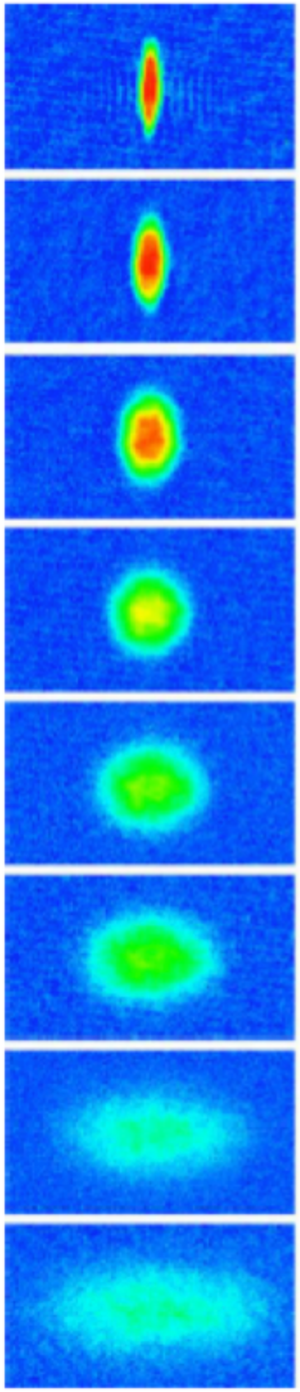
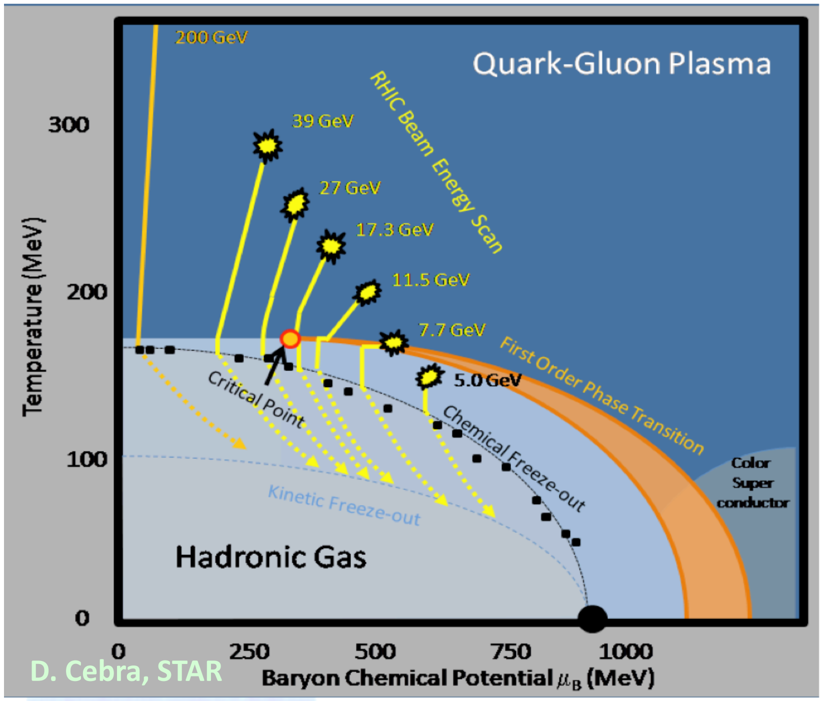


azimuthally-sensitive femtoscopy and the energy scan program(s)

Mike Lisa

In collaboration with: E. Frodermann (U. Minn),
M. Mitrovski, H. Petersen, M. Bleicher (Frankfurt)

RHIC energy scan: $\sqrt{s}$=7-40 GeV (2010~2012 (?))

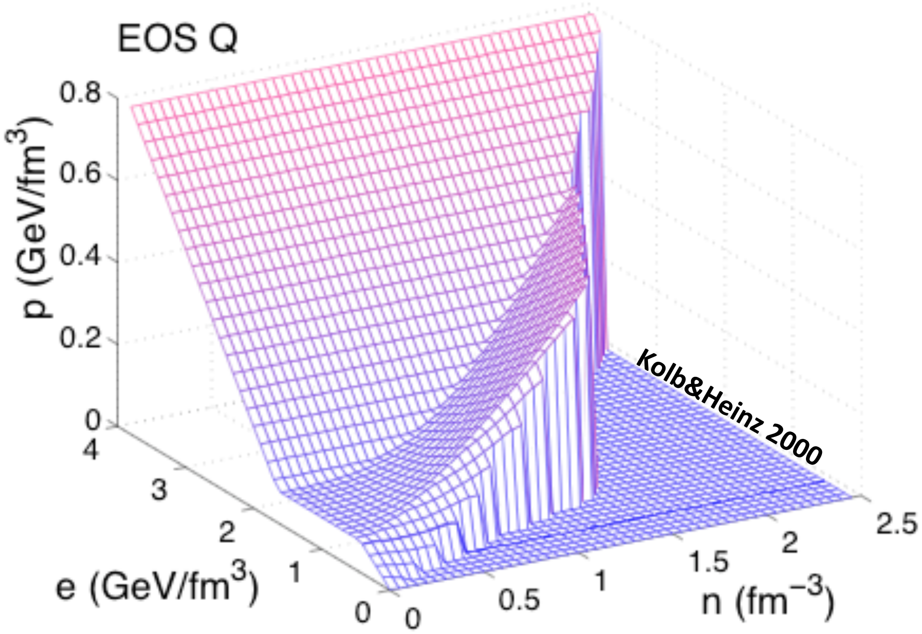

D. Cebra, STAR

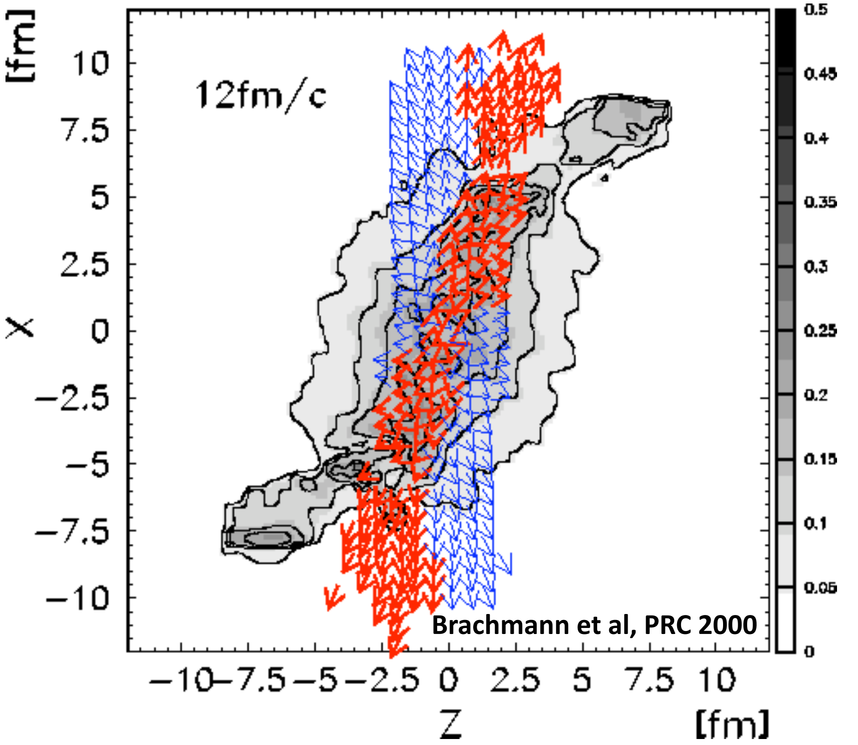
Probe QCD phase diagram via

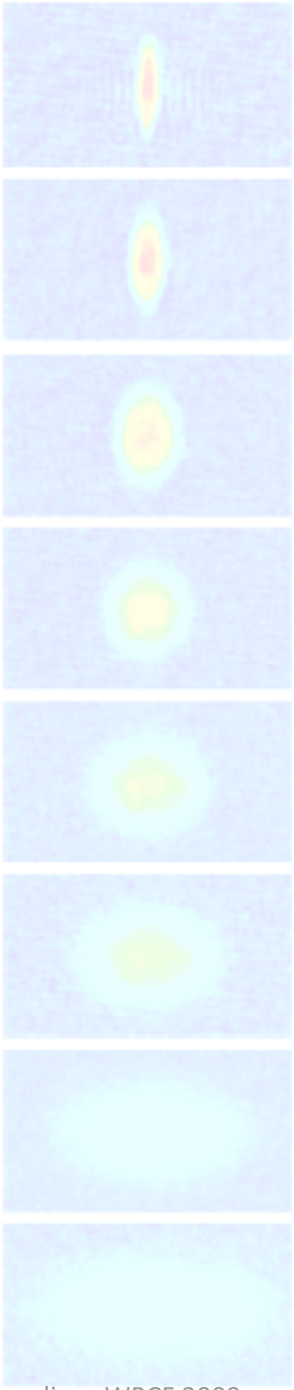
- statistics/fluctuations

✓ dynamic system response

  - transport models (phase structure in EoS)
  - bulk collectivity (low-p_T measurements)


Kolb&Heinz 2000

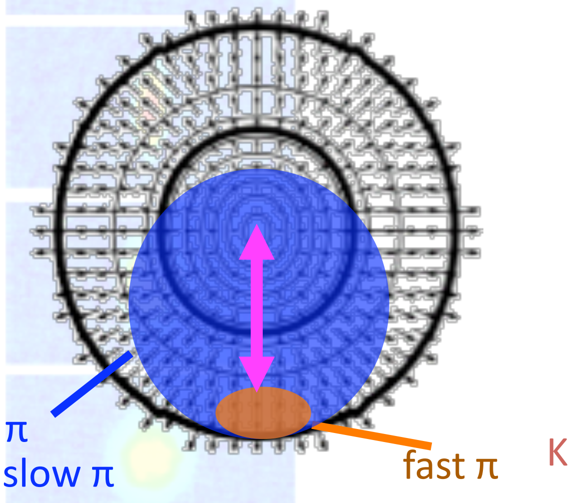

Brachmann et al, PRC 2000

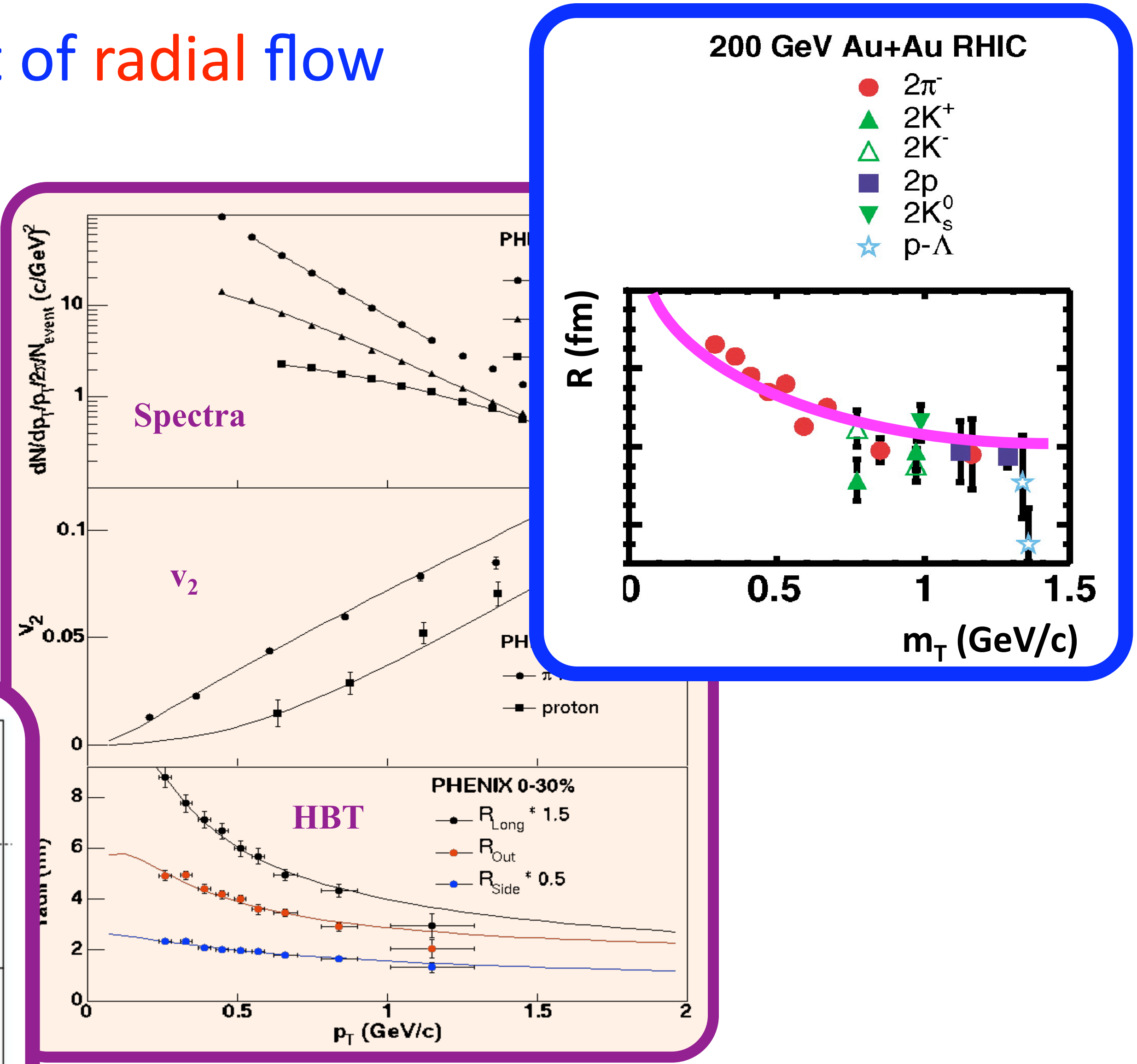


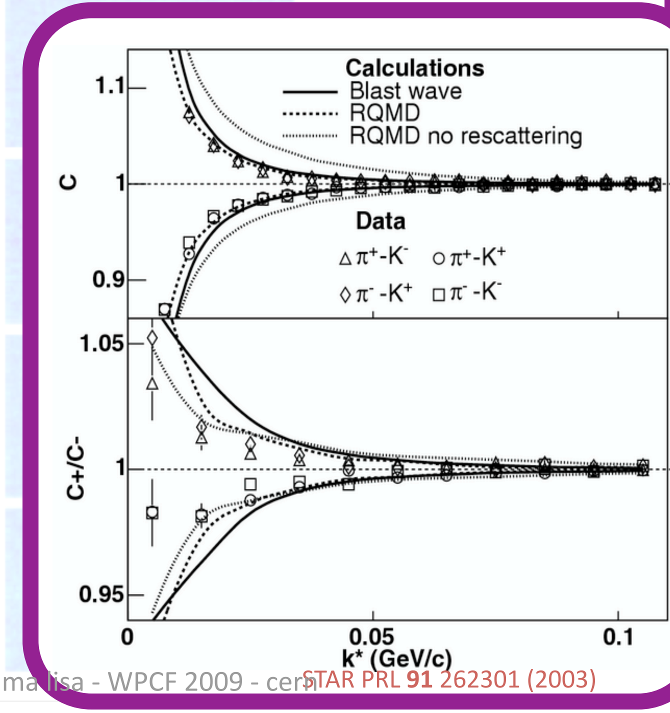
Outline

- femtoscopy (HBT) and collectivity in R.H.I.C.
  - radial, longitudinal, **directed, elliptic**
- azimuthally-sensitive HBT (asHBT)
  - what is measured
  - what it measures
  - what's been measured
  - what needs to be measured!
- model calculations
  - 2D hydro
  - RQMD, UrQMD
  - 3D hydro + UrQMD
- status

R(mT) – spatial aspect of radial flow



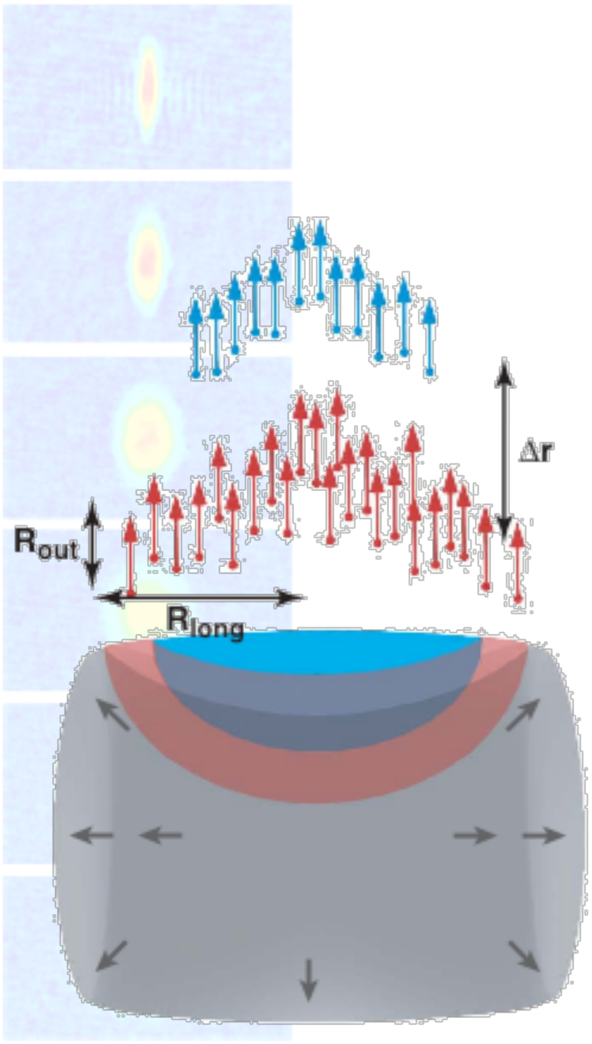




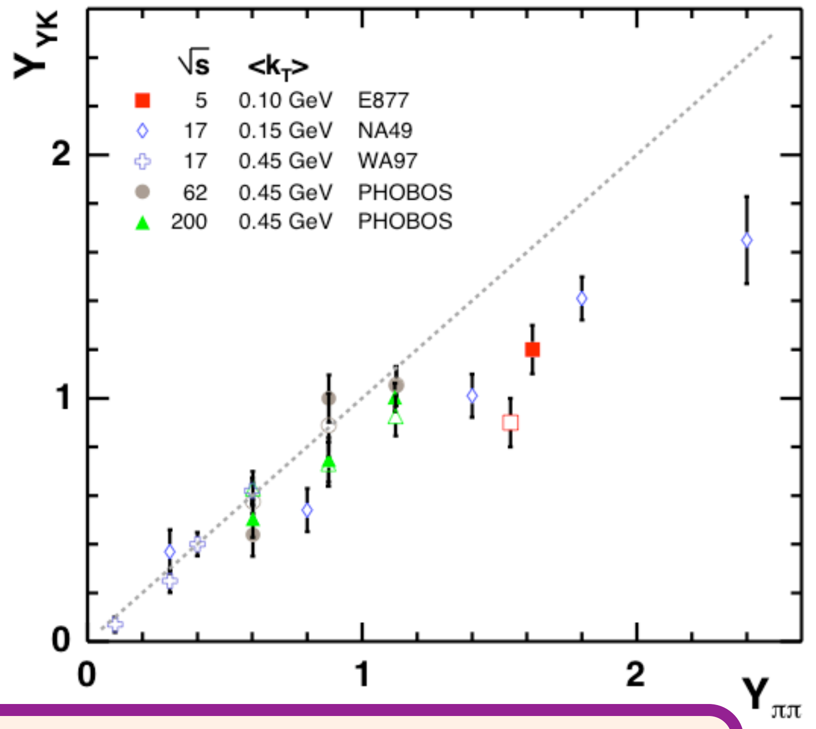
STAR PRL **91** 262301 (2003)

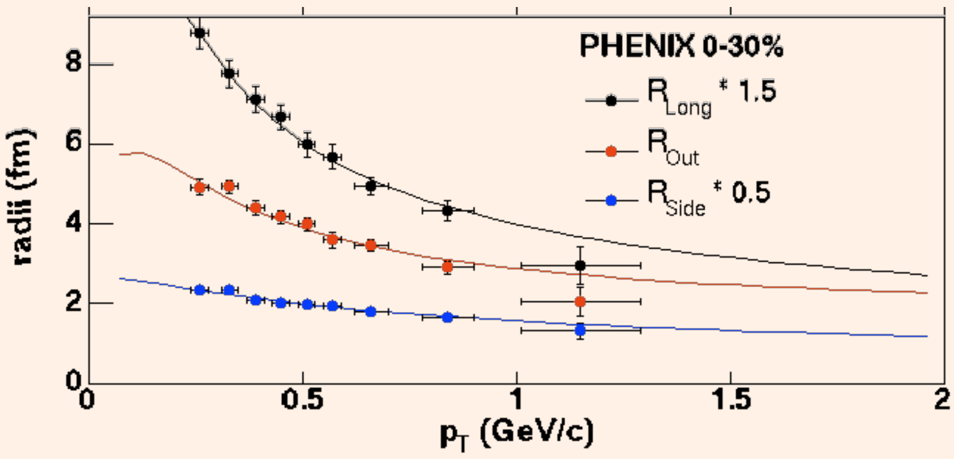
(radial) space-momentum substructure mapped *in detail*

strong longitudinal flow (not necc B.I.)



Ann Rev Nucl Part Sci (2005) nucl-ex/0505014

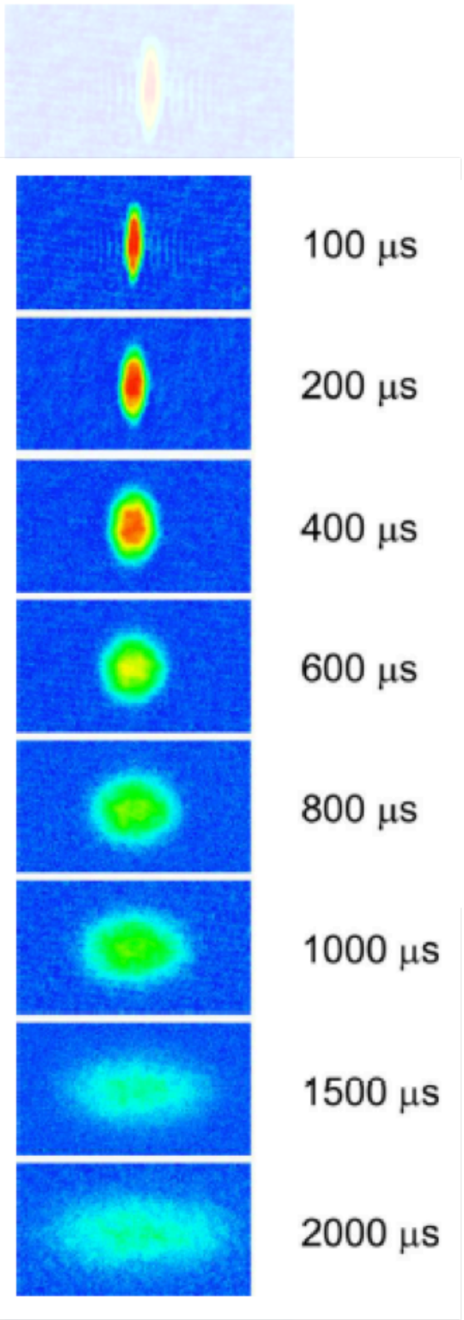




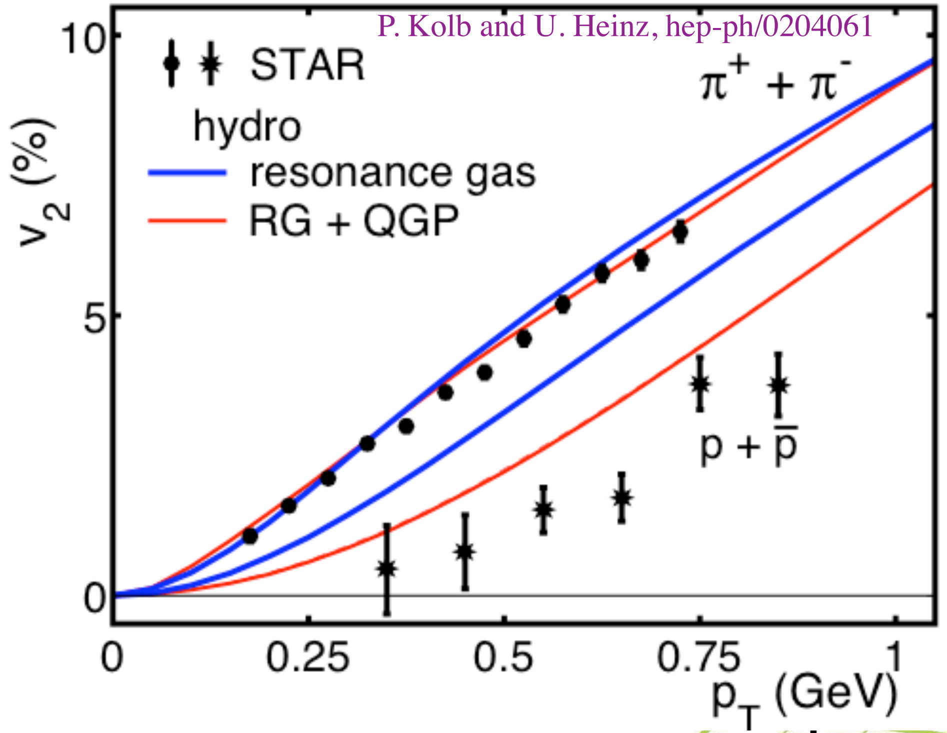
Also: $R^2_{ol}\left(y, p_T\right)$

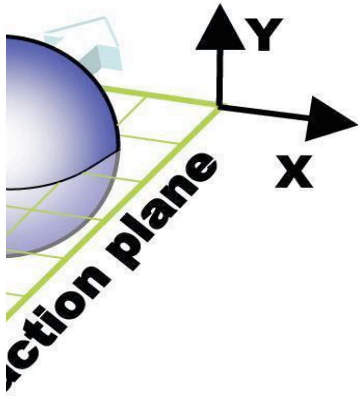
less attention to longitudinal d.o.f. in HBT

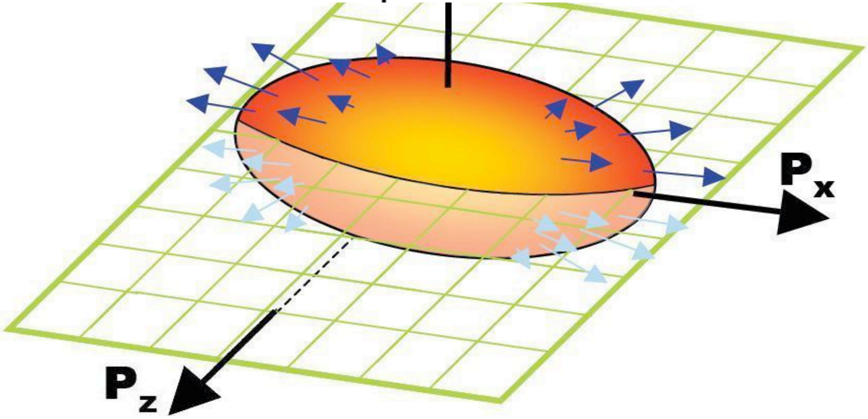
phi- the sexy direction



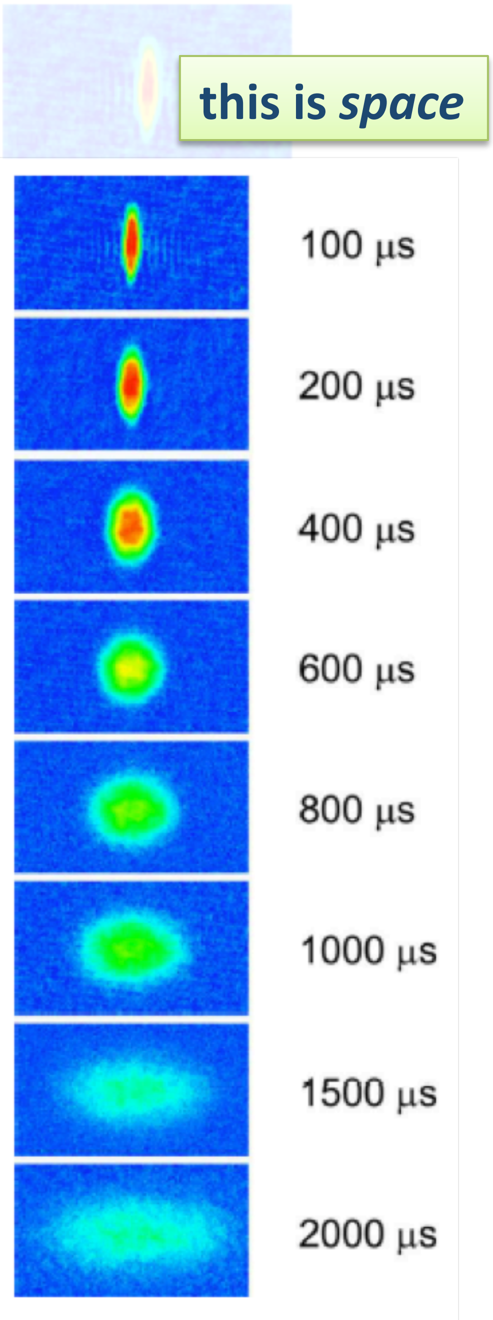
O'Hara et al, *Science* 2002





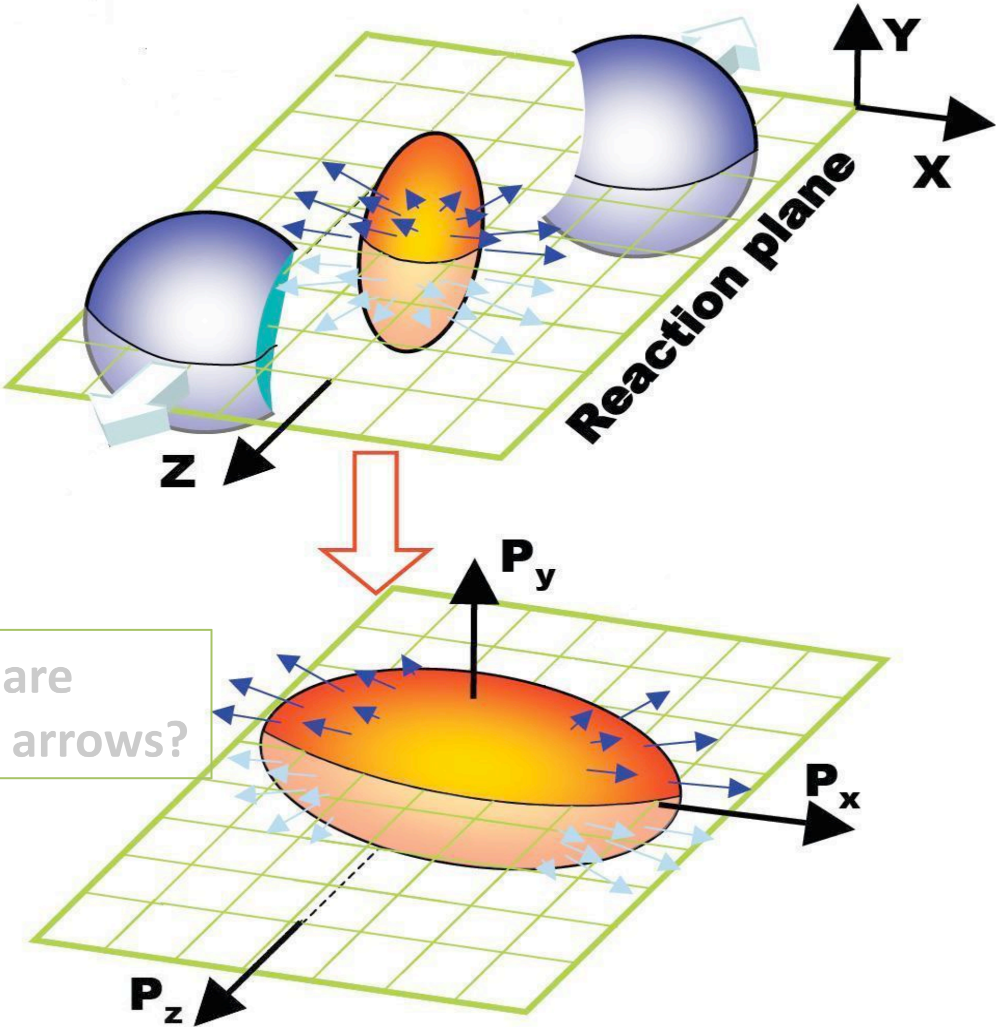


phi- the sexy direction



this is *space*

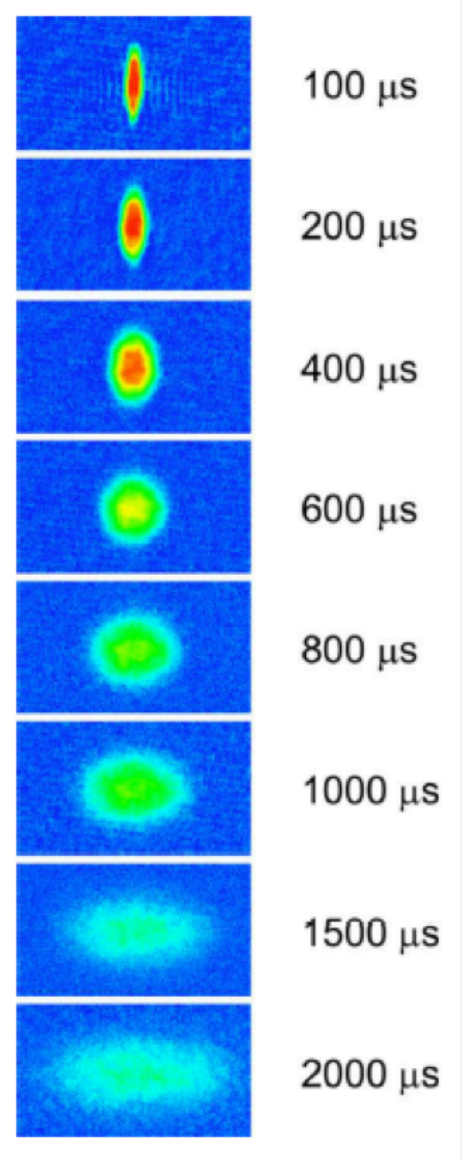
O'Hara et al, *Science* 2002



what are these arrows?

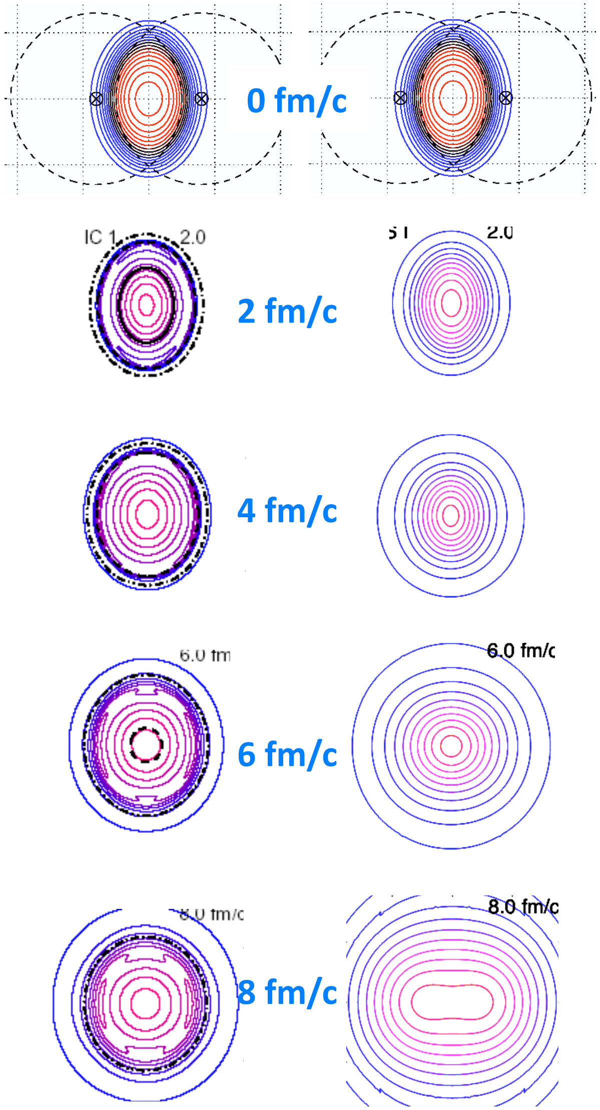
phi- the sexy direction

ultra-cold atoms



O'Hara et al, *Science* 2002

ultra-hot partons



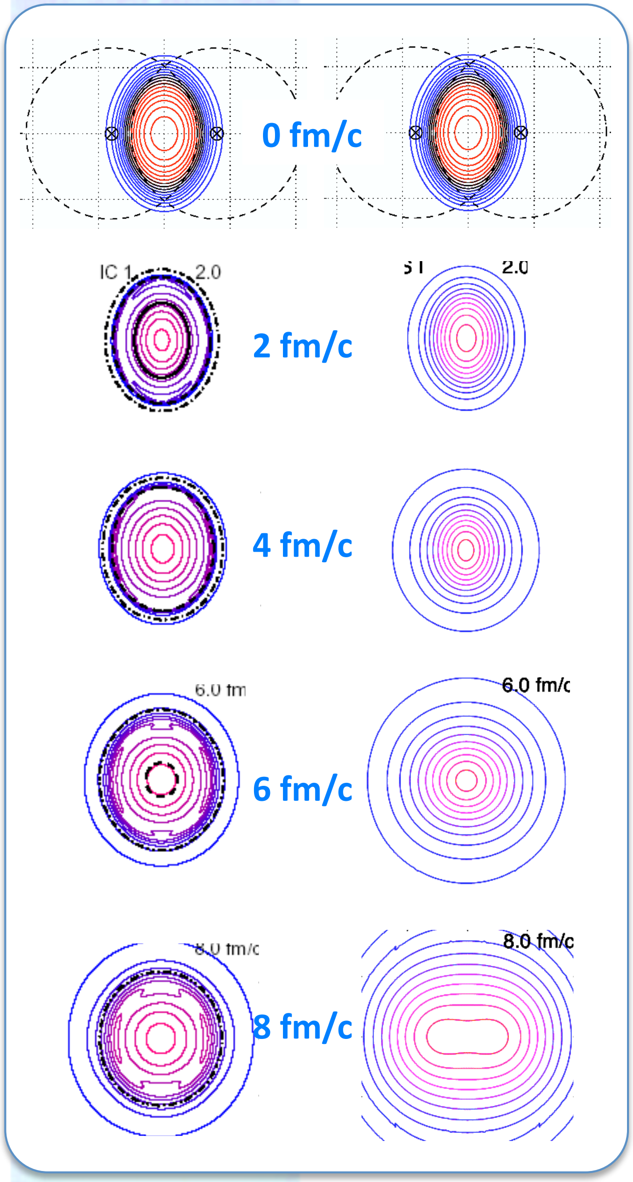
P. Kolb, PhD 2002

evolution from initial "known" shape depends on

- pressure anisotropy ("stiffness")
- lifetime *

* O'Hara could *choose* when to destroy his system

phi- the sexy direction



evolution from initial “known” shape depends on

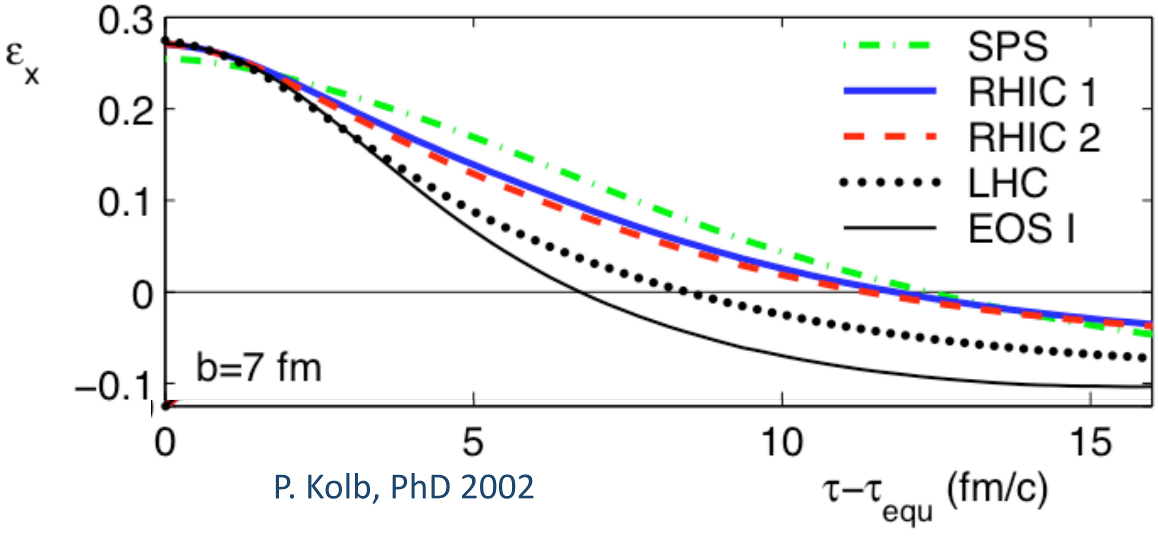
- pressure anisotropy (“stiffness”)
- lifetime

Both are interesting!

We will measure a convolution over freezeout

  - model needed

$$\varepsilon \equiv \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

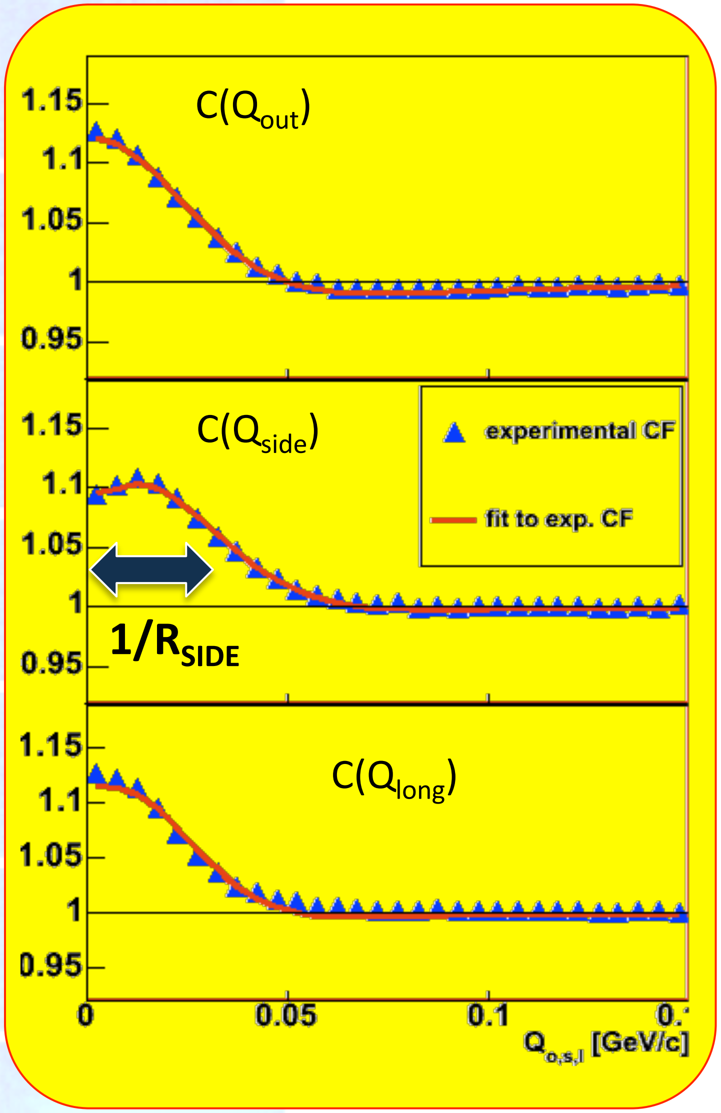


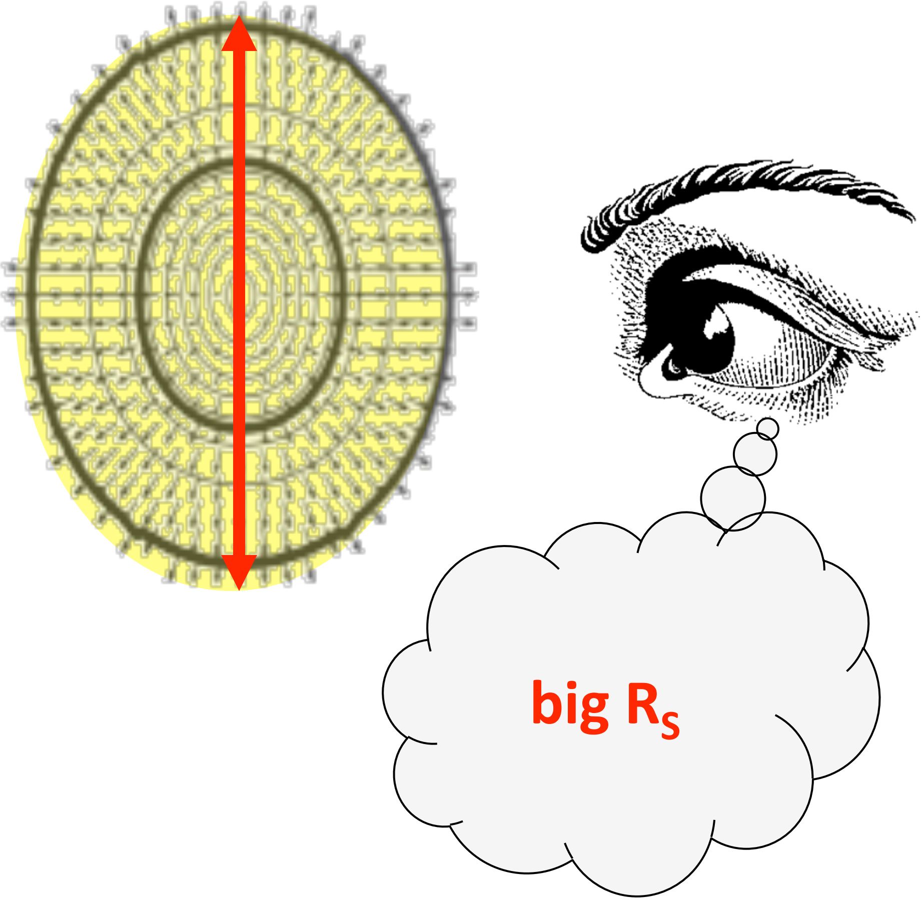
P. Kolb, PhD 2002

measuring lengths

$$C(\vec{q}) = N \cdot \left[1 + \lambda \cdot \left(K_{coul}(\vec{q}) \cdot \left\{1 + e^{-\left(q_o^2 R_o^2 + q_s^2 R_s^2 + q_l^2 R_l^2\right)}\right\} - 1\right)\right]$$

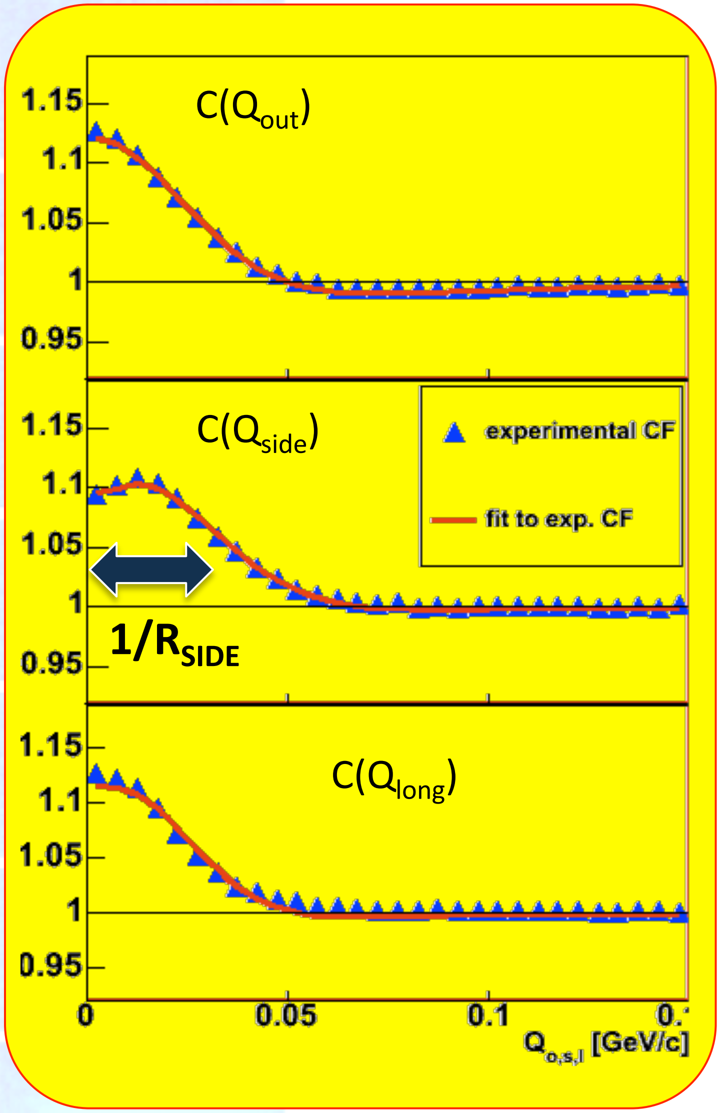
typical “Gaussian” fitting function

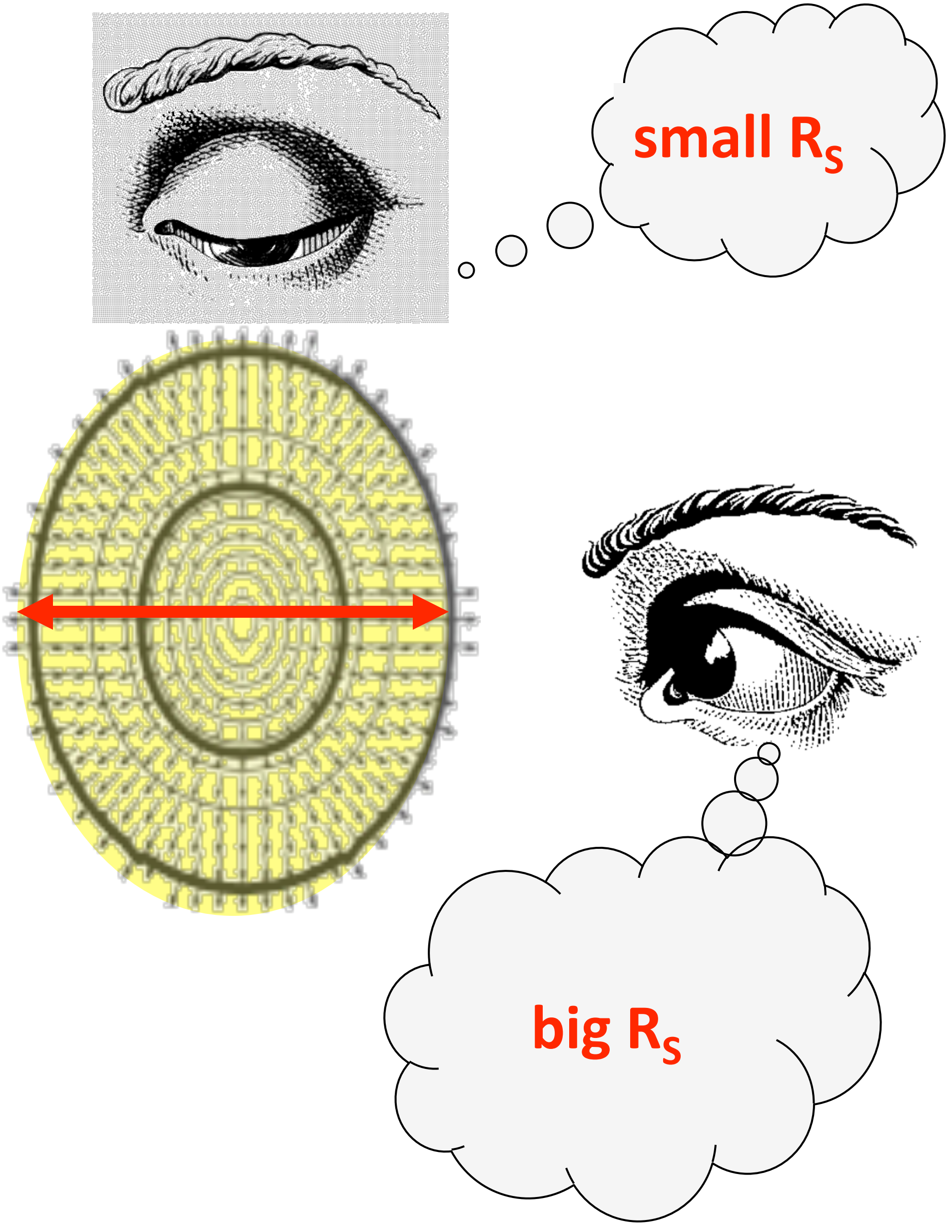




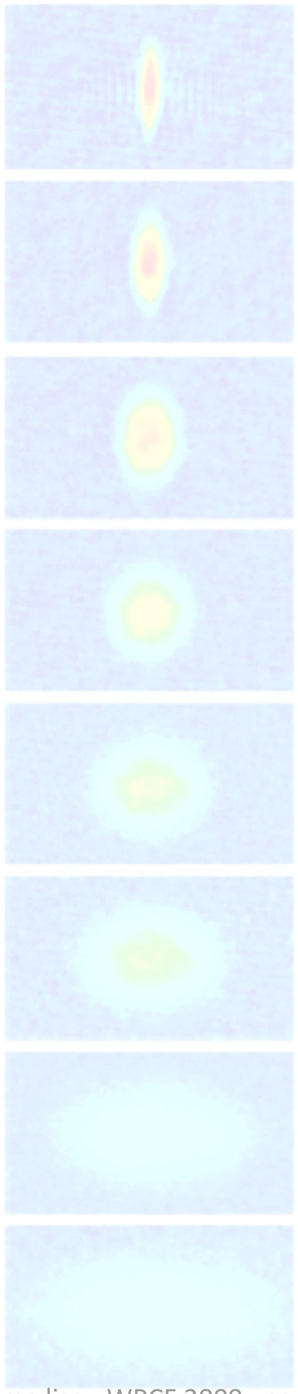
big R_S

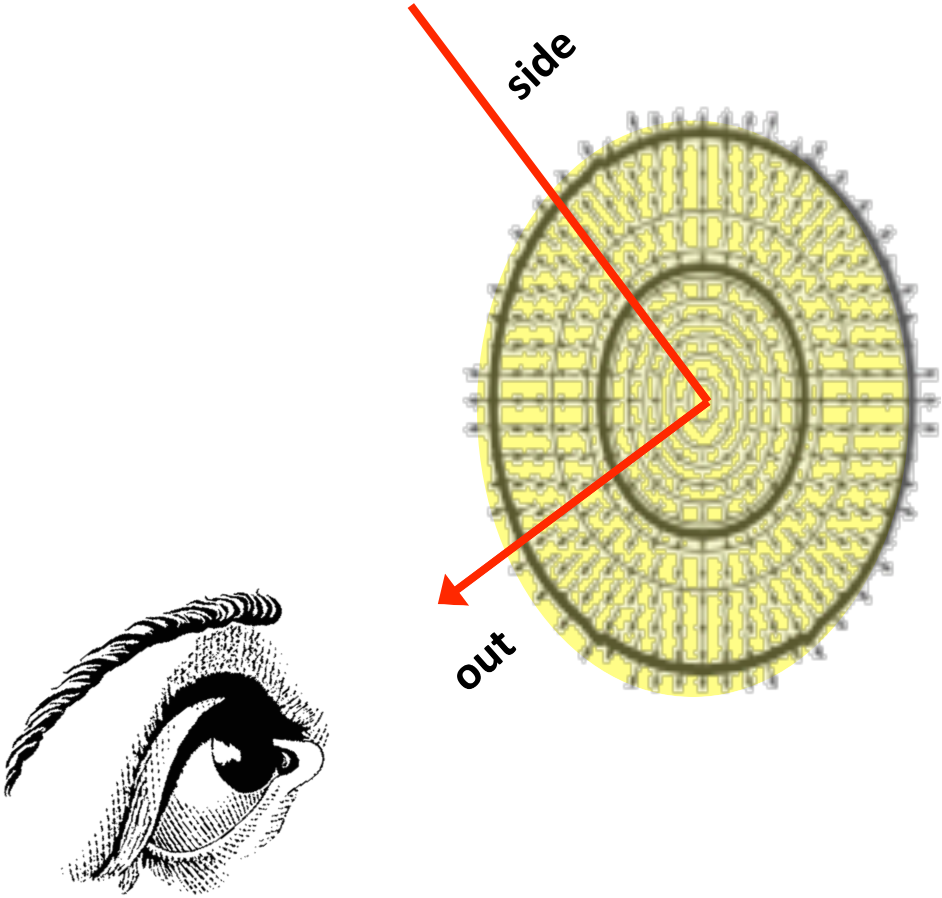
measuring shape



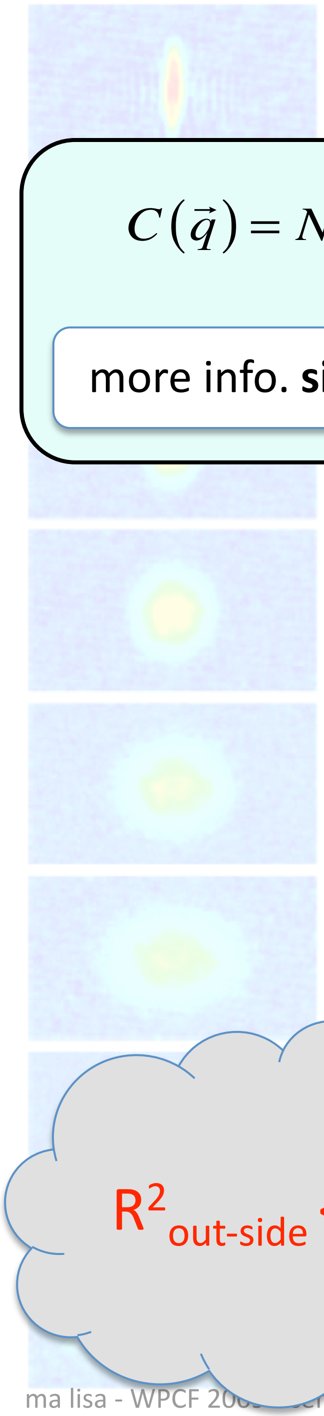


measuring shape



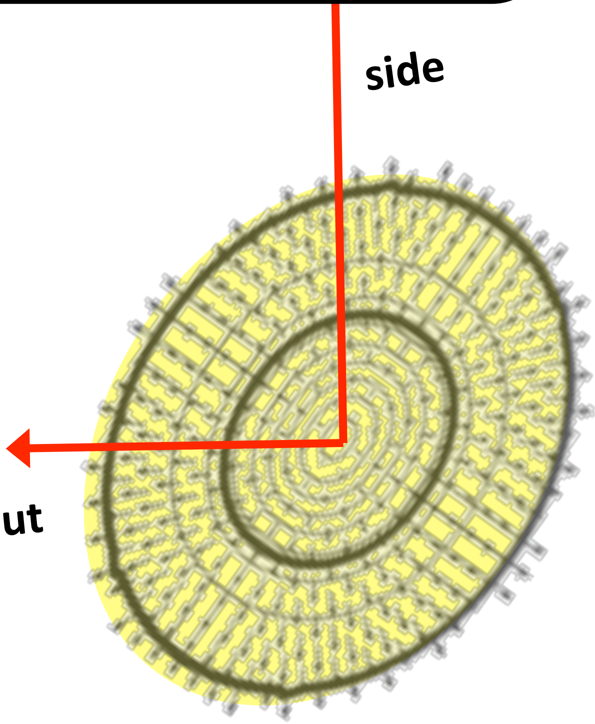


measuring shape



$$C(\vec{q}) = N \cdot \left[1 + \lambda \cdot \left(K_{coul}(\vec{q}) \cdot \left\{1 + \exp\left(-q_i q_j R_{ij}^2\right)\right\} - 1\right)\right]$$

more info. **six** “HBT radii” $R_o^2, R_s^2, R_l^2, R_{os}^2, R_{sl}^2, R_{ol}^2$

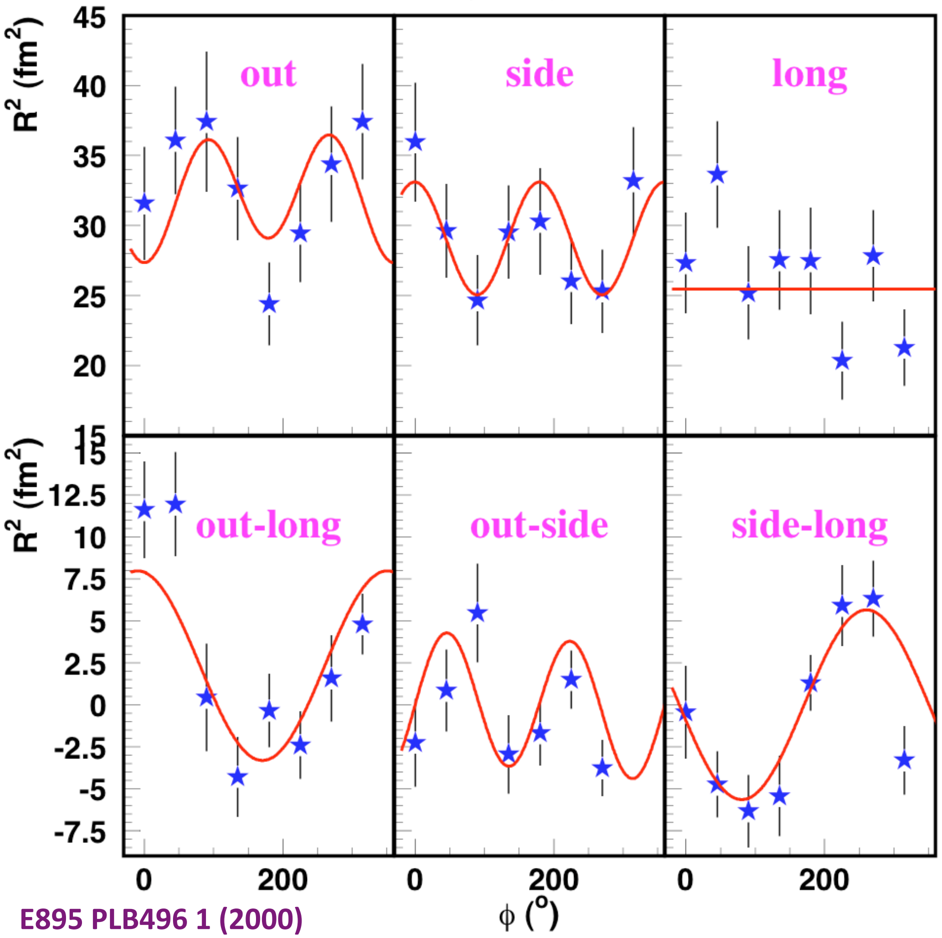


$R^2_{\text{out-side}} < 0$

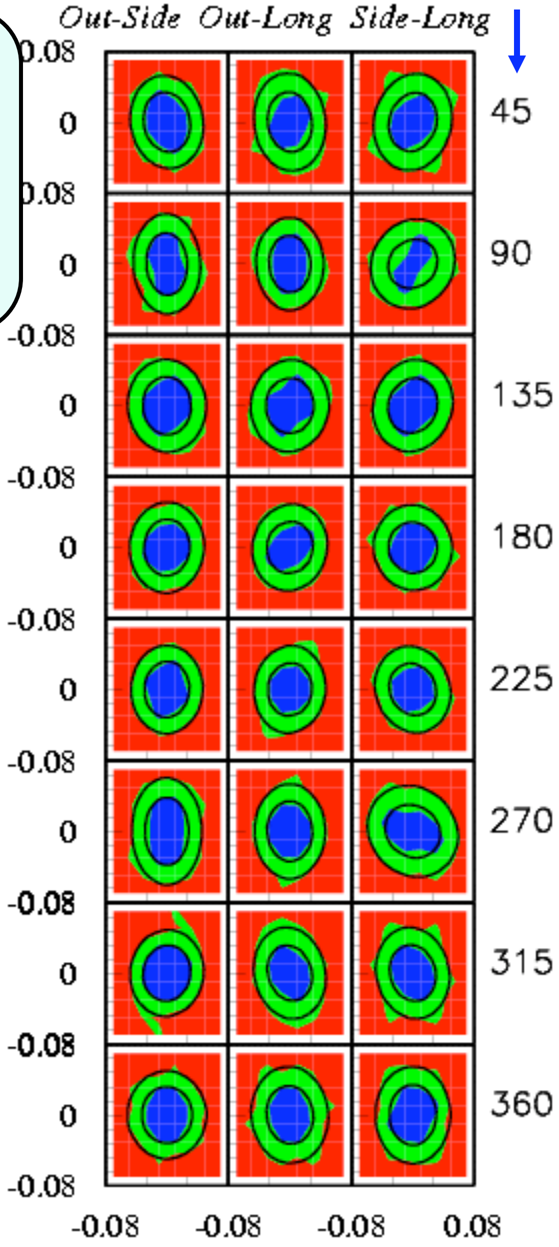
measuring shape

$$C(\vec{q}) = N\cdot\left[1+\lambda\cdot\left(K_{coul}(\vec{q})\cdot\left\{1+\exp\left(-q_i q_j R_{ij}^2\right)\right\}-1\right)\right]$$

more info. **six** “HBT radii” $R_o^2, R_s^2, R_l^2, R_{os}^2, R_{sl}^2, R_{ol}^2$



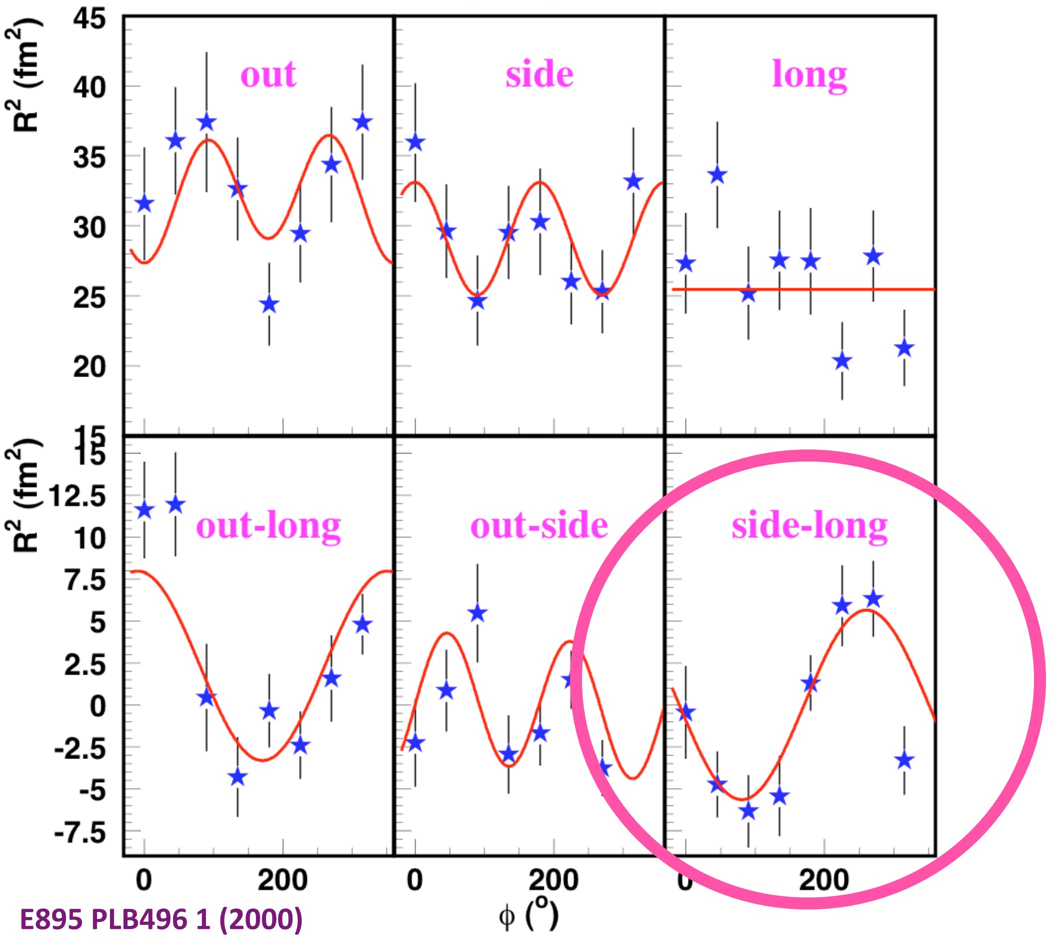
E895 PLB496 1 (2000)



measuring shape

$$C(\vec{q}) = N \cdot \left[1 + \lambda \cdot \left(K_{coul}(\vec{q}) \cdot \left\{1 + \exp\left(-q_i q_j R_{ij}^2\right)\right\} - 1\right)\right]$$

more info. **six** “HBT radii” $R_o^2, R_s^2, R_l^2, R_{os}^2, R_{sl}^2, R_{ol}^2$



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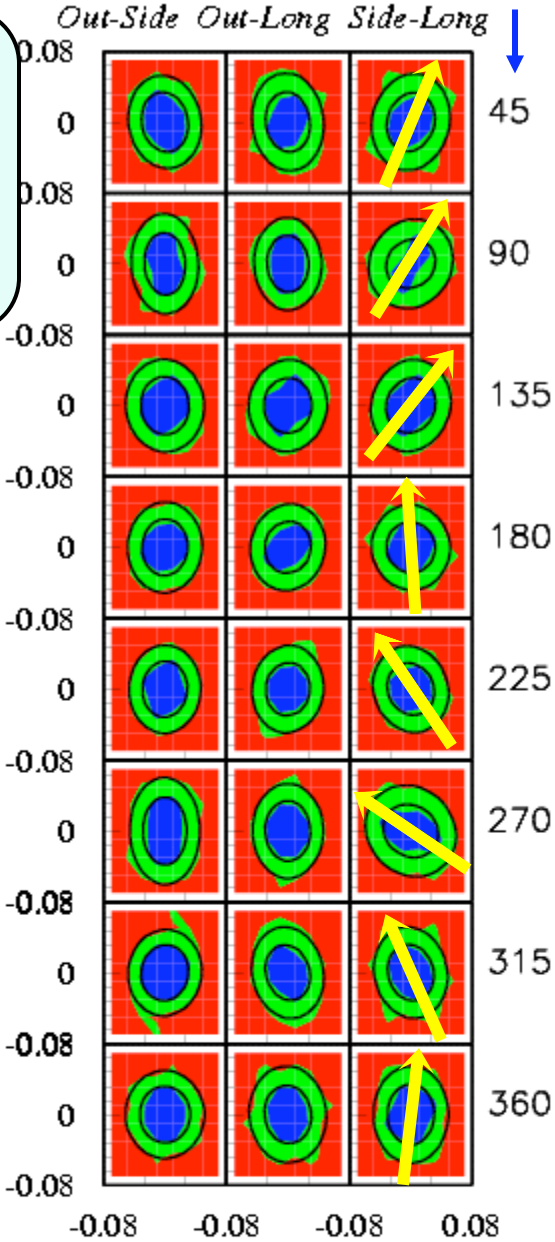


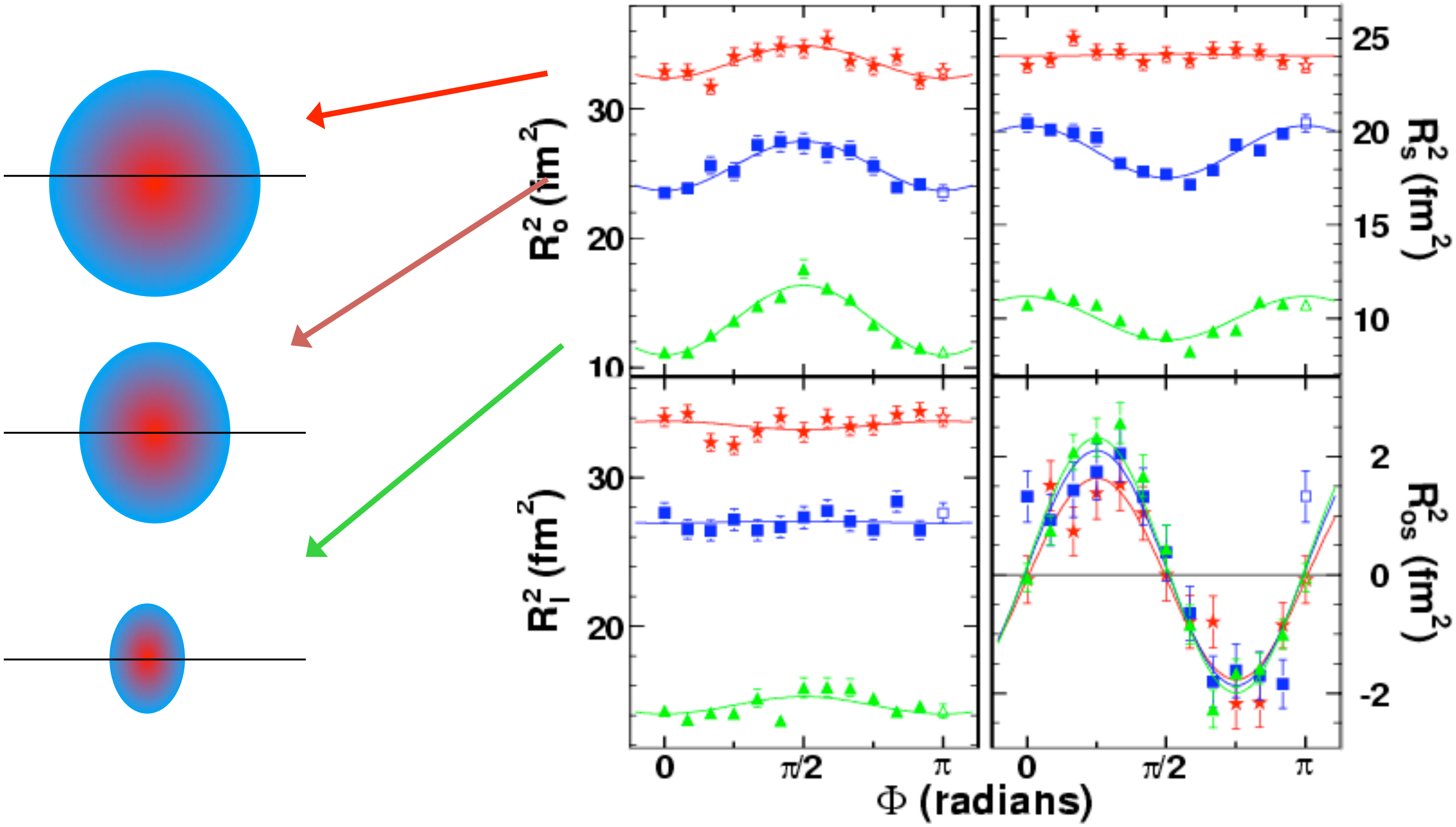
expected systematics

central collisions

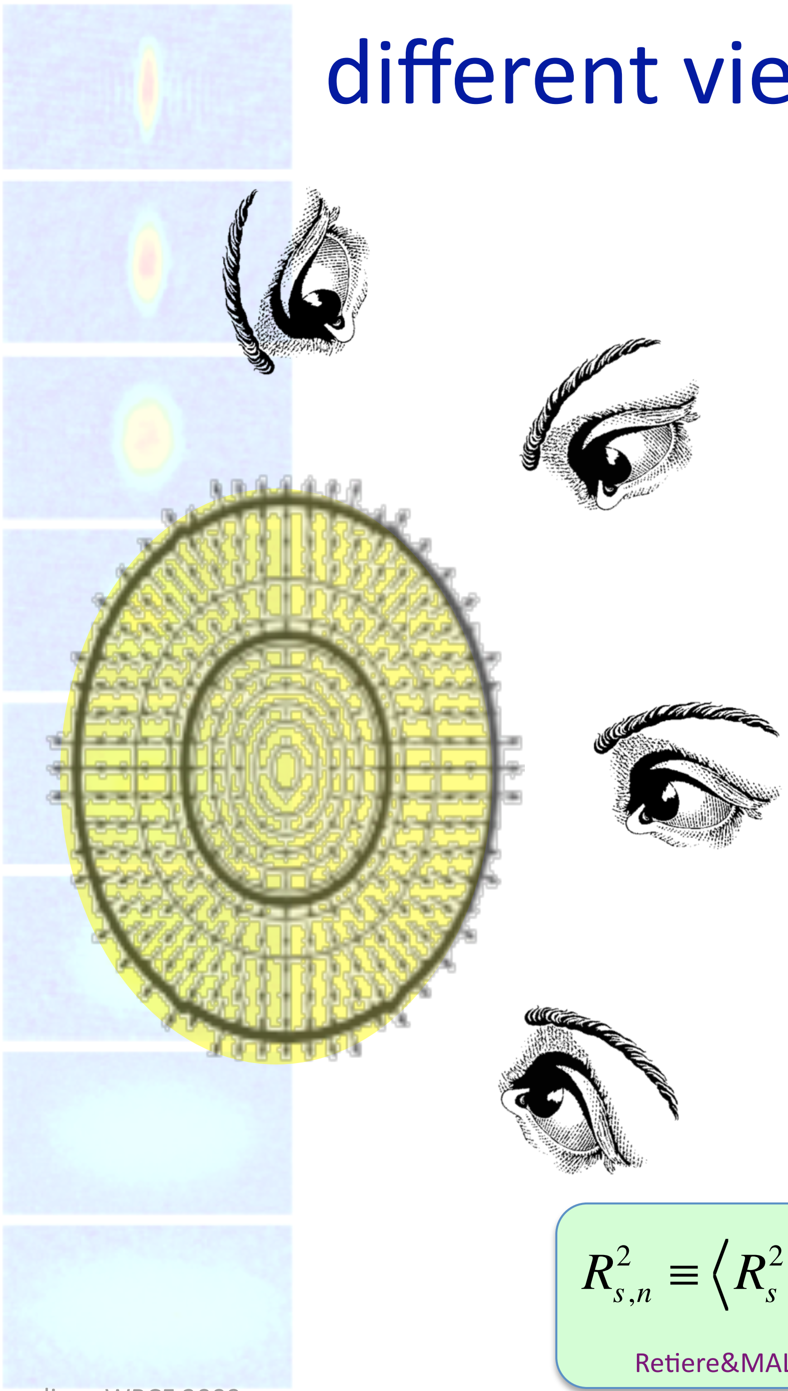
mid-central collisions

peripheral collisions

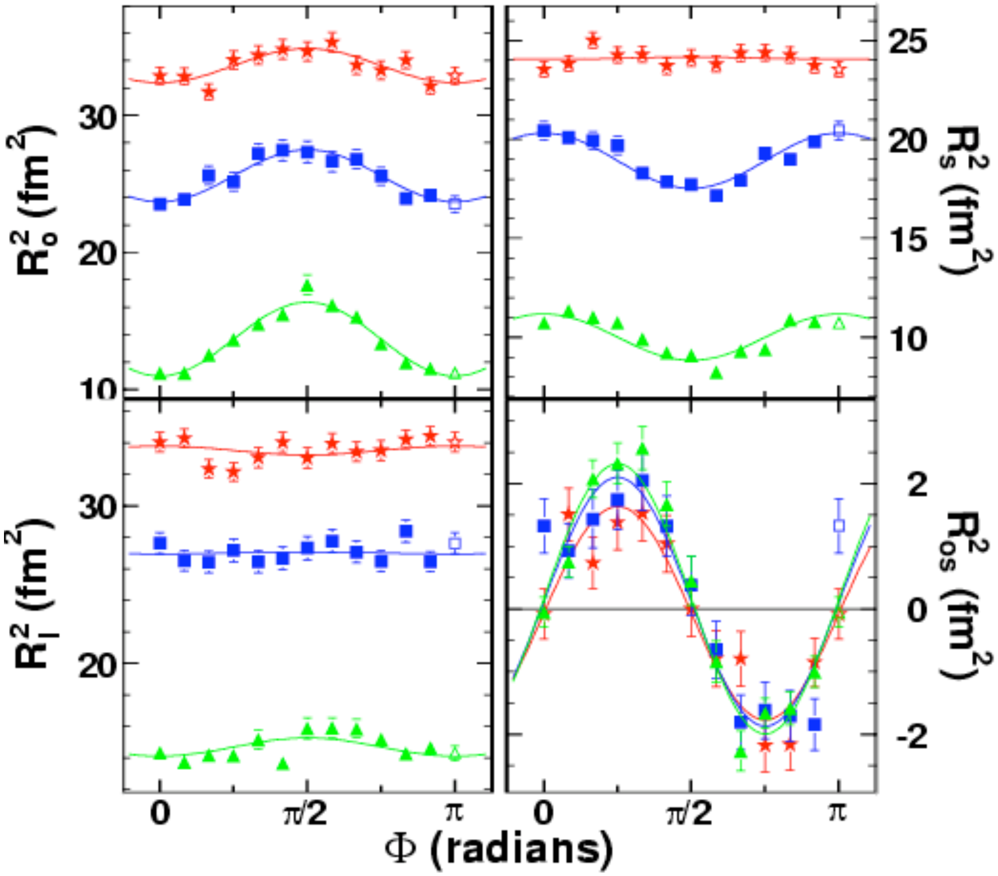
STAR, PRL93 012301 (2004)



different views of the “same” source?



STAR, PRL93 012301 (2004)

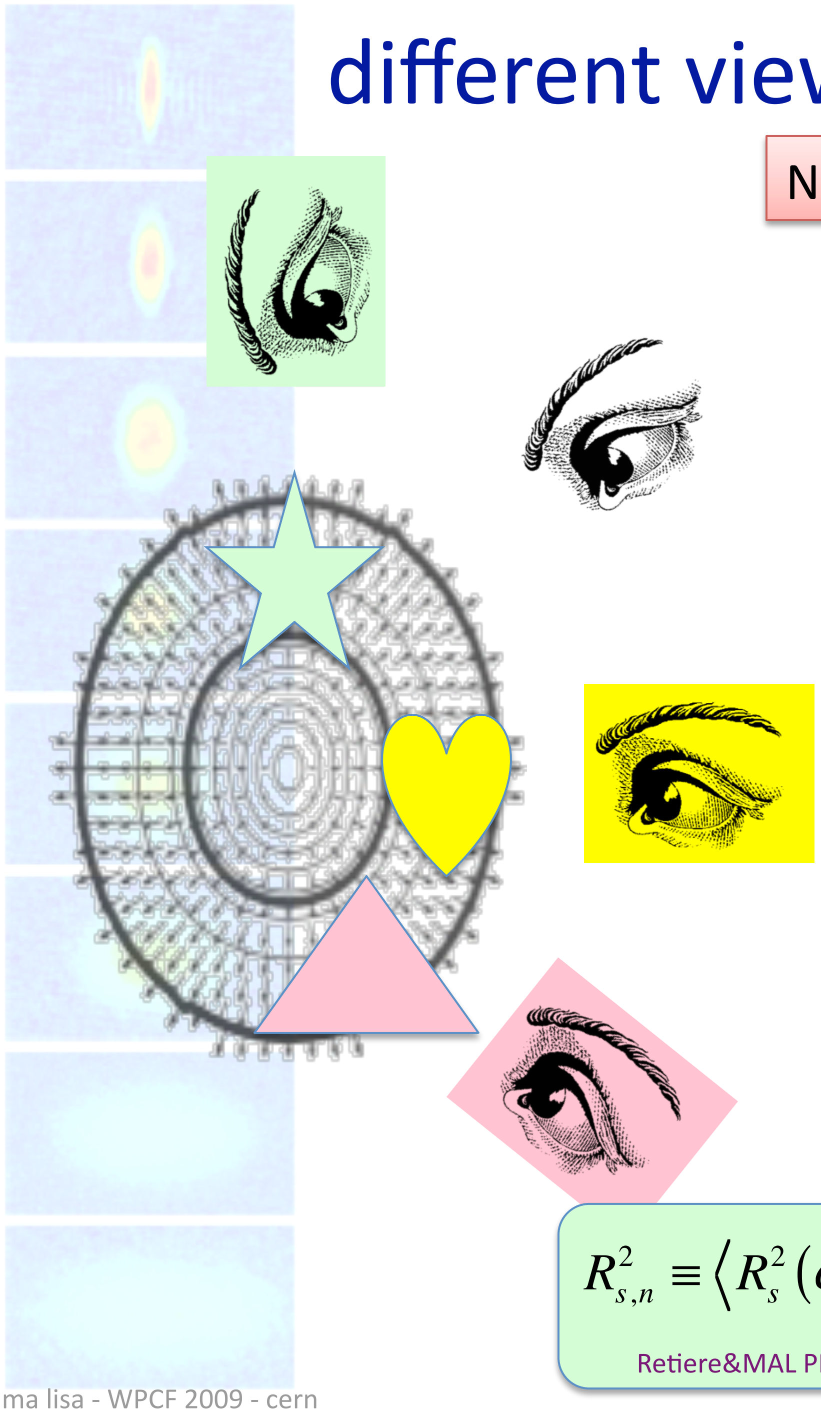


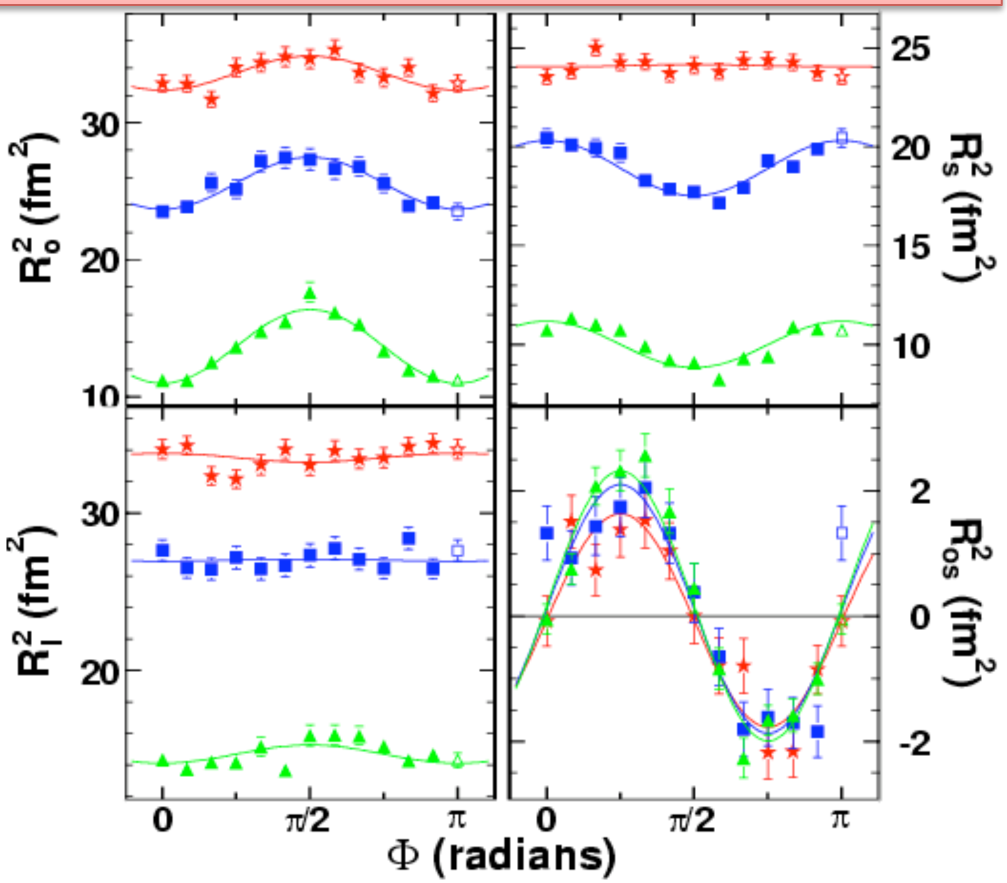
$$R^2_{s,n} \equiv \left\langle R^2_s(\phi)\cdot\cos(n\phi)\right\rangle \qquad \varepsilon = 2\frac{R^2_{s,2}}{R^2_{s,0}} = 2\frac{R^2_{os,2}}{R^2_{s,0}} = -2\frac{R^2_{o,2}}{R^2_{s,0}}$$

Retiere&MAL PRC70 (2004) 044907

different views of the “same” source?

No! Homogeneity regions can be totally different!





$$R_{s,n}^2 \equiv \left\langle R_s^2(\phi)\cdot\cos(n\phi)\right\rangle \qquad \varepsilon = 2\frac{R_{s,2}^2}{R_{s,0}^2} = 2\frac{R_{os,2}^2}{R_{s,0}^2} = -2\frac{R_{o,2}^2}{R_{s,0}^2}$$

Retiere&MAL PRC70 (2004) 044907

White cow perspectives


copyright 2005 eveandersson@

There are white cows in Ohio!

(American) undergraduate

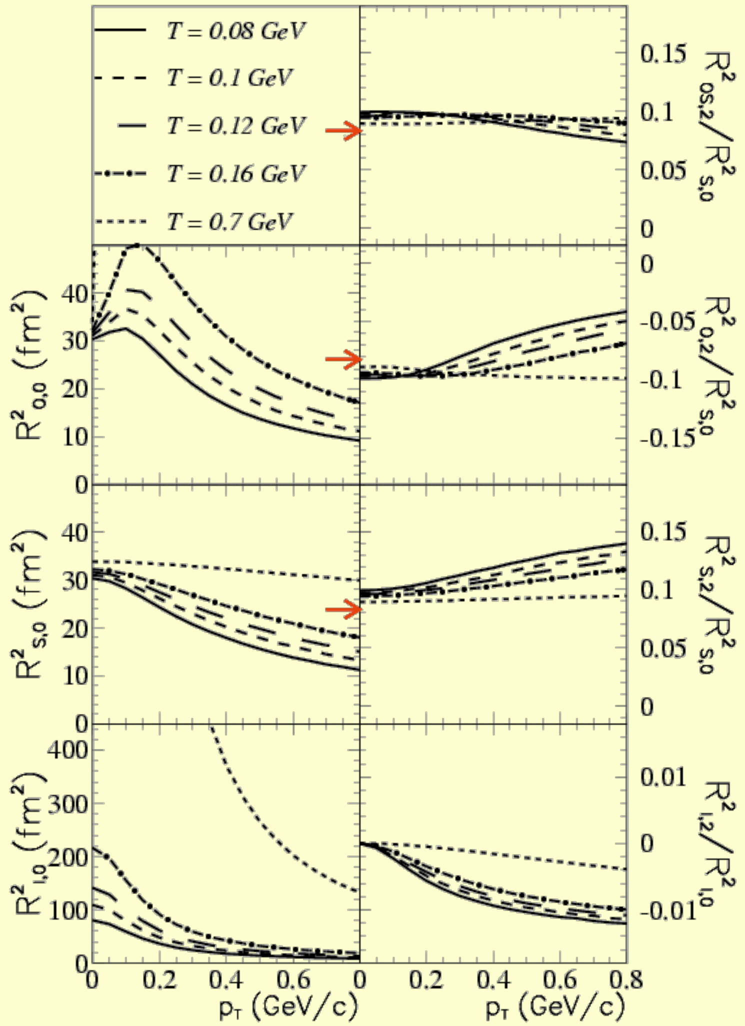
There is a white cow in Ohio.

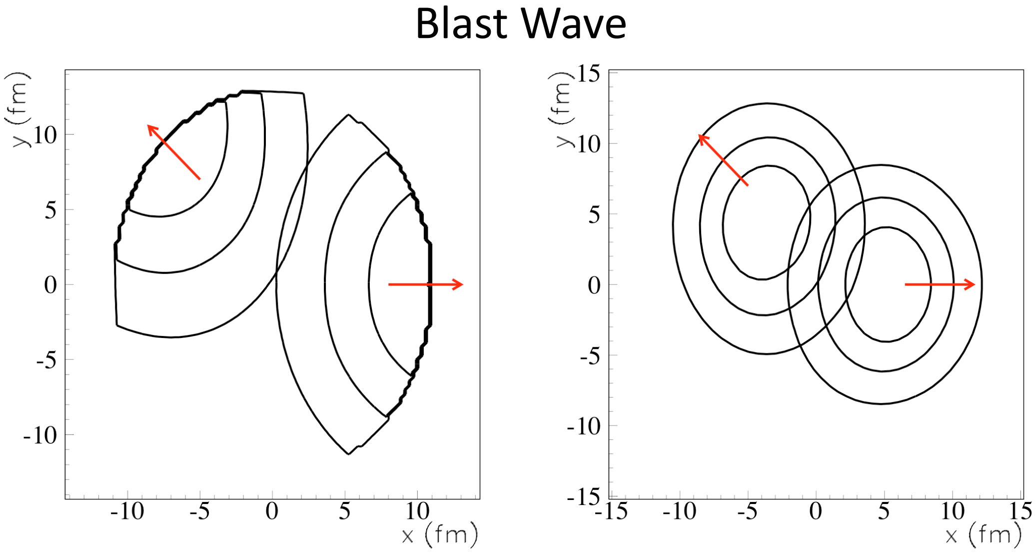
physicist

There is a cow in Ohio, with one white side

Mathematician

BW: “typical” model of flow-induced substructure





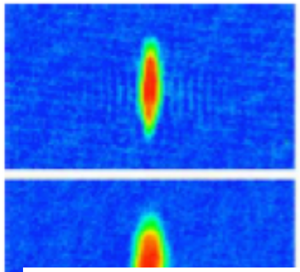
Homogeneity regions for pions moving to 0, 135 degrees

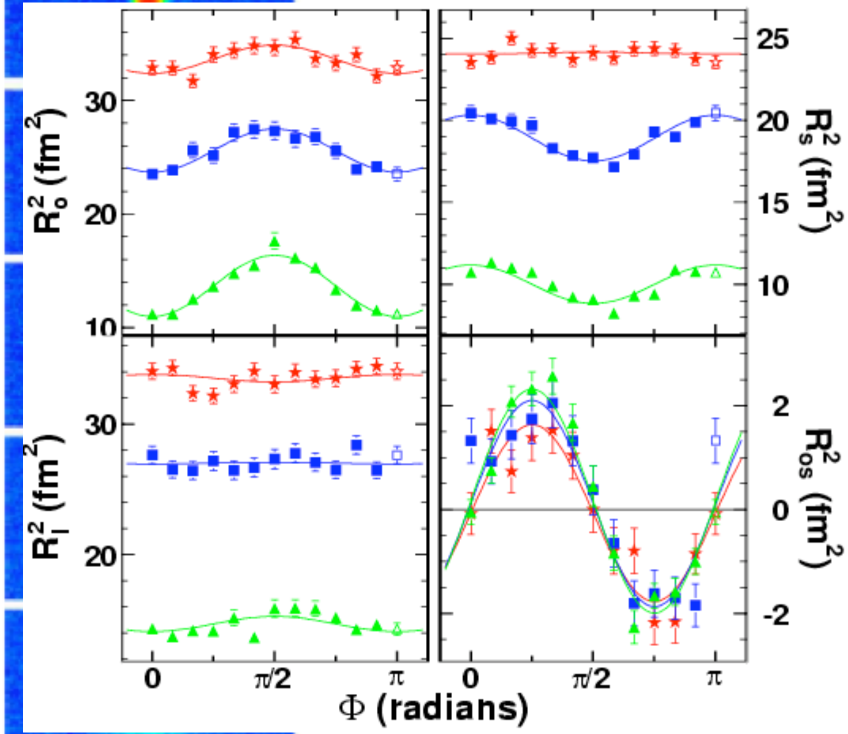
“No-flow formula” estimated good within ~ 30% (low pT)

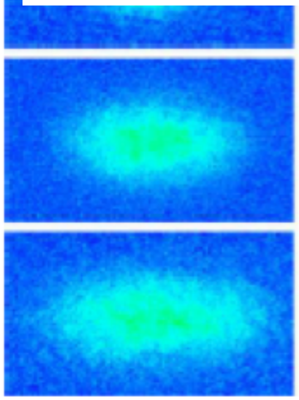
$$R^2_{s,n} \equiv \left\langle R^2_s(\phi) \cdot \cos(n\phi) \right\rangle \qquad \varepsilon \approx 2\frac{R^2_{s,2}}{R^2_{s,0}} \approx 2\frac{R^2_{os,2}}{R^2_{s,0}} \approx -2\frac{R^2_{o,2}}{R^2_{s,0}}$$

Retiere&MAL PRC70 (2004) 044907

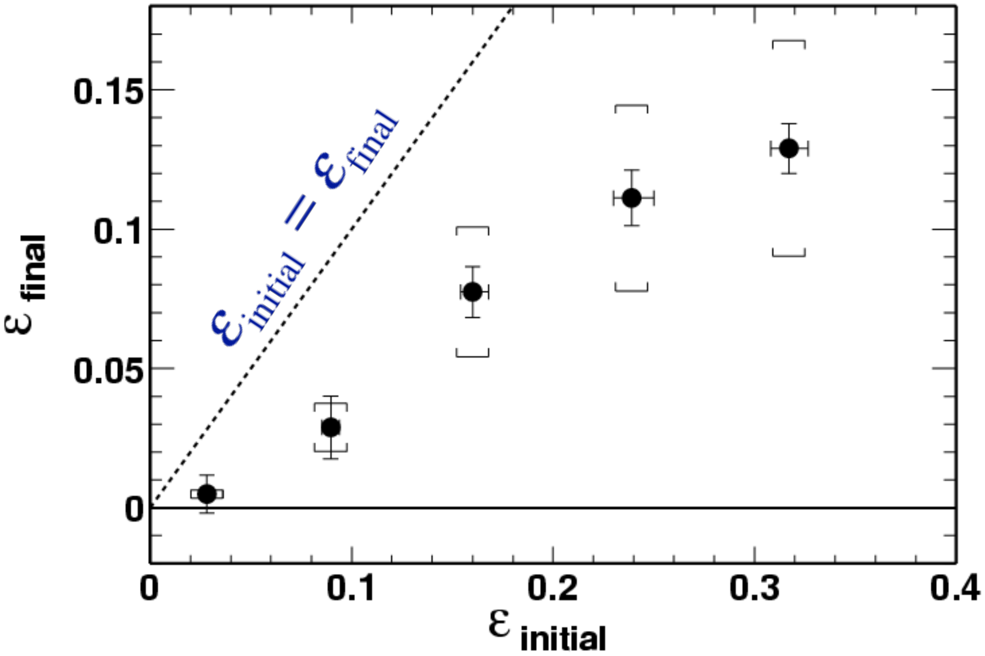
“Spatial elliptic flow”: Centrality Evolution at RHIC







STAR PRL93 012301 (2004)



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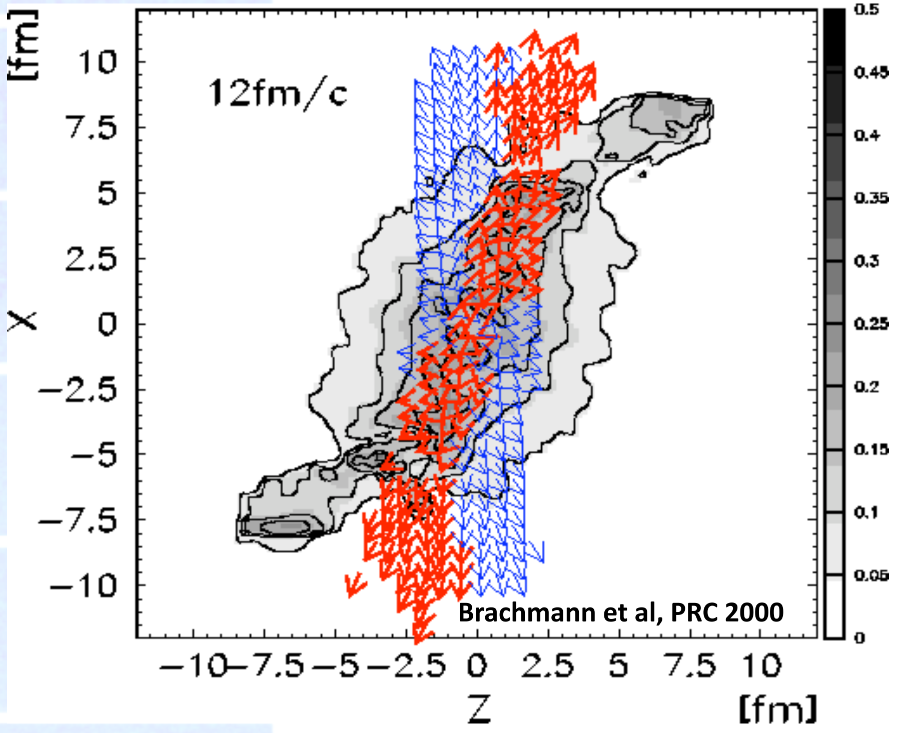
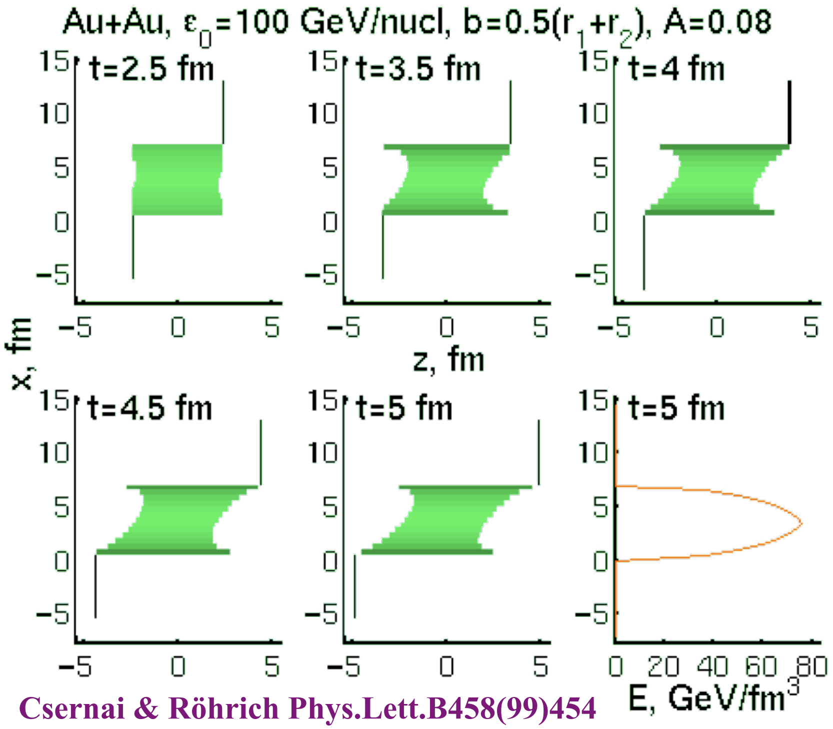
Retiere&MAL PRC70 (2004) 044907

Effects of “spatial *directed* flow?”



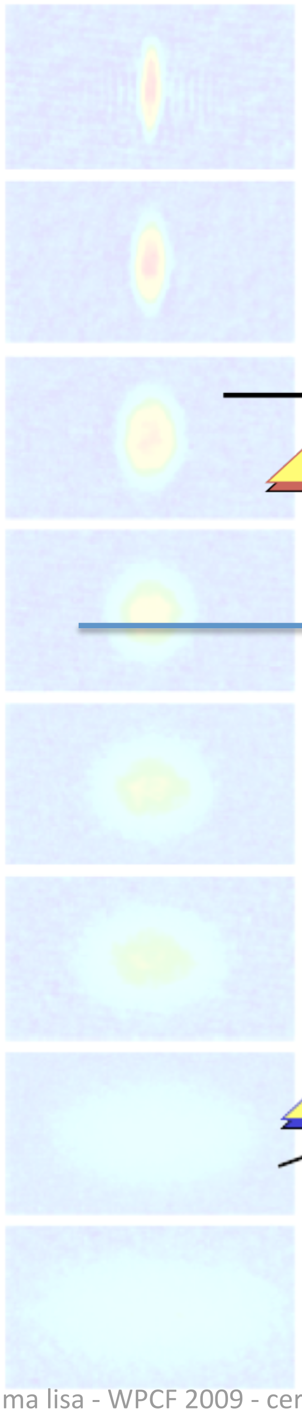
Brachmann et al, PRC 2000



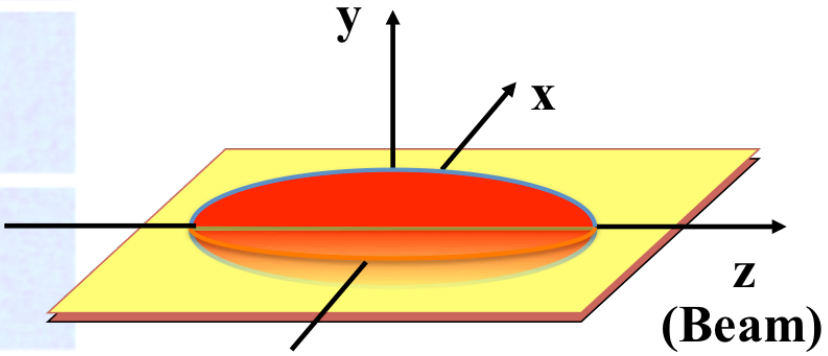
Csernai & Röhrich Phys.Lett.B458(99)454

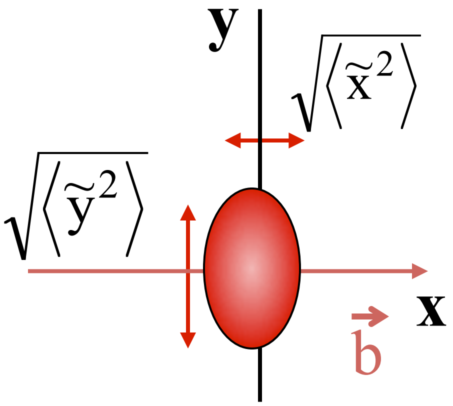
$$R^2_{s,n} \equiv \left\langle R^2_s(\phi)\cdot\cos(n\phi)\right\rangle \qquad \varepsilon \approx 2\frac{R^2_{s,2}}{R^2_{s,0}} \approx 2\frac{R^2_{os,2}}{R^2_{s,0}} \approx -2\frac{R^2_{o,2}}{R^2_{s,0}}$$

Retiere&MAL PRC70 (2004) 044907



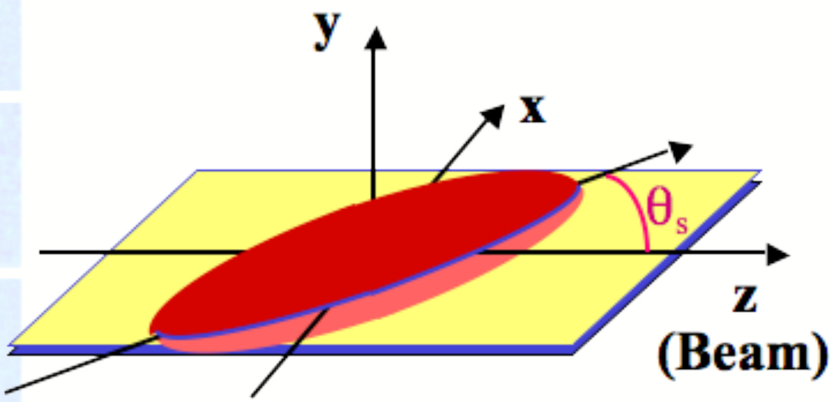
Effects of “spatial *directed* flow?”

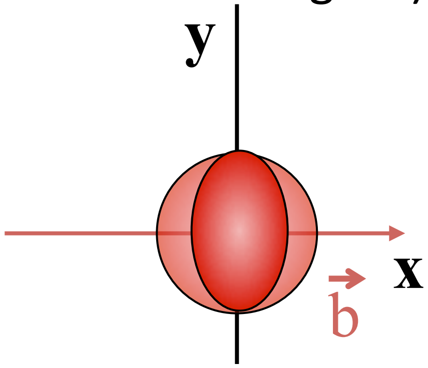




Tilt angle θ_s – analog of “flow angle”

(… and “squeezeout” should be referenced to flow angle…)





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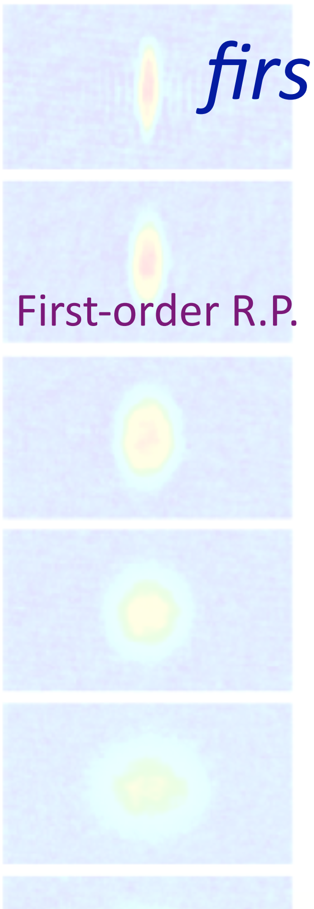
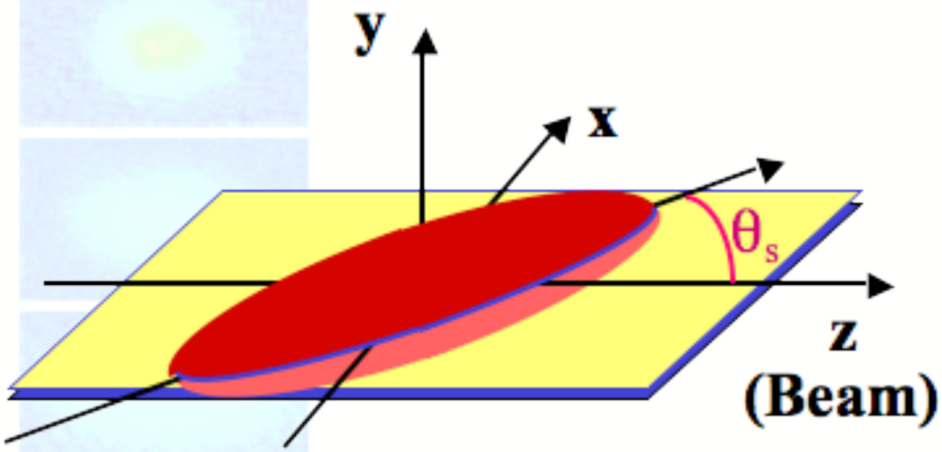
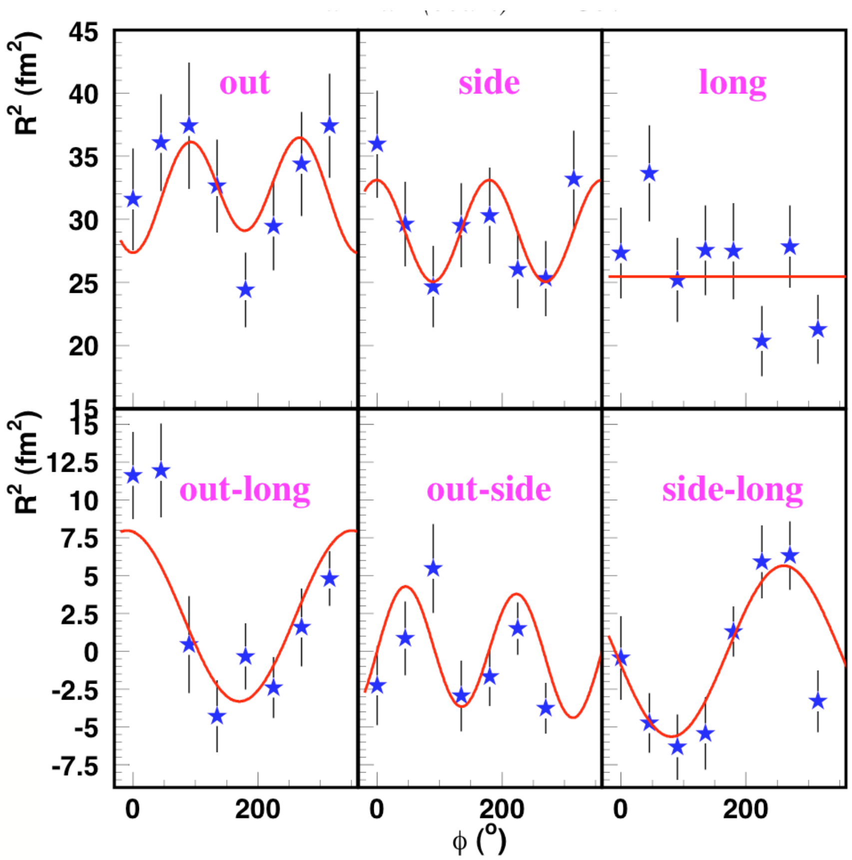
Retiere&MAL PRC70 (2004) 044907

first-order oscillations reveal large tilts @ AGS



First-order R.P. needed

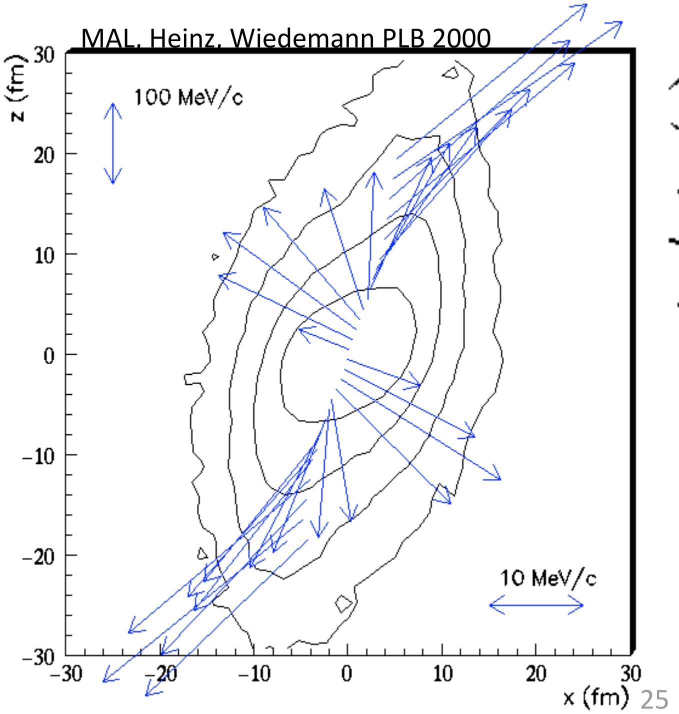


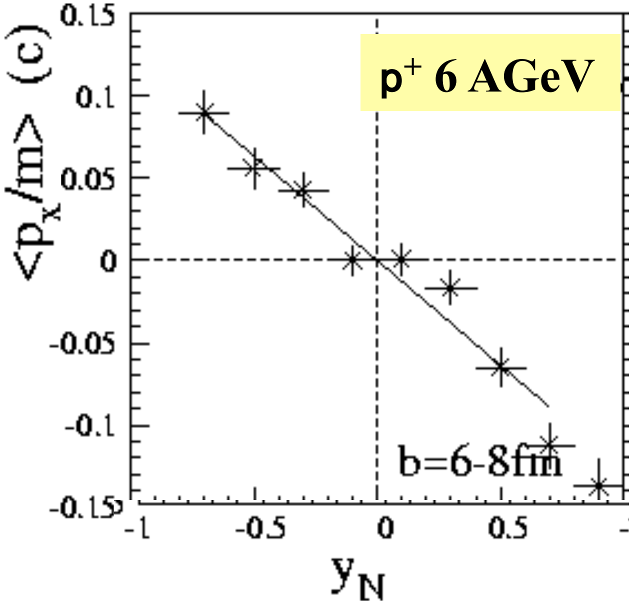


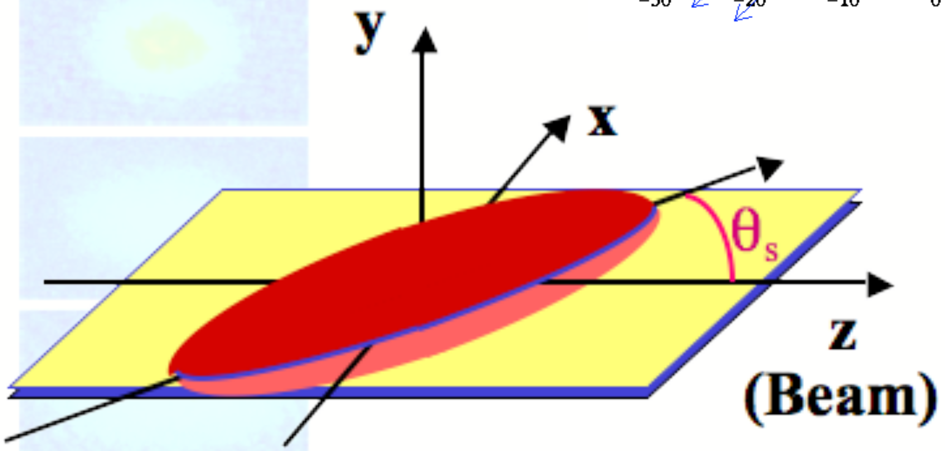
first-order oscillations reveal large tilts @ AGS

First-order R.P. needed

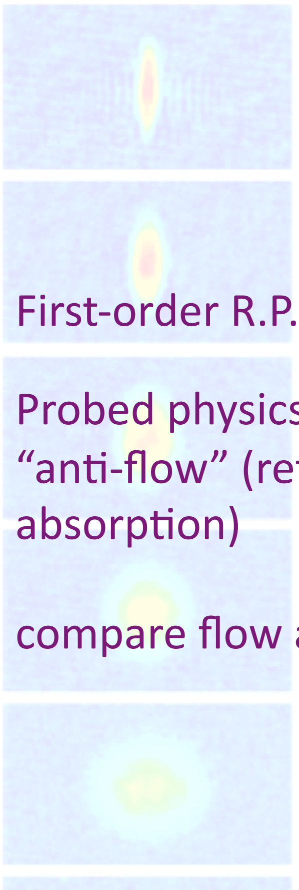
Probed physics *behind* pion "anti-flow" (reflection, not absorption)


MAL, Heinz, Wiedemann PLB 2000





large tilts @ AGS

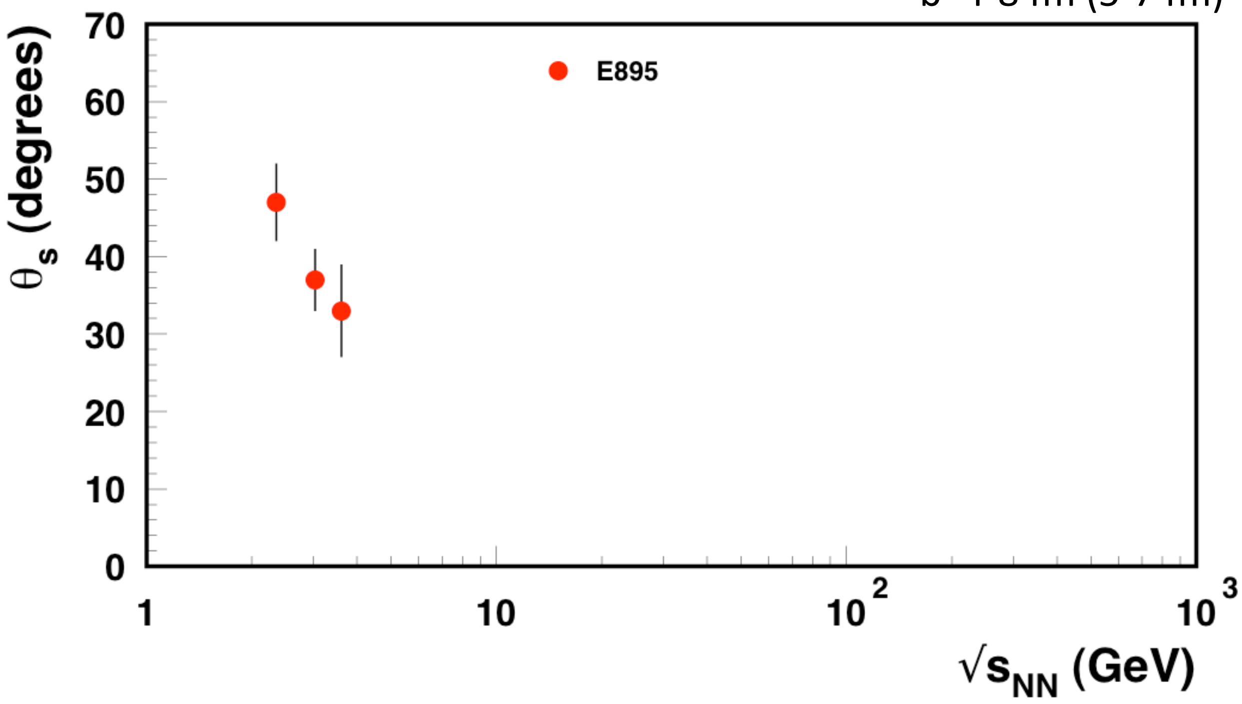


First-order R.P. needed

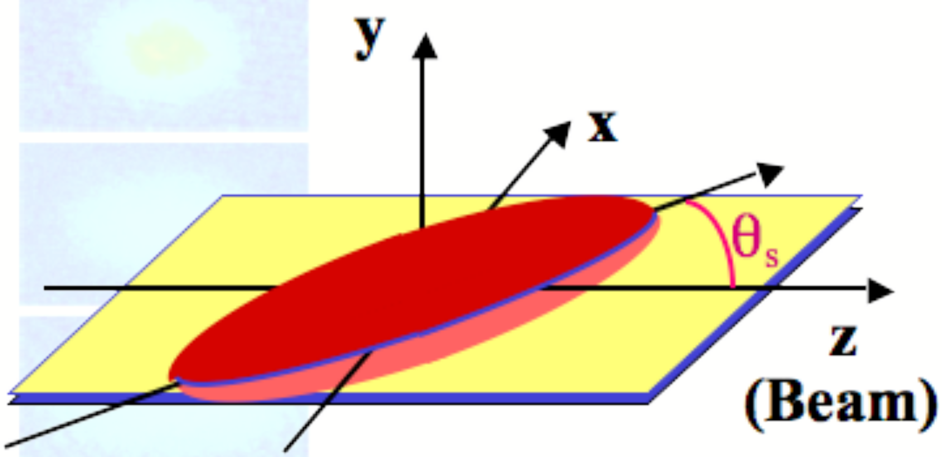
Probed physics *behind* pion “anti-flow” (reflection, not absorption)

compare flow angle ~ 1^o

b=4-8 fm (5-7 fm)



- θ_s large, falls rapidly



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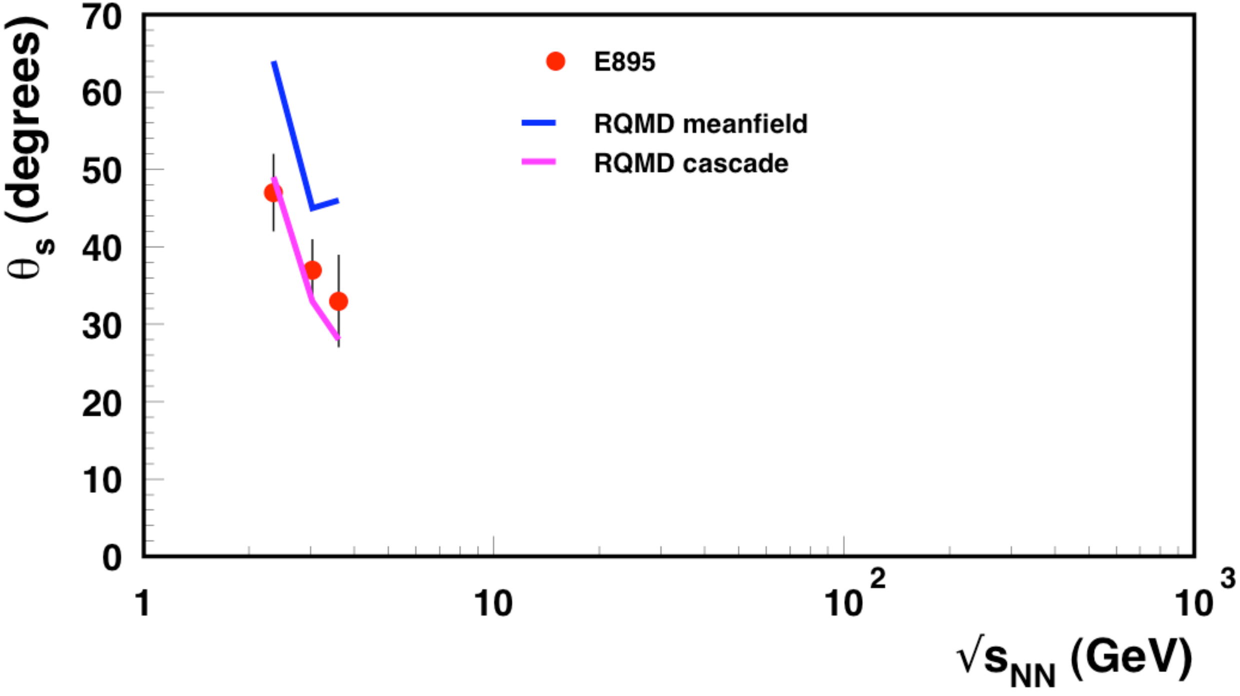
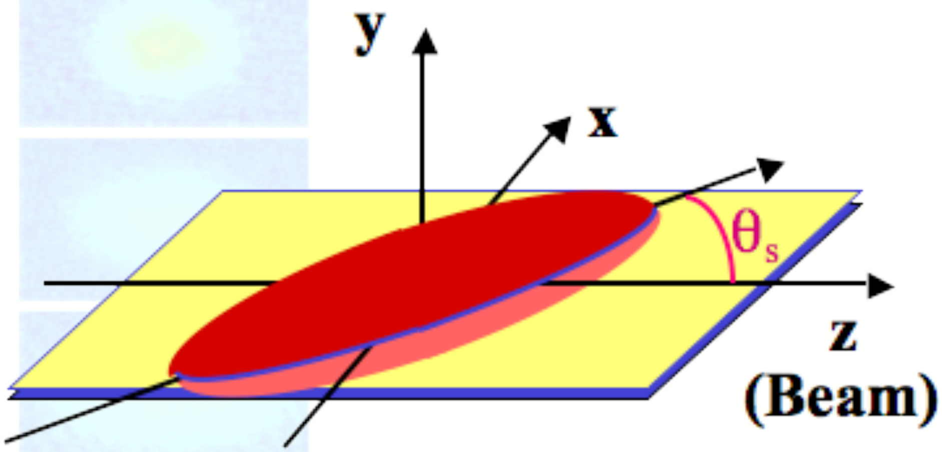


- θ_s large, falls rapidly
- spatial tilt disfavors mf, contrary directed flow



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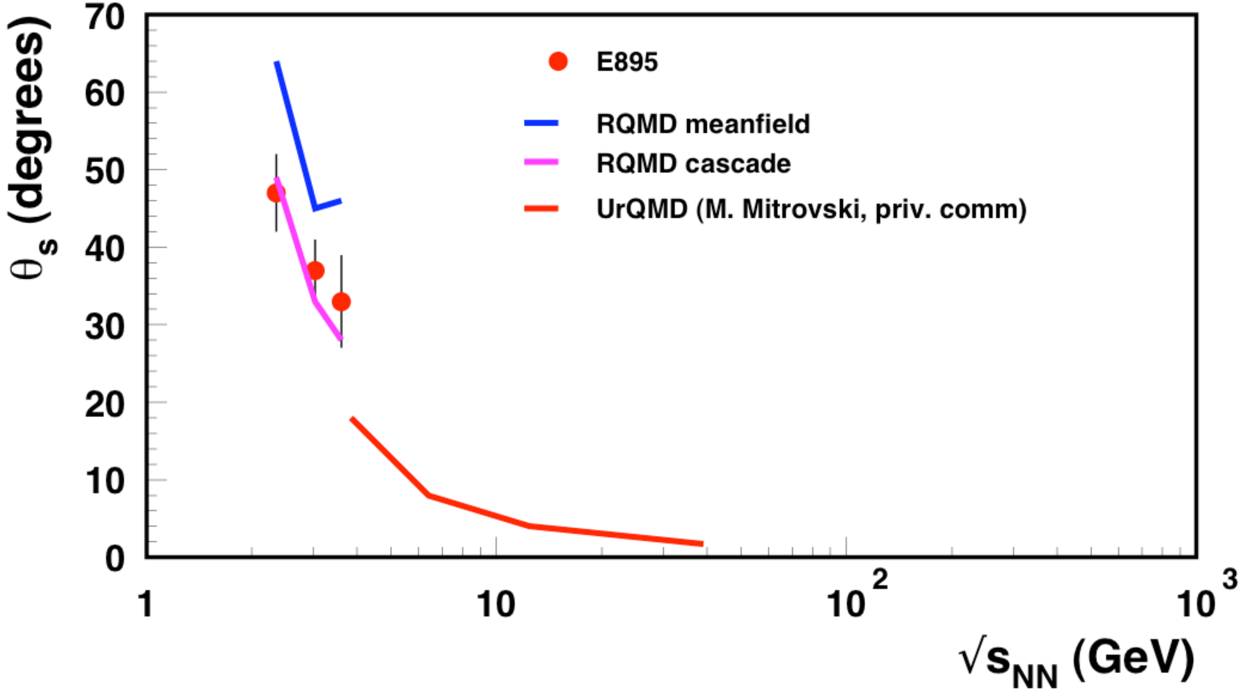

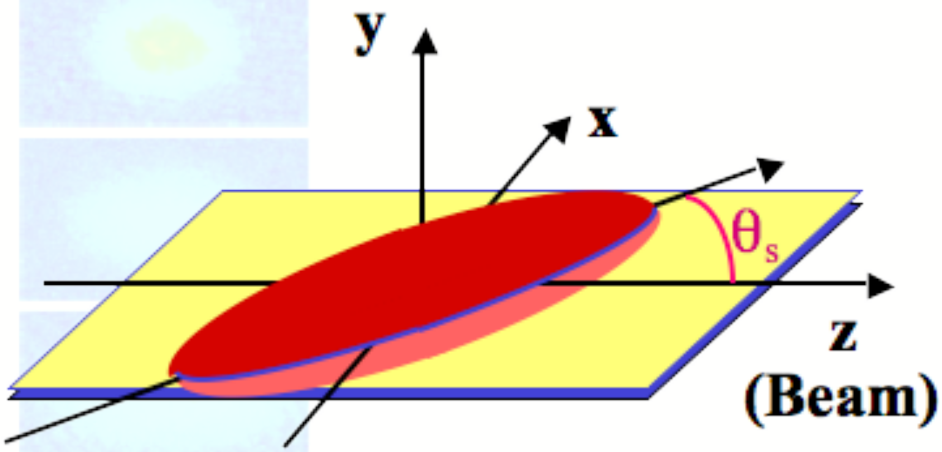

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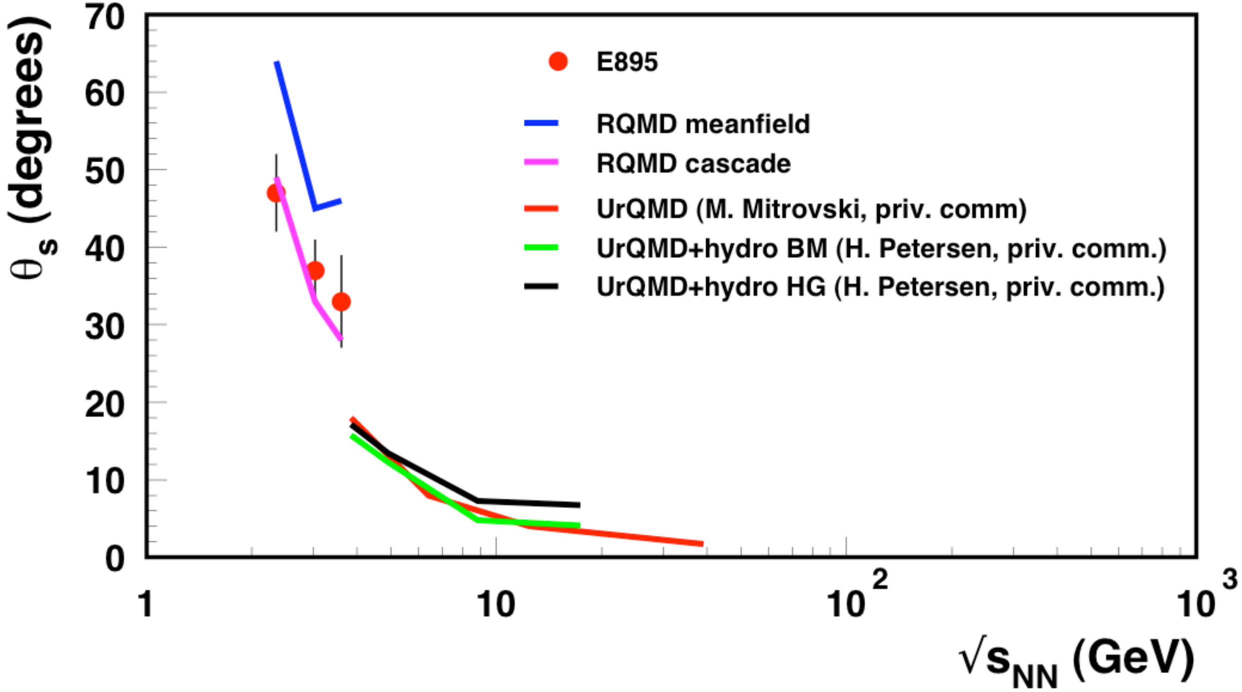
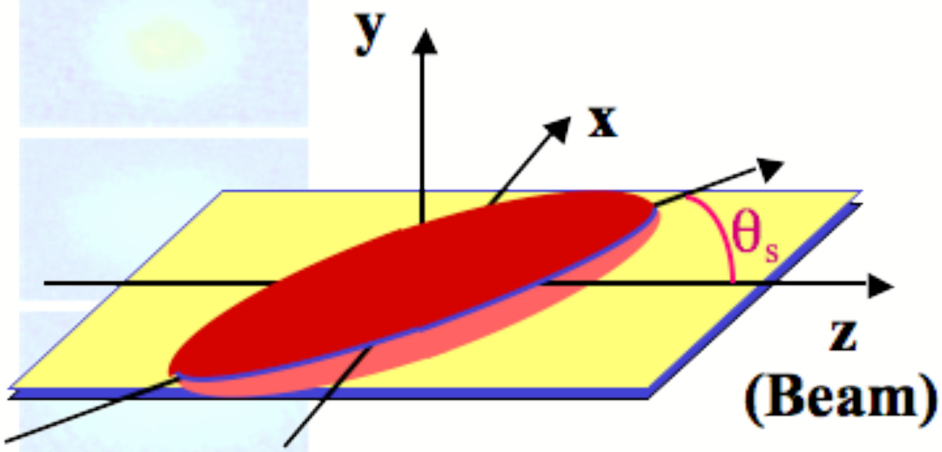




- θ_s large, falls rapidly
- spatial tilt disfavors mf, contrary directed flow
- significantly lower tilt (too low?) predicted by UrQMD & hybrids
- RHIC energies – probably negligible
  - **2D hydro OK?**
- **SPS?**

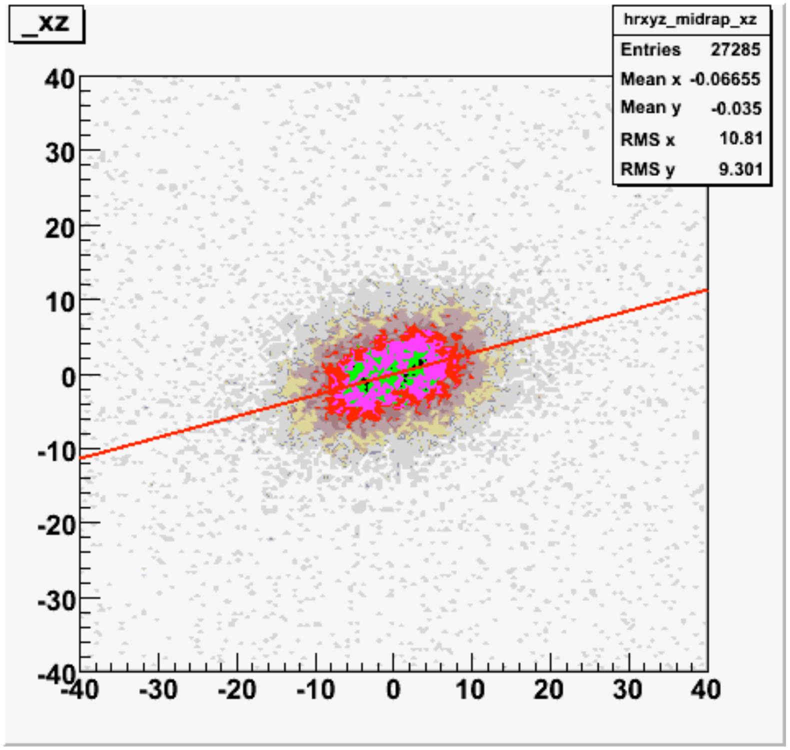
complications from large tilts?

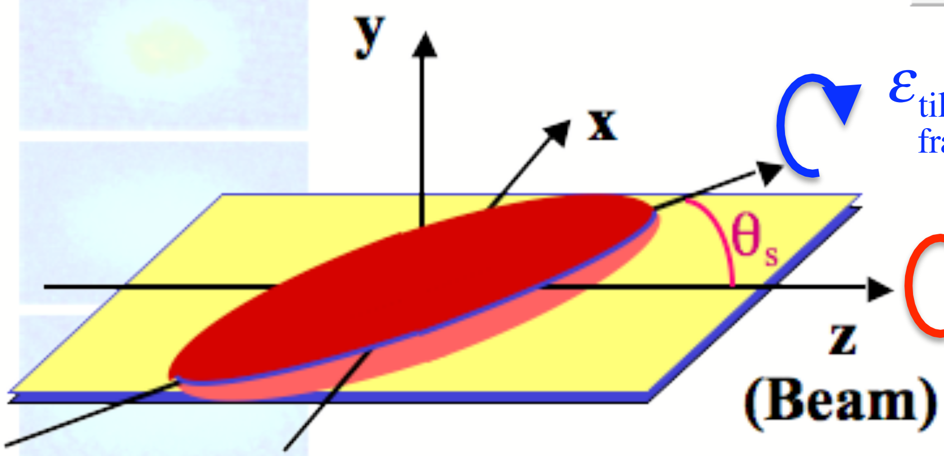
measurement:

UrQMD+hydro[BM]@ 3.8 GeV:

ε in non-natural frame significantly reduced from ε in natural (tilted) frame

affects CERES measurement?





$\varepsilon_{\substack{\text{tilted}\\\text{frame}}} = +0.01$ (out-of-plane)

$\varepsilon_{\substack{\text{beam}\\\text{frame}}} = -0.03$ (in-plane)

complications from large tilts?

measurement:

UrQMD+hydro[BM]@ 3.8 GeV:

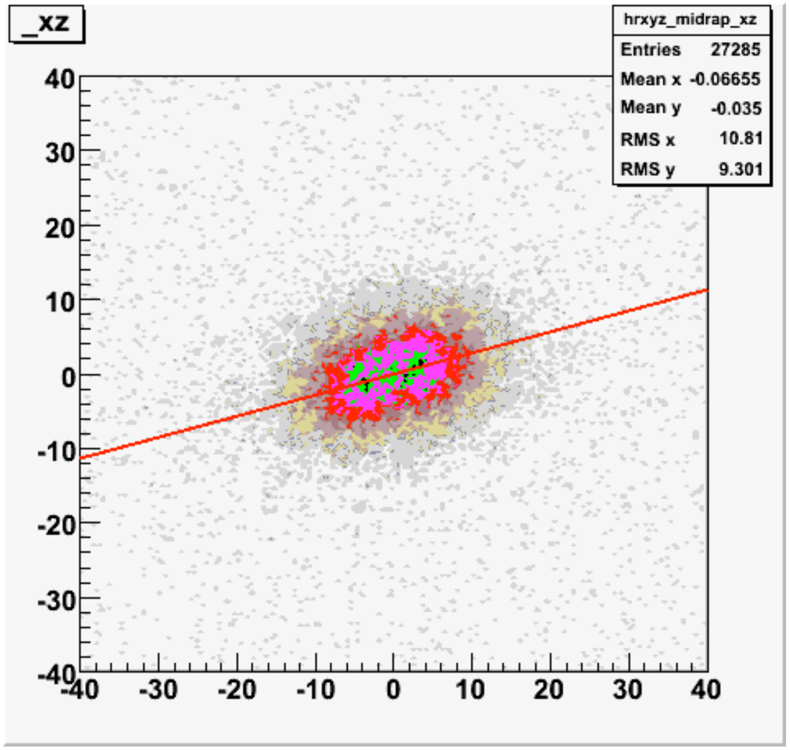
ε in non-natural frame significantly reduced from ε in natural (tilted) frame

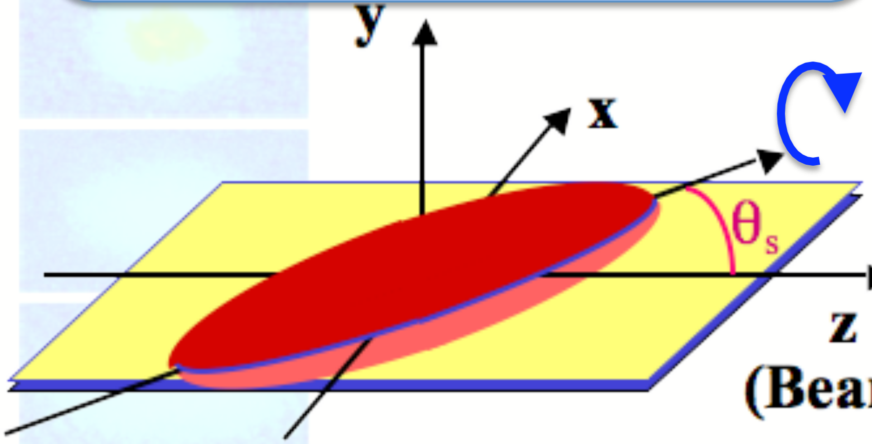
affects CERES measurement?

transport

Tilts are manifestly “boost variant,” in *space* even *at* y=0

2D hydro codes?





$$\varepsilon_{\substack{\text{tilted}\\\text{frame}}} = +0.01 \quad \text{(out-of-plane)}$$

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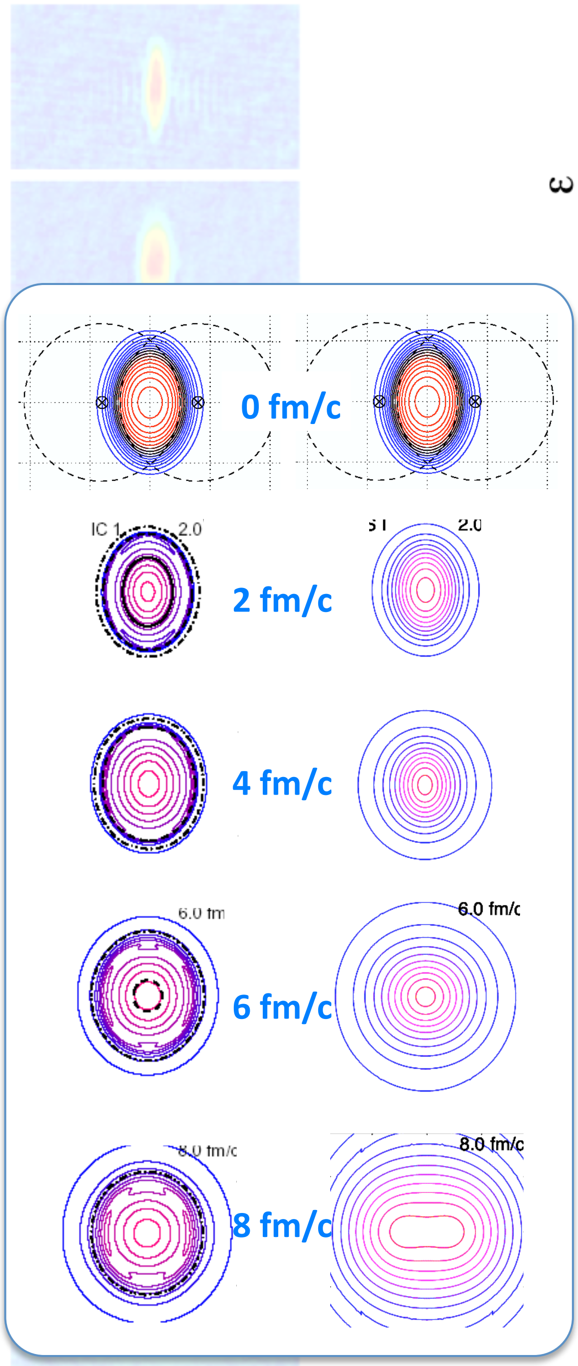
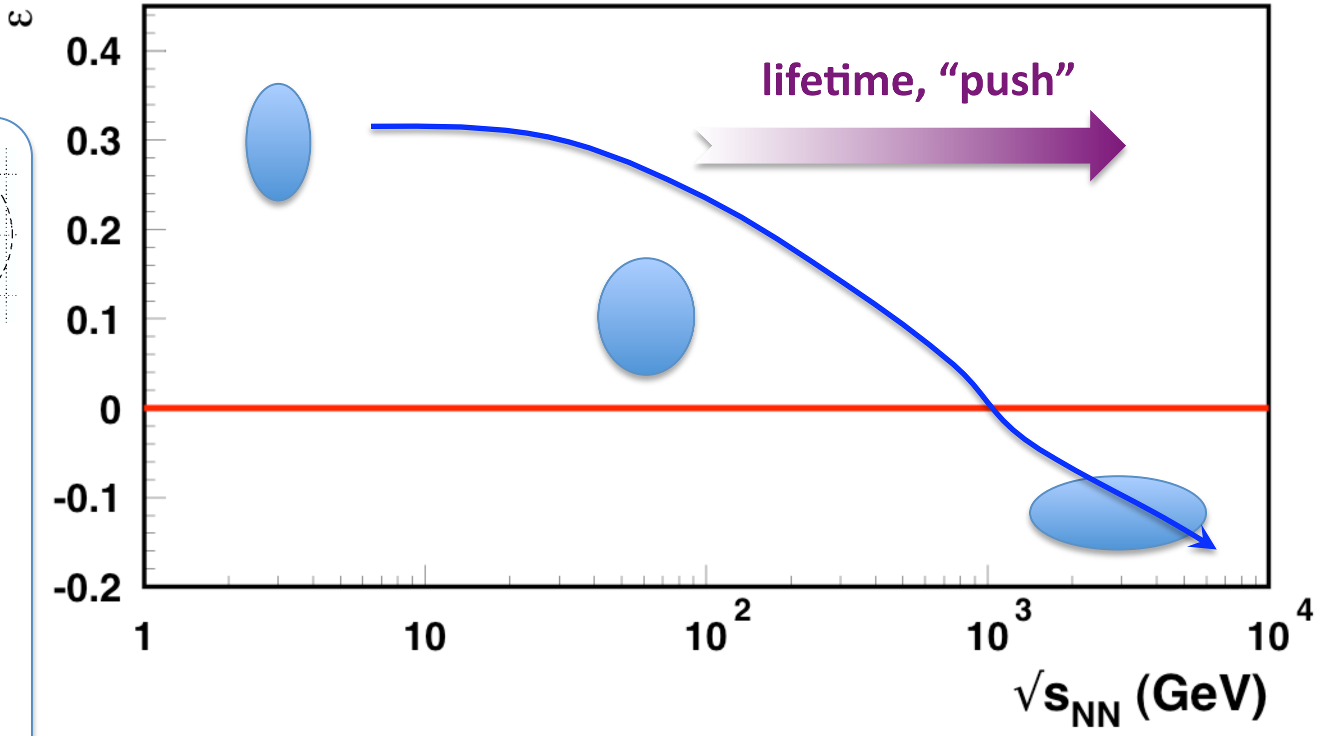
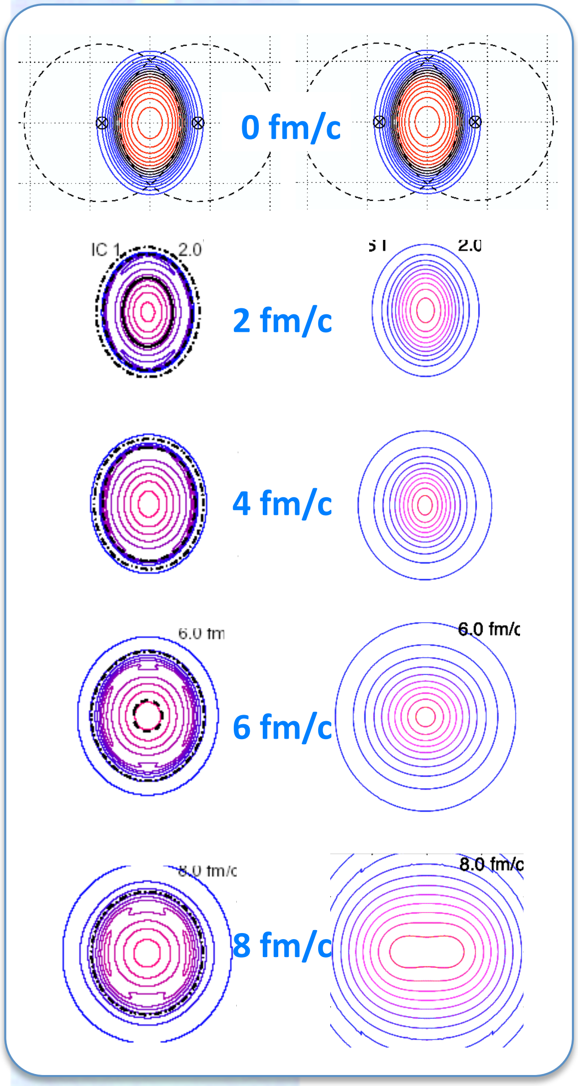
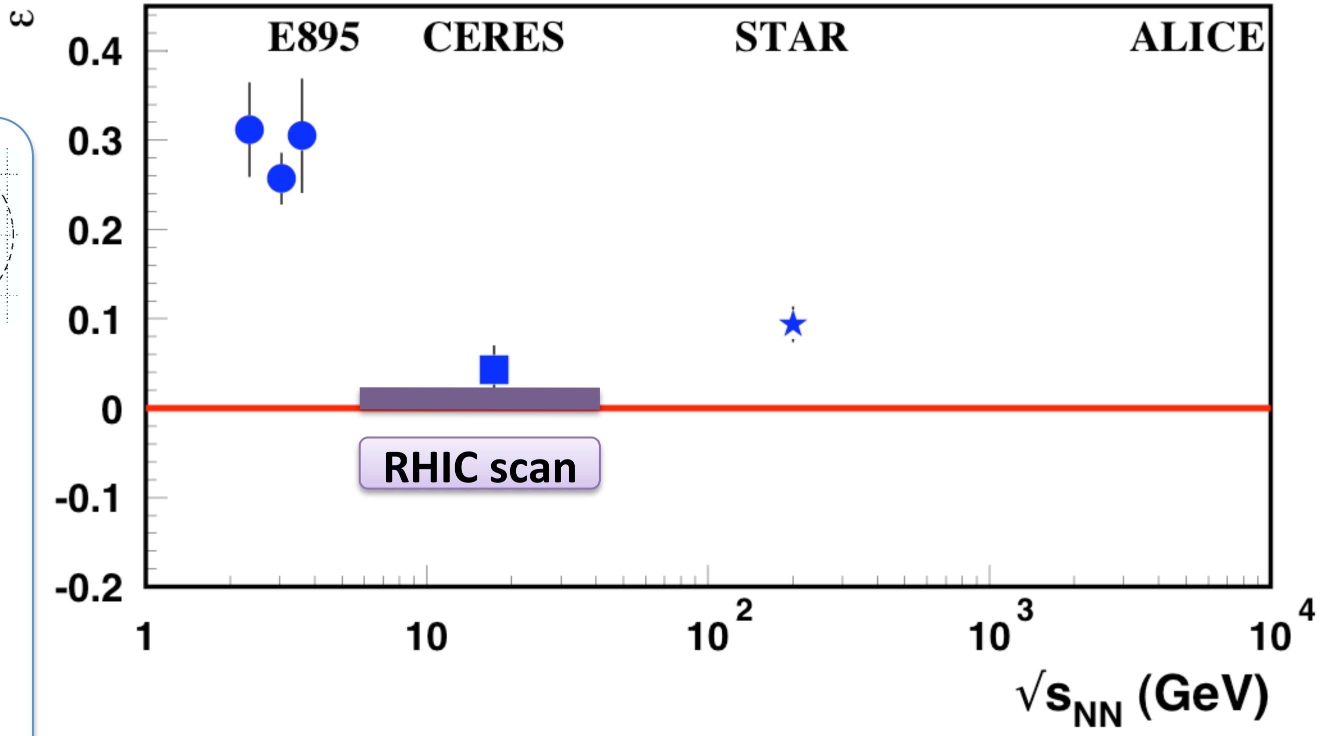
Generic expectation





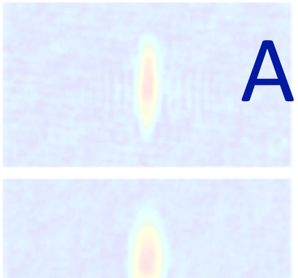
An excitation function begging for more

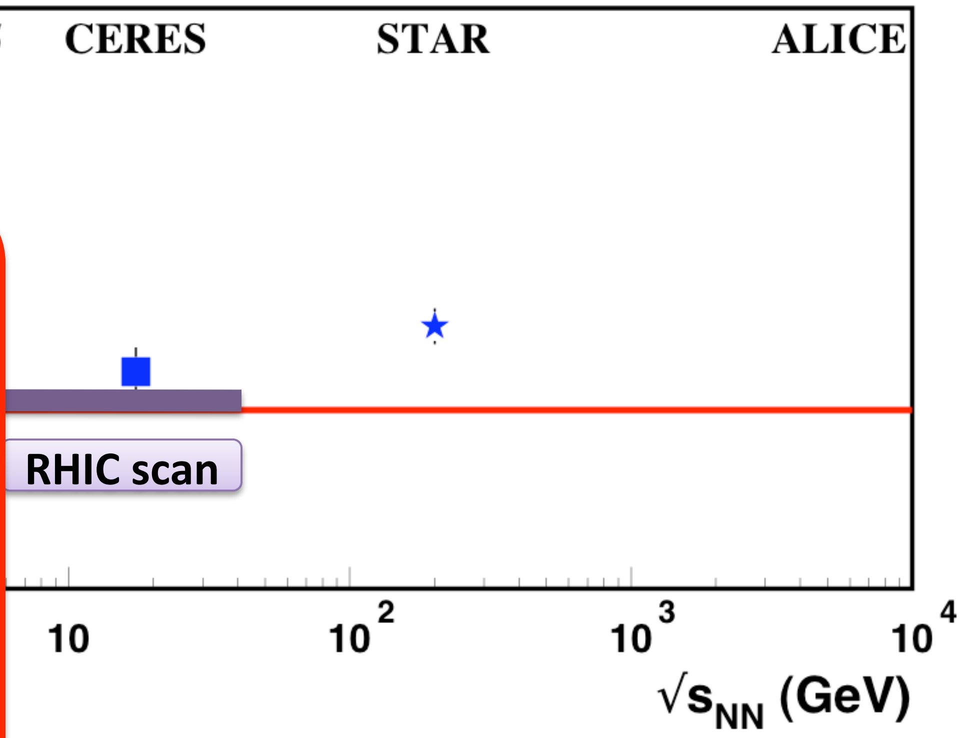


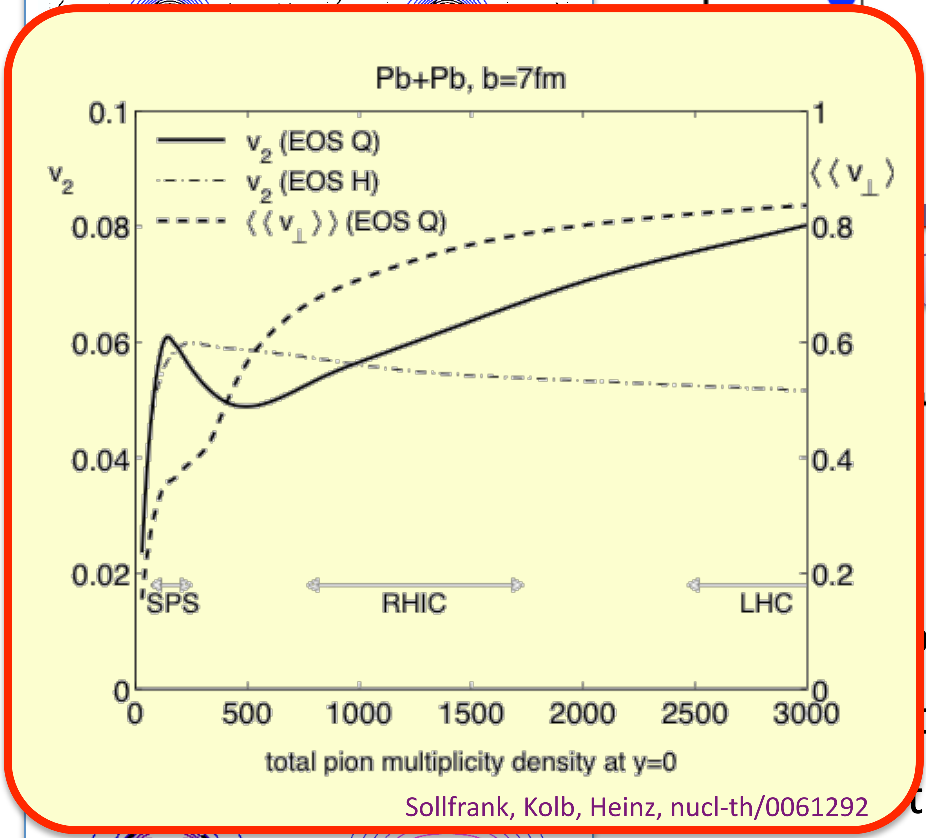


- non-monotonic excitation function of bulk observable?
  - interesting in proposed scan region
  - but: tilt issue – need 1^{st}-order plane in scan!!

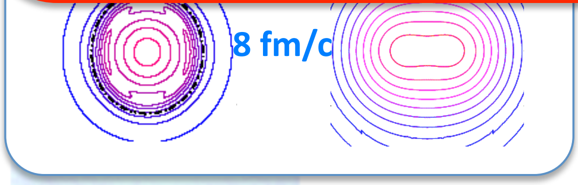
An excitation function begging for more







Sollfrank, Kolb, Heinz, nucl-th/0061292



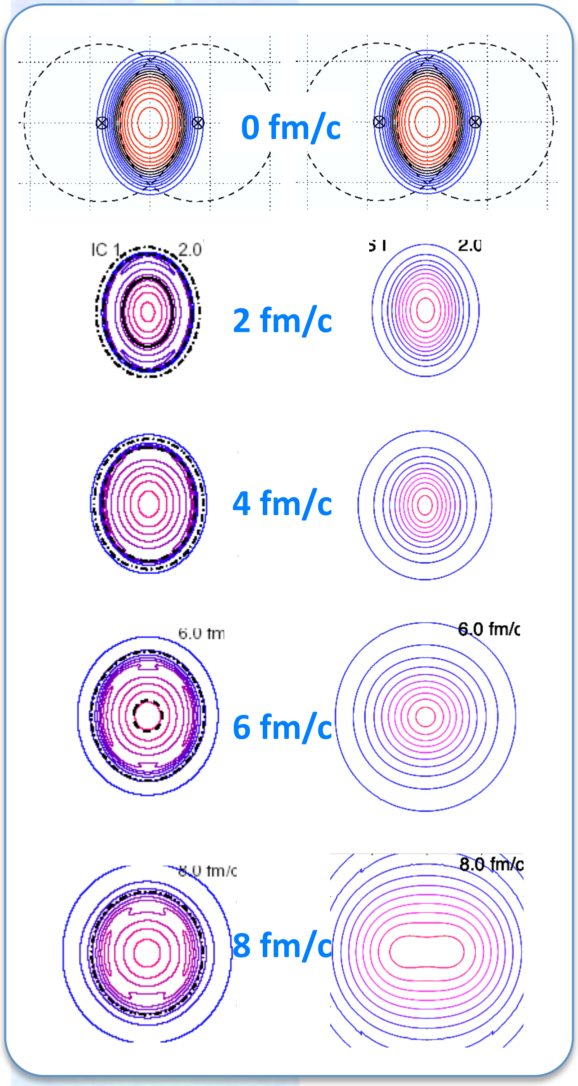
tonic excitation function of bulk observable?

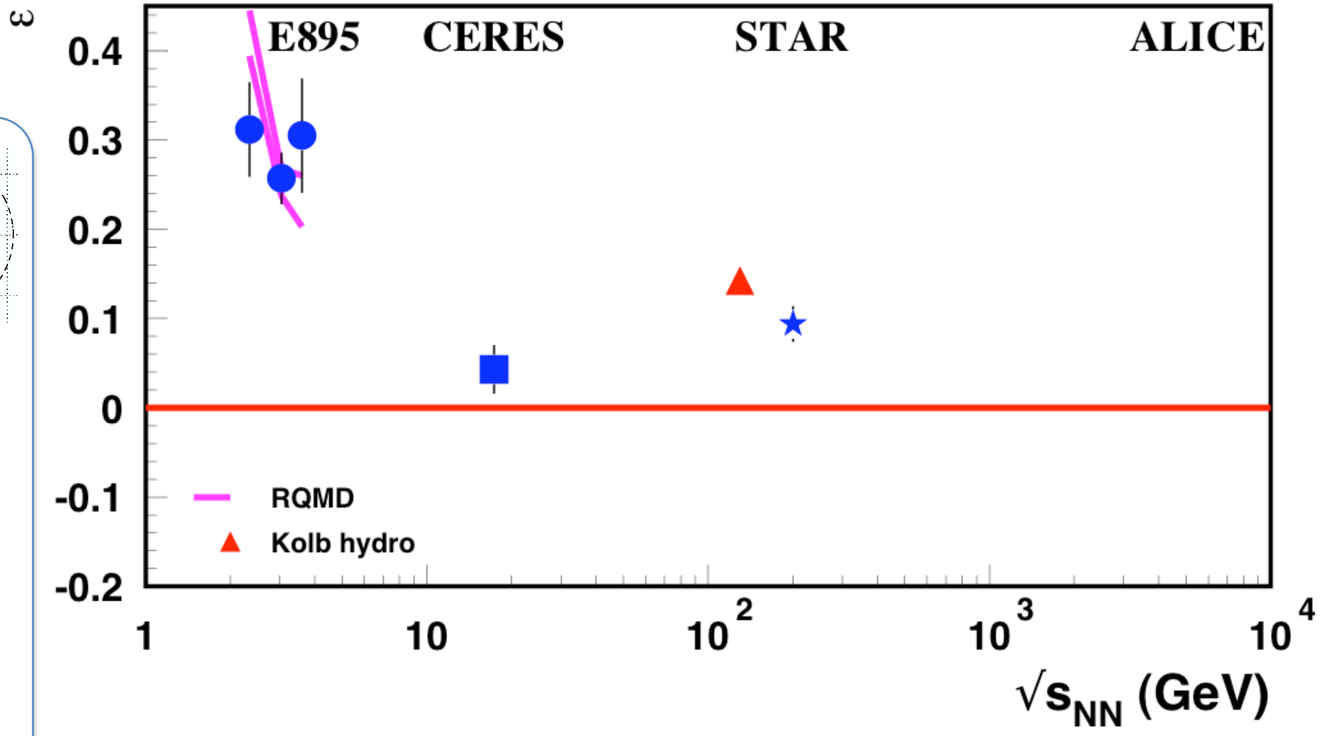
ting in proposed scan region

t issue – need 1st-order plane in scan!!

- reminiscent of (unobserved) non-monotonic v2(root(s))

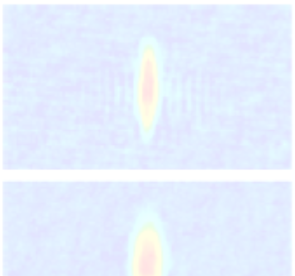
Model comparisons

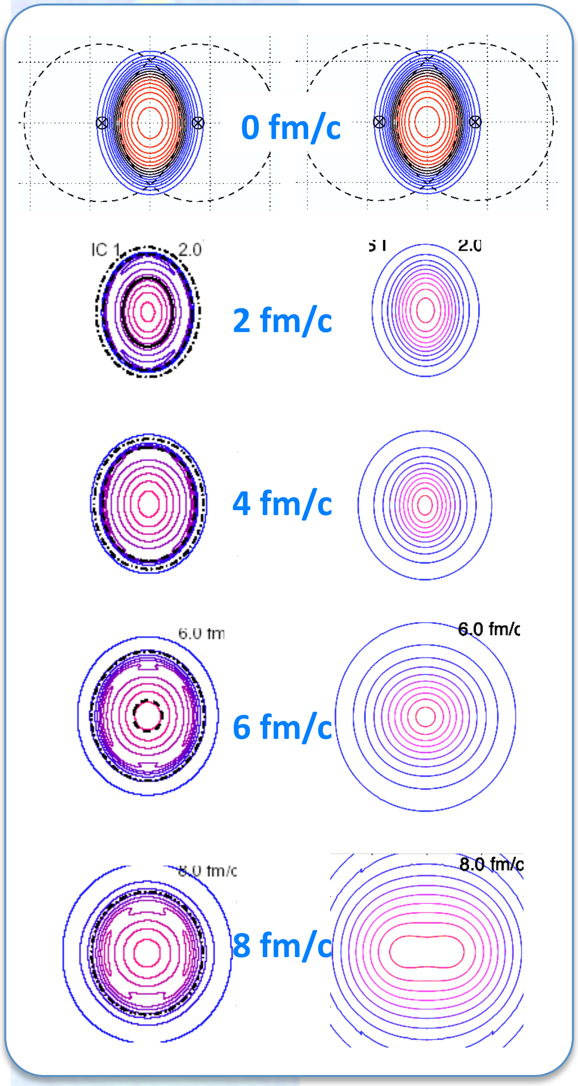


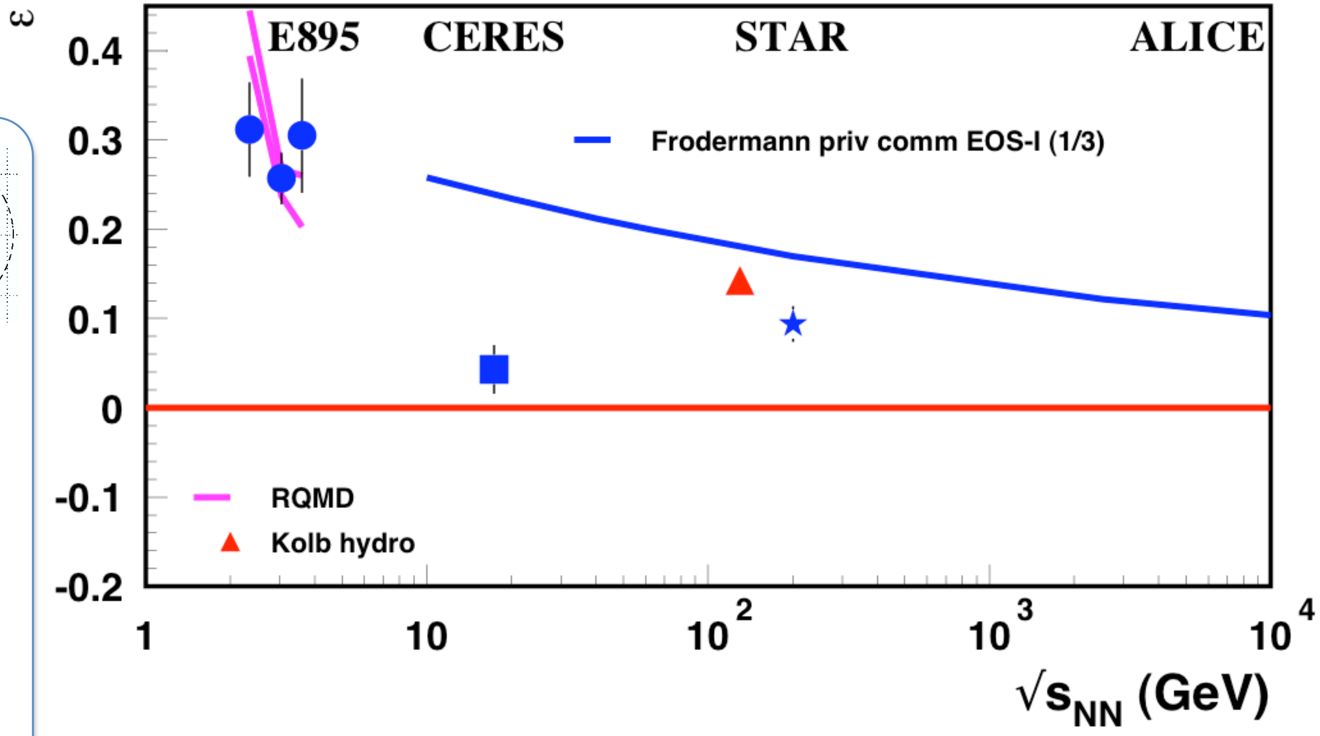


- ✓RQMD (not UrQMD) @ low energy
- ✓2D hydro of Kolb/Heinz @ RHIC

effect of EoS – 2D hydro







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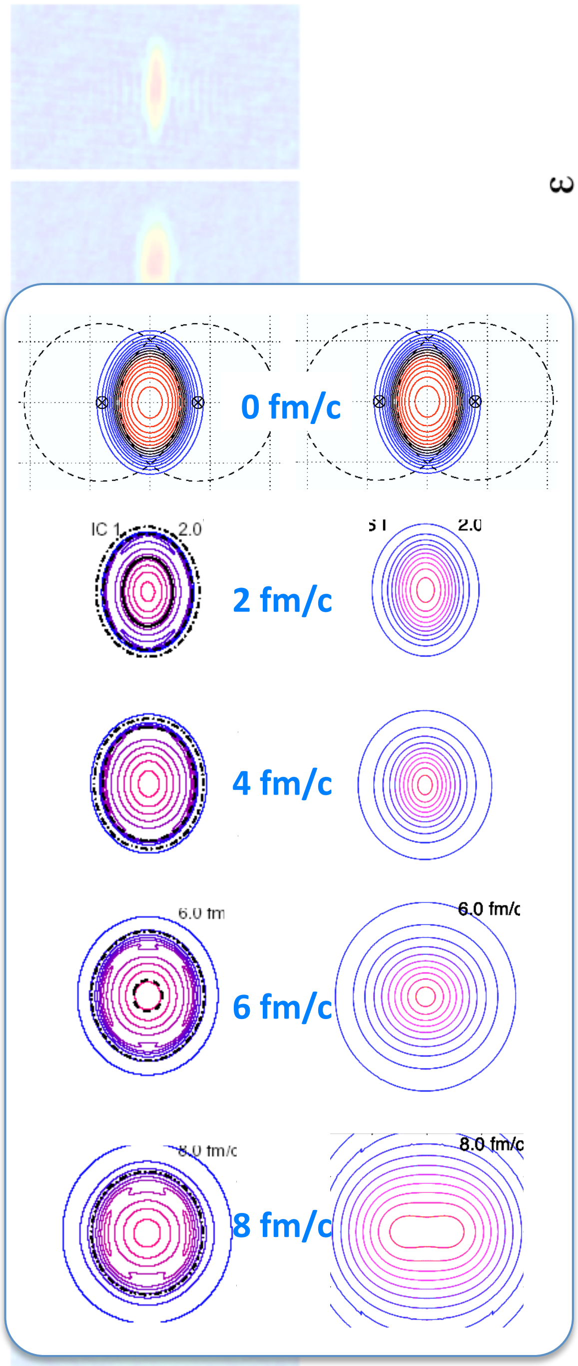

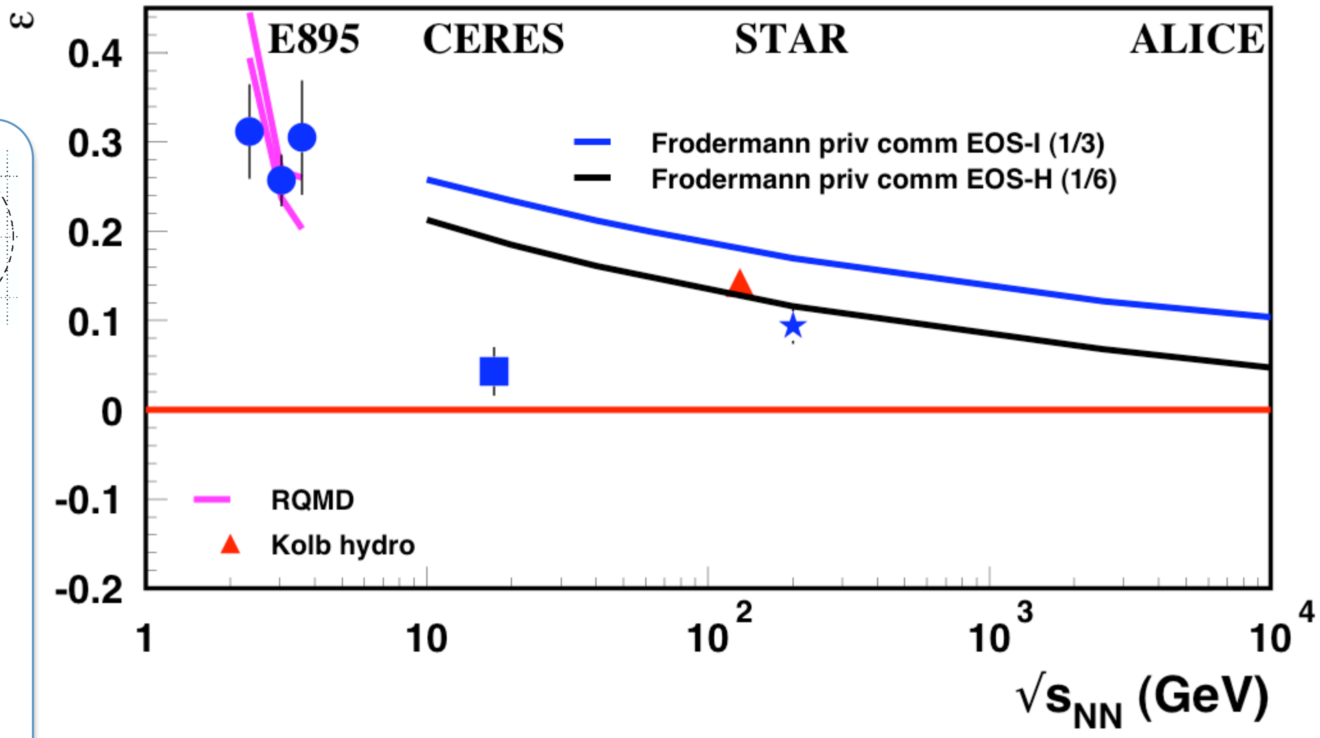

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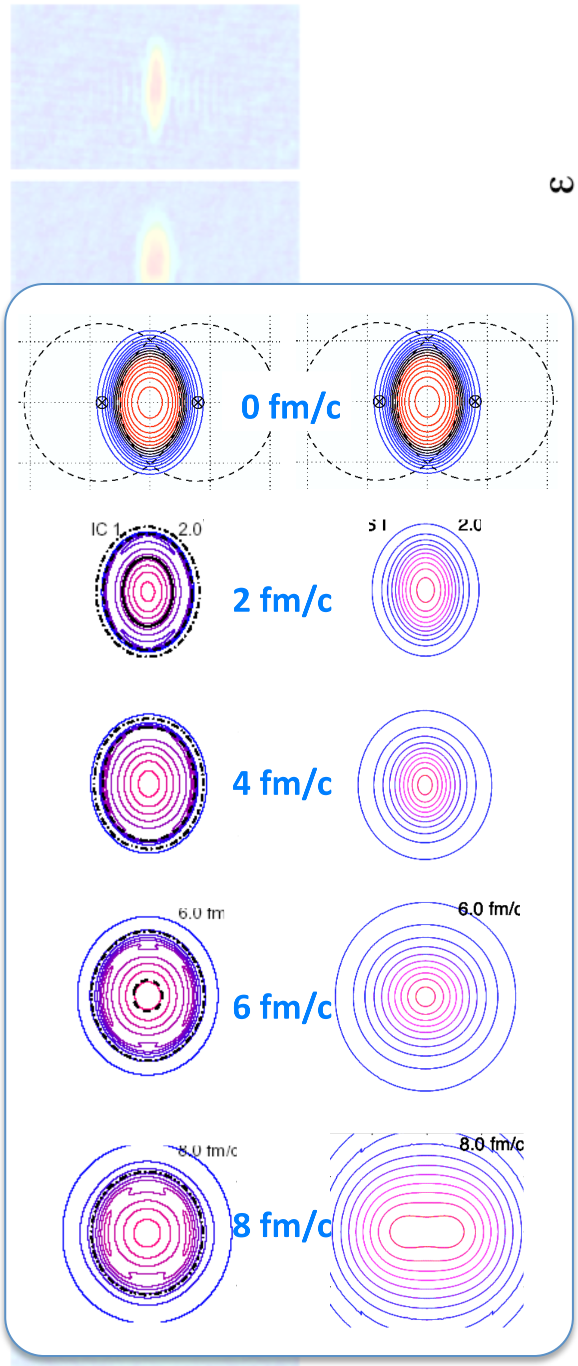
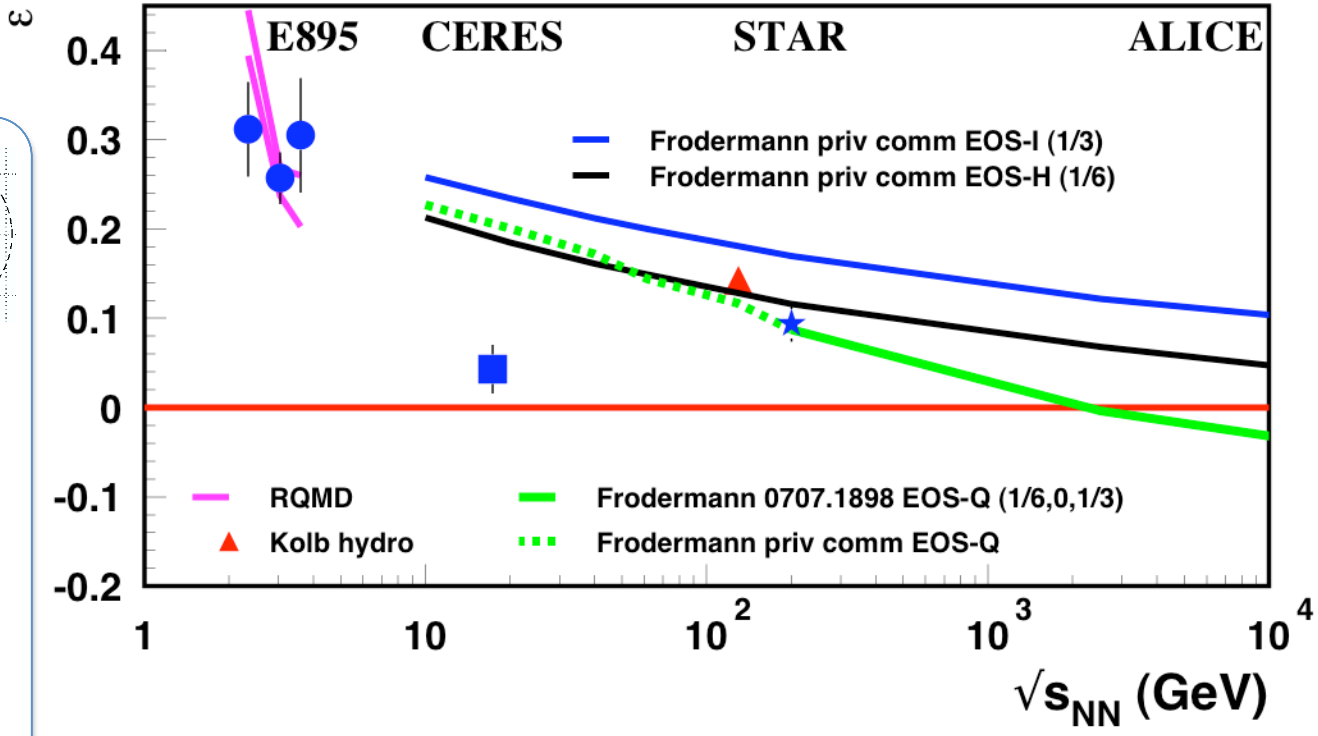
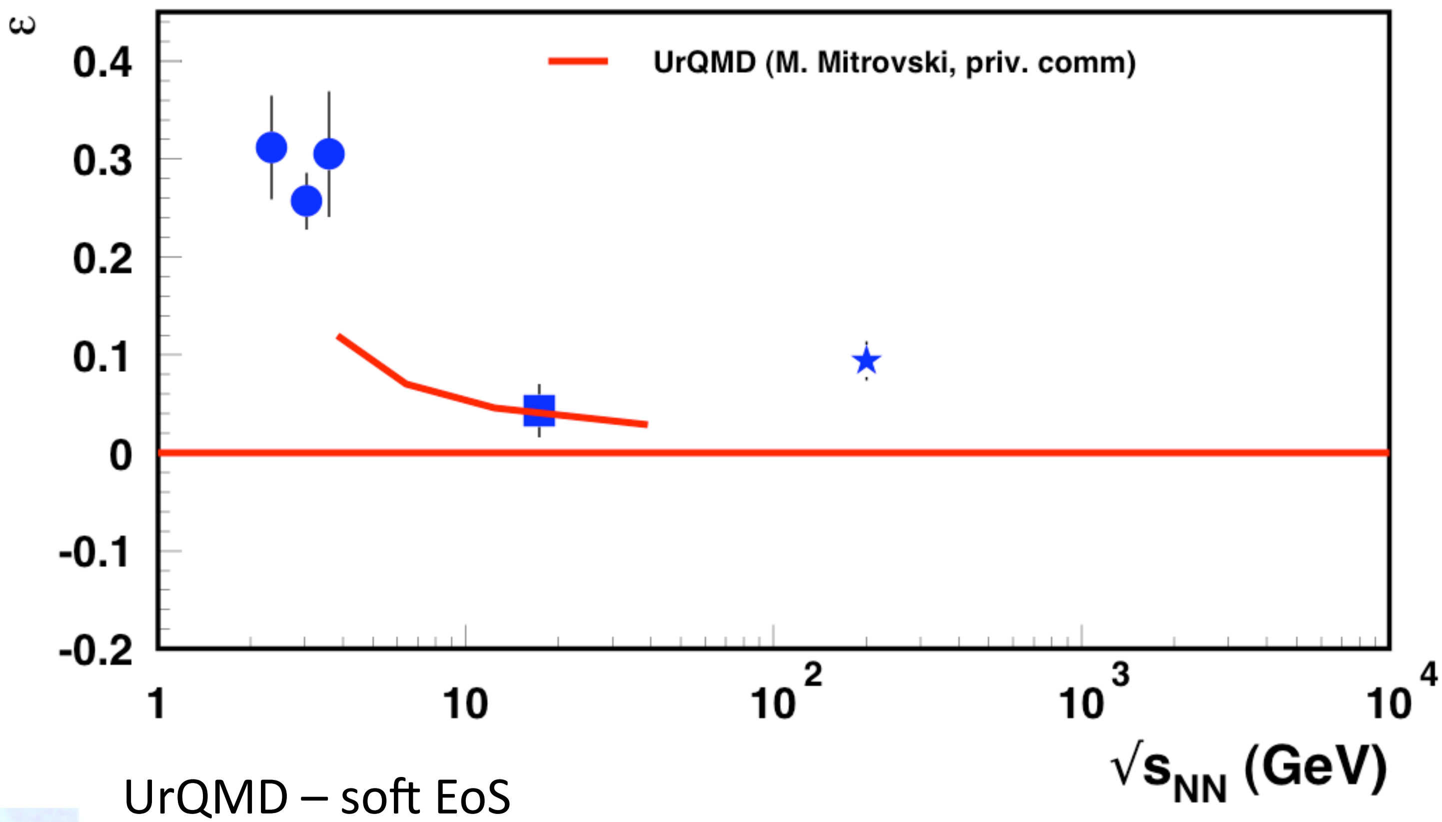




- ✓RQMD (not UrQMD) @ low energy
- ✓2D hydro of Kolb/Heinz @ RHIC
- scan with varying EoS 2D hydro
  - dependence on stiffness stresses lifetime
  - no non-monotonic behaviour predicted
  - **but**: 2D boost-invariant – no tilt

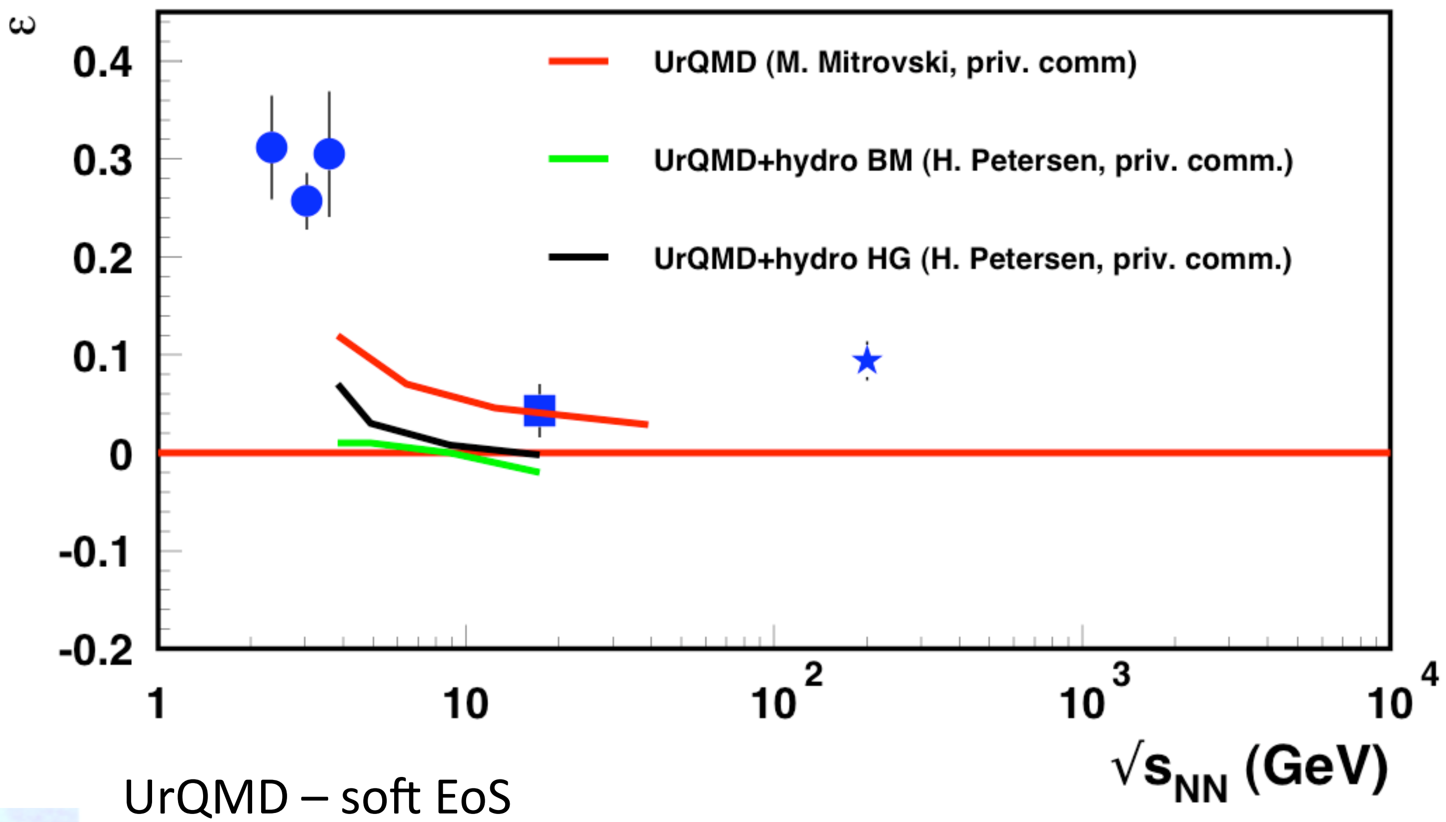
3D transport



UrQMD – soft EoS

- ✓ reproduces CERES' anisotropy
- root(s) dependence looks unlikely

3D transport



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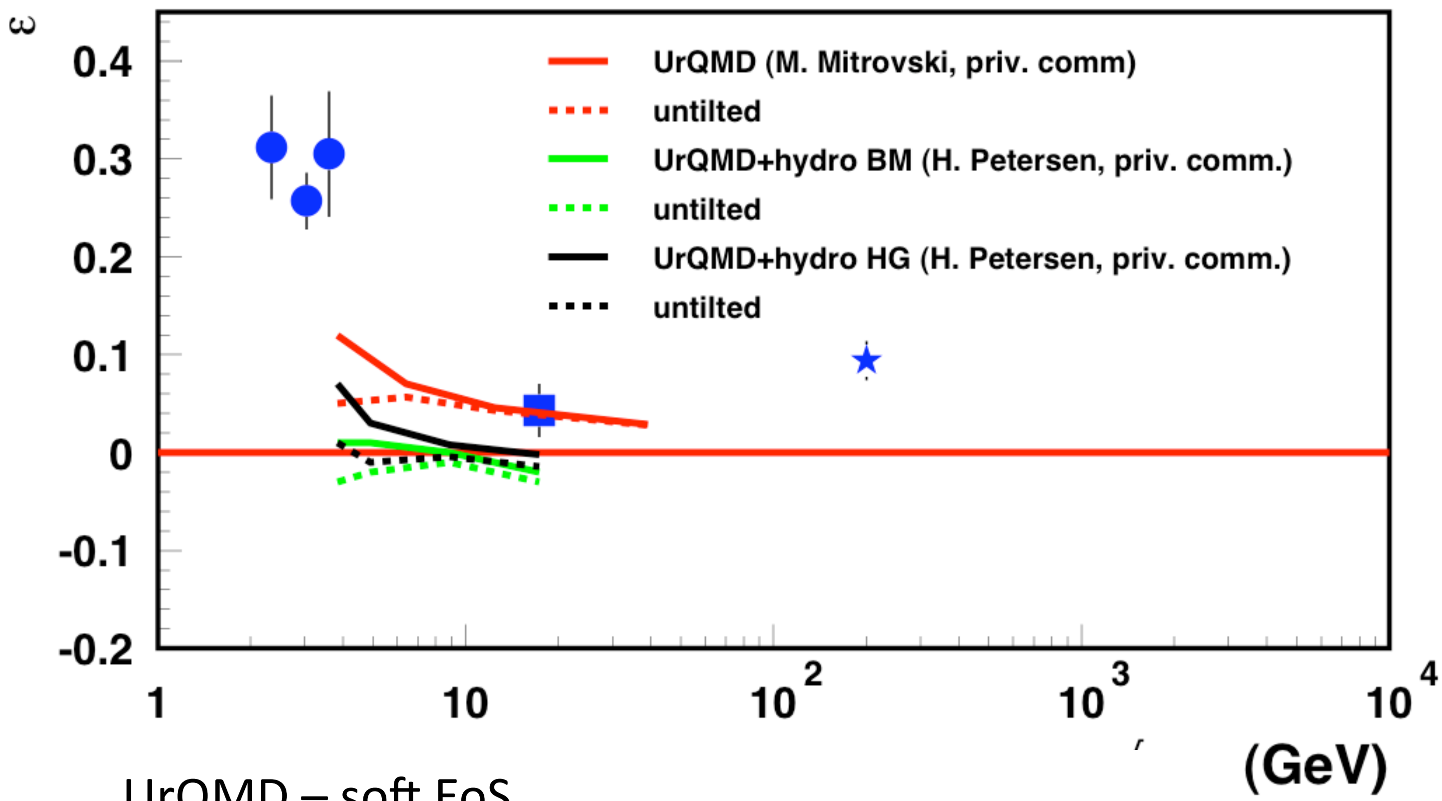
hybrid models: long-lived system evolves to round

see also Teaney, Lauret, & Shuryak nucl-th/0110037

3D transport



UrQMD – soft EoS

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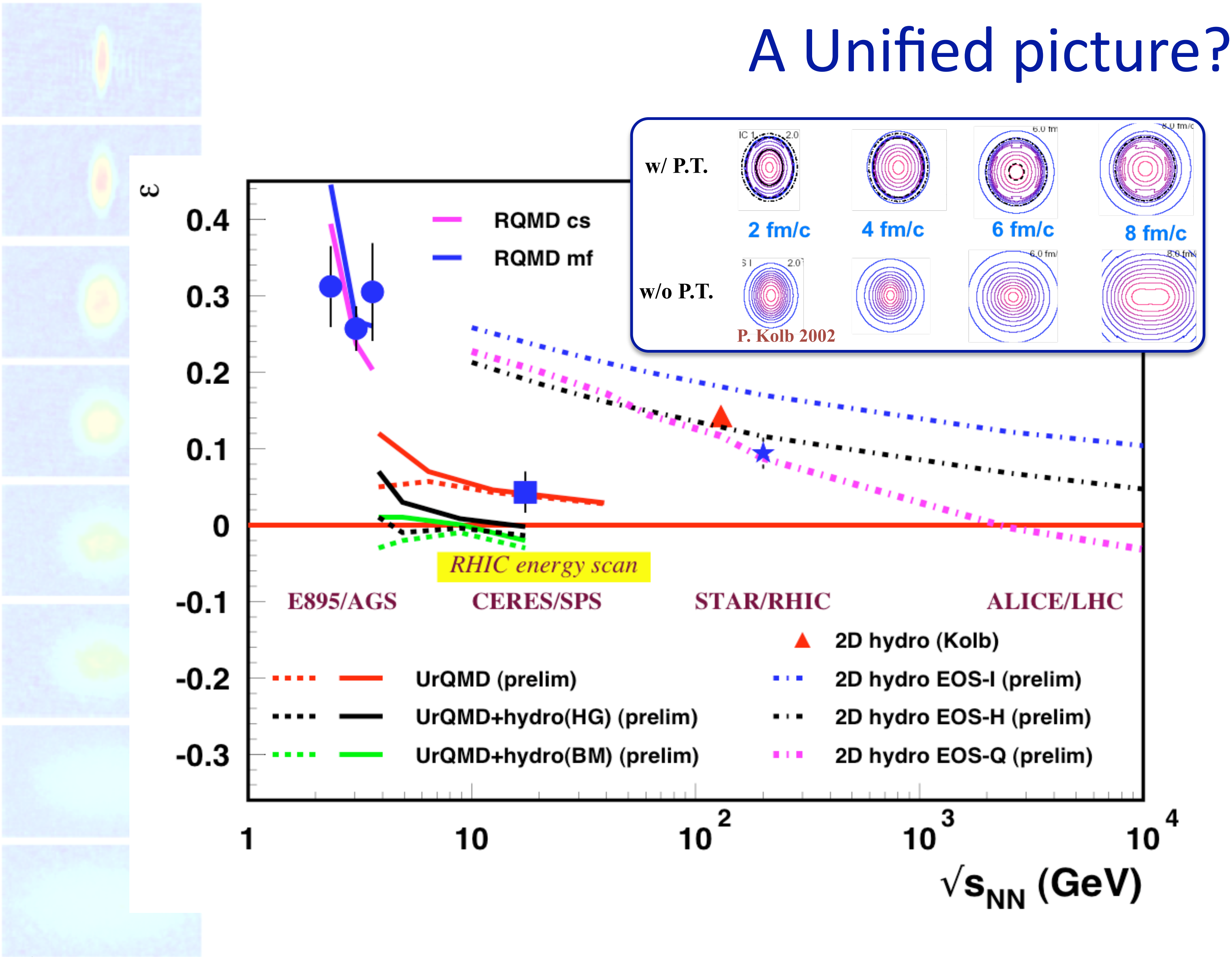
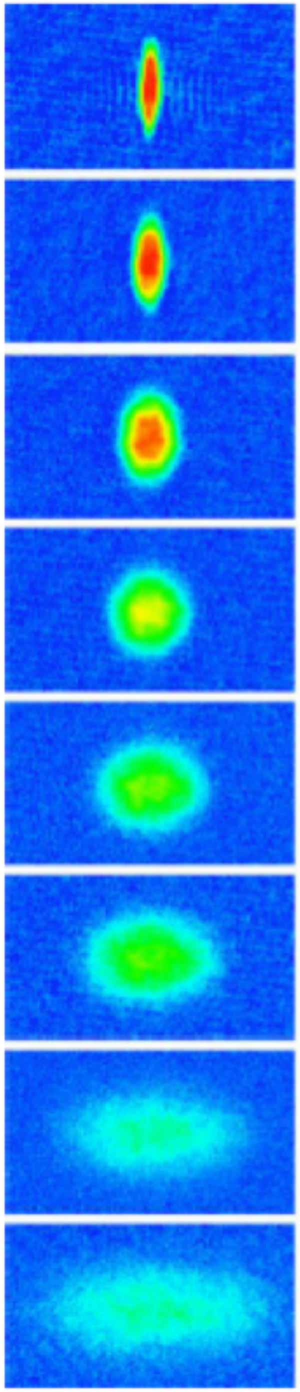
- root(s) dependence looks unlikely

hybrid models: long-lived system evolves to round

* tilt not important (because θ and ε both small)

A Unified picture?





how to spend 30 min discussing 5 data points

- **p**-dep femtoscopy reveals flow-generated substructure
  - mT-dependence: radial flow
  - y-dependence: longitudinal flow
  - asHBT measures detailed spatial analogs of v1, v2
- bulk observable with
  - sensitivity to EoS & dynamical time (& 3rd flow component, early softening…?)

  ‼ non-monotonic excitation function:
  interesting feature @ “interesting” energy
  asHBT part of B.E.S. program
- true 3D, unified modeling important, to map out spatial dynamics
- 1st-order R.P. necessary during RHIC energy scan
- much more work on experimental and theoretical/modeling side

asHBT model calculations- *THANKS!*

- **P. Kolb** [Regensburg, Ohio] – 2D hydro EOS-Q @ 130 GeV
- **E. Frodermann** [Minnesota]– 2D hydro EOS-Q, EOS-I, EOS-H, 10 GeV - 300 TeV
- **M. Mitrovski & M. Bleicher** [Frankfurt] – UrQMD, sqrt(s) = 4-39 GeV
- M. Lisa [Ohio] – RQMD meanfield on/off sqrt(s) = 2-4 GeV
- **H. Petersen** [Frankfurt] – UrQMD + 3D hydro, sqrt(s)=4 – 17 GeV, BM & HG EoS

See also:

- A. Kisiel et al – hydro+Therminator: PR **C79** 014902 (2009)
- T. Humanic – hadronic rescattering (HRM): Int.J.Mod.Phys.**E15,** 197 (2006)
- D. Teaney, J. Lauret, & E. Shuryak – RQMD & hybrid - nucl-th/0110037