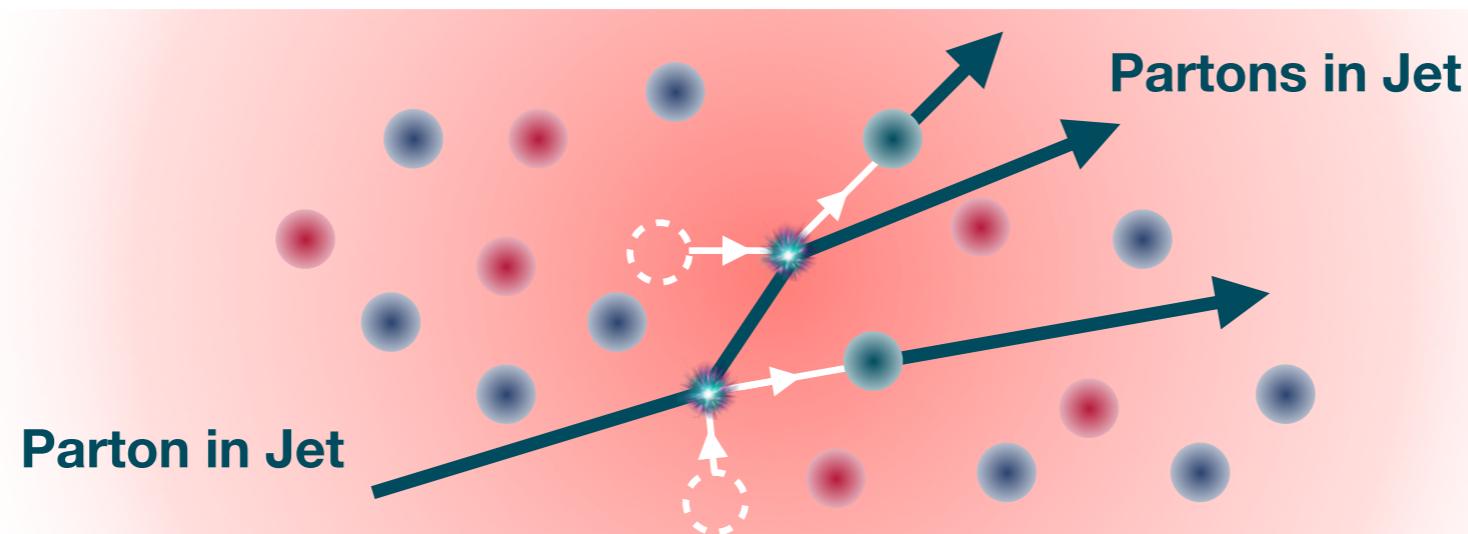
C. Park, S. Jeon, C. Gale, B. Schenke,...

[Talk by C. Park]

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[Talk by X.-N. Wang and S.-L. Zhang]

[Poster by T. Luo and G.-Y. Qin]

MARTINI

C. Park, S. Jeon, C. Gale, B. Schenke,...

[Talk by C. Park]

Recoils can interact with medium

Models: hydrodynamic response

● Jet evolution + full hydro model with source term

A. K. Chaudhuri, U. Heinz ('06), A. K. Chaudhuri ('06, '07), B. Betz, J. Noronha, G. Torrieri, M. Gyulassy, I. Mishustin, D. H. Rischke ('09), YT, T. Hirano ('14, '16), R. P. G. Andrade, J. Noronha, G. S. Denicol ('14), M. Schulc, B. Tomášik ('14)

- Medium response to thermalized energy and momentum (**soft**)
- Description by hydrodynamics together with medium

Hydrodynamic equation with source term

$$\partial_\mu T_{\text{fluid}}^{\mu\nu} = J_{\text{jet}}^\nu(x)$$

Energy-momentum tensor
of the QGP fluid

Energy and momentum
deposited from the jet

- Source term J_{jet}^ν constructed from jet evolution calculation
- Use Cooper-Frye for particles from medium response

Models: Hydrodynamic response

Coupled Jet-Fluid Model

YT, N.-B. Chang, G.-Y. Qin,...

[Poster by YT]

- Ideal hydro
- Sudden in-medium thermalization

Coupled LBT Hydro Model

W. Chen, T. Luo, S. Cao, L. Pang, X.-N. Wang,...

[Talk by X.-N. Wang]

- Ideal hydro → Viscous hydro
- **Recoil effects included**
 - Recoil with $p_{\text{LRF}} > p_{\text{cut}}$
 - kept in jet (**remnant recoil**)
 - Particle in jet with $p_{\text{LRF}} < p_{\text{cut}}$
 - absorbed in fluid via source term

p_{LRF} : momentum at local rest frame of the fluid

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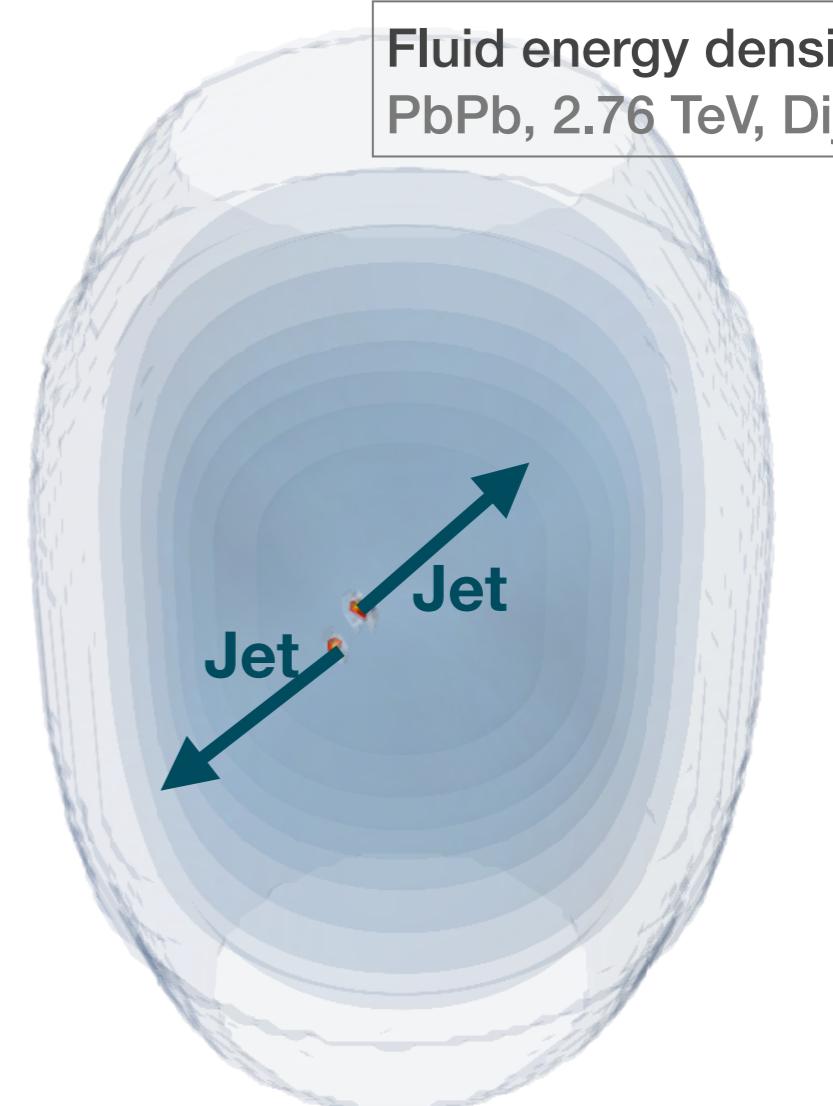
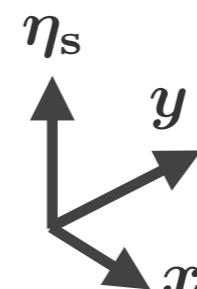
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Fluid energy density
PbPb, 2.76 TeV, Dijet

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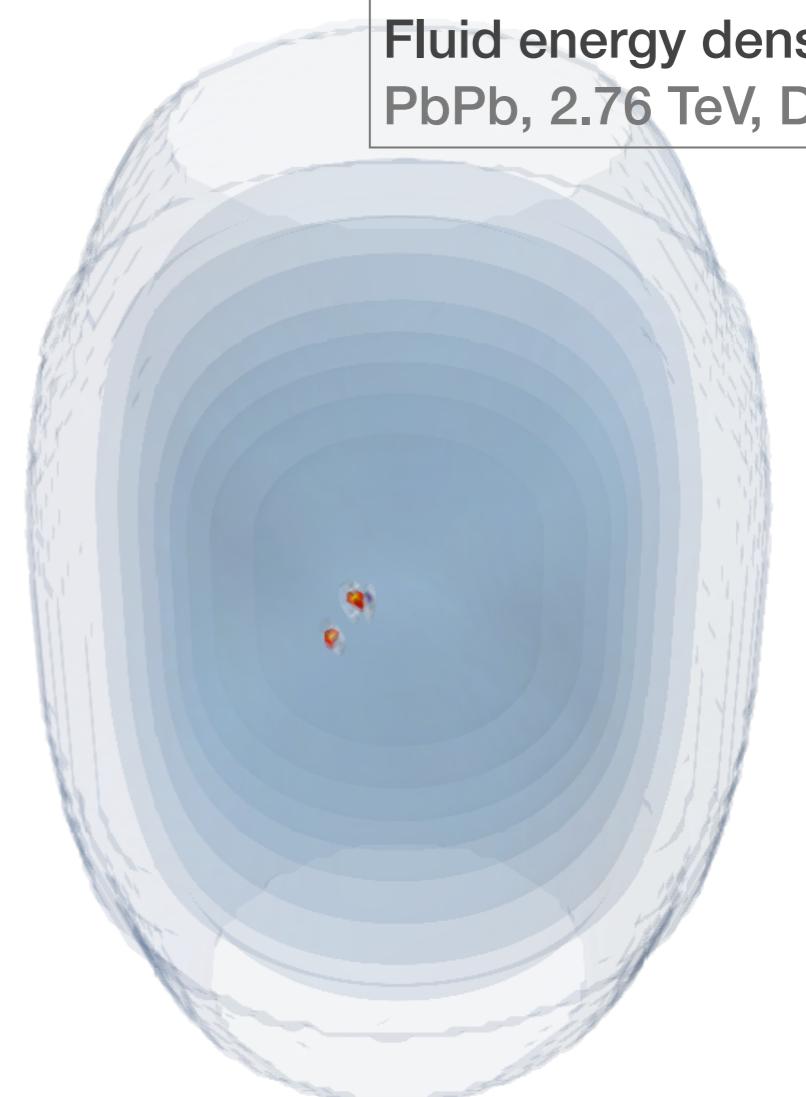
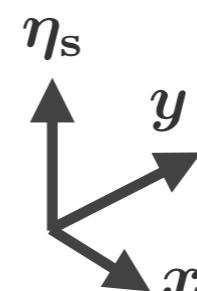
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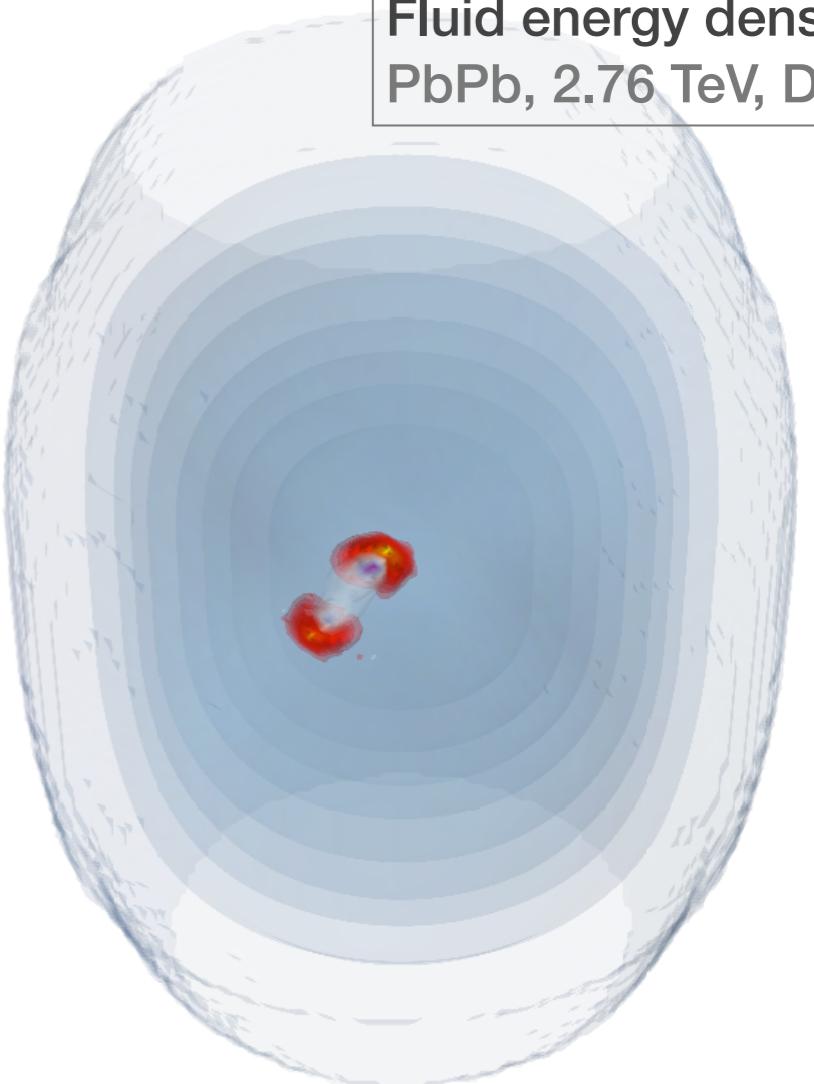
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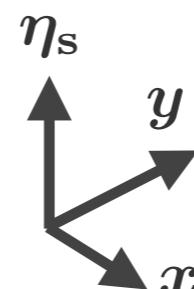


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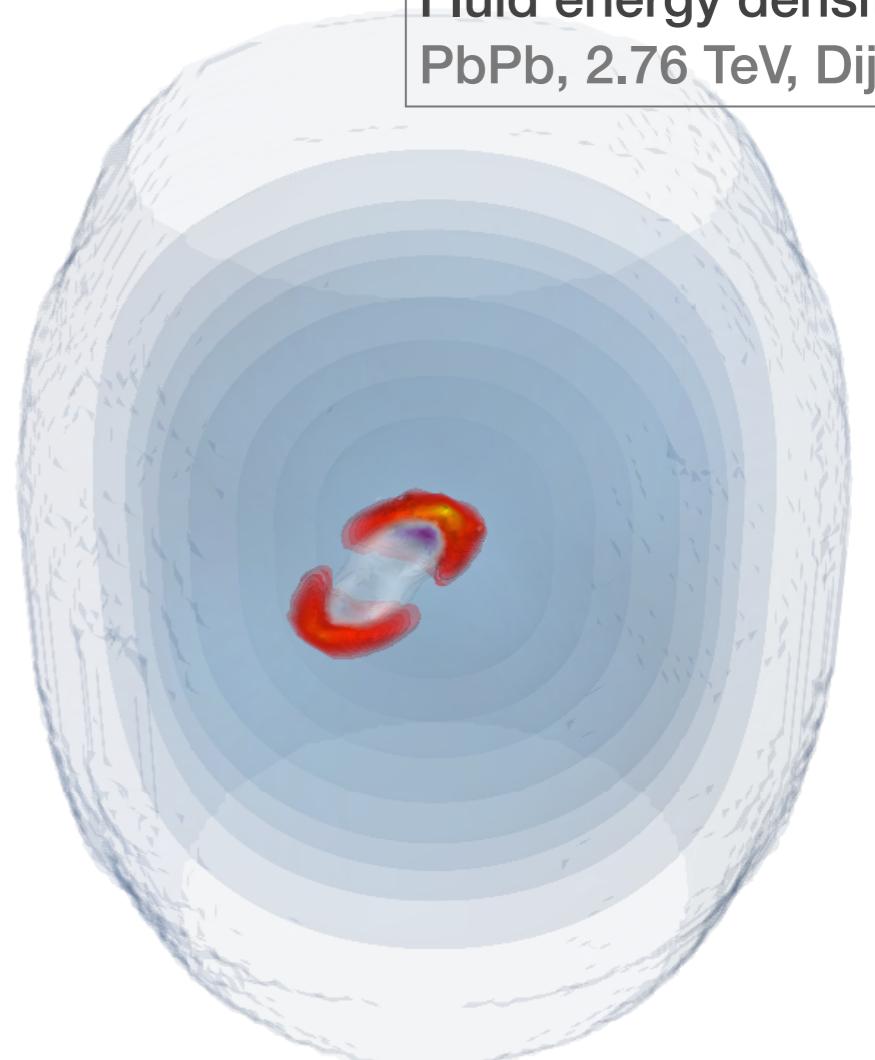
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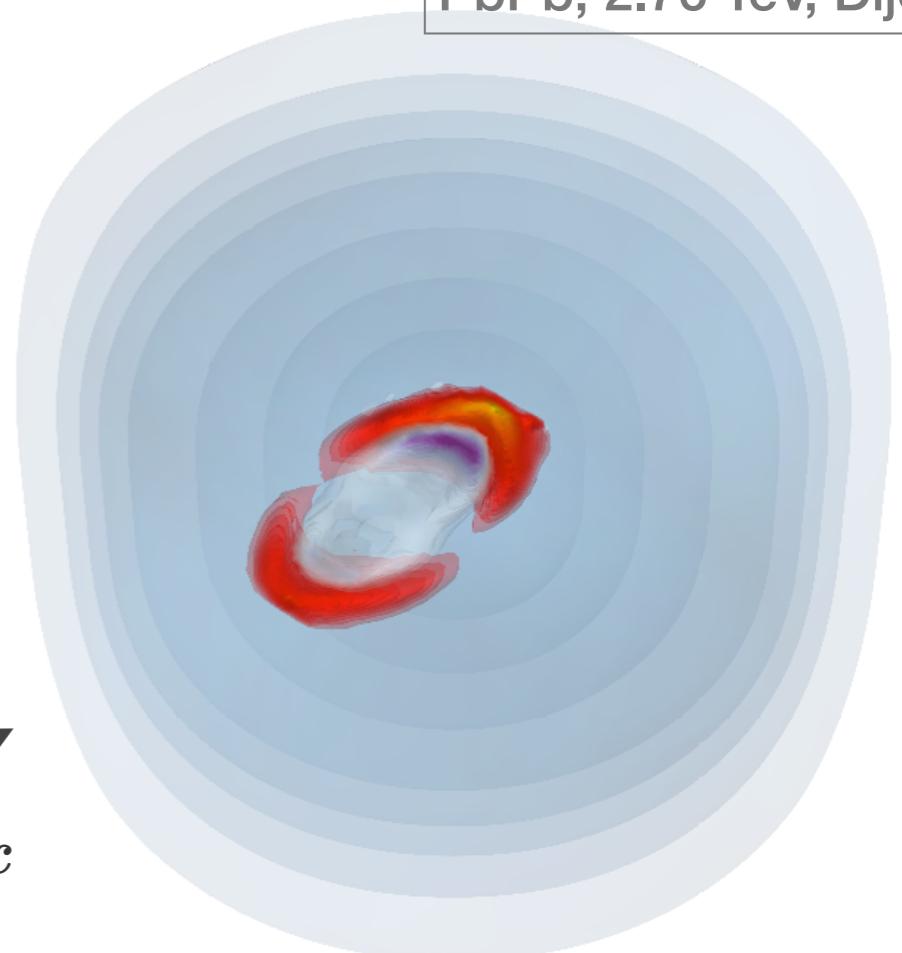
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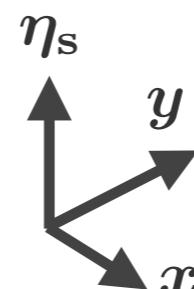
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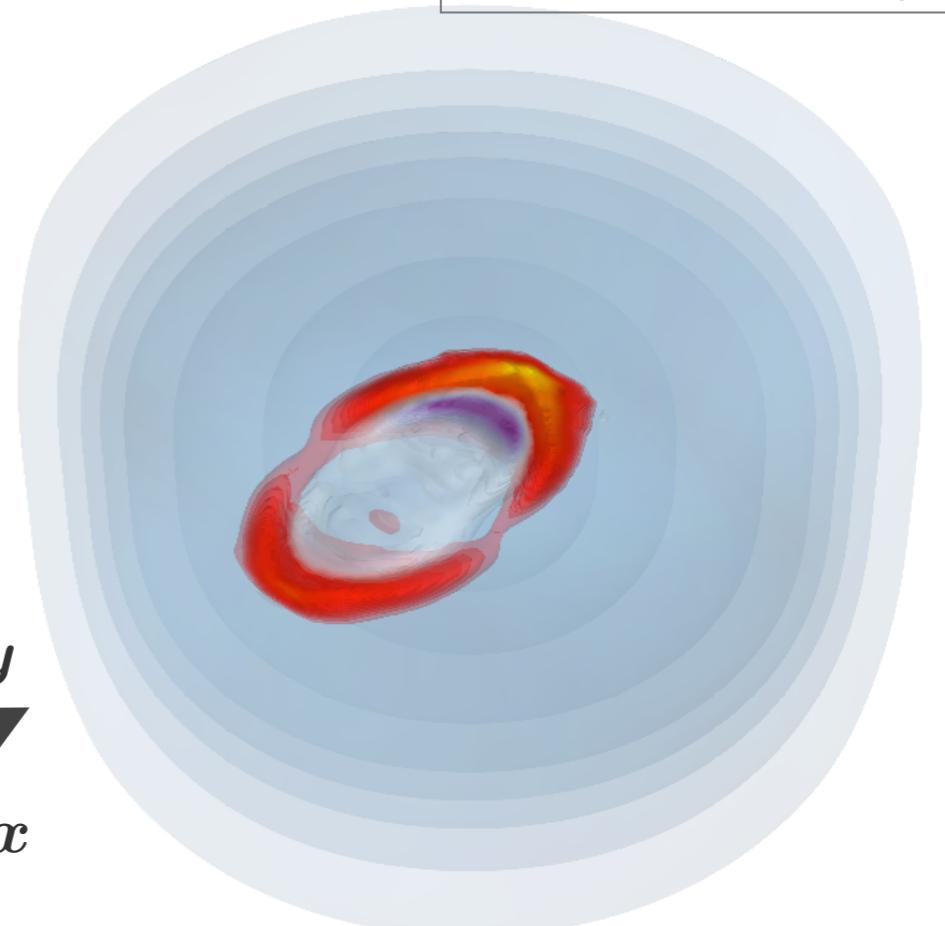
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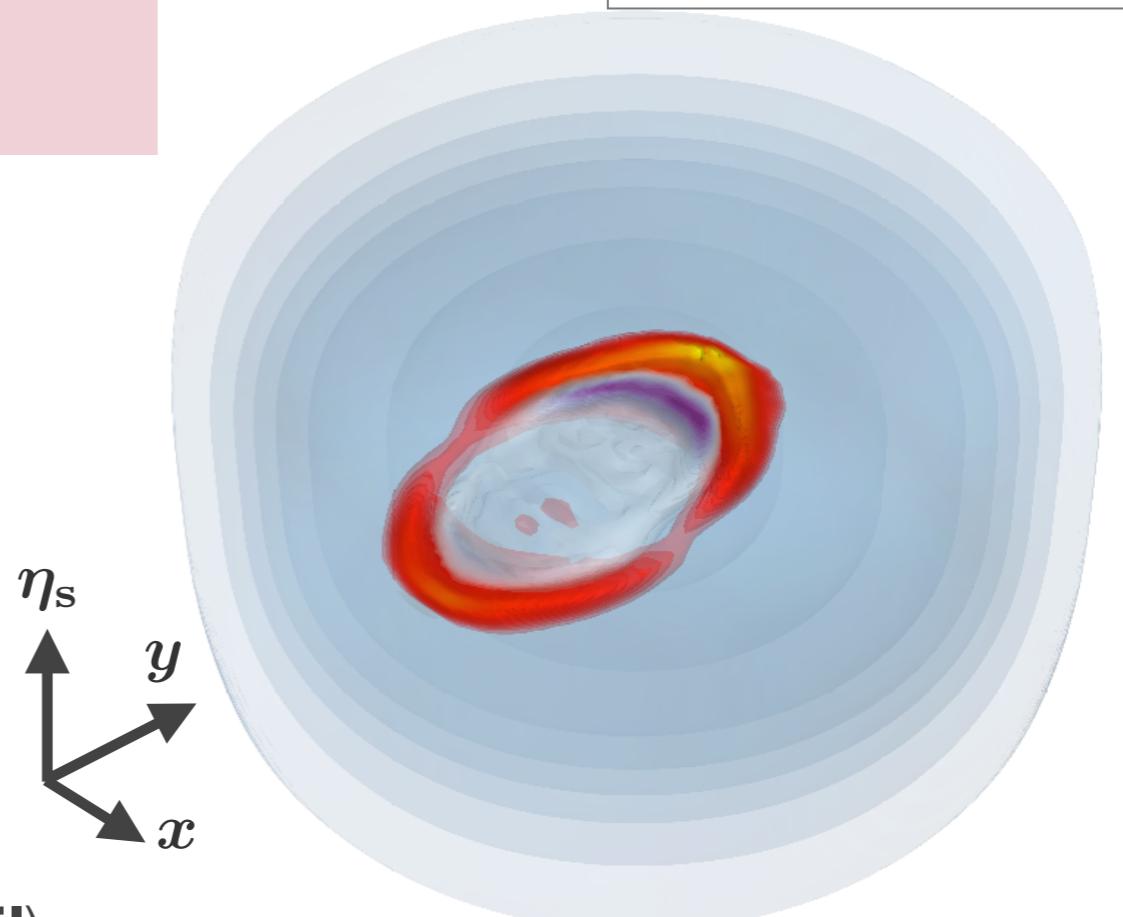
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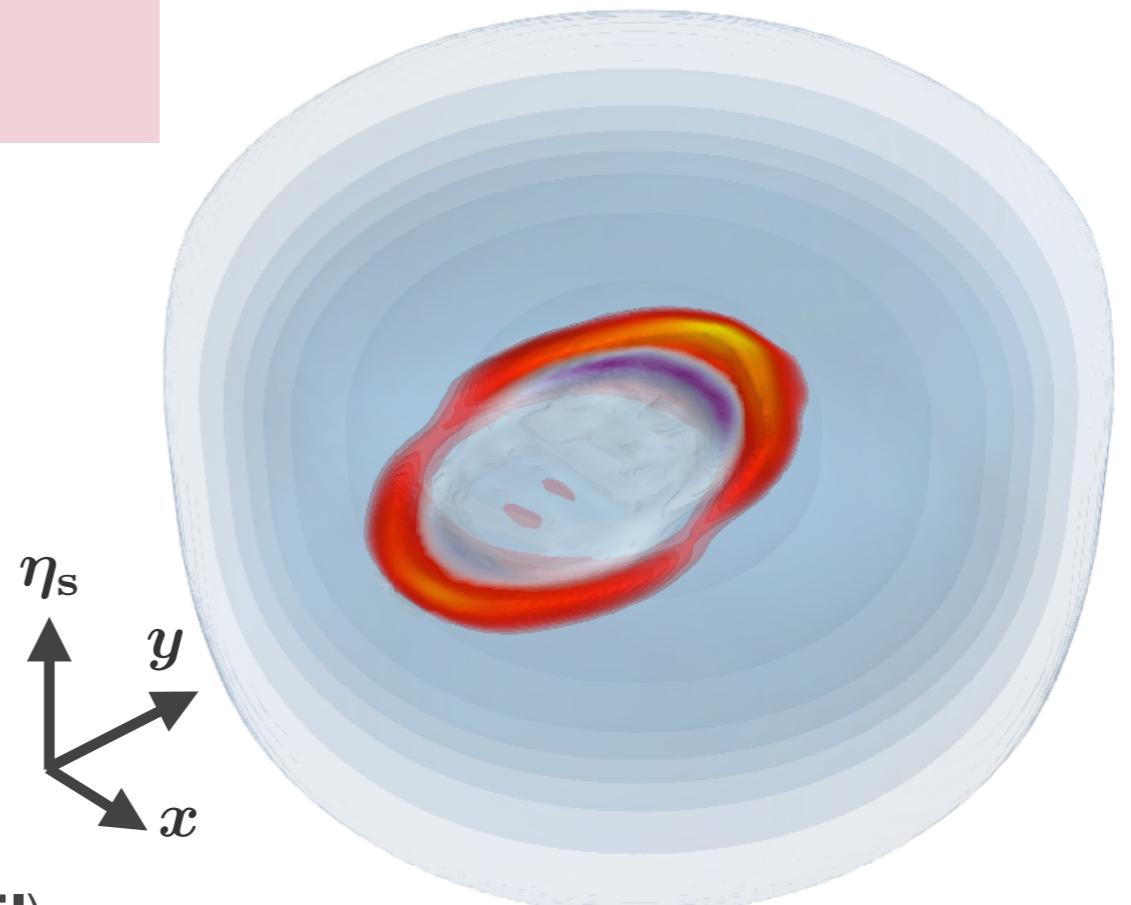
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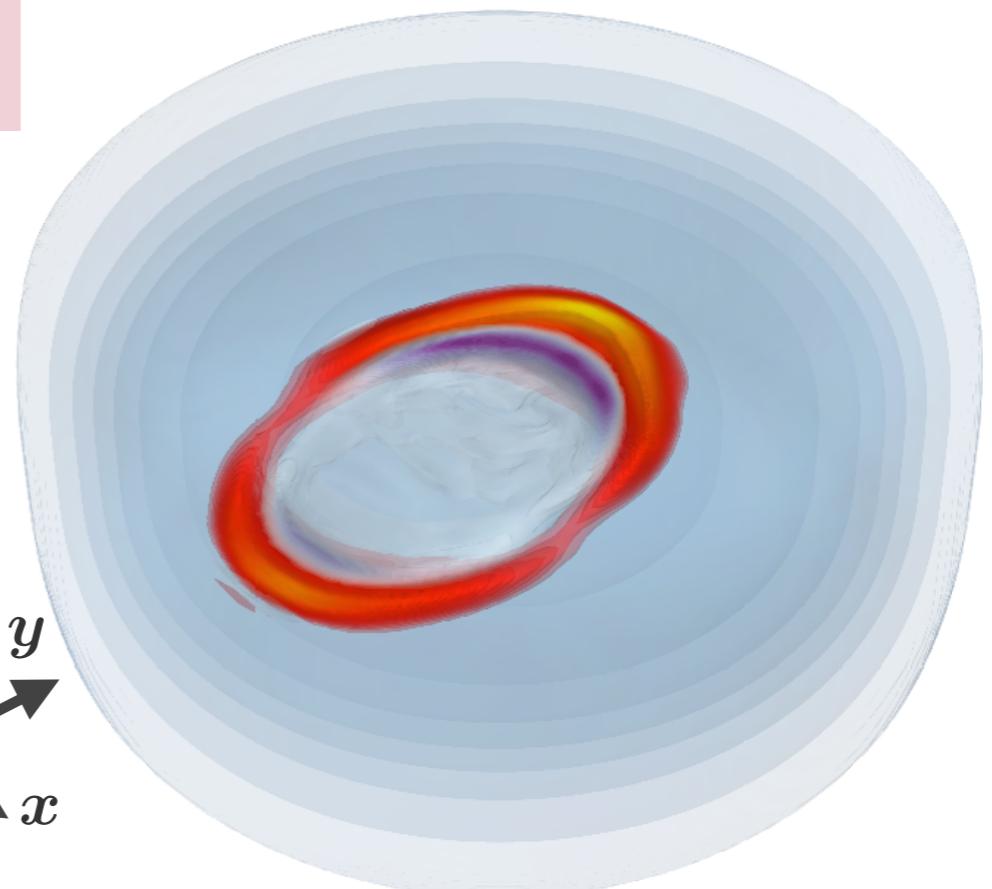
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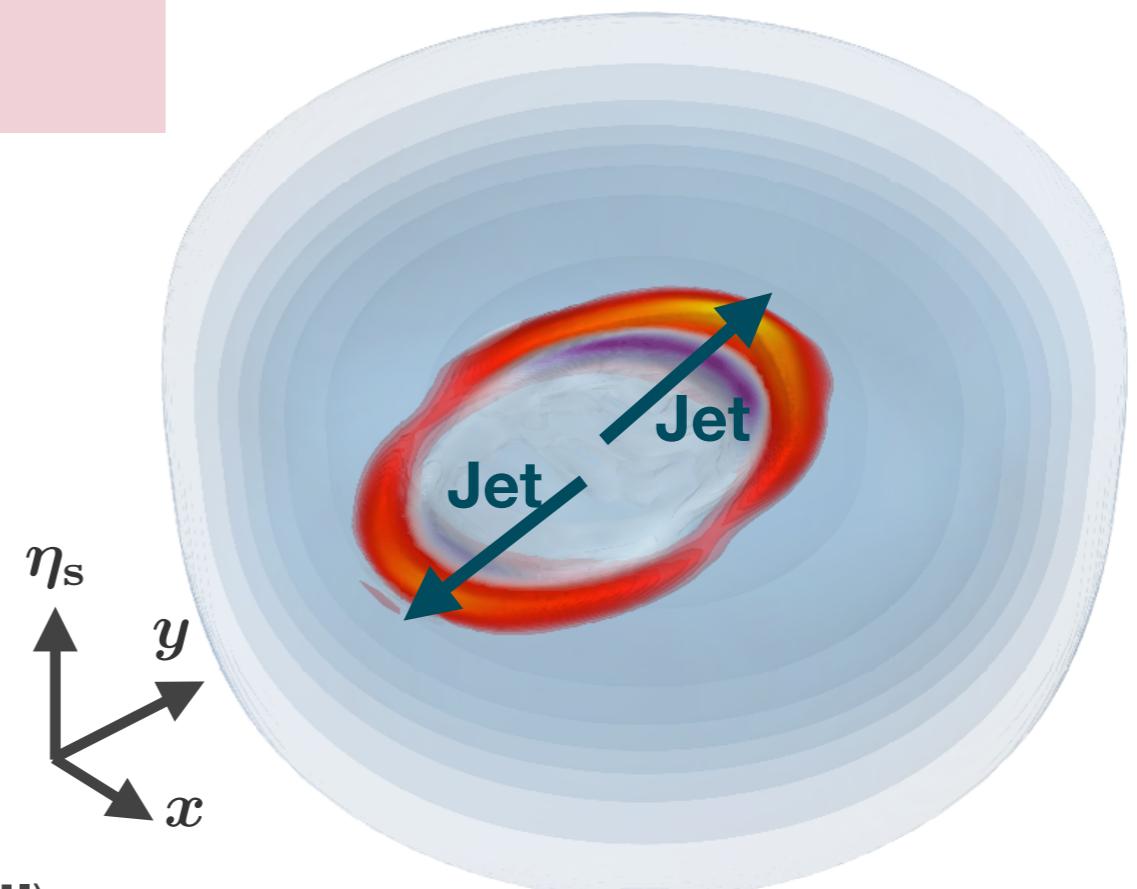
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Models: Others

● Estimation of medium response contribution

- Deposited energy as a perturbation (no propagation)

Hybrid Strong/Weak Coupling Model

D. Pablos, Z. Hulcher, J. Casalderrey-Solana, K. Rajagopal, J. G. Milhano D. C. Gulhan

[Talk by D. Pablos]

[Poster by Z. Hulcher]

● Boltzmann equation based approach

- Particle picture description both for medium and jet

AMPT

G.-L. Ma, X.-N. Wang, Z. Gao, A. Luo, H.-Z. Zhang, G.-Y. Qin,...

[Poster by A. Luo]

BAMPS

I. Bouras, Z. Xu, C. Greiner, B. Betz,...

● Linearized viscous hydrodynamics with source term

G.-Y. Qin, A. Majumder, H. Song, U. Heinz ('09), R. B. Neufeld, B. Muller ('10), R. B. Neufeld, T. Renk ('10), R. B. Neufeld, I. Vitev ('12), A. Ayala, I. Dominguez, J. Jalilian-Marian, M. E. Tejeda-Yeomans ('09), L. Yan, S. Jeon, C. Gale ('17),...

- Good approach to study Mach cone with fluid properties

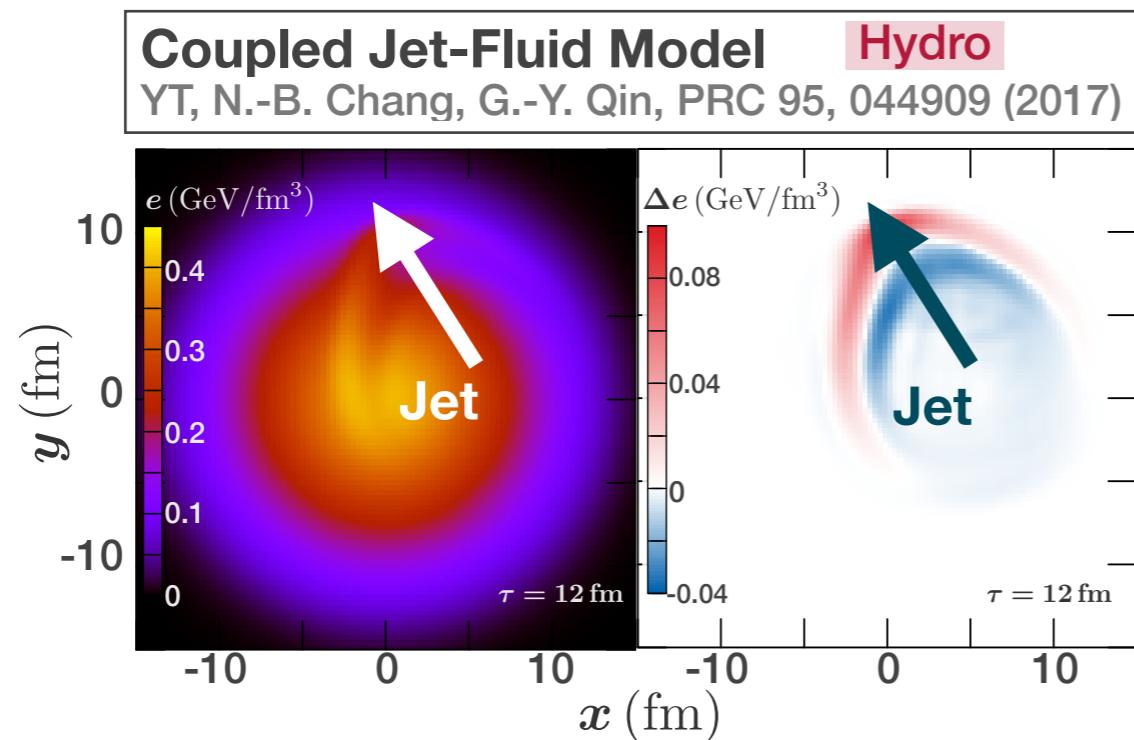
Models: Brief summary

	JEWEL	LBT	MARTINI	Coupled Jet-Fluid	Coupled LBT Hydro
Energy loss model	BDMPS-Z	Higher-Twist	AMY	Higher-Twist	Higher-Twist
Monte Carlo jet evolution	✓	✓	✓		✓
Recoil	✓	✓	✓		✓
Recoil-medium interaction		✓	✓		✓
Hydro response via source term				✓	✓ (concurrent)

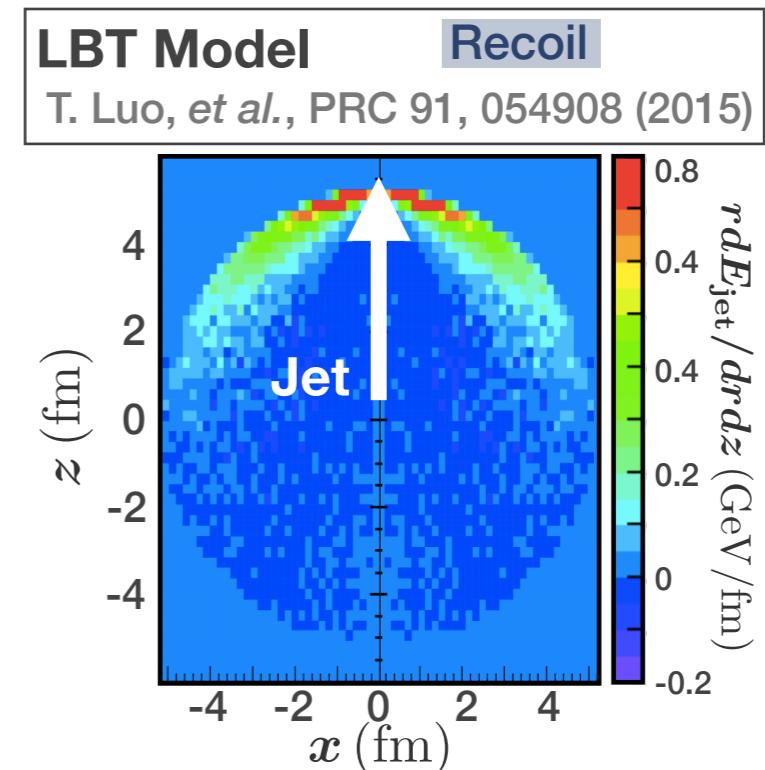
Results from recent theoretical studies

Structures of medium response

Mach cone as hydro response

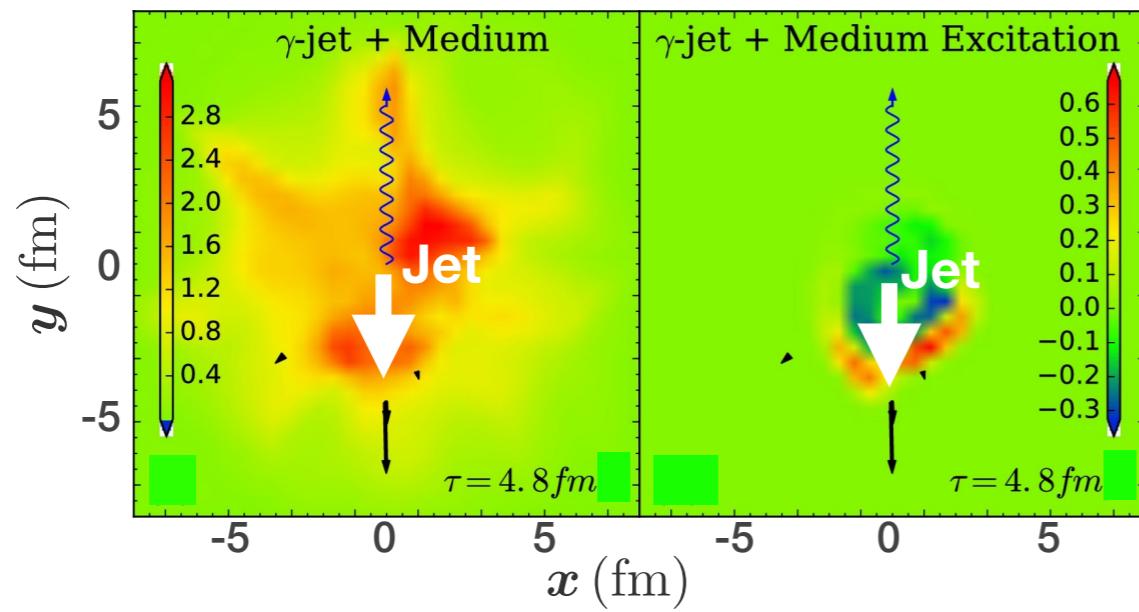


Mach cone-like structure



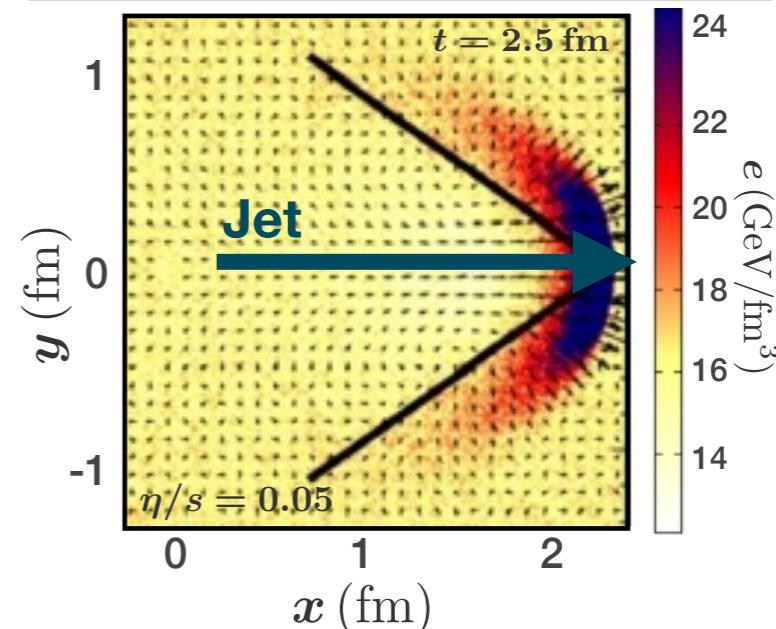
Coupled LBT Hydro Model Recoil+Hydro

W. Chen, et al., PLB 777, 86 (2018)



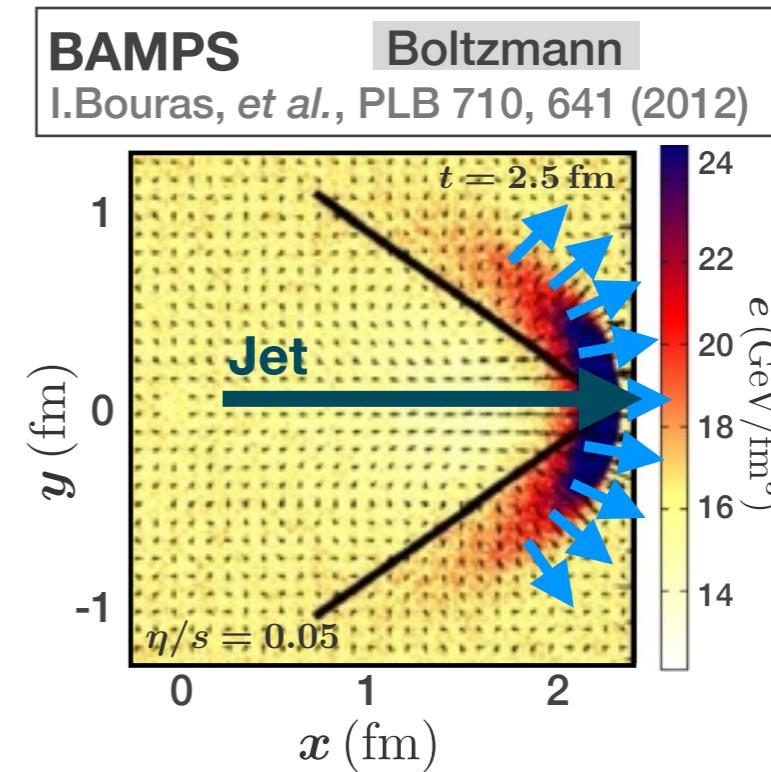
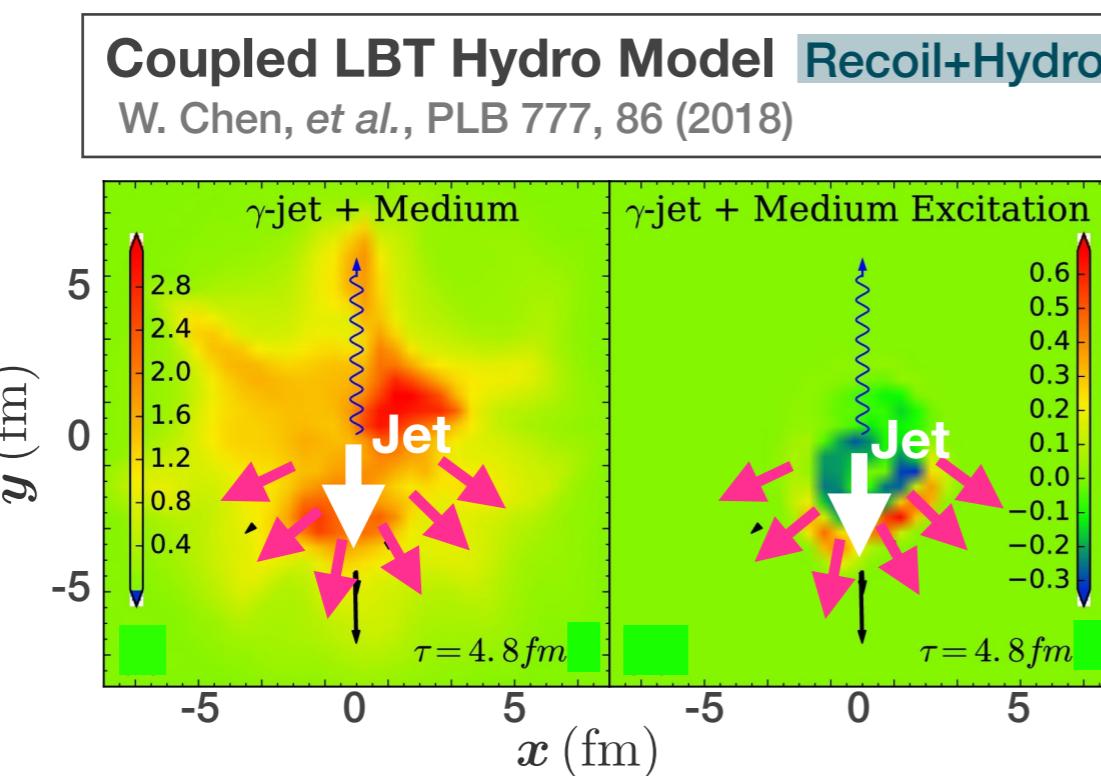
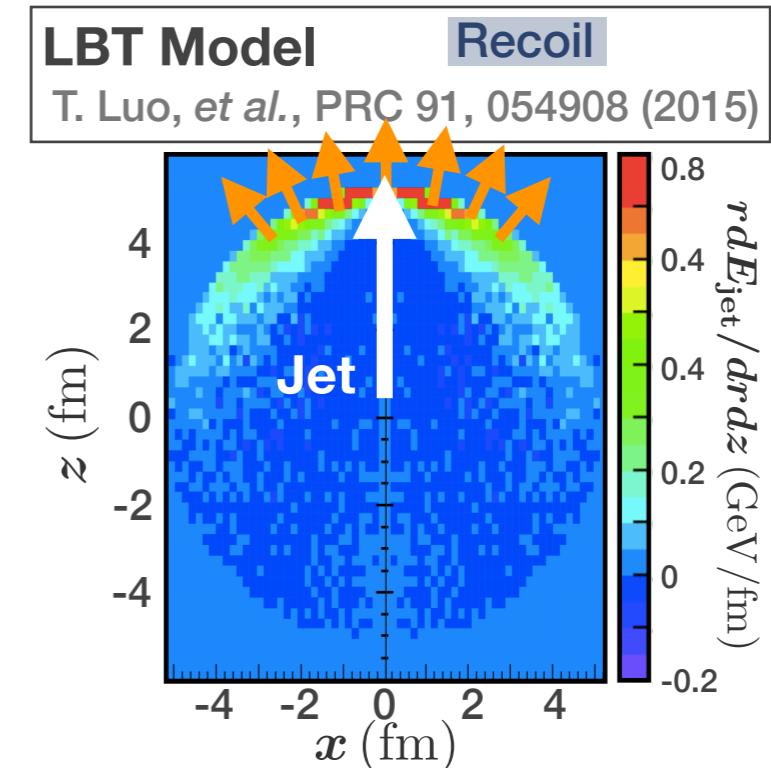
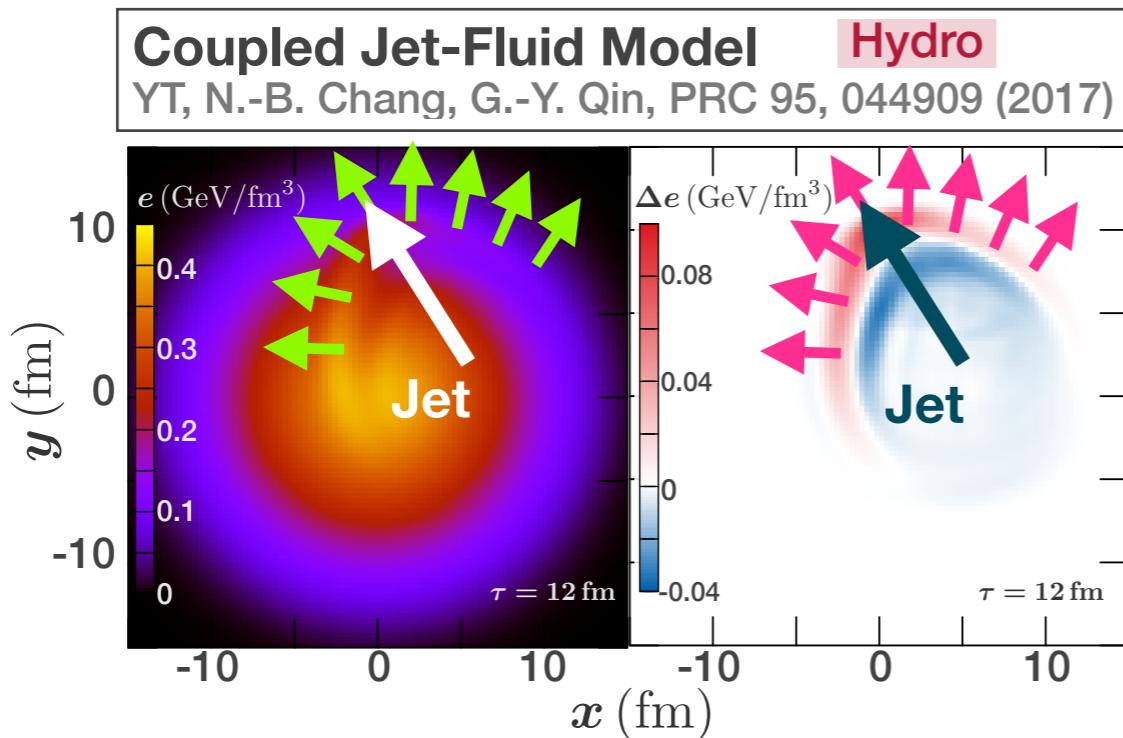
BAMPS Boltzmann

I.Bouras, et al., PLB 710, 641 (2012)



Structures of medium response

Momentum transport away from jet

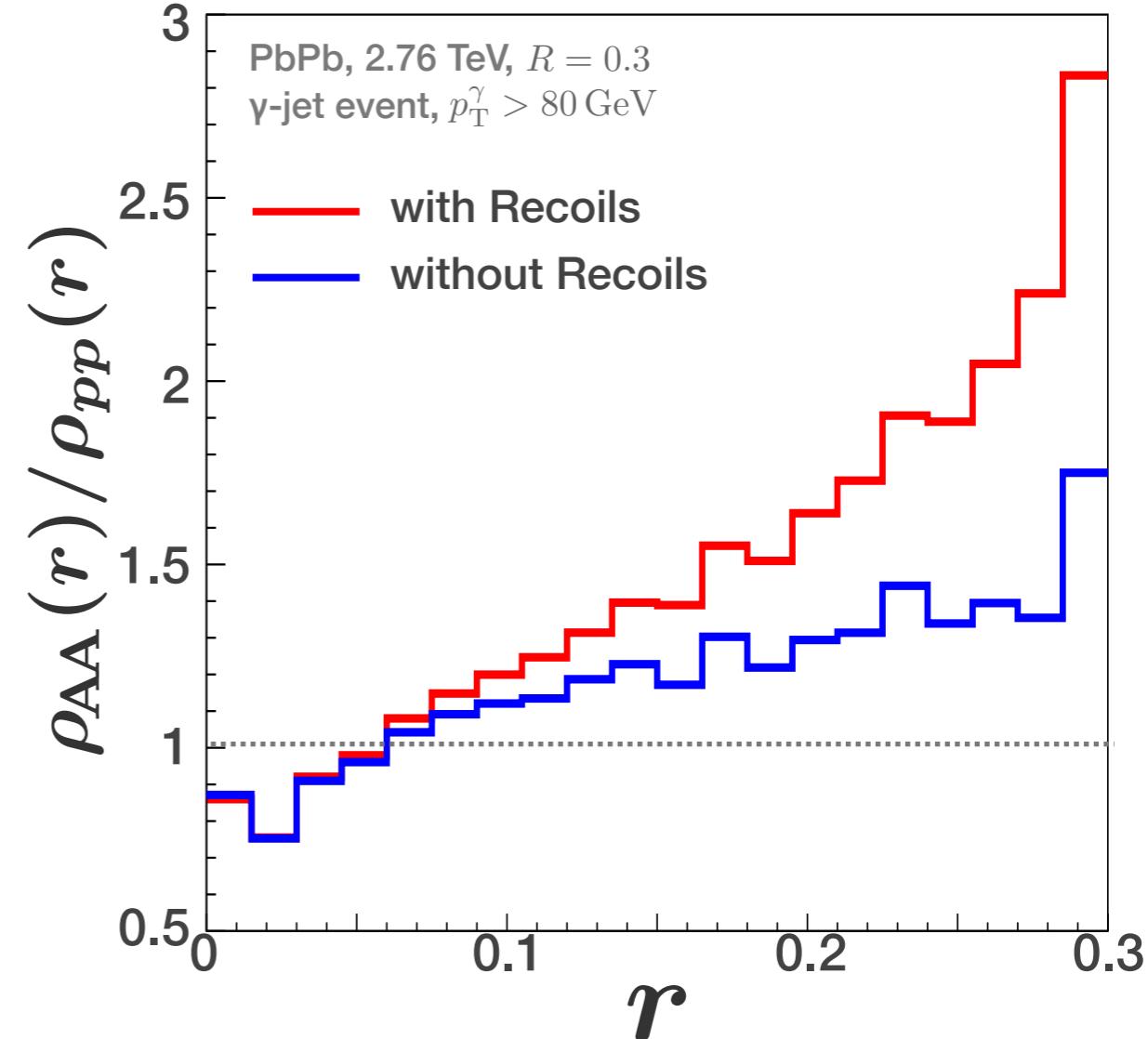
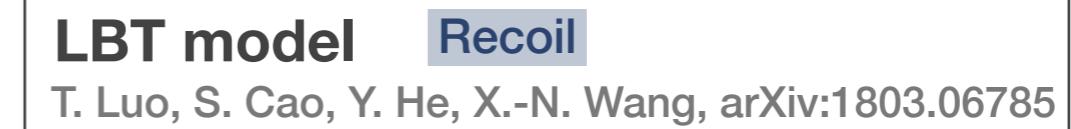
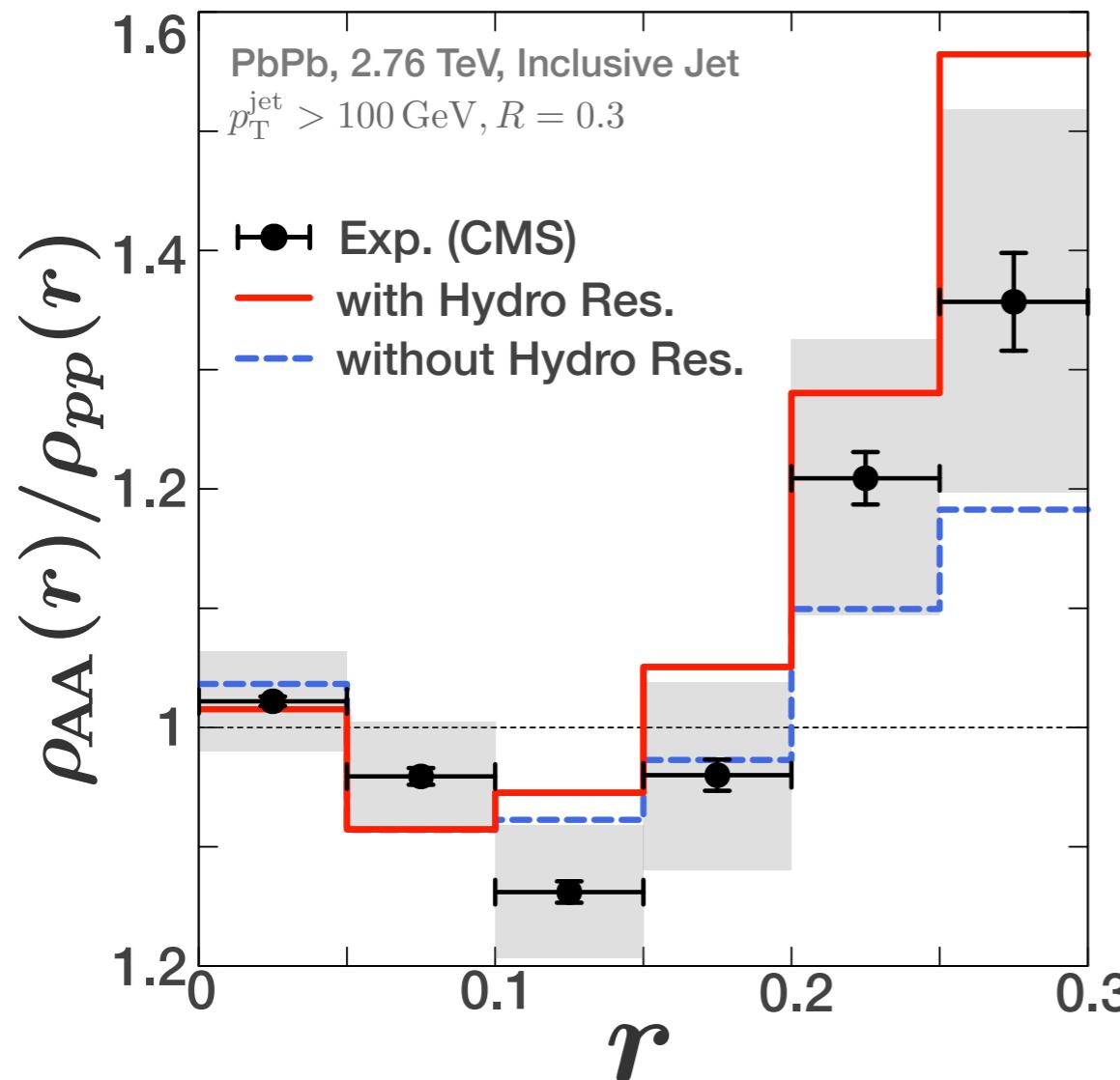
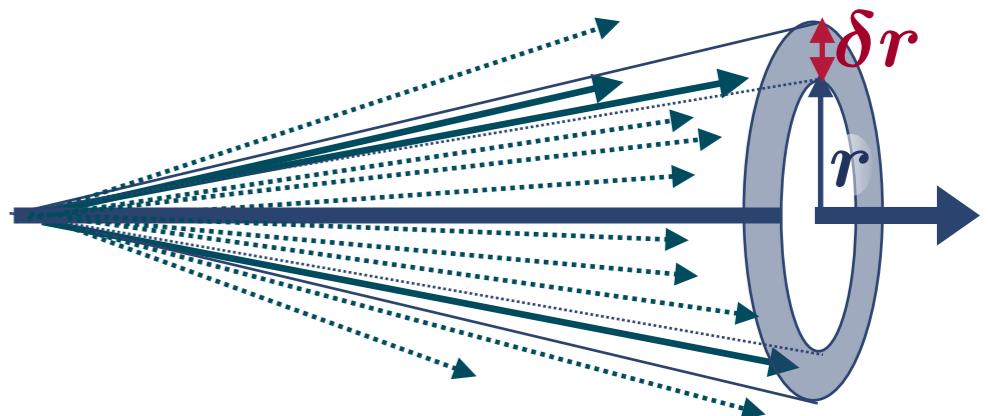


Angular structures of jets

- Jet Shape Function

$$\rho(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \left[\frac{1}{p_T^{\text{jet}}} \frac{\sum_{\text{trk} \in (r - \delta r/2, r + \delta r/2)} p_T^{\text{trk}}}{\delta r} \right]$$

$(r = \sqrt{(\eta_p - \eta_{\text{jet}})^2 + (\phi_p - \phi_{\text{jet}})^2})$

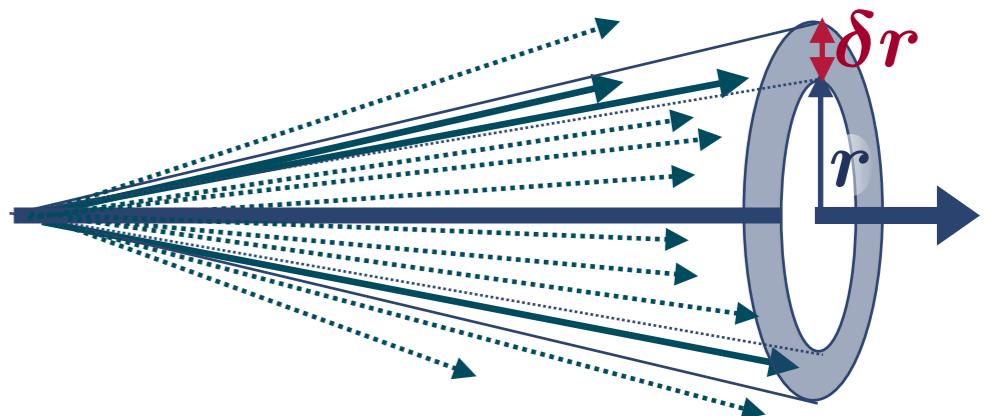


Angular structures of jets

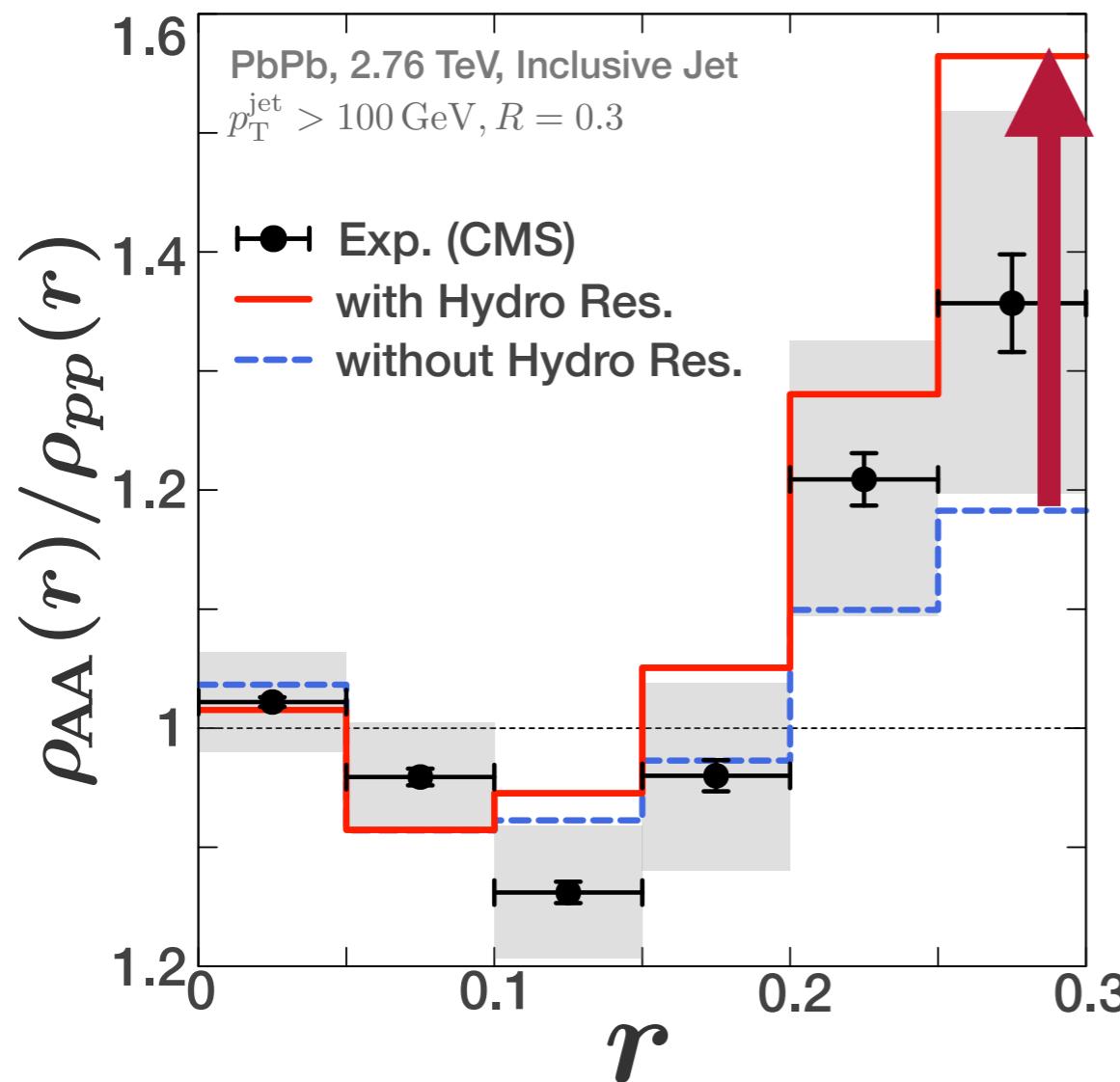
- Jet Shape Function

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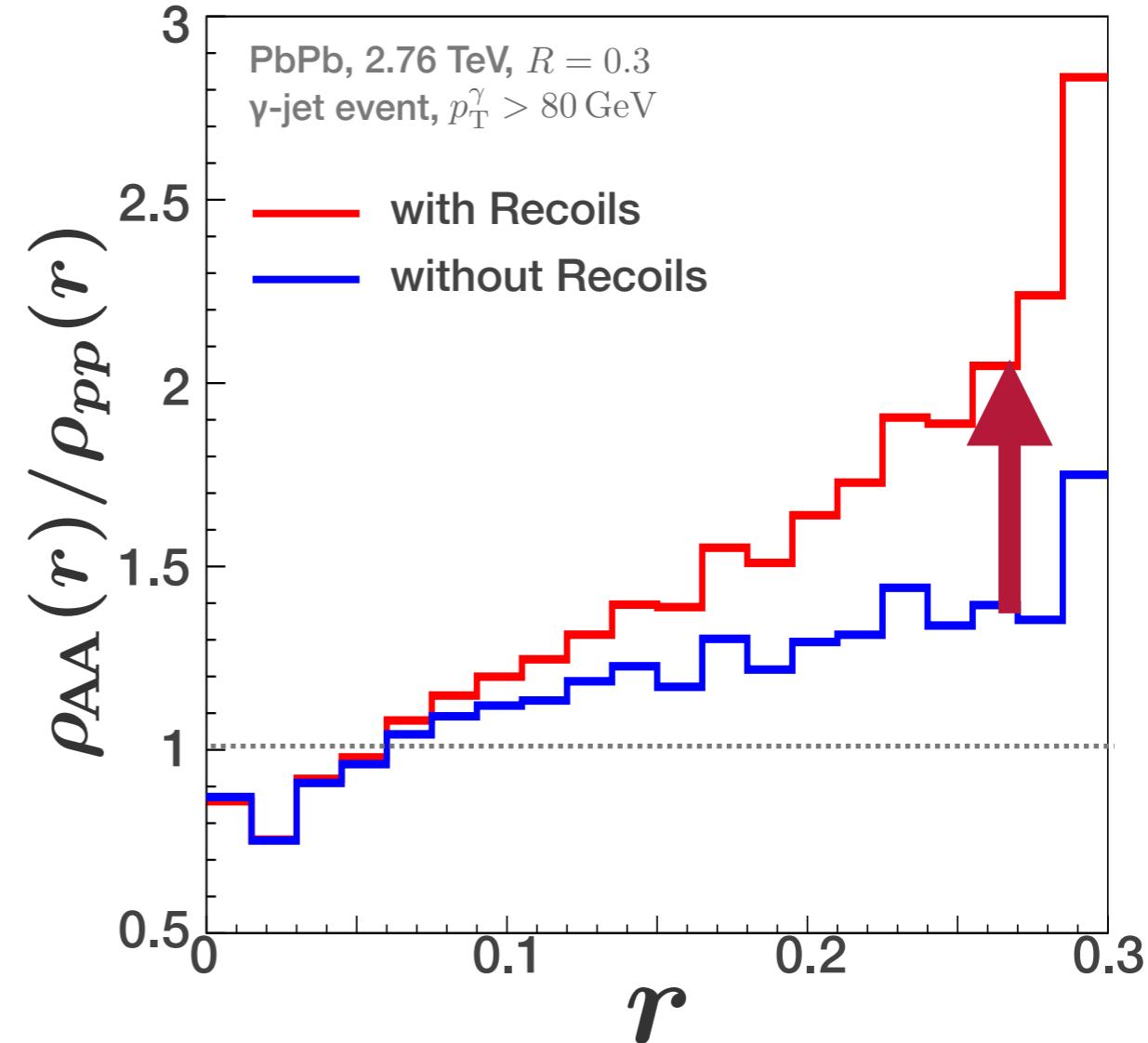
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Coupled Jet-Fluid Model Hydro
YT, N.-B. Chang, G.-Y. Qin, PRC 95, 044909 (2017)



LBT model Recoil
T. Luo, S. Cao, Y. He, X.-N. Wang, arXiv:1803.06785

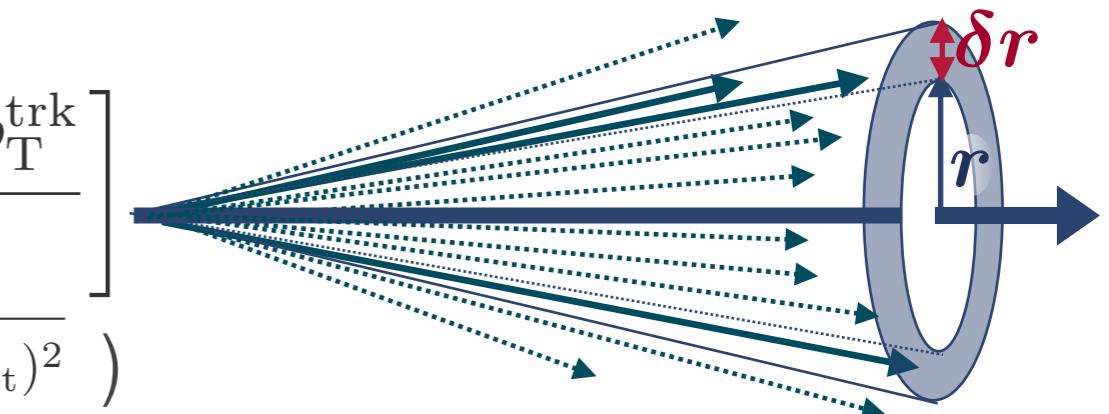


Angular structures of jets

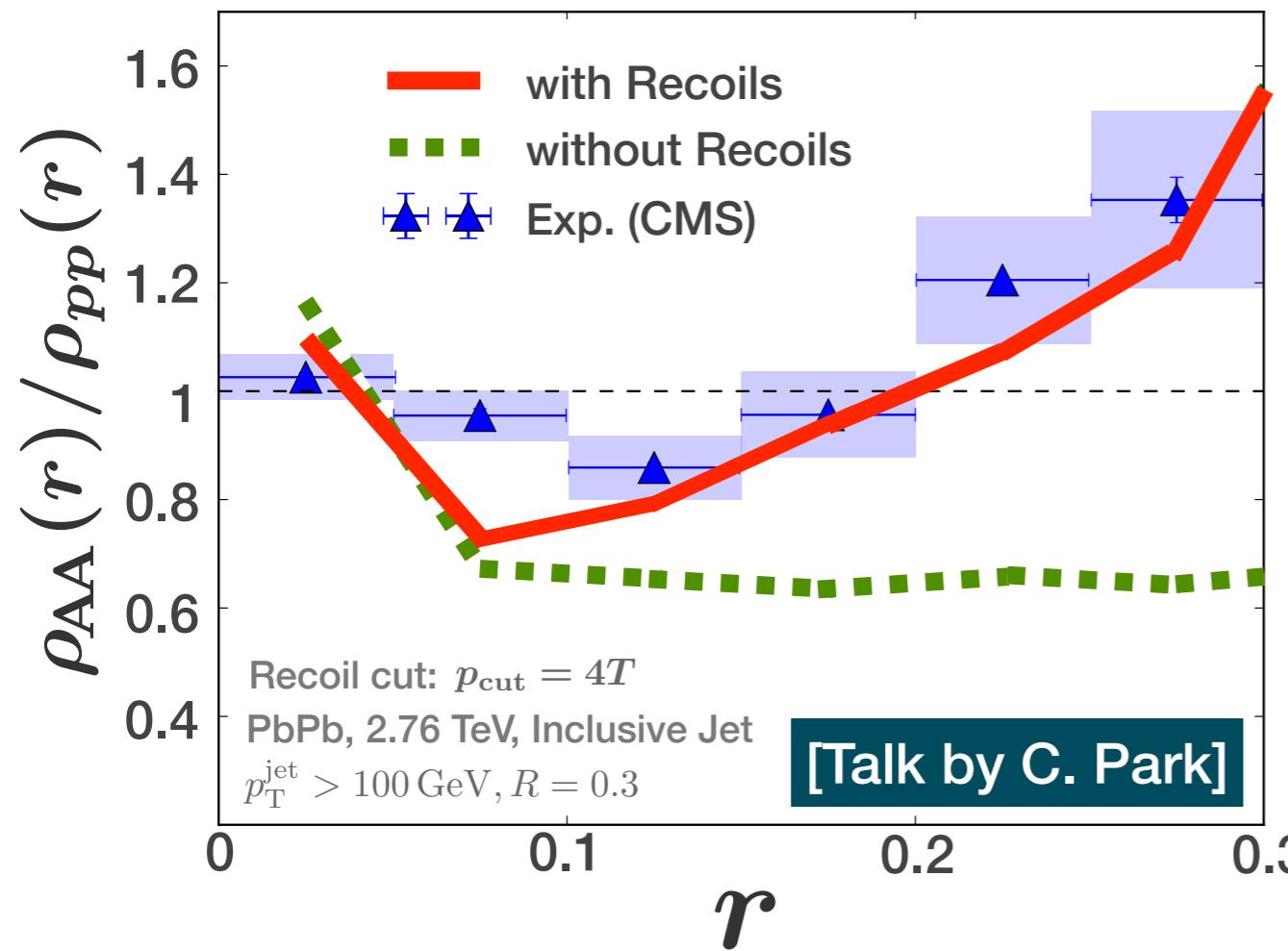
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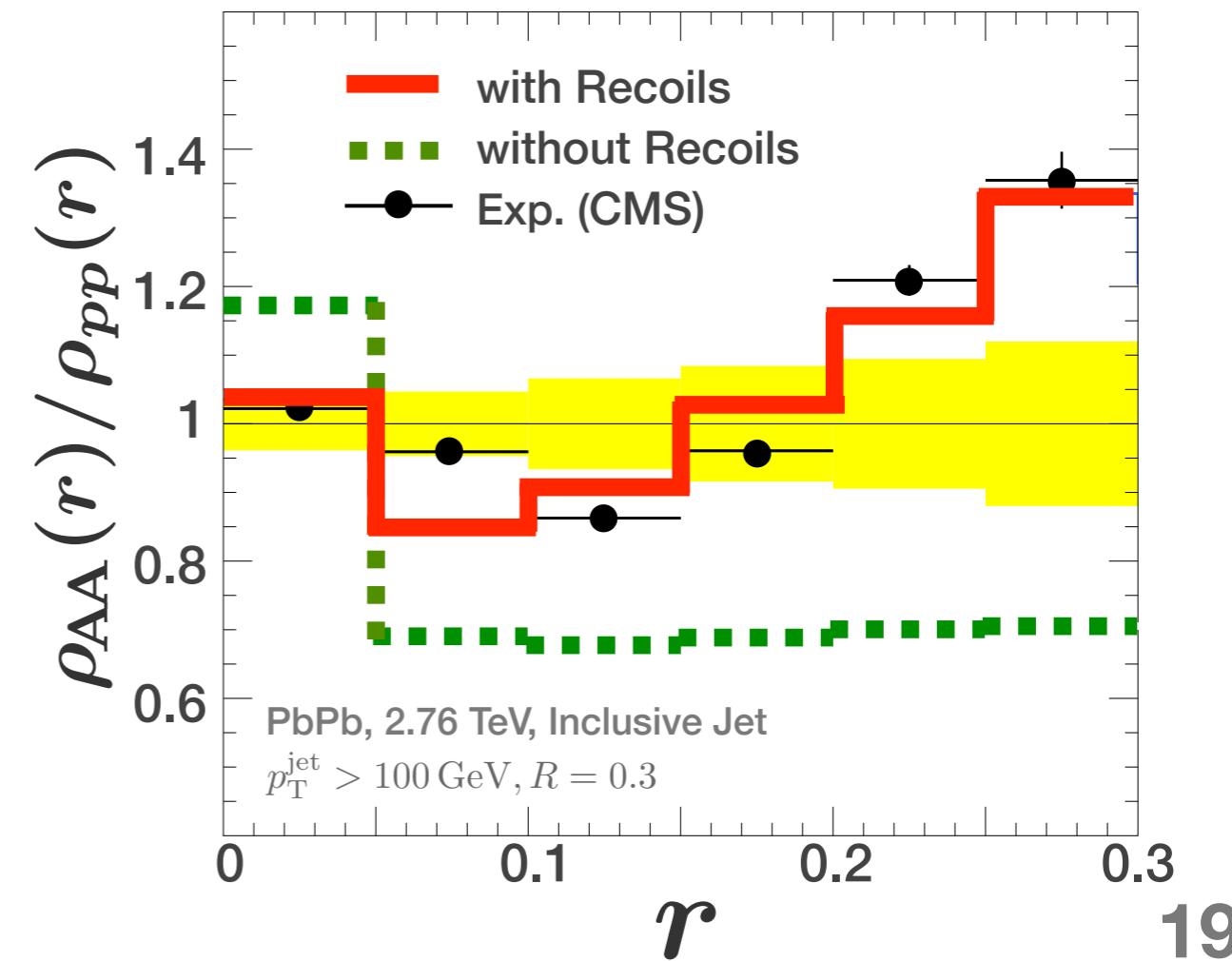
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MARTINI Recoil
C. Park, S. Jeon, C. Gale ('18)



JEWEL Recoil
R. Kunnawalkam Elayavalli, K. C. Zapp, JHEP 1707, 141 (2017)

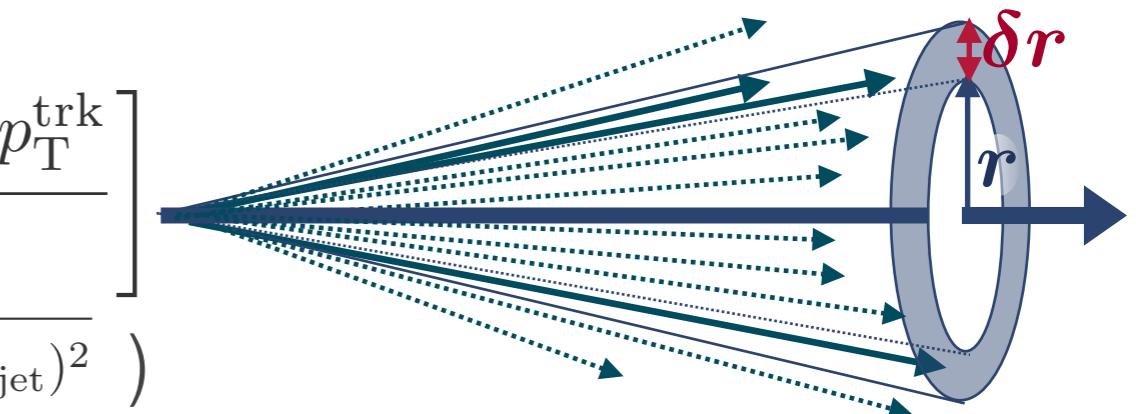


Angular structures of jets

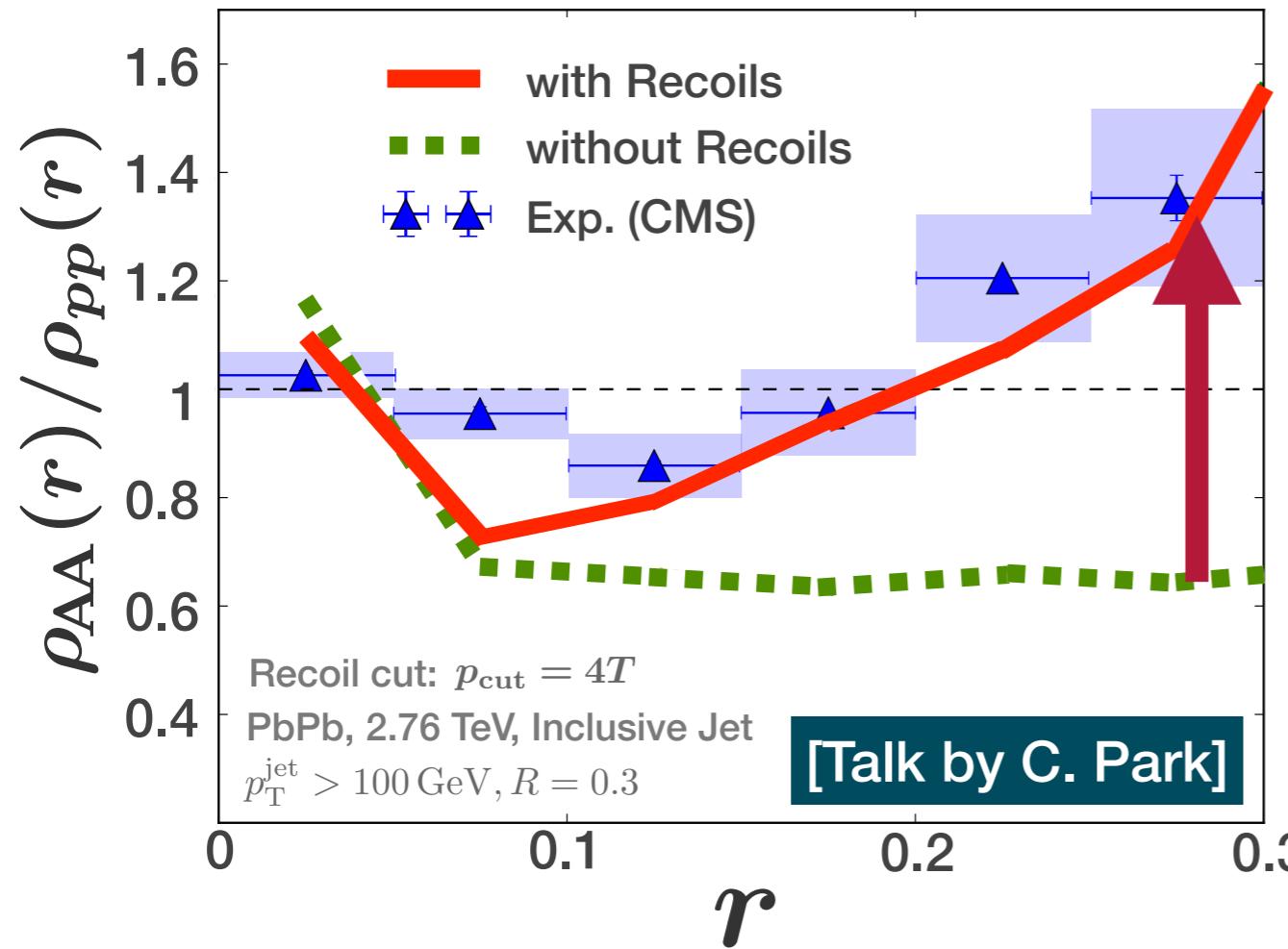
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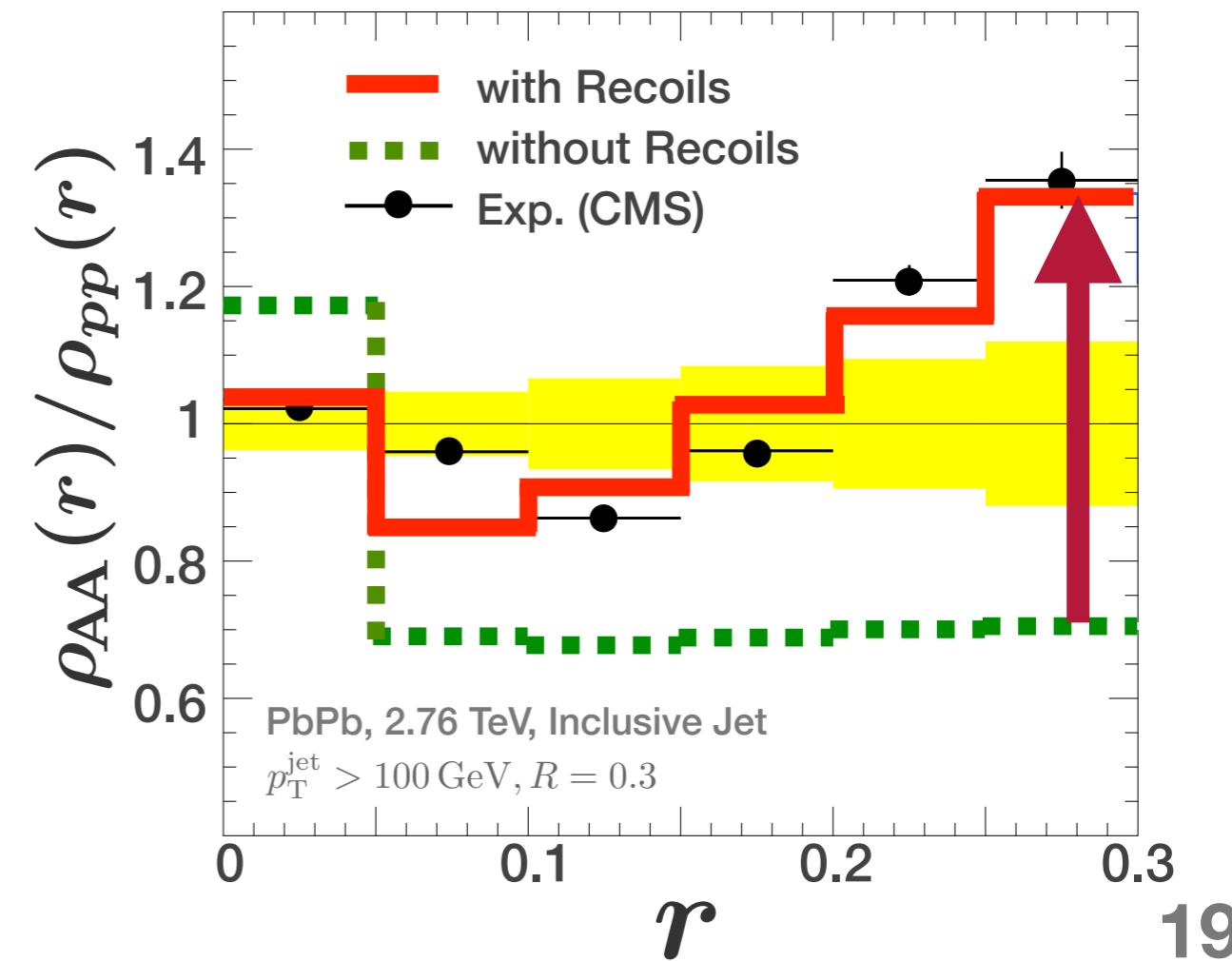
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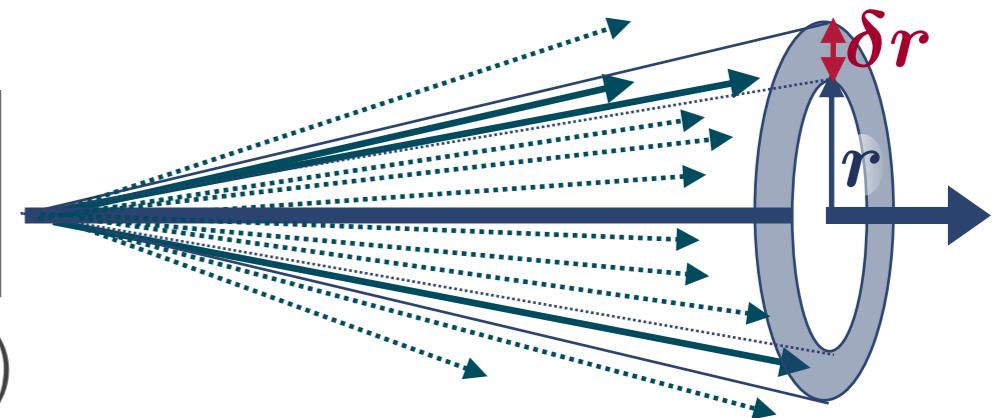
JEWEL Recoil
R. Kunnawalkam Elayavalli, K. C. Zapp, JHEP 1707, 141 (2017)



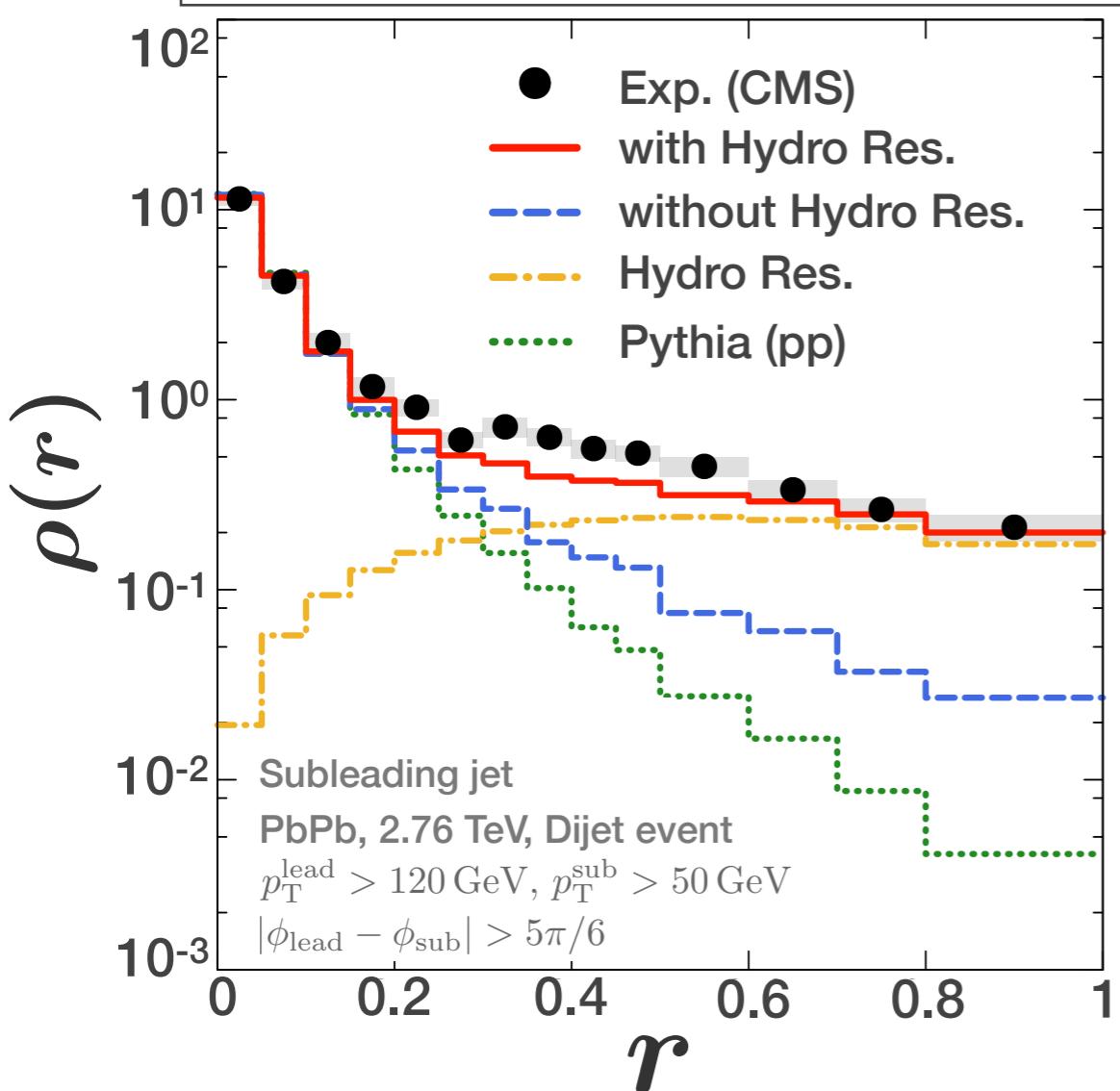
Angular structures of jets

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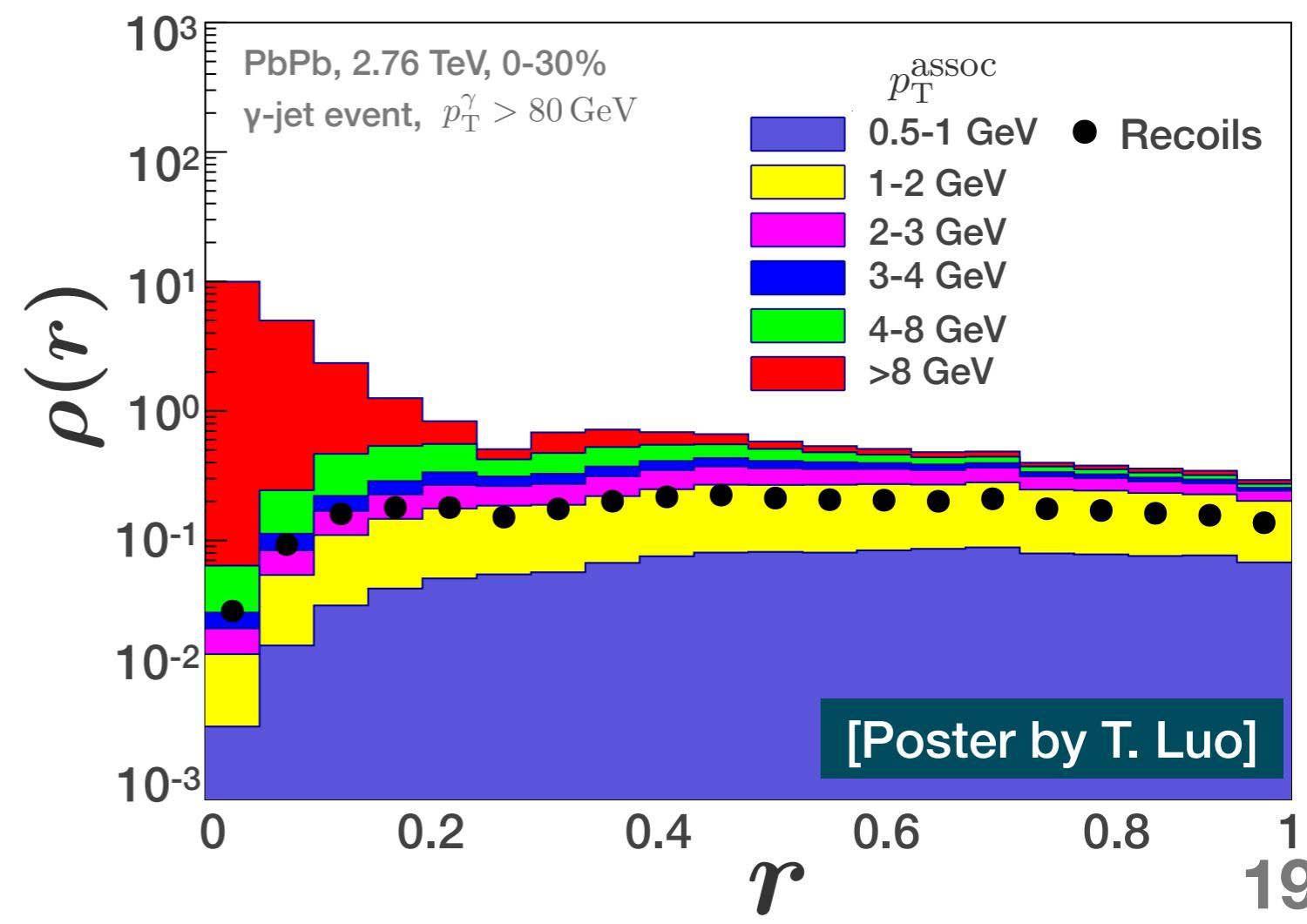
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Coupled Jet-Fluid Model Hydro
YT, N.-B. Chang, G.-Y. Qin, PRC 95, 044909 (2017)



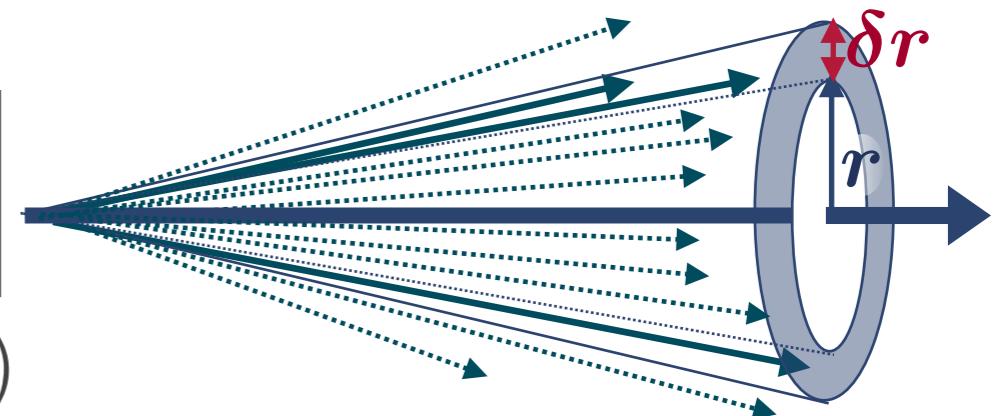
LBT model Recoil
T. Luo, S. Cao, Y. He, X.-N. Wang, arXiv:1803.06785



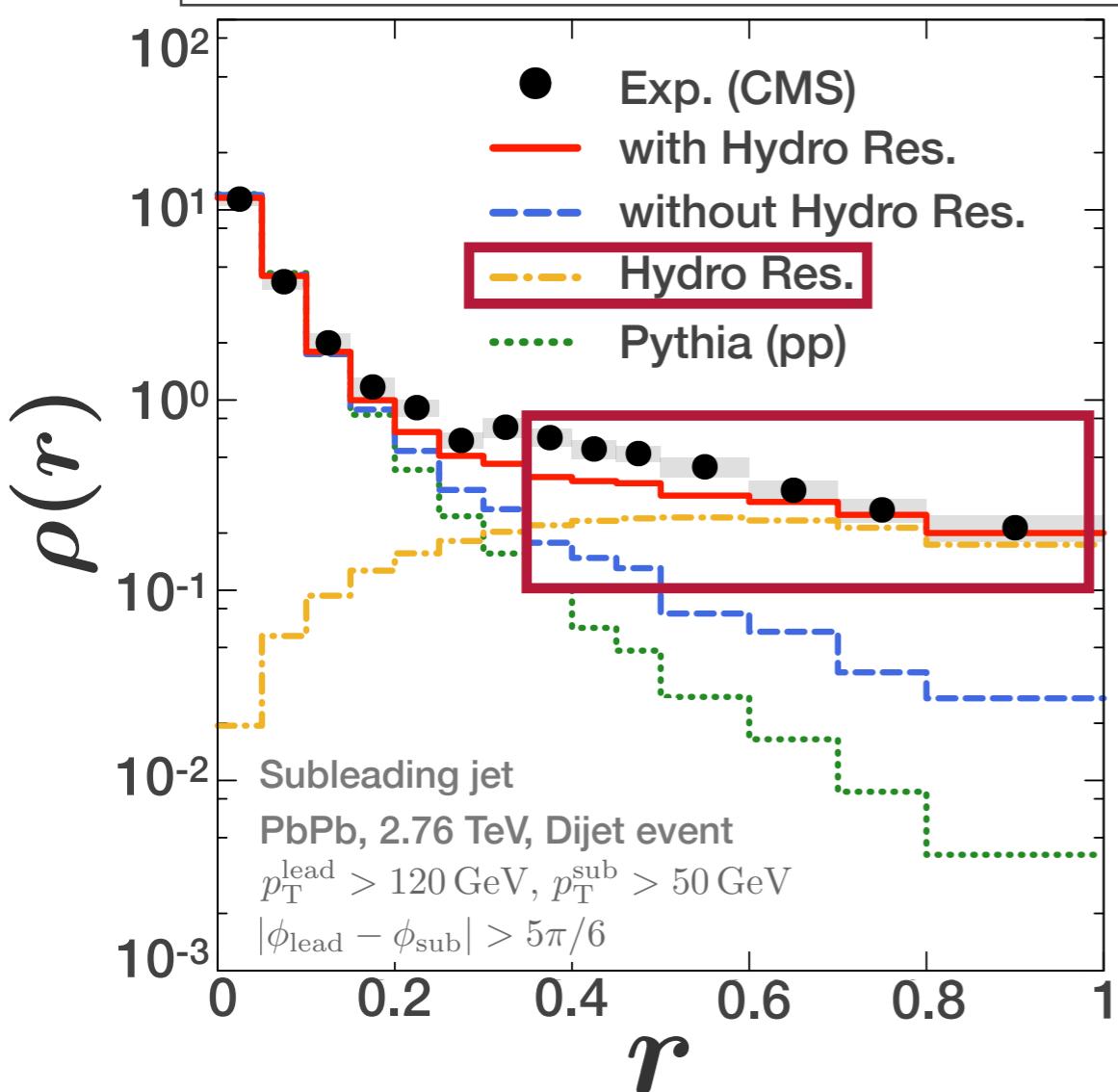
Angular structures of jets

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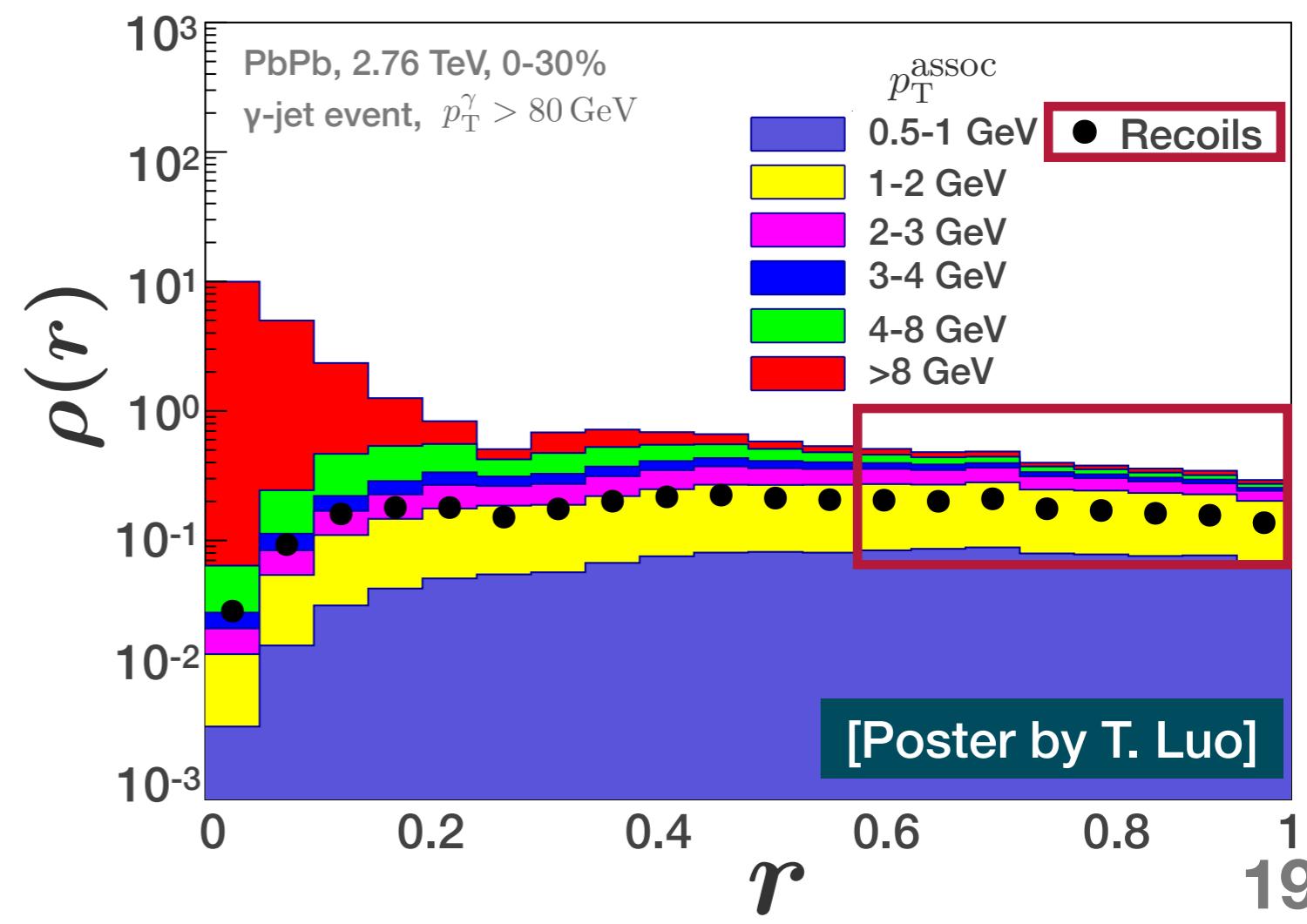
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Coupled Jet-Fluid Model Hydro
YT, N.-B. Chang, G.-Y. Qin, PRC 95, 044909 (2017)



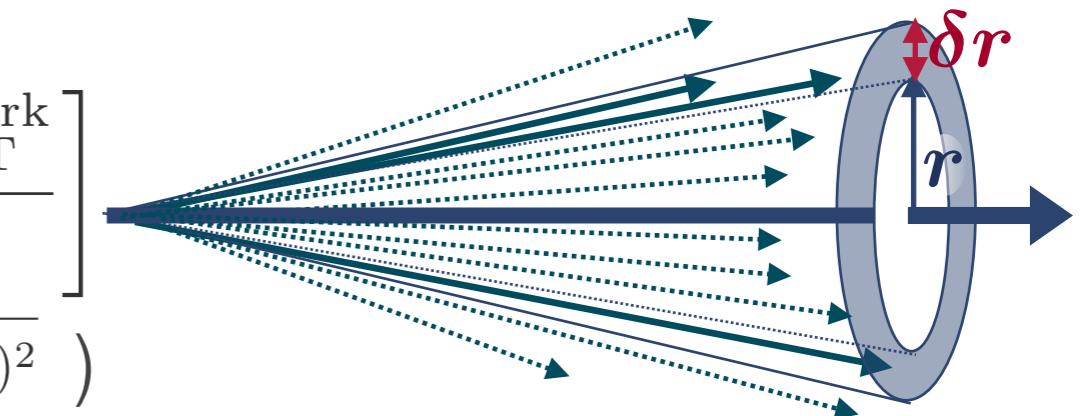
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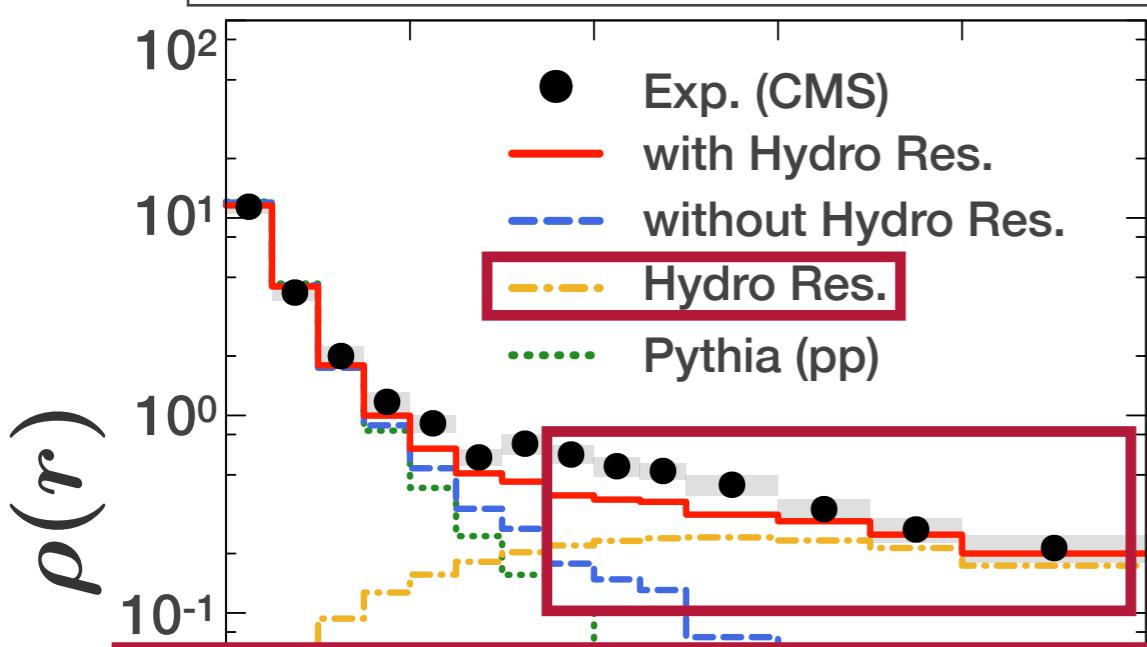
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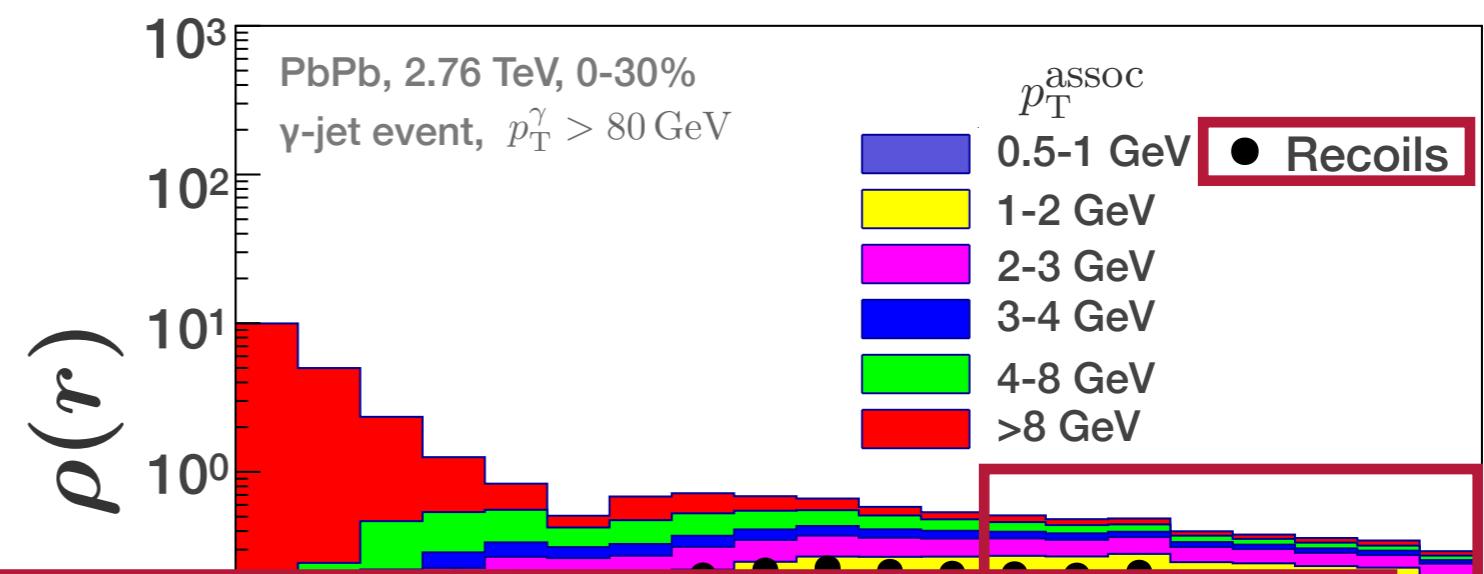
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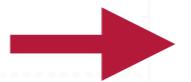
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LBT model Recoil
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Medium response to jet



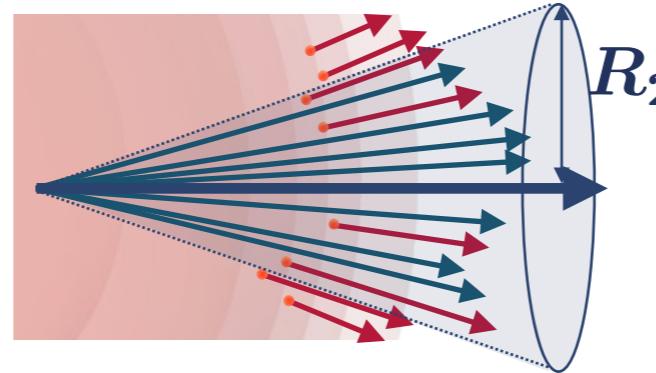
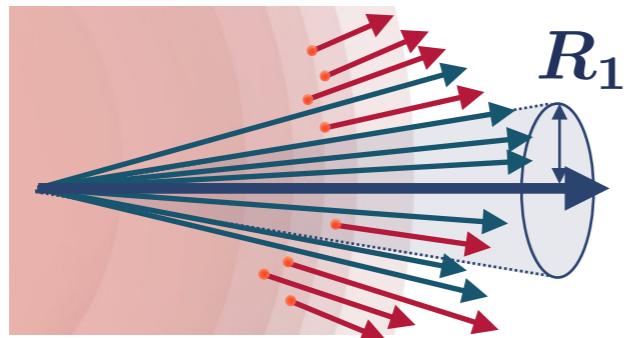
Enhancement at large angles

Similar behavior by medium response shown in other observables

YT, T. Hirano, PRC 90 021902 (2014), Z. Gao, et al., PRC 97, 044903 (2018), D. Pablos, et al., JHEP1703, 135 (2017)

Energy loss and angular structure of jet

- Cone size dependence of jet energy loss



$$p_T^{R_2, \text{jet}} > p_T^{R_1, \text{jet}} \\ (R_2 > R_1)$$

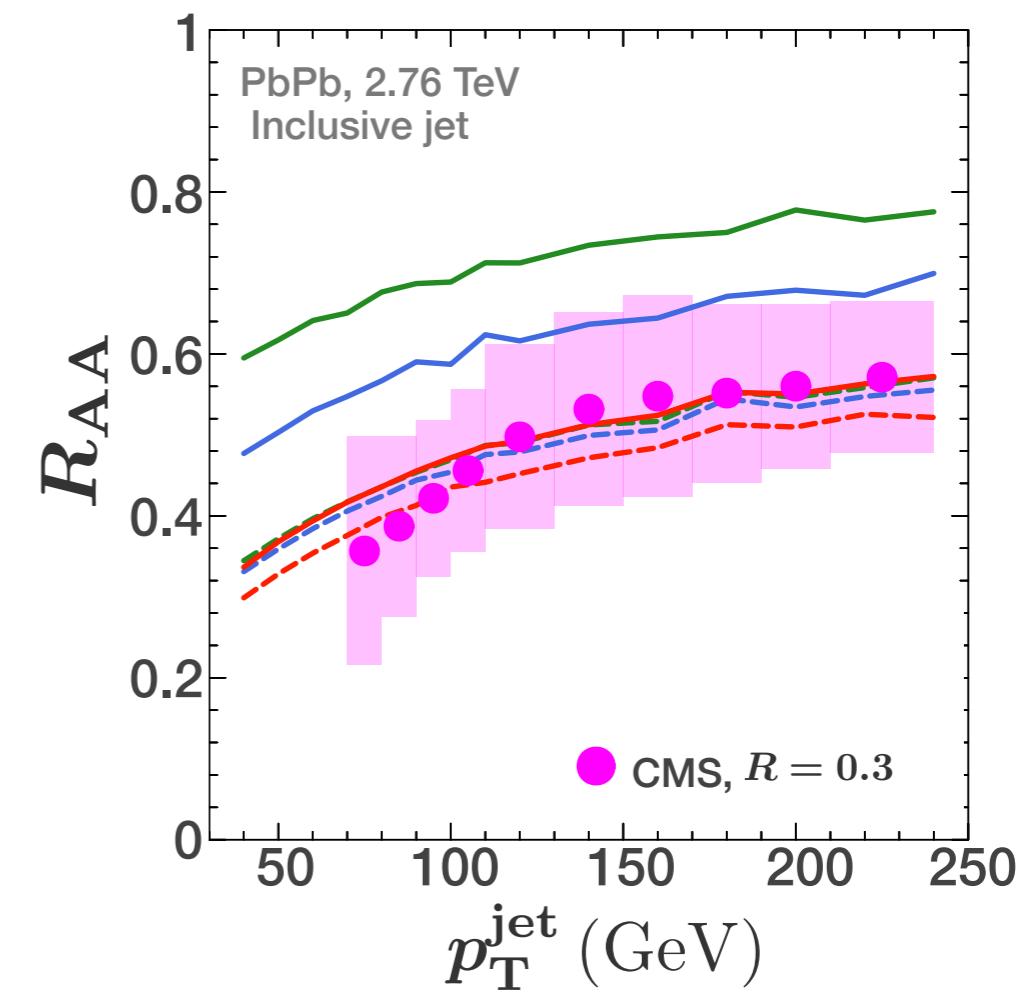
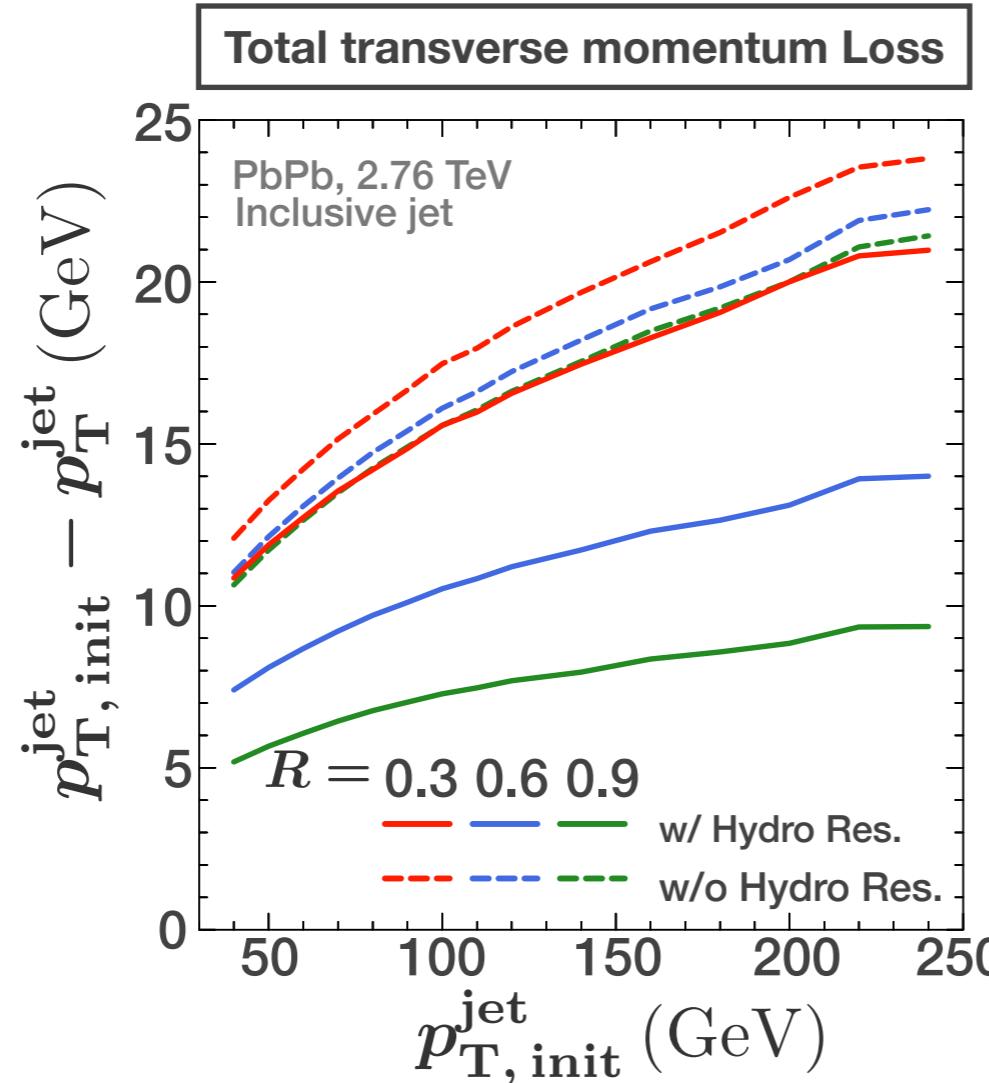
Nuclear modification factor

$$R_{\text{AA}} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{d^2 N_{\text{jet}}^{\text{AA}} / d\eta_p dp_T^{\text{jet}}}{d^2 N_{\text{jet}}^{\text{pp}} / d\eta_p dp_T^{\text{jet}}}$$

Coupled Jet-Fluid Model

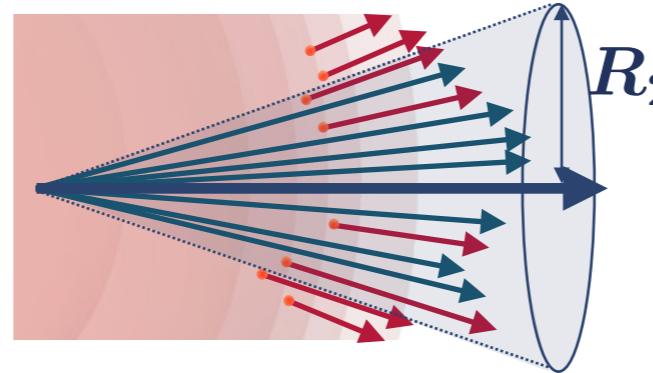
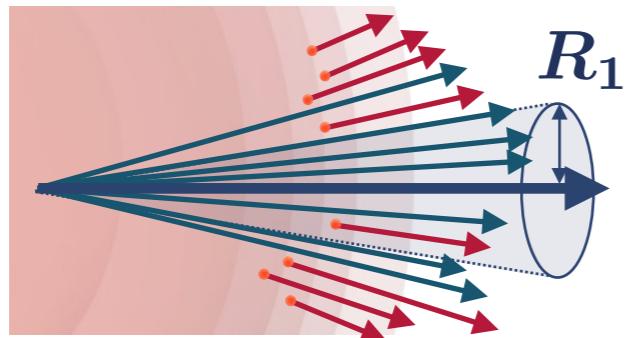
Hydro

YT, N.-B. Chang,
G.-Y. Qin, PRC 95,
044909 (2017)



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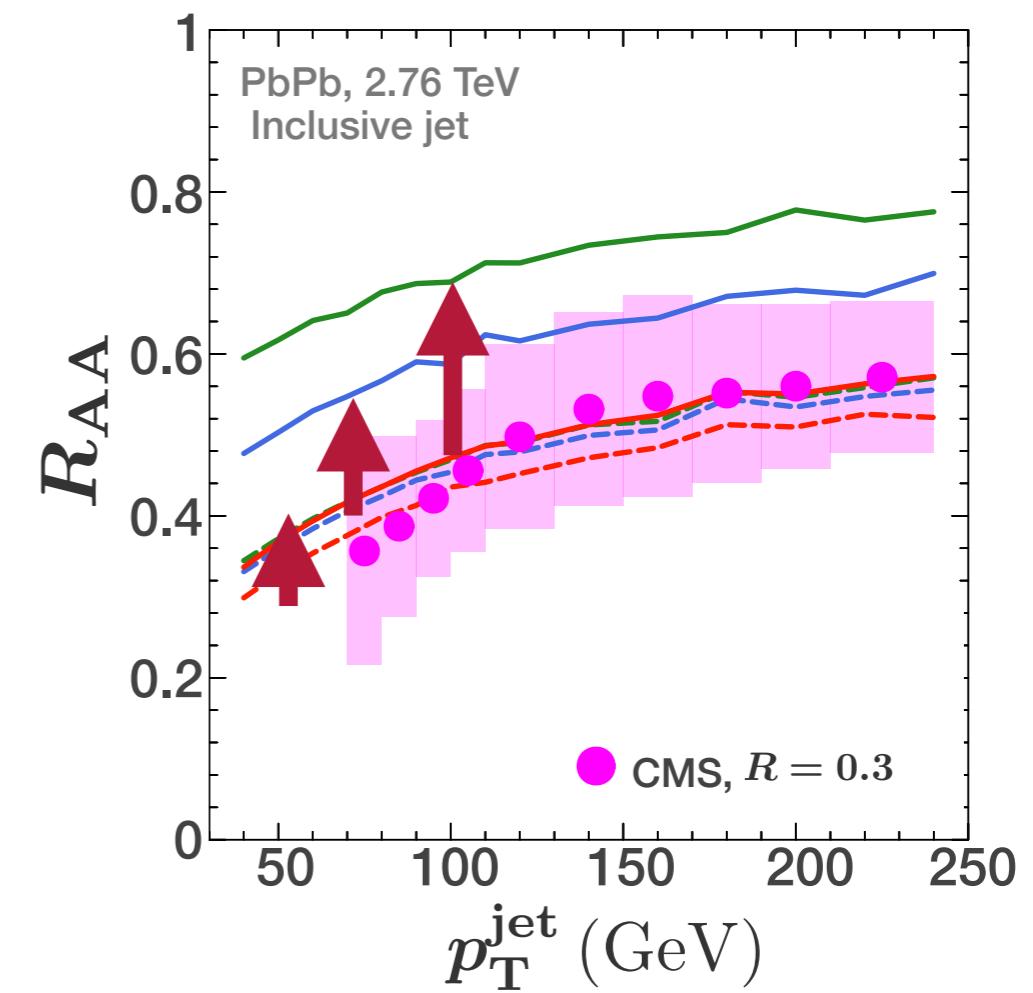
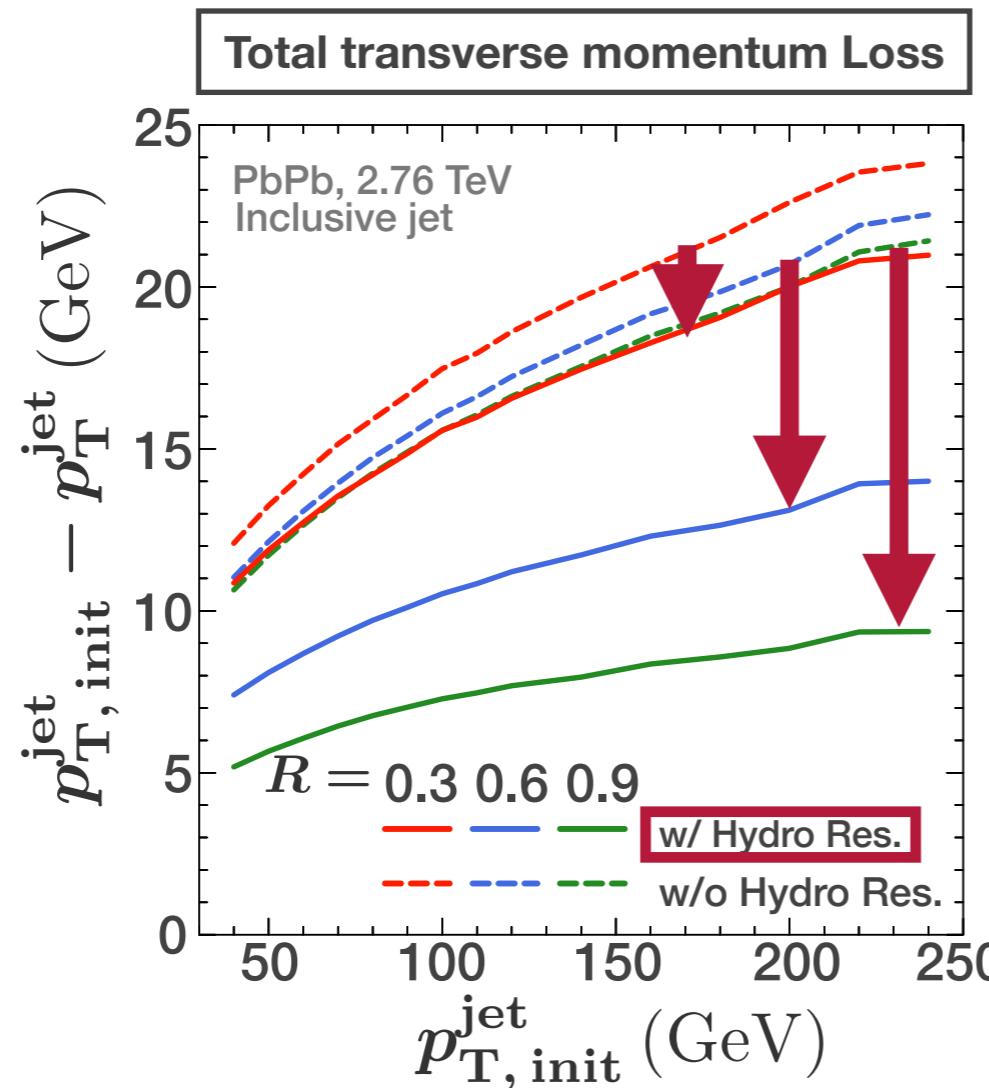
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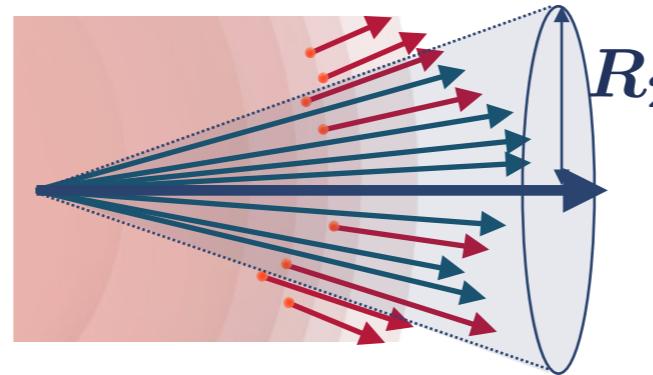
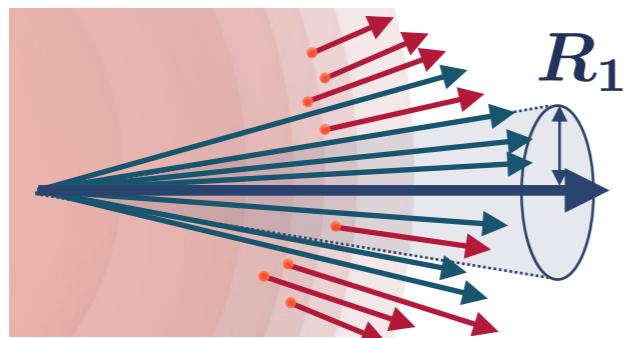
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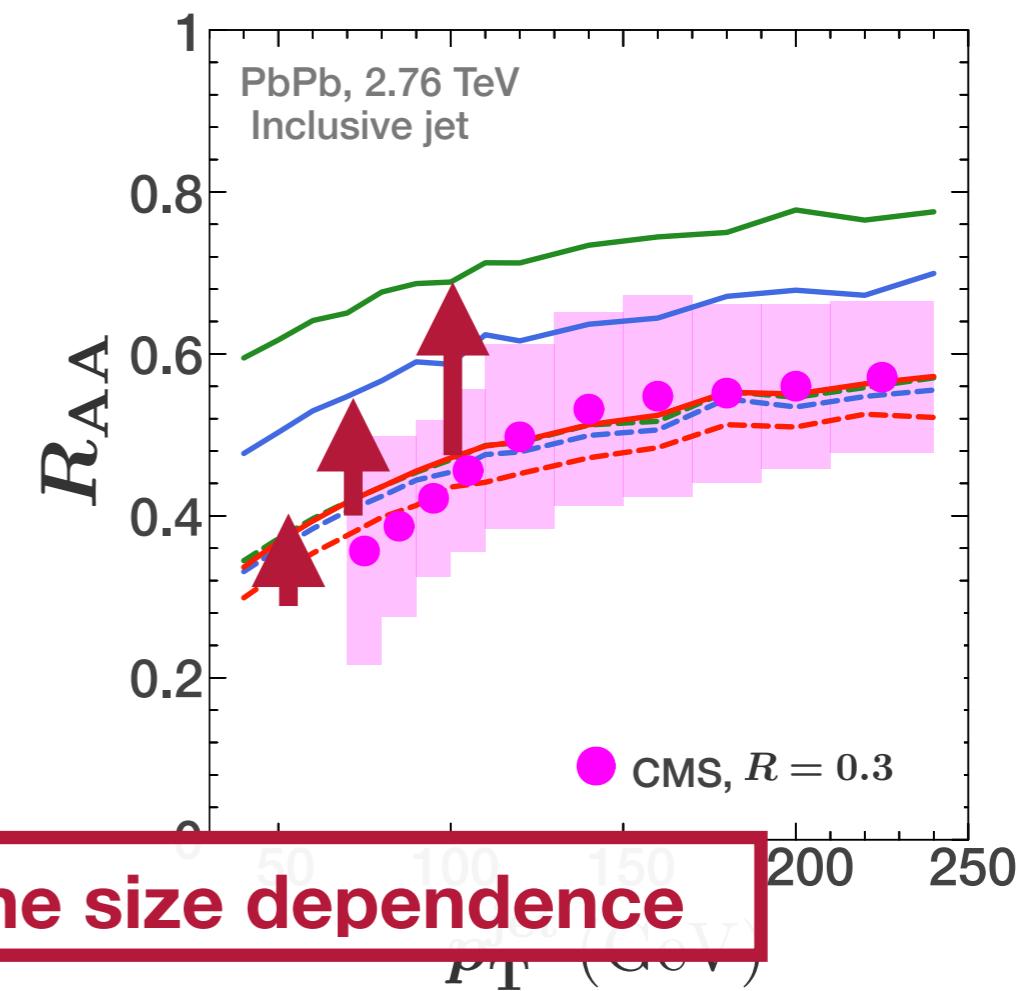
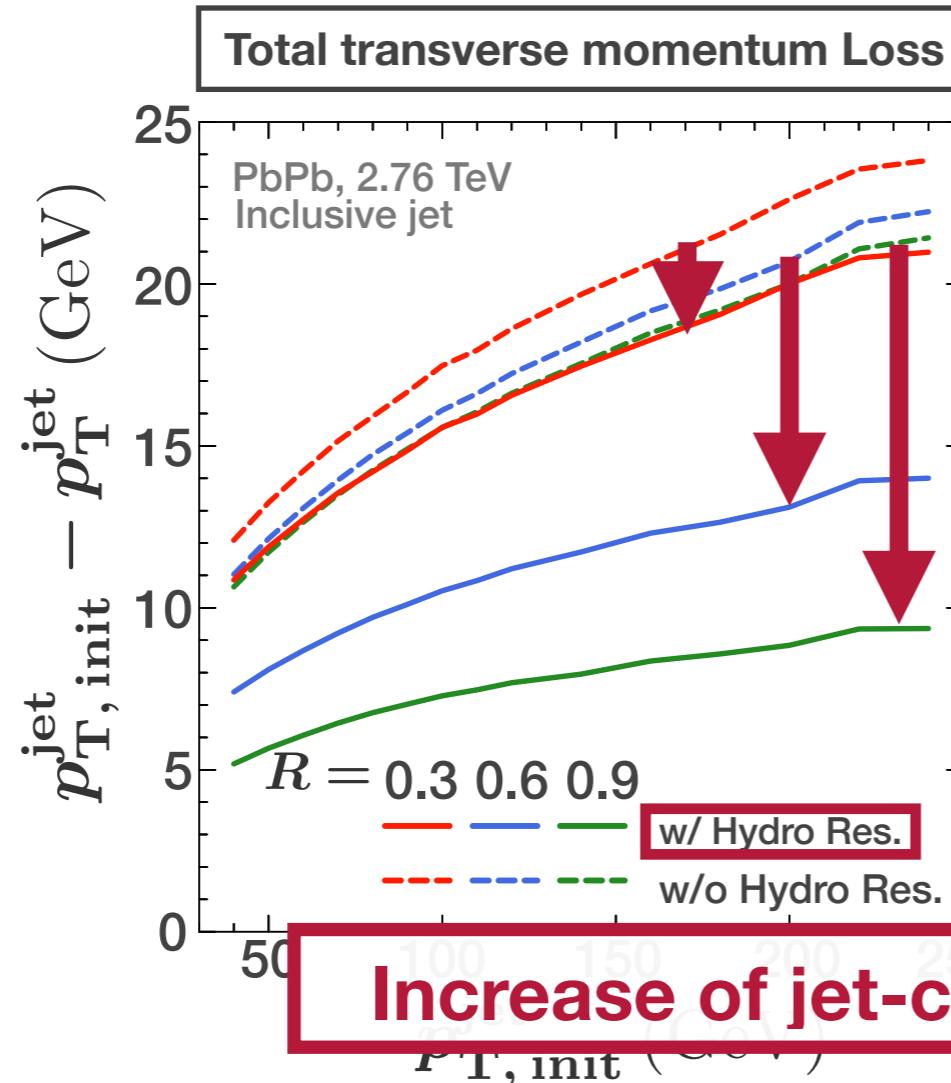
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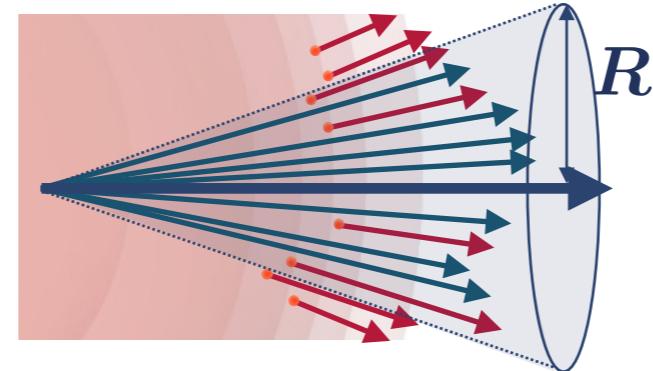
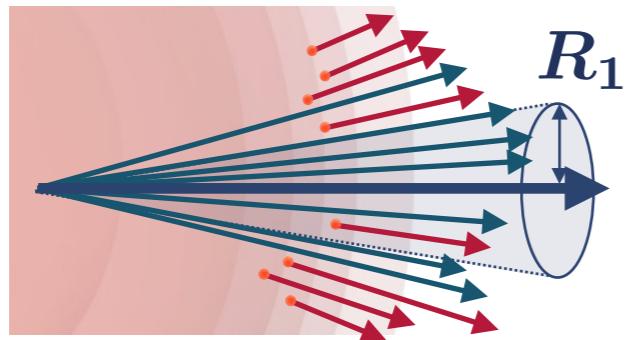
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YT, N.-B. Chang,
G.-Y. Qin, PRC 95,
044909 (2017)



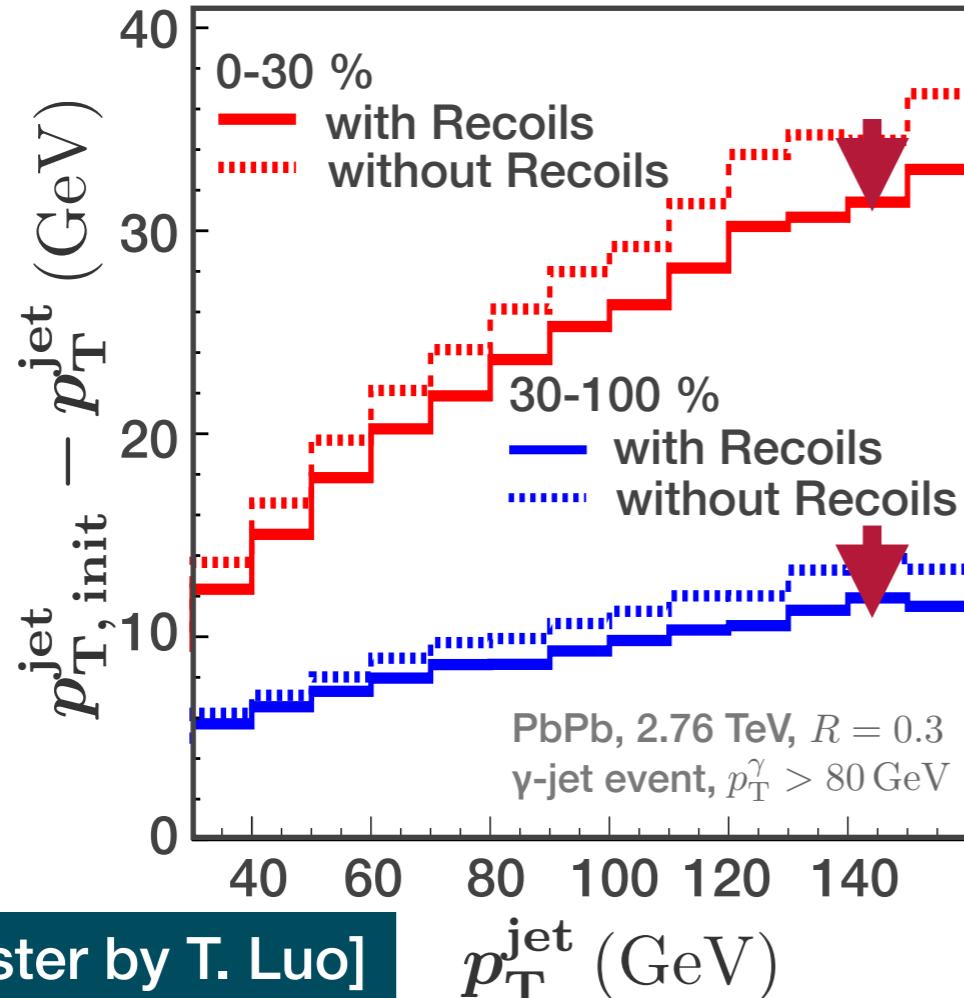
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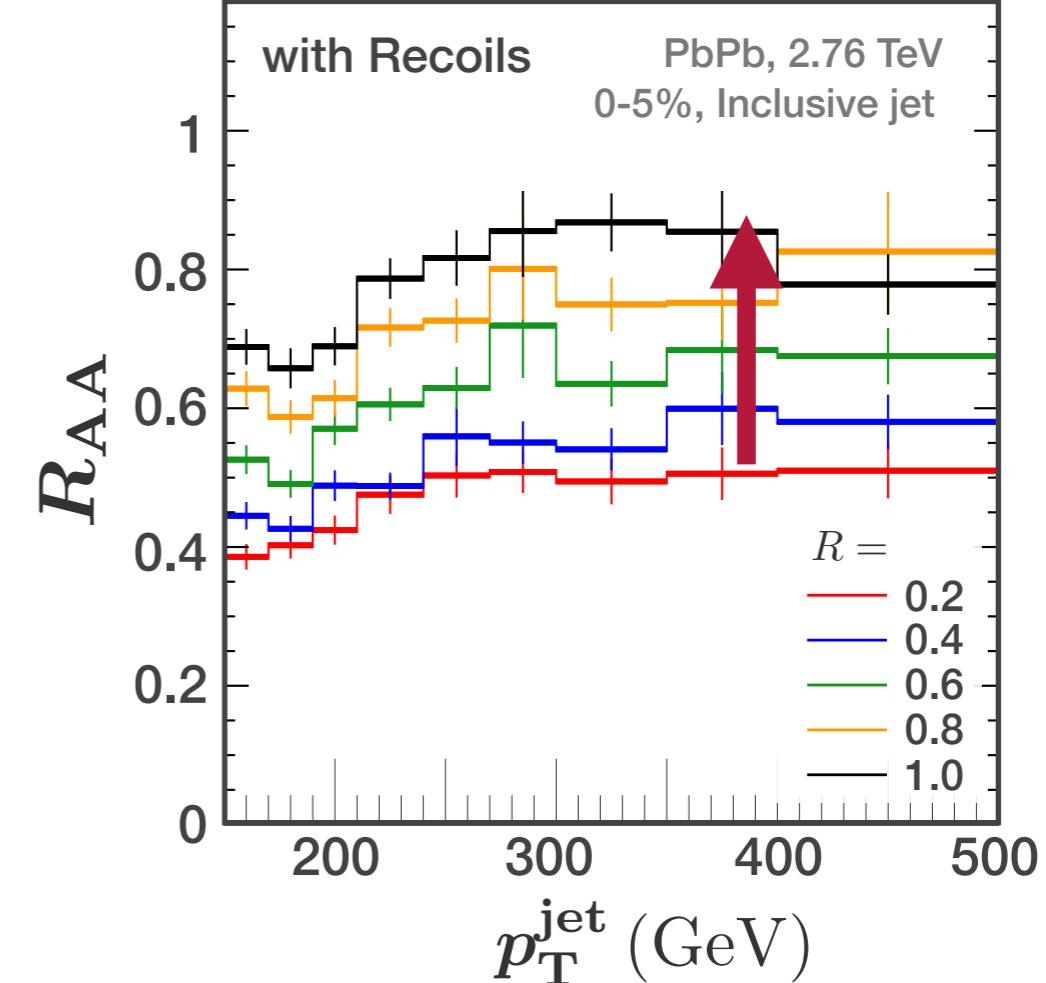


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LBT model Recoil
T. Luo, S. Cao, Y. He, X.-N. Wang, arXiv:1803.06785

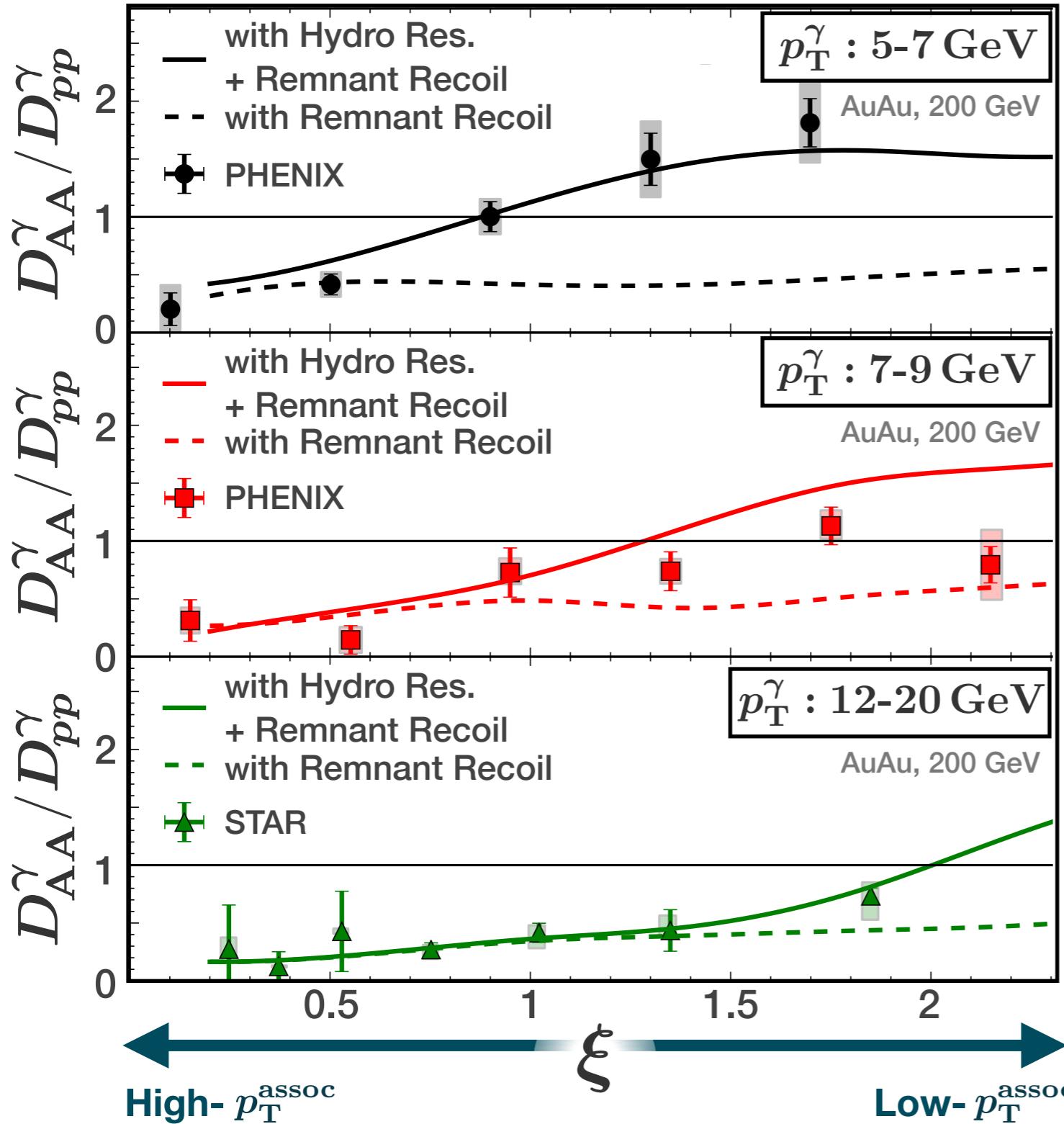


JEWEL Recoil
R. Kunnawalkam Elayavalli, K. C. Zapp, JHEP 1707, 141 (2017)



Soft particle enhancement

- Fragmentation function (γ -triggered)



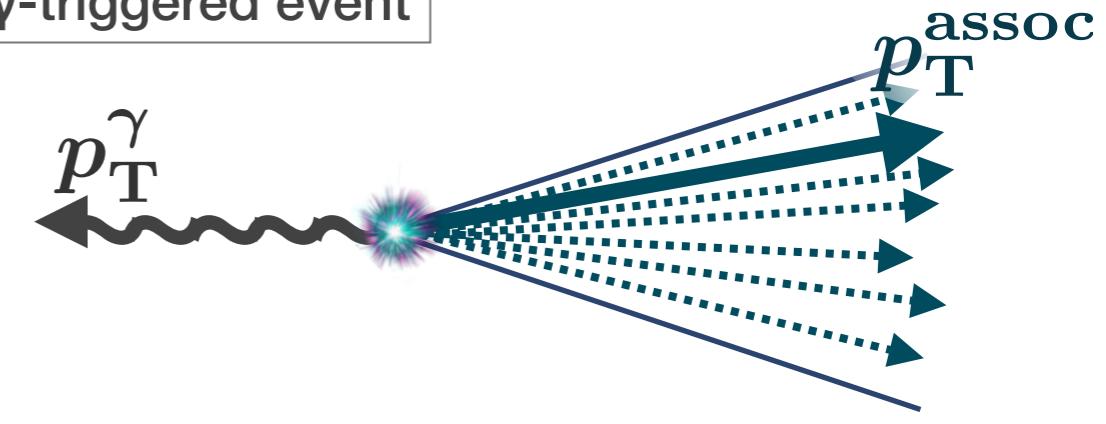
Coupled LBT Hydro Model Recoil+Hydro
W. Chen, et al., PLB 777, 86 (2018)

[Talk by X.-N. Wang]

$$D^\gamma(\xi) = \frac{1}{N^\gamma} \frac{dN^{\text{assoc}}}{d\xi}$$

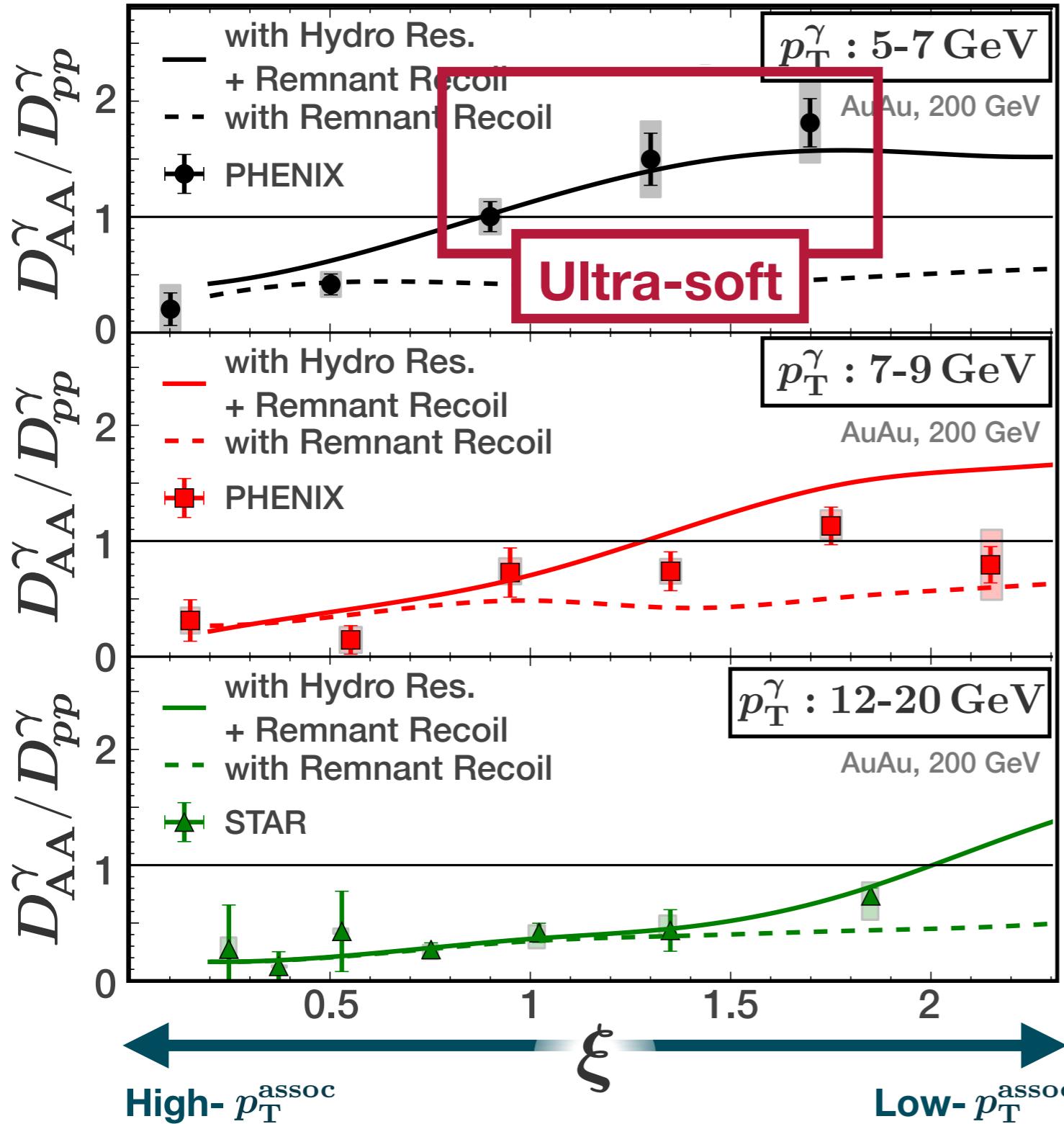
$$\xi = -\ln \frac{p_T^{\text{assoc}}}{p_T^\gamma}$$

γ -triggered event



Soft particle enhancement

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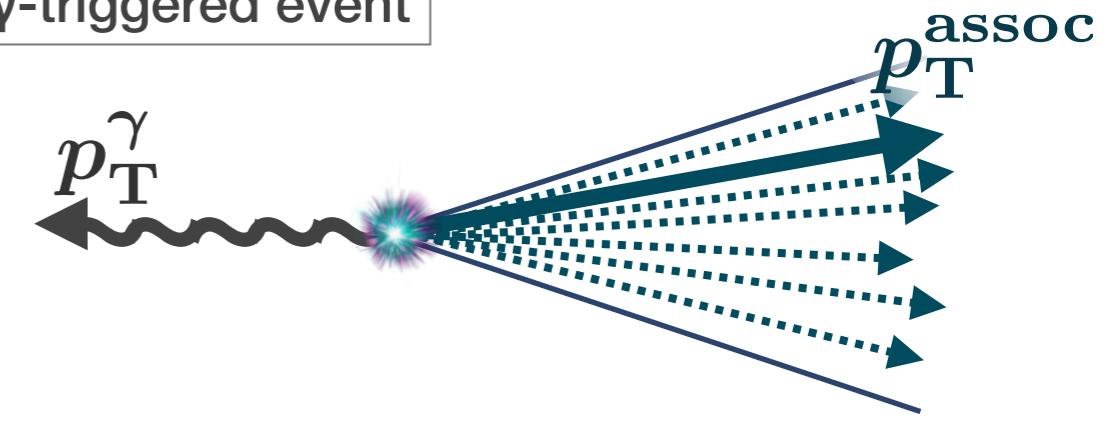
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Effect on other observables

- Jet mass

JEWEL

R. Kunnawalkam Elayavalli, K. C. Zapp, JHEP 1707, 141 (2017)

MARTINI [Talk by C. Park]

- Splitting function

JEWEL [Talk by G. Milhano]

R. Kunnawalkam Elayavalli, K. C. Zapp, JHEP 1707, 141 (2017)

G. Milhano, U. A. Wiedemann, K. C. Zapp PLB 779, 409 (2018)

LBT [Talk by X.-N. Wang]

- Fragmentation function

JEWEL

R. Kunnawalkam Elayavalli, K. C. Zapp, JHEP 1707, 141 (2017)

Hybrid Strong/Weak Coupling Model

[Talk by D. Pablos]

D. Pablos, et al., JHEP 1603 053 (2016)

Z. Hulcher, D. Pablos, K. Rajagopal, JHEP 1803 010 (2018)

[Poster by Z. Hulcher]

Coupled LBT Hydro Model [Talk by X.-N. Wang]

- Girth

JEWEL

R. Kunnawalkam Elayavalli, K. C. Zapp, JHEP 1707, 141 (2017)

Summary and outlook

Summary

- **Medium response to jet quenching**

- Medium's reaction to interactions with jet
- Included in jets observed in heavy ion collisions
- Contains a lot of information (thermalization, viscosity, etc.)
- Necessary for comprehensive understanding of the jet quenching

- **Models for medium response**

- Far enough from thermalization → Recoil
- Medium response to thermalized part → Hydro w/ source term

- **Effect from medium response**

- Soft particles in wide angle regions around jets
- Various modification in jet substructures

Outlook

- **Model development for more quantitative study**
 - Extract medium properties by comparison with data
 - Concurrent running of full even-by-event jet and 3D viscous hydro
- **Medium response to heavy quarks** [Talk by S. Cao]
 - Slower propagation, effect from medium excited by themselves

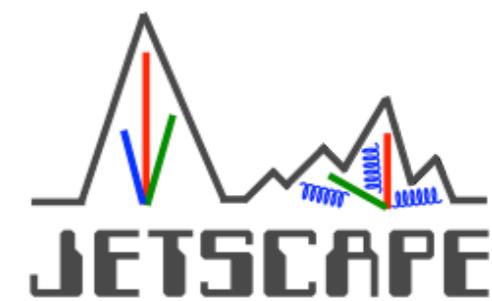
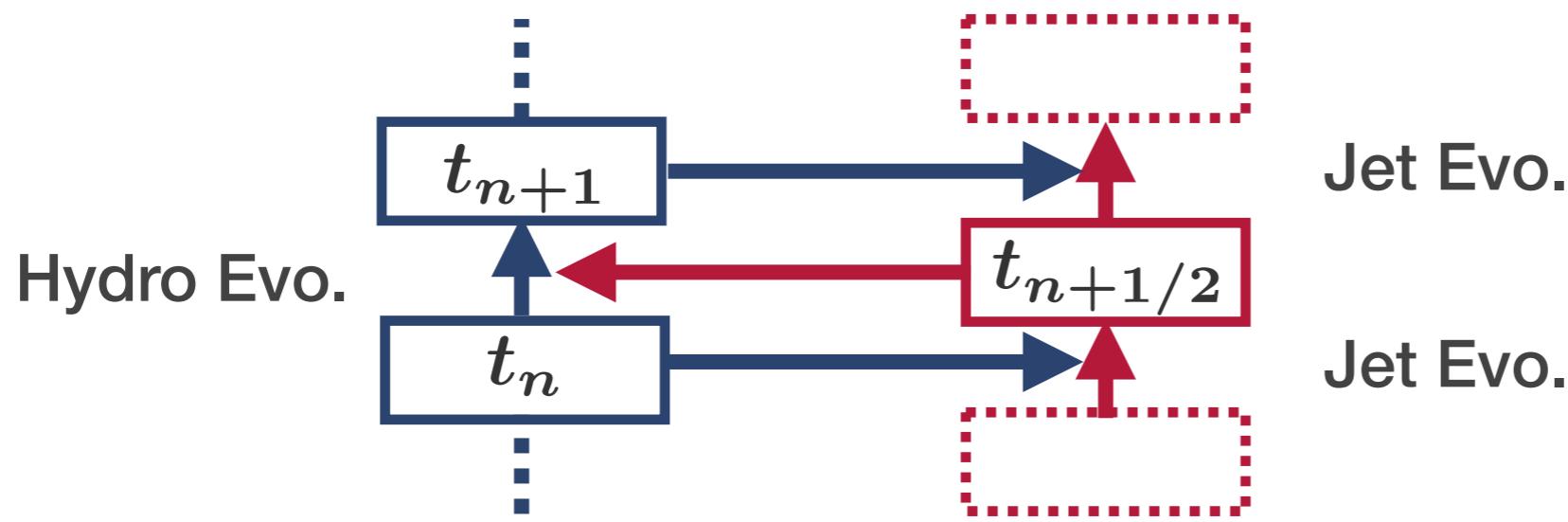
JETSCAPE: “Framework” of Event Generator for heavy ion collisions

JETSCAPE 1.0 (Released!!)

[Talk by K. Kauder]

JETSCAPE 2.0 (future update)

- Enable concurrent running at framework level



Outlook

- **Formulation of in-medium thermalization**

- Modeling of source term for hydrodynamic equation

- **Other observables**

- Ensure medium response effect in jet (vs large angle radiation)
- Extraction of thermalized part contribution

e.g. baryon to meson ratio in/around jet

