公立大学法人
国際教養大学
Akita International University

JETSCAPE

FLUID + JET

Yasuki Tachibana

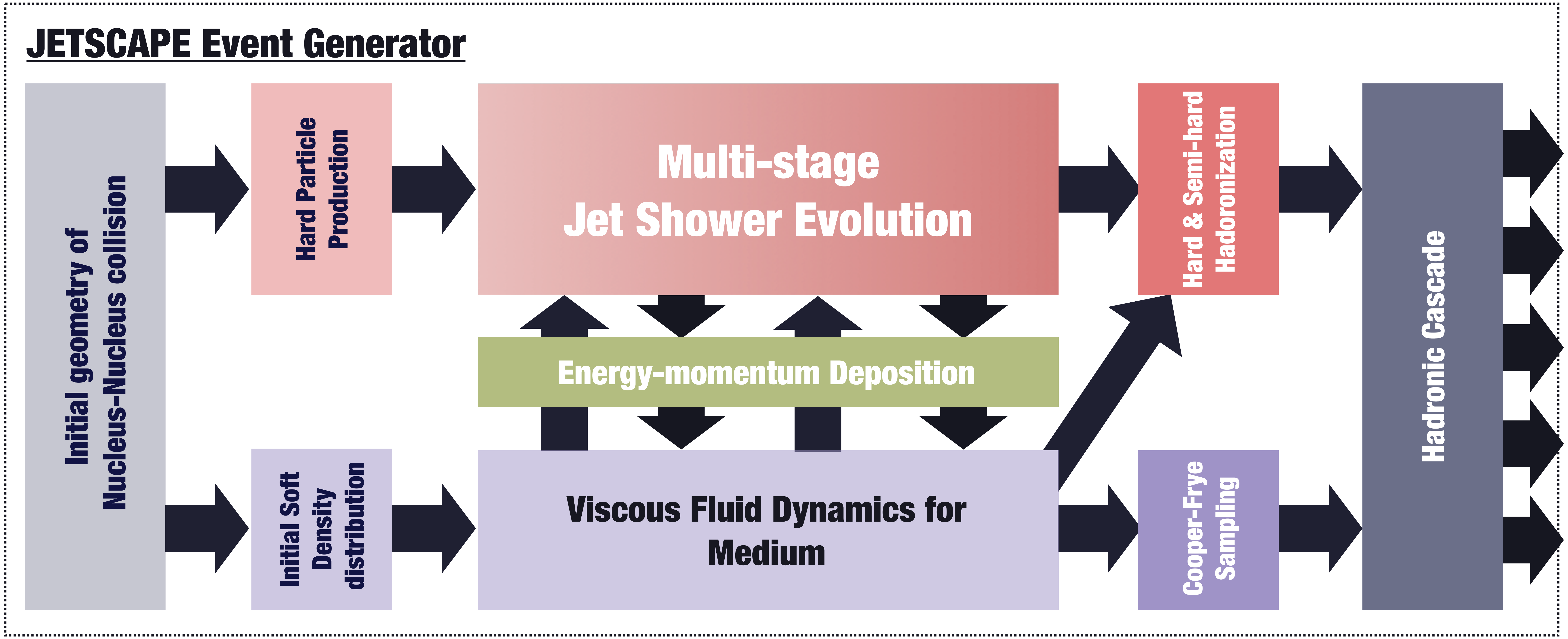
QCD相転移やQGP生成のモデル化による
重イオン衝突の時空発展の理解に向けた理論・実験共同研究会

September 24th, 2021

Jet Evolution in JETSCAPE

JETSCAPE framework

- **MC event generator package for heavy ion collisions**
  - General, modular and extensible
  - Communication between modules

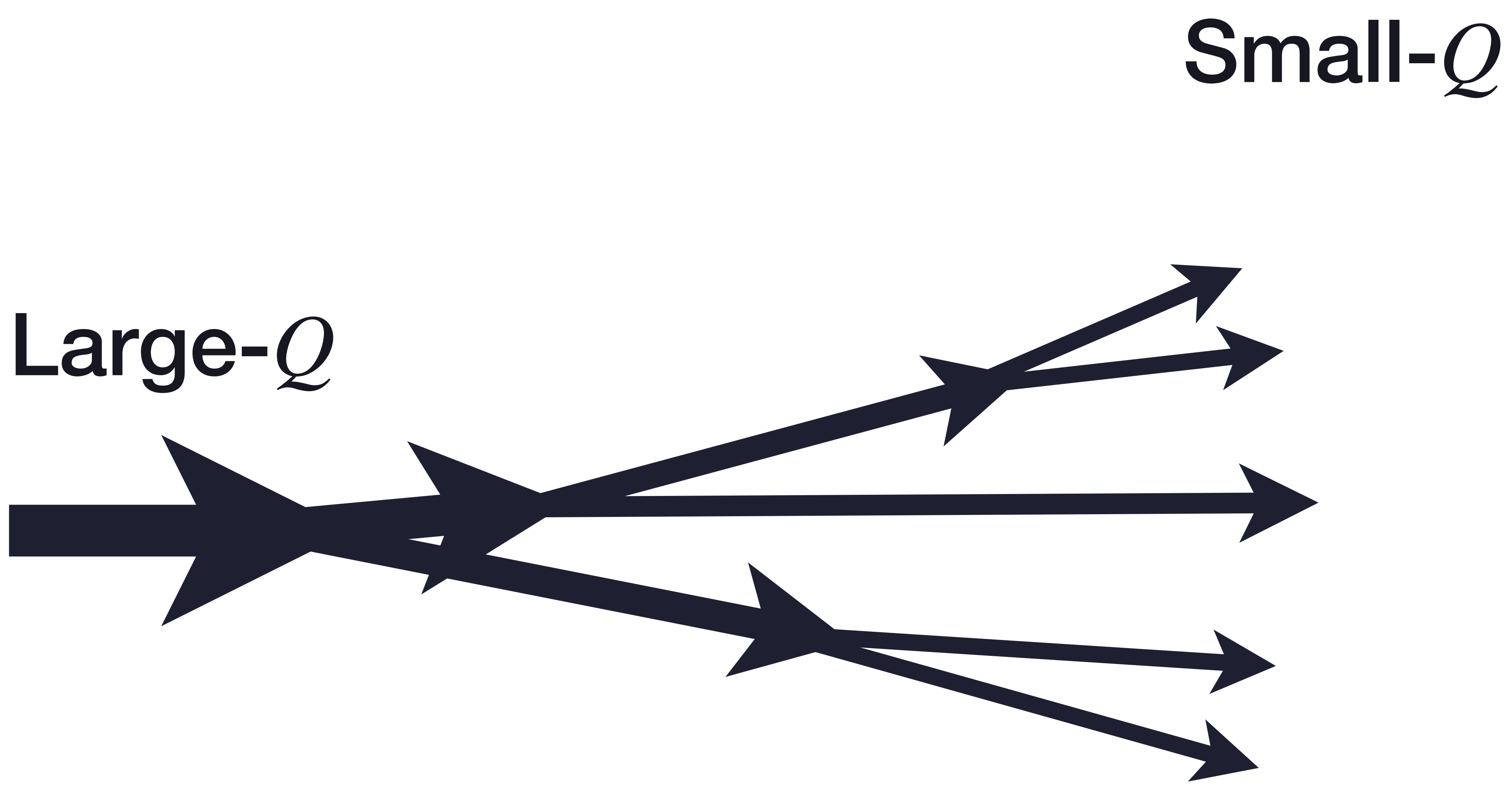


Multi-scale jet evolution

Majumder, Putschke (16), JETSCAPE (17)

In-vacuum

- In-vacuum: Virtuality ordered splitting



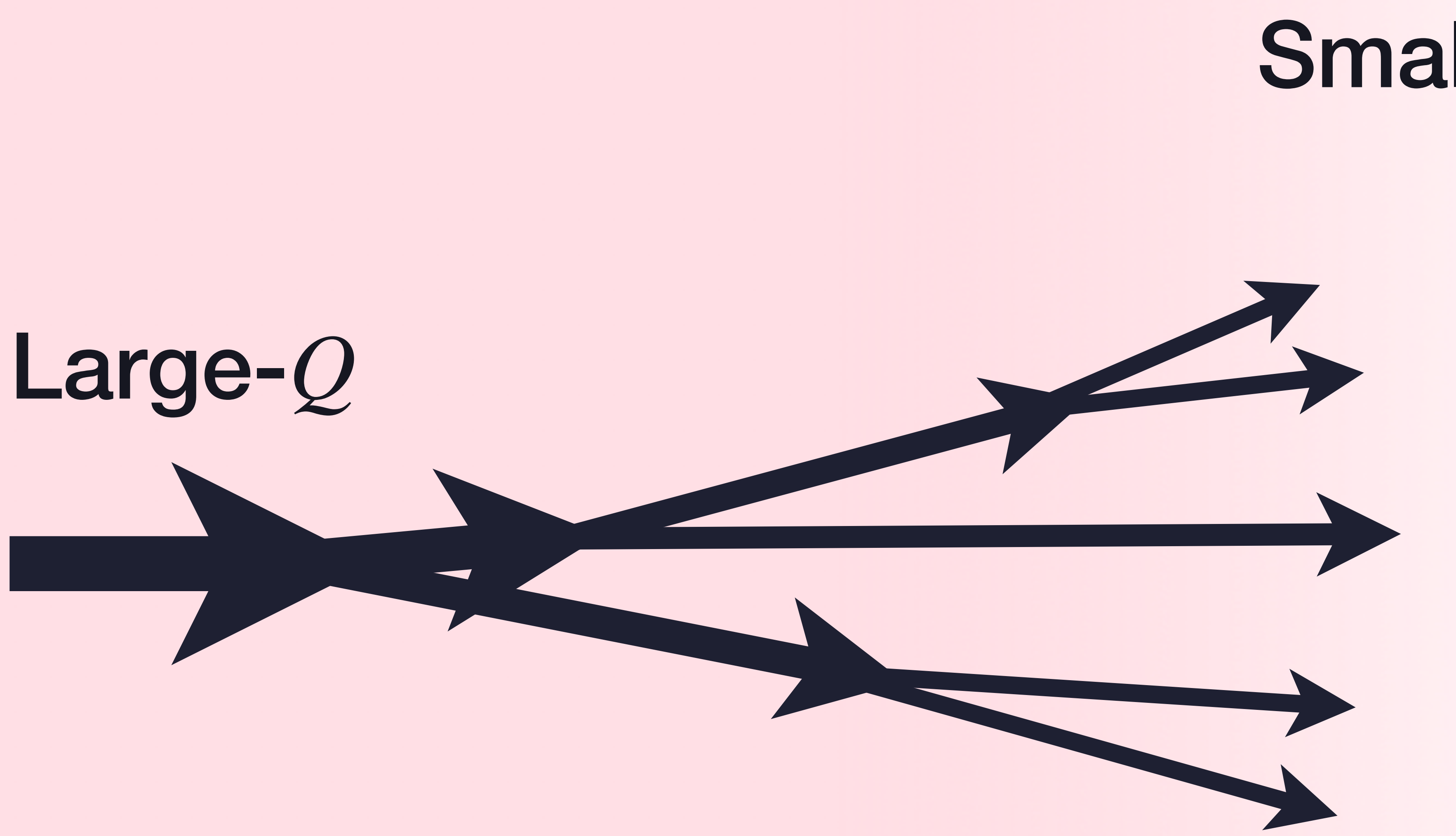
Q^2: virtuality (off-shellness)

Multi-scale jet evolution

Majumder, Putschke (16), JETSCAPE (17)

In-medium

- In-vacuum: Virtuality ordered splitting



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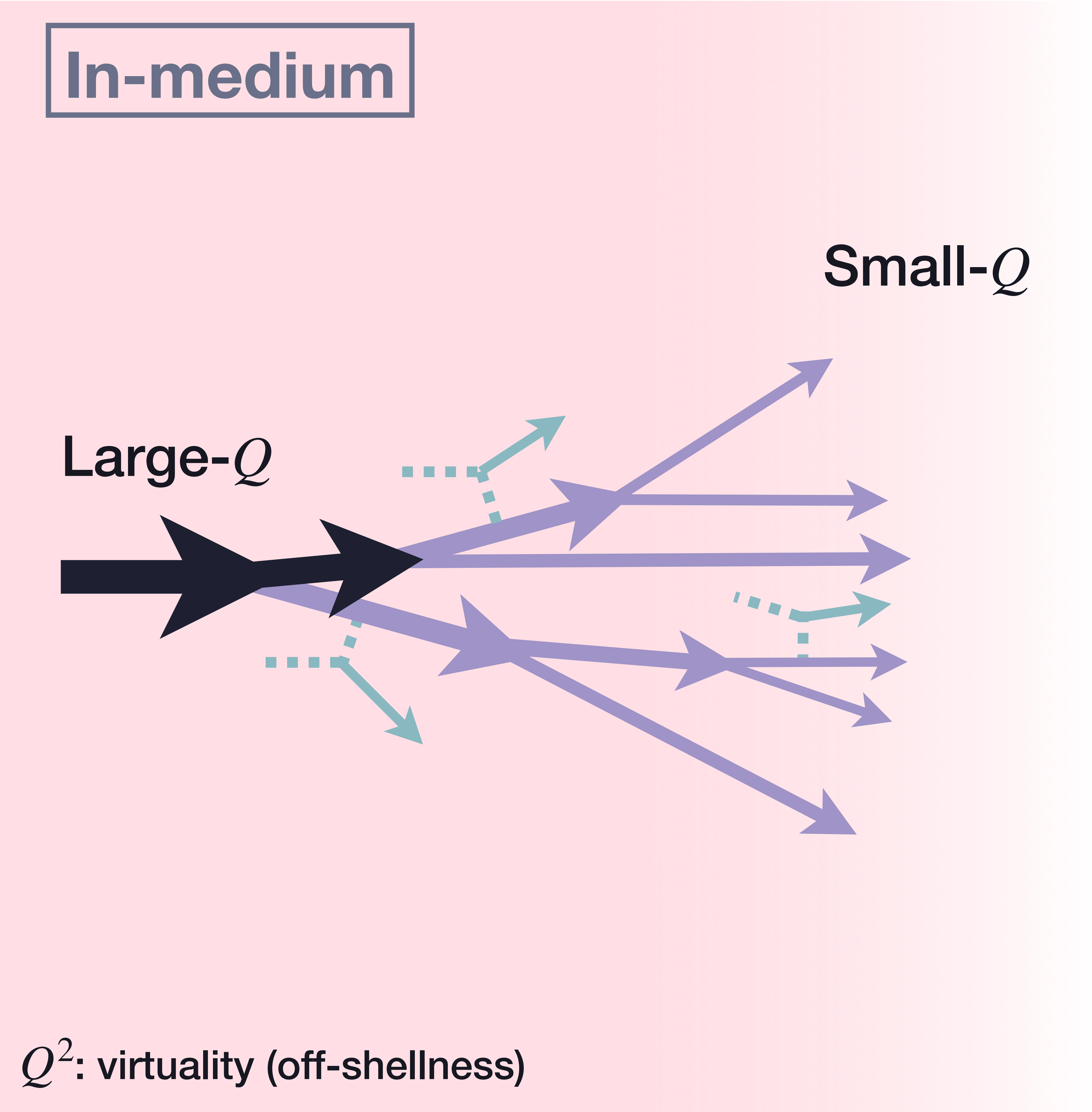
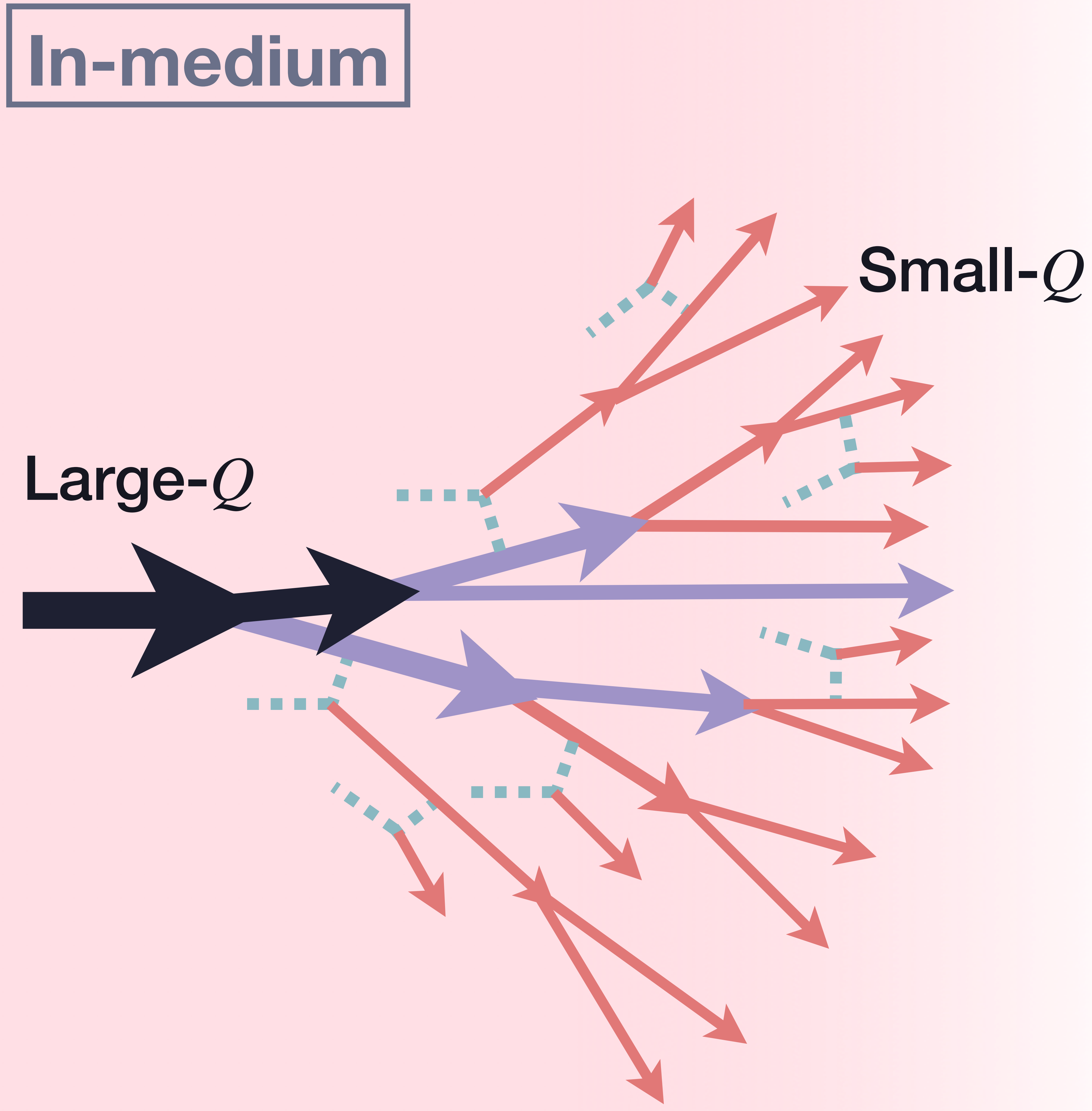


- In-vacuum: Virtuality ordered splitting
- Large-Q: Medium effect on the top of in-vacuum splitting
  (Medium modified splitting)

Multi-scale jet evolution

Majumder, Putschke (16), JETSCAPE (17)



Q^2: virtuality (off-shellness)

- In-vacuum: Virtuality ordered splitting
- Large-Q: Medium effect on the top of in-vacuum splitting
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Multi-scale jet evolution

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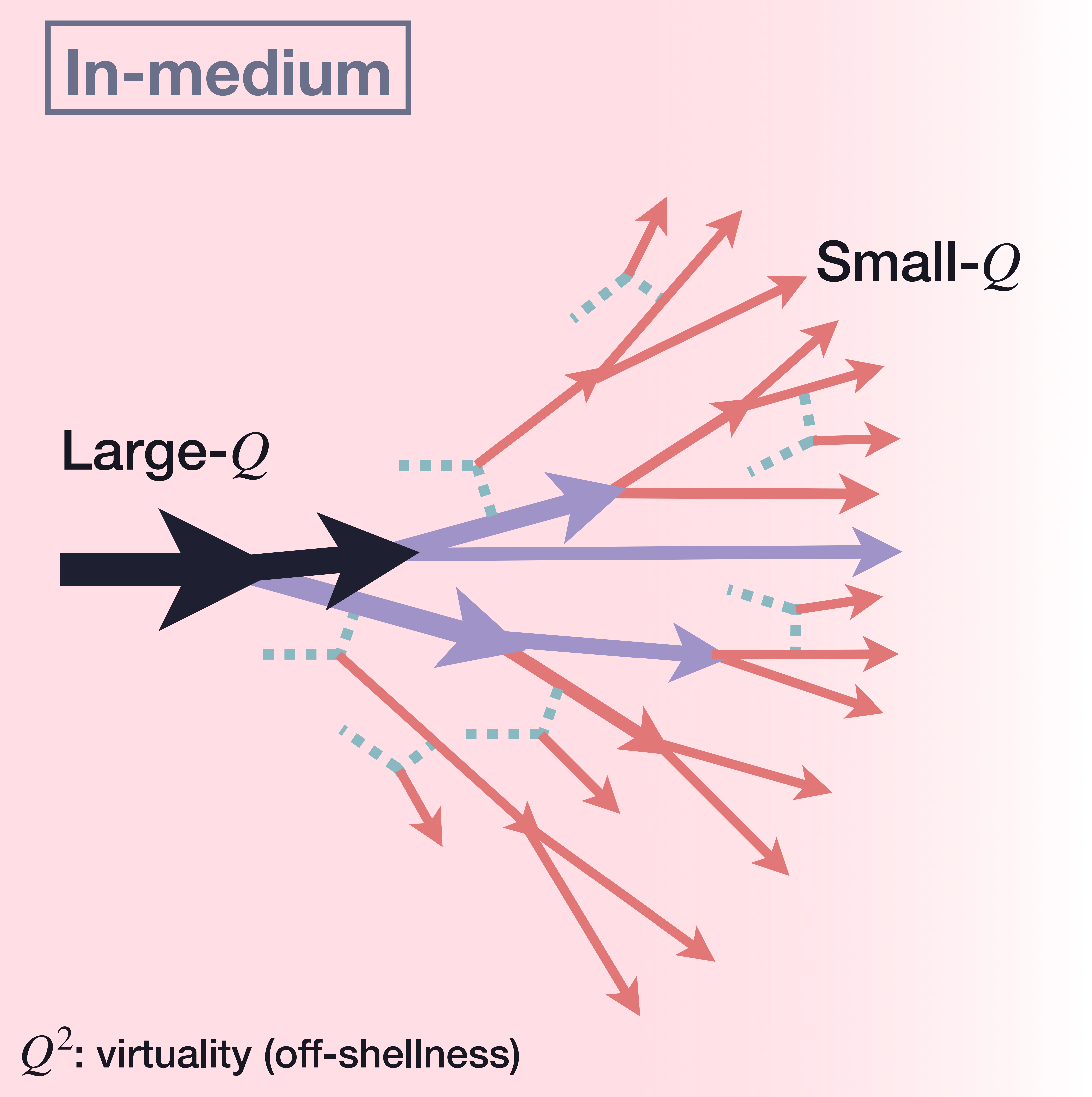
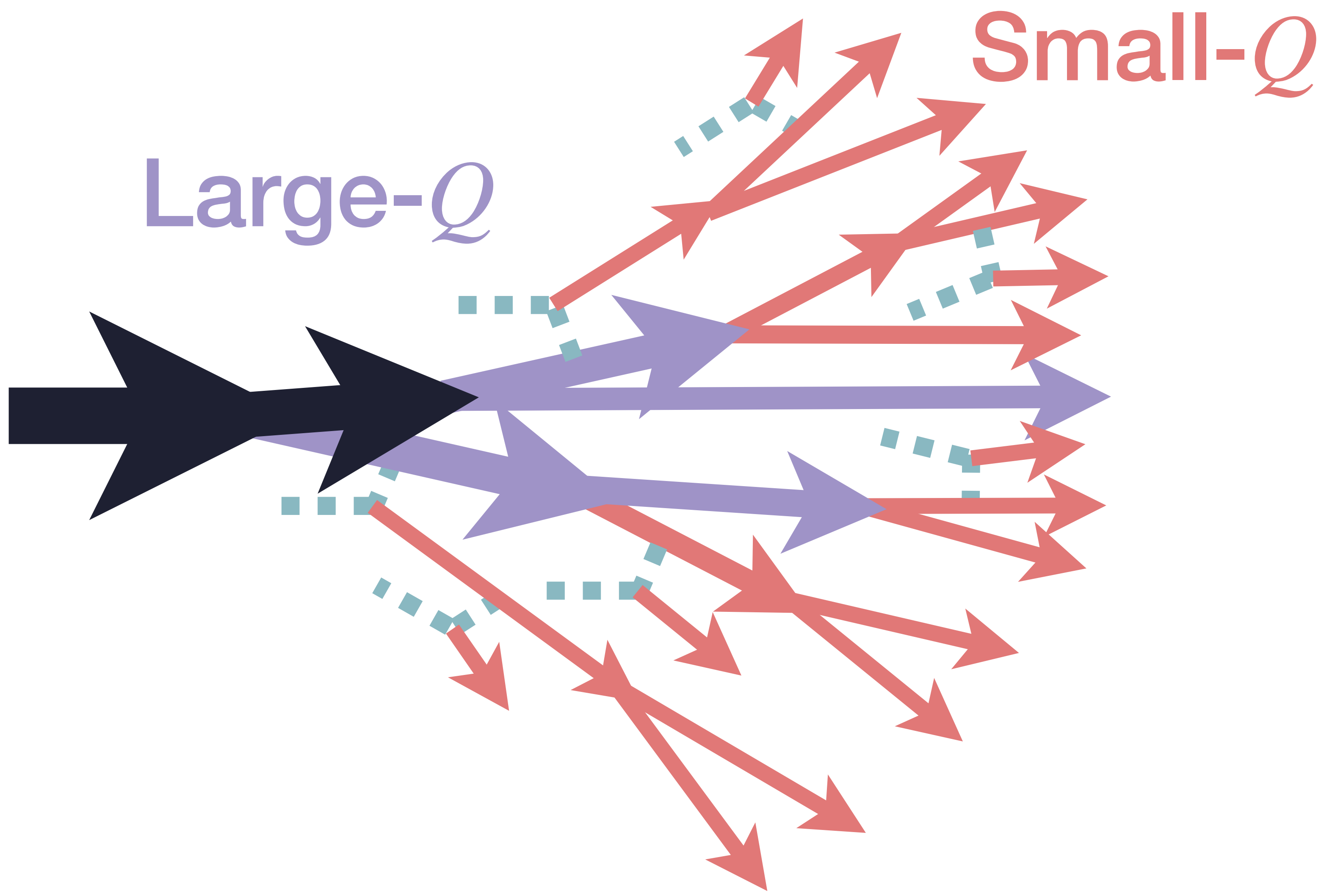


- In-vacuum: Virtuality ordered splitting
- Large-Q: Medium effect on the top of in-vacuum splitting
  (Medium modified splitting)
- Small-Q: Splitting driven almost purely by medium effect
  (Medium induced splitting)

Cannot be described by a single model
→ Combination of multiple models

Multi-stage description for jet evolution

JETSCAPE (17)

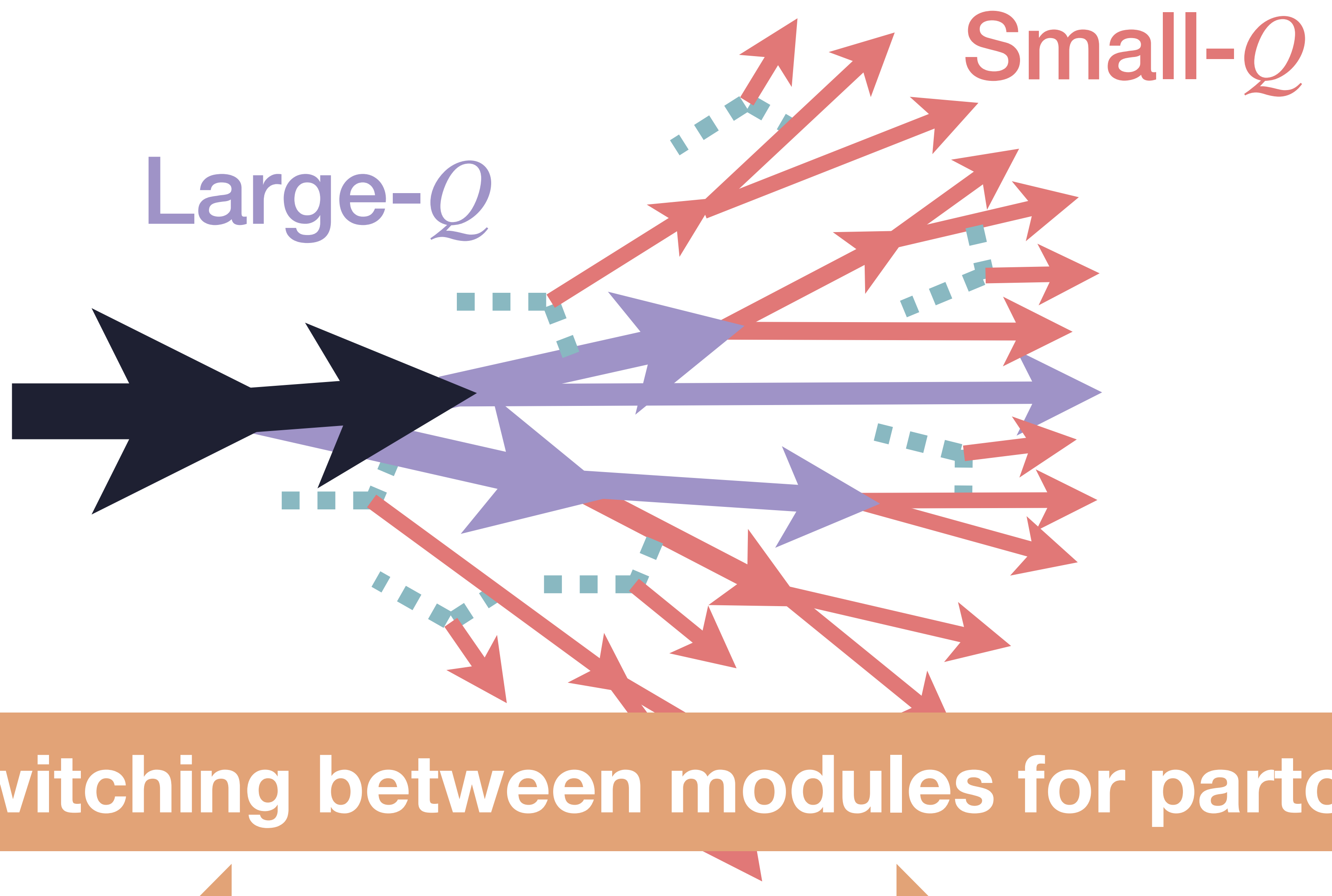


Virtuality separation scale: $Q_{\rm sw}$

Large-Q $(> Q_{\rm sw})$	Small-Q $(< Q_{\rm sw})$		
MATTER	**LBT**	**MARTINI**	**AdS/CFT**
Majumder(13), Kordell, Majumder(17), Cao, Majumder(17)	Wang, Zhu(13), Luo, et al.(15,18) Cao, et al.(16,17), He, et al.(18)	Schenke, Gale, Jeon(09), Park, Jeon, Gale(17,18)	Chesler, Rajagopal(14, 15) Pablos, et al.(15,16,17)
Virtuality ordered splitting	On-shell parton transport		Diffusion into medium
Higher Twist formalism	Higher Twist formalism	AMY formalism	$\mathcal{N} = 4$ super Yang-Mills

Multi-stage description for jet evolution

JETSCAPE (17)



…aration scale: Q_{sw}

Switching between modules for parton by parton

Large-Q ($> Q_{\mathrm{sw}}$)

Small-Q ($< Q_{\mathrm{sw}}$)

MATTER

Majumder(13), Kordell, Majumder(17), Cao, Majumder(17)

LBT

Wang, Zhu(13), Luo, et al.(15,18) Cao, et al.(16,17), He, et al.(18)

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AdS/CFT

Chesler, Rajagopal(14, 15) Pablos, et al.(15,16,17)

Virtuality ordered splitting

On-shell parton transport

Diffusion into medium

Higher Twist formalism

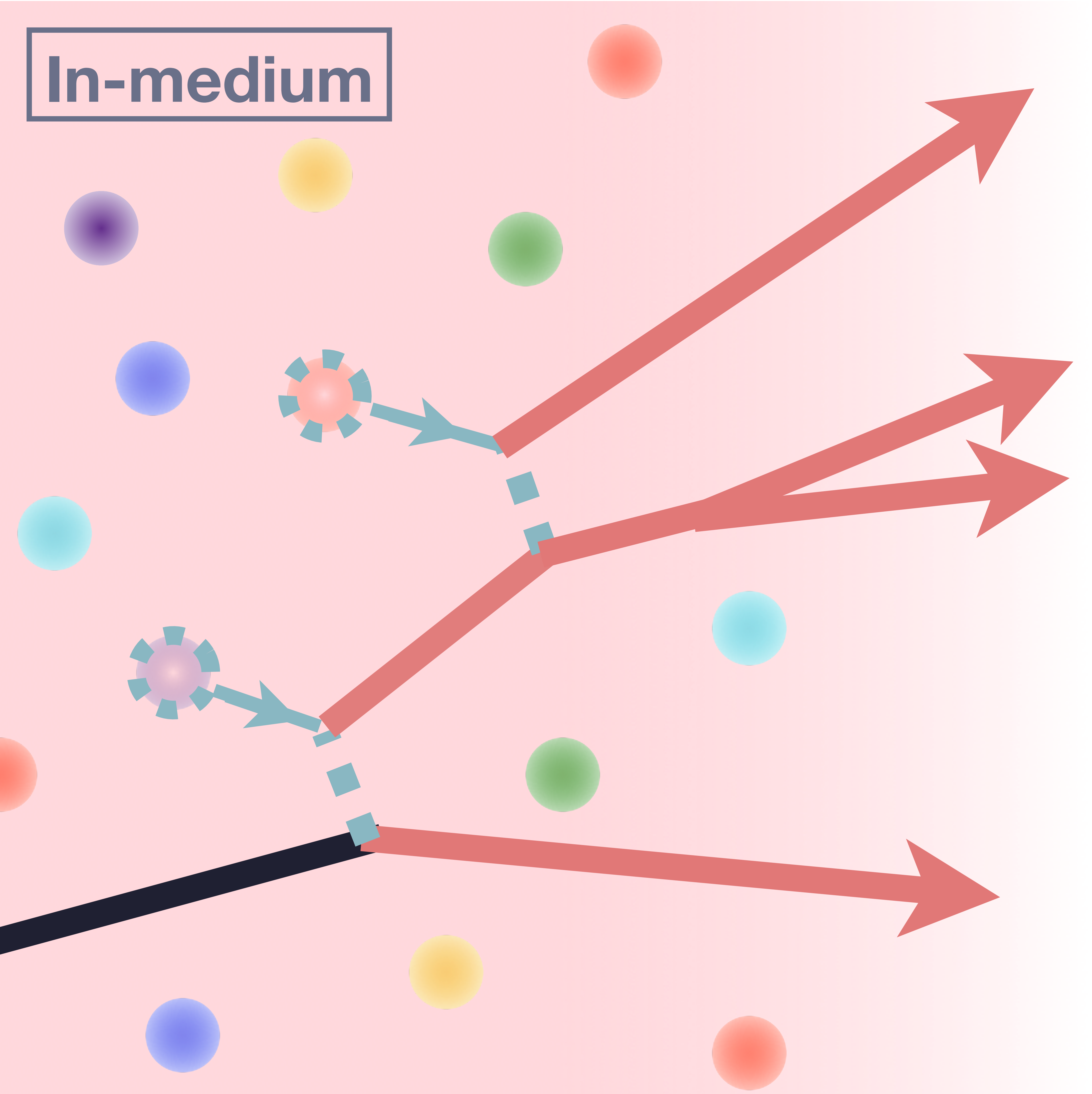
Higher Twist formalism

AMY formalism

$\mathcal{N} = 4$ super Yang-Mills

Medium response by weakly-coupled recoils

Zapp *et al.* ('13), Wang, Zhu (13), Luo, *et al.* (15,18), Park, Jeon, Gale (18), Cao, Majumder (18)



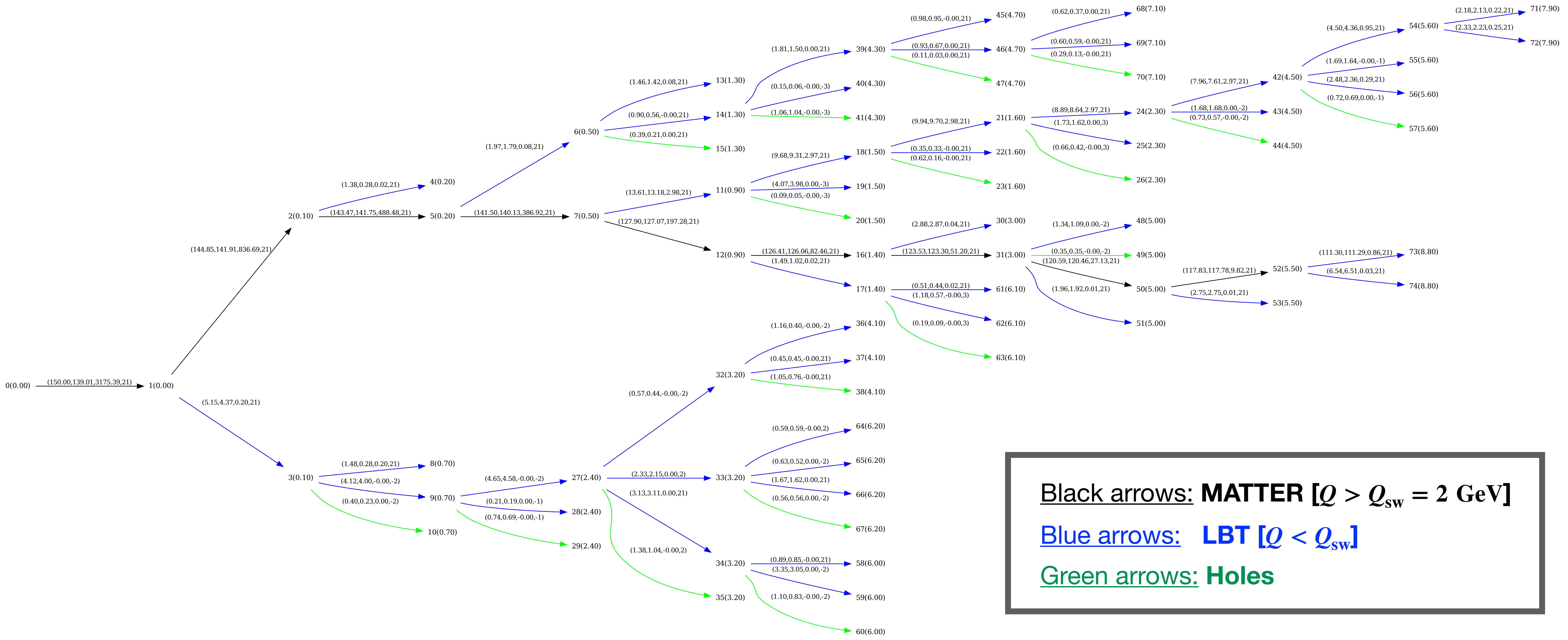
- **Recoils**
  - Medium partons kicked out by jet partons
  - Evolve as small-Q^2 partons in jet shower
  - Infinite thermalization time $(E > E_{\rm med})$
- **Hole: Picked up energy and momentum**
  - Sampled from thermal medium
  - Subtracted from final signal

$$\left.\frac{dp^\mu}{d\eta d\phi}\right|_{\rm signal} = \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\rm jet\ shower} - \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\rm picked{-}up}$$

Multi-stage description for jet evolution

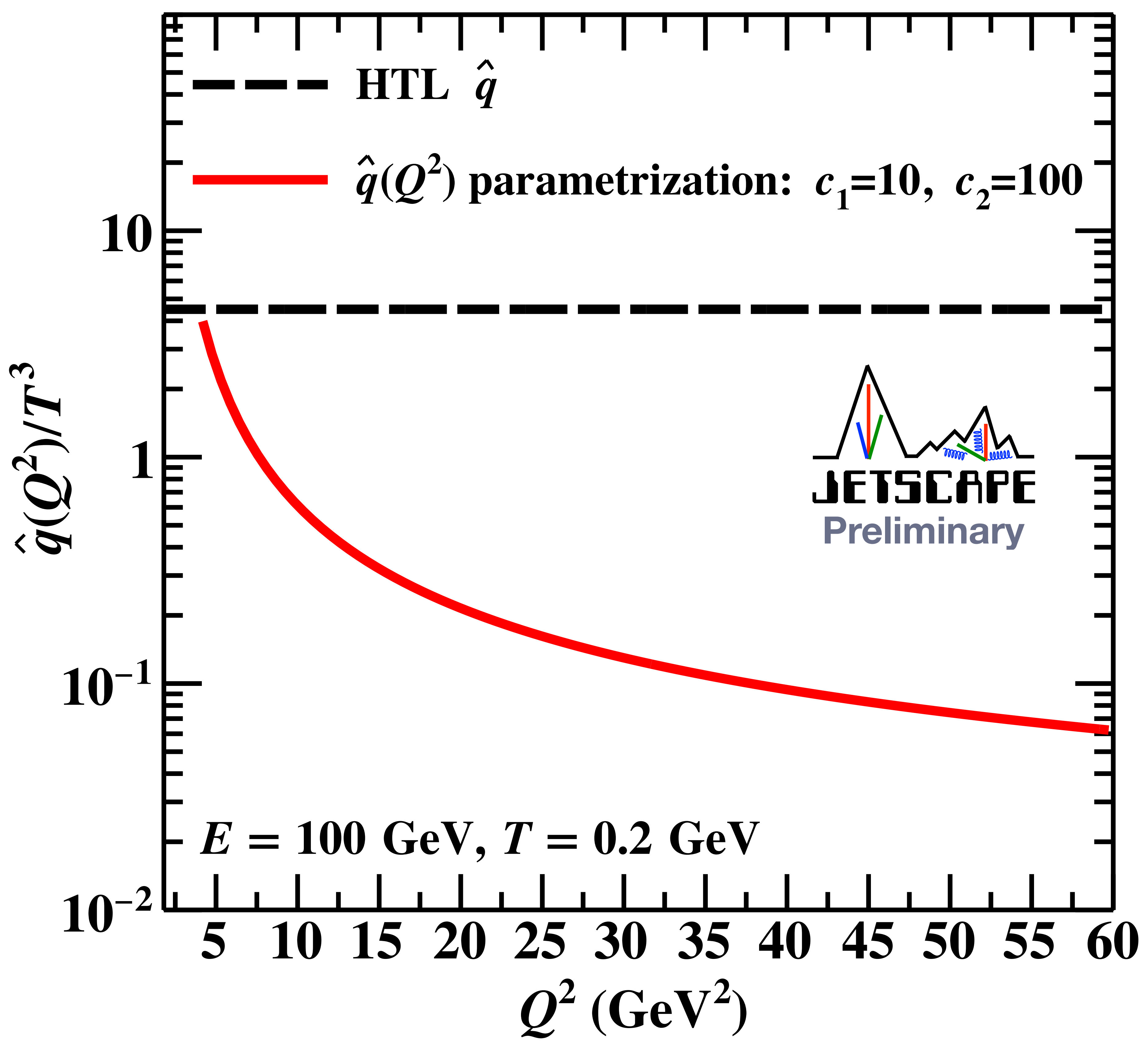
JETSCAPE (17)

- **Graph of parton shower generated by JETSCAPE**

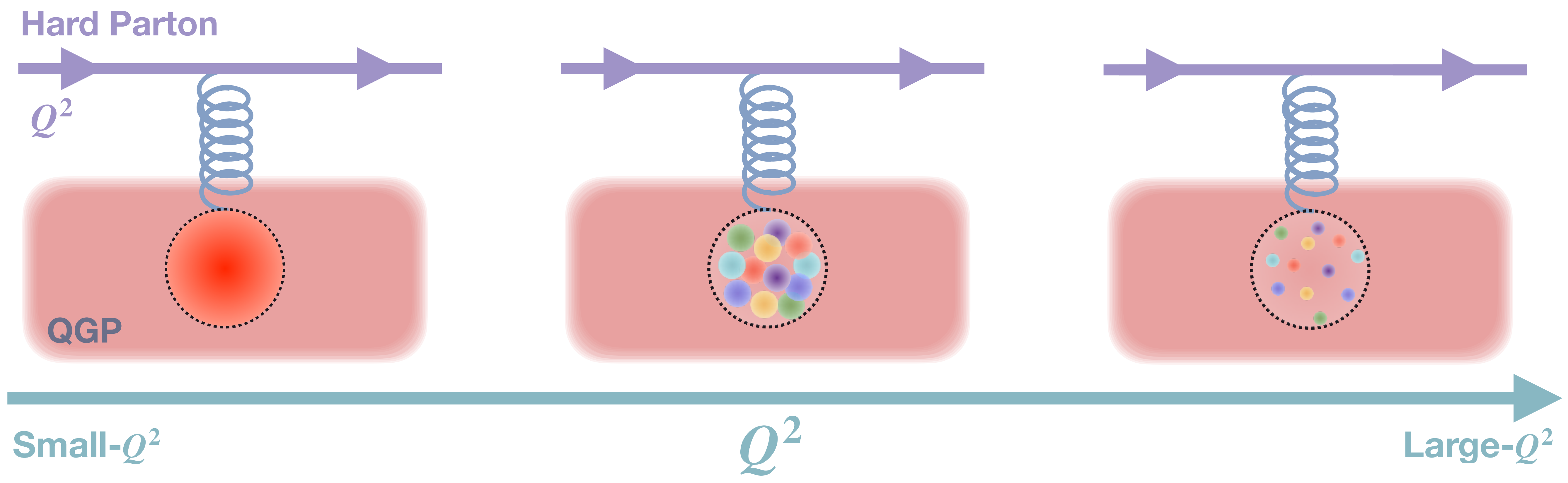


Recent Update

JERSCAPE (in preperation)



- **Virtuality dependence in jet quenching parameter $\hat{q}$**
  - Based on scale evolution of QGP constituent distribution
    Kumar, Majumder, Shen (20)

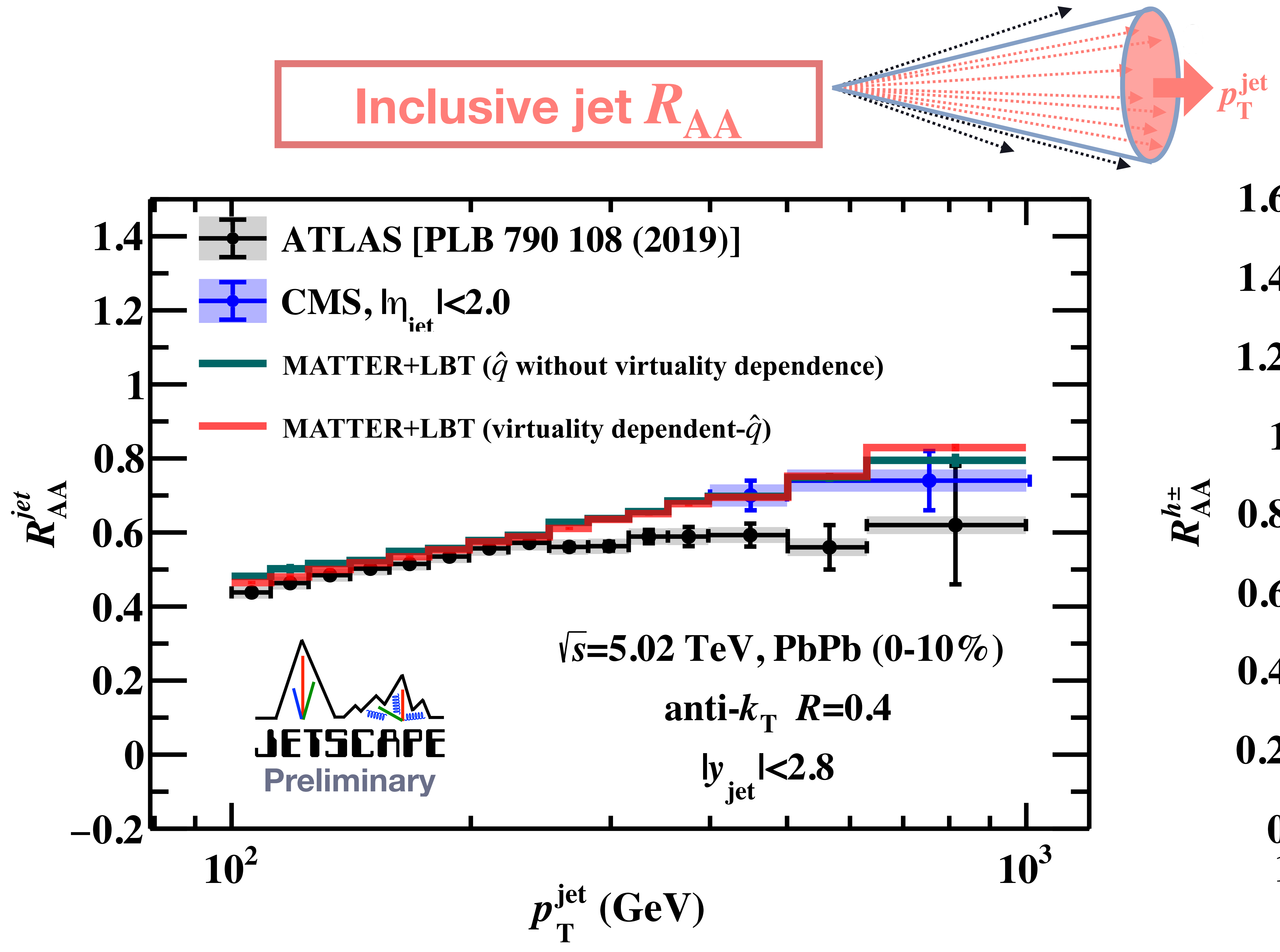


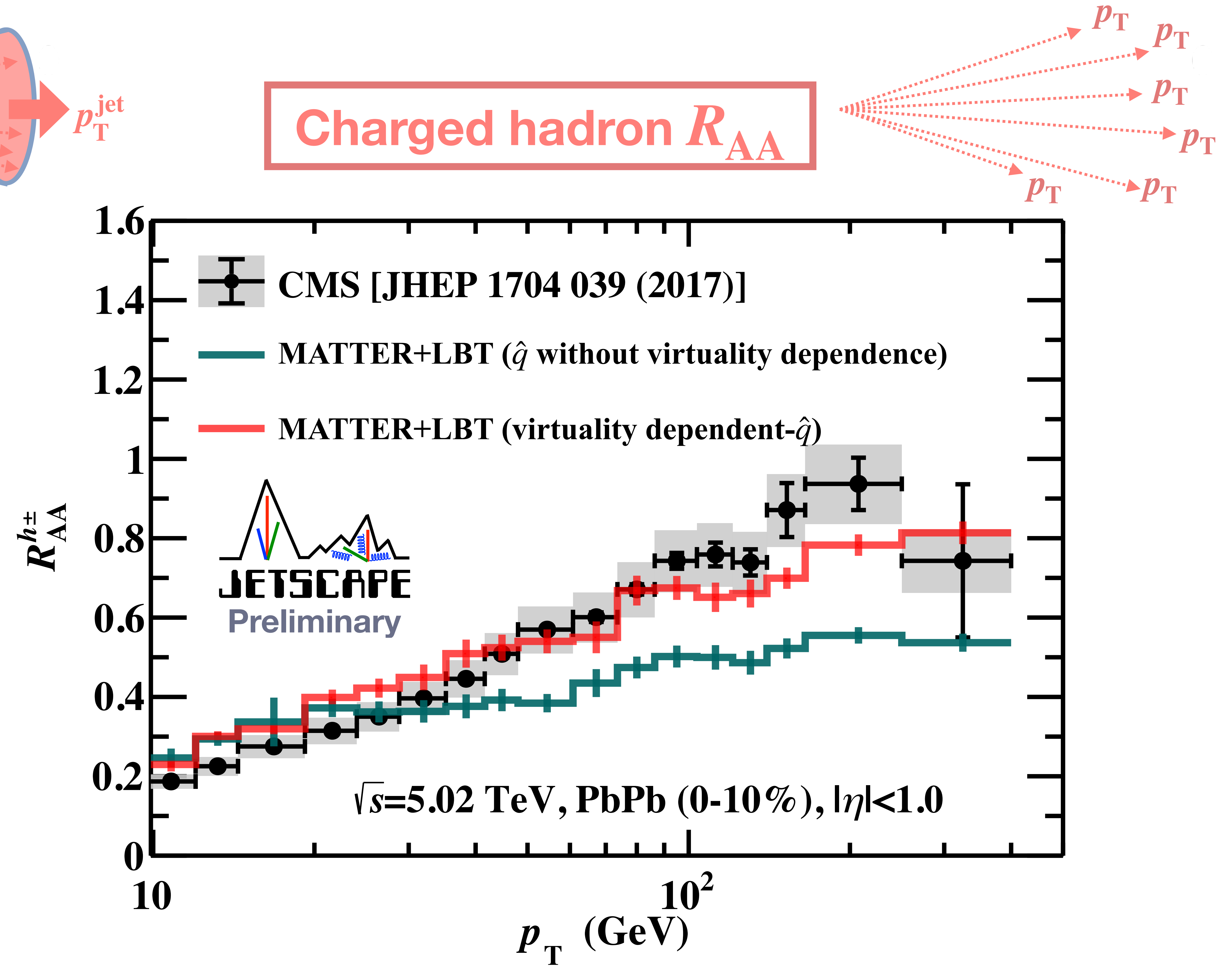
  - Less interaction for larger virtuality partons
  - Extend the model applicability to further broader scale

Jet and high-p_T particle energy loss

JERSCAPE (in preperation)

- **Jet and high-p_T particle energy loss for PbPb@5.02 TeV**



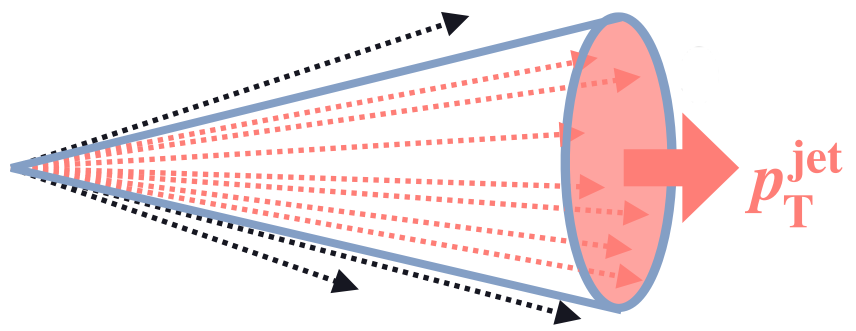


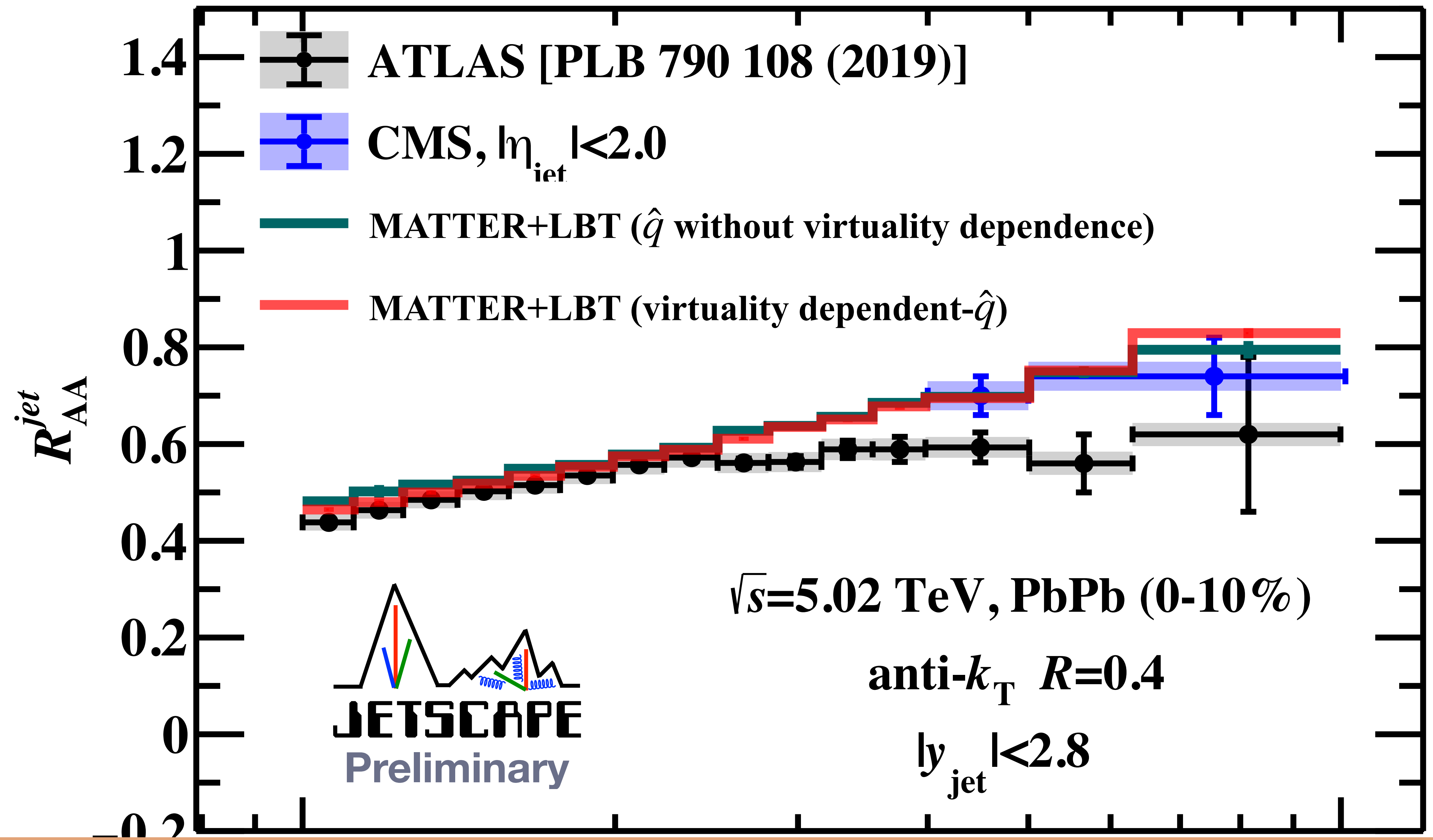
Jet and high-p_T particle energy loss

JERSCAPE (in preperation)

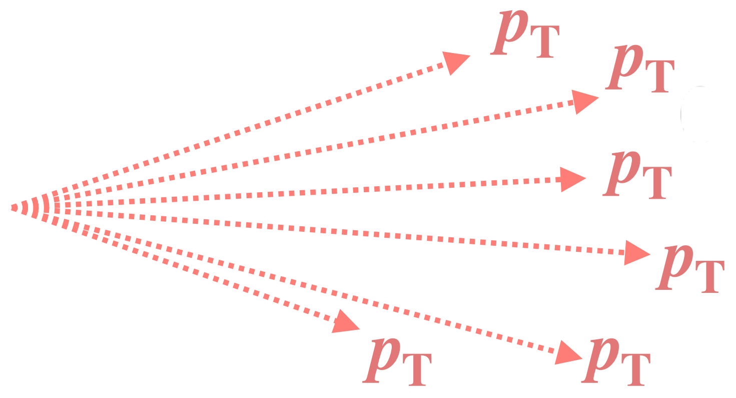
- Jet and high-p_T particle energy loss for PbPb@5.02 TeV

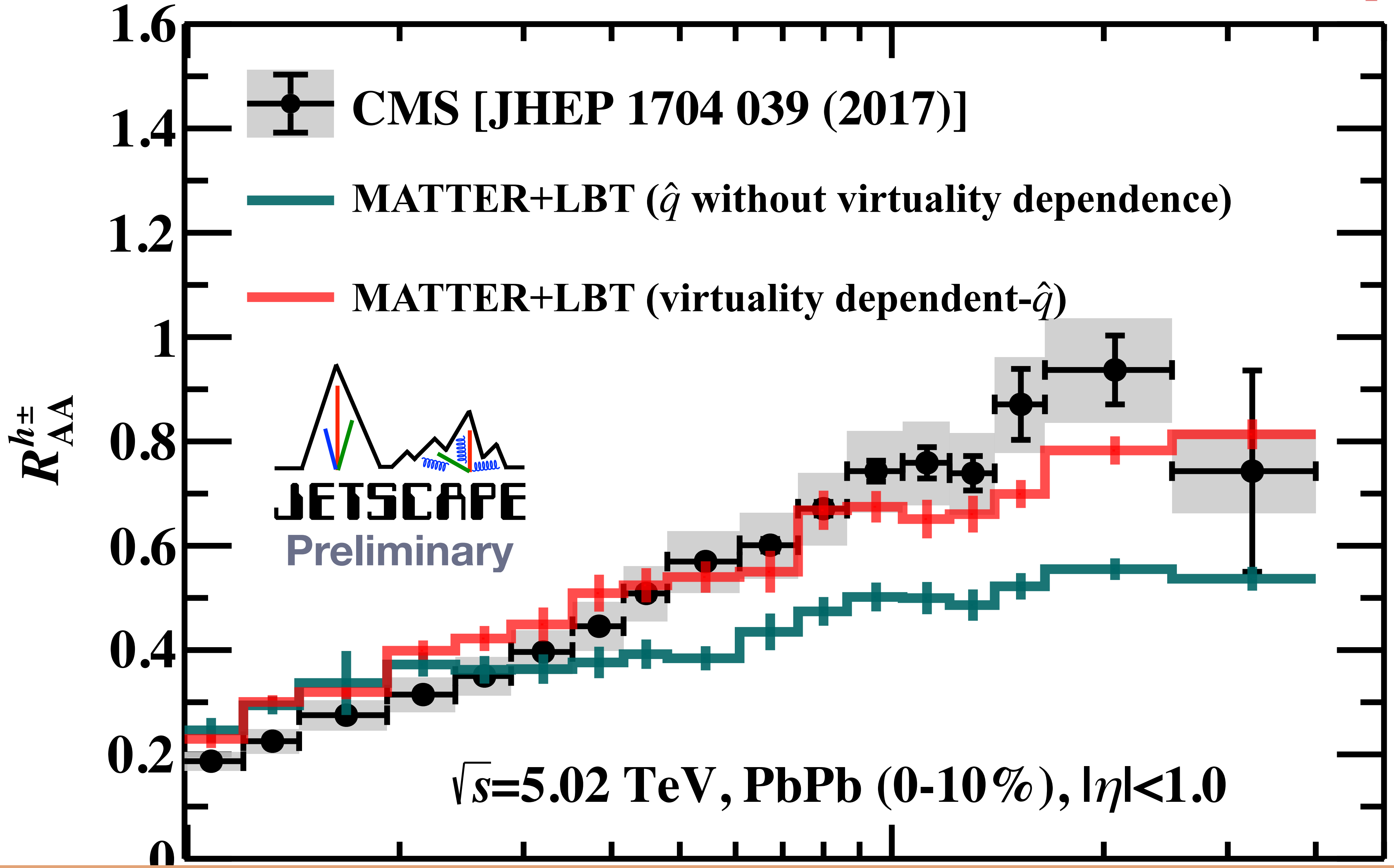
Inclusive jet R_{AA}





Charged hadron R_{AA}





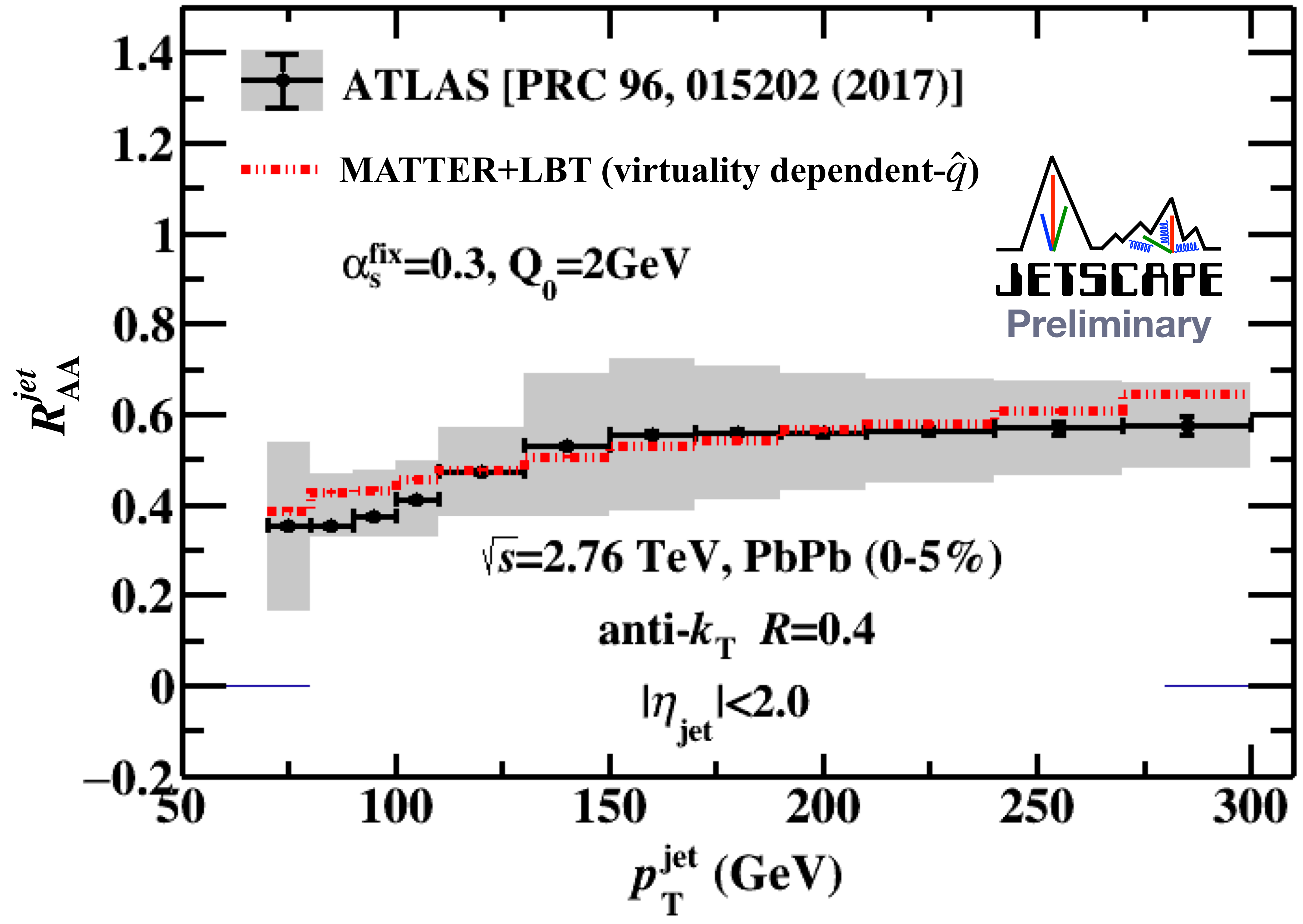
- Very first success in simultaneous description of data for jet and hadrons
- Significant effect of virtuality dependence in energy loss

Jet and high-p_T particle energy loss

- **Jet and high-p_T particle energy loss for PbPb@2.76 TeV**

The same parameter set as 5.02 TeV is used

Inclusive jet R_{AA}



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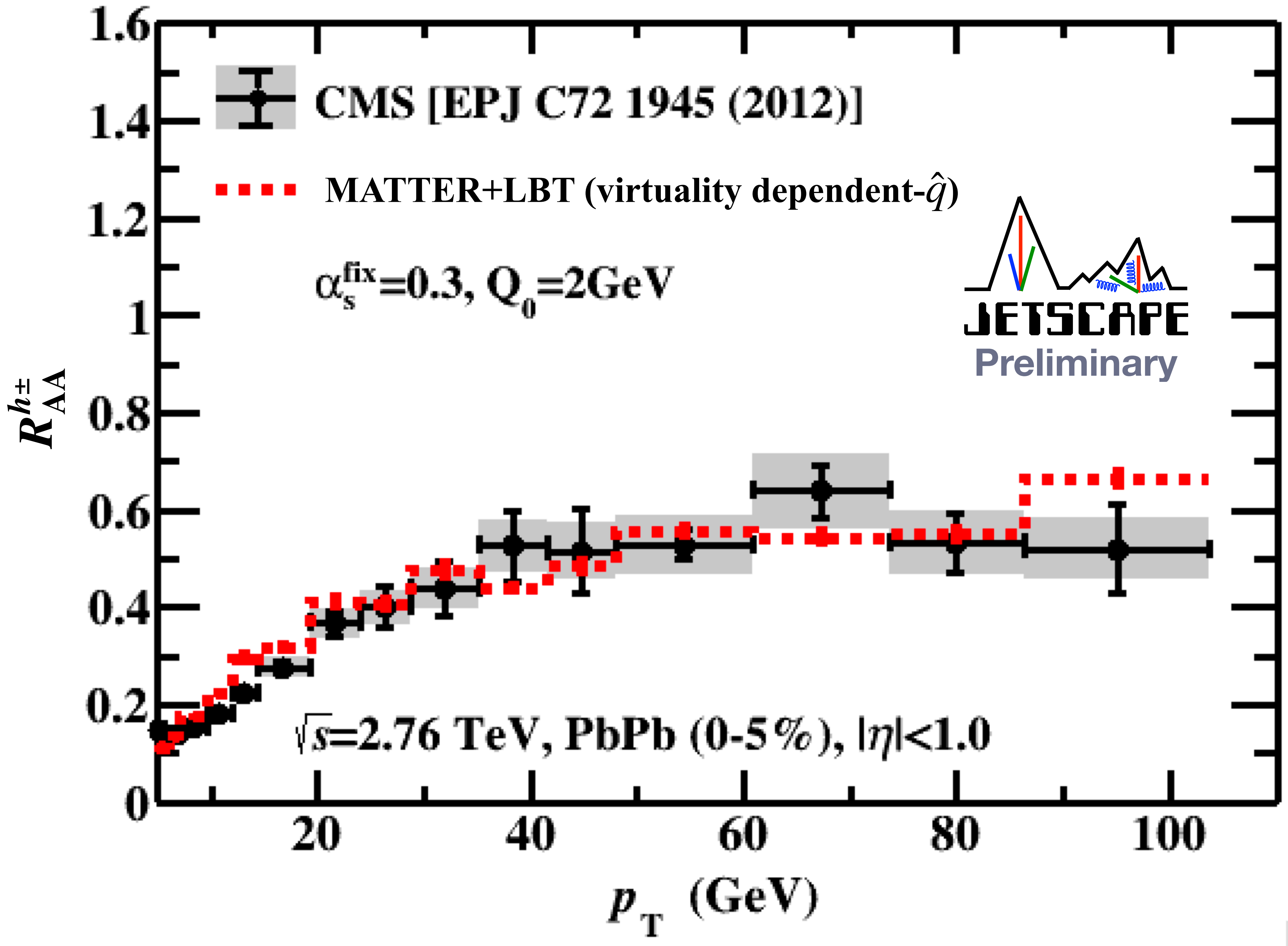


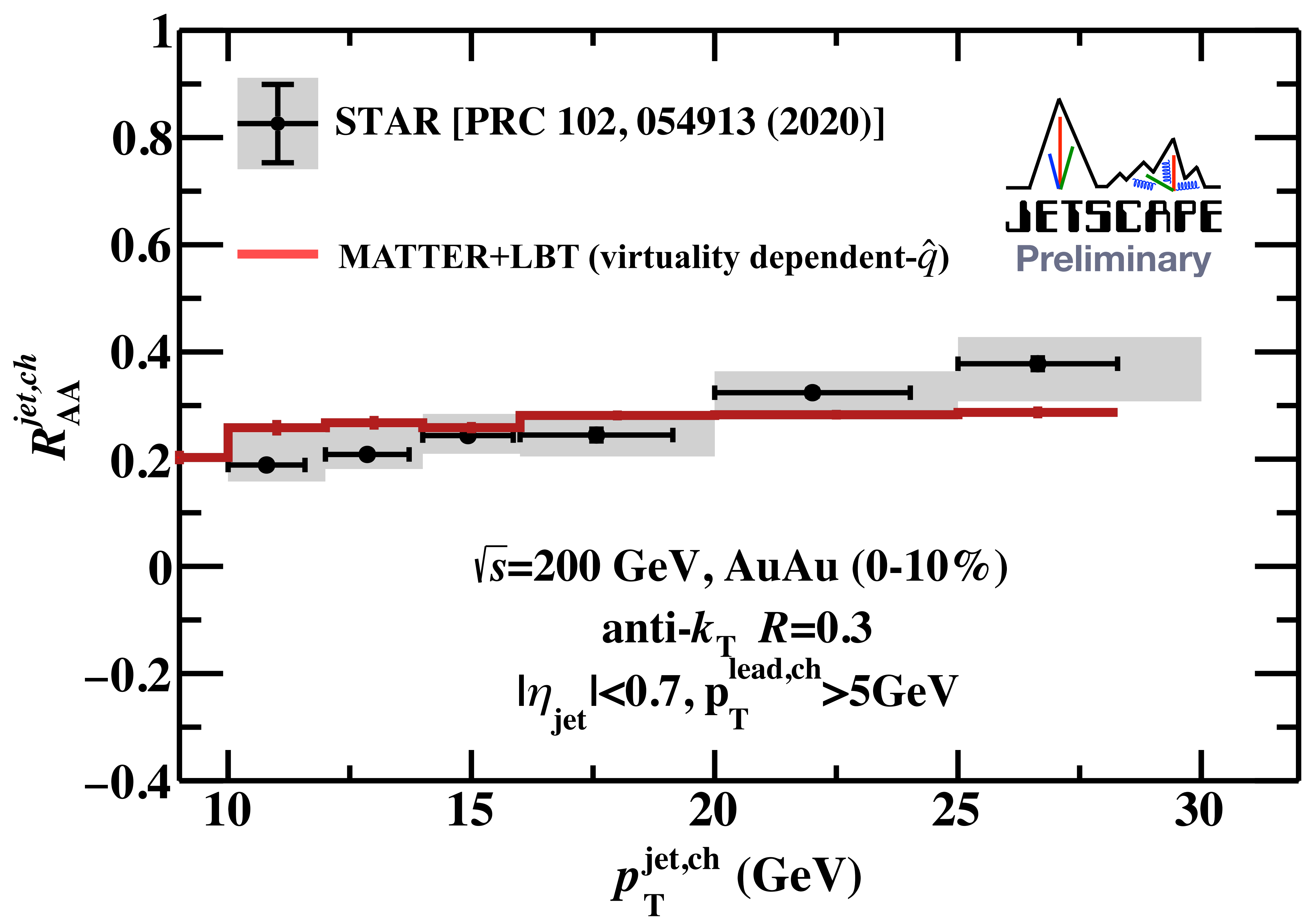
Jet and high-p_T particle energy loss

JERSCAPE (in preperation)

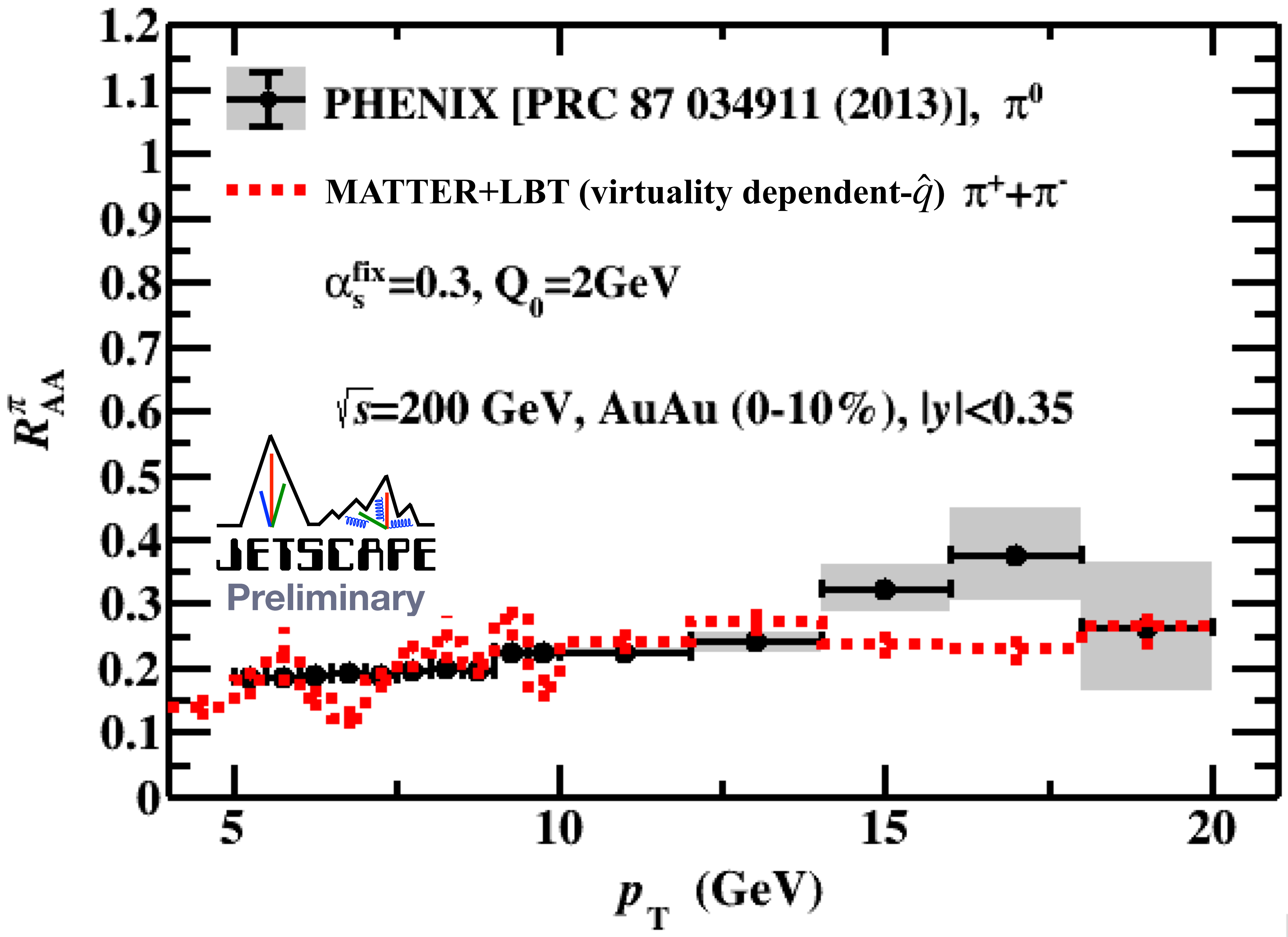
- Jet and high-p_T particle energy loss for AuAu@200 GeV

The same parameter set as 5.02 TeV is used

Charged jet R_{AA}



Pion R_{AA}



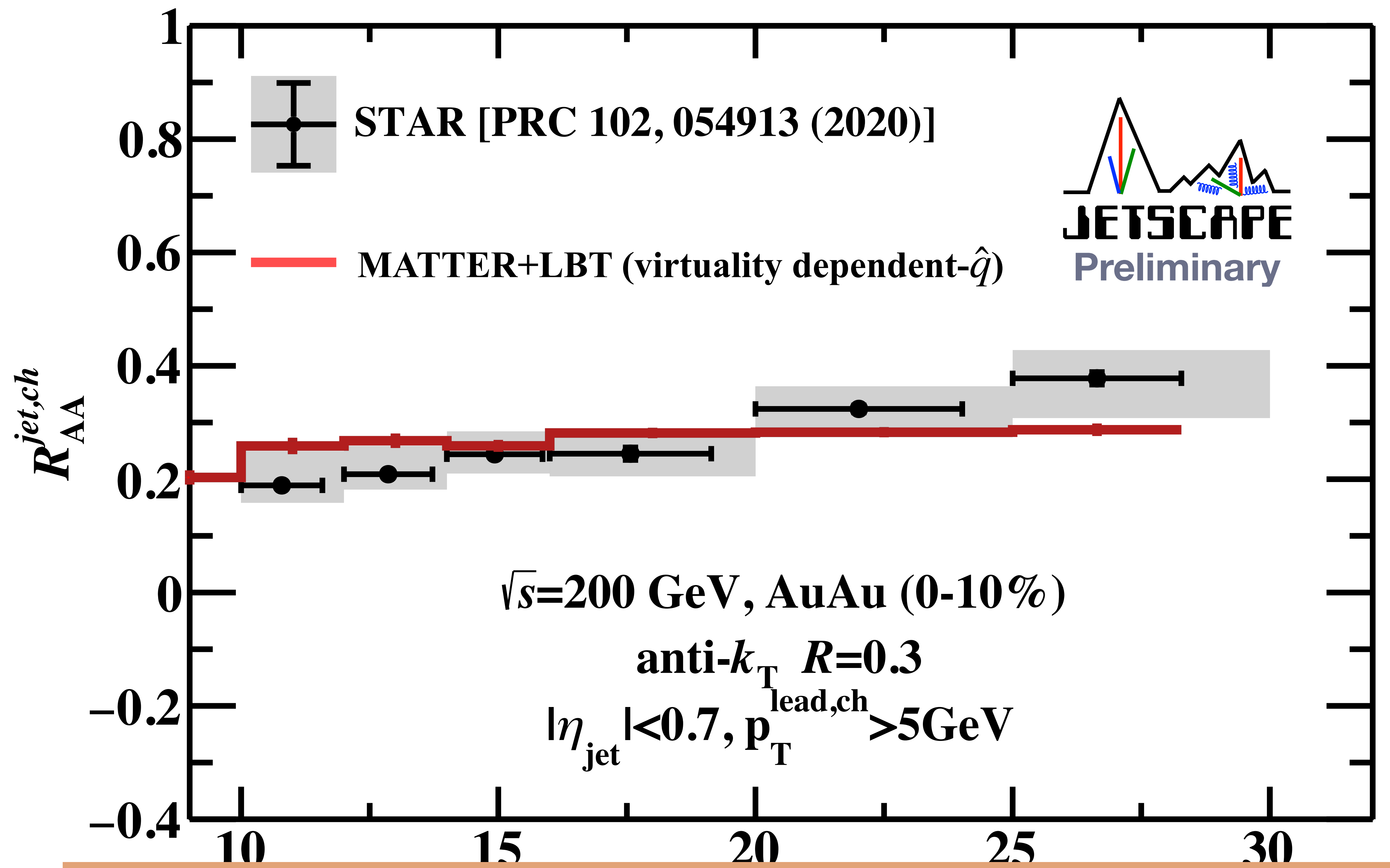
Jet and high-p_T particle energy loss

JERSCAPE (in preperation)

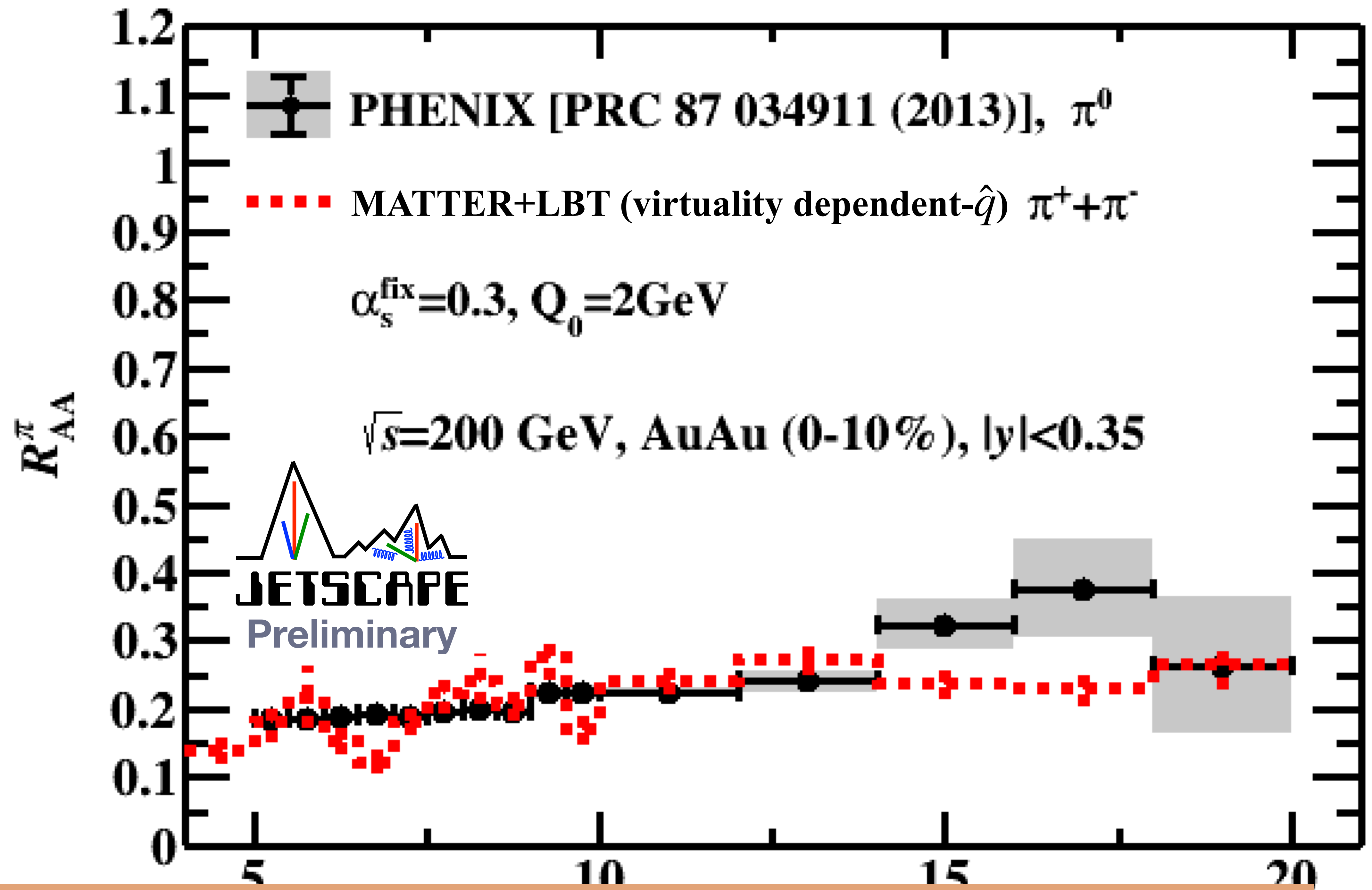
- Jet and high-p_T particle energy loss for AuAu@200 GeV

The same parameter set as 5.02 TeV is used

Charged jet R_{AA}



Pion R_{AA}



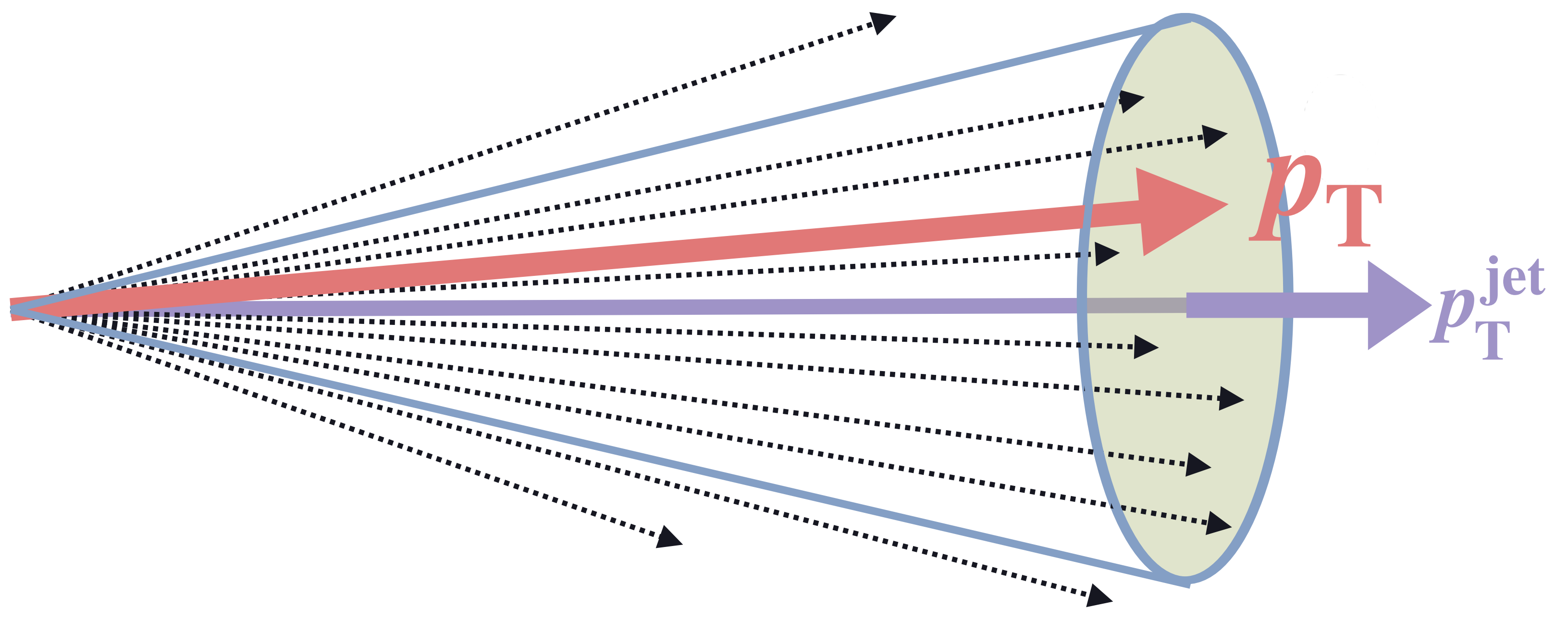
- Simultaneous description of different $\sqrt{s_{NN}}$ with the same parameter set

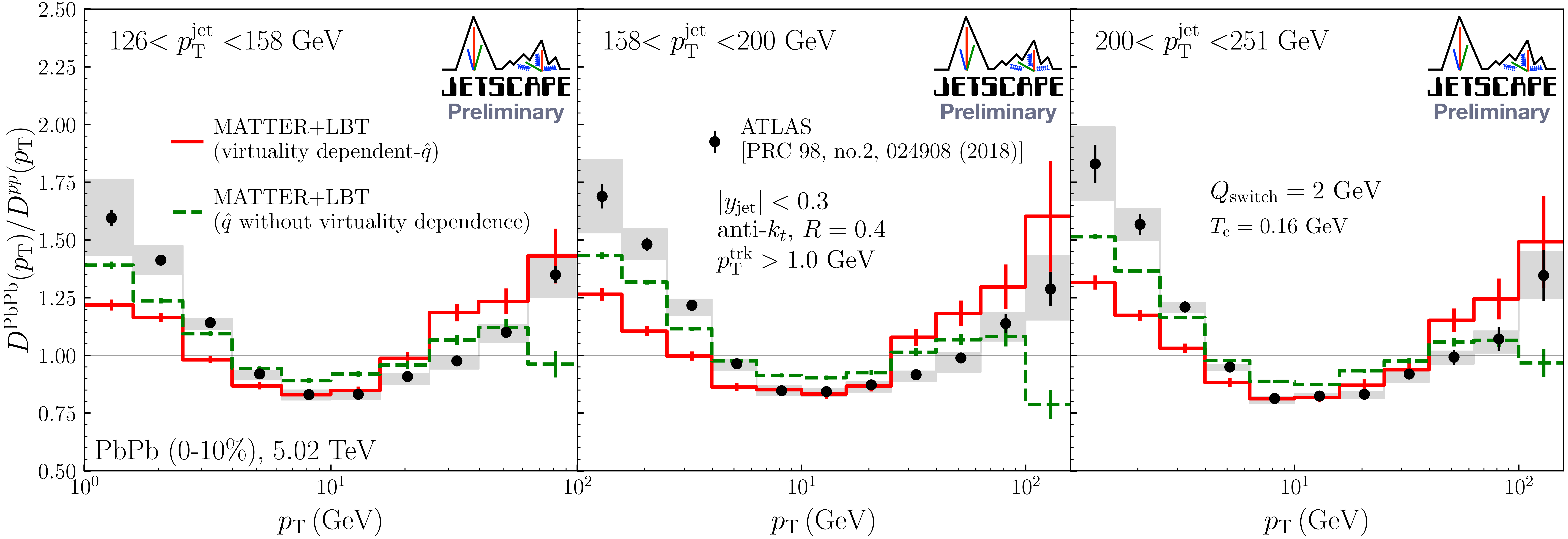
Jet substructure

JERSCAPE (in preperation)

- **Jet Fragmentation Function**
  - p_T distribution of charged particle inside jets

$$D(p_T) = \frac{1}{N_{\mathrm{jet}}} \sum_{\mathrm{jet}} \frac{dN_{\mathrm{ch}}}{dp_T}\Bigg|_{\mathrm{in\ jet}}$$





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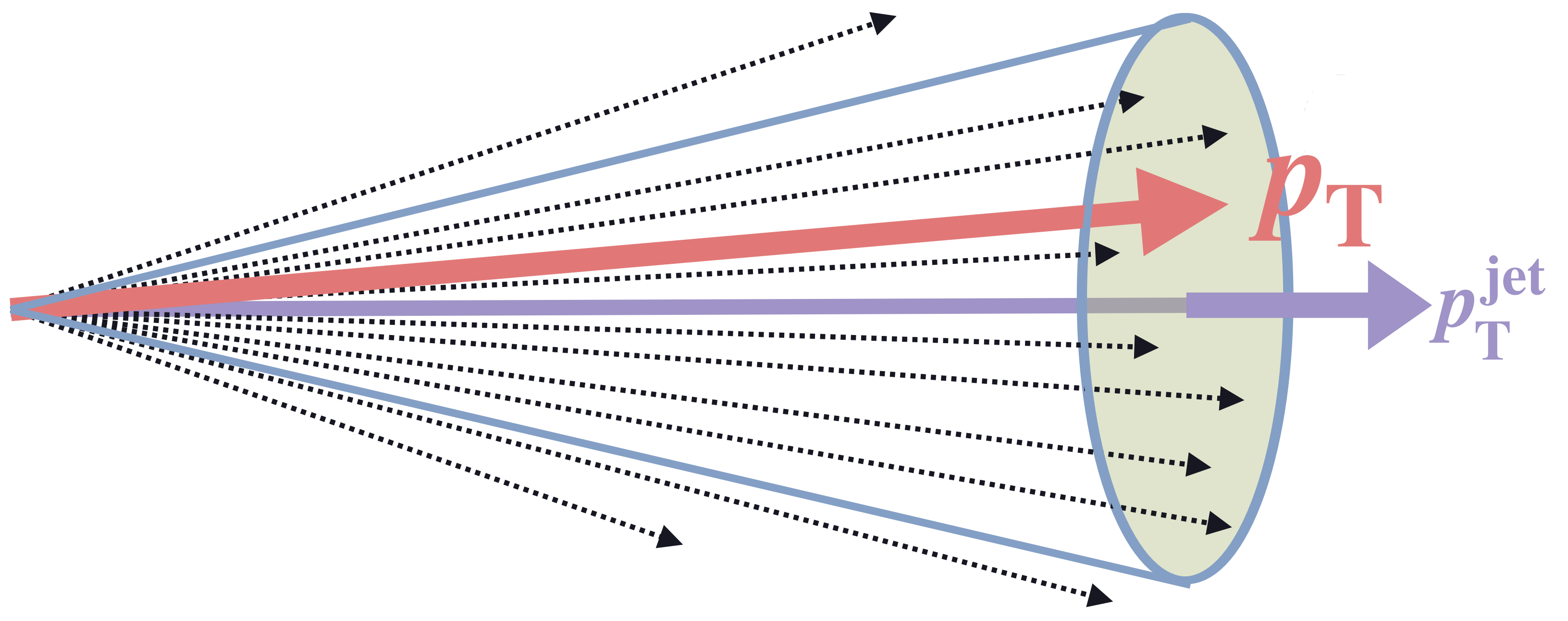

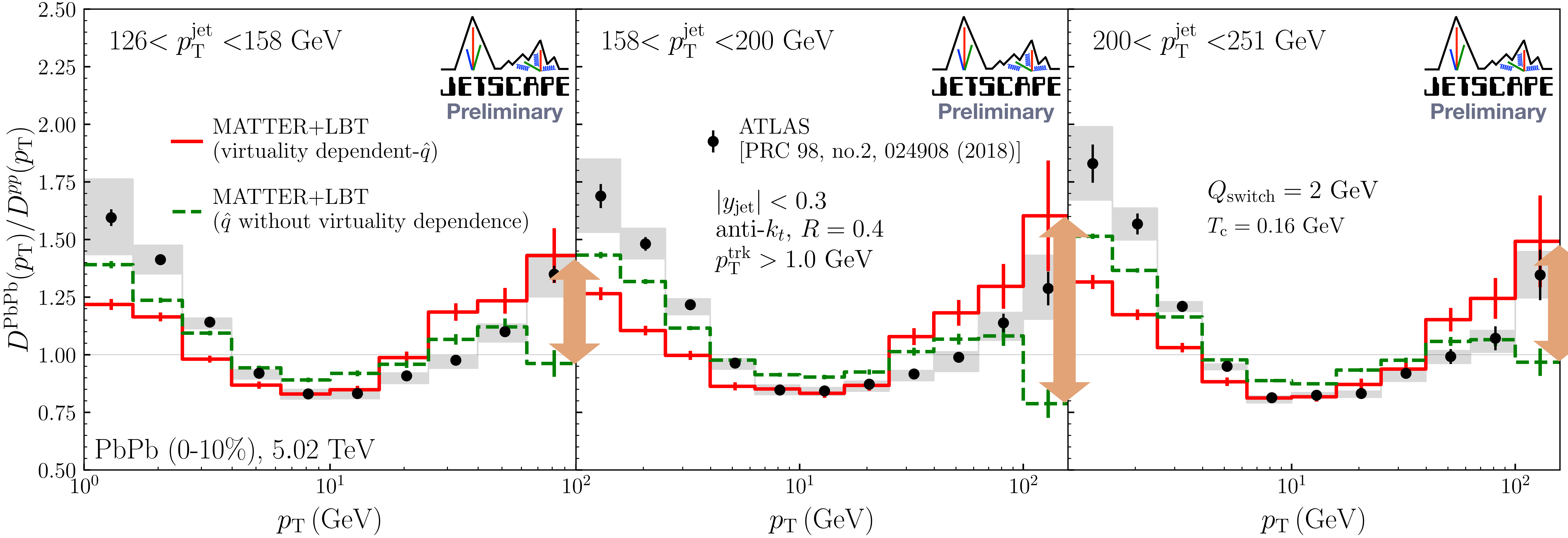

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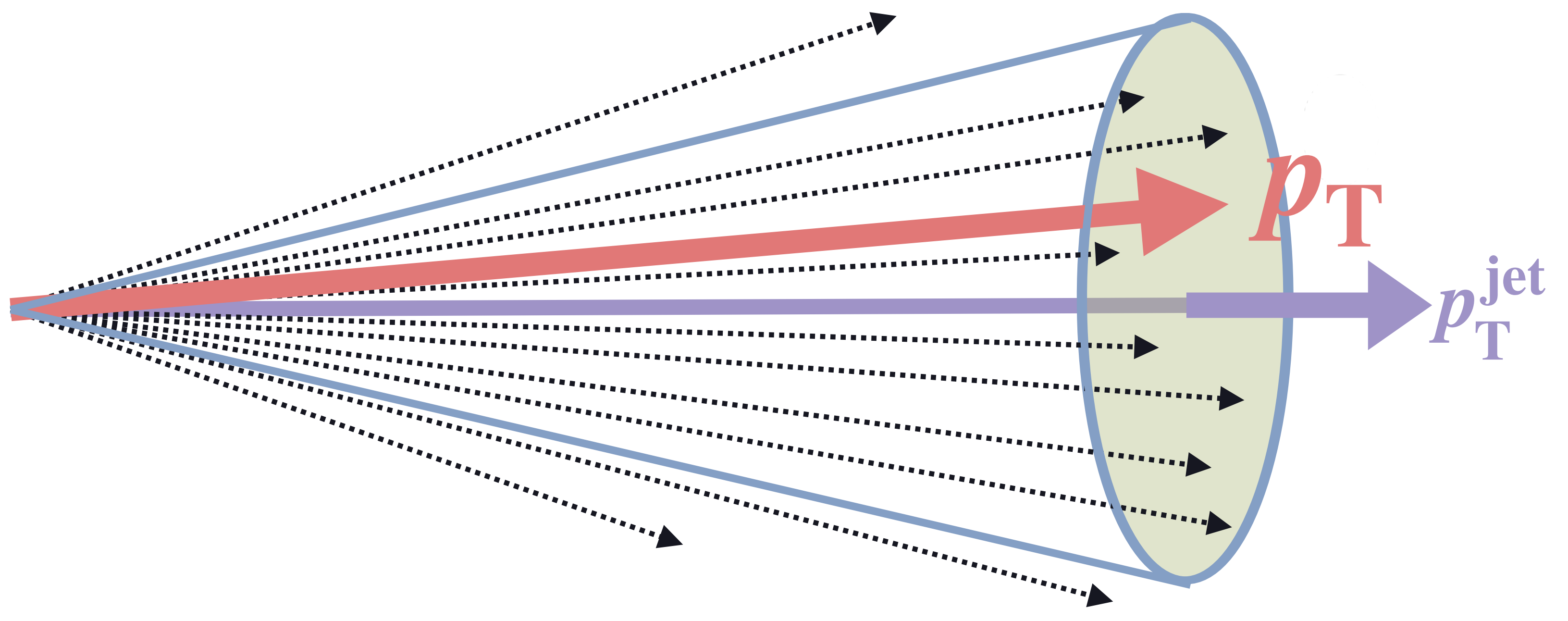
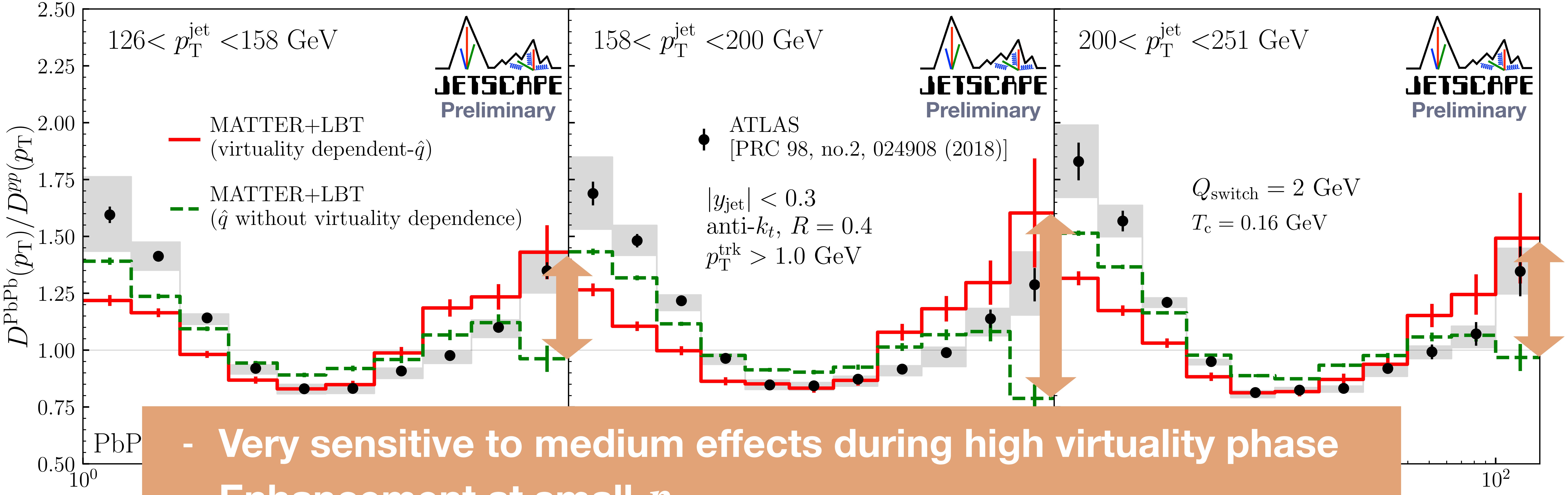




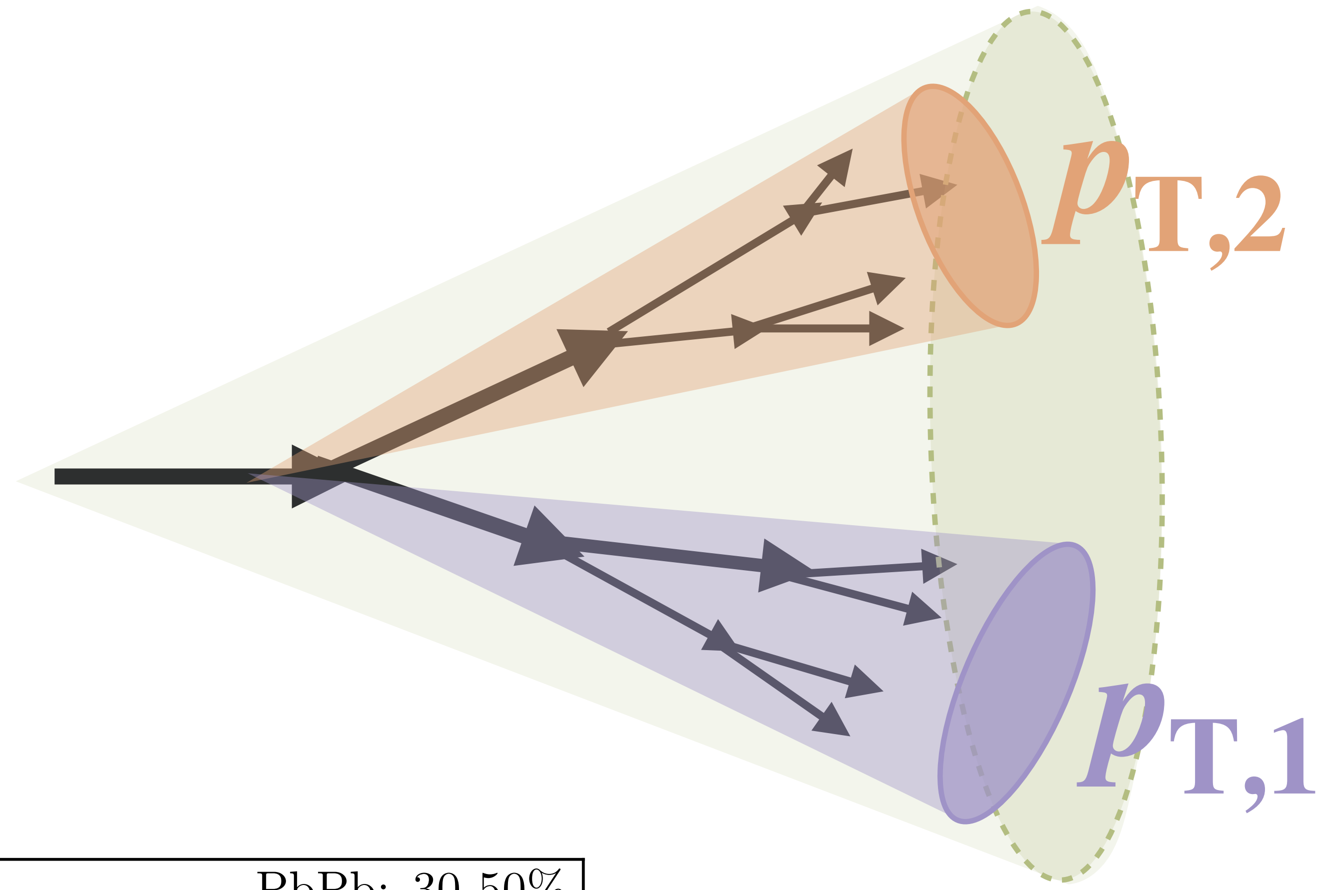
- **Very sensitive to medium effects during high virtuality phase**
- **Enhancement at small-p_T**

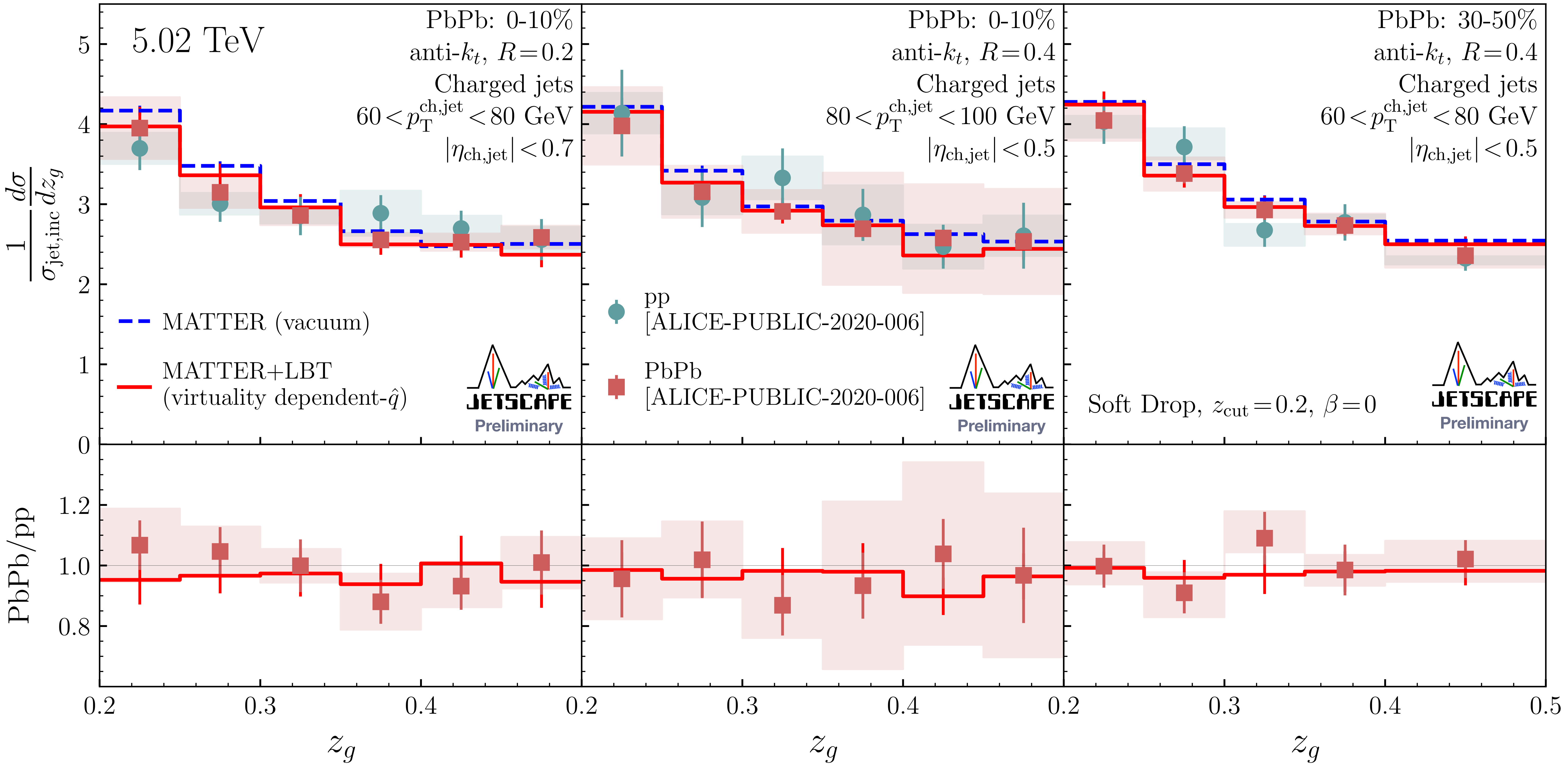
Jet substructure

JERSCAPE (in preperation)

- **Jet splitting function**
  - Momentum fraction in the hardest splitting of jet (z_g)

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$





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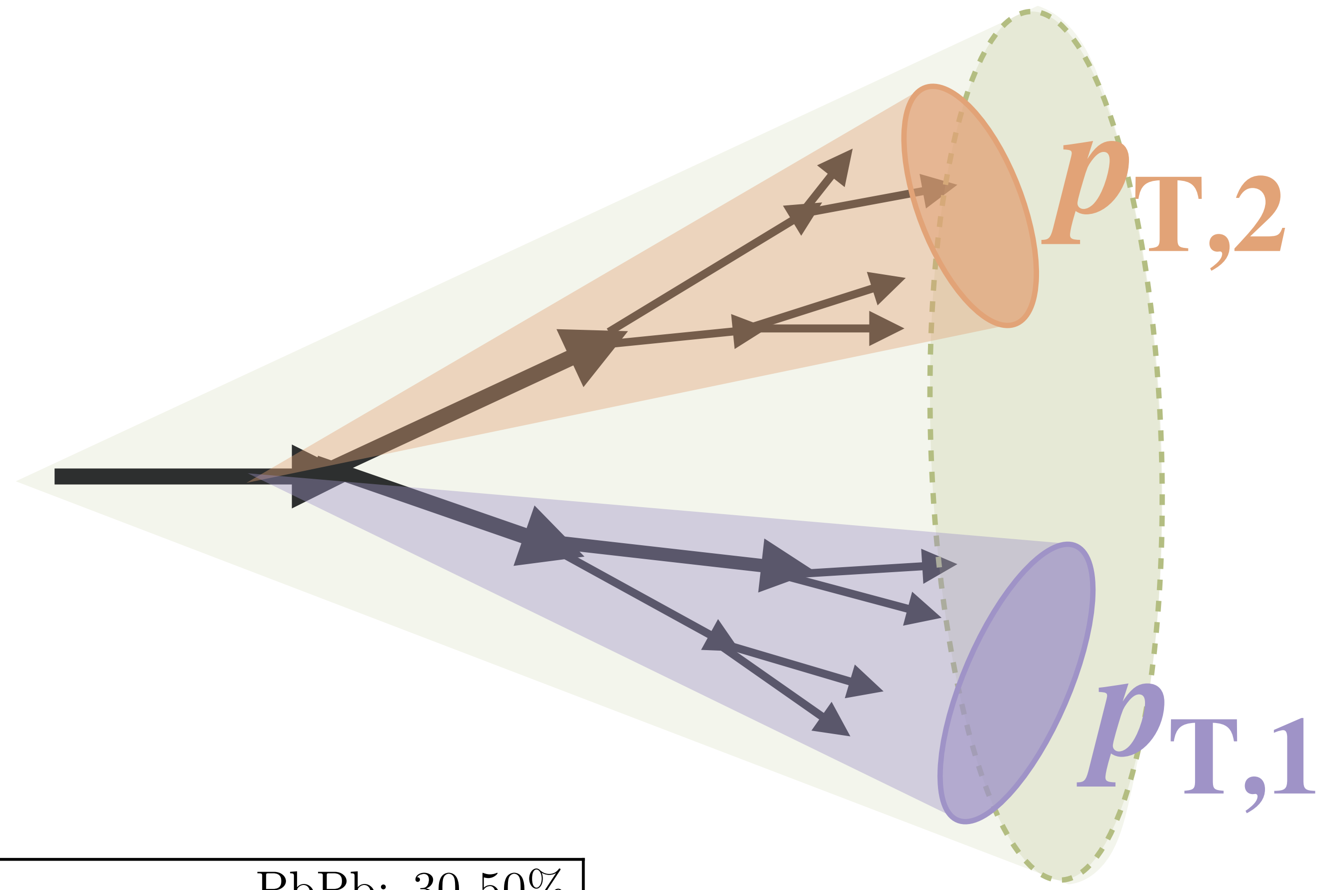
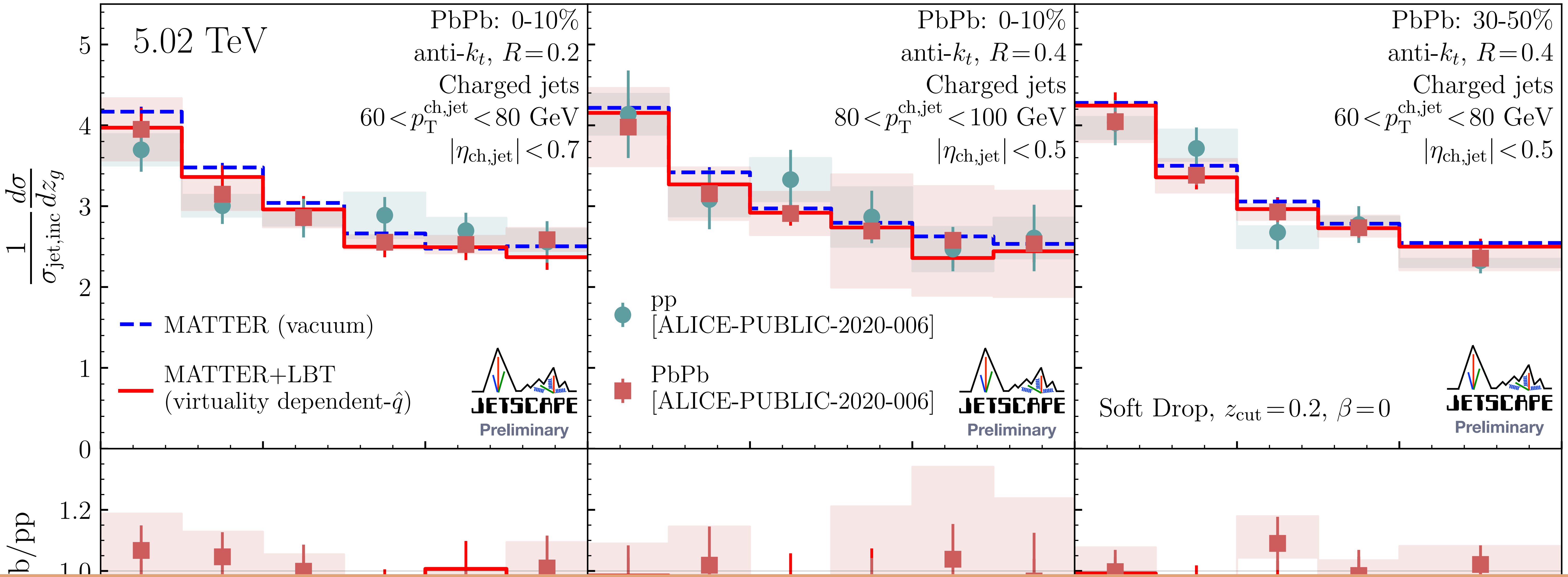
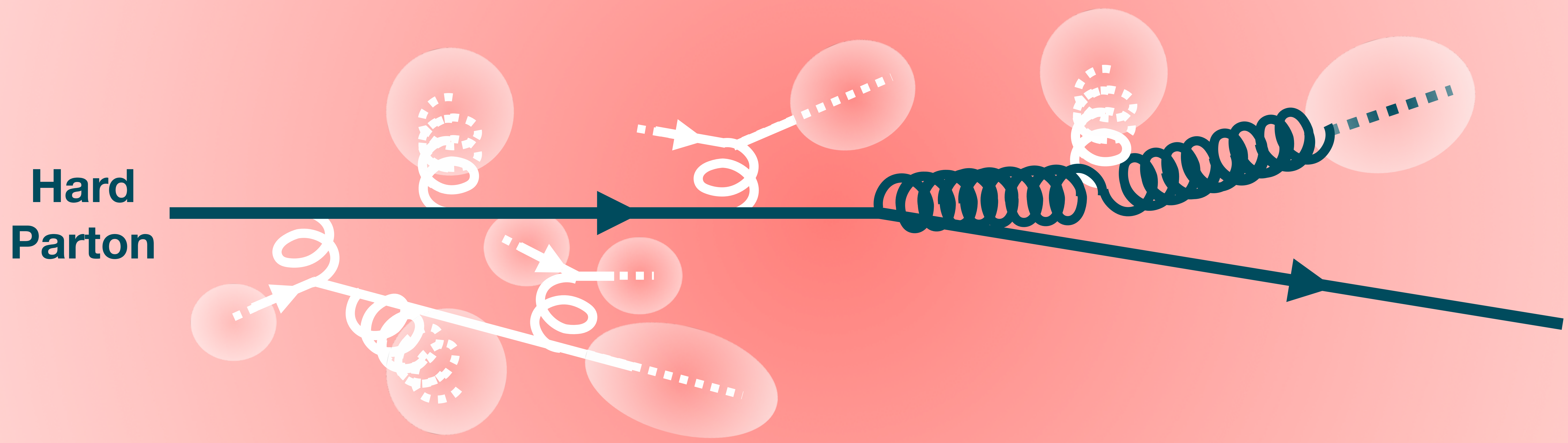




- **Good agreement with experimental data**
- **Almost no medium modification in hardest splittings**

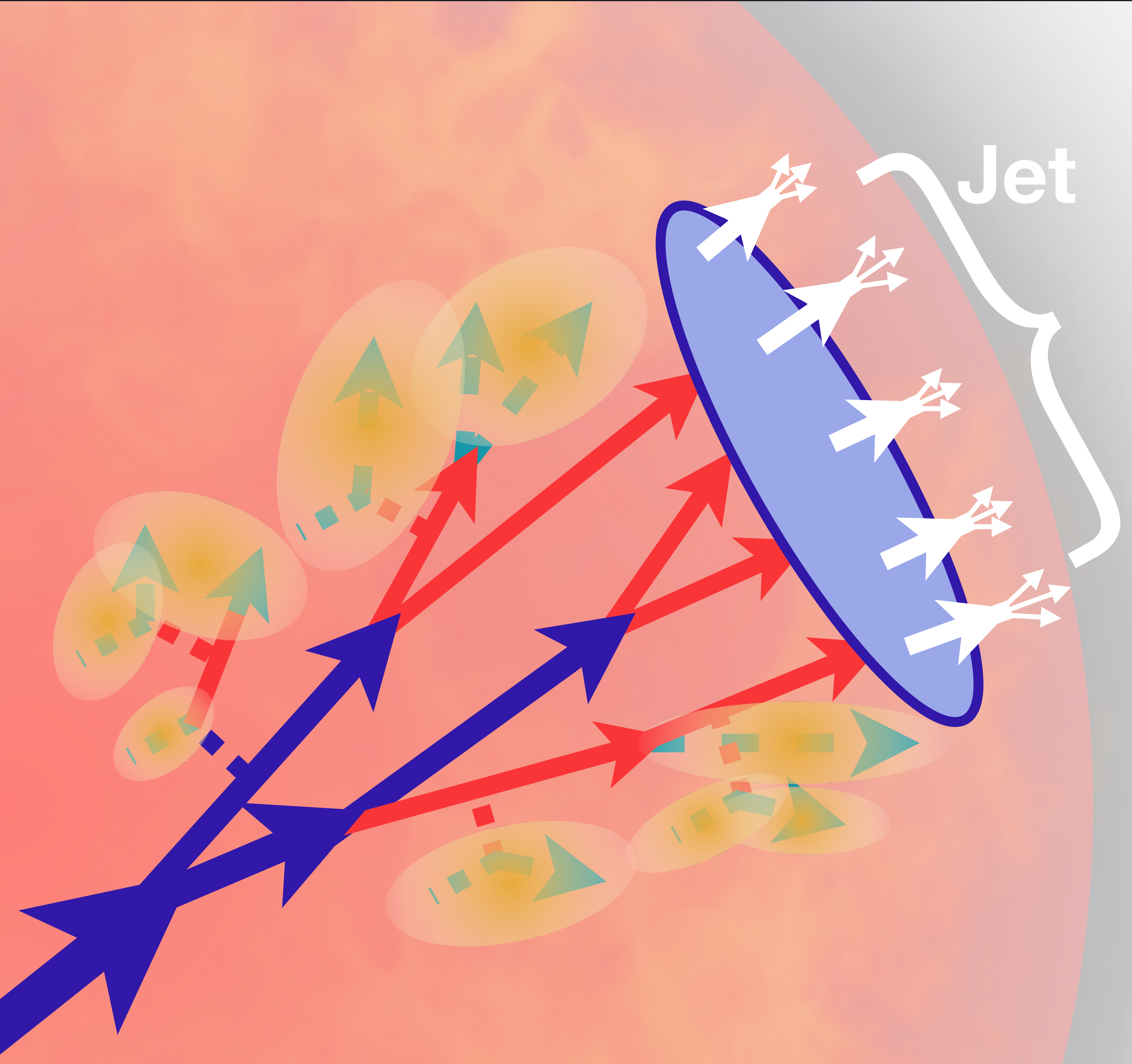
Fluid + Jet Approach for Hydro Response

Hydrodynamic Medium Response to Hard Partons



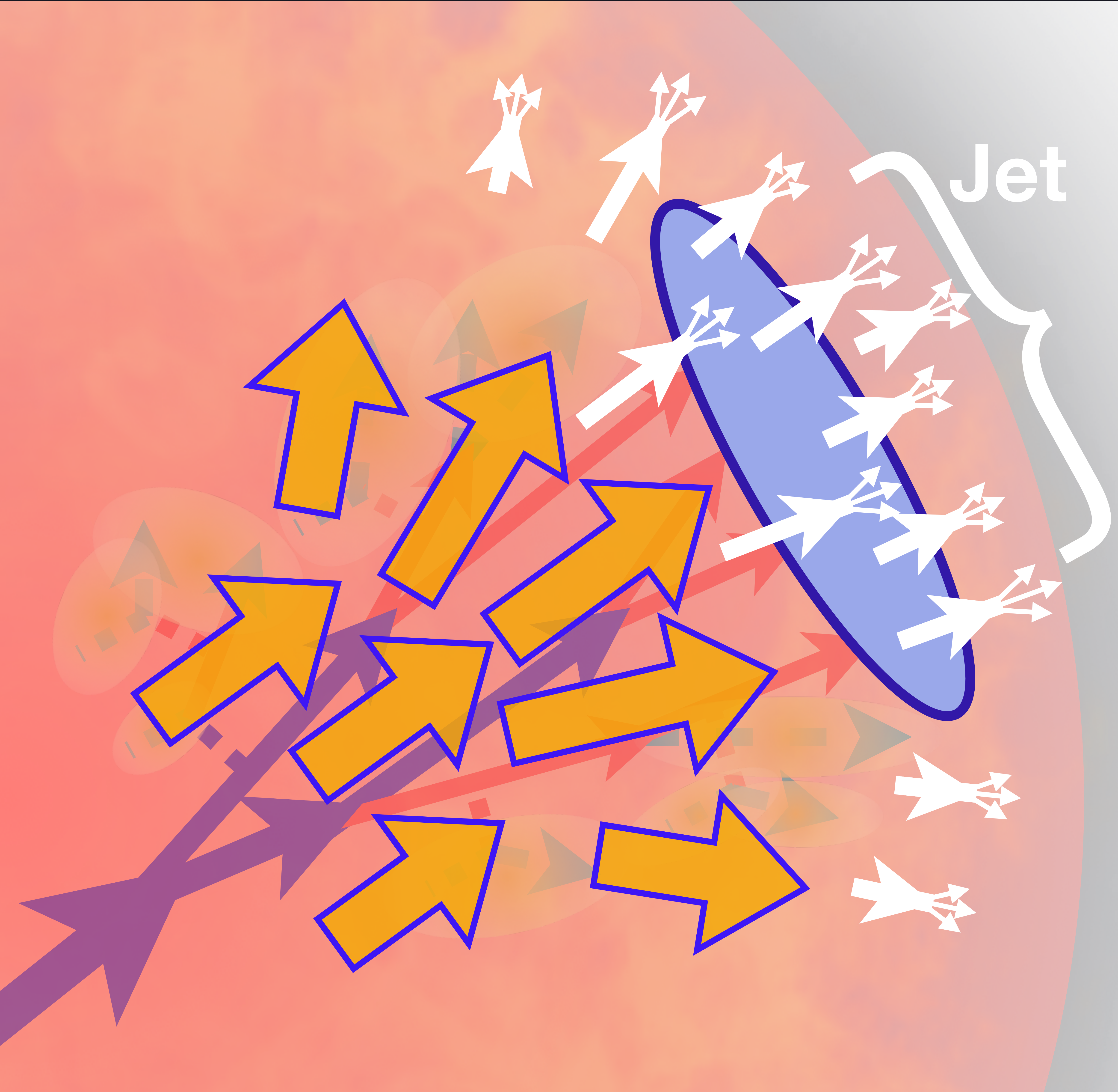
- **In-medium thermalization**
  - Drop to typical scale of thermalized medium constituents ($E \sim E_{\rm med}$)
  - Transition to hydrodynamic transport → Hydrodynamic medium response

Hydrodynamic Medium Response Effect on Jets



- **Jet-induced flow in medium**
  - Transport momentum deposited by jet
  - Modify particle emission around jet
- **Hydro medium response contribution**
  - Soft, spread out from jet
  - Jet-correlated, cannot be subtracted
  - Affect structures inside/around jet

Hydrodynamic Medium Response Effect on Jets



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Description of Hydro Medium Response to Jets

- **Medium fluid evolution with energy-momentum deposition**

  Coupled Jet-Fluid (YT, N.-B. Chang, G.-Y. Qin), CoLBT-hydro (W. Chen, X.-N. Wang, W. Zhao,…) EPOS3-HQ (I. Karpenko,…), JETSCAPE (JETSCAPE), Hybrid+Linearized Hydro (X. Yao, D. Pablos,…), LEXUS+MUSIC (C.Shen, B. Schenke,…), DCCI2 (Y. Kanakubo, YT, T. Hirano,…), JAM (Y.Nara),…

  - Hydrodynamic transport of jet energy-momentum via thermal partons
  - Evolution together with the bulk QGP fluid

Hydrodynamic equation with source term

$$\nabla_\mu T^{\mu\nu}_{\mathrm{med}}(x) = J^{\nu}_{\mathrm{jet}}(x)$$

Energy-momentum tensor of the QGP fluid ($T^{\mu\nu}_{\mathrm{med}}$)

Energy and momentum deposited into the fluid (J^{ν}_{jet})

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

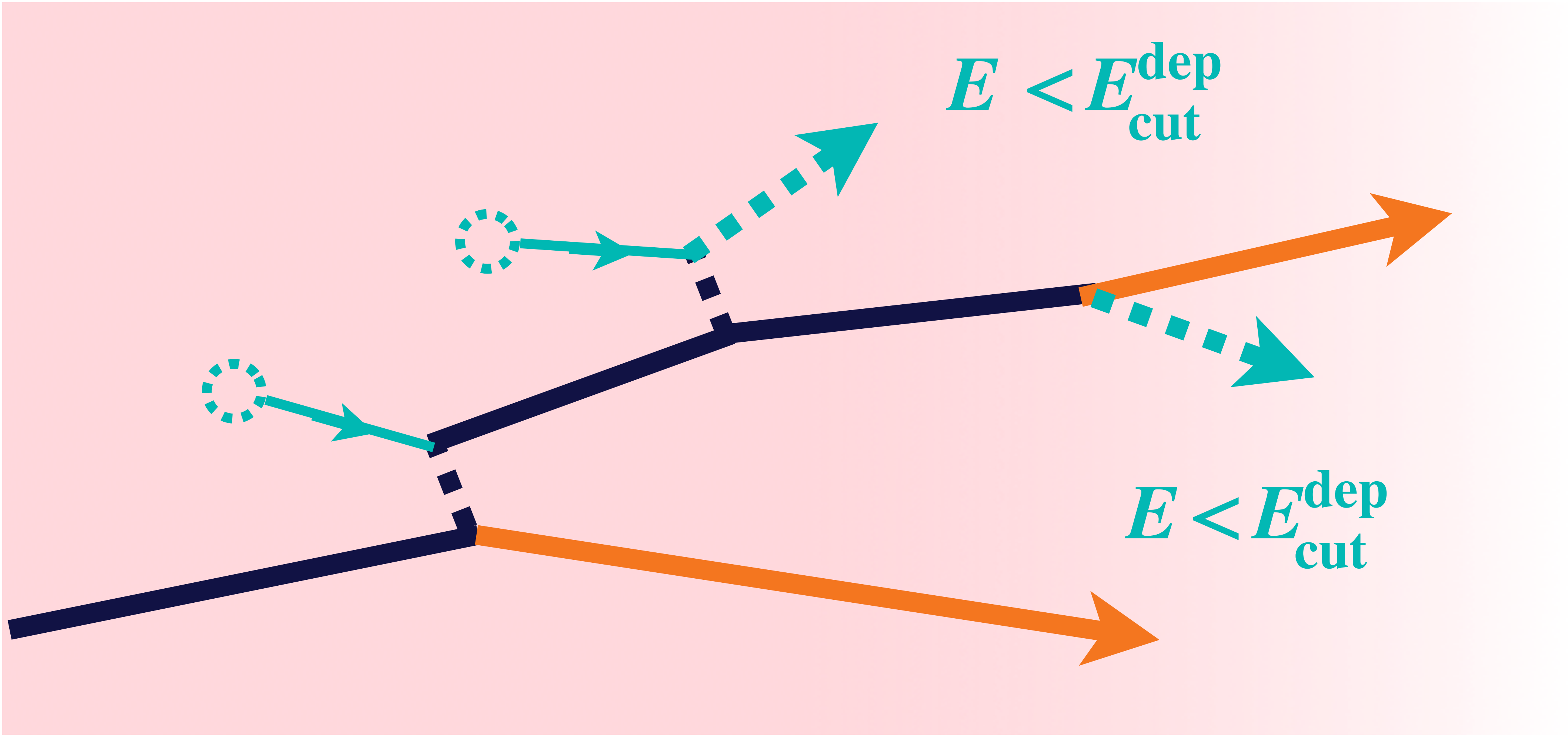
Causal Formulation for Source Term

YT, C. Shen and A. Majumder, arXiv:2001.08321

- **Energy-momentum deposition**

  CoLBT-hydro (W. Chen, X.-N. Wang *et al.*)

  - Soft partons
  - Holes



$E_{\rm cut}^{\rm dep}$: Energy scale for in-medium thermalization

- **Causal source profile**

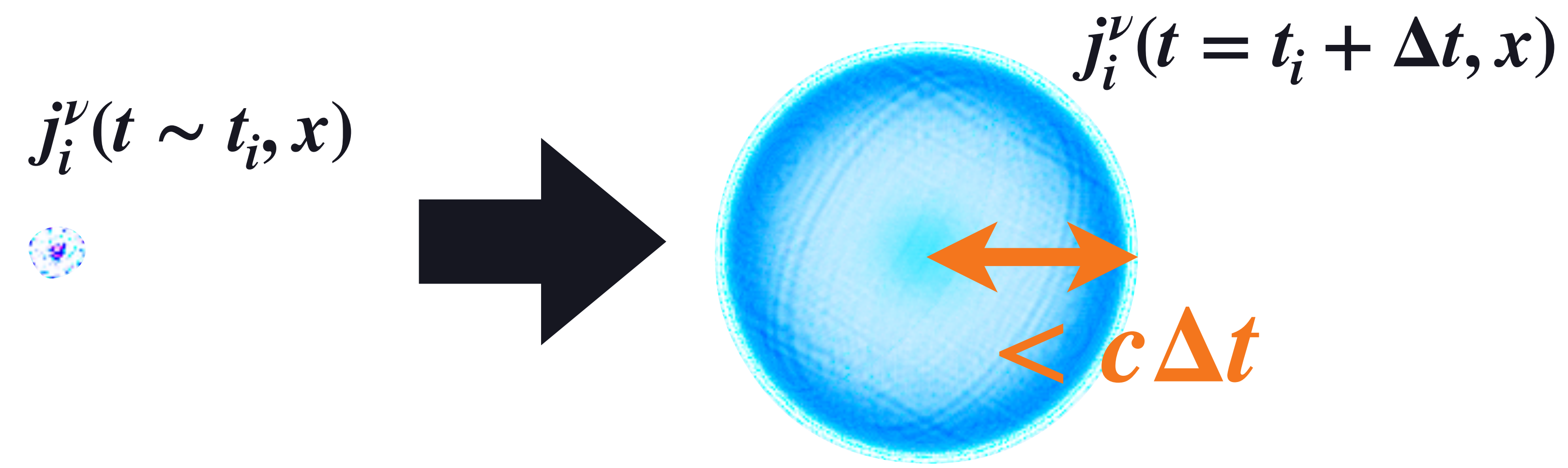
  JETSCAPE (JETSCAPE)

  - Relativistic diffusion equation

$$\left[\frac{\partial}{\partial t} + \tau_{\rm diff}\frac{\partial^2}{\partial t^2} - D_{\rm diff}\nabla^2\right] j^\nu(x) = 0$$

with initial condition

$$j^\nu(t = t_{\rm dep}, \vec{x}) = p^\nu_{\rm dep.}\delta^{(3)}(\vec{x} - \vec{x}_{\rm dep})$$



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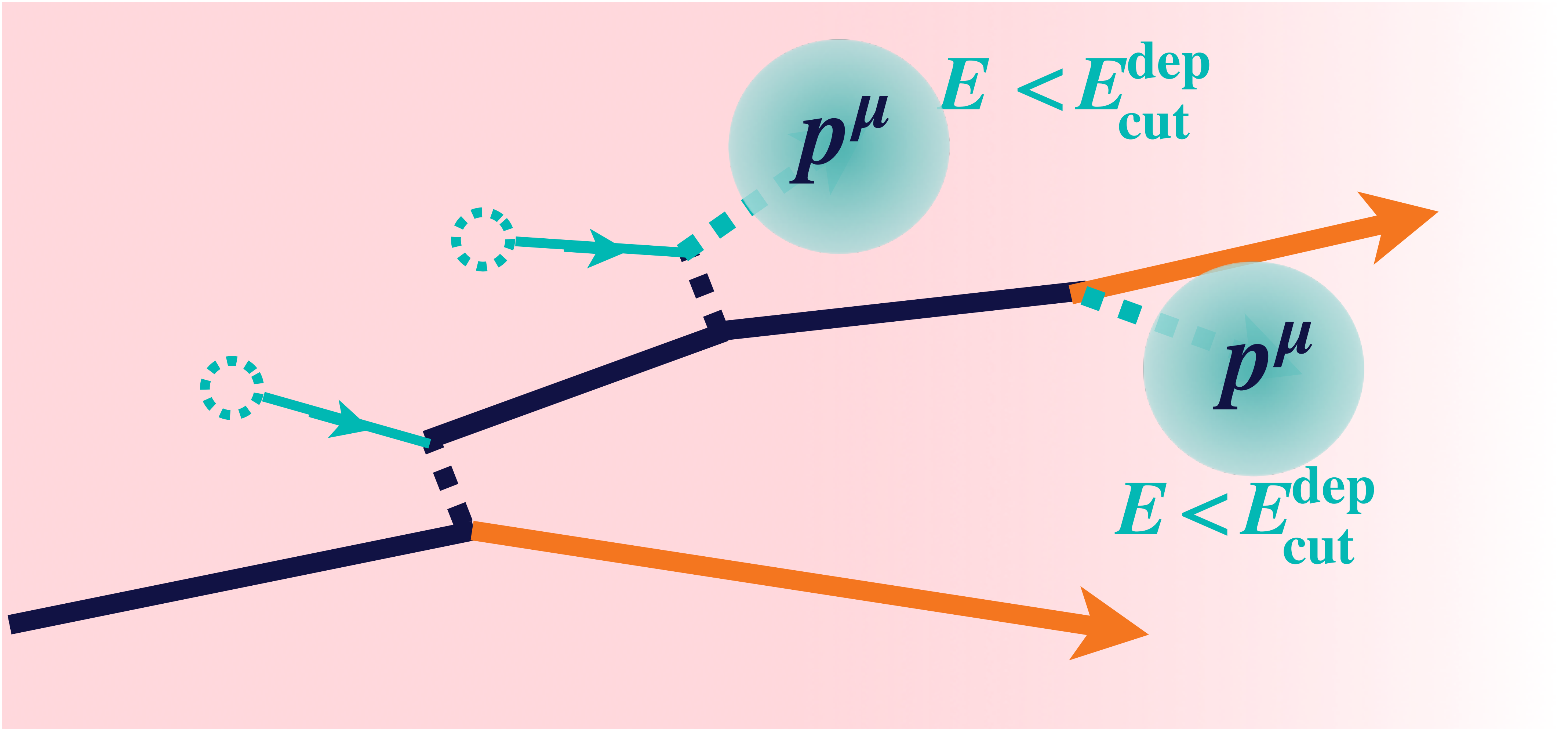

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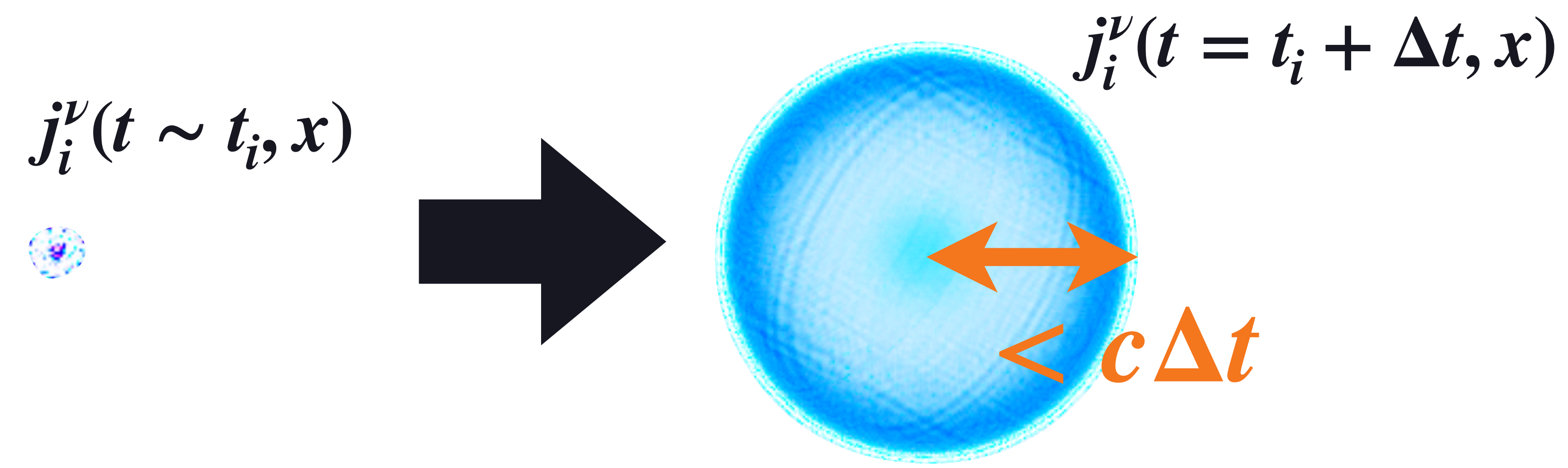

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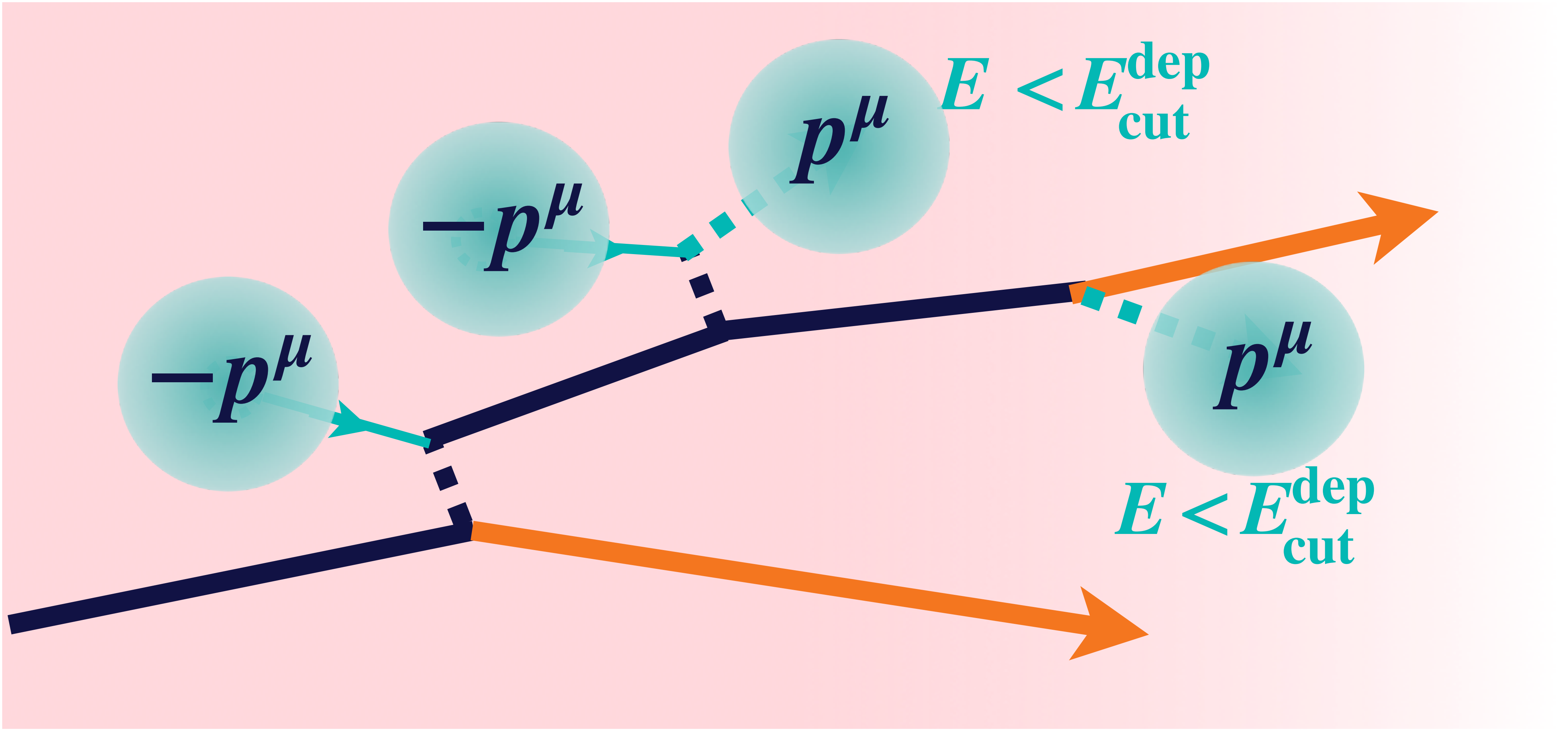

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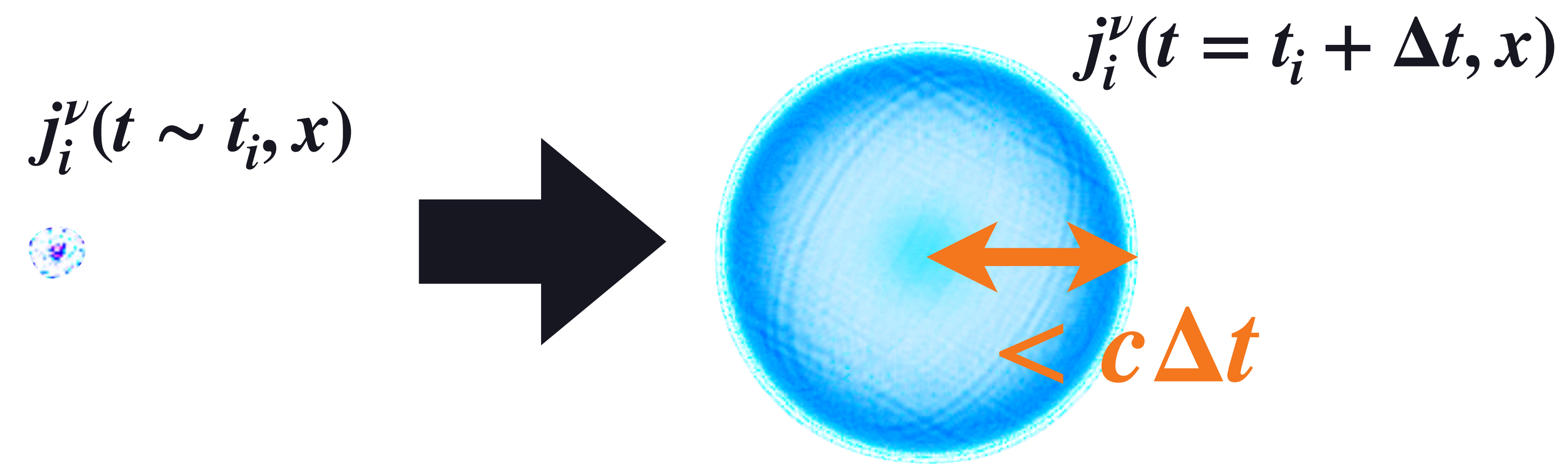
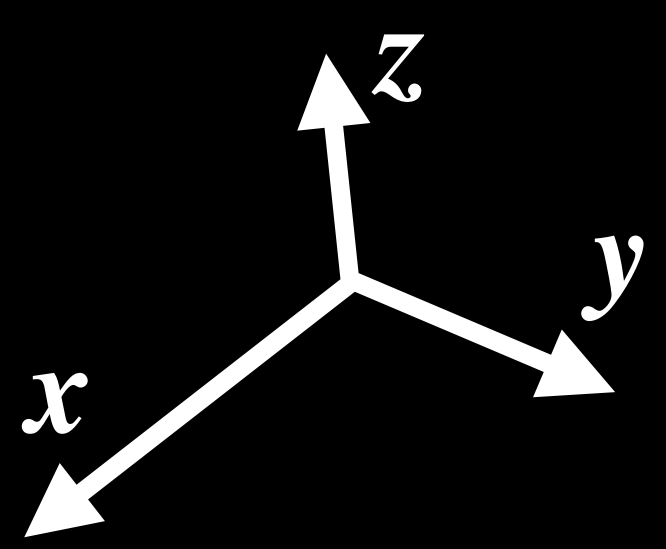


Evolution of Hydrodynamic Medium Response

MATTER + LBT + Causal Diff. + Ideal Hydro [Static Brick, $T_{\mathrm{brick}} = 250\ \mathrm{MeV}$]
YT, C. Shen, A. Majumder, arXiv:2001.08321

- Jet-Induced flow induced by a parton shower propagating in the x direction



Orange: Region with $T > 250\ \mathrm{MeV}$

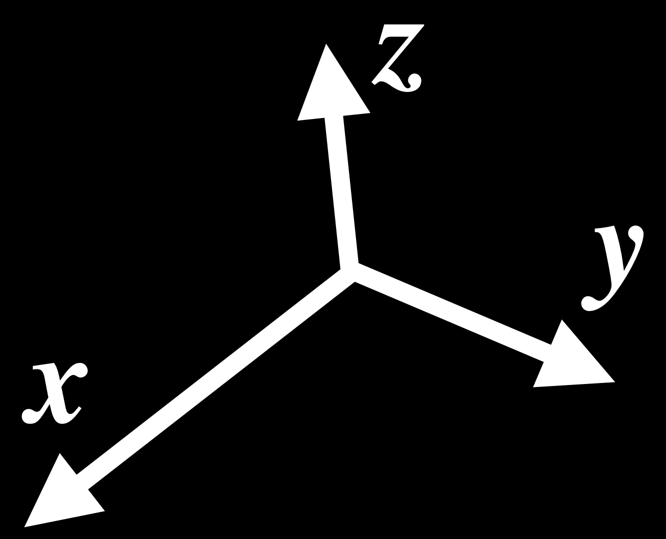
Blue: Region with $T < 250\ \mathrm{MeV}$

Red: Energetic Partons

Evolution of Hydrodynamic Medium Response

MATTER + LBT + Causal Diff. + Ideal Hydro [Static Brick, $T_{\mathrm{brick}} = 250\ \mathrm{MeV}$]
YT, C. Shen, A. Majumder, arXiv:2001.08321

- Jet-Induced flow induced by a parton shower propagating in the x direction



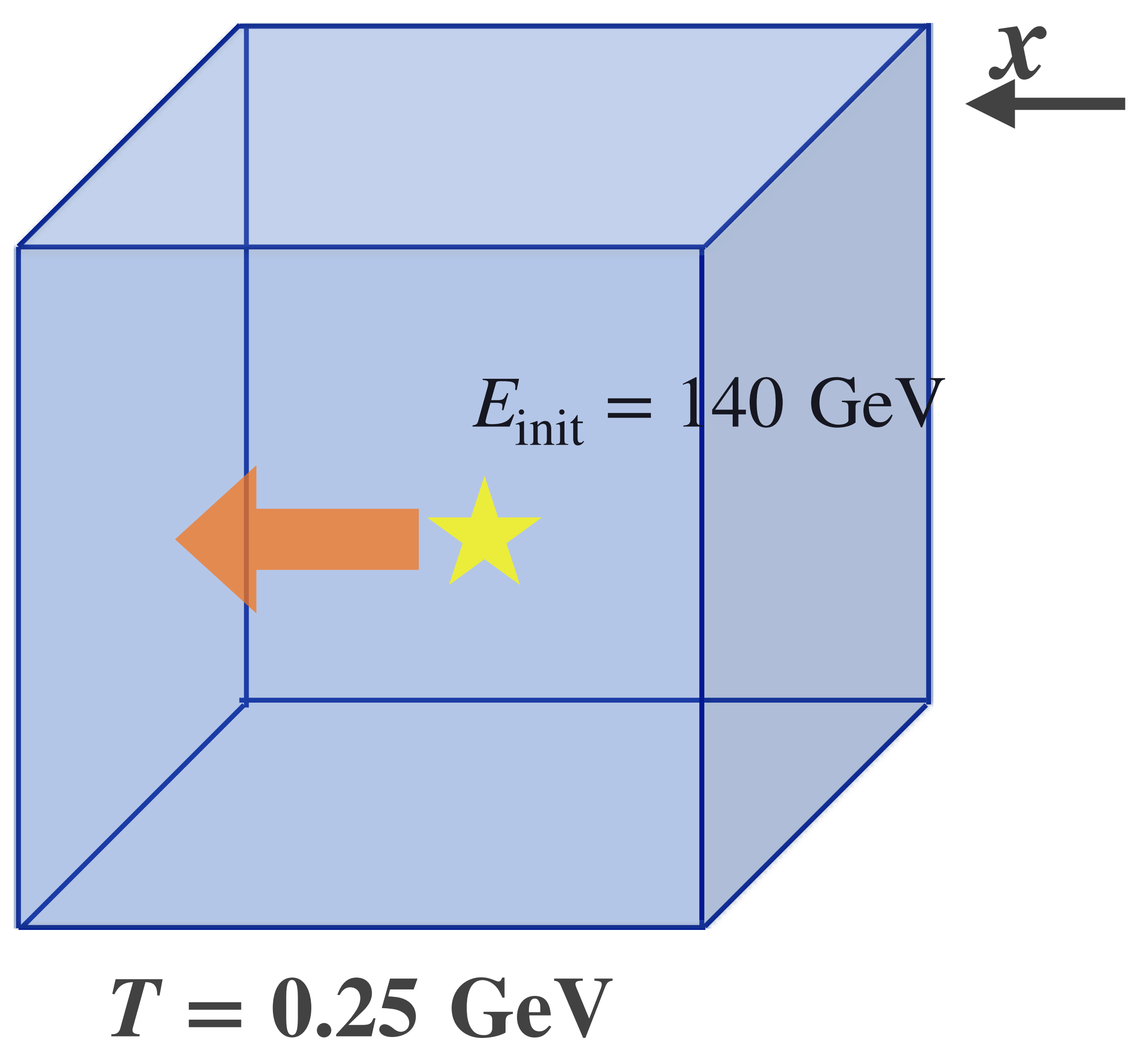
Orange: Region with $T > 250\ \mathrm{MeV}$

Blue: Region with $T < 250\ \mathrm{MeV}$

Red: Energetic Partons

Recoil vs Recoil+Hydro response: Static brick case

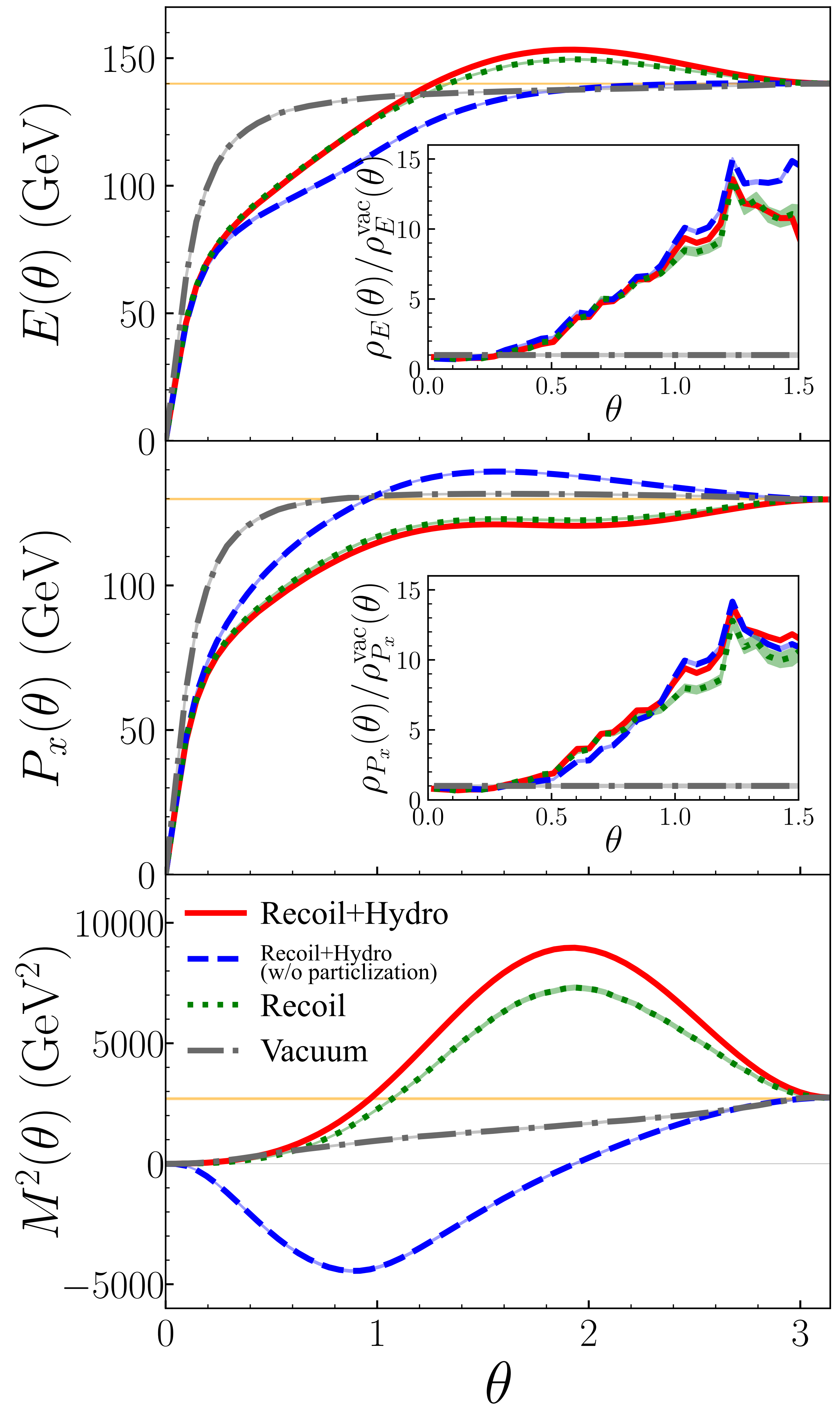
YT, C. Shen and A. Majumder, arXiv:2001.08321



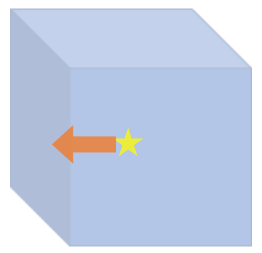
- Jet propagation in medium with static uniform initial condition
- Energy loss by MATTER+LBT with recoils
- Medium evolves upto $t = 10$ fm

Recoil vs Recoil+Hydro response: Static brick case

YT, C. Shen and A. Majumder, arXiv:2001.08321

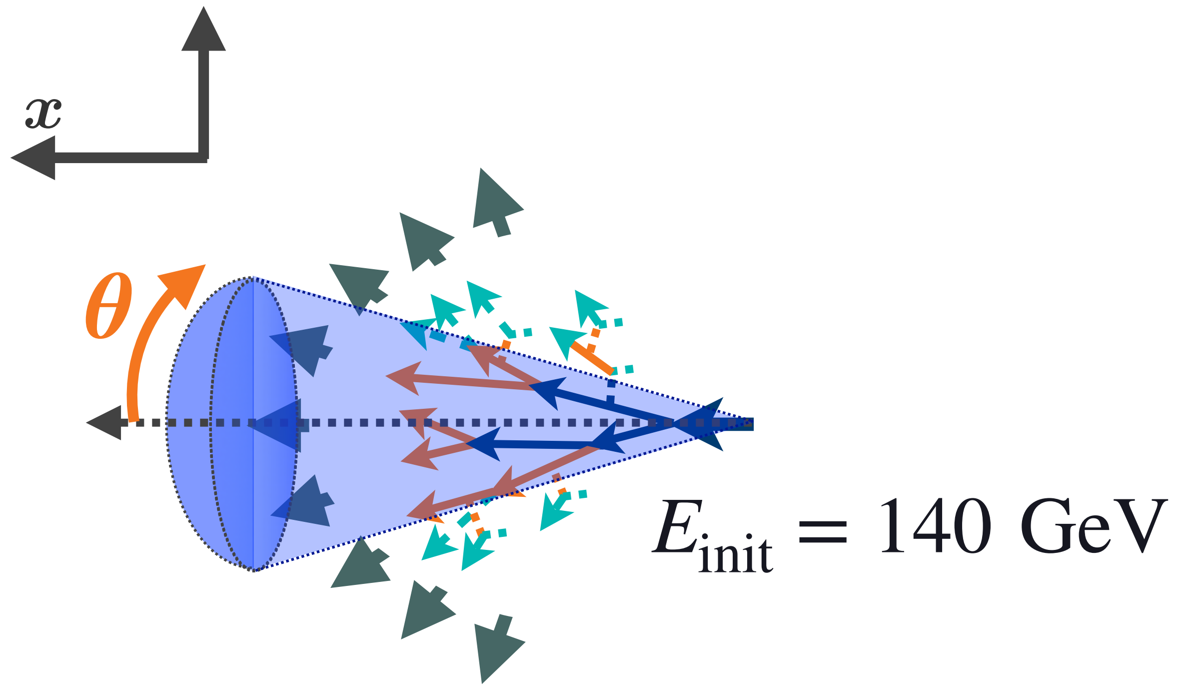


- **Angular structure of jet in brick**



- Jet energy, momentum and mass

$$P^\mu(\theta) = \int_0^\theta d\theta' \frac{dP^\mu}{d\theta'}, \quad M^2(\theta) = P^\mu(\theta)P_\mu(\theta)$$



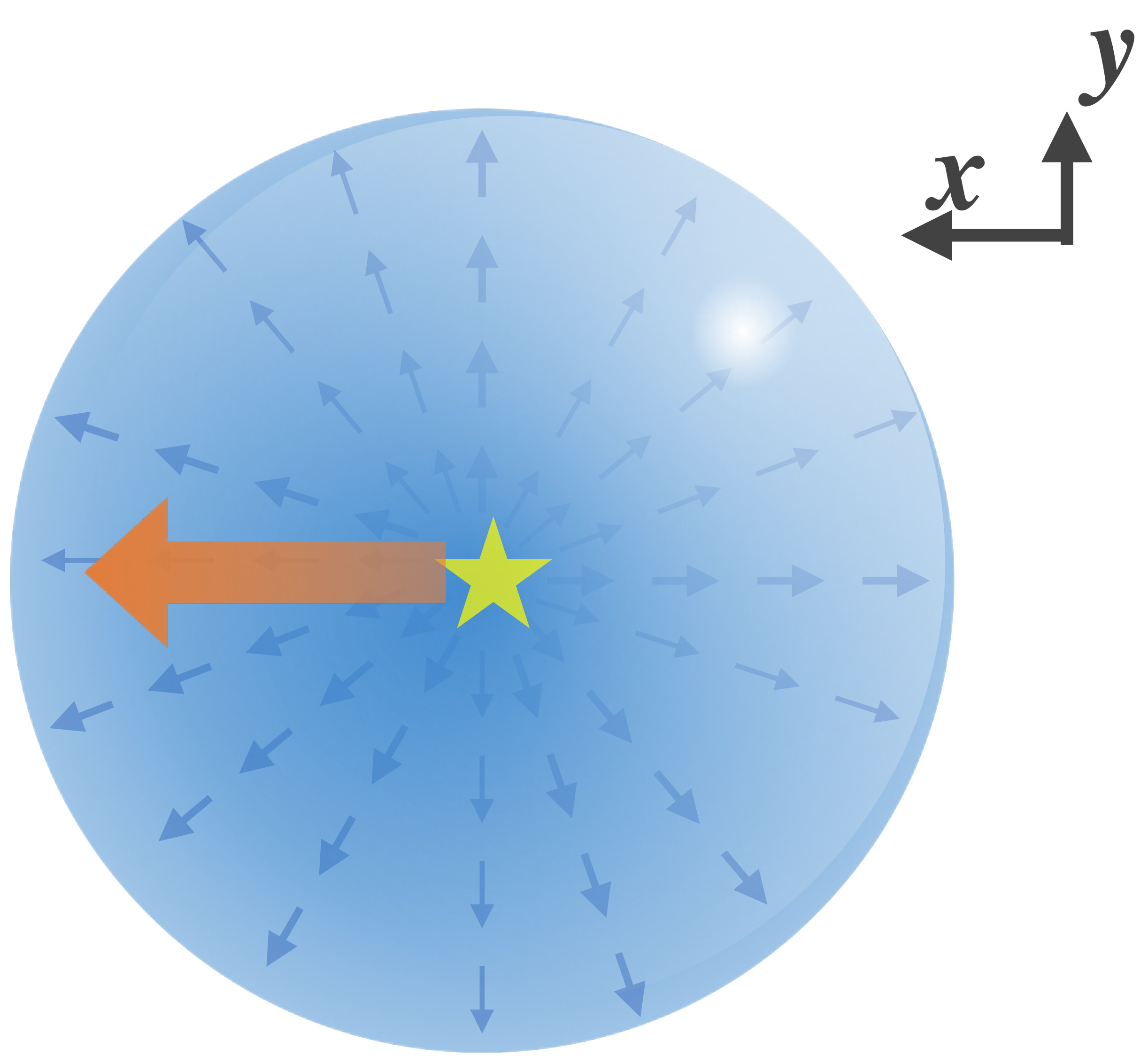
- Detailed substructure

$$\rho_E(\theta) = \frac{1}{E(\theta=1)}\frac{dE}{d\theta}, \quad \rho_{P_x}(\theta) = \frac{1}{P_x(\theta=1)}\frac{dP_x}{d\theta}$$

- Backward suppression due to particlization (Recoil+Hydro)
- Backward suppression due to holes (Recoil)

Recoil vs Recoil+Hydro response: Expanding medium case

YT, C. Shen and A. Majumder, arXiv:2001.08321

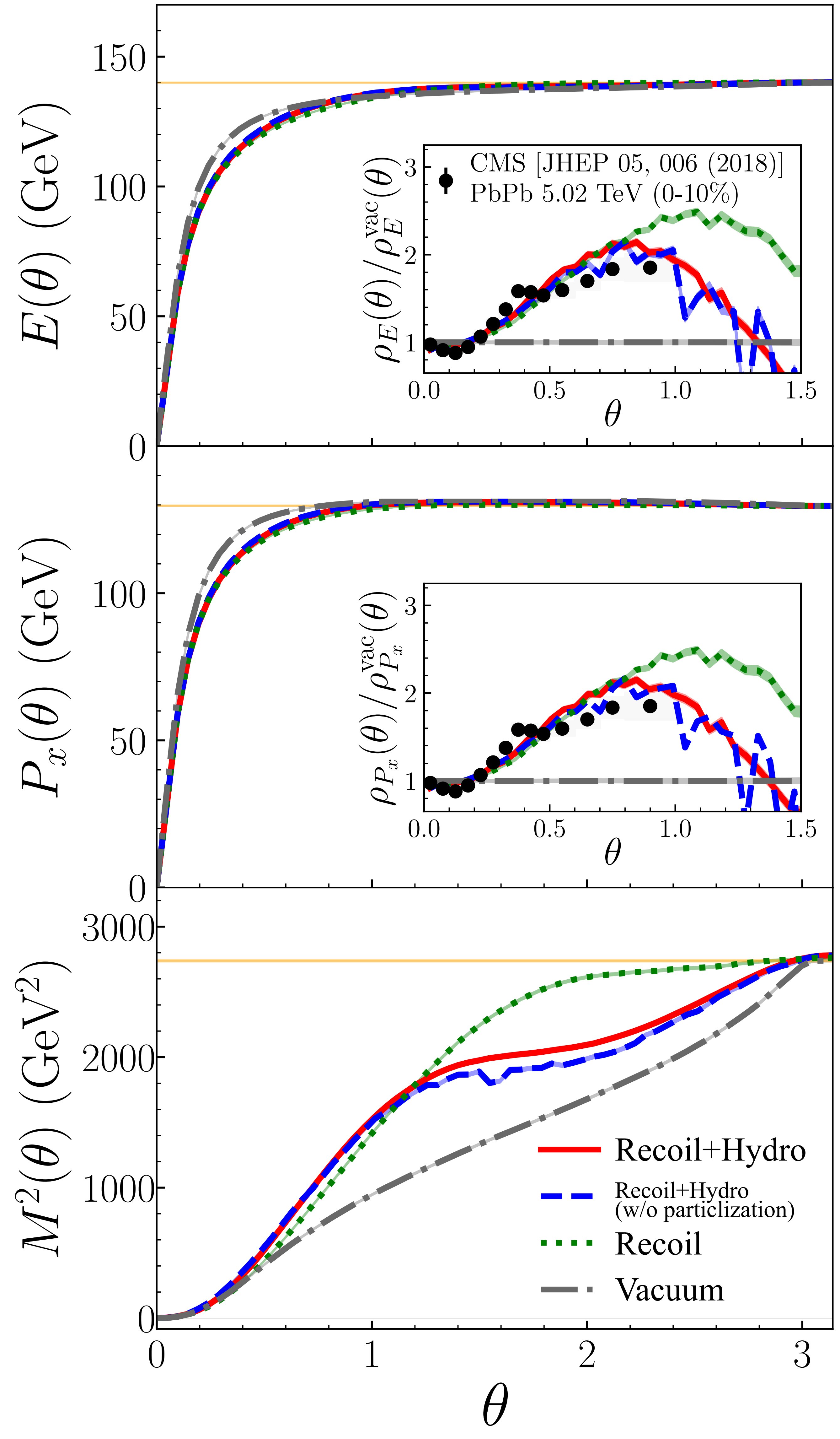


$T_{\mathrm{center}} = 0.5\ \mathrm{GeV}$

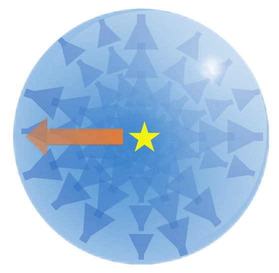
- Jet propagation in medium with oblate 3-D Gaussian ($\sigma_{\mathrm{T}} = 1.5\ \mathrm{fm},\ \sigma_z = 0.75\ \mathrm{fm}$)
- Medium size is chosen to reproduce the full simulation results
- Radial flow following the jet propagation

Recoil vs Recoil+Hydro response: Expanding medium case

YT, C. Shen and A. Majumder, arXiv:2001.08321

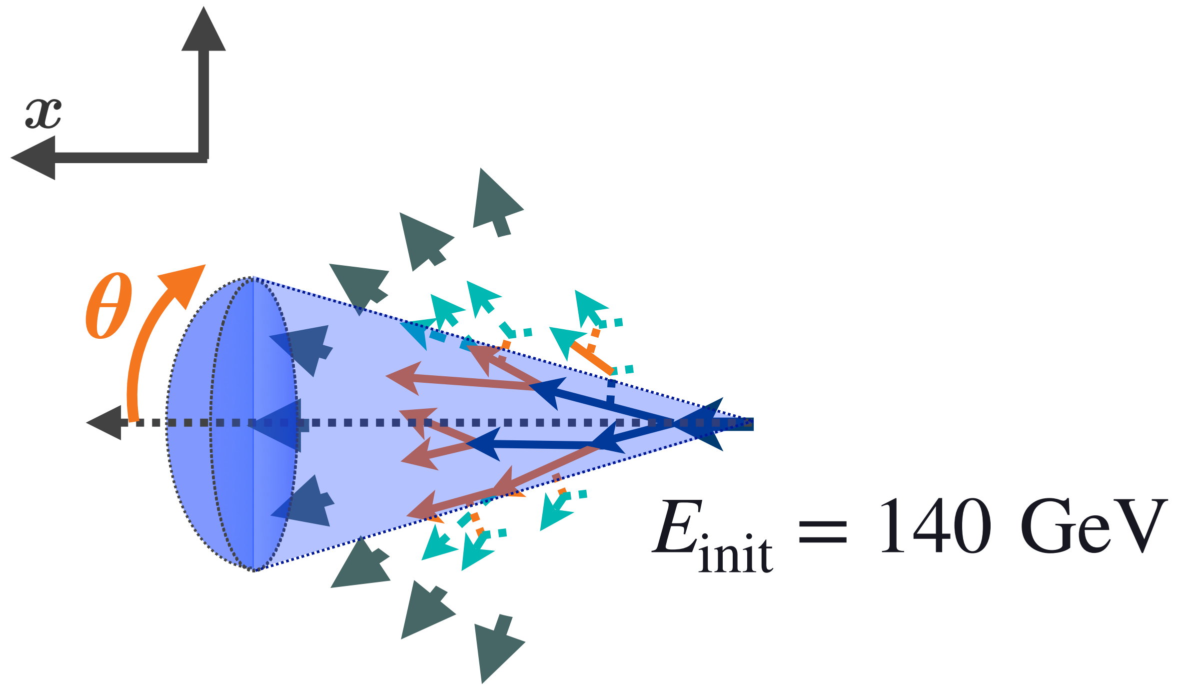


- **Angular structure of jet in oblate medium**



  - Jet energy, momentum and mass

$$P^\mu(\theta) = \int_0^\theta d\theta' \frac{dP^\mu}{d\theta'}, \quad M^2(\theta) = P^\mu(\theta)P_\mu(\theta)$$



  - Detailed substructure

$$\rho_E(\theta) = \frac{1}{E(\theta=1)}\frac{dE}{d\theta}, \quad \rho_{P_x}(\theta) = \frac{1}{P_x(\theta=1)}\frac{dP_x}{d\theta}$$

  - Collimation due to push by the radial flow
  - Small effect of particlization (Recoil+Hydro)
  - Clear difference at very large angle region ($\theta > 1$)

Summary

- **Jet evolution in JETSCAPE**
  - Multi-stage description by switching modules with virtuality
  - Further extension by Q^2-dependence in jet quenching parameter $\hat{q}$
  - Simultaneous description of jet and high-p_{T} particle energy loss in various $\sqrt{s_{\mathrm{NN}}}$
  - Further systematic studies for jet substructure

- **Hydrodynamic medium response**
  - Transport of thermalized jet energy and momentum
  - Described by hydrodynamic equation with source terms
  - Difference from recoils led by background flow

Backup

Causal Formulation for Source Term

YT, C. Shen and A. Majumder, arXiv:2001.08321