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

Effects of multi-scale jet-medium interactions on jet substructures

JETSCAPE, PRC107, 034911 (2023) [arXiv:2204.01163]; arXiv:2301.02485

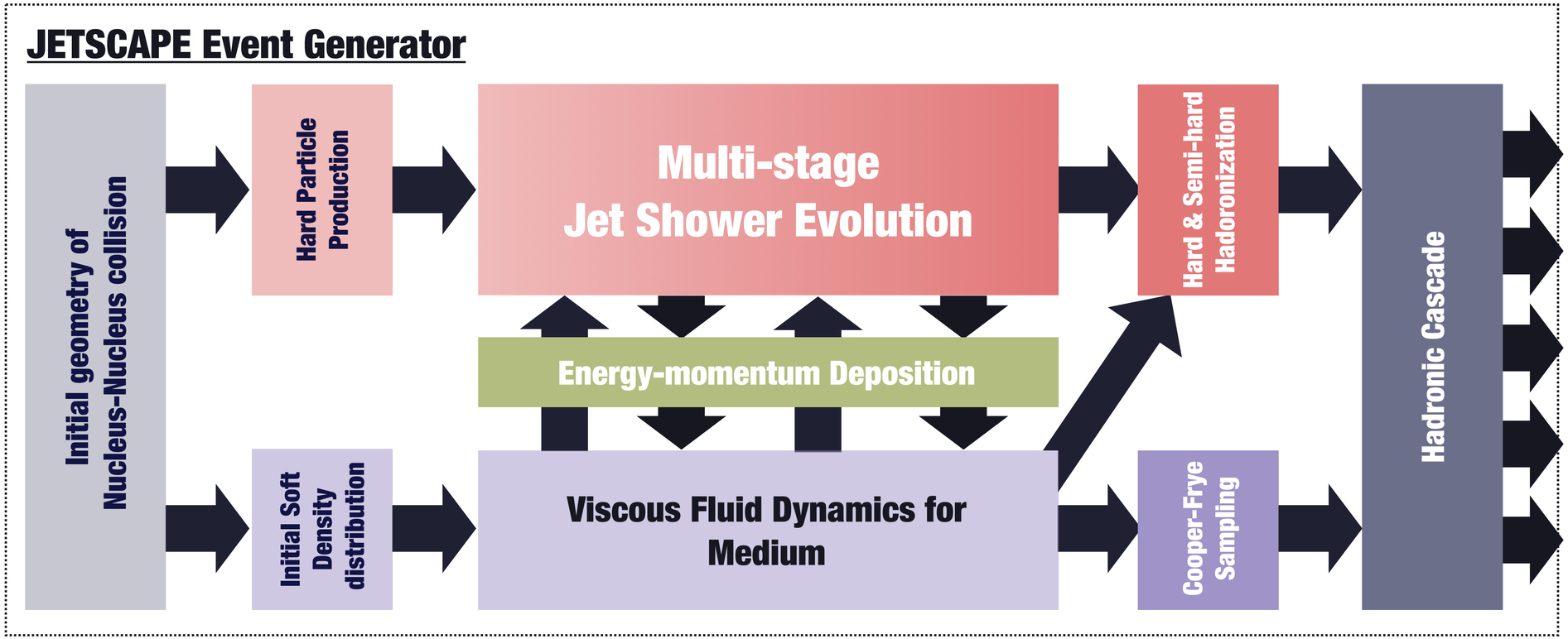
Yasuki Tachibana for the JETSCAPE Collaboration

Aschaffenburg, March 29th 2023

JETSCAPE framework

JETSCAPE, arXiv:1903.07706

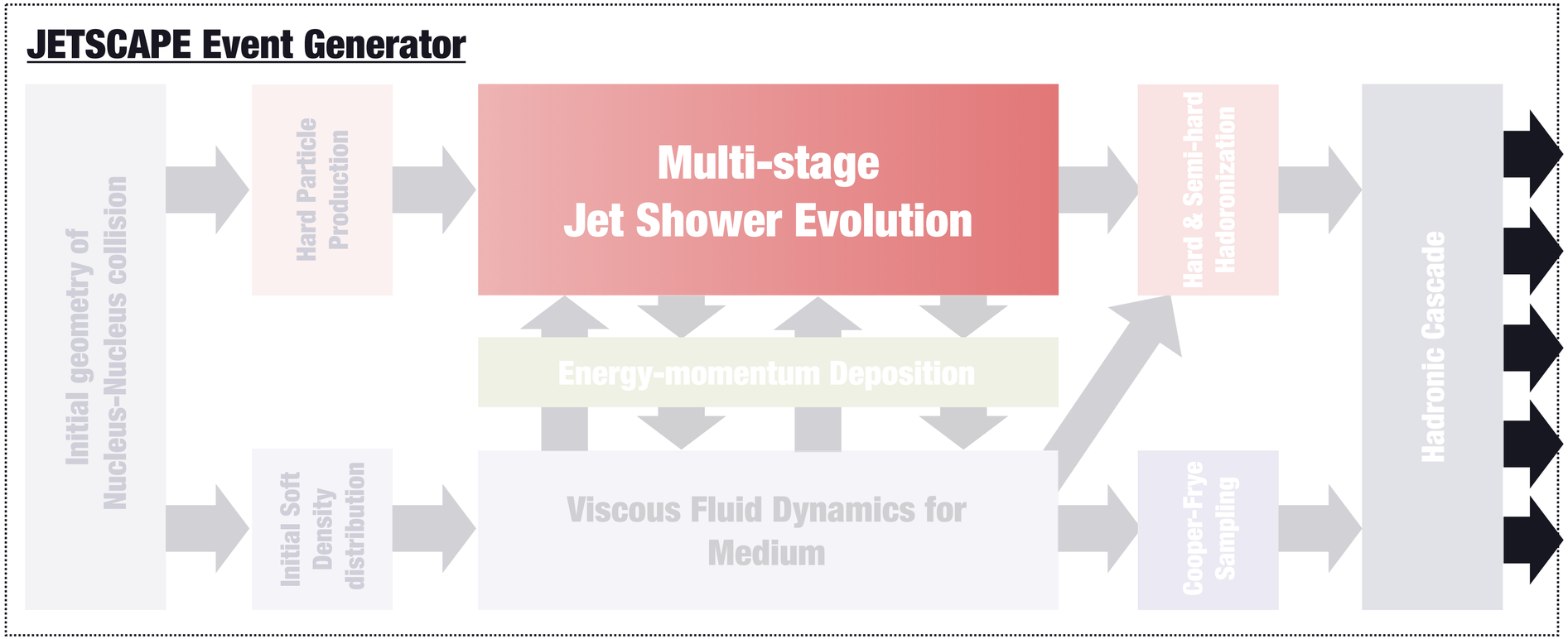
- **MC event generator package for heavy ion collisions**
  - Generic, modular and extensible
  - Communication between modules
  - Available on GitH github.com/JETSCAPE



JETSCAPE framework

JETSCAPE, arXiv:1903.07706

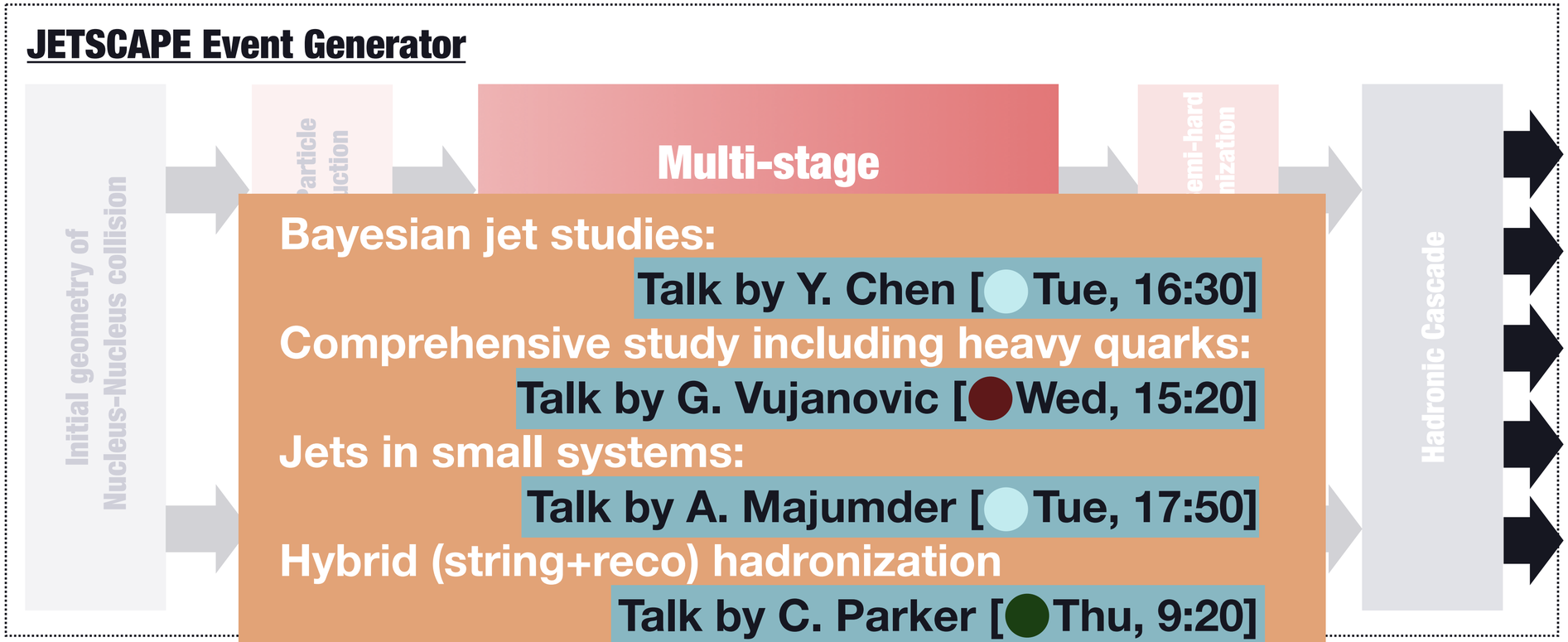
- **MC event generator package for heavy ion collisions**
  - Generic, modular and extensible
  - Communication between modules
  - Available on GitH github.com/JETSCAPE



JETSCAPE framework

JETSCAPE, arXiv:1903.07706

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



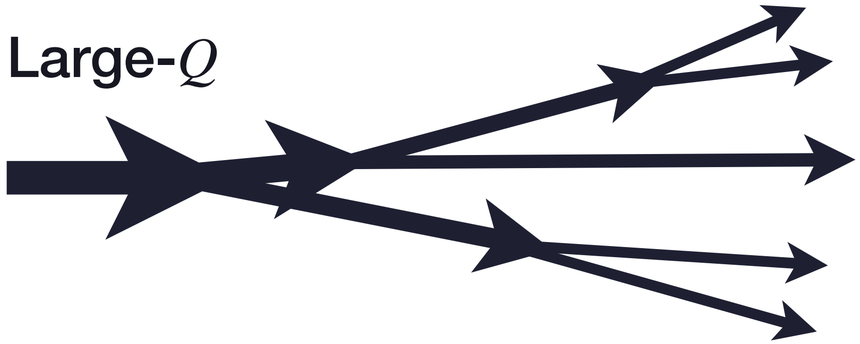
Multi-stage jet evolution in JETSCAPE

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

In-vacuum

- In-vacuum: Virtuality ordered splitting

Small-Q



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

Multi-stage jet evolution in JETSCAPE

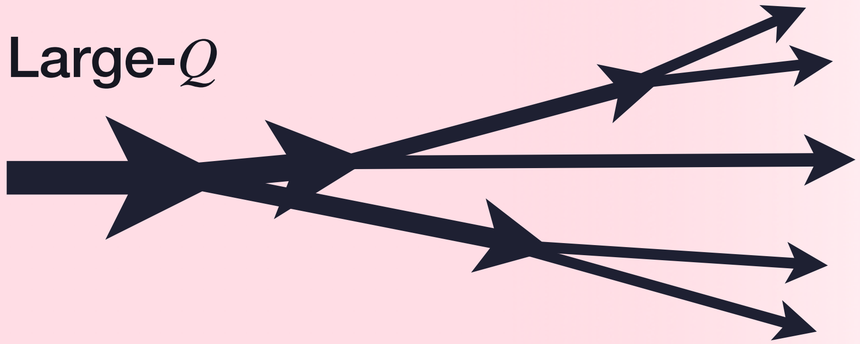
Majumder, Putschke, PRC 93, 054909 (2016), JETSCAPE, PRC96, 024909 (2017)

In-medium

- In-vacuum: Virtuality ordered splitting

Small-Q

Large-Q



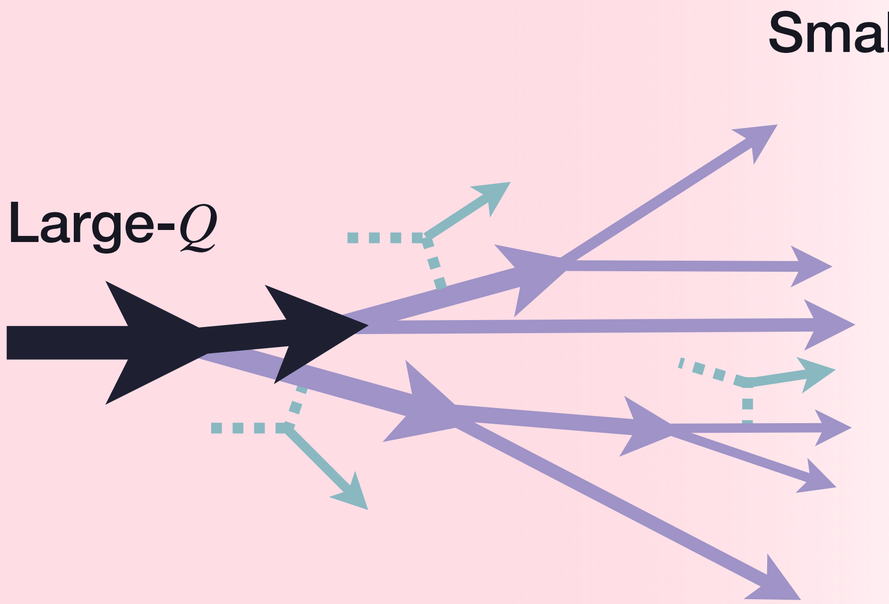
$Q^2 = p^\mu p_\mu - m^2$: virtuality (off-shellness)

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

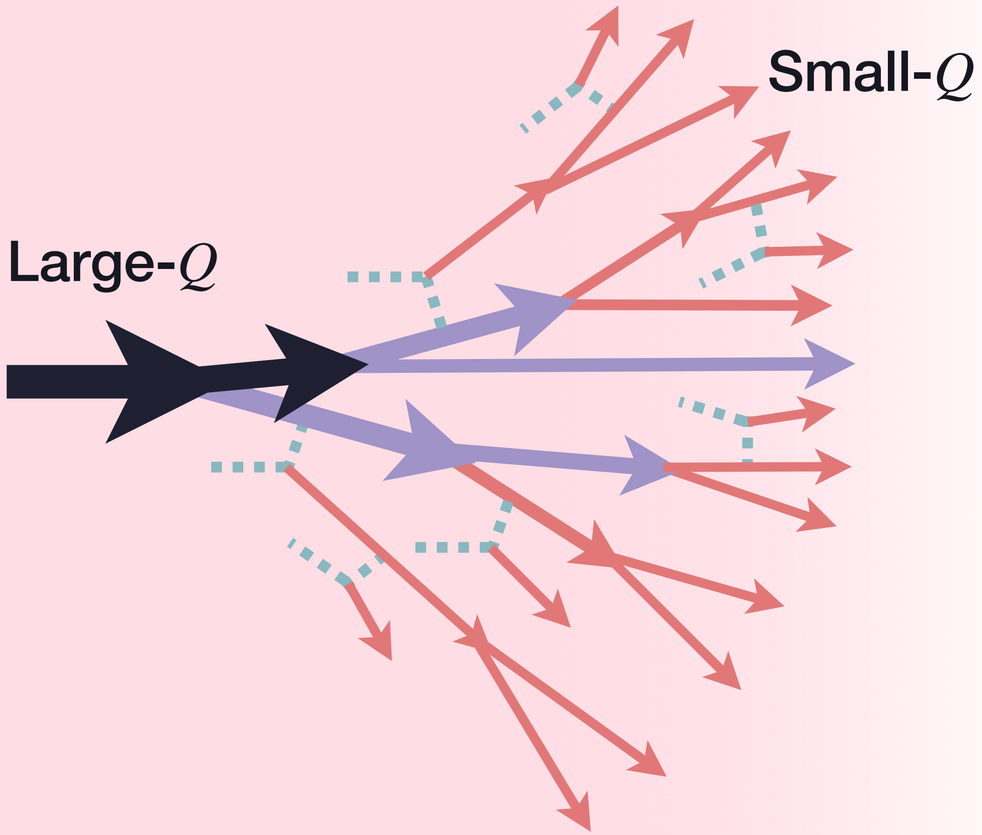


$Q^2 = p^\mu p_\mu - m^2$: virtuality (off-shellness)

Multi-stage jet evolution in JETSCAPE

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

In-medium



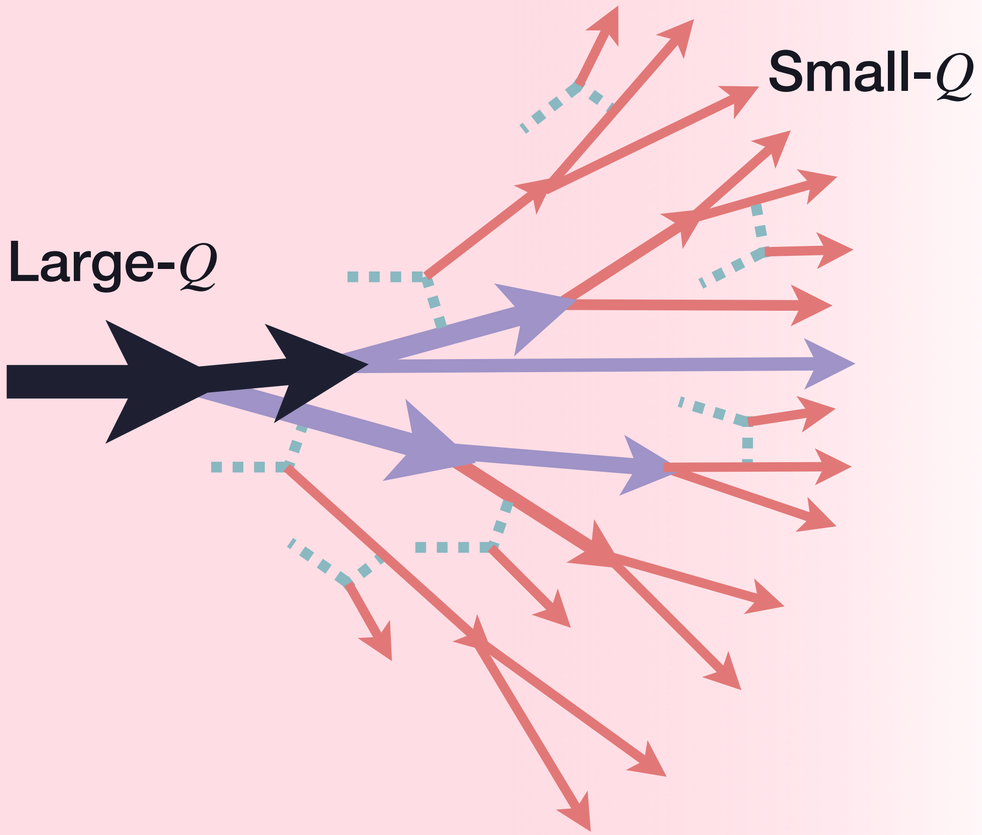
$Q^2 = p^\mu p_\mu - m^2$: virtuality (off-shellness)

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



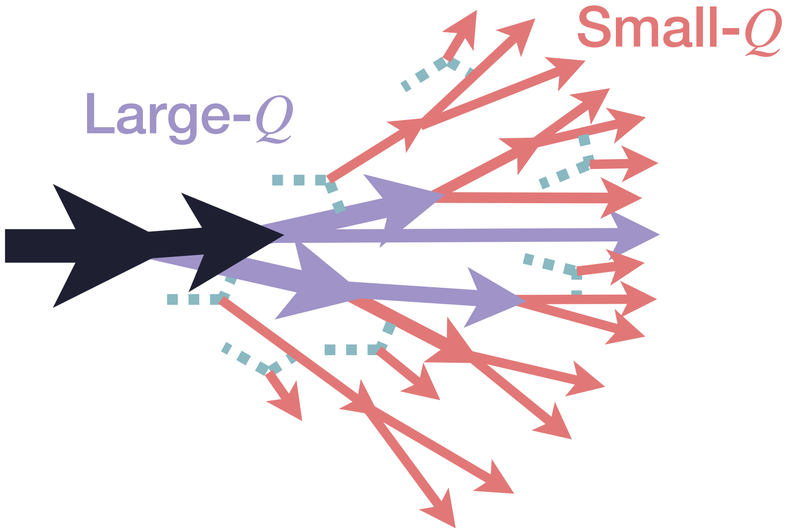
$Q^2 = p^\mu p_\mu - m^2$: virtuality (off-shellness)

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

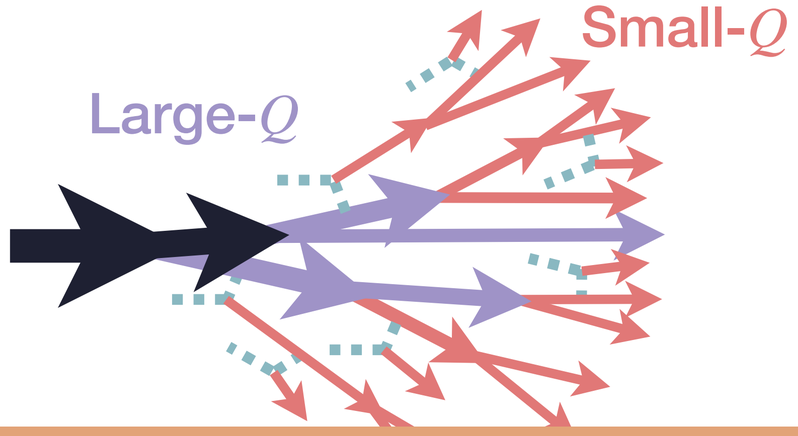


Virtuality separation scale: Q_{sw}

Large-Q ($> Q_{\mathrm{sw}}$)	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)	Pablos, et al.(15-)
Virtuality ordered splitting	On-shell parton transport		Diffusion into medium
Higher Twist formalism	Higher Twist formalism	AMY formalism	$\mathcal{N} = 4$ super Yang-Mills
Guo, Wang(00,01), Abir, Kaur, Majumder(14), Abir, Majumder(16)	Guo, Wang(00,01), Zhang, Wang, Wang(04,05)	Arnold, Moore, Yaffe(01,02,03), Jeon, Moore(05), Turbide, Gale, Jeon, Moore(05)	Chesler, Rajagopal(14, 15)

Multi-stage jet evolution in JETSCAPE

JETSCAPE, PRC96, 024909 (2017)



Switching between modules for parton by parton

aration scale: Q_{sw}

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

MATTER

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

Virtuality ordered splitting

Higher Twist formalism

Guo, Wang(00,01), Abir, Kaur, Majumder(14), Abir, Majumder(16)

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

LBT

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

On-shell parton transport

Higher Twist formalism

Guo, Wang(00,01), Zhang, Wang, Wang(04,05)

MARTINI

Schenke, Gale, Jeon(09), Park, Jeon, Gale(17,18)

AMY formalism

Arnold, Moore, Yaffe(01,02,03), Jeon, Moore(05), Turbide, Gale, Jeon, Moore(05)

AdS/CFT

Pablos, et al.(15-)

Diffusion into medium

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

Chesler, Rajagopal(14, 15)

Multi-stage jet evolution in JETSCAPE

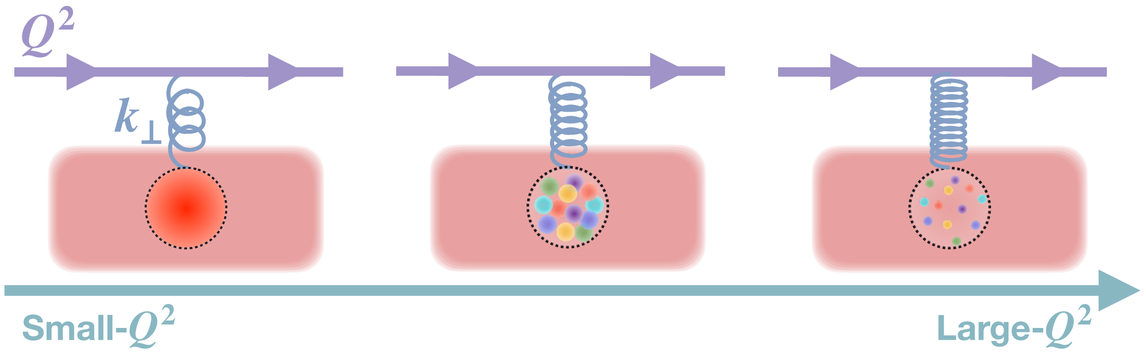
JETSCAPE, PRC107, 034911 (2023)

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

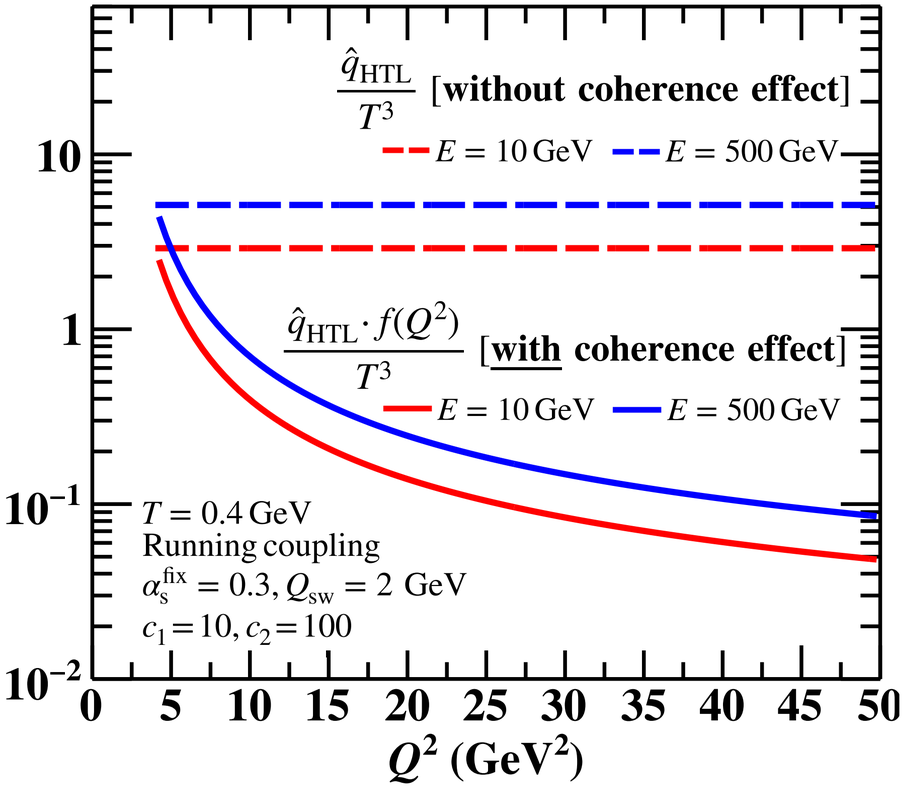


Effective jet-quenching strength

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

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

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



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, $Q_{\mathrm{sw}} = 2\ \mathrm{GeV}$)
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, $Q_{\mathrm{sw}} = 2\ \mathrm{GeV}$)
Hadronization: Lund String

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

Bulk Medium

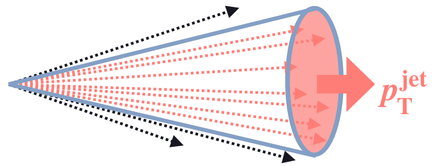
Initial Condition: TRENTo+Freestreaming
Moreland, Bernhard, Bass (14) , Liu, Shen, Heinz(15)
Hydro Evolution: VISHNU (2+1D viscous)
Shen, Qiu, Song, Bernhard, Bass, Heinz(16)

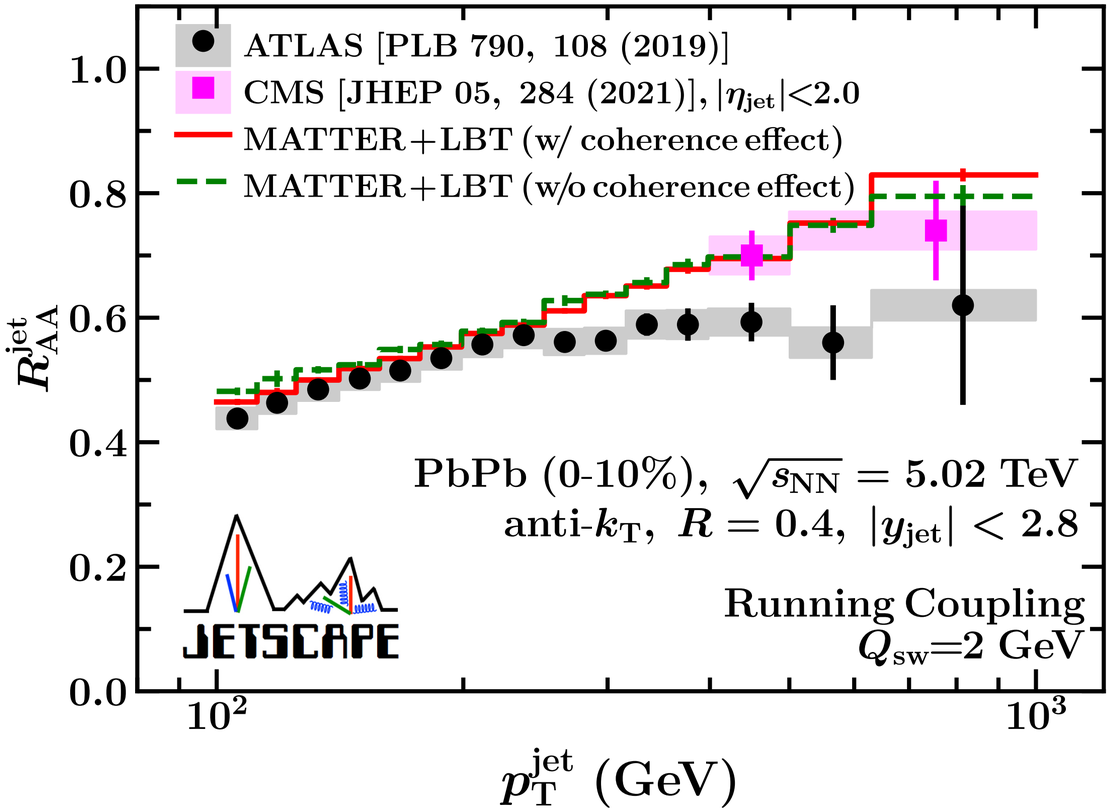
Jet and single particle energy loss

JETSCAPE, PRC107, 034911 (2023)

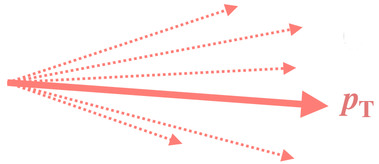
- **Pb+Pb collisions at 5.02 TeV**

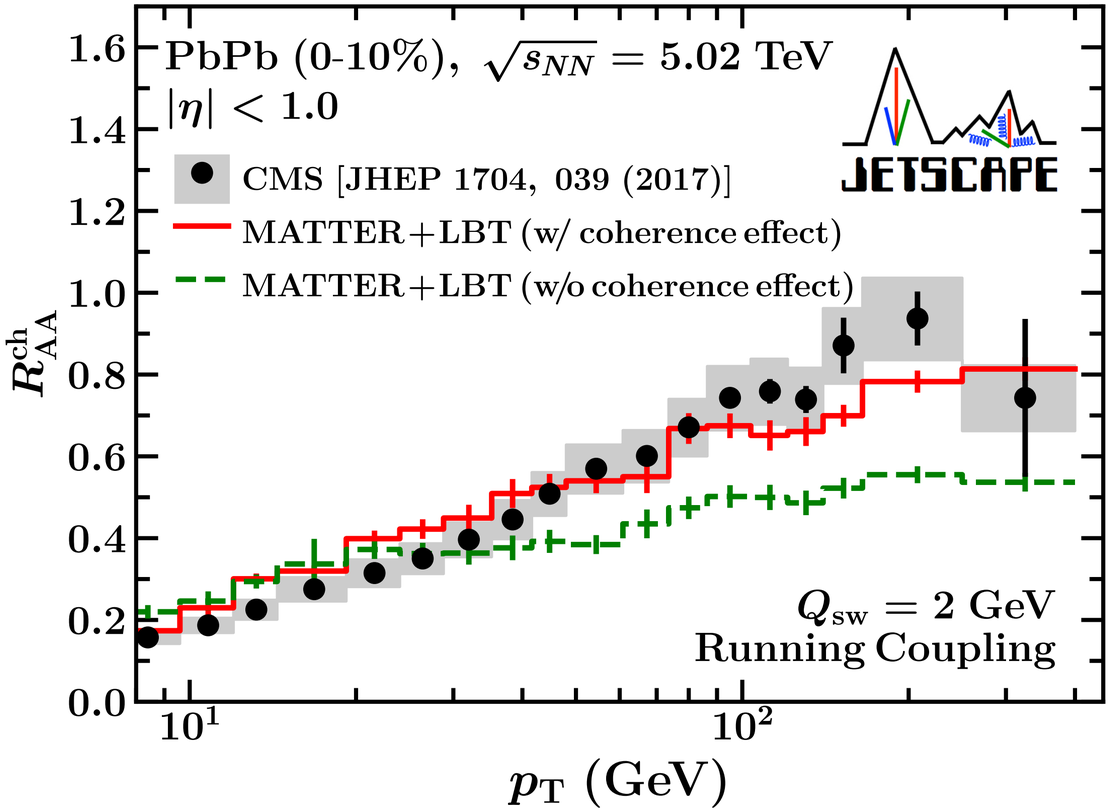
Inclusive jet R_{AA}





Charged particle R_{AA}



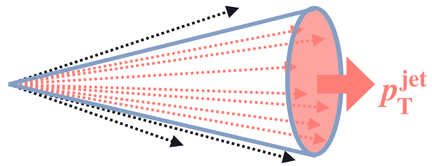


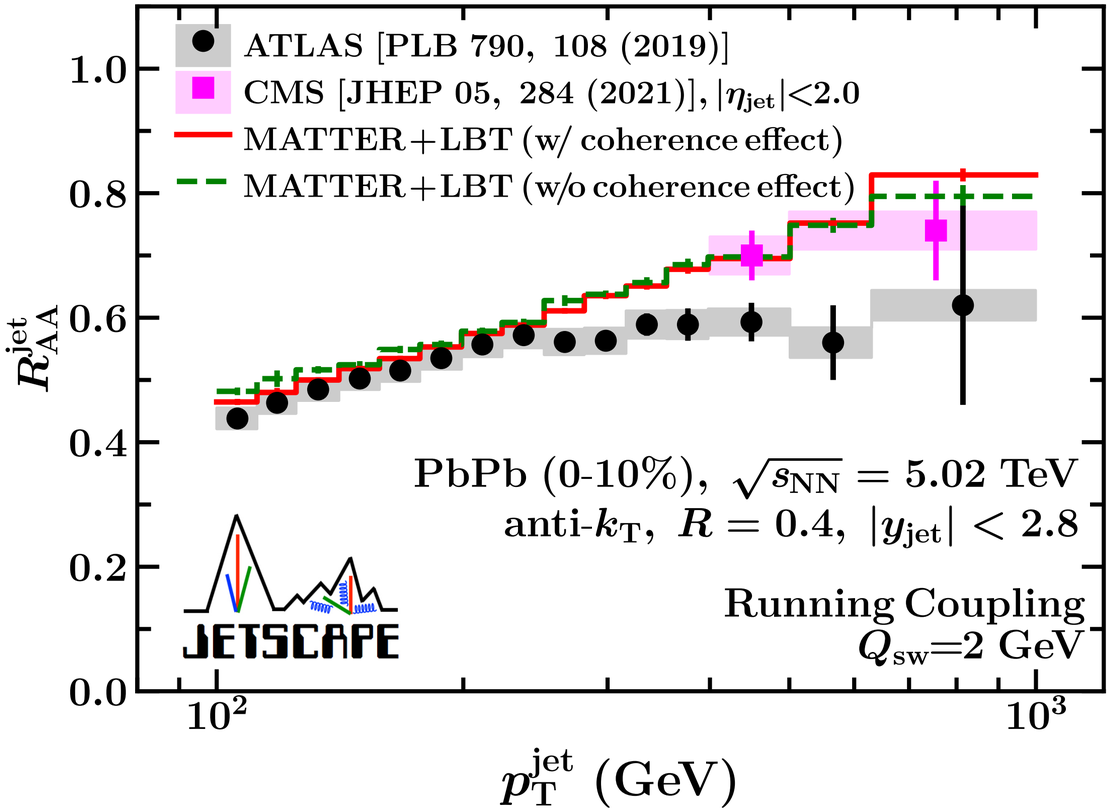
Jet and single particle energy loss

JETSCAPE, PRC107, 034911 (2023)

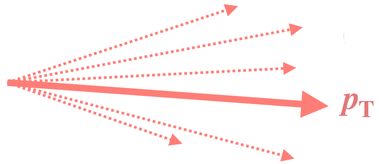
- **Pb+Pb collisions at 5.02 TeV**

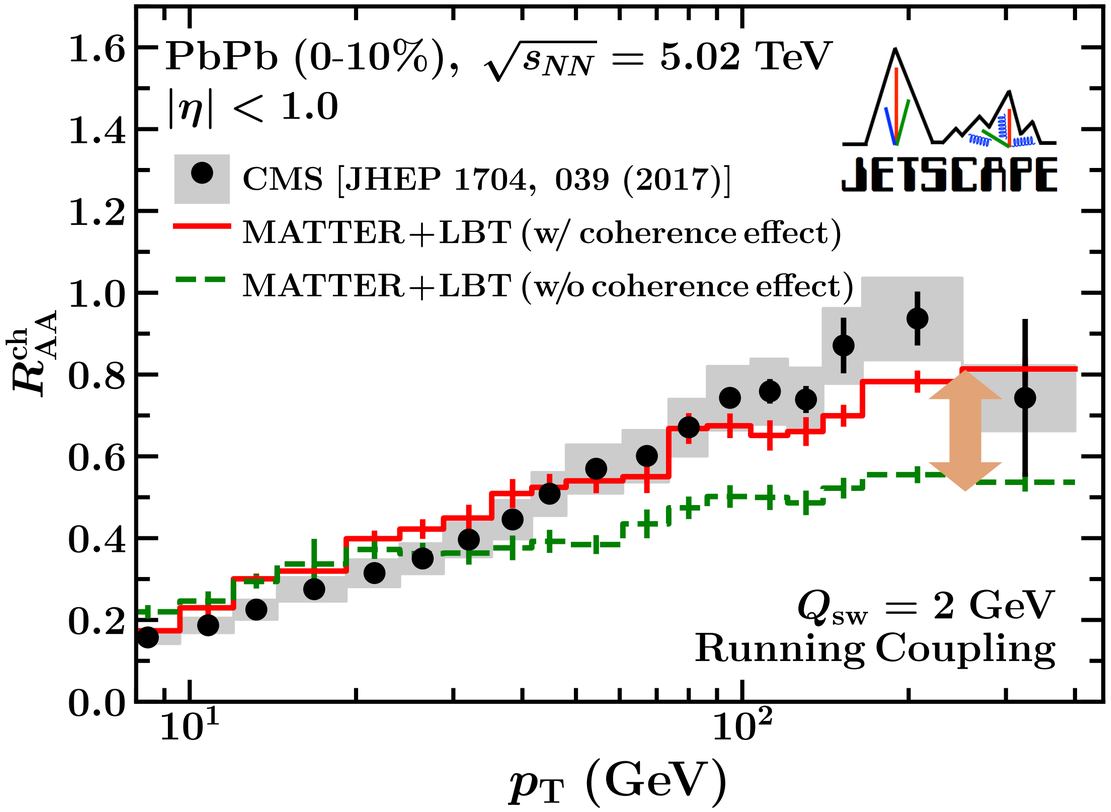
Inclusive jet R_{AA}





Charged particle R_{AA}



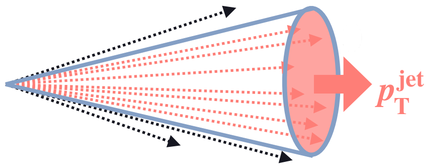


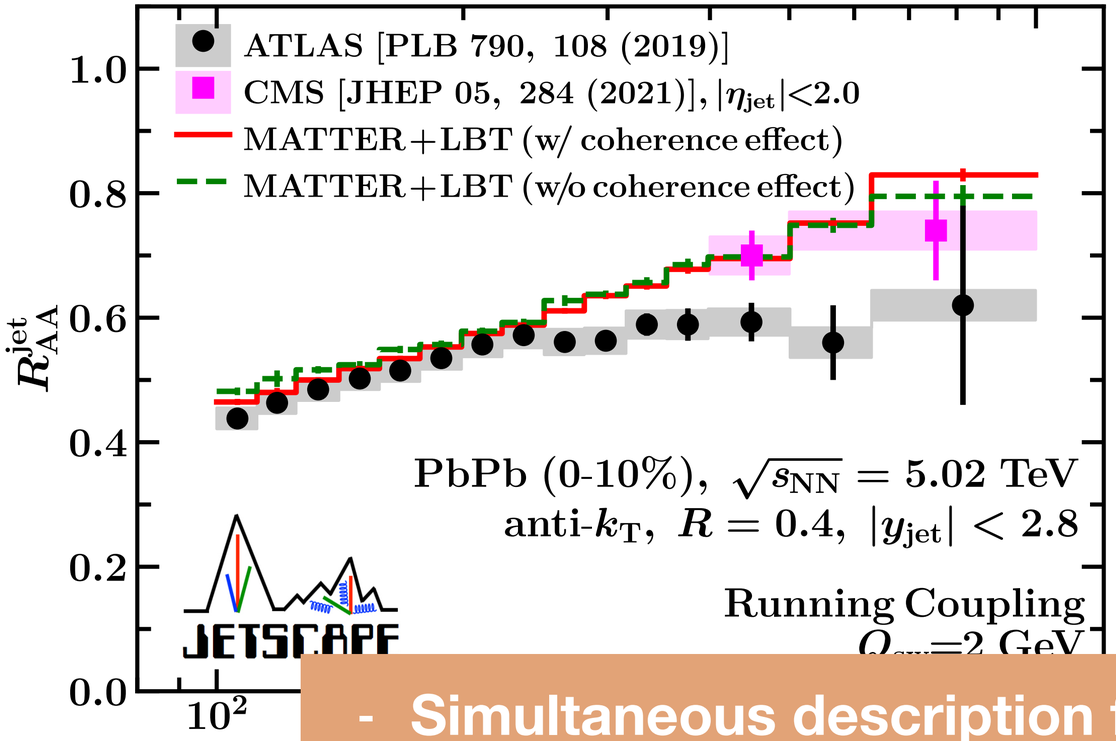
Jet and single particle energy loss

JETSCAPE, PRC107, 034911 (2023)

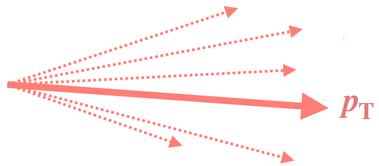
- Pb+Pb collisions at 5.02 TeV

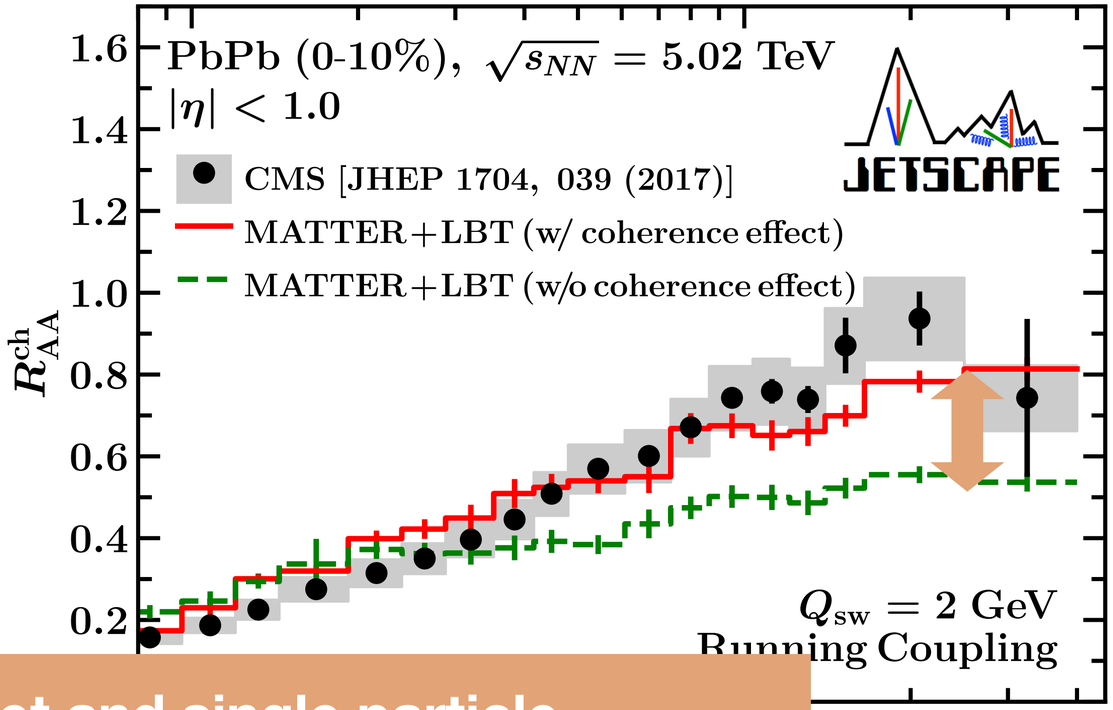
Inclusive jet R_{AA}





Charged particle R_{AA}





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

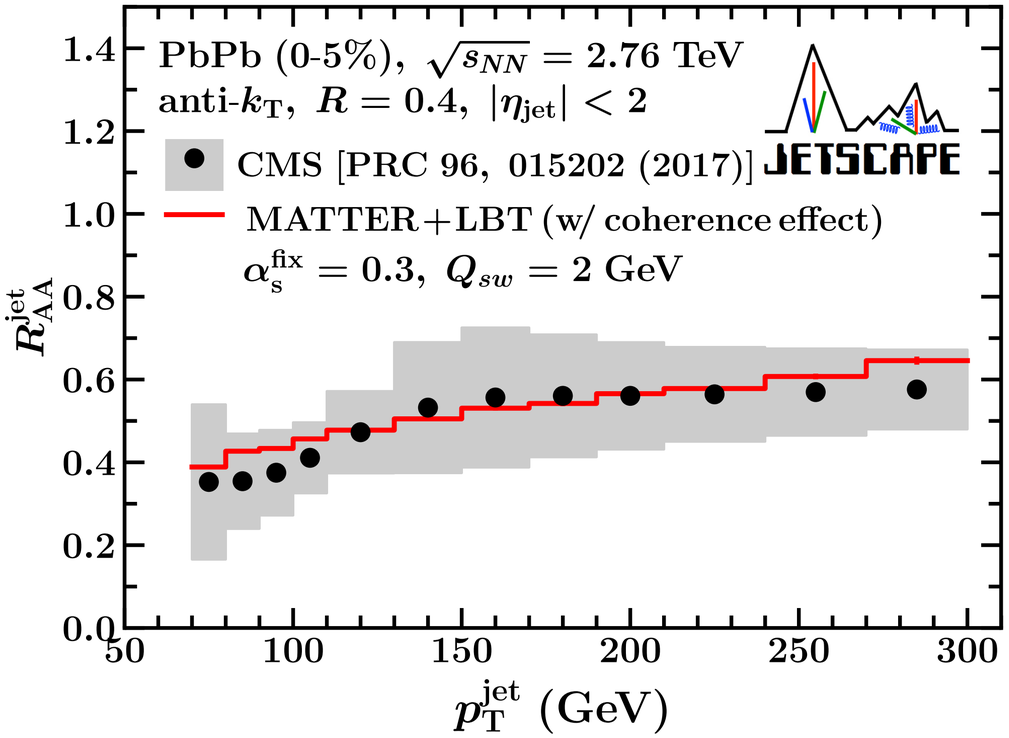
Jet and single particle energy loss

JETSCAPE, PRC107, 034911 (2023)

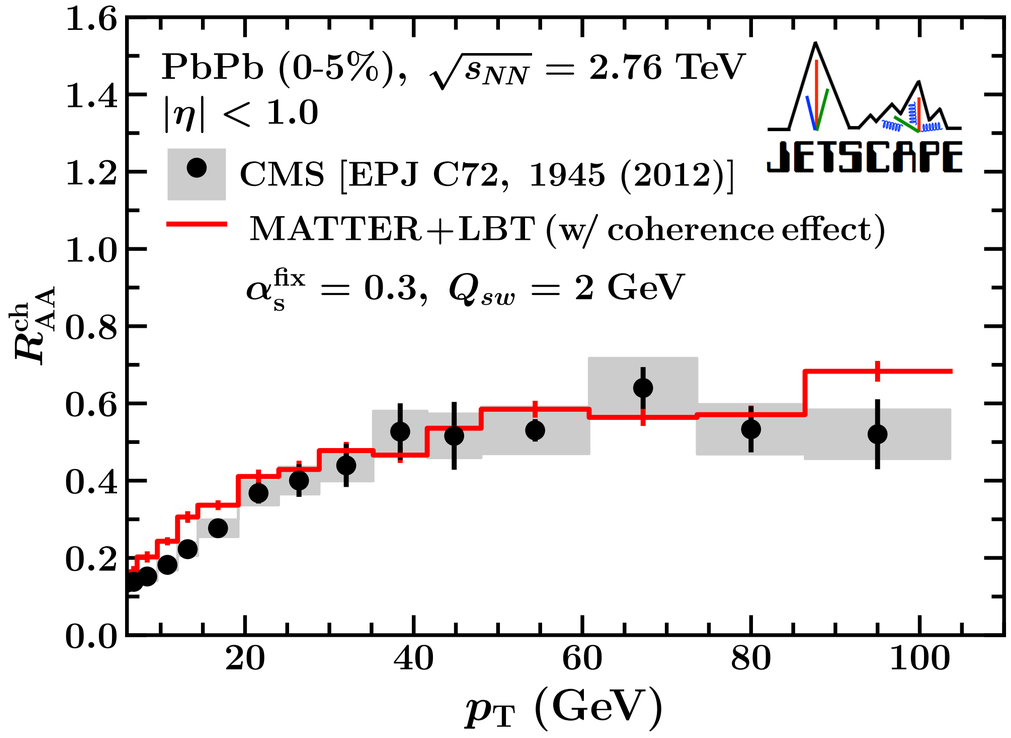
- **Pb+Pb collisions at 2.76 TeV**

The same parameter set as 5.02 TeV is used

Inclusive jet R_{AA}



Charged particle R_{AA}



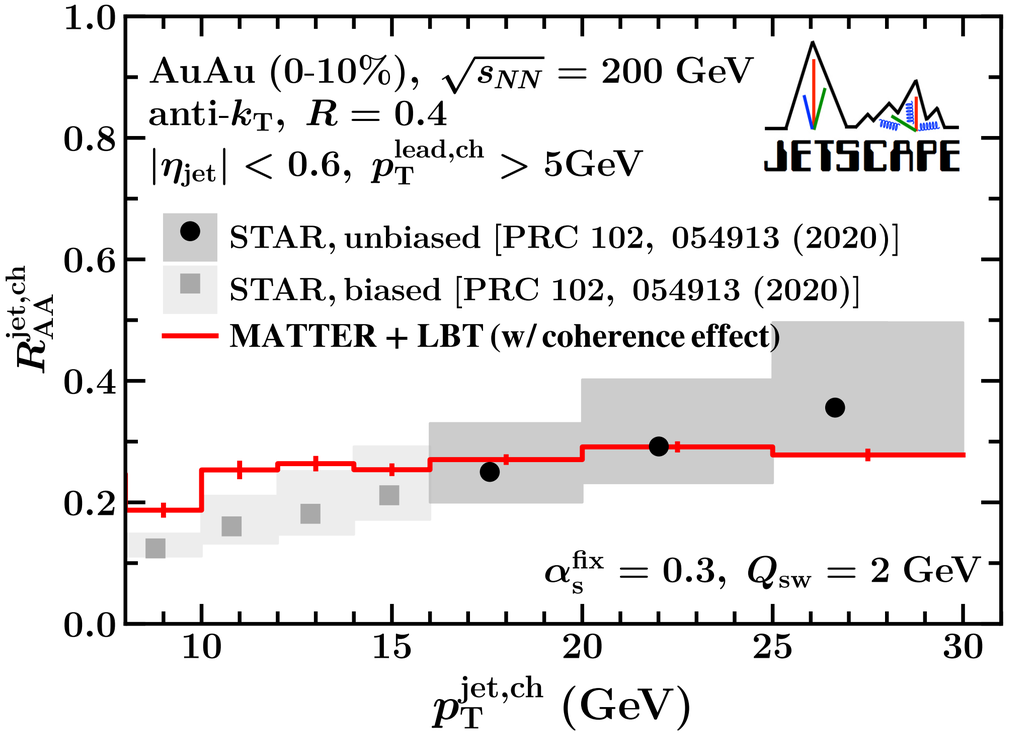
Jet and single particle energy loss

JETSCAPE, PRC107, 034911 (2023)

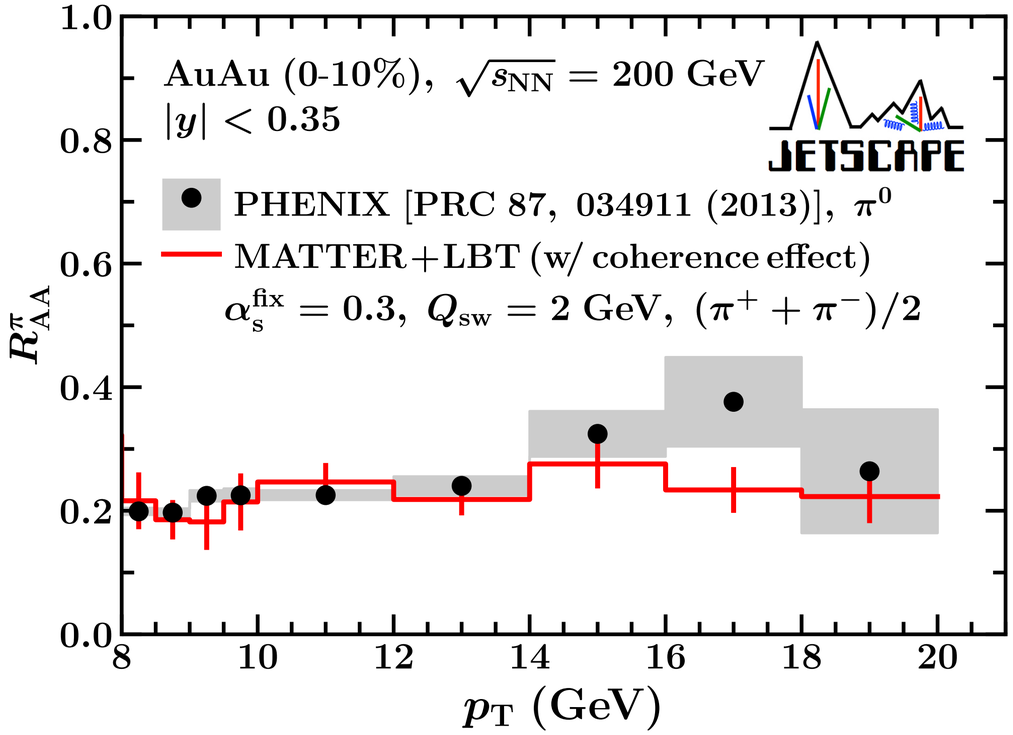
- **Au+Au collisions at 200 GeV**

The same parameter set as 5.02 TeV is used

Charged jet R_{AA}



Pion R_{AA}



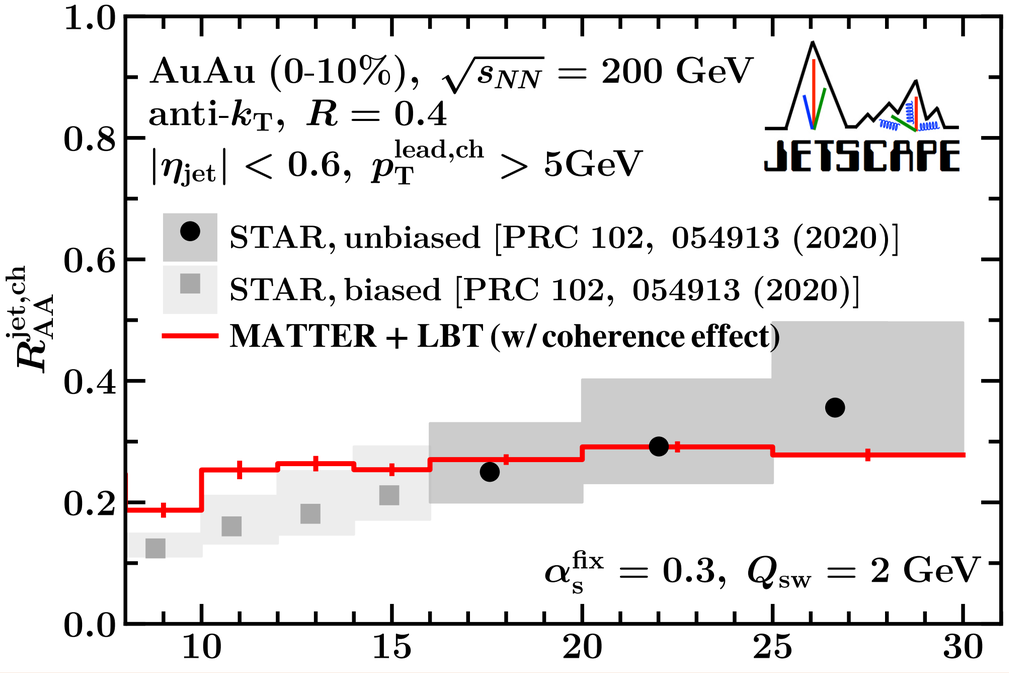
Jet and single particle energy loss

JETSCAPE, PRC107, 034911 (2023)

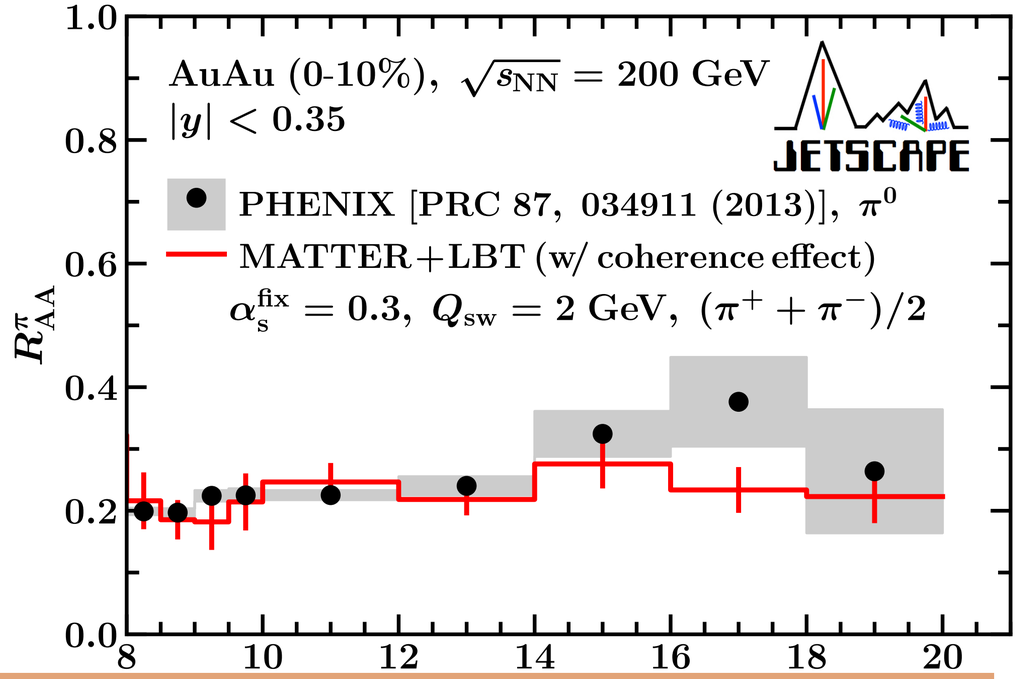
- Au+Au collisions at 200 GeV

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**

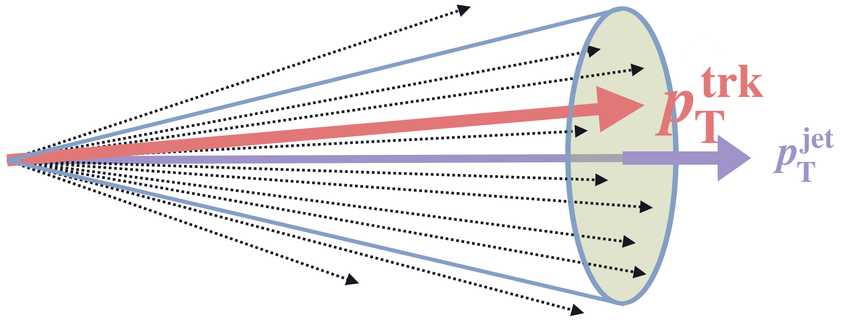
Jet Substructures

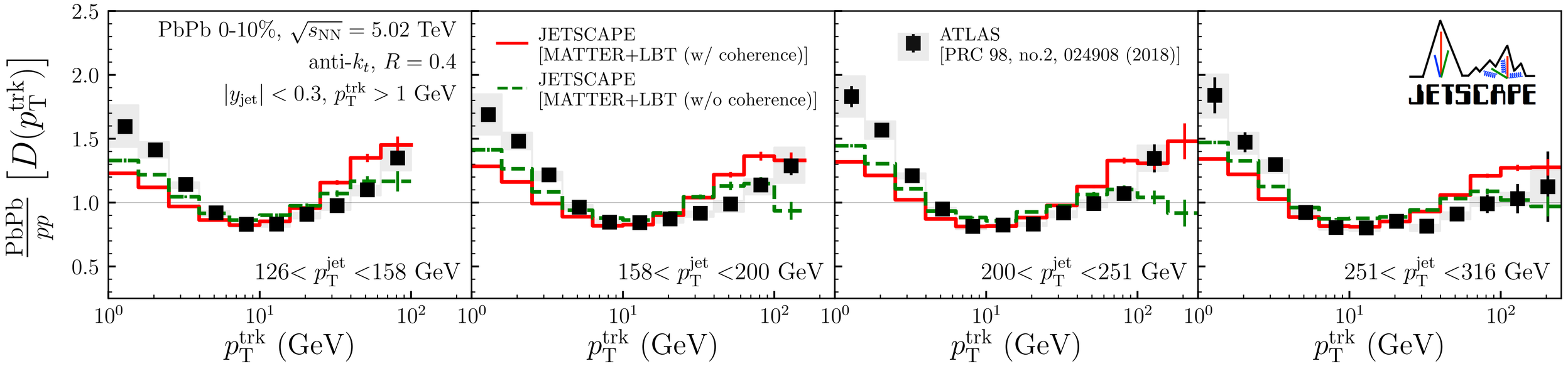
Jet substructures

JETSCAPE, arXiv:2301.02485

- **Jet Fragmentation Function**

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



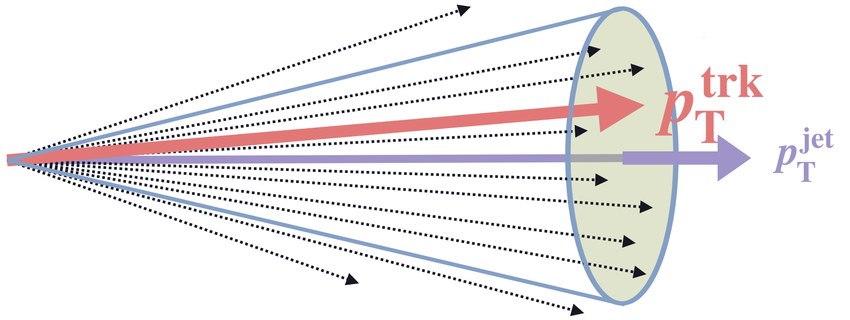


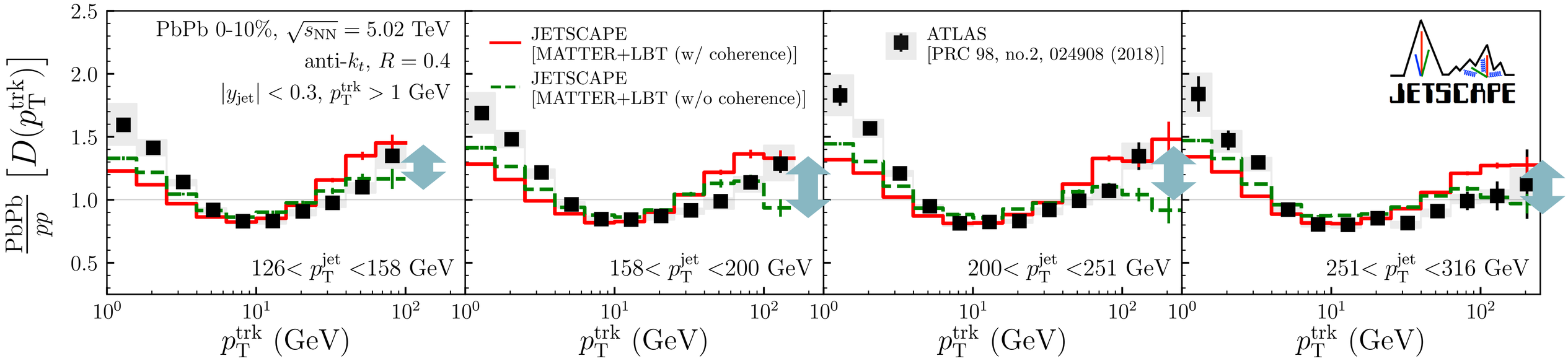
Jet substructures

JETSCAPE, arXiv:2301.02485

- **Jet Fragmentation Function**

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



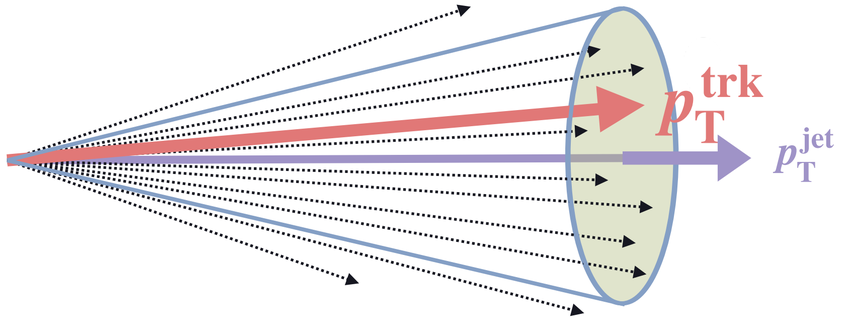


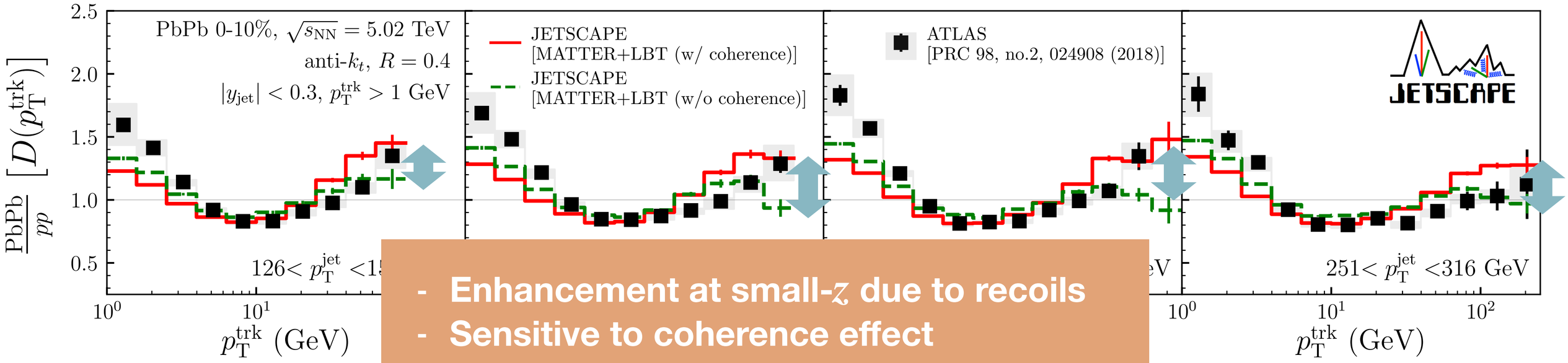
Jet substructures

JETSCAPE, arXiv:2301.02485

- **Jet Fragmentation Function**

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





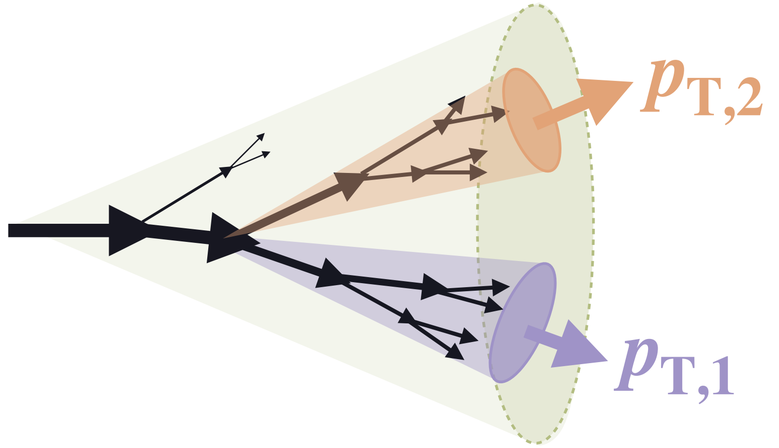
- **Enhancement at small-z due to recoils**
- **Sensitive to coherence effect**

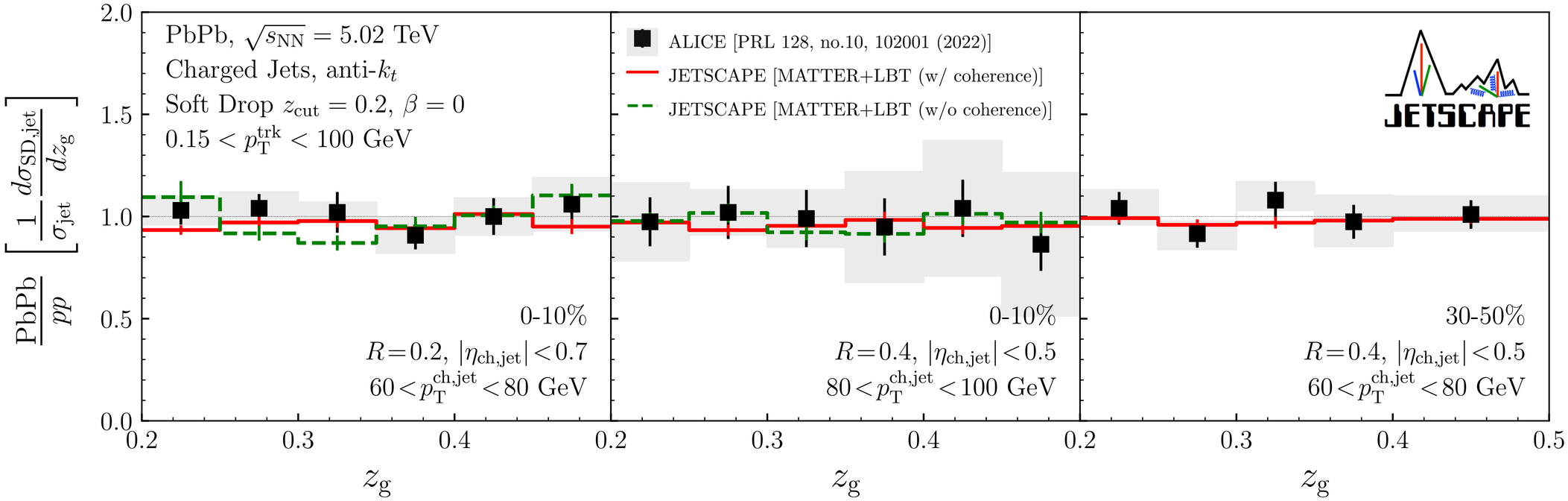
Jet substructures

JETSCAPE, arXiv:2301.02485

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

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



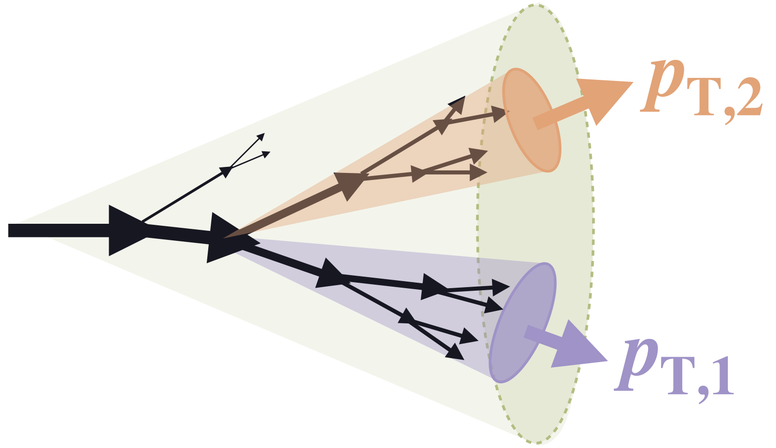


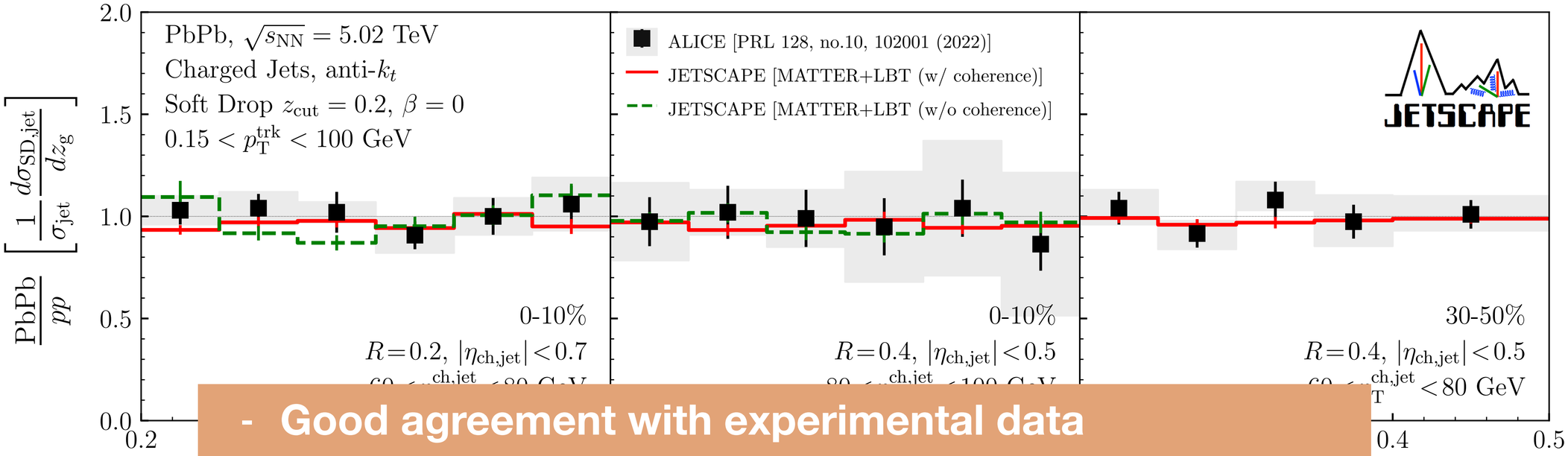
Jet substructures

JETSCAPE, arXiv:2301.02485

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

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





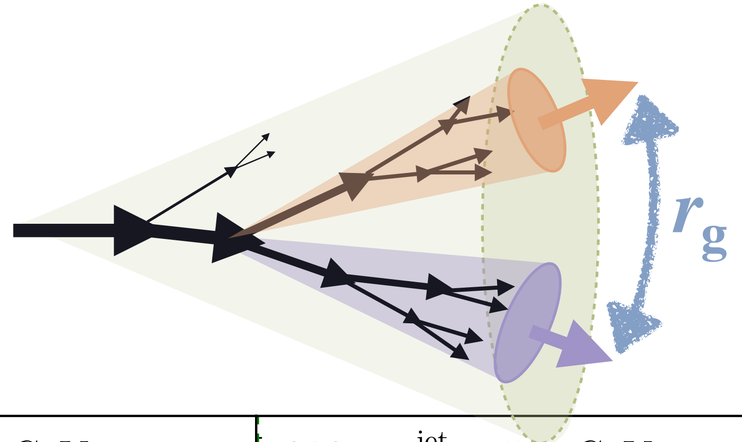
- **Good agreement with experimental data**
- **Almost no medium modification in z_g-distribution**

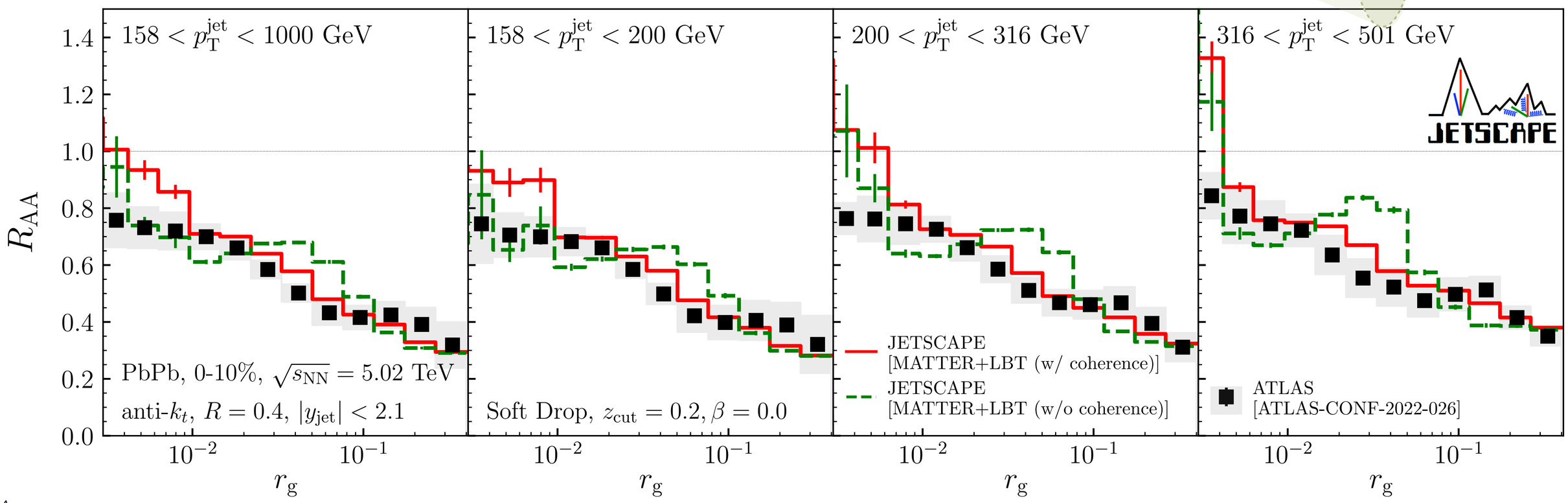
Jet substructures

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



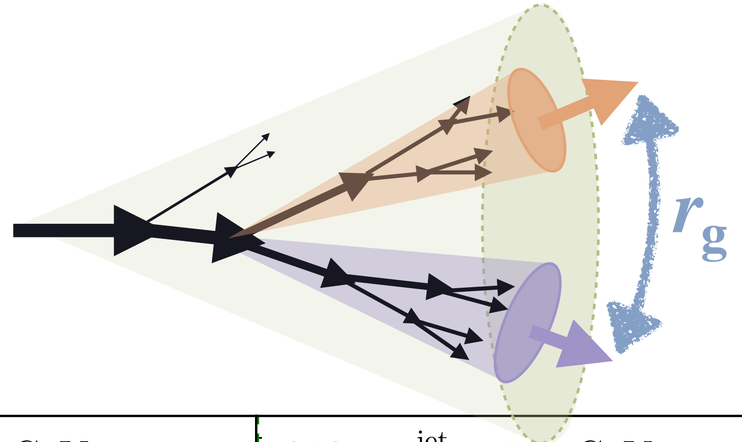


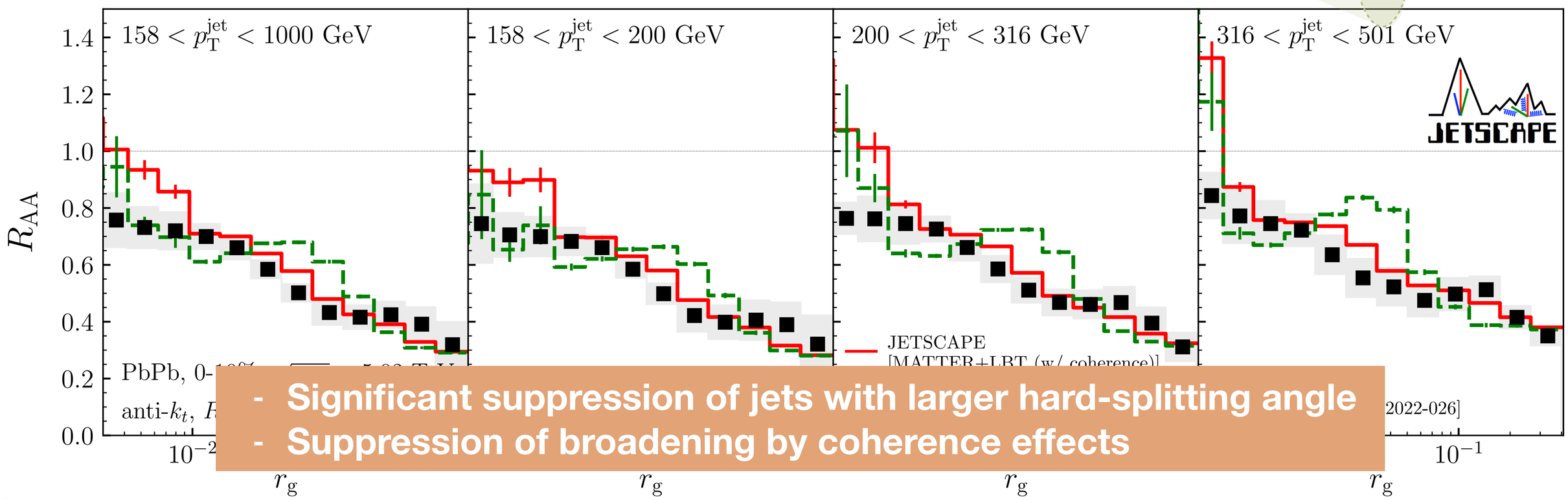
Jet substructures

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





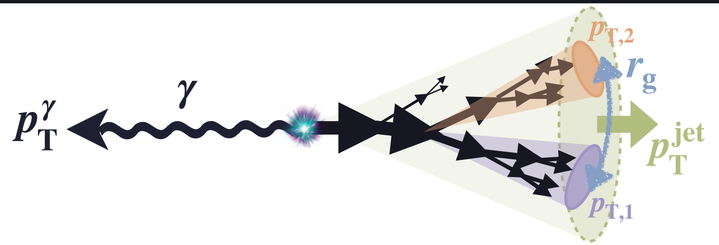
- **Significant suppression of jets with larger hard-splitting angle**
- **Suppression of broadening by coherence effects**

Jet substructures

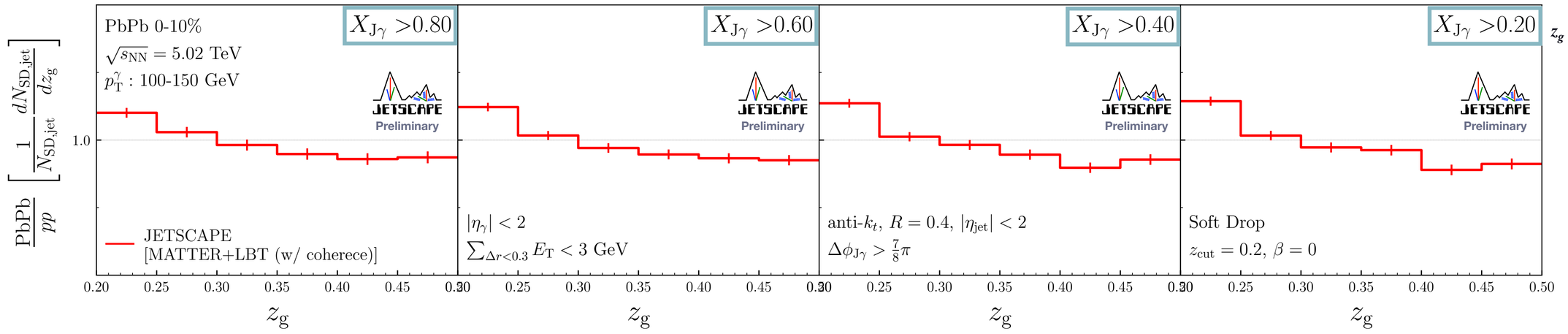
JETSCAPE, in preparation

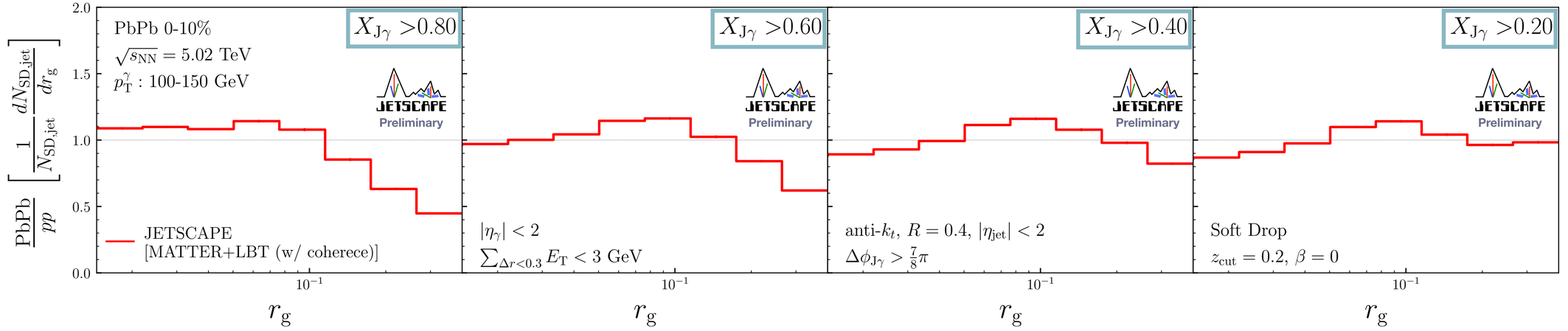
γ-tagged jet substructures

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



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



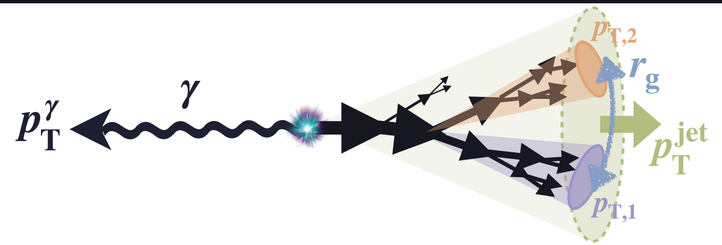


Jet substructures

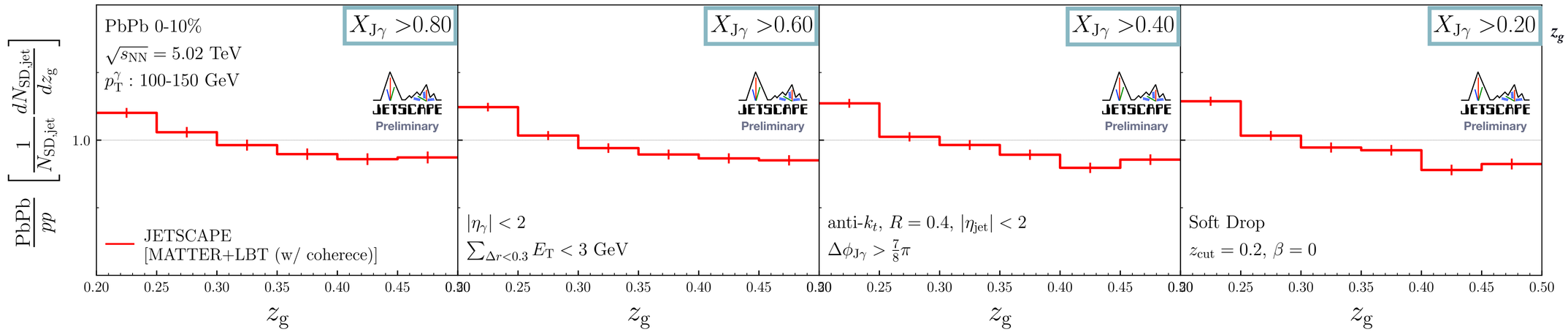
JETSCAPE, in preparation

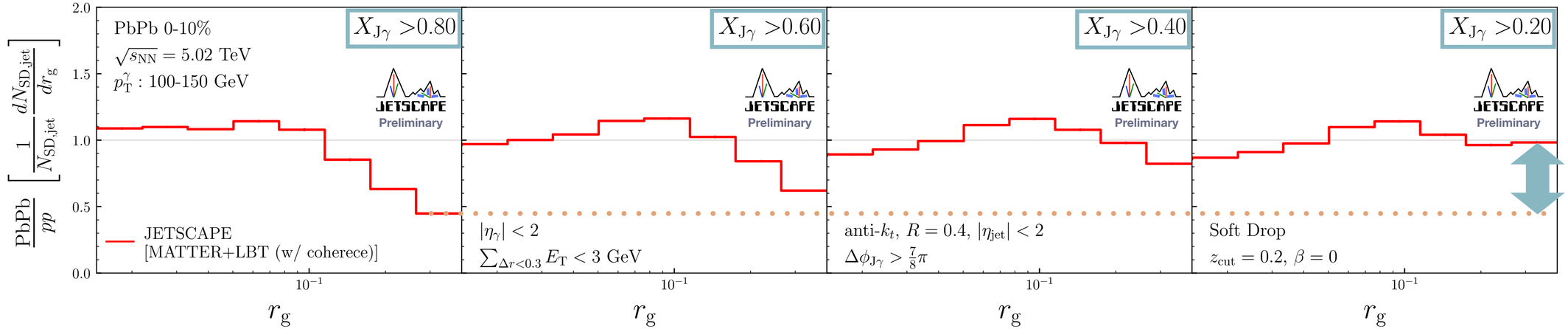
γ-tagged jet substructures

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



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



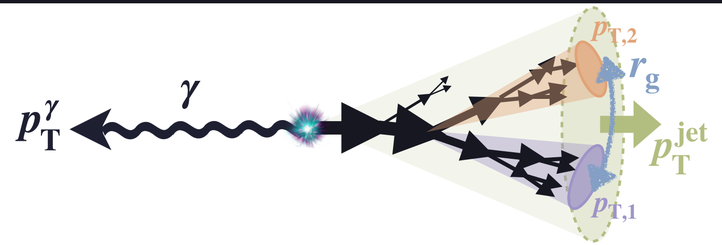


Jet substructures

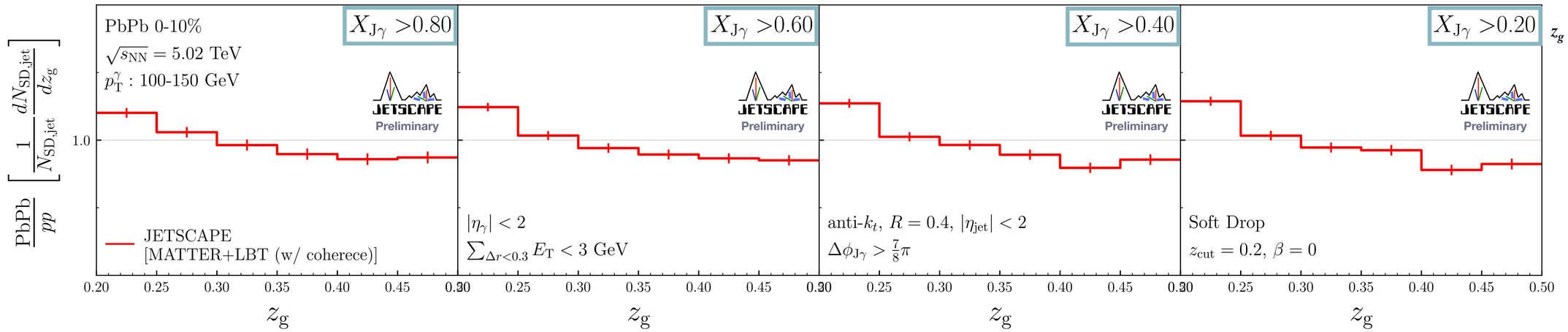
JETSCAPE, in preparation

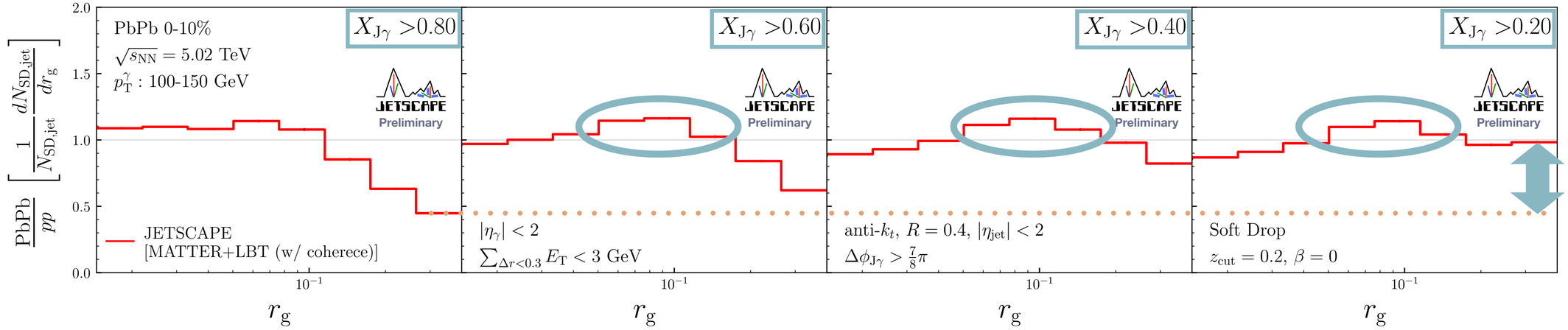
γ-tagged jet substructures

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



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

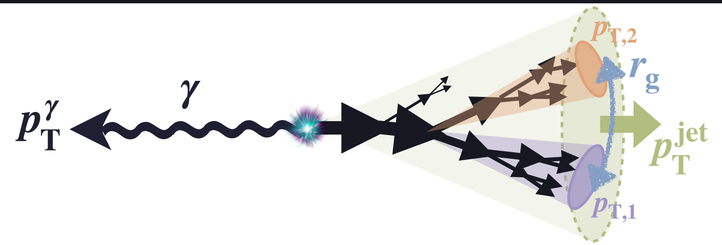




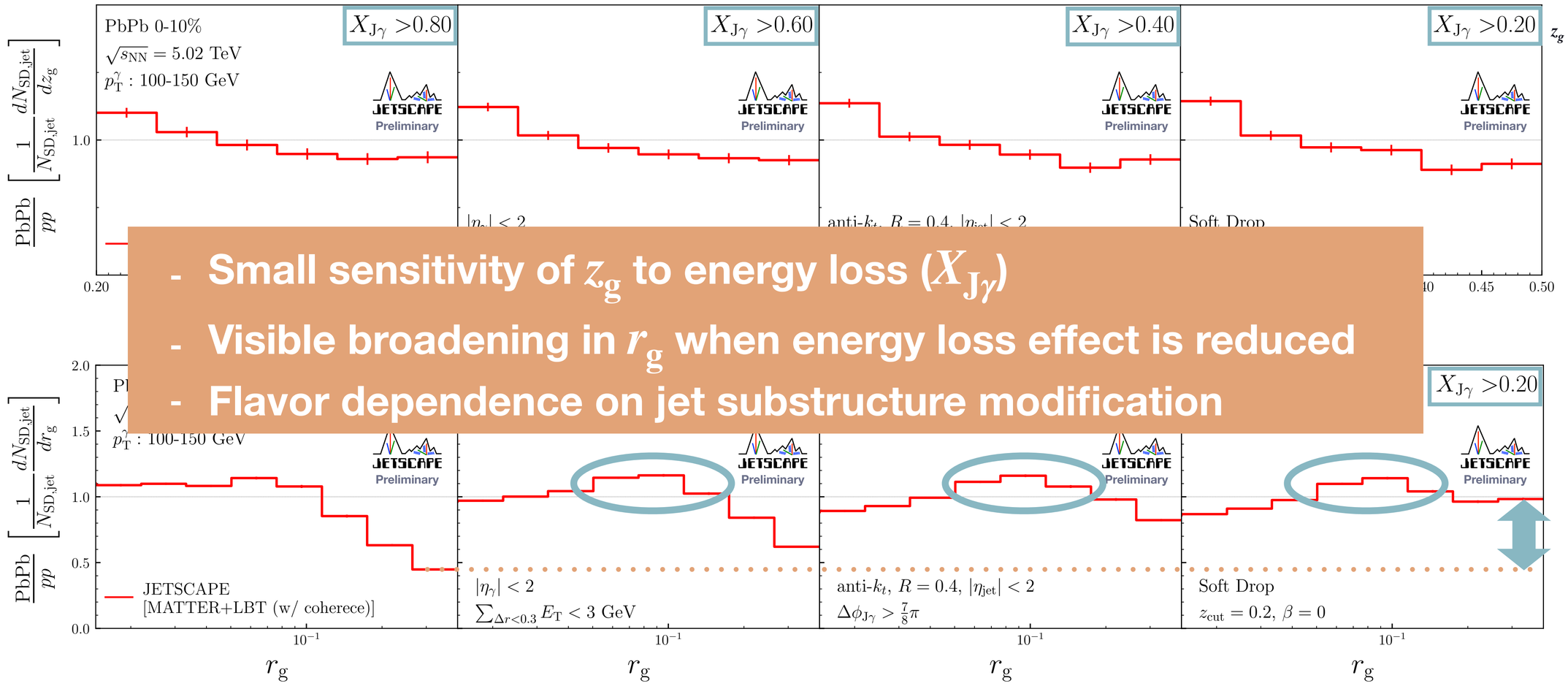
Jet substructures

JETSCAPE, in preparation

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



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



- **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

JETSCAPE Collaboration

Thanks to my collaborators!

- **Presentations at Hard Probes 2023**
  - Bayesian jet studies

    Talk by Y. Chen [Tue, 16:30]
  - Heavy quarks

    Talk by G. Vujanovic [Wed, 15:20]
  - Small systems

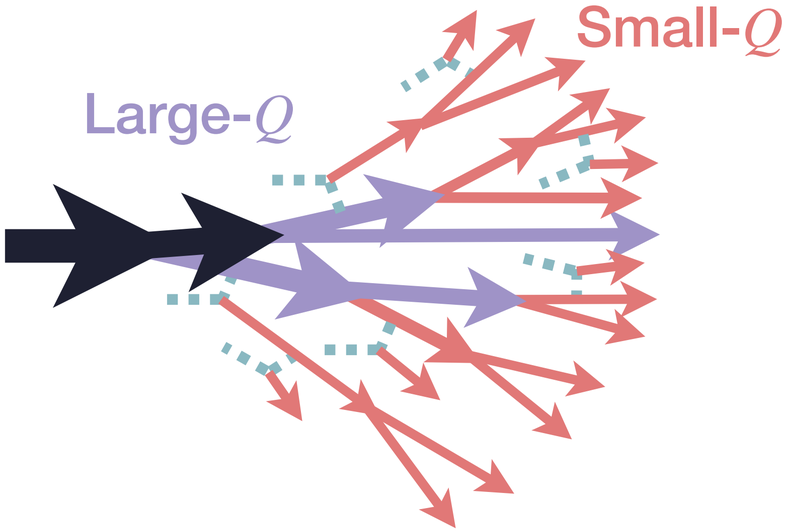
    Talk by A. Majumder [Tue, 17:50]
  - Hybrid (string+reco) hadronization

    Talk by C. Parker [Thu, 9:20]
  - Extensive Bayesian jet studies

    Poster by P. M. Jacobs [Tue, 18:15]

Multi-stage jet evolution in JETSCAPE

JETSCAPE, PRC96, 024909 (2017)

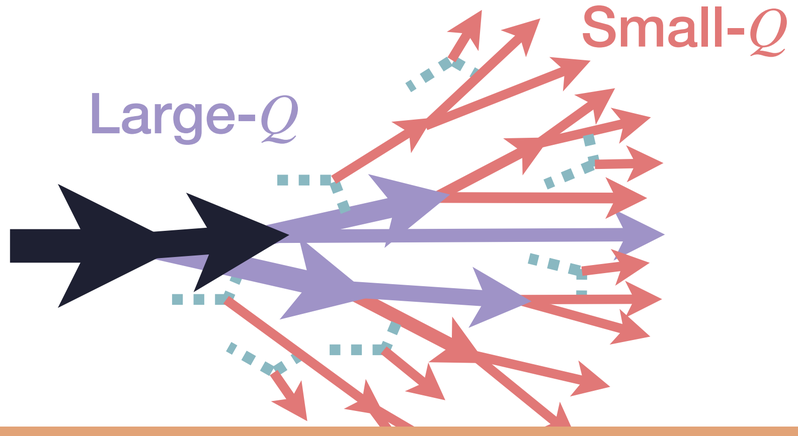


Virtuality separation scale: Q_{sw}

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)



Switching between modules for parton by parton

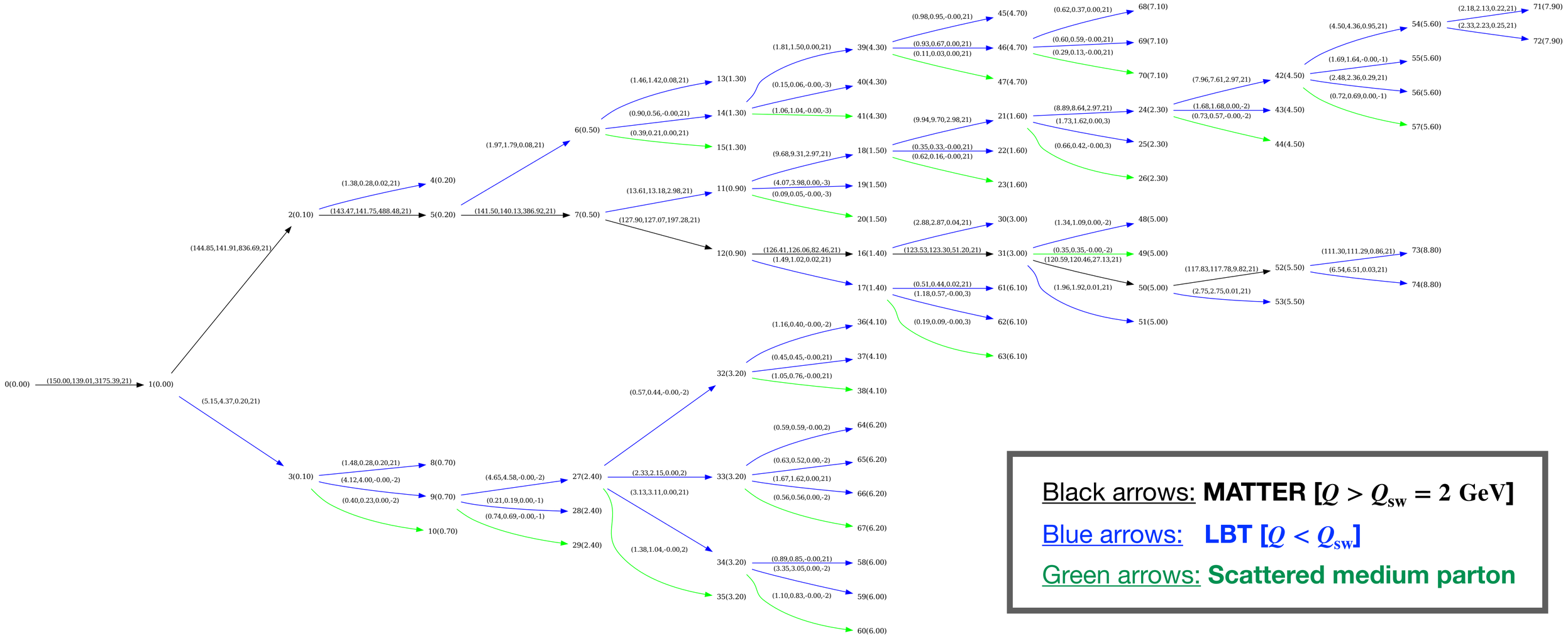
aration scale: Q_{sw}

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]**

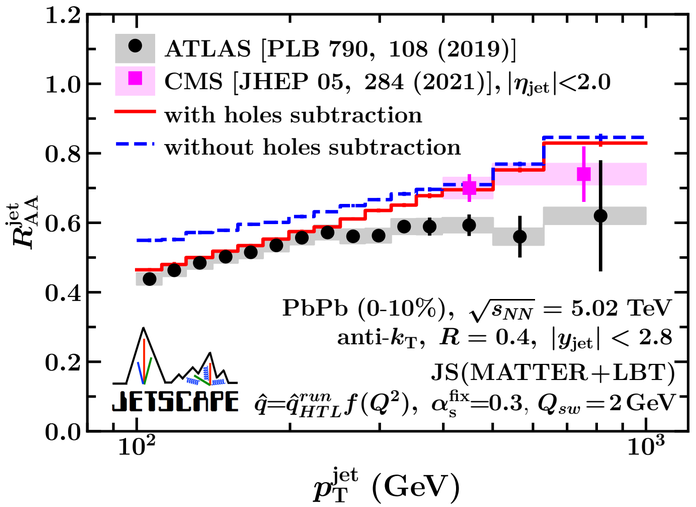
Blue arrows: **LBT [$Q < Q_{sw}$]**

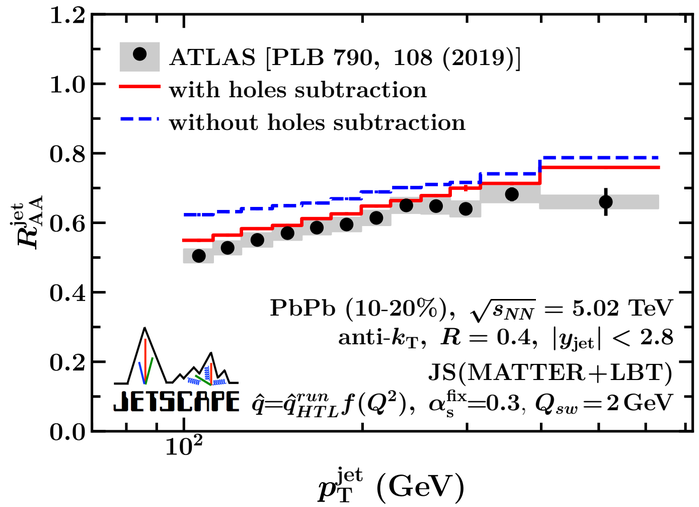
Green arrows: **Scattered medium parton**

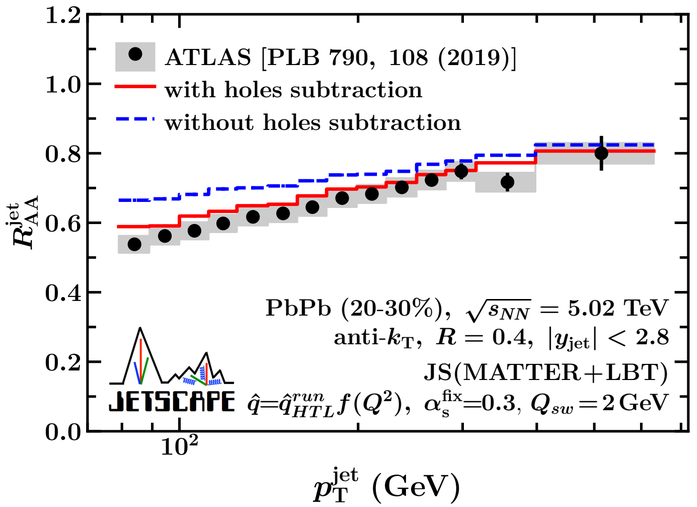
Centrality dependence

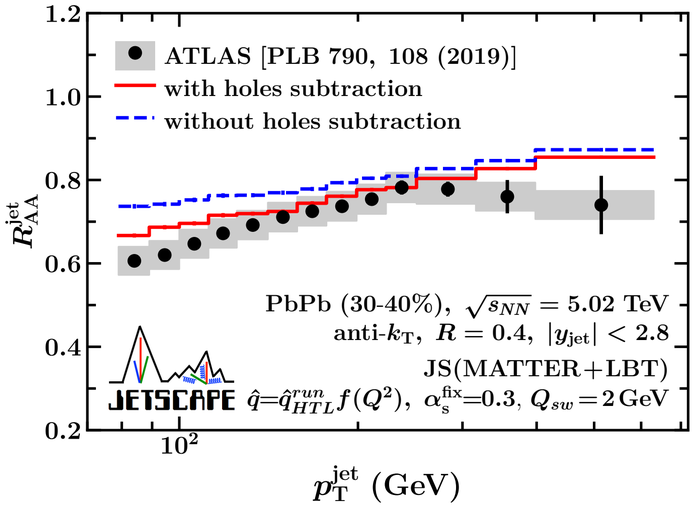
JETSCAPE, PRC107, 034911 (2023)

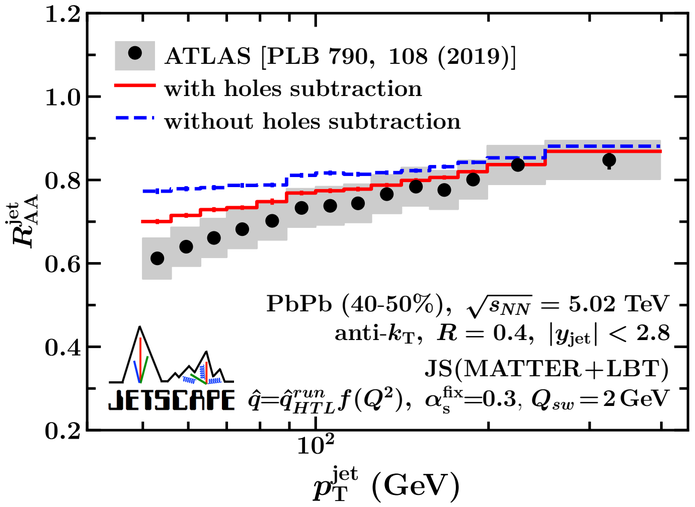
- **Inclusive jet R_{AA} in Pb+Pb collisions at 5.02 TeV**

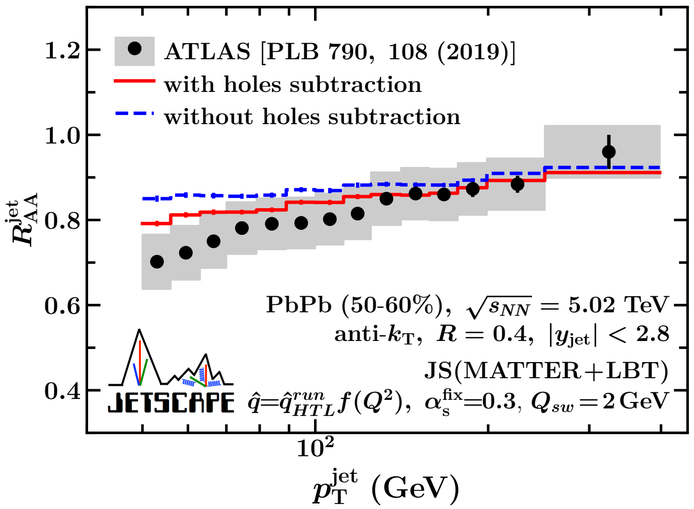








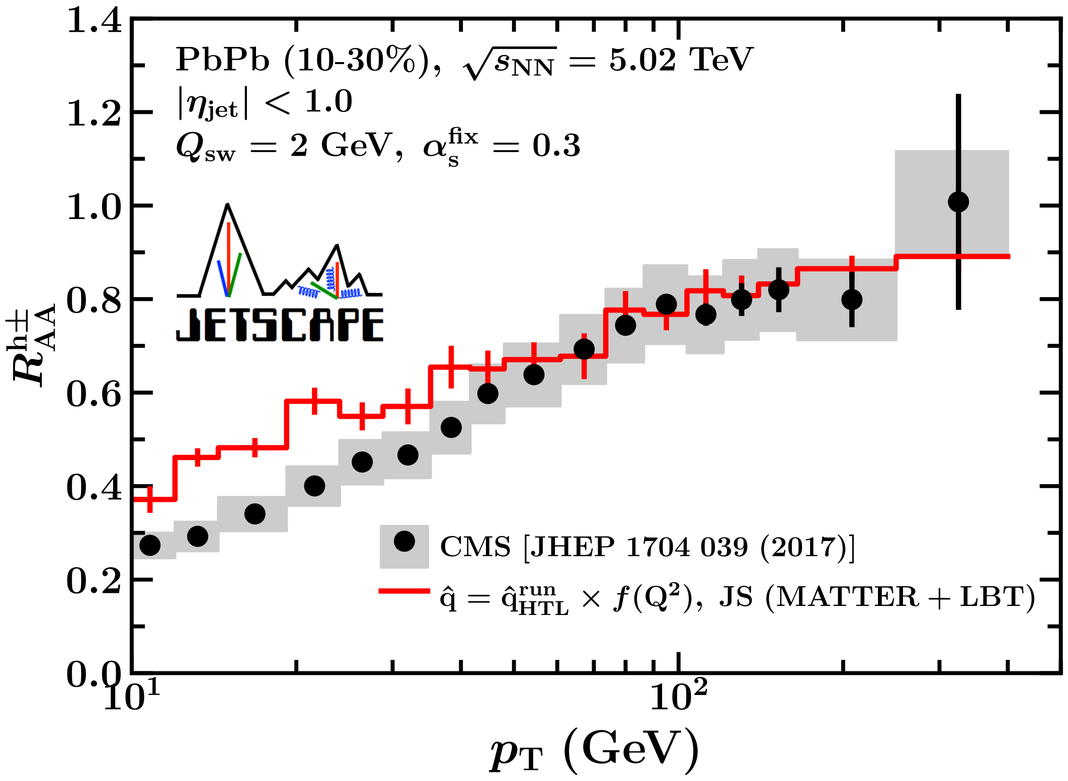


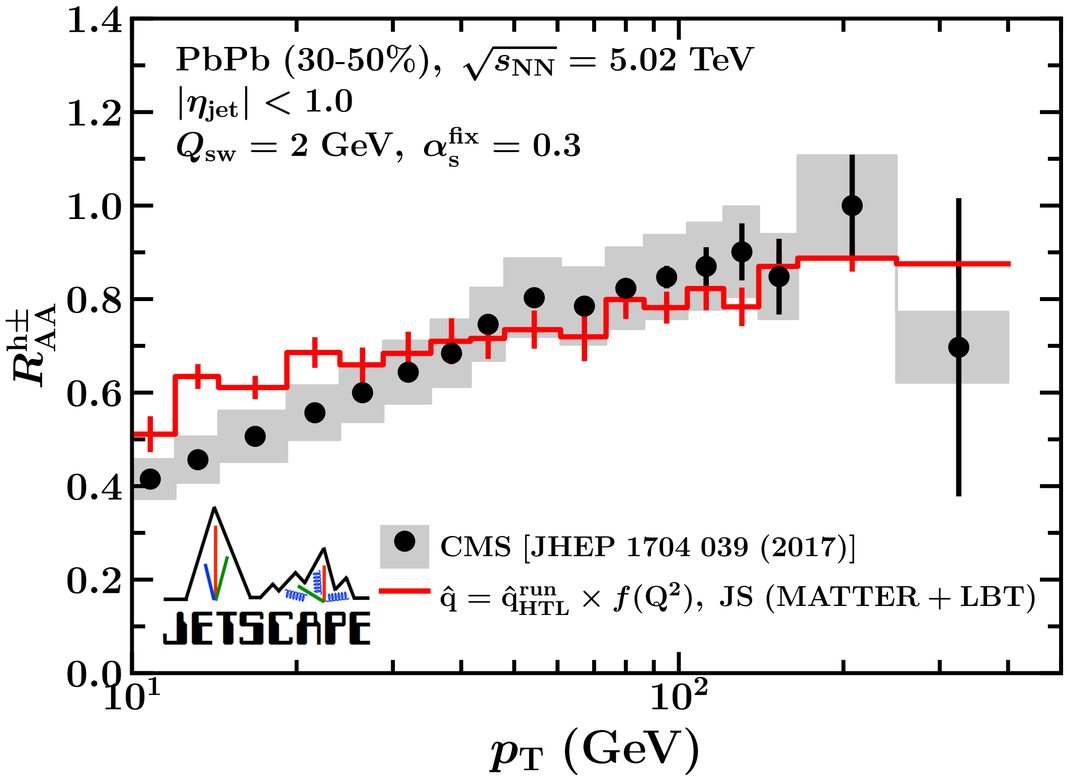


Centrality dependence

JETSCAPE, PRC107, 034911 (2023)

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

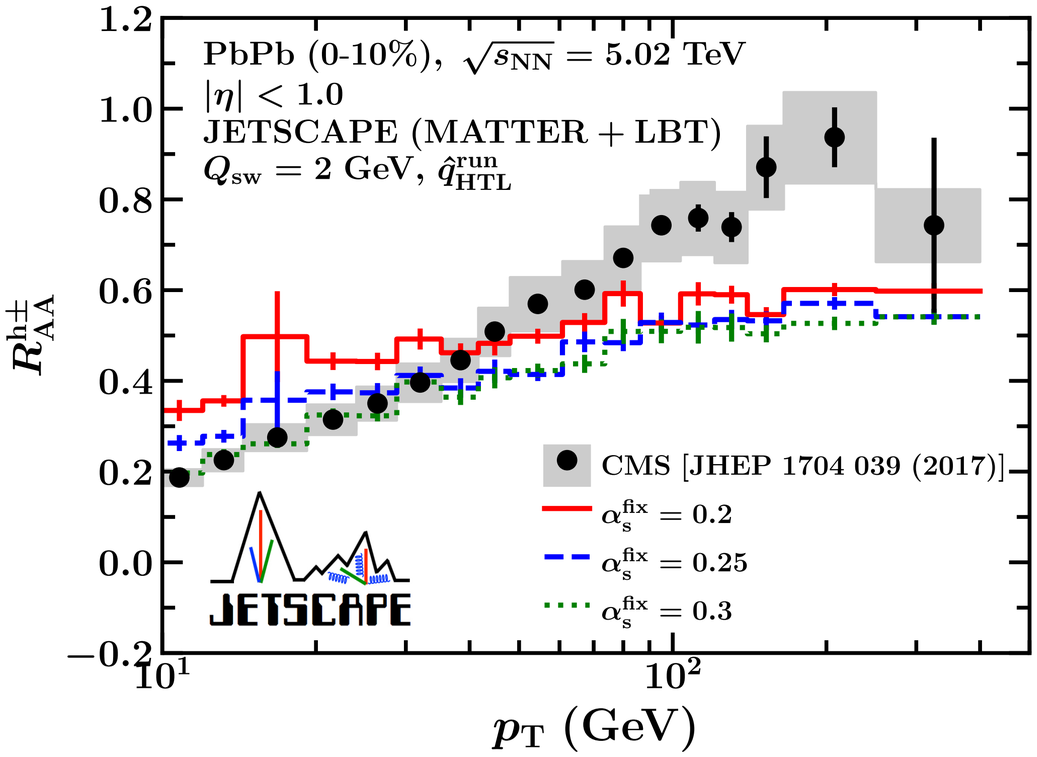


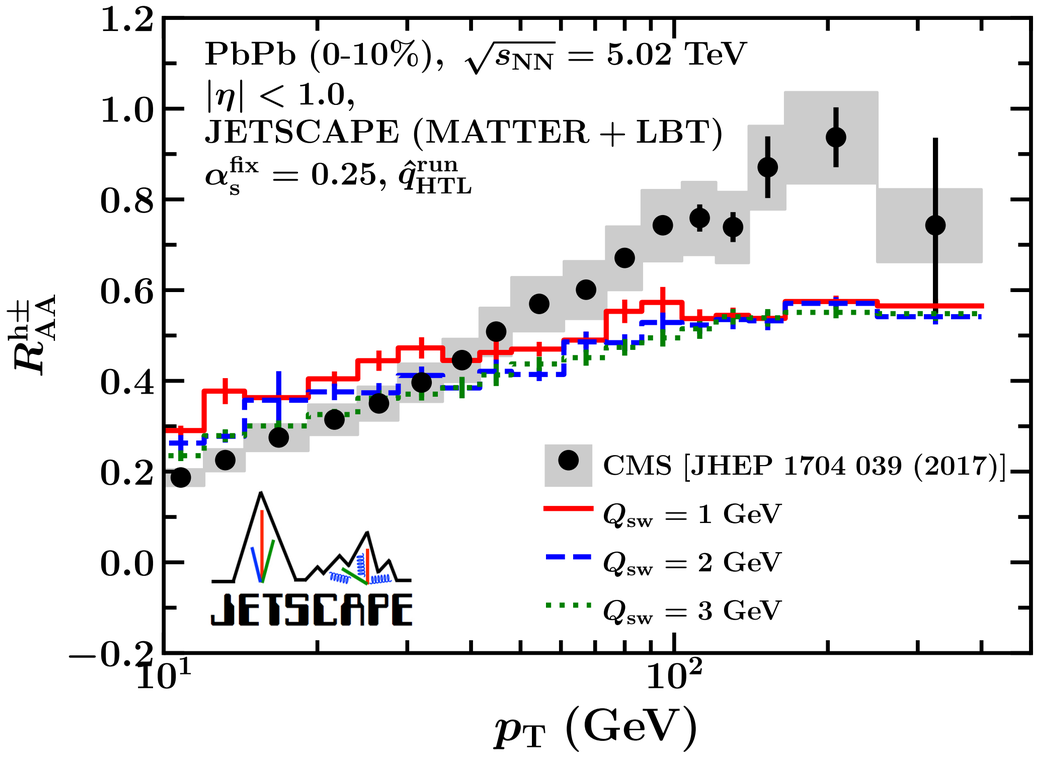


$\alpha_s^{\rm fix}$, $Q_{\rm sw}$ dependence

JETSCAPE, PRC107, 034911 (2023)

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





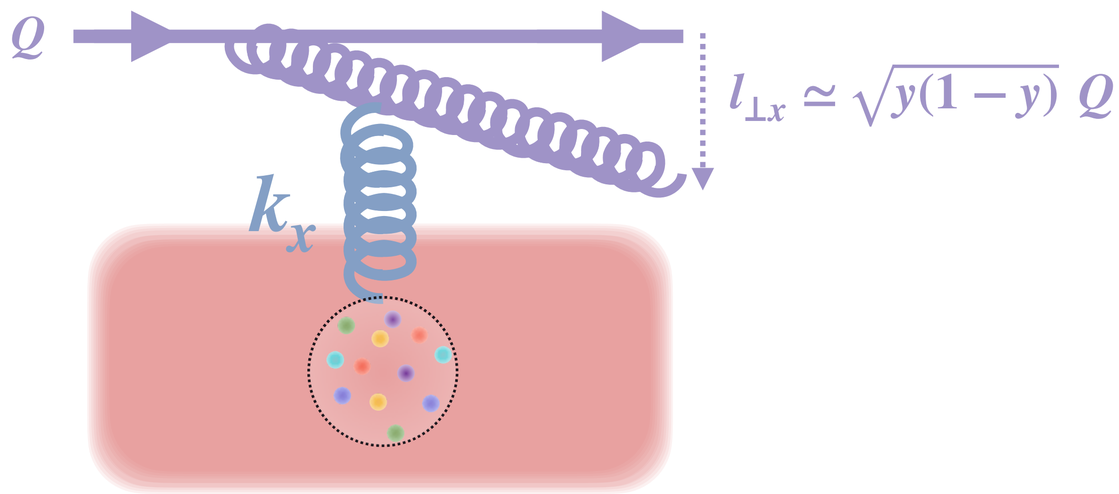
Coherence effects at high virtuality

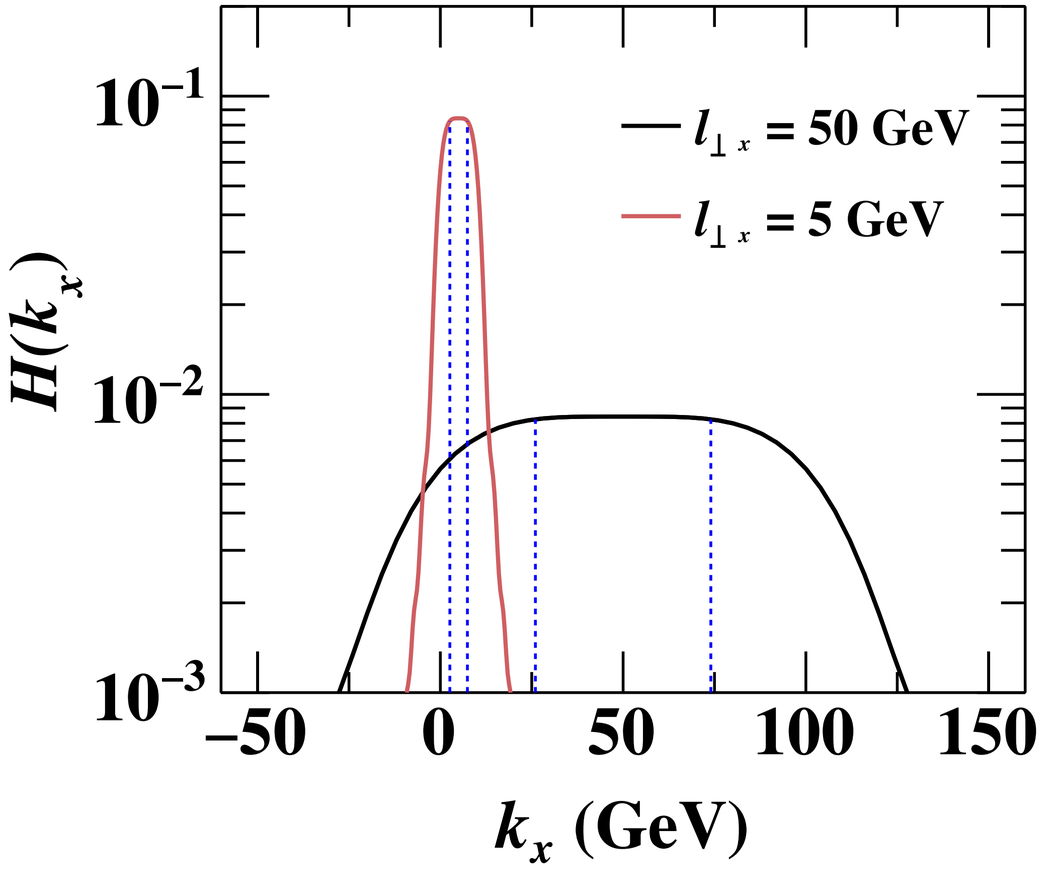
- **Spectrum of induced gluons (Higher-Twist)**

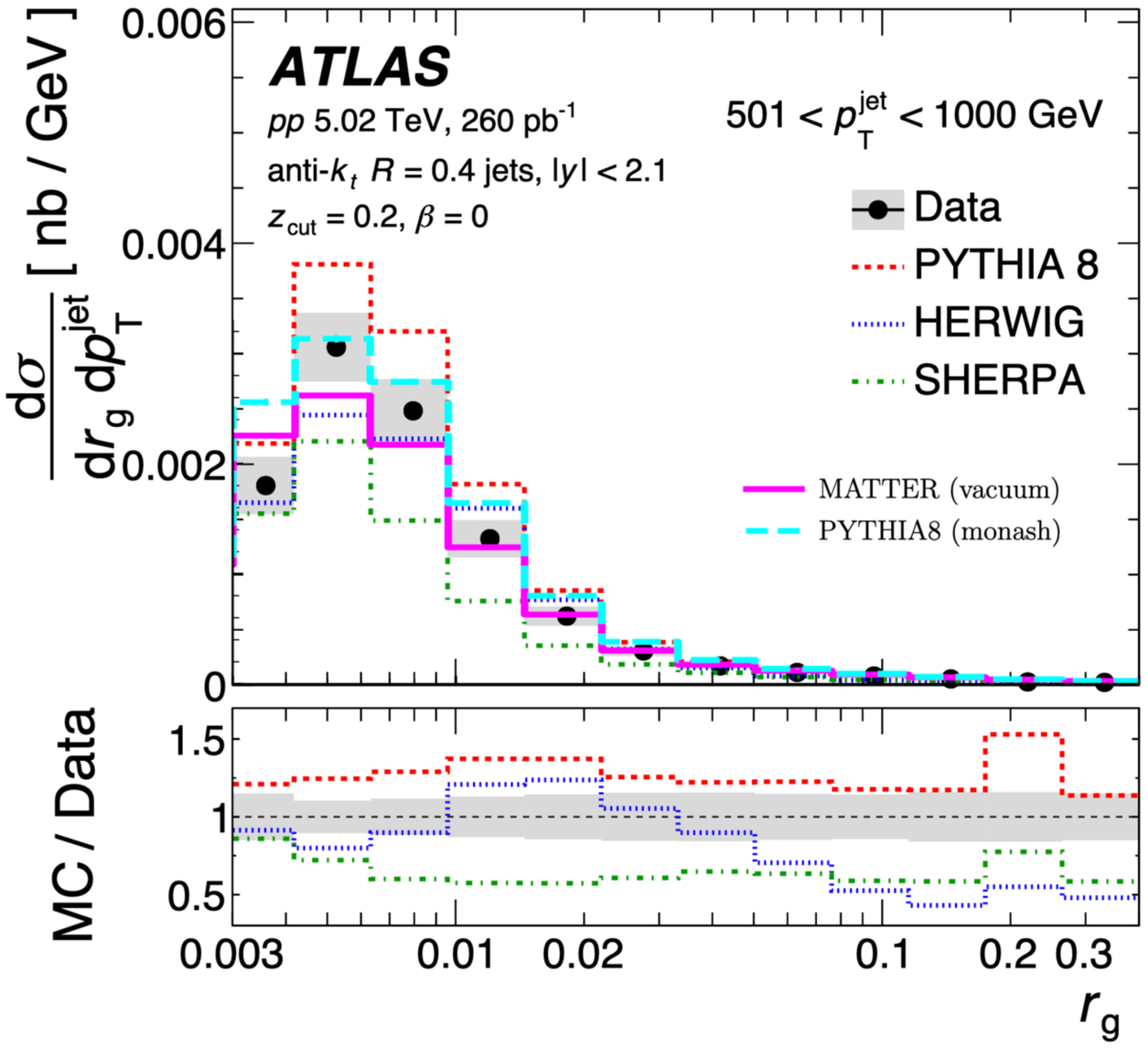
Kumar, Majumder, Shen, PRC101, 034908 (2020)

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

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






ATLAS
pp 5.02 TeV, 260 pb-1
anti-kt R = 0.4 jets, |y| < 2.1
zcut = 0.2, β = 0
501 < pTjet < 1000 GeV
Data
PYTHIA 8
HERWIG
SHERPA
MATTER (vacuum)
PYTHIA8 (monash)
dσ / dr_g dp_T^jet [nb / GeV]
MC / Data
r_g