Universality of high-p_T hadron suppression from radiative energy loss in AA collisions

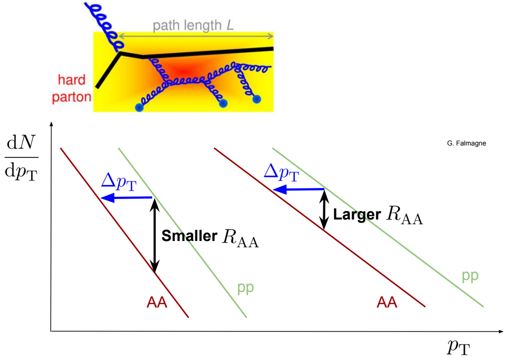
Guillaume Falmagne

Subatech, IMT Atlantique, Nantes

QGP France, Tours
May 3rd, 2022

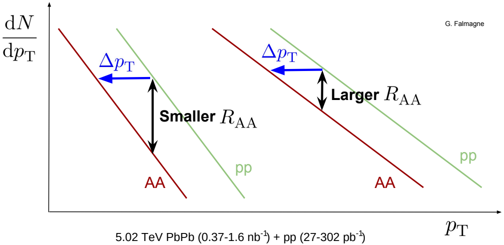
Energy loss in QGP, using high-p_T hadrons

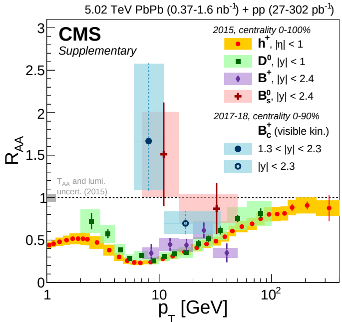
- Produced partons interact with the QGP
  - → reduced p_{T} (= 'energy loss')
  - → apparent suppression $R_{AA} < 1$ ('quenching')



Energy loss in QGP, using high-p_T hadrons

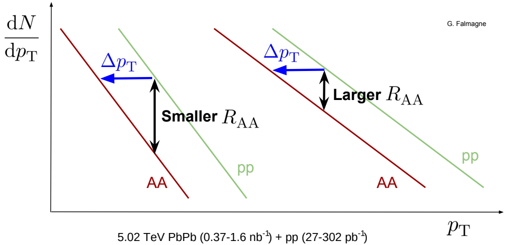
- Produced partons interact with the QGP
  - → reduced p_{T} (= 'energy loss')
  - → apparent suppression $R_{AA} < 1$ ('quenching')
- Collisional energy loss: low-$p_T \lesssim m_Q$
- Mass dependence of energy loss: low to mid-p_T

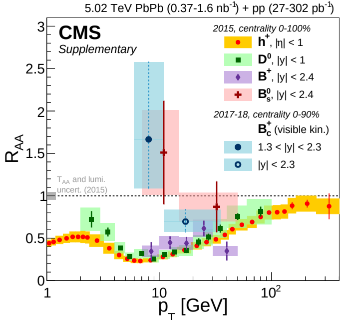




Energy loss in QGP, using high-p_T hadrons

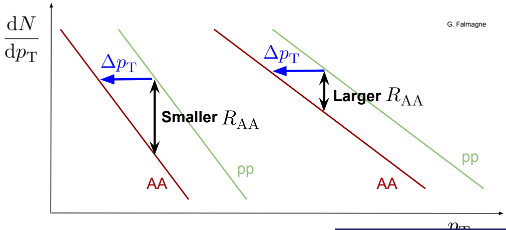
- Produced partons interact with the QGP
  - ⟶ reduced p_T (= 'energy loss')
  - ⟶ apparent suppression $R_{AA} < 1$ ('quenching')
- Collisional energy loss: low-$p_T \lesssim m_Q$
- Mass dependence of energy loss: low to mid-p_T
- Radiative energy loss dominates $p_T \gtrsim 10$ GeV modification (other effects fade out)
  - ⟶ medium-induced gluon emission



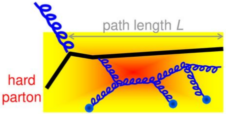


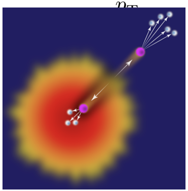
Energy loss in QGP, using high-p_T hadrons

- Produced partons interact with the QGP
  - ⟶ reduced p_{T} (= 'energy loss')
  - ⟶ apparent suppression $R_{AA} < 1$ ('quenching')
- Collisional energy loss: low-$p_T \lesssim m_Q$
- Mass dependence of energy loss: low to mid-p_T



- Radiative energy loss dominates $p_T \gtrsim 10$ GeV modification (other effects fade out)
  - ⟶ medium-induced gluon emission

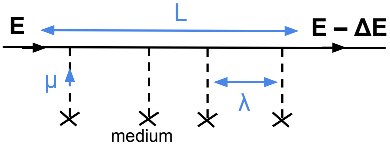




- High-p_T **hadron** ∼ daughter of precursor **hard parton** traversing the QGP
- Quenching first studied with hadrons (RHIC), then di-jet asymmetry (RHIC+LHC)... but jets ≠ partons (= particles)
  - ⟶ Hadron 'simply' takes momentum fraction $\langle z \rangle$ from parton ⟶ use hadron spectra

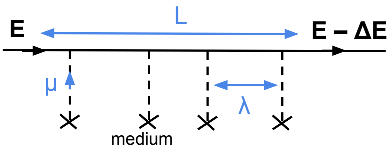
BDMPS radiative energy loss

- QGP diffusion properties characterised by transport coefficient $\hat{q} = \frac{\mu^2}{\lambda} \propto n$
  - Momentum kick in 1 rescaterring: Debye mass μ
  - Mean free path between 2 rescatterings: λ
  - Total path length in the medium: L

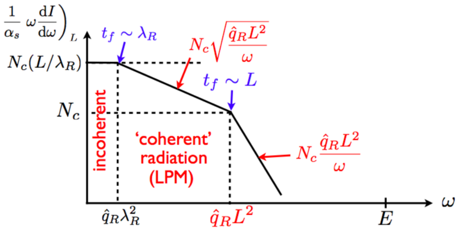


BDMPS radiative energy loss

- QGP diffusion properties characterised by transport coefficient $\hat{q} = \frac{\mu^2}{\lambda} \propto n$
  - Momentum kick in 1 rescaterring: Debye mass μ
  - Mean free path between 2 rescatterings: λ
  - Total path length in the medium: L

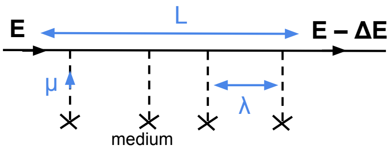


- Depending on t_f (emitted gluon formation time), 3 regimes: incoherent ($t_f \ll \lambda$), LPM ($\lambda \ll t_f \lesssim L$), fully coherent ($t_f \gg L$)



BDMPS radiative energy loss

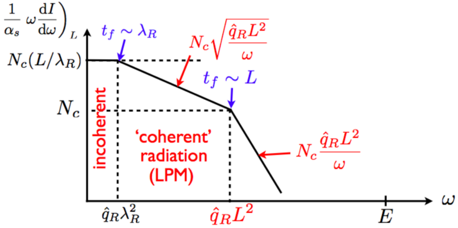
- QGP diffusion properties characterised by transport coefficient $\hat{q} = \frac{\mu^2}{\lambda} \propto n$
  - Momentum kick in 1 rescaterring: Debye mass μ
  - Mean free path between 2 rescatterings: λ
  - Total path length in the medium: L



- Depending on t_f (emitted gluon formation time), 3 regimes: incoherent ($t_f \ll \lambda$), LPM ($\lambda \ll t_f \lesssim L$), fully coherent ($t_f \gg L$)

- Integrating the energy spectrum of emitted gluons
  ⟶ BDMPS mean energy loss:

$$\varepsilon \sim \frac{\alpha_S C_R}{4} \hat{q} L^2$$



- Hypotheses: $\varepsilon \ll E$, and $L \gg \lambda$
  ⟶ $=$ small fractional energy loss & large medium

Hadron suppression from parton energy loss

- Model describing *only* BDMPS radiative energy loss of partons (Arleo, PRL119, 2017)
- Using quenching weight $P(\varepsilon)$:

$$\frac{\mathrm{d}\sigma_{AA}^{q/g}}{\mathrm{d}p_T}(p_T) = A^2 \int \mathrm{d}\varepsilon \, P(\varepsilon) \, \frac{\mathrm{d}\sigma_{pp}^{q/g}}{\mathrm{d}p_T}(p_T + \varepsilon)$$

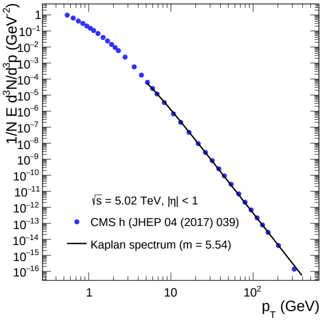
Hadron suppression from parton energy loss

- Model describing *only* BDMPS radiative energy loss of partons (Arleo, PRL119, 2017)
- Using quenching weight $P(\varepsilon)$:

$$\frac{\mathrm{d}\sigma_{AA}^{q/g}}{\mathrm{d}p_T}(p_T) = A^2 \int \mathrm{d}\varepsilon\, P(\varepsilon)\, \frac{\mathrm{d}\sigma_{pp}^{q/g}}{\mathrm{d}p_T}(p_T + \varepsilon)$$

- Hadron takes fraction $\langle z \rangle$ of parton momentum (smooth FF assumed)
- Scaleless $\bar{P}$, with free parameter $\langle \varepsilon \rangle$: $P(\varepsilon) = \frac{1}{\langle \varepsilon \rangle} \bar{P}\left(\frac{\varepsilon}{\langle \varepsilon \rangle}\right)$
- Fit high-p_{T} pp cross section $\mathrm{d}\sigma/\mathrm{d}p_T \sim p_T^{-n}$ (depending on hadron species)

Fit $\mathrm{d}\sigma_{pp}/\mathrm{d}p_T$, light hadrons, 5.02 TeV



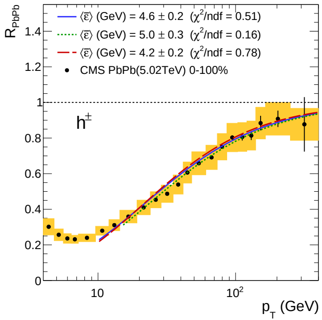
Hadron suppression from parton energy loss

- Model describing *only* BDMPS radiative energy loss of partons (Arleo, PRL119, 2017)
- Using quenching weight $P(\varepsilon)$:

$$\frac{\mathrm{d}\sigma_{AA}^{q/g}}{\mathrm{d}p_T}(p_T) = A^2 \int \mathrm{d}\varepsilon\, P(\varepsilon)\, \frac{\mathrm{d}\sigma_{pp}^{q/g}}{\mathrm{d}p_T}(p_T+\varepsilon)$$

- Hadron takes fraction $\langle z \rangle$ of parton momentum (smooth FF assumed)
- Scaleless $\bar{P}$, with free parameter $\langle\varepsilon\rangle$: $P(\varepsilon) = \frac{1}{\langle\varepsilon\rangle}\bar{P}\left(\frac{\varepsilon}{\langle\varepsilon\rangle}\right)$
- Fit high-p_T pp cross section $\mathrm{d}\sigma/\mathrm{d}p_T \sim p_T^{-n}$ (depending on hadron species)

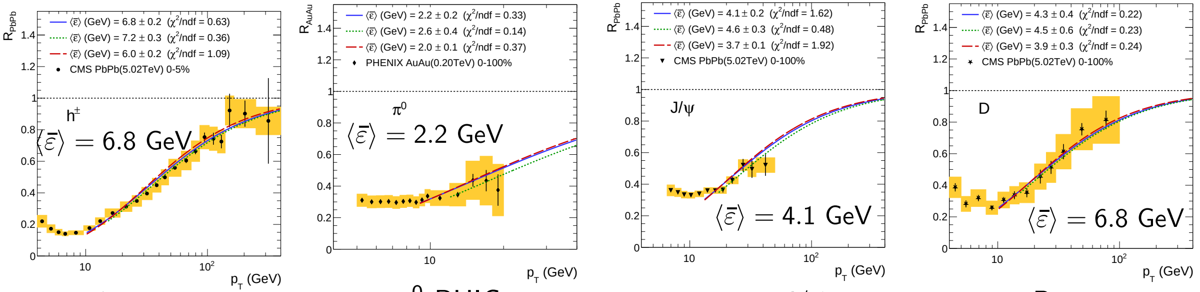
Fit $R_{PbPb}(p_\mathrm{T})$, light hadrons



$$\rightarrow R_{AA}(p_T) = \int_0^\infty \mathrm{d}x \frac{\bar{P}(x)}{\left(1 + x\frac{\langle z\rangle\langle\varepsilon\rangle}{p_T}\right)^n} \simeq \int_0^\infty \mathrm{d}x \exp\left(-x\, n \frac{\langle z\rangle\langle\varepsilon\rangle}{p_T}\right) \bar{P}(x)$$

Fits of $R_{AA}(p_{\mathrm{T}})$

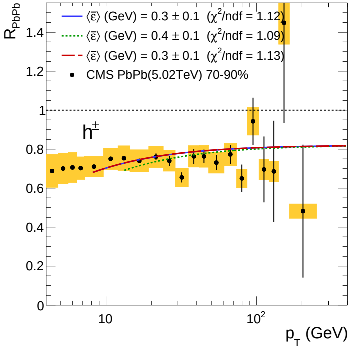
- Fit mean energy loss $\langle \bar{\varepsilon} \rangle = \langle z \rangle \langle \varepsilon \rangle$ from many $R_{AA}(p_{\mathrm{T}})$ measurements
- $p_{\mathrm{T}} > 7$ to 13 GeV, depending on system (varied for systematic on $\langle \bar{\varepsilon} \rangle$)
- $\langle \bar{\varepsilon} \rangle$ uncertainties: from correlated and uncorrelated (vs p_{T} bins) measurement uncert.

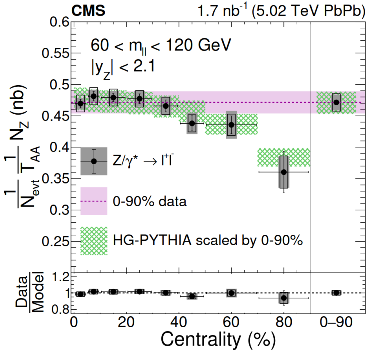


$h^{\pm}$ 5.02 TeV 0-5% centr. | π^0 RHIC AuAu 200 GeV | prompt J/ψ 5.02 TeV | D 5.02 TeV

Bias in peripheral collisions

- Event-selection and geometry bias set forth by Loizides and Morsch (PLB773 (2017))
- Multiply the R_{AA} model by their correction factors, relevant for centralities $> 50\%$



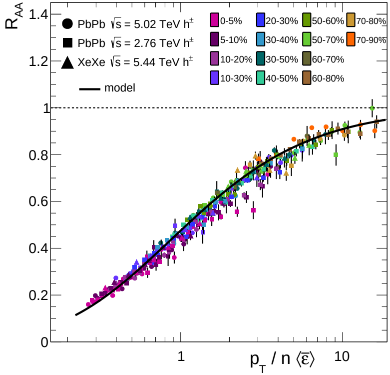


- Goes up to 18% in 70-90% centr. PbPb collisions
- Obvious in electroweak probes apparent suppression

Universal high-p_T shape: $R_{AA}(p_T, \langle\bar{\varepsilon}\rangle) \simeq R_{AA}(p_T/\langle\bar{\varepsilon}\rangle)$

- 62 fits to measured $R_{AA}(p_T)$, all consistent with model at high p_T!
  - 3 particles: light hadrons (and π^0), J/ψ, D
  - 4 energies: 0.2, 2.76, 5.02, 5.44 TeV
  - 4 experiments: CMS, ALICE, ATLAS, PHENIX
  - Many centrality classes + pp spectrum

$\longrightarrow$ Scaling of $R_{AA}(hadrons)$ for $p_T \gtrsim 8-10$ GeV

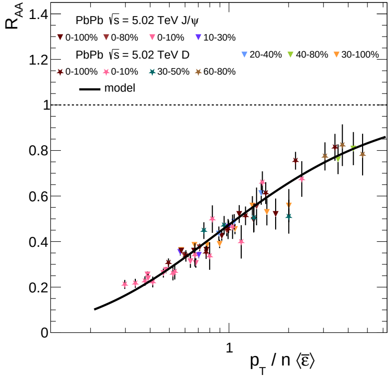


Universal high-p_T shape: $R_{AA}(p_{\mathrm{T}}, \langle\bar{\varepsilon}\rangle) \simeq R_{AA}(p_{\mathrm{T}}/\langle\bar{\varepsilon}\rangle)$

- 62 fits to measured $R_{AA}(p_{\mathrm{T}})$, all consistent with model at high p_{T}!
  - 3 particles: light hadrons (and π^0), J/ψ, D
  - 4 energies: 0.2, 2.76, 5.02, 5.44 TeV
  - 4 experiments: CMS, ALICE, ATLAS, PHENIX
  - Many centrality classes + pp spectrum

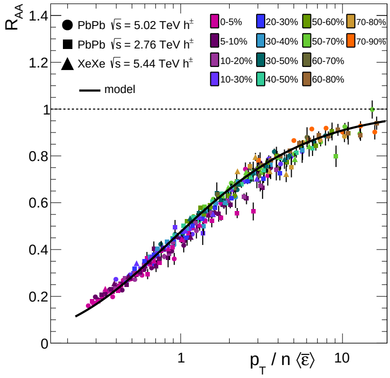
→ Scaling of $R_{AA}(hadrons)$ for $p_{\mathrm{T}} \gtrsim 8 - 10$ GeV

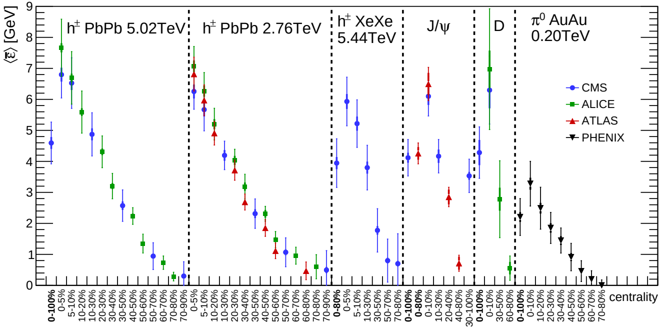
→ J/ψ and D mesons also scaling!



Universal high-p_T shape: $R_{AA}(p_T, \langle\bar{\varepsilon}\rangle) \simeq R_{AA}(p_T/\langle\bar{\varepsilon}\rangle)$

- 62 fits to measured $R_{AA}(p_T)$, all consistent with model at high p_T!
  - → Scaling of $R_{AA}(hadrons)$ for $p_T \gtrsim 8 - 10$ GeV
  - → J/ψ and D mesons also scaling!





- Fitted mean energy loss $\langle\bar{\varepsilon}\rangle$ is related to medium geometry (L and transverse area A_T), $\hat{q}$, and expansion dynamics

Energy loss vs medium geometry+density

- Salgado & Wiedemann PRL89 (2003) model the decreasing medium density with

$$\hat{q} \propto \hat{q}_0 \left(\frac{\tau_0}{\tau}\right)^{\alpha}$$

  - $\hat{q}_0 \propto n \propto \left(\frac{dN_{ch}}{dy}\Big|_{y=0} \right) / A_\perp \tau_0$ (Bjorken estimate)
  - α characterises the medium expansion
  - τ_0 = QGP formation time (assumed $\ll L$)

Energy loss vs medium geometry+density

- Salgado & Wiedemann PRL89 (2003) model the decreasing medium density with

$$\hat{q} \propto \hat{q}_0 \left(\frac{\tau_0}{\tau}\right)^{\alpha}$$

  - $\hat{q}_0 \propto n \propto \left(\left.\frac{dN_{ch}}{dy}\right|_{y=0} \right) / A_\perp \tau_0$ (Bjorken estimate)
  - α characterises the medium expansion
  - τ_0 = QGP formation time (assumed $\ll L$)

- Equivalent transport coefficient in static medium:

$$\langle \hat{q} \rangle = \frac{2}{L^2} \int_{\tau_0}^{\tau_0+L} \mathrm{d}\tau \, (\tau - \tau_0) \times \hat{q}_0 \left(\frac{\tau_0}{\tau}\right)^{\alpha} \simeq \frac{2}{2-\alpha} \, \hat{q}_0 \left(\frac{\tau_0}{L}\right)^{\alpha}$$

Energy loss vs medium geometry+density

- Salgado & Wiedemann PRL89 (2003) model the decreasing medium density with
$$\hat{q} \propto \hat{q}_0 \left(\frac{\tau_0}{\tau}\right)^{\alpha}$$
  - $\hat{q}_0 \propto n \propto \left(\frac{dN_{ch}}{dy}\bigg|_{y=0} \right) / A_\perp \tau_0$ (Bjorken estimate)
  - α characterises the medium expansion
  - τ_0 = QGP formation time (assumed $\ll L$)
- Equivalent transport coefficient in static medium:

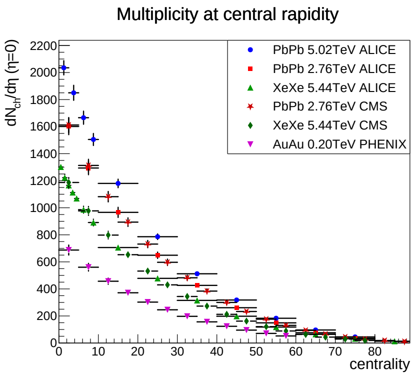
$$\langle \hat{q} \rangle = \frac{2}{L^2} \int_{\tau_0}^{\tau_0+L} \mathrm{d}\tau \, (\tau - \tau_0) \times \hat{q}_0 \left(\frac{\tau_0}{\tau}\right)^{\alpha} \simeq \frac{2}{2-\alpha} \hat{q}_0 \left(\frac{\tau_0}{L}\right)^{\alpha}$$

$$\longrightarrow \varepsilon \propto \langle \hat{q} \rangle L^2 \propto \tau_0^{\alpha-1} \frac{\frac{dN_{ch}}{dy}\Big|_{y=0}}{A_T} \times L^{2-\alpha}$$

Medium geometry and density

$$\varepsilon \propto \tau_0^{\alpha-1} \frac{\left.\frac{dN_{ch}}{dy}\right|_{y=0}}{A_T} \times L^{2-\alpha}$$

- Multiplicities from measurements

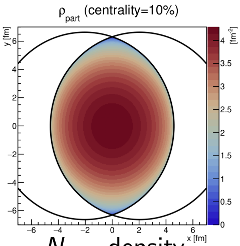


Medium geometry and density

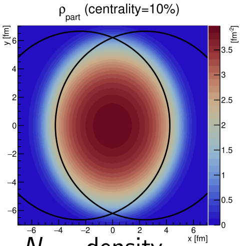
$$\varepsilon \propto \tau_0^{\alpha-1} \frac{\left.\frac{dN_{ch}}{dy}\right|_{y=0}}{A_T} \times L^{2-\alpha}$$

- Multiplicities from measurements
- Path length L and area A_T through 4 Glauber models:
  - MC Glauber from
    Loizides, Kamin, d'Enterria, PRC97 (2018)
  - 1 pure hard sphere nuclei: constant QGP density, fully analytic
  - 2 custom optical Glauber: hard spheres or Woods-Saxon
    → L less straightforward there:

$$\langle L \rangle = \frac{\int L(\vec{s},\phi)\, \rho_{coll}\, \mathrm{d}\vec{s}\, \mathrm{d}\phi}{2\pi \int \rho_{coll}\, \mathrm{d}\vec{s}}$$



N_{part} density (hard spheres)



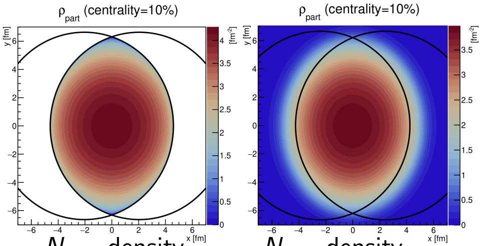
N_{part} density (Woods-Saxon)

Medium geometry and density

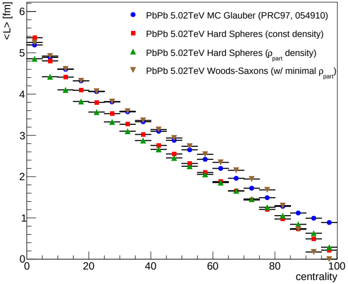
$$\varepsilon \propto \tau_0^{\alpha-1} \frac{\left.\frac{dN_{ch}}{dy}\right|_{y=0}}{A_T} \times L^{2-\alpha}$$

- Multiplicities from measurements
- Path length L and area A_T through 4 Glauber models:
  - MC Glauber from
    Loizides, Kamin, d'Enterria, PRC97 (2018)
  - 1 pure hard sphere nuclei: constant density, fully analytic
  - 2 custom optical Glauber: hard spheres or Woods-Saxon
    → L less straightforward there:

$$\langle L \rangle = \frac{\int L(\vec{s},\phi)\,\rho_{coll}\,\mathrm{d}\vec{s}\,\mathrm{d}\phi}{2\pi \int \rho_{coll}\,\mathrm{d}\vec{s}}$$

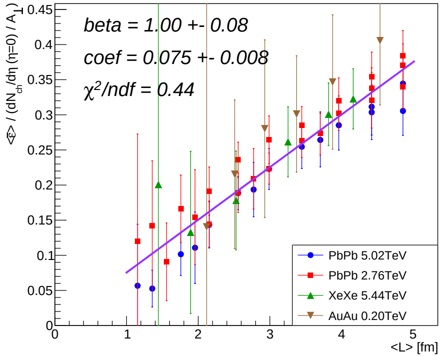


N_{part} density N_{part} density
(hard s



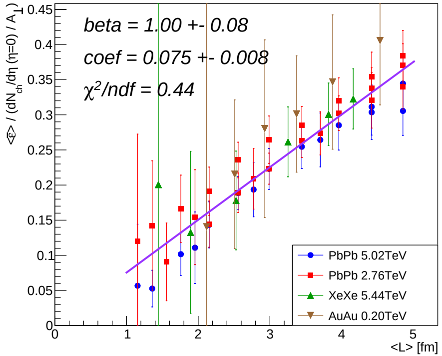
Fitting energy loss VS medium geometry

Fit of $\beta = 2 - \alpha$



Fitting energy loss VS medium geometry

Fit of $\beta = 2 - \alpha$



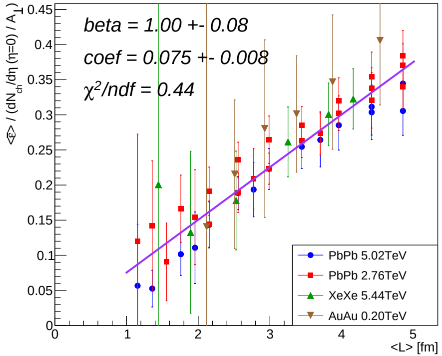
example of hard-spheres Glauber

small dispersion of β with $\neq$ Glauber models $\longrightarrow$ $\Delta\alpha = 0.03$

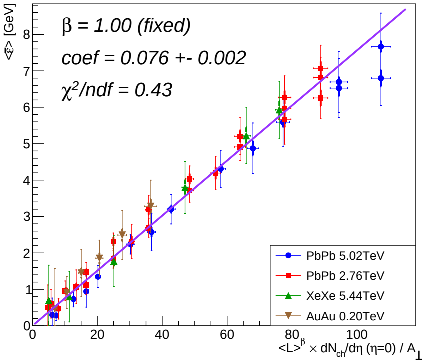
$\longrightarrow$ Multiple systems scale! $\longrightarrow$ $\alpha = 1.00 \pm 0.09$, compatible with Bjorken expansion ($\alpha = 1$)

Fitting energy loss VS medium geometry

Fit of $\beta = 2 - \alpha$



Resulting energy loss scaling



example of hard-spheres Glauber

small dispersion of β with $\neq$ Glauber models

→ $\Delta\alpha = 0.03$

→ Multiple systems scale! → $\alpha = 1.00 \pm 0.09$, compatible with Bjorken expansion ($\alpha = 1$)

$$\langle z \rangle \langle \varepsilon \rangle = (0.26 \pm 0.03) \frac{\alpha_S C_R}{2} \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta} \frac{\langle L \rangle^{1.00 \pm 0.09}}{A_T} \ [\mathrm{GeV}]$$

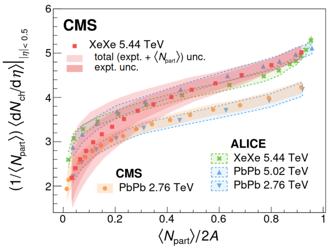
(no τ_0 dependence due to $\alpha \simeq 1$)

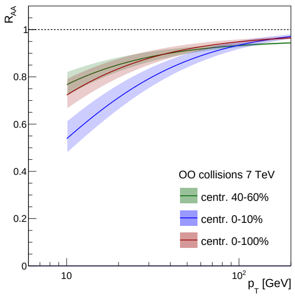
Predictions of $R_{AA}(p_\mathrm{T})$ at high-p_T in various systems

- Knowing $\mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta$ + hypothesis on $\langle z \rangle$ and C_R
  → can predict $\langle \bar{\varepsilon} \rangle$ in any system! → gives $R_{AA}(p_\mathrm{T})$
- Uncertainty on $\langle \bar{\varepsilon} \rangle$ from fit (considering fully correlated energy loss values, overestimated for now)
- Calculations: ALICE $R_{AA}(J/\psi)$ measurement in PbPb 5 TeV:
  - Similar C_R (gluon-dominated) and $\langle z \rangle$ than $h^{\pm}$ assumed + 20% uncertainty
  - Smaller multiplicity for $2.5 < |\eta| < 4$ (+ uncertainty)

Predictions of $R_{AA}(p_\mathrm{T})$ at high-p_T in various systems

- Knowing $\mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta$ + hypothesis on $\langle z \rangle$ and C_R
  → can predict $\langle \bar{\varepsilon} \rangle$ in any system! → gives $R_{AA}(p_\mathrm{T})$
- Uncertainty on $\langle \bar{\varepsilon} \rangle$ from fit (considering fully correlated energy loss values, overestimated for now)
- Calculations: ALICE $R_{AA}(J/\psi)$ measurement in PbPb 5 TeV:
  - Similar C_R (gluon-dominated) and $\langle z \rangle$ than $h^\pm$ assumed + 20% uncertainty
  - Smaller multiplicity for $2.5 < |\eta| < 4$ (+ uncertainty)
- Predictions: $R_{AA}(h^\pm)$ in OO collisions at 7 TeV
  - Multiplicity extrapolated from PbPb and XeXe measurements + 6% uncertainty
  - L and A_T as in other systems
- pPb collisions? Formalism breaks, but predicts $R_{pPb} \gtrsim 0.8 - 0.9$

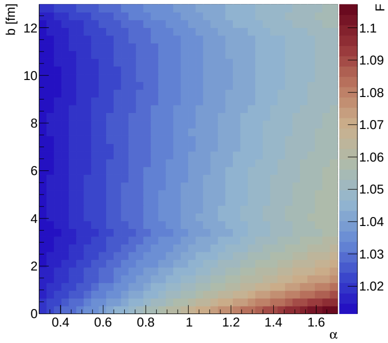




Checks of formalism

- Small influence of inhomogeneity on energy loss (constant VS N_{part} QGP density)

→ Similar results from two models with hard spheres



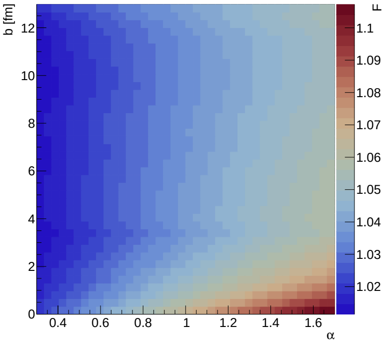
Checks of formalism

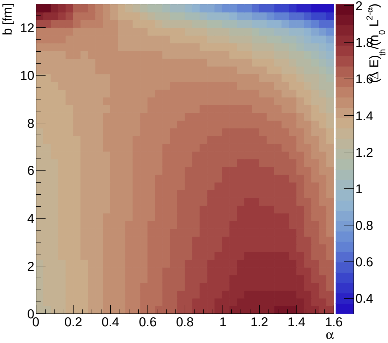
- Small influence of inhomogeneity on energy loss (constant VS N_{part} QGP density)

  → Similar results from two models with hard spheres

- Model assumes same rules for single-particle quantities VS average over active area and centrality

  → significant influence, to be studied

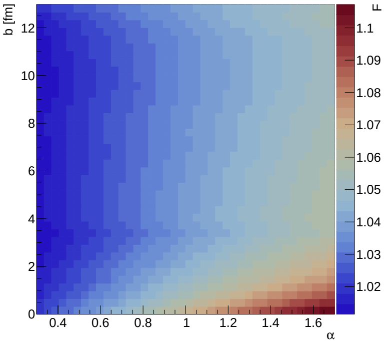




Checks of formalism

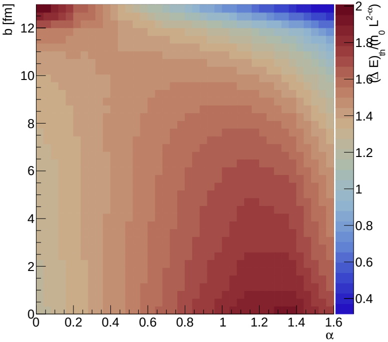
- Small influence of inhomogeneity on energy loss (constant VS $N_{\rm part}$ QGP density)

  → Similar results from two models with hard spheres



- Model assumes same rules for single-particle quantities VS average over active area and centrality

  → significant influence, to be studied



- Only one parton nature assumed now

  → possible small impact of quark/gluon mix on $R_{AA}(p_{\rm T})$ scaling (to be checked)

- Influence of $\log(E)$ corrections on $R_{AA}(p_{\rm T})$ scaling?

v_2

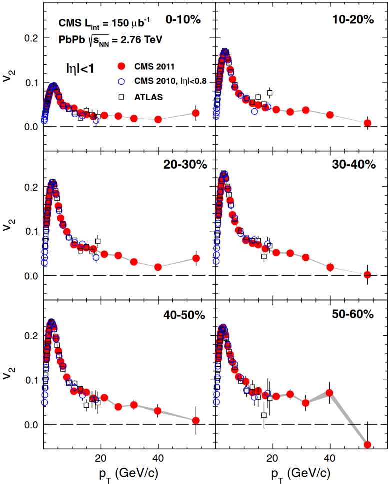
- L depends on φ $\longrightarrow$ path-length dependence of energy loss
- Formalism of custom Glauber model gives energy loss of particles produced at various φ angles

  $\longrightarrow$ φ dependence of suppression from energy loss

  $\longrightarrow$ $R_{AA}(\varphi)$

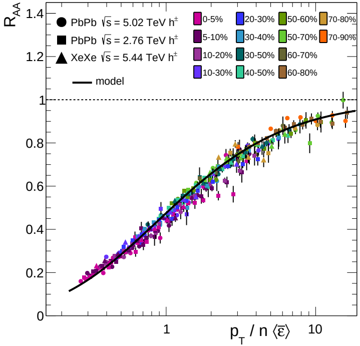
  $\longrightarrow$ Possible to predict v_2 of hadrons at $p_{\mathrm{T}} \gtrsim 10$ GeV (to be done)

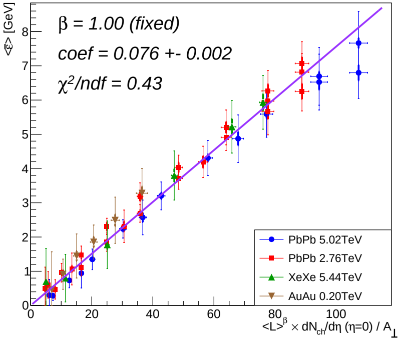
- Convergence of v_2 for all species at high p_{T}?



Conclusion

- Universal $R_{AA}(p_\mathrm{T})$ behaviour of hadrons from radiative energy loss
- Extracted energy loss values scale $\propto$ variable describing medium density and geometry
  → Path length dependence $\langle\varepsilon\rangle \propto \langle L\rangle^1$ consistent with Bjorken (longitudinal) expansion
- All measured systems (PbPb, XeXe, AuAu, 0.2 to 5 TeV) consistent with both scalings





BACKUP

List of measurements

Particle	System	$\sqrt{s_{\mathrm{NN}}}$	**experi-ment**	already in Ref. [2]?	pp fit and **centrality** classes	Kinematic range
Light charged hadrons $\mathbf{h}^{\pm}$	**PbPb**	2.76 TeV	CMS	yes	**pp**, 0-5%, 5-10%, 10-30%, 30-50%, 50-70%, 70-90%	$\lvert\eta\rvert < 1$, $p_\perp < 103\,\mathrm{GeV}$
			ATLAS	no	0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-80%	$\lvert\eta\rvert < 2$, from $p_\perp < 95\,\mathrm{GeV}$ to $p_\perp < 150\,\mathrm{GeV}$
			ALICE	no	0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80%	$\lvert\eta\rvert < 0.8$, $p_\perp < 50\,\mathrm{GeV}$
		5.02 TeV	ALICE	no		
			CMS	yes	**pp**, 0-5%, 5-10%, 10-30%, 30-50%, 50-70%, 70-90%, 0-100%	$\lvert\eta\rvert < 1$, $p_\perp < 400\,\mathrm{GeV}$ (250 GeV for centr.> 70%)
	XeXe	5.44 TeV	CMS	no	**pp**, 0-5%, 5-10%, 10-30%, 30-50%, 50-70%, 70-80%, 0-80%	$\lvert\eta\rvert < 1$, $p_\perp < 103\,\mathrm{GeV}$ (48 GeV for centr.> 50%)
π^0	**AuAu**	**0.20 TeV**	PHENIX	no	**pp**	$\lvert y\rvert < 0.35$, $p_\perp < 25\,\mathrm{GeV}$
					0-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%	$\lvert y\rvert < 0.35$, $p_\perp < 20\,\mathrm{GeV}$
$\mathbf{D^0}$	PbPb	5.02 TeV	CMS	yes (except pp)	pp, 0-10%, 0-100%	$\lvert y\rvert < 1$, $p_\perp < 100\,\mathrm{GeV}$
			ALICE	no	0-10%, 30-50%, 60-80%	$\lvert y\rvert < 0.5$, $p_\perp < 50\,\mathrm{GeV}$ (35 GeV for centr.> 50%)
$\mathbf{J/\psi}$	PbPb	5.02 TeV	CMS	no (except 0-100%)	**pp**, 0-10%, 10-30%, 30-100%, 0-100%	$\lvert y\rvert < 2.4$, $p_\perp < 30\,\mathrm{GeV}$ (50 GeV for centr. 0-100%)
			ATLAS	no	0-10%, 20-40%, 40-80%, 0-80%	$\lvert y\rvert < 2$, $p_\perp < 40\,\mathrm{GeV}$

Energy loss in proton-lead collisions?

- The geometric formalism developed for the $\varepsilon \propto \frac{\left.\frac{dN_{ch}}{dy}\right|_{y=0}}{A_T \tau_0} \times L^{\beta}$ scaling might not be transferable to p-Pb collisions (and the hypothesis $\Delta E \ll E$ breaks)

- However, taking the numerical values from the scaling to measurements, and these ingredients:
  - path length $\langle L \rangle \sim r_0 \simeq 1$ fm
  - transverse area $\langle A_T \rangle = \pi r_0^2 \simeq \pi(1 \text{ fm})^2$
  - Measured average multiplicity ~ 22 in p-Pb collisions at 8.16 TeV

→ $\langle z \rangle \langle \varepsilon \rangle = 0.5$ GeV
→ Similar to energy loss in PbPb 5.02 TeV at centralities 60-80%
→ $R_{pA} \simeq 0.8 - 0.9$ at $p_T = 10$ GeV
→ Comparable or smaller than cold nuclear matter effects (and formalism might not be valid)