Contribution of minijets to the elliptic flow

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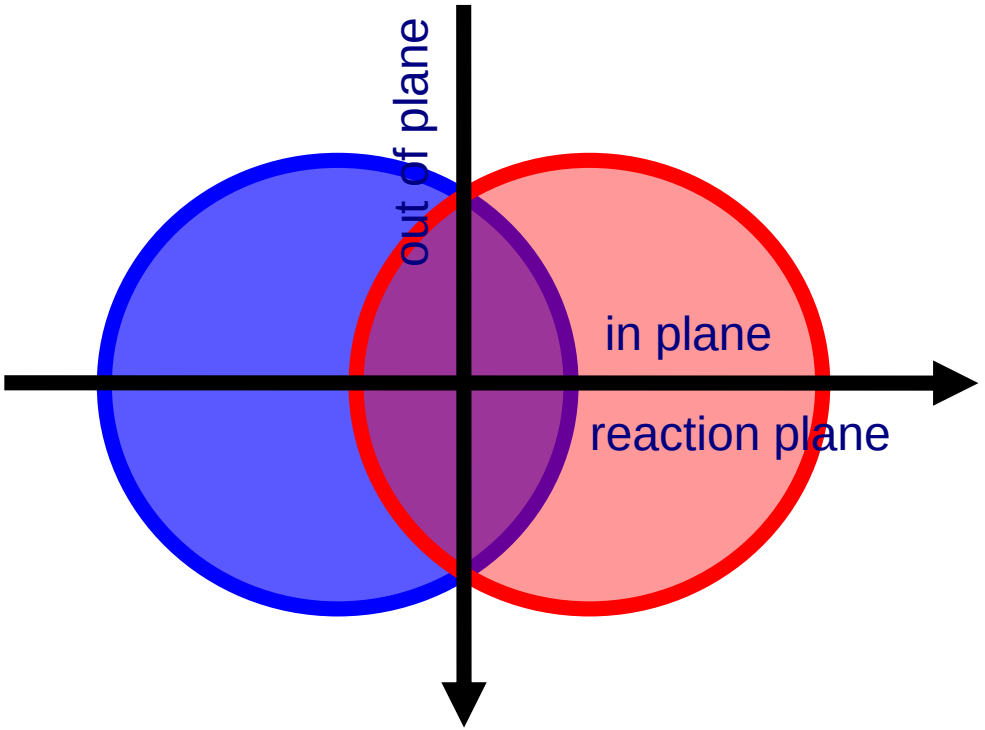
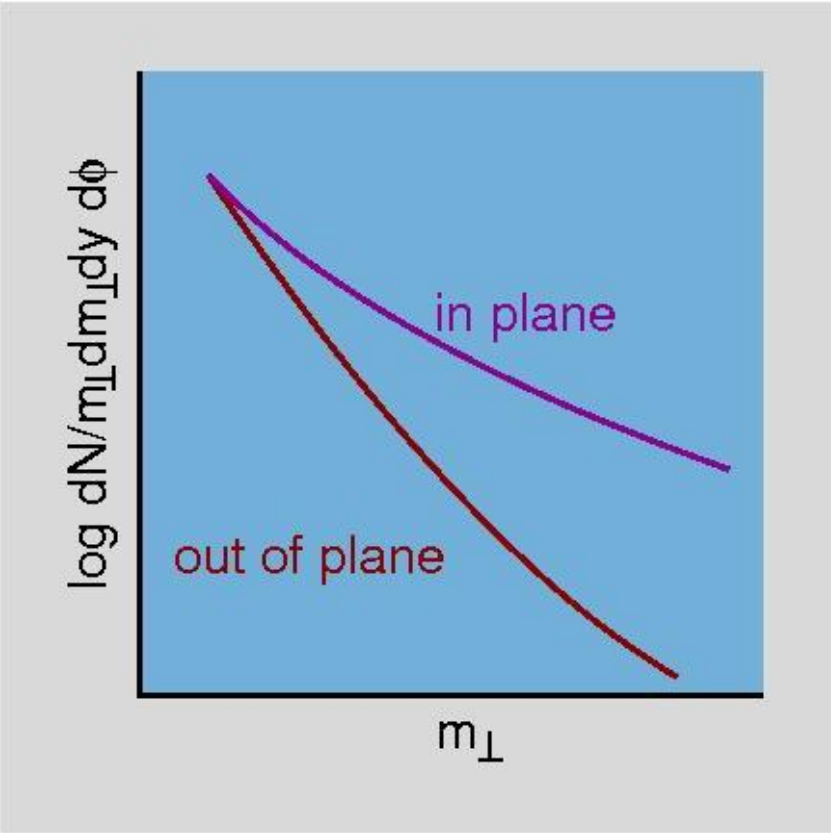
The first heavy ion collisions at the LHC
CERN, August 17, 2010

Elliptic flow

- Asymmetry in particle production in non-central collisions



- Transverse mass spectra are flatter in the reaction plane

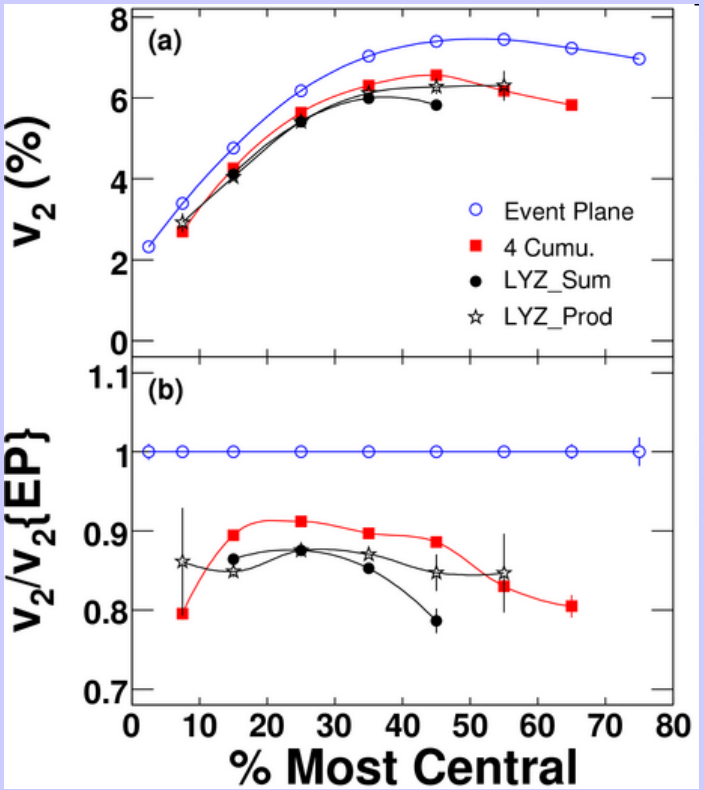


- Anisotropy in production correlated to collision geometry

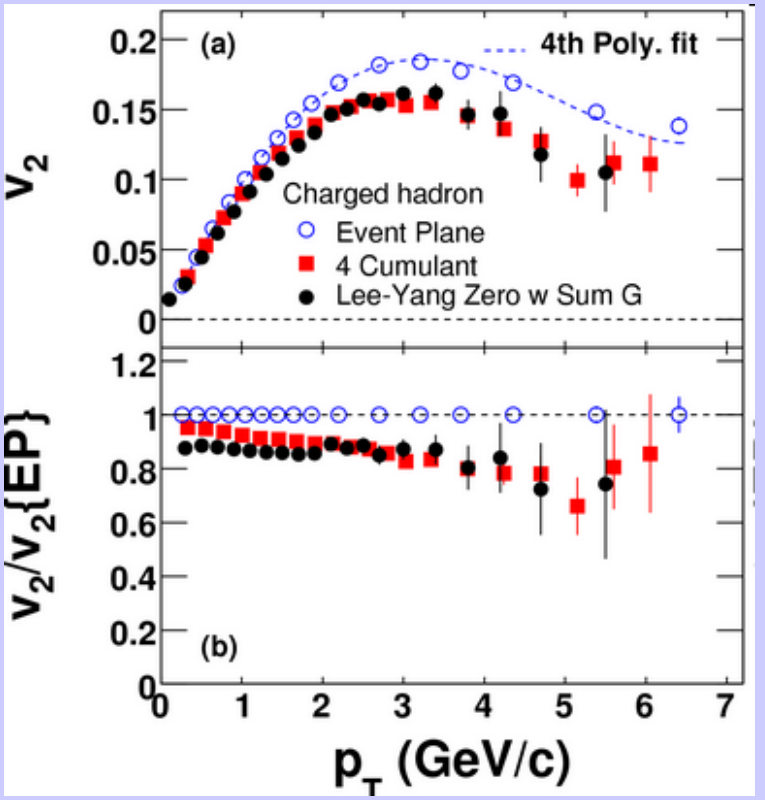
Elliptic flow: typical size

$$\frac{d^3n}{p_t\,dp_t\,dy\,d\phi} = \frac{1}{2\pi}\frac{d^2n}{p_t\,dp_t\,dy}\left(1 + 2v_2\,\cos\left(2(\phi-\phi_R)\right) + 2v_4\,\cos\left(4(\phi-\phi_R)\right) + \ldots\right)$$

p_t-integrated v_2 of charged hadrons



v_2 for c=10-40% for charged hadrons



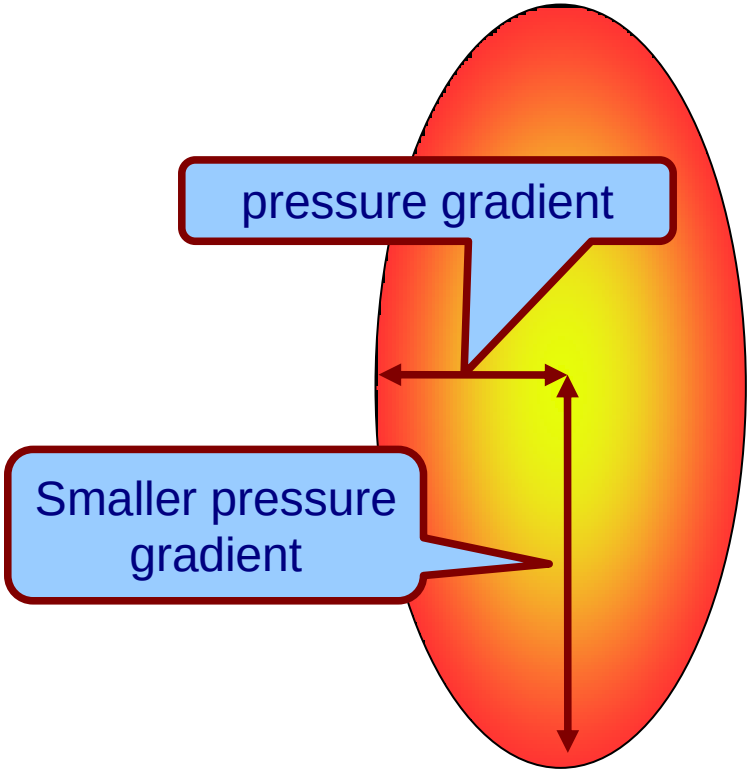
Data: Au+Au @ 200 AGeV
STAR collaboration, Phys. Rev. C **77** (2008) 054901

The interpretation of v_2

Hydrodynamic phenomenon!

- flattening of spectra is due to transverse expansion

- Expansion results from pressure gradients

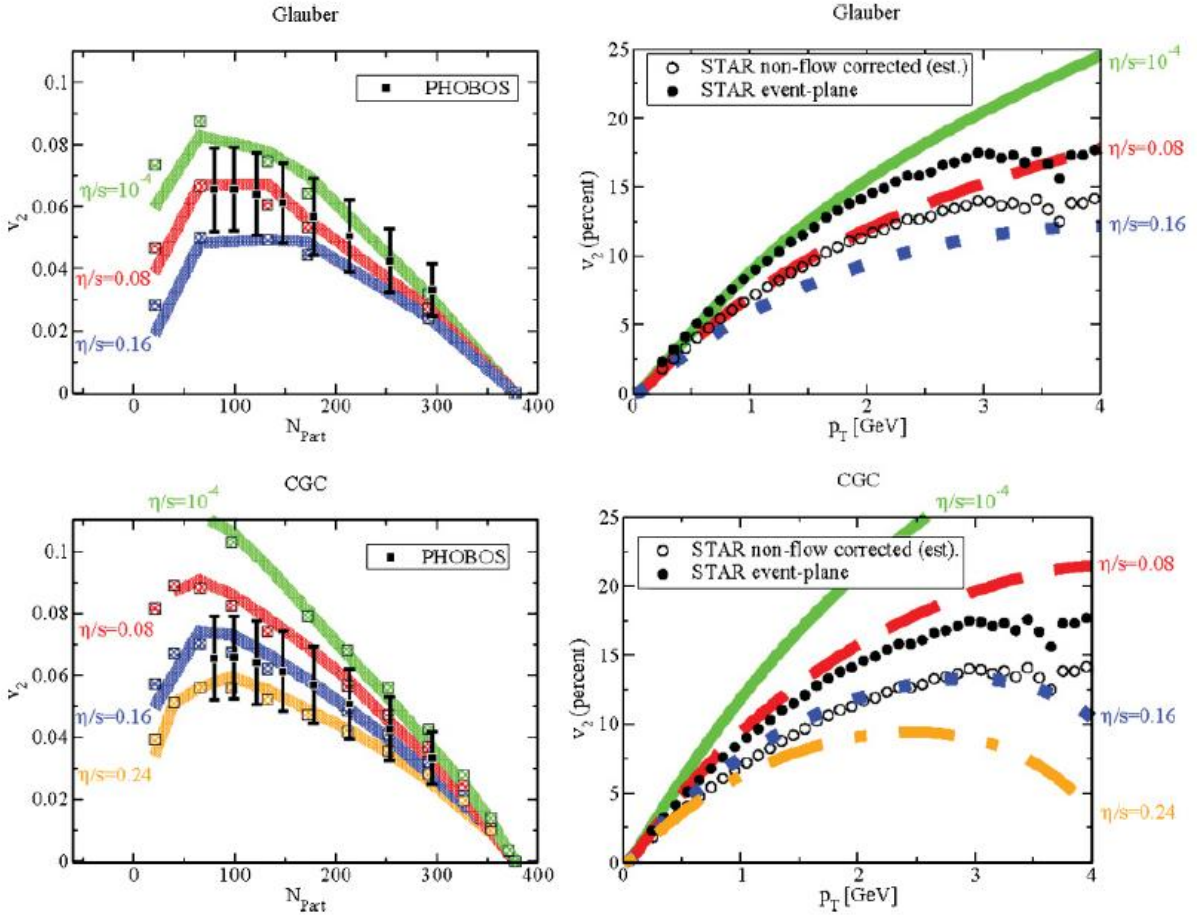


=> stronger expansion in the reaction plane

Elliptic flow in hydrodynamics: details

Talk by Ulrich Heinz yesterday…

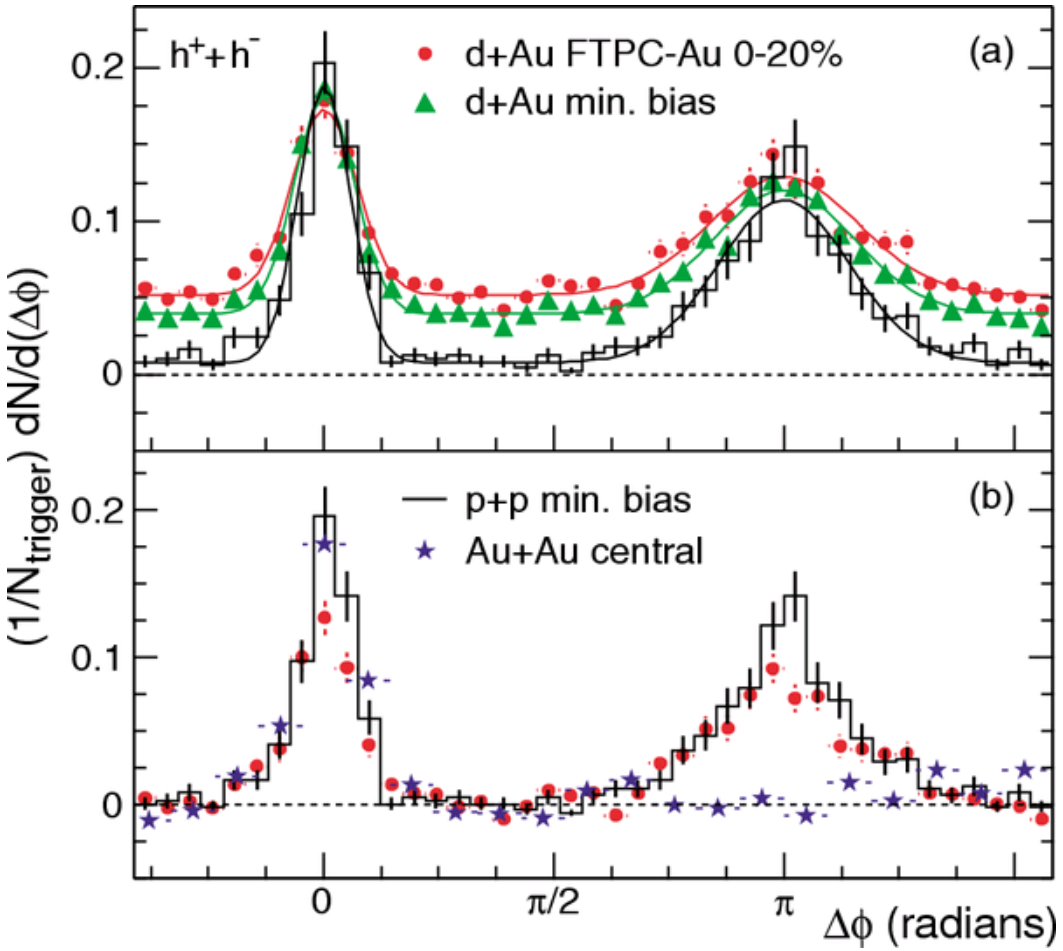
Calculation: M. Luzum, P. Romatschke: PRC **78** (2008) 034915



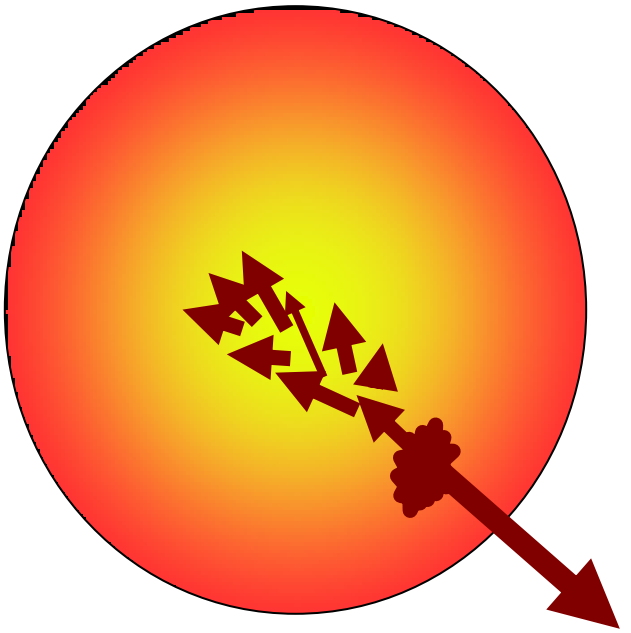
- Dependence on η/s
- Sensitivity to
  - initial profile
  - chemical non-equilibrium
  - hadronic rescattering
  - e-by-e fluctuations
  - …

Important to understand elliptic flow quantitatively well!

Jets in nuclear collisions: QGP suppression



[STAR Collaboration, PRL **91** (2003) 072304]



Second jet eaten up by the medium

=> Quark-Gluon Plasma

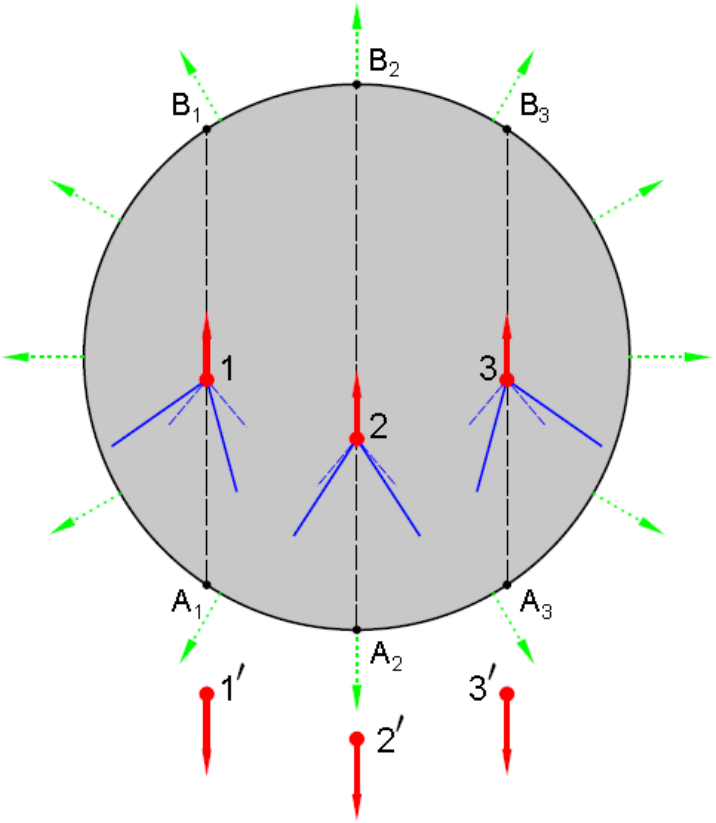
One jet in medium

- Momentum is being transferred to the bulk
  => expect collective response of the bulk

- Mach cones and wakes
  [H. Stöcker, NPA 750 (2005) 121, L.M. Satarov, H. Stöcker, I.N. Mishustin, PLB **627** (2005) 64,
  J. Casalderrey-Solana, E.V. Shuryak, D. Teaney, NPA **774** (2006) 577,
  T. Renk and J. Ruppert, PRC **73** (2006) 011901(R)
  J. Ruppert and B. Müller, PLB **618** (2005) 123]

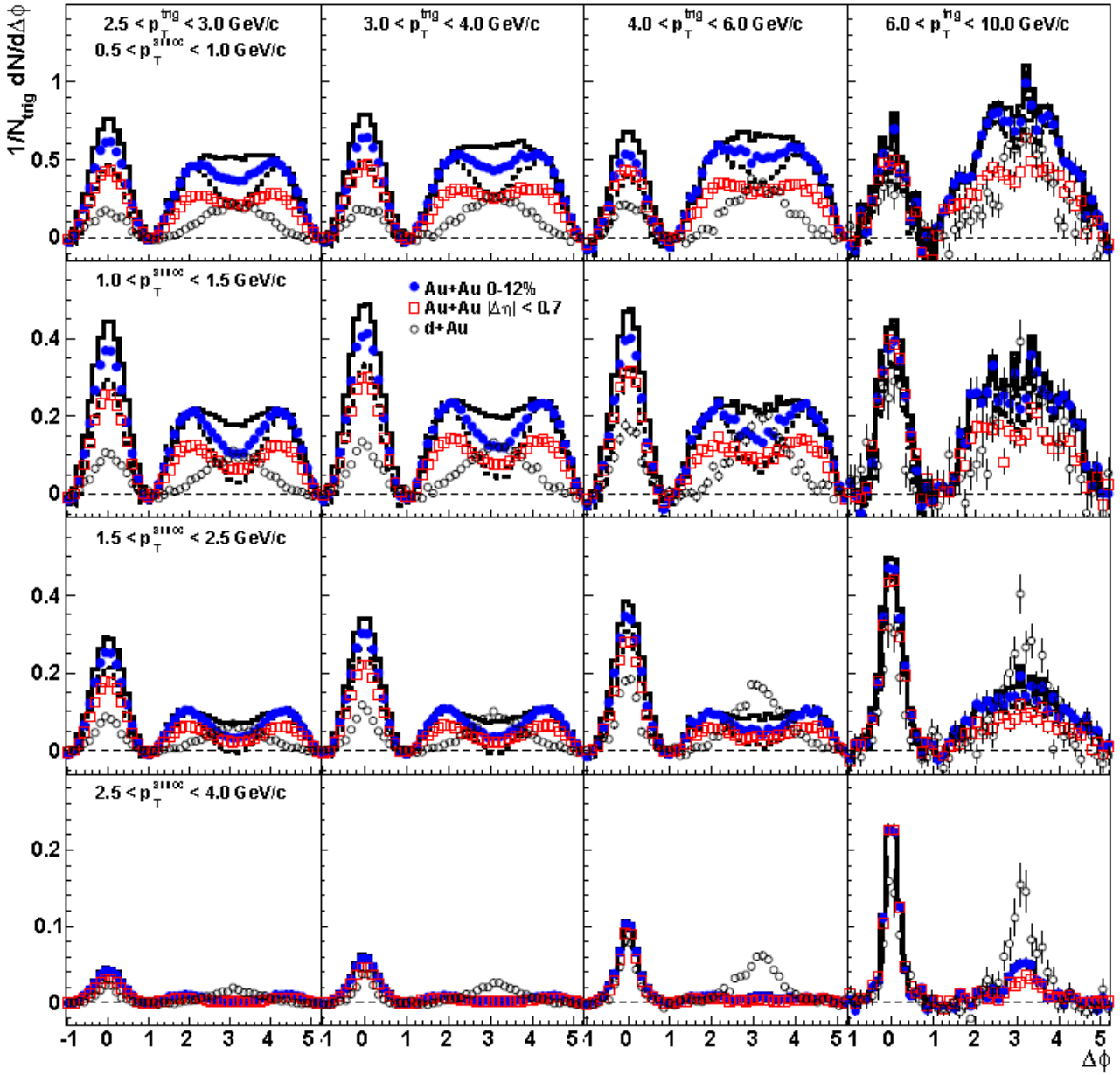
  -> cones correlated to leading particle
  (not *primarily* correlated to elliptic flow)

  -> possible signals seen in correlation data



[Figure from L.M. Satarov, H. Stöcker, I.N. Mishustin, PLB **627** (2005) 64]

Angular correlations: maybe Mach cones?



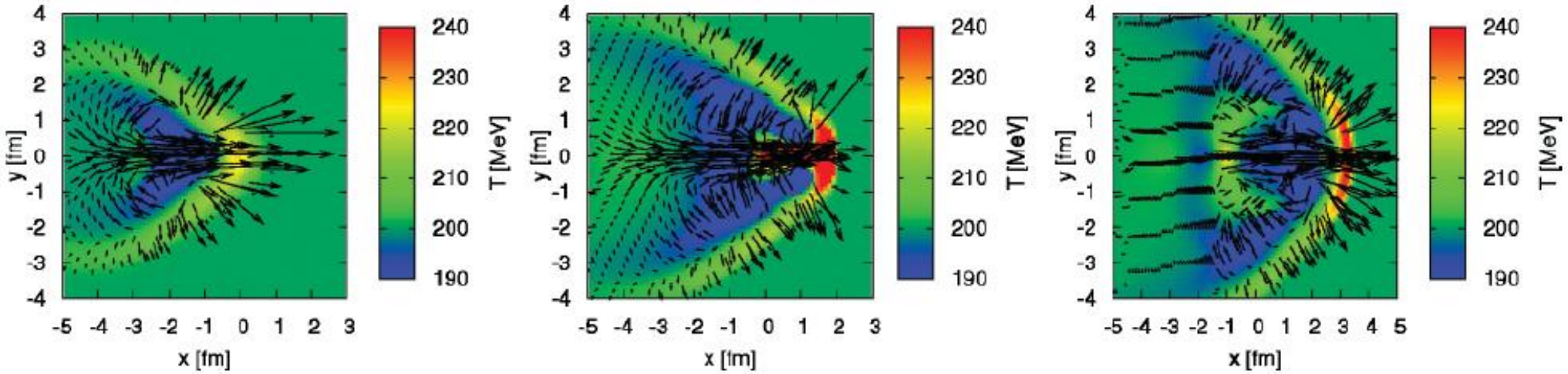
Central Au+Au @ 200 AGeV

[STAR collaboration: ArXiv:1004.2377]

Medium flows even after jet is fully stopped

B. Betz, *et al.,* Phys.Rev.C **79** (2009) 034902

Fully stopped jet with previous momentum deposition



Jet stoped here

After 2 fm/c

After 4 fm/c

Both punch through and fully stopped jets leave behind streams

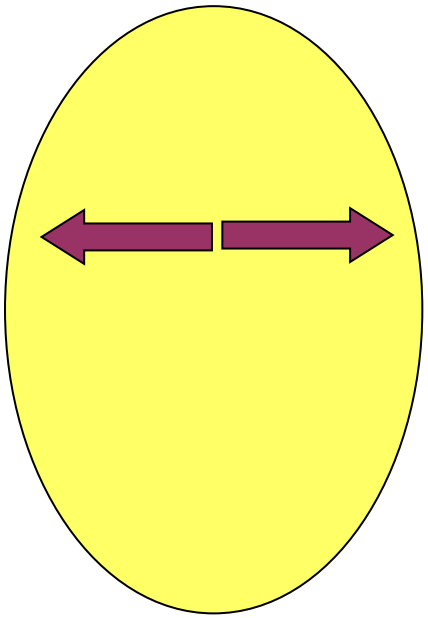
More jets in medium

LHC: clearly more than one (mini)jet in single event

What is the influence of two or more (pairs of) jets which transfer momentum on the bulk?

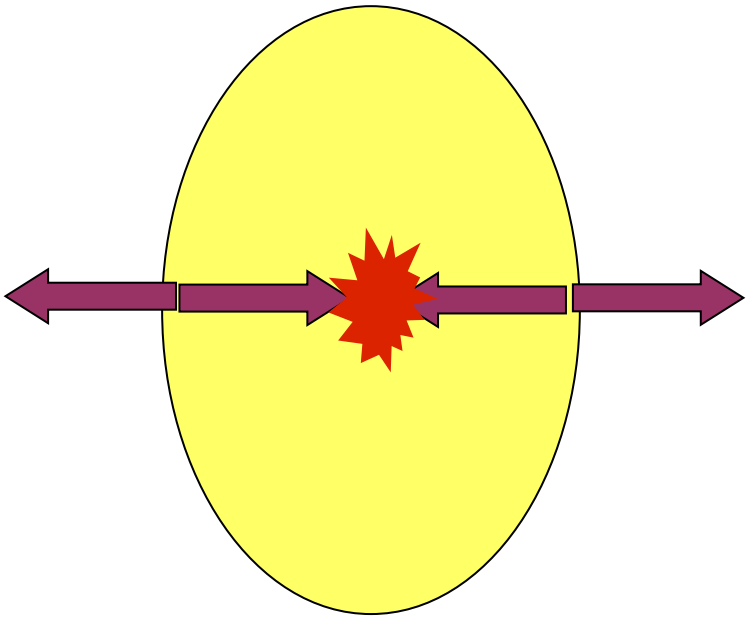
Jets/streams in medium

One pair of jets



Contribution to v_2

Two pairs of jets



Momenta cancel out
- energy deposition
=> less v_2 generation
=> decrease of flow in <--> direction

But jets are produced isotropically!
Why should there be any elliptic flow induced by them?

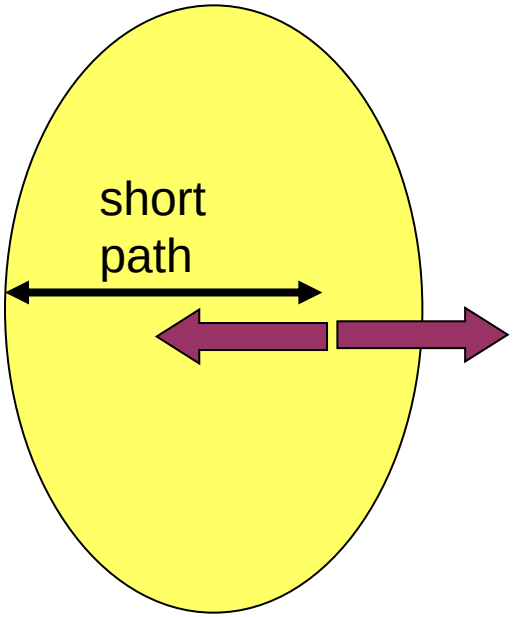
Answer on the next page…

Flow anisotropy from isotropically produced jets

Jets/streams directed out of reaction plane traverse more matter and have larger chance to collide/merge.

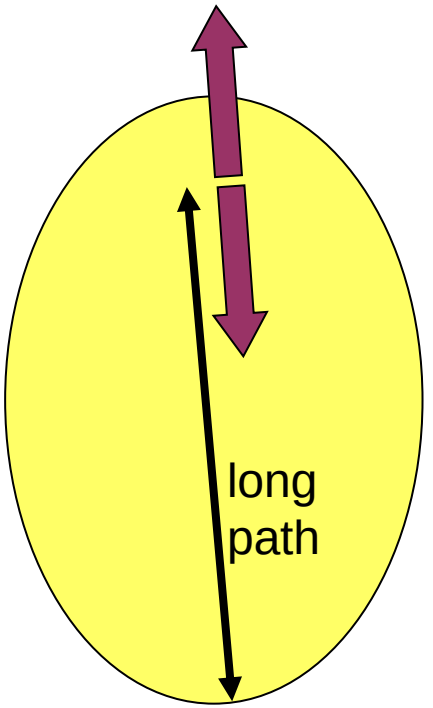
In that direction we shall have less flow.

This will give contribution to v_2.



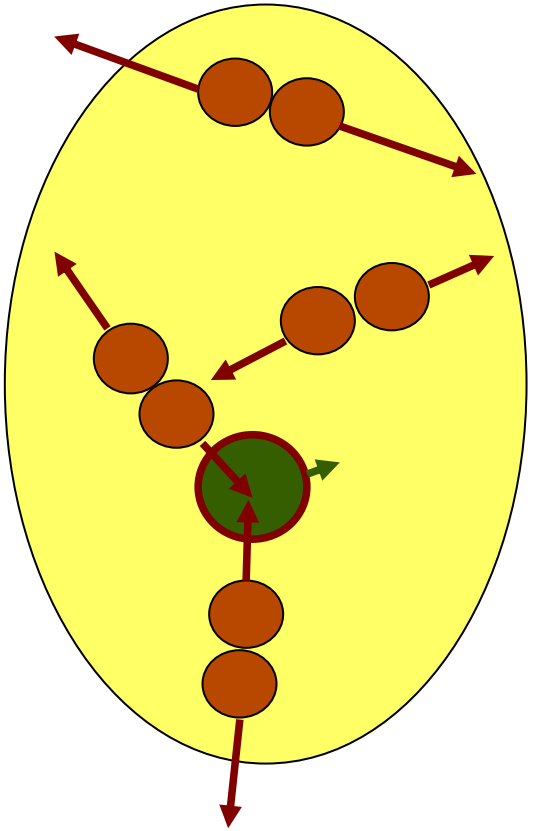
More chance of merging on the long path.

Momentum deflection into in-plane direction.



A toy model

- “Streams” are represented by droplets of matter
- Produced back-to-back (with some k_t broadening)
- When droplets collide, they merge into a heavier droplet
- Droplet size represented by stream radius (calculated with 2.5 and 1.5 fm)
- Droplets evaporate pions at T=175 MeV



A toy model: minijet production

Glauber model calculation of the distribution in transverse plane: binary collisions scaling

$$U_{AA}(\vec{b},\vec{x}) = T_{AA}(b,\vec{x})T_{AA}(b,\vec{x}-\vec{b})$$

Uniform rapidity distribution over y=[-2,2]

Isotropic distribution of momenta in transverse direction

p_t spectrum parametrised (per pp collision) [Peter Levai]

$$\frac{dN}{p_t\,dp_t} = \frac{B}{(p_0+p_t)^n}$$

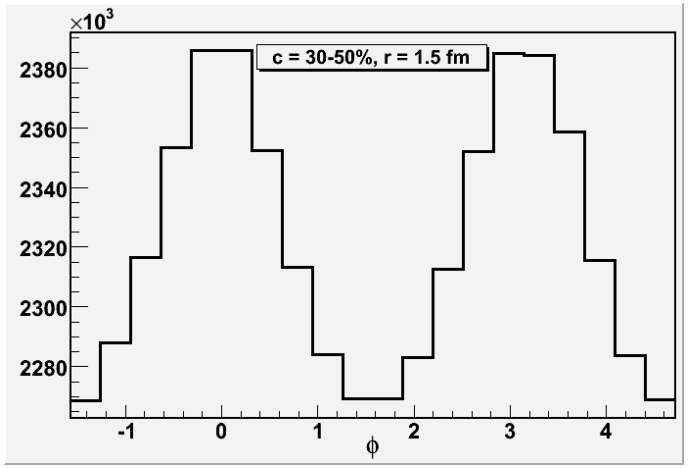
$$B = 14.7, \qquad n = 9.5, \qquad p_0 = 6\,\mathrm{GeV}$$

Transverse momenta taken down to p_t = 3 GeV/*c*

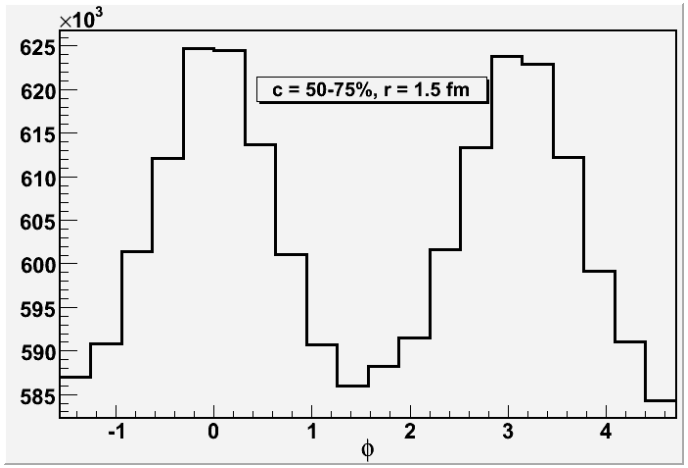
Integrated angular distributions

Stream radius 1.5 fm

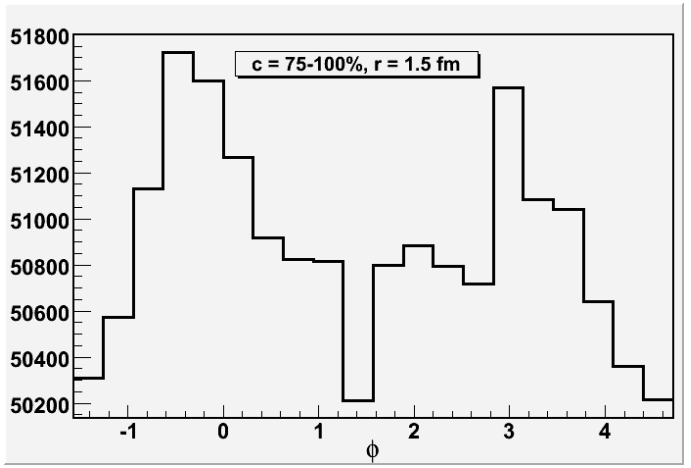
Simulations: 10^5 events



30-50%, v_2=1.2%

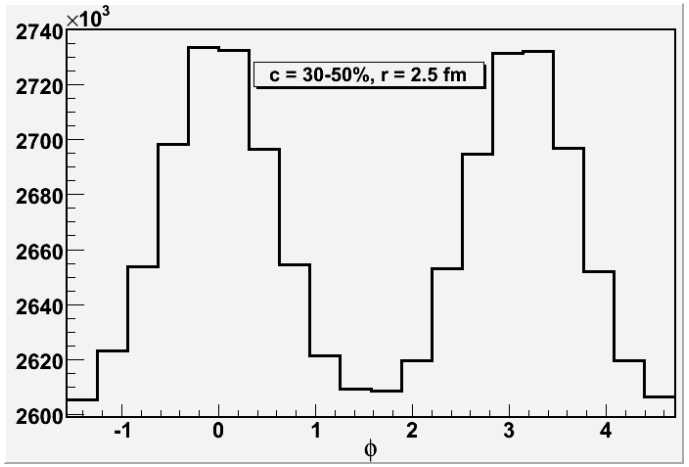


50-75%, v_2=1.7%

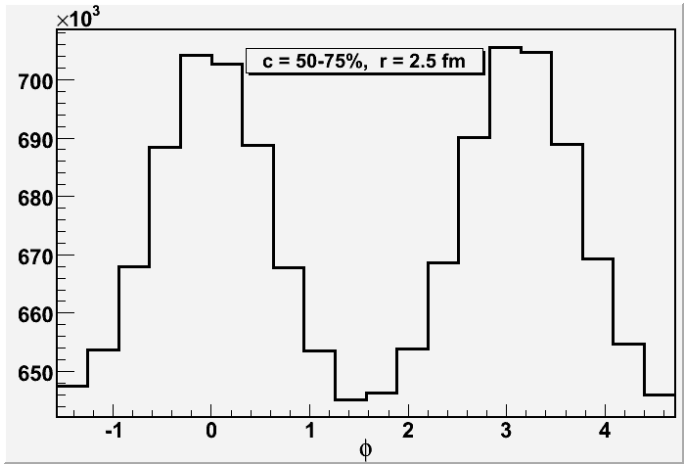


75-100%, v_2=1%

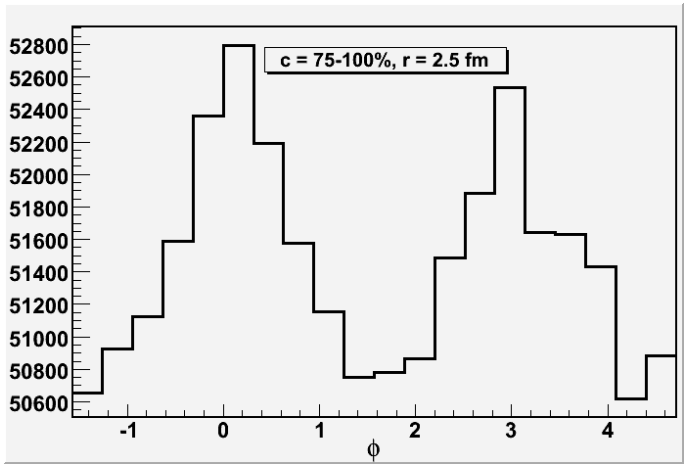
Stream radius 2.5 fm



30-50%, v_2=1.2%



50-75%, v_2=2%



75-100%, v_2=0.8%

Comments

This azimuthal distribution is correlated with the reaction plane!

Contribution to azimuthal anisotropy at 1-2% level out of 6-8%
If taken seriously, this is about

15-20% of the elliptic flow signal!
(RAPPEL: to be compared with 20-25% from viscosity)

At LHC, it will be interesting to look at contributions to elliptic flow from the action of many jets

Need to integrate this into hydrodynamic simulation

How to recognise this contribution? Maybe by v_2 fluctuations!

Comments on fluctuations

- Expect inhomogeneities in momentum space in hadron production

- Even within narrow homogeneity class expect events with non-statistically different momentum distributions

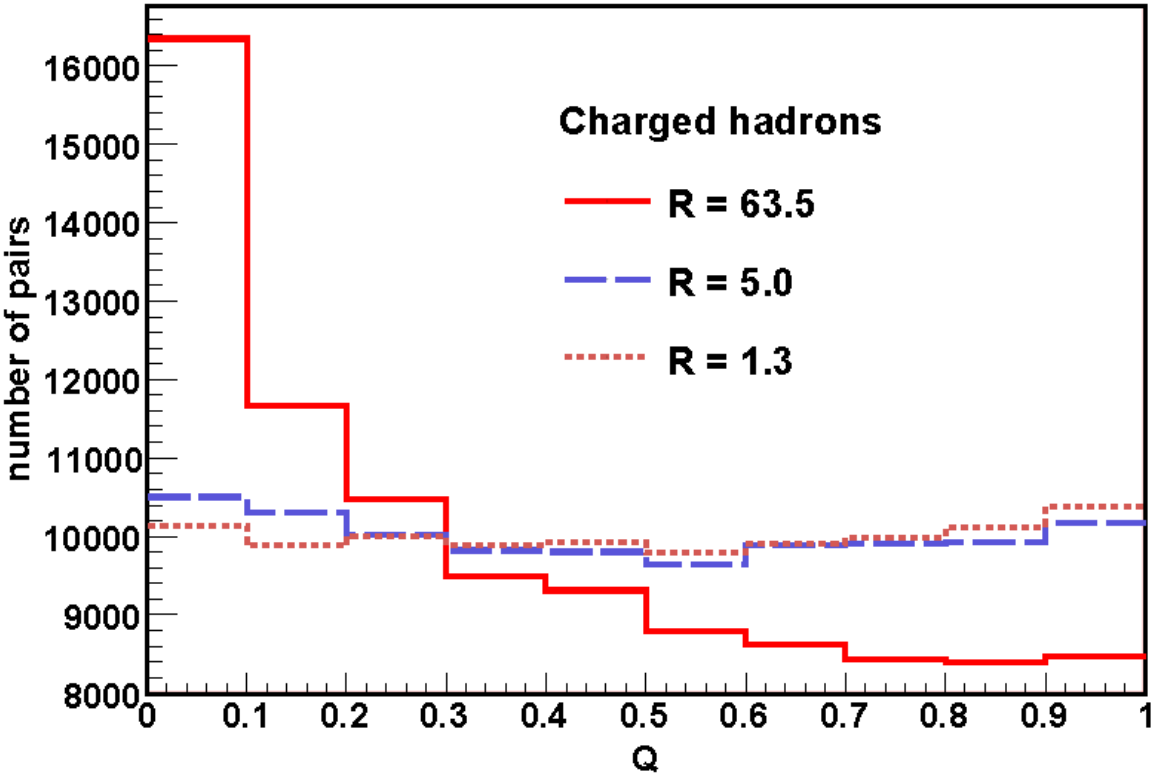
- Use Kolmogorov-Smirnov (KS) test to control if there are large non-statistical differences between individual events
  - To what extent the difference between two empirical distributions (e.g. rapidity distributions) can be only caused by statistical fluctuation?
  - Measure *Q* for many pairs of events
  - *Q* is the probability that two events would look more differently provided they are drawn from the same rapidity distribution
  - Interpretation: many pairs of events at small *Q* signal statistically different events

Kolmogorov-Smirnov test: an illustration

The use of a *Q* histogram:
here for a study of fireball fragmentation
(10^5 pairs out of 10^4 events)
[I. Melo, B. Tomášik, *et al.,* PRC **80** (2009) 024904]

Red solid curve:
fireball decayed to droplets

Dashed and dotted curves:
continuous fireball



Summary

•Minijets at the LHC will be copious and will deposit energy and momentum to the medium

•Momentum deposition will induce and influence collective flow

•From interaction of “streams” on the medium there will be second order anisotropy in collective flow correlated with the reaction plane

•Effect may be comparable with the influence of viscosity

•For more precise statements one needs hydrodynamics with included jets

•This is e-by-e fluctuating effect – may be worth looking into event differences