Simulating jets at the LHC

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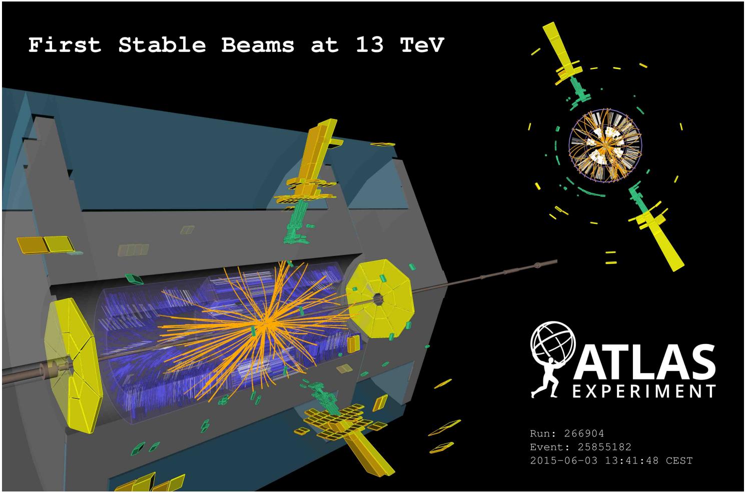
Outline

A di-jet event at LHC



What is a jet?

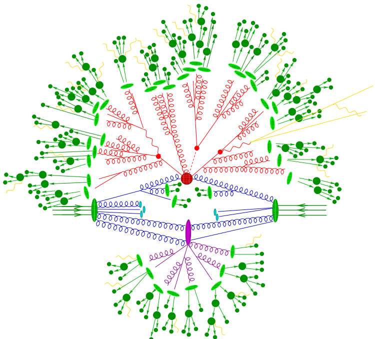
Jet definition

- jets are collimated sprays of hadrons
- jets are defined by jet algorithm
- modern jet algorithms: sequential recombination
  - define measure for distance in phase space
  - define resolution R — jet radius
  - combine pair with smallest distance
  - repeat until mutual distance of all objects $> R$
  - theoretically controlled — infra-red safe

Theoretical interpretation

- jet $\approx$ parton
- production of hard partons calculable in fixed order PT
- but: hard partons radiate $\rightarrow$ jet substructure
- but: hadronisation & underlying event corrections

Theorist's view



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

matrix elements: fixed order perturbation theory

(LO or NLO)

final state parton shower: resummation of collinear logs

(LL)

initial state parton shower: like final state parton shower

hadronisation: non-perturbative QCD: modelling

multiple interactions: beyond factorisation: modelling

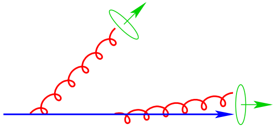
Jets and jet structure

- 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

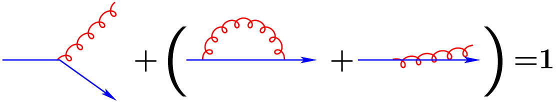


- classify emissions with $t < t_c$ as unresolvable

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

ANTS: A new antenna shower for SHERPA

Motivation

- coherent radiation off colour dipole
- local recoil compensation
- relation to antenna subtraction

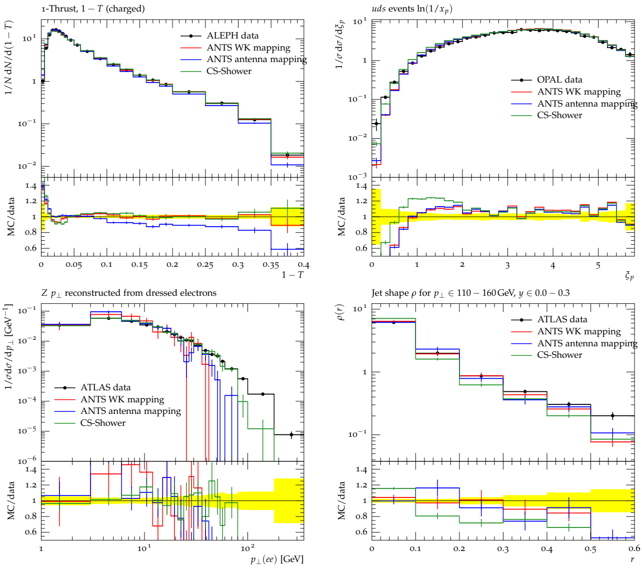
Status

- ANTenna Shower (ANTS) implemented (WK kernels)

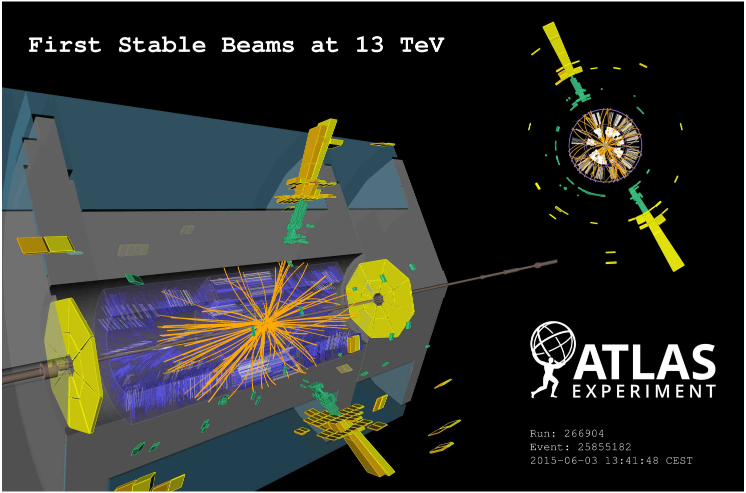
  Winter & Krauss, JHEP **0807** (2008) 040
- two kinematics mappings: WK & antenna mapping

  Gehrmann-De Ridder, Gehrmann, Glover & Heinrich, JHEP **0711** (2007) 058
  Daleo, Gehrmann & Maitre, JHEP **0704** (2007) 016
- needs validation & tuning
- multi-jet merging under construction

ANTS: preliminary results



A di-jet event at LHC

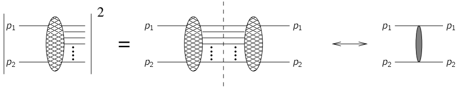


Soft QCD with SHRiMPS

Soft and Hard Reactions involving Multi-Pomeron Scattering

with V. Khoze, F. Krauss, A. Martin, M. Ryskin, H. Schulz

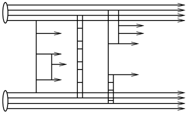
- exploits optical theorem



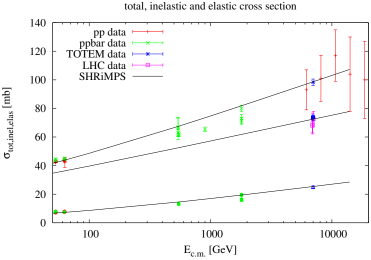
- based on Khoze-Martin-Ryskin model

modern model combining pQCD with unitarity

- Monte Carlo event generator: module in SHERPA
- complete view:
  - elastic, diffractive & inelastic scattering
  - cross sections and fully differential final states



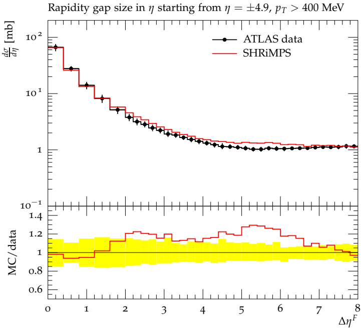
Preliminary results



- total, inelastic & elastic cross section
- used to constrain parameters

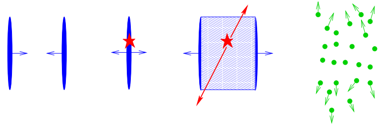
- cross section for events with rapidity gaps
- mixture of diffractive and inelastic events

ATLAS, Eur. Phys. J. C **72** (2012) 1926

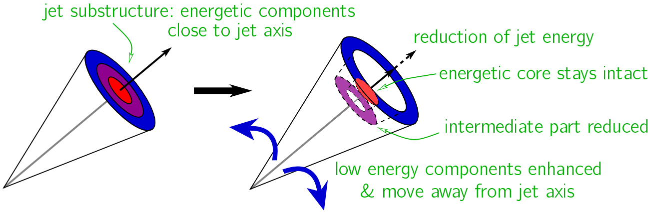


Jets in heavy ion collisions

- modification of jets in A+A collisions compared to p+p
- naive picture of heavy ion collision:



- jets propagate through dense and hot QCD matter
- jet quenching: experimental findings:

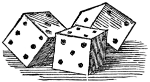


JEWEL: Assumptions

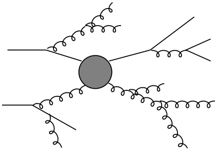
Jet Evolution With Energy Loss

- medium as seen by jet: collection of quasi-free partons
- use 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

KCZ, Krauss & Wiedemann, JHEP **1303** (2013) 080
KCZ, Eur.Phys.J. **C74** (2014) 2762
KCZ, Phys.Lett. **B735** (2014) 157
jewel.hepforge.org



JEWEL in a nutshell



- jet production in initial N+N collisions: ME+PS

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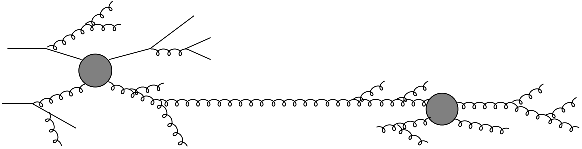

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- re-scattering: ME+PS
  - generates elastic & inelastic processes
  - with leading log correct relative rates
  - general kinematics

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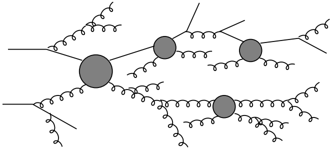

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  - all emission ("vacuum" & "medium induced") are equal
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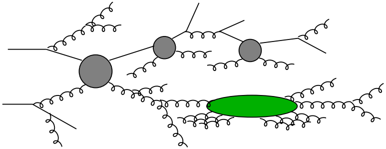

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  - all emission ("vacuum“ & "medium induced“) are equal
  - hard structures remain unperturbed
- LPM interference KCZ, Stachel, Wiedemann, JHEP **1107** (2011) 118
  - also governed by formation times
  - without kinematic restrictions

The background

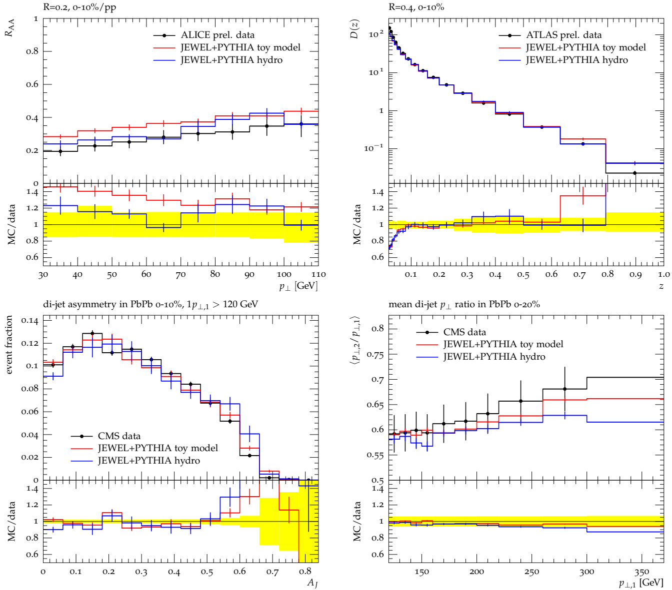
Hydro: 1+1 viscous hydro

Floerchinger & Wiedemann, Phys. Lett. B **728** (2014) 407

- azimuthally symmetric ($b = 0$)
- boost-invariant long. expansion + transv. expansion
- viscosity: $\eta/s = 0.08$
- EOS: parametrisation of lattice + hadron resonance gas Huovinen & Petreczky, Nucl. Phys. A **837** (2010) 26
- initial conditions: $T_{\text{i}} = 485\,\text{MeV}$ and $\tau_{\text{i}} = 0.6\,\text{fm}$ transverse profile from Glauber model

Shen & Heinz, Phys. Rev. C **85** (2012) 054902

JEWEL+hydro: some results



CMS, Eur. Phys. J. C **72** (2012) 1945; ALICE, arXiv:1208.6169
ALTAS-CONF-2012-115; CMS, Phys. Lett. B **712** (2012) 176

Effect of jets on background

with S. Flörchinger

- want to study interplay between jets and bulk
- fully self-consistent description difficult
  $\rightarrow$ combine jets & hydrodynamic evolution of bulk
- need to iterate
  1. solve hydro without jets
  2. compute jets in hydro background
  3. re-solve hydro with input from jets
  4. re-compute jets in modified background
     $\rightarrow$ neglected due to causality
- want to avoid having to do it event-by-event
- characterise effect of jets in terms of n-point functions
- caveat: separation between jets and bulk ill-defined

The source term

Definitions

- interface: 4-momentum transfer in scattering processes
- source term: $J^\mu(x) = \sum_i \Delta p_i^\mu \delta^{(4)}(x - x_i)$
- hydro equations: $\partial_\mu T^{\mu\nu} = J^\nu$
- projections w.r.t. fluid velocity:
  $J_S = u_\nu J^\nu \quad \& \quad J_V^\mu = \Delta^\mu{}_\nu J^\nu$
- characterise J^μ in terms of
  - event averages: $\langle J_S(x)\rangle$, $\langle J_V^\mu(x)\rangle$
  - correlators: $\langle J_S(x) J_S(y)\rangle$, $\langle J_S(x) J_V^\mu(y)\rangle$, $\langle J_V^\mu(x) J_V^\nu(y)\rangle$

for Gaussian fluctuations this is sufficient

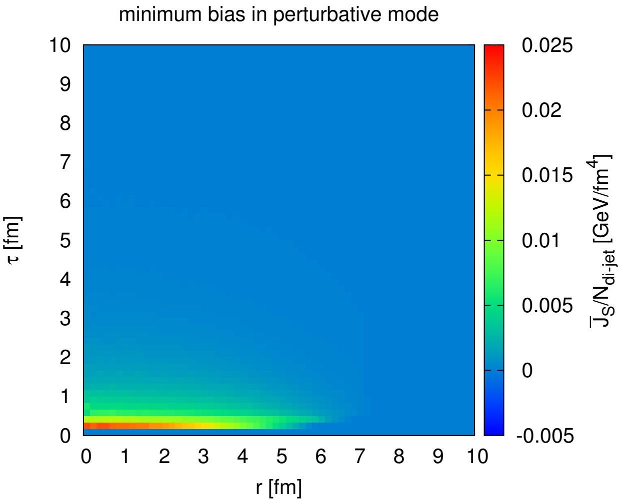
Setup for 'typical event'

- restrict first study to $b = 0$, $|\eta| < 0.5$

this is simply a matter of convenience

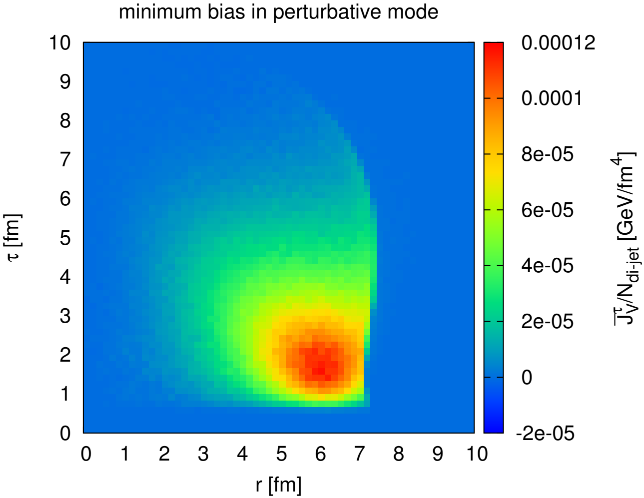
- $p_{\perp,\mathrm{cut}} = 3\,\mathrm{GeV}$ generate jets where they dominate over bulk
- $\langle N_{\text{di-jet}}\rangle = T_{AA}\sigma_{\text{di-jet}} \approx 1700$

The source term of MinBias events: averages



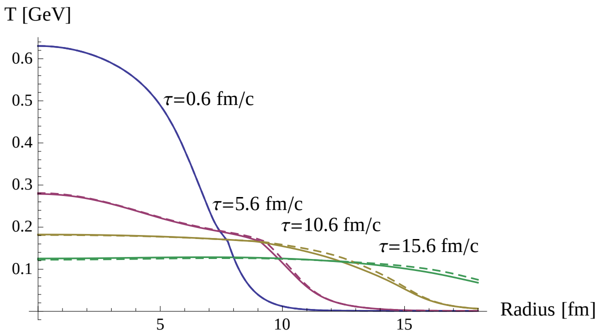
- follows temperature profile

The source term of MinBias events: averages



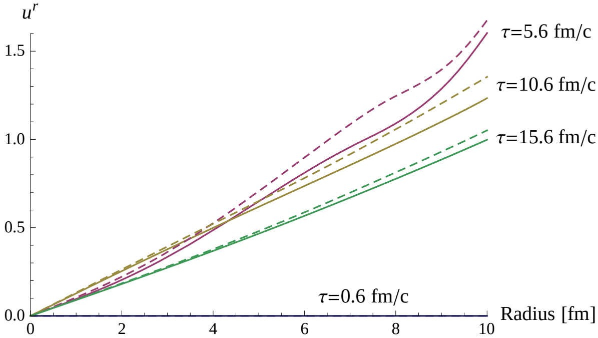
- non-trivial functional dependence

Hydro with source term of MinBias events



- effect of jets on temperature negligible

Hydro with source term of MinBias events



- small increase of transverse flow

Outlook

ANTS

- finish multi-jet merging
- antenna subtraction

SHRiMPS

- finish tuning
- extend as underlying event model

JEWEL

- improved version of JEWEL based on ANTS
- lots of phenomenology
- background: study correlators