Jet Quenching in the light of perturbative QCD

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Outline

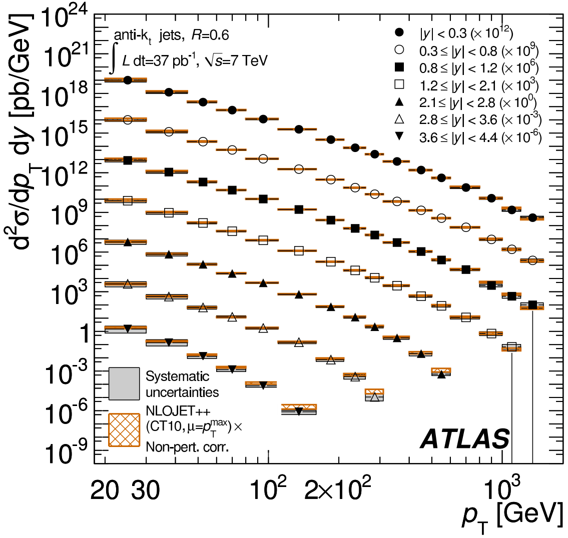
Experimental findings

Analytical approach

MC approach

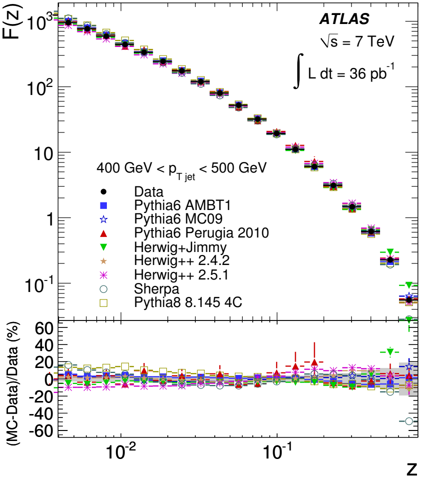
Conclusions

Differential jet cross section



ATLAS, arXiv:1112.6297

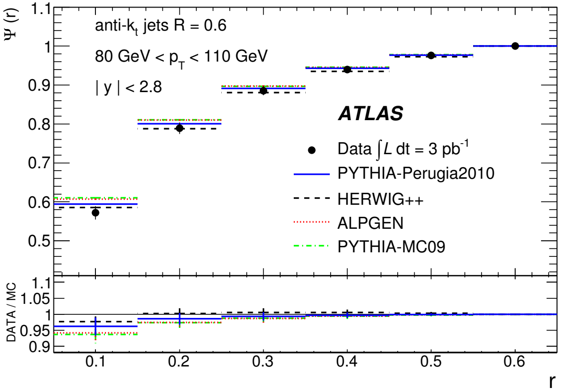
Fragmentation function



$$z = \frac{\mathbf{p}_{\text{jet}} \cdot \mathbf{p}_{\text{track}}}{\mathbf{p}_{\text{jet}}^2}$$

ATLAS, Eur. Phys. J. C **71** (2011) 1795

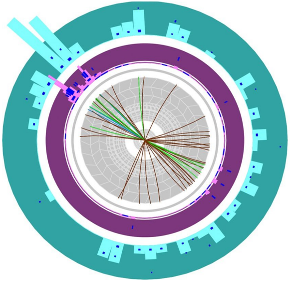
Jet shapes

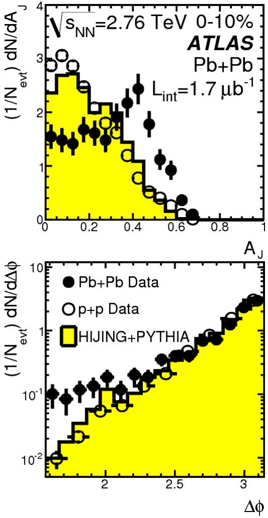


$$r = \sqrt{(\Delta\phi)^2 + (\Delta y)^2}$$

ATLAS, Phys. Rev. D **83** (2011) 052003

Jets in Pb+Pb





tracks: $p_\perp > 2.6$ GeV

calorimeter cells: $E_\perp > 0.7/1$ GeV

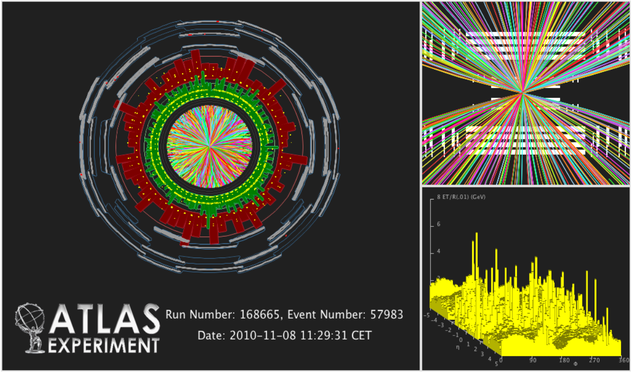
$$A_\mathrm{J} = \frac{E_{\perp 1} - E_{\perp 2}}{E_{\perp 1} + E_{\perp 2}}$$

$E_{\perp 1} > 100$ GeV $\quad$ $E_{\perp 2} > 25$ GeV

- clear energy asymmetry between jets
- jet axis largely unchanged

ATLAS, Phys. Rev. Lett. **105** (2010) 024901

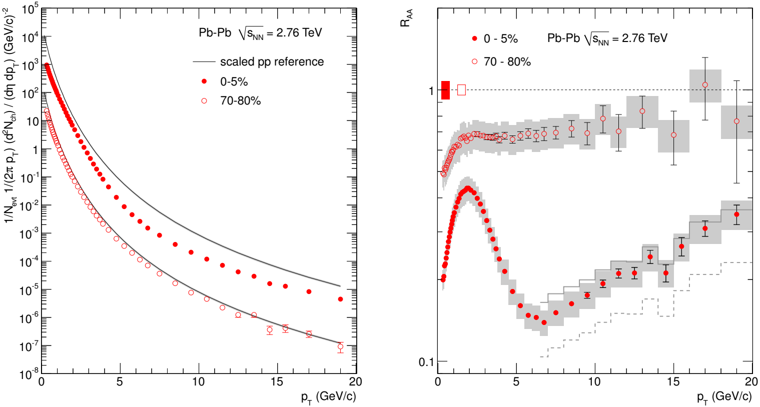
Heavy ion challenge



- jet reconstruction challenging due to large background
- maybe look for more robust observables. . .

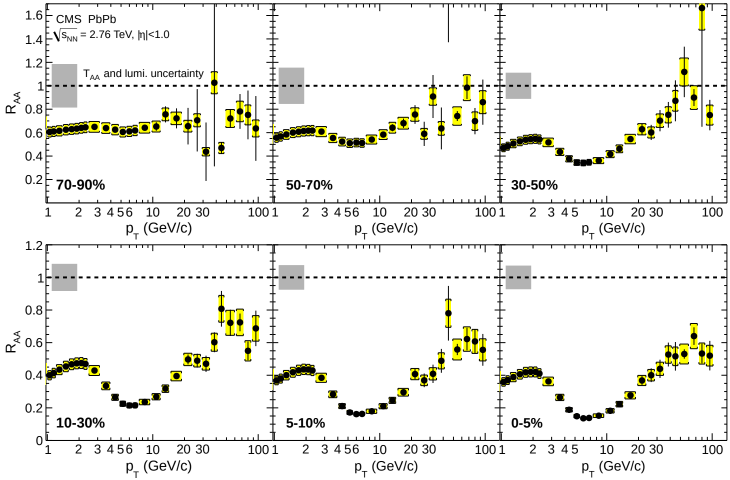
Single-inclusive hadron suppression

$$R_{AA}(p_\perp) = \frac{\mathrm{d}N^{AA}/\mathrm{d}p_\perp}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N^{pp}/\mathrm{d}p_\perp} = \frac{\text{spectrum in A+A}}{\langle N_{\mathrm{coll}}\rangle \times \text{spectrum in p+p}}$$



ALICE, Phys. Lett. B **696** (2011) 30

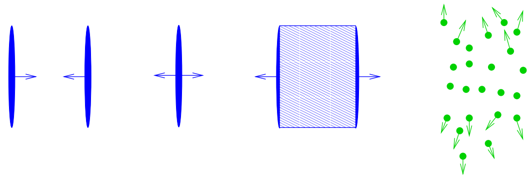
Single-inclusive hadron suppression



CMS, Eur. Phys. J. C (2012) 72:1945

Heavy ion collisions

- high multiplicity
- nuclei large objects (radius $\sim 7\,\mathrm{fm}$)
- expect extended system with very high density
- estimate of initial energy density: $\epsilon_0 \simeq 5.5\,\frac{\mathrm{GeV}}{\mathrm{fm}^3}$ at RHIC and $\epsilon \gtrsim 40\,\frac{\mathrm{GeV}}{\mathrm{fm}^3}$ at LHC
- theoretical expectation: nucleons melt around $1\,\frac{\mathrm{GeV}}{\mathrm{fm}^3}$ $\rightarrow$ quark gluon plasma
- naive picture



- jets involve high scale $\rightarrow$ early production
- apparently: interactions in dense medium

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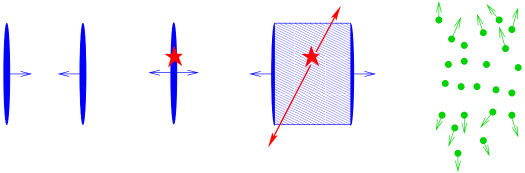

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Jet quenching

Motivation

- 'deep inelastic scattering' of jet on medium
- interplay between weakly and strongly coupled regimes
- emergence of collectivity from microscopic theory of individual quanta

Executive summary of experimental findings

- strong suppression of hadron production at large $p_\perp$
- reduction of jet energy
- fragmentation function inside remainder jet looks as in vacuum
- jet axis remains unchanged
- soft modes get transported to large angles

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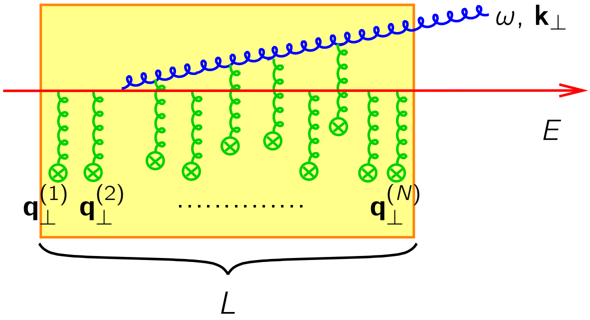
Gluon radiation in eikonal limit



- high energy approximation: $E \gg \omega \gg k_\perp, q_\perp$
- static scattering centres → no collisional energy loss
- medium characterised by transport coefficient
  $\hat{q} = \frac{\langle q_\perp^2 \rangle}{\lambda}$

Baier, Dokshitzer, Mueller, Peigne, Schiff, Nucl. Phys. B **484** (1997) 265

LPM-effect: heuristic discussion

Brownian motion of the gluon: $\langle k_\perp^2 \rangle = \hat{q} L$

gluon decoheres from projectile when relative phase $\varphi > 1$

$$\varphi = \left\langle \frac{k_\perp^2}{2\omega} L \right\rangle = \frac{\hat{q} L^2}{2\omega} = \frac{\omega_c}{\omega}$$

formation time of the radiated gluon:

$$t_f \simeq \frac{2\omega}{k_\perp^2} \simeq \frac{2\omega}{\hat{q} t_f} \quad \Rightarrow \quad t_f = \sqrt{\frac{2\omega}{\hat{q}}} \quad \text{and} \quad N_{coh} = \frac{t_f}{\lambda}$$

gluon energy spectrum:

$$\frac{d^2 I^{coh}}{d\omega dz} \simeq \frac{1}{N_{coh}} \frac{d^2 I^{incoh}}{d\omega dz} \propto \sqrt{\frac{\hat{q}}{2\omega}} \frac{\alpha_s}{\omega}$$

radiative energy loss:

$$\Delta E = \int_0^L dz \int_0^{\omega_c} d\omega \, \omega \frac{d^2 I}{d\omega dz} \propto \alpha_s \hat{q} L^2$$

Baier, Schiff, Zakharov, Ann. Rev. Nucl. Part. Sci. **50** (2000) 37

Is it any good?

- formation time of medium induced emissions:

$$\tau_{\text{med}} = \sqrt{\frac{2\omega}{\hat{q}}}$$

$\Rightarrow$ soft gluons decohere first...

- formation angle:

$$\theta_{\text{med}} \approx \frac{k_\perp}{\omega} = \frac{\sqrt{\hat{q}\tau_{\text{med}}}}{\omega} = \frac{(2\hat{q})^{1/4}}{\omega^{3/4}}$$

$\Rightarrow$ ...and at large angles

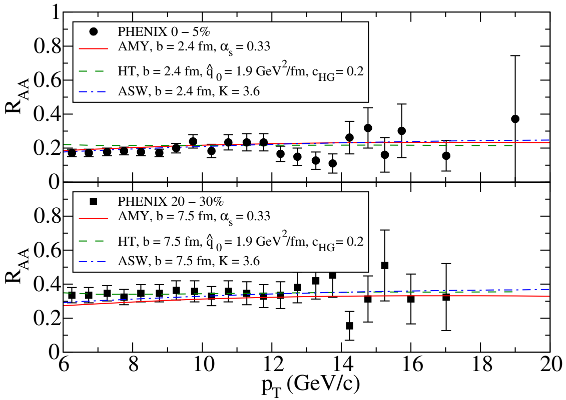
- formation time of vacuum emissions:

$$\tau_{\text{vac}} = \frac{2\omega}{k_\perp^2}$$

$\Rightarrow$ decoherence of energetic gluons delayed

Casalderrey-Solana, Milhano, Wiedemann, J. Phys. G **38** (2011) 035006

Confrontation with data



Bass *et al.*, Phys. Rev. C **79** (2009) 024901

- but extracted values for transport coefficient $\hat{q}_0$ differ by factor 5
- experimentally accessible region not near eikonal limit
- calculations are applied outside their range of validity

Armesto *et al.*, arXiv:1106.1106

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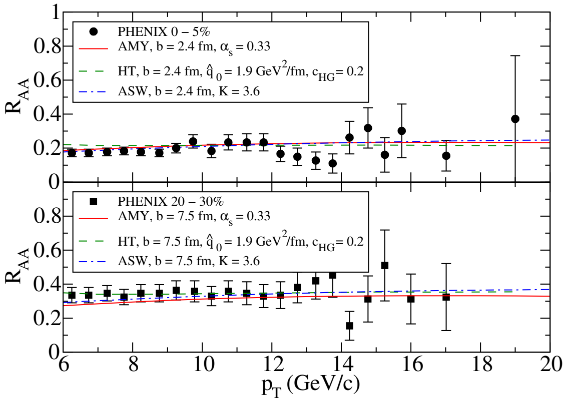

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Beyond analytical calculations

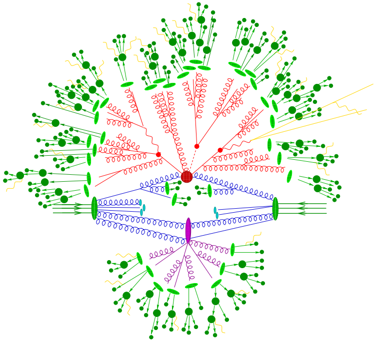
Kinematics beyond eikonal limit

- phase space restrictions due to E/p-conservation
- no clear distinction between elastic & inelastic scattering
- dynamical scattering centres
  - → collisional energy loss
  - → radiation off scattering centres
- no clear separation of vacuum and medium radiation

Futher limitations of analytical models

- single gluon radiation probabilistic iteration thereof
- not suitable for exclusive observables & jets
- no control over recoils

State of the art MC's in p+p



(multi-purpose event generators: Herwig, Pythia, Sherpa)

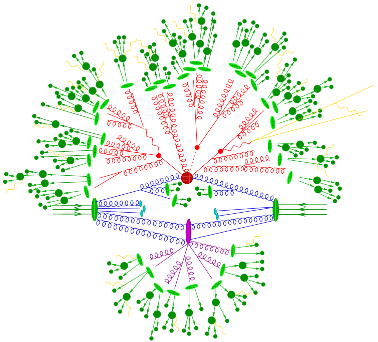
matrix elements: fixed order perturbation theory

final state parton shower: resummation of collinear/soft logarithms

initial state parton shower: like final state parton

hadronisation: non-perturbative QCD: modelling

Situation in A+A



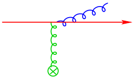
matrix elements: unmodified due to high scale

final state parton shower: modified by medium interactions
only calculations for special cases
e.g. single gluon radiation spectrum in eikonal limit

initial state parton shower: found to be unmodified at RHIC
except for pdf's

hadronisation: probably modified, no theoretical guidance

JEWEL approach



Zapp, Krauss, Wiedemann, arXiv:1111.6838

JEWEL approach

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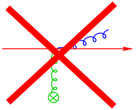
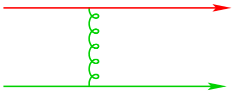
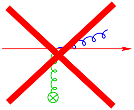


leave eikonal limit



- scattering in medium: pQCD ME

JEWEL approach



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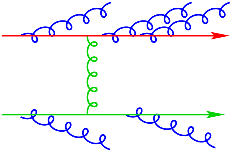
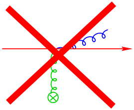


- scattering in medium: pQCD ME
- scattering in medium: pQCD ME + PS

JEWEL approach



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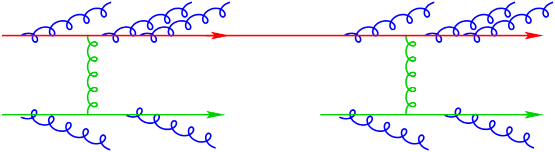
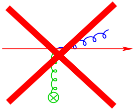


- scattering in medium: pQCD ME
- scattering in medium: pQCD ME + PS
- need to understand spacio-temporal structure

JEWEL approach



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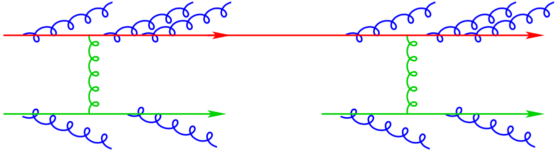
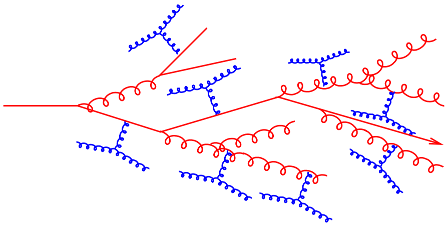


- scattering in medium: pQCD ME
- scattering in medium: pQCD ME + PS
- need to understand spacio-temporal structure
- formation time $\tau \simeq \frac{1}{Q}\frac{E}{Q} \simeq \frac{\omega}{k_\perp^2}$
- emission with shortest formation time wins

JEWEL overview

- nuclear pdf's — EPS09
- jet production: hard ME's and ISR: PYTHIA
- FSR and medium interactions: treated on same footing
  controlled by formation times
- includes LPM effect
- take care of colour connection between jet and recoils
- hadronisation: PYTHIA — Lund string model



JEWEL scattering cross section

- cross section for scattering in medium

$$\sigma_i(E,T) = \int\limits_0^{|\hat{t}|_{\max}(E,T)} \mathrm{d}|\hat{t}| \int\limits_{x_{\min}(|\hat{t}|)}^{x_{\max}(|\hat{t}|)} \mathrm{d}x \sum_{j\in\{\mathrm{q},\bar{\mathrm{q}},\mathrm{g}\}} f_j^i(x,|\hat{t}|) \frac{\mathrm{d}\hat{\sigma}_j}{\mathrm{d}|\hat{t}|}(x\hat{s},|\hat{t}|)$$

- keep only leading contribution to partonic cross section

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}|\hat{t}|}(\hat{s},|\hat{t}|) \approx C_\mathrm{R} 2\pi\alpha_\mathrm{s}^2(|\hat{t}|+\mu_\mathrm{D}^2)\frac{1}{(|\hat{t}|+\mu_\mathrm{D}^2)^2}$$

- regulated by $\mu_\mathrm{D}^2 \approx 3T$
- requires a 'partonic pdf' $f_j^i(x,|\hat{t}|)$
- also need the Sudakov form factor

$$\mathcal{S}_a(Q^2,Q_0^2) = \exp\left[-\int\limits_{Q_0^2}^{Q^2}\frac{\mathrm{d}q^2}{q^2}\int \mathrm{d}z \frac{\alpha_\mathrm{s}(k_\perp^2)}{2\pi}\sum_b \hat{P}_{ba}(z)\right]$$

JEWEL partonic pdf's

- partonic pdf's defined through DGLAP equation

$$f_i^j(x, Q^2) = \mathcal{S}_j(Q^2, Q_0^2) f_i^j(x, Q_0^2) \delta_{ij} + \int\limits_{Q_0^2}^{Q^2} \frac{\mathrm{d}q^2}{q^2} \mathcal{S}_i(Q^2, q^2) \int\limits_x^{z_{\max}} \frac{\mathrm{d}z}{z} \frac{\alpha_s(k_\perp^2)}{2\pi} \sum_k \hat{P}_{ik}(z) f_k^j(x/z, q^2)$$

- at the cut-off scale Q_0 one has

$$f_i^j(x, Q_0^2) = \begin{cases} \delta(1-x) & ; \quad i = j \\ 0 & ; \quad i \neq j \end{cases}$$

- considering at most one emission one gets

$$f_q^q(x, Q^2) = \mathcal{S}_q(Q^2, Q_0^2) \delta(1-x) + \int\limits_{Q_0^2}^{Q^2} \frac{\mathrm{d}q^2}{q^2} \mathcal{S}_q(Q^2, q^2) \frac{\alpha_s(k_\perp^2)}{2\pi} \hat{P}_{qq}(x)$$

etc.

Probabilistic formulation of the LPM-effect

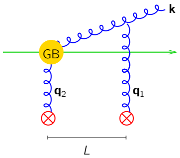
- naive MC purely incoherent
- consider gluon radiation with two momentum transfers

Wiedemann, Nucl. Phys. **B 588**(2000),303

- analytical calculation interpolates between

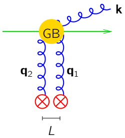
incoherent production

$\tau_1 \ll L$



coherent production

$\tau_1 \gg L$



- $\tau_1 \equiv \dfrac{2\omega}{(\mathbf{k}+\mathbf{q}_1)^2}$ inverse transverse gluon energy
- can be interpreted as gluon formation time

$\rightarrow$ momentum transfers during formation time act coherently

Coherent emission

Kinematics

- coherent scattering centres act as one

  one momentum transfer:

$$\omega \frac{d^3 I^{(1)}}{d\omega d\mathbf{k}} \propto \int d\mathbf{q}\, |A(\mathbf{q})|^2 R(\mathbf{k}, \mathbf{q})$$

  two momentum transfers:

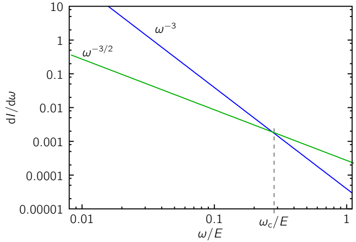
$$\omega \frac{d^3 I^{(2)}}{d\omega d\mathbf{k}} \propto \int d\mathbf{q}_1\, d\mathbf{q}_2\, |A(\mathbf{q}_1)|^2 |A(\mathbf{q}_2)|^2 R(\mathbf{k}, \mathbf{q}_1 + \mathbf{q}_2)$$

- consistent determiation of scattering centres and formation time

Emission probability

- suppression compared to incoherent emission by factor $1/N_{\mathrm{coh}}$ N_{coh}: number of coherent momentum transfers

Probabilistic formulation of the LPM-effect

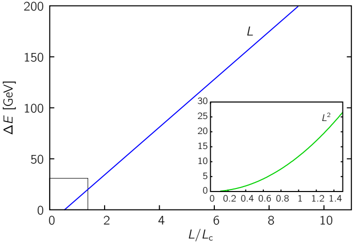


analytical results:

$\frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \omega^{-3/2}$ für $\omega < \omega_\mathrm{c}$

$\frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \omega^{-3}$ für $\omega > \omega_\mathrm{c}$

deviation in infra-red due to regularisation



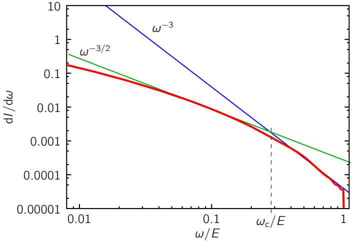
$\Delta E \propto L^2$ für $L < L_\mathrm{c}$

$\Delta E \propto L$ für $L > L_\mathrm{c}$

Zapp, Stachel, Wiedemann, Phys. Rev. Lett. **103** (2009) 152302

Zapp, Stachel, Wiedemann, JHEP **1107** (2011) 118

Probabilistic formulation of the LPM-effect



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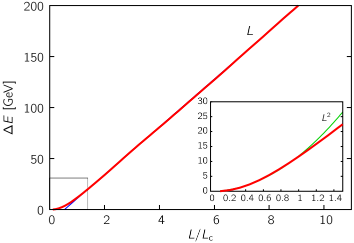

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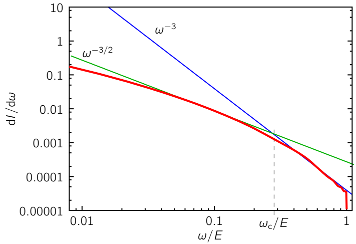

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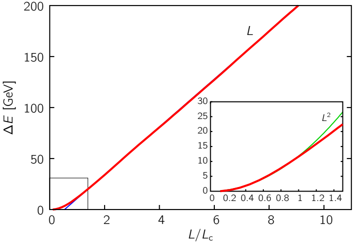

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$$\Delta E \propto L \quad \text{für} \quad L > L_c$$

understand prefactor up to 30 %

Zapp, Stachel, Wiedemann, Phys. Rev. Lett. **103** (2009) 152302

Zapp, Stachel, Wiedemann, JHEP **1107** (2011) 118

Modelling the medium

geometry: overlap, N_{part}, N_{coll} etc. from Glauber model

Eskola, Kajantie, Lindfors, Nucl. Phys. B **323** (1989)

EOS: ideal relativistic quark-gluon gas

$\Rightarrow n = \propto T^3 \quad \& \quad \epsilon = \propto T^4$

expansion: boost-invariant longitudinal expansion

$T(\tau) \propto \tau^{-1/3} \quad \Rightarrow \quad n(\tau) \propto \tau^{-1} \quad \& \quad \epsilon(\tau) \propto \tau^{-4/3}$

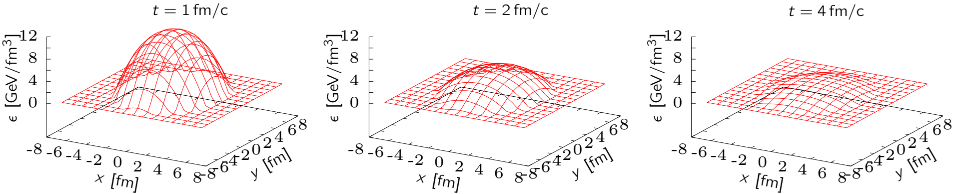
$(\tau = \sqrt{t^2 - z^2})$

Bjorken, Phys. Rev. D **27** (1983)

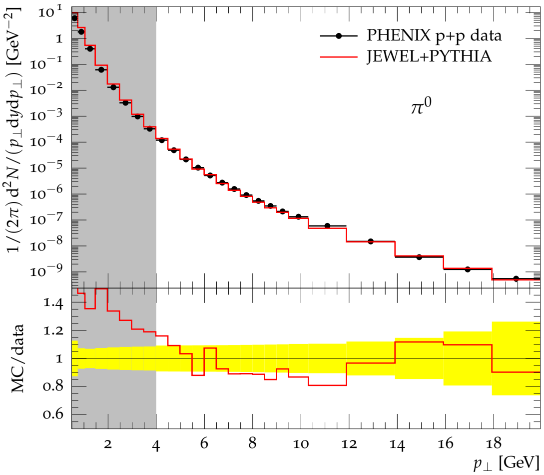
local energy density: $\epsilon(x, y, \tau) \propto N_{\text{coll}}(x, y) \cdot \tau^{-4/3}$

jet production: pQCD matrix elements (PYTHIA) + distribution according to $N_{\text{coll}}(x, y)$

$b = 4\,\text{fm} \qquad z = 0$



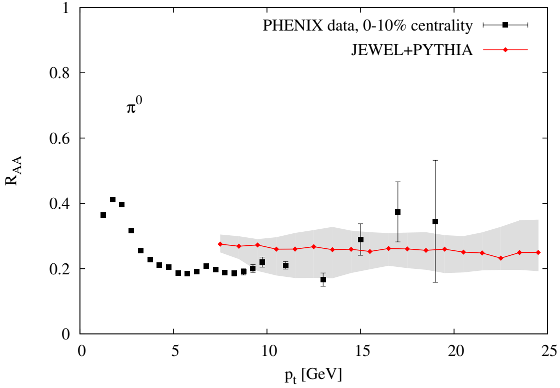
JEWEL validation



- π^0 $p_\perp$-spectrum at $\sqrt{s} = 200$ A GeV

PHENIX, Phys. Rev. D **76** (2007) 051106

JEWEL hadron suppression at RHIC

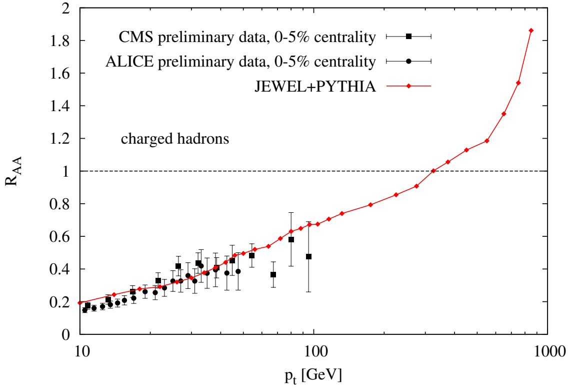


- π^0 suppression at $\sqrt{s} = 200\,\text{A GeV}$
- grey band: variation of μ_D by $\pm 10\,\%$

$T_i = 350\,\text{MeV}, \ \tau_i = 0.8\,\text{fm}, \ T_c = 165\,\text{MeV}$

PHENIX, Phys. Rev. Lett. **101** (2008) 232301

JEWEL hadron suppression at the LHC

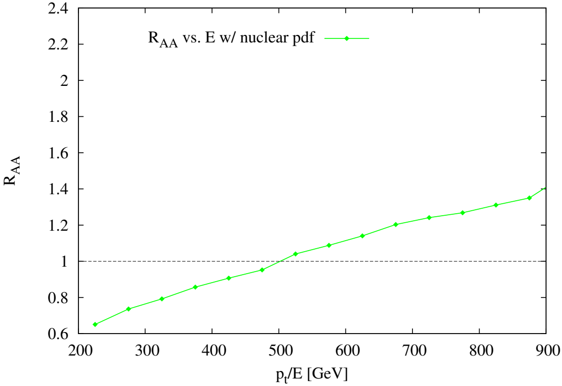


- charged hadron suppression at $\sqrt{s} = 2.76$ A TeV
- interesting behaviour at very high $p_\perp$

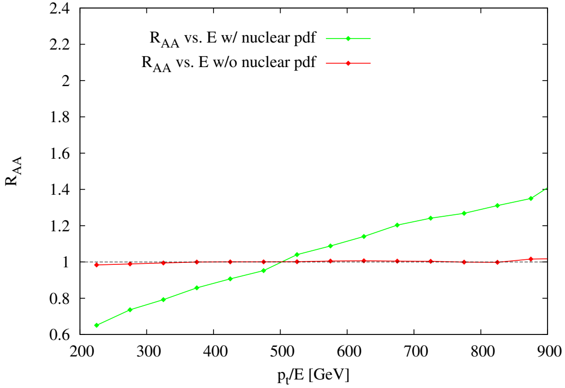
$T_\mathrm{i} = 530\,\mathrm{MeV}$, $\tau_\mathrm{i} = 0.5\,\mathrm{fm}$, $T_\mathrm{c} = 165\,\mathrm{MeV}$, scaled using multiplicity

CMS, Eur. Phys. J. C (2012) 72:1945; ALICE J. Phys. G G **38** (2011) 124014

An interesting piece of kinematics

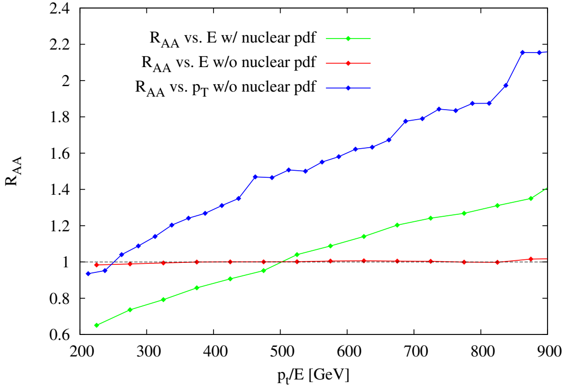


An interesting piece of kinematics



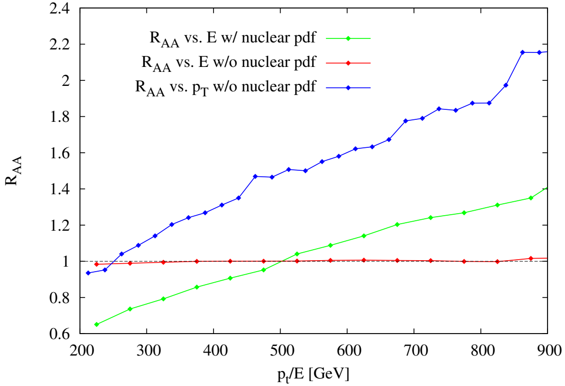
- no energy loss at very high $p_{\perp}$

An interesting piece of kinematics



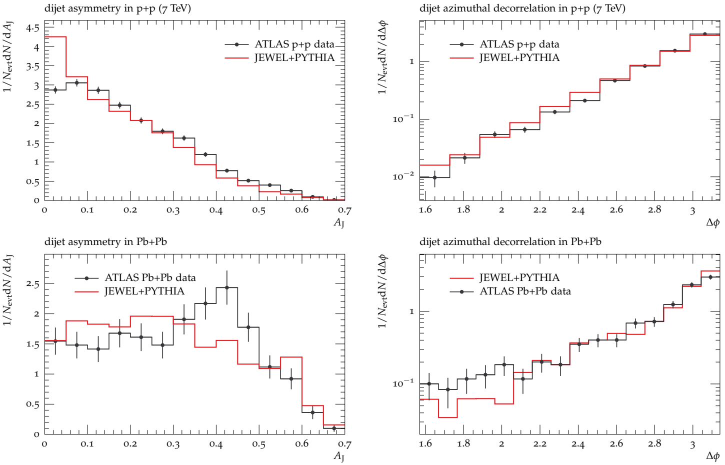
- no energy loss at very high $p_\perp$
- conversion of longitudinal into transverse momentum due to multiple scattering

An interesting piece of kinematics



- no energy loss at very high $p_\perp$
- conversion of longitudinal into transverse momentum due to multiple scattering
- only possible in non-eikonal kinematics

Outlook: reconstructed jets (preliminary)



- p+p baseline missing underlying event
- Pb+Pb not bad
- need to understand possible artefacts of background subtraction in Pb+Pb

Conclusions

- jet quenching is there, it is big and it is interesting
- analytical approaches: may give theoretical insight, but not suitable for describing data
- JEWEL: MC model for jet quenching based on perturbative QCD in general kinematics
- consistent with all analytically known limiting cases
- first confrontation with data looks very promising
- next: go for exclusive observables & jets