Parton shower and jets in the quark-gluon plasma

Grégory Soyez

IPhT, CNRS, CEA Saclay

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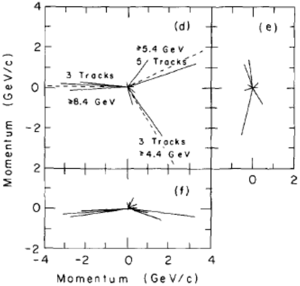
based on arXiv:1801.09703 (PRL120(2018)232001) and arXiv:1907.04866
in collaboration with Paul Caucal, Edmond Iancu and Al Mueller

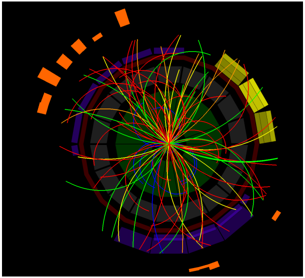
Jets in different environments

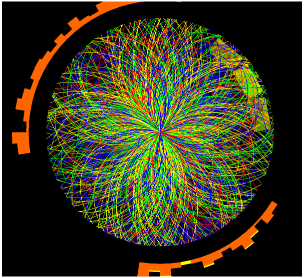
increasing complexity →

precision | searches | qualitative behaviour

e^+e^- | pp | $PbPb$

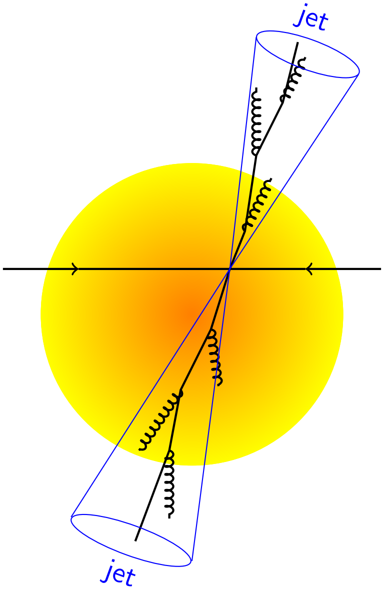






- Jets used everywhere (especially with LHC kinematic reach)
- We are used to jets for precision and searches
- This talk: what can we learn from pQCD in *AA* collisions?

Jets propagating through the QGP



- high-p_T jet and QGP interact
- measure differences wrt *pp* ("vacuum")
- infer properties of the QGP

Seeking driving physics mechanisms

"jet $\leftrightarrow$ parton shower"
$\Rightarrow$ need to understand parton showers

Main idea

Start from the most fundamental (simple) point of view in pQCD

Seeking driving physics mechanisms

"jet ↔ parton shower"
⇒ need to understand parton showers

Main idea

Start from the most fundamental (simple) point of view in pQCD

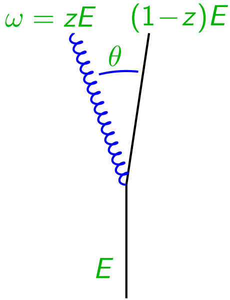
Assumptions:

1. target a "leading-logarithmic" (often double logs) accuracy
2. simple, fixed, medium of size L and transport coefficient $\hat{q}$
   ($\hat{q}$ is the averaged $k_\perp^2$ per unit length via kicks from the medium)

emission in QCD:

vacuum-like or medium-induced

Vacum-like emissions



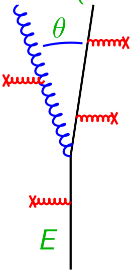
Standard "DGLAP" splitting rate:

$$d^2\mathcal{P}_{\text{vle}} = \frac{\alpha_s(k_\perp)}{\pi} P(z)dz \, \frac{d\theta}{\theta} \approx \frac{2\alpha_s(k_\perp)}{\pi} \frac{dz}{z} \frac{d\theta}{\theta}$$

✓ includes soft&collinear divergence

✓ Iterated (Markovian process) for successive branchings with angular ordering $\theta_{i+1} < \theta_i$

Medium-induced emissions



Medium interactions $\Rightarrow$ additional emissions

BDMPS-Z spectrum ($\omega_c = \frac{1}{2}\hat{q}L^2$)

$$d^2\mathcal{P}_{\text{mie}} \approx \frac{\alpha_{s,\text{med}}C_R}{\pi}\sqrt{\frac{2\omega_c}{E}}\,\frac{dz}{z^{3/2}}\,\mathcal{P}_{\text{broad}}(\theta,\omega)$$

✓ strong peak at small z, no collinear div.
✓ Here: assume θ from Gaussian $k_\perp$ broadening
✓ Iterated (Markovian process) for successive branchings in formation time $t_f = \frac{2}{\omega\theta^2}$
✓ NO ANGULAR ORDERING

Mainly 3 scales in the problem:

- In first approximation θ comes from (Gaussian) broadening
  Typical $k_\perp = \omega\theta \approx Q_s = \sqrt{\hat{q}L}$
- (Semi-)hard emission with $\omega \lesssim \omega_c$ follow the BDMPS-Z spectrum
  $\omega \lesssim \omega_c \;\Rightarrow\; \theta \gtrsim \theta_c \ll R$: i.e. these mostly stay in the jet
- Avalanche (turbulent flow) of soft emission $\omega \lesssim \omega_{\text{br}} = \alpha_s^2\omega_c$
  Large angles $> R \Rightarrow$ jet energy loss

A full (parton) shower in heavy-ion collisions
including both VLEs and MIEs

Double-logarithmic approximation

Idea: compare the transverse momenta over the formation time: $t_f = \frac{2}{\omega\theta^2}$

$$k^2_{\perp,\text{vac}} = \omega^2\theta^2$$
$$k^2_{\perp,\text{med}} = \hat{q}t_f = \frac{2\hat{q}}{\omega\theta^2}$$

Double-logarithmic approximation

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$$k^2_{\perp,\text{med}} = \hat{q}t_f = \frac{2\hat{q}}{\omega\theta^2}$$

2 possible cases:

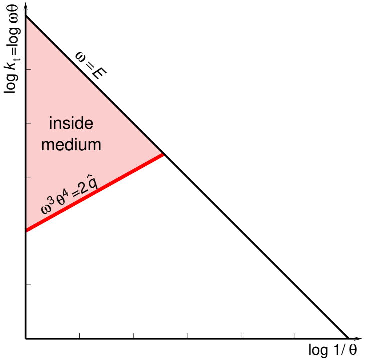
- $k^2_{\perp,\text{vac}} \gg k^2_{\perp,med}$: VLE
- $k^2_{\perp,\text{vac}} \ll k^2_{\perp,med}$: MIE

transition at $k^2_{\perp,\text{med}} = k^2_{\perp,vac}$ i.e. $\omega^3\theta^4 = 2\hat{q}$

Factorised physical picture

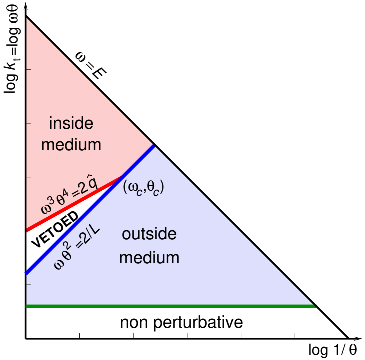
Double-log accuracy:

- in-medium VLEs



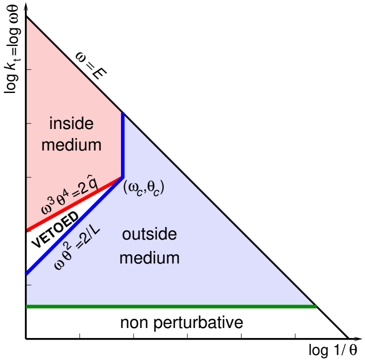
Double-log accuracy:

- in-medium VLEs
- medium length ($t_f = L$)
- VLEs vetoed in between



Double-log accuracy:

- in-medium VLEs
- medium length ($t_f = L$)
- VLEs vetoed in between
- colour (de)coherence
  - ✓ in-medium has $\theta > \theta_c$
  - ✓ in-medium: angular-ordered
  - ✓ in→out jump: no orgering



Factorised physical picture

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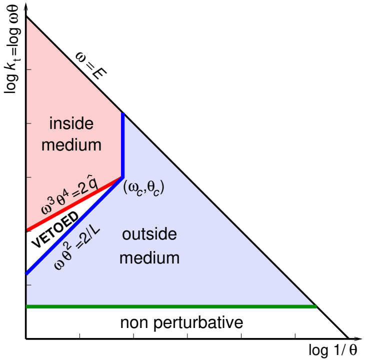


Full picture: parton shower factorised in 3 stages

1. in-medium angular-ordered VLEs
2. each VLE sources MIEs propagating through the medium
3. out-medium VLEs with first emission at any angle

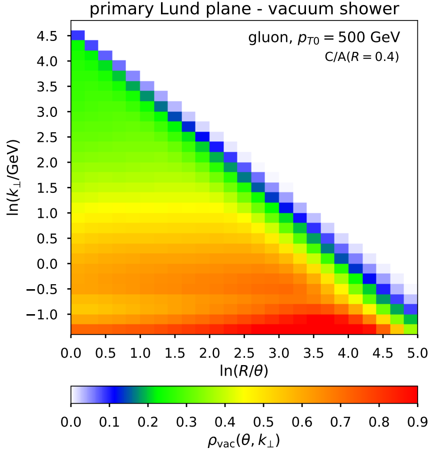
Easily amenable to a Monte-Carlo implementation

- Collinear limit (with full DGLAP splitting)
- 5 parameters:
  2 "non-physical": $\theta_{\max}$ and $k_{\perp,\min}$ [probe approximations]
  3 physical: $\hat{q}$, L, $\alpha_{s,\text{med}}$ [probe medium effects]
- Test scale dependence around default setup:

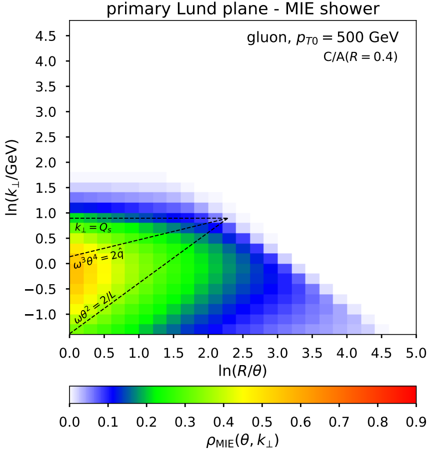
	parameters			physics constants		
	$\hat{q}$ [GeV^2/fm]	L [fm]	$\alpha_{s,\text{med}}$	θ_c	ω_c [GeV]	ω_{br} [GeV]
default	1.5	4	0.24	0.041	60	3.5
vary θ_c	0.667	6	0.24	0.033	60	3.5
	3.375	2.667	0.24	0.050	60	3.5
vary ω_c	0.444	6	0.294	0.041	40	3.5
	5.063	2.667	0.196	0.041	90	3.5
vary ω_{br}	1.5	4	0.196	0.041	60	2.3
	1.5	4	0.294	0.041	60	5.2

Emission patterns

“*pp*” shower

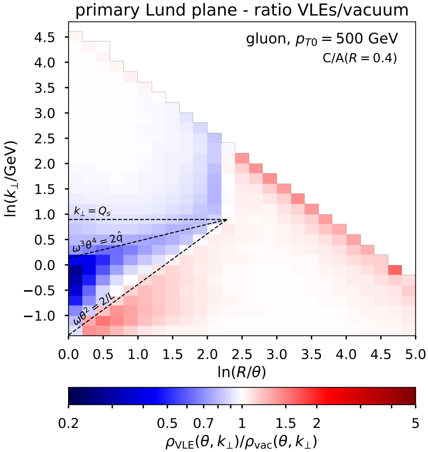


MIE shower

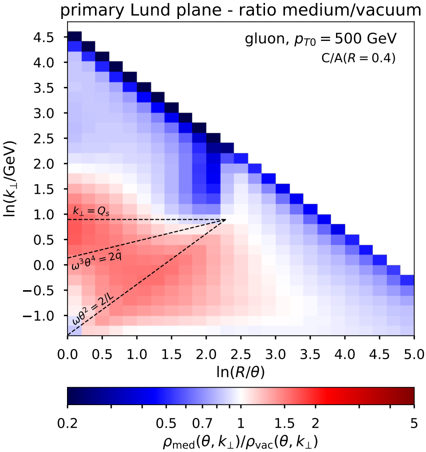


Emission patterns

AA/pp(VLEs only)

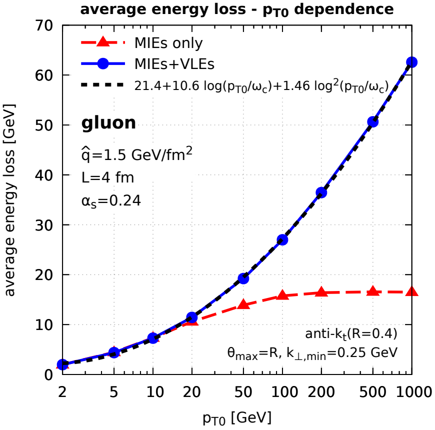


AA/pp(VLEs+MIEs)



Basic phenomenology

jet spectrum: energy loss and R_{AA}



Shower from single parton with p_{T0}

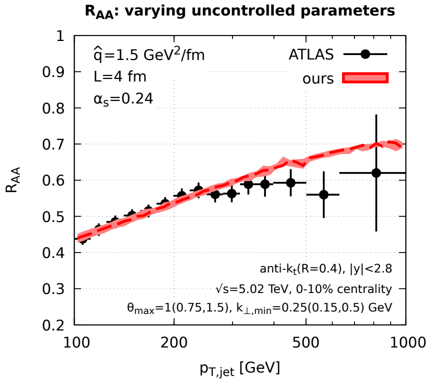
Main message

multiple sources for MIEs

(from the in-medium VLE shower)

$\Rightarrow$ $E_{\rm loss}$ increases with p_{T0}

Jet nuclear modification factor



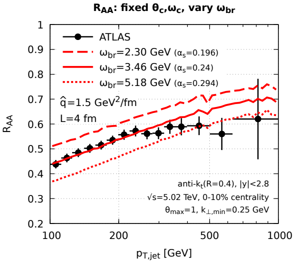
✓Decent description of R_{AA}

✓VLE multiplicity keeps R_{AA} small

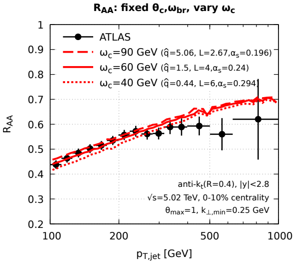
(independent of non-phys parameters)

R_{AA} mostly affected by (the multiple emission scale) $\omega_{\rm br}$

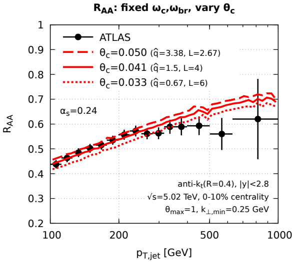
varying $\omega_{\rm br}$



varying ω_c



varying θ_c



Basic phenomenology

jet substructure: z_g distribution

Two effects, two regimes

Two basic phenomena:

1. SoftDrop condition triggered either by a VLE or by a MIE
2. both subjets lose energy by MIE emissions

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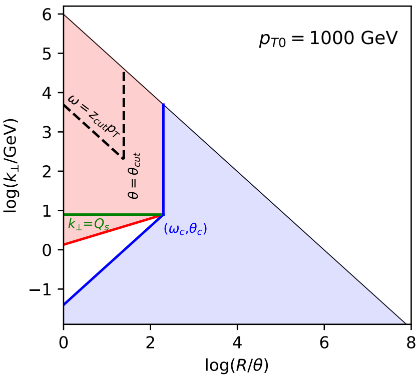

Note: (i) use mMDT (SD, $\beta = 0$)

(ii) impose condition $\theta_g > \theta_{cut}$

High-p_T ($p_T z_{cut} \theta_{cut} \gg \omega_c \theta_c$)

only VLEs can contribute

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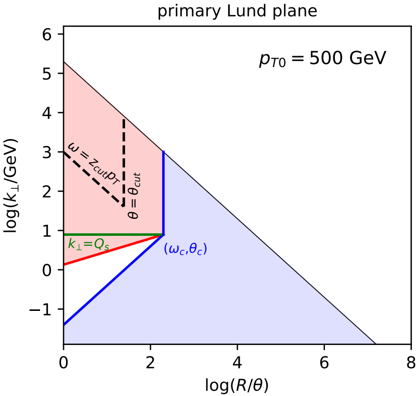

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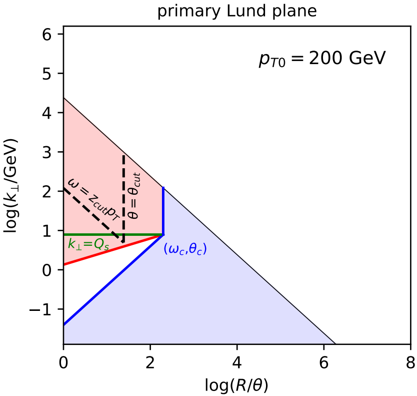

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High-p_T ($p_T z_{cut} \theta_{cut} \gg \omega_c \theta_c$)

only VLEs can contribute

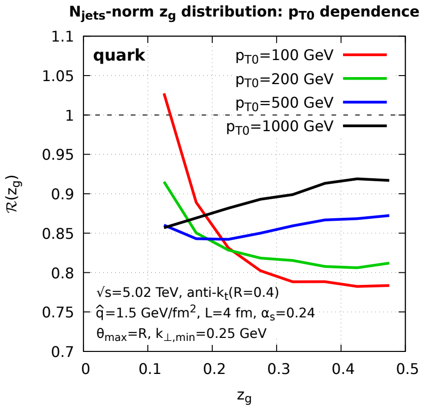
Low-p_T ($p_T z_{cut} \theta_{cut} \lesssim \omega_c \theta_c$)

both VLEs and MIEs

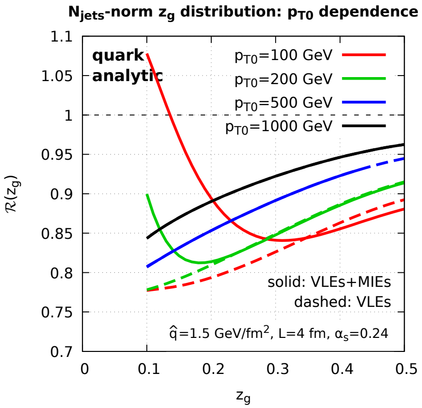
MIEs add peak at small z_g

Parton with fixed p_{T0}

Monte Carlo

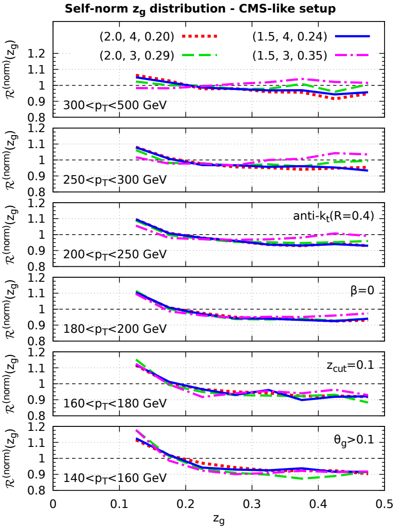


Analytic

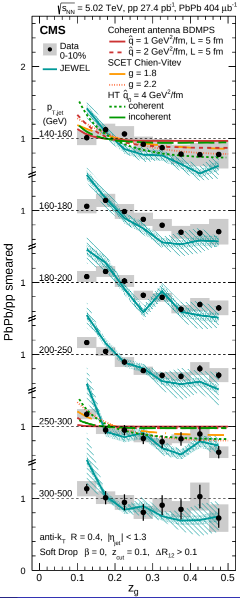


- good (qualitative) agreement MC v. analytic
- clear MIE peak visible at smaller p_{T0} as well as E_{loss} effect
- transition low→high p_{T0}

Monte Carlo



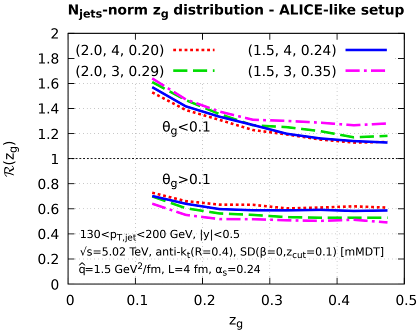
CMS (CMS-HIN-16-006)



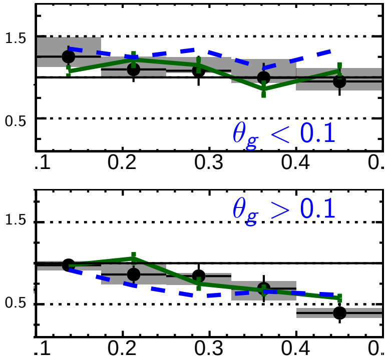
hint of a transition in the data?

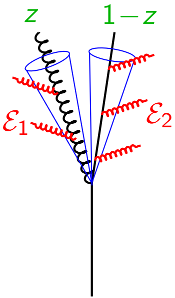
Full jet spectrum

Monte Carlo



ALICE (CERN-EP-2019-087)





With (subjet) energy loss:

$$z_g \approx \frac{z p_{T0} - \mathcal{E}_1}{p_{T0} - \mathcal{E}_1 - \mathcal{E}_2}$$

$$\overset{\mathcal{E}_1=\mathcal{E}_1=\mathcal{E}}{\Rightarrow} \quad z = z_g + (1-2z_g)\frac{\mathcal{E}}{p_{T0}} > z_g$$

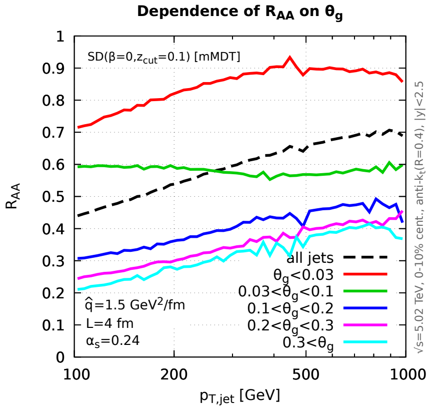
i.e. physical splitting z larger than measured z_g

Soft limit:

$$\mathcal{R}(z_g) \approx \left(1 - 2\frac{\mathcal{E}}{p_{T0}}\right)\left(1 - \frac{1-2z_g}{z_g}\frac{\mathcal{E}}{p_{T0}}\right)$$

i.e. a suppression more pronounced at small z_g

Suggestion for future measurements



R_{AA} in bins of θ_g

R_{AA} and z_g both controlled by $E_{\rm loss}$

smaller θ_g

- $\Rightarrow$ less phase-space for VLEs
- $\Rightarrow$ less $E_{\rm loss}$
- $\Rightarrow$ R_{AA} increases

Summary and future plans

Summary and future plans

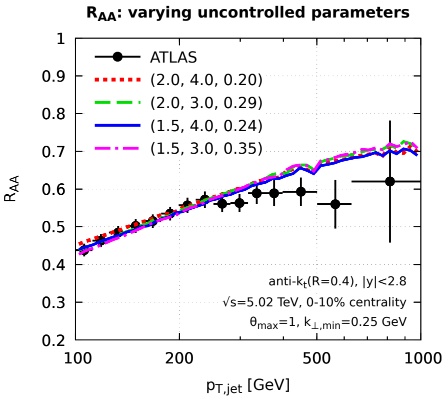
Take-home messages

- ✓ Simple, factorised, picture of *AA* parton showers
- ✓ Easy Monte Carlo implementation
- ✓ First pheno study are convincing

Future plans

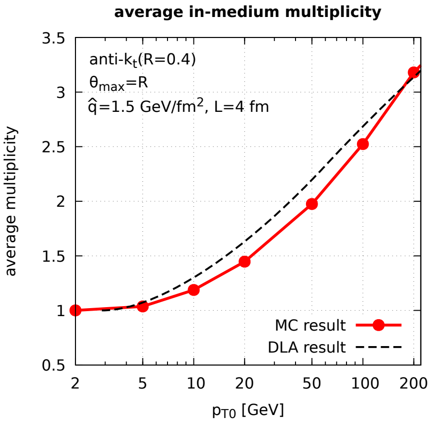
- *pp* side: move to full dipole shower
- *AA* side: long list of improvements, including
  - expanding medium
  - running coupling
  - improved broadening
  - elasic collisions
  - collision geometry
  - hadronisation model
- More pheno studies

Backup



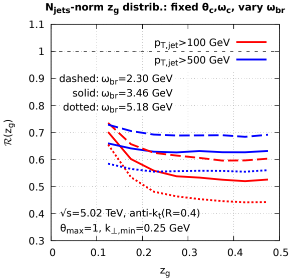
RAA: varying uncontrolled parameters
ATLAS
(2.0, 4.0, 0.20)
(2.0, 3.0, 0.29)
(1.5, 4.0, 0.24)
(1.5, 3.0, 0.35)
anti-kt(R=0.4), |y|<2.8
√s=5.02 TeV, 0-10% centrality
θmax=1, k⊥,min=0.25 GeV
RAA
pT,jet [GeV]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
100
200
500
1000

multiplicity of sources

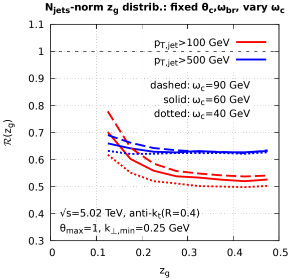


z_g mostly affected by (the multiple emission scale) $\omega_{\rm br}$

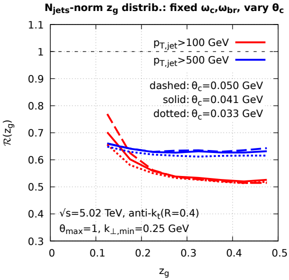
varying $\omega_{\rm br}$



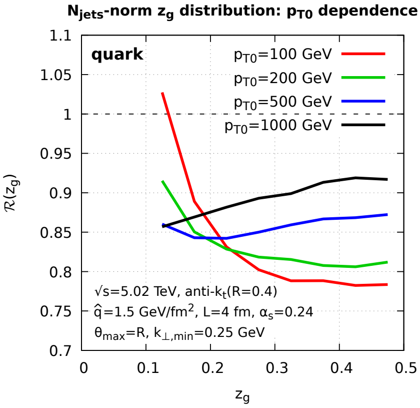
varying ω_c

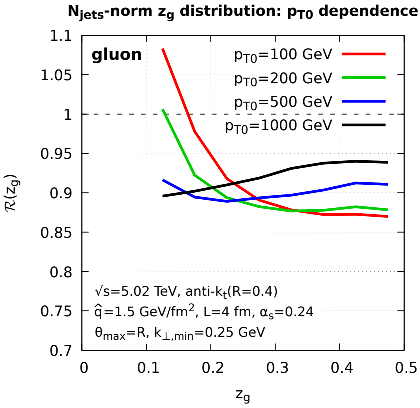


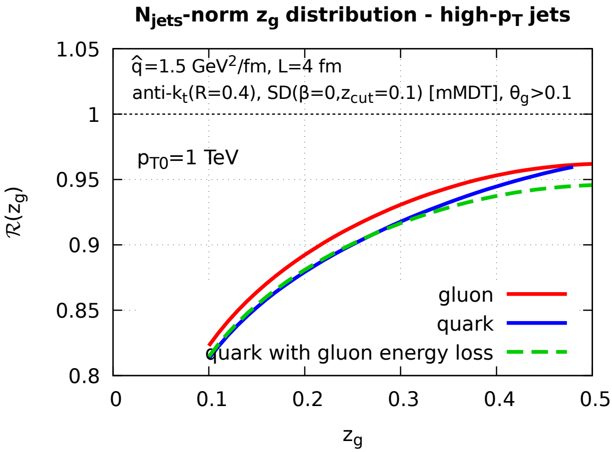
varying θ_c



quarks v. gluons

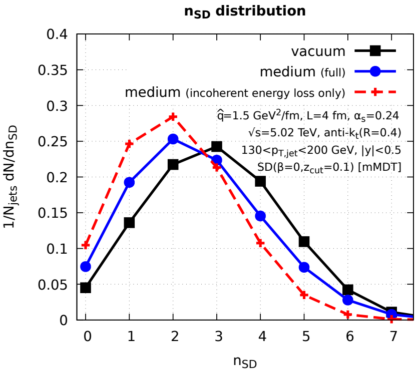


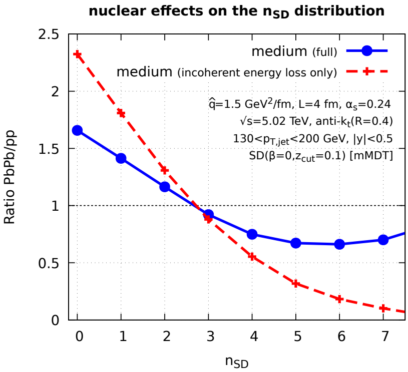




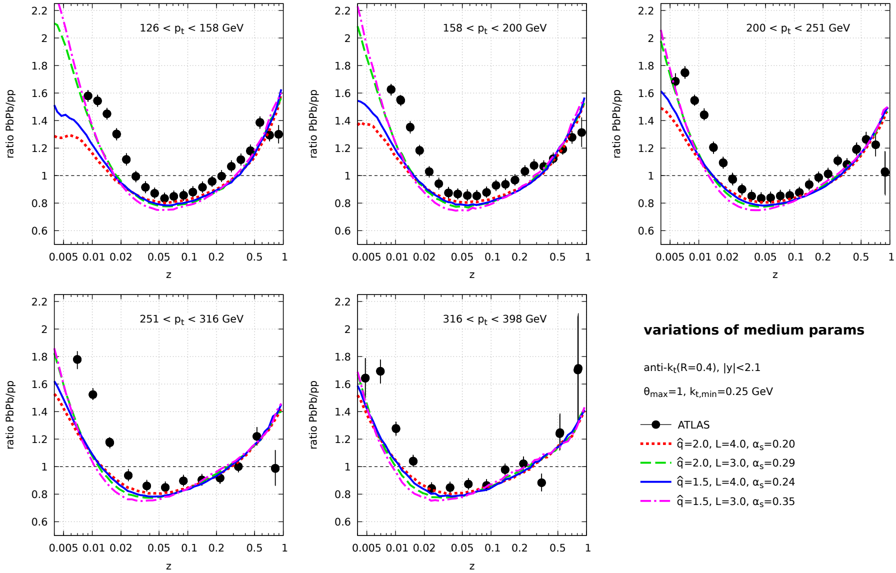
N_{jets}-norm z_g distribution - high-p_T jets
$\hat{q}$=1.5 GeV^2/fm, L=4 fm
anti-k_t(R=0.4), SD(β=0,z_{cut}=0.1) [mMDT], θ_g>0.1
p_{T0}=1 TeV
gluon
quark
quark with gluon energy loss
$\mathcal{R}(z_g)$
z_g
1.05
1
0.95
0.9
0.85
0.8
0
0.1
0.2
0.3
0.4
0.5

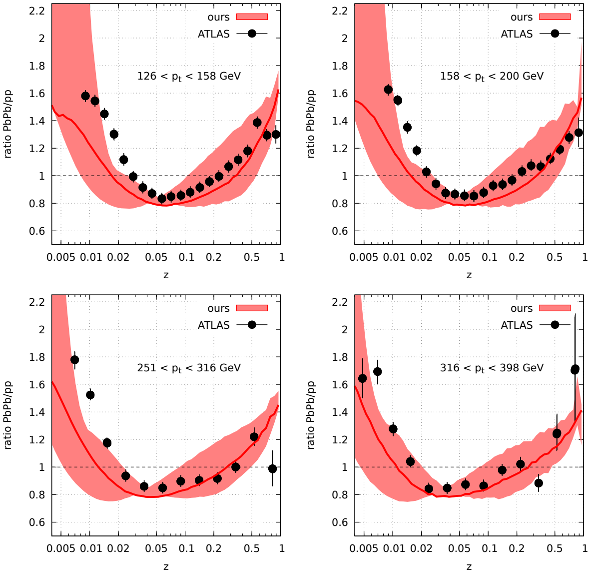
SD multiplicity





Fragmentation function





varying uncontrolled parameters

anti-k_t(R=0.4), |y|<2.1

$\hat{q}$=1.5, L=4, α_s=0.25

solid: θ_{max}=1, $k_{t,min}$=0.25 GeV
vary $k_{t,min}$ = 0.15, 0.5
vary θ_{max} = 0.75, 1.5