Nuclear effects on jets at the EIC

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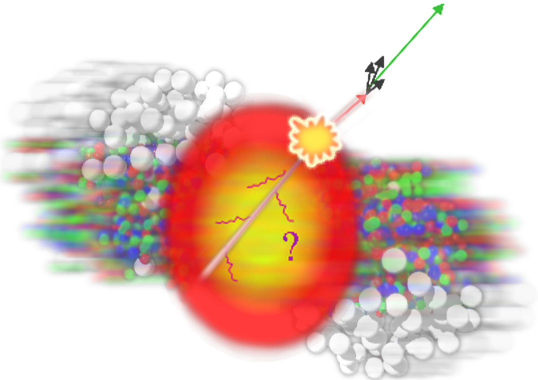
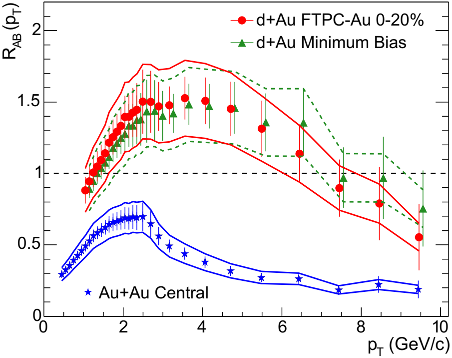


Outline

- The main focus
    - nuclear effects on jet production at the EIC, in the light of our lessons from RHIC and the LHC
- A brief overview of (particularly insightful) experimental results
    - their common denominator: the physics of high parton densities
- Multiple scattering in a dense partonic system
    - transverse momentum broadening in a quark gluon plasma
    - p_T-broadening in a large nucleus & its relation to gluon saturation
    - p_T-broadening in eA collisions: what is new as compared to pA ?
- Medium-induced radiation and energy loss
    - the most distinguished nuclear effect on jets in heavy ion collisions
    - deeply related to the transverse momentum broadening
    - what a kind of (medium-induced) energy loss can we expect at the EIC?

Nuclear modification factor for hadrons at RHIC

- Au+Au, d+Au, and p+p collisions at RHIC with $\sqrt{s_{\rm NN}} = 200$ GeV
  - dense-dense (AA), dilute-dense (pA), dilute-dilute (pp)
- Ratio of particle yield in AA (or pA) and pp scaled by # of binary collisions



- would be 1 in the absence of collective nuclear effects
- data by STAR, nucl-ex/0501009
- midrapidities $(\eta \sim 0)$, minimum bias
- 2 types of nuclear effects

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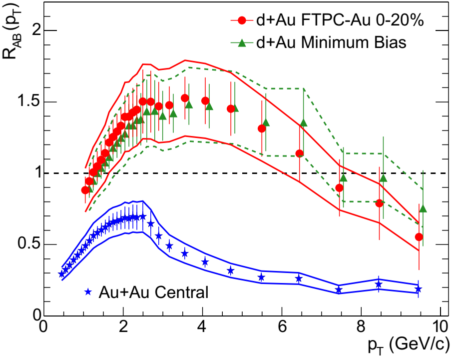
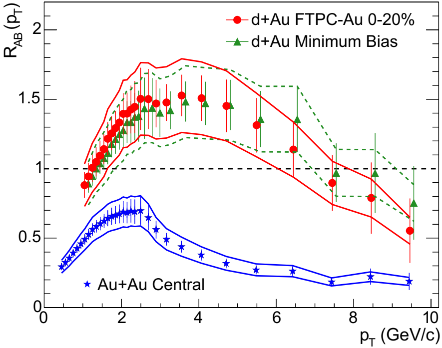


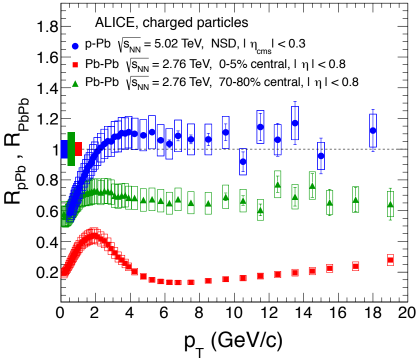
- d+Au: Cronin peak
- multiple scattering in the Cold Nuclear Matter
- Au+Au: suppression at all p_T's
- partonic energy loss in the Quark Gluon Plasma (“jet quenching”)

- Both phenomena reflect the physics of dense partonic systems

Nuclear modification factor for hadrons at the LHC

- Pb+Pb collisions: jet quenching still present and even stronger
    - central collisions (head-on Pb+Pb scattering) look denser

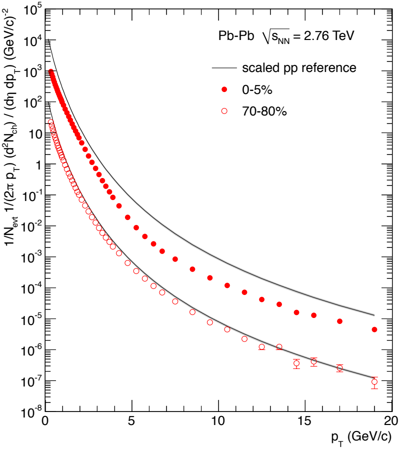




- p+Pb collisions: R_{pA} is consistent with 1 within the error bars
    - "no jet quenching in pA collisions"

Energy loss

- Hadrons measured with a given energy E have been produced with $E+\epsilon$



$$\frac{\mathrm{d}\sigma^{\mathrm{med}}(E)}{\mathrm{d}E} = \int \mathrm{d}\epsilon\, \mathcal{P}(\epsilon)\, \frac{\mathrm{d}\sigma^{\mathrm{vac}}(E+\epsilon)}{\mathrm{d}E}$$

- $\mathcal{P}(\epsilon)$: probability density for losing ϵ

$$\frac{\mathrm{d}\sigma^{\mathrm{vac}}(E)}{\mathrm{d}E} \propto \frac{1}{E^n}\,, \qquad n = 7 \div 10$$

- Rapidly falling spectrum for the hard process
- Bias towards small values for ϵ

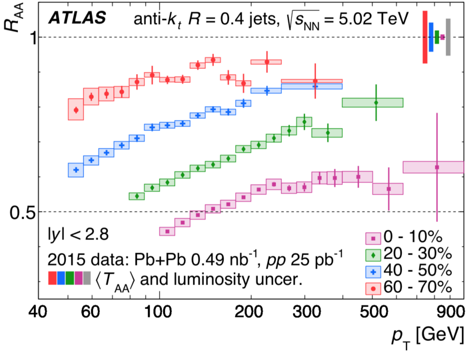
- Even a small ϵ may imply strong suppression

What about real jets ?

- LHC: the jet yield in Pb+Pb collisions normalized by p+p times the average nuclear thickness function $\langle T_{AA}\rangle$

$$R_{AA} \equiv \frac{\frac{1}{N_{\rm evt}}\frac{{\rm d}^2 N_{\rm jet}}{{\rm d}p_T{\rm d}y}\Big|_{AA}}{\langle T_{AA}\rangle\frac{{\rm d}^2\sigma_{\rm jet}}{{\rm d}p_T{\rm d}y}\Big|_{pp}}$$

- ATLAS, arXiv:1805.05635
- stronger suppression for more central collisions

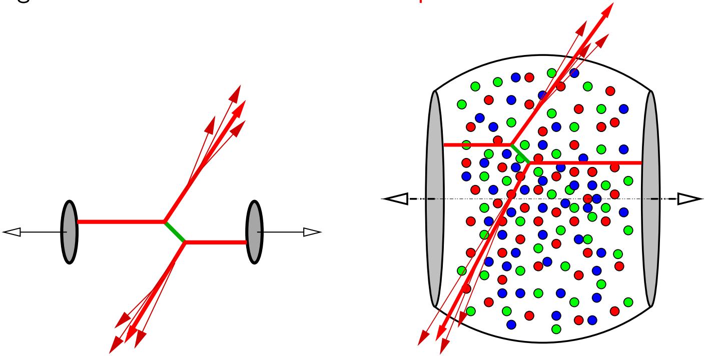


- Energy loss by the jet: transported at large angles $\theta > R$
- R_{AA} is almost flat at very high p_T: energy loss increases with p_T

Jet quenching

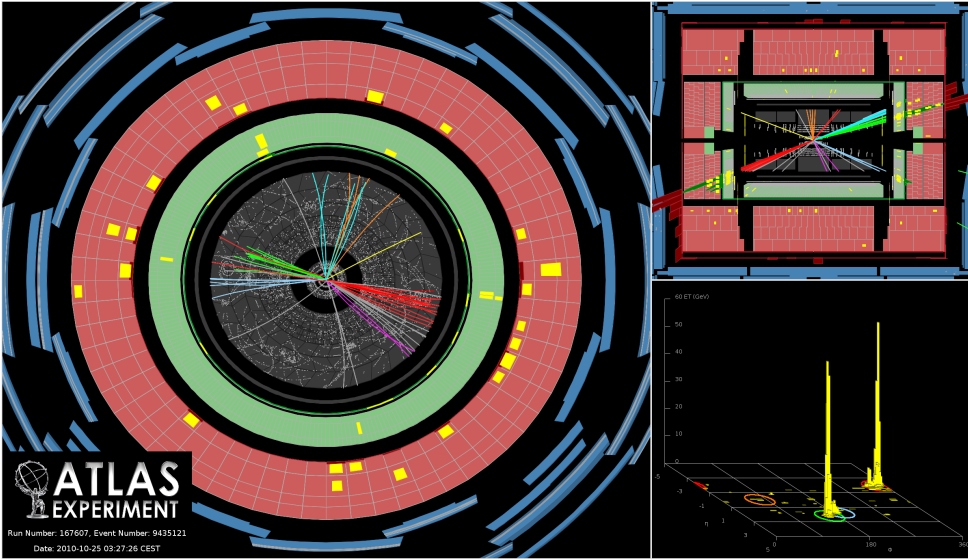
- Jets: collimated spray of particles generated via successive parton branchings followed by hadronisation

- The leading partons are generally created in pairs, by a hard process, and propagate back-to-back in the transverse plane

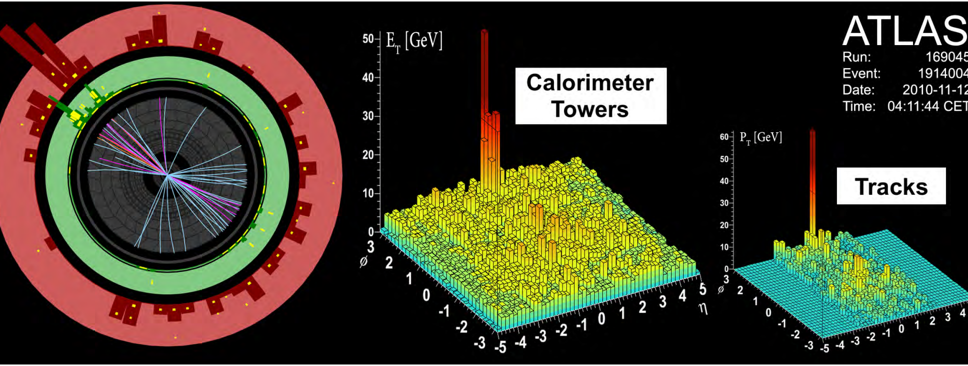


- AA collisions: the jets are created within a dense partonic medium and can be modified by the latter: "jet quenching"

LHC: Di-jets in p+p collisions

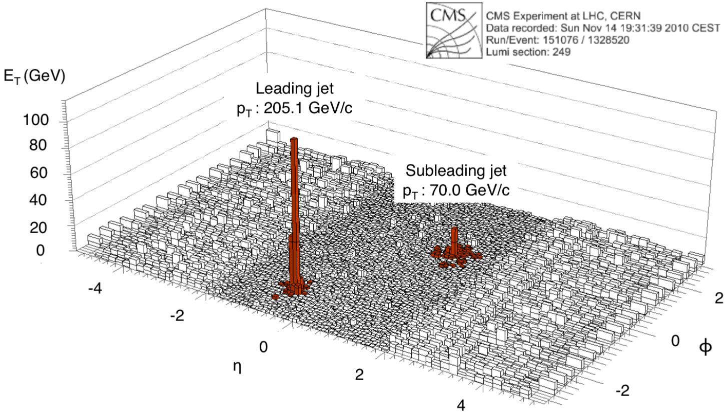


“Mono-jets” in Pb+Pb collisions



- Central Pb+Pb: ‘mono–jet’ events
- The secondary jet can barely be distinguished from the background: $E_{T1} \geq 100$ GeV, $E_{T2} > 25$ GeV
- This phenomenon was a real surprise: never predicted

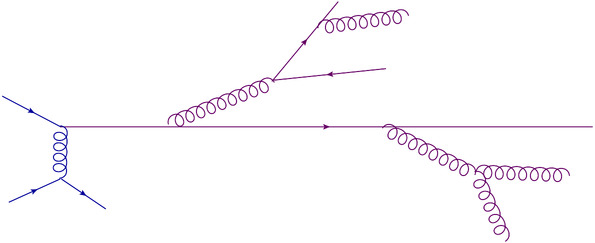
Di–jet asymmetry at the LHC



- The missing energy is found in the underlying event:
  - many soft ($p_\perp < 2$ GeV) hadrons propagating at large angles
- Very different from the usual jet fragmentation pattern in the vacuum
- Suggests a new mechanism for parton radiation, specific to medium

Medium-induced jet evolution

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



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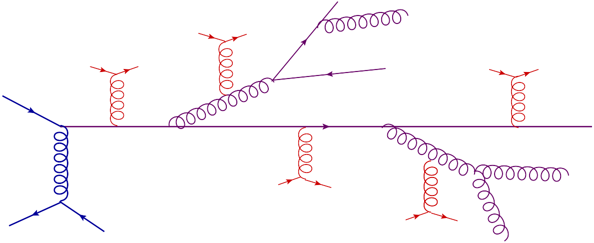

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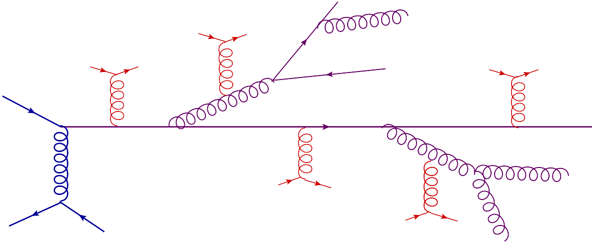
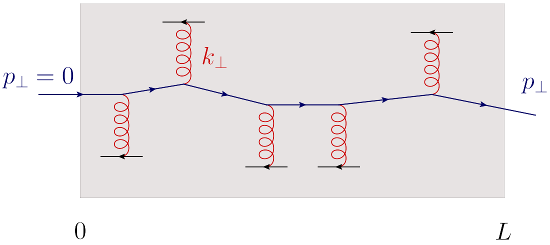


- ... and via collisions off the medium constituents
- Collisions can have several effects
  - transfer energy and momentum between the jet and the medium
  - trigger additional radiation (“medium-induced”)
  - wash out the color coherence (destroy interference pattern)

p_T-broadening in AA collisions

- Weakly coupled QGP: an energetic quark acquires a transverse momentum $p_\perp$ via independent successive collisions, after propagating over a distance L



- A random walk in transverse momentum: $\langle p_\perp^2 \rangle \simeq \hat{q} L$

$$\hat{q}_{\rm hot} = \int^{Q^2} {\rm d}^2\boldsymbol{k}\, \frac{{\rm d}\Gamma_{\rm el}}{{\rm d}^2\boldsymbol{k}}\, \boldsymbol{k}^2 \simeq 4\pi\alpha_s^2 C_F \rho_{\rm hot} \ln \frac{Q^2}{m_D^2}$$

- $\rho_{\rm hot} = C_F n_q + N_c n_g \sim T^3$: density of the thermal quarks & gluons

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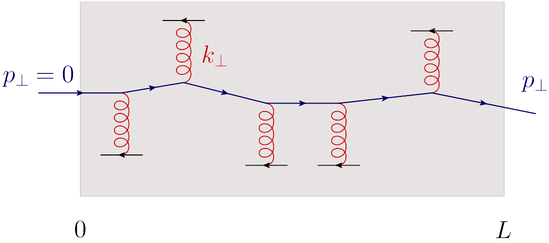

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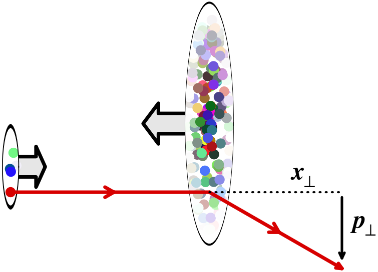
- Typical values: $\hat{q} = 1 \div 2$ ${\rm GeV}^2/{\rm fm}$, $L = 4 \div 6$ fm, $\langle p_\perp^2 \rangle = 4 \div 12$ ${\rm GeV}^2$

p_T-broadening in pA collisions (1)

- A quark (or gluon) initially collinear with the proton acquires a transverse momentum $p_\perp$ via multiple scattering off the saturated gluons



$$\eta = -\ln\tan\frac{\theta}{2}$$

$$x_p \equiv \frac{p^+}{q^+} = \frac{p_\perp}{\sqrt{s}}\,\mathrm{e}^{\eta}$$

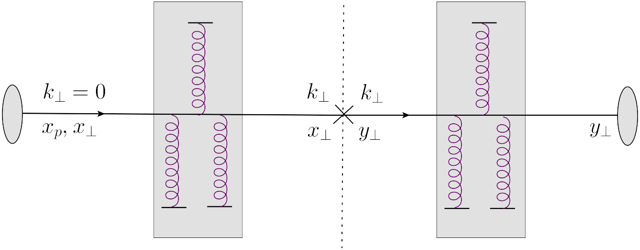
$$x_g \equiv \frac{p^-}{P^-} = \frac{p_\perp}{\sqrt{s}}\,\mathrm{e}^{-\eta}$$

  - $\eta \simeq 0$ and RHIC kinematics: $x_p \simeq x_g \simeq 10^{-2}$
  - $\eta \simeq 3$ (“forward rapidity”): $x_p \simeq 0.2$, $x_g \simeq 5 \times 10^{-4}$

- Forward particle production probes the nuclear gluon distribution at small x_g

p_T-broadening in pA collisions (2)

- Multiple scattering in the eikonal approximation: Wilson lines



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\eta\mathrm{d}^2k_\perp} \simeq x_p q(x_p) \int_{\boldsymbol{x},\boldsymbol{y}} \mathrm{e}^{-\mathrm{i}(\boldsymbol{x}-\boldsymbol{y})\cdot\boldsymbol{k}} \frac{1}{N_c} \left\langle \mathrm{tr}\big(V_{\boldsymbol{x}} V_{\boldsymbol{y}}^\dagger\big)\right\rangle_{x_g}$$

- An unintegrated gluon distribution: “dipole TMD”
- Target average computed within the CGC
- BK-JIMWLK evolution with decreasing x_g (increasing η)

p_T-broadening in pA collisions (3)

- $\eta \sim 0$: no evolution $\Longrightarrow$ scattering off the valence quarks ("MV model")

$$\frac{\mathrm{d}N}{\mathrm{d}\eta \mathrm{d}^2 p_\perp} \simeq \frac{1}{\pi Q_s^2}\,\mathrm{e}^{-p_\perp^2/Q_s^2}, \quad Q_s^2 \equiv \hat{q}L, \quad L = 2R_A \frac{M}{P}$$

$$\hat{q}_{\mathrm{cold}} = \frac{4\pi^2 \alpha_s C_F}{N_c^2 - 1} \rho_{\mathrm{cold}}\, xG_N(x, Q_s^2) \sim \alpha_s^2 C_F \rho_{\mathrm{cold}} \ln \frac{Q_s^2}{\Lambda^2}$$

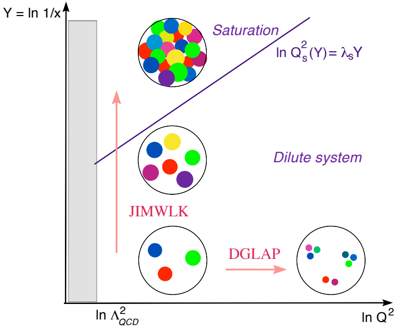
- Similar to QGP, except that ρ_{cold} (the nucleon density) is smaller than ρ_{hot}
- Typical value: $Q_s^2(A, x_g \sim 10^{-2}) \sim 1$ GeV (from fits to d+Au at RHIC)
- This can explain the Cronin peak at mid-rapidity in R_{pA} at RHIC

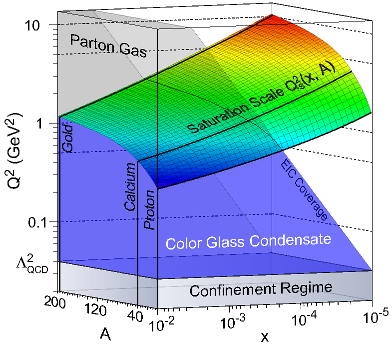
  (Kovchegov, Tuchin, 2003; E. I., Itakura, Triantafyllopoulos, 2004)
- Large $\eta \gtrsim 3$: rapid increase of the gluon density via BK-JIMWLK evolution

$$Q_s^2(x, A) \sim \frac{A^{1/3}}{x^{\lambda_s}}, \quad \lambda_s = 0.20 \div 0.25$$

The saturation momentum

- Non-linear evolution of the gluon distribution with increasing $Y \equiv \ln(1/x)$.
  - presently known to next-to-leading order accuracy
- It stops when the occupation number becomes of order $1/\alpha_s$: saturation

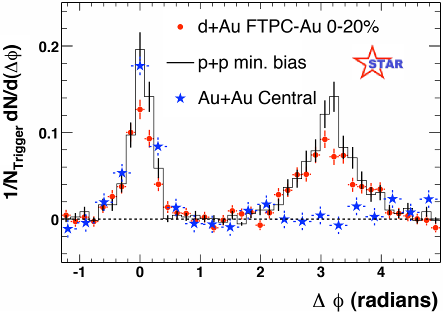


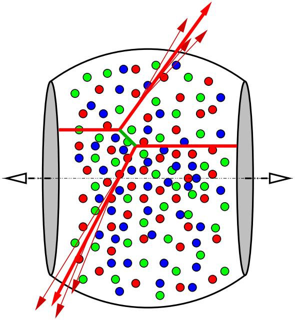


- For $A = 200$ and $x = 10^{-4}$, one has $Q_s^2 \simeq 6$ GeV^2 (quark projectile)
  - p_T broadening in pA or eA becomes as strong as in AA

Di-hadron azimuthal correlations

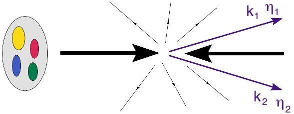
- Distribution of pairs of particles w.r.t. the relative azimuthal angle $\Delta\Phi$
  - peak at $\Delta\Phi \sim 0$: both hadrons belong to a same jet
  - peak at $\Delta\Phi \sim \pi$: they belong to two back-to-back jets

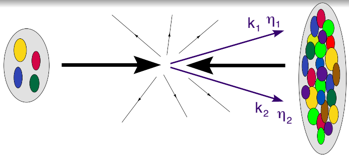


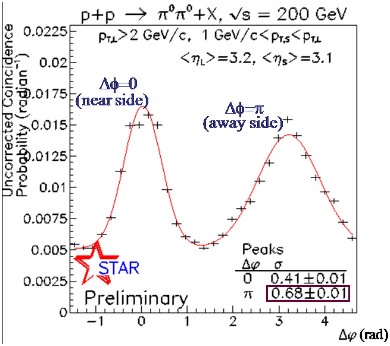


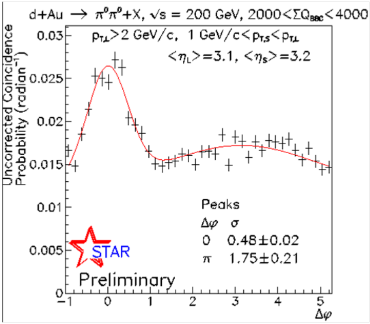
- RHIC: $4 < p_{T,\mathrm{trig}} < 6$ GeV, mid-rapidity ($\eta \sim 0$)
- Au+Au: no peak at $\Delta\Phi \sim \pi$: p_T-broadening in the QGP

Di-hadrons at forward rapidities







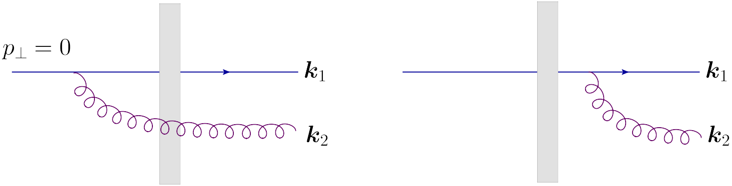


- The scattering transfers an overall momentum $|\boldsymbol{k}_1 + \boldsymbol{k}_2| \simeq Q_s(x_g)$
- Predicted by the CGC *(Marquet, 2007; Albacete and Marquet, 2010)*

Forward di-hadrons in pA collisions

(Marquet, NPA796, 2007; Dominquez, Marquet, Xiao, Yuan, PRD83, 2011)

- The collinear quark radiates a gluon prior to, or after, the scattering

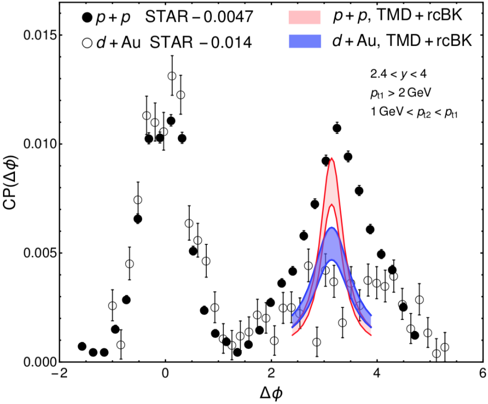


- 4 Wilson lines in the cross-section: color quadrupole $\frac{1}{N_c}\langle \mathrm{tr}(V^\dagger_{\boldsymbol{x}_1} V_{\boldsymbol{x}_2} V^\dagger_{\boldsymbol{x}_3} V_{\boldsymbol{x}_4})\rangle$
- Generalization of Weiszäcker-Williams gluon TMD (occupation number)
- Reduces to the latter in the "correlation" limit $k_{1\perp} \simeq k_{2\perp} \gg |\boldsymbol{k}_1 + \boldsymbol{k}_2|$
  - the 2 hadrons are nearly back-to-back and harder than Q_s
- Saturation effects still important: the broadening of the peak at $\Delta\Phi = \pi$

Forward di-hadrons: the state of art (1)

(Albacete, Giacalone, Marquet, and Matas, arXiv:1805.05711)

- Reasonable description of the away peaks in both p+p and d+Au at RHIC

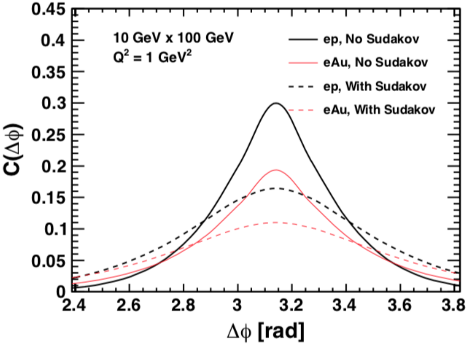


- The broadening predictions still too small, since no Sudakov effects yet

Forward di-hadrons: the state of art (2)

(Zheng, Aschenauer, Lee, and Xiao, arXiv:1403.2413)

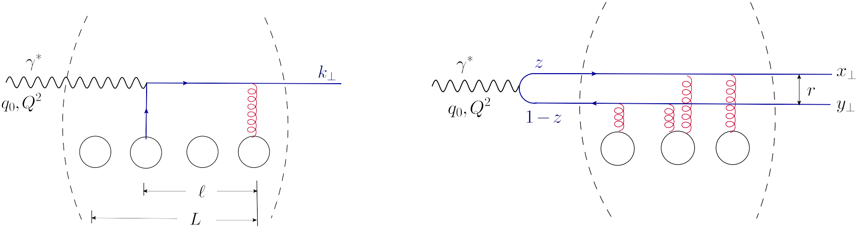
- A calculation illustrating the effect of the Sudakov factor (radiation)



- This applies to DIS (eA and ep), but physics is indeed very similar

p_T-broadening in eA collisions

- 2 kinematical regimes: large x and small x (coherence time vs. $L = 2R_A/\gamma$)



- To study nuclear effects, one clearly needs x as small as possible
  - high gluon density, maximal in-medium path length

$$t_{coh} = \frac{2q_0}{Q^2} > L = 2R_A \frac{M_N}{P_N} \implies x \equiv \frac{Q^2}{2P \cdot q} \lesssim 0.01$$

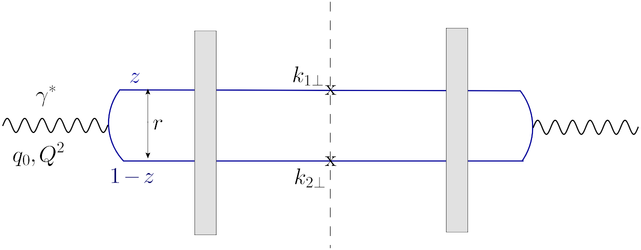
- Assume maximal energy $E_e = 20$ GeV, $E_N = 100$ GeV

$\implies Q^2 < 0.01ys = 80y \sim 40$ GeV^2 when $y = 0.5$

- N.B. q and $\bar{q}$ have an intrinsic $k_\perp^2 \sim 1/r^2 \simeq z(1-z)Q^2 \lesssim 10$ GeV^2

Forward jets/dijets in eA collisions

- In the Lab frame, $\gamma = 100 \Rightarrow$ the dipole scatters of a shockwave



- If $z \sim 1-z \sim 1/2 \Longrightarrow$ two mostly forward jets
- Longitudinal momenta $(k_1^+ = zq^+,\, k_2^+ = (1-z)q^+)$ are not affected
- Transverse momenta receive contributions from the scattering (transfer from the target) on top of the intrinsic momenta in the γ^* wavefunction
- Eikonal approximation: convenient to use transverse coordinate repres.

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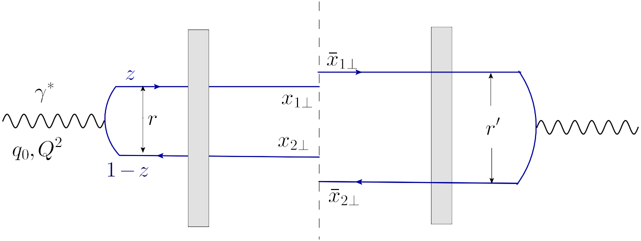

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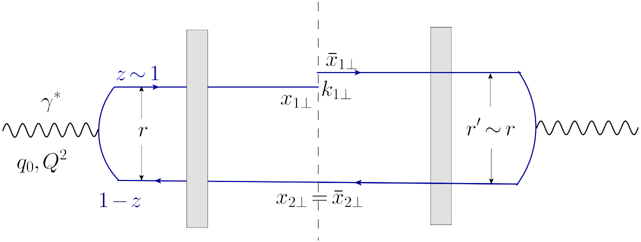
Forward single jet

(Al Mueller, Nucl.Phys. B558, 1999; see also Al's talk this morning)

- It is convenient to tag on a jet, or leading parton, with $z \sim 1$



- Large dipole: $r^2 \simeq \frac{1}{(1-z)Q^2} \gg \frac{1}{Q^2} \Longrightarrow$ sensitivity to saturation even for a relatively hard process: $Q_s^2 \sim (1-z)Q^2 \ll Q^2,\, k_{1\perp}^2$
- A simple calculation suggests geometric scaling, like in DIS at HERA:

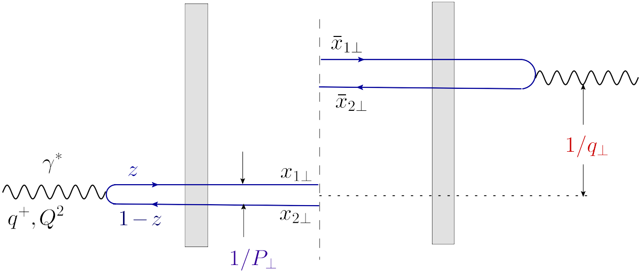
$$\frac{\mathrm{d}N}{\mathrm{d}\eta \mathrm{d}^2 k_\perp} \propto \left(\frac{Q_s^2(x)}{k_\perp^2}\right)^{\gamma_s}, \quad \gamma_s \simeq 0.63$$

Azimuthal asymmetries in dijets (1)

(Dominquez, Marquet, Xiao, Yuan, PRD83, 2011)

- 2 jets which are nearly back-to-back, in the correlation limit $P_\perp \gg q_\perp$

$$P_\perp \equiv (1-z)\boldsymbol{k}_{1\perp} - z\boldsymbol{k}_{2\perp} \ \text{(relative } p_T\text{)}, \quad \boldsymbol{q}_\perp \equiv \boldsymbol{k}_{1\perp} + \boldsymbol{k}_{2\perp} \ \text{(imbalance)}$$



- $P_\perp^2 \sim z(1-z)Q^2$ controlled by the γ^* decay; $q_\perp \sim Q_s$ by saturation
- Access to the "conventional" WW gluon TMD $xG^{(1)}(x, q_\perp)$
  - measure the suppression of the back-to-back correlation, as in pA

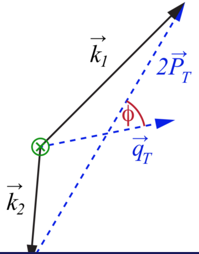
Azimuthal asymmetries in dijets (2)

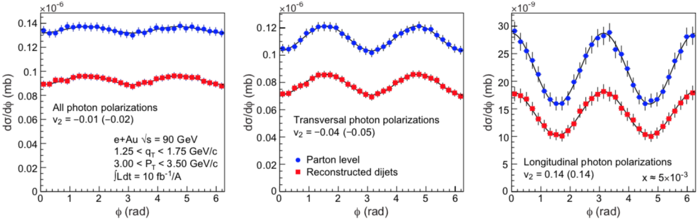
(Metz, Zhou, 1105.1991; Dumitru, Lappi, Skokov, 1508.04438; Marquet, Petreska, Roiesnel, 1608.02577; Dumitru, Skokov, Ullrich, 1809.02615)

- One can also measure the linearly polarized WW gluon TMD $xh_\perp^{(1)}(x, q_\perp)$
  - distribution of linearly polarized gluons inside an unpolarized nucleon
- Proportional to the azimuthal anisotropy in the angle ϕ between $P_\perp$ and $q_\perp$

$$\langle \cos 2\phi \rangle \propto \frac{xh_\perp^{(1)}(x, q_\perp)}{xG^{(1)}(x, q_\perp)}$$

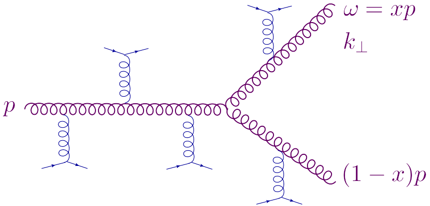
- Monte-Carlo generator MCDijet using JIMWLK solutions for WW TMDs





What about energy loss ?

- Recall: the main mechanism for jet quenching in AA collisions is energy loss via medium-induced radiation
- Such emissions have a limited formation time, hence a limited energy



$$t_{\mathrm{f}} = \frac{2\omega}{k_\perp^2} \le L$$

$$k_\perp^2 \sim Q_s^2 = \hat{q}L$$

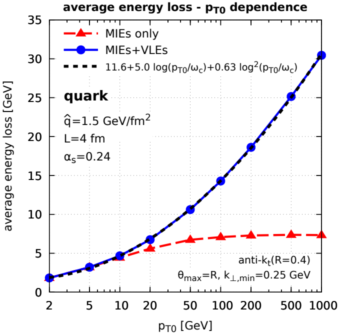
$$\Longrightarrow \ \omega \le \omega_c \equiv \frac{1}{2} Q_s^2 L$$

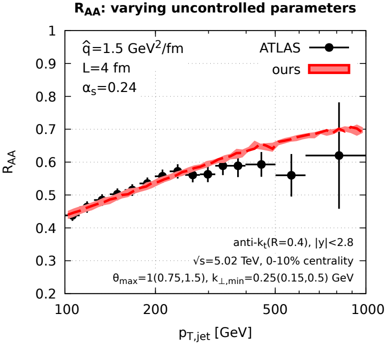
- ... which is however quite high: $\omega_c \simeq 60$ GeV
- LHC found strong jet quenching for jets with $p_T = 1$ TeV
- eA at EIC: the electron has $E_e^{\mathrm{RF}} = 4$ TeV in the target rest frame
- The target is dense at small x: $Q_s^2(x) R_A \gtrsim 50$ GeV for $x < 10^{-3}$

Some lessons from R_{AA} for jets (LHC)

(Caucal, E.I., Mueller, Soyez, PRL120 (2018); Caucal, E.I., Soyez, 1907.04866)

- What matters for jets is the typical energy loss at large angles
- For a single parton, this saturates at a value $\alpha_s^2\omega_c \sim 10$ GeV
- The number of partons in a jet increases with p_T, via vacuum-like emissions





- This explains why R_{AA} rises so slowly with p_T as seen in the data.

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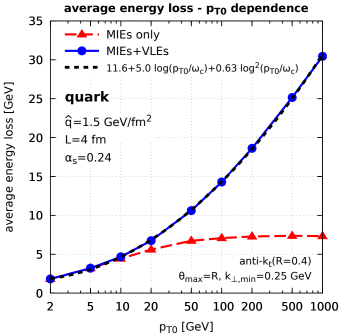
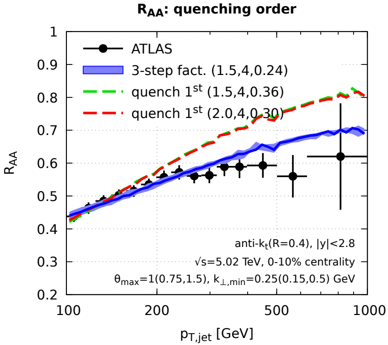




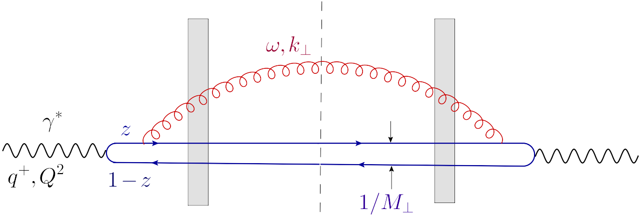
- If one excludes vacuum-like emissions, R_{AA} rises much faster at high p_T.

Coherent energy loss in eA

- AA: jets are created as highly virtual, bare, partons in the medium RF
  - they radiate thus creating new partons $\Longrightarrow$ more sources for energy loss
- eA: the $q\bar{q}$ pair are asymptotic (nearly on-shell) partons
  - they fragment only after the scattering and far away from it
  - in-medium energy loss is negligible: $\alpha_s^2 Q_s^2 L \ll E_e^{\mathrm{RF}} = s/2M$
- Yet, there is another possible mechanism for medium induced energy loss
- q and $\bar{q}$ develop space-like quanta that can be freed by the collision
  - "(fully) coherent energy loss" *(Arleo, Peigné, PRL 109, 2012)*
  - used as an interpretation for J/ψ suppression in d+Au at RHIC
- CGC calculation for di-jets in pA *(Liou, Mueller, PRD89, 2014)*

Coherent energy loss for di-jets in eA

- Consider the production of a pair of heavy flavors (M_Q), or a pair of light quarks, but with high $P_\perp$: $M_\perp^2 \equiv M_Q^2 + P_\perp^2 \gg Q_s^2(x)$
- A gluon w/ energy ω can be emitted long before, or long after, the scattering
  - large formation time $t_{\rm f} = \frac{2\omega}{k_\perp^2} \Longrightarrow$ large ω (restricted only by q^+)



- For initial-state emissions in both the DA and the CCA, the scattering of the gluon does not matter: it cancels out by unitarity.
  - same result as for $ep \Longrightarrow$ no net nuclear effect

Coherent energy loss for di-jets in eA

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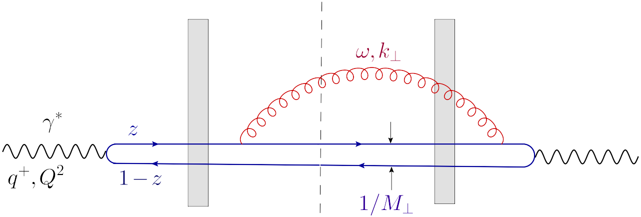


- For the interference terms though (IS/FS or FS/IS), it does not cancel !
  - the gluon is typically soft, $k_\perp \sim Q_s$, hence it is sensitive to saturation
  - net nuclear energy loss, which scales with the total energy: $\Delta E \propto E$

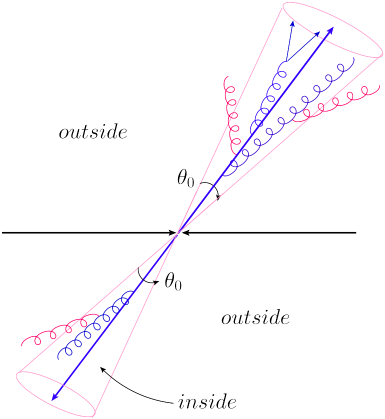
Conclusions

- The nuclear physics at the EIC (in particular in relation with jets) is even more interesting than I thought !
- The role of the quark-gluon plasma is taken over by the gluon saturation
- Bulk observables are replaced by subtle, interference, phenomena
- Leading-order (tree-level) physics is not sufficient anymore: quantum evolution is already essential in order to create the medium (CGC)
- Many fine observables, that can be accurately measured and computed
- Many surprises to come, but we should do our best to anticipate them!

THANK YOU FOR YOUR ATTENTION !

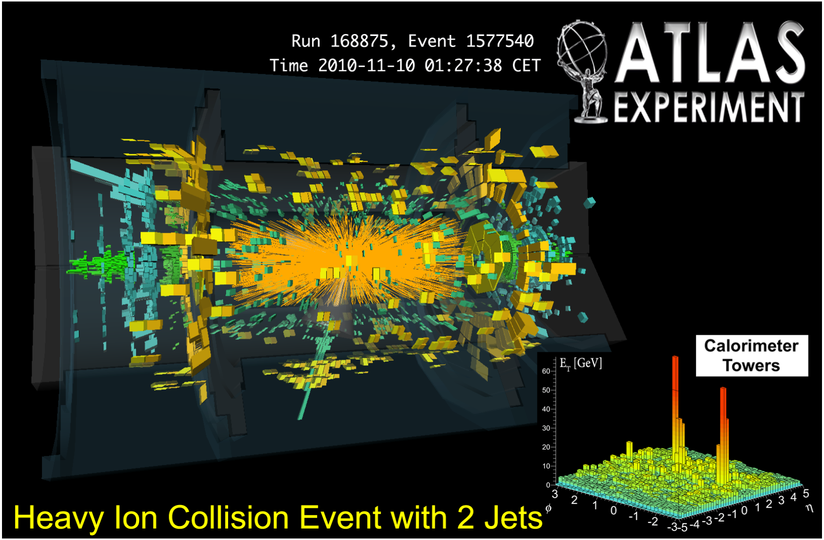
Jets in practice

- Experimentally, jets are constructed by grouping together hadrons which propagate at nearby angles $\theta < \theta_0 \equiv R$
- The jet opening angle θ_0 (or R) is the same for both jets



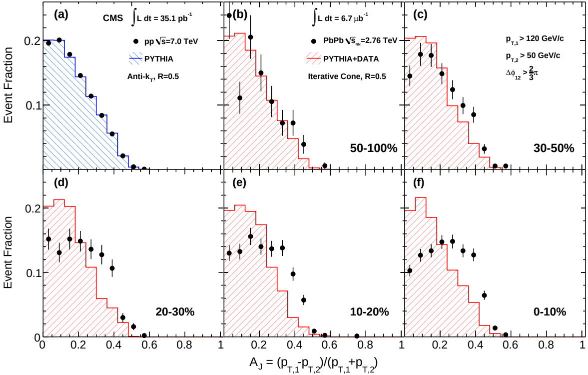
- Medium modifications refer both to the jets and to the outer regions

Jets in peripheral Pb+Pb collisions



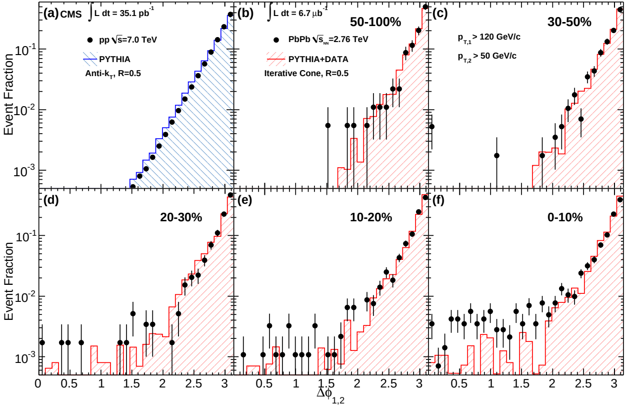
- Jets in peripheral AA collisions look very much like in pp collisions

Di-jet asymmetry: A_J



- Event fraction as a function of the di–jet energy imbalance in p+p (a) and Pb+Pb (b–f) collisions for different bins of centrality
- N.B. A pronounced asymmetry already in p+p collisions !
  - 3-jets events, fluctuations in the branching process
- Central Pb+Pb : the asymmetric events occur more often

Di-jet asymmetry: $\Delta\phi$ distribution

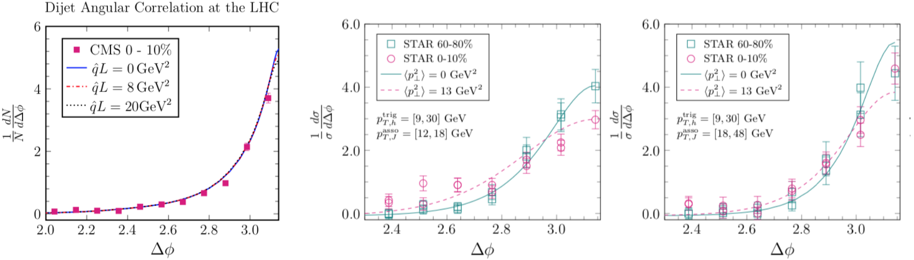


- No significant angular decorrelation beyond pp collisions
- The angular distribution shows a large width already in pp collisions
- Why? Recoil due to standard gluon radiation after a hard scattering

Sudakov vs. medium-induced p_T-broadening

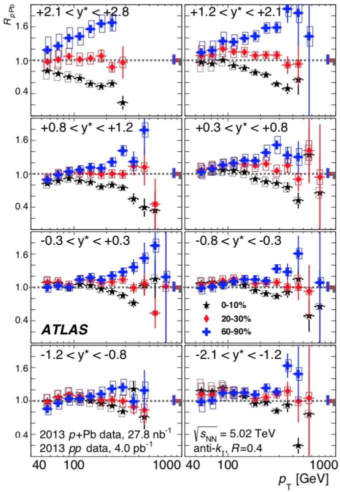
Mueller, Wu, Xiao, Yuan, PLB 763 (2016); Chen et al, arXiv:1607.01932

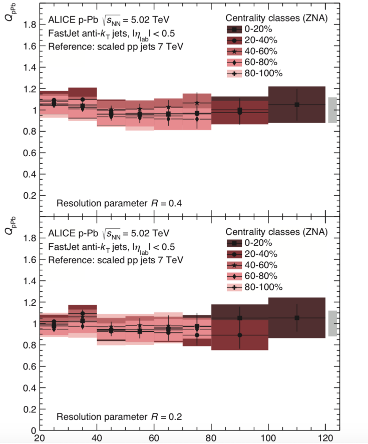
- "Sudakov effect": the effects of the radiation are visible since the measurements is non-inclusive (one measures an angular correlation)
  - incomplete cancellation between "real" and "virtual" corrections
  - effect $\sim \alpha_s \ln^2(p_T^2/Q_s^2)$: the phase-space for radiation at $Q_s < \omega < p_T$



  - medium-induced p_T-broadening has no effect for dijets at the LHC
  - at RHIC, there seems to be a small but measurable effect

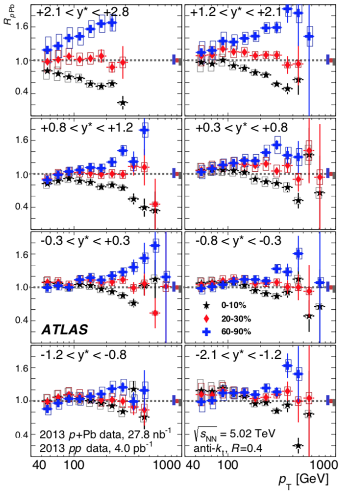
R_{pA} for high-multiplicity events: jet quenching?

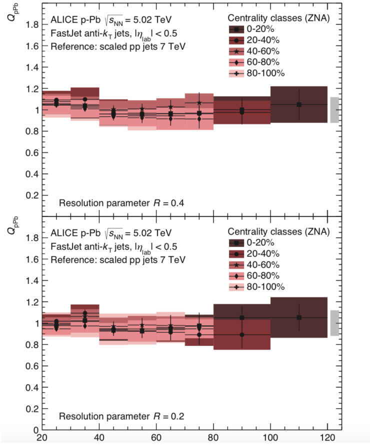




- Events divided in "centrality classes" reflecting the "event activity"
  - forward (or central) particle multiplicity, forward transverse energy...
  - the correlation with the collision geometry remains obscure

R_{pA} for high-multiplicity events: jet quenching?

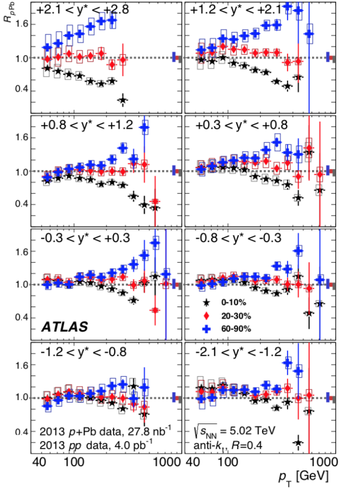


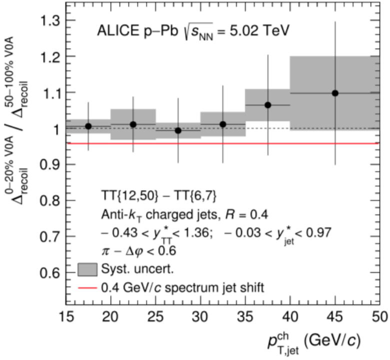


- Nuclear effects reported by PHENIX and ATLAS for both "central" and "peripheral" events (@ forward rapidity, in the proton direction)

(PHENIX: Phys.Rev.Lett. 116, 2016; ATLAS: Phys.Lett.B 748, 2015)

R_{pA} for high-multiplicity events: jet quenching?

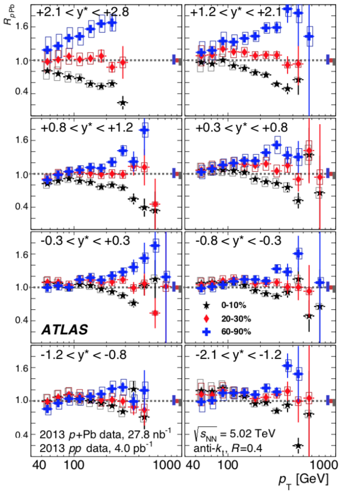


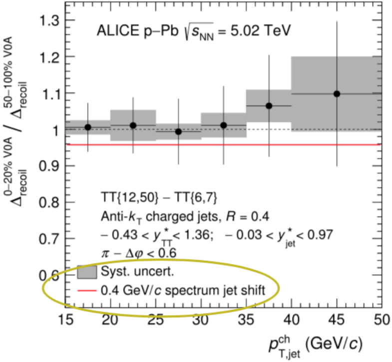


ALICE, arXiv:1712.05603

- However, not seen by ALICE: use semi-inclusive observables
  - the correlation between $\langle T_{pPb}\rangle$ and the event activity is subjected to uncertainties (large fluctuations, bias from energy conservation ...)

R_{pA} for high-multiplicity events: jet quenching?

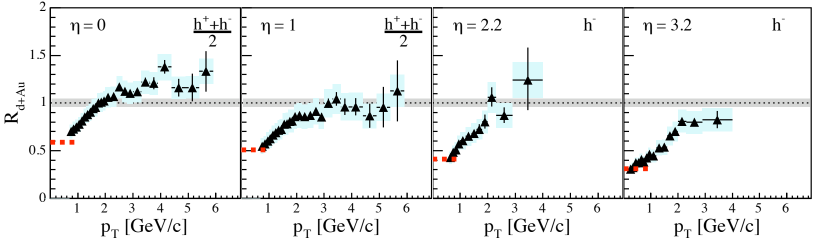




ALICE, arXiv:1712.05603

- An energy loss as small as $\epsilon = 0.4$ GeV could have been observed!

Forward rapidities: R_{pA} suppression



- The Cronin peak disappears already after one unit of rapidity ! Why ?
- R_{pA} is the ratio of 2 "dipole" TMDs: for the nucleus and for the proton
- With increasing η, the gluon distribution in the proton rises faster (via the BK-JIMWLK evolution) than that in the nucleus
  - growth driven by BFKL dynamics in the dilute tail at $p_\perp > Q_s$
  - the logarithmic phase-space $\rho = \ln(p_\perp^2/Q_s^2)$ is larger for the proton than for the nucleus, since $Q_s(p) < Q_s(A)$

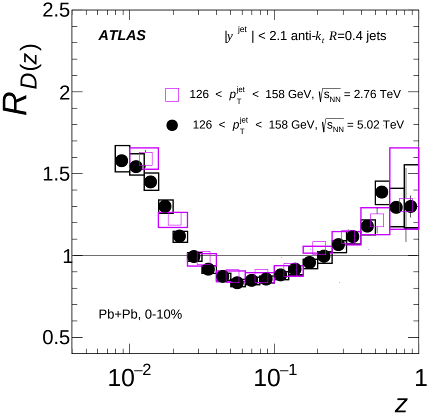
Nuclear effects on the jet substructure

- The internal structure of the jet, at angles $\theta < R$, is strongly modified as well

$$D(\omega) \equiv \omega \frac{\mathrm{d}N}{\mathrm{d}\omega}$$

$$= \int_0^R \mathrm{d}\theta\, \omega \frac{\mathrm{d}N}{\mathrm{d}\theta \mathrm{d}\omega}$$

- ratio of FFs in Pb+Pb and p+p
- enhancement at small $z \equiv p_T/p_T^{jet}$
- ... and at z close to 1
- slight suppression at intermediate z



- Naturally interpreted as a combination of energy loss and additional, soft, medium-induced radiation