Elliptic flow and nuclear modification factor within a partonic transport model

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with J. Uphoff, O. Fochler, C. Wesp, Z. Xu and C. Greiner

based on arXiv:1401.1364

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H-QM Helmholtz Research School Quark Matter Studies

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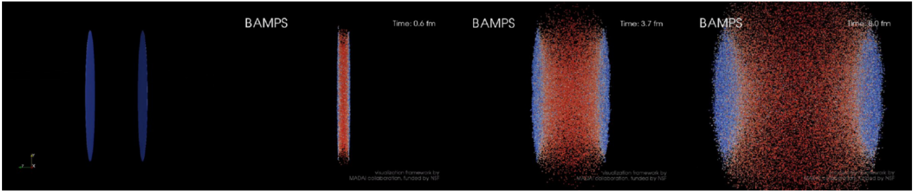
Outline

1. Motivation
2. The partonic transport model BAMPS
3. Recent results about the...
   - ... nuclear modification factor R_{AA}
   - ... elliptic flow v_2
   - ... momentum imbalance A_J of reconstructed jets

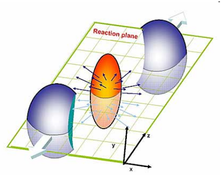


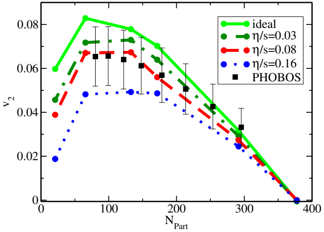
Visualization by Jan Uphoff
Visualization framework courtesy MADAI collaboration
funded by the NSF under grant NSF-PHY-09-41373

Collectivity of the bulk regime: Elliptic flow v_2

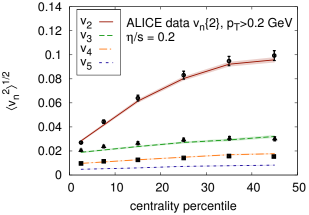
Fourier decomposition of particle spectra

$$\frac{d^3N}{p_t dp_t dy d\phi}(p_t, y, \phi) = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left[1 + 2v_2(p_t, y)\cos(2\phi) + ...\right]$$





by Romatschke, Phys.Rev.Lett. 99, (2007)



by Gale et al., Phys.Rev.Lett. 110 (2013)

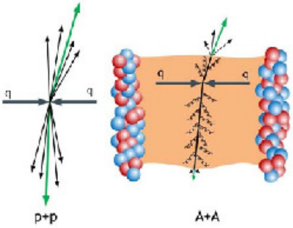
State-of-the-art

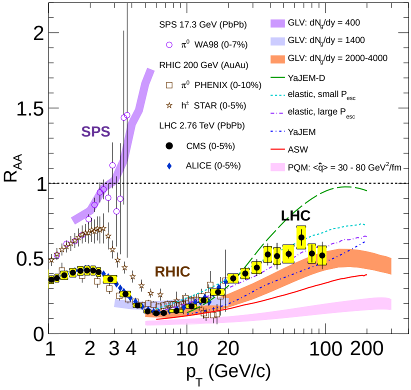
✓ Well described by relativistic (viscous) hydrodynamics

Jet quenching: Nuclear modification factor R_{AA}

Suppression of inclusive particle spectra

$$R_{AA} = \frac{d^2N_{AA}/dp_t dy}{N_{bin}\, d^2N_{pp}/dp_t dy}$$





by CMS Collaboration, Eur. Phys. J. C (2012)

State-of-the-art

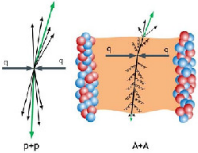
✓ Well described by perturbative quantum chromodynamics

Our question:

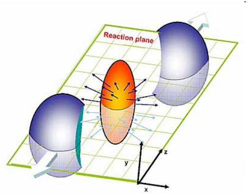
Can perturbative QCD interactions explain in a common framework

both the high p_t and the bulk medium regime

and thereby give microscopical insight into the QGP?



$\overset{\text{pQCD?}}{\longleftrightarrow}$



The partonic transport model BAMPS

BAMPS $\widehat{=}$ Boltzmann Approach to Multi-Parton Scattering[1]

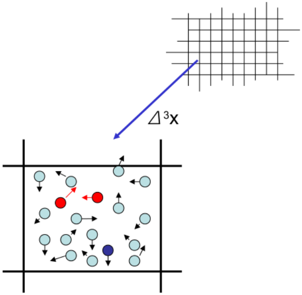
Numerical solver for the (3+1)D Boltzmann transport equation for partons on the mass-shell:

$$\frac{\partial f}{\partial t} + \frac{\mathbf{p}}{E}\frac{\partial f}{\partial \mathbf{r}} = C_{2\to 2} + C_{2\leftrightarrow 3}$$

- Massless particles (gluons & quarks)
- Discretized space ΔV and time Δt:

$$P_{2\to 2} = v_{rel}\sigma_{2\to 2}\frac{\Delta t}{\Delta V} \qquad P_{2\to 3} = v_{rel}\sigma_{2\to 3}\frac{\Delta t}{\Delta V}$$

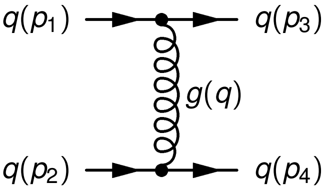
$$P_{3\to 2} = \frac{I_{3\to 2}}{8E_1E_2E_3} v_{rel}\frac{\Delta t}{\Delta V^2}$$



- Test-particles ansatz N_{test}

[1] Xu and Greiner, Phys.Rev.C71 (2005); Xu and Greiner, Phys.Rev.C76 (2007)

Implemented processes - elastic collisions



Screened ME with running coupling

$$\overline{|\mathcal{M}_{X\to Y}|}^2 = C_{X\to Y}\, 64\pi^2 \alpha_s^2(t) \frac{s^2}{[t - m_D^2(\alpha_s(t))]^2}$$

with $m_D^2(\alpha_s(t)) = d_G \pi \alpha_s(t) \int \frac{d^3p}{(2\pi)^3} \frac{1}{p} (N_c f_g + N_f f_q)$

LO pQCD cross-sections

$g\,g \to g\,g$

$g\,g \to q\,\bar{q}$

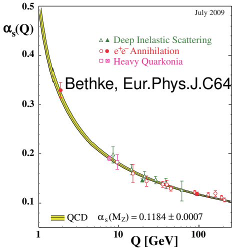
$q\,\bar{q} \to g\,g$ and $q\,\bar{q} \to q'\,\bar{q}'$

$q\,g \to q\,g$ and $\bar{q}\,g \to \bar{q}\,g$

$q\,\bar{q} \to q\,\bar{q}$

$q\,q \to q\,q$ and $\bar{q}\,\bar{q} \to \bar{q}\,\bar{q}$

$q\,q' \to q\,q'$ and $q\,\bar{q}' \to q\,\bar{q}'$



Uphoff, Fochler, Xu, Greiner: Phys.Rev.C84 (2011)

Implemented processes - radiative processes

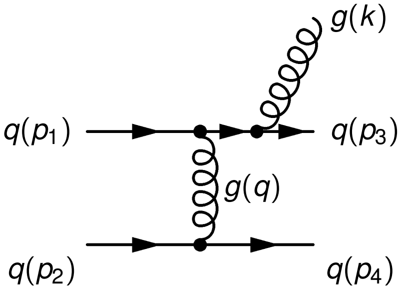
Improved Gunion-Bertsch ME

$$\left|\overline{\mathcal{M}}_{X\to Y+g}\right|^2 = \left|\overline{\mathcal{M}}_{X\to Y}\right|^2 48\pi\alpha_s(k_\perp^2)\,(1-\bar{x})^2 \times \left[\frac{\mathbf{k}_\perp}{k_\perp^2} + \frac{\mathbf{q}_\perp - \mathbf{k}_\perp}{(\mathbf{q}_\perp - \mathbf{k}_\perp)^2 + m_D^2\left(\alpha_s(k_\perp^2)\right)}\right]^2$$

with $\bar{x} = k_\perp e^{|y|}/\sqrt{s}$

$2 \to 3$ processes

$g\,g$	$\to$	$g\,g\,g$				
$q\,g$	$\to$	$q\,g\,g$	and	$\bar{q}\,g$	$\to$	$\bar{q}\,g\,g$
$q\,\bar{q}$	$\to$	$q\,\bar{q}\,g$				
$q\,q$	$\to$	$q\,q\,g$	and	$\bar{q}\,\bar{q}$	$\to$	$\bar{q}\,\bar{q}\,g$
$q\,q'$	$\to$	$q\,q'\,g$	and	$\bar{q}\,\bar{q}'$	$\to$	$\bar{q}\,\bar{q}'\,g$

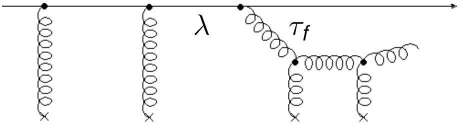


- Gunion, Bertsch: Phys.Rev.D25 (1982)
- Fochler, Uphoff, Xu, Greiner: Phys.Rev.D88 (2013)

Effective modeling of the LPM effect

Issue

Coherence effects within a semi-classical approach are not trivial.



Effective method

Parent parton is not allowed to scatter before emitted gluon is formed:

$$|\mathcal{M}_{2\to 3}|^2 \to |\mathcal{M}_{2\to 3}|^2 \, \Theta\left(\lambda - X_{\mathrm{LPM}} \, \tau_f\right)$$

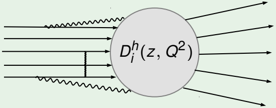
$X_{\mathrm{LPM}} = 0$	No LPM suppression
$X_{\mathrm{LPM}} = 1$	Only independent scatterings (forbids too many emissions)
$X_{\mathrm{LPM}} \in (0;1)$	Allows effectively some interference effects

From partons to hadronic observables

"High p_t" observables

- Folding with fragmentation functions $D_i^h\left(z, Q^2\right)$,

$$\frac{\mathrm{d}^2 N^h}{\mathrm{d}p_t \mathrm{d}y}\left(p_t^h\right) = \sum_i \int_{z_{min}}^1 \mathrm{d}z \frac{\mathrm{d}^2 N^i}{\mathrm{d}p_t \mathrm{d}y}\left(\frac{p_t^h}{z}\right) D_i^h\left(z, Q^2\right) \text{ with } z = \frac{p_t^h}{p_t^i}$$

partons i 

hadrons h

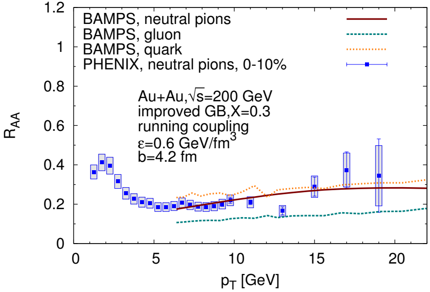
Fragmentation functions by e.g. Albino, Kniehl, Kramer: Nucl.Phys.B803(2008)

"Low p_t" observables

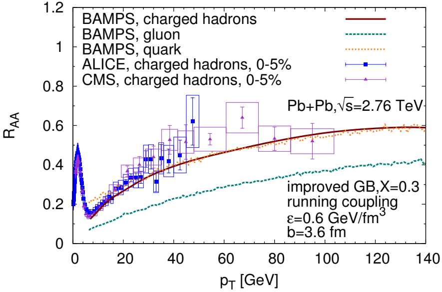
- Microscopic hadronization processes are unknown.
- Integrated flow should not be sensitive to phase transition.

Nuclear modification factor R_{AA} of central HI-collisions

RHIC

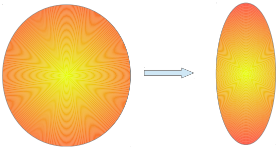


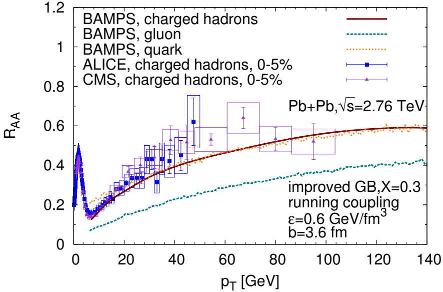
LHC

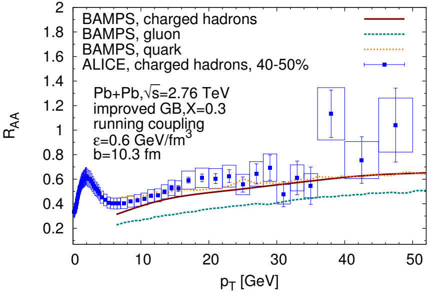


- PYTHIA initial conditions distributed by Glauber model.
- After fixing the LPM parameter $X_{\mathrm{LPM}} = 0.3$ by comparing to RHIC data, BAMPS describes the R_{AA} also at LHC.
- Suppression caused by the interplay between the improved GB matrix element and the microscopic running coupling.

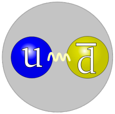
R_{AA} of peripheral HI-collisions

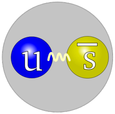


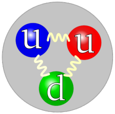


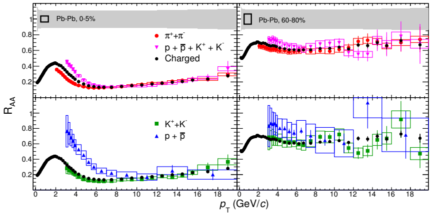


R_{AA} of central HI collisions for different hadron species

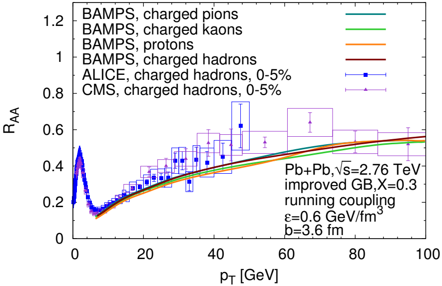






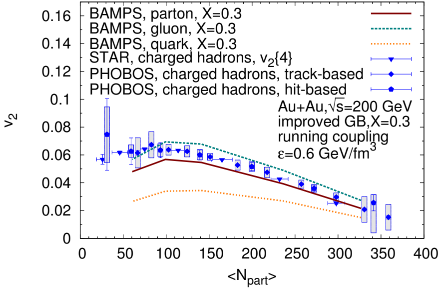


ALICE Collaboration, arXiv:1401.1250

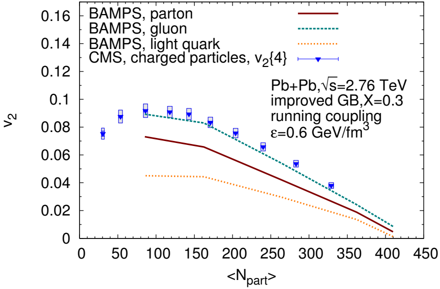


Integrated elliptic flow $v_2\,(N_{\text{part}})$

RHIC



LHC

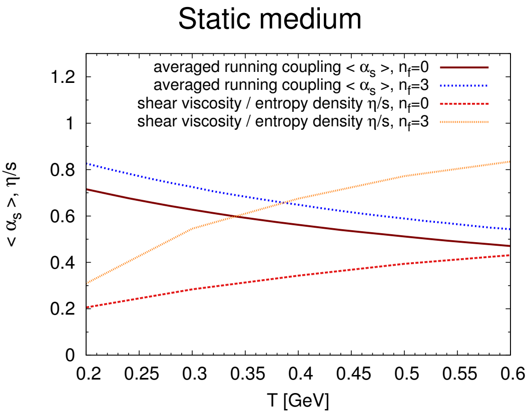


Same setup with LPM parameter $X_{\text{LPM}} = 0.3$ leads to a sizable elliptic flow built up in the partonic phase.

Attention

No hadronization for bulk ⇒ No hadronic after-burner ⇒ Missing 10-20%?!

Macroscopic quantities from microscopic interactions



Shear viscosity ratio η/s

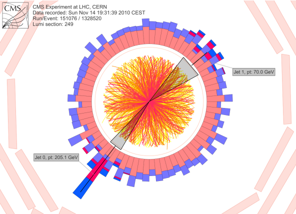
- Reason for large flow: small shear viscosity over entropy ratio
- Calculated with Green-Kubo formalism
- Recent viscous hydro: $\eta/s = 0.2$

Running coupling $\alpha_s(T)$

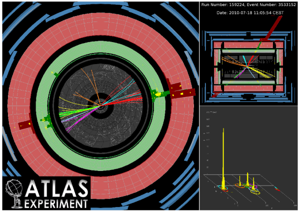
- Temperature dependent coupling by microscopically evaluated interactions.

Reconstructed jets in heavy-ion collisions

$\longrightarrow$



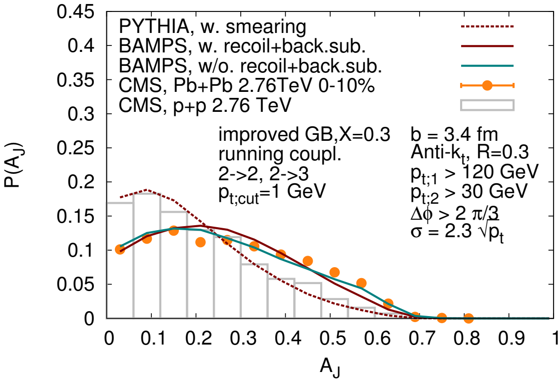
$\longrightarrow$



Momentum imbalance A_J of reconstructed di-jets

Definition

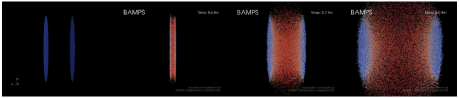
$$A_J = \frac{p_{t;Leading\ Jet} - p_{t;Subleading\ Jet}}{p_{t;Leading\ Jet} + p_{t;Subleading\ Jet}}$$



FS, Fochler, Uphoff, Xu, Greiner: arXiv:1309.1657

Conclusions

- Partonic transport provides means for...
  - exploring dynamics of the QGP evolution based on pQCD processes.
  - exploring different observables within a common framework.
- Realistic suppression of jets both at RHIC and LHC.
- Sizable collective flow within the medium by microscopic pQCD cross sections.



Future plans:

- How does a revisited modeling of the LPM effect change the energy loss and its path-length dependence?
- Systematic studies!

Conclusions

- Partonic transport provides means for...
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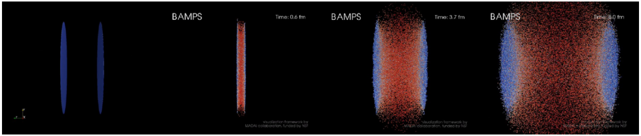
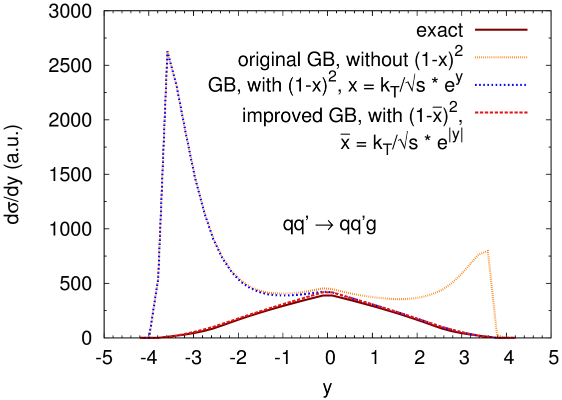
BAMPS@QM2014

- Heavy quarks: Talk by J. Uphoff
- Mach cones: Poster by I. Bouras
- Reconstructed jets: Poster by FS



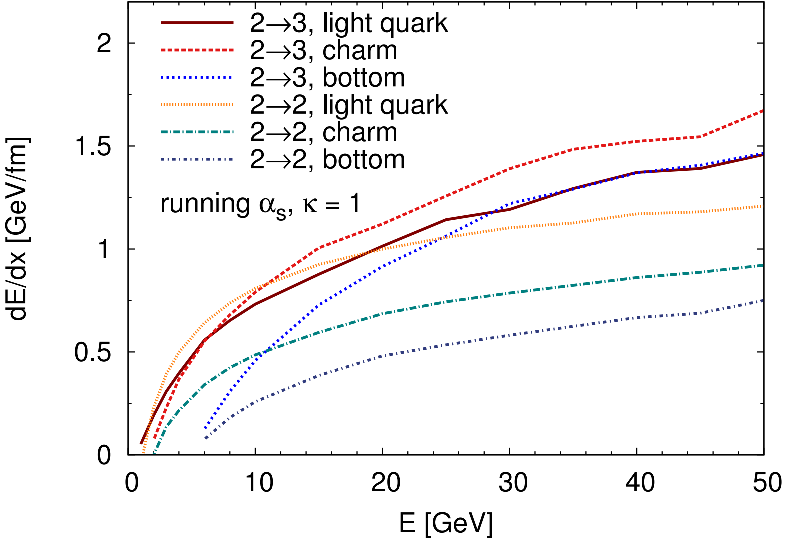
Backup slides

Improved Gunion-Bertsch matrix element



- Infrared screening for both GB and exact: $\theta\,(\text{cut}) = \theta\,(p_i p_j - \lambda)$.
- Integration both in GB coordinates and in standard phase space with numeric δ-functions.

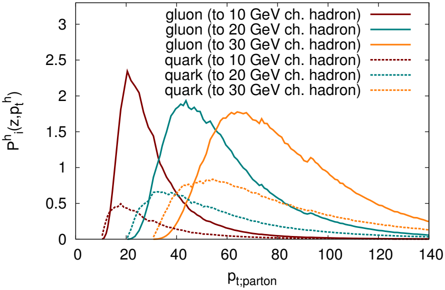
Differential energy loss in a static medium

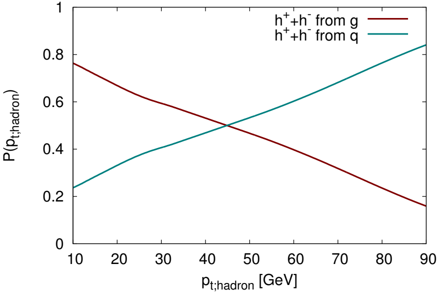


Closer look on the role of fragmentation

Probability for hadron h with p_t^h out of parton i with $p_t^i = p_t^h/z$

$$P^{i\to h}\left(z, p_t^h\right) = \frac{1}{\frac{d^2N^h}{dp_t dy}\left(p_t^h\right)} \frac{d^2N^i}{dp_t dy}\left(\frac{p_t^h}{z}\right) D_i^h\left(z, Q^2\right)$$



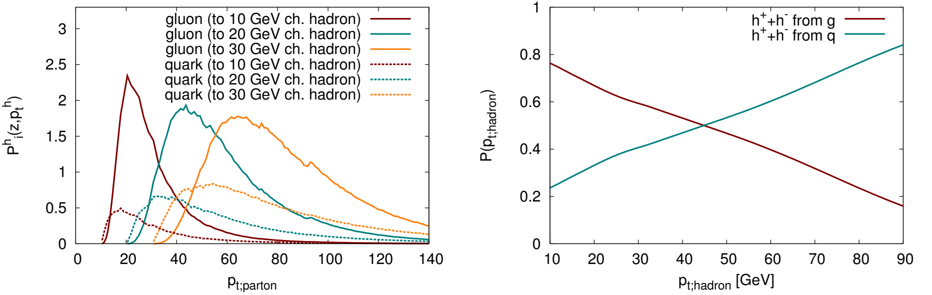


Example: R_{AA} for hadrons with $p_t^h = 30\,\text{GeV}$

Hadrons with $p_t^h = 30\,\text{GeV}$ stem...

... mainly from $\approx 60\,\text{GeV}$ gluon and $\approx 45\,\text{GeV}$ quark.

... $\approx 60\,\%$ from gluons and $\approx 40\,\%$ from quarks. 6



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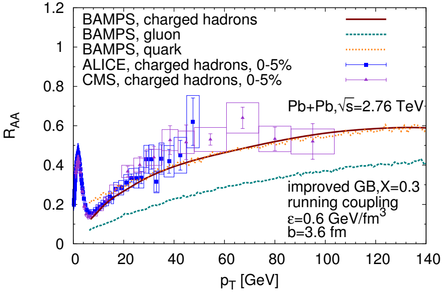

$$R_{AA}^{h}(30\,\mathrm{GeV}) = 0.4\,R_{AA}^{g}(60\,\mathrm{GeV}) + 0.6\,R_{AA}^{q}(45\,\mathrm{GeV}) \approx 0.3$$

Example: Shower event with first 100 recoil partons