

Heavy ions: jets and correlations



Gábor Veres
(CERN)



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Outline

- Introduction
 - Some concepts of heavy ion physics, jets and experiments
- **Jets**
 - Energy **imbalance** (Pb+Pb)
 - **Suppression** of jets compared to p+p
 - **Modification** of jets:
 - shape and fragmentation
 - Jets in **p+Pb** collisions
- **Correlations**
 - **Asymmetries** of particle and jet production →
 - **Two-particle** correlations
 - **Long-range** correlations: from p+p to Pb+Pb
- **Conclusions**

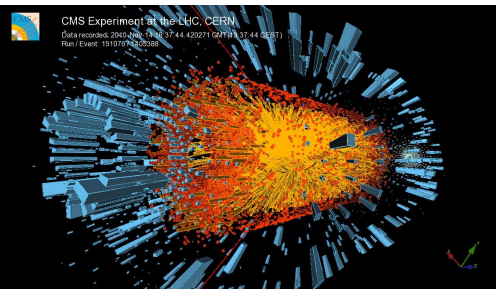


APOLOGIES: I had to omit MANY nice results and theoretical ideas



Heavy ion physics

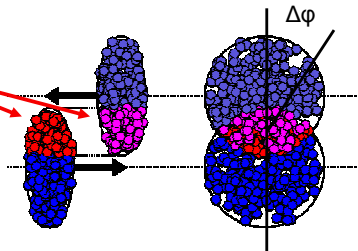
- QCD and strong interaction: a simple-looking Lagrangian contains a wealth of **complicated phenomena**
- Relativistic heavy ion collisions are the experimental tools to study many of these
 - Large energy **density** and **temperature**, emerging new **phases** of matter, **partonic** degrees of freedom, ...
 - Interplay of **perturbative** and **non-perturbative** processes



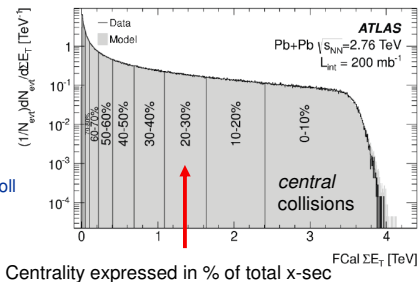
Goal is to learn about:
Hadron **structure** at high energy
- saturation, nPDFs, ...
Properties of the created **medium**
- thermalization, hydro
- building blocks
- characterization

Centrality and comparison to p+p

- Physics depends on impact parameter
- N_{part} : number of participant nucleons
- N_{coll} : number of binary N+N collisions
 - Used as scaling factor to compare to p+p x-sections

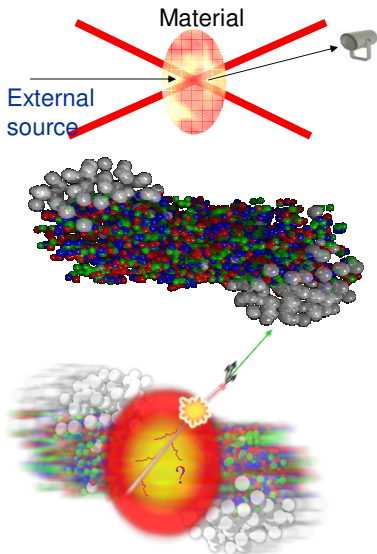


- Estimation:
 - slicing the x-sec in forward energy
 - Simulation
 - Glauber model
- EWK boson x-sections **scale with N_{coll}**
 - (nPDF modifications are small)
 - see previous talk



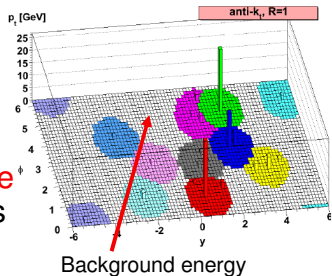
Jets: motivation

- *Problem:* lifetime of QGP is short
 - cannot probe it with an **external source**.
- *Solution:* many **high p_T jets**, $\gamma/W/Z$, quarkonia at the LHC:
 - use these hard probes, **produced in the collision itself**.
- **Jets** are **well-studied** both experimentally and theoretically
- **Comparisons** between **A+A** and **p+p** collisions reveal medium properties
- “**Jet quenching**” studies started at RHIC, e.g. two-hadron **correlations** (STAR experiment, 2003)

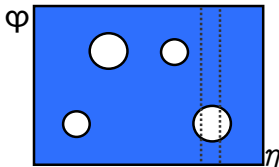


Jet algorithm and background subtraction

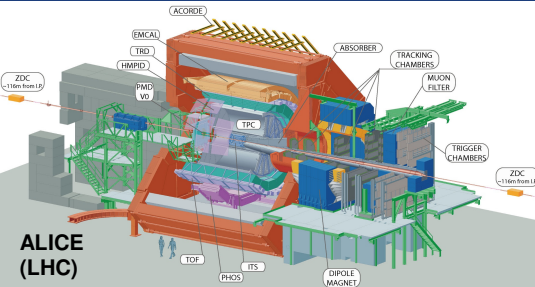
- Jet algorithm: anti- k_T
 - Radius parameter: usually small (0.2 – 0.5) in heavy ion collisions, to minimize background fluctuations
- To measure jets, we have to **separate** them from "*background*" (correlations and fluctuations)
- Background subtraction (example):
 - Calculate **background** in constant η slices
 - Find **jets** in subtracted calorimeter towers
 - Re-calculate **background**, excluding jets
 - Re-run **jet** finder on subtracted calorimeter towers



JHEP 04 (2008) 063

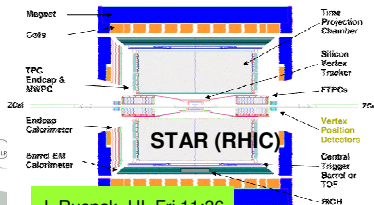


The ALICE, STAR and PHENIX experiments

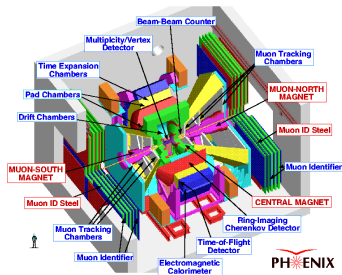


ALICE
(LHC)

- Dedicated to heavy ions
- ALICE, STAR: large volume TPCs, optimized for particle identification (~all known techniques) with low-mass tracker
- excellent vertexing capabilities
- efficient low-momentum tracking (~ 0.1 GeV/c)
- PHENIX: central arms (π , K, p, γ), muon arms (μ)



J. Rusnak, HI, Fri 11:36

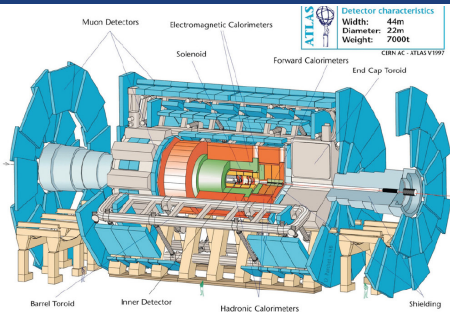


E. Atomssa, HI, Fri 10:12

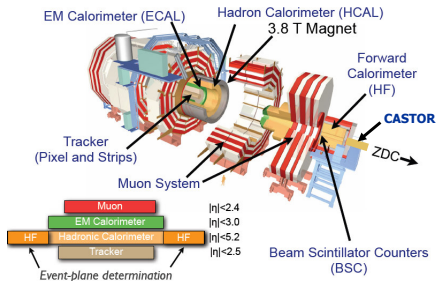
PHENIX
(RHIC)



The ATLAS and CMS experiments



ATLAS (LHC)



CMS (LHC)

- **Calorimetry** ($|\eta| < 5$) and **tracking** ($|\eta| < 2.5$) in a **wide η -region**
- **Jets** reconstructed using complete event information
- Excellent track **momentum resolution** and μ detection
- **Forward** detectors (ZDC, CASTOR, HF)
- Flexible multi-level **trigger** systems, designed for **high luminosity**

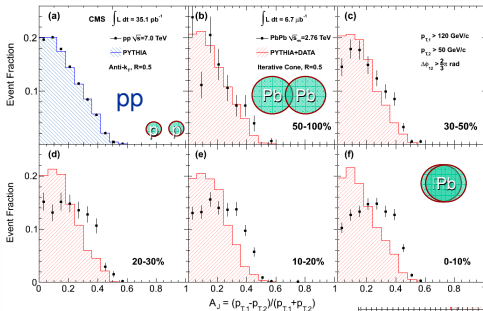
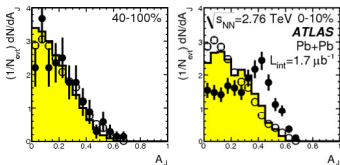
Data sets:

2010: Pb+Pb $8.3 \mu\text{b}^{-1}$
 2011: Pb+Pb $150 \mu\text{b}^{-1}$
 2013: p+Pb 31nb^{-1}
 p+p@2.76 5pb^{-1}

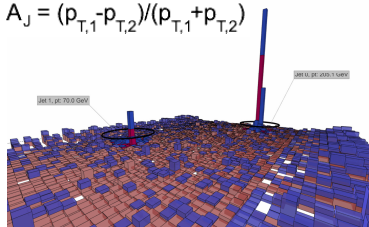
Di-jet energy imbalance

- Parton energy loss manifests itself as a pronounced di-jet energy imbalance in central Pb+Pb collisions:

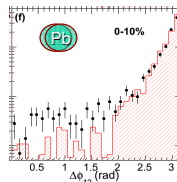
PRL 105 (2010) 252303



$$A_J = (p_{T,1} - p_{T,2}) / (p_{T,1} + p_{T,2})$$



But jets are still **back-to-back** in ϕ :



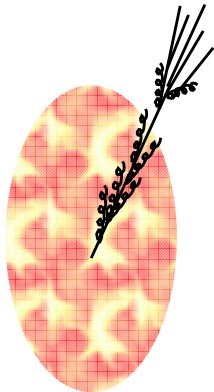
M. Lobodzinska, HI, Fri 12:28

P. Kurt, HI, Fri 12:44

PRC 84 (2011) 024906

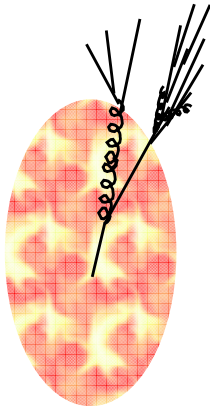


Some possible scenarios for energy loss



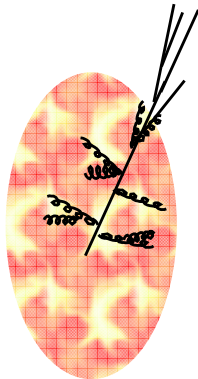
Soft collinear radiation

GLV + others



Hard radiation

PYTHIA-inspired models
Modified splitting functions



Large angle soft radiation

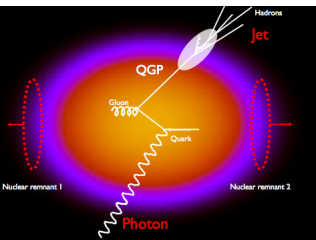
“QGP heating”

AdS/CFT

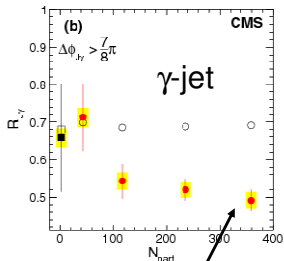
More details needed to be measured →

Calibrated energy loss: γ -jet and Z-jet pairs

Colorless particles **do not lose** energy in the medium



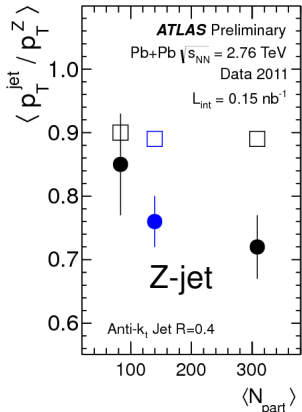
$R_{J\gamma}$ = fraction of photons with jet partner >30 GeV/c



Less jet partners above threshold

$\sim 20\%$ of photons lose their jet partner

PLB 718 (2013) 773



Increasing energy loss vs. centrality

ATLAS-CONF-2012-119

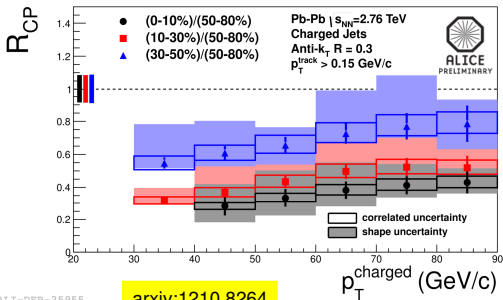
M. Lobodzinska, HI, Fri 12:28

Photon or **Z** tag:

- Provides initial quark **direction**
- Provides initial quark \mathbf{p}_T



Single jets: central-to-peripheral ratio



Ratio of jet p_T spectra in a given central ('cent') and peripheral (50-80% or 60-80%) bin:

$$R_{CP}^{\text{meas}}(p_T)|_{\text{cent}} = \frac{1}{R_{\text{coll}}^{\text{cent}}} \left(\frac{N_{\text{jet}}^{\text{cent}}(p_T)}{N_{\text{evt}}^{\text{cent}}} \frac{N_{\text{jet}}^{60-80}(p_T)}{N_{\text{evt}}^{60-80}} \right)$$

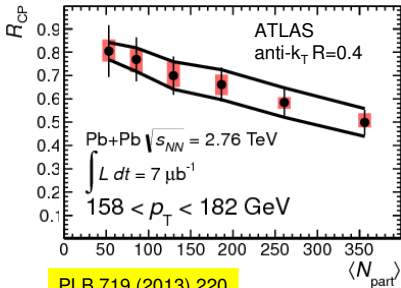
ALI-DER-35955

arxiv:1210.8264

Single jets are more and more **suppressed** as a function of centrality:

R. Sandstrom, HI, Thu 17:54

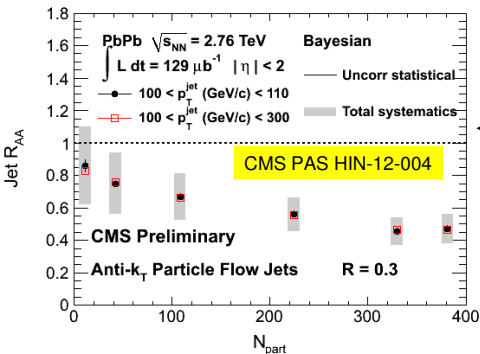
Similar observation by STAR and PHENIX



PLB 719 (2013) 220

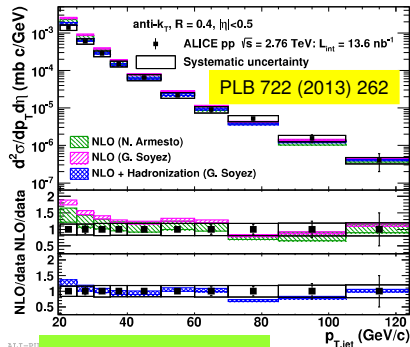


Single jets: (Pb+Pb)/(p+p) ratio



Ratio of jet p_T spectra in Pb+Pb and p+p collisions, scaled by N_{coll} :

$$R_{AA} = \frac{dN_{\text{jets}}^{AA}/dp_T}{\langle N_{\text{coll}} \rangle dN_{\text{jets}}^{pp}/dp_T} = \frac{dN_{\text{jets}}^{AA}/dp_T}{\langle T_{AA} \rangle d\sigma_{\text{jets}}^{pp}/dp_T}$$

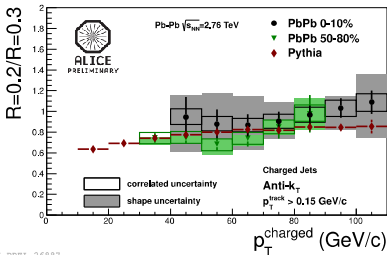


Again, increasing suppression of jets

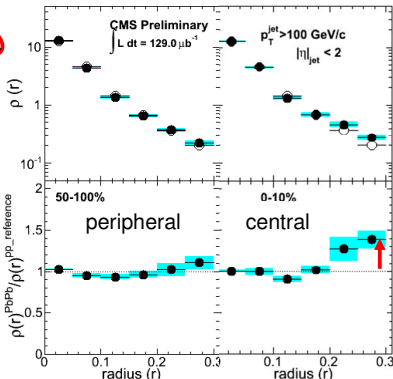
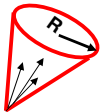
- Precise p+p reference is important!
- Jet production between 20 and 120 GeV, in pp collisions (2.76 TeV) – compared to pQCD + hadronization



How do jets get modified? – Jet shape



The simplest measure of jet shape:
ratio of x-sections with different R.
→ no strong modifications w.r.t p+p



Fraction of p_T carried by particles
at a distance r from the jet axis:

$$\rho(r) = \frac{1}{f_{\text{ch}}} \frac{1}{\delta r} \frac{1}{N_{\text{jet}}} \sum_{\text{jets}} \frac{p_T(r - \delta r/2, r + \delta r/2)}{p_T^{\text{jet}}}$$

More sensitive to small changes at large r ,
where an **excess** is observed in Pb+Pb:

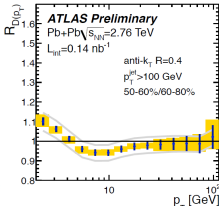
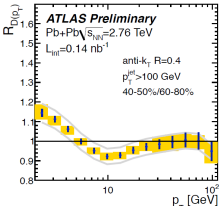
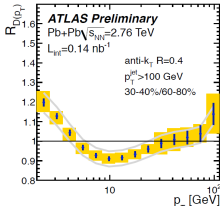
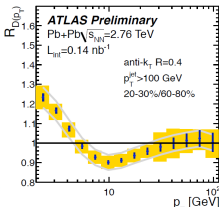
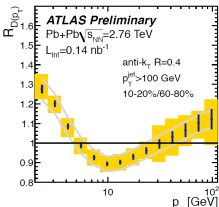
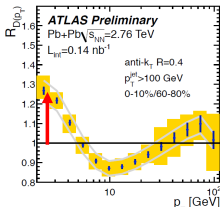
CMS PAS HIN-12-013

P. Kurt, HI, Fri 12:44



How do jets get modified? – Fragmentation

Ratios of track p_T distributions within jets (central/peripheral):



Some excess at low p_T in central wrt. peripheral Pb+Pb collisions

ATLAS-CONF-2012-115

γ -hadron correlations by PHENIX:

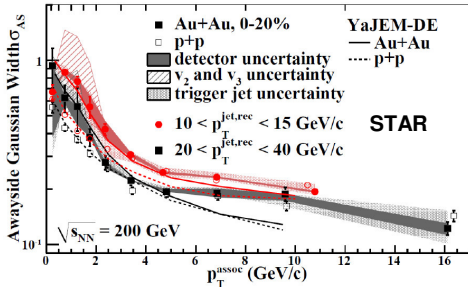
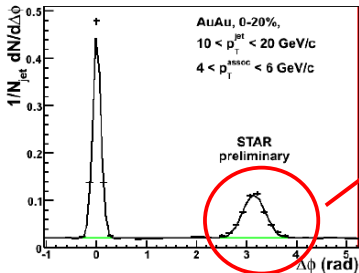
R. Sandstrom, HI, Thu 17:54

arXiv:1212.3323



Jet modifications at RHIC

- **Low- p_T jets** and associated hadrons may be of key importance to study jet modification
- RHIC (200 GeV): harder to avoid biases, but large amount of data gives access to “low- p_T ” jets



Away-side widths suggest
jet broadening to large angles at low p_T

arXiv:1302.6184



Physical picture for jet quenching?

- partons/jets **lose** a lot of **energy** in the medium (QGP)
- while jet pairs remain **back-to-back**
- fragmentation patterns **not modified**, **except** at low p_T
- excess energy \rightarrow **low- p_T** particles at **large angles**

Theory: advancing from **parton energy loss** and leading hadrons to modification of **parton showers and jets**.

- Jet production is a **weakly-coupled** phenomenon, while QGP is a **strongly coupled** fluid
 - Probably need a hybrid theoretical approach.
- **Correlations** between photons and hadrons, jets and hadrons, etc. may differentiate between theoretical ideas

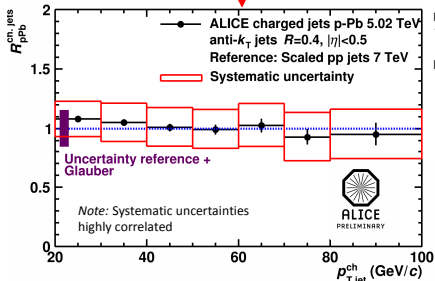
L. Apolinario, HI, Fri 11:00

P. Levai, HI, Fri 11:52



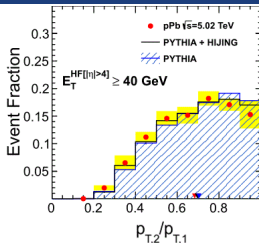
Jets in p+Pb collisions: a “reference”

Charged jets: ratio of p_T -spectra in p+Pb and p+p



Consistent with unity: **no strong modification** of charged jets in cold nuclear matter, no strong influence of nPDF.

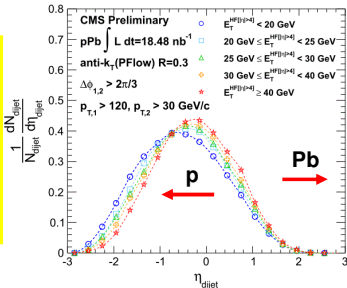
R. Haake, HI, Fri 11:20



No visible di-jet imbalance compared to p+p

M. Nguyen, HI, Fri 12:12

CMS PAS HIN-13-001



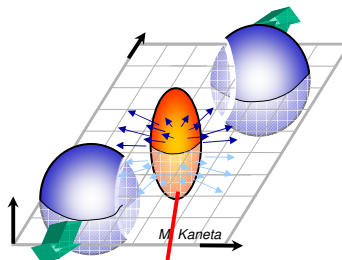
However, di-jet η distribution is strongly shifting vs. “centrality”

Correlations + flow: motivation

- Nuclear collisions also show *collective motion of (most) produced particles; flow*
- The medium behaves like a **droplet of fluid**
 - Successful hydrodynamical models
 - fluid properties, like η/s
 - results suggest partonic degrees of freedom

Topic pioneered by SPS and RHIC experiments!

- Correlations** are important experimental tools to study these **collective phenomena**
- (Other type of correlations address:
 - jet structure/modifications and
 - jet-medium interactions)



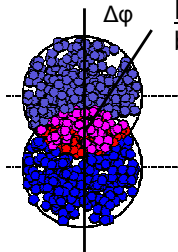
ϕ -asymmetric initial state

ϕ -asymmetric final state (!)

ϕ -distribution of final particles:

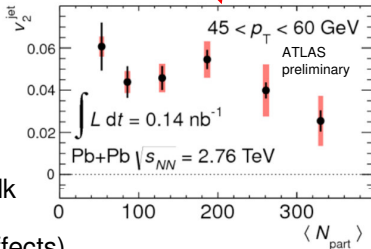
$$1 + \sum_{n=1}^{\infty} 2v_n(p_T, y) \cos [n(\phi - \Psi)]$$

Notes on correlations and jets



Note 1: jets are NOT emitted uniformly in ϕ either, but for very **different reasons**:

- Energy loss in the QCD medium depends on the **path length**
- *consequence*: $v_2 > 0$ for jets and high- p_T hadrons



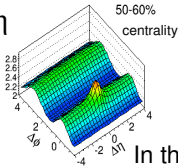
arXiv:1306.6469

M. Lobodzinska, HI, Fri 12:28

R. Sandstrom, HI, Thu 17:54

Note 2: to measure correlations of the bulk particles (low p_T), we have to mitigate *correlations* induced by *jets* (“non-flow” effects).

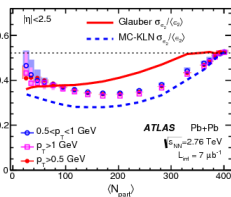
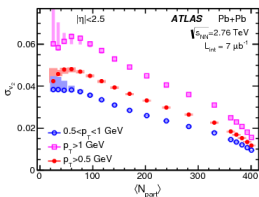
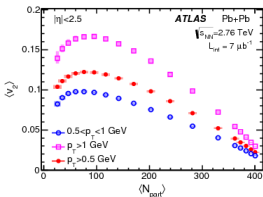
Example: separation in $\Delta\eta$ in case of the 2-particle correlation function:



In the following, jets do not contribute →

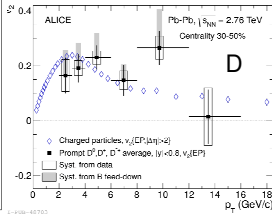
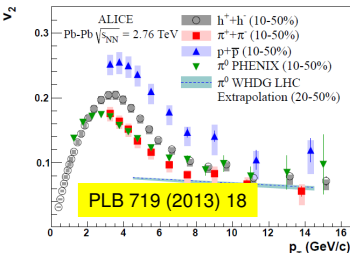
Low- p_T : flow of the QCD medium

The v_2 “elliptic” flow was measured vs. centrality, η , particle mass, and even its event-by-event fluctuations!

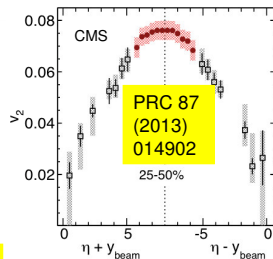


arXiv:1305.2942

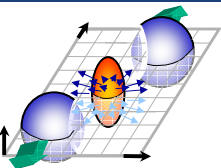
R. Sandstrom, HI, Thu 17:54



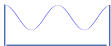
arXiv:1205.2707



Measuring the full Fourier-spectrum



Non-uniform single-particle ϕ distribution
(Fourier-coefficients: v_n)

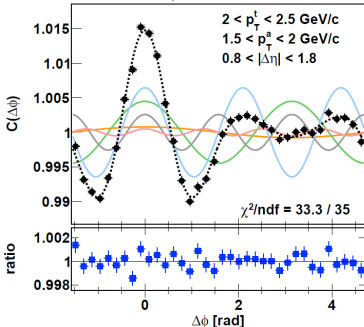


Non-uniform two-particle $\Delta\phi$ distribution
(at second order: v_n^2)

Measured at large $\Delta\eta$

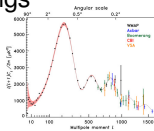
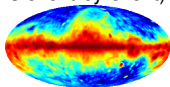
v_n deduced

Pb-Pb 2.76 TeV, 0-2% central



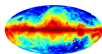
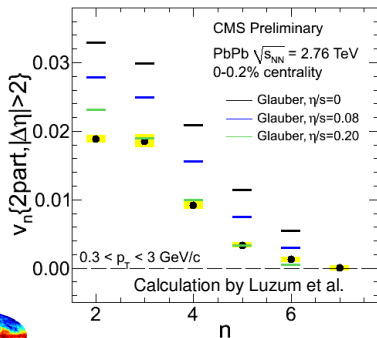
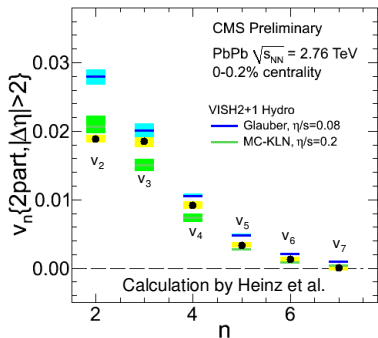
PLB 708 (2012) 249

Resembles CMB measurements (Big Bang)
– but these are many little bangs
(with fluctuations event-by-event)



Flow in ultra-central Pb+Pb collisions

Various Fourier-harmonics measured in the 0.2% most central collisions



Unique perspective on hydrodynamic flow

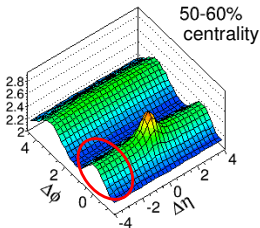
- Hierarchy of Fourier-coefficients reproduced by hydro, sensitive to η/s

CMS PAS HIN-12-011



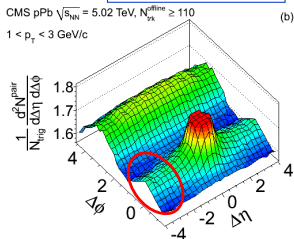
Long-range correlations: Pb+Pb, p+Pb, p+p

Pb+Pb 2.76 TeV



EPJC 72 (2012) 2012

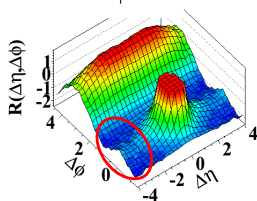
p+Pb 5.02 TeV



PLB 718 (2013) 795

p+p 7 TeV

(d) $N > 110, 1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



JHEP 09 (2010) 091

Interpretations:

Fluctuations of the initial geometry and hydrodynamical evolution

Competing theories:

- | hydrodynamical behaviour
- | (but not really expected)
- | initial state effects alone
- | (high-density Color Glass Condensate)

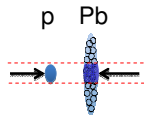
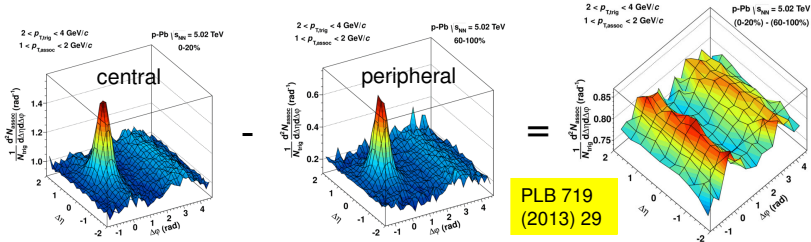
A. Quadri, HI, Thu 12:44

Which one is more important?



p+Pb: more detailed measurements...

No ridge seen in 60-100% (peripheral) p+Pb, and similar to p+p
 → what remains if we subtract *peripheral* from *central*?



A “double-ridge” structure emerges:
 There is also a correlation structure on **the away side**,
 in addition to the away-side **jet** contribution!

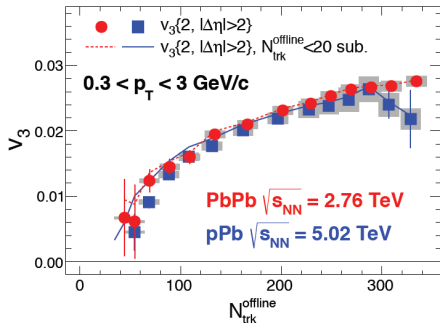
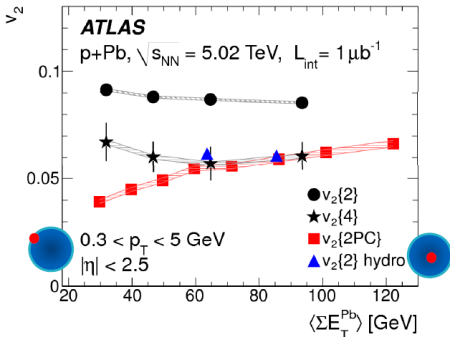
M. Villa, HI, Thu 9:16

M. Weber, HI, Thu 9:00

v_2 and v_3 measured in p+Pb collisions

- v_2 and v_3 can be measured using **two-particle** correlations
- The v_3 three-fold asymmetry (Fourier) coefficient reflects the **fluctuations** of the initial state

- v_3 in p+Pb and Pb+Pb reach **similar magnitude** (at the same multiplicity)...



M. Villa, HI, Thu 9:16

arXiv:1303.2084

PLB 724 (2013) 213

v_2, v_3 also observed in d+Au at RHIC!

E. Atomssa, HI, Fri 10:12

arXiv:1303.1794

M. Sharma, HI, Thu 9:32

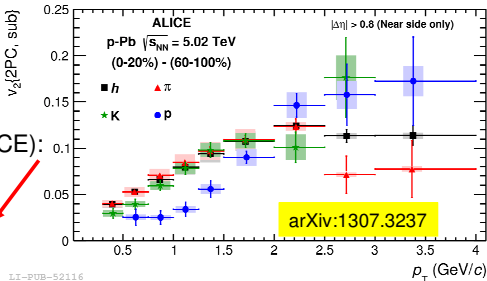


p+Pb: asymmetry of identified particles

Mass-ordering observed:

$$v_2(p) < v_2(\pi) \text{ for } p_T < 2 \text{ GeV}/c !$$

Qualitatively similar to A+A collisions as observed at RHIC and at LHC (ALICE):

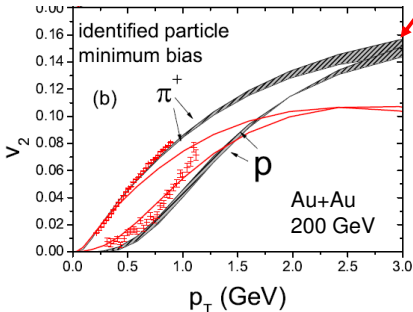


LI-PUB-52116

In case of Au+Au, viscous hydrodynamics calculations reproduce this effect well...
But in p+Pb... this was unexpected!

M. Weber, HI, Thu 9:00

K. Werner, HI, Thu 9:48



data: STAR, PRC 72 (2005) 014904

Theory: Shen *et al.*, PRC 84 (2011) 0044903

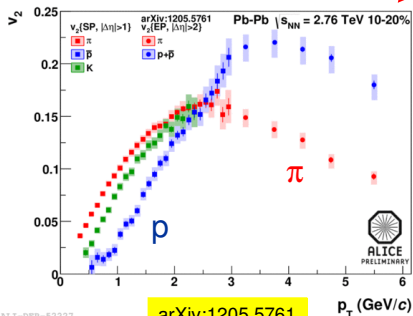


p+Pb: asymmetry of identified particles

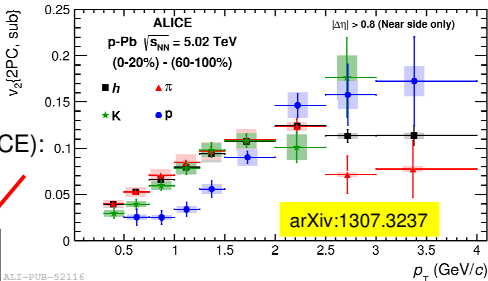
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arXiv:1205.5761



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M. Weber, HI, Thu 9:00

K. Werner, HI, Thu 9:48

Conclusions

- The LHC has completed 2.5 years of **successful Heavy Ion program** and opened a new era, while the RHIC program is still at its best:
 - Jets and hard probes: high cross sections, tools to study the QCD medium
 - High-multiplicity events in p+p, p+Pb: **remarkably similar behaviour as in heavy ions**
- Various **properties** of the created **medium** are studied at a quantitative level, with new tools at the LHC:
 - **Energy loss** via single jets, di-jets, γ -jet and Z-jet pairs
 - Jet **fragmentation** and jet shape measurements
 - Effects of **initial geometry**
 - Correlations, hydrodynamical evolution, viscosity, ...
- We are looking forward to the high luminosity runs starting in 2015!

<https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults>
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN>
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults>
<http://www.star.bnl.gov/central/publications/>
<http://www.phenix.bnl.gov/results.html>

Many more results to come!

