Flow fluctuations in heavy-ion collisions

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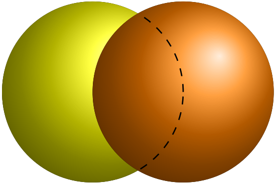
OUTLINE: FLOW FLUCTUATIONS

TAKE-AWAY MESSAGES

- Flow encompasses more phenomena than previously realized.
- New flow observables will tightly constrain models.

(Elliptic) Flow *c. QM09*



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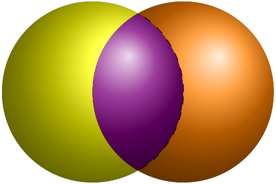

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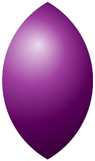

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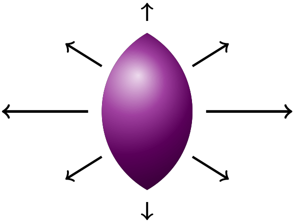
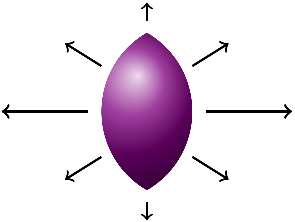
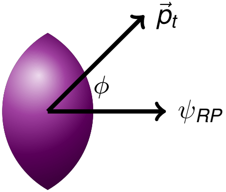


Azimuthal distribution of emitted particles :



Azimuthal distribution of emitted particles :

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2\phi + 2v_4 \cos 4\phi + \ldots$$



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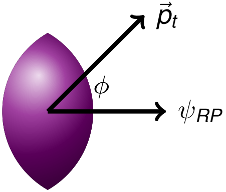

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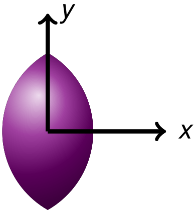

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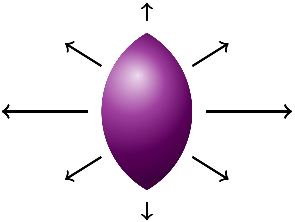

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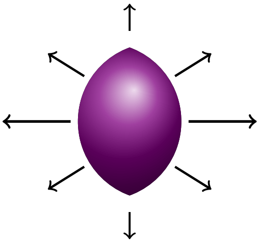

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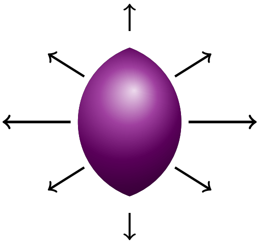
$$\left\langle \langle e^{i2(\phi_1 - \phi_2)} \rangle \right\rangle$$



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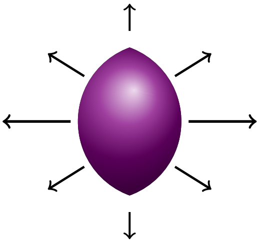

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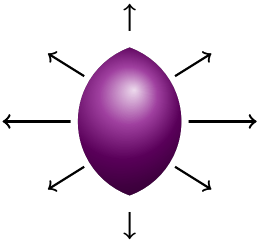

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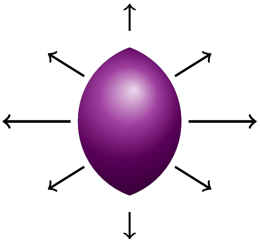

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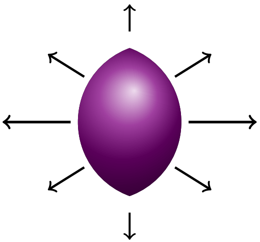
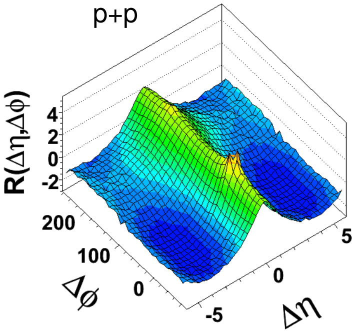
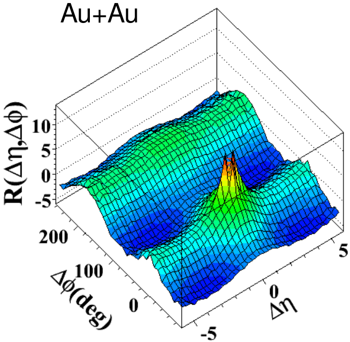
$$\left\langle \frac{dN_{\text{pairs}}}{d\Delta\phi} \right\rangle \overset{\text{(flow)}}{\propto} 1 + \left\langle {v_2}^2 \right\rangle \cos 2(\Delta\phi) + \left\langle {v_4}^2 \right\rangle \cos 4(\Delta\phi) + \ldots$$



Two-particle correlations

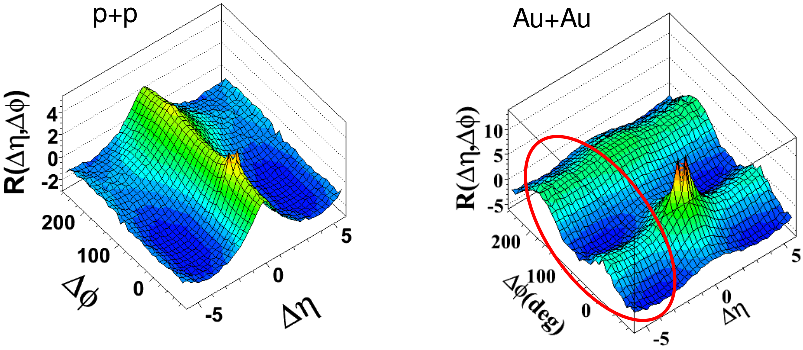
Unique long-range correlations in heavy-ion collisions...





(PHOBOS, Phys. Rev. C75(2007)054913)

Unique long-range correlations in heavy-ion collisions. . .



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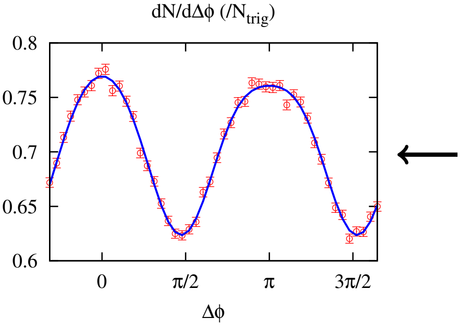

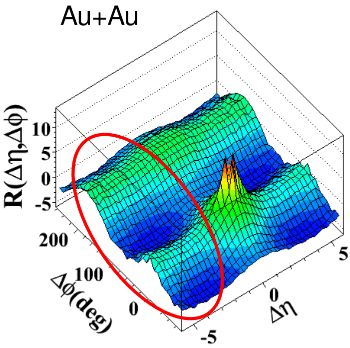

(STAR, arXiv:1010.0690)

(PHOBOS, Phys.Rev. C81 (2010) 024904)

TWO-PARTICLE CORRELATIONS

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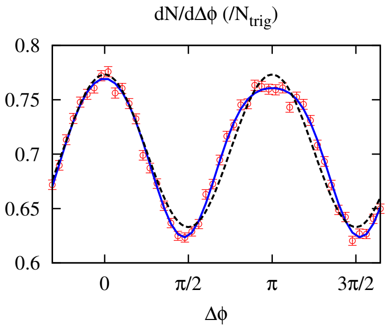

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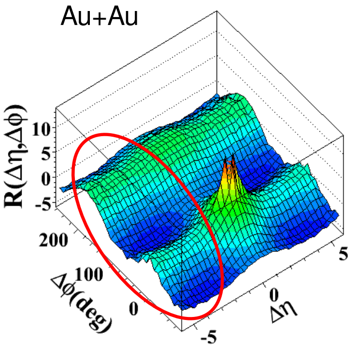

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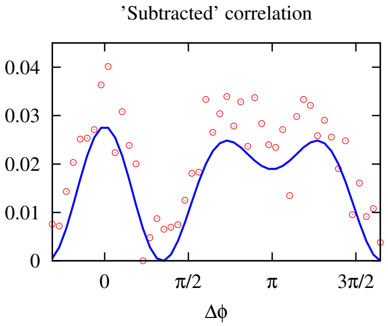

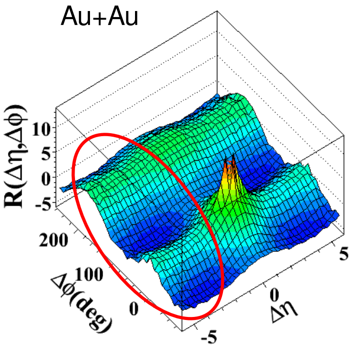

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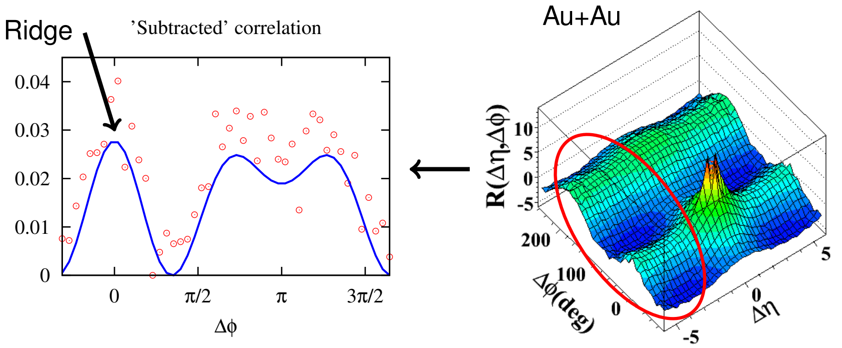

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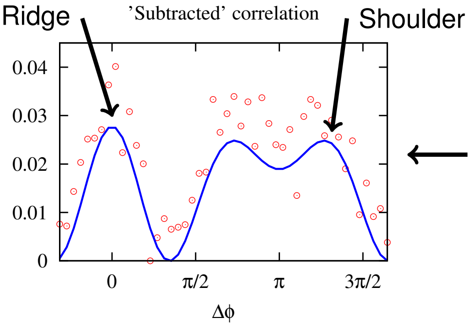

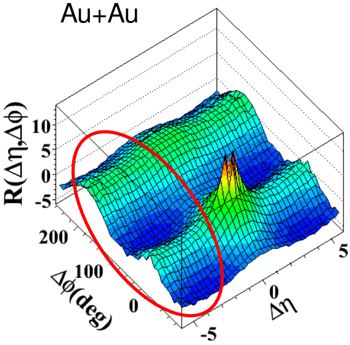

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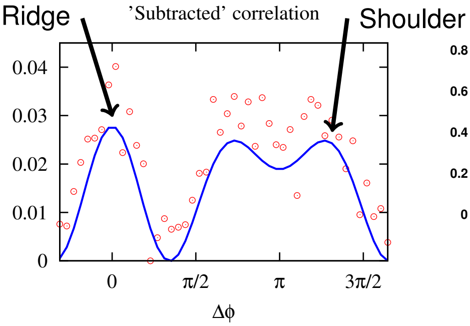

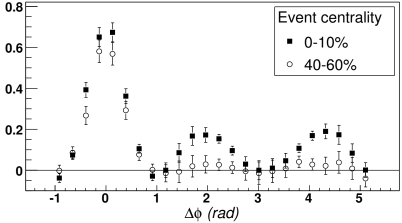

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(Takahashi, Tavares, Andrade, Grassi, Hama, Kodama, Xu, Phys.Rev.Lett.103, 242301 (2009))

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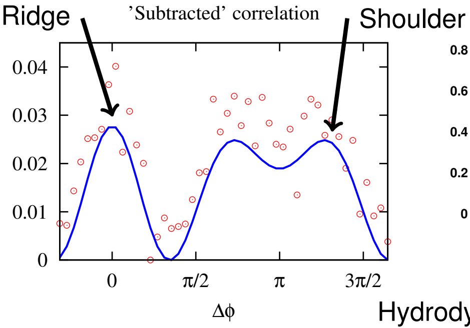

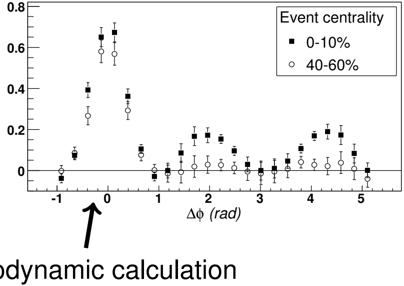

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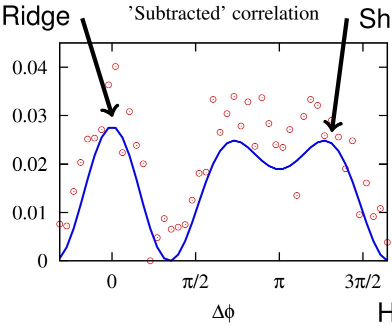

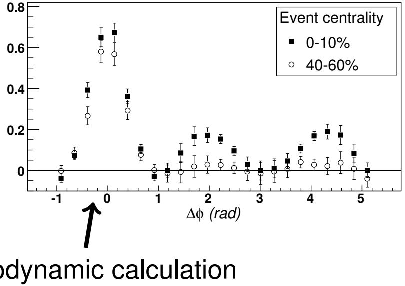

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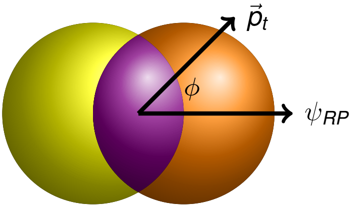

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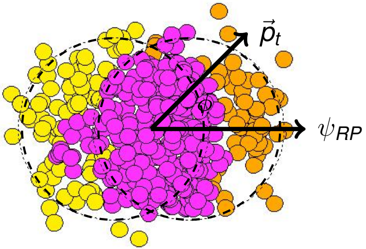
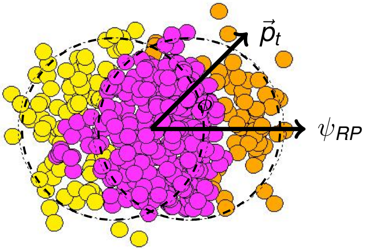


Flow fluctuations

$$\frac{dN}{d\phi} \propto 1 + 2v_1 \cos\phi \qquad + 2v_2 \cos 2\phi \qquad + 2v_3 \cos 3\phi + \ldots$$



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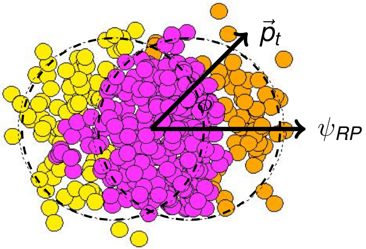
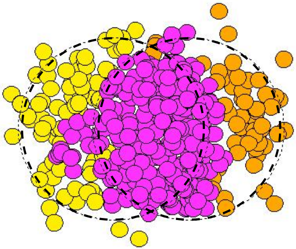
$$\frac{dN}{d\phi} \propto 1 + 2v_1 \cos\phi + 2v_1^s \sin\phi + 2v_2 \cos 2\phi + 2v_2^s \sin 2\phi + 2v_3 \cos 3\phi + \ldots$$



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



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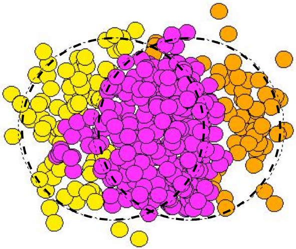

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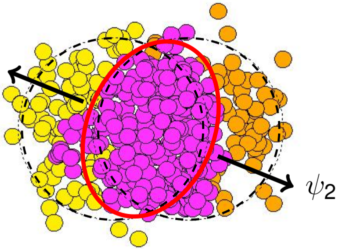

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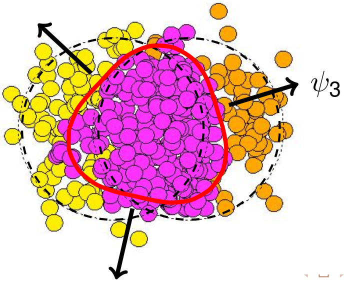

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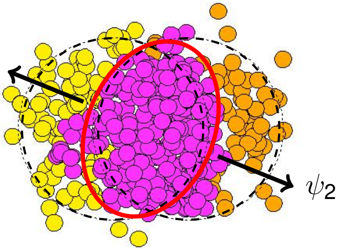
$$v_2 e^{2i\psi_2} \propto \varepsilon_2 e^{2i\Phi_2} \equiv -\frac{\{r^2 e^{2i\phi}\}}{\{r^2\}}$$

(Holopainen, Niemi, Eskola, Phys.Rev.C83, 034901 (2011))



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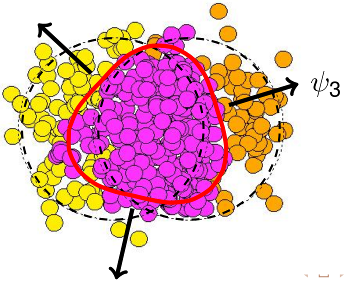
$$v_3 e^{3i\psi_3} \propto \varepsilon_3 e^{3i\Phi_3} \equiv -\frac{\{r^3 e^{3i\phi}\}}{\{r^3\}}$$

(Qin, Petersen, Bass, Muller, Phys. Rev. C 82, 064903 (2010); Qiu, Heinz, arXiv:1104.0650)



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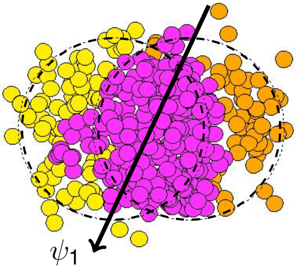
$$v_1 e^{i\psi_1} \propto \varepsilon_1 e^{i\Phi_1} \equiv -\frac{\{r^3 e^{i\phi}\}}{\{r^3\}}$$

(Teaney & Yan, arXiv:1010.1876; Gardim, Grassi, Hama, Luzum, Ollitrault, arXiv:1103.4605)



Flow explains long-range correlations

Quantitative evidence of flow hypothesis:

1. Centrality dependence, size, of v_3 and v_2
   (Alver & Roland, Phys.Rev. C81 (2010) 054905)
2. p_t-dependence and orientation with respect to event plane
   (Luzum, Phys.Lett. B696 (2011) 499-504)
   (Luzum & Ollitrault, Phys.Rev.Lett. 106 (2011) 102301)
3. Centrality dependence of “ridge amplitude”
   (Sorensen, Bolliet, Mocsy, Pandit, Pruthi, arXiv:1102.1403)
4. Factorization, mass dependence, . . .
   (See plenary/parallel talks from ALICE, ATLAS, CMS, . . .)

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$$* \langle \cos \Delta\phi \rangle = v_1^{(t)} v_1^{(a)} - \frac{p_t^{(t)} p_t^{(a)}}{\langle \sum p_t^2 \rangle}$$

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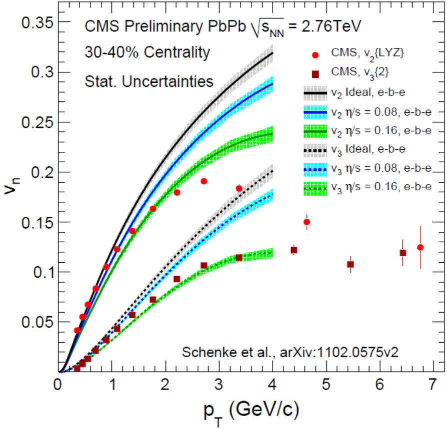
Current long-range 2-particle data can be explained by flow alone*.

$\Longrightarrow$ can accurately measure many new flow observables with little non-flow contamination

New flow observables: v_3, v_4, v_5, ...

CMS preliminary, Velkovska plenary

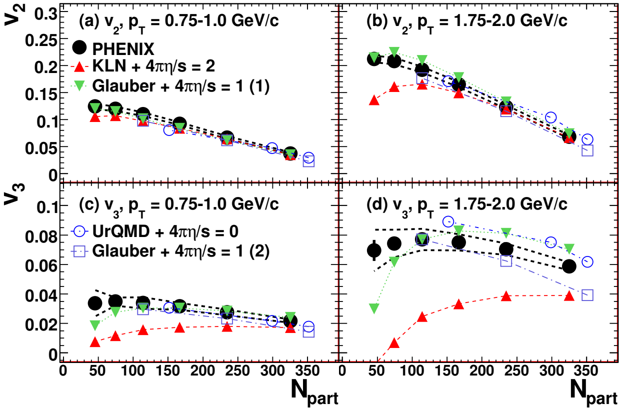


Lessons:

v_3 is a more sensitive probe of η/s

New flow observables: v_3, v_4, v_5, ...

PHENIX, arXiv:1105.3928



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Combining v_2 and v_3 can rule out IC models

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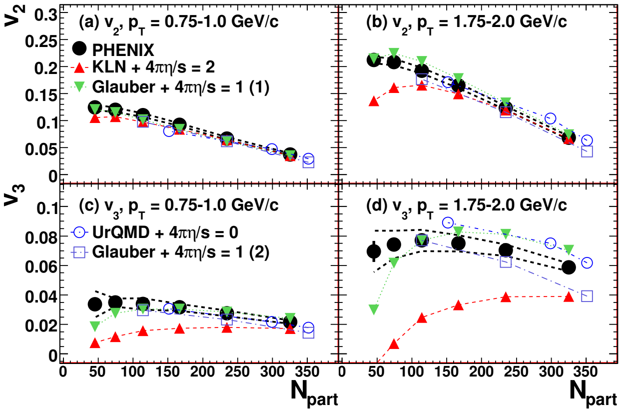
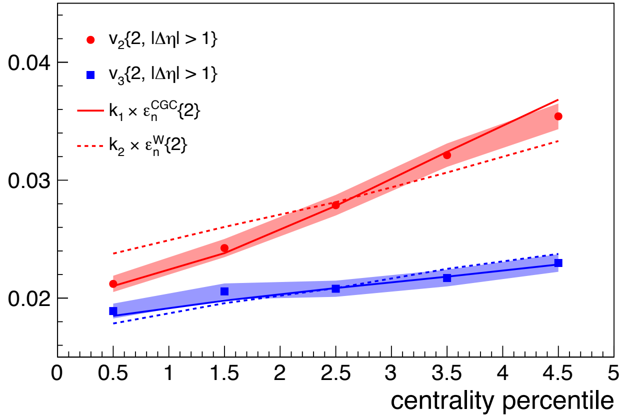


Lessons:

Combining v_2 and v_3 can rule out IC models (CGC is *not* ruled out)

ALICE, arXiv:1105.3865

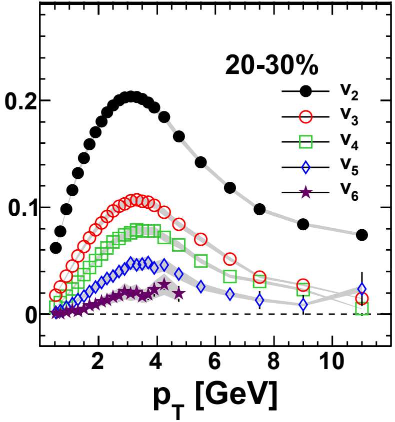


LESSONS:

Glauber may not work either

NEW FLOW OBSERVABLES: v_3, v_4, v_5, ...

ATLAS, Jia plenary

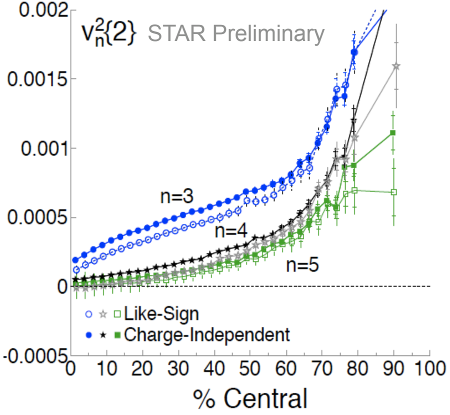


LESSONS:

Higher coefficients are measurable and add more constraints

NEW FLOW OBSERVABLES: v_3, v_4, v_5, . . .

STAR preliminary, Sorensen plenary



LESSONS:

Stay tuned (see Paul Sorensen's talk later this session)

Other flow observables

Many other independent flow observables can be measured:

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- $\Longrightarrow$ flow has further-reaching effects than was previously realized
- With this understanding comes many new possible independent flow measurements
- In the near future, look for more precise extraction of medium properties (e.g., η/s) in addition to strong constraints on geometry and fluctuations of the early-time evolution.

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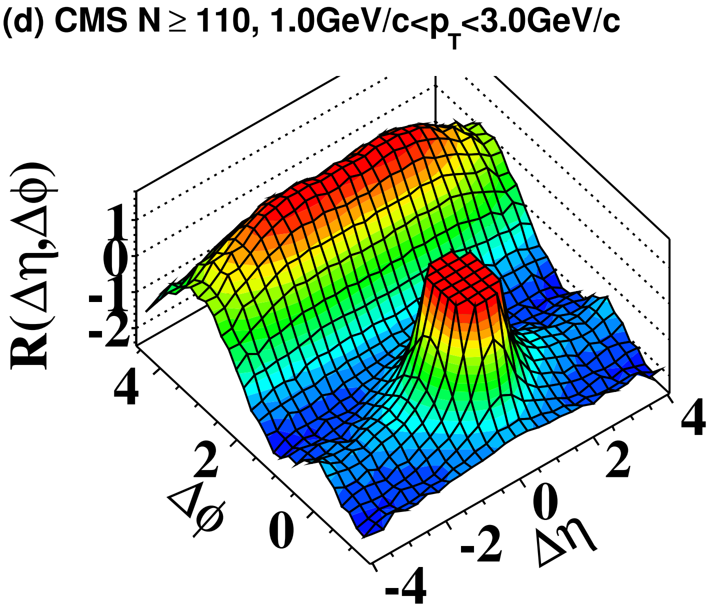
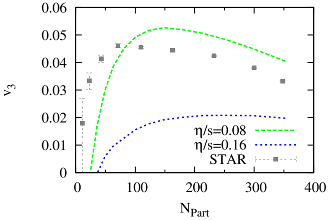
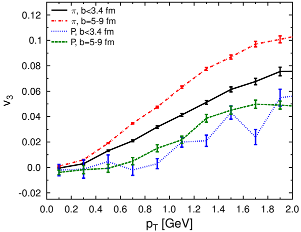

(d) CMS N ≥ 110, 1.0GeV/c<p_T<3.0GeV/c
R(Δη,Δφ)
1
0
-1
-2
4
2
Δφ
0
-4
-2
0
2
4
Δη

New flow observables: triangular flow

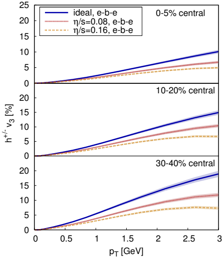
Predictions:



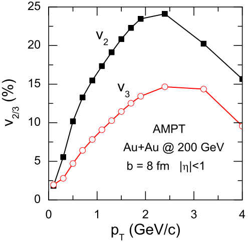
(Alver, Gombeaud, Luzum, Ollitrault, Phys.Rev. C82 (2010) 034913)



(Petersen, Qin, Bass, Muller, Phys.Rev. C82 (2010) 041901)



(Schenke, Jeon, Gale, Phys.Rev.Lett. 106 (2011) 042301)



(Xu, Ko Phys.Rev. C83 (2011) 021903)

Still missing: new v_1 from fluctuations *(Teaney & Yan, arXiv:1010.1876)*

- $v_1 = v_1^a + v_1^s$
- $v_1^a(\eta) = -v_1^a(-\eta)$ = usual directed flow
- $v_1^s(\eta) = v_1^s(-\eta)$ = new "directed flow at midrapidity"
- To measure from a 2-particle correlation, must remove "momentum conservation" correlation *(Luzum, Ollitrault, Phys.Rev.Lett.106:102301,2011)*

NEW FLOW OBSERVABLES: DIRECTED FLOW AT MIDRAPIDITY

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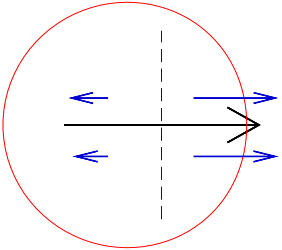

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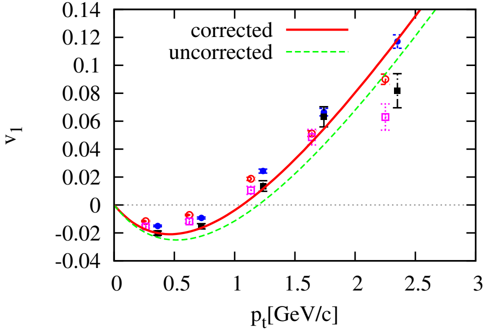

(Gardim, Grassi, Hama, Luzum, Ollitrault, arXiv:1103.4605)