Multi-stage jet evolution through QGP using the JETSCAPE framework: inclusive jets, correlations and leading hadrons

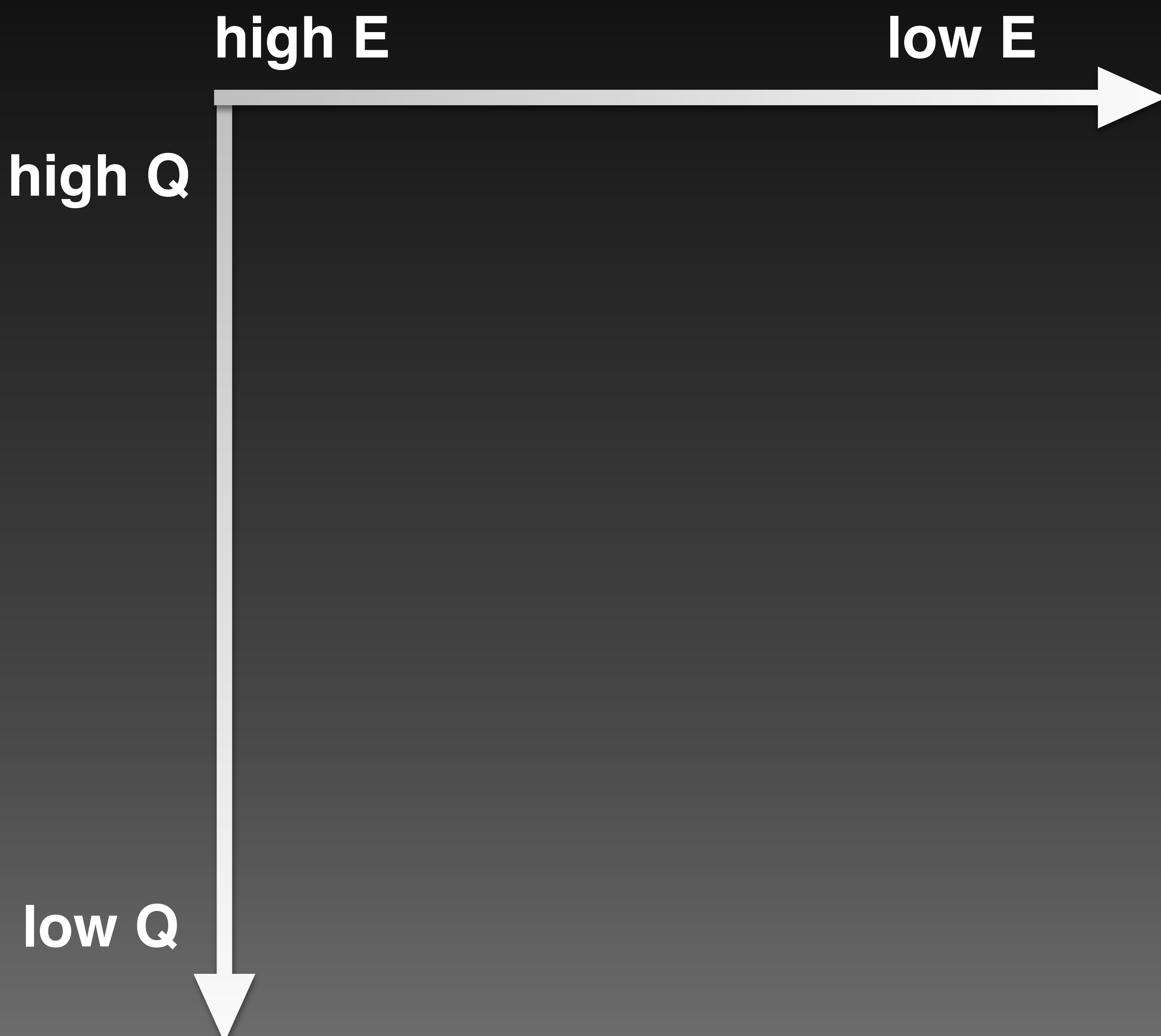
Chanwook Park

McGill University

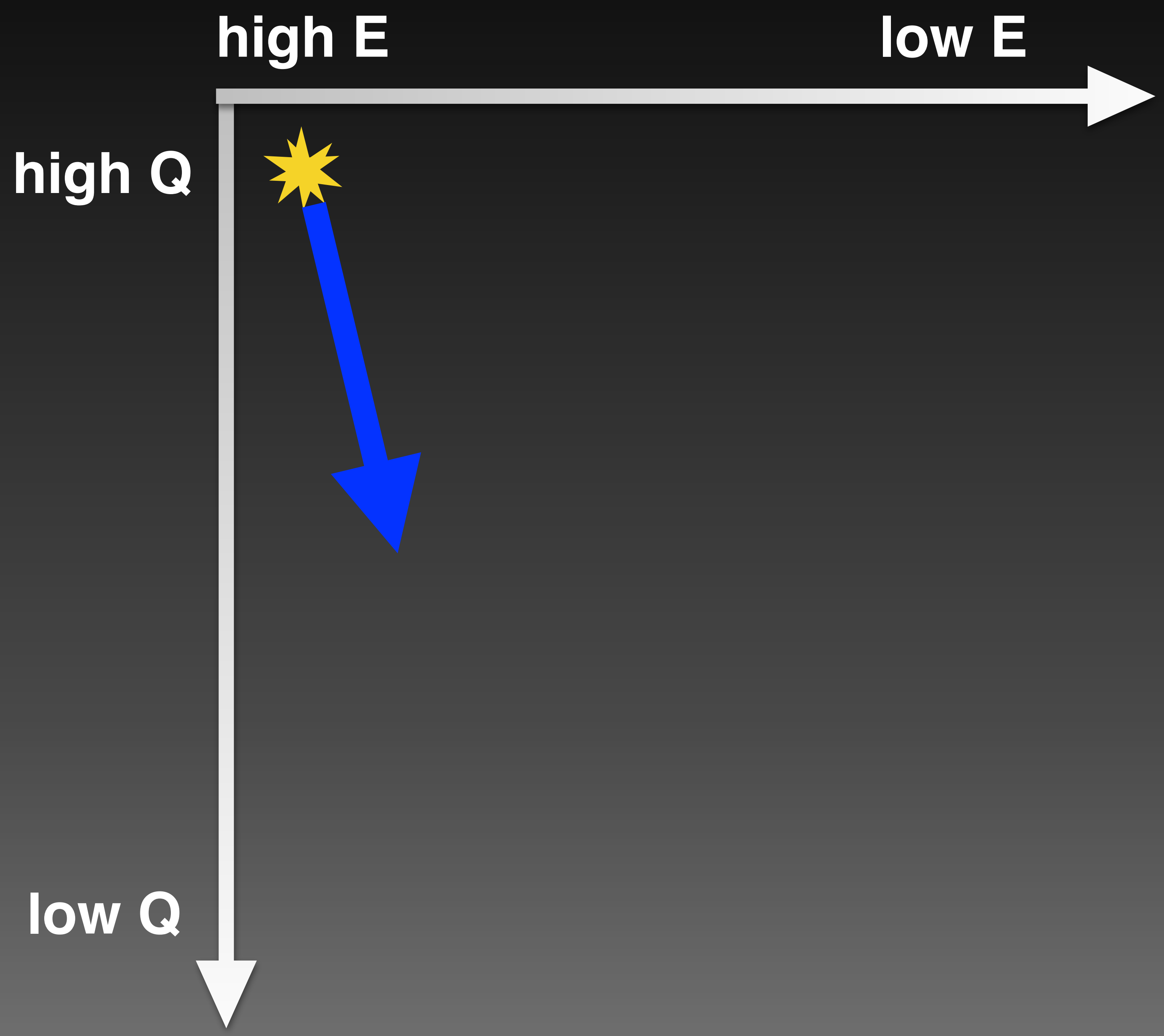
for the JETSCAPE collaboration

4 Oct. 2018

Multi-stage jet evolution



Multi-stage jet evolution



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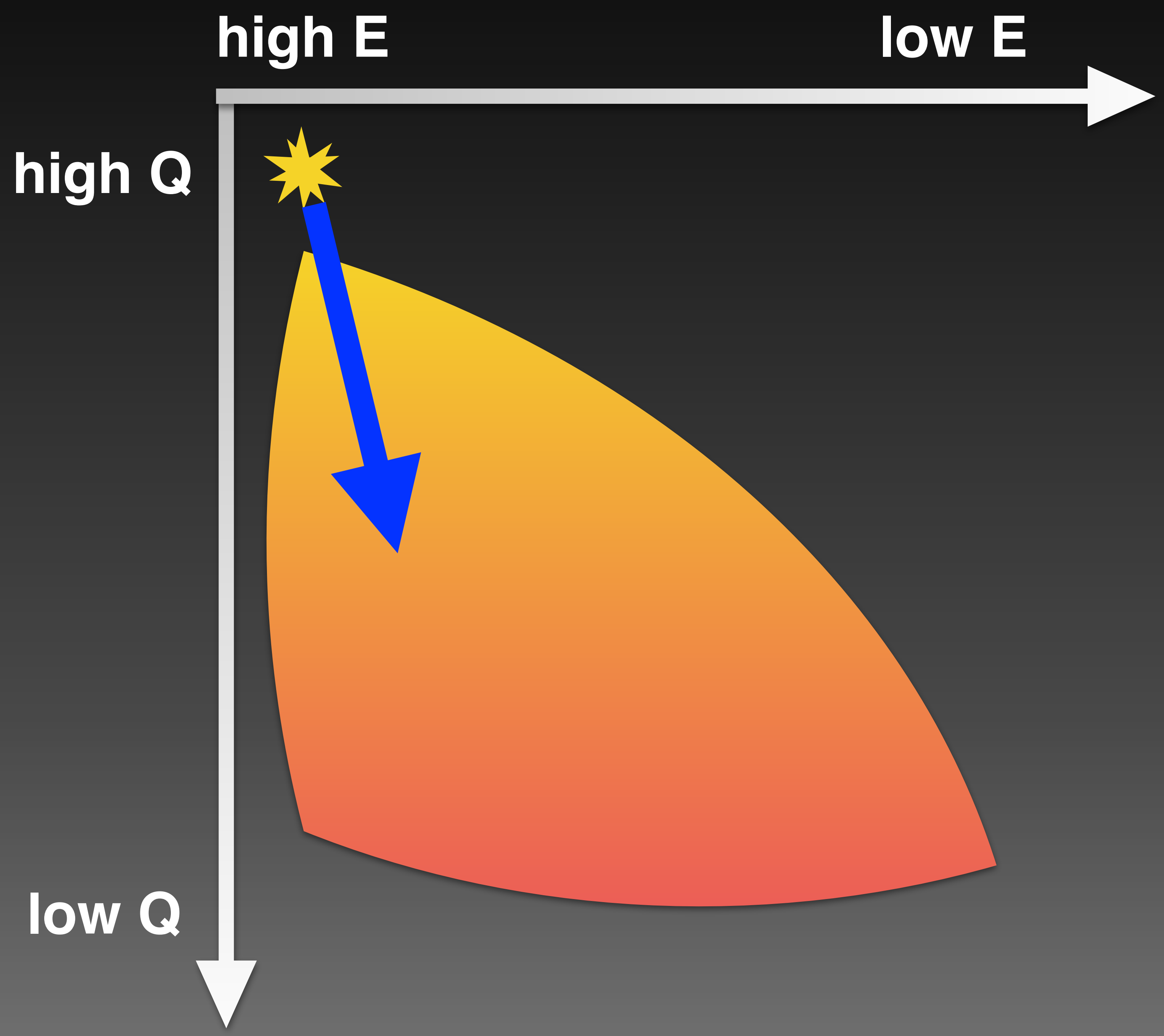
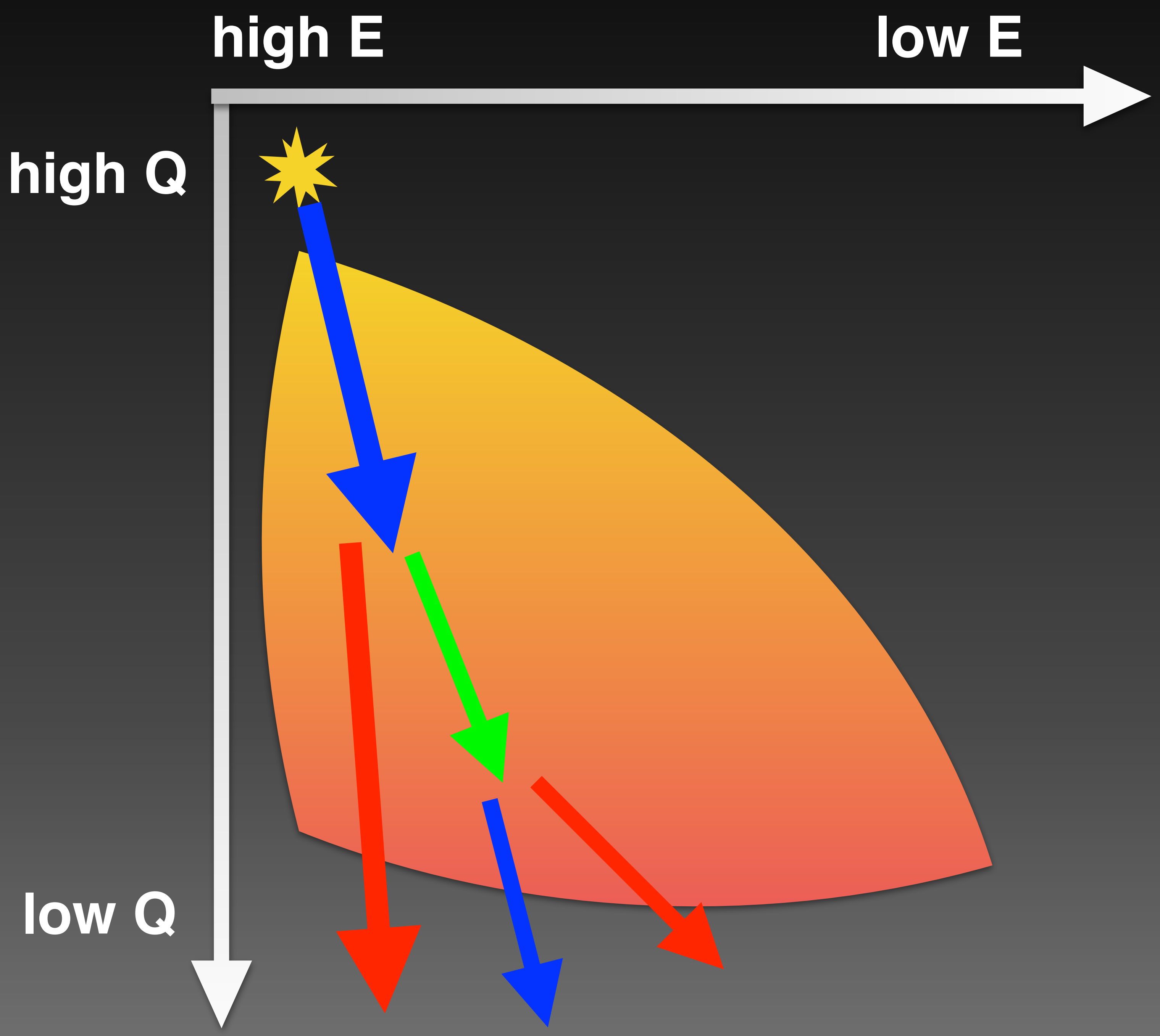


- High Q, high E: Radiation dominated, few scatterings (DGLAP, Higher Twist)

Multi-stage jet evolution



- High Q, high E: Radiation dominated, few scatterings (DGLAP, Higher Twist)
- Low Q, high E: Scattering becomes important (Transport, AMY, Higher-twist)

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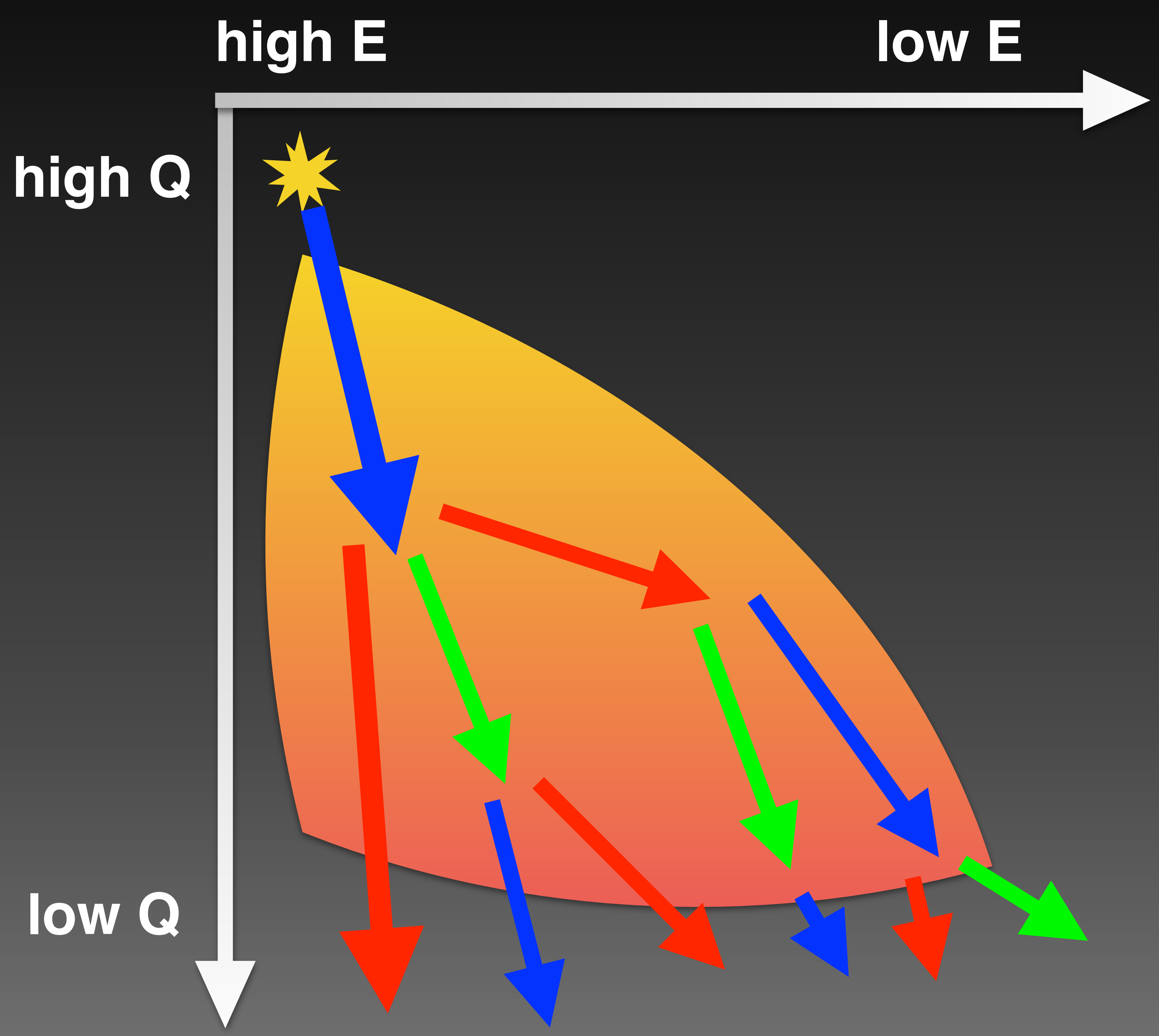
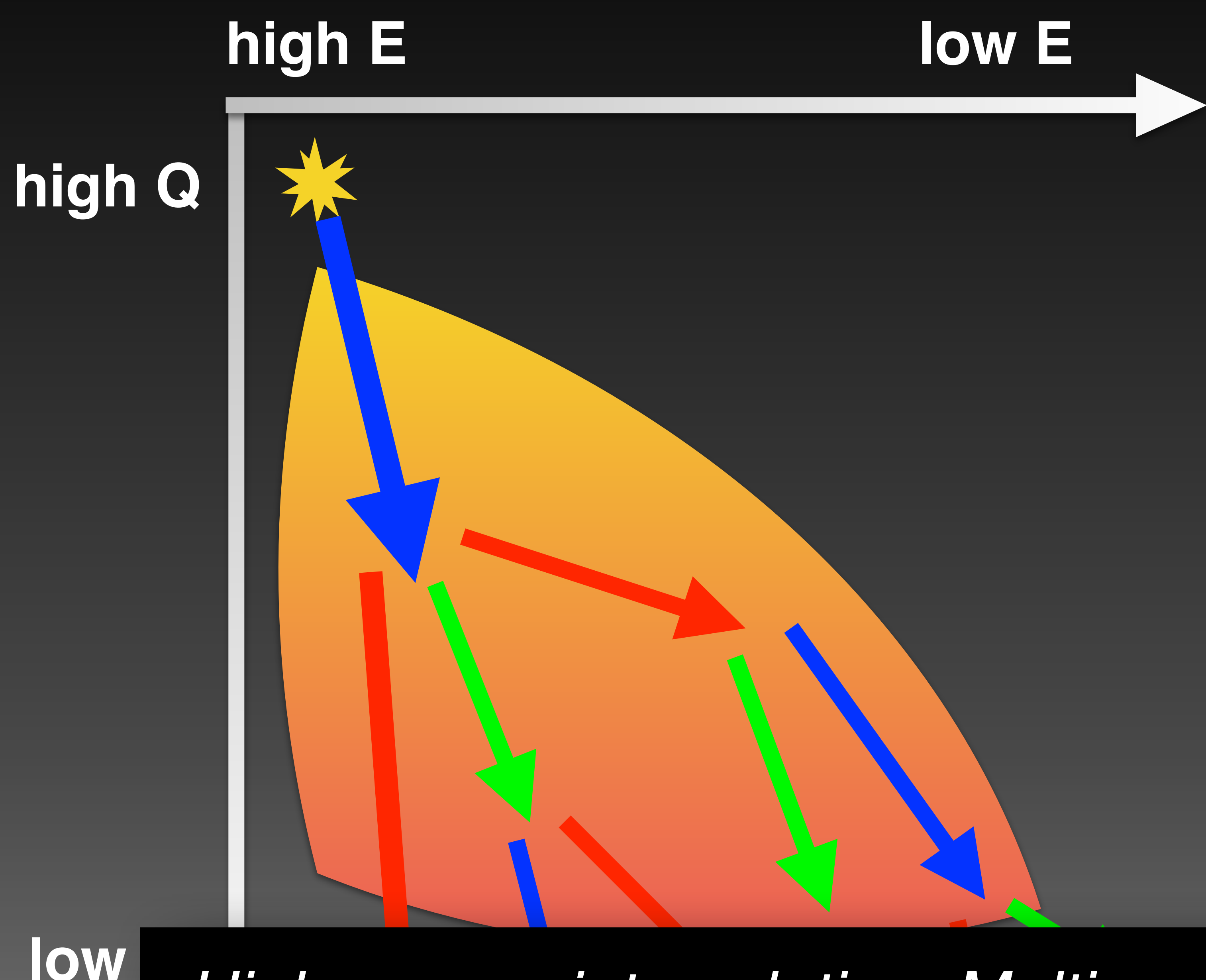


- High Q, high E: Radiation dominated, few scatterings (DGLAP, Higher Twist)
- Low Q, high E: Scattering becomes important (Transport, AMY, Higher-twist)
- Low Q, low E: Nearly thermal - strongly coupled approach (AdS/CFT)

Multi-stage jet evolution



- High Q, high E: Radiation dominated, few scatterings (DGLAP, Higher Twist)
- Low Q, high E: Scattering becomes important (Transport, AMY, Higher-twist)
- Low Q, low E: Nearly

High-energy jet evolution: Multi-scale problem that involves different stages.

Difficult for a single model to cover all the stages.

JETSCAPE

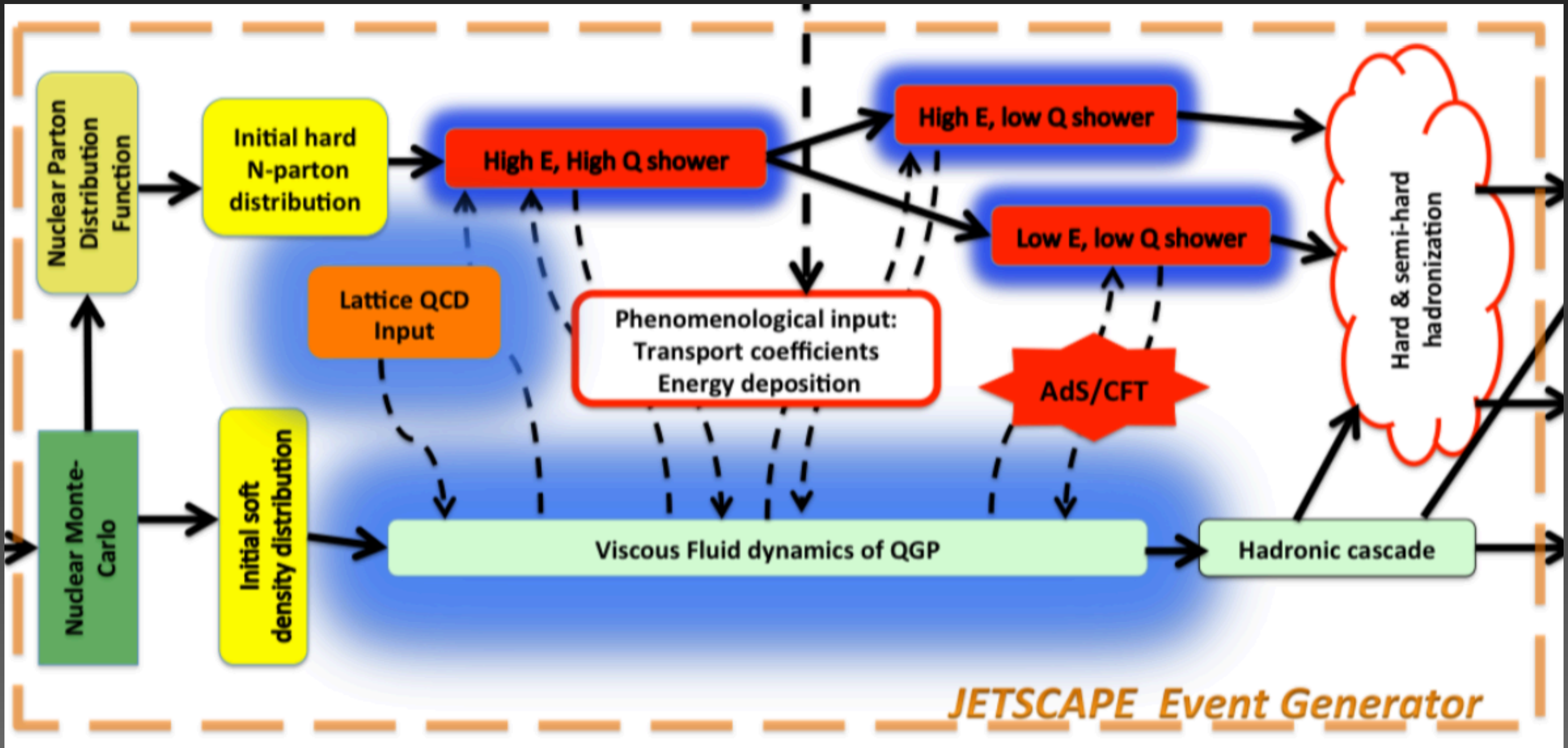
Jet Energy loss Tomography with a Statistically and Computationally Advanced Program Envelope

- Modular, extensive framework that covers multi-stage energy loss.
- Advanced concepts.
  - C++11, communication via Signals & Slots, XML reader, etc.
- Bayesian statistical analysis for parameter fitting.
- Large-scale computation resources by OSIRIS; parallelization and GPU optimization under development.

Poster by Joern Putschke

JETSCAPE 1.0

What's included in JETSCAPE 1.0
(3rd party packages)



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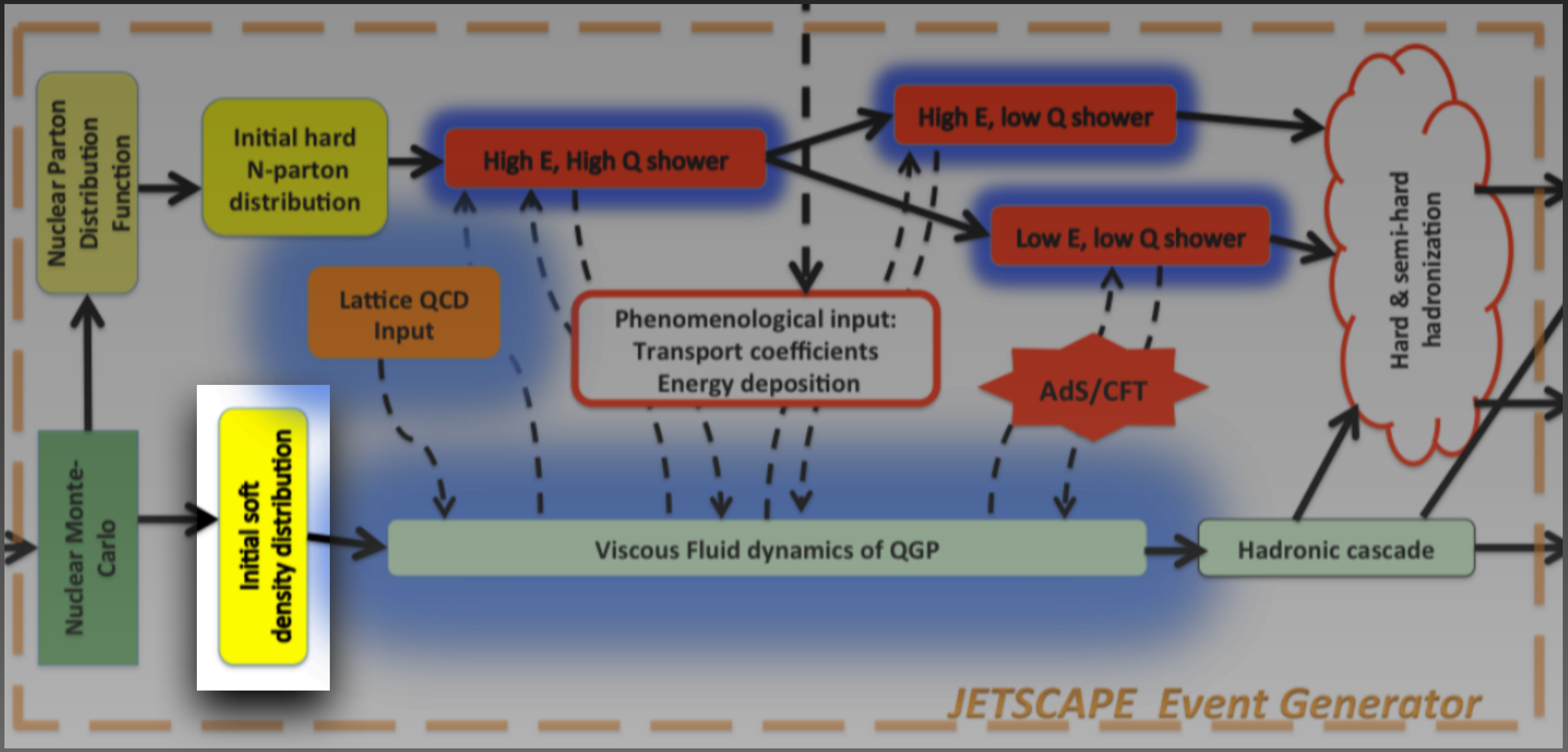

- Trento(2+1)
- Free Streaming
- MUSIC (2+1, 3+1), external reader, brick, Gubser
- Pythia8, Parton gun
- MATTER, LBT, MARTINI, Hybrid model
- Cooper-Frye
- Pythia8 Lund model
- ASCII, Gzip, HepMC output

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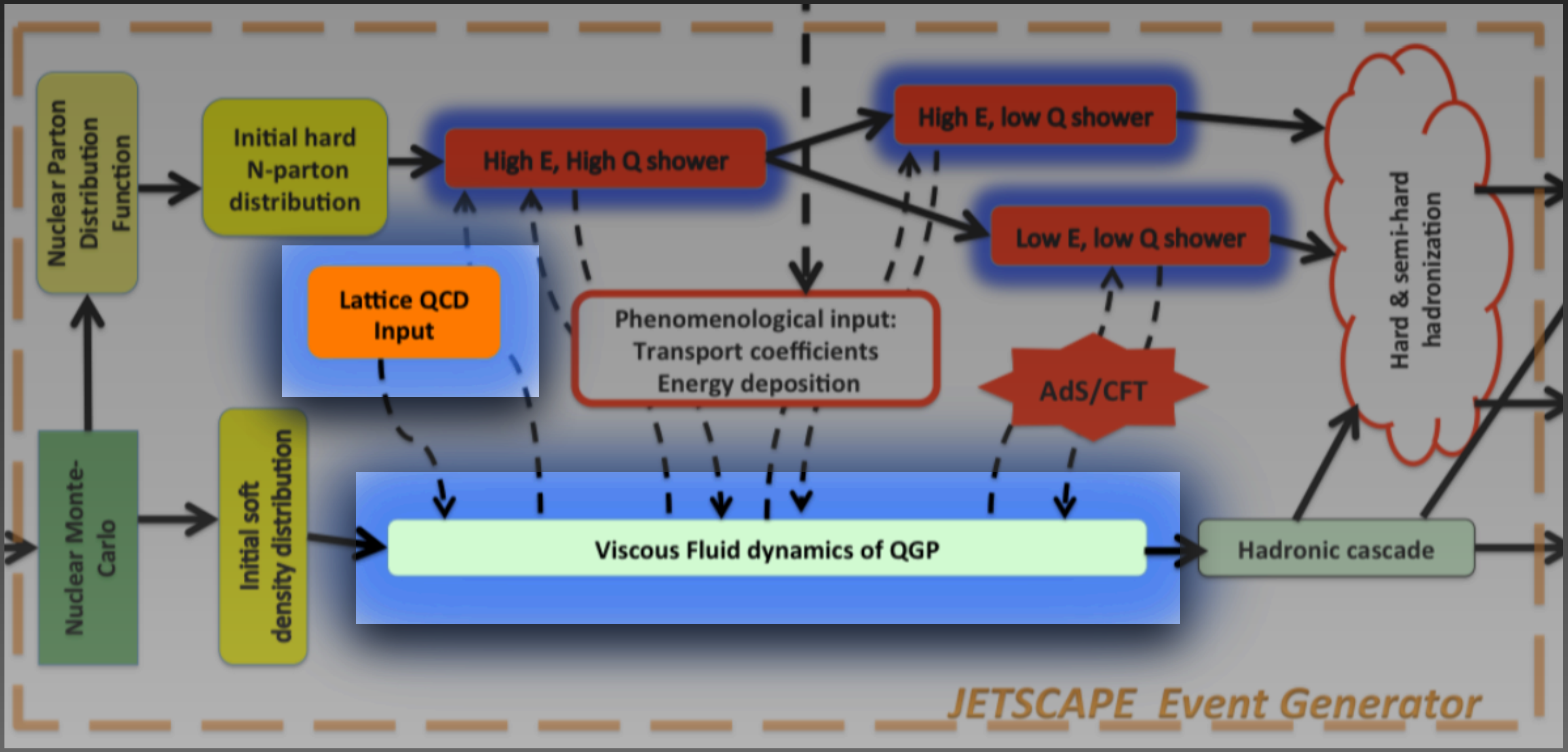

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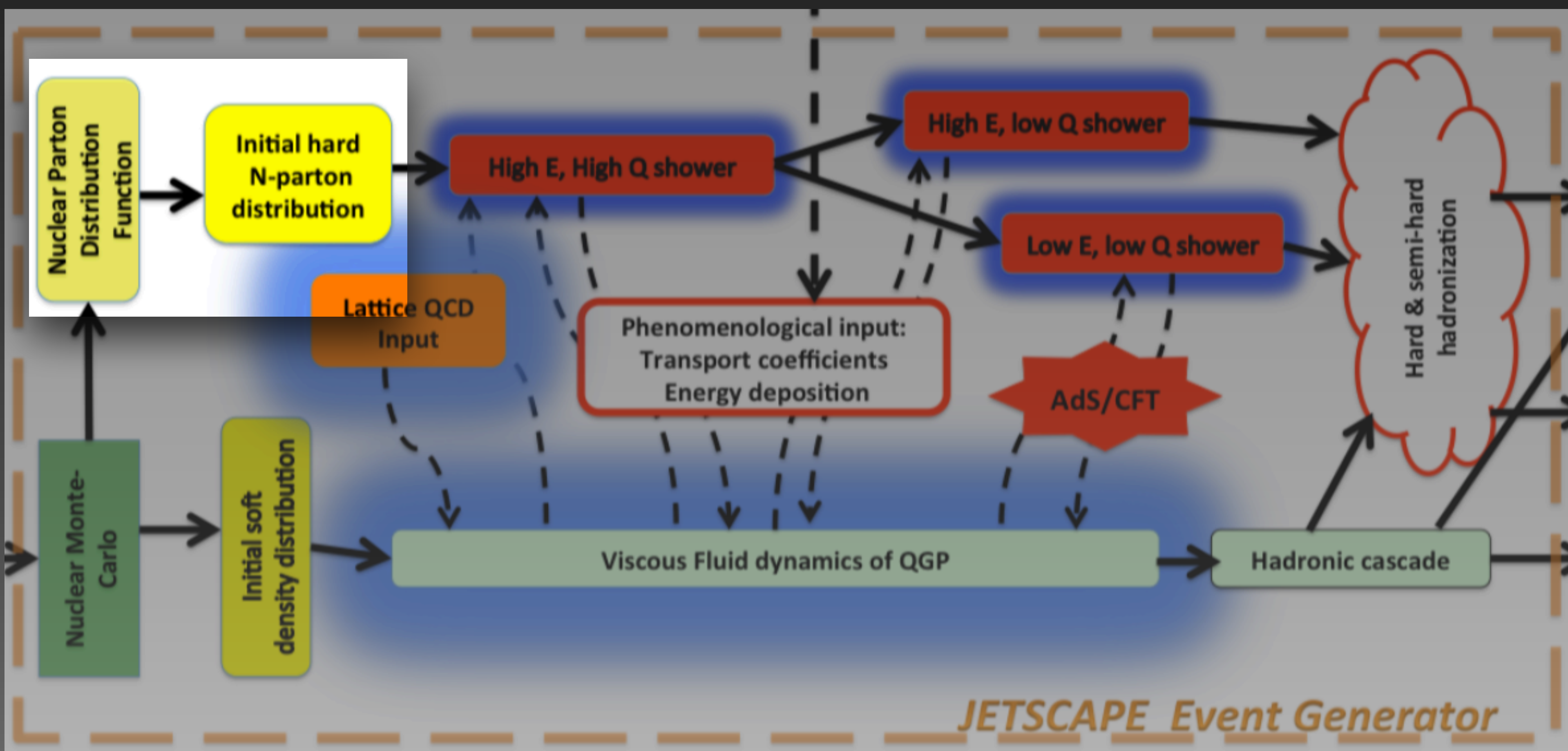

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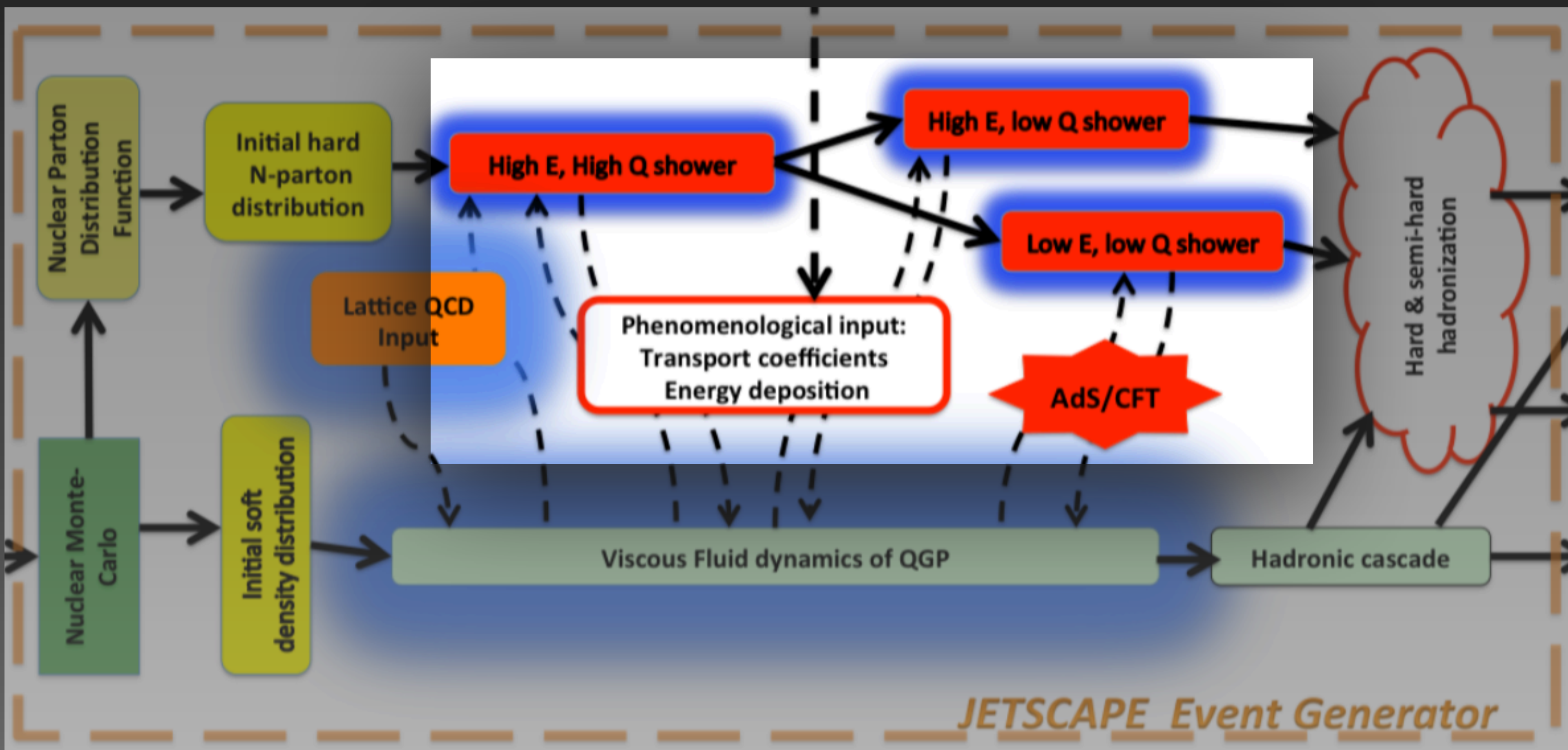

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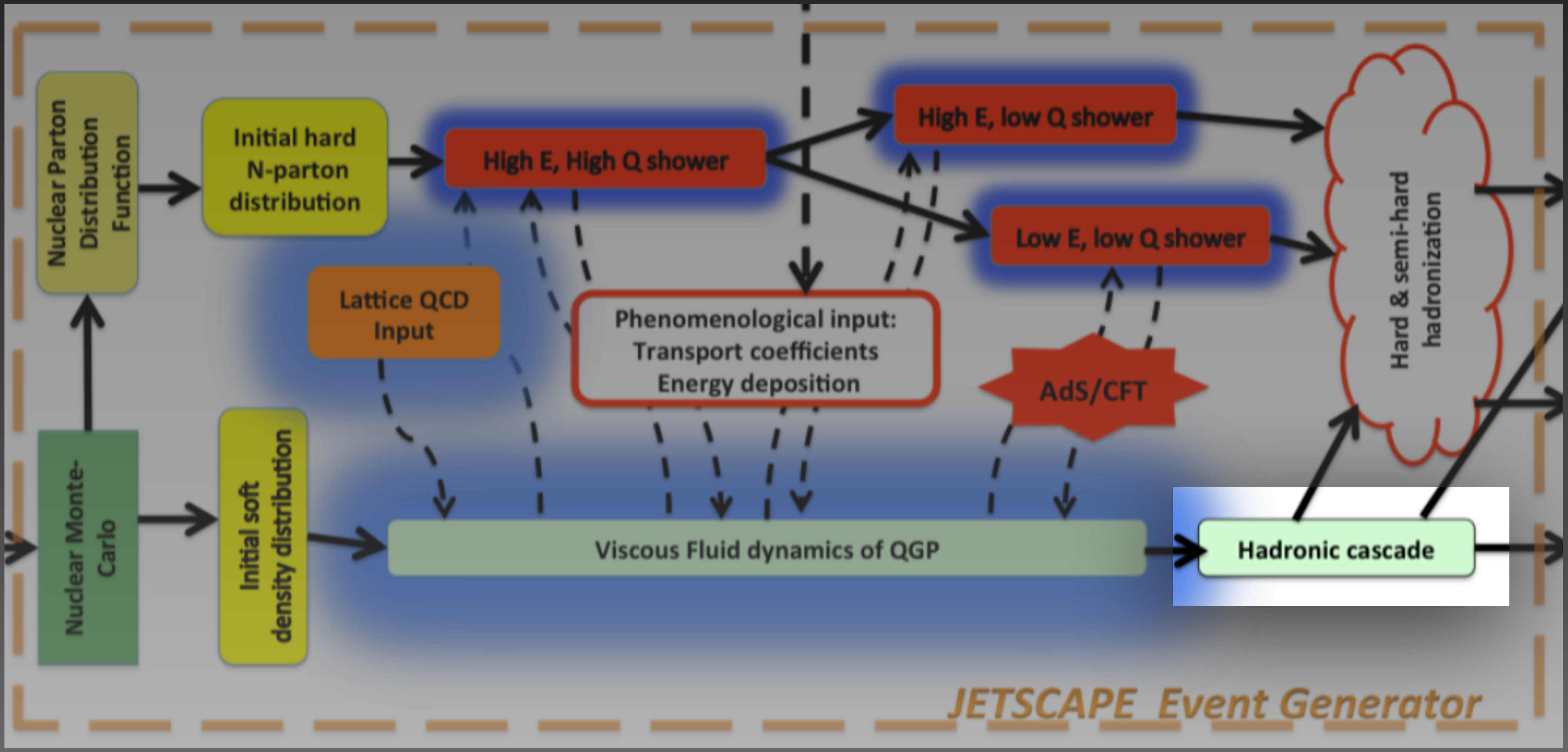

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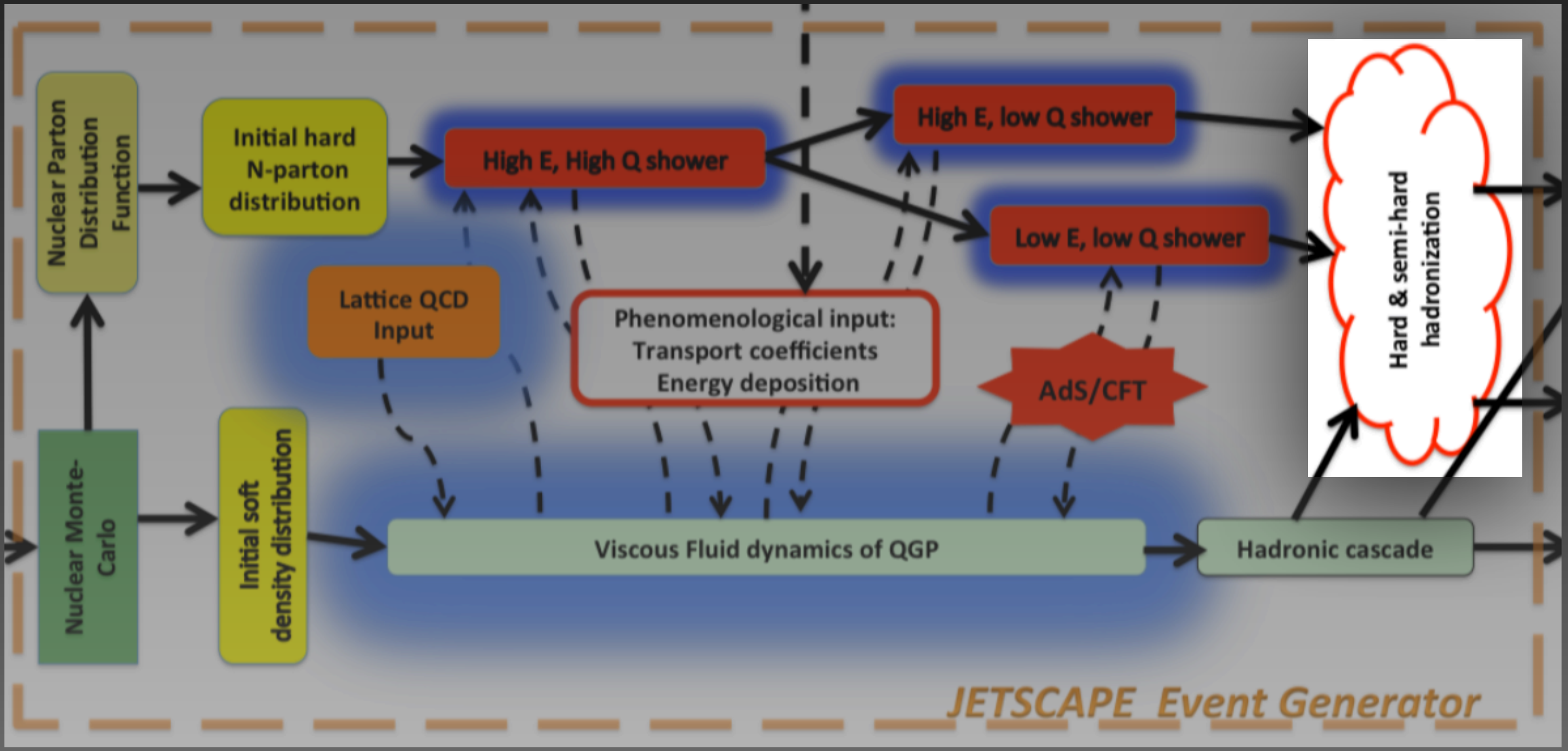

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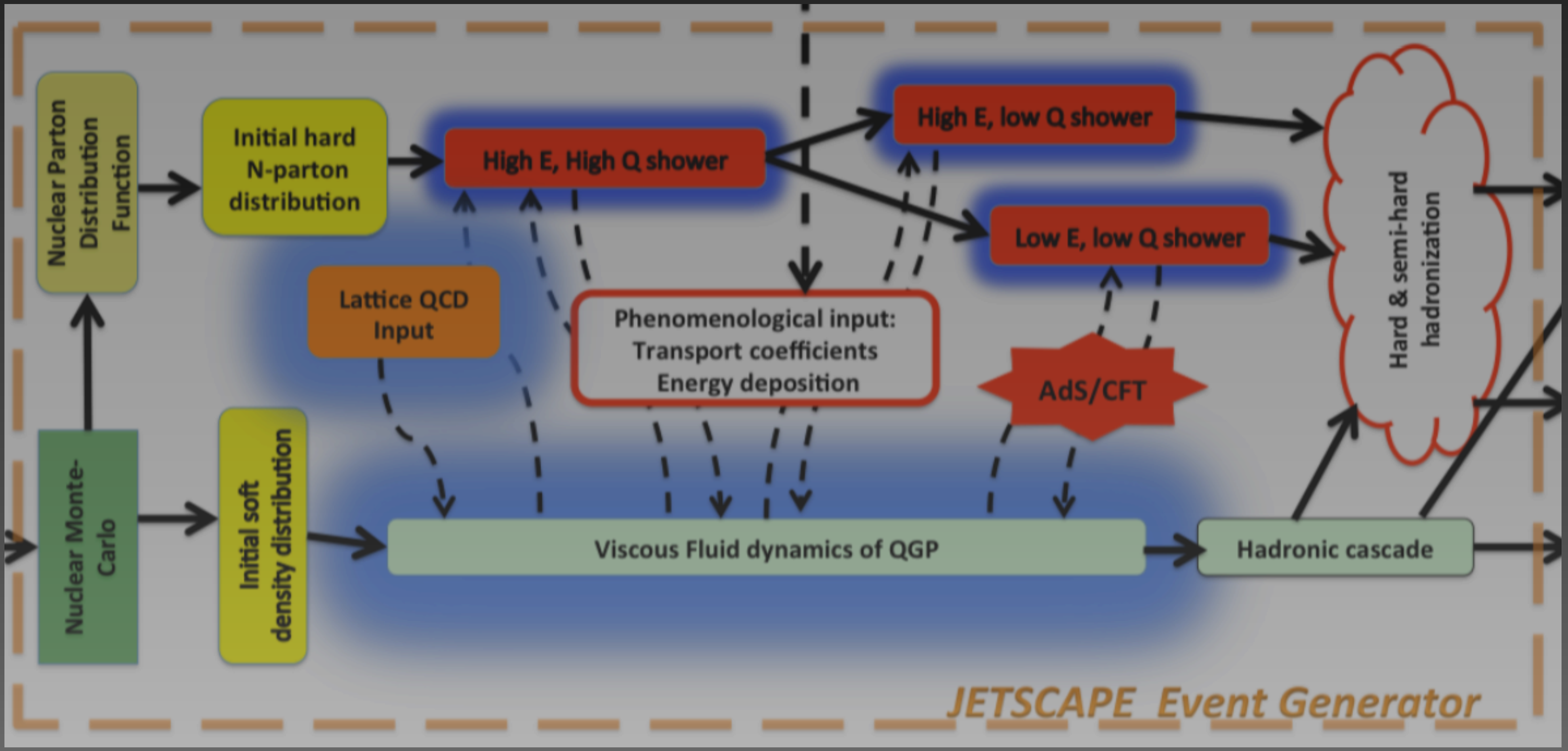

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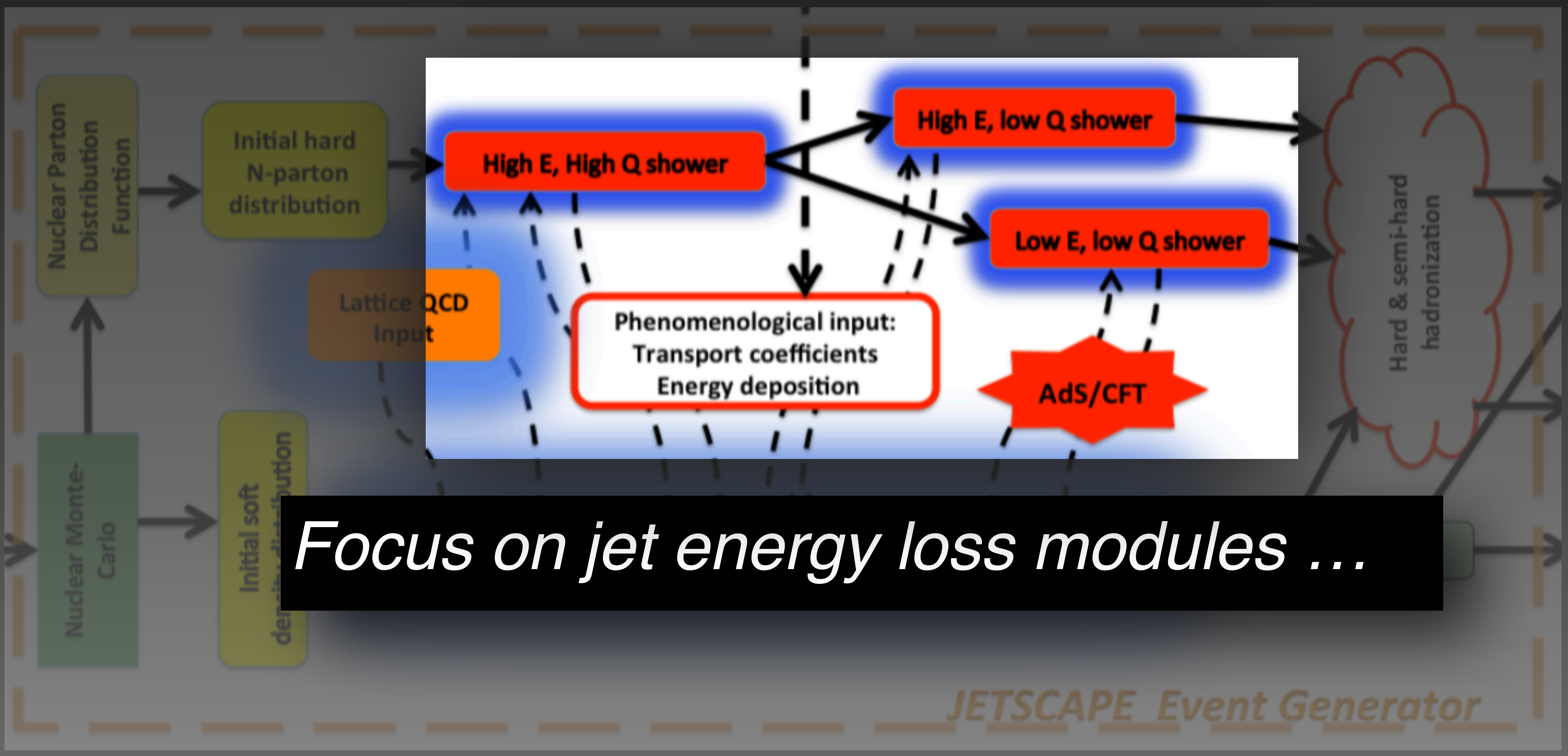

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High Q, high E shower

A. Majumder, Phys. Rev. C **88**, 014909

MATTER (The **M**odular **A**ll **T**wist **T**ransverse-scattering **E**lastic-drag and **R**adiation)

- Splitting of jets whose virtuality $Q^2 \gg \sqrt{\hat{q}E}$.
- Virtuality-ordered shower.
- Sudakov form factor:

$$\Delta(Q_{max}, Q) = \exp\left[-\frac{\alpha_s}{2\pi}\int_{Q^2}^{Q^2_{max}}\frac{dQ^2}{Q^2}\int_{z_c}^{1-z_c}\frac{dy}{y}P(y)\right]$$

- Splitting function by Higher Twist.

X-N. Wang, X-F. Guo, Nucl.Phys. A696 (2001) 788-832
A. Majumder, Phys.Rev. D85 (2012) 014023

$$P_i(y) = P_i^{vac}(y) + P_i^{med}(y)$$

$$P_i^{med}(y, k_\perp^2) = \frac{2C_A\alpha_s}{\pi k_\perp^4}P_i^{vac}(y)\int_{t_i}^{\tau_f} dt\hat{q}_i(t)\sin^2\left(\frac{t-t_i}{2\tau_f}\right)$$

Low Q, high E shower

LBT (**L**inear **B**oltzmann **T**ransport)

X-N. Wang, Y. Zhu, Phys. Rev. Lett. **111**, 062301
S. Cao, T. Luo, G-Y. Qin, and X-N. Wang, Phys. Rev. C **94**, 014909

- Time-ordered transport model with on-shell approximation.
- The evolution of phase-space distribution:

$$p_i \cdot \partial f_i(x_i, p_i) = E_i(\mathscr{C}_{el} + \mathscr{C}_{inel})$$

- Elastic scattering term $\mathscr{C}_{el}$ evaluated with LO 2↔2 process.
- Inelastic scattering rate:

$$\Gamma^{inel} = \langle N_g \rangle (E, T, t, \Delta t)/\Delta t = \int dx dk_\perp^2 \frac{d\Gamma_g}{dx dk_\perp^2}$$

- Medium induced differential gluon spectrum by Higher Twist:

$$\frac{d\Gamma_g}{dx dk_\perp^2} = \frac{2\alpha_s C_A \hat{q} P(x) k_\perp^4}{\pi (k_\perp^2 + x^2 m^2)^4} \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

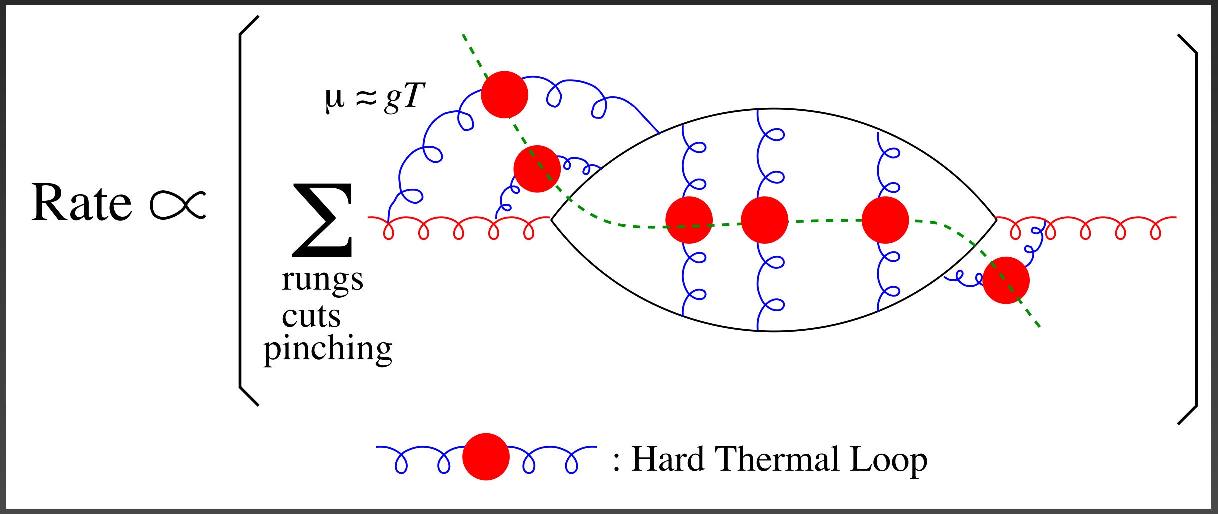
Low Q, high E shower

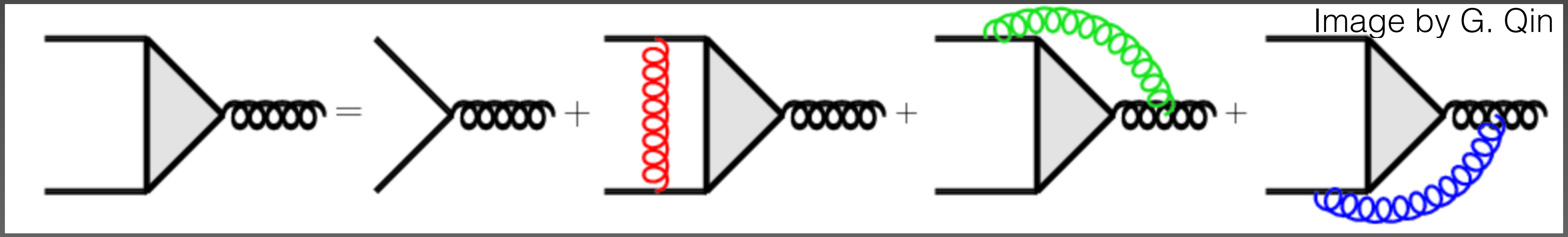
B. Schenke, C. Gale, and S. Jeon, Phys. Rev. C **80**, 054913

MARTINI (**M**odular **A**lgorithm for **R**elativistic **T**reatment of **H**eavy **I**o**N** **I**nteractions)

- AMY formalism for gluon radiation process.
  - Assuming asymptotically high T.

P. Arnold, G. Moore, and L. Yaffe, JHEP 0206 (2002) 030
S. Jeon, G. D. Moore, Phys. Rev. C **71**, 034901 (2005)





- Elastic scattering rate from LO 2↔2 process (similar to LBT).
- Quark-gluon conversion is included.

Low Q shower

AdS/CFT (**A**nti-**d**e **S**itter/**C**onformal **F**ield **T**heory)

J. Casalderrey-Solana, D-C. Gulhan, J-G. Milhano, D. Pablos, and K. Rajagopal, JHEP 1410 (2014) 019

- Non-perturbative holographic prescription for parton energy loss.
  - Assuming plasma-jet interaction dominated by $T \sim \Lambda_{QCD}$ scale.
- Energy flowing into hydro modes:

$$\frac{1}{E_{in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{stop}^2}\frac{1}{\sqrt{x_{stop}^2 - x^2}}$$

- Stopping distance x_{stop} is determined by a free parameter $\kappa_{SC} \sim \mathcal{O}(1)$.

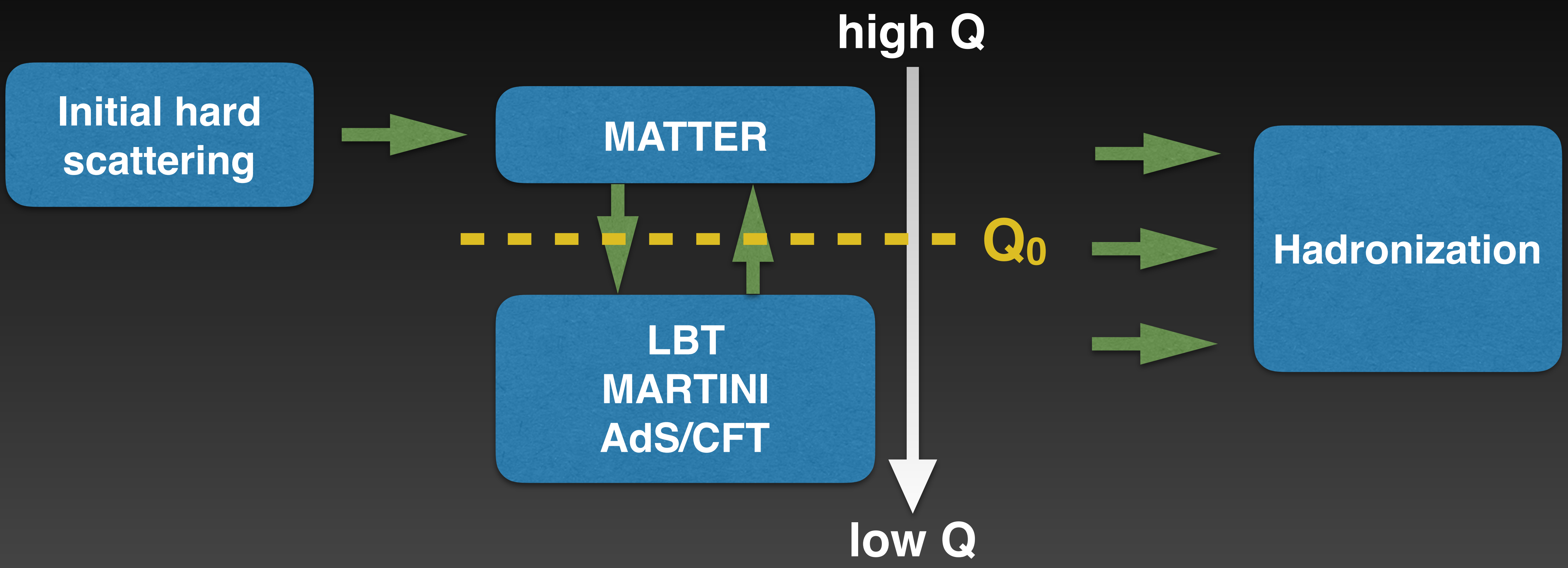
$$x_{stop} = \frac{1}{2\kappa_{SC}}\frac{E_{in}^{1/3}}{T^{4/3}}$$

Unified approach in JETSCAPE

- Single model: Constrained by its assumptions.
- In the unified approach:
  - The domain of validity is extended in the Q-E space.
  - The effect of each component can be studied.
  - Each component can be replaced with another.
    (e.g., LBT, MARTINI, AdS/CFT for low Q shower)
    - Extract meaningful physics!

Results

Model setups



- Separation scale Q_0: 2 GeV.
- Hadronization: Modified Lund model, no color information.
- pp baseline: MATTER vacuum shower down to $Q_0 = 1$ GeV.
- Event-averaged hydro.
- MATTER, LBT: recoil ON; MARTINI, AdS/CFT: not yet implemented.
- *Precision tuning on-going work.*

Credits

Modules

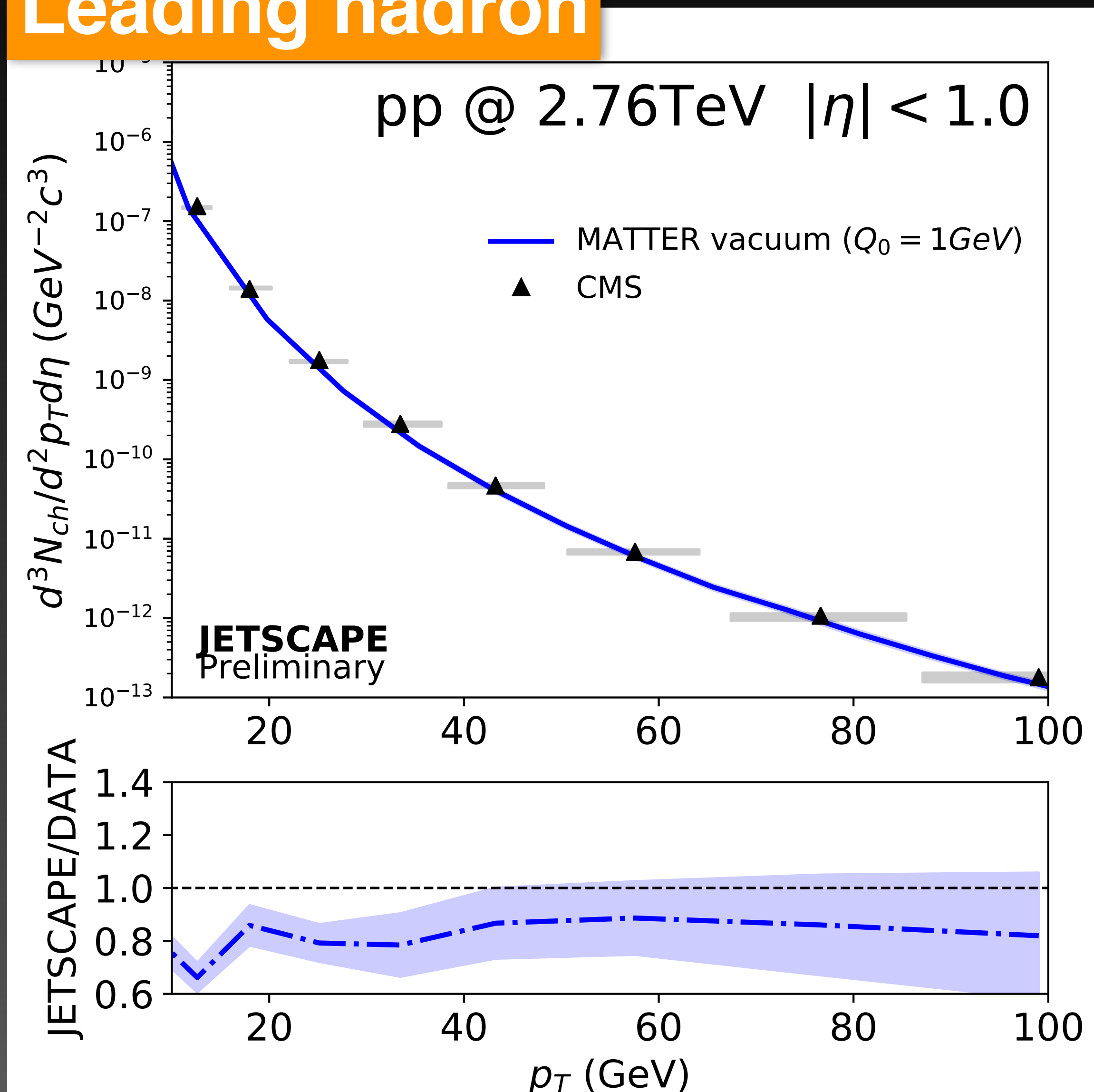
- MATTER, LBT — S. Cao, A. Kumar, and Y. Tachibana
- MARTINI — C. Park
- AdS/CFT — D. Pablos

Observables

- Leading hadron R_{AA} — C. Park, C. Sirimanna
- Jet R_{AA} — A. Kumar, C. Park
- Elliptic flow — Y. He

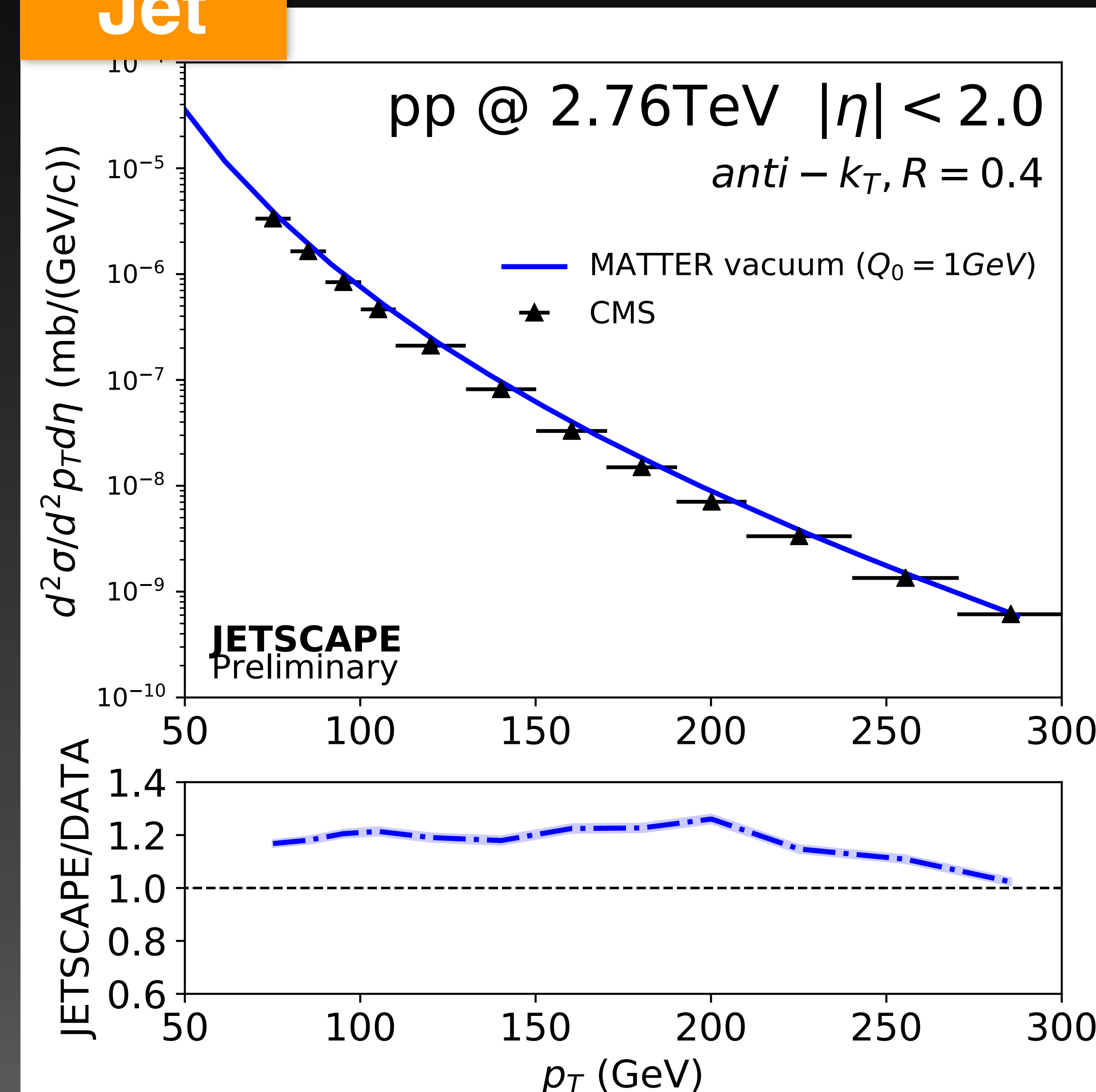
JETSCAPE Results : p-p

Leading hadron



CMS from Eur.Phys.J. **C72** (2012)

Jet



CMS from Phys.Rev. **C96** 015202 (2017)

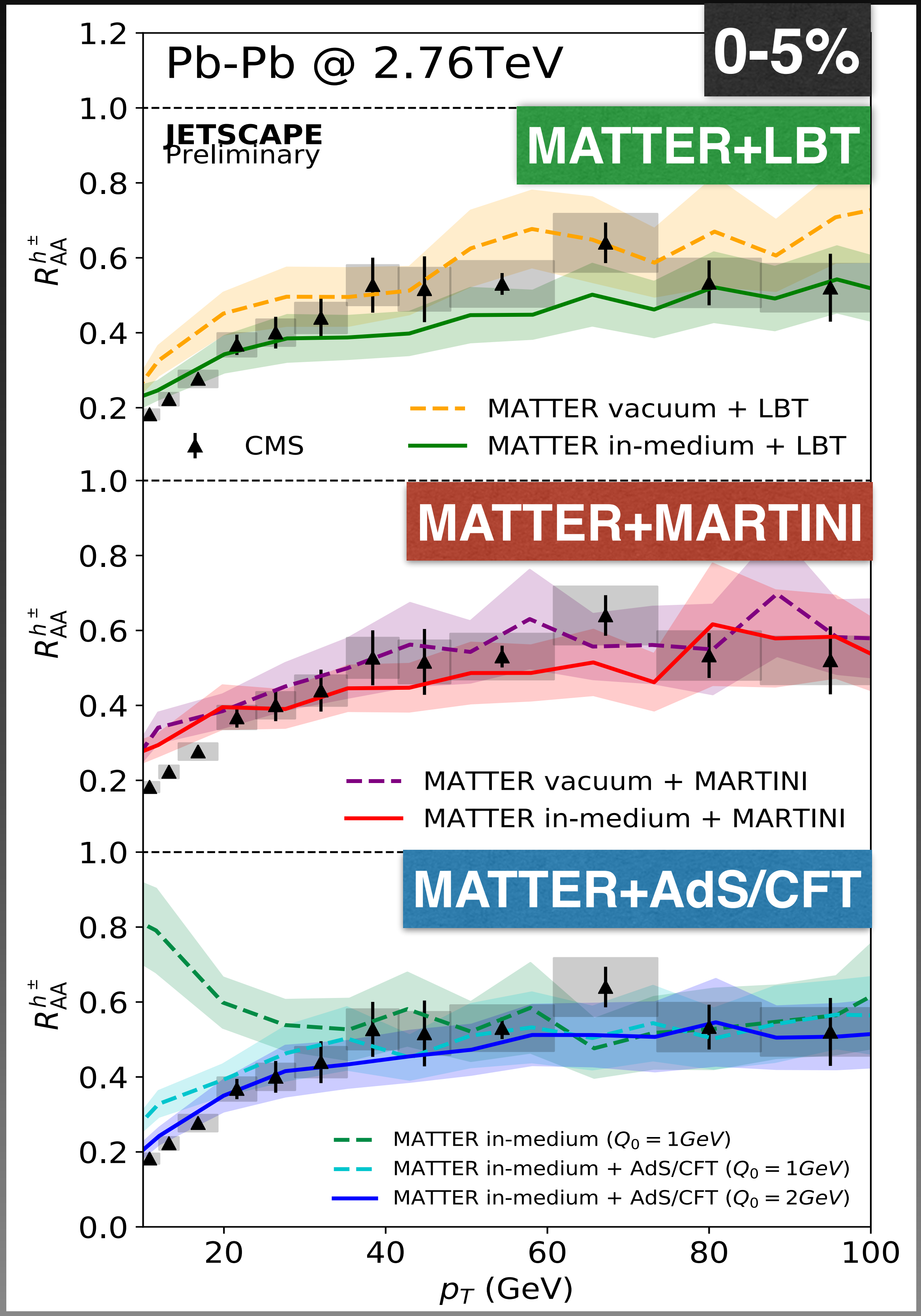
- p-p results generally describe data well.
- Deviation < 20%; further tuning required.

Poster by Rainer Fries

JETSCAPE Results : Single hadrons

CMS from Eur.Phys.J. **C72** (2012)

- All low-Q e-loss modules consistent.
- At Q_0=1GeV, high p_T particles already quenched by Q-ordered shower; low pT part done by low-Q shower.
- Q_0 affects e-loss at low p_T more than at high p_T.
  - Can be constrained by low p_T.



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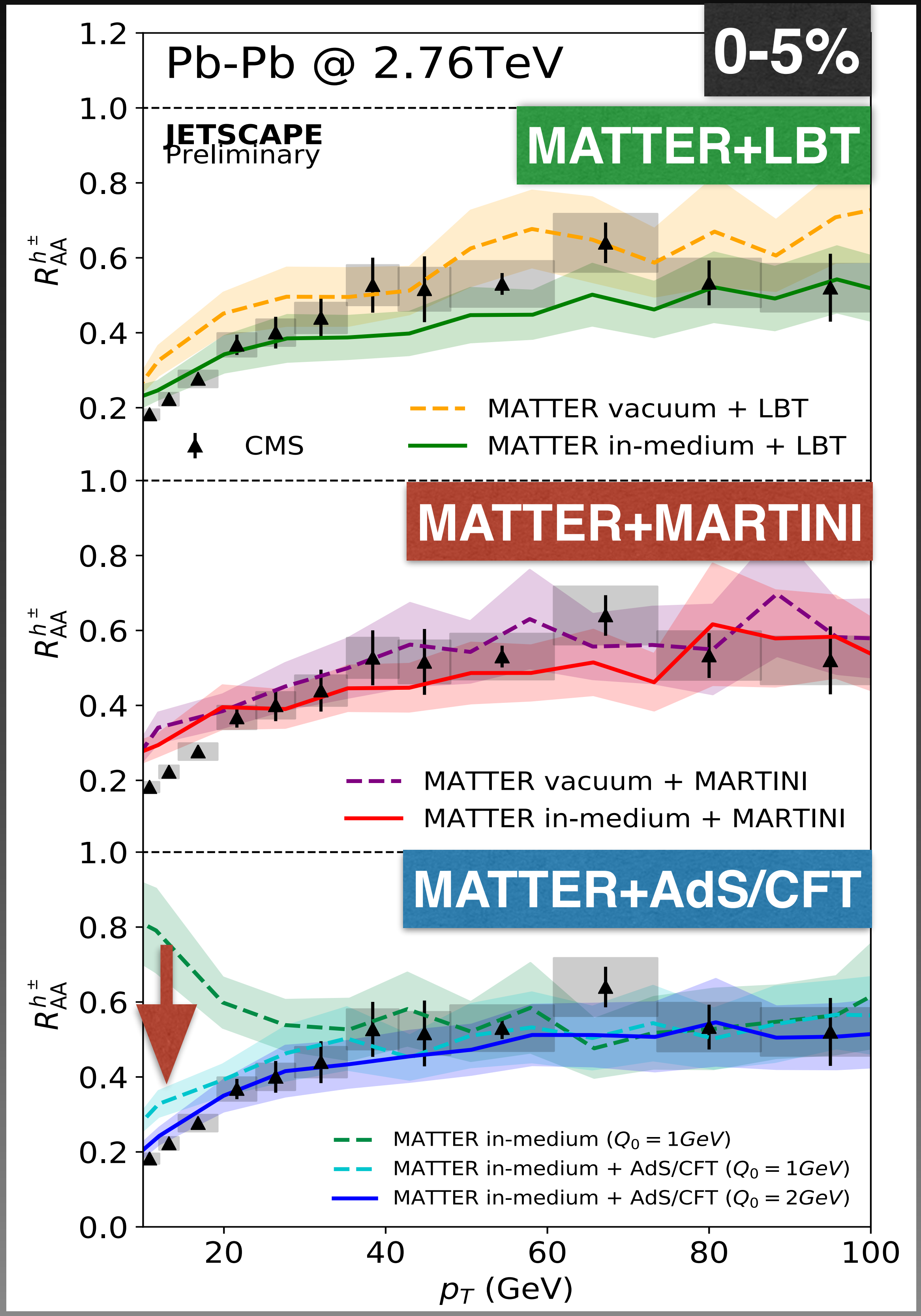

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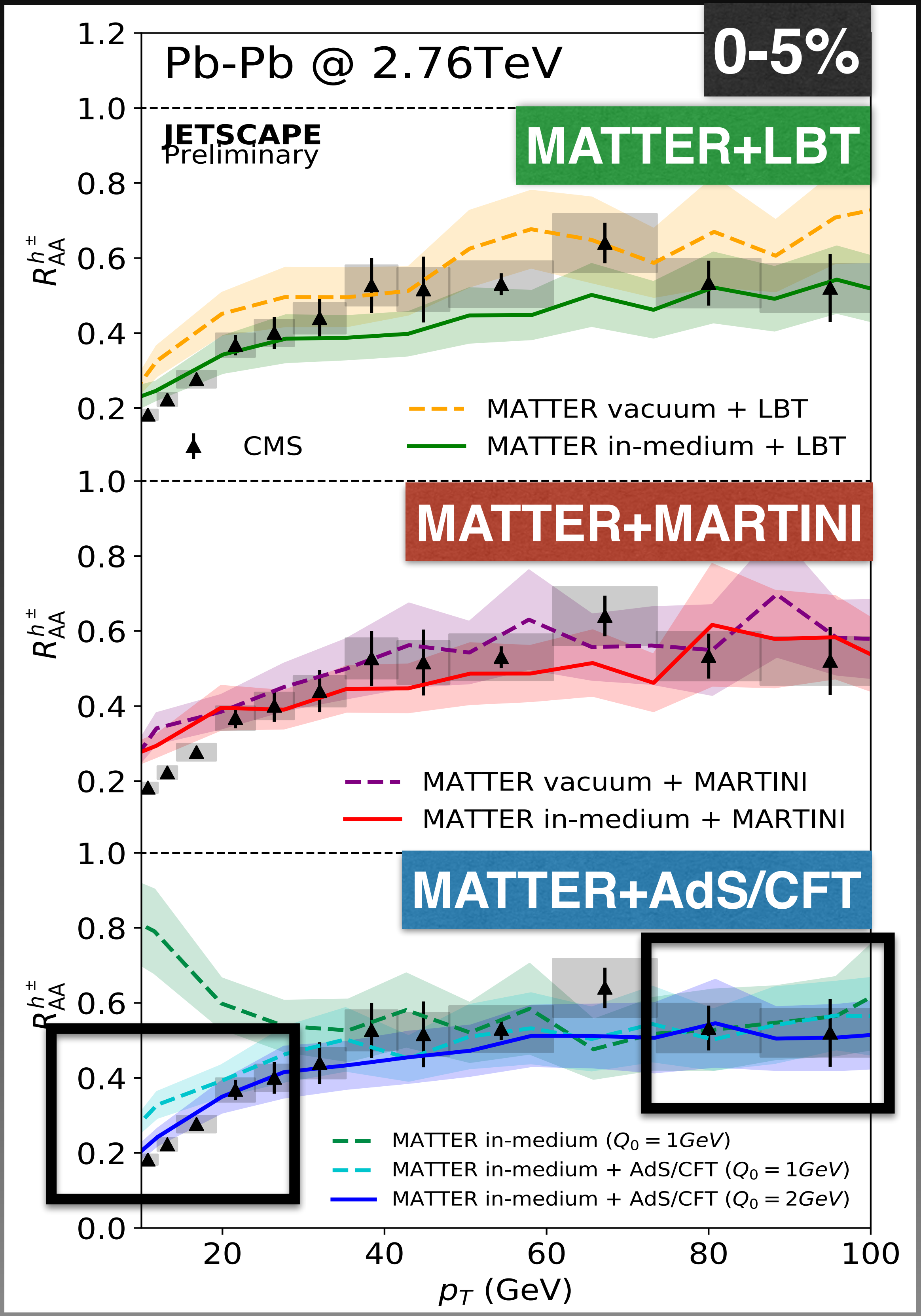
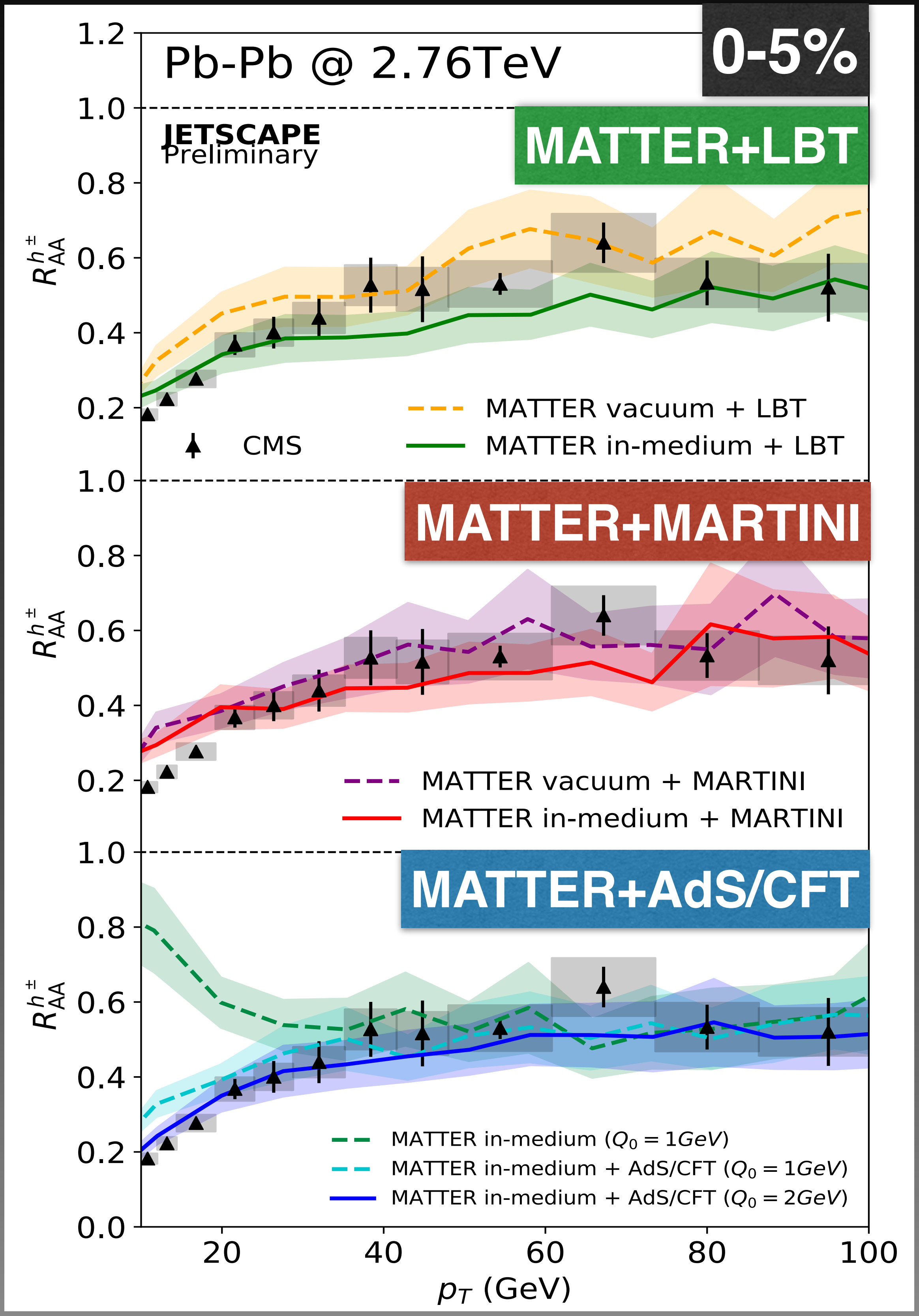
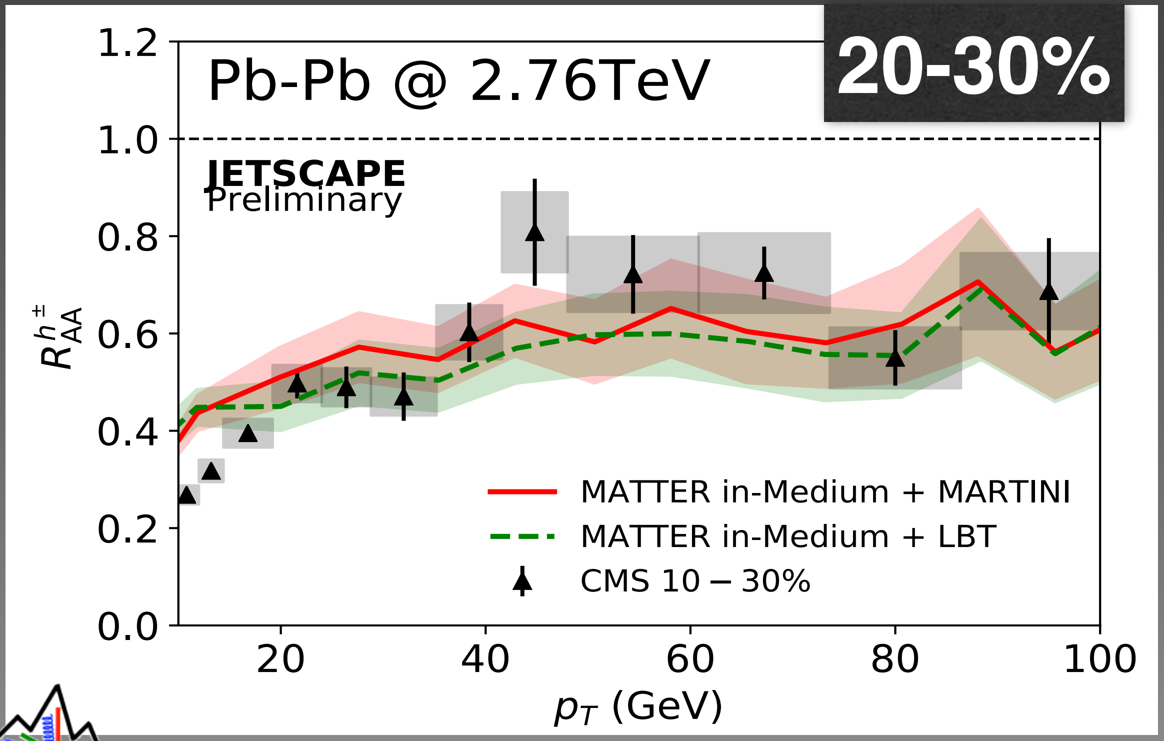


JETSCAPE Results : Single hadrons

CMS from Eur.Phys.J. **C72** (2012)

- Centrality dependence works as well.
- All module combinations give reasonable descriptions with data.

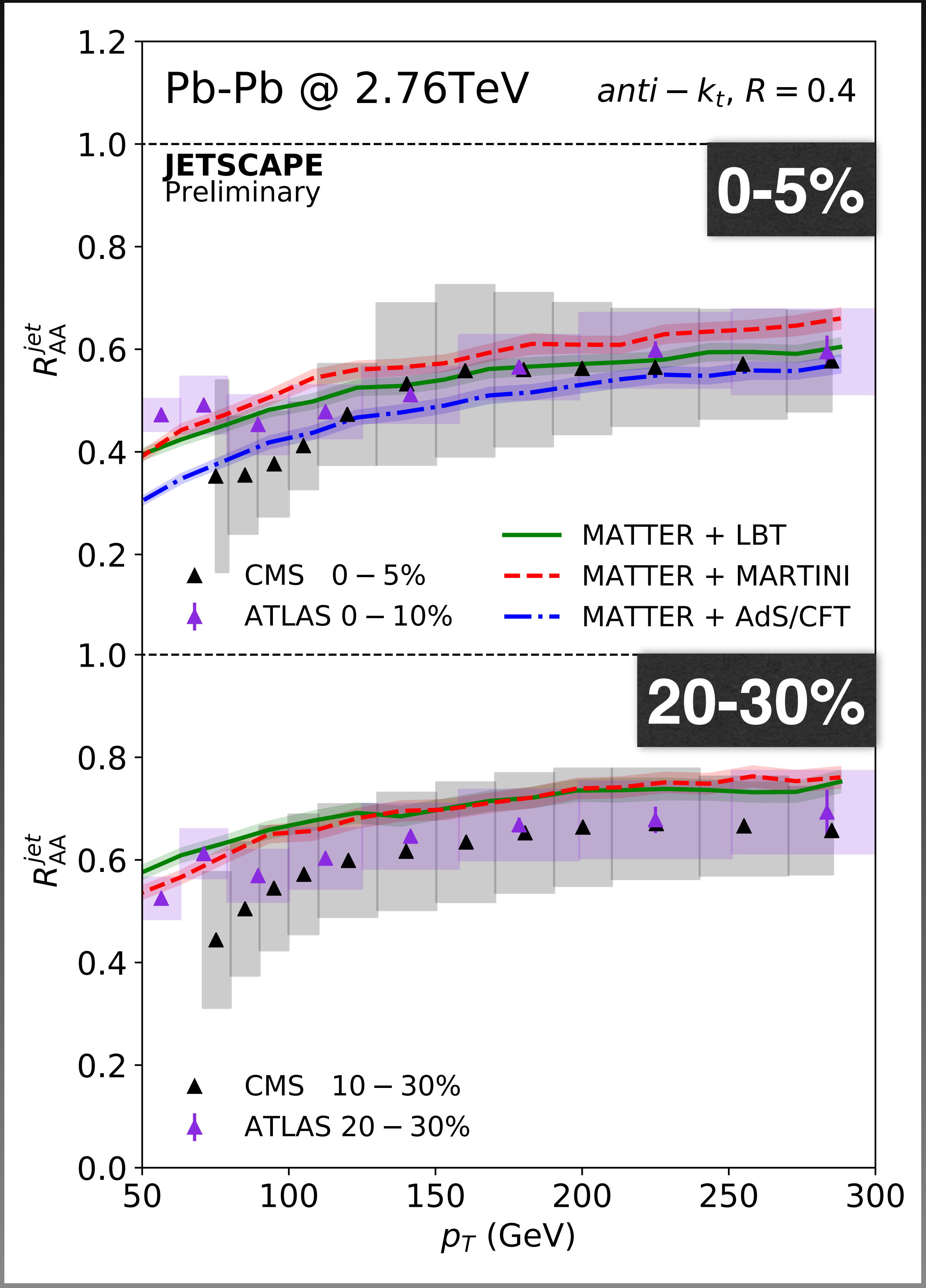




JETSCAPE Results : Inclusive jets

CMS from Phys.Rev. **C96** 015202 (2017)
ATLAS from Phys. Rev. Lett. **114**, 072302 (2015)

- Similar p_T dependence, magnitude within error bars.
- Test of centrality dependence: Further examination required.



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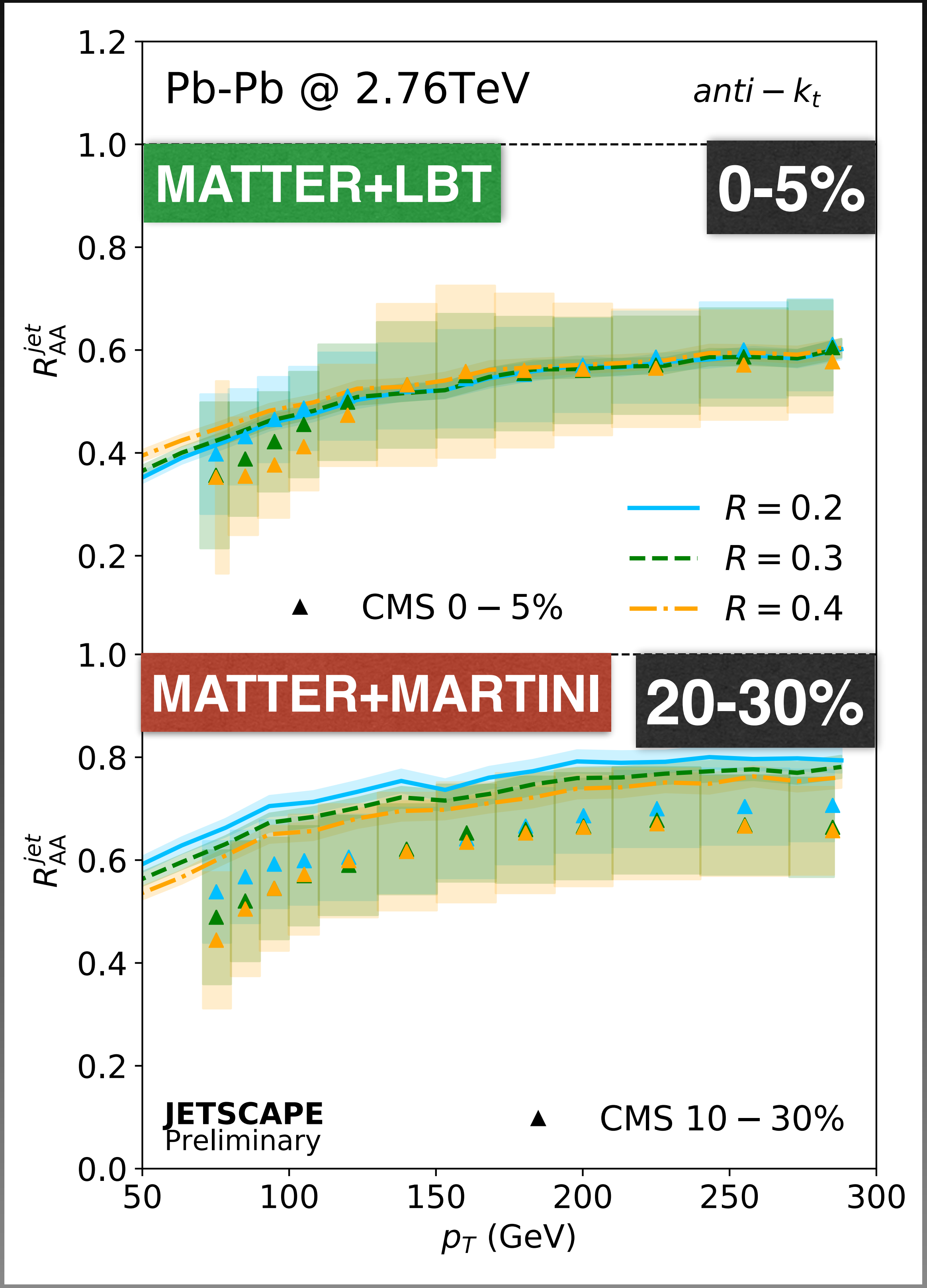
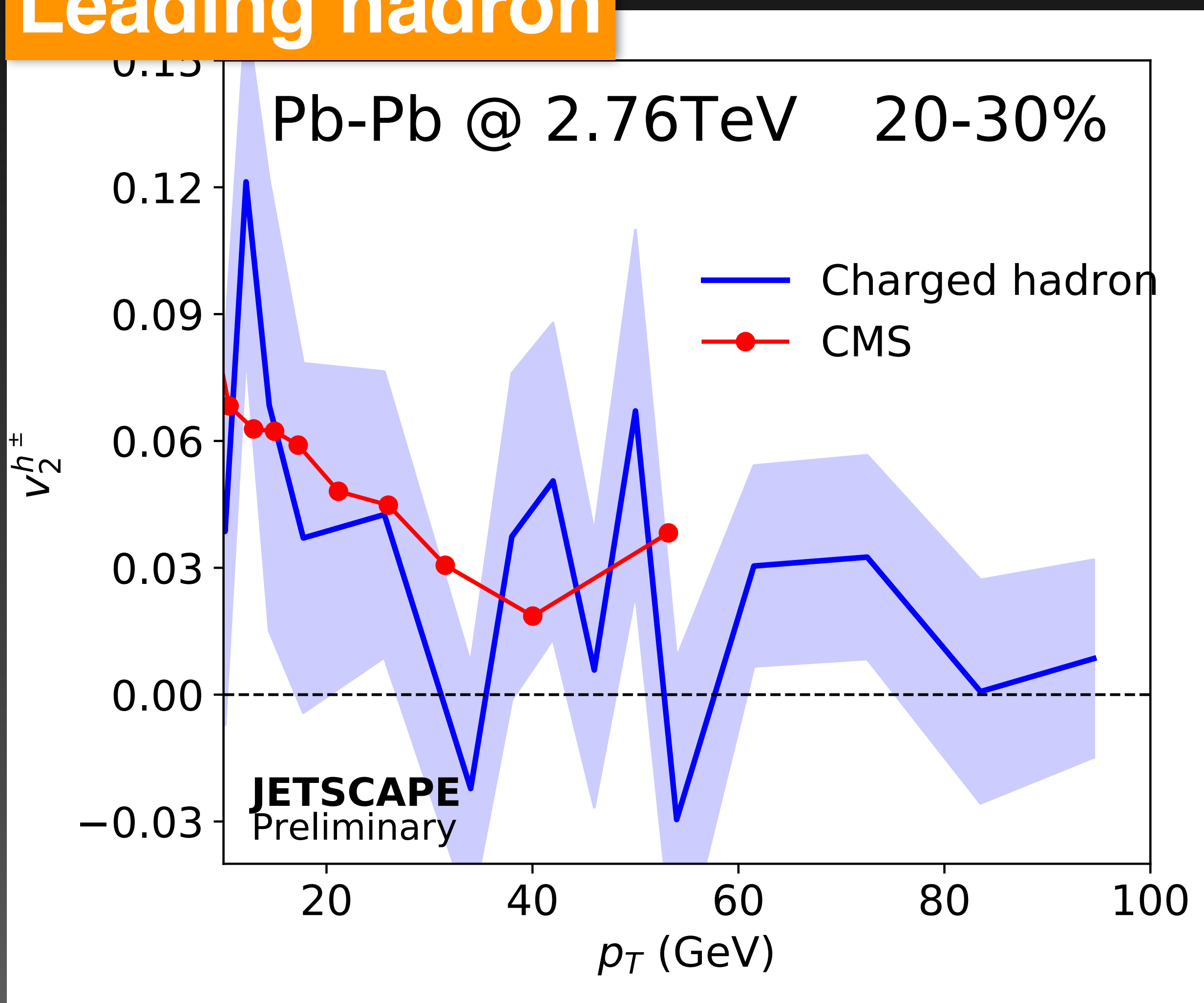


- Similar p_T dependence, magnitude within error bars.
- Test of centrality dependence: Further examination required.
- R dependence consistently small across models, centralities.

JETSCAPE Results : Correlations

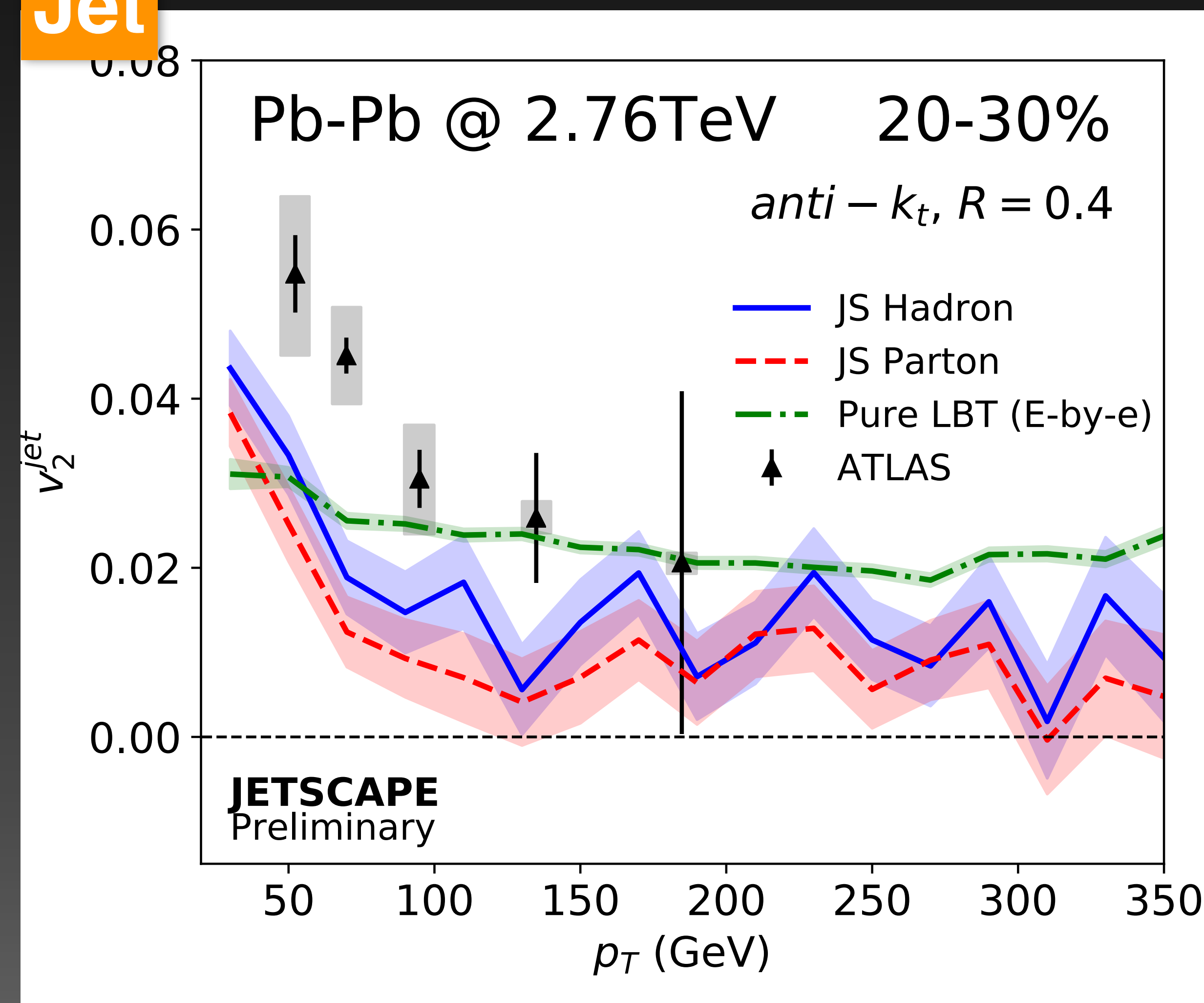
MATTER+LBT

Leading hadron



$$v_2 = \langle \cos(2[\phi^{jet} - \Psi_2]) \rangle$$

Jet

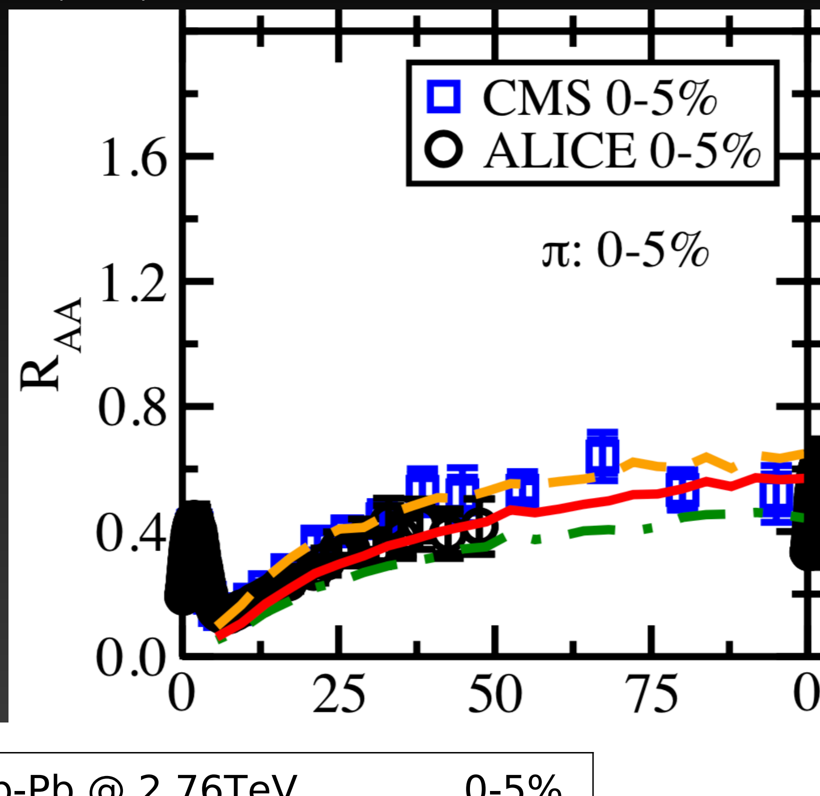


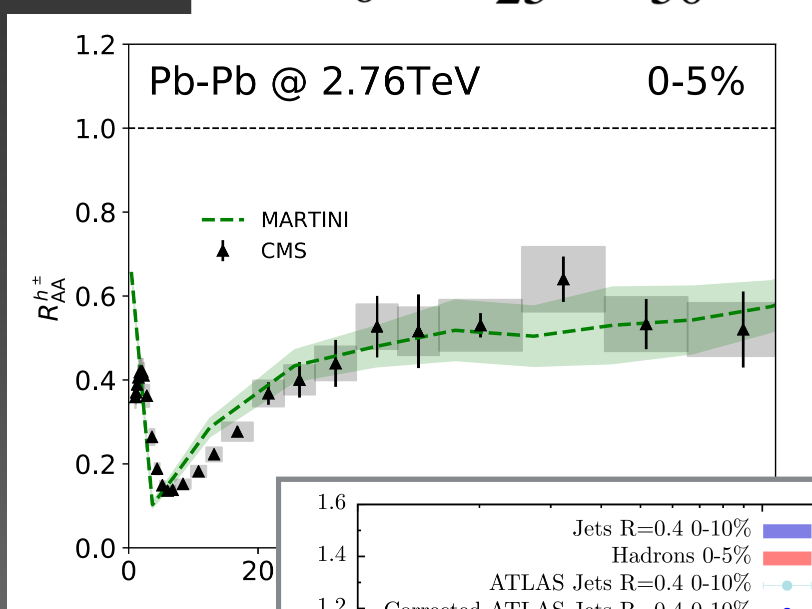
CMS from Phys. Rev. C **87**, 014902 (2017)
ATLAS from Phys. Rev. Lett. **111**, 152301 (2013)

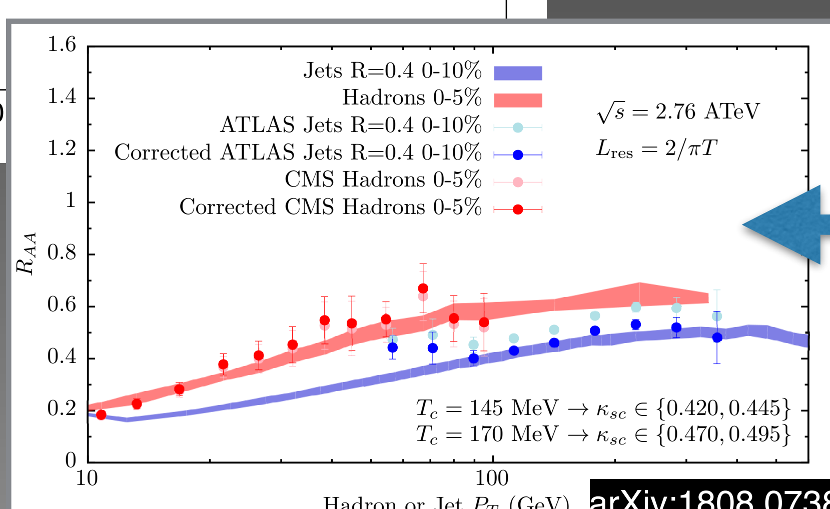
- Low statistics; general trend in the right direction
- Stronger correlation developed after hadronization.
- Event-averaged hydro used: *Event-by-event for improvement.*

JETSCAPE vs original models

Phys.Lett. B777 (2018) 255-259





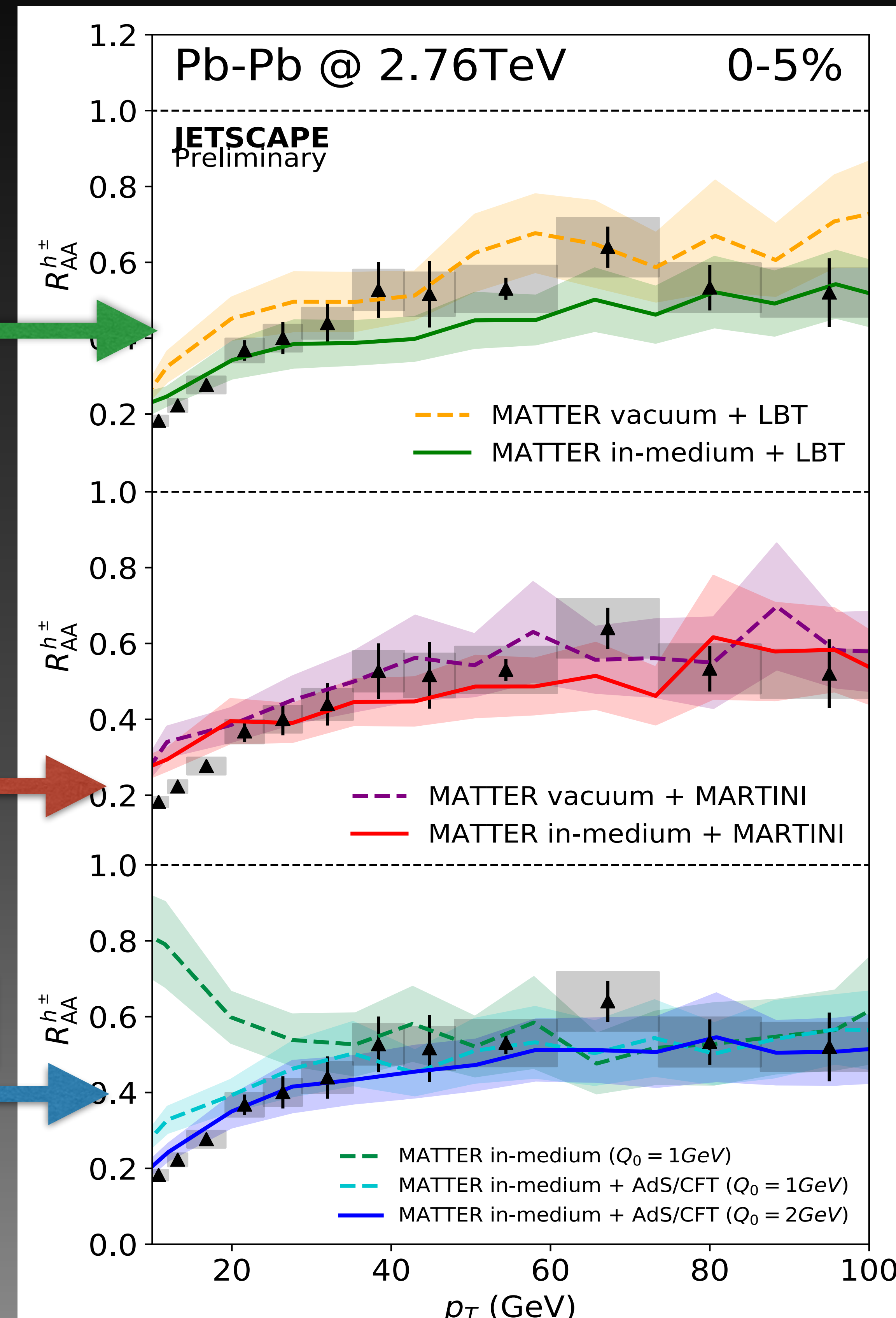


arXiv:1808.07386 [hep-ph]

LBT

MARTINI

Hybrid



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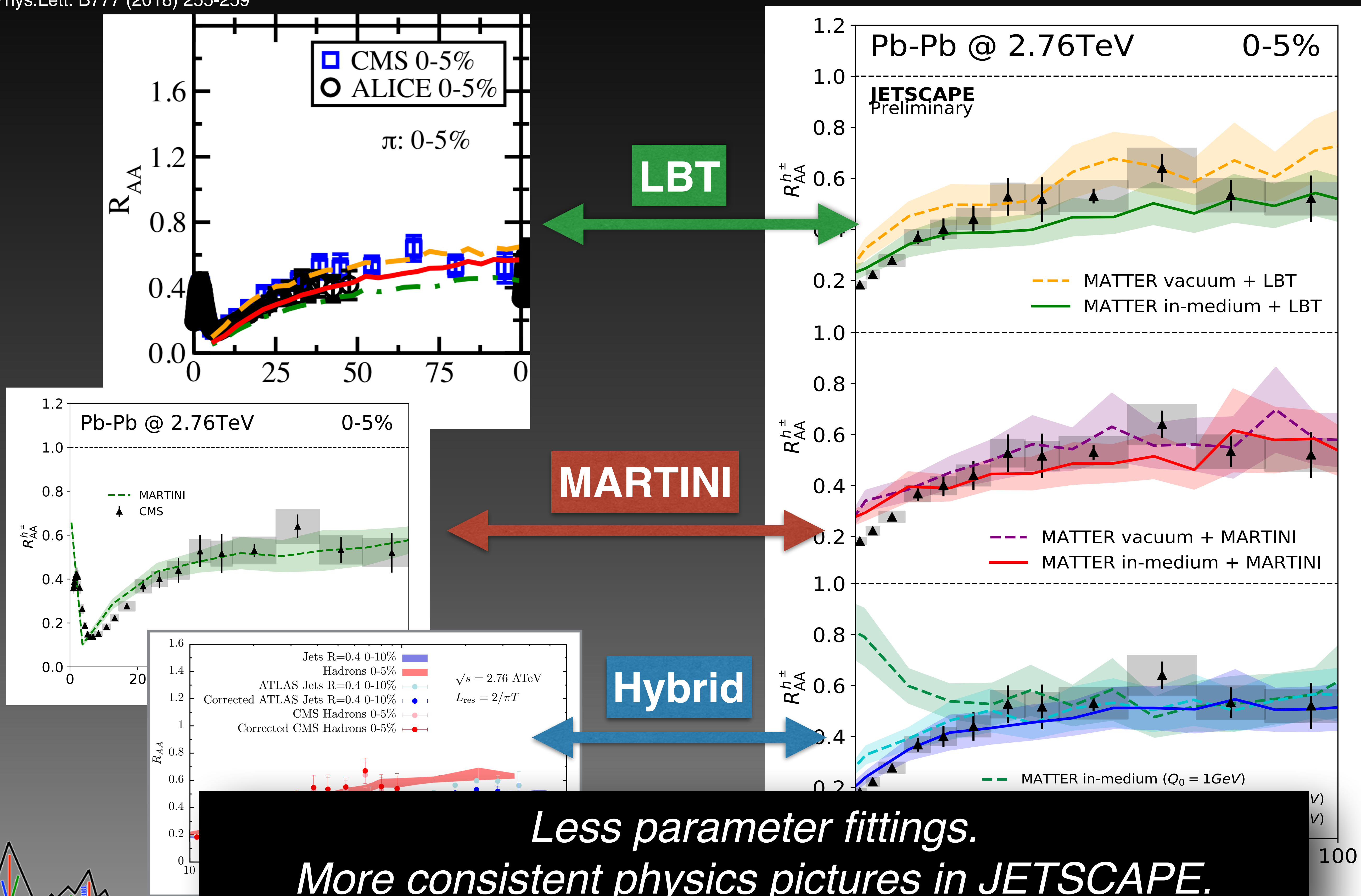


Less parameter fittings.
More consistent physics pictures in JETSCAPE.

Summary and outlook

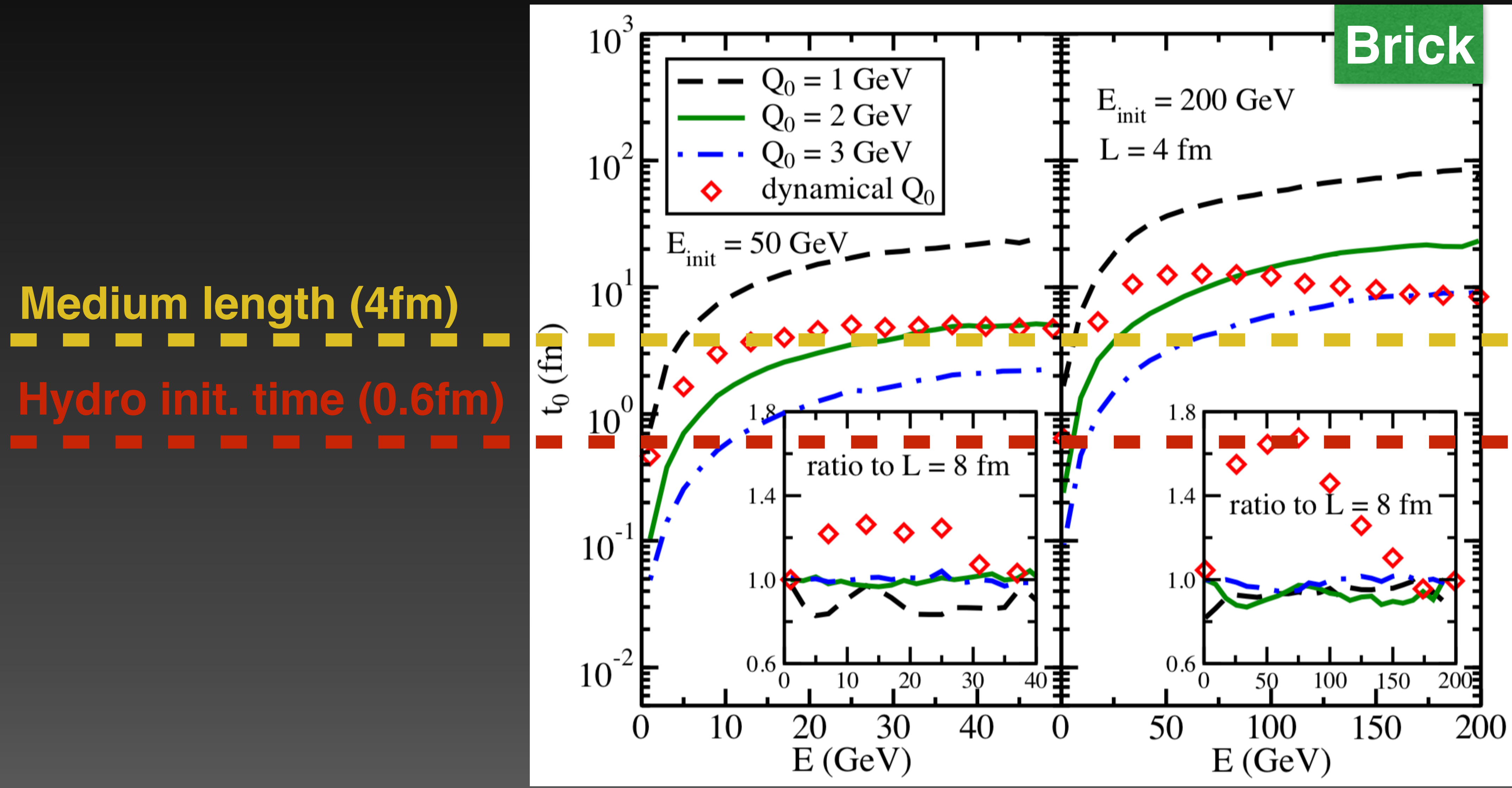
- JETSCAPE framework— an innovative, flexible event generator — has developed and released for the heavy-ion community.
- The first JETSCAPE results are convincing that the unified approach effectively captures the physics of multi-scale jet quenching in QCD plasma.
- JETSCAPE enables systematic studies on jet shower in different stages.
- JETSCAPE provides an unified approach, in which multi-scale formalisms are combined.
- A full accounting of the jet/plasma interaction and the concurrent simulation will be implemented: *JETSCAPE 2.0*

More on JETSCAPE in HP2018

- "Bayesian extraction of $\hat{q}$ with a multi-stage jet evolution approach" by Ron Soltz
- "Jet substructure modifications in a QGP from multi-scape description of jet evolution with JETSCAPE" by Yasuki Tachibana
- "JETSCAPE 1.0: The first software release of the JETSCAPE collaboration" by Joern Putschke
- "p+p physics with the JETSCAPE 1.0 framework" by Rainer Fries

Backup

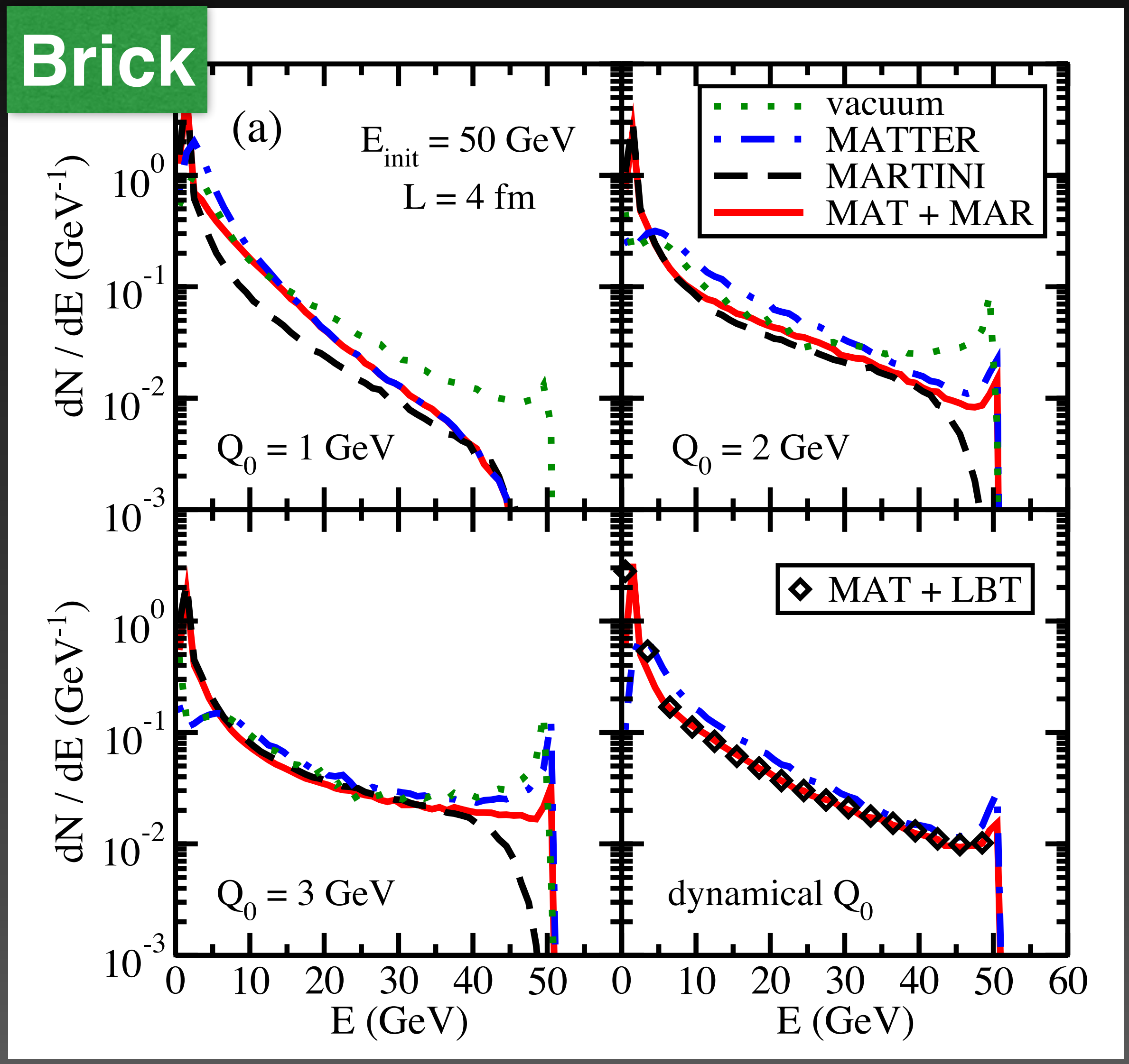
Separation scale Q_0



JETSCAPE from Phys. Rev. C **96**, 024909 (2017)

- t_0 : time for a parton hit Q_0 in virtuality-ordered shower.
- t_0 depends on Q_0 and initial energy of a parton.
- In LHC, Q_0 = 2GeV is reasonable.

Combined shower in brick



JETSCAPE from Phys. Rev. C **96**, 024909 (2017)

- At Q_0 = 2GeV,
  - Shower for High pT particles is mostly done.
  - Low pT particles are further suppressed by MARTINI.
- MARTINI and LBT results are similar.