Highlights from ALICE Pb-Pb results

Andrew Adare

for the

US LHC Users Meeting Argonne National Lab Chicago, IL November 4, 2011

AMC HSERS

THAT

The science of ALICE erties. Using next-generation computing facilities, theorists will be able to calculate the nucleon's internal quark substructure using $A \cap A$ lications. The Merger

.

Defining questions:

is fineenough to accurately simulate our world's spacetime continuum

What are the phases of strongly interacting natter, and what roles do they play in the cosmos? Physicists Innovate ture and the properties of hot and dense $s \in \mathcal{L}$ at $s \in \mathbb{R}$, the Blue General by IBM. Advances in lattice quality in the control of the set lat roles do they play in the

turned out to be extremely useful useful

ment of the world's currently most of the world's currently most of the world's currently most

What does QCD predict for the properties | of strongly interacting matter? $\begin{array}{ccc} \hline \end{array}$ physical designations of the interest of the i
International materials and interest $\mathsf D$ prodict for the

"The Frontiers of Science: A Long Range Plan"

the energy density from lattice [Q](http://science.energy.gov/np/nsac/)CD as **[http://science.energy.gov/np/ns](http://science.energy.gov/np/nsac/)a[c/](http://science.energy.gov/np/nsac/)**

Heavy-ion collisions for HEP folks a

radius !

σ NN

Collision anatomy

Impact parameter

0 < b < ∼2R_{Pb} (R_{Pb} ≈ 6.6 fm)

Nucleon position s Nuclear density ρ(s, z)

Key quantities

Npart: # nucleons participating in collision er. Part. Part. Sci. 2007.
Beg i
Pr
-

Ncoll: # binary (nucleon-nucleon) collisions .
.
. by University of Colorado - Boulder on 04/06/09. For personal use only.

Annu. Rev. Nucl. Part. Sci. 2007.57:205-243
Annu. Rev. Nucl. Part. Sci. 2007.57:205-243 **"Glauber Modeling in High-Energy Nuclear C** Notice that *T*ˆ (**b**) has the unit of inverse area. We can interpret this as the effective B. The probability of an interaction of *Annual Tev. Nucl. Fart. Sul. 2001.01.200-2*40 inel , where $\frac{1}{\sqrt{2}}$ inel is the **"Glauber Modeling in High-Energy Nuclear Collisions" [Annu. Rev. Nucl. Part. Sci. 2007.57:205-243](http://science.energy.gov/np/nsac/)**

inel / marker circles representation of the later participating nucleons. The circles representation of the circles

Figure 3

(*b*) views.

Schematic representation of the optical Glauber model geometry, with transverse

(*a*) and longitudinal

Heavy-ion collisions for HEP folks

Collision Centrality

b, N_{part}, N_{coll} aren't directly **measurable...** but multiplicity is (e.g. E_{zdc}, N_{ch}).

Assume measured N_{ch} relates monotonically (& inversely) to b

Bin real events in N_{ch} quantiles, Glauber events in b quantiles, & match them r:
qu.
| ua
ar
Di

The procedure has an uncertainty.

ALICE centrality resolution < 1%.

and a large number of spectator nucleons at beam rapidity, whereas for small *b* events

Pb-Pb @ LHC: the November revolution

November 2009 First p-p collisions, 900 GeV November 2010 First Pb-Pb collisions, 2.76 TeV L_{PbPb} reached 2 x 10^{25} cm⁻² s⁻¹ (Pb-Pb Design luminosity = 10^{27}) **November 2011 Expect 5x increase over 2010 ∫Ldt**

5

A Large Ion Collider Experiment 6

Friday, November 4, 2011

A Large Ion Collider Experiment 6

Bulk/Global Observables

Multiplicity Transverse Energy Source Imaging

Charged Particle Multiplicity

For 0-5% most central collisions at 2.76 TeV:

dNch/dη = 1584 ± 76 (sys.)

an_{ch}/aη = 1584 ± 76 (sys.)
8.3 ± 0.4 per participating nucleon pair - higher than many expectations

Centrality dependence of Nch

A. Adare (ALICE) in 2.76 TeV PbPb collisions from this analysis and the ALICE experiment [20], from RHIC [21] at 2. And From extrapolated products from extrapolated particle particle particle particle particle in the ALICE α

Figure 5. Left: measured (*dN*ch*/d*η*|*η=0)*/*(*N*part*/*2) as a function of the number of participants

Transverse Energy

dET/dη vs. Npart

Measured using ALICE tracking detectors

Corrected by ftotal from MC to get charged \rightarrow total E_T

Trends

Again, LHC and RHIC have similar centrality dependence

~2.5x higher than at RHIC Consistent with larger $\langle p_T \rangle$

Source size from interferometry

Anisotropy and Correlations

Elliptic flow Higher-order anisotropy harmonics Correlations and Fourier decomposition

Hydrodynamics and nuclear collisions ¹³

Initial spatial eccentricity ⇒ final momentum eccentricity vn from AA is corrected FIG. 5. Time evolution for EOS *I* of the transverse energy den-

Measure 2nd Fourier coefficient v2

$$
v_n = \langle \cos n(\phi - \Psi_n) \rangle
$$

Measure 2nd Fourier coefficient v₂
$$
\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n(\phi - \Psi_n)
$$

$$
v_n = \langle \cos n(\phi - \Psi_n) \rangle
$$

field in the transverse (*x*,*y*) plane for the cases with

A. Adare (ALICE) sions between spherical nuclei. For noncentral collisions the LICE the energy distribution of the energy distribution of the energy distribution and flow

transition region was predicted to lead to a reduction of the

between spherical nuclei were discussed earlier in Refs. $13-15$, and the radial flow \sim observed in azimuthally symmetric central collisions and the anisotropic directed and elliptic flows in noncentral colli-

concentrated around the QGP/mixed interface %thick contour \mathcal{L}^{max}

transition. The spacing between energy density contours is again 150

corresponding maximum energy densities are 5.97, 3.97, 1.67, and

 \sim

mixed phase shell apart %the ''nutcracker phenomenon'' dis-

covered in Ref. #12\$&, the energy density contours develop an

Integrated v₂ $R_{\rm H}$ and the LHC of pt-differential elliptic flow at low $\bf 2$ is consistent with predictions of hydrodynamic models of hydrodynamic models $\bf 1$

v₂ vs. collision energy for 20-30% most central collisions \mathcal{T}_1 , that the integrated elliptic flow increases that the integrated elliptic flow increases the increases of \mathcal{T}_2

Hydro behavior follows extrapolated RHIC trend

measurement at the LHC. The contract similar is the observed similar interved similar in the observed similarit

Matches RHIC within 5% 0.05

0.15

Differential v2: pions, kaons, protons

Significant mass dependence

Expected: radial flow gives all species similar β, thus different p_T

Need hadronic rescattering to match antiprotons in central data (UrQMD/VISHNU, arXiv:1108.5323v1)

assoc *N* d trig 0.40 0.42 **Two-particle correlations** ALICE INTERNAL ONLY 1999 AND THE RESIDENCE INTERNAL ONLY 1999 AND THE RESIDENCE INTERNAL ONLY 1999 AND THE RES
ALICE INTERNAL ONLY 1999 AND THE RESIDENCE INTO A REPORT OF THE RESIDENCE INTO A REPORT OF THE RESIDENCE INTO

17

the TPC was fully efficient to ensure uniform as fully efficient to ensure uniform acceptance. Events are accept

 $_{\Delta \phi}$ [rad]

0-20%

Pb-Pb 2.76 TeV

Two-particle correlations of χ²*/n*d*.*o*.*f*. <* 4 is imposed.

in the longitudinal (radial) direction. At least 70 TPC pad rows must be traversed by each

Low-p_T correlations

Broad away side Near side "ridge" at large Δη

Ultra-central (0-2%), Δη > 0.8

n=3 is strongest harmonic

Fig. 2: (Color online) Left: *C*(∆φ) for particle pairs at *|*∆η*| >* 0*.*8. The Fourier harmonics for *V*1[∆] to *V*5[∆] Friday, November 4, 2011

Higher-order harmonics involving higher-order involving high-pT particles, hydrodynamics is unlikely a strategy of the strat central collisions of \mathcal{L} becomes \mathcal{L} becomes \mathcal{L} becomes \mathcal{L} becomes \mathcal{L} equal to v2 at lower pt and reaches significantly larger pt and reaches significantly larger pt and reaches significantly larger 19 \parallel to be a dominant influence on trigger particles at the upper end of the upper end of the momentum range α

vn from 2-particle cumulant hydro models V_n Irom ∠-particle cumulant

Uisher p terms help equatrain viese was about $\rho_3 = \frac{2}{\pi} \frac{v_3}{v_3}$

Stronger damping expected for higher n

Weak for v3+: fluctuations

Fig. 6: (Color online) The global-fit parameters, *vn{GF}*, for 2 ≤ *n* ≤ 5. Statistical uncertainties are

0

0

0.05

0.15 {GF} n

v

0.1

0.2

0.25

recoil jet peak.

also reaches the same magnitude as v2 and v3. For more magnitude as v2 and v3. For more magnitude as v2 and v3

Identified Particles

Spectra Particle ratios

Identified Particles

Friday, November 4, 2011

π, K, p spectra

Harder spectra and larger yield than at RHIC

Comparison with hydro models

Harder spectra and lower proton yield than predictions identified than predictions and the spectra of the s
See the spectra of the spectra of

Chemical freezeout temperature T_{ch} lower than hydro expectation

Particle ratios ²³

Symmetric particle - antiparticle production at LHC μ **B** \approx 0

A. Adare (ALICE)

Energy Loss Observables

RAA

- **unidentified particles**
- **heavy-flavor**
- **event-plane dependence**

High-p_T correlations

Not included:

high-p_T v2 (see talk by A. Dobrin)

ment non-perturbatively into a set of final-state hadrons. The characteristic colli-state hadrons. The characteristic colli-state hadrons. The characteristic colli-state hadrons. The characteristic colli-state hadrons. Th

mated spray of hadrons resulting from the fragmentation of an outgoing parton is α

Jet quenching 3

Fig. 2. "Jet Quenching", D. d'Enterria t_{c} one goes out directl[y to the vacuu](http://science.energy.gov/np/nsac/)m, $\frac{1}{2}$, $\frac{1}{2}$ or $\frac{1}{2}$ and $\frac{1}{2}$ **[arxiv:0902.2011](http://science.energy.gov/np/nsac/)**

goes through the dense plasma created (characterised by transport coefficient ˆ*q*, gluon density

Charged particle RAA The experimental data used in our analysis are given in terms of the nuclear modification \sim

$$
R_{AA} = \frac{dN_{AA}/dp_T^2 dy}{\langle N_{\text{coll}} \rangle dN_{pp}/dp_T^2 dy}
$$

PT dependence

5. Results and discussion

factors and the second sec

For $\frac{1}{2}$ $\frac{1}{2}$ **Min. at 6-7 GeV, rising with proton– appearing in the density in the consistent with pQCD expectations**

> **Centrality dependence** Centrality depende
Greater suppression **nce**

Greater suppression for more central collisions e

 $\frac{1}{\sqrt{2}}$

dytrig dptrig

^T , and we use as factorization scales the *pT* of the hadrons. We highlight

h1

AA

Identified particle RAA ²⁶

Strange quark nuclear modification

Strange baryon enhancement < 9 GeV Strange meson modification similar to charged particles All yields similarly suppressed at high p_T

Reaction plane dependence

Friday, November 4, 2011

Jet pair yield modification arxiv:1110.0121 28

High-pT correlations How do Pb-Pb yields compare to pp?

Calculate integrated yield per trigger particle in both systems Requires removal of combinatoric nonjet background

Keep to high p_T Flow ≪ **jet-induced correlation**

IAA: Two-particle version of RAA

$$
I_{AA} = \frac{\left[\frac{1}{N_{\text{trig}}} \frac{dN_{\text{pairs}}}{d\Delta\phi}\right]_{PbPb}}{\left[\frac{1}{N_{\text{trig}}} \frac{dN_{\text{pairs}}}{d\Delta\phi}\right]_{pp}}
$$

P article-yield modification in jet-like azimuthal di-hadron in jet-like azimuthal di-hadron correlations in P **IAA VS. associated pT**

$\overline{}$ **No strong modification Central (0-5%)**

d
Se
de
So zuu al (0 0 /0)
2011 oide enheneement (1 = 2.4 0) : euev. = 2.76 TeV NN *s* **Near-side enhancement (IAA ≈ 1.2); away-side suppression (IAA ≈ 0.6) Both consistent with in-medium energy loss**

Heavy Flavor and Quarkonia

meson suppression

pp reference from 7 TeV data, scaled to 2.76 with FONLL

Charm is suppressed x4-5!

Compatible with pion R_{AA}, perhaps R_{AA}^D > R_{AA}^π? Stay tuned for 2011 run

Open charm v₂ 32

D⁰ v₂: first heavy-ion measurement

Friday, November 4, 2011

J/ψ suppression

From $J/\psi \rightarrow \mu^{+}\mu^{-}$ **at forward rapidity RAA larger than at RHIC**

Many effects to consider: initial-state / cold nuclear matter, recombination, color screening, ….

Medium properties from Pb-Pb collisions

Source:

energy density > 15 GeV/fm3 - 3x higher than at RHIC particle multiplicity and source size 2x RHIC lives 30% longer

Opacity:

strong quenching, even for heavy quarks size & geometry-dependent; similar to RHIC

Fluidity:

viscous hydro (+ hadronic rescattering) describes anisotropy well at low-intermediate p_T **hydro + fluctuations naturally explain higher harmonics & correlation features strong radial flow - β ≈ 2/3 higher flow harmonics are helping to pin down QGP viscosity**

Outlook

5x increase in dataset this November p + Pb collisions! EMCal trigger - jets to 200 GeV

Centrality determination

centrality determination

Single vs. pair Fourier decomposition ously at RHIC μ at RHIC μ at RHIC μ and μ after subtraction of a correlated component whose shape was shape was μ l Single I Single ve nair Fourier decomposition 38 equal to value the value of

Single-particle anisotropy and the emitted of the emitted **(the familiar v_n coefficients)** da
N *n*=1

∞

$$
\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n(p_T) \cos(n(\phi - \Psi_n))
$$

⁵⁰ also extends over a large range in *|*∆η*|* [17, 18]. The latter feature has been observed previ-

higher-order flow components $\tilde{3}$ –38. The azimuthal momentum distribution of the emitted of the

Similar form, but indep. of Ψⁿ

$$
\frac{dN^{pairs}}{d\Delta\phi} \propto 1 + \sum_{n=1}^{\infty} 2V_{n\Delta}(p_T^t, p_T^a) \cos(n\Delta\phi)
$$

Extract directly from 2-particle azimuthal d correlations! t root d **Extract directly from 2-particle azimuthal**

■ **This is a measurement of the** *Theorie* **from the azimuthal** separated (*|*∆η*| >* 0*.*8) pair azimuthal correlations in Pb–Pb collisions in different centrality **the convention of the convention of the two-particle fourier coefficients as** *Fourier coefficients* **as** *Pourier coefficients* **as** *Pourier coefficients* **as** *Vn*

$$
V_{n\Delta} \equiv \langle \cos(n\Delta\phi) \rangle = \sum_i C_i \cos(n\Delta\phi_i) / \sum_i C_i.
$$

A. Adare (ALICE) classes and in several transverse momentum intervals. Details of the experimental setup and $A \quad A \quad A$ and C F $A.$ *Adare (ALICE)*

 $\mathcal{L}_{\mathcal{A}}$ and at pt v3 and at p

0.05

38

032301-4

 \sim 3 GeV \sim

Single vs. pair Fourier decomposition ously at RHIC μ at RHIC μ at RHIC μ and μ after subtraction of a correlated component whose shape was shape was μ l Single I Single ve nair Fourier decomposition 38 equal to value the value of

Single-particle anisotropy and the emitted of the emitted **(the familiar v_n coefficients)** da
N *n*=1

∞

$$
\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n(p_T) \cos(n(\phi - \Psi_n))
$$

⁵⁰ also extends over a large range in *|*∆η*|* [17, 18]. The latter feature has been observed previ-

higher-order flow components $\tilde{3}$ –38. The azimuthal momentum distribution of the emitted of the

Pair anisotropy Similar form, but indep. of Ψⁿ Similar form, but indep. of Ψ_n
Similar form, but indep. of Ψ_n

$$
\frac{dN^{pairs}}{d\Delta\phi} \propto 1 + \sum_{n=1}^{\infty} 2V_{n\Delta}(p_T^t, p_T^a) \cos(n\Delta\phi)
$$

Extract directly from 2-particle azimuthal d correlations! t root d *Extract directly from 2-particle azimuthal* of the *Total and the active of the analysis* the convention of the convention of the two-particle fourier coefficients as a set of the two-particle as a value of the two-particle $\frac{1}{2}$

$$
V_{n\Delta}\equiv\left\langle \cos\left(n\Delta\phi\right)\right\rangle =\sum_{i}C_{i}\cos(n\Delta\phi_{i})\left/\sum_{i}C_{i}. \hspace{1cm} \underbrace{\sum_{i}C_{i}}_{0.998+} \underbrace{1.002}_{1+\frac{1}{2}+\frac{1}{4}
$$

 $\mathcal{L}_{\mathcal{A}}$ and at pt v3 and at p

0.05

 \sim 3 GeV \sim

]

-2 [10

V

Fourier Decomposition

"Power spectrum" of pair Fourier components Vn^Δ

For ultra-central collisions, n = 3 dominates. In bulk-dominated correlations, the n > 5 harmonics are weak. \parallel in buik-dominated correlations, the n $>$ 5 narmonics are weak.

V_{2△} dominates as collisions become less central. $\frac{1}{2}$ and intrinsic as comsions become ress central.
Collision geometry, rather than fluctuations, becomes primary effect are superimposed in color. The ratio of the ratio of data the data to the primer for data to the *n* ≤ 5 sum is s
The ratio of data to the *n* ≤ 5 sum is shown in the *n* ≤ 5 sum is shown is the *n* ≤ 5 sum is sum is sum i

shown in the lower panel. Center: Amplitude of *Vn*[∆] harmonics vs. *n* for the same *pt*

A. Adare (ALICE) class. Right: *Vn*∆ spectra for a variety of centrality classes. A variety classes are represented with a variety contract with α variety $\$

Fourier Decomposition

"Power spectrum" of pair Fourier components Vn^Δ

For ultra-central collisions, n = 3 dominates. In bulk-dominated correlations, the n > 5 harmonics are weak. \parallel in buik-dominated correlations, the n $>$ 5 narmonics are weak.

V_{2△} dominates as collisions become less central. $\frac{1}{2}$ and intrinsic as comsions become ress central.
Collision geometry, rather than fluctuations, becomes primary effect are superimposed in color. The ratio is shown as the data to the data to the primer of data to the *n* ≤ 5 sum is shown as the *n* ≤ 5 sum is shown is shown in the *n* ≤ 5 sum is shown in the *n* ≤ 5 sum is shown in the *n* are superimposed in color. The ratio of the ratio of data the data to the primer for data to the *n* ≤ 5 sum is s
The ratio of data to the *n* ≤ 5 sum is shown in the *n* ≤ 5 sum is shown is the *n* ≤ 5 sum is sum is sum i

shown in the lower panel. Center: Amplitude of *Vn*[∆] harmonics vs. *n* for the same *pt*

shown in the lower panel. Center: Amplitude of *Vn*[∆] harmonics vs. *n* for the same *pt*

A. Adare (ALICE) class. Right: *Vn*∆ spectra for a variety of centrality classes. A variety classes are represented with a variety contract with α variety $\$ class. Right: *Vn*∆ spectra for a variety of centrality classes. A variety classes are represented with a variety contract with α variety $\$

Fourier Decomposition

"Power spectrum" of pair Fourier components Vn^Δ

For ultra-central collisions, n = 3 dominates. In bulk-dominated correlations, the n > 5 harmonics are weak. \parallel in buik-dominated correlations, the n $>$ 5 narmonics are weak.

V_{2△} dominates as collisions become less central. $\frac{1}{2}$ and intrinsic as comsions become ress central.
Collision geometry, rather than fluctuations, becomes primary effect are superimposed in color. The ratio is shown as the data to the data to the primer of data to the *n* ≤ 5 sum is shown as the *n* ≤ 5 sum is shown is shown in the *n* ≤ 5 sum is shown in the *n* ≤ 5 sum is shown in the *n* are superimposed in color. The ratio of the ratio of data the data to the primer for data to the *n* ≤ 5 sum is s
The ratio of data to the *n* ≤ 5 sum is shown in the *n* ≤ 5 sum is shown is the *n* ≤ 5 sum is sum is sum i

shown in the lower panel. Center: Amplitude of *Vn*[∆] harmonics vs. *n* for the same *pt*

shown in the lower panel. Center: Amplitude of *Vn*[∆] harmonics vs. *n* for the same *pt*

A. Adare (ALICE) class. Right: *Vn*∆ spectra for a variety of centrality classes. A variety classes are represented with a variety contract with α variety $\$ class. Right: *Vn*∆ spectra for a variety of centrality classes. A variety classes are represented with a variety contract with α variety $\$

The factorization hypothesis state particles at large *|*∆η*|* is induced by a collective response to initial-state coordinate-space anisotropy from collision geometry and fluctuations and fluctuations and $\mathcal{I}(\mathcal{S})$

Factorization of two-particle anisotropy mechanism that affects all particles in the event, and *Vn*[∆] depends only on the single-particle

For pairs correlated to one another through a common symmetry plane Ψn, r or pairs correlated to one another unbugh a d
| their correlation is dictated by bulk anisotropy: azimuthal distribution with respect to the *n*-th order symmetry plane Ψ*n*. Under these circum-

¹⁷⁵ anisotropic flow analyses [17, 30, 39]. This is expected if the azimuthal anisotropy of final

$$
V_{n\Delta}(p_T^t, p_T^a) = \langle \langle e^{in(\phi_a - \phi_t)} \rangle \rangle
$$

= $\langle \langle e^{in(\phi_a - \Psi_n)} \rangle \rangle \langle \langle e^{-in(\phi_t - \Psi_n)} \rangle \rangle$
= $\langle v_n \{2\} (p_T^t) v_n \{2\} (p_T^a) \rangle$.

the flow-dominated mechanism, dijet-related processes do not directly influence every particle;

V_n Δ would be generated from one v_n(p_T) curve, $\mathbf{v}_{\mathsf{n}\Delta}$ would be generated from one $\mathbf{v}_{\mathsf{n}}(\mathsf{p}_{\mathsf{T}})$ curve,
evaluated at $\mathsf{p}_{\mathsf{T}}^t$ and $\mathsf{p}_{\mathsf{T}}^a$. events, and **v**_{*2*} seems the use of a two-particle measurement to obtain $\frac{1}{2}$ such that $\frac{1}{2$

Factorization expected: Factorization expected:

✔ For correlations from collective flow. **is Flow is global and affects all particles in the event.** The *azimuthal shapes* $\frac{1}{2}$

✘ **Not for pairs from fragmenting di-jets.** of these peaks are similar to those from pp or d–Au collisions (albeit suppressed), reflecting *K* Not for pairs from fragmenting di-jets.

A. Adare (ALICE) Di-jet shapes are "local", not strongly connected to Ψn. correlations between high-produced between high-produced fractions are not expected to formulations are factori
A. Adare (ALICE)

Friday, November 4, 2011 **and resonances in a set of pairs in a set of particles with a small number of particles without a small number of particles with** σ **and** σ **and** σ **are sonall number of particles with** σ **and** Friday, November 4, 2011

^T , high-*p^a*

The factorization hypothesis state particles at large *|*∆η*|* is induced by a collective response to initial-state coordinate-space anisotropy from collision geometry and fluctuations and fluctuations and $\mathcal{I}(\mathcal{S})$ reduce the rate of random associations and preserve a #⁰ identification signal-to-background ratio (S/B) larger than 4:1 for central Au þ Au and 20:1 in p þ p. A systematic $u_{\rm eff} = 1.6$ –6%, depending on S/B, is included for ~ 1.6 , included for ~ 1.6 between previously reported in much broader points for the pT ranges for the pT ranges for the pT ranges for the p \mathbf{e} i \mathbf{e} and triggers \mathbf{f} tify the trends in the shape and yield between these two extremes.

are used in more central events and for lower-pT α in more central events and for lower-pT α

Factorization of two-particle anisotropy mechanism that affects all particles in the event, and *Vn*[∆] depends only on the single-particle arms using the drift chambers α with α

the #0 signal extraction.

For pairs correlated to one another through a common symmetry plane Ψn, r or pan's correlated to one another un'ough a d
| their correlation is dictated by bulk anisotropy: ractorization of two-particle anisotropy
For pairs correlated to one another through a common symmetry plane Ψ_{n-} ion is dictated by buik anisotropy distribution. Figure 2 shows the results. In p $\mathcal{L}_{\mathcal{L}}$ mmon symmetry plane Ψ_{n} $\sum_{i=1}^{n}$

¹⁷⁵ anisotropic flow analyses [17, 30, 39]. This is expected if the azimuthal anisotropy of final

$$
V_{n\Delta}(p_T^t, p_T^a) = \langle \langle e^{in(\phi_a - \phi_t)} \rangle \rangle
$$

= $\langle \langle e^{in(\phi_a - \Psi_n)} \rangle \rangle \langle \langle e^{-in(\phi_t - \Psi_n)} \rangle \rangle$
= $\langle v_n \{2\} (p_T^t) v_n \{2\} (p_T^a) \rangle.$

V_nΔ</sub> would be generated from one v_n(p_T) curve, evaluated at p_T^t and p_T^a. The village over the controlles and p_{articl}es are averaging over the controlles and p_{articl}es and p_{articl}es and p_{articl}es and p_{articl}es and p_{articl}es and p_{articl}es and p_a dNpair ^d!% ^¼ ^N^a

185 for correlations from collective flow. The state distribution of the state of the stat Flow is global and affects all particles in the event. and affects all particles in the event. $\;$

A. Adare (ALICE) ✘ **Not for pairs from fragmenting di-jets. Di-jet shapes are "local", not strongly connected to Ψn. K** Not for pairs from fragmenting di-jets.
Pions and charged hadrons in Weak shape departments on Participal and Charged Reserves to the background of the **Di-jet shapes are "local", not strongly connected to** Ψ_n **.** $\qquad \qquad 0 \qquad 2 \qquad 4 \qquad 0 \qquad 2 \qquad 4$
A. Adare (ALICE) level, 'n Autonomiese is determined in Australia
The Au design of the August using the August of the Au

consistent with the measurement in the measurement in the p μ μ

Improving on $V_{n\Delta} = v_n(p_T)^2$ **with triggered correlations...**

12 p_T ^t bins, 12 p_T ^a bins; p_T ^t $\geq p_T$ ^a \Rightarrow 78 $V_{n\Delta}$ points.

Fit all simultaneously to find $v_n(p_T)$ curve with best-fit $v_n(p_T t)$ x $v_n(p_T t)$ product.

- Fit supports factorization at low p_T^a
- **⇒ suggests flow correlations.**
- **Fit deviates from data in jet-dominated high** p_T^a **region**
- ⇒ collective description less appropriate._{A. Adare} (ALICE)

Improving on $V_{n\Delta} = v_n(p_T)^2$ **with triggered correlations...**

12 p_T ^t bins, 12 p_T ^a bins; p_T ^t $\geq p_T$ ^a \Rightarrow 78 $V_{n\Delta}$ points.

Fit all simultaneously to find $v_n(p_T)$ curve with best-fit $v_n(p_T t)$ x $v_n(p_T t)$ product.

- Fit supports factorization at low p_T^a
- 㱺 **suggests flow correlations.**
- **Fit deviates from data in jet-dominated high** p_T^a **region**
- ⇒ collective description less appropriate._{A. Adare} (ALICE)

Improving on $V_{n\Delta} = v_n(p_T)^2$ **with triggered correlations...**

12 p_T ^t bins, 12 p_T ^a bins; p_T ^t $\geq p_T$ ^a \Rightarrow 78 $V_{n\Delta}$ points.

Fit all simultaneously to find $v_n(p_T)$ curve with best-fit $v_n(p_T t)$ x $v_n(p_T t)$ product.

- Fit supports factorization at low p_T^a
- **⇒ suggests flow correlations.**
- **Fit deviates from data in jet-dominated high** p_T^a **region**
- ⇒ collective description less appropriate._{A. Adare} (ALICE)

Improving on $V_{n\Delta} = v_n(p_T)^2$ **with triggered correlations...**

12 p_T ^t bins, 12 p_T ^a bins; p_T ^t $\geq p_T$ ^a \Rightarrow 78 $V_{n\Delta}$ points.

Fit all simultaneously to find $v_n(p_T)$ curve with best-fit $v_n(p_T t)$ x $v_n(p_T t)$ product.

- Fit supports factorization at low p_T^a
- 㱺 **suggests flow correlations.**
- **Fit deviates from data in jet-dominated high** p_T^a **region**
- ⇒ collective description less appropriate._{A. Adare} (ALICE)

Improving on $V_{n\Delta} = v_n(p_T)^2$ **with triggered correlations...**

12 p_T ^t bins, 12 p_T ^a bins; p_T ^t $\geq p_T$ ^a \Rightarrow 78 $V_{n\Delta}$ points.

Fit all simultaneously to find $v_n(p_T)$ curve with best-fit $v_n(p_T t)$ x $v_n(p_T t)$ product.

- Fit supports factorization at low p_T^a
- 㱺 **suggests flow correlations.**
- **Fit deviates from data in jet-dominated high** p_T^a **region**
- ⇒ collective description less appropriate._{A. Adare} (ALICE)

Improving on $V_{n\Delta} = v_n(p_T)^2$ **with triggered correlations...**

12 p_T ^t bins, 12 p_T ^a bins; p_T ^t $\geq p_T$ ^a \Rightarrow 78 $V_{n\Delta}$ points.

Fit all simultaneously to find $v_n(p_T)$ curve with best-fit $v_n(p_T t)$ x $v_n(p_T t)$ product.

- Fit supports factorization at low p_T^a
- 㱺 **suggests flow correlations.**
- **Fit deviates from data in jet-dominated high** p_T^a **region**
- ⇒ collective description less appropriate._{A. Adare} (ALICE)

Improving on $V_{n\Delta} = v_n(p_T)^2$ **with triggered correlations...**

12 p_T ^t bins, 12 p_T ^a bins; p_T ^t $\geq p_T$ ^a \Rightarrow 78 $V_{n\Delta}$ points.

Fit all simultaneously to find $v_n(p_T)$ curve with best-fit $v_n(p_T t)$ x $v_n(p_T t)$ product.

- Fit supports factorization at low p_T^a
- **⇒ suggests flow correlations.**
- **Fit deviates from data in jet-dominated high** p_T^a **region**
- ⇒ collective description less appropriate._{A. Adare} (ALICE)

$High-pr^t$ anisotropy

0

If from pathlength-dependent quenching, correlations should reflect (fte V/c) High-pt v_n is finite, in fact faitly large 8 4 10 12 14 16 18 20 **proposal for** High-p_T^t, low p_T^a pair correlation due to quenching and flow, respectively.

V. Loggins

Comparison with ALICE v_n{2} 43 \blacksquare central collisions \blacksquare equal to v2 at lower points and reaches significantly larger parties of the significantly larger \sim

Published ALICE vn{2}

PRL 107 032301 (2011) Scalar-product (SP) method |Δη| > 1.0

 2π GeV \sim 2π becomes equal to v2 and at pt \sim 2 and at pt \sim 2 and at pt \sim

 $\mathcal{S} = \{ \mathcal{S} \mid \mathcal{S} \in \mathcal{S} \mid \mathcal{S} \neq \emptyset \}$

particles in 1 < pt < 2 GeV=c for pairs in j!!j > 1. We

particle azimuthal correlations are measured by calculating

observe a clear double a clear double $\mathcal{O}(\mathcal{C})$

 $\mathcal{S}_{\mathcal{S}}$, but only after subtraction of the elliptic flow

component. This two-peak structure has been interpreted

as an indication for various jet-medium modifications

where $\mathcal{M} = \mathcal{M} \times \mathcal{M}$

 $\mathcal{O}(\mathcal{S}_1)$ and more recently as a manifestor \mathcal{S}_2

is the number of associated particles as function of $\mathcal{O}(n)$

tation of triangular flow $\mathcal{O}(10^4)$

with the same (different) event, and N

azimuthal correlation shape expected from v2, v3, v3, v3, v4, and v3, v4, and

 τ

v⁵ evaluated at corresponding transverse momenta with the

 \mathcal{A}^{max}

measured two-particle azimuthal triggered correlation and

observed in very central collisions \mathcal{C}

find that the combination of these harmonics gives a natu-

 $p_{\rm eff}$ and 2 GeV \sim 3 GeV c

ral description of the observed correlation structure on the

 $p_{\rm c}$ in 2π and 2π for pairs in \mathcal{L}

observe a clear doubly peaked correlation structure cen-

tered opposite to the trigger particle. This feature has been

observed at lower energies in broader centrality bins in broader centrality bins in broader centrality bins in
The centrality bins in broader centrality bins in broader centrality bins in broader centrality bins in broad

 $\begin{bmatrix} 3 & 3 & 3 \ 2 & 3 & 3 \end{bmatrix}$

component. This two-peak structure has been interpreted

as an indication for various jet-medium modifications

 $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 &$

tation of triangular flow $\mathbf{1}_{\mathbf{1}_{\mathbf{1}}}$

azimuthal correlation shape expected from v2, v3, v3, v3, v4, and v3, v4, and

 $\frac{1}{2}$ evaluated at corresponding transverse momenta with the set of $\frac{1}{2}$

measured two-particle azimuthal triggered correlation and

find that the combination of the combination of the combination of the combination of these harmonics gives a natural \mathbf{f}_i

ral description of the observed correlation structure on the

FIG. 4 (color online). The two-particle azimuthal correlation,

measured in 0 < !" < # and shown symmetrized over 2#,

between a trigger particle with 2 < pt < 3 GeV=c and an asso-

Identified hadron〈**pT**〉

About 20% higher than at RHIC for pions, kaons, and protons

Yields

Tfo and "

 \mathcal{L}^p

Compared to RHIC

Reflects larger PbPb system

