Substructures of gamma-tagged jets in a multistage approach

JETSCAPE, Phys. Rev. C 111, 064911 (2025); Phys. Rev. C 113, 034910 (2026)

Yasuki Tachibana

for the JETSCAPE Collaboration

C3NT Workshop: Jet-soft dynamical medium interaction in high-energy heavy-ion collisions

March 24th, 2026

Soft-drop groomed jet substructures

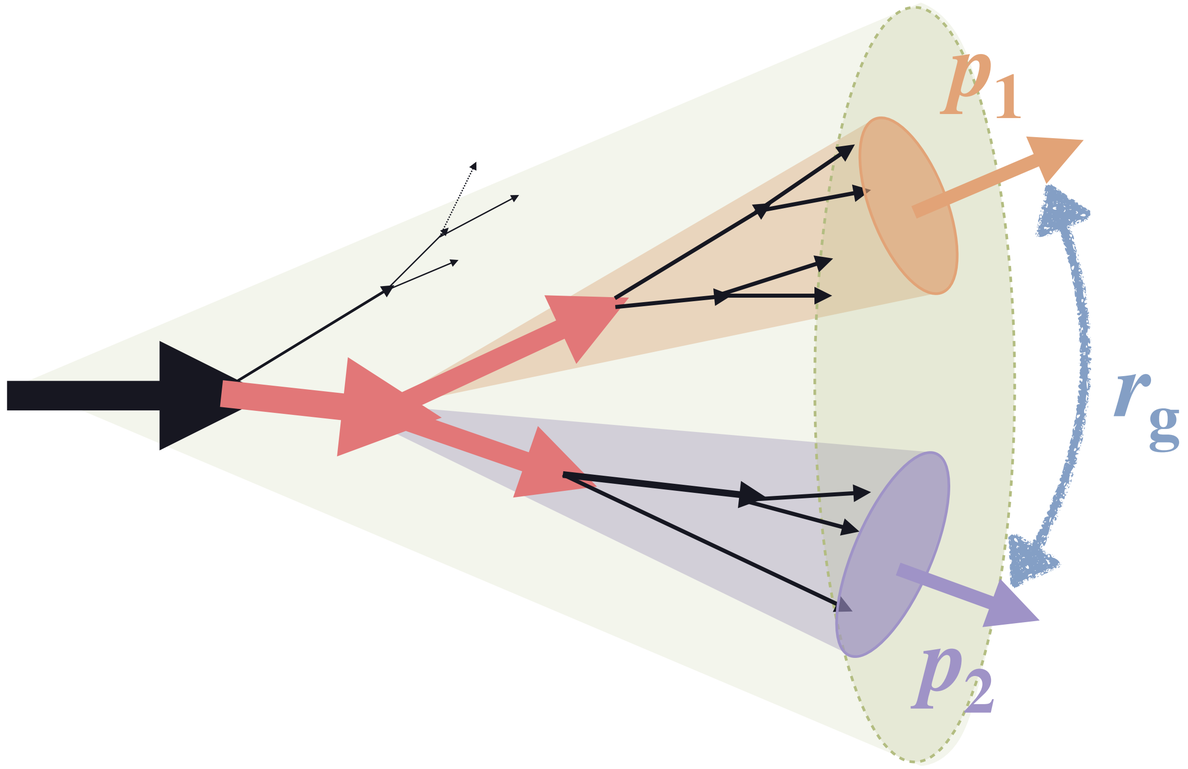
A. J. Larkoski, S. Marzani, G. Soyez and J. Thaler, JHEP 05, 146 (2014)

- **Hard splitting identified by Soft Drop**

  - Largest angular branching with a sufficient momentum fraction ($z_g > z_{\rm cut}$) within a jet

  - Relatively well dominated by perturbative vacuum parton splitting

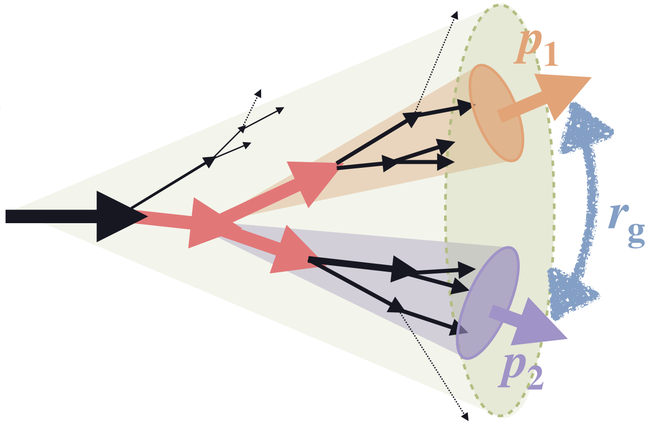
$$z_{\rm g} = \frac{\min\{p_{\rm T,1}, p_{\rm T,2}\}}{p_{\rm T,1} + p_{\rm T,2}}$$



Soft-drop groomed substructures modification in inclusive jets

- **Medium effects on inclusive jet substructure**

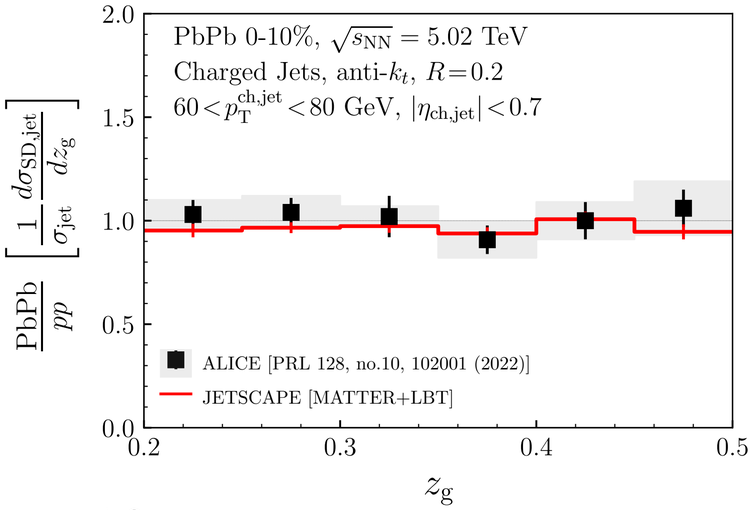
$$z_g = \frac{\min\{p_{T,1}, p_{T,2}\}}{p_{T,1} + p_{T,2}}$$

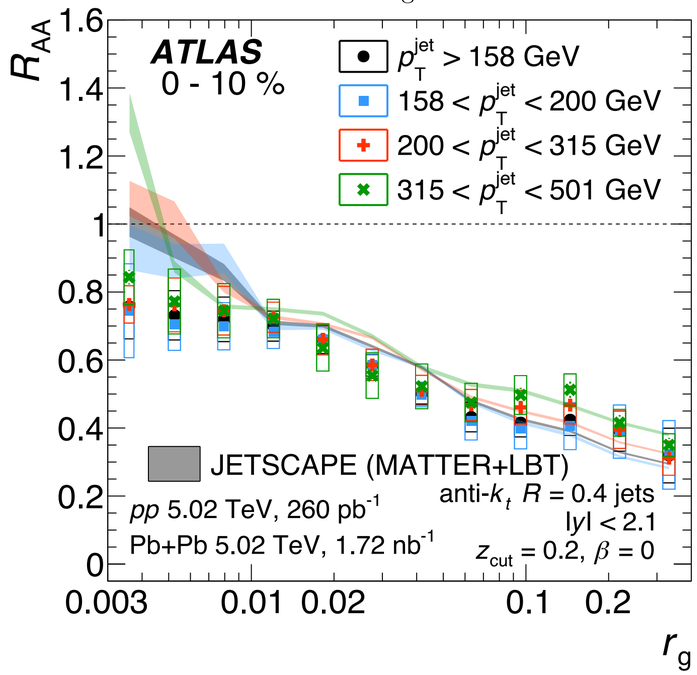


- Barely noticeable modification in z_g
- Narrower splittings in jets with medium effects
- Trigger jets by jet-p_T (after energy loss)

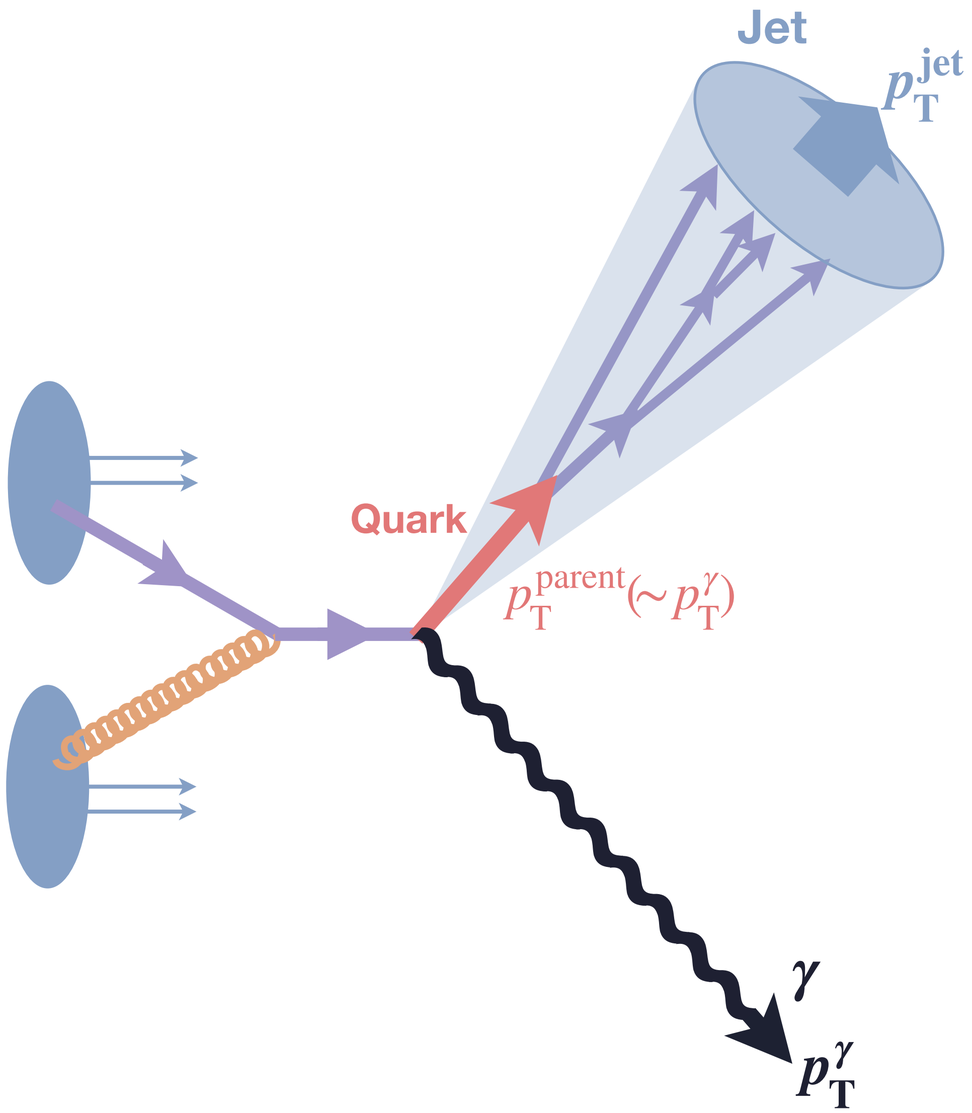
- Actual substructure modification?
- Selection bias (substructure dependence in E-loss)?

JETSCAPE, Phys. Rev. C 110, 044907 (2024)





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 ($p_{\mathrm{T}}^{\gamma} \sim p_{\mathrm{T}}^{\mathrm{parent}}$)

- Exploring flavor dependence with $x_{\mathrm{J}\gamma}$
- Controlling the effects of selection bias with energy loss measure $x_{\mathrm{J}\gamma}$

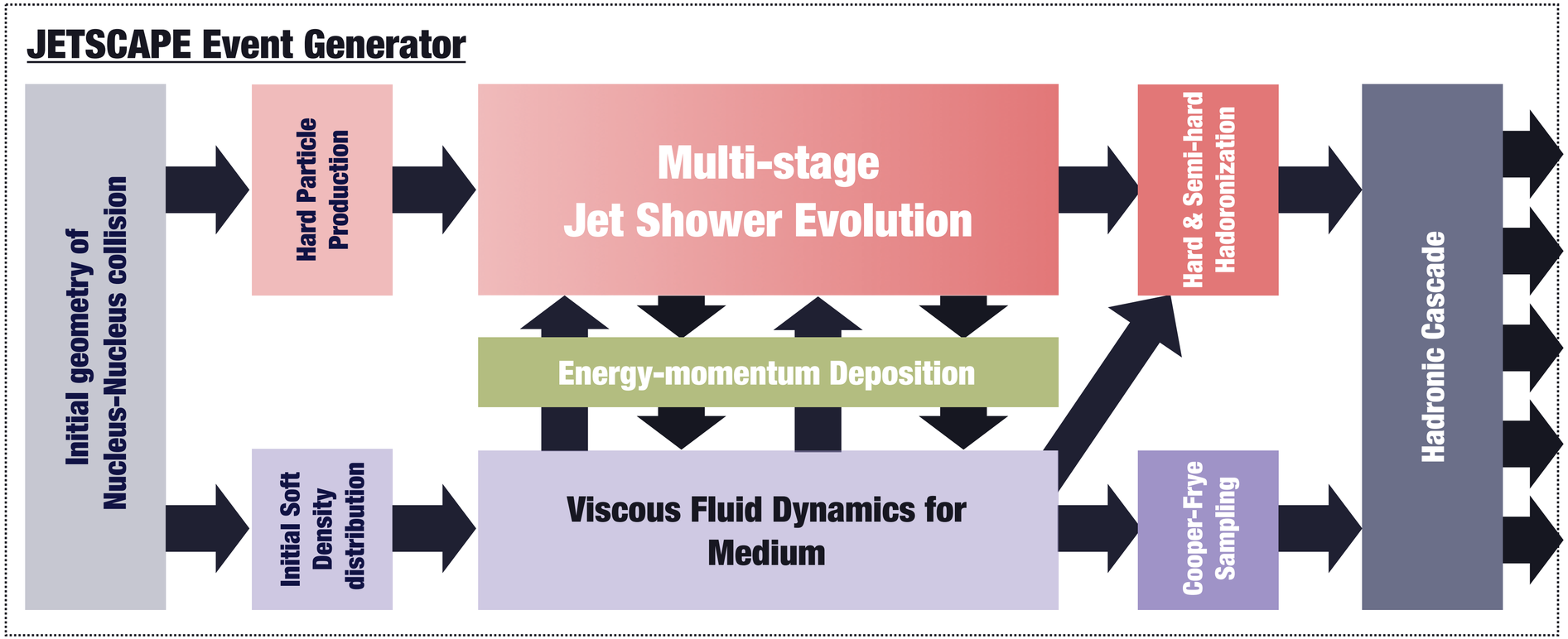
- γ-jet assymetry: $x_{J\gamma} = \dfrac{p_{\mathrm{T}}^{\mathrm{jet}}}{p_{\mathrm{T}}^{\gamma}}$

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



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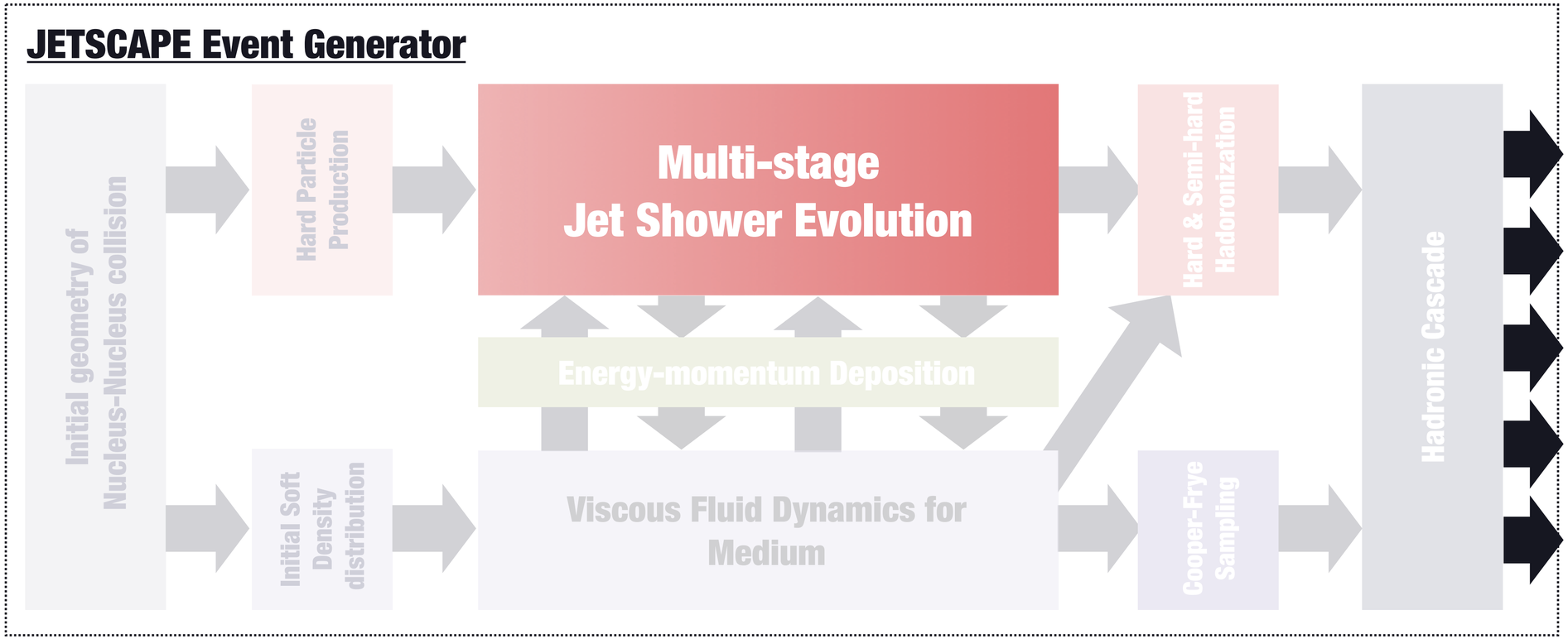


Multi-stage jet evolution in JETSCAPE

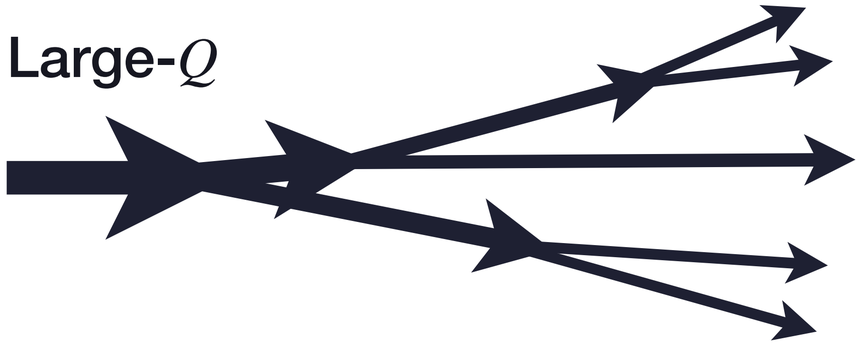
Majumder, Putschke, PRC 93, 054909 (2016), JETSCAPE, PRC96, 024909 (2017)

In-vacuum

- In-vacuum: Virtuality ordered splitting

Small-Q

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

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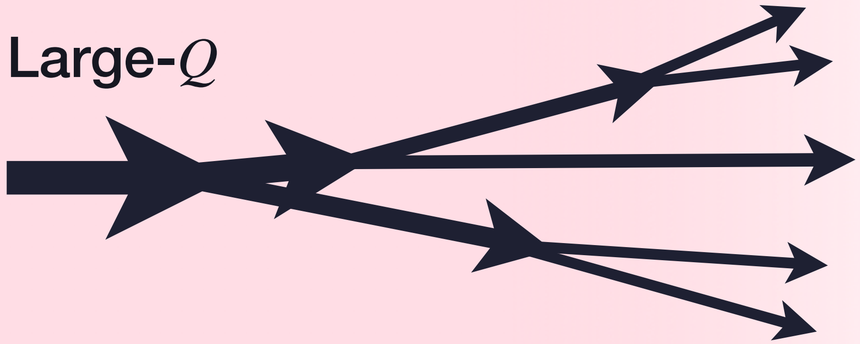

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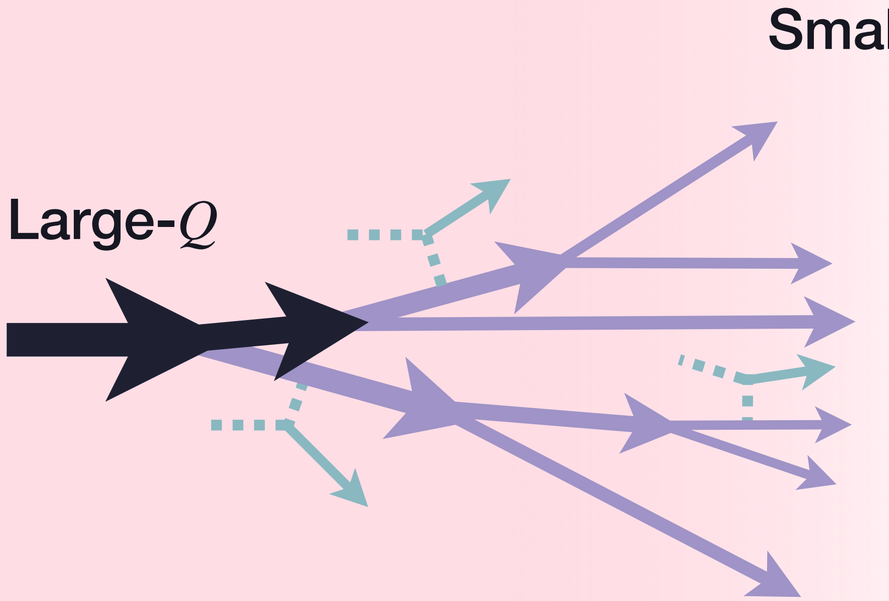

- Large-Q: Medium effect on top of in-vacuum splitting

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

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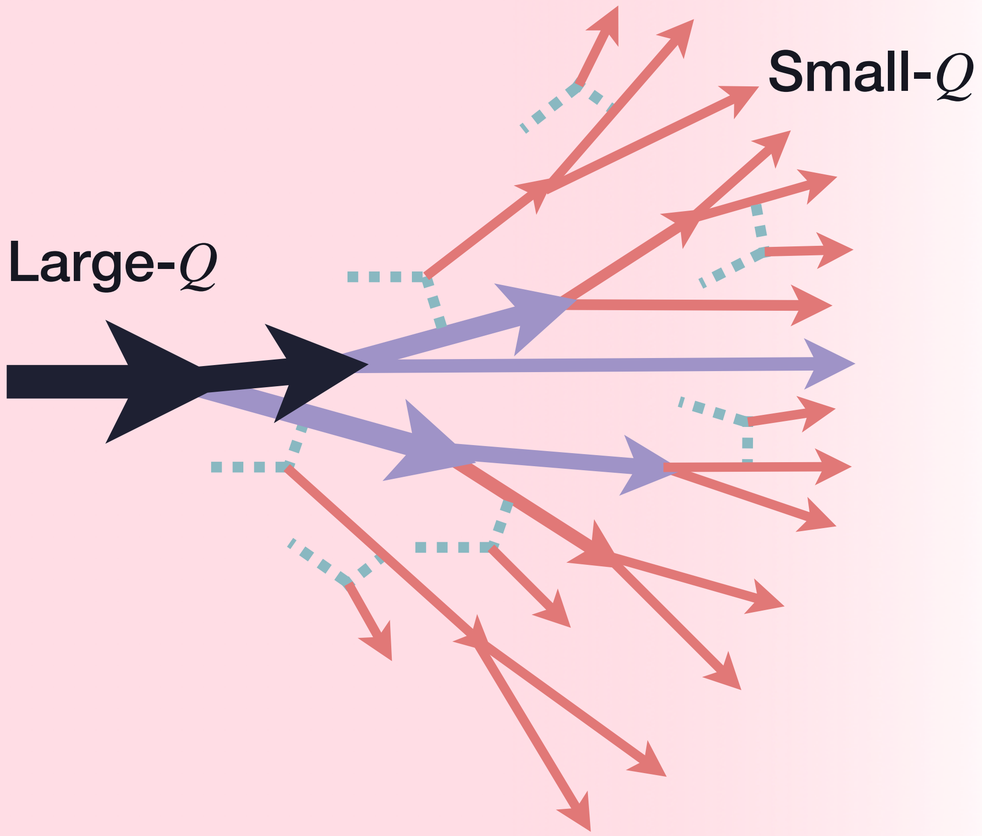

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- Large-Q: Medium effect on top of in-vacuum splitting
- Small-Q: Splitting driven almost purely by medium effects

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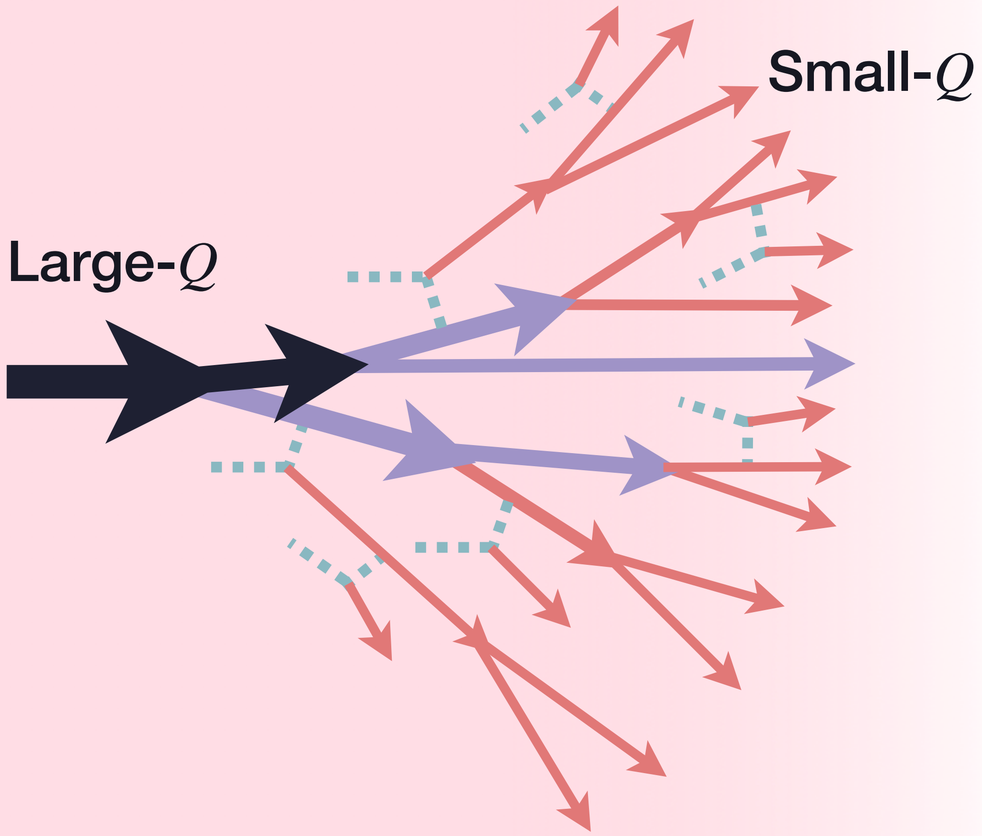

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- In-vacuum: Virtuality ordered splitting

- 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.

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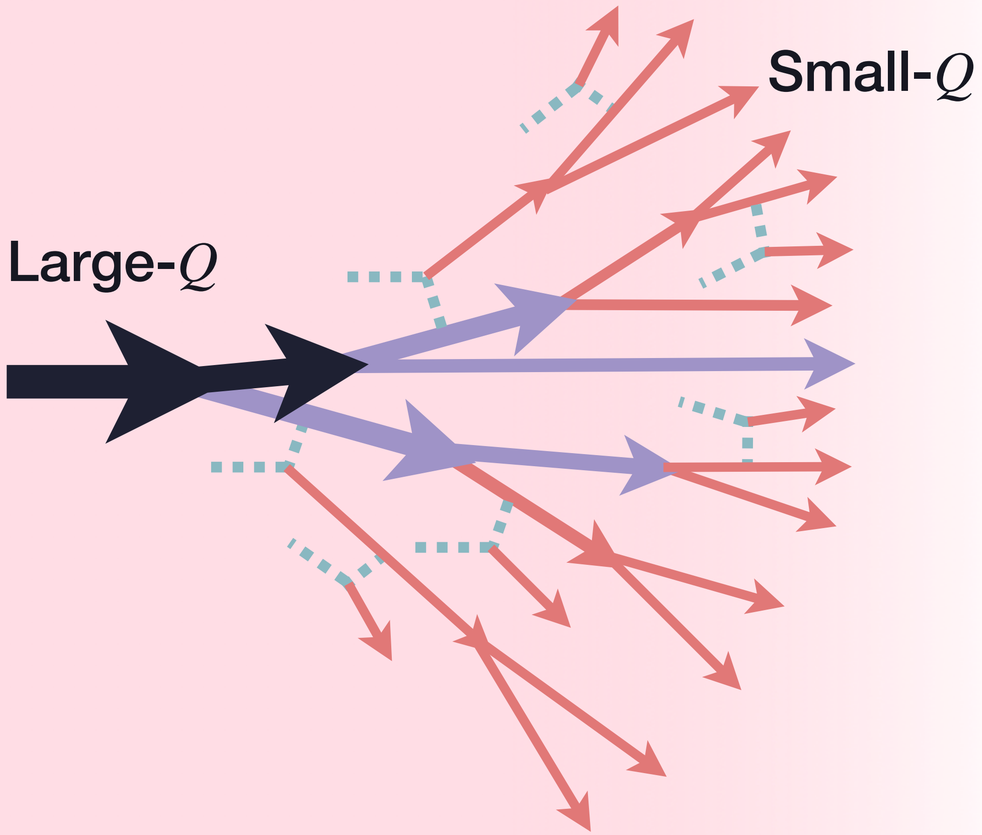

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- In-vacuum: Virtuality ordered splitting

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

$Q \geq Q_{\rm sw}$

Switching between modules for parton by parton

$Q < Q_{\rm sw}$

- 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, $Q_{\mathrm{sw}} = 2\ \mathrm{GeV}$)

Hadronization: Lund String

Initial Geometry

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

Bulk Medium

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

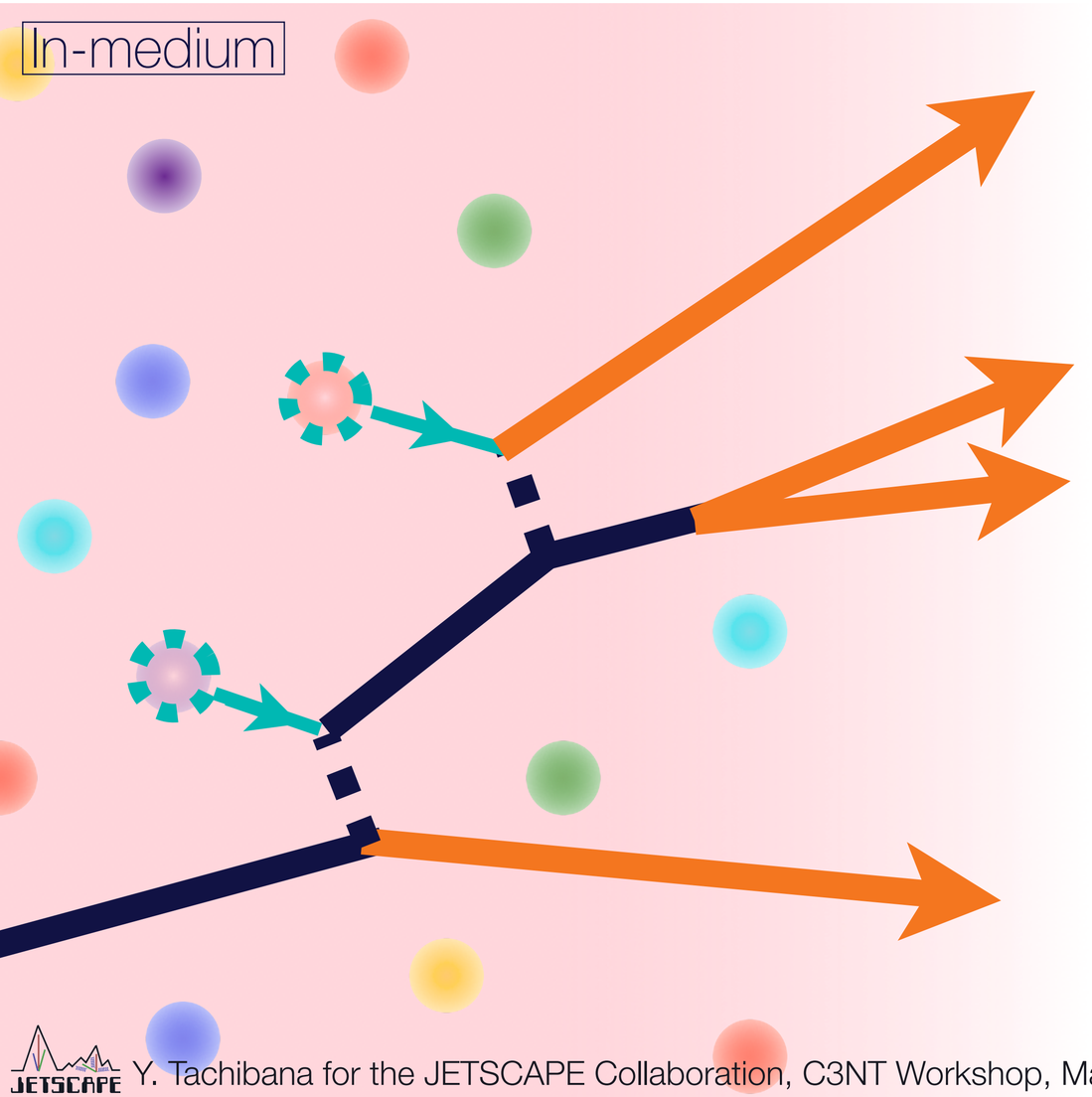
Prehydro Evolution: Freestreaming
Liu, Shen, Heinz(15)

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

Setups

- **Recoil medium response**

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)



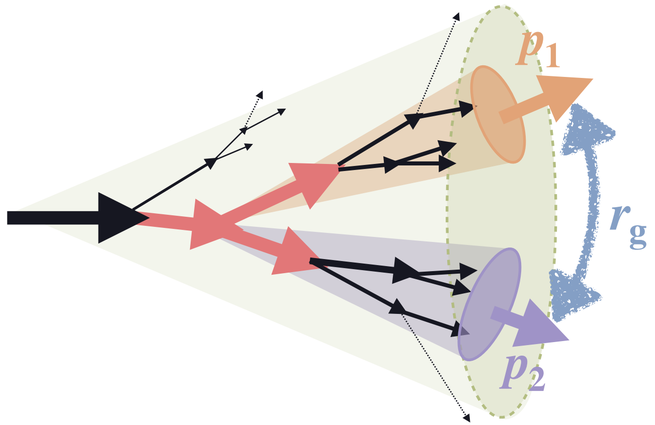
- Thermal medium partons kicked out by jet parton
- Propagate as part of the jet with subsequent medium interactions.
- Holes: local depletion left by recoils (free-streaming, separately hadronized for subtraction)

- Effective description of medium response
- Ensure energy momentum conservation

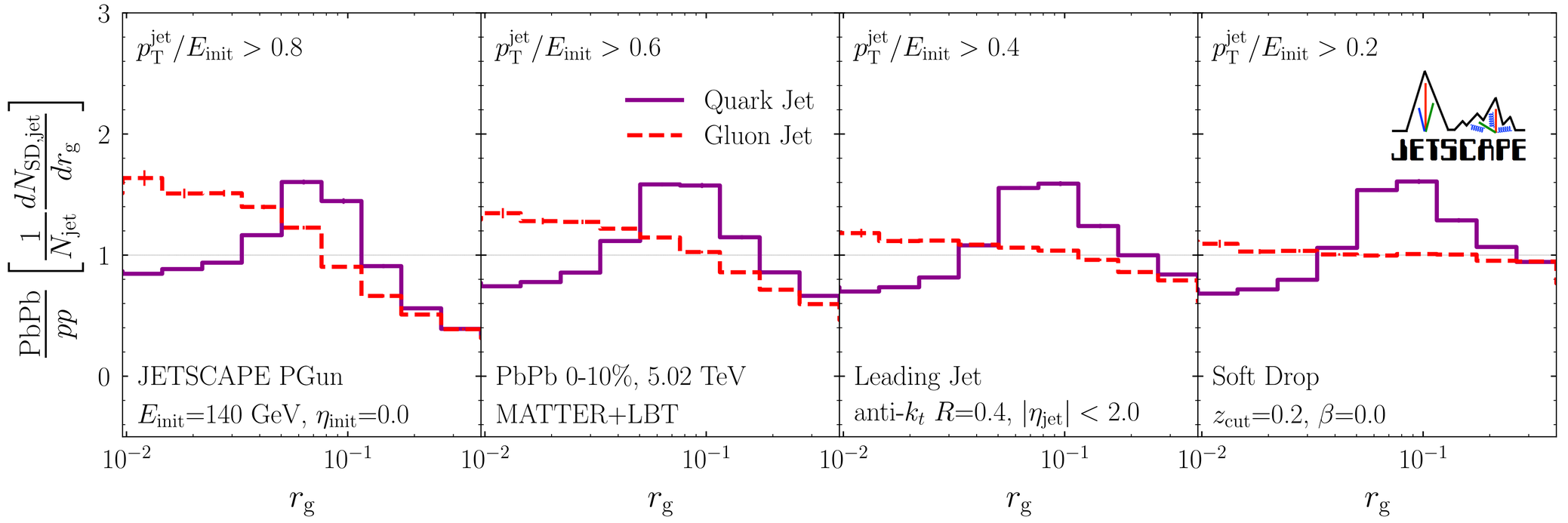
Results

r_g-modification: single parton simulations

JETSCAPE, Phys. Rev. C 113, 034910 (2026)



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



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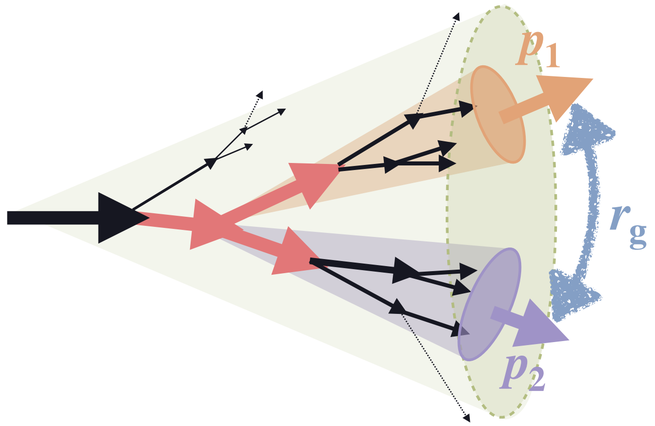
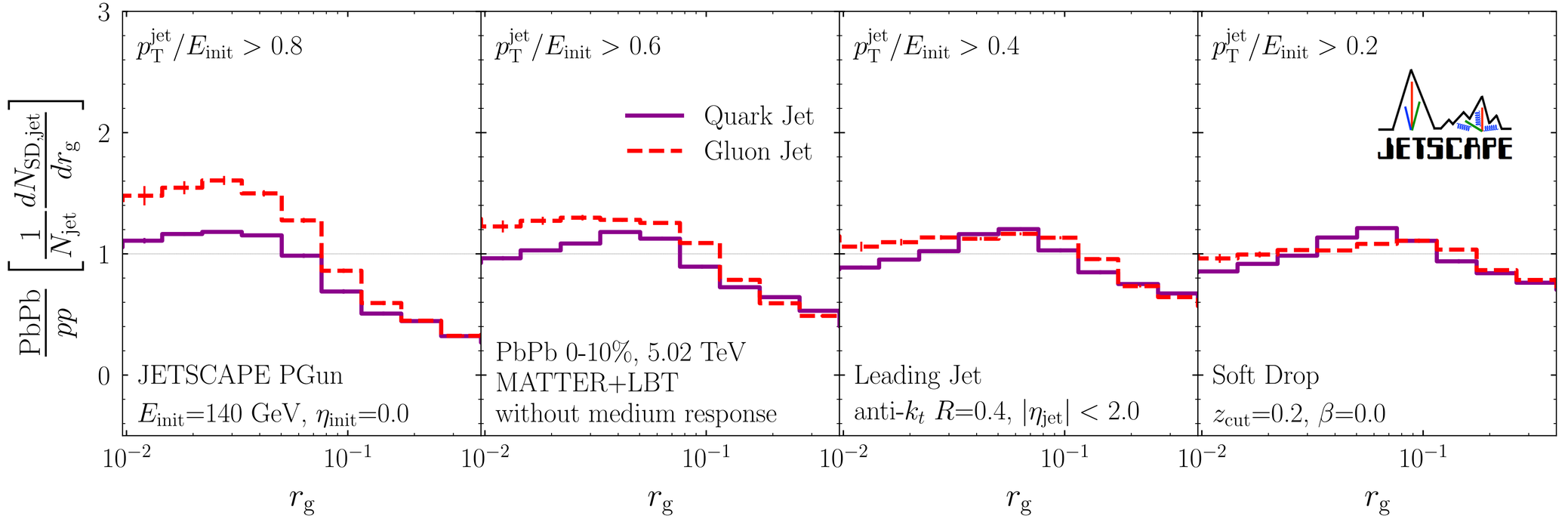


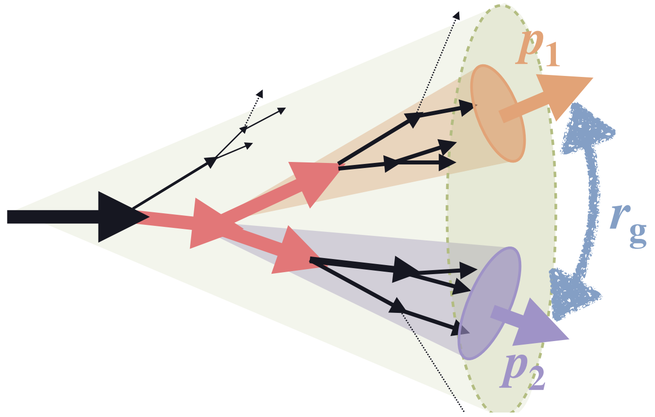
- Recoils dominate the bump in quark jets

Recoils and holes artificially removed

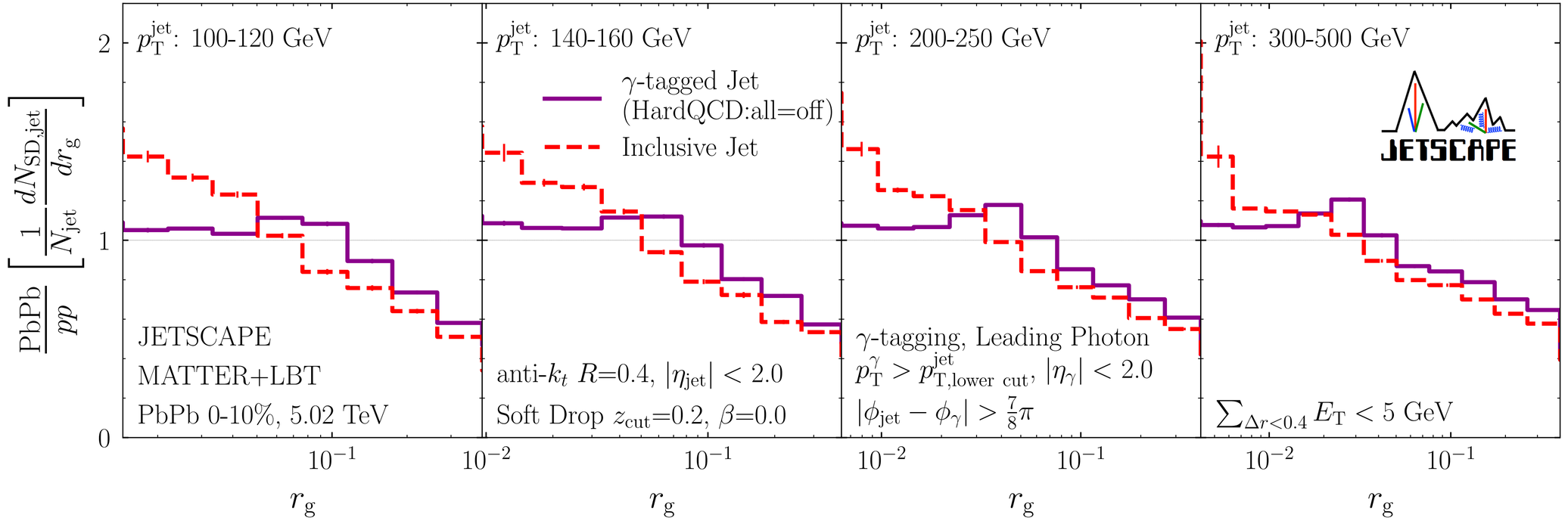


r_g-modification: inclusive vs γ-tagged

JETSCAPE, Phys. Rev. C 113, 034910 (2026)

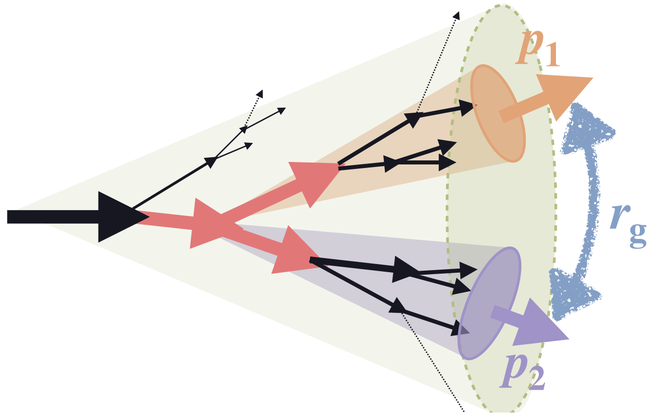


- Quark jet characteristics observed in γ-tagged jets
- Gluon jet characteristics observed in inclusive jets

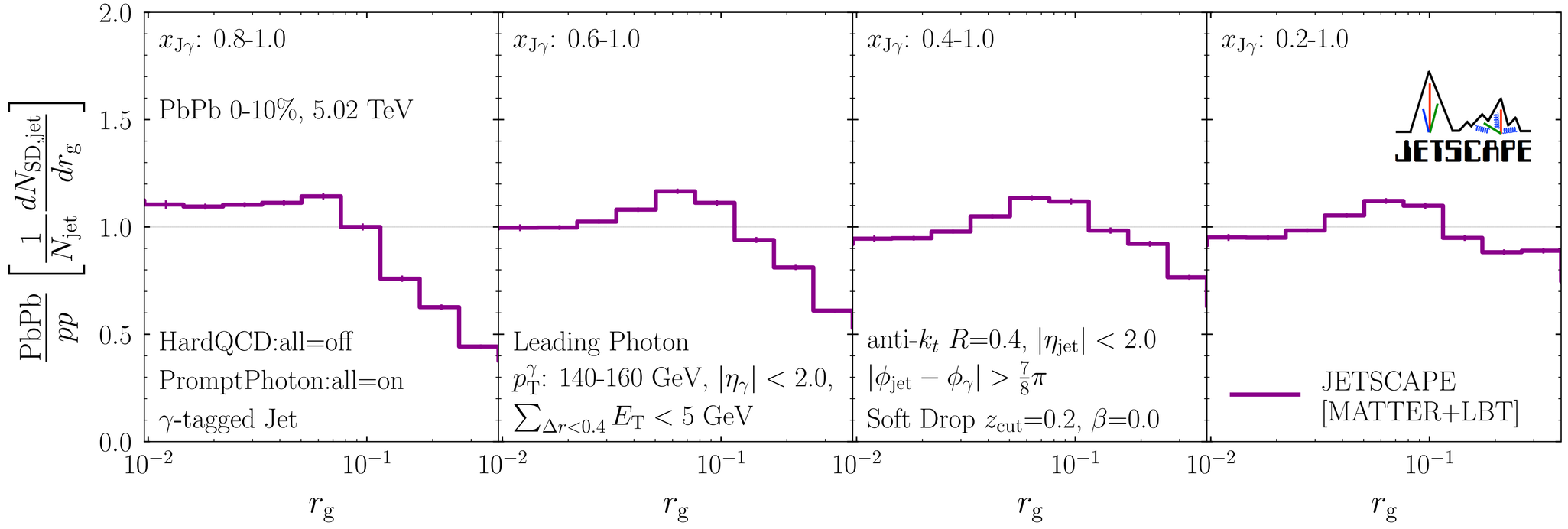


r_g-modification for γ-tagged

JETSCAPE, Phys. Rev. C 113, 034910 (2026)



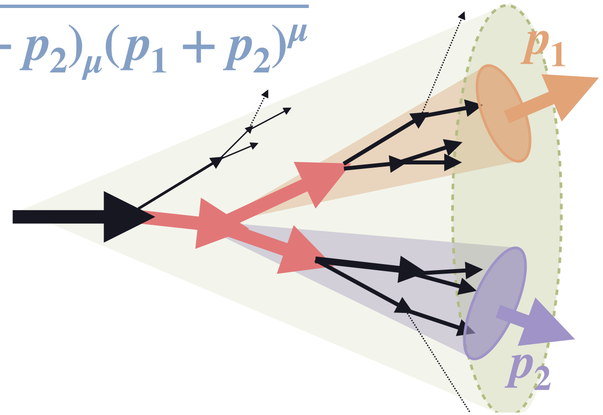
- Disappearance of narrowing due to reduced selection bias



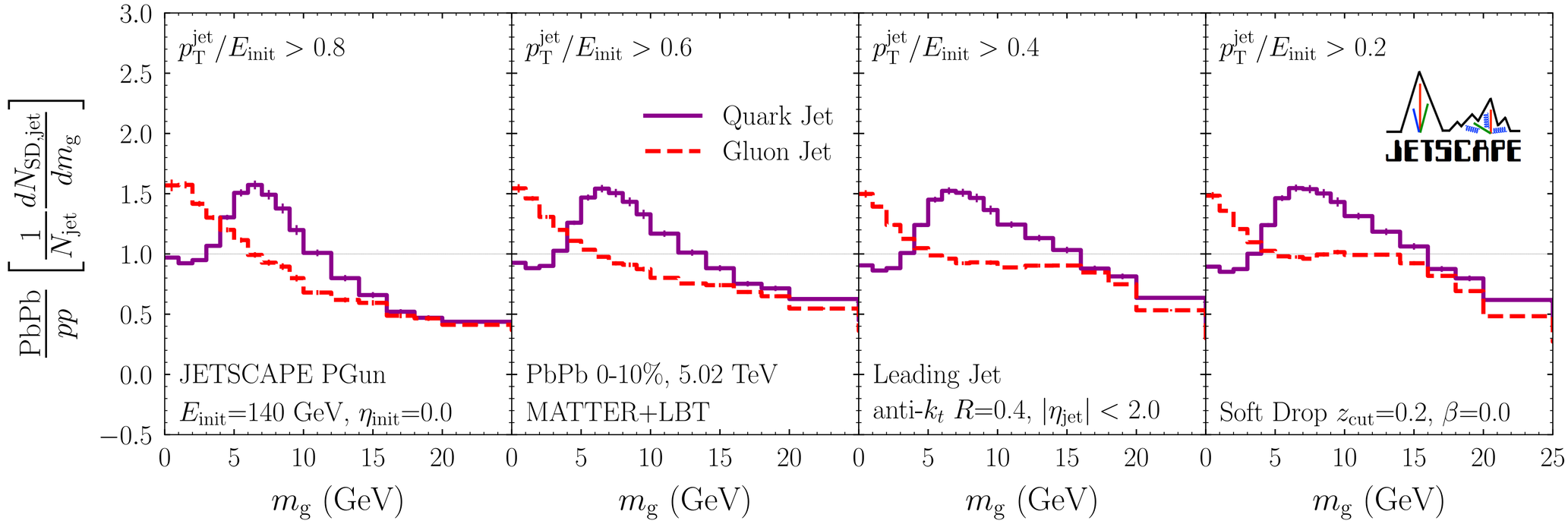
m_g-modification from single parton simulations

JETSCAPE, Phys. Rev. C 113, 034910 (2026)

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



- Prominent bump in quark jets
- Barely noticeable modification in gluon jets
- Mass loss due to out-of-cone radiations/scatterings (radius effects)



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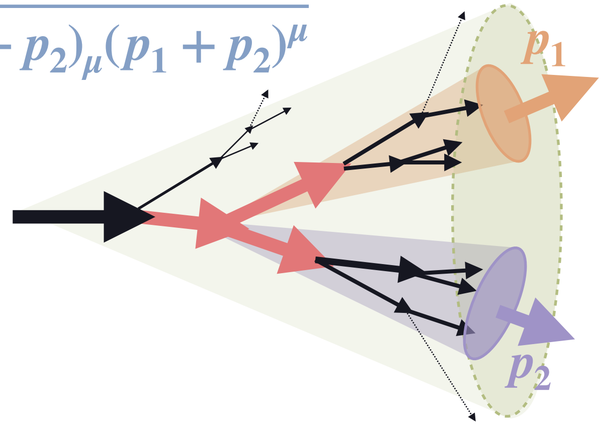
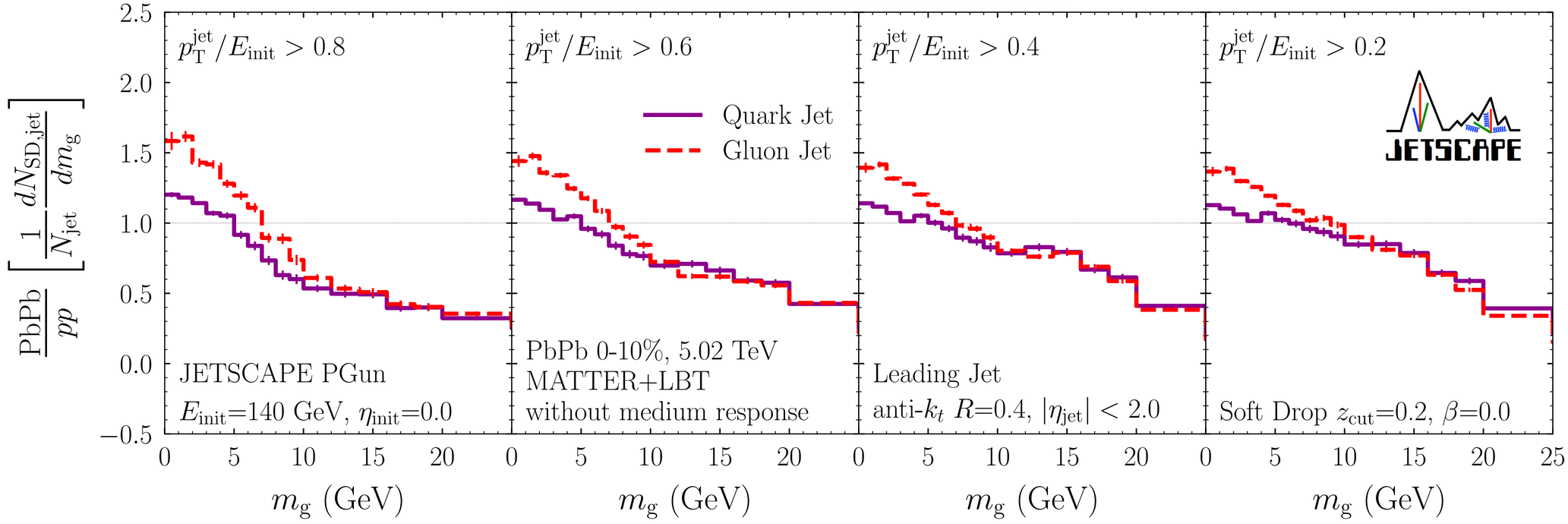


- Recoils dominate the bump in quark jets

Recoils and holes artificially removed



Eliminating the E-loss selection bias

m_g-modification: inclusive vs γ-tagged

JETSCAPE, Phys. Rev. C 113, 034910 (2026)

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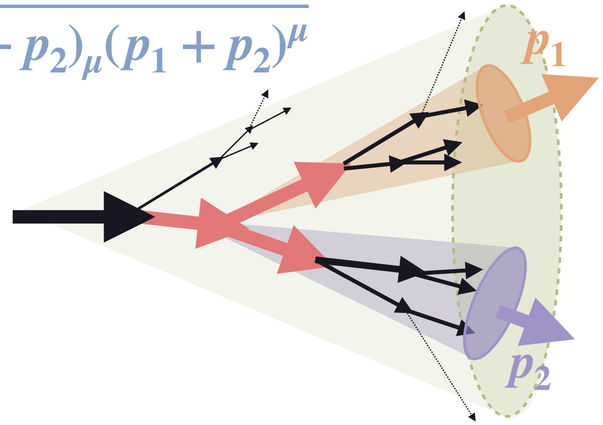

- Quark jet characteristics observed in γ-tagged jets
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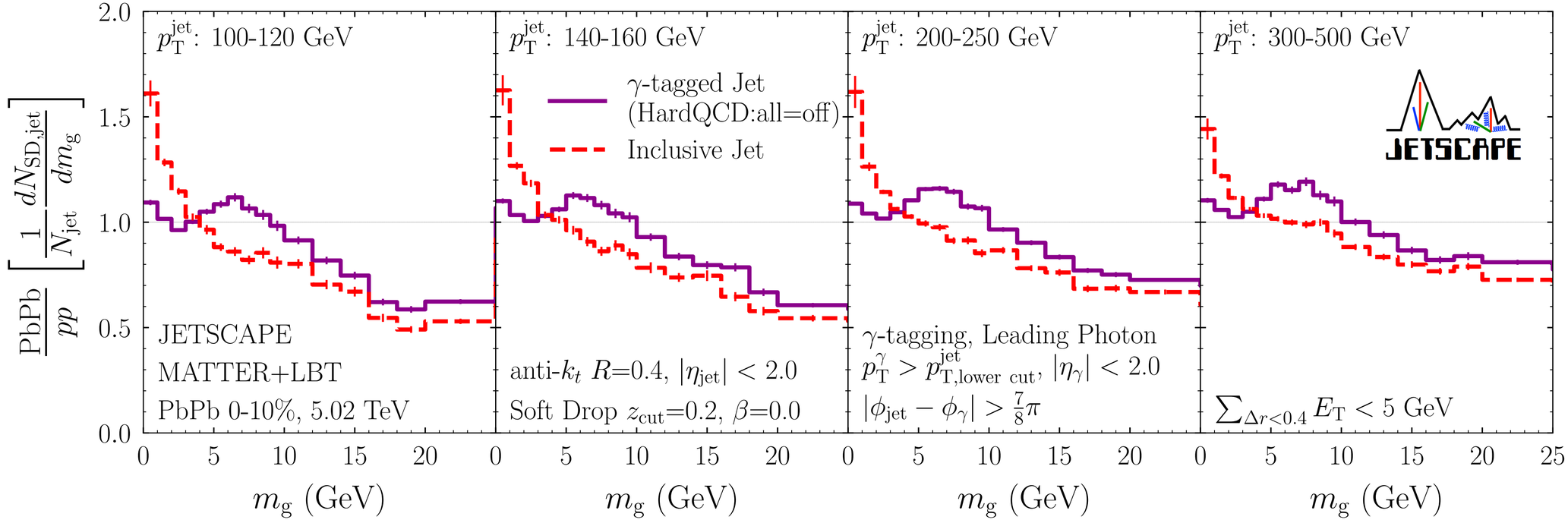

m_g-modification for γ-tagged

JETSCAPE, Phys. Rev. C 113, 034910 (2026)

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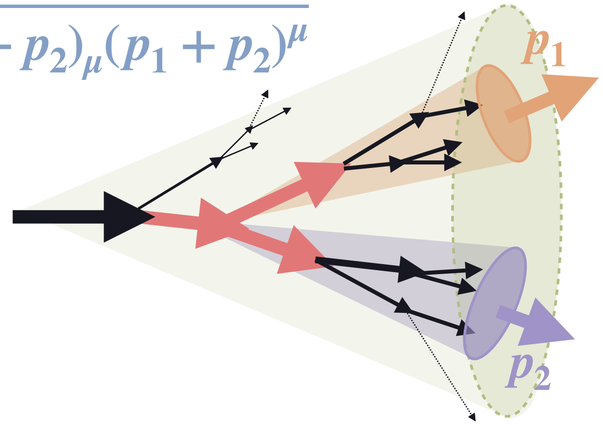
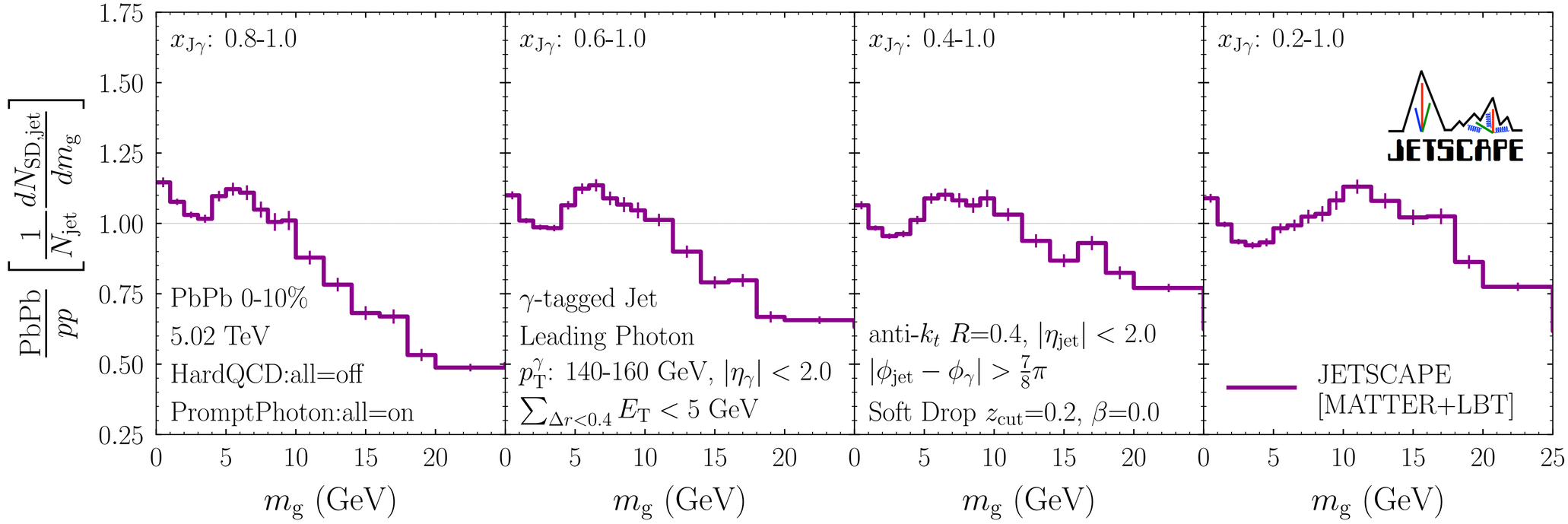


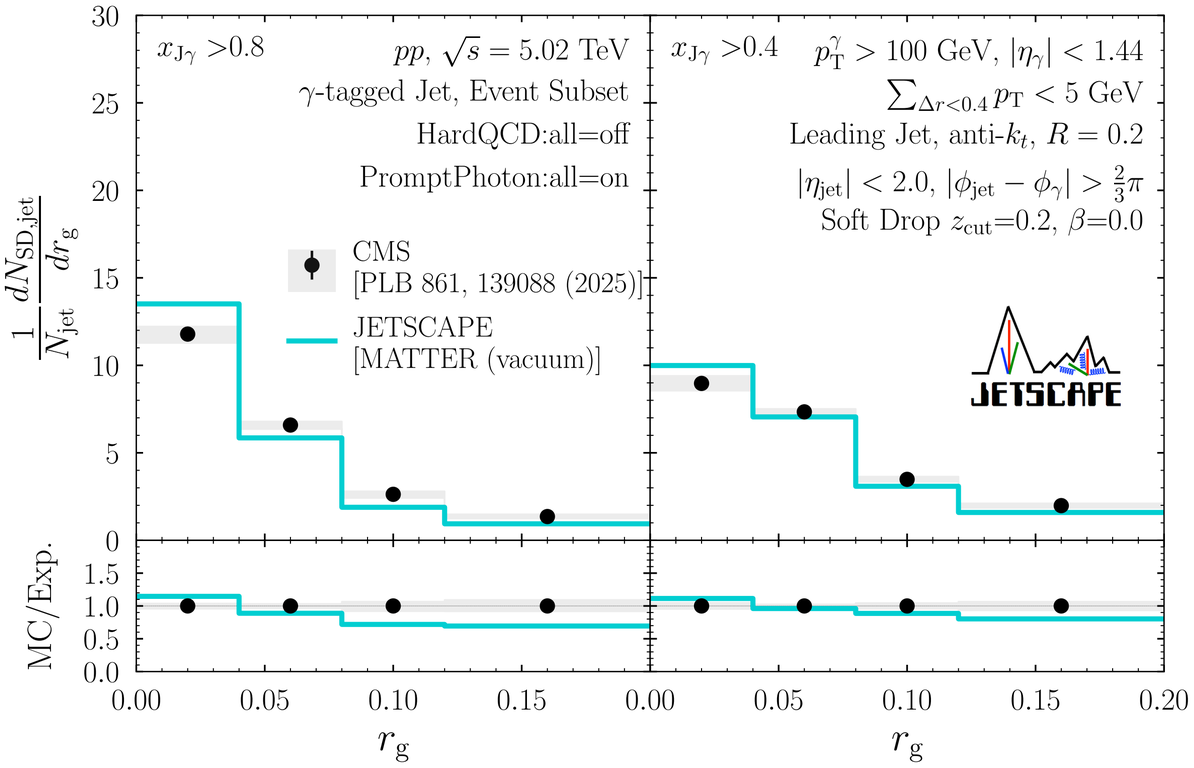
- Persistence of the radius effect despite reduced selection bias

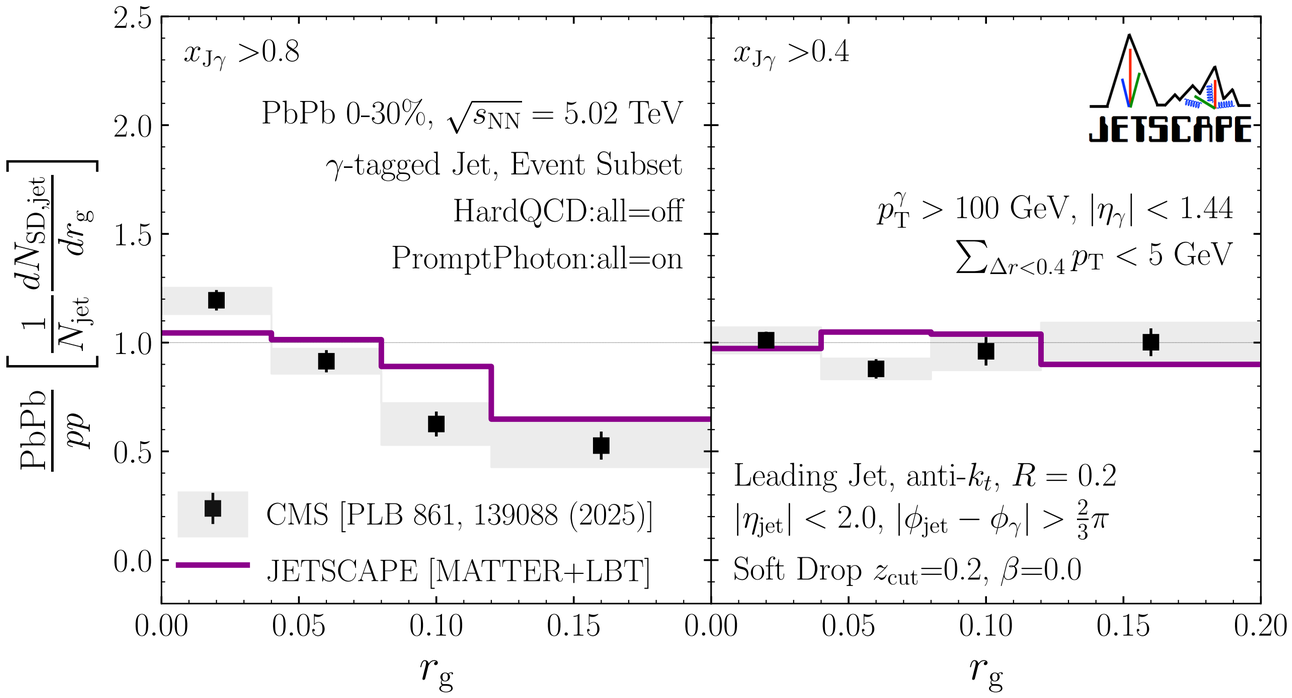


Comparison with Experimental Data

JETSCAPE, Phys. Rev. C 113, 034910 (2026)

- 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 in γ-jet**
  - Reduce/control the selection bias arising from triggering on jet p_{T}
  - Explore flavor dependence
- **Simulations with the JETSCAPE framework**
  - Multi-stage jet shower description with the recoil medium response
  - 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 broadening by recoils in γ-tagged jets, dominated by quark jet characteristics
  - Moderate modification in inclusive jets, dominated by gluon jet characteristics
  - Selection bias can be controlled in γ-jet events, while the radius effect remains, particularly for dimensionful observables.

Summary

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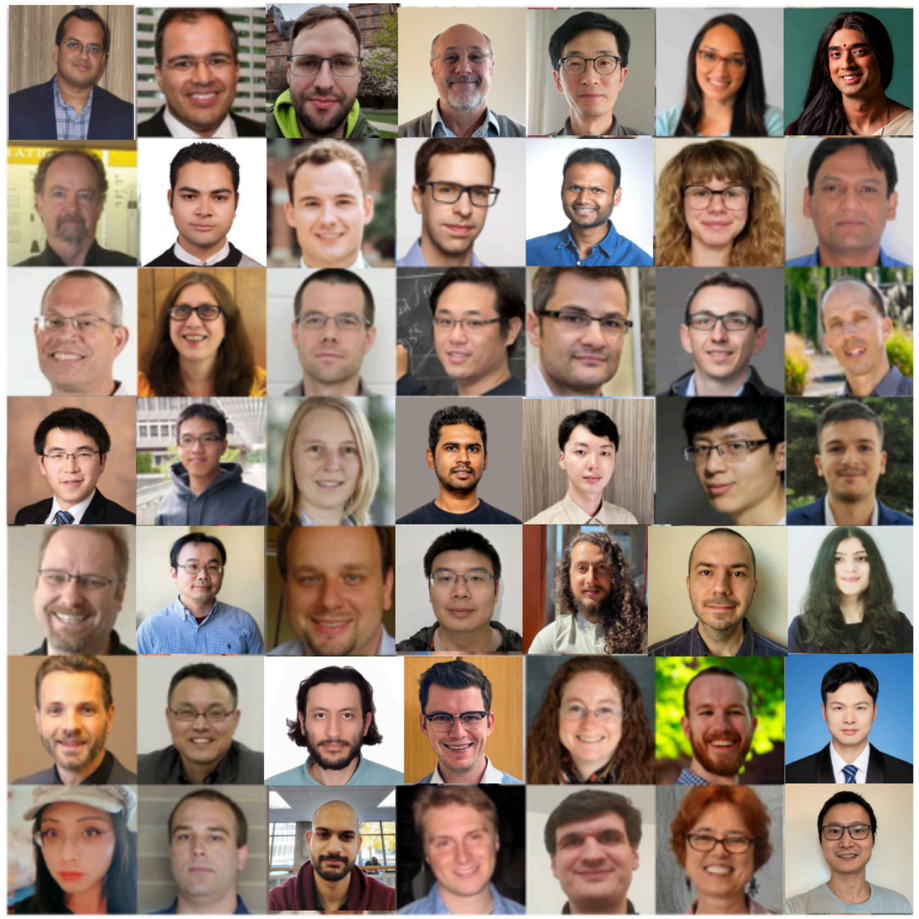
- **Inclusive vs γ-tagged jet substructures**
  - Prominent broadening by recoils in γ-tagged jets, dominated by quark jet characteristics

- Potentially powerful tool to probe the medium scattering processes generating recoils
- Future studies incorporating the transition to hydrodynamic response

JETSCAPE Collaboration



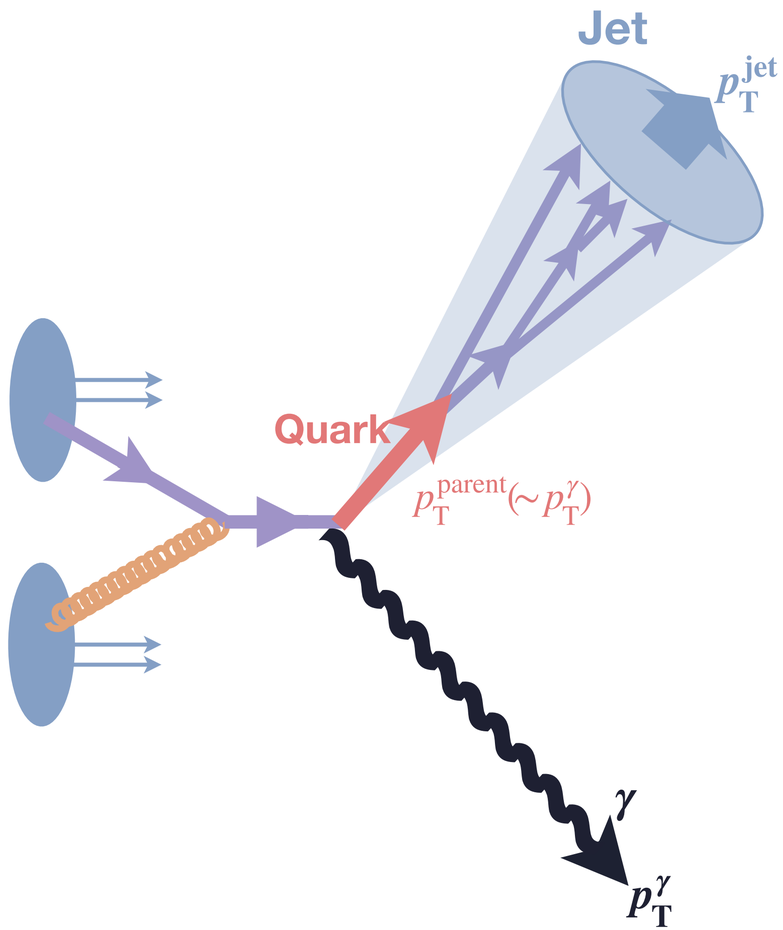
Thanks to my collaborators!

Backup

Publication 1: γ-tagged Jet Production w/ γ from Partons Showers

Led by C. Sirimanna, Y. Tachibana, A. Majumder

(Leading Order) Prompt Photon Events



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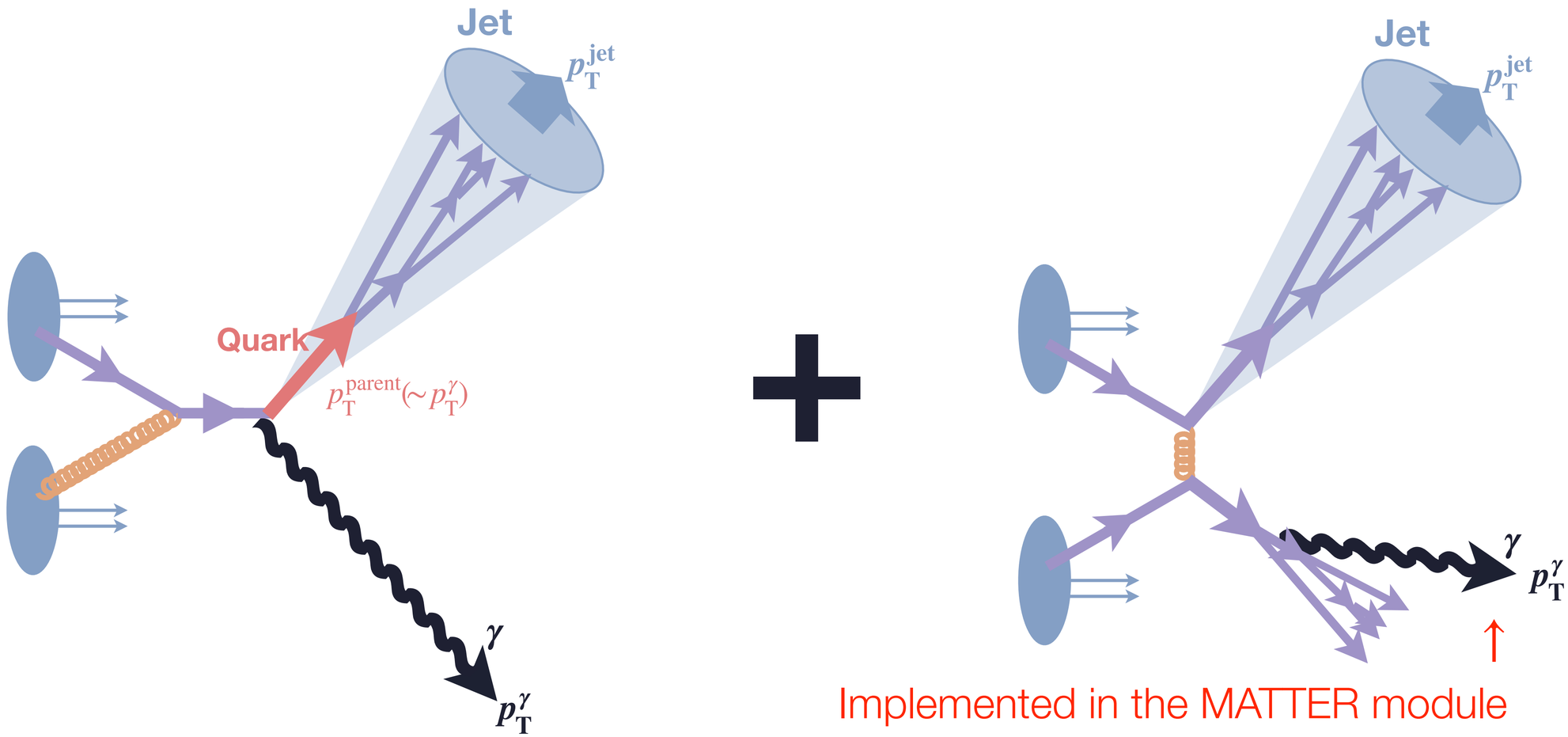
Led by C. Sirimanna, Y. Tachibana, A. Majumder

~~(Leading Order) Prompt γ Events~~

Full Events (Including γ from Showers)

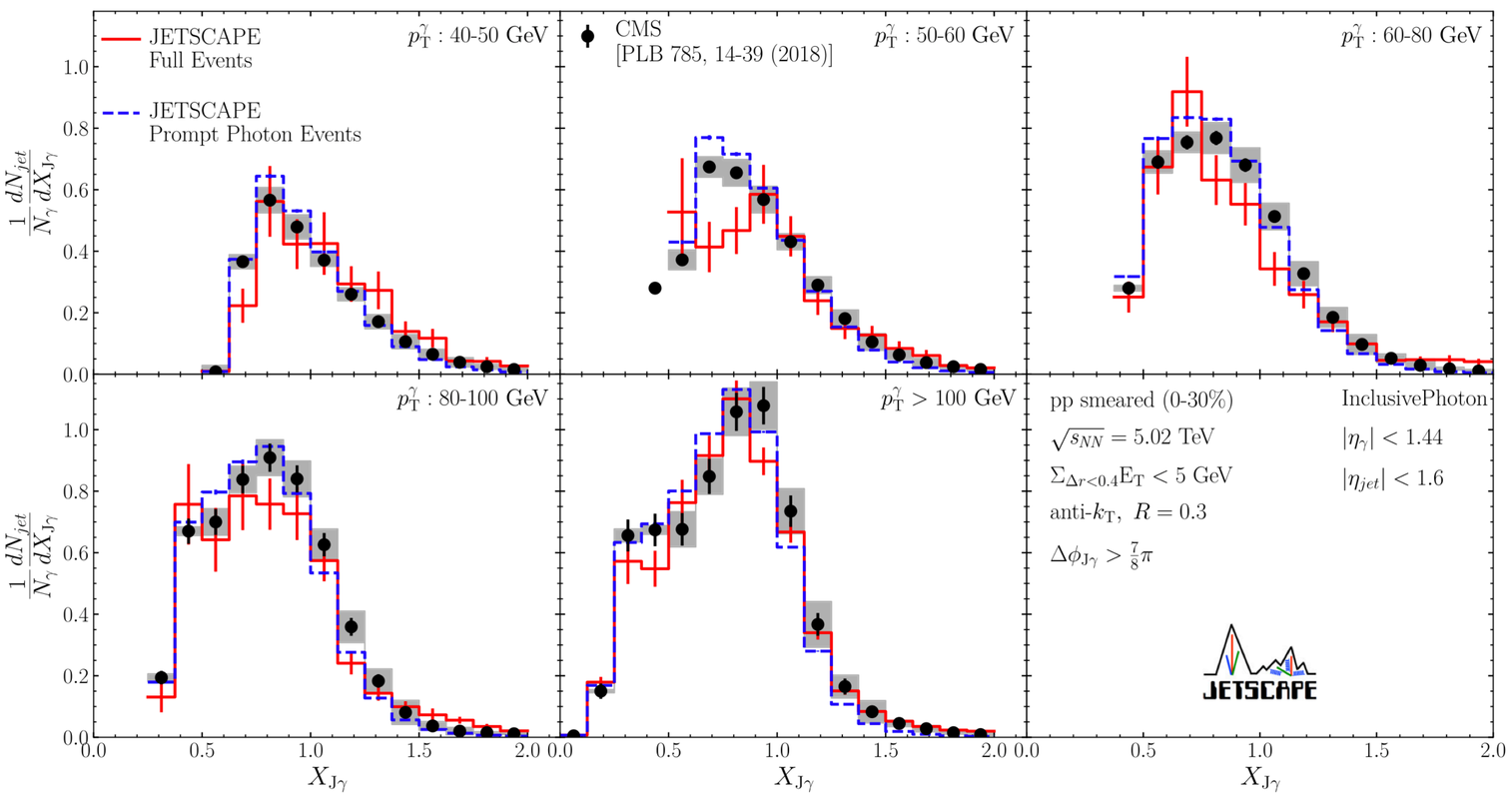


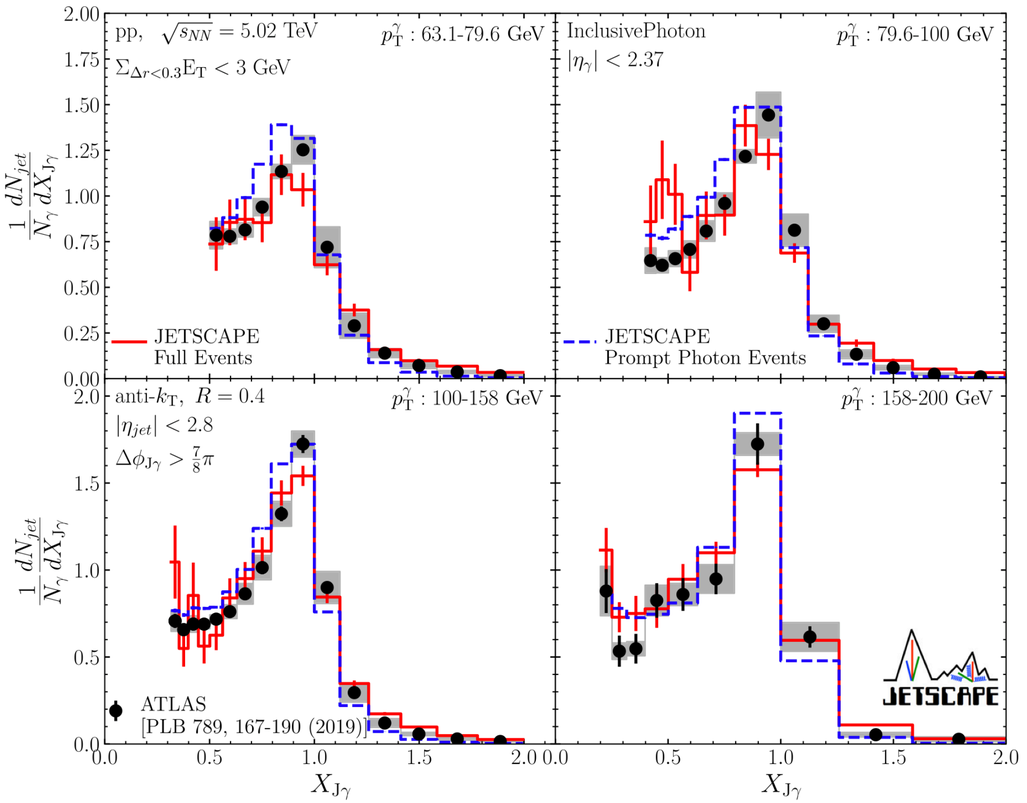
Implemented in the MATTER module

Publication 1: γ-tagged Jet Production w/ γ from Partons Showers

Led by C. Sirimanna, Y. Tachibana, A. Majumder

- **γ-jet Asymmetry ($X_{J\gamma} = p_T^{jet}/p_T^{\gamma}$) in pp**
  - The vacuum MATTER parton shower within JETSCAPE
  - CMS: smeard, ATLAS: unfolded



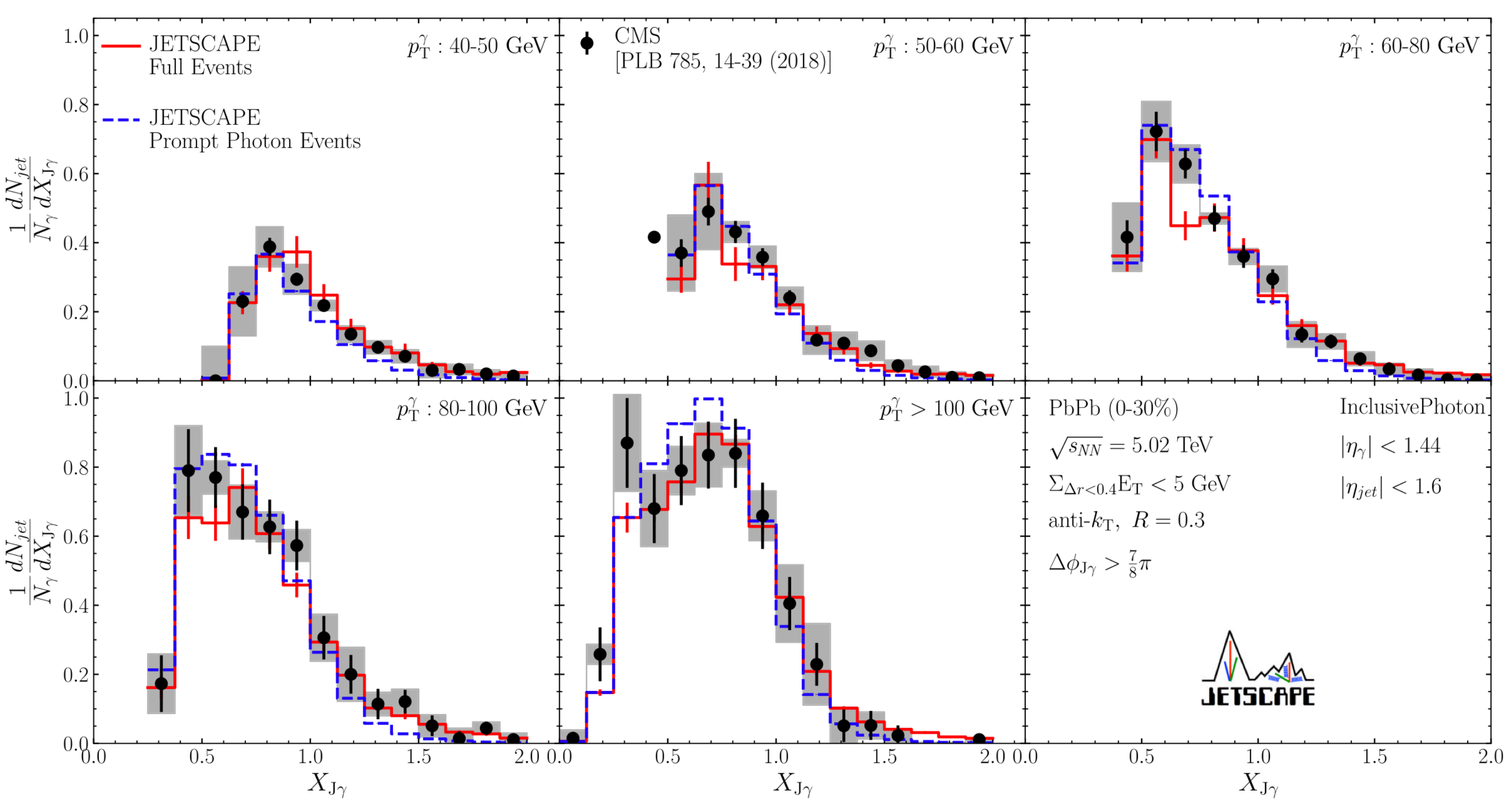


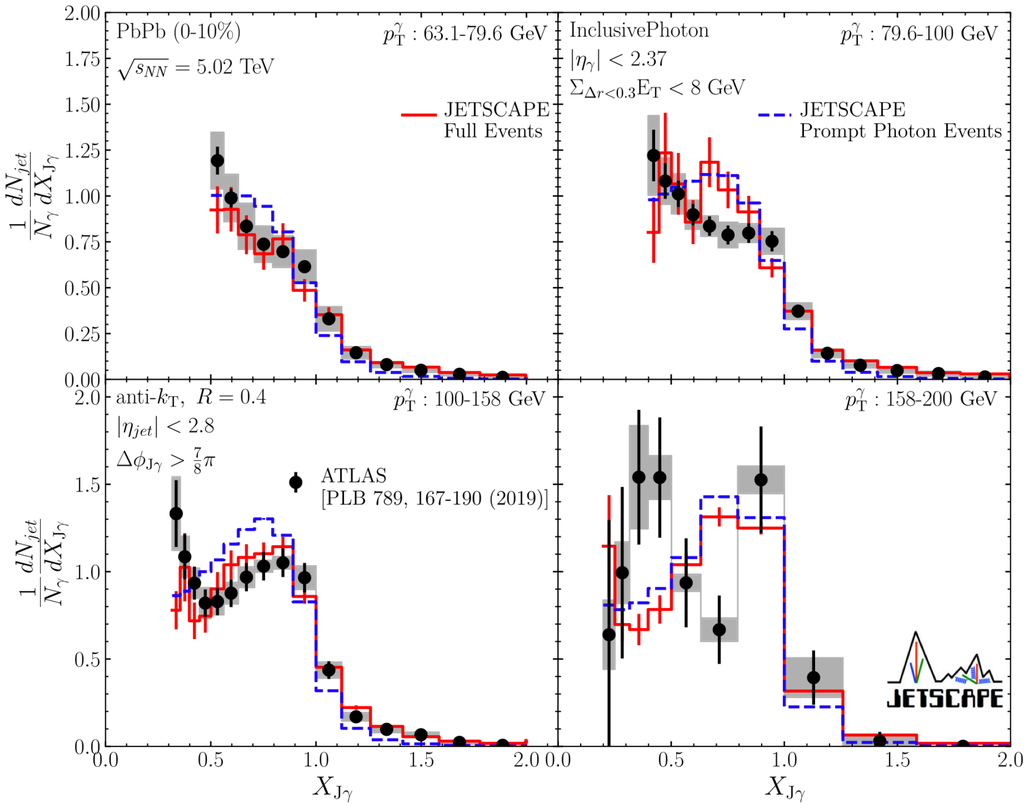
Slightly broader tail for the case with the full event set

Publication 1: γ-tagged Jet Production w/ γ from Partons Showers

Led by C. Sirimanna, Y. Tachibana, A. Majumder

- **γ-jet Asymmetry ($X_{J\gamma} = p_T^{jet}/p_T^{\gamma}$) in PbPb**
  - The in-medium MATTER+LBT parton shower within JETSCAPE
  - CMS: smeard, ATLAS: unfolded



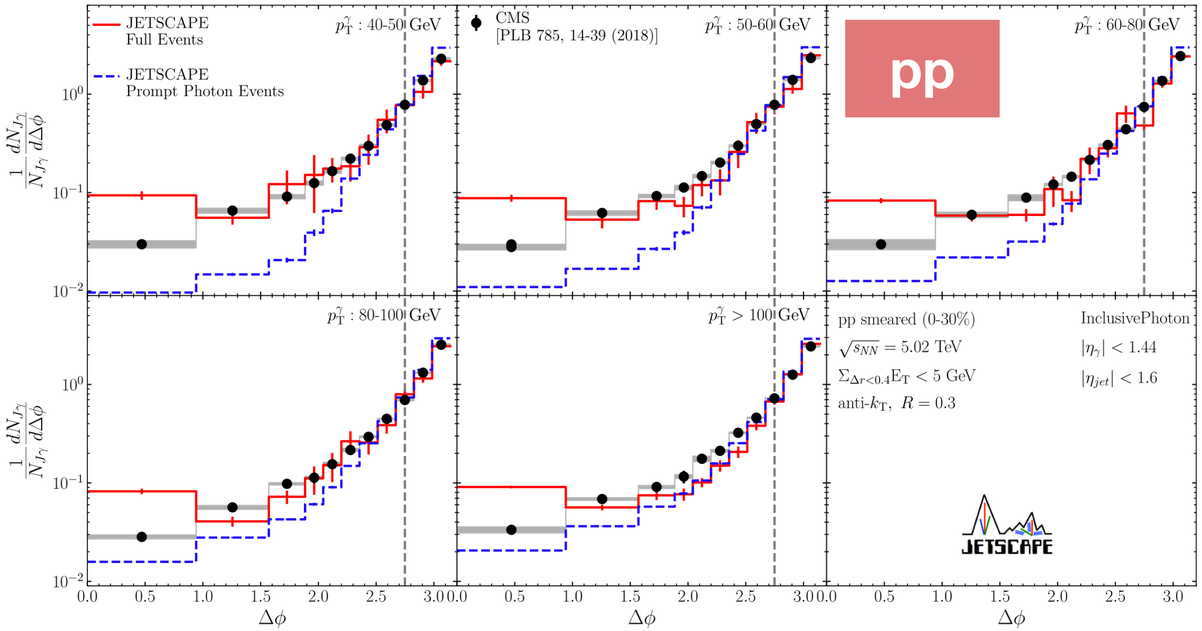


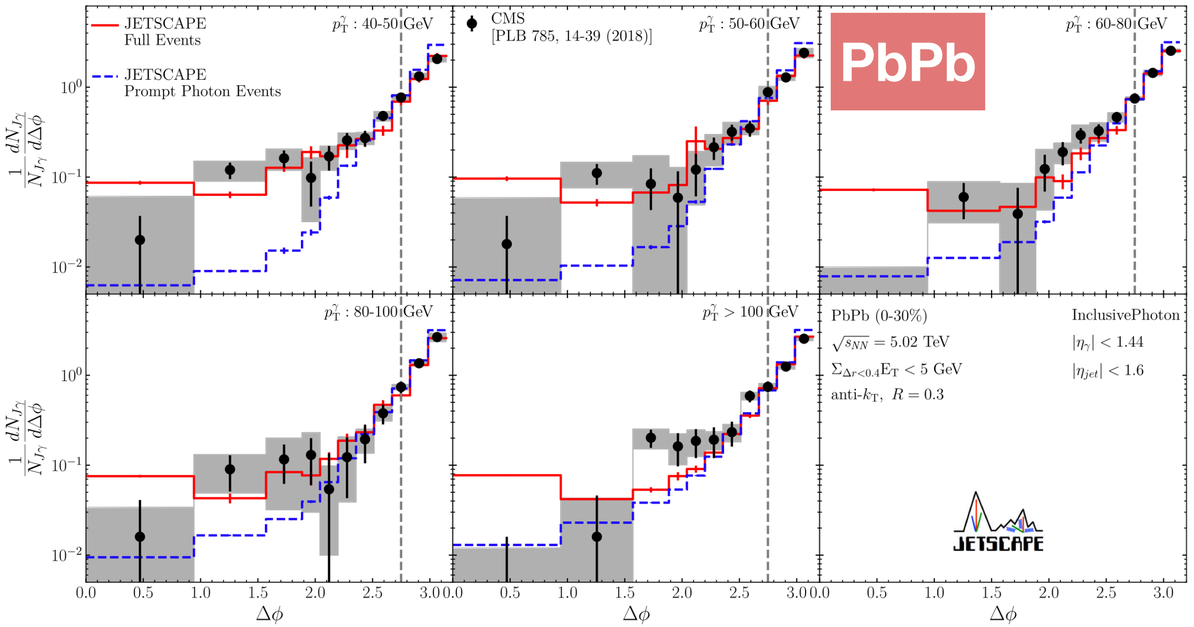
Slightly broader tail for the case with the full event set

Publication 1: γ-tagged Jet Production w/ γ from Partons Showers

Led by C. Sirimanna, Y. Tachibana, A. Majumder

- **Augular Correlation $\Delta\phi = |\phi_{\rm jet} - \phi_\gamma|$**
  - The vacuum MATTER parton shower for pp
  - The in-medium MATTER+LBT parton shower for PbPb





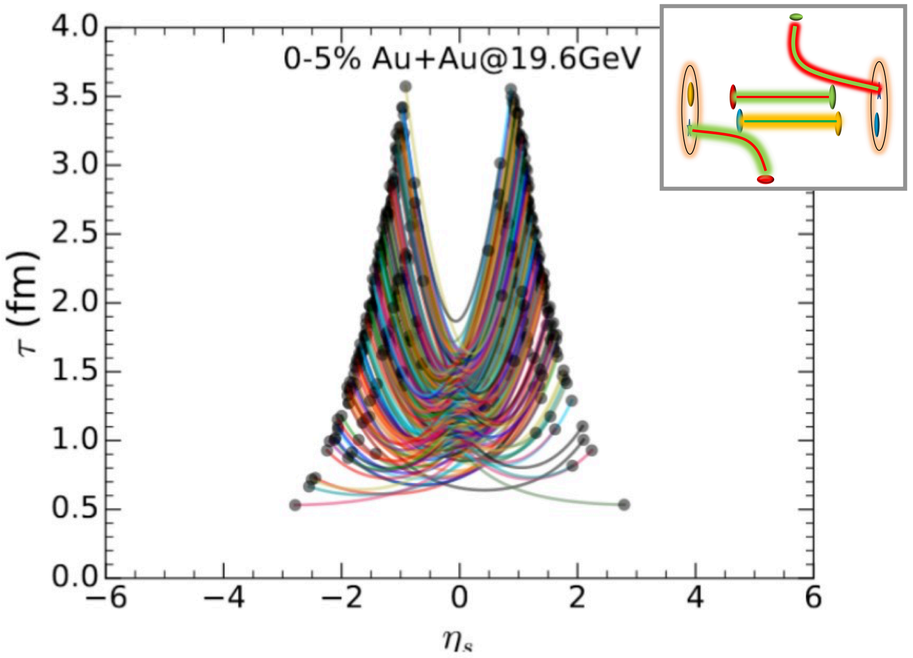
Contributions from the shower beyond leading order are essential at small angles.

Publication 2: Hard-Soft Correlation in Small Systems

Led by I. Soudi, W. Zhao, A. Majumder, C. Shen

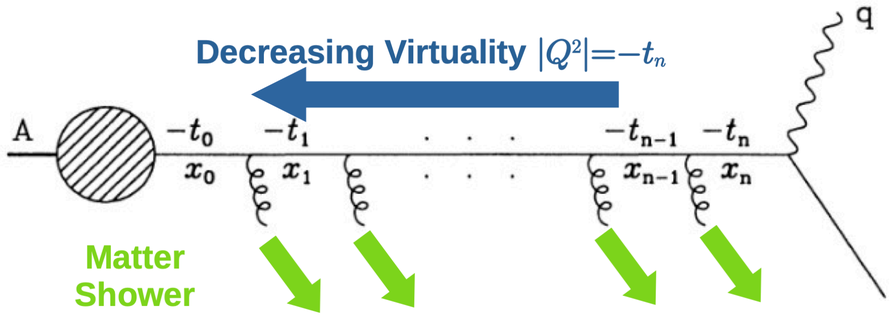
- **Soft-hard coupled initial condition: 3D MC-Glauber + i-MATTER within XSCAPE**

3D MC-Glauber



- String deceleration of valence quarks
- Dynamical Initialization of hydro via source term

i-MATTER



- ISR simulated by negative virtuality evolution
- Initial energy subtracted from 3D Glauber

Exact four-momentum conservation

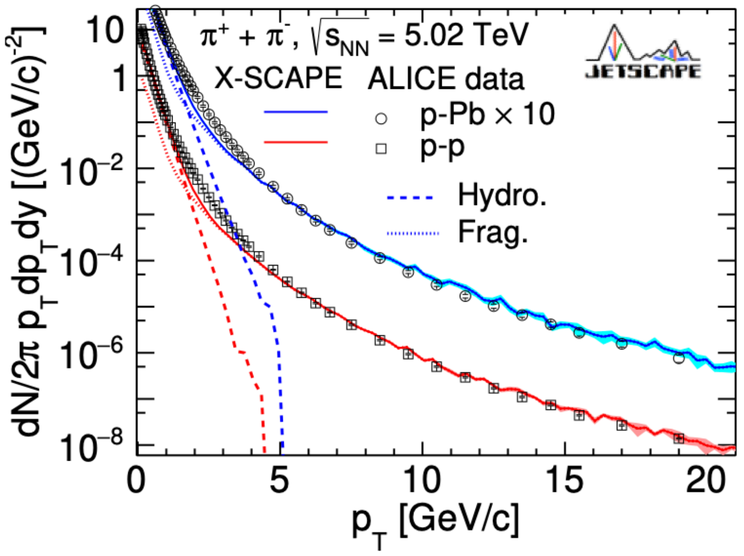
Publication 2: Hard-Soft Correlation in Small Systems

Led by I. Soudi, W. Zhao, A. Majumder, C. Shen

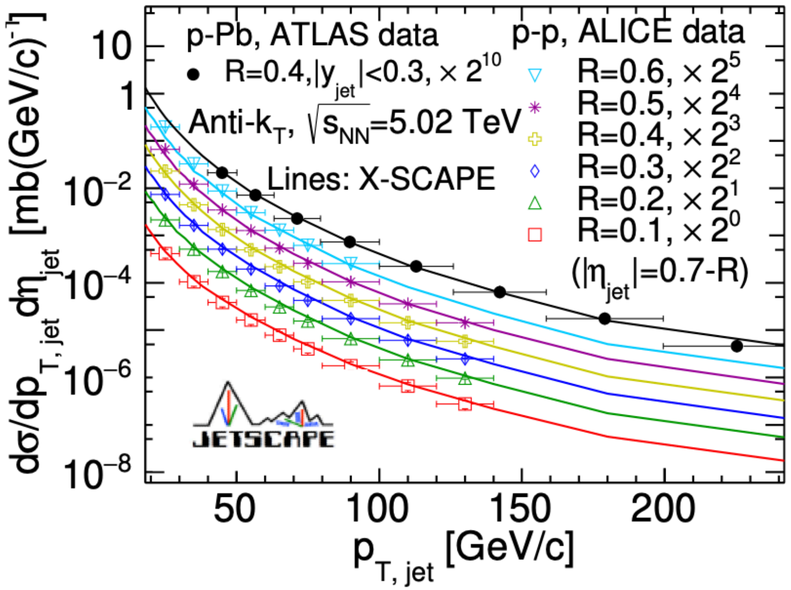
- **Spectra including both soft and hard contributions**

- Hydro (soft): 3-D Glauber → MUSIC (3D Hydro with Sources) → Cooper- Frye
- Frag (hard): i-MATTER → Pythia (Hard Scattering) → MATTER (Parton Shower) → Pythia (Hadronization)

- $\pi^+ + \pi^-$



- Jet



Description power spanning wide momentum ranges

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Spectra including both soft and hard contributions

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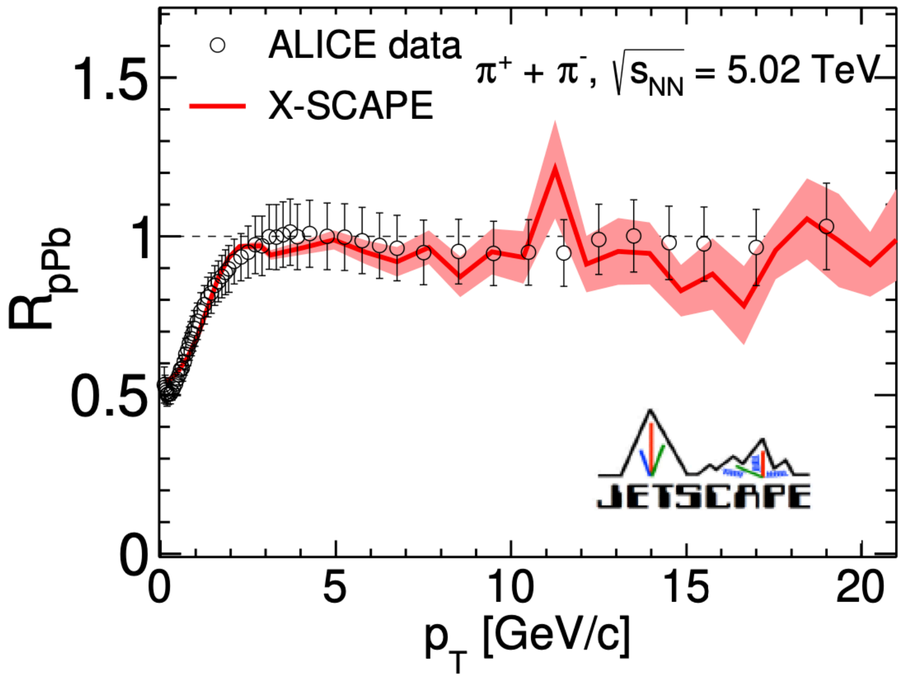
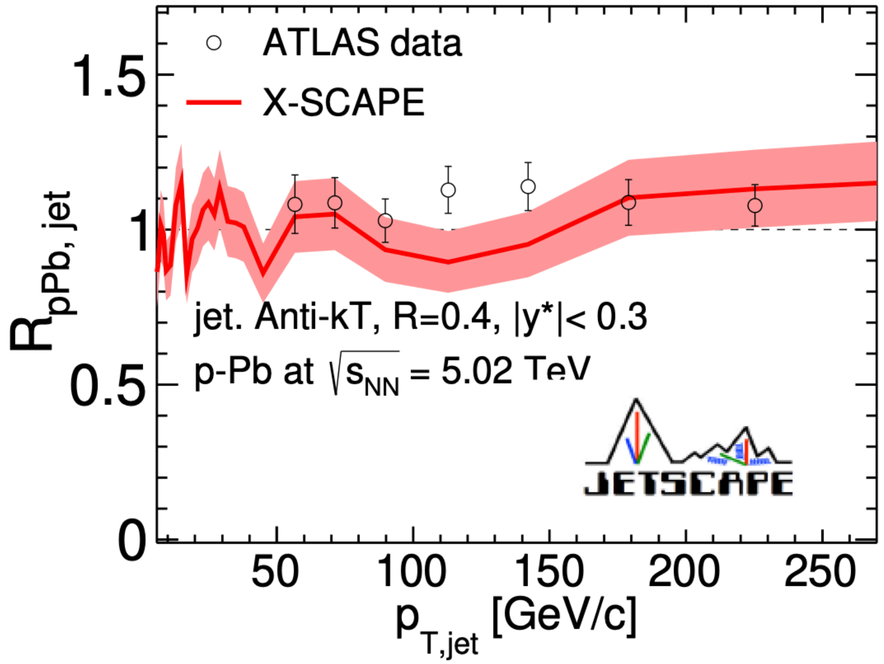


- Jet



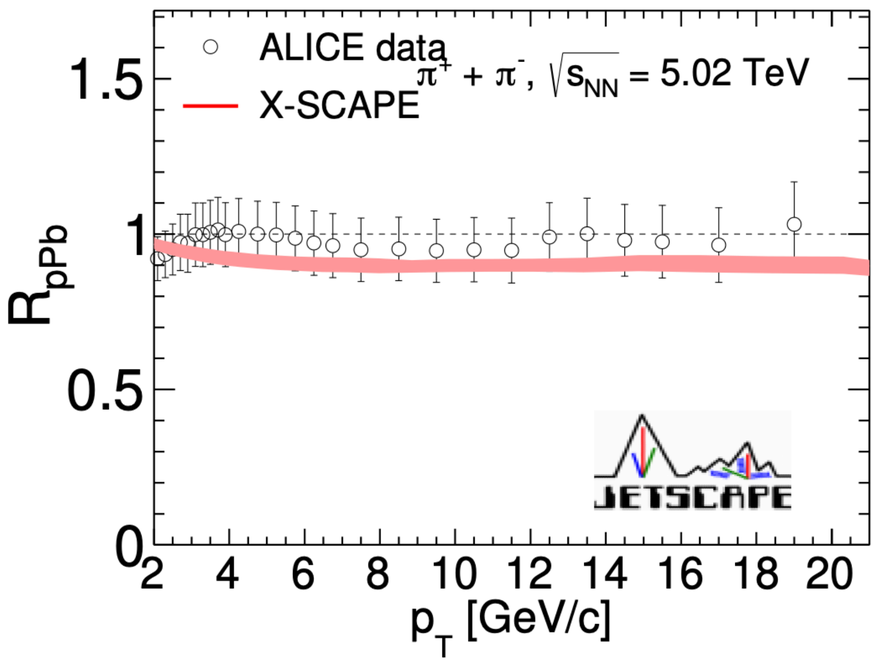
Description power spanning wide momentum ranges

Publication 2: Hard-Soft Correlation in Small Systems

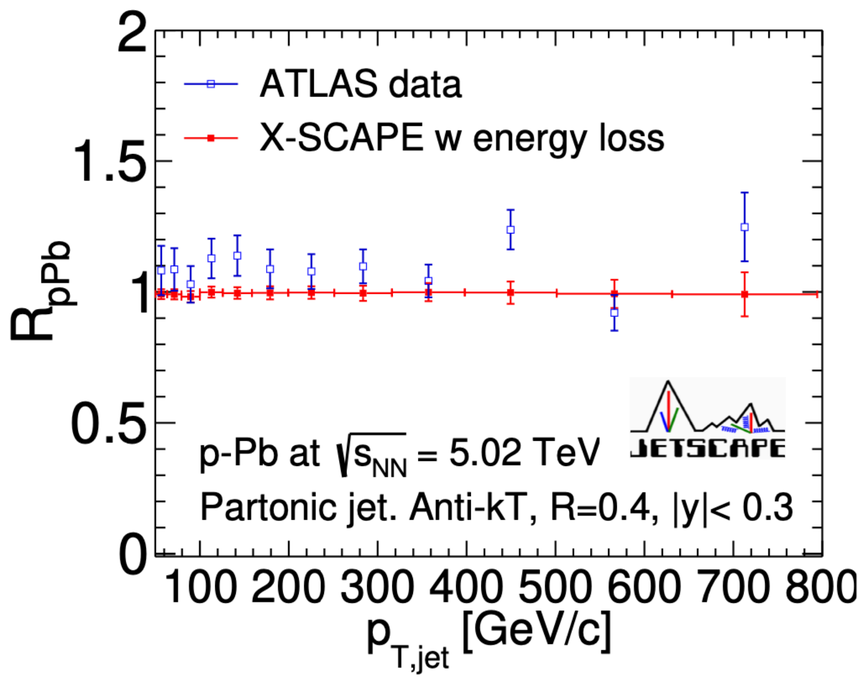
Led by I. Soudi, W. Zhao, A. Majumder, C. Shen

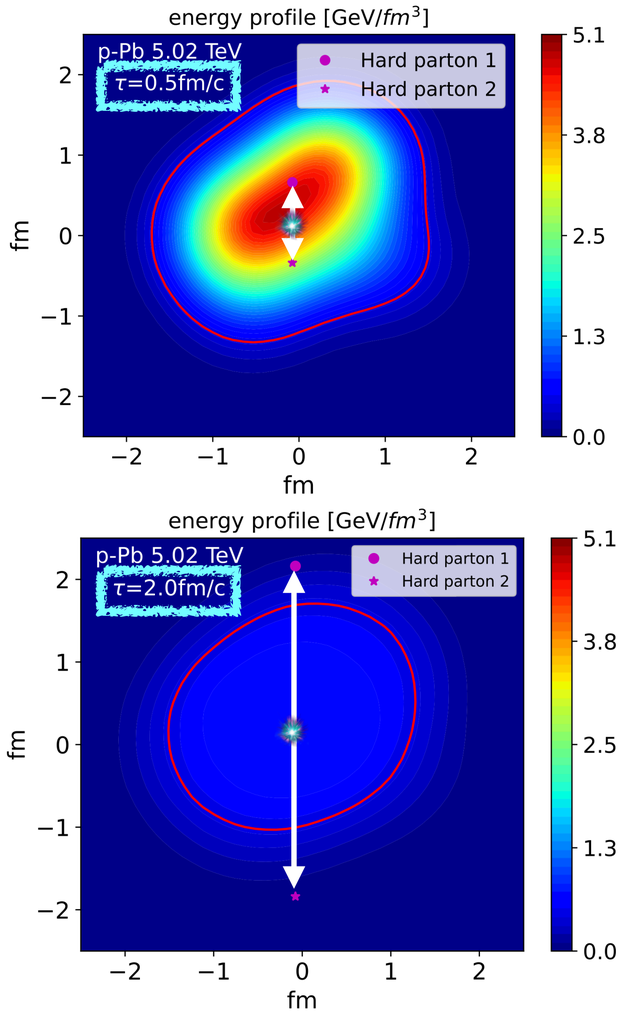
- **Evaluation of energy loss with jet-medium interaction**

- $\pi^+ + \pi^-$



- Jet





No energy loss in pPb due to the small size of the medium

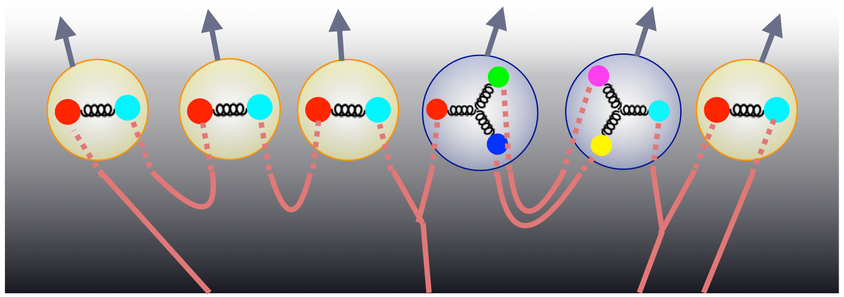
Preprint 1: In-medium Hadronization by Hybrid Hadronization

Led by A. Sengupta, R. J. Fries, M. Kordell II, B. Kim

String Fragmentation and Recombination

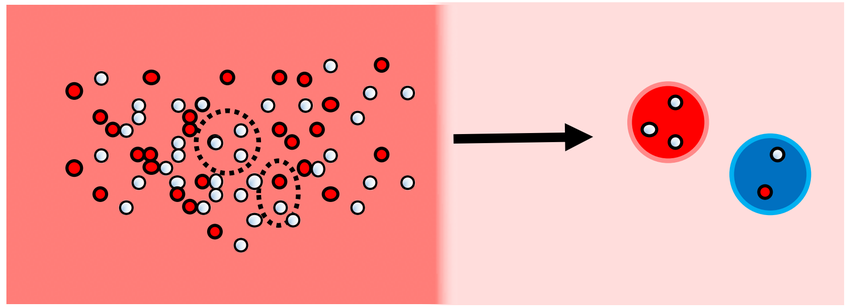
- In-vacuum hadronization (high-p_{T})

String Fragmentation



- In-medium hadronization (mid-p_{T})

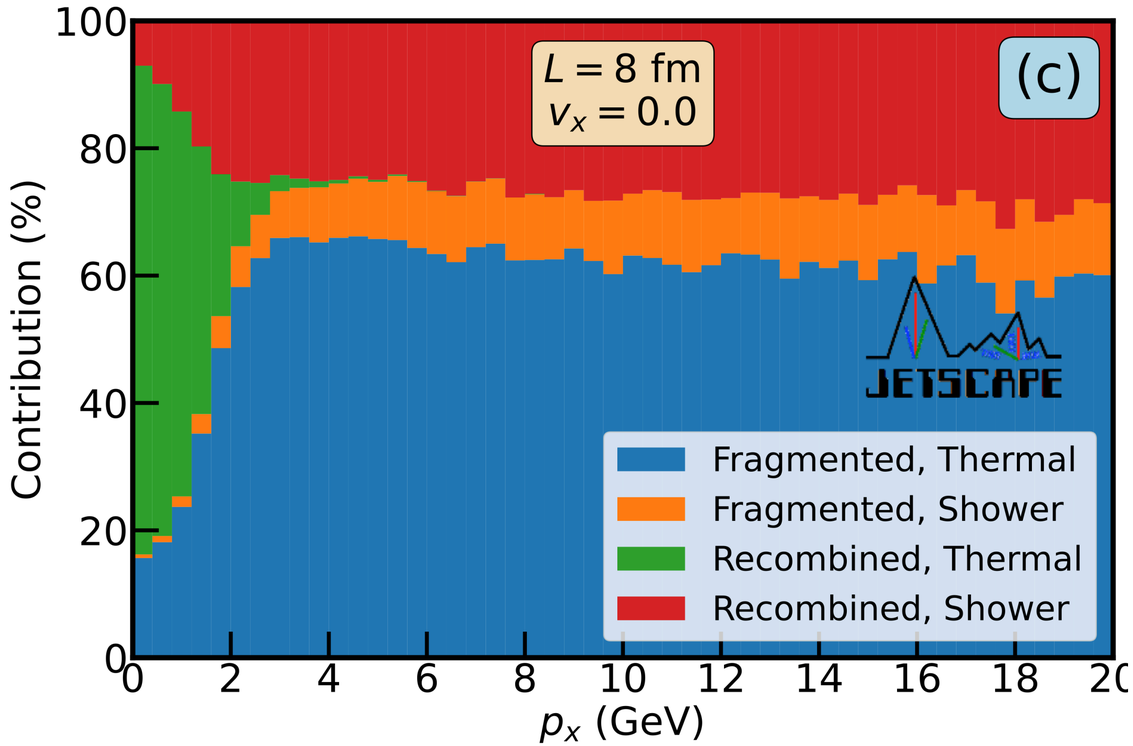
Recombination



Hybrid hadronization model

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

- A hybrid of string frag. and recombination
- Allow string frag. and recombination including thermal partons sampled at $T = T_{\mathrm{c}}$



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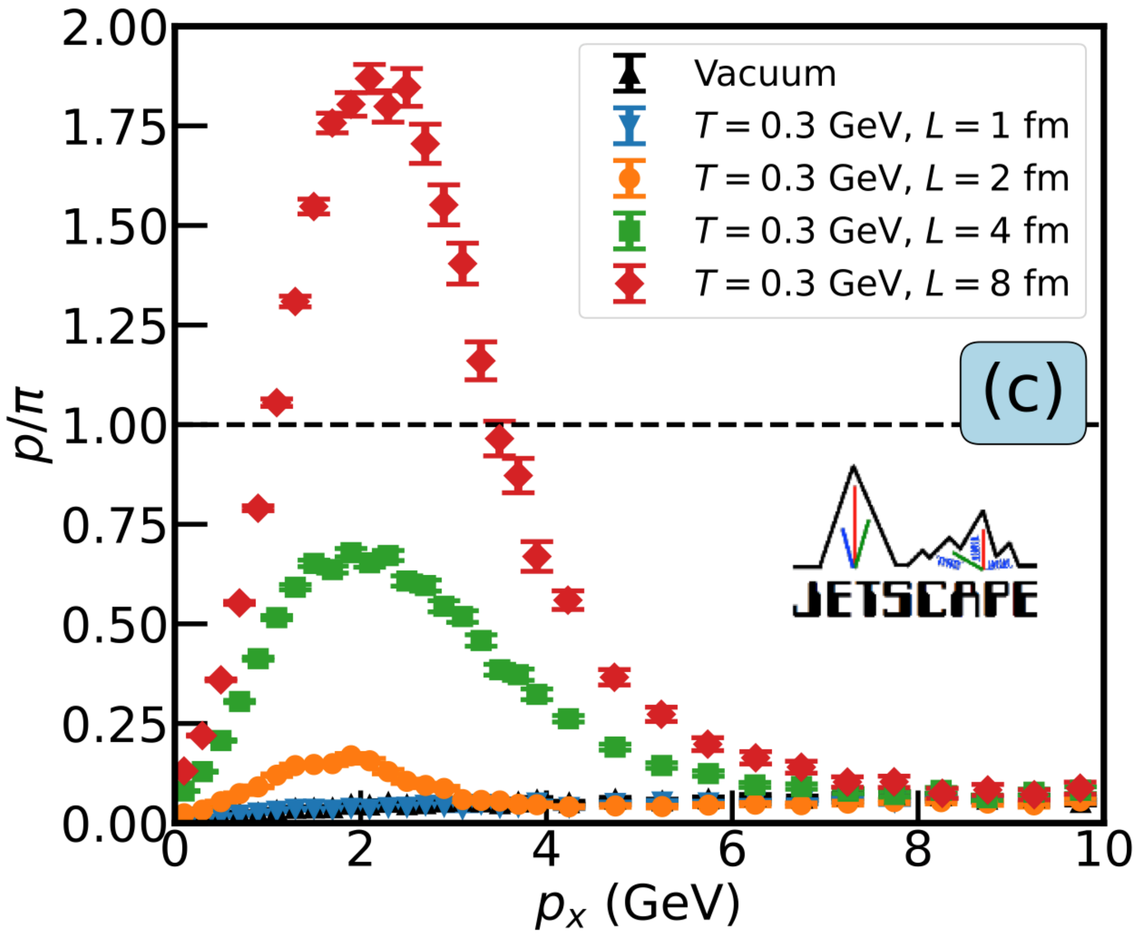
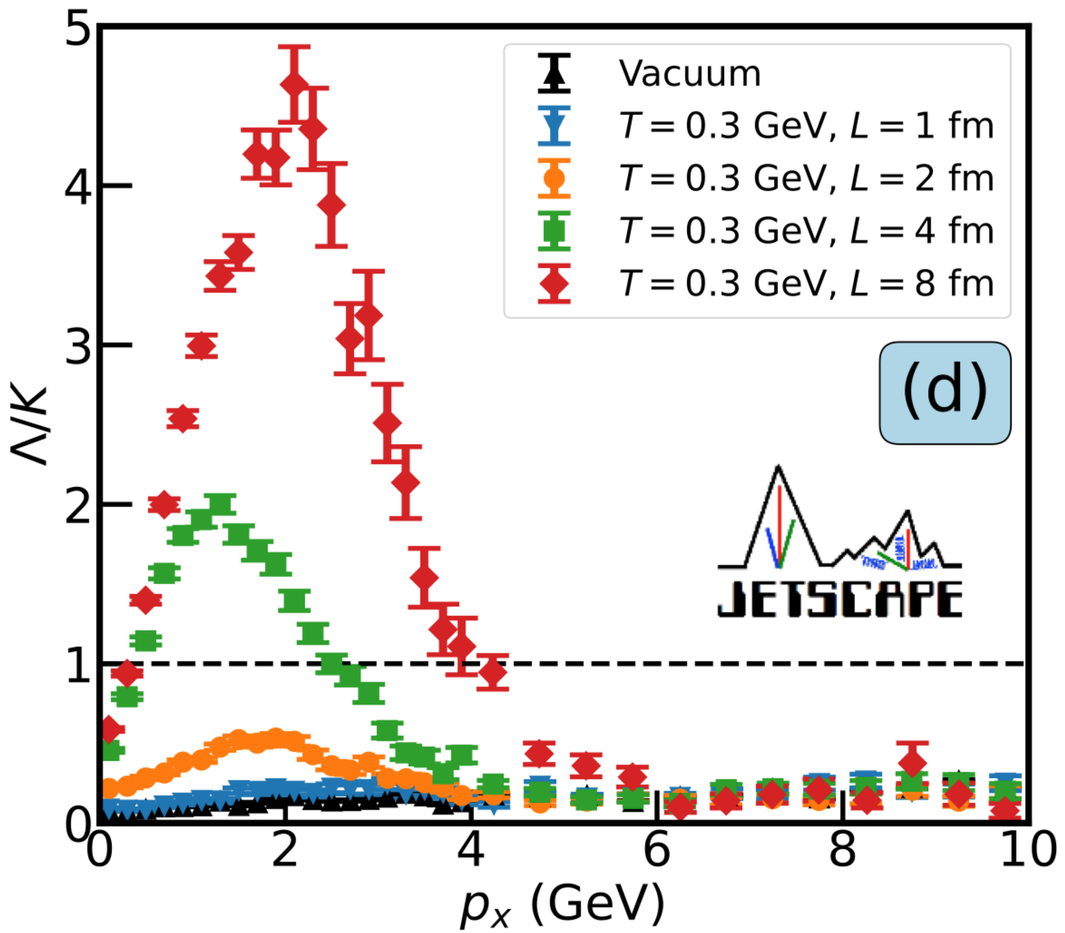
Baryon Ratio Enhancement



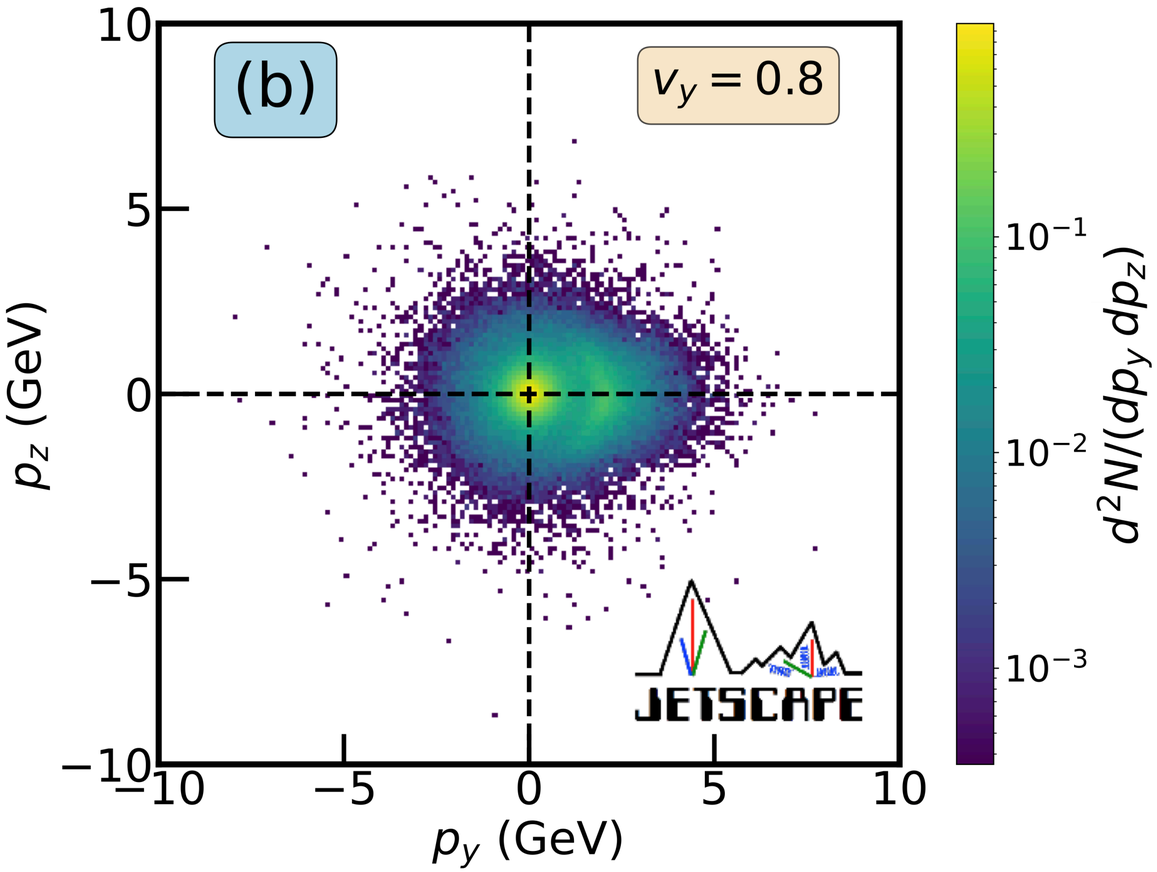


Preprint 1: In-medium Hadronization by Hybrid Hadronization

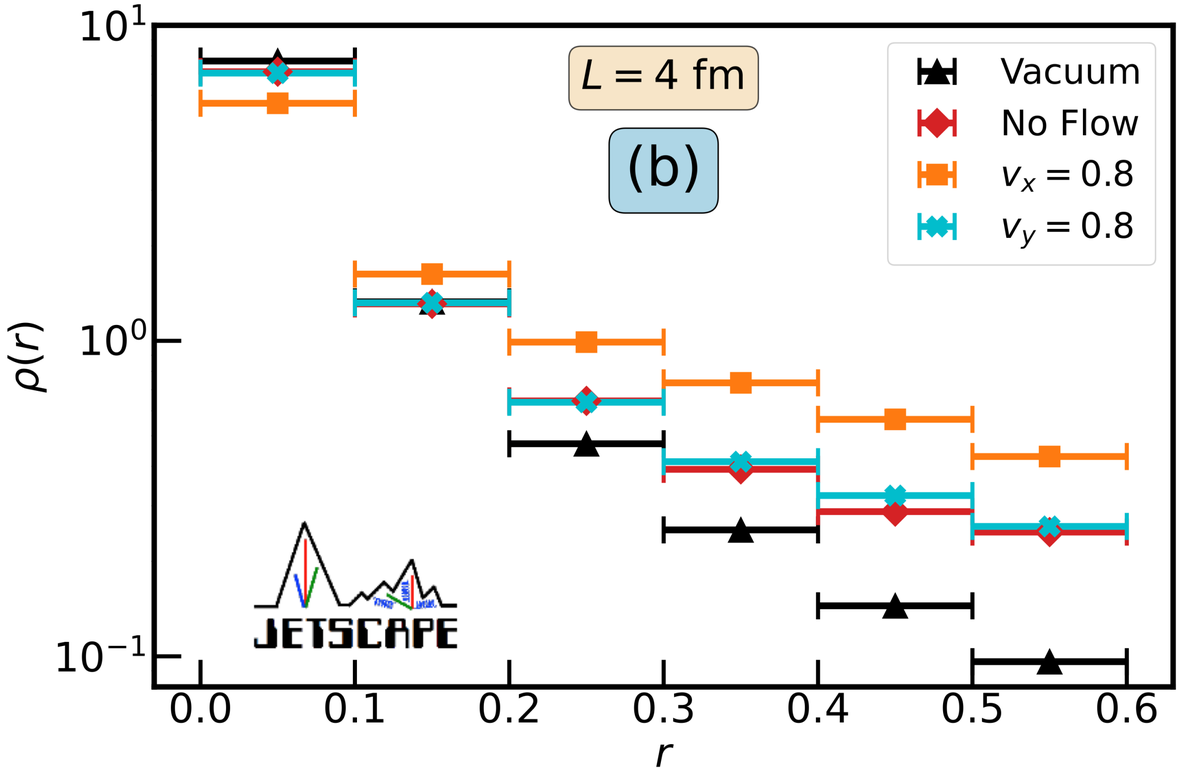
Led by A. Sengupta, R. J. Fries, M. Kordell II, B. Kim

Medium Flow Effects on Jet Profiles

Distortion

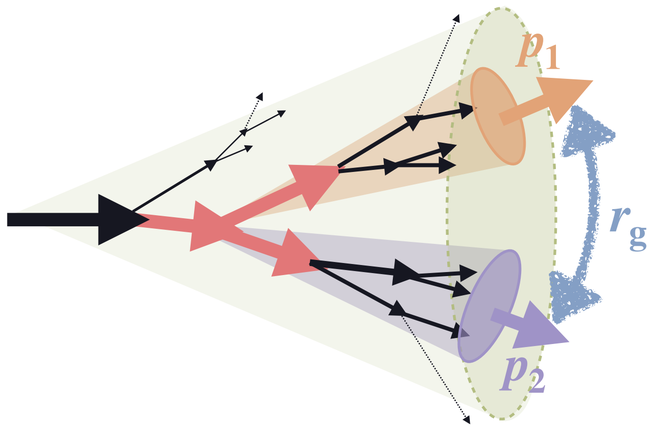


Broadening by thermal partons



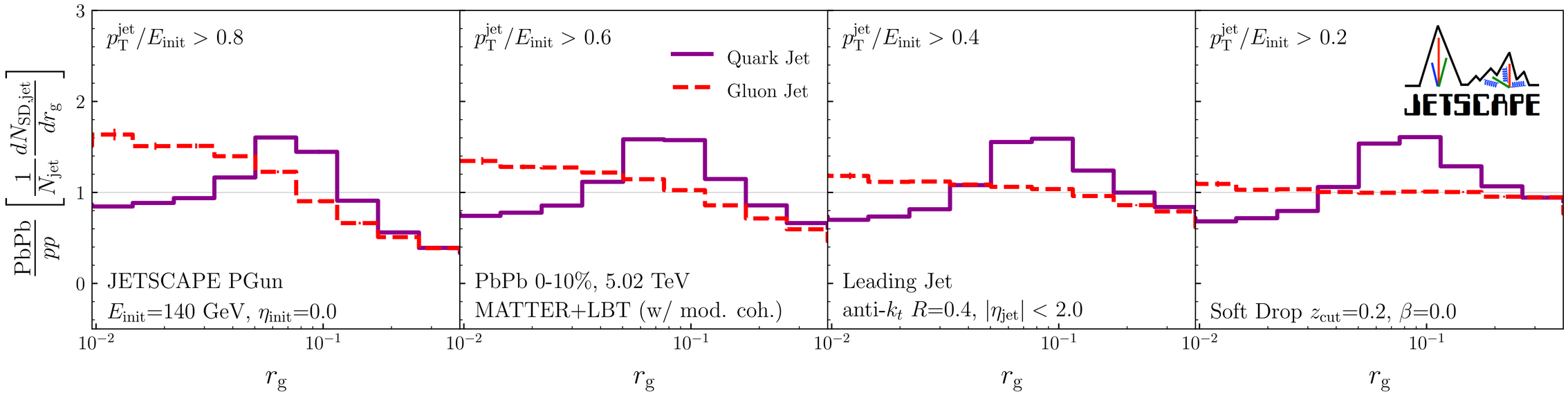
Preprint 2: Substructures of γ-tagged jets

Led by Y. Tachibana, C. Sirimanna, A. Majumder



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

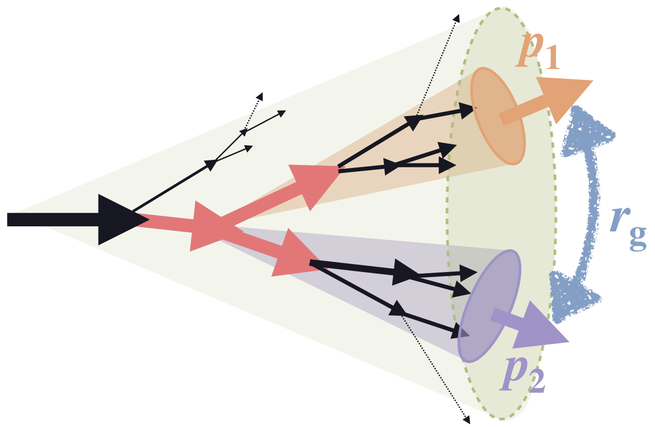
- Prominent modification in quark jets by *recoils*
- Barely noticeable modification in gluon jets
- No narrowing in actual substructure modification



Eliminating the E-loss selection bias

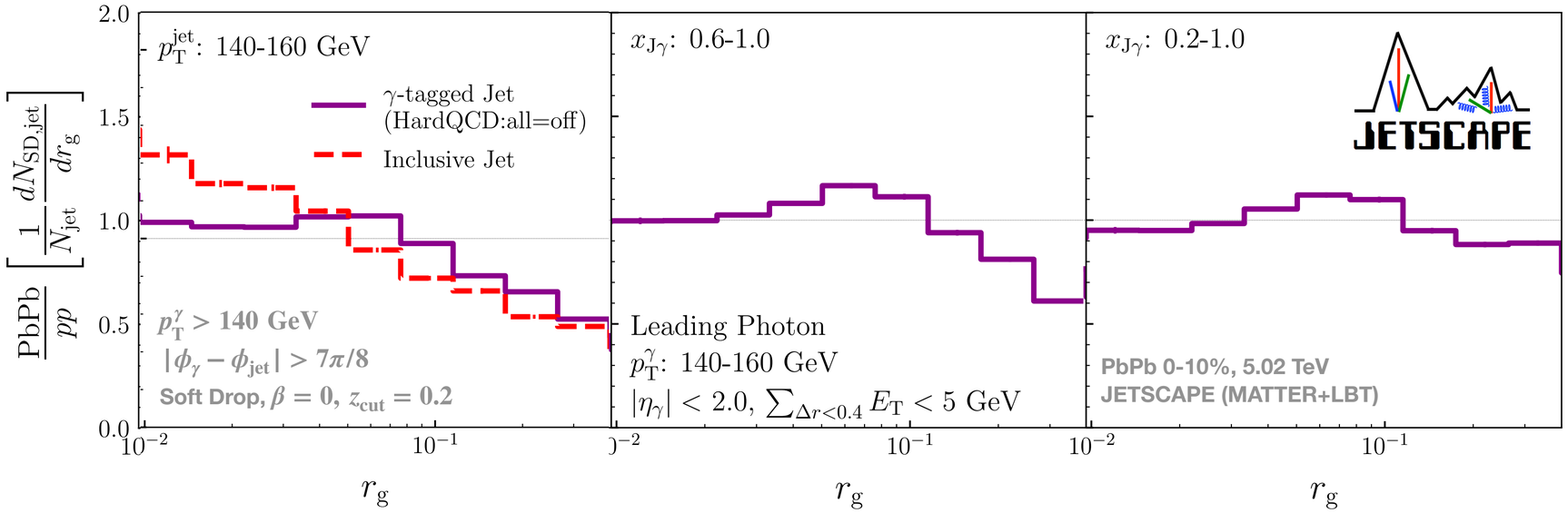
Preprint 2: Substructures of γ-tagged jets

Led by Y. Tachibana, C. Sirimanna, A. Majumder



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

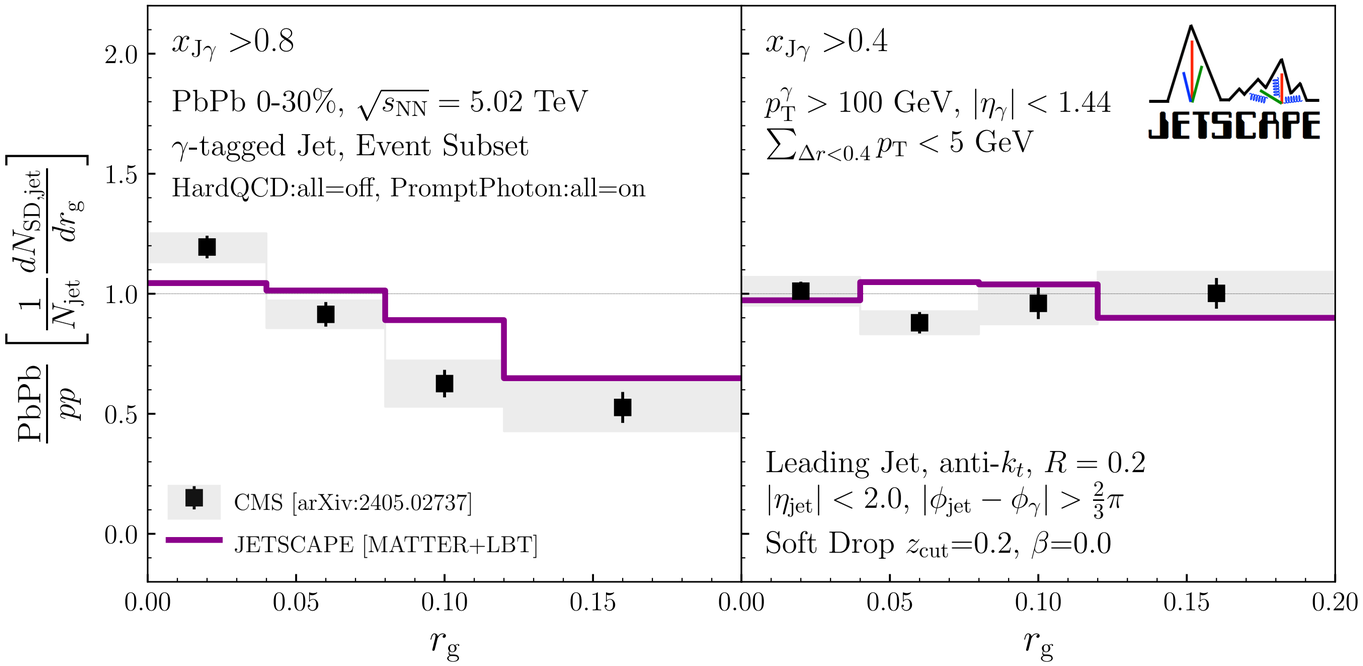
- Quark jet characteristics observed in γ-tagged jets
- Gluon jet characteristics observed in inclusive jets
- Narrowing due to selection bias can be controlled



Preprint 2: Substructures of γ-tagged jets

Led by Y. Tachibana, C. Sirimanna, A. Majumder

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



- Capture the trend of less narrowing for smaller $x_{J\gamma}$-cut