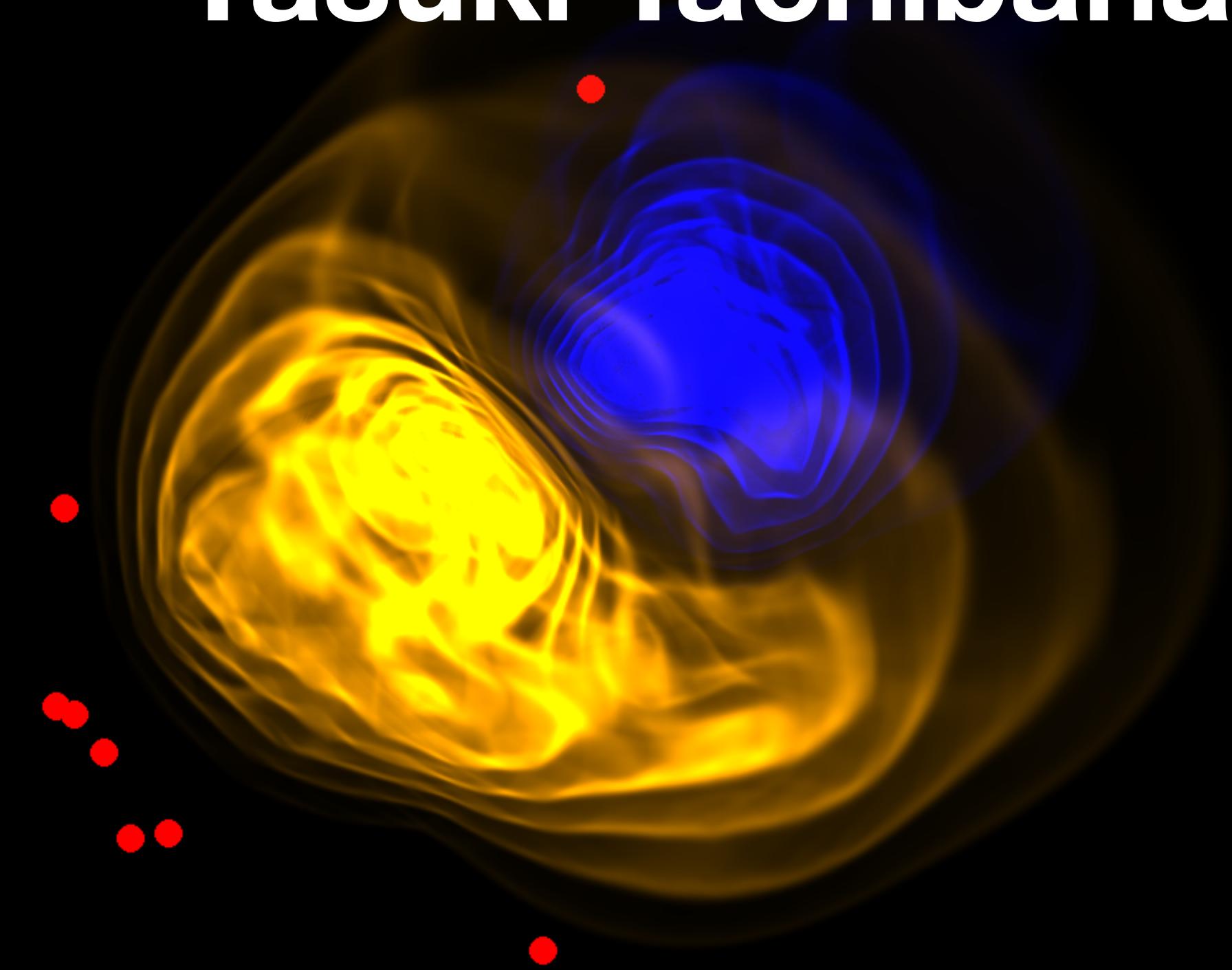


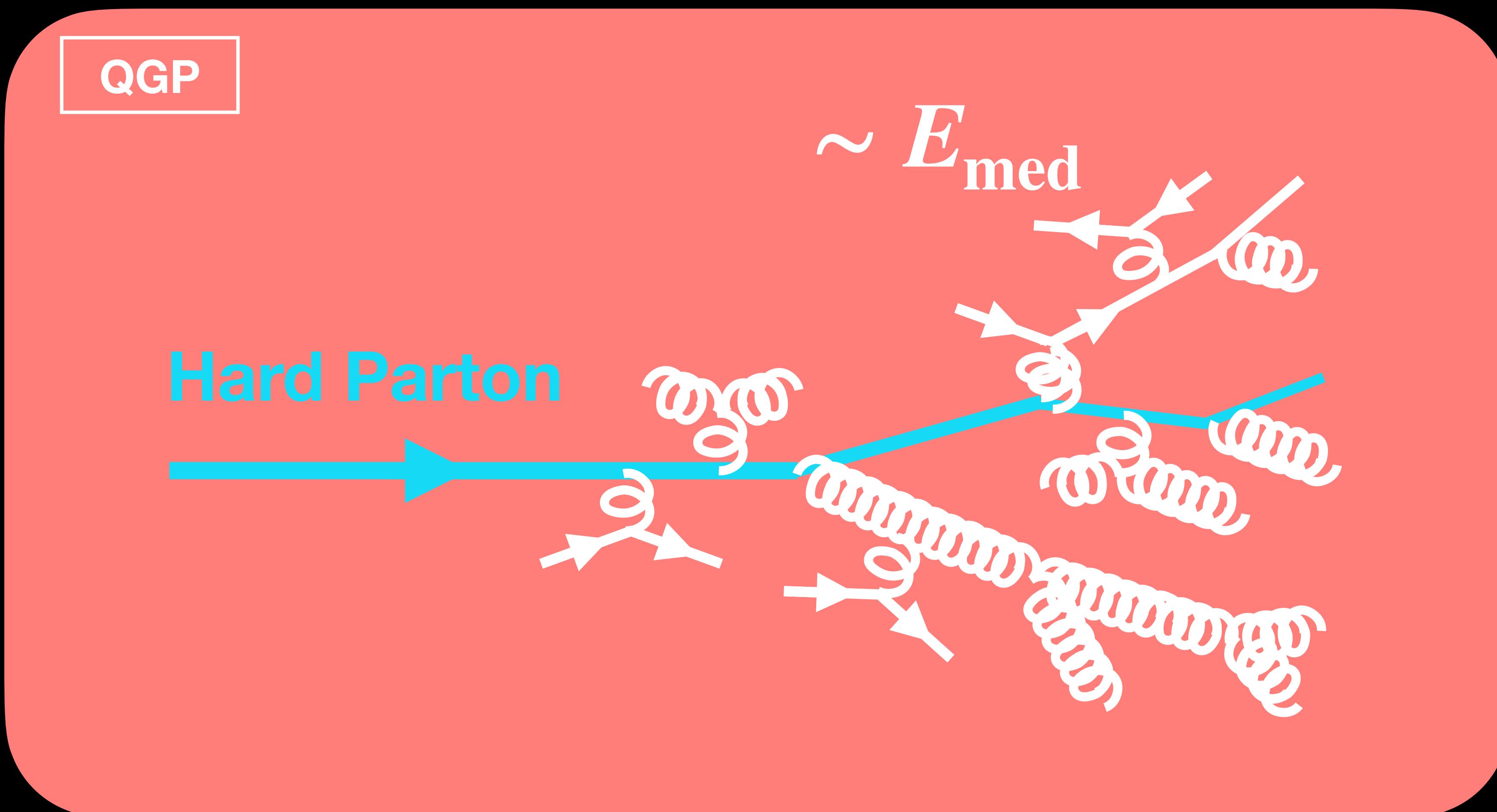
Jets: Back Reaction onto the Medium

Yasuki Tachibana



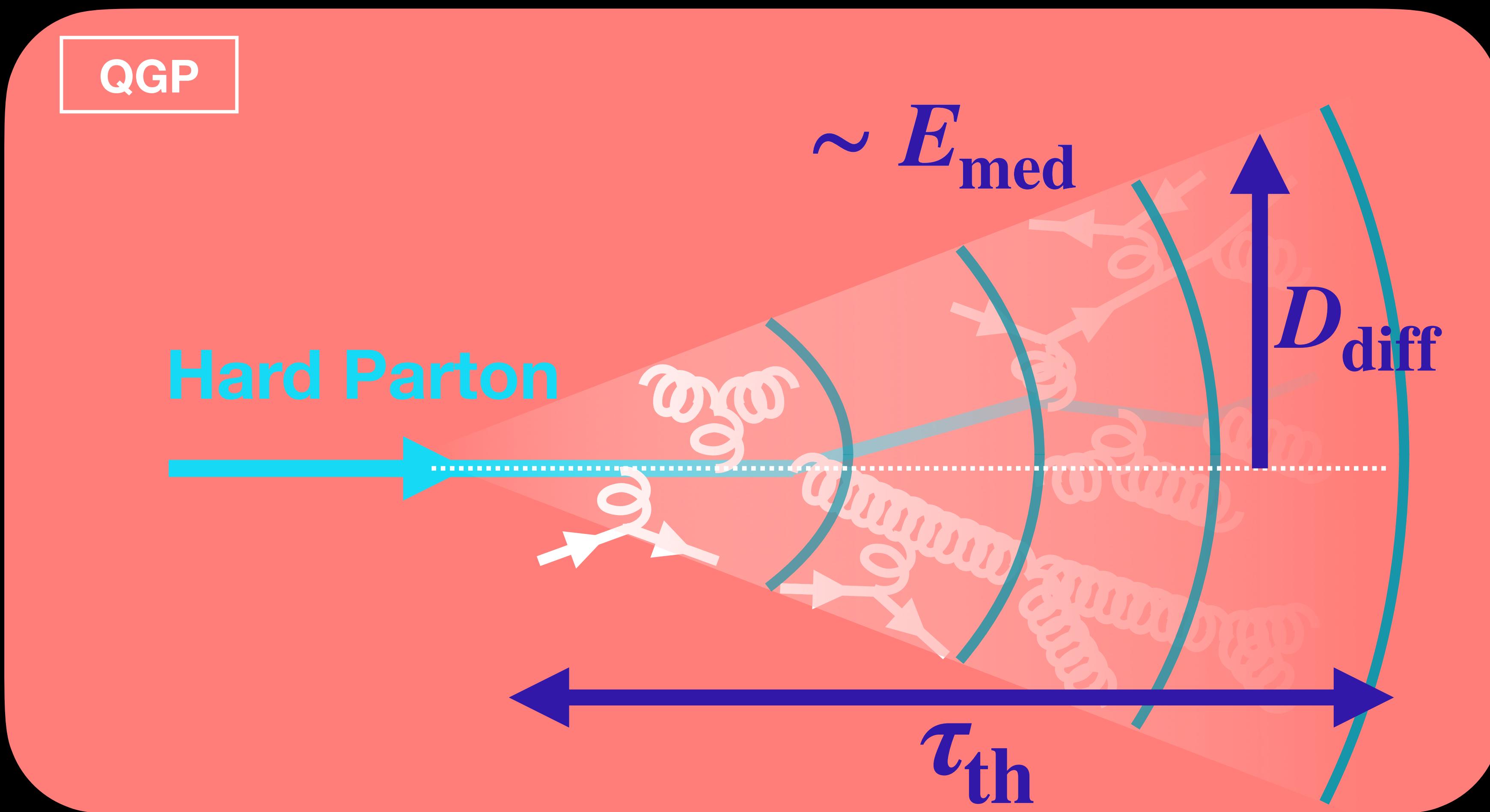
Theoretical Motivation

In-medium Thermalization



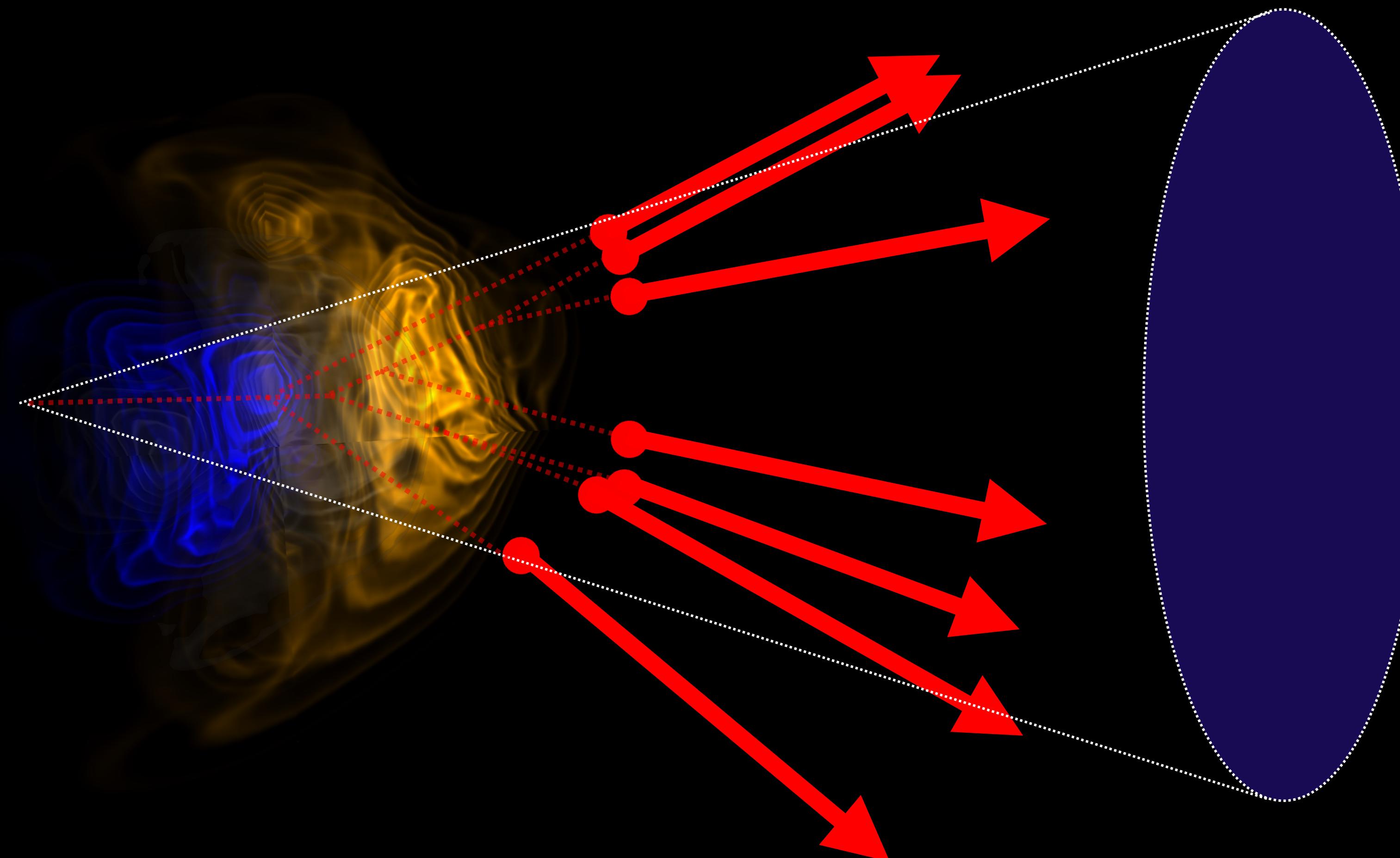
Theoretical Motivation

In-medium Thermalization



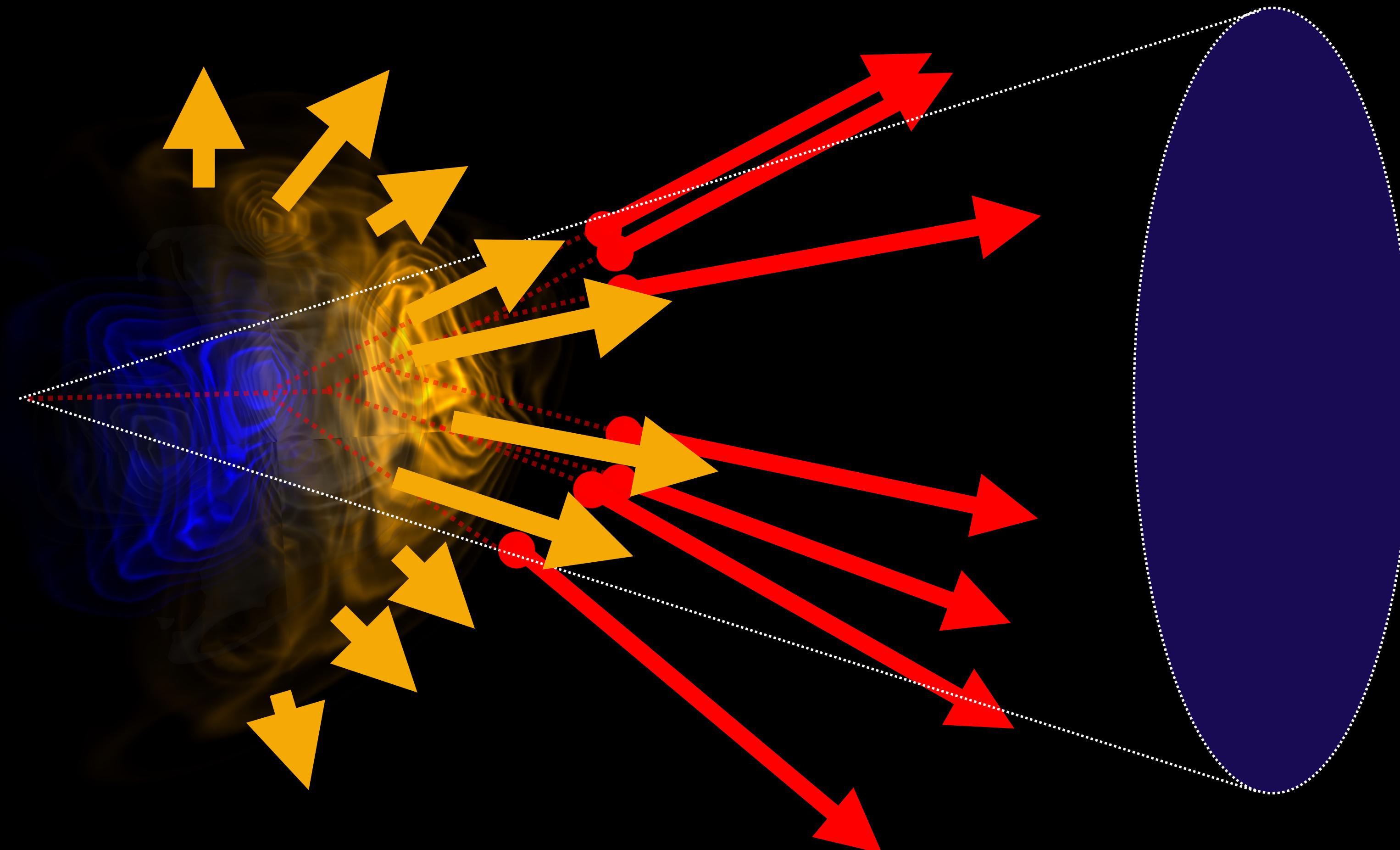
Signals in Observables

Affect Jet's p_T and Substructures



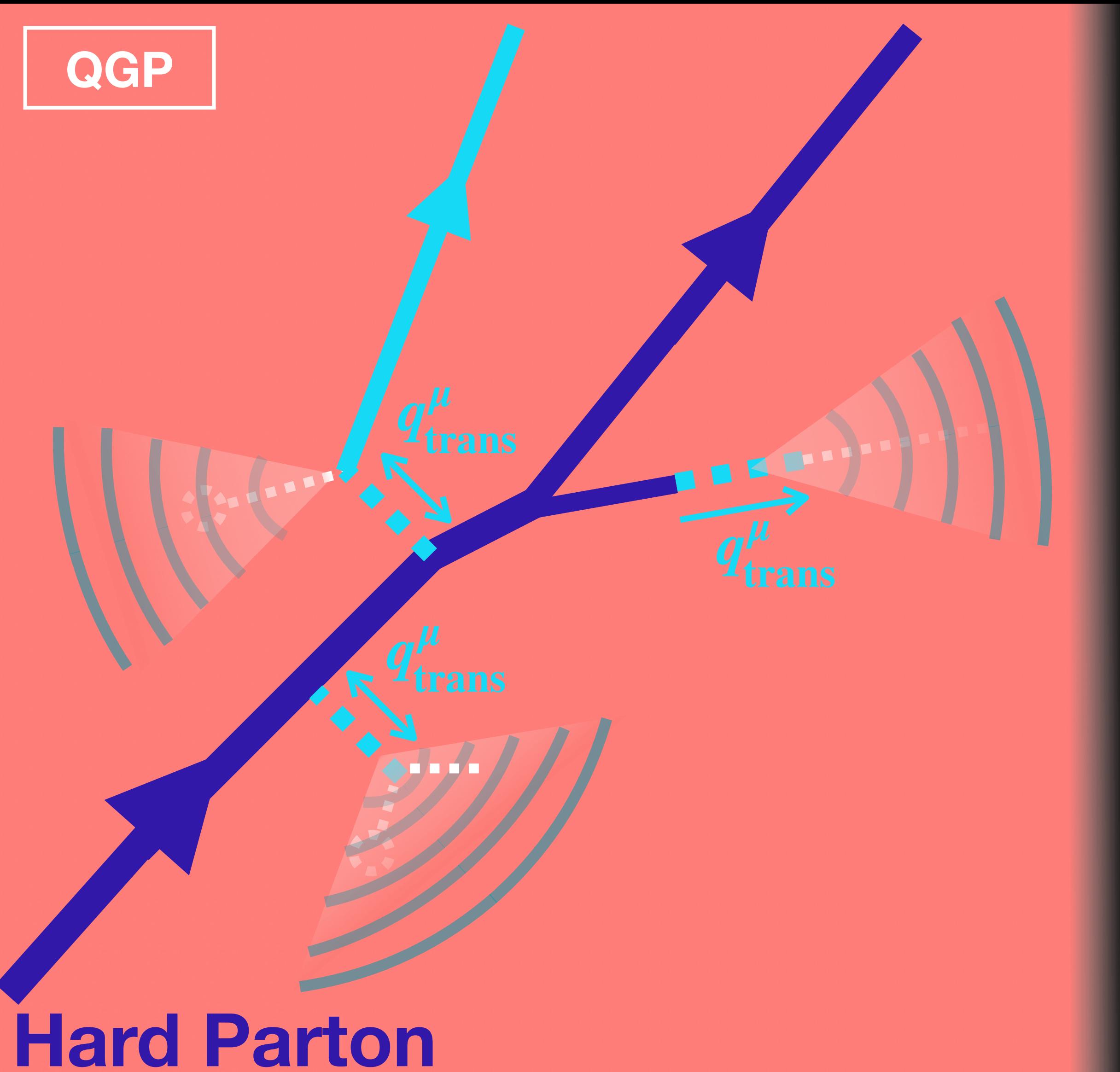
Signals in Observables

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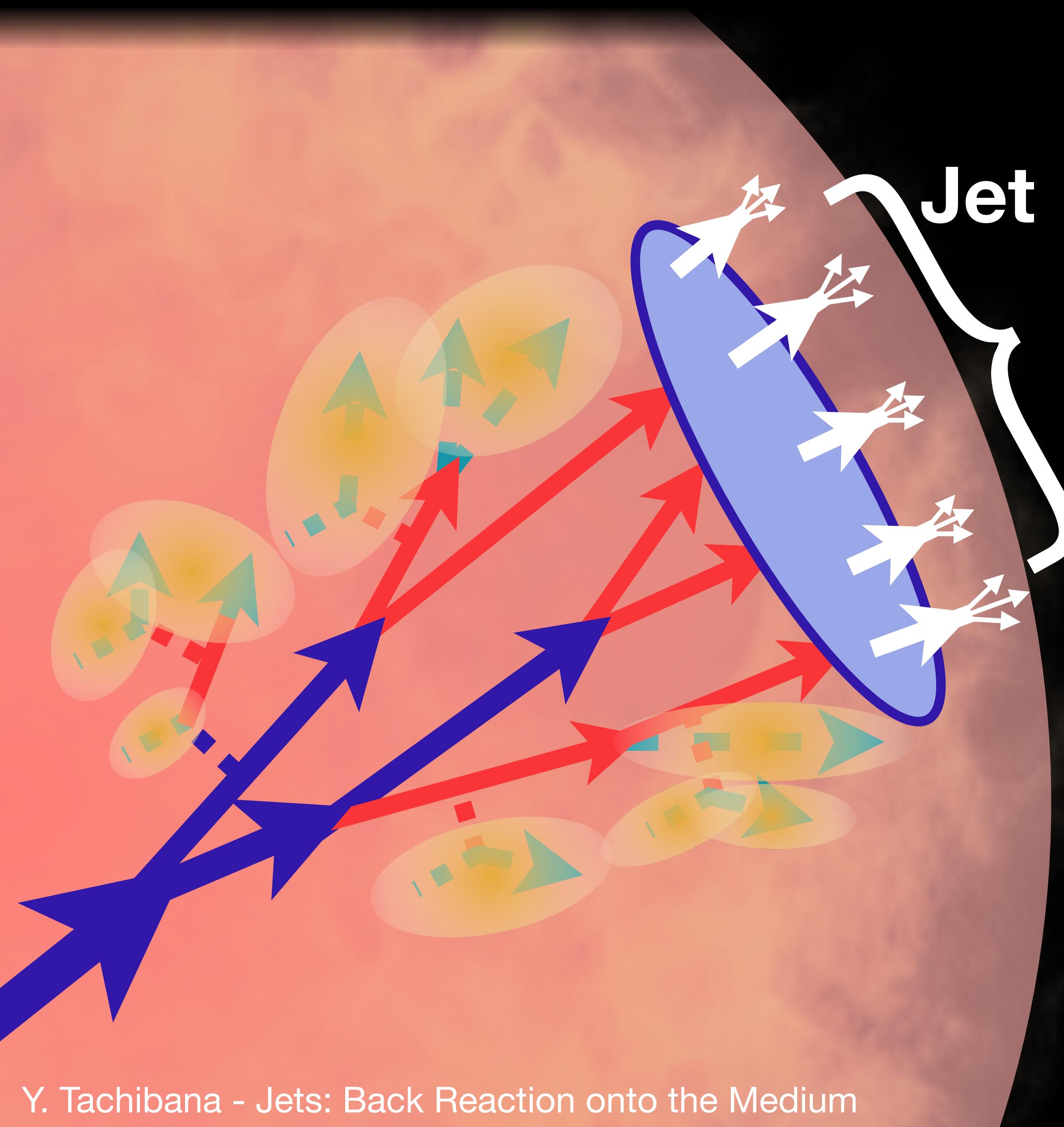
Introduction

Medium Response to Hard Parton



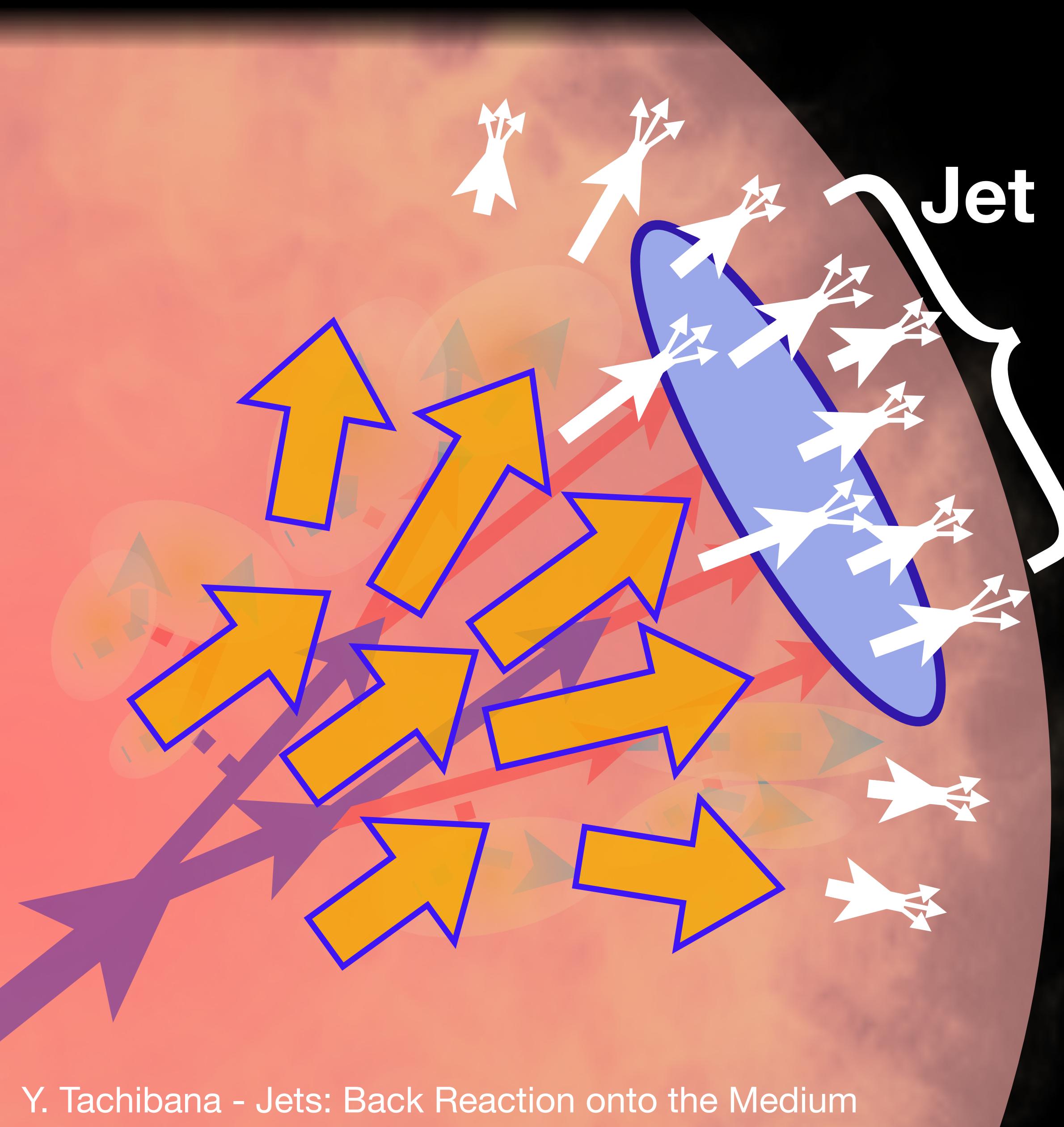
- **Interaction with QGP medium**
 - Medium constituents' reactions to momentum transferred from hard partons
 - Lead nonequilibrium processes involving medium constituents
- **In-medium thermalization** Talk by I. Soudi
 - Transferred momentum carried by (locally) thermalized medium
 - Transition to hydrodynamic transport

Medium Response Effect in Heavy Ion Collisions



- **Jet-induced excitation of medium**
 - Transport momentum deposited by jet
 - Modify particle emission around jet
- **Particles from medium response**
 - Soft, spread out from jet
 - Jet-correlated, cannot/should not be subtracted
 - Affect structures inside/around jet

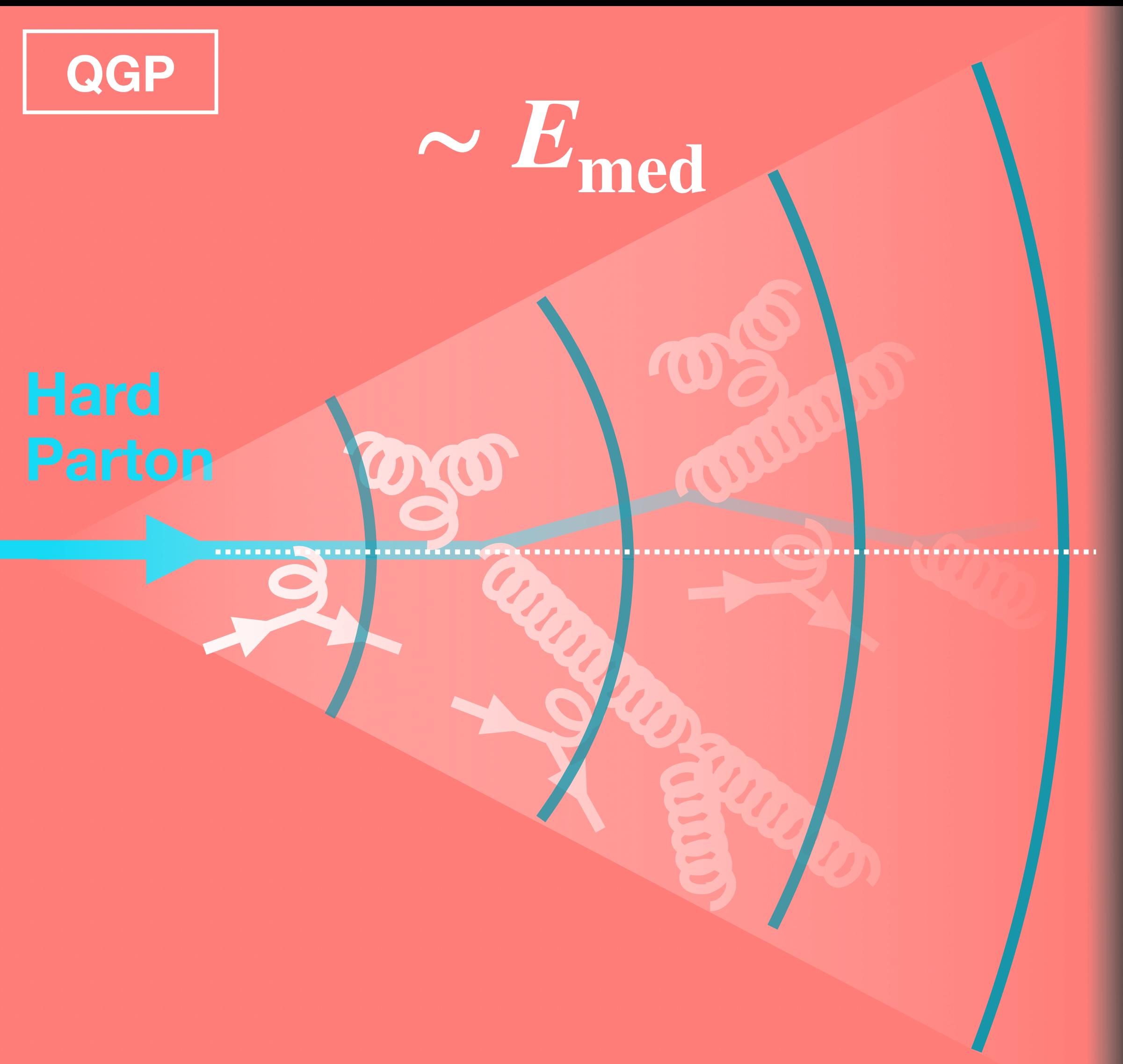
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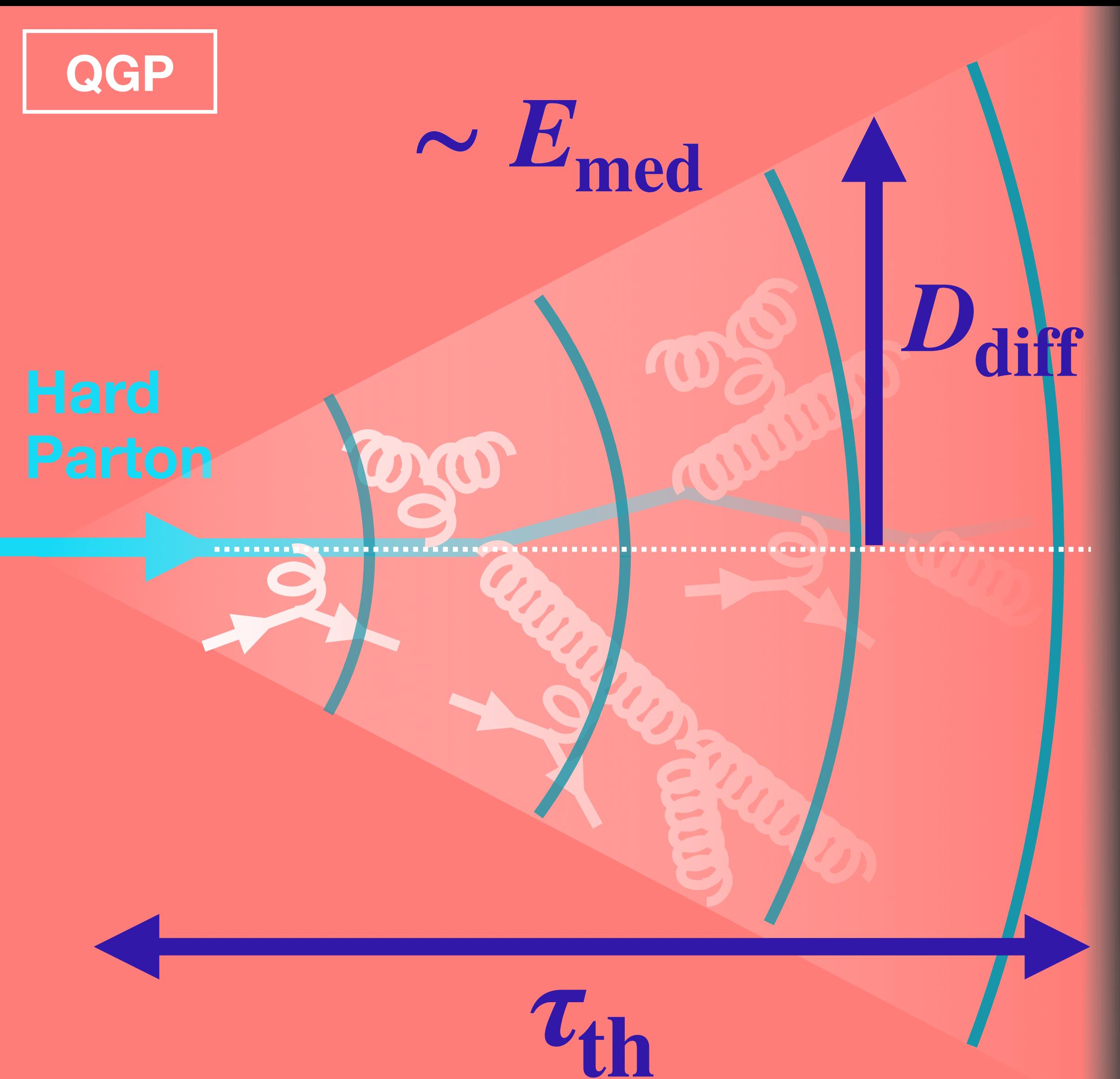
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Motivations



- QGP properties involved with **in-medium thermalization**
E. Iancu, B. Wu ('15), YT, C. Shen, A. Majumder ('19), JETSCAPE ('19)...
 - Partial thermalization of jet energy and momentum
 - Propagation as jet-induced hydrodynamic flow in medium
- Thermalized part contribution in jet**
- Information of in-medium thermalization**
- Thermalization time τ_{th} ,**
Diffusion coefficient D_{diff} ,
Typical energy scale E_{med} , etc.

Motivations



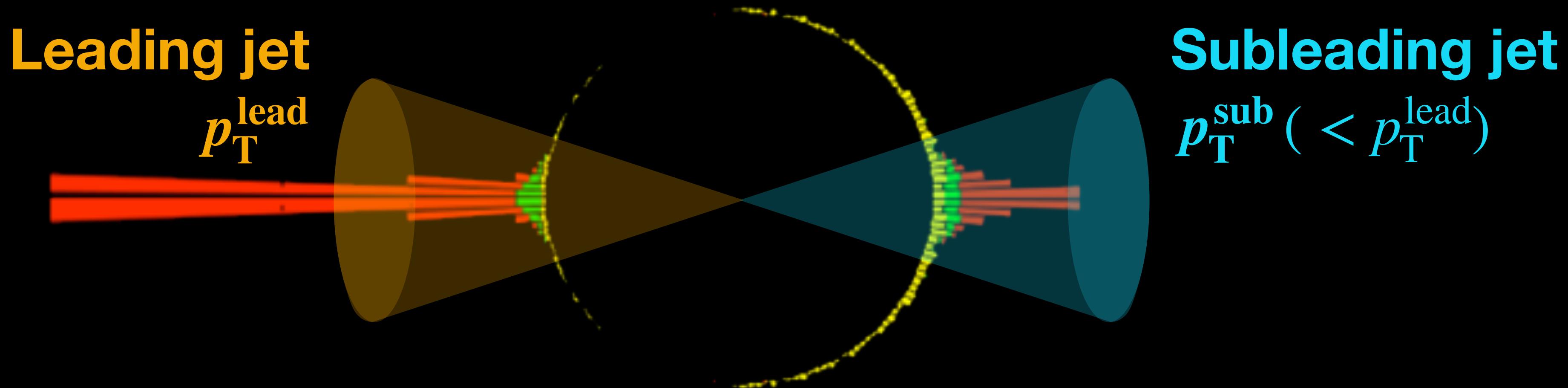
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Motivations

- Full picture of jet quenching in heavy-ion collisions
 - Re-distribution of the jet energy and momentum

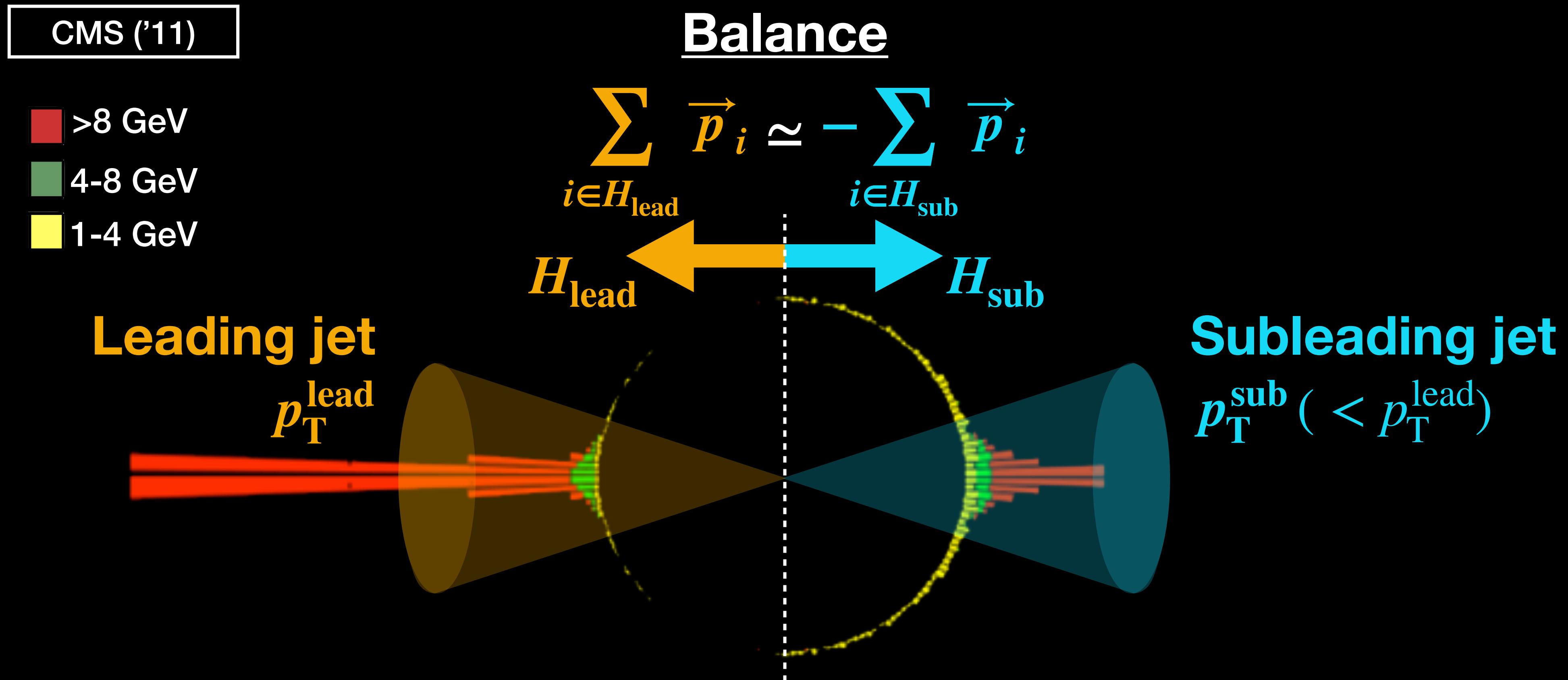
CMS ('11)

- >8 GeV
- 4-8 GeV
- 1-4 GeV



Motivations

- Full picture of jet quenching in heavy-ion collisions
Re-distribution of the jet energy and momentum



Motivations

- Full picture of jet quenching in heavy-ion collisions

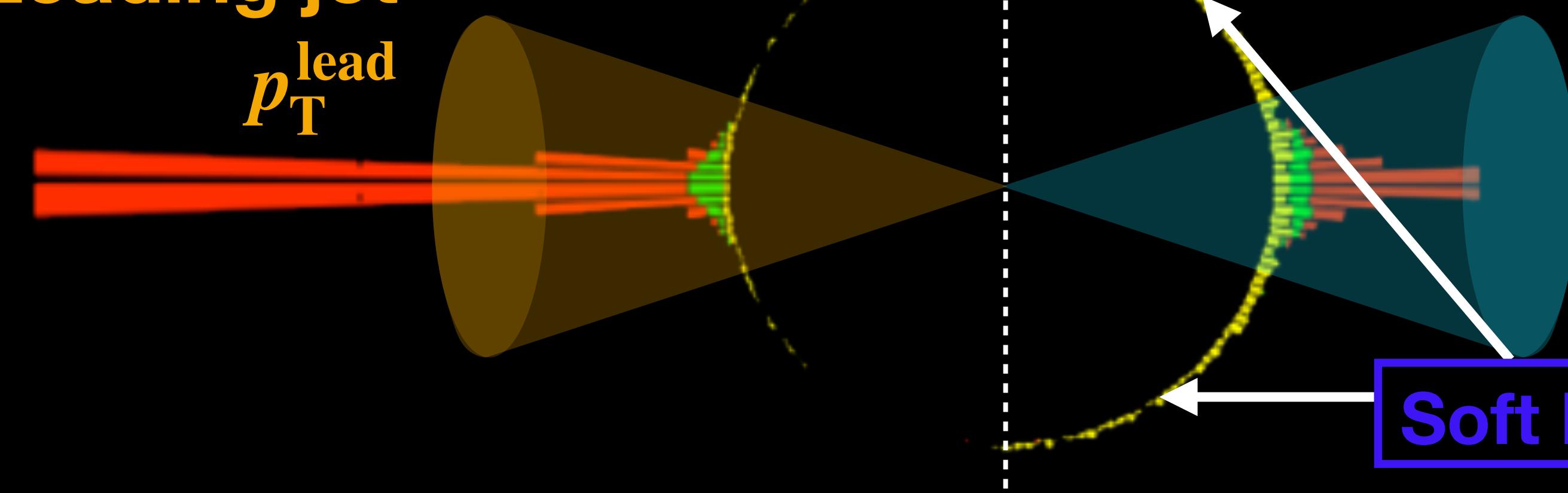
Re-distribution of the jet energy and momentum

CMS ('11)

- >8 GeV
- 4-8 GeV
- 1-4 GeV

Leading jet

p_T^{lead}



Balance

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

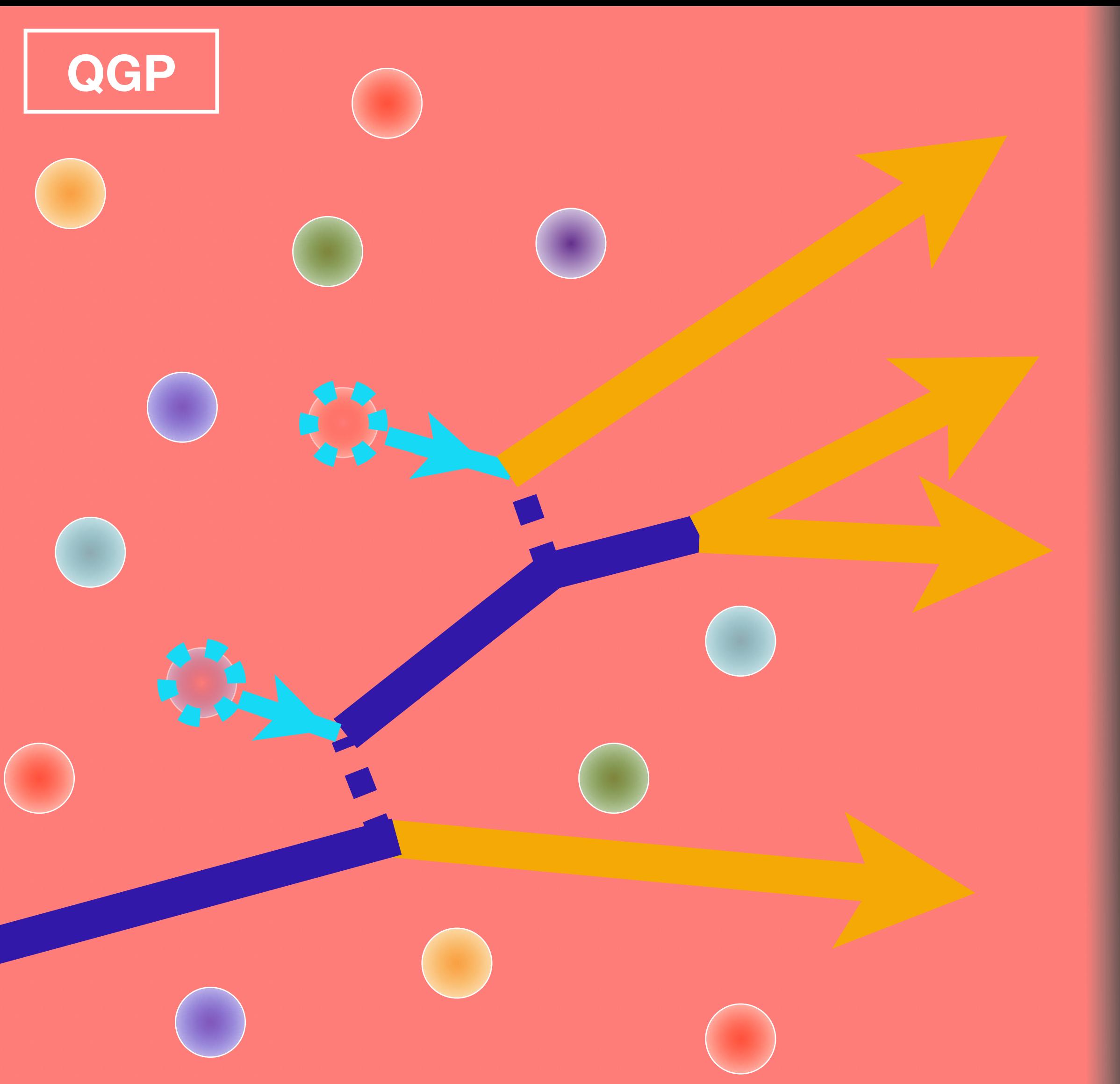
Subleading jet

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

Involve entire process in jet quenching

Implementation of Medium Response

Weakly-coupled Description: Recoils



Kinetic theory based approach

- **Partons scattered off from medium**
 - Sample a parton from thermal QGP medium for each scattering
 - Add the recoiled partons to the jet shower
 - Reasonable for partons with $E > E_{\text{med}}$

JEWEL [BDMPS-Z]

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

Talk by F. M. Canedo

LBT [Higher Twist, Low Virtuality]

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

Talks by S.-L. Zhang, T. Luo, X.-N. Wang and Y. He

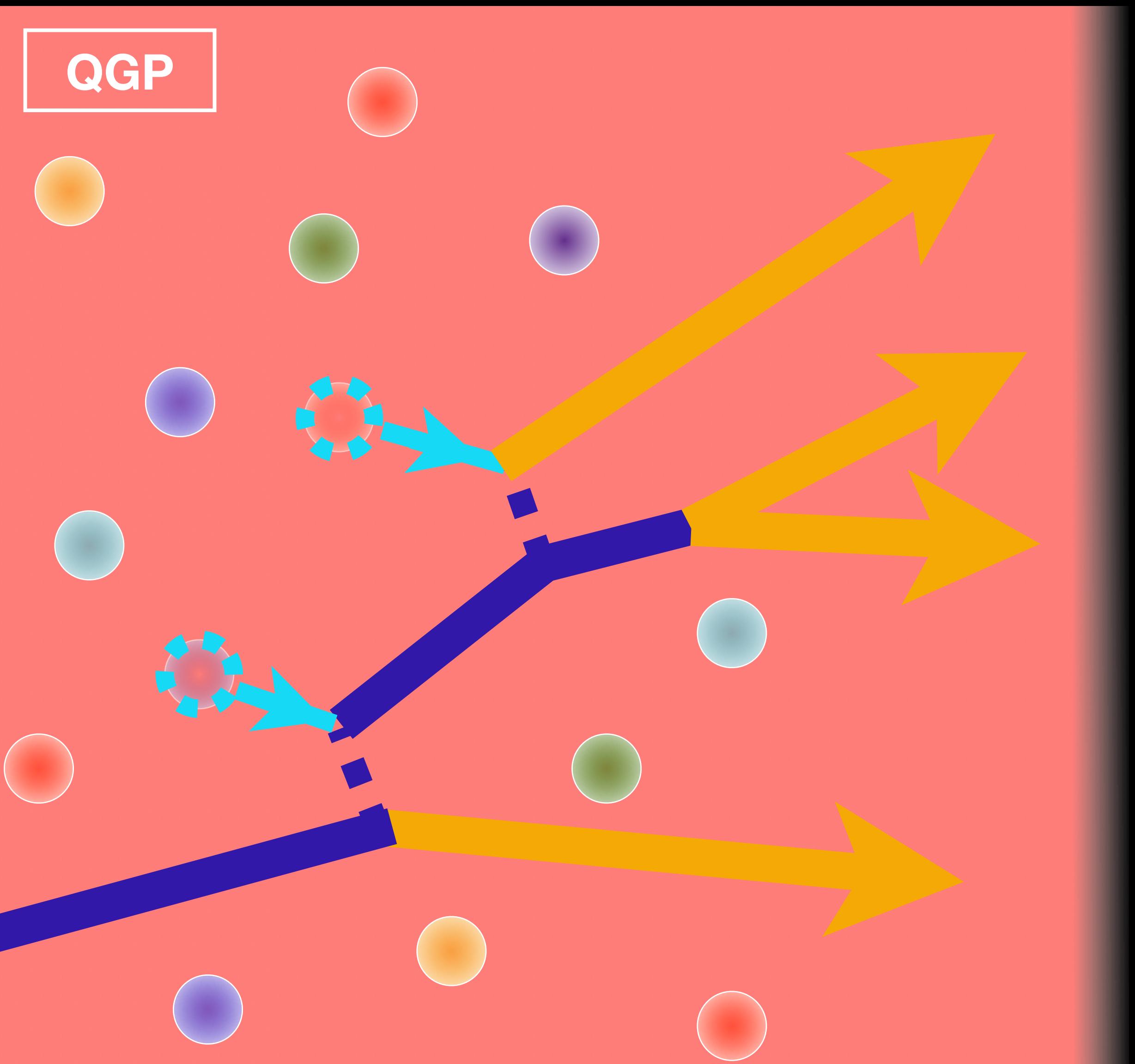
MARTINI [AMY, Low Virtuality]

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

MATTER [Higher Twist, High Virtuality]

A. Majumder, S. Cao, G. Vujanovic, M. Kordell,...

Weakly-coupled Description: Recoils



QGP

Kinetic theory based approach

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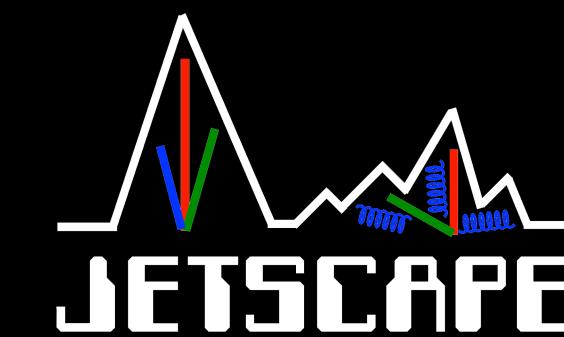
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Talks by C. Park, C. Sirimanna, W. Fan and M. Kordell

Strongly-coupled Description: Hydro Response

Hydrodynamics based approach

● Medium fluid evolution with energy-momentum deposition

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)

- Jet energy-momentum transport via thermal partons with $E \lesssim E_{\text{med}}$
- Hydrodynamics evolution *together with bulk medium*

Hydrodynamic equation with source term

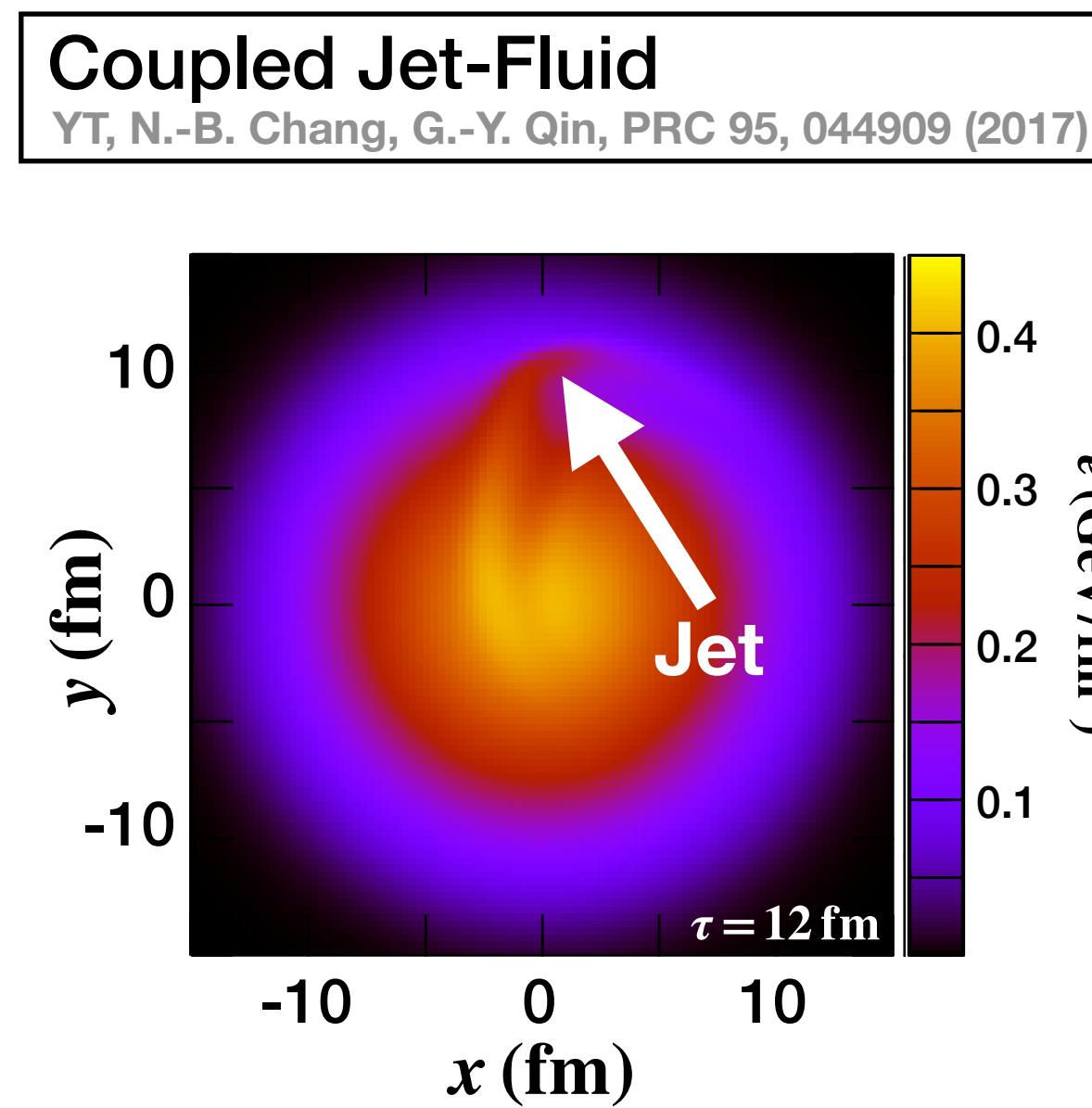
$$\partial_\mu T_{\text{fluid}}^{\mu\nu} = J_{\text{jet}}^\nu$$

Energy-momentum tensor
of the QGP fluid

Energy and momentum
deposited into the fluid

- Source term J_{jet}^ν constructed from jet-shower evolution calculation
- Bulk part particle with hydro response obtained via the Cooper-Frye

Strongly-coupled Description: Hydro Response



Coupled Jet-Fluid Talk by N.-B. Chang

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

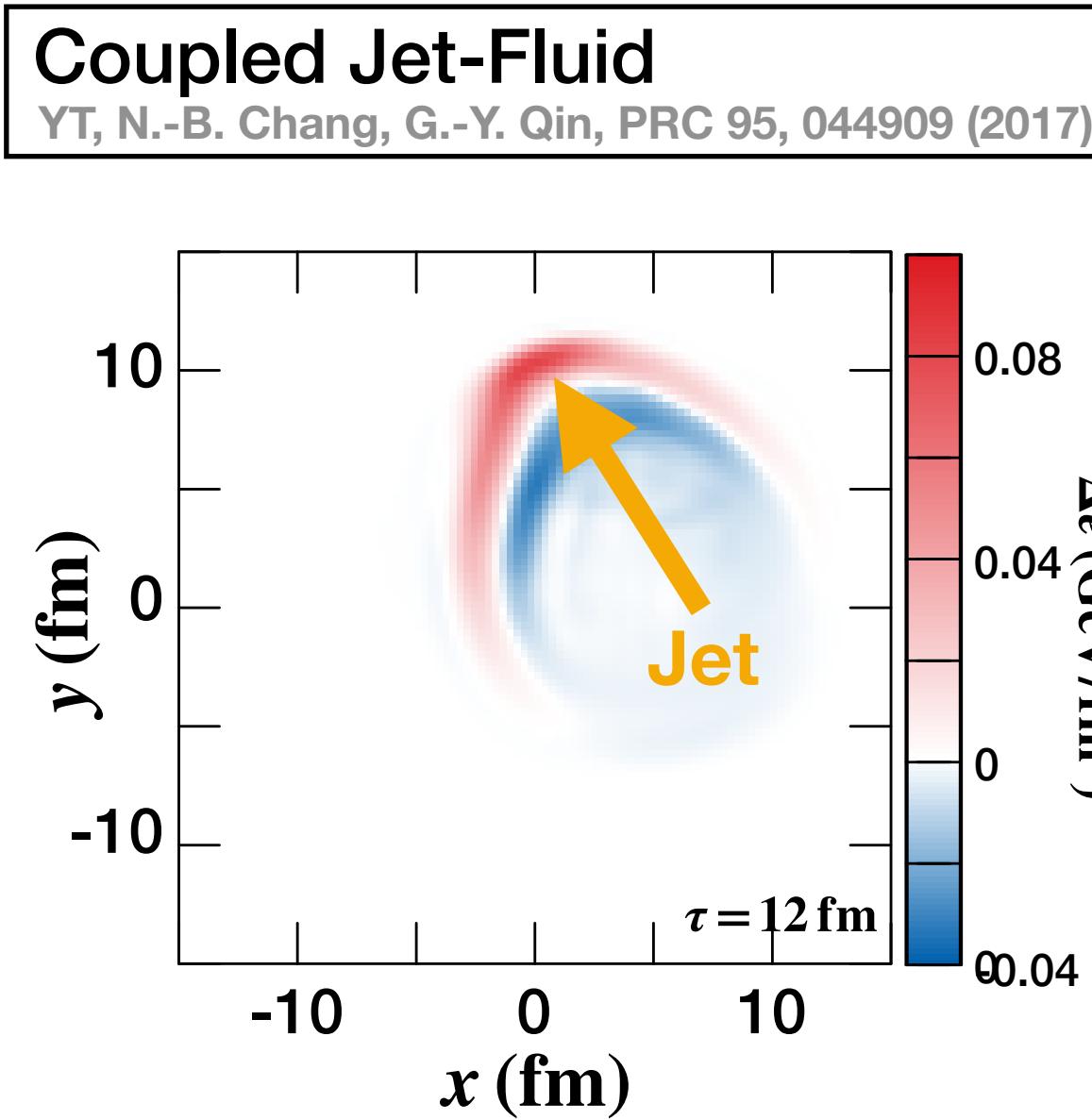
- Parton shower transport [Higher Twist] + ideal hydro (PPM)

EPOS3-HQ Talk by I. Karpenko

I. Karpenko, M. Rohrmoser, J. Aichelin, P. Gossiaux, K. Werner

- YaJEM + viscous hydro (vHLL)
- Multi (mini) jets production and propagation w/ hydro response
- Simultaneous production of jet and medium by EPOS Initial state

Strongly-coupled Description: Hydro Response



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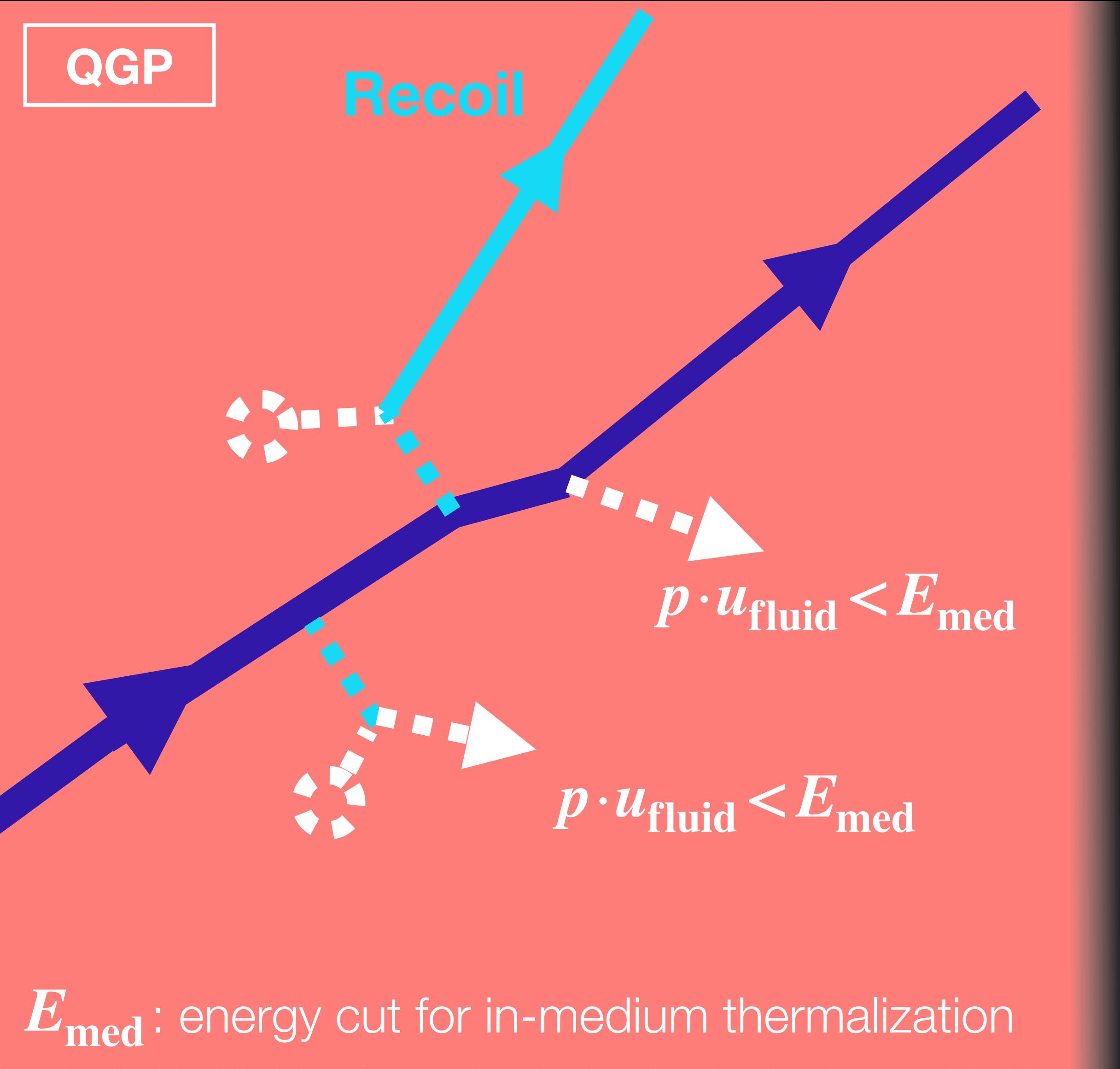
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Hybrid Description: Recoil + Hydro Response



Source term: $J_{\text{jet}}^{\nu}(x) = \sum_{i \in \text{thermalized}} j_i^{\mu}(x)$

CoLBT-hydro

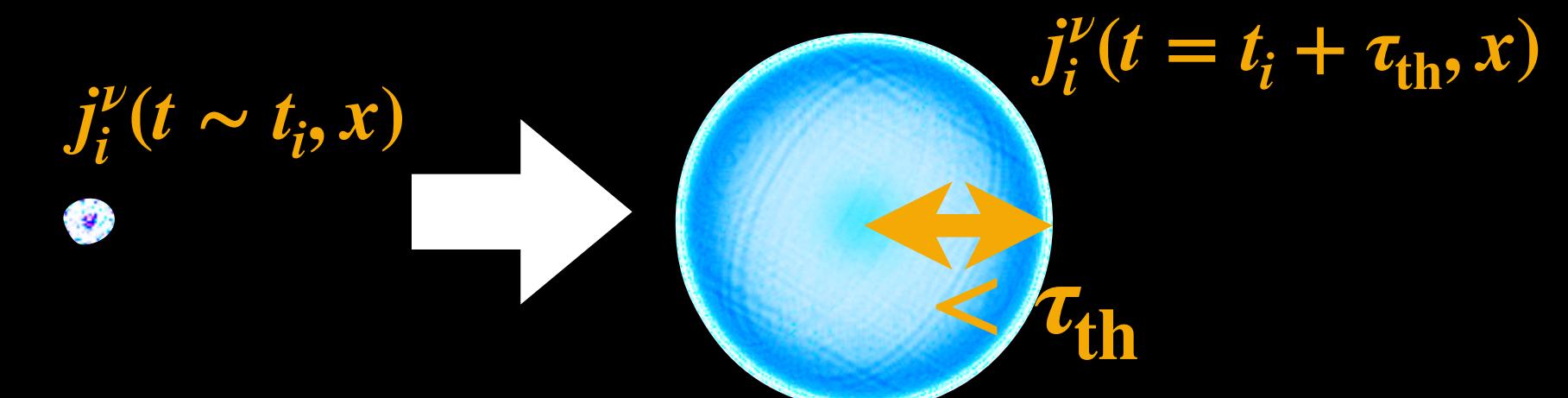
W. Chen, T. Luo, S. Cao, L.-G. Pang, X.-N. Wang, ...

- LBT + viscous hydro (CLvisc)

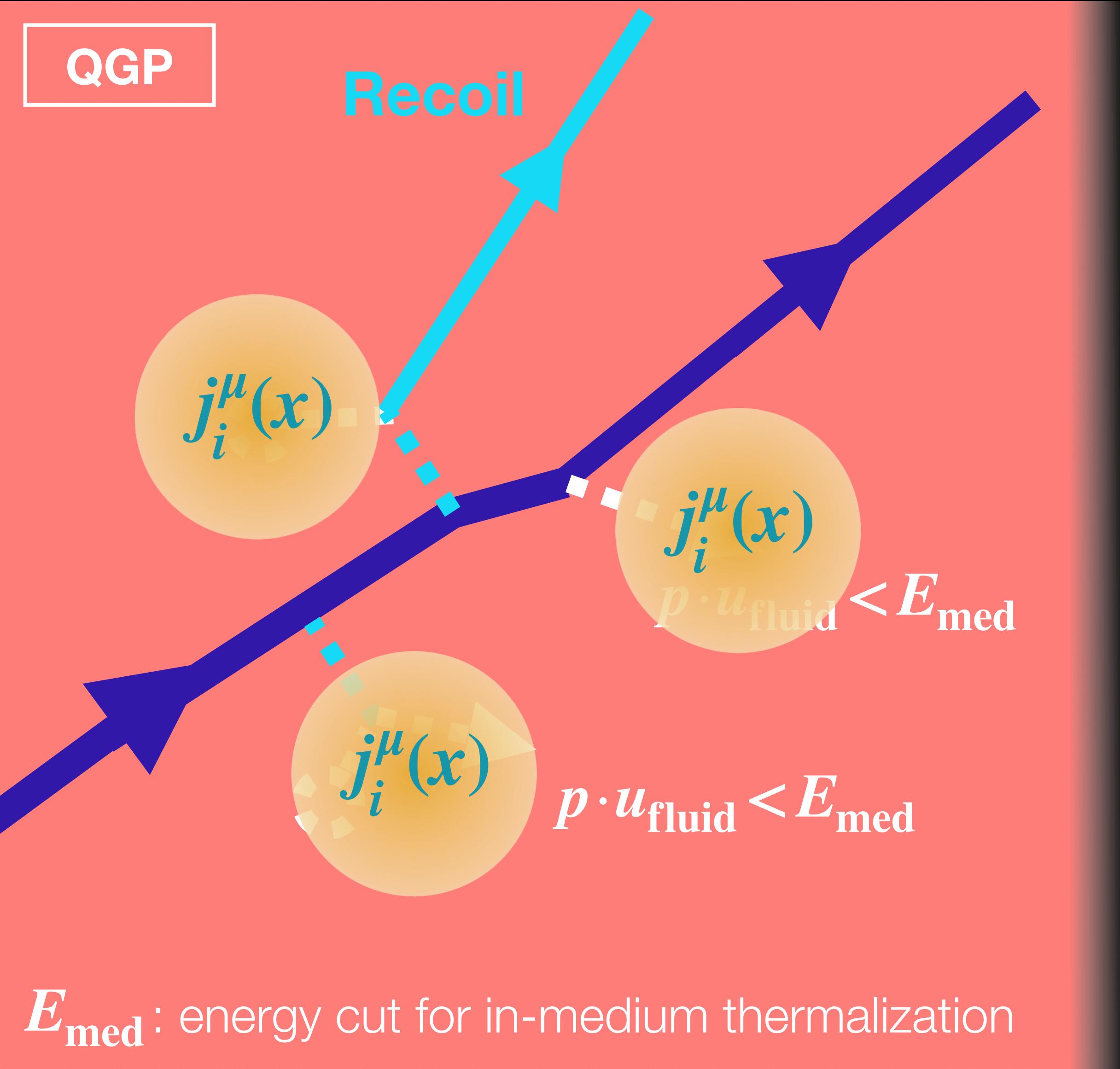
JETSCAPE Framework

JETSCAPE

- MATTER + LBT/MARTINI + viscous hydro (MUSIC)
- Source profile based on *causal* diffusion
- Parameters characterizing in-medium thermalization
(Thermalization time τ_{th} , Diffusion coefficient D_{diff} , etc.)



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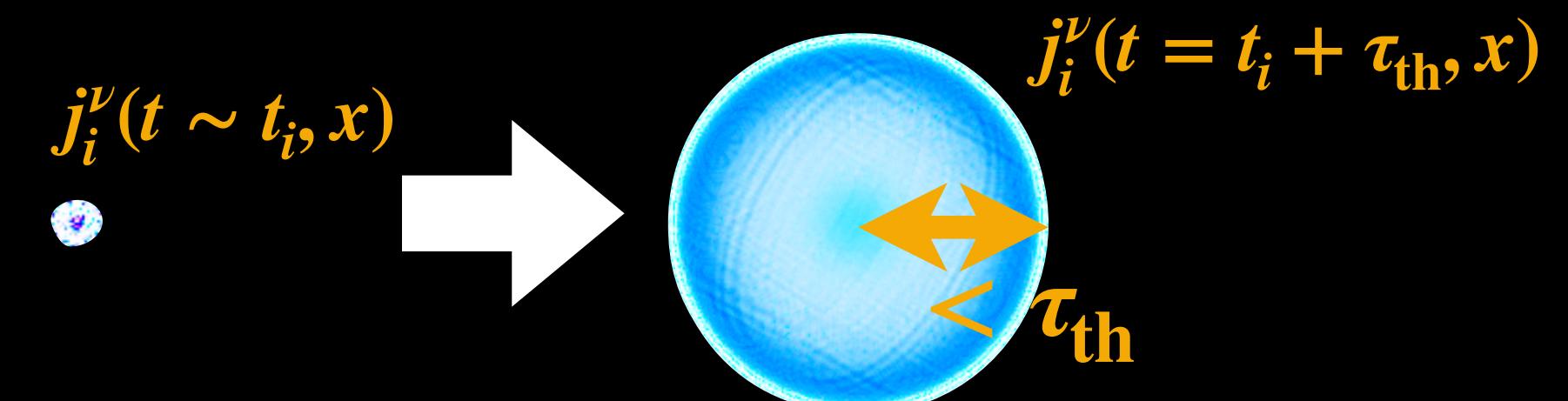
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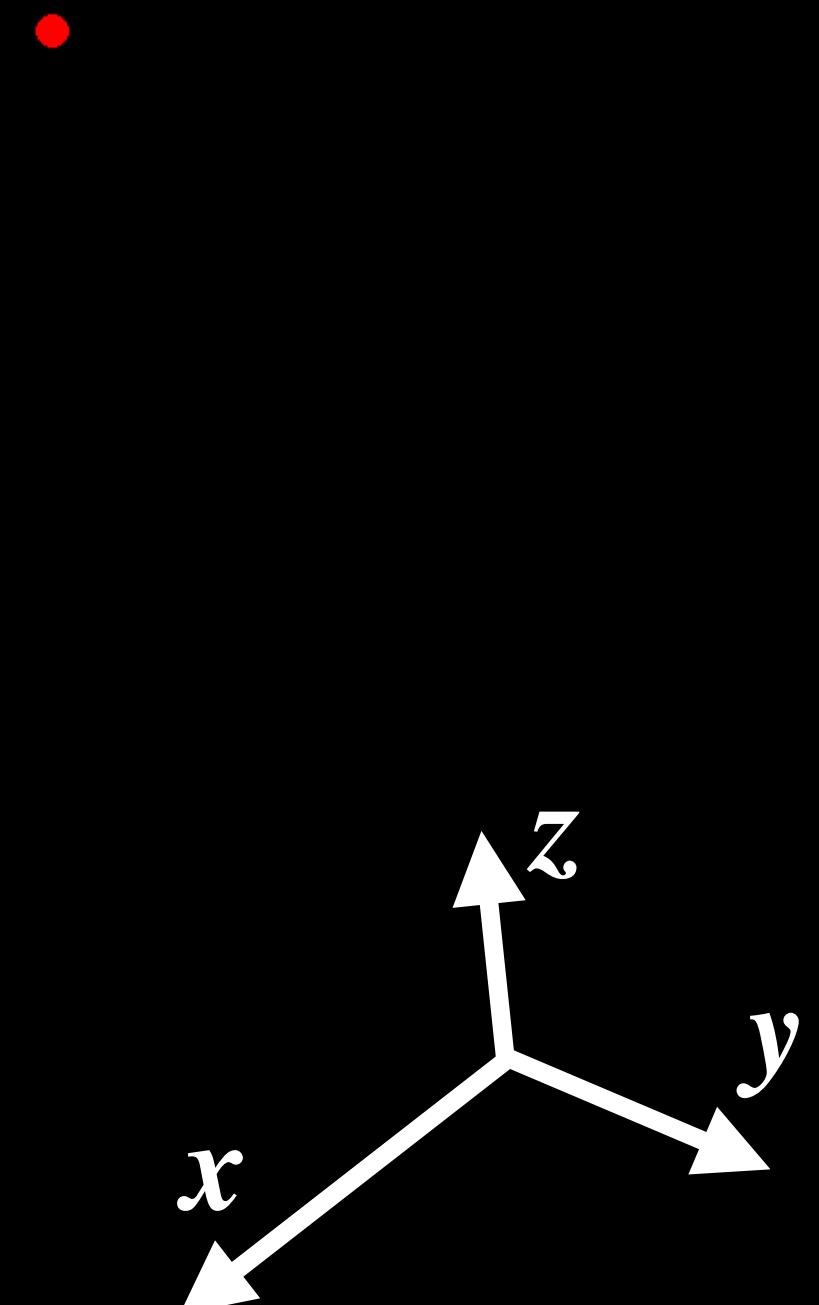
MATTER + LBT + Causal Diff. + Ideal Hydro [Static Brick]
YT, C. Shen, A. Majumder, arXiv:2001.08321

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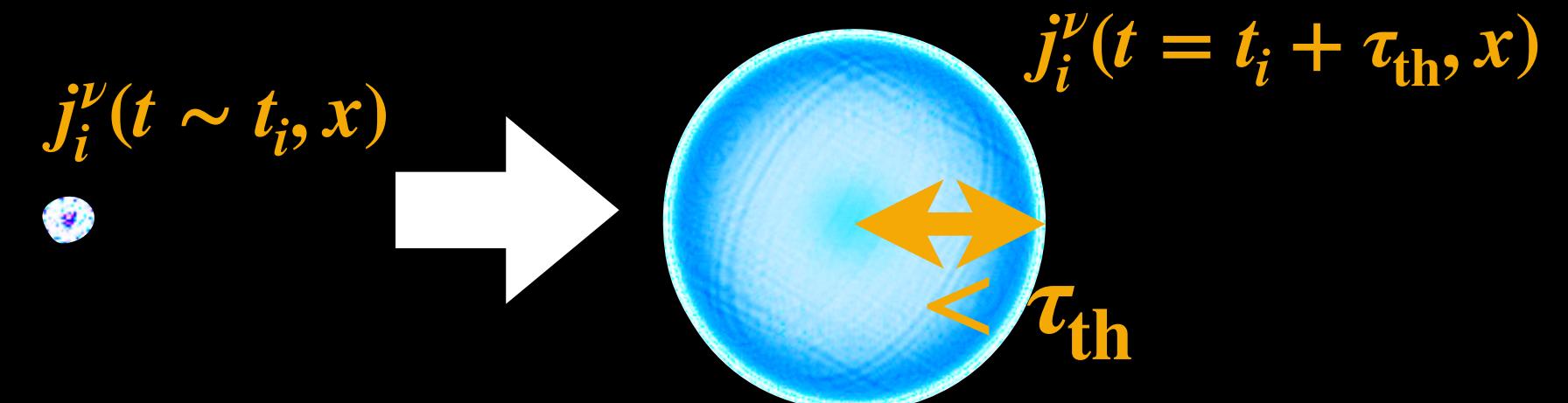
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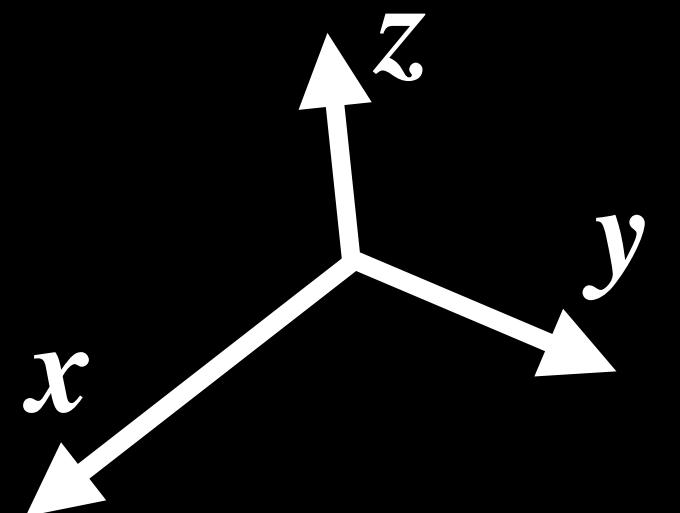
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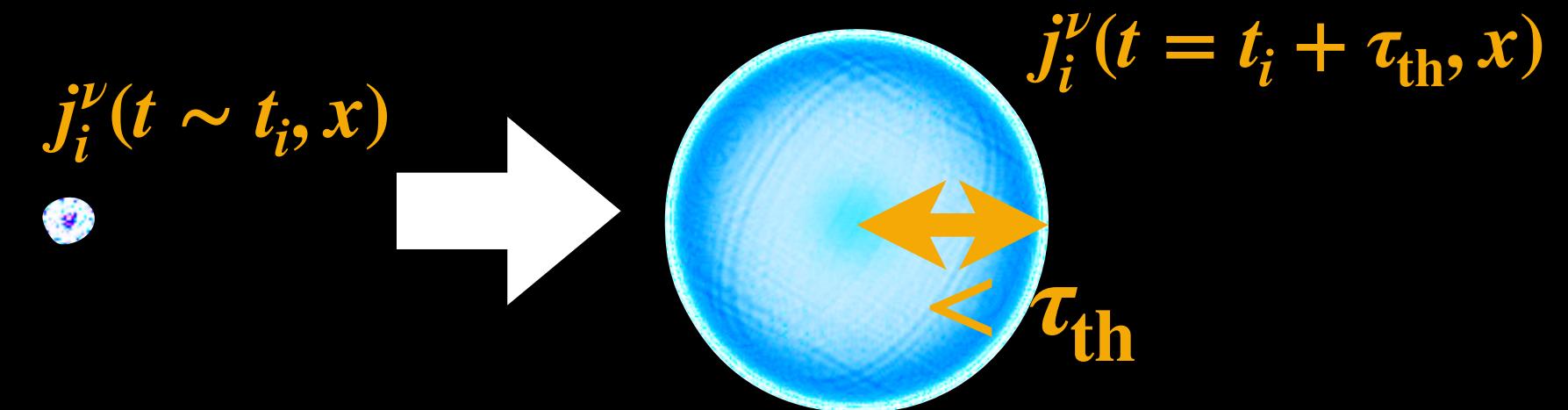
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(Thermalization time τ_{th} , Diffusion coefficient D_{diff} , etc.)



Other implementations of medium response to jet

- **Boltzmann equation based approach**

- Particle picture applied both for medium and jet shower

AMPT

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

BAMPS

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

- **Perturbation due to jet energy deposition in the Cooper-Frye**

- Estimation of medium response effect w/o its dynamical description

Hybrid Strong/Weak Coupling [AdS/CFT] [Talk by D. Pablos](#)

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

- **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),...

- Semi-analytical approach to study fluid properties in jet-induced flow

Hybrid Strong/Weak Coupling + Linearized Hydro [Talk by J. Casalderrey-Solana](#)

D. Pablos, X. Yao, J. Casalderrey-Solana, K. Rajagopal, J. G. Milhano

- **Causal diffusion as perturbations on top of hydrodynamic flow**

MARTINI + Causal Diffusion [Talk by S. Ryu](#)

S. Ryu, S. McDonald, C. Shen S. Jeon, C. Gale

Brief Summary of Models for Medium Response

Recoil

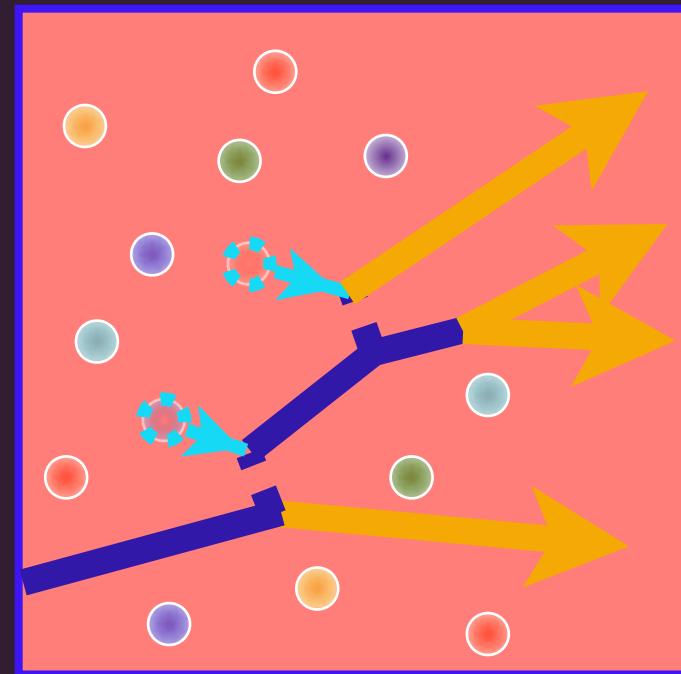
JEWEL

LBT

MARTINI

MATTER

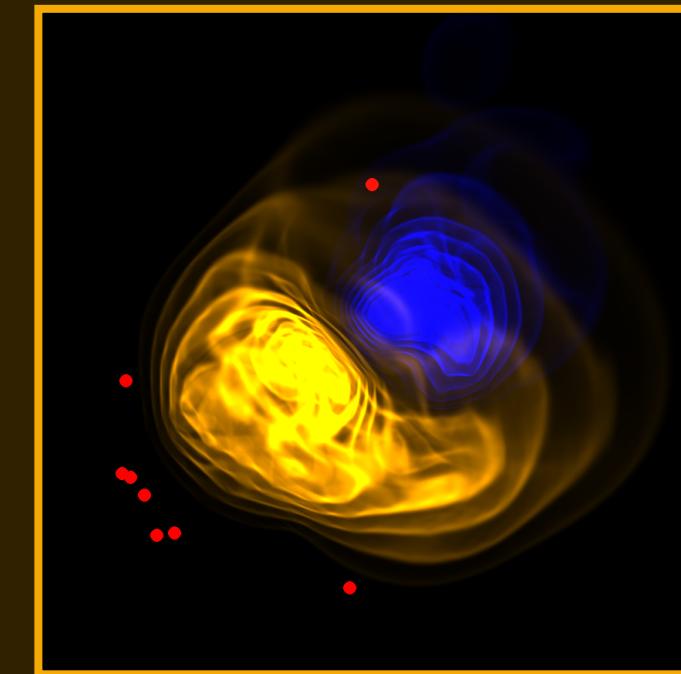
JETSCAPE Framework
[MATTER + LBT/MARTINI]



Recoil + Hydro Res.

CoLBT-hydro

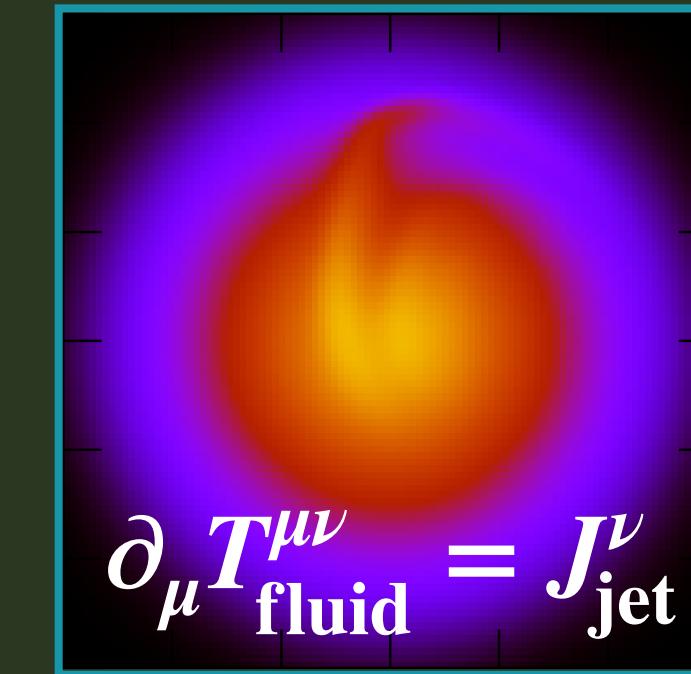
JETSCAPE Framework
[MATTER+LBT/MARTINI+CausalDiff.+MUSIC]



Hydro Response

Coupled Jet-Fluid

EPOS3-HQ

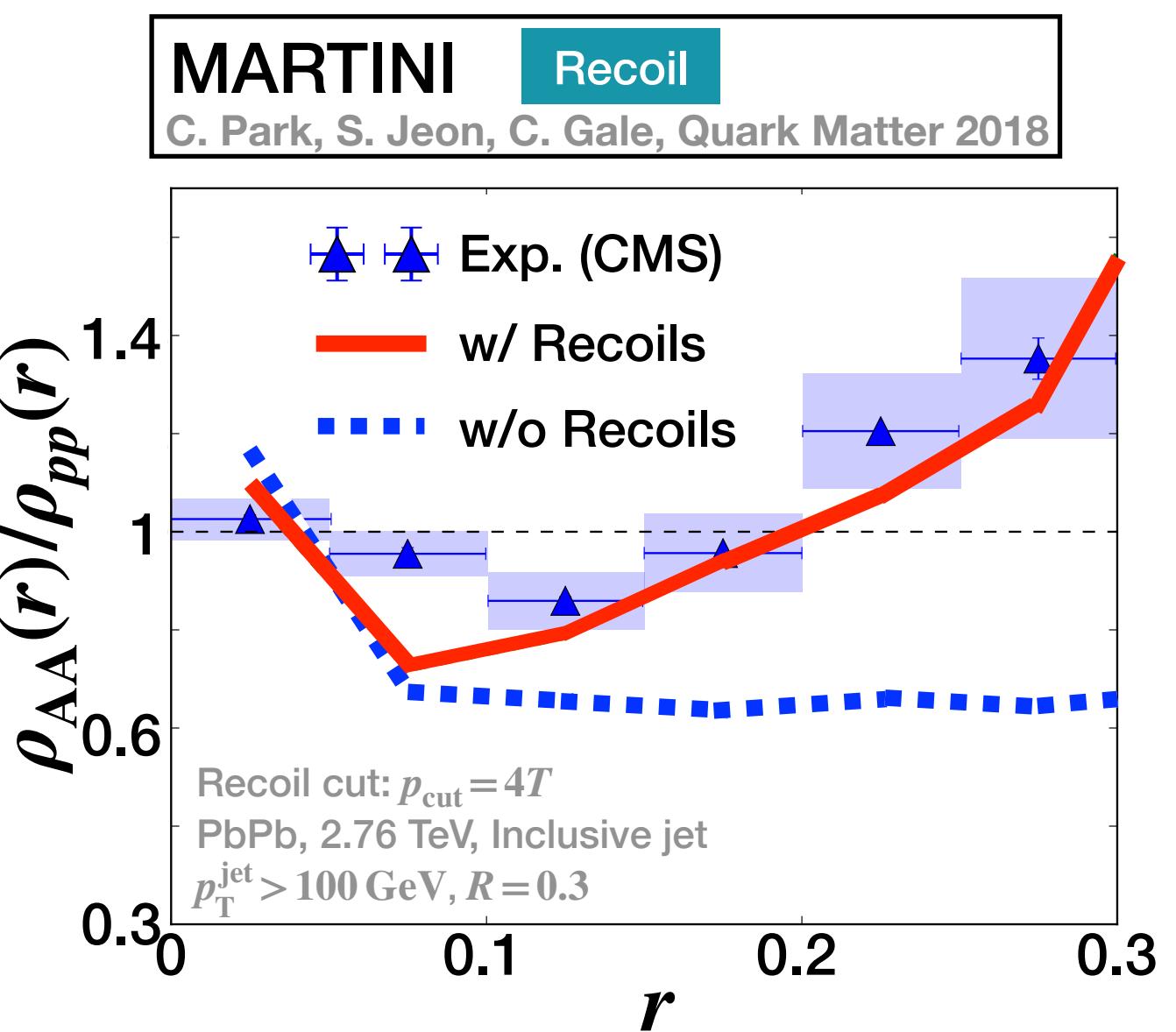
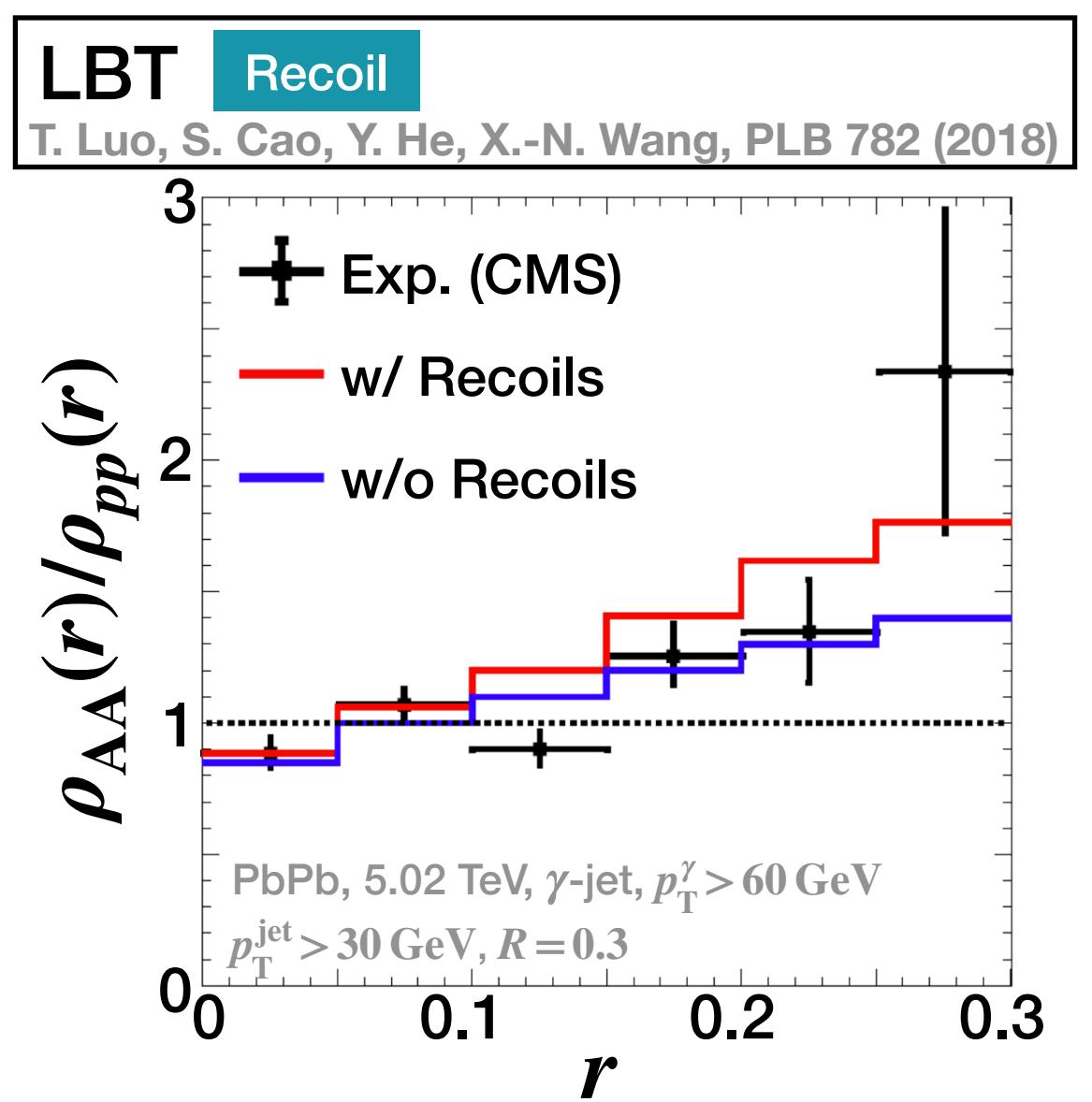
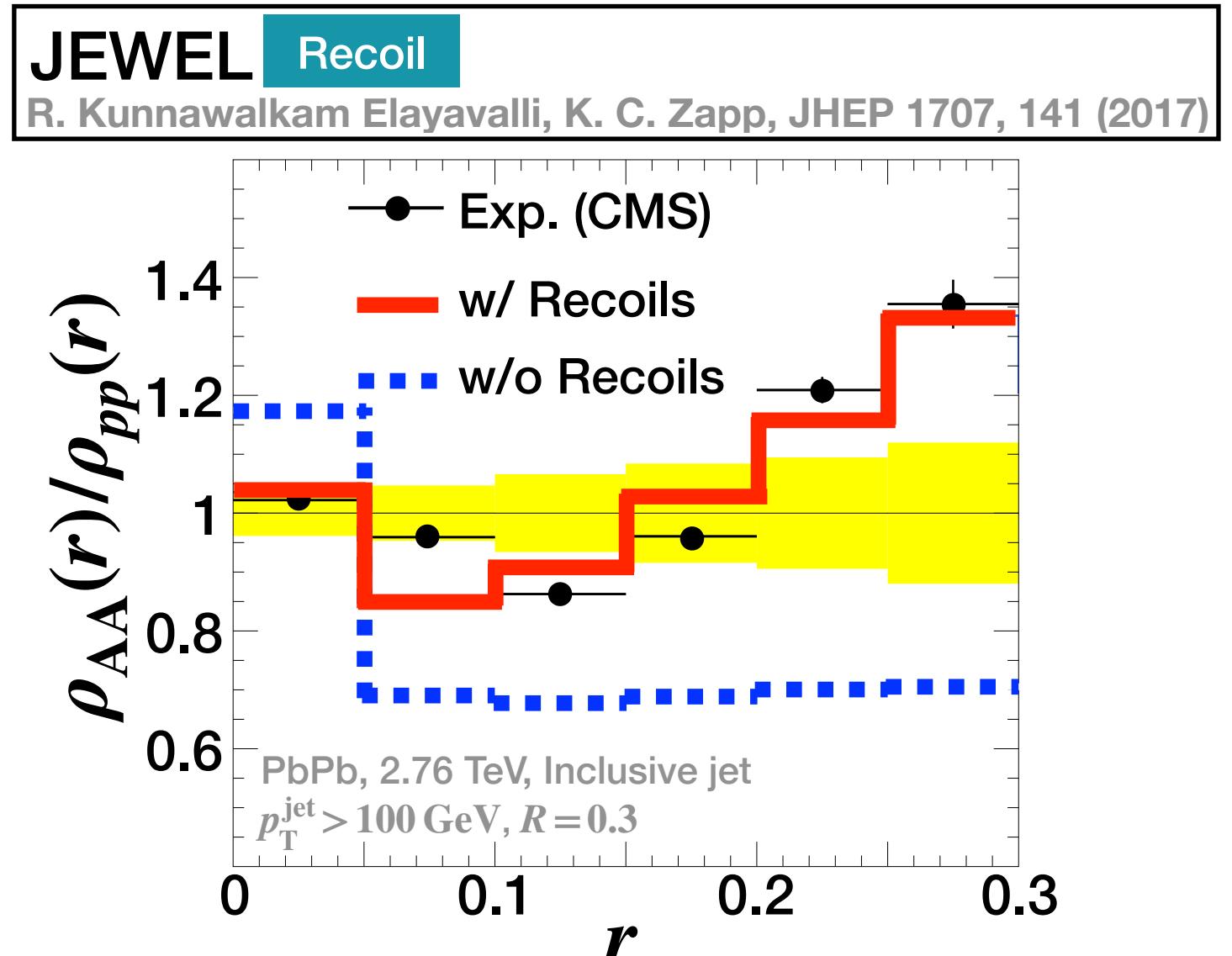
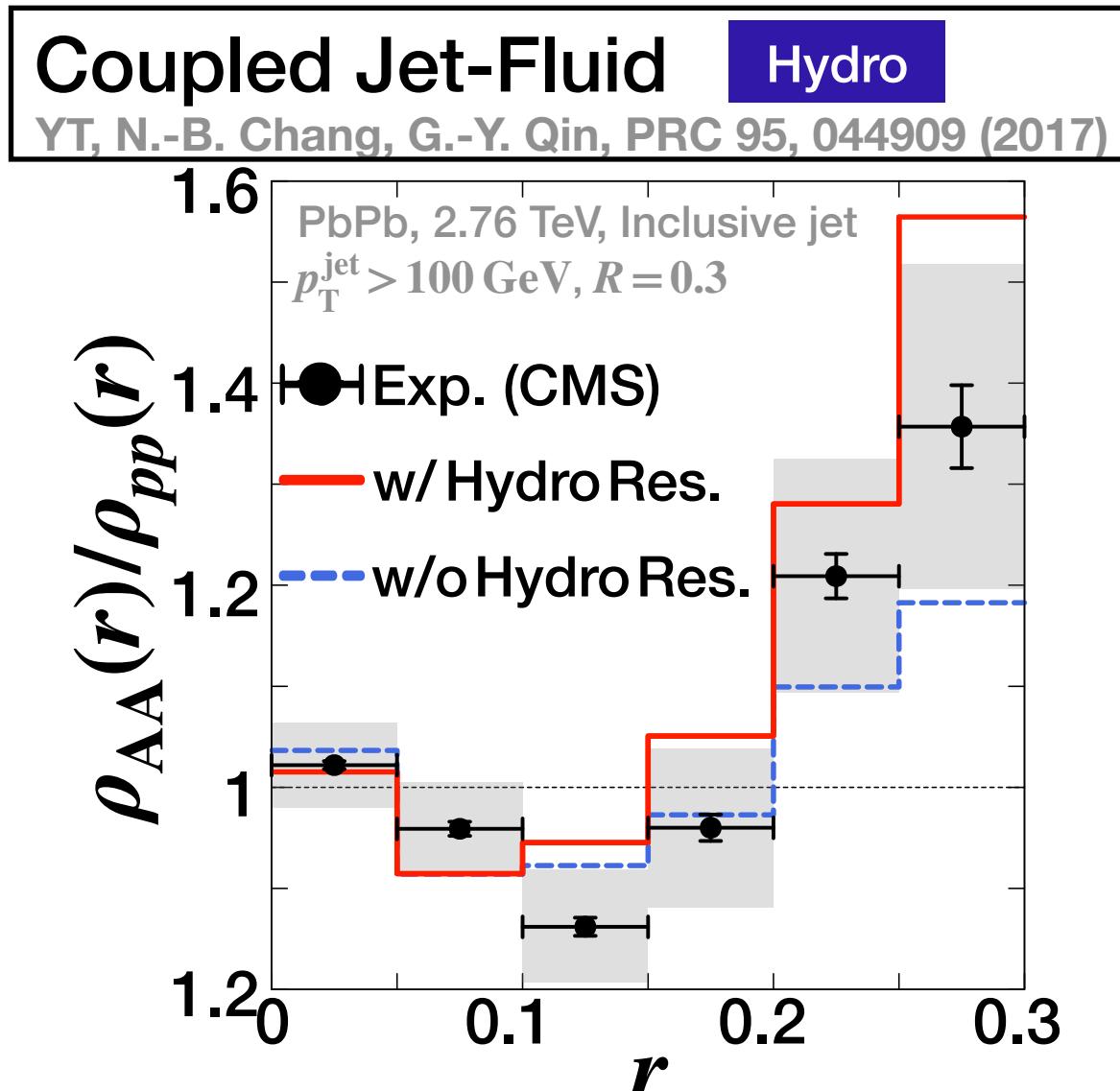


$\sim E_{\text{med}}$

Strongly-coupled ($\lesssim E_{\text{med}}$)

Medium Response Effects

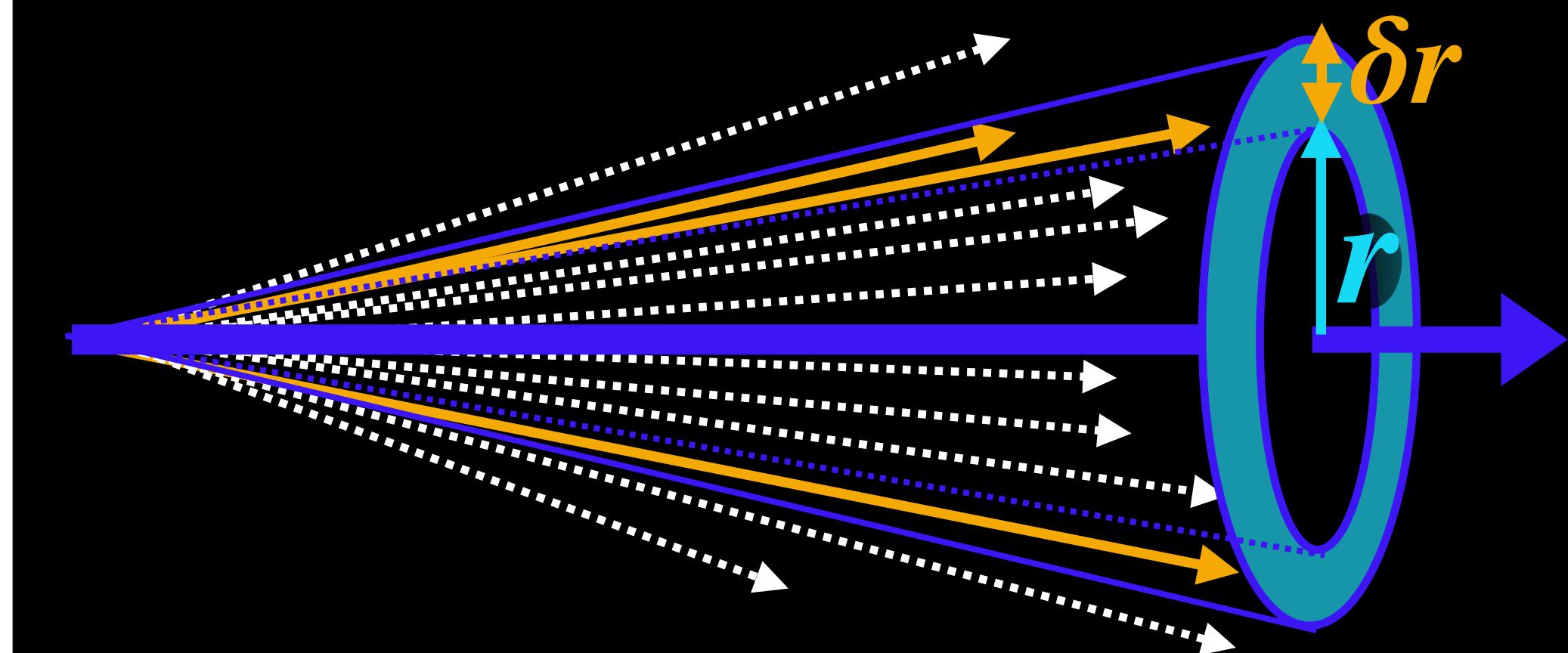
Angular Structure (Inside Jet Cone)



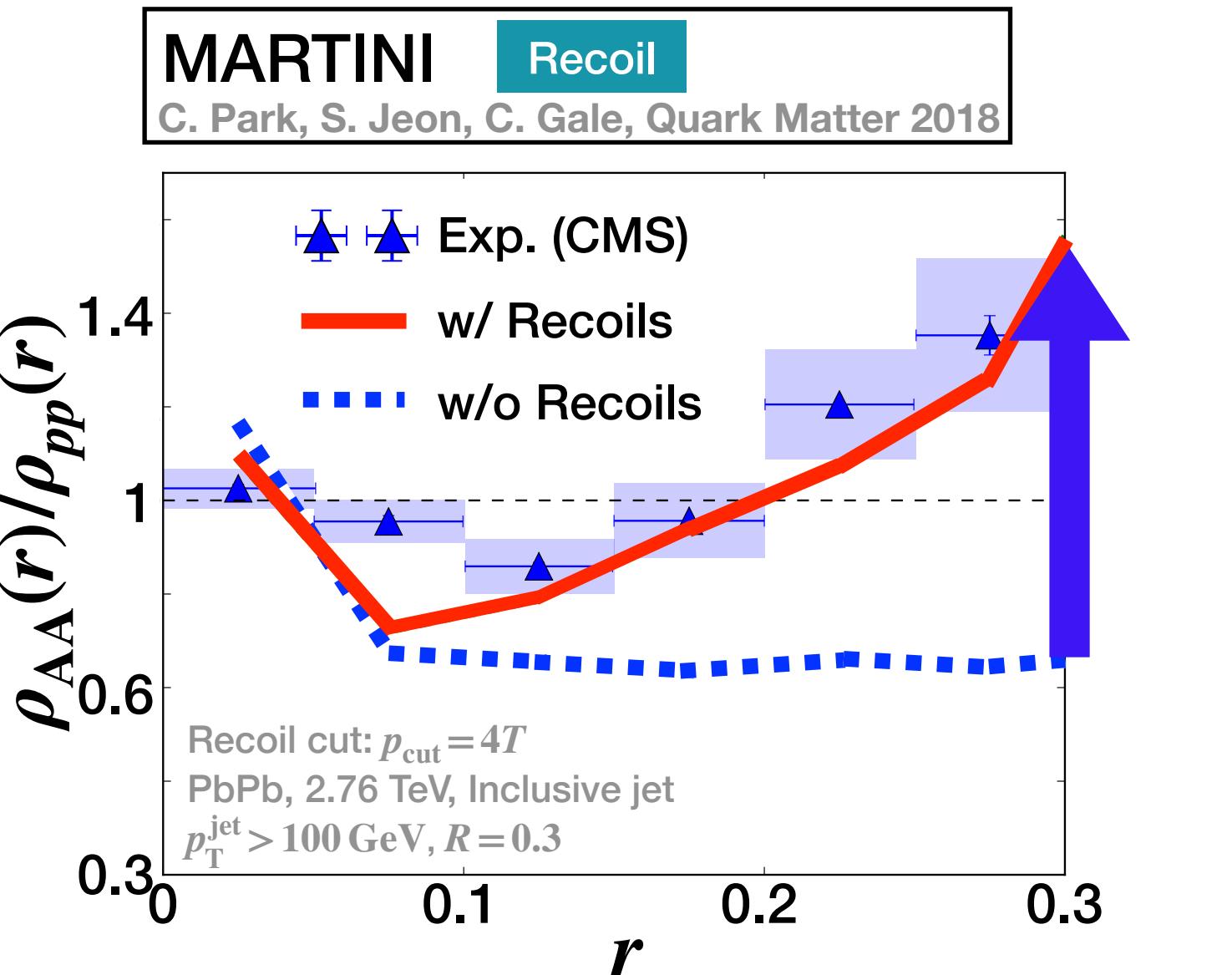
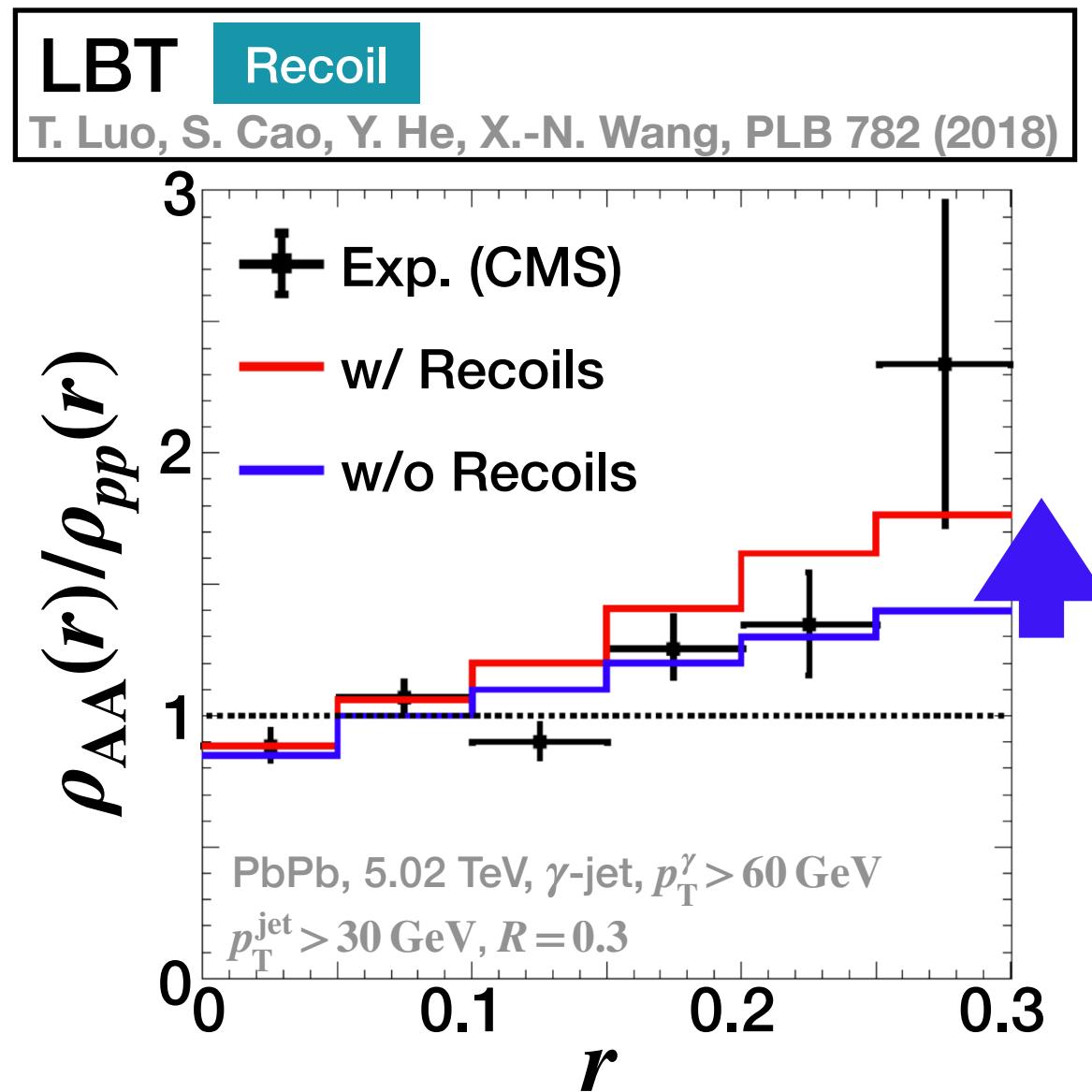
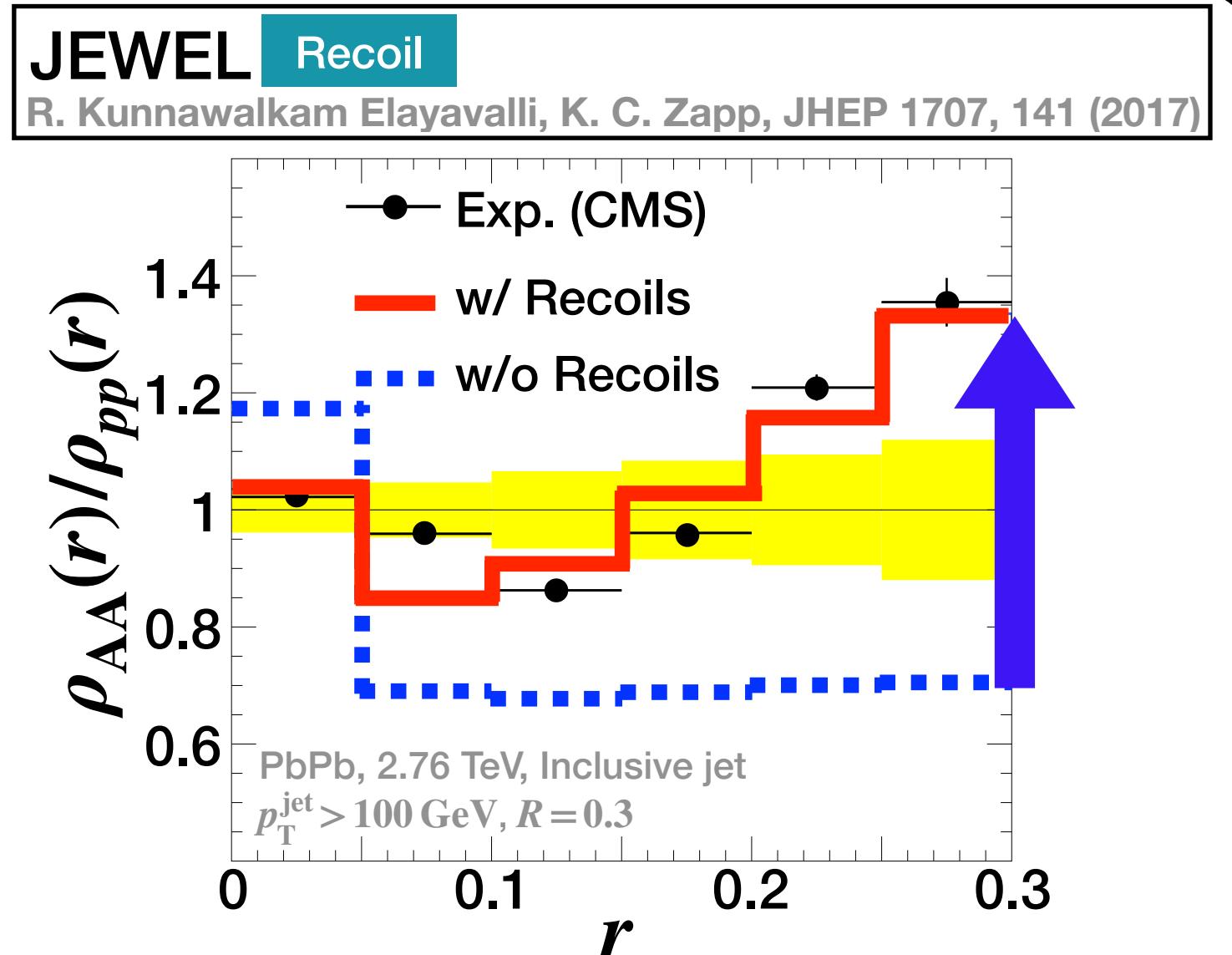
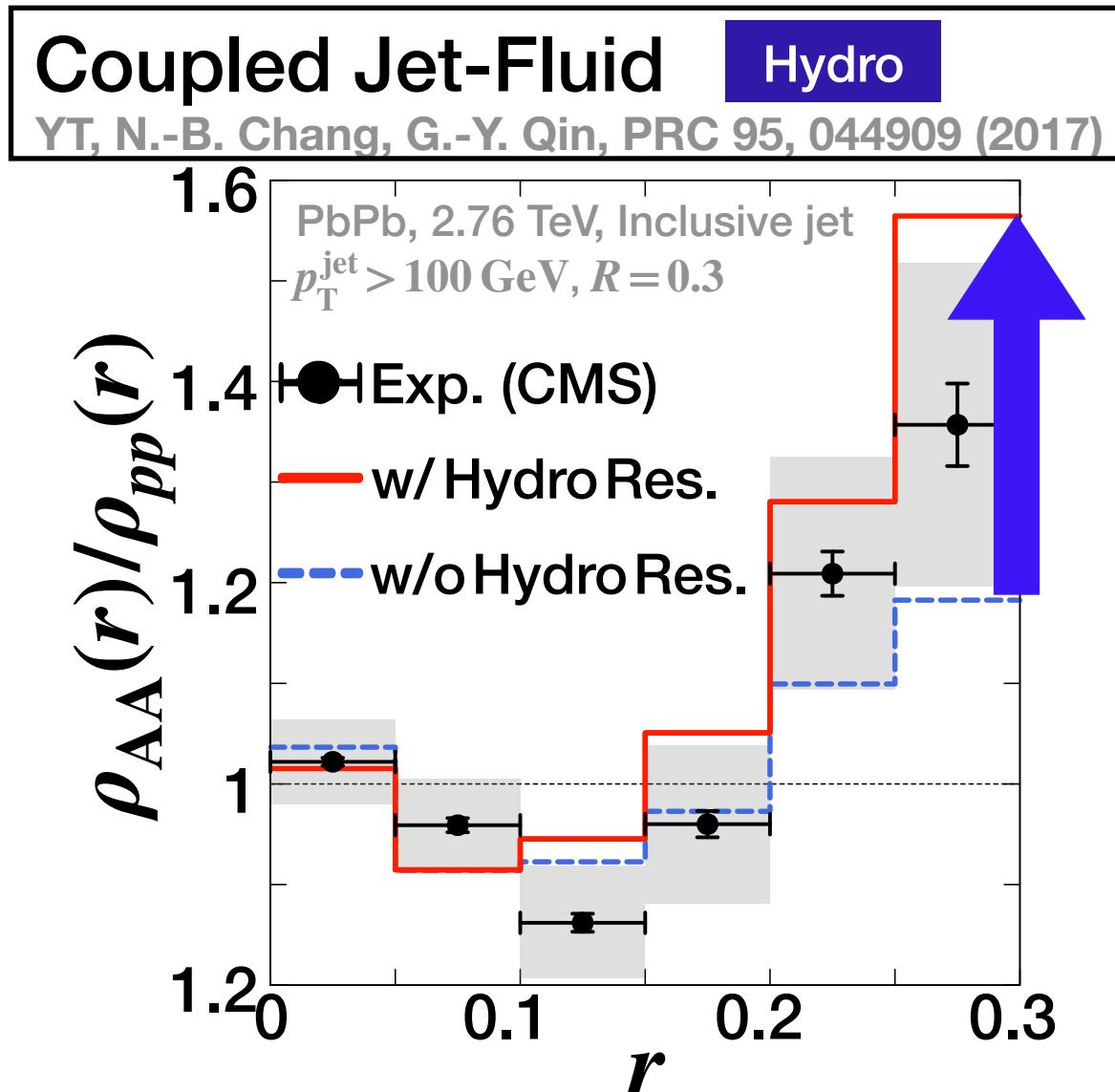
- Jet shape

$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{i \in (r - \delta r/2, r + \delta r/2)} p_T^i}{\sum_{i \in (0, R)} p_T^i}$$

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



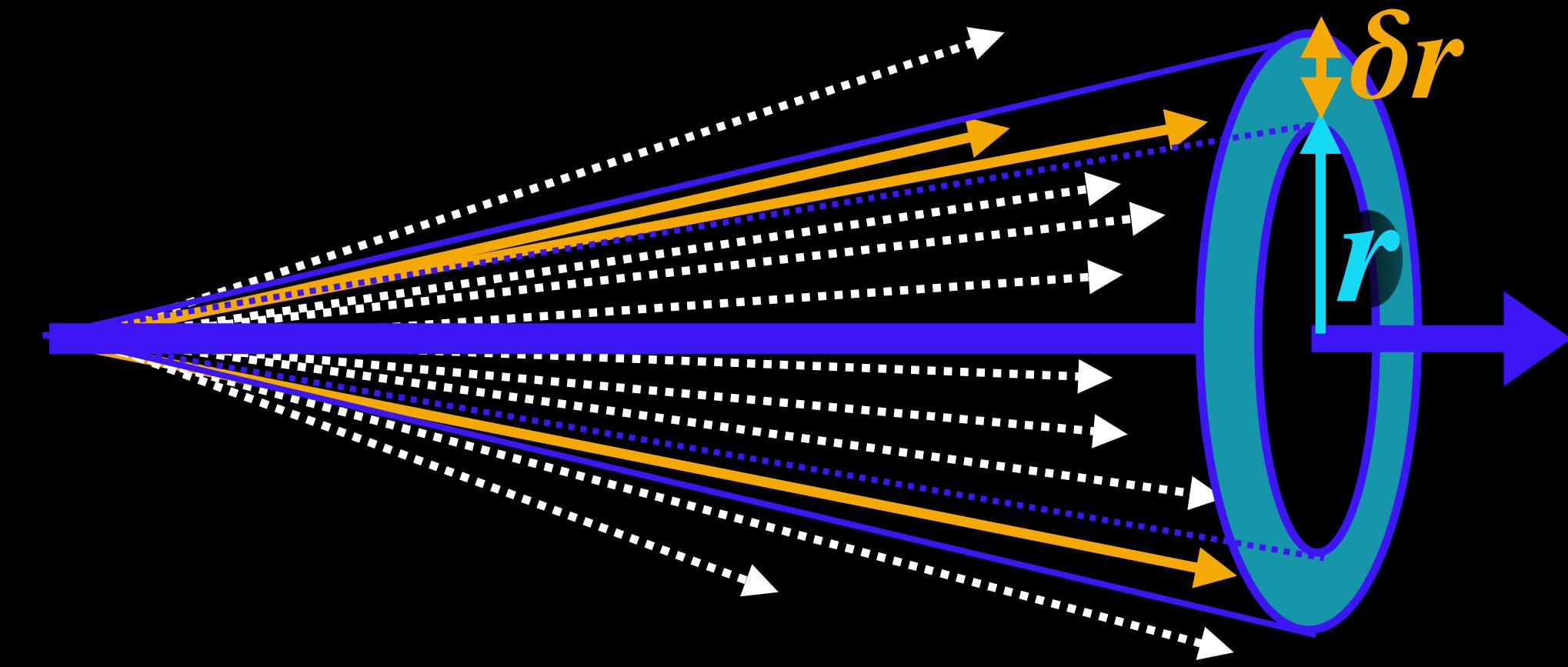
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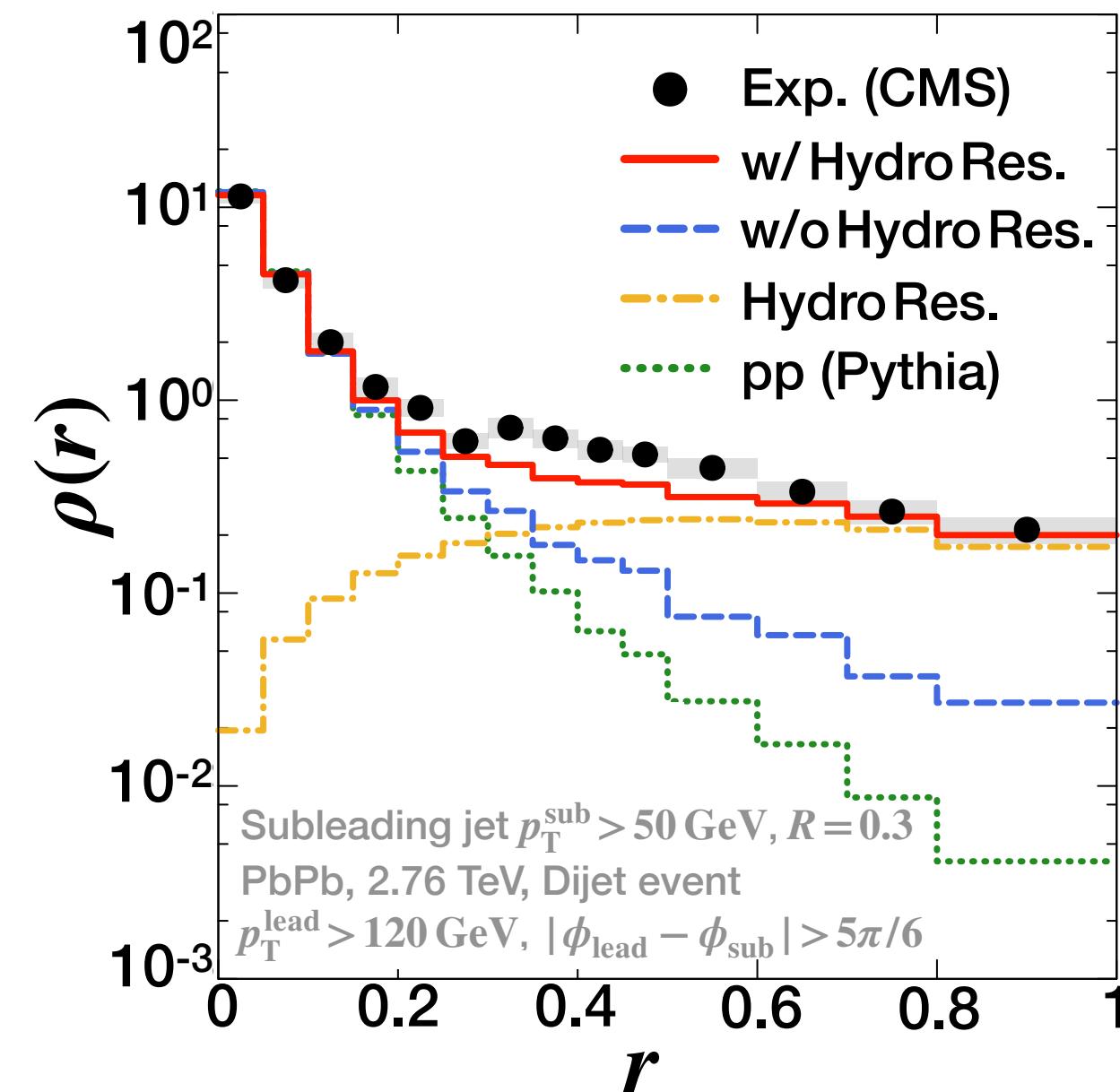
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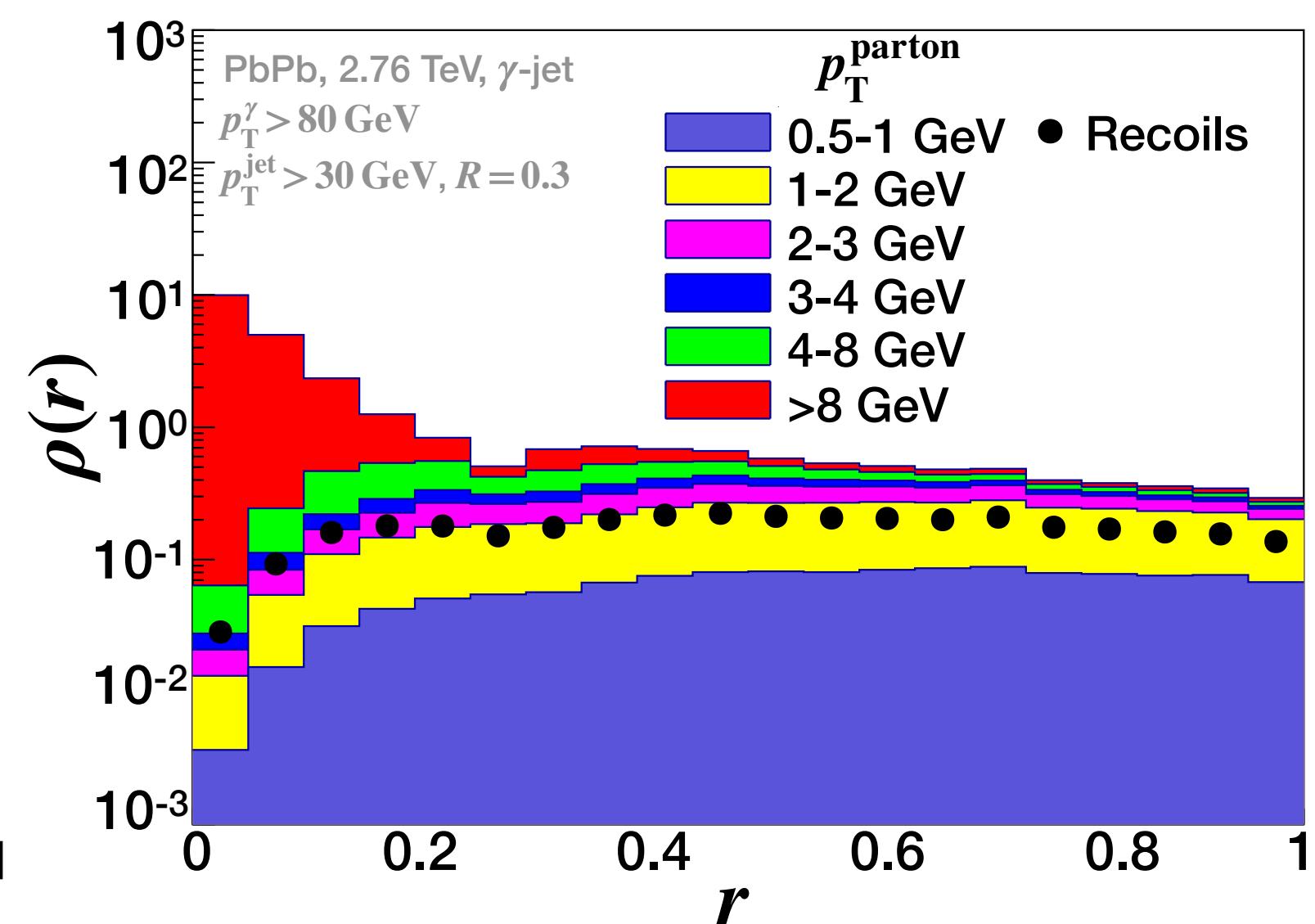


Angular Structure (Outside Jet Cone)

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



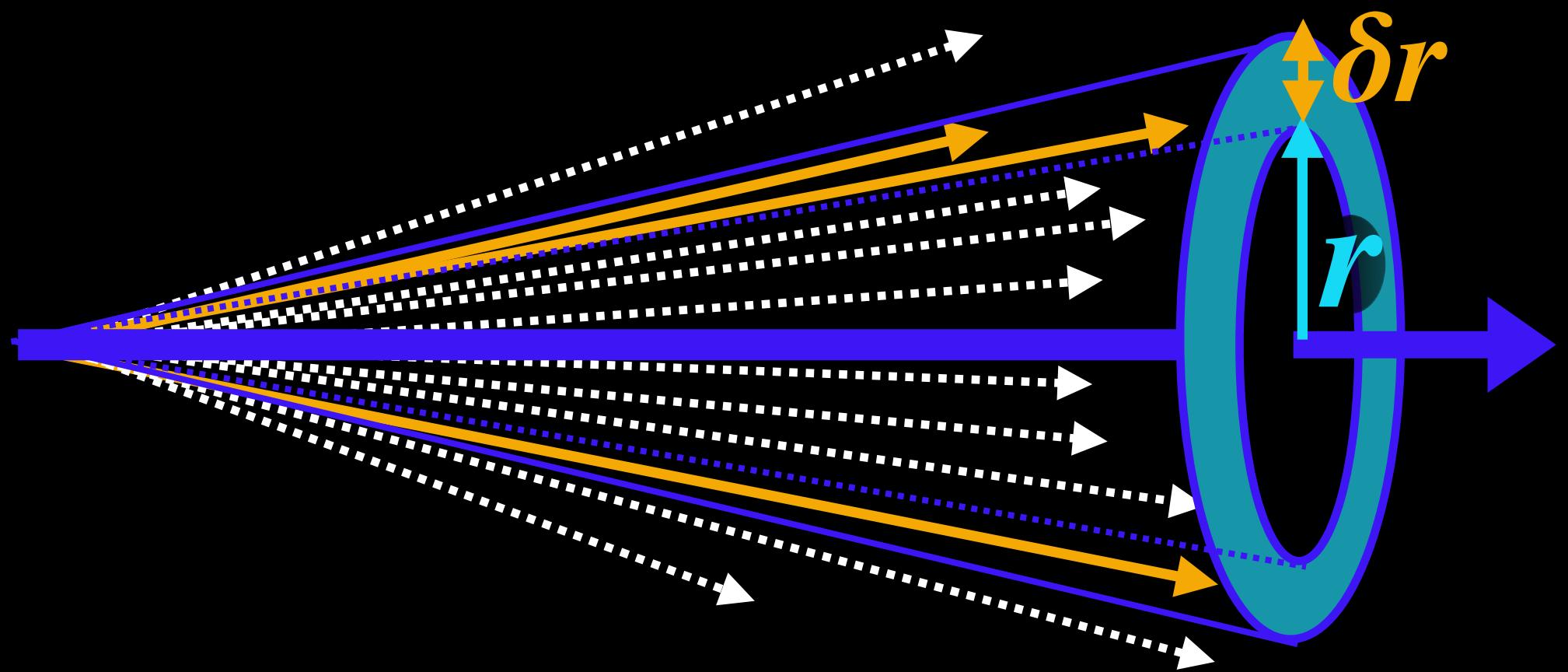
LBT **Recoil**
 T. Luo, S. Cao, Y. He, X.-N. Wang, PLB 782 (2018)



- **Jet shape**

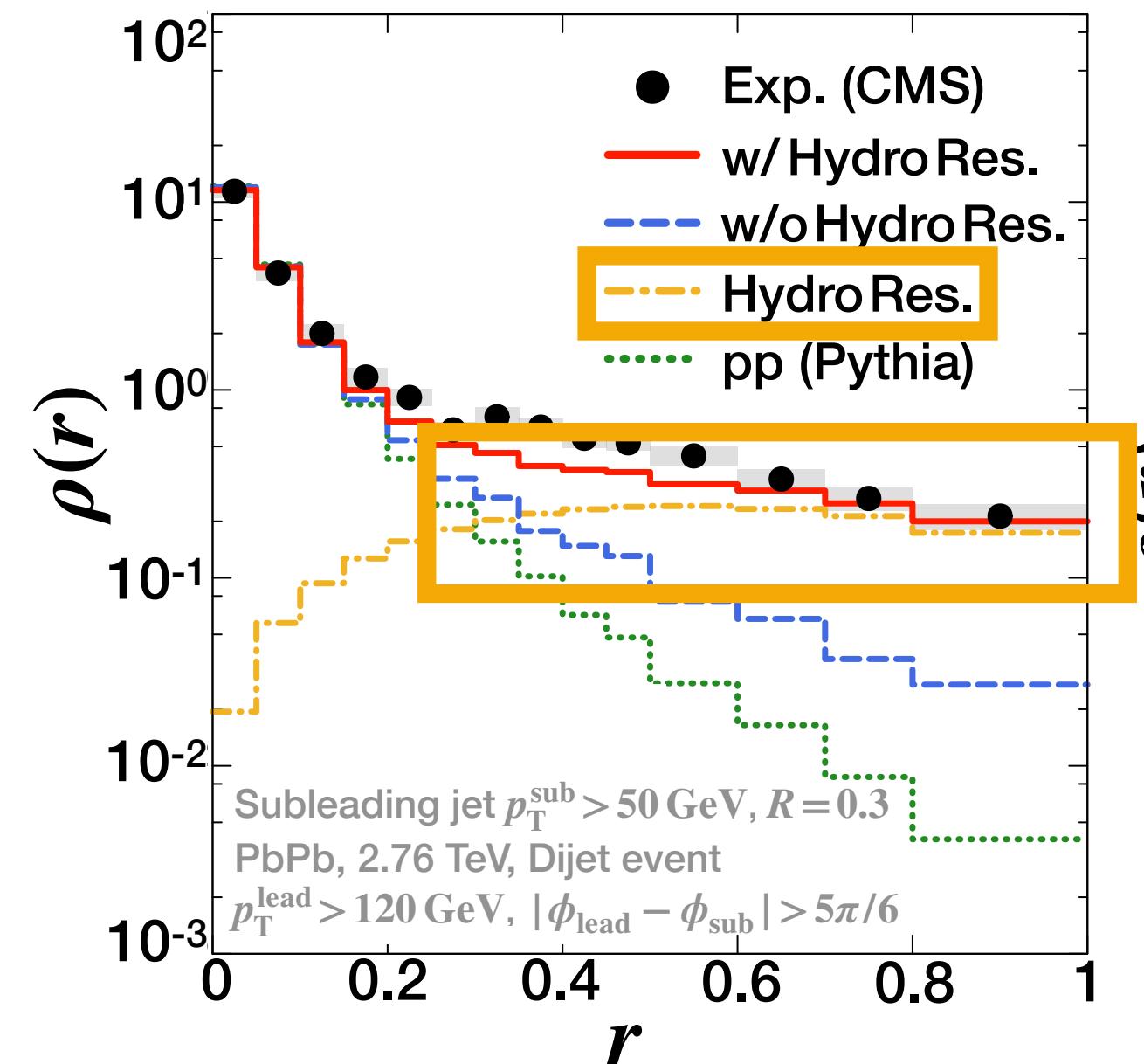
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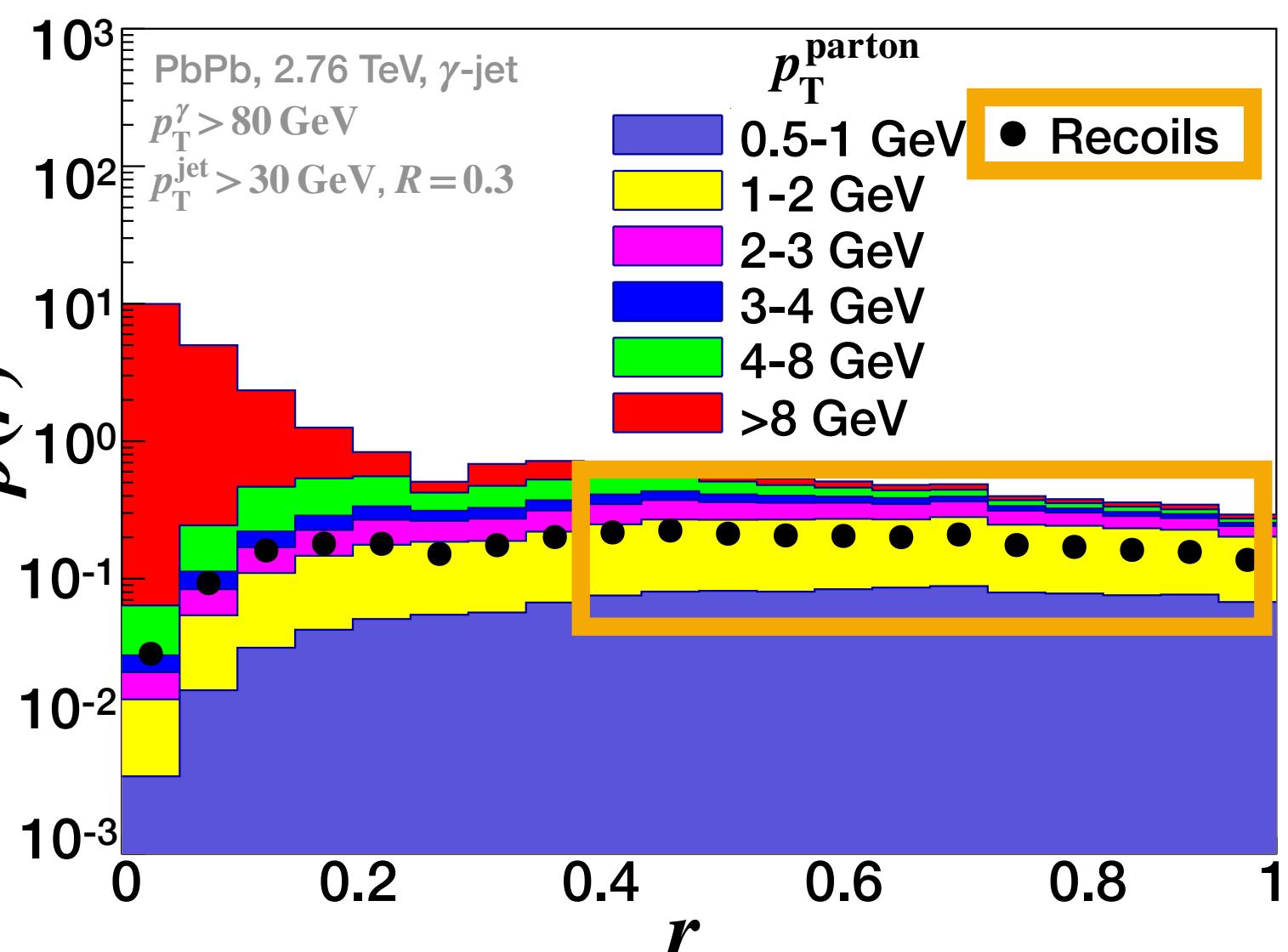


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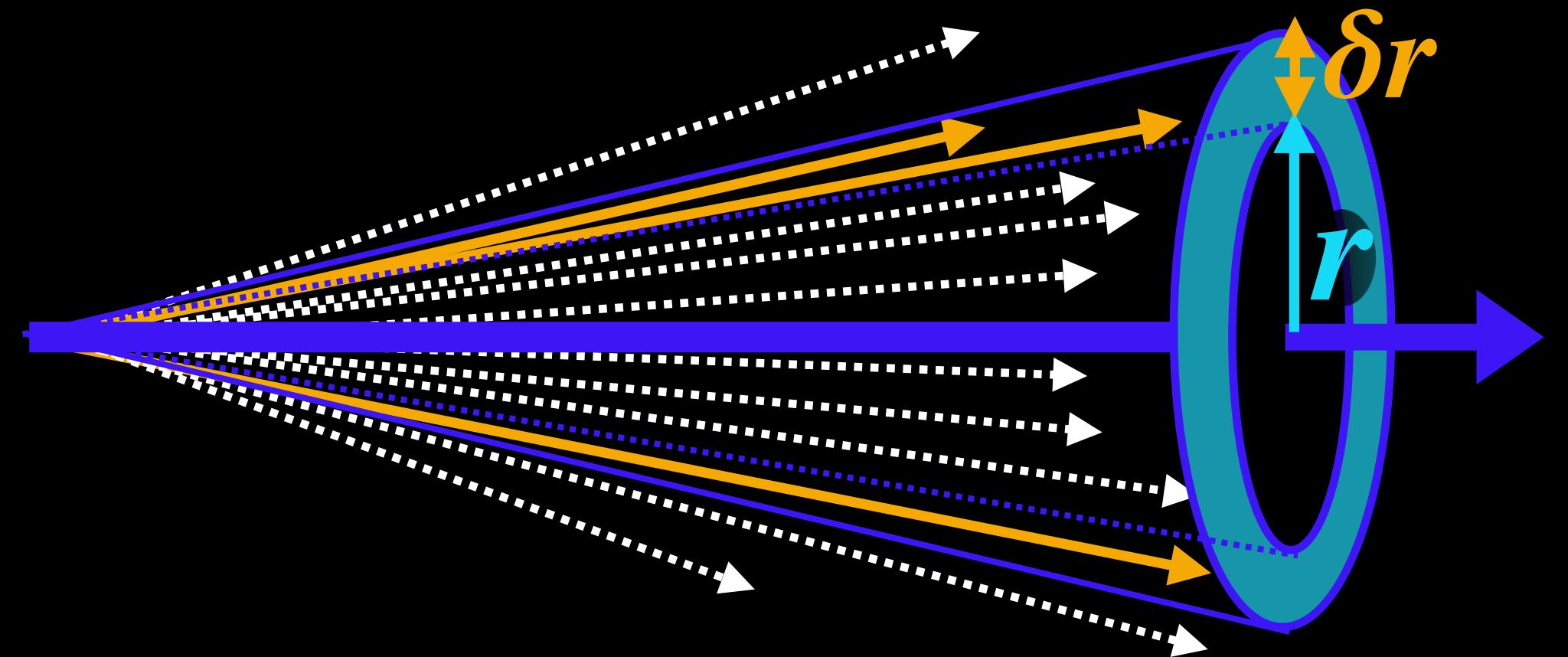
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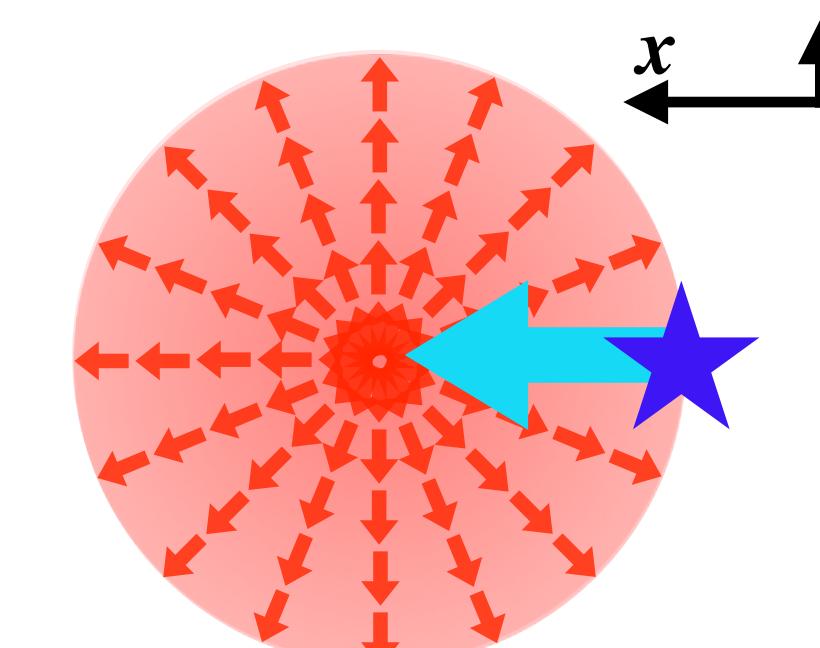
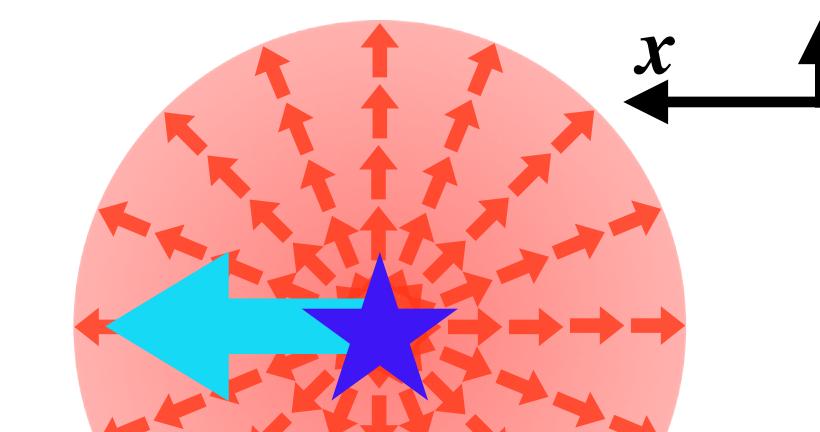
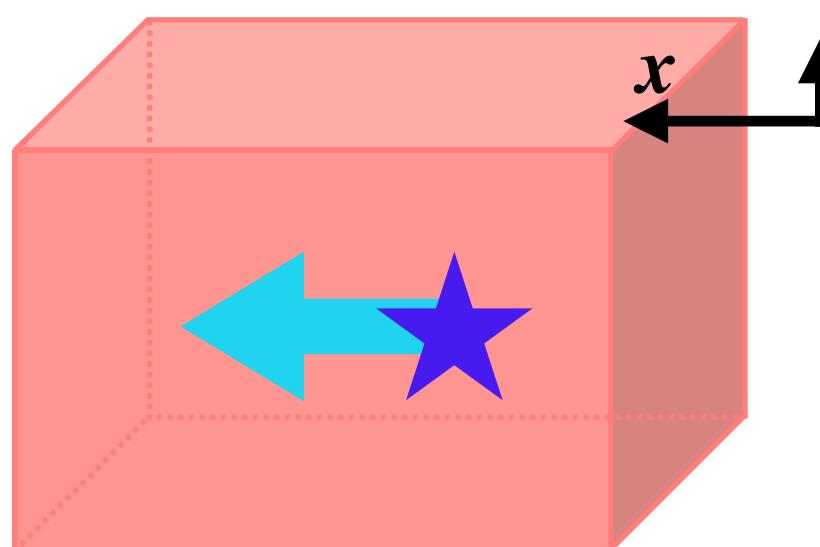
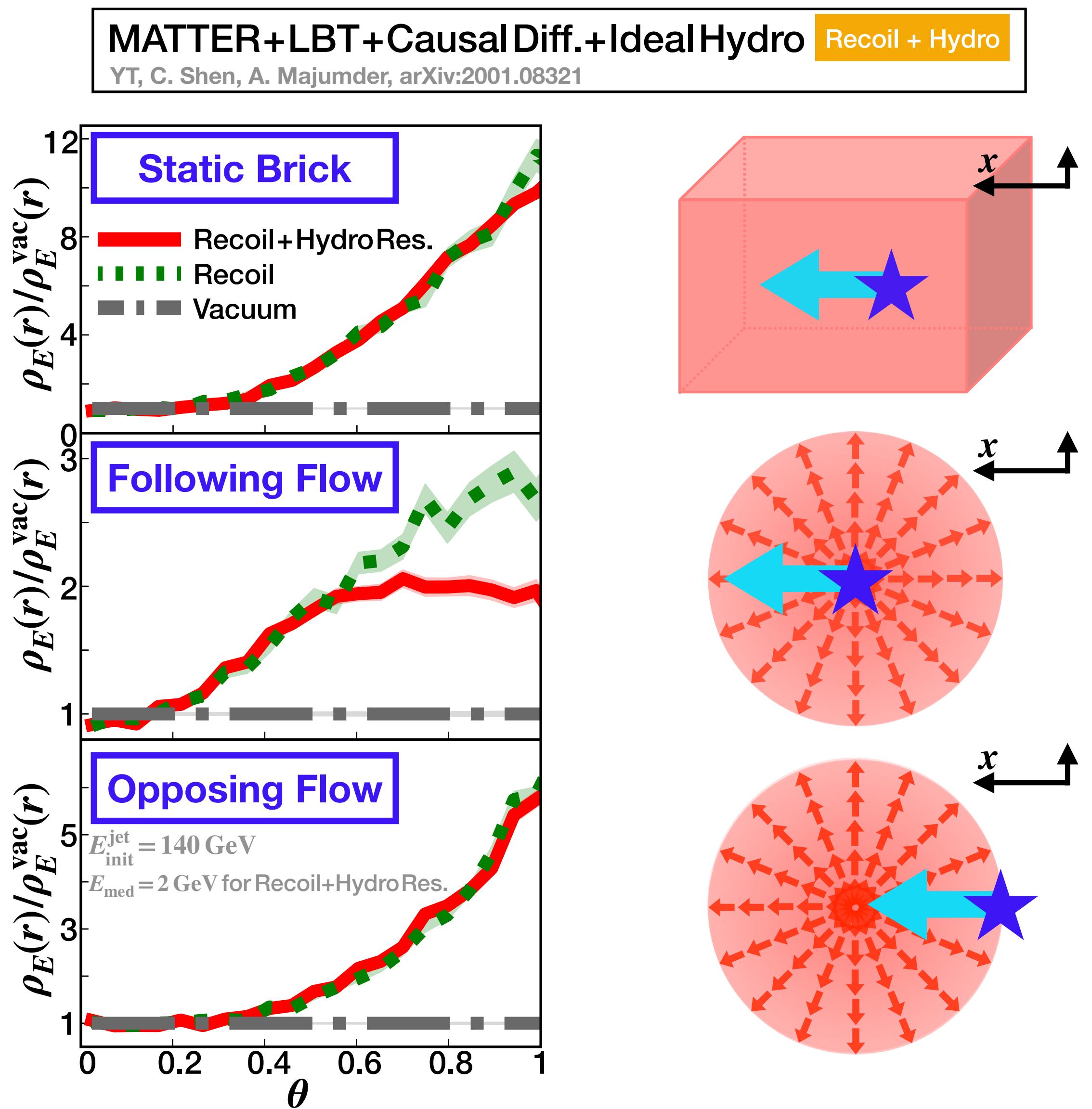
Medium response effect

→ Enhancement at large angles

Similar behavior by medium response shown in other observables

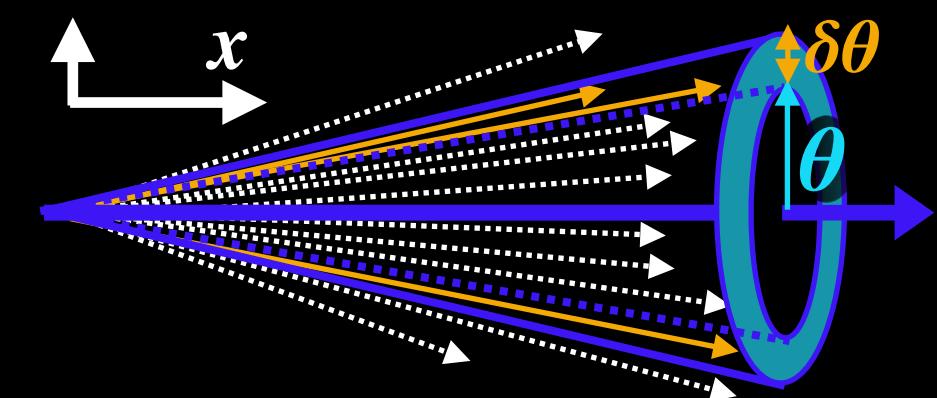
YT, T. Hirano ('14) D. Pablos, et al. ('17), Z. Gao, et al. ('18)

Angular Structure (Recoil VS Hydro Res.)



- Jet energy angular distribution

$$\rho(\theta) = \frac{1}{\delta\theta} \frac{\sum_{i \in (\theta - \delta\theta/2, \theta + \delta\theta/2)} E^i}{\sum_{i \in (0, R=0.4)} E^i}$$

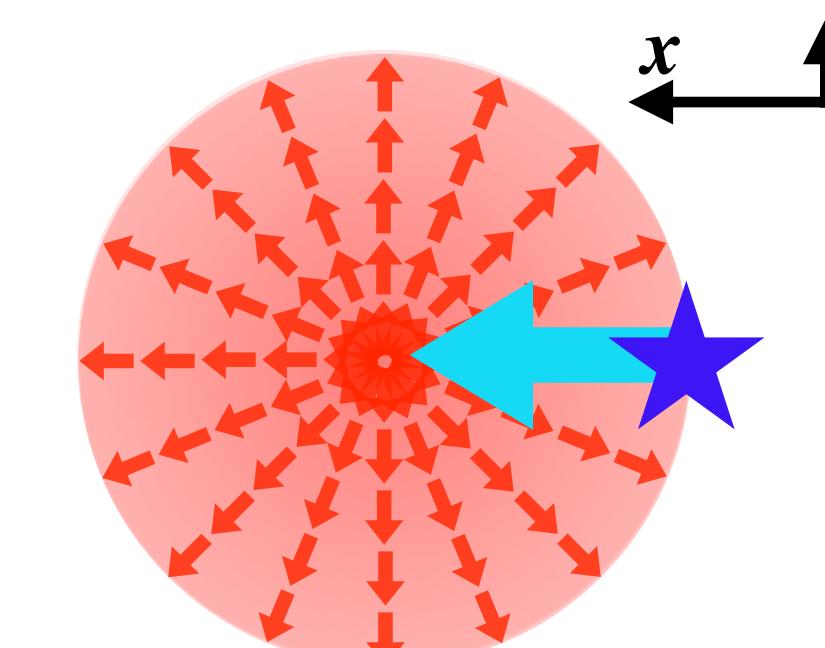
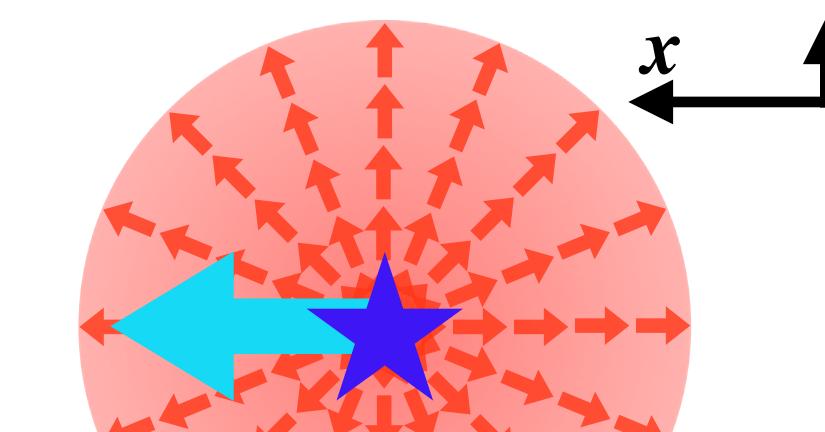
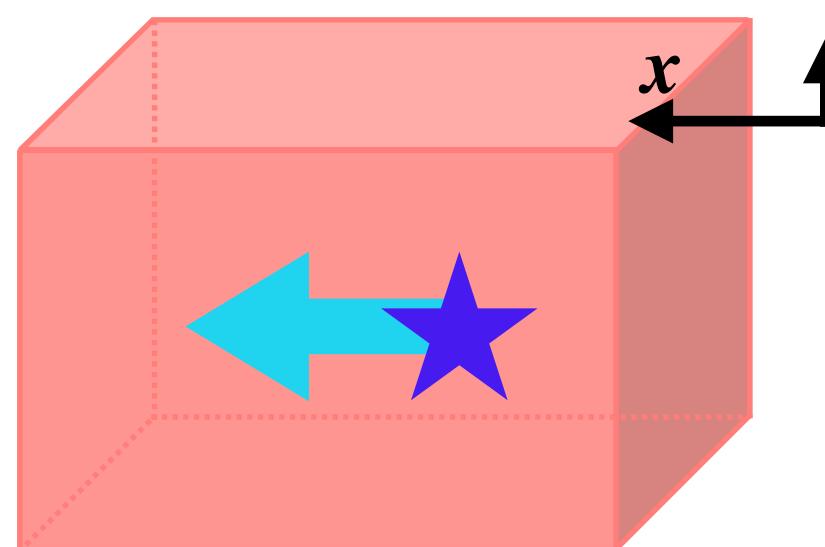
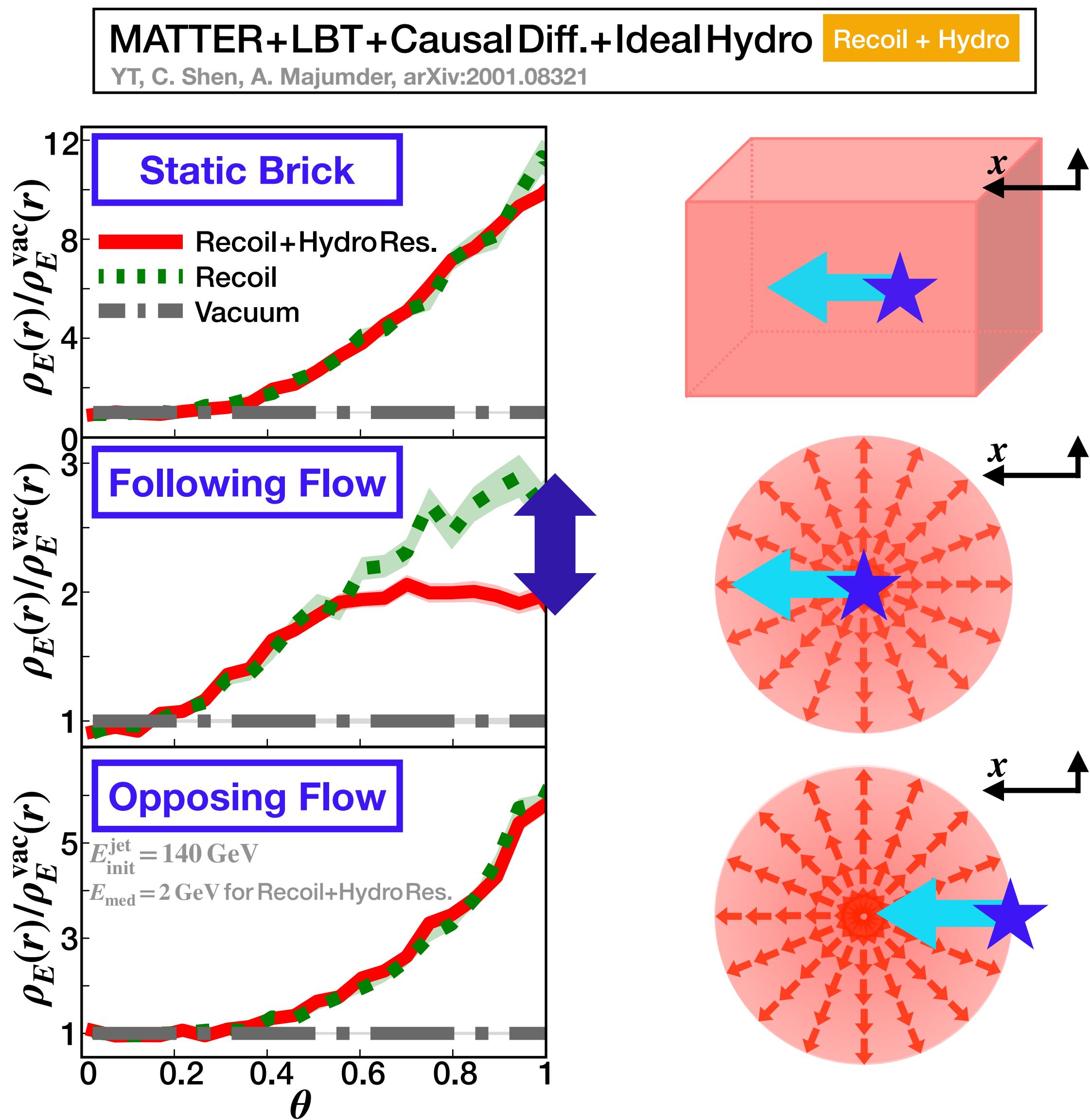


- Systematic study with simple media

- Clear difference brought by background medium flow

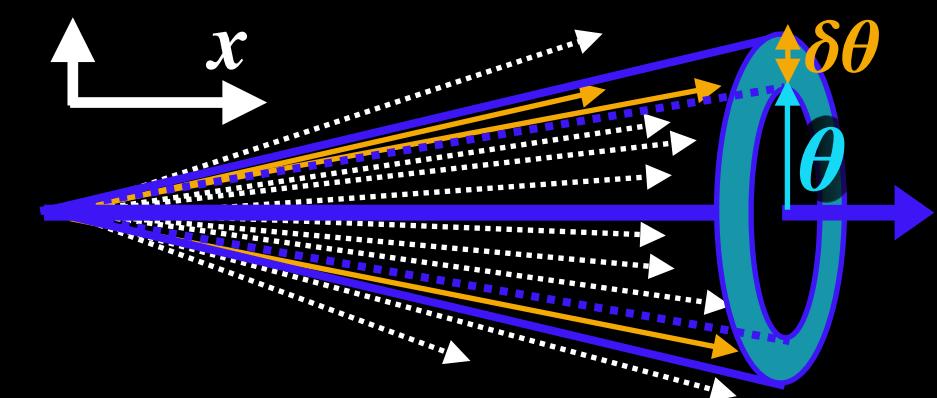
Need more systematic studies with realistic medium configurations

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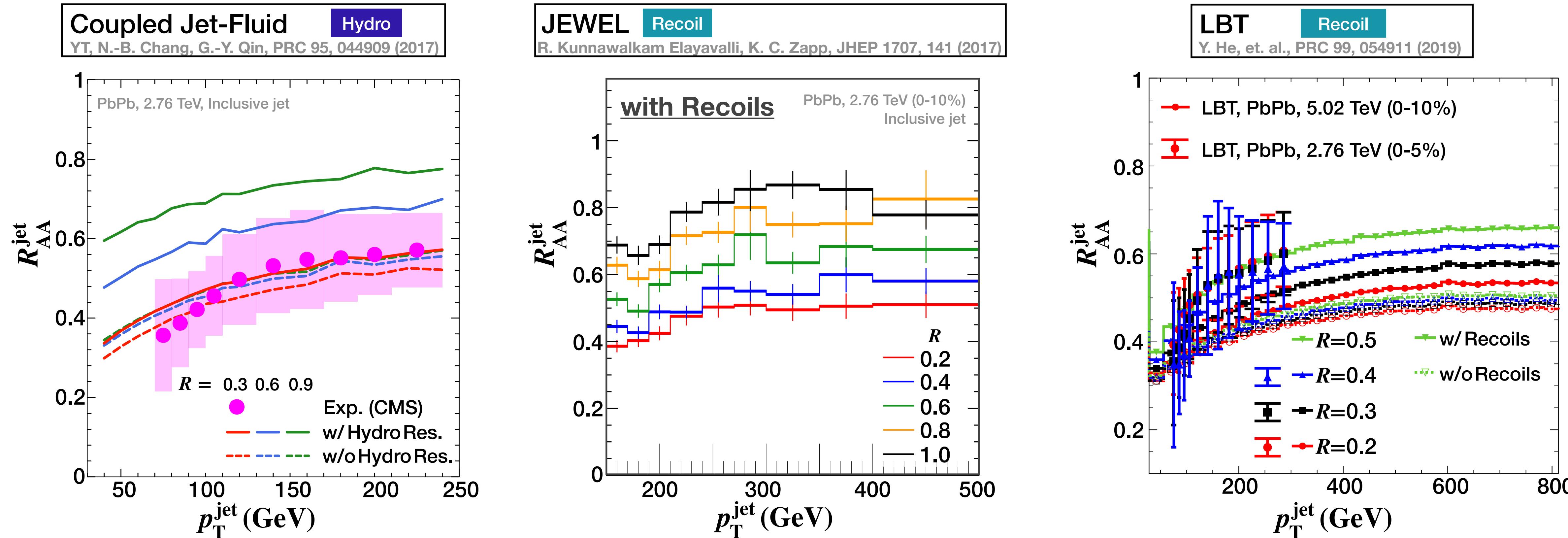


- Systematic study with simple media

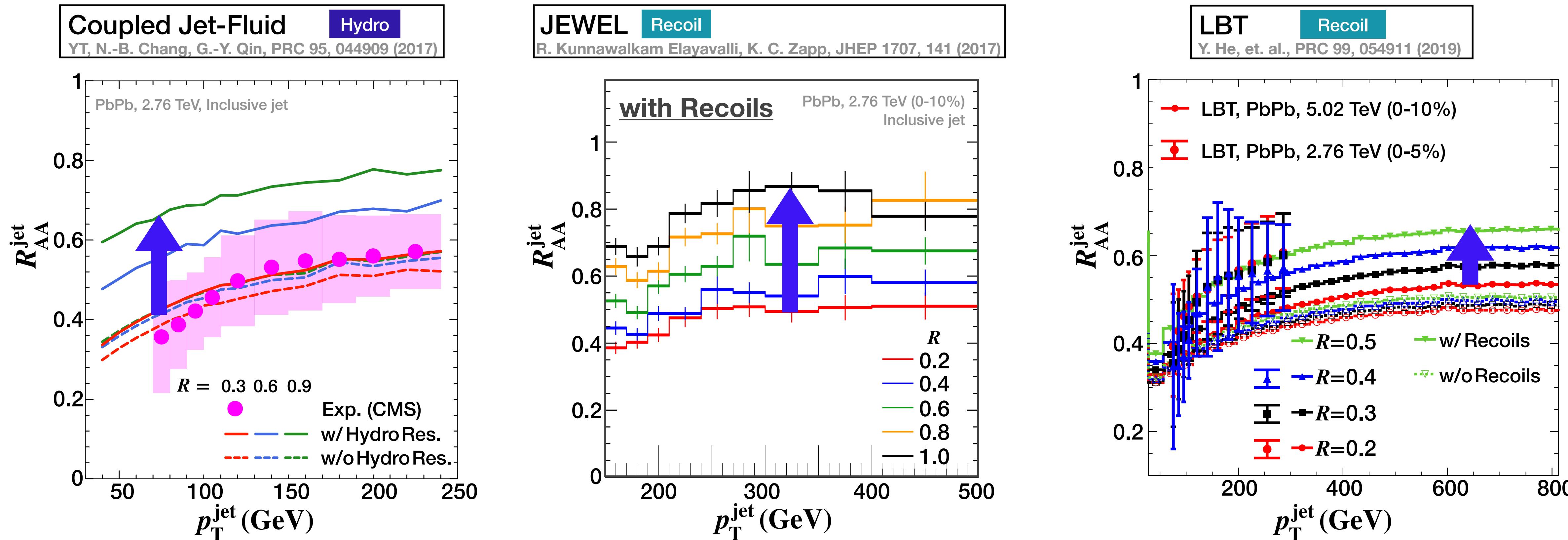
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Cone Size Dependence in Jet Energy loss



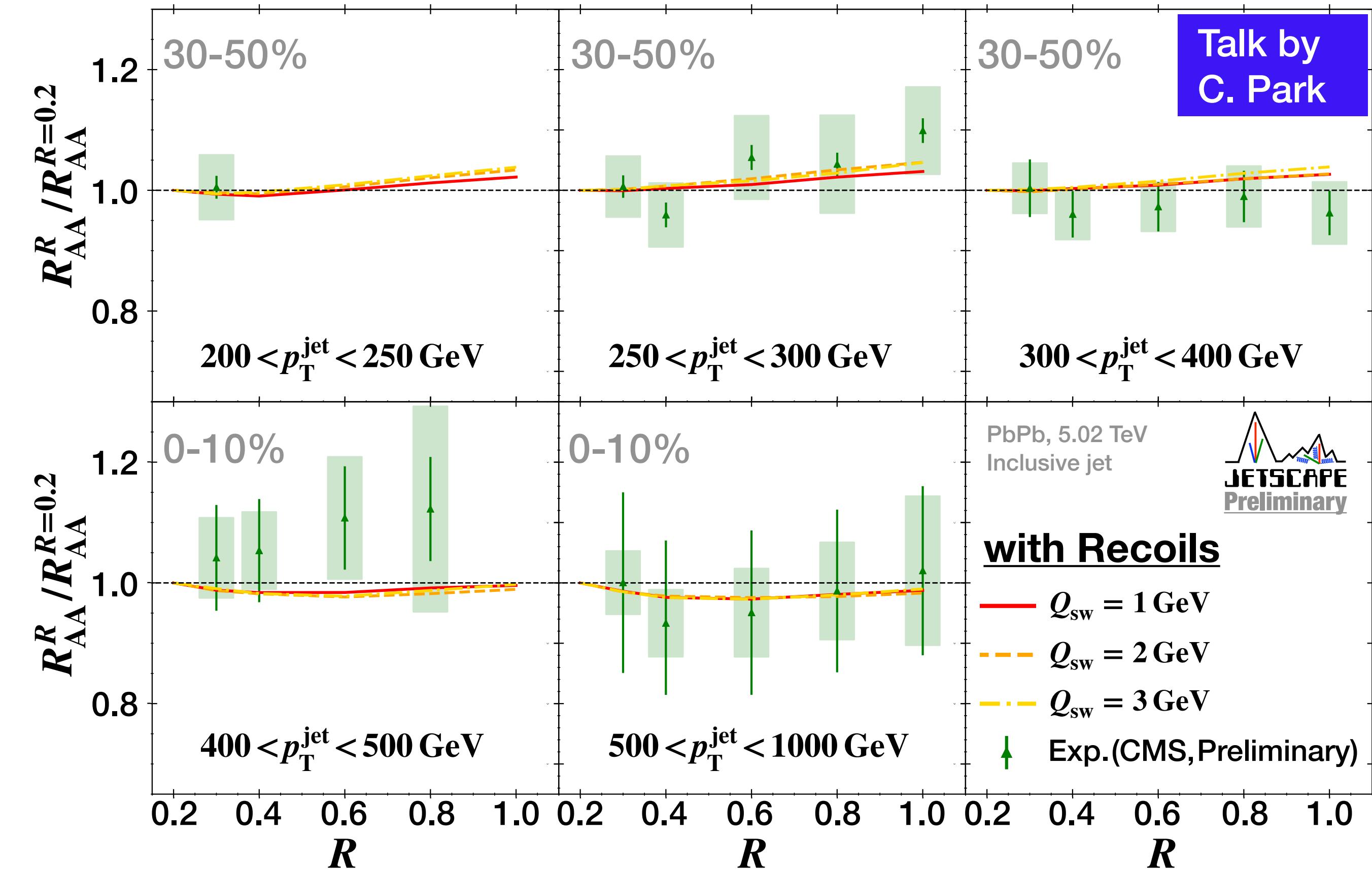
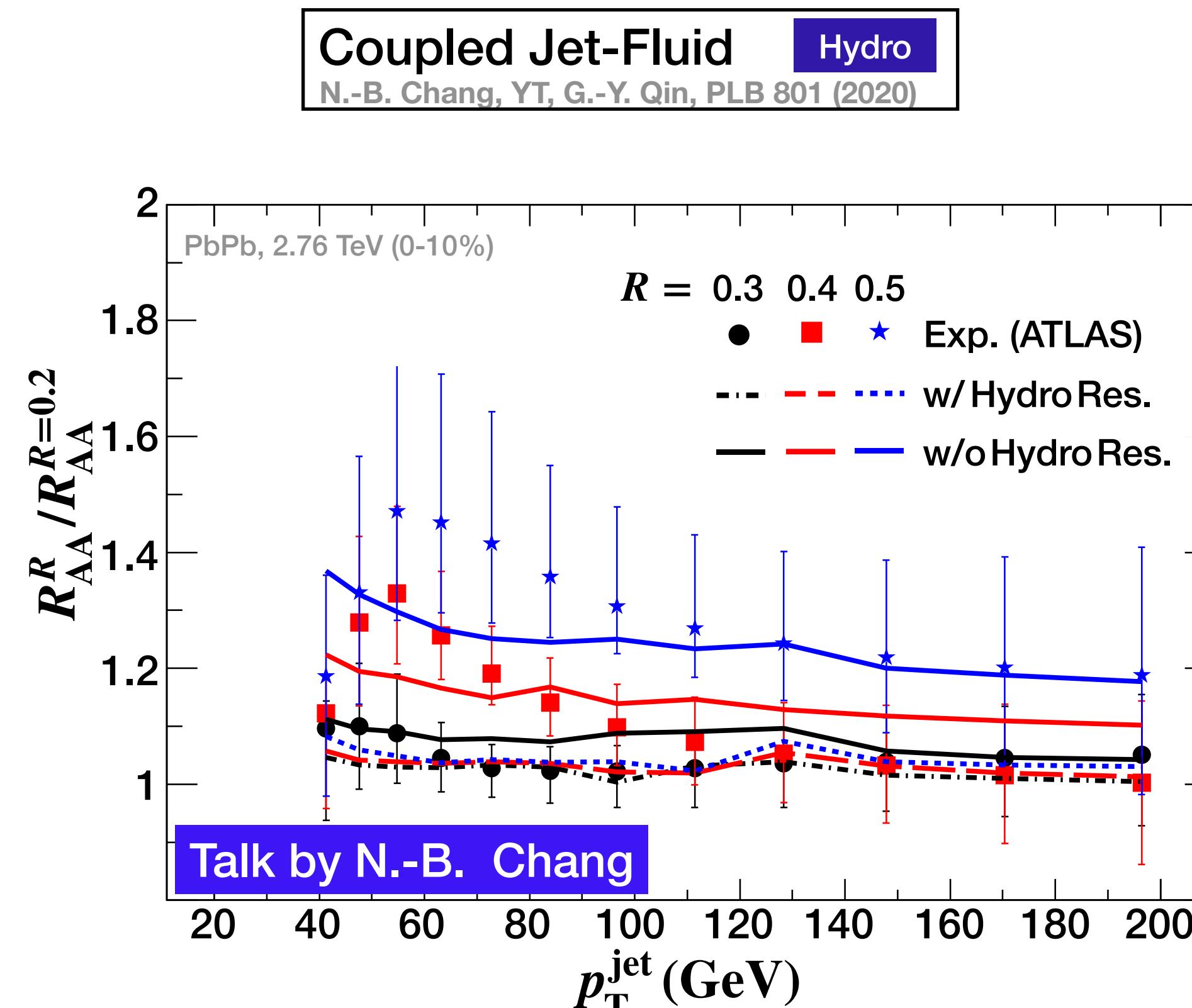
Cone Size Dependence in Jet Energy loss



Increase of jet-cone size dependence

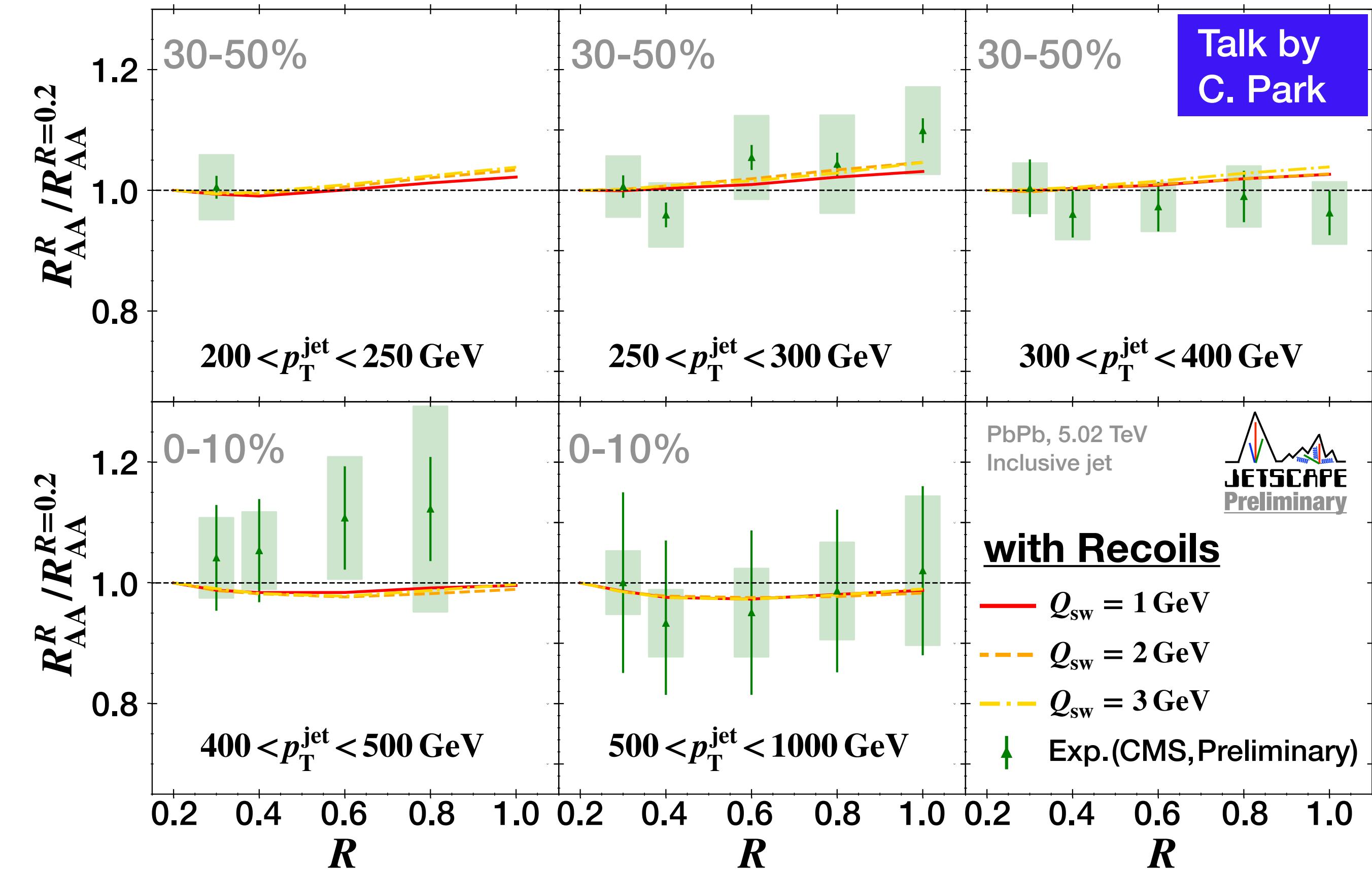
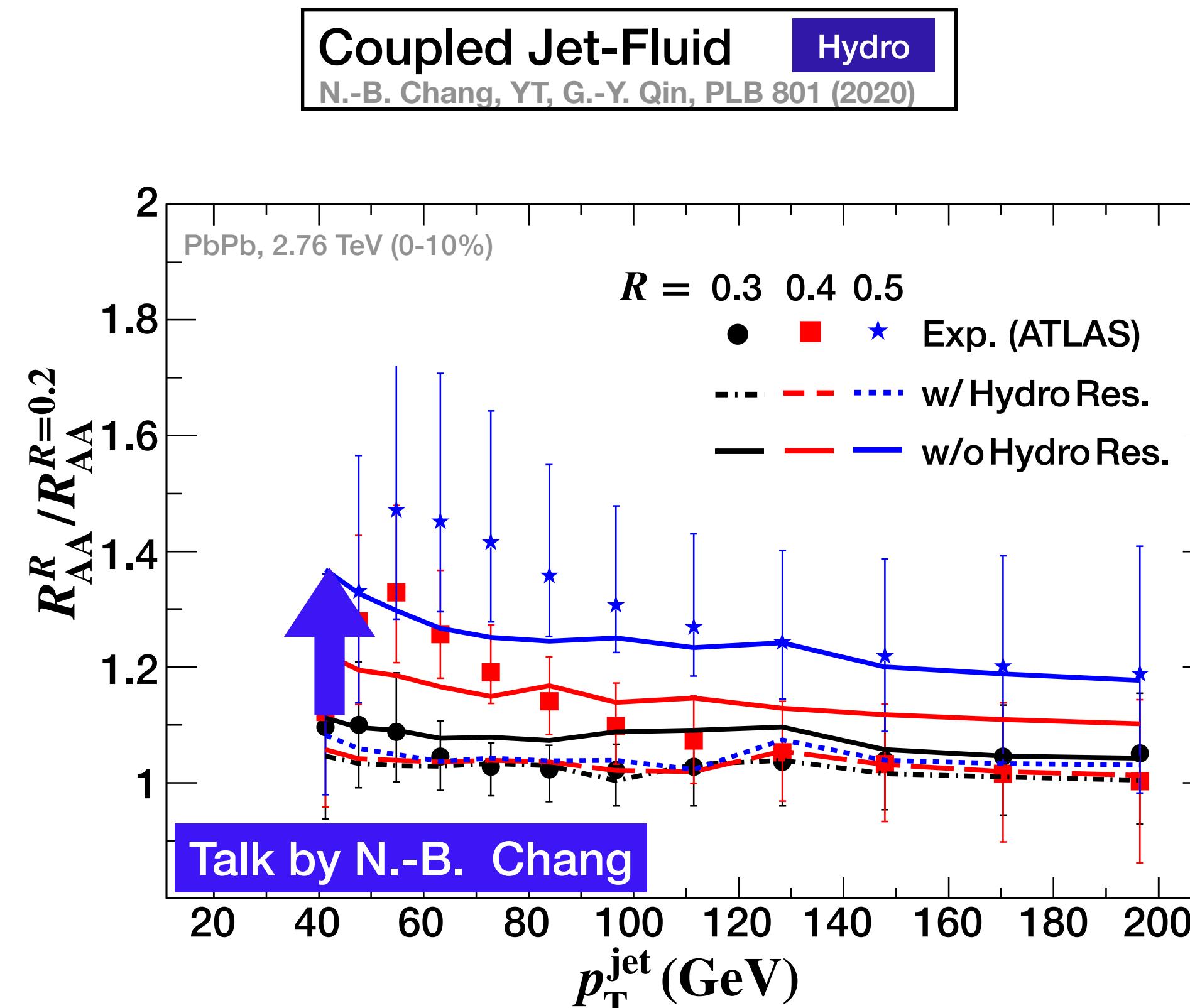
Cone Size Dependence in Jet Energy loss

MATTER+LBT[JETSCAPE] Recoil
C. Park for the JETSCAPE Collaboration, Hard Probes 2020



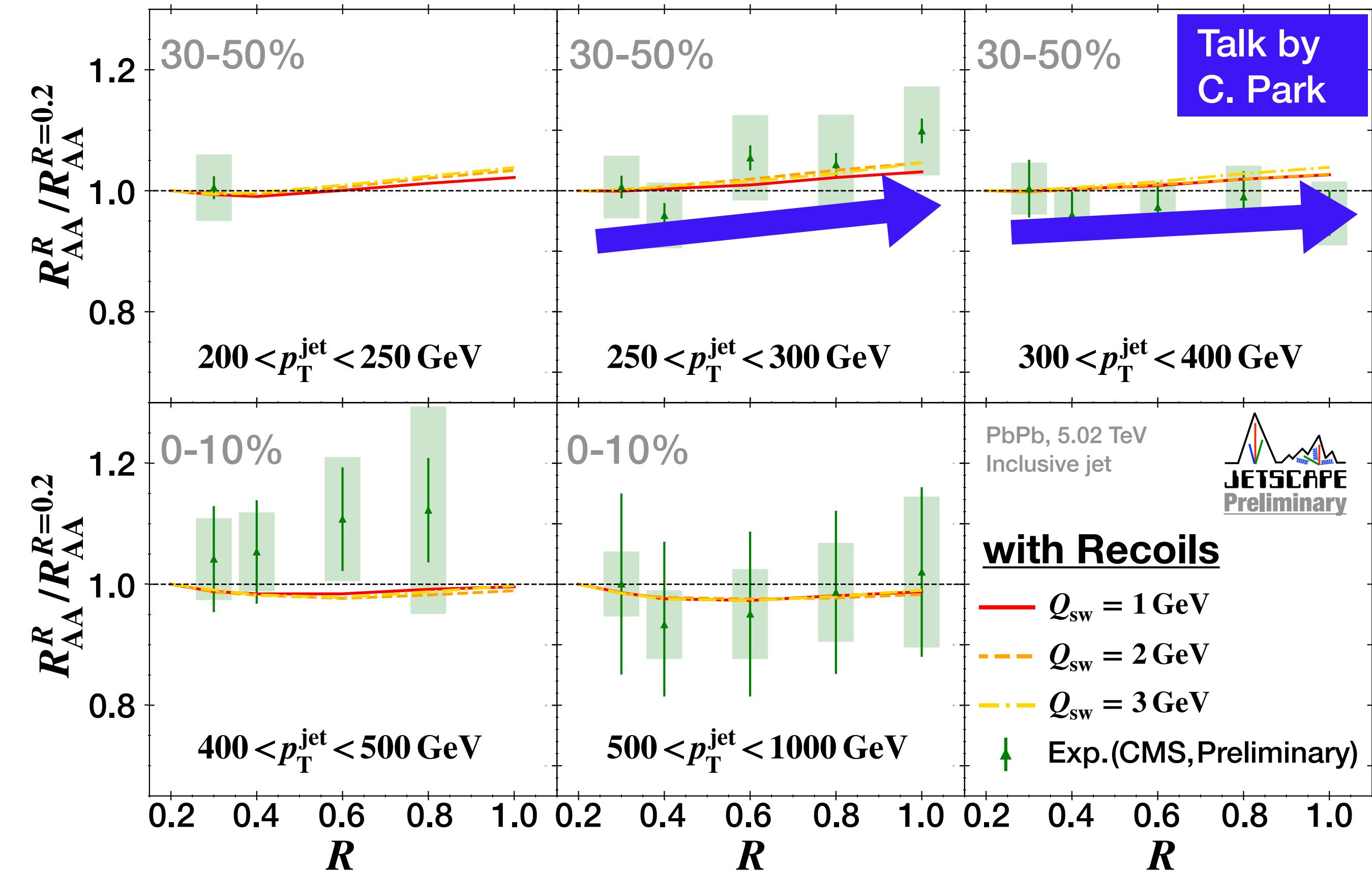
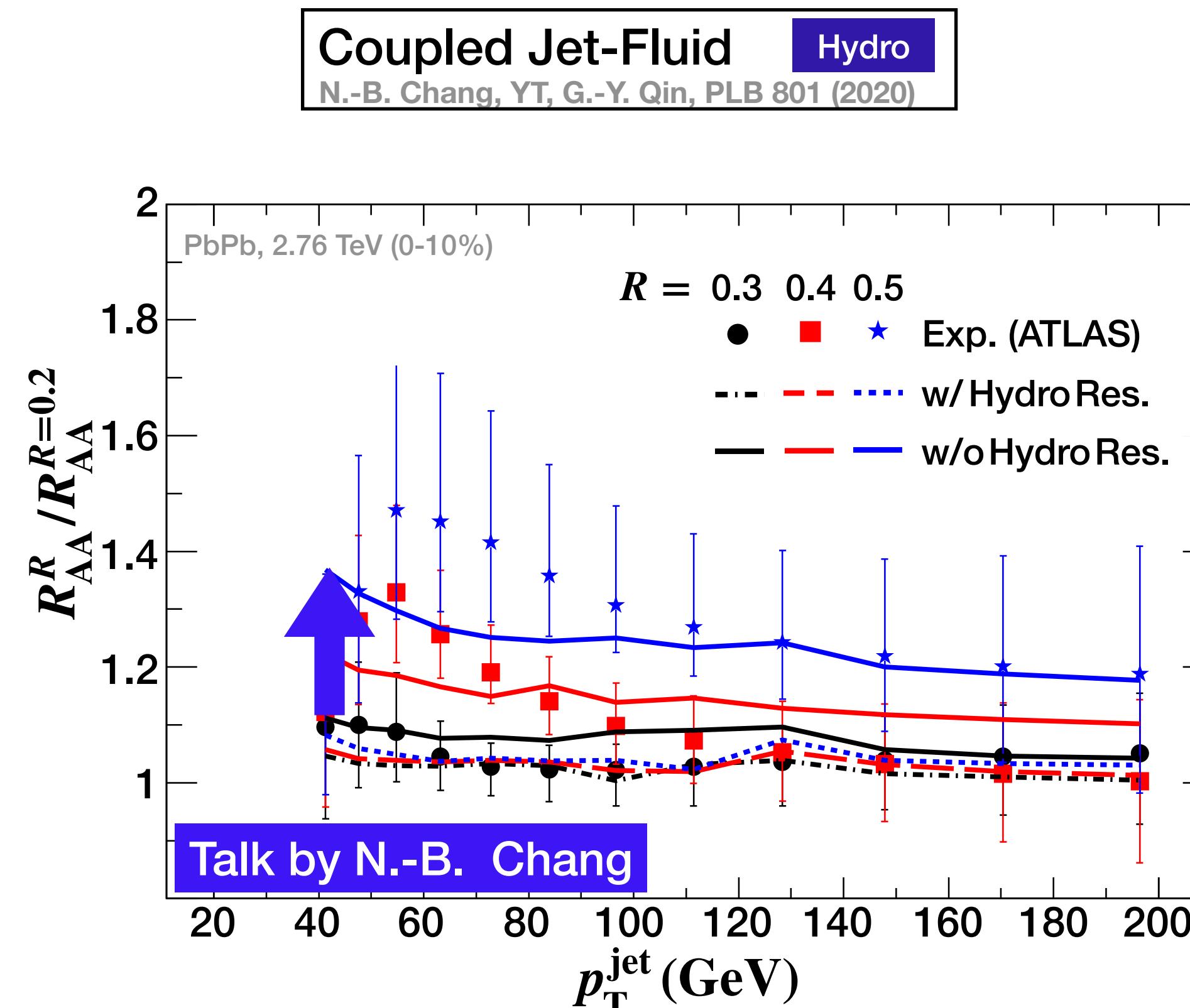
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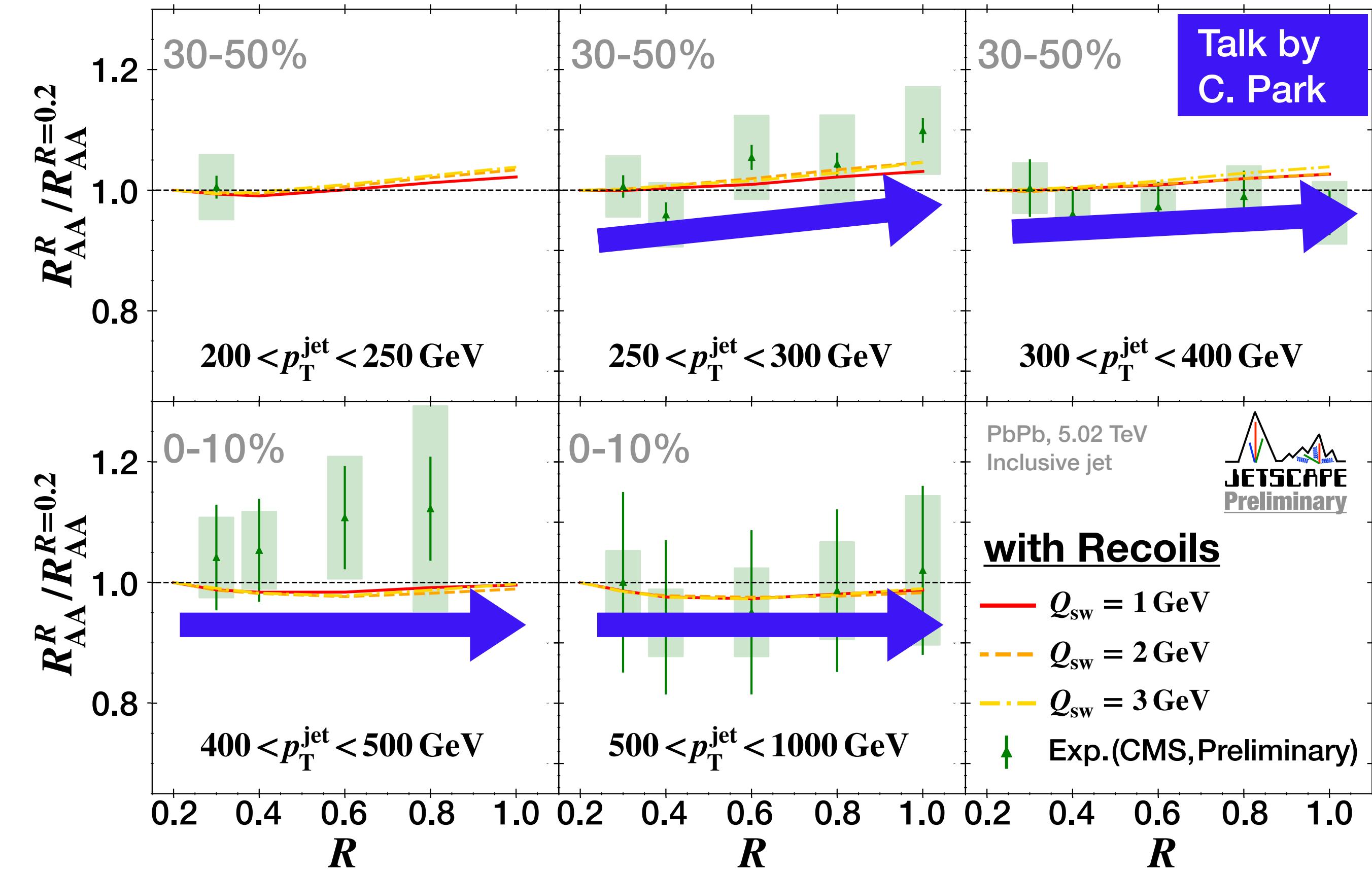
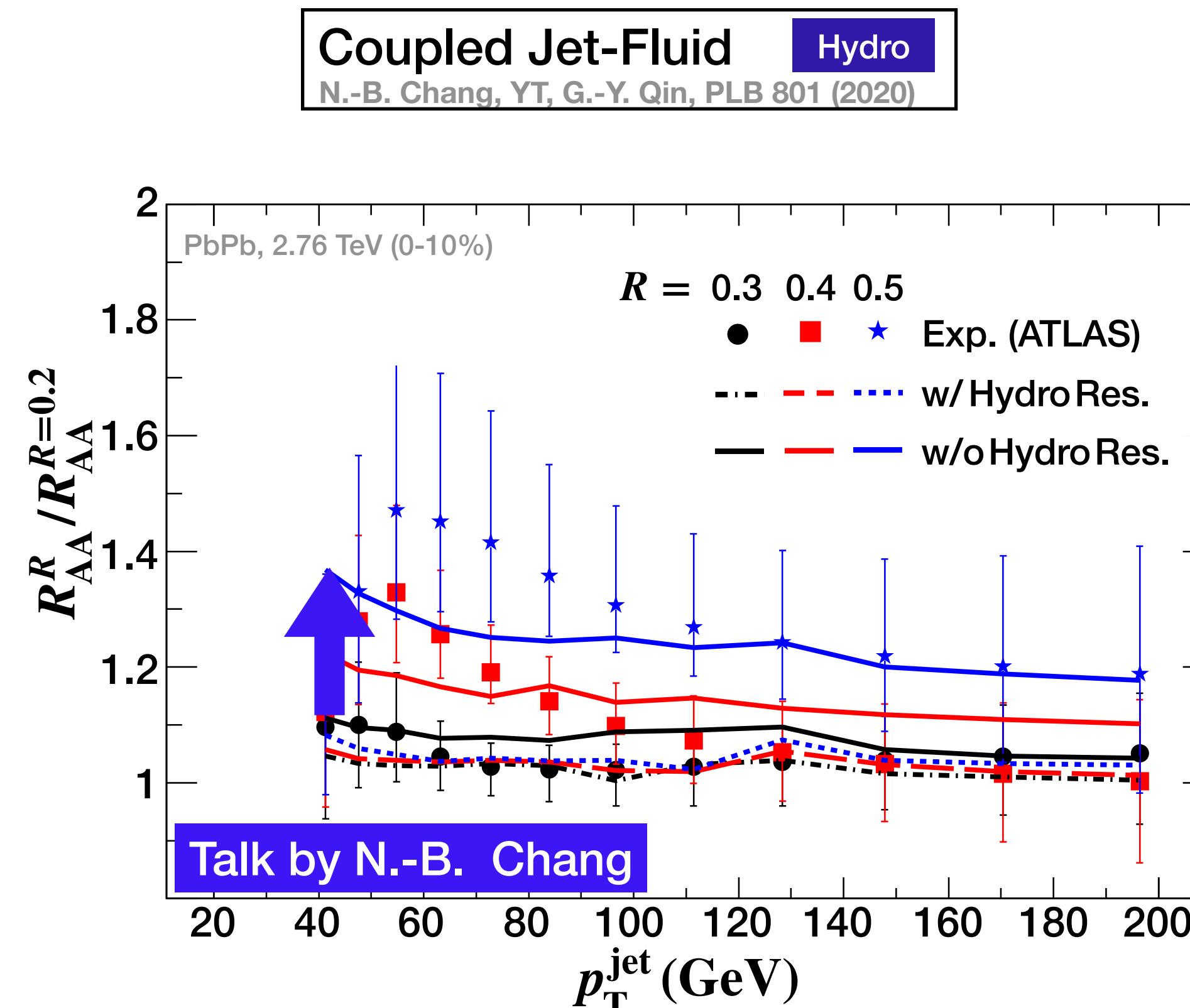
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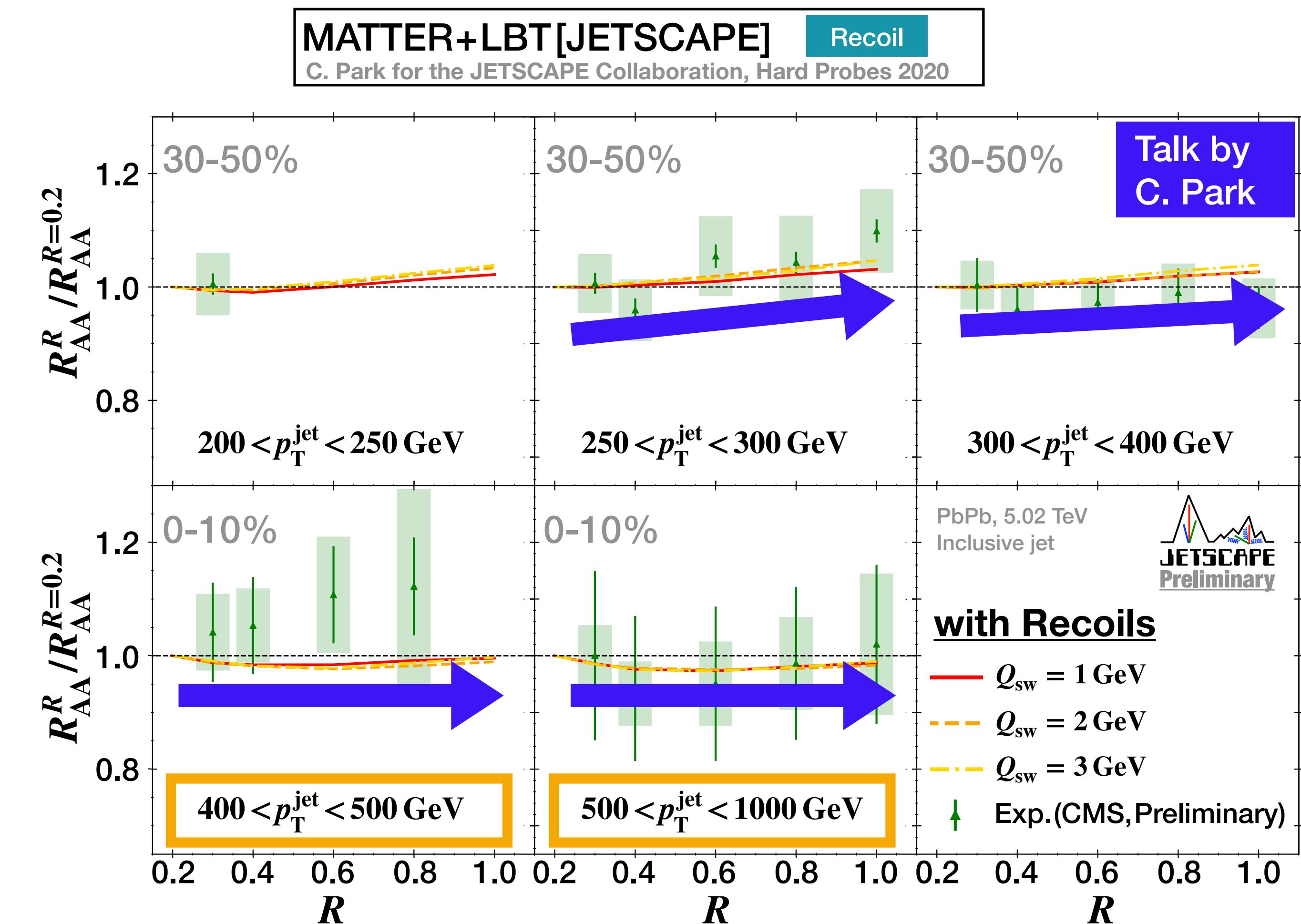
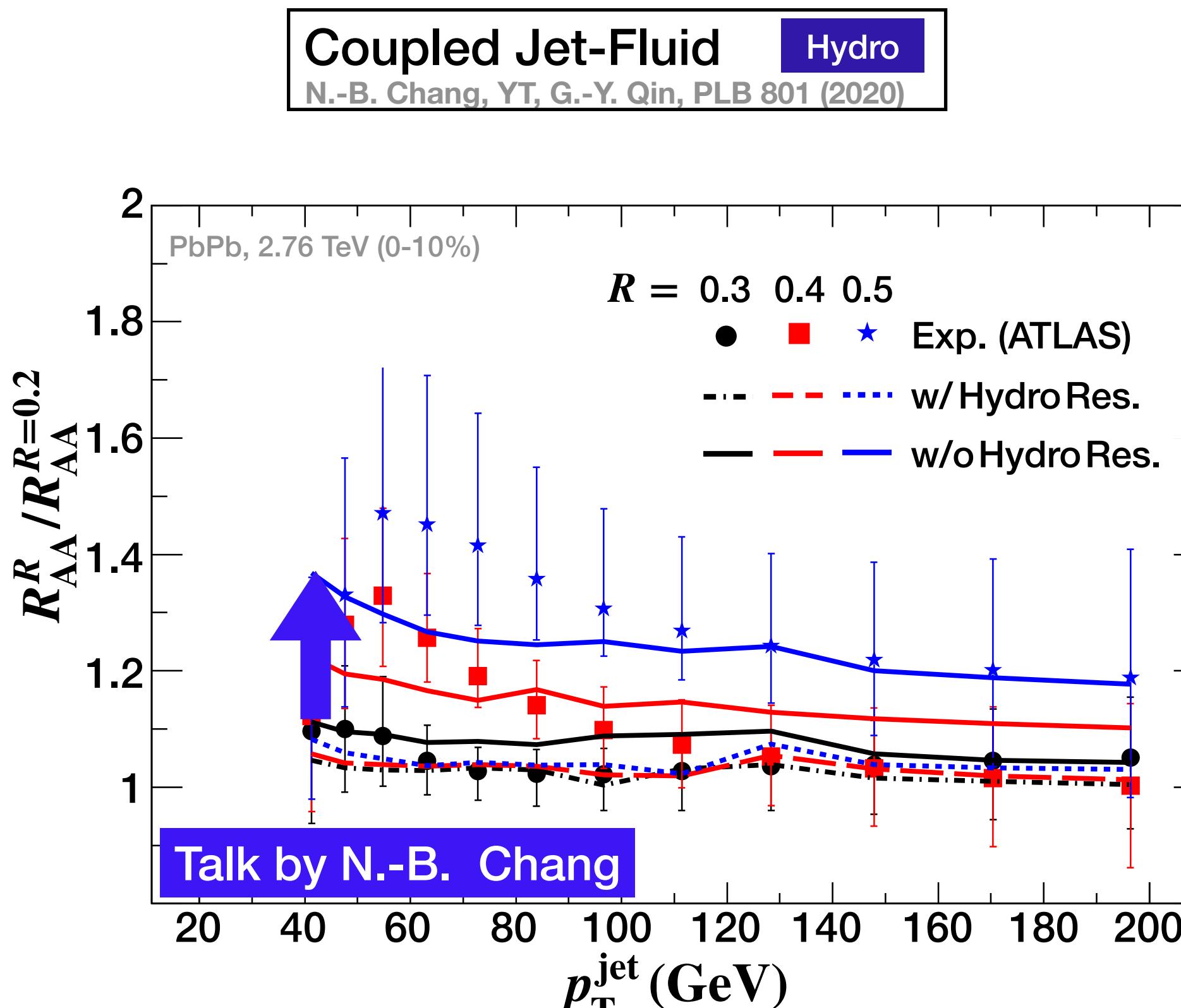


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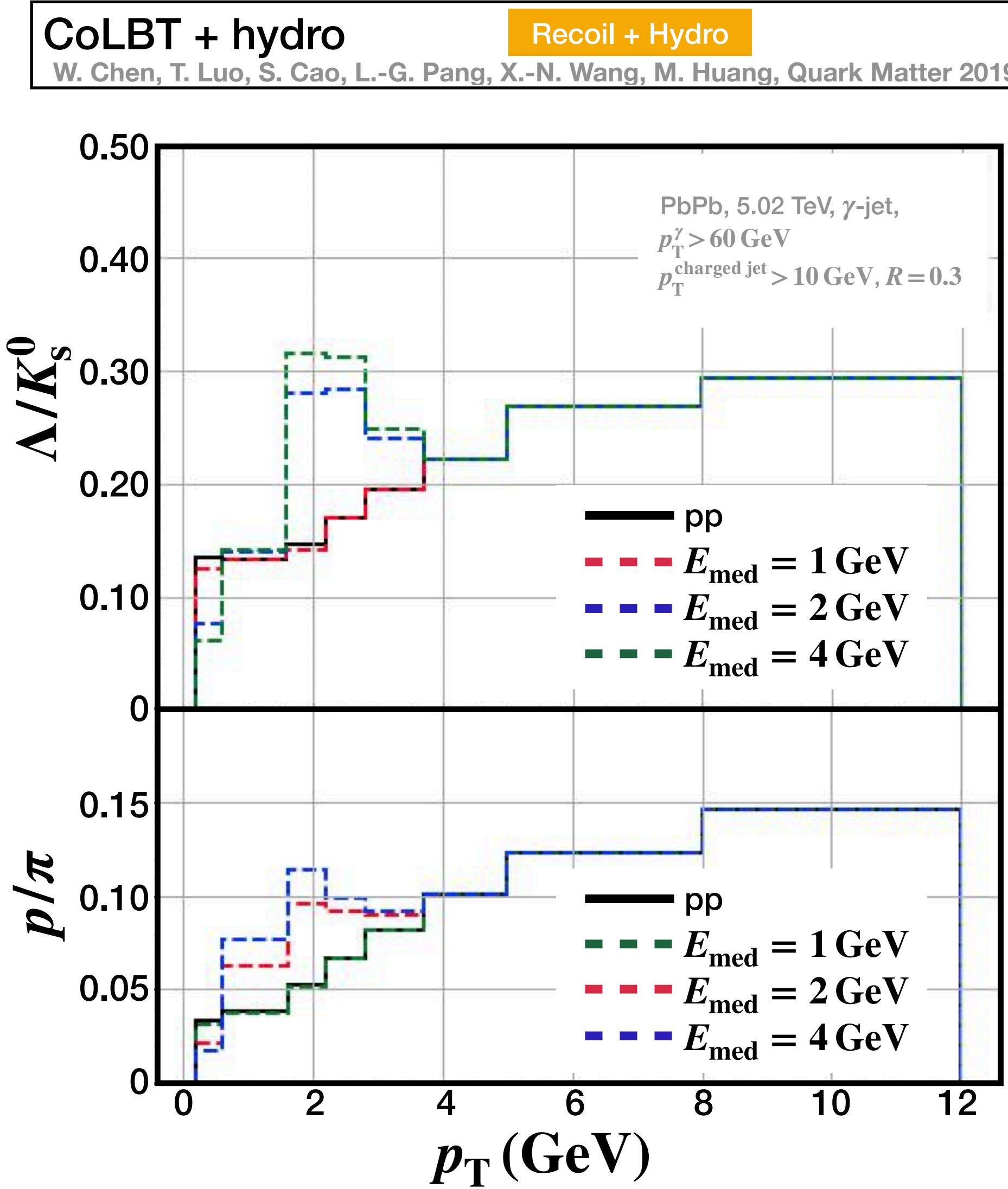


Cone Size Dependence in Jet Energy loss



Small cone size dependence due to strong core contribution in huge- p_T jet

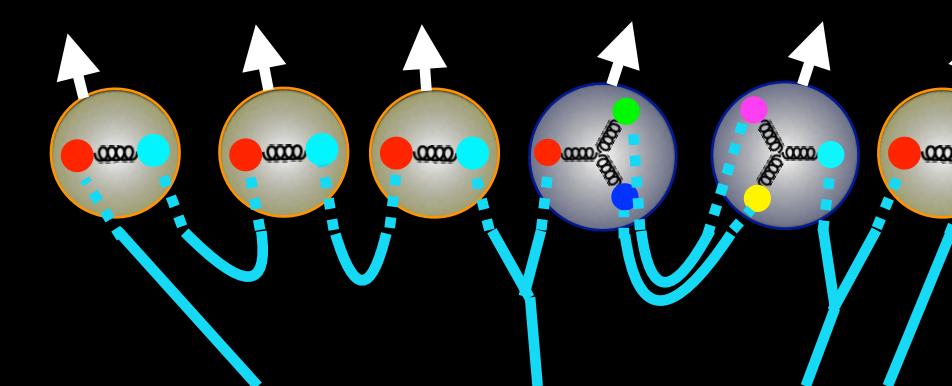
Hadron Composition inside Jet



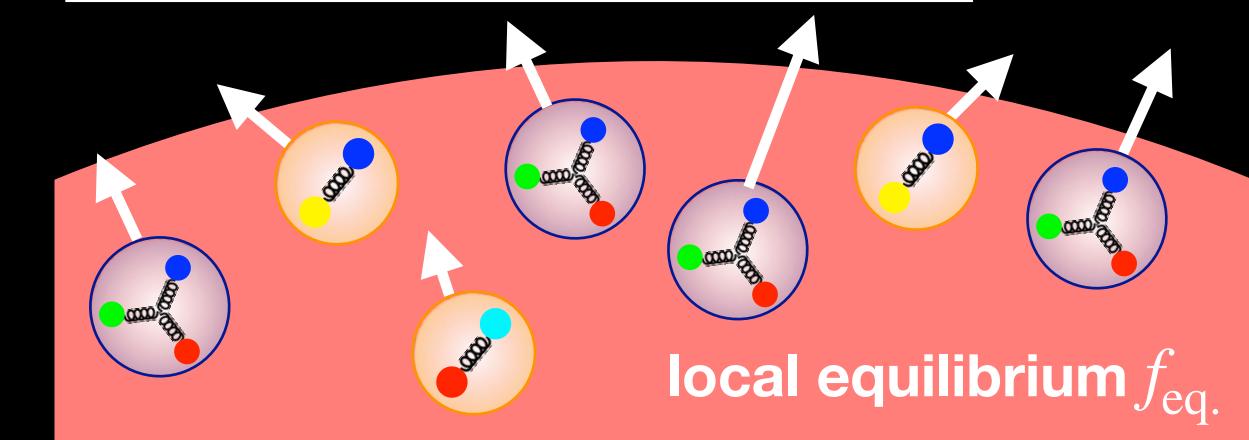
Hadronization in jets

- Different mechanism between showering partons and medium
- More baryons form medium

Jet Fragmentation



Hadronization in medium

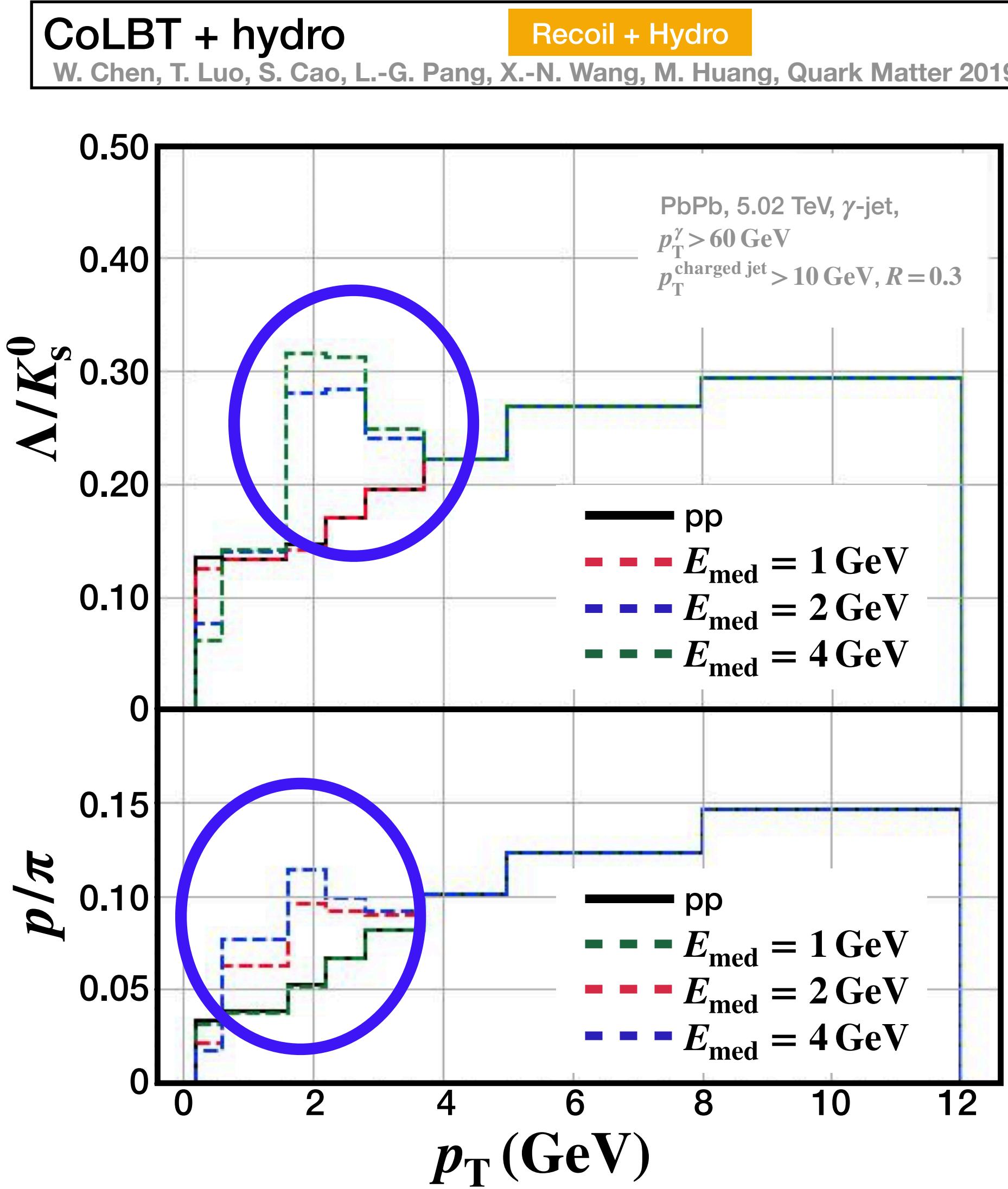


Baryon meson ratio in jet

- Enhancement around 2 GeV
- Sensitive to E_{med}

Possible tool to explore
hydrodynamic response and
in-medium thermalization

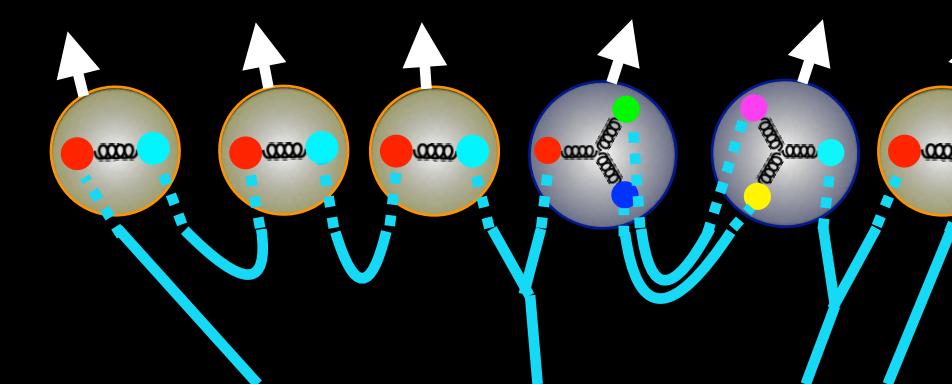
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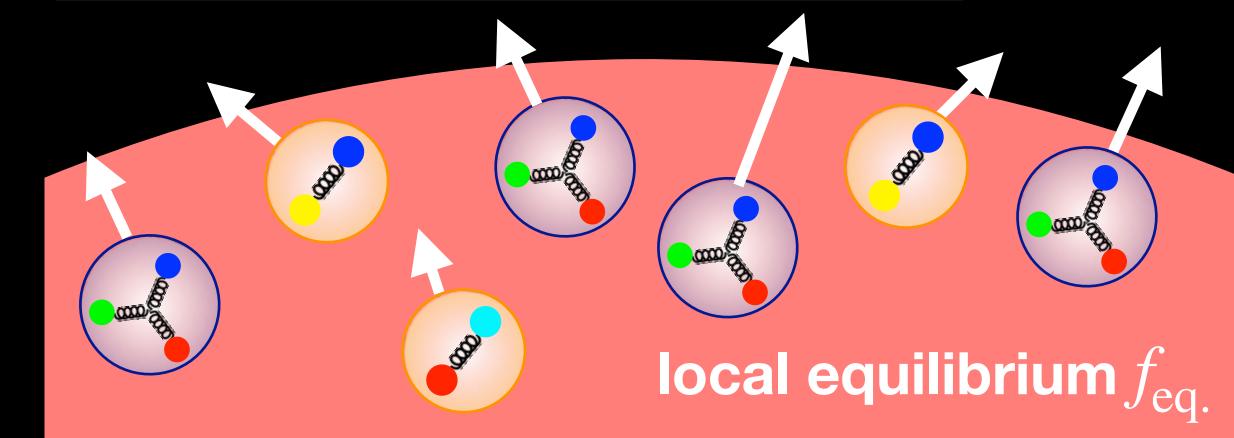
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Hadronization in medium



Baryon meson ratio in jet

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Possible tool to explore
hydrodynamic response and
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Medium Response Effect on Other Observables

● Jet fragmentation function

Hybrid Strong/Weak [AdS/CFT], JEWEL,

D. Pablos, et al., JHEP 03, 135 (2017)

CoLBT + hydro

W. Chen, et al., arXiv:2005.09678

● Jet mass

Hybrid Strong/Weak [AdS/CFT], JEWEL,

D. Pablos, et al., JHEP 01, 044 (2020)

MARTINI

C. Park, et al., Quark Matter 2018

● Jet splitting function

JEWEL,

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

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

Hybrid Strong/Weak [AdS/CFT], LBT

D. Pablos, et al., JHEP 01, 044 (2020)

X.-N. Wang, et. al., Hard Probes 2018

● Groomed jet mass

JEWEL,

CMS, JHEP 10, 161 (2018)

Hybrid Strong/Weak [AdS/CFT],

D. Pablos, et al., JHEP 01, 044 (2020)

LBT

X.-N. Wang, et. al., Hard Probes 2018

● Backward jet- p_T^{jet} suppression (clear signal of med. res.)

Hybrid Strong/Weak [AdS/CFT] Talk by D. Pablos

D. Pablos, PRL 124, 052301 (2020)

Summary and Outlook

Summary

● Medium response to jet quenching

- Medium constituents' reactions to interactions with jet
- Contribute to jets observed in heavy ion collisions
- Carry information of the in-medium thermalization process
- Essential for comprehensive understanding of the jet quenching

● Implementation of medium response

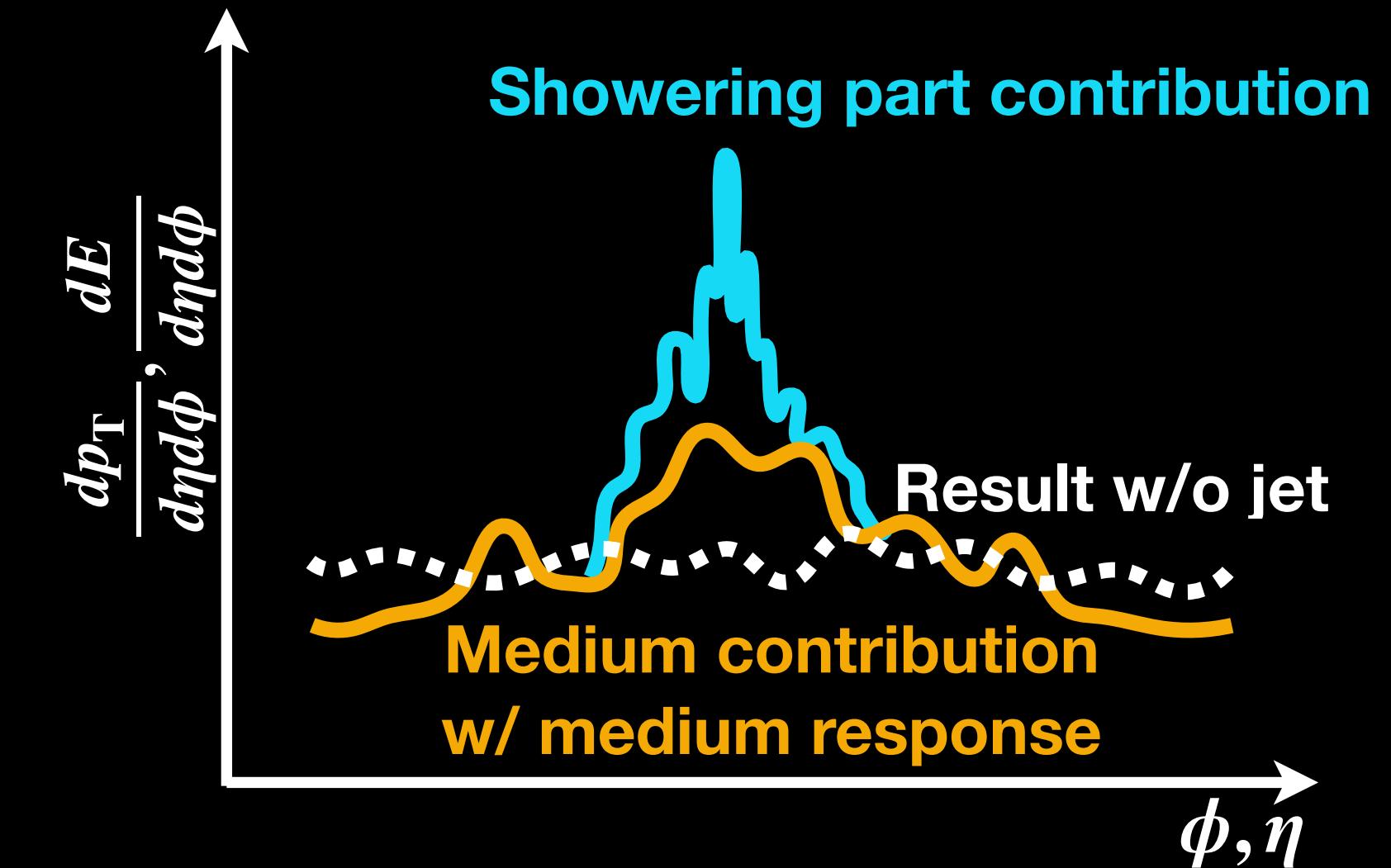
- Weakly-coupled description → **Recoil**
- Strongly-coupled description → **Hydrodynamic Response**
- Hybrid description → **Recoil + Hydro Response (w/ switching scale E_{med})**

● Effect from medium response

- (Soft) particles in wide angle regions around jets
- Strongly affected by background medium flow
- Various modification in jet p_T and substructures

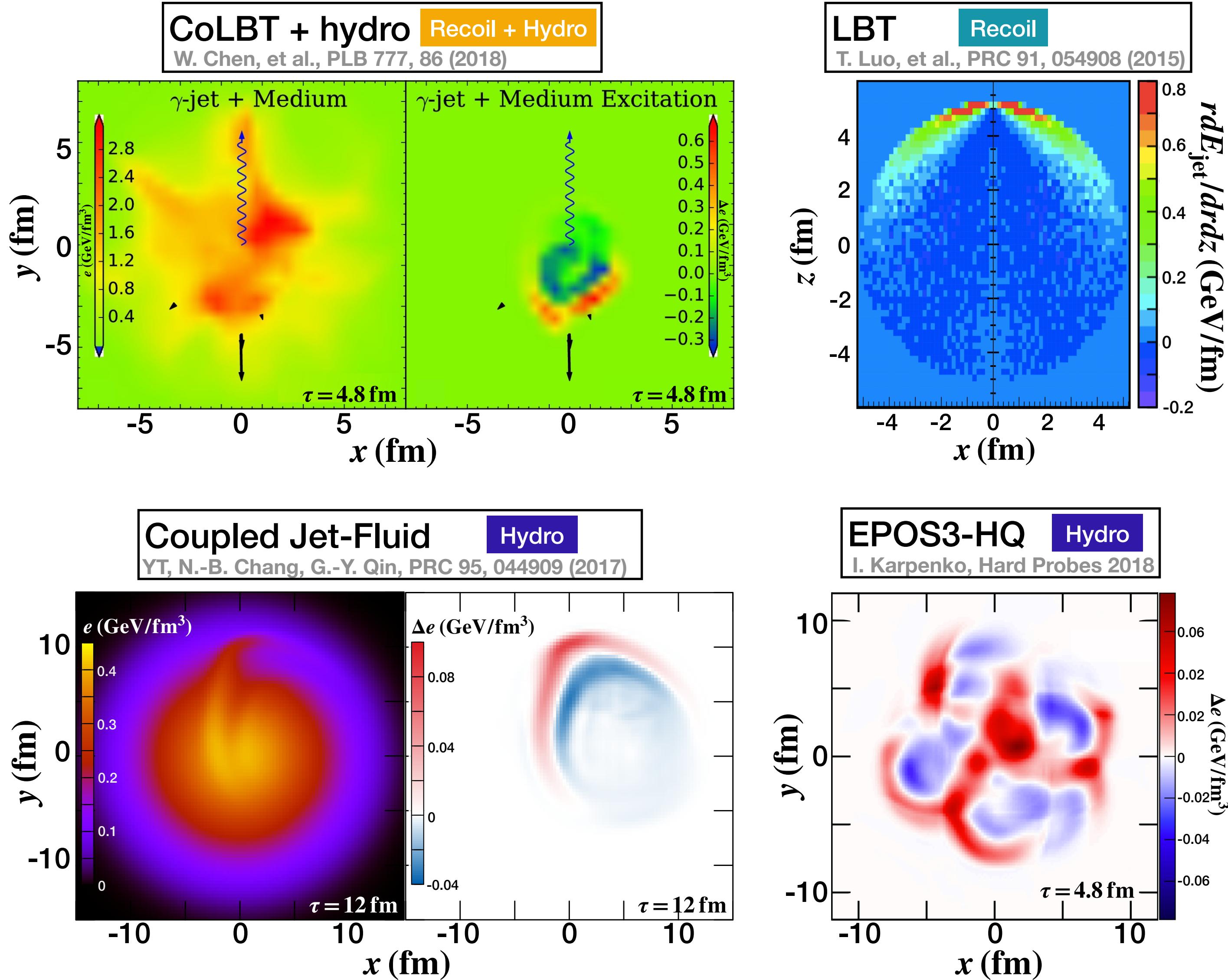
Outlook

- **Formulation of in-medium thermalization** Talk by I. Soudi
 - More clear picture of thermalization of jets
 - Modeling of source term for hydrodynamic equation
- **More systematic studies**
 - Recoil vs Hydro Response vs large angle radiation
 - Comparison between different models with the same configuration
- **Background subtraction in theoretical analysis**
 - Signals in jet observables after background subtraction
 - Development of background subtraction method with theoretical calculation



Backup

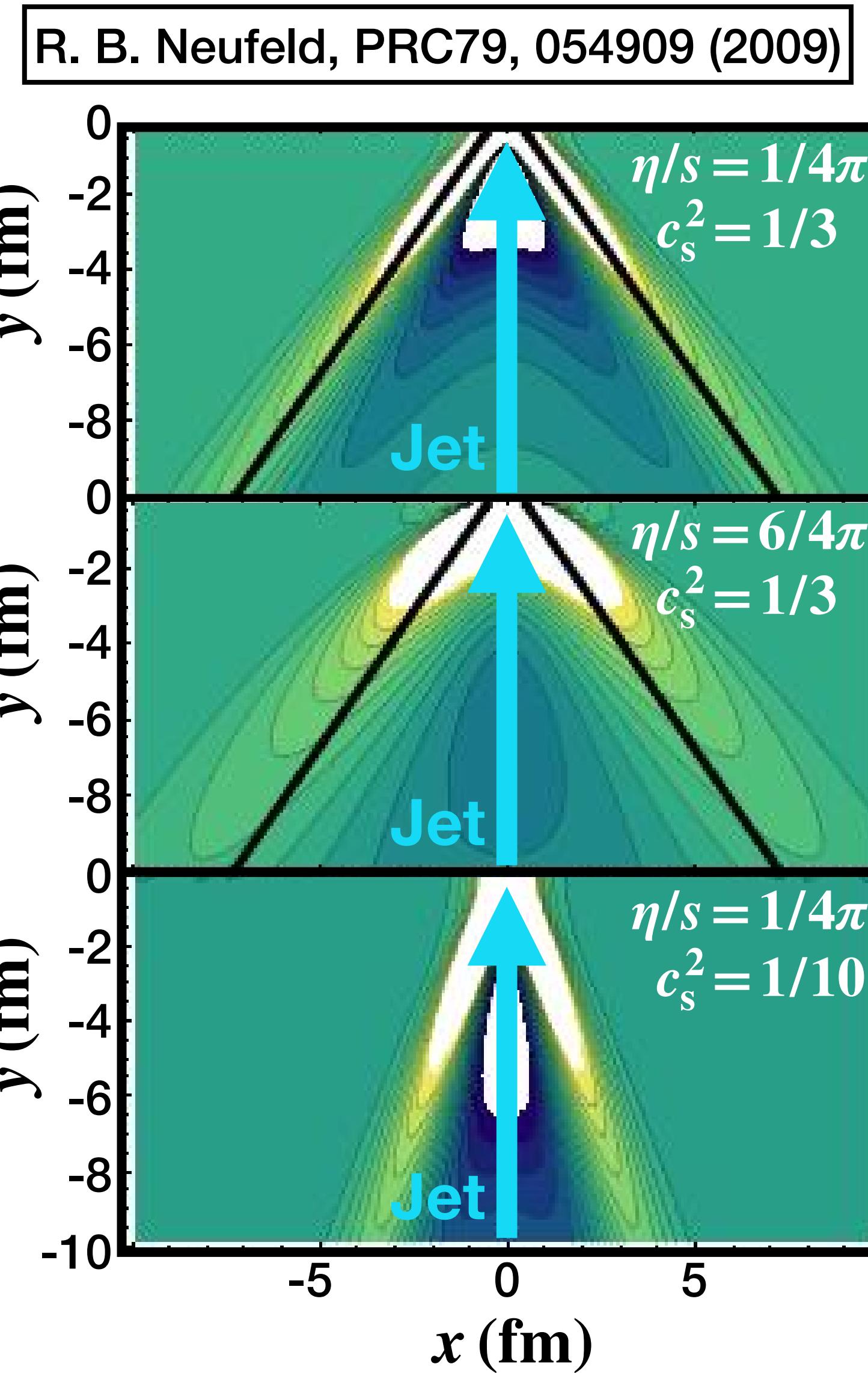
Structures Formed in Medium Response



- **Jet-induced hydro flow**
 - Mach cone
 - Interference between flows
- **Recoils' evolution**
 - Successive scatterings with medium constituents
 - Mach cone like structure

Energy-momentum transport away from jet

Motivations

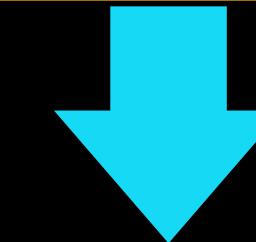


Shockwave (Mach cone)

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)

- Induced by jet partons faster than medium sound velocity
- Structure characterized by fluid properties (shear viscosity, sound velocity, etc.)
R. B. Neufeld ('09), R. B. Neufeld, I. Vitev ('12), A. Ayala et al. ('16), L. Yan, S. Jeon, C. Gale ('17)
- Transportation of thermalized part of jet

Thermalized part contribution in jet



Fluid Properties of QGP

Shear viscosity η/s

Sound velocity c_s , etc.

Backward (leading) jet- p_T suppression in dijet event

The subleading jet pushes medium in its direction

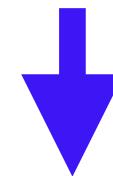
Hybrid Strong/Weak [AdS/CFT]
D. Pablos, PRL 124, 052301 (2020)

Large overlap between the structures of the leading jet and the subleading jet

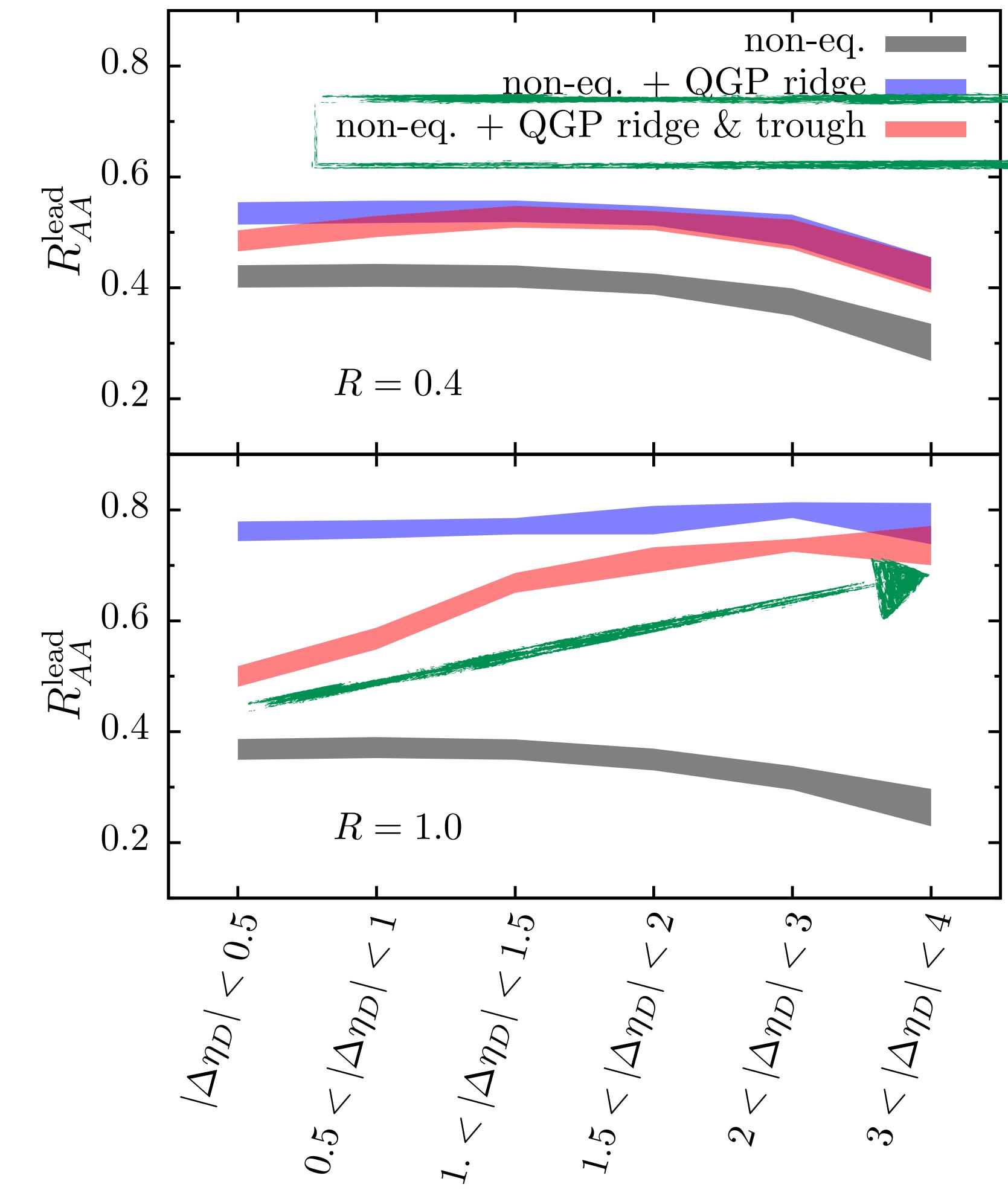
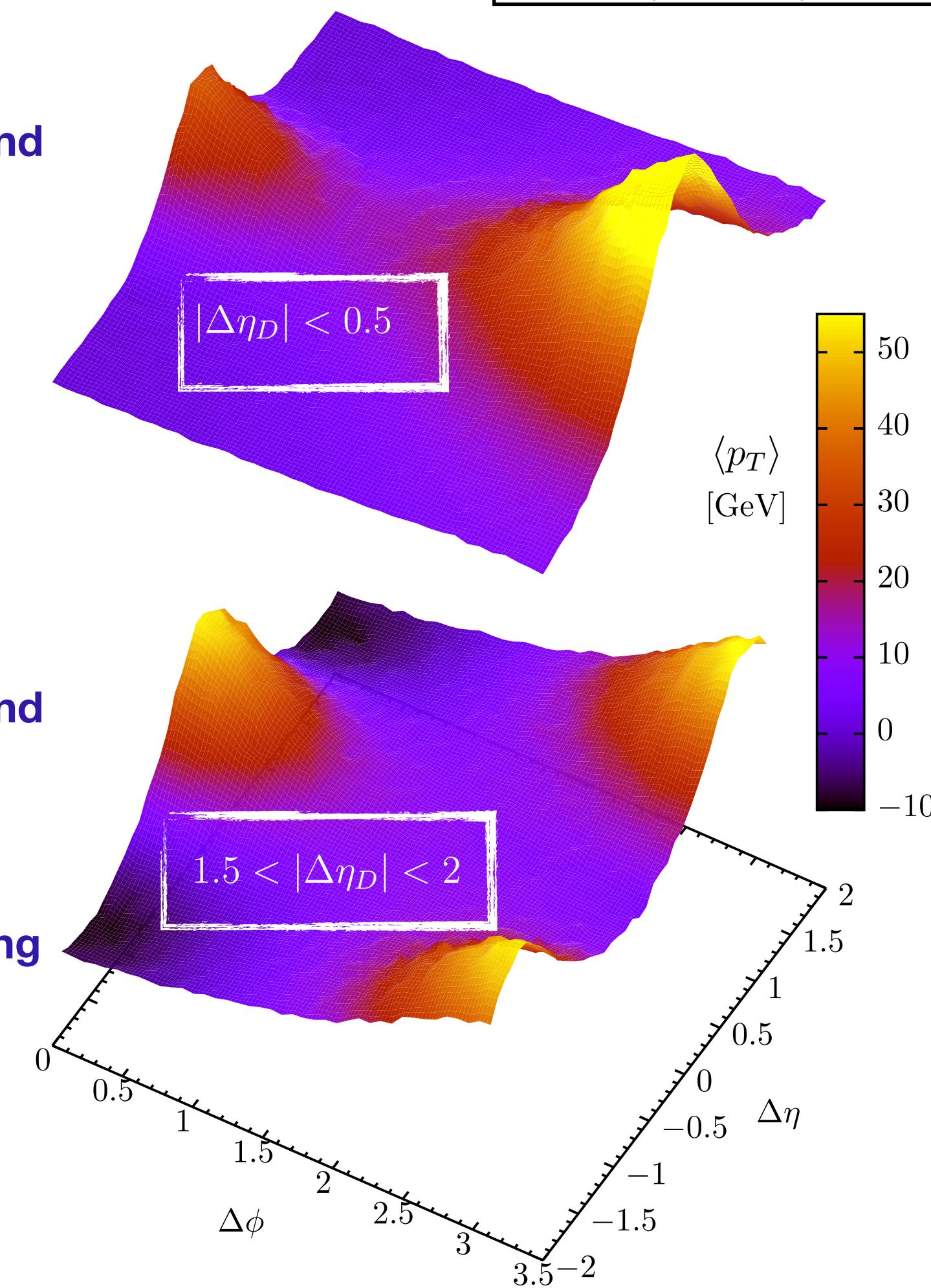


More suppression of the leading jet

Small overlap between the structures of the leading jet and the subleading jet



Less suppression of the leading jet

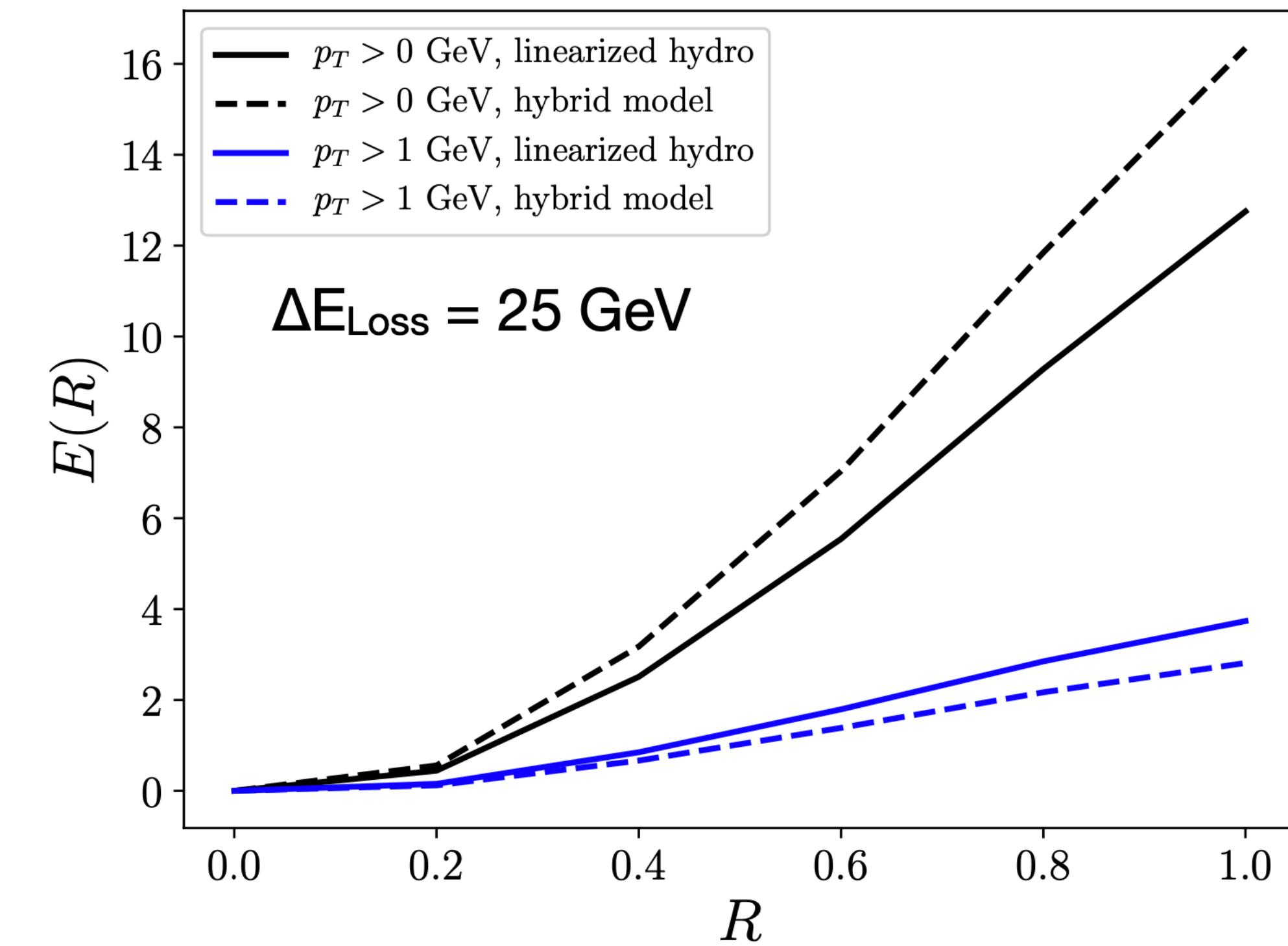
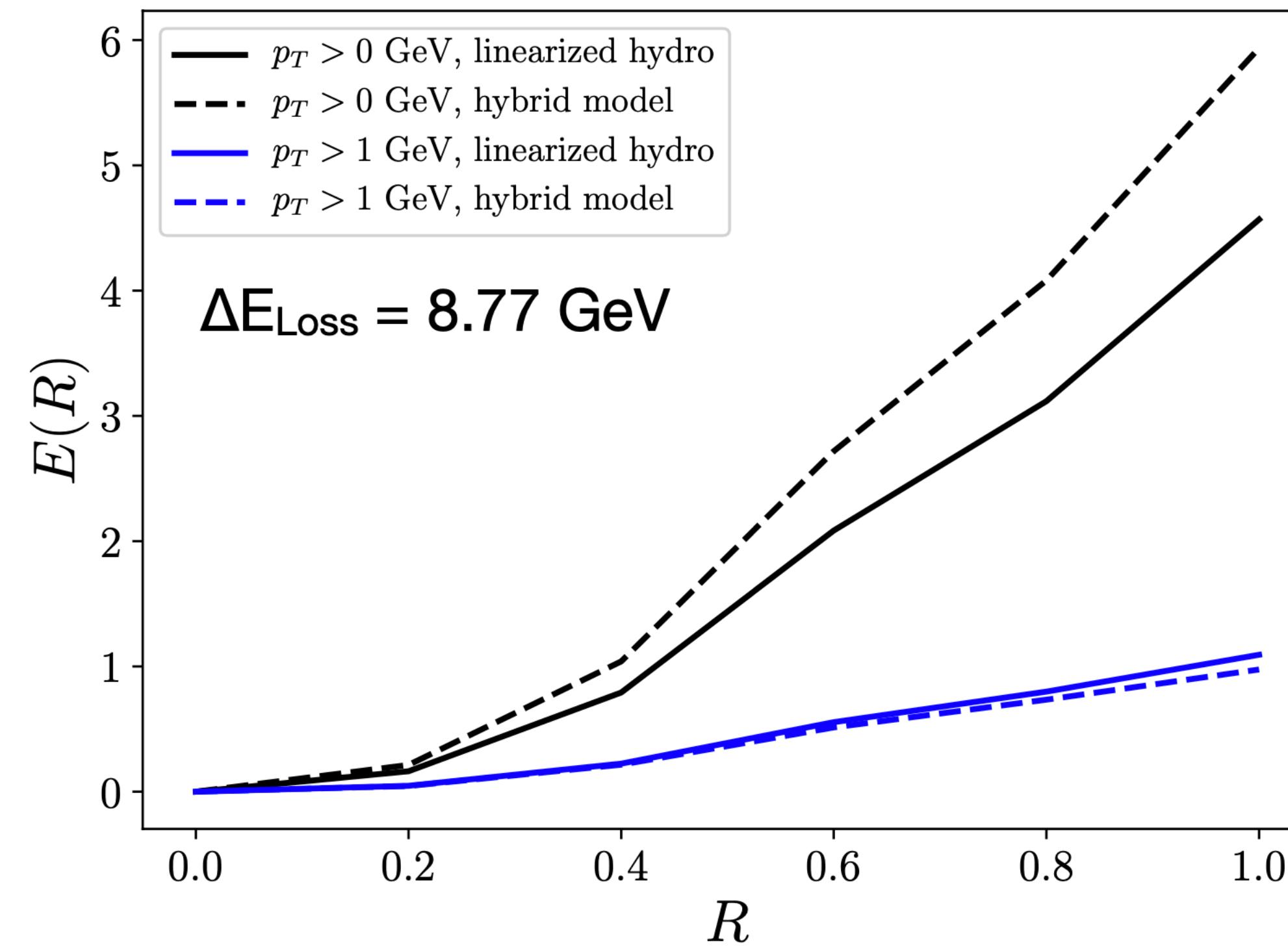


Full results

Effect from Dynamics of Medium Response

Talk by J. Casalderrey-Solana

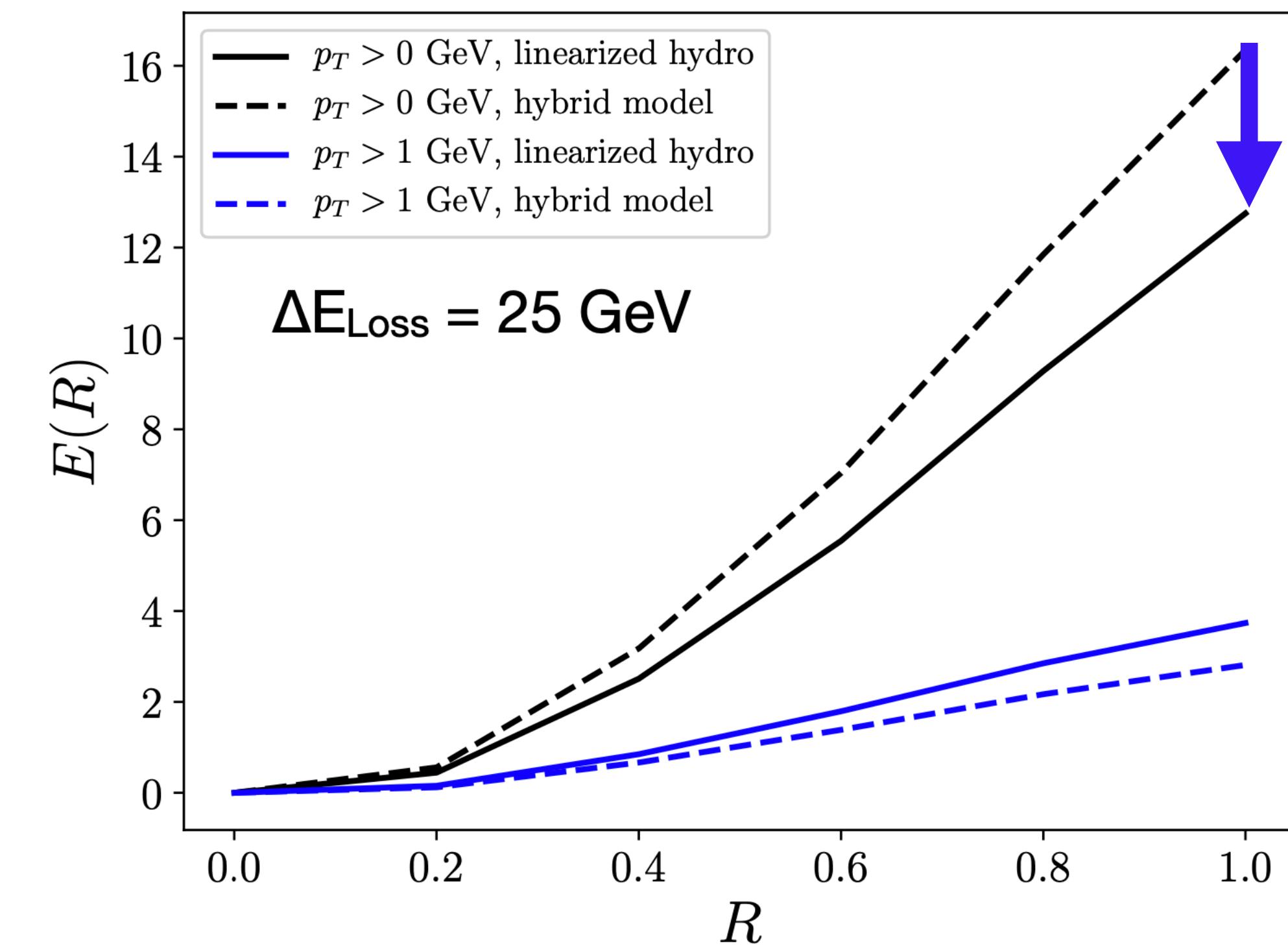
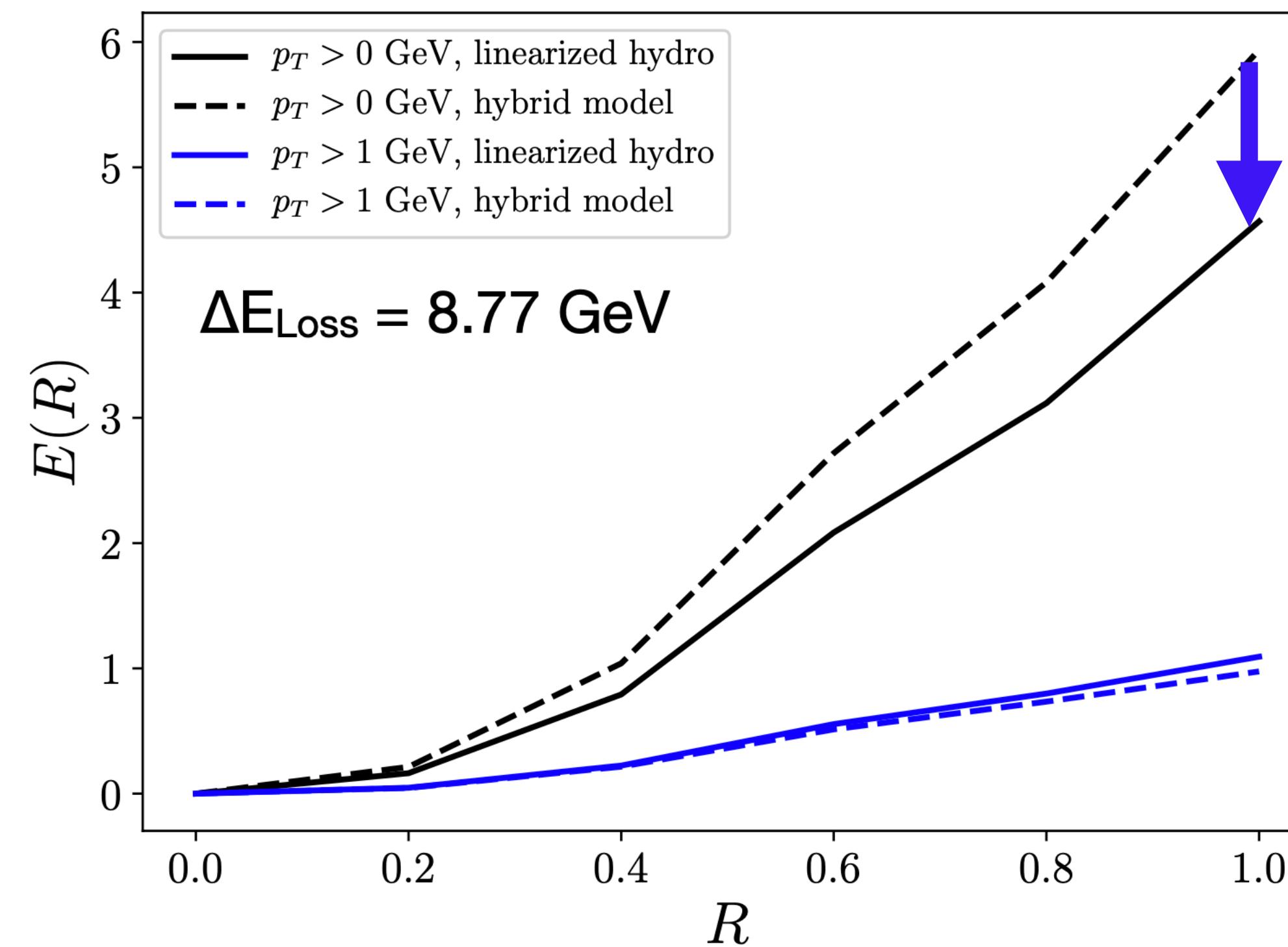
Hybrid Strong/Weak [AdS/CFT] + Linearized Hydro Linearized Hydro
D. Pablos, X. Yao, J. Casalderrey-Solana, K. Rajagopal, J. G. Milhano, Hard Probes 2020



Effect from Dynamics of Medium Response

Talk by J. Casalderrey-Solana

Hybrid Strong/Weak [AdS/CFT] + Linearized Hydro Linearized Hydro
D. Pablos, X. Yao, J. Casalderrey-Solana, K. Rajagopal, J. G. Milhano, Hard Probes 2020

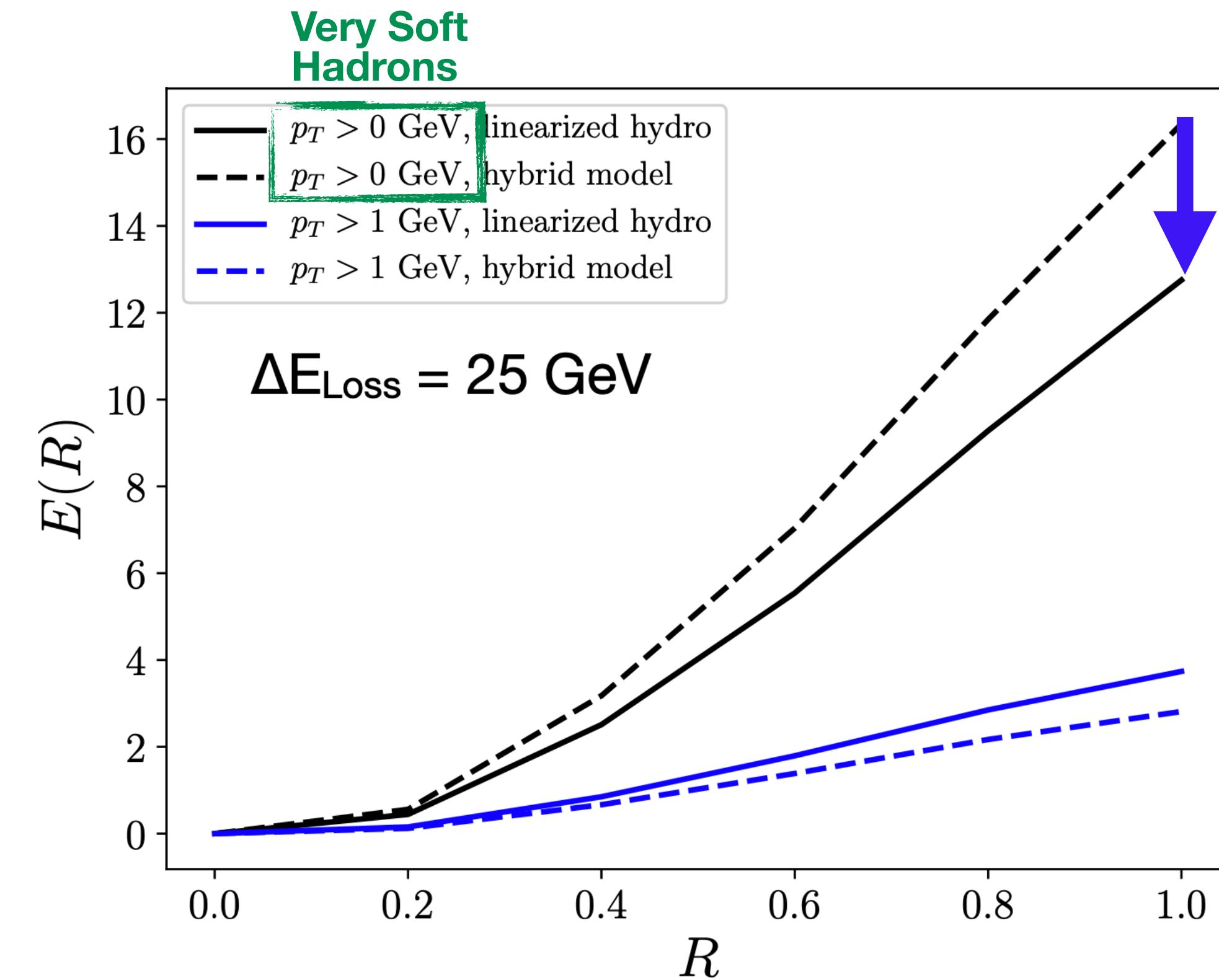
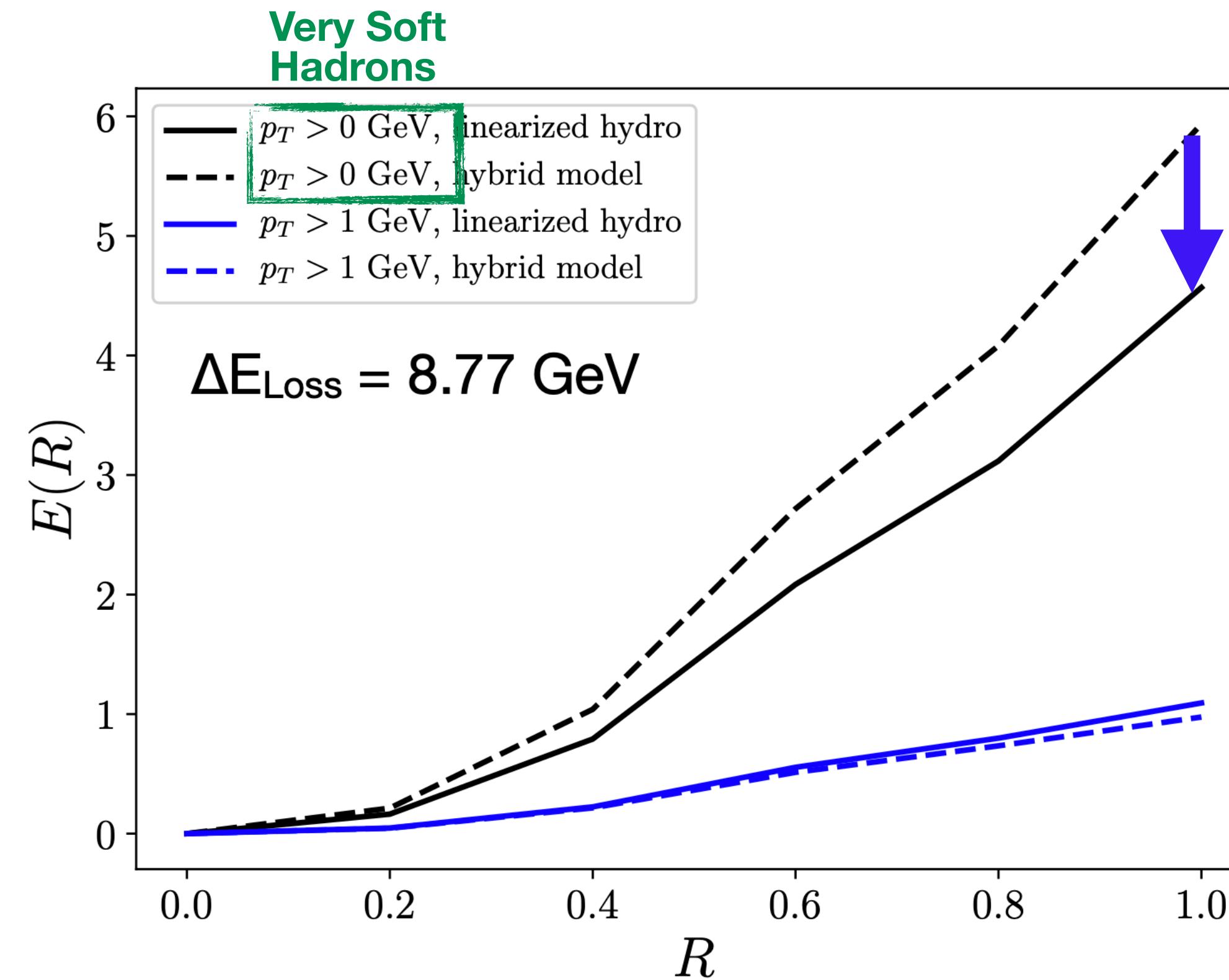


Slower recovery of jet energy as a function of R with hydro evolution

Effect from Dynamics of Medium Response

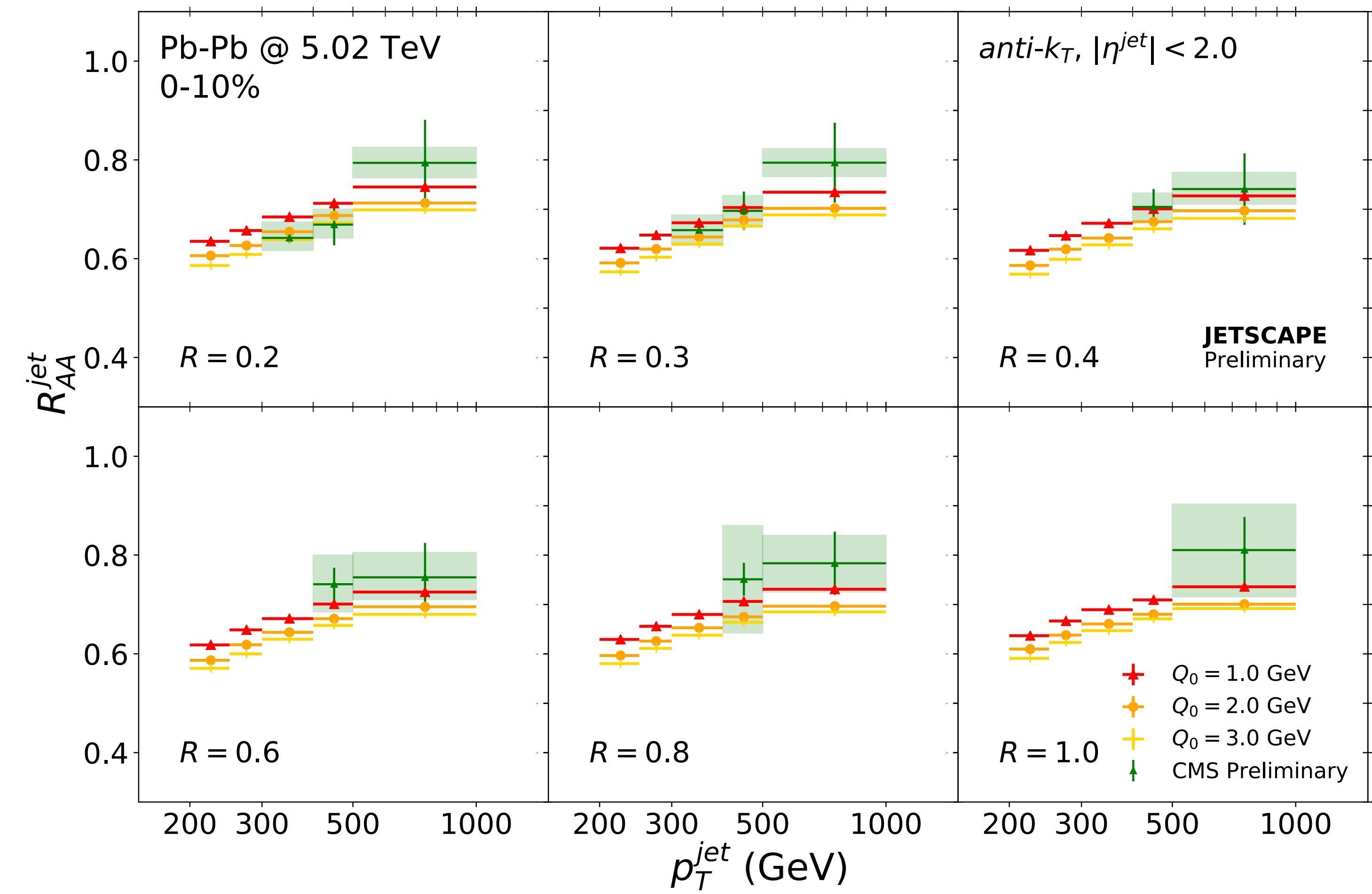
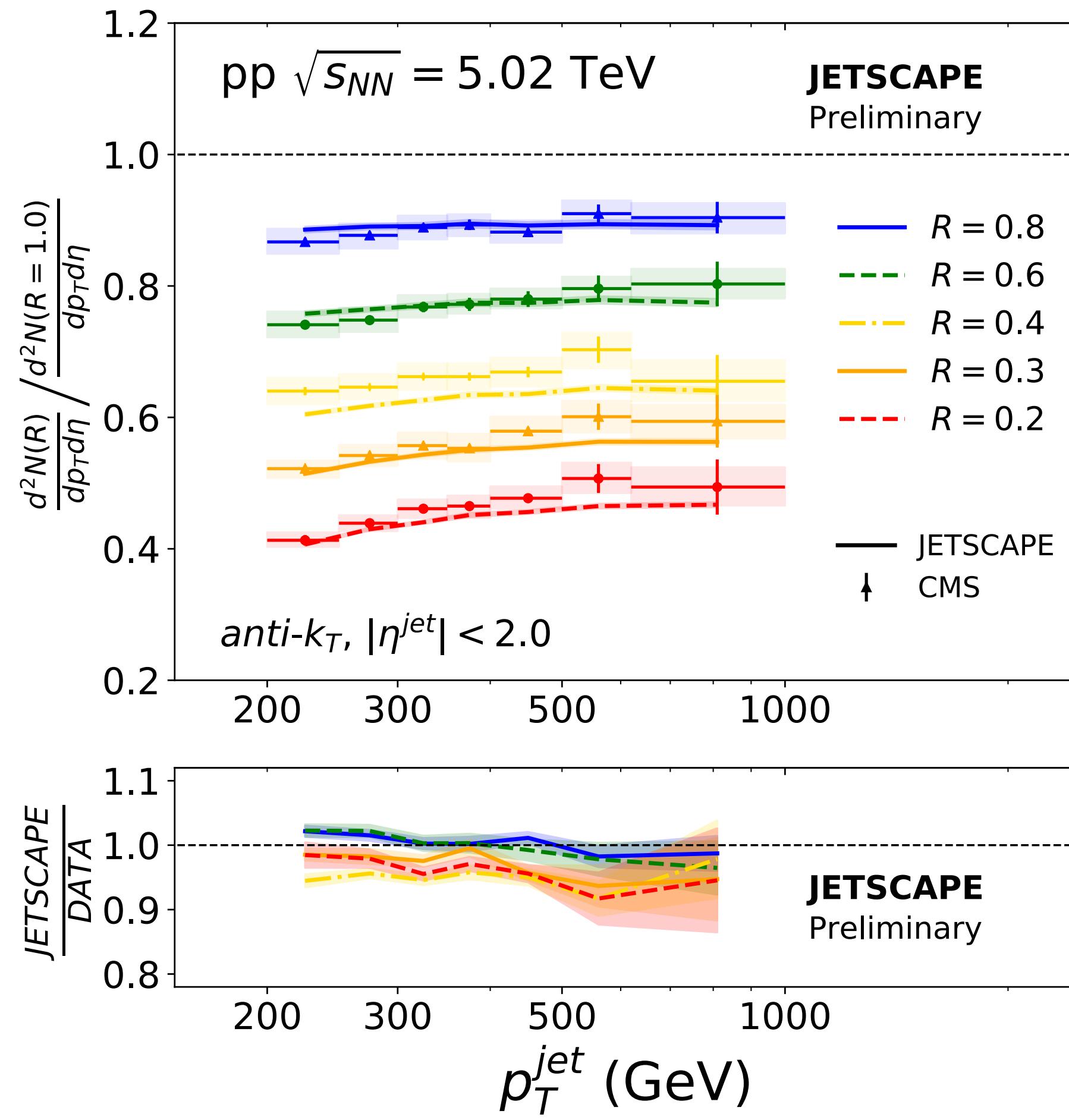
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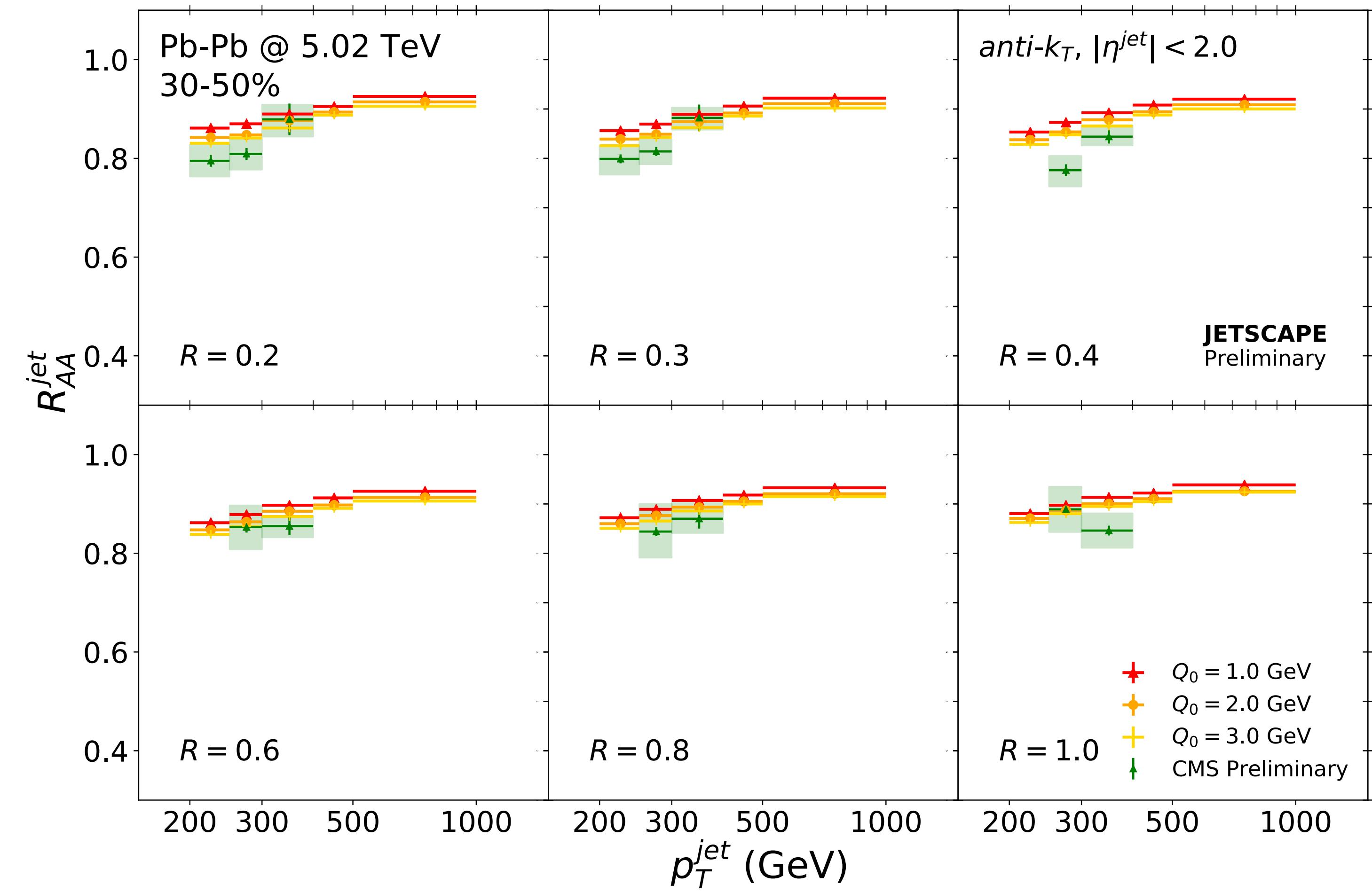
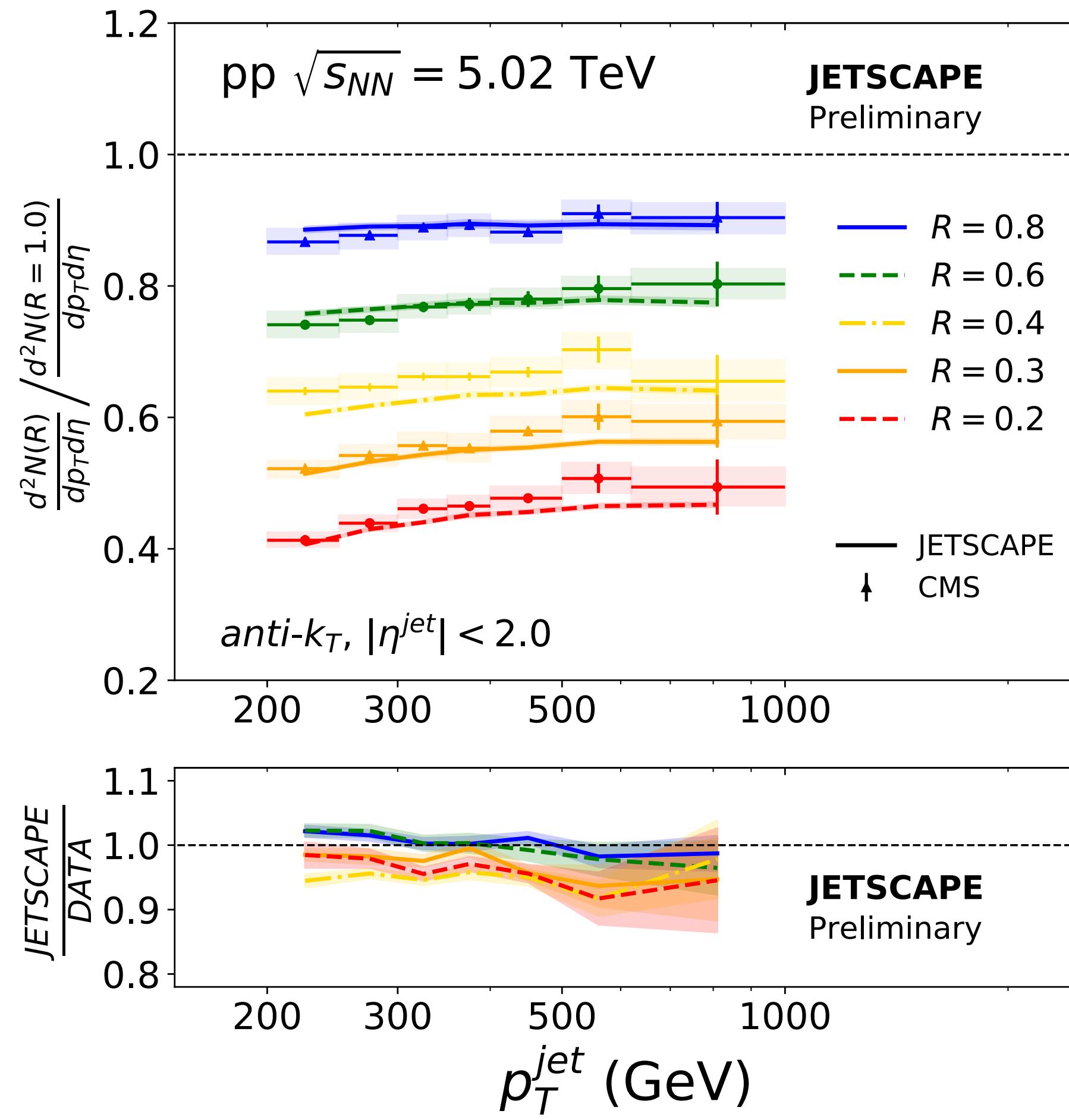


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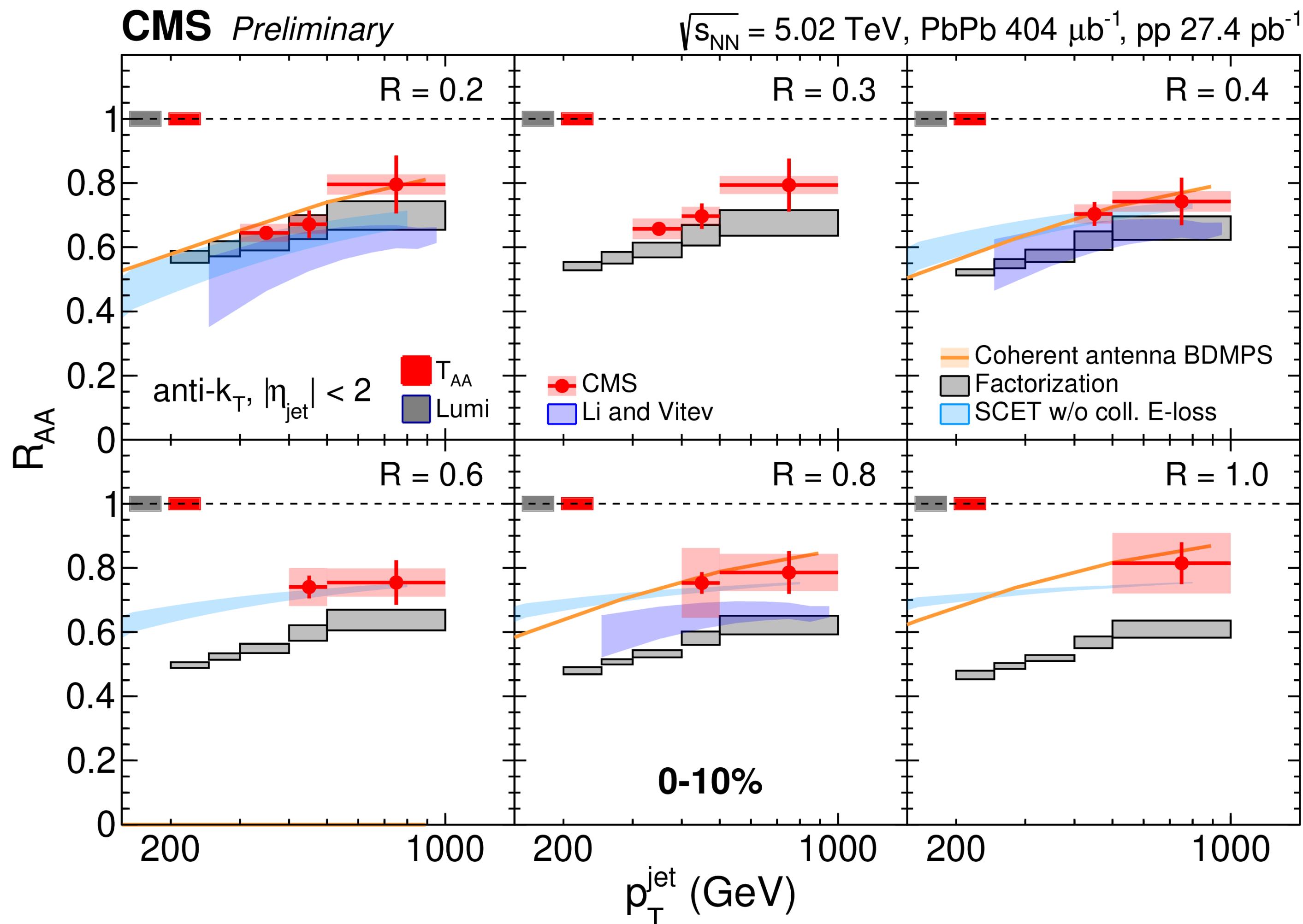
Cone Size Dependence in Jet Energy loss



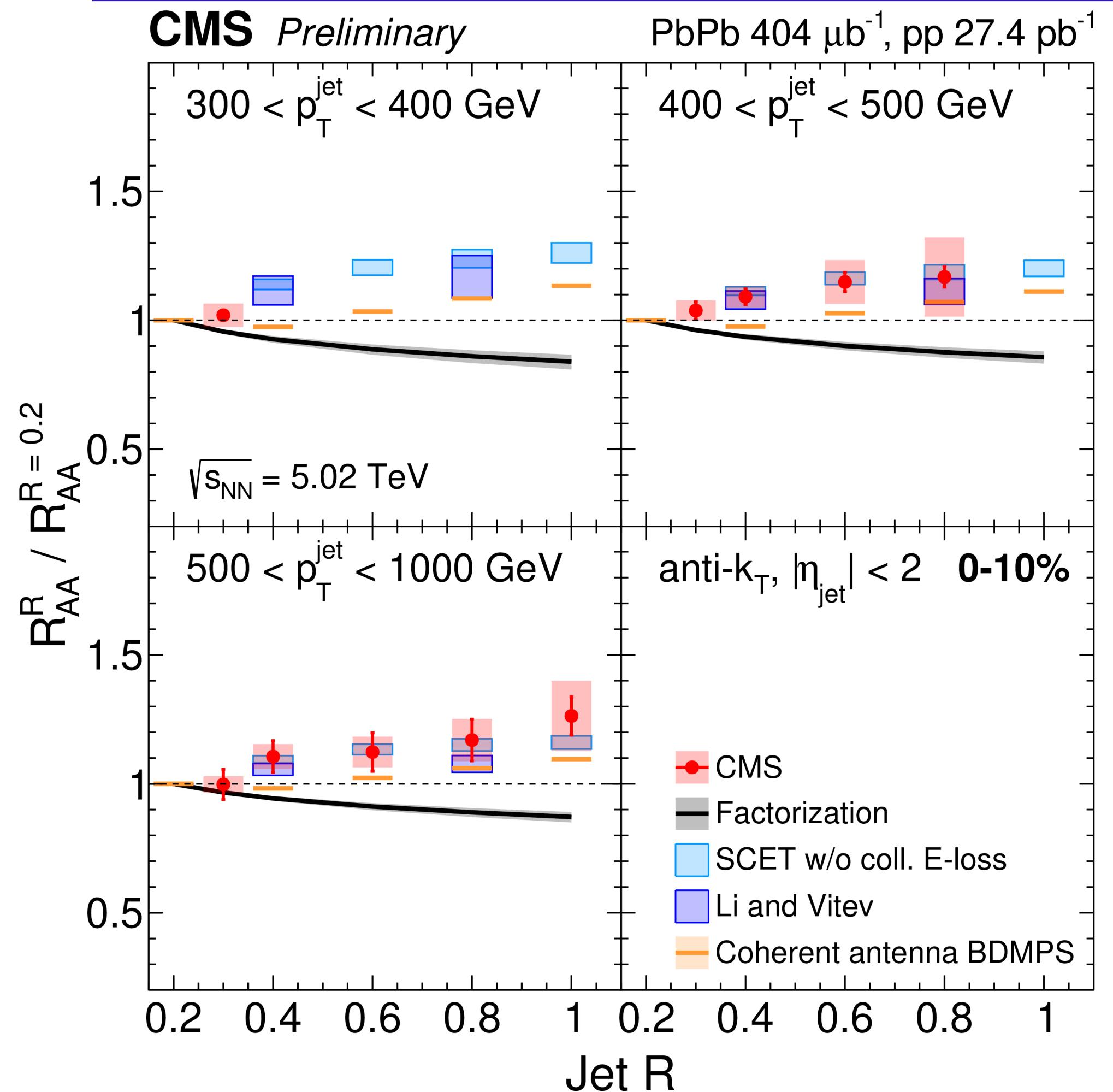
Cone Size Dependence in Jet Energy loss



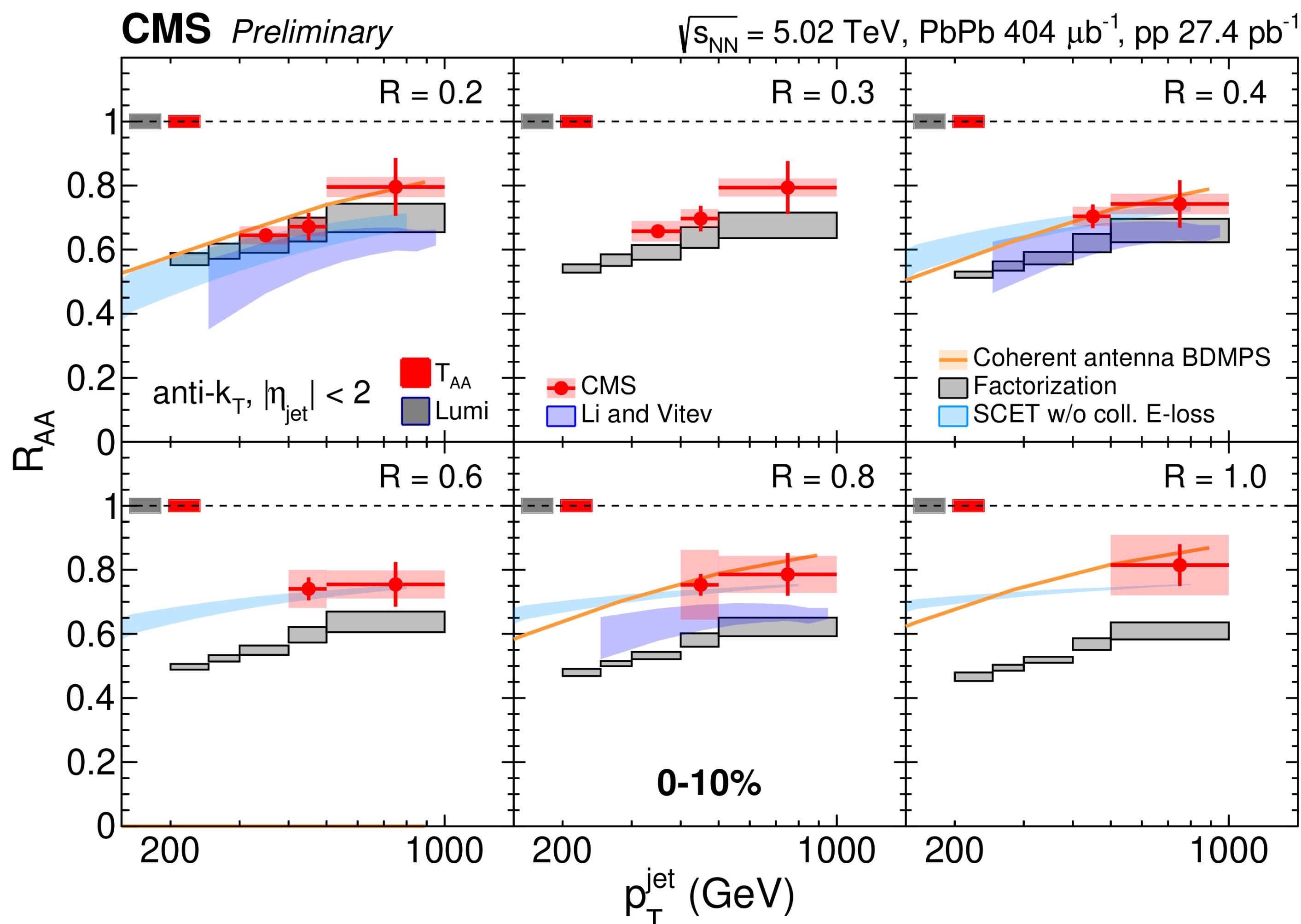
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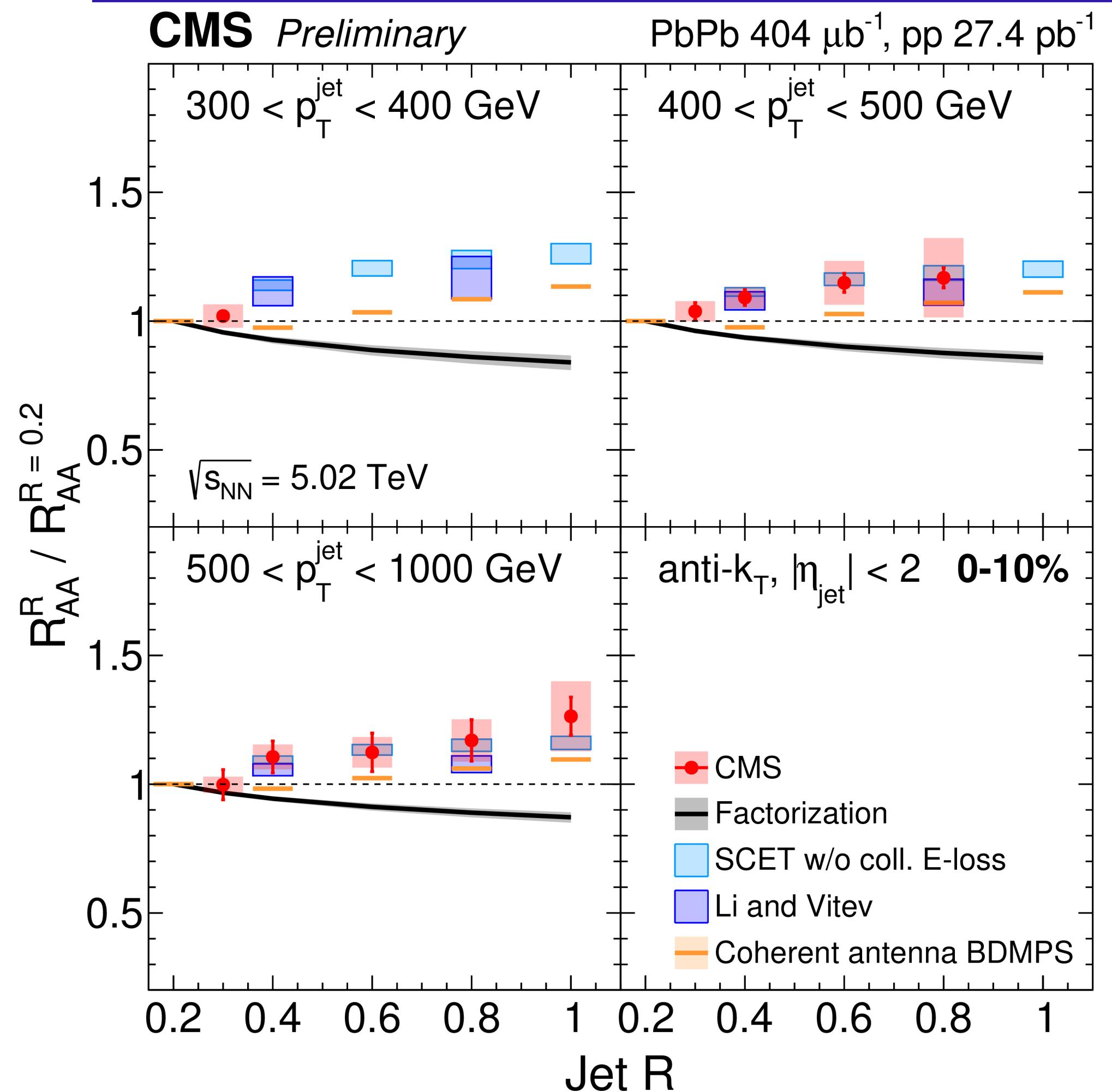
CMS is now updating the data points



Cone Size Dependence in Jet Energy loss

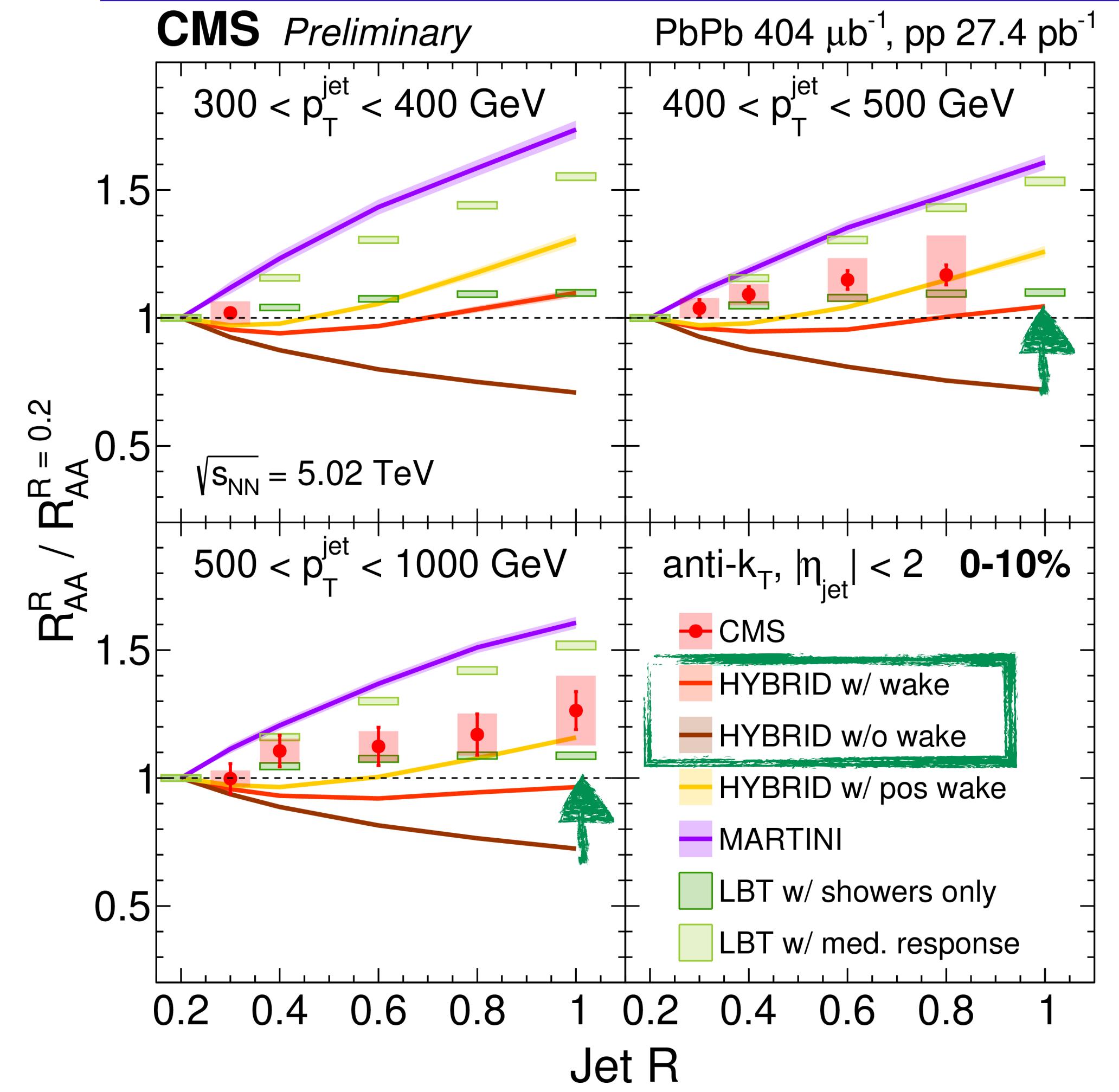
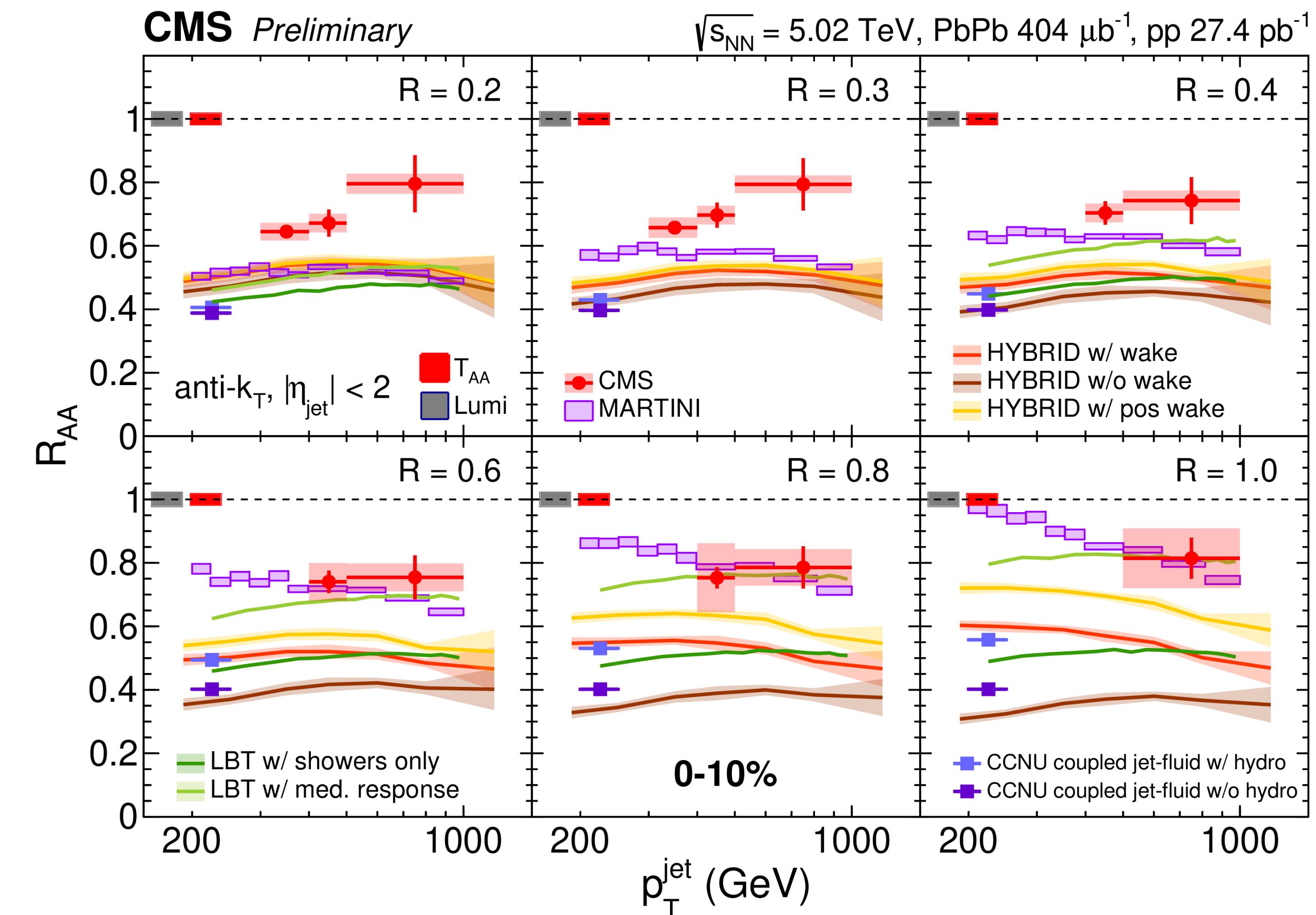


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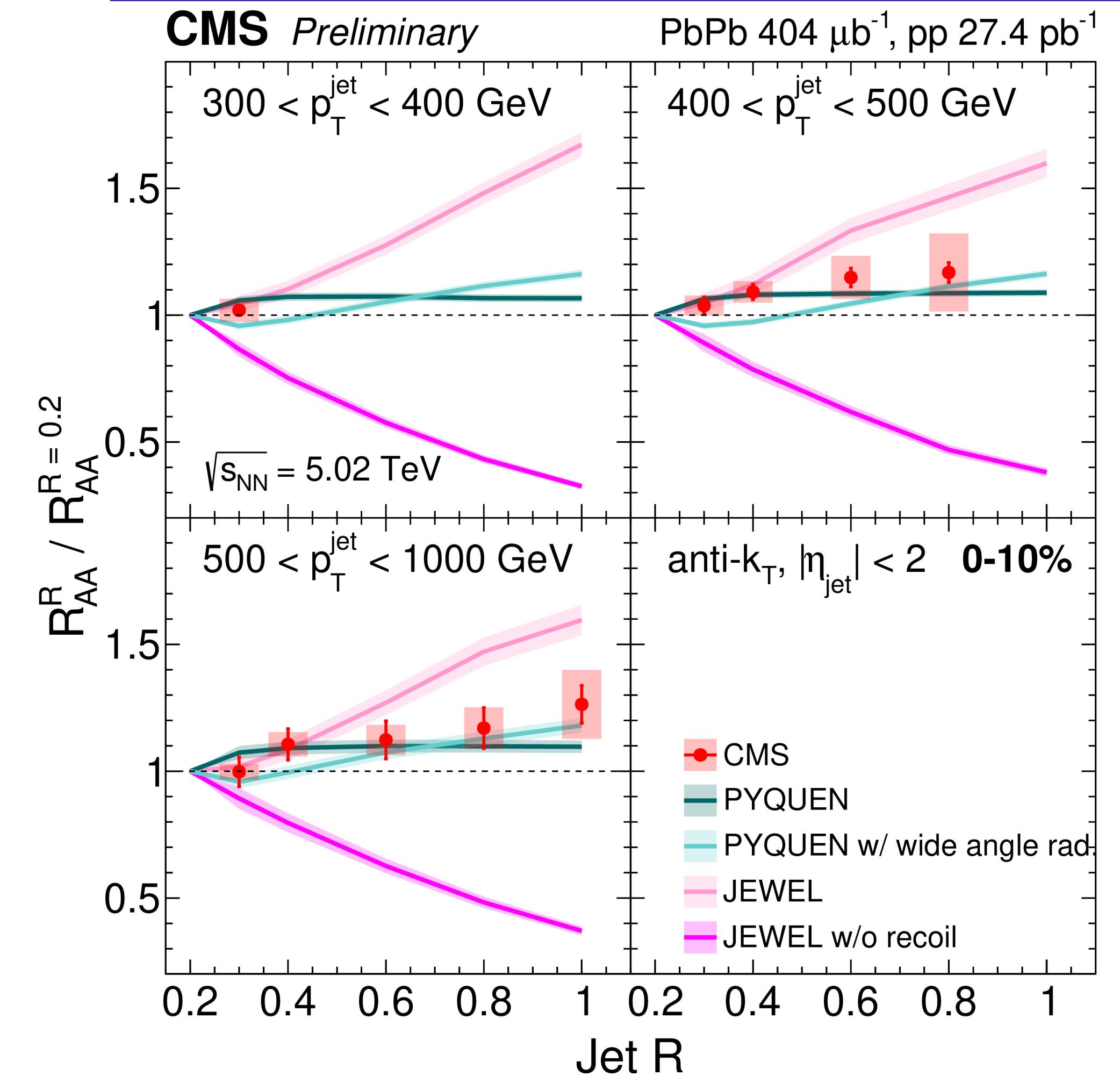
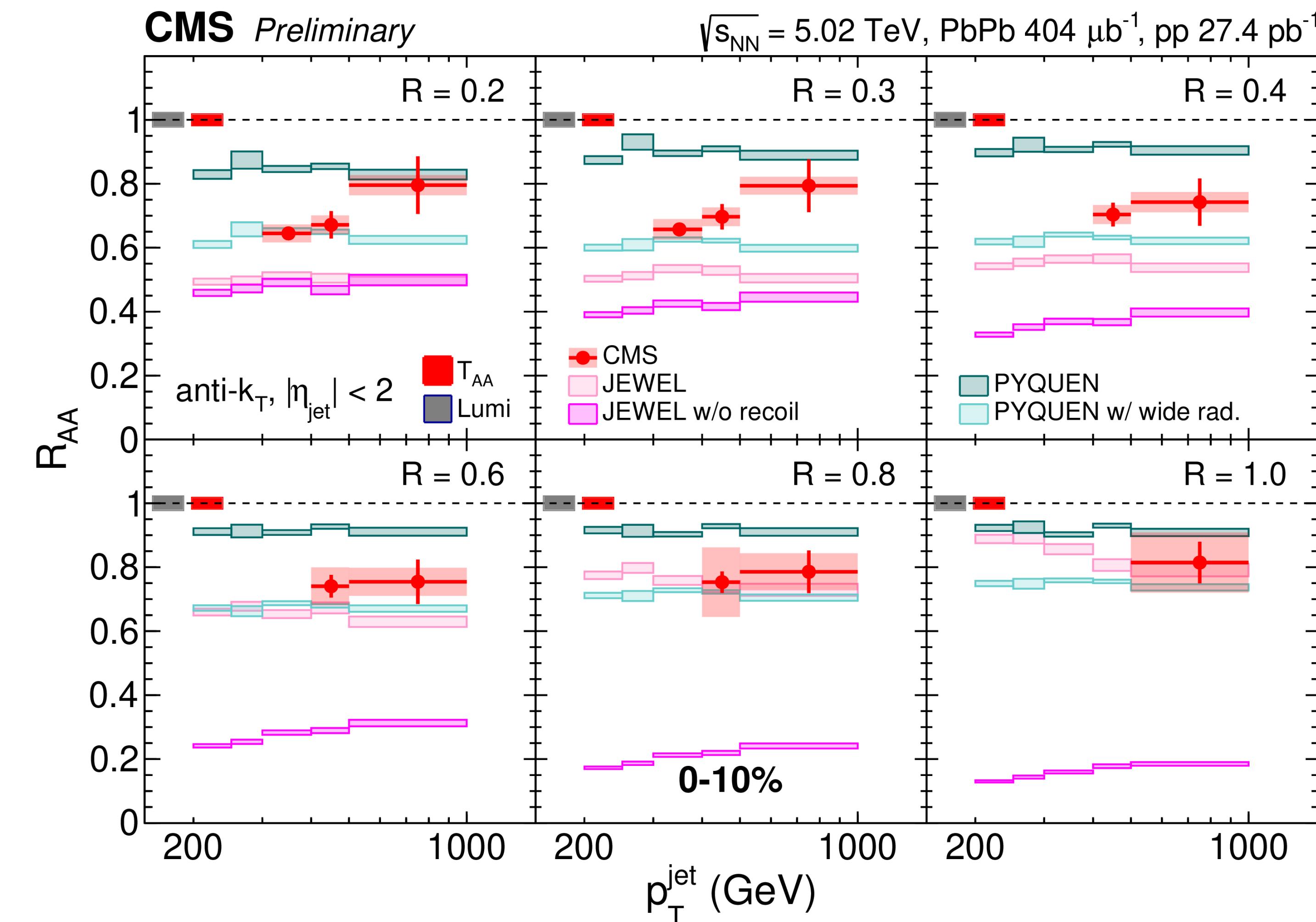
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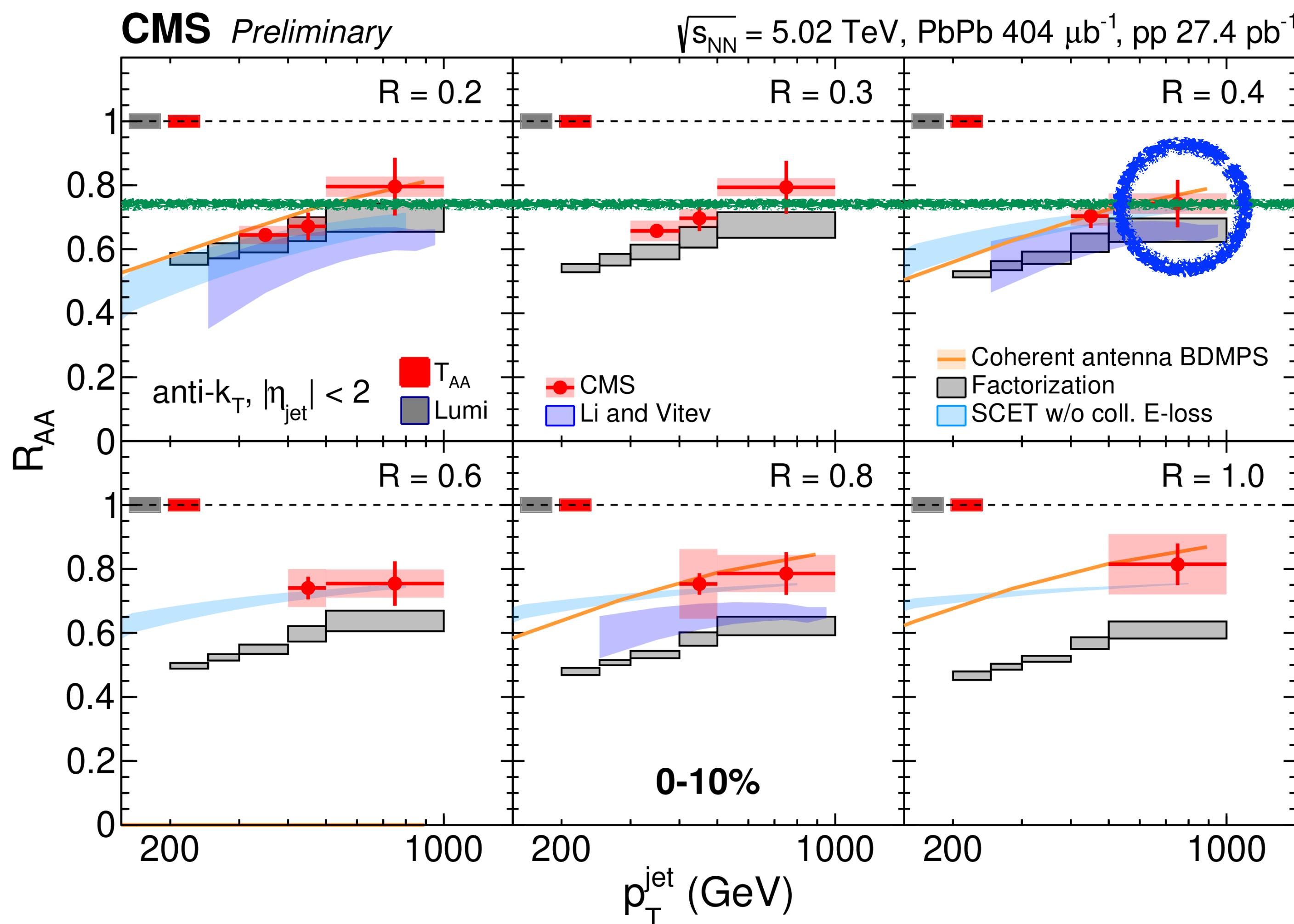


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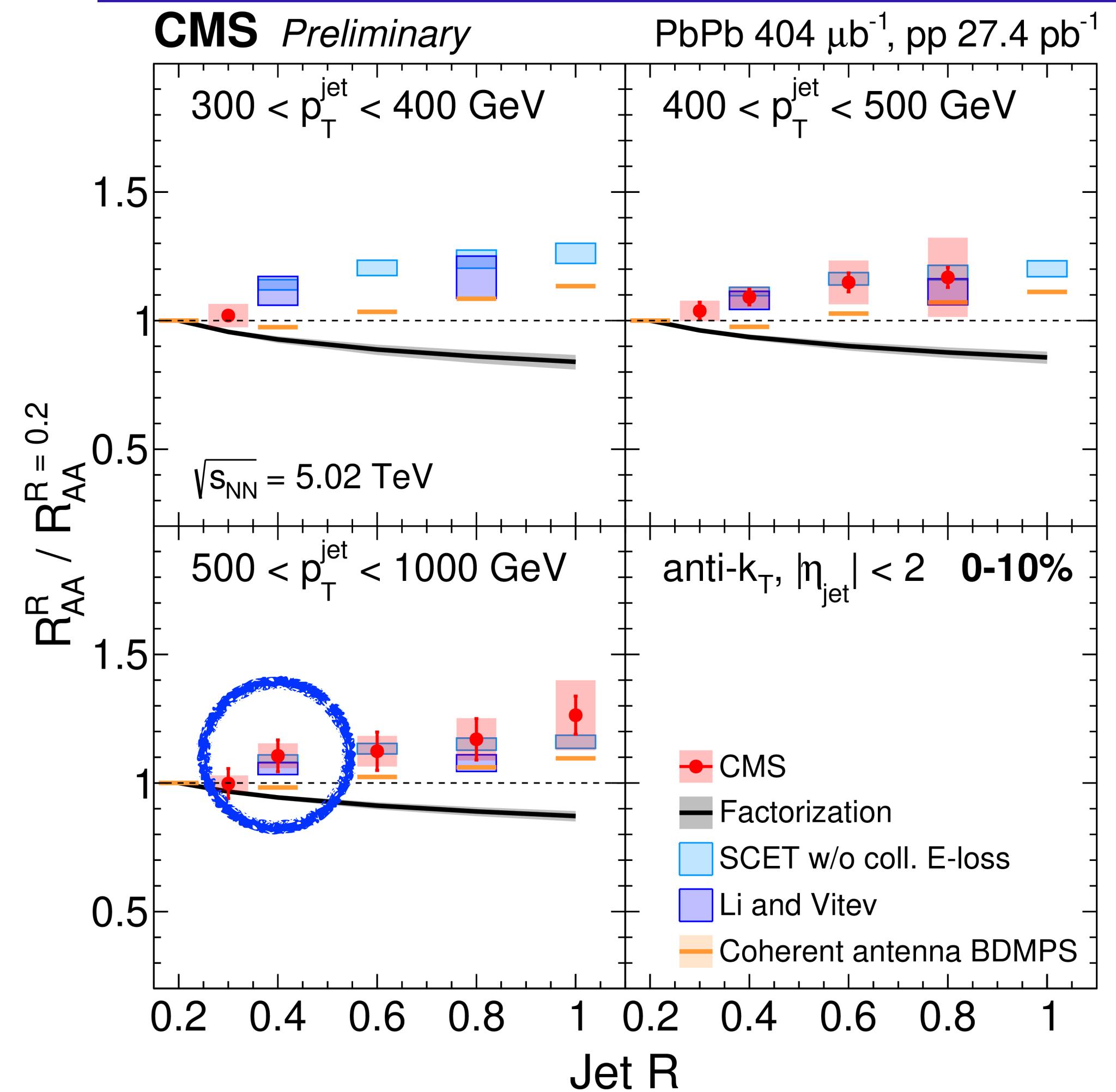
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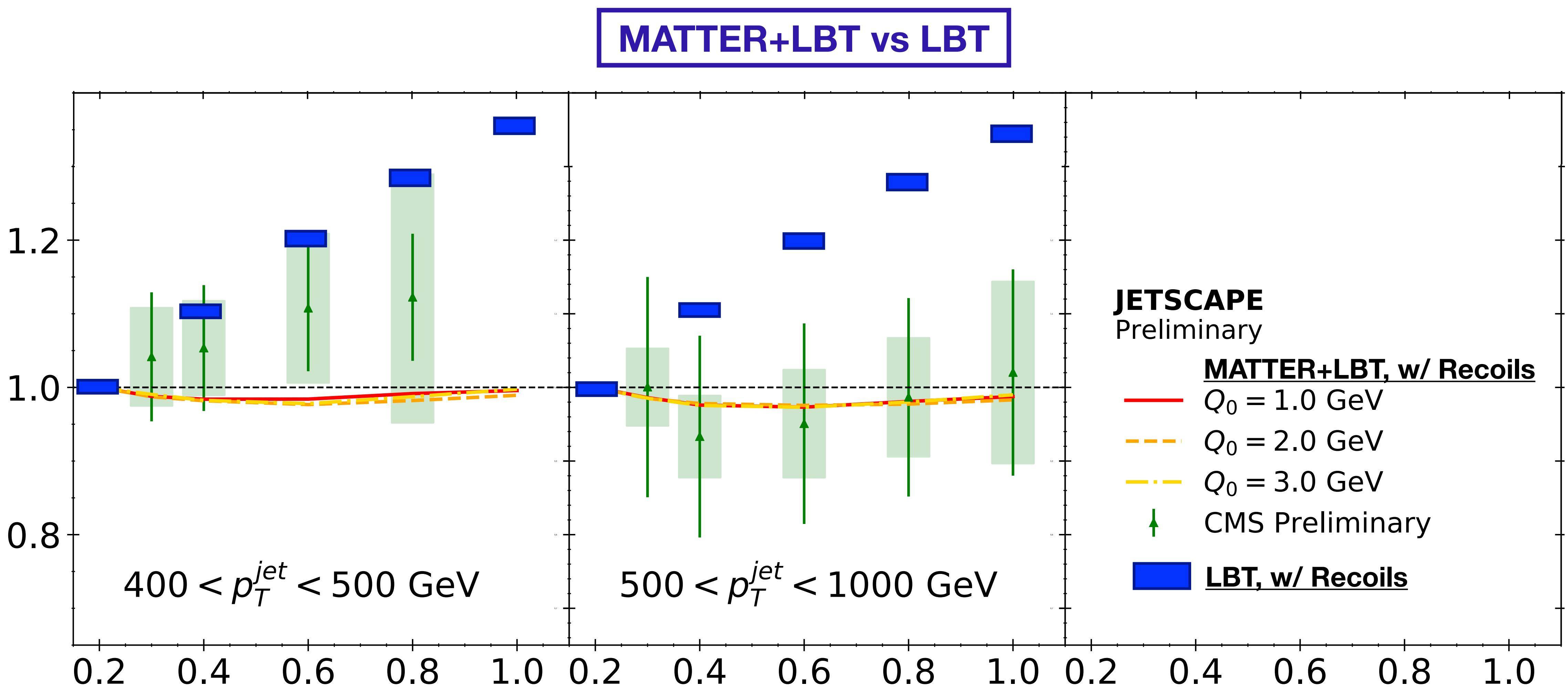
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Cone Size Dependence in Jet Energy loss



Outline

- Introduction
- Implementation of Medium Response
- Medium Response Effects
- Summary and Outlook