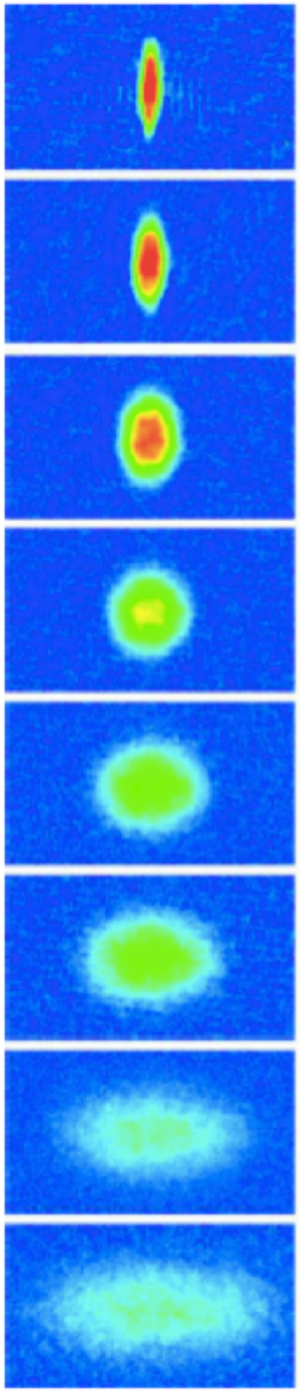


WPCF 2011

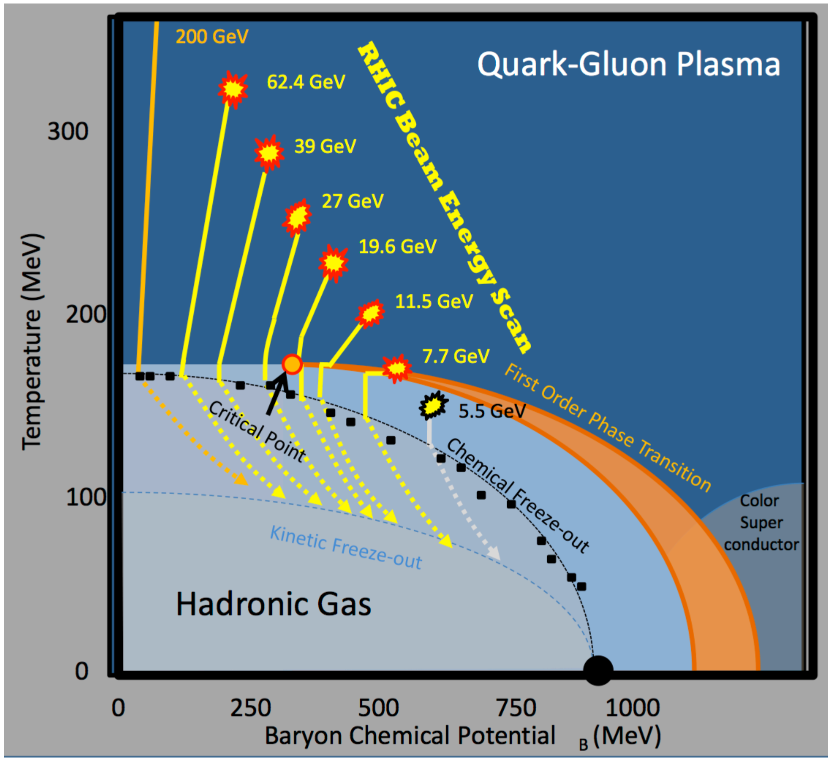
The freeze-out source shape: recent results from the STAR energy scan

Mike Lisa (Ohio State University)
for the STAR Collaboration

Outline

- general motivation
  - RHIC BES program
  - asHBT
- a growing database of asHBT systematics
  - (another) anomalous behaviour at SPS?
  - new STAR data
  - reconciling RHIC, SPS results?
    - centrality cuts
    - RP resolution correction schemes
    - rapidity (underway)
- conclusion

RHIC energy scan: √s=7-40 GeV (2010~2012 (?))

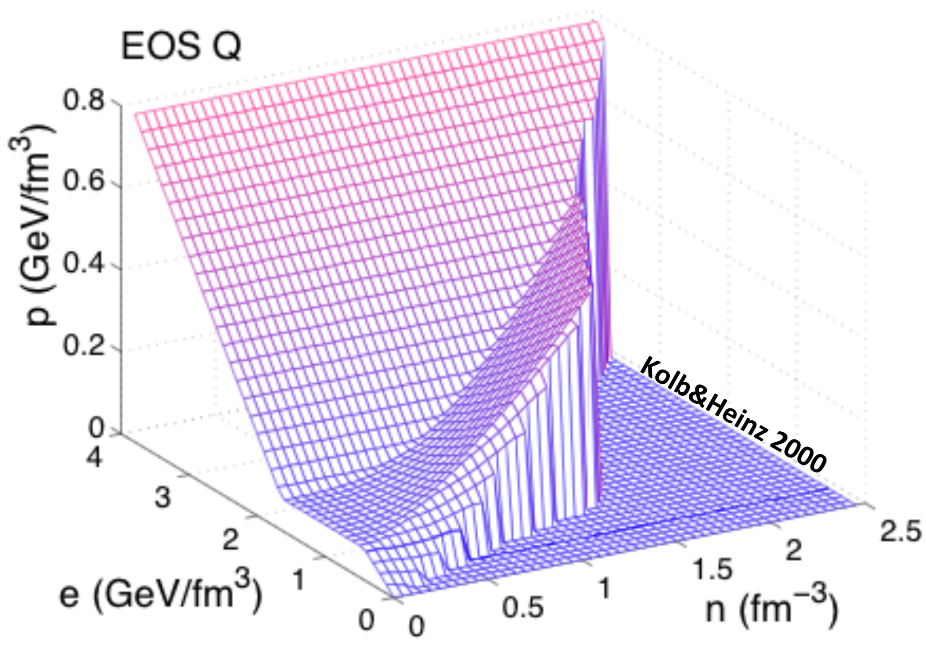


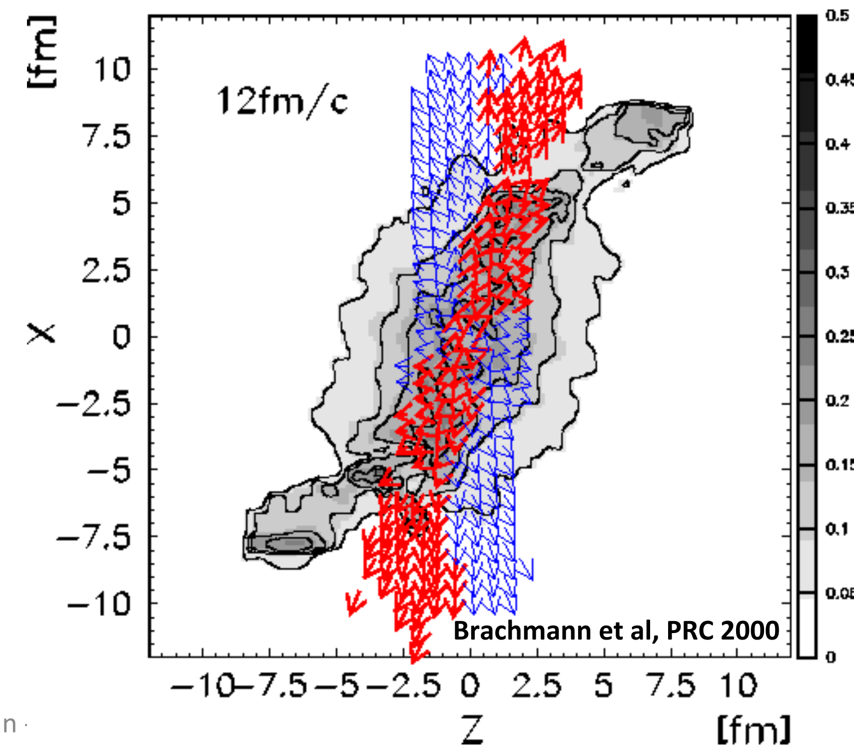
Probe QCD phase diagram via

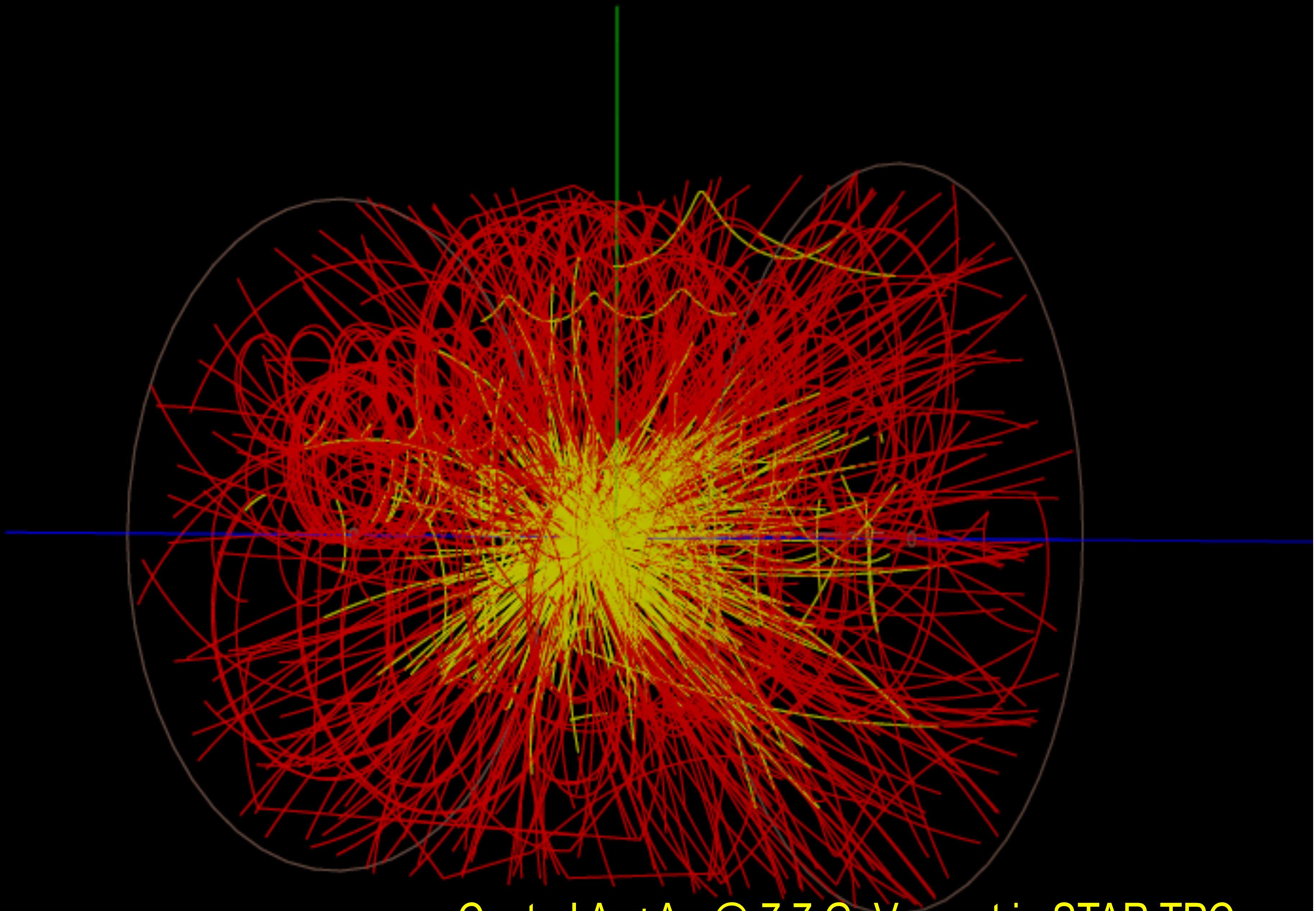
- statistics/fluctuations

✓dynamic system response

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



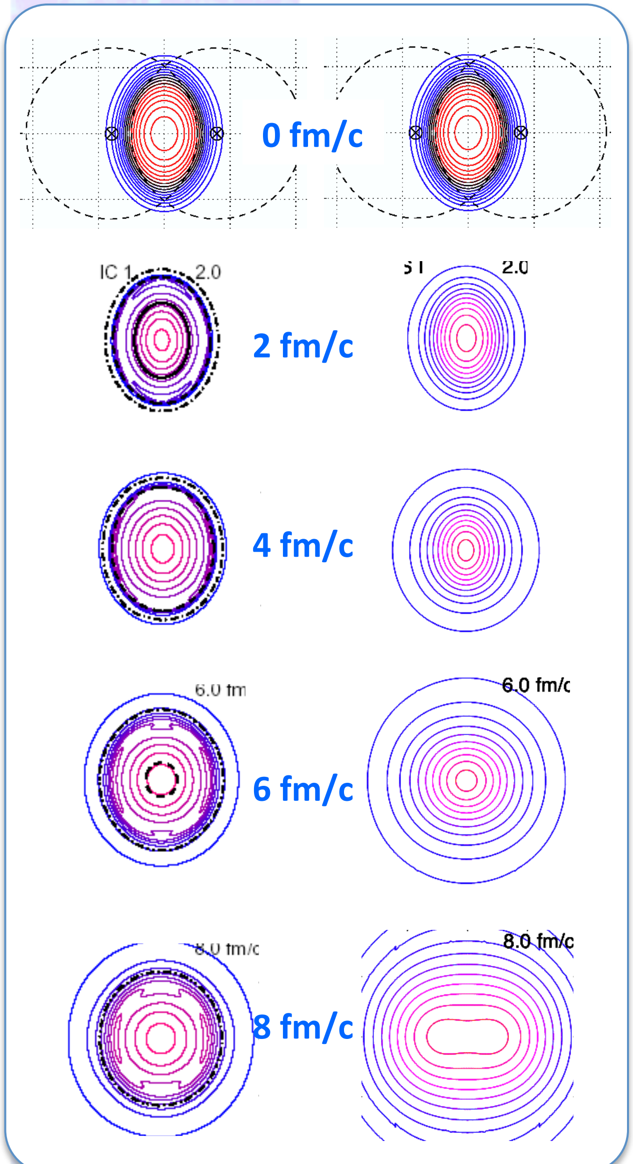




Central Au+Au @ 7.7 GeV event in STAR TPC *http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493*

Collision Energies (GeV)	**5**	**7.7**	**11.5**	**17.3**	**27**	**39**
Observables	Millions of Events Needed					
v_2 (up to ~1.5 GeV/c)	**0.3**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**
v_1	0.5	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Azimuthally sensitive HBT	4	**4**	**3.5**	**3.5**	**3**	**3**
PID fluctuations (K/p)	1	**1**	**1**	**1**	**1**	**1**
net-proton kurtosis	5	**5**	**5**	**5**	**5**	**5**
differential corr & fluct vs. centrality	4	**5**	**5**	**5**	**5**	**5**
n_q scaling p/K/p/L $(m_T-m_0)/n<2$GeV	8.5	**6**	**5**	**5**	**4.5**	**4.5**
f/W up to p_T/n_q=2 GeV/c		56	25	**18**	**13**	**12**
R_{CP} up to p_T ~4.5 GeV/c (at 17.3) 5.5 (at 27) & 6 GeV/c (at 39)				**15**	**33**	**24**
untriggered ridge correlations		27	13	**8**	**6**	**6**
parity violation		**5**	**5**	**5**	**5**	**5**

phi- the sexy direction



evolution from initial “known” shape depends on

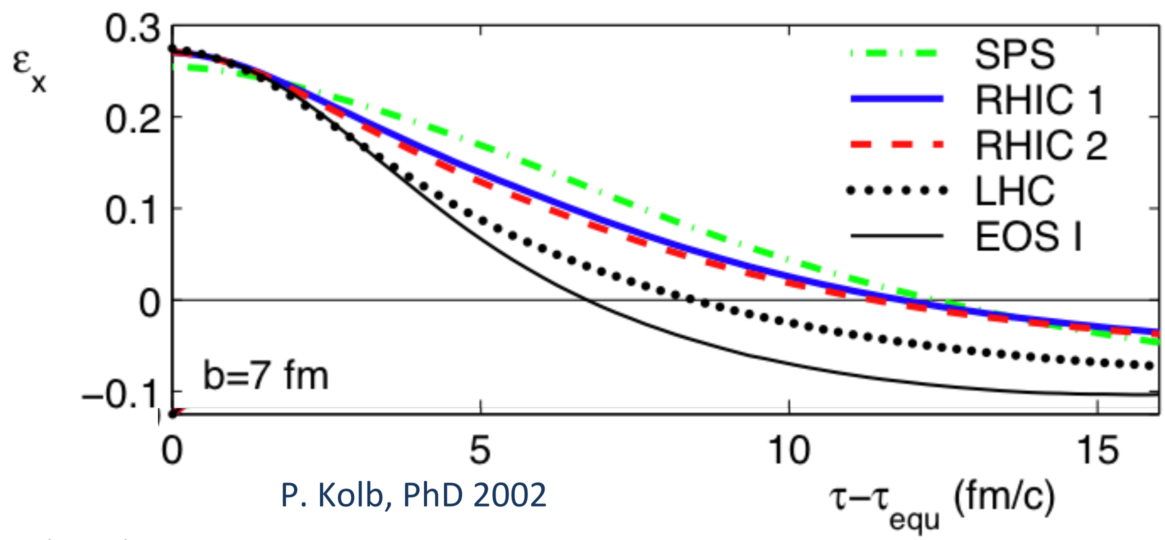
- pressure anisotropy (“stiffness”)
- lifetime

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

our program, a billion times larger (but still "micro")

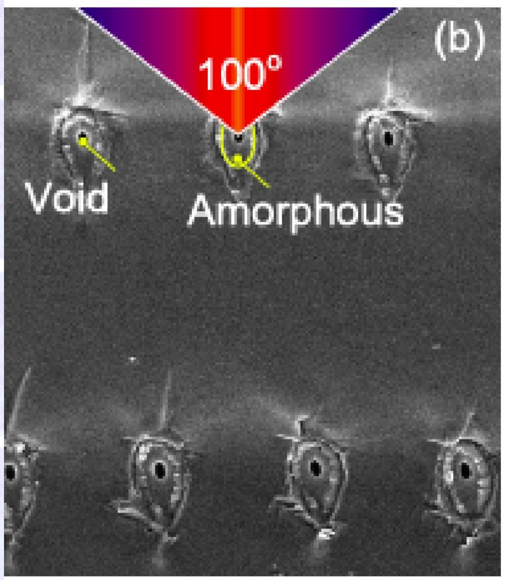
fs laser pulses on crystals → "micro-explosions" & pressures unattainable any other way

- interesting for inertial confinement studies, as well as fundamental plasma physics

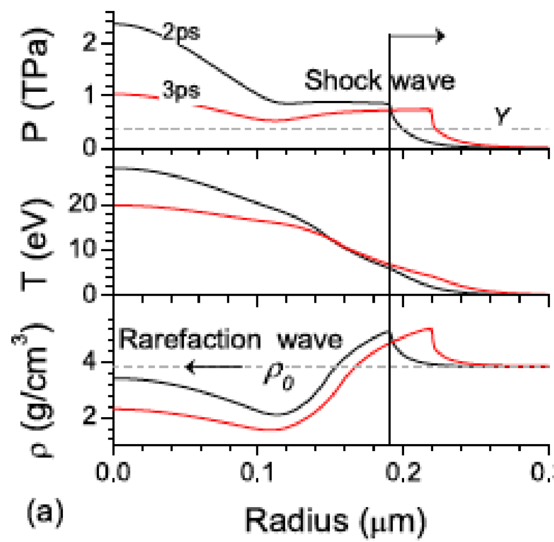
dynamic evolution too fast to capture: modeled by plasma hydrodynamics

- confined initial and final states, deconfined intermediate state

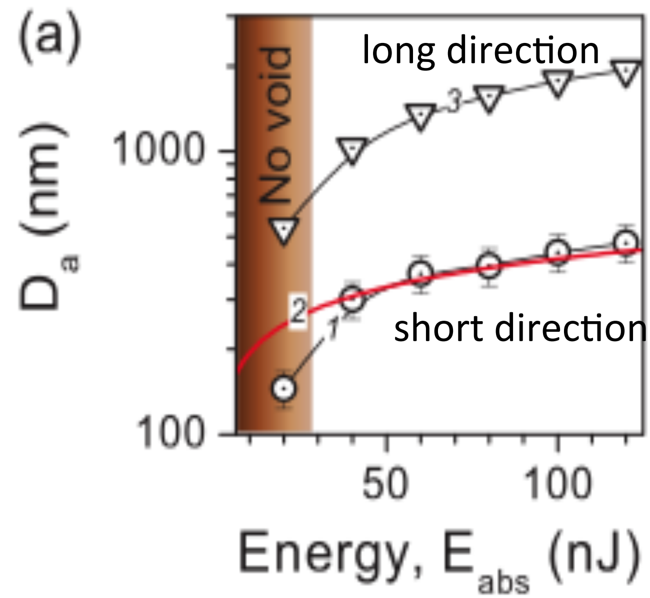
energy dependence of final shape compared to hydro calculations with different EoS



different "events"



plasma hydro calculations



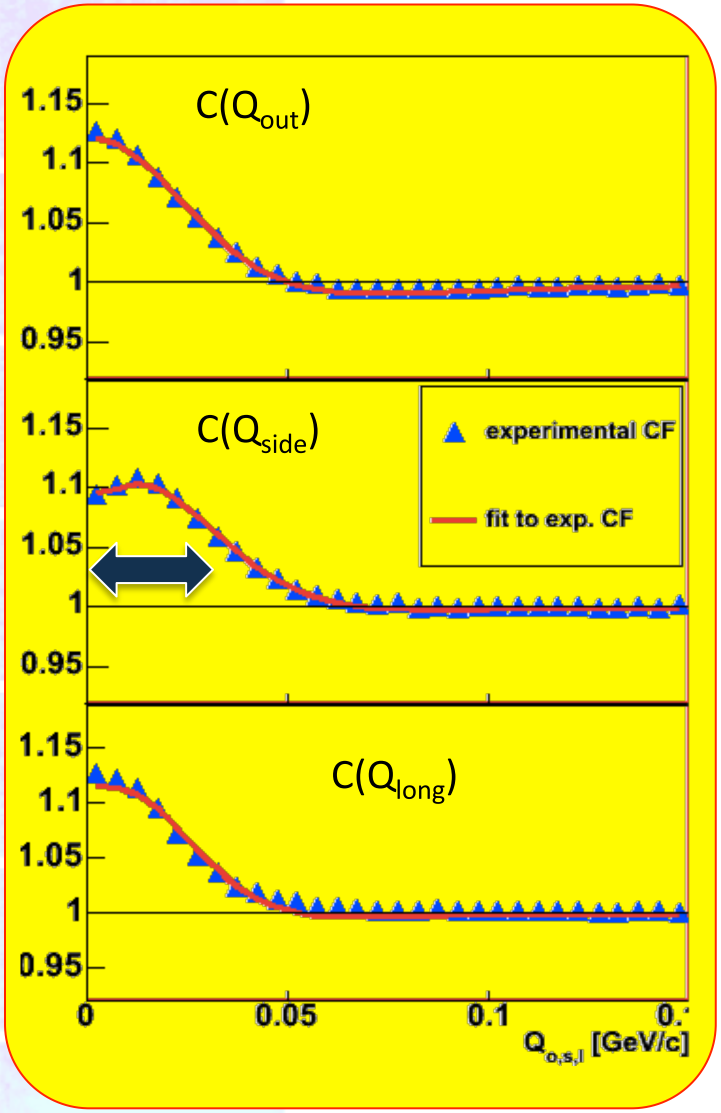
excitation function of freezeout shape

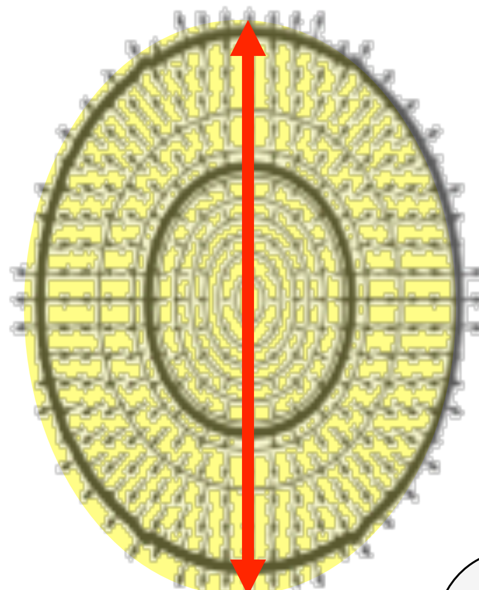
c.f. Lisa et al, New J. Phys 13 065006 (2011)

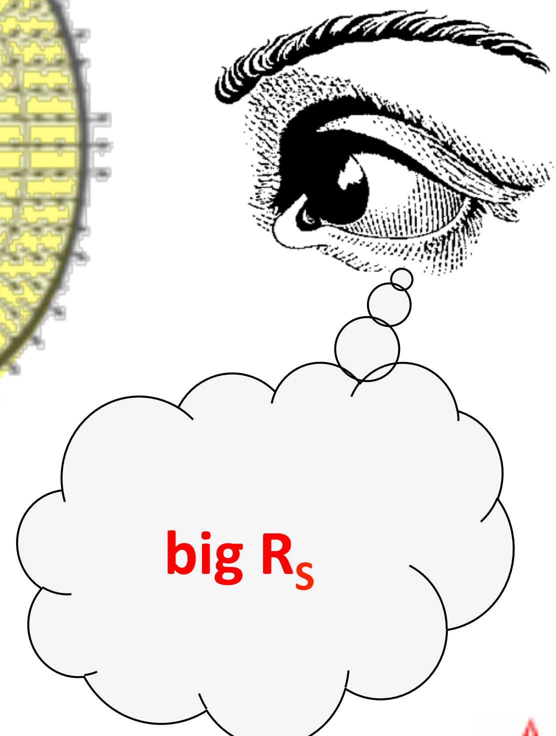
measuring lengths

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

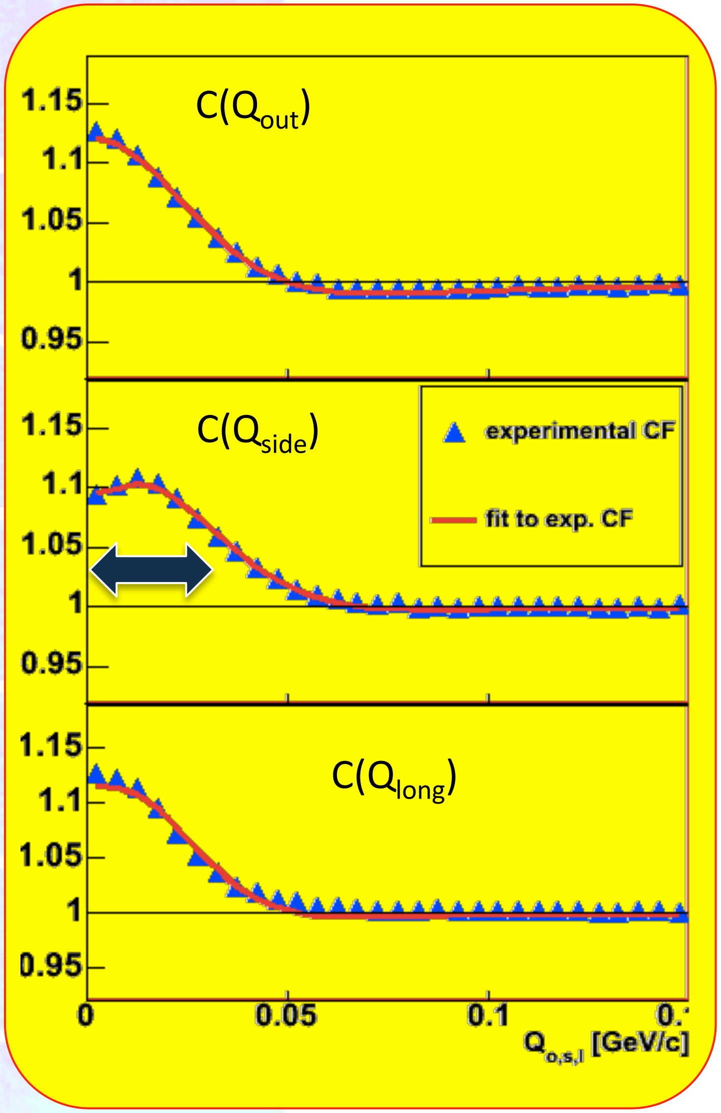
typical “Gaussian” fitting function

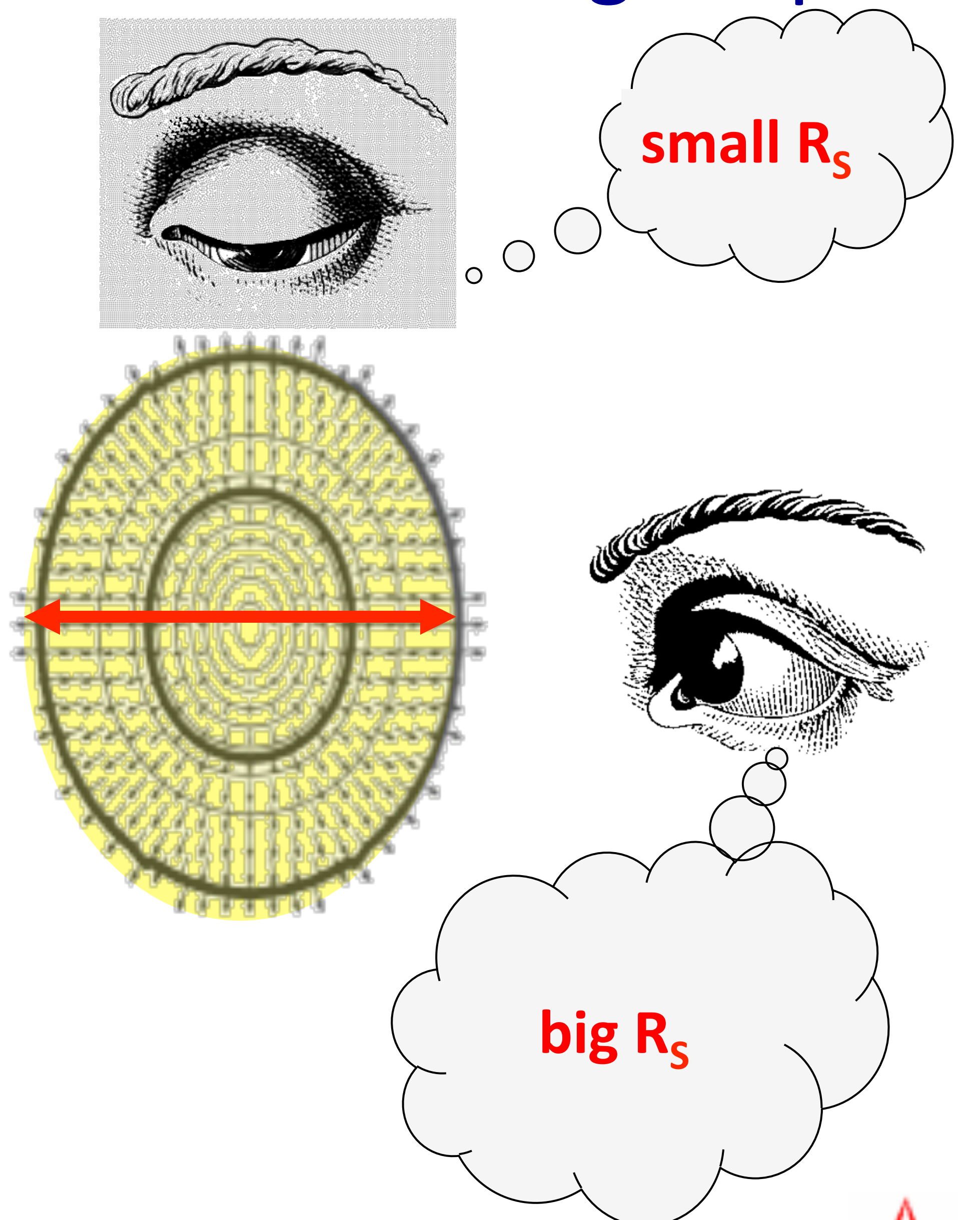




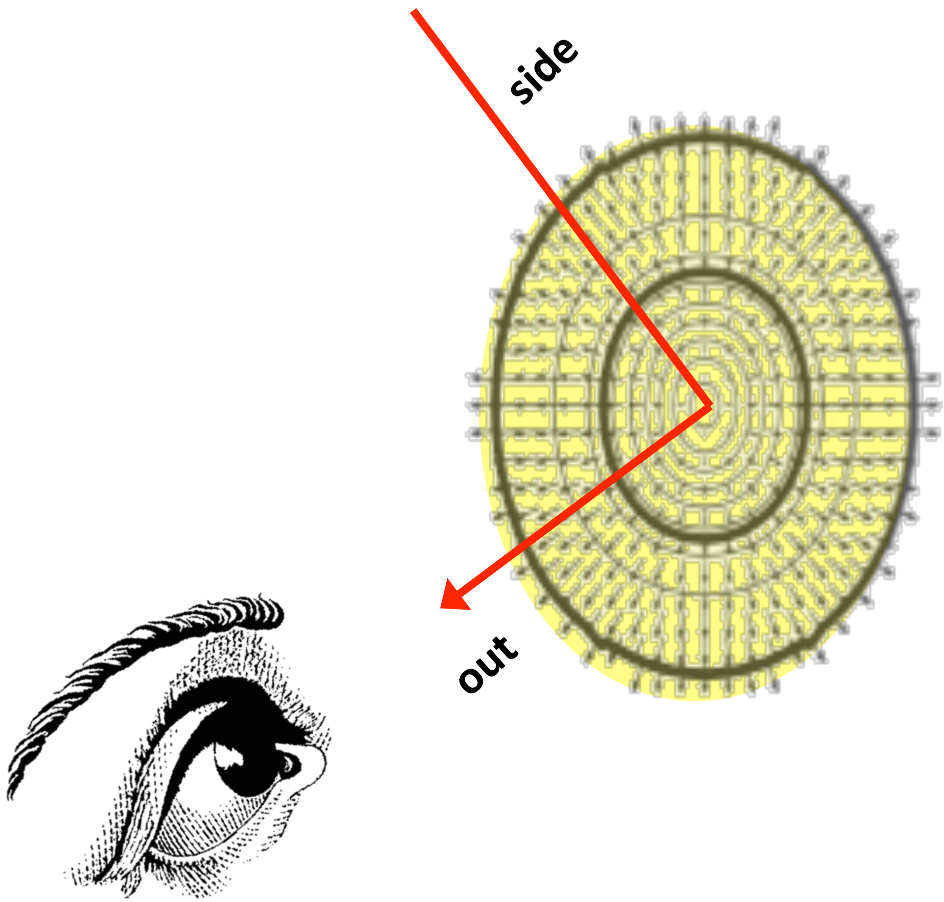


measuring shape





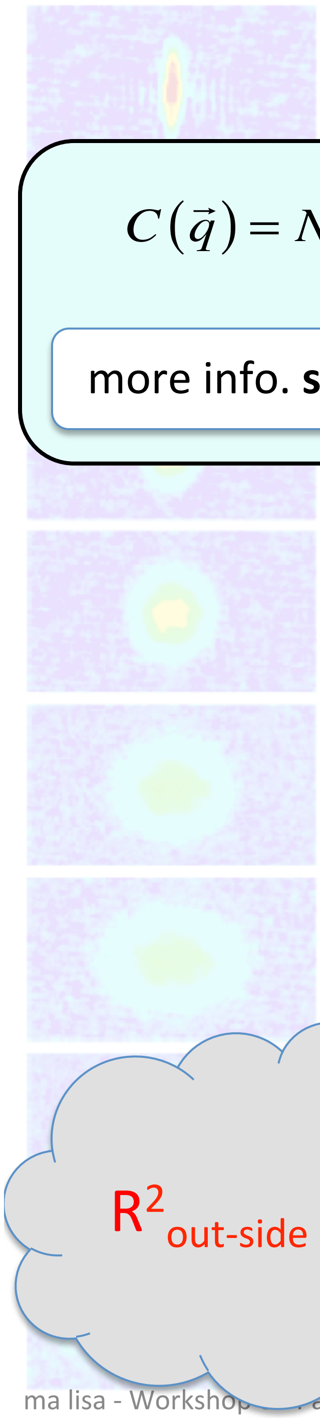
measuring shape

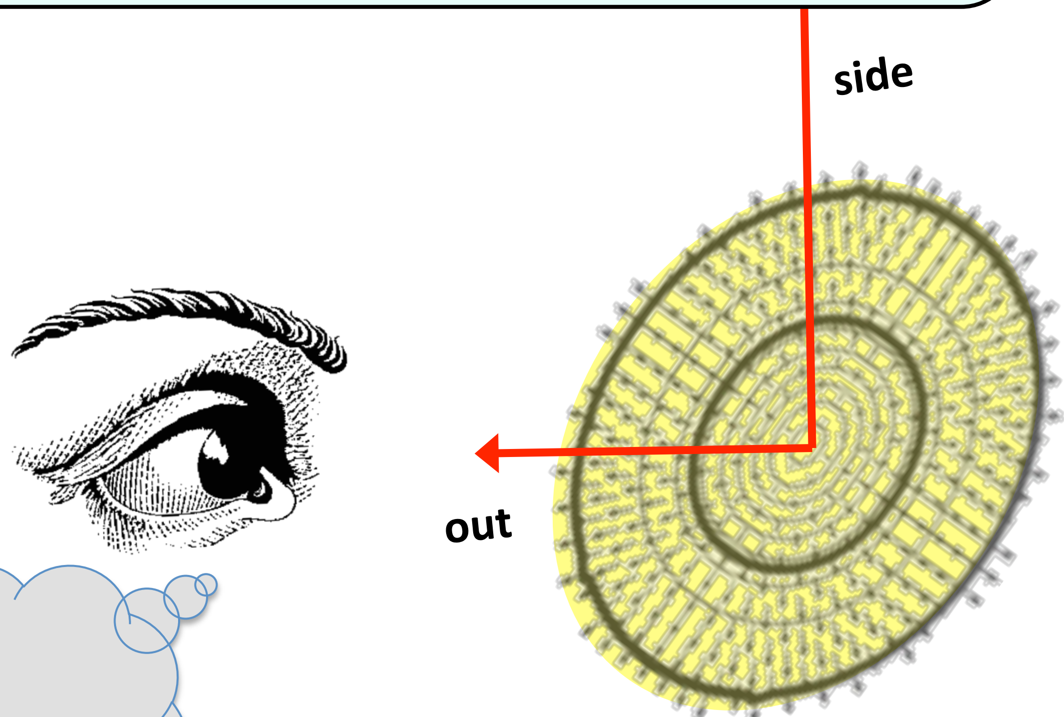


measuring shape

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

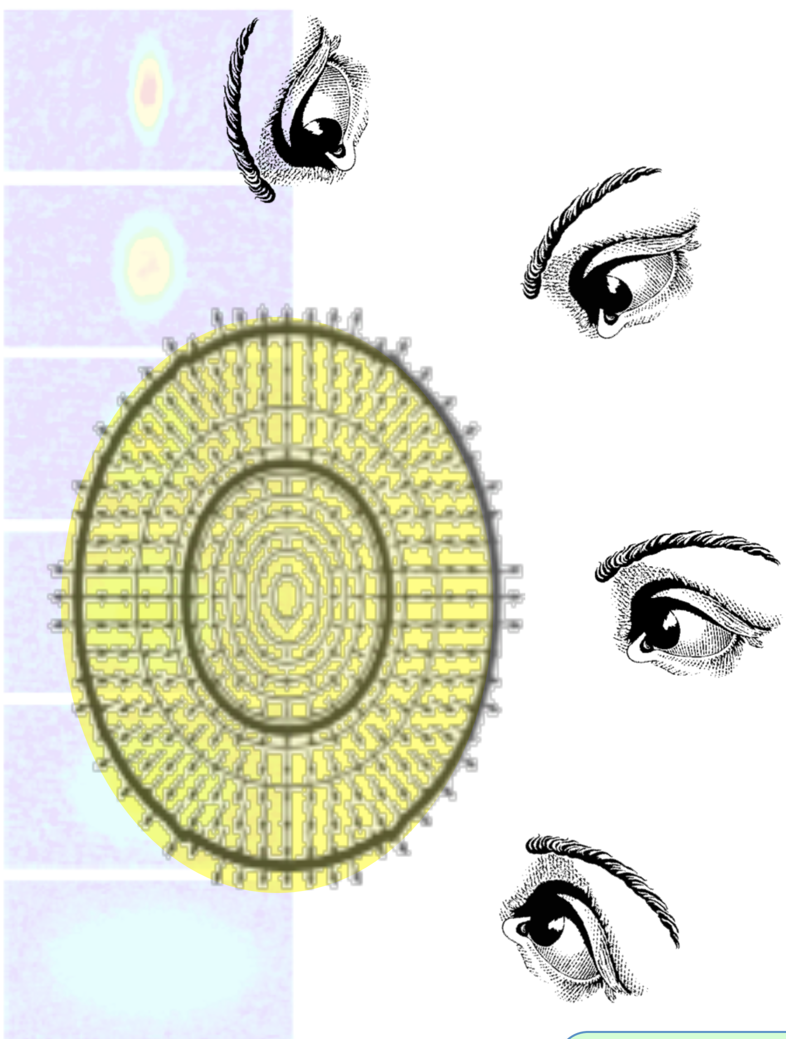
more info. **six** “HBT radii” $R_o^2, R_s^2, R_l^2, R_{os}^2, R_{sl}^2, R_{ol}^2$



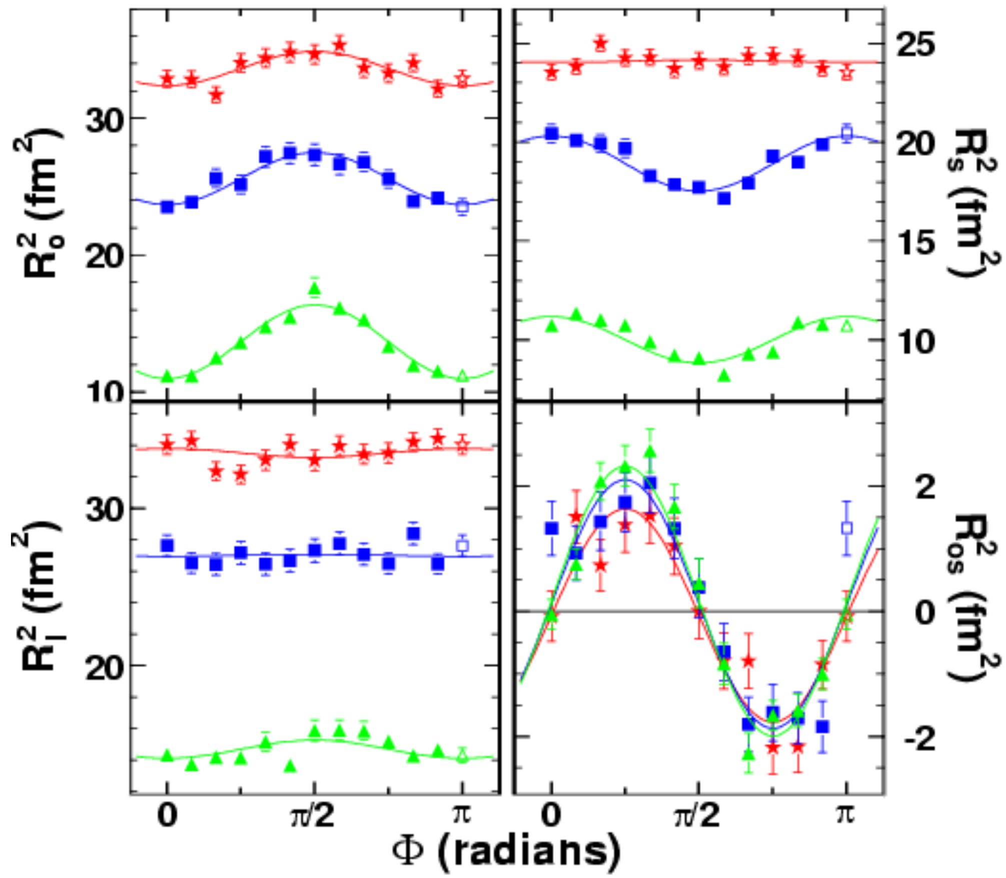


$R^2_{\text{out-side}} < 0$

Azimuthal dependence of HBT radii at RHIC



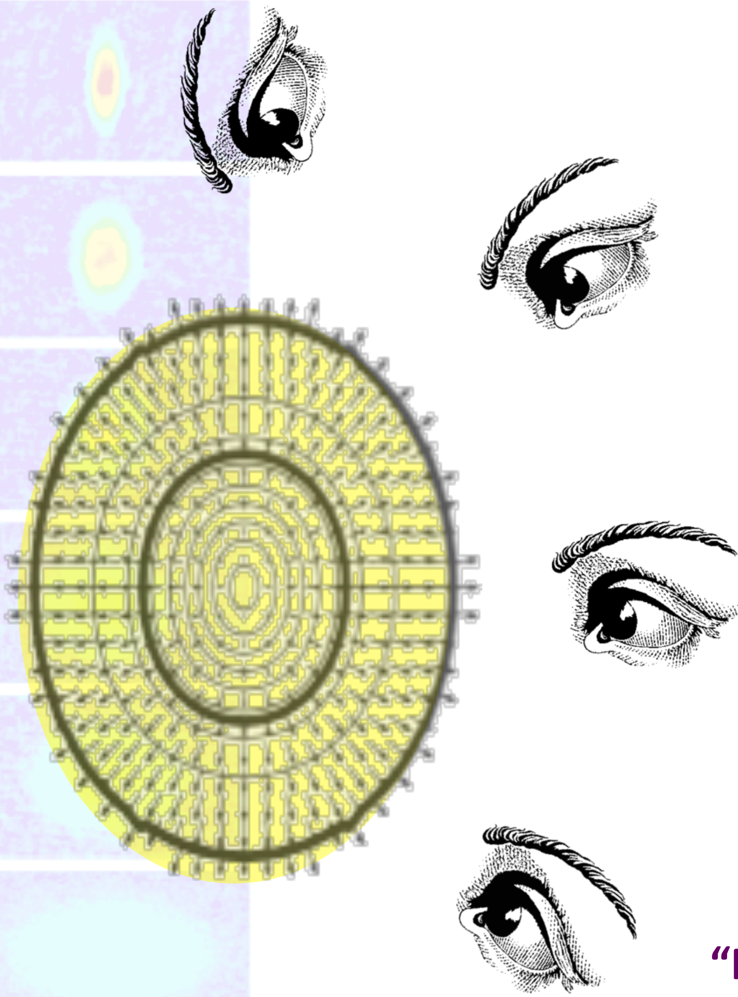
STAR, PRL93 012301 (2004)



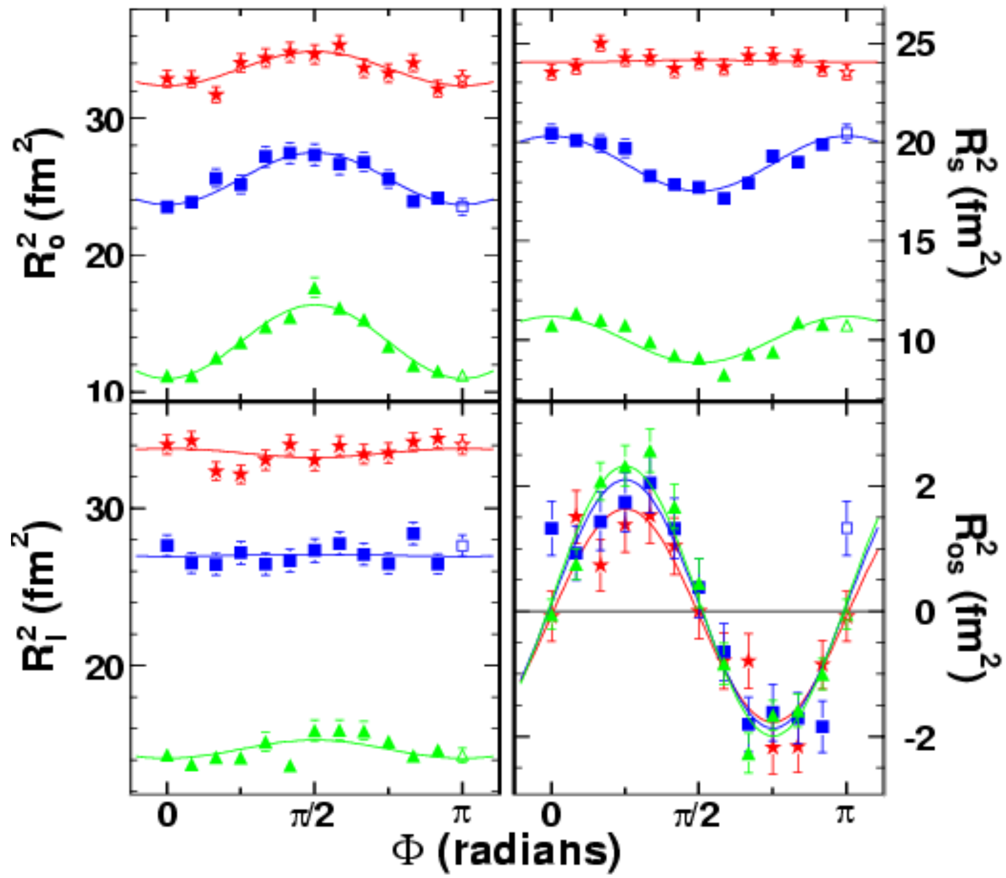
$$R^2_{s,n} \equiv \left\langle R_s^2(\phi)\cdot\cos(n\phi)\right\rangle \qquad \varepsilon \approx 2\frac{R^2_{s,2}}{R^2_{s,0}} \approx 2\frac{R^2_{os,2}}{R^2_{s,0}} \approx -2\frac{R^2_{o,2}}{R^2_{s,0}}$$

Retiere&MAL PRC70 (2004) 044907

Azimuthal dependence of HBT radii at RHIC



STAR, PRL93 012301 (2004)

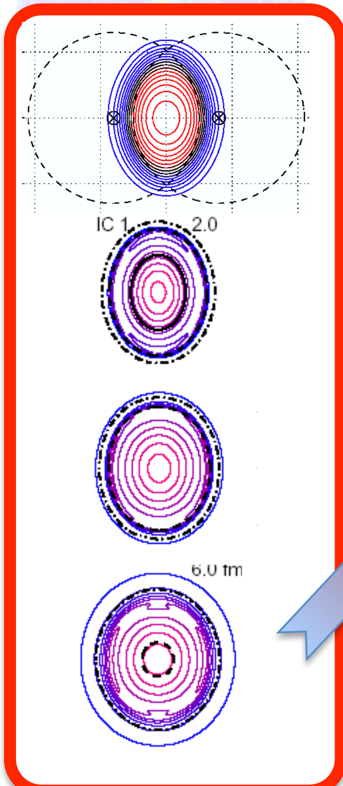


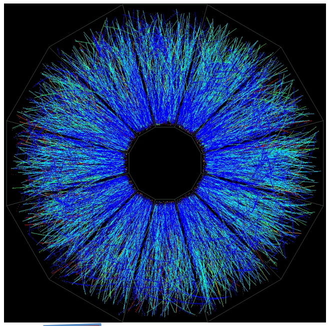
"No-flow formula" estimated good within ~ 30% (low pT)

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

Retiere&MAL PRC70 (2004) 044907
Mount et al, PRC84:014908,2011

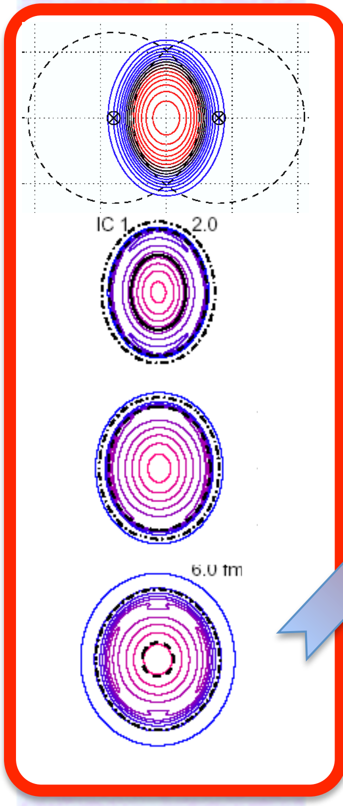
Welcome to the machine

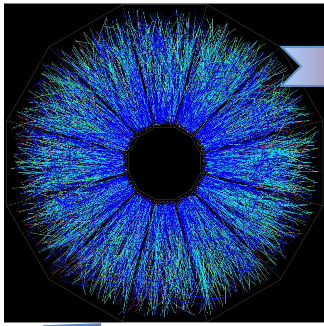




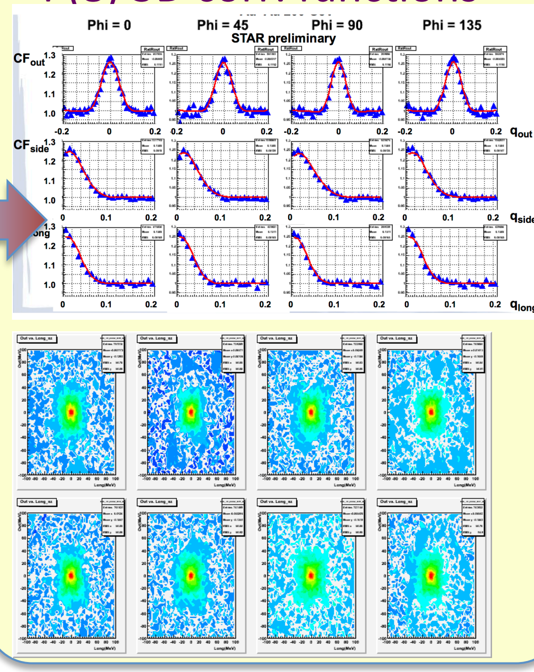
It's a bit more complicated than using a microscope like the femtosecond laser guys do...

Welcome to the machine





4 (8) 3D corr. functions



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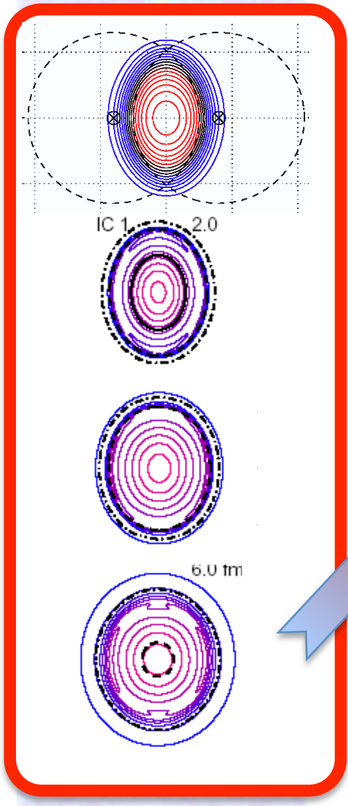

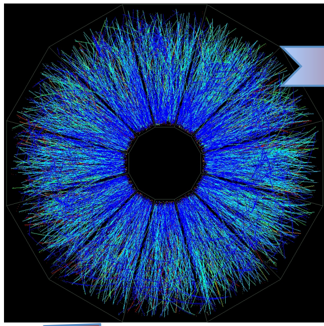

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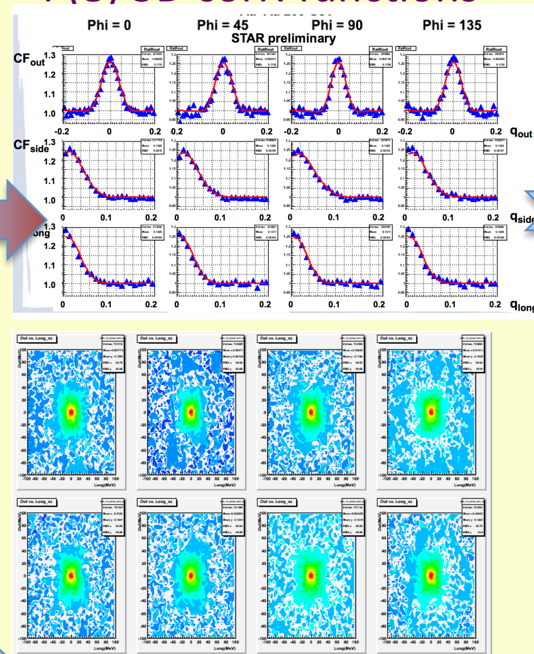


4 (8) RP-corrected CFs

$$N_{\rm exp}(\vec{q},\Phi_j)=N_0^{\rm exp}(\vec{q})+2\sum_{n=1}^{n_{bins}/2}\left[N_{c,n}^{\rm exp}(\vec{q})\cos(n\Phi_j)+N_{s,n}^{\rm exp}(\vec{q})\sin(n\Phi_j)\right]$$

where

$$N_{c,n}^{\rm exp}(\vec{q})=\frac{1}{n_{bins}}\sum_{j=1}^{n_{bins}}N_{\rm exp}(\vec{q},\Phi_j)\cos(n\Phi_j)$$

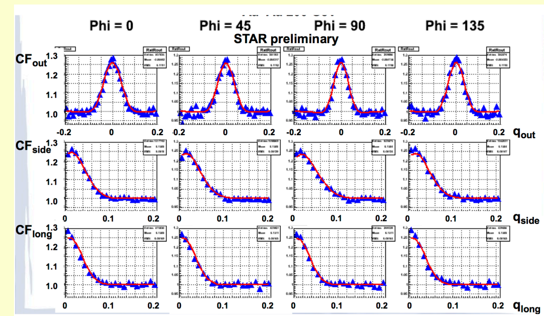
$$N_{s,n}^{\rm exp}(\vec{q})=\frac{1}{n_{bins}}\sum_{j=1}^{n_{bins}}N_{\rm exp}(\vec{q},\Phi_j)\sin(n\Phi_j)$$

The true numerator is then given by

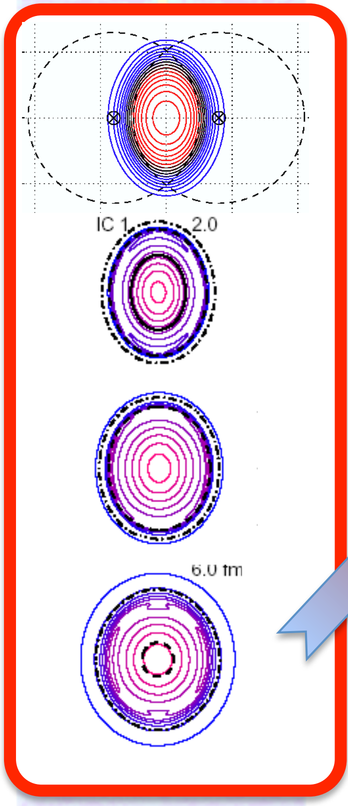
$$N(\vec{q},\Phi_j)=N_{\rm exp}(\vec{q})+2\sum_{n=1}^{n_{bins}/2}\zeta_{n,m}\left[N_{c,n}^{\rm exp}(\vec{q})\cos(n\Phi_j)+N_{s,n}^{\rm exp}(\vec{q})\sin(n\Phi_j)\right]$$

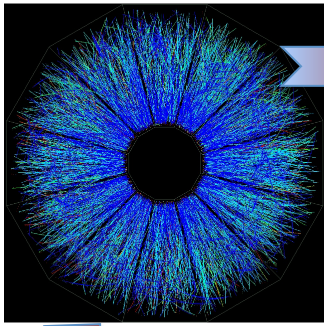
where the correction term is

$$\zeta_{n,m}=\frac{n\Delta/2}{\sin(n\Delta/2)}\frac{1}{\langle\cos[n(\Psi_m-\Psi_R)]\rangle}-1$$

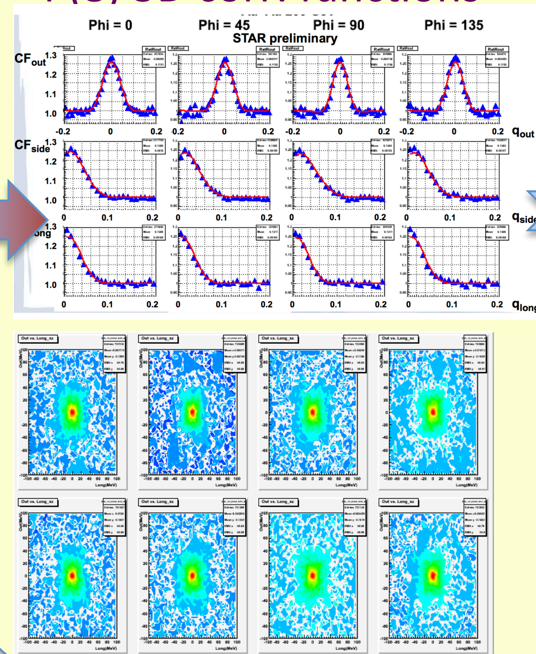


Welcome to the machine





4 (8) 3D corr. functions



4 (8) RP-corrected CFs

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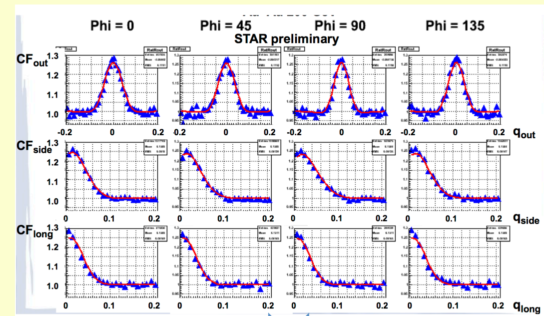
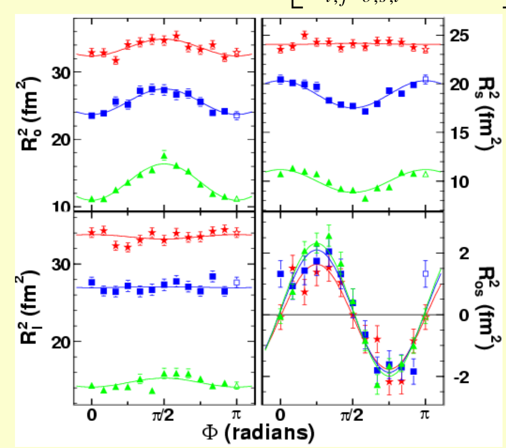
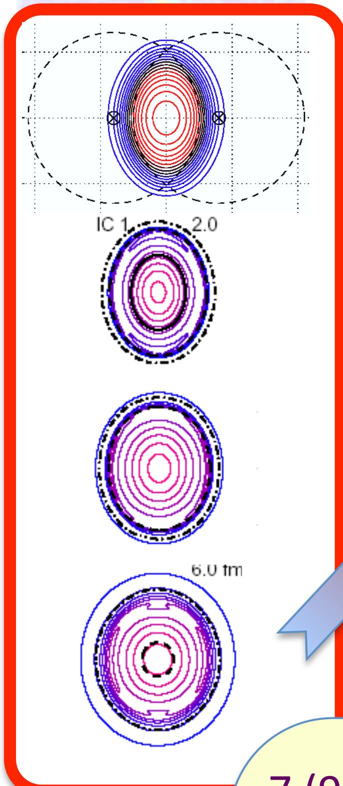


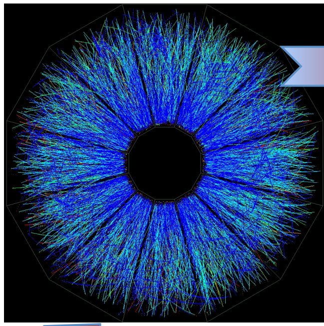
4 (8) sets of 4 (6) radii

$$C^{fit}(\vec{q})=1+\lambda\exp\left[-\sum_{i,j=o,s,l}q_iq_jR_{i,j}^2\right]$$

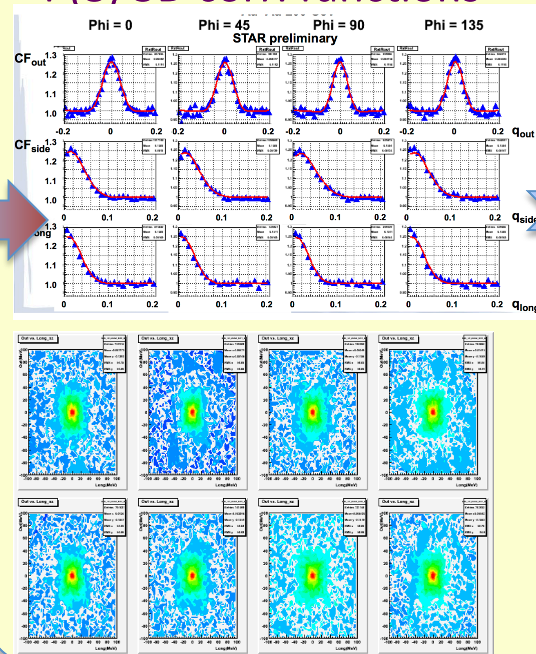


Welcome to the machine





4 (8) 3D corr. functions



4 (8) RP-corrected CFs

$$N_{exp}(\vec{q},\Phi_j)=N_0^{exp}(\vec{q})+2\sum_{n=1}^{n_{bins}/2}\left[N_{c,n}^{exp}(\vec{q})\cos(n\Phi_j)+N_{s,n}^{exp}(\vec{q})\sin(n\Phi_j)\right]$$

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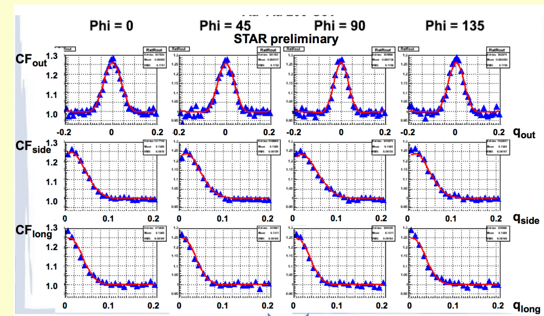

4 (8) sets of 4 (6) radii

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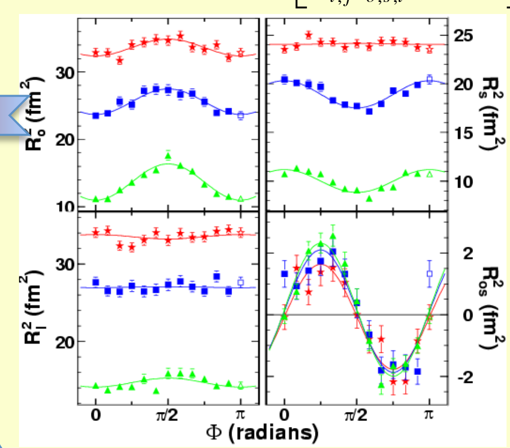
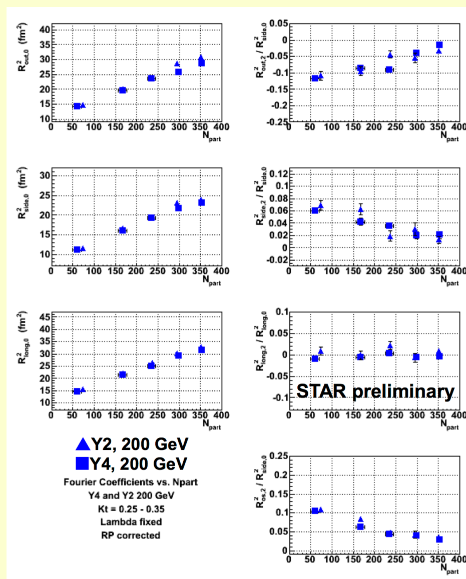
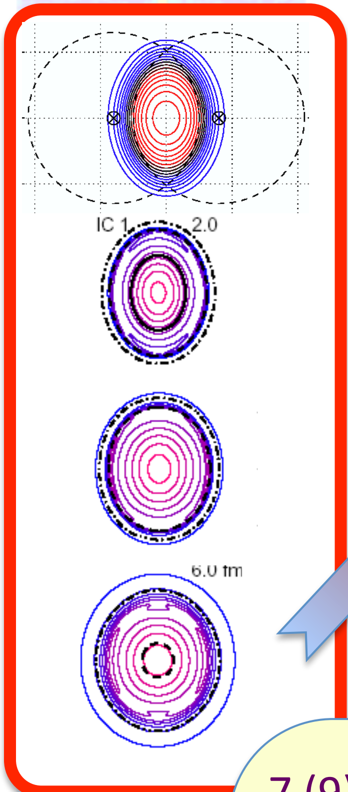


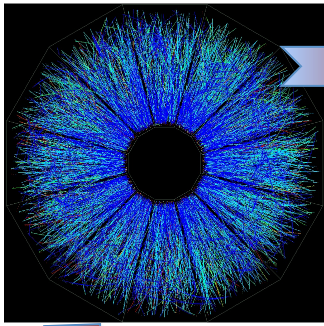
7 (9) Fourier Coefficients

$$R_{ij,n}^2=\left\langle R_{ij}^2(\phi)\left\{\begin{array}{c}\sin n\phi\\ \cos n\phi\end{array}\right\}\right\rangle$$

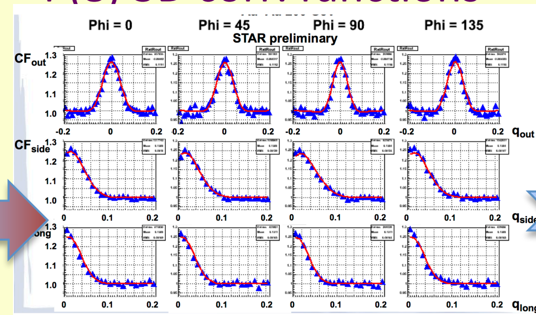


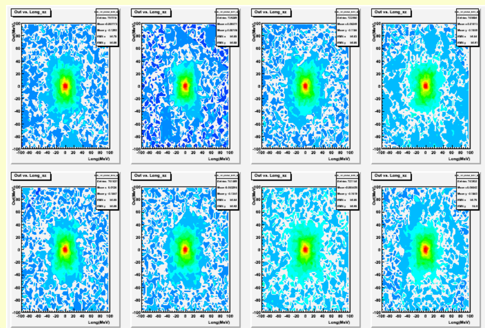
Welcome to the machine





4 (8) 3D corr. functions





4 (8) RP-corrected CFs

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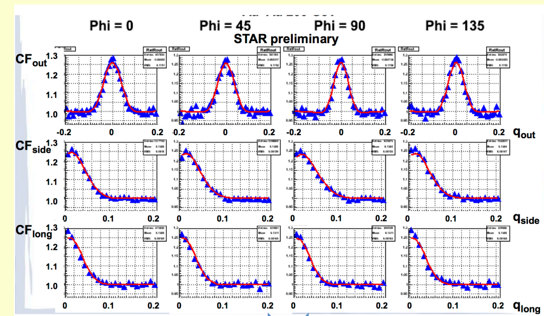
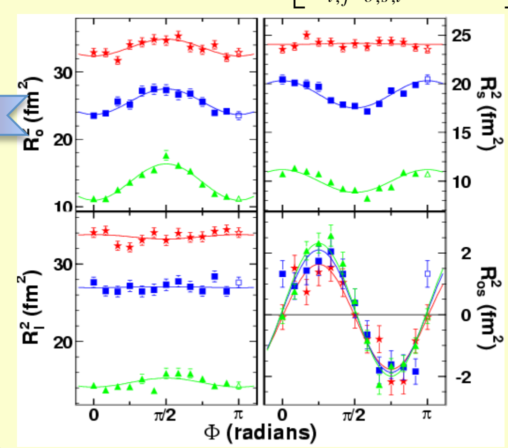


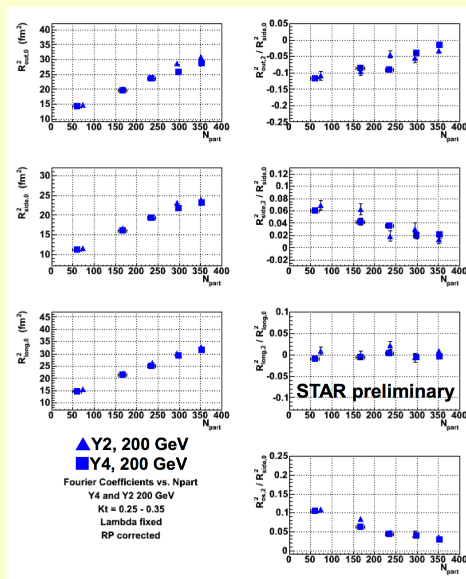
4 (8) sets of 4 (6) radii

$$C^{fit}(\vec{q})=1+\lambda\exp\left[-\sum_{i,j=o,s,l}q_iq_jR_{i,j}^2\right]$$



7 (9) Fourier Coefficients

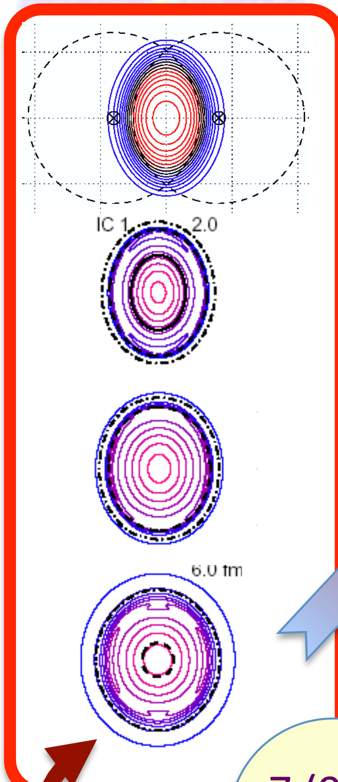
$$R_{ij,n}^2=\left\langle R_{ij}^2(\phi)\begin{Bmatrix}\sin n\phi\\ \cos n\phi\end{Bmatrix}\right\rangle$$

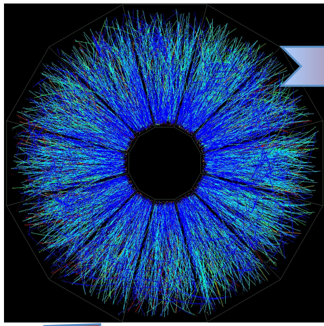


1 eccentricity estimate

$$\varepsilon=2\frac{R_{s,2}^2}{R_{s,0}^2}$$

Welcome to the machine





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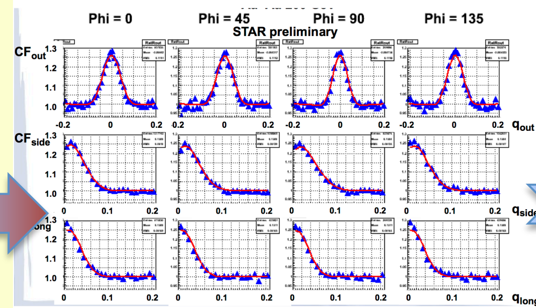

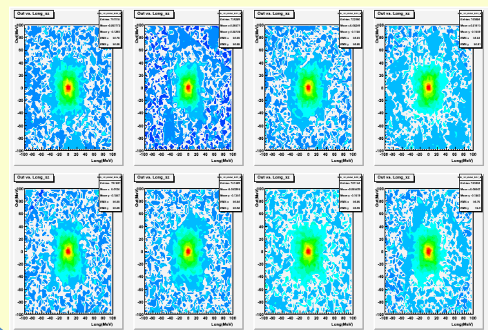

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where

$$N_{c,n}^{\exp}(\vec{q})=\frac{1}{n_{bins}}\sum_{j=1}^{n_{bins}}N_{\exp}(\vec{q},\Phi_j)\cos(n\Phi_j)$$

$$N_{s,n}^{\exp}(\vec{q})=\frac{1}{n_{bins}}\sum_{j=1}^{n_{bins}}N_{\exp}(\vec{q},\Phi_j)\sin(n\Phi_j)$$

The true numerator is then given by

$$N(\vec{q},\Phi_j)=N_{\exp}(\vec{q})+2\sum_{n=1}^{n_{bins}/2}\zeta_{n,m}\left[N_{c,n}^{\exp}(\vec{q})\cos(n\Phi_j)+N_{s,n}^{\exp}(\vec{q})\sin(n\Phi_j)\right]$$

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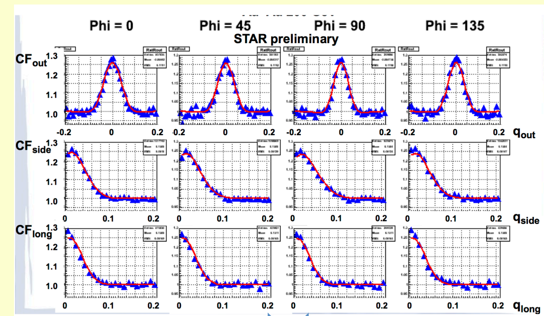
$$\zeta_{n,m}=\frac{n\Delta/2}{\sin(n\Delta/2)}\frac{1}{\langle\cos[n(\Psi_m-\Psi_R)]\rangle}-1$$



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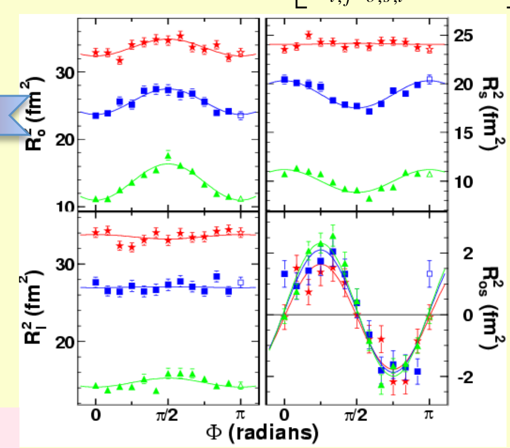

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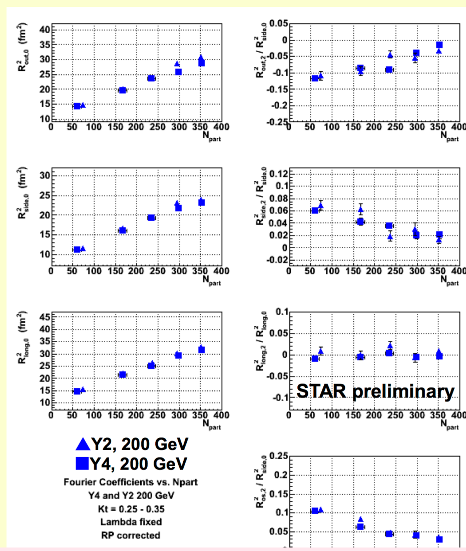


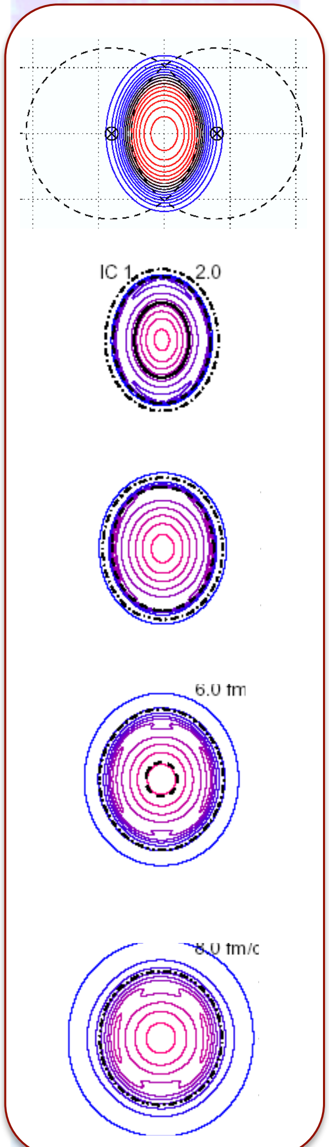
~30%

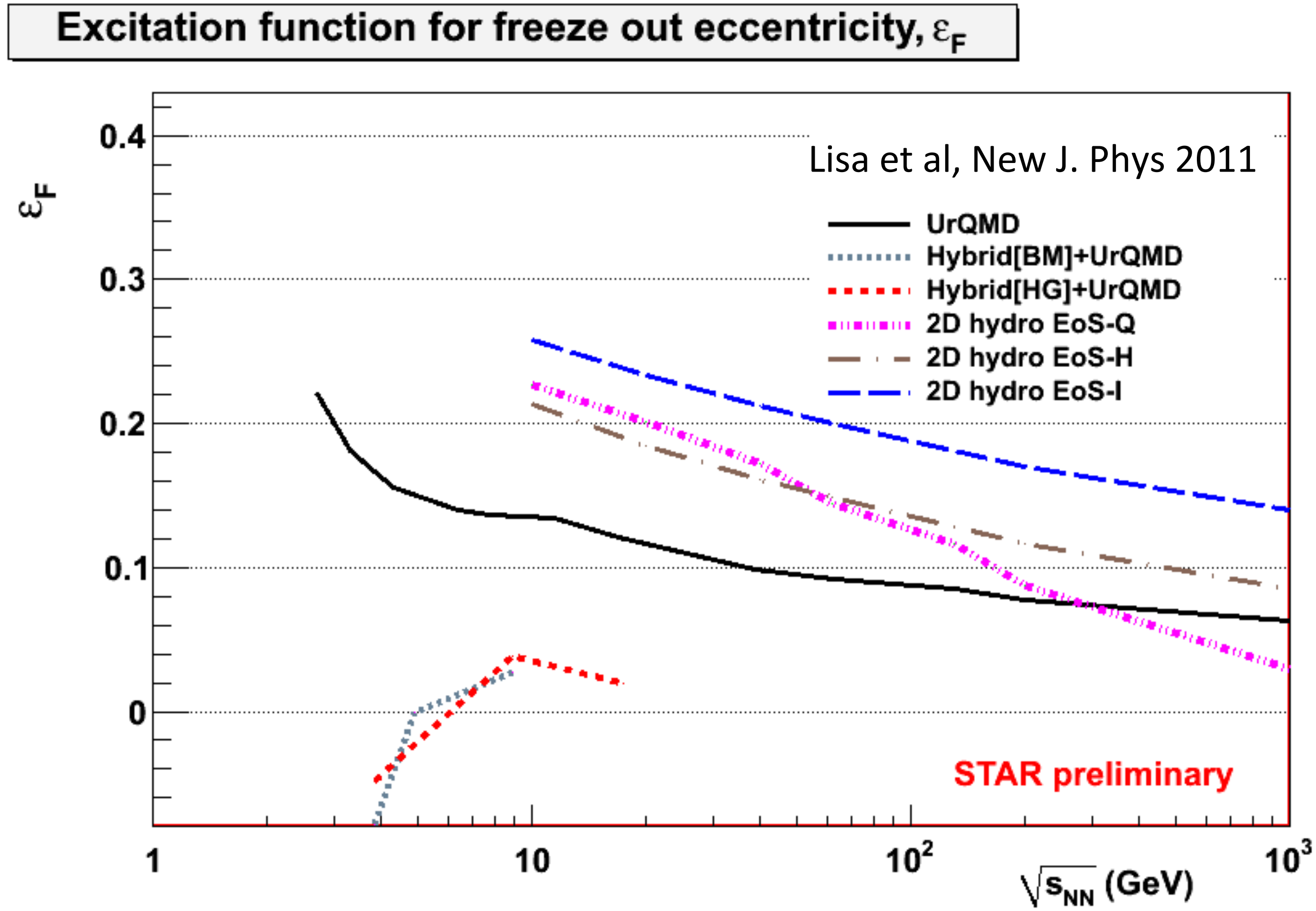
1 eccentricity estimate

$$\varepsilon=2\frac{R_{s,2}^2}{R_{s,0}^2}$$

see, e.g. E. Mount et al PRC84:014908,2011

transport predictions (or "untuned postdictions")





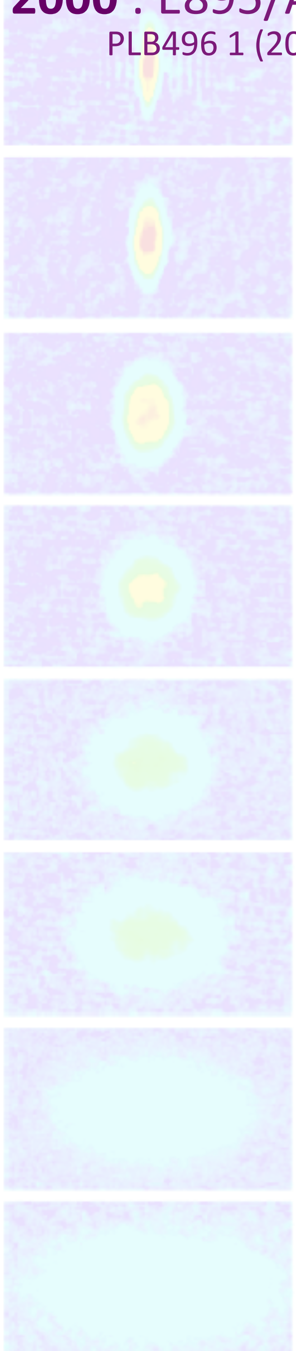
naive expectation: absent something special, monotonic decrease

- higher energy → more pressure → evolve to smaller ε_F
- higher energy → longer lifetime → evolve to smaller ε_F

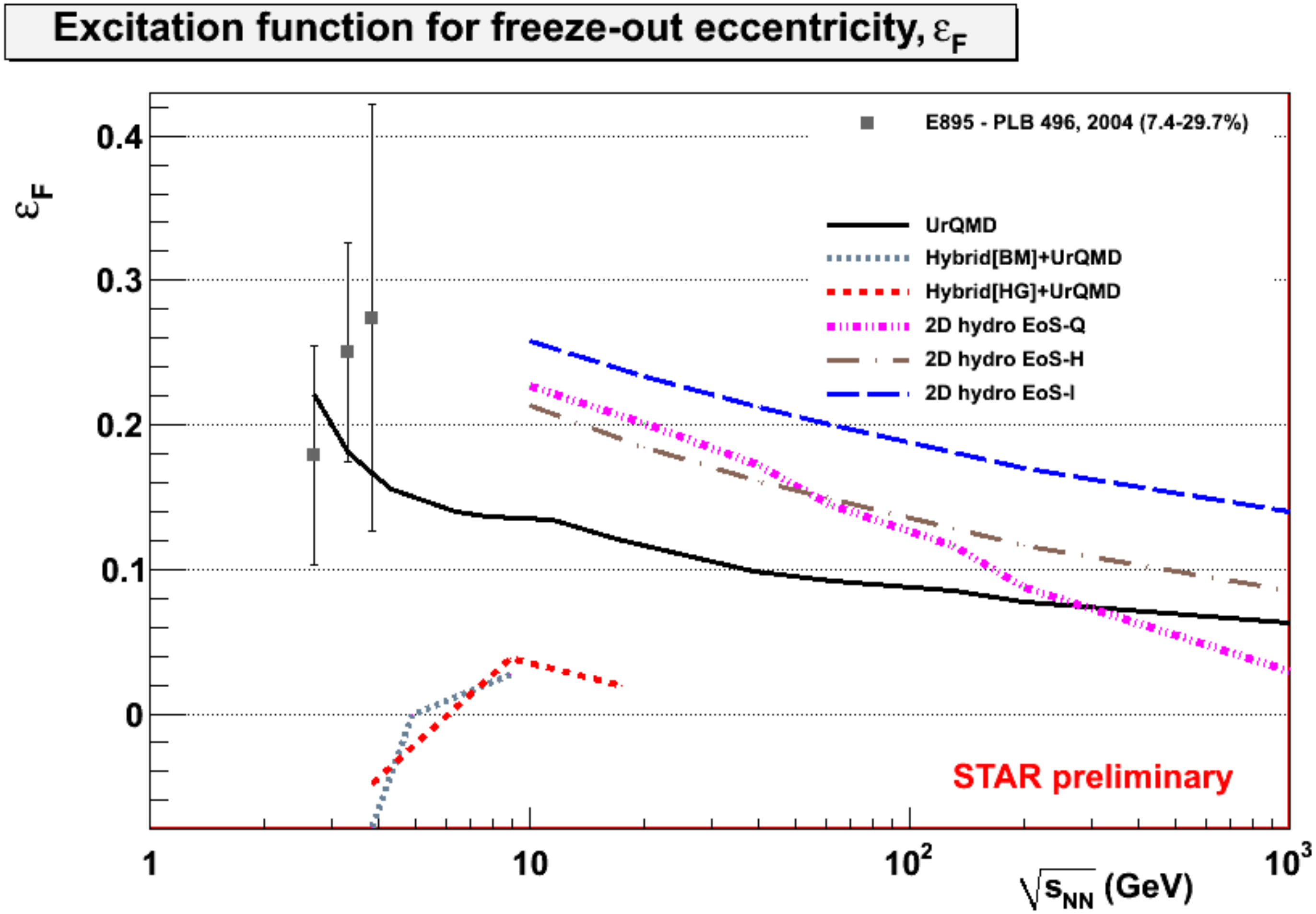
(hybrid models – special case)

certainly no minimum

2000 : E895/AGS
PLB496 1 (2000)



10+ years of asHBT systematics



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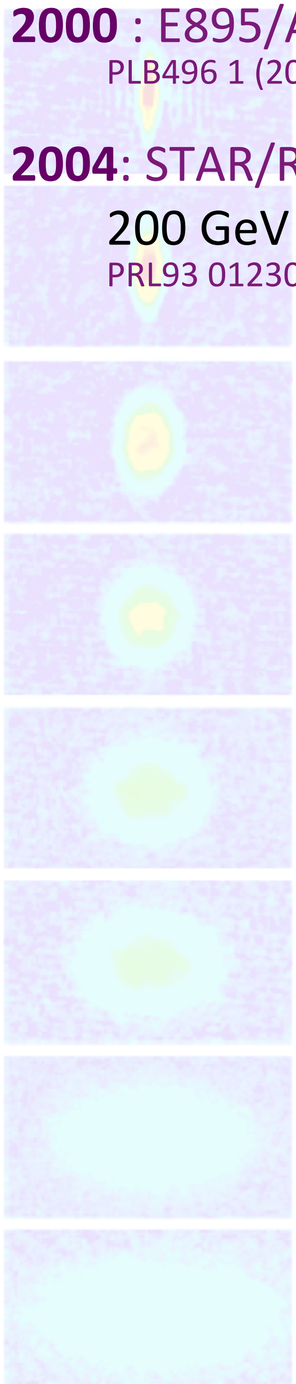

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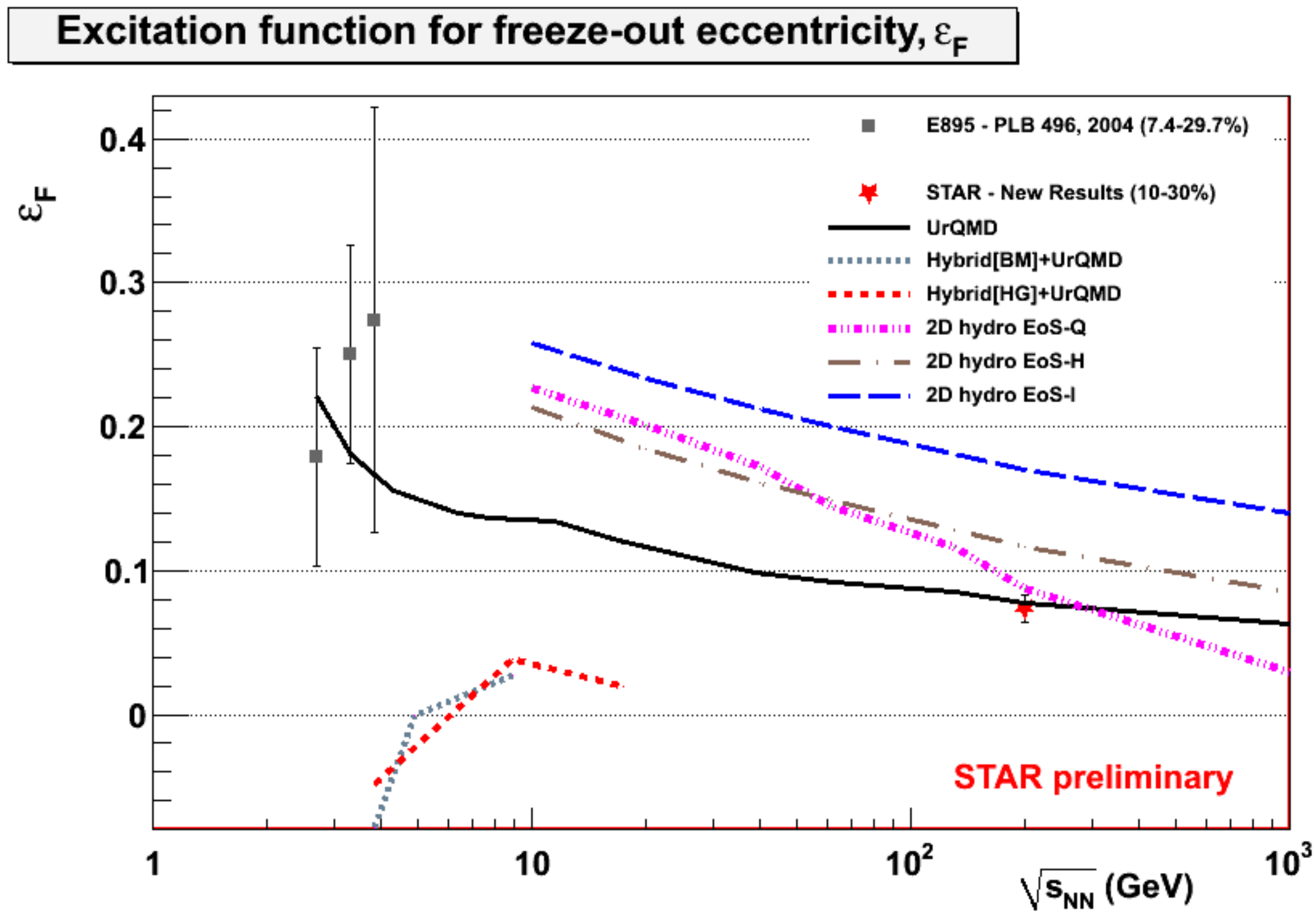
2004: STAR/RHIC
200 GeV
PRL93 012301 (2004)



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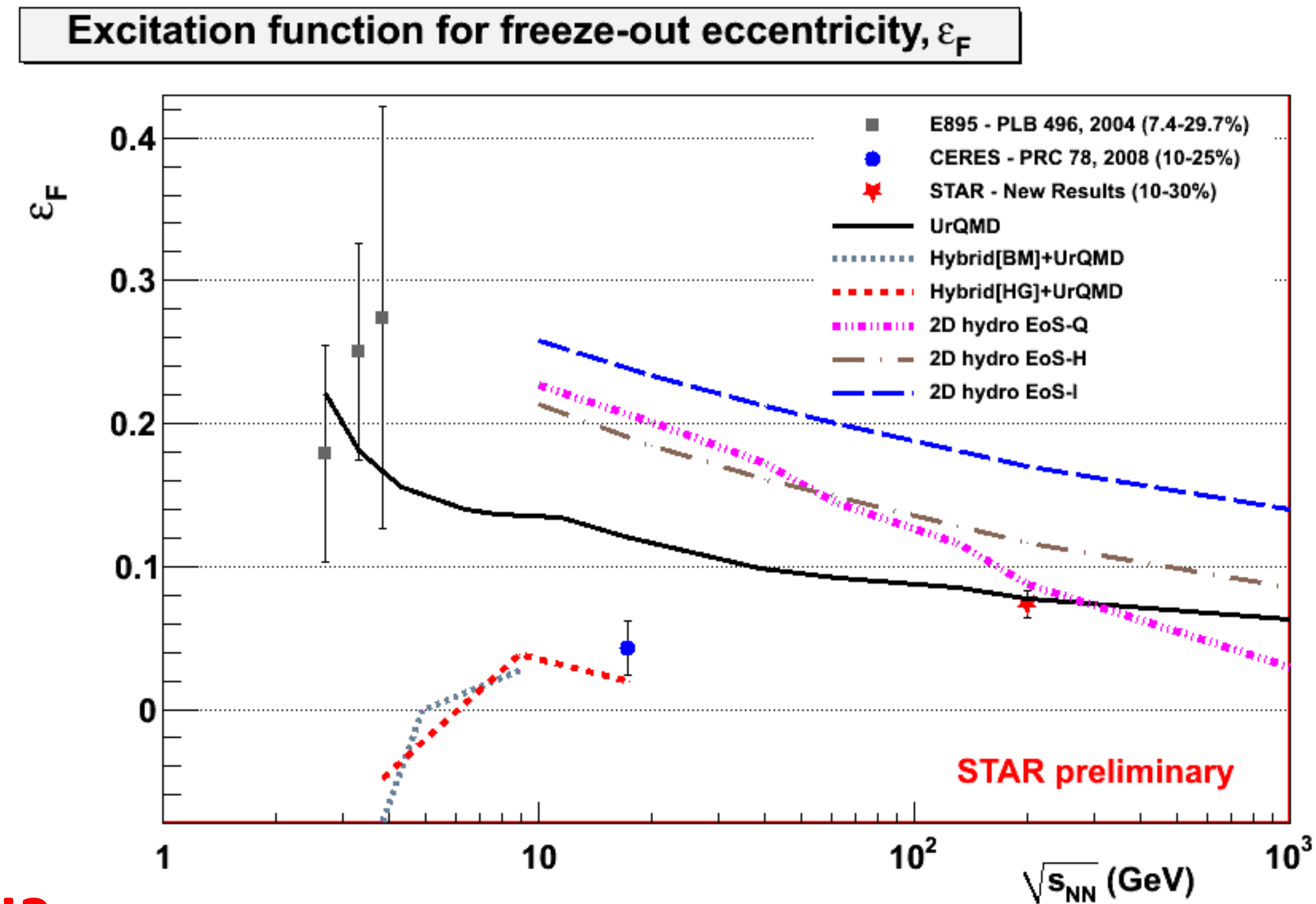

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STAR/RHIC 62.4 GeV

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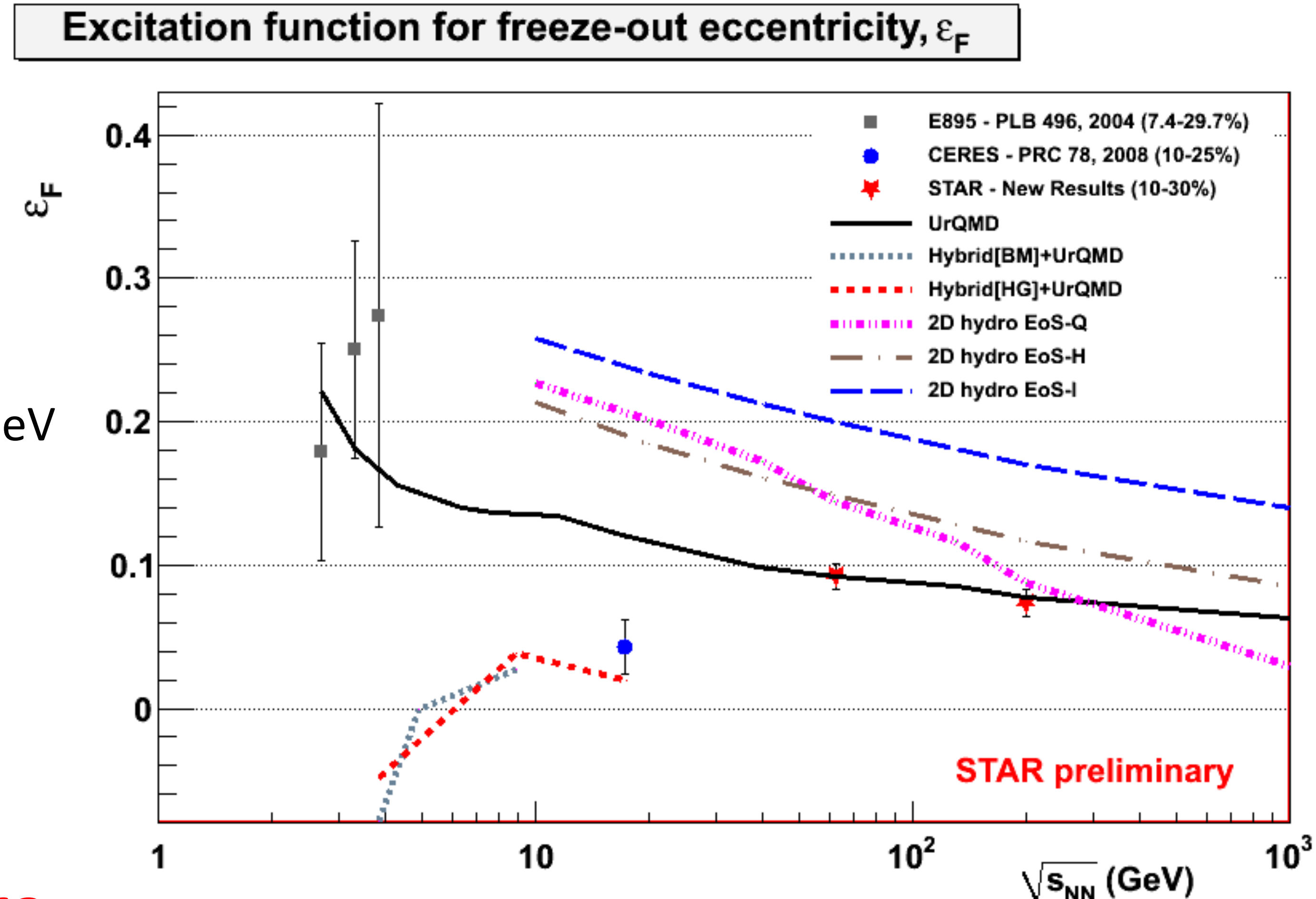

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!? A real minimum? – speculation of P.T. (Lisa et al, New J. Phys 2011)

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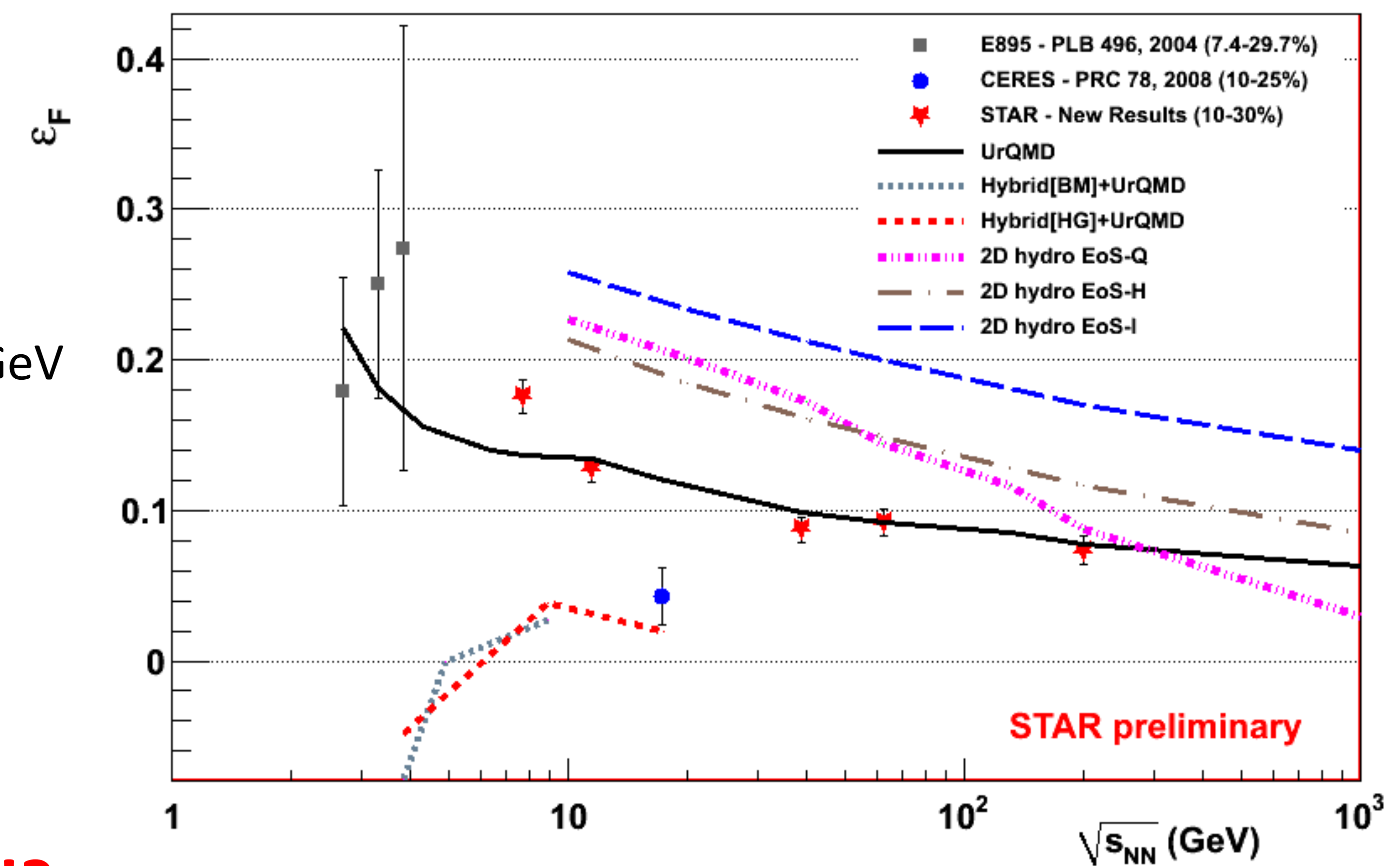
STAR/RHIC
7.7, 11.5, 39 GeV
arXiv:1107.1527

10+ years of asHBT systematics

Excitation function for freeze-out eccentricity, ε_F



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!!!? A real **sharp** minimum at the “special” kink/horn/step energy?

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2010 (WPCF Kiev):
STAR/RHIC 62.4 GeV

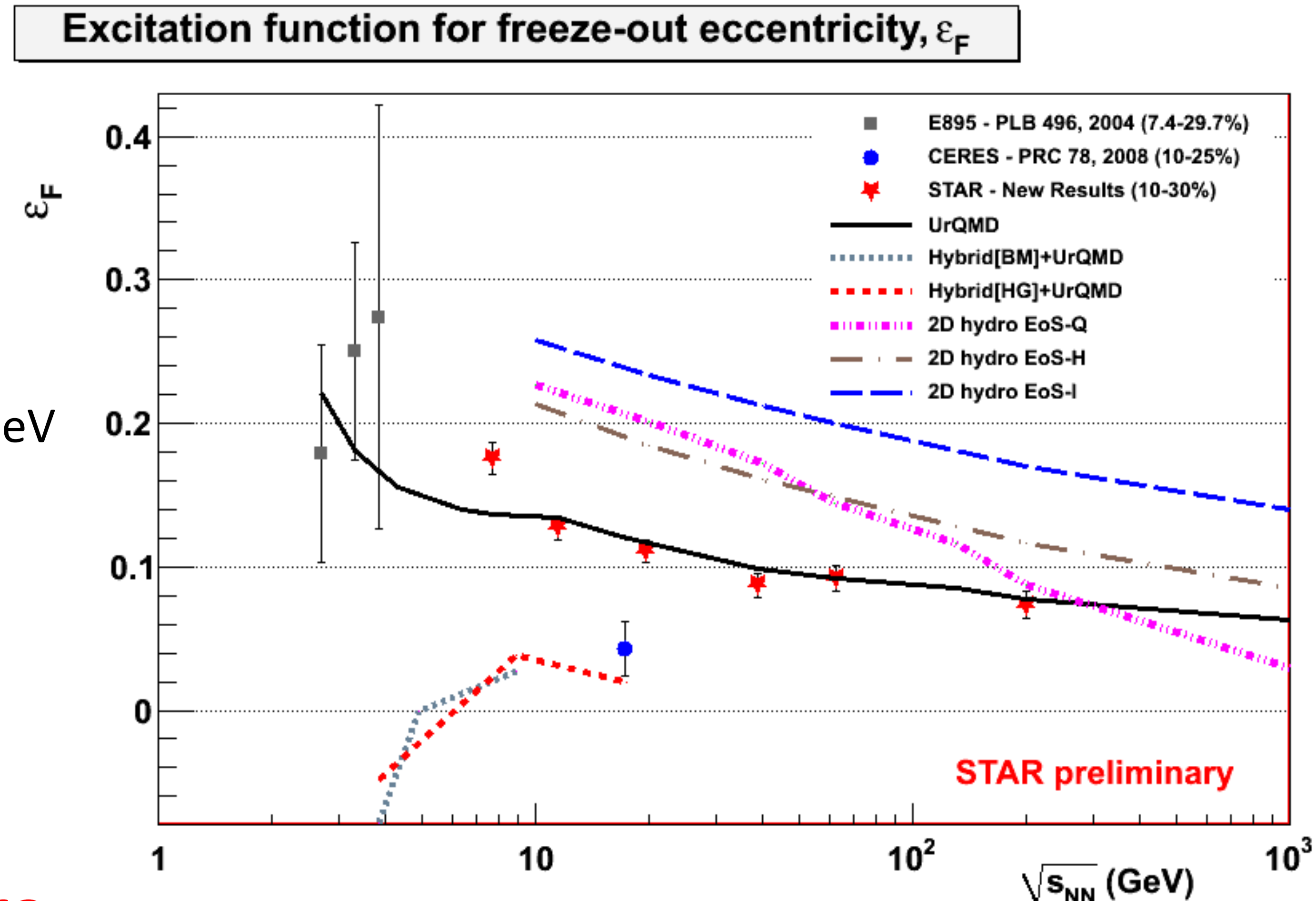
2011 (QM Annecy):
STAR/RHIC
7.7, 11.5, 39 GeV
arXiv:1107.1527

2011 (WPCF Tokyo)
STAR/RHIC
19.6 GeV

2011 (WPCF Tokyo)
PHENIX/RHIC
200 GeV

Soon: ALICE/LHC

10+ years of asHBT systematics



!? Something special?

!? A real minimum? – speculation of P.T. (Lisa et al, New J. Phys 2011)

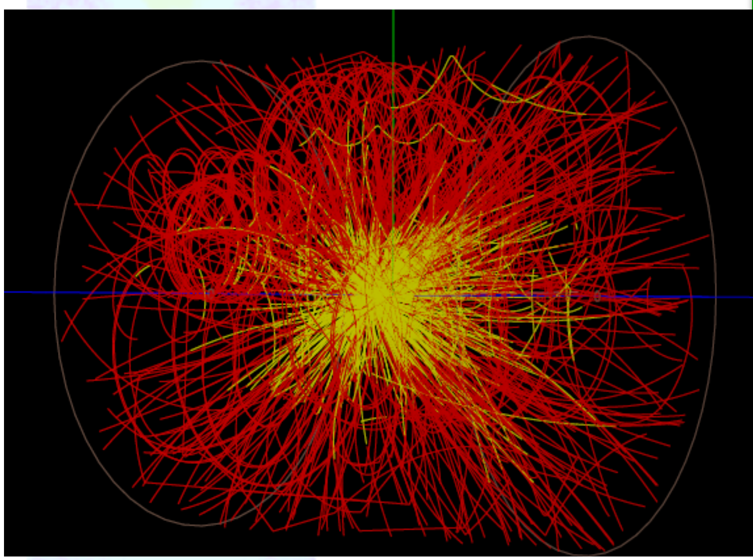
!!!? A real **sharp** minimum at the "special" kink/horn/step energy?

Uh-oh

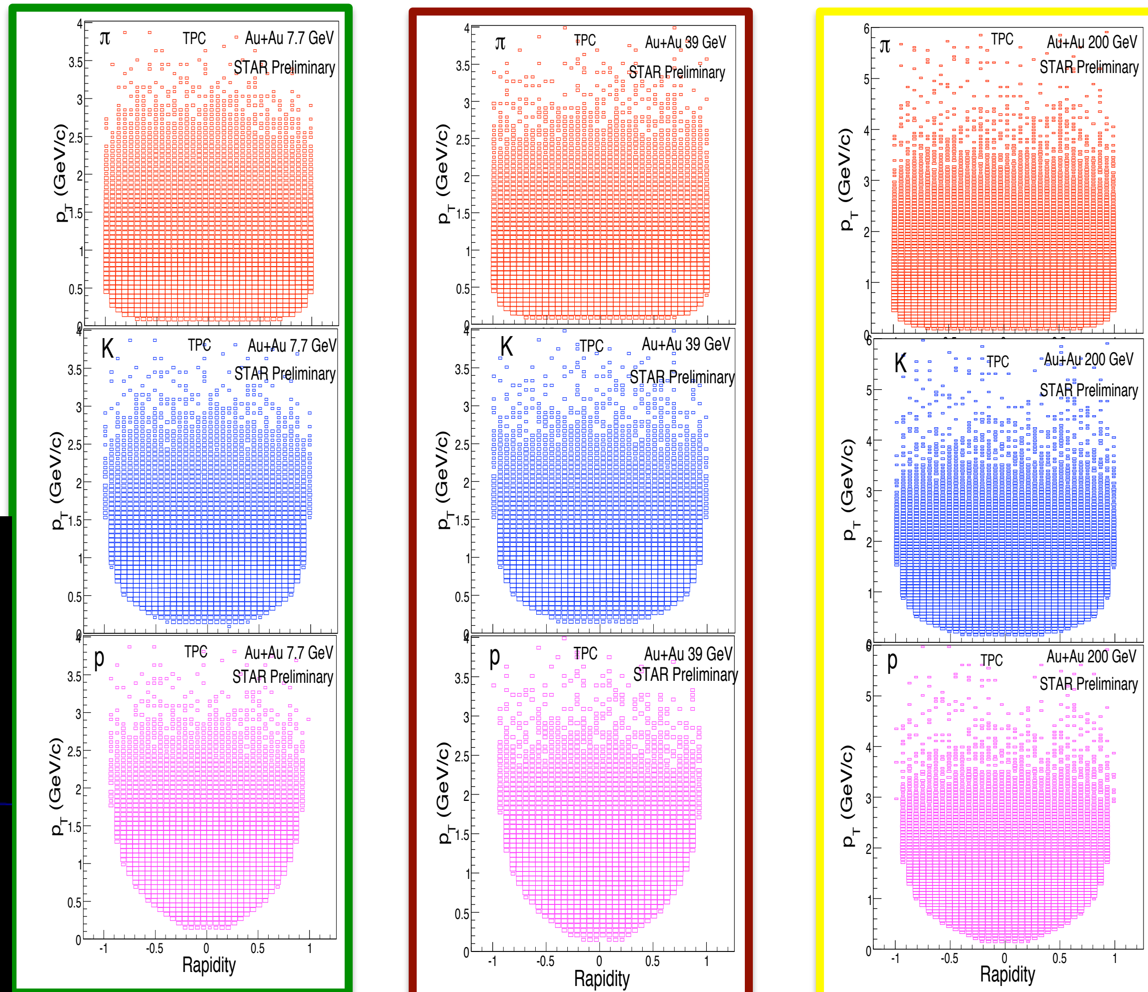
the beauty of a single, collider detector

Identical techniques, systematics, acceptance...

BUT: cannot get complacent
Important measurement, and cross-checks are important, if we take data at all seriously.



Au+Au 7.7 GeV | Au+Au 39 GeV | Au+Au 200 GeV



can CERES and STAR be reconciled?

at this point, the energies measured are too close to reasonably expect such a difference.

What else could it be?

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Table 2. Measurements of the anisotropic shapes from heavy ion collisions. The third column indicates which centrality bins were averaged to obtain the shape parameters of figures 6 and 7. See the text for details.

Experiment	$\sqrt{s_{NN}}$ (GeV)	Centrality (%)	Rapidity
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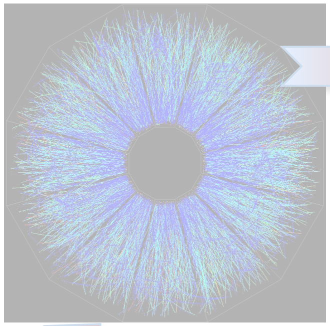
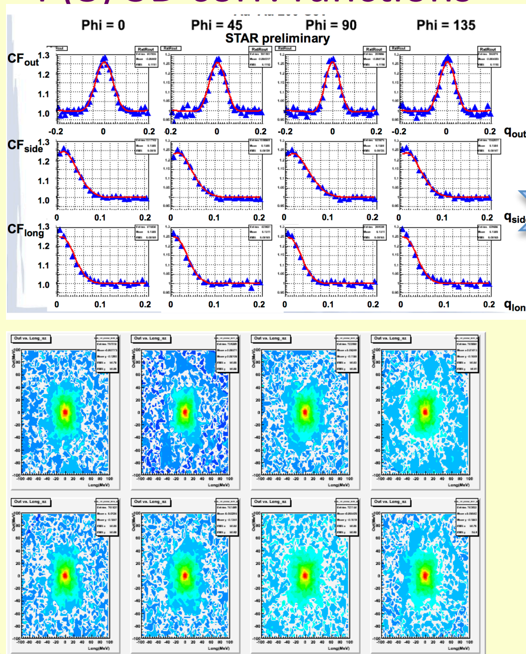
New J. Phys. **13** 065006 (2011)

Welcome to the machine



4 (8) 3D corr. functions



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$$N_{exp}(\vec{q},\Phi_j)=N_0^{exp}(\vec{q})+2\sum_{n=1}^{n_{bins}/2}[N_{c,n}^{exp}(\vec{q})\cos(n\Phi_j)+N_{s,n}^{exp}(\vec{q})\sin(n\Phi_j)]$$

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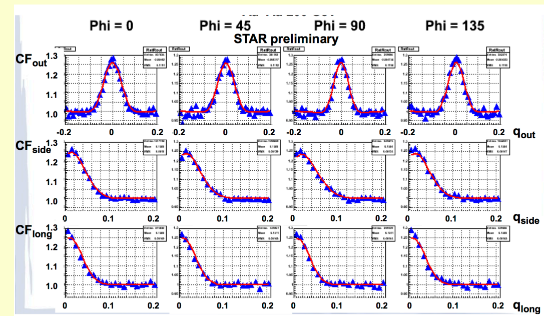


Reaction-plane resolution correction:

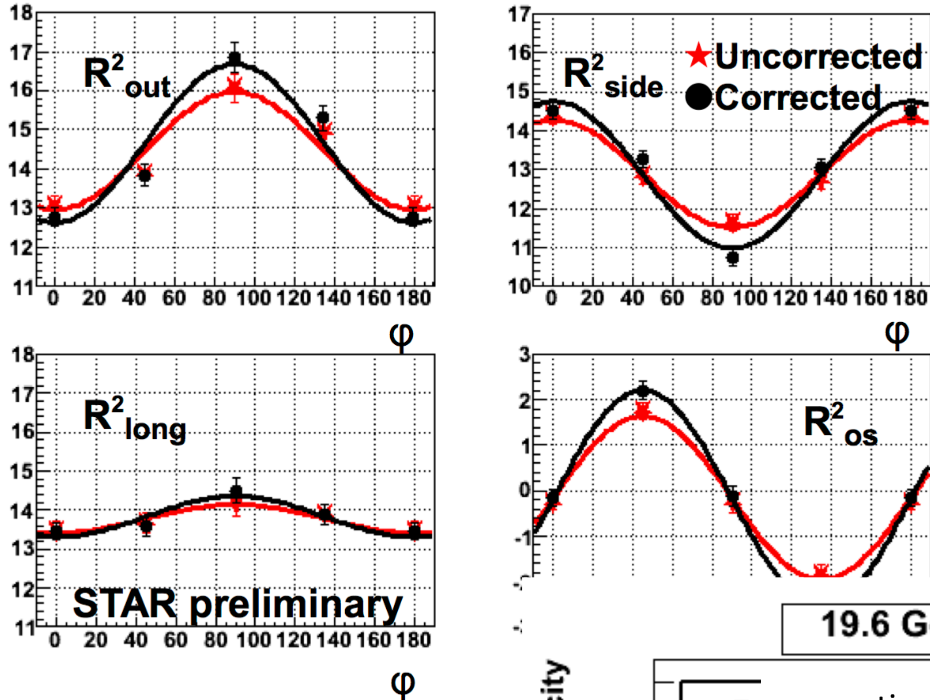
STAR: RP resolution correction done bin-by-bin to correlation functions

CERES: correction done to HBT radius parameters (similar to v2)

(question to CERES: was finite bin-width also accounted for? (Δ/2)/sin(Δ/2)) ~5% effect)

R. Wells PhD thesis (2002): methods yielded similar results *in that case*

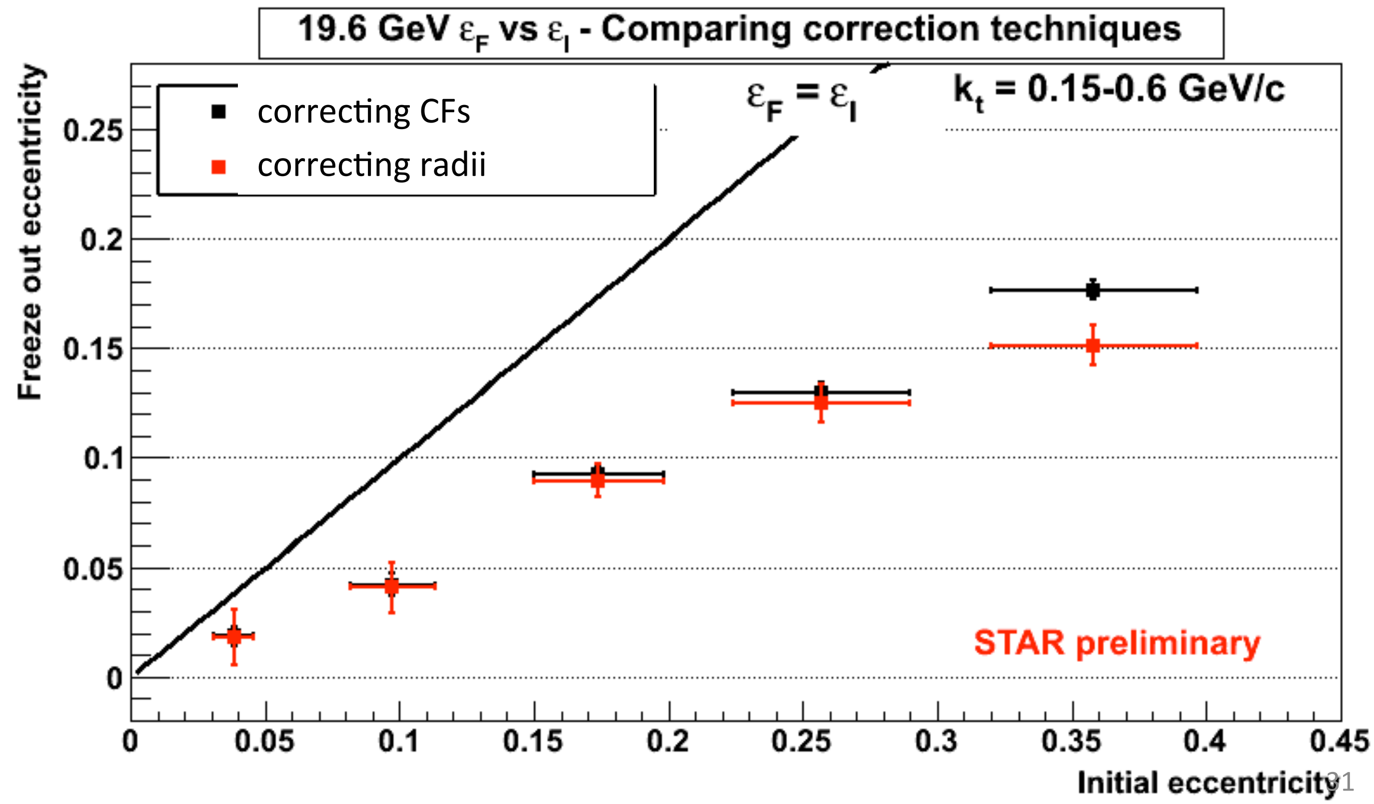
RP resolution correction



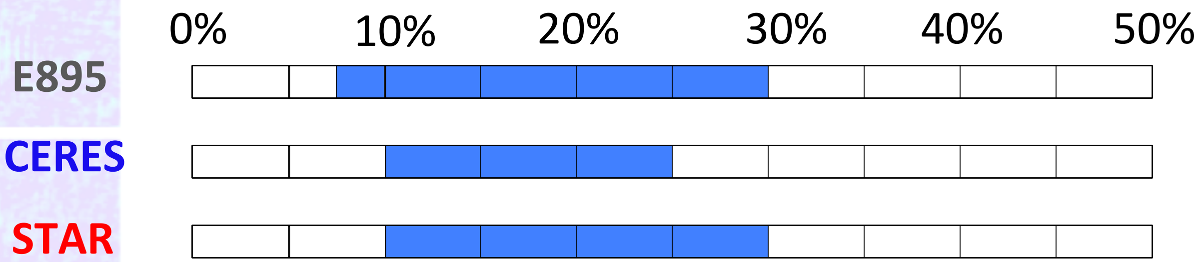
very small effect in STAR analysis

Similar at other energies

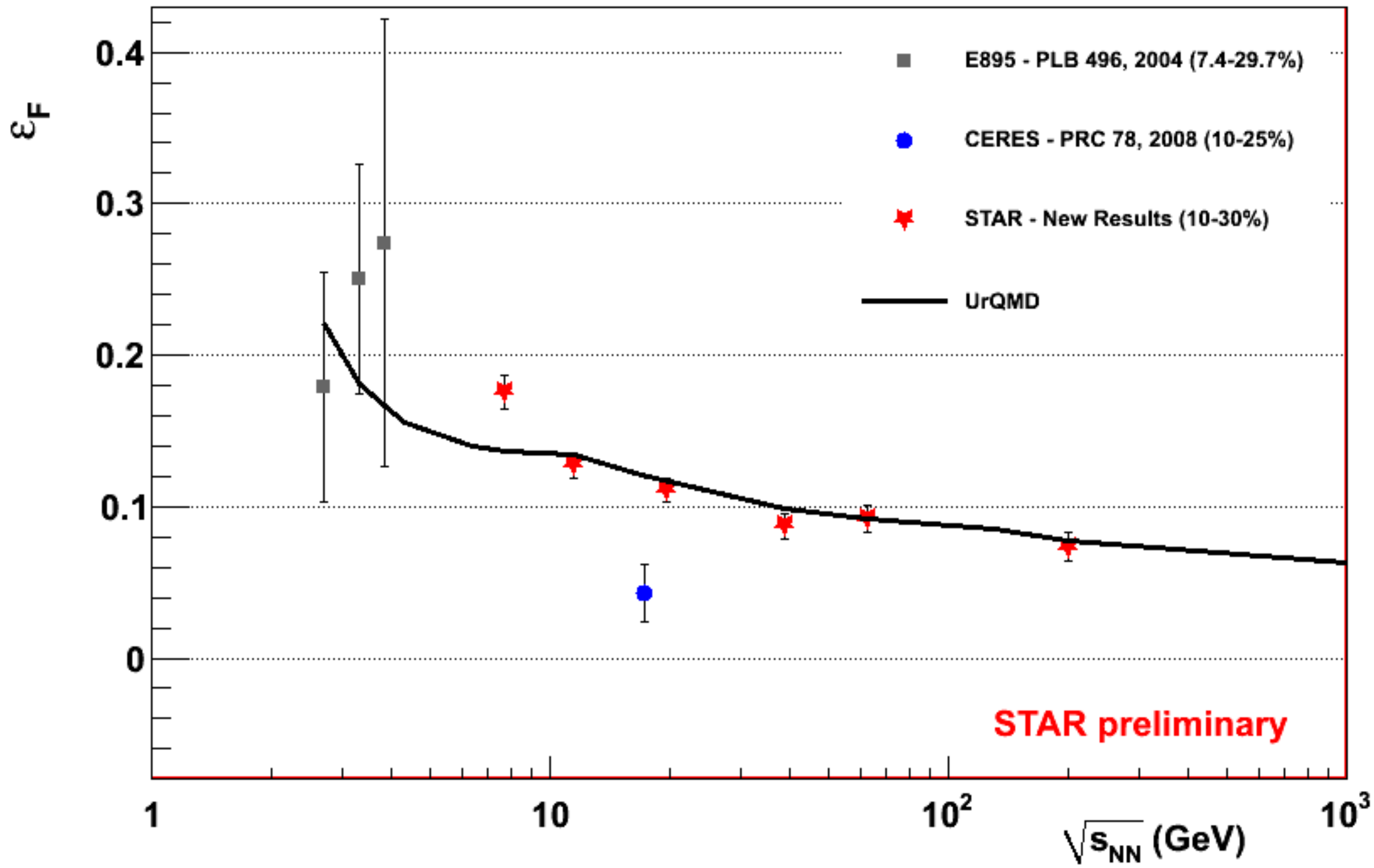
No guarantee this will be true for any other experiment, but probably not the issue



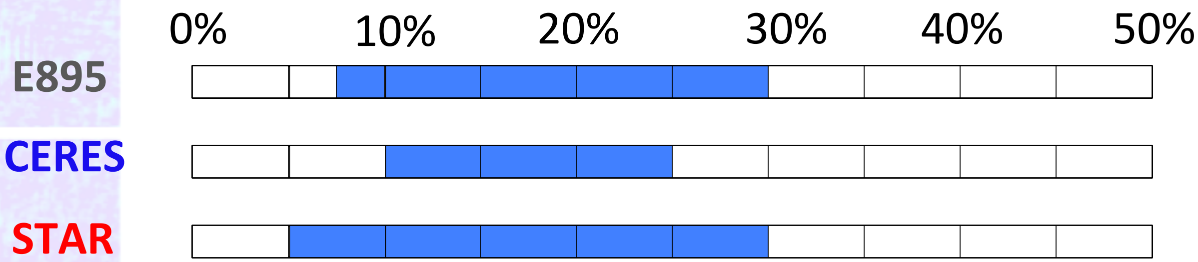
Centrality



Excitation function for freeze-out eccentricity, ε_F



Centrality



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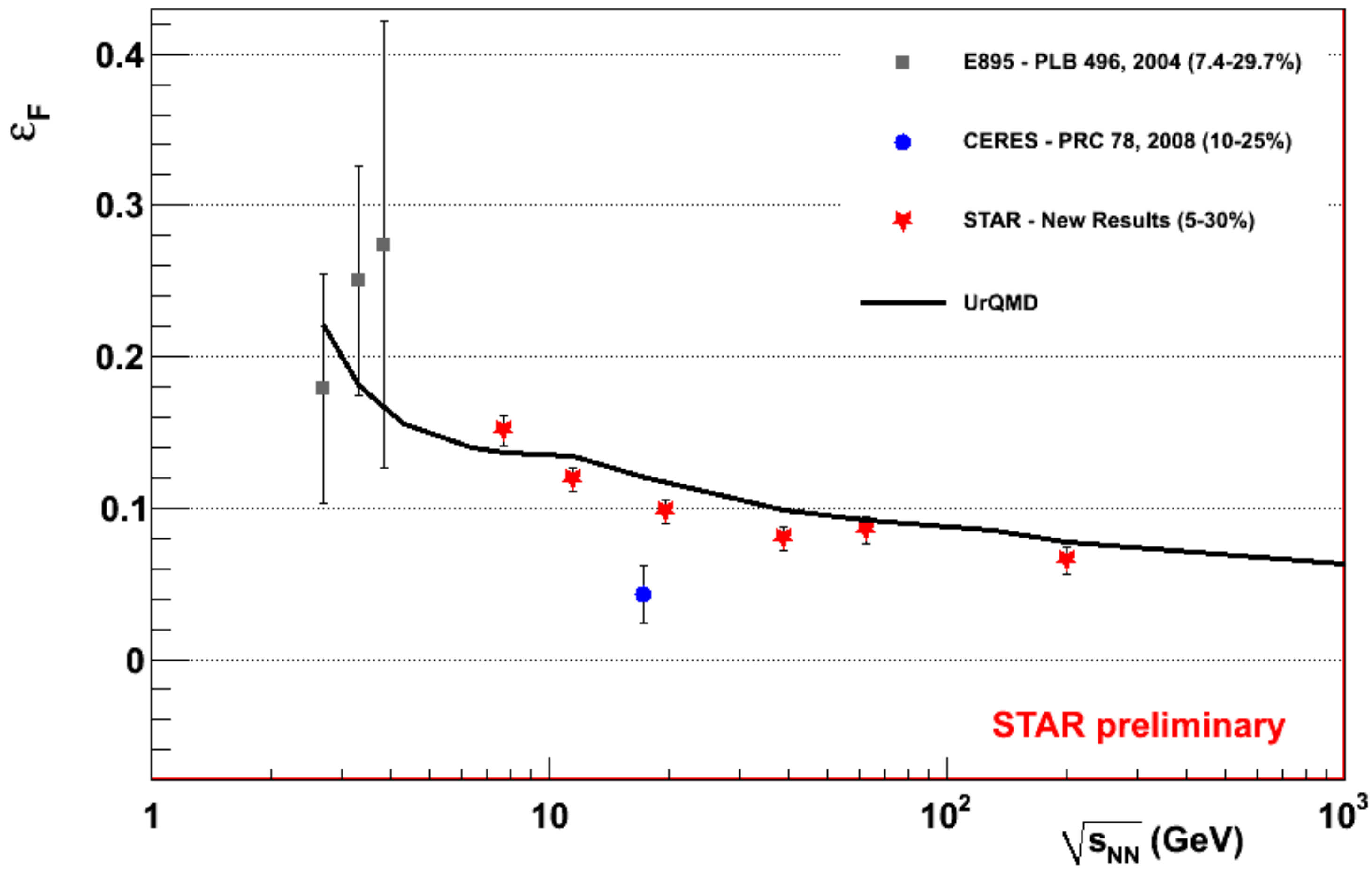
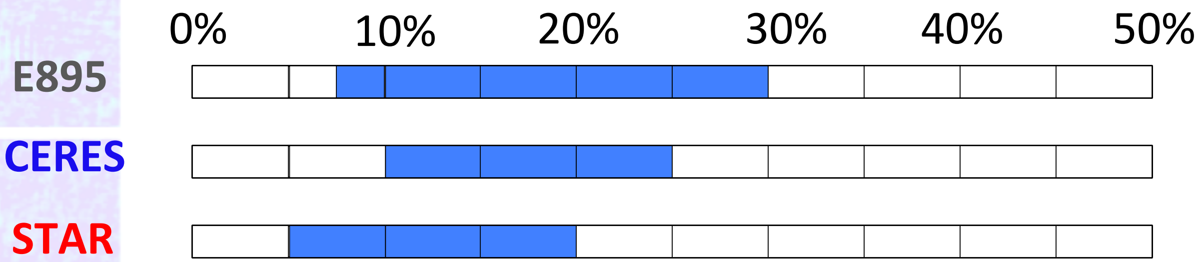
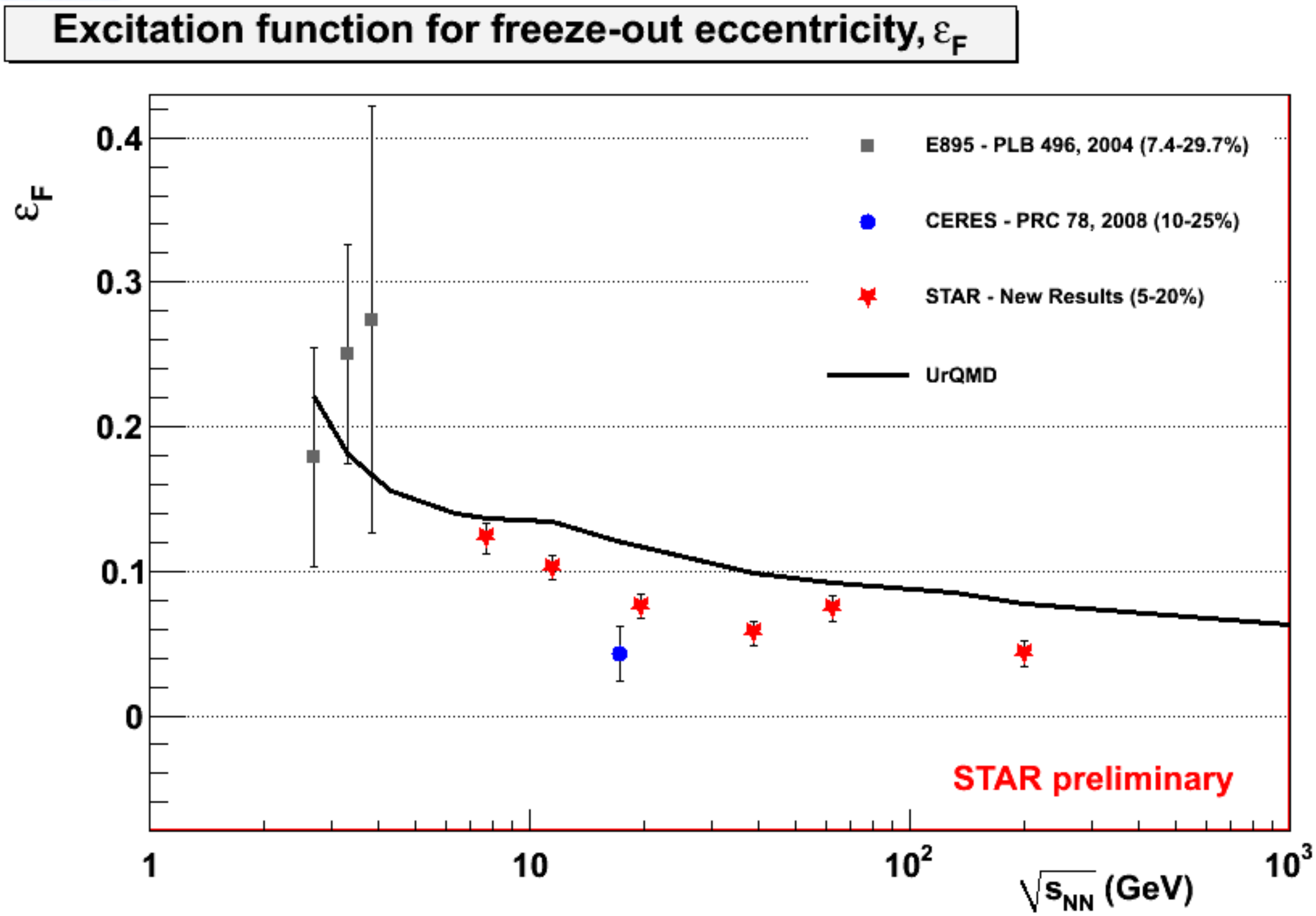


Centrality

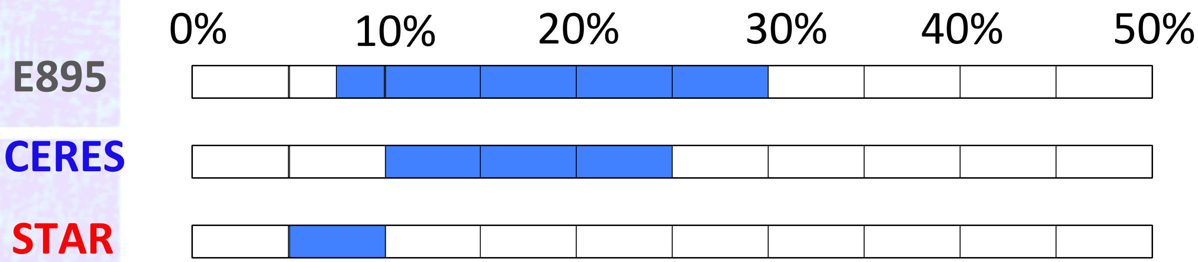


0%
10%
20%
30%
40%
50%
E895
CERES
STAR



Excitation function for freeze-out eccentricity, ε_F
ε_F
0.4
0.3
0.2
0.1
0
E895 - PLB 496, 2004 (7.4-29.7%)
CERES - PRC 78, 2008 (10-25%)
STAR - New Results (5-20%)
UrQMD
STAR preliminary
1
10
10^2
10^3
$\sqrt{s_{NN}}$ (GeV)

Centrality



0%
10%
20%
30%
40%
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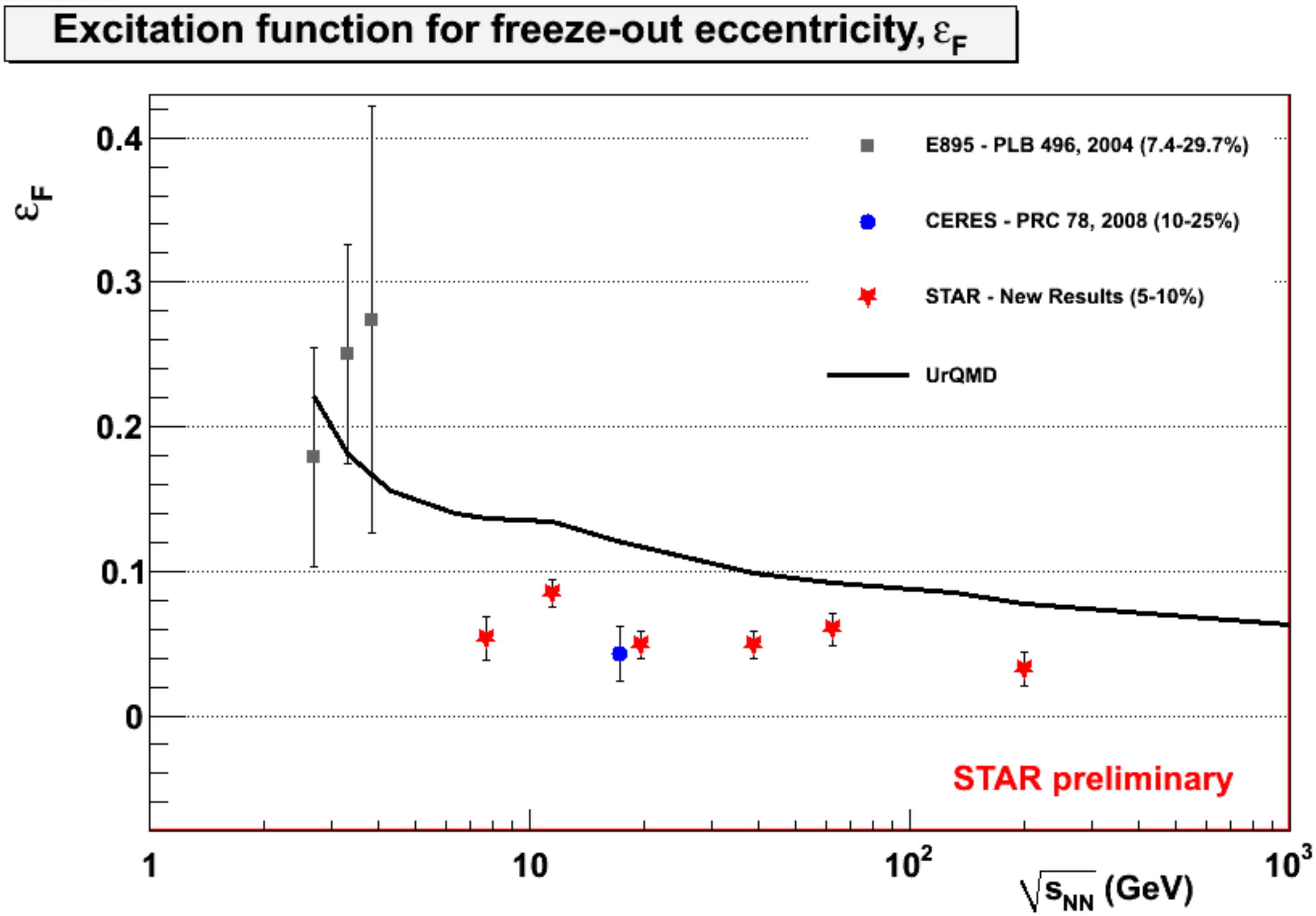
CERES
STAR



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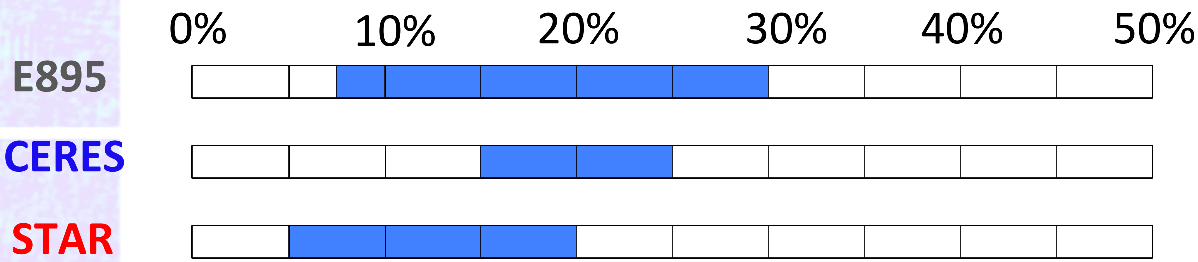
Centrality



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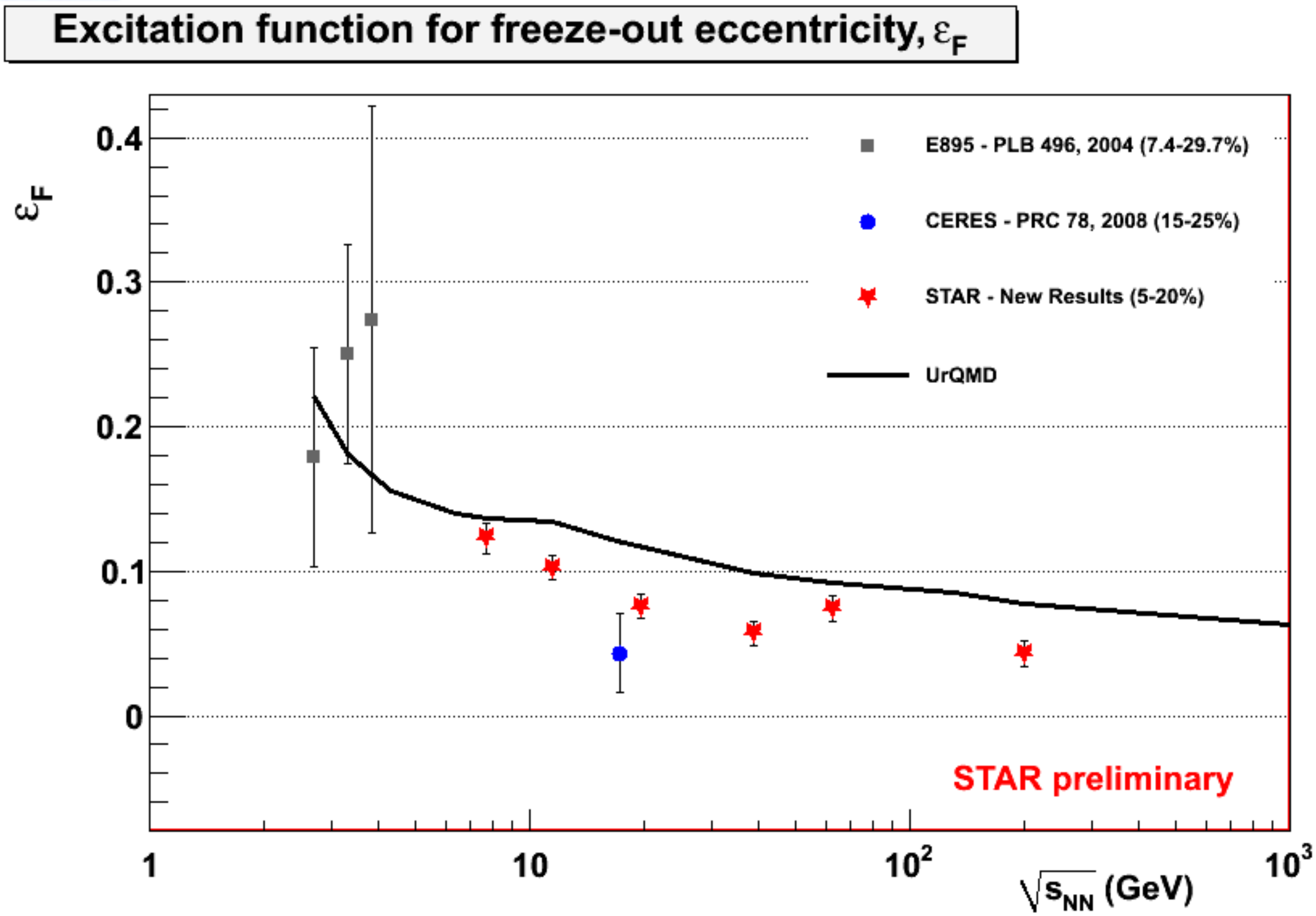
CERES
STAR



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UrQMD
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Fitting techniques

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

6 radii: $R_o^2, R_s^2, R_l^2, R_{os}^2, R_{sl}^2, R_{ol}^2$

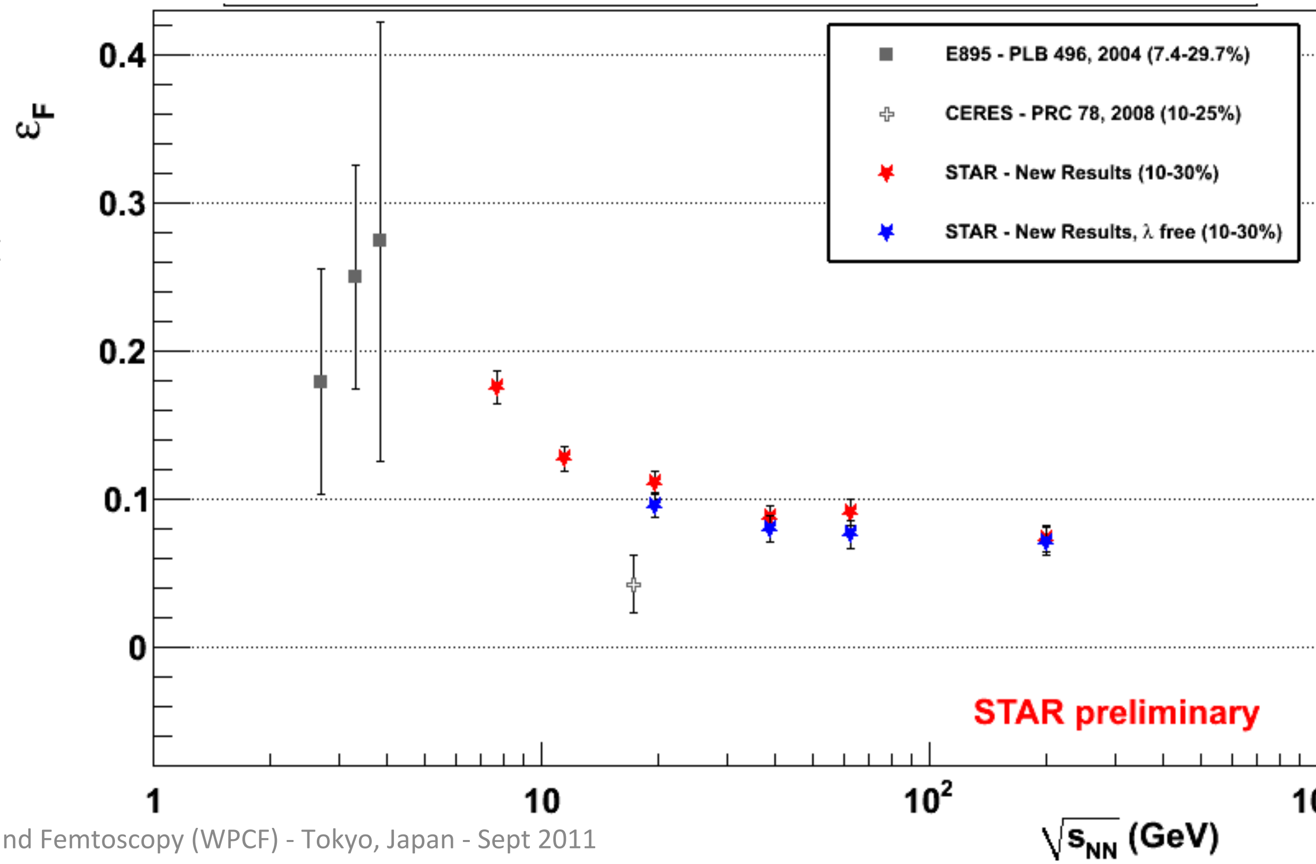
symmetry [Phys. Rev. **C66**, 044903 (2002)]: vanish at y=0

no 1st-order oscillations at any y, using 2nd-order RP

no symmetry rule against λ, oscillation, but keeping it fixed reduces #parameters

small effect

(maybe more than gut intuition?)



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at this point, the energies measured are too close to reasonably expect such a difference.

What else could it be?

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- different fitting parameters?
- different rapidity range? ← presently under investigation in data (models may help, too)

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New J. Phys. **13** 065006 (2011)

summary & outlook

- asHBT in HIC: probe for non-trivial structure on the QCD phase diagram
  - unique, valuable information, but nontrivial analysis...
  - models show significant sensitivity to important physics

- growing systematics of asHBT over the past decade
  - intriguing possible minimum in ε(√s) not supported by preliminary STAR BES
  - other than CERES point, slow gradual decrease of eccentricity with √s
  - any possible structure would be remarkably narrow
  - remarkable agreement with *pre*diction of UrQMD

- outlook
  - rapidity study in STAR in continuing attempt to understand CERES and develop systematic errors
  - next talk: PHENIX studies with π, K.   Also, 3^{rd}-order (!) studies
  - Adam: ongoing asHBT studies in ALICE