Probing path-length dependence of parton energy loss in (not so) heavy ion collisions

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Light ion collisions at the LHC 2025

CERN – December 2025

FA, G. Falmagne, Phys. Rev. D109 (2024) L051503 + work in progress

This talk

Simple analytic energy loss model to describe the quenching of single hadrons at large $p_\perp$

- Hadrons simpler than jets: good proxy for parton energy loss
- Cold nuclear matter effects weaken when $p_\perp \gg Q_s$
- Radiative energy loss likely the dominant physical process

Data-driven approach

- Very precise data at the LHC
- Several energies, wide $p_\perp$ coverage. . . and now several nuclei

Energy loss model

Assuming pp cross section to follow a power-law spectrum $d\sigma/dp_\perp \propto p_\perp^{-n}$, R_{AA} is simply given by

$$R_{AA}(p_\perp, \bar{\epsilon}, n) \simeq \int_0^\infty dx\ \bar{P}(x) \exp\left(-\frac{x}{u}\right) = R_{AA}(u = p_\perp/n\bar{\epsilon})$$

- **Universal shape** of $R_{AA}(u)$ for all centralities, collision energies, hadron species. . . and nuclei
  - Depends only slightly on the radiative spectrum (BDMPS, GLV. . .)

FA, Phys. Rev. Lett. 119 (2017) 062302

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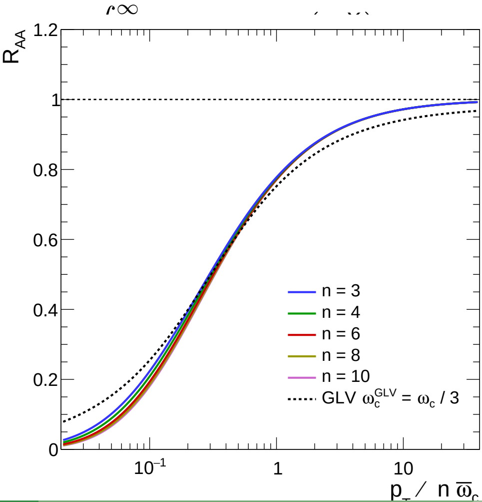
  - Depend … MPS, GLV…)

119 (2017) 062302



Energy loss model

Assuming pp cross section to follow a power-law spectrum $\mathrm{d}\sigma/\mathrm{d}p_\perp \propto p_\perp^{-n}$, $R_{\rm AA}$ is simply given by

$$R_{\rm AA}(p_\perp, \bar{\epsilon}, n) \simeq \int_0^\infty \mathrm{d}x\ \bar{P}(x)\, \exp\left(-\frac{x}{u}\right) = R_{\rm AA}(u = p_\perp/n\bar{\epsilon})$$

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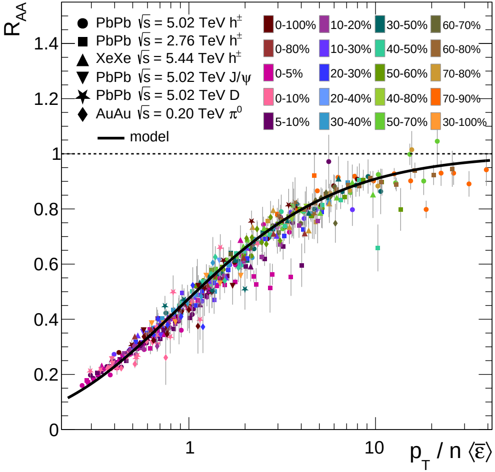
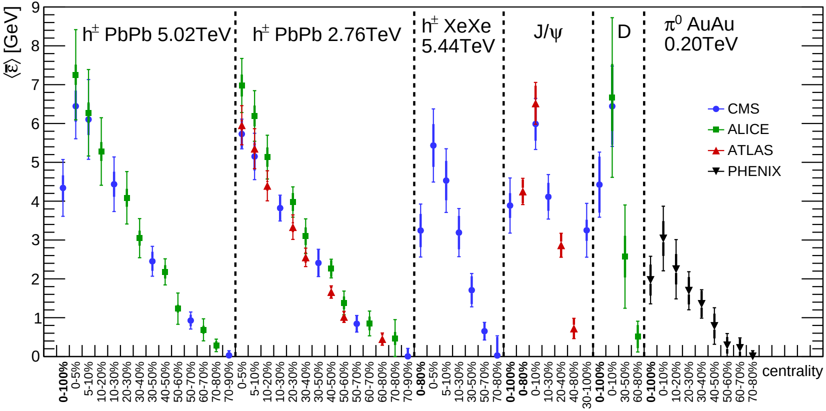
- For a given collision system $R_{\rm AA}$ **uniquely predicted** once the (single) parameter $\bar{\epsilon}$ is known
  - Determined from a fit to $R_{\rm AA}$
  - In the model $\bar{\epsilon} = \langle z \rangle \langle \epsilon \rangle$

Scaling



☞ Scaling **nicely observed** in 6 collision systems and many centralities

Average parton energy loss from data



- Nice systematic behavior from central to peripheral collisions
- Smaller energy loss scales at RHIC
- **Next step:** need to relate $\bar{\epsilon}$ to other physical quantities

Energy loss vs. multiplicity and path-length

BDMPS $\langle \epsilon \rangle = \frac{1}{4} \alpha_s \, C_k \, \langle \hat{q} \rangle \, L^2$

QGP expansion $\langle \hat{q} \rangle = \frac{2}{2 - \alpha} \hat{q}_0 \left(\frac{\tau_0}{L} \right)^{\alpha}$

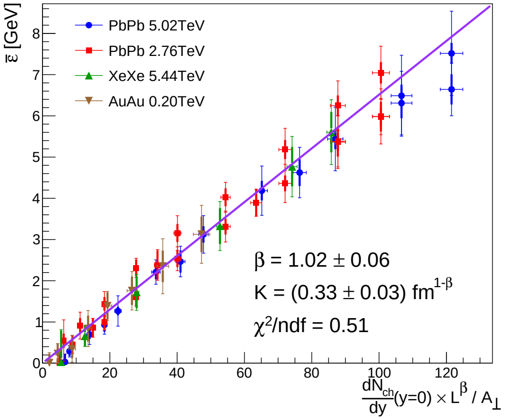
Bjorken density $\hat{q}_0 \propto n_0 = \frac{3}{2} \frac{1}{A_\perp \tau_0} \left. \frac{dN_{ch}}{dy} \right|_{y=0}$

Expected (another) scaling with multiplicity and path-length

$$\bar{\epsilon} = K \times \frac{1}{A_\perp} \frac{dN_{ch}}{dy} L^{\beta}$$

- Simple linear relationship between $\bar{\epsilon}$ and a scaling variable
- Free parameters $\beta = 2 - \alpha$ and $K = 27\pi/(8\beta) \times \alpha_s^3 \, \tau_0^{1-\beta} \, \langle z \rangle_k \, C_k$
- L, $A_\perp$ taken from Glauber models, dN_{ch}/dy from experiment

Scaling with multiplicity and path-length



- Very nice scaling observed for all energy loss scales
- $\beta = 1.02 \pm^{0.09}_{0.06}$, compatible with pQCD in longitudinally exp. QGP
- Value of K also in the ballpark of pQCD estimates

Predicting light ion collisions

Scaling with multiplicity and L allows for predicting R_{AA} in other systems, e.g. OO and NeNe collisions at $\sqrt{s} = 5.36$ TeV

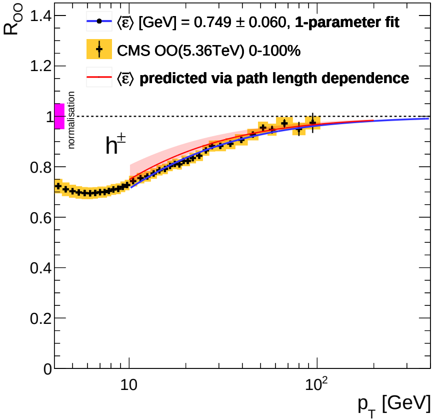
- Path-length L and transverse area $A_\perp$ obtained from Glauber model
- Multiplicity taken from ALICE/CMS data dN_{ch}/dy

OO collisions

$$\bar{\epsilon}^{th}_{OO} = 0.59^{+0.07}_{-0.16}\ \text{GeV}$$

Fitting R_{AA}

$$\bar{\epsilon}^{fit}_{OO} = 0.75 \pm 0.06\ \text{GeV}$$



Predicting light ion collisions

Scaling with multiplicity and L allows for predicting R_{AA} in other systems, e.g. OO and NeNe collisions at $\sqrt{s} = 5.36\,\text{TeV}$

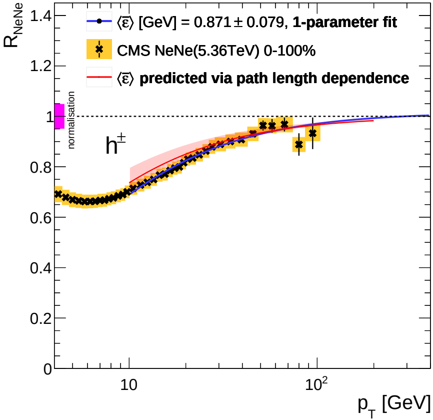
- Path-length L and transverse area $A_\perp$ obtained from Glauber model
- Multiplicity taken from ALICE/CMS data $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$

NeNe collisions

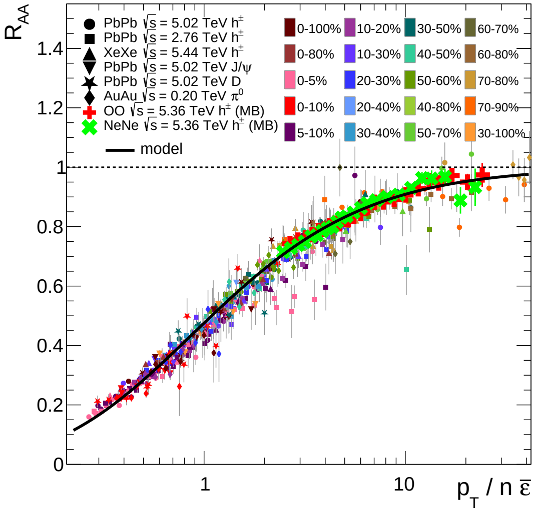
$$\bar{\epsilon}^{\,\mathrm{th}}_{\mathrm{NeNe}} = 0.63^{+0.08}_{-0.17}\,\mathrm{GeV}$$

Fitting R_{AA}

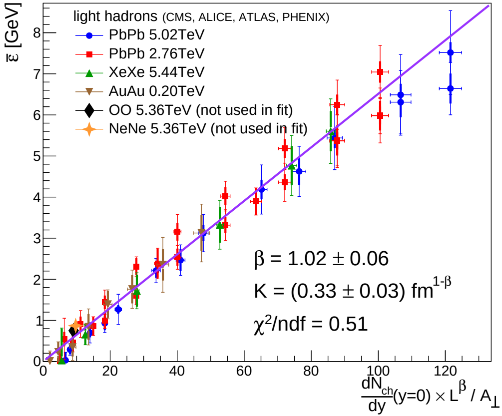
$$\bar{\epsilon}^{\,\mathrm{fit}}_{\mathrm{NeNe}} = 0.87 \pm 0.08\ \mathrm{GeV}$$



Fitting OO and NeNe



Scaling with multiplicity including OO & NeNe data



- Follows nicely the scaling despite much smaller A
- Compatible with RHIC AuAu and LHC peripheral PbPb data
- Centrality dependence of OO and NeNe would definitely help

Azimuthal anisotropy and path-length dependence

Neglecting higher harmonics at large $p_\perp$

$$2v_2 \simeq \frac{R_{AA}(\phi=0) - R_{AA}(\phi=\pi/2)}{R_{AA}(\phi=0) + R_{AA}(\phi=\pi/2)} = \frac{R_{AA}(u/(1-e)^\beta) - R_{AA}(u/(1+e)^\beta)}{R_{AA}(u/(1-e)^\beta) + R_{AA}(u/(1+e)^\beta)}$$

$$\text{with eccentricity}\, e \equiv \frac{L(\pi/2) - L(0)}{L(\pi/2) + L(0)}$$

Taylor expansion at small e leads to

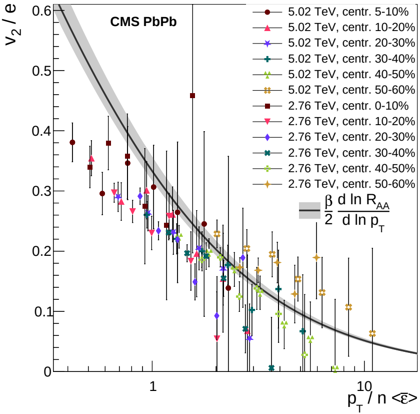
$$\frac{v_2(u,n)}{e} \simeq \frac{\beta}{2}\,\frac{n}{u} \int \mathrm{d}x\bar{P}(x)\frac{x}{(1+x/u)^{n+1}} \Big/ \int \mathrm{d}x\bar{P}(x)\,\frac{1}{(1+x/u)^n}$$

☞ v_2/e should exhibit the same $p_\perp/\langle\epsilon\rangle$ scaling as R_{AA}

$$\frac{v_2(p_\perp)}{e} \simeq \frac{\beta}{2}\,\frac{p_\perp}{R_{AA}(p_\perp)}\,\frac{\partial R_{AA}(p_\perp)}{\partial p_\perp}$$

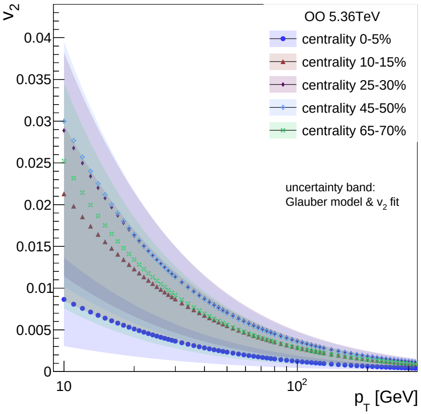
☞ Simple relation between v_2/e and R_{AA} could be tested **using measurements only**, allowing for a direct access to β

v_2/e scaling



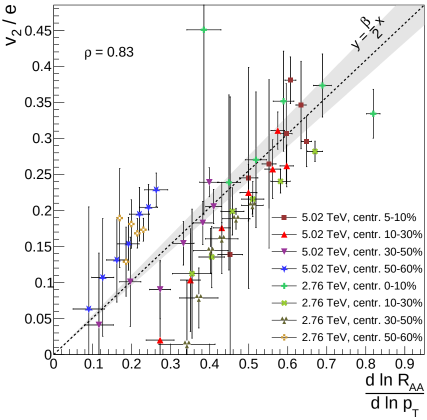
- Scaling observed in CMS data, within uncertainties
  - might be improved with more realistic eccentricity parameter
- Good trend of the model except at lower $p_\perp \lesssim 15\,\text{GeV}$

v_2/e scaling



- Allows for predicting v_2 in OO collisions

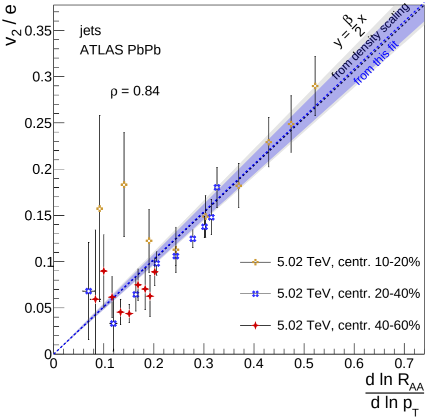
v_2/e vs. R_{AA} for hadrons and jets



- Significant correlation observed ($\rho = 0.83$)
- Linear behavior for all centrality classes at both energies
- Larger v_2/e in the most peripheral 50-60% class

☞ Independent but consistent estimate of $\beta \simeq 1$

v_2/e vs. R_{AA} for hadrons and jets



FA, G. Falmagne, PoS ICHEP2024 (2025) 604

- Also works for jets (!) with same value of β
- Suggests similar path-length dependence of parton and jet energy loss (not that obvious a priori)

Summary

- Measured R_{AA} exhibit a universal shape
  - At different centralities and at different energies
  - New OO and NeNe data follow the same trend
- Energy loss values $\langle\epsilon\rangle$ scales linearly with $L^{\beta} \times \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$
  - $\beta = 1.02\pm^{0.09}_{0.06}$ consistent with pQCD and Bj longitudinal expansion
  - OO and NeNe data consistent with all data **despite much smaller A** !
- Azimuthal anisotropy v_2/e data scale with $p_{\perp}/\langle\epsilon\rangle$
  - Same universal behavior as R_{AA}, predicted trend consistent with data
  - Allows for predicting v_2 in OO and NeNe collisions
- Relation between v_2/e and R_{AA} offers purely data-driven access to β
  - PbPb data are consistent with this prediction and leads to $\beta \simeq 1$
  - Could be measured in OO and NeNe for a sensitive test

Data used

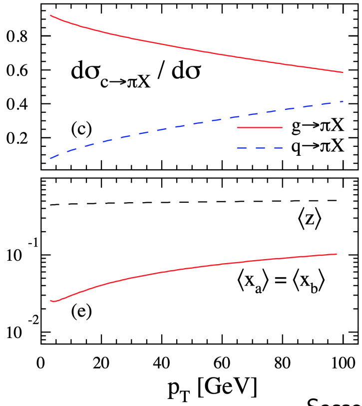
Species	Collision	$\sqrt{s}$ [TeV]	Experiment
π^0	AuAu	0.2	PHENIX
$h^\pm$	PbPb	2.76	ALICE, ATLAS, CMS
$h^\pm$	PbPb	5.02	ALICE, CMS
$h^\pm$	XeXe	5.44	CMS
D	PbPb	5.02	ALICE, CMS
J/ψ	PbPb	5.02	ATLAS, CMS

- Energies from $\sqrt{s} = 0.2$ TeV (RHIC) to $\sqrt{s} = 5.44$ TeV (LHC)
- Different collision systems (AuAu, XeXe, PbPb) and centrality classes
- Various hadron species: π^0, $h^\pm$, J/ψ, D

2-flavour model extension

So far only one parton flavour is assumed while at LHC both quarks (fraction $x_q = 0.1$-0.3) and gluons ($1 - x_q$) fragment into hadrons

- different color factors ($C_F \neq C_A$) and possibly different partonic slopes ($n_q \lesssim n_g$) and momentum fractions ($z_q \gtrsim z_g$)



Sassot Stratmann Zurita 2010

2-flavour model extension

In the more general case

$$R_{\text{AA}}^{\text{2f}} = \int \mathrm{d}\epsilon \left[P_q(\epsilon)\, x_q(p_\perp) \left(1 + \frac{\langle z_q \rangle\, \epsilon}{p_\perp}\right)^{-n_q} + P_g(\epsilon)\,(1 - x_q(p_\perp)) \left(1 + \frac{\langle z_g \rangle\, \epsilon}{p_\perp}\right)^{-n_g} \right]$$

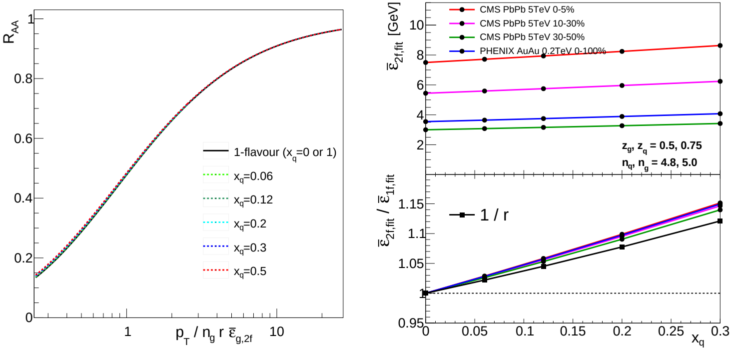
Within approximations, $R_{\text{AA}}^{\text{2f}}$ formally analogous to the 1-flavour model

$$R_{\text{AA}}^{\text{2f}}(p_\perp, \bar{\epsilon}_{\text{2f}}, x_q) \simeq \int \mathrm{d}x\, \bar{P}(x) \left(1 + \frac{x\, r(x_q)\, \bar{\epsilon}_{\text{2f}}}{p_\perp}\right)^{-n_g} = R_{\text{AA}}^{\text{1f}}(p_\perp, r(x_q)\, \bar{\epsilon}_{\text{2f}})$$

up to a (small) rescaling of the expected average energy loss scale

$$r(x_q) \equiv 1 - x_q + x_q \frac{n_q}{n_g} \frac{C_F}{C_A} \frac{\langle z_q \rangle}{\langle z_g \rangle} \simeq 0.9$$

2-flavour model extension



- Fitting data with 2-flavour model indeed affects $\bar{\epsilon}$ by $\sim 10\%$
- Rescaling only affects prefactor K (not the scaling) which is in any case very uncertain ($K \propto \alpha_s^3$)
- Variation of n and z have marginal impact

The model

Take the simplest energy loss model for production of parton k

$$\frac{\mathrm{d}N^k_{\mathrm{AA}}}{\mathrm{d}y\,\mathrm{d}p_\perp} = N_{\mathrm{coll}} \int_0^\infty \mathrm{d}\epsilon\, \frac{\mathrm{d}N^k_{\mathrm{pp}}(p_\perp + \epsilon)}{\mathrm{d}y\,\mathrm{d}p_\perp}\, P_k(\epsilon)$$

Quenching weight

- In BDMPS, the quenching weight depends on a single energy loss scale $\langle\epsilon\rangle$ at high parton energy

$$P(\epsilon) = \frac{1}{\langle\epsilon\rangle}\, \bar{P}\left(\frac{\epsilon}{\langle\epsilon\rangle}\right)$$

- Computed numerically from the BDMPS (and GLV) gluon spectrum
- Due to hadronization, scale accessible from data is $\bar{\epsilon} \equiv \langle z\rangle\langle\epsilon\rangle$

The model

Take the simplest energy loss model for production of hadron h

$$\frac{\mathrm{d}N^h_{\mathrm{AA}}}{\mathrm{d}y\,\mathrm{d}p_\perp} = N_{\mathrm{coll}} \int_0^\infty \mathrm{d}\epsilon\ \frac{\mathrm{d}N^h_{\mathrm{pp}}(p_\perp + \langle z \rangle \epsilon)}{\mathrm{d}y\,\mathrm{d}p_\perp}\ P_k(\epsilon)$$

pp production cross section

- Power-law behavior expected at high $p_\perp \gg \Lambda_{\mathrm{QCD}}$

$$\frac{\mathrm{d}N^k_{\mathrm{pp}}}{\mathrm{d}y\,\mathrm{d}p_\perp} \propto p_\perp^{-n}$$

- Power law index $n(h, \sqrt{s}) \simeq 5 - 6$ fitted from pp data
- Absolute magnitude of cross section irrelevant to compute R_{AA}

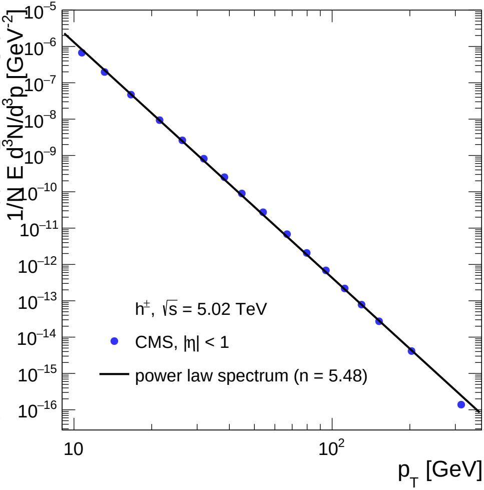
The model

Take the simplest energy loss model for production of hadron h

$\frac{d}{dy}$ (ϵ)

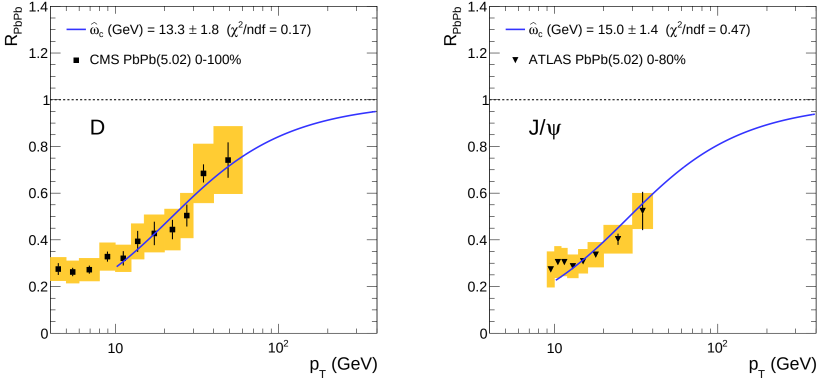
pp production

- Power-law l
- Power law i
- Absolute m pute R_{AA}



Heavy hadrons into the game

At large $p_\perp \gg M$, production of heavy hadrons (D/B, heavy quarkonia) should also proceed from the collinear fragmentation of a single parton



- Fit to D & J/ψ using the same BDMPS (massless) quenching weight
- R_{AA} of heavy hadrons follow the same trend
  - need for more precise data, more centrality & even larger $p_\perp$