Medium response to jets in JETSCAPE

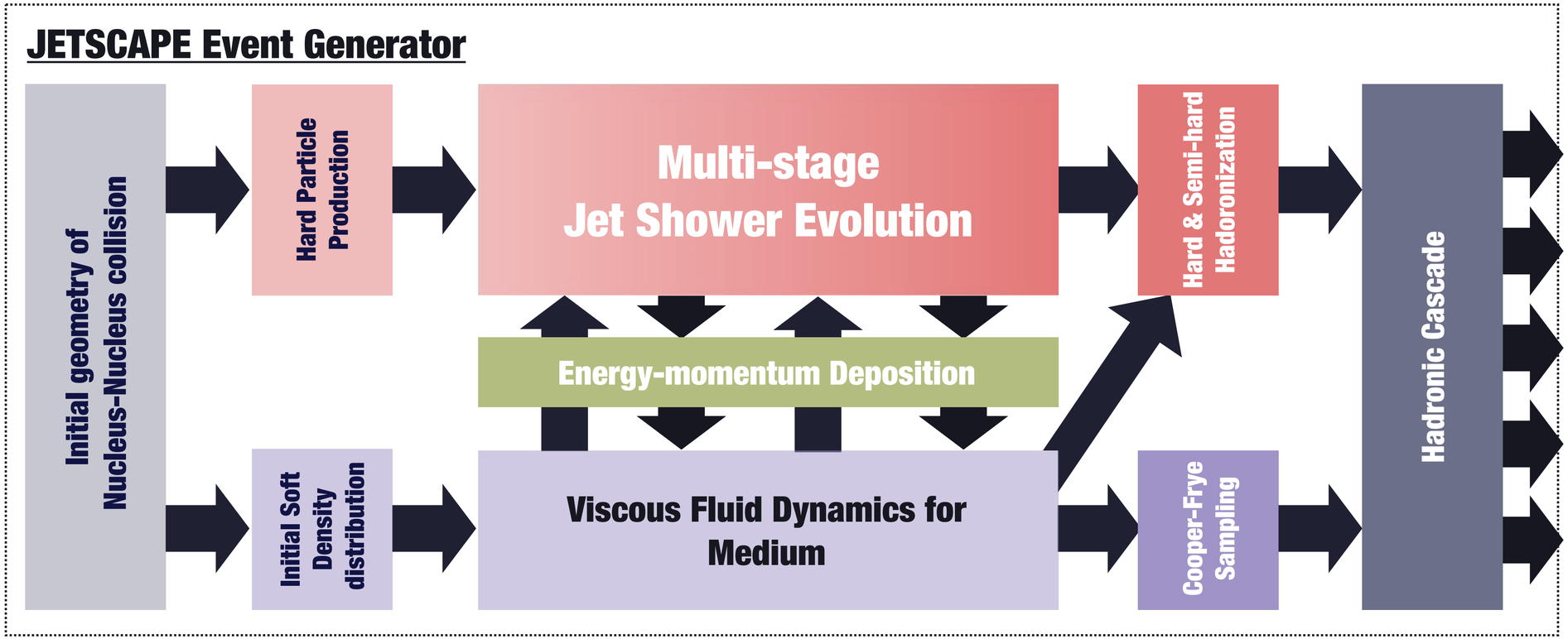
Yasuki Tachibana for the JETSCAPE Collaboration

Jet Quenching In The Quark-Gluon Plasma, ECT*, June 15th 2022

JETSCAPE framework

JETSCAPE, arXiv:1903.07706

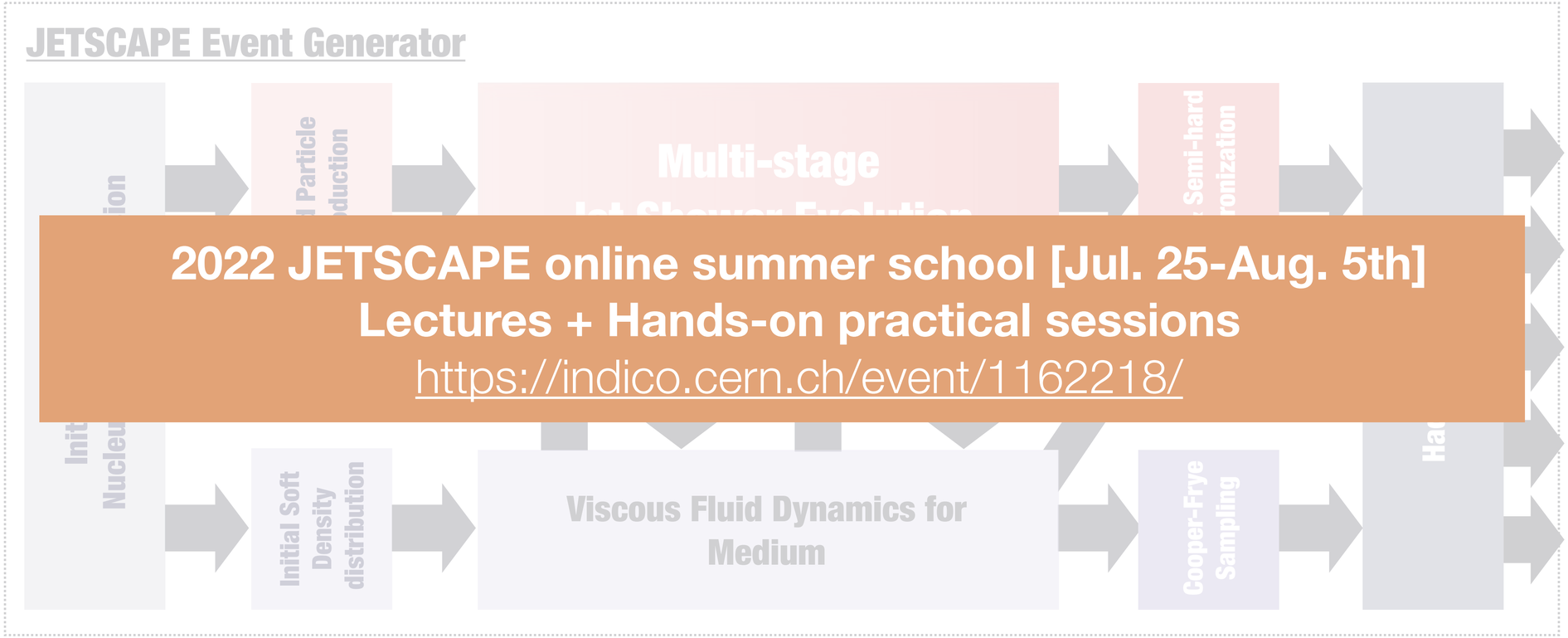
- **MC event generator package for heavy ion collisions**
  - General, modular and customizable (*users can add their own modules*)
  - Support communications between modules
  - Available on GitHub github.com/JETSCAPE



JETSCAPE framework

JETSCAPE, arXiv:1903.07706

- **MC event generator package for heavy ion collisions**
  - General, modular and customizable (*users can add their own modules*)
  - Support communications between modules
  - Available on GitHub **github.com/JETSCAPE**

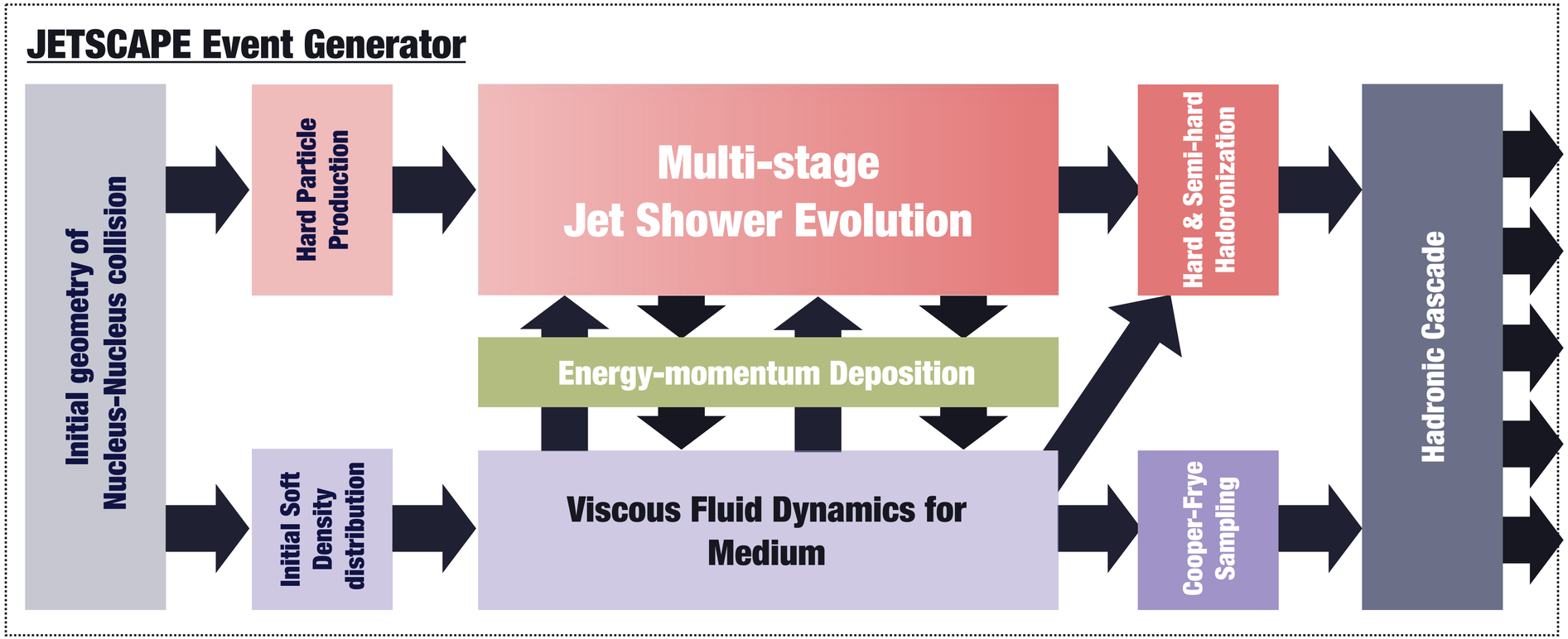


2022 JETSCAPE online summer school [Jul. 25-Aug. 5th]
Lectures + Hands-on practical sessions
https://indico.cern.ch/event/1162218/

JETSCAPE framework

JETSCAPE, arXiv:1903.07706

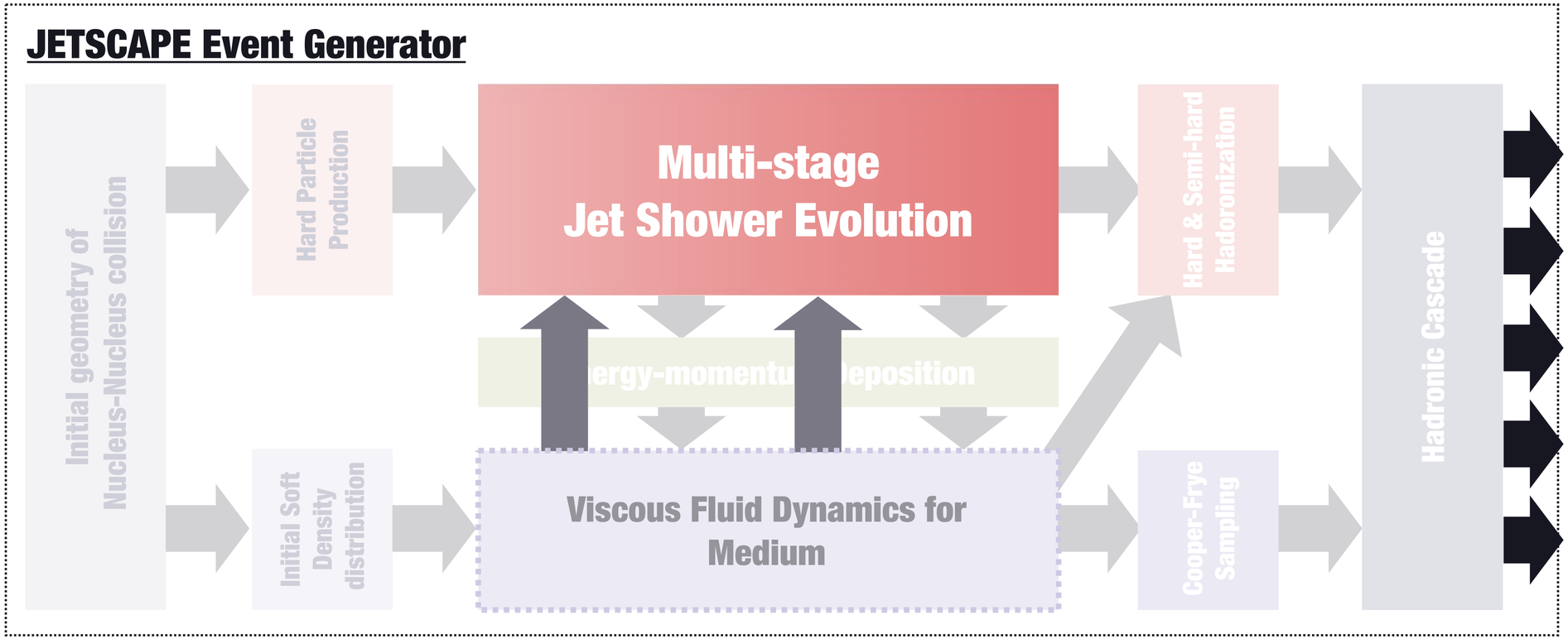
- **Medium response to jets in JETSCAPE framework**



JETSCAPE framework

JETSCAPE, arXiv:1903.07706

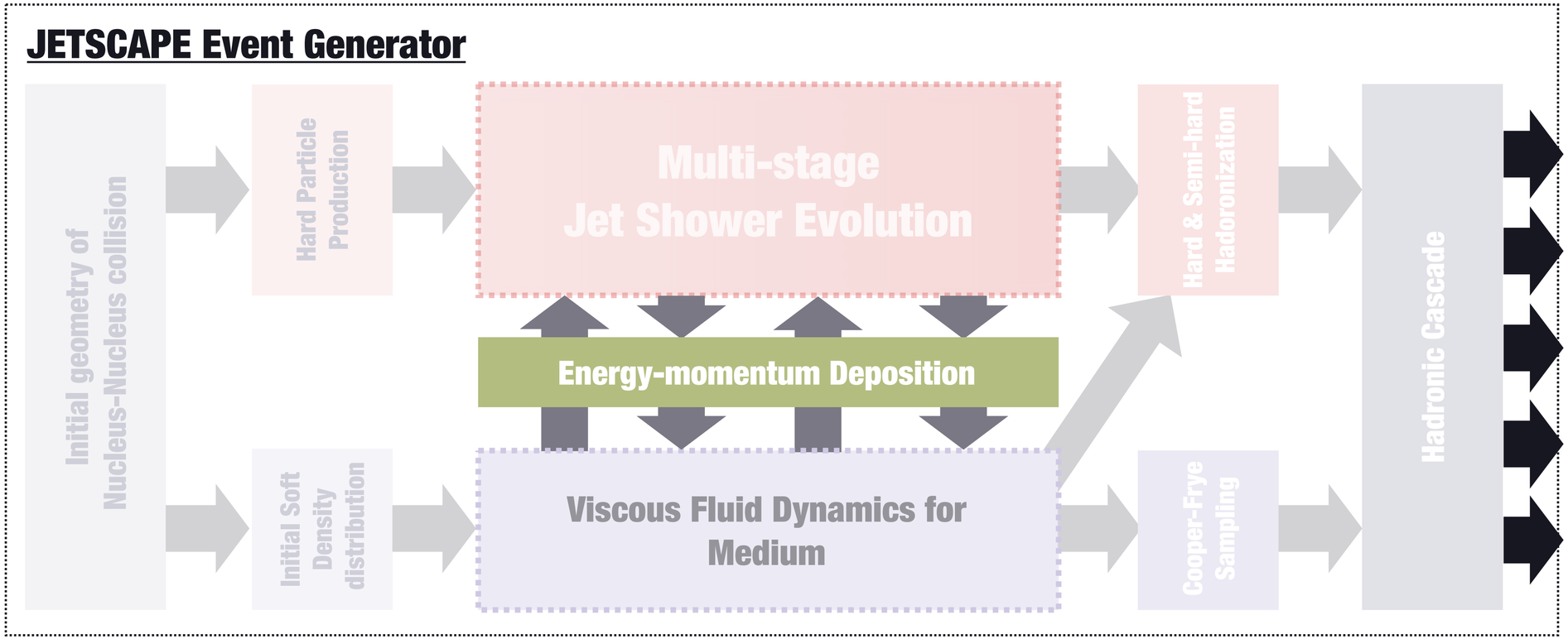
- **Medium response to jets in JETSCAPE framework**
  - Recoil partons ($\gg E_{\mathrm{med}}$) by jet energy loss modules



JETSCAPE framework

JETSCAPE, arXiv:1903.07706

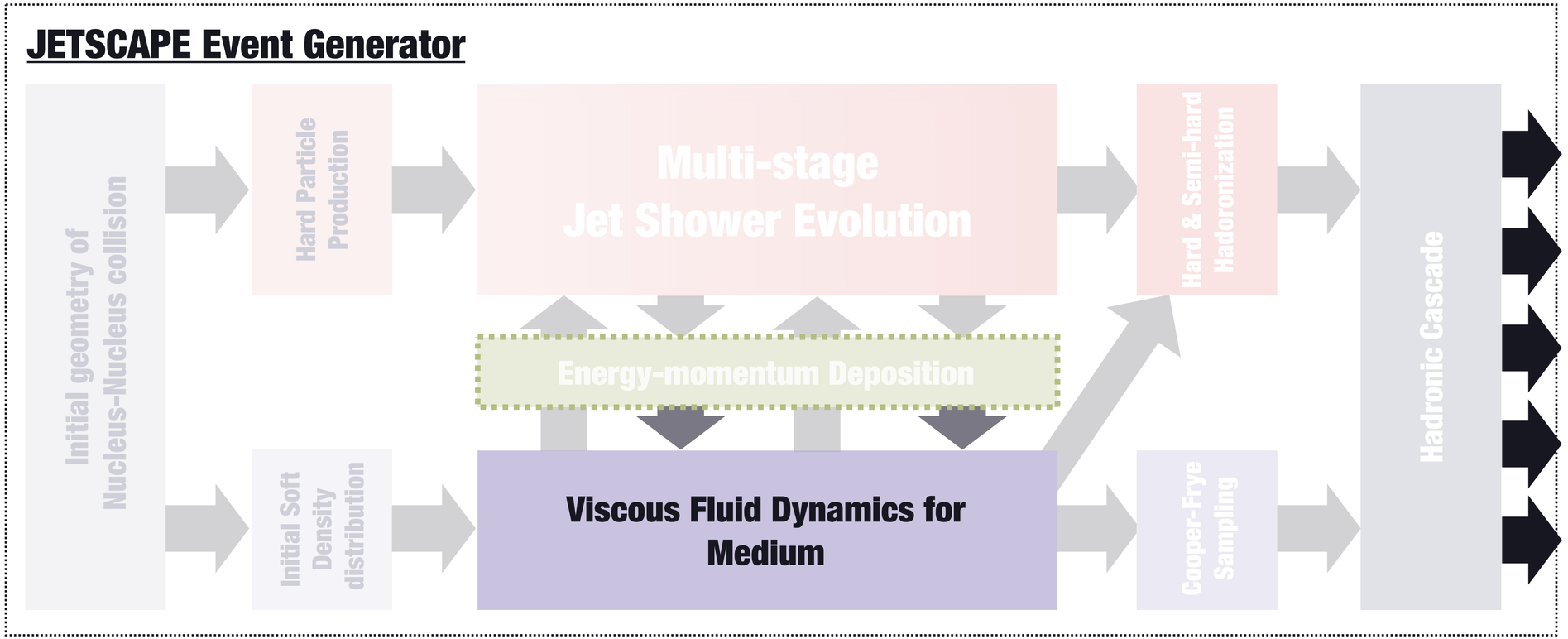
- **Medium response to jets in JETSCAPE framework**
  - Recoil partons ($\gg E_{\mathrm{med}}$) by jet energy loss modules
  - Diffusion into medium ($\gtrsim E_{\mathrm{med}}$) by energy-momentum deposition modules



JETSCAPE framework

JETSCAPE, arXiv:1903.07706

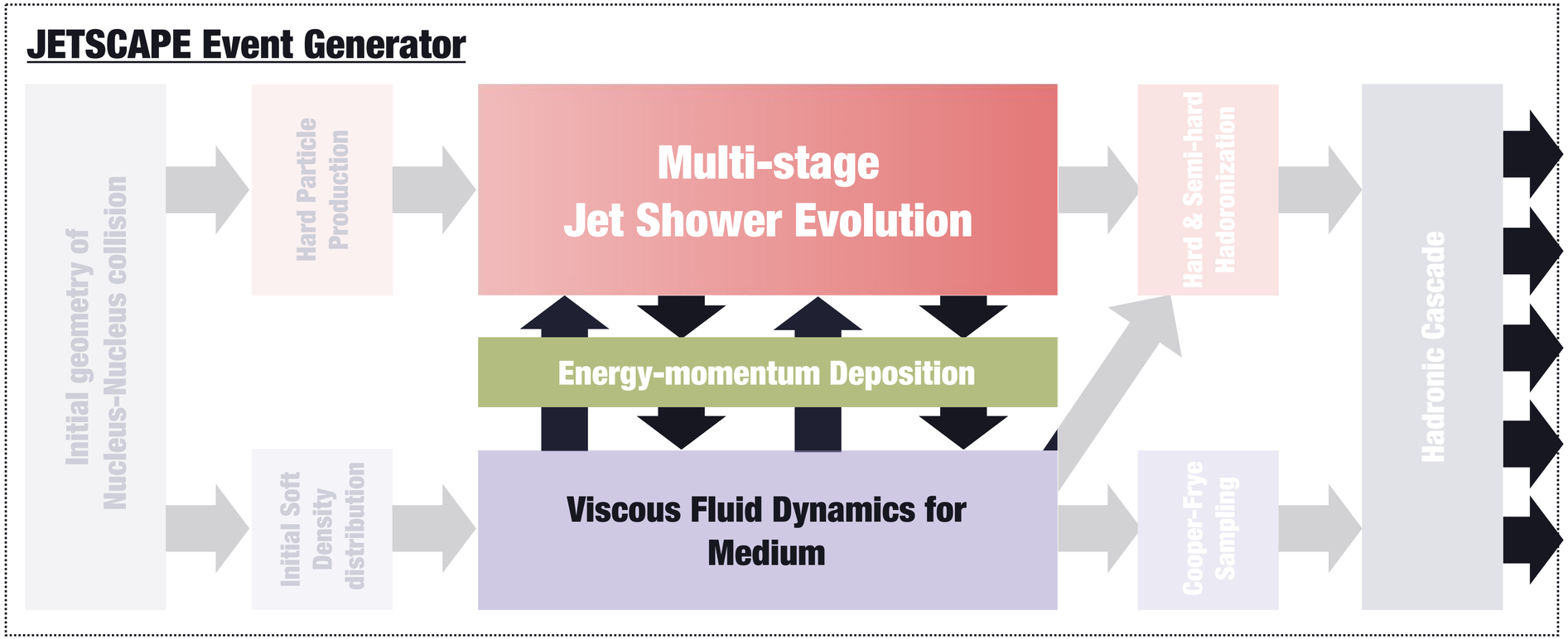
- **Medium response to jets in JETSCAPE framework**
  - Recoil partons ($\gg E_{\mathrm{med}}$) by jet energy loss modules
  - Diffusion into medium ($\gtrsim E_{\mathrm{med}}$) by energy-momentum deposition modules
  - Hydrodynamic evolution ($\sim E_{\mathrm{med}}$) by hydrodynamic models



JETSCAPE framework

JETSCAPE, arXiv:1903.07706

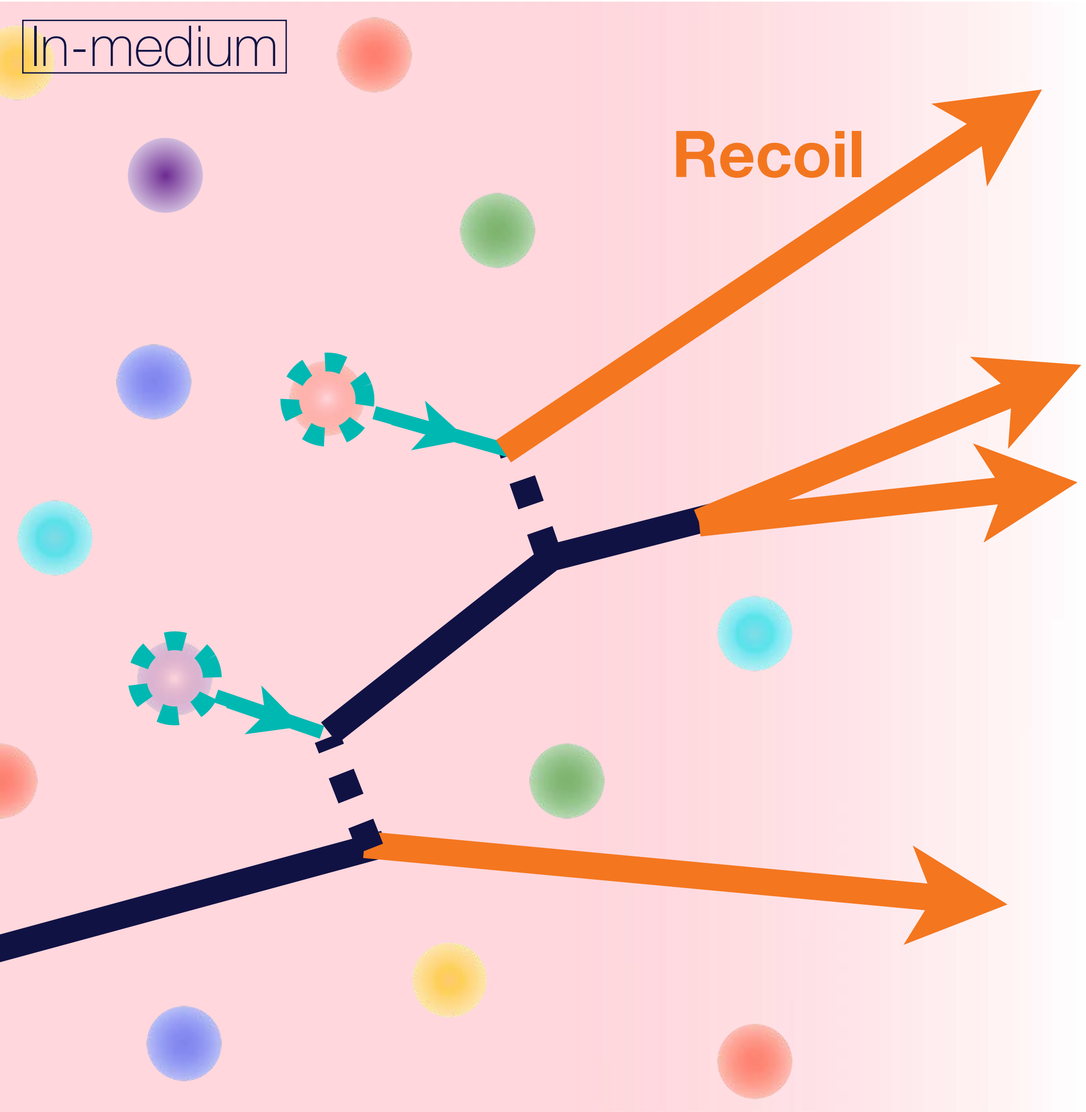
- **Medium response to jets in JETSCAPE framework**
  - Recoil partons ($\gg E_{\mathrm{med}}$) by jet energy loss modules
  - Diffusion into medium ($\gtrsim E_{\mathrm{med}}$) by energy-momentum deposition modules
  - Hydrodynamic evolution ($\sim E_{\mathrm{med}}$) by hydrodynamic models



Description of medium response by modules in JETSCAPE package

Recoils

K. C. Zapp, F. Krauss, U. A. Wiedemann ('13), X.-N. Wang, Y. Zhu(13), T. Luo, et al.(15,18), C. Park, S. Jeon, C. Gale(18), S. Cao, A. Majumder (18)

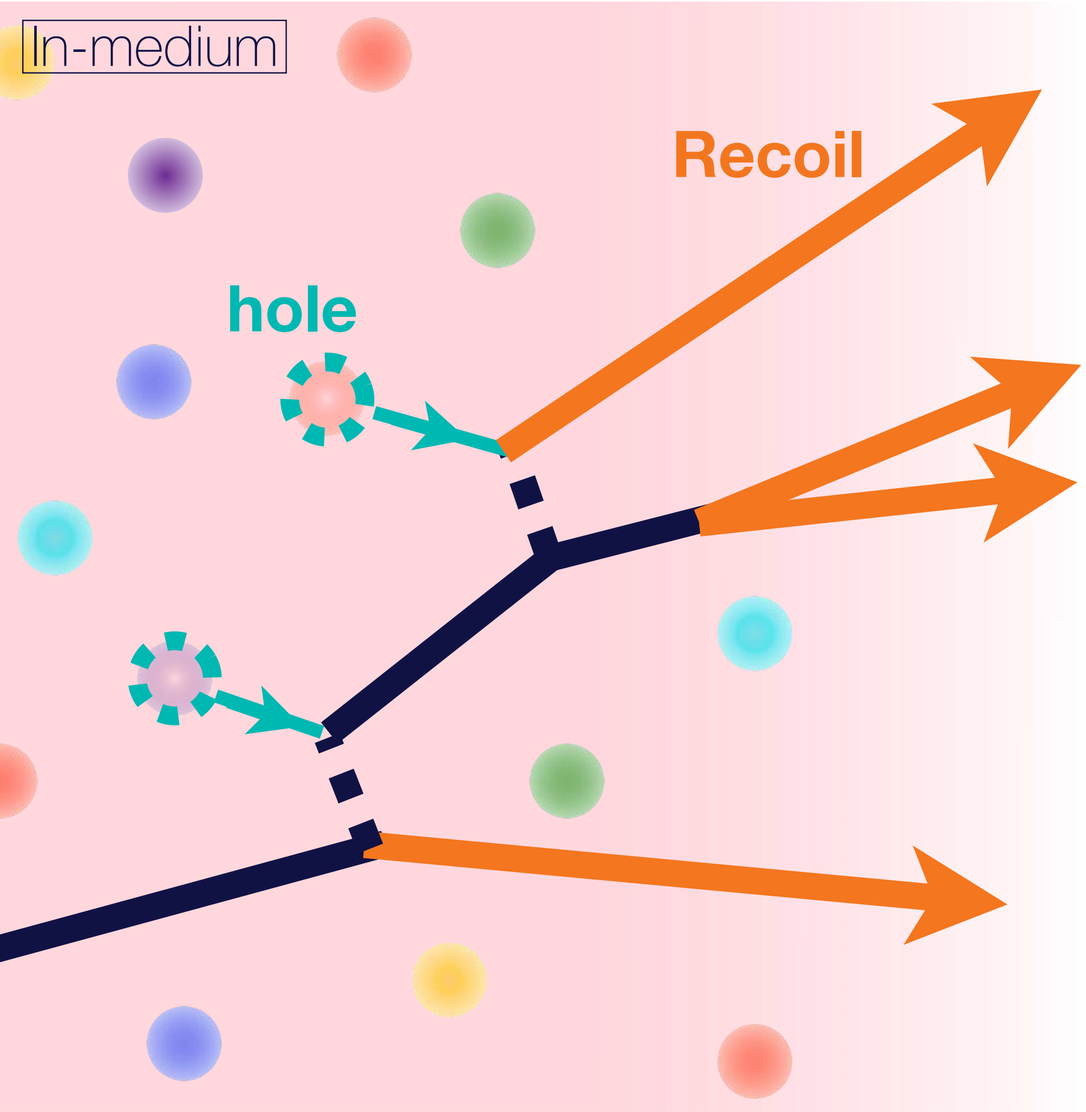


Implemented in MATTER, LBT and MARTINI

- **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 $E \gg E_{\mathrm{med}}$
  - Weakly coupled with the medium

Recoils

K. C. Zapp, F. Krauss, U. A. Wiedemann ('13), X.-N. Wang, Y. Zhu(13), T. Luo, et al.(15,18), C. Park, S. Jeon, C. Gale(18), S. Cao, A. Majumder (18)

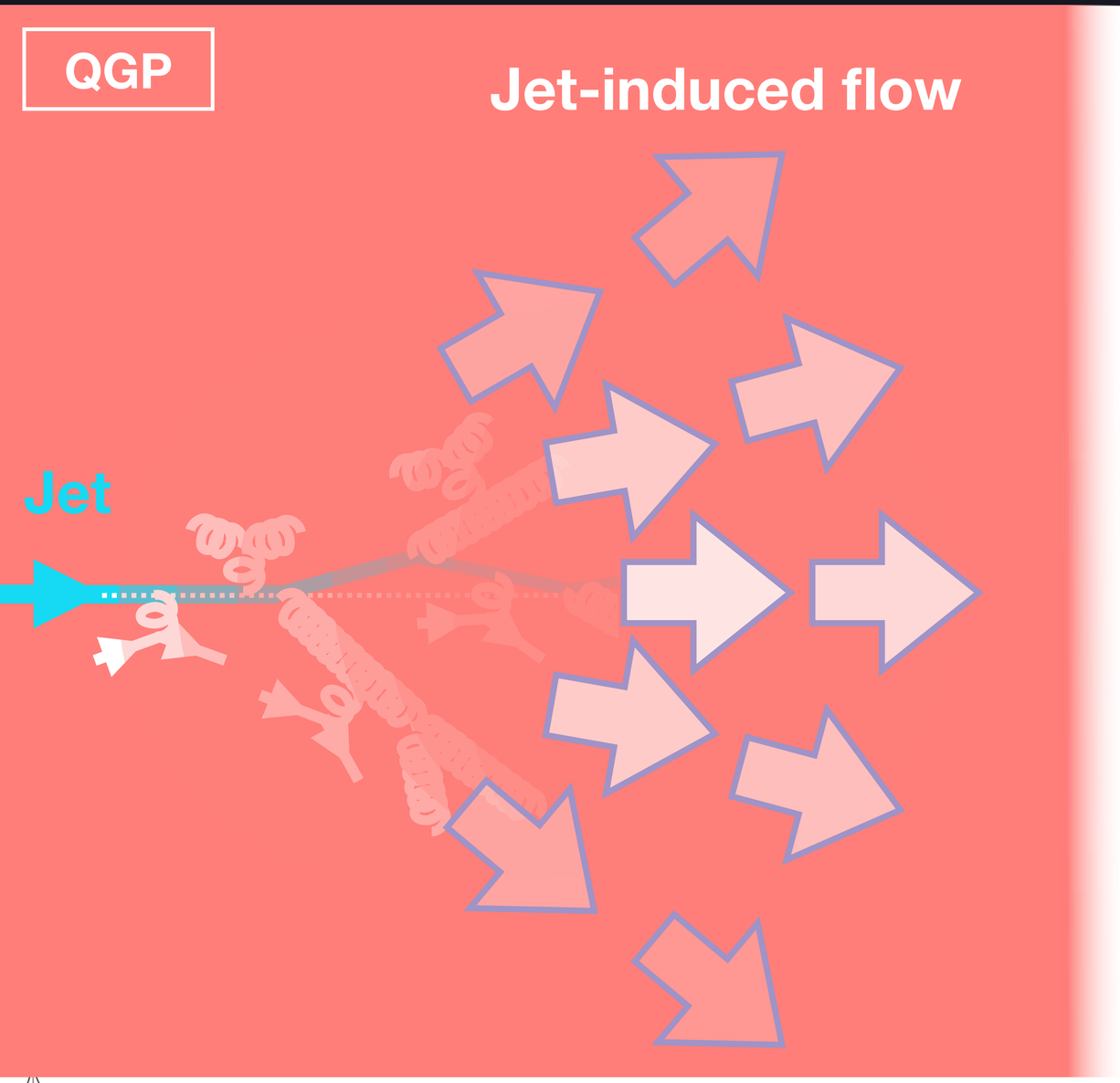


Implemented in MATTER, LBT and MARTINI

- **Picked up momentum from medium (a.k.a negative partons or holes)**
  - Original momenta of sampled thermal partons
  - Assumed to freestream
  - Not necessarily isotropic (background flow)
  - To be subtracted from final signal

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

Hydrodynamic evolution of jets



Implemented in MUSIC and CLVisc

- **Thermalized part of jets**
  - Evolve as a part of the bulk medium

Hydrodynamic equation with source term

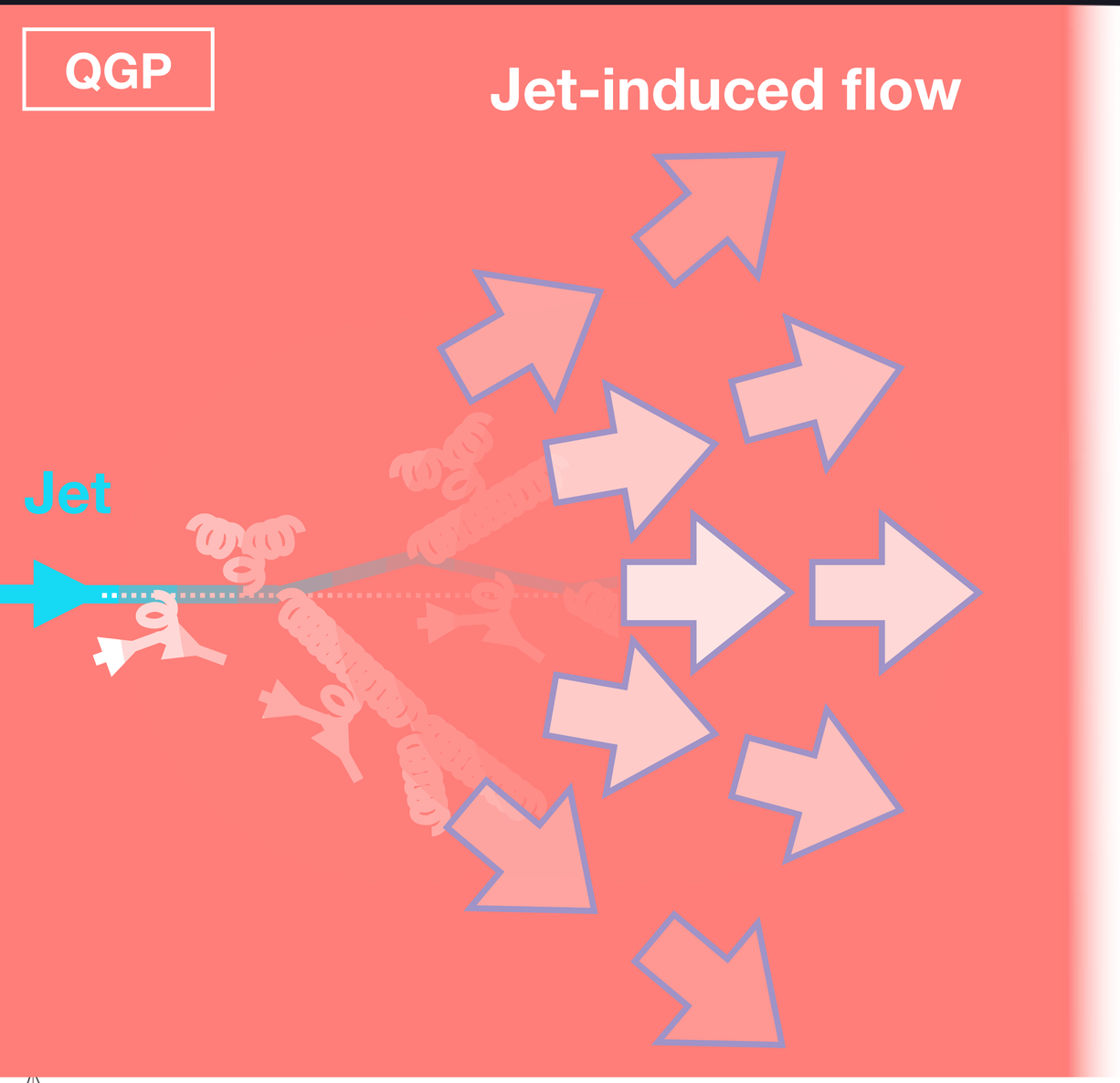
$$\nabla_\mu T^{\mu\nu}(x) = J^\nu(x)$$

$T^{\mu\nu}$: energy-momentum tensor of bulk medium

J^ν: energy-momentum exchange with the non-thermalized part of jet

- Reasonable description for $\sim E_{\mathrm{med}}$
- Strongly coupled with the other medium constituents

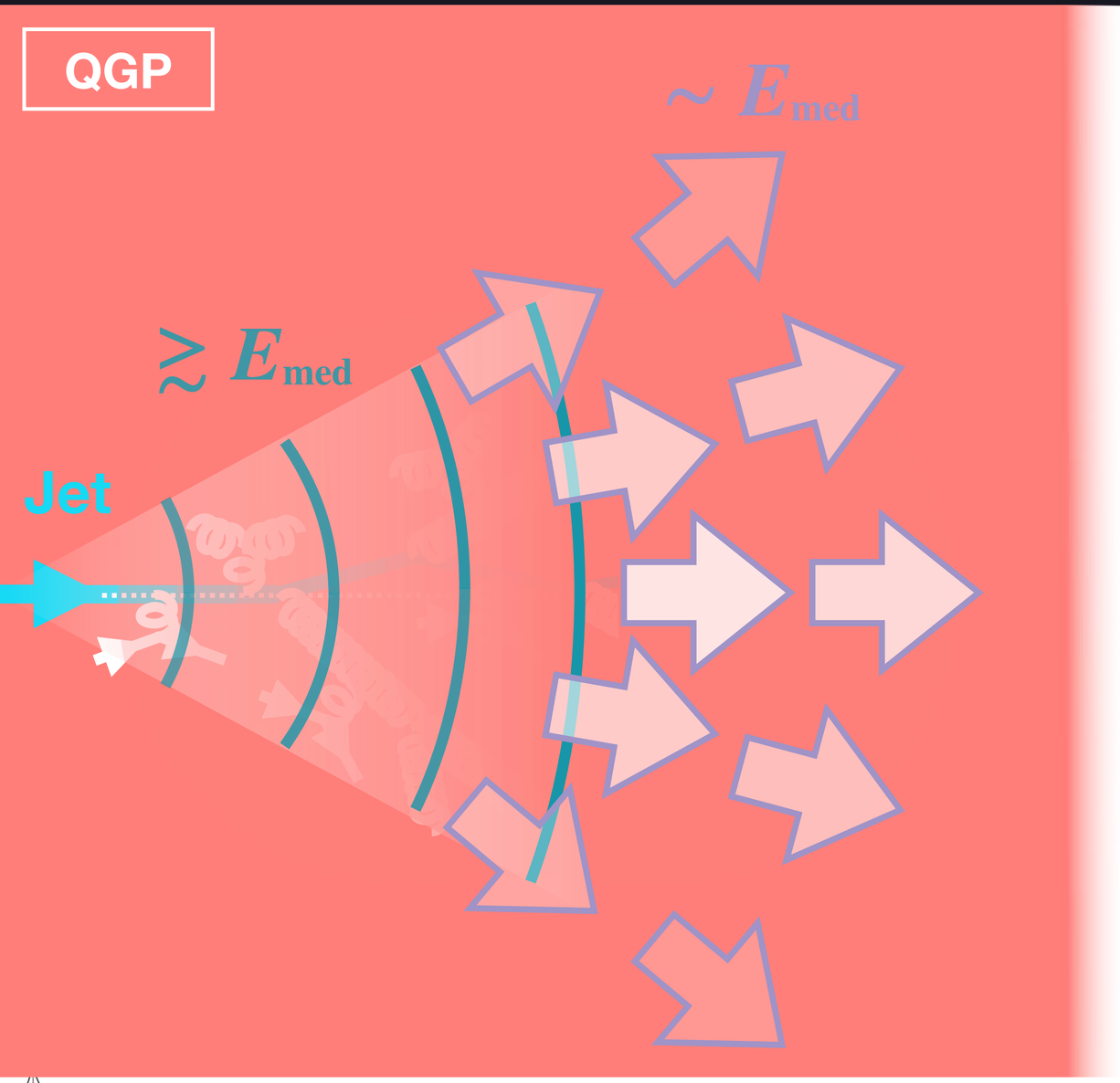
Hydrodynamic evolution of jets



Implemented in MUSIC and CLVisc

- **Jet-correlated medium hadrons**
  - Brought by jet-induced flow
  - Cannot/should not be subtracted
  - Calculated by Cooper-Frye together with the entire bulk medium
  - Require appropriate background subtraction

Diffusion during thermalization



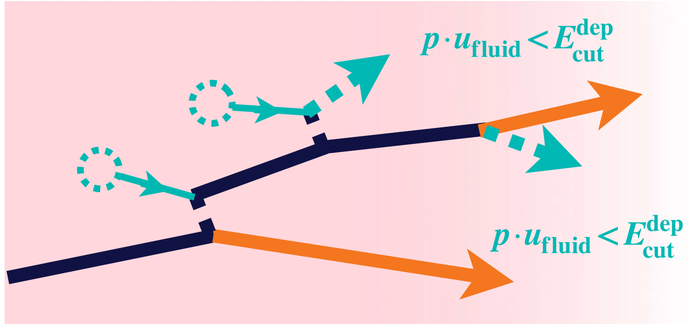
Implemented in Causal Liquefier

- **Thermalization of jet**
  - Diffusion of jet energy and momentum
  - Transition from particle ($E \gg E_{\mathrm{med}}$) to fluid field ($\sim E_{\mathrm{med}}$)
  - Provide source term J^{ν} for hydro equation

Diffusion during thermalization

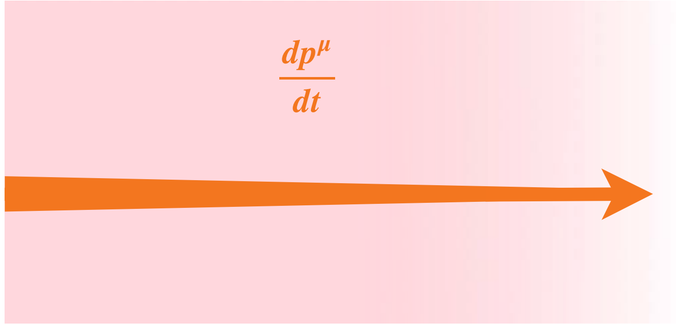
Energy-momentum deposition

- Soft parton and hole absorption (for hybrid with recoils)



- Reaction to momentum change (e.g. simulation w/ AdS/CFT module)

D.Pablos (16)



Hydro source term (J^ν) generation

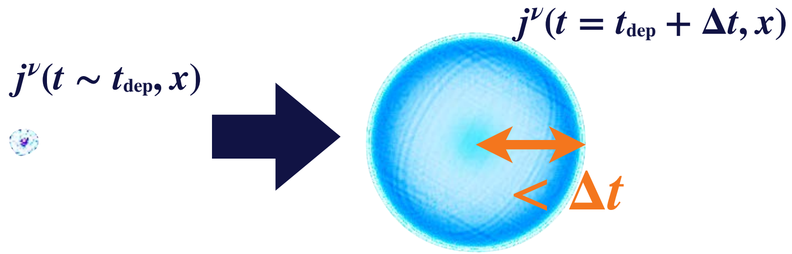
Implemented in Causal Liquefier

- 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 point-like initial condition

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



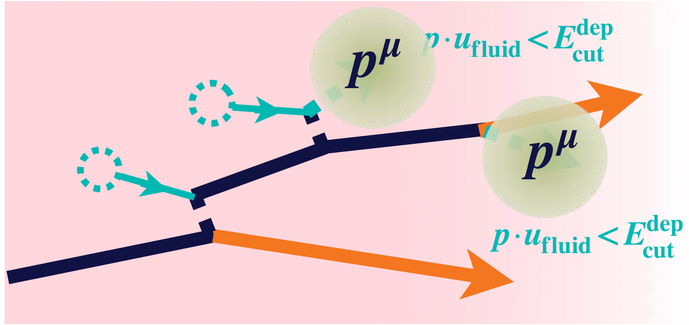
- Return analytic solution without flow or temperature effect

  → further update or new module

Diffusion during thermalization

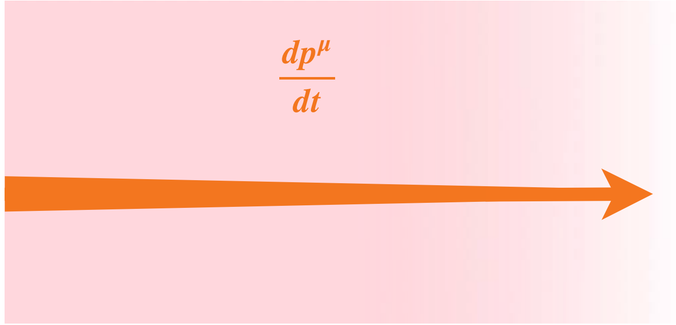
Energy-momentum deposition

- Soft parton and hole absorption (for hybrid with recoils)



- Reaction to momentum change (e.g. simulation w/ AdS/CFT module)

D.Pablos (16)



Hydro source term (J^ν) generation

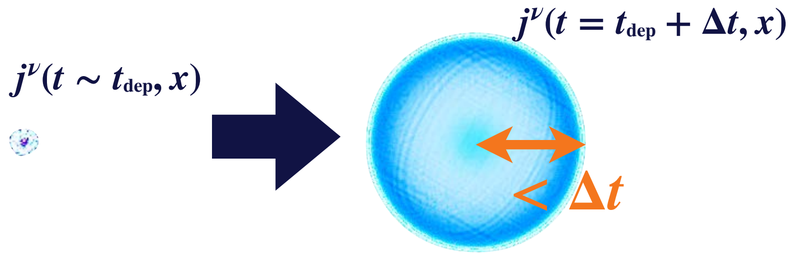
Implemented in Causal Liquefier

- 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 point-like initial condition

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



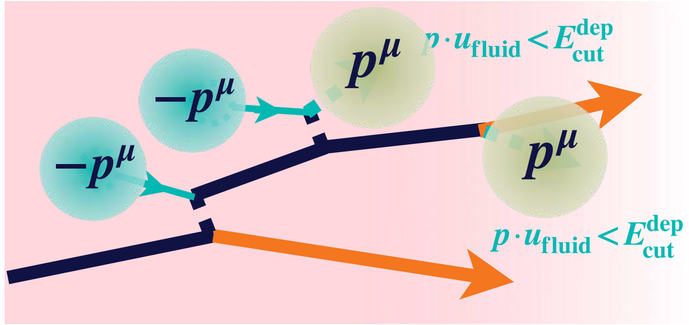
- Return analytic solution without flow or temperature effect

  → further update or new module

Diffusion during thermalization

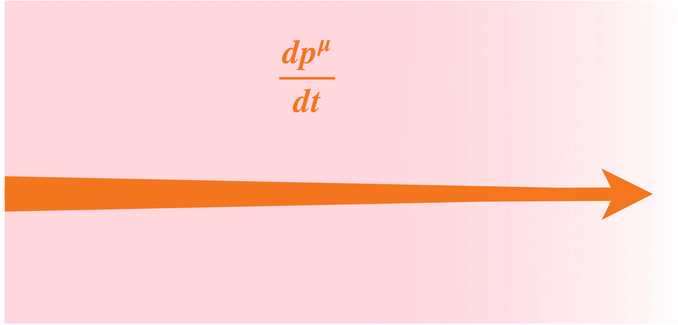
Energy-momentum deposition

- Soft parton and hole absorption (for hybrid with recoils)



- Reaction to momentum change (e.g. simulation w/ AdS/CFT module)

D.Pablos (16)



Hydro source term (J^ν) generation

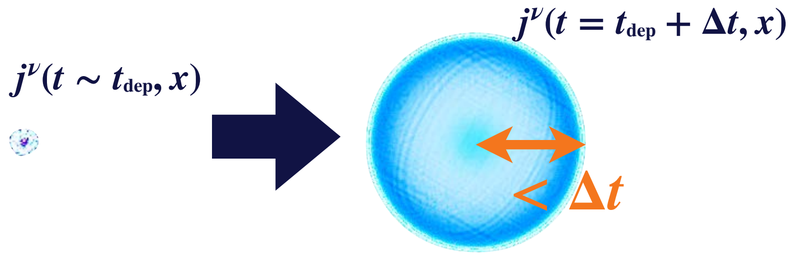
Implemented in Causal Liquefier

- 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 point-like initial condition

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



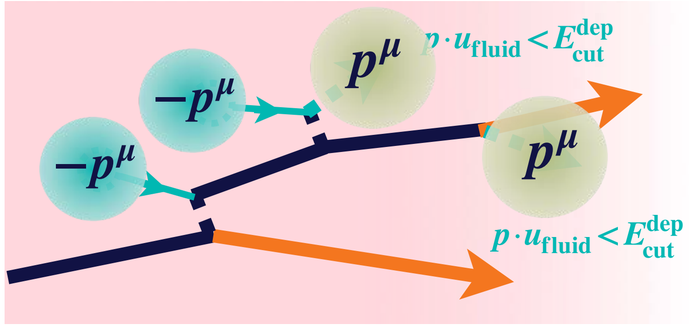
- Return analytic solution without flow or temperature effect

  → further update or new module

Diffusion during thermalization

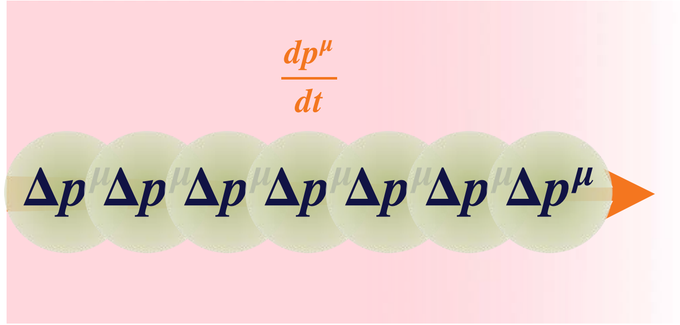
Energy-momentum deposition

- Soft parton and hole absorption (for hybrid with recoils)



- Reaction to momentum change (e.g. simulation w/ AdS/CFT module)

D.Pablos (16)



Hydro source term (J^ν) generation

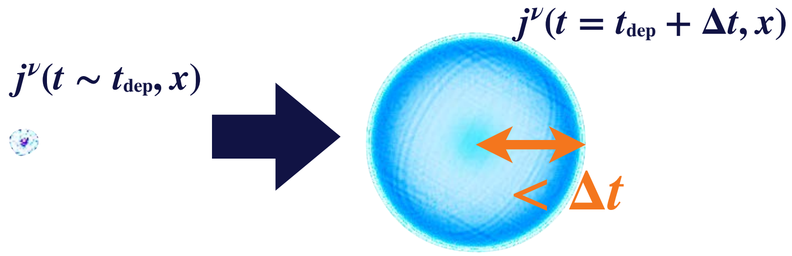
Implemented in Causal Liquefier

- 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 point-like initial condition

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



- Return analytic solution without flow or temperature effect

  → further update or new module

Results from JETSCAPE simulations with recoil medium response

Jet simulation with recoils using JETSCAPE

- p+p simulation setup JETSCAPE PRC102, 054906 (2020)

Jet simulation with recoils using JETSCAPE

- p+p **simulation setup** JETSCAPE PRC102, 054906 (2020)

Jet Shower

Hard Scattering: Pythia8 (w/ ISR FSR)
Parton Shower: MATTER (vacuum)
Hadronization: Lund String

Jet simulation with recoils using JETSCAPE

- p+p **simulation setup** JETSCAPE PRC102, 054906 (2020)

Jet Shower

Hard Scattering: Pythia8 (w/ ISR FSR)
Parton Shower: MATTER (vacuum)
Hadronization: Lund String

JETSCAPE PP19 tune [jetscape_user_PP19.xml]

Jet simulation with recoils using JETSCAPE

- p+p simulation setup JETSCAPE PRC102, 054906 (2020)

Jet Shower

Hard Scattering: Pythia8 (w/ ISR FSR)
Parton Shower: MATTER (vacuum)
Hadronization: Lund String

JETSCAPE PP19 tune [jetscape_user_PP19.xml]

- A+A simulation setup JETSCAPE, arXiv:2204.01163

Jet simulation with recoils using JETSCAPE

- ***p*+*p* simulation setup** JETSCAPE PRC102, 054906 (2020)

Jet Shower

Hard Scattering: Pythia8 (w/ ISR FSR)
Parton Shower: MATTER (vacuum)
Hadronization: Lund String

JETSCAPE PP19 tune [jetscape_user_PP19.xml]

- **A+A simulation setup** JETSCAPE, arXiv:2204.01163

Jet Shower

Hard Scattering: Pythia8 (w/ ISR FSR)
Parton Shower: MATTER+LBT (recoil on, $Q_{sw} = 2$ GeV)
Hadronization: Lund String

Jet simulation with recoils using JETSCAPE

- ***p+p* simulation setup** JETSCAPE PRC102, 054906 (2020)

Jet Shower

Hard Scattering: Pythia8 (w/ ISR FSR)
Parton Shower: MATTER (vacuum)
Hadronization: Lund String

JETSCAPE PP19 tune [jetscape_user_PP19.xml]

- **A+A simulation setup** JETSCAPE, arXiv:2204.01163

Jet Shower

Hard Scattering: Pythia8 (w/ ISR FSR)
Parton Shower: MATTER+LBT (recoil on, $Q_{\rm sw} = 2$ GeV)
Hadronization: Lund String

Initial Condition
$T(x)$
$u^{\mu}(x)$

Bulk Medium

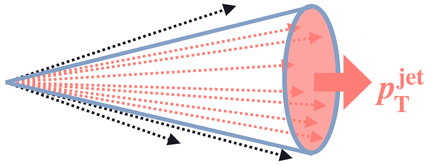
Initial Condition: TRENTo+Freestreaming
Moreland, Bernhard, Bass (14) , Liu, Shen, Heinz(15)
Hydro Evolution: VISHNU (2+1D viscous)
Shen, Qiu, Song, Bernhard, Bass, Heinz(16)

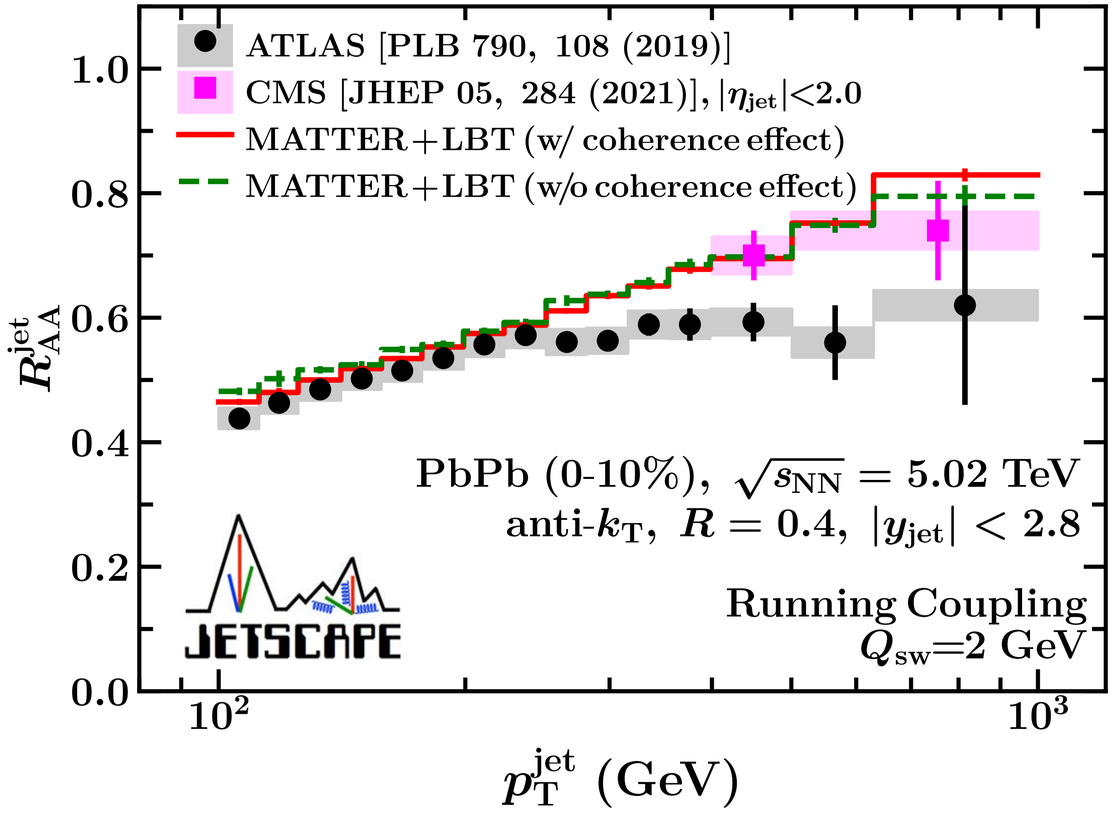
Jet and single particle energy loss

JETSCAPE, arXiv:2204.01163

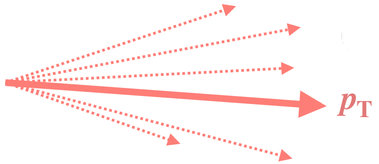
- **Pb+Pb collisions at 5.02 TeV**

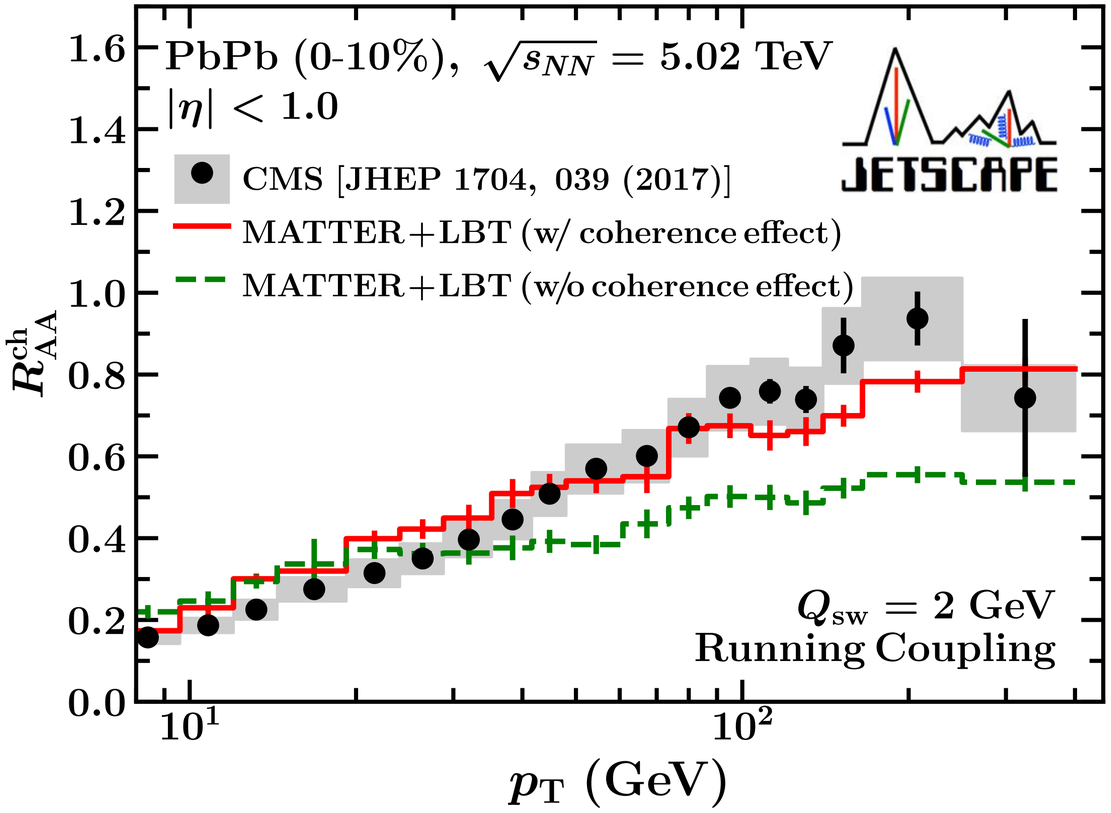
Inclusive jet R_{AA}





Charged particle R_{AA}



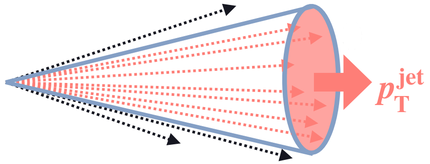


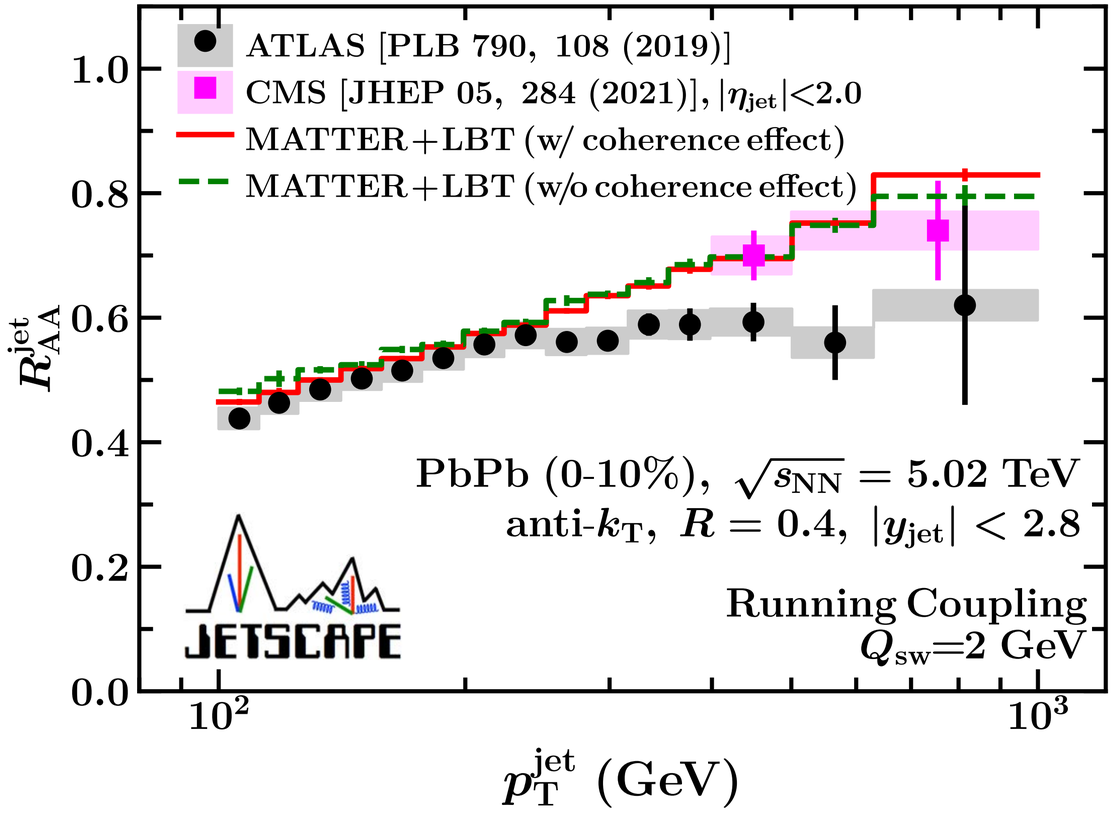
Jet and single particle energy loss

JETSCAPE, arXiv:2204.01163

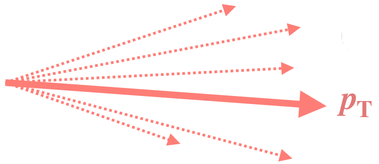
- **Pb+Pb collisions at 5.02 TeV**

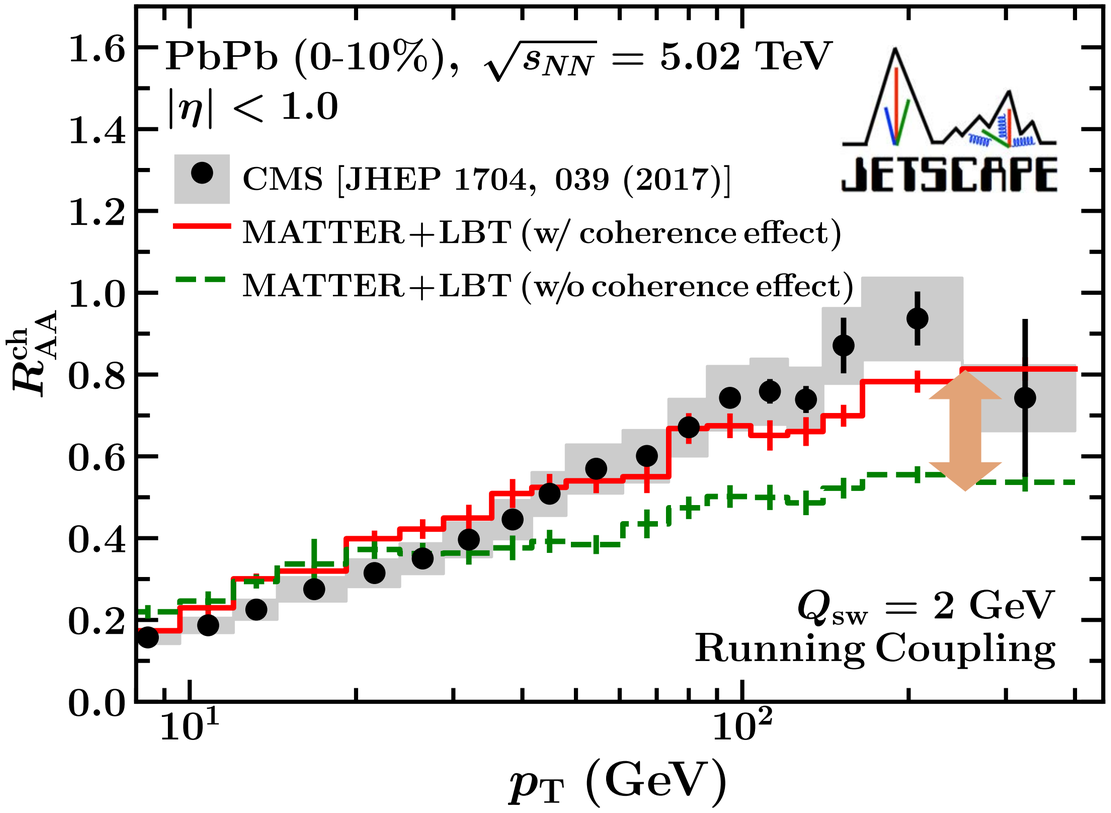
Inclusive jet R_{AA}





Charged particle R_{AA}



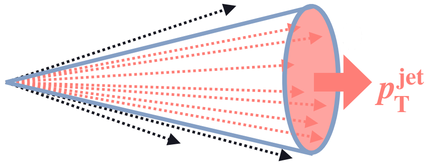


Jet and single particle energy loss

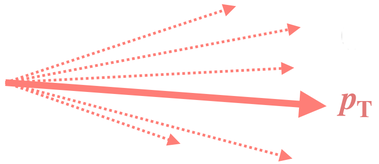
JETSCAPE, arXiv:2204.01163

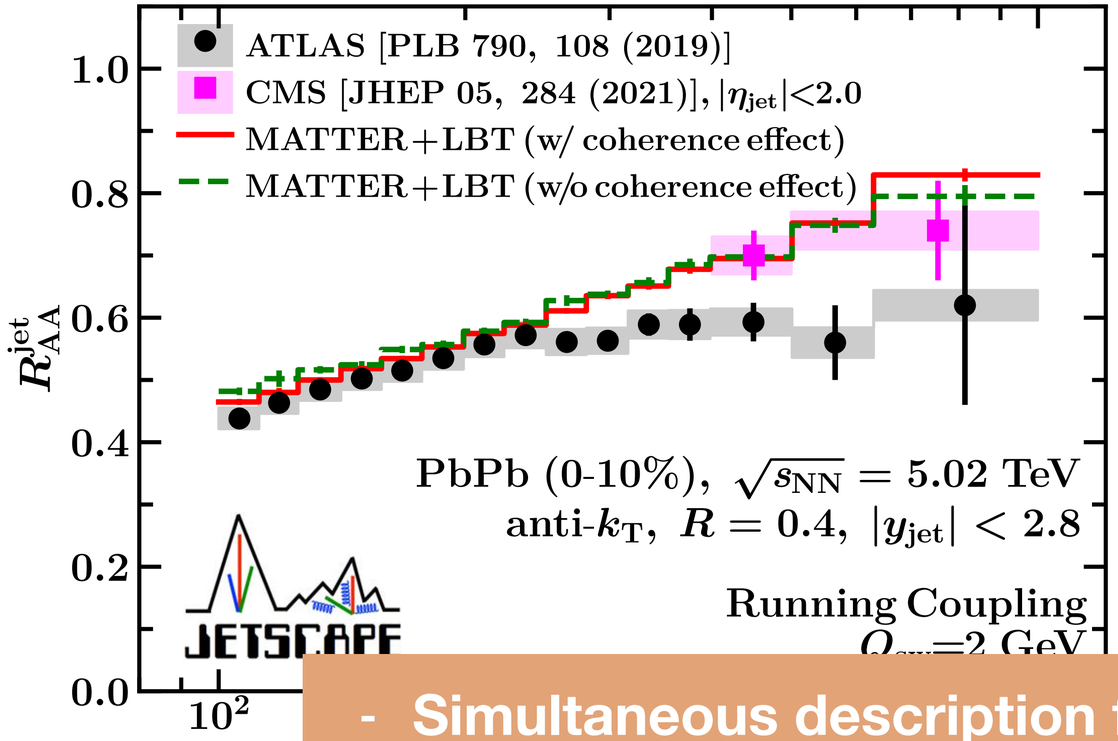
- **Pb+Pb collisions at 5.02 TeV**

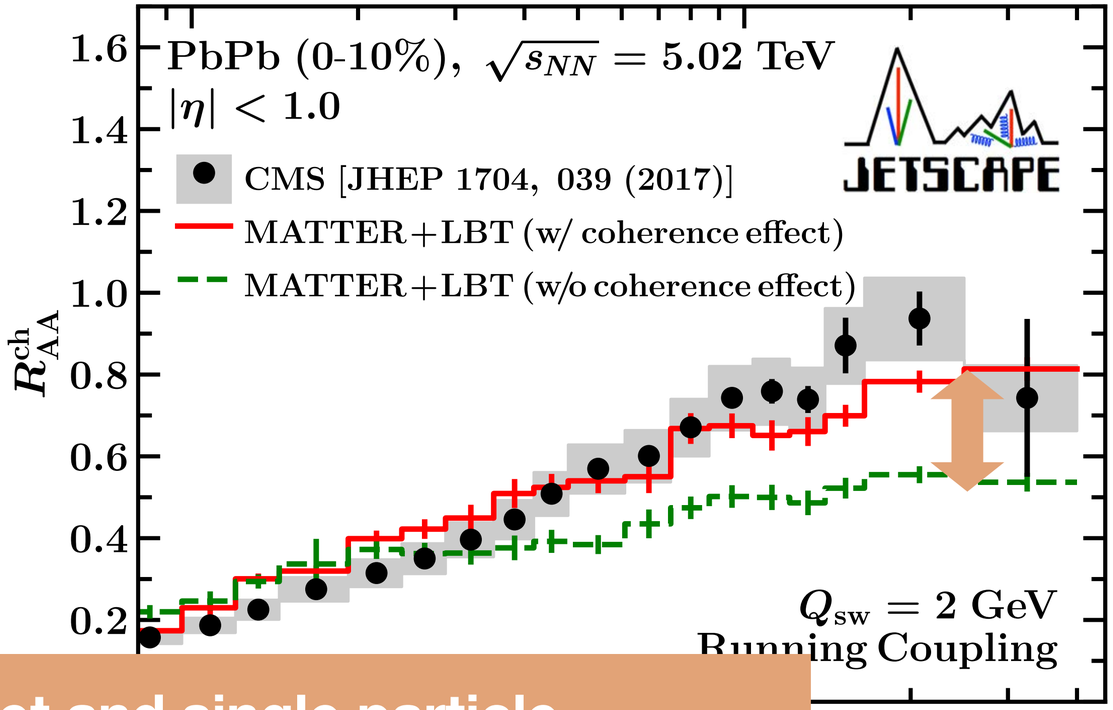
Inclusive jet R_{AA}



Charged particle R_{AA}







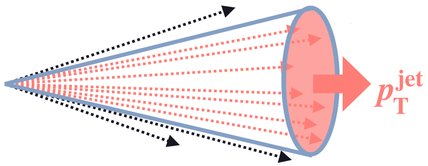
- Simultaneous description for jet and single particle
- Significant coherence effect in single particle energy loss

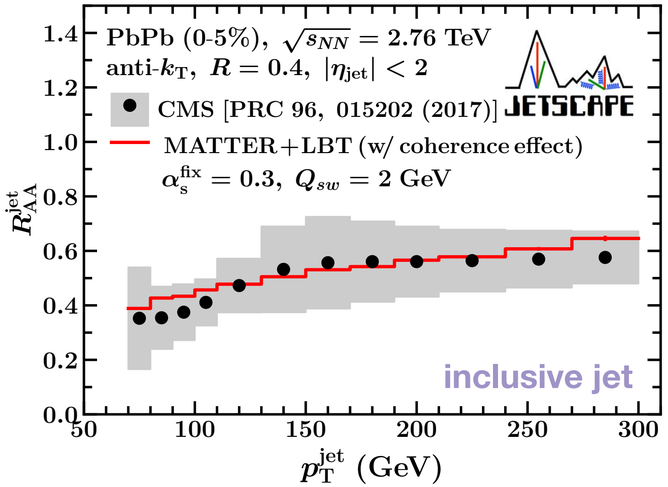
Jet and single particle energy loss

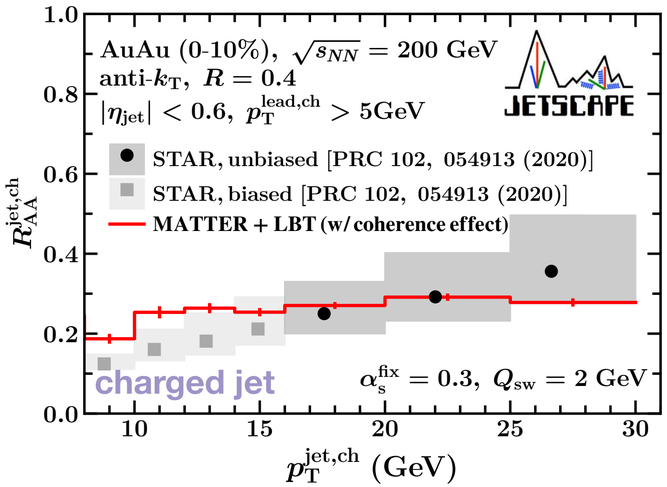
JETSCAPE, arXiv:2204.01163

- **Pb+Pb at 2.76 TeV**
- **Au+Au at 200 GeV**

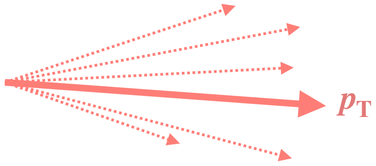
Jet R_{AA}

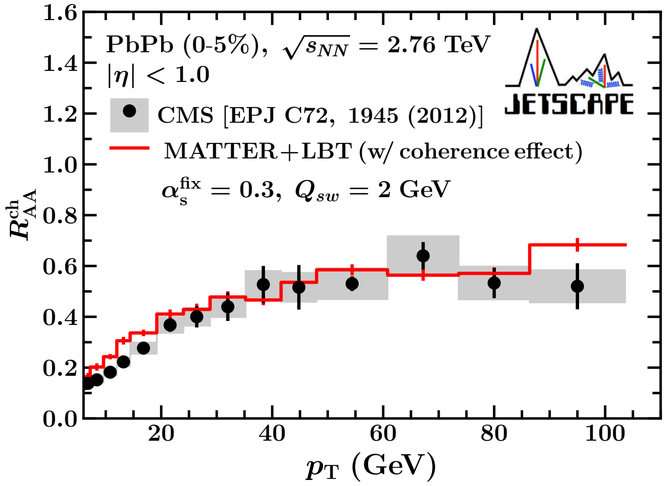


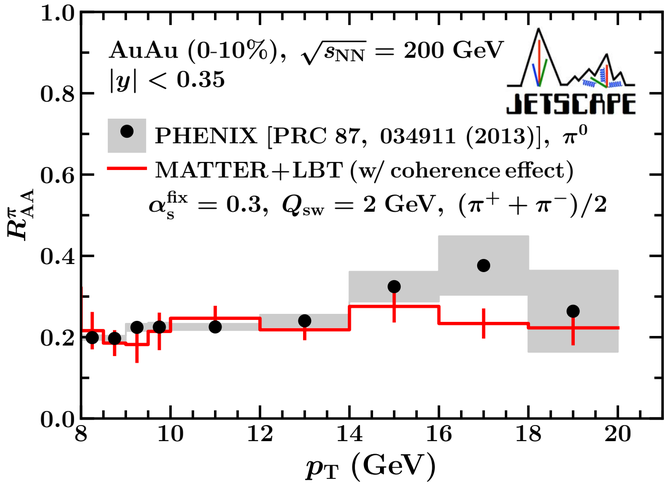




Particle R_{AA}







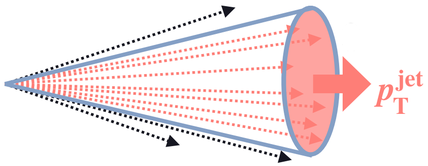
The same parameter set is used for all $\sqrt{s_{NN}}$

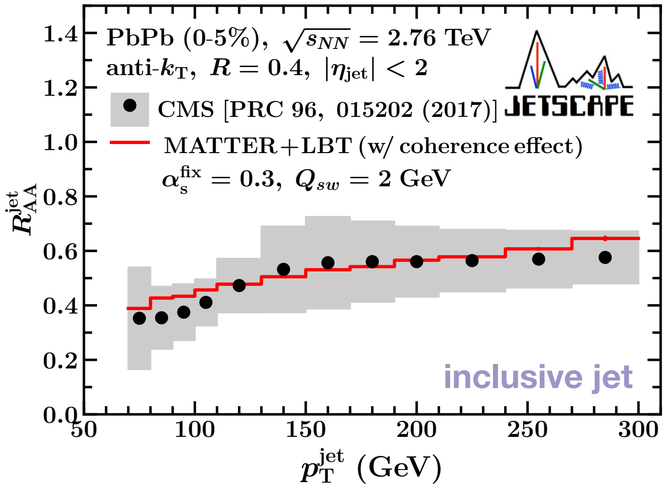
Jet and single particle energy loss

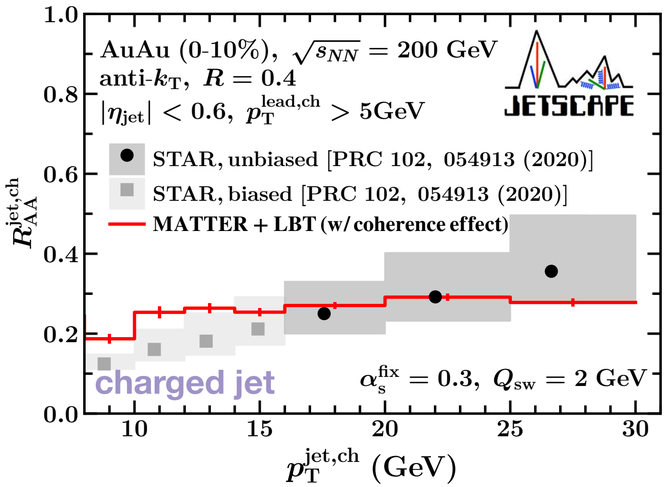
JETSCAPE, arXiv:2204.01163

- **Pb+Pb at 2.76 TeV**
- **Au+Au at 200 GeV**

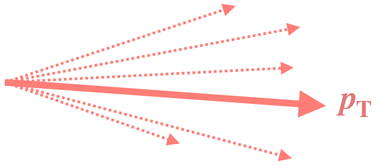
Jet R_{AA}

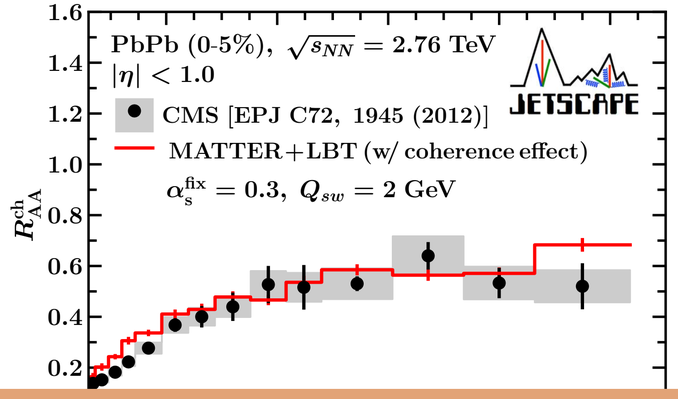


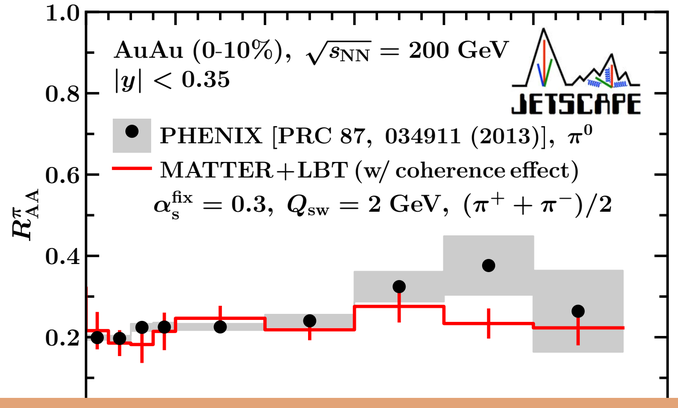




Particle R_{AA}







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

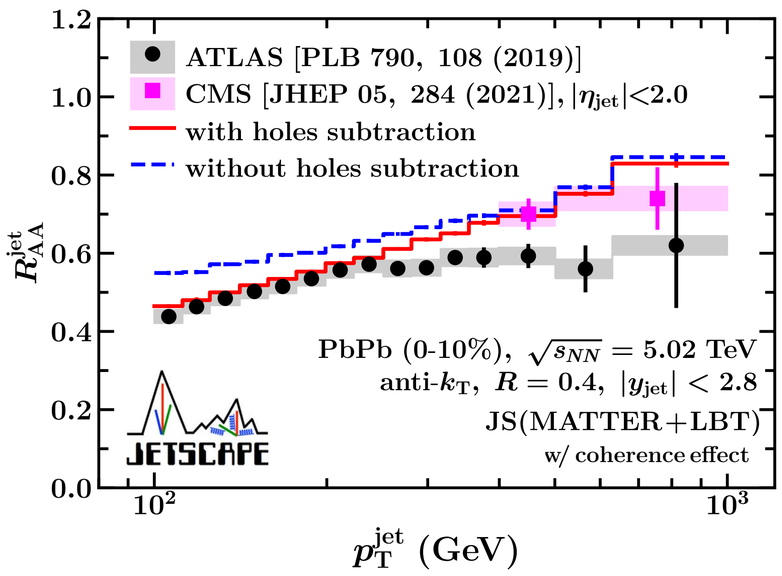
The same parameter set is used for all $\sqrt{s_{NN}}$

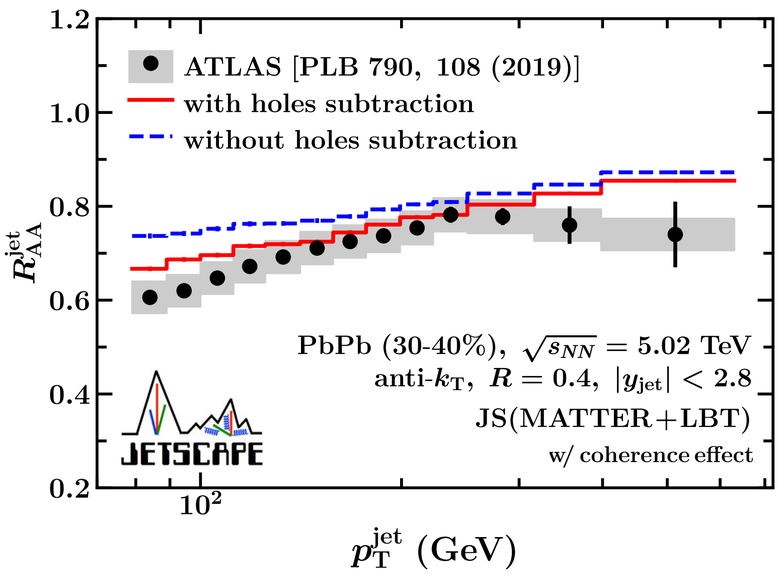
Recoils' contribution to jet R_{AA}

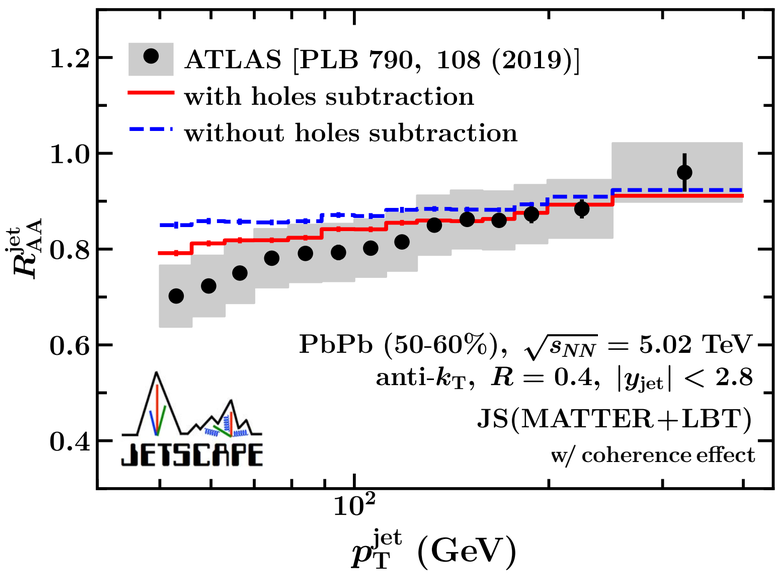
JETSCAPE, arXiv:1903.07706

- **Pb+Pb collisions at 5.02 TeV**
  - With VS without the hole subtraction

$$p_T^{jet} = p_T^{shower} - \sum_{holes \in jet\ cone} p_T$$





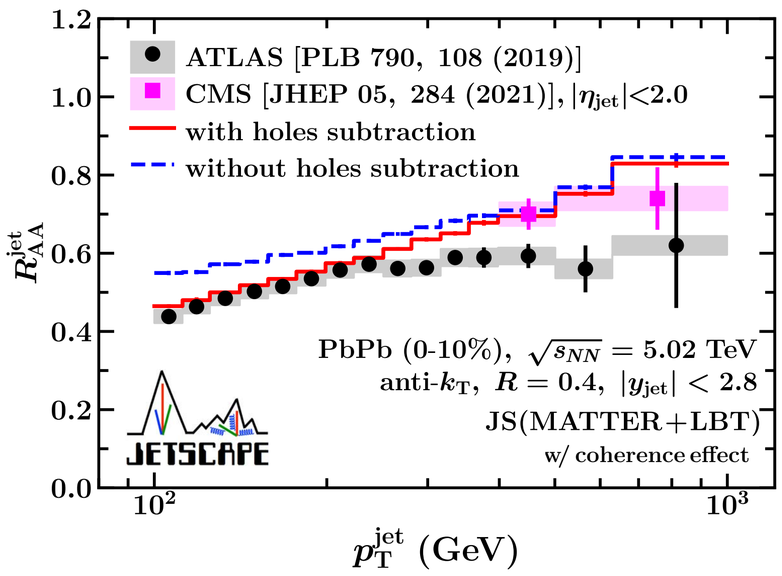


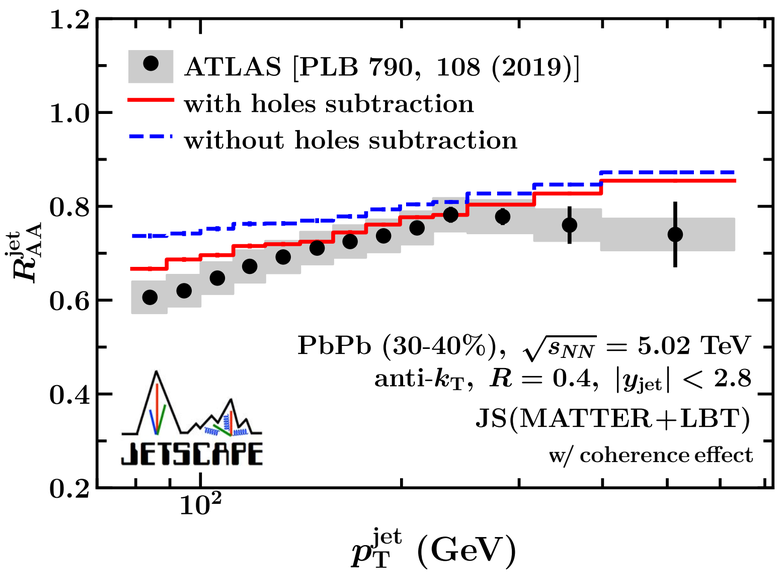
Recoils' contribution to jet R_{AA}

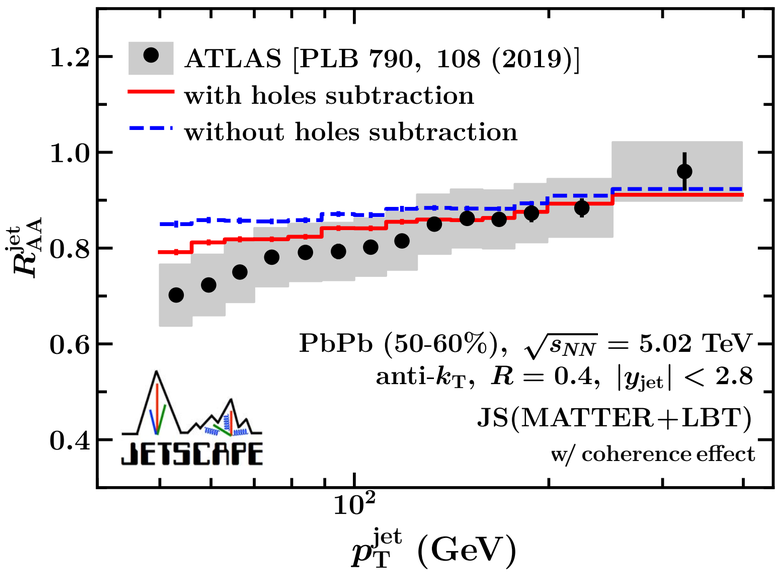
JETSCAPE, arXiv:1903.07706

- **Pb+Pb collisions at 5.02 TeV**
  - With VS without the hole subtraction

$$p_T^{jet} = p_T^{shower} - \sum_{holes \in jet\ cone} p_T$$







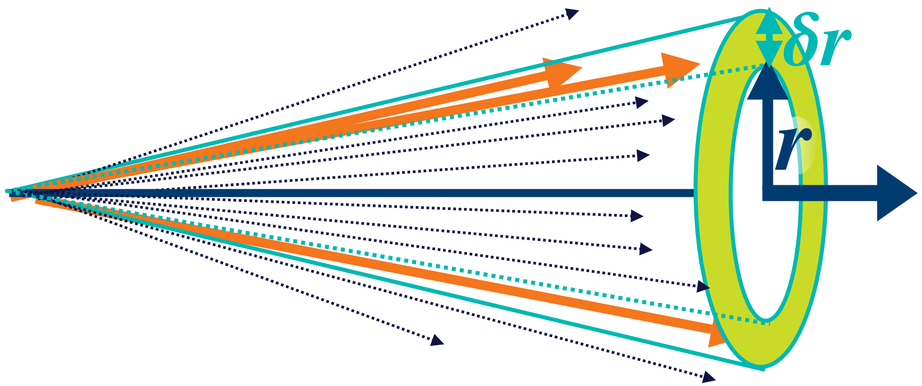
- **Significant for lower-p_T jets even in peripheral**

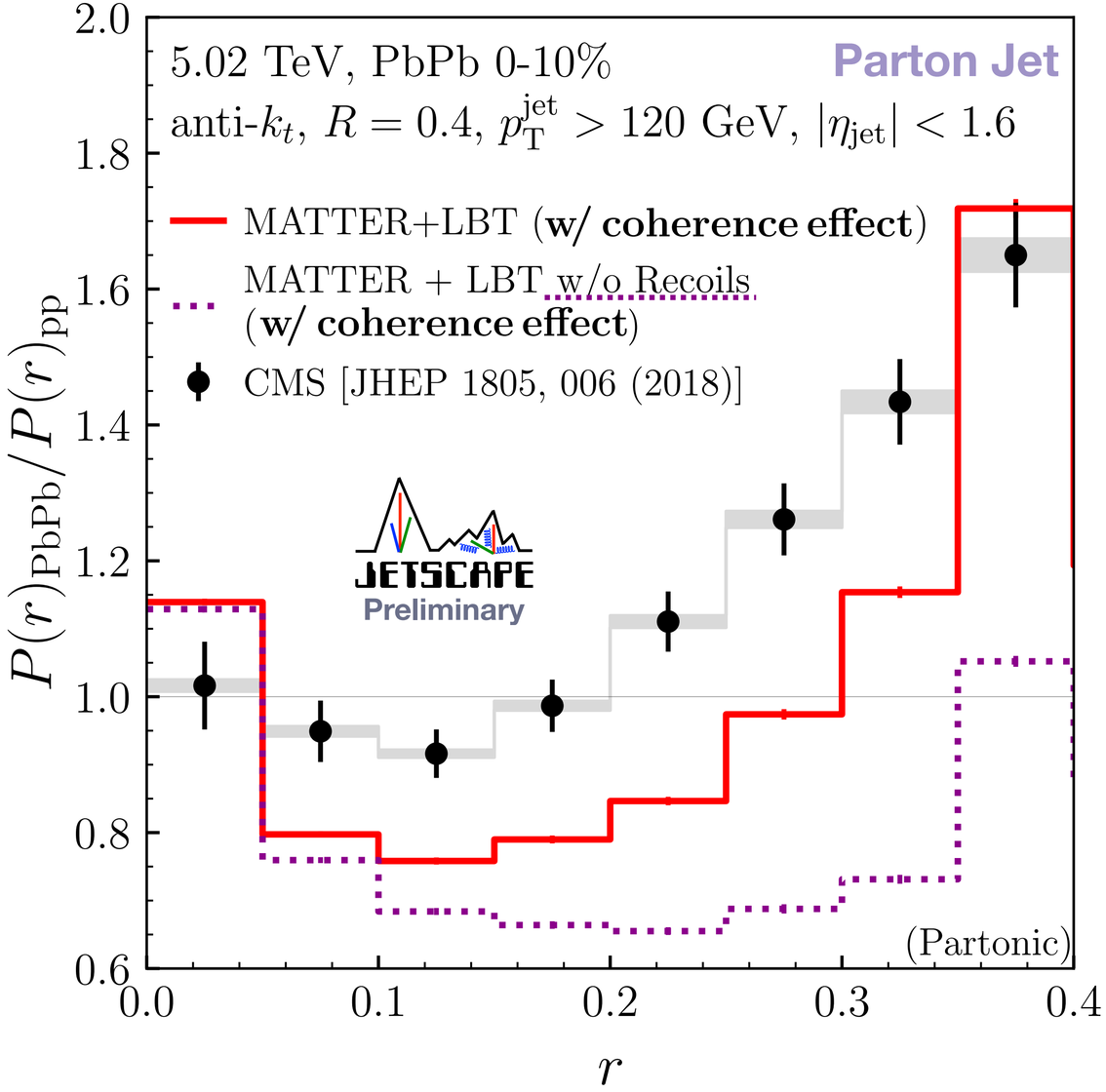
Recoils' contribution in Jet Substructures

JETSCAPE (in preparation)

- **Jet shape function**
  - Angular structure of jet

$$P(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{\sum_{\text{trk}\in(r\pm\delta r/2)} p_{\text{T}}^{\text{trk}}}{\delta r}$$



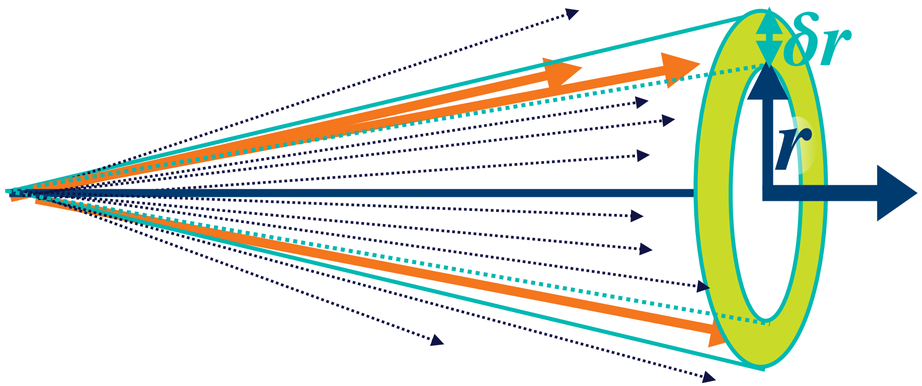


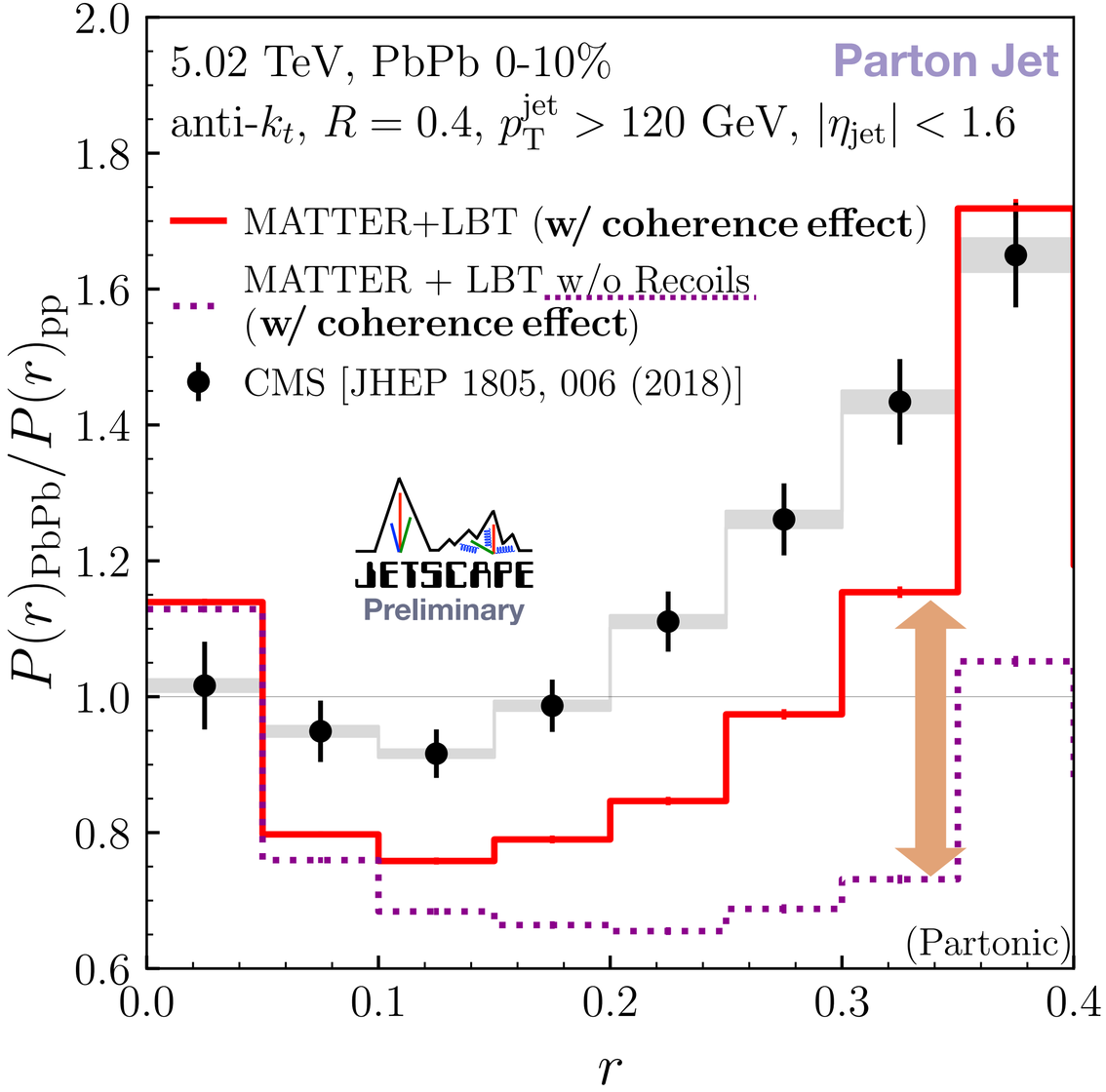
Recoils' contribution in Jet Substructures

JETSCAPE (in preparation)

- **Jet shape function**
  - Angular structure of jet

$$P(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{\sum_{\text{trk}\in(r\pm\delta r/2)} p_{\text{T}}^{\text{trk}}}{\delta r}$$



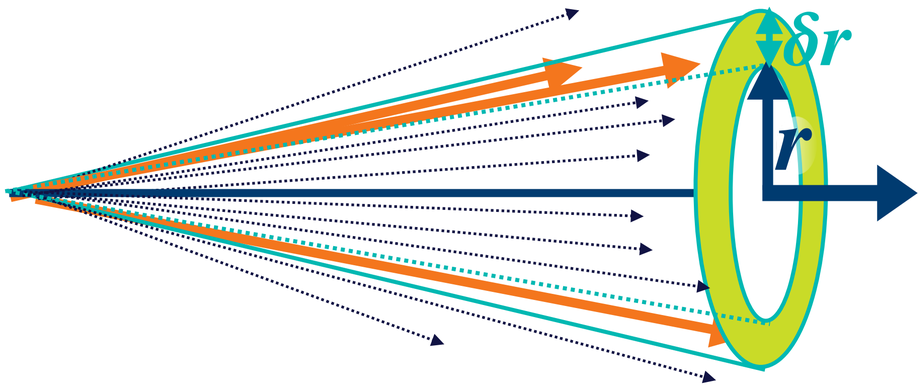


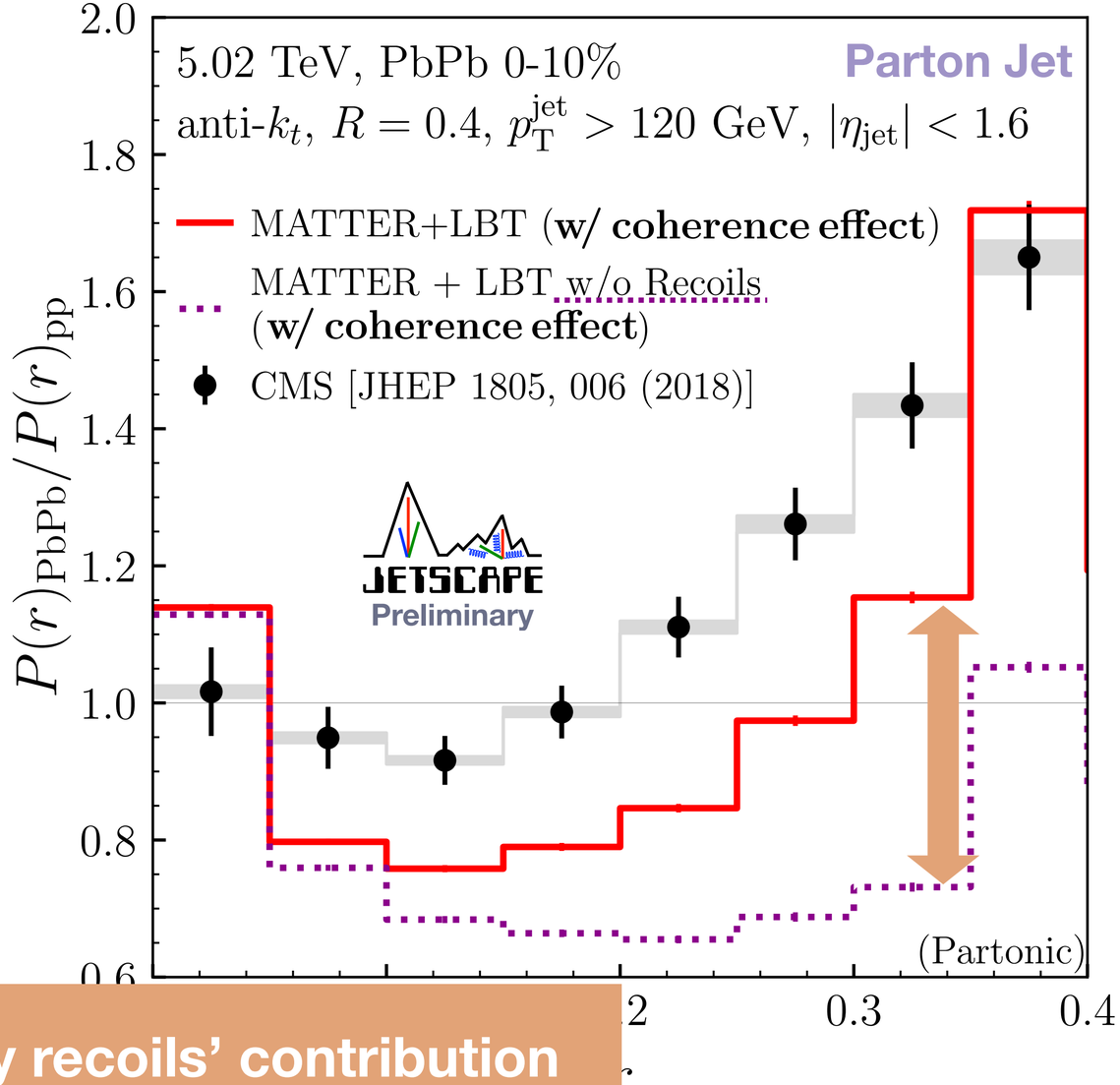
Recoils' contribution in Jet Substructures

JETSCAPE (in preparation)

- **Jet shape function**
  - Angular structure of jet

$$P(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{\sum_{\text{trk}\in(r\pm\delta r/2)} p_{\text{T}}^{\text{trk}}}{\delta r}$$





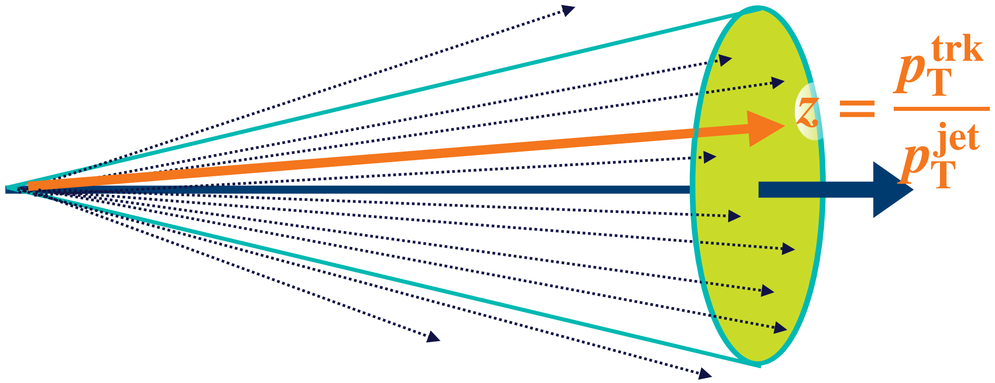
- **Broadening at large-*r* by recoils' contribution**

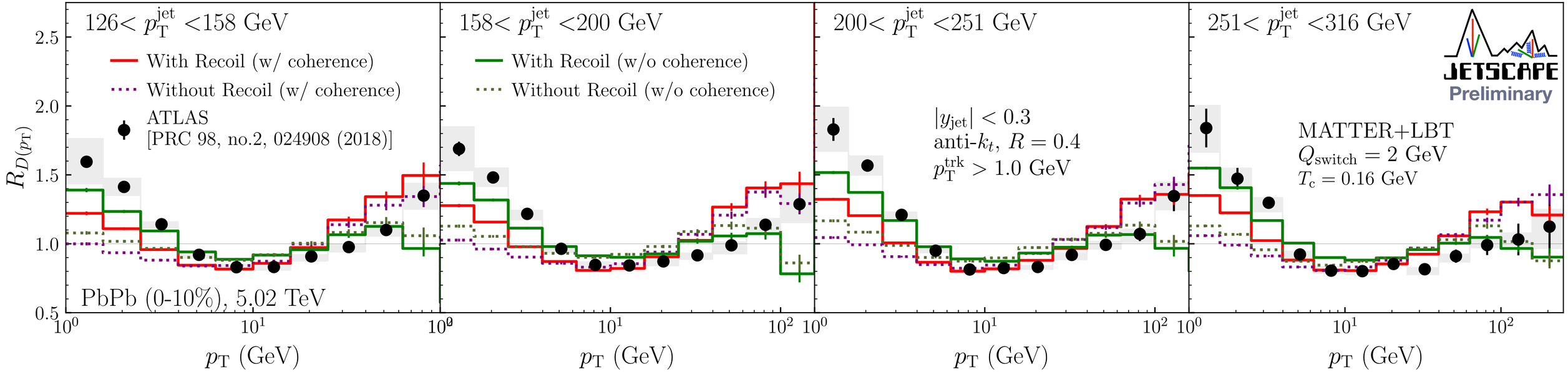
Recoils' contribution in Jet Substructures

JETSCAPE (in preparation)

- **Jet fragmentation**
  - Momentum structure of jet

$$D(z) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{dN_{\text{trk}}}{dz}\bigg|_{\text{in jet}}$$



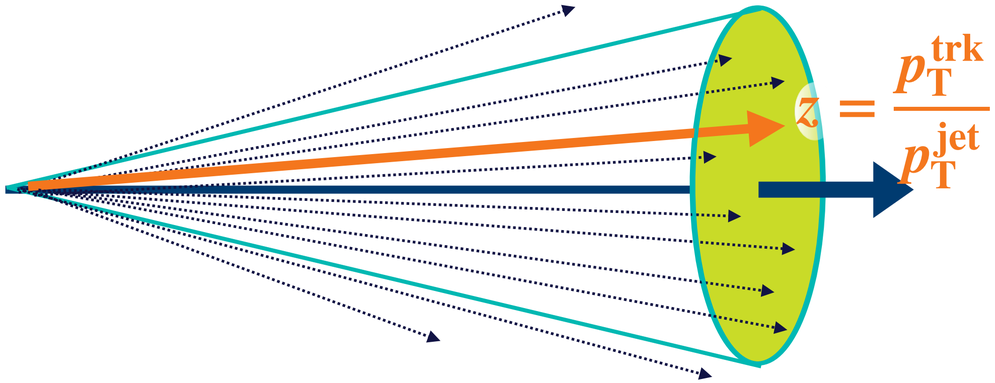


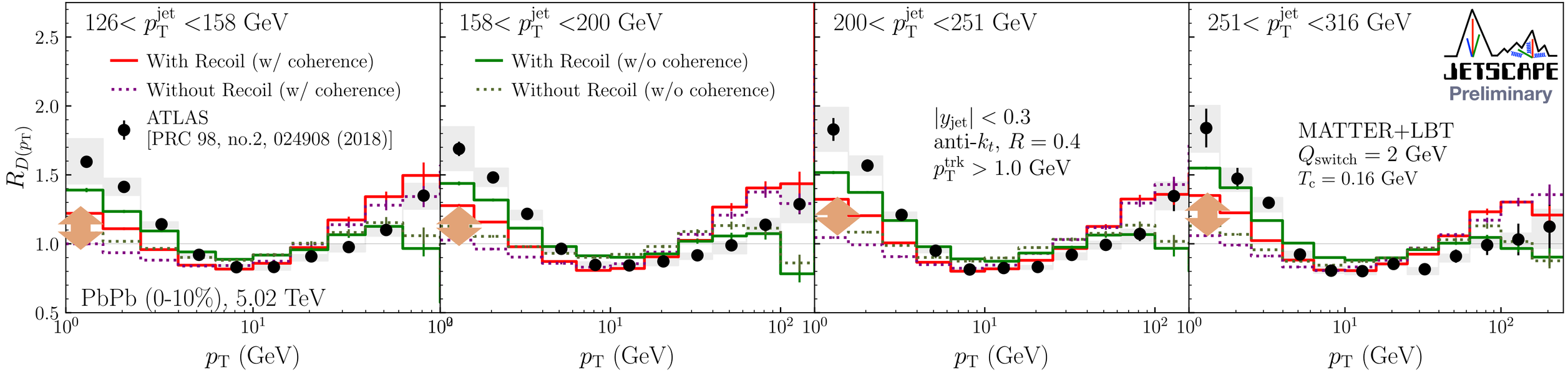
Recoils' contribution in Jet Substructures

JETSCAPE (in preparation)

- **Jet fragmentation**
  - Momentum structure of jet

$$D(z) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{dN_{\text{trk}}}{dz}\Bigg|_{\text{in jet}}$$



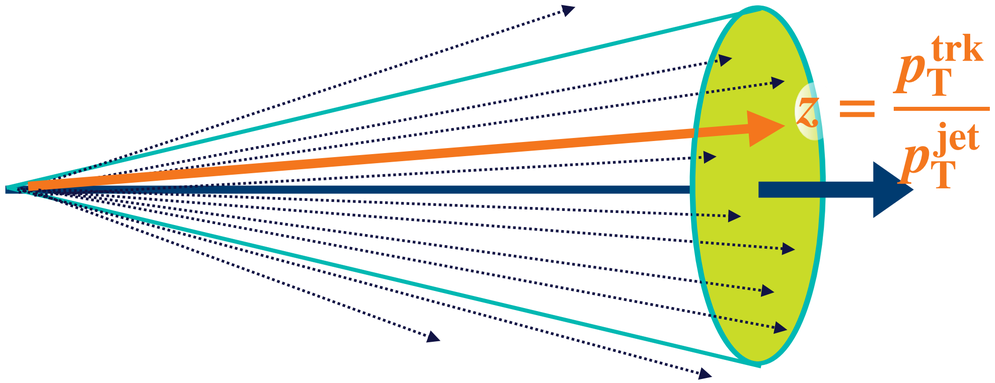


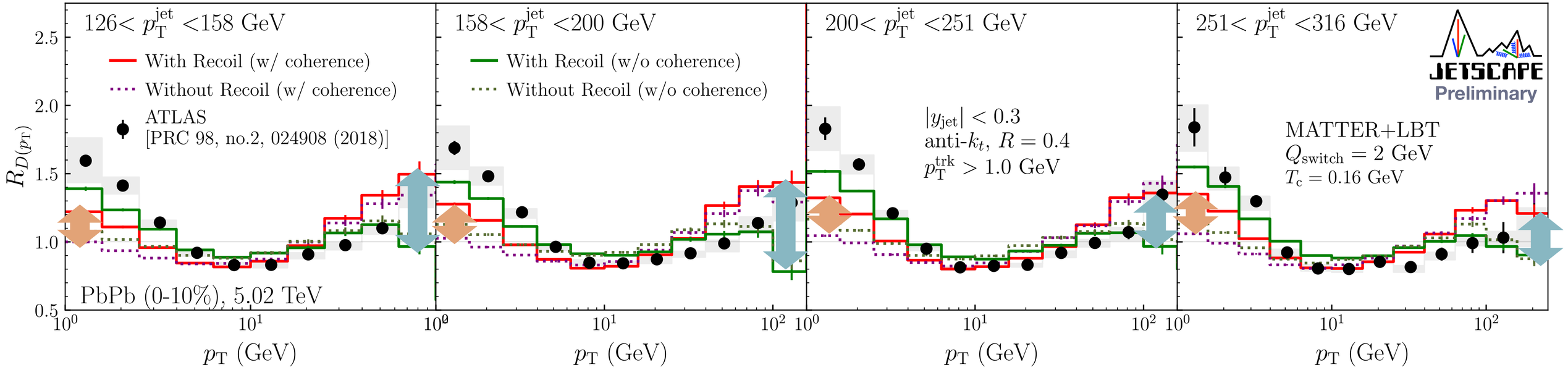
Recoils' contribution in Jet Substructures

JETSCAPE (in preparation)

- **Jet fragmentation**
  - Momentum structure of jet

$$D(z) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{dN_{\text{trk}}}{dz}\Bigg|_{\text{in jet}}$$



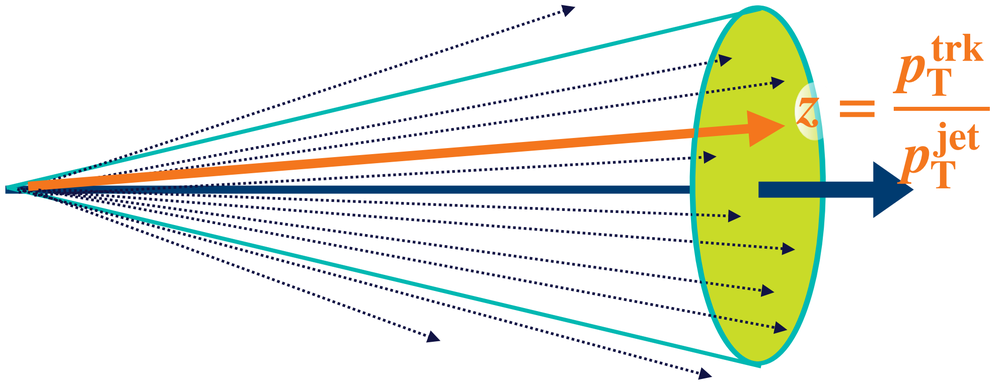


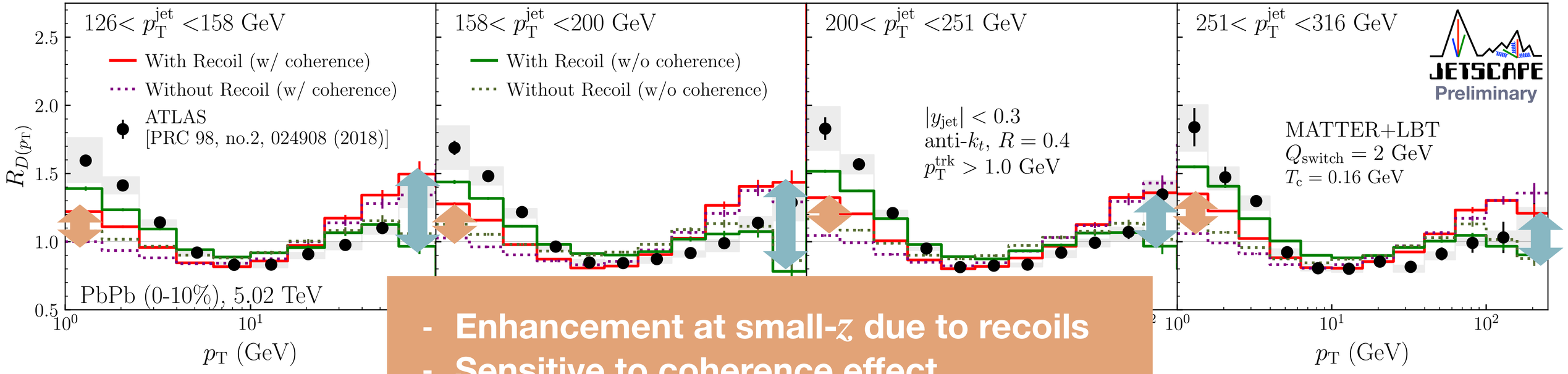
Recoils' contribution in Jet Substructures

JETSCAPE (in preparation)

- **Jet fragmentation**
  - Momentum structure of jet

$$D(z) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{dN_{\text{trk}}}{dz}\bigg|_{\text{in jet}}$$





- **Enhancement at small-z due to recoils**
- **Sensitive to coherence effect**

JETSCAPE simulations with hydrodynamic medium response

Hydrodynamic medium response in JETSCAPE

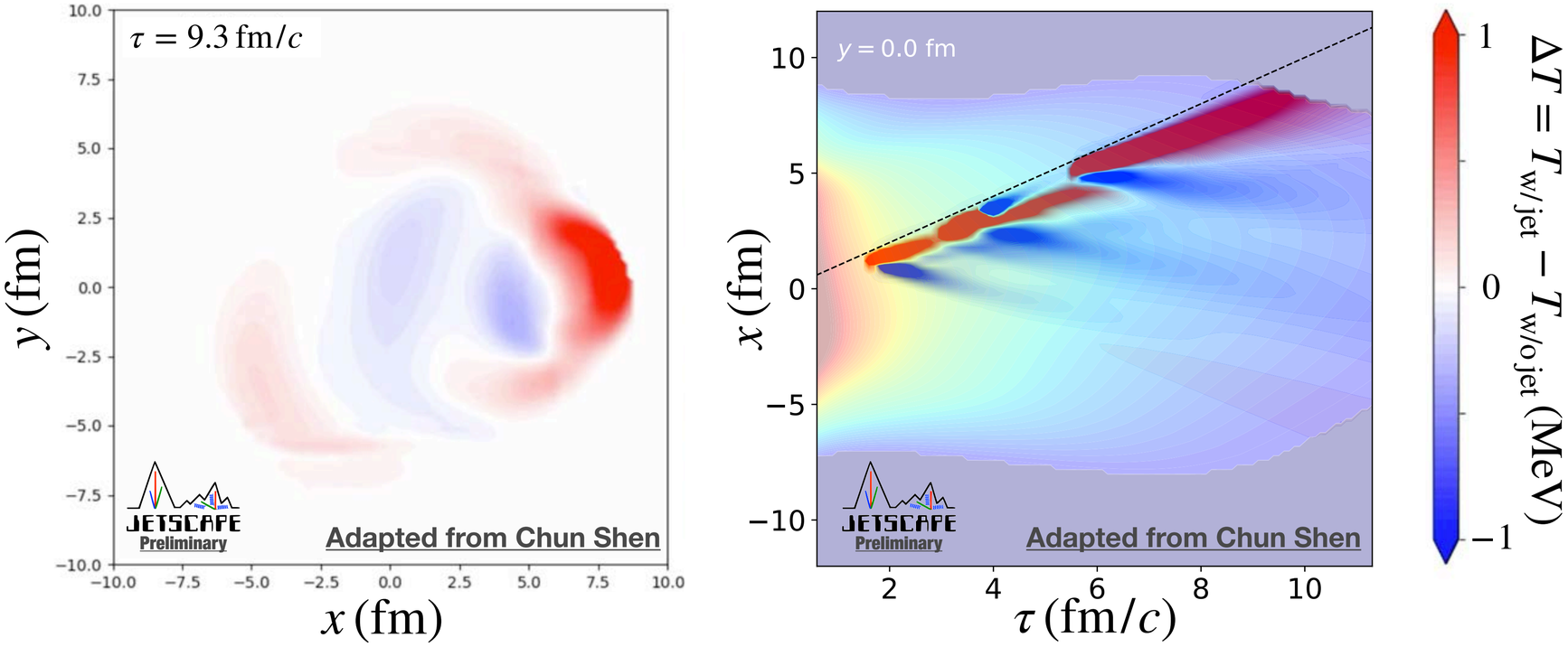
JETSCAPE (in preparation)

Jet-medium hadron correlation

- Jet following flow by positive energy deposition
- Diffusion wakes and flow by momentum picked-up from medium

Temperature field modification in medium by jet propagation

MATTER+LBT (Recoil ON) + Causal Diffusion + MUSIC Viscous Hydro



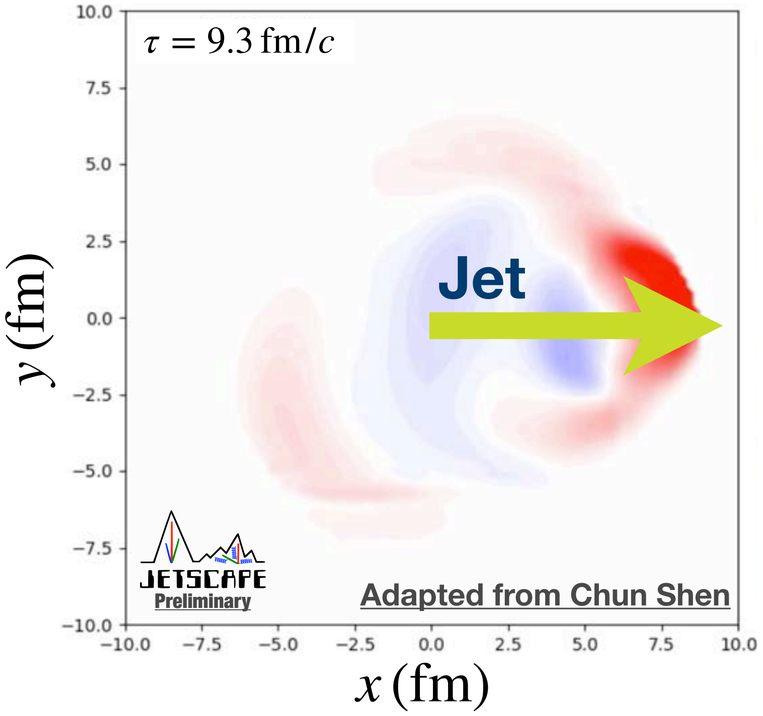
Hydrodynamic medium response in JETSCAPE

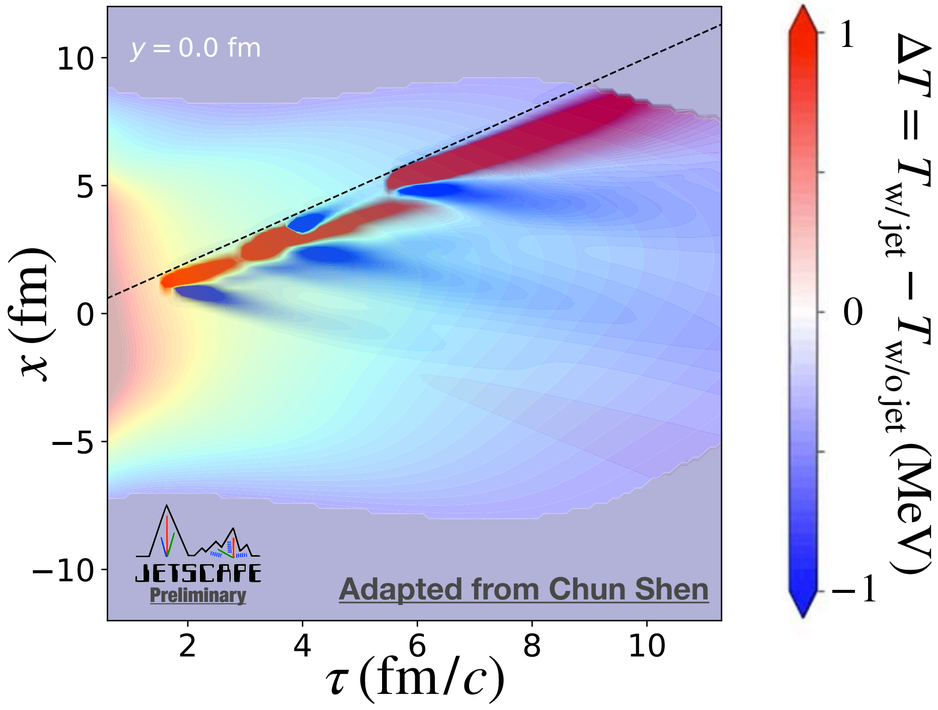
JETSCAPE (in preparation)

- **Jet-medium hadron correlation**
  - Jet following flow by positive energy deposition
  - Diffusion wakes and flow by momentum picked-up from medium

Temperature field modification in medium by jet propagation

MATTER+LBT (Recoil ON) + Causal Diffusion + MUSIC Viscous Hydro





Hydrodynamic medium response in JETSCAPE

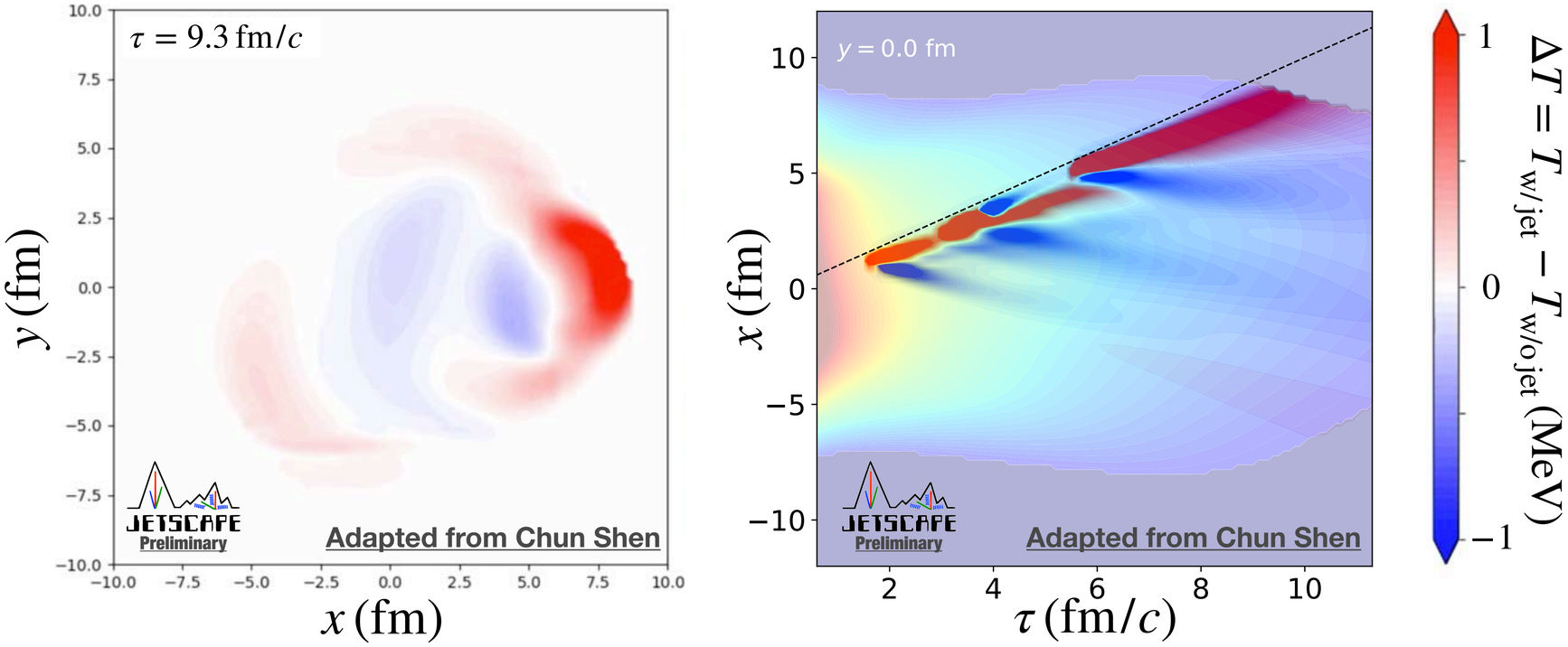
JETSCAPE (in preparation)

Jet-medium hadron correlation

- Jet following flow by positive energy deposition
- Diffusion wakes and flow by momentum picked-up from medium

Temperature field modification in medium by jet propagation

MATTER+LBT (Recoil ON) + Causal Diffusion + MUSIC Viscous Hydro



Hydrodynamic medium response in JETSCAPE

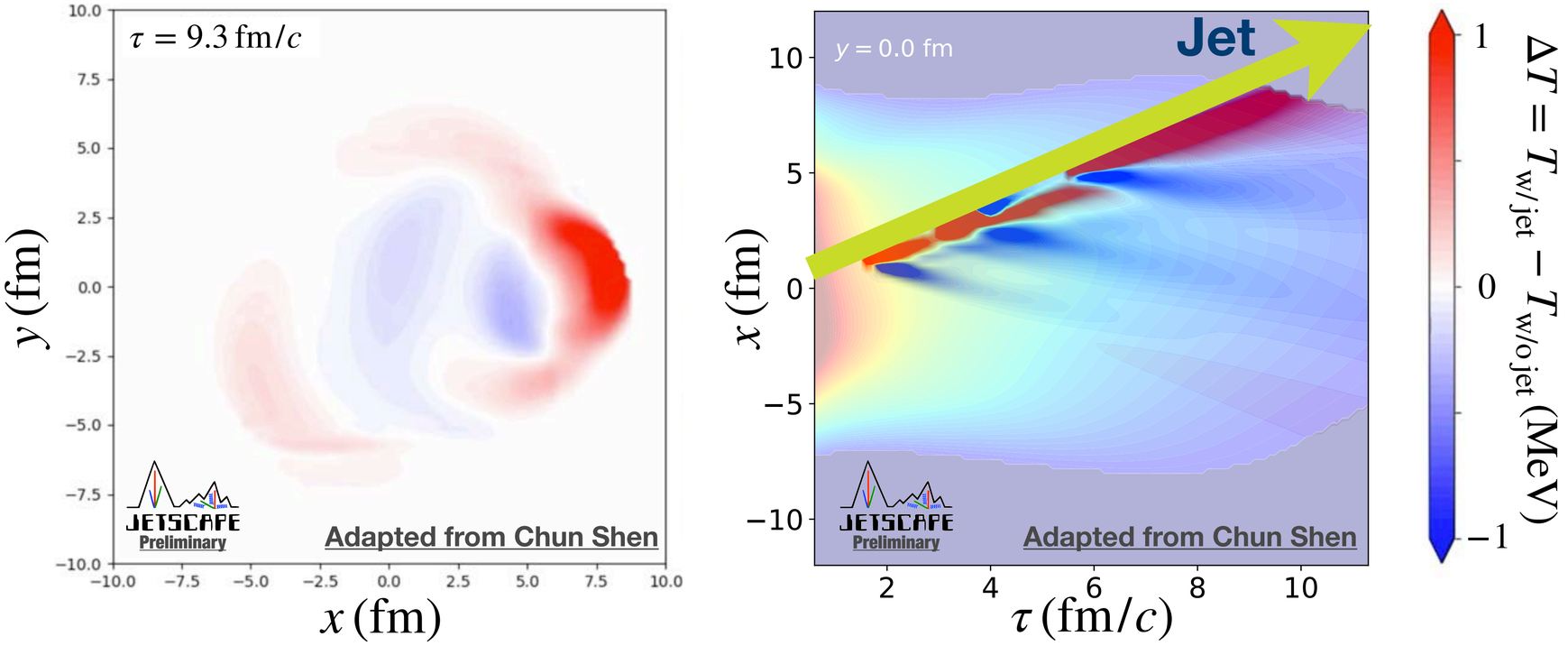
JETSCAPE (in preparation)

Jet-medium hadron correlation

- Jet following flow by positive energy deposition
- Diffusion wakes and flow by momentum picked-up from medium

Temperature field modification in medium by jet propagation

MATTER+LBT (Recoil ON) + Causal Diffusion + MUSIC Viscous Hydro



Hydrodynamic medium response in JETSCAPE

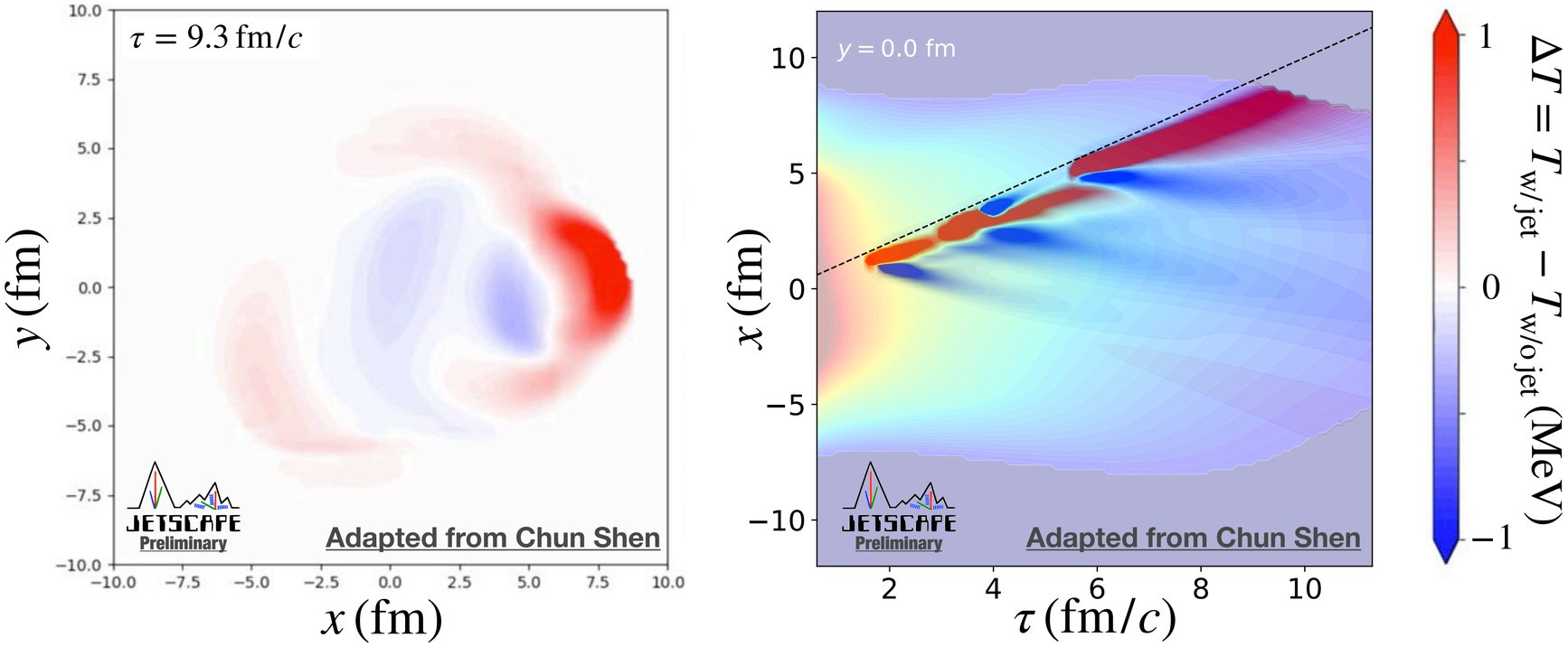
JETSCAPE (in preparation)

Jet-medium hadron correlation

- Jet following flow by positive energy deposition
- Diffusion wakes and flow by momentum picked-up from medium

Temperature field modification in medium by jet propagation

MATTER+LBT (Recoil ON) + Causal Diffusion + MUSIC Viscous Hydro



Hydrodynamic flow induced by jet momentum deposition

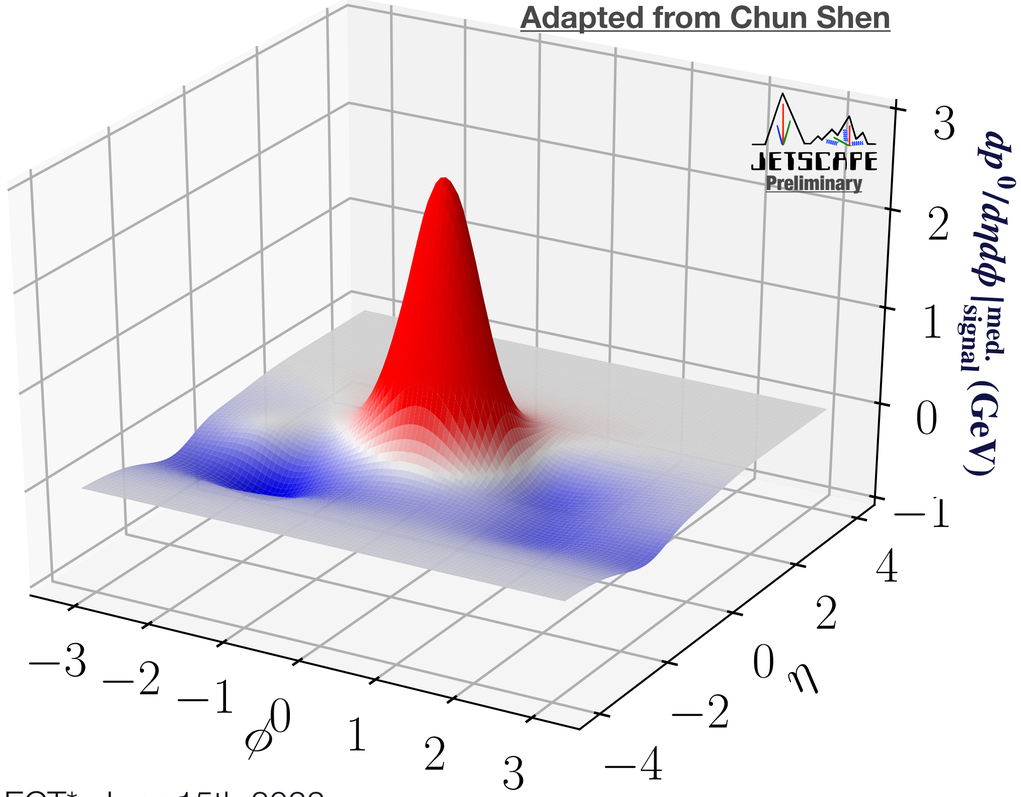
JETSCAPE (in preparation)

- **Jet-medium hadron correlation**

$$\left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{med. signal}} \quad \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{med. w/ jet}} - \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{med. w/o jet}}$$

MATTER+LBT (Recoil ON) + Causal Diffusion + Viscous Hydro

Adapted from Chun Shen



Hydrodynamic flow induced by jet momentum deposition

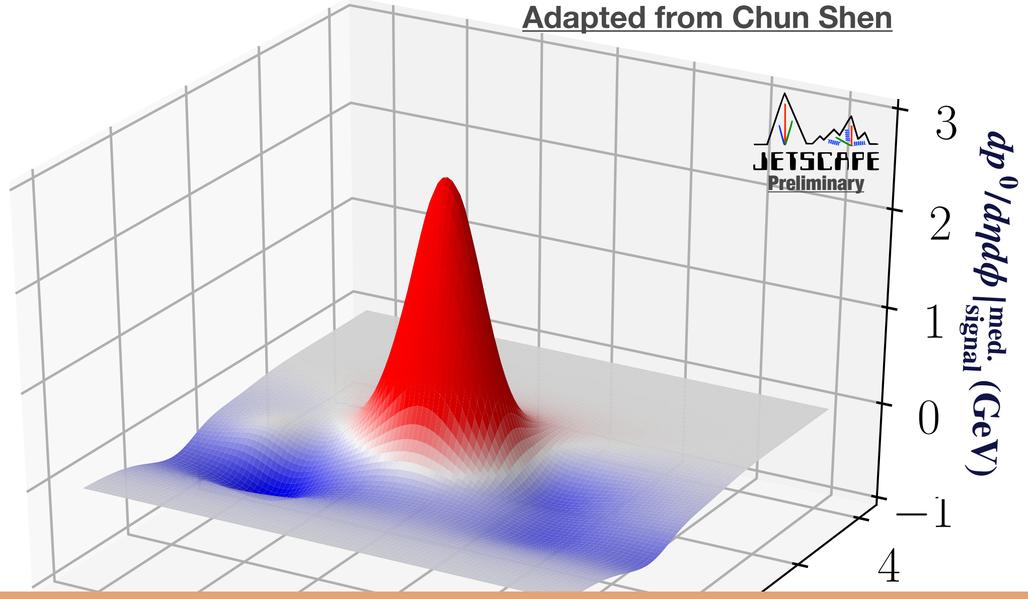
JETSCAPE (in preparation)

- **Jet-medium hadron correlation**

$$\left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{med. signal}} \quad \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{med. w/ jet}} - \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{med. w/o jet}}$$

MATTER+LBT (Recoil ON) + Causal Diffusion + Viscous Hydro

Adapted from Chun Shen



- Jet-correlated structure in hadron emission from the bulk medium
- Negative contribution by medium response

Summary

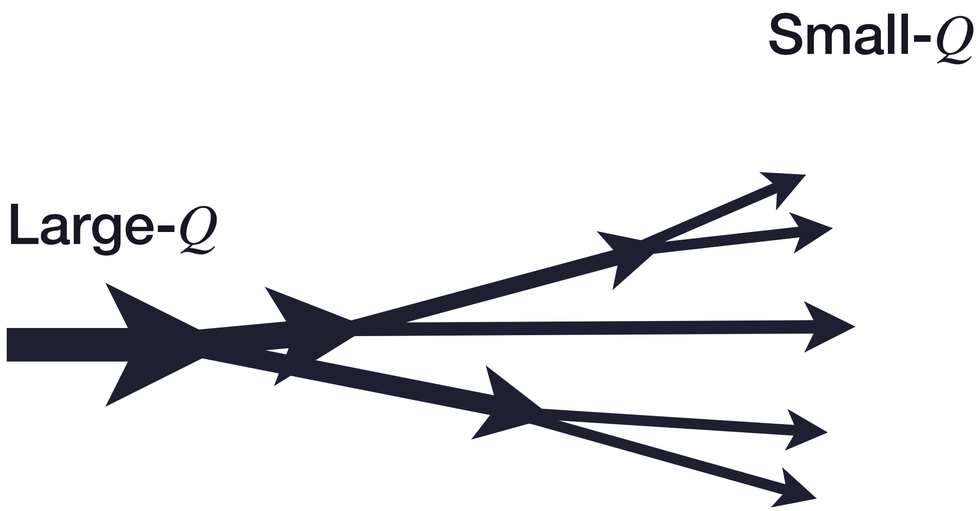
- **Medium response to jets in JETSCAPE framework**
  - Recoil in jet shoer evolution modules ($\gg E_{\mathrm{med}}$)
    → sampling of thermal parton for scattering in MATTER, LBT, and MARTINI modules
  - Source term generation by energy-momentum deposition modules ($\gtrsim E_{\mathrm{med}}$)
    → diffusion of jet energy momentum in Causal Liquefier module
  - Jet-induced flow in the medium by hydrodynamic models ($\sim E_{\mathrm{med}}$)
    → solving hydro equation with source term in MUSIC and CLVisc modules
- **Results from JETSCAPE with recoils**
  - Sizable effect in jet R_{AA}
  - Angular structure broadening and soft component enhancement
- **Hydrodynamic medium response in JETSCAPE**
  - Jet-induced flow with causal structure
  - Jet-correlated structure in hadron emission from the bulk medium

Multi-stage jet evolution in JETSCAPE

Majumder, Putschke, PRC 93, 054909 (2016), JETSCAPE, PRC96, 024909 (2017)

In-vacuum

- In-vacuum: Virtuality ordered splitting



$Q^2 = p^\mu p_\mu - m^2$: virtuality (off-shellness)

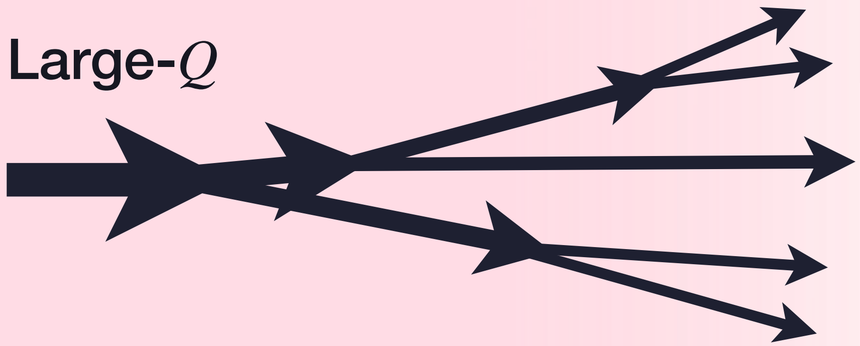
Multi-stage jet evolution in JETSCAPE

Majumder, Putschke, PRC 93, 054909 (2016), JETSCAPE, PRC96, 024909 (2017)

In-medium

Small-Q

Large-Q



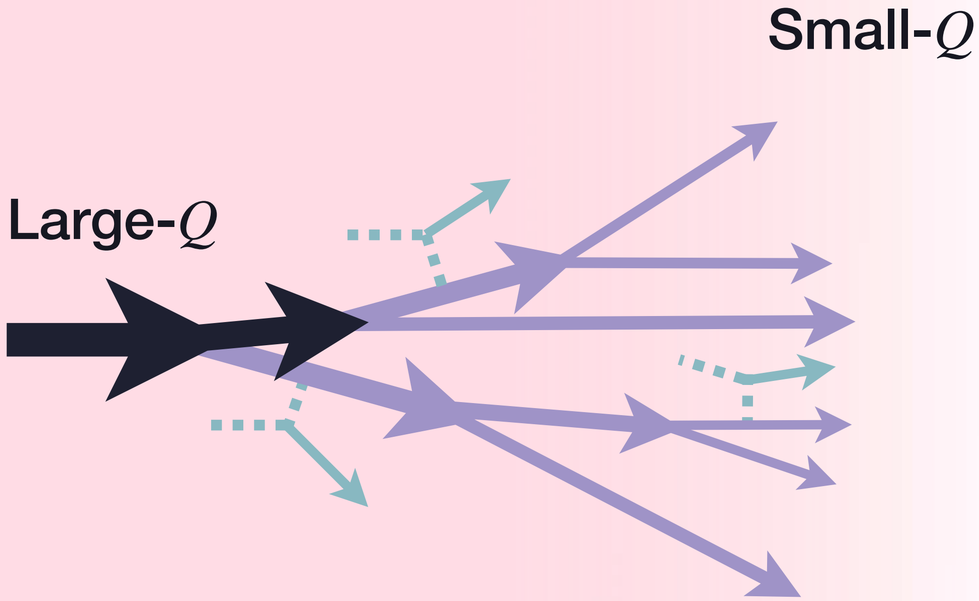
$Q^2 = p^\mu p_\mu - m^2$: virtuality (off-shellness)

- In-vacuum: Virtuality ordered splitting

Multi-stage jet evolution in JETSCAPE

Majumder, Putschke, PRC 93, 054909 (2016), JETSCAPE, PRC96, 024909 (2017)

In-medium

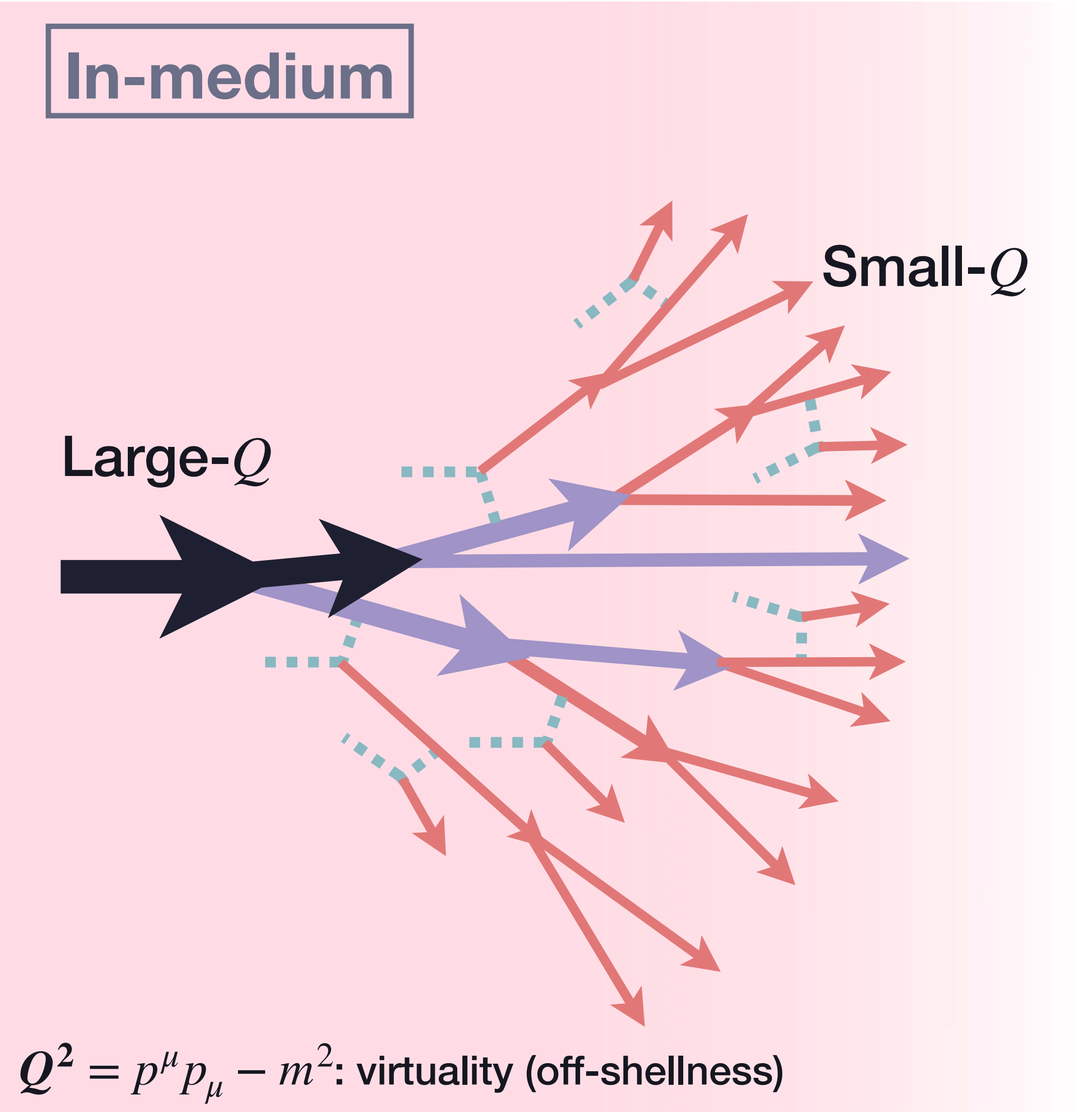


$Q^2 = p^\mu p_\mu - m^2$: virtuality (off-shellness)

- In-vacuum: Virtuality ordered splitting
- Large-Q: Medium effect on top of in-vacuum splitting

Multi-stage jet evolution in JETSCAPE

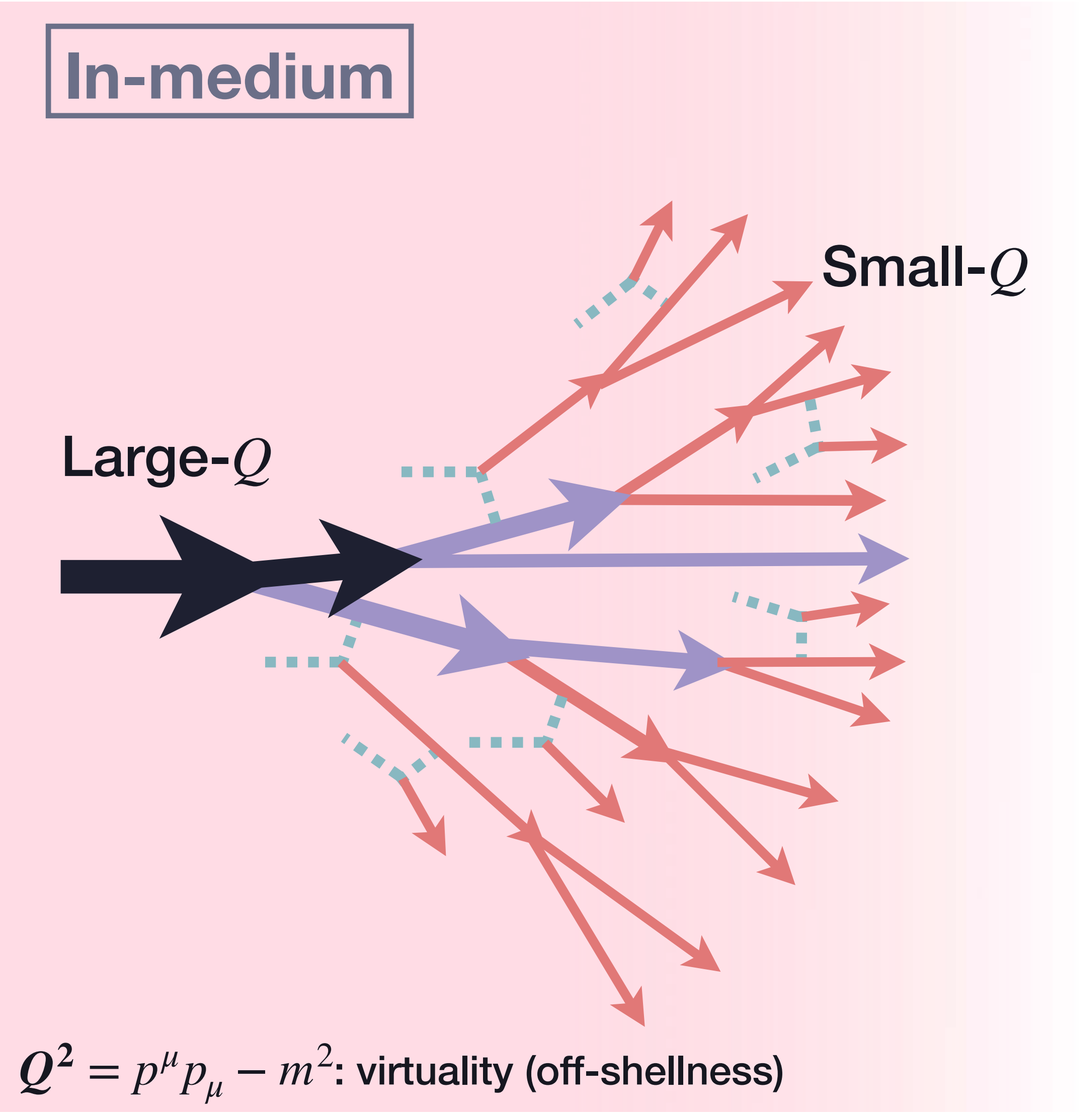
Majumder, Putschke, PRC 93, 054909 (2016), JETSCAPE, PRC96, 024909 (2017)



- In-vacuum: Virtuality ordered splitting
- Large-Q: Medium effect on top of in-vacuum splitting
- Small-Q: Splitting driven almost purely by medium effects

Multi-stage jet evolution in JETSCAPE

Majumder, Putschke, PRC 93, 054909 (2016), JETSCAPE, PRC96, 024909 (2017)

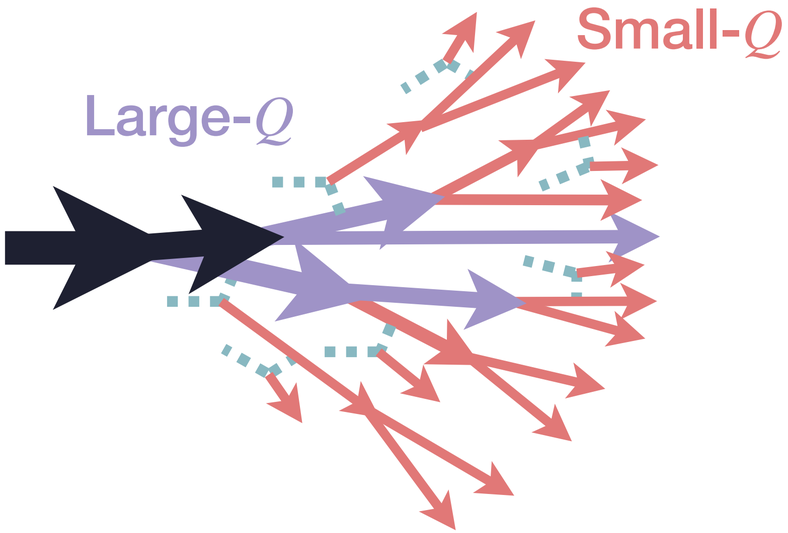


- In-vacuum: Virtuality ordered splitting
- Large-Q: Medium effect on top of in-vacuum splitting
- Small-Q: Splitting driven almost purely by medium effects

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

Multi-stage jet evolution in JETSCAPE

JETSCAPE, PRC96, 024909 (2017)

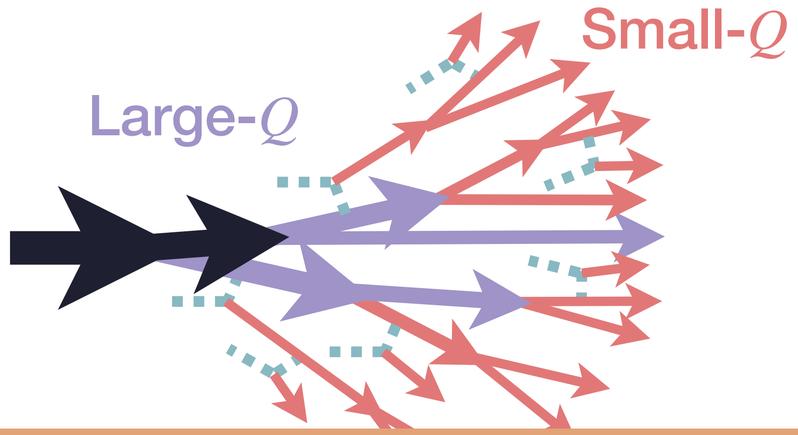


Virtuality separation scale: Q_{sw}

Large-Q ($> Q_{sw}$)	Small-Q ($< Q_{sw}$)		
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 jet evolution in JETSCAPE

JETSCAPE, PRC96, 024909 (2017)



Switching between modules for parton by parton

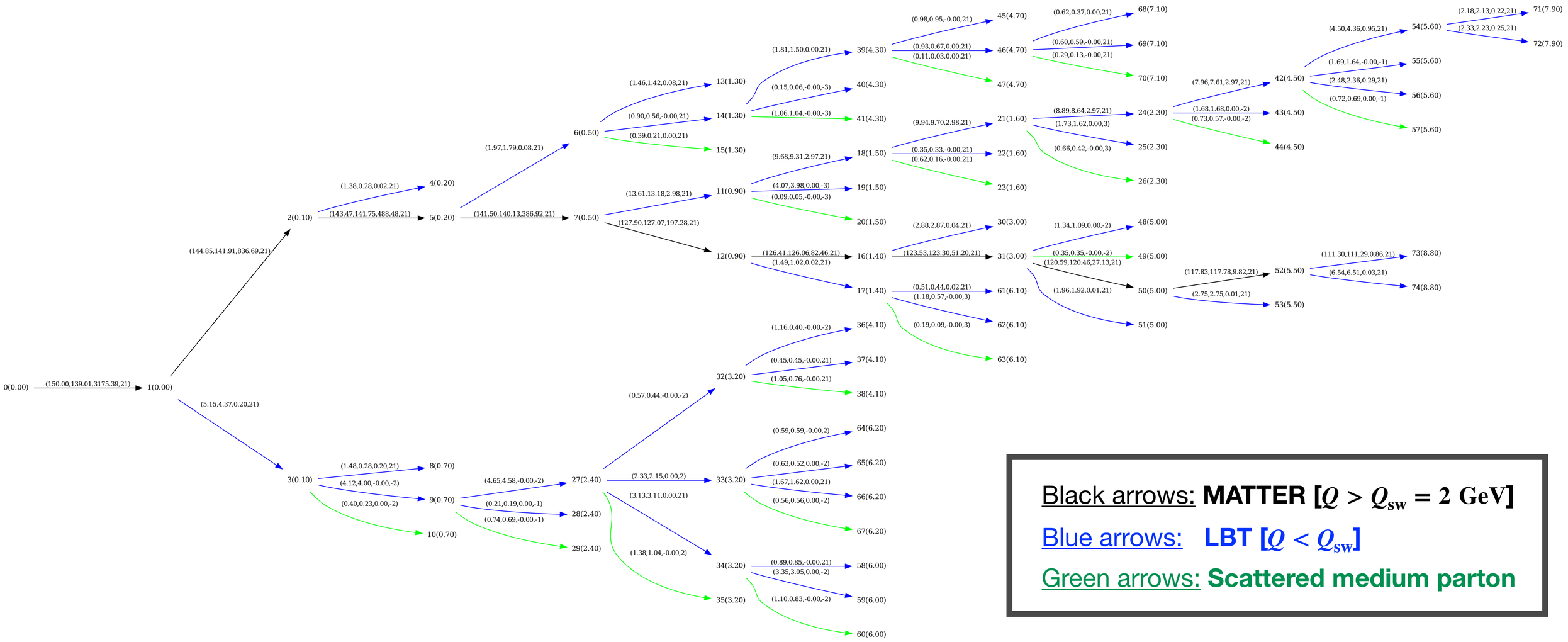
aration scale: Q_{sw}

Large-Q ($> Q_{sw}$)	Small-Q ($< Q_{sw}$)		
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 jet evolution in JETSCAPE

JETSCAPE, PRC96, 024909 (2017)

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



Black arrows: **MATTER** [$Q > Q_{sw} = 2$ GeV]

Blue arrows: **LBT** [$Q < Q_{sw}$]

Green arrows: **Scattered medium parton**

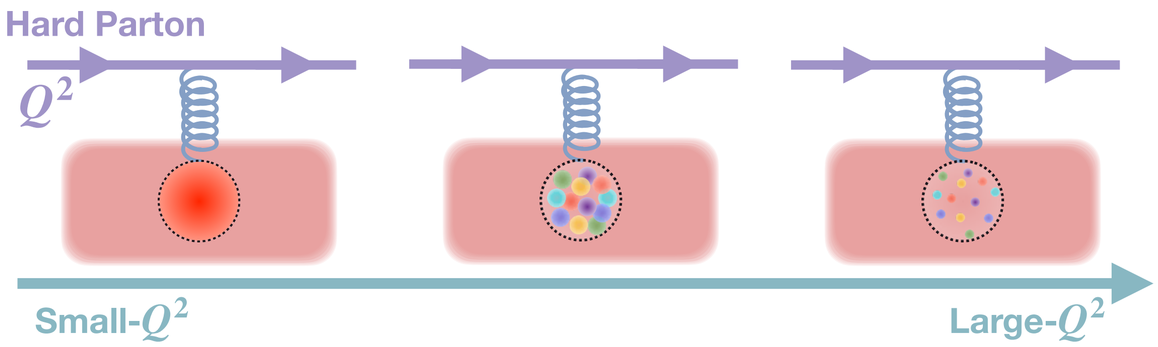
Multi-stage jet evolution in JETSCAPE

JETSCAPE, arXiv:2204.01163

Coherence effects

Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, PLB707, 156-159 (2012)
J. Casalderrey-Solana, E. Iancu, JHEP08, 015 (2011)

- Scale evolution of QGP constituent distribution
  Kumar, Majumder, Shen, PRC101, 034908 (2020)
- Less interaction for large-Q^2 partons
  → Implemented in MATTER

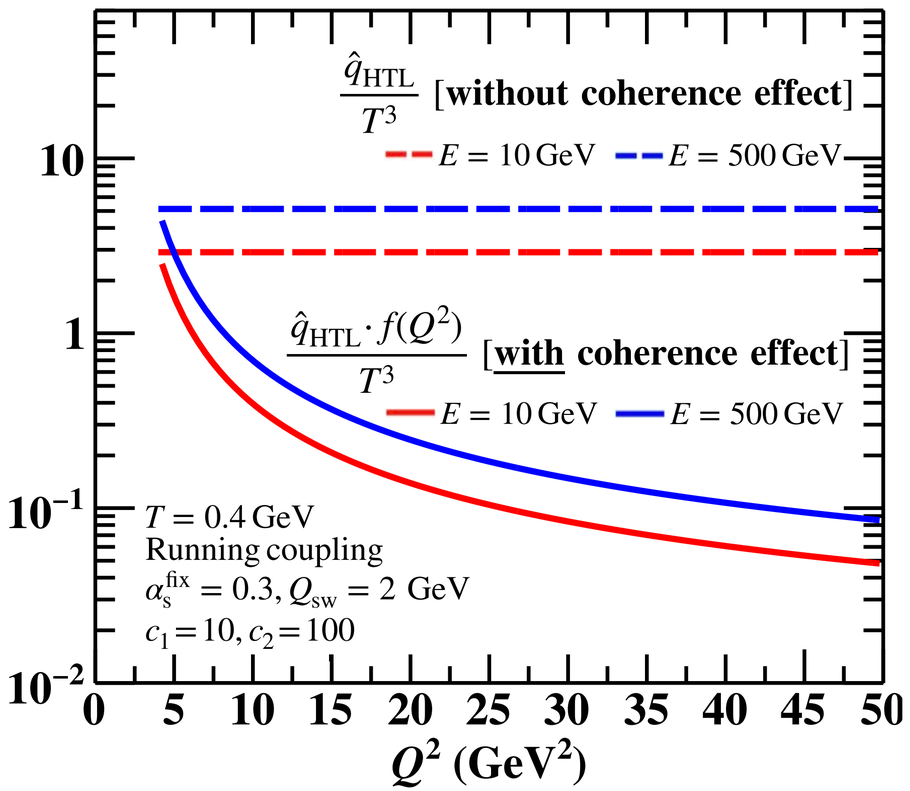


Effective jet-quenching strength

$$\hat{q}_{\mathrm{HTL}} \cdot f(Q^2)$$

$$f(Q^2) = \frac{1 + c_1 \ln^2(Q^2_{\mathrm{sw}}) + c_2 \ln^4(Q^2_{\mathrm{sw}})}{1 + c_1 \ln^2(Q^2) + c_2 \ln^4(Q^2)}$$

$$\hat{q}_{\mathrm{HTL}} = C_a \frac{42\zeta(3)}{\pi} \alpha_s^{\mathrm{run}} \alpha_s^{\mathrm{fix}} T^3 \ln\left[\frac{2ET}{6\pi T^2 \alpha_s^{\mathrm{fix}}}\right]$$



Jet and single particle energy loss

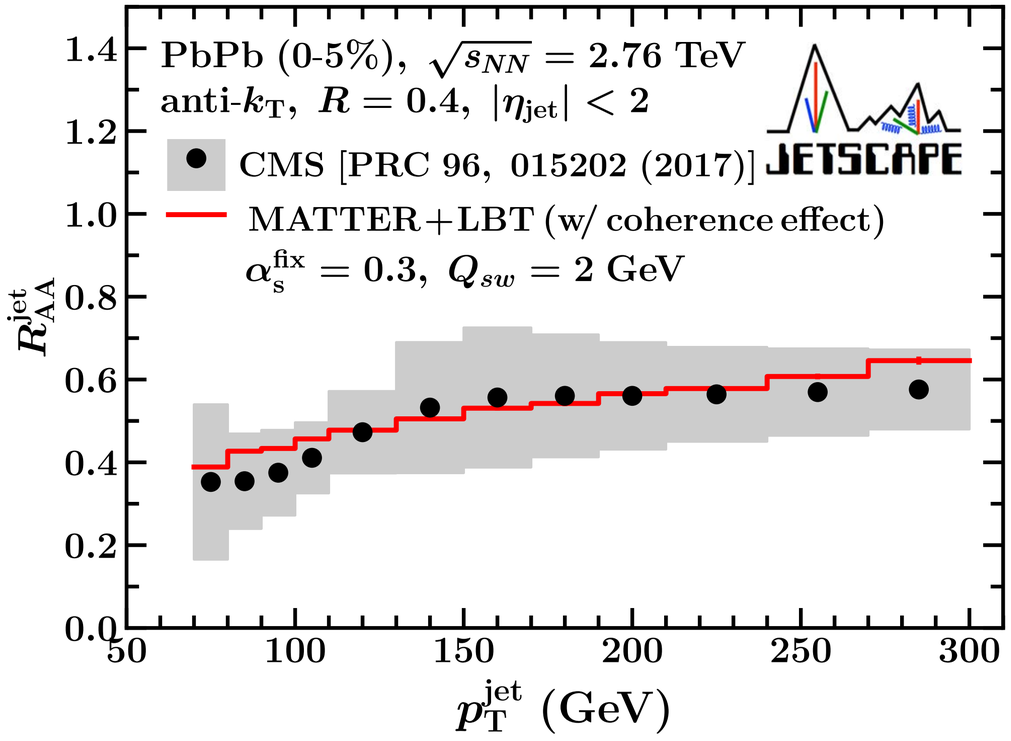
JETSCAPE, arXiv:2204.01163

- Pb+Pb collisions at 2.76 TeV

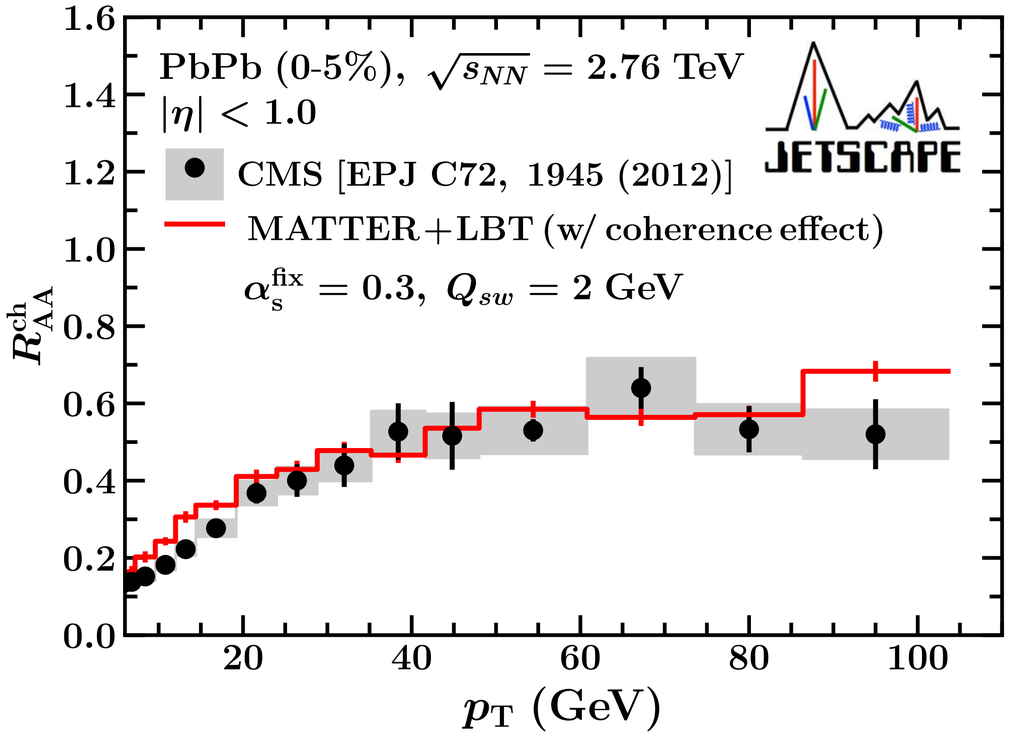
Poster by A. Majumder [1 T04_2, Wed. 17:46]

The same parameter set as 5.02 TeV is used

Inclusive jet R_{AA}



Charged particle R_{AA}



Jet and single particle energy loss

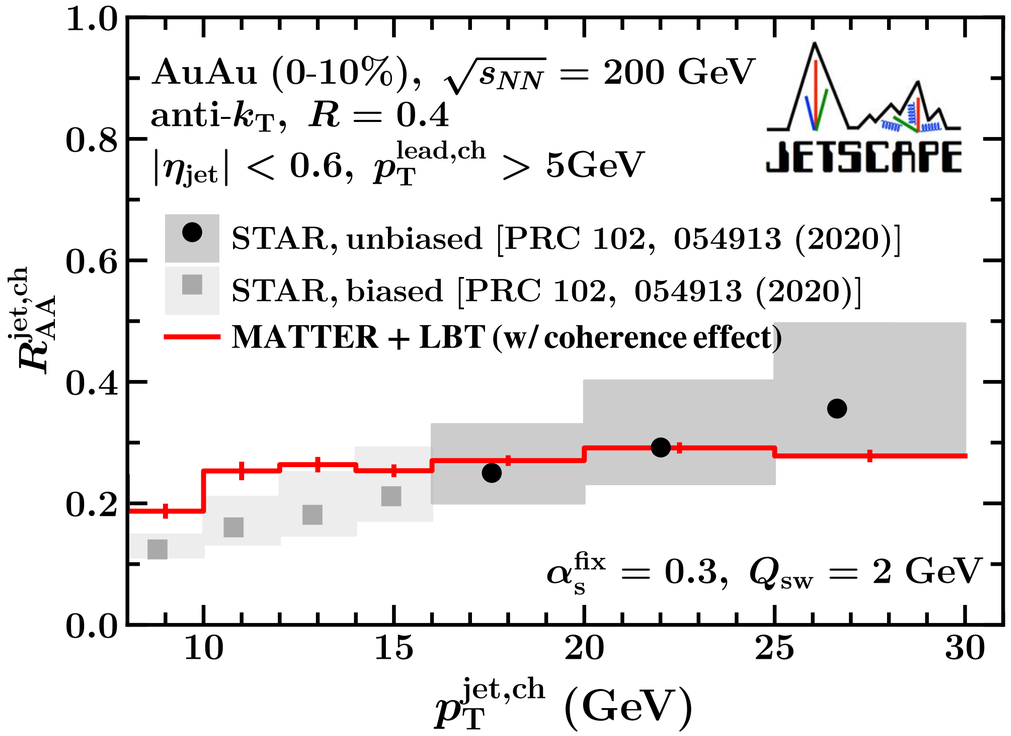
JETSCAPE, arXiv:2204.01163

- Au+Au collisions at 200 GeV

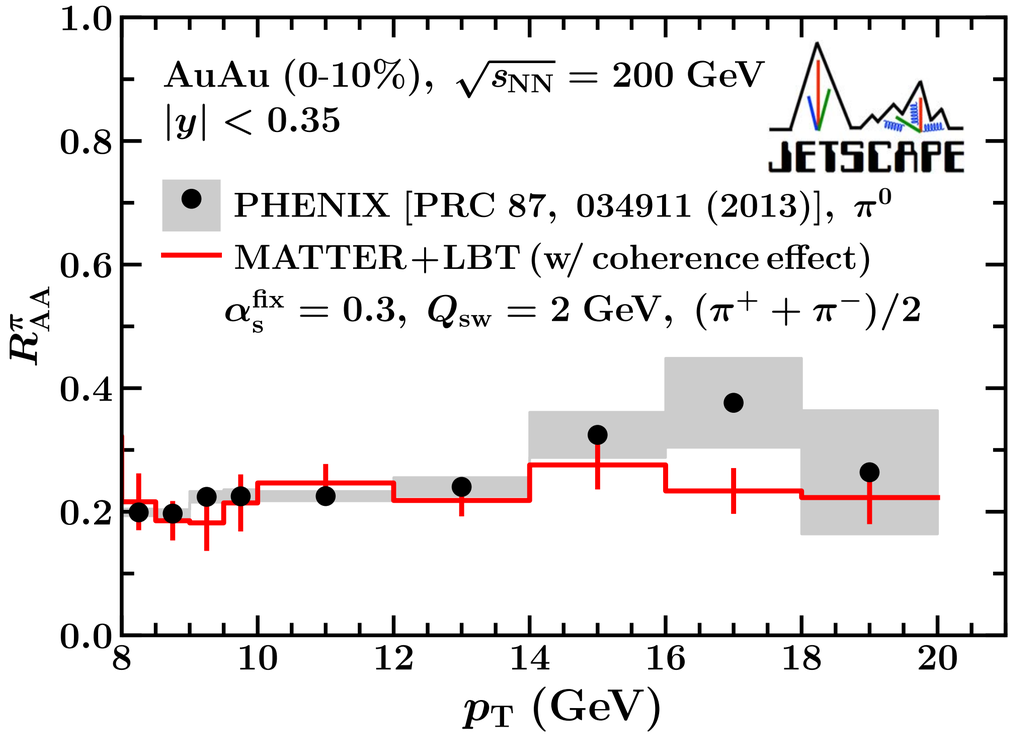
Poster by A. Majumder [1 T04_2, Wed. 17:46]

The same parameter set as 5.02 TeV is used

Charged jet R_{AA}



Pion R_{AA}



Jet and single particle energy loss

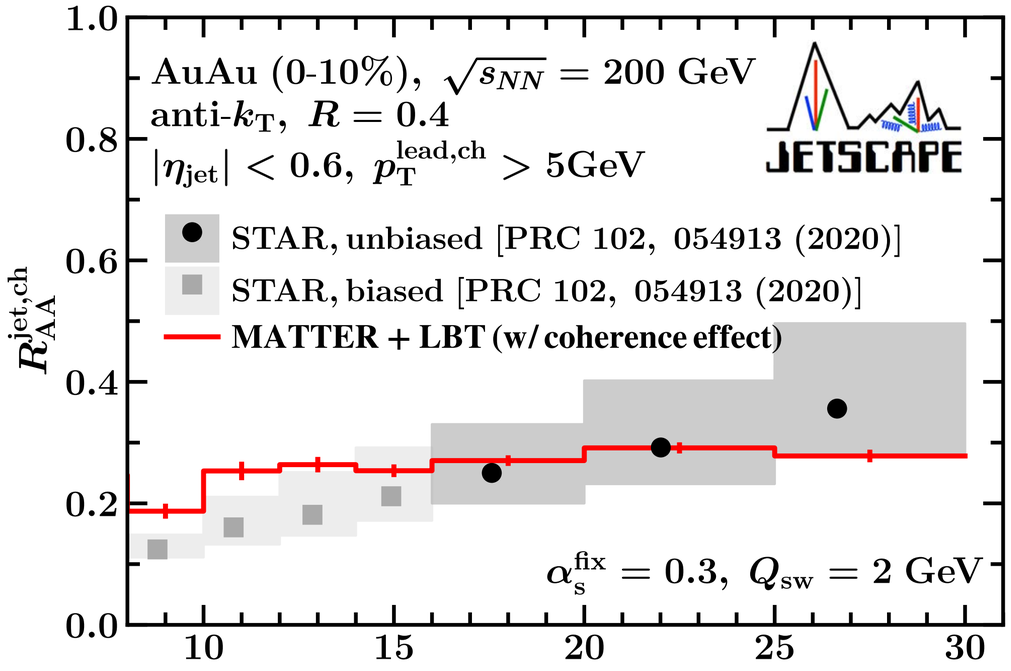
JETSCAPE, arXiv:2204.01163

- Au+Au collisions at 200 GeV

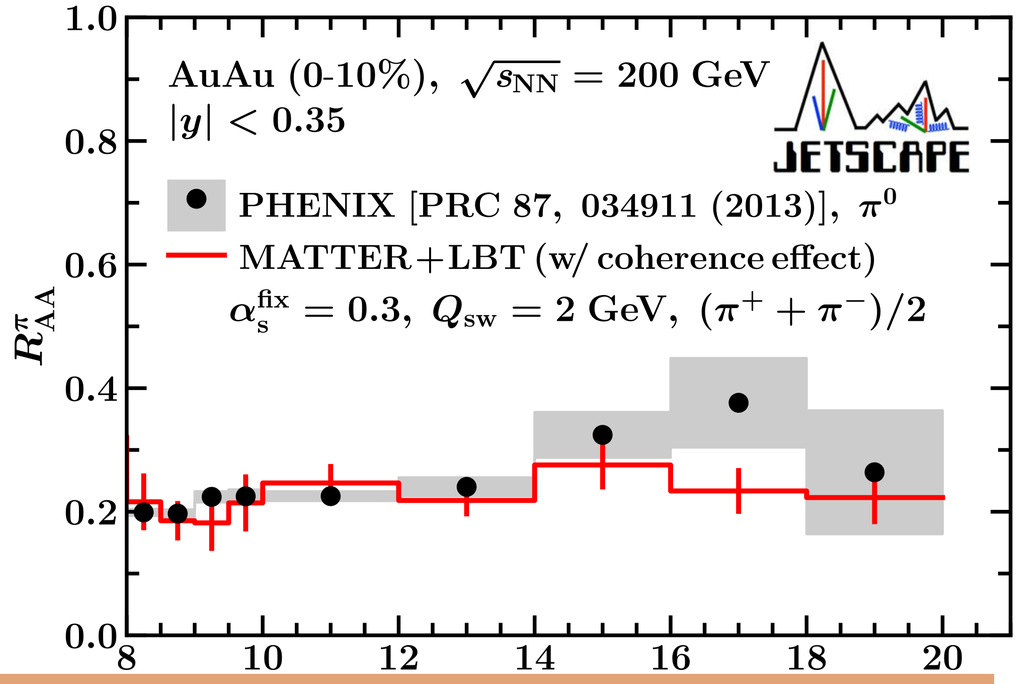
Poster by A. Majumder [1 T04_2, Wed. 17:46]

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

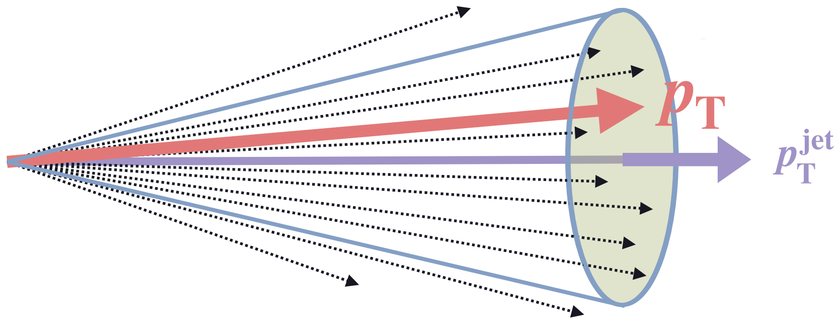
Jet substructures

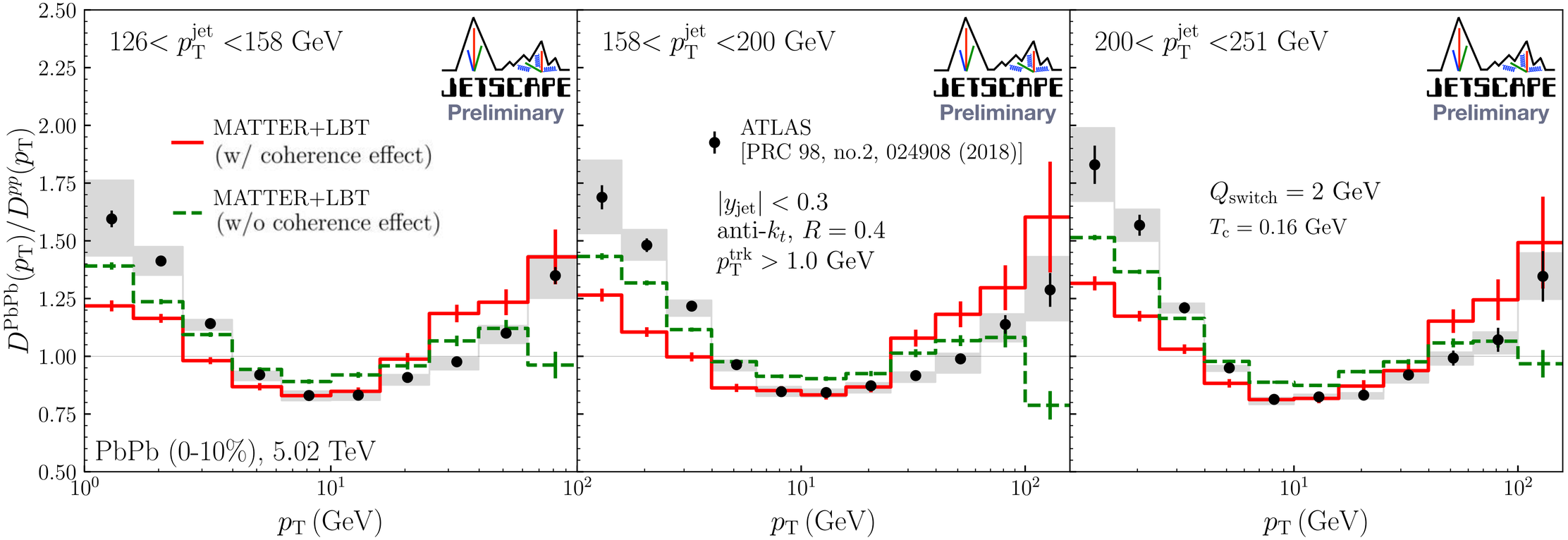
JETSCAPE (in preparation)

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

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

Poster by A. Silva and C. Nattrass [1 T04_2, Wed. 17:42]





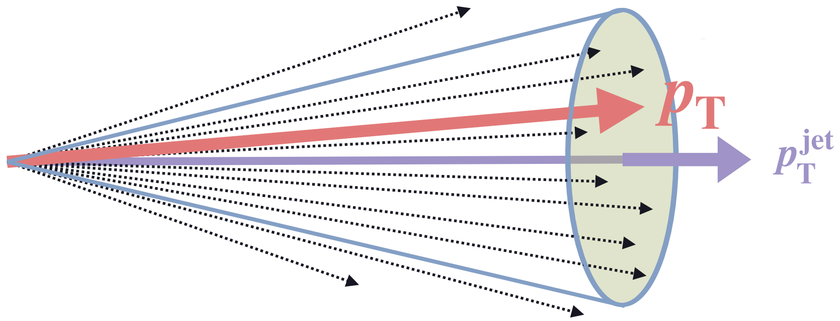
Jet substructures

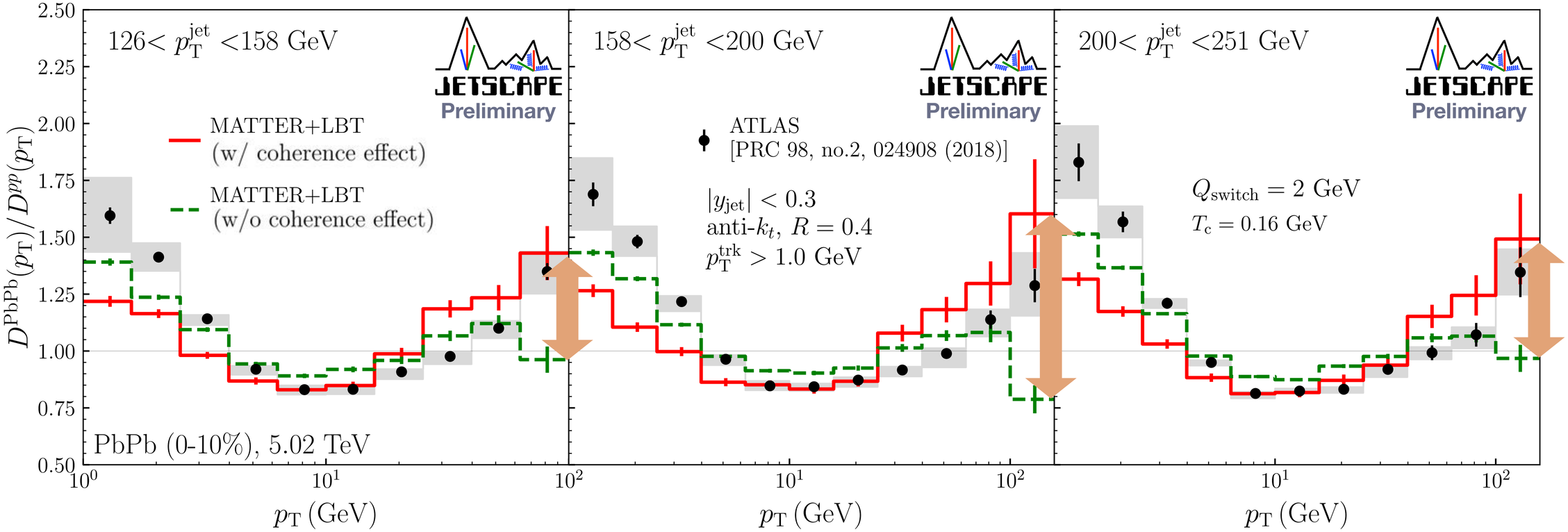
JETSCAPE (in preparation)

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

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

Poster by A. Silva and C. Nattrass [1 T04_2, Wed. 17:42]





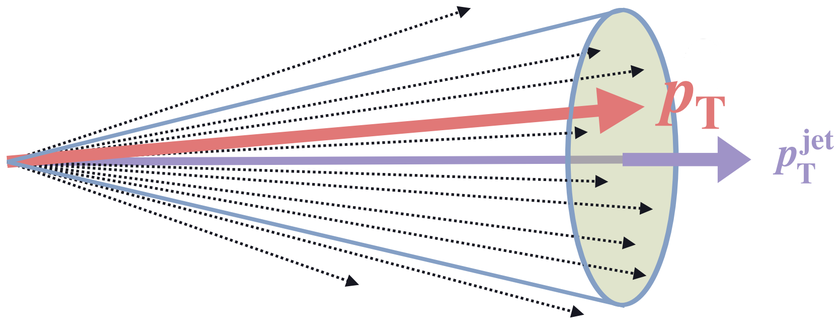
Jet substructures

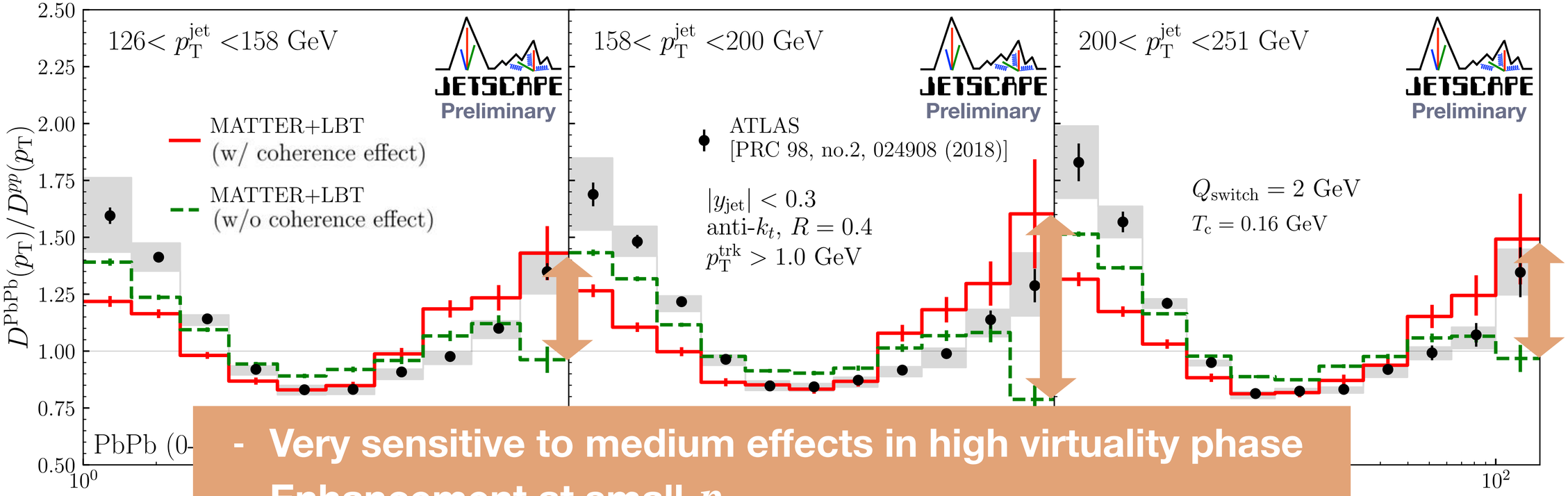
JETSCAPE (in preparation)

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

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

Poster by A. Silva and C. Nattrass [1 T04_2, Wed. 17:42]





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

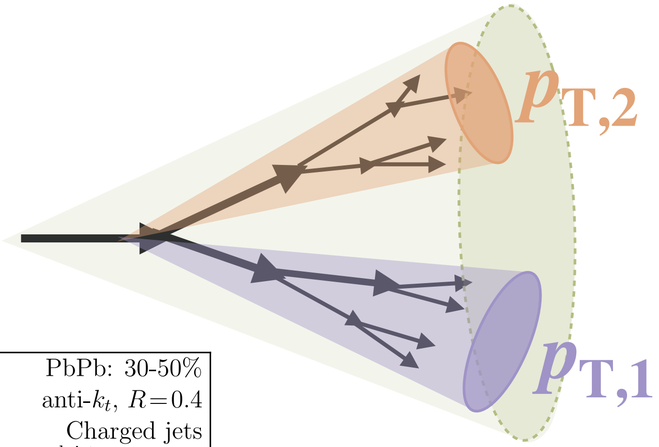
Jet substructures

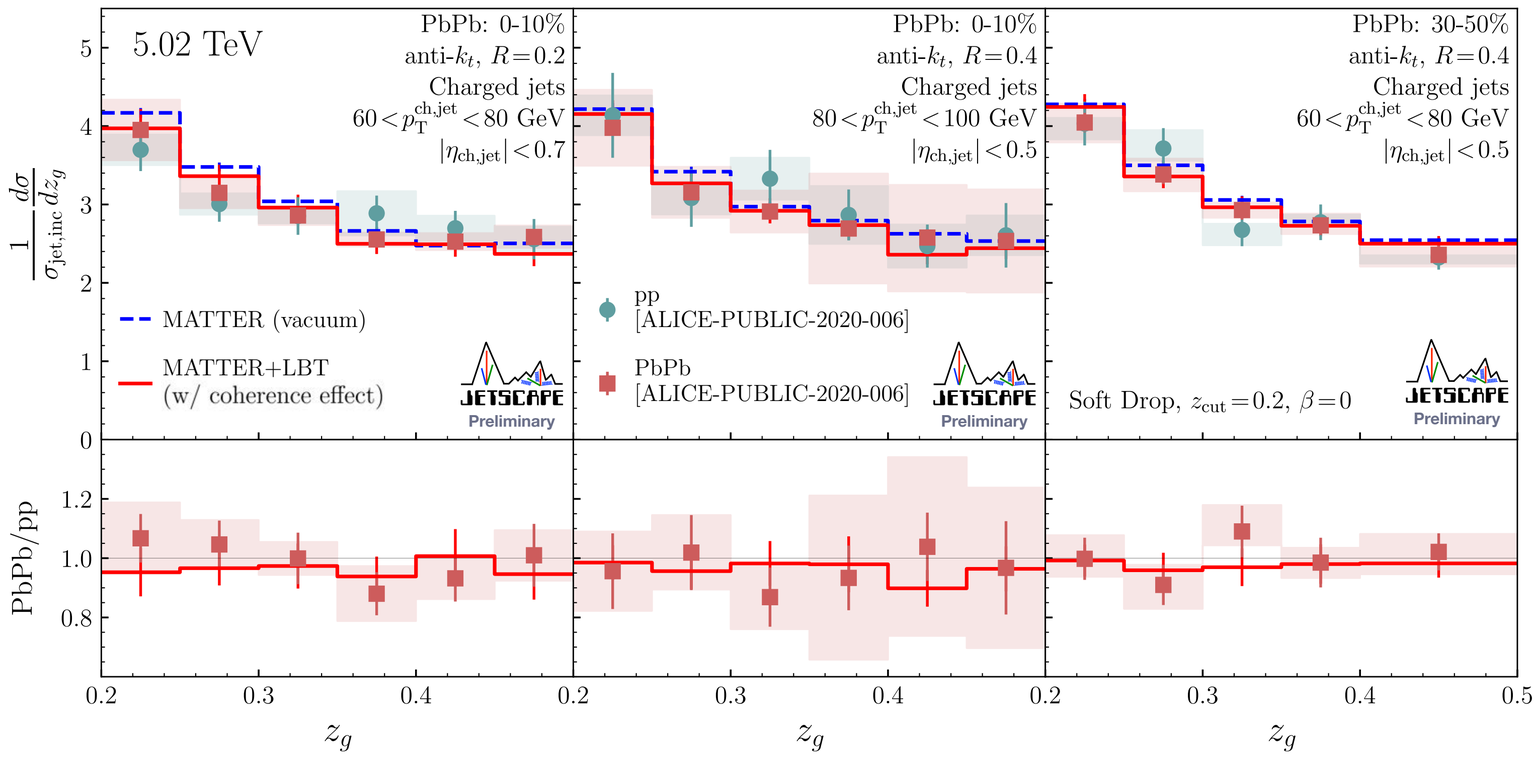
JETSCAPE (in preparation)

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

Poster by A. Silva and C. Nattrass [1 T04_2, Wed. 17:42]

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





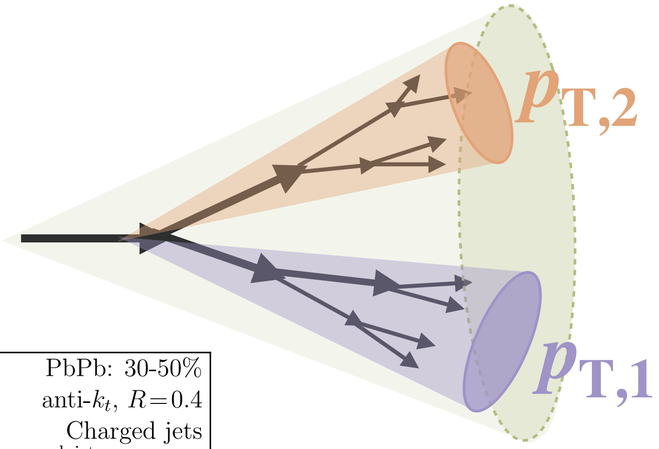
Jet substructures

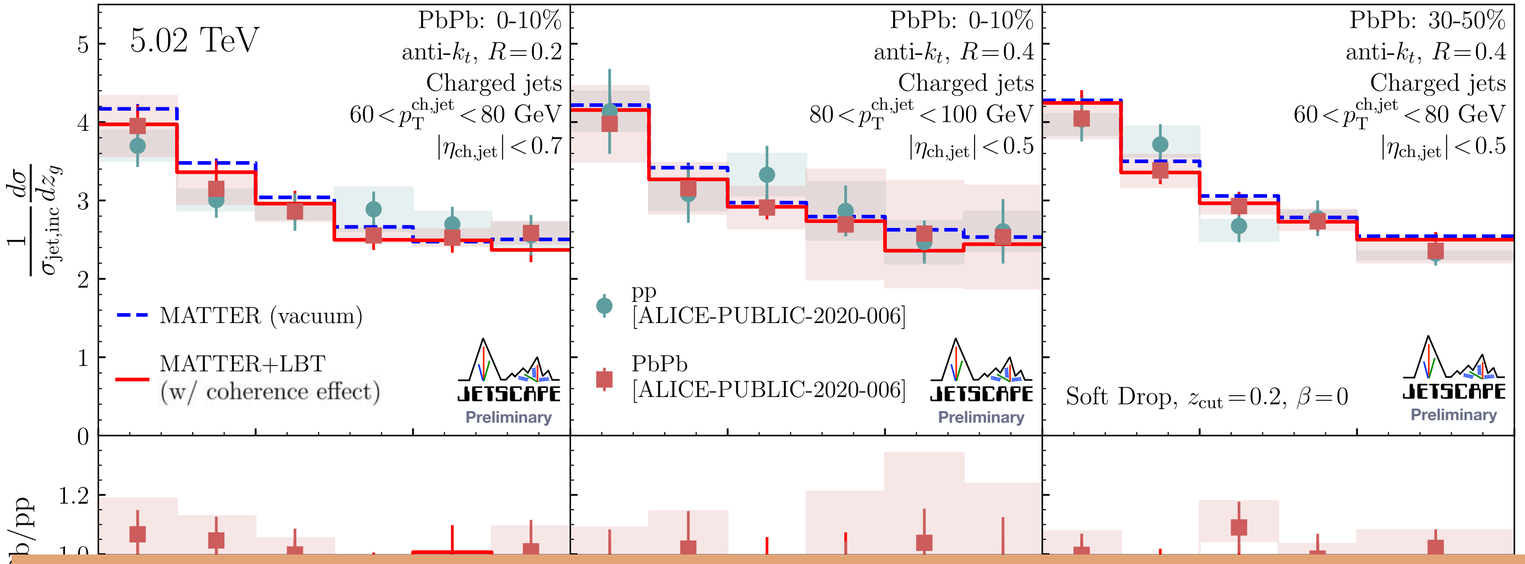
JETSCAPE (in preparation)

Poster by A. Silva and C. Nattrass [1 T04_2, Wed. 17:42]

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

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





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

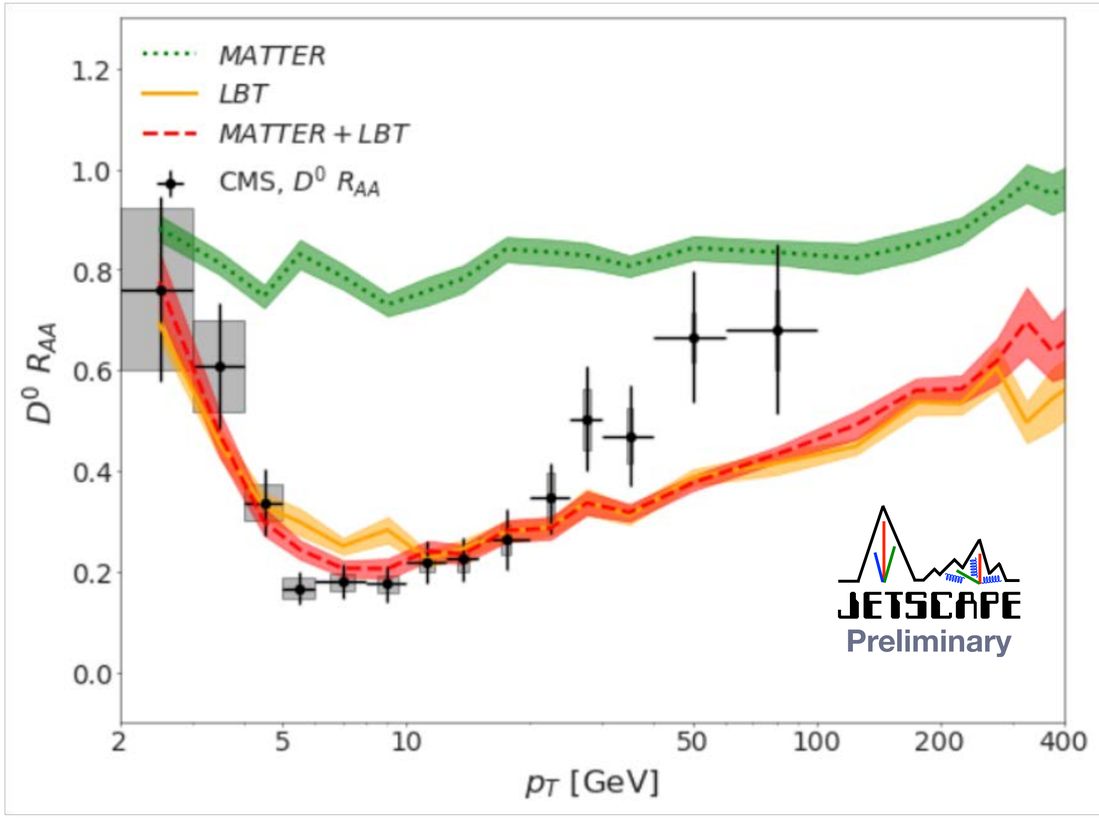
Heavy flavor energy loss

JETSCAPE (in preparation)

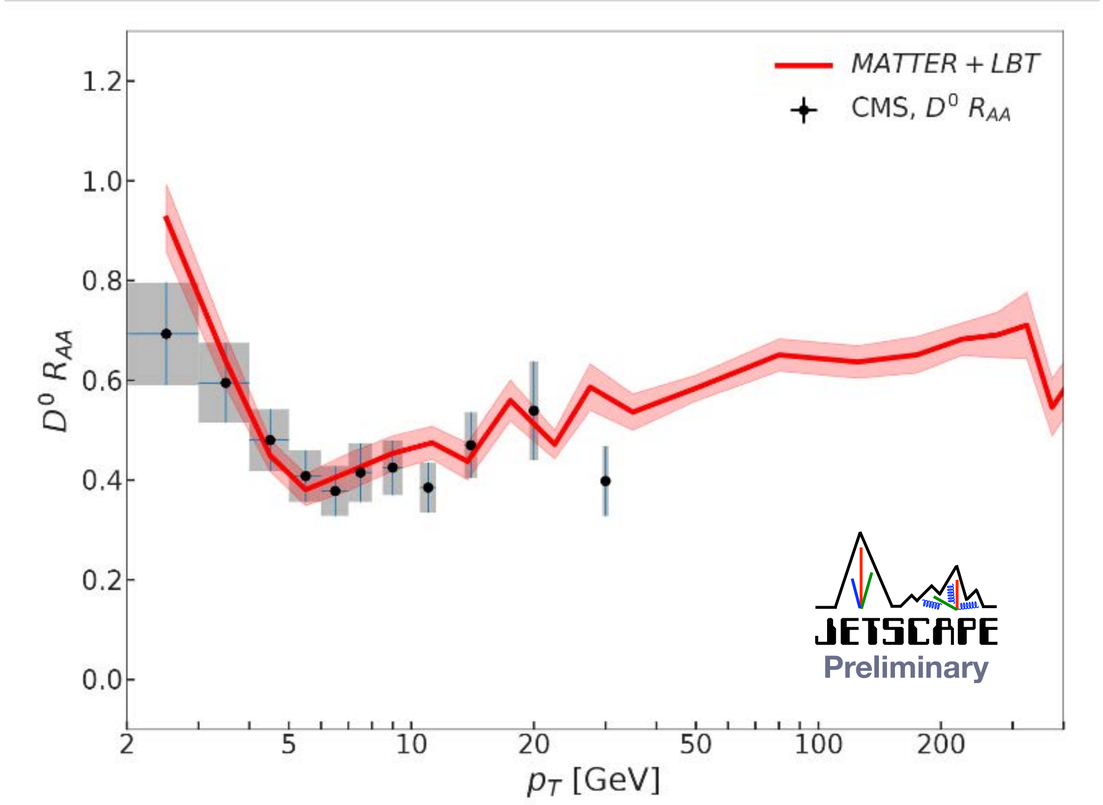
Poster by W. Fan [3 T11_3, Fri. 14:24]

- D^0 meson R_{AA}

PbPb 0-10%, 5.02TeV



PbPb 30-50%, 5.02TeV



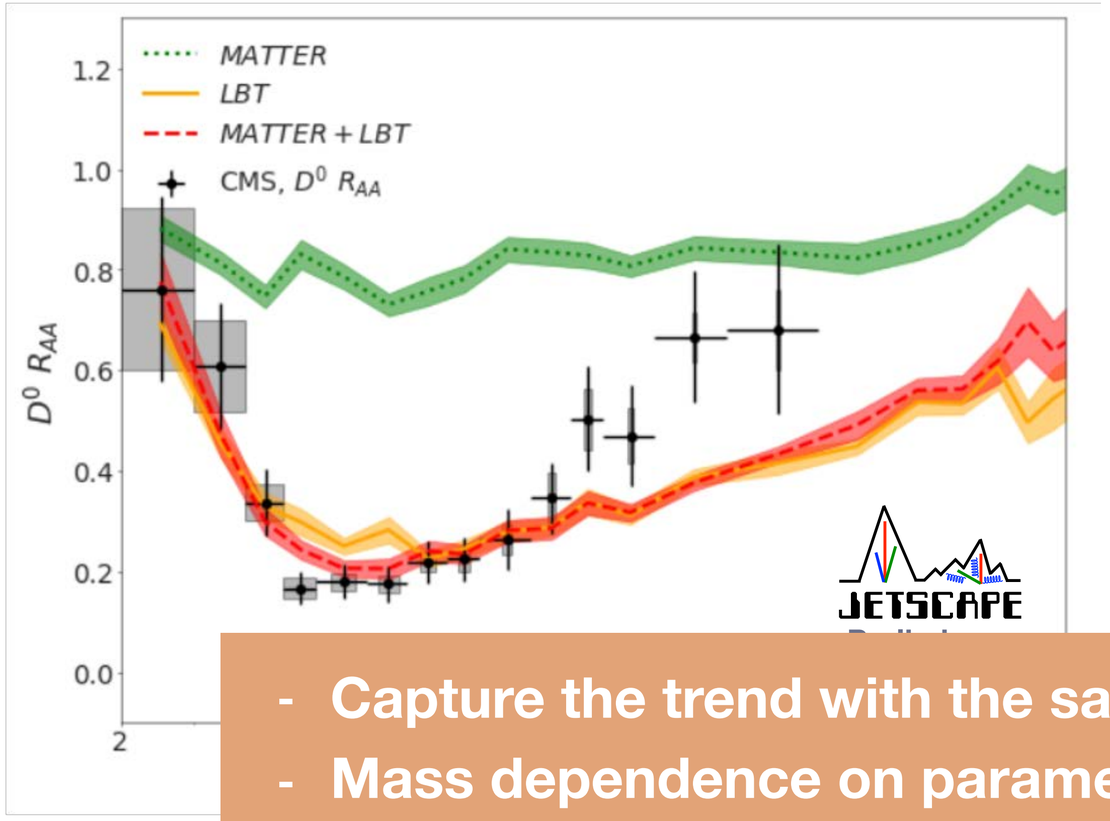
Heavy flavor energy loss

JETSCAPE (in preparation)

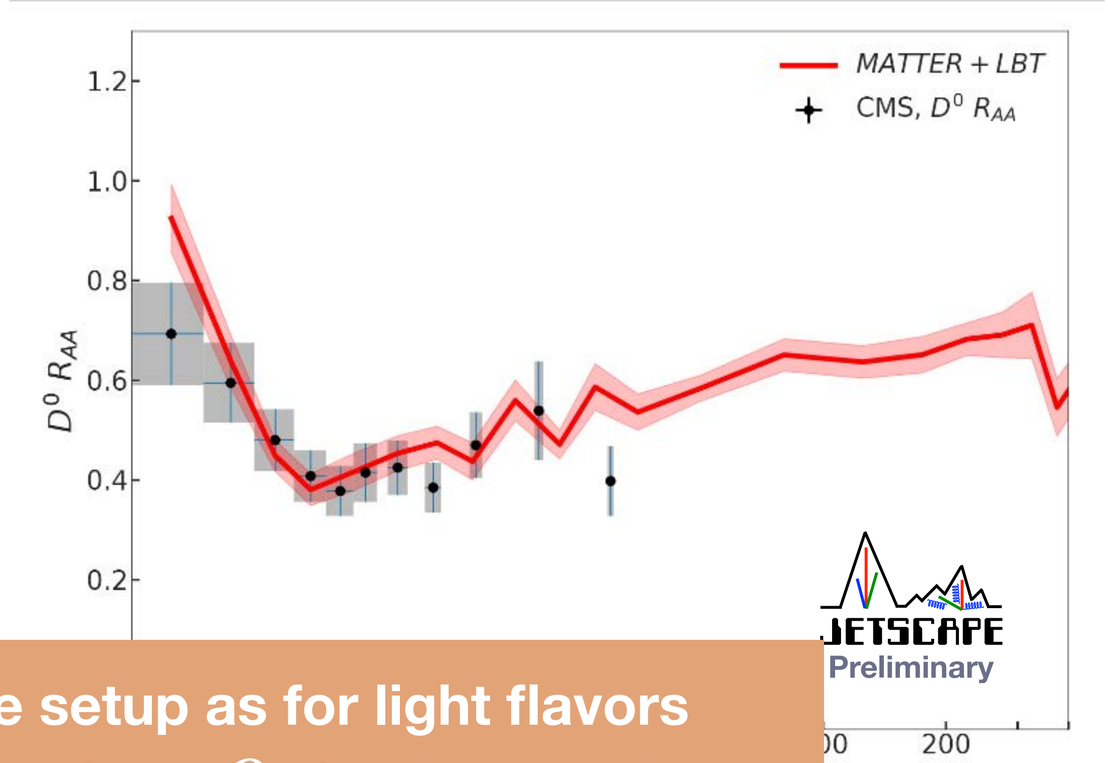
Poster by W. Fan [3 T11_3, Fri. 14:24]

- D^0 meson R_{AA}

PbPb 0-10%, 5.02TeV



PbPb 30-50%, 5.02TeV



- Capture the trend with the same setup as for light flavors
- Mass dependence on parameters (e.g., Q_{sw}) will be explored

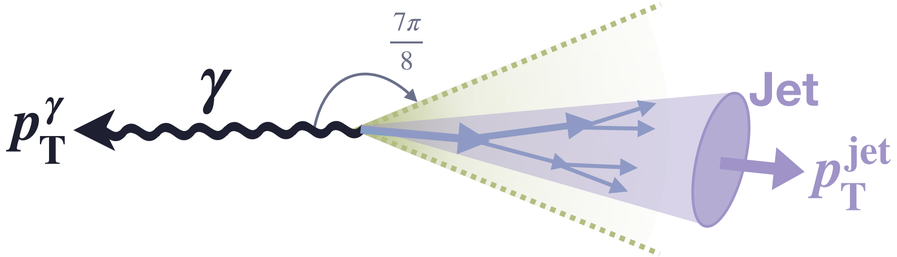
γ-jet correlations

JETSCAPE (in preparation)

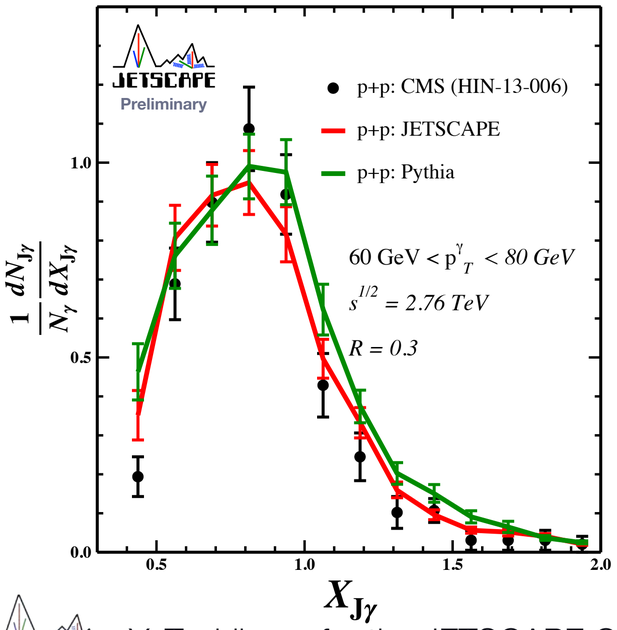
Poster by C. Sirimanna [2 T13, Wed. 18:42]

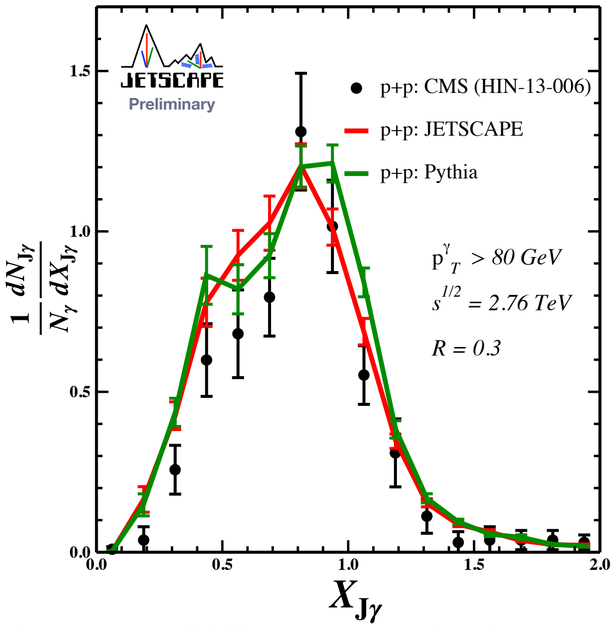
- **γ-jet imbalance**
  - Back-to-back γ-jet pairs
  - Isolated γ

$$X_{J\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$

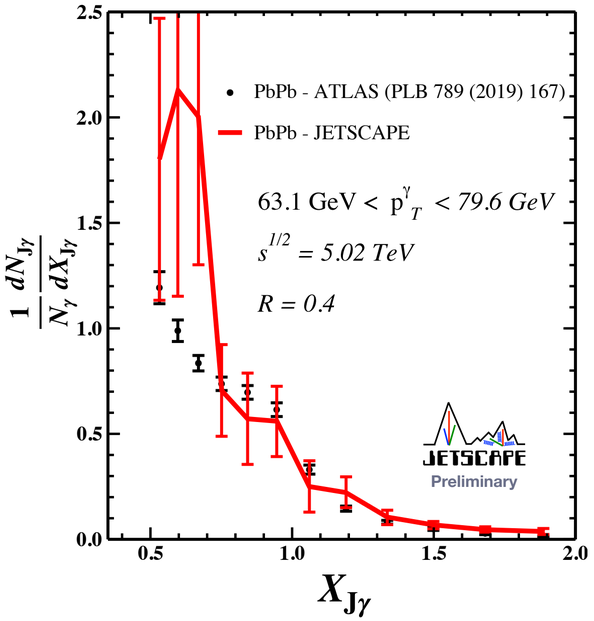


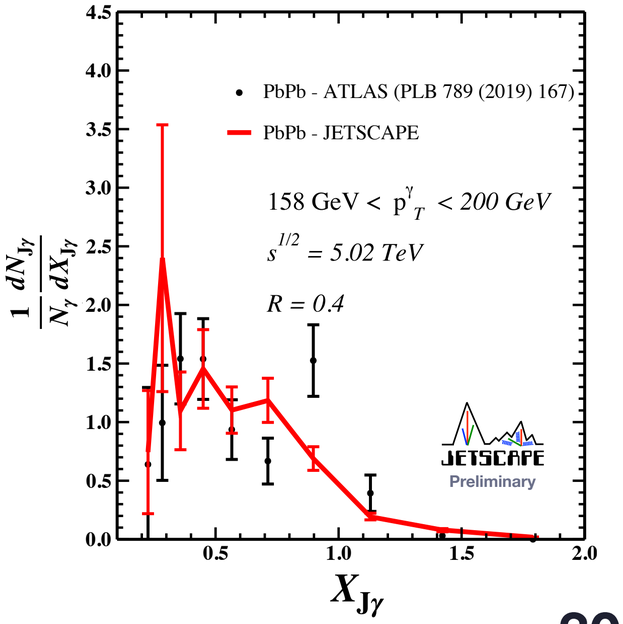
pp, 2.76 TeV





PbPb, 5.02 TeV





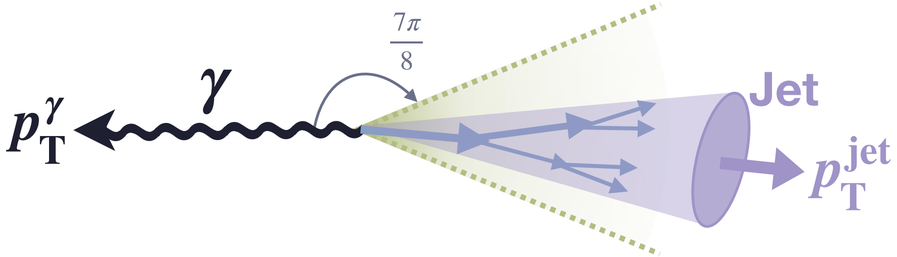
γ-jet correlations

JETSCAPE (in preparation)

Poster by C. Sirimanna [2 T13, Wed. 18:42]

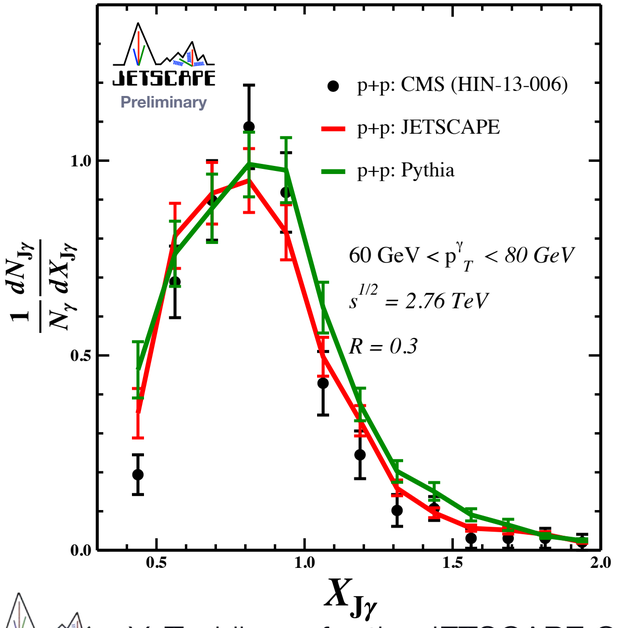
- **γ-jet imbalance**
  - Back-to-back γ-jet pairs
  - Isolated γ

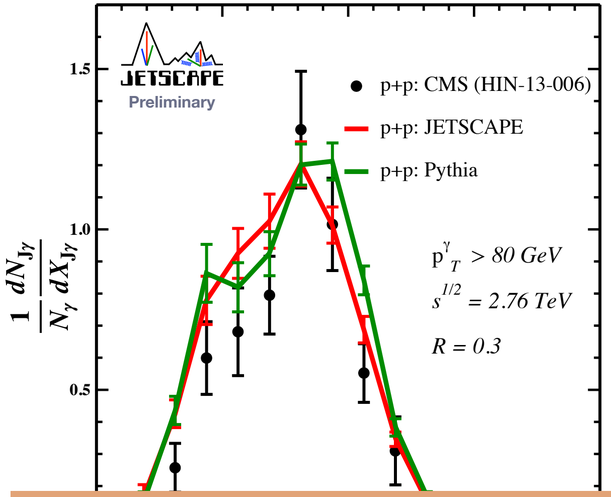
$$X_{J\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$

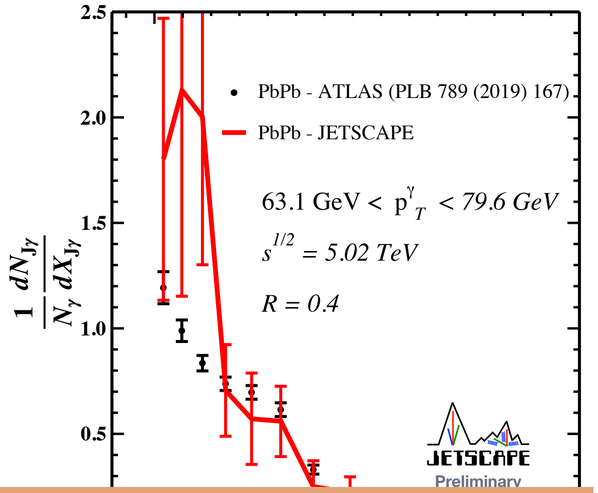


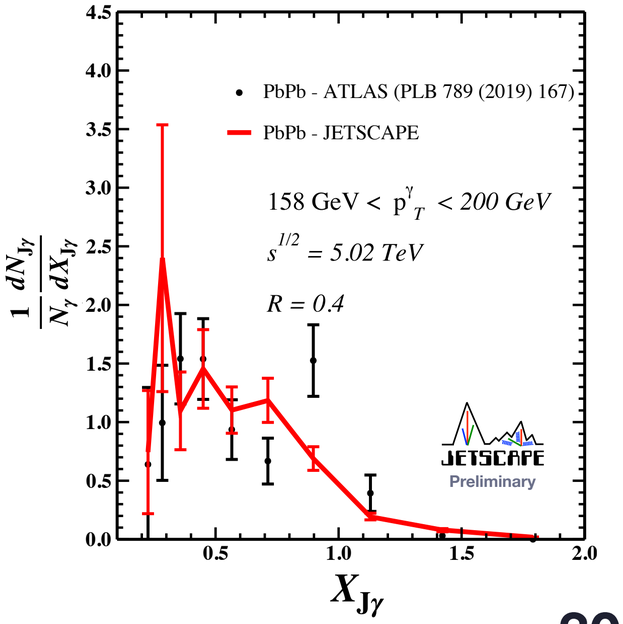
pp, 2.76 TeV

PbPb, 5.02 TeV









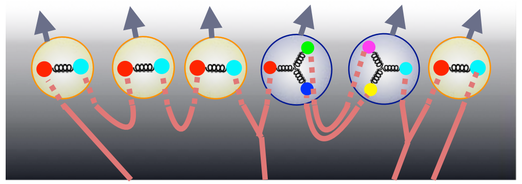
- **γ-jet analysis requires very high statistics**

Jet-medium interaction in hadronization

- **Hybrid hadronization model**
  Han, Fries, Ko, PRC 93, 045207 (2016)

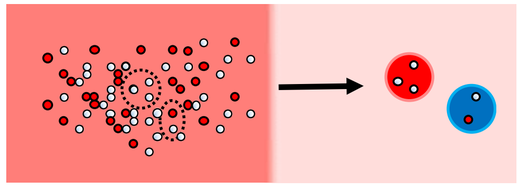
  - Smoothly combines two hadronization models

String Fragmentation



(vacuum like, high-p_T)

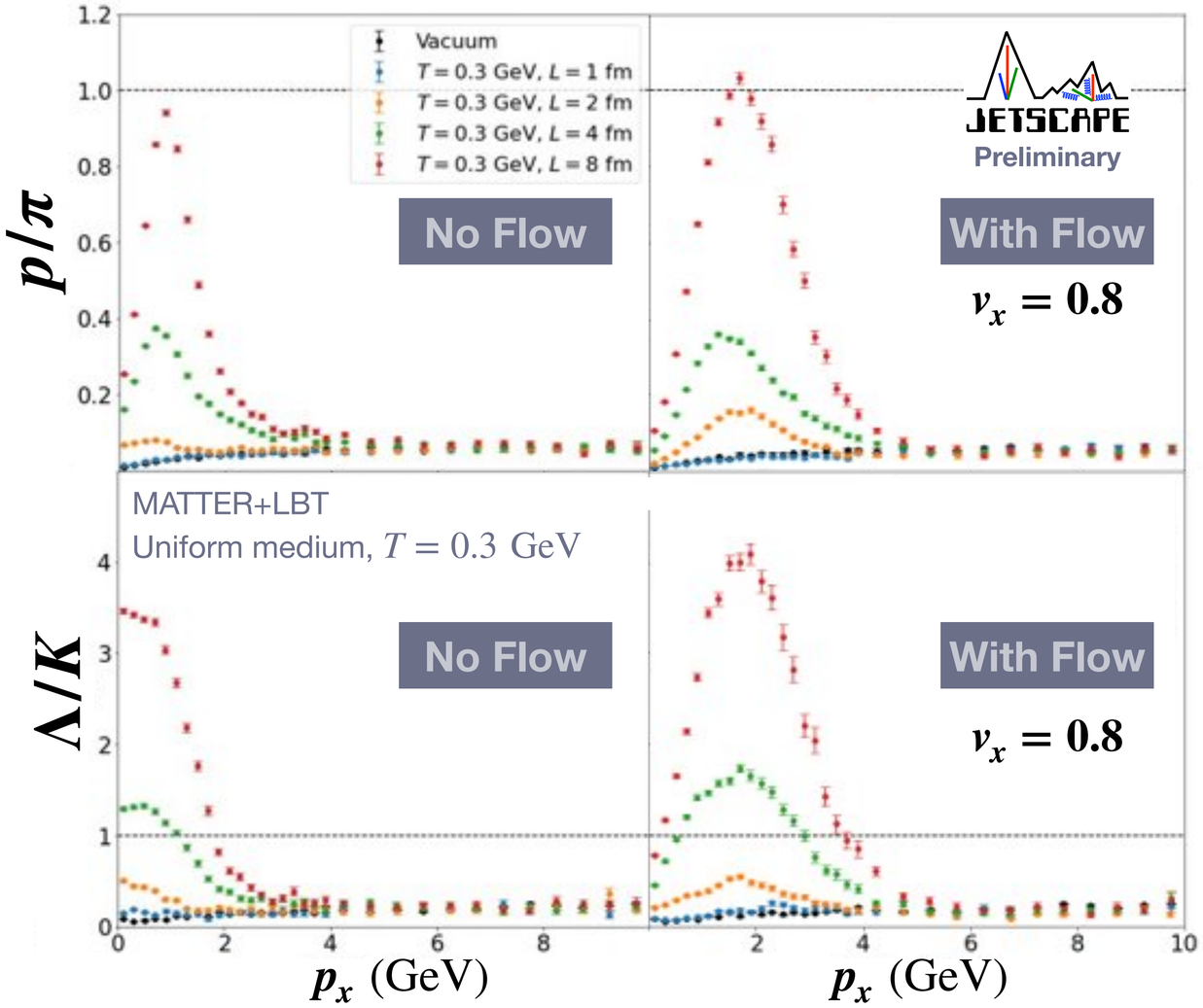
Recombination



(in-medium, mid- p_T)

  - Recombination between jet partons and medium partons

Poster by A. Sengupta [2 T14_1, Wed. 16:46]

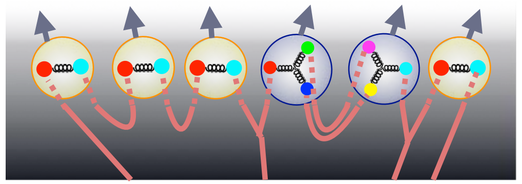


Jet-medium interaction in hadronization

- **Hybrid hadronization model**
  Han, Fries, Ko, PRC 93, 045207 (2016)

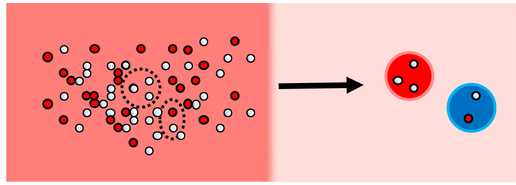
  - Smoothly combines two hadronization models

String Fragmentation



(vacuum like, high-p_T)

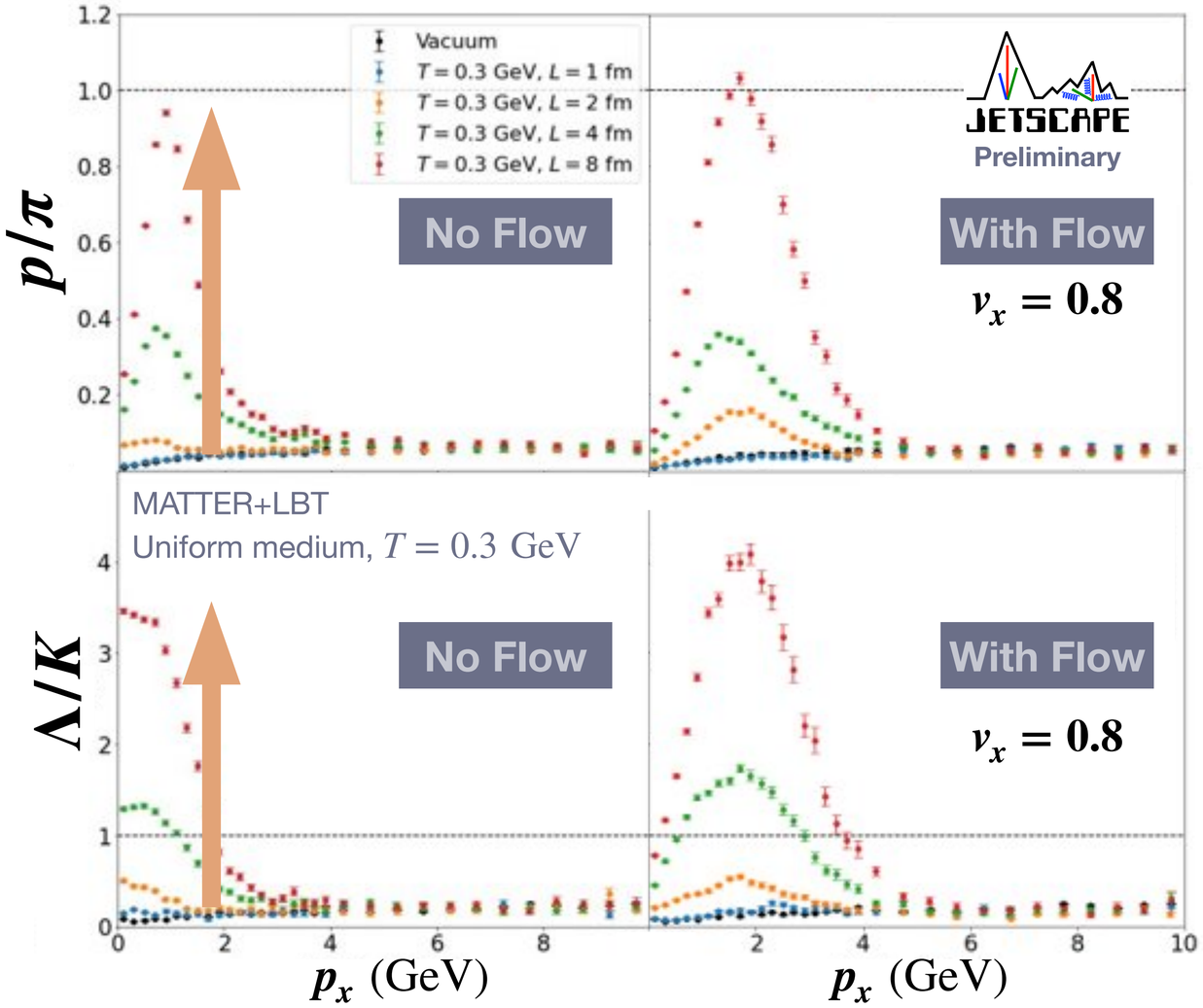
Recombination



(in-medium, mid- p_T)

  - Recombination between jet partons and medium partons

Poster by A. Sengupta [2 T14_1, Wed. 16:46]

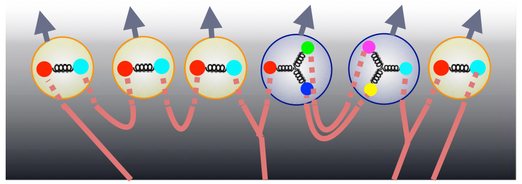


Jet-medium interaction in hadronization

- **Hybrid hadronization model**
  Han, Fries, Ko, PRC 93, 045207 (2016)

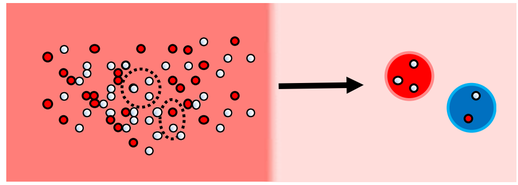
  - Smoothly combines two hadronization models

String Fragmentation



(vacuum like, high-p_T)

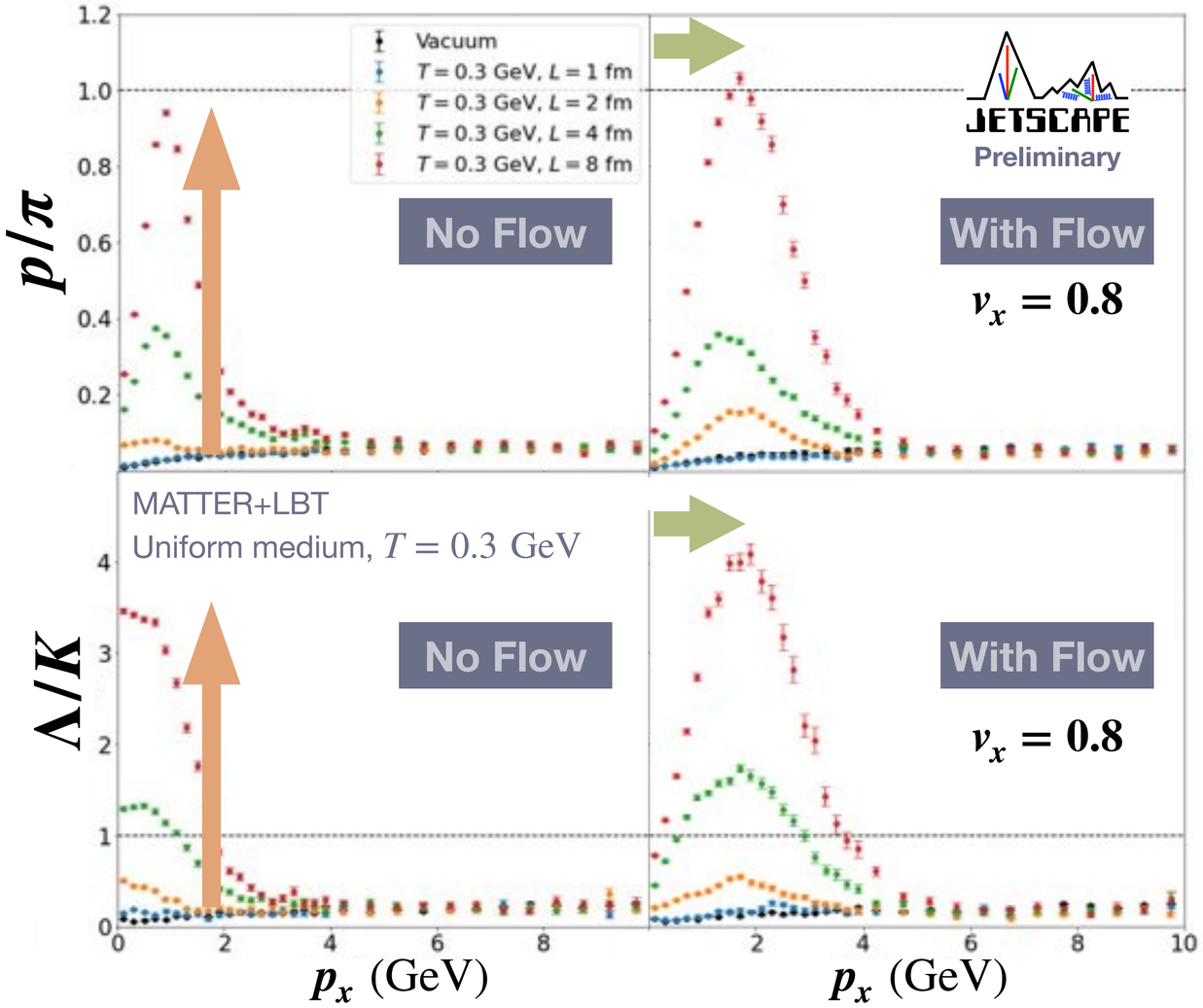
Recombination



(in-medium, mid- p_T)

  - Recombination between jet partons and medium partons

Poster by A. Sengupta [2 T14_1, Wed. 16:46]



Jet-medium interaction in hadronization

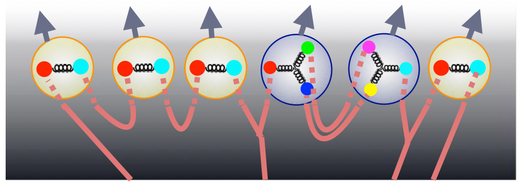
Poster by A. Sengupta [2 T14_1, Wed. 16:46]

Hybrid hadronization model

Han, Fries, Ko, PRC 93, 045207 (2016)

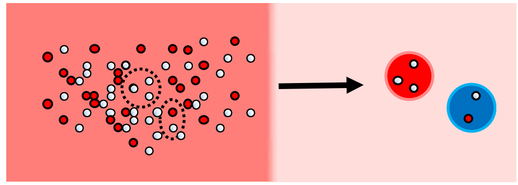
- Smoothly combines two hadronization models

String Fragmentation



(vacuum like, high-p_T)

Recombination



(in-medium, mid- p_T)

- Recombination between jet partons and medium partons

- **Baryon enhancement due to recombination**
- **Blue shift by the background medium flow**