WAYNE STATE UNIVERSITY

NSF

JETSCAPE Workshop 2019

Jet substructure modification in multi-stage jet evolution with JETSCAPE

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for the JETSCAPE Collaboration

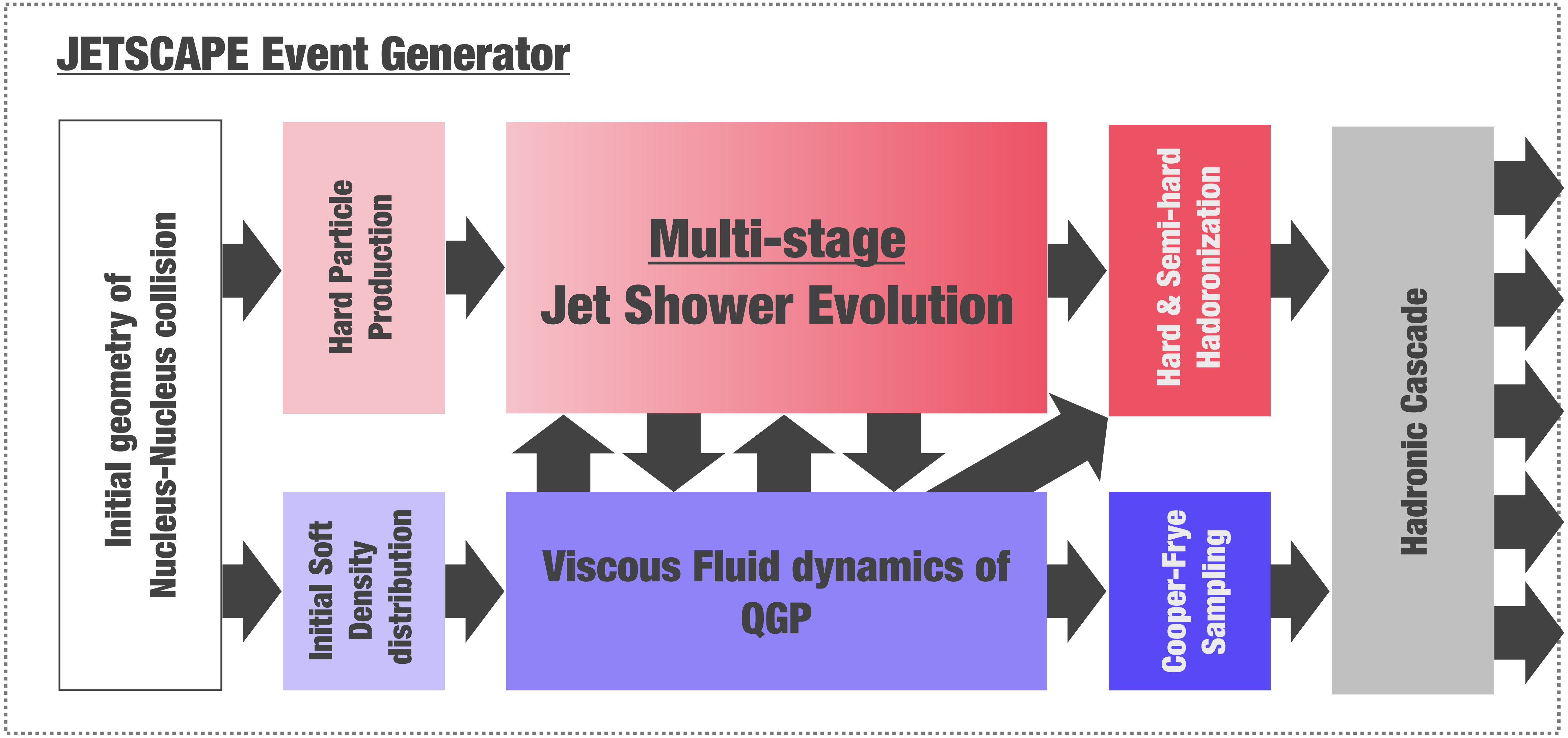
JETSCAPE

Texas A&M University, January 12th 2019

JETSCAPE

- **Package of MC event generator for heavy ion collision**
  - Current version, JETSCAPE 1.0 available at https://github.com/JETSCAPE
  - General, modular and highly extensible

Lecture by E.Khalaj and J. Putschke



JETSCAPE

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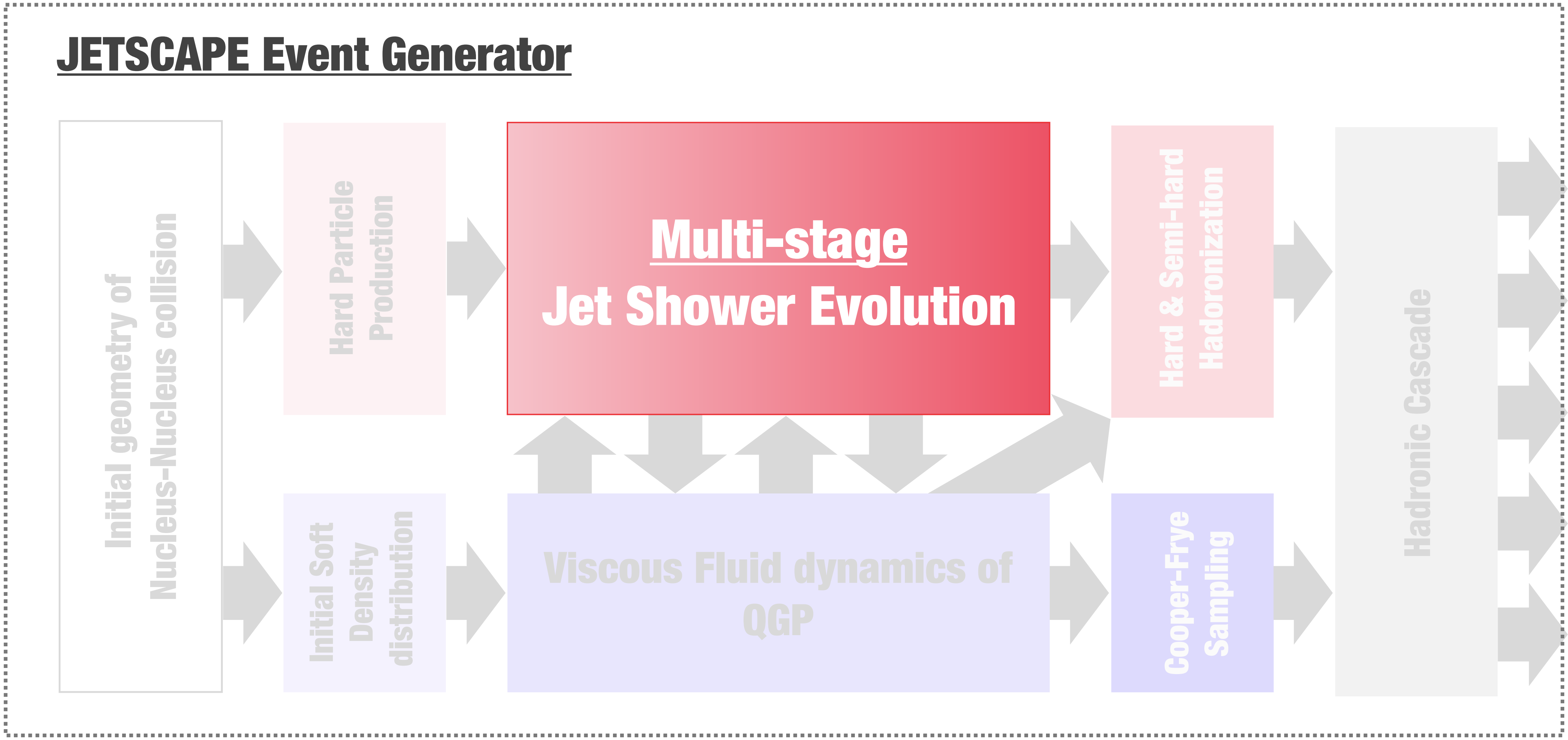
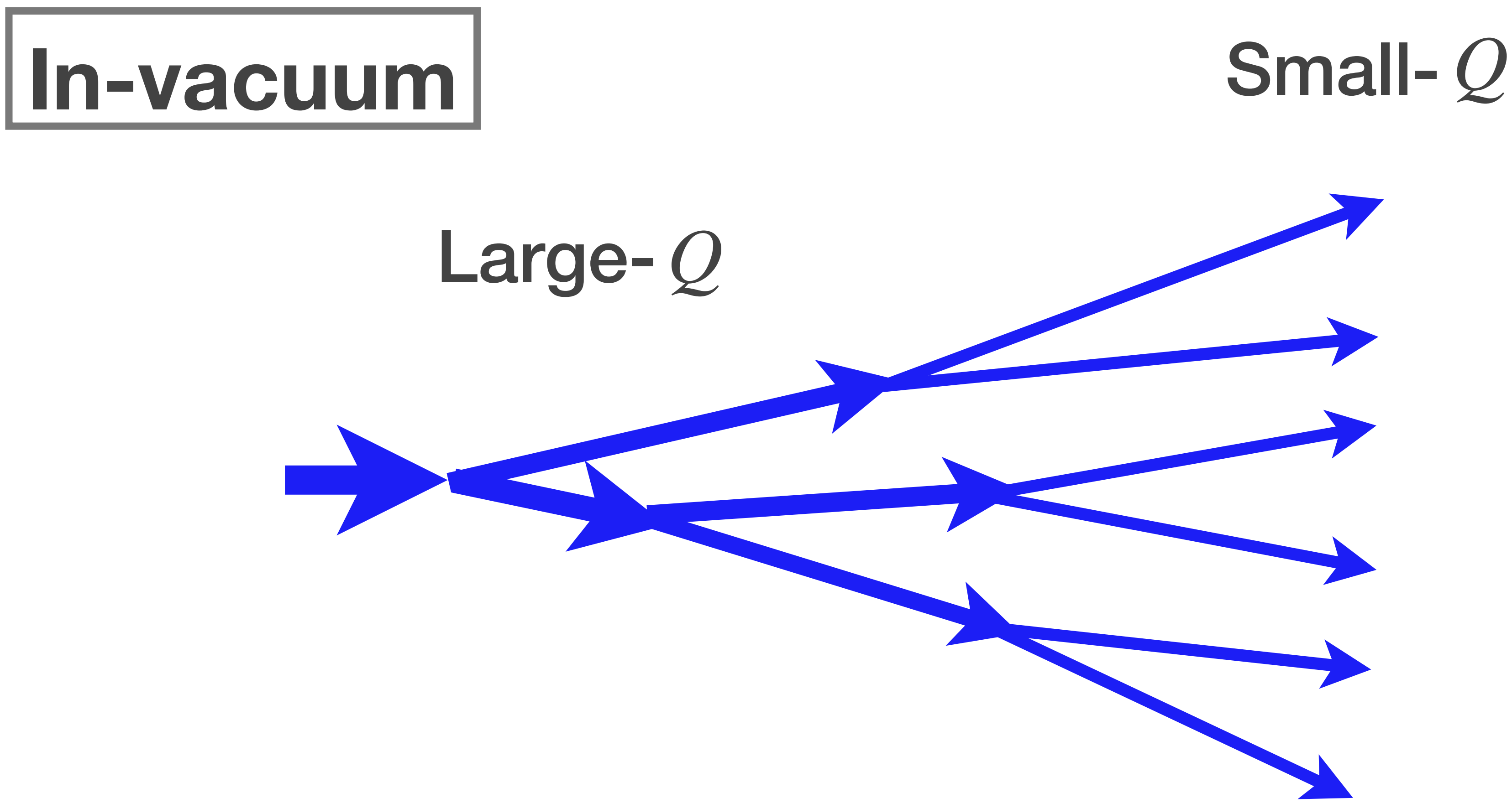


Multi-stage jet evolution in JETSCAPE

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



Q^2: virtuality (off-shellness)

- **Virtuality ordered splitting in vacuum**

Multi-stage jet evolution in JETSCAPE

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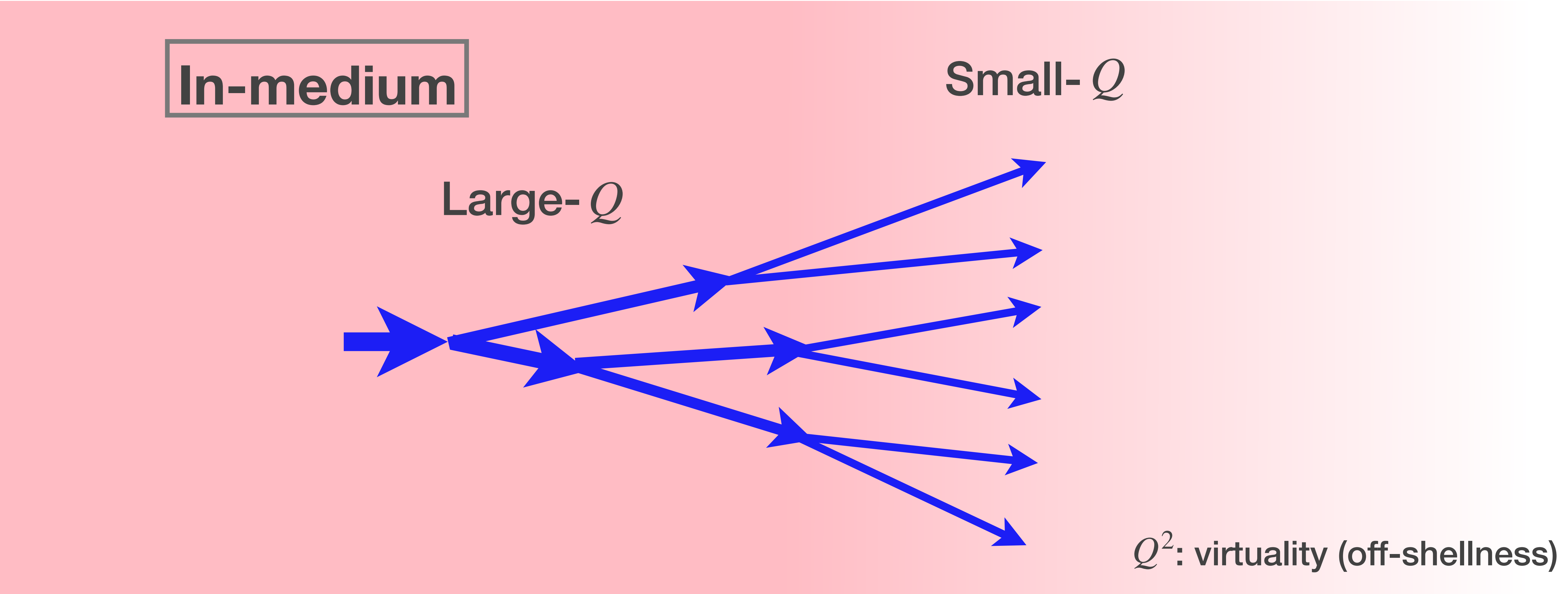

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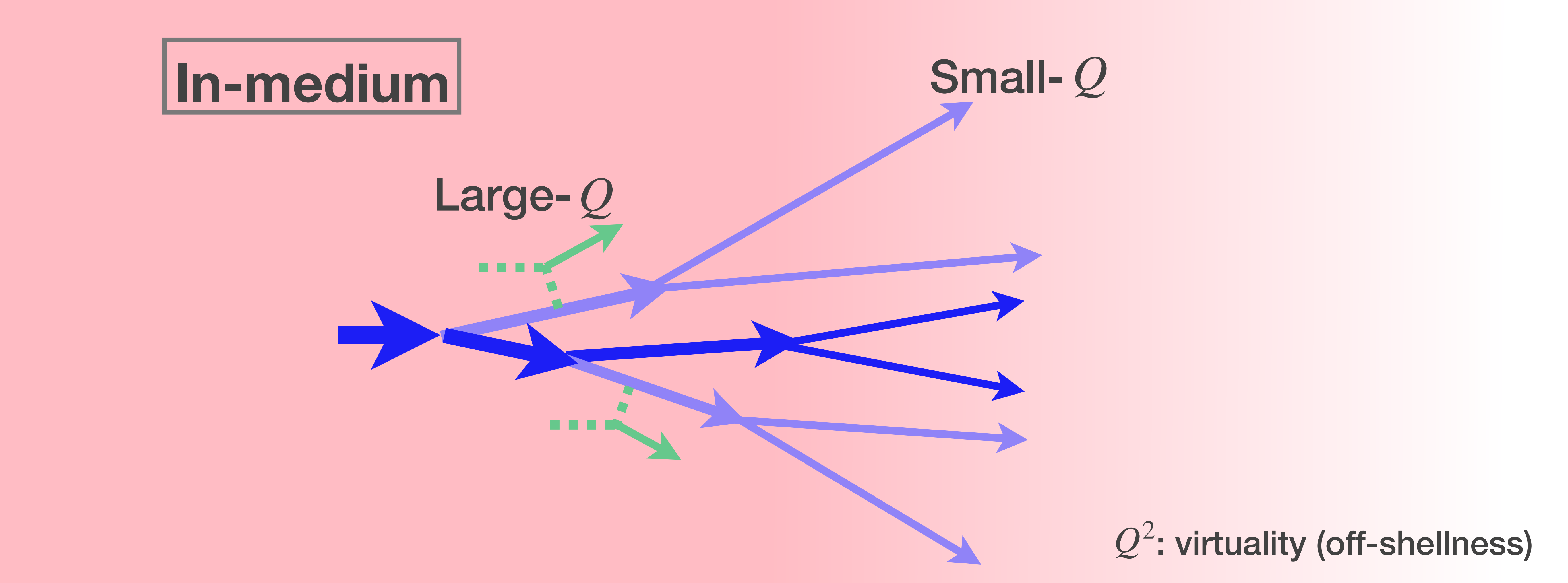

- Virtuality ordered splitting in vacuum
- **Large-** Q ⟶ **Medium effect on the top of in-vacuum splitting**

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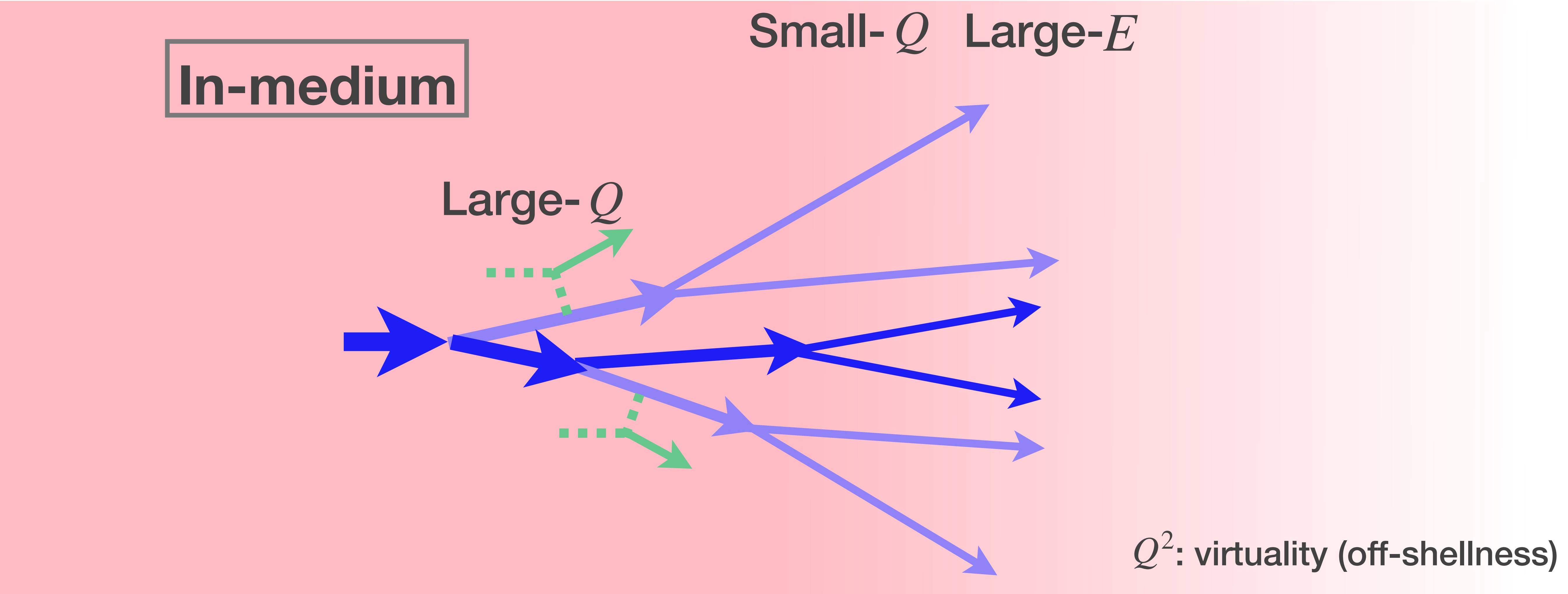

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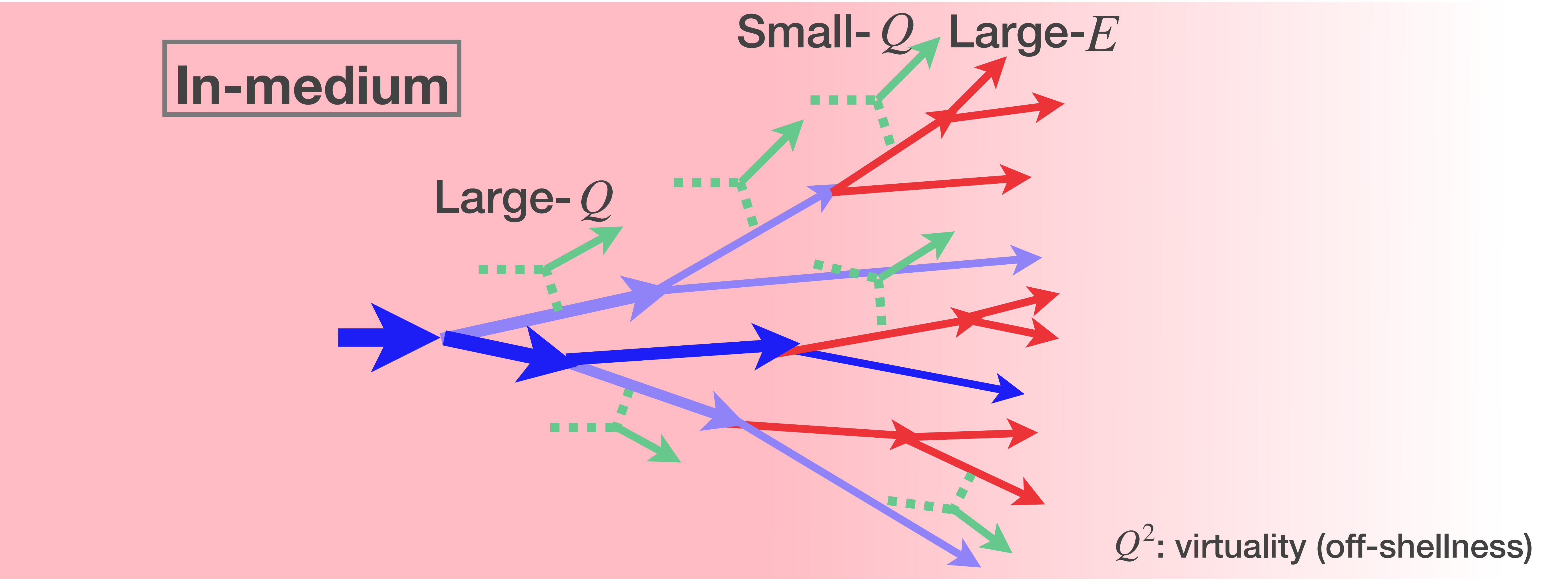

- Virtuality ordered splitting in vacuum
- Large-Q ⟶ Medium effect on the top of in-vacuum splitting
- **Small-Q , Large-E ⟶ Splitting driven almost purely by medium effect**

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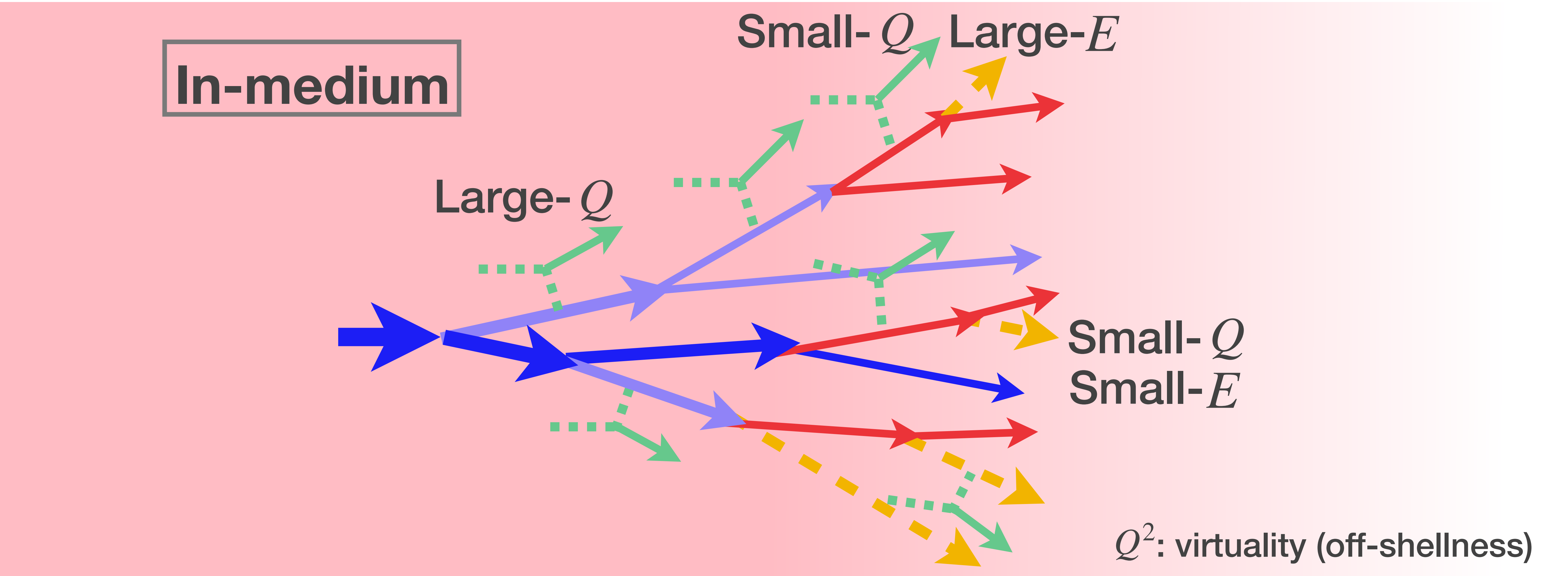

- Virtuality ordered splitting in vacuum
- Large-Q ⟶ Medium effect on the top of in-vacuum splitting
- Small-Q , Large-E ⟶ Splitting driven almost purely by medium effect
- **Small-Q , Small-E ⟶ Energy-momentum diffusion into medium**

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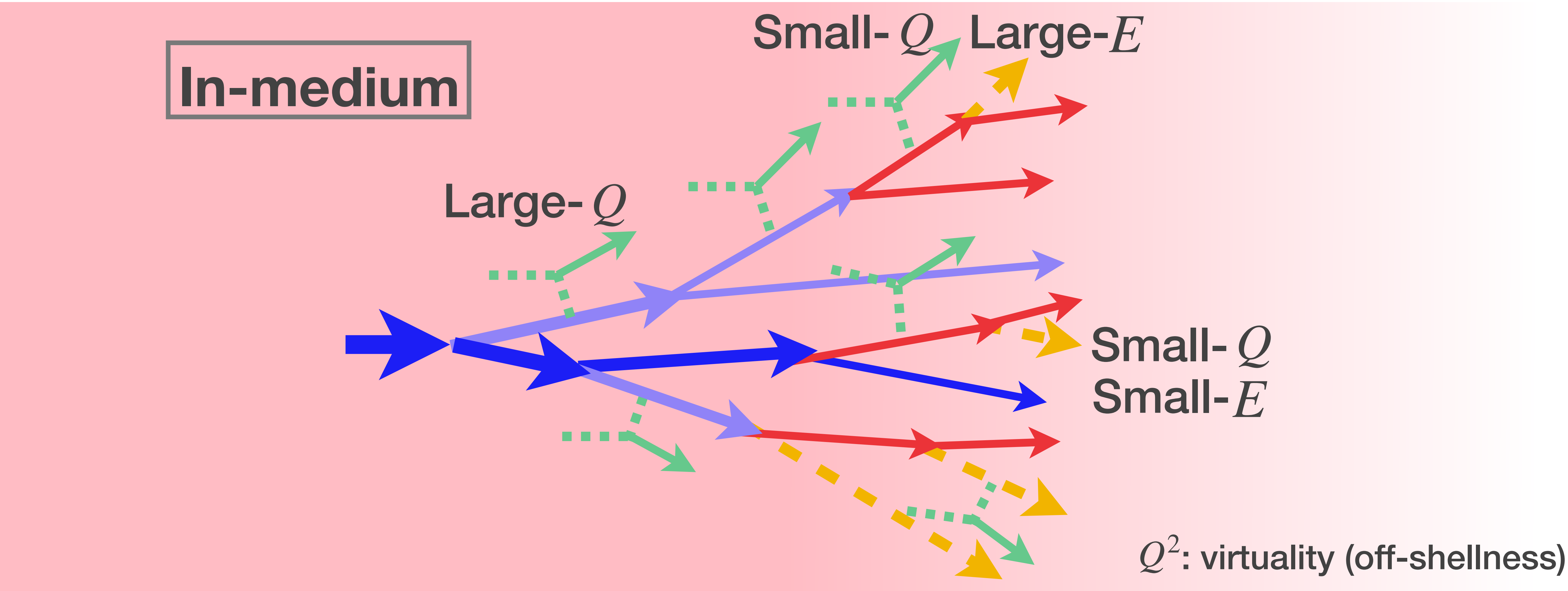

- Virtuality ordered splitting in vacuum
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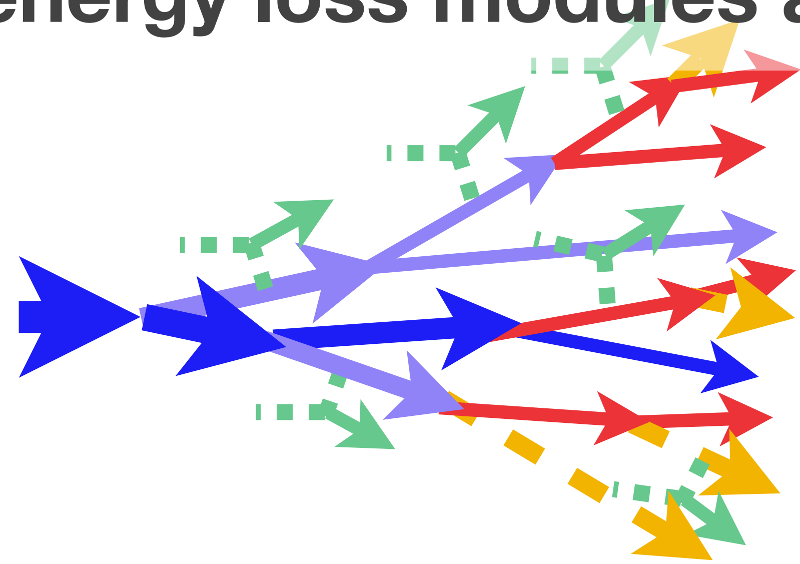
- Small- Q , Large- E ⟶ Splitting driven almost purely by medium effect
- Small- Q , Small- E ⟶ Energy-momentum diffusion into medium

No single model can describe all stages of jet evolution

Multi-stage jet evolution in JETSCAPE

- **Jet energy loss modules and their transition in JETSCAPE**



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

Multi-stage jet evolution in JETSCAPE

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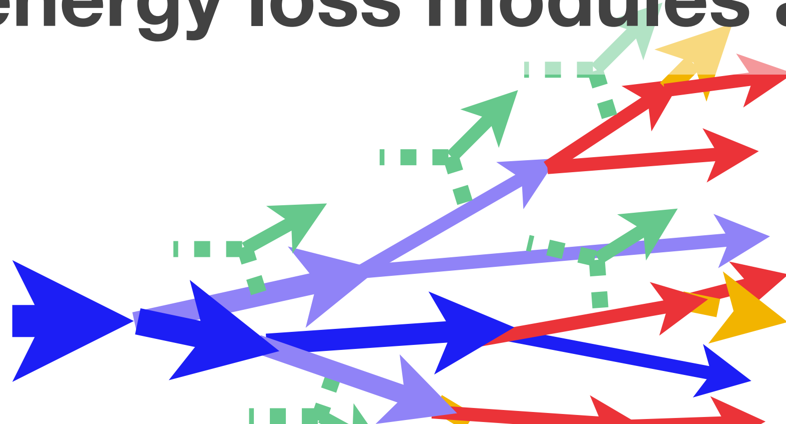

Virtuality separation scale: Q_0

Switching between modules for parton by parton

Large-$Q\,(>Q_0)$ ⟷ Small-$Q\,(<Q_0)$

MATTER

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

Radiation dominated
Virtuality ordered splitting

Higher Twist Formalism

Large-E

LBT

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

MARTINI

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

Scattering dominated
On-shell parton transport

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Chesler, Rajagopal(14, 15) Pablos, et al.(15, 16, 17)

Diffusion into medium

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

Multi-stage jet evolution in JETSCAPE

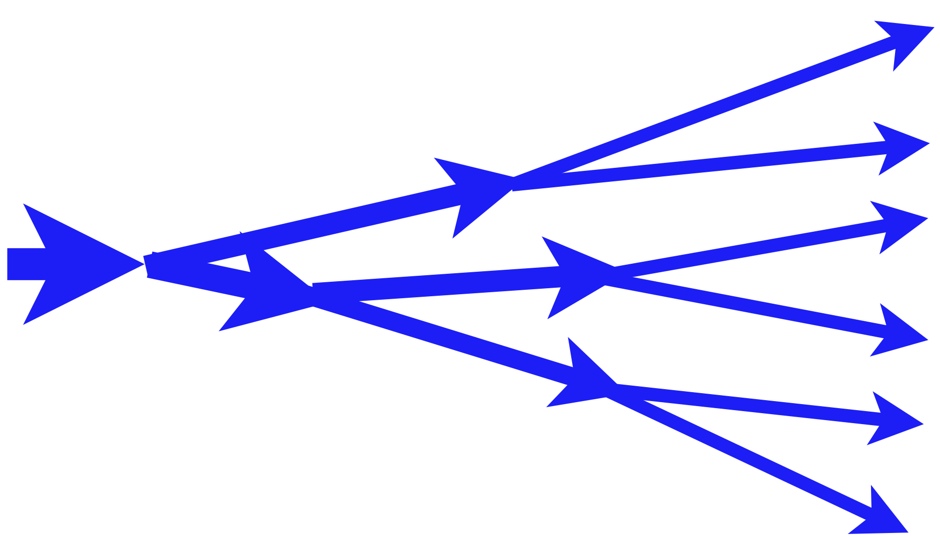
- **Jet substructure observables**
  - Jet shape (angular structure)
  - Jet fragmentation distribution (momentum distribution)
  - Sensitive to details of jet energy propagation and dissipation

  jet $R_{\rm AA}$, single hadron $R_{\rm AA}$, jet v_2, hadron v_2 → **Talk by C. Park**

- **Purpose of this study**
  - Demonstrate results from multi-stage jet evolution in JETSCAPE
  - Comparison among different module settings (**MATTER+LBT**, **MATTER+MARTINI**, **MATTER+AdS/CFT**, **etc.**)
  - Fine tuning of parameters both for pp and for AA are not done yet

Simulation for pp collisions with JETSCAPE

- **Settings in simulations for pp collisions**



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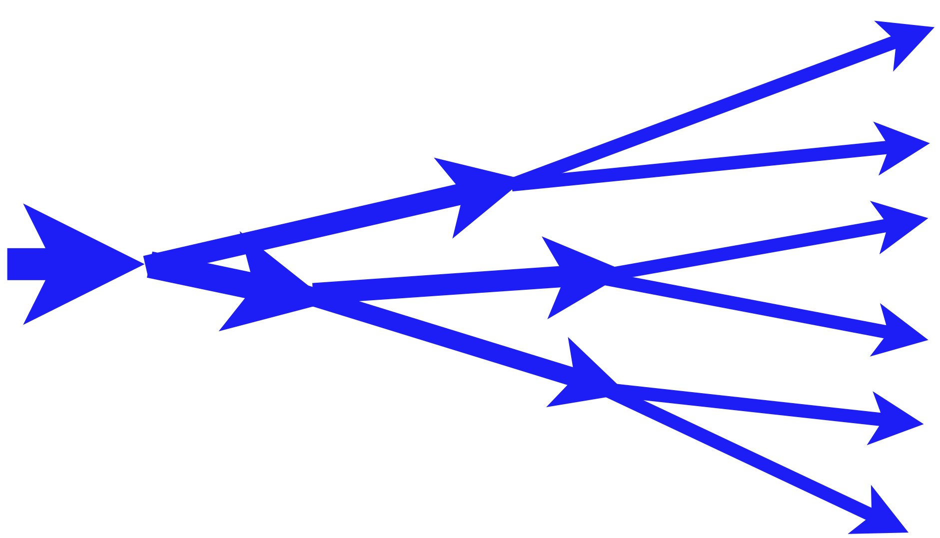
- **Settings in simulations for pp collisions**

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



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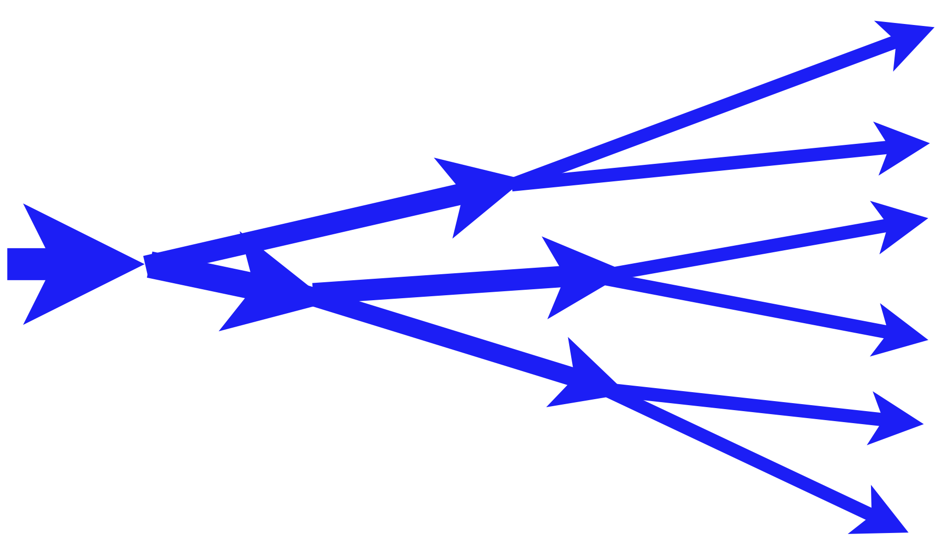

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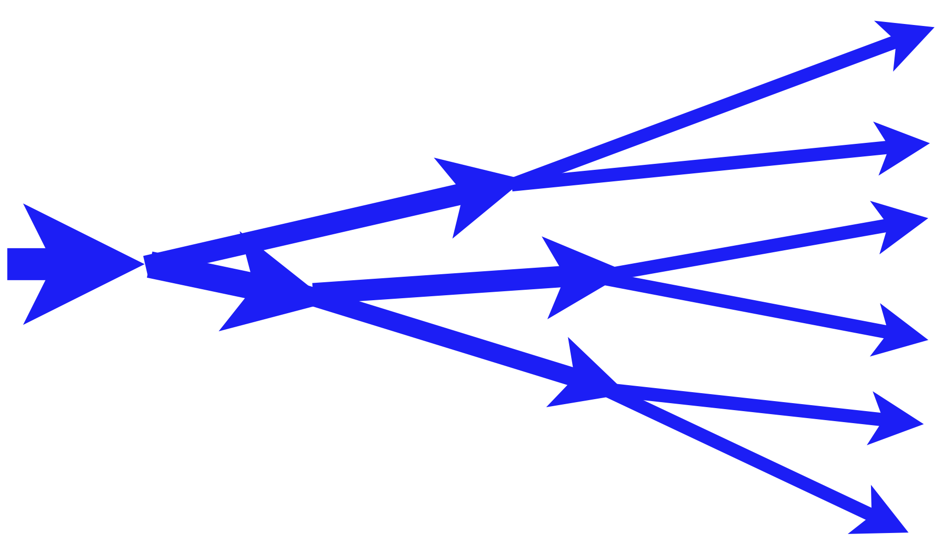

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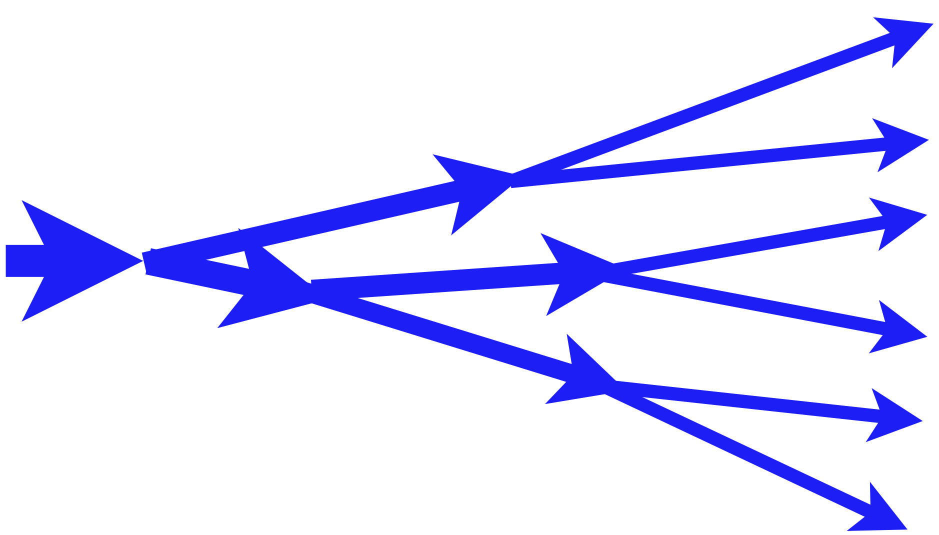

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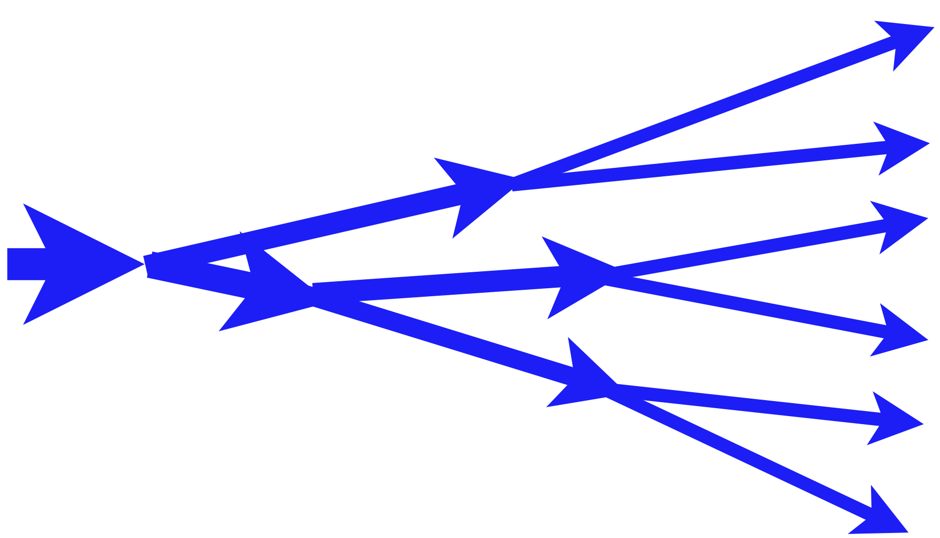
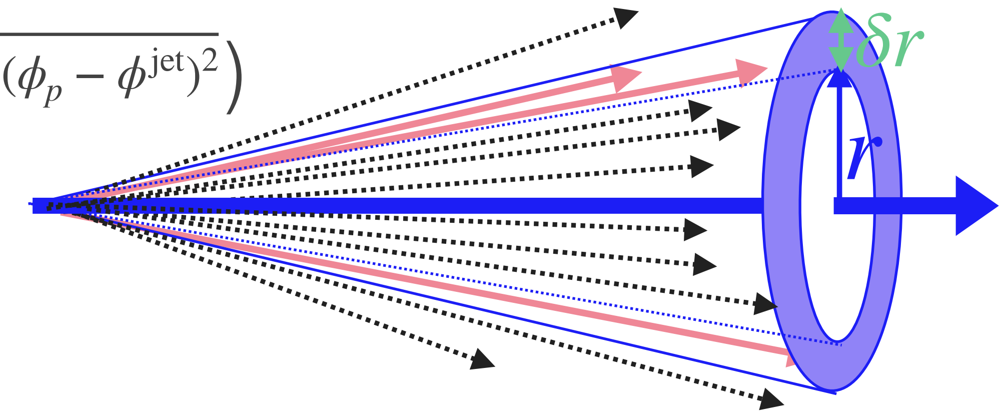


Jet Shape (pp)

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

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

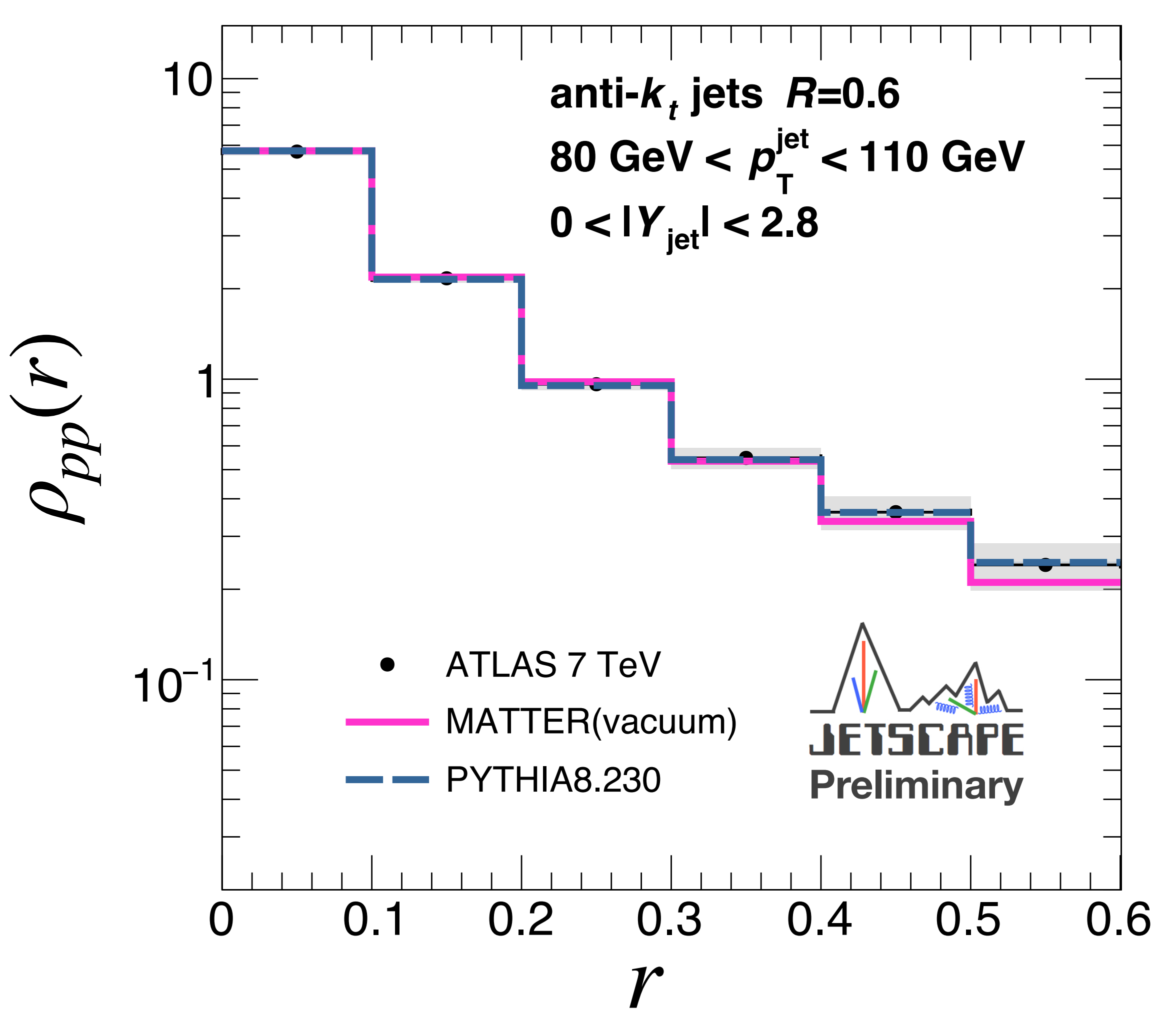


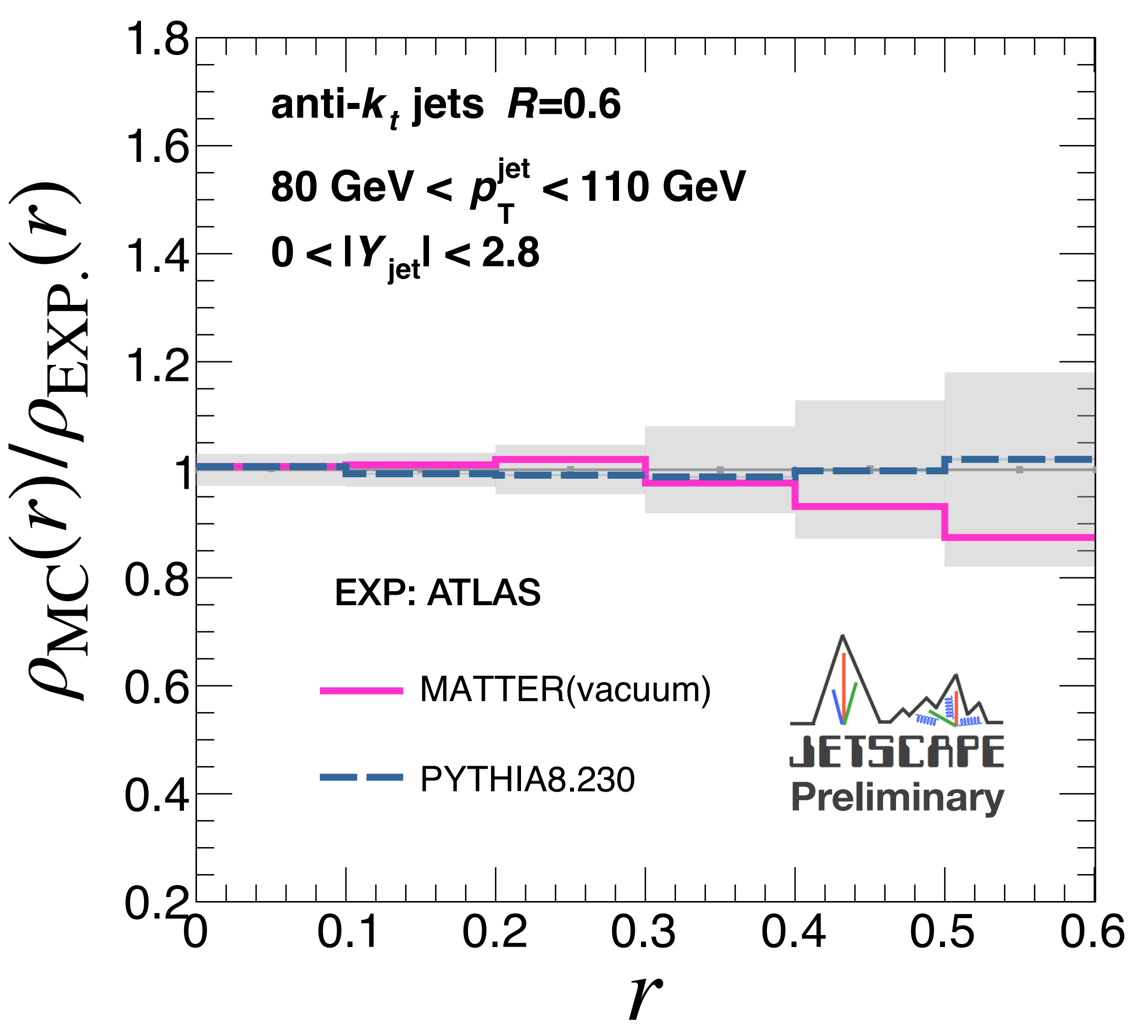
note: self-normalized observable

7 TeV

*Parameters in Pythia8.230 are default

ATLAS from PRD 83 (2011) 052003





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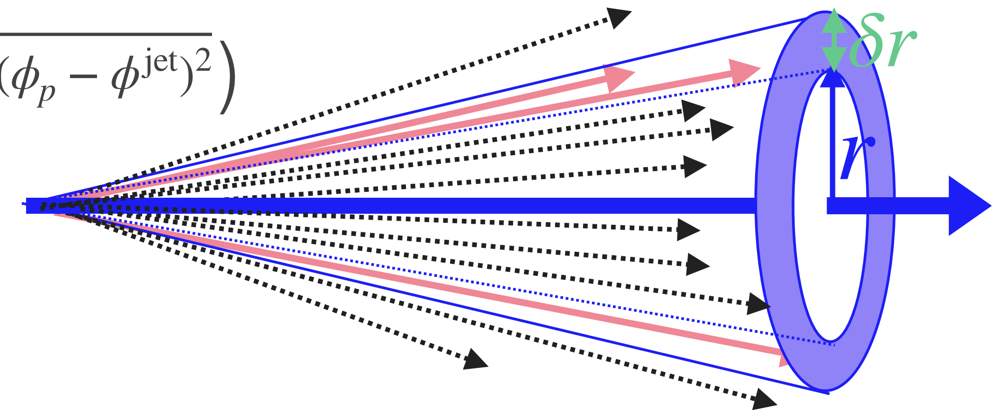

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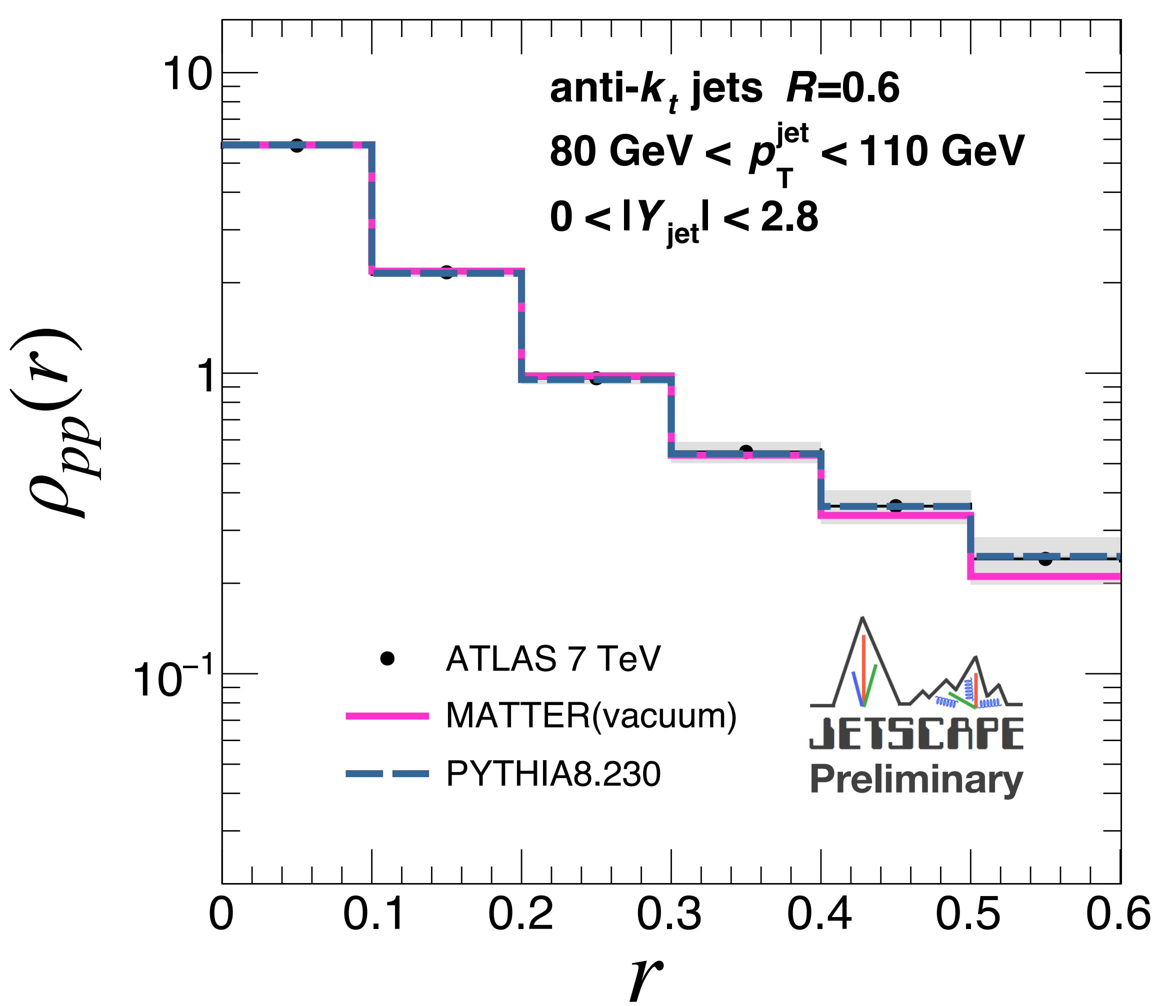

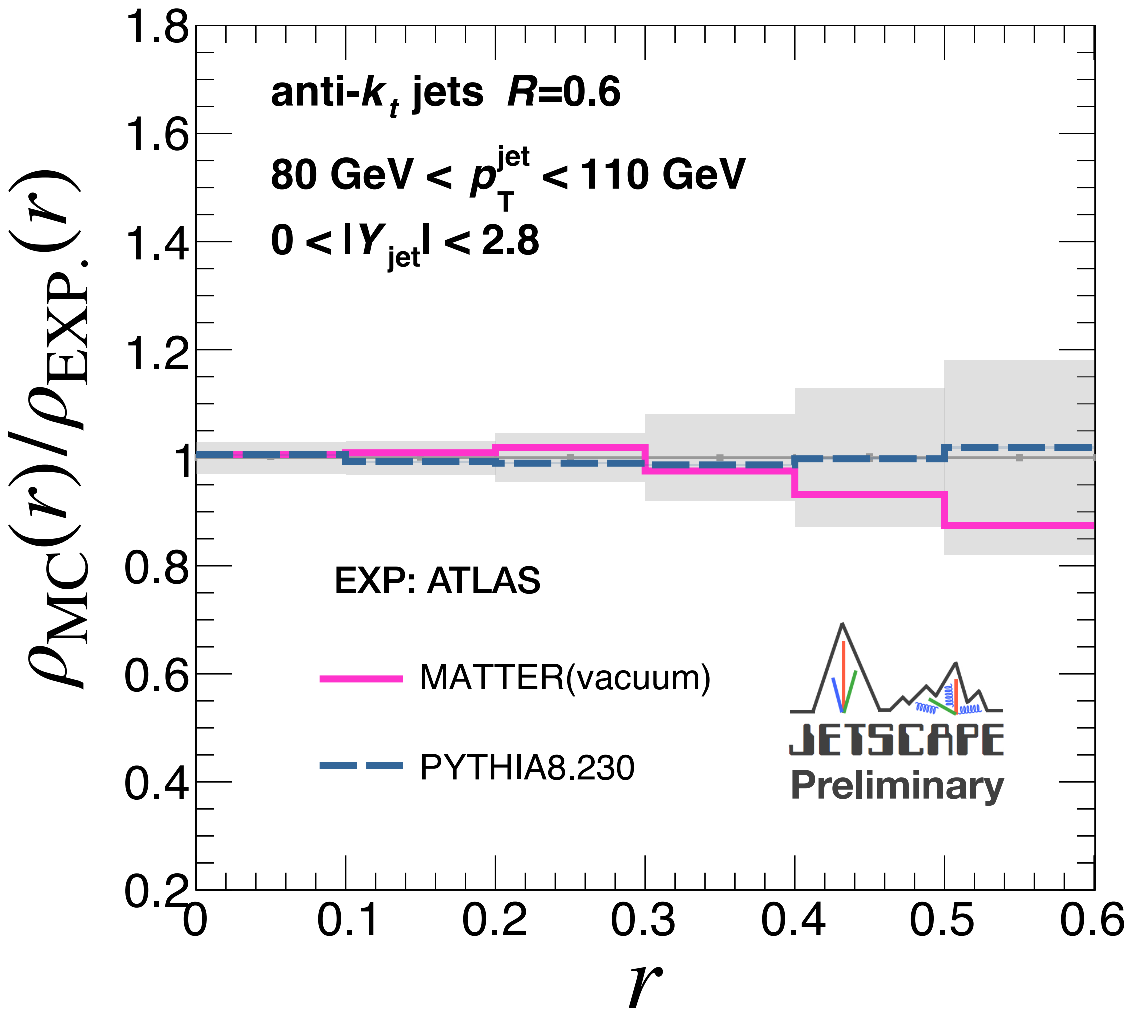

Very good agreement with experimental data

Jet Shape (pp)

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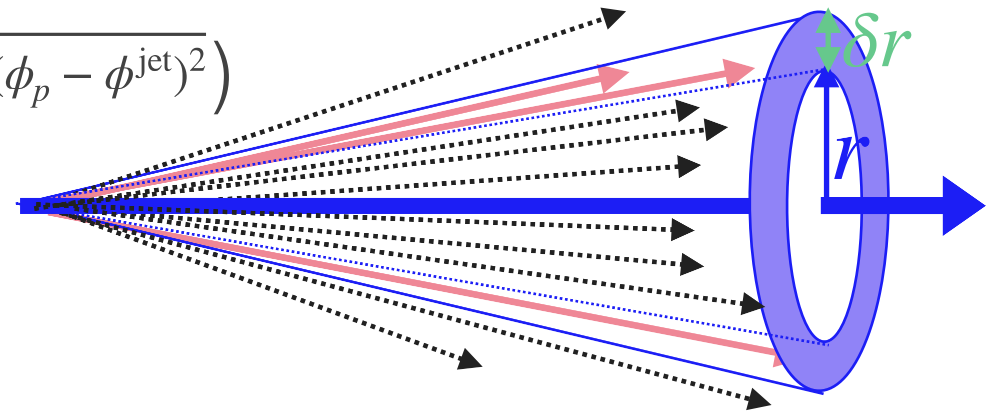
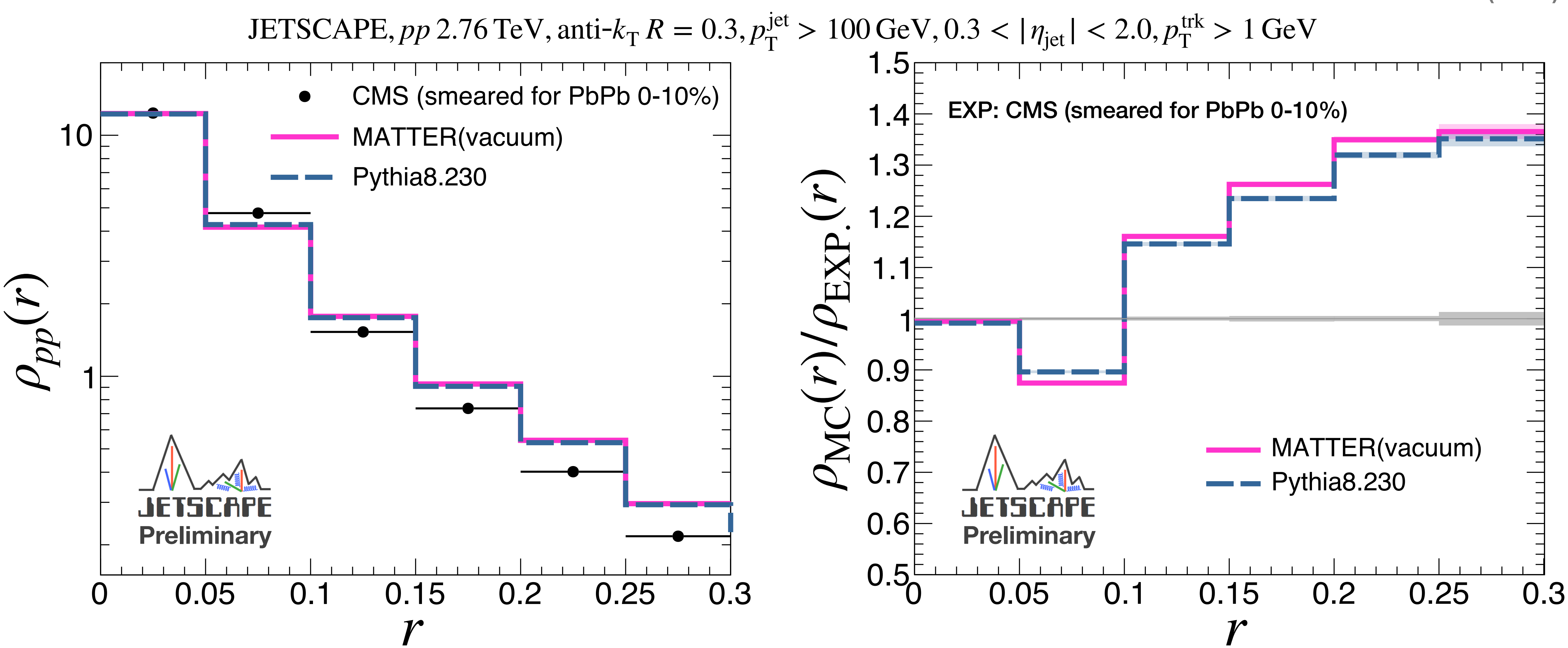


note: self-normalized observable

2.76 TeV

*Parameters in Pythia8.230 are default

CMS from PLB 730 (2014) 243



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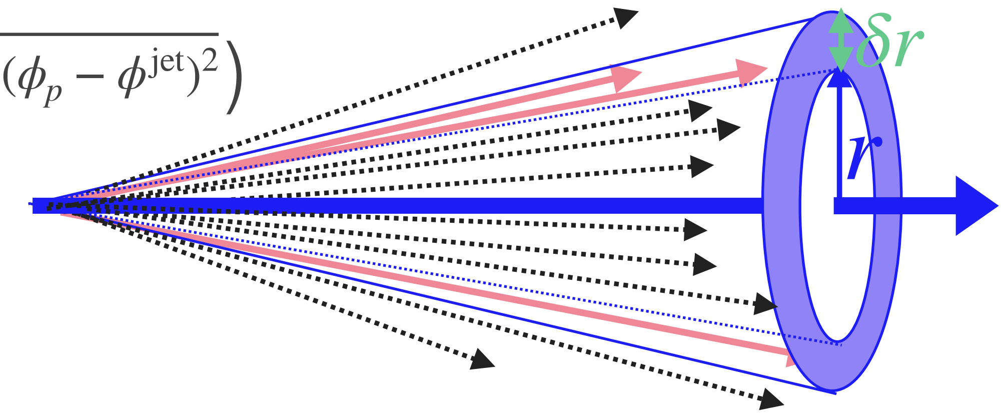

note: <u>self-normalized observable</u>

2.76 TeV

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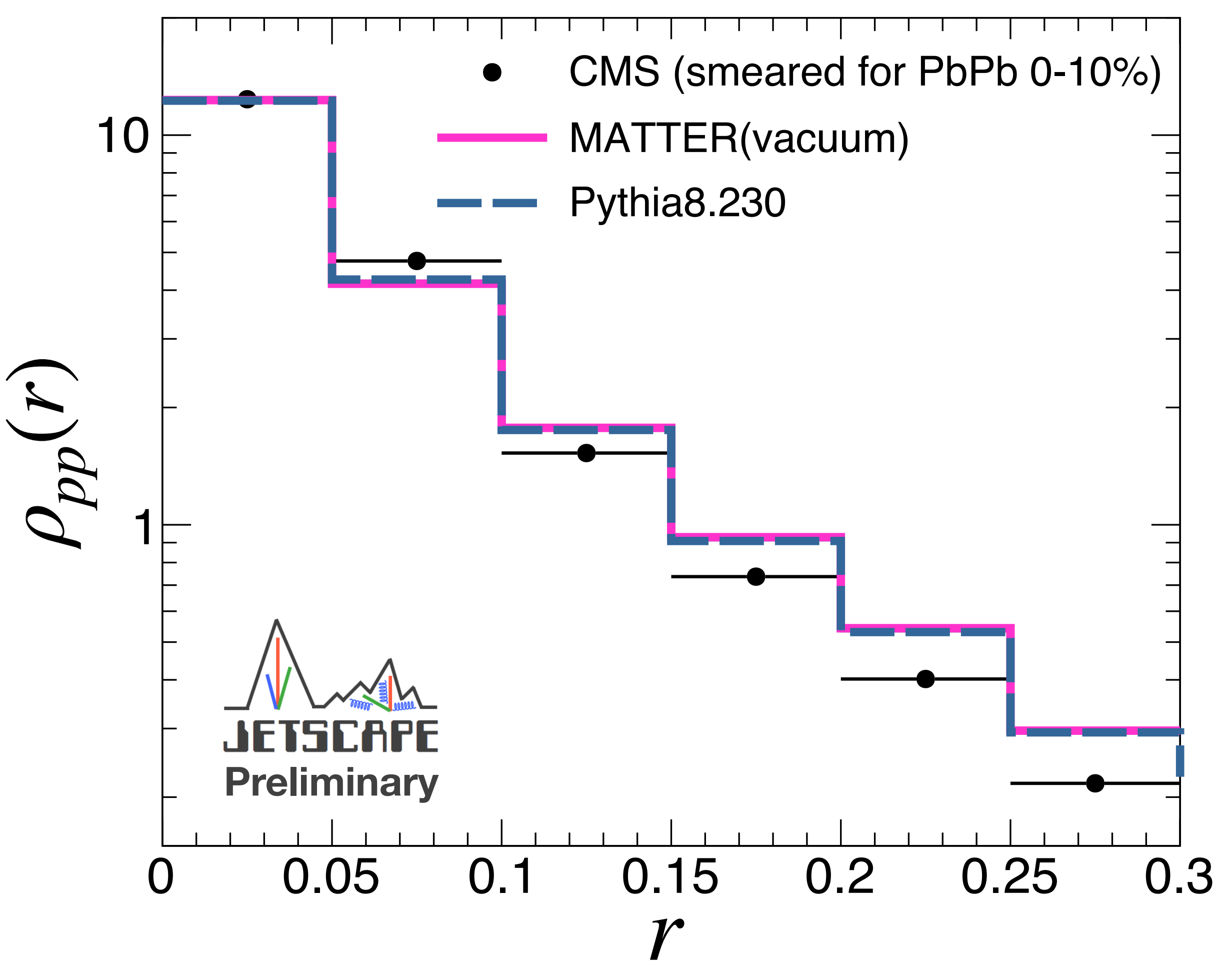
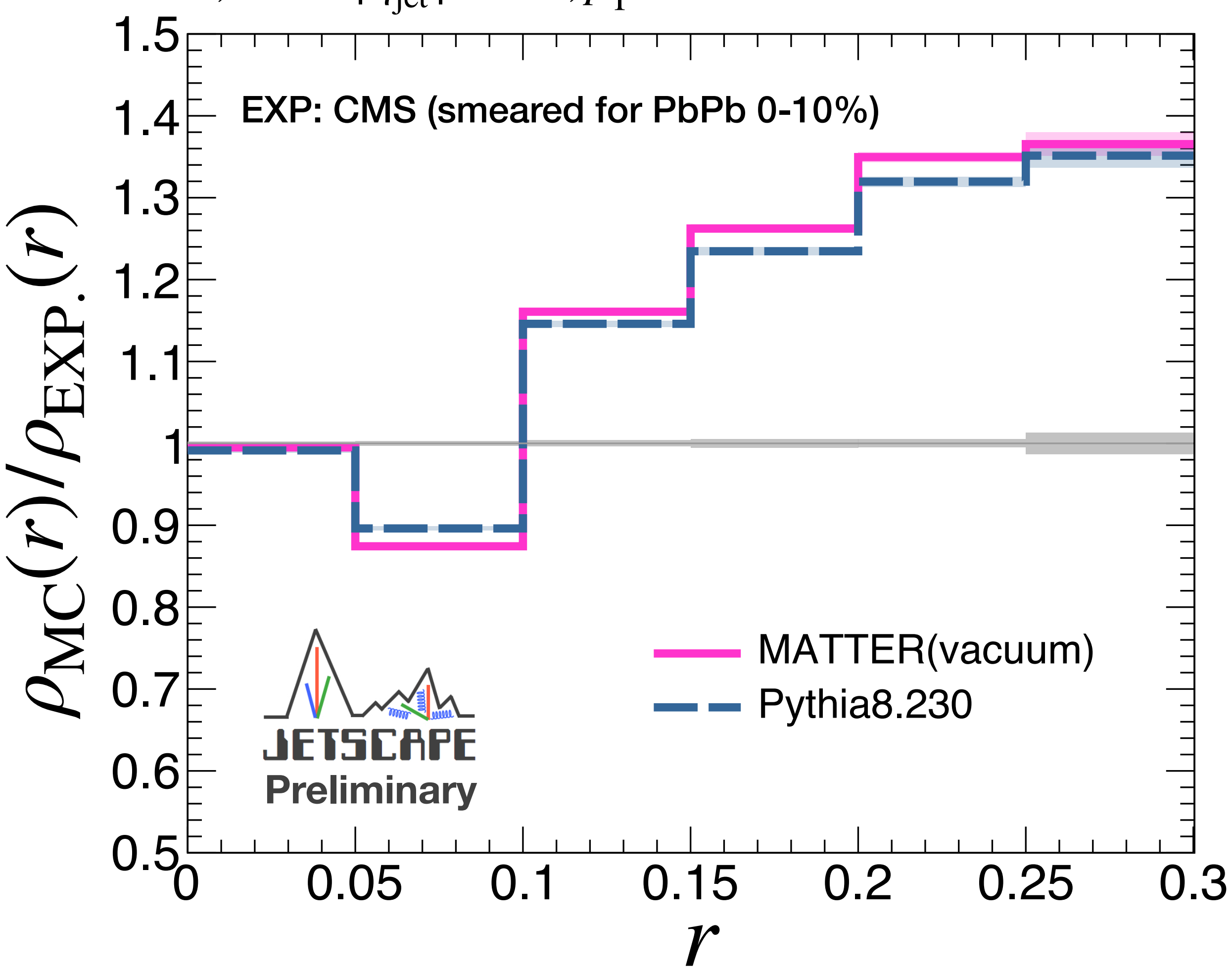
CMS from PLB 730 (2014) 243

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

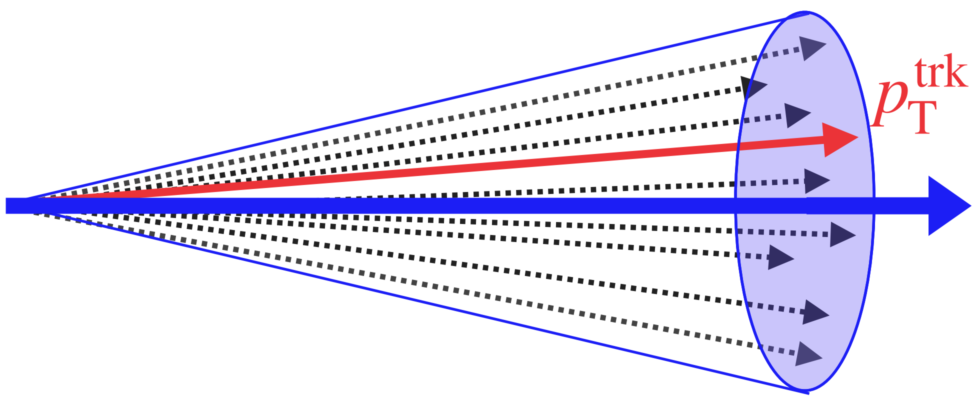




Similar behavior to default Pythia8

Jet Fragmentation Function (pp)

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

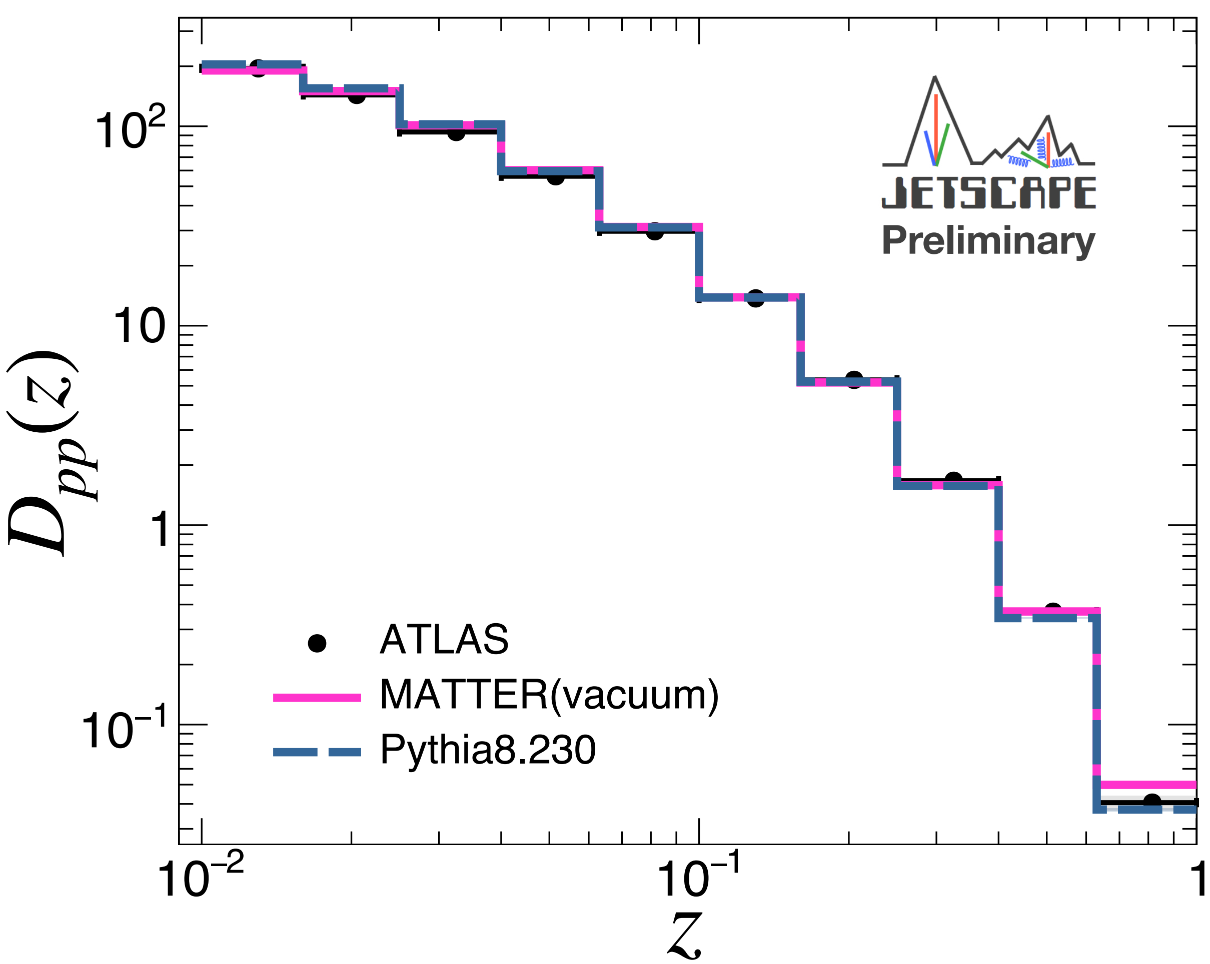


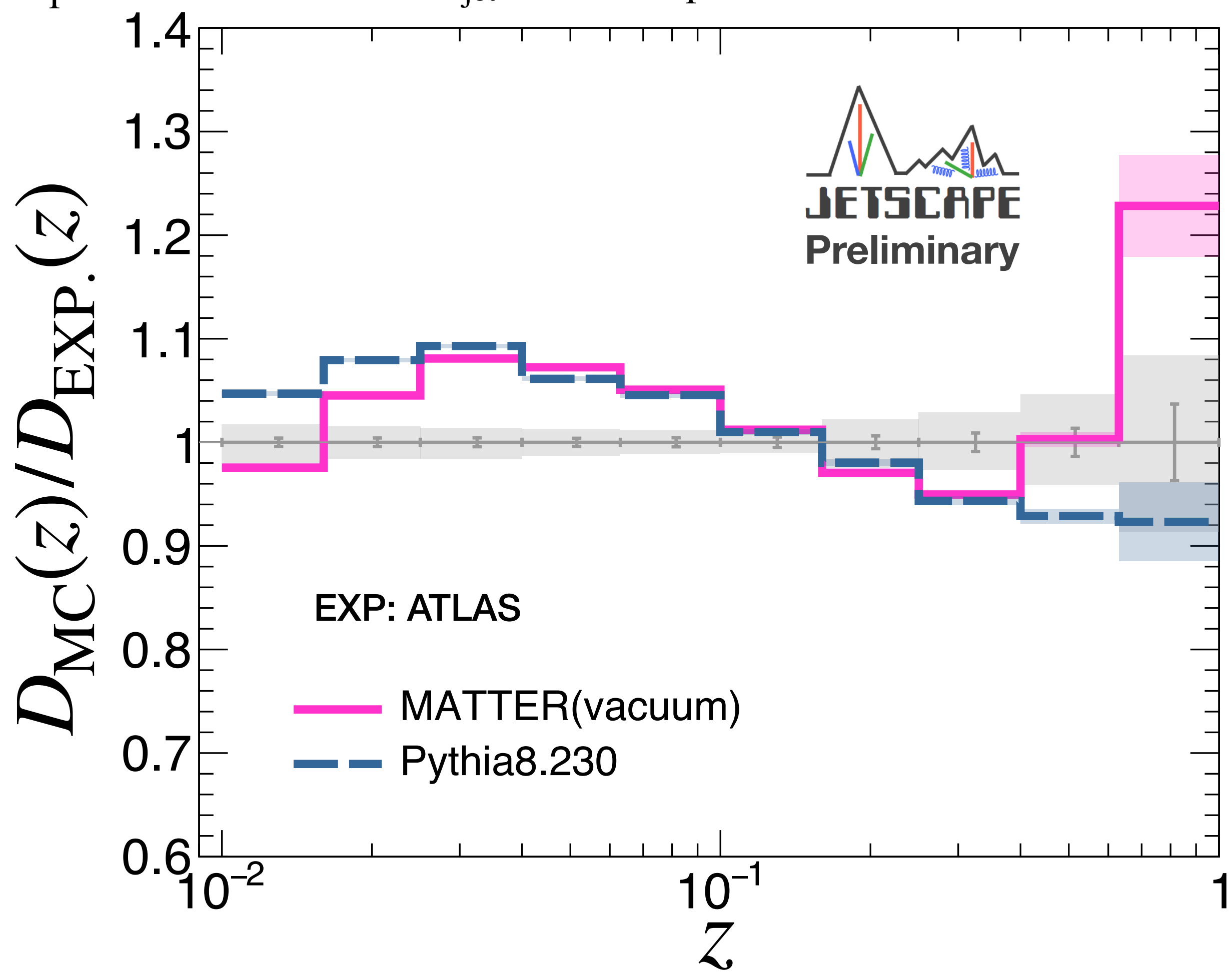
2.76 TeV

*Parameters in Pythia8.230 are default

ATLAS from EPJ C77 (2017) 379

JETSCAPE, 2.76 TeV, pp, 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





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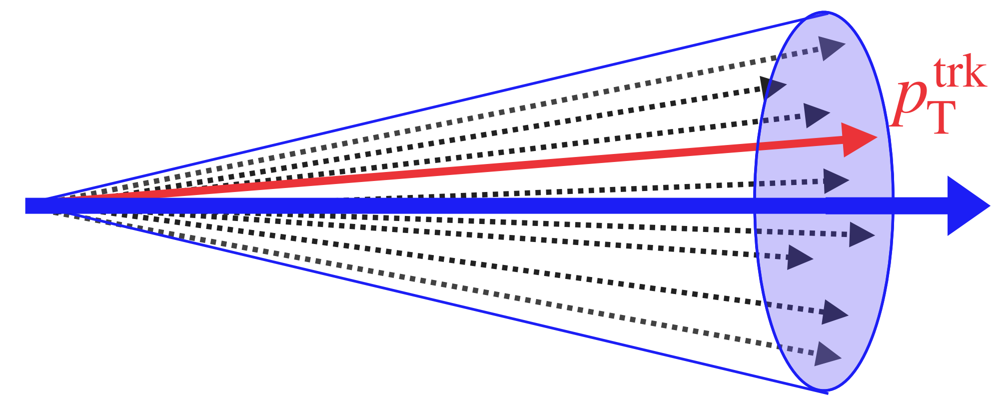

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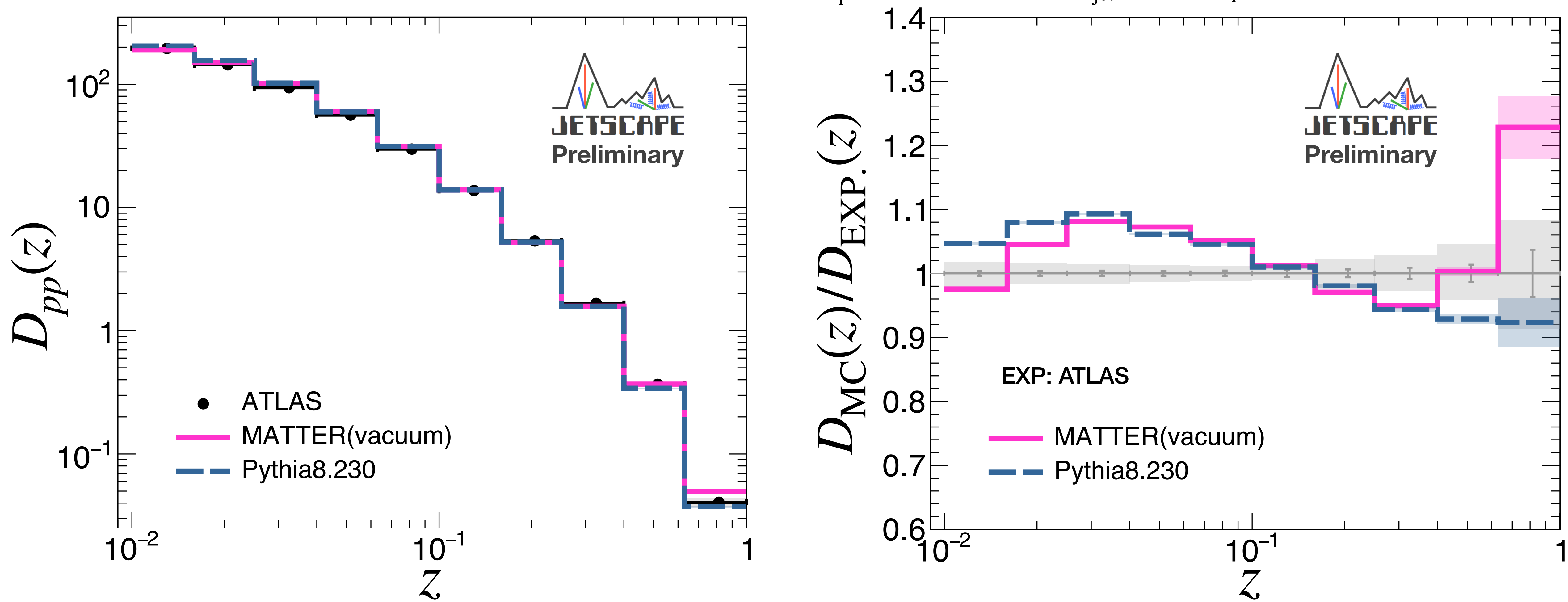


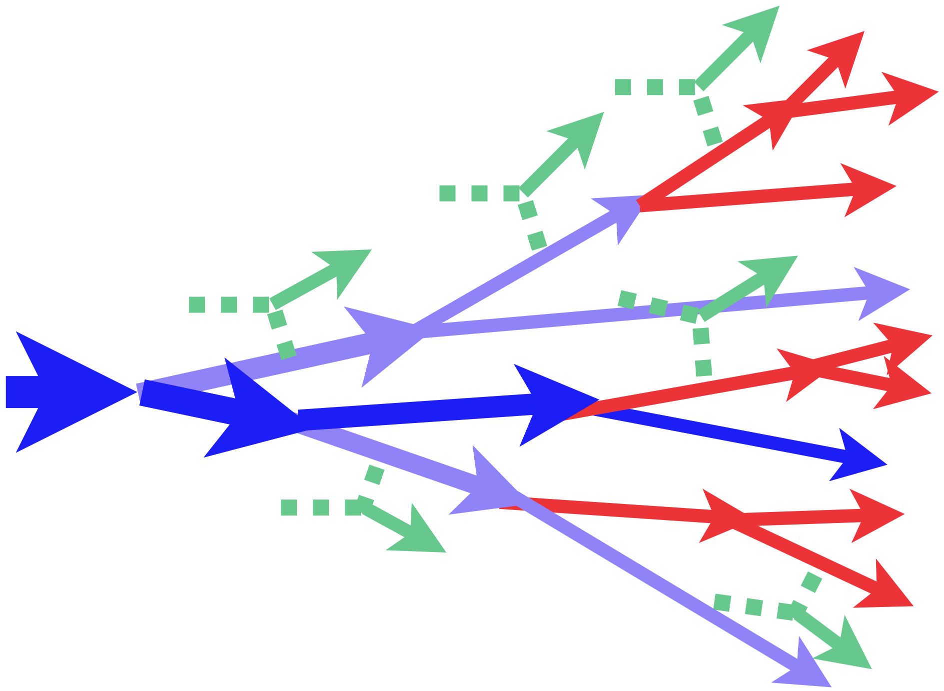
Deviation at high-z , need further tunings

Simulation for PbPb collisions with JETSCAPE

- **Settings in simulations for PbPb at 2.76 TeV**

Jet

QGP fluid



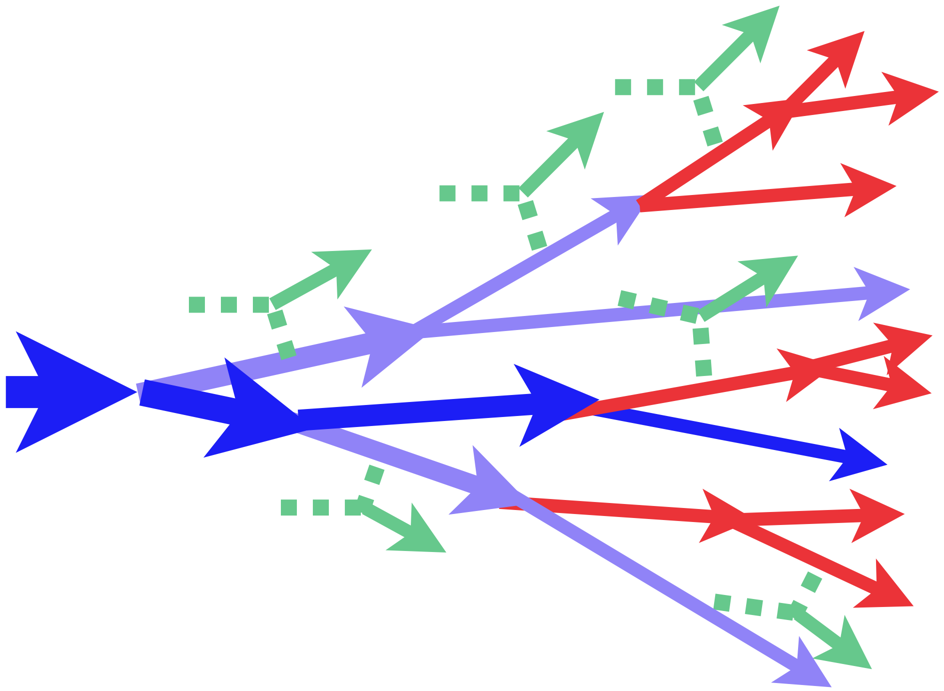
Simulation for PbPb collisions with JETSCAPE

- 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)

QGP fluid



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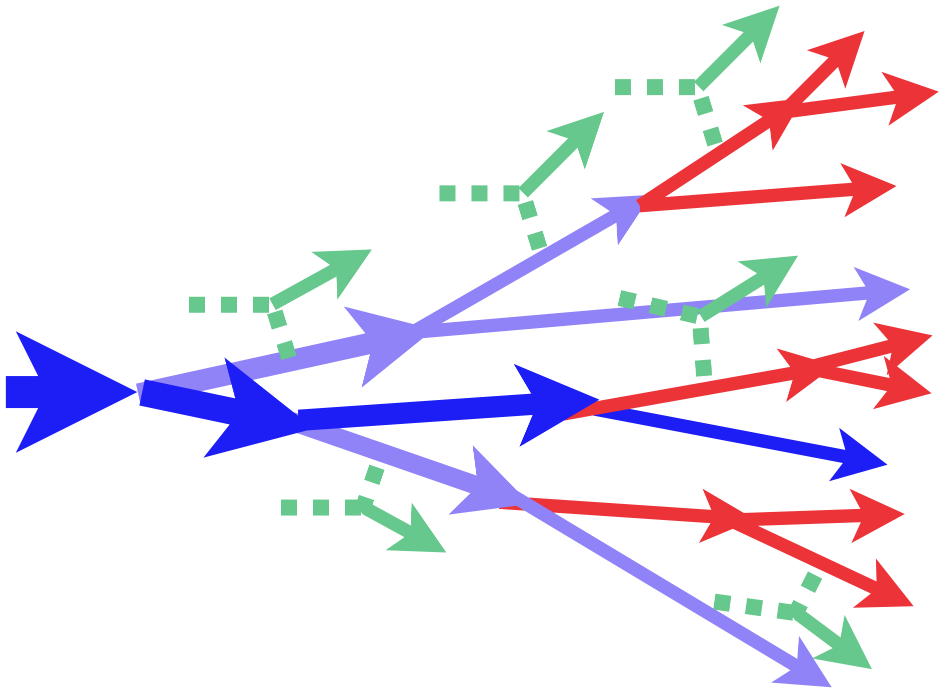
QGP fluid



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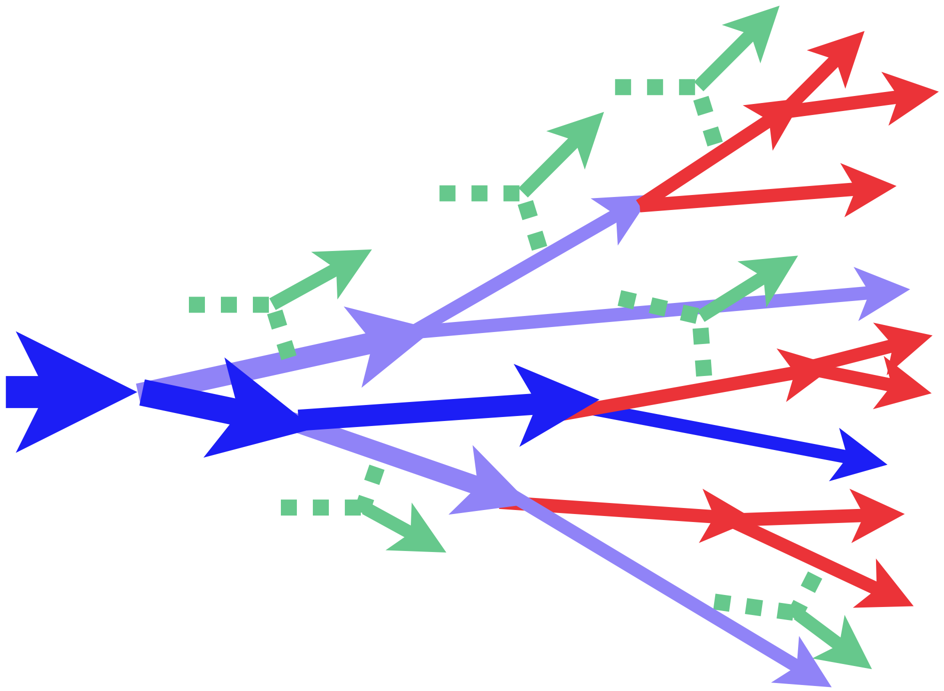
- Initial condition from TRENTo+Pythia (MPI, ISR: ON)

Moreland, Bernhard, Bass(14)

QGP fluid



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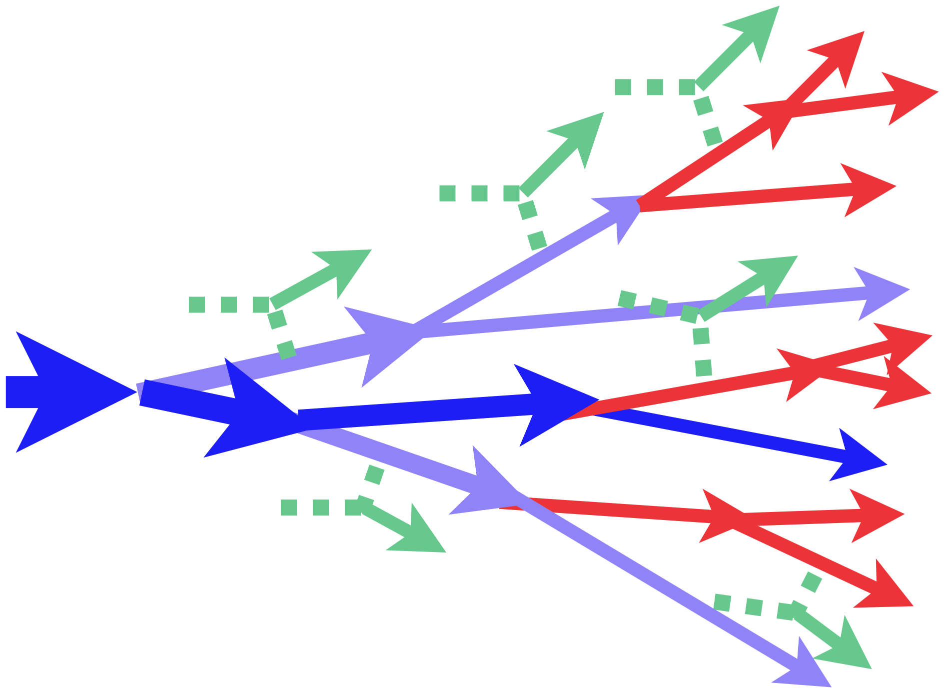

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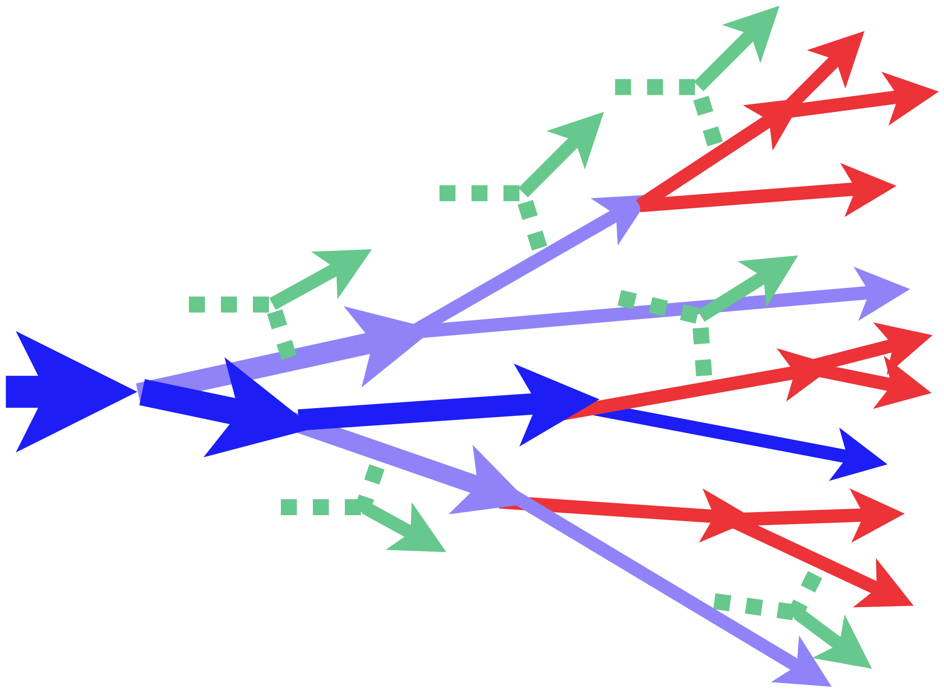
- **2+1D, event-averaged (data table)**



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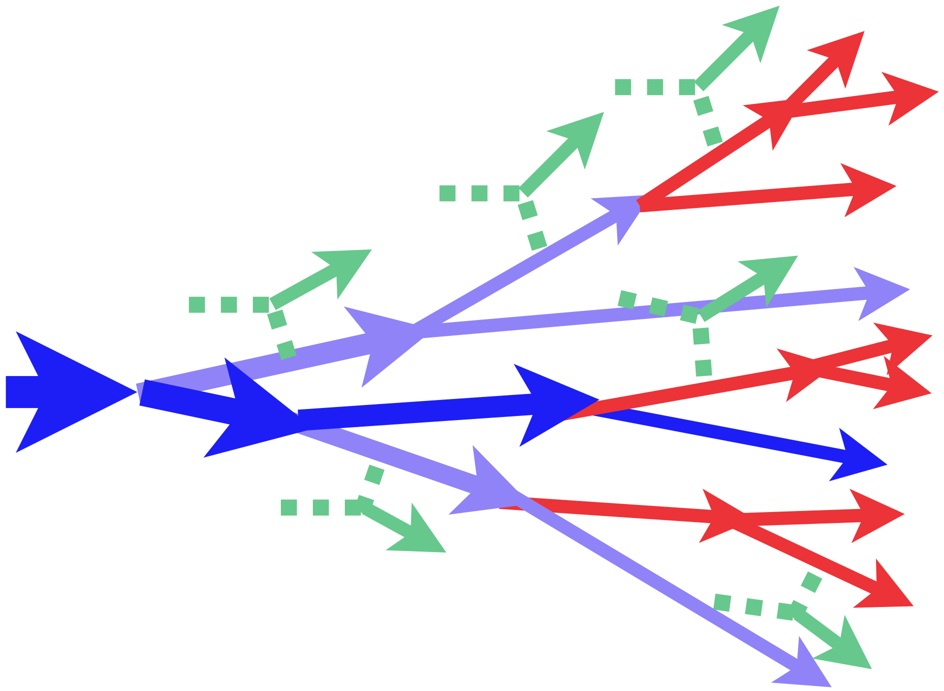
- 2+1D, event-averaged (data table)
- **TRENTo initial condition+free-streaming**
  Liu, Shen, Heinz(15)



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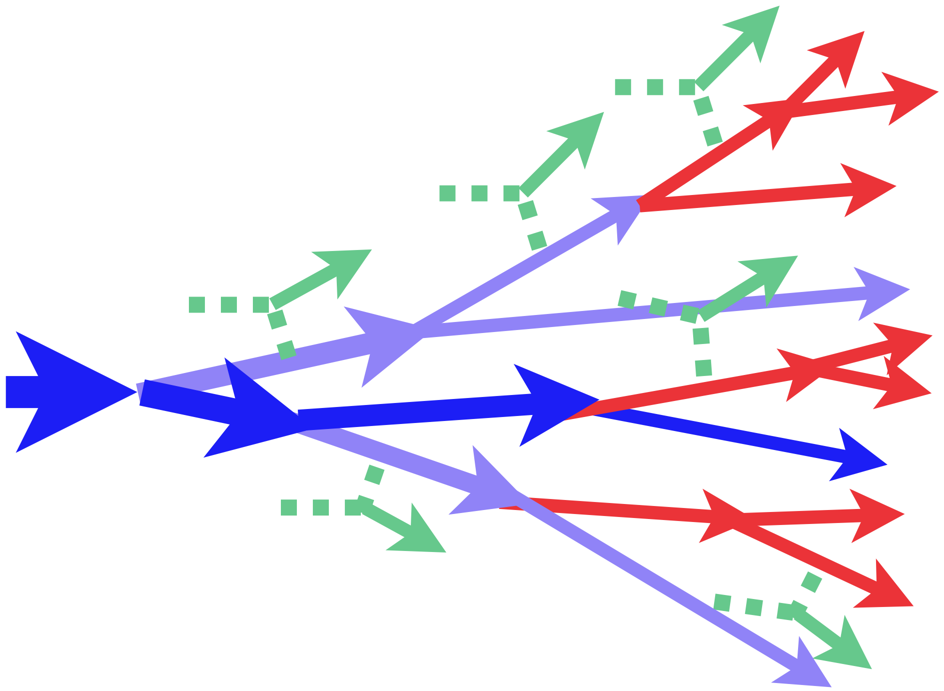
  Liu, Shen, Heinz(15)
- **VISHNU (viscous hydro calculation)**
  Shen, Qiu, Song, Bernhard, Bass, Heinz(16)



Simulation for PbPb collisions with JETSCAPE

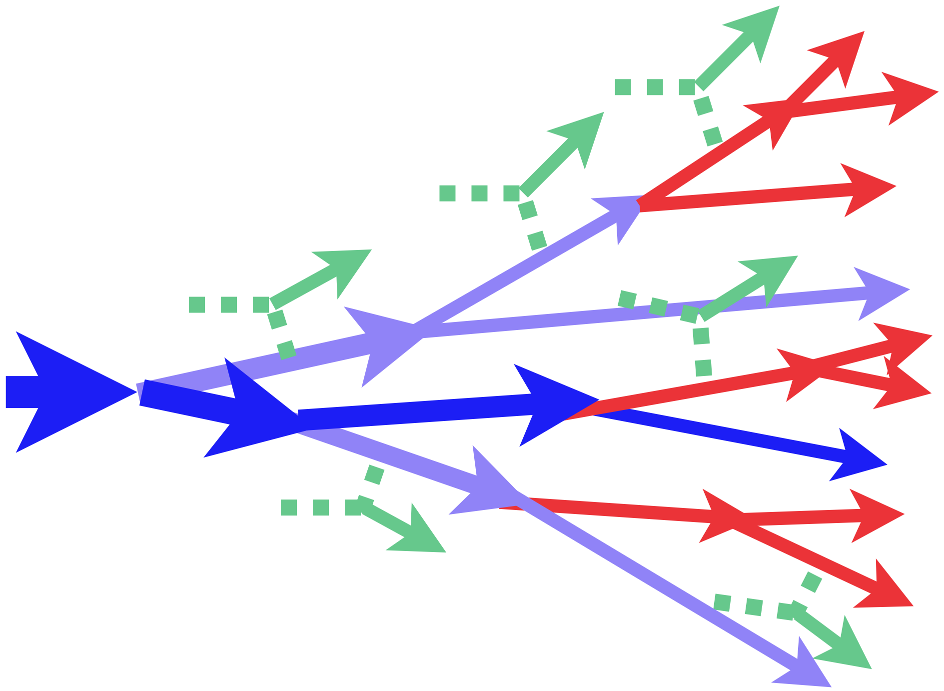
- **Settings in simulations for PbPb at 2.76 TeV**

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

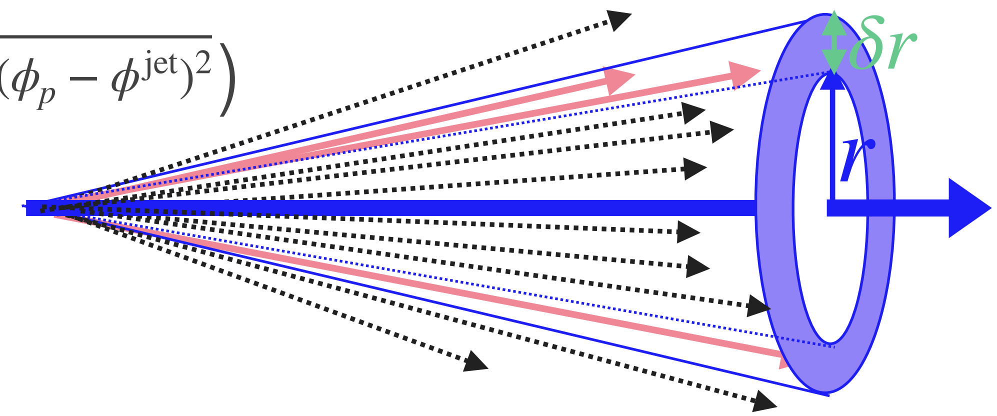
QGP fluid

- 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 (PbPb)

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

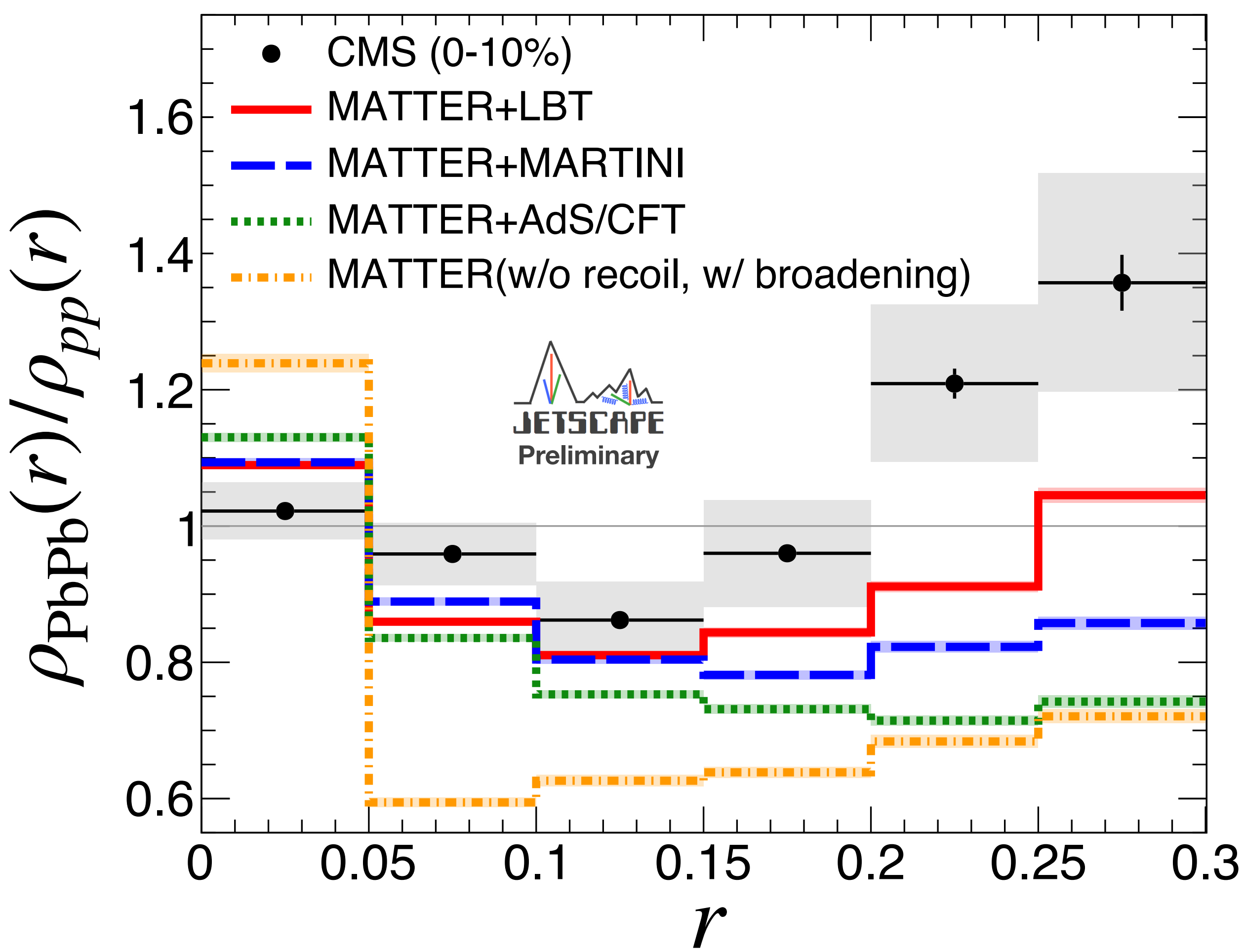


note: self-normalized observable

PbPb/pp

CMS from PLB 730 (2014) 243

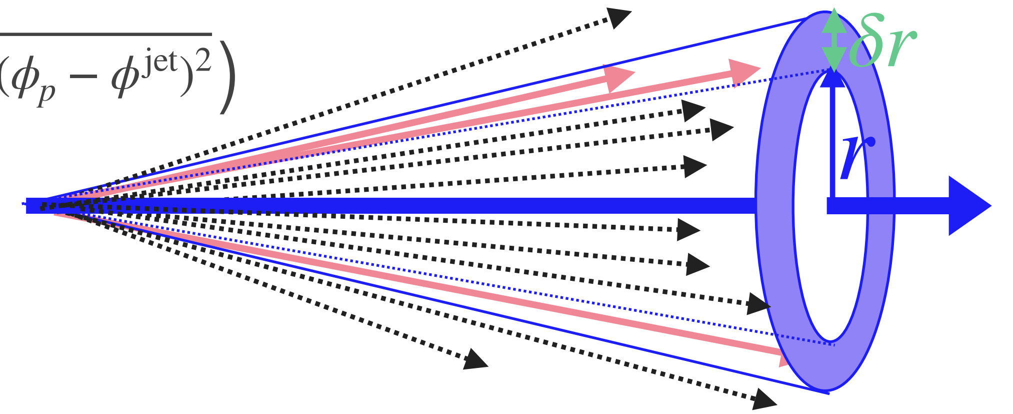
JETSCAPE, 2.76 TeV, PbPb : 0-5 % , anti-$k_{\rm T}$ $R = 0.3$, $p_{\rm T}^{\rm jet} > 100$ GeV, $0.3 < |\eta_{\rm jet}| < 2.0$, $p_{\rm T}^{\rm trk} > 1$ GeV



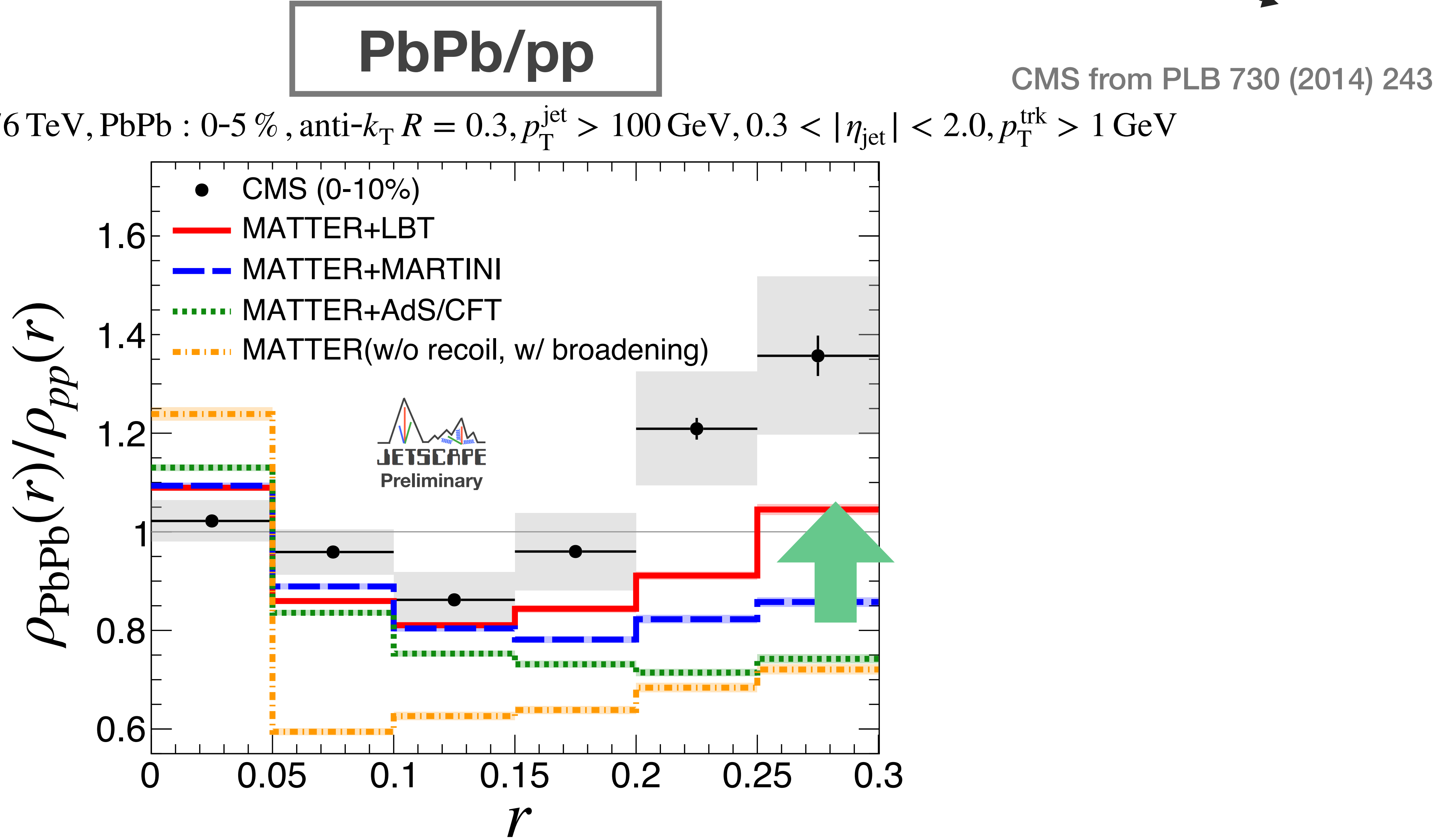
Jet Shape (PbPb)

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

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



note: self-normalized observable

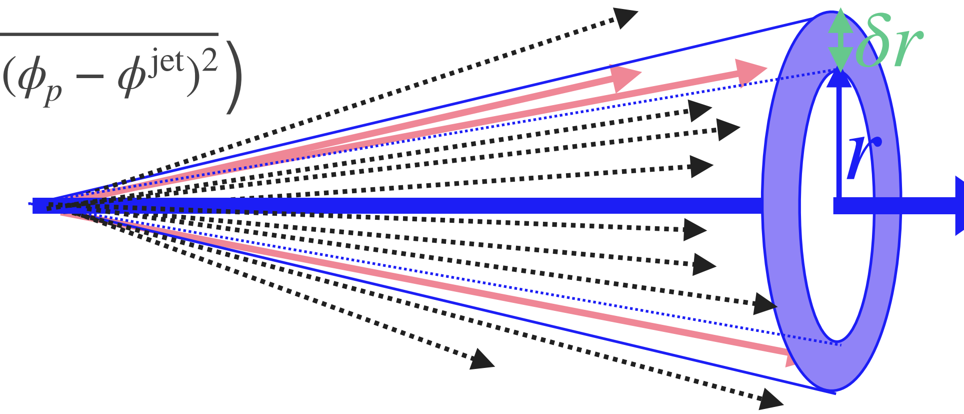


Enhancement around the edge of jet cone due to recoils in LBT

Jet Shape (PbPb)

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

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

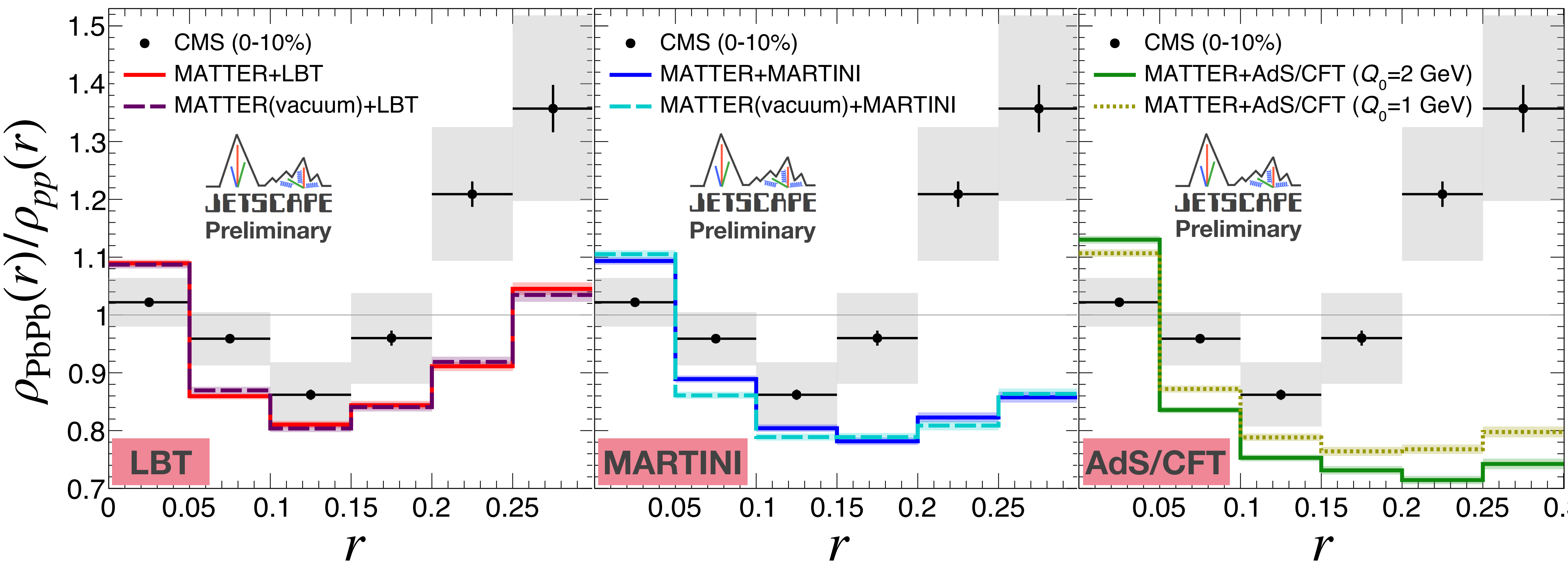


note: <u>self-normalized observable</u>

PbPb/pp

CMS from PLB 730 (2014) 243

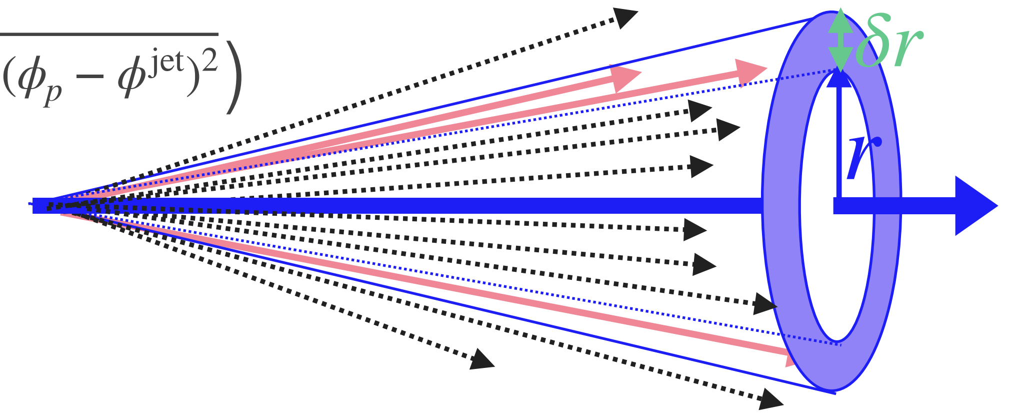
JETSCAPE, 2.76 TeV, PbPb : 0-5 % , anti-$k_{\rm T}$ $R = 0.3$, $p_{\rm T}^{\rm jet} > 100$ GeV, $0.3 < |\eta_{\rm jet}| < 2.0$, $p_{\rm T}^{\rm trk} > 1$ GeV



Jet Shape (PbPb)

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

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

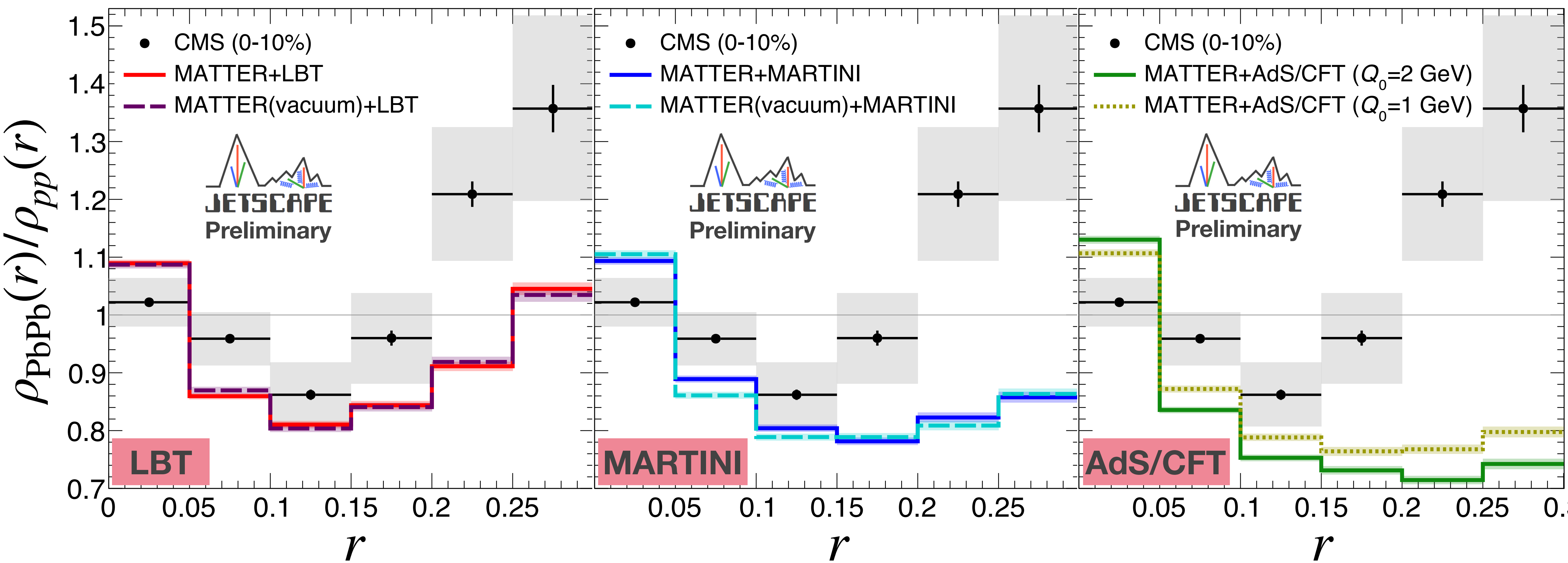


note: self-normalized observable

PbPb/pp

CMS from PLB 730 (2014) 243

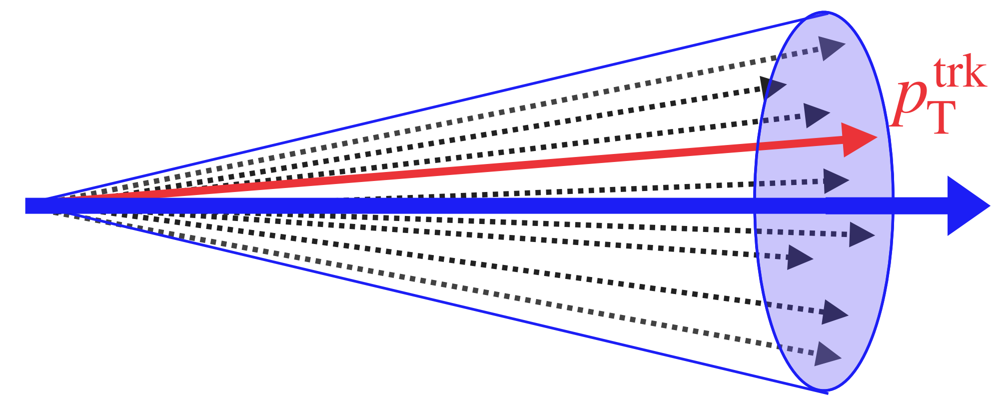
JETSCAPE, 2.76 TeV, PbPb : 0-5 %, anti-$k_{\rm T}$ $R = 0.3$, $p_{\rm T}^{\rm jet} > 100$ GeV, $0.3 < |\eta_{\rm jet}| < 2.0$, $p_{\rm T}^{\rm trk} > 1$ GeV



Medium effect during virtuality ordered splitting cannot be seen

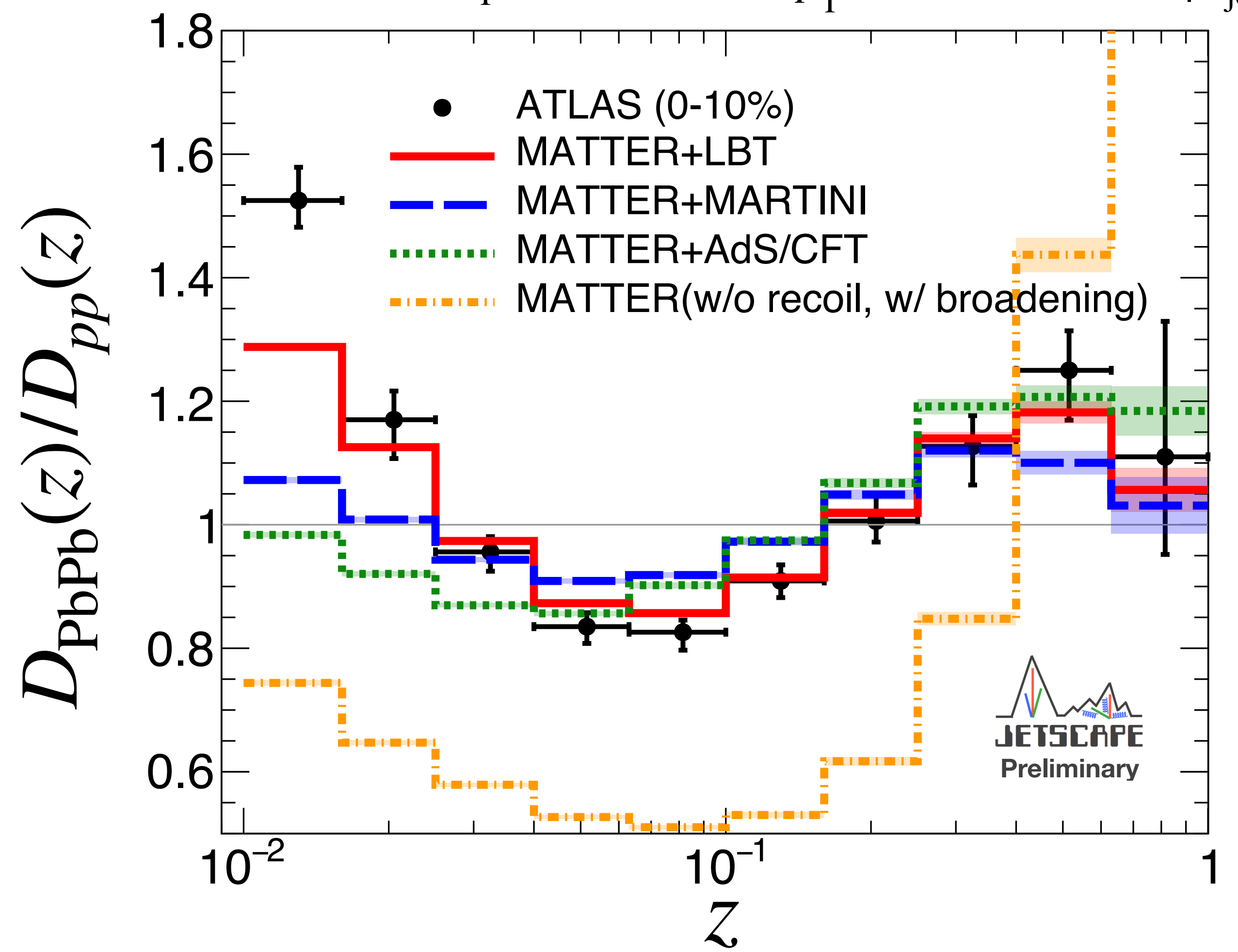
Jet Fragmentation Function (PbPb)

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



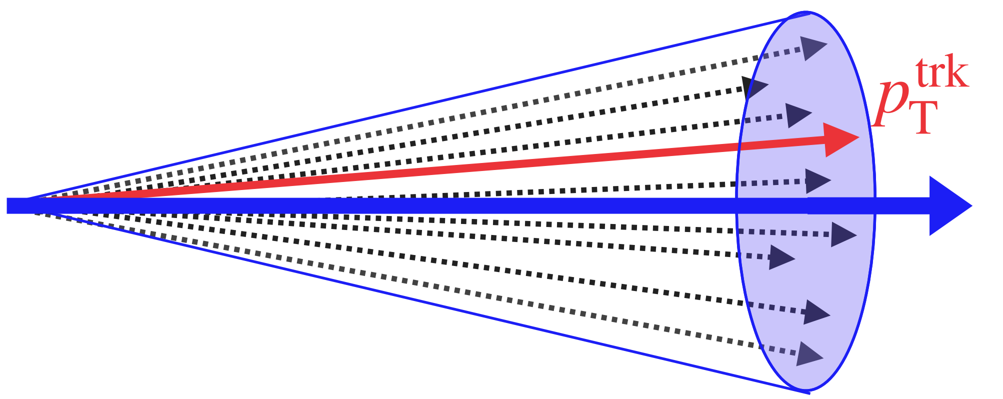
PbPb/pp

ATLAS from EPJ C77 (2017) 379



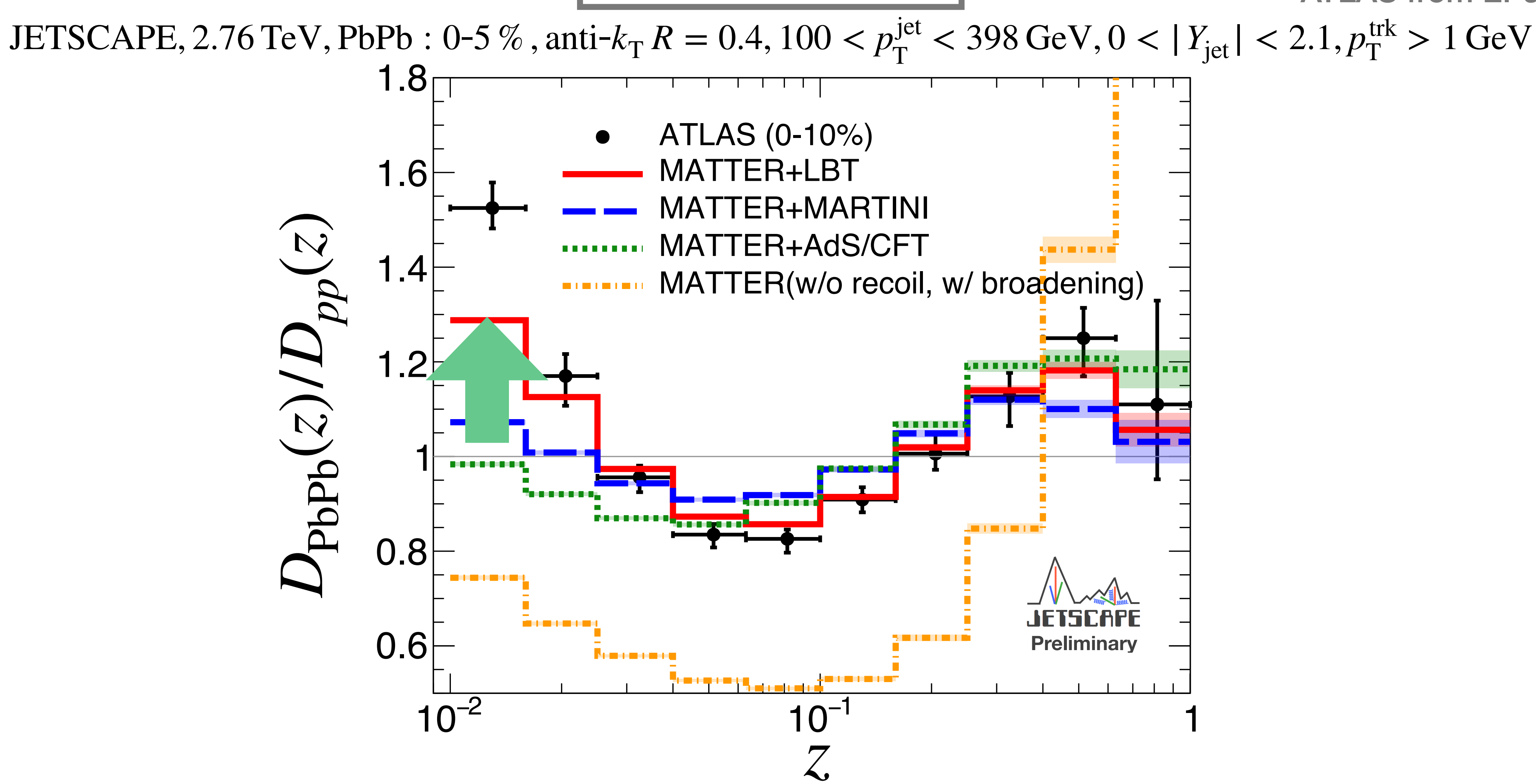
Jet Fragmentation Function (PbPb)

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



PbPb/pp

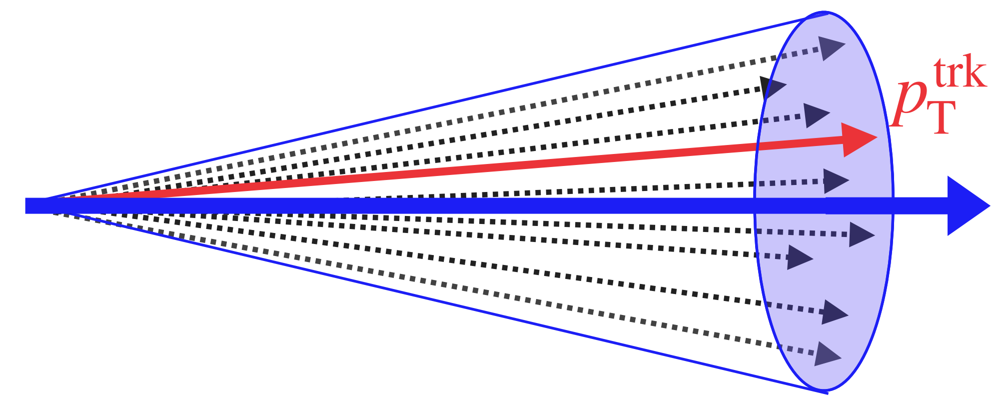
ATLAS from EPJ C77 (2017) 379



Small-z enhancement due to recoils in LBT

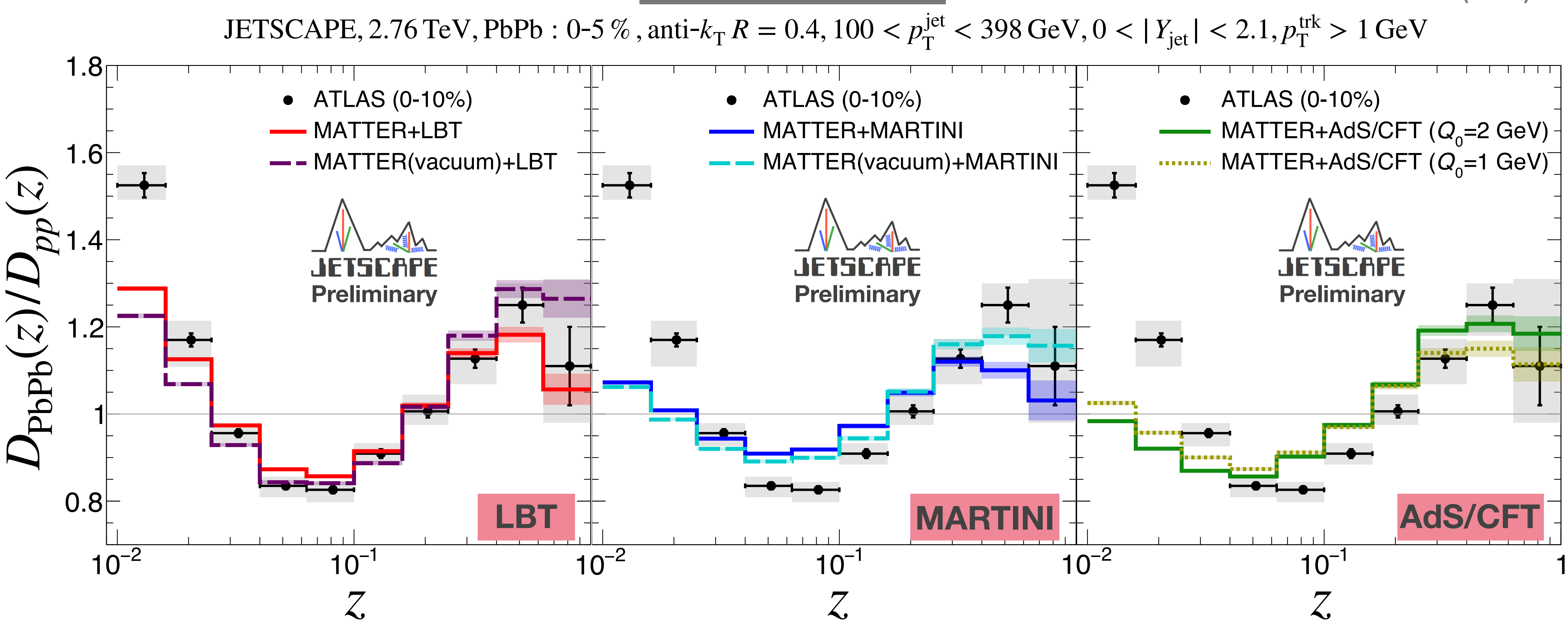
Jet Fragmentation Function (PbPb)

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



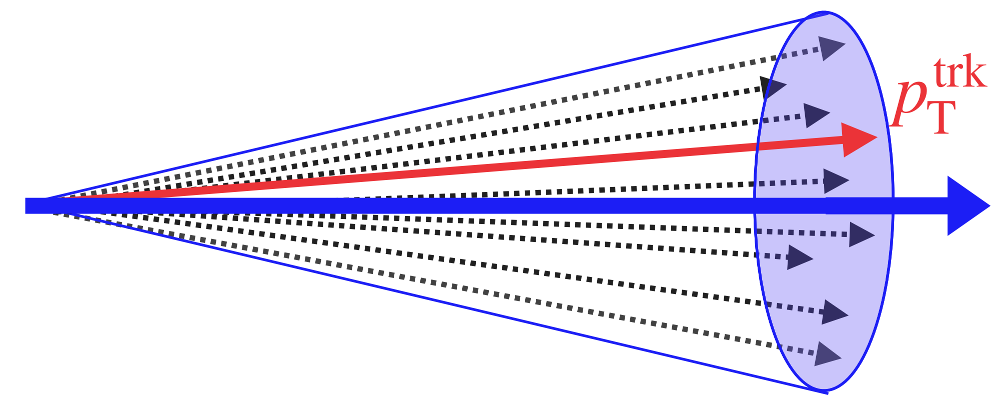
PbPb/pp

ATLAS from EPJ C77 (2017) 379



Jet Fragmentation Function (PbPb)

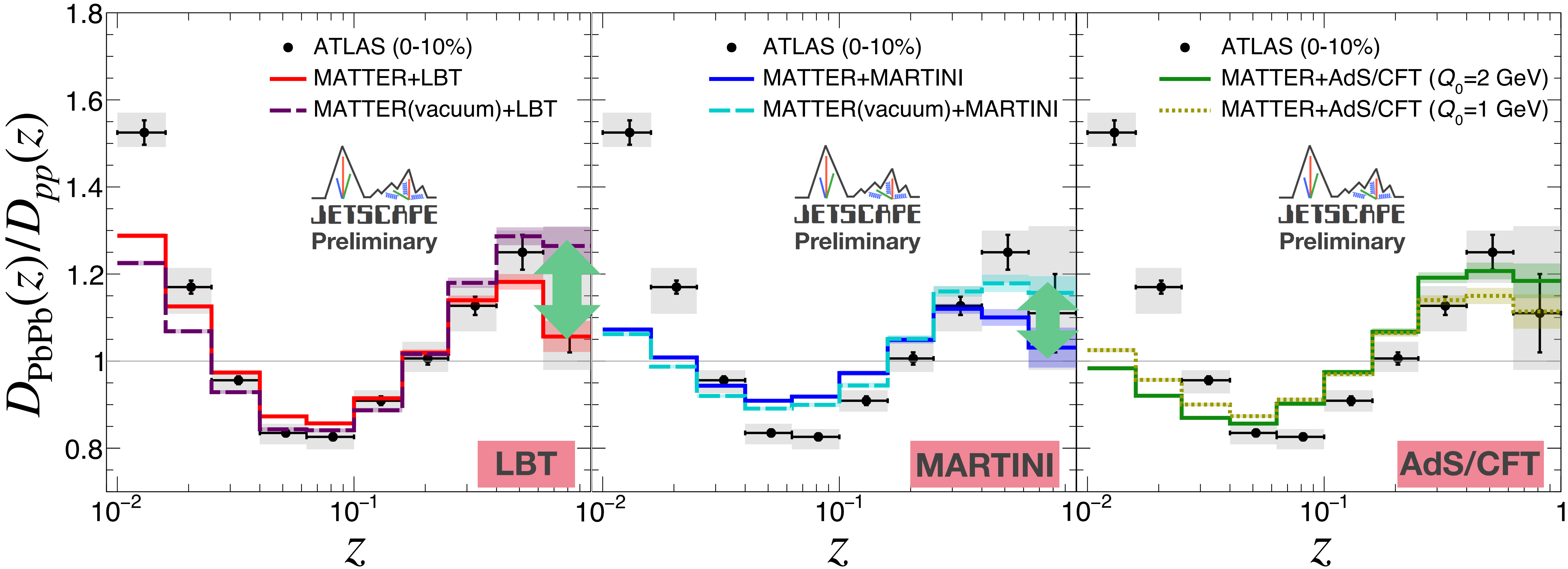
$$D(z) = \frac{1}{N_{\rm jet}} \frac{dN_{\rm trk}}{dz} \qquad \left(z = p_{\rm T}^{\rm trk} / p_{\rm T}^{\rm jet} \right)$$



PbPb/pp

ATLAS from EPJ C77 (2017) 379

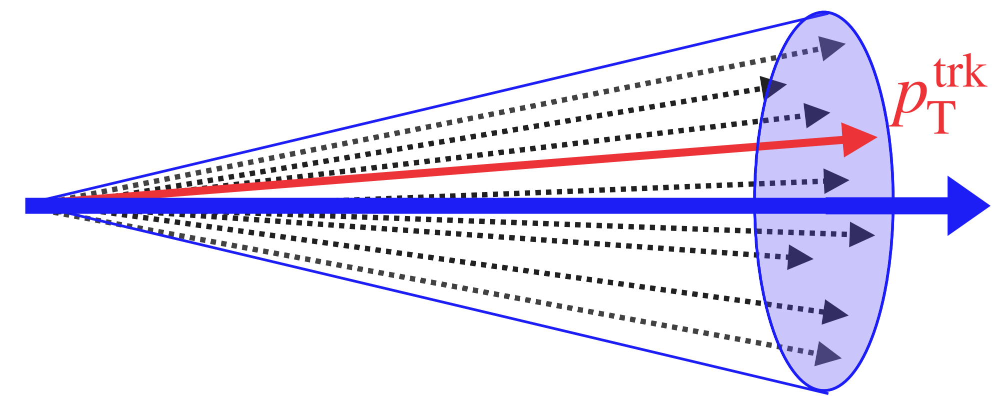
JETSCAPE, 2.76 TeV, PbPb : 0-5 % , anti-$k_{\rm T}$ $R = 0.4$, $100 < p_{\rm T}^{\rm jet} < 398$ GeV, $0 < |Y_{\rm jet}| < 2.1$, $p_{\rm T}^{\rm trk} > 1$ GeV



Medium effect during virtuality ordered splitting

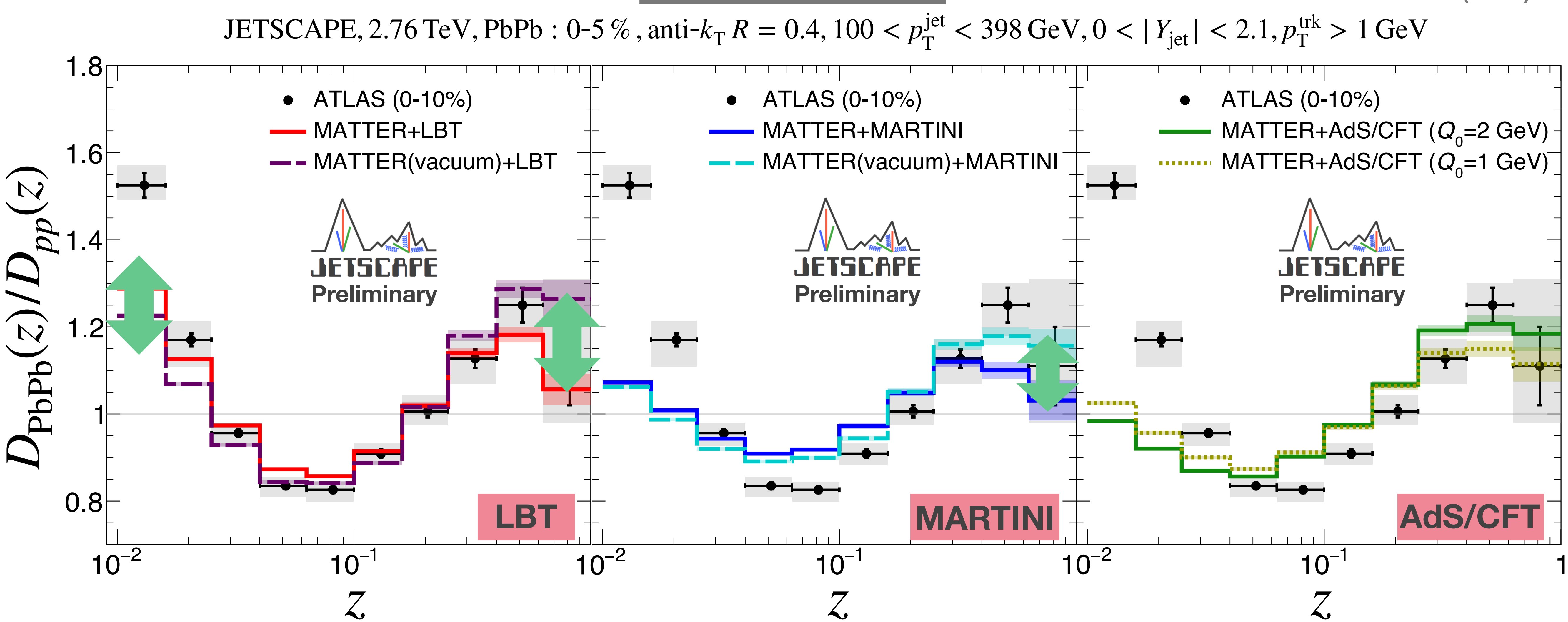
Jet Fragmentation Function (PbPb)

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



PbPb/pp

ATLAS from EPJ C77 (2017) 379



Medium effect during virtuality ordered splitting

Summary

- **Multi-stage jet evolution in JETSCAPE**
  - Switching between different energy loss modules by virtuality of partons

    Large-Q : virtuality ordered splitting (**MATTER**)

    Small-Q : on-shell transport or strong coupling (**LBT**, **MARTINI** or **AdS/CFT**)

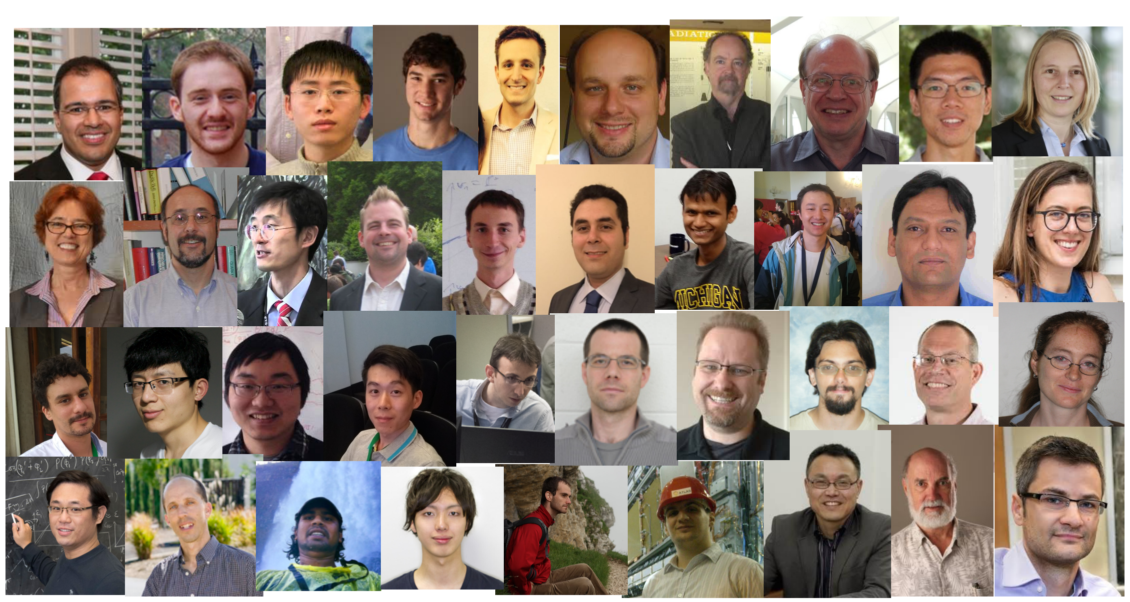
- **Jet substructure from multi-scale description of jet shower**
  - Significant contribution from recoil effect in LBT
  - Medium effect during virtuality ordered splitting

    Jet shape: small

    Jet fragmentation function: sizable at large-z

Outlook

- **Rigorous analysis**
  - Further parameters tuning both for pp and for AA
  - Other observables (more sensitive to details of jet evolution)
- **Updates**
  - Recoils in MARTINI and medium response in AdS/CFT
  - Hydro back reaction to deposited energy and momentum from jet
  - Other modules and their combinations



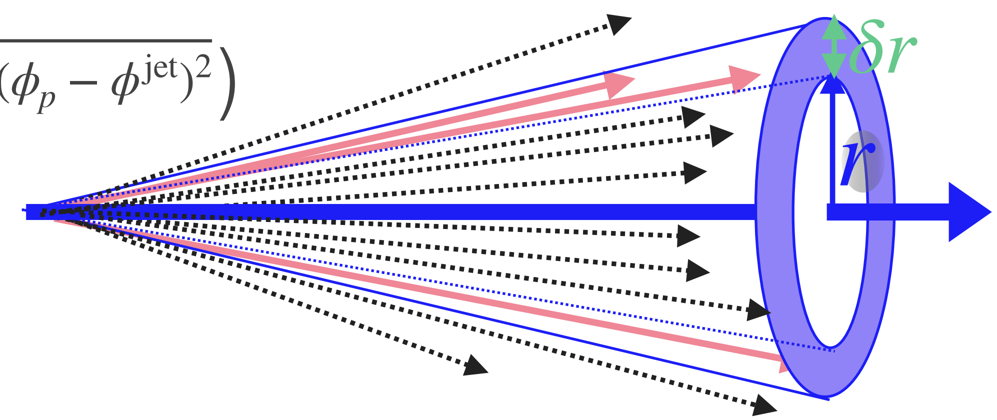
JETSCAPE

Thanks to all collaborators!

Backup

Jet Shape

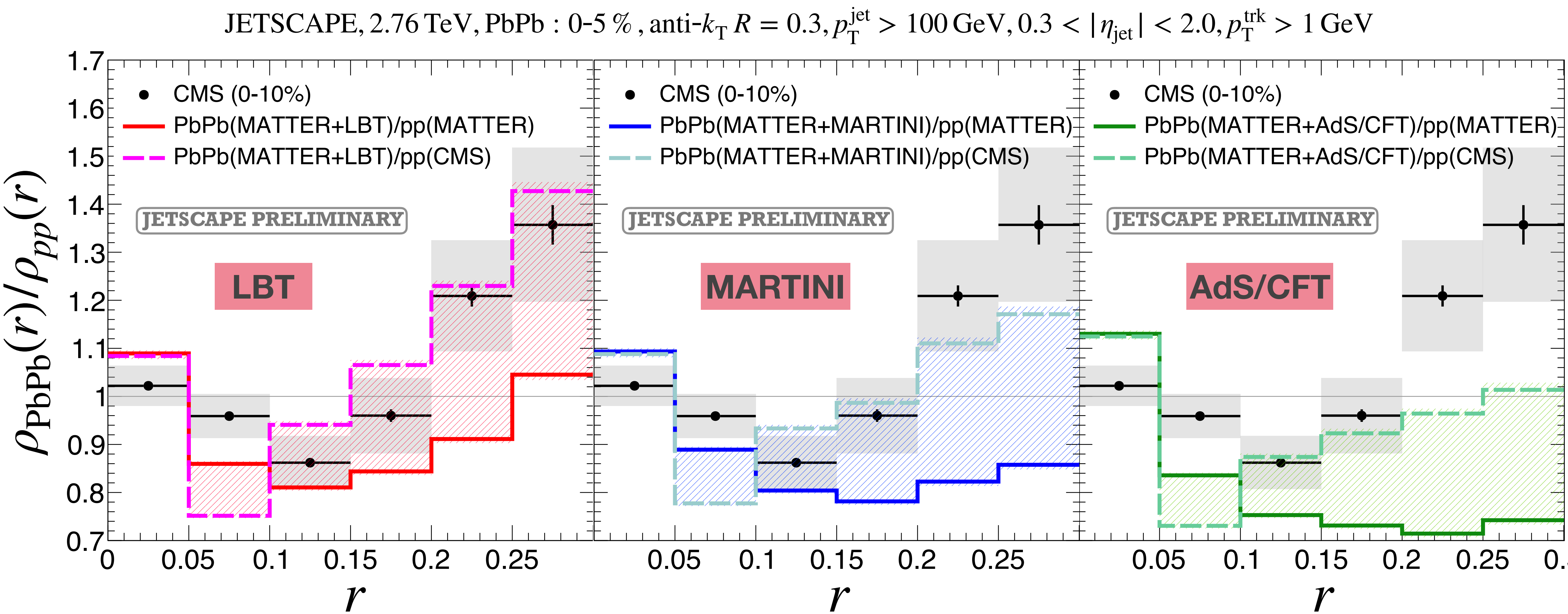
$$\rho(r) = \frac{1}{N_{\mathrm{jet}}} \sum_{\mathrm{jet}} \left[\frac{1}{p_T^{\mathrm{jet}}} \frac{\sum_{\mathrm{trk}\in(r-\delta r/2, r+\delta r/2)} p_T^{\mathrm{trk}}}{\delta r} \right] \quad \left(r = \sqrt{(\eta_p - \eta^{\mathrm{jet}})^2 + (\phi_p - \phi^{\mathrm{jet}})^2} \right)$$



note: self-normalized observable

PbPb/pp

CMS from PLB 730 (2014) 243

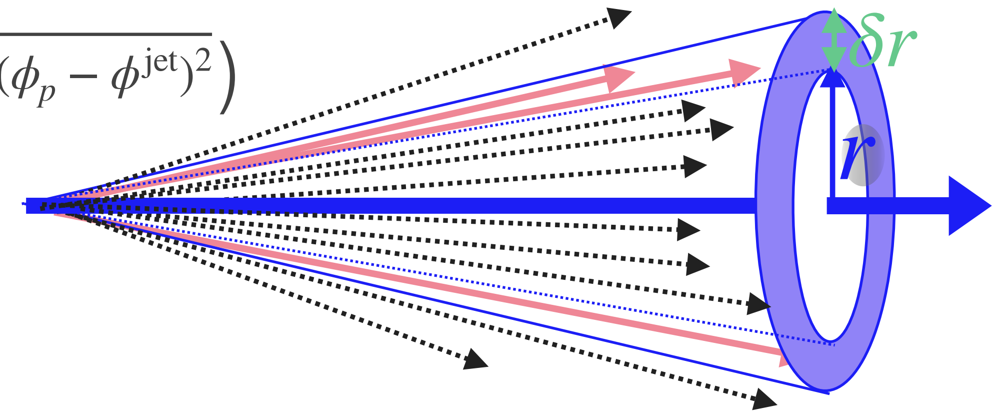


pp baseline dependence

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