Riding a Jet through a Quark-Gluon Plasma

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Personal touch: *Datong, China, Sept 2001 ...*

Xin-Nian was 39 for the 1st time !

Personal touch: *Berkeley, yesterday ...*

Xin-Nian is 39 ... again

Happy birthday Xin-Nian !

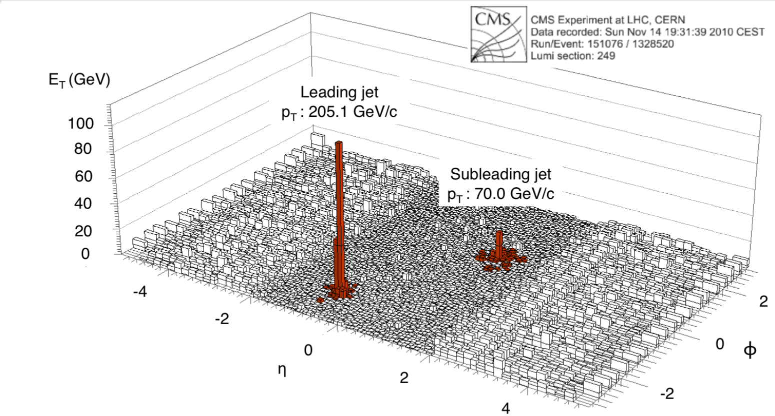
Outline

- The phenomenology of jet quenching (very short)
- Jets interactions in a dense quark-gluon plasma
  - collisions, medium-induced radiation, energy loss
  - adding bremsstrahlung (parton virtualities, vacuum-like radiation)
- A unified description of parton showers in a QGP in perturbative QCD
  - Monte Carlo implementation
  - applications to Pb+Pb collisions at the LHC
- Work done since 2011 together with several collaborators

  J.P. Blaizot, J. Casalderrey-Solana, P. Caucal, F. Dominguez,

  M. Escobedo, L. Fister, Y. Mehtar-Tani, A. Mueller, G. Soyez, B. Wu

Di–jet asymmetry at the LHC

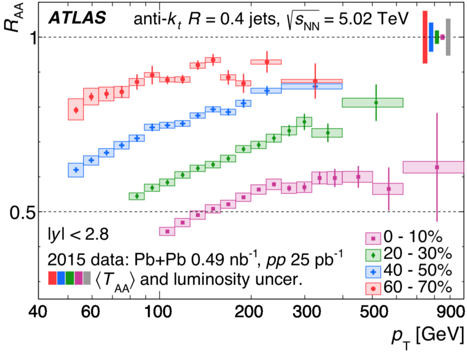


- Huge difference between the energies of the two jets
- The missing energy is found in the underlying event:
  - many soft ($p_\perp \leq 2$ GeV) hadrons propagating at large angles
- Very different from the usual jet fragmentation pattern in the vacuum

Nuclear modification factor for jets

- Jet yield in Pb+Pb normalized by p+p times the # $N_{\rm coll}$ of binary collisions
  - would be 1 if Pb+Pb = incoherent superposition of p+p

$$R_{AA} \equiv \frac{\left.\frac{\mathrm{d}^2 N_{\rm jet}}{\mathrm{d}p_T \mathrm{d}y}\right|_{AA}}{N_{\rm coll} \left.\frac{\mathrm{d}^2 N_{\rm jet}}{\mathrm{d}p_T \mathrm{d}y}\right|_{pp}}$$



- suppression in Pb+Pb: $R_{AA} < 1$
- increases with centrality

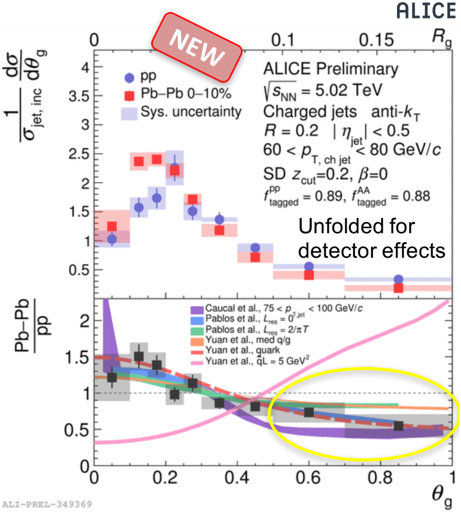
- General explanation: energy loss by the jet
- R_{AA} is almost flat at very high p_T: energy loss increases with p_T

Jet substructure

- SoftDrop: identify the first sufficiently hard splitting: $z \geq z_{\text{cut}} = 0.2$
- Measure the associated splitting fraction z_g and emission angle θ_g

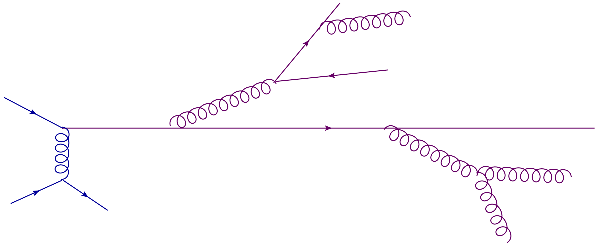
- Recent measurement by ALICE

  (talk by A. Dainese at LHCP2020)
- Nuclear enhancement at small θ_g ...
- ... and suppression at larger θ_g
- Collimated jets lose less energy
- What is the "critical" value of θ_g ?



Medium-induced jet evolution

- The leading particle (LP) is produced by a hard scattering
- It subsequently evolves via radiation (branchings) ...



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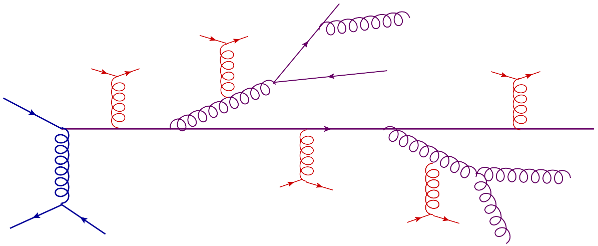
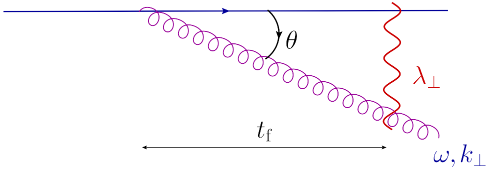


- ... and via collisions off the medium constituents
- Collisions can have several effects
  - transfer energy and momentum between the jet and the medium
  - trigger additional radiation (“medium-induced”)
  - wash out the color coherence (destroy interference pattern)

Radiation: Formation time

- The time it takes the daughter partons to lose their mutual coherence
- The gluon has been emitted when it has no overlap with its source



$$\Delta x_\perp = \theta t_f$$

$$\lambda_\perp \simeq \frac{2}{k_\perp} \simeq \frac{2}{\omega\theta}$$

$$\Delta x_\perp \sim \lambda_\perp \implies t_f = \frac{2\omega}{k_\perp^2} \simeq \frac{2}{\omega\theta^2}$$

- This argument universally applies to radiation: in vacuum & in the medium
  - based only on the uncertainty principle

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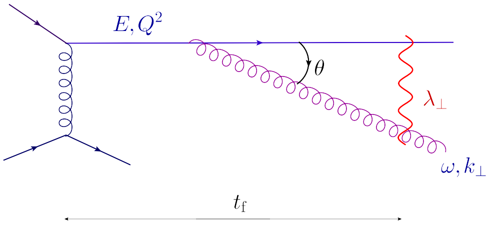

$$t_\mathrm{f} \simeq \frac{2\omega}{k_\perp^2} \simeq \frac{2E}{Q^2}$$

$$\mathrm{d}^2\mathcal{P}_\mathrm{Brem} \simeq \frac{\alpha_s C_R}{\pi}\frac{\mathrm{d}\omega}{\omega}\frac{\mathrm{d}\theta^2}{\theta^2}$$

- In the vacuum: the emission is triggered by a hard scattering
- t_f is controlled by the parton virtuality & measured from the hard vertex
- Log enhancement for soft ($\omega \ll E$) and collinear ($\theta \ll 1$) gluons

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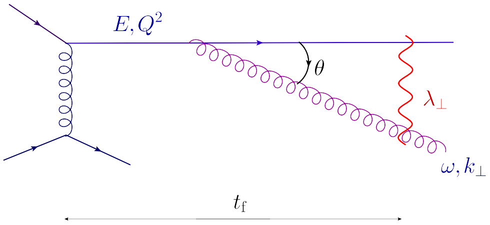

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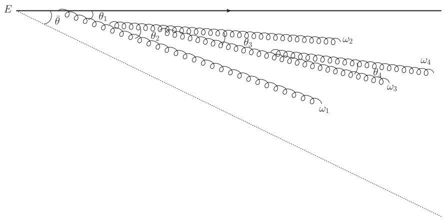
- Log enhancement for soft ($\omega \ll E$) and collinear ($\theta \ll 1$) gluons
- In a dense medium (QGP): additional virtuality due to collisions

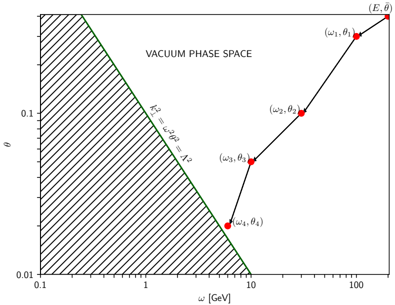
Jets in the vacuum (in a nut-shell)

- Double logarithmic approximation (DLA): strong double ordering

$$E \gg \omega_1 \gg \omega_2 \gg \cdots \gg \omega \quad \& \quad \bar{\theta} \gg \theta_1 \gg \theta_2 \gg \cdots \gg \theta$$

- Emissions can be depicted as points in the $(\omega,\, \theta)$ plane (Lund plane)



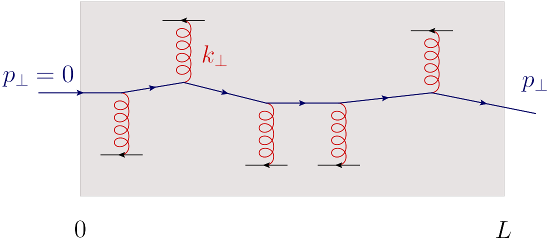


- Evolution stopped by hadronisation: $k_\perp \simeq \omega\theta \gtrsim \Lambda_{\rm QCD}$

- Beyond DLA: angular ordering still holds due to color coherence

Jets in a QGP: Collisional broadening

- An energetic parton crossing a weakly coupled QGP along a distance L



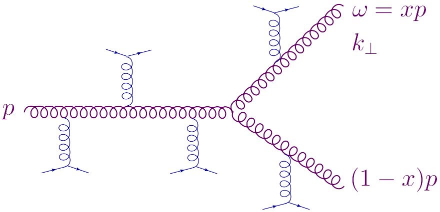
- Random kicks $\Longrightarrow$ Gaussian broadening: $\langle p_\perp^2 \rangle \simeq \hat{q}L$

$$\hat{q} = \int^{Q^2} \mathrm{d}^2\boldsymbol{k}\, \frac{\mathrm{d}\Gamma_{\rm el}}{\mathrm{d}^2\boldsymbol{k}}\, \boldsymbol{k}^2 \sim \alpha_s^2 C_R n(T) \ln \frac{Q^2}{m_D^2}$$

- $n(T) = C_F n_q + N_c n_g \sim T^3$: density of thermal quarks & gluons
  - typical values: $\hat{q} \sim 1\ \mathrm{GeV}^2/\mathrm{fm}$, $L \sim 5$ fm, $\langle p_\perp^2 \rangle \sim 5\ \mathrm{GeV}^2$

QGP: Medium-induced radiation

- Each collision inside the medium is an additional source of $k_\perp$
- The gluon $k_\perp$ cannot be lower than $k_{\rm med}^2 \equiv \hat{q} t_{\rm f}$



$$t_{\rm f} = \frac{2\omega}{k_\perp^2} \;\; \& \;\; k_\perp^2 \gtrsim \hat{q} t_{\rm f}$$

$$t_{\rm f} \lesssim \sqrt{\frac{2\omega}{\hat{q}}} \equiv t_{\rm med}$$

  - vacuum-like emissions (VLEs): $k_\perp^2 \gg \hat{q} t_{\rm f}$, or $t_{\rm f} \ll t_{\rm med}$
  - medium-induced emissions (MIEs): $k_\perp^2 \simeq \hat{q} t_{\rm f}$, or $t_{\rm f} \simeq t_{\rm med}$

- The MIEs can occur anywhere inside the medium: $t_{\rm med} \leq L$

$$\omega \leq \omega_c \equiv \frac{1}{2}\hat{q} L^2 \quad \text{and} \quad \theta \geq \theta_c \equiv \frac{\sqrt{\hat{q} L}}{\omega_c}$$

MIEs: the BDMPSZ spectrum

(Baier, Dokshitzer, Mueller, Peigné, Schiff; Zakharov; 1996-97)

- MIEs are naturally described in terms of an emission rate:

$$\mathrm{d}^2\mathcal{P}_{\textsf{MIE}} = \frac{\alpha_s C_R}{\pi}\,\frac{\mathrm{d}\omega}{\omega}\,\frac{\mathrm{d}t}{t_{\rm med}}$$

- No collinear ($k_\perp \to 0$) singularity: $k_\perp^2 \simeq \hat{q}t_{\rm med} \simeq \sqrt{\hat{q}\omega}$
- Stronger soft ($\omega \to 0$) singularity: $\omega t_{\rm med}(\omega) \propto \omega^{3/2}$
- Emission spectrum integrated over $k_\perp$ and over $t \le L$:

$$\omega\frac{\mathrm{d}\mathcal{P}_{\textsf{MIE}}}{\mathrm{d}\omega} \simeq \bar{\alpha}\,\frac{L}{t_{\rm med}} = \bar{\alpha}\sqrt{\frac{\omega_c}{\omega}} \qquad \text{with} \quad \omega \le \omega_c = \frac{1}{2}\hat{q}L^2$$

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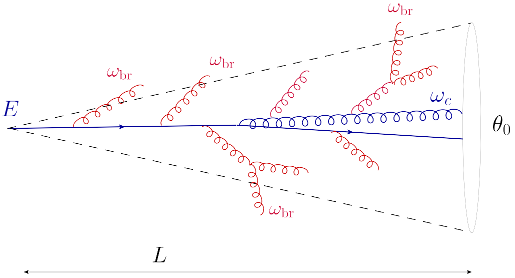
$$\omega\frac{\mathrm{d}\mathcal{P}_{\mathsf{MIE}}}{\mathrm{d}\omega} \simeq \bar{\alpha}\sqrt{\frac{\omega_c}{\omega}} \sim 1 \quad\Longrightarrow\quad \omega \lesssim \omega_{\mathrm{br}} \equiv \bar{\alpha}^2\omega_c$$

- For low enough ω, the probability for a single branching becomes of $\mathcal{O}(1)$
- Multiple branchings $\Longrightarrow$ medium-induced partonic cascades

MIEs: Wave turbulence

(J.-P. Blaizot, E. I., Y. Mehtar-Tani, PRL 111, 2013)

- A jet created via medium-induced emissions alone ("on-shell leading parton")



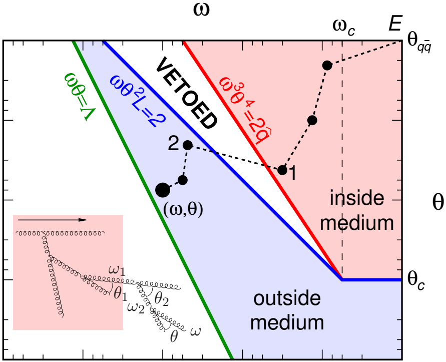
  - no angular ordering: color coherence lost during formation
  - a large number of soft gluons with $\omega \leq \omega_{\rm br}$, which leave the jet
  - democratic branchings: $z \sim 1/2$

- Many soft quanta at large angles: natural explanation for di-jet asymmetry
  - the energy lost by the jet: $\Delta E_{\rm jet} \sim \omega_{\rm br} \sim 5$ GeV

Adding the vacuum-like emissions

(P. Caucal, E.I., A. H. Mueller and G. Soyez, PRL 120, 2018)

- VLEs inside the medium have large transverse momenta $k_\perp^2 \gg \hat{q} t_{\rm f}$, hence short formation times: $t_{\rm f} = \frac{2}{\omega\theta^2} \ll t_{\rm med}$
- VLEs can also occur directly outside the medium: $t_{\rm f} > L$



- Two boundaries in Lund plane:

$$\frac{2}{\omega\theta^2} = L \quad \& \quad \frac{2}{\omega\theta^2} = \sqrt{\frac{2\omega}{\hat{q}}}$$

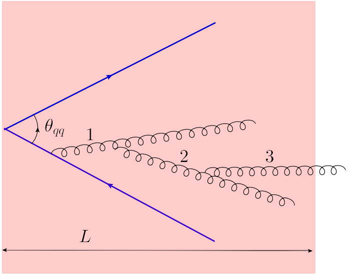
- The 2 lines cross each other at

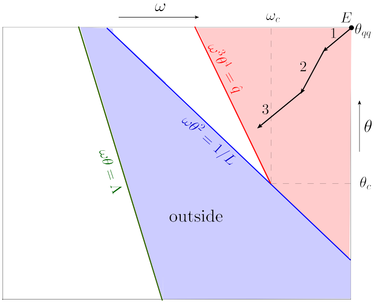
$$\omega_c = \frac{1}{2}\hat{q}L^2 \,, \quad \theta_c = \frac{2}{\sqrt{\hat{q}L^3}}$$

- Vetoed region: would-be collinear VLEs, that cannot exist in the medium

VLEs inside the medium

- VLEs inside the medium obey angular ordering, like in the vacuum
  - formation times are much shorter than the decoherence time
- After formation, partons propagate in the medium along a distance $\sim L$

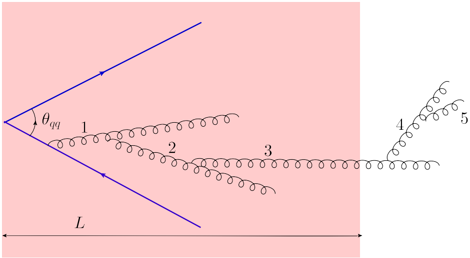


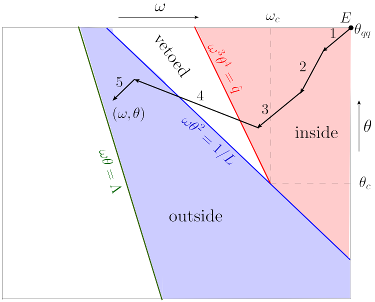


  - they lose colour coherence via collisions
  - independent sources for medium-induced radiation: energy loss
  - ... and for vacuum-like emissions outside the medium

VLEs outside the medium

- First outside emission can violate angular ordering
  - re-opening of the angular phase-space
  - enhanced radiation at low energies and large angles
- Subsequent "outside" emissions obey angular ordering, as usual

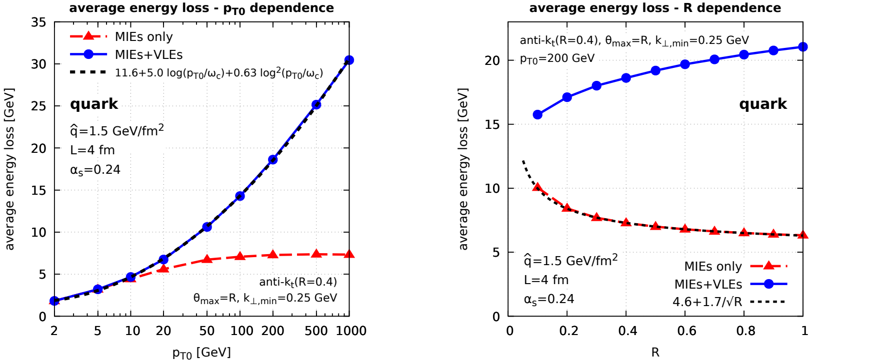




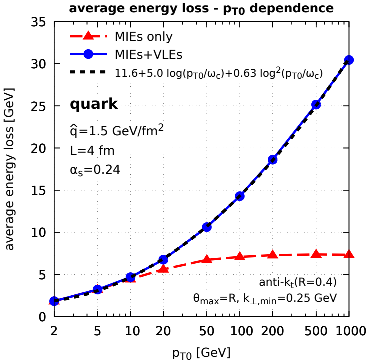
- Factorized parton showers, separately Markovian, for VLEs and MIEs
- Monte Carlo implementation *(P. Caucal, E.I., G. Soyez, arXiv:1907.04866)*

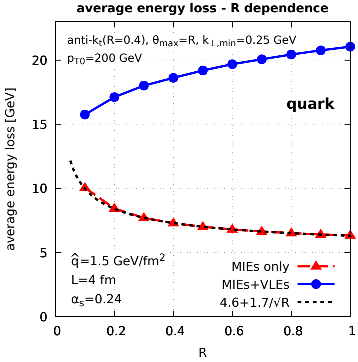
Monte Carlo results: Jet energy loss

- Modular structure: one can switch the VLEs off and on
- Red curves: MIEs only
  - $\Delta E_{\rm jet} \sim \omega_{\rm br} = \alpha_s^2 \hat{q} L^2$, independent of p_{T0}
  - $\Delta E_{\rm jet}$ decreases with R: some of the MIEs are recovered



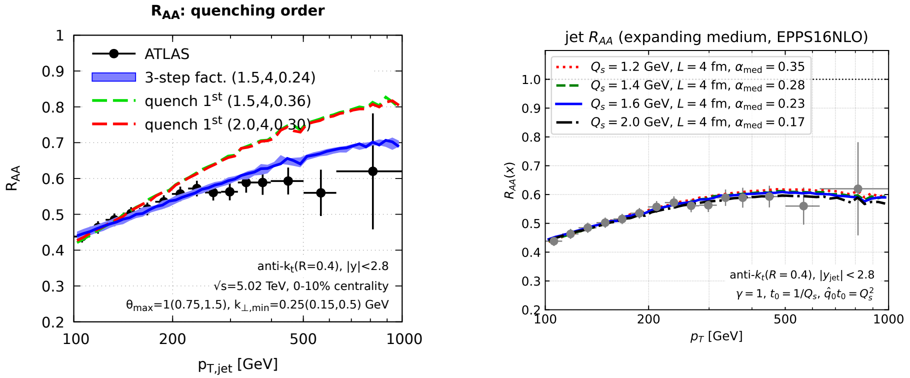
- Modular structure: one can switch the VLEs off and on
- Blue curves: both VLEs and MIEs
  - the number of partonic sources increases via VLEs
  - $\Delta E_{\rm jet}$ increases with both p_{T0} and R: phase-space for VLEs





Monte Carlo results: jets R_{AA}

- Left: our original calculation in *arXiv:1907.04866*
- "quenched": no VLEs $\Longrightarrow$ R_{AA} rises too fast at high p_T (less energy loss)

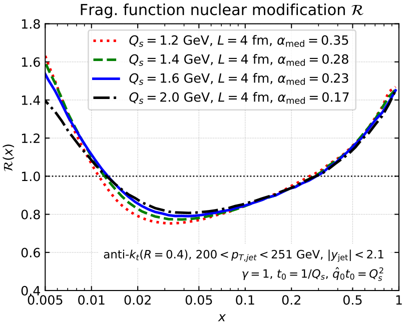


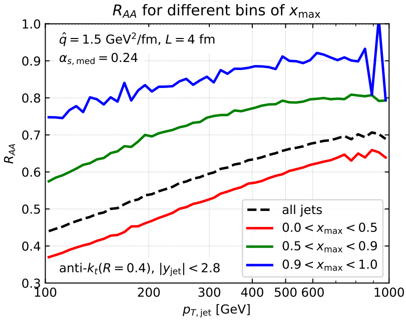
- Right: adding longitudinal expansion and nuclear PDFs *(arXiv:2012.01457)*
- Better agreement at high $p_{T,\mathrm{jet}}$ due to the nuclear PDFs

Monte Carlo results: Fragmentation function

(P. Caucal, E.I., and G. Soyez, arXiv: 2005.05852, 2012.01457)

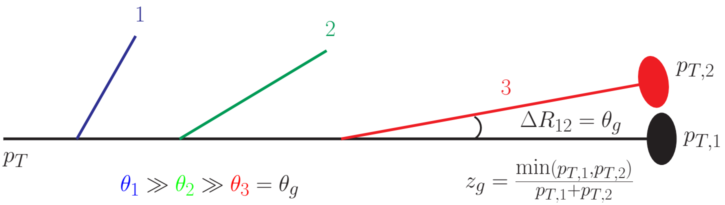
- Good agreement with LHC (warning: not an infrared-safe quantity!)





- Enhancement at small x even without medium back-reaction
  - colour decoherence $\Rightarrow$ large-angle radiation outside the medium
- Enhancement at large x : medium favors the hard-fragmenting jets
  - less parton evolution, hence less energy loss

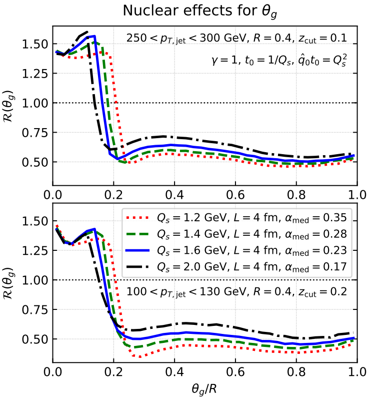
Jet substructure: the z_g distribution

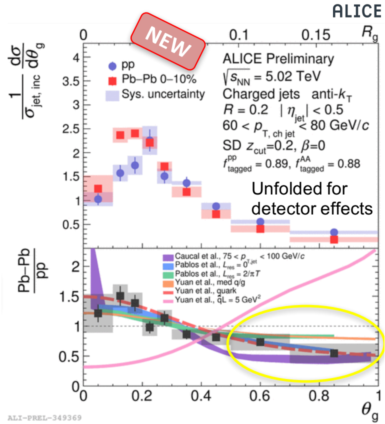


- Probability distribution for a first splitting with sufficiently large splitting fraction $z_g \geq z_{\text{cut}}$ and emission angle $\theta_g \geq \theta_{\text{cut}}$
  - if such a hard splitting is found, the original jet contains 2 sub-jets
  - softer emissions at larger angles are removed from the jet: Soft Drop
- For jets in the vacuum: a direct measure of the parton splitting functions
- $\mathcal{R}(z_g)$, $\mathcal{R}(\theta_g)$ = ratios of the z_g & θ_g distributions in PbPb and pp

Nuclear modification factors for SoftDrop

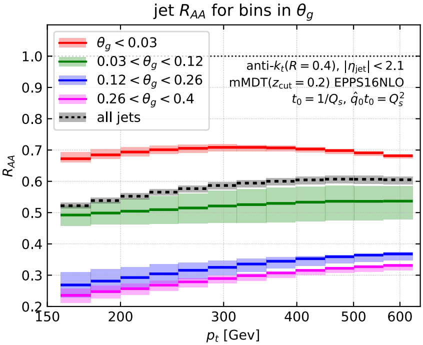
(P. Caucal, E.I., and G. Soyez, arXiv:1907.04866, 2012.01457)

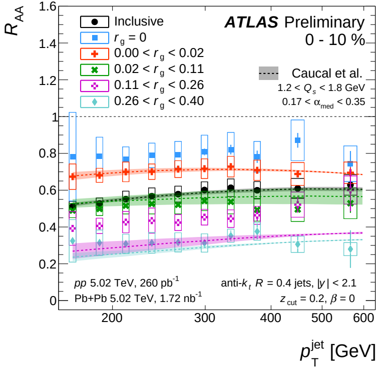




- Two competing effects, depending upon θ_g vs. $\theta_c \simeq 0.1$ (medium resolution)
  - $\theta_g < \theta_c$: enhancement due to MIEs which trigger SD
  - $\theta_g > \theta_c$: suppression due to incoherent energy loss by the 2 subjets

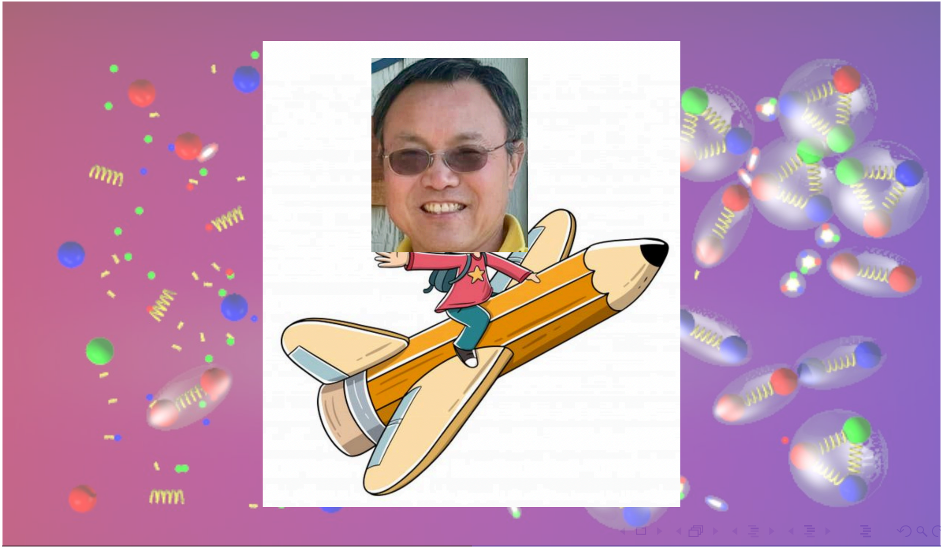
(P. Caucal, E.I., and G. Soyez: May 2022, using the ATLAS set-up)





- Left: jet R_{AA} in bins of θ_g (colors) and for inclusive jets (black, dotted)
  - sub-jets with small $\theta_g \leq \theta_c$ lose less energy than the average jet
- Right: ATLAS data with our predictions shown in dotted lines

(Instead of) Conclusions



Happy 60th birthday, Xin-Nian, and keep riding the jets !