Heavy ion physics

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LIP (Lisbon) & CERN

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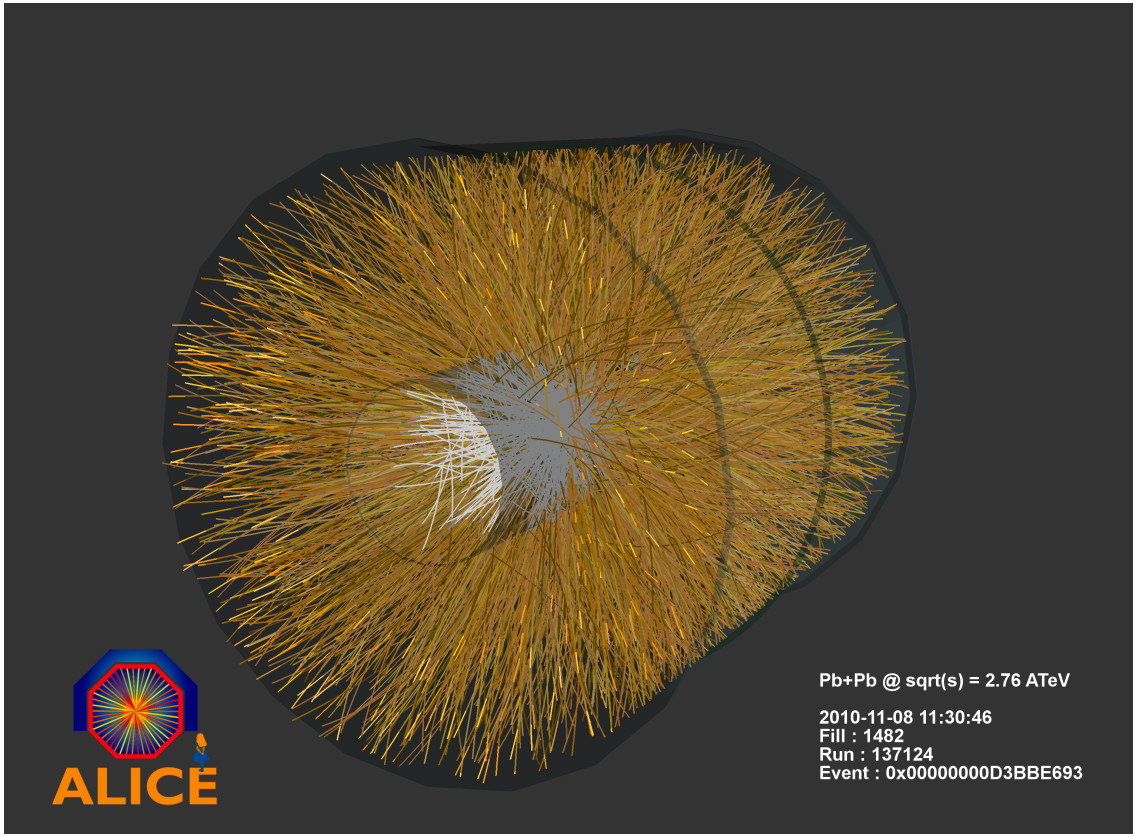
A heavy ion collision



- $\sim$ 1600 primary charged hadrons per unit rapidity
- p+p at comparable $\sqrt{s}$: $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \simeq 4 - 5$

Heavy ion collisions: bird's eye view

- heavy ion collisions create strongly interacting system of high density
- Bjorken's energy density estimate:

$$\epsilon_0 \simeq \frac{1}{\pi R^2 \tau_0} \left. \frac{\mathrm{d}E_\perp}{\mathrm{d}\eta} \right|_{\eta=0} \simeq 25\,\mathrm{GeV/fm}^3$$

Bjorken, Phys. Rev. D 27 (1983) 140
ALICE, Phys. Rev. C 94 (2016) 034903

- there has to be re-scattering in the final state
- scattering drives a system towards thermal equilibrium
- How and to what extent does the final state in heavy ion collisions equilibrate?
- What are "material properties" of hot and dense QCD matter?

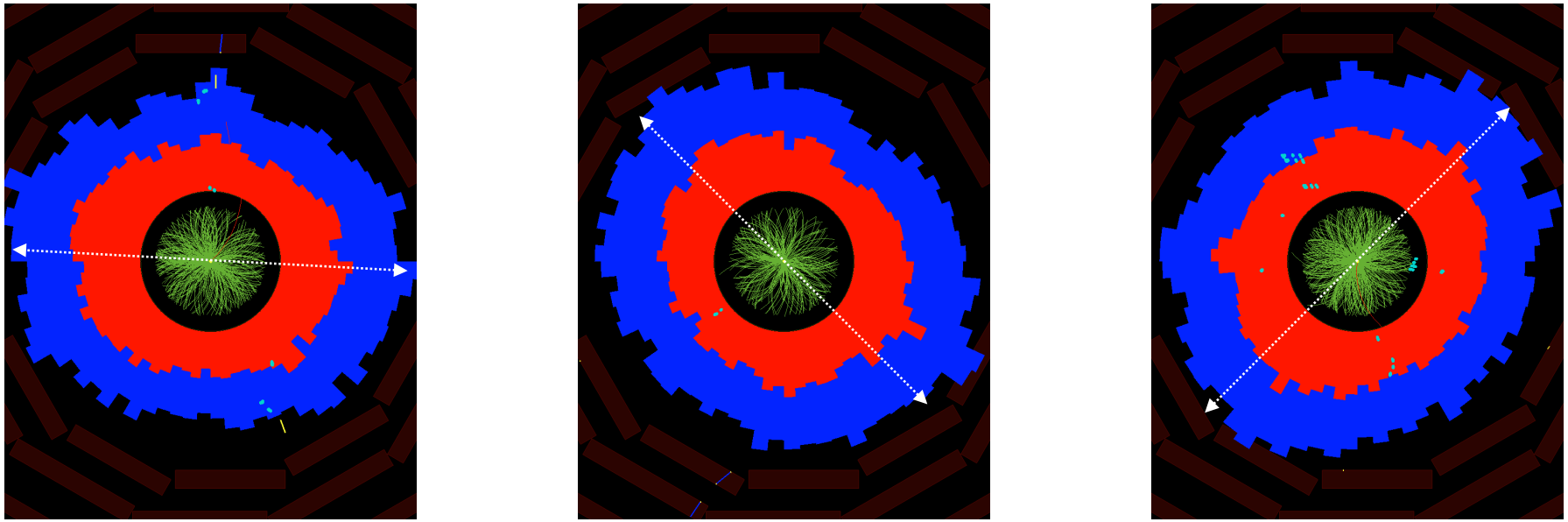
Three main discoveries in heavy ion physics

1. hydrodynamic behaviour
2. jet quenching
3. similarity between p+p and A+A

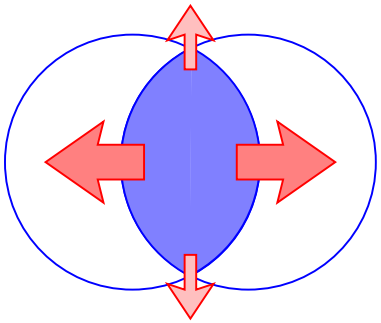
Discovery # 1: Hydrodynamic behaviour

Soft particles in A+A collisions behave like an almost perfect fluid.

soft = low transverse momentum



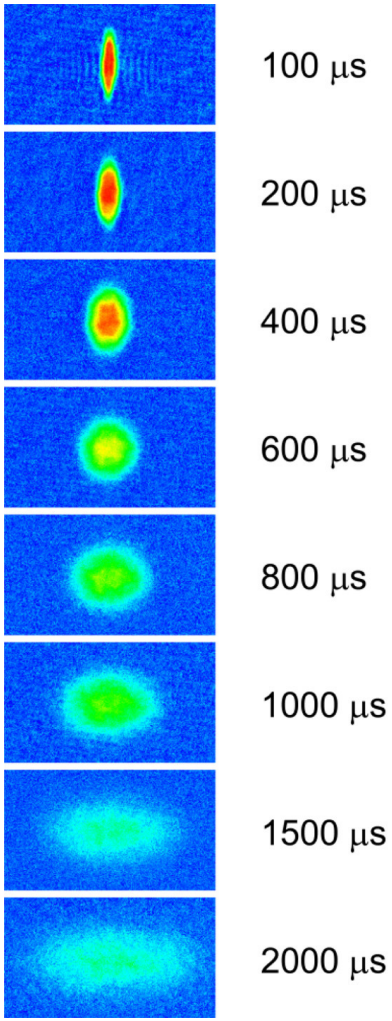
event displays from G. Roland, CMS



- anisotropy due to different pressure gradients

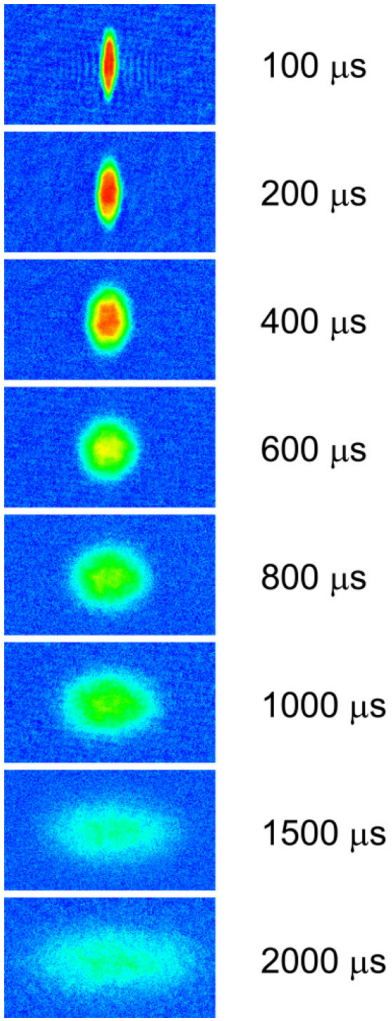
→ collective flow

Collective flow



O'Hara et al., Science 298 (2002) 2179

Collective flow



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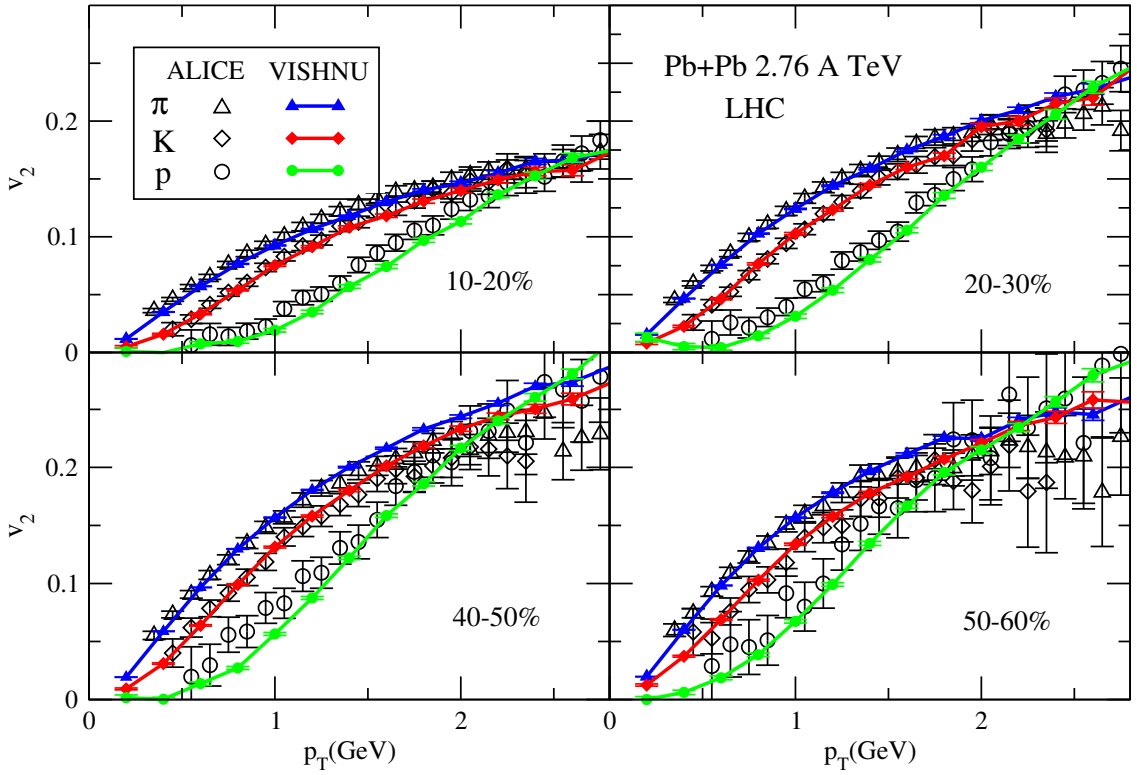


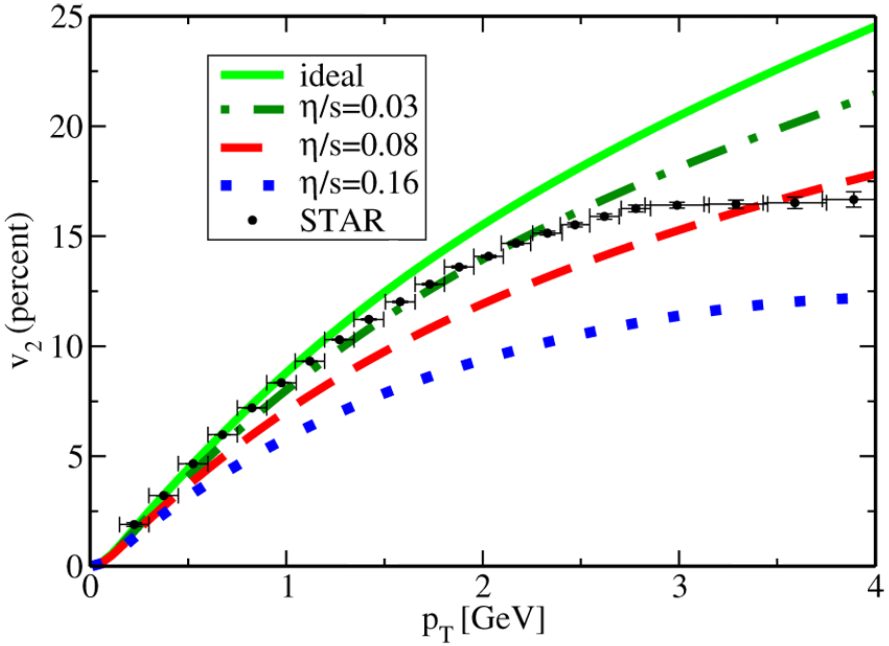
Song, Bass & Heinz, Phys. Rev. C 89 (2014) no.3, 034919

$$v_2 = \langle \cos(2\phi) \rangle$$

- at large coupling hydrodynamics correct description
- mass ordering due to common velocity

Shear viscosity and black holes

- efficiency of v_2 generation sensitive to shear viscosity η
- heavy ion collisions least dissipative system known



Romatschke & Romatschke, Phys. Rev. Lett. 99 (2007) 172301

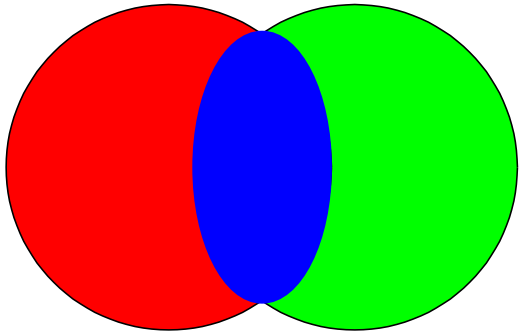
- conjectured lower bound form obtained with AdS/CFT techniques

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

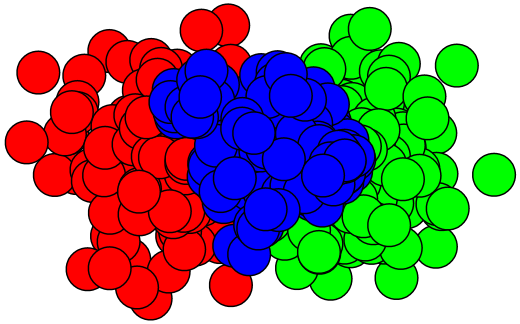
saturated by field theories with gravity duals

Kovtun, Son, Starinets, Phys. Rev. Lett. 94 (2005) 111601

Higher harmonics



no odd harmonics



fluctuations generate odd harmonics

Alver, Roland, Phys. Rev. C 81 (2010) 054905

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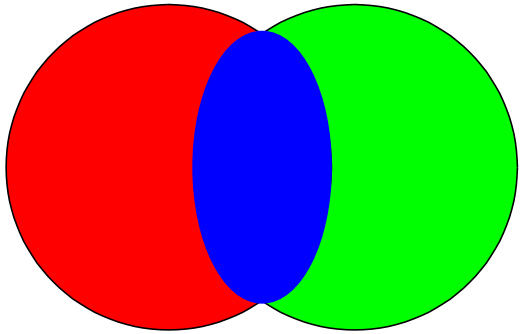

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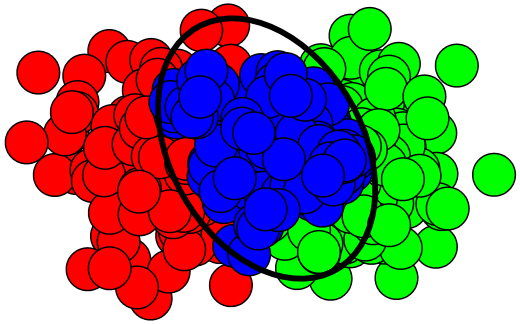

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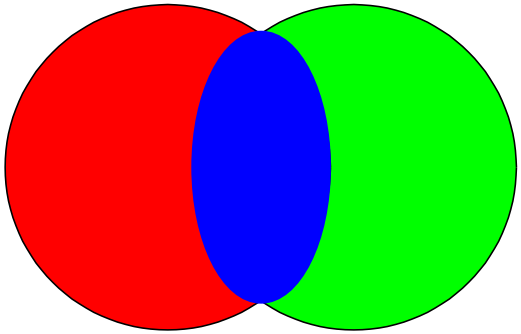

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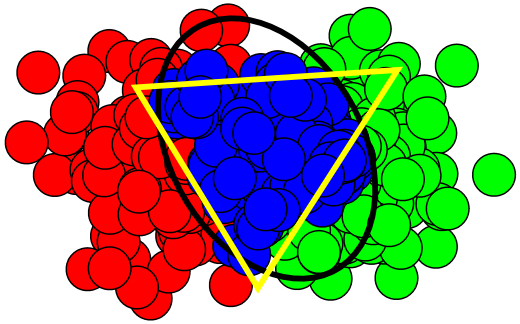

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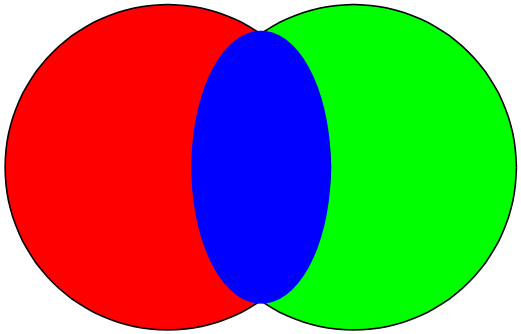

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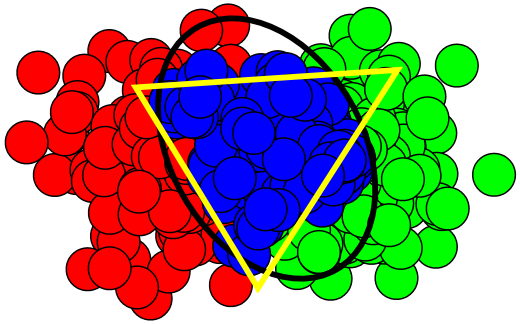

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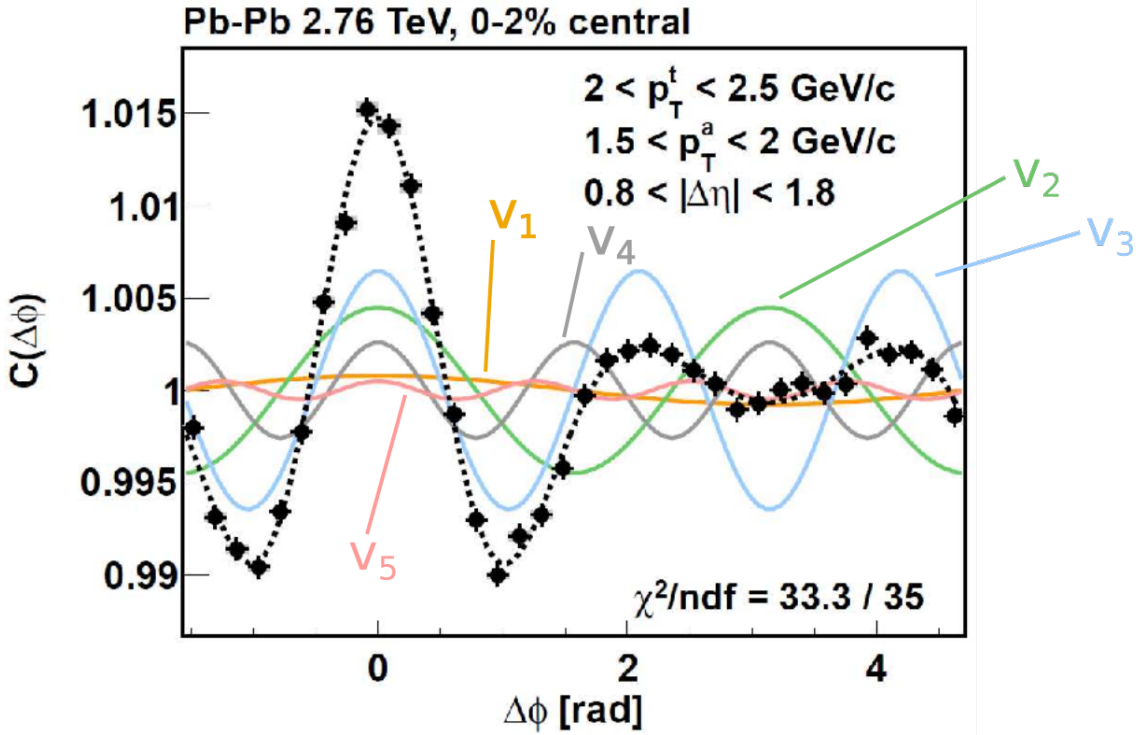


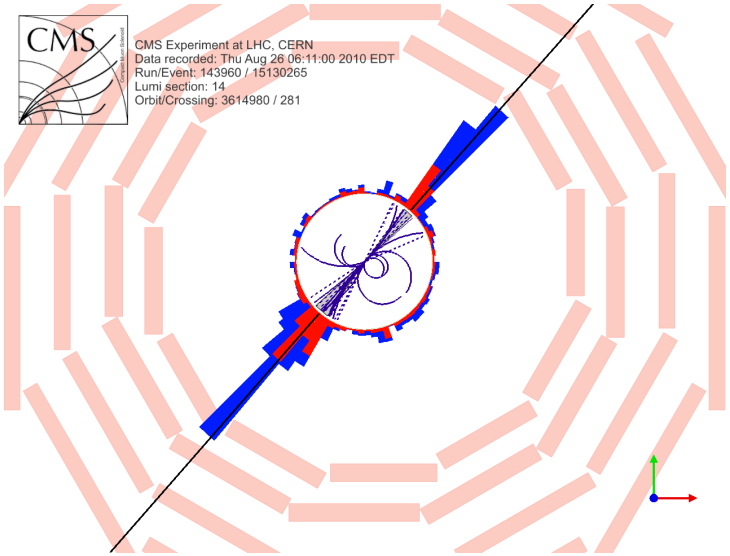
- very central collisions
- v_2 small

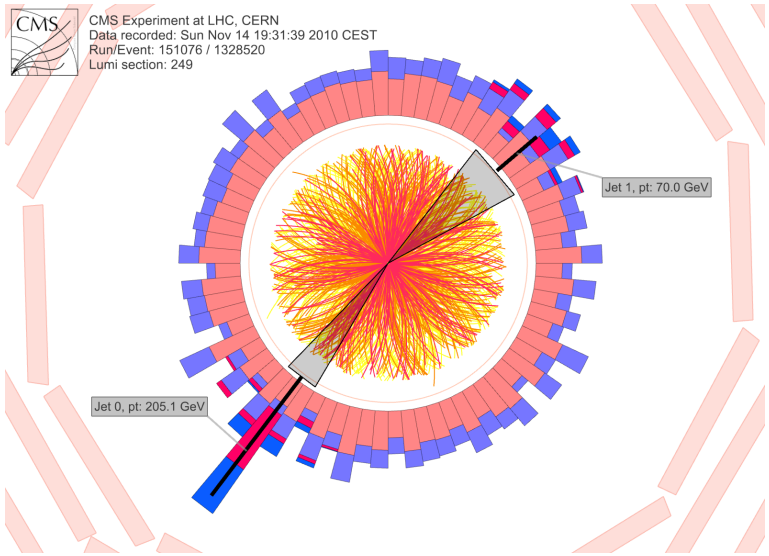
ALICE, Phys. Lett. B 708 (2012) 249

Discovery # 2: Jet quenching

Jet quenching: Hard jets are suppressed and their structure modified.

hard = high transverse momentum





- proton-proton collisions: 2 jets with balancing transverse momentum
- in heavy ion collisions: significant softening of jets

→ thermalisation of a far-from-equilibrium system

→ jet quenching informs us about equilibration in QCD

What happens to jets in medium?

Scenario I: hard partons don't resolve quasi-particles

- interactions between jet & medium at large coupling
- AdS/CFT techniques

Scenario II: hard partons do resolve quasi-particles

- jet – medium interactions at weak(ish) coupling
- perturbative techniques
- thermalisation through elastic re-scattering (slow)
- parton energy loss through QCD bremsstrahlung
- destructive interference in multiple scattering LPM effect

relevant scale: momentum transfer q between hard parton and medium

Jets and thermalisation

In both scenarios jet quenching related to thermalisation:

- early stages of HIC and jets are far-from-equilibrium systems
- jet quenching can be seen as "jet thermalisation"
- effective kinetic theory describing thermalisation

Arnold, Moore, Yaffe, JHEP **0301** (2003) 030
Kurkela, Zhu, Phys. Rev. Lett. **115** (2015) no.18, 182301

$$-\frac{\mathrm{d}f_{\mathbf{p}}}{\mathrm{d}\tau} = \mathcal{C}_{1\leftrightarrow 2}[f_{\mathbf{p}}] + \mathcal{C}_{2\leftrightarrow 2}[f_{\mathbf{p}}] + \mathcal{C}_{\mathrm{exp}}[f_{\mathbf{p}}]$$

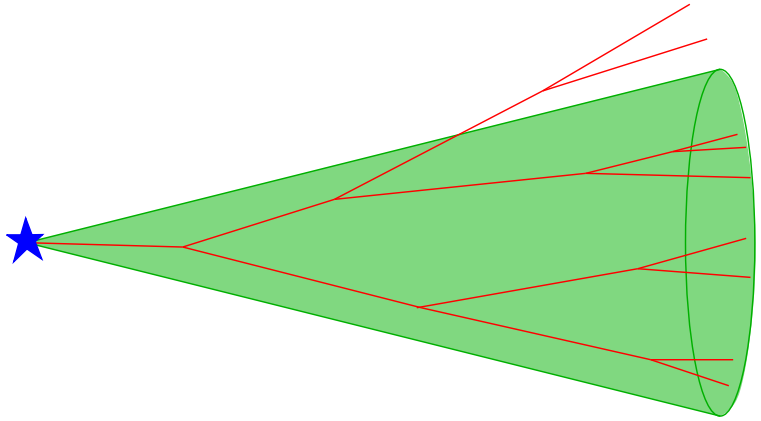
- $\mathcal{C}_{1\leftrightarrow 2}$: splitting/merging rate in presence of multiple scattering including LPM effect
- $\mathcal{C}_{2\leftrightarrow 2}$: elastic scattering rate
- both processes also responsible for parton energy loss

Jet quenching: setting the stage

Jets in p+p

- jets in proton-proton collisions fairly well understood in pQCD
  - jet production
  - jet sub-structure
  - jet reconstruction using dedicated algorithms

most commonly used at LHC: anti-$k_\perp$



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Jets in A+A

- jet production in heavy ion collisions understood

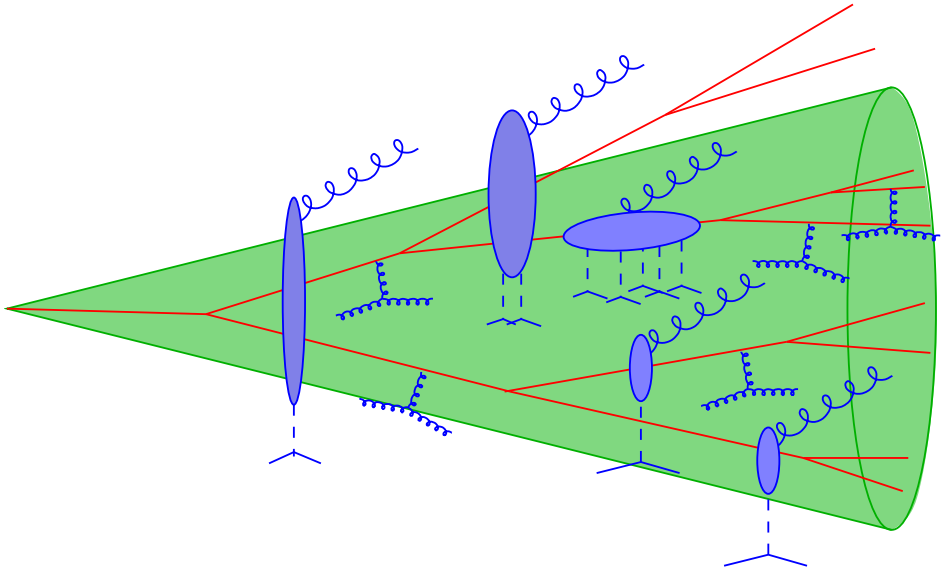
only nuclear modification in pdf's

- cross-check: vector boson production
- observed: strong modifications of jets
- due to re-scattering in final state

What happens to jets in medium?

- time it takes to radiate a gluon: $t_{\text{form}} \approx \omega / k_\perp^2$
- time needed for jet evolution $\sim$ medium size
- jet evolution & re-scattering happen simultaneously
- multi-scale problem
- cannot be solved exactly

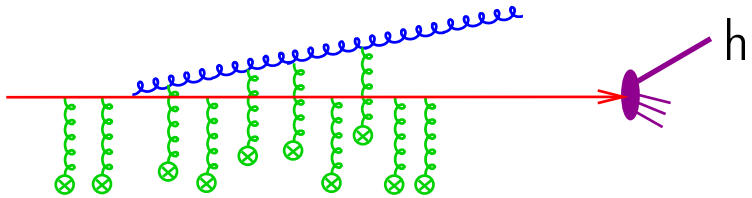
analytic results for special cases



What is known analytically

- single gluon emission off a hard parton in eikonal limit

multiple soft or single hard scattering



Gyulassy, Wang, Nucl. Phys. B **420** (1994) 583
Baier, Dokshitzer, Mueller, Peigne, Schiff, Nucl. Phys. B **484** (1997) 265
Zakharov, JETP Lett. **65** (1997) 615
Wiedemann, Nucl. Phys. B **588** (2000) 303
Gyulassy, Levai, Vitev, Nucl. Phys. B **594** (2001) 371
Wang, Guo, Nucl. Phys. A **696** (2001) 788

- non-Abelian LPM effect plays important role
- 2-gluon emission

Arnold, Chang, Iqbal, JHEP 1610 (2016) 124
Casalderrey-Solana, Pablos, Tywoniuk, JHEP 1611 (2016) 174

- radiation off colour dipole

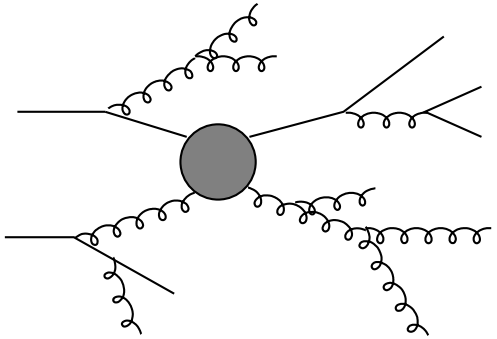
Mehtar-Tani, Salgado, Tywoniuk, JHEP 1204 (2012) 064 & JHEP 1210 (2012) 197

- non-eikonal kinematics

Apolinário, Armesto, Milhano, Salgado, JHEP 1502 (2015) 119

A Monte Carlo model for jet quenching: JEWEL

Zapp, Krauss, Wiedemann, JHEP 1303 (2013) 080



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

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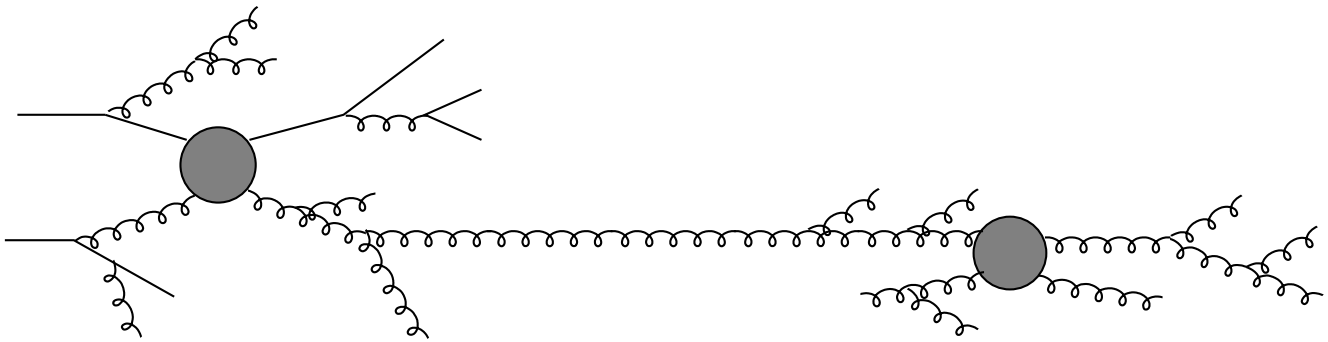
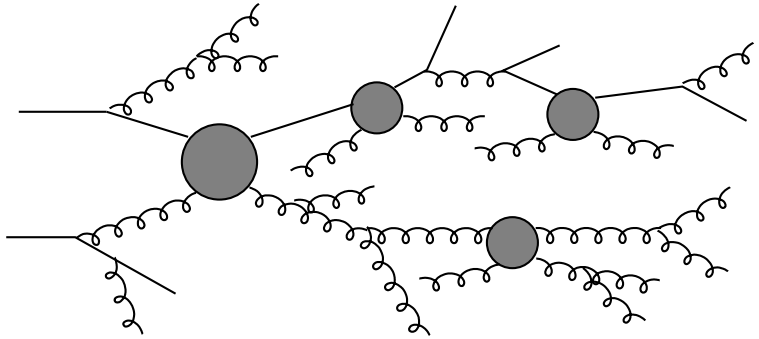
Zapp, Krauss, Wiedemann, JHEP 1303 (2013) 080



- jet production in initial N+N collisions: ME+PS
- re-scattering: ME+PS
  - generates elastic & inelastic processes
  - with leading log correct relative rates
  - general kinematics

A Monte Carlo model for jet quenching: JEWEL

Zapp, Krauss, Wiedemann, JHEP 1303 (2013) 080



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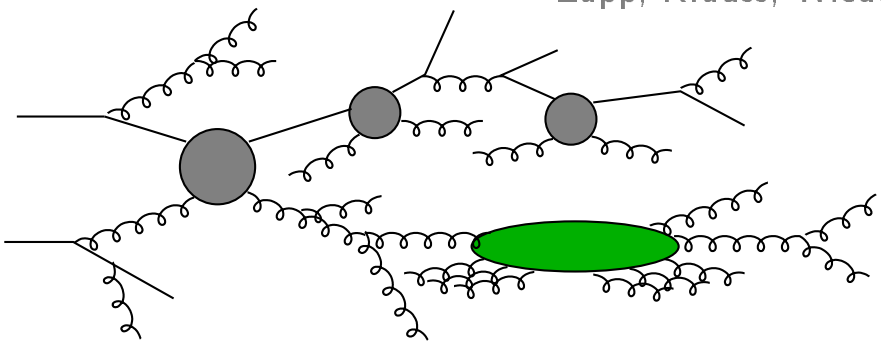
- emission with shortest formation time is realised
  - all emissions (vacuum & medium induced) treated equally
  - hard structures remain unperturbed

A Monte Carlo model for jet quenching: JEWEL

Zapp, Krauss, Wiedemann, JHEP 1303 (2013) 080



- jet production in initial N+N collisions: ME+PS
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  - general kinematics
- emission with shortest formation time is realised
  - all emissions (vacuum & medium induced) treated equally
  - hard structures remain unperturbed
- LPM interference Zapp, Stachel, Wiedemann, JHEP 1107 (2011) 118
  - also governed by formation times
  - without kinematic restrictions

Jet shape and jet sub-structure observables

- observables built from jet constituents

  particles, partons, calorimeter cells, ...

- characterise distribution of momentum & find structures inside jet

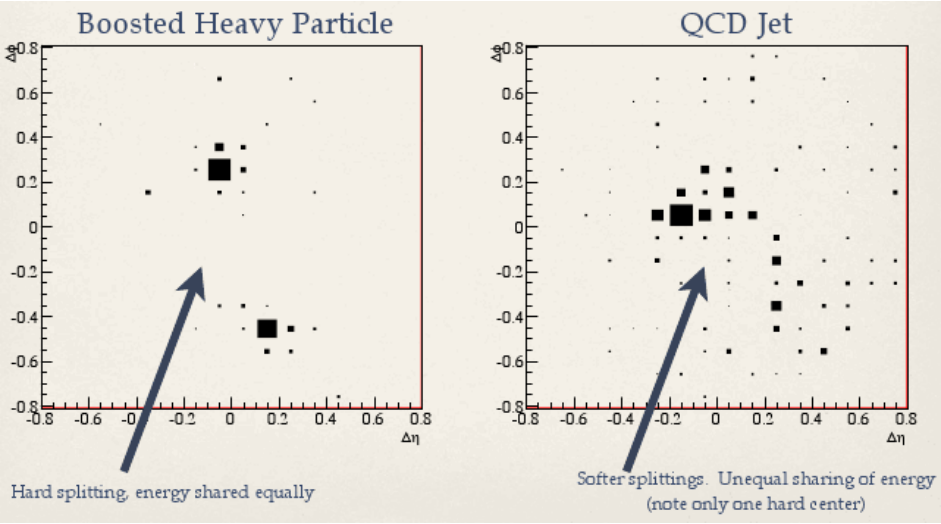


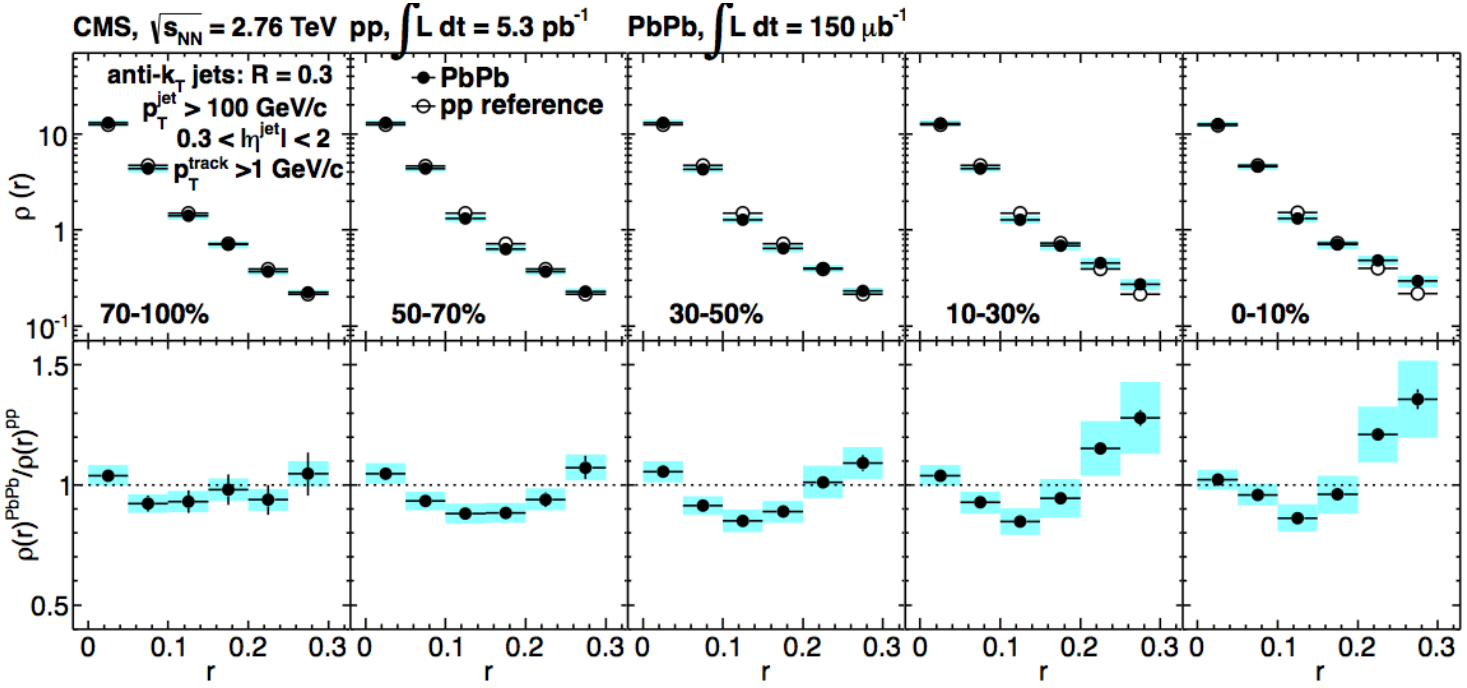
image from David Krohn

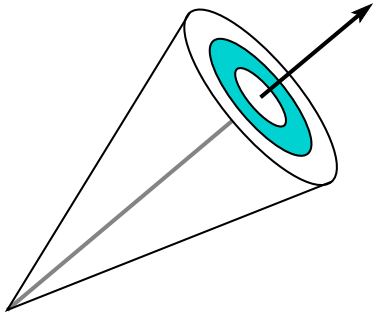
- various grooming techniques studied in p+p to separate hard structure from soft contaminations

  filtering, trimming, pruning, ...

- shapes/sub-structure of quenched jets sensitive to medium's reaction to energy & momentum deposited by jets

Intra-jet energy distribution: Jet profile

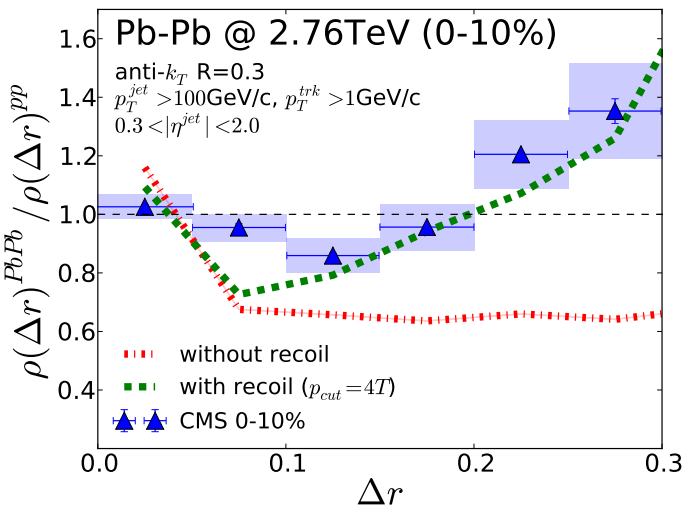




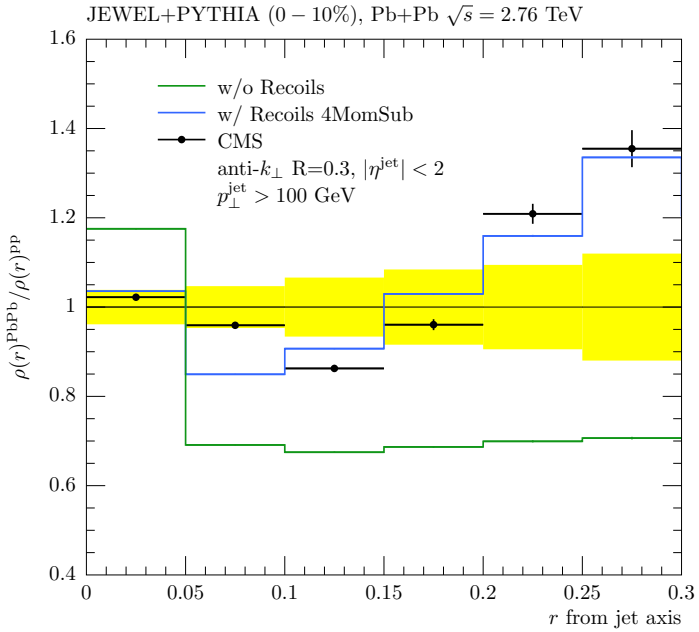
CMS, Phys. Lett. B 730 (2014) 243

- suppression of activity at intermediate *r*
- increase near the edge of the jet

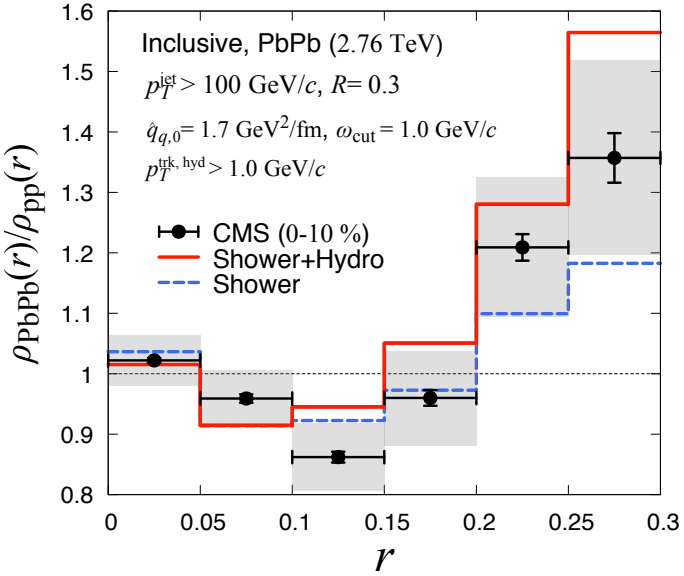
Theory results



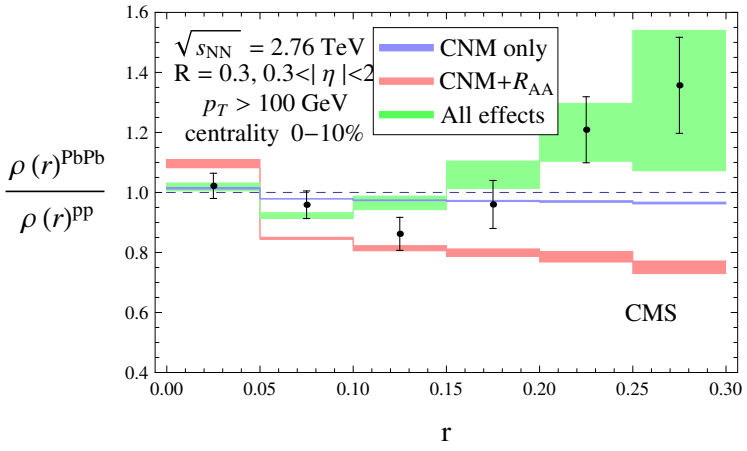
Park, Jeon, Gale, arXiv:1807.06550



Kunnawalkam Elayavalli, Zapp, JHEP 1707 (2017) 141



Tachibana, Chang, Qin, Phys. Rev. C 95 (2017) no.4, 044909



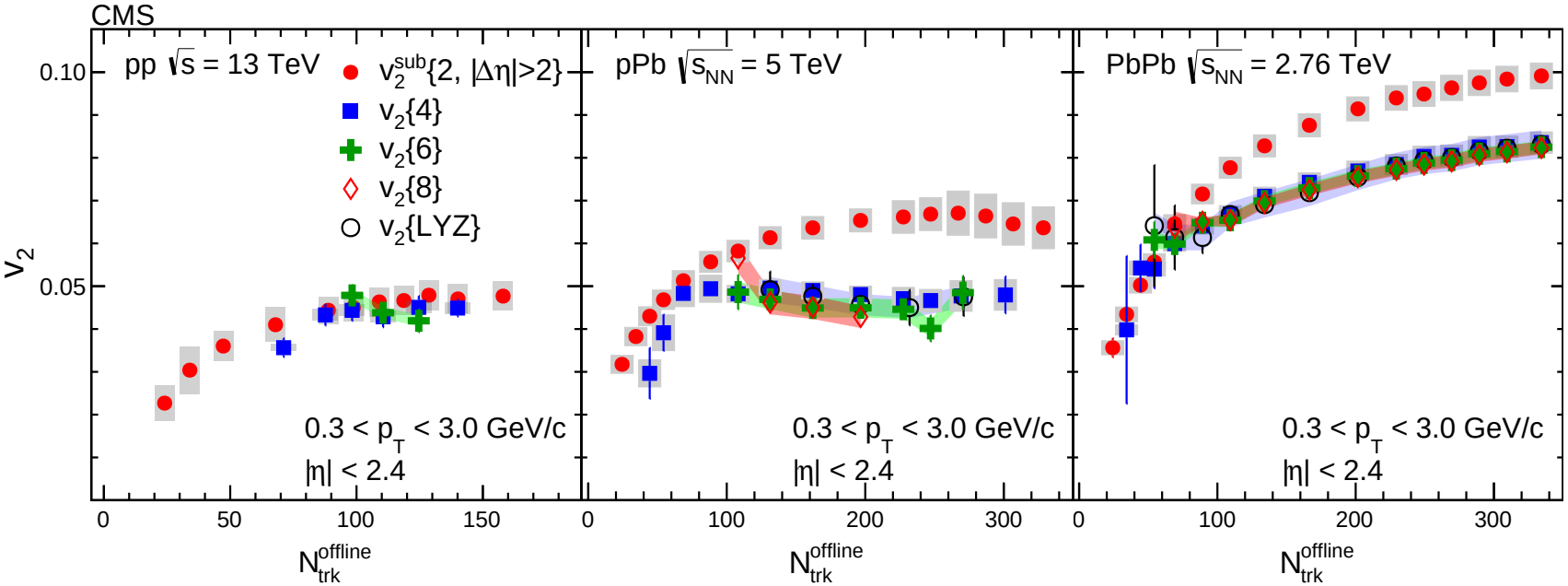
Chien, Vitev, JHEP 1605 (2016) 023

Discovery # 3: similarity between p+p and A+A

- (partial) equilibration of final state in A+A
- expectation: p+p qualitatively different from A+A

  p+p collisions too dilute to develop collectivity
- observed:

Soft particle production in high-multiplicity p+p and p+A closely resembles A+A, but so far no jet quenching is observed.



CMS, Phys. Lett. B 765 (2017) 193

Possible explanations

Final state interactions

azimuthal anisotropies due to response to initial geometry

- hydrodynamics — Weller, Romatschke, Phys. Lett. B 774 (2017) 351
- kinetic theory — Kurkela, Wiedemann, Wu, Phys. Lett. B 783 (2018) 274

Initial state correlations

initial state correlations imprinted on final state

- color-glass condensate — Schenke, Schlichting, Venugopalan, Phys. Lett. B 747 (2015) 76

  effective field theory of saturated gluons generated by color sources in nuclei

Alternative explanations

models inspired by p+p physics

- string shoving — Bierlich, Gustafson, Lönnblad, arXiv:1612.05132

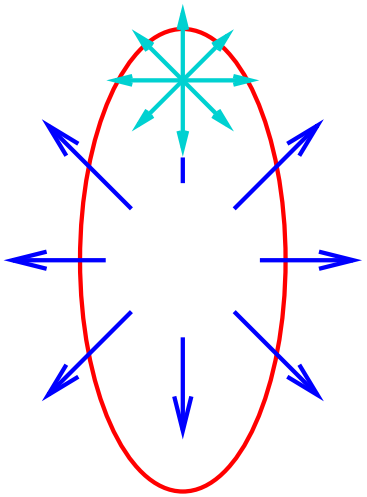
  at hadronisation densely packed strings repel each other

The escape mechanism

- kinetic theory set-up:

  Kurkela, Wiedemann, Wu, Phys. Lett. B 783 (2018) 274

  - initially isotropic particle distribution
  - with spatial anisotropy
  - number of scatterings $\mathcal{O}(1)$
  - scattering isotropises particles
  - anisotropic scattering probability
  - generates v_n's closely resembling hydrodynamic v_n's



- also observed in transport code AMPT

  He, Edmonds, Lin, Liu, Molnar, Wang, Phys. Lett. B 753 (2016) 506

- have to reassess hydrodynamic interpretation of A+A data

Conclusions

1. Soft particles in A+A collisions behave like an almost perfect fluid.
   - very well described by hydrodynamics with $\eta/s \gtrsim 1/4\pi$
   - indications of at least partial equilibration
2. Jet quenching: Hard jets are suppressed and their structure modified.
   - jet quenching closely related to thermalisation
   - chance to resolve quasi-particles in background medium
   - jet shape/sub-structure may be sensitive to medium response

     chance to observe thermalisation of deposited energy
   - no consensus about relevant processes
3. Soft particle production in high-multiplicity p+p (and p+A) closely resembles A+A, but so far no jet quenching is observed.
   - largely unresolved
   - possible explanations: final state interactions, initial state correlations, hadronisation effects
   - questions our understanding of soft particle production in p+p and/or collectivity in A+A