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

JETSCAPE

NSF

Extraction of jet-medium interaction details through jet substructure for inclusive and gamma-tagged jets

JETSCAPE, arXiv:2301.02485; JETSCAPE, in preparation

Yasuki Tachibana for the JETSCAPE Collaboration

HP2024
NAGASAKI

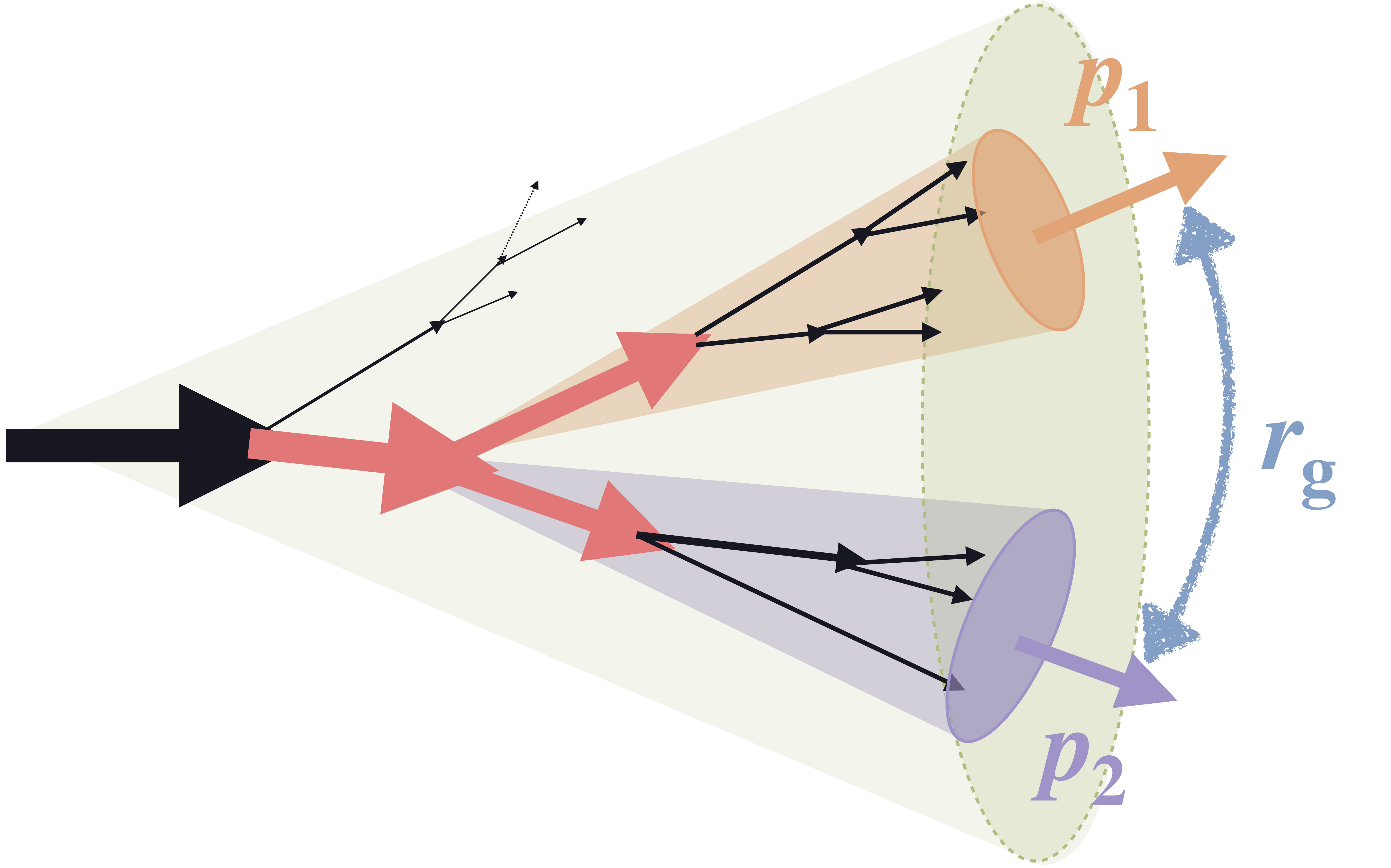
September 23rd, 2024

Groomed jet substructures

A. J. Larkoski, S. Marzani, G. Soyez and J. Thaler, JHEP 05, 146 (2014)

- **Hard splitting identified by Soft Drop**
  - Largest angular branching with a sufficient momentum fraction ($z_g > z_{cut}$) within a jet
  - Relatively well dominated by perturbative parton splitting

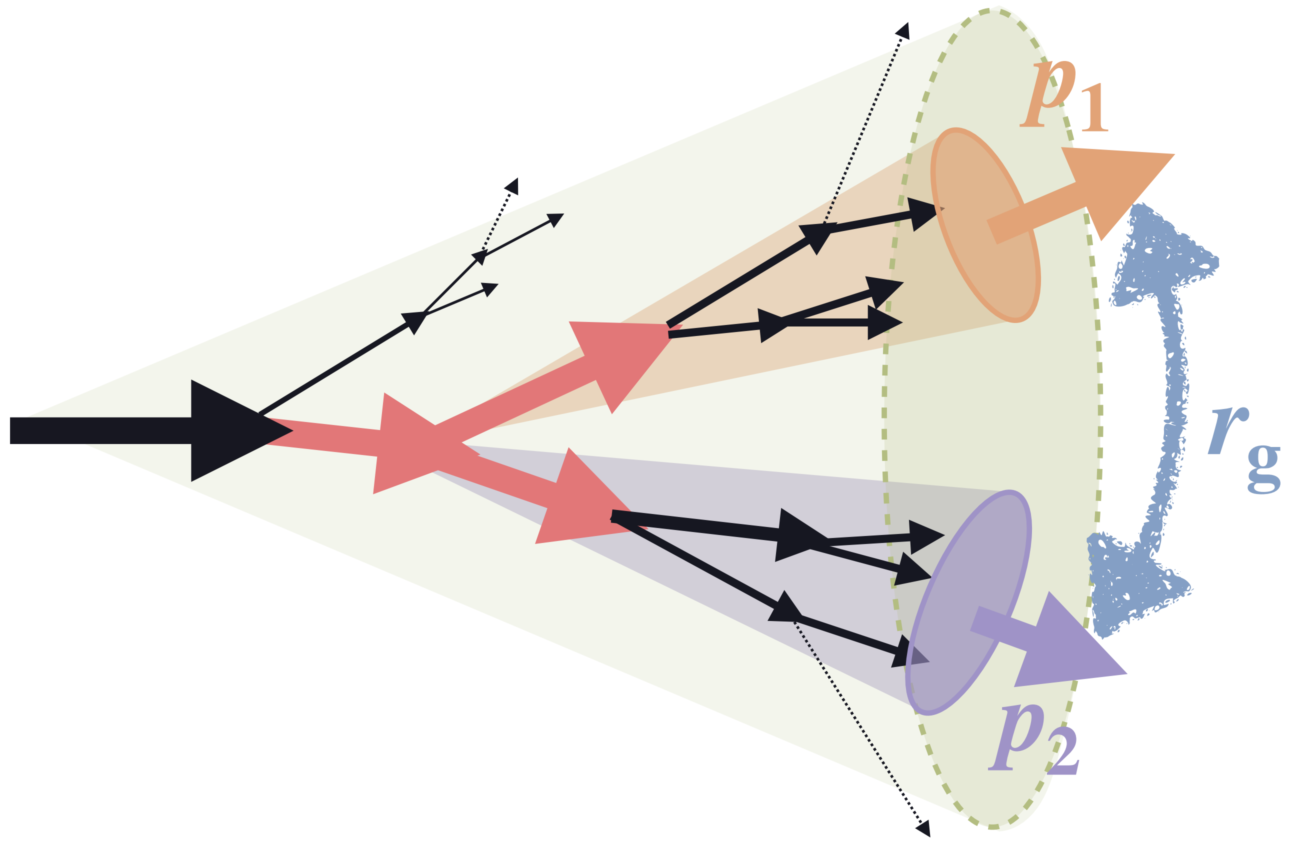
$$z_g = \frac{\min\{p_{T,1}, p_{T,2}\}}{p_{T,1} + p_{T,2}}$$



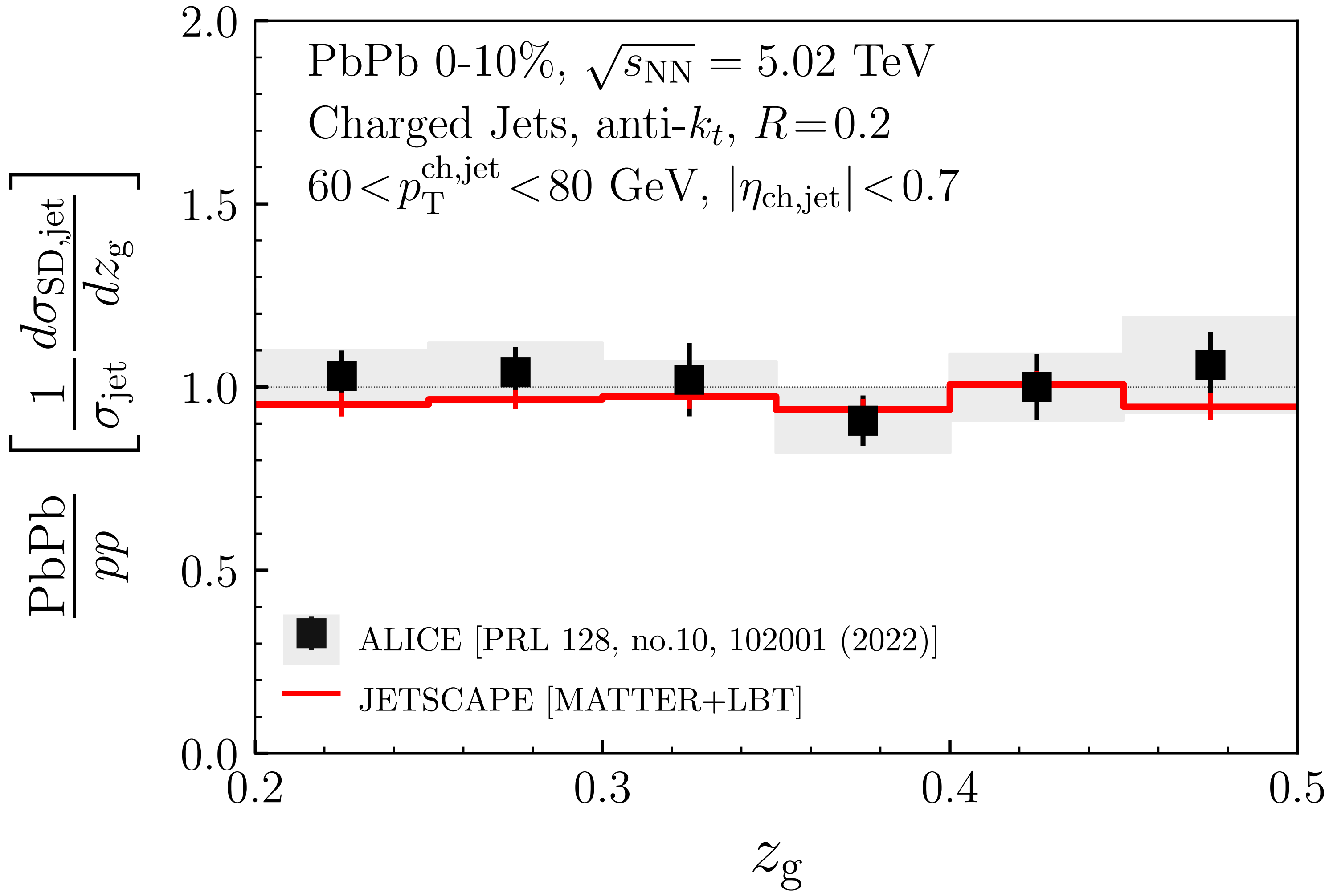
Groomed substructures modification in inclusive jets

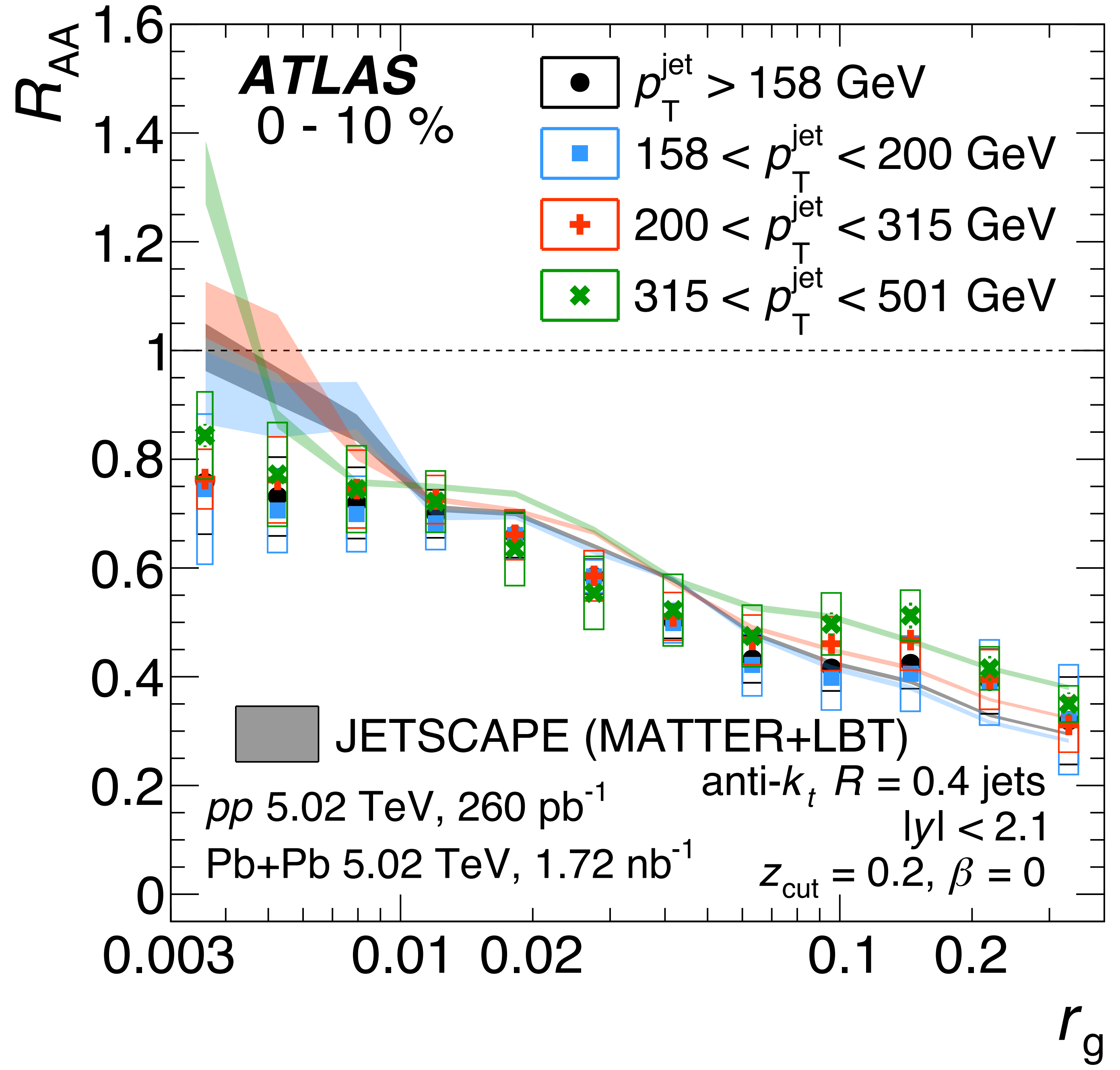
- **Medium effects on inclusive jet substructure**

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



JETSCAPE, arXiv:2301.02485

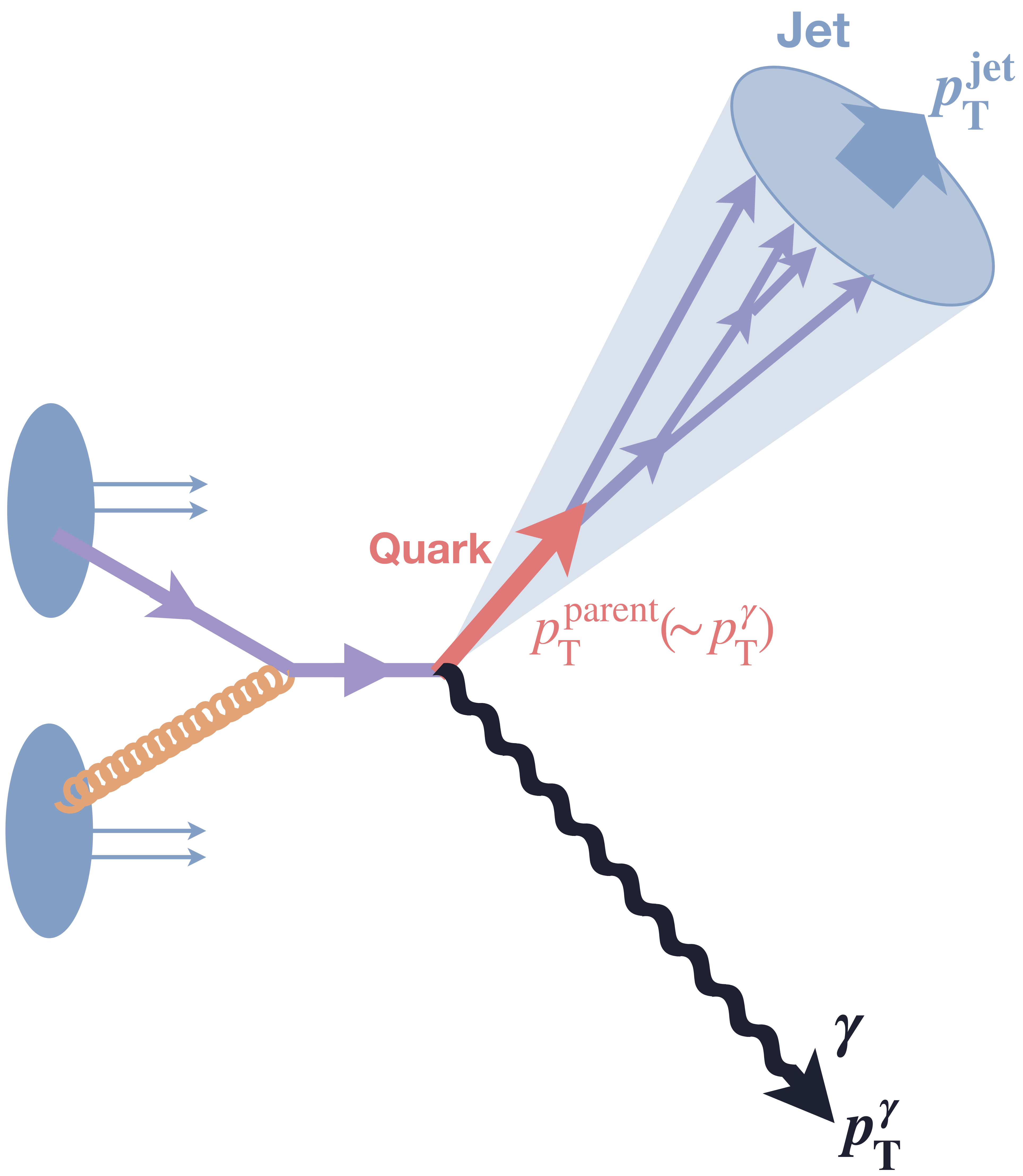




- Barely noticeable modification in z_g
- Narrower splittings in jets with medium effects
- Trigger jets by jet-p_T (after energy loss)

- Actual substructure modification?
- Selection bias (substructure dependence in E-loss)?

γ-tagged jet



- Jets detected with a hard photon in the backward direction
- Primarily produced via initial hard Compton scattering (quark jet dominance)
- No medium effects on the photon ($p_T^{\gamma} \sim p_T^{parent}$)

- Exploring flavor dependence
- Controlling the effects of selection bias

- γ-jet Correlations

  → **Talk by C. Sirimanna [Wed, 9:40 AM]**

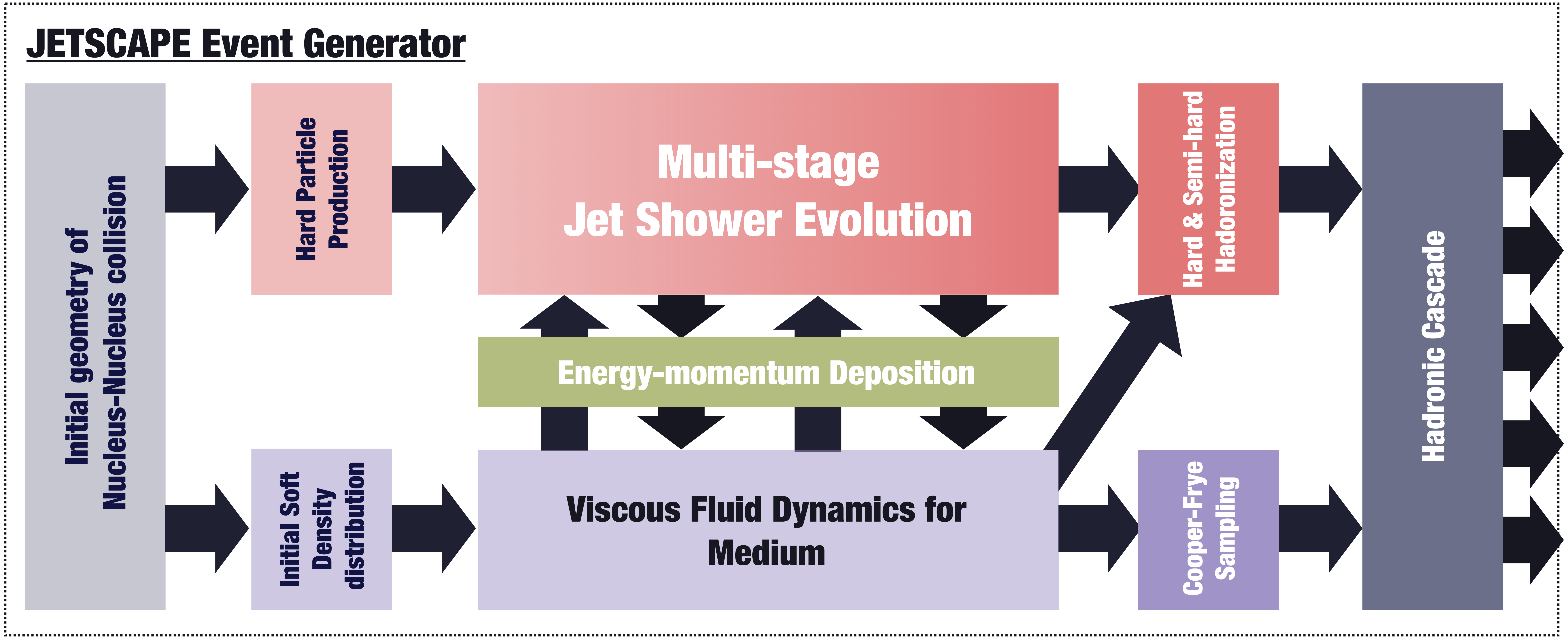
- Substructures → This Talk

Simulations with the JETSCAPE framework

JETSCAPE framework

JETSCAPE, arXiv:1903.07706

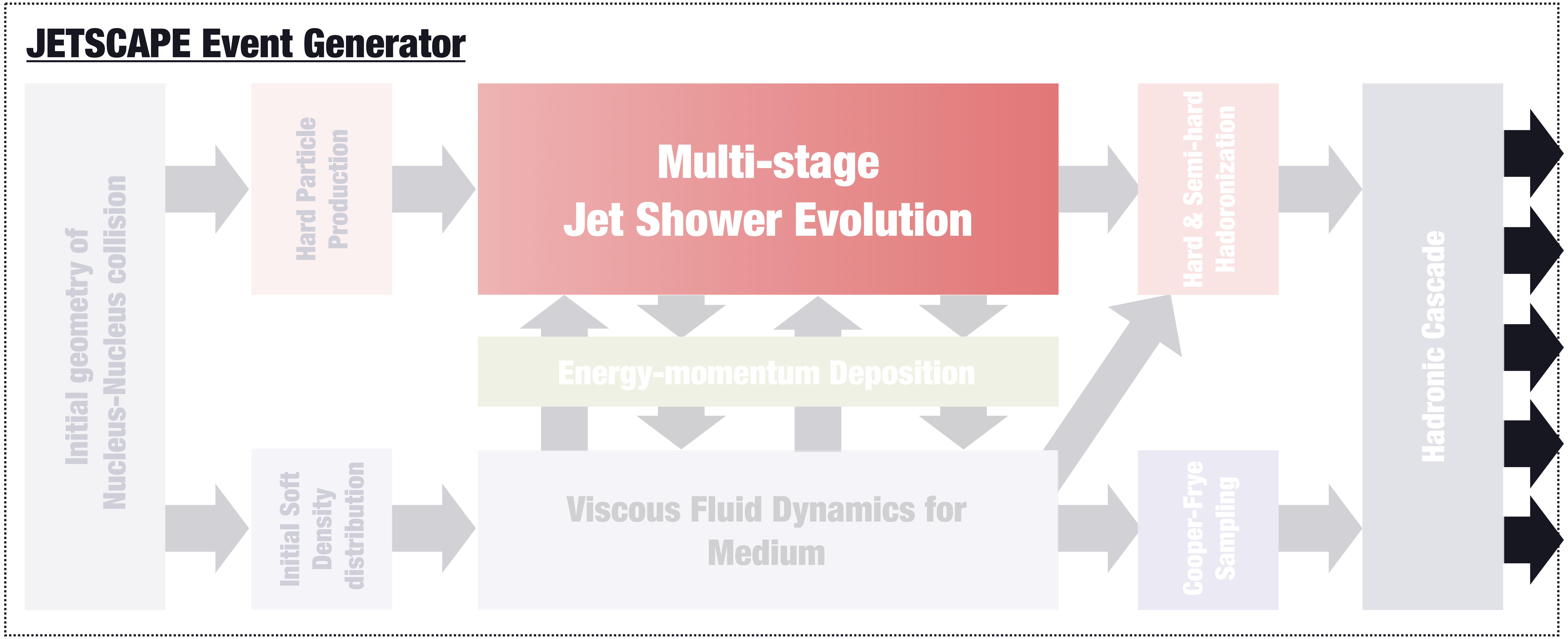
- **MC event generator package for heavy ion collisions**
  - General, modular and extensible
  - Communication between modules
  - Available on GitH github.com/JETSCAPE



JETSCAPE framework

JETSCAPE, arXiv:1903.07706

- **MC event generator package for heavy ion collisions**
  - General, modular and extensible
  - Communication between modules
  - Available on GitH github.com/JETSCAPE

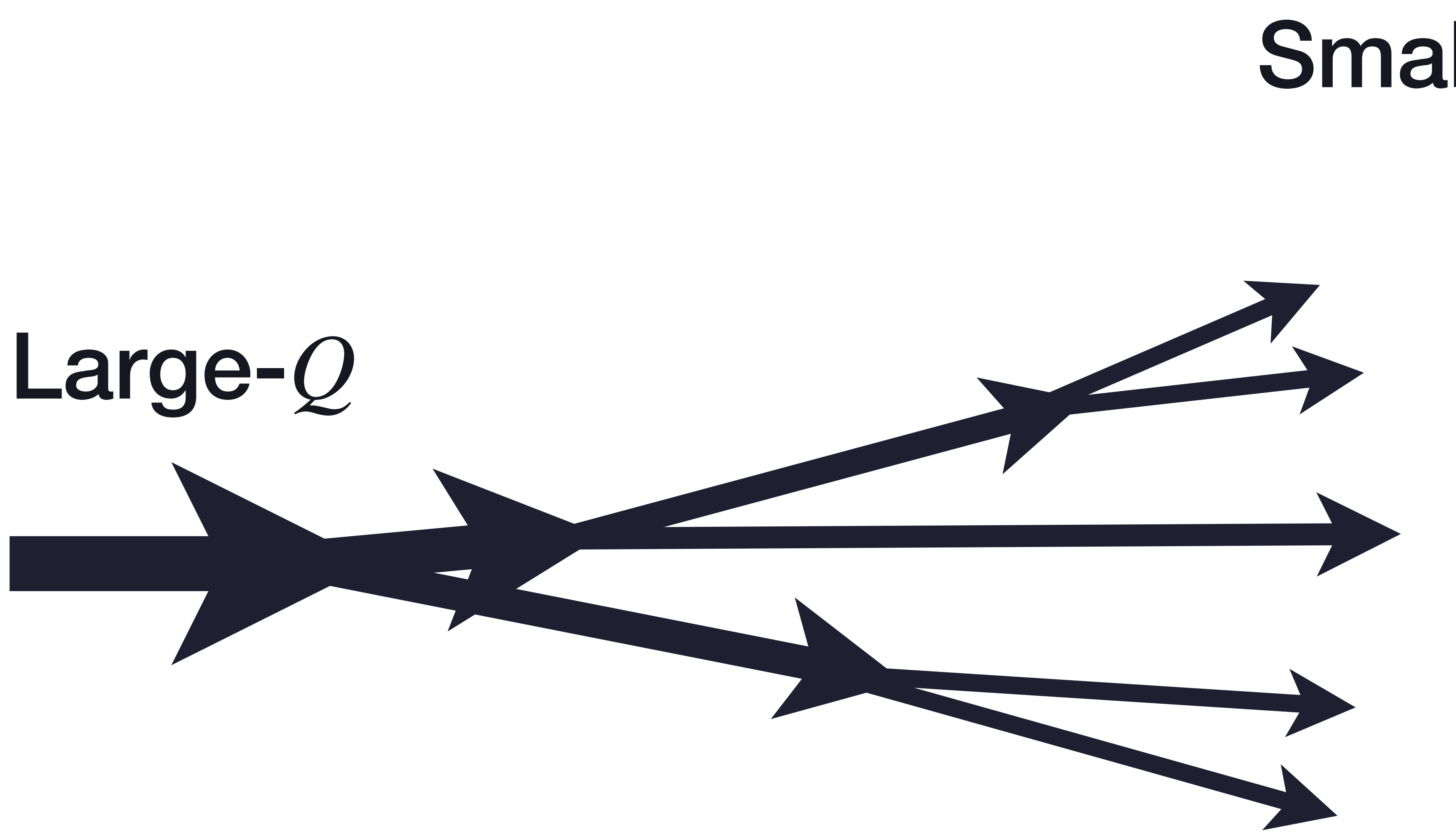


Multi-stage jet evolution in JETSCAPE

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

In-vacuum

- In-vacuum: Virtuality ordered splitting



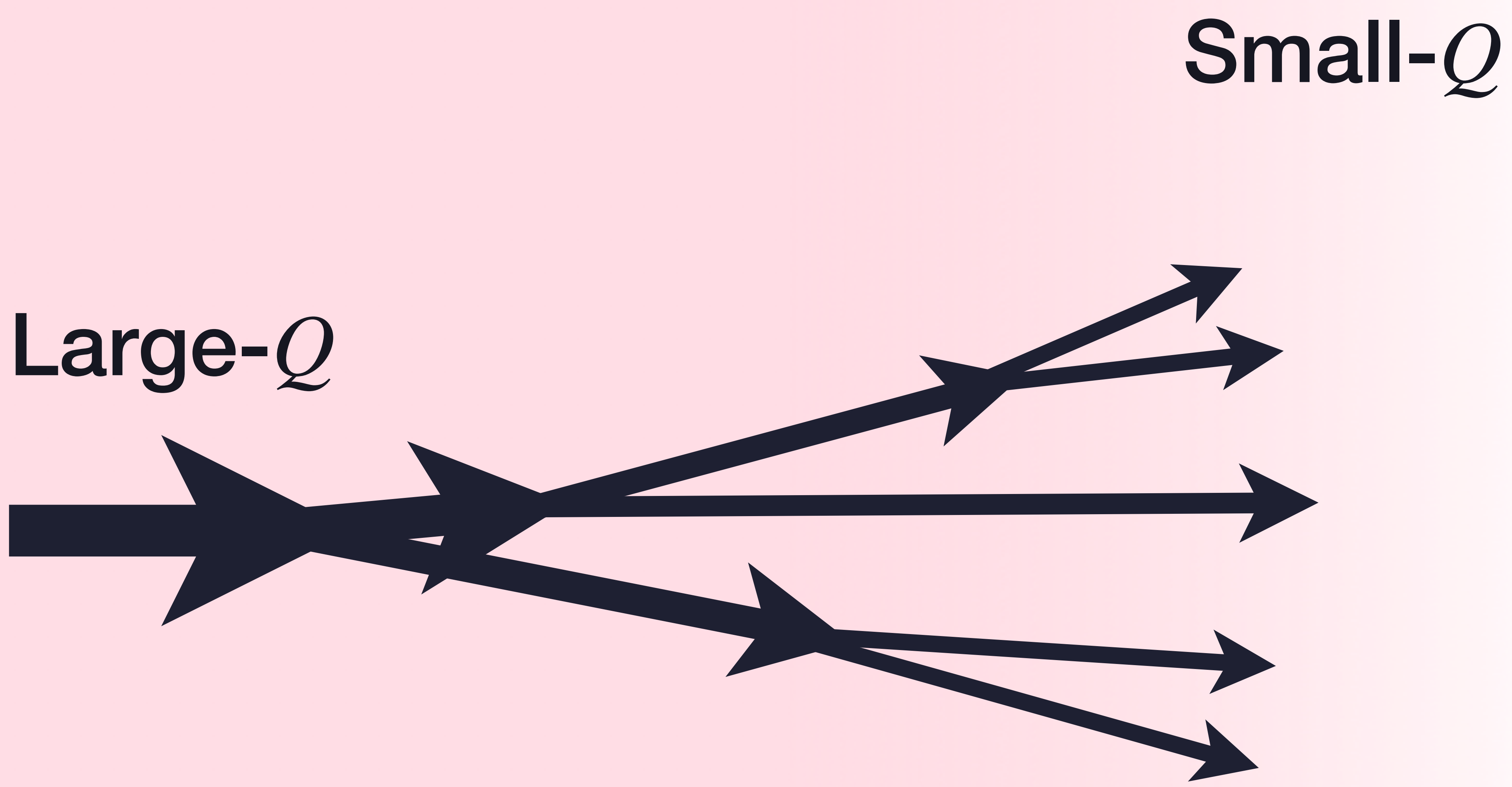
$Q^2 = p^\mu p_\mu - m^2$: virtuality (off-shellness)

Multi-stage jet evolution in JETSCAPE

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

In-medium

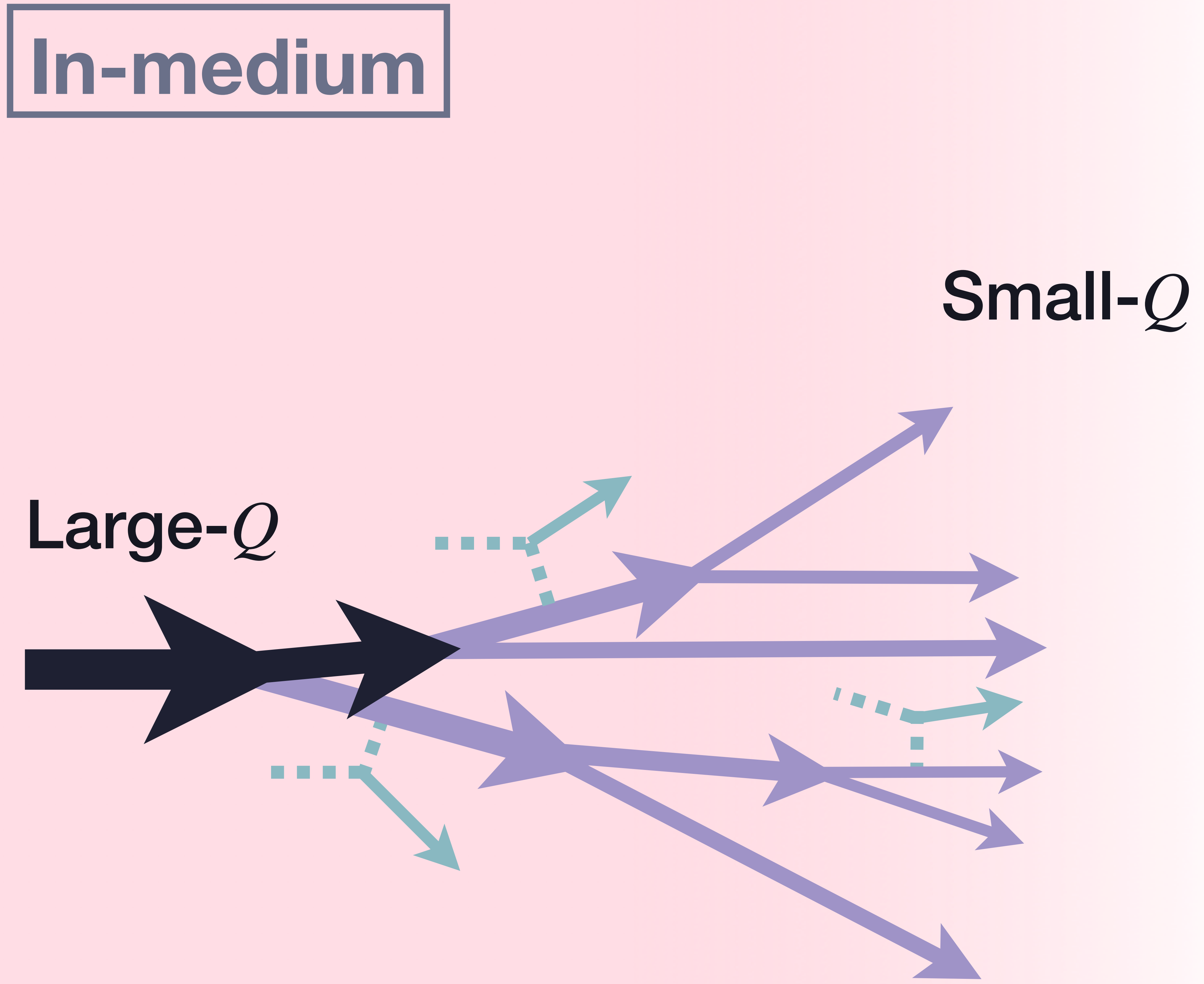
- In-vacuum: Virtuality ordered splitting



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

Multi-stage jet evolution in JETSCAPE

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



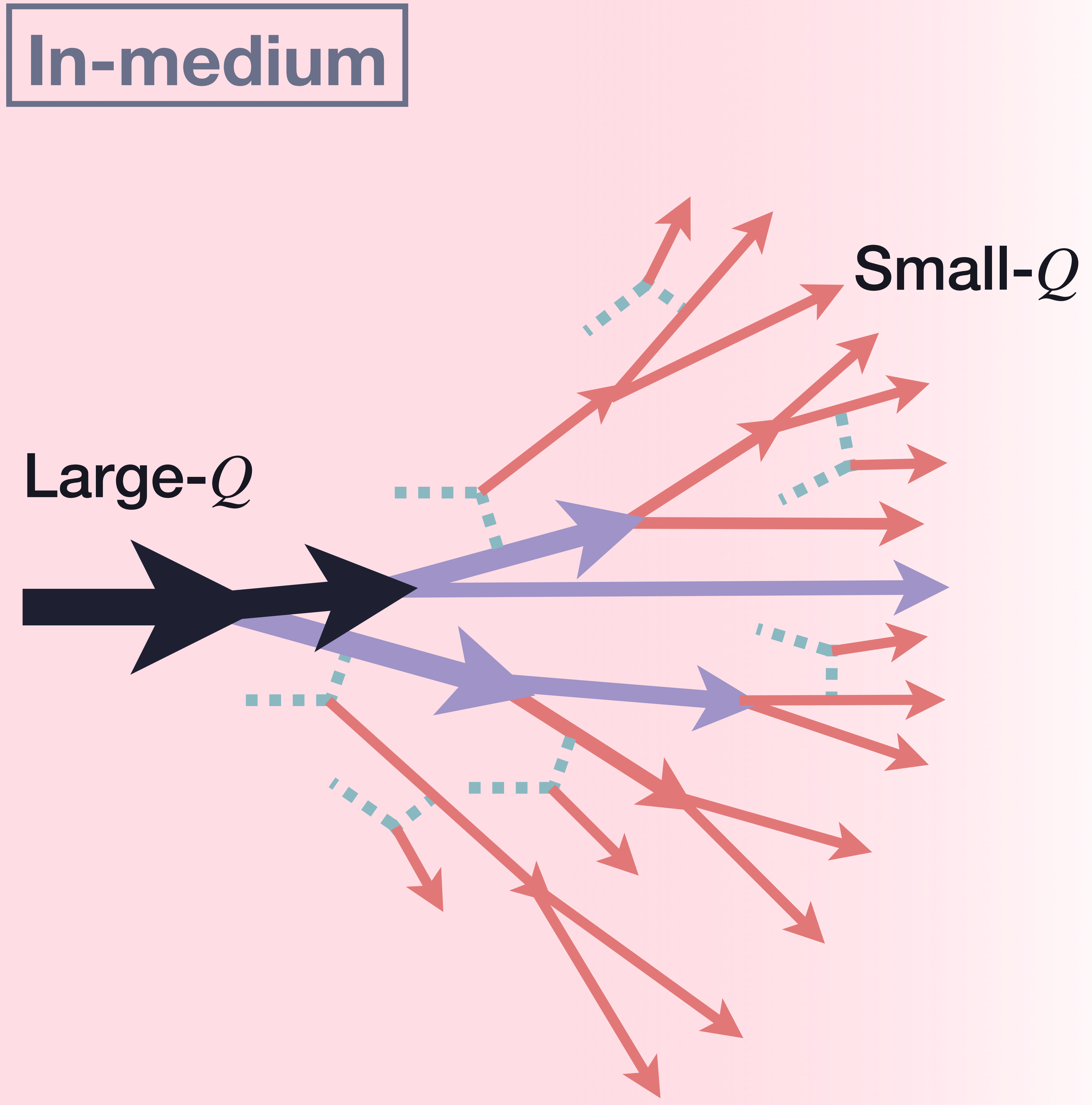
- In-vacuum: Virtuality ordered splitting

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

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

Multi-stage jet evolution in JETSCAPE

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



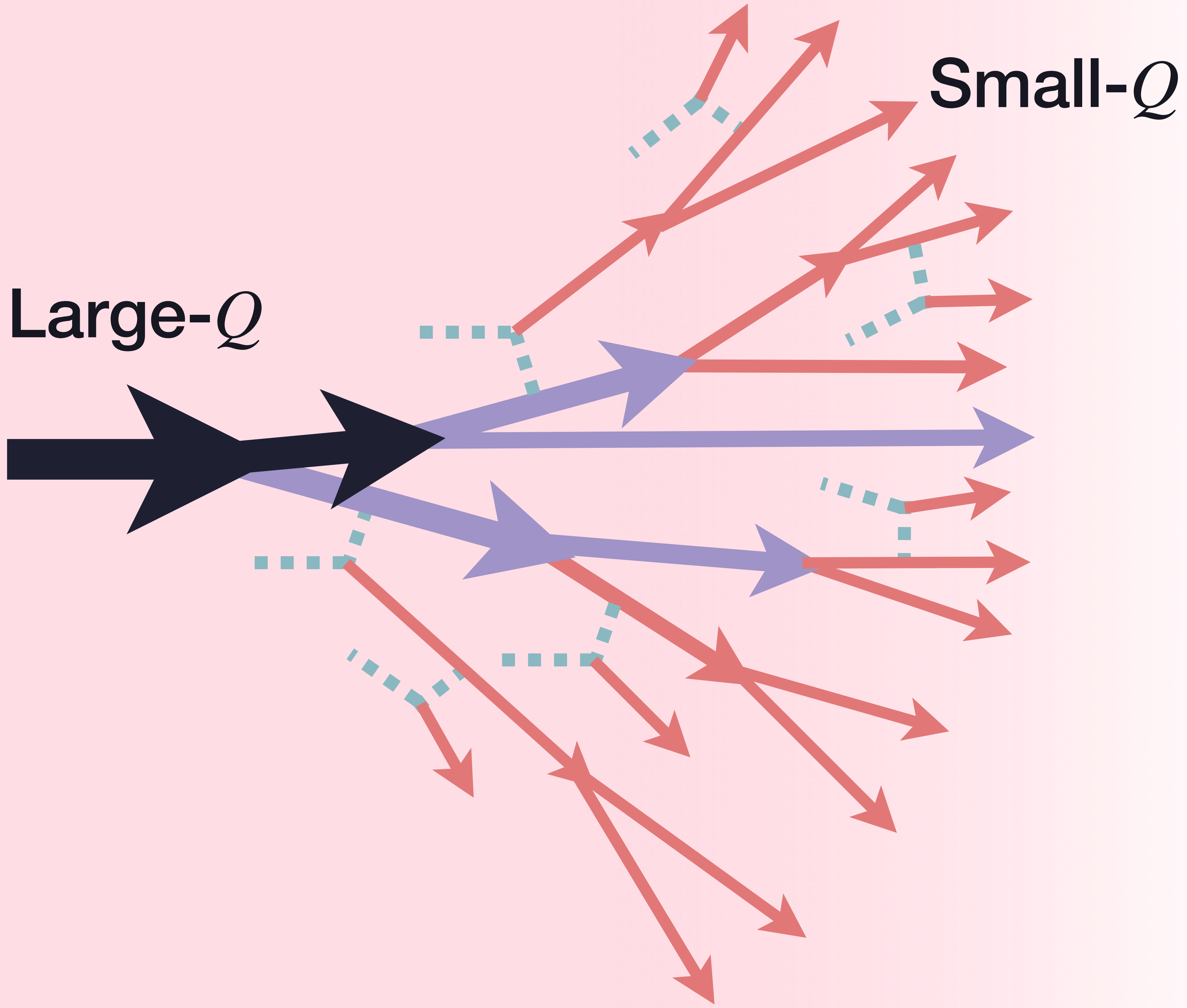
$Q^2 = p^\mu p_\mu - m^2$: virtuality (off-shellness)

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

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

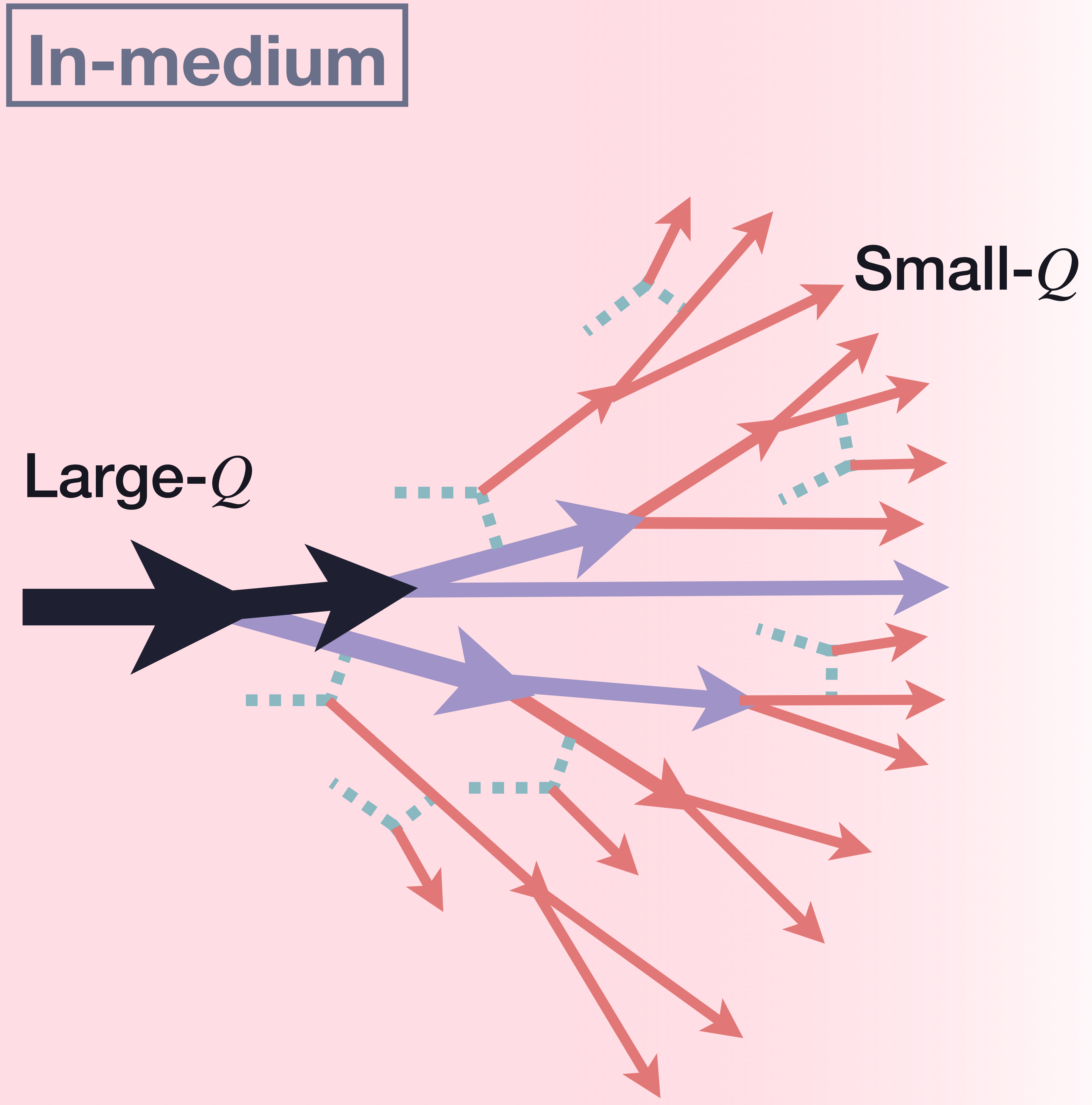
  Module(s): MATTER
  Majumder, Kordell, Cao, Kumar

- Small-Q: Splitting driven almost purely by medium effects

  Module(s): LBT, Wang, Zhu, Luo, He, Cao **MARTINI,** Schenke, Park, Gale, Jeon **AdS/CFT** Pablos, et al.

Multi-stage jet evolution in JETSCAPE

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



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

- In-vacuum: Virtuality ordered splitting

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

Module(s): MATTER

Majumder, Kordell, Cao, Kumar

$Q \geq Q_{\mathrm{sw}}$

Switching between modules for parton by parton

$Q < Q_{\mathrm{sw}}$

- Small-Q: Splitting driven almost purely by medium effects

Module(s): LBT, Wang, Zhu, Luo, He, Cao **MARTINI,** Schenke, Park, Gale, Jeon **AdS/CFT** Pablos, et al.

Setups

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

Jet Shower

Hard Scattering: (1) Single Parton *[For Testing Purpose]*
(Fixed initial Energy, no ISR, no MPI)

(2) Pythia8 *[Realistic Event Generation]*
(w/ ISR and MPI)

Parton Shower: MATTER (vacuum)

Hadronization: Lund String

Setups

- **A+A simulation setup** JETSCAPE, PRC107, 034911 (2023)

Jet Shower

Hard Scattering: (1) Single Parton *[For Testing Purpose]*
(Fixed initial Energy, no ISR, no MPI)
(2) Pythia8 *[Realistic Event Generation]*
(w/ ISR and MPI)

Parton Shower: MATTER+LBT
(recoil on, $Q_{\rm sw} = 2\ {\rm GeV}$)

Hadronization: Lund String

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

Bulk Medium

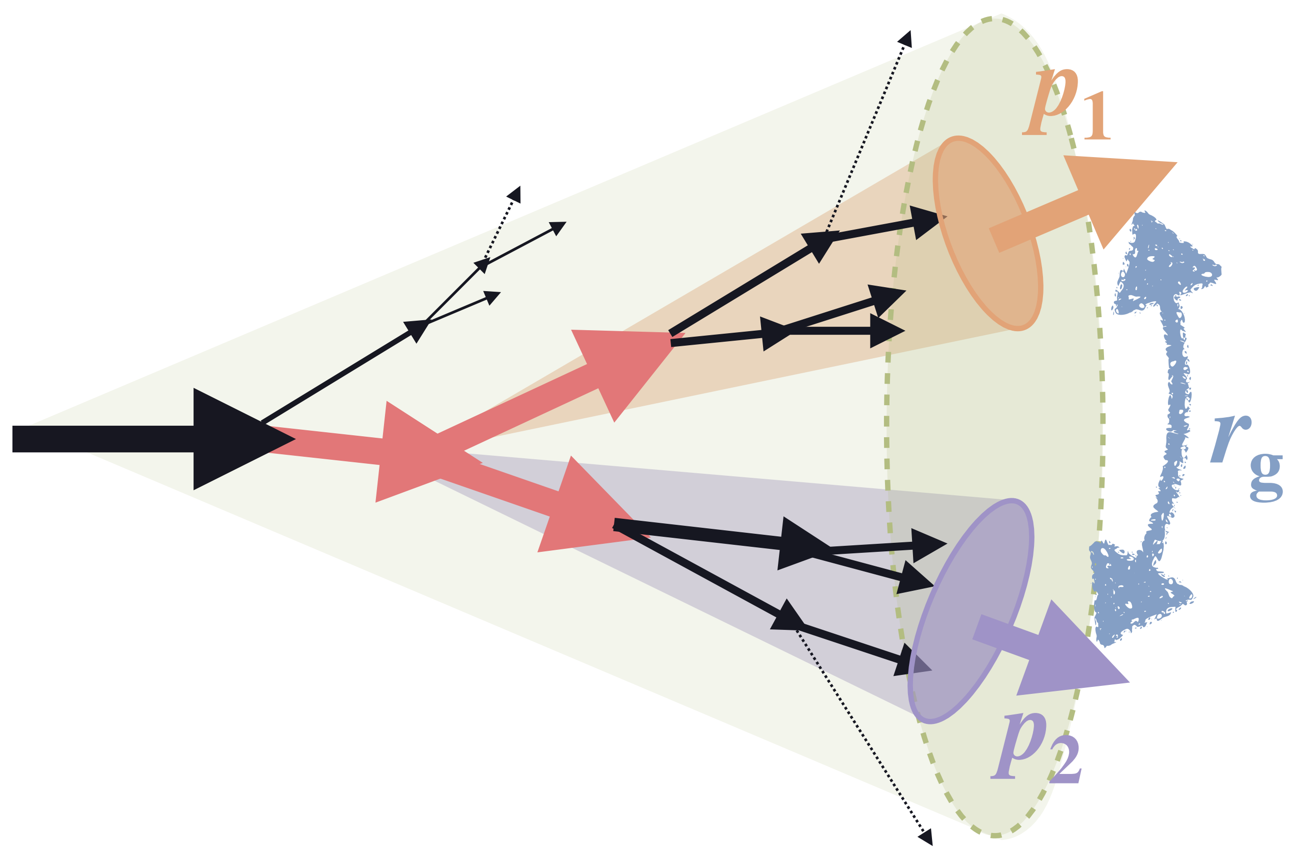
Initial Condition: TRENTo
Moreland, Bernhard, Bass (14)

Prehydro Evolution: Freestreaming
Liu, Shen, Heinz(15)

Hydro Evolution: VISHNU (2+1D viscous)
Shen, Qiu, Song, Bernhard, Bass, Heinz(16)

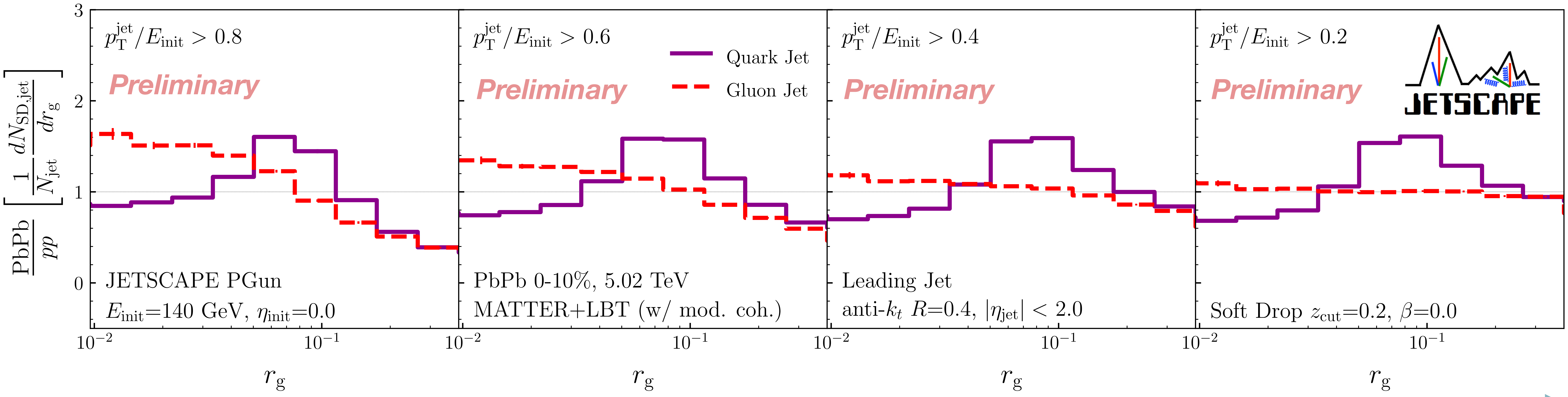
Results

r_g-modification: single parton simulations



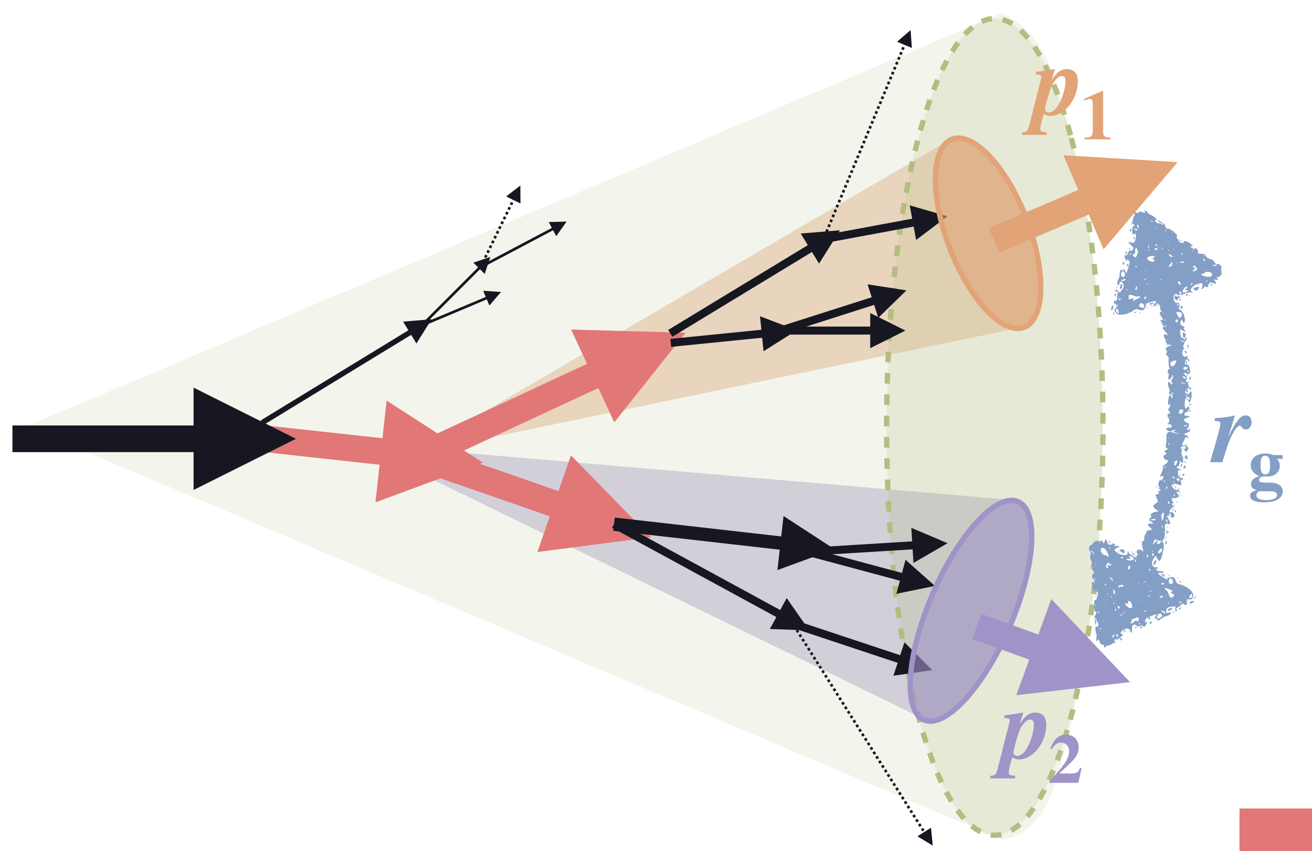
- Fixed energy and flavor (quark/gluon) of the initial parent

- Prominent modification in quark jets
- Barely noticeable modification in gluon jets
- No narrowing in actual substructure modification



Eliminating the E-loss selection bias

r_g-modification: inclusive vs γ-tagged

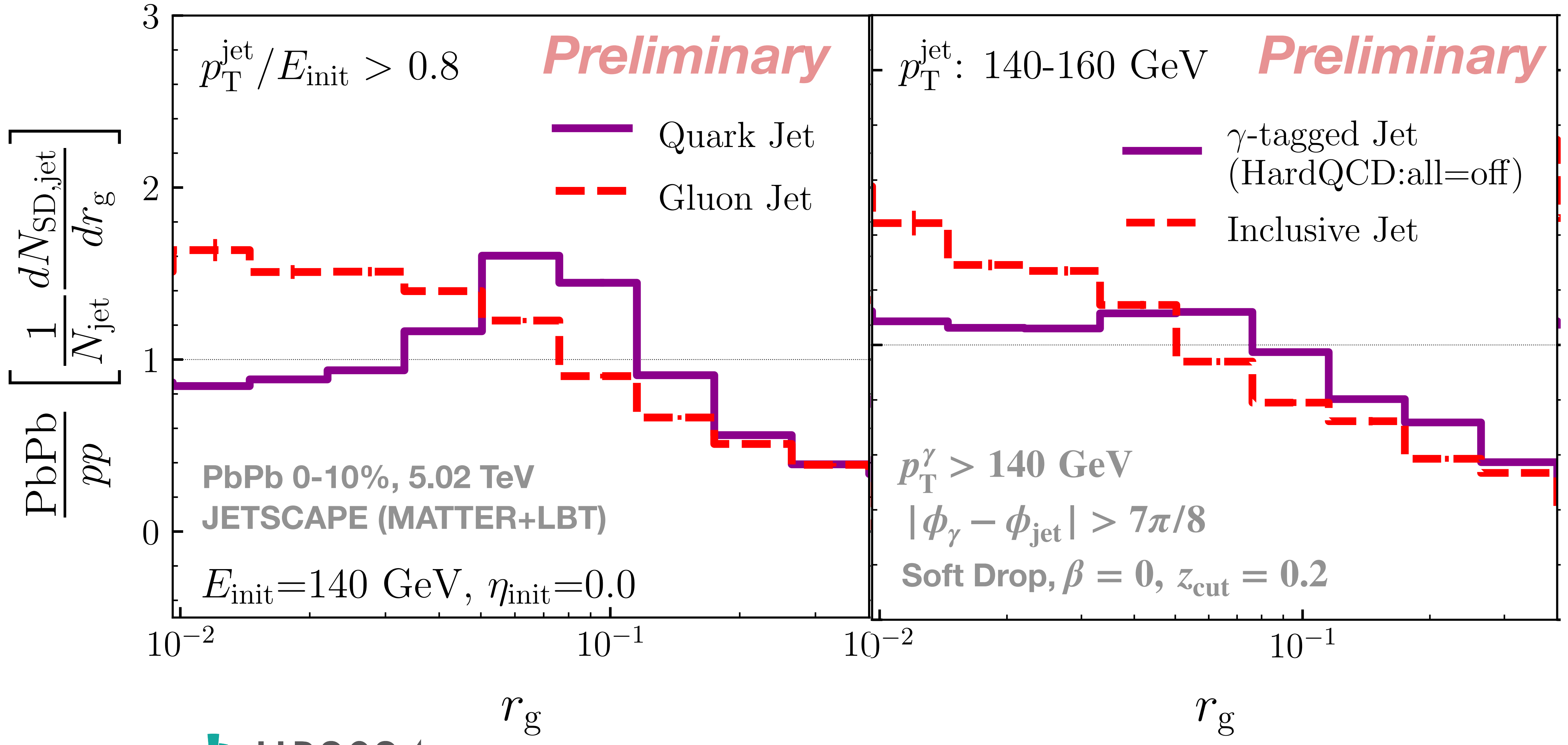


- Realistic event generation by Pythia8 hared scatterings (MPI: ON, ISR: ON)

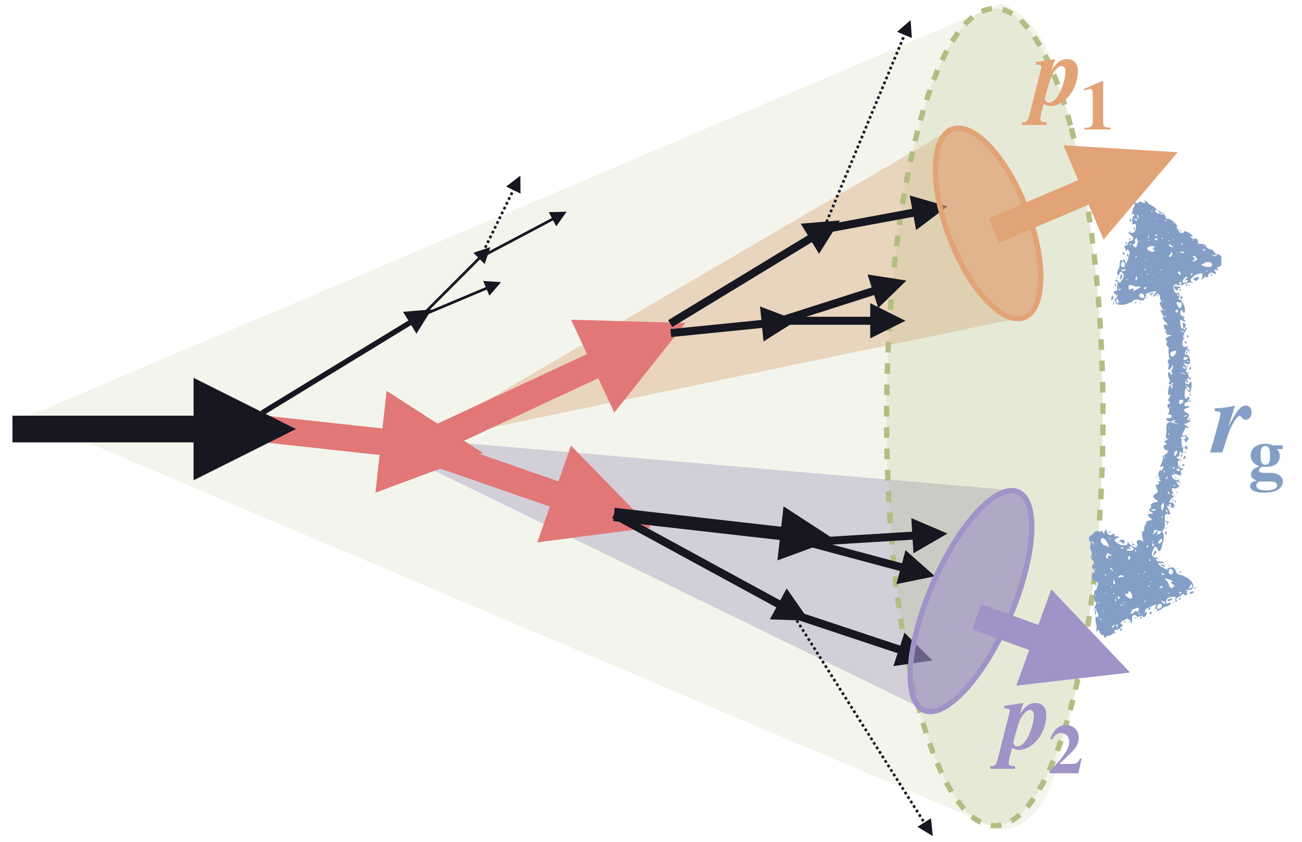
- Quark jet characteristics observed in γ-tagged jets
- Gluon jet characteristics observed in inclusive jets

(1) Single parton

(2) Pythia8 Hard Scattering

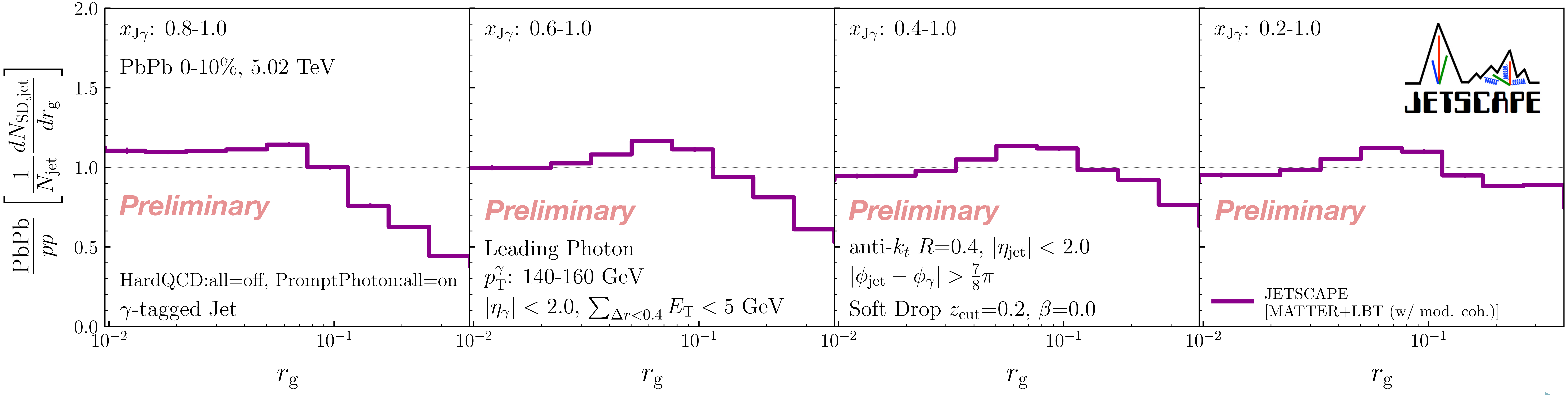


r_g-modification: γ-tagged jets



- Realistic event generation by Pythia8 hared scatterings (MPI: ON, ISR: ON)

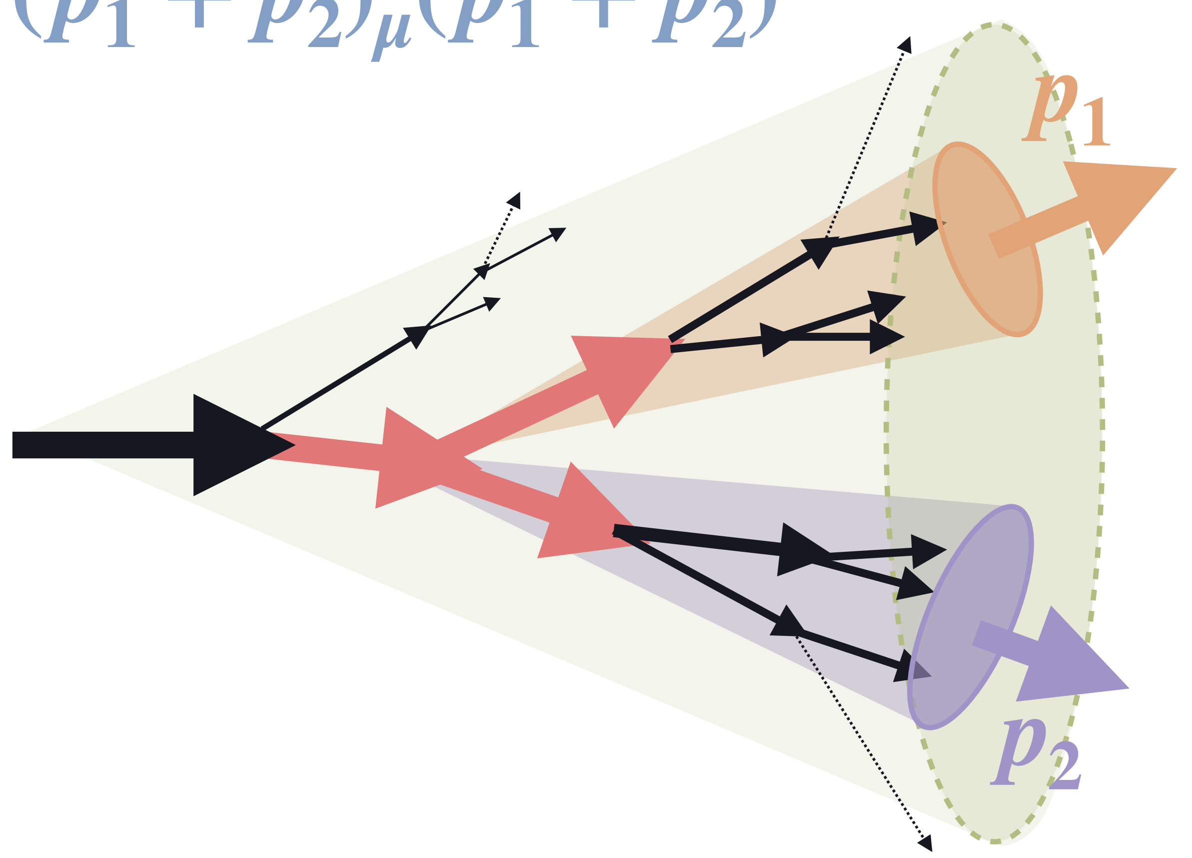
- Quark jet characteristics observed in γ-tagged jets
- No narrowing in actual substructure modification



Eliminating the E-loss selection bias

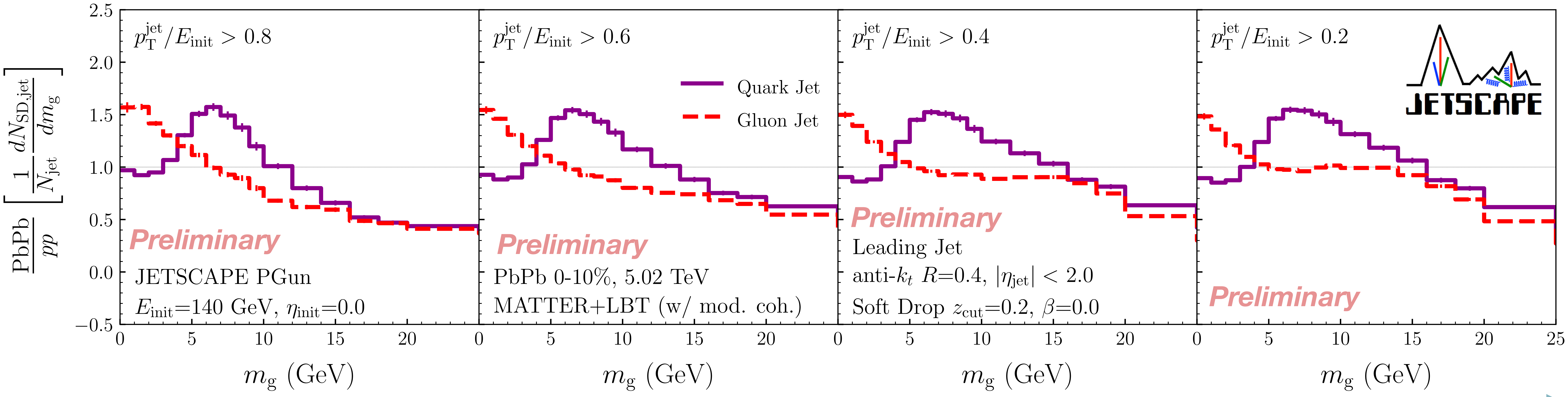
m_g-modification from single parton simulations

$$m_g = \sqrt{(p_1 + p_2)_\mu (p_1 + p_2)^\mu}$$



- Fixed energy and flavor (quark/gluon) of the initial parent

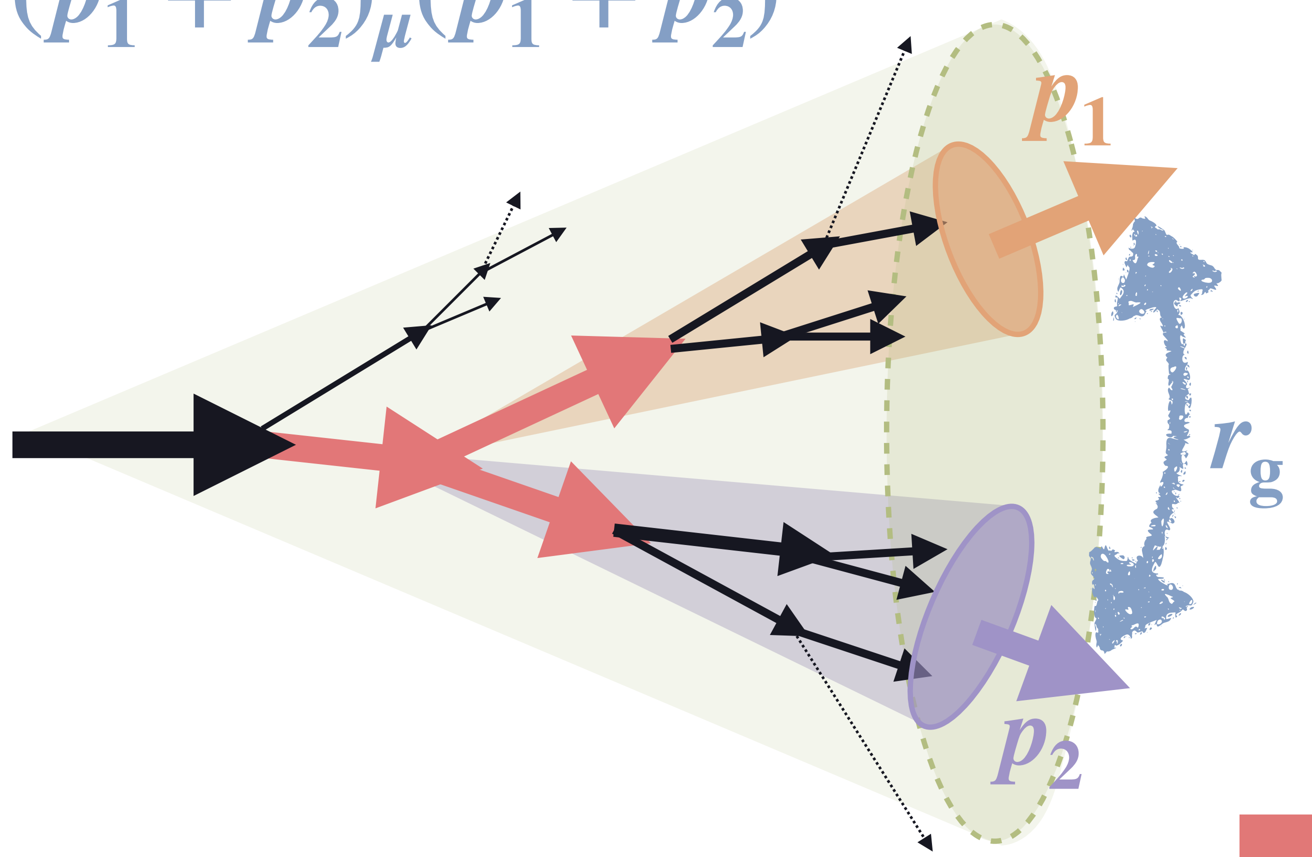
- Mass loss due to out-of-cone radiations/scatterings
- Mass gain manifested as bump in quark jets
- Mass gain bearly visible/invisible in gluon jets



Eliminating the E-loss selection bias

m_g-modification: inclusive vs γ-tagged

$m_g = \sqrt{(p_1 + p_2)_\mu (p_1 + p_2)^\mu}$

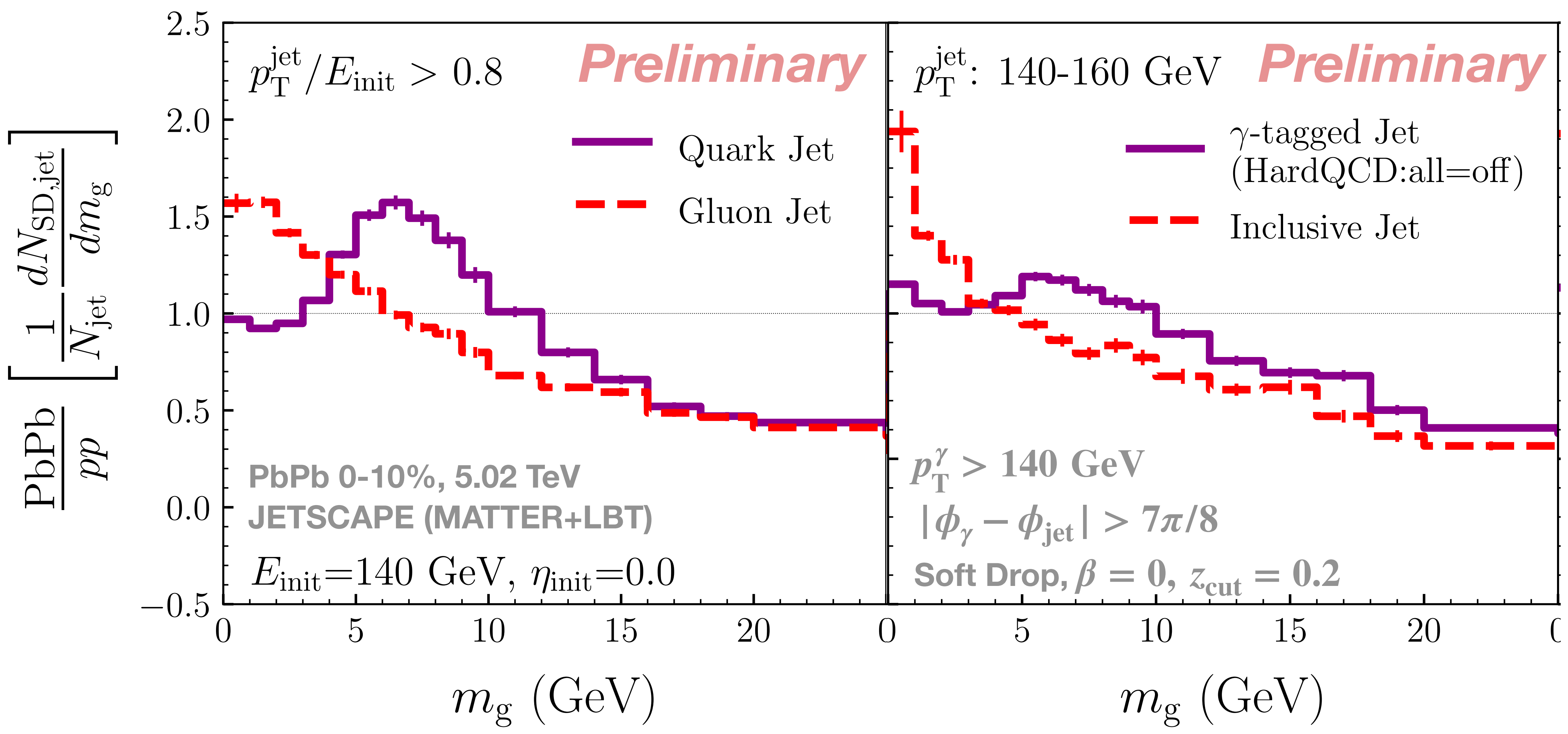


- Realistic event generation by Pythia8 hared scatterings (MPI: ON, ISR: ON)

- Quark jet characteristics observed in γ-tagged jets
- Gluon jet characteristics observed in inclusive jets

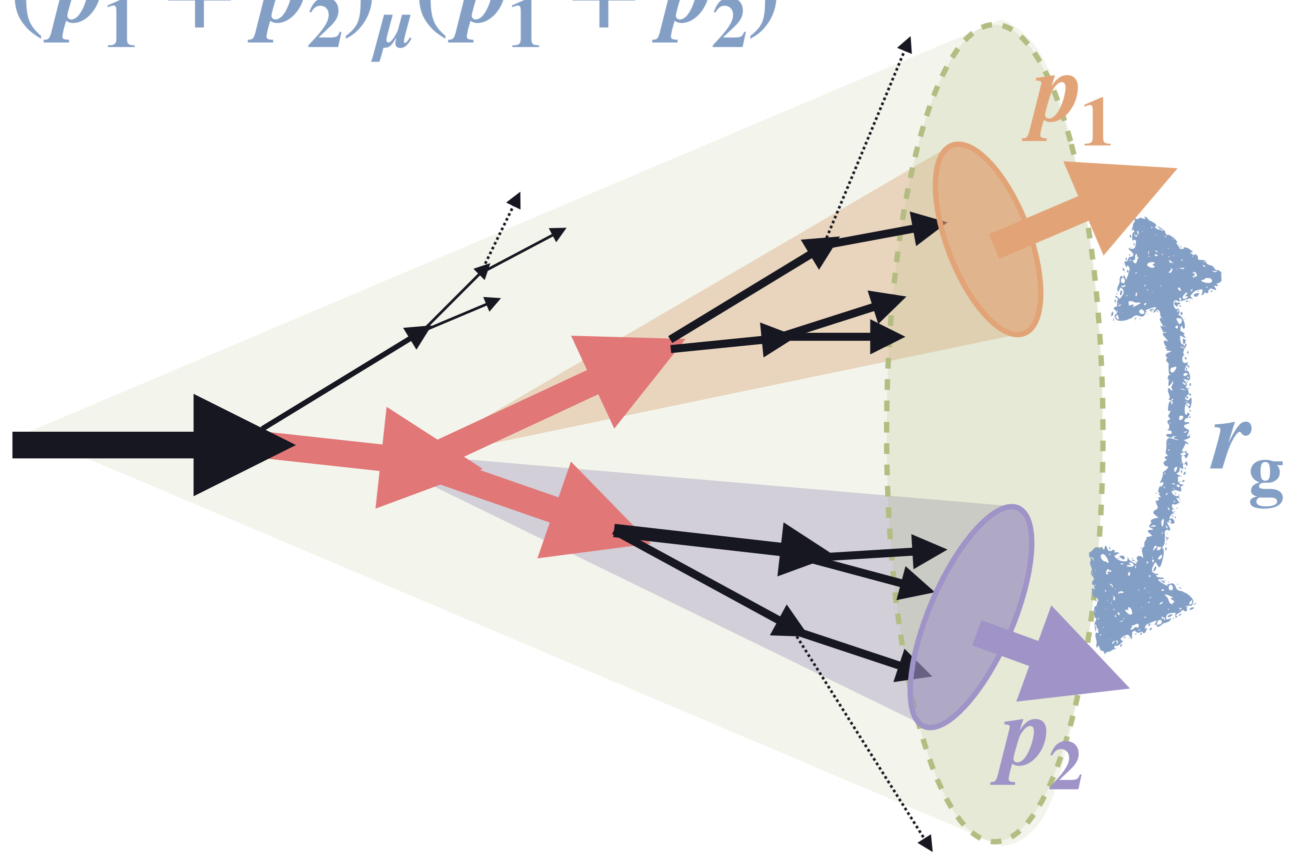
(1) Single parton

(2) Pythia8 Hard Scattering



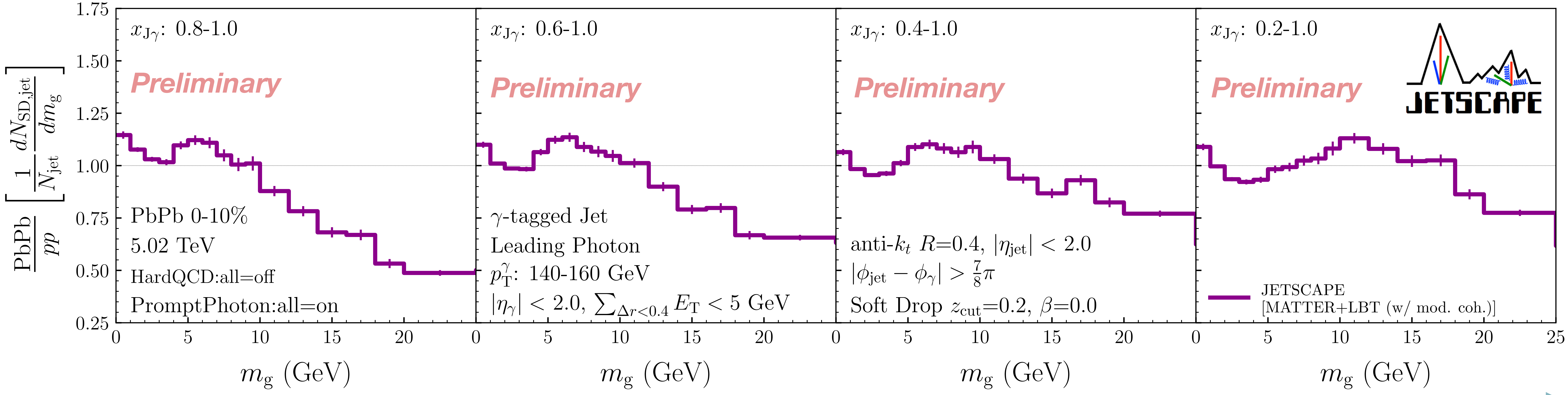
m_g-modification: inclusive vs γ-tagged

$$m_g = \sqrt{(p_1+p_2)_\mu (p_1+p_2)^\mu}$$



- Realistic event generation by Pythia8 hared scatterings (MPI: ON, ISR: ON)

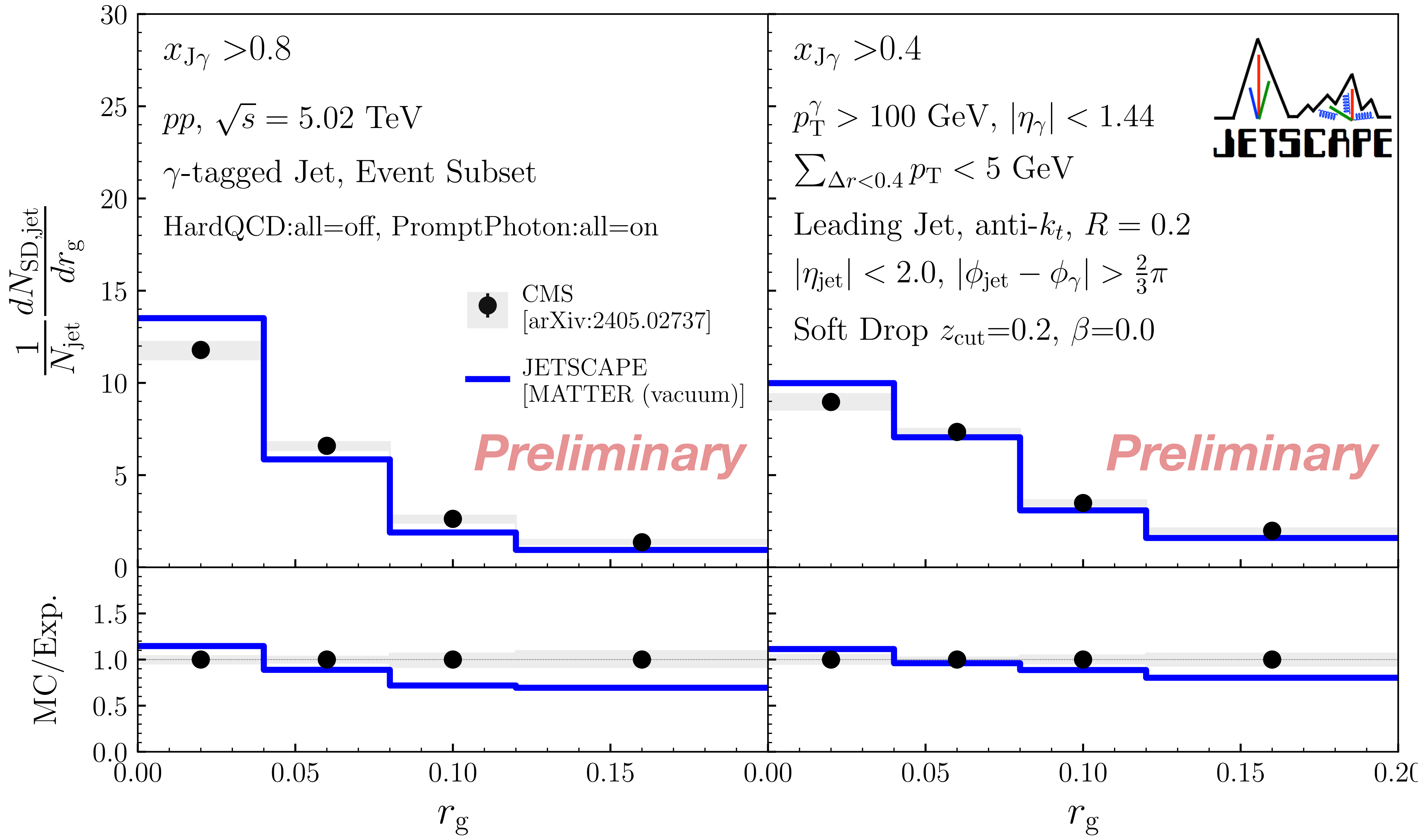
- Quark jet characteristics observed in γ-tagged jets
- Mass loss due to out-of-cone radiations/scatterings

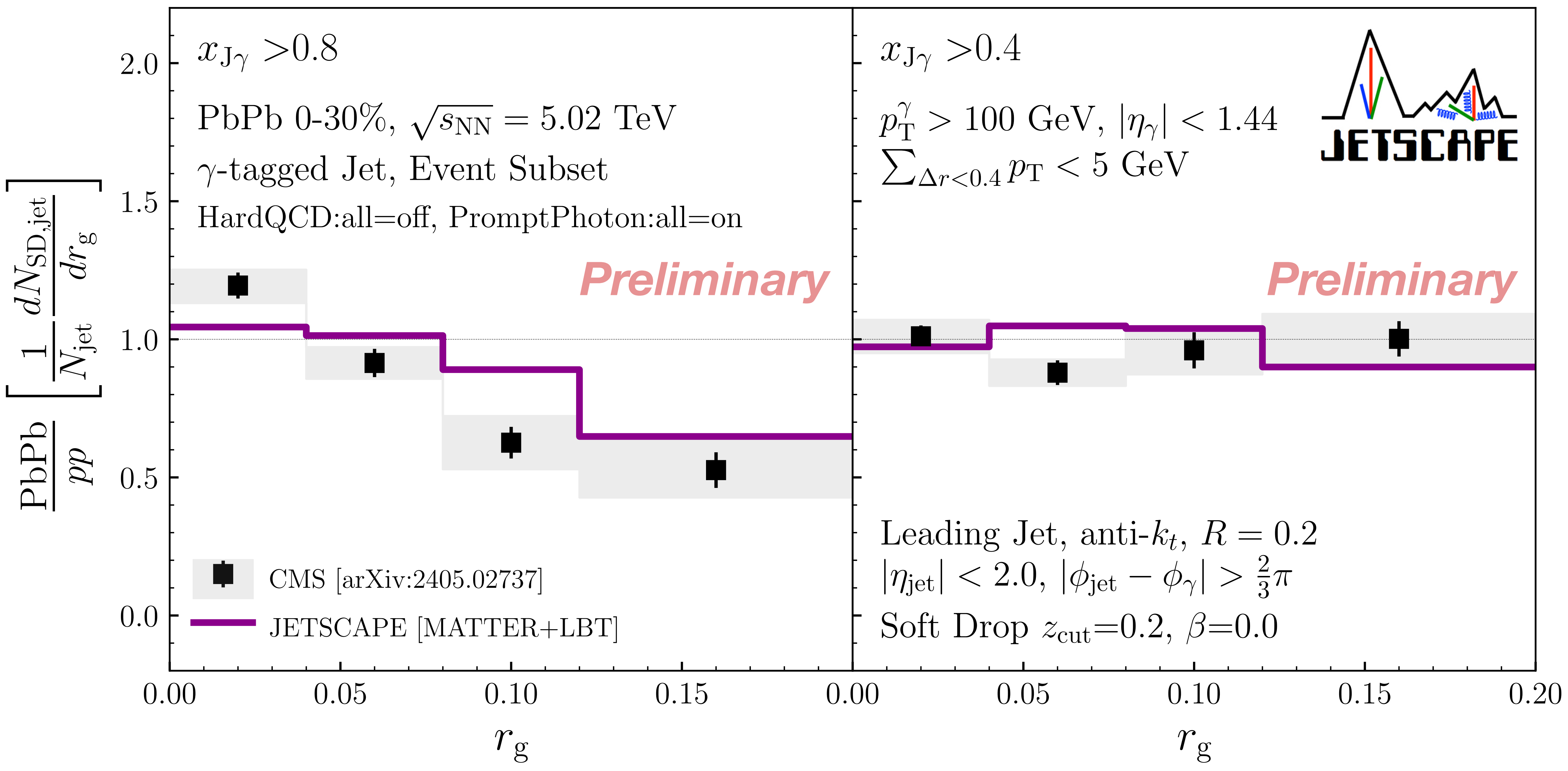


Eliminating the E-loss selection bias

Comparison with Experimental Data

- r_g-distribution for γ-tagged jet, compared with CMS data



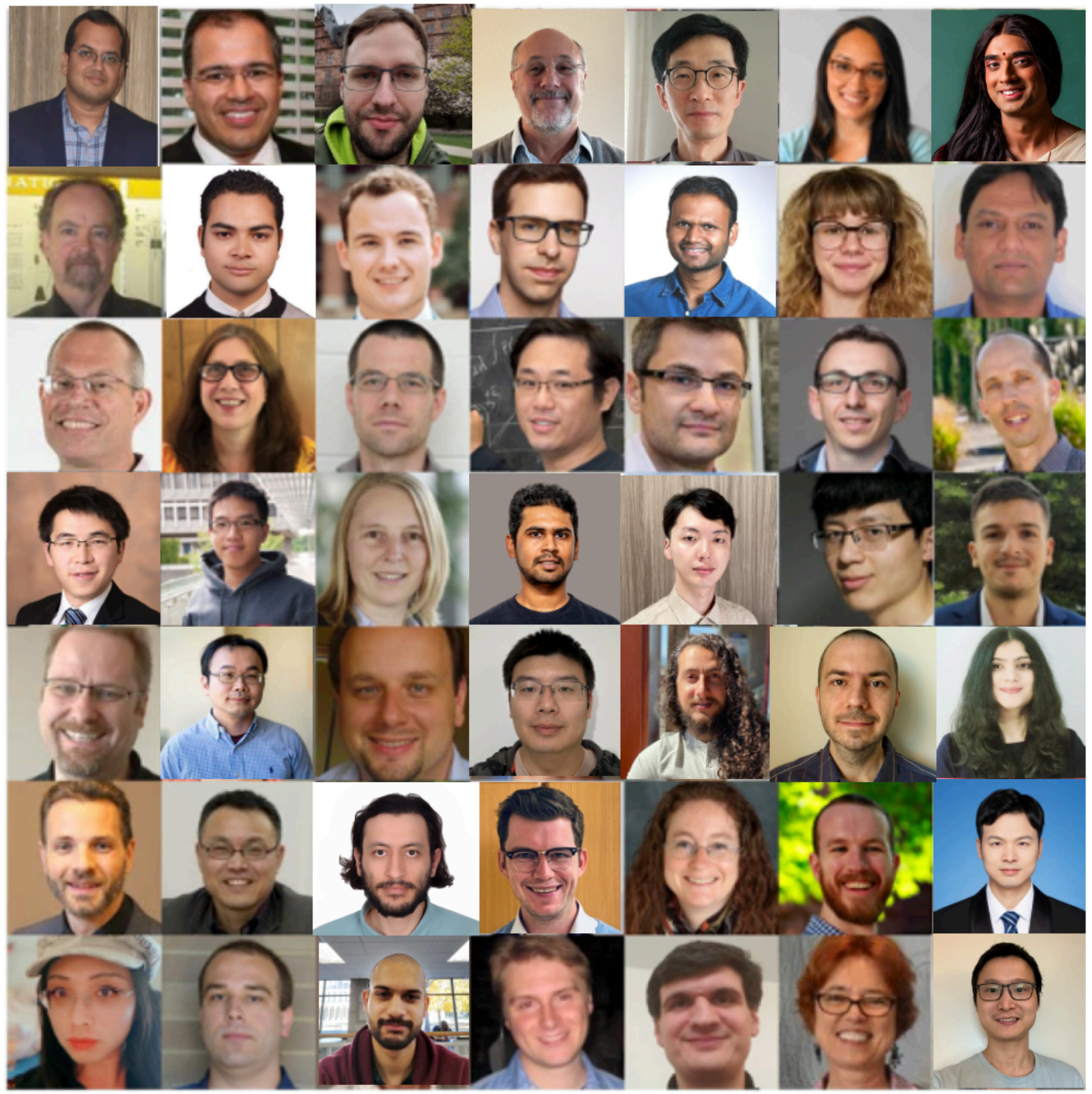


- Capture the trend of less narrowing for smaller $x_{J\gamma}$-cut
- Awaiting data with finer bins to observe flavor dependence

Summary

- **Soft Drop groomed jet substructure**
  - Relatively well dominated by perturbative parton splitting
  - Selection bias rather than actual structural modification for inclusive jets (e.g. narrowing)
  - γ-tagged jet → control of the selection bias, flavor dependence (quark-jet dominance)
- **Simulations with the JETSCAPE framework**
  - Multi-stage jet shower description (high-Q: virtuality-driven, low-Q: medium effect-driven)
  - 2-initial hard process setups:
    (1) Single parent parton with fixed flavor and energy, (2) Realistic Pythia8 hard scatterings
- **Inclusive vs γ-tagged jet substructures**
  - Prominent modification (broadening) in γ-tagged jets, dominated by quark jet characteristics
  - Moderate modification in inclusive jets, dominated by gluon jet characteristics
  - Actual structural modification accessible by controlling the selection bias effects via $x_{J\gamma}$-cut

JETSCAPE Collaboration



Thanks to my collaborators!

- **Presentations at HP2024 NAGASAKI**
  - Jets with hadronic rescatterings
    Talk by H. Roch [Mon, 6:10 PM]
  - Bayesian jet studies
    Talk by P. Jacobs [Mon, 3:40 PM]
  - Jet EEC
    Talk by Y. He [Tue, 9:20 AM]
  - Jet-soft correlations in small systems
    Talk by S. Jeon [Tue, 4:15 PM]
  - Photon-jet correlations
    Talk by C. Sirimanna [Wed, 9:40 AM]
  - ep, e^+e^-, pp studies with the XSCAPE framework
    Poster by R. Fries [Tue, Poster]

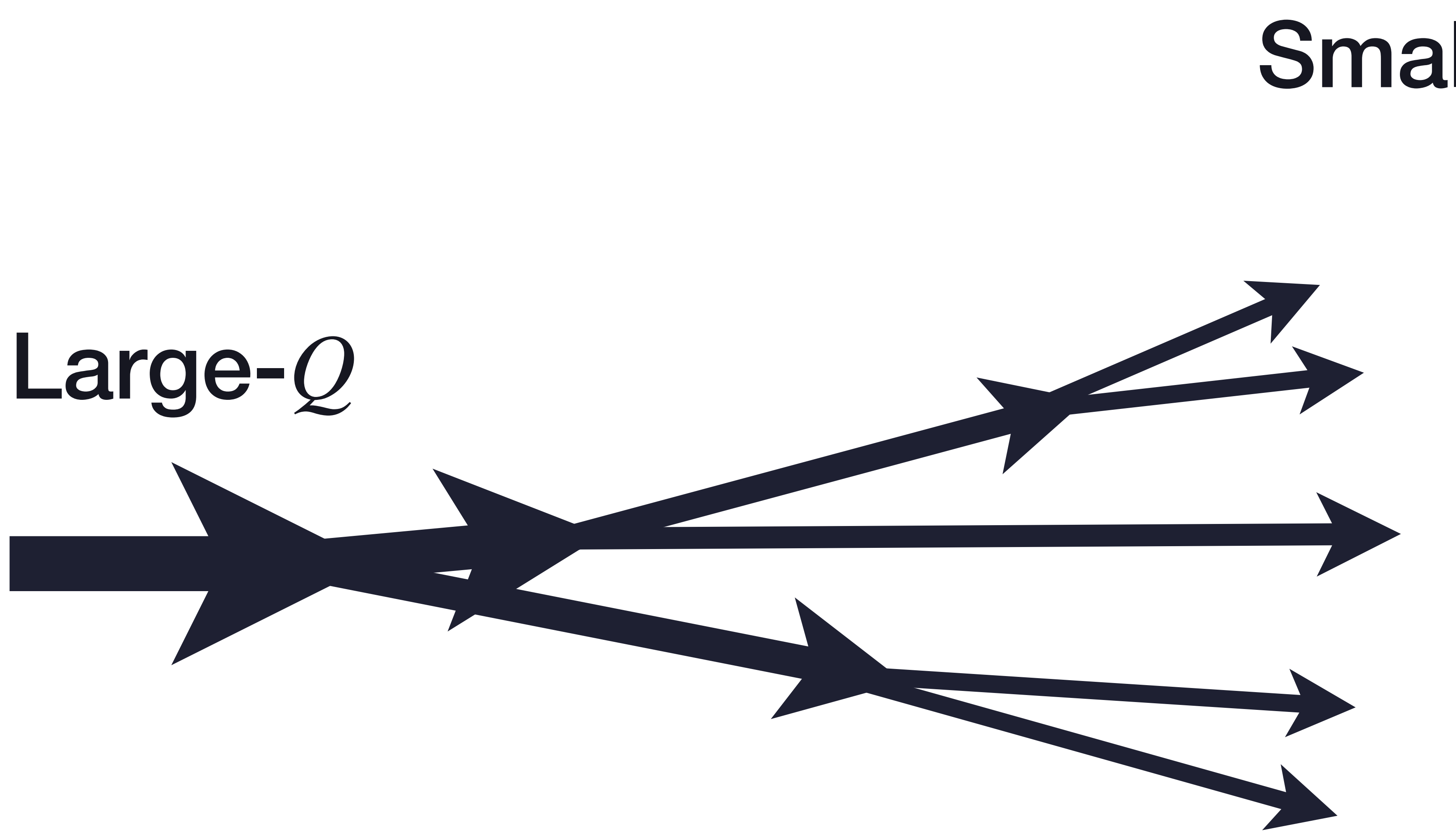
Backup Slides

Multi-stage jet evolution in JETSCAPE

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

In-vacuum

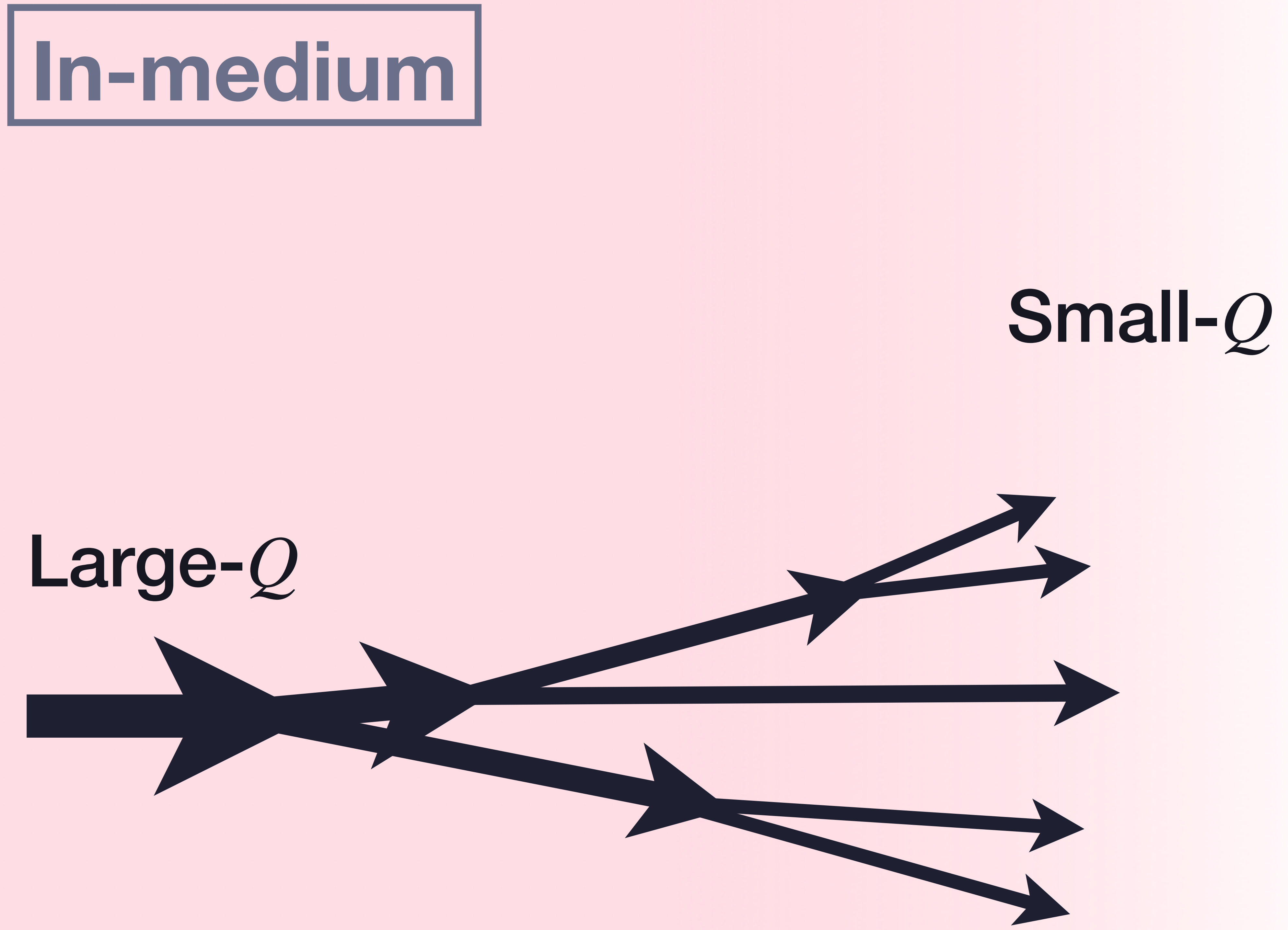
- In-vacuum: Virtuality ordered splitting



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

Multi-stage jet evolution in JETSCAPE

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



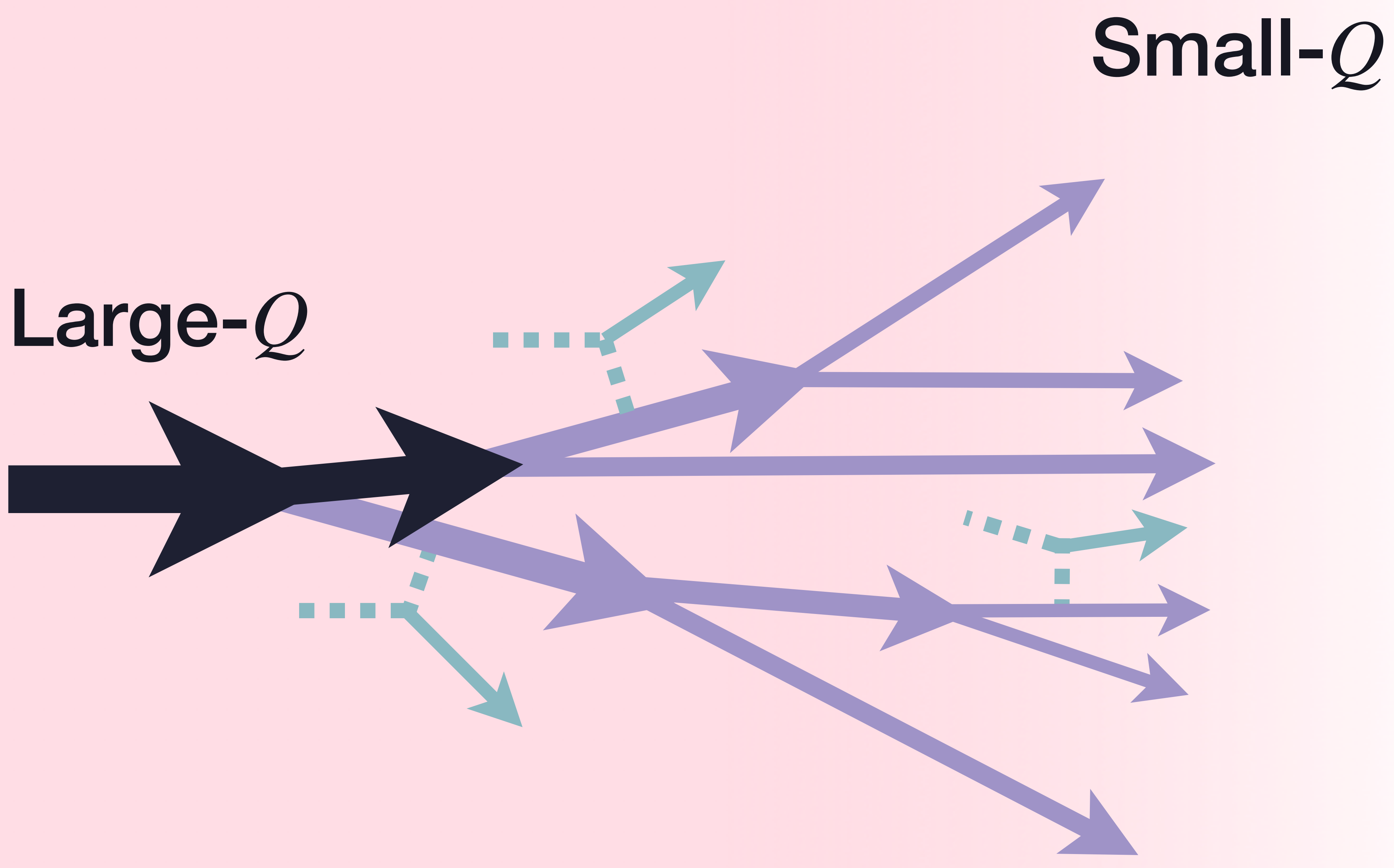
- In-vacuum: Virtuality ordered splitting

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

Multi-stage jet evolution in JETSCAPE

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

In-medium

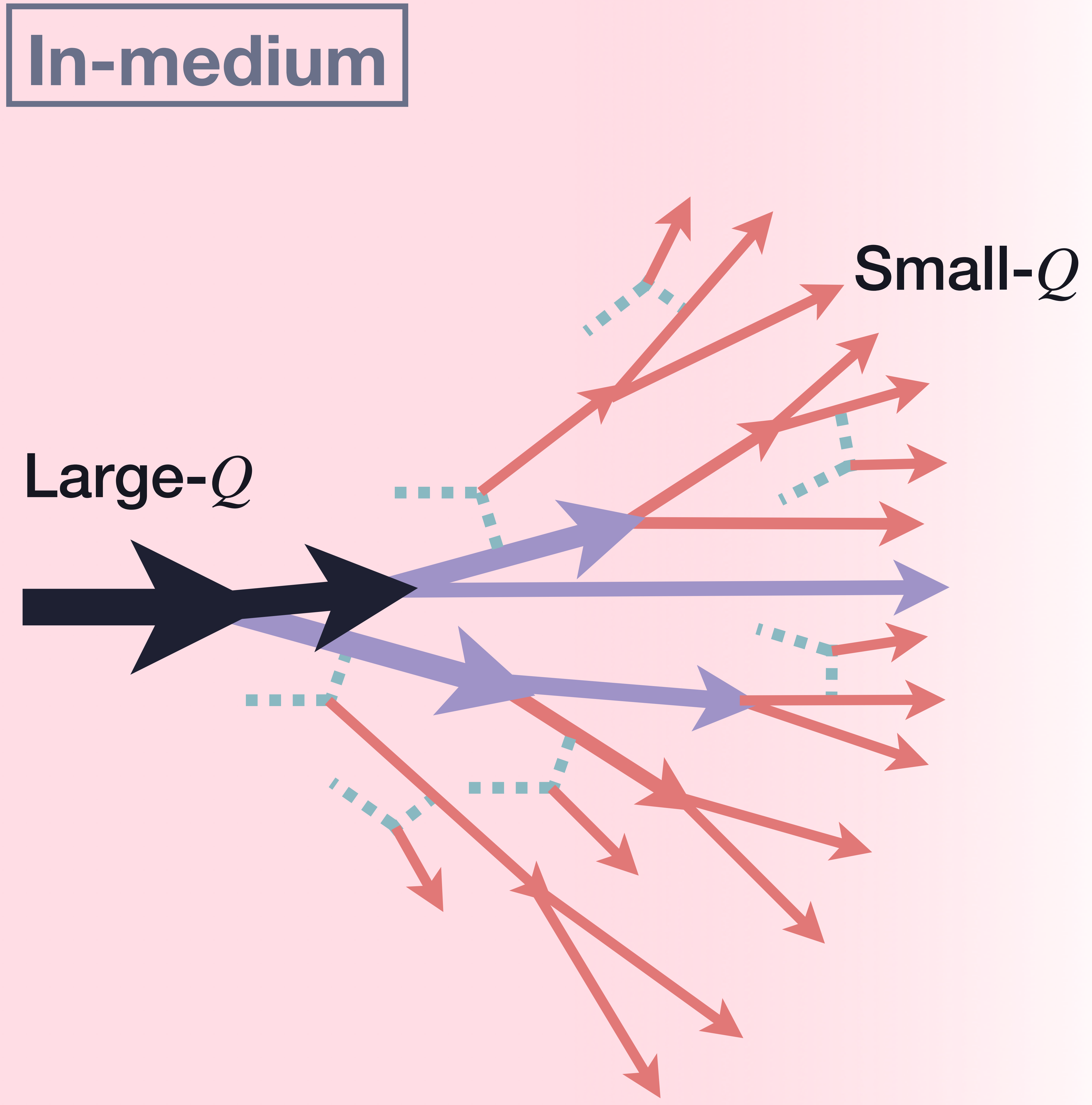


- In-vacuum: Virtuality ordered splitting
- Large-Q: Medium effect on top of in-vacuum splitting

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

Multi-stage jet evolution in JETSCAPE

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

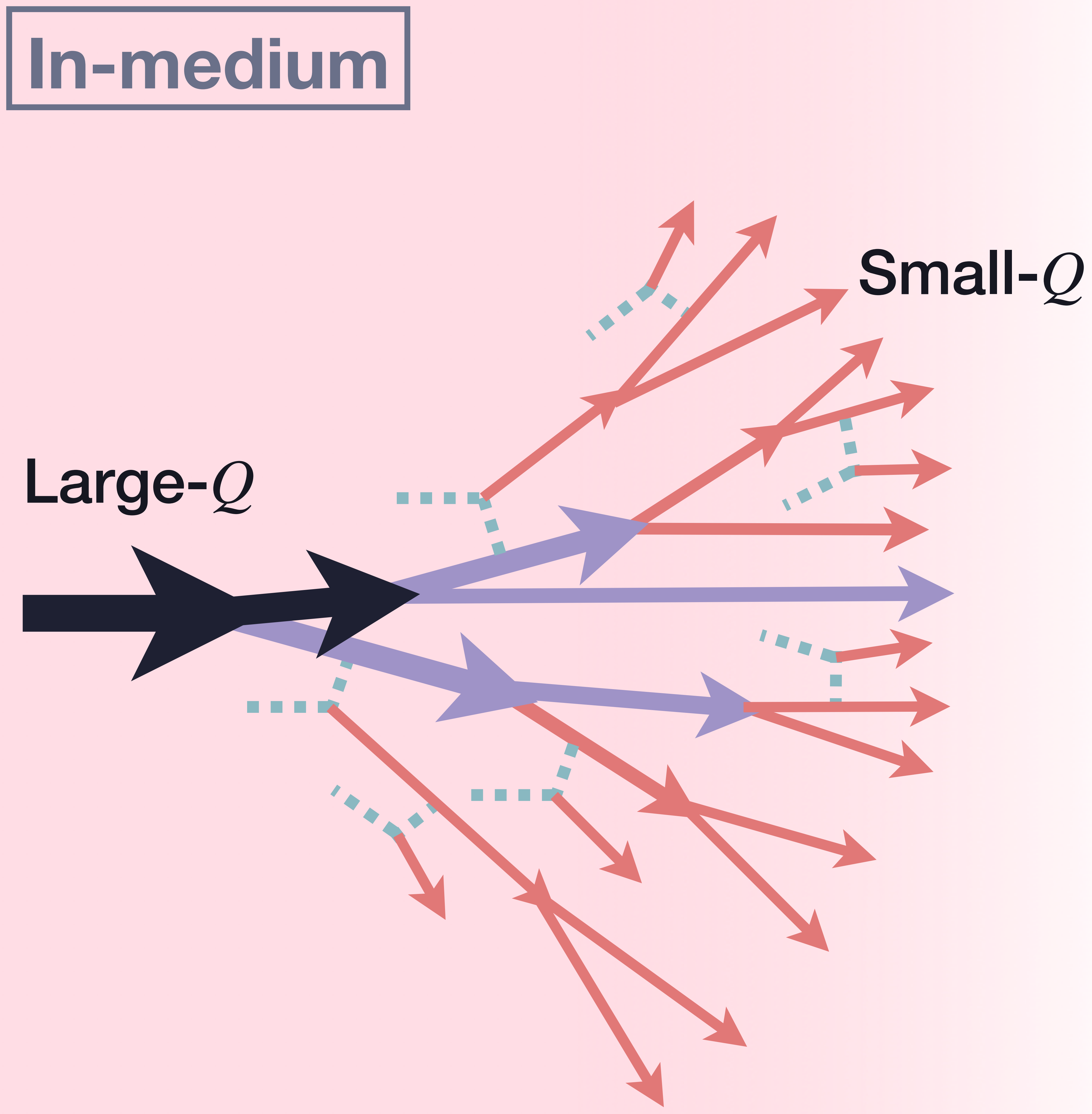


$Q^2 = p^{\mu} p_{\mu} - m^2$: virtuality (off-shellness)

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

Multi-stage jet evolution in JETSCAPE

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



$Q^2 = p^\mu p_\mu - m^2$: 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

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

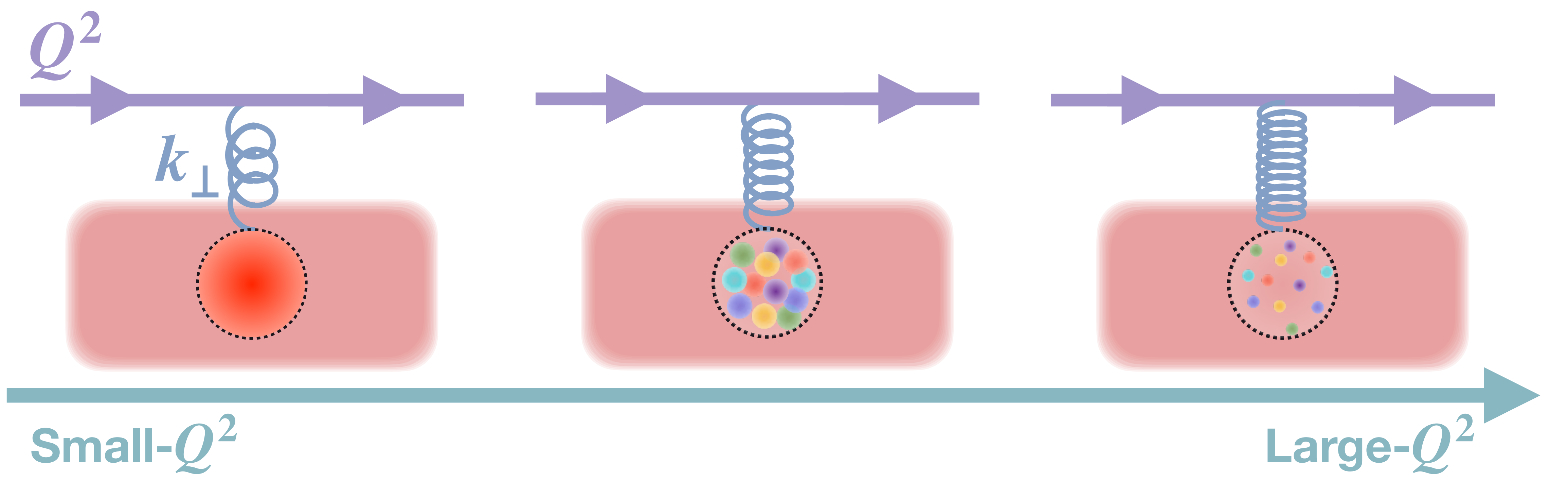
Multi-stage jet evolution in JETSCAPE

JETSCAPE, PRC107, 034911 (2023)

- **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

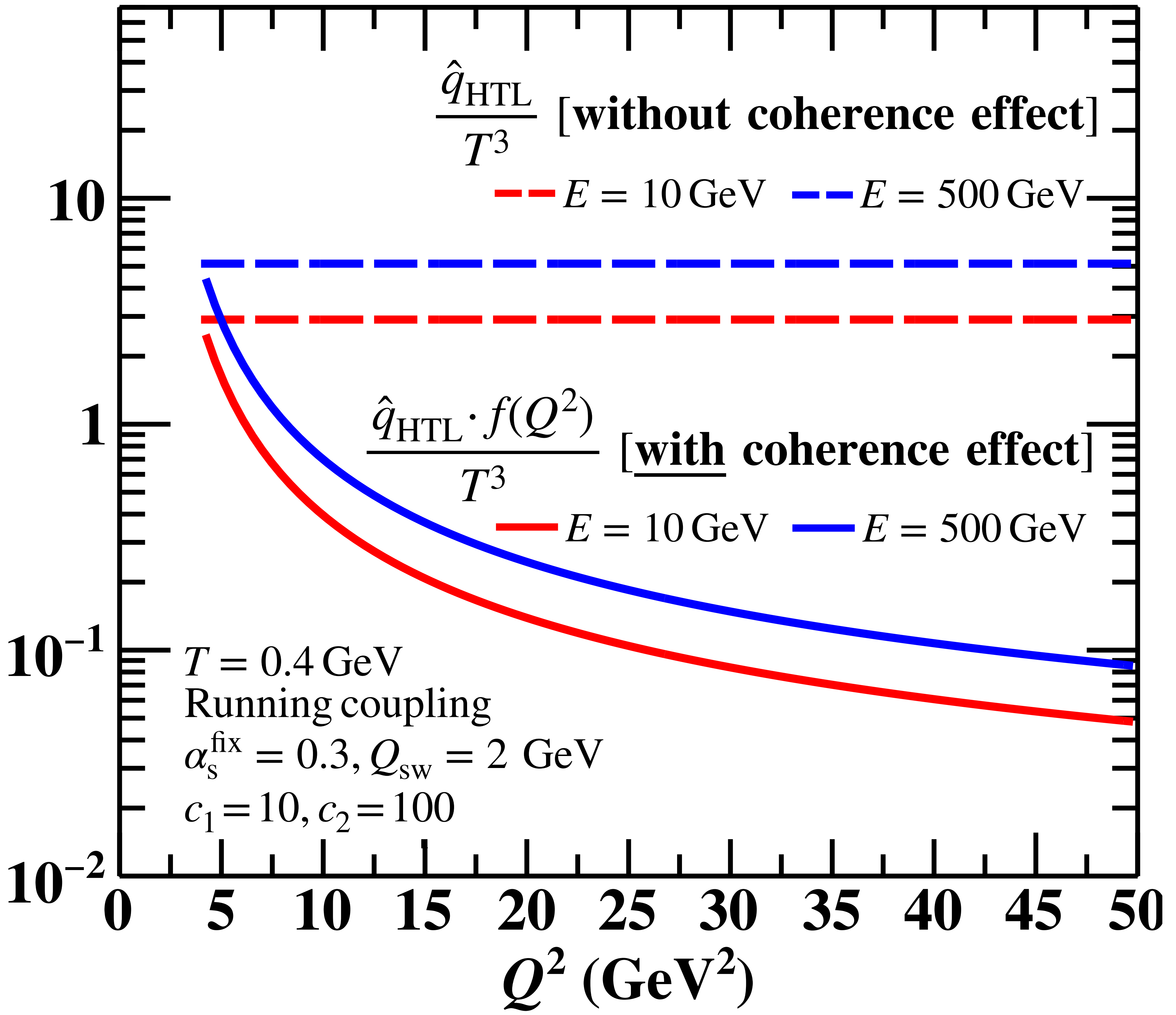


Effective jet-quenching strength

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

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

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



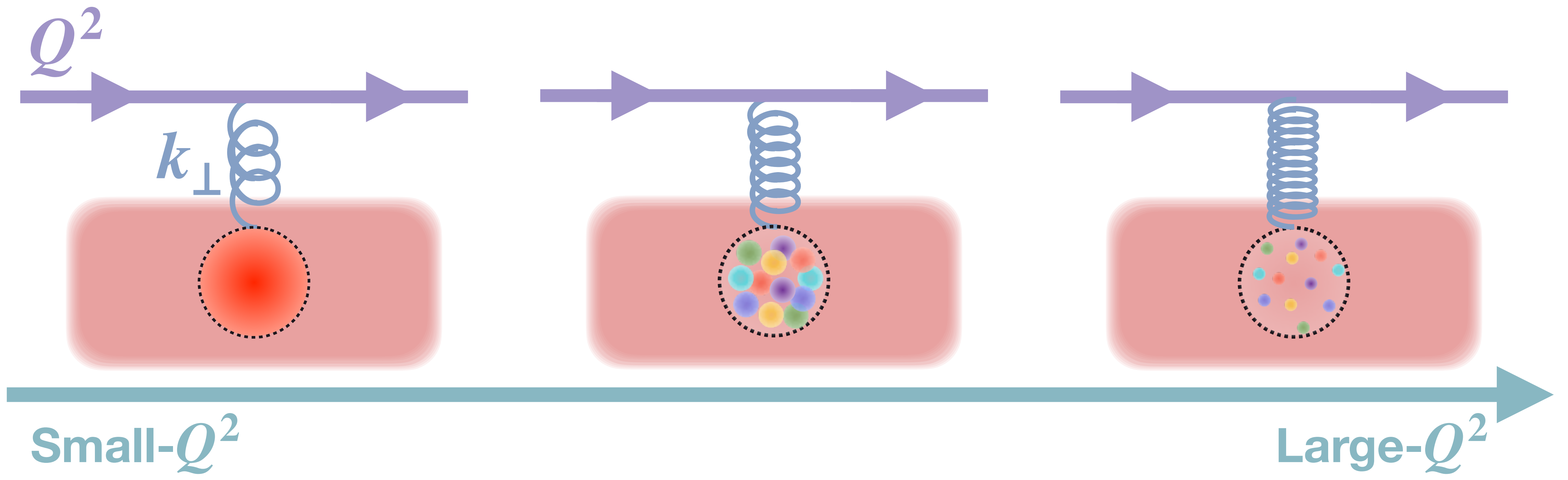
Multi-stage jet evolution in JETSCAPE

JETSCAPE, PRC107, 034911 (2023)

- **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

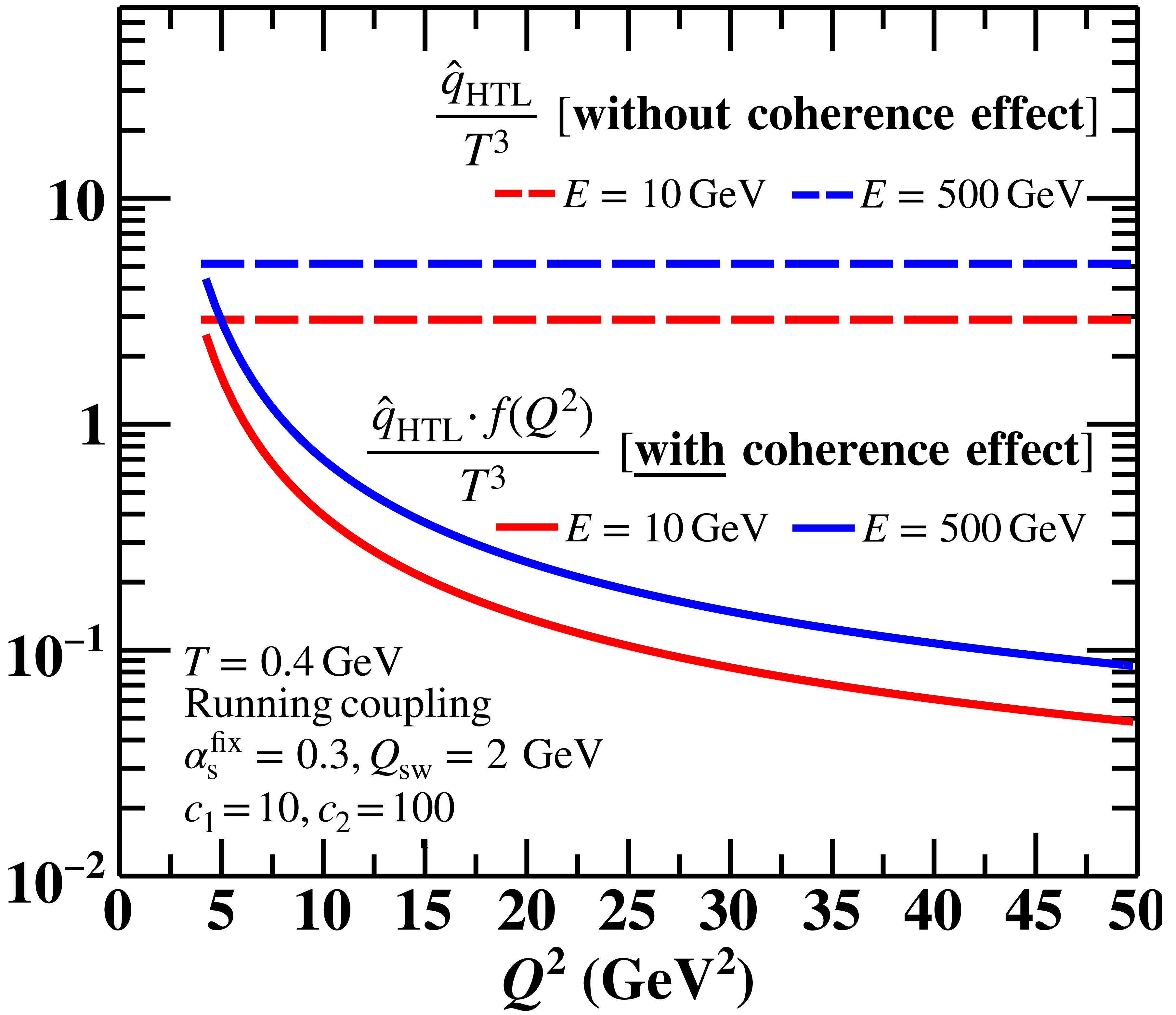


Effective jet-quenching strength

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

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

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



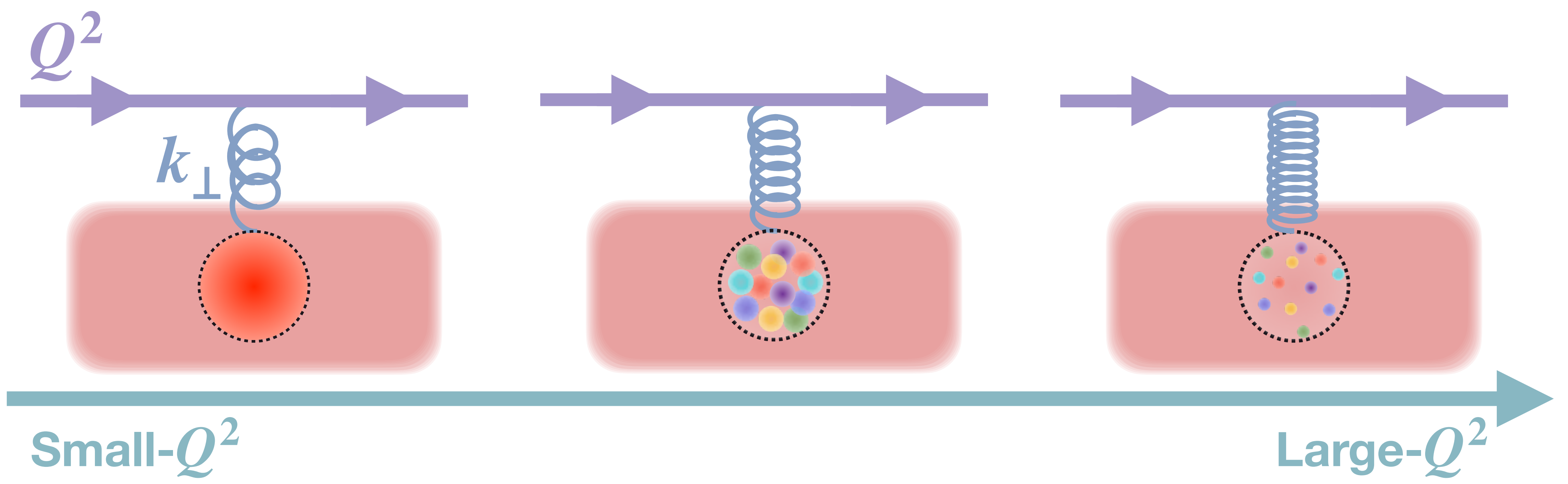
Multi-stage jet evolution in JETSCAPE

JETSCAPE, PRC107, 034911 (2023)

- **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

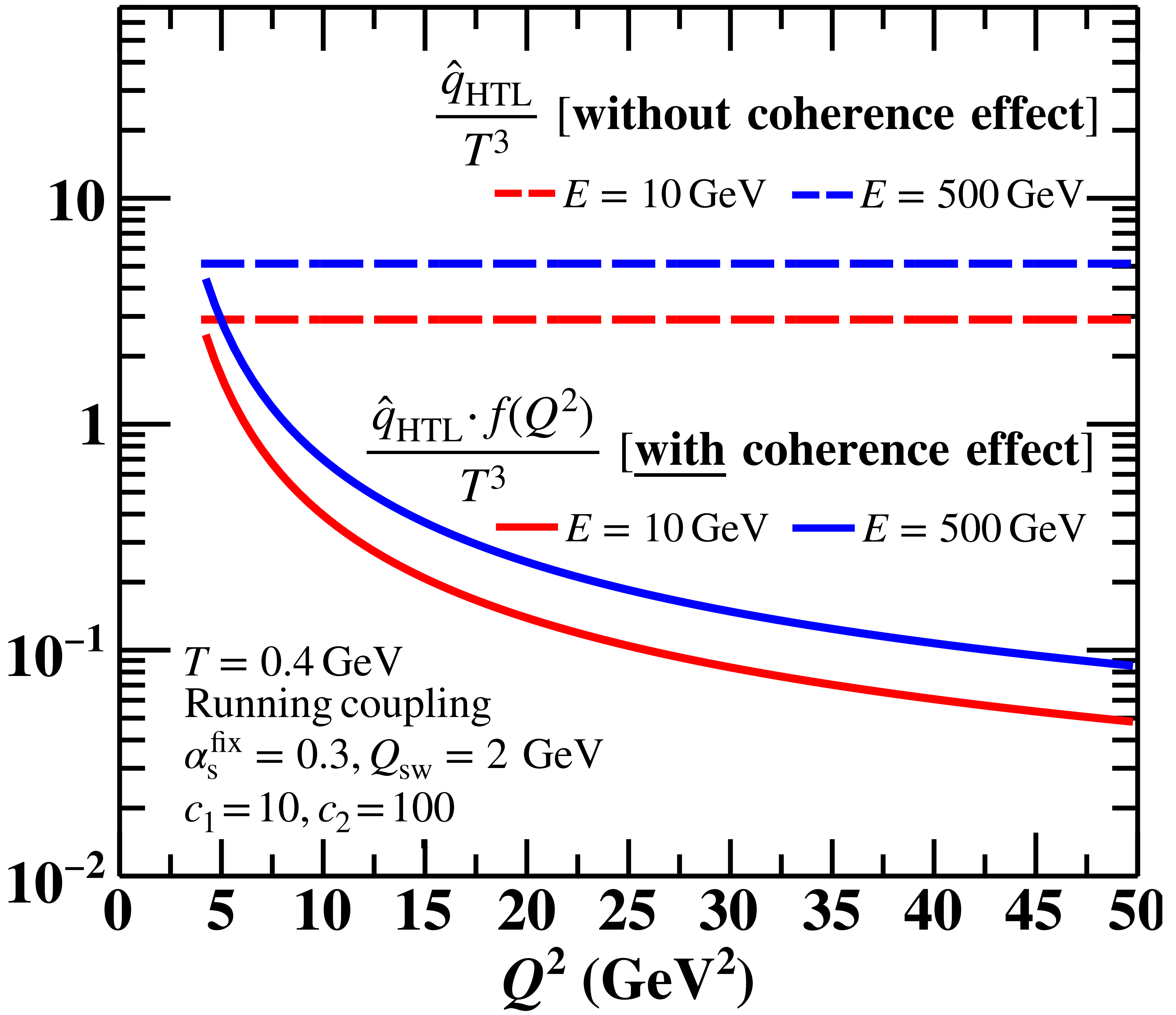


Effective jet-quenching strength

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

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

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



Jet simulation with JETSCAPE

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

Jet simulation with 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 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 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, PRC107, 034911 (2023)

Jet simulation with 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, PRC107, 034911 (2023)

Jet Shower

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

Jet simulation with 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, PRC107, 034911 (2023)

Jet Shower

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

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

Bulk Medium

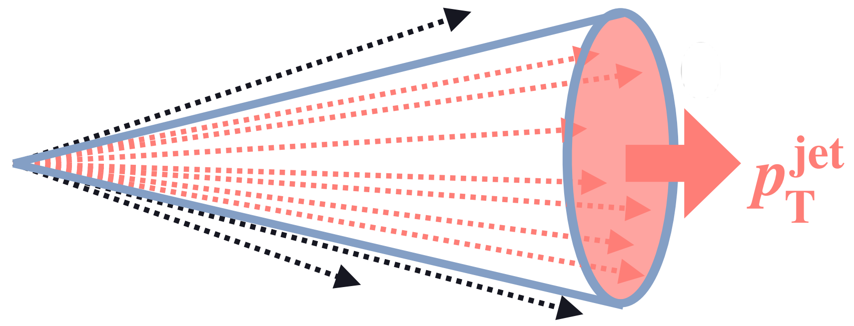
Initial Condition: TRENTo+Freestreaming
Moreland, Bernhard, Bass (14) , Liu, Shen, Heinz(15)
Hydro Evolution: VISHNU (2+1D viscous)
Shen, Qiu, Song, Bernhard, Bass, Heinz(16)

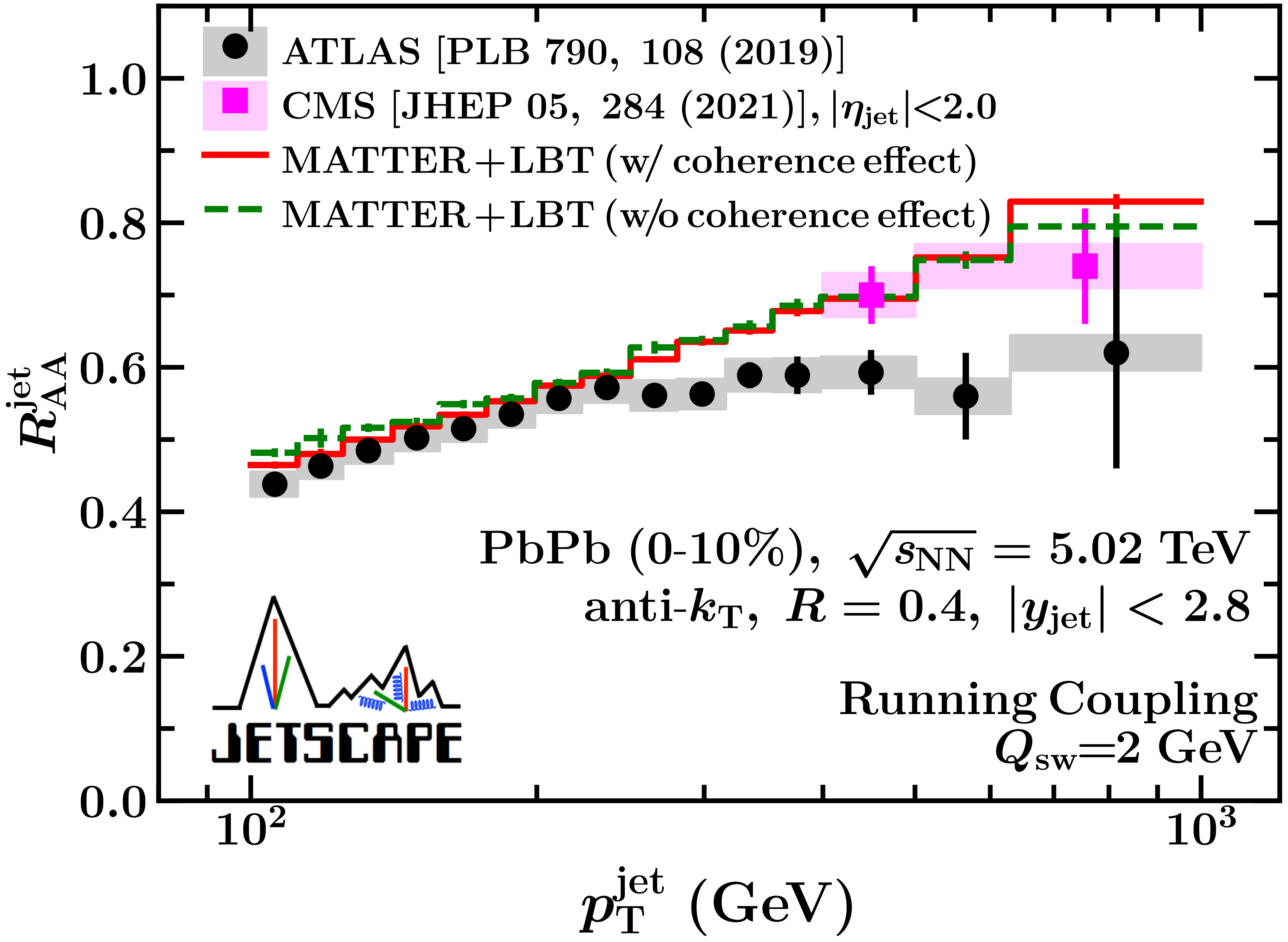
Jet and single particle energy loss

JETSCAPE, PRC107, 034911 (2023)

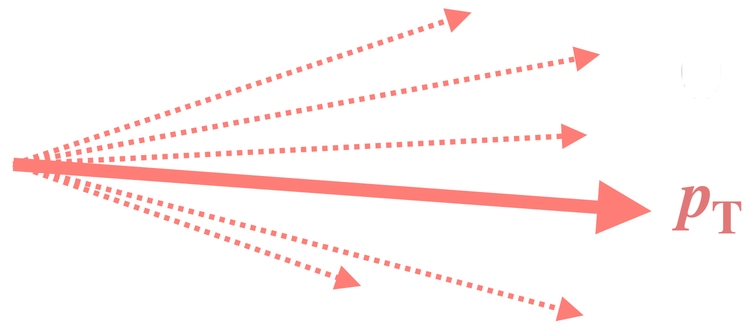
- **Pb+Pb collisions at 5.02 TeV**

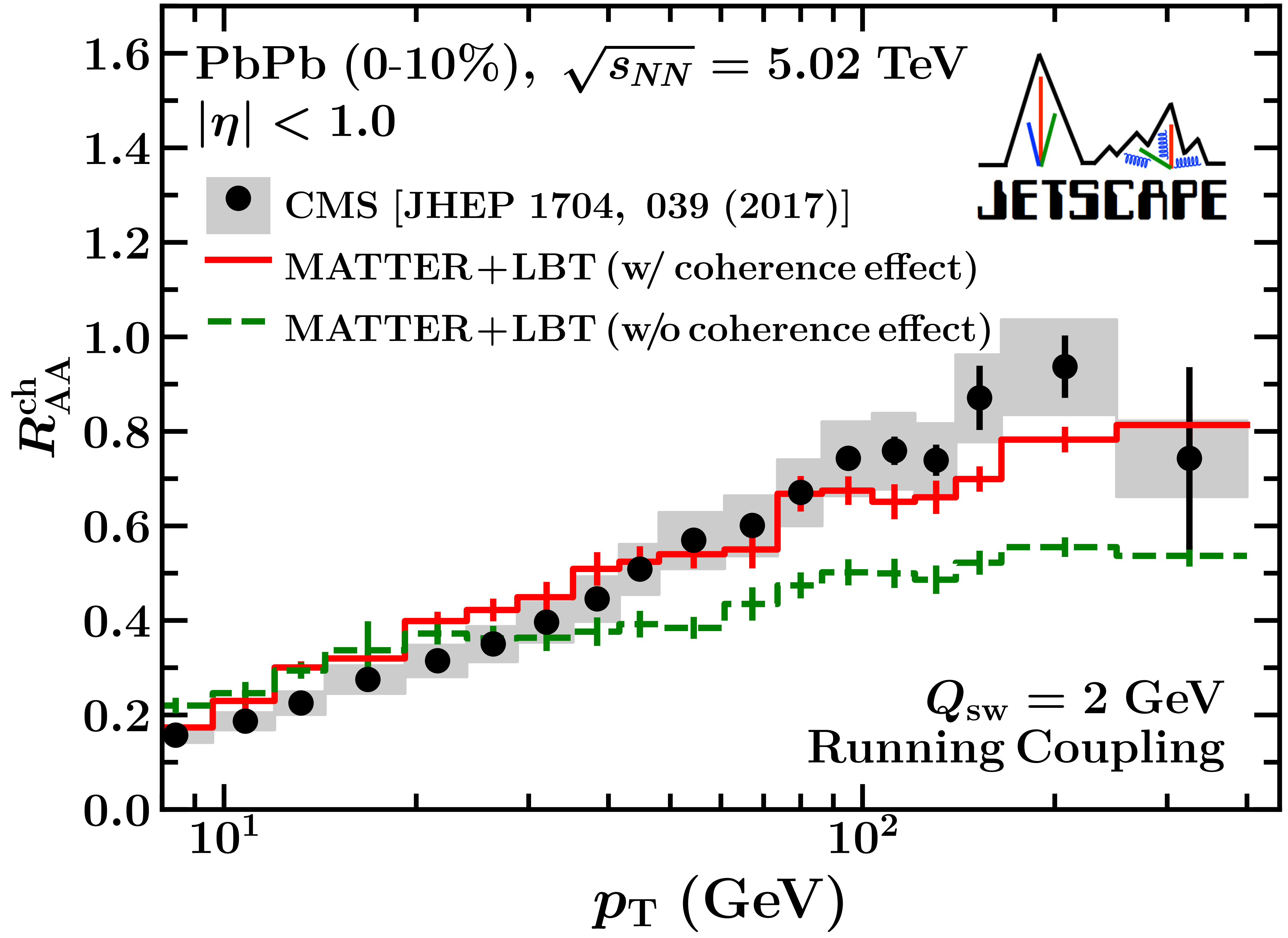
Inclusive jet R_{AA}





Charged particle R_{AA}





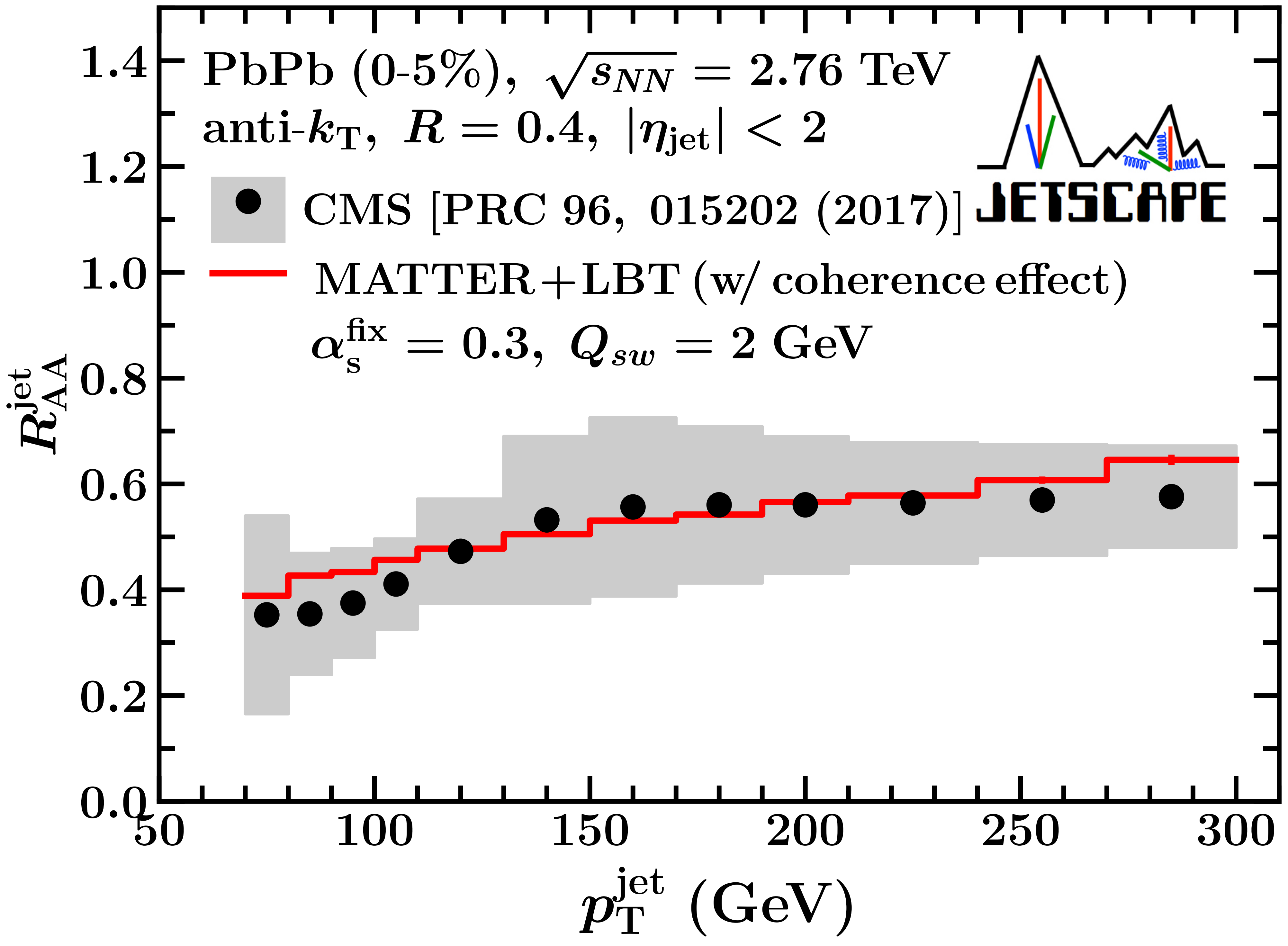
Jet and single particle energy loss

JETSCAPE, PRC107, 034911 (2023)

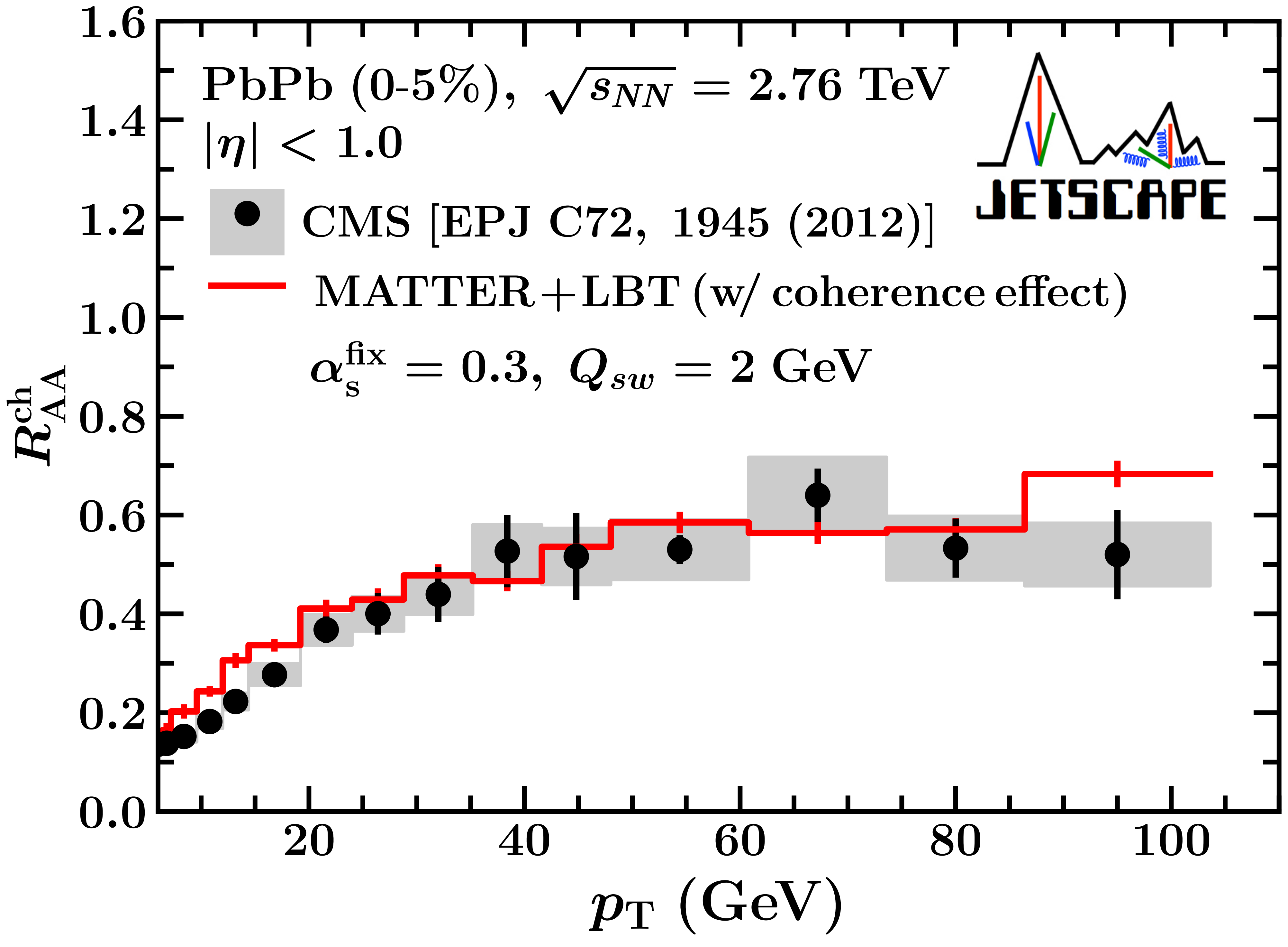
- **Pb+Pb collisions at 2.76 TeV**

The same parameter set as 5.02 TeV is used

Inclusive jet R_{AA}



Charged particle R_{AA}



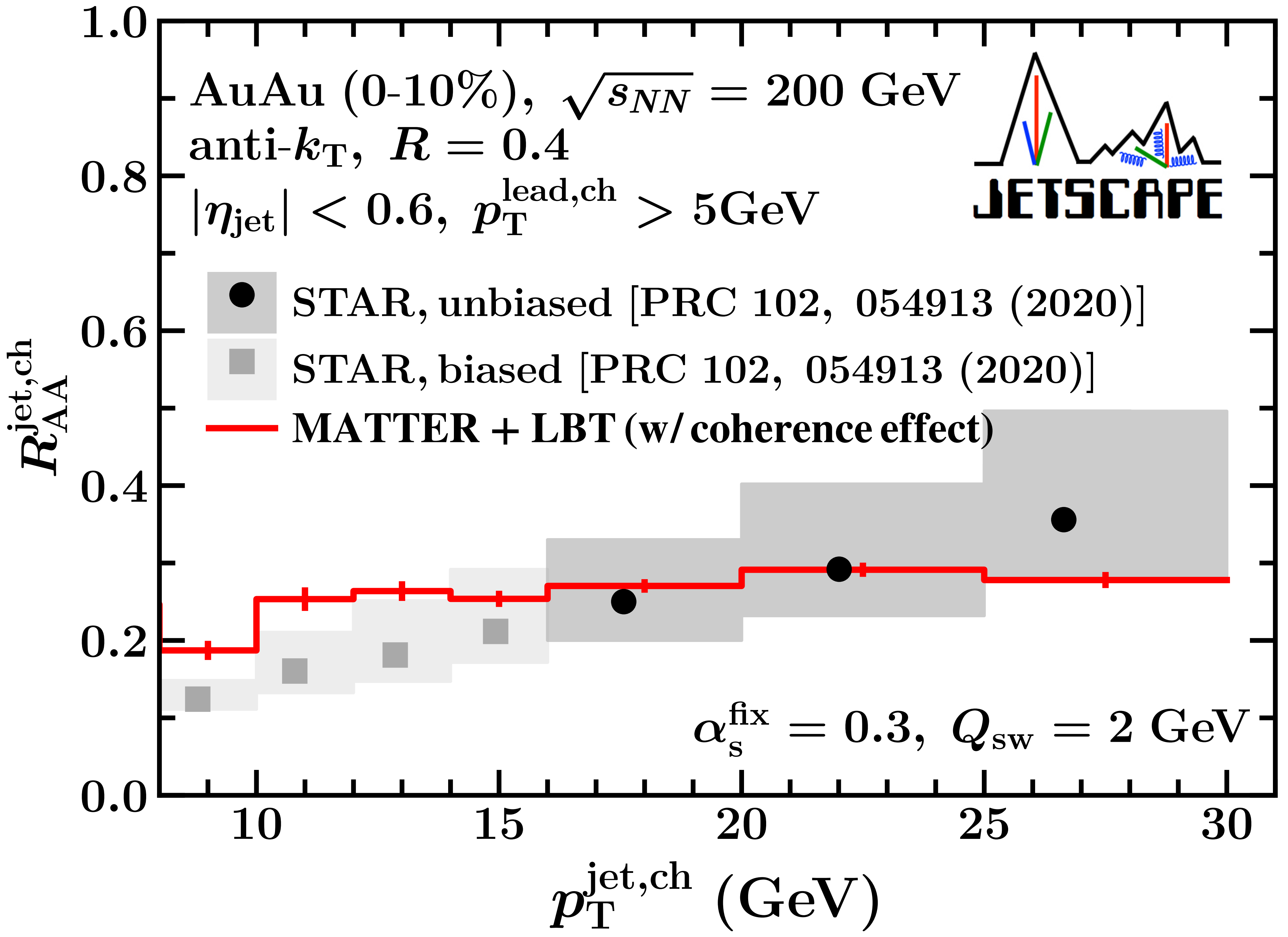
Jet and single particle energy loss

JETSCAPE, PRC107, 034911 (2023)

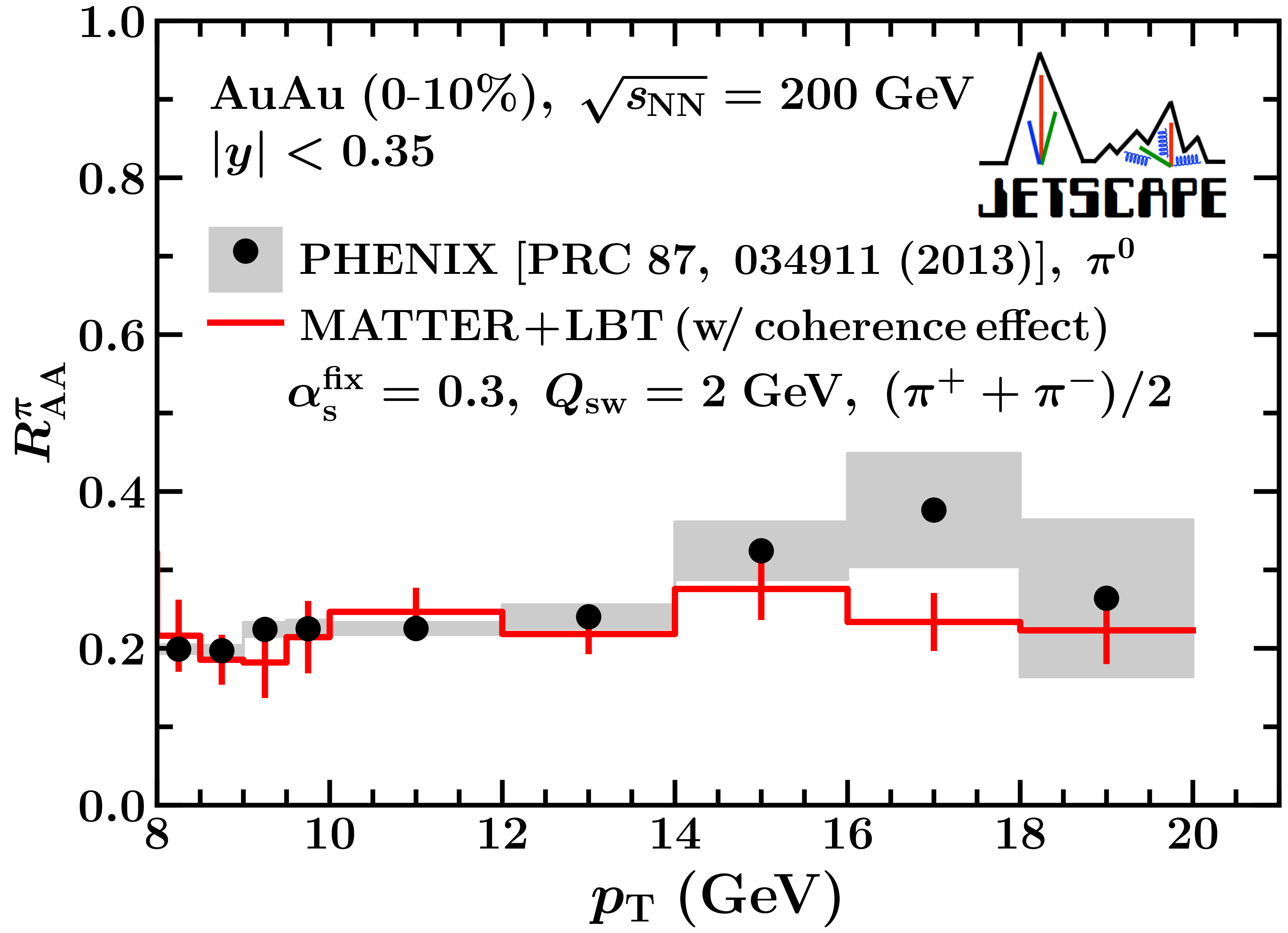
- **Au+Au collisions at 200 GeV**

The same parameter set as 5.02 TeV is used

Charged jet R_{AA}



Pion R_{AA}



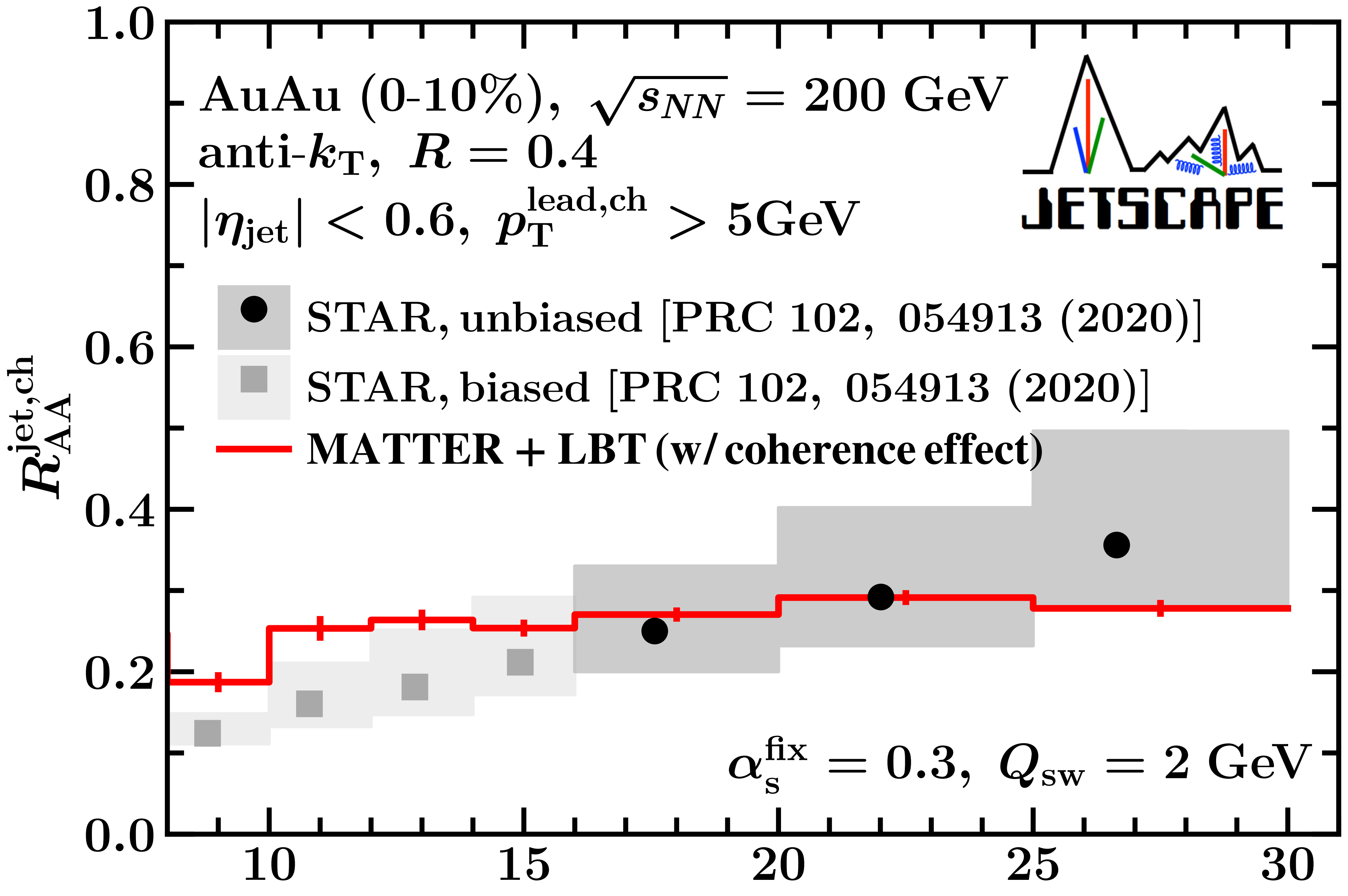
Jet and single particle energy loss

JETSCAPE, PRC107, 034911 (2023)

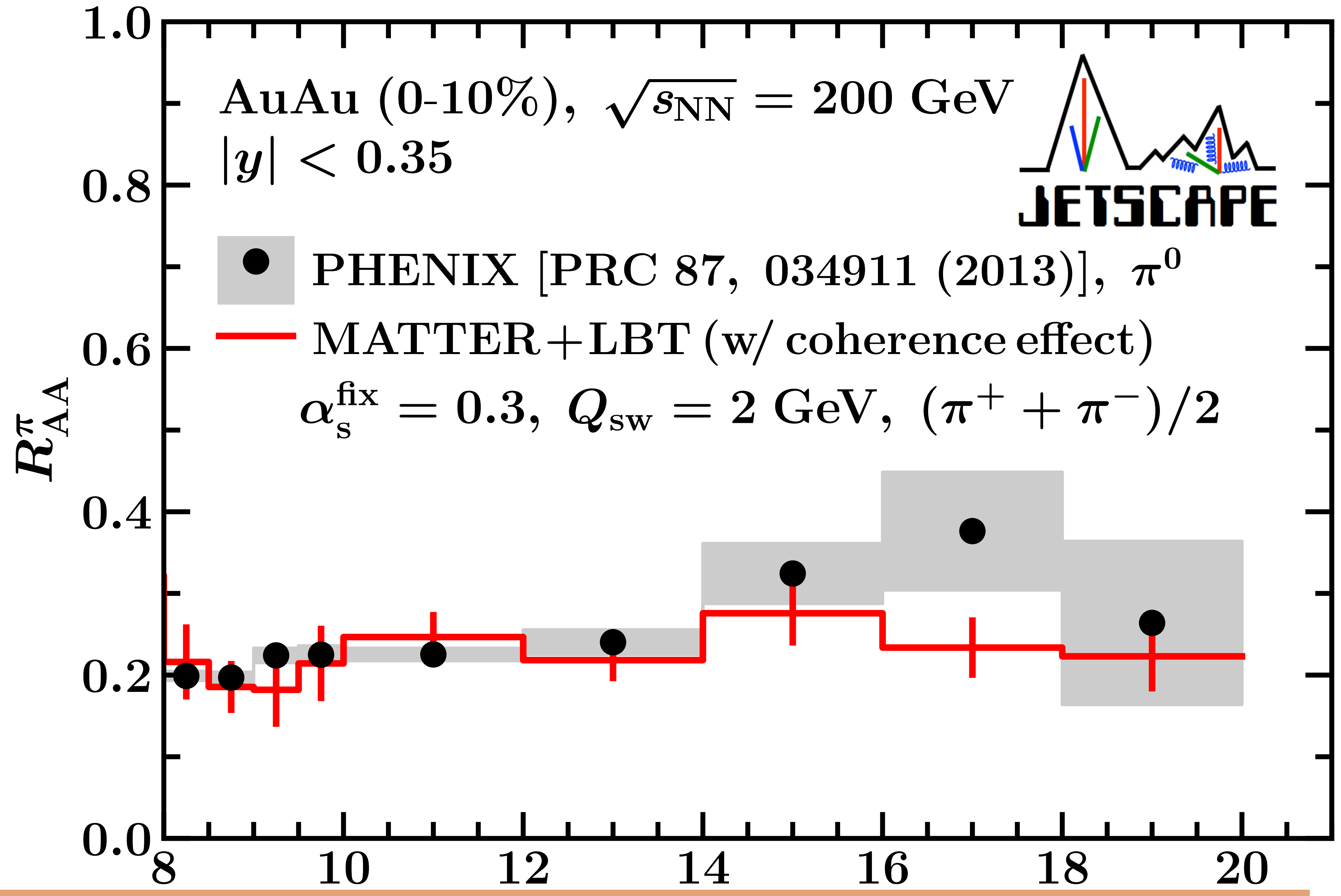
- **Au+Au collisions at 200 GeV**

The same parameter set as 5.02 TeV is used

Charged jet R_{AA}



Pion R_{AA}



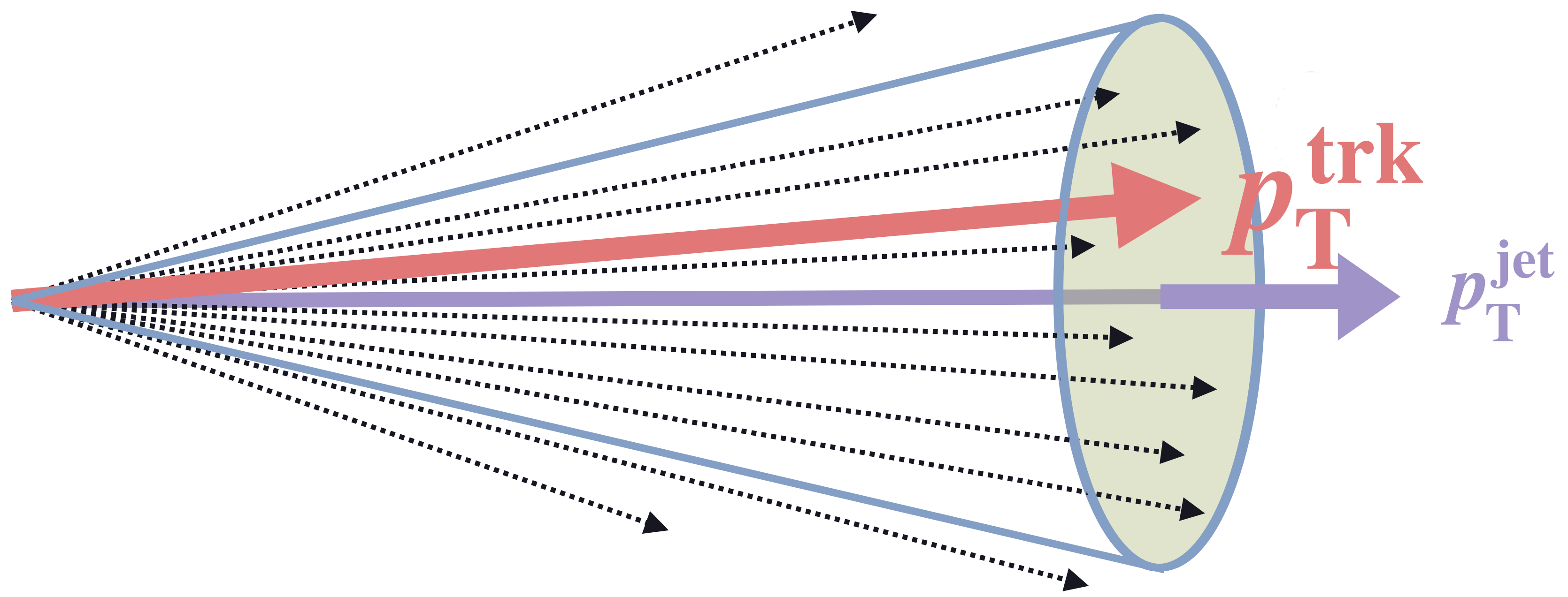
- **Simultaneous description of different $\sqrt{s_{NN}}$ with the same parameter set**

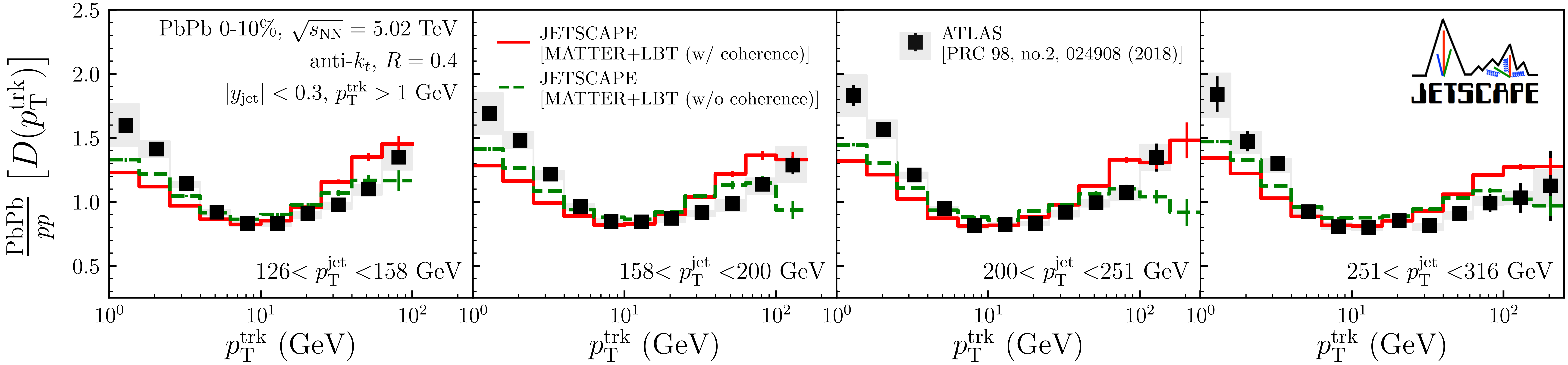
Jet substructures

JETSCAPE, arXiv:2301.02485

- **Jet Fragmentation Function**

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



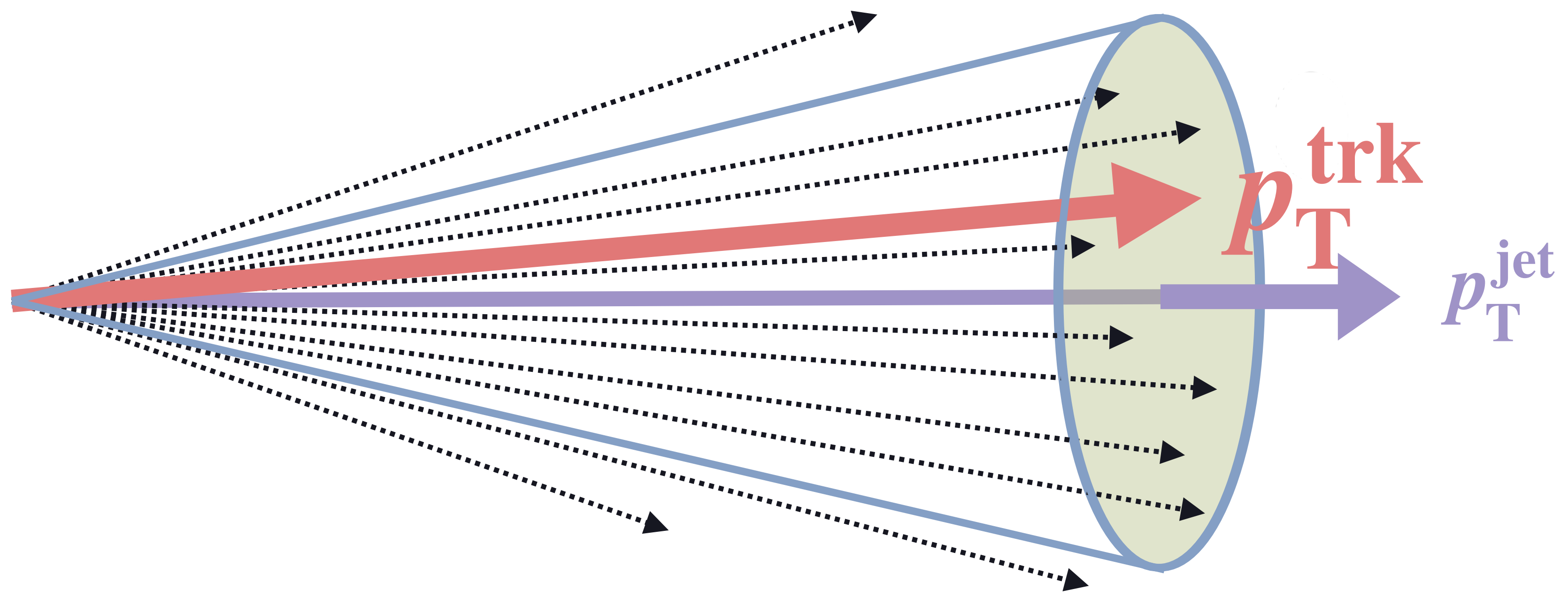


Jet substructures

JETSCAPE, arXiv:2301.02485

- **Jet Fragmentation Function**

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

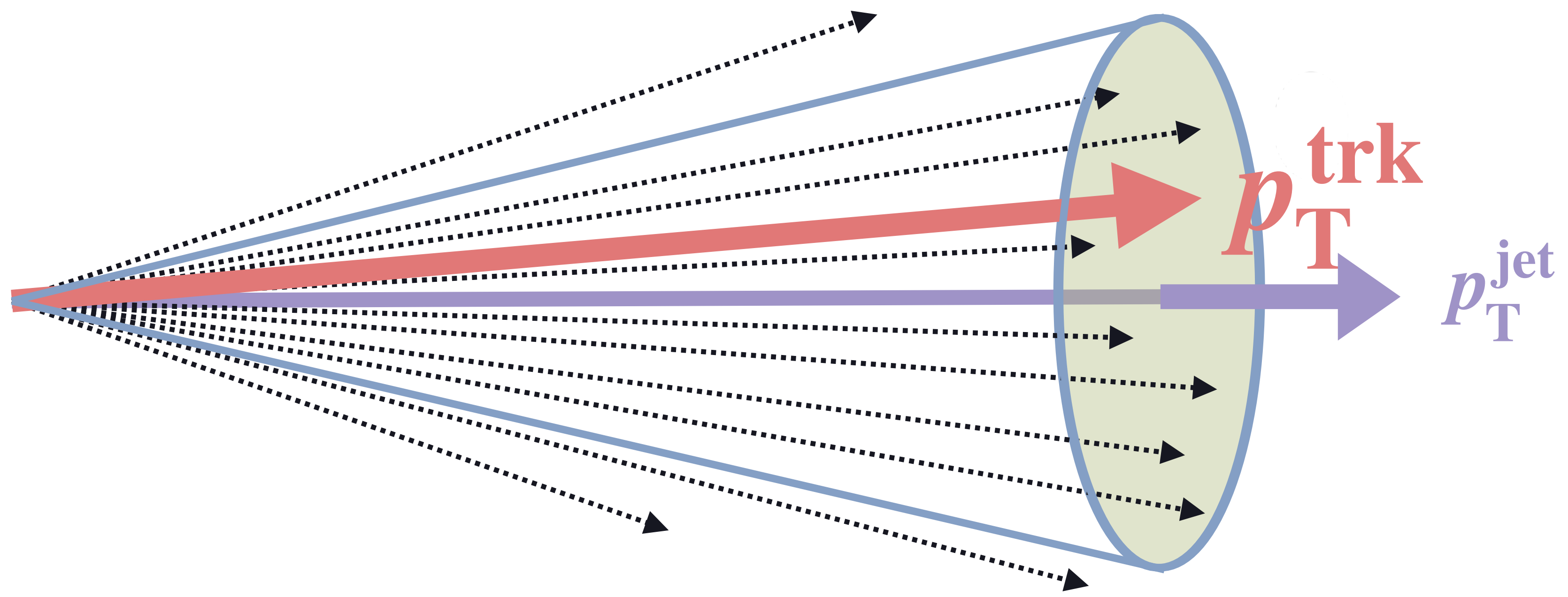


Jet substructures

JETSCAPE, arXiv:2301.02485

- **Jet Fragmentation Function**

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



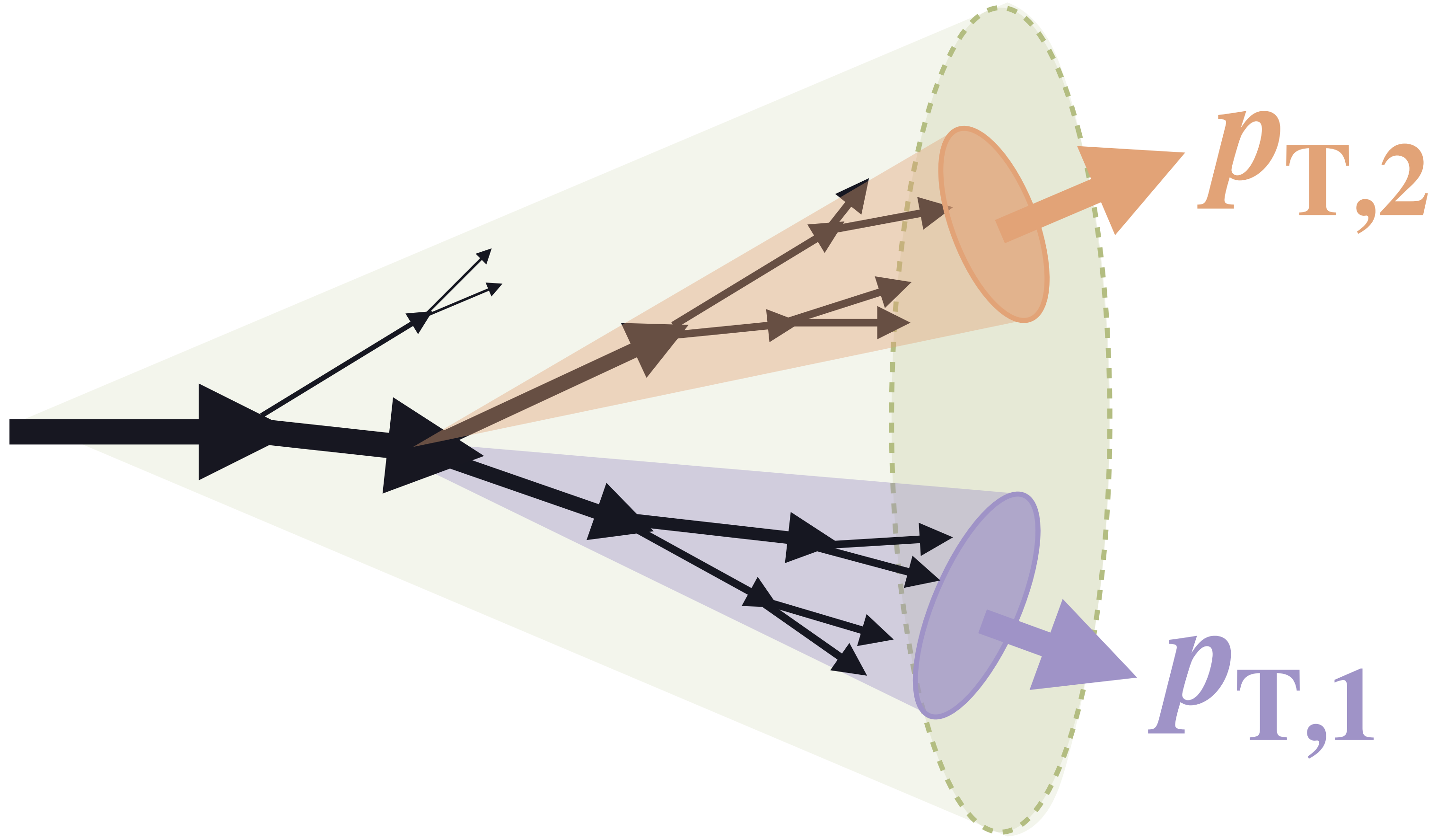
- **Enhancement at small-z due to recoils**
- **Sensitive to coherence effect**

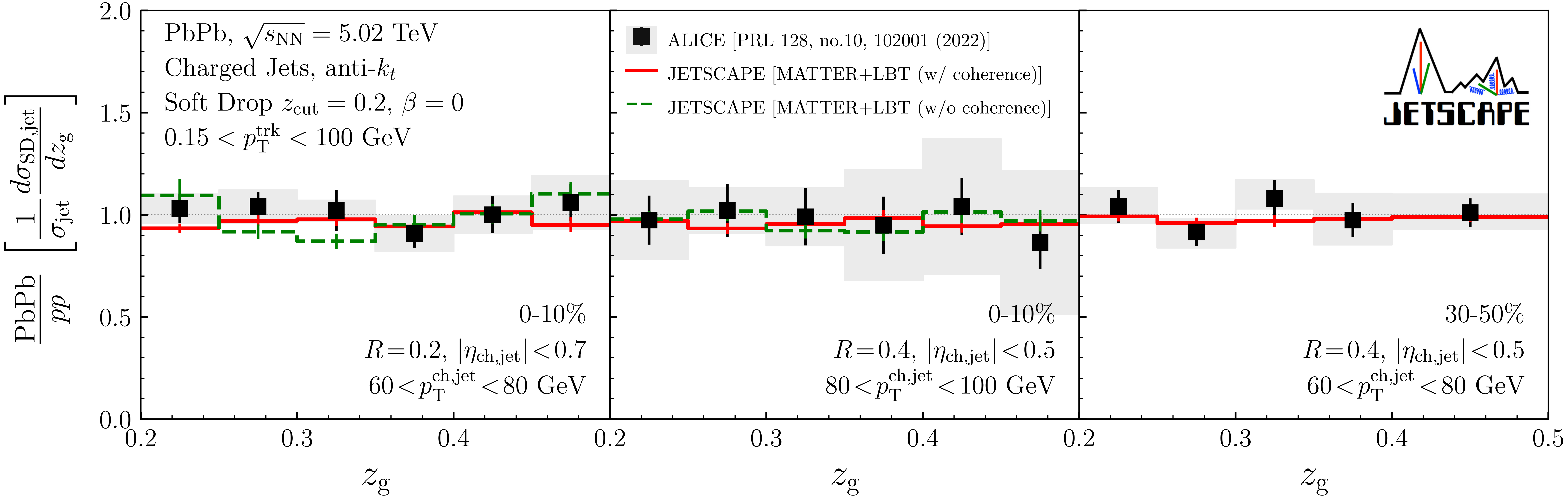
Jet substructures

JETSCAPE, arXiv:2301.02485

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

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



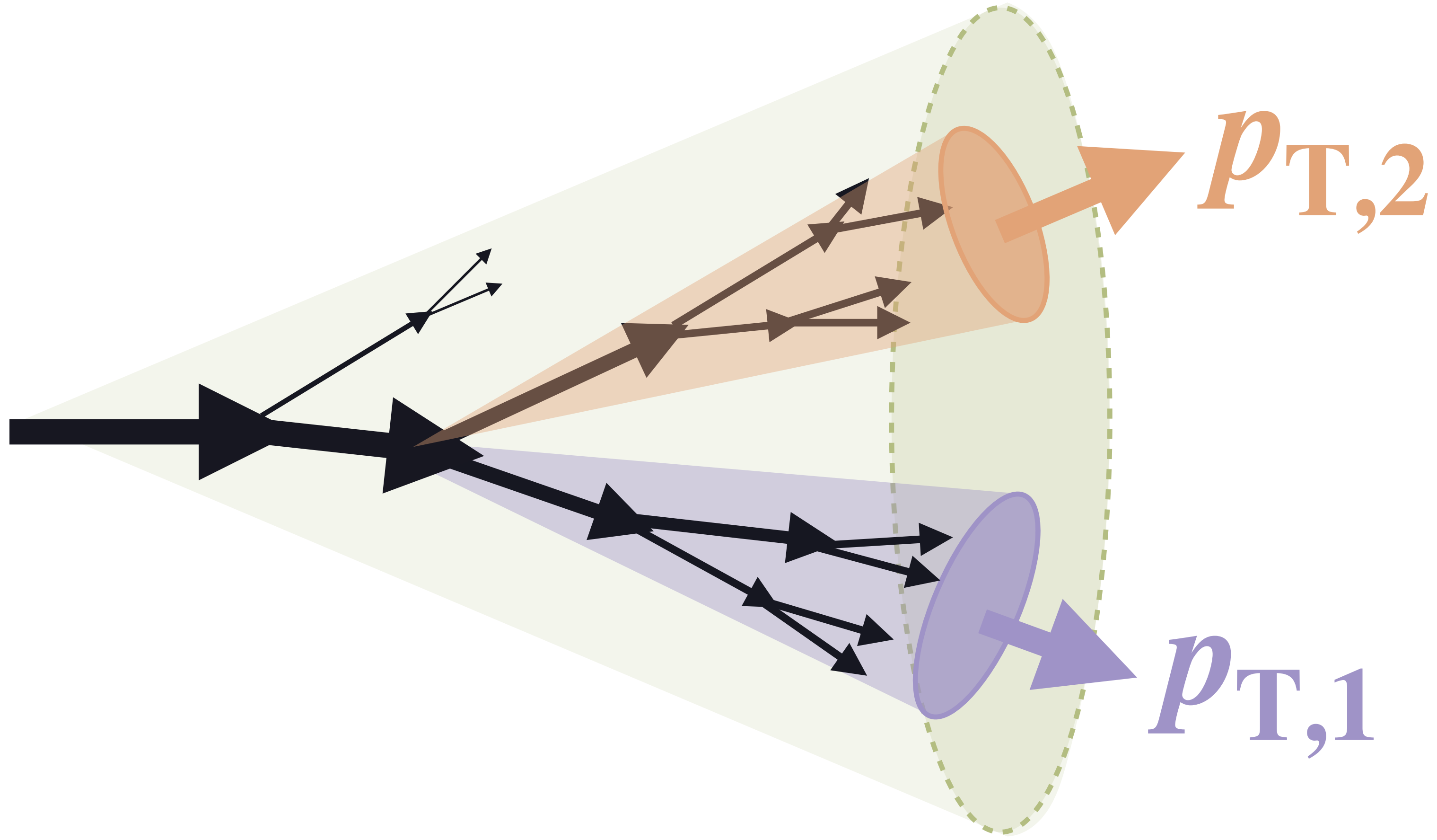


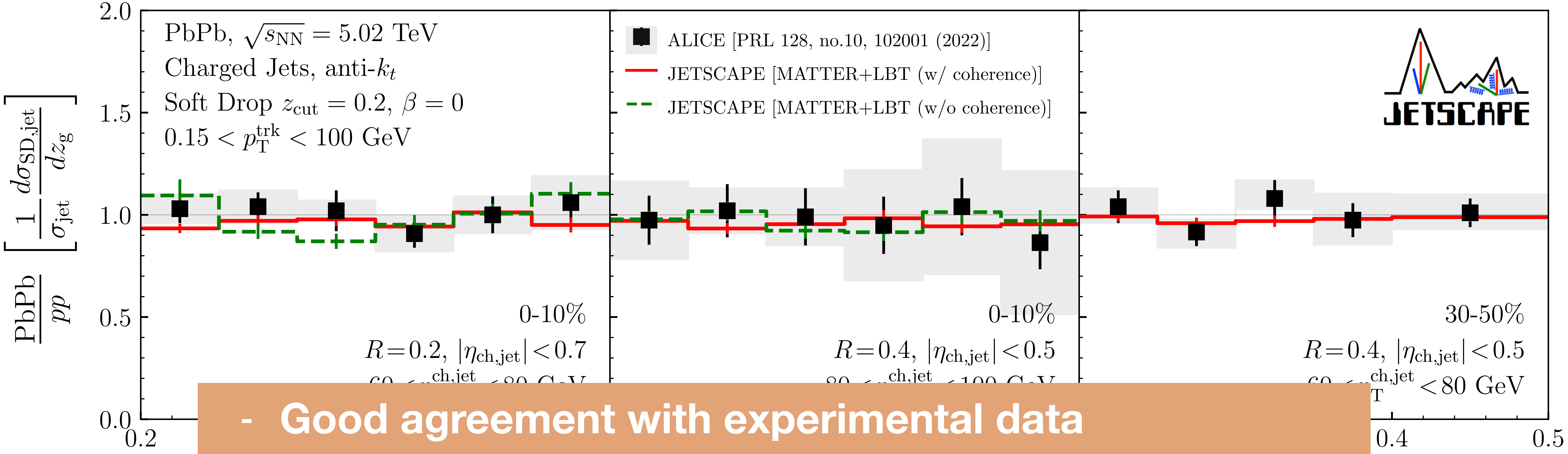
Jet substructures

JETSCAPE, arXiv:2301.02485

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

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





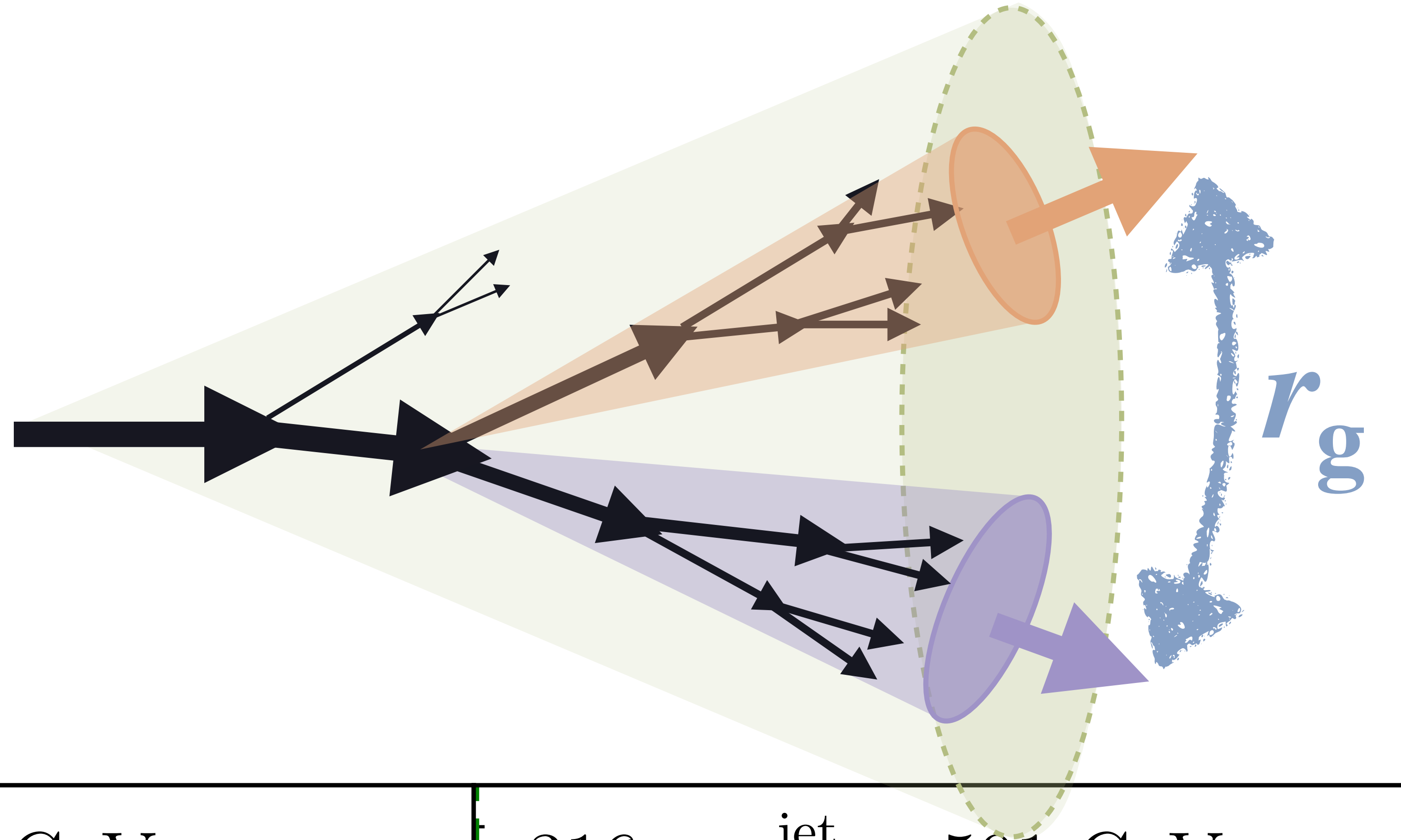
- **Good agreement with experimental data**
- **Almost no medium modification in z_g-distribution**

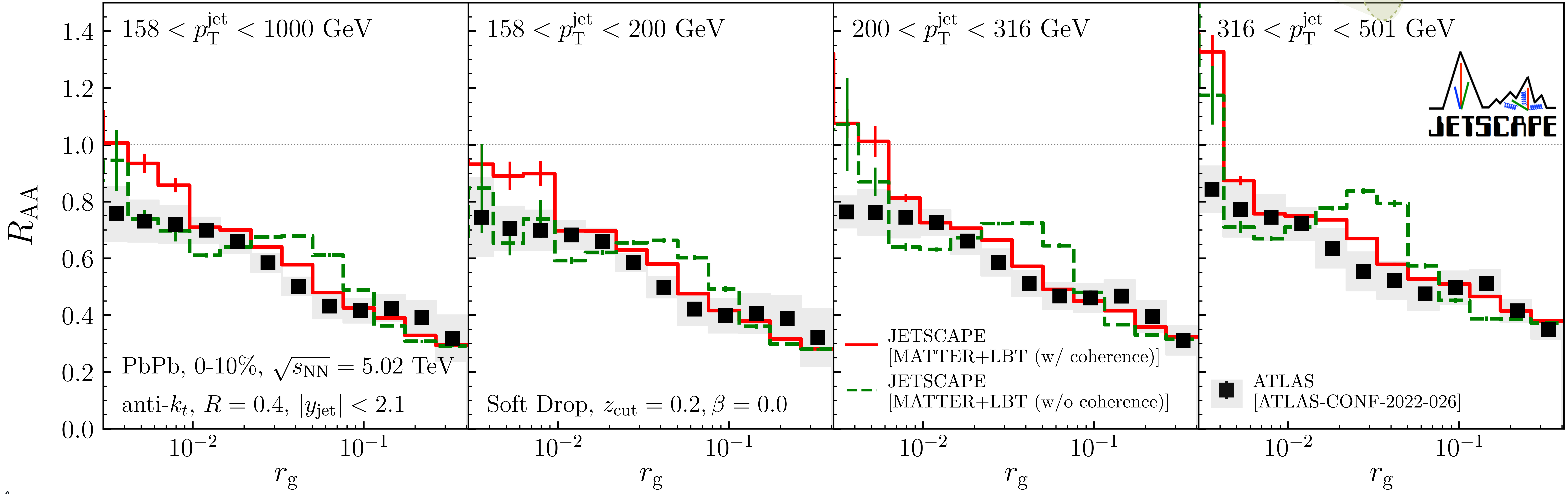
Jet substructures

JETSCAPE, arXiv:2301.02485

- **Splitting radial distance distribution**
  - Competition between two opposing effects

Jet broadening by medium effect
VS
Larger energy loss for broader jets



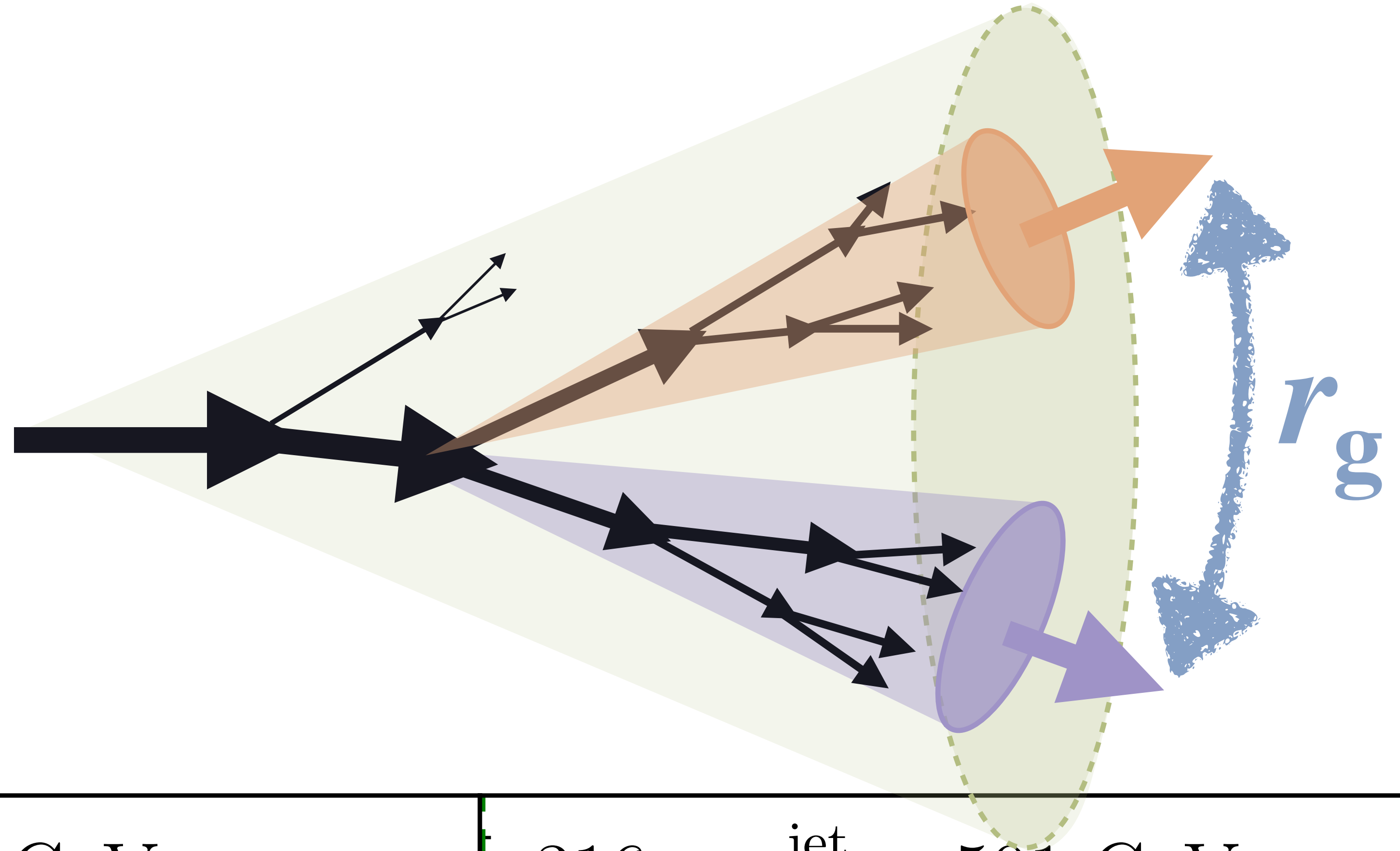


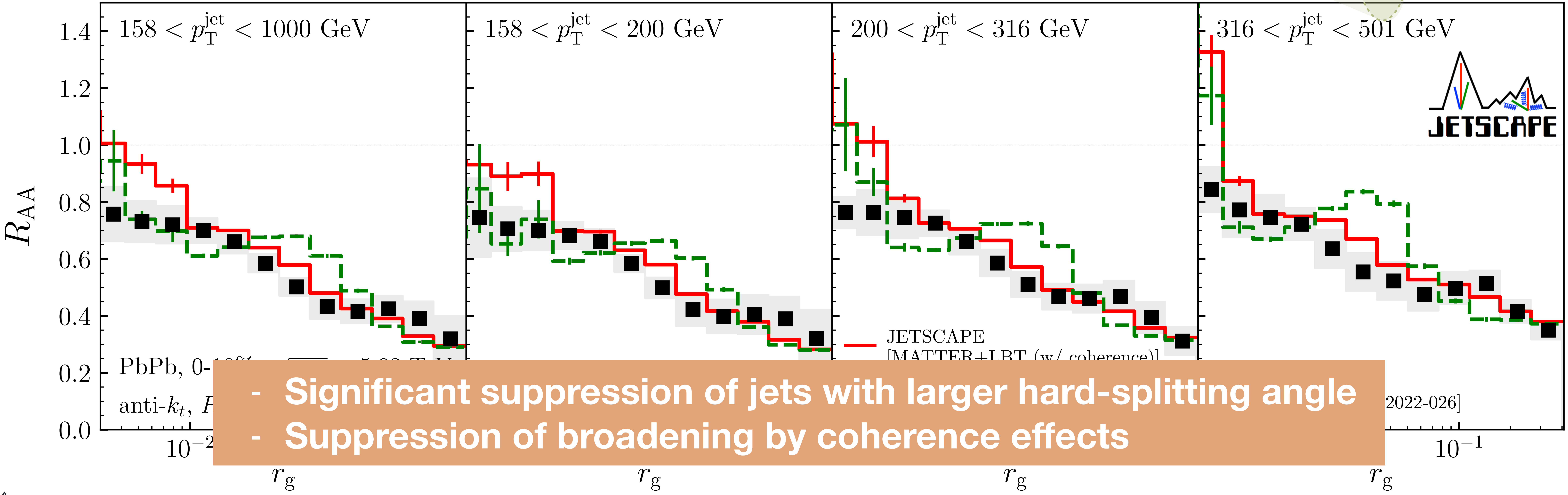
Jet substructures

JETSCAPE, arXiv:2301.02485

- **Splitting radial distance distribution**
  - Competition between two opposing effects

Jet broadening by medium effect
VS
Larger energy loss for broader jets



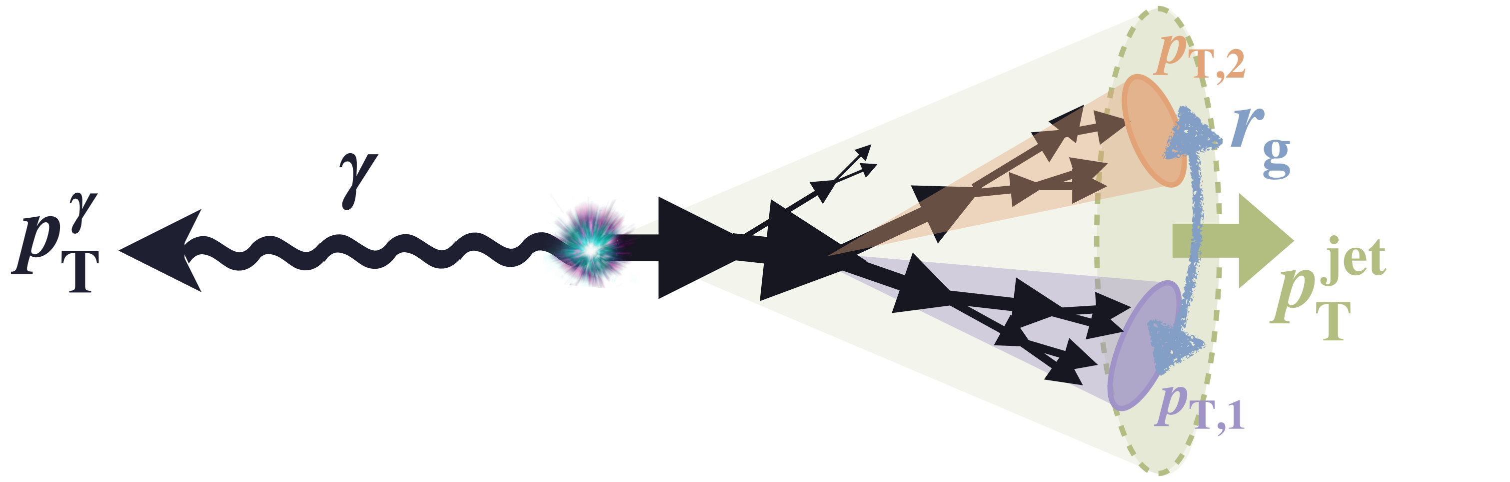


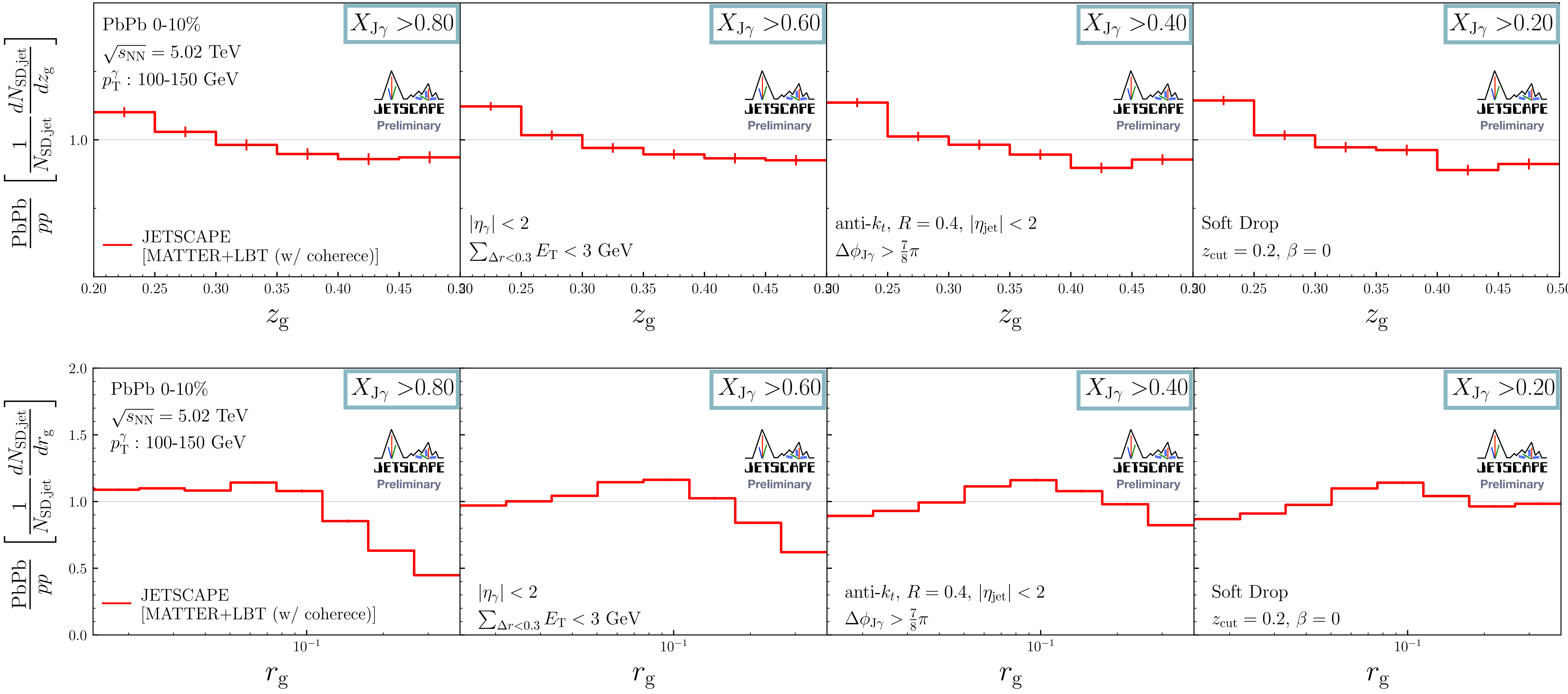
- **Significant suppression of jets with larger hard-splitting angle**
- **Suppression of broadening by coherence effects**

Jet substructures

JETSCAPE, in preparation

- **γ-tagged jet substructures**
  - $X_{J\gamma} = p_T^{jet}/p_T^{\gamma}$ dependence → energy-loss effect (trigger-bias)



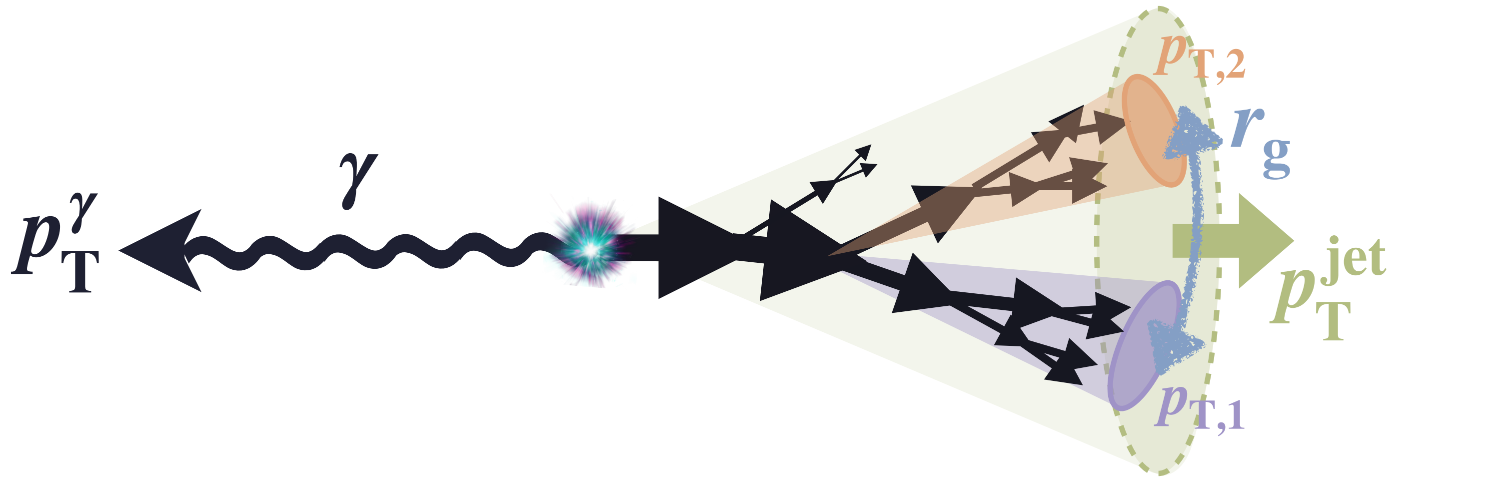


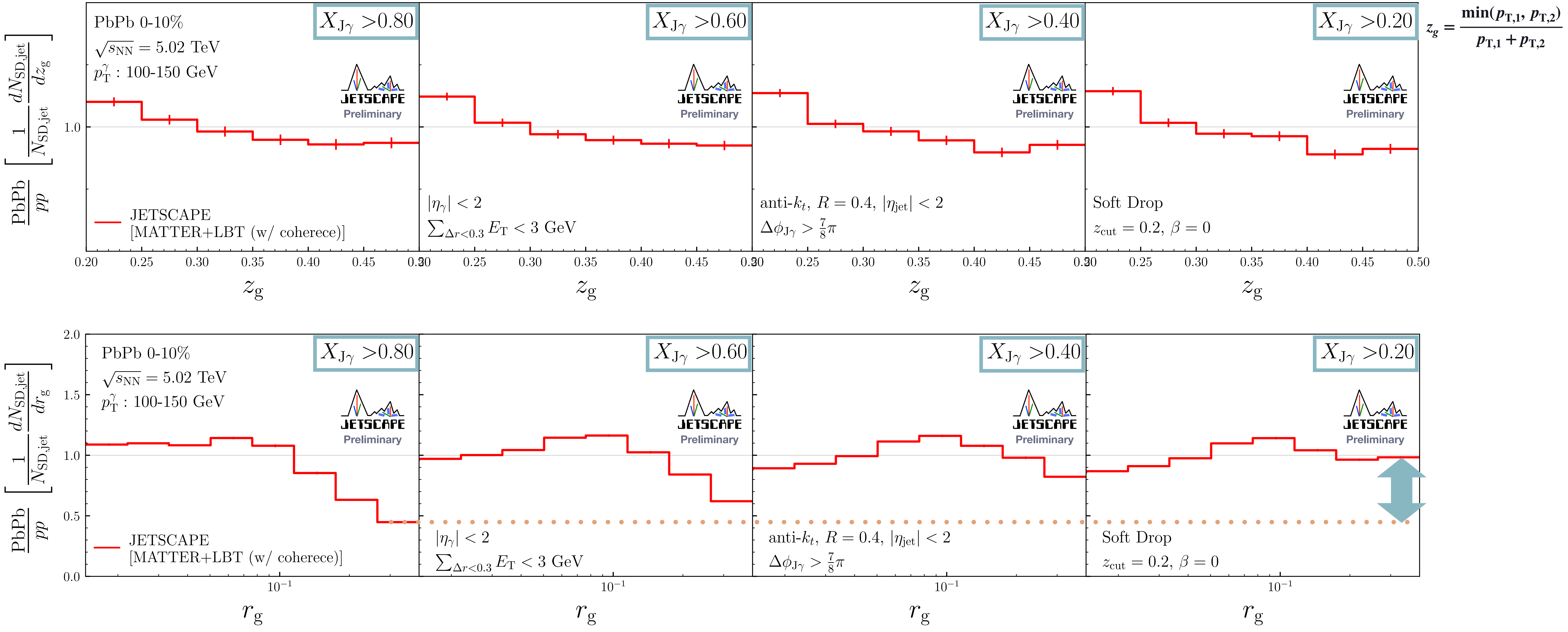
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

Jet substructures

JETSCAPE, in preparation

- **γ-tagged jet substructures**
  - $X_{J\gamma} = p_T^{jet}/p_T^{\gamma}$ dependence → energy-loss effect (trigger-bias)

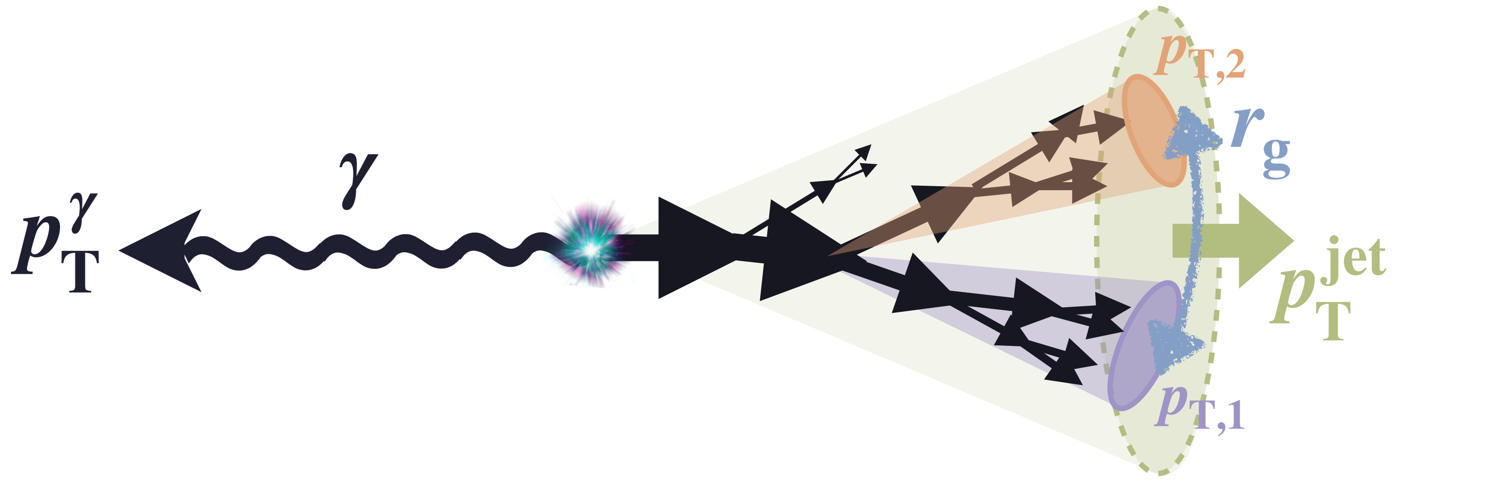


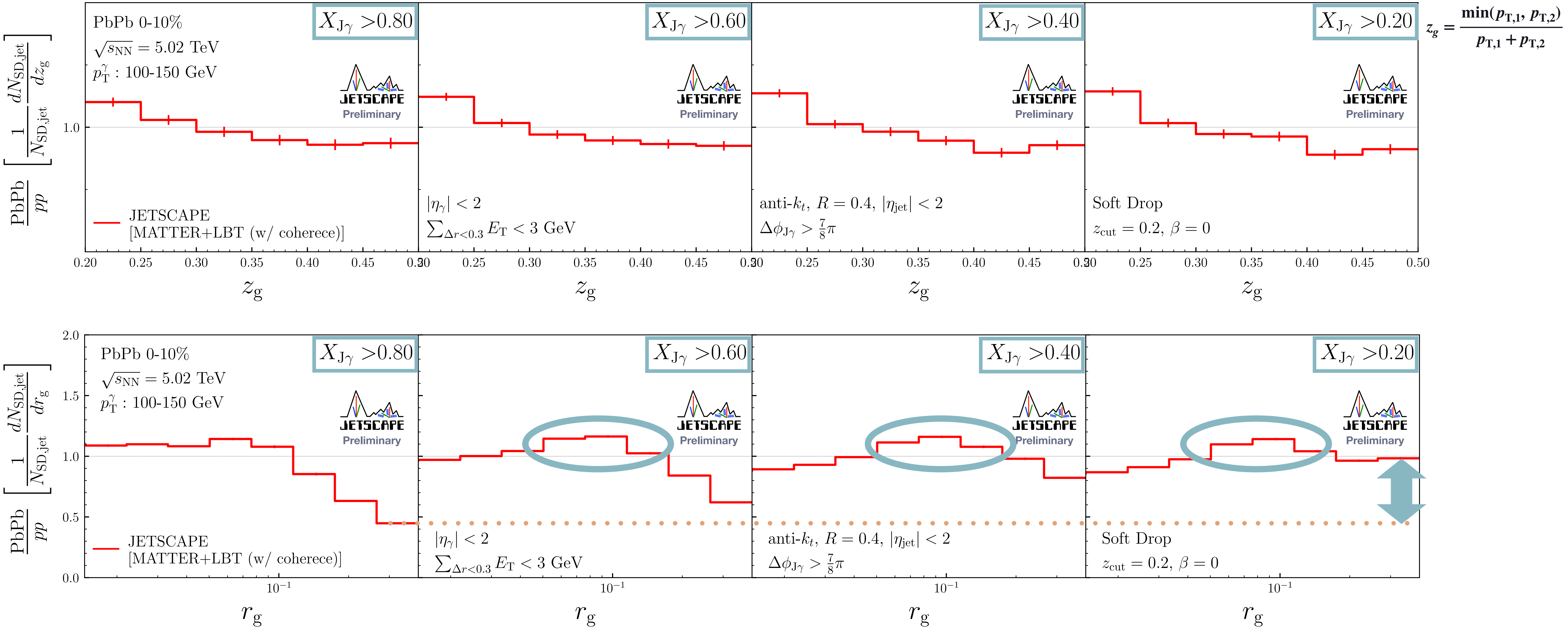


Jet substructures

JETSCAPE, in preparation

- **γ-tagged jet substructures**
  - $X_{J\gamma} = p_T^{jet}/p_T^{\gamma}$ dependence → energy-loss effect (trigger-bias)

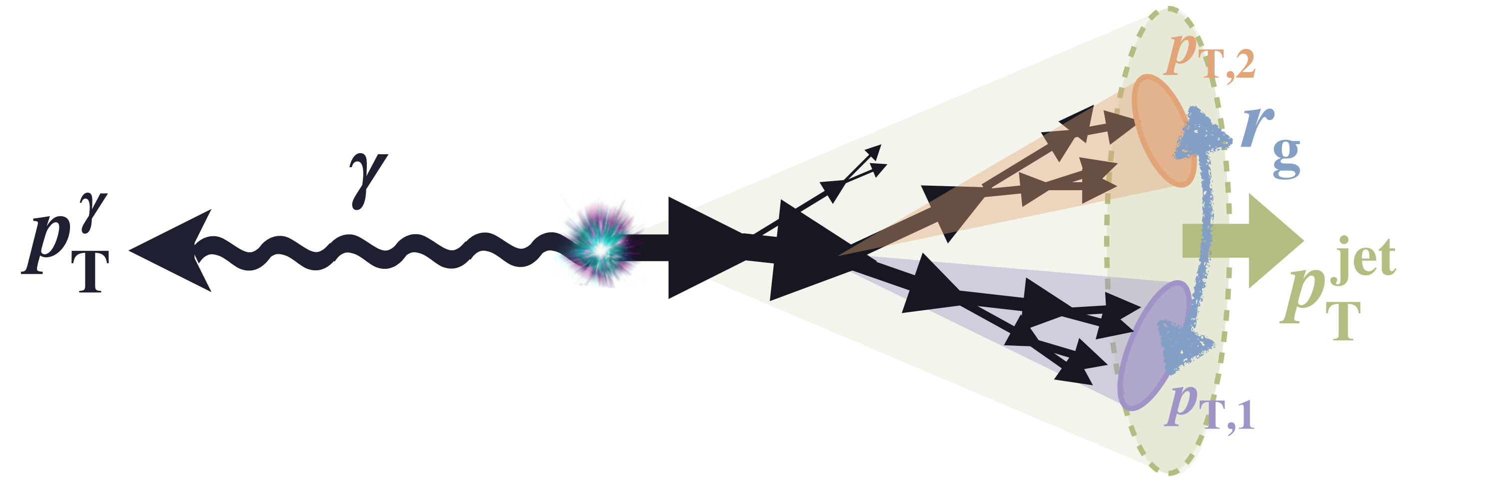


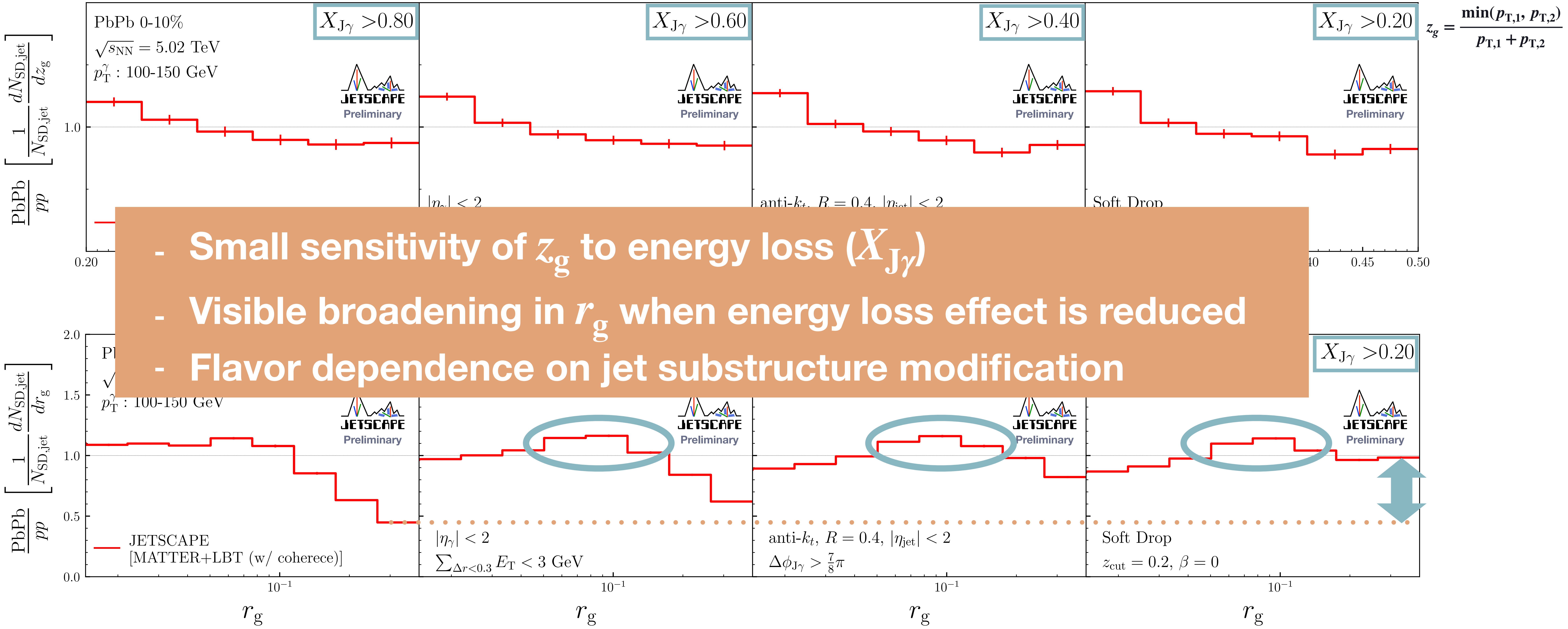


Jet substructures

JETSCAPE, in preparation

- **γ-tagged jet substructures**
  - $X_{J\gamma} = p_T^{jet}/p_T^{\gamma}$ dependence → energy-loss effect (trigger-bias)





- **Small sensitivity of z_g to energy loss ($X_{J\gamma}$)**
- **Visible broadening in r_g when energy loss effect is reduced**
- **Flavor dependence on jet substructure modification**

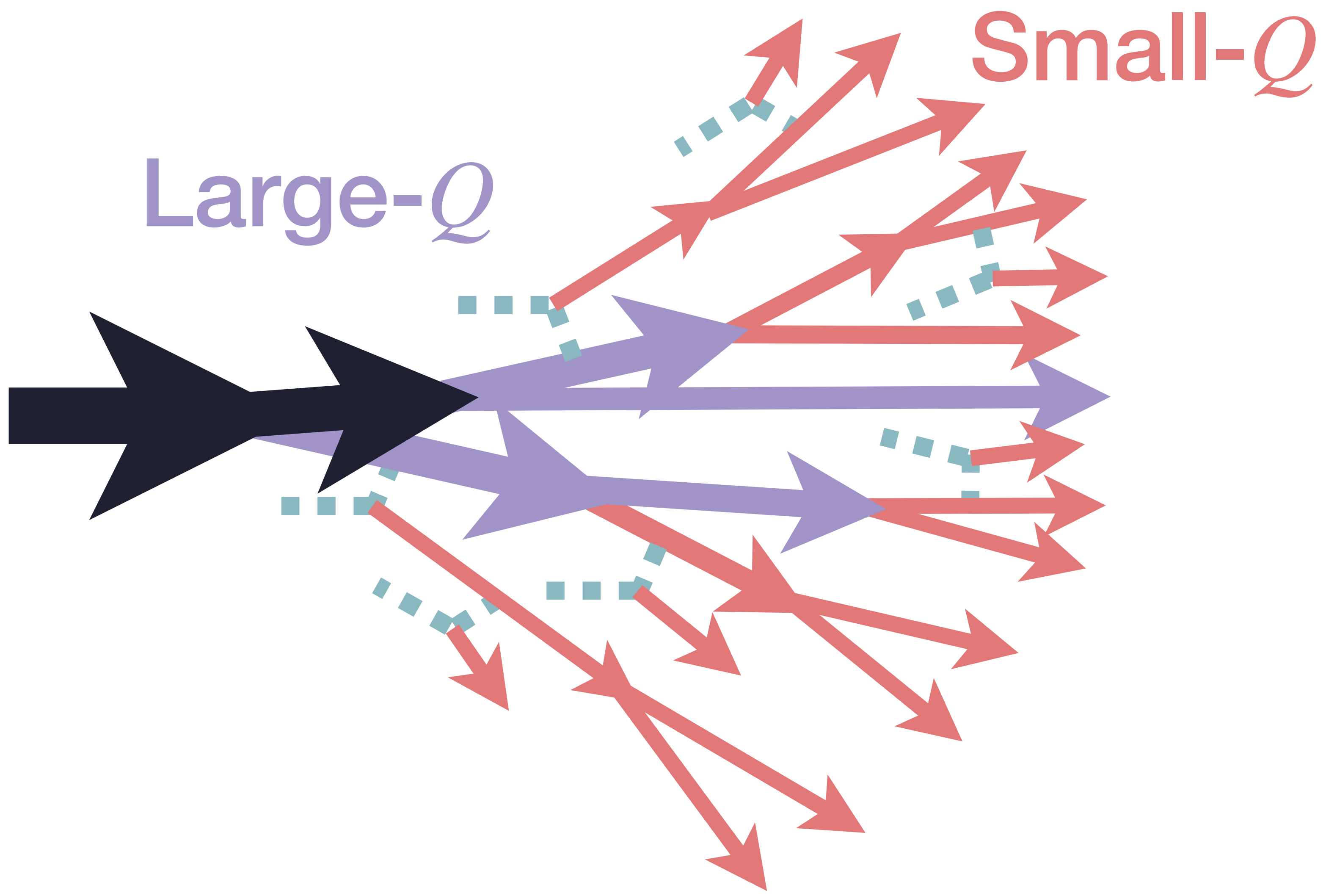
Summary

- **Multi-stage evolution of jet shower in JETSCAPE**
  - Q^2-dependence in jet-medium interaction due to coherence effects
  - Simultaneous description of jet and single particle at various $\sqrt{s_{\mathrm{NN}}}$

- **Jet substructure modifications**
  - Sizable sensitivity of fragmentation function at large-p_{T} to coherence effects
  - Small sensitivity of momentum fraction of hard partonic splittings to medium effects
  - Narrowing of hard partonic splittings of *inclusive triggered* jets due to energy loss
  - Suppression of broadening in hard partonic splittings due to coherence effects
  - Decomposition of multiple contributing effects by cross-analyses with γ-tagged jet

Multi-stage jet evolution in JETSCAPE

JETSCAPE, PRC96, 024909 (2017)

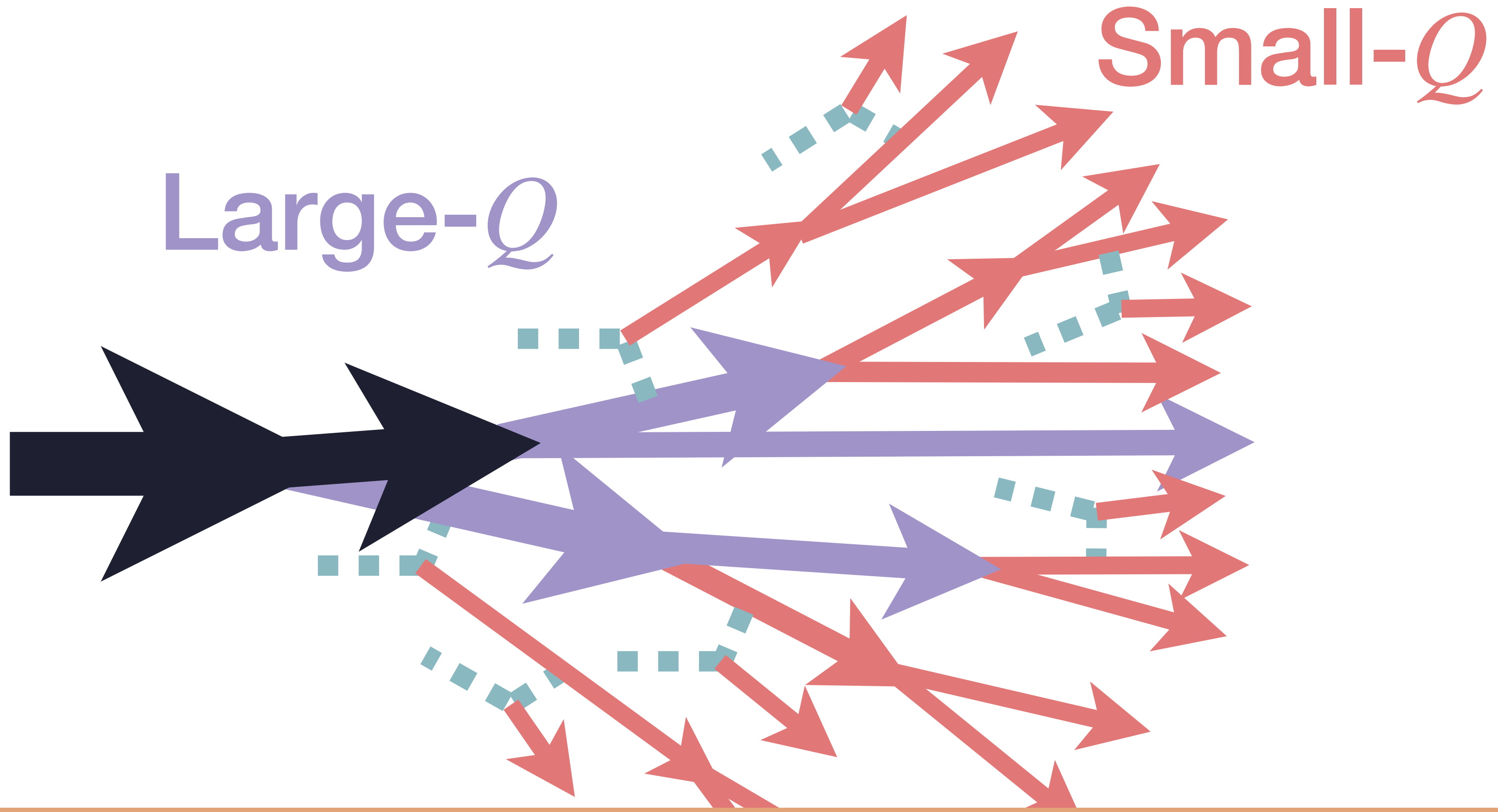


Virtuality separation scale: Q_{sw}

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

Multi-stage jet evolution in JETSCAPE

JETSCAPE, PRC96, 024909 (2017)



aration scale: Q_{sw}

Switching between modules for parton by parton

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

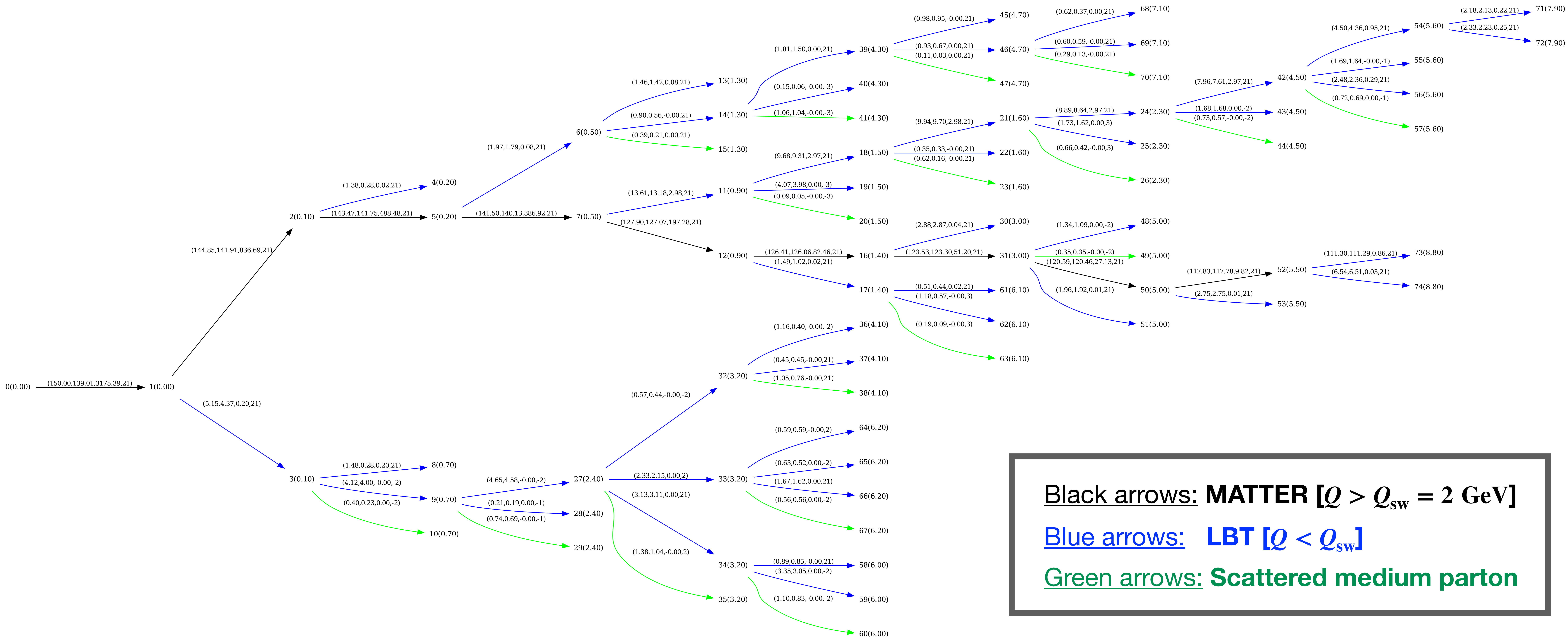
Small-Q $(< Q_{sw})$

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	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]**

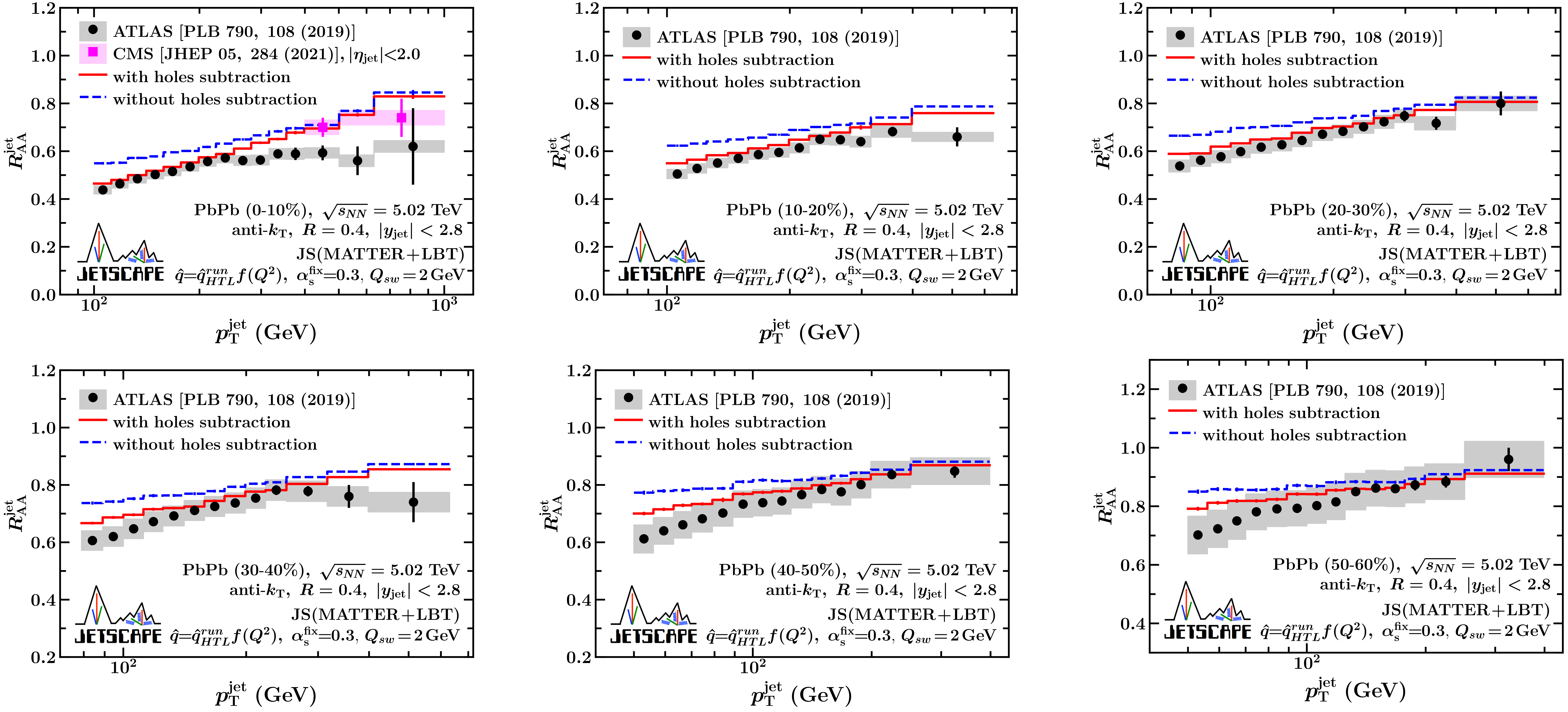
Blue arrows: **LBT [$Q < Q_{sw}$]**

Green arrows: **Scattered medium parton**

Centrality dependence

JETSCAPE, PRC107, 034911 (2023)

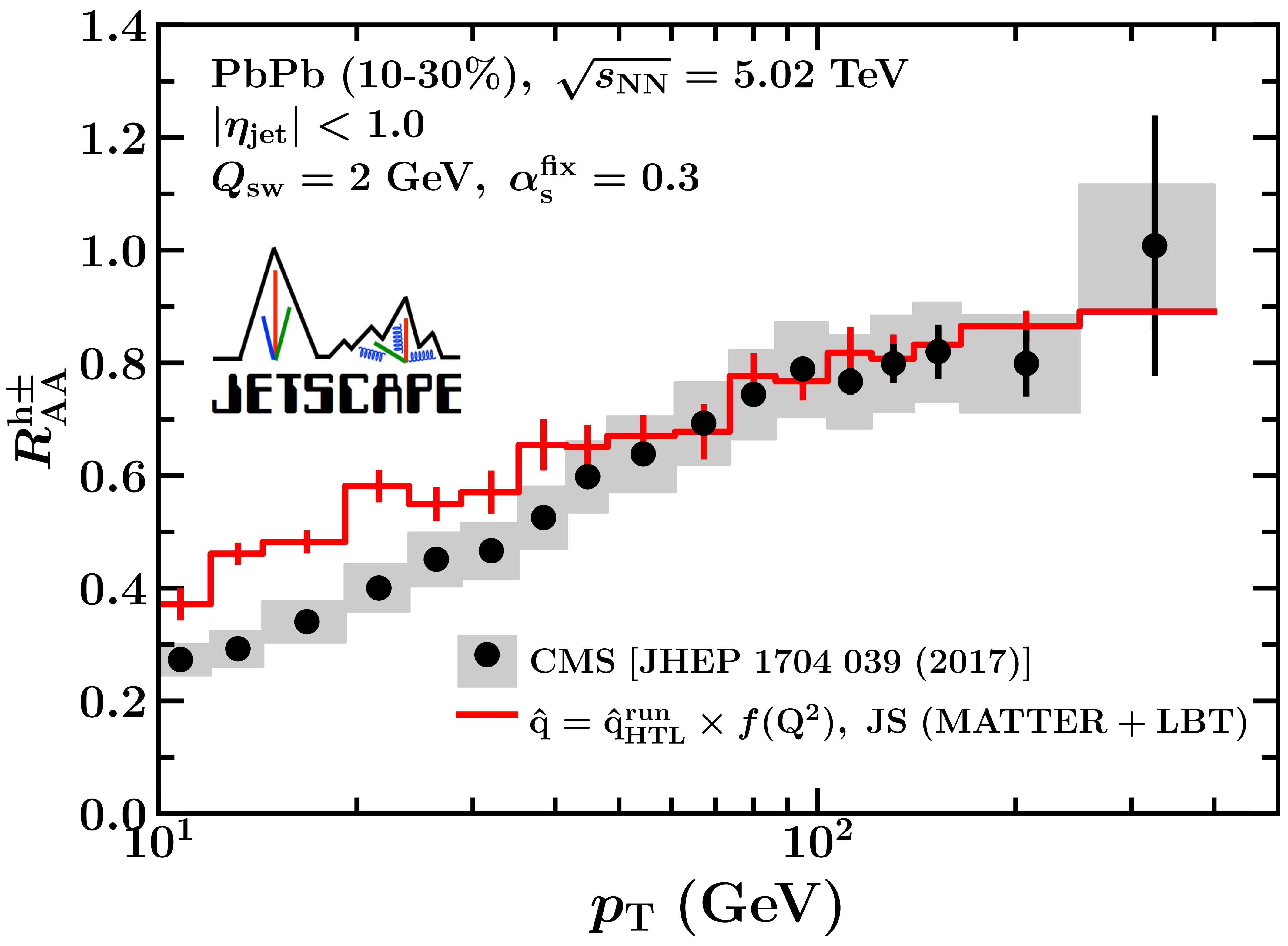
- **Inclusive jet R_{AA} in Pb+Pb collisions at 5.02 TeV**

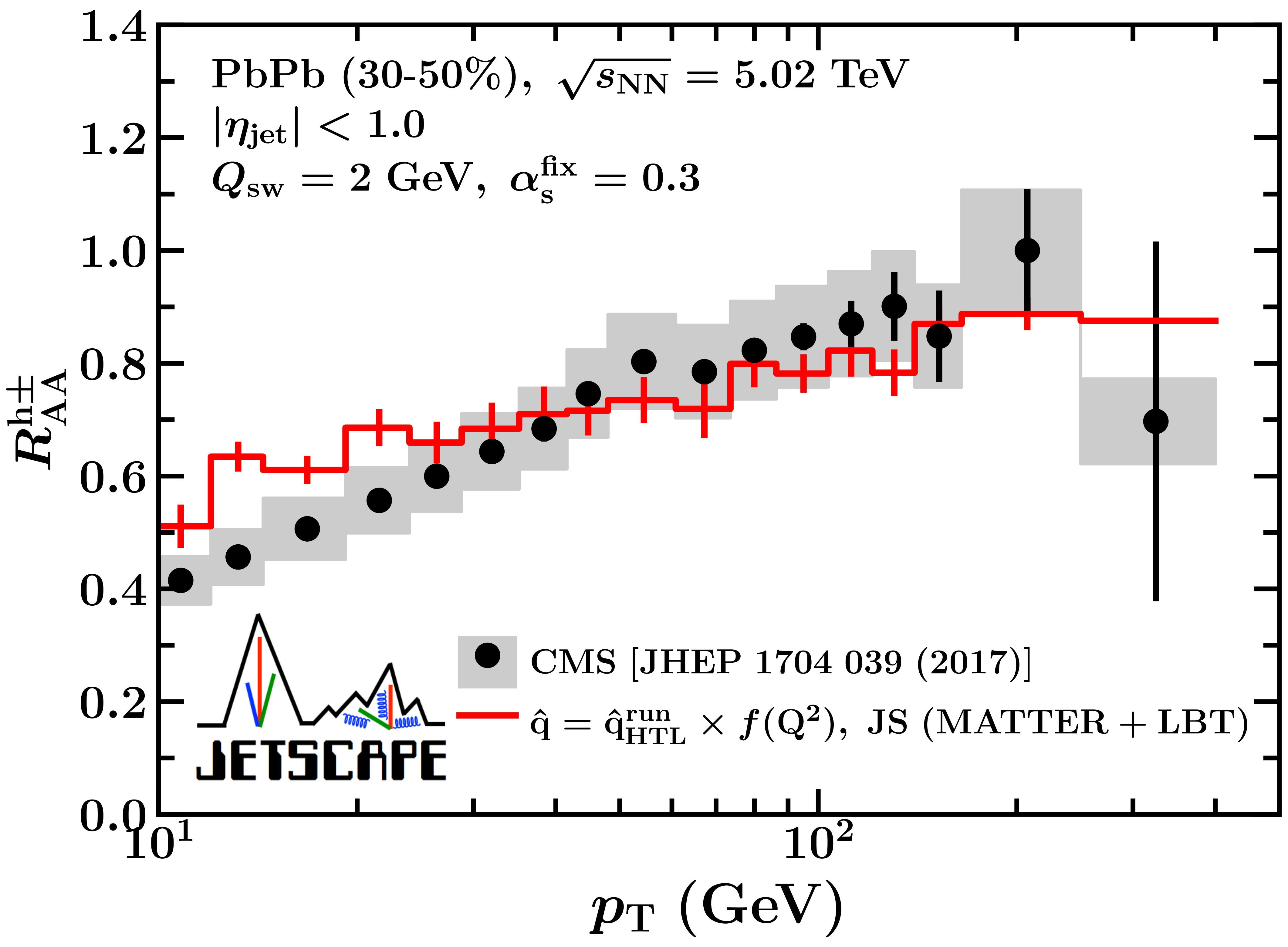


Centrality dependence

JETSCAPE, PRC107, 034911 (2023)

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

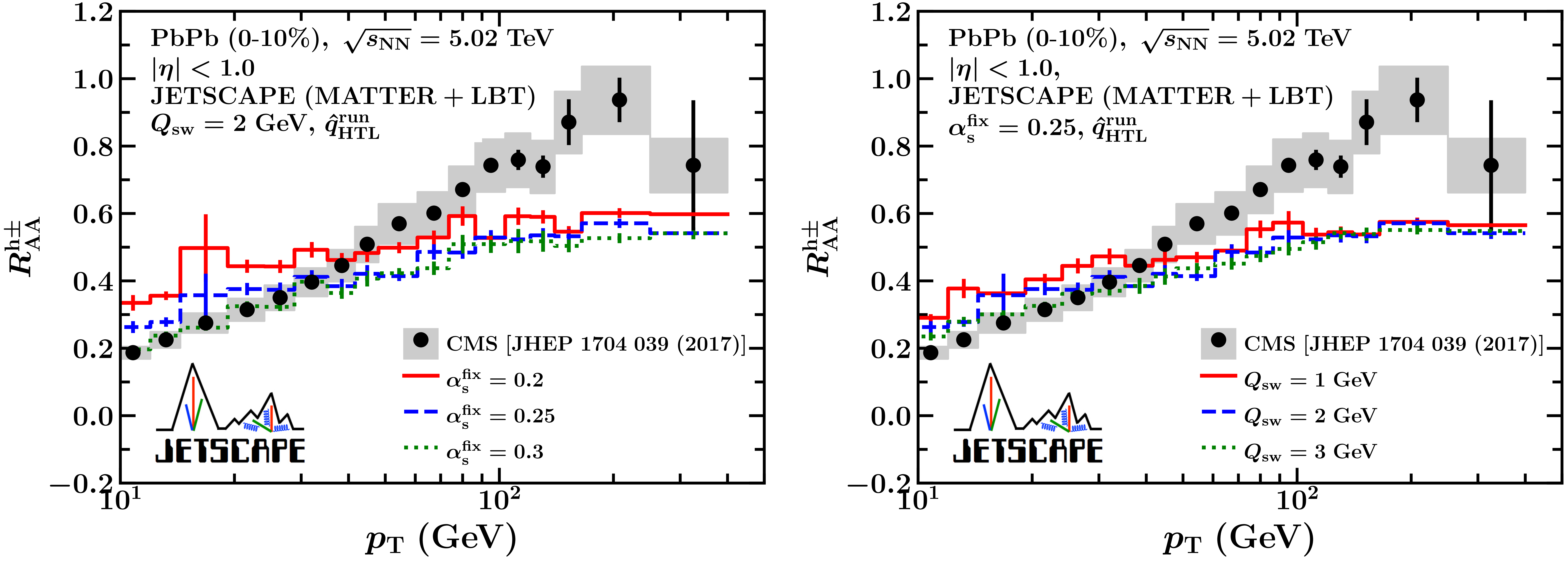




$\alpha_s^{\rm fix}$, $Q_{\rm sw}$ dependence

JETSCAPE, PRC107, 034911 (2023)

- **Charged particle $R_{\rm AA}$ in Pb+Pb collisions at 5.02 TeV**
  - Results without coherence effects



Coherence effects at high virtuality

- **Spectrum of induced gluons (Higher-Twist)**

Kumar, Majumder, Shen, PRC101, 034908 (2020)

$$\frac{dN_g}{dy\,dl_\perp^2} = \frac{\alpha_s}{2\pi^2}P(y)\int \frac{d^2k_\perp}{(2\pi)^2}H(k_\perp, l_\perp, q^-, y)$$
$$\times \int d\delta\zeta^- d^2\zeta_\perp e^{-i\frac{k_\perp^2}{2q^-}\delta\zeta^- + i\vec{k}_\perp\cdot\vec{\zeta}_\perp}\langle p_B \mid A^{a+\alpha}(\delta\zeta^-, \vec{\zeta}_\perp)\, A^{a+}_{\alpha}(0,0_\perp) \mid p_B\rangle$$

$$H(k_\perp, l_\perp, q^-, y) = \int_0^{\tau^-} d\zeta^- \frac{2 - 2\cos\left\{\frac{(l_\perp - k_\perp)^2\zeta^-}{2q^- y(1-y)}\right\}}{(l_\perp - k_\perp)^4}$$