Jet Quenching in the light of perturbative QCD

Korinna Zapp

in collaboration with F. Krauss and U. Wiedemann

CERN

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Outline

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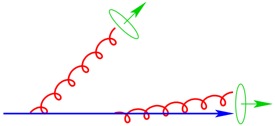
Reminder: jets and jet structure

- partons scattered at large angles give rise to jets
- hard parton scattering: QCD ME (LO: $2 \to 2$)
- higher order corrections
  - large angle: extra jets (fixed order matrix elements)
  - small angle: jet structure (large logs $\to$ resummation)
- in collinear region factorisation to all orders

$$d\sigma_{n+1} \approx d\sigma_n \frac{dt}{t} \frac{d\phi}{2\pi} dz \frac{\alpha_s}{2\pi} \mathcal{P}(z)$$

$t : k_\perp^2 \approx Q^2 \approx \vartheta^2 \quad \to \quad$ hardness of splitting

- nearly collinear emissions don't produce hadrons



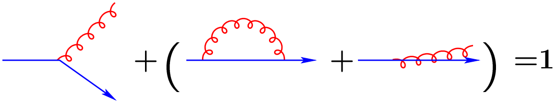
- classify emissions with $t < t_c$ as unresolvable

Reminder: jets and jet structure

- combine unresolved emissions with virtual corrections
  $\rightarrow$ divergences cancel

  Kinoshita-Lee-Nauenberg, Bloch-Nordsieck theorems

- unitarity: probabilities add up to unity



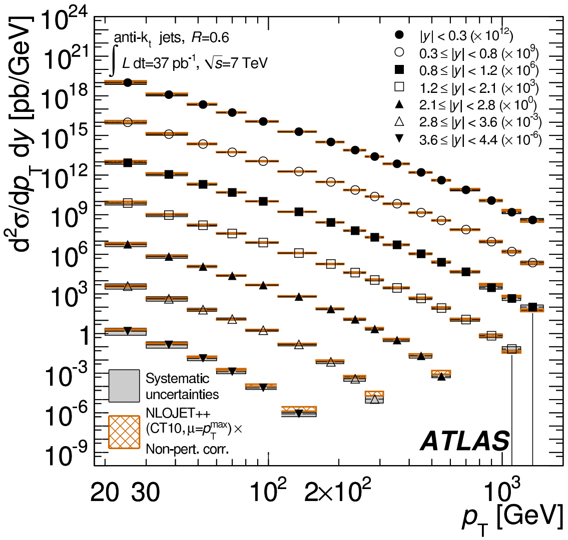
- probability for no emission: Sudakov form factor

$$\mathcal{S}(t_{\mathrm{h}}, t_{\mathrm{c}}) = \exp\left\{ -\int_{t_{\mathrm{c}}}^{t_{\mathrm{h}}} \frac{\mathrm{d}t}{t} \int \mathrm{d}z \, \frac{\alpha_{\mathrm{s}}}{2\pi} \mathcal{P}(z) \right\}$$

- suitable for MC implementation $\rightarrow$ parton shower
- resums real emissions to all orders

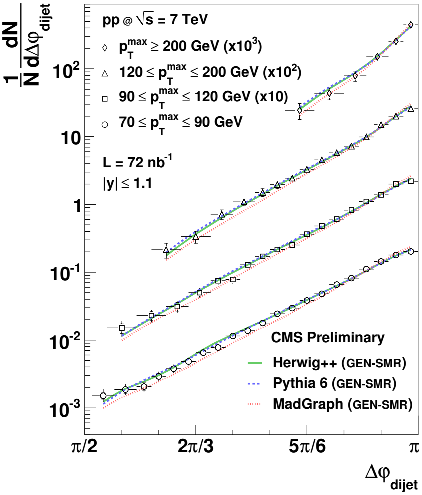
  to leading logarithmic accuracy

Differential jet cross section



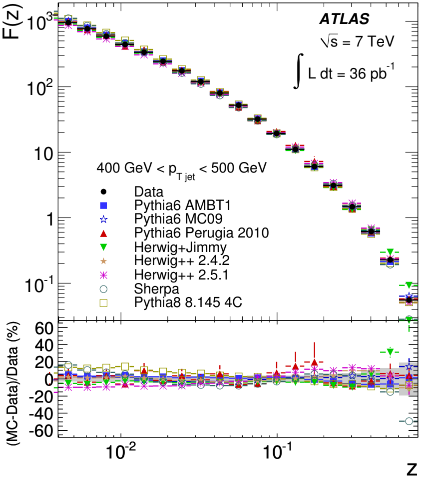
ATLAS, arXiv:1112.6297

Azimuthal Decorrelation



CMS Collaboration, CMS PAS QCD-10-015

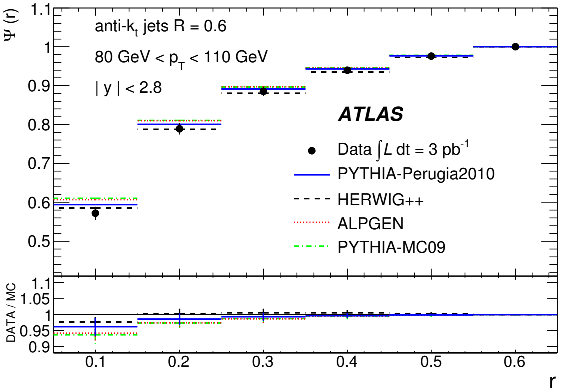
Fragmentation function



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

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

Jet shapes

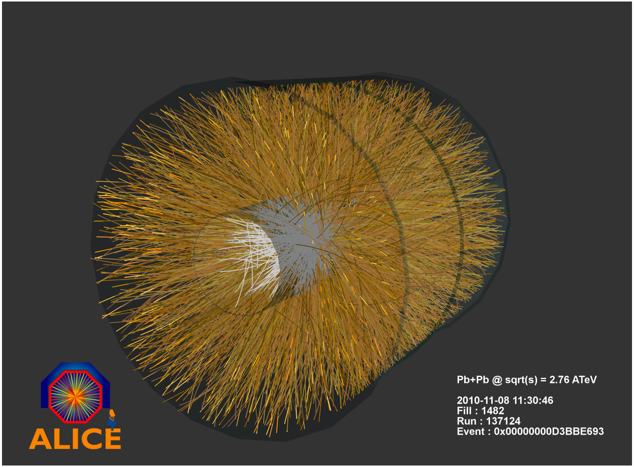


$$r = \sqrt{(\Delta\phi)^2 + (\Delta y)^2}$$

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

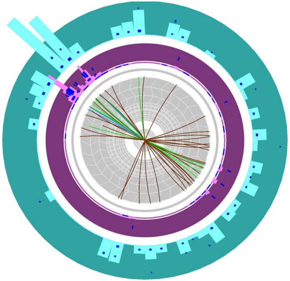
Outline

Heavy ion challenge



- jet reconstruction challenging due to large background

Jets in Pb+Pb

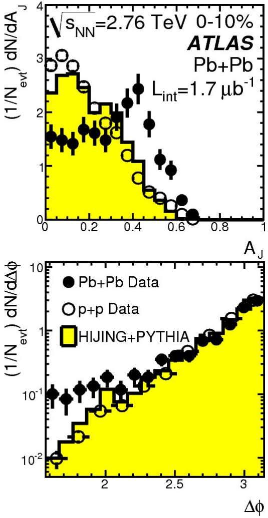


tracks: $p_\perp > 2.6$ GeV

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

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

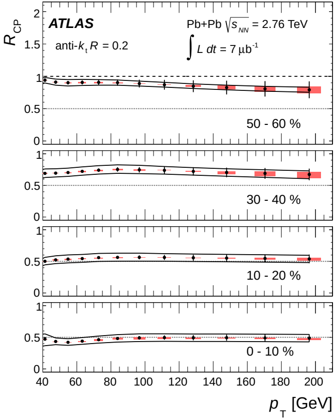
$E_{\perp 1} > 100$ GeV $\qquad E_{\perp 2} > 25$ GeV



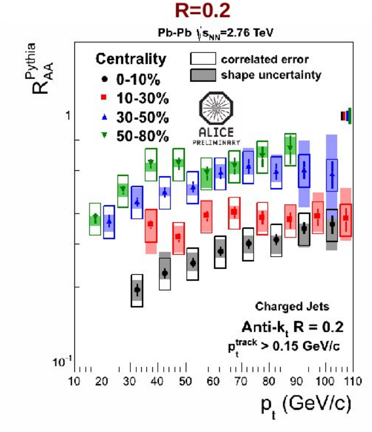
- clear transverse energy asymmetry between jets
- jet axis largely unchanged

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

Jets in Pb+Pb



ATLAS, arXiv:1208.1967

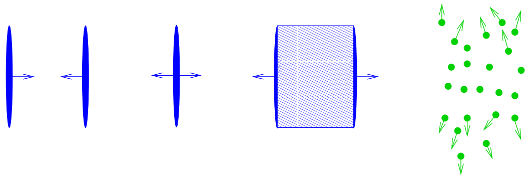


M. Verweij for ALICE, Hard Probes 2012

- strong, centrality dependent suppression of jets
- nearly independent of jet radius R

Heavy ion collisions

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



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

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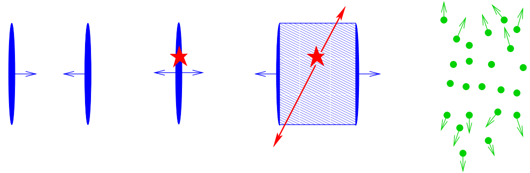

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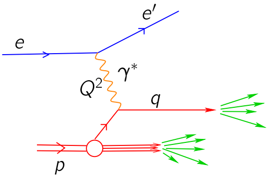
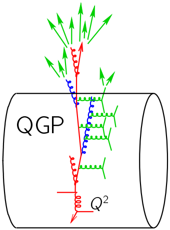
Why is this interesting?

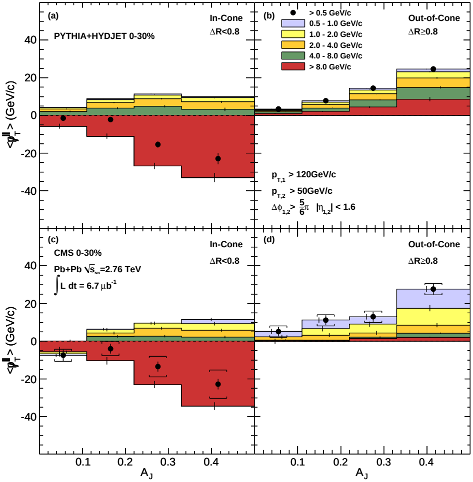
- jet propagation through medium: DIS on medium





- may reveal information about medium properties
- probes wide range of (intermediate to high) scales
- might give access to interplay of weakly and strongly coupled regimes
- might shed light on how collectivity arises in QCD

Jets in Pb+Pb

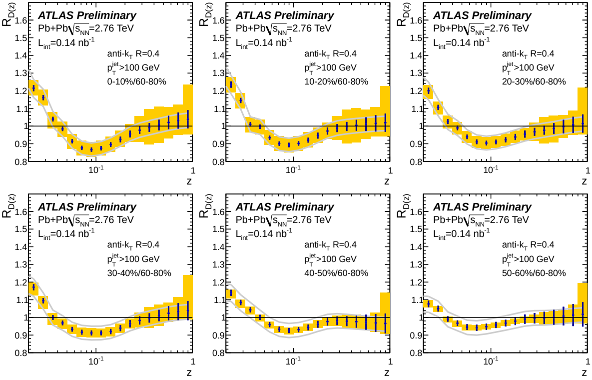


- leading jet momentum not balanced by subleading jet
- momentum goes into soft activity far away from jet

$$p_\perp^{||} = -\sum_i p_\perp^i \cos(\phi_i - \phi_{\text{leading jet}})$$

CMS, Phys. Rev. C **84** (2011) 024906

Jets in Pb+Pb



ATLAS, ATLAS-CONF-2012-115

- intra-jet fragmentation functions largely unchanged

Executive summary

Experimental findings

- strong suppression of jets and high-$p_\perp$ hadrons
- intra-jet fragmentation function vacuum-like
- jet axis remains unchanged
- soft modes get transported to large angles

Theoretical interpretation

- medium-induced gluon bremsstrahlung
- 'traditional (analytical) approaches': in eikonal limit

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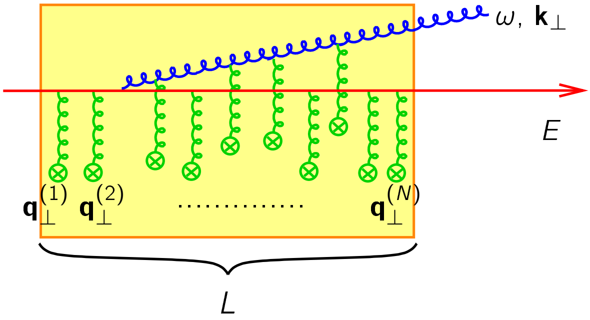
Gluon radiation in eikonal limit



- high energy approximation: $E \gg \omega \gg k_\perp, q_\perp$
- static scattering centres → no collisional energy loss
- single gluon radiation → unsuitable for jet description
- destructive interference → LPM-effect

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

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

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- phenomenologically successful
- but conceptual and practical limitations
- Monte Carlo codes: mostly based on analytical results

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Basic ideas

Medium

- the 'medium' is strongly interacting
- its structure may be inherently non-perturbative

  cf. proton structure
- but hard interactions should resolve quasi-free partons

  cf. DIS
- at high scales the scale dependence should be described by pQCD

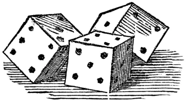
Interactions

- jet-medium interactions: collisions of hard partons with quasi-free partons in medium
- at high scales perturbation theory should be applicable
- use standard techniques: LO ME + PS

Basic ideas

Assumptions

- medium as seen by jet modelled as collection of quasi-free partons
- infra-red continued perturbation theory to describe all jet-medium interactions
- formation times govern the interplay of different sources of radiation
- use results from eikonal limit to include LMP-effect

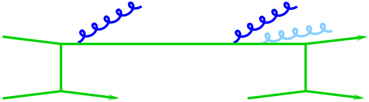


Radiation in JEWEL

- virtuality ordered parton shower
- every gluon emission has formation time

$$\tau \approx \frac{E}{Q^2} \approx \frac{2\omega}{k_\perp^2}$$

- in case of competing emissions the one with shorter formation time gets realised



- radiation off scattering centre neglected
- at most one emission from initial state shower for scatterings in medium

Probabilistic formulation of the LPM-effect

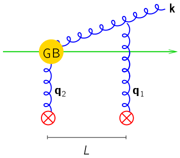
- naive MC purely incoherent
- consider gluon radiation with two momentum transfers

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

- analytical calculation interpolates between

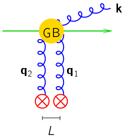
incoherent production

$\tau_1 \ll L$



coherent production

$\tau_1 \gg L$



- $\tau_1 \equiv \dfrac{2\omega}{(\mathbf{k}+\mathbf{q}_1)^2}$ is the 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:

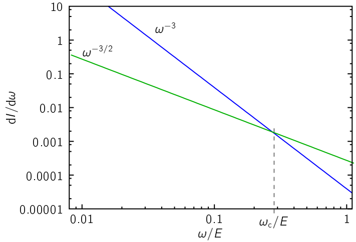
$$\omega \frac{d^3 I^{(2)}}{d\omega d\mathbf{k}} \propto \int d\mathbf{q}_1\, d\mathbf{q}_2\, |A(\mathbf{q}_1)|^2 |A(\mathbf{q}_2)|^2 R(\mathbf{k}, \mathbf{q}_1 + \mathbf{q}_2)$$

- consistent determination of scattering centres and formation time

Emission probability

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

Probabilistic formulation of the LPM-effect

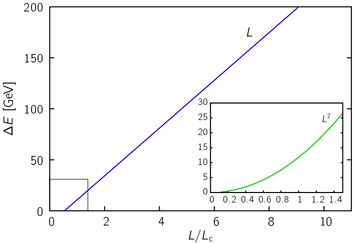


analytical results:

$$\frac{dI}{d\omega} \propto \omega^{-3/2} \quad \text{für} \quad \omega < \omega_c$$

$$\frac{dI}{d\omega} \propto \omega^{-3} \quad \text{für} \quad \omega > \omega_c$$

deviation in infra-red due to regularisation



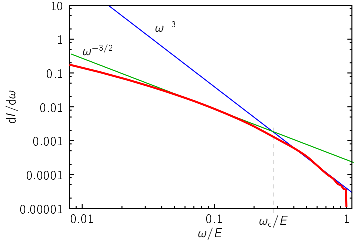
$$\Delta E \propto L^2 \quad \text{für} \quad L < L_c$$

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

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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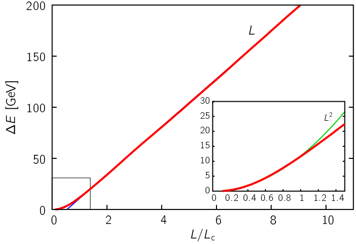

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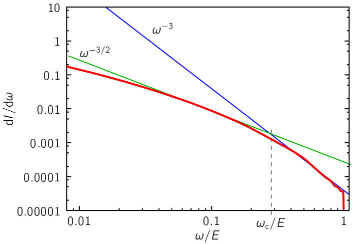

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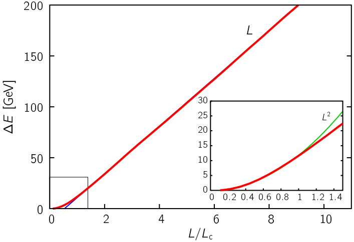


$\Delta E \propto L^2$ für $L < L_c$

$\Delta E \propto L$ für $L > L_c$

understand pre-factor up to 30 %

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

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

Scattering cross section

- cross section for scattering in medium

$$\sigma_i(E,T) = \int_0^{|\hat{t}|_{\max}(E,T)} \mathrm{d}|\hat{t}| \int_{x_{\min}(|\hat{t}|)}^{x_{\max}(|\hat{t}|)} \mathrm{d}x \sum_{j\in\{\mathrm{q},\bar{\mathrm{q}},\mathrm{g}\}} f_j^i(x,|\hat{t}|) \frac{\mathrm{d}\hat{\sigma}_j}{\mathrm{d}|\hat{t}|}(x\hat{s},|\hat{t}|)$$

- 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' $f_j^i(x,|\hat{t}|)$

Partonic pdf's

- partonic pdf's defined through DGLAP equation

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

- 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

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

etc.

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

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

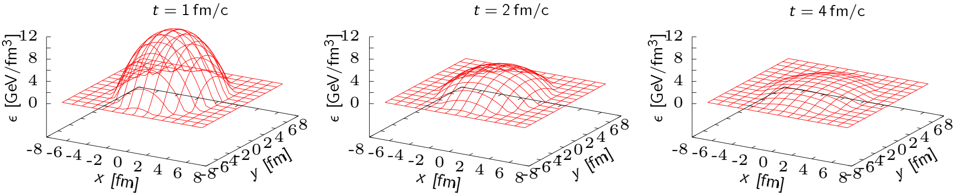
$$(\tau = \sqrt{t^2 - z^2})$$

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

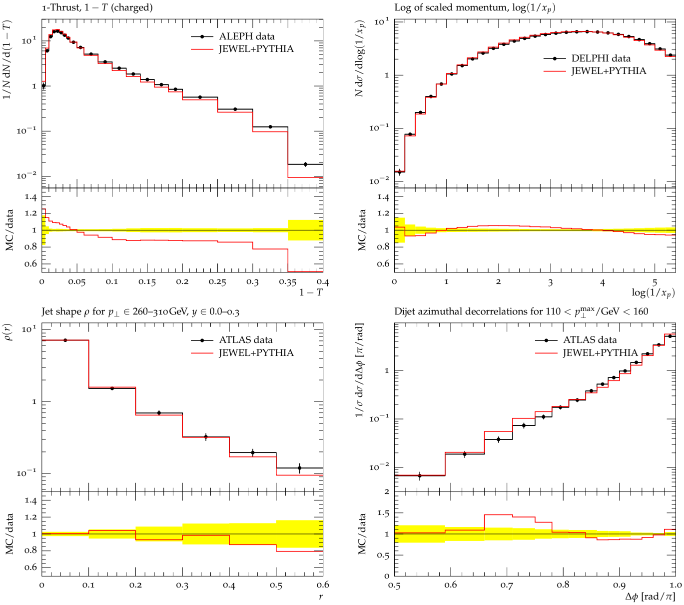
local energy density: $\epsilon(x, y, \tau) \propto n_{\text{part}}(x, y) \cdot \tau^{-4/3}$

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

$b = 4$ fm $\quad z = 0$

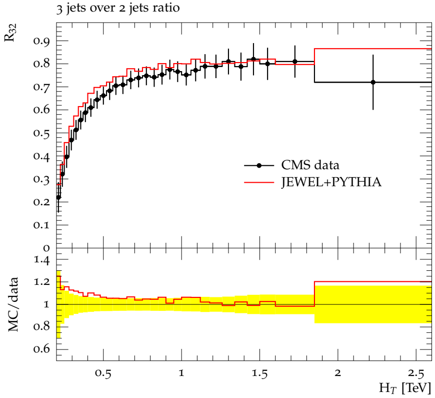


Validation



ALEPH, Phys. Rept. **294**; DELPHI, Z. Phys. C **73**; ATLAS Phys. Rev. D **83** & Phys. Rev. Lett. **106**

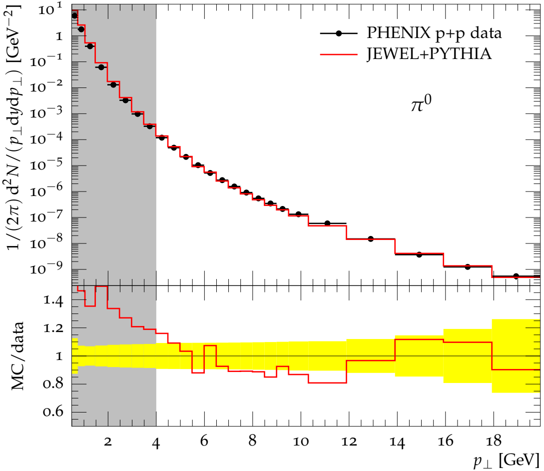
Validation



- parton shower even describes wide angle radiation

CMS, Phys. Lett. B 702 (2011) 336

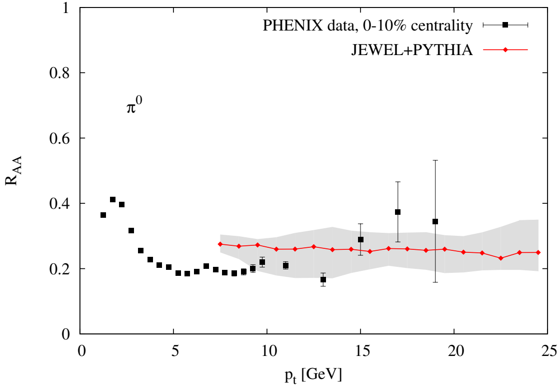
Validation



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

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

Hadron suppression at RHIC

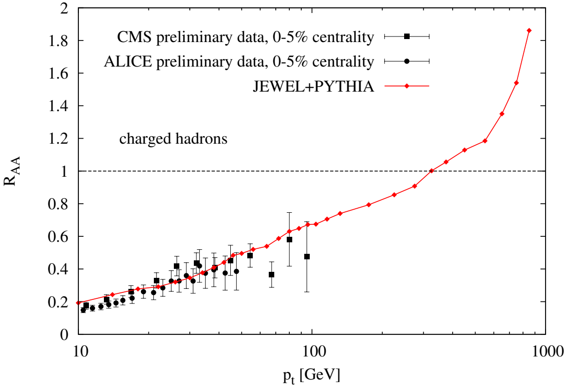


- π^0 suppression at $\sqrt{s} = 200$ A GeV
- grey band: variation of μ_D by $\pm 10\,\%$

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

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

Hadron suppression at the LHC

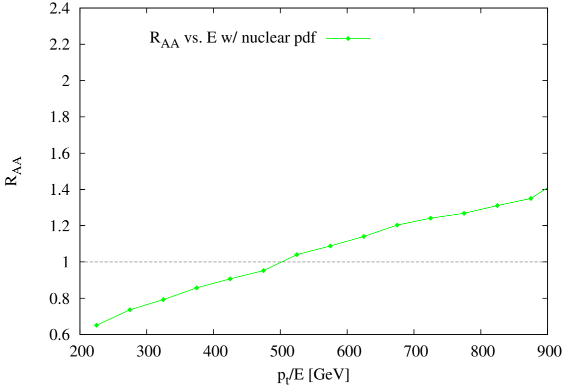


- charged hadron suppression at $\sqrt{s} = 2.76$ A TeV
- interesting behaviour at very high $p_\perp$

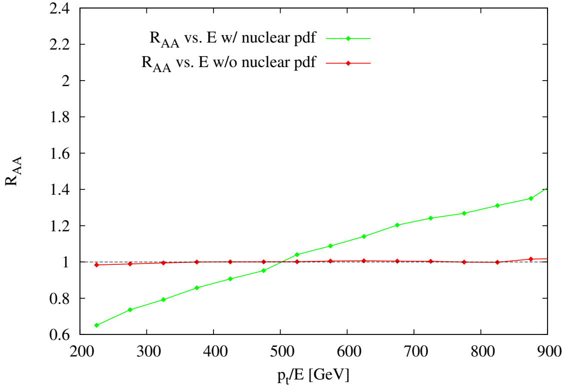
$T_\text{i} = 530\,\text{MeV}$, $\tau_\text{i} = 0.5\,\text{fm}$, $T_\text{c} = 165\,\text{MeV}$, scaled using multiplicity

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

An interesting kinematics effect

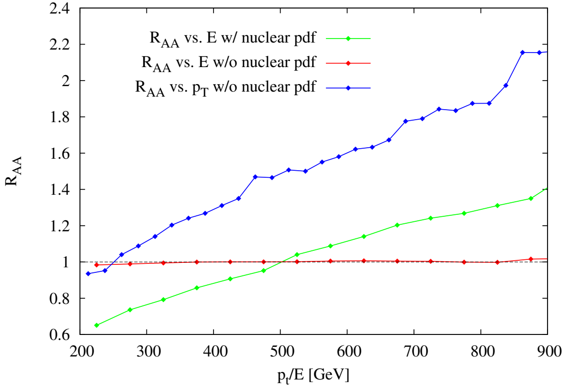


An interesting kinematics effect



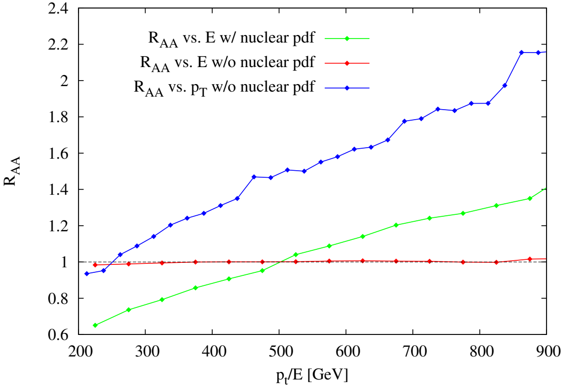
- no energy loss at very high $p_\perp$

An interesting kinematics effect



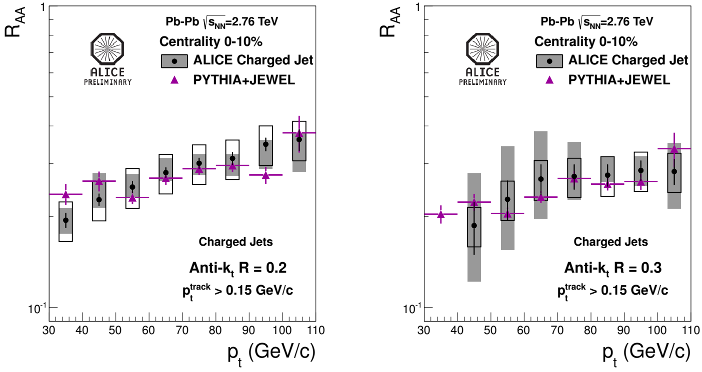
- no energy loss at very high $p_\perp$
- conversion of longitudinal into transverse momentum due to multiple scattering

An interesting kinematics effect



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

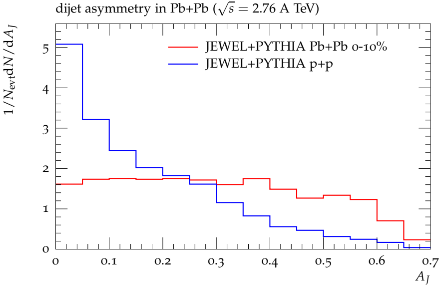
Jet Suppression at the LHC

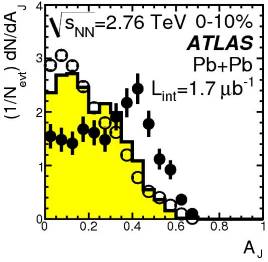


- fit very well for both jet radii
- same parameters as for hadron R_{AA}, no tuning

M. Verweij for ALICE, Hard Probes 2012 (arXiv:1208.6169)

Dijet Asymmetry

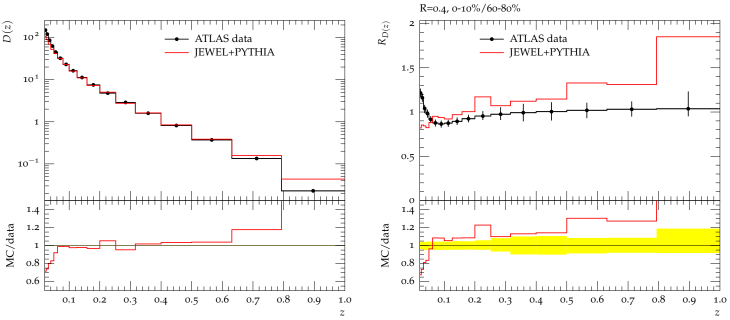




- qualitatively same behaviour as in data
- no quantitative comparison possible: data not unfolded for jet energy resolution

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

Fragmentation Function



- FF in central events looks good
- slightly too soft in peripheral events
- in JEWEL hard core of jet undisturbed by medium
- but jet energy is reduced

→ FF gets harder

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Aside: Background Subtraction

Experimental procedure

- background subtracted for jets and FF measurements
- issues due to background fluctuations
- correlation of jet and background not understood

→ uncorrelated background subtracted

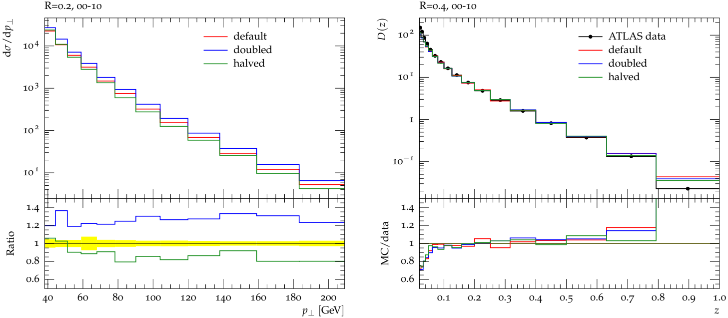
JEWEL

- JEWEL simulates only jets

→ cannot follow experimental procedure exactly

- can hadronise jet with and without recoiling scattering centres
- final state not incoherent sum of jet and recoils
- for comparison with jet data hadronise without recoils
- residual uncertainty in comparison to data

Uncertainties: formation times



- variation of formation times by factor 2
- $\sim$ 20 % change in jet rate
- FF insensitive

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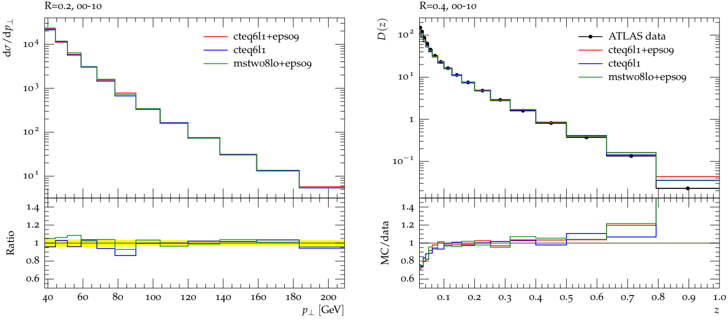
Uncertainties: pdf's



- pdf uncertainties smaller than current statistical errors

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Outline

Jets in p+p

Jets in A+A

JEWEL
- Basic ideas
- The model in detail
- Comparison to data

Conclusions

Conclusions

- JEWEL: consistent and controlled formulation of jet evolution in a medium in pQCD
- based on standard perturbative technology
- can quantify uncertainties
- general, non-eikonal kinematics
- no distinction between elastic and inelastic scattering
- and between vacuum and medium-induced radiation
- presently simple Bjorken model of medium

  can use any model in principle
- very reasonable description of data

  the data JEWEL can be expected to describe
- no tuning medium parameters extrapolated from RHIC