WAYNE STATE UNIVERSITY

NSF

HARD PROBES 2018

Jet substructure modifications in a QGP from multi-scale description of jet evolution with JETSCAPE

Yasuki Tachibana

for the JETSCAPE Collaboration

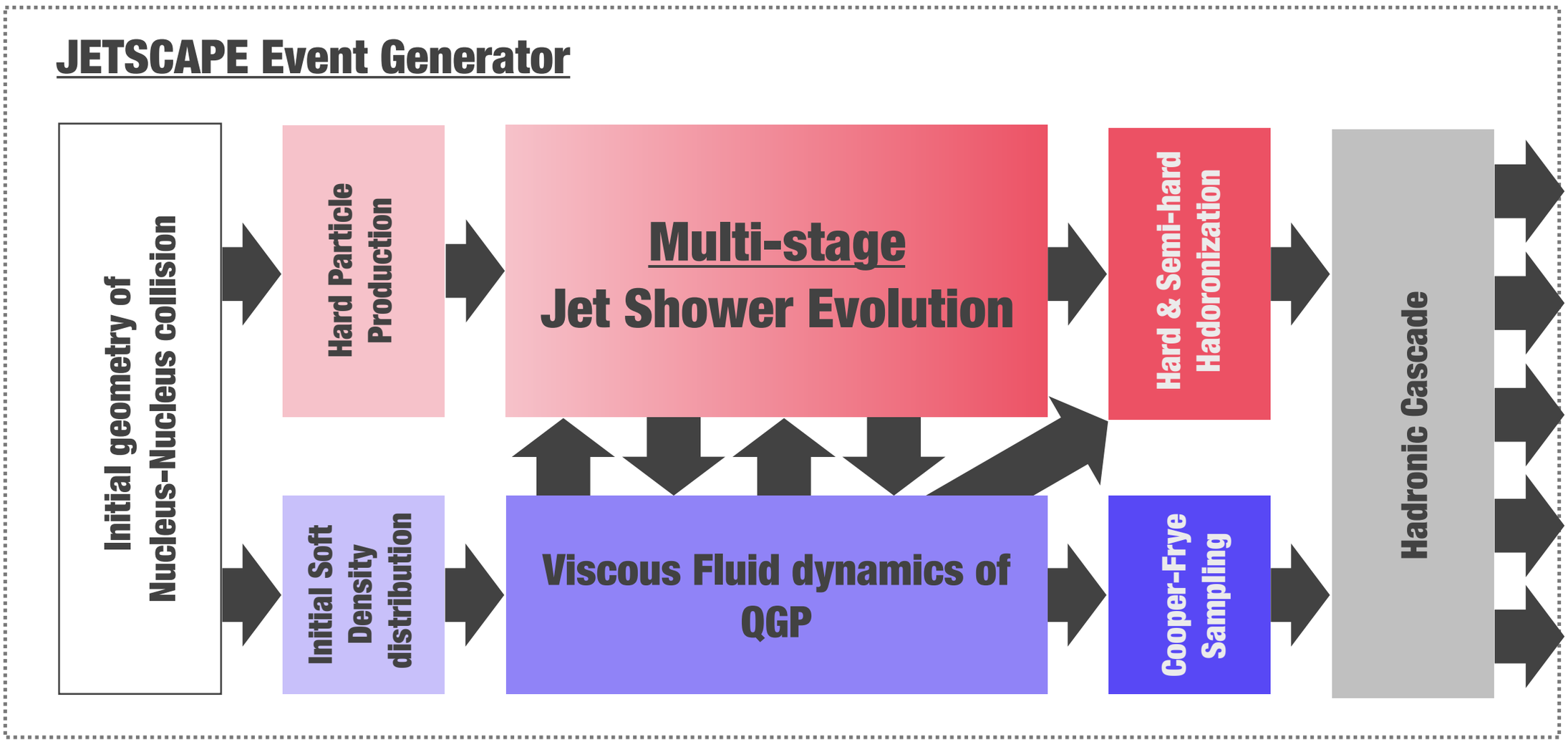
JETSCAPE

Aix-Les-Bains, October 3rd 2018

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

Poster by J. Putschke



STAT part (future release) → **Talk by R. Soltz (Tue)**

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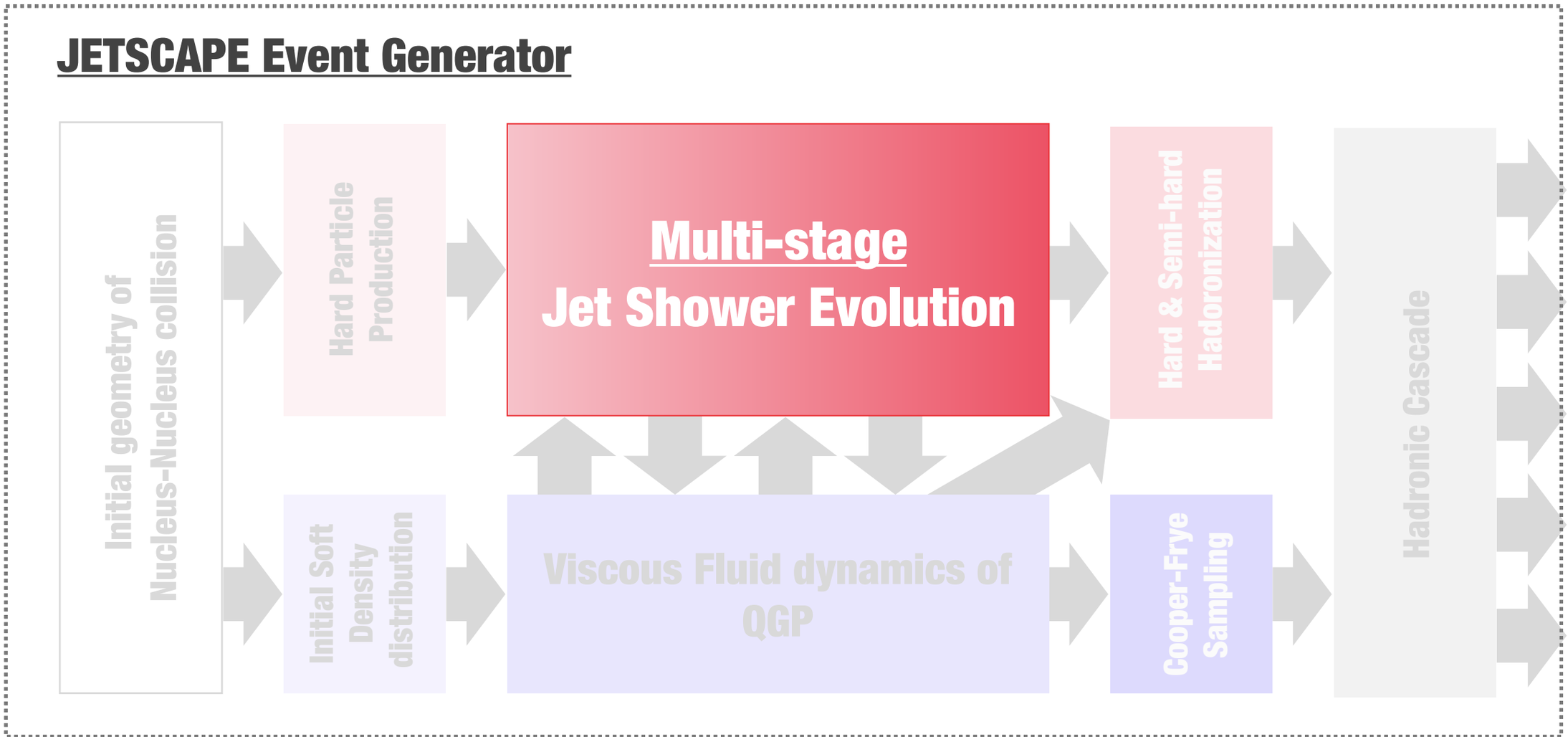

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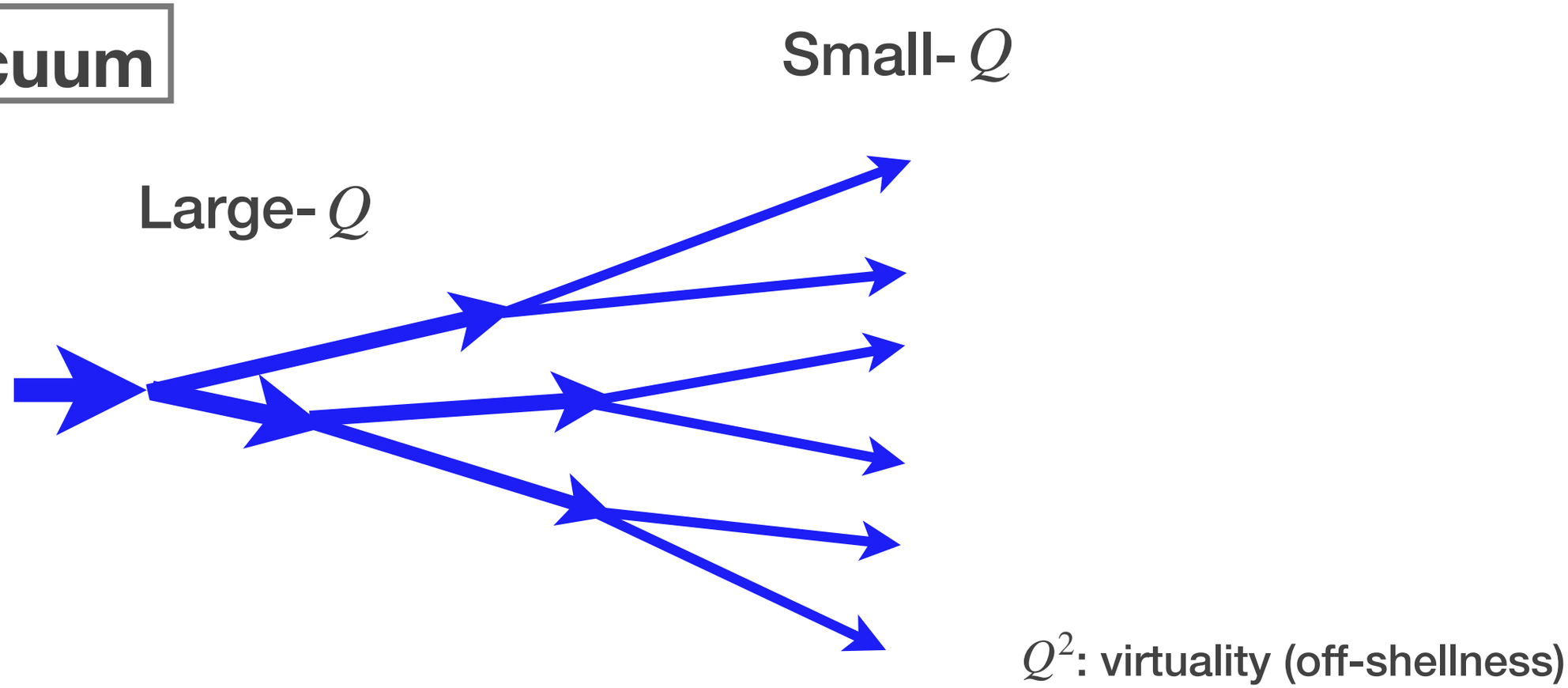
Multi-stage jet evolution in JETSCAPE

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

In-vacuum



- **Virtuality ordered splitting in vacuum**

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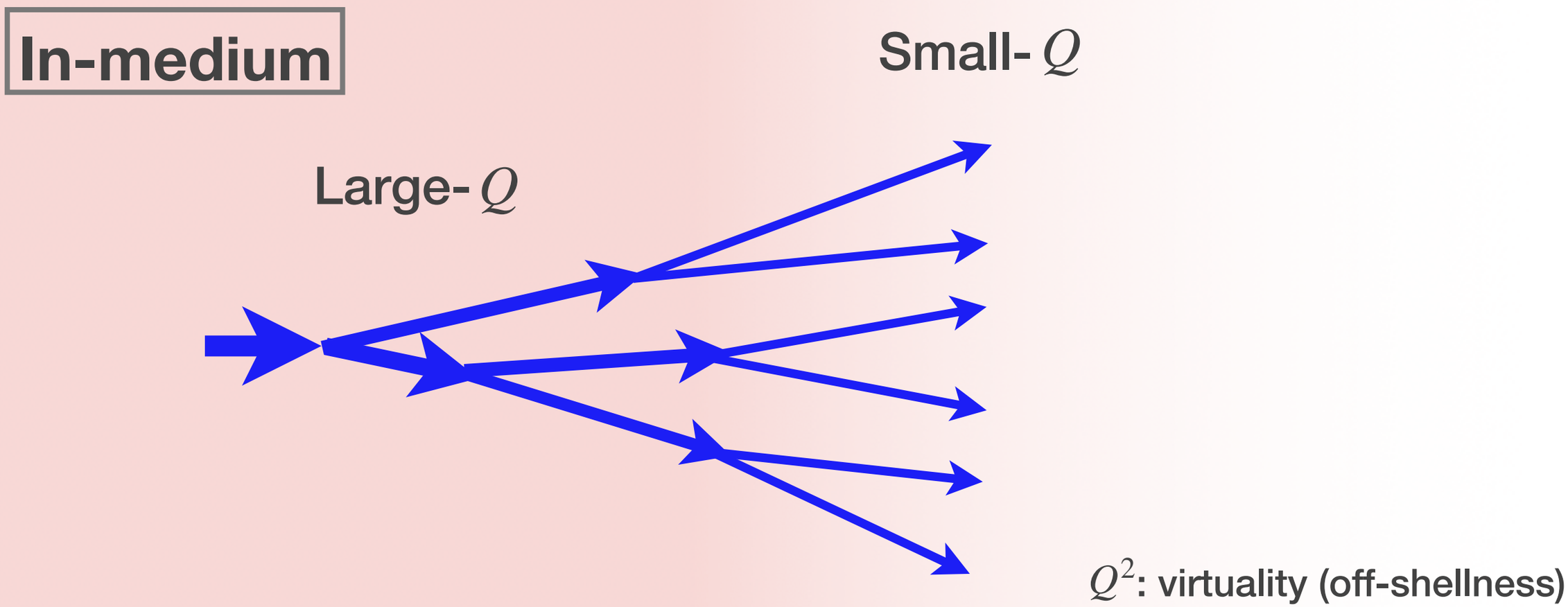

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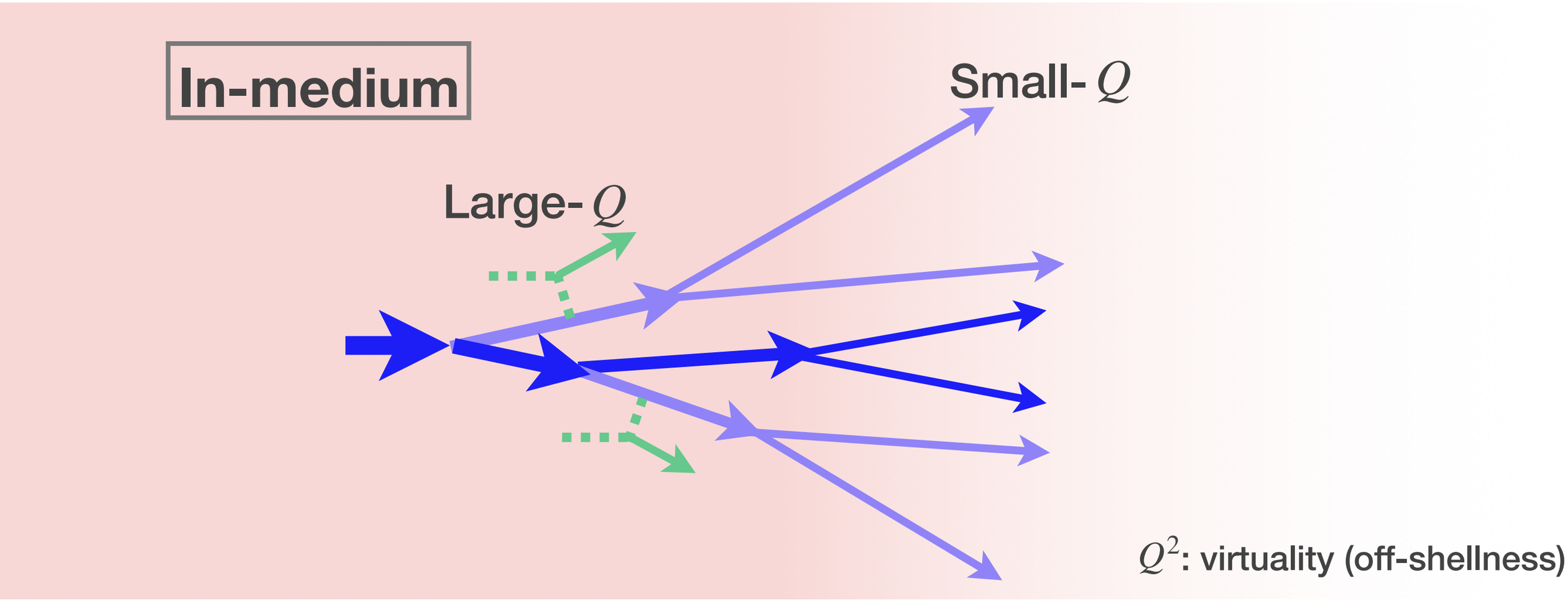

- Virtuality ordered splitting in vacuum
- **Large-Q ⟶ Medium effect on the top of in-vacuum splitting**

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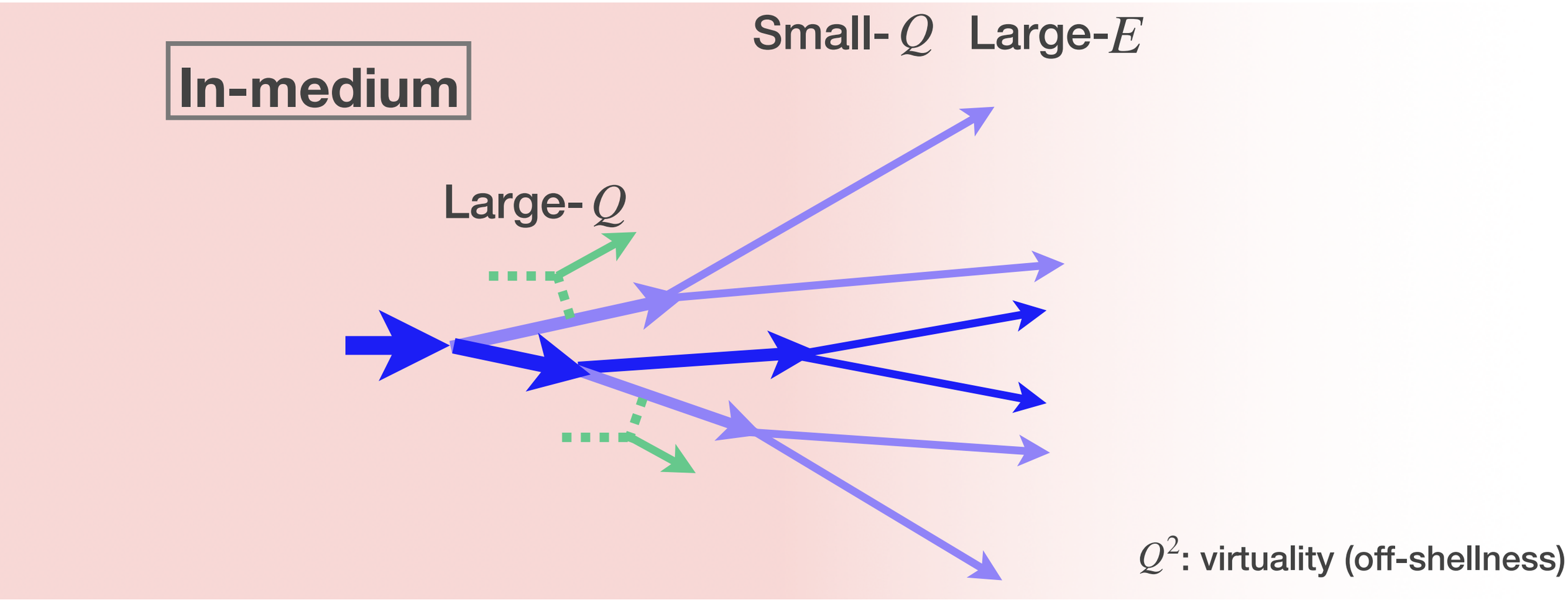

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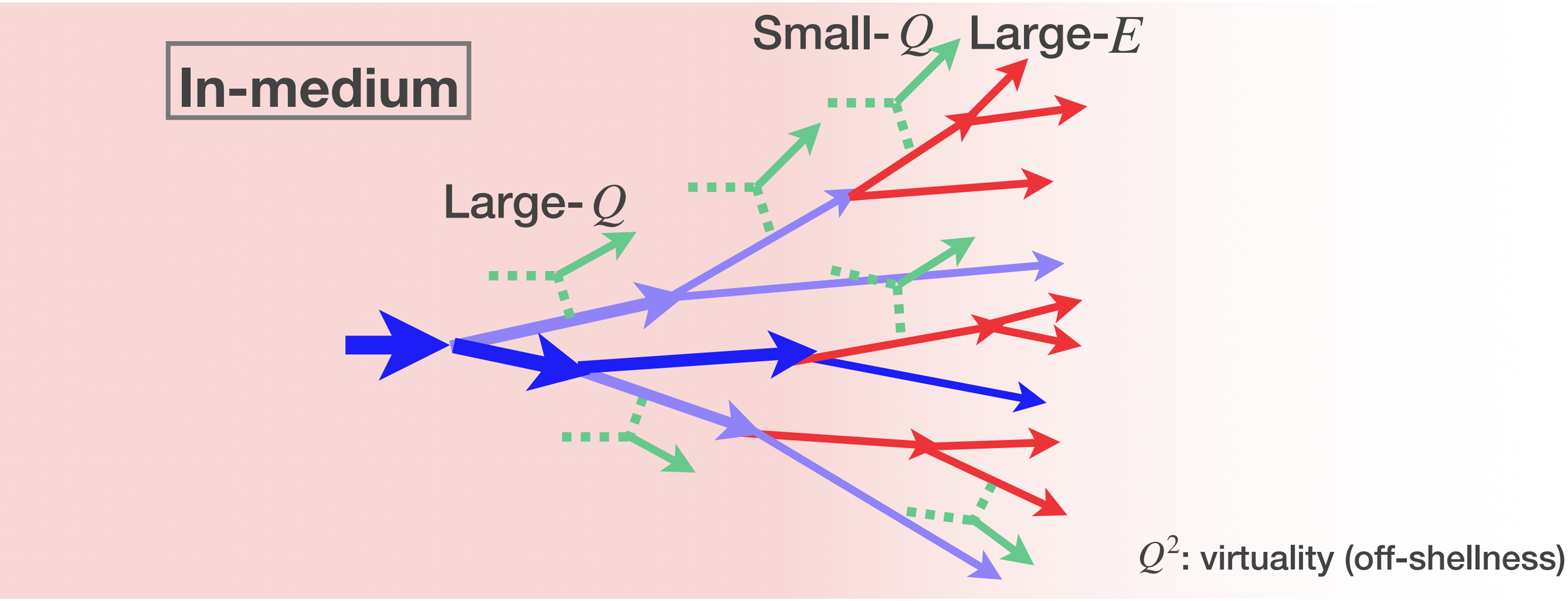

- Virtuality ordered splitting in vacuum
- Large- Q ⟶ Medium effect on the top of in-vacuum splitting
- **Small-Q , Large-E ⟶ Splitting driven almost purely by medium effect**

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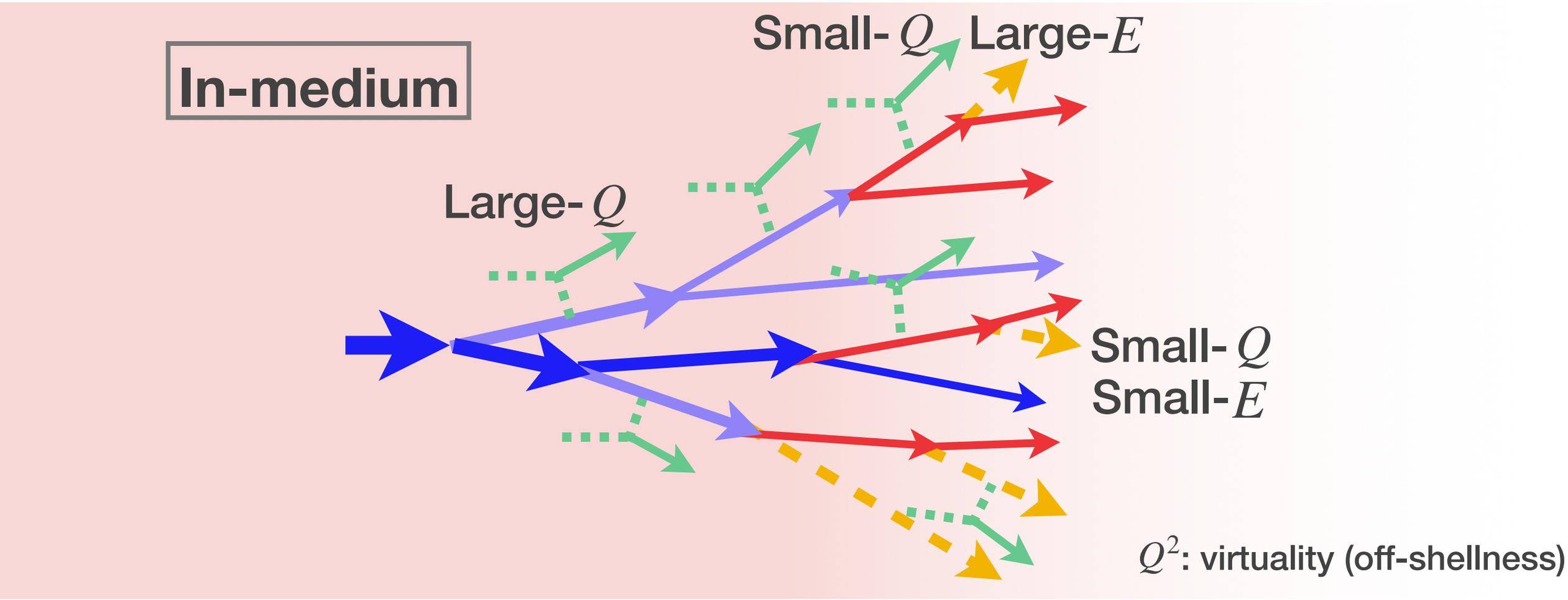

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- **Small-Q , Small-E ⟶ Energy-momentum diffusion into medium**

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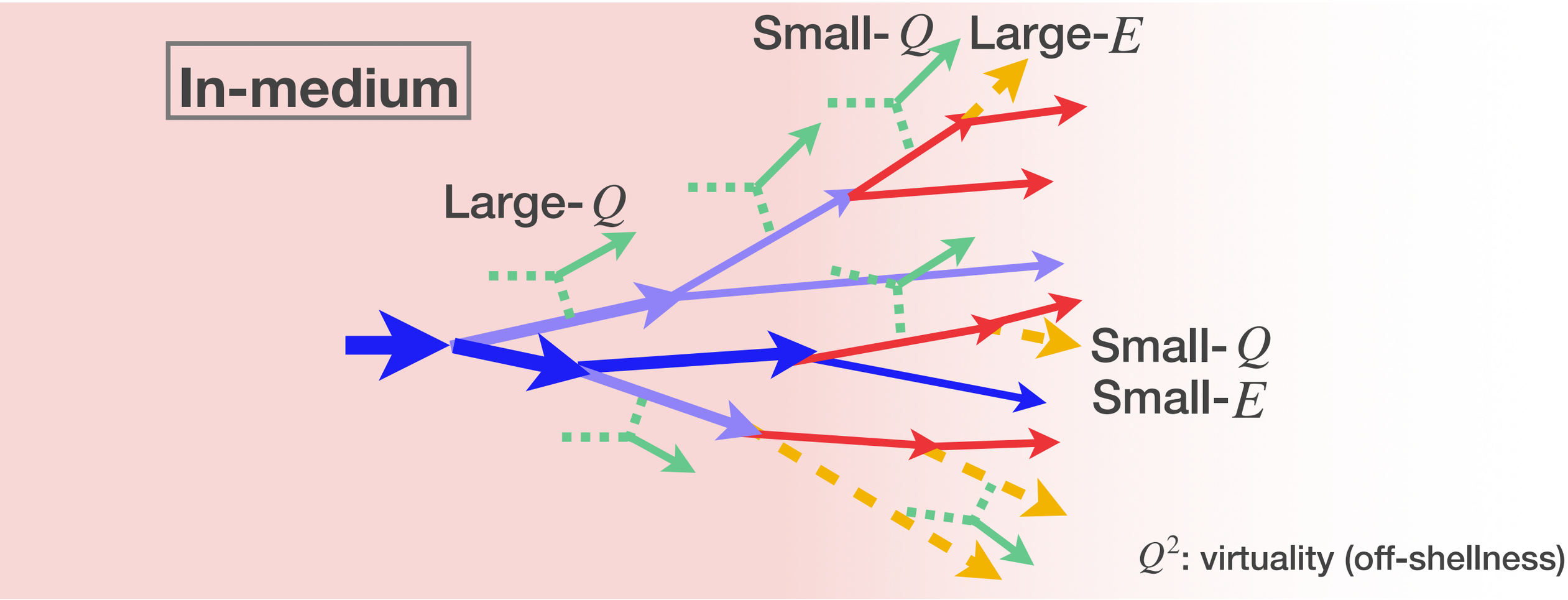

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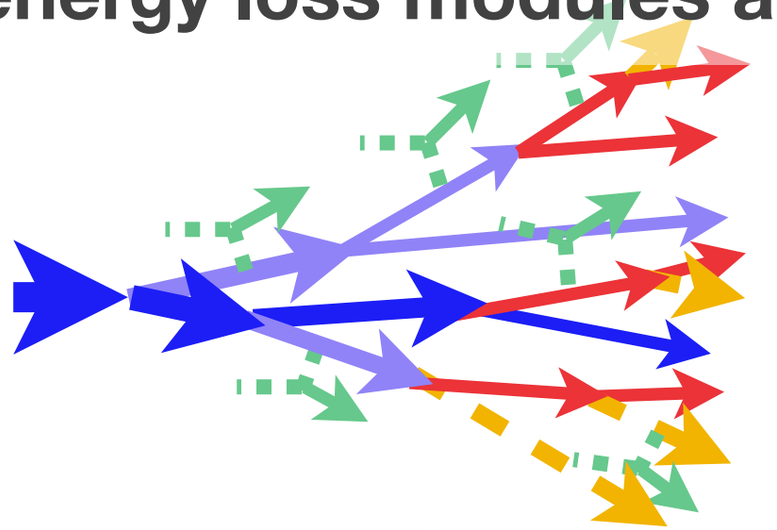
No single model can describe all stages of jet evolution

Multi-stage jet evolution in JETSCAPE

- **Jet 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 Majumder(13), Kordell, Majumder(17), Cao, Majumder(17)	**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)	**AdS/CFT** 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

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

Virtuality separation scale: Q_0

Switching between modules for parton by parton

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)
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Jet evolution simulation with JETSCAPE

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

jet R_{AA}, single hadron R_{AA}, jet v_2, hadron v_2 → **Talk by C. Park (Thu)**

- **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

Jet evolution simulation with JETSCAPE

- **Settings in simulations (PbPb 2.76 TeV)**

Jet

QGP fluid

Jet evolution simulation with JETSCAPE

- **Settings in simulations (PbPb 2.76 TeV)**

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- MATTER, LBT: <u>Recoil ON</u>
MARTINI, AdS/CFT: No medium response (to be implemented in future)

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- **Initial condition from TRENTo+Pythia (MPI, ISR: ON)**
  Moreland, Bernhard, Bass(14)

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- **Lund Hadronization**

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

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

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QGP fluid

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

Liu, Shen, Heinz(15)

Jet evolution simulation with JETSCAPE

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- **VISHNU (viscous hydro calculation)**
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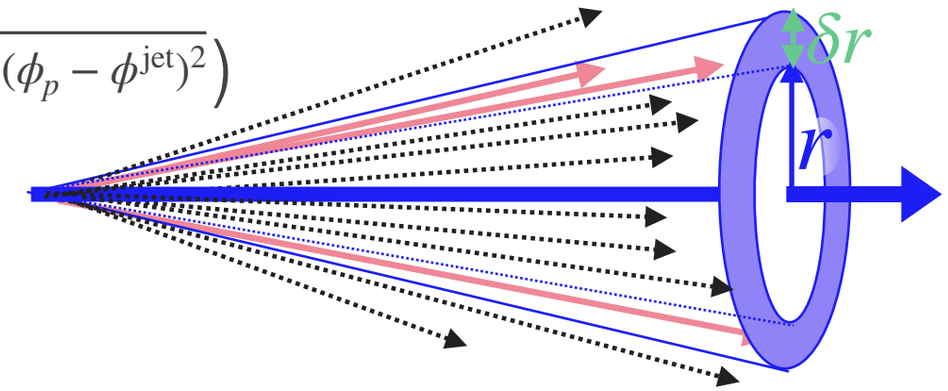
Jet Shape

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

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



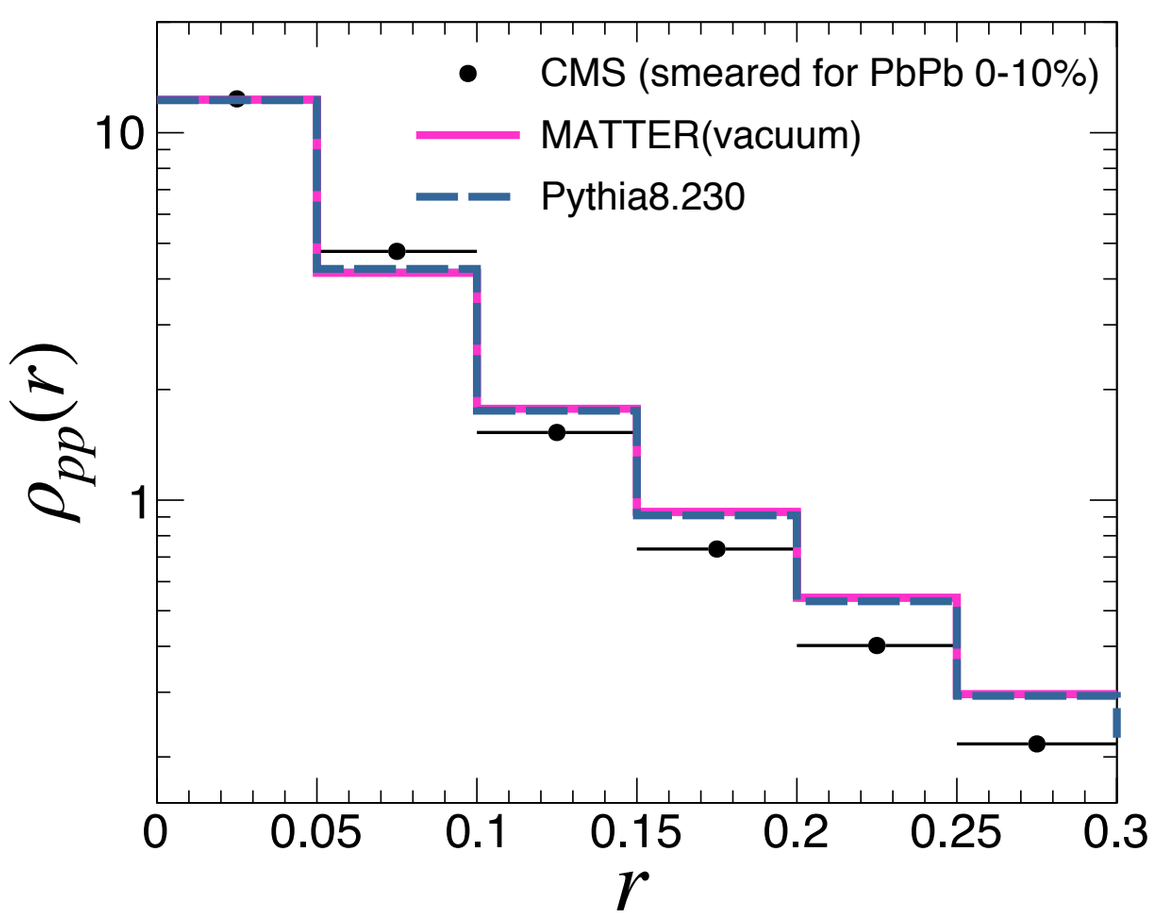
note: self-normalized observable

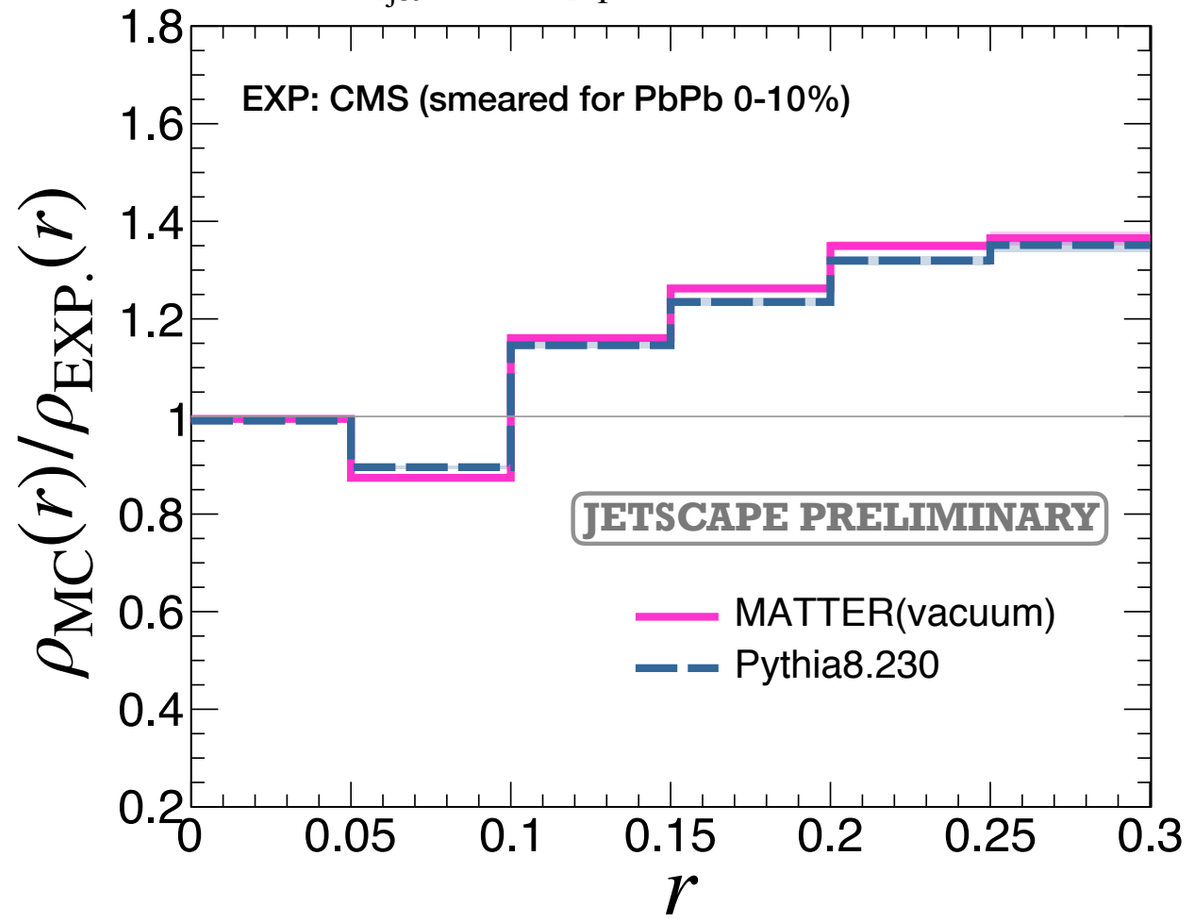
pp baseline

*Parameters in Pythia8.230 are default

CMS from PLB 730 (2014) 243

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





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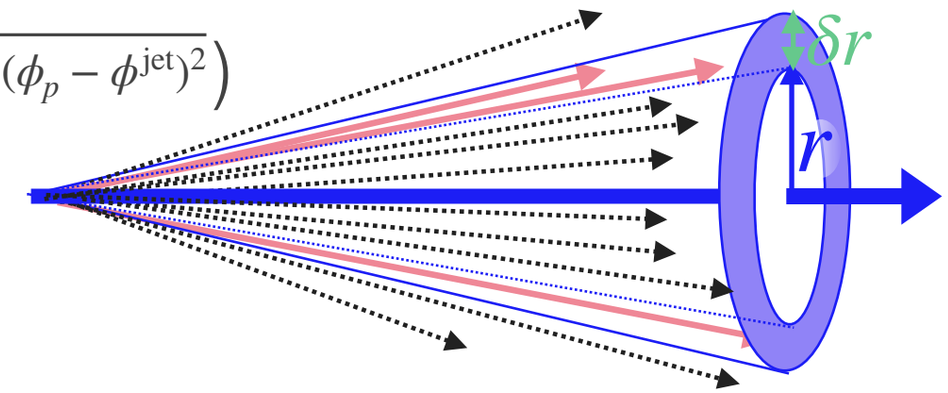

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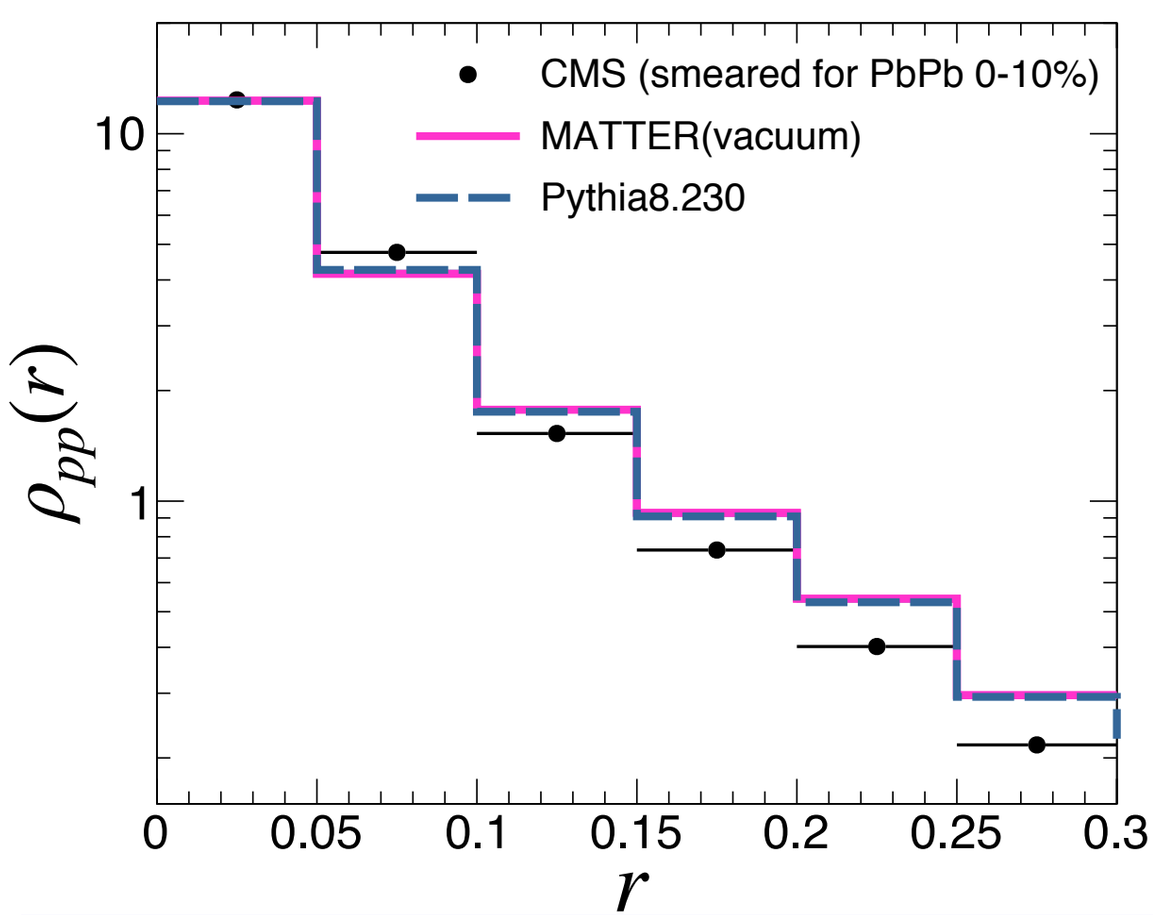

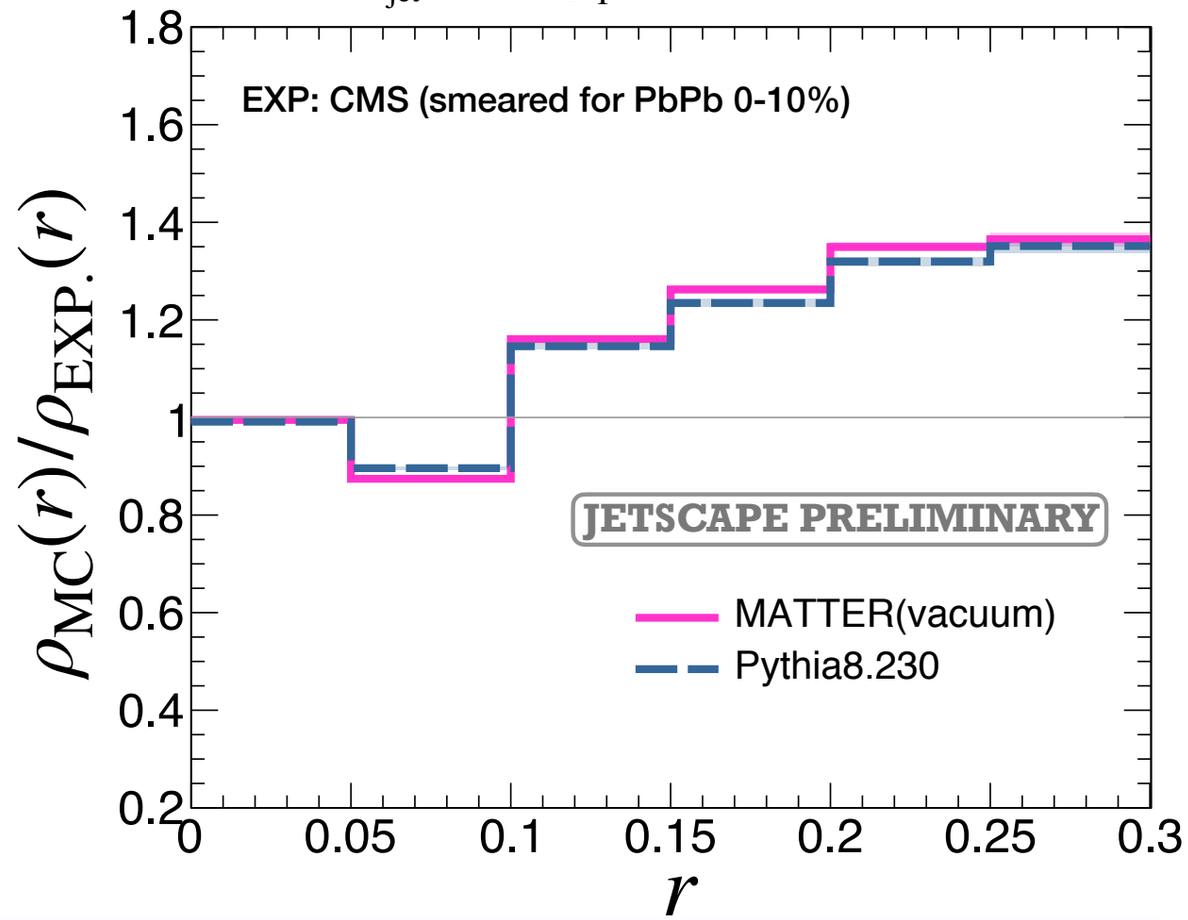

Need further parameters tuning, very similar behavior to default Pythia8

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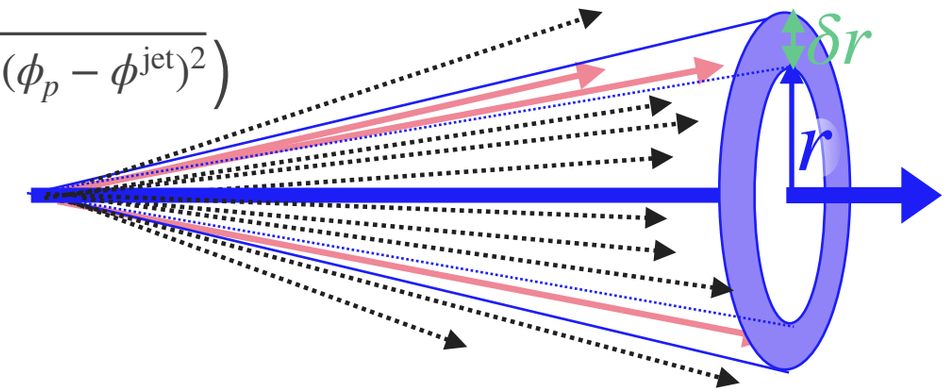

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PbPb/pp

CMS from PLB 730 (2014) 243

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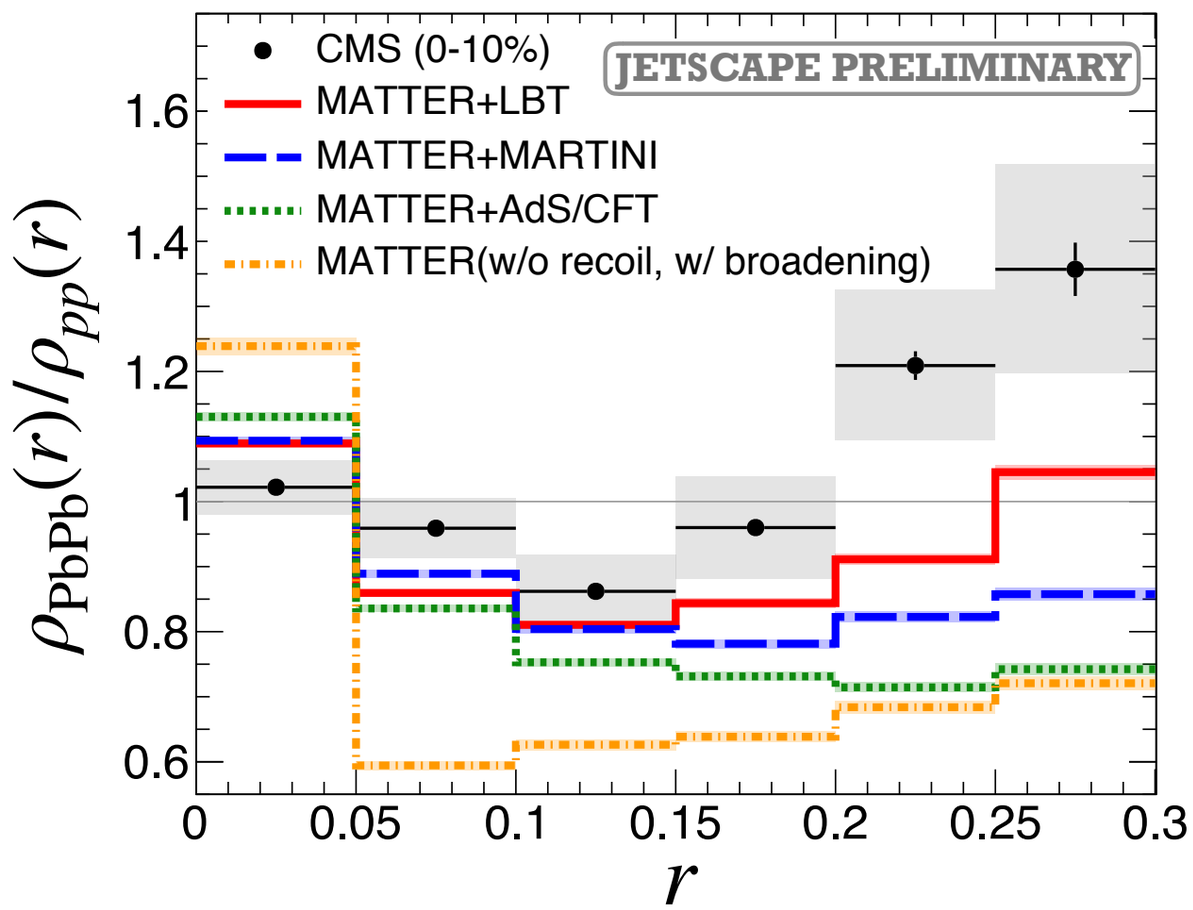

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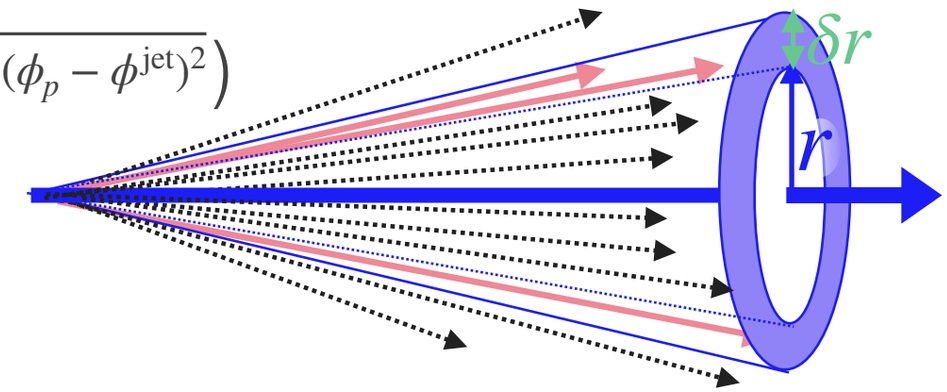

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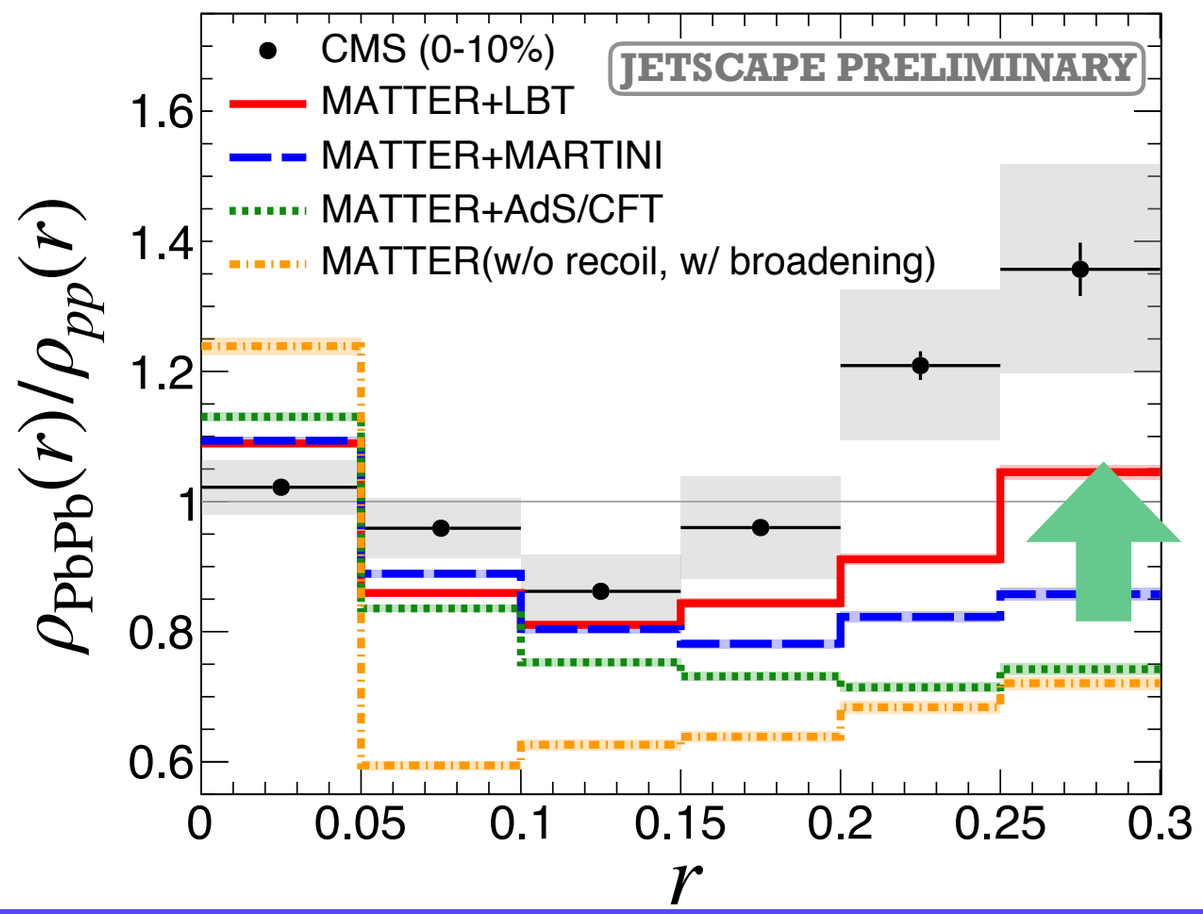

Enhancement around the edge of jet cone due to recoils in LBT

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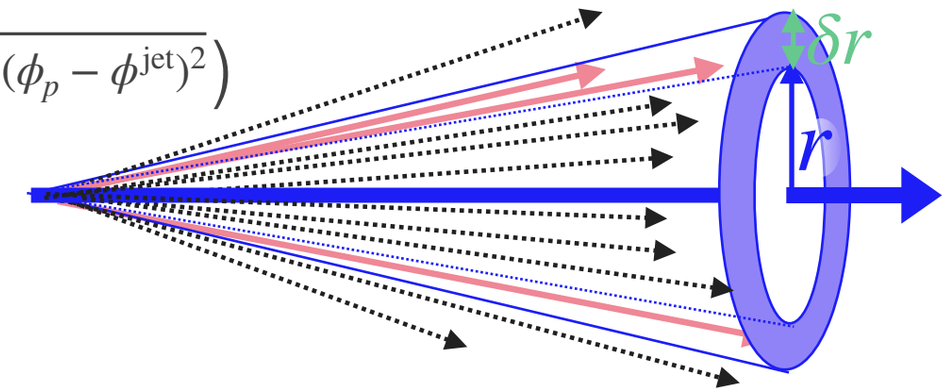

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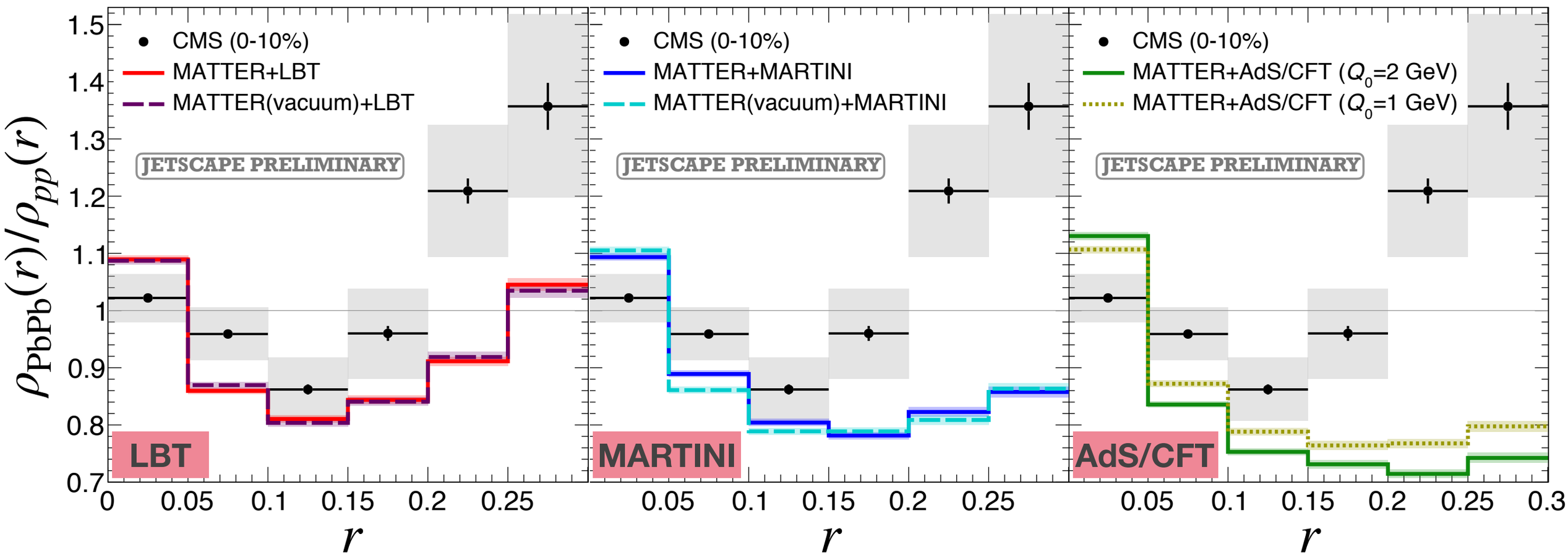

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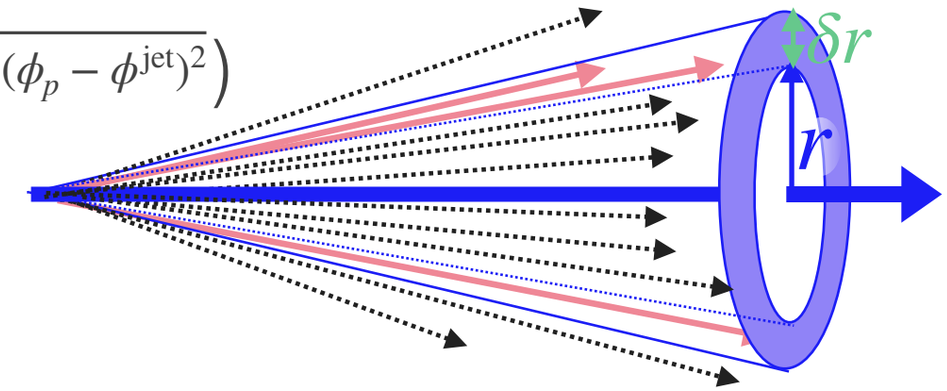

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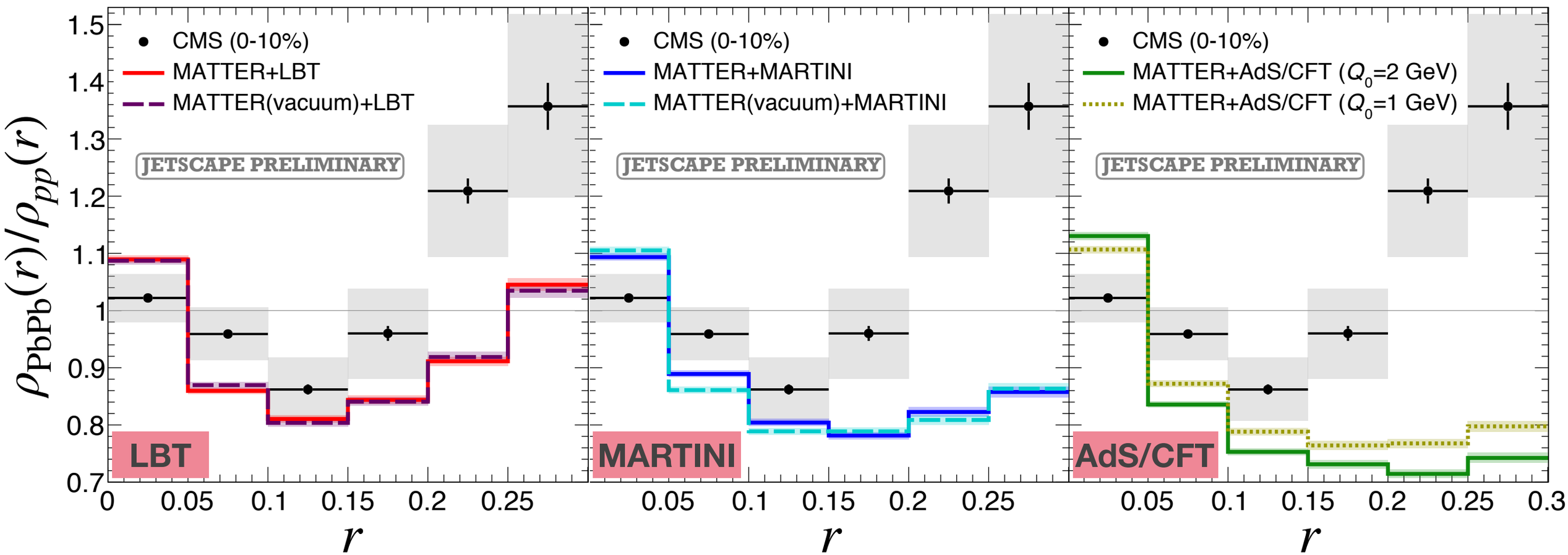
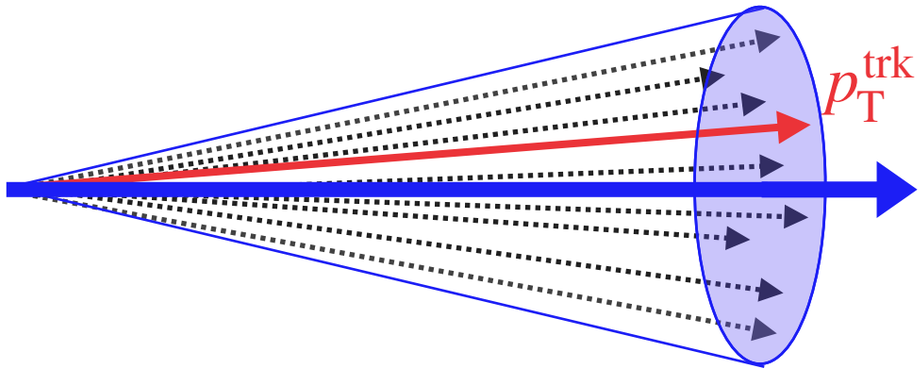


Medium effect during virtuality ordered splitting cannot be seen

Fragmentation Function

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



pp baseline

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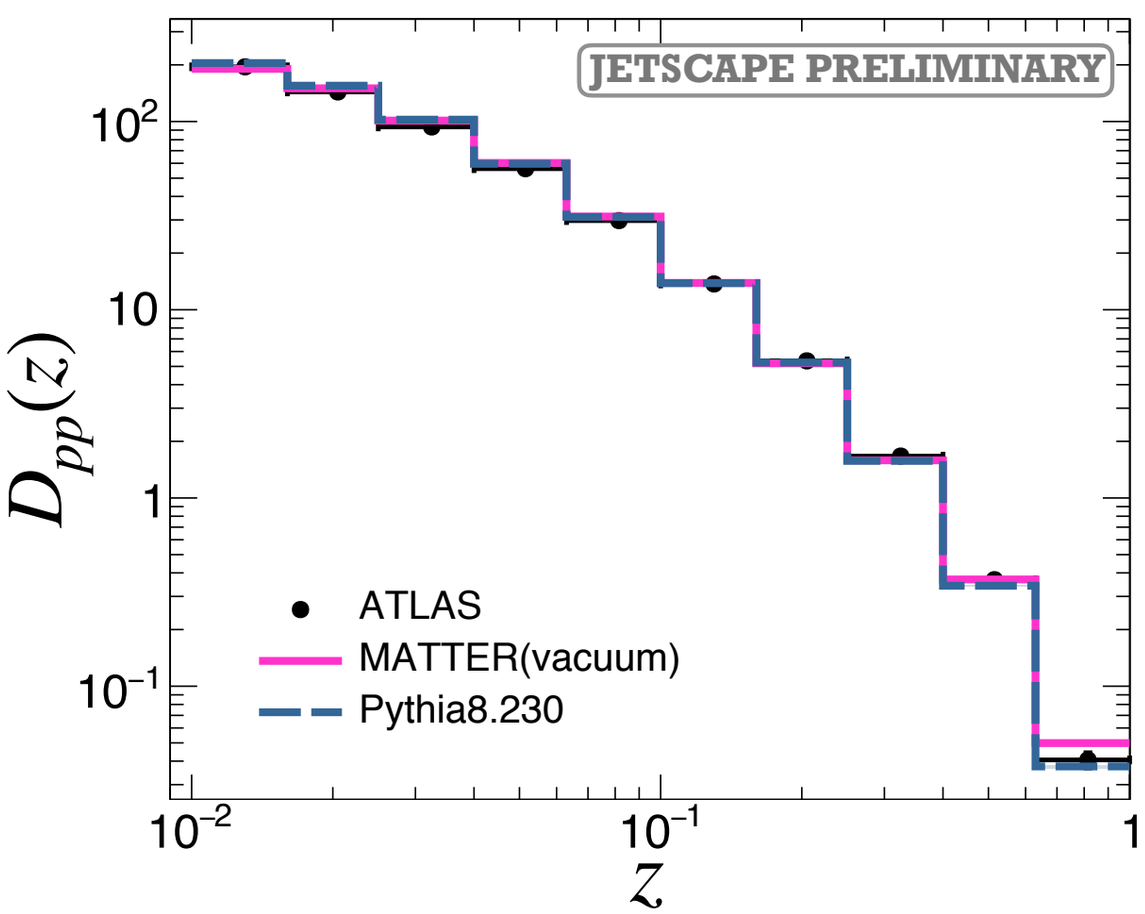
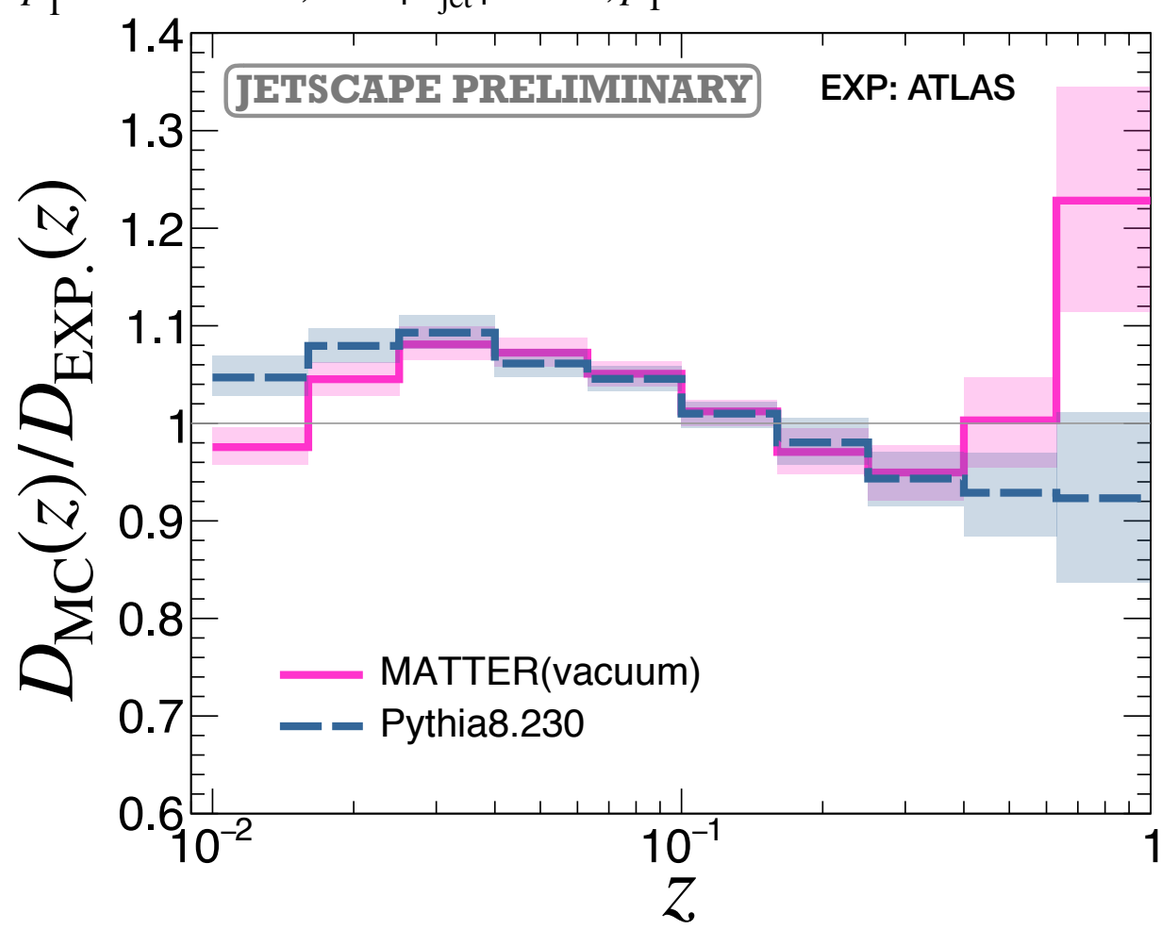
ATLAS from EPJ C77 (2017) 379

JETSCAPE, 2.76 TeV, pp, anti-k_{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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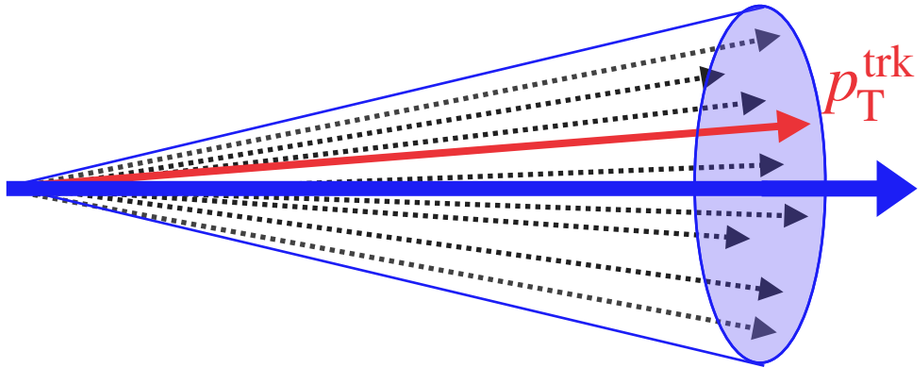
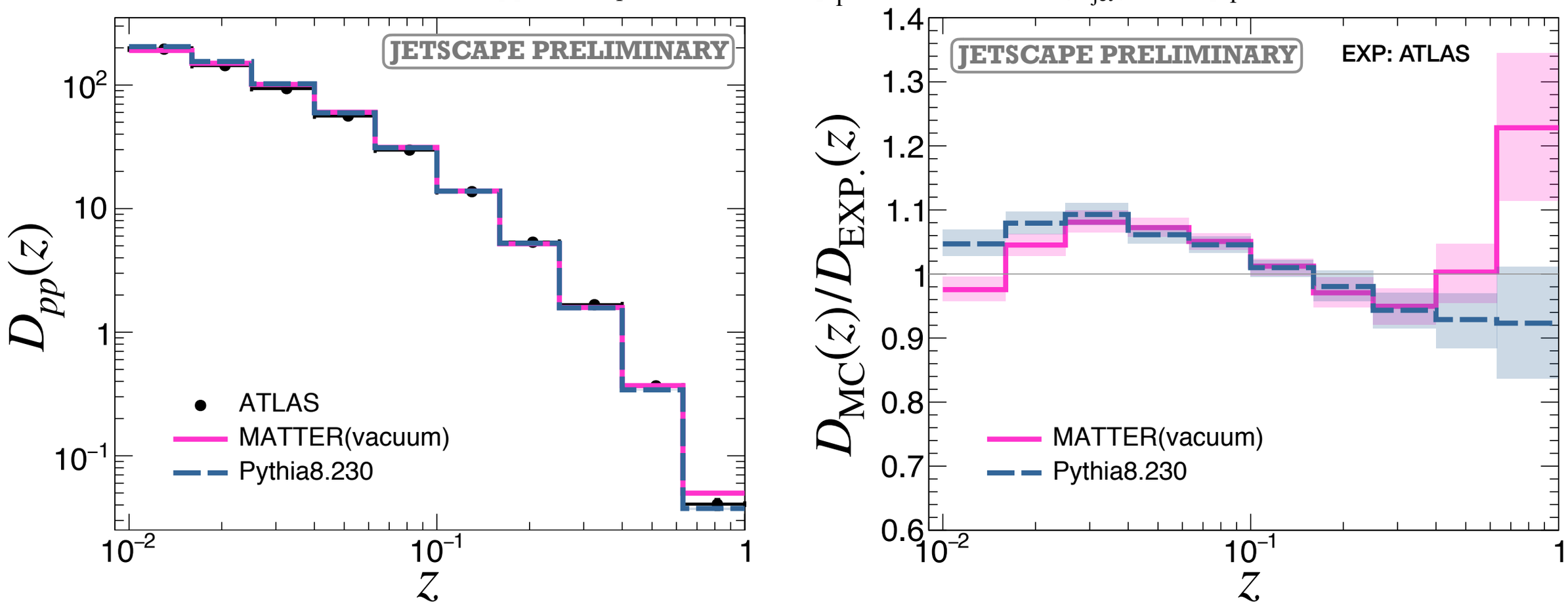


pp baseline

*Parameters in Pythia8.230 are default

ATLAS from EPJ C77 (2017) 379

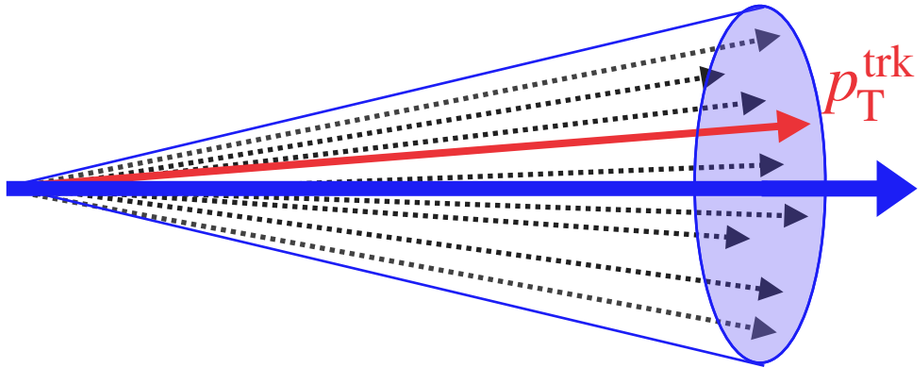
JETSCAPE, 2.76 TeV, pp, anti-$k_{\rm T}$ $R = 0.4$, $100 < p_{\rm T}^{\rm jet} < 398$ GeV, $0 < |Y_{\rm jet}| < 2.1$, $p_{\rm T}^{\rm trk} > 1$ GeV



Deviation at high-z, need further tunings

Fragmentation Function

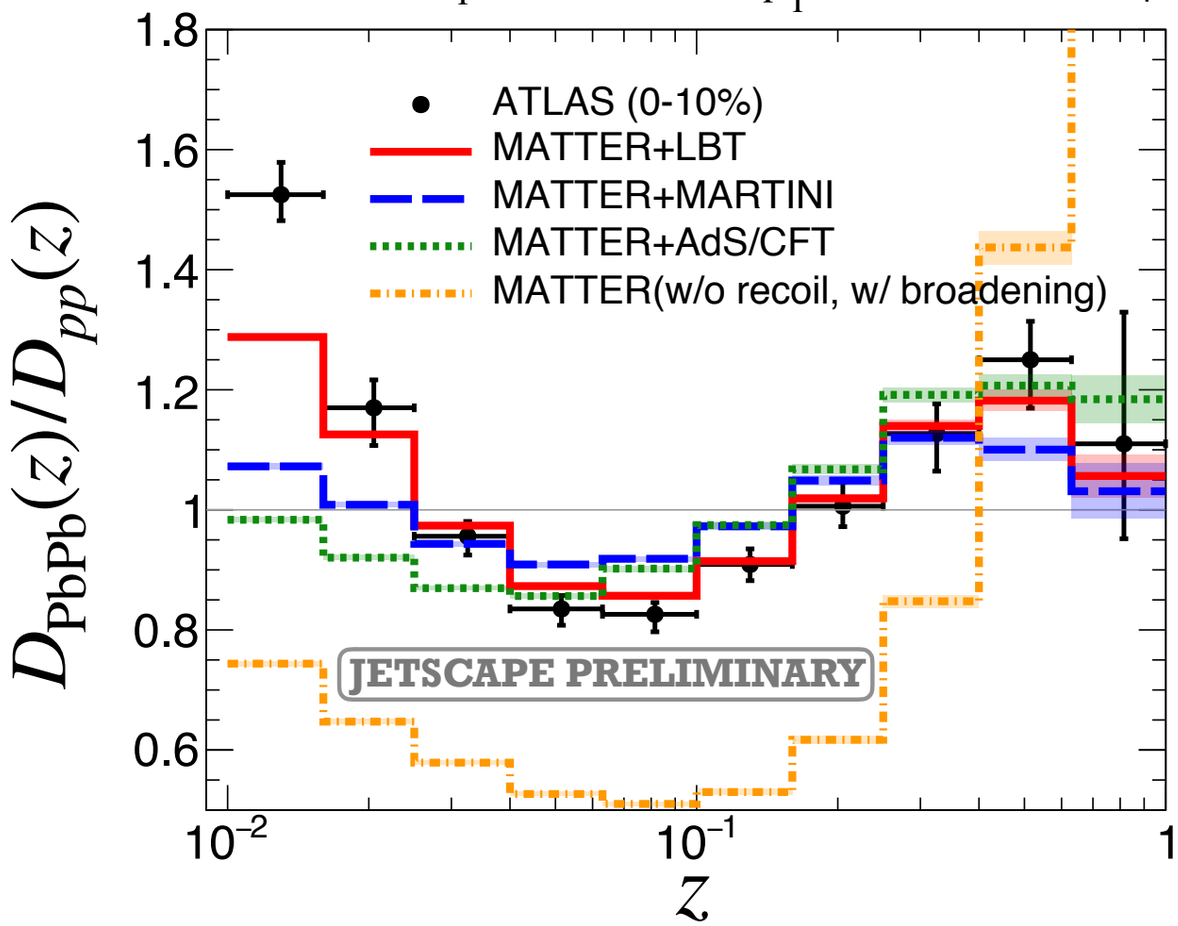
$$D(z) = \frac{1}{N_{\rm jet}} \frac{dN_{\rm trk}}{dz} \qquad \left(z = p_{\rm T}^{\rm trk} / p_{\rm T}^{\rm jet} \right)$$



PbPb/pp

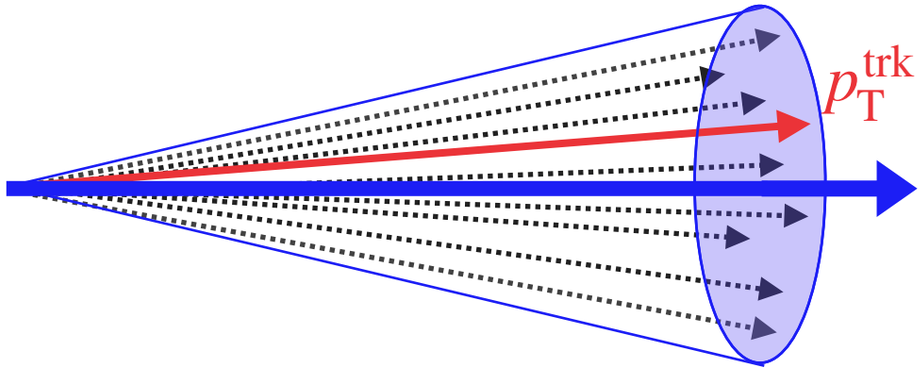
ATLAS from EPJ C77 (2017) 379

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



Fragmentation Function

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



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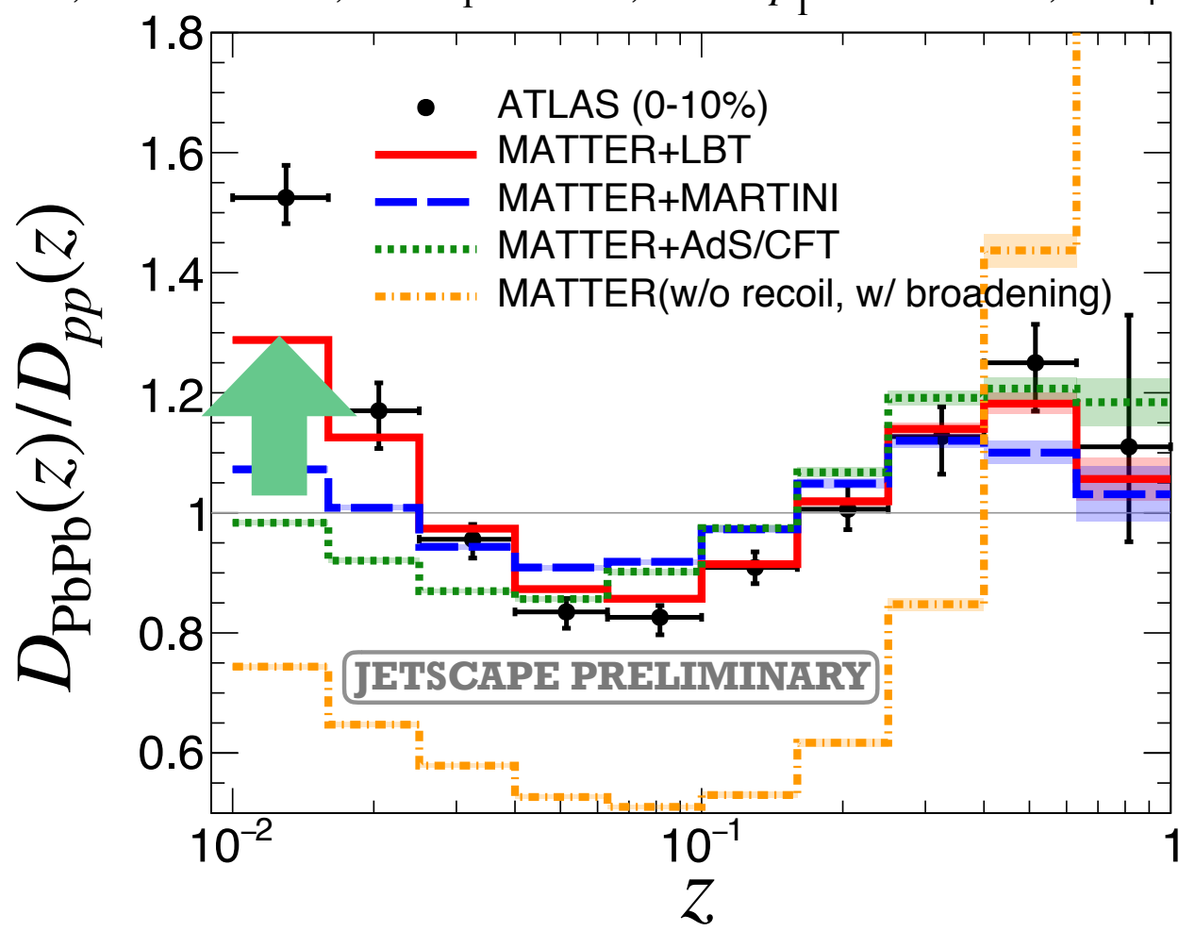
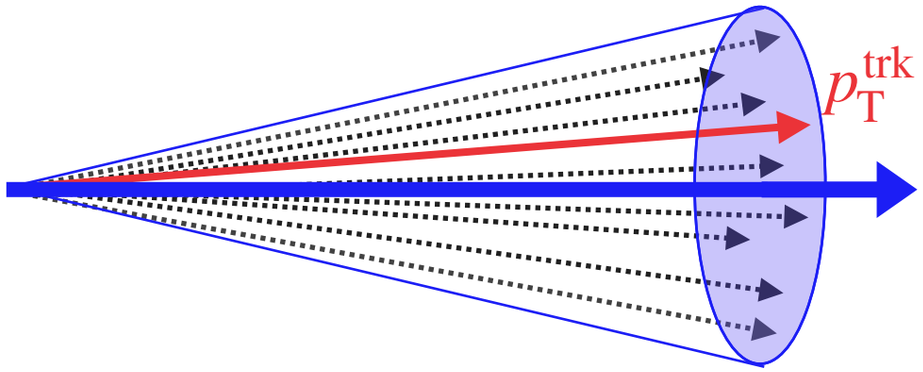


Small-z enhancement due to recoils in LBT

Fragmentation Function

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



PbPb/pp

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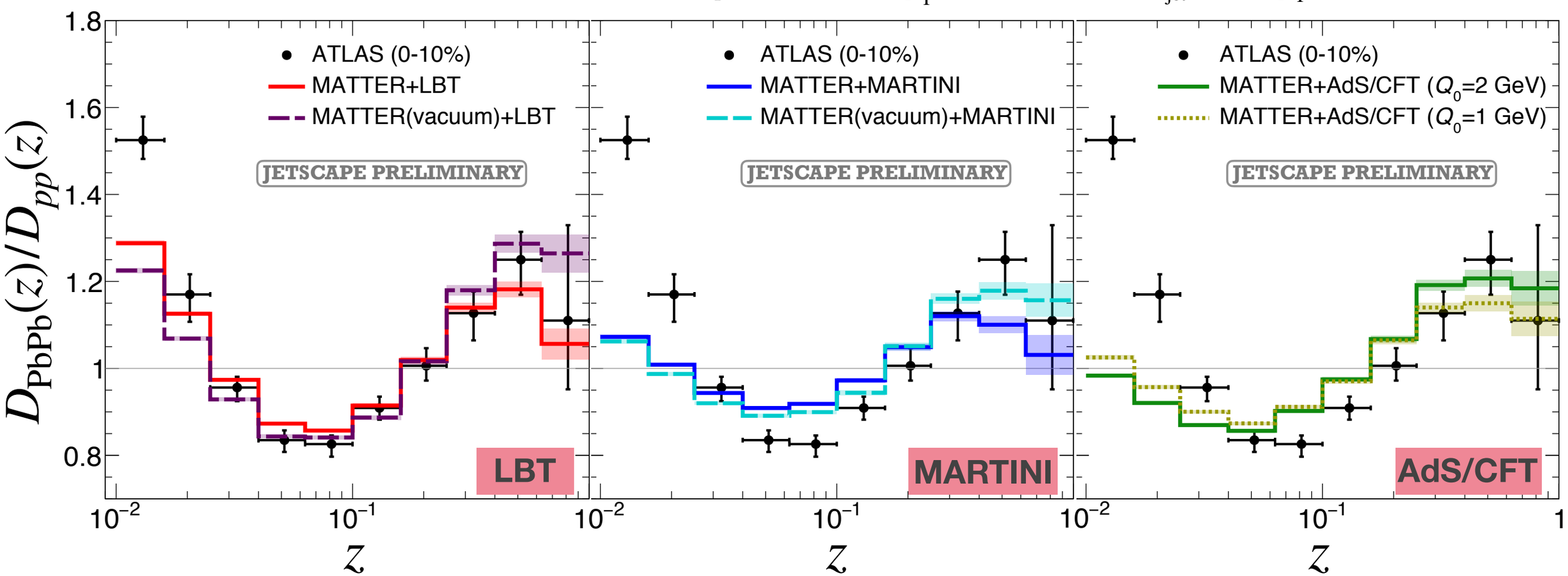
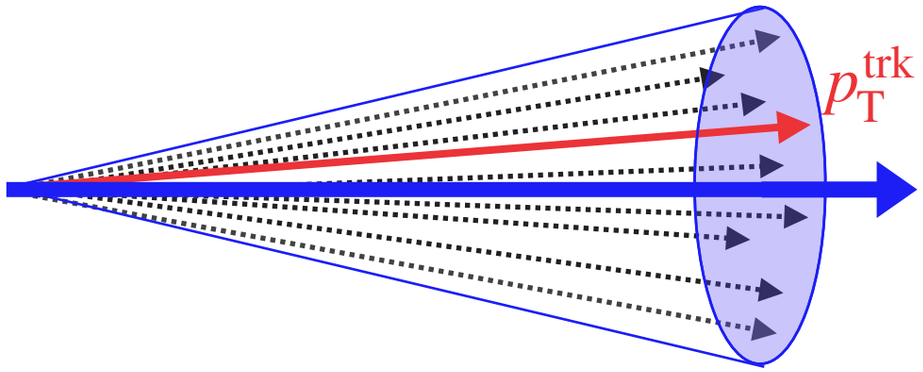


Fragmentation Function

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



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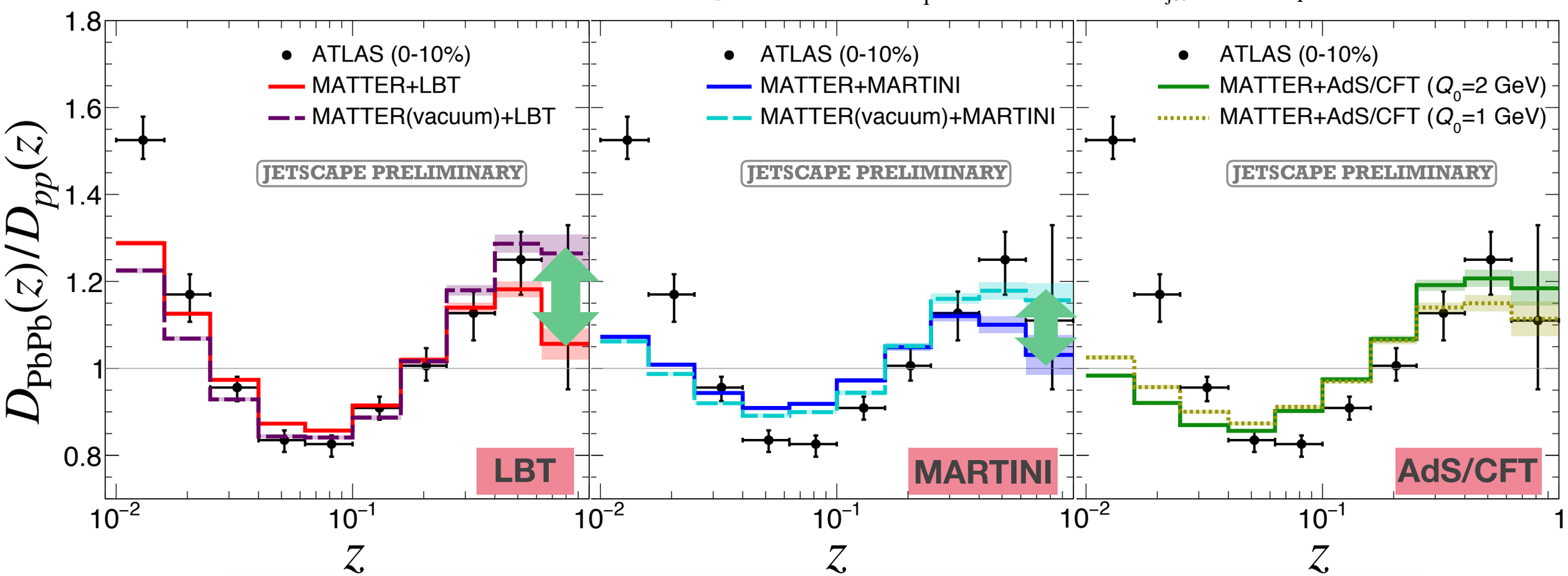


Medium effect during virtuality ordered splitting at large-z

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

    Fragmentation function: sizable at large-z

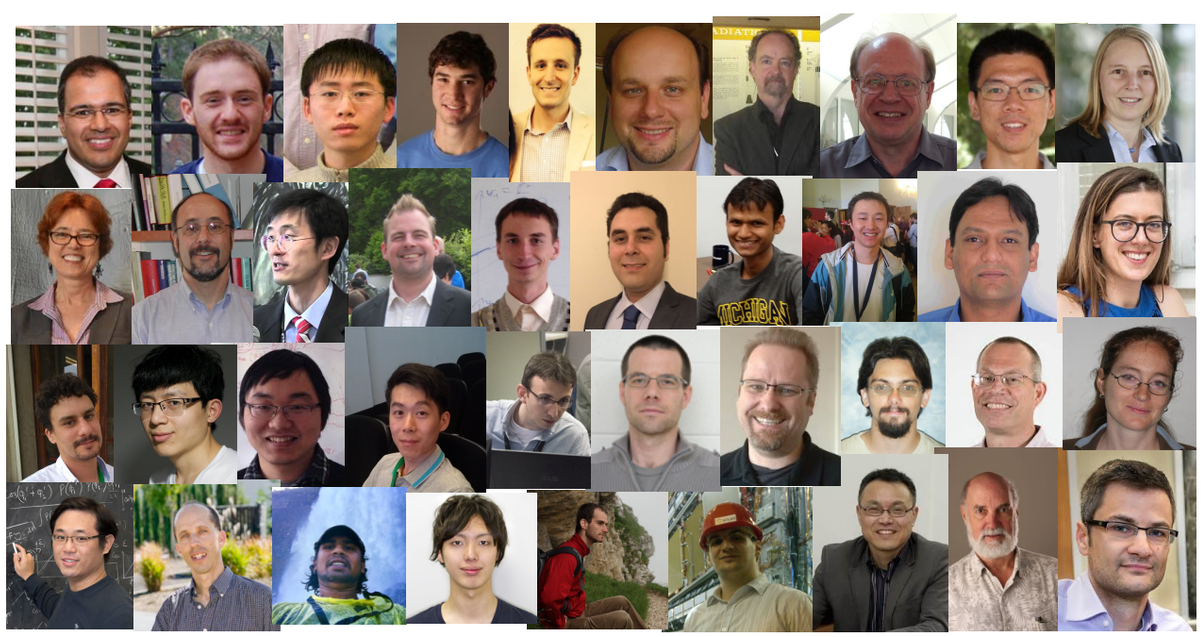
Outlook

- **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

The JETSCAPE Collaboration

- **Presentations from JETSCAPE Collaboration**
  - "Bayesian extraction of $\hat{q}$ with a multi-stage jet evolution approach" **by Ron Soltz (Tuesday)**
  - "Multi-stage jet evolution through QGP using the JETSCAPE framework: inclusive jets, correlations and leading hadrons" **by Chanwook Park (Thursday)**
  - "JETSCAPE 1.0: The first software release of the JETSCAPE collaboration" **by Joern Putschke (Poster)**
  - "p+p physics with the JETSCAPE 1.0 framework" **by Rainer Fries (Poster)**



JETSCAPE

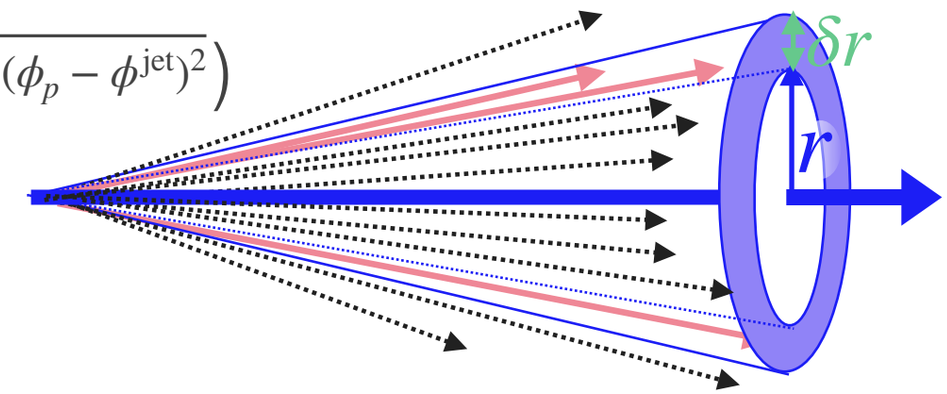
Thanks to all collaborators!

Backup

Jet Shape

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

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

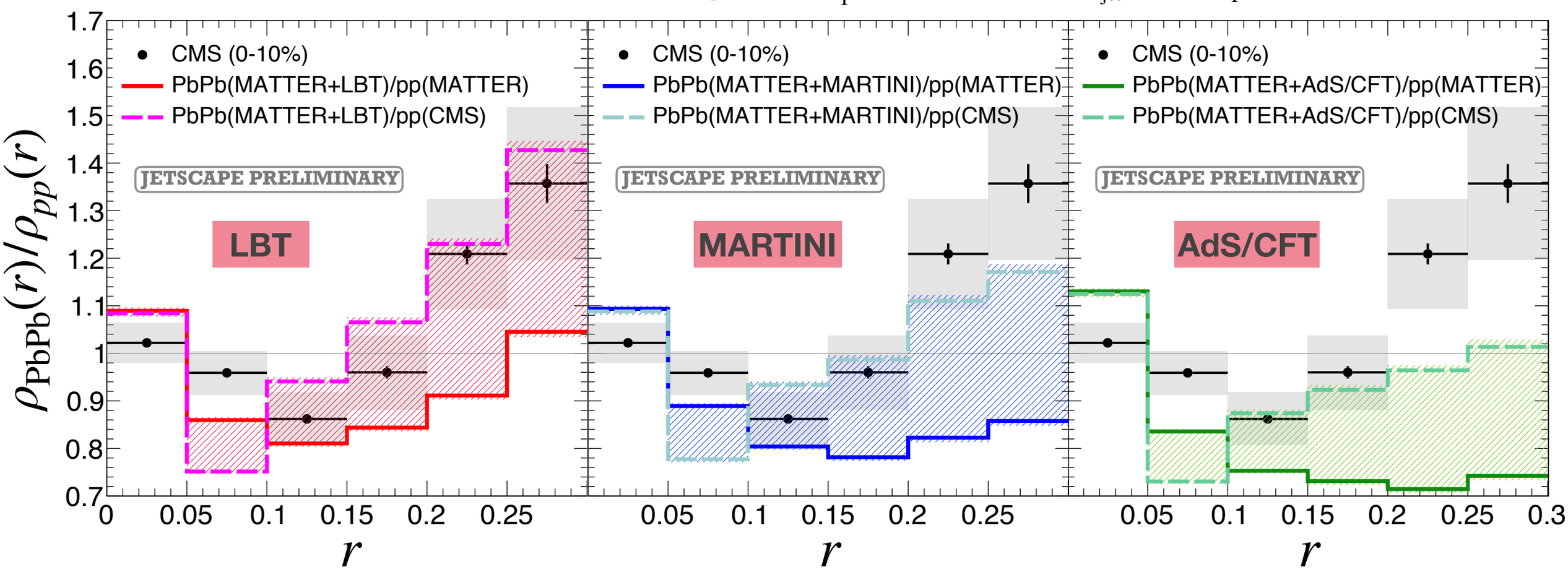


note: self-normalized observable

PbPb/pp

CMS from PLB 730 (2014) 243

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



pp baseline dependence

Jet Shape

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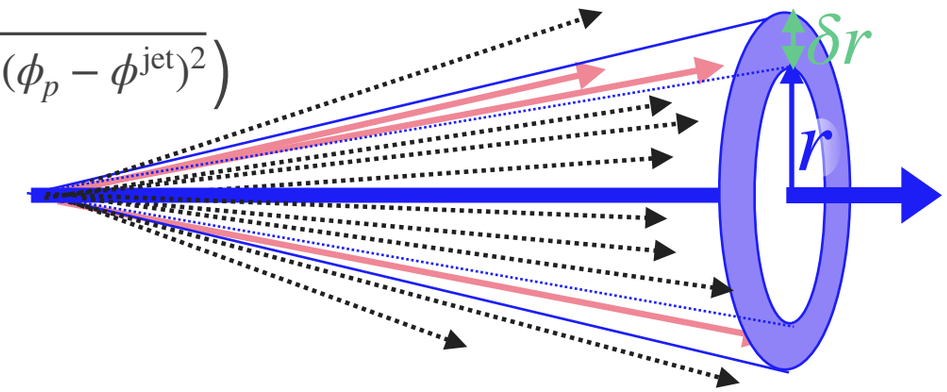

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