Estimation of electric conductivity of QGP via asymmetric heavy-ion collisions
[arXiv:1211.1114]

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Properties of quark gluon plasma

Properties of quark gluon plasma

Viscosity (shear/bulk)
Elastic modulus

EOS
- sound velocity
- specific heat

…

Jet stopping power

Temperature

Diffusion constants

Dielectric constant
Magnetic permeability

Electric conductivity

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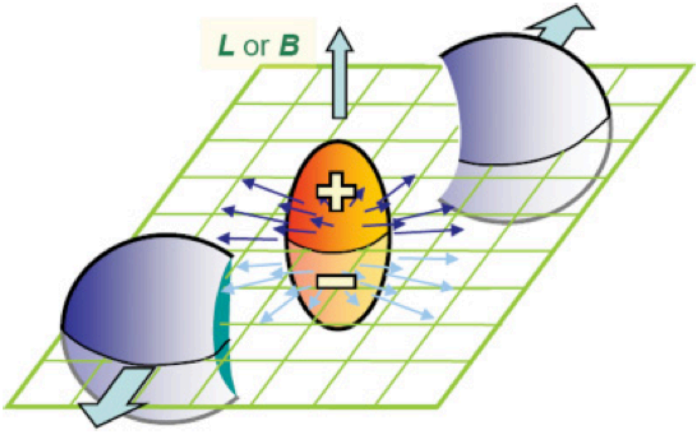
Electric conductivity can be estimated via asymmetric HIC!
[arXiv:1211.1114]

Outline

- Introduction
- Idea
- Electric fields in Cu-Au collisions
- Observable sensitive to the electric conductivity
- Summary

Electromagnetic fields in HIC

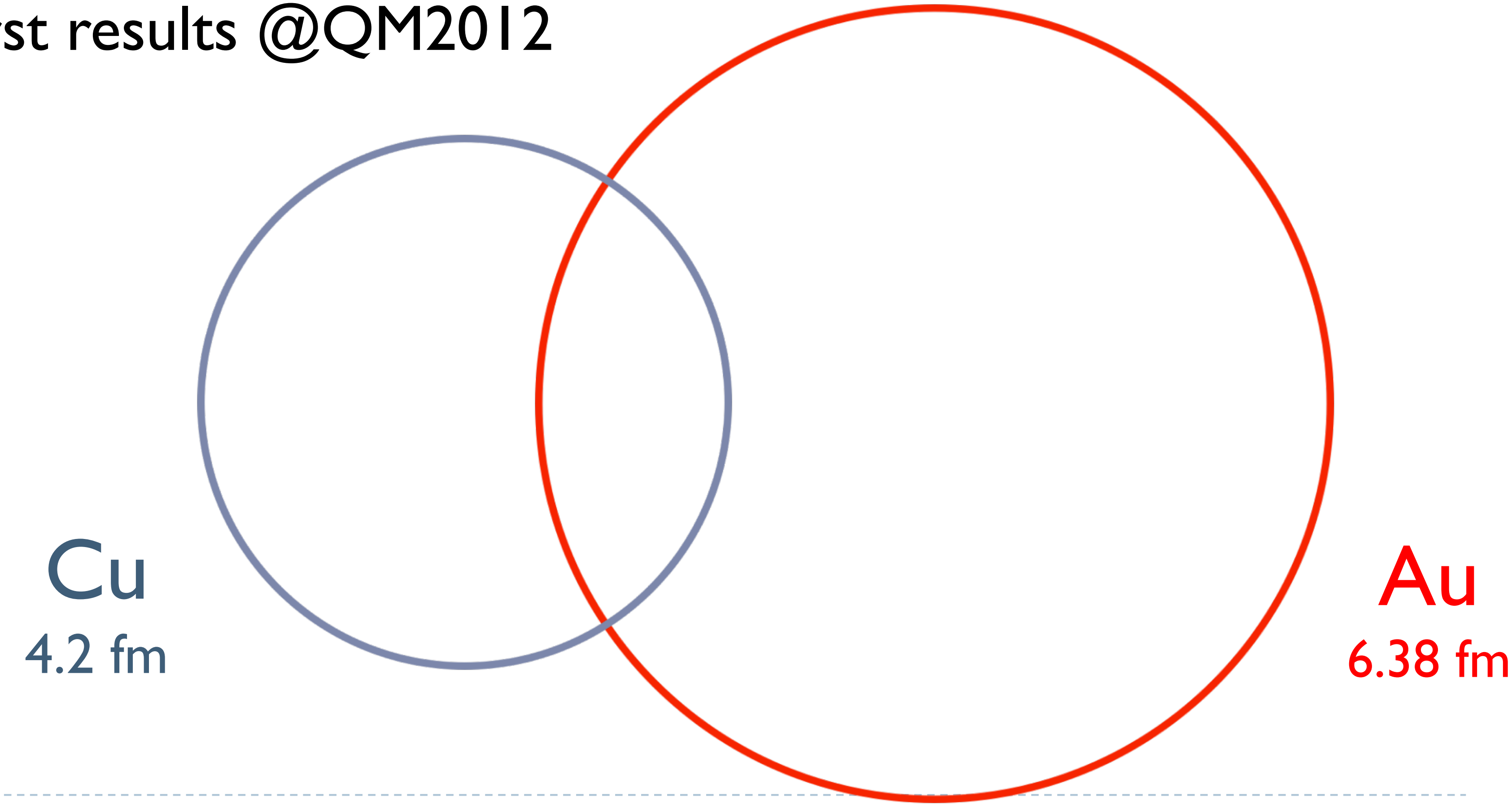
- Magnetic fields in off-central collisions
  - $e|\vec{B}| \sim m_\pi^2 \sim 10^{14}\ \mathrm{T}$
  - Neutron star $10^{8}\ \mathrm{T}$
  - Magnetar $10^{11}\ \mathrm{T}$



- Electric fields also exist
  - $e|\vec{E}| \sim m_\pi^2$
  - [A. Bzdak and V. Skokov, Phys. Lett. B 710, 171 (2012)]
  - [W. -T. Deng and X. -G. Huang, Phys. Rev. C 85, 044907 (2012)]
  - …

Asymmetric collisions

- Cu-Au collisions @RHIC
- Asymmetric in transverse plane & longitudinal direction
- First results @QM2012

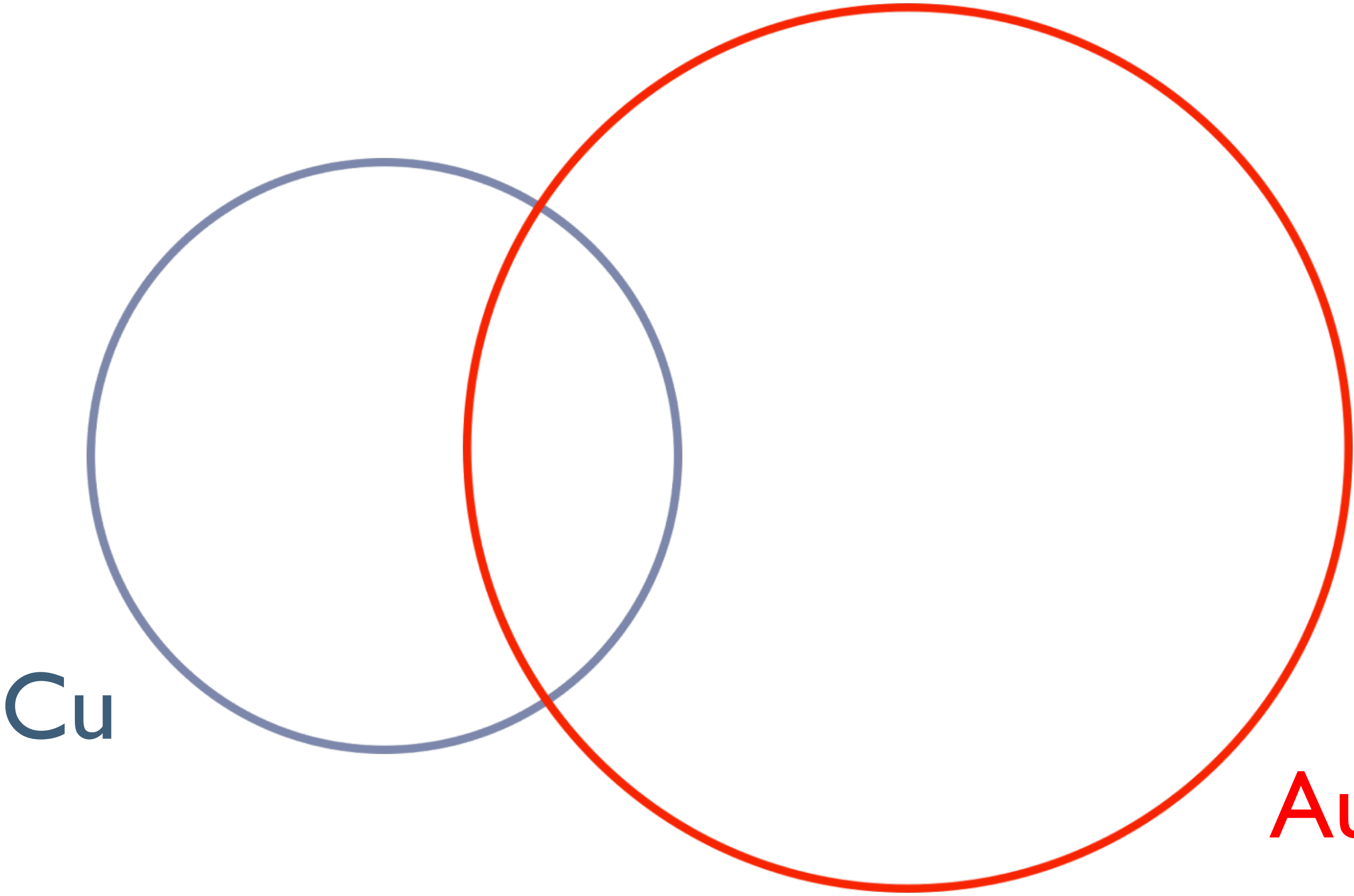


Idea

Number of protons

Cu: 29

Au: 79



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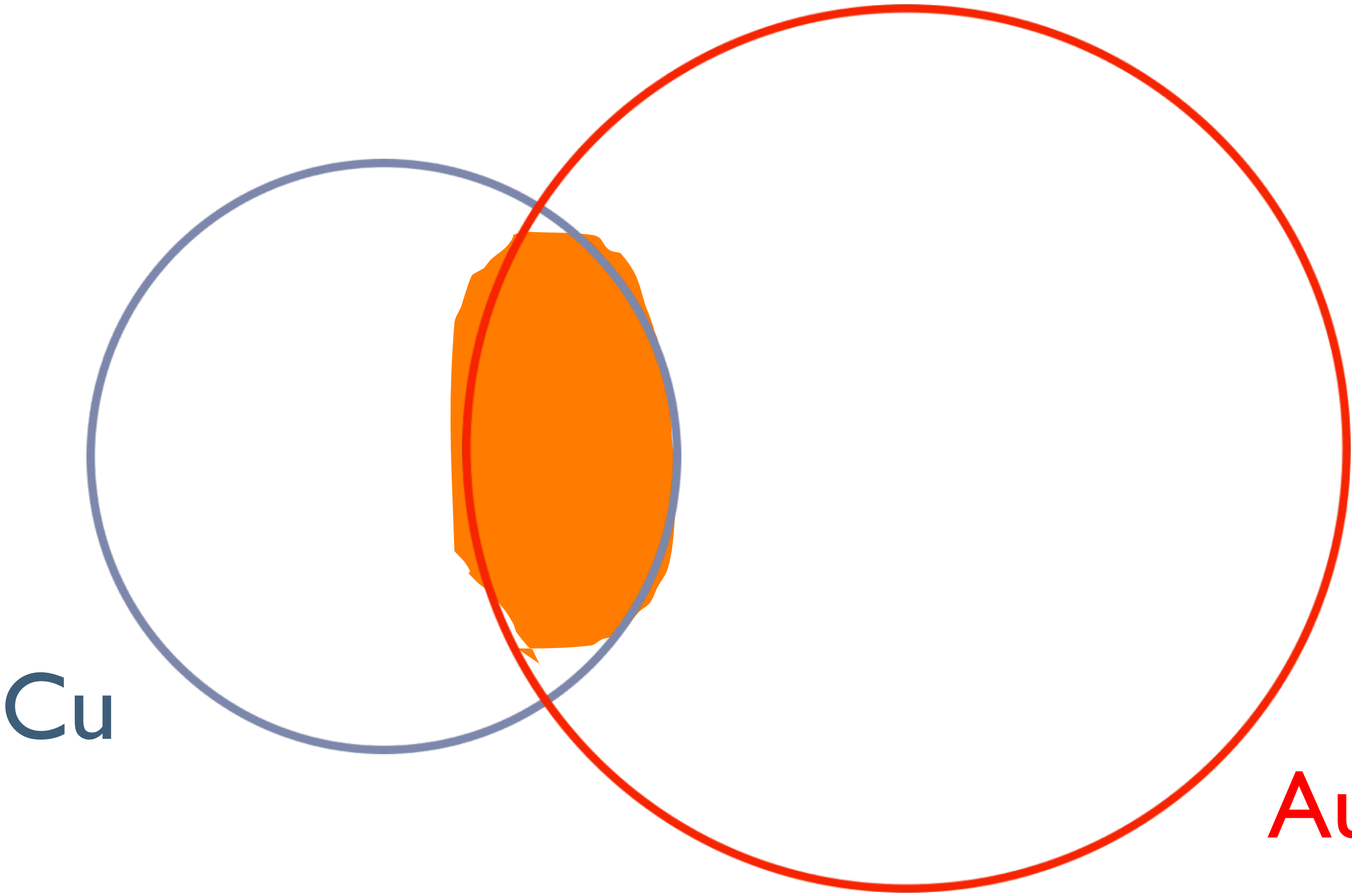

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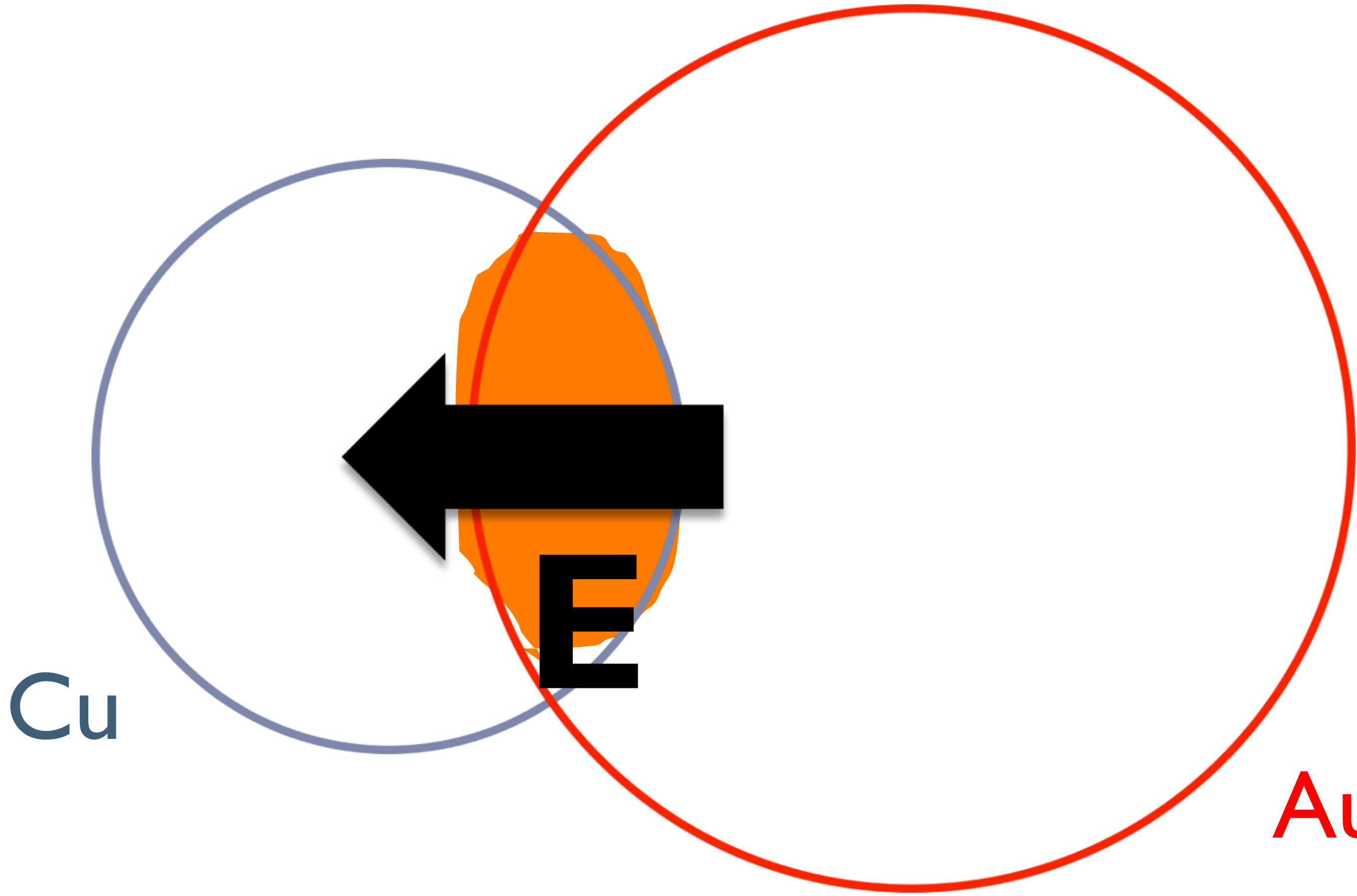

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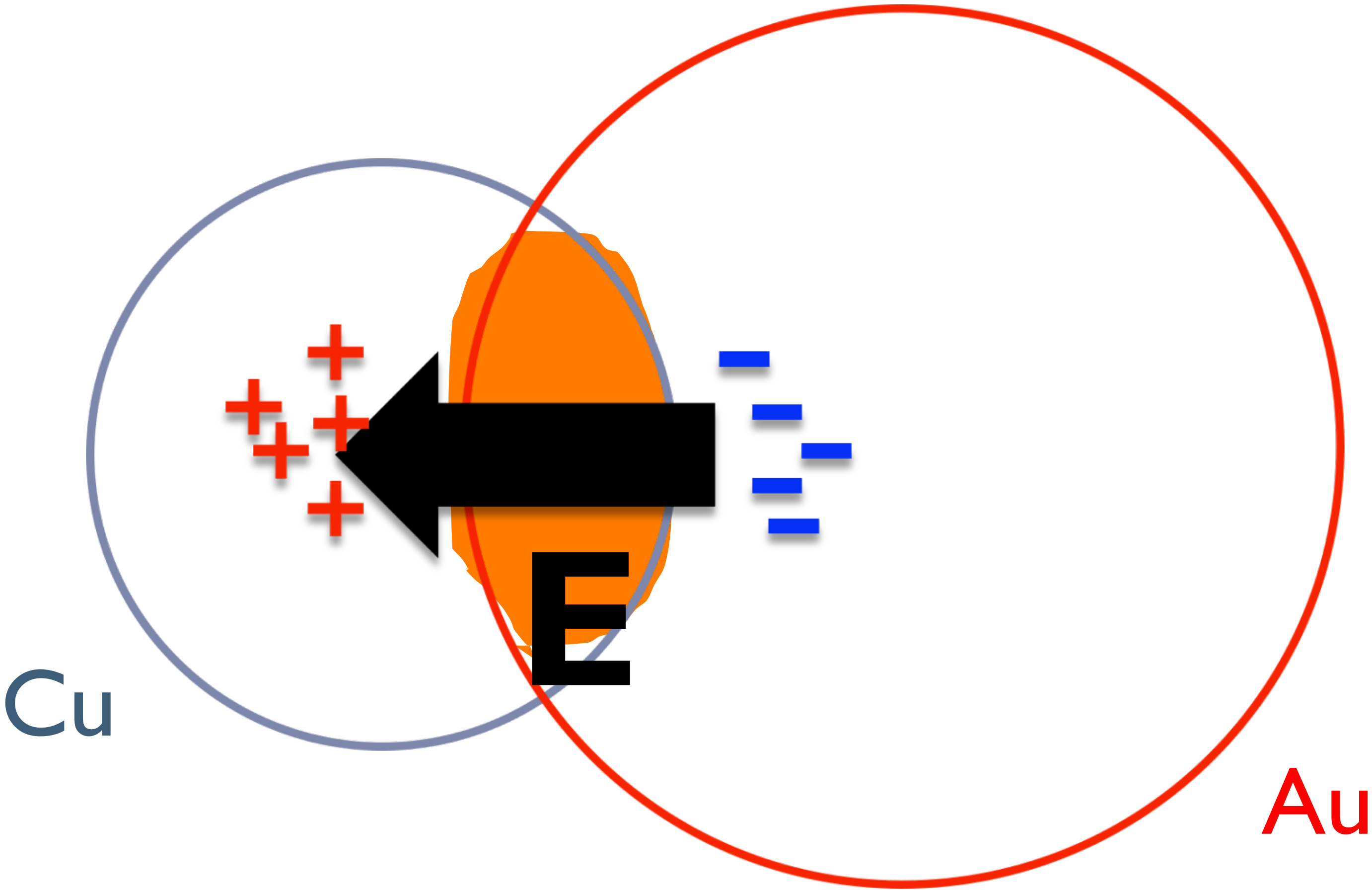
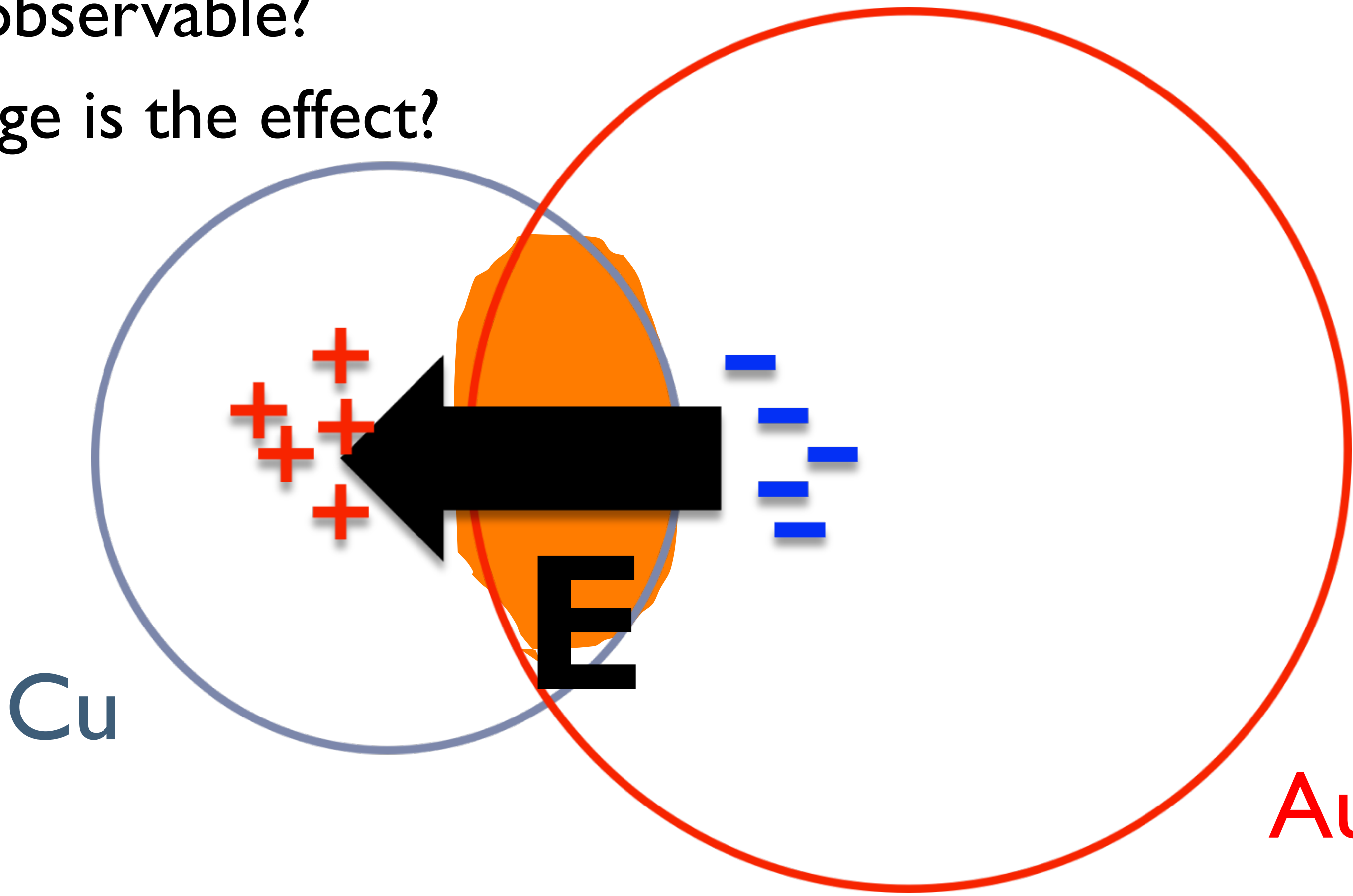


Idea

- Is the electric field actually created?
- Which observable?
- How large is the effect?



Electric fields in Cu-Au collisions

Electromagnetic fields in Cu-Au collisions

- Lienard-Wiechert potential

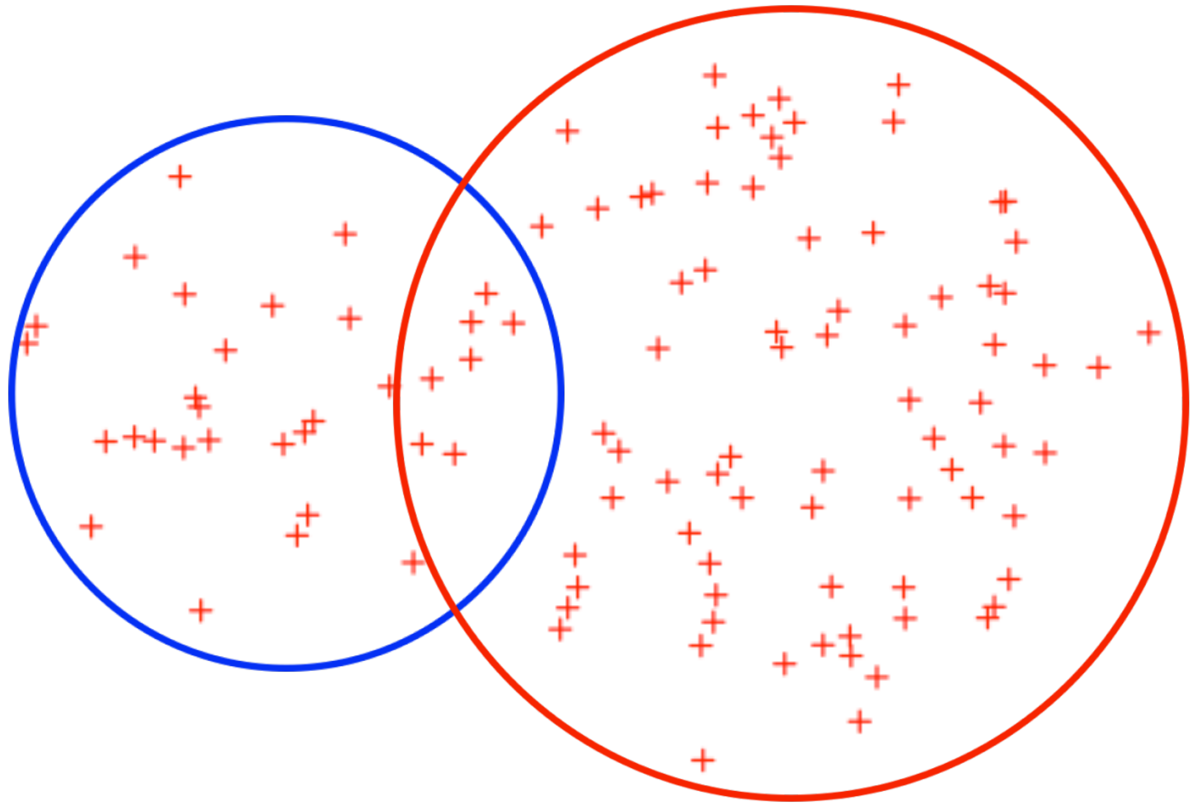
$$|e|\vec{E}(t,\vec{x}) = \alpha_{\mathrm{EM}} \sum_n \frac{1-v_n^2}{R_n^3\left[1-(\vec{R}_n \times \vec{v}_n)^2/R_n^2\right]^{3/2}} \vec{R}_n$$

$$|e|\vec{B}(t,\vec{x}) = \alpha_{\mathrm{EM}} \sum_n \frac{1-v_n^2}{R_n^3\left[1-(\vec{R}_n \times \vec{v}_n)^2/R_n^2\right]^{3/2}} \vec{v}_n \times \vec{R}_n$$

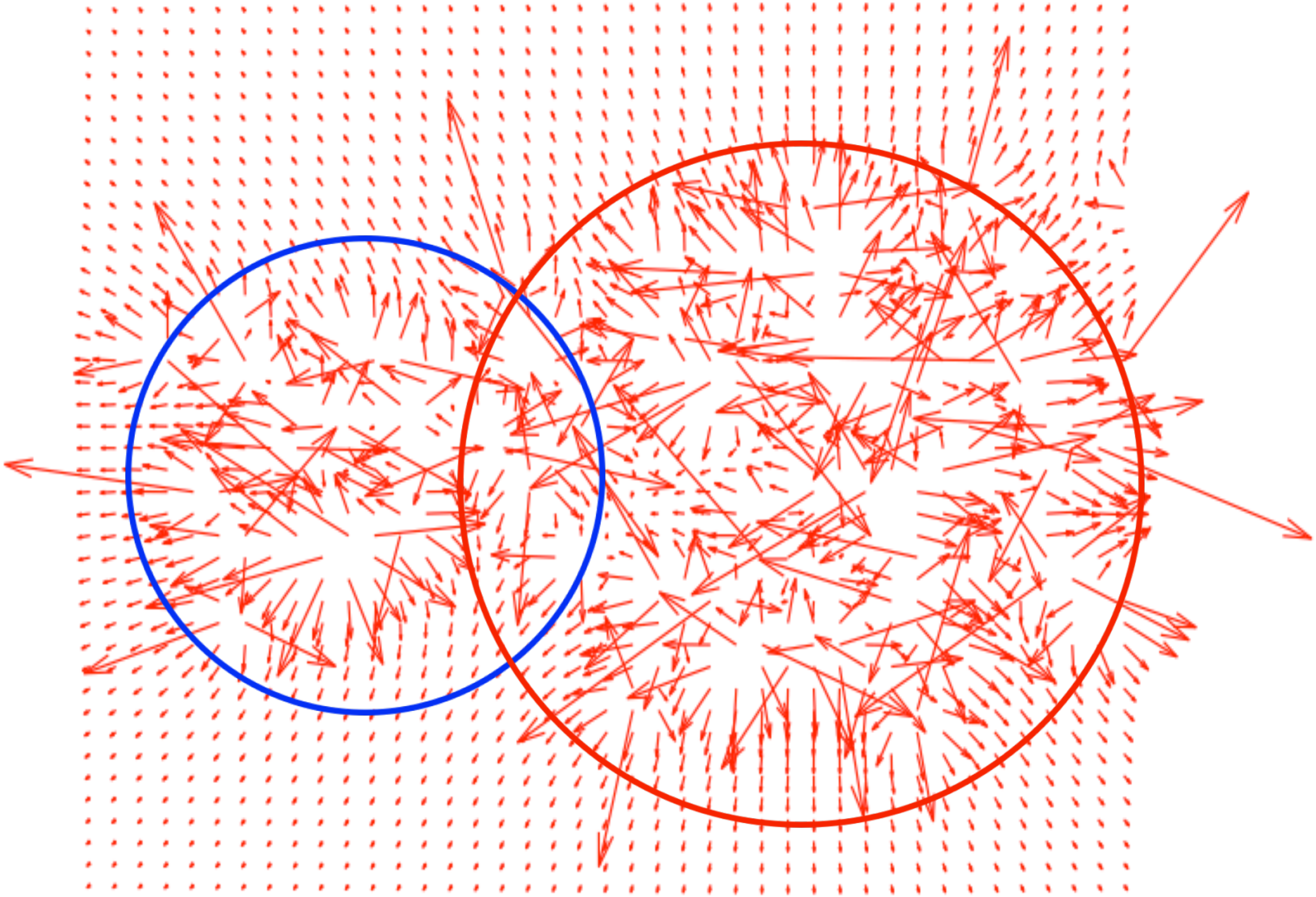
$\vec{R}_n \equiv \vec{x} - \vec{x}_n(t)$ $\quad$ $\vec{x}_n(t)$:position of protons in a nucleus

- Proton distribution in a nucleus: Woods-Saxon distribution

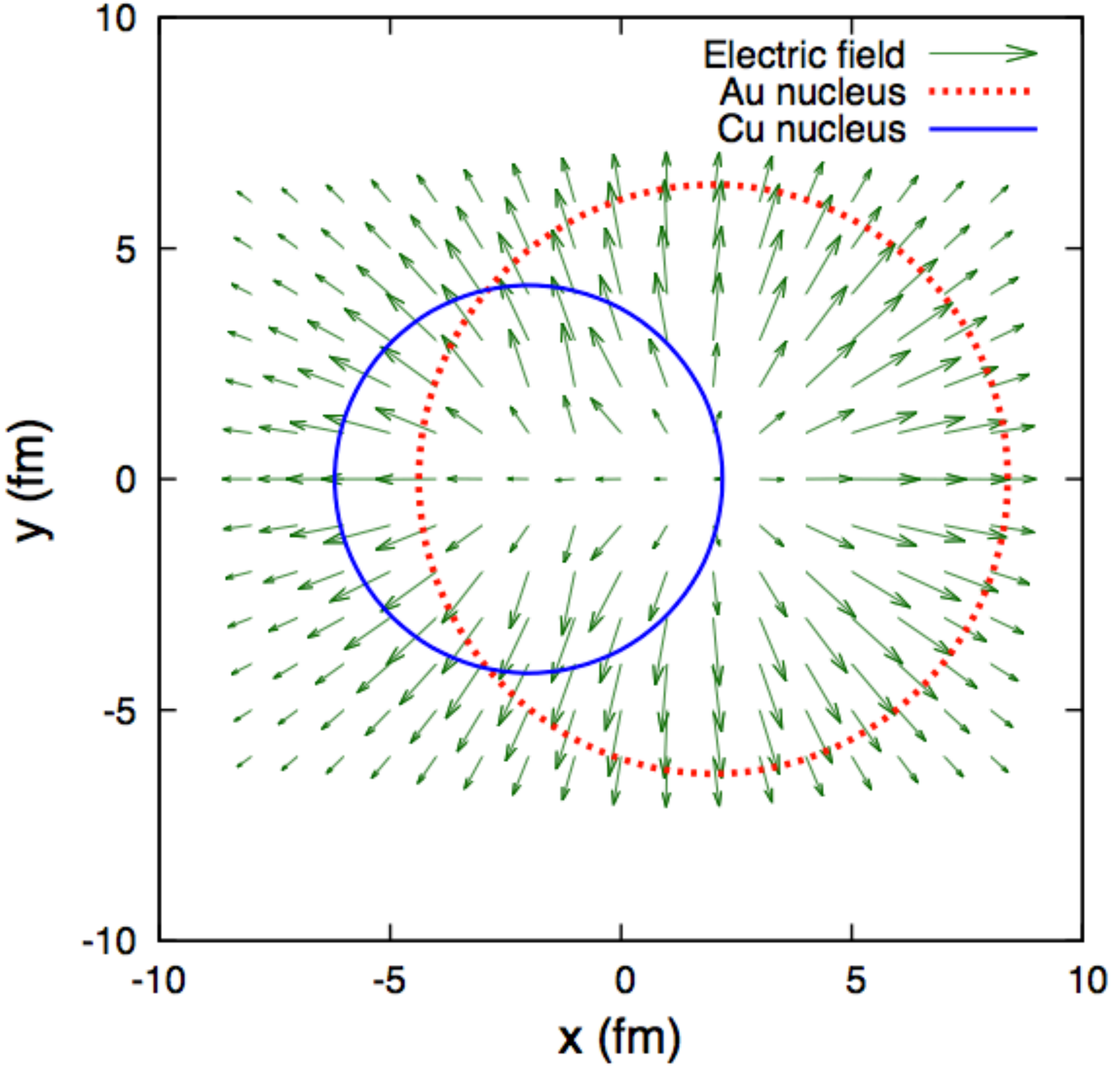
Dist. of protons in Cu-Au collisions



Electric fields (transverse plane)



Event-averaged electric fields



b = 4 fm

# of events: 10000

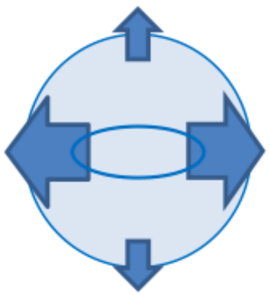
Which observable is sensitive to the conductivity?

Harmonics v_n

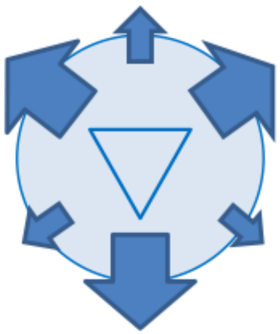
- Azimuthal angle distribution of observed particles

$$\frac{dN}{d\phi} = \bar{N}\left[1 + \sum_{n=1}^{\infty} 2 v_n \cos n(\phi - \Psi_n)\right]$$

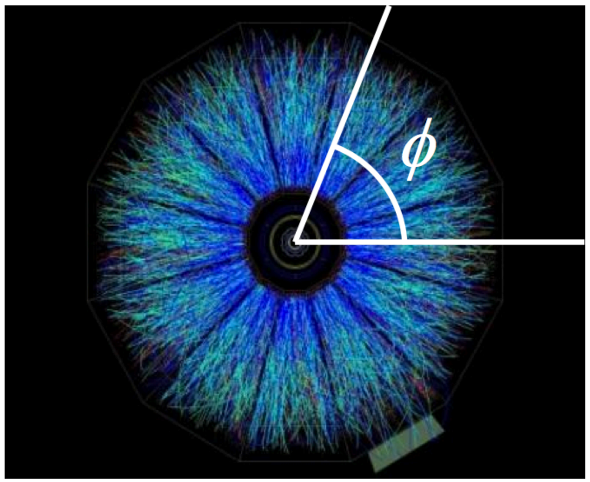
- Reflects the shape of the flow



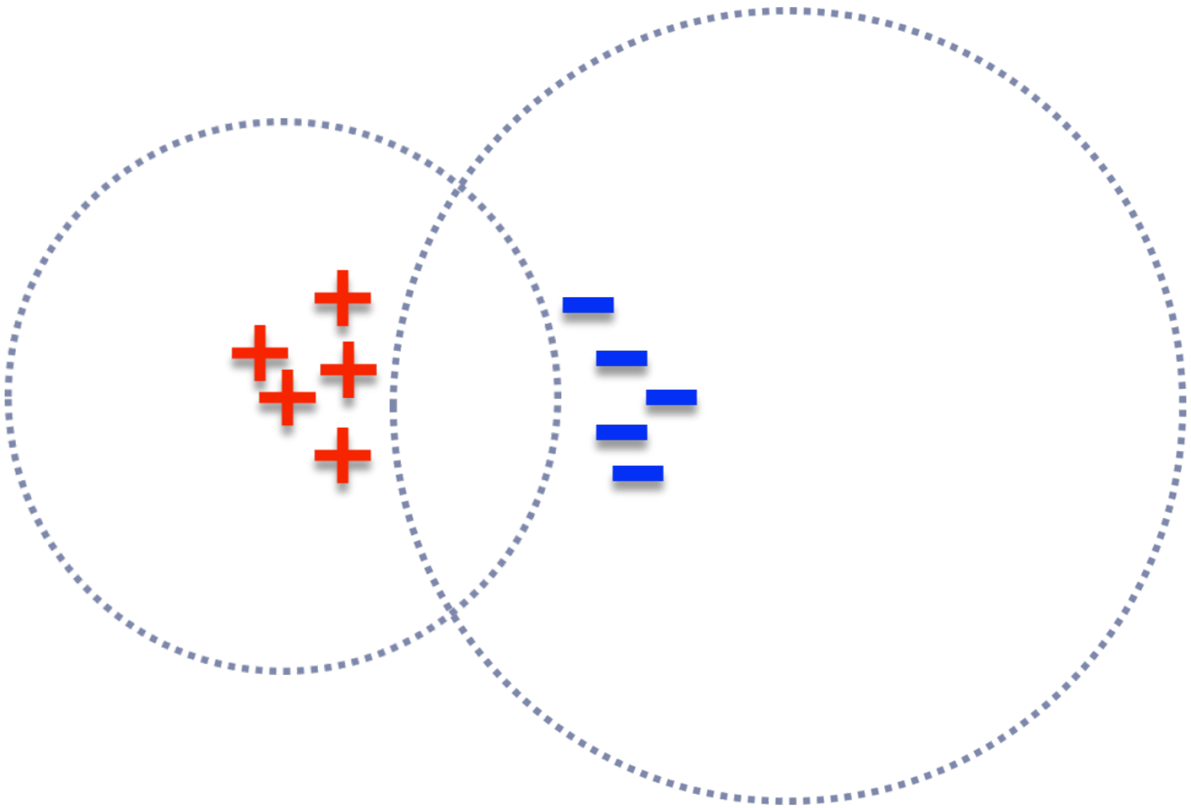
v_2 “elliptic”



v_3 “trianglar”



Observable sensitive to the conductivity



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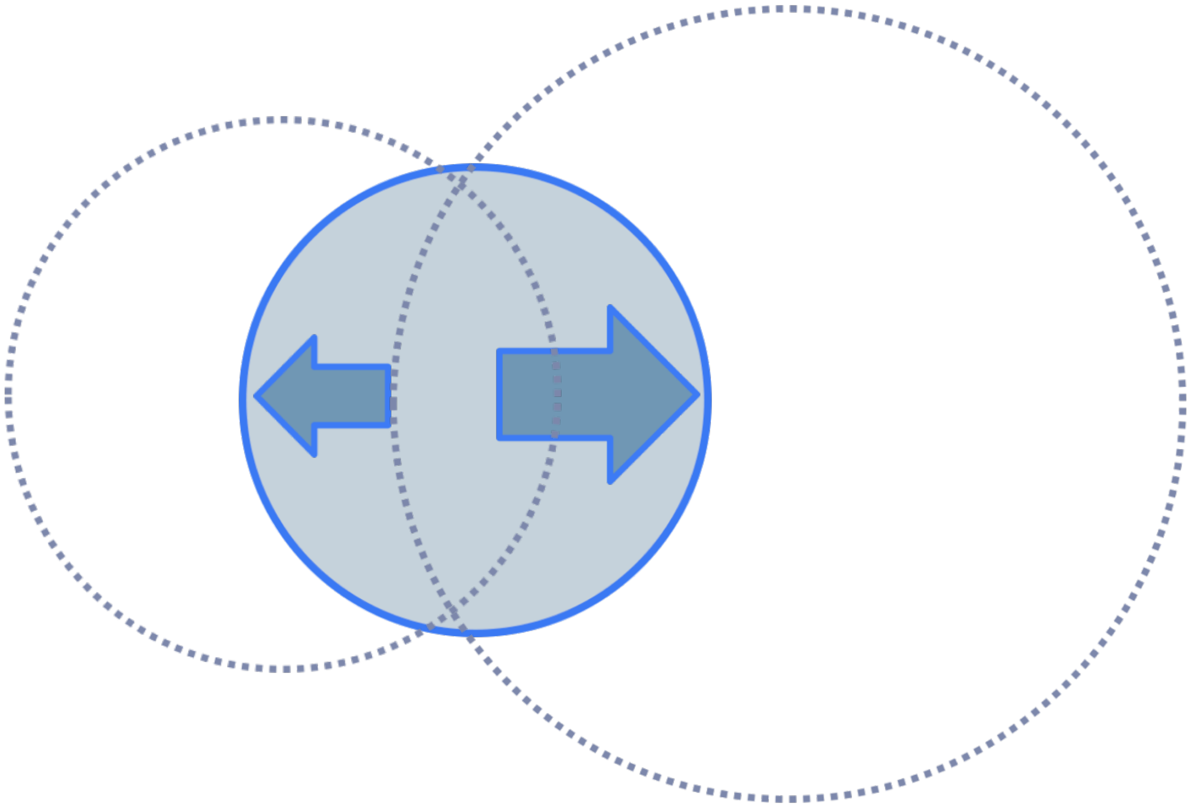

v_1 is charge-dependent

Observable sensitive to the conductivity

- charge-dependent v_1

$$\boxed{v_1^{\pm} = v_1 \pm A d'_e}$$

$$A \equiv (\bar{N}_+ - \bar{N}_-)/(\bar{N}_+ + \bar{N}_-), \quad \bar{N}_\pm \equiv \int \frac{d\phi}{2\pi} \frac{dN_\pm}{d\phi}$$

  - Proportional to charge asymmetry
  - The coefficient quantify the dipole deformation of the charge dist.

$$d'_e = \frac{1}{\bar{N}_+ - \bar{N}_-} \int r dr d\phi \, \cos\phi \, \left[j_e^0(r,\phi) - j^0_{e,\vec{E}=\vec{B}=0}(r,\phi) \right]$$

How large is it?

Theoretical prediction for the conductivity

- Electric conductivity

$$\boxed{\sigma = BC_{\mathrm{EM}}T} \qquad C_{\mathrm{EM}} \equiv \sum_f e_f^2 = 8\pi\alpha_{EM}/3$$

- Lattice QCD
  - $B \simeq 0.4$ [Aarts et. al (2007)][Ding et. al (2011)]
  - $B \simeq 7$ [Gupta (2004)]

- pQCD
  - $\sigma \simeq 6T/e^2$ [Arnold et. al (2003)]
  - $B \sim 10^2$

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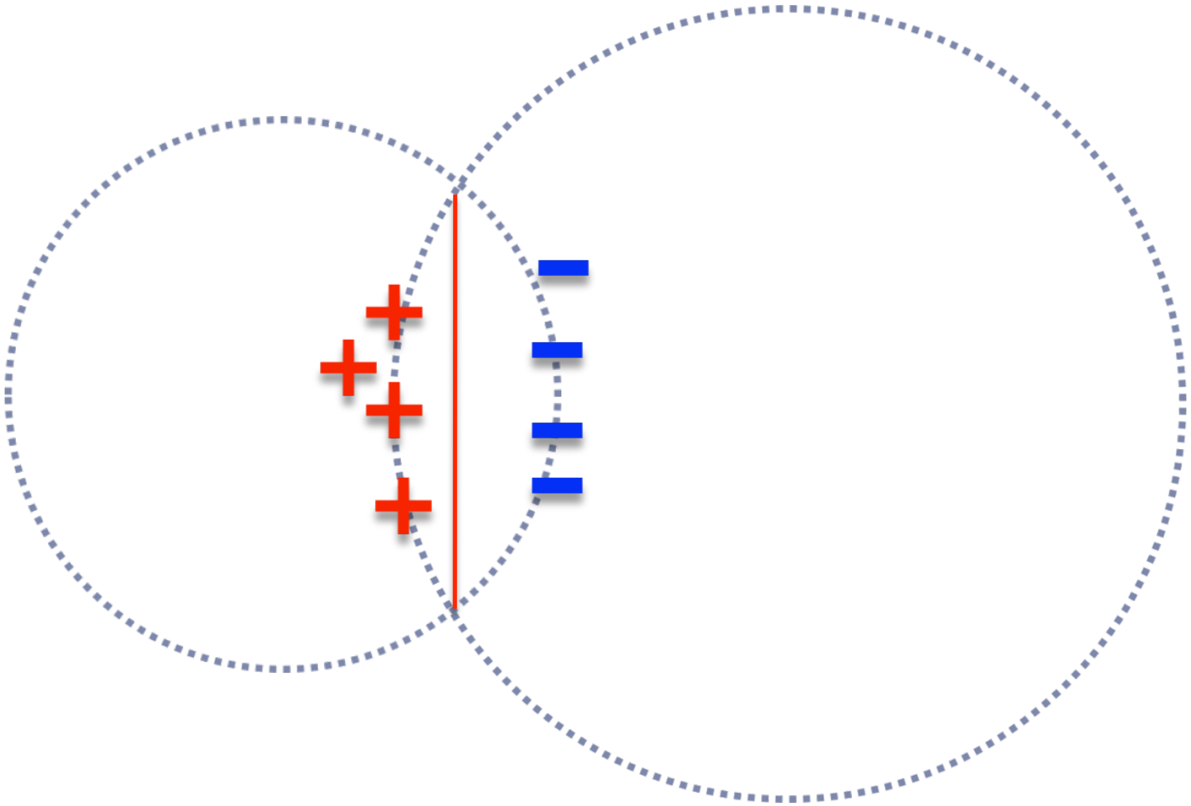
Estimation of the charge-dep. part of v_1



Estimation of the charge-dep. part of v_1

$$\boxed{A d'_e \sim -\frac{\sigma\tau}{N_{\rm tot}|e|}\int_S \vec{E}\cdot d\vec{S}}$$

$$T \sim 200\ \text{MeV},\ \tau \sim 1\ \text{fm}/c,\ N_{\rm tot} \sim 10^3$$

$$\boxed{A d'_e \sim -B \times 10^{-3}}$$

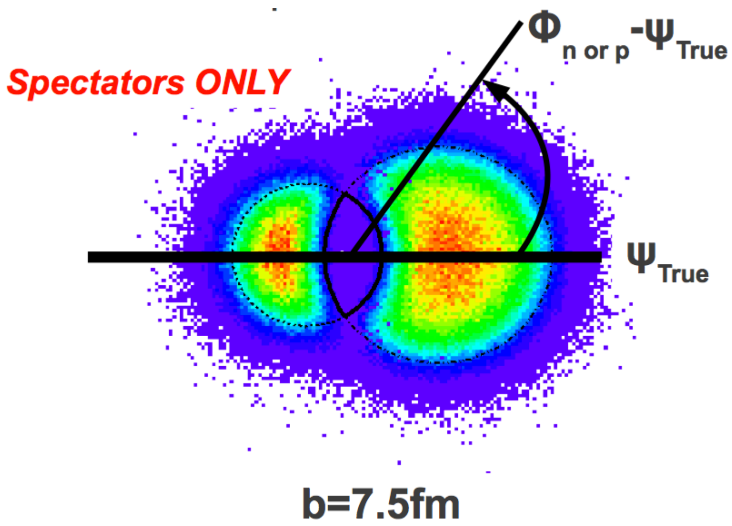
Summary & Outlook

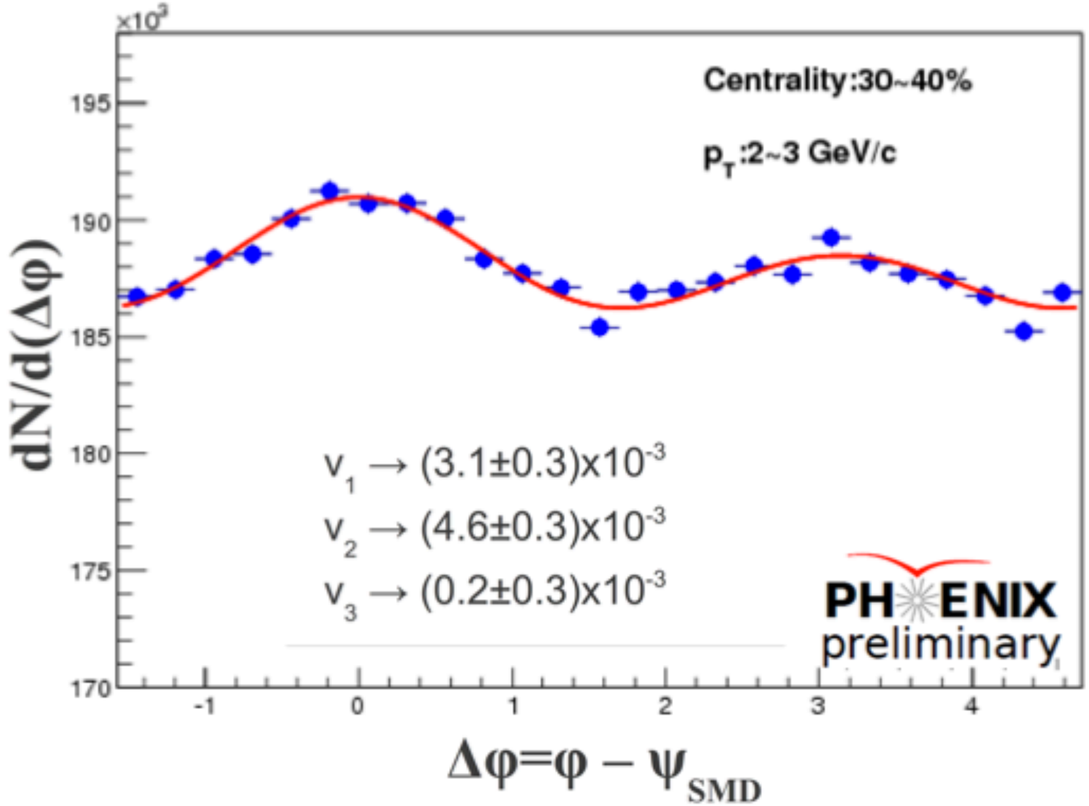
- Electric conductivity of QGP
  - Asymmetric collisions
  - Charge-dependent directed flow $v_1^{\pm} = v_1 \pm A d'_e$
- Outlook
  - More elaborate estimate
    - Time dep. of matter / field
    - Differential signal
      - transverse momentum / rapidity / impact parameter dependence

Back up slides

v_n at Cu+Au collisions

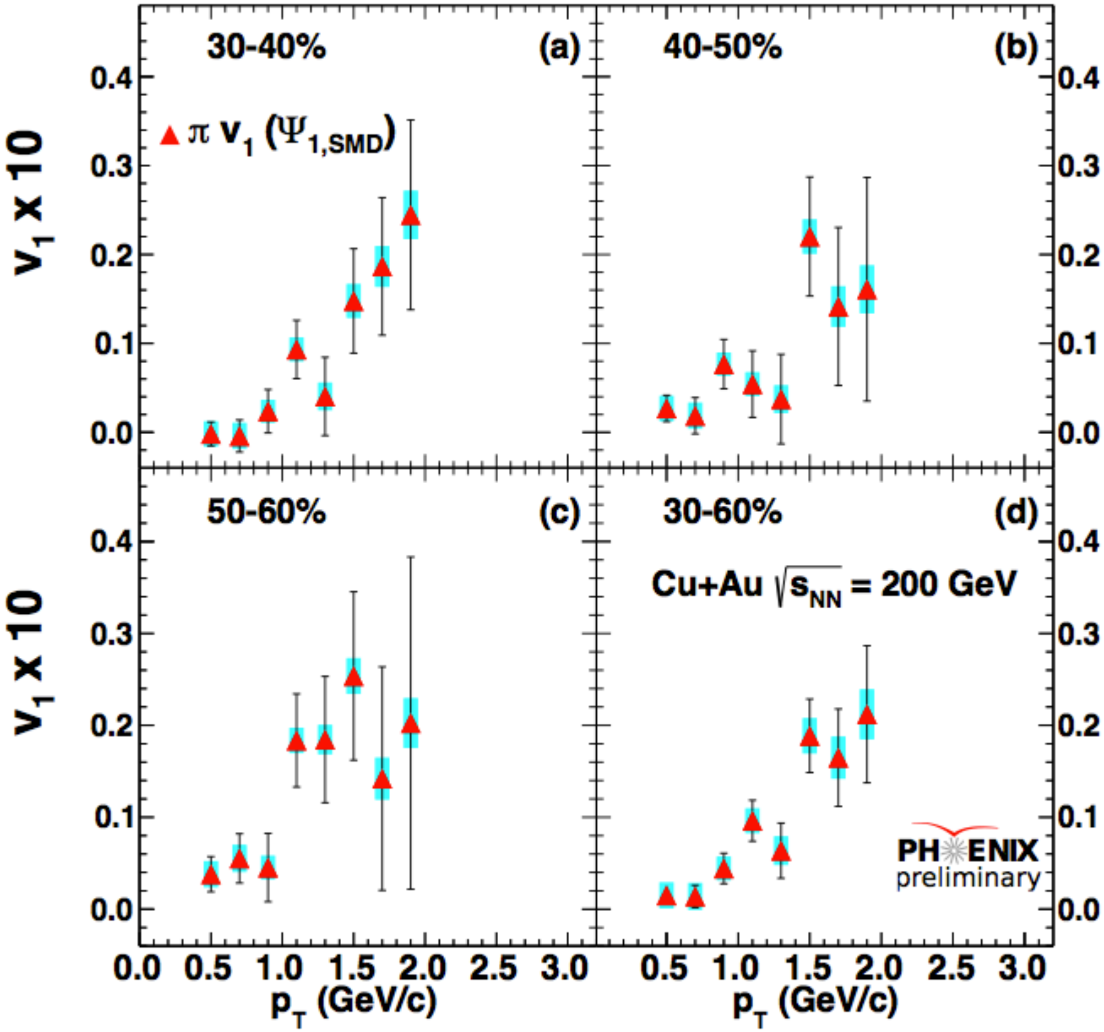
- Results from PHENIX collaboration





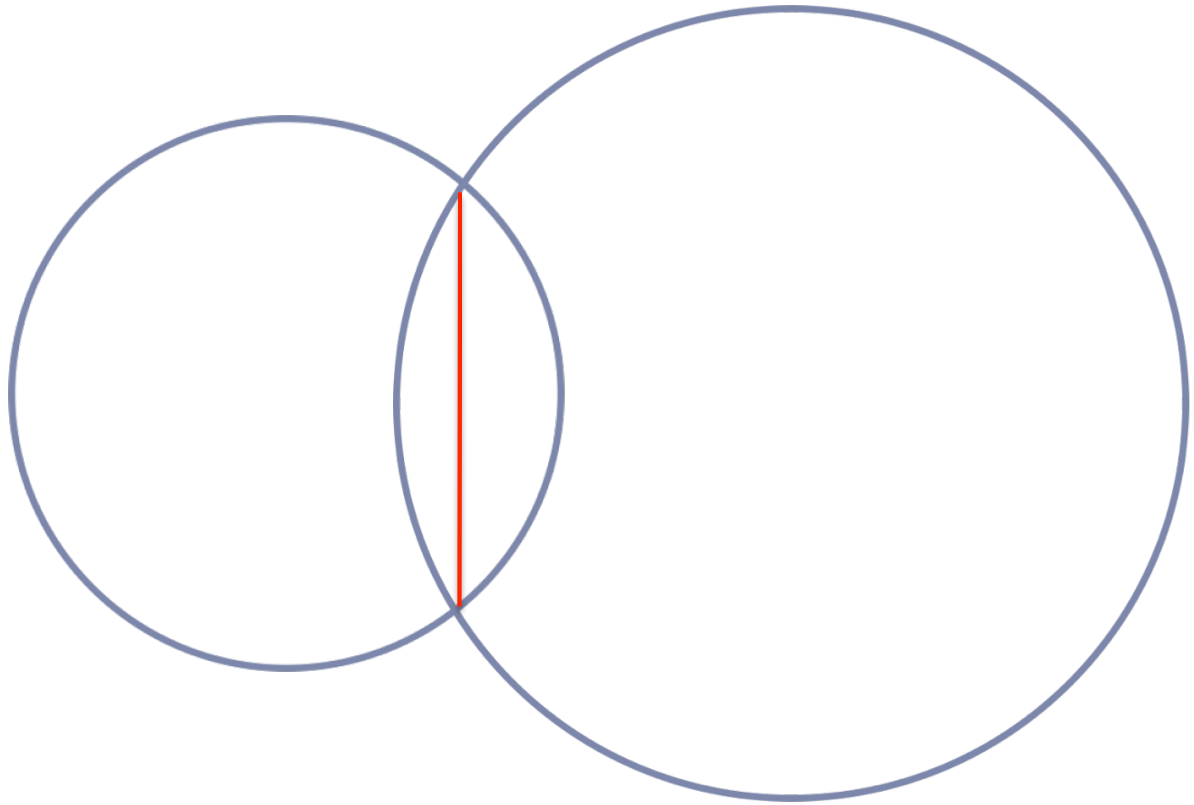
[taken from R. Hollis's slide @ QM12]

v_n at Cu+Au collisions



[1210.5570]

Centrality dependence of electric flux



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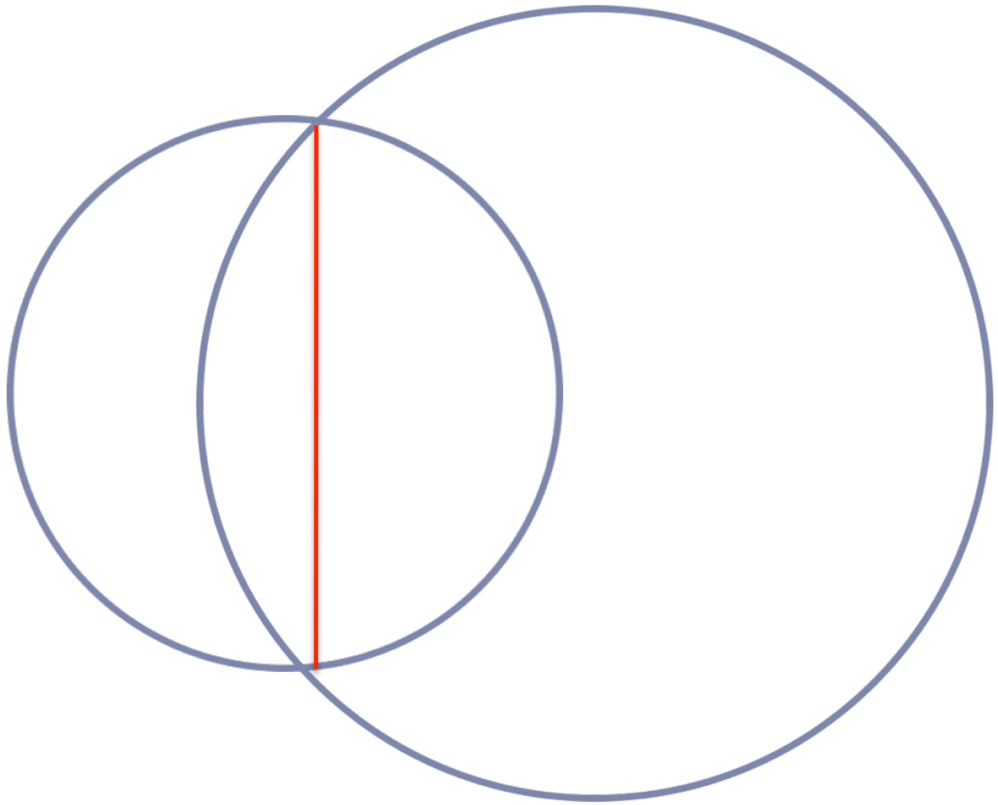

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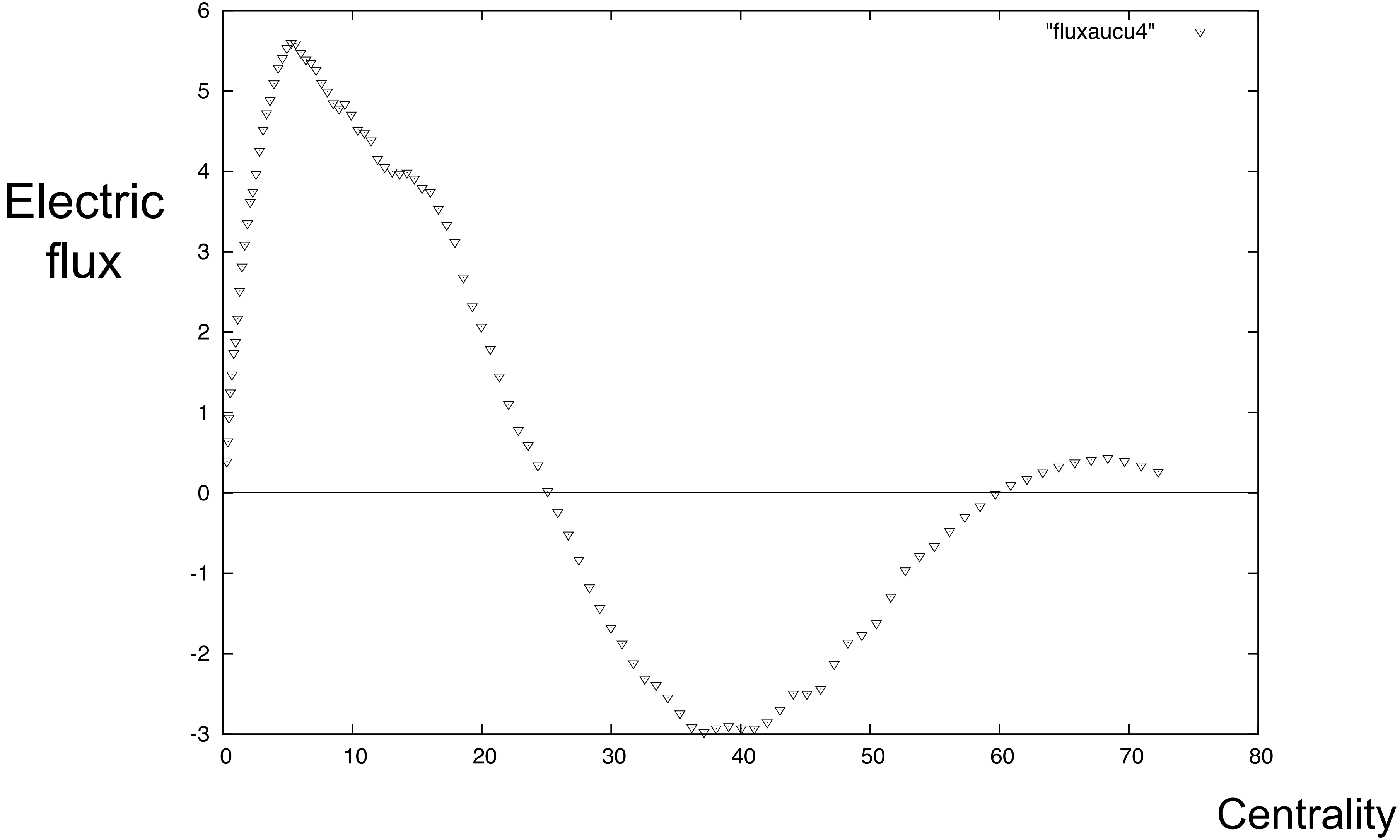

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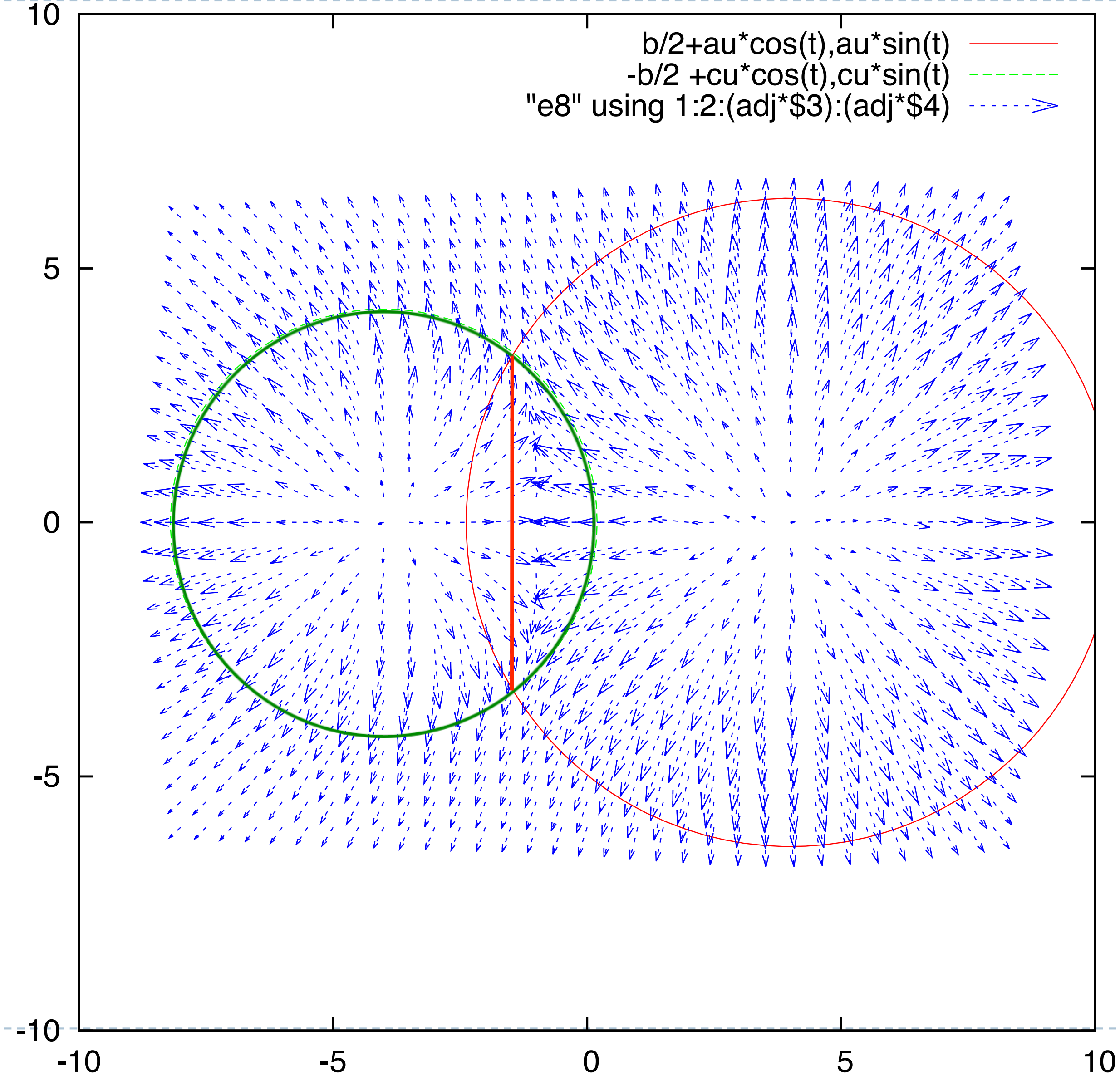

Observables sensitive to the conductivity

- Net charge dist.

$$\frac{d\left(N_+ - N_-\right)}{d\phi}(\phi) = \left(\bar{N}_+ - \bar{N}_-\right)\left(1 + 2d_e \cos\phi\right)$$

$$\bar{N}_\pm \equiv \int \frac{d\phi}{2\pi}\frac{dN_\pm}{d\phi}$$

- Total particle dist.

$$\frac{d\left(N_+ + N_-\right)}{d\phi} = \left(\bar{N}_+ + \bar{N}_-\right)\left(1 + 2v_1 \cos\phi\right)$$