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

Overview and recent progress on JETSCAPE

Yasuki Tachibana for the JETSCAPE Collaboration

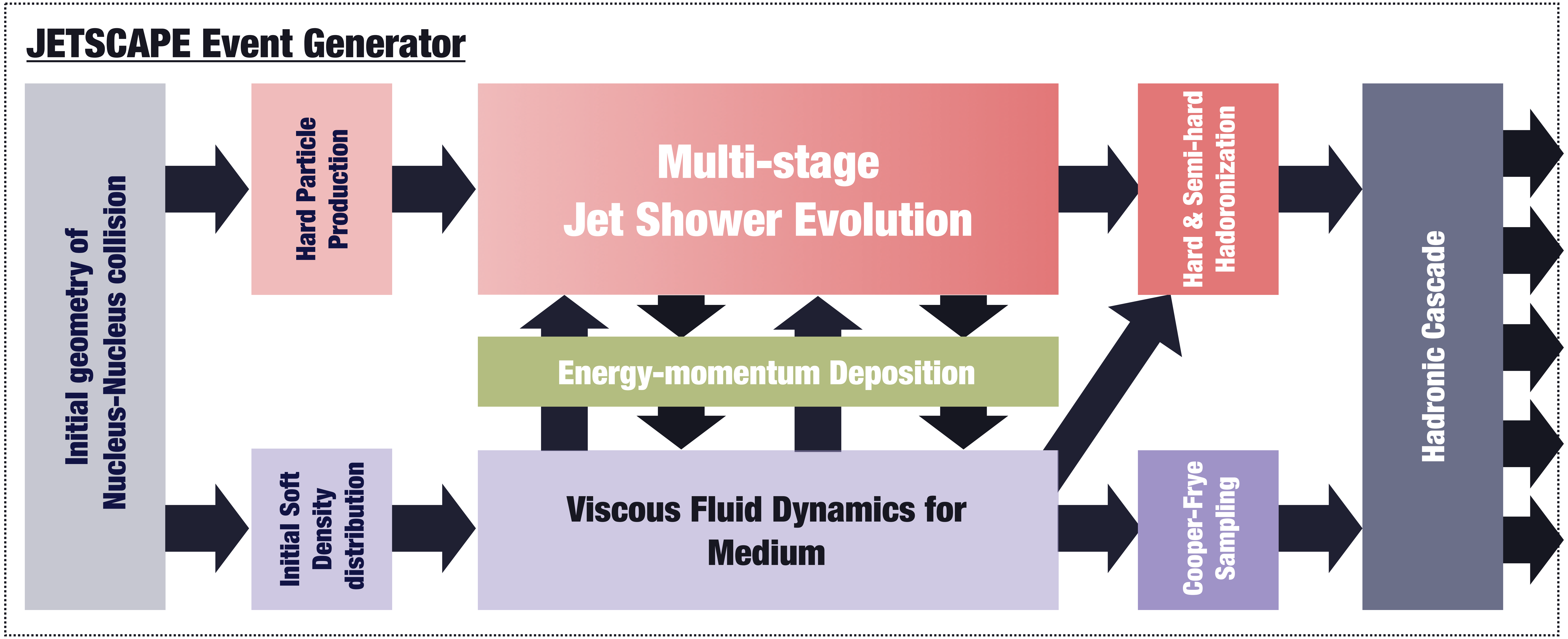
JETSCAPE

Jet Physics: From RHIC/LHC to EIC, CFNS, Stony Brook University, June 29th, 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 GitH github.com/JETSCAPE



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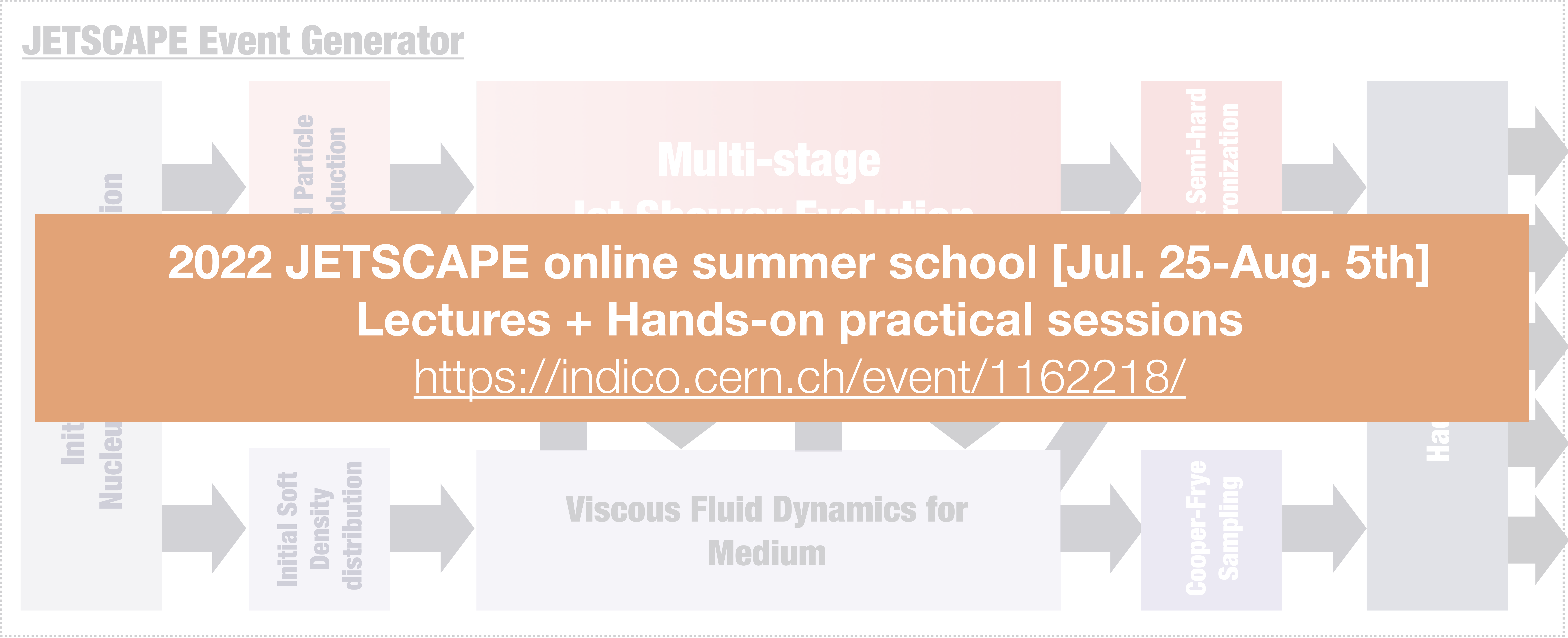
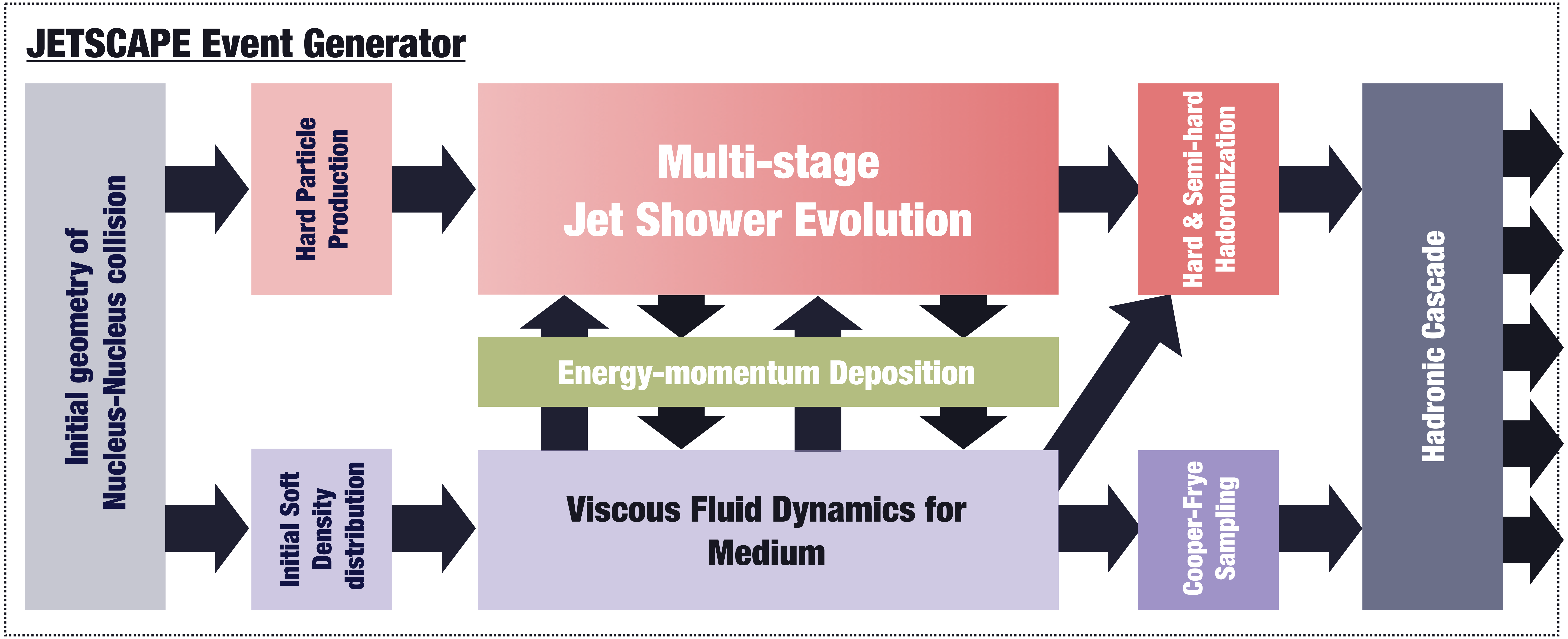


2022 JETSCAPE online summer school [Jul. 25-Aug. 5th]
Lectures + Hands-on practical sessions
https://indico.cern.ch/event/1162218/

The JETSCAPE Collaboration

- **Development of JETSCAPE framework** (by COMP working group)
- **Using JETSCAPE framework,**
  - studies for implications of QGP physics (by PHYS working group)
  - bayesian studies focusing on in-medium jet modification (by STAT working group)
  - bayesian studies focusing on bulk QGP dynamics (by SIMS working group)



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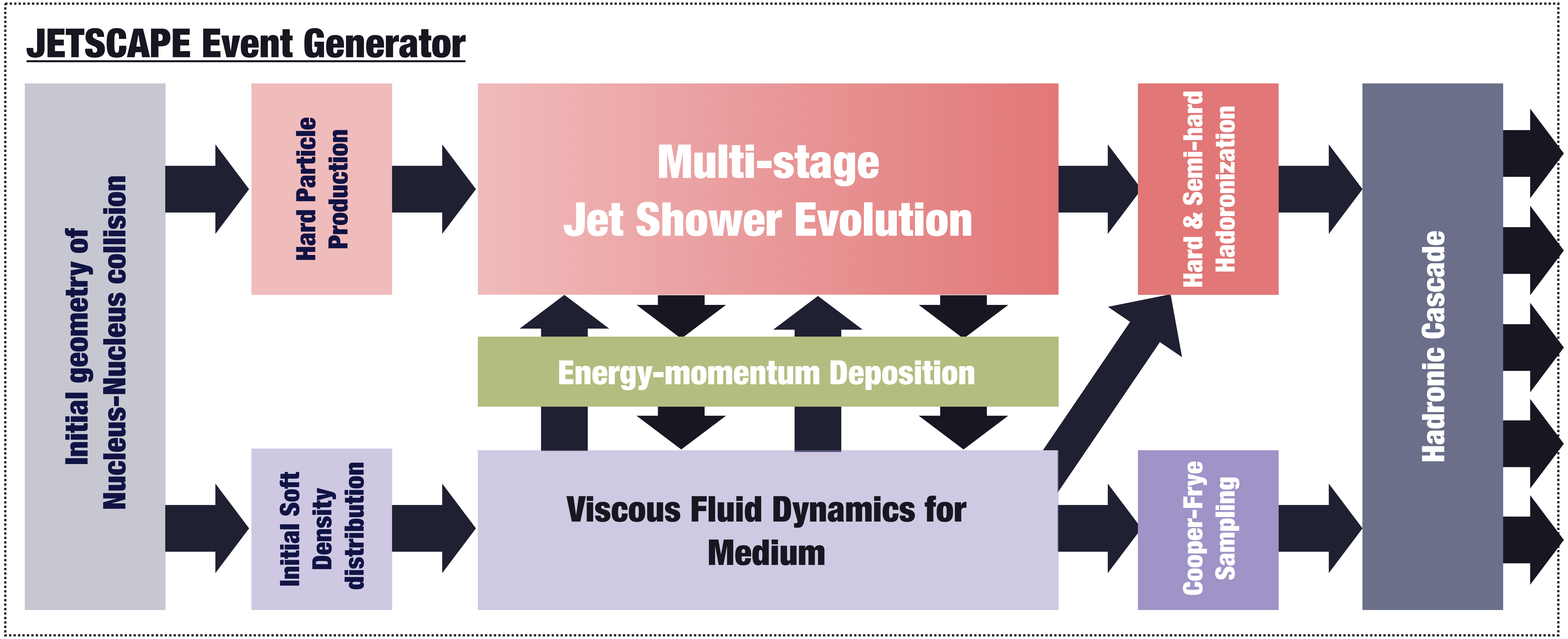

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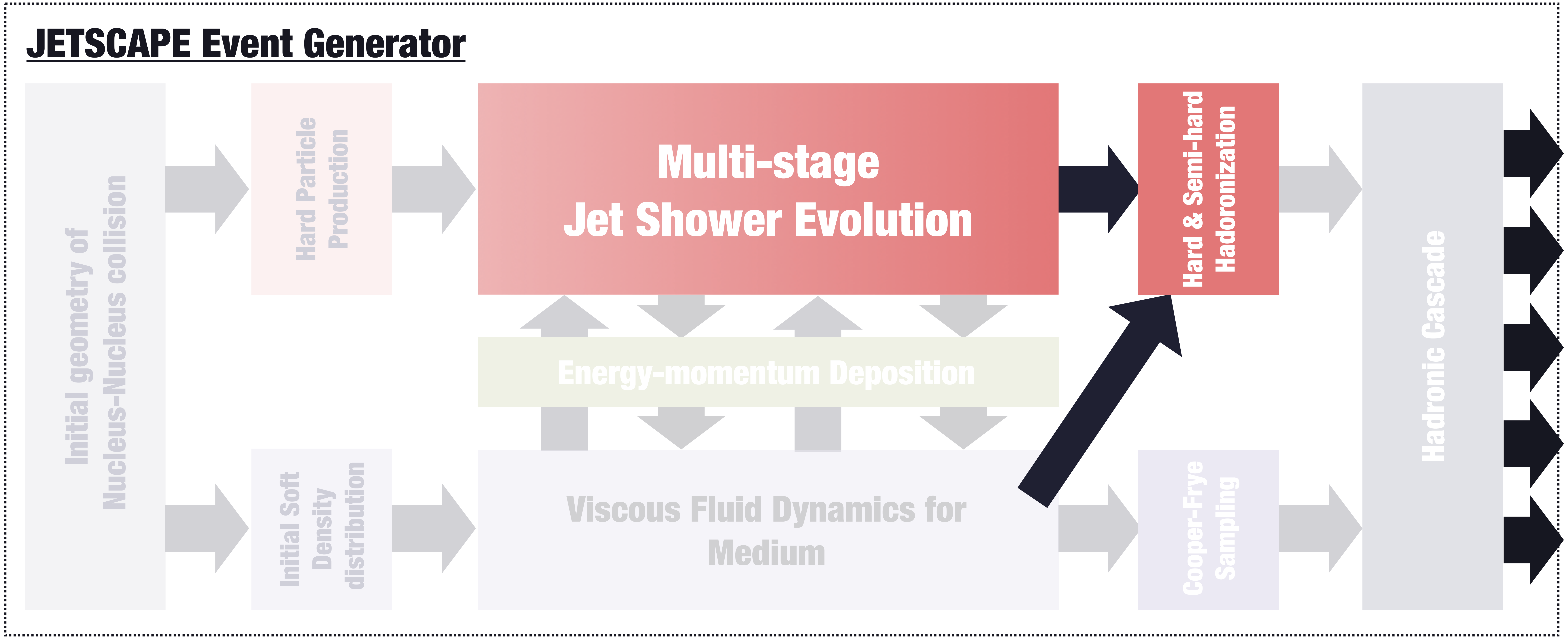

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References for other JETSCAPE studies
- **Framework Establishment: arXiv:1903.07706**
- **Bayesian for hard jet sector: PRC104, 024905**
- **Bayesian for soft bulk sector: PRL126, 242301, PRC 103, 054904, arXiv:2203.08286**

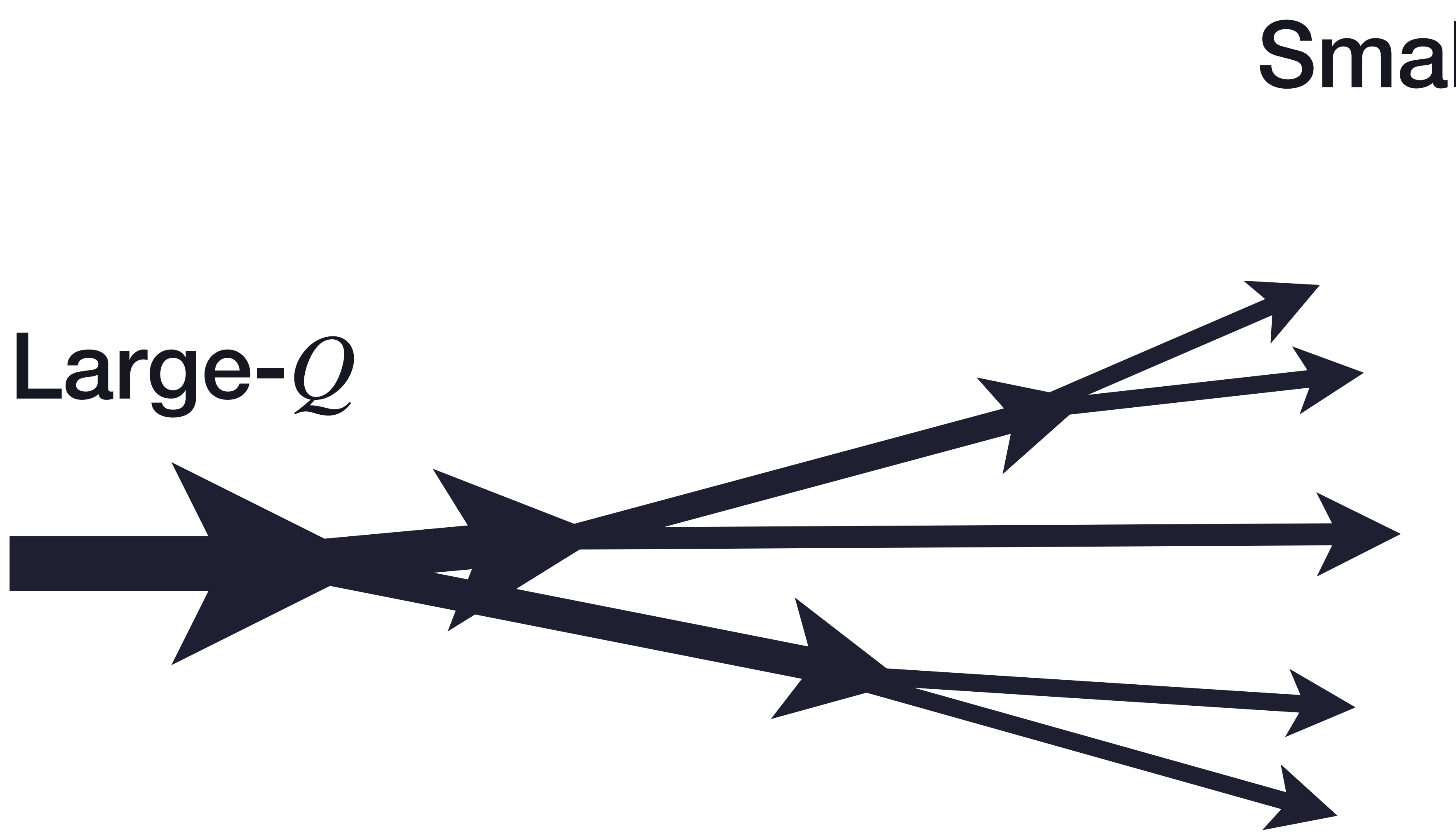
Multi-stage evolution of jet shower in JETSCAPE

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)

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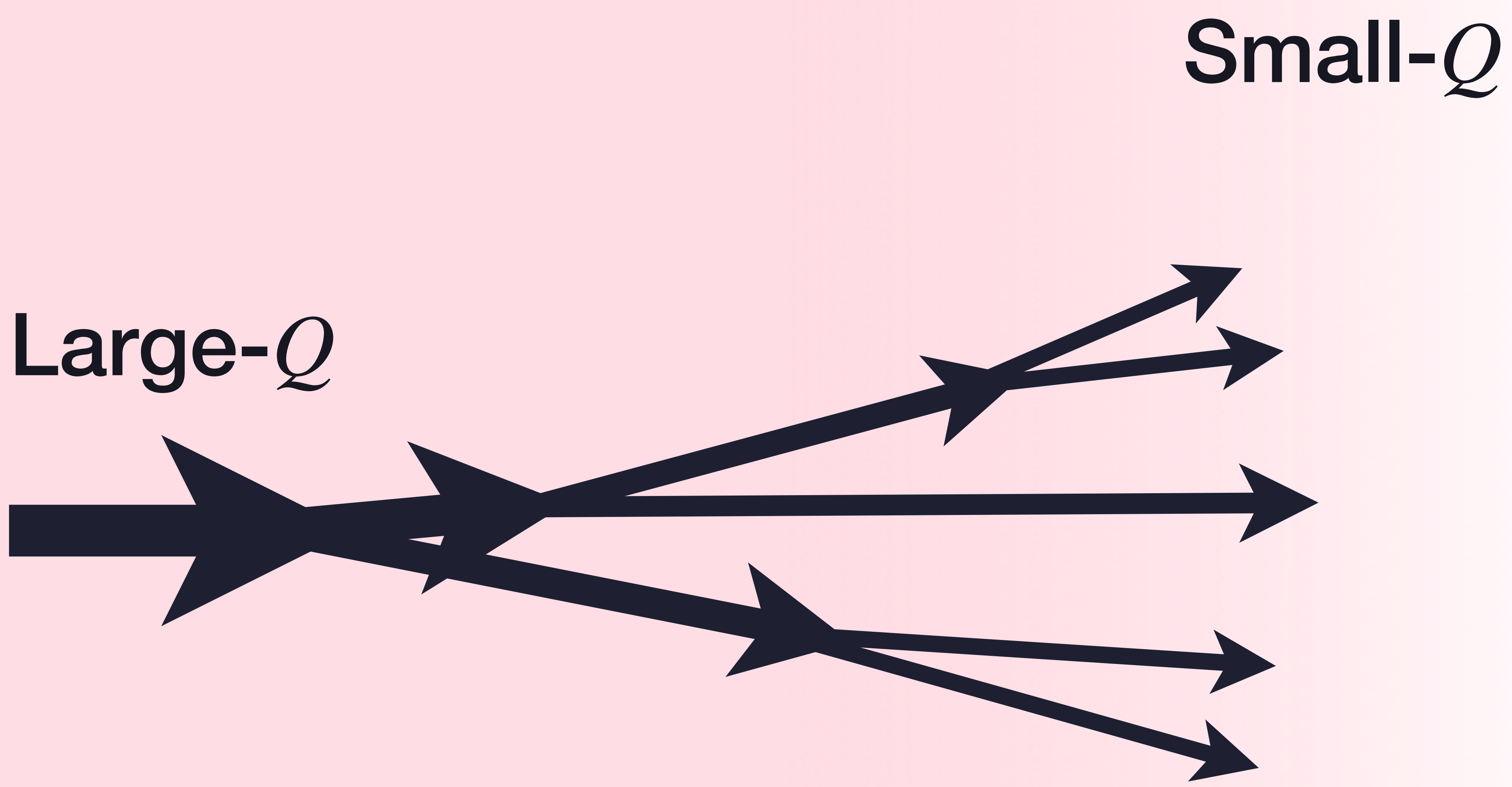
In-medium

- In-vacuum: Virtuality ordered splitting



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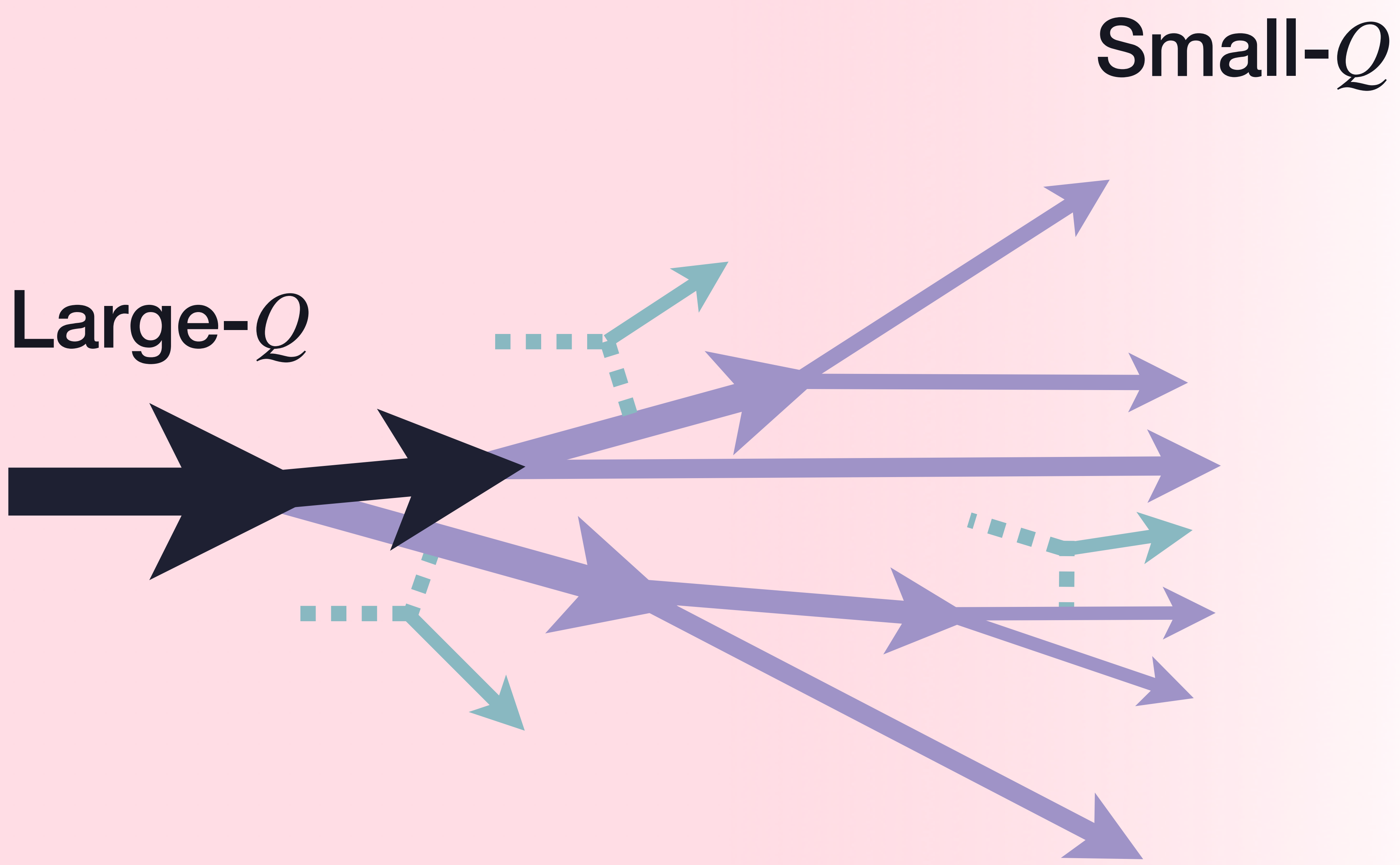

- In-vacuum: Virtuality ordered splitting
- Large-Q: Medium effect on top of in-vacuum splitting

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

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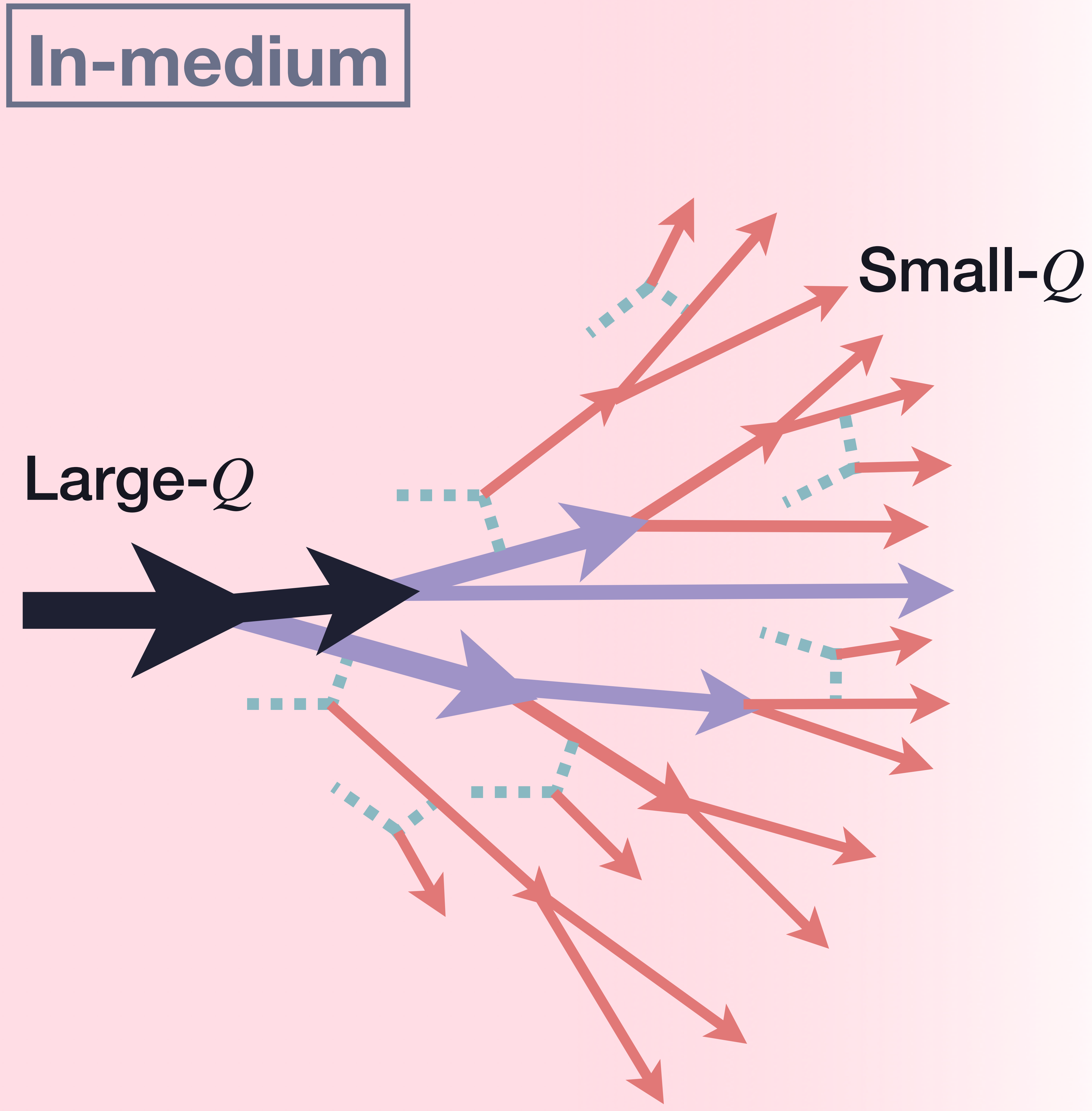

$Q^2 = p^\mu p_\mu - m^2$: virtuality (off-shellness)

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

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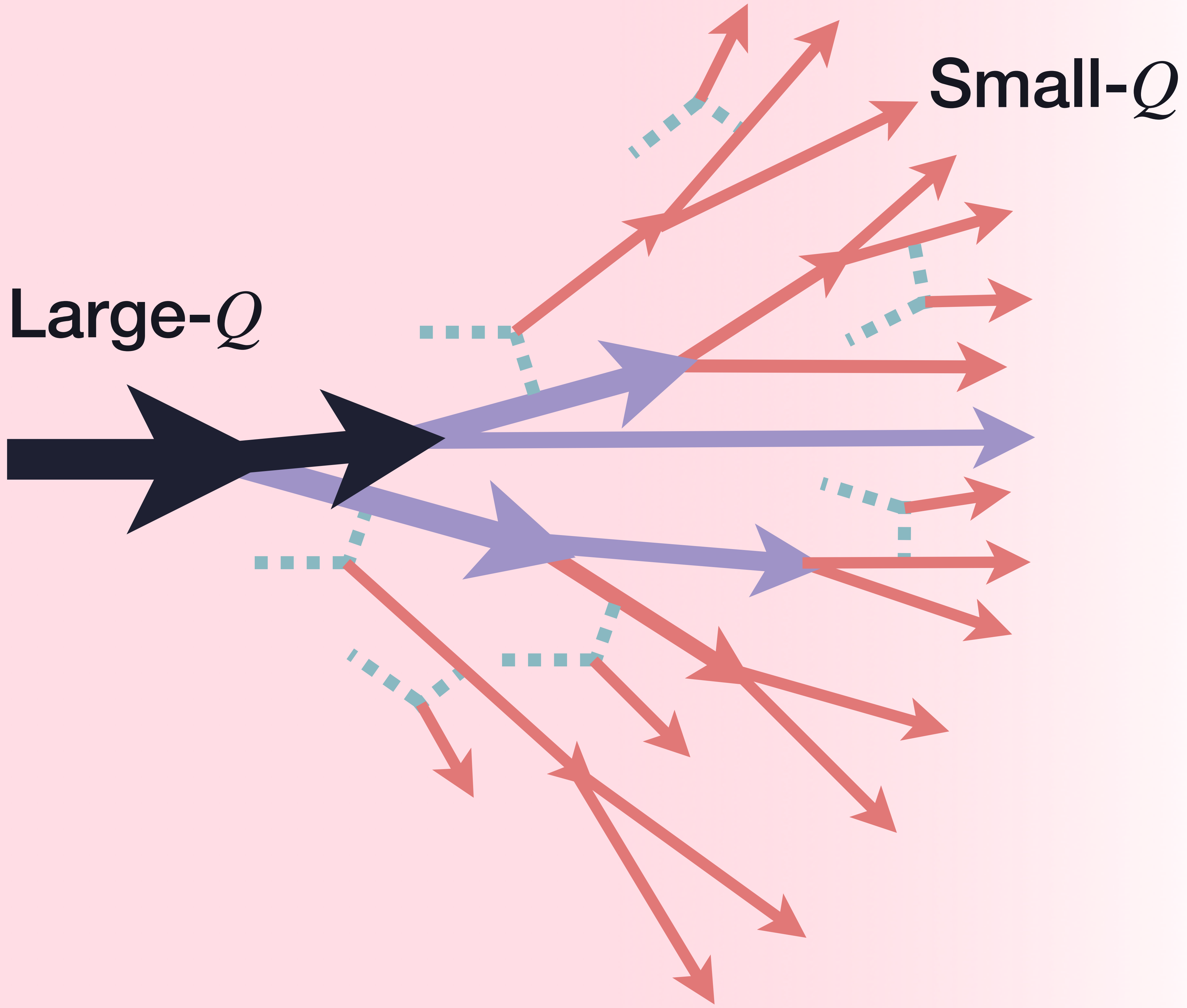

$Q^2 = p^\mu p_\mu - m^2$: virtuality (off-shellness)

- In-vacuum: Virtuality ordered splitting
- Large-Q: Medium effect on top of in-vacuum splitting
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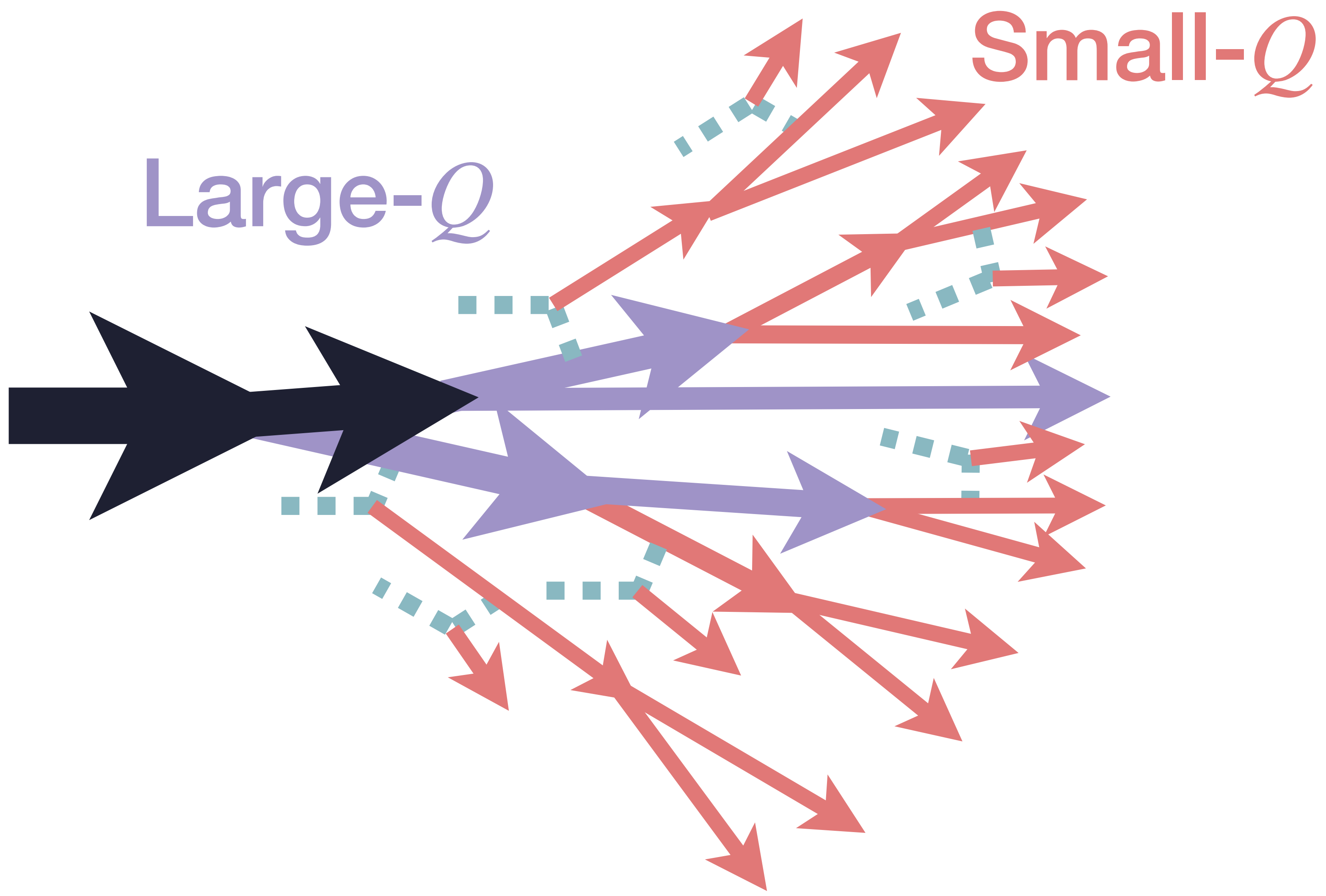
Cannot be described by a single model
→ Combination of multiple models

Multi-stage jet evolution in JETSCAPE

JETSCAPE, PRC96, 024909 (2017)



Virtuality separation scale: Q_{sw}

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

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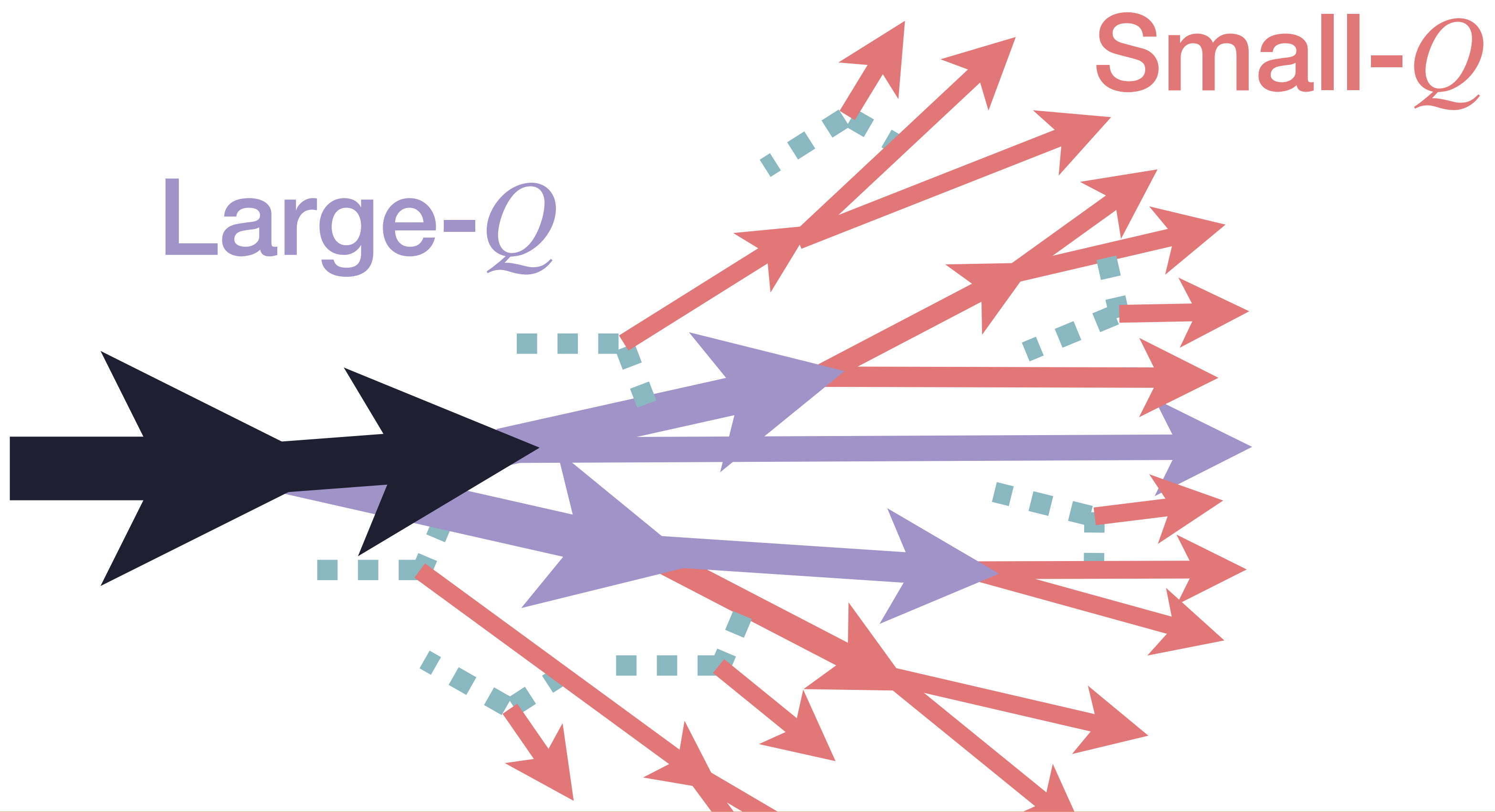

aration scale: Q_{sw}

Switching between modules for parton by parton

Large-Q $(> Q_{sw})$	Small-Q $(< Q_{sw})$		
MATTER	**LBT**	**MARTINI**	**AdS/CFT**
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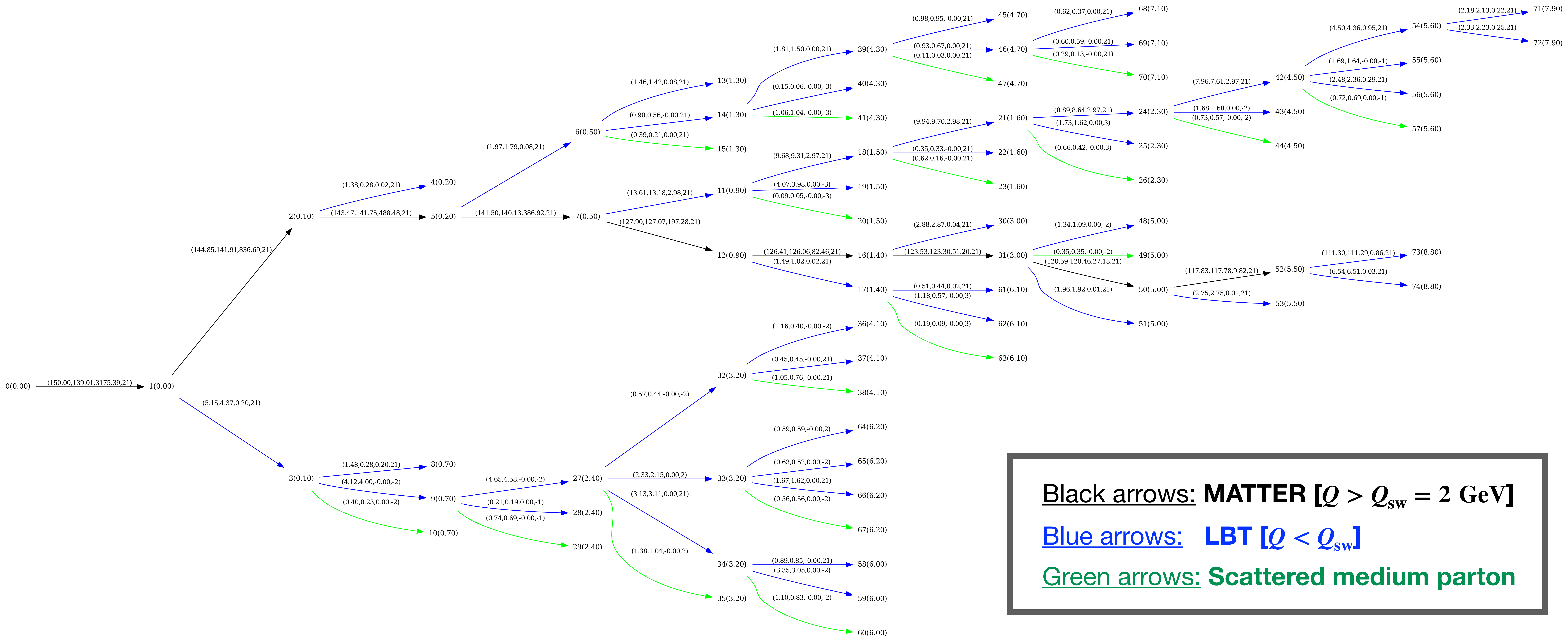
JETSCAPE, PRC96, 024909 (2017)

- **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**

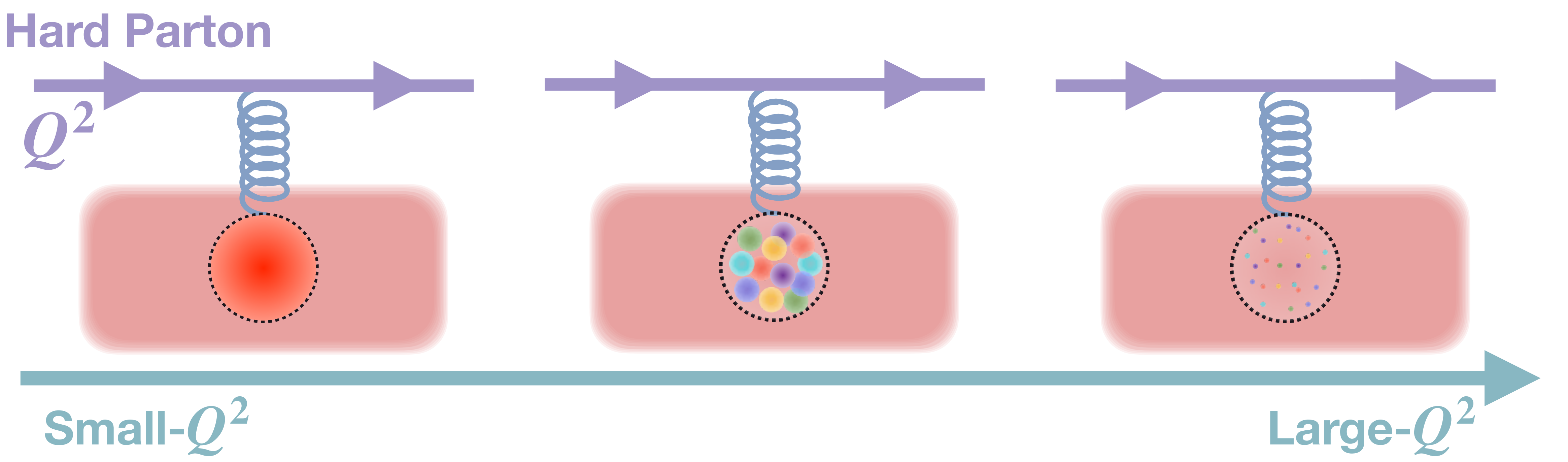
Multi-stage jet evolution in JETSCAPE

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

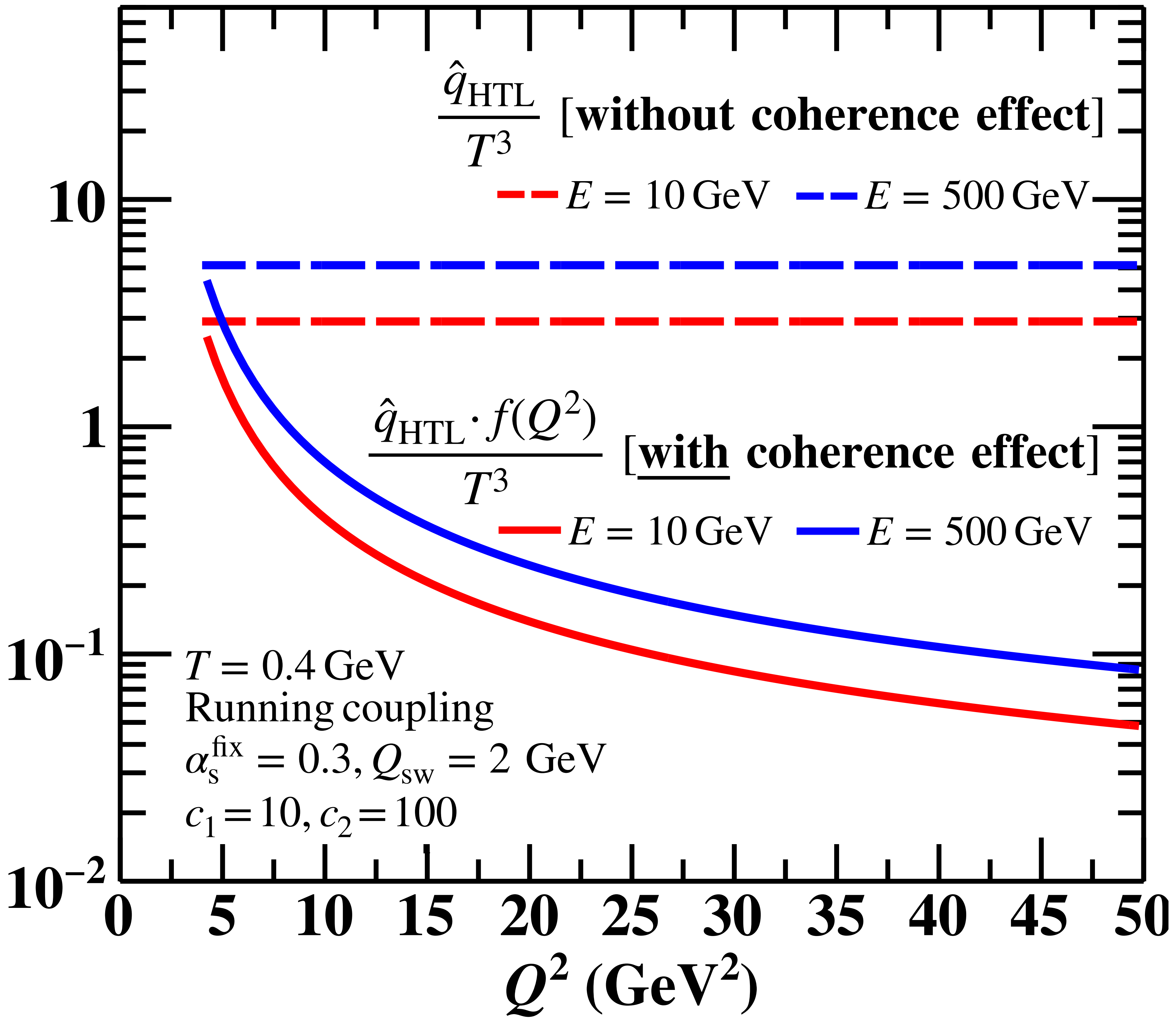


Effective jet-quenching strength

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

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

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



Jet simulation with JETSCAPE

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

Jet simulation with JETSCAPE

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Jet Shower

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

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JETSCAPE PP19 tune [jetscape_user_PP19.xml]

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

Bulk Medium

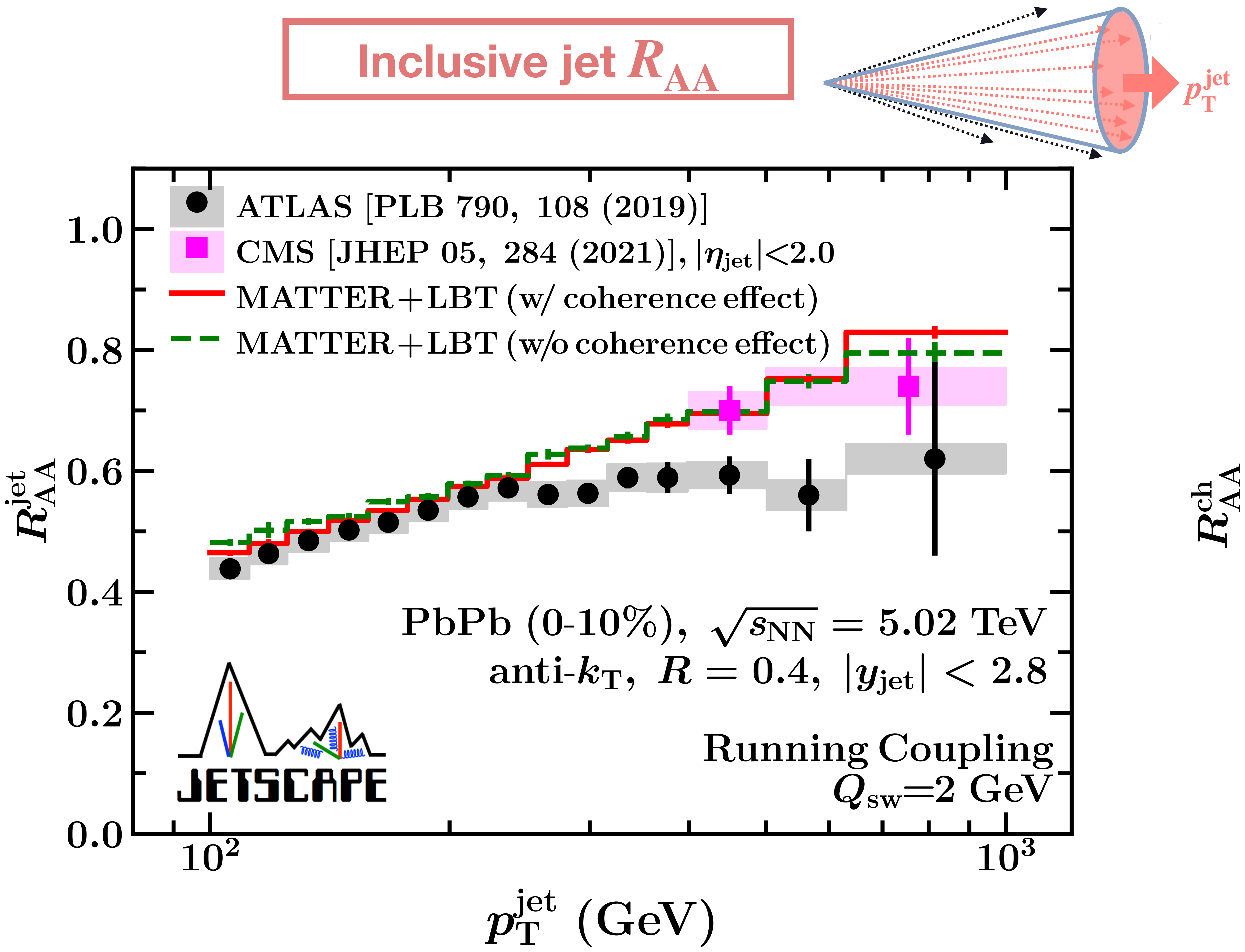
Initial Condition: TRENTo+Freestreaming
Moreland, Bernhard, Bass (14) , Liu, Shen, Heinz(15)
Hydro Evolution: VISHNU (2+1D viscous)
Shen, Qiu, Song, Bernhard, Bass, Heinz(16)

Jet and single particle energy loss

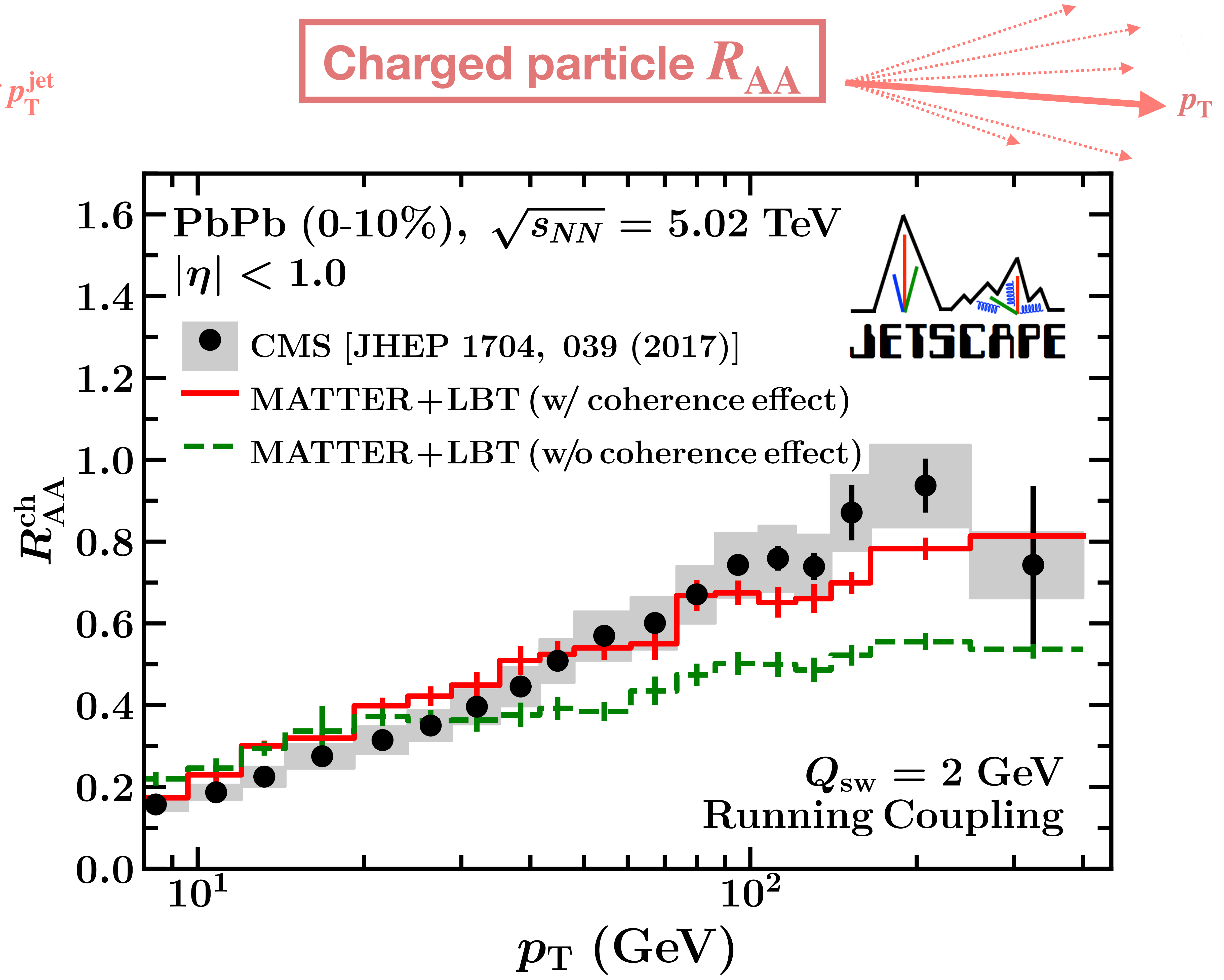
JETSCAPE, arXiv:2204.01163

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

Inclusive jet R_{AA}



Charged particle R_{AA}



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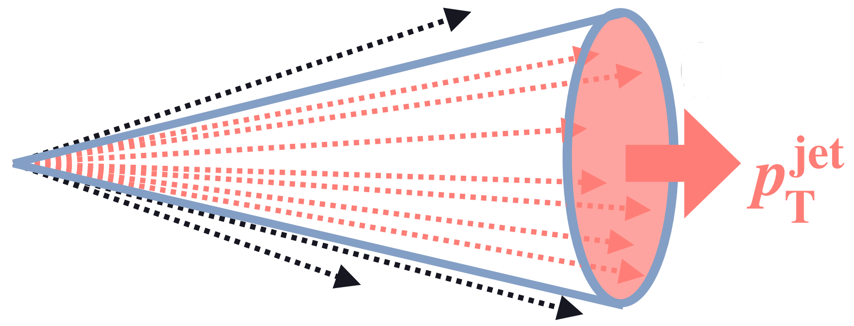

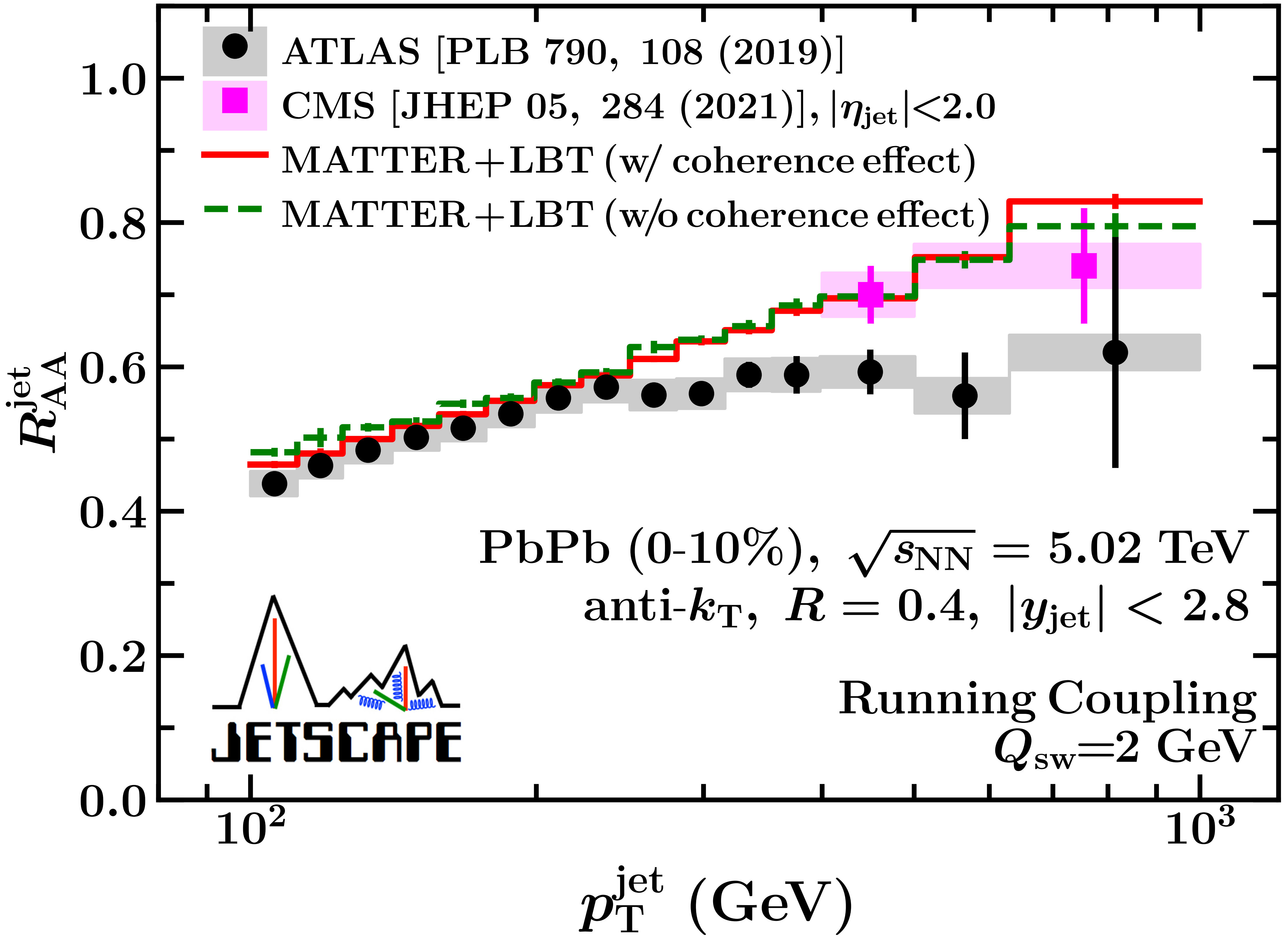

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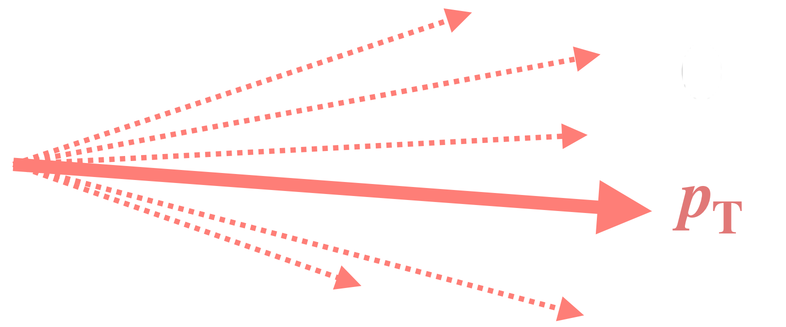

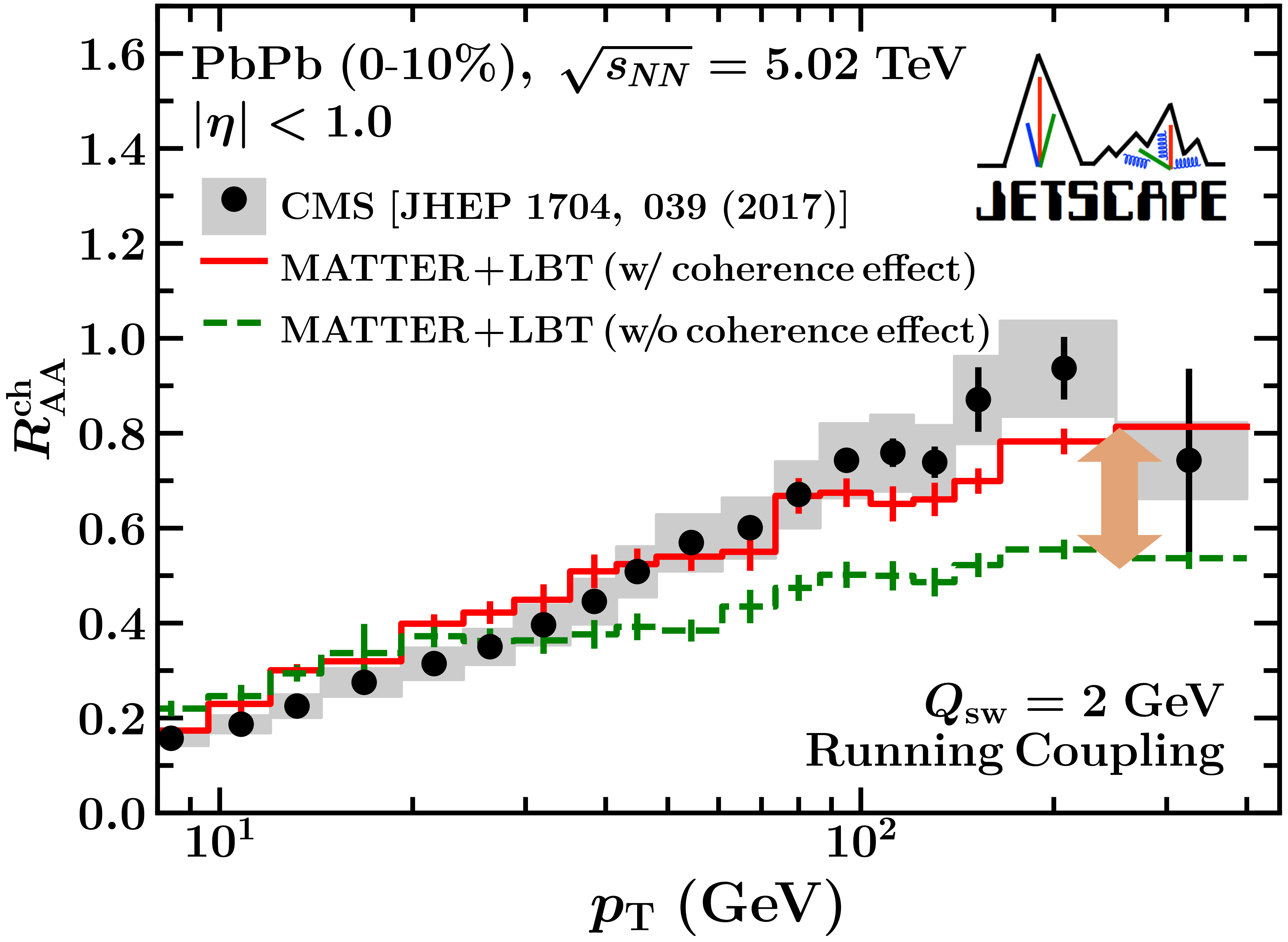

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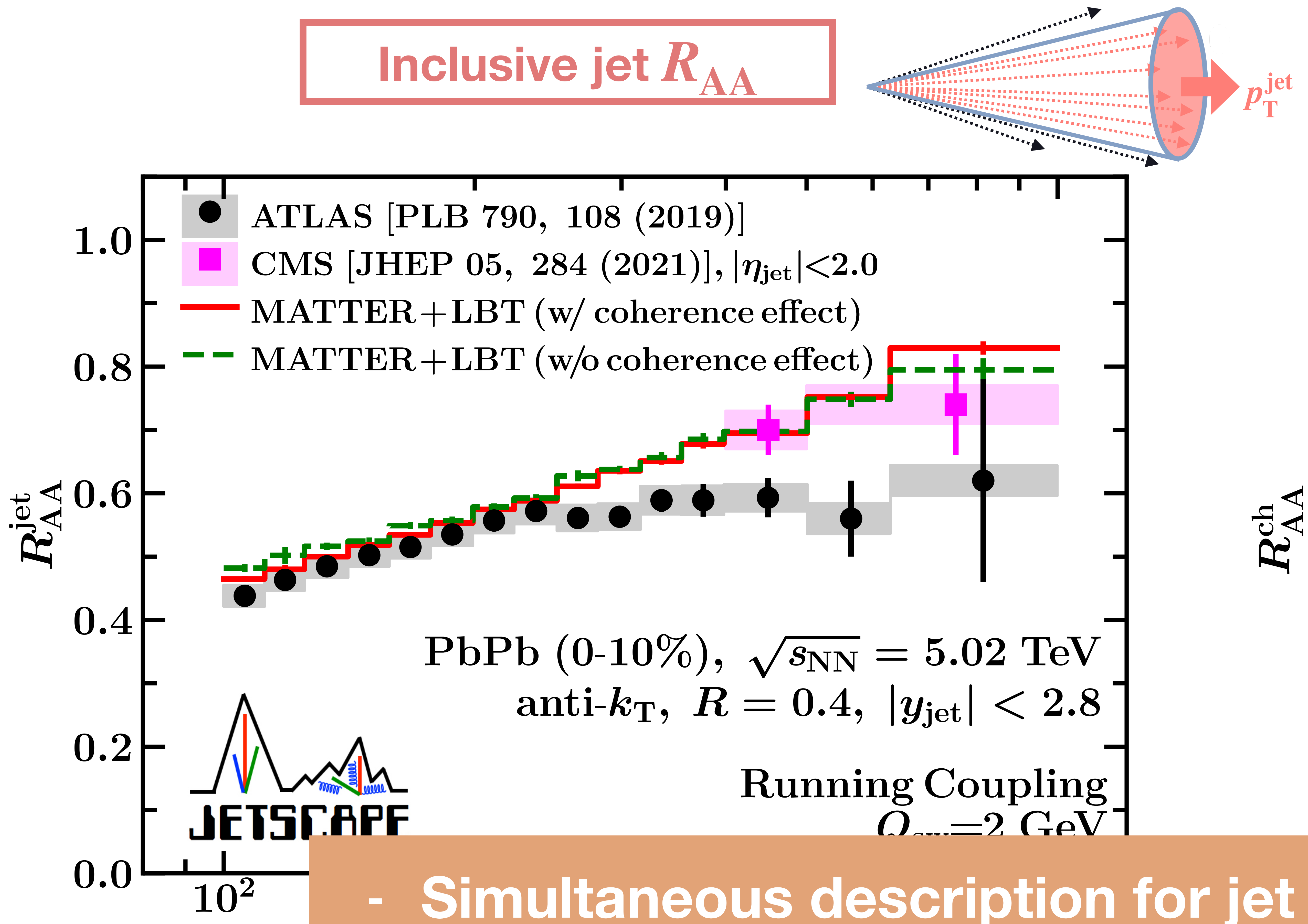
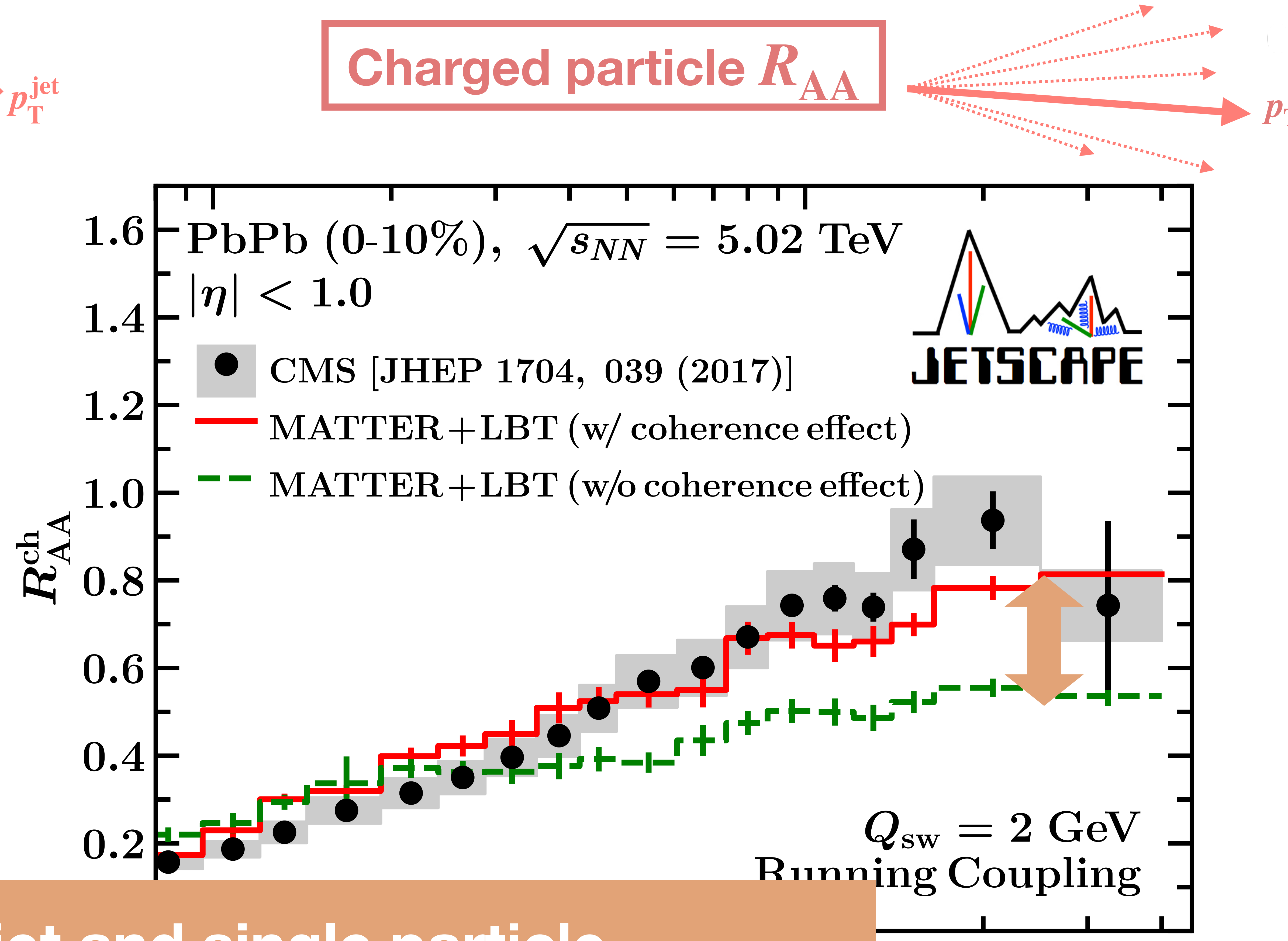




- Simultaneous description for jet and single particle
- Significant coherence effect in single particle energy loss

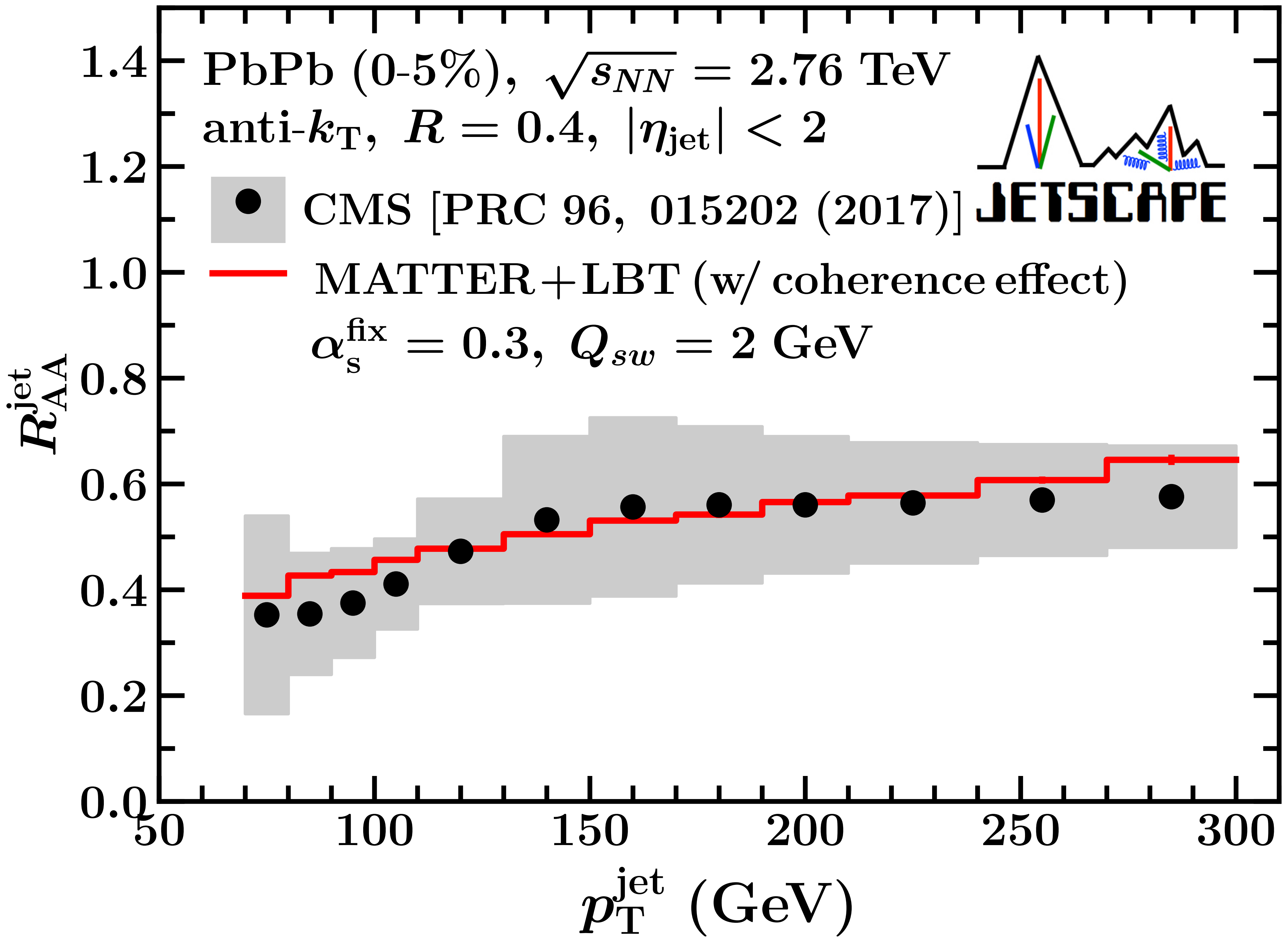
Jet and single particle energy loss

JETSCAPE, arXiv:2204.01163

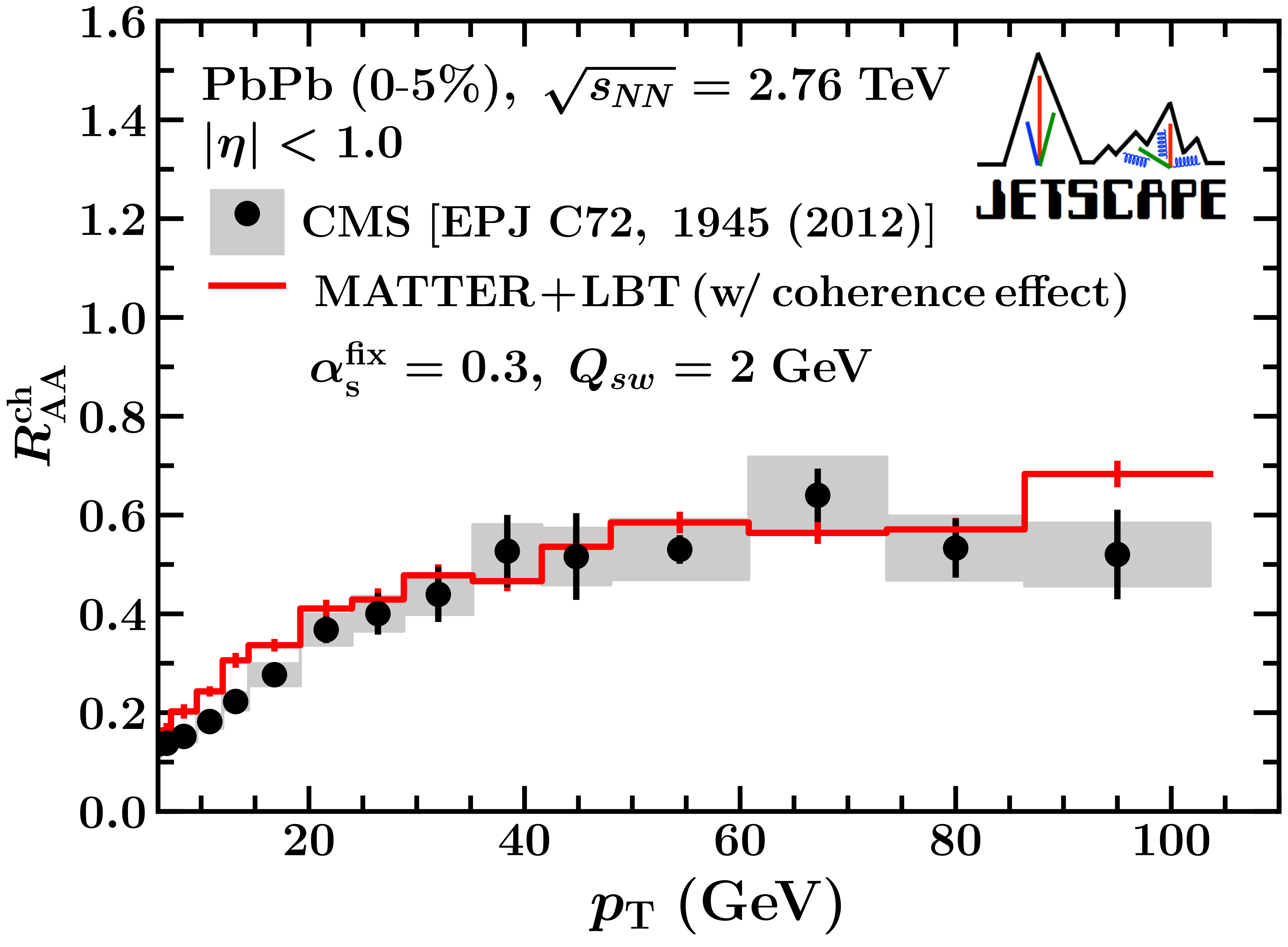
- **Pb+Pb collisions at 2.76 TeV**

The same parameter set as 5.02 TeV is used

Inclusive jet R_{AA}



Charged particle R_{AA}



Jet and single particle energy loss

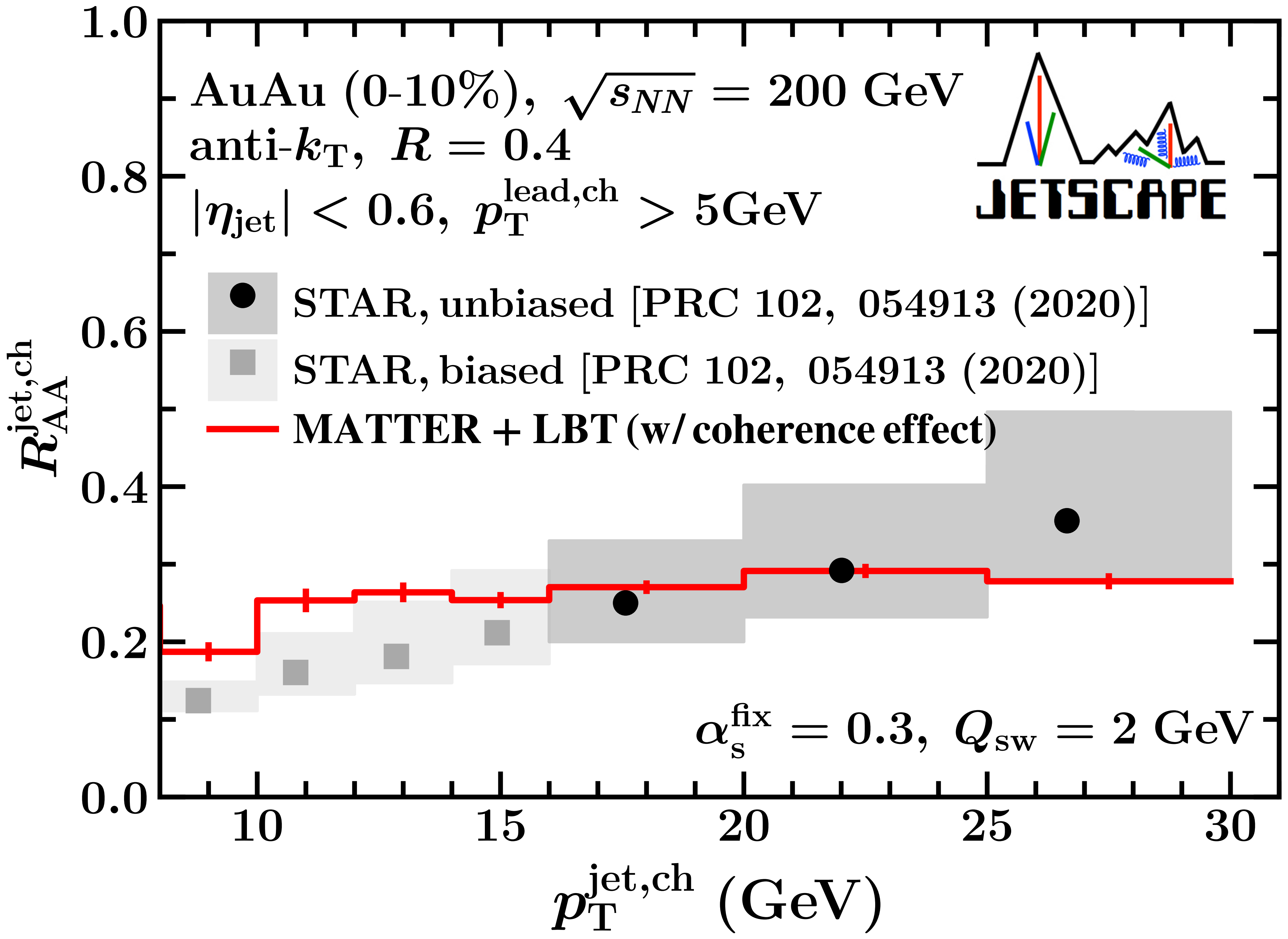
JETSCAPE, arXiv:2204.01163

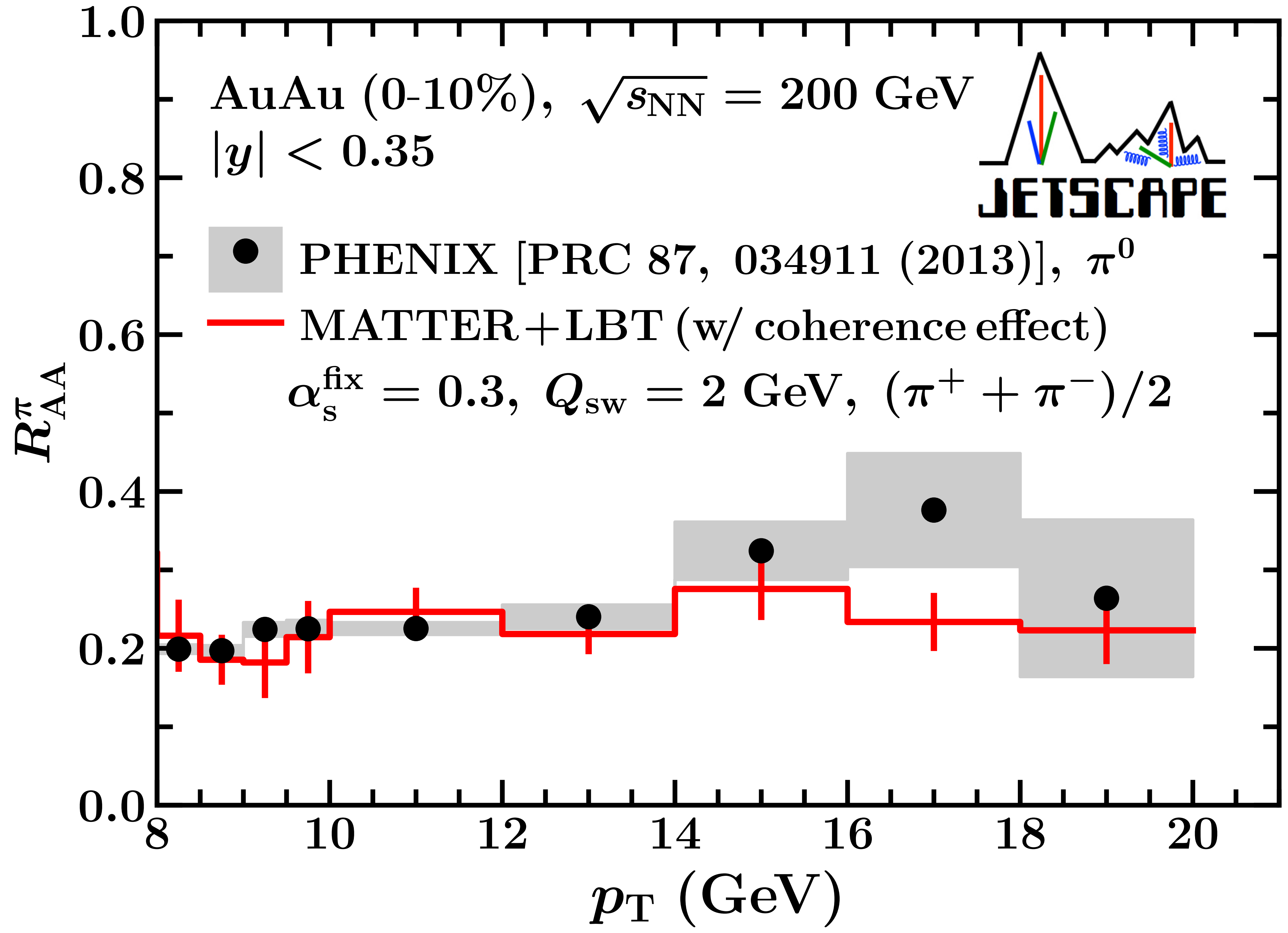
- **Au+Au collisions at 200 GeV**

The same parameter set as 5.02 TeV is used

Charged jet R_{AA}

Pion R_{AA}





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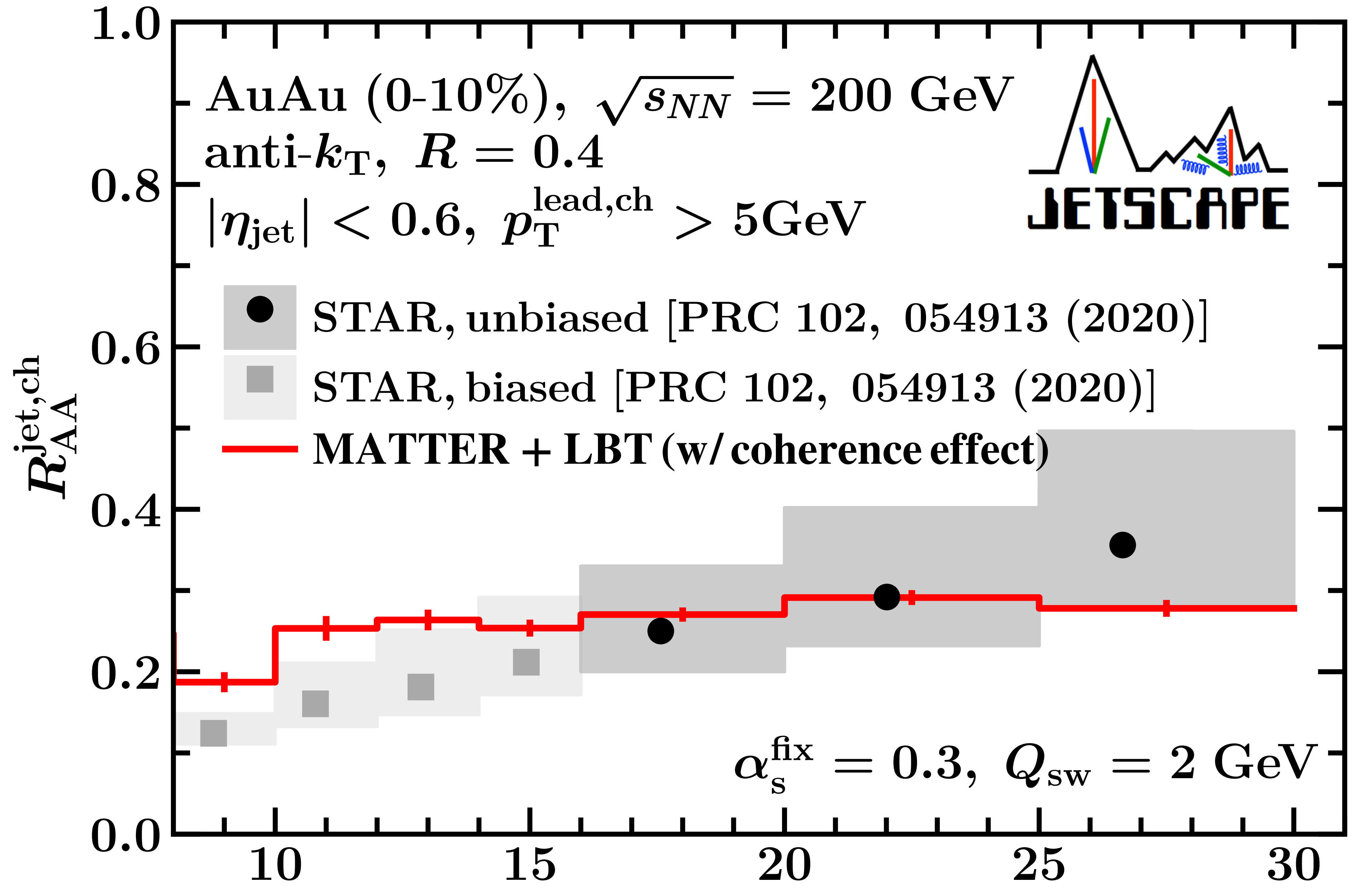
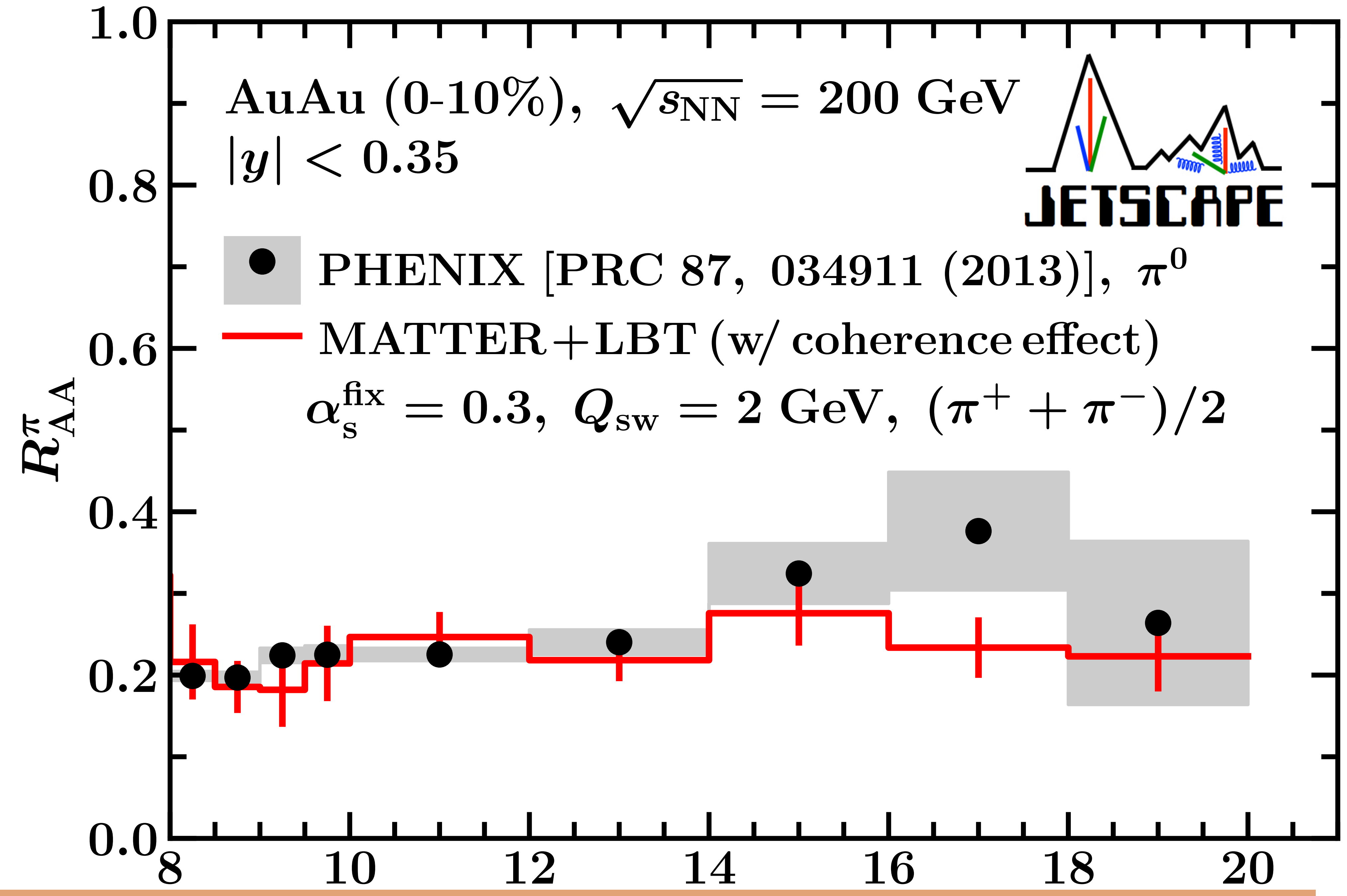


Pion R_{AA}



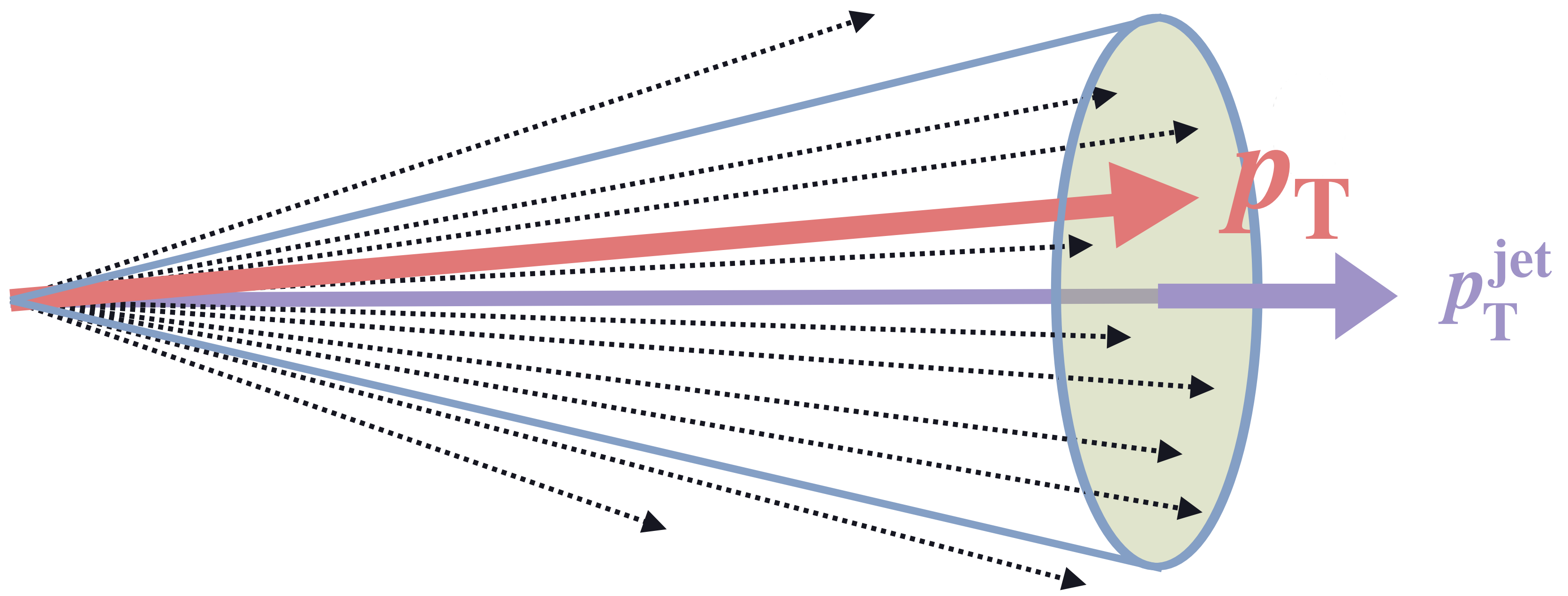
- **Simultaneous description of different $\sqrt{s_{NN}}$ with the same parameter set**

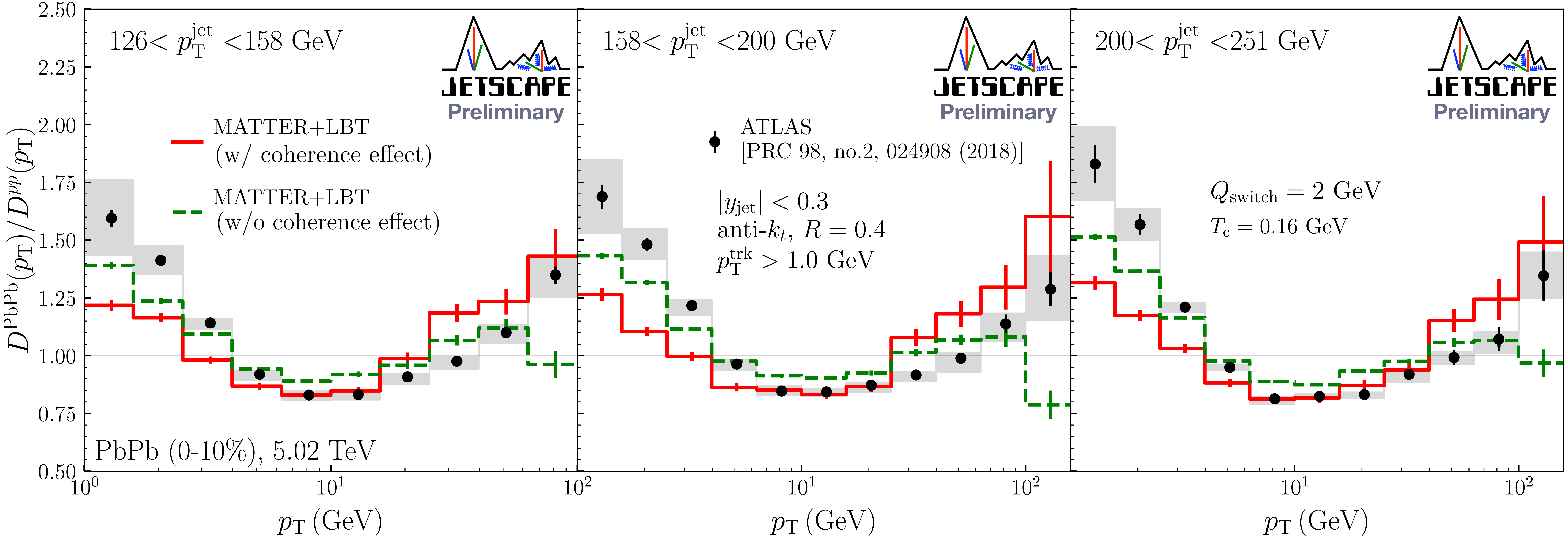
Jet substructures

JETSCAPE (in preparation)

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

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





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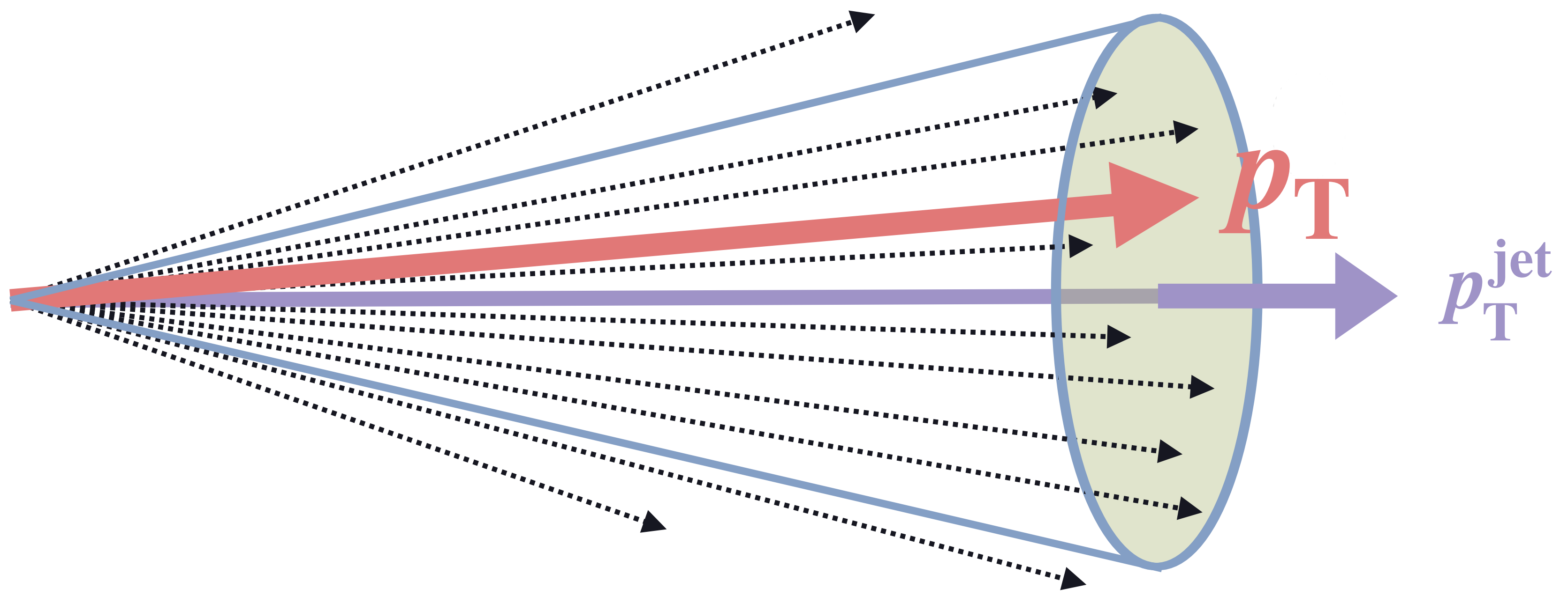

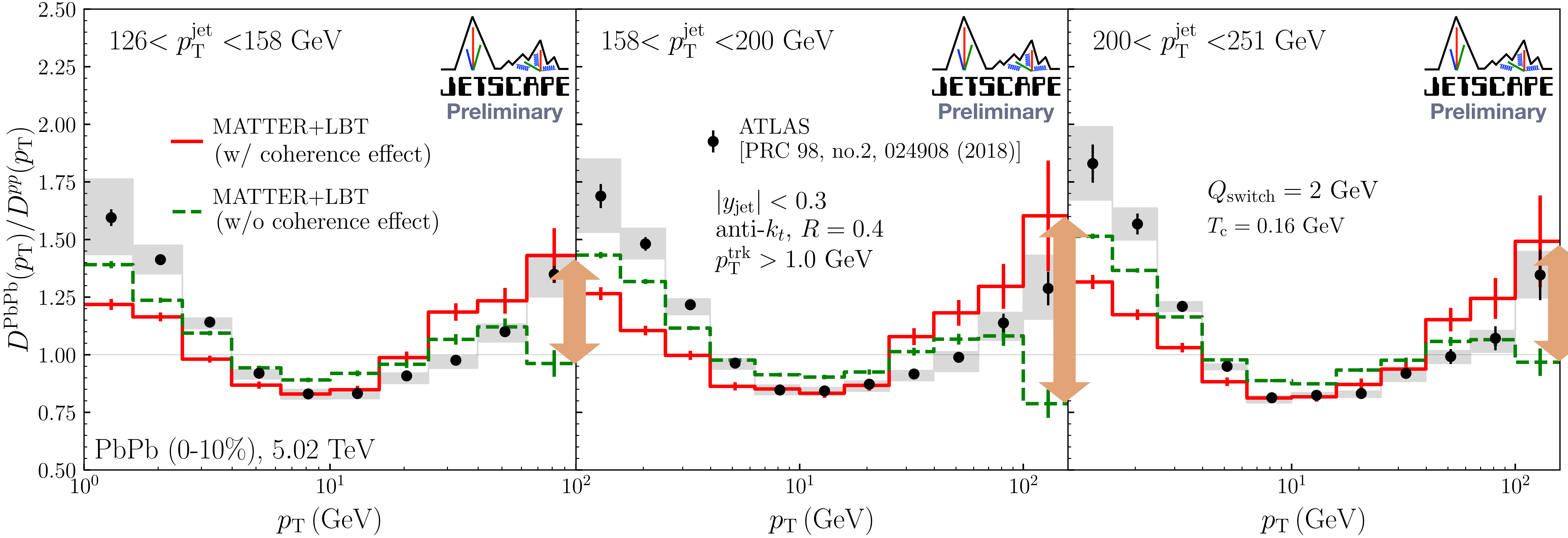

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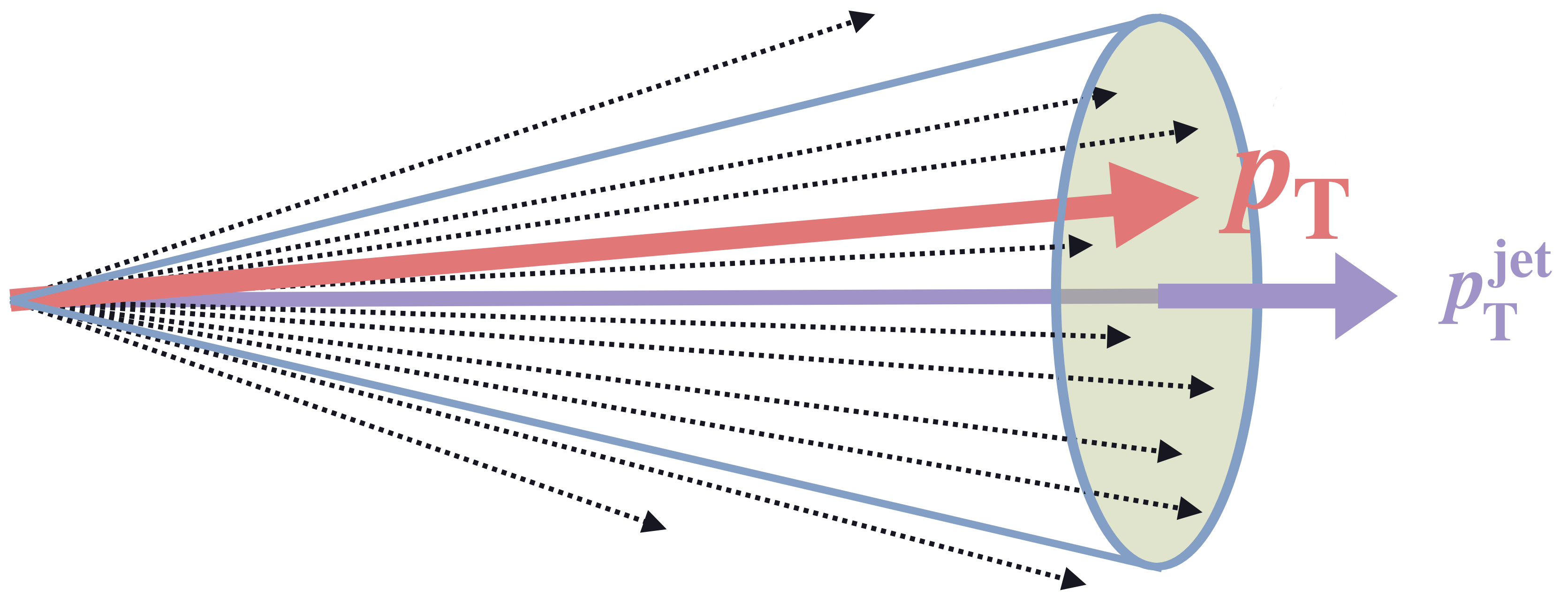
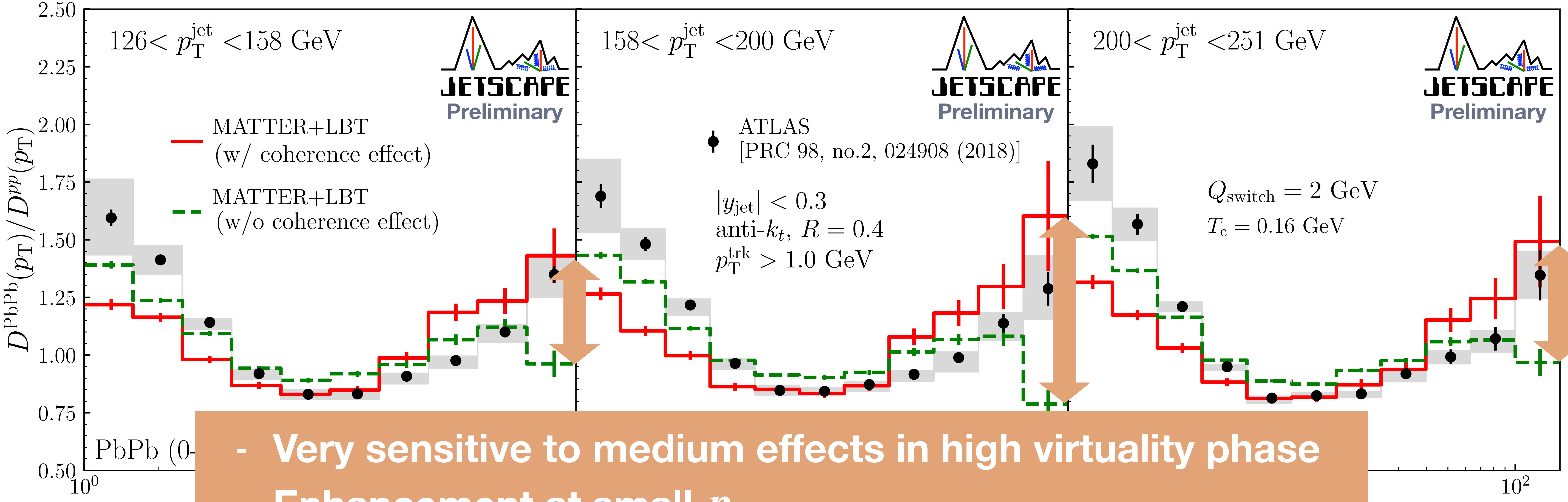




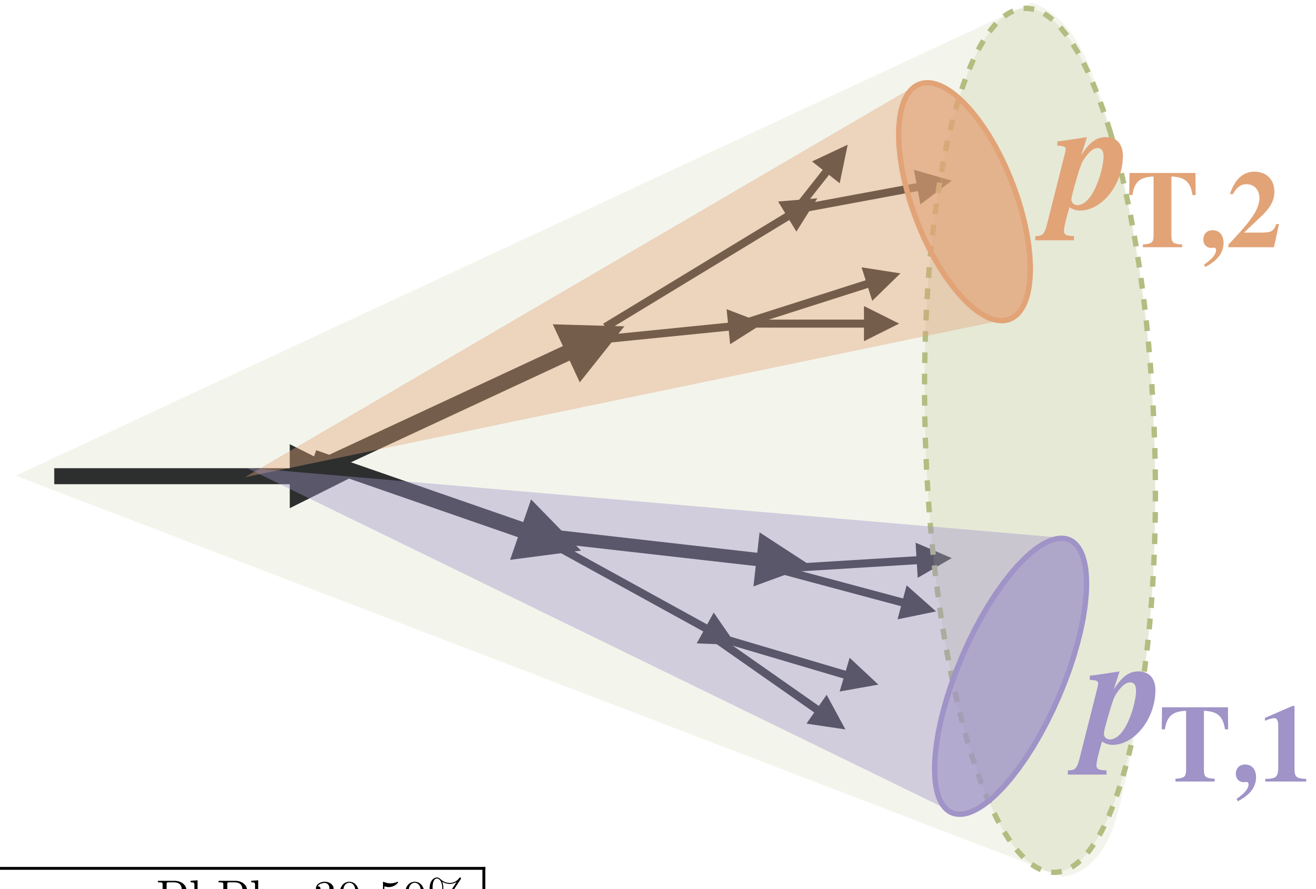
- Very sensitive to medium effects in high virtuality phase
- Enhancement at small-p_T

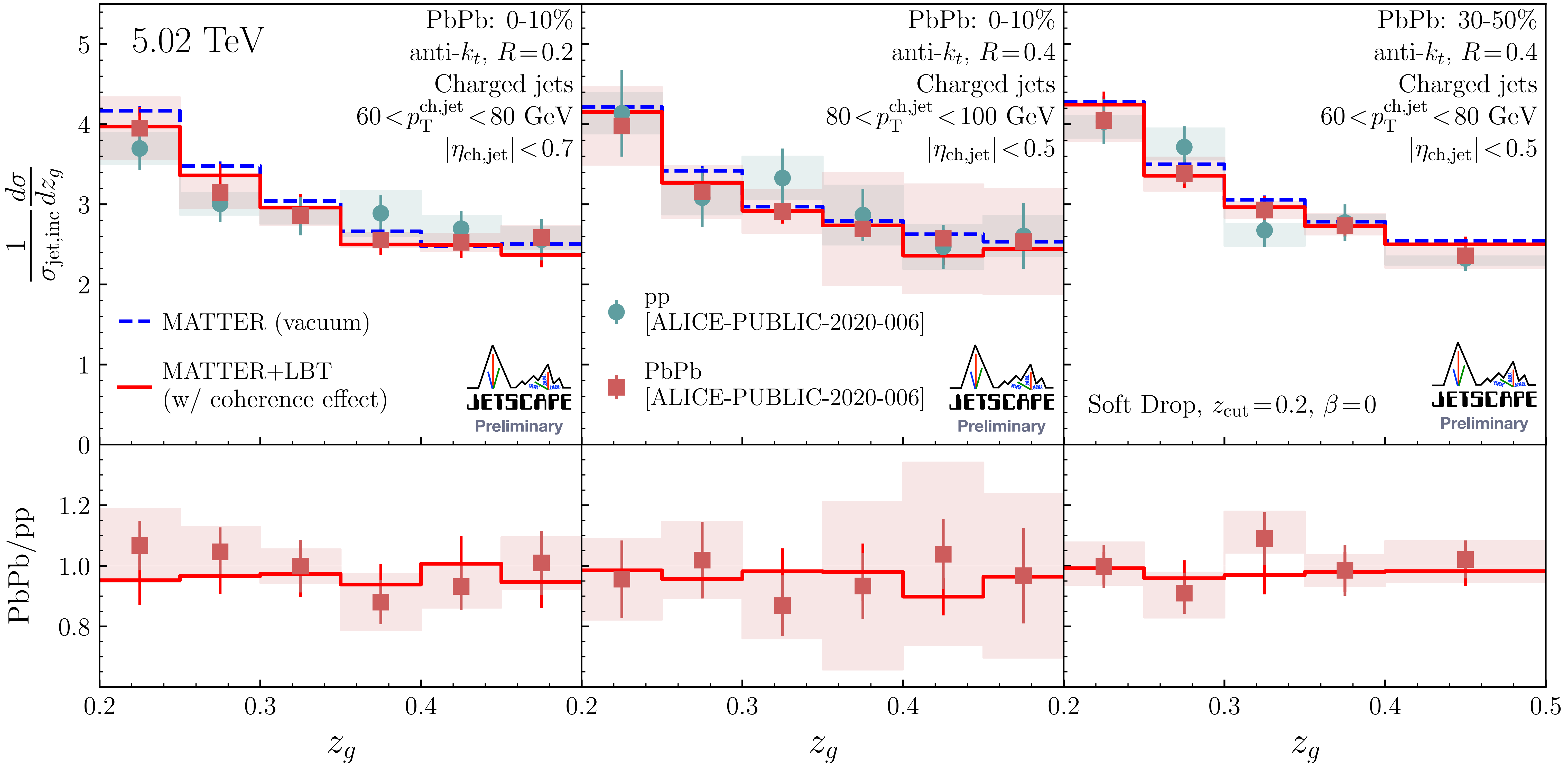
Jet substructures

JETSCAPE (in preparation)

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

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





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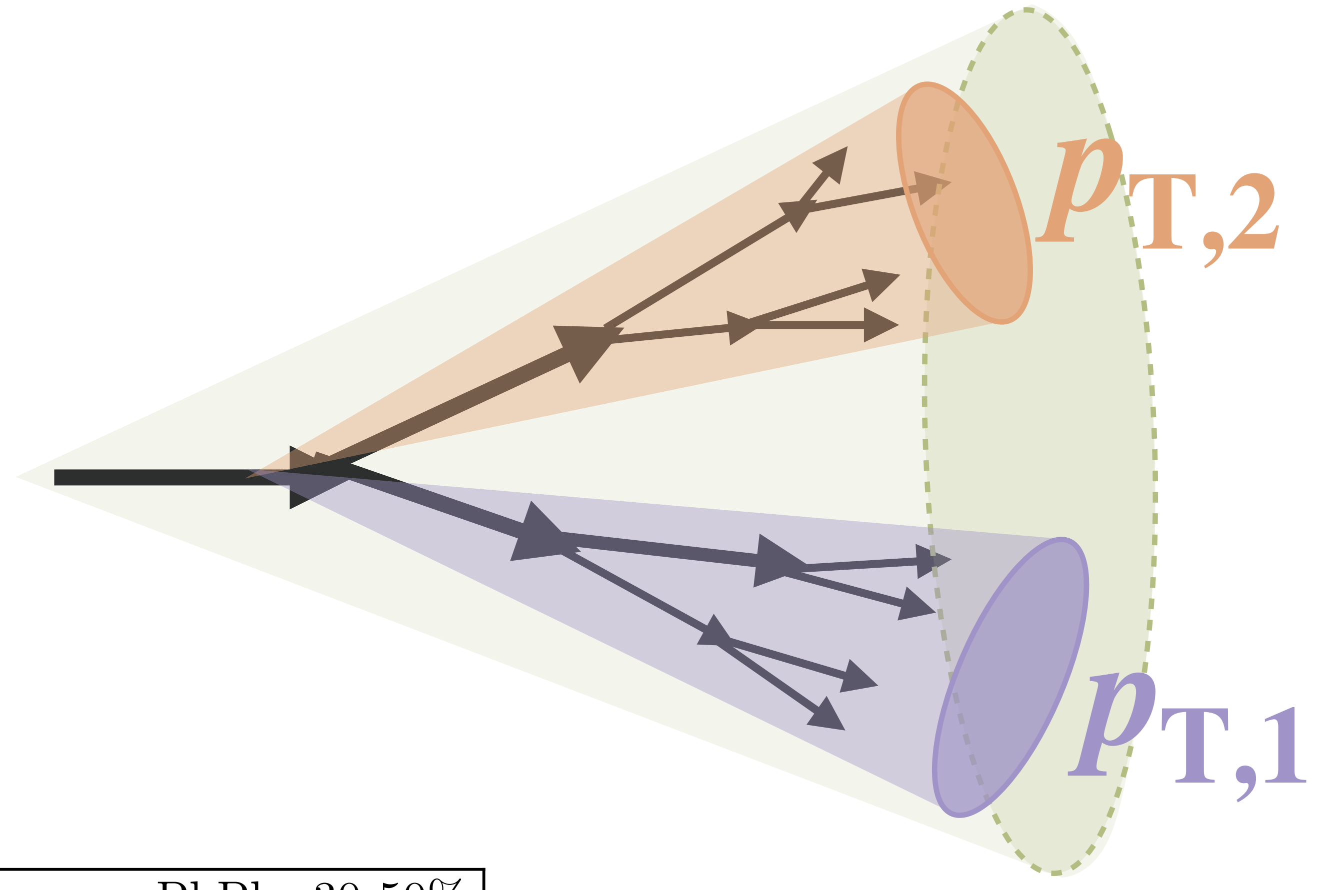
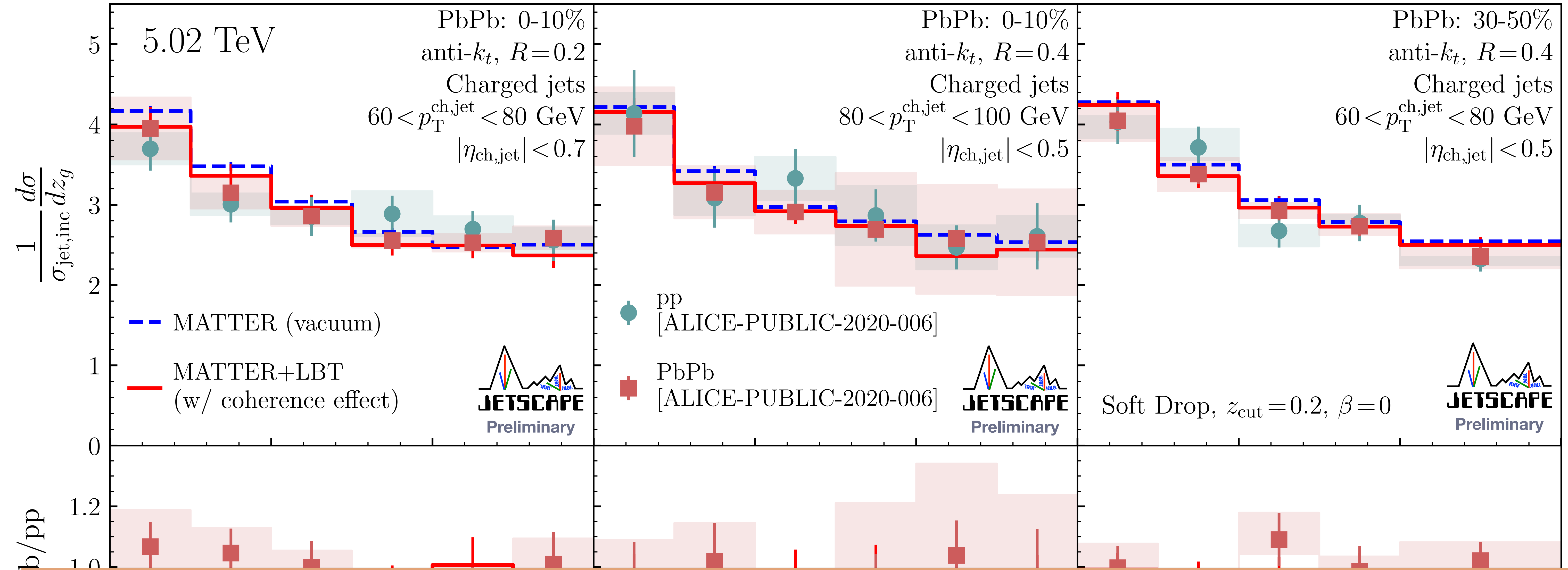




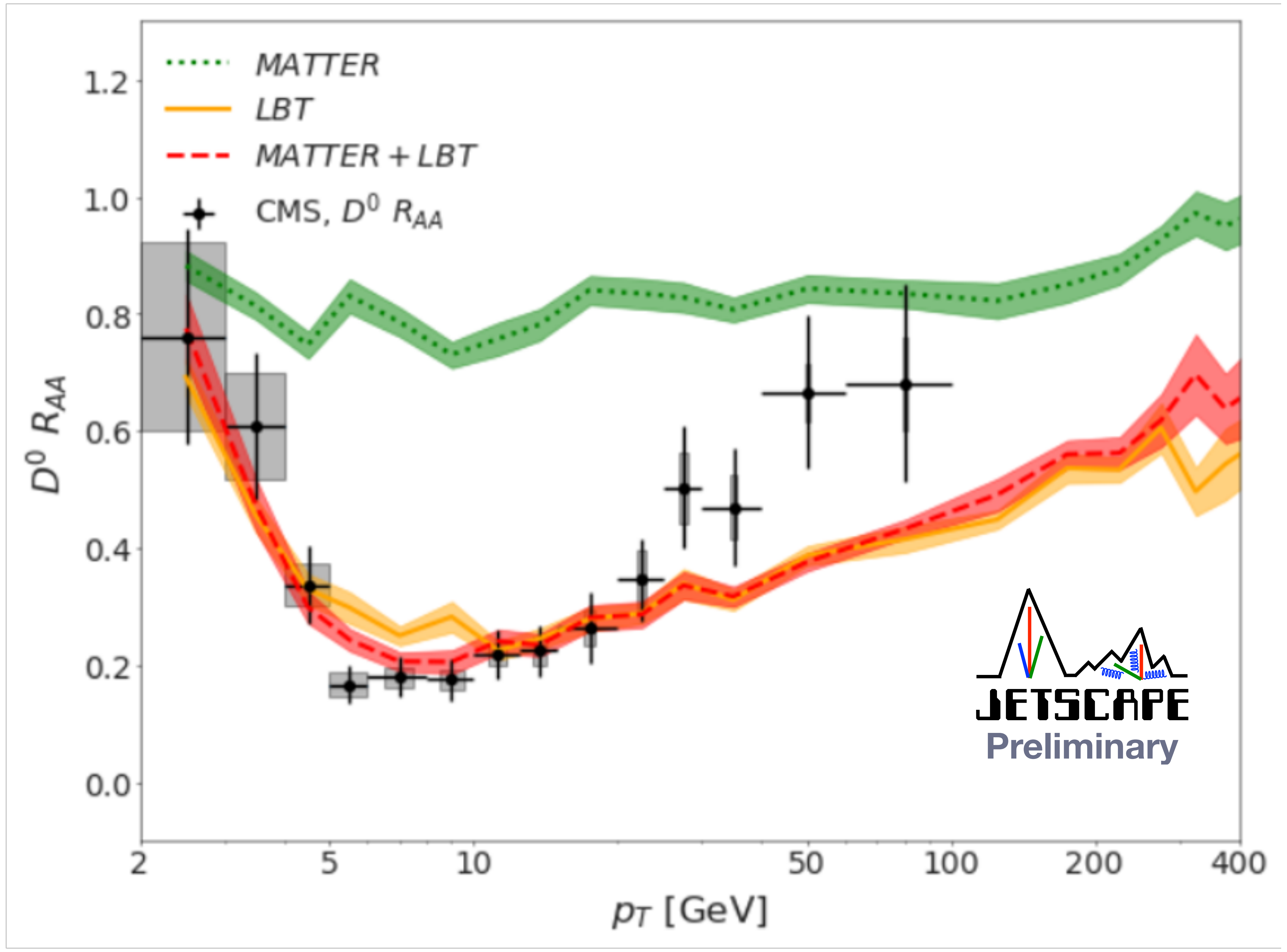
- **Good agreement with experimental data**
- **Almost no medium modification in hardest splittings**

Heavy flavor energy loss

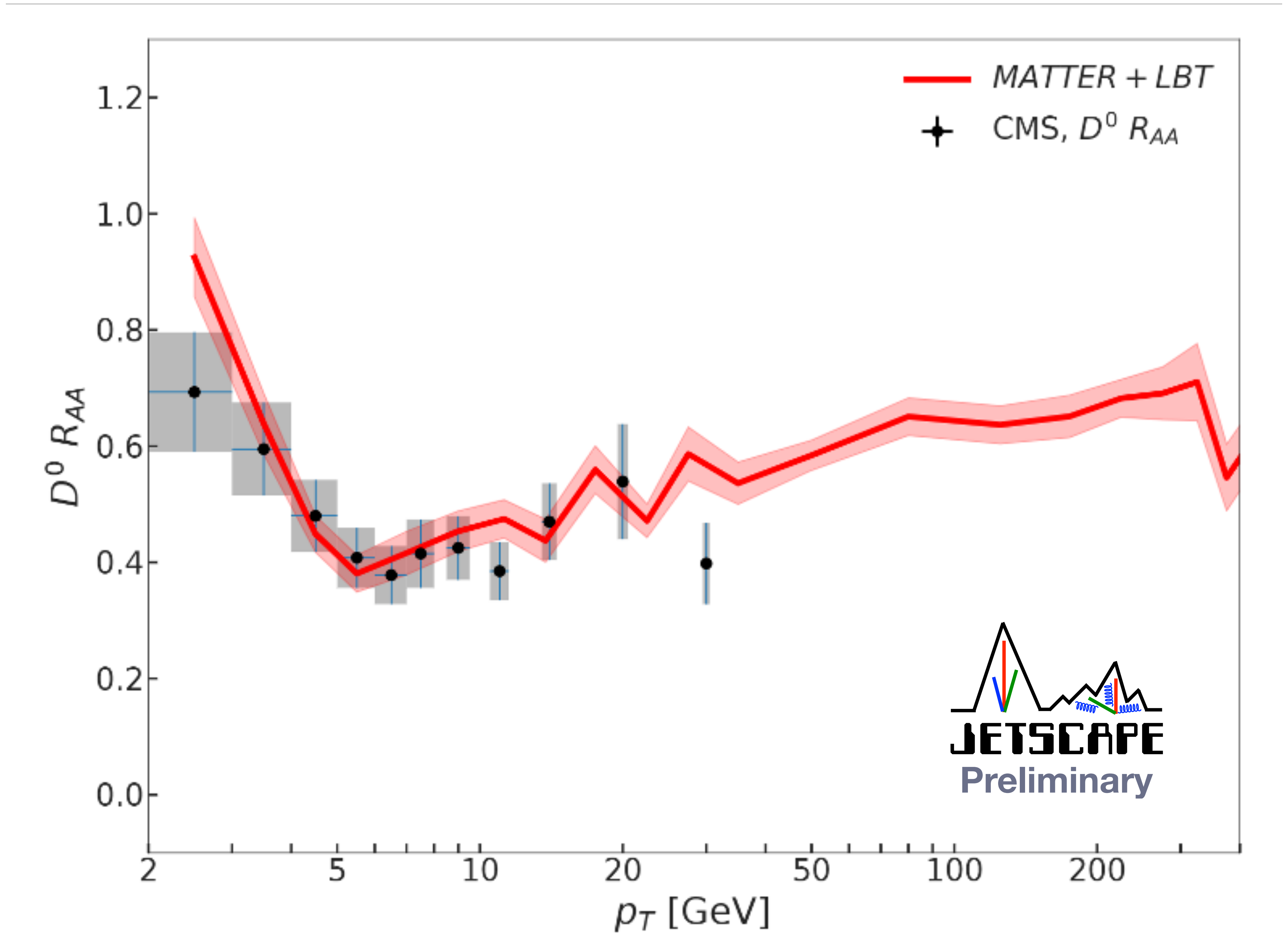
JETSCAPE (in preparation)

- D^0 meson R_{AA}

PbPb 0-10%, 5.02TeV



PbPb 30-50%, 5.02TeV

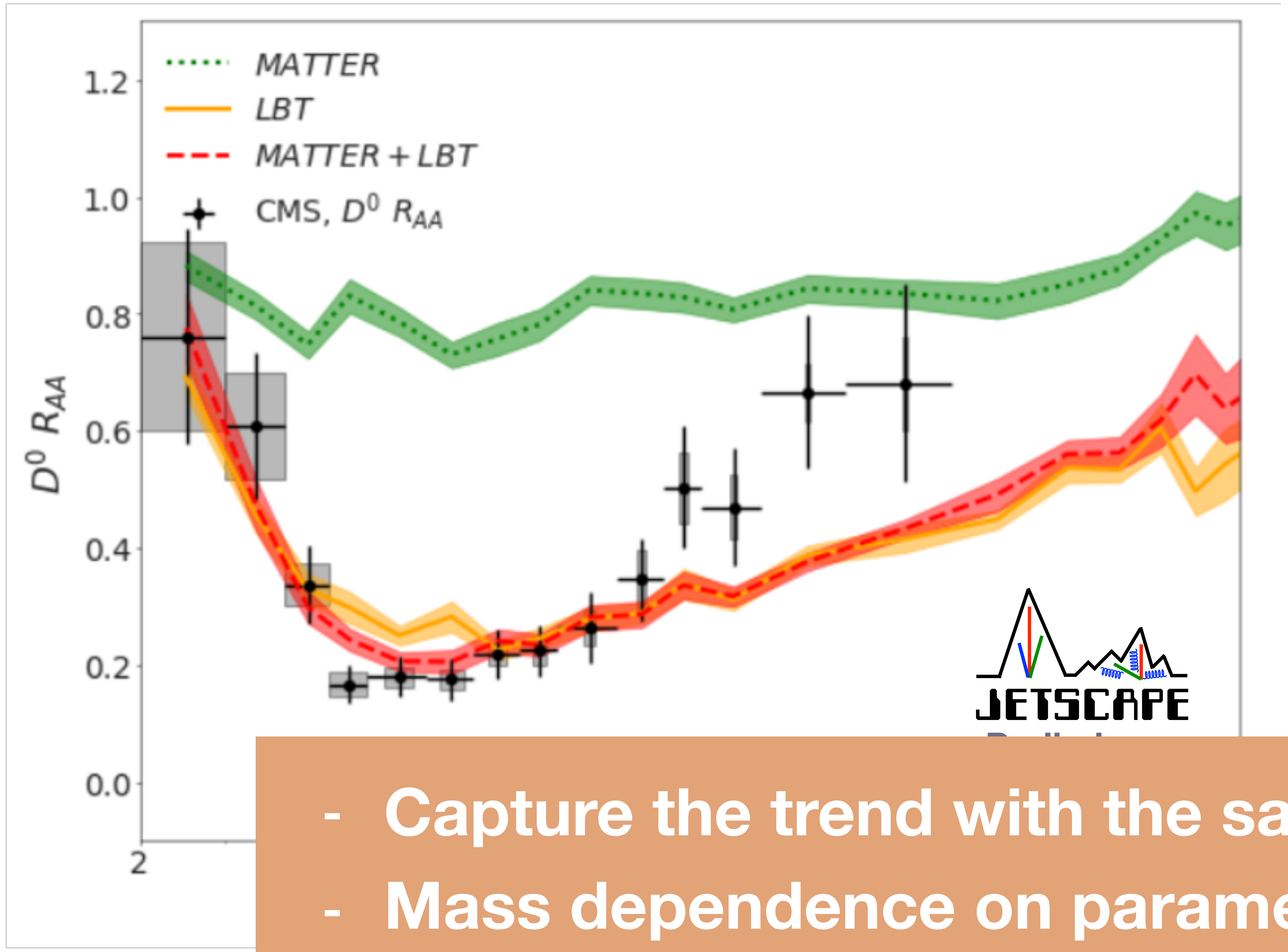


Heavy flavor energy loss

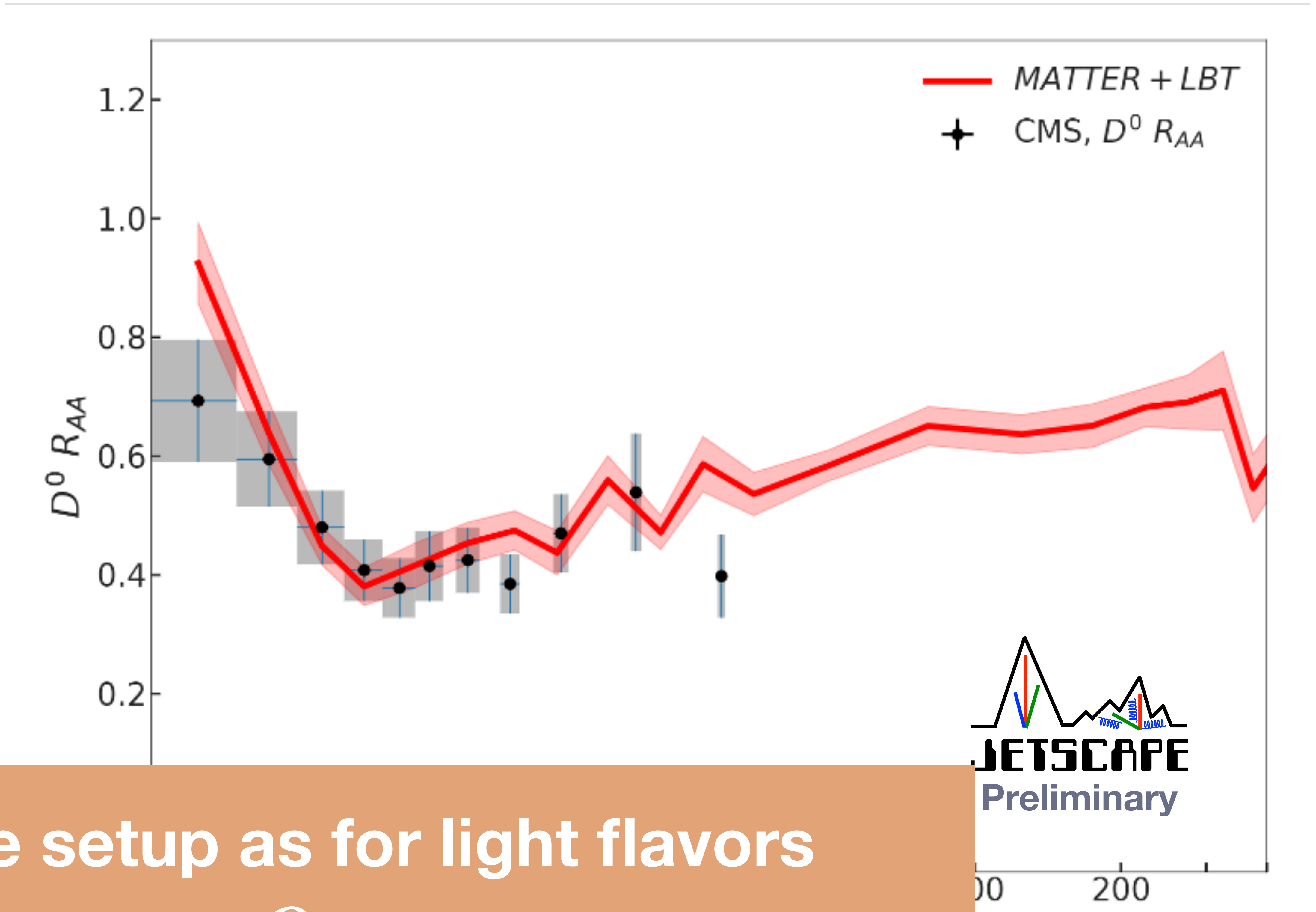
JETSCAPE (in preparation)

- D^0 meson R_{AA}

PbPb 0-10%, 5.02TeV



PbPb 30-50%, 5.02TeV



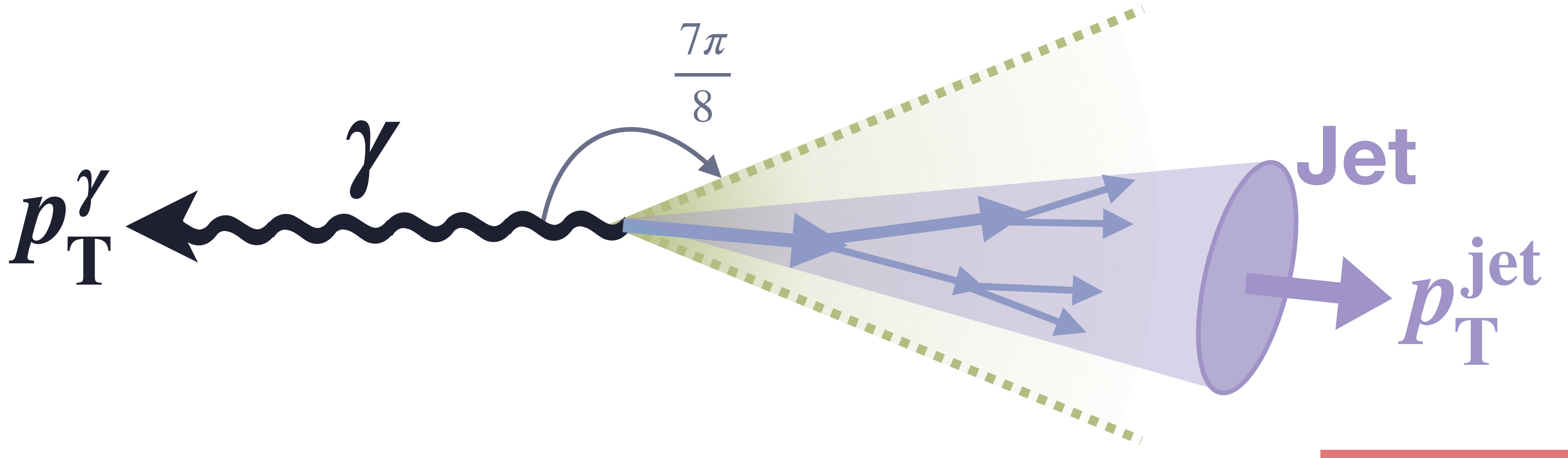
- Capture the trend with the same setup as for light flavors
- Mass dependence on parameters (e.g., Q_{sw}) will be explored

γ-jet correlations

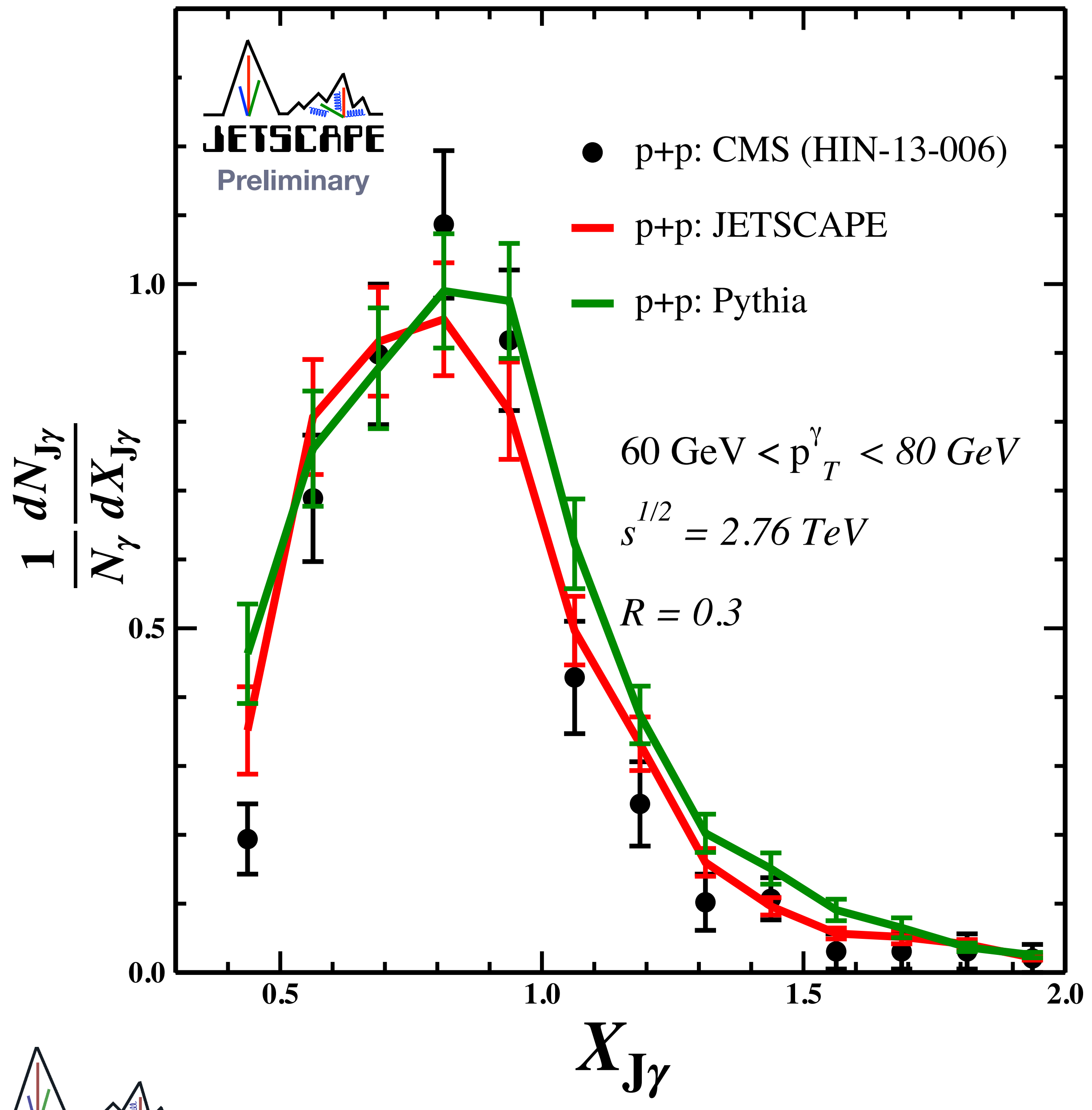
JETSCAPE (in preparation)

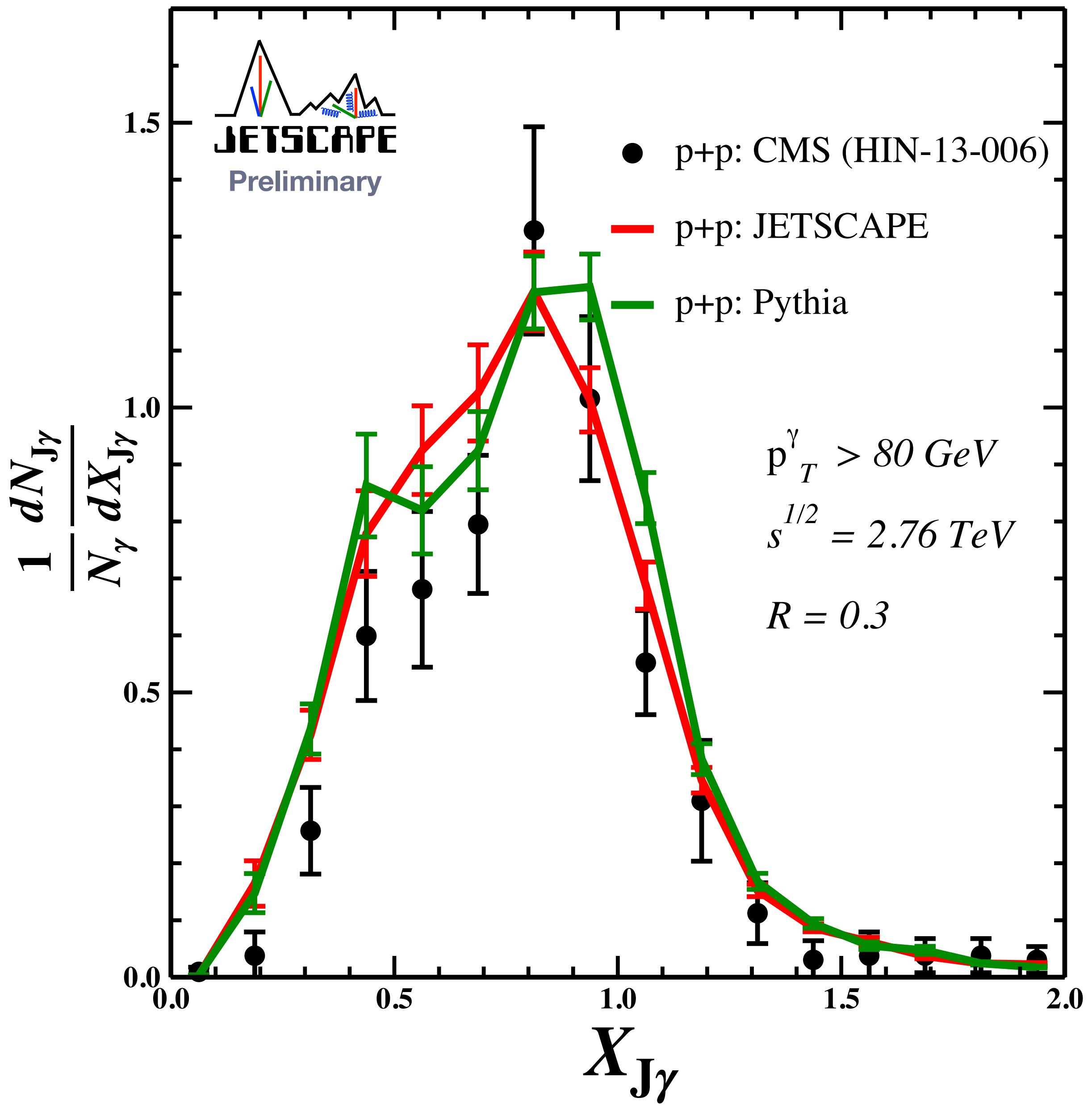
- **γ-jet imbalance**
  - Back-to-back γ-jet pairs
  - Isolated γ

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

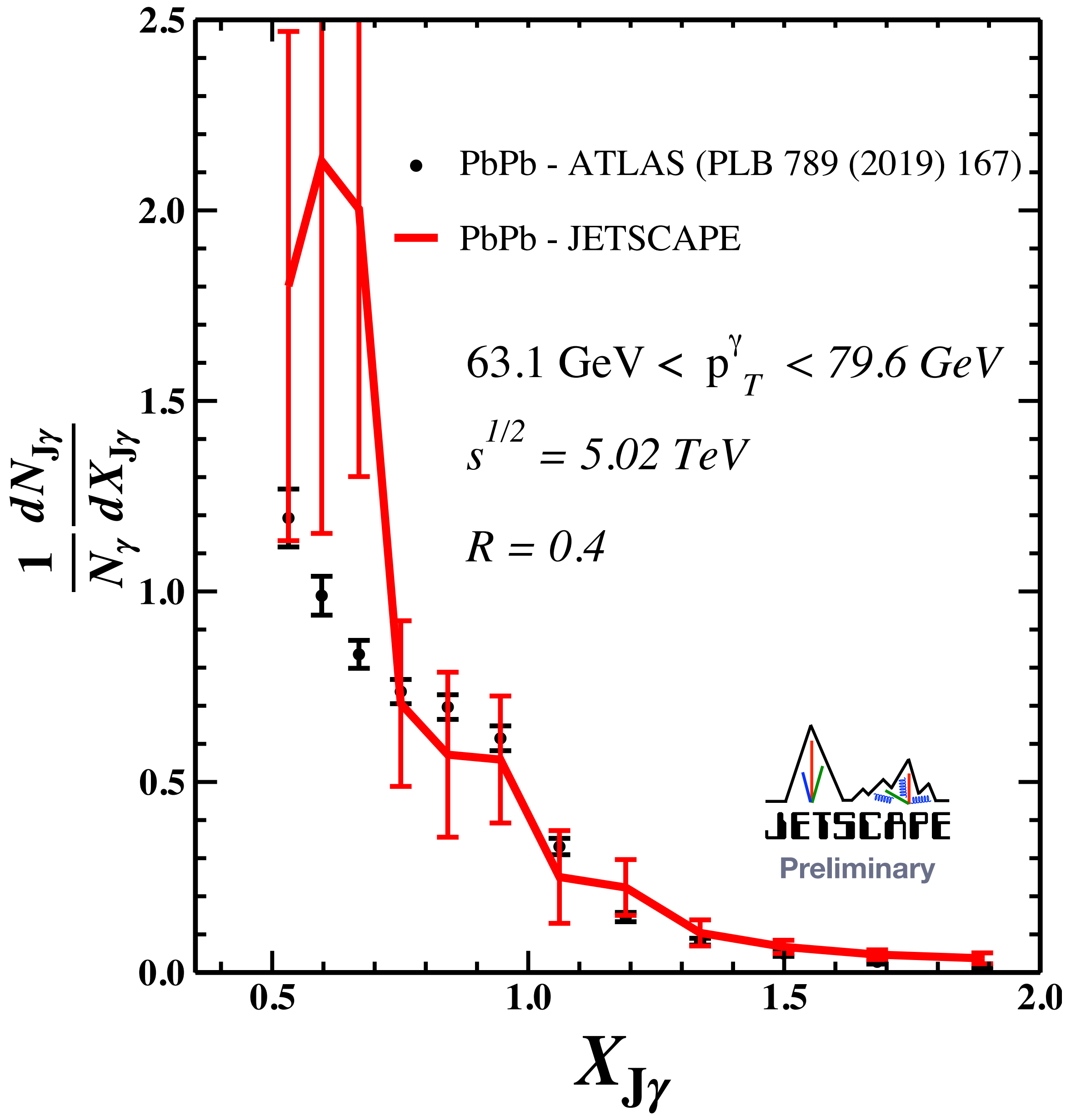


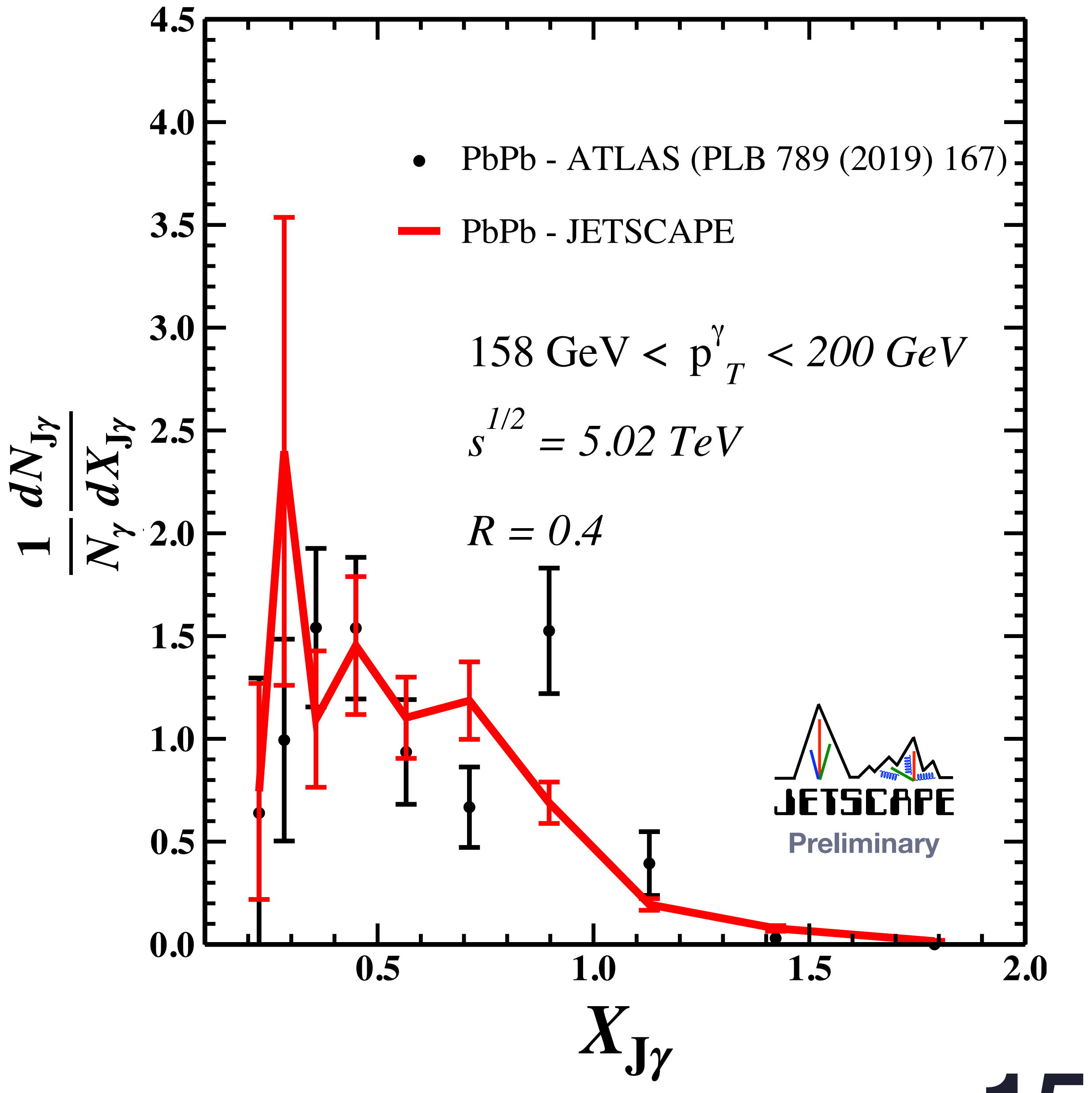
pp, 2.76 TeV





PbPb, 5.02 TeV





γ-jet correlations

JETSCAPE (in preparation)

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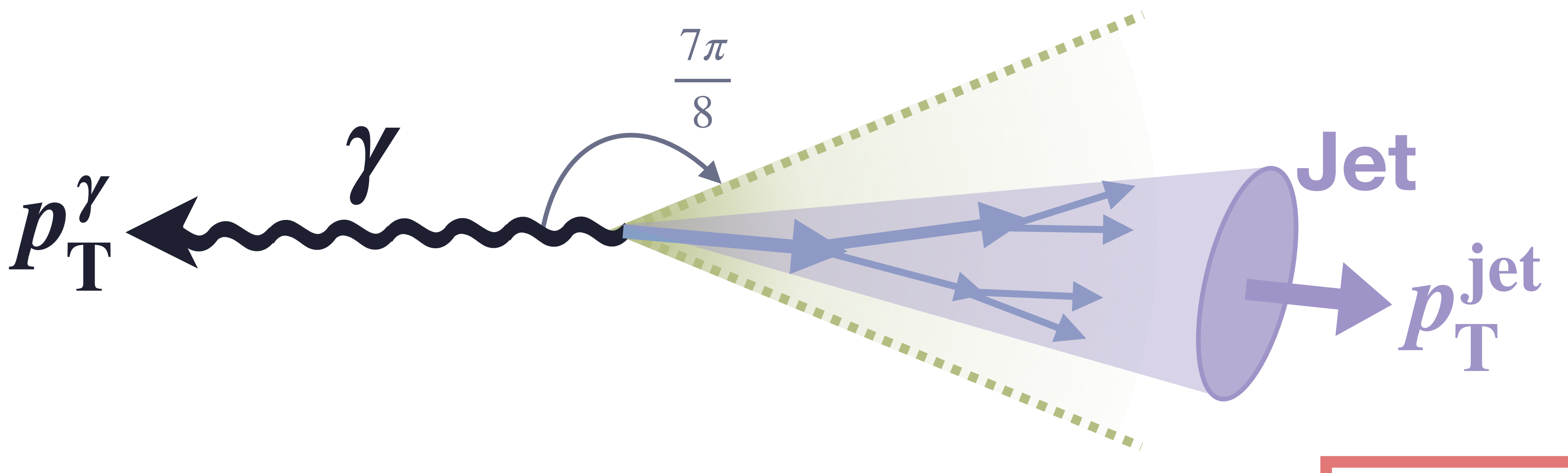

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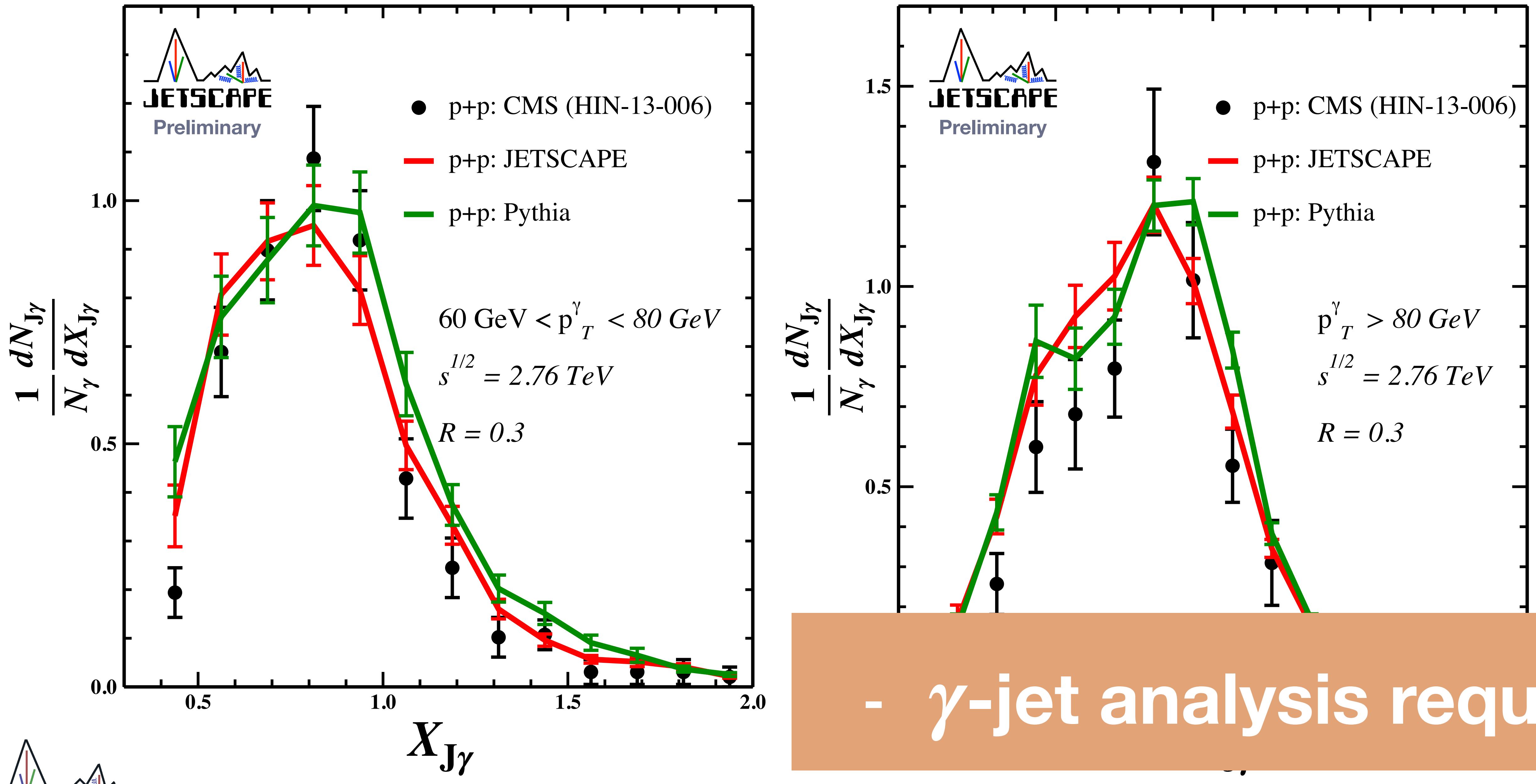
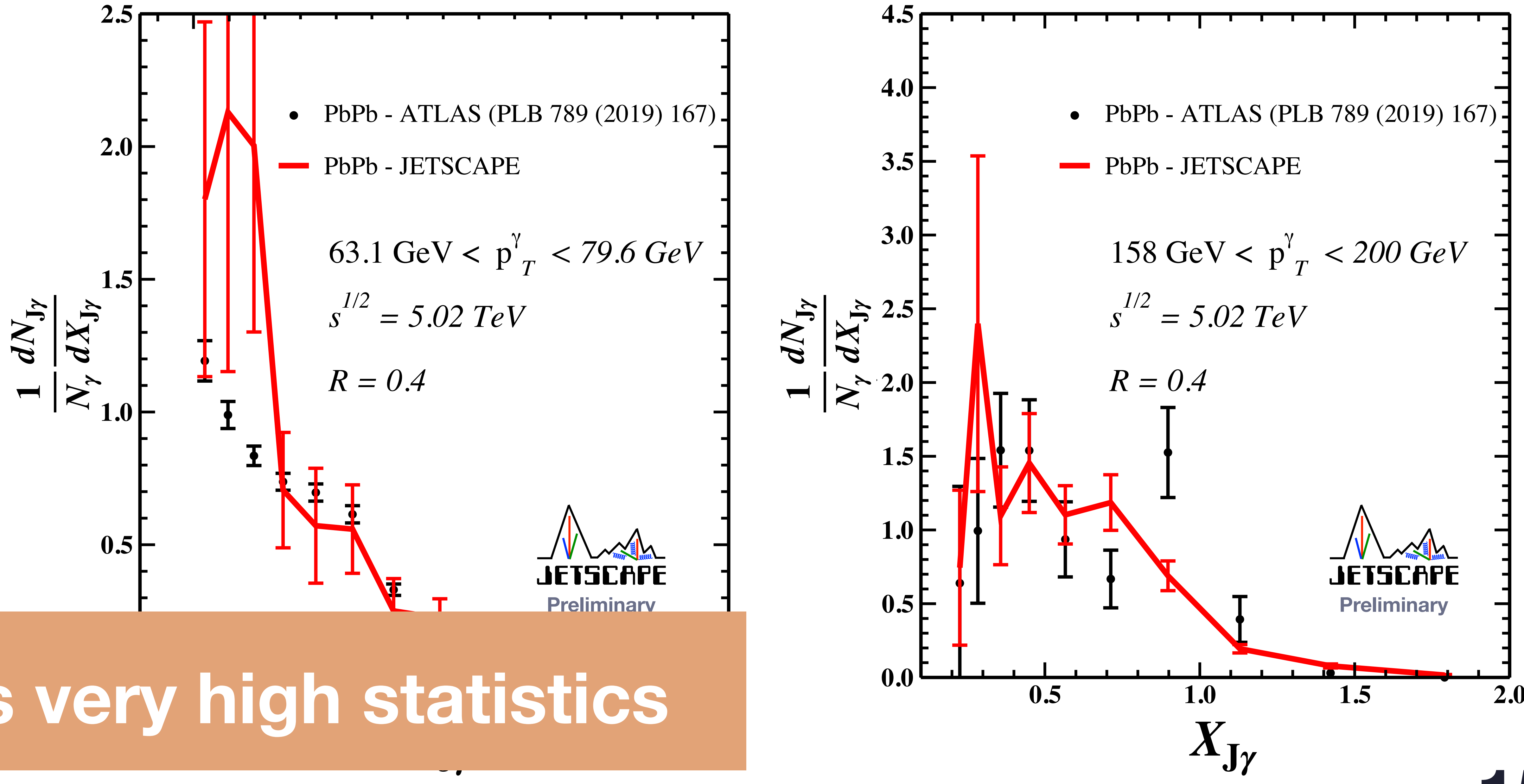


PbPb, 5.02 TeV



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

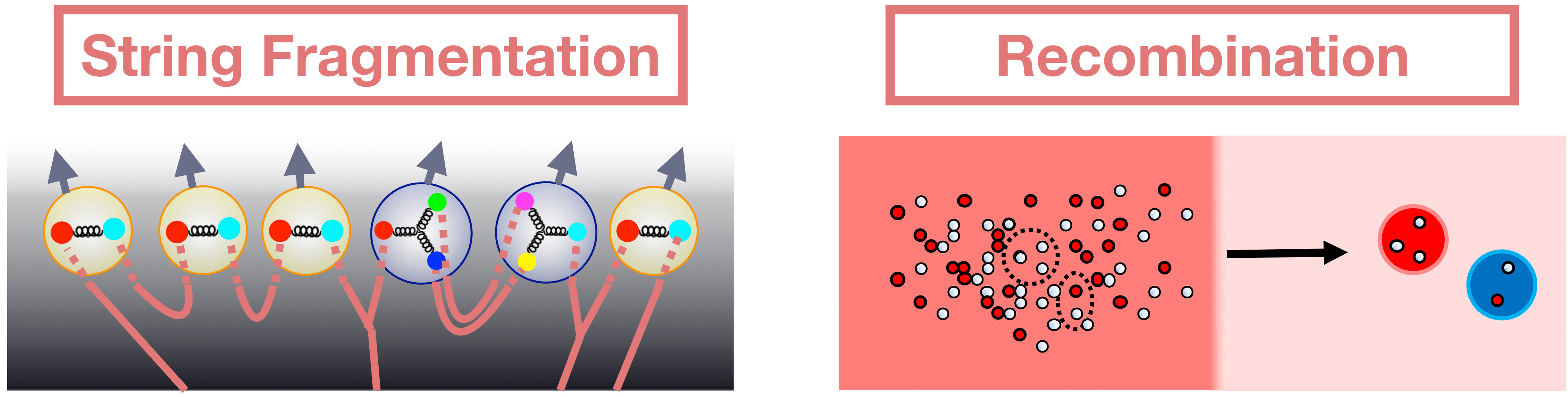
Jet-medium interaction in hadronization process

Jet-medium interaction in hadronization

Hybrid hadronization model

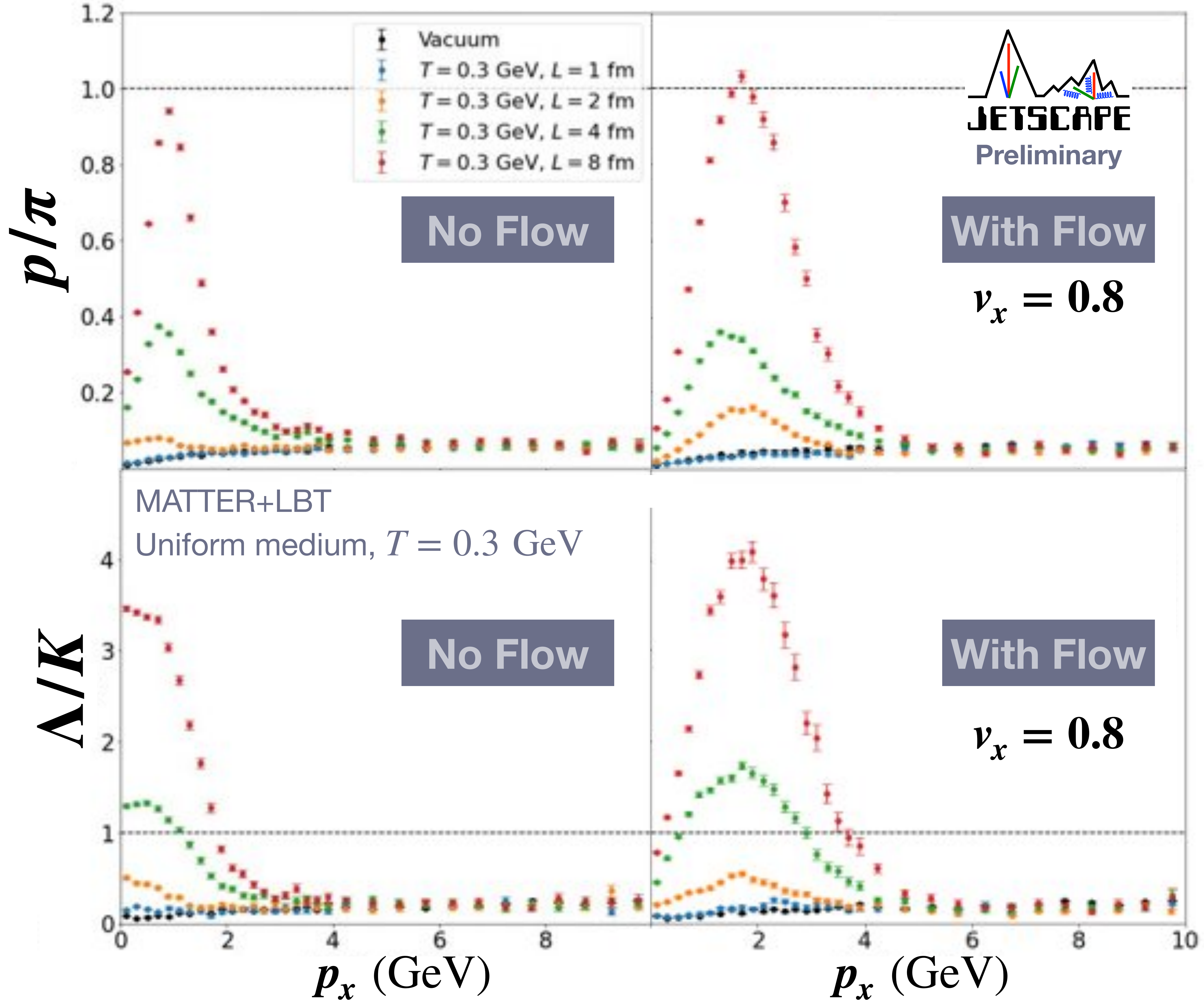
Han, Fries, Ko, PRC 93, 045207 (2016)

- Smoothly combines two hadronization models



(vacuum like, high-p_T) (in-medium, mid- p_T)

- Recombination between jet partons and medium partons



Jet-medium interaction in hadronization

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

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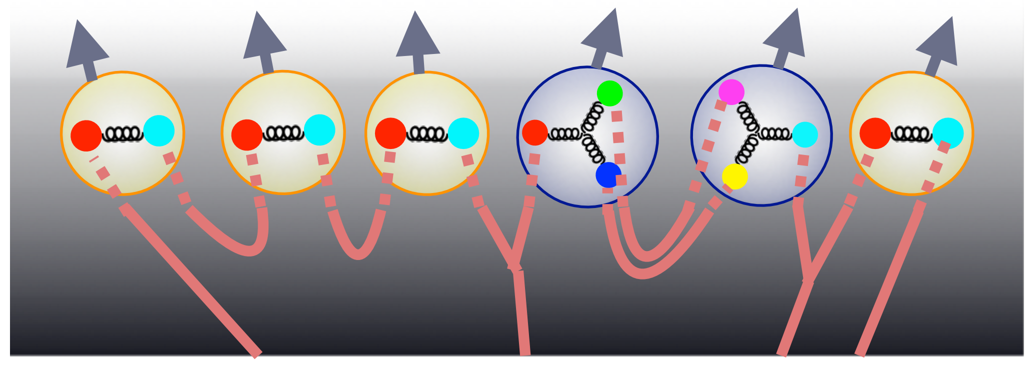
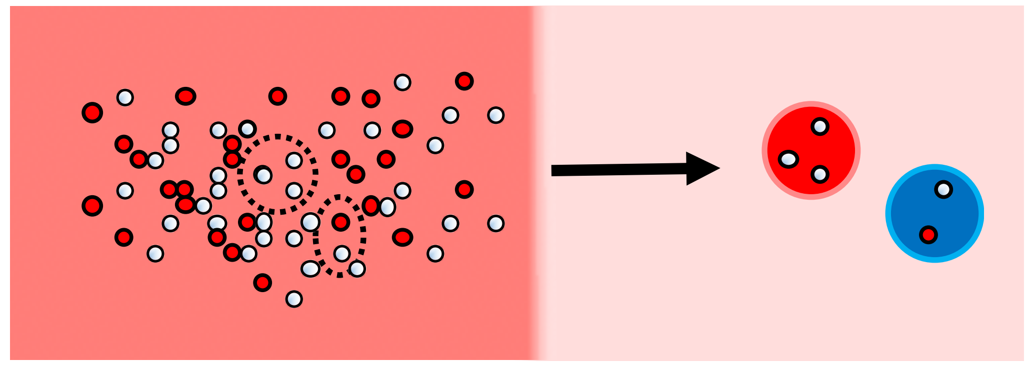
String Fragmentation



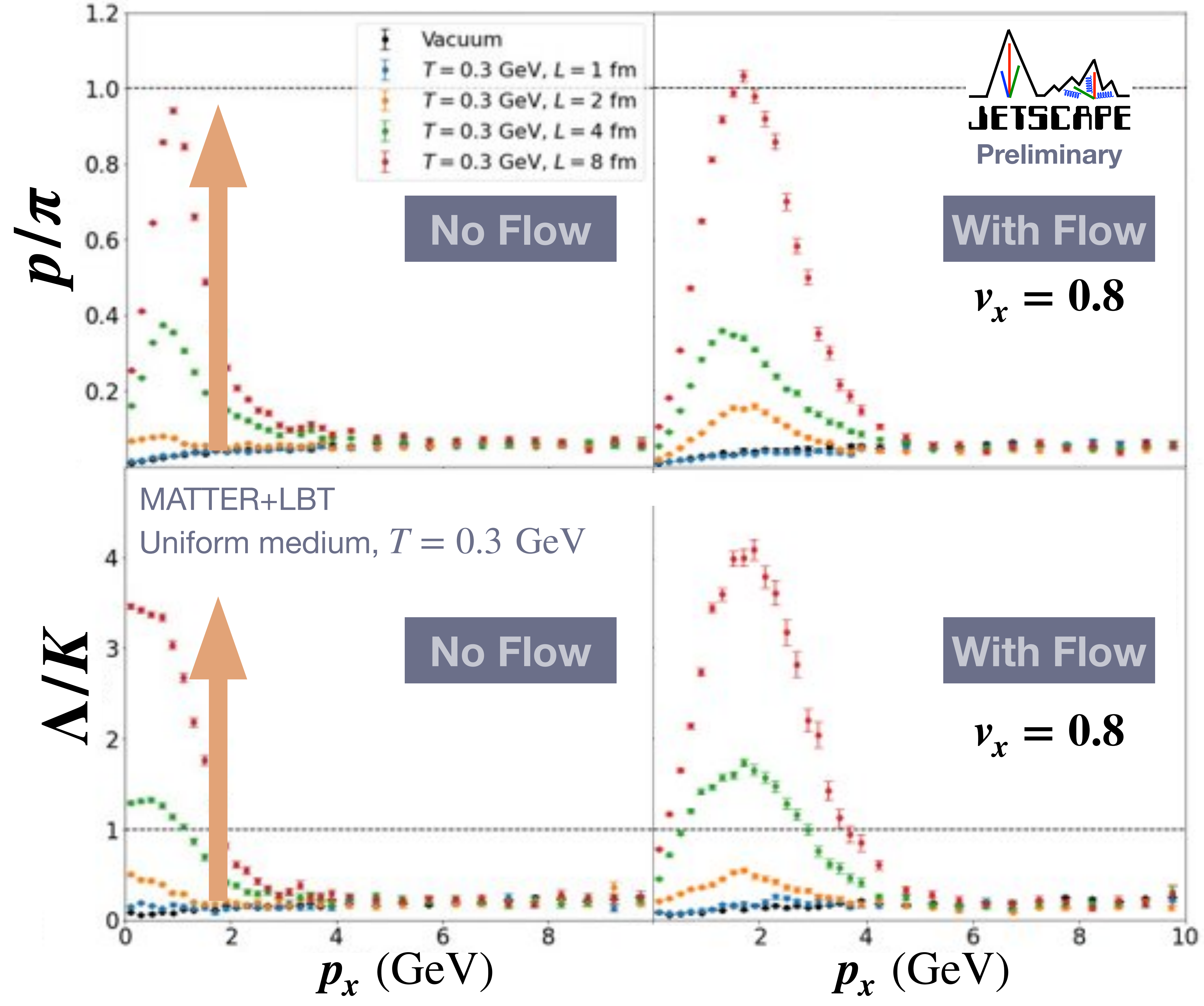
(vacuum like, high-p_T)

Recombination



(in-medium, mid- p_T)

- Recombination between jet partons and medium partons

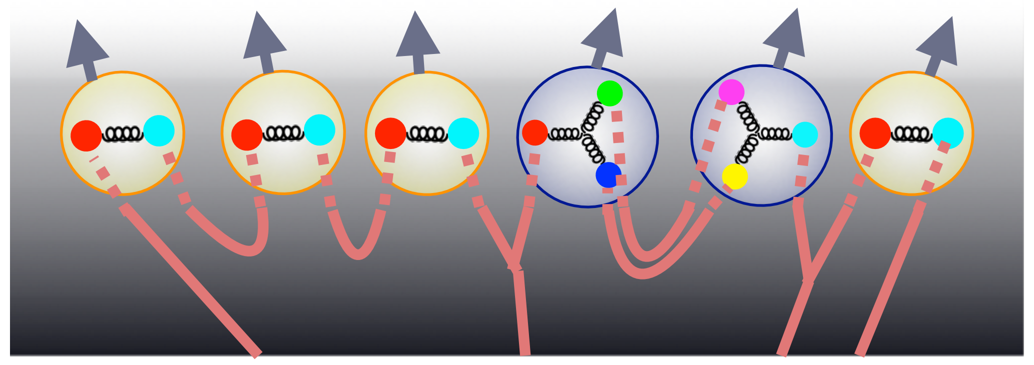


Jet-medium interaction in hadronization

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

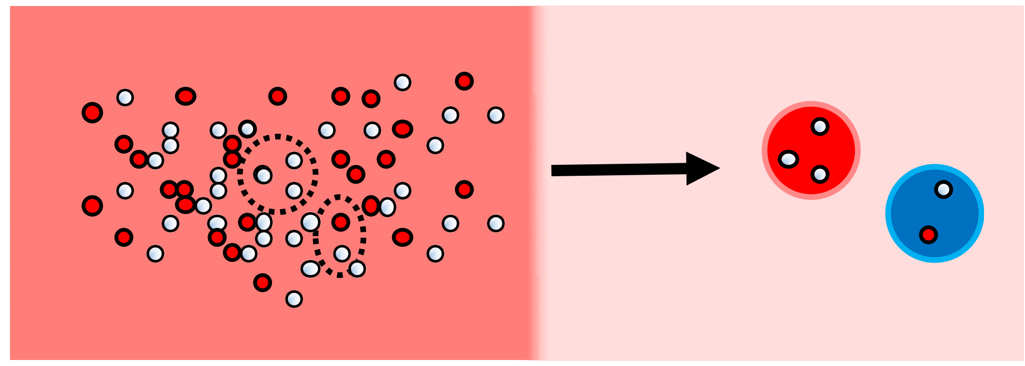
  - Smoothly combines two hadronization models

String Fragmentation



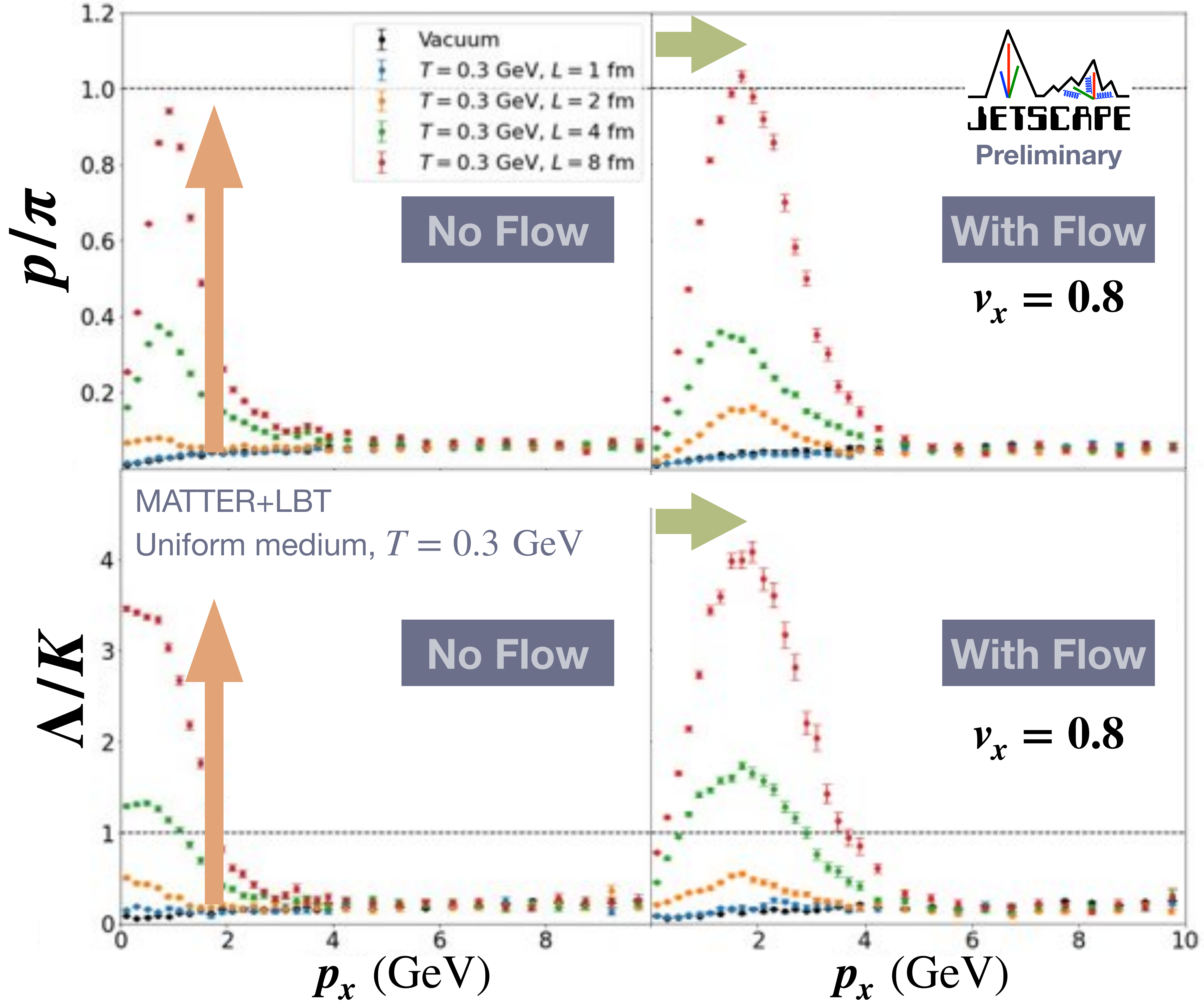
(vacuum like, high-p_T)

Recombination



(in-medium, mid- p_T)

  - Recombination between jet partons and medium partons



Jet-medium interaction in hadronization

Hybrid hadronization model

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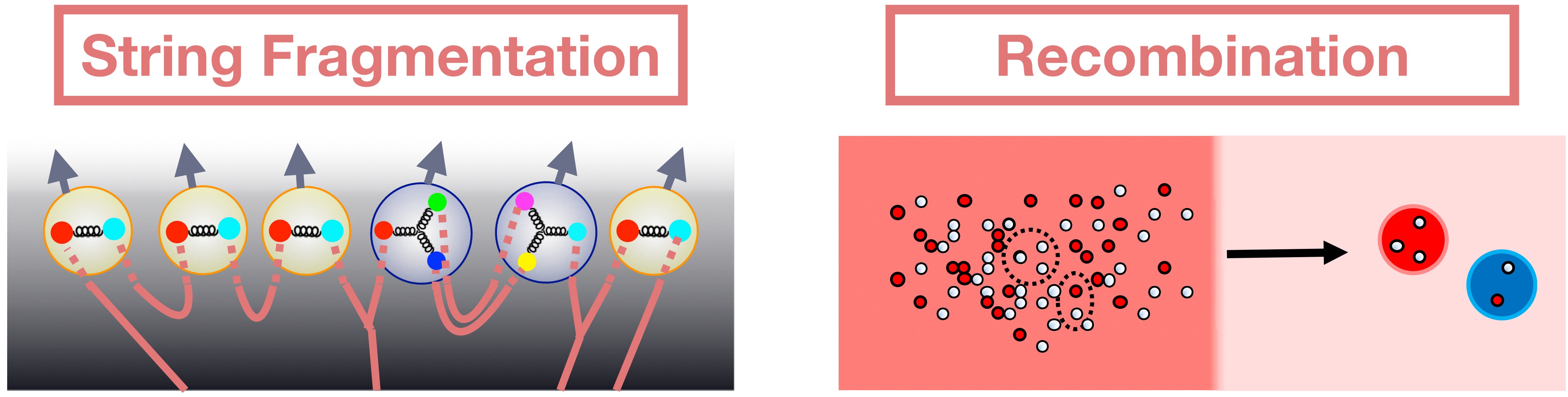

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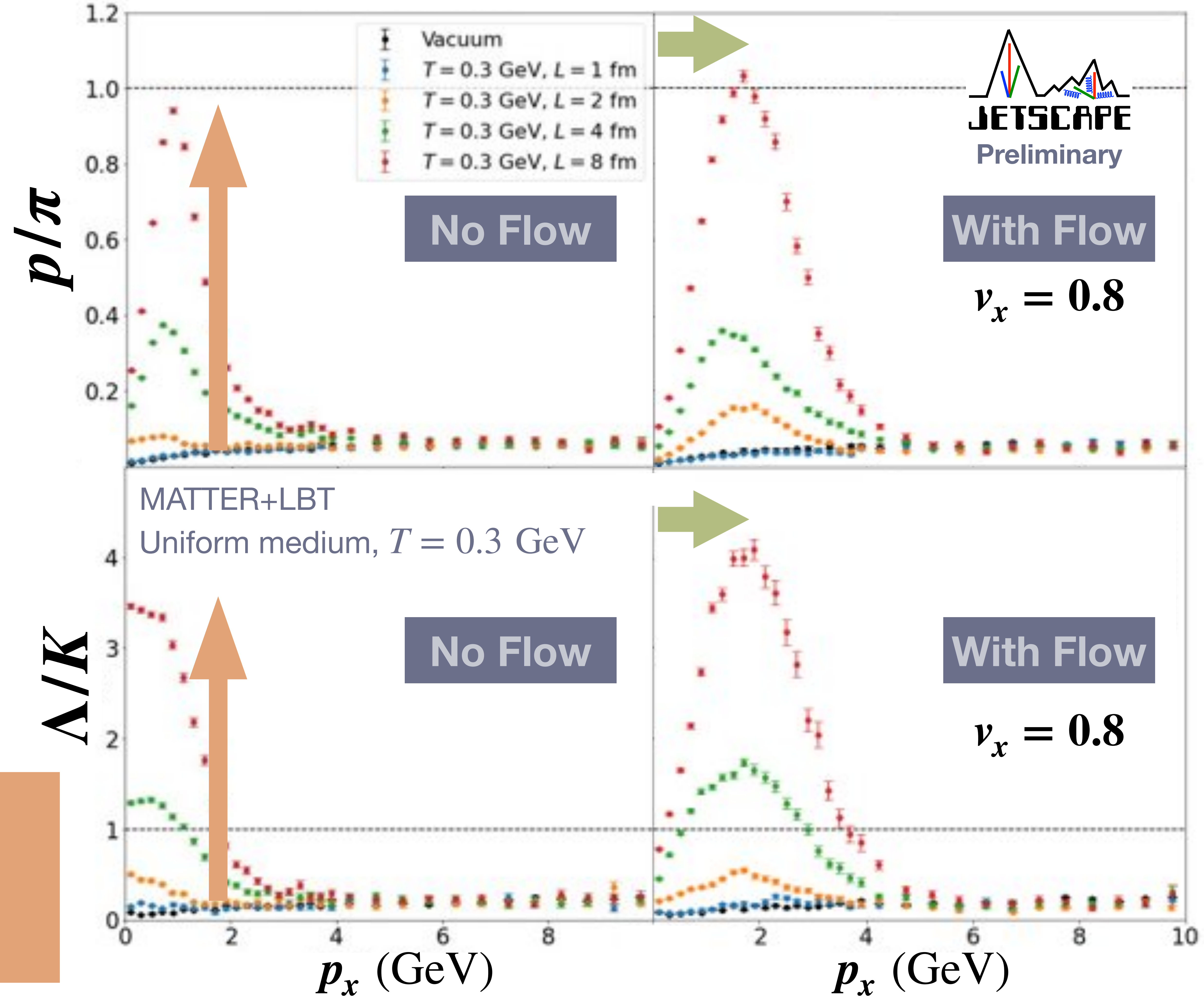


- **Baryon enhancement due to recombination**
- **Blue shift by the background medium flow**

Summary

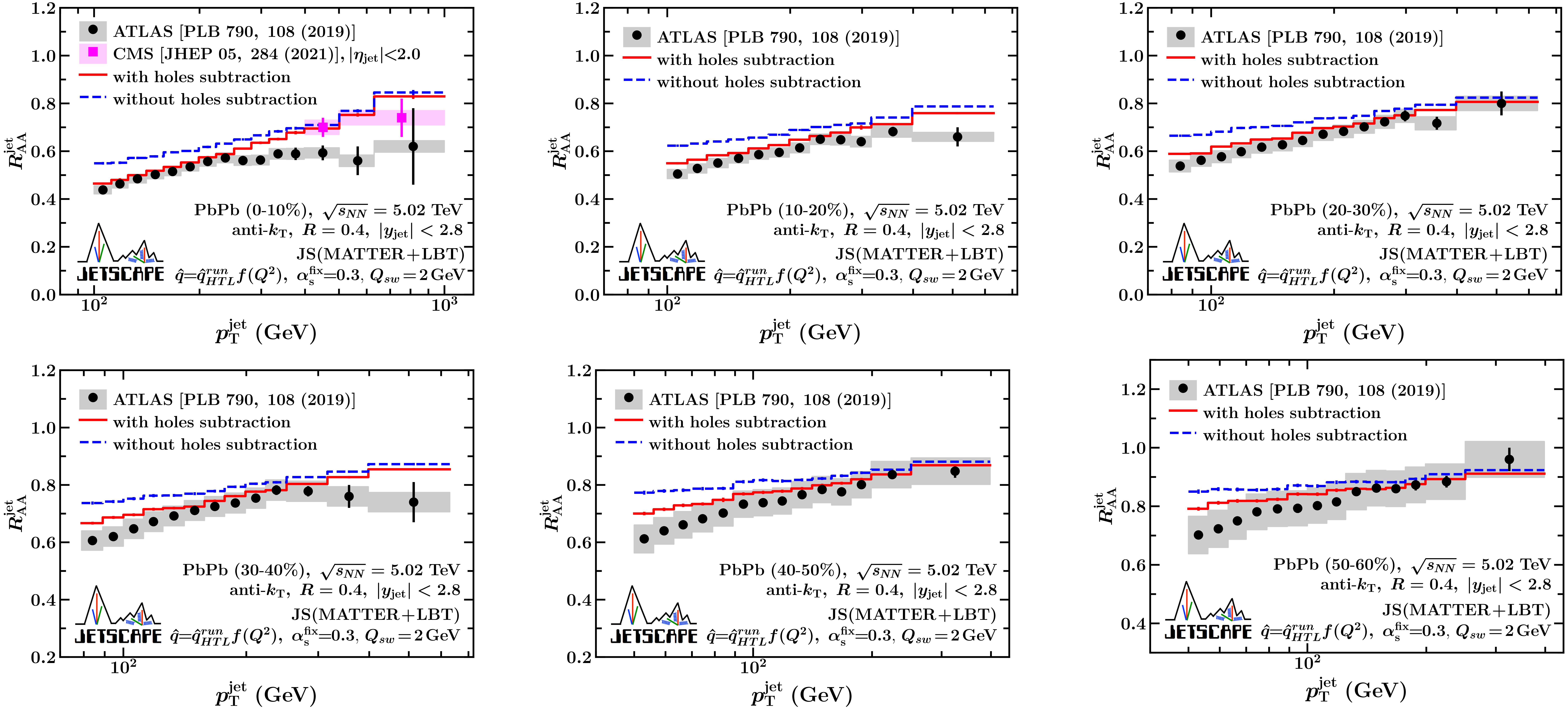
- **Multi-stage evolution of jet shower in JETSCAPE**
  - Extension of multi-stage jet energy loss by coherence effect (Q^2-dependence)
  - Simultaneous description of jet and single particle at various $\sqrt{s_{\mathrm{NN}}}$
  - Details of interaction encoded in jet substructures
  - Further systematic studies for heavy-quark and γ-jet
- **Jet-medium interaction in hadronization**
  - Enhancement of baryon/meson ratio due to recombination
  - Blue shift by the medium background flow

- **Bayesian studies with JETSCAPE**
  - Jet quenching parameter $\hat{q}$: PRC104, 024905
  - Bulk transport coefficients: PRL126, 242301, PRC 103, 054904, arXiv:2203.08286

Centrality dependence

JETSCAPE, arXiv:2204.01163

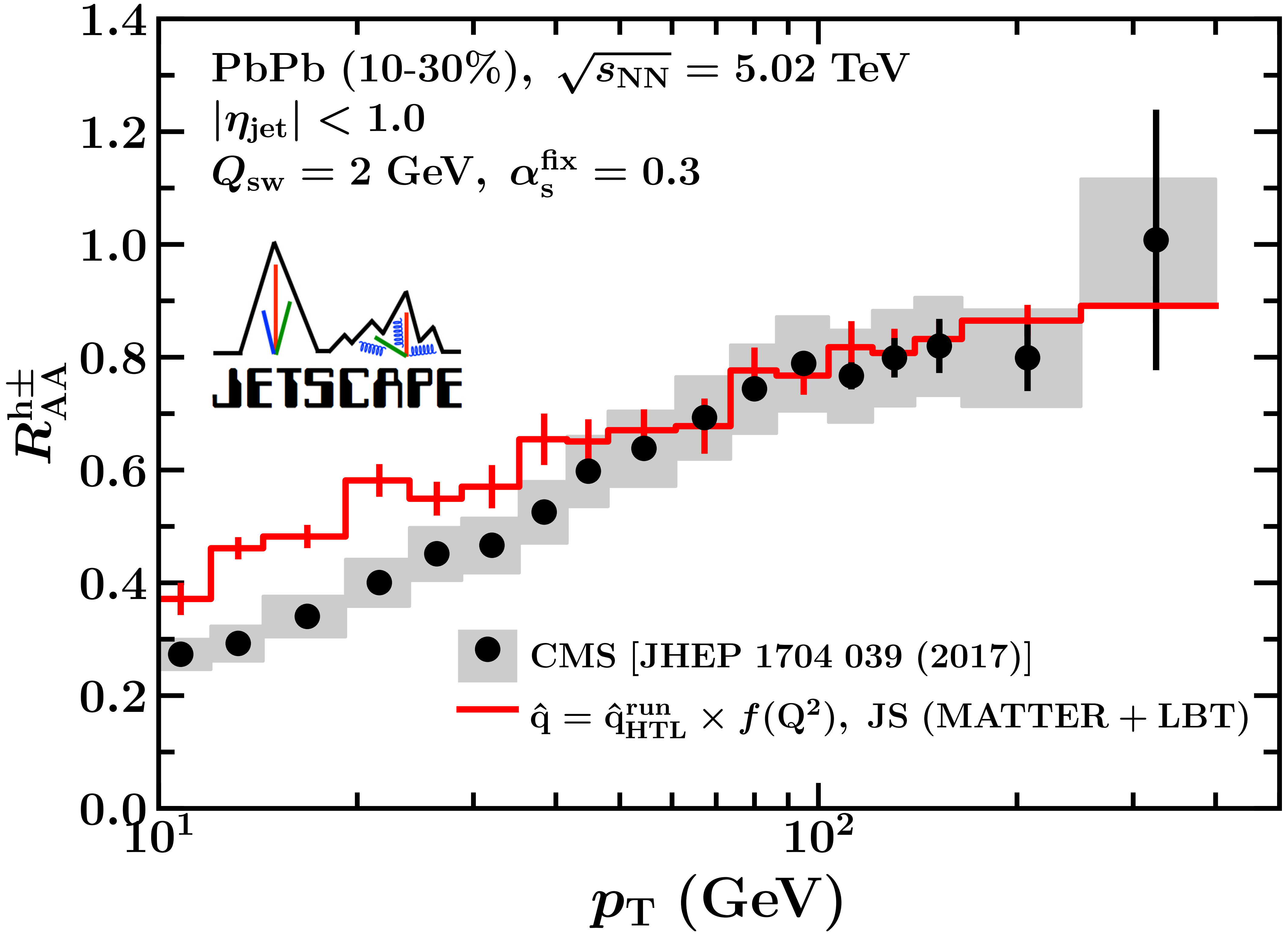
- **Inclusive jet R_{AA} in Pb+Pb collisions at 5.02 TeV**

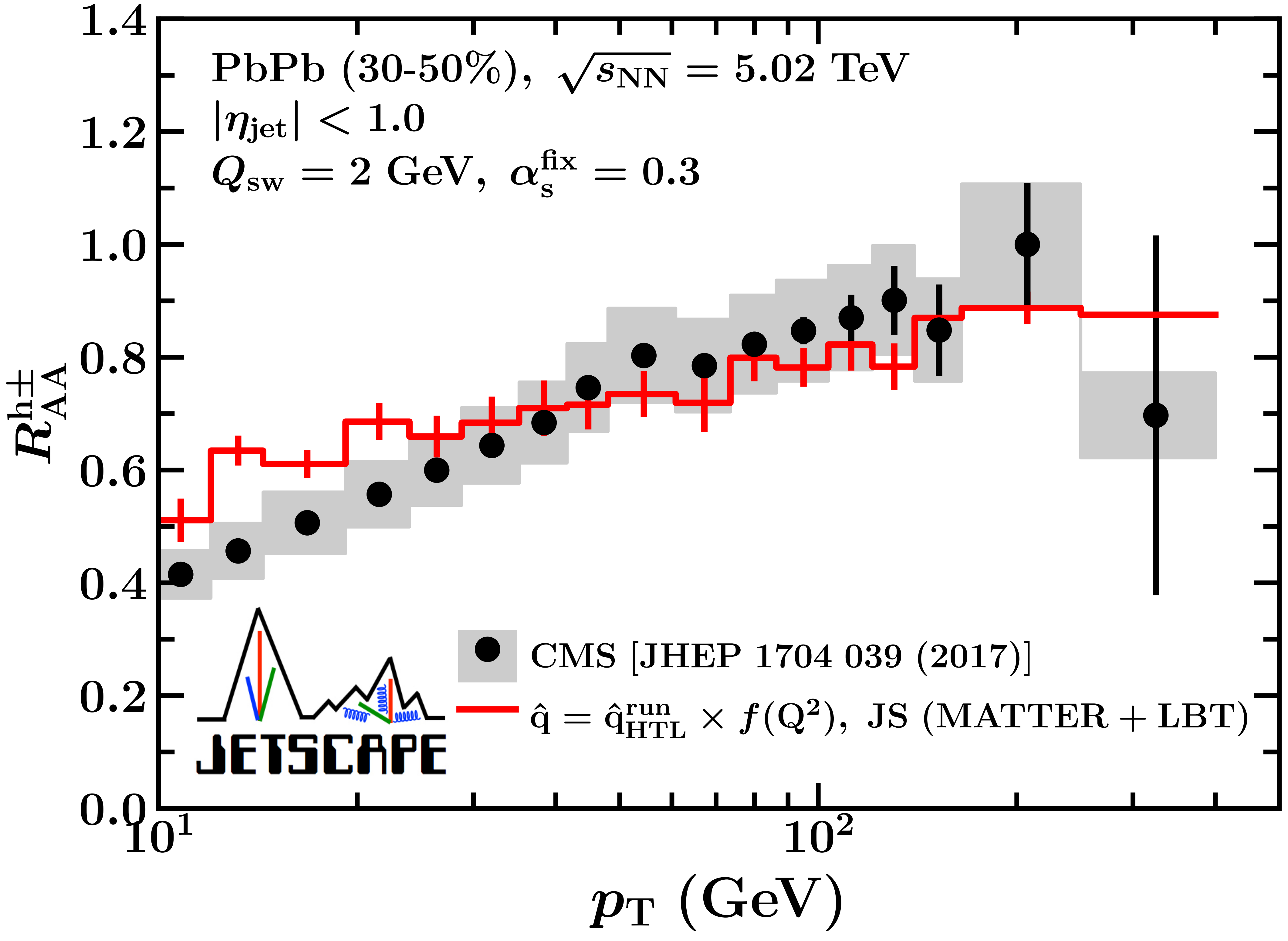


Centrality dependence

JETSCAPE, arXiv:2204.01163

- **Charged particle R_{AA} in Pb+Pb collisions at 5.02 TeV**

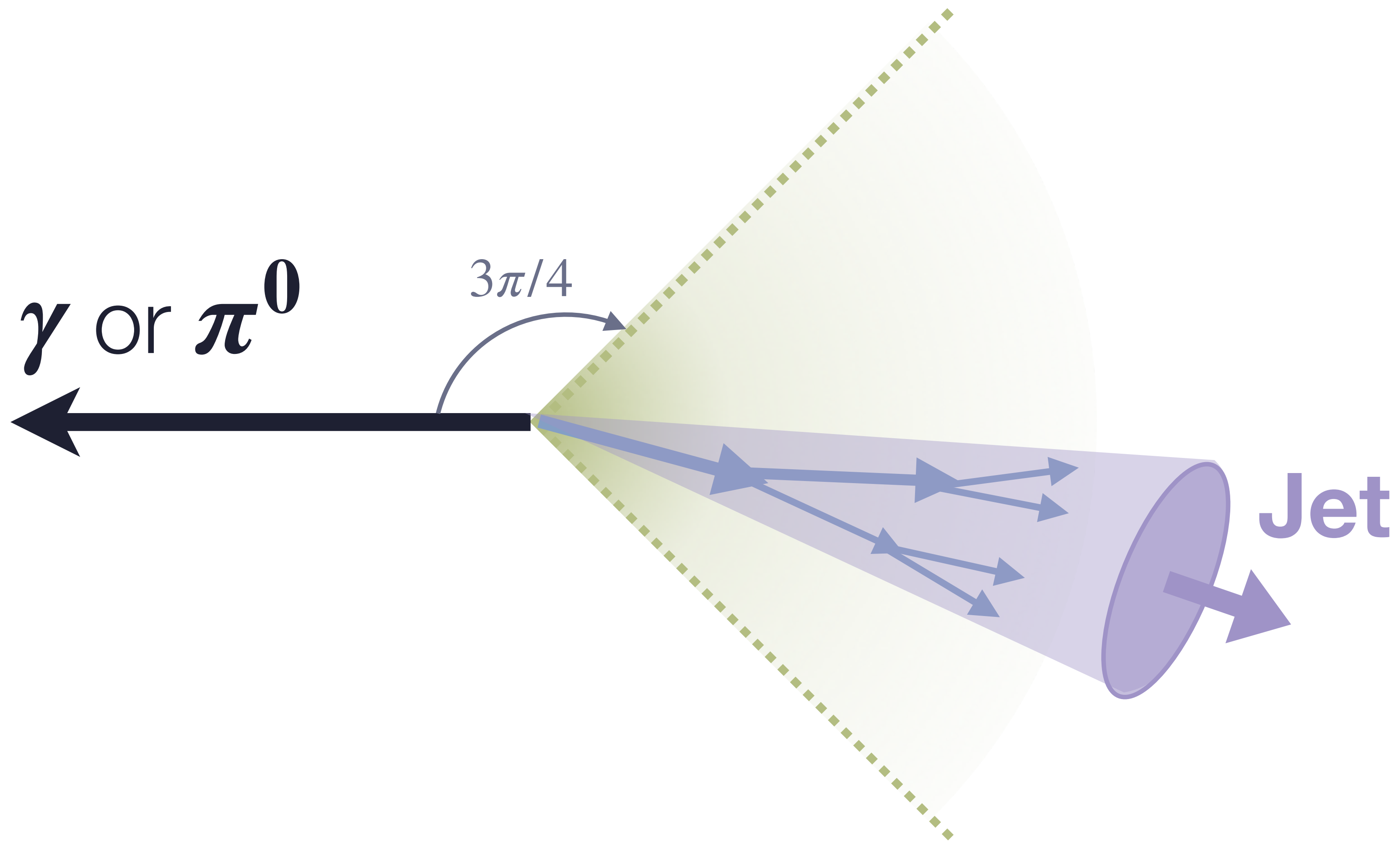


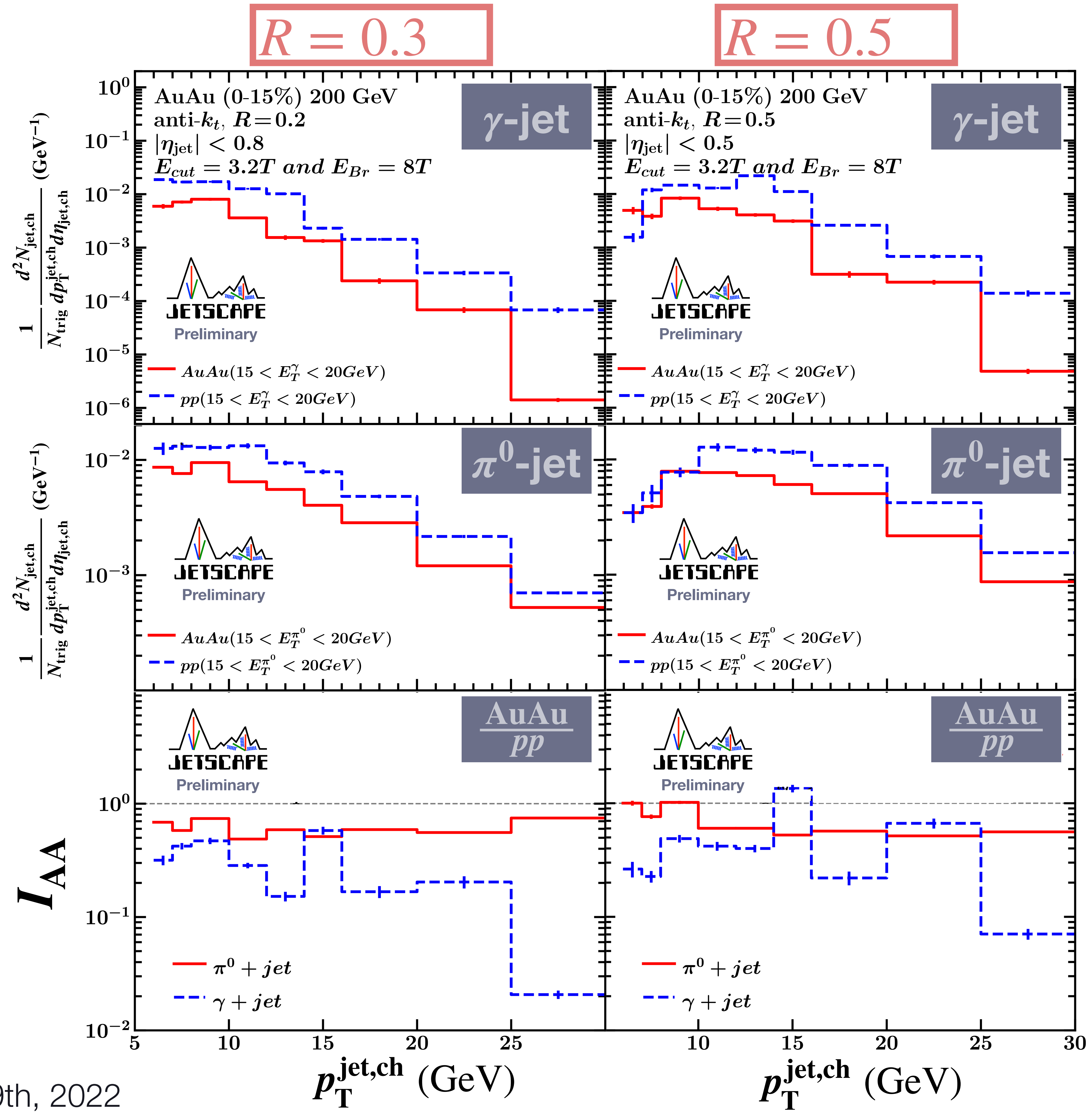


γ-jet and π^0-jet correlations

JETSCAPE (in preparation)

- **Au+Au collisions at 200 GeV**
  - Trigger back-to-back jet with $\frac{3\pi}{4} < \Delta\phi < \frac{5\pi}{4}$





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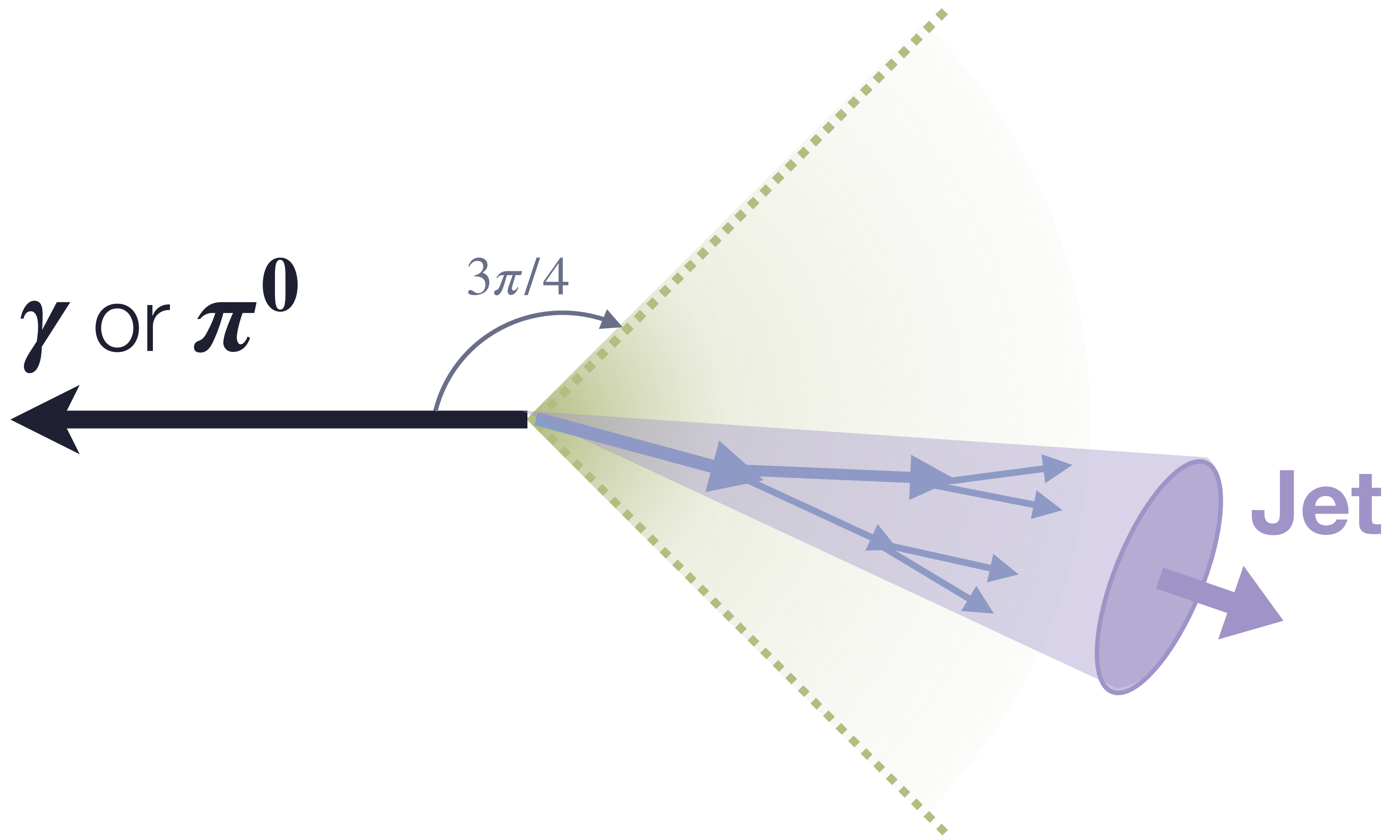

- **Need more statistics to capture the modification patterns**