WAYNE STATE UNIVERSITY

NSF

2019 RHIC & AGS
Annual Users' Meeting
The Golden Age of Heavy Ion Collisions
Hosted at Brookhaven National Laboratory
June 4–7, 2019

# Status of JETSCAPE


## Yasuki Tachibana

for the JETSCAPE Collaboration

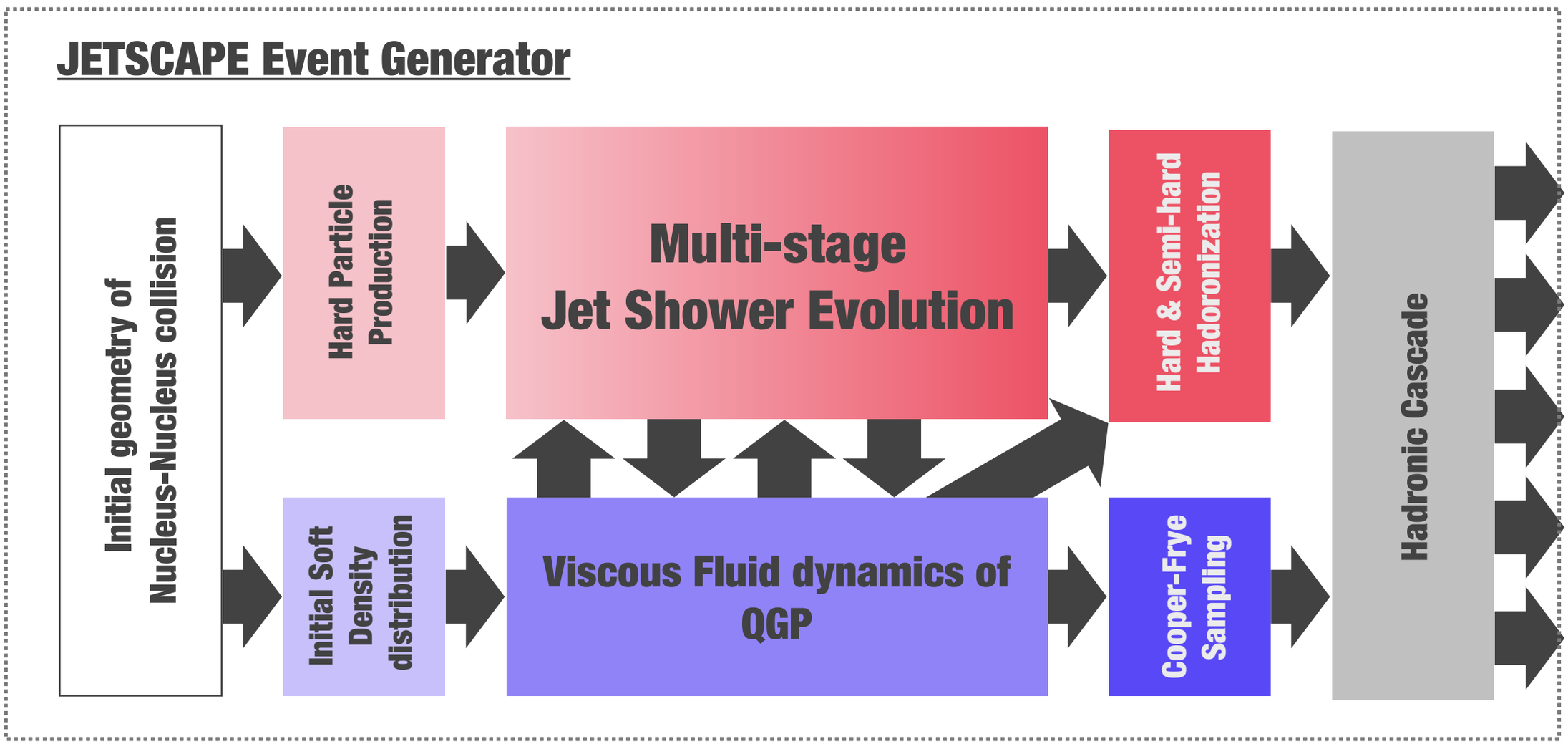

JETSCAPE

**Brookhaven National Laboratory, June 4th, 2019**

# JETSCAPE

http://jetscape.org

- **Package of MC event generator for heavy ion collision**
  - Current version, JETSCAPE 1.4 available on GitHub: **github.com/JETSCAPE**
  - General, modular and highly extensible
  - "Manual": **arXiv:1903.07706**



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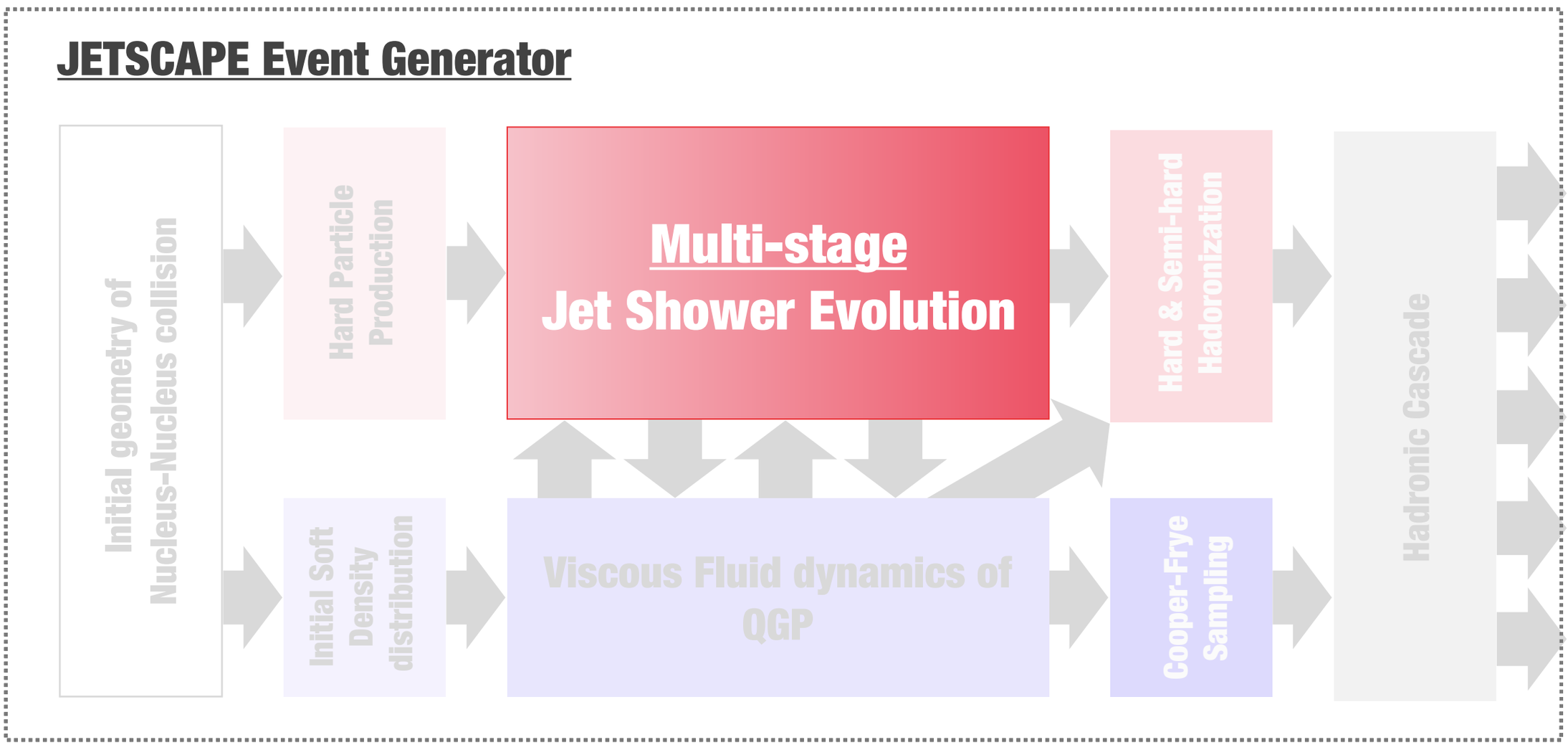

# Multi-stage jet evolution in JETSCAPE

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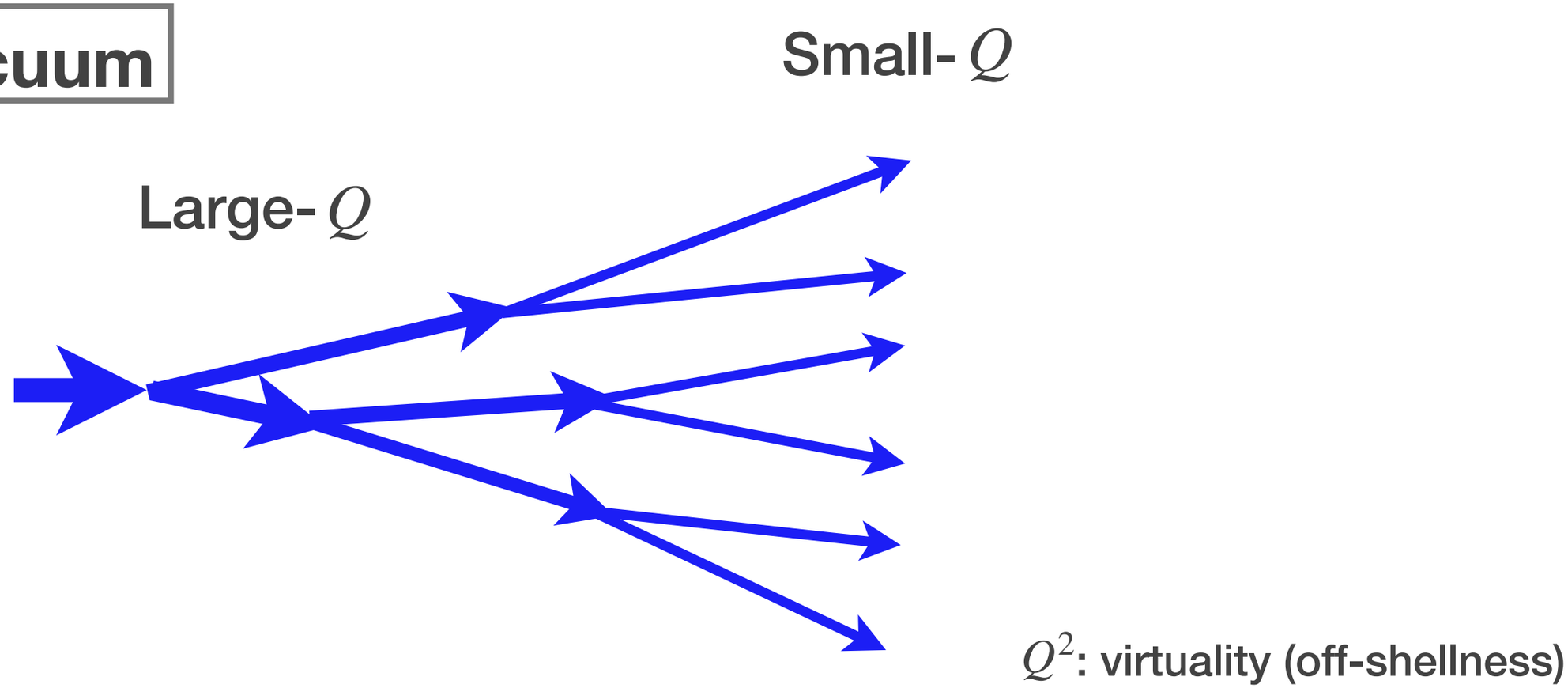
- **Multi-scale description of parton shower** Majumder, Putschke(16), JETSCAPE(17)

**In-vacuum**




- **Virtuality ordered splitting in vacuum**

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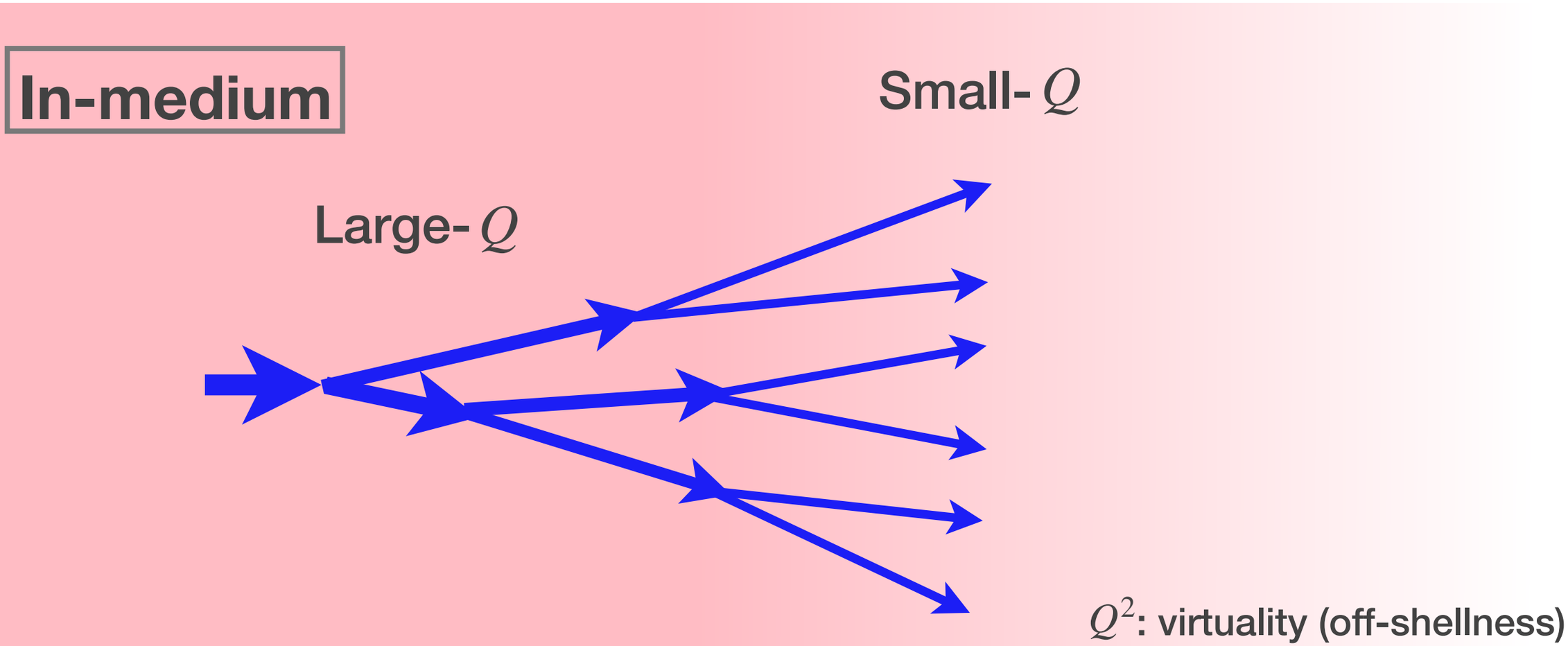


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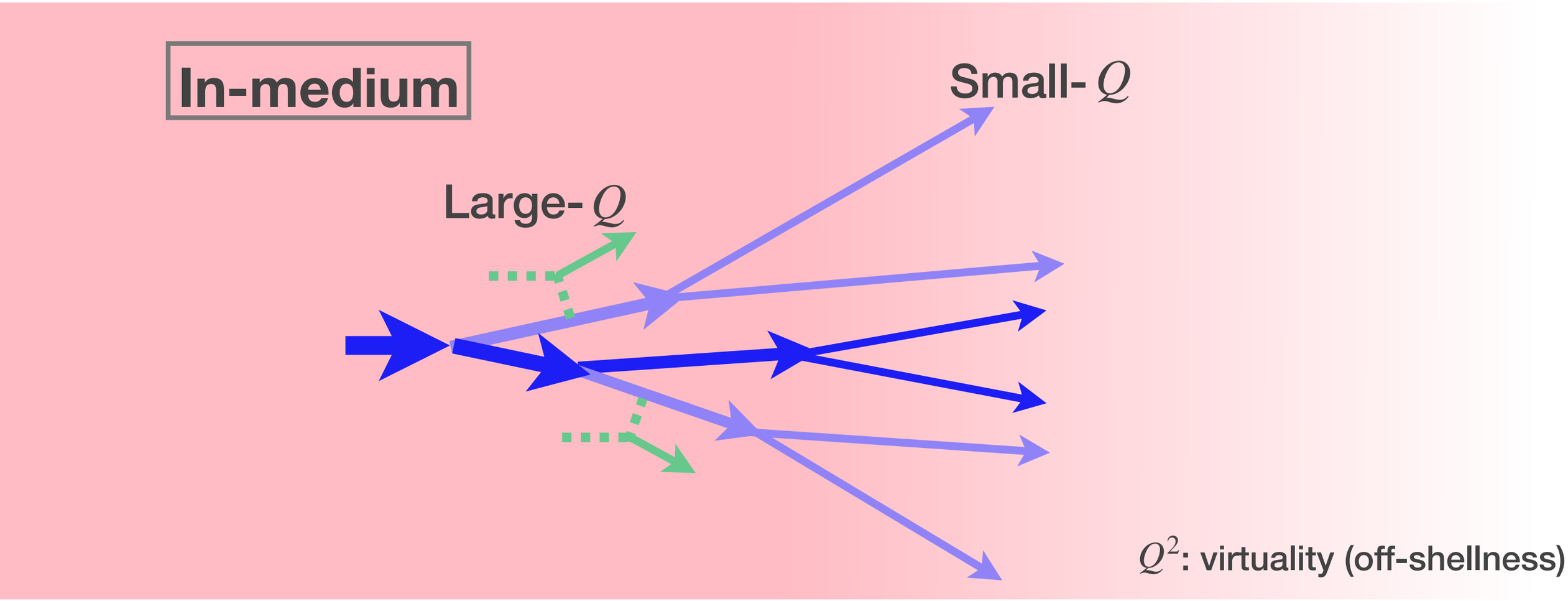


- Virtuality ordered splitting in vacuum
- **Large-$Q$ ⟶ Medium effect on the top of in-vacuum splitting**

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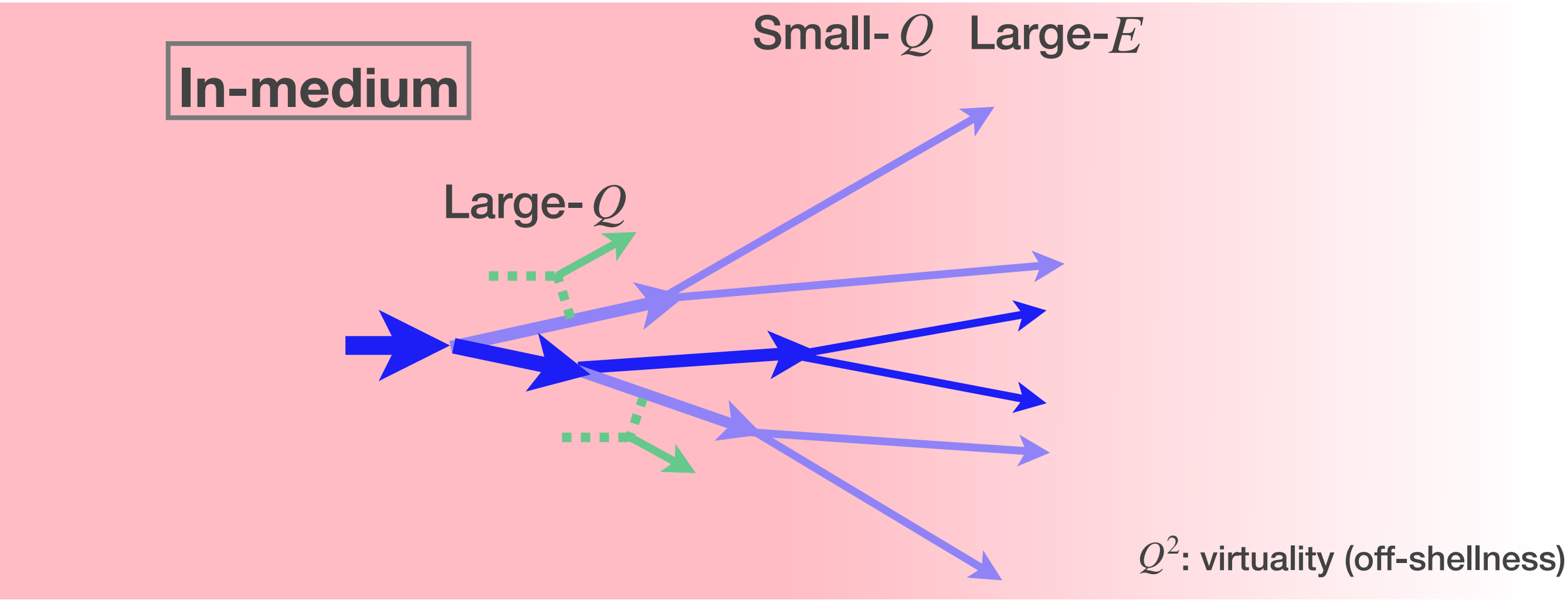


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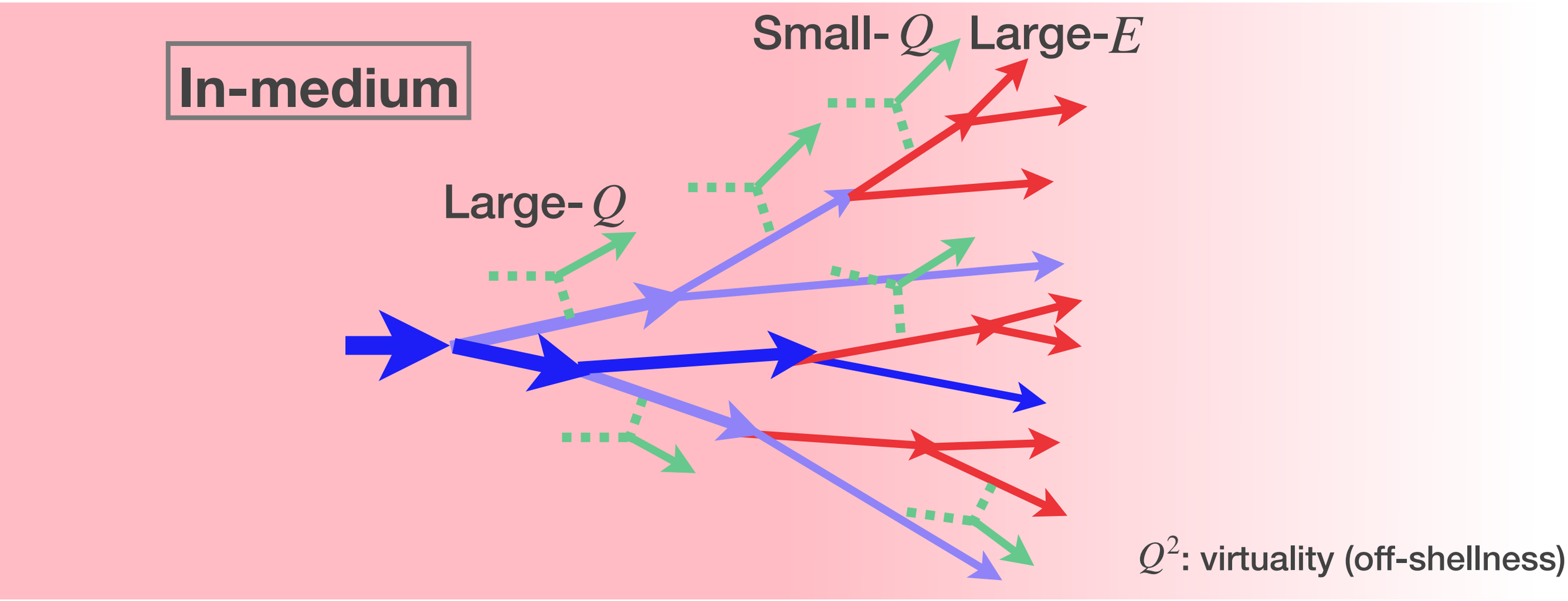


- Virtuality ordered splitting in vacuum
- Large- $Q$ ⟶ Medium effect on the top of in-vacuum splitting
- **Small-$Q$ , Large-$E$ ⟶ Splitting driven almost purely by medium effect**

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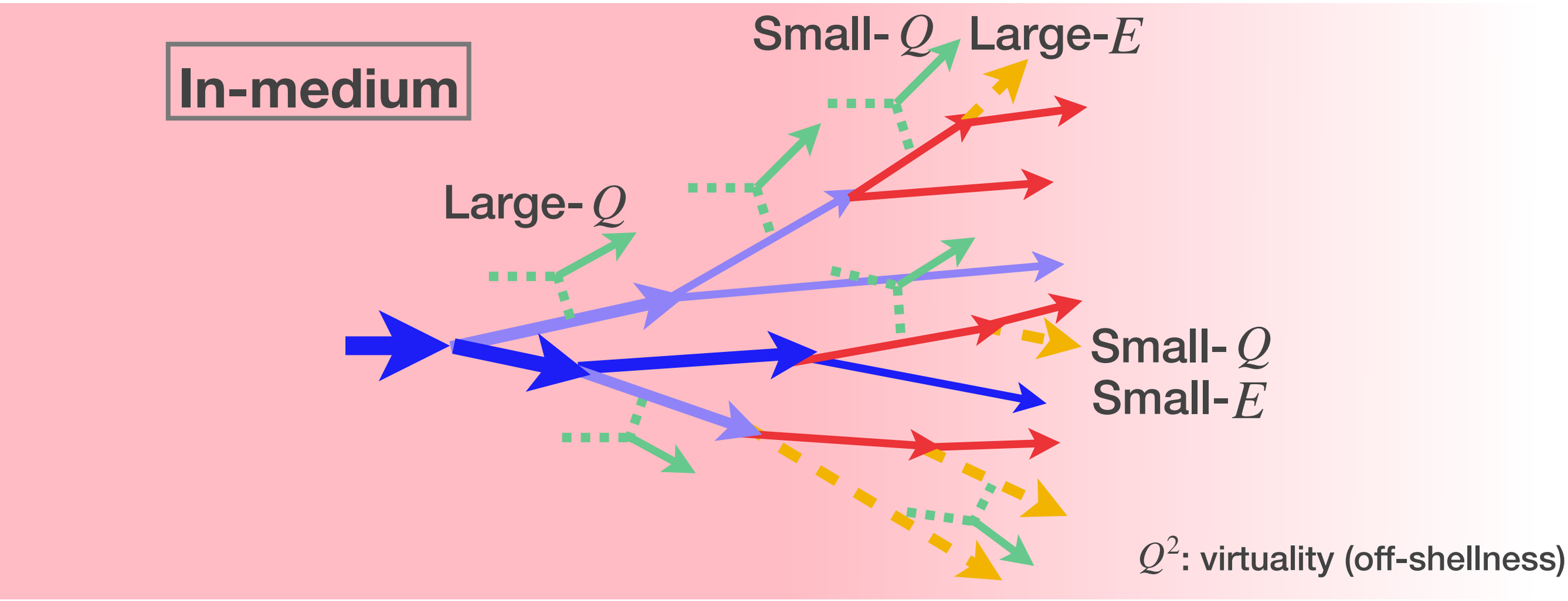


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- **Small- $Q$ , Small- $E$ ⟶ Energy-momentum diffusion into medium**

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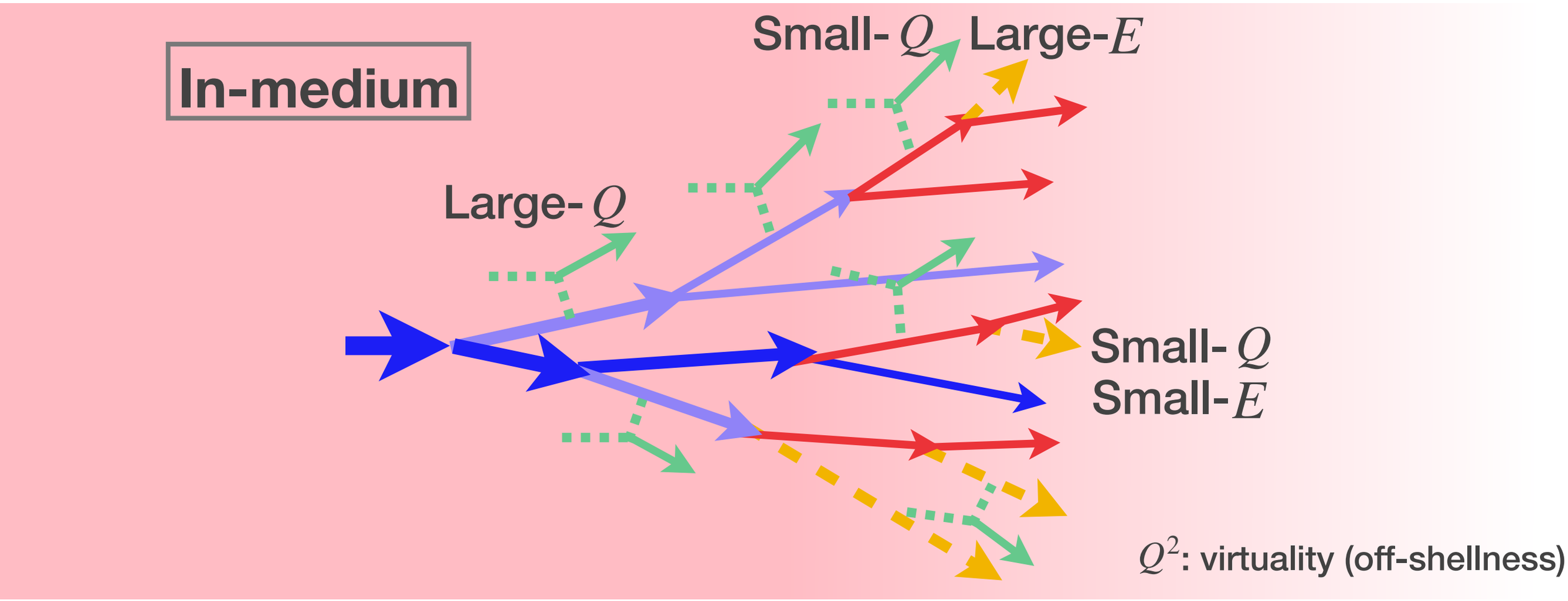


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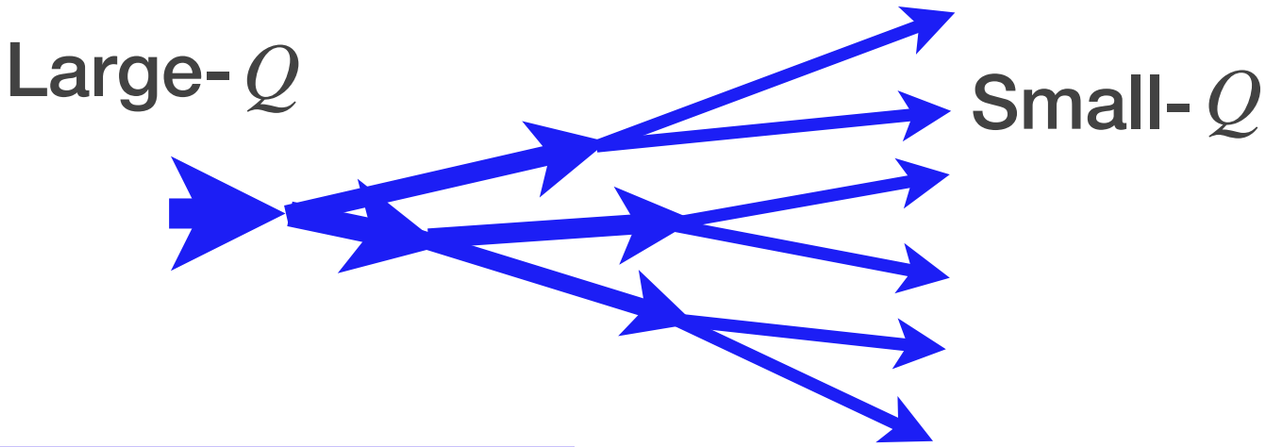
**No single model can describe all stages of jet evolution**

# Multi-stage jet evolution in JETSCAPE

- **Jet evolution module in JETSCAPE (vacuum)**




**MATTER**

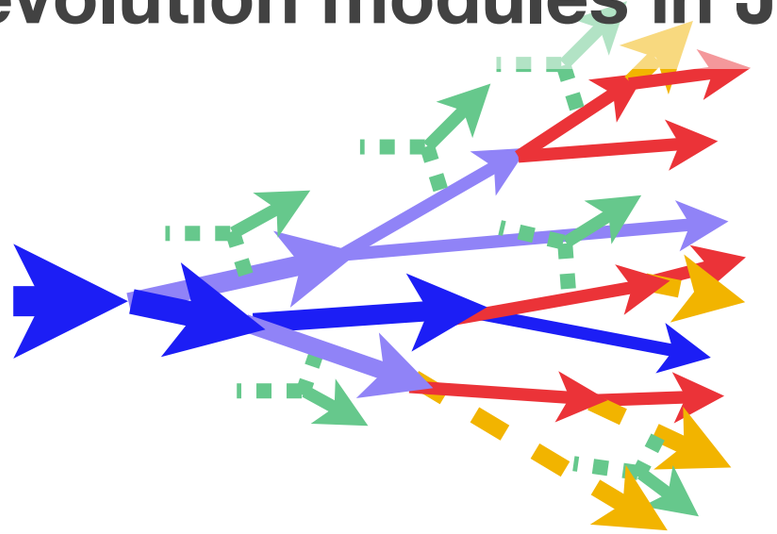
Majumder(13), Kordell, Majumder(17), Cao, Majumder(17)

Virtuality ordered splitting

Vacuum
Splitting Function

# Multi-stage jet evolution in JETSCAPE

- **Jet evolution modules in JETSCAPE (in-medium)**



Virtuality separation scale: $Q_0$

| Large-$Q$ ( $> Q_0$) | Small-$Q$ ( $< Q_0$) | |
|---|---|---|
| | Large-$E$ | Small-$E$ |
| **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) |
| Radiation dominated Virtuality ordered splitting | Scattering dominated On-shell parton transport | Diffusion into medium |
| Higher Twist formalism | Higher Twist formalism / AMY formalism | $\mathcal{N}$ = 4 super Yang-Mills |

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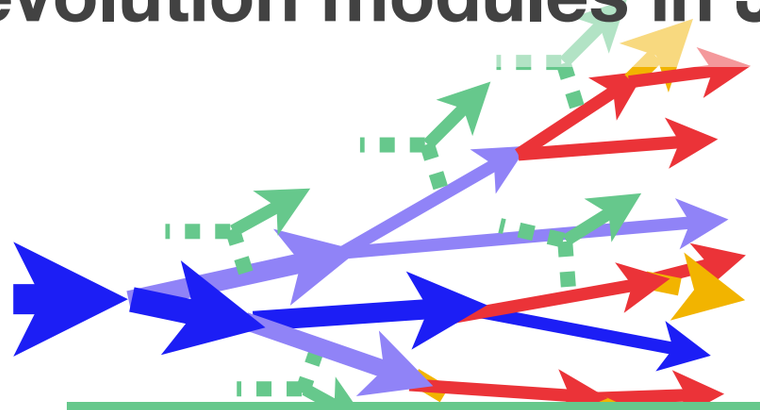

Virtuality separation scale: $Q_0$

**Switching between modules for parton by parton**

| Large-$Q$ ( $> Q_0$) | Small-$Q$ ( $< Q_0$) | |
|---|---|---|
| | Large-$E$ | Small-$E$ |
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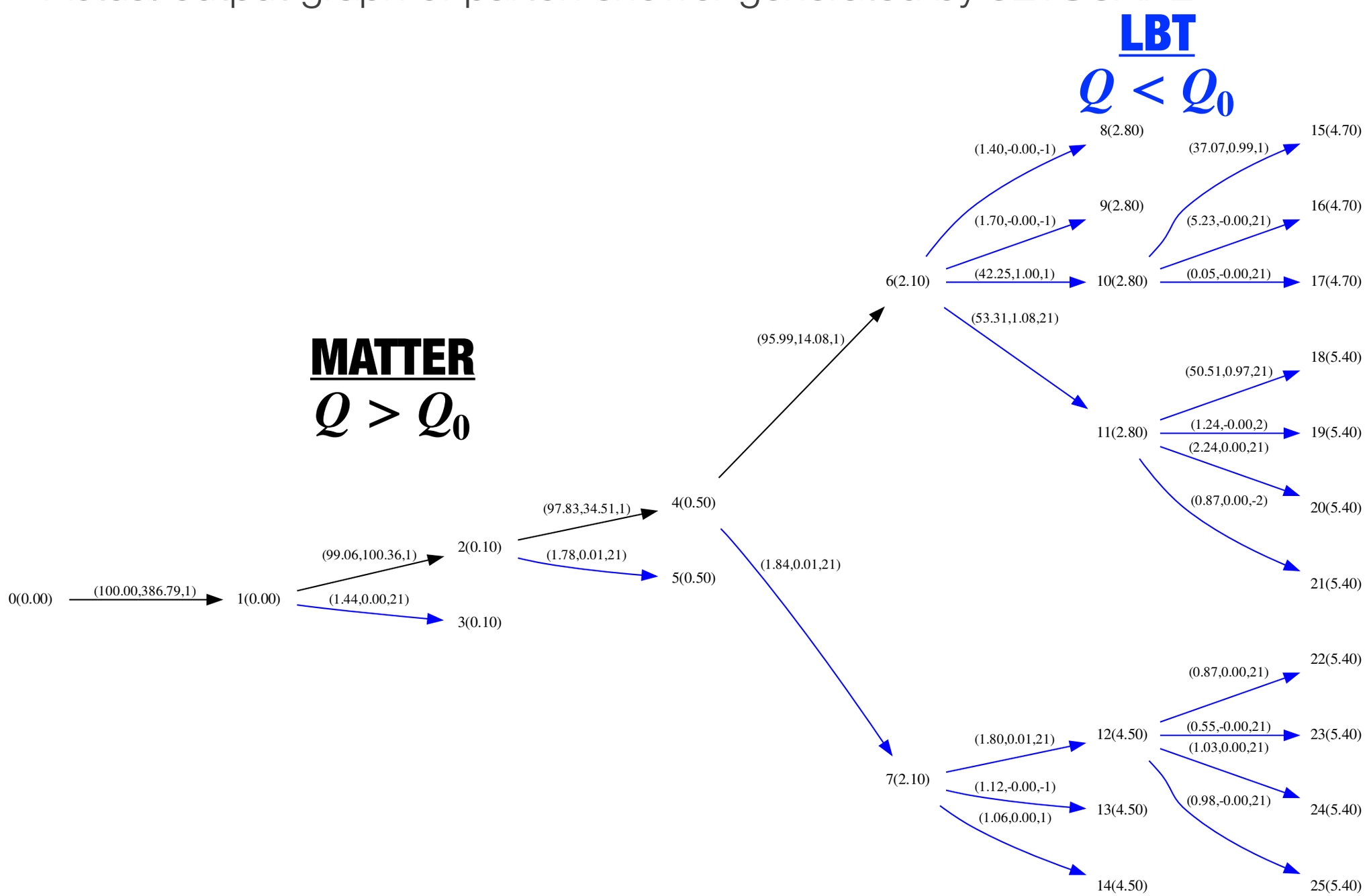
  - Actual output graph of parton shower generated by JETSCAPE



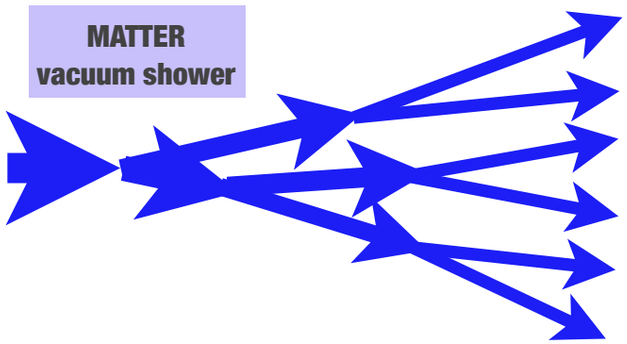

A. Kumar

# pp baseline from JETSCAPE

# pp baseline

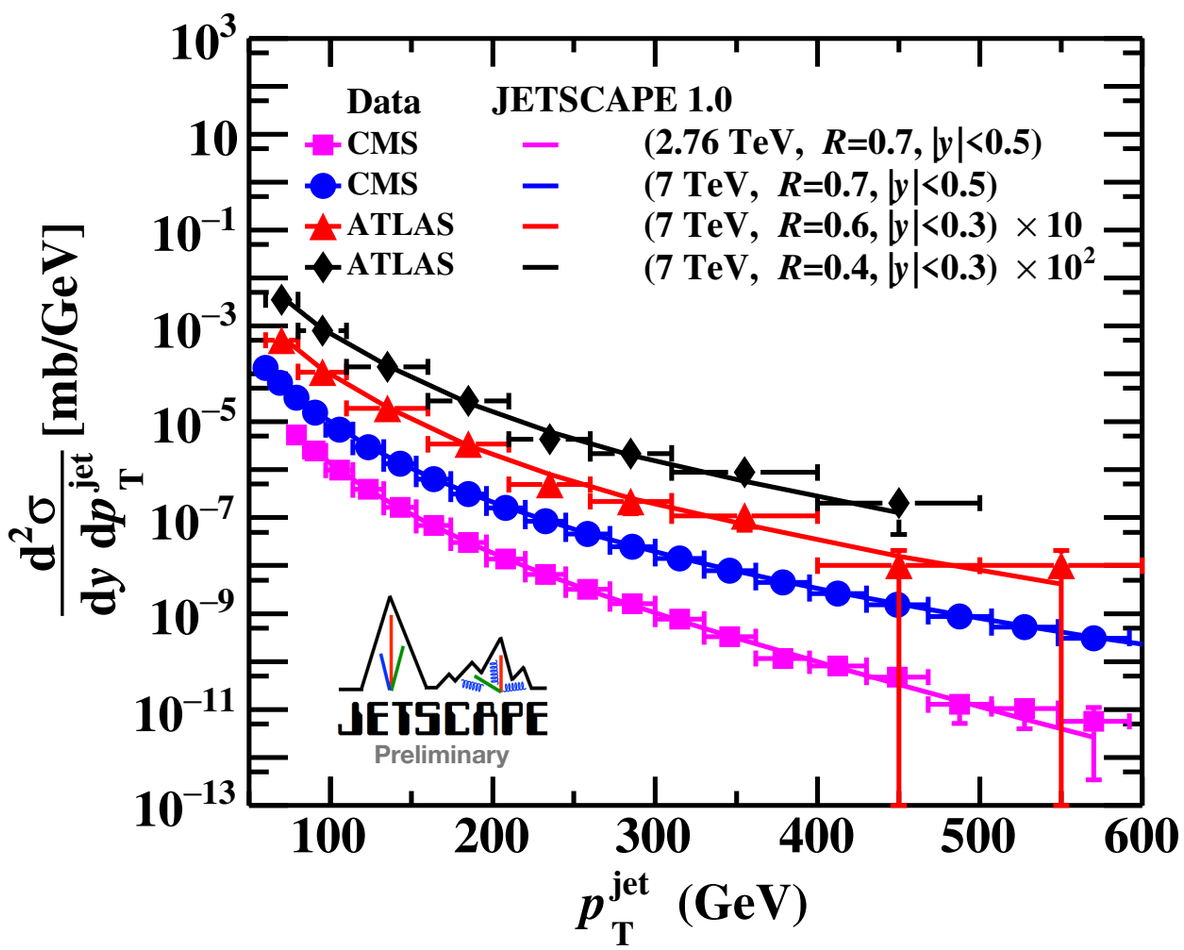
JETSCAPE, *in preparation*

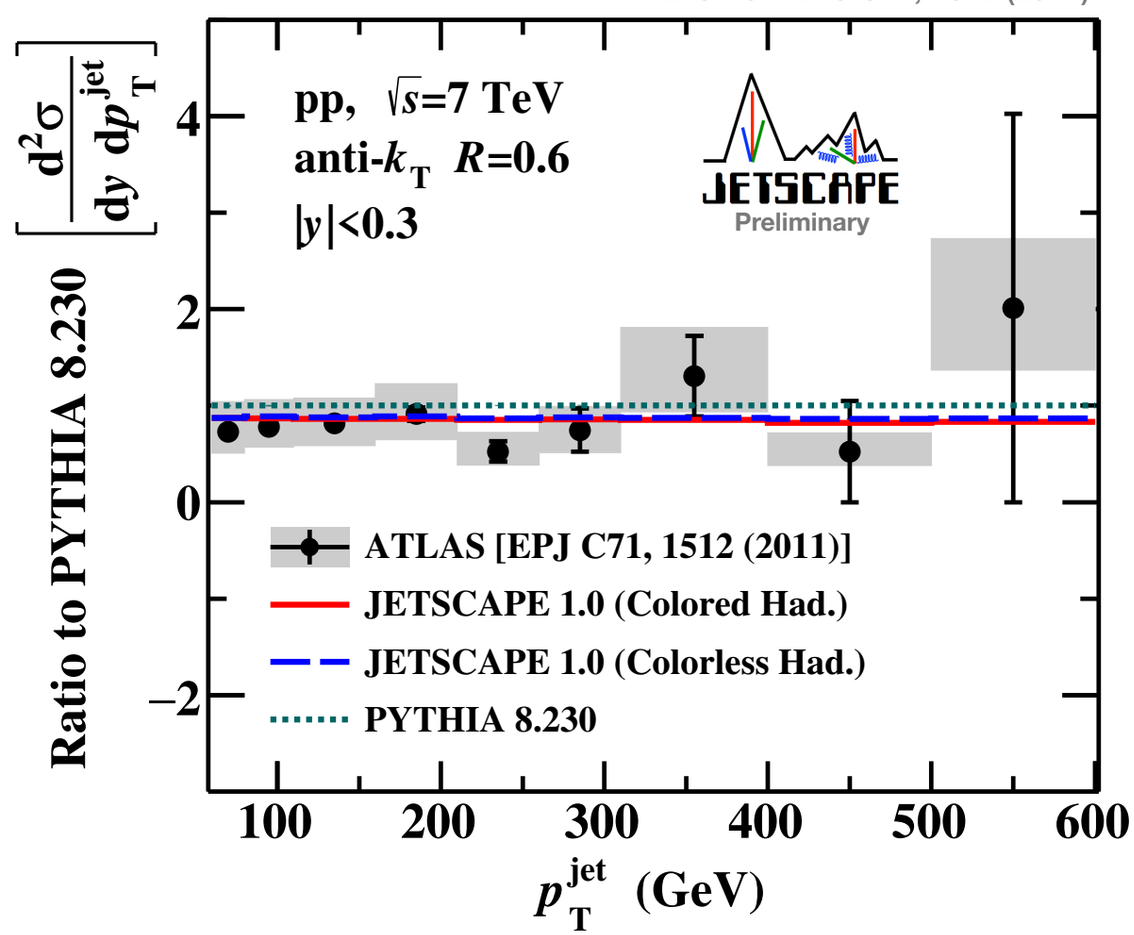
- **Configuration for pp simulation**
  - Initial hard scattering by Pythia8 (w/ ISR and MPI)
  - Vacuum parton shower by MATTER
  - Hadronization by Lund string model (two variations)




- **Inclusive full jet cross-section**

CMS for 2.76 TeV from PRC 96, 015202 (2017)
CMS for 7 TeV from PRD 87, 112002 (2013)
ATLAS from EPJ C71, 1512 (2011)



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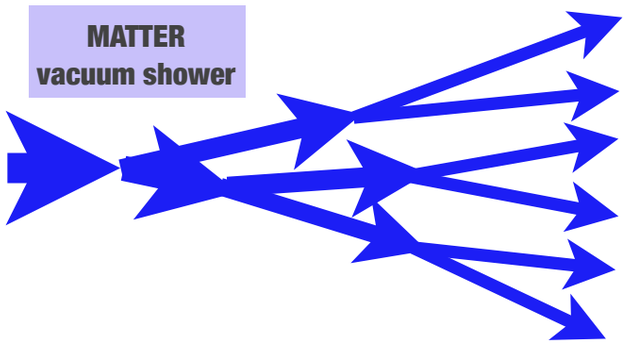


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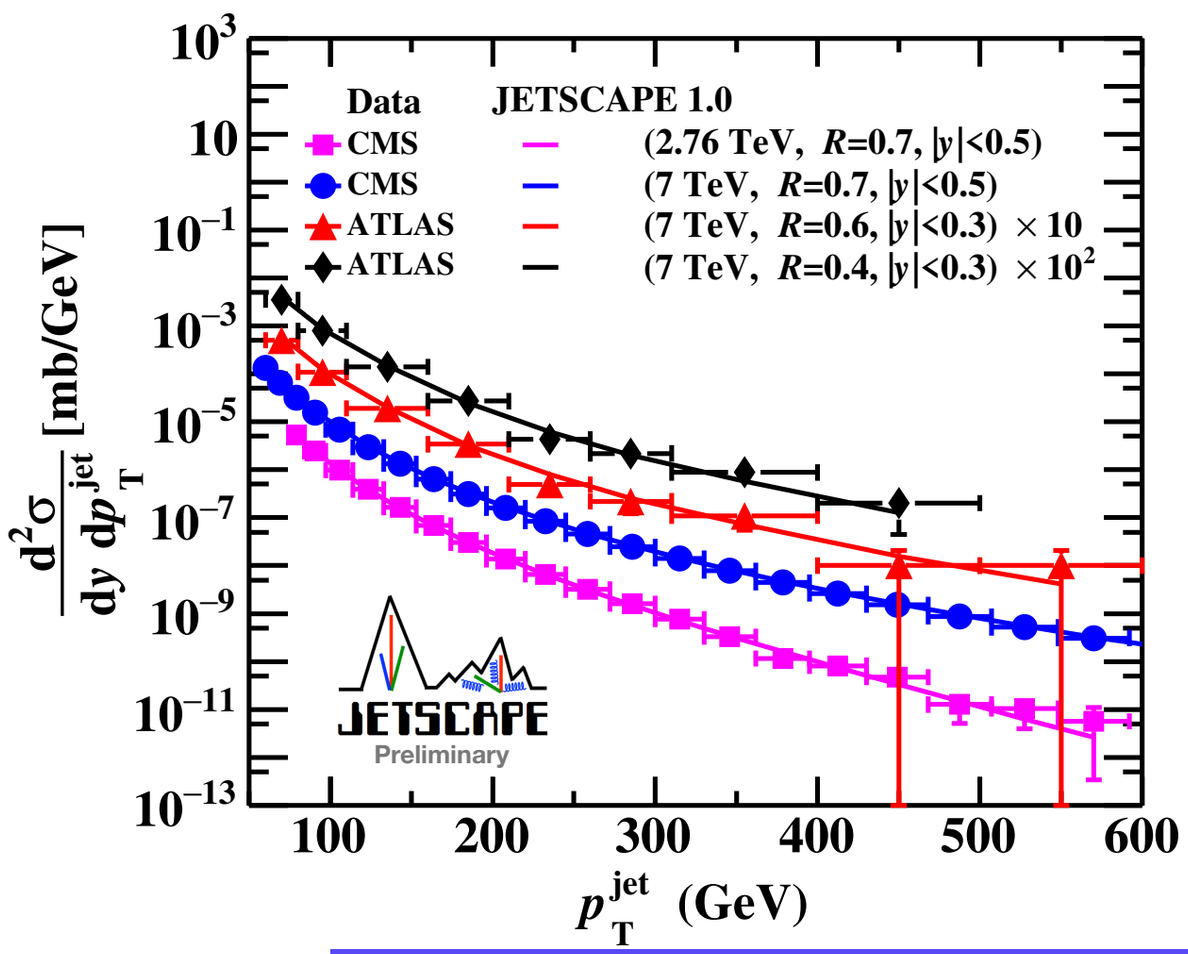
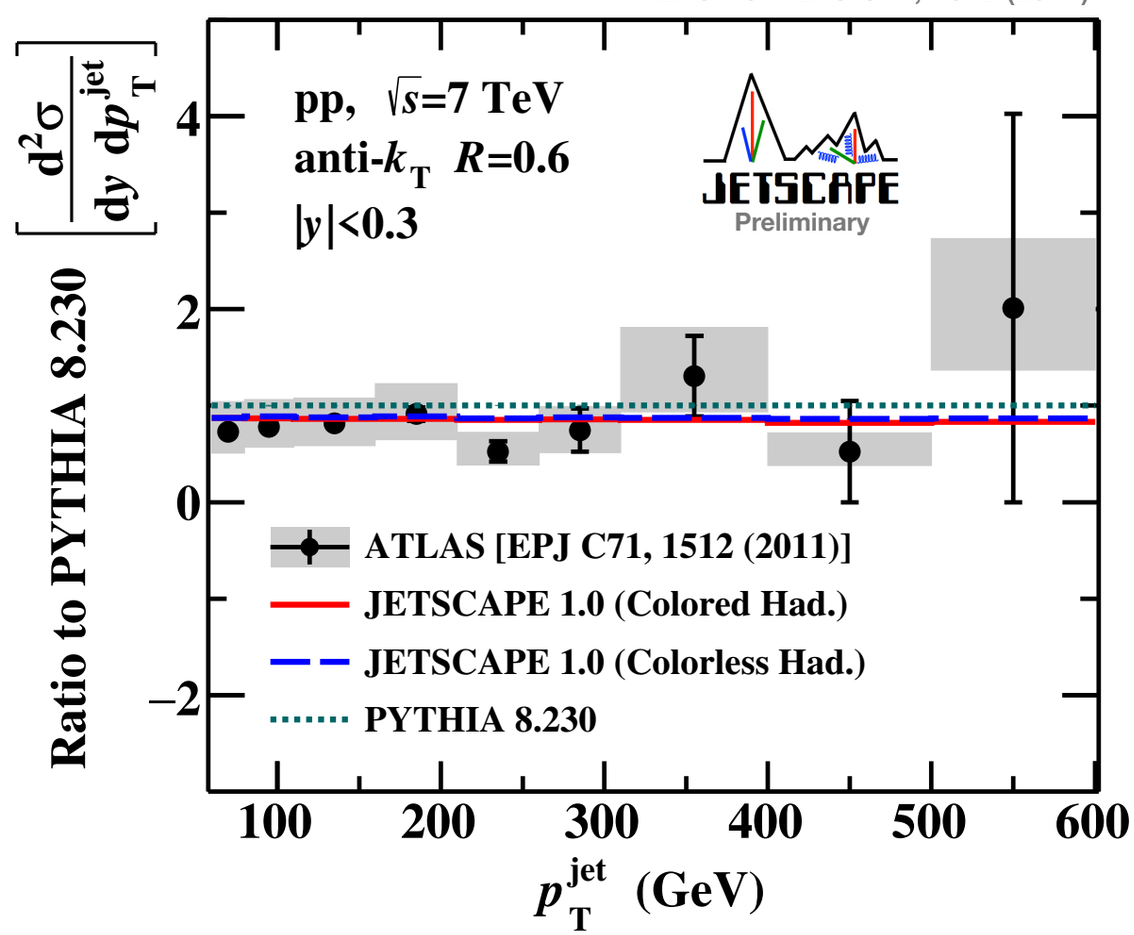


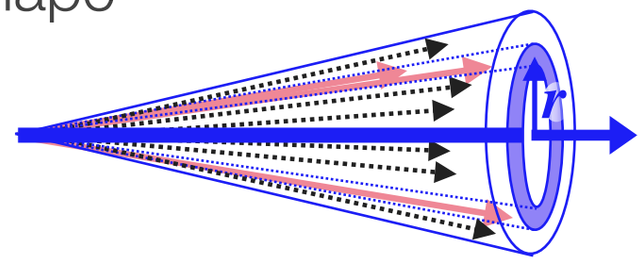



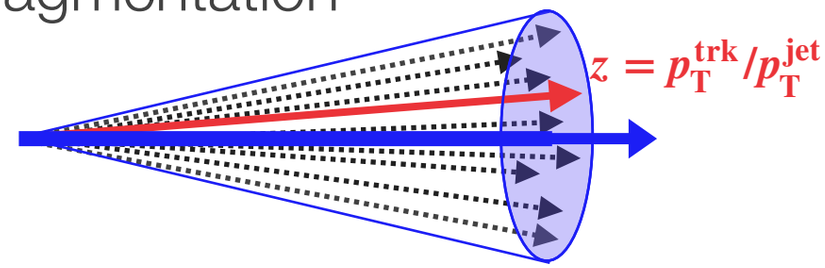

**Comparable performance to Pythia 8**

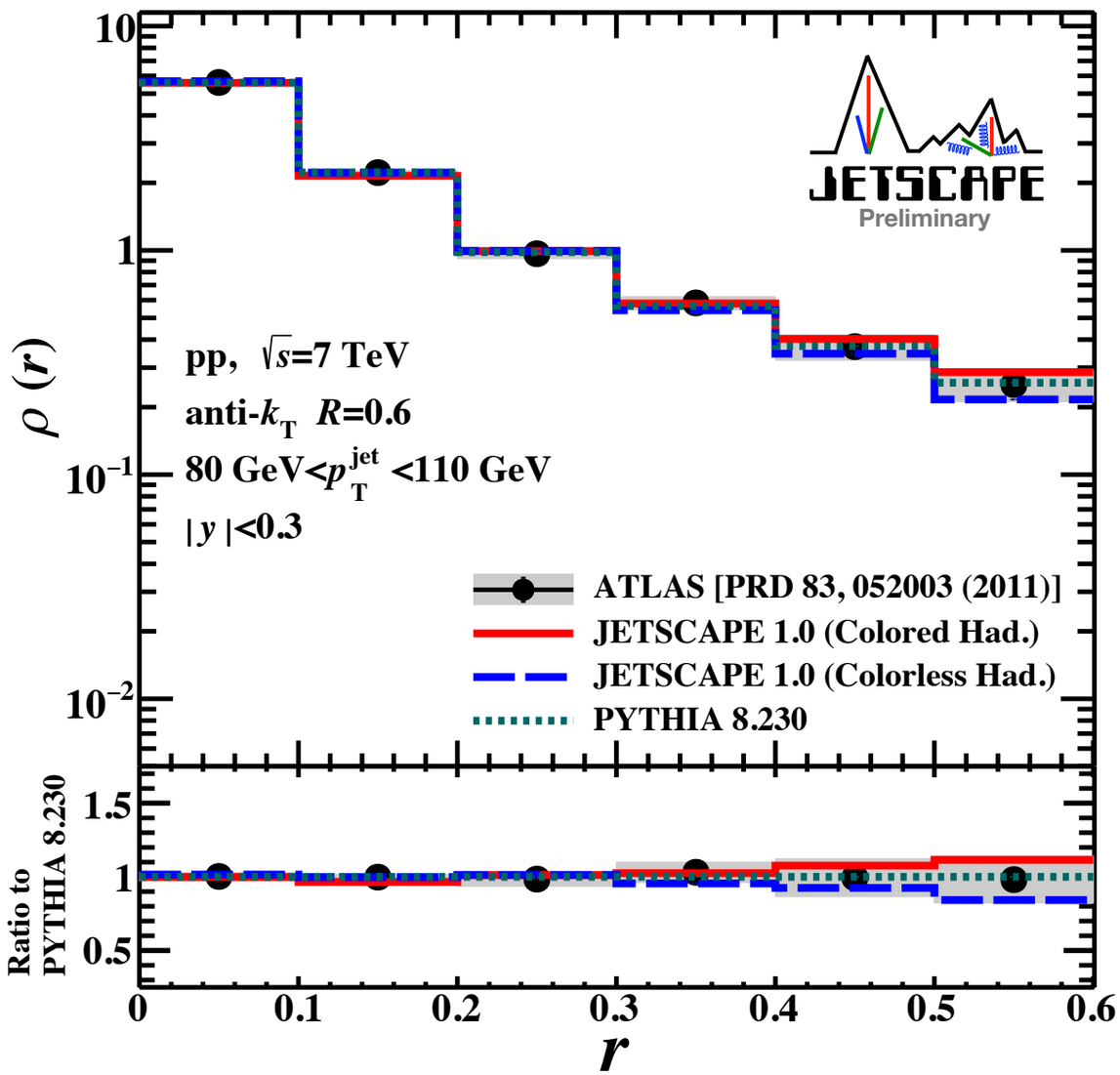
# pp baseline

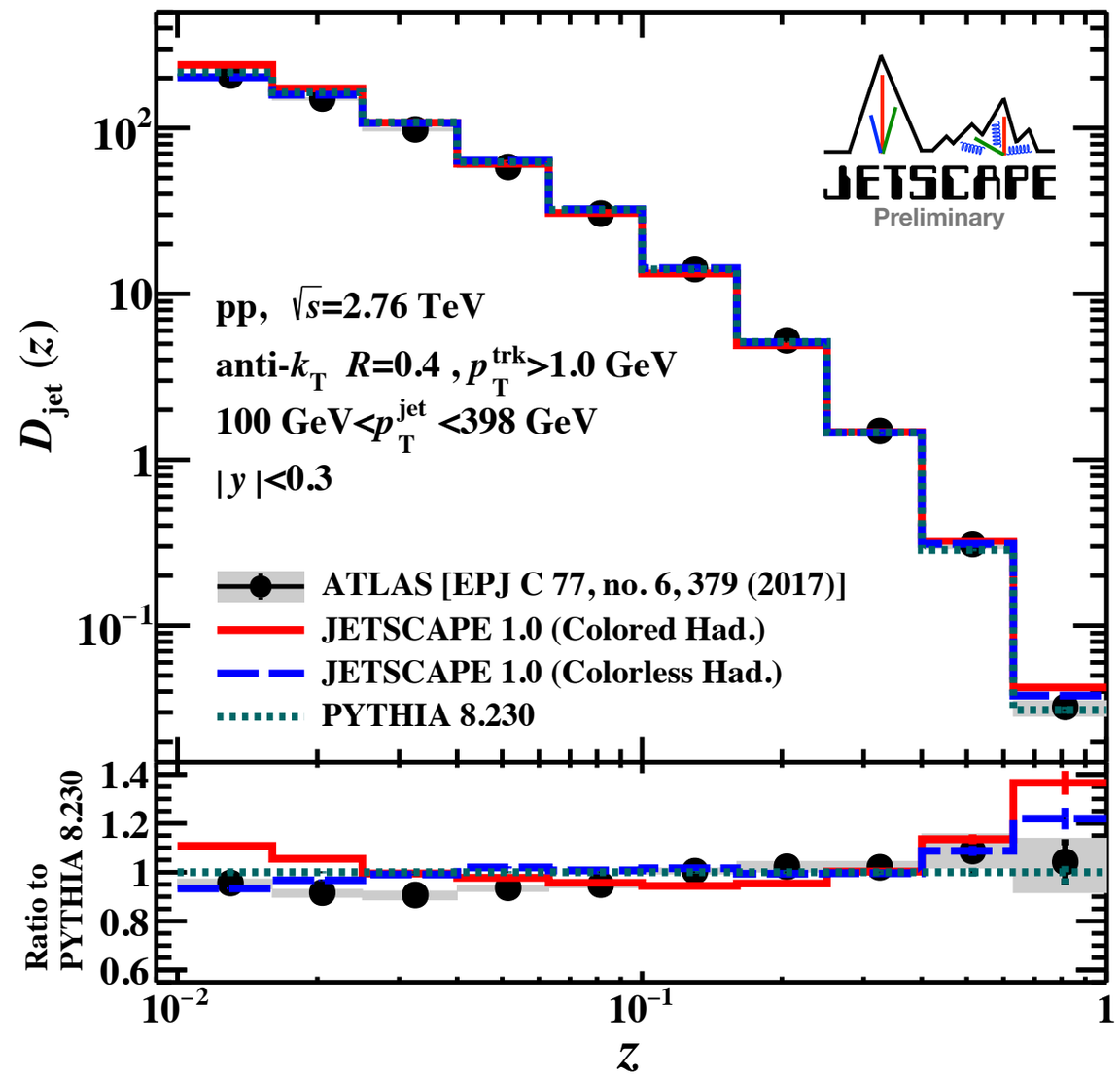
JETSCAPE, *in preparation*

- **Jet substructures**
  - Jet shape
  - Jet fragmentation



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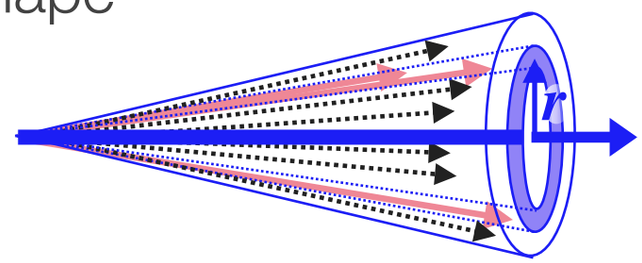
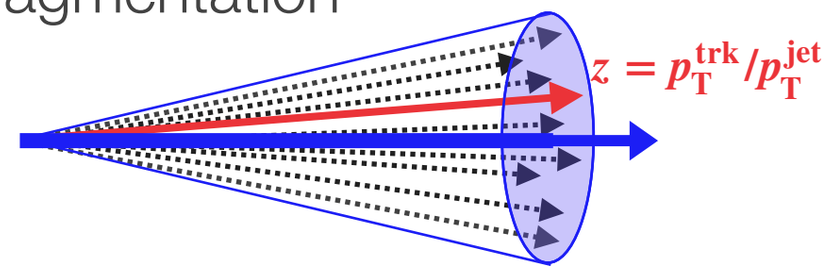
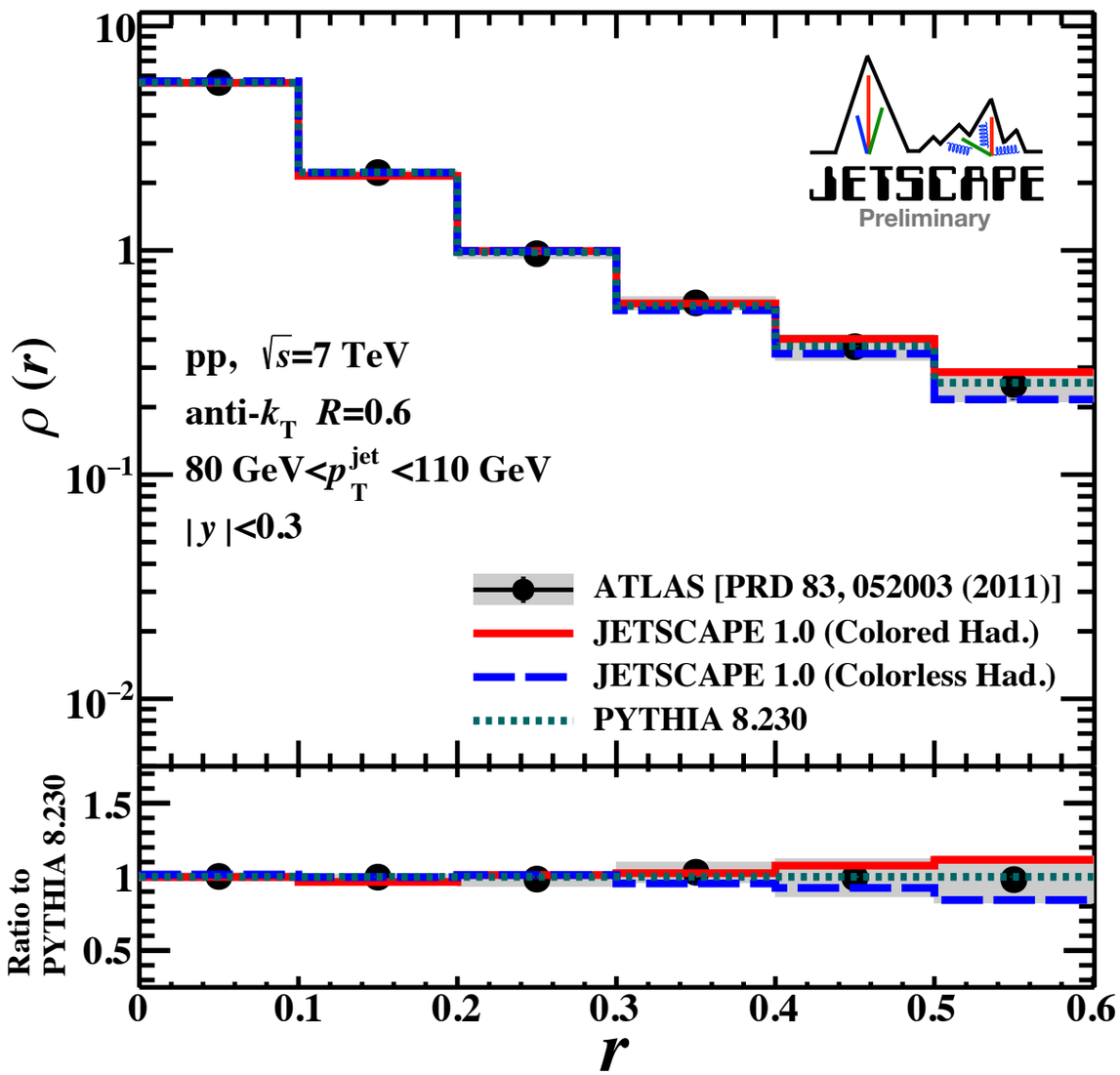
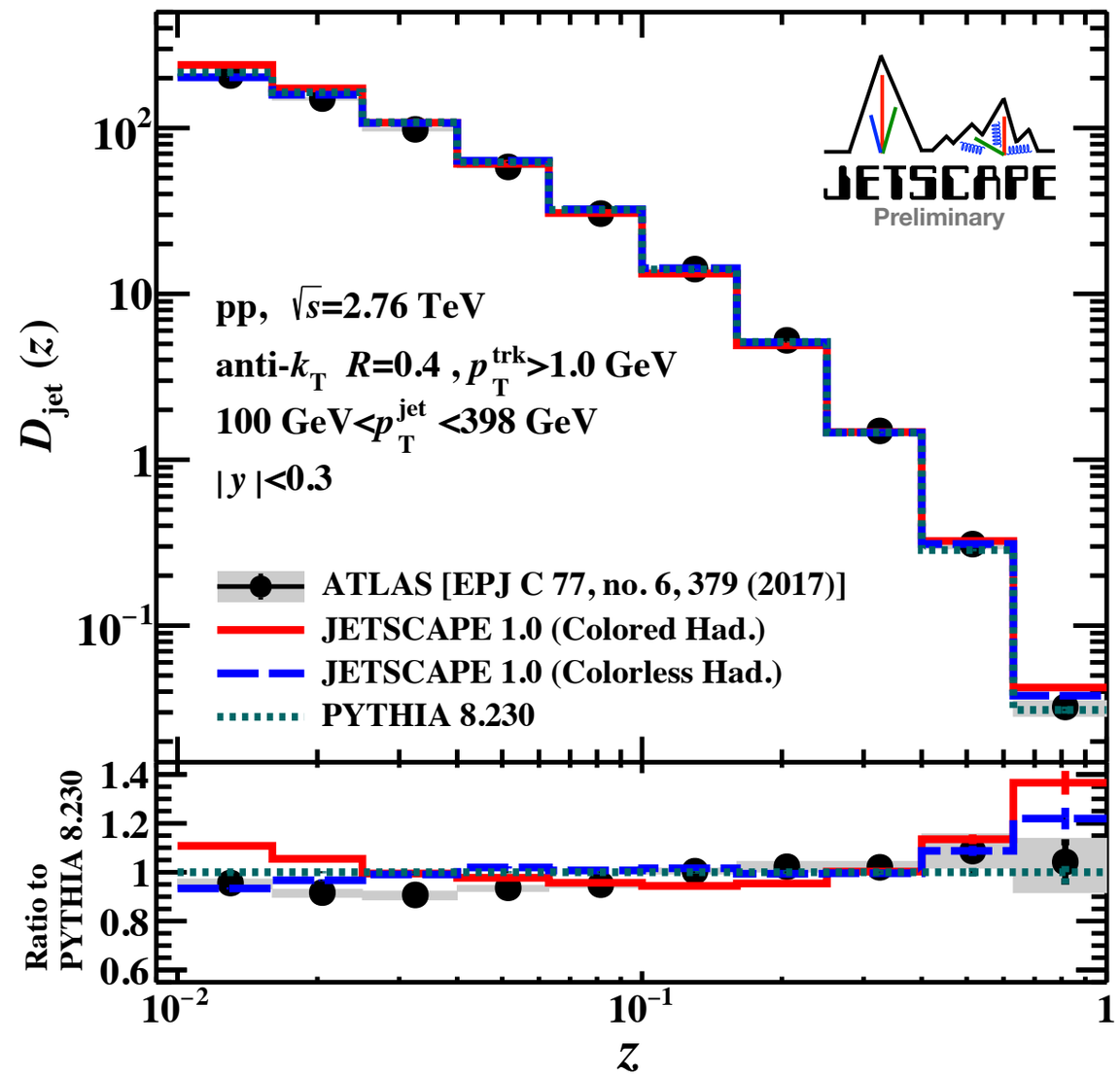


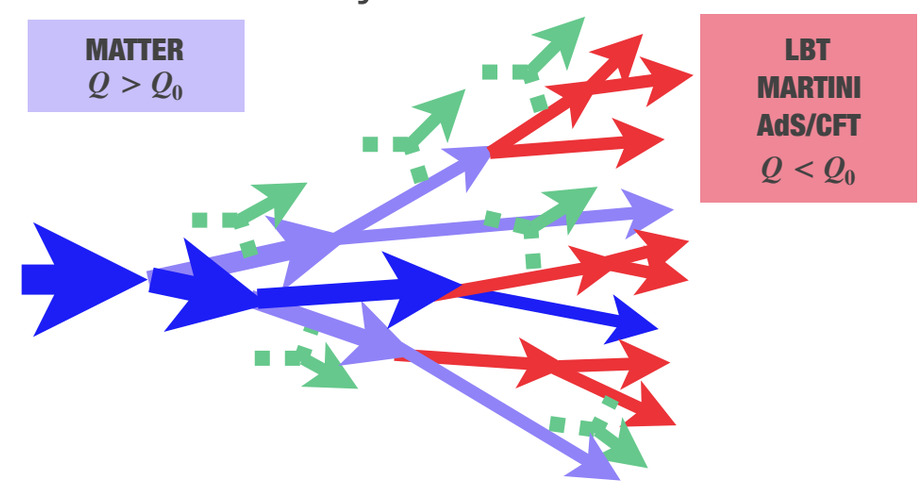

**Comparable performance to Pythia 8**

# PbPb@2.76 results from JETSCAPE

# PbPb@2.76 TeV

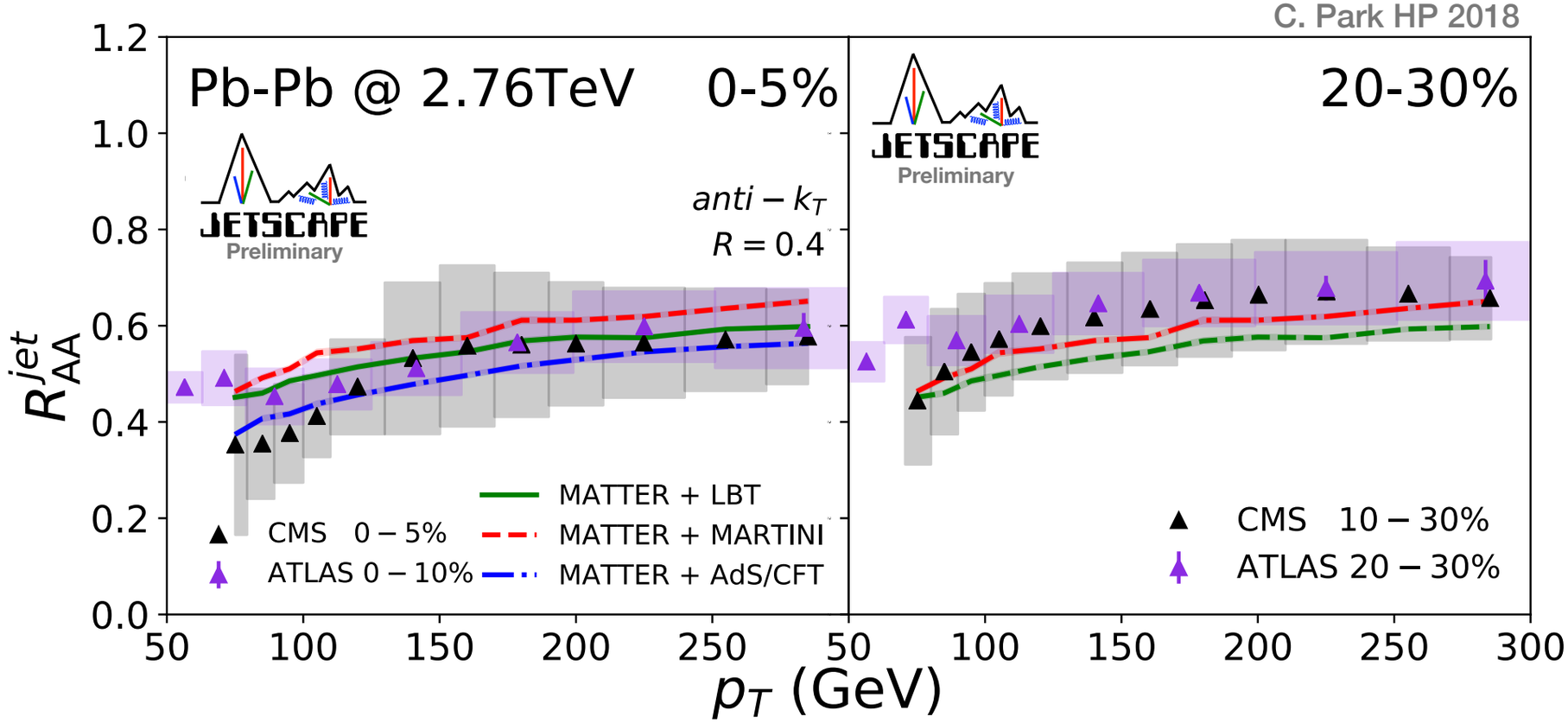


- **Configuration for PbPb simulation**
  - TRENTo initial condition + free streaming + (2+1)-D VISHNU hydro
  - MATTER (recoil ON) + { LBT (recoil ON), MARTINI (no recoil), AdS/CFT (no med. res.) }
  - Switching virtuality scale $Q_0 = 2\mathrm{GeV}$




- **Inclusive full jet $R_{AA}$**

C. Park HP 2018



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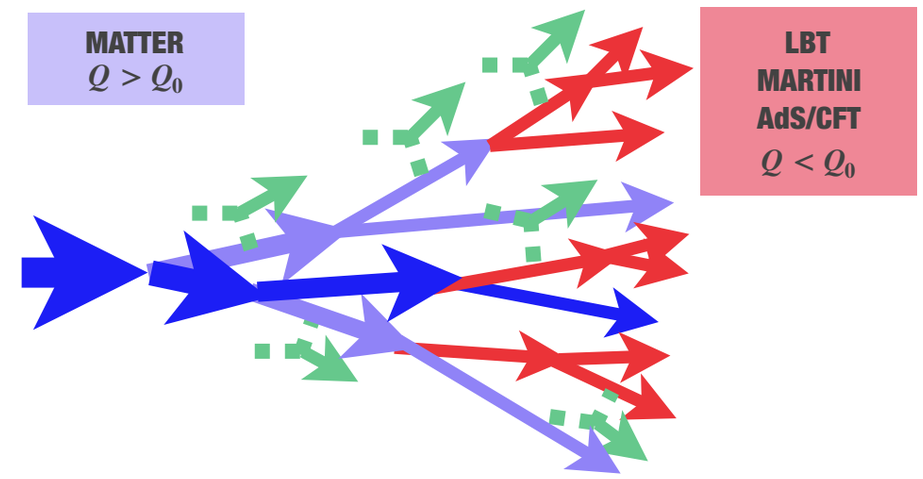


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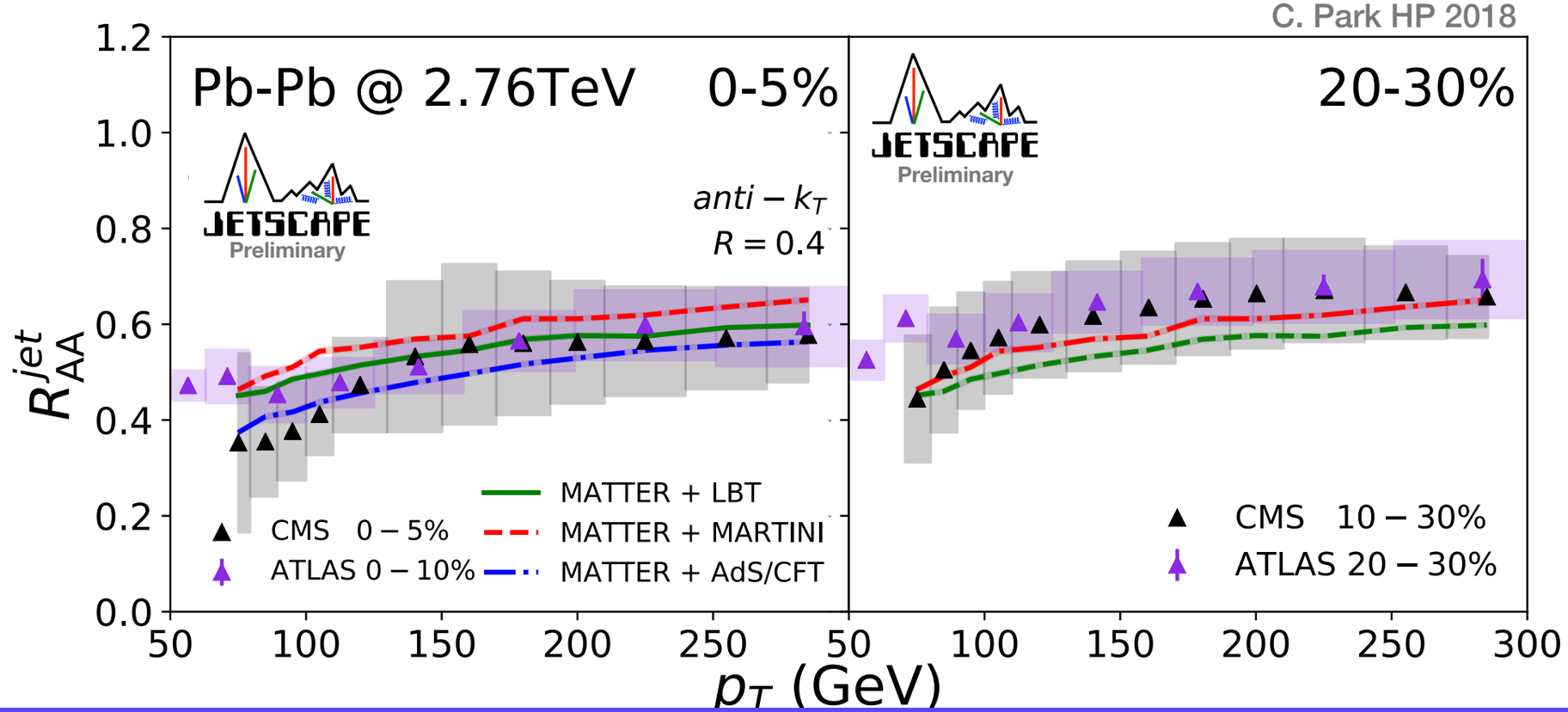


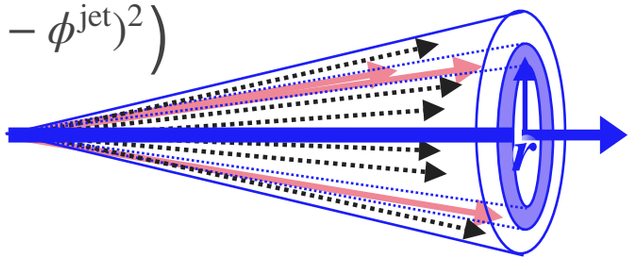

**Similar $p_T^{jet}$ dependence, need further examination for centrality dep.**

# PbPb@2.76 TeV



- **Jet Shape**

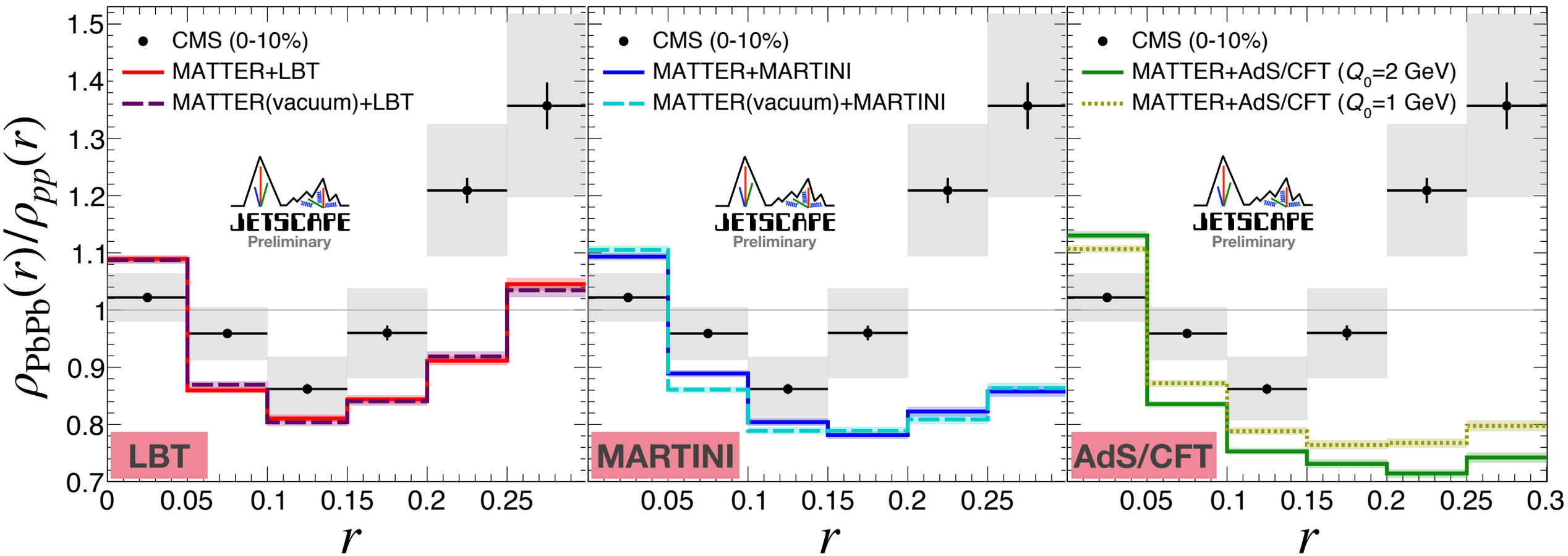
$$\rho(r) = \frac{1}{N_{\rm jet}} \sum_{\rm jet} \left[ \frac{1}{p_{\rm T}^{\rm jet}} \frac{\sum_{{\rm trk}\in(r-\delta r/2, r+\delta r/2)} p_{\rm T}^{\rm trk}}{\delta r} \right] \quad \left( r = \sqrt{(\eta_p - \eta^{\rm jet})^2 + (\phi_p - \phi^{\rm jet})^2} \right)$$




**note: self-normalized observable**

CMS from PLB 730 (2014) 243

JETSCAPE, 2.76 TeV, PbPb : 0-5 % , anti-$k_{\rm T}$ $R = 0.3$, $p_{\rm T}^{\rm jet} > 100$ GeV, $0.3 < |\eta_{\rm jet}| < 2.0$, $p_{\rm T}^{\rm trk} > 1$ GeV



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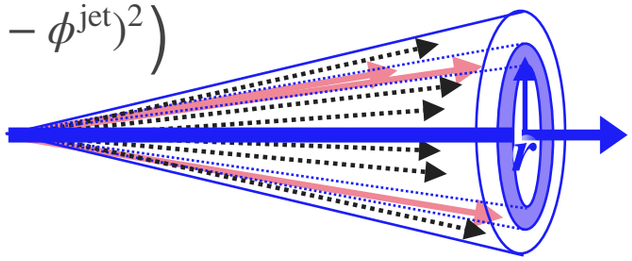


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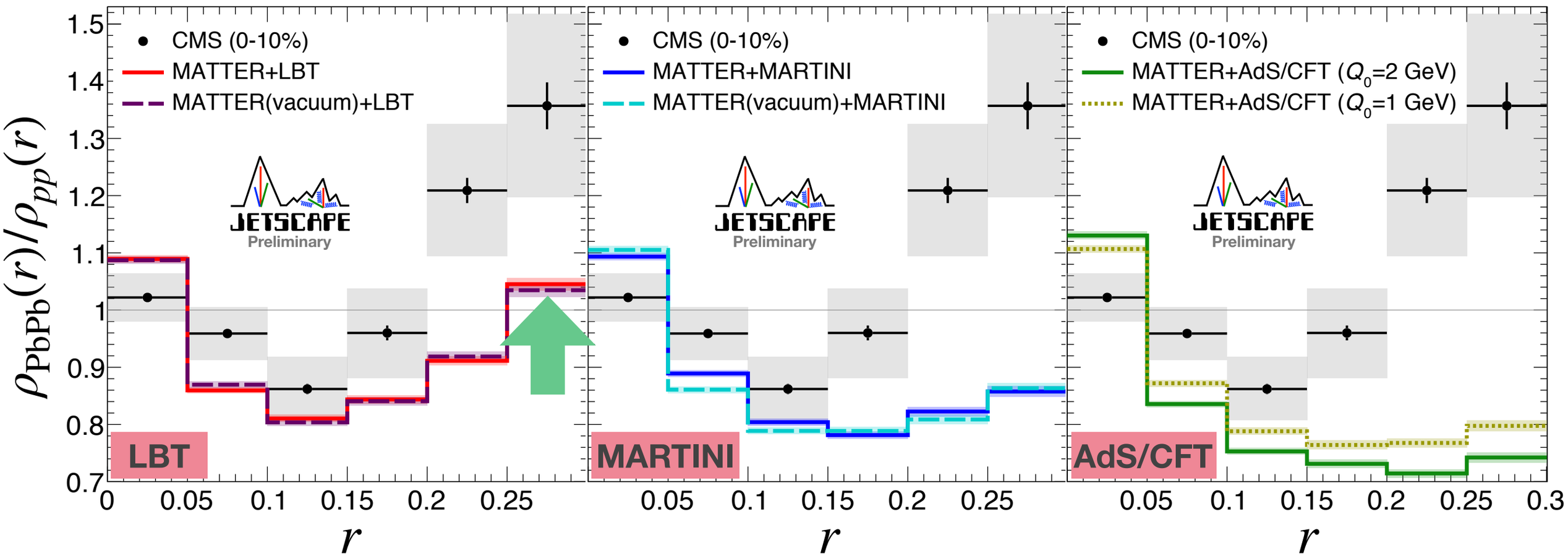

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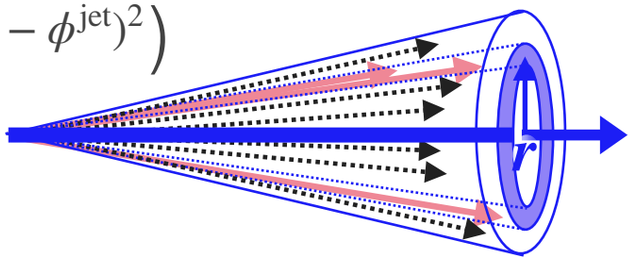


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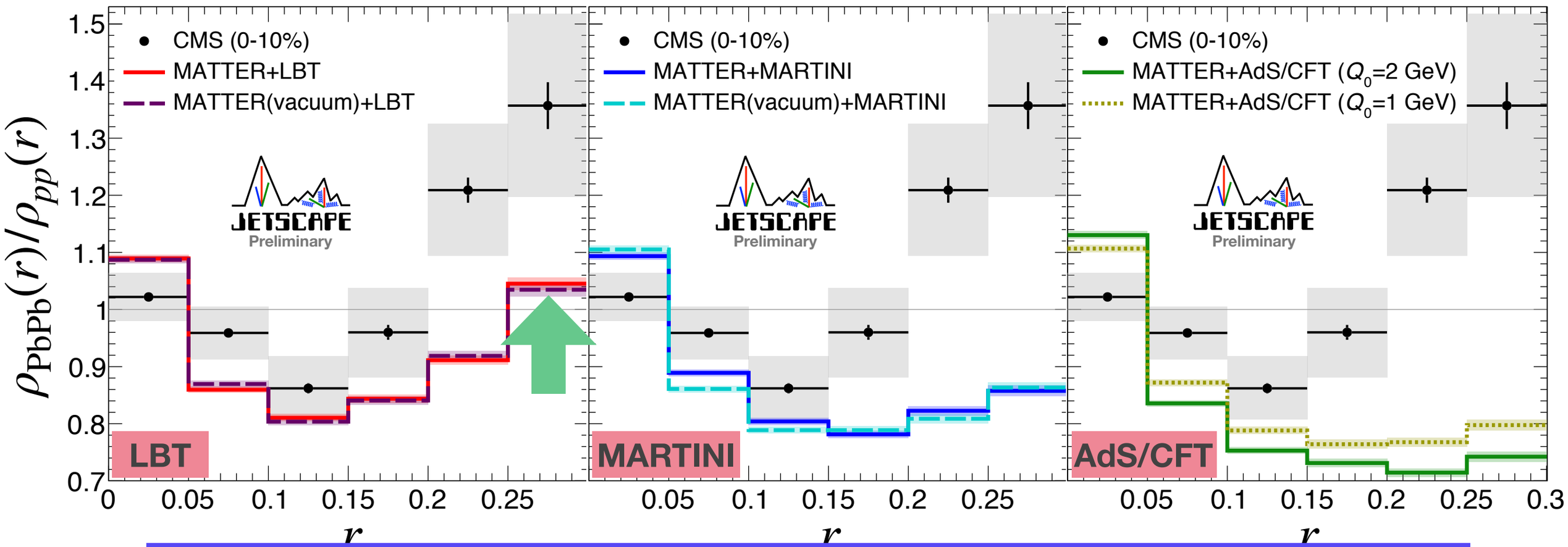


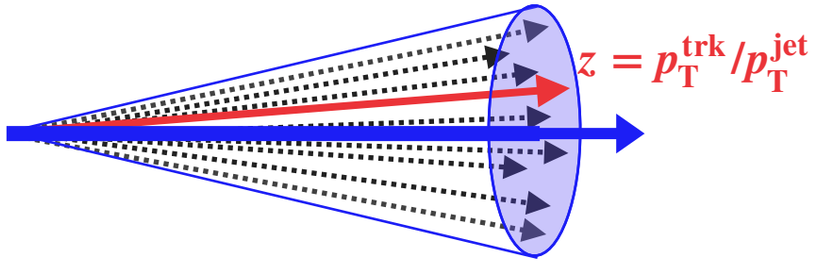

**Enhancement at large angles partially described by recoils in LBT**
**Need further mechanism (adjustment of $Q_0$, hydro response,…)**

# PbPb@2.76 TeV



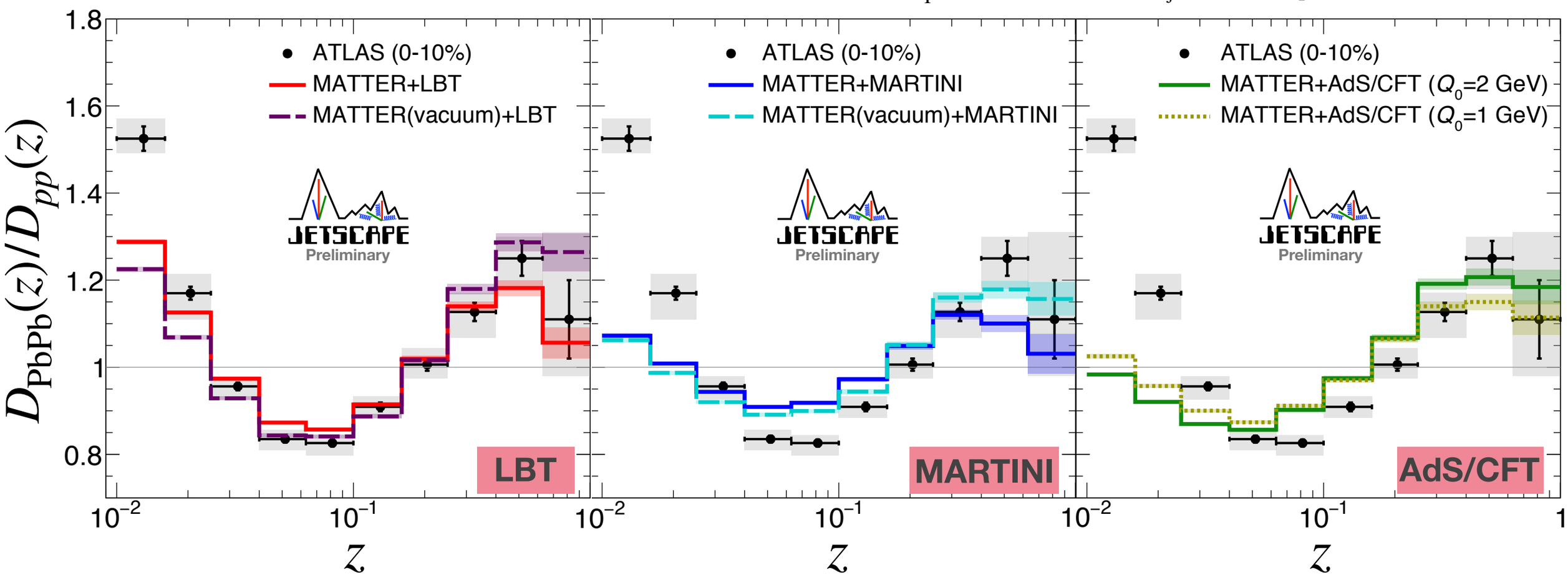
- **Jet Fragmentation**

$$D(z) = \frac{1}{N_{\rm jet}} \frac{dN_{\rm trk}}{dz} \qquad \left( z = p_{\rm T}^{\rm trk} / p_{\rm T}^{\rm jet} \right)$$




ATLAS from EPJ C77 (2017) 379

JETSCAPE, 2.76 TeV, PbPb : 0-5 % , anti-$k_{\rm T}$ $R = 0.4$, $100 < p_{\rm T}^{\rm jet} < 398$ GeV, $0 < |Y_{\rm jet}| < 2.1$, $p_{\rm T}^{\rm trk} > 1$ GeV

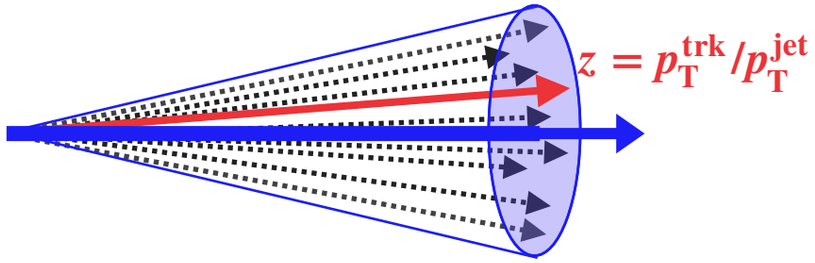


# PbPb@2.76 TeV



- **Jet Fragmentation**

$$D(z) = \frac{1}{N_{\rm jet}} \frac{dN_{\rm trk}}{dz} \qquad \left( z = p_{\rm T}^{\rm trk} / p_{\rm T}^{\rm jet} \right)$$

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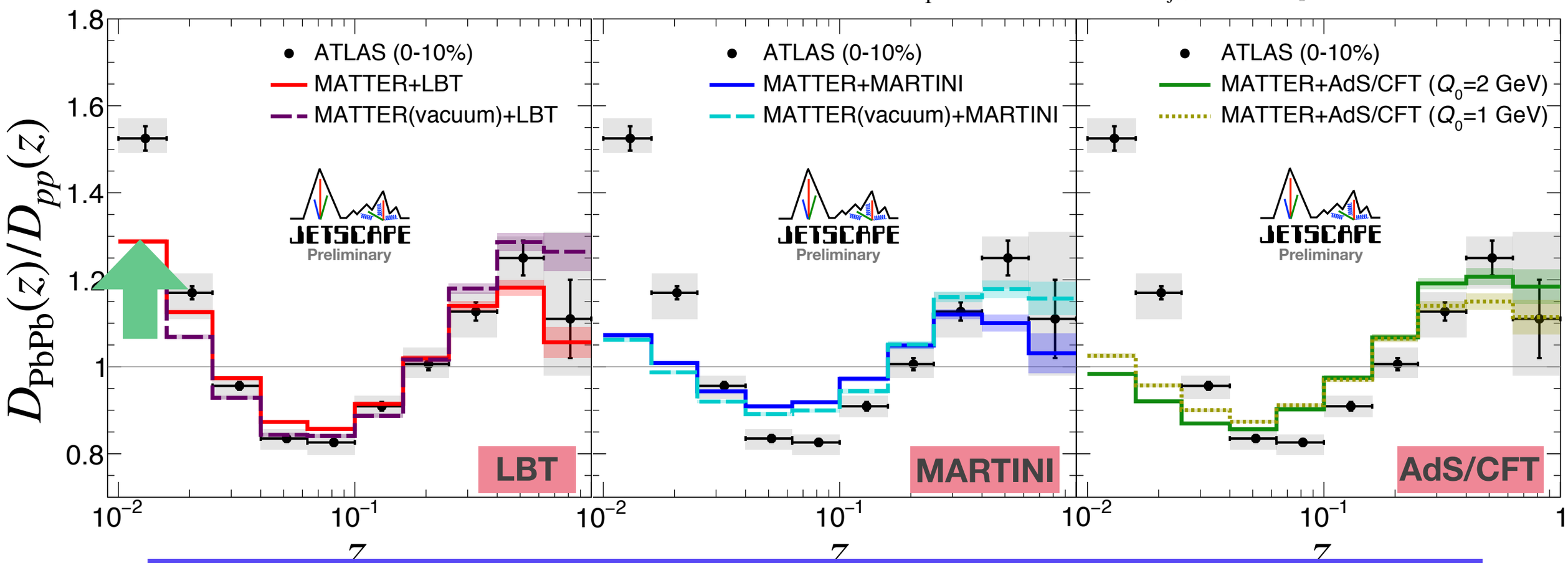


**Small- $z$ enhancement partially described by recoils in LBT**
**Need further mechanism (adjustment of $Q_0$, hydro response,…)**

# PbPb@2.76 TeV



- **Jet Fragmentation**

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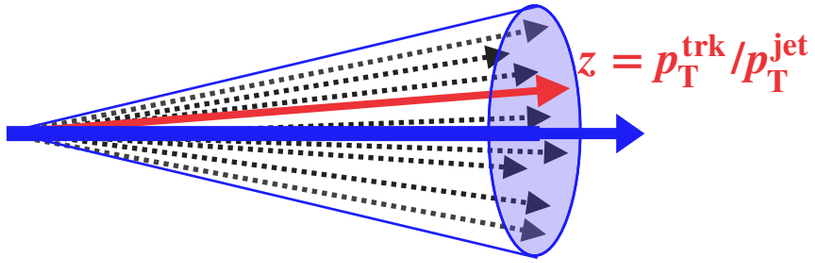


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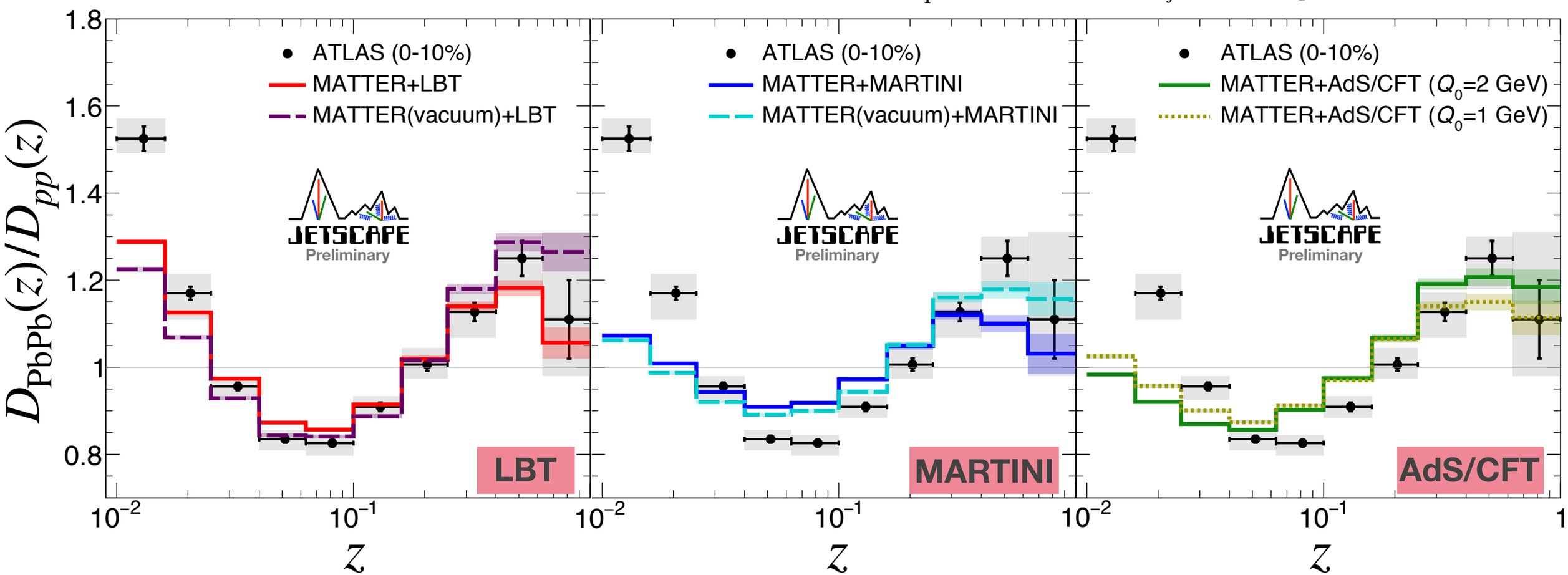

# PbPb@2.76 TeV



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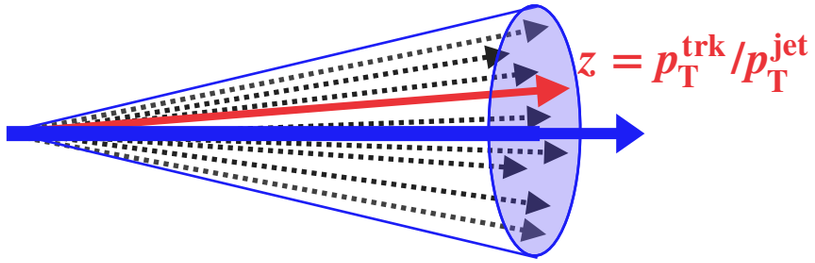


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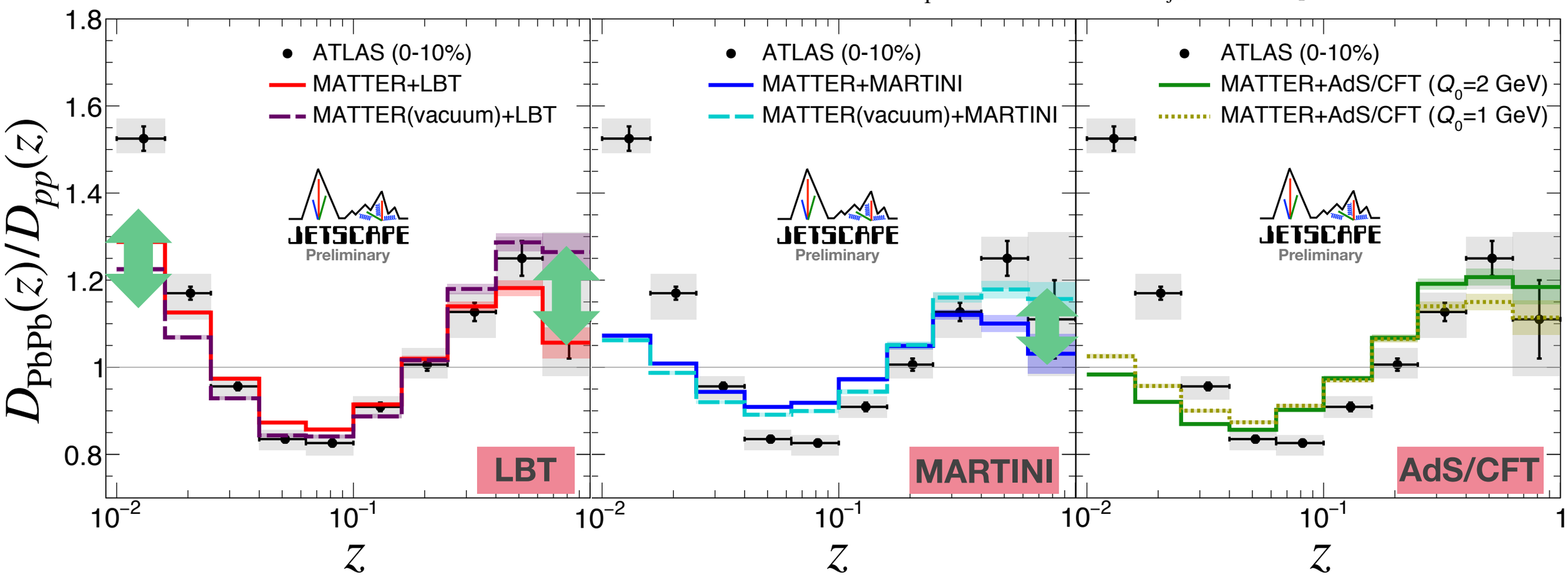



**Medium effect during virtuality ordered splitting**

# Bayesian analysis with JETSCAPE

# Bayesian Analysis with JETSCAPE

JETSCAPE, *in preparation*

- **Extraction of $\hat{q}$ and $Q_0$ from experimental data**
  - Use STAT package of JETSCAPE (to be released with next update)
  - $\hat{q}$ with parametrization:

$$\frac{\hat{q}}{T^3} = 42 C_{\mathrm{R}} \frac{\zeta(3)}{\pi} \left(\frac{4\pi}{9}\right)^2 \left[ \frac{A \ln \frac{E}{\Lambda} - \ln B}{\left(\ln \frac{E}{\Lambda}\right)^2} + \frac{C \ln \frac{E}{T} - \ln D}{\left(\ln \frac{ET}{\Lambda^2}\right)^2} \right]$$

  - Observable: single inclusive hadron $R_{\mathrm{AA}}$ (RHIC&LHC)
  - Simulation results by MATTER + LBT to train Gaussian Process Emulator
  - Determine input parameters with Markov-Chain Monte-Carlo (MCMC) by comparing with experimental data

# Bayesian Analysis with JETSCAPE

JETSCAPE, *in preparation*

**Model Parameters - System Properties**
- energy loss scale
- medium coupling constant

calculate events on Latin hypercube

**Physics Package:**
- MATTER + LBT
- VISHNU

**Gaussian Process Emulator**
- non-parametric interpolation
- fast surrogate to full Physics Model

**Experimental Data**
- RAA @ RHIC & LHC

**MCMC**
(Markov-Chain Monte-Carlo)
- random walk through parameter space weighted by posterior probability

after many steps, MCMC equilibrates to

**Posterior Distribution**
- **diagonals**: probability distribution of each parameter, integrating out all others
- **off-diagonals**: pairwise distributions showing dependence between parameters

**Bayes' Theorem**

posterior $\propto$ likelihood $\times$ prior

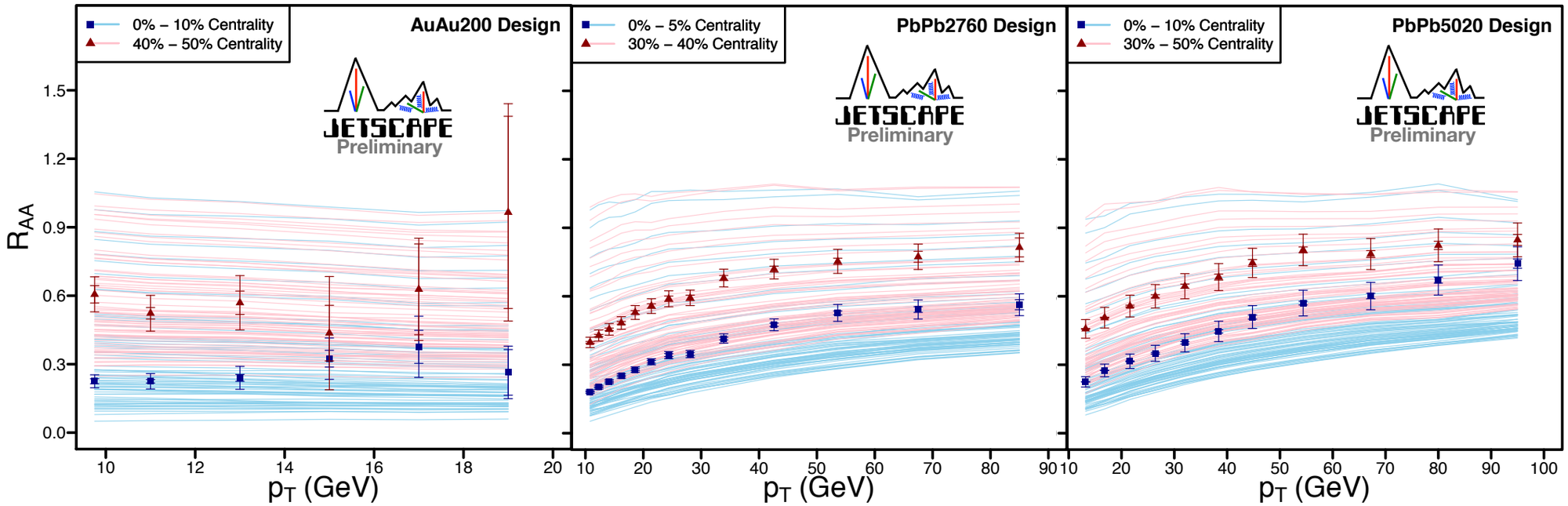
- **prior**: initial knowledge of parameters
- **likelihood:** probability of observing exp. data, given proposed parameters

R. Soltz HP 2018
[figure adapted from Bass, Bernhard, Moreland]

# Bayesian Analysis with JETSCAPE

JETSCAPE, *in preparation*

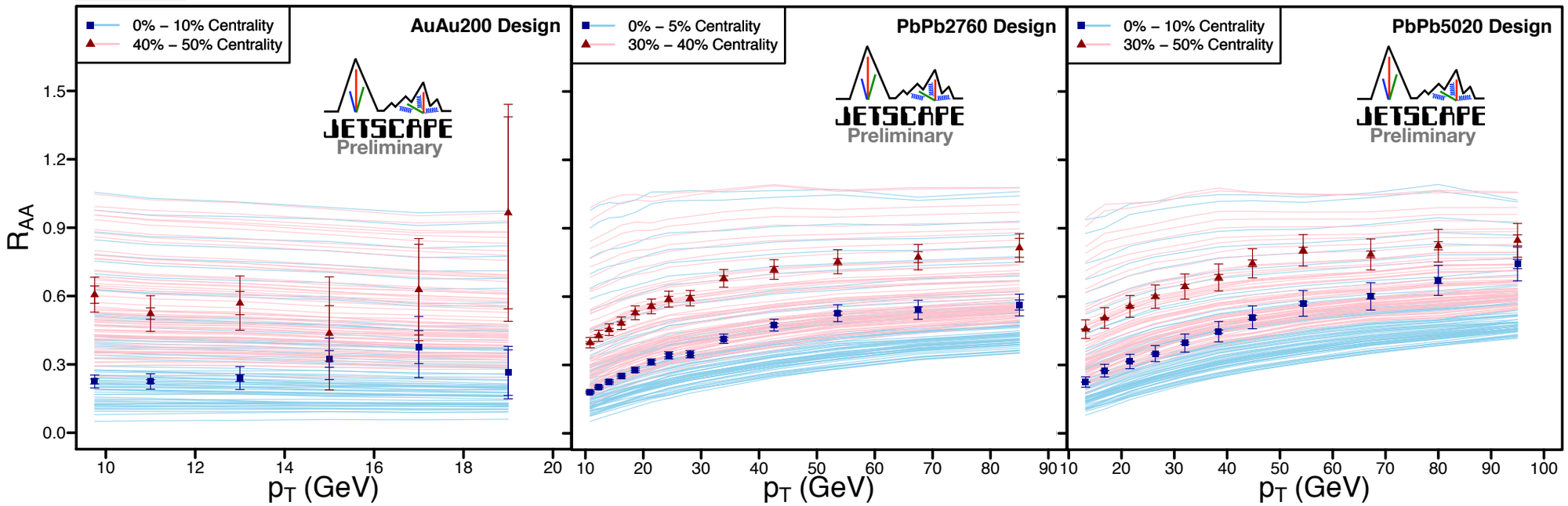
## Prior



# Bayesian Analysis with JETSCAPE

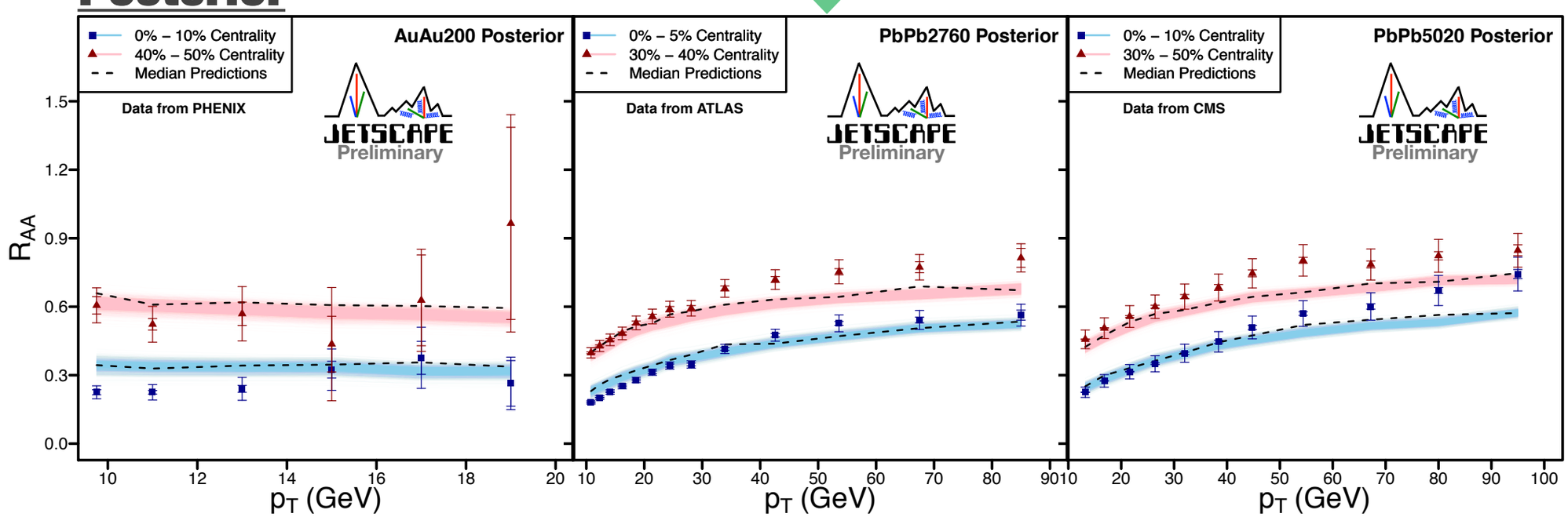
JETSCAPE, *in preparation*

## Prior




**Applied Bayes' theorem by MCMC**

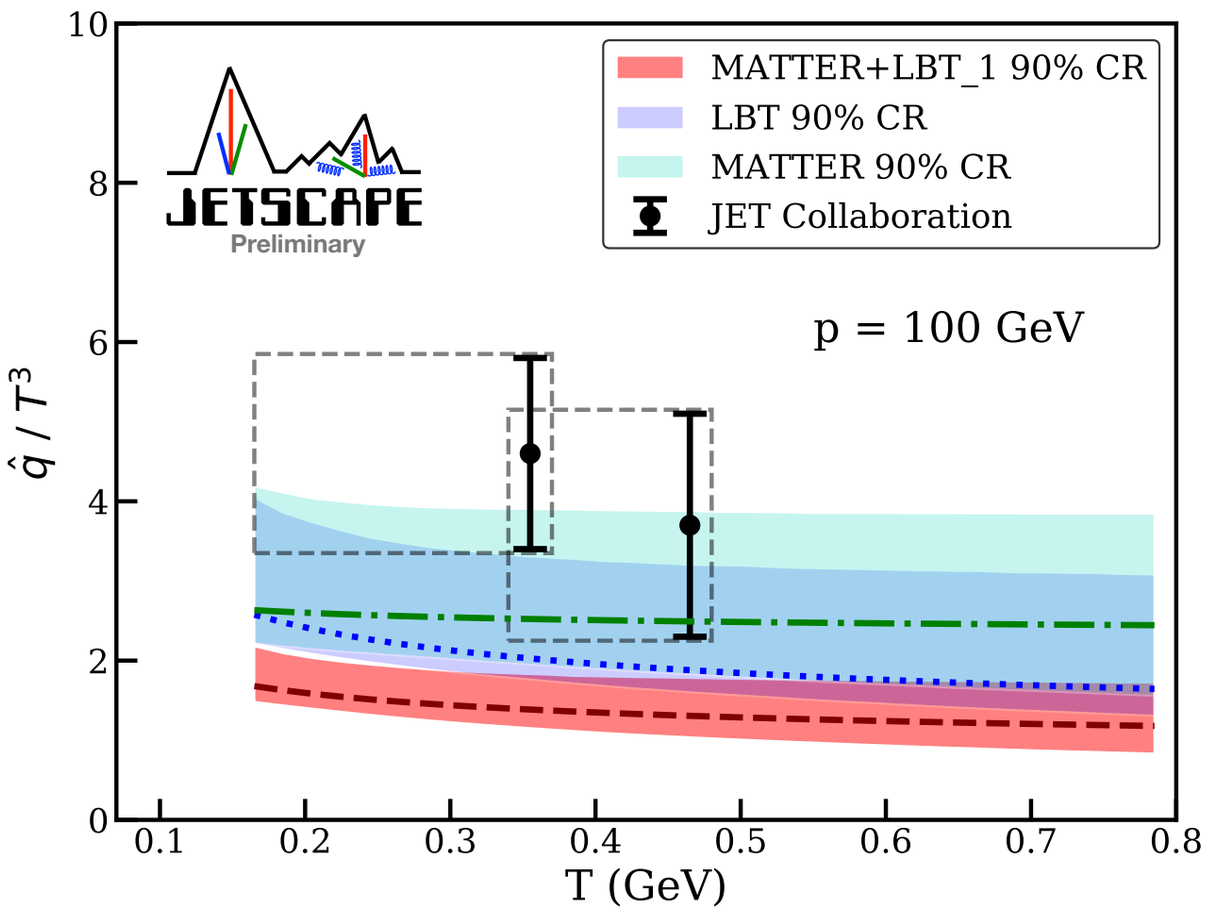
## Posterior

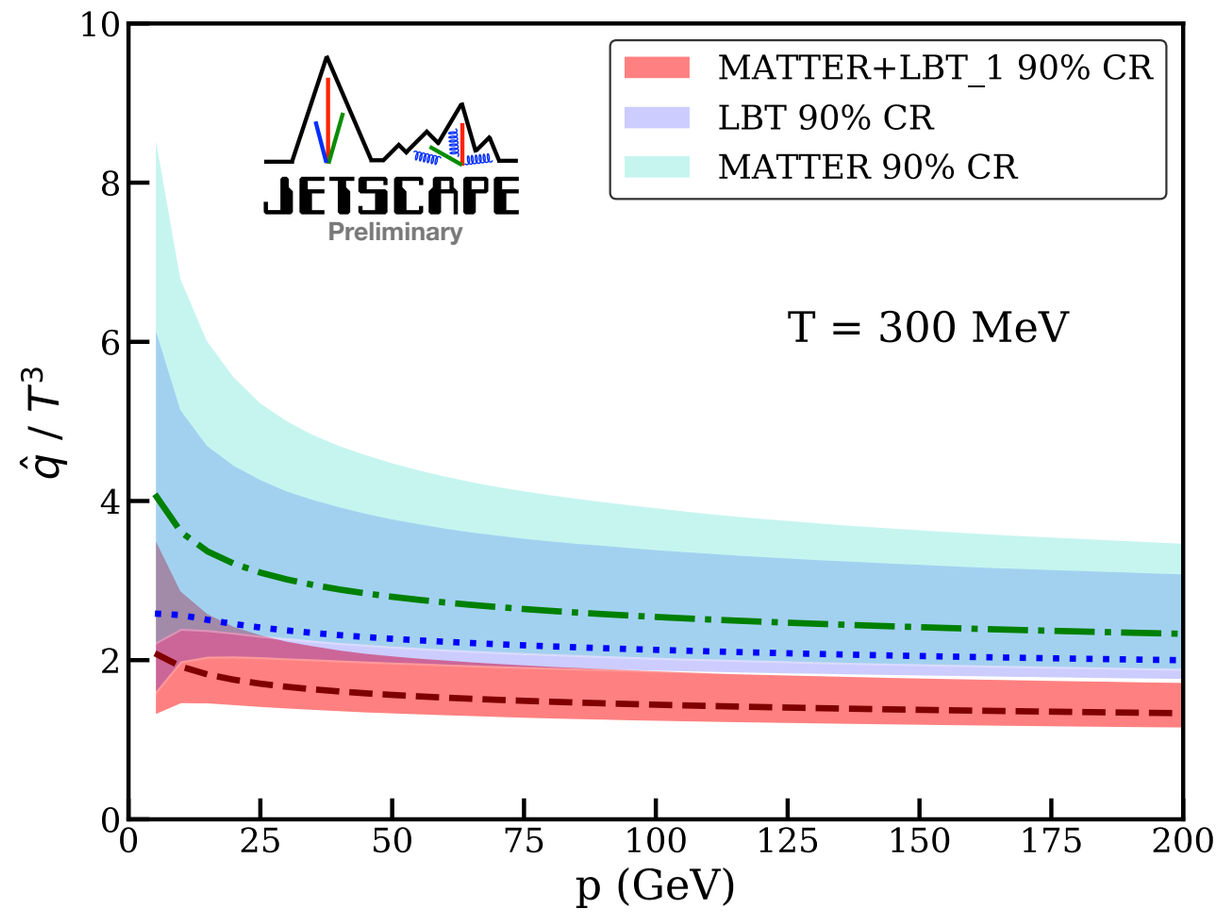


# Bayesian Analysis with JETSCAPE

JETSCAPE, *in preparation*

- **Extracted $\hat{q}$ as a function of $T$ and $p$**



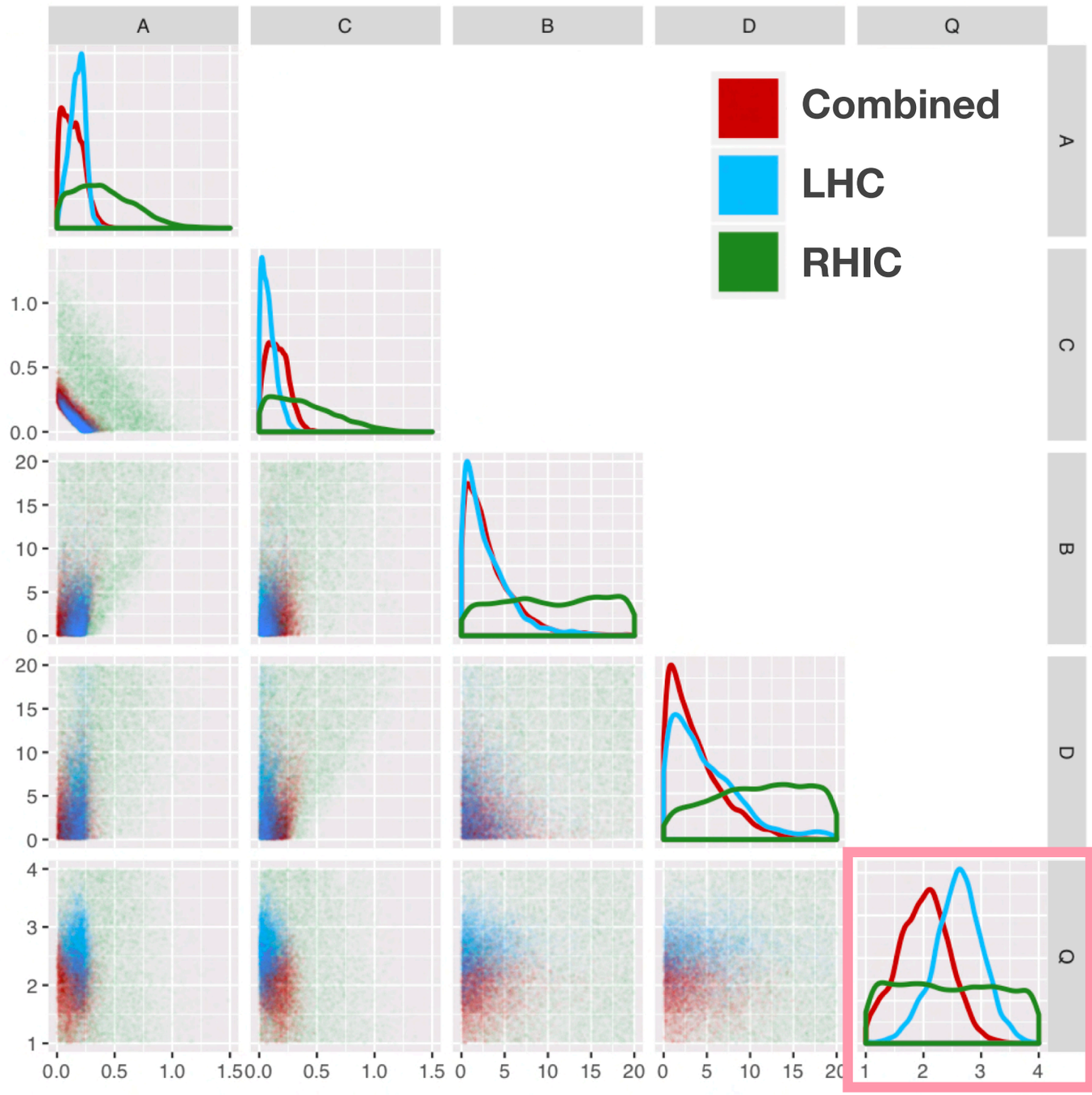




- Extracted from single inclusive hadron $R_{AA}$
- More observables available to constrain parameters (future perspective)

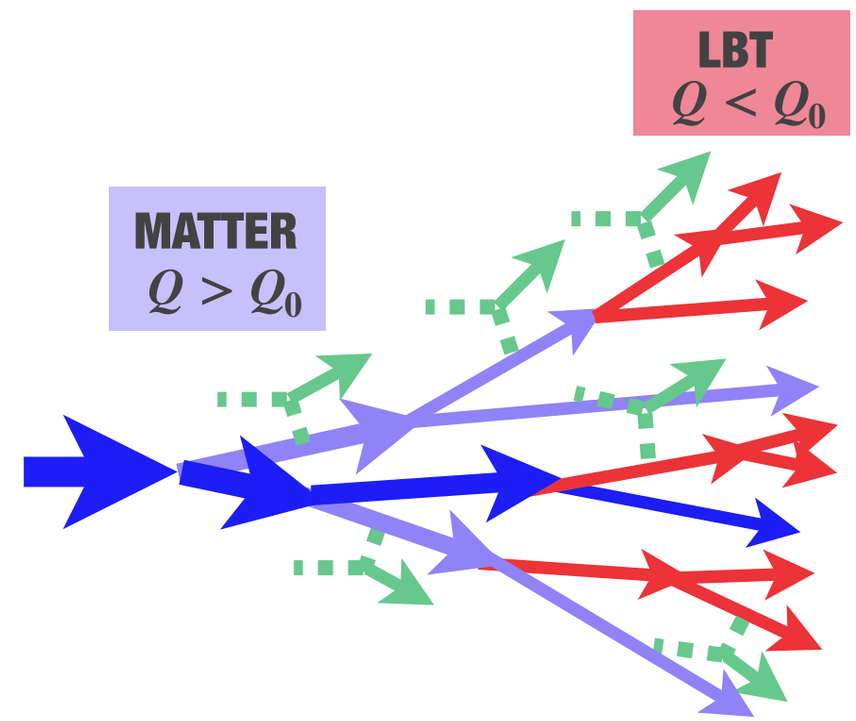
# Bayesian Analysis with JETSCAPE

JETSCAPE, *in preparation*

- **Extracted switching virtuality scale $Q_0$**




$$\frac{\hat{q}}{T^3} = 42 C_R \frac{\zeta(3)}{\pi}\left(\frac{4\pi}{9}\right)^2 \left[\frac{A \ln\frac{E}{\Lambda} - \ln B}{\left(\ln\frac{E}{\Lambda}\right)^2} + \frac{C \ln\frac{E}{T} - \ln D}{\left(\ln\frac{ET}{\Lambda^2}\right)^2}\right]$$




**90% credible region**

$$Q_0 = 1.25\text{-}2.76\ \text{GeV}$$

# Update to JETSCAPE 2.0

# Update to JETSCAPE 2.0

- **To be released this month (June 24th, 2019)**
  - On our GitHub account: **https://github.com/JETSCAPE**
- **New physics features**
  - Hydrodynamic medium response

**Hydrodynamic equation with source term**

$$\nabla_\mu T^{\mu\nu}_{\text{fluid}}(x) = J^\nu(x)$$

$J^\nu(x)$ : Source term constructed from jet energy loss + *causal diffusion*

  - Heavy Quarks
  - Photon emission from jet shower with medium effect
- **New STAT package**
  - Bayesian analysis to extract parameters from experimental data

# Summary

- **The JETSCAPE Collaboration**
  - **http://jetscape.org**
- **JETSCAPE 1.4**
  - Available at **https://github.com/JETSCAPE**
  - Manual: arXiv:1903.07706
- **Various results from simulations with JETSCAPE**
  - pp-baseline comparable to Pythia 8's performance
  - Systematic study with multi-stage jet evolution
  - Extraction of $\hat{q}$ value via Bayesian analysis
- **Update to JETSCAPE 2.0**
  - On June 24th (this month)
  - Hydrodynamic medium response, heavy quarks, photons from jets,…
  - STAT package for Bayesian Analysis

# Backup

# Simulation for pp collisions with JETSCAPE

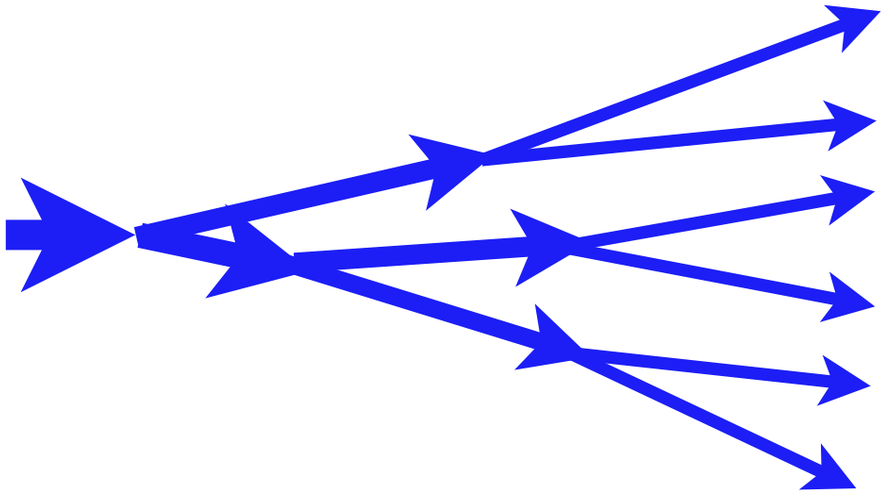
- **Settings in simulations for pp collisions**

  - MATTER vacuum shower down to $Q = 1\,\mathrm{GeV}$

  - Initial hard partons generated by Pythia (MPI, ISR: ON)

  - Lund Hadronization

  - No underlying-event (UE) subtraction



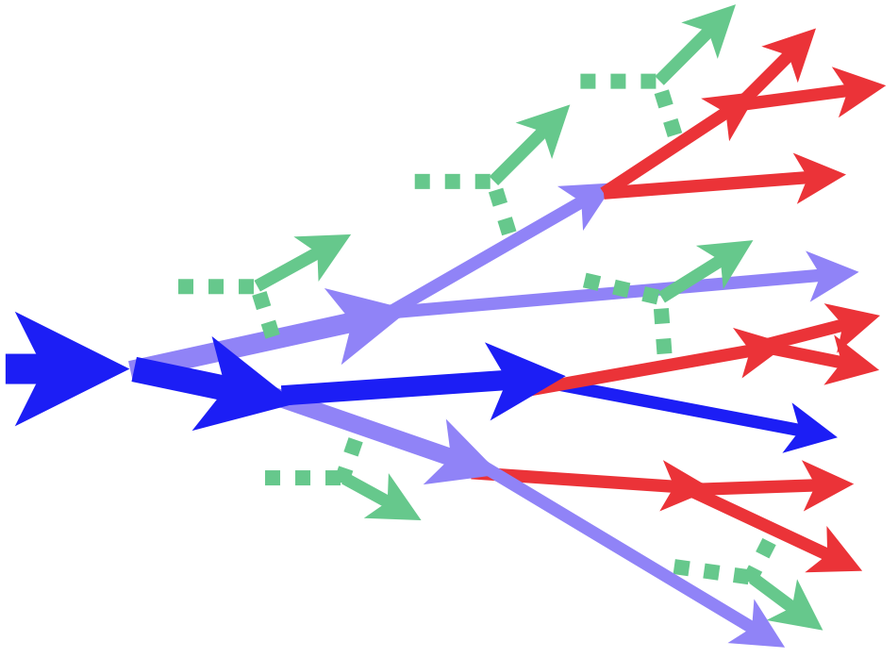
# Settings in simulations for PbPb at 2.76 TeV

**Jet**

- MATTER, LBT: Recoil ON
  MARTINI, AdS/CFT: No medium response (to be implemented in future)
- Virtuality separation scale: $Q_0 = 2\,\mathrm{GeV}$
- Initial condition from TRENTo+Pythia (MPI, ISR: ON)
  Moreland, Bernhard, Bass(14)
- Lund Hadronization

**QGP fluid**

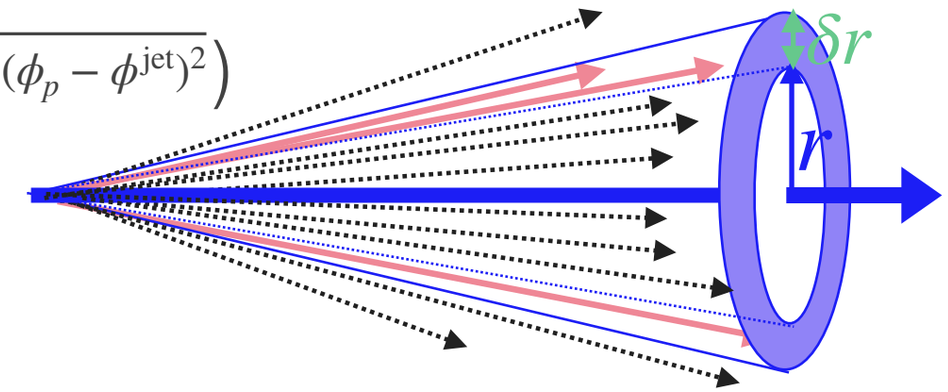
- 2+1D, event-averaged (data table)
- TRENTo initial condition+free-streaming
  Liu, Shen, Heinz(15)
- VISHNU (viscous hydro calculation)
  Shen, Qiu, Song, Bernhard, Bass, Heinz(16)



# Jet Shape (pp)

$$\rho(r) = \frac{1}{N_{\rm jet}} \sum_{\rm jet} \left[ \frac{1}{p_{\rm T}^{\rm jet}} \frac{\sum_{{\rm trk}\in(r-\delta r/2, r+\delta r/2)} p_{\rm T}^{\rm trk}}{\delta r} \right]$$

$$\left( r = \sqrt{(\eta_p - \eta^{\rm jet})^2 + (\phi_p - \phi^{\rm jet})^2} \right)$$

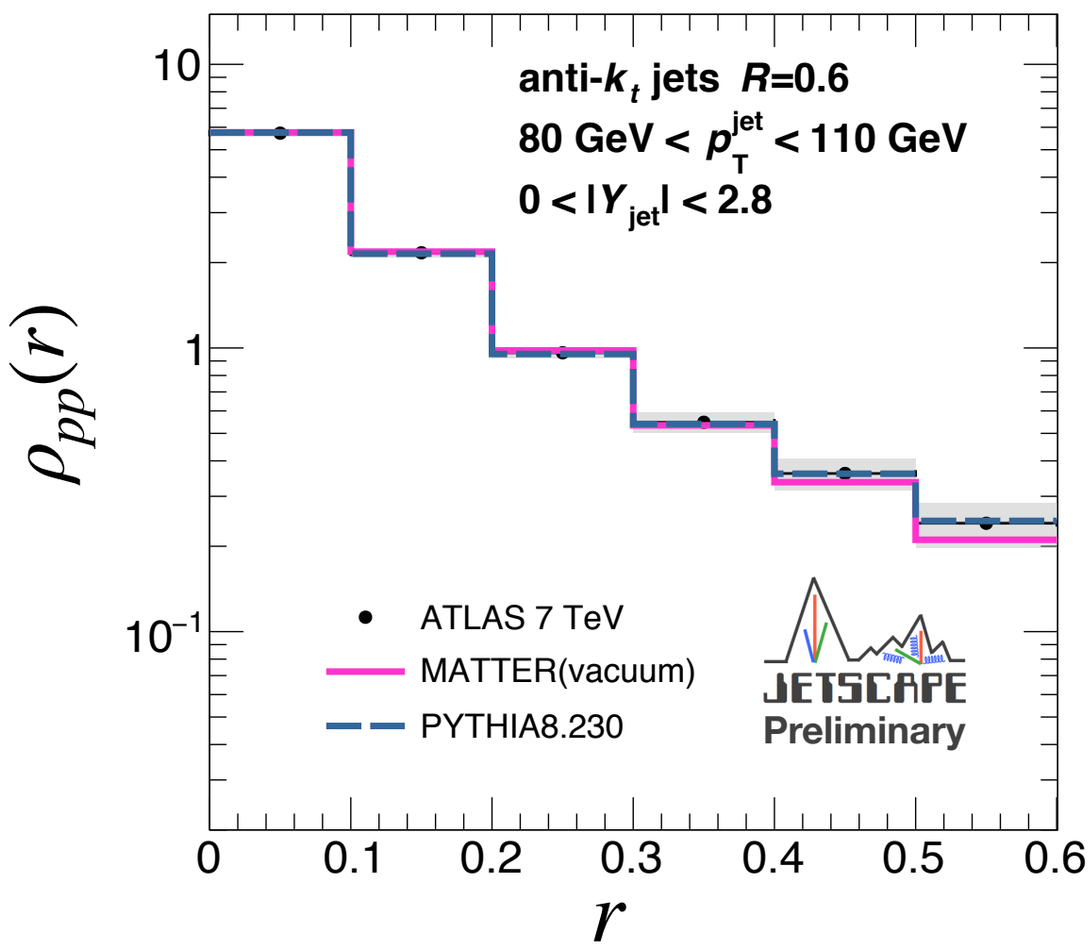


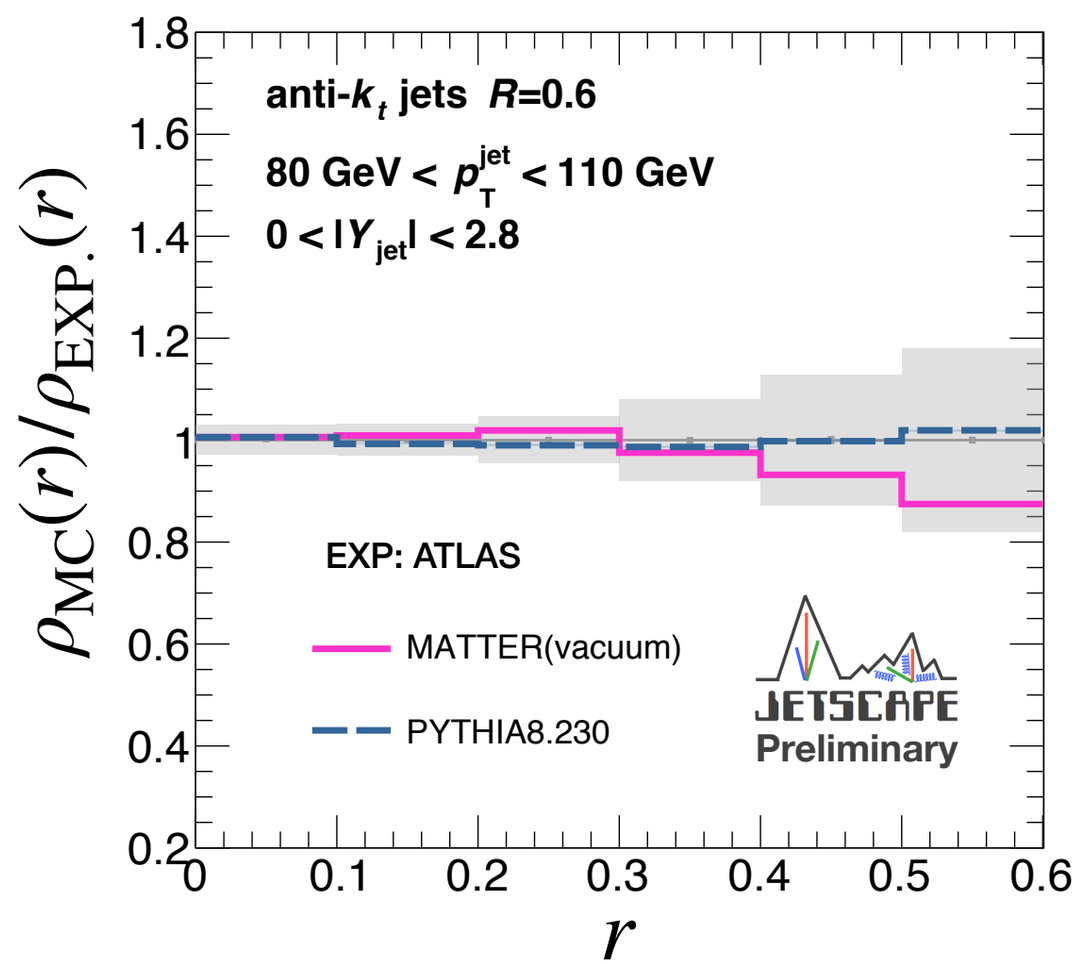

**note: self-normalized observable**

**7 TeV**

*Parameters in Pythia8.230 are default

ATLAS from PRD 83 (2011) 052003



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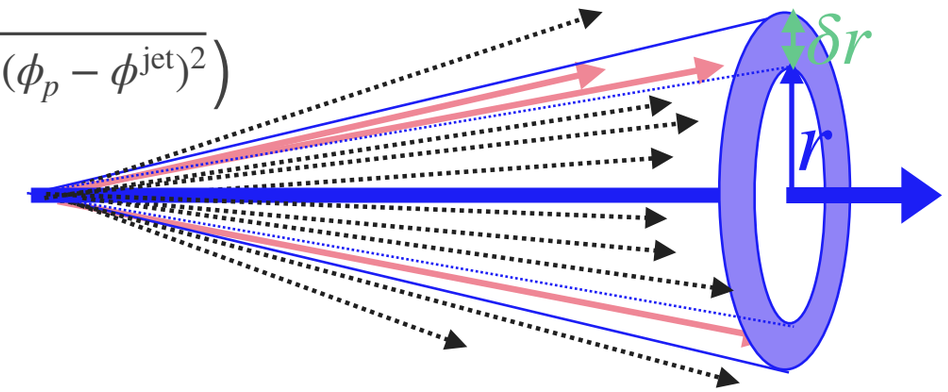


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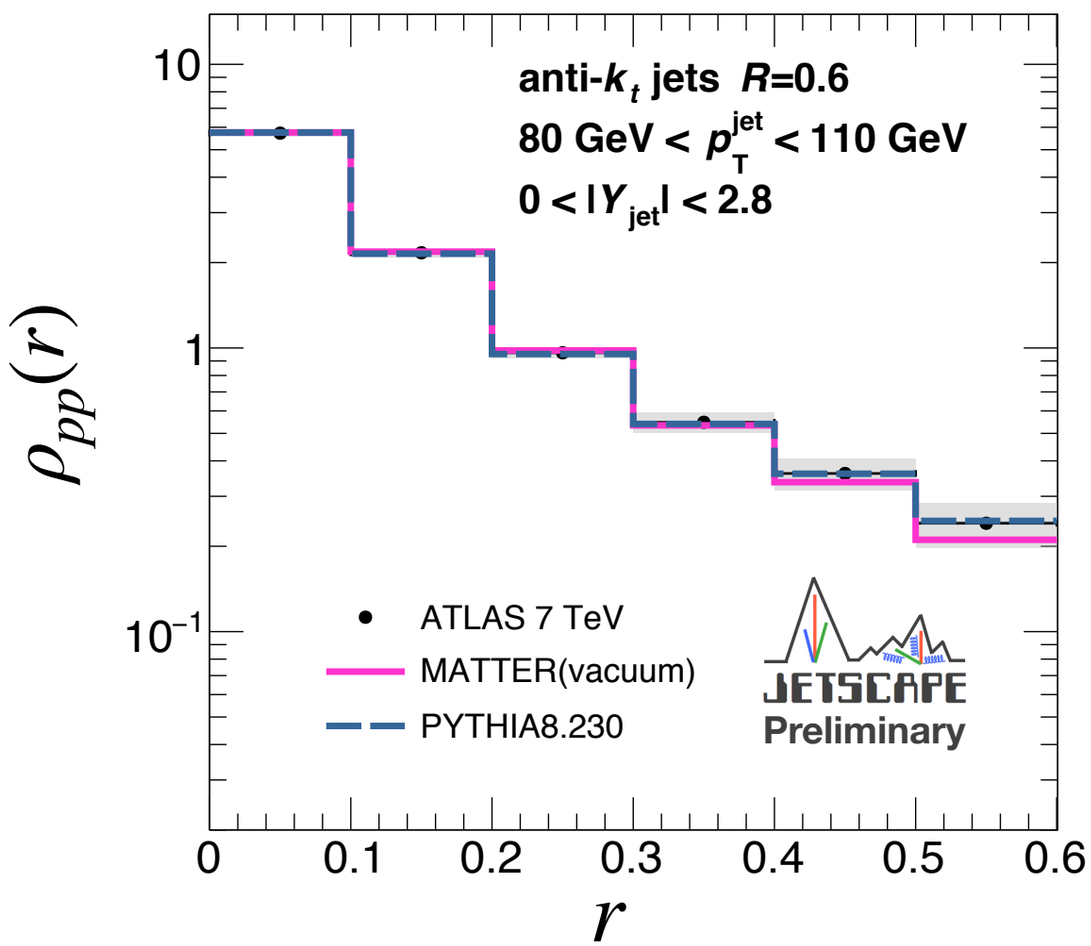


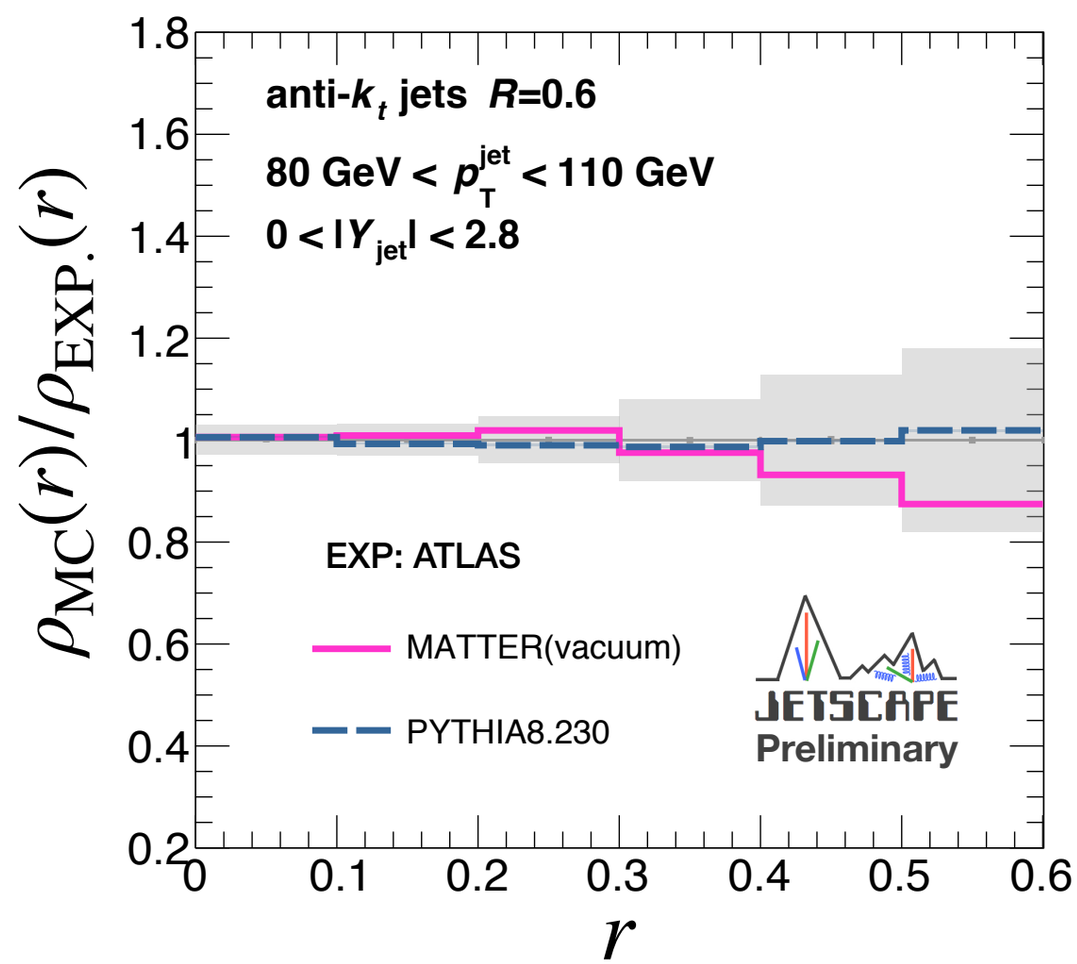


**Very good agreement with experimental data**

# Jet Shape (pp)

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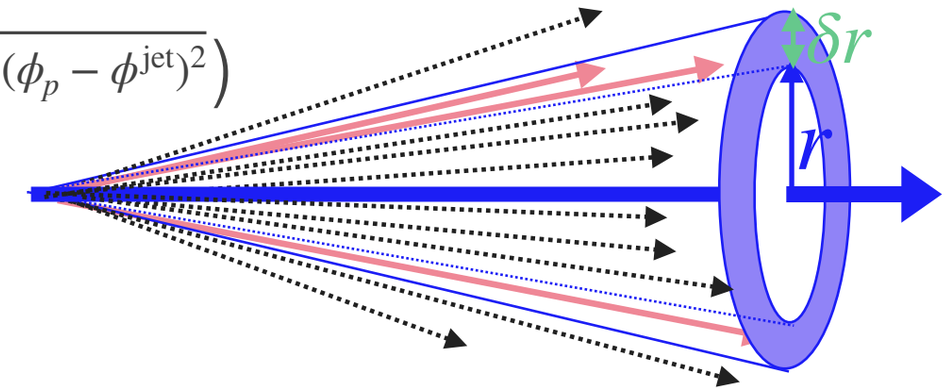


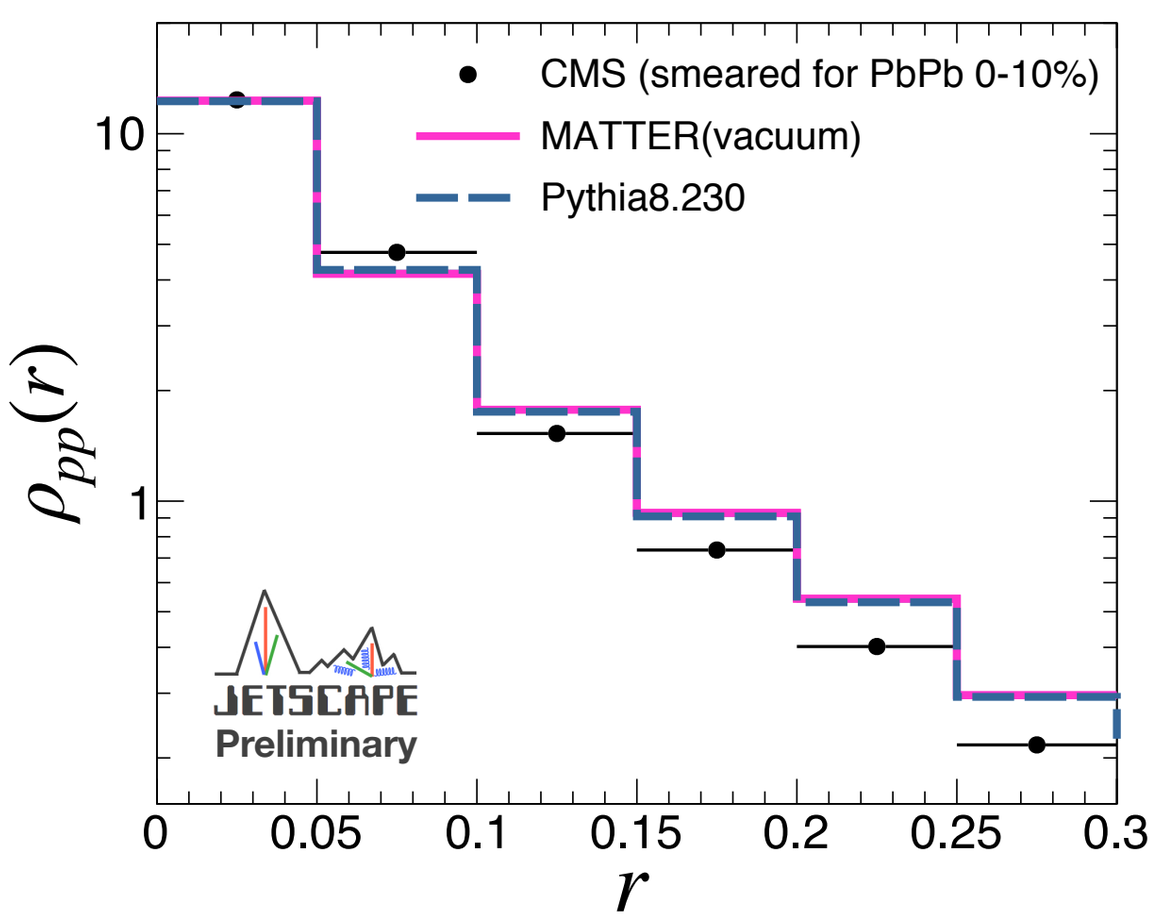

**note: self-normalized observable**

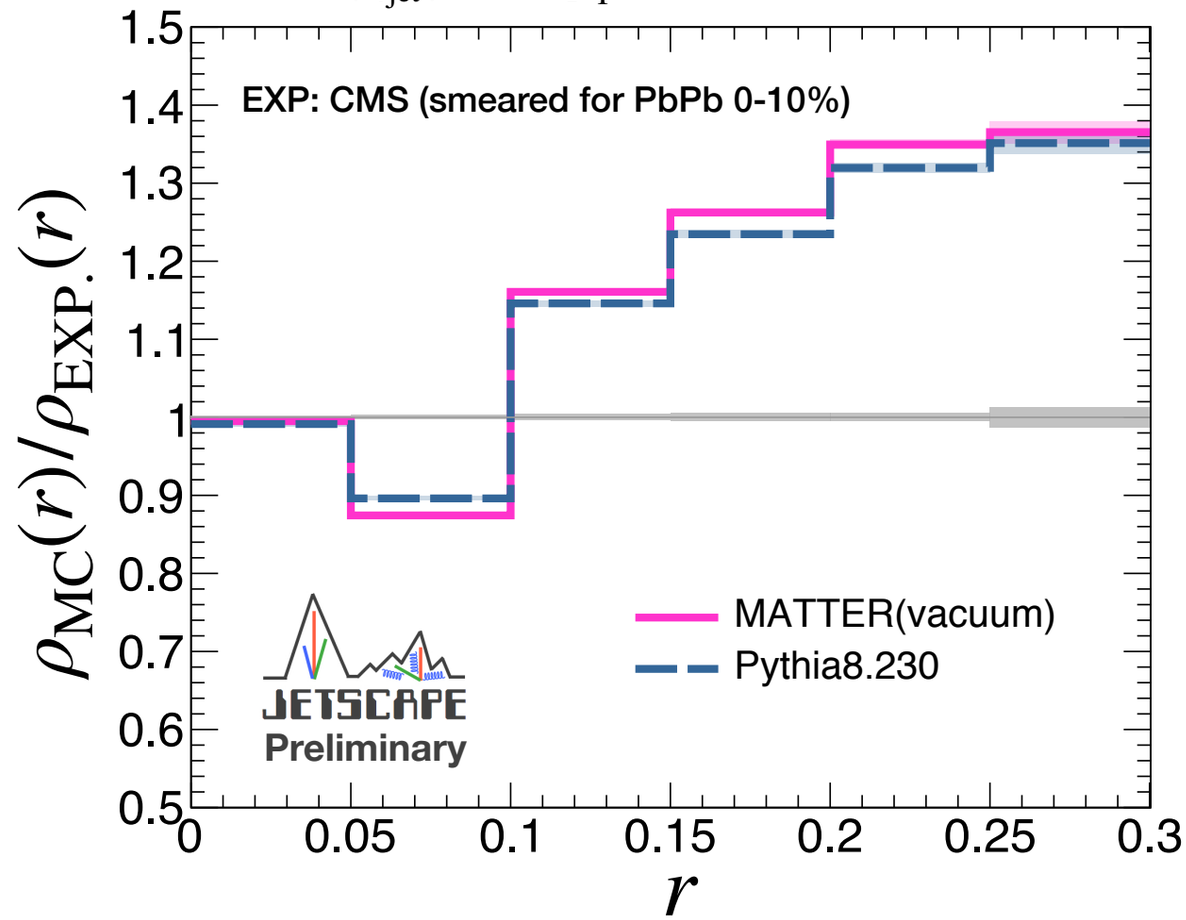
**2.76 TeV**

*Parameters in Pythia8.230 are default

CMS from PLB 730 (2014) 243

JETSCAPE, $pp$ 2.76 TeV, anti-$k_{\rm T}$ $R = 0.3$, $p_{\rm T}^{\rm jet} > 100$ GeV, $0.3 < |\eta_{\rm jet}| < 2.0$, $p_{\rm T}^{\rm trk} > 1$ GeV



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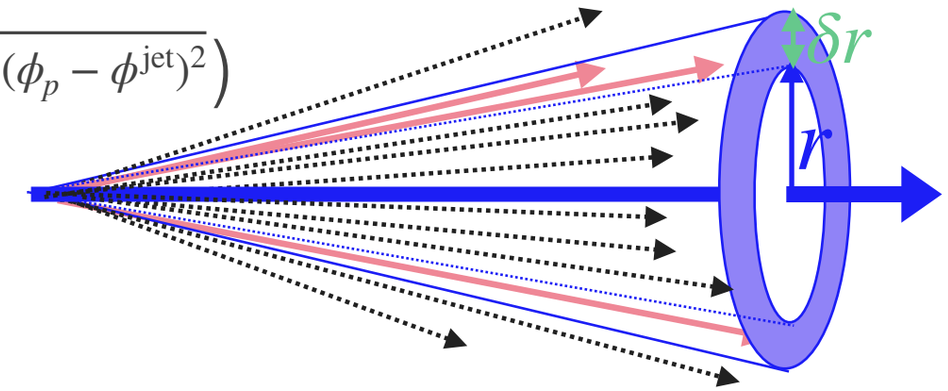


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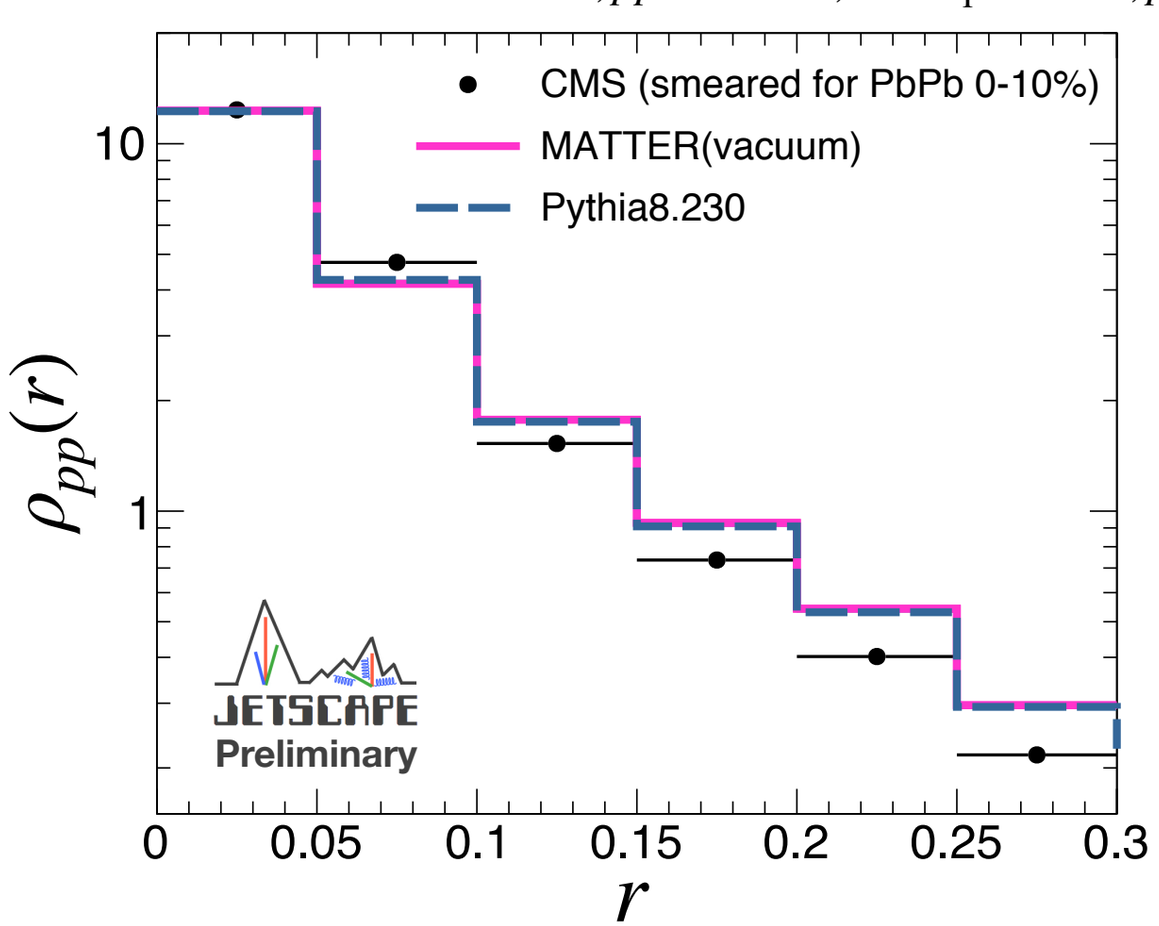


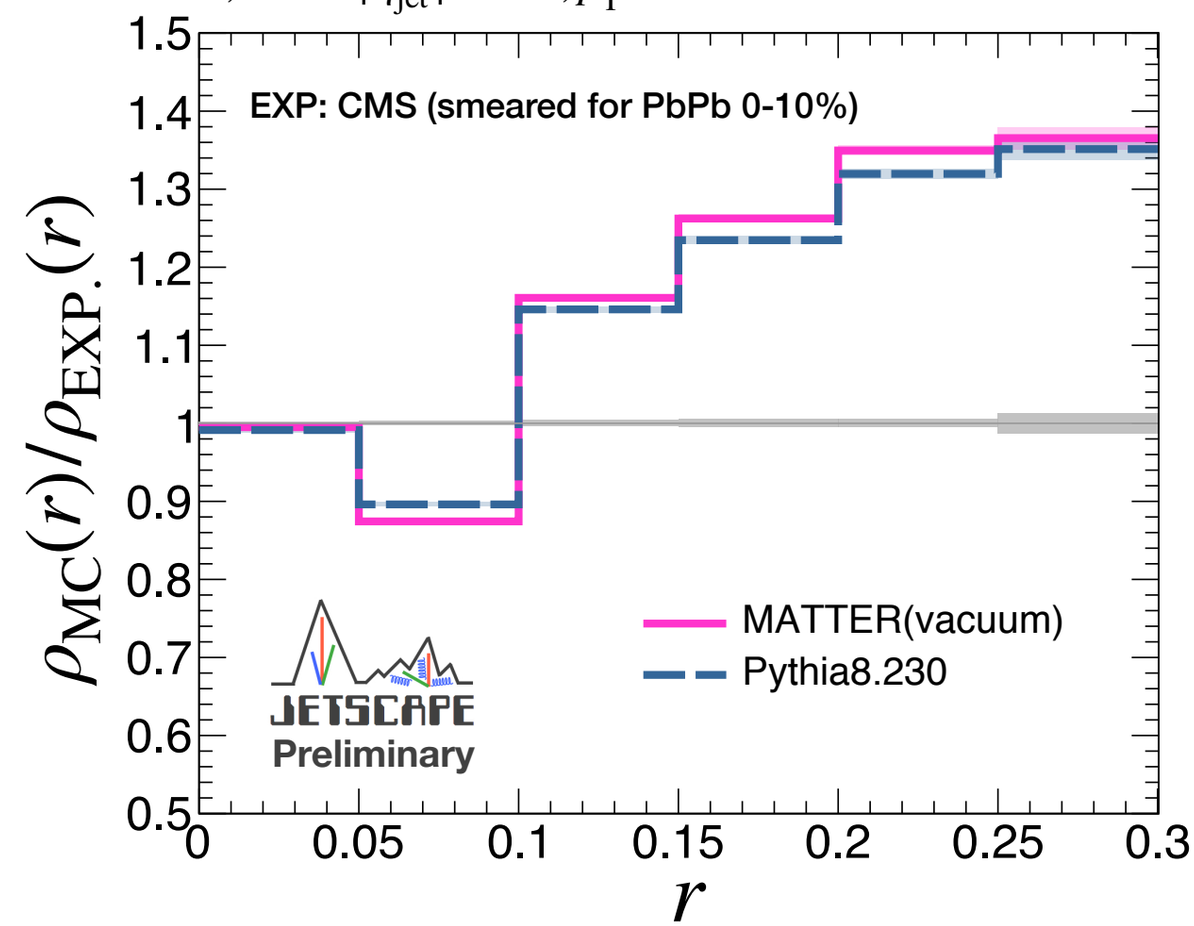


**Similar behavior to default Pythia8**

# Jet Fragmentation Function (pp)

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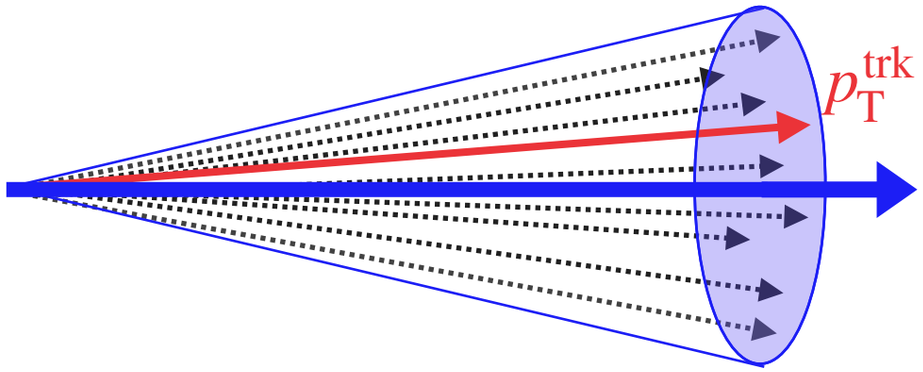


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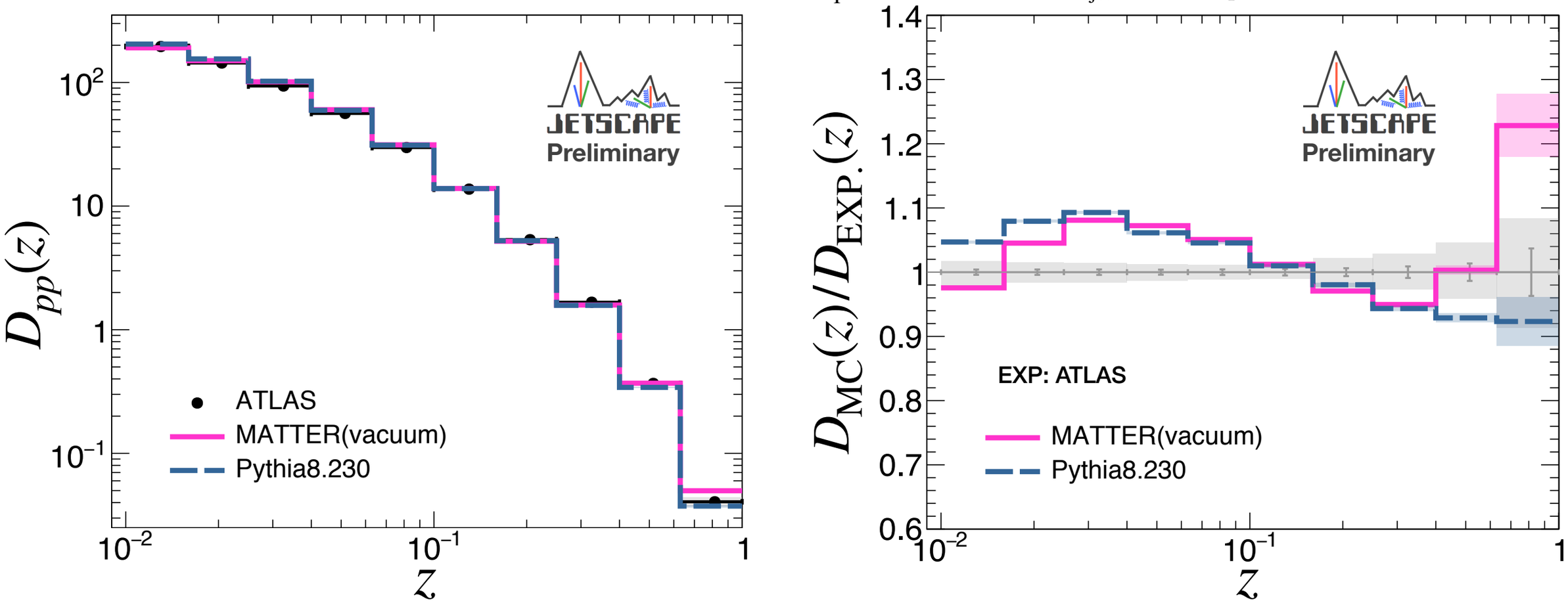
ATLAS from EPJ C77 (2017) 379

JETSCAPE, 2.76 TeV, $pp$, anti-$k_{\text{T}}$ $R = 0.4$, $100 < p_{\text{T}}^{\text{jet}} < 398$ GeV, $0 < |Y_{\text{jet}}| < 2.1$, $p_{\text{T}}^{\text{trk}} > 1$ GeV



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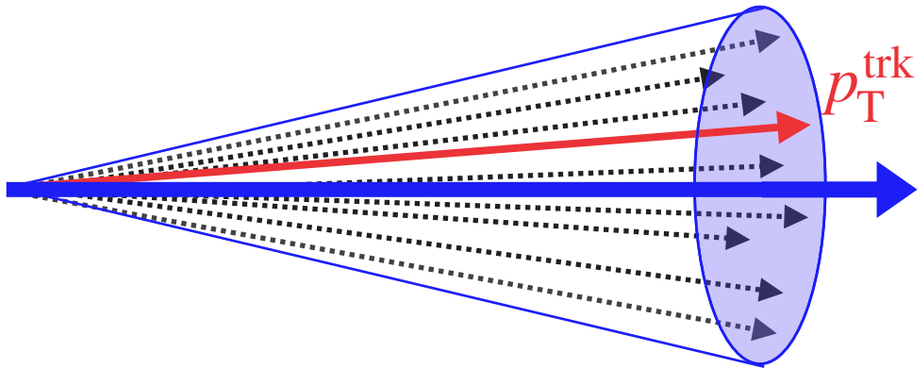


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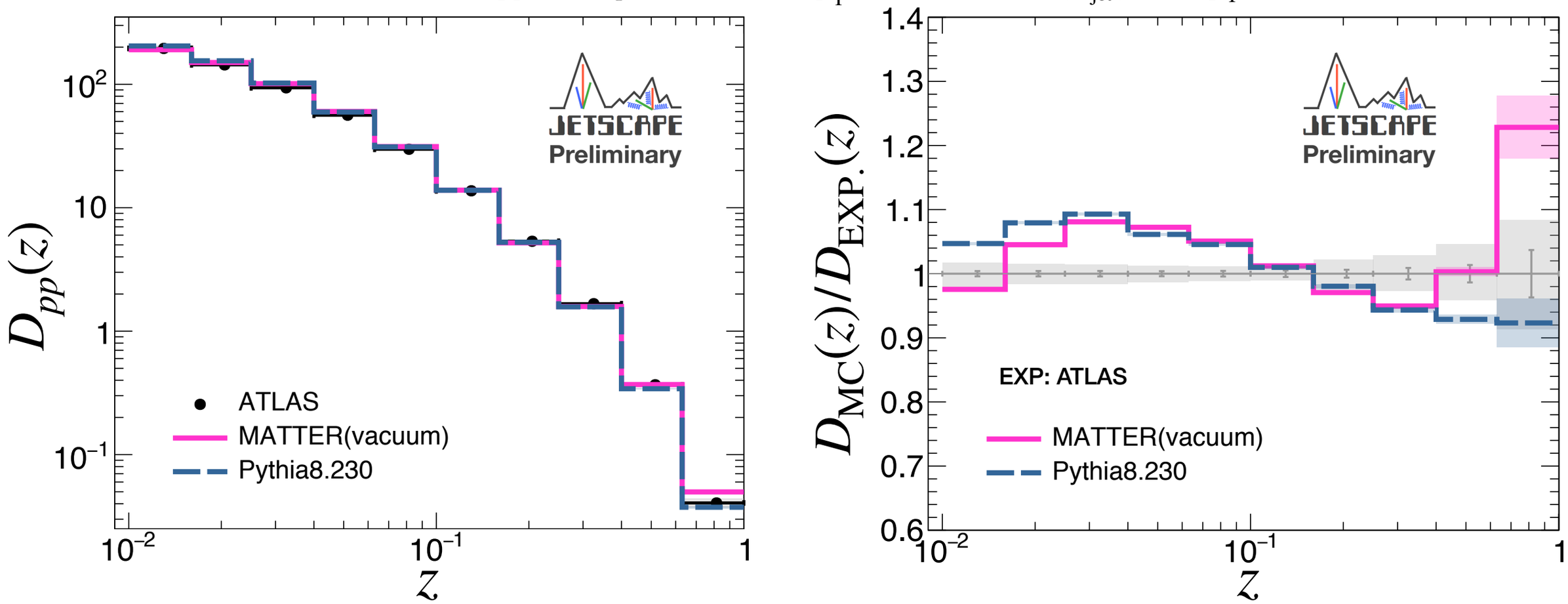


**Deviation at high-$z$, need further tunings**

# Jet Shape (PbPb)

$$\rho(r) = \frac{1}{N_{\rm jet}} \sum_{\rm jet} \left[ \frac{1}{p_{\rm T}^{\rm jet}} \frac{\sum_{{\rm trk}\in(r-\delta r/2, r+\delta r/2)} p_{\rm T}^{\rm trk}}{\delta r} \right]$$

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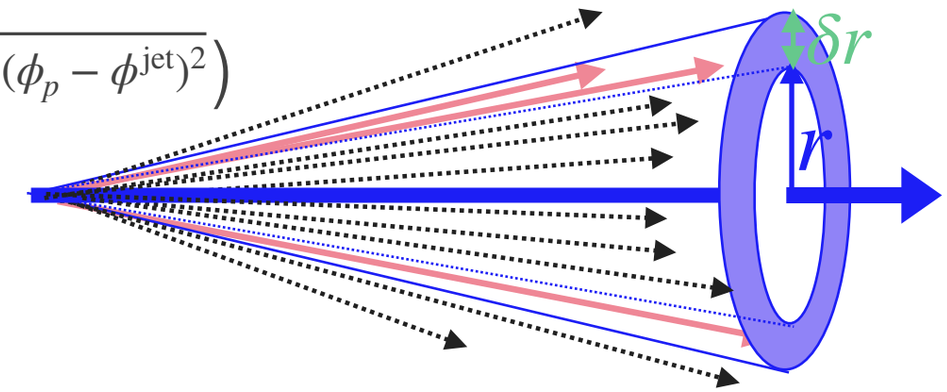
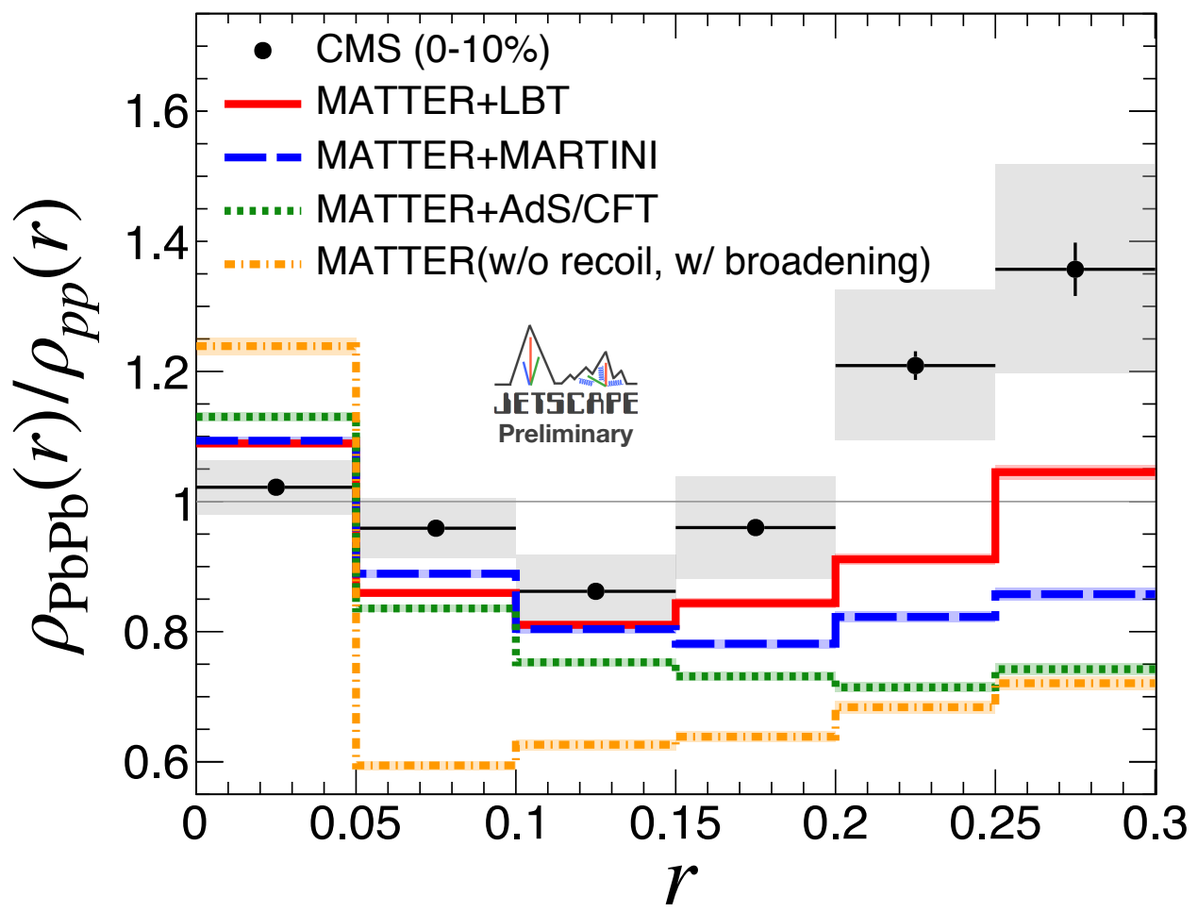



**note: self-normalized observable**

**PbPb/pp**

CMS from PLB 730 (2014) 243

JETSCAPE, 2.76 TeV, PbPb : 0-5 % , anti-$k_{\rm T}$ $R = 0.3$, $p_{\rm T}^{\rm jet} > 100$ GeV, $0.3 < |\eta_{\rm jet}| < 2.0$, $p_{\rm T}^{\rm trk} > 1$ GeV



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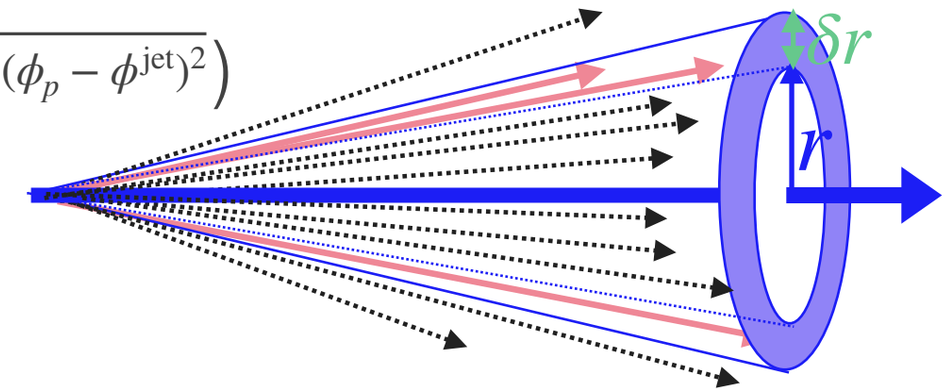
$$\rho(r) = \frac{1}{N_{\rm jet}} \sum_{\rm jet} \left[ \frac{1}{p_{\rm T}^{\rm jet}} \frac{\sum_{{\rm trk}\in(r-\delta r/2, r+\delta r/2)} p_{\rm T}^{\rm trk}}{\delta r} \right]$$

$$\left( r = \sqrt{(\eta_p - \eta^{\rm jet})^2 + (\phi_p - \phi^{\rm jet})^2} \right)$$

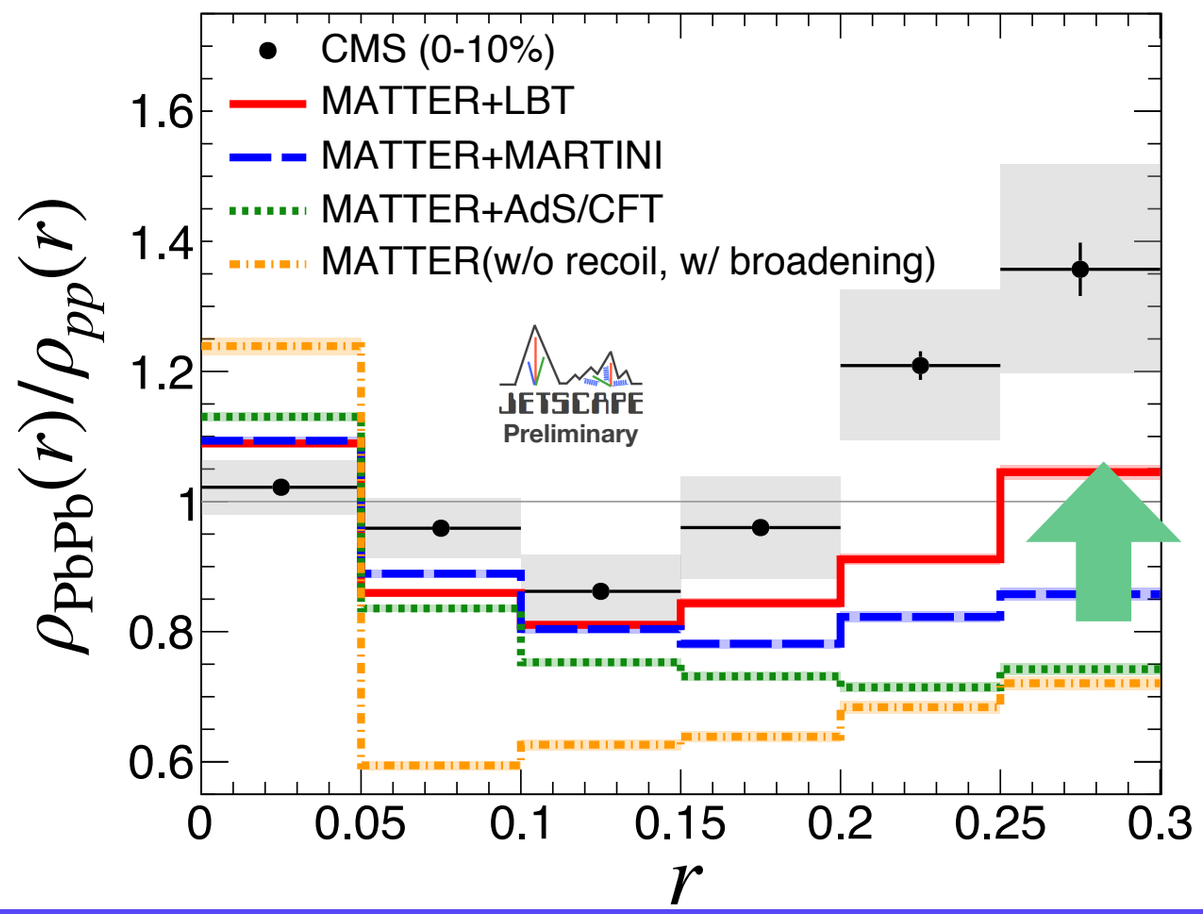



**note: self-normalized observable**

**PbPb/pp**

CMS from PLB 730 (2014) 243

JETSCAPE, 2.76 TeV, PbPb : 0-5 % , anti-$k_{\rm T}$ $R = 0.3$, $p_{\rm T}^{\rm jet} > 100$ GeV, $0.3 < |\eta_{\rm jet}| < 2.0$, $p_{\rm T}^{\rm trk} > 1$ GeV

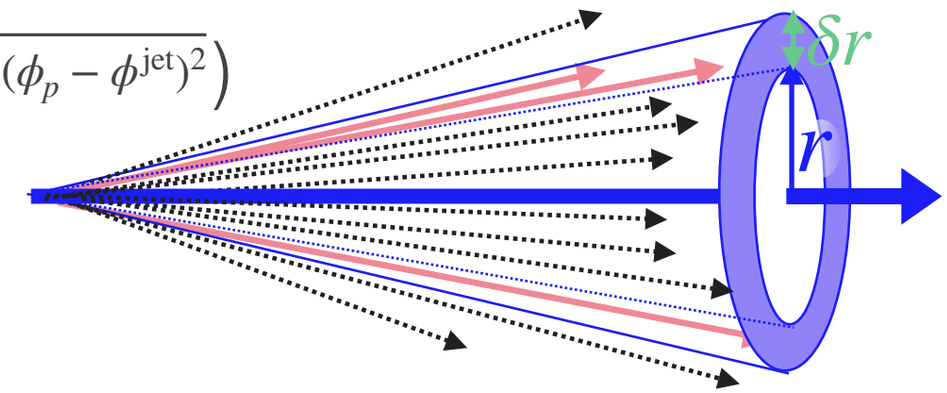



**Enhancement around the edge of jet cone due to recoils in LBT**

# Jet Shape

$$\rho(r) = \frac{1}{N_{\rm jet}} \sum_{\rm jet} \left[ \frac{1}{p_{\rm T}^{\rm jet}} \frac{\sum_{{\rm trk}\in(r-\delta r/2, r+\delta r/2)} p_{\rm T}^{\rm trk}}{\delta r} \right]$$

$$\left( r = \sqrt{(\eta_p - \eta^{\rm jet})^2 + (\phi_p - \phi^{\rm jet})^2} \right)$$

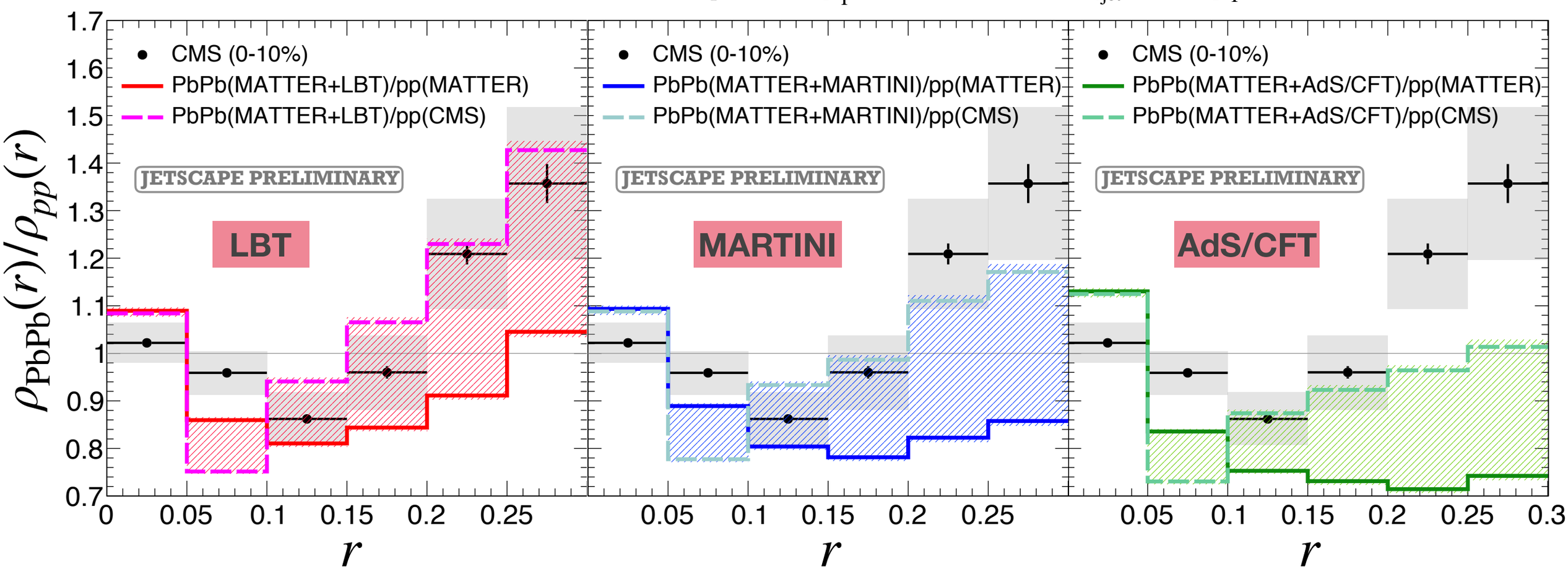



**note: self-normalized observable**

**PbPb/pp**

CMS from PLB 730 (2014) 243

JETSCAPE, 2.76 TeV, PbPb : 0-5 % , anti-$k_{\rm T}$ $R = 0.3, p_{\rm T}^{\rm jet} > 100$ GeV, $0.3 < |\eta_{\rm jet}| < 2.0, p_{\rm T}^{\rm trk} > 1$ GeV

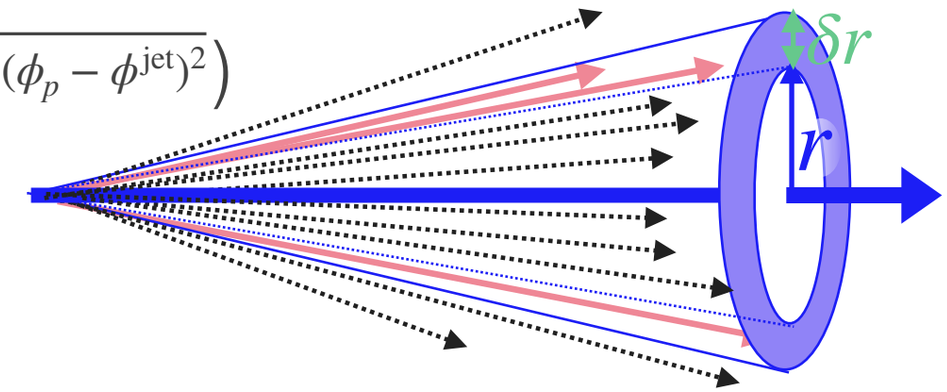



**pp baseline dependence**

# Jet Shape

$$\rho(r) = \frac{1}{N_{\rm jet}} \sum_{\rm jet} \left[ \frac{1}{p_{\rm T}^{\rm jet}} \frac{\sum_{{\rm trk}\in(r-\delta r/2, r+\delta r/2)} p_{\rm T}^{\rm trk}}{\delta r} \right]$$

$$\left( r = \sqrt{(\eta_p - \eta^{\rm jet})^2 + (\phi_p - \phi^{\rm jet})^2} \right)$$



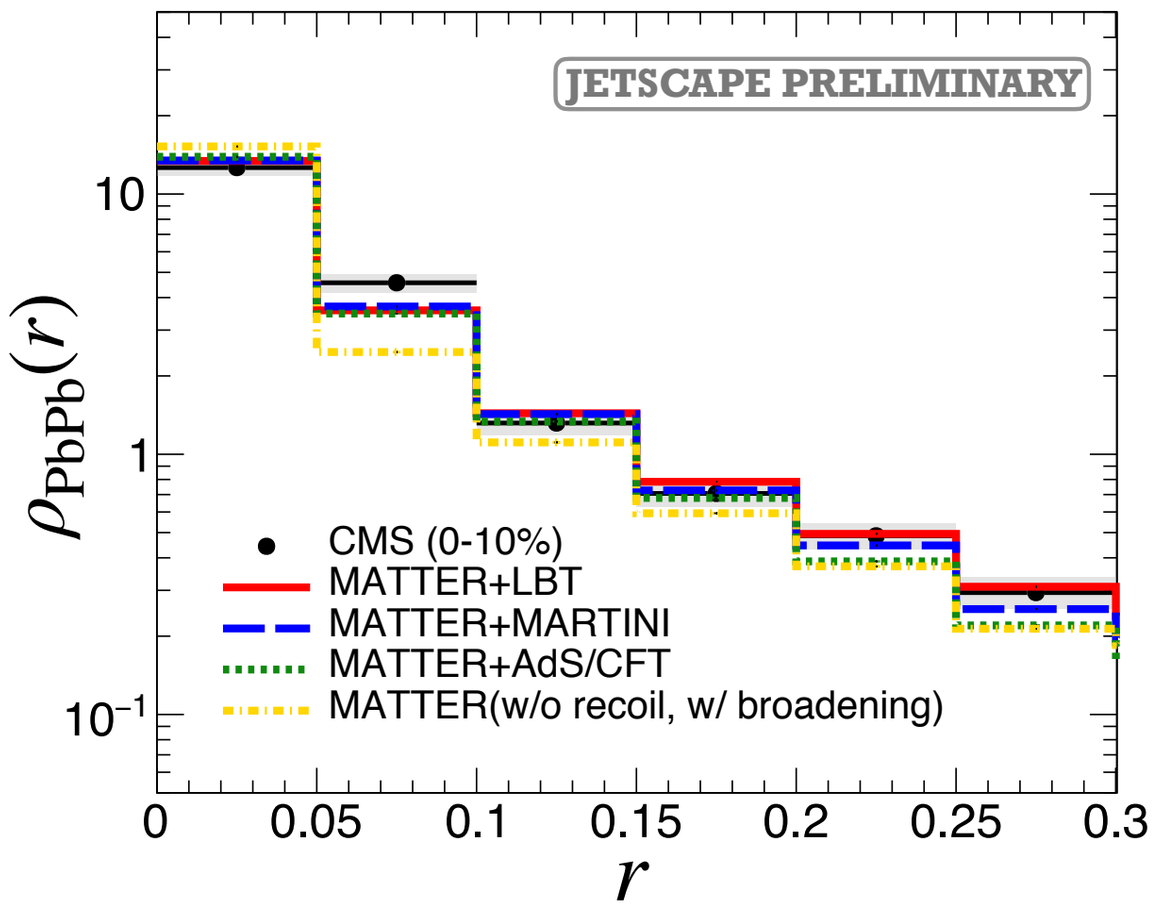

**note: self-normalized observable**

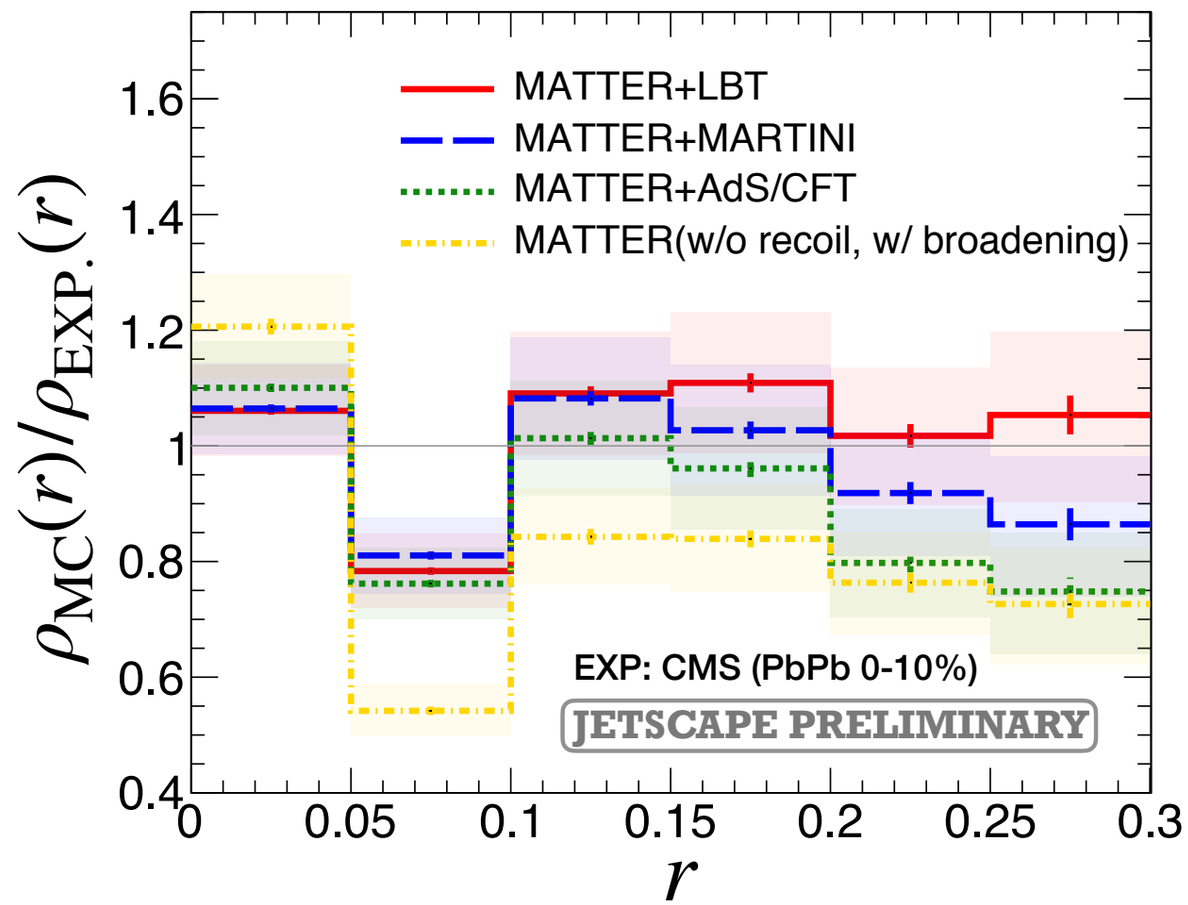
**PbPb**

*Parameters in Pythia8.230 are default

CMS from PLB 730 (2014) 243

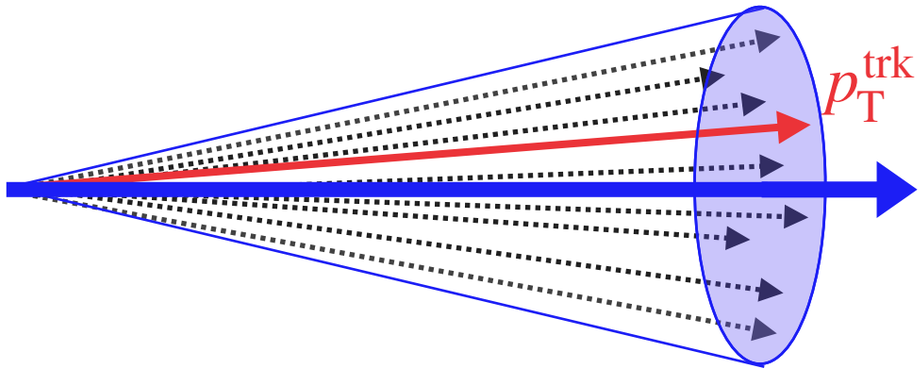
JETSCAPE, 2.76 TeV, PbPb : 0-5 % , anti-$k_{\rm T}$ $R = 0.3$, $p_{\rm T}^{\rm jet} > 100$ GeV, $0.3 < |\eta_{\rm jet}| < 2.0$, $p_{\rm T}^{\rm trk} > 1$ GeV



# Jet Fragmentation Function (PbPb)

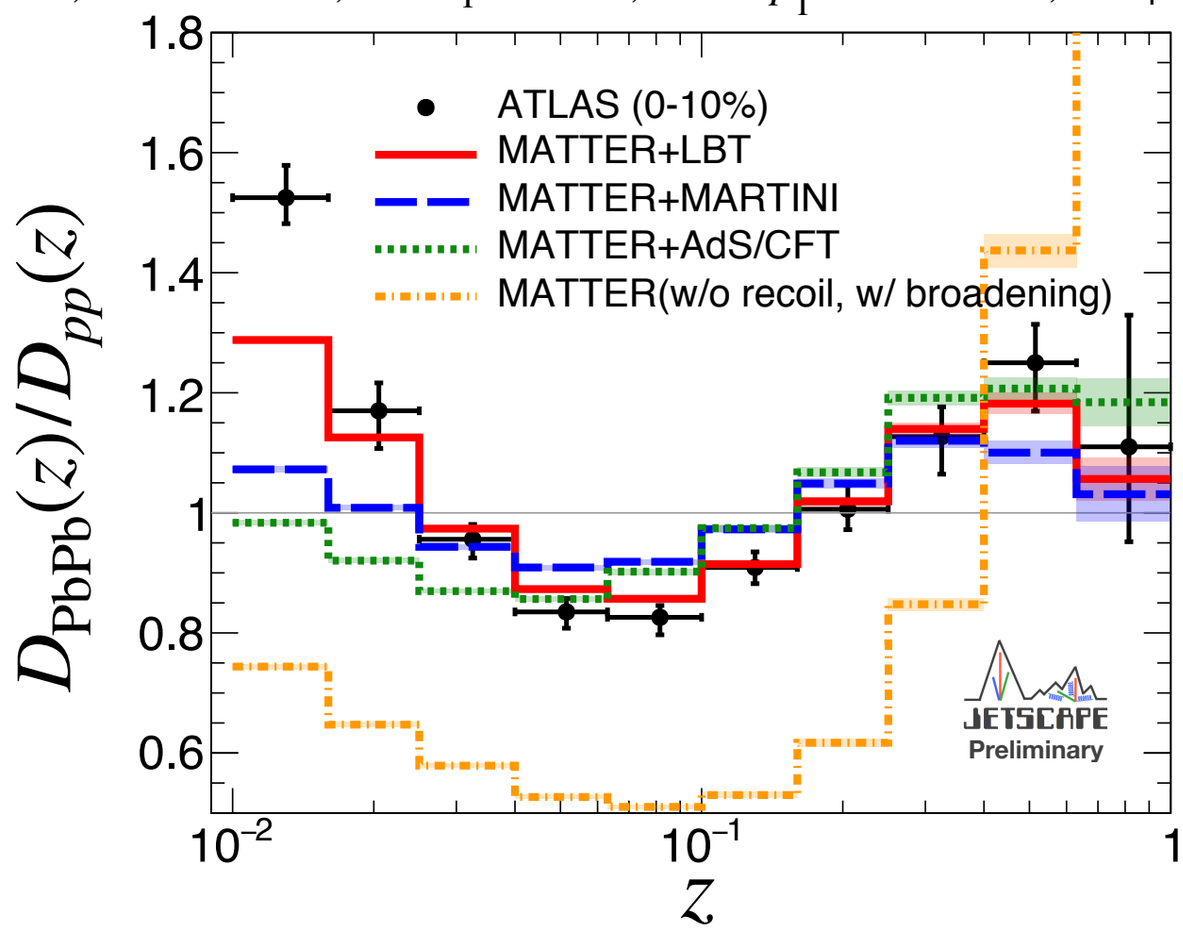
$$D(z) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{trk}}}{dz} \qquad \left( z = p_{\text{T}}^{\text{trk}} / p_{\text{T}}^{\text{jet}} \right)$$




**PbPb/pp**

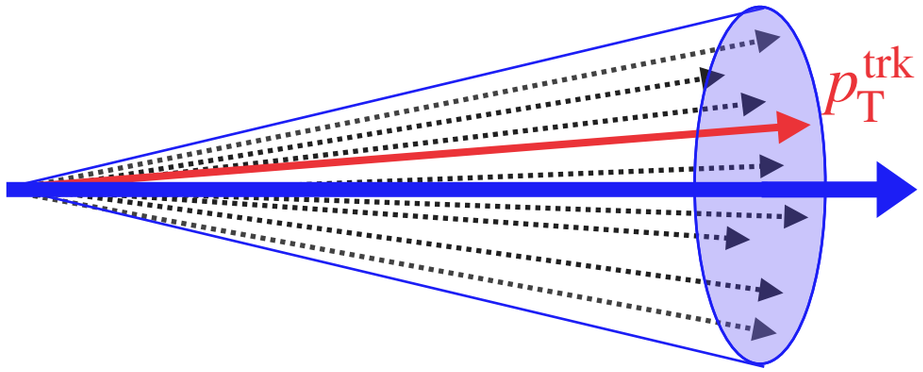
ATLAS from EPJ C77 (2017) 379

JETSCAPE, 2.76 TeV, PbPb : 0-5 % , anti-$k_{\text{T}}$ $R = 0.4$, $100 < p_{\text{T}}^{\text{jet}} < 398$ GeV, $0 < |Y_{\text{jet}}| < 2.1$, $p_{\text{T}}^{\text{trk}} > 1$ GeV



# Jet Fragmentation Function (PbPb)

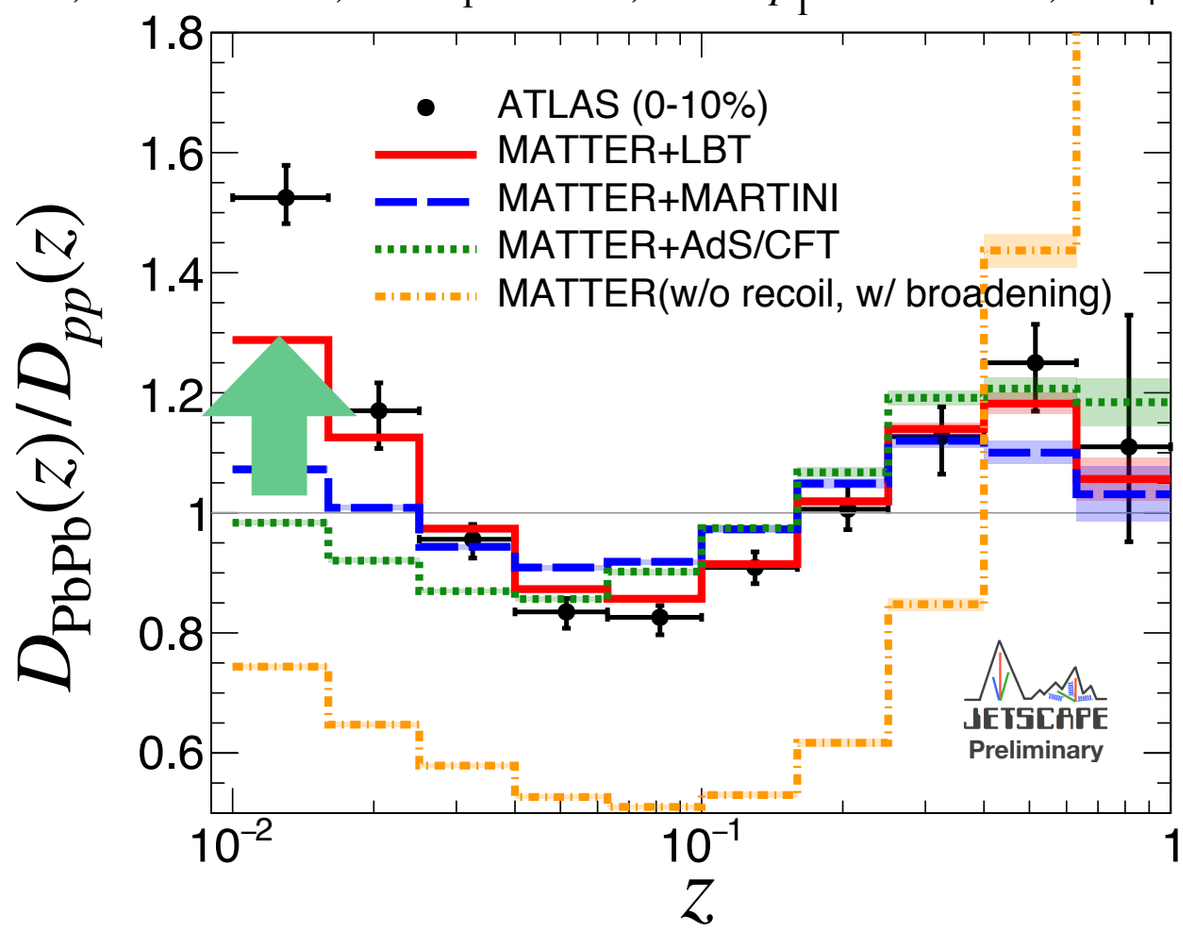
$$D(z) = \frac{1}{N_{\rm jet}} \frac{dN_{\rm trk}}{dz} \qquad \left( z = p_{\rm T}^{\rm trk} / p_{\rm T}^{\rm jet} \right)$$




**PbPb/pp**

ATLAS from EPJ C77 (2017) 379

JETSCAPE, 2.76 TeV, PbPb : 0-5 % , anti-$k_{\rm T}$ $R = 0.4$, $100 < p_{\rm T}^{\rm jet} < 398$ GeV, $0 < |Y_{\rm jet}| < 2.1$, $p_{\rm T}^{\rm trk} > 1$ GeV




**Small-$z$ enhancement due to recoils in LBT**