Azimuthal anisotropy of $R = 0.2$ charged jet production in $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV Pb–Pb collisions

Redmer Alexander Bertens - Utrecht University

NIKHEF Jamboree 2015

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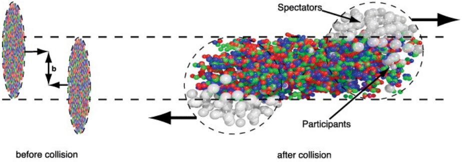
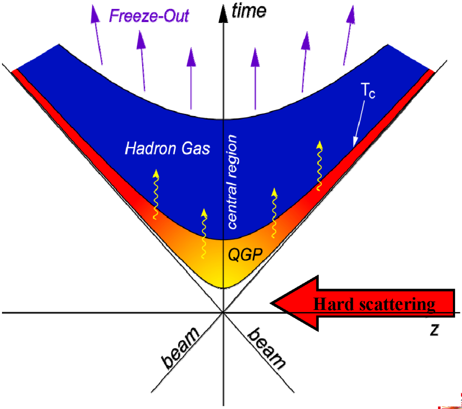
The ALICE experiment is aimed at studying the Quark Gluon Plasma

'Our aim is to study the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma, is expected.'



What happens in a Pb–Pb collision?

1. Hot, dense system is created
2. Deconfined quarks and gluons undergo multiple interactions
3. Collective expansion
4. Chemical freeze-out to hadrons and finally kinetic freeze-out



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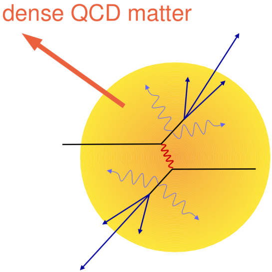
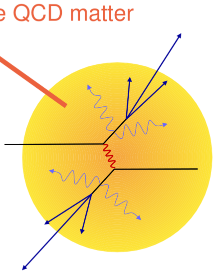
Jets in heavy-ion collisions



Hard scattering ($Q^2 > 1$ (GeV/c)^2)

- Radiation of quarks and gluons
- Hadronization into colorless spray of particles: *'jets'*

Pb–Pb collisions: scattered partons interact with medium
$\longrightarrow$ *'jet quenching'*



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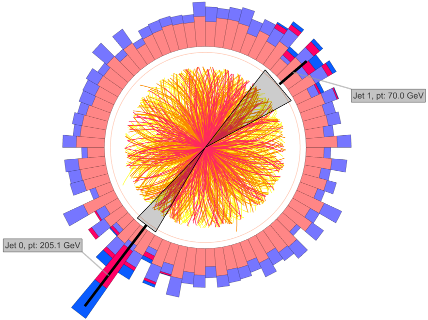

Experimental signatures of parton energy loss in Pb–Pb collisions

- Di-jet energy asymmetry
- Jet broadening
- *Suppression of yield*

This talk: *path-length dependence of parton energy loss*

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Jet suppression: R_{AA} of jets

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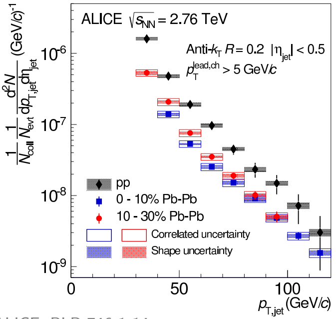
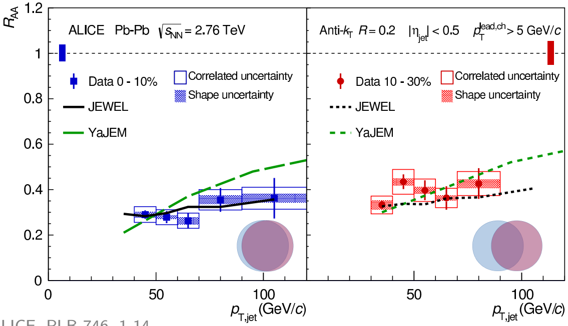


ALICE, PLB 746 1-14



ALICE, PLB 746, 1-14

$$R_{AA} = \frac{d^2 N^{AA}/dp_T d\eta}{\langle T_{AA}\rangle \cdot d^2\sigma_{pp}/dp_T d\eta}$$

- Strong suppression in central and peripheral collisions
- Model comparisons (JEWEL[1], YaJEM[2]): constrain energy loss mechanism

$v_2^{\text{ch jet}}$: 'differential' approach to energy loss

[1] K.C.Zapp *et al.* JHEP 1303 080

[2] T.Renk, PRC 78 034908

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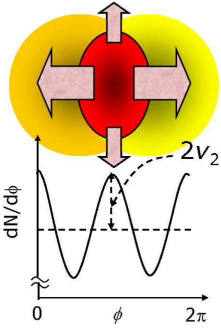
$v_2^{\text{ch jet}}$: energy loss and medium geometry

$$\underbrace{\left.\frac{dN}{E}\right|_{\text{jets, Pb-Pb}}}_{\text{final state}} = \underbrace{\left.\frac{dN}{dE}\right|_{\text{jets}}}_{\text{pQCD, PDF's}} \otimes \underbrace{P(\Delta E)}_{\text{energy loss distribution}}$$

Different theoretical predictions on path-length (L) dependence of parton energy loss (ΔE)[3,4,5]

$$\underbrace{\Delta E \propto L}_{\text{collisional}} \leftrightarrow \underbrace{\Delta E \propto L^2}_{\text{radiative}} \leftrightarrow \underbrace{\Delta E \propto L^3}_{\text{AdS/CFT}}?$$



$v_2^{\text{ch jet}}$: comparing short to long L at fixed medium density

$L_{\text{in}} \approx L_{\text{out}}$

$v_2^{\text{ch jet}} \approx 0$?

$L_{\text{in}} < L_{\text{out}}$

$v_2^{\text{ch jet}} > 0$?

[3] R.Baier *et al.* NPB484 265-282 ($\propto L$)

[4] R.Baier *et al.* NPB483 291-320 ($\propto L^2$)

[5] C. Marquet, T. Renk, PLB685 270-276 ($\propto L^3$)

DATA ANALYSIS

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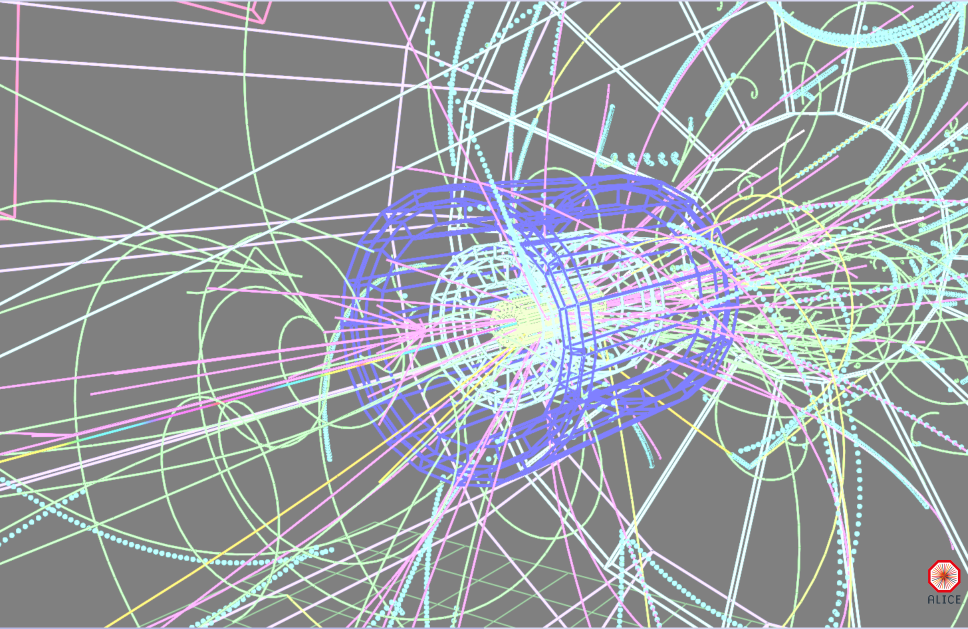

Outline of $v_2^{\text{ch jet}}$ measurement

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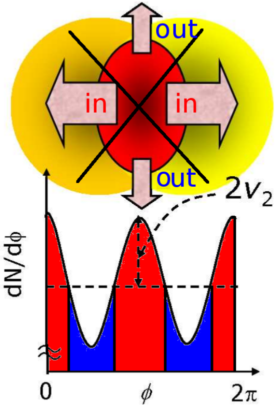
$v_2^{\text{ch jet}}$ is measured using the 'in-plane' and 'out-of-plane' p_T-differential jet yields N_{in}, N_{out}



$$v_2^{\text{ch jet}} = \frac{\pi}{4}\frac{1}{R}\frac{N_{\text{in}} - N_{\text{out}}}{N_{\text{in}} + N_{\text{out}}}$$

resolution R corrects for the finite precision of symmetry plane estimate $\Psi_{\text{EP, 2}}$

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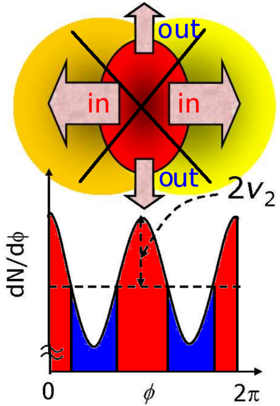

$$v_2^{\text{ch jet}} = \frac{\pi}{4}\frac{1}{R}\frac{N_{\text{in}} - N_{\text{out}}}{N_{\text{in}} + N_{\text{out}}}$$

resolution R corrects for the finite precision of symmetry plane estimate $\Psi_{\text{EP, 2}}$

$v_2^{\text{ch jet}}$ is the second coefficient of a Fourier series

$$\frac{dN_{\text{jet}}}{d(\varphi_{\text{jet}} - \Psi_n)} \propto 1 + \sum_{n=1}^{\infty} 2 v_n^{\text{ch jet}} \cos[n(\varphi_{\text{jet}} - \Psi_n)]$$

$$N_{\text{in}} = \int_{in} \frac{dN_{\text{jet}}}{d(\varphi_{\text{jet}} - \Psi_{\text{EP, 2}}^{\text{V0}})} = a\left(\pi + 4 v_2^{\text{ch jet}}\right)$$

$$N_{\text{out}} = \int_{out} \frac{dN_{\text{jet}}}{d(\varphi_{\text{jet}} - \Psi_{\text{EP, 2}}^{\text{V0}})} = a\left(\pi - 4 v_2^{\text{ch jet}}\right)$$

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Short intermezzo: 'hydrodynamic' flow

ALICE has published many times on *flow* (v_2, v_3...)

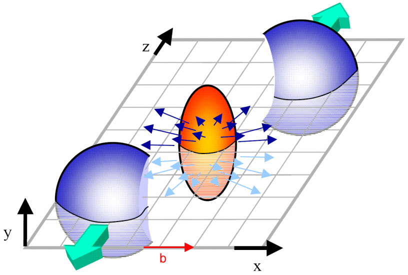
In a nutshell ...

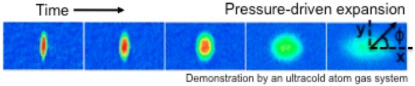
- Almond-shaped overlap region
- Collective expansion of thermalized medium in vacuum
- Spatial anisotropy is converted to momentum-space anisotropy

Result: cosine modulation (v_2) of azimuthal track distribution at low p_T

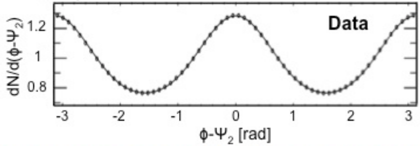
... beware ...: though techniques and terminology are similar

- *flow*: modulation of track azimuth at low p_T from collective expansion
- $v_2^{\text{ch jet}}$: azimuthal modulation of jet distribution (high p_T) from energy loss





Anisotropic azimuthal distribution:



ANALYSIS OVERVIEW

Charged tracks ← Start

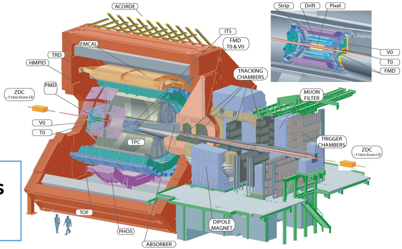
Signal jets
Jet finder anti-k_T

Background jets
Jet finder k_T

Background subtraction

Detector level jets

Particle level
Jet spectrum



Charged particle tracks
- ITS: silicon detector
- TPC: gas detector

|η| < 0.9, 0 < φ < 2π

Centrality and Event Plane determination
- V0: scintillator counters
- Forward rapidity

2.8 < η < 5.1, -3.7 < η < -1.7

Unfolding

$$M(p_{\mathrm{T,ch}}^{\mathrm{jet,rec}}) = \int G(p_{\mathrm{T,ch}}^{\mathrm{jet,rec}}, p_{\mathrm{T,ch}}^{\mathrm{jet,gen}}) T(p_{\mathrm{T,ch}}^{\mathrm{jet,gen}}) \varepsilon(p_{\mathrm{T,ch}}^{\mathrm{jet,gen}}) \mathrm{d}p_{\mathrm{T,ch}}^{\mathrm{jet,gen}}$$

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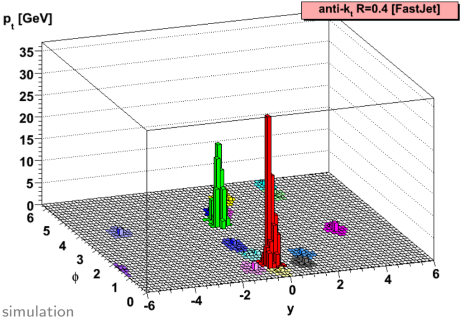
Jet reconstruction in Pb–Pb collisions

'Jets' in heavy-ion collisions are not so easy to understand ...

- Theoretical definition of jet: colorless spray of particles emitted by parton
- Experimental definition of jet: fully determined by jet finding algorithm
  (this analysis: anti-k_T with $R = 0.2$: maximum η–φ distance of jet constituent tracks to jet axis)



simulation

Jet reconstruction in Pb–Pb collisions

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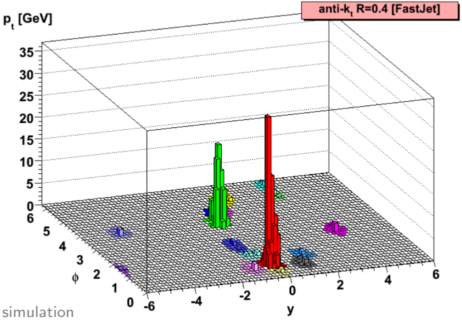

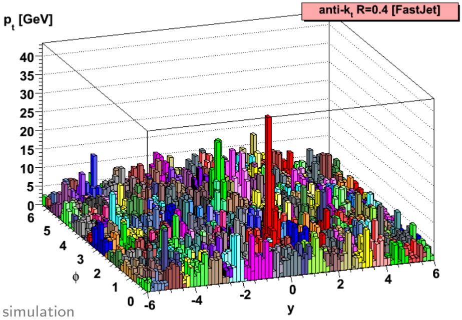

Main difficulties in Pb–Pb jet analyses

- 'Background' (*Underlying Event*) large [1] compared to jet energy
- UE is *not uniform* (hydrodynamic flow [2], statistical fluctuations [3])

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Event-by-event estimate of energy density of UE

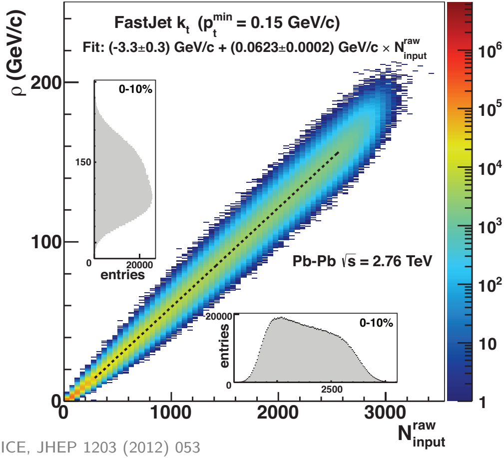
$$\langle \rho_{ch} \rangle = \text{median}\left(\frac{p_{T,\,ch}^{jet}}{A^{jet}} \right)$$

Linear dependence of $\langle \rho_{ch} \rangle$ on multiplicity

Quick example: 0–10% centrality

- $\langle \rho_{ch} \rangle \approx 140$ GeV/c A^{-1}
- $A \propto \pi R^2$

$\propto$ 20 GeV/c background for a $R = 0.2$ jet



ALICE, JHEP 1203 (2012) 053

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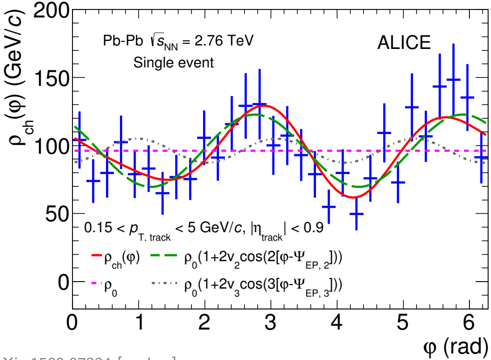
[2] Jet-by-jet UE subtraction

Jet energy in Pb–Pb is adjusted for underlying event (UE) energy jet-by-jet

$$p_{\mathrm{T,\,ch}}^{\mathrm{jet}} = p_{\mathrm{T,\,ch}}^{\mathrm{raw}} - \rho_{\mathrm{ch\ local}} A$$

using jet area A and flow-modulated UE energy density $\rho_{\mathrm{ch\ local}}$



arXiv:1509.07334 [nucl-ex]

UE flow (v_2 and v_3) is accounted for in $\rho_{\mathrm{ch\ local}}$ by fitting a Fourier expansion to the azimuthal p_{T} distribution event-by-event:

$$\rho_{\mathrm{ch}}(\varphi) = \rho_0 \left(1 + 2\{v_2 \cos[2(\varphi - \Psi_{\mathrm{EP},\,2}^{\mathrm{V0}})] + v_3 \cos[3(\varphi - \Psi_{\mathrm{EP},\,3}^{\mathrm{V0}})]\}\right)$$

Note: maxima of v_2, v_3 naturally indicate symmetry angles $\Psi_{EP,\,2}$ and $\Psi_{EP,\,3}$!

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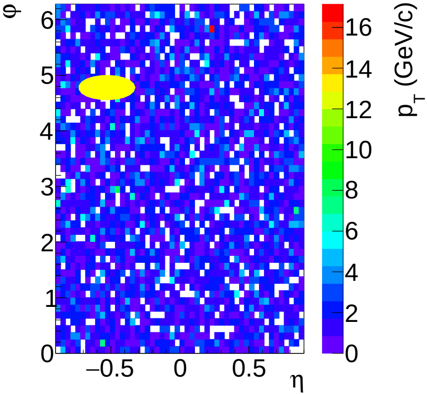
UE fluctuations in φ, η around $\langle \rho_{ch} \rangle$

- A jet of $p_T = x$ sitting on an upward fluctuation of magnitude a will be reconstructed at $p_T = x + a$ ...
- ... likewise a jet of $p_T = x$ sitting on a downward fluctuation of magnitude a will be reconstructed at $p_T = x - a$



Random cone procedure to determine magnitude fluctuations

$$\delta p_T = \underbrace{\sum p_T^{\text{track}}}_{\text{cone } p_T} - \underbrace{\rho \pi R^2}_{\text{expectation}}$$

δp_T distribution used to *unfold* jet spectra:

$$M(p_{T,ch}^{jet,rec}) = \int G(p_{T,ch}^{jet,rec}, p_{T,ch}^{jet,gen}) T(p_{T,ch}^{jet,gen}) \varepsilon(p_{T,ch}^{jet,gen}) dp_{T,ch}^{jet,gen}$$

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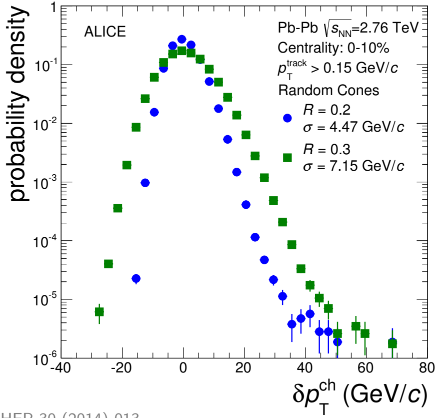

JHEP 30 (2014) 013

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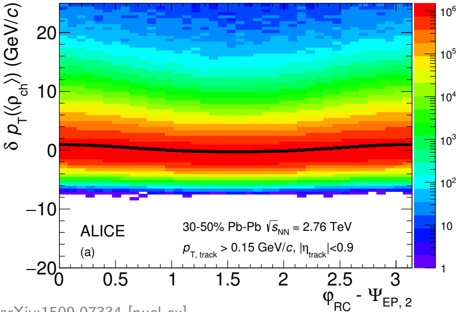
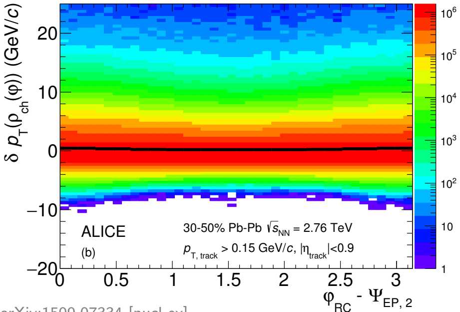
Fluctuations quantified by δp_T



arXiv:1509.07334 [nucl-ex]

δp_T distribution built using $\langle \rho_{ch} \rangle$



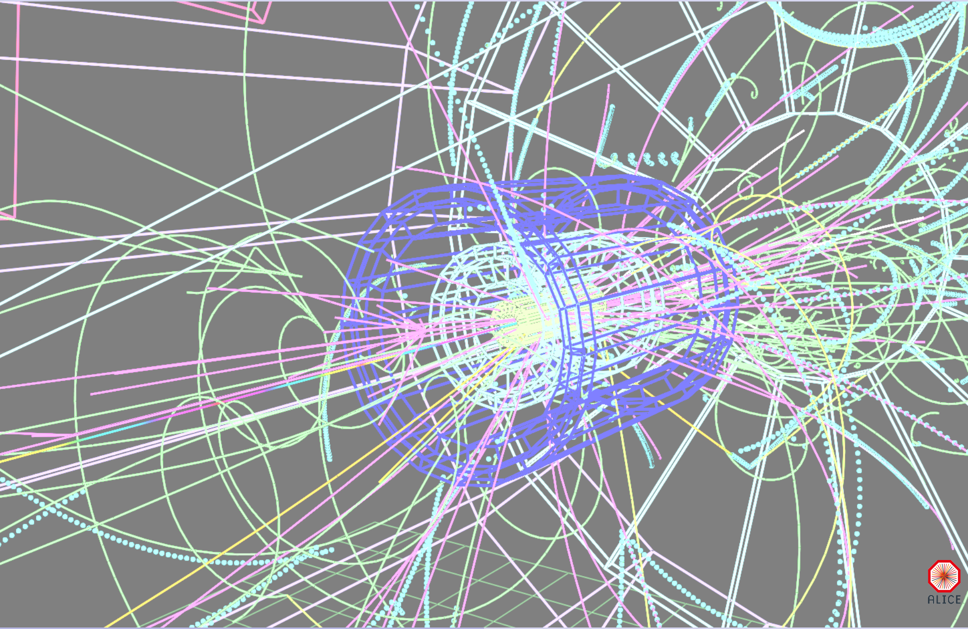
arXiv:1509.07334 [nucl-ex]

δp_T distribution built using $\rho_{ch\ local}$

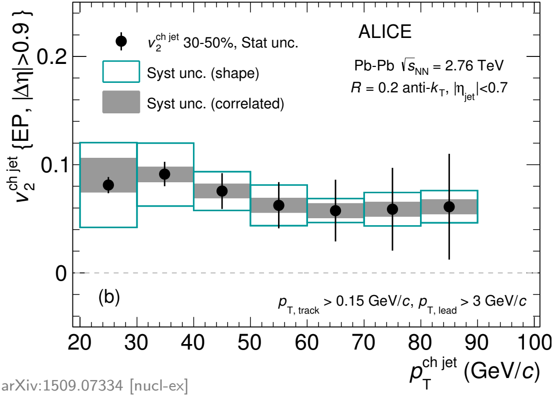
UE subtraction technique succesfully removes flow bias from UE

- Modulation of mean δp_T decreases strongly
- Width of δp_T in-plane is larger than out-of-plane
- In-plane and out-of-plane jet spectra need to be unfolded independently to properly treat UE fluctuations

RESULTS



$v_2^{\text{ch jet}}$ in 30–50% collision centrality



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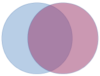
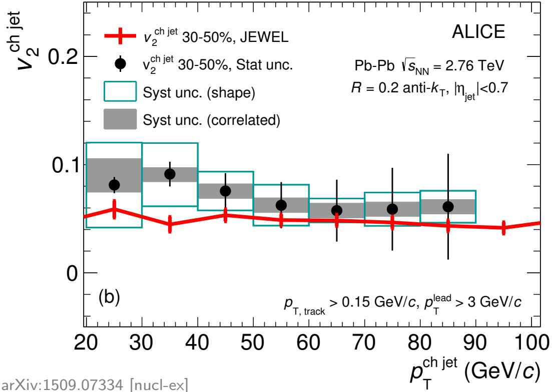


$L_{\text{in}} < L_{\text{out}}$

$v_2^{\text{ch jet}} > 0?$

- Non-zero $v_2^{\text{ch jet}}$ over entire p_{T} range
- Confirmation of jet energy loss in the collision medium
- Energy loss sensitive to collision geometry up to high p_{T}



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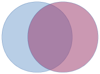

$L_{in} < L_{out}$

$v_2^{\text{ch jet}} > 0$?

JEWEL[6]: energy loss in presence of QCD medium

- Good agreement with model prediction (effective L^2 dependence of energy loss)
- Additional modeling and high-precision measurements necessary to truly constrain energy loss mechanisms

[6] K.C.Zapp *et al.* JHEP 1303 080

K.C.Zapp, EPJC74 2, 2762

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What about central collisions ?

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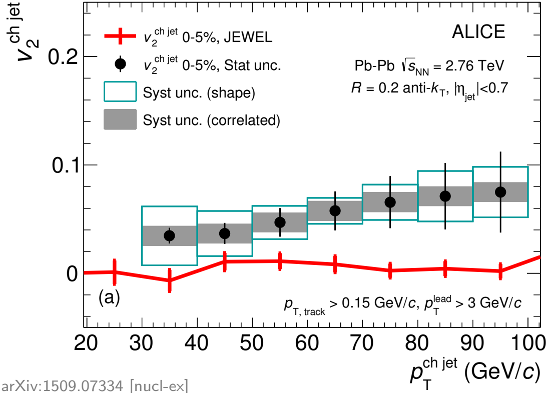
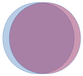


arXiv:1509.07334 [nucl-ex]



$L_{\text{in}} \approx L_{\text{out}}$

$v_2^{\text{ch jet}} \approx 0$?

Non-zero $v_2^{\text{ch jet}}$ also observed in central (0–5%) collisions

- (Correlated) uncertainties on the measurement preclude a strong statement
- Non-zero $v_2^{\text{ch jet}}$ as result of fluctuations in the density of nuclei?
- JEWEL (homogeneous nuclei) underestimates $v_2^{\text{ch jet}}$

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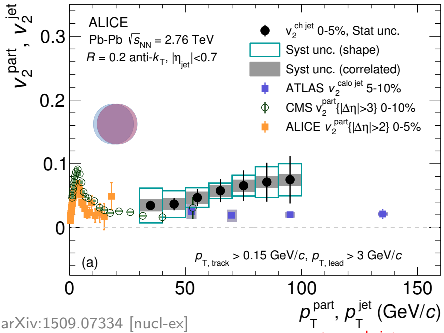
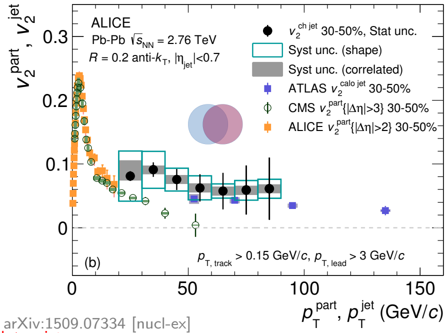
Comparison to previous measurements

Other observables sensitive to parton energy loss

- High-p_{T} single particle v_2^{part} (ALICE[7], CMS[8])
- $v_2^{\mathrm{ch+emjet}}$ of jets comprising charged and neutral fragments (ATLAS[9])





Different energy scales for v_2^{part}, $v_2^{\mathrm{ch\ jet}}$ and $v_2^{\mathrm{ch+emjet}}$, qualitative comparison only

- Non-zero v_2^{part}, $v_2^{\mathrm{ch\ jet}}$ and $v_2^{\mathrm{ch+emjet}}$ up to high p_{T}
- Qualitatively consistent picture in central and semi-central collisions

[7] ALICE, PLB719 (2013) 18-28
[8] CMS, PRL 109 (2012) 022–301
[9] ATLAS, PRL 111 (2013) 152–301

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Conclusion

$v_2^{\text{ch jet}}$ measured in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV by ALICE

[analysis] Main difficulty in jet analyses in Pb–Pb collisions

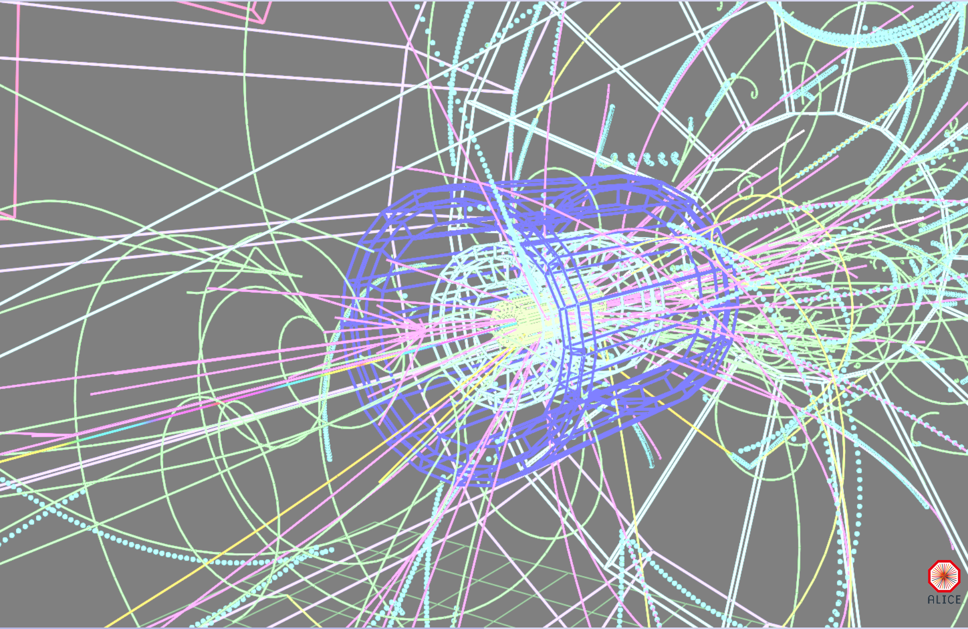
- Large, non-uniform background (UE)
- UE treatment succesfully accounts for fluctuations and flow

[observations] Non-zero $v_2^{\text{ch jet}}$

- Strong parton energy loss
- Senstitive to the collision geometry up to high p_{T}

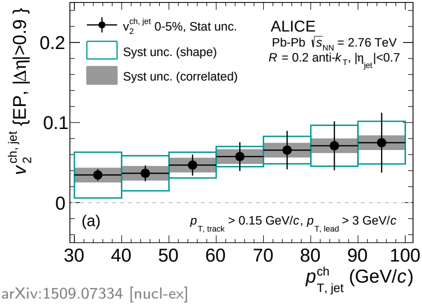
Thank you for your attention

BACKUP



$v_2^{\text{ch jet}}$ is measured in 0-5% (left) and 30-50% (right) collision centrality

- [0-5%] $\approx 2\ \sigma$ deviation from 0
- [30-50%] ≈ 3 - $4\ \sigma$ deviation from 0



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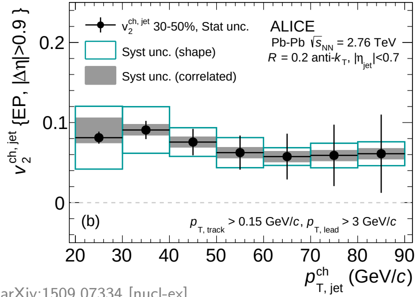

arXiv:1509.07334 [nucl-ex]

p-value is derived from minimizing a modified[10] χ^2-function w.r.t. $\epsilon_{corr}, \epsilon_{shape}$

$$\tilde{\chi}^2(\epsilon_{corr}, \epsilon_{shape}) = \left[\left(\sum_{i=1}^{n} \frac{(v_{2\,i} + \epsilon_{corr}\sigma_{corr,i} + \epsilon_{shape})^2}{\sigma_i^2} \right) + \epsilon_{corr}^2 + \frac{1}{n} \sum_{i=1}^{n} \frac{\epsilon_{shape}^2}{\sigma_{shape,i}^2} \right]$$

[10] Phys.Rev. C77, 064907 (2008), 0801.1665

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UE flow under control?

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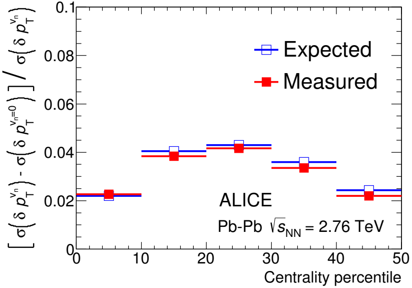
Expected δp_T width without flow from charged particles from N_A (multiplicity in a cone) $\langle p_T \rangle$ (mean p_T of particle spectrum) $\sigma(p_T)$ (width of particle spectrum)

$$\sigma(\delta p_T^{v_n=0}) = \sqrt{N_A \sigma^2(p_T) + N_A \langle p_T \rangle^2}$$

Adding v_n by introducing non-Poissonian fluctuations $\sigma_{NP}^2(N_A) = 2N_A^2(v_2^2 + v_3^2)$

$$\sigma(\delta p_T^{v_n}) = \sqrt{N_A \sigma^2(p_T) + (N_A + \sigma_{NP}^2(N_A)) \langle p_T \rangle^2}$$



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- 'expected' as above: from N_A and $\langle p_T \rangle$, etc.
- 'measured': from δp_T distributions
  - $\sigma(\delta p_t^{v_n})$ from $\langle \rho_{ch} \rangle$
  - $\sigma(\delta p_t^{v_n=0})$ from $\rho_{ch\ local}$

$\rho_{ch\ local}$ gives expected reduction of flow contribution to the δp_T width

ALICE