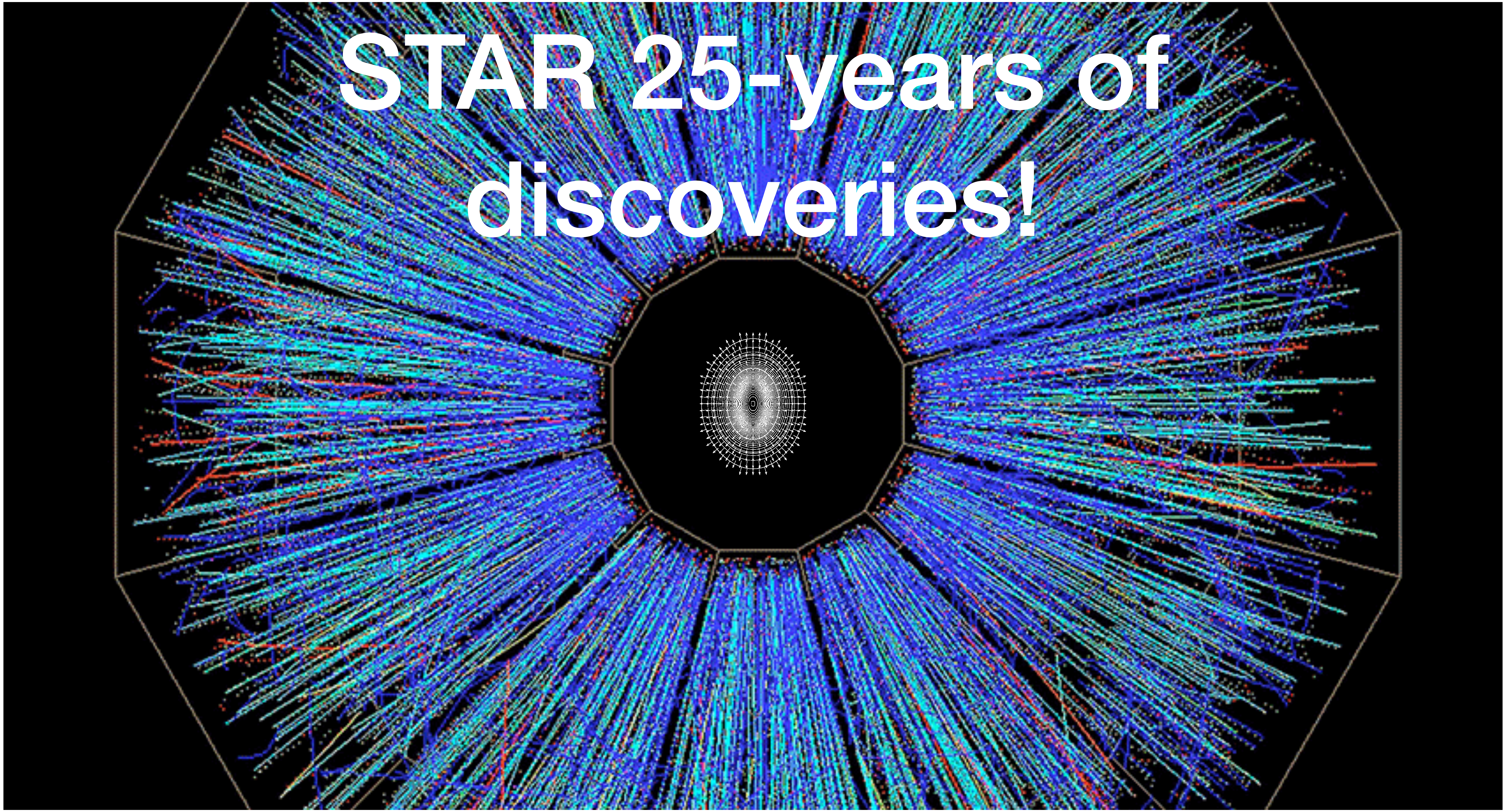
First Flow studies & discovery "Perfect Fluid"



Anisotropic transverse flow and the quark-hadron phase transition

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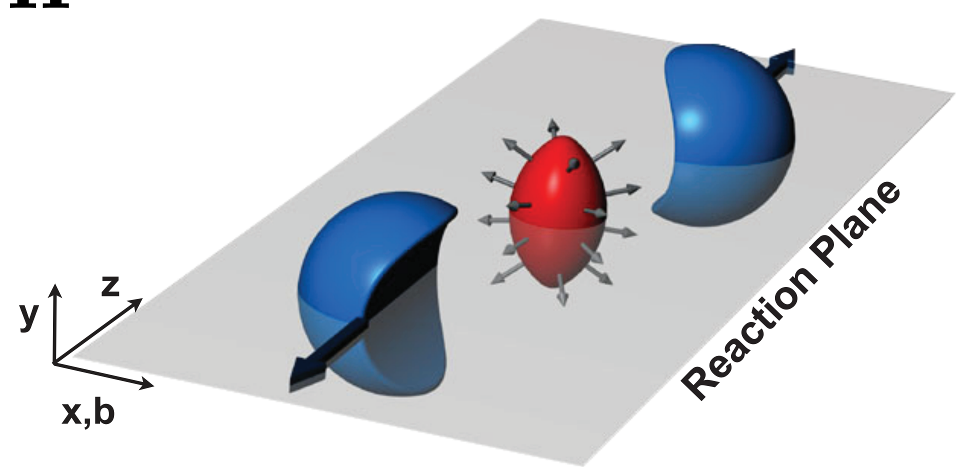
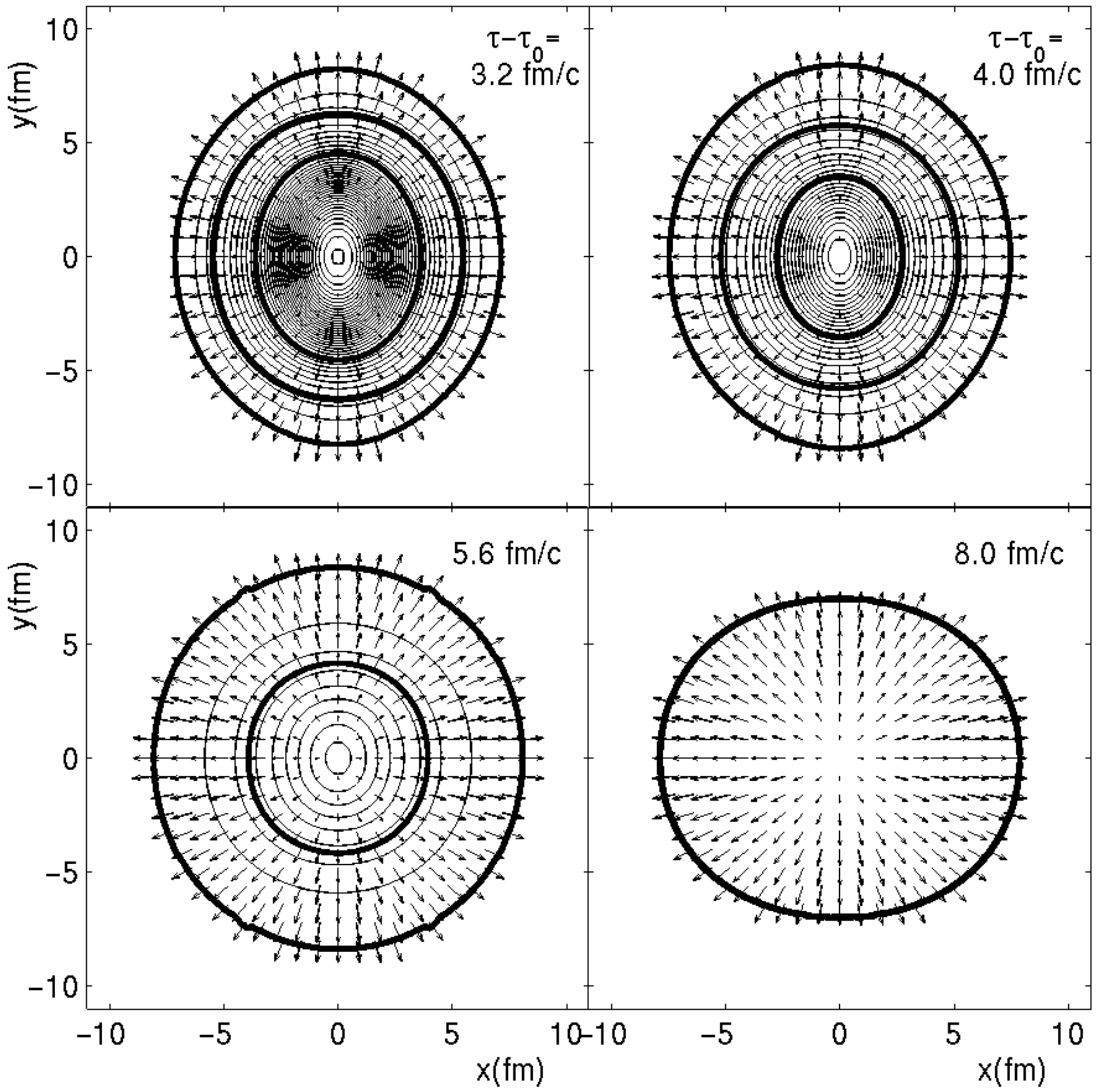
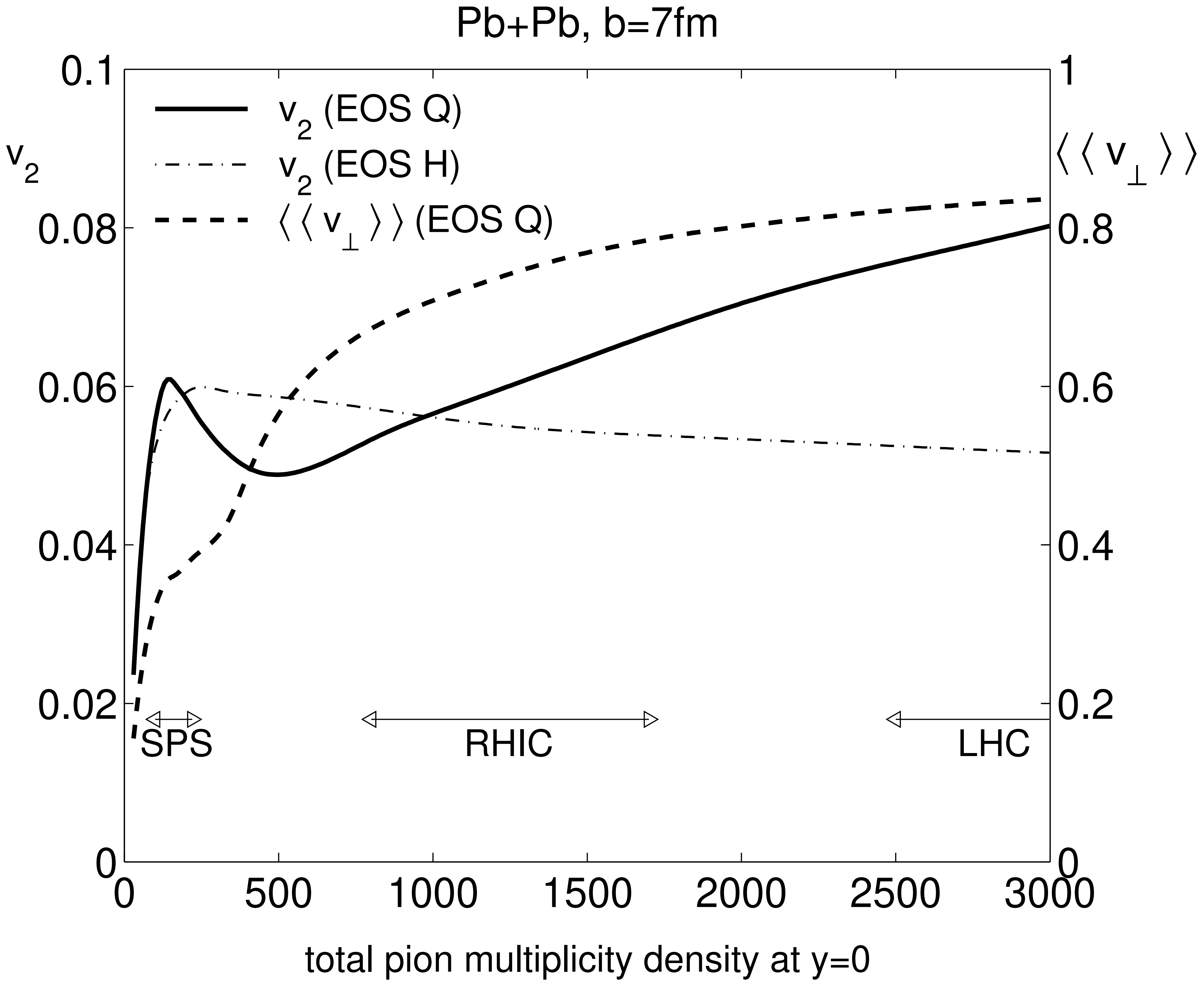
[a] *Theoretical Physics Division, CERN, CH-1211 Geneva 23, Switzerland*

[b] *Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany*



Picture: Howard Wieman





Phys.Rev.C 62 (2000) 054909 • e-Print: hep-ph/0006129 [hep-ph]

Day-1 physics at RHIC

RHIC Winter Workshop at LBNL 1998

RHIC — Flow

- **Radial:**
  - Will (continue to) be a very large effect
  - Essential component to understanding spectra at RHIC.
- **Directed:**
  - Already small at SPS
  - Almost irrelevant at RHIC
- **Elliptic:**
  - Zero for truly central events (at any energy)
  - Is it
    - A necessary evil for understanding events with non-zero impact parameter?

    Or

    - An essential tool to our understanding of EoS+(time evolution) of (non-isotropic) initial conditions?
  - My *prejudice:*
    Effects of elliptic flow will be small at RHIC

09-Jan-98 W.A. Zajc

RHIC — Time to Physics

Again, learn from the past:

First CDF publication:

Transverse-Momentum Distributions of Charged Particles Produced in p-pbar Interactions at 630 and 1800 GeV, F. Abe et al., Phys. Rev. Lett. 61, 1819 (1988).

- ~One year from data-taking.
- Much simpler final state!

➨ *We will be hard-pressed to reach this goal*

➨ *And much harder-pressed to maintain "CDF-like" rate*

VOLUME 61, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1988

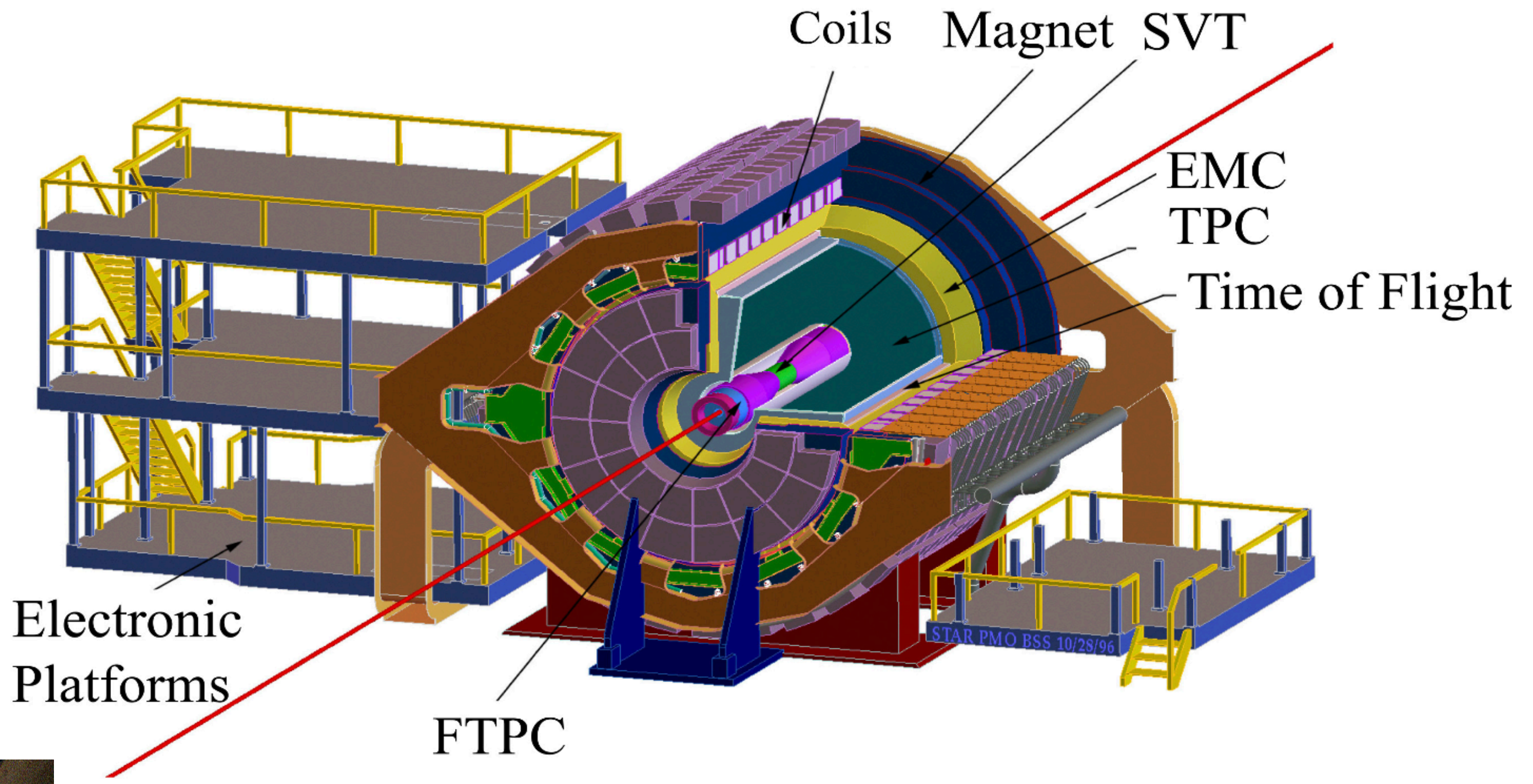
Transverse-Momentum Distributions of Charged Particles Produced in $\bar{p}p$ Interactions at $\sqrt{s}$ = 630 and 1800 GeV

1819

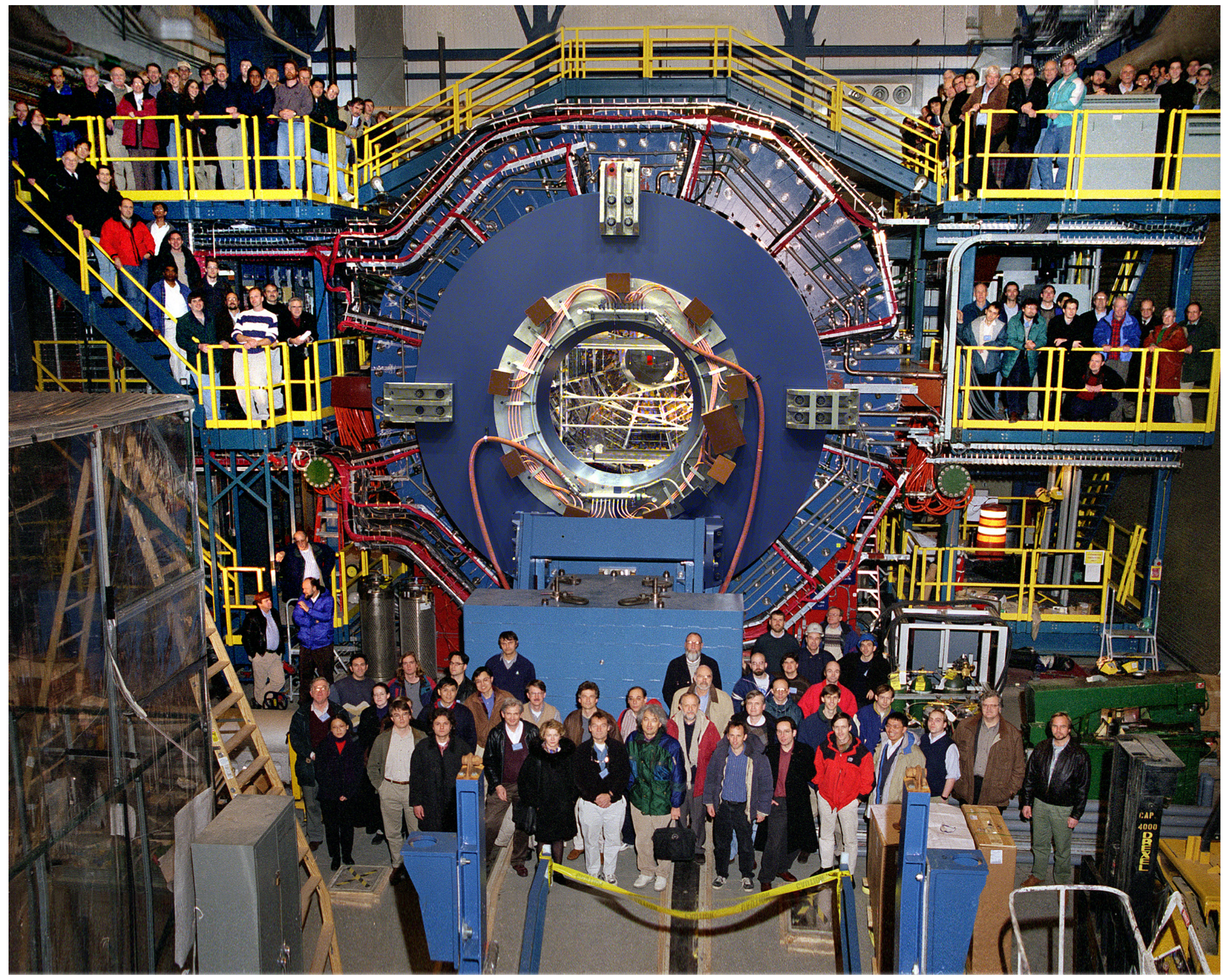
09-Jan-98 W.A. Zajc

May the force be with you (1998-1999)

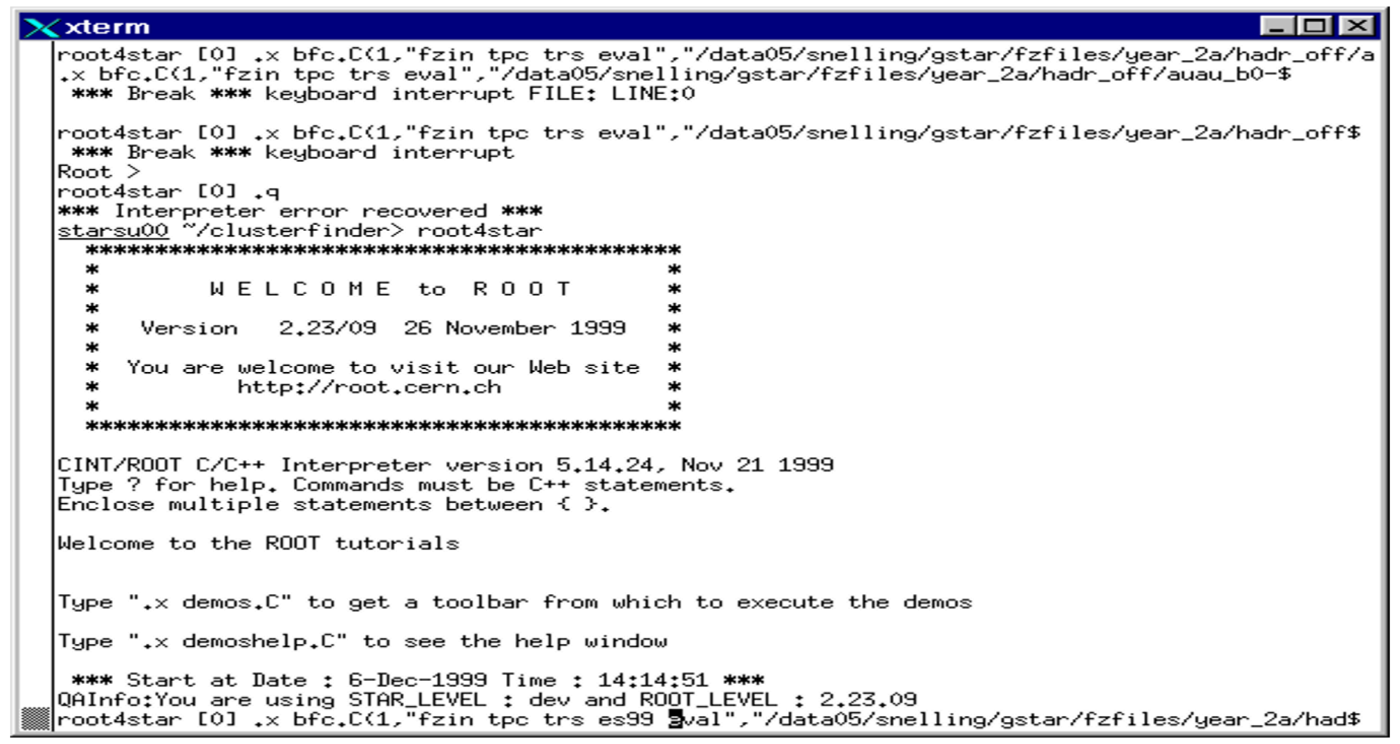
STAR TPC Cluster and Hit Finder Software



Raimond Snellings

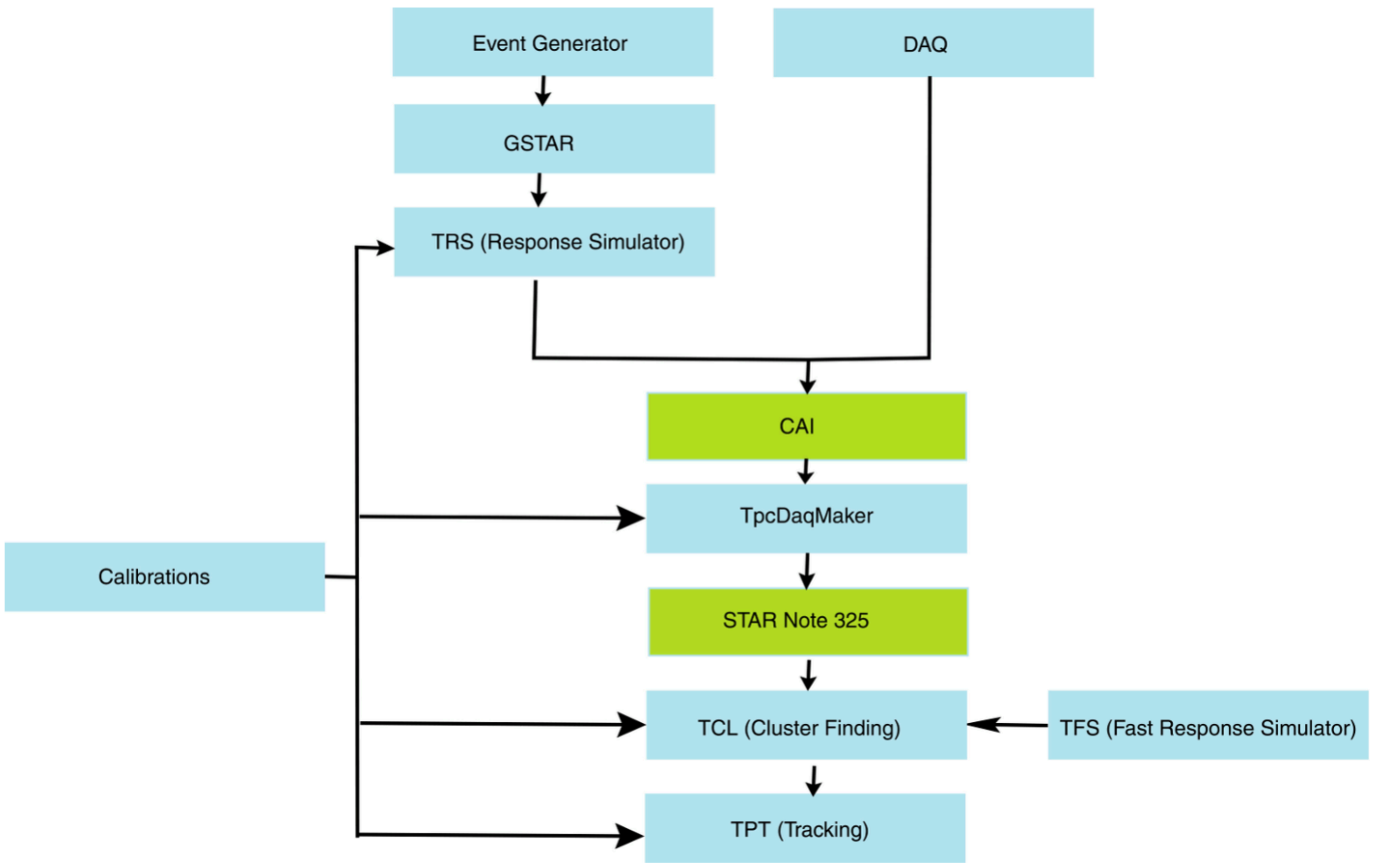


Running BFC



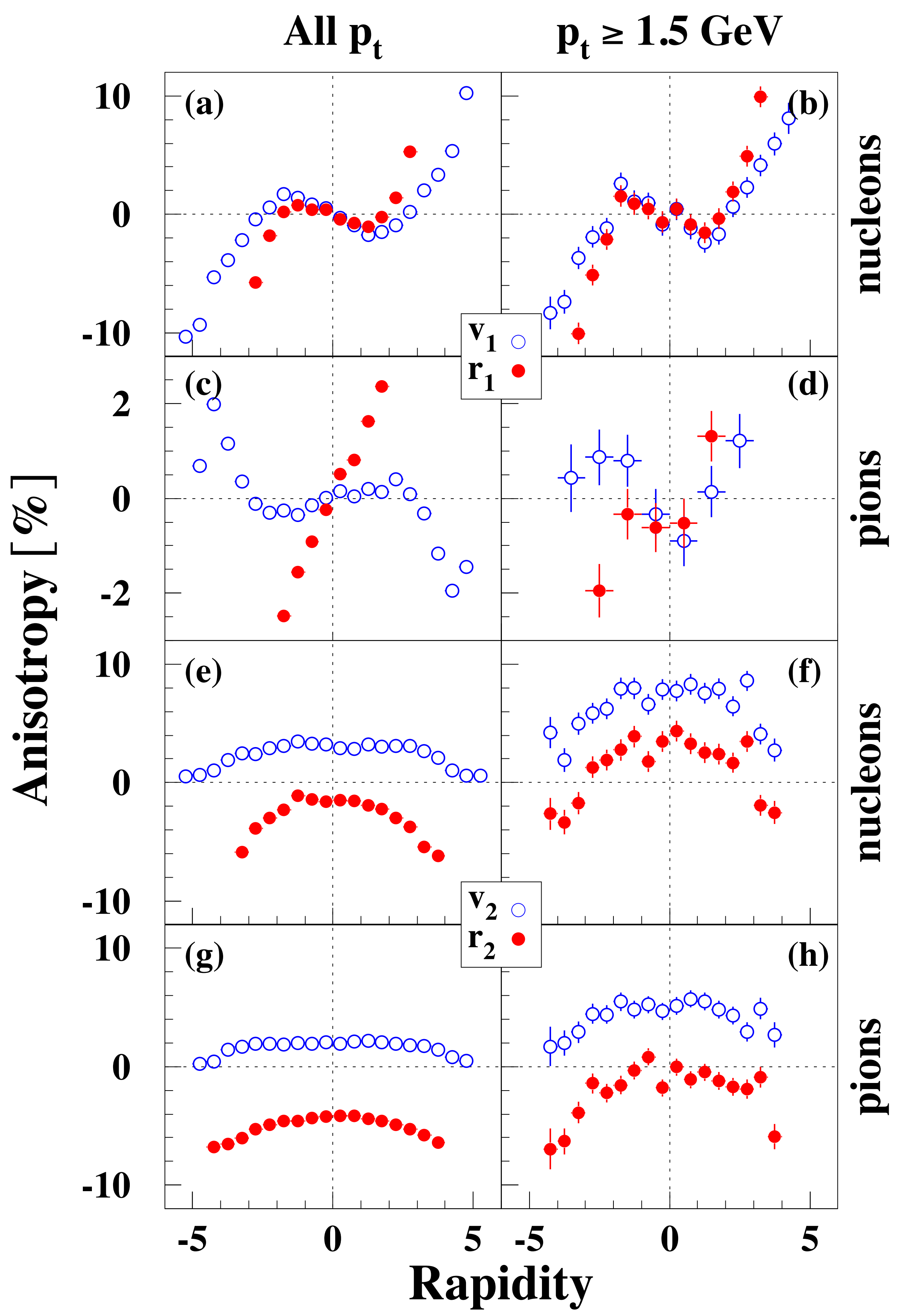
```
xterm
root4star [0] .x bfc.C(1,"fzin tpc trs eval","/data05/snelling/gstar/fzfiles/year_2a/hadr_off/a
.x bfc.C(1,"fzin tpc trs eval","/data05/snelling/gstar/fzfiles/year_2a/hadr_off/auau_b0-$
 *** Break *** keyboard interrupt FILE: LINE:0

root4star [0] .x bfc.C(1,"fzin tpc trs eval","/data05/snelling/gstar/fzfiles/year_2a/hadr_off$
 *** Break *** keyboard interrupt
Root >
root4star [0] .q
*** Interpreter error recovered ***
starsu00 ~/clusterfinder> root4star
  ****************************************
  *                                      *
  *        W E L C O M E  to  R O O T    *
  *                                      *
  *   Version   2.23/09  26 November 1999 *
  *                                      *
  *  You are welcome to visit our Web site *
  *          http://root.cern.ch         *
  *                                      *
  ****************************************

CINT/ROOT C/C++ Interpreter version 5.14.24, Nov 21 1999
Type ? for help. Commands must be C++ statements.
Enclose multiple statements between { }.

Welcome to the ROOT tutorials


Type ".x demos.C" to get a toolbar from which to execute the demos

Type ".x demoshelp.C" to see the help window

 *** Start at Date : 6-Dec-1999 Time : 14:14:51 ***
QAInfo:You are using STAR_LEVEL : dev and ROOT_LEVEL : 2.23.09
root4star [0] .x bfc.C(1,"fzin tpc trs es99 eval","/data05/snelling/gstar/fzfiles/year_2a/had$
```

Data Flow

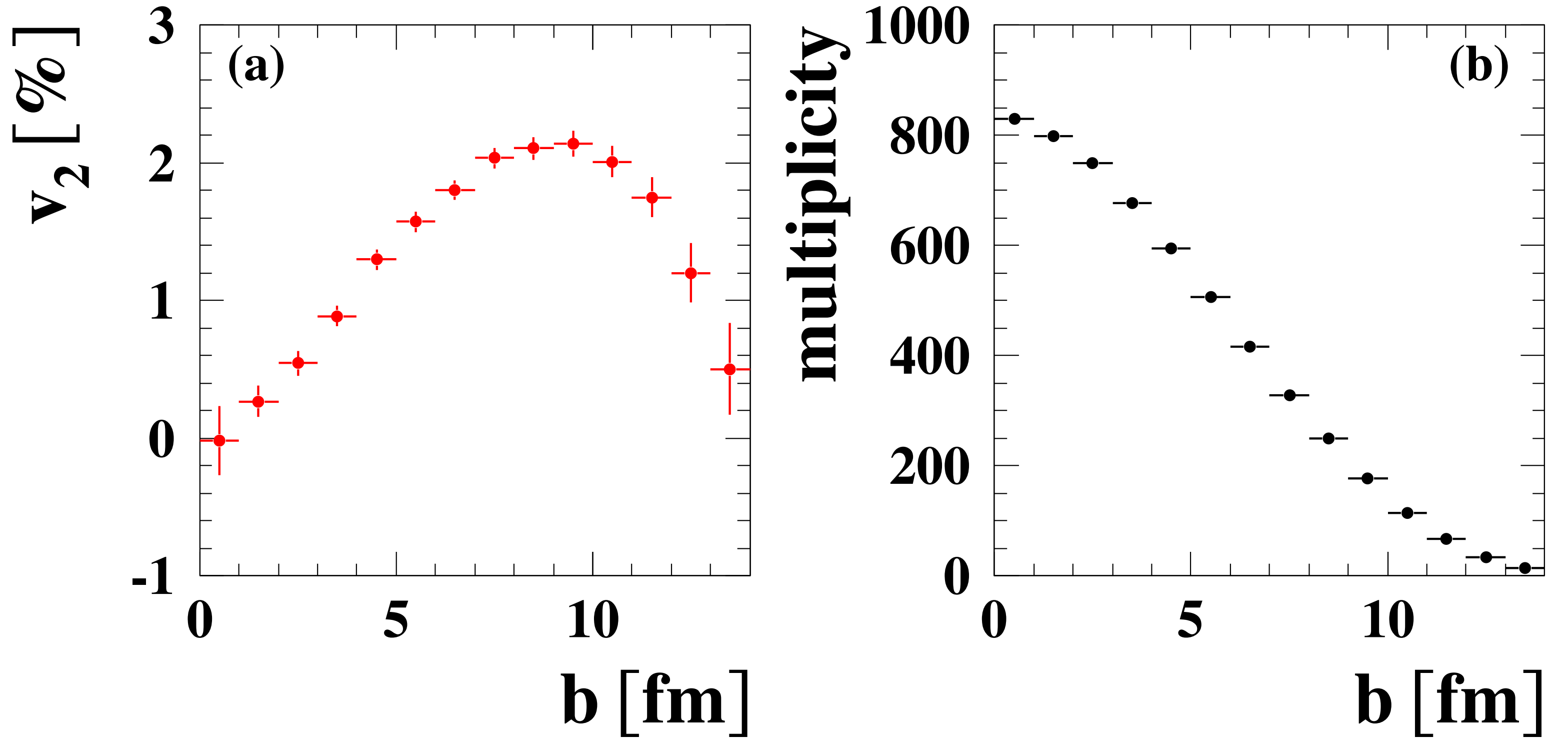


Anisotropic Flow (pre-RHIC)

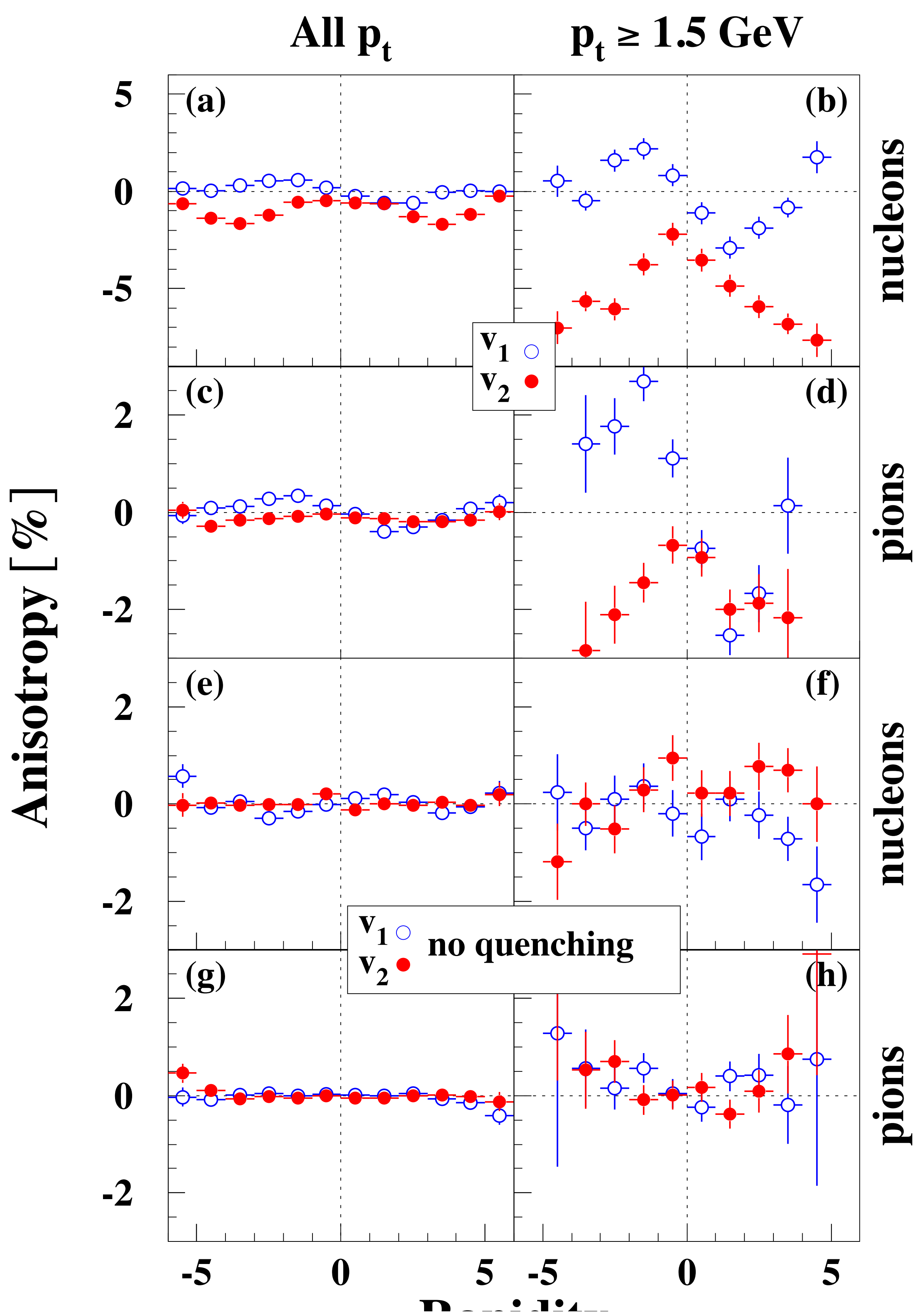
RQMD



RQMD



HIJING

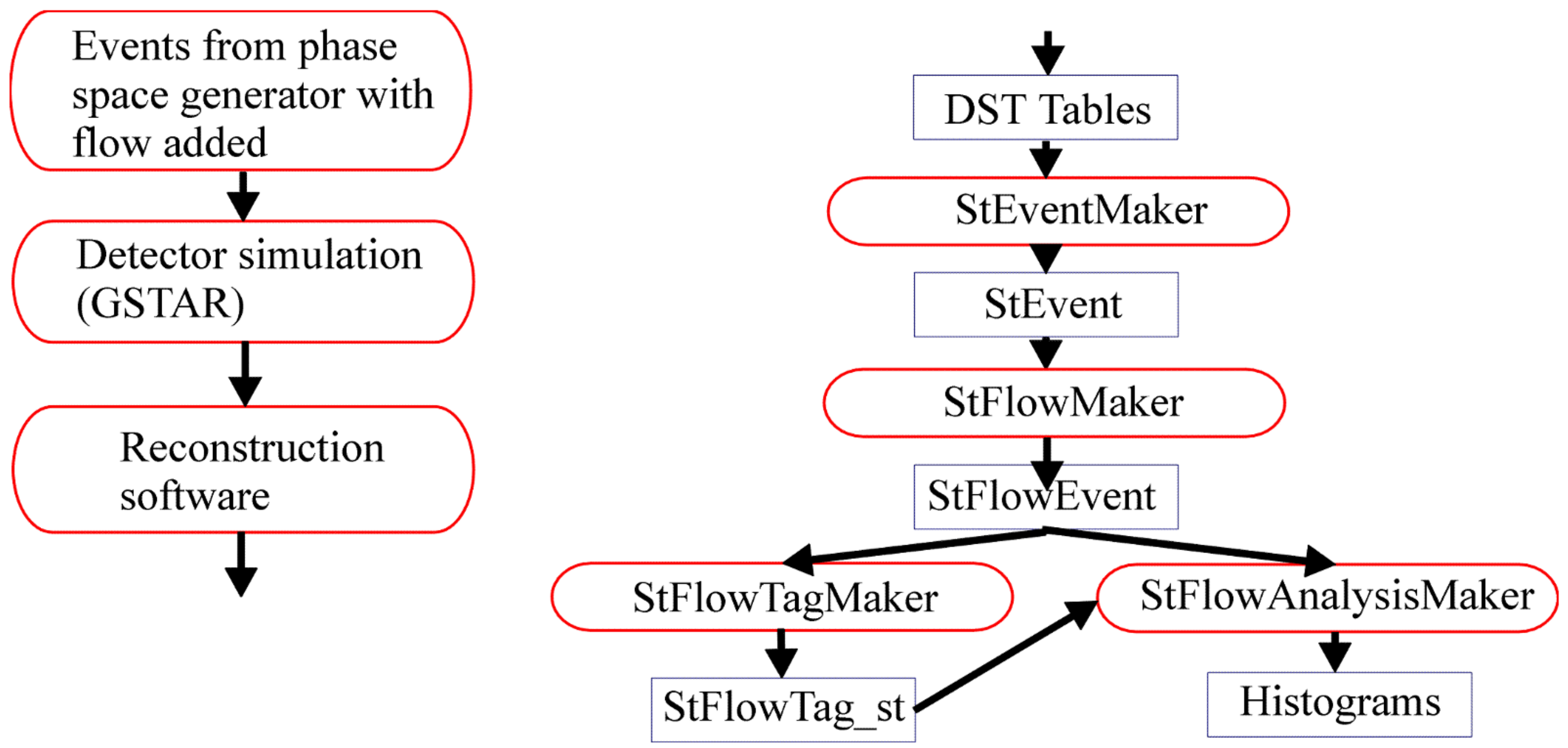


we only need the momenta of the charged hadrons and thus anisotropic flow could be one of the first results from STAR. For future analyses it would be good to have particle identification.

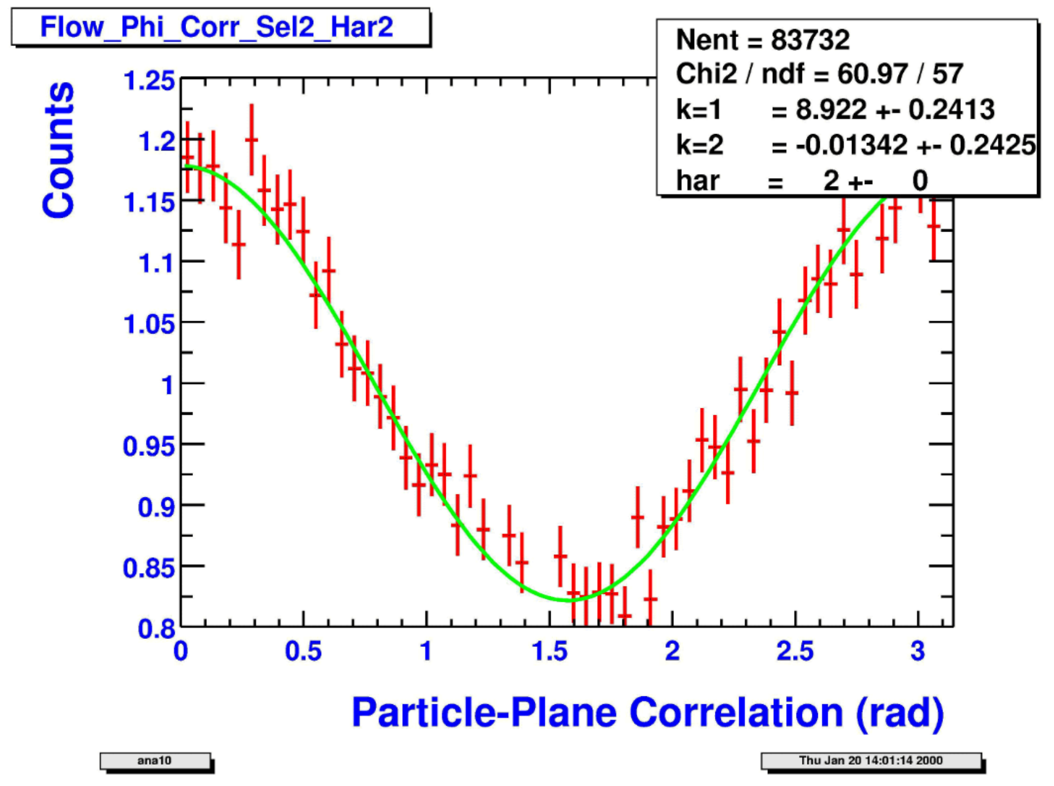
We realized that the v_2 is sensitive to jet quenching, which is of course no surprise as energy loss is expected to depend on path lenght but we had not thought of it before

R.J.M.Snellings, A.M. Poskanzer and S.A. Voloshin (STAR Note SN388) nucl-ex/9904003

Anisotropic flow software



Phi angle pions with respect to the reaction plane



60 events

1 minute of data taking

Flow values and multiplicity a bit overly optimistic

Put in 10%
expect 8.9%
found 8.9%

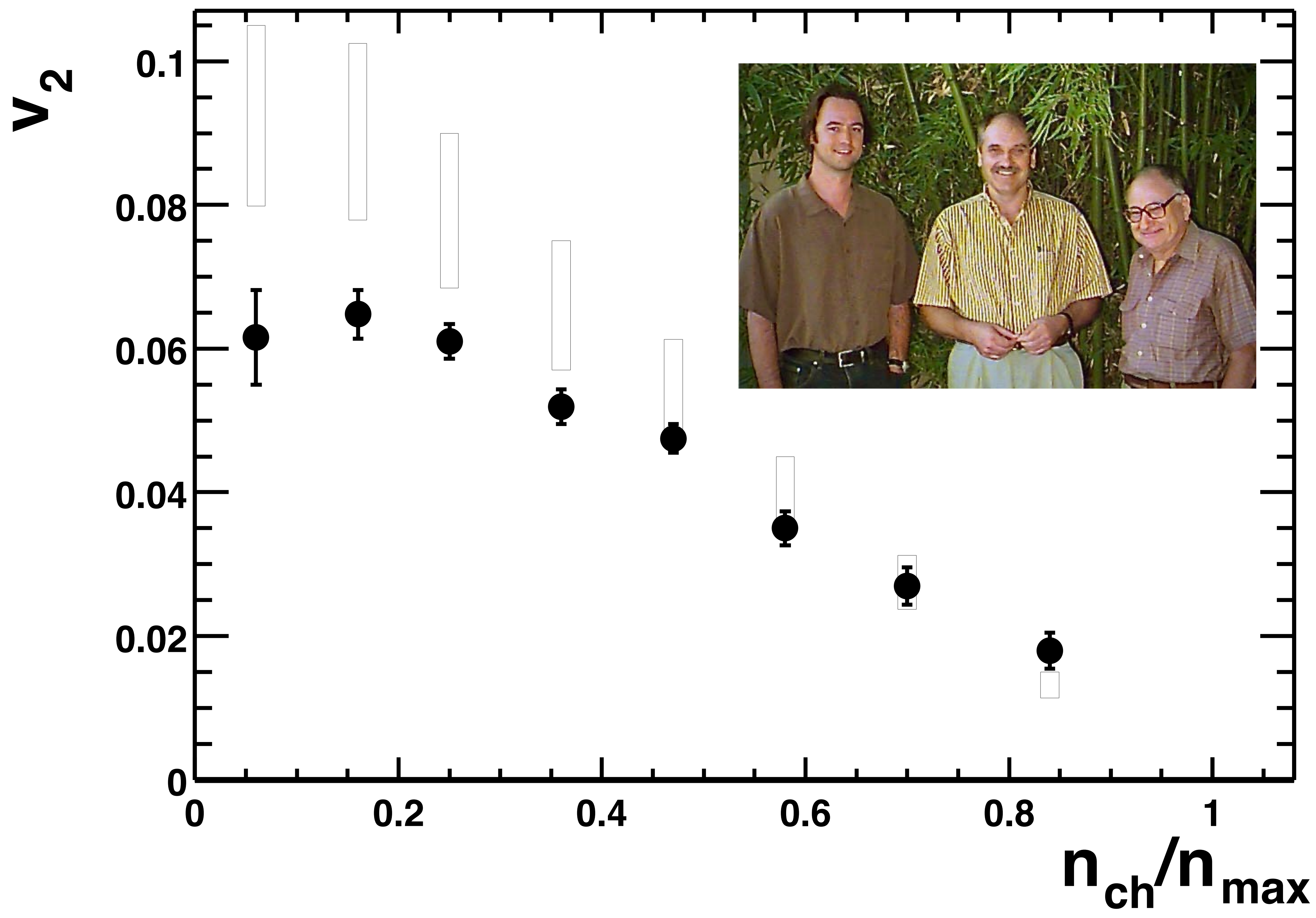
Raimond Snellings

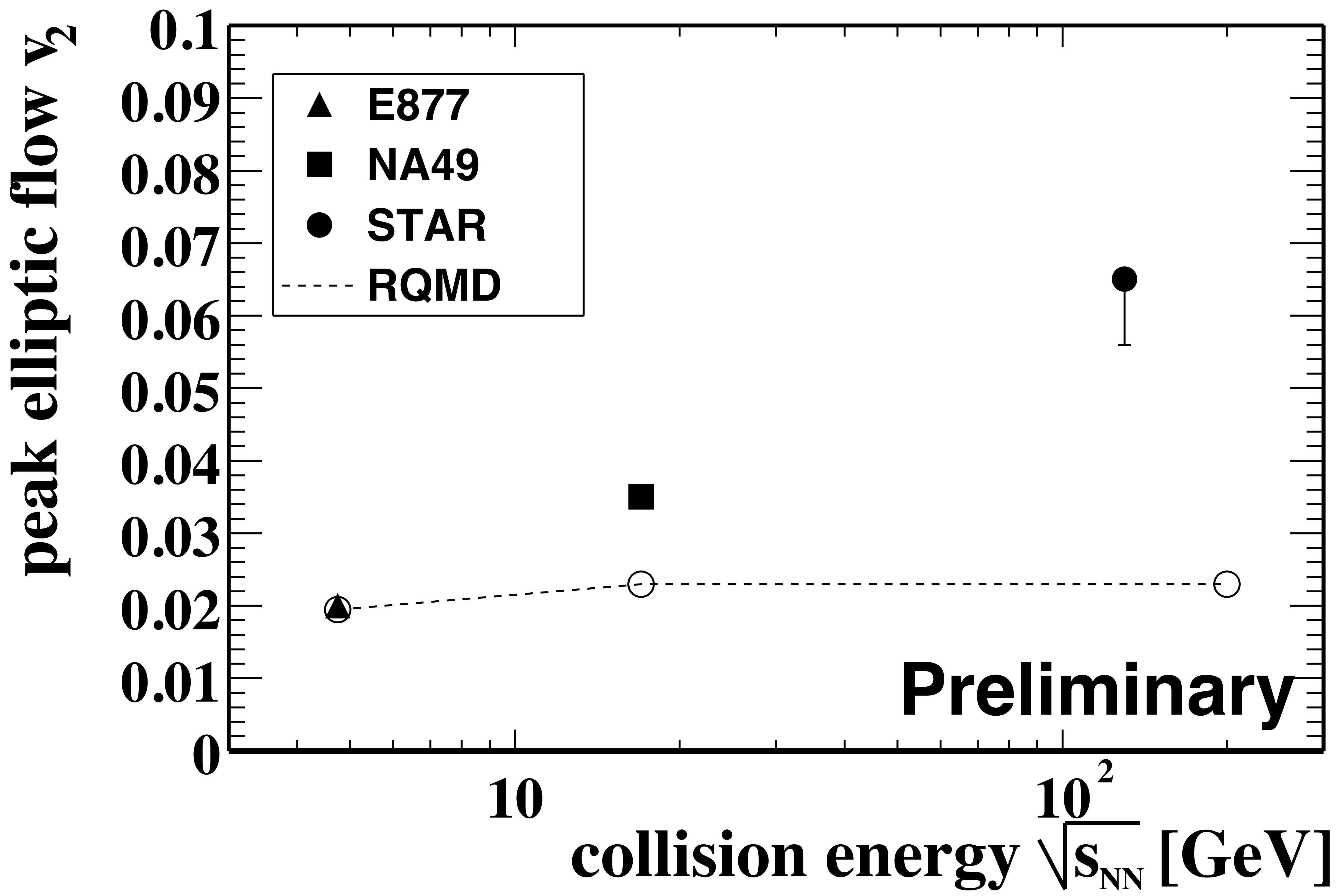
Summary

- RHIC will provide beam-beam collisions real soon (mid-April)
- STAR detector (TPC) is in good shape (engineering run shown by Iwona)
- Anisotropic flow measurements will tell us what kind of matter is produced
- STAR software i.e. reconstruction software (led by Iwona Sakrejda), infrastructure (BNL) and anisotropic flow analysis software (Art Poskanzer and myself) is ready for physics analysis

Raimond Snellings

First STAR paper (2001)





in good agreement for mid-central collisions with “hydro”

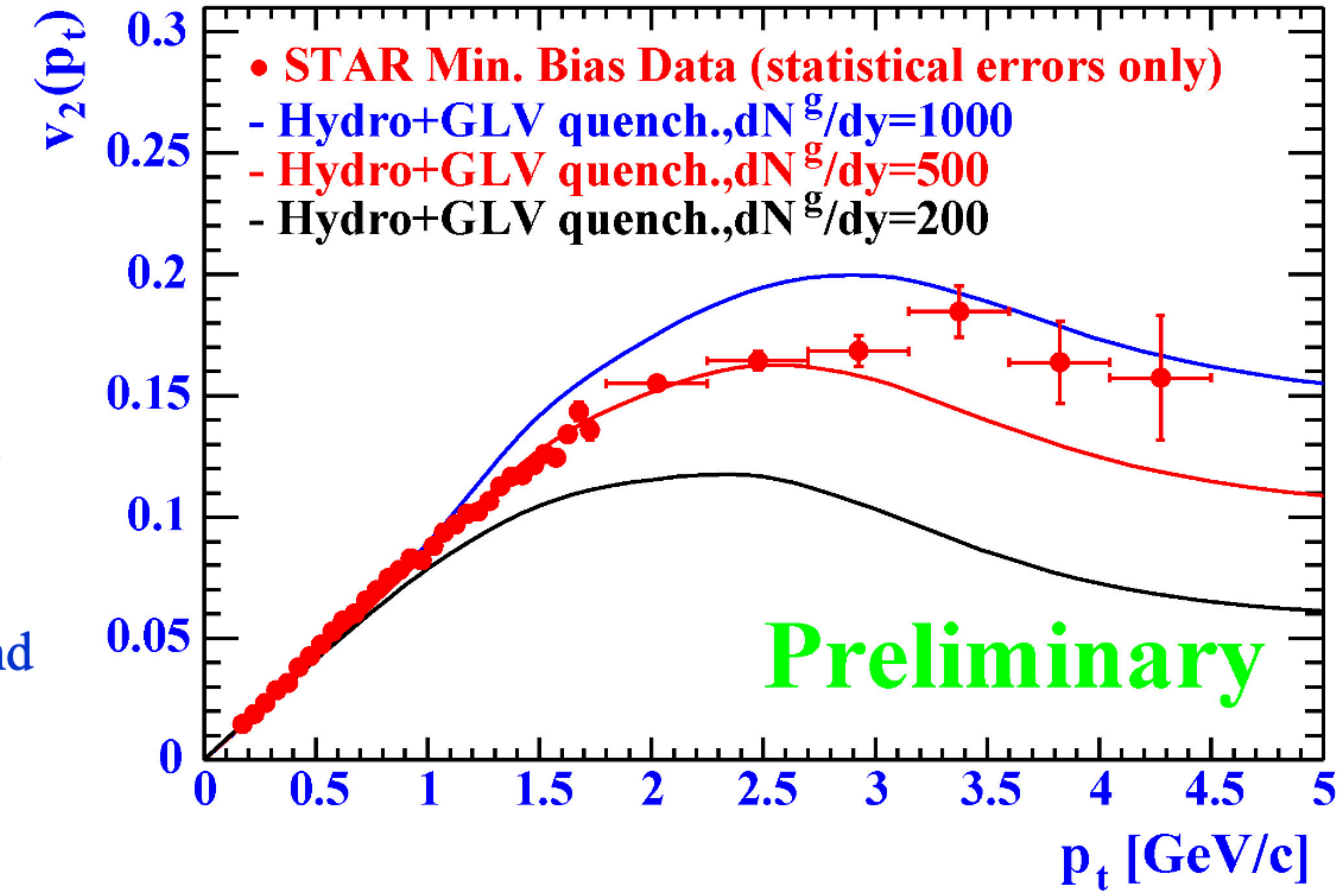
big increase measured compared to predictions hadron cascade model(s)

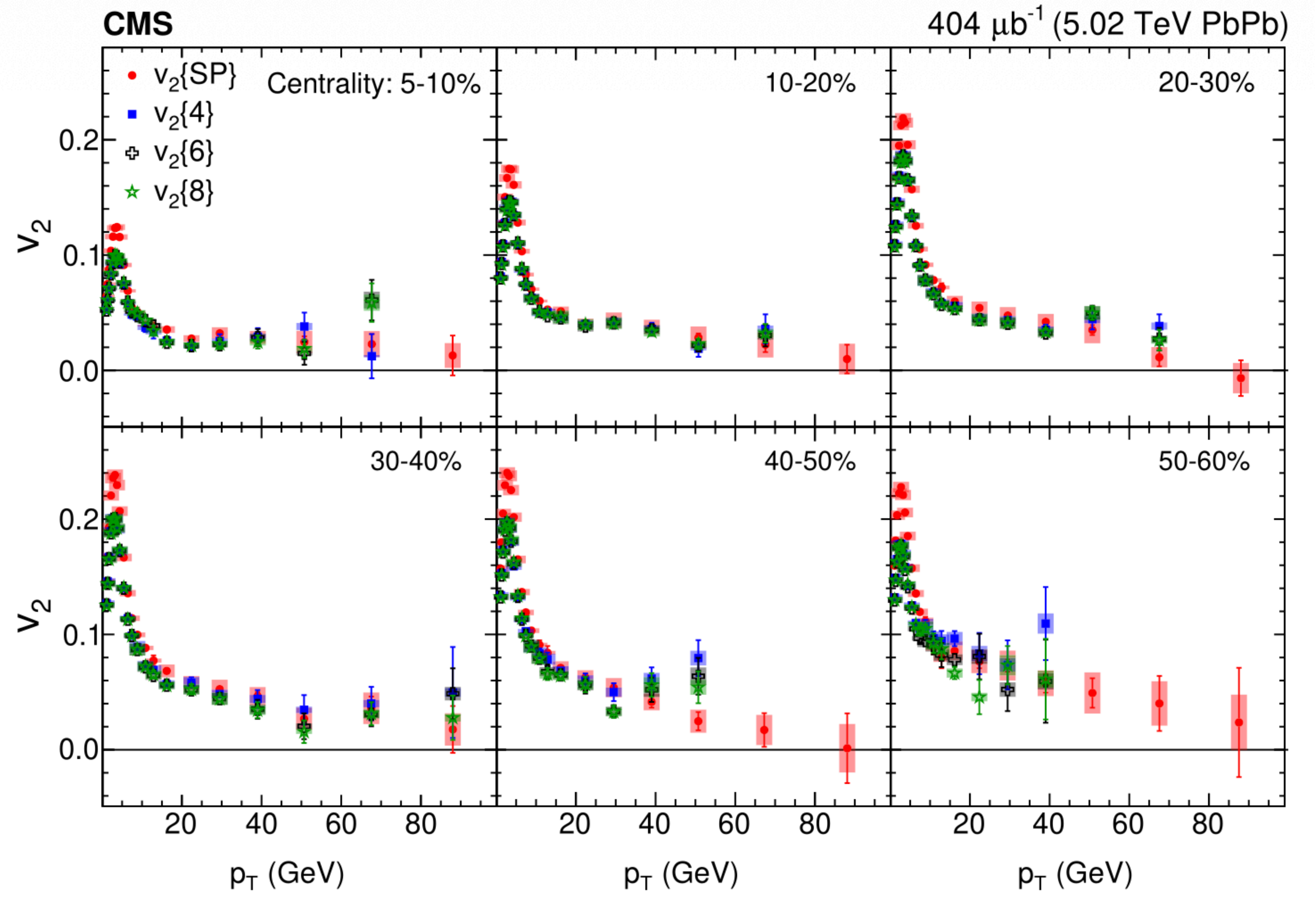
STAR Collaboration: Phys.Rev.Lett. 86 (2001) 402-407

Charged particle anisotropy
$0 < p_t < 4.5$ GeV/c

STAR

- STAR data: only statistical errors plotted. Systematic error 10% - 20% for $p_t = 2 - 4.5$ GeV/c
- Hydro+GLV: M. Gyulassy, I. Vitev and X.N. Wang, nucl-th/00012092



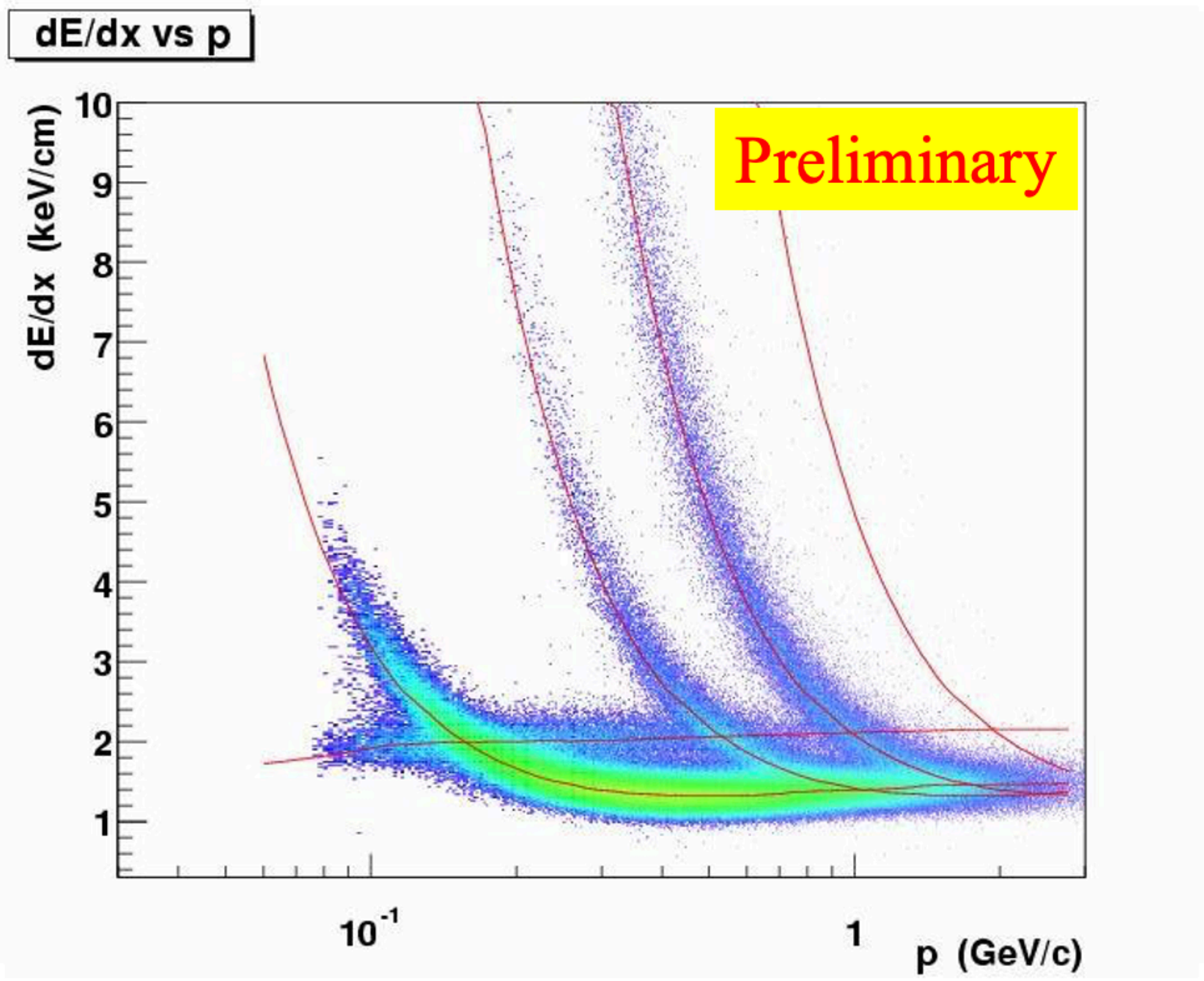


1/17/2001 Raimond Snellings, Quark Matter 2001 24

STAR (2001)

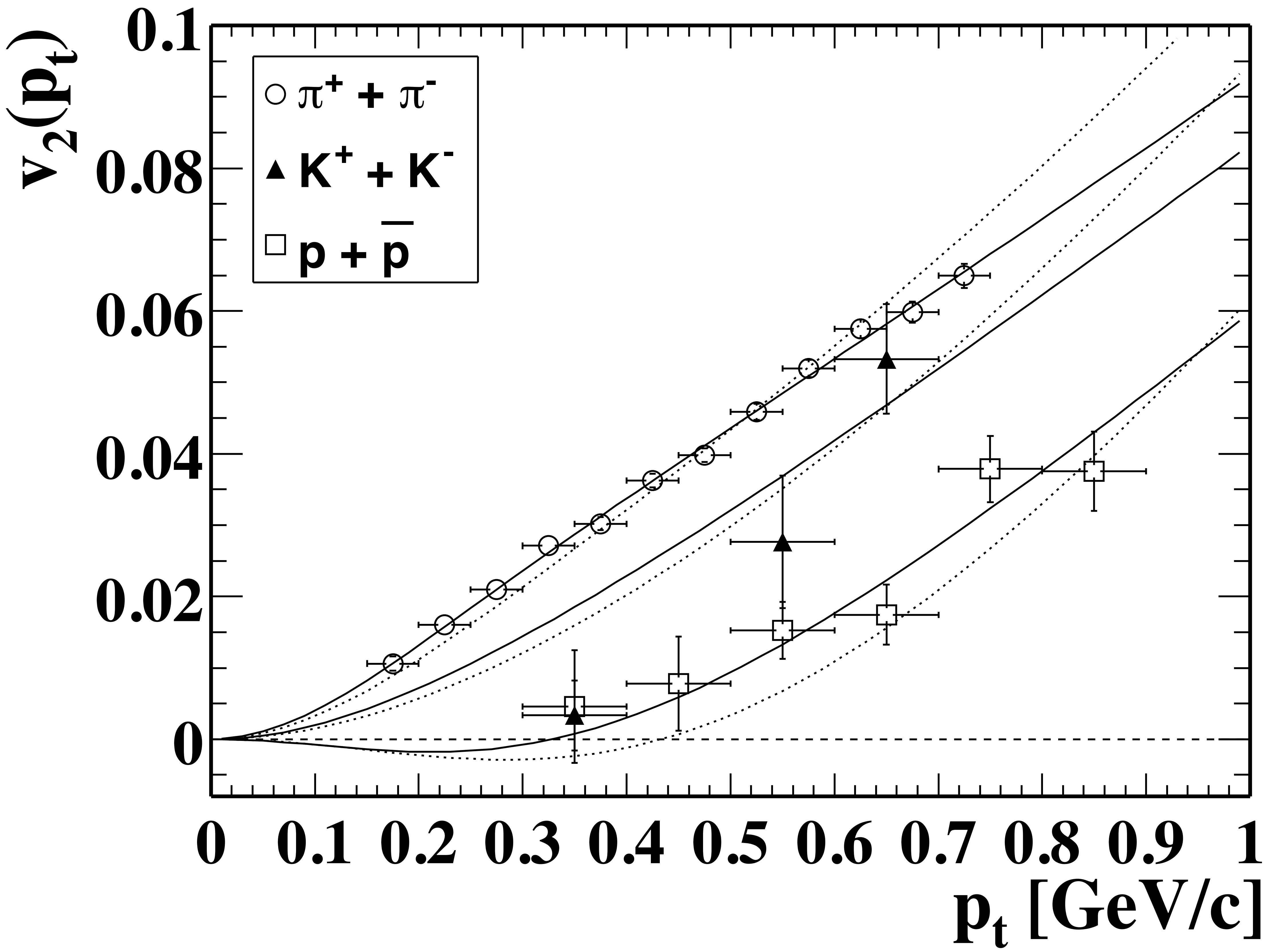
Particle Identification via dE/dx in TPC - June 2000

Excellent dE/dx resolution
approaching expected 8%



R. Snellings

STAR

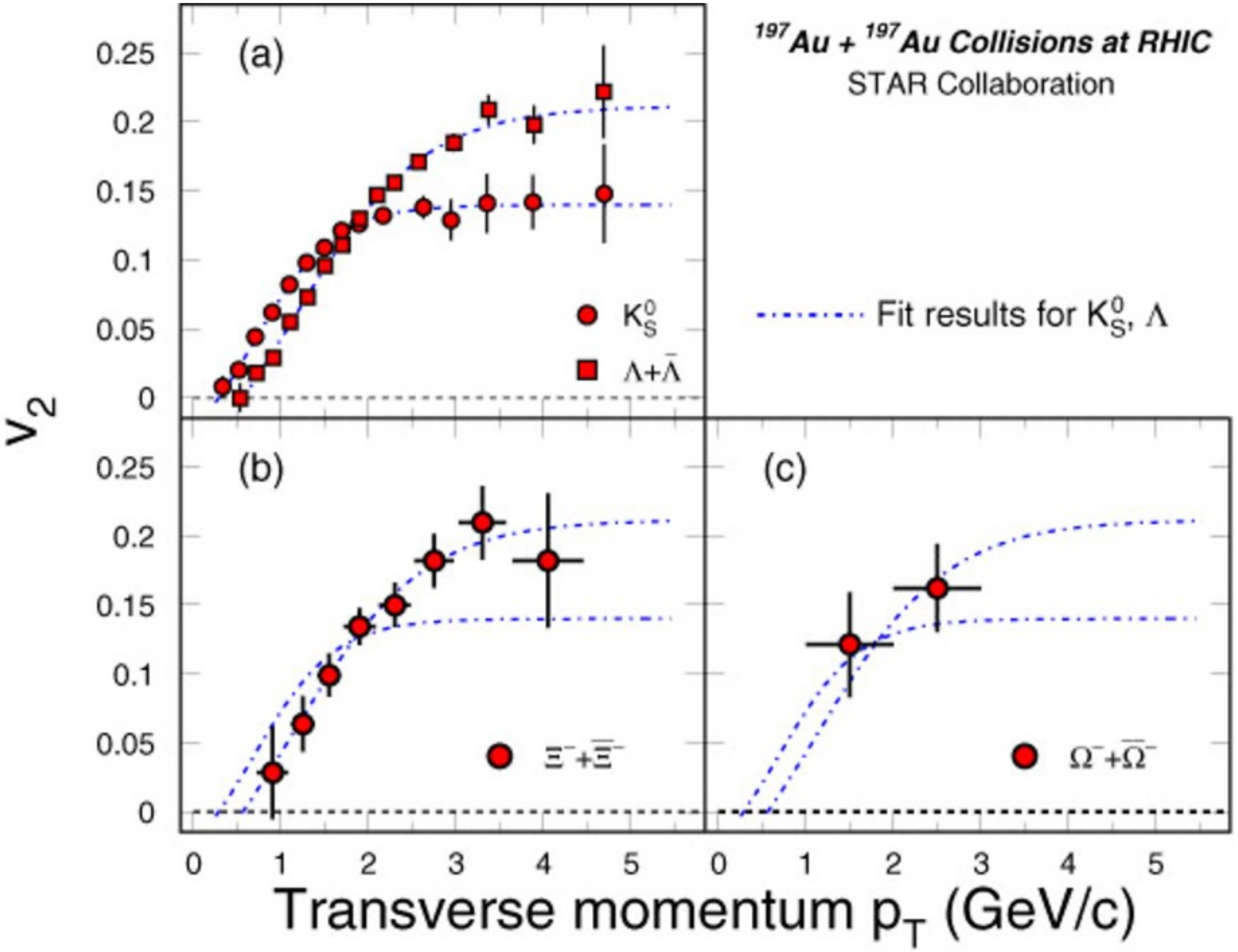


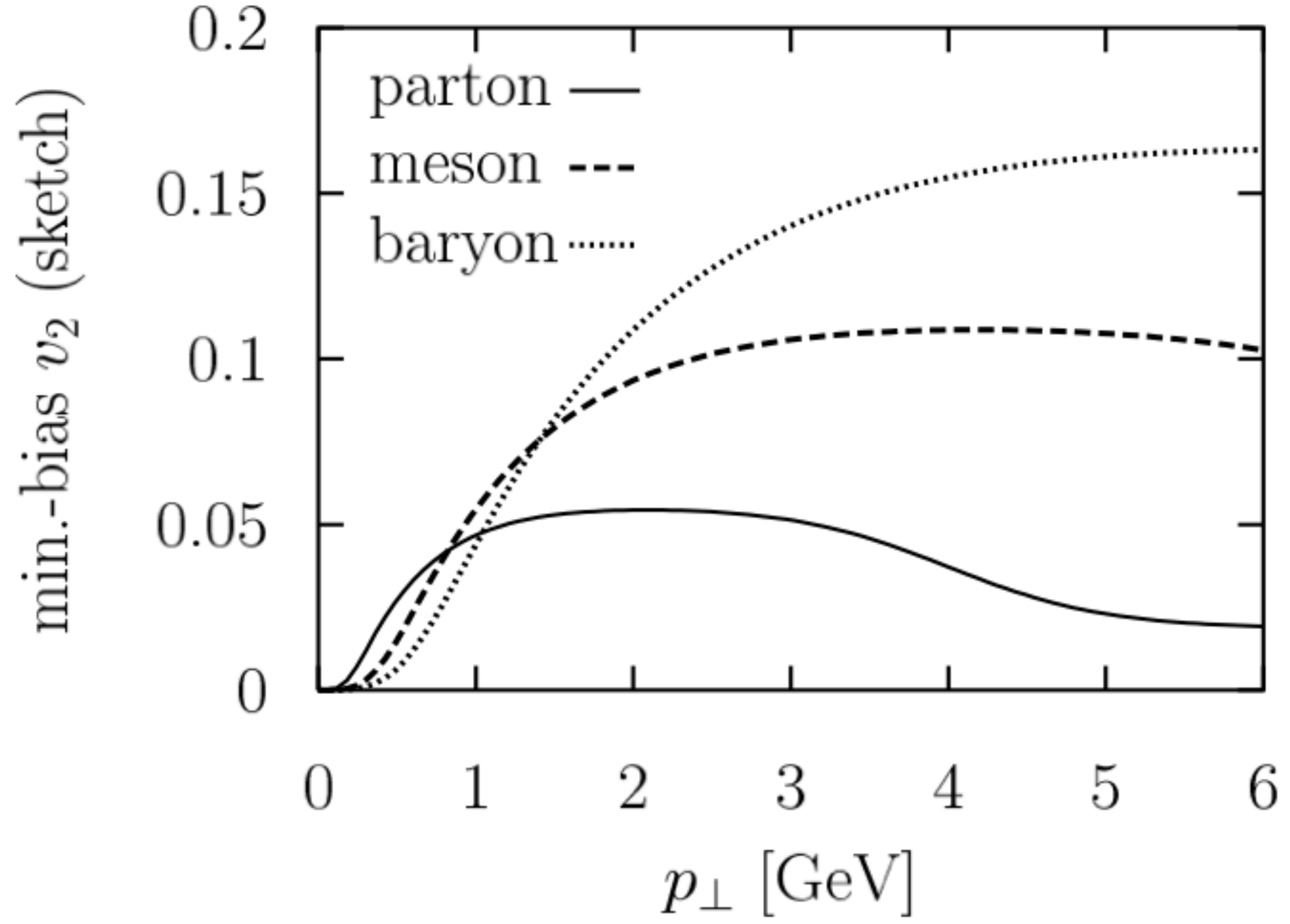
Behaves like a system with common temperature and flow boost

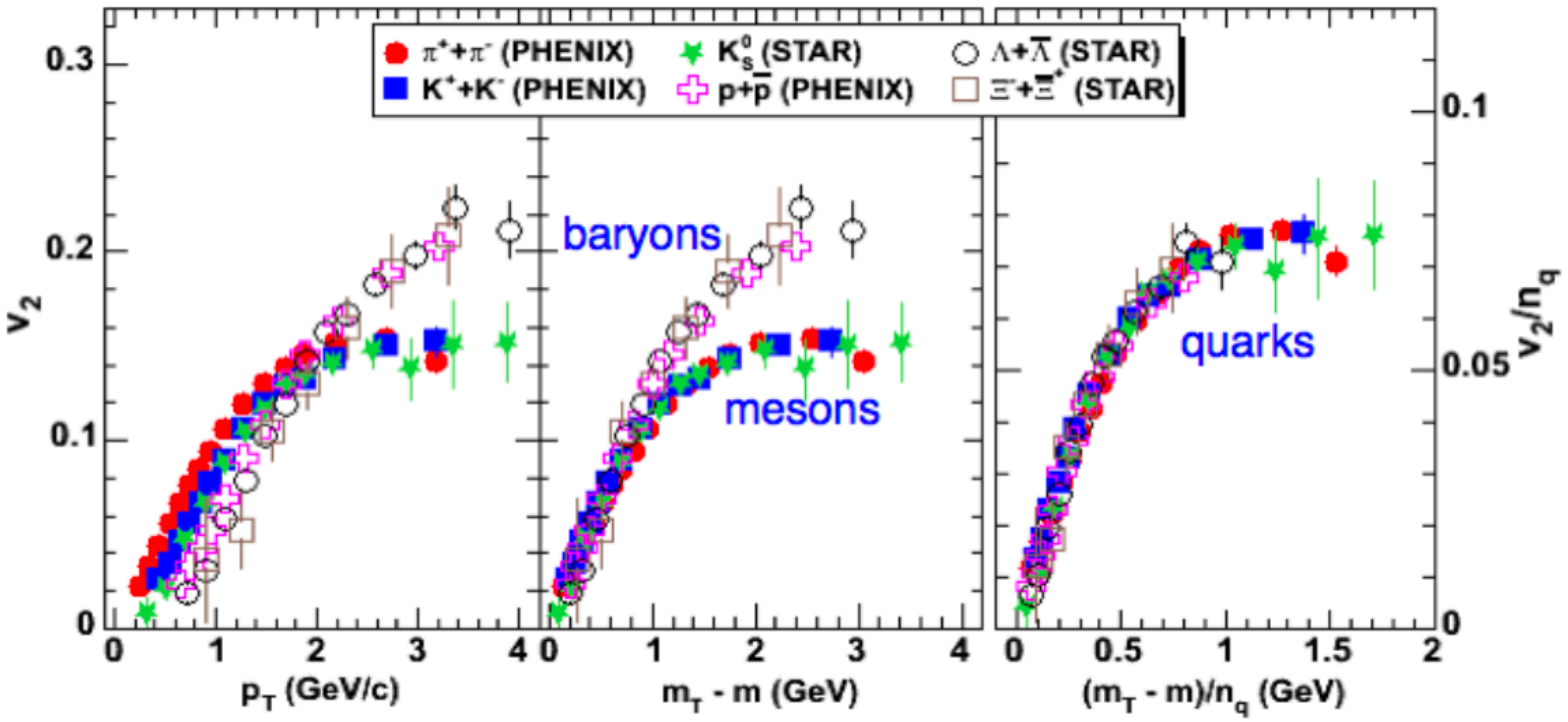
Quark Matter Nantes (2002)

Elliptic flow at large transverse momenta from quark coalescence

Dénes Molnár[1] and Sergei A. Voloshin[2]
[1] *Department of Physics, Ohio State University, 174 West 18th Ave, Columbus, OH 43210*
[2] *Department of Physics and Astronomy, Wayne State University, 666 W. Hancock, Detroit, MI 48201*
(Dated: November 26, 2024)







STAR Collaboration: *Phys.Rev.Lett.* 92 (2004) 052302 • e-Print: nucl-ex/0306007

STAR Whitepaper Preparations (2004)

Discovery of the suppression phenomena at RHIC

- The observed strong suppression can be described efficiently by parton energy loss in matter starting with large energy and gluon densities
- Does the magnitude of parton energy loss inferred from these observations ***demand*** an explanation in terms of traversal through deconfined matter?
  - What are the uncertainties due to factorization in-medium, in-medium fragmentation versus vacuum fragmentation?
  - How are possible uncertainties amplified due to the longitudinal (and also transverse) expansion of the system?
- Can we ***prove*** from the inferred densities that deconfined matter has been created?

NSAC Subcommittee on Heavy-Ion Physics 24

Identified particles at intermediate to high-p_t

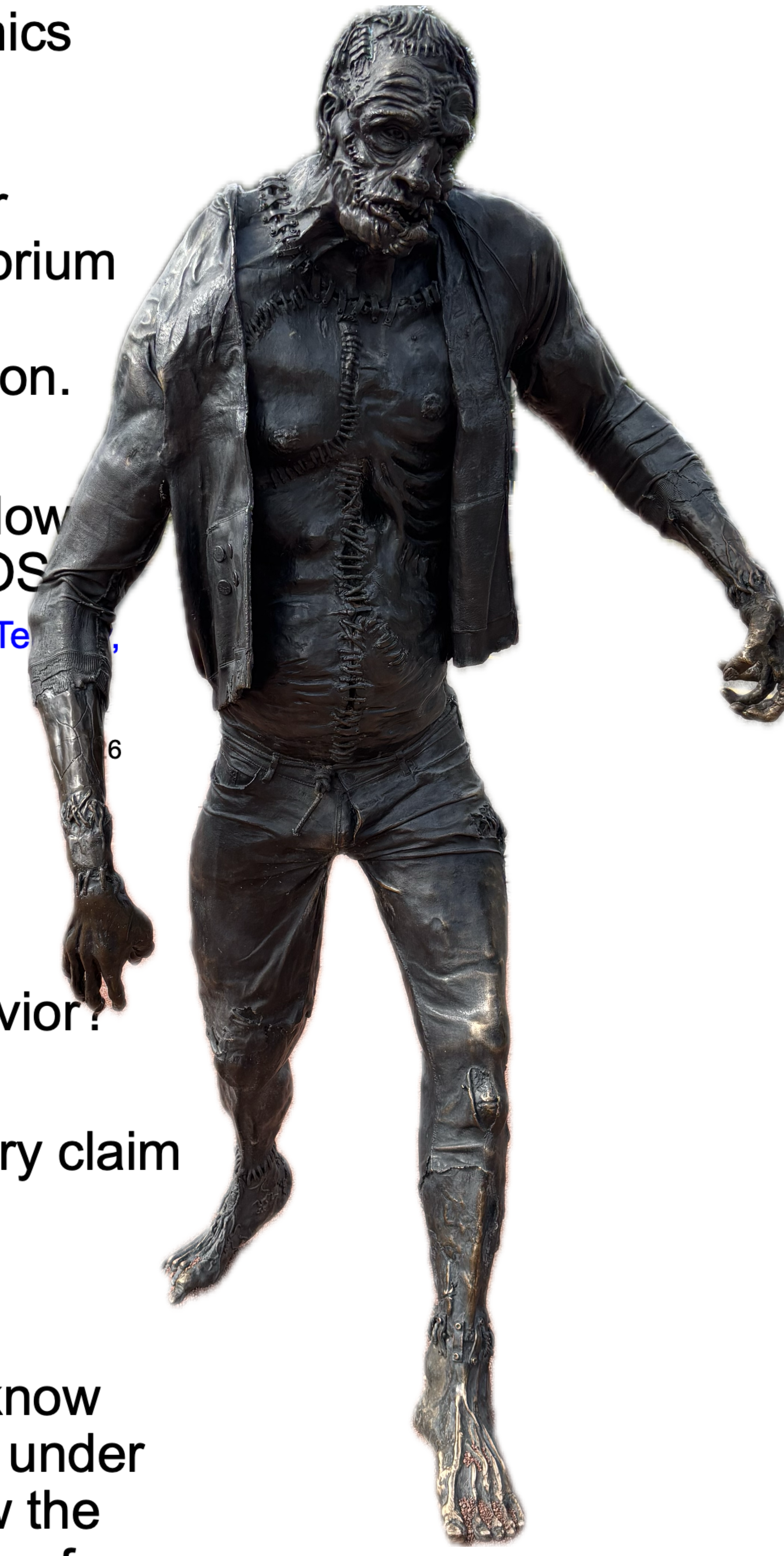
- Baryons and mesons scaling is suggestive of importance of constituent quark degree of freedom in hadronization and suggestive of collective flow at the constituent quark level
- This scaling is compactly described in a coalescence/recombination model
- Aside from providing an organizing principle, what predictive power do these models have? Can they predict the correct centrality-dependence of these ratios, or meson vs. baryon correlations (angular or otherwise) at moderate p_t? Does it also still work when applied on models with a more complete space-time evolution?

NSAC Subcommittee on Heavy-Ion Physics 25

Is the system in approximate local thermal equilibrium?

- The unprecedented success of hydrodynamics calculations assuming ideal relativistic fluid behavior in accounting for RHIC elliptic flow results has been interpreted as evidence for both early attainment of local thermal equilibrium and softening of the equation of state, characteristic of the predicted phase transition.
- How do we know that the observed elliptic flow can not result alternatively from a harder EOS coupled with incomplete thermalization? (D. Te
J. Lauret, E.V. Shuryak; Phys. Rev. Lett 86, 4783 (2001))

NSAC Subcommittee on Heavy-Ion Physics 6



HBT, spectra and v_2; the soft sector

- The indirect evidence for a phase transition in the elliptic flow results comes primarily from the sensitivity in hydrodynamic calculations of the magnitude and hadron mass-dependence of v_2 to the EOS
- How does the level of this EOS sensitivity compare quantitatively to that of uncertainties in the calculations, based the range of adjustable parameters and the failure to describe the spectra, elliptic flow and HBT at the same time?

NSAC Subcommittee on Heavy-Ion Physics 27

Initial conditions (CGC)

- If there is a truly universal gluon density saturation scale, determined already from HERA *e*-p deep inelastic scattering measurements, why has it been necessary to refit parameters of the saturation scale to RHIC A+A particle multiplicities? Is not the A-dependence of the gluon densities at the relevant Bjorken x-ranges predicted in gluon saturation treatments

NSAC Subcommittee on Heavy-Ion Physics 28

Critical behavior?

- Is it naïve to expect non-monotonic behavior?
- Can we make a convincing QGP discovery claim without a rapid change in an observable characteristic of a phase transition?
  - Where is the smoking gun?
- Can we predict, based on what we now know from SPS and RHIC, at what energies or under what conditions we produce matter below the critical temperature and which observables from those collisions will show a non-monotonic behavior?

NSAC Subcommittee on Heavy-Ion Physics 29

We concluded we had beautiful experimental discoveries but theory description was still a stitch-work of models :-)

The "Perfect Fluid" in Boulder (march 2005)

Shear Viscosity of Strongly Coupled $\mathcal{N} = 4$ Supersymmetric Yang-Mills Plasma

G. Policastro[1,2], D.T. Son[3,4], and A.O. Starinets[1]
[1] *Department of Physics, New York University, New York, New York 10003*
[2] *Scuola Normale Superiore, Piazza dei Cavalieri 7, 56100, Pisa, Italy*
[3] *Physics Department, Columbia University, New York, New York 10027*
[4] *RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973*
(April 2001)

Using the anti–de Sitter/conformal field theory correspondence, we relate the shear viscosity η of the finite-temperature $\mathcal{N} = 4$ supersymmetric Yang-Mills theory in the large N, strong-coupling regime with the absorption cross section of low-energy gravitons by a near-extremal black three-brane. We show that in the limit of zero frequency this cross section coincides with the area of the horizon. From this result we find $\eta = \frac{\pi}{8}N^2T^3$. We conjecture that for finite 't Hooft coupling $g^2_{YM}N$ the shear viscosity is $\eta = f(g^2_{YM}N)N^2T^3$, where $f(x)$ is a monotonic function that decreases from $\mathcal{O}(x^{-2}\ln^{-1}(1/x))$ at small x to $\pi/8$ when $x \to \infty$.

arXiv:hep-th/0104066v2 28 Jul 2001

Introduction.—At finite temperatures, the large distance, long time behavior of gauge theories is described, as in any other fluid, by a hydrodynamic theory [1]. To write down the hydrodynamic equations one has to know the thermodynamics (i.e., the equation of state) of the medium, as well as the transport coefficients: the shear and the bulk viscosities, the electrical conductivity [in the presence of a U(1) gauge group], and the diffusion constants (in the presence of conserved global charges). Knowledge of these quantities in hot gauge theories is crucial for numerous applications, the most notable of which belong to the physics of the electroweak phase transition in the early Universe [2] and of the quark-gluon plasma possibly created in heavy-ion collisions [3].

When the gauge coupling is small (which requires, in the case of QCD, temperatures much larger than the confinement scale), both the equation of state and the transport coefficients are calculable perturbatively. At strong coupling (i.e., at temperatures not much larger than the confinement scale), thermodynamics can be found non-perturbatively by lattice simulations, but transport coefficients are beyond the reach of all current numerical techniques. This situation is very unfortunate, since the quark-gluon plasma one hopes to create in heavy-ion experiments has relatively low temperature at which the perturbation theory works very poorly.

Lacking methods to reliably compute the transport coefficients of finite-temperature QCD, one should try to gain insight into models where these coefficients can be computed nonperturbatively. Recently, powerful techniques based on the anti–de Sitter/conformal field theory (AdS/CFT) correspondence have been developed, establishing, in particular, the connection between the $\mathcal{N} = 4$ supersymmetric Yang-Mills (SYM) theory in the large coupling, large N limit and classical ten-dimensional gravity on the background of black three-branes [4–7]. This allows one to perform analytical calculations in a strongly coupled four-dimensional gauge theory.

In this Letter, we compute the shear viscosity η of the strongly coupled finite-temperature $\mathcal{N} = 4$ SYM theory (the bulk viscosity of this theory vanishes due to scale invariance). We first relate, using previously known results from the AdS/CFT correspondence, the shear viscosity with the absorption cross section of low-energy gravitons falling perpendicularly onto near-extremal black three-branes. We further show that this cross section is equal to the the area of the horizon, in a way very similar to the case of black holes [8]. These facts provide enough information for us to find that $\eta = \frac{\pi}{8}N^2T^3$, provided both the 't Hooft coupling and N are large. Remarkably, the shear viscosity approaches a constant value in the large 't Hooft coupling limit, and this value is related to the area of the horizon of the black brane.

The viscosity.—To start our discussion, we briefly review the notion of viscosity in the context of finite-temperature field theory. Consider a plasma slightly out of equilibrium, so that there is local thermal equilibrium everywhere but the temperature and the mean velocity slowly vary in space. We define, at any point, the local rest frame as the one where the three-momentum density vanishes: $T_{0i} = 0$. The stress tensor, in this frame, is given by the constitutive relation,

$$T_{ij} = \delta_{ij}p - \eta\left(\partial_i u_j + \partial_j u_i - \frac{2}{3}\delta_{ij}\partial_k u_k\right) - \zeta\delta_{ij}\partial_k u_k\,, \quad (1)$$

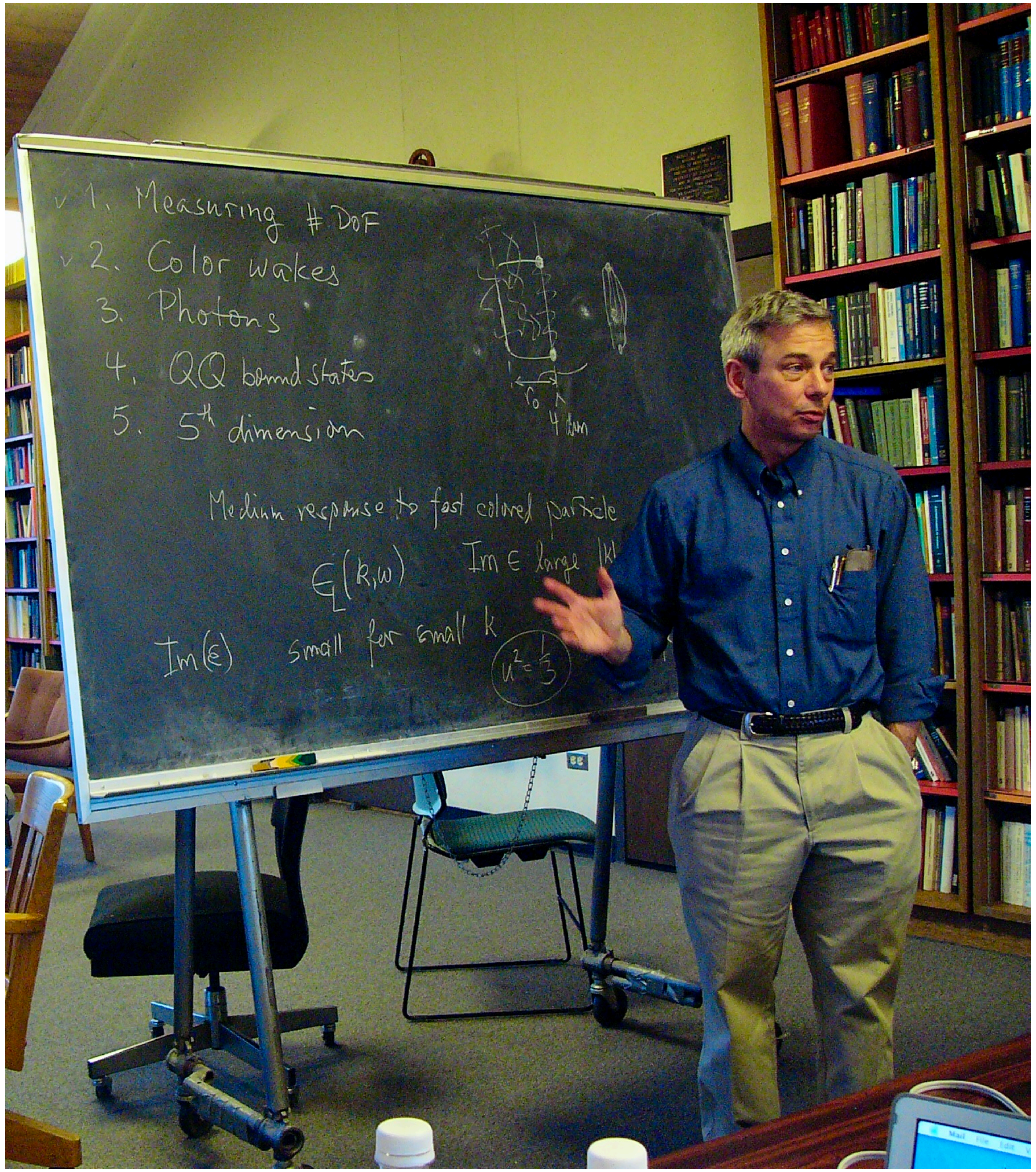
where u_i is the flow velocity, p is the pressure, and η and ζ are, by definition, the shear and bulk viscosities respectively. In conformal field theories like the $\mathcal{N} = 4$ SYM theory, the energy momentum tensor is traceless, $T^\mu{}_\mu = 0$, so $\varepsilon \equiv T_{00} = 3p$ and the bulk viscosity vanishes identically, $\zeta = 0$.

All kinetic coefficients can be expressed, through Kubo relations, as the correlation functions of the corresponding currents [9]. For the shear viscosity, the correlator is that of the stress tensor,

$$\eta = \lim_{\omega\to 0}\frac{1}{2\omega}\int dt\, d\mathbf{x}\, e^{i\omega t}\langle[T_{xy}(t,\mathbf{x}), T_{xy}(0,0)]\rangle$$

1

The “Perfect Fluid”

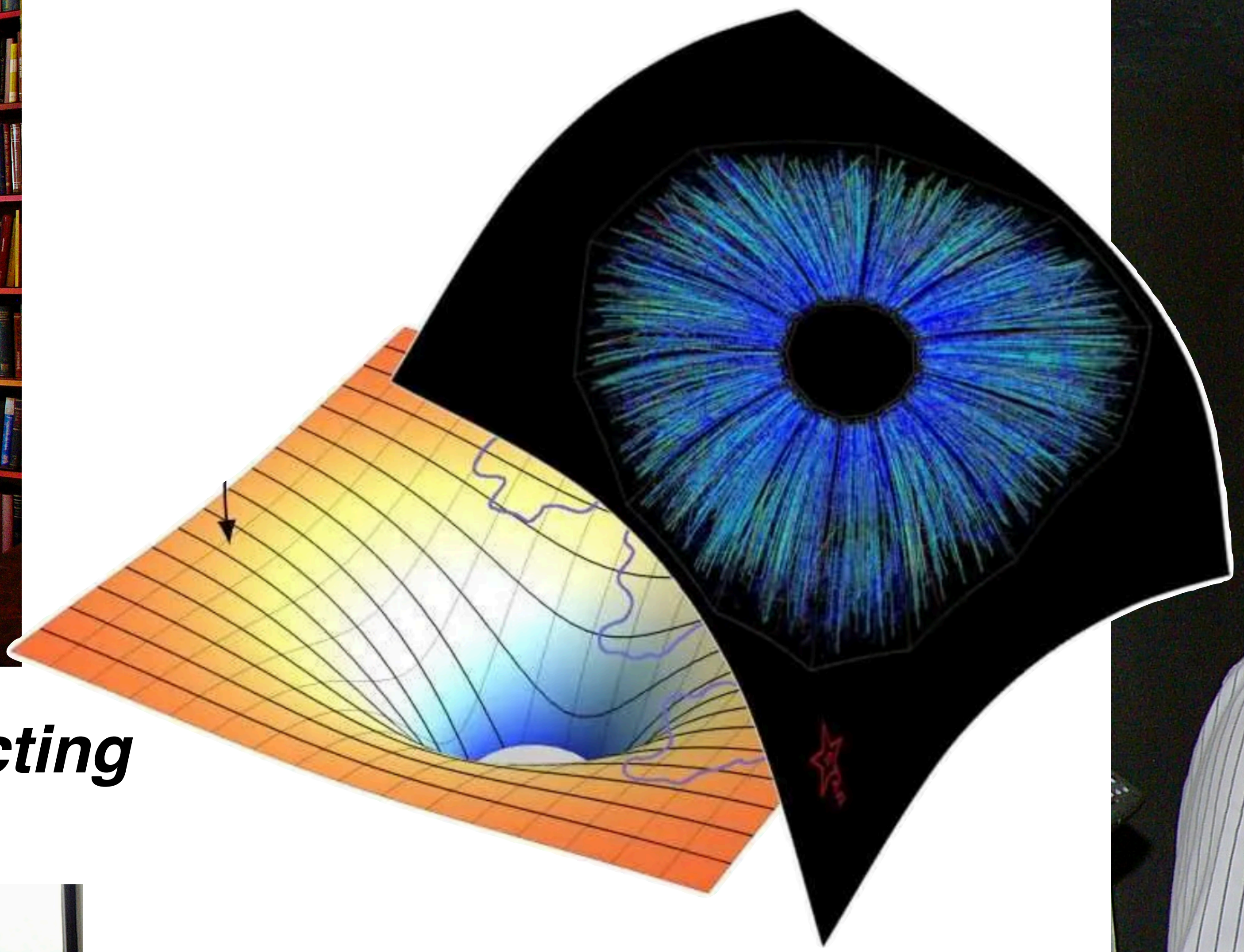


Pictures credit:Peter Steinberg

The “Perfect Fluid”

Started quite happy the meeting

Got a bit overwhelmed by connecting to holography (AdS/CFT)



Was happy with connecting to the perfect liquid :-)

Pictures credit:Peter Steinberg

The “Perfect Fluid”

Cited over 4000 times

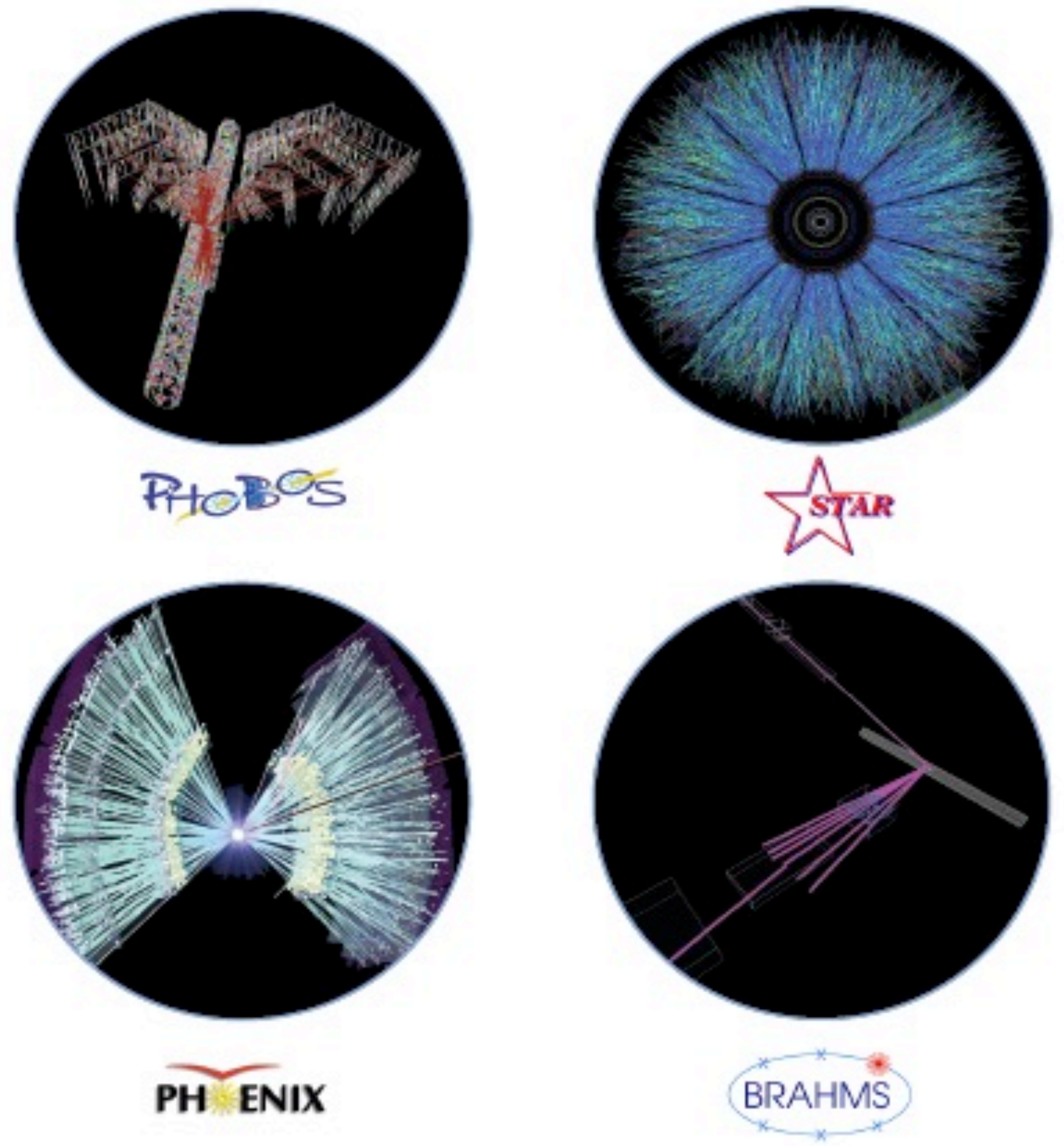
BNL -73847-2005
Formal Report

Hunting the Quark Gluon Plasma

RESULTS FROM THE FIRST 3 YEARS AT RHIC

ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005



Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

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Contact: Karen McNulty Walsh, (631) 344-8350, or Peter Genzer, (631) 344-3174   share:

RHIC Scientists Serve Up 'Perfect' Liquid

New state of matter more remarkable than predicted — raising many new questions

April 18, 2005

TAMPA, FL — The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) — a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory — say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

Secretary of Energy Samuel Bodman

"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain fundamental properties of the universe using 10 dimensions instead of the usual three spatial dimensions plus time.

"The possibility of a connection between string theory and RHIC collisions is unexpected and exhilarating," Dr. Orbach said. "String theory seeks to unify the two great intellectual achievements of twentieth-century physics, general relativity and quantum mechanics, and it may well have a profound impact on the physics of the twenty-first century."

The papers, which the four RHIC collaborations (BRAHMS, PHENIX, PHOBOS, and STAR) have been working on for nearly a year, will be published simultaneously by the journal *Nuclear Physics A*, and will also be compiled in a special Brookhaven report, the Lab announced at the April 2005 meeting of the American Physical Society in Tampa, Florida.

These summaries indicate that some of the observations at RHIC fit with the theoretical predictions for a quark-gluon plasma (QGP), the type of matter postulated to have existed just microseconds after the Big Bang. Indeed, many theorists have concluded that RHIC has already demonstrated the creation of quark-gluon plasma. However, all four collaborations note that there are discrepancies between the experimental data and early theoretical predictions bas Screenshot quark-gluon plasma formation.

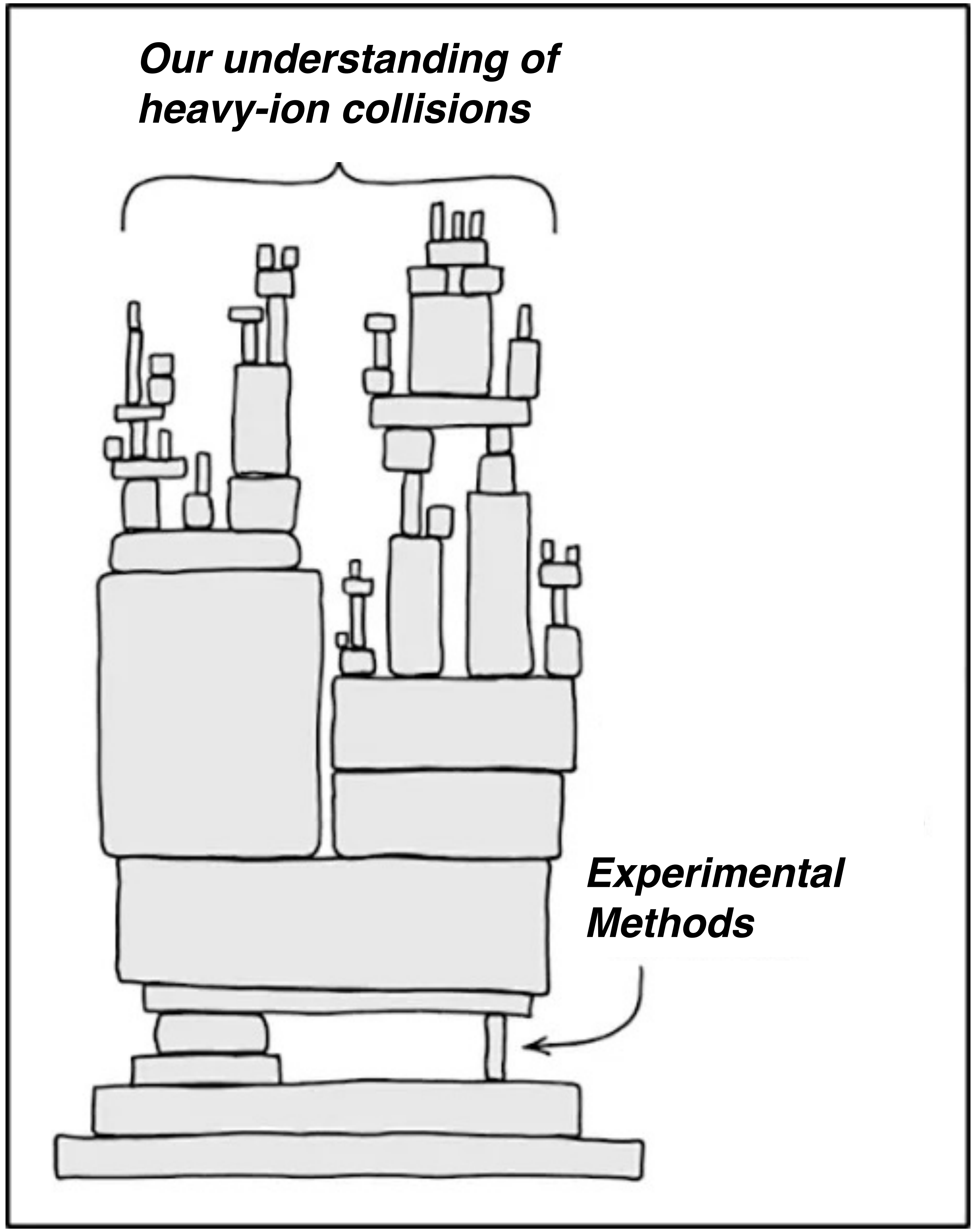
STAR Collaboration: 10.1016/j.nuclphysa.2005.03.085

The “Perfect Fluid” ???

Color by Roberta Weir

Exploring the secrets
of the universe

Art Poskanzer



Experimental Methods

$$v_n(p_t, y) = \langle \cos[n(\varphi - \Psi_{\mathrm{RP}})] \rangle$$

STAR: Phys.Rev.C 66 (2002) 034904 • e-Print: nucl-ex/0206001 [nucl-ex]

$$\langle\langle e^{i2(\varphi_1-\varphi_2)}\rangle\rangle = \langle\langle e^{i2(\varphi_1-\Psi_{\mathrm{RP}}-(\varphi_2-\Psi_{\mathrm{RP}}))}\rangle\rangle$$

$$= \langle\langle e^{i2(\varphi_1-\Psi_{\mathrm{RP}})}\rangle\langle e^{-i2(\varphi_2-\Psi_{\mathrm{RP}})}\rangle + \delta_2\rangle,$$

$$= \langle v_2^2 + \delta_2\rangle,$$

$$c_2\{2\} \equiv \left\langle\left\langle e^{i2(\varphi_1-\varphi_2)}\right\rangle\right\rangle = \left\langle v_2^2 + \delta_2\right\rangle.$$

$$c_2\{4\} \equiv \left\langle\left\langle e^{i2(\varphi_1+\varphi_2-\varphi_3-\varphi_4)}\right\rangle\right\rangle - 2\left\langle\left\langle e^{i2(\varphi_1-\varphi_2)}\right\rangle\right\rangle^2,$$

$$= \left\langle v_2^4 + \delta_4 + 4v_2^2\delta_2 + 2\delta_2^2\right\rangle - 2\left\langle v_2^2 + \delta_2\right\rangle^2,$$

$$= \left\langle -v_2^4 + \delta_4\right\rangle.$$

Non flow $\delta_2 \propto 1/M_c \quad \delta_4 \propto 1/M_c^3$

Generating function cumulants N. Borghini, P.M. Dinh, and J.-Y. Ollitrault, PRC 64, 054901 (2001)

Fluctuations

$$\langle v_2^2\rangle = \langle v_2\rangle^2 + \sigma^2$$

if $\sigma \ll \langle v\rangle$ then

$$v_2\{2\} = \langle v_2\rangle + \frac{1}{2}\frac{\sigma^2}{\langle v_2\rangle},$$

$$v_2\{4\} = \langle v_2\rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2\rangle},$$

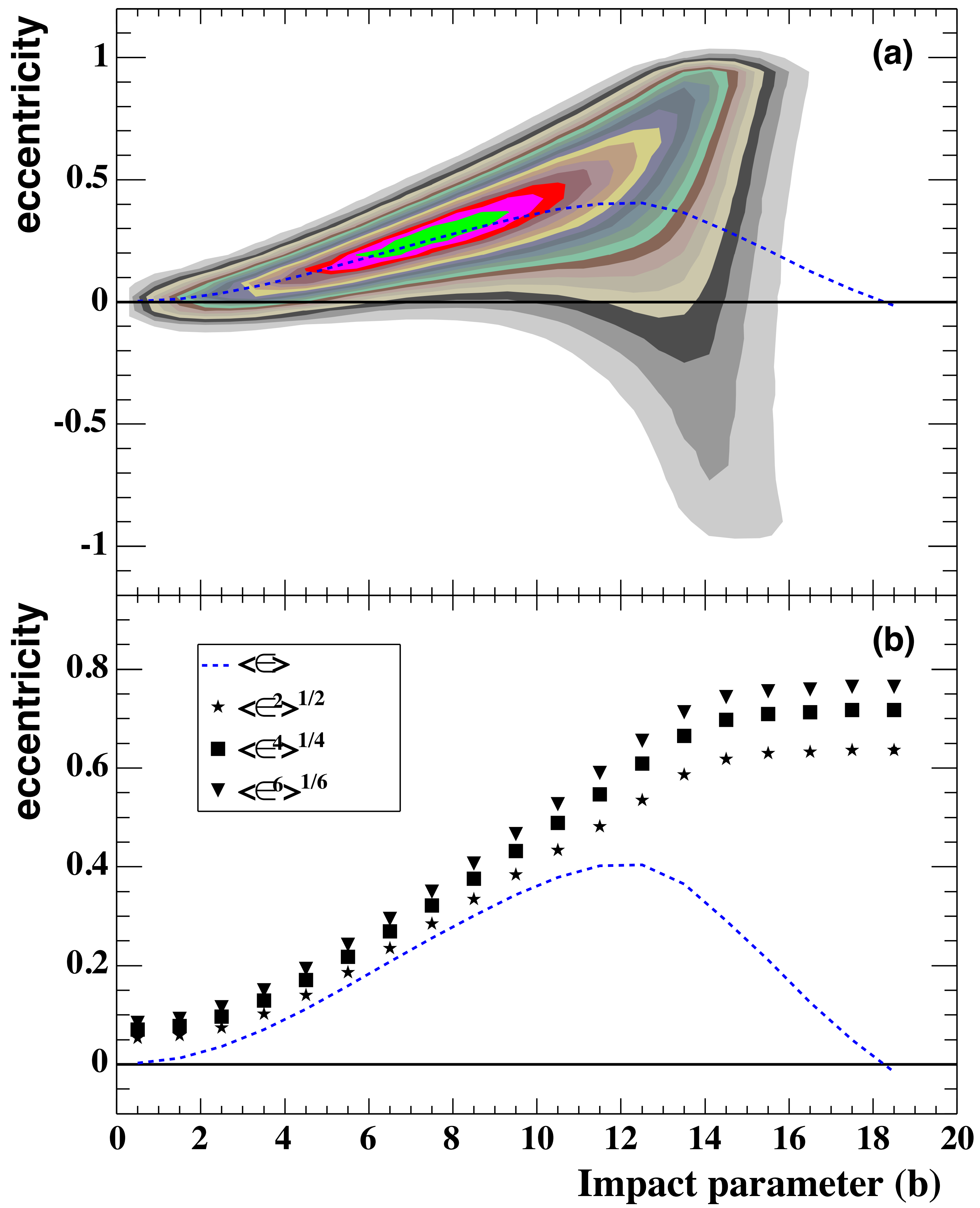
$$v_2\{6\} = \langle v_2\rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2\rangle}.$$

Experimental Methods

Eccentricity fluctuations and its possible effect on elliptic flow measurements

Mike Miller[(a)] and Raimond Snellings[(b)]
(a) Yale University, New Haven, Connecticut 06520, USA
(b) NIKHEF, Kruislaan 409, 1098 SJ Amsterdam, The Netherlands

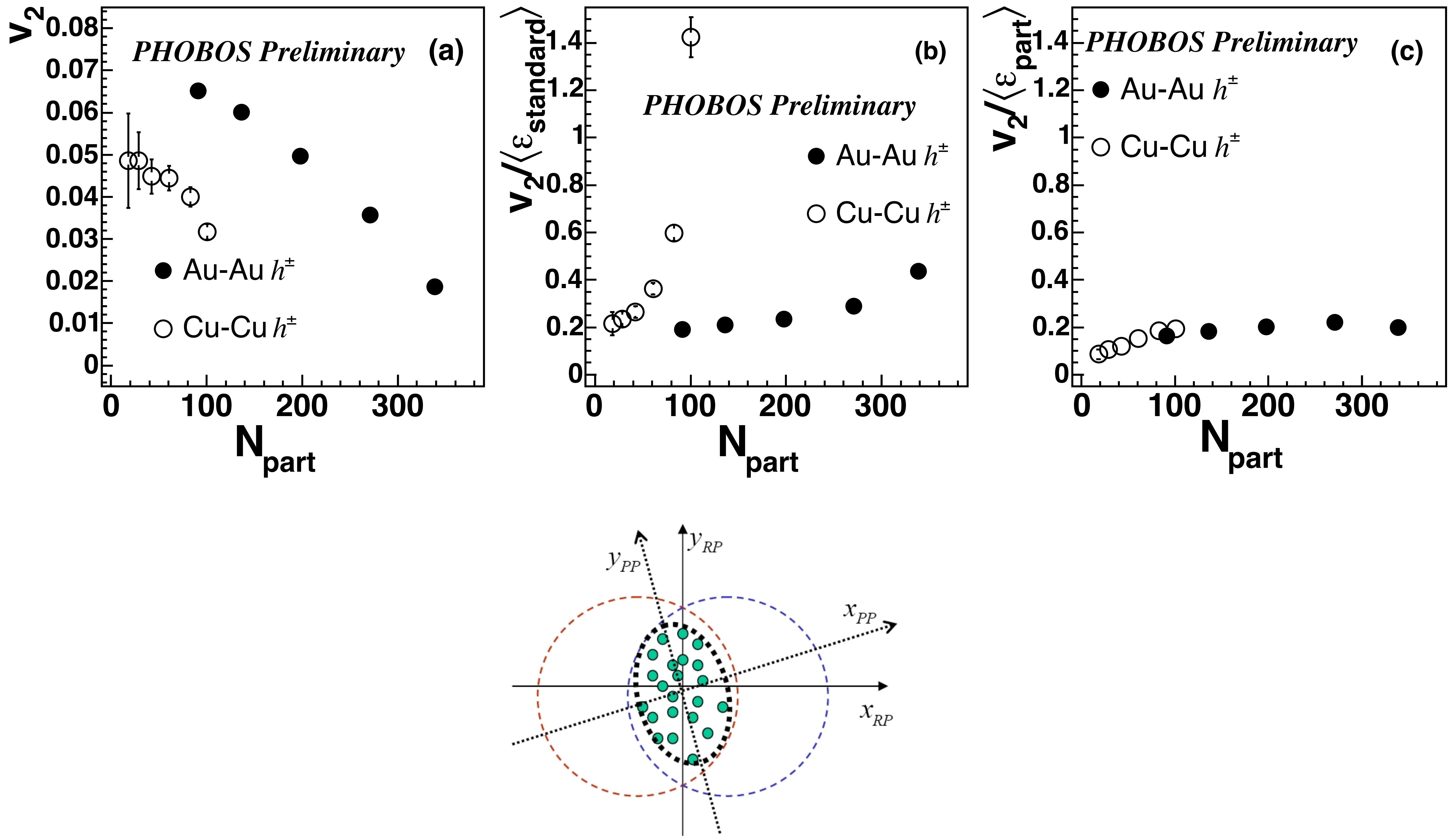
2003



2005

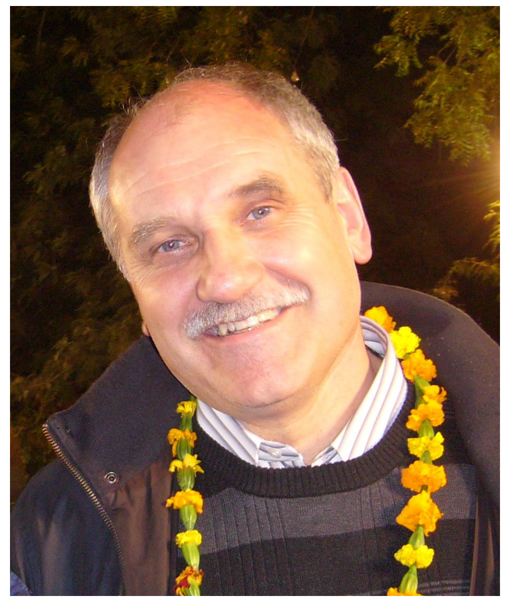
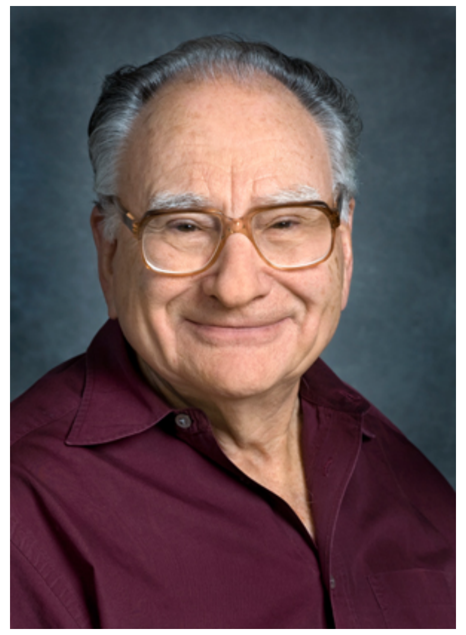
System size, energy and pseudorapidity dependence of directed and elliptic flow at RHIC

S. Manly* for the PHOBOS Collaboration:



Collective phenomena in non-central nuclear collisions

Sergei A. Voloshin, Arthur M. Poskanzer, and Raimond Snellings


Contents

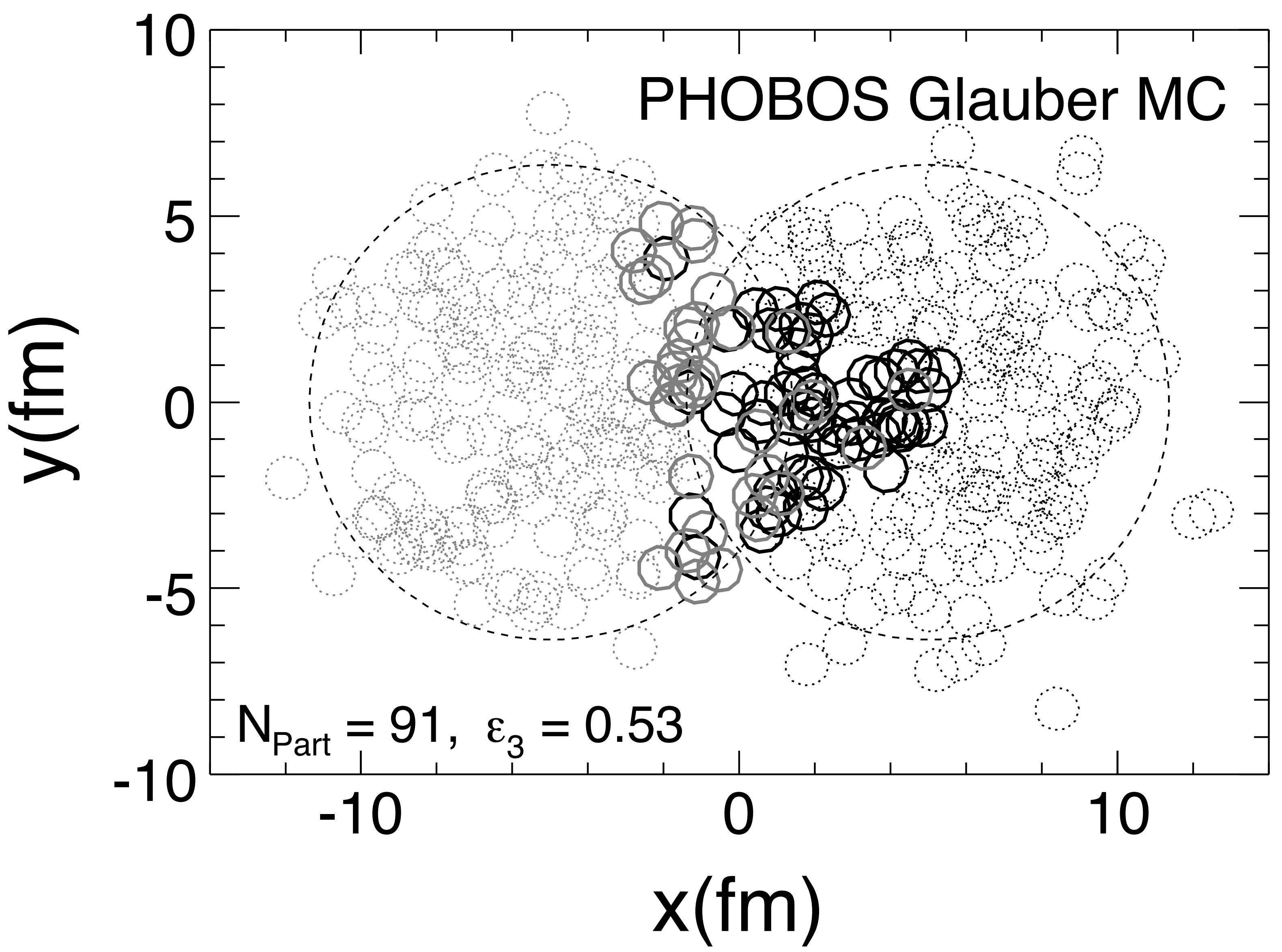
S. Voloshin, A. Poskanzer, R. Snellings: *Landolt-Bornstein* 23 (2010) 293-333 e-Print: 0809.2949

Collision geometry fluctuations and triangular flow in heavy-ion collisions

B.Alver, G.Roland **2010**

Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA

We introduce the concepts of participant triangularity and triangular flow in heavy-ion collisions, analogous to the definitions of participant eccentricity and elliptic flow. The participant triangularity characterizes the triangular anisotropy of the initial nuclear overlap geometry and arises from event-by-event fluctuations in the participant-nucleon collision points. In studies using a multi-phase transport model (AMPT), a triangular flow signal is observed that is proportional to the participant triangularity and corresponds to a large third Fourier coefficient in two-particle azimuthal correlation functions. Using two-particle azimuthal correlations at large pseudorapidity separations measured by the PHOBOS and STAR experiments, we show that this Fourier component is also present in data. Ratios of the second and third Fourier coefficients in data exhibit similar trends as a function of centrality and transverse momentum as in AMPT calculations. These findings suggest a significant contribution of triangular flow to the ridge and broad away-side features observed in data. Triangular flow provides a new handle on the initial collision geometry and collective expansion dynamics in heavy-ion collisions.

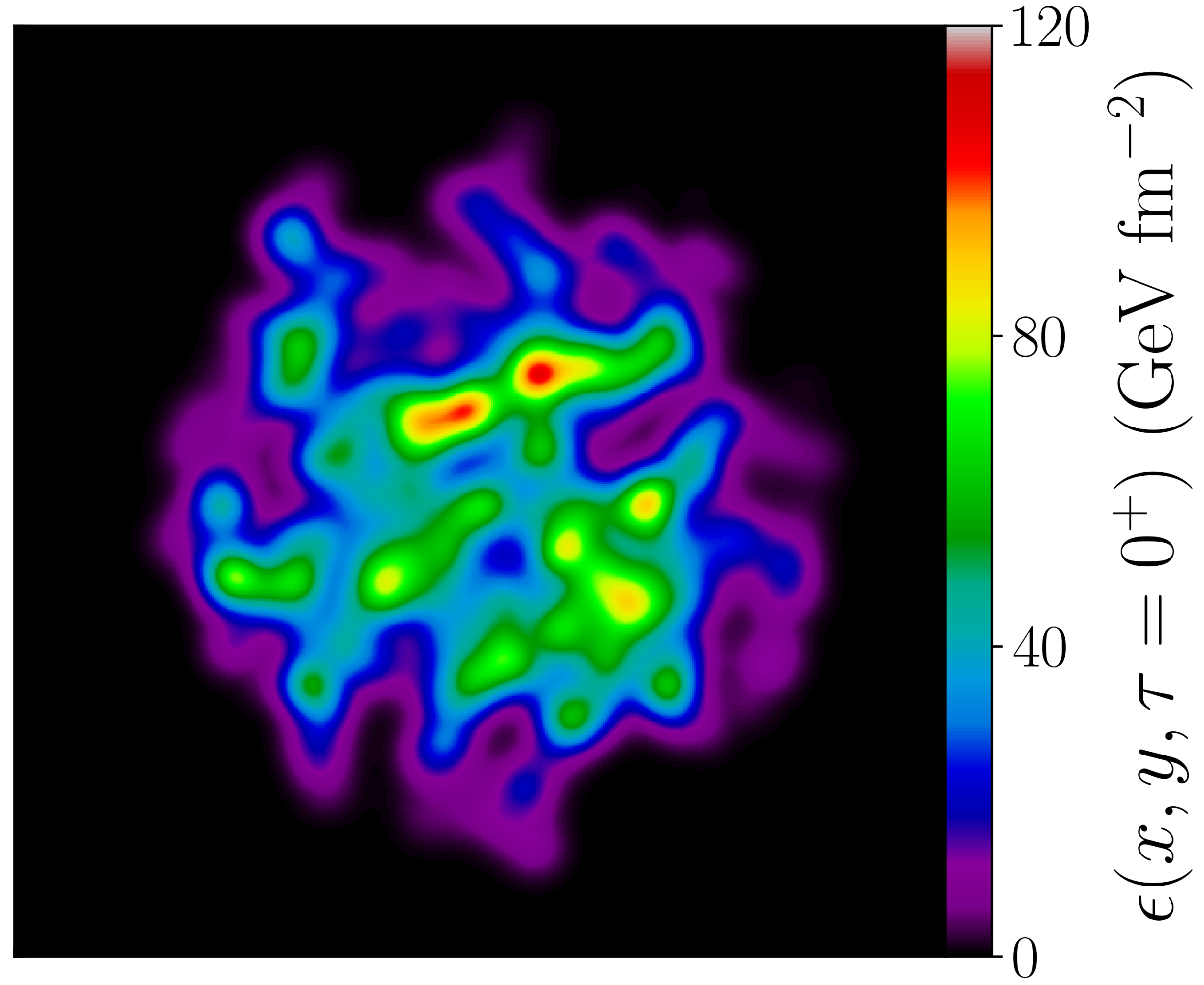


Collective flow and long-range correlations in relativistic heavy ion collisions

Matthew Luzum **2011**

CEA, Institut de physique théorique de Saclay (IPhT), F-91191 Gif-sur-Yvette, France

Making use of recently released data on dihadron correlations by the STAR collaboration, I analyze the long-range ("ridge-like") part of these data and show that the dependence on both transverse momentum as well as orientation with respect to the event plane are consistent with correlations expected from only collective flow. In combination with previously analyzed centrality-dependent data, they provide strong evidence that only collective flow effects are present at large relative pseudorapidity. In contrast, by analyzing a "background subtracted" signal, the authors presenting the new data concluded that the ridge-like part of the measured correlation could not in fact be entirely generated from collective flow of the medium. I explain the discrepancy and illustrate some pitfalls of using the ZYAM prescription to remove flow background.



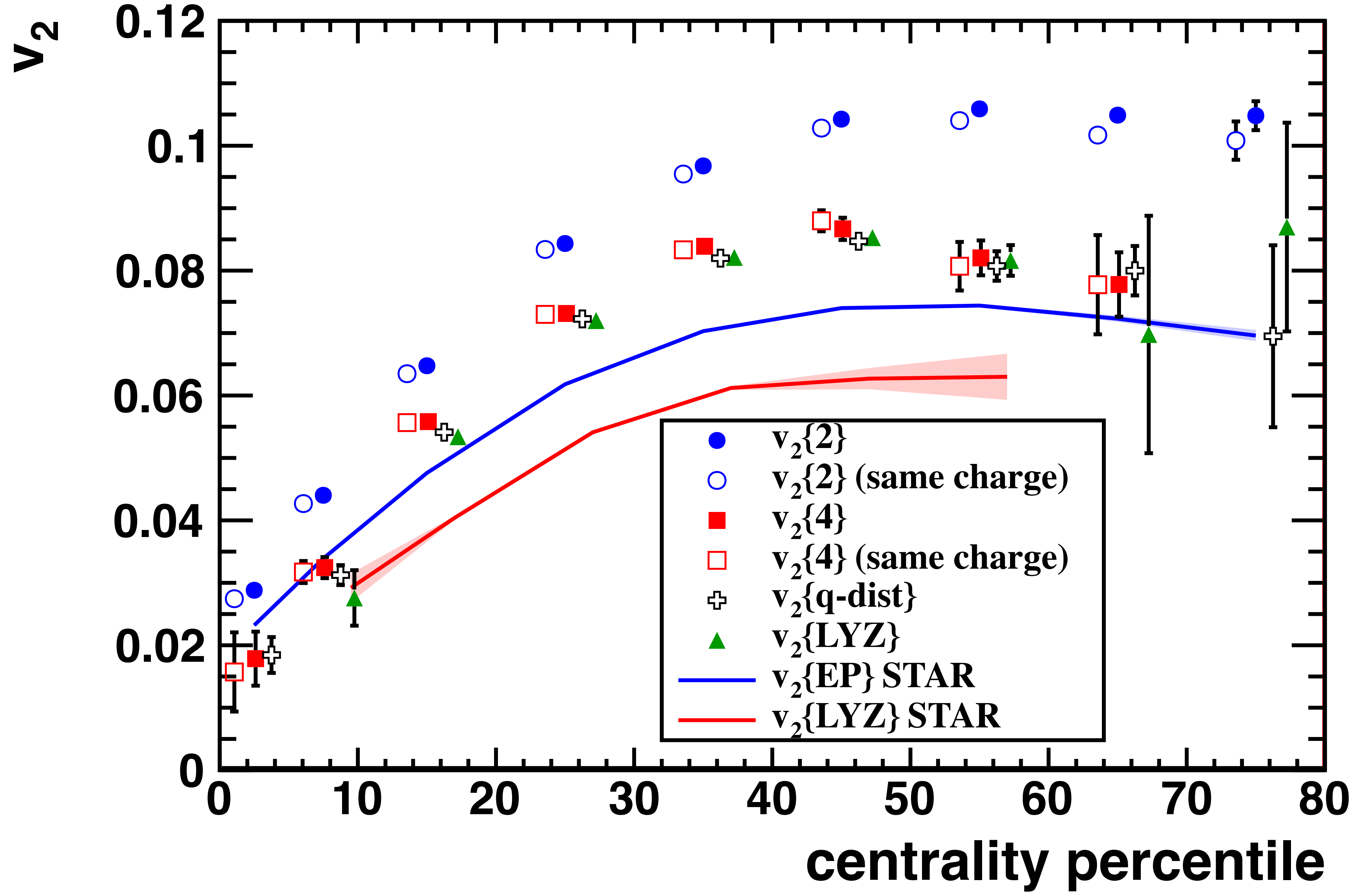
The first ALICE PbPb paper (2010)

Elliptic flow of charged particles in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

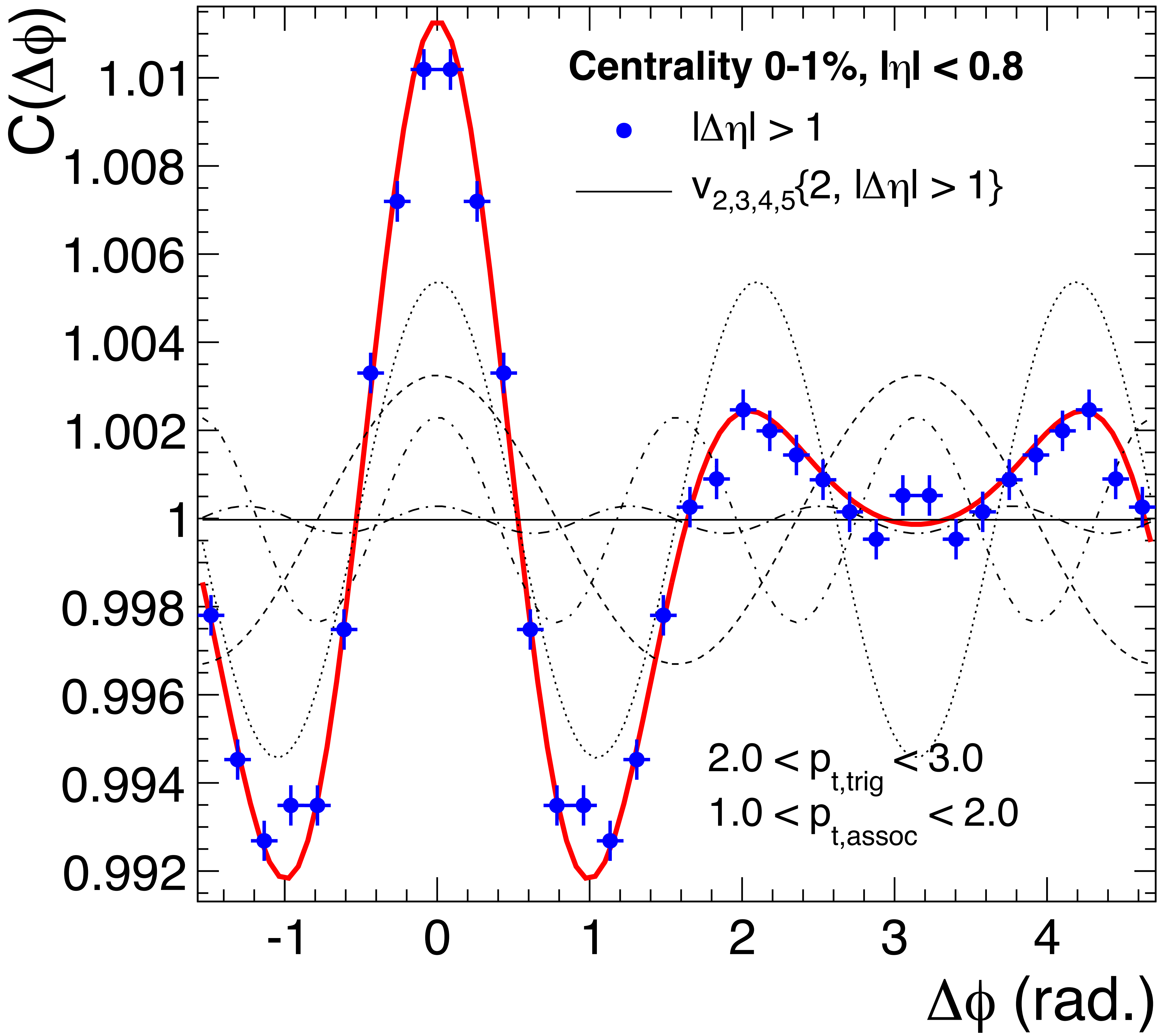
de M. Michel Nostradamus

We report the first measurement of charged particle elliptic flow in Pb+Pb collisions at $\sqrt{s_{NN}}$= 2.76 TeV with the ALICE detector at the CERN Large Hadron Collider. The measurement is performed in the central pseudorapidity region ($|\eta| < 0.8$) and transverse momentum range $0.25 < p_t < 5$ GeV/c. The elliptic flow signal, v_2, averaged over transverse momentum and pseudorapidity, reaches values of 0.085 for relatively peripheral collisions (40–50% most central). The differential elliptic flow $v_2(p_t)$ reaches a maximum of 0.25 around $p_t = 3$ GeV/c. Compared to RHIC Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV, the elliptic flow increases by about 15% in agreement with expectations based on the observed trend at lower energies.

PACS numbers: 25.75.Ld, 25.75.Gz, 05.70.Fh



No shock waves - convincing measurement of the higher harmonics with non-Glauber initial conditions



ALICE Collaboration: Phys. Rev. Lett. 105 (2010) 252302, Phys. Rev. Lett. 107 (2011) 032301

Key Theory Advancements (2013)

Hybrid modeling is needed, hadron cascade for hadronic phase, hydro for dense QGP phase

Viscosities have to be included

Initial conditions fluctuate event by event

Collective Flow and Viscosity in Relativistic Heavy-Ion Collisions

Ulrich Heinz[1] and Raimond Snellings[2]
[1] *Physics Department, The Ohio State University, Columbus, OH 43210-1117, USA; email: heinz@mps.ohio-state.edu*
[2] *Physics Department, Utrecht University, NL-3584 CC Utrecht, The Netherlands; email: R.J.M.Snellings@uu.nl*

The Little Bang Standard Model

Annu. Rev. Nucl. Part. Sci. 63 (2013) 123-151

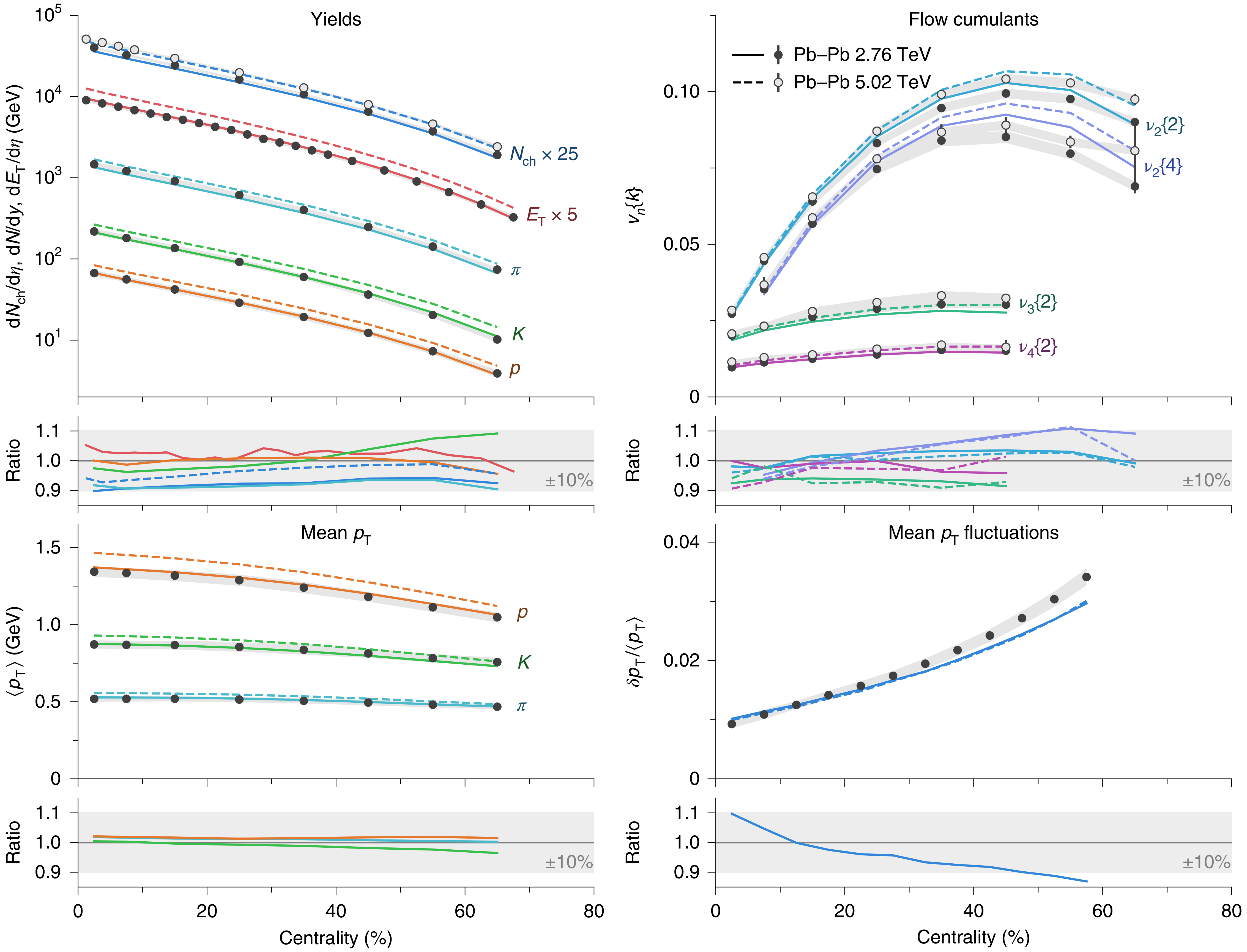
Combining measurements

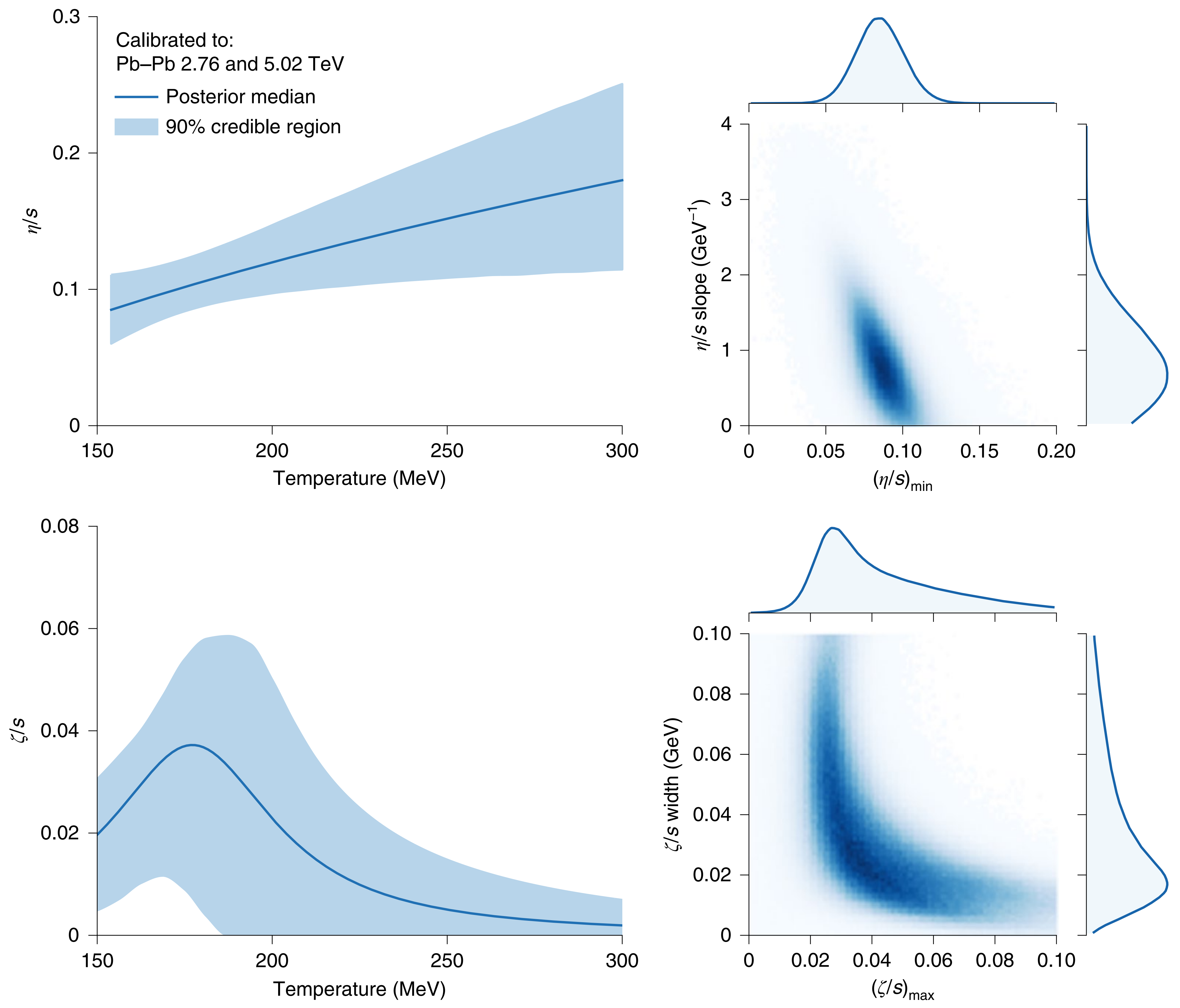
nature physics
LETTERS
https://doi.org/10.1038/s41567-019-0611-8

2019

Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma

Jonah E. Bernhard*, J. Scott Moreland and Steffen A. Bass





Heavy-Ion Collisions (pre-STAR)

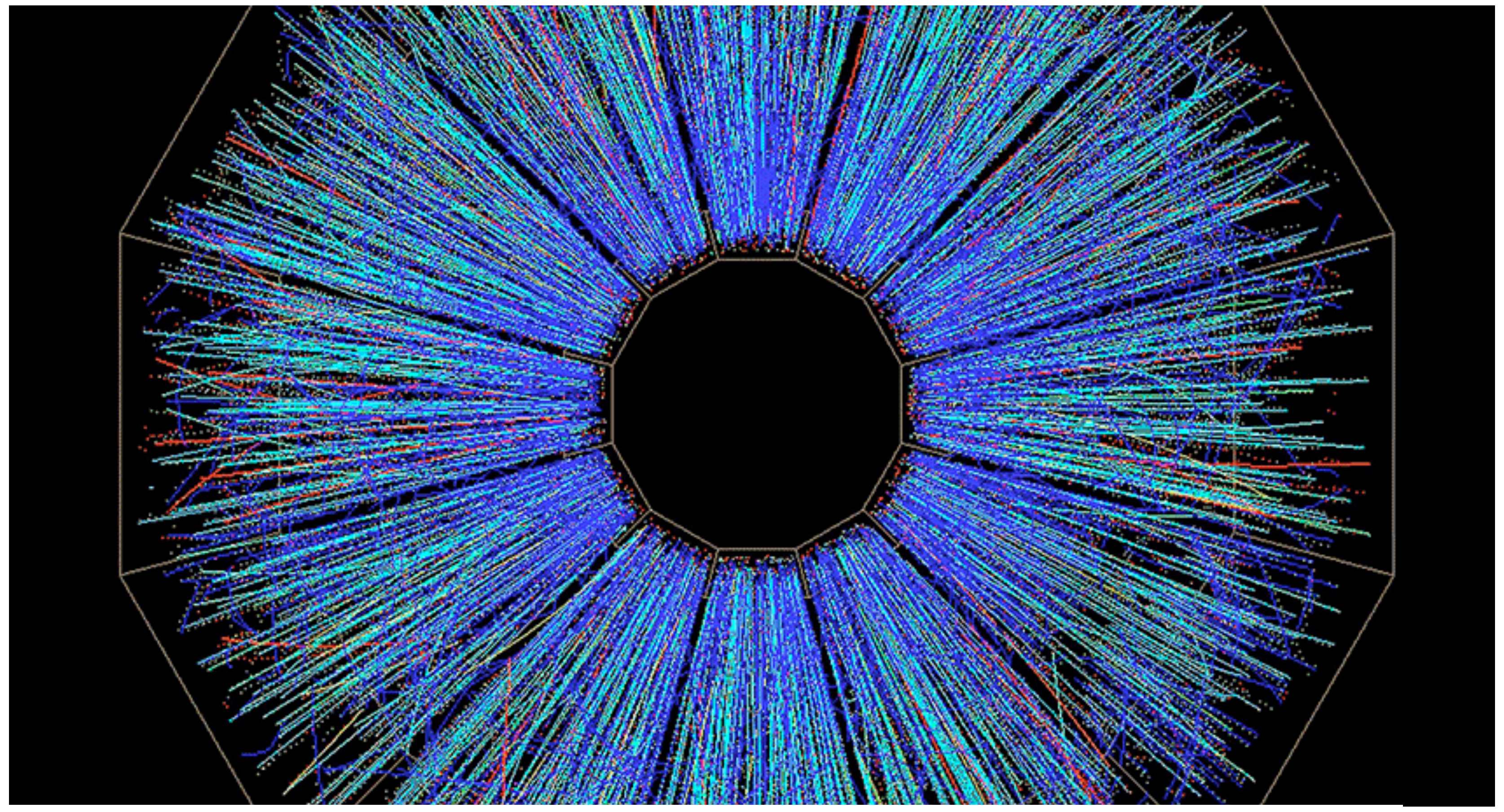
The model of heavy-ion collisions (pre-STAR) ***The model of heavy-ion collisions (current best model)***

pre-STAR heavy-ions were modelled by a stitch work of specific models.
A lot of progress has been made to smooth (Bayesian) out the wrinkles :-)
The “perfect fluid” has become quantitative!

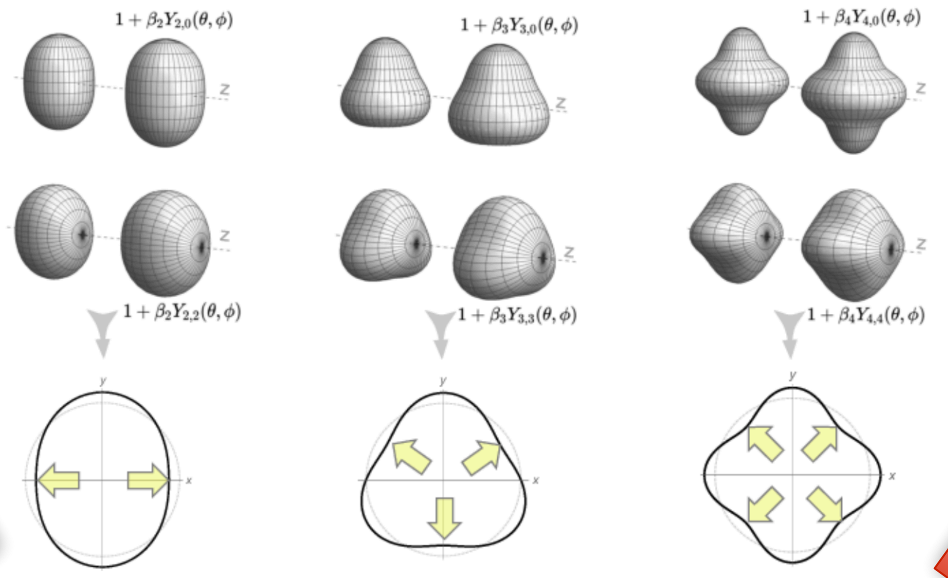
The next decade(s)

Precision tests of hot and dense QCD

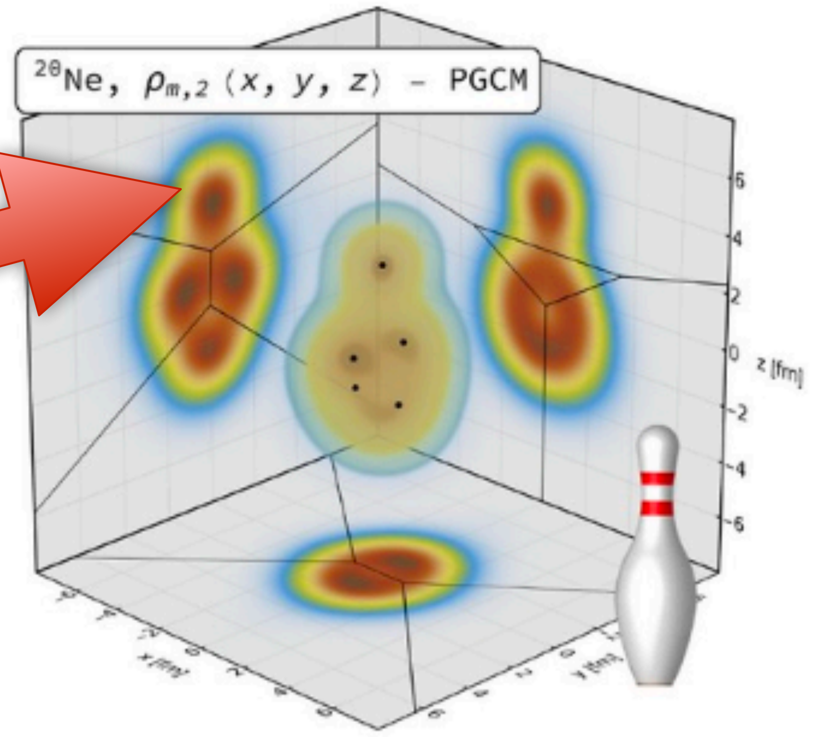
Low energy nuclear physics

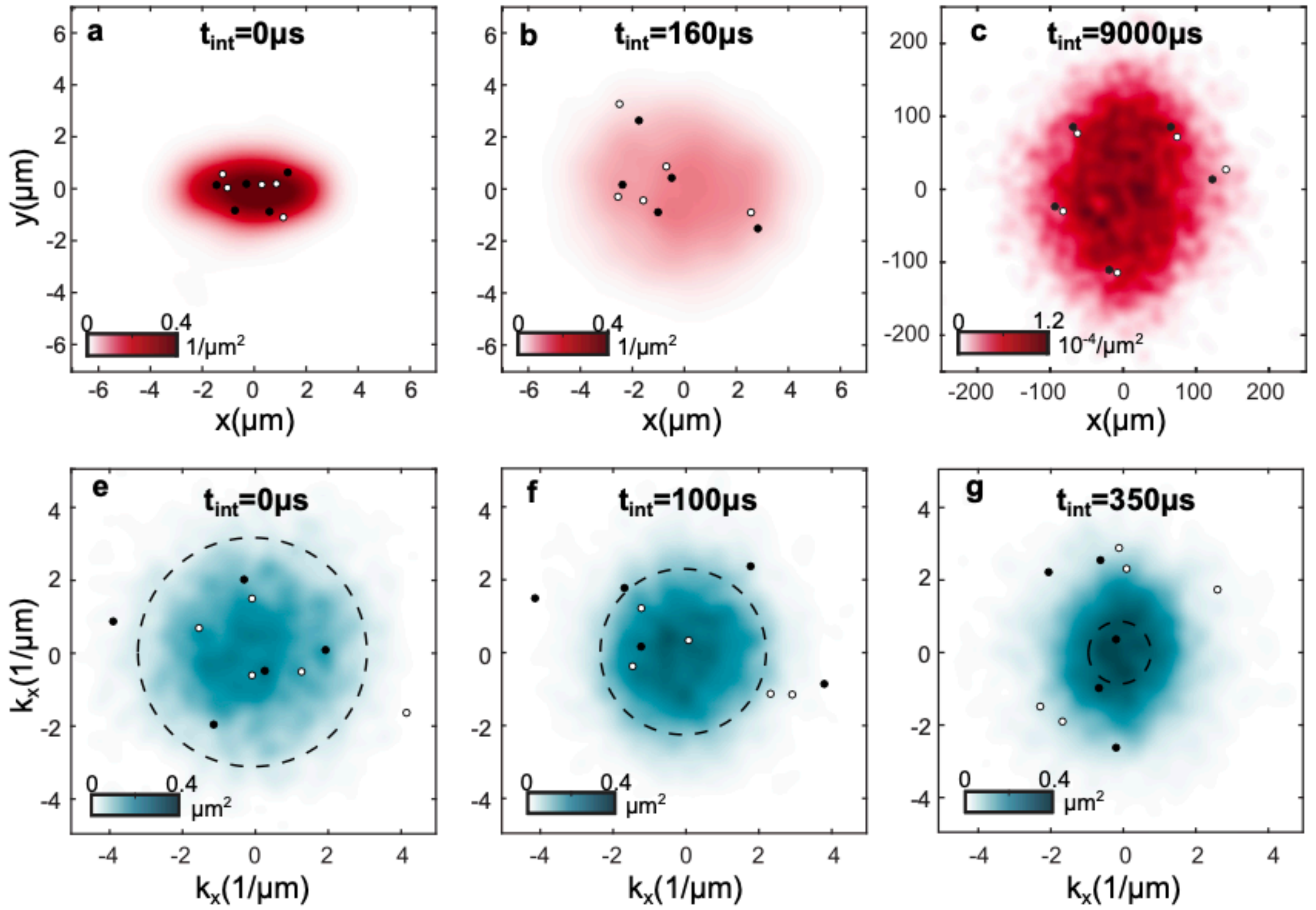


Realizations from STAR isobar run

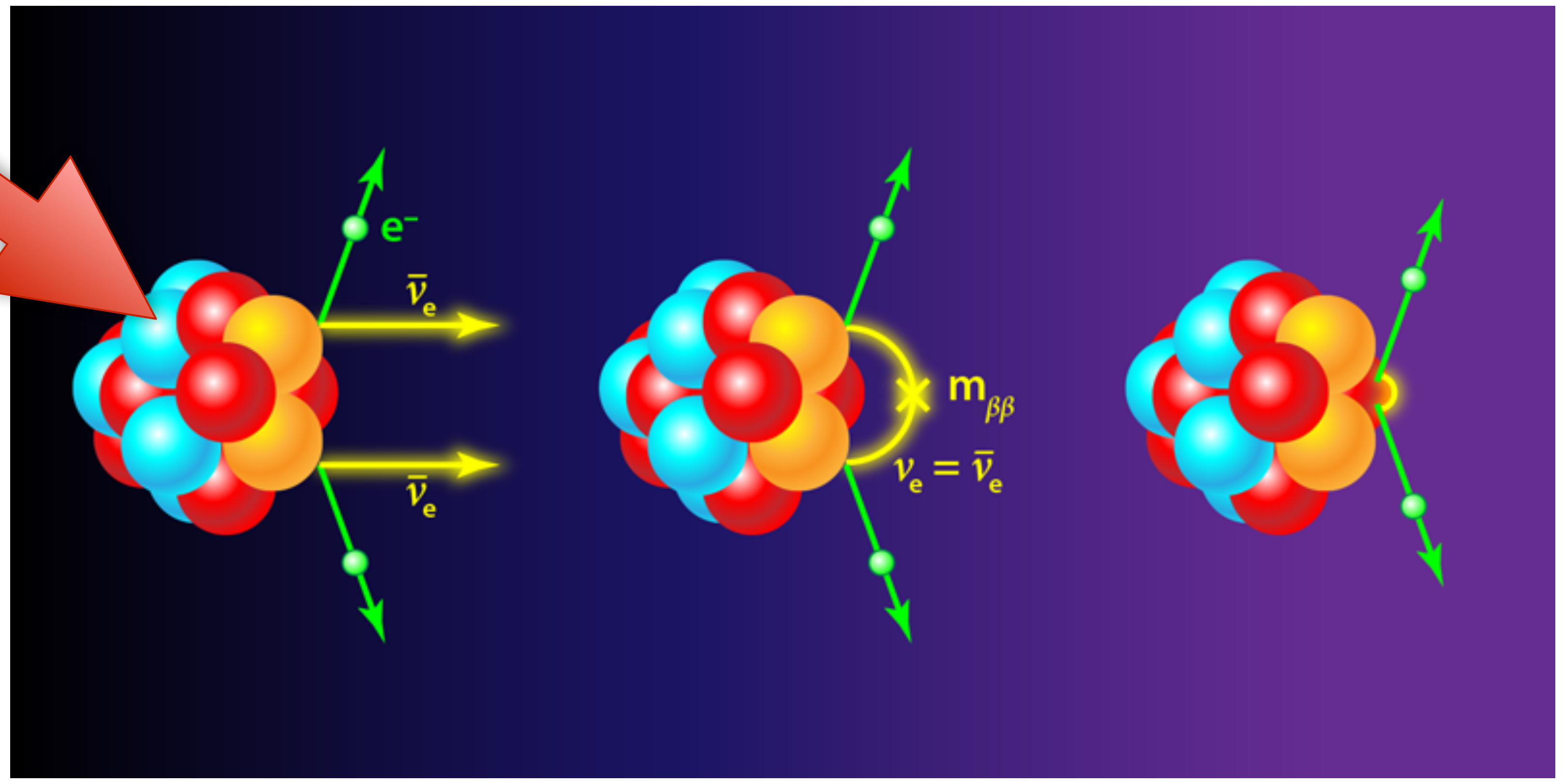


Consequences of the "perfect fluid"





Ultra Cold Atoms



Precision QCD & BSM


Thank you all STARs!
May the FLOW of
discoveries continue!