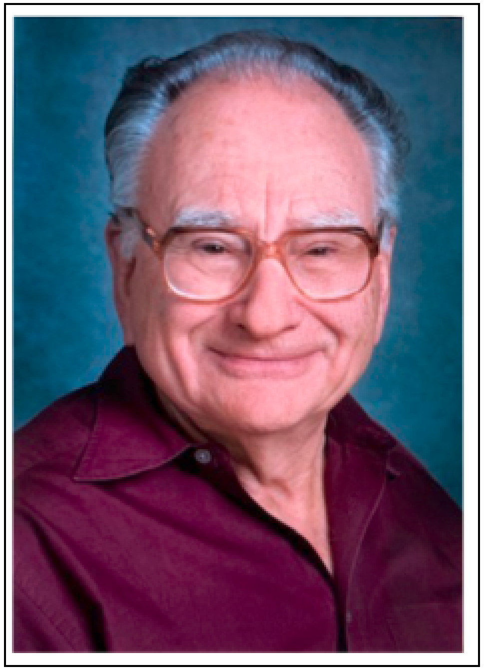
Symposium on collective flow in nuclear matter: a celebration of Art Poskanzer's life and career



This two-day symposium will celebrate the life and career of Art Poskanzer, a founder of the field of Relativistic Heavy Ion Physics. The scientific part of the symposium will focus on collective flow in nuclear collisions in all its aspects, from its discovery in nuclear collisions at the Bevalac by Art and his collaborators to its widespread application today to measure the structure and dynamics of the Quark-Gluon Plasma at RHIC and the LHC.

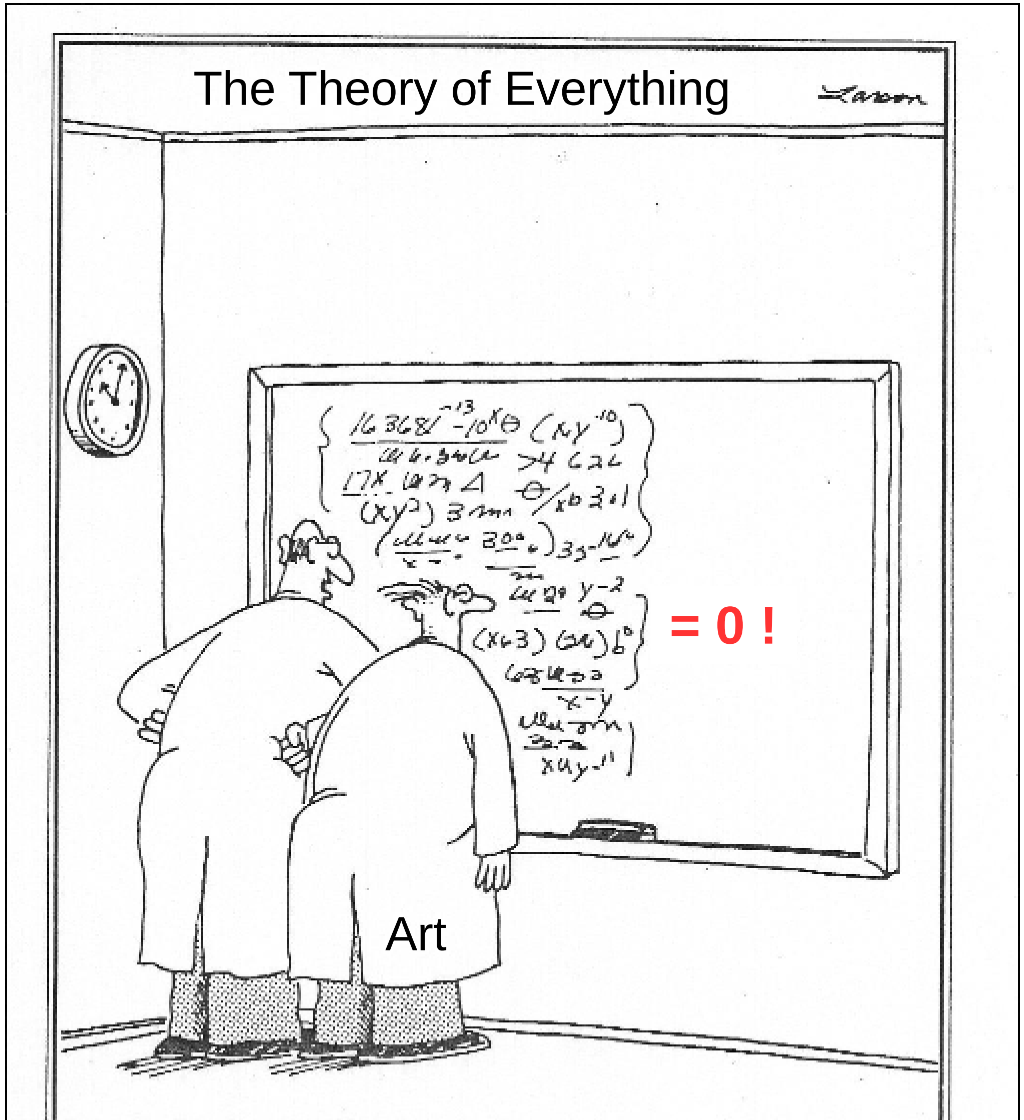
In fond memory of half century of heated physics debates with Art about

"Consistency of **Hard** (pQCD) and **Soft** (Hydrodynamic) observables in A+A"

microscopic and macroscopic

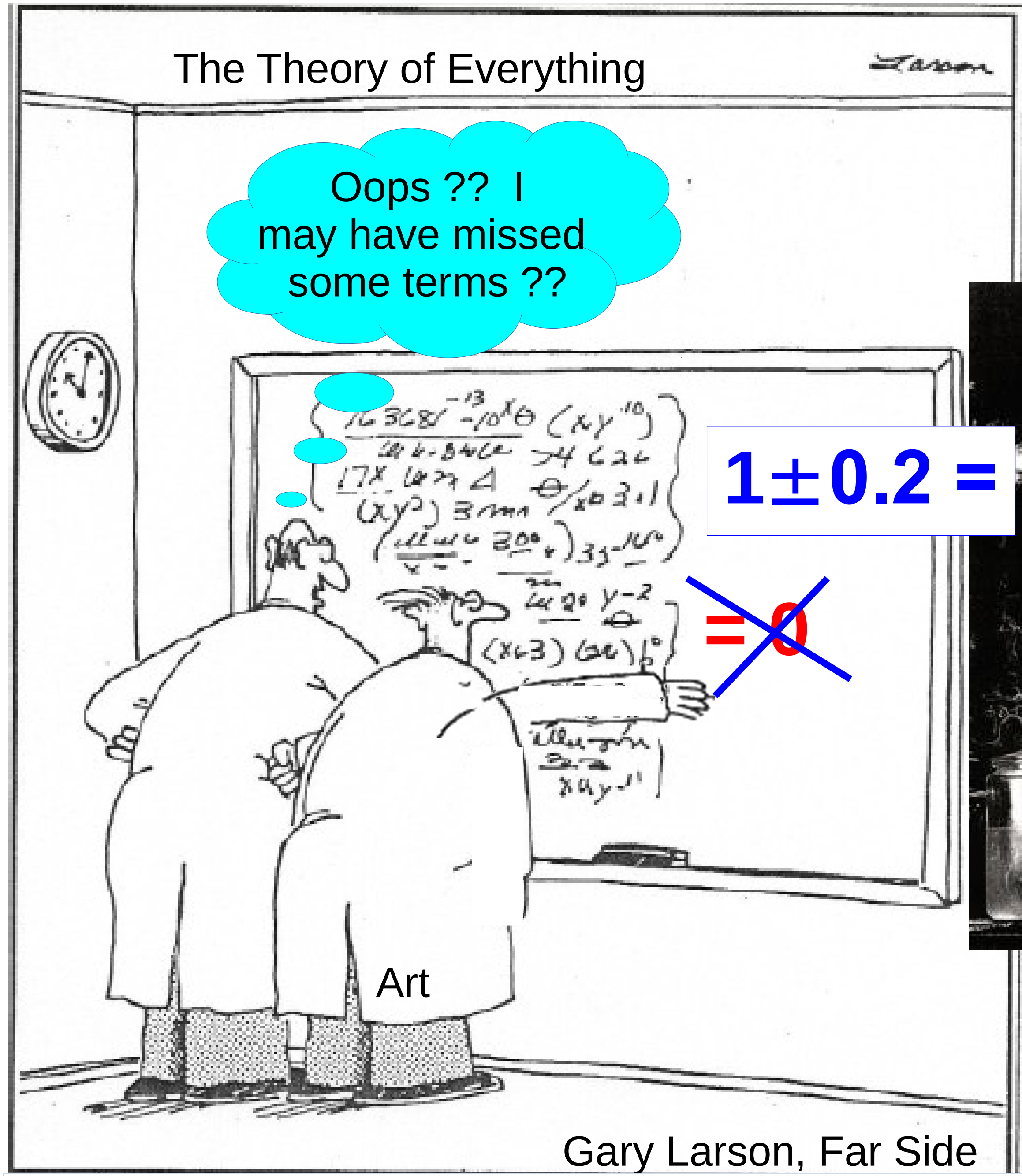
Miklos Gyulassy Dec 9, 2022

Our typical chalkboard discussion. I try to convince Art of my latest “gedanken” idea.
Art shakes his head and returns to his lab to measure reality.

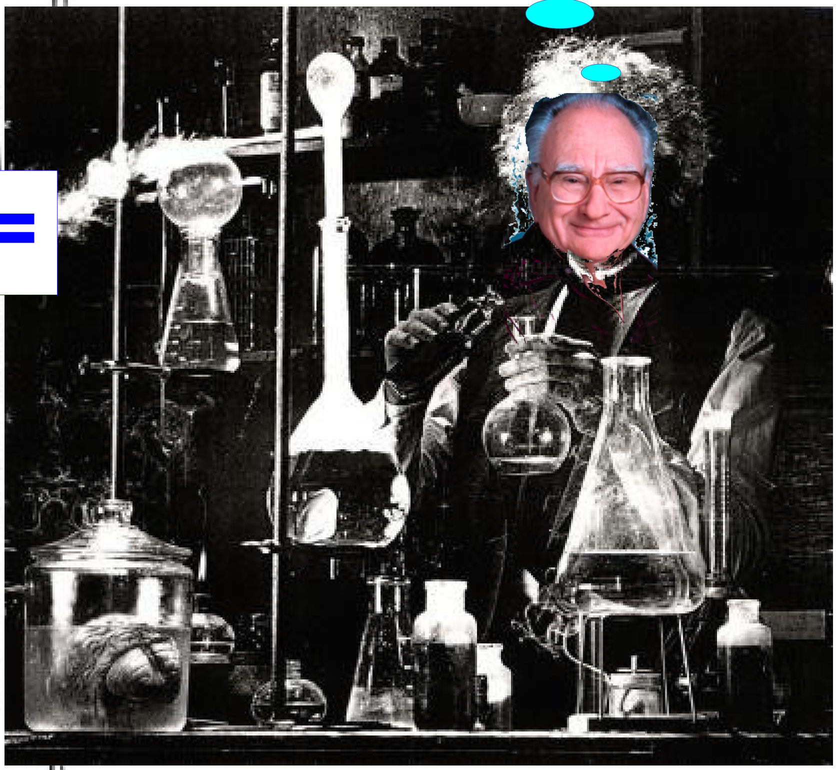


"No doubt about it, ***Art*** —we've mathematically expressed the purpose of the universe. Gad, how I love the thrill of scientific discovery!"

Theorist work in Ivory Towers: the “Oops” moment



The Universe apparently ***does have*** a Purpose at 5 σ !



Experimentalists
Always have the
Last Word In Physics !!

I enjoyed being forced by Art’s data to look for missing terms in my equations

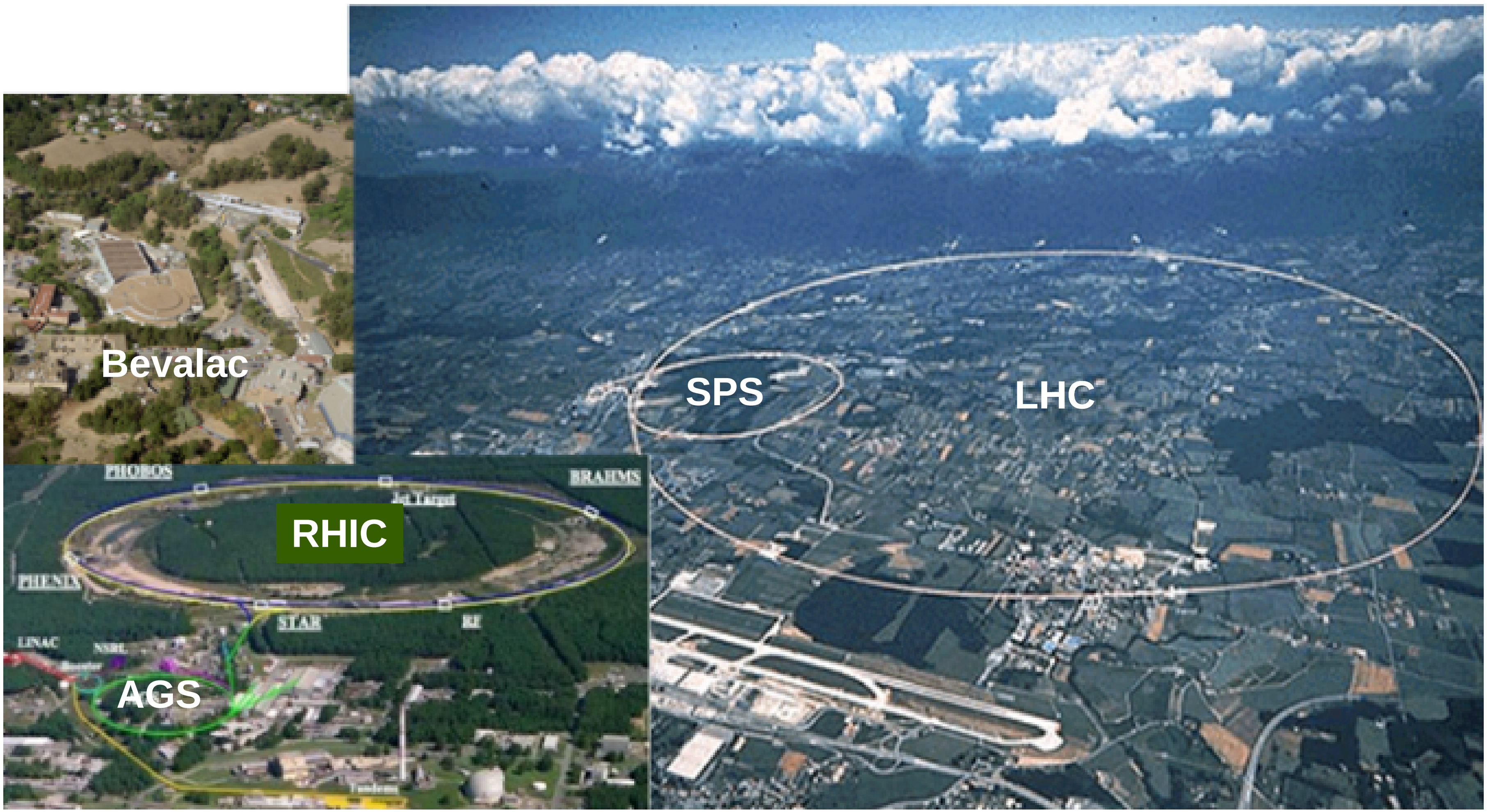
Art's Experimental Playgrounds

50, 000 Man Years of Exploration and Discovery of New Forms of QCD Matter

$\sqrt{s} = 1\ \mathrm{AGeV} - 5\ \mathrm{ATeV}$

Via p+p to p+Pb to Pb+Pb

50 years of A+A accelerator and detector development from 1972 - today



I started my PhD thesis with **Wladek Swiatecki** at UCB **1972**, Art was of course measuring data

Nuclear Physics **A192** (1972) 517

SEARCH FOR SUPER-HEAVY ELEMENTS PRODUCED BY SECONDARY REACTIONS IN URANIUM

L. WESTGAARD, B. R. ERDAL †, P. G. HANSEN ††, E. KUGLER, G. SLETTEN ††† and S. SUNDELL
CERN, Geneva, Switzerland,

T. FRITSCH, E. HENRICH, W. THEIS and G. K. WOLF
Lehrstuhl für Radiochemie, University of Heidelberg, Germany,

J. CAMPLAN, R. KLAPISCH, R. MEUNIER and A. M. POSKANZER ‡
Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, Orsay, France

Lawrence Berkeley Lab

NUCLEAR REACTIONS natural U (p, secondary reactions); $E = 24$ GeV; measured production σ for ^{236,238,239}Pu, ^{241}Am, ^{242}Cm, ^{248}Cf; deduced upper

Wladek worked on the theory of **super-heavy Z~114 N~184** gedanken elements and the theory of their **production via few MeV/A A+B**.

Walter Greiner came to UCB in 1972 to give a seminar on **high Z >137 QED in U+U** and **nuclear shock waves in super*sonic* A+B**. These ideas inspired me to work on A+A.

As the beam energies increased over 50 years, my wavefunction inevitably became highly “entangled” with Art’s and led to frequent “actions at a distance” that I have greatly enjoyed and profited from

BEV/NUCLEON COLLISIONS OF HEAVY IONS - HOW AND WHY

November 29–December 1, 1974

Bear Mountain, New York

Bear Mountain workshop launched relativistic A+A physics in 1974 !

Session I. Chairman: R. Serber

Session II. Chairman: J. Weneser

HEAVY ION ACCELERATION AT THE BEVATRON * **eConf C710920 (1971) 574**

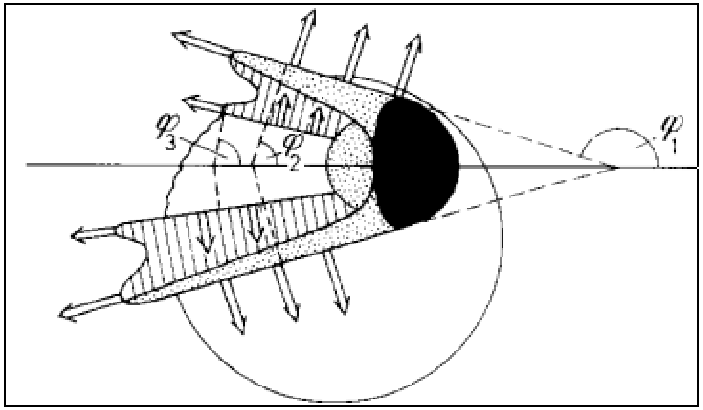
H.A. Grunder, W.D. Hartsough, H.H. Heckmann and E.J. Lofgren created BEVALAC

Chapline, G.F., Johnson, M.H., Teller, E., Weiss, M.S.: PRD (1973) Highly Excited Nuclear Matter

Nuclear Shock Waves in Relativistic Heavy Ion Collisions

W. Scheid (Frankfurt U.), J. Hofmann (Frankfurt U.), W. Greiner (Frankfurt U.) (1974)

PRL 32, 741 (1974)

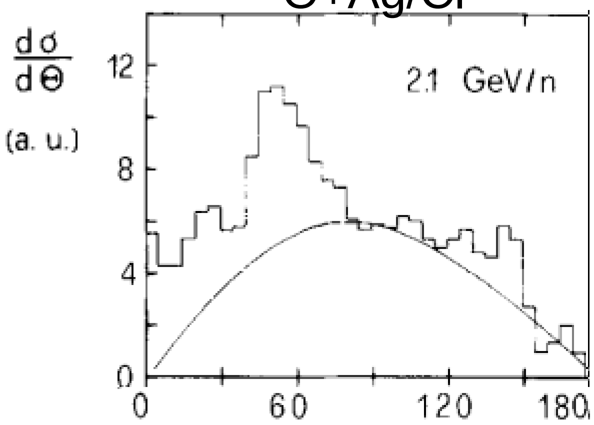


Shock Waves and MACH Cones in Fast Nucleus-Nucleus Collisions

H.G. Baumgardt (Frankfurt U.), J.U. Schott (Frankfurt U.), Y. Sakamoto (Frankfurt U.), E. Schopper (Frankfurt U.), Horst Stoecker (Frankfurt U.) et al. (1975)

Published in: Z.Phys.A 273 (1975) 359-371

O+Ag/Cl



First emulsion data appeared to confirm ideal Landau hydrodynamic predictions of Mach cones in super***sonic*** A+B reactions

PRL VOLUME 44 12 MAY 1980 NUMBER 19

Emission Patterns in Central and Peripheral Relativistic Heavy-Ion Collisions

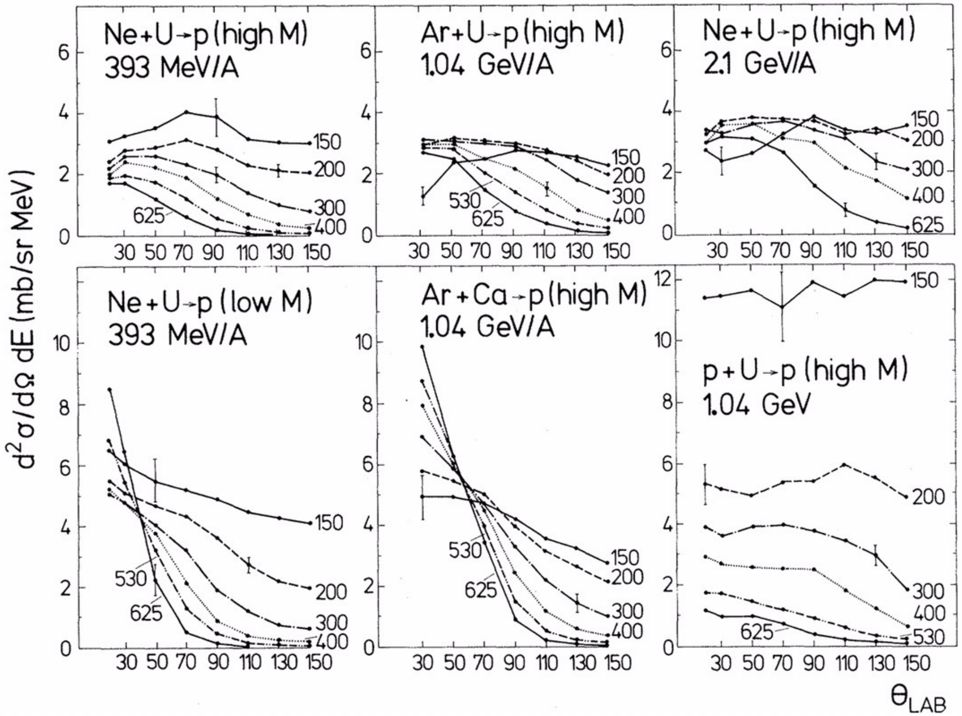
R. Stock, H. H. Gutbrod, W. G. Meyer,[a] A. M. Poskanzer, A. Sandoval, J. Gosset,[b] C. H. King,[c] G. King,[d] Ch. Lukner, Nguyen Van Sen,[e] G. D. Westfall, and K. L. Wolf[f]
Lawrence Berkeley Laboratory, Berkeley, California 94720, and Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, West Germany, and Fachbereich Physik, Universität Marburg, D-3550 Marburg, West Germany
(Received 10 December 1979)

Proton emission in relativistic nuclear collisions is examined for events of low and high multiplicity, corresponding to large and small impact parameters. Peripheral reactions exhibit distributions of protons in agreement with spectator-participant decay modes. Central collisions of equal-size nuclei are dominated by the formation and decay of a fireball system. Central collisions of light projectiles with heavy targets exhibit an enhancement in sideward emission which is predicted by recent hydrodynamical calculations.

It took ~10 years
for theory to catch up
to the data

and extract constraints
on the nuclear equation
of state

$P(\rho_B, T)$



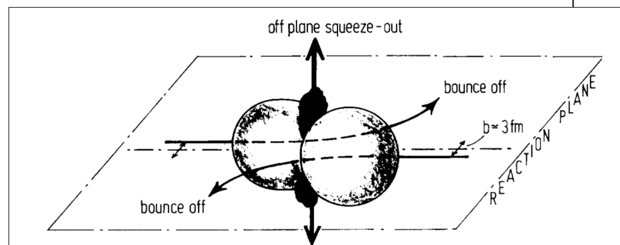
H. Gutbrod, **A. Poszkanzer**, **H.J. Ritter**
Rep. Prog. Phys.52 (1989) 1267

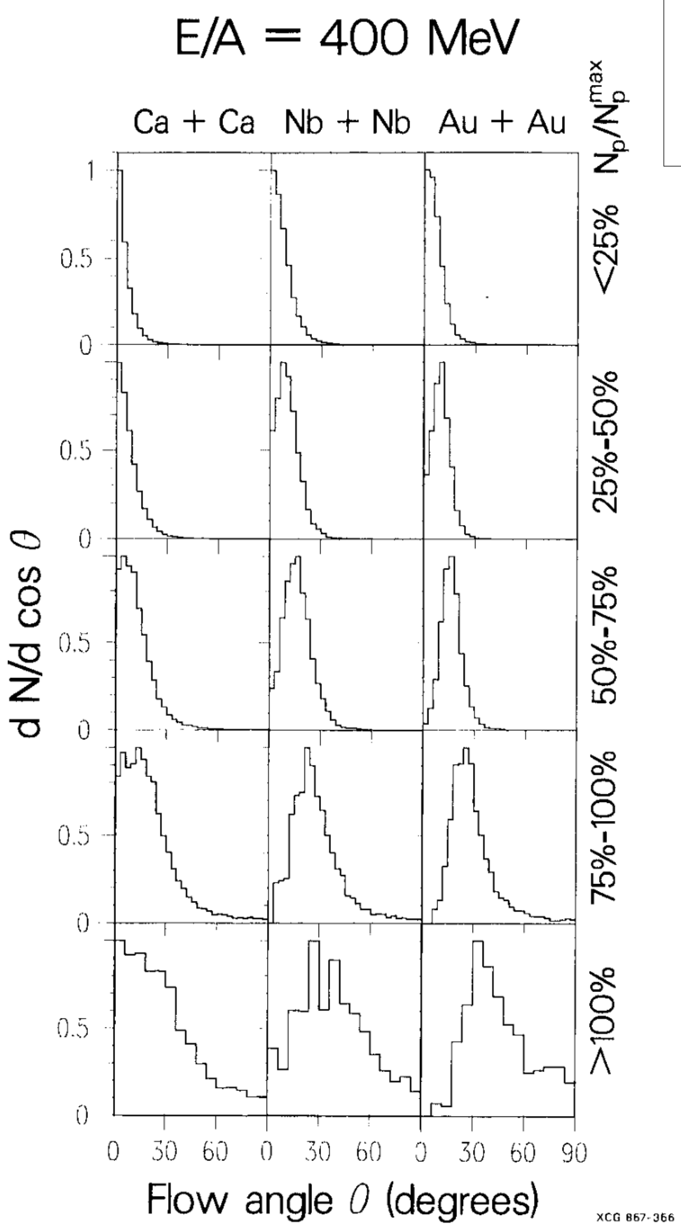
HIGH ENERGY HEAVY ION COLLISIONS – PROBING THE EQUATION OF STATE OF HIGHLY EXCITED HADRONIC MATTER

Horst STÖCKER and Walter GREINER

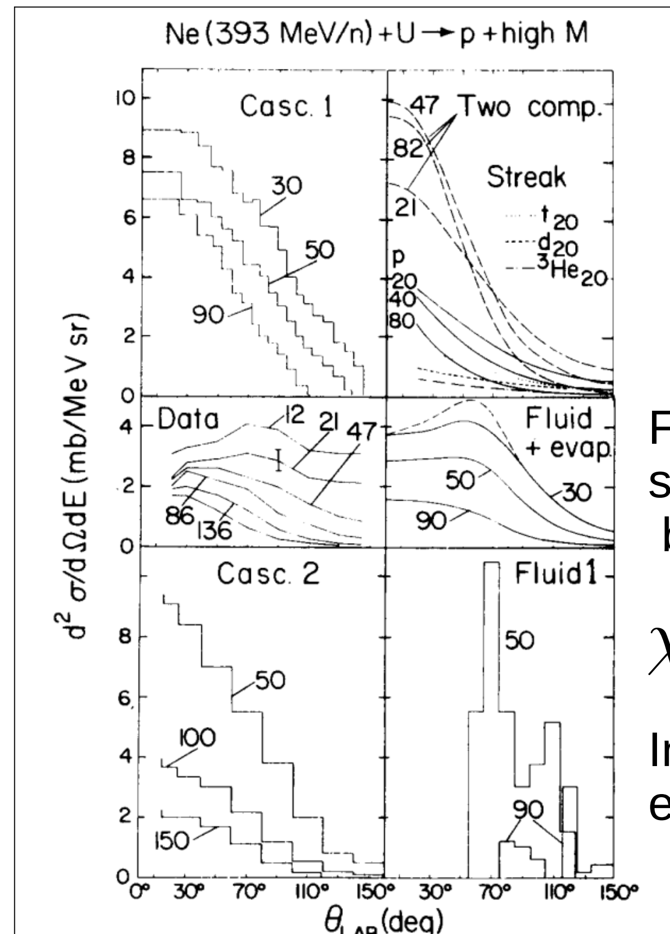
Phys.Rep.137 (1986) 277

Plastic Ball Data provided conclusive evidence for collective flow in Au+Au





1980 data falsified many early models
Csernai et al, PRL47 (1981) 1807

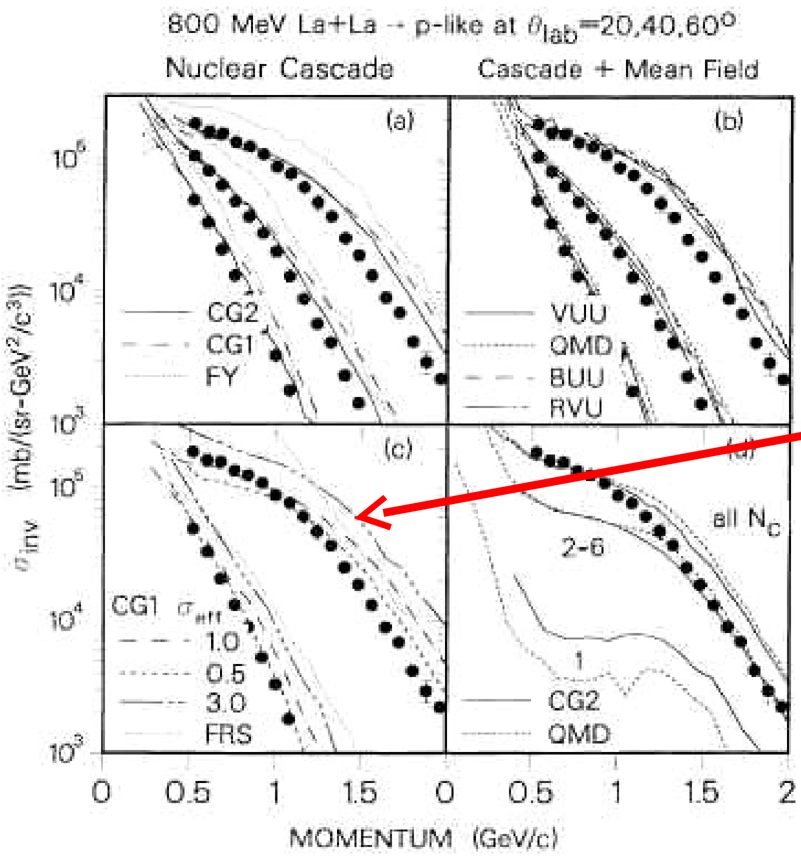


Fluid+Evap survived but no χ^2/dof

In those early years

Comparison of Nuclear Transport Models with 800A-MeV La+La Data

J. Aichelin,[1] J. Cugnon,[2] Z. Fraenkel,[3] K. Frankel,[4] C. Gale,[5] M. Gyulassy,[6] D. Keane,[7] C. M. Ko,[8] J. Randrup,[6] A. Rosenhauer,[9] H. Stöcker,[10] G. Welke,[11] and J. Q. Wu[8]



The results in Fig. 1(c) show that no simple rescaling of those cross sections is satisfactory. It is possible that momentum-dependent effective cross sections, reducing from free-space values for low-momentum nucleons to about half that value for the

Data Prefer $\sigma_{eff} : \frac{1}{2}\sigma_{NN}$

FIG. 1. Comparison of nuclear transport calculations to data (Ref. 13). (a) Comparison of Cugnon cascade model versions CG1 (Ref. 3) and CG2 (Ref. 14) with the Fraenkel-Yariv cascade model FY (Ref. 2). (b) Comparison of momentum-independent VUU (Ref. 8) and QMD (Ref. 12) with $K=380$ MeV, to momentum-dependent BUU (Ref. 9) with $K=210$ MeV, and relativistic RVU (Ref. 11). (c) Effects at 20° and 60° of rescaling the free-space NN cross sections in CG1 by factors of 0.5, 1.0, and 3.0. The dotted curves show results of the FREESCO fireball model FRS (Ref. 17). (d) The contributions to the 20° yield for QMD and CG2 from single-collision ($N_c=1$) and multiple-collision ($N_c=2$–6) components.

S.Nagamiya etal spectrometer data
Did not show flow in La+La !

Highly Relativistic Nucleus-Nucleus Collisions: **The Central Rapidity Region**

Soft Dynamics: Hydro

J.D. Bjorken, PRD 27 (1983) 140, cited so far ~ 3500 times !!

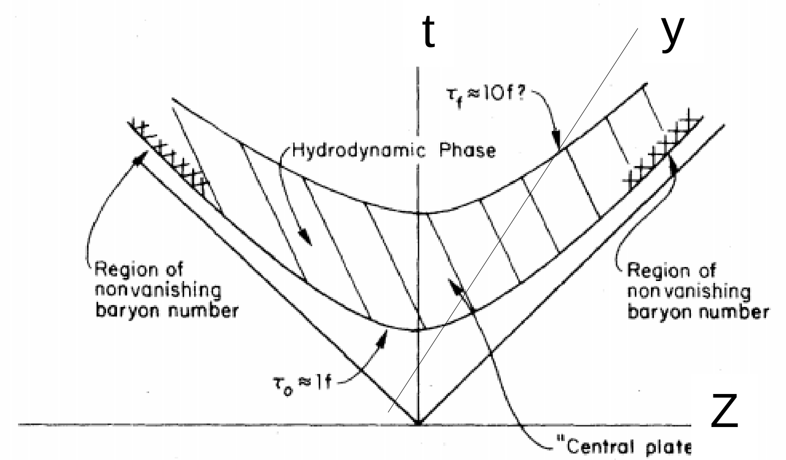


FIG. 3. Space-time diagram of longitudinal evolution of the quark-gluon plasma.

$$t = \tau \; cosh \; y$$
$$z = \tau \; sinh \; y$$

Ultra relativistic
Boost invariant 1 + 1 dim
Baryon free ***QGP*** * hydrodynamics

$$E = m_\perp \; cosh \; y$$
$$p_z = m_\perp \; sinh \; y$$

Hard Dynamics: pQCD

Energy Loss of Energetic Partons in Quark - Gluon Plasma:
Possible Extinction of High **p(t) Jets** in ***Hadron - Hadron*** Collisions

J.D. Bjorken (Aug, 1982) unpublished but has ~ 400 citations!

Inspirehep does not point to a pdf , but the pdf can be found online at https://lss.fnal.gov/archive/1982/pub/Pub-82-059-T.pdf

* E. Shuryak invented term ***QGP*** in 1979 (Phys.Rep.61) (See his talk Sat 11am) and discussed both perturbative and non-perturbative QCD deg of freedom in the QGP

My 1982 compilation initial central energy density from the then few known cosmic ray events

Bjorken's
Inside-Outside
Energy density
At formation time

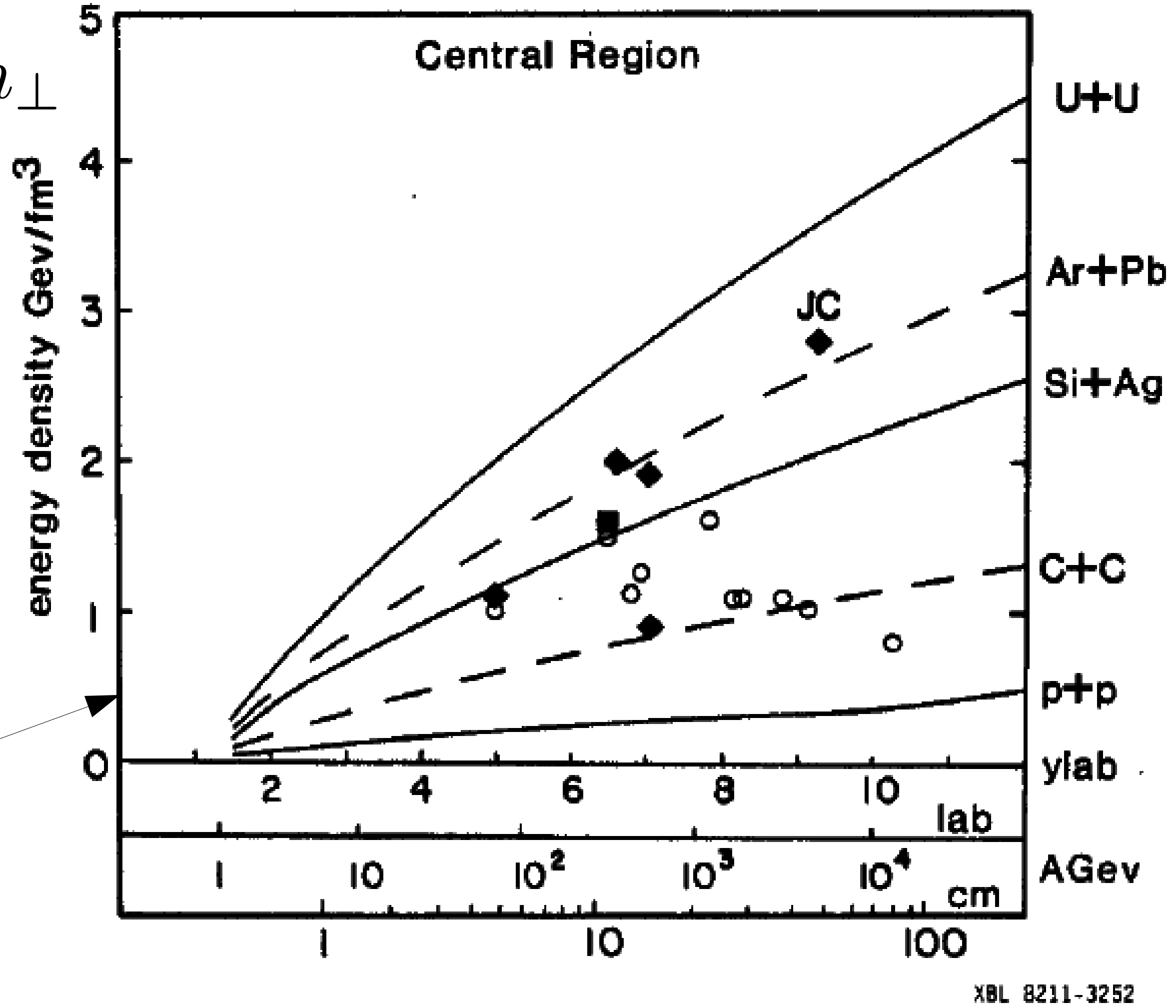
$$\tau = \hbar / m_\perp$$

$$\left(\frac{\mathbf{E}}{\mathbf{V}}\right)_{\mathbf{form}} = \frac{\mathbf{m_T^2}}{\pi \mathbf{R^2}} \frac{dN}{dy}$$

Larry Mc and I used such estimates to support G. Baym's 1983 NSAC LRP case for RHIC construction

$$\epsilon_N = 0.5 GeV/fm^3$$

MG, LBL-14512, LBL-15175 (1982)



Maximum energy density achieved in low baryon density regions[14] (midrapidity). Eq. (19) was used to convert measured multiplicities [12,13] into proper energy densities. Diamonds correspond to Si + Ag, square to Ar + Pb, open circles to "light" (α, B, C, N) + Ag collisions. Theoretical estimates for various systems are based on eqs. (19,21) using tube-tube geometry as discussed in text.

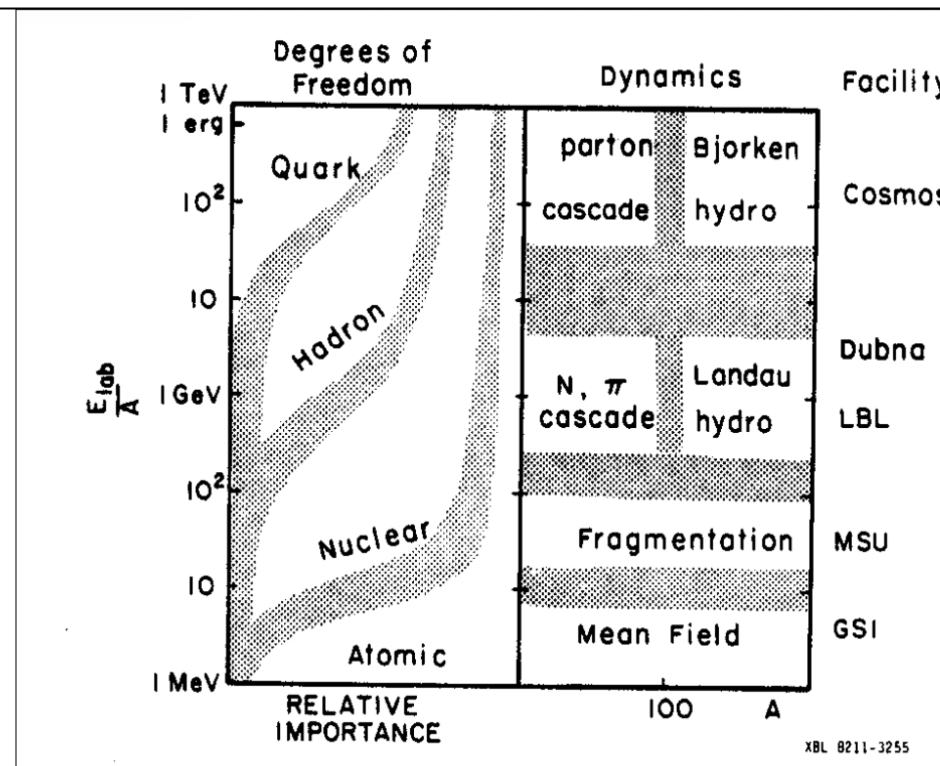
Presented at the Workshop on Experiments and Detectors for RHIC
Upton, NY, July 2-7, 1988 (July 1990 LBL-29488)

Concept for an Experiment on Particle and Jet Production at Midrapidity

J.W. Harris,[7] M. Bloomer,[7] P. Brady,[1] J. Carroll,[2] S.I. Chase,[7] W. Christie,[7] J. Cramer,[12] E. Friedlander,[7] D. Greiner,[7] C. Gruhn,[7] M. Gyulassy,[7] T. Hallman,[4] E. Hjort,[10] G. Igo,[2] P. Jacobs,[7] K. Kadija,[13] D. Keane,[5] L. Madansky,[4] C. Naudet,[7] D. Nygren,[7] G. Odyniec,[7] D. Olson,[7] G. Paic,[13] A. Poskanzer[7] G. Rai,[7] H.G. Ritter,[7] R. Scharenberg,[10] L.S. Schroeder,[7] P. Seidl,[7] P. Seyboth,[8] D. Shy,[7] R. Stock,[3] T.J. M. Symons,[7] L. Teitelbaum,[7] M.L. Tincknell,[9] H. van Hecke,[6] X.N. Wang,[7] R. Welsh,[4] W. Wenzel,[7] H. Wieman,[7] and K.L. Wolf[11]

Art's interest in the STAR detector
was to measure collective (Soft) hydrodynamic
radial and elliptic "flow" observables in
Ultra-relativistic A+A
as degrees of freedom evolve from
initial quarks+gluons to final state hadronic .

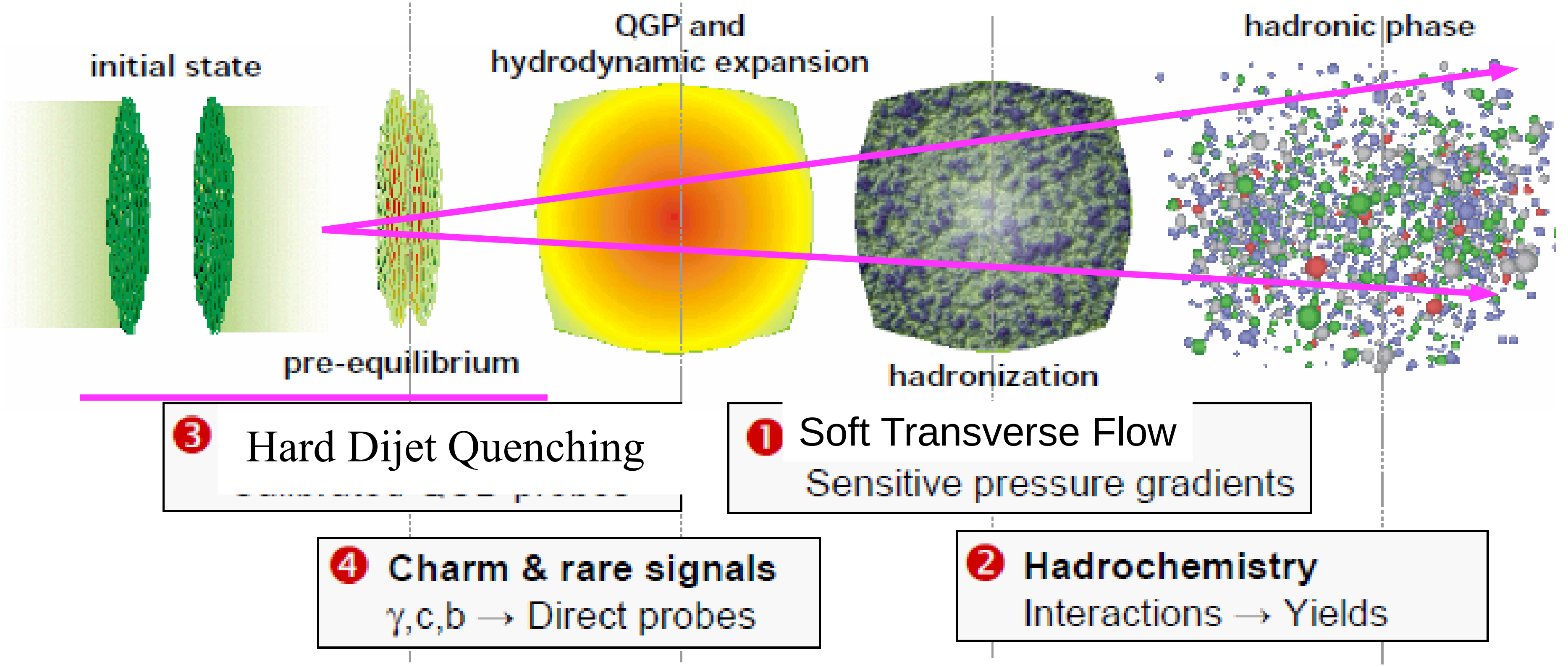
MG and XNW were "Theoretische Mitfahrer"
to make cartoons and falsifiable predictions
in their proposal



MG 12/9/22

The ***harrowing*** *task : (still in progress today 2022)*
of deconvoluting Multiple components that must be theoretically and exp controlled to enable unambiguous interpretation of high energy A+A data

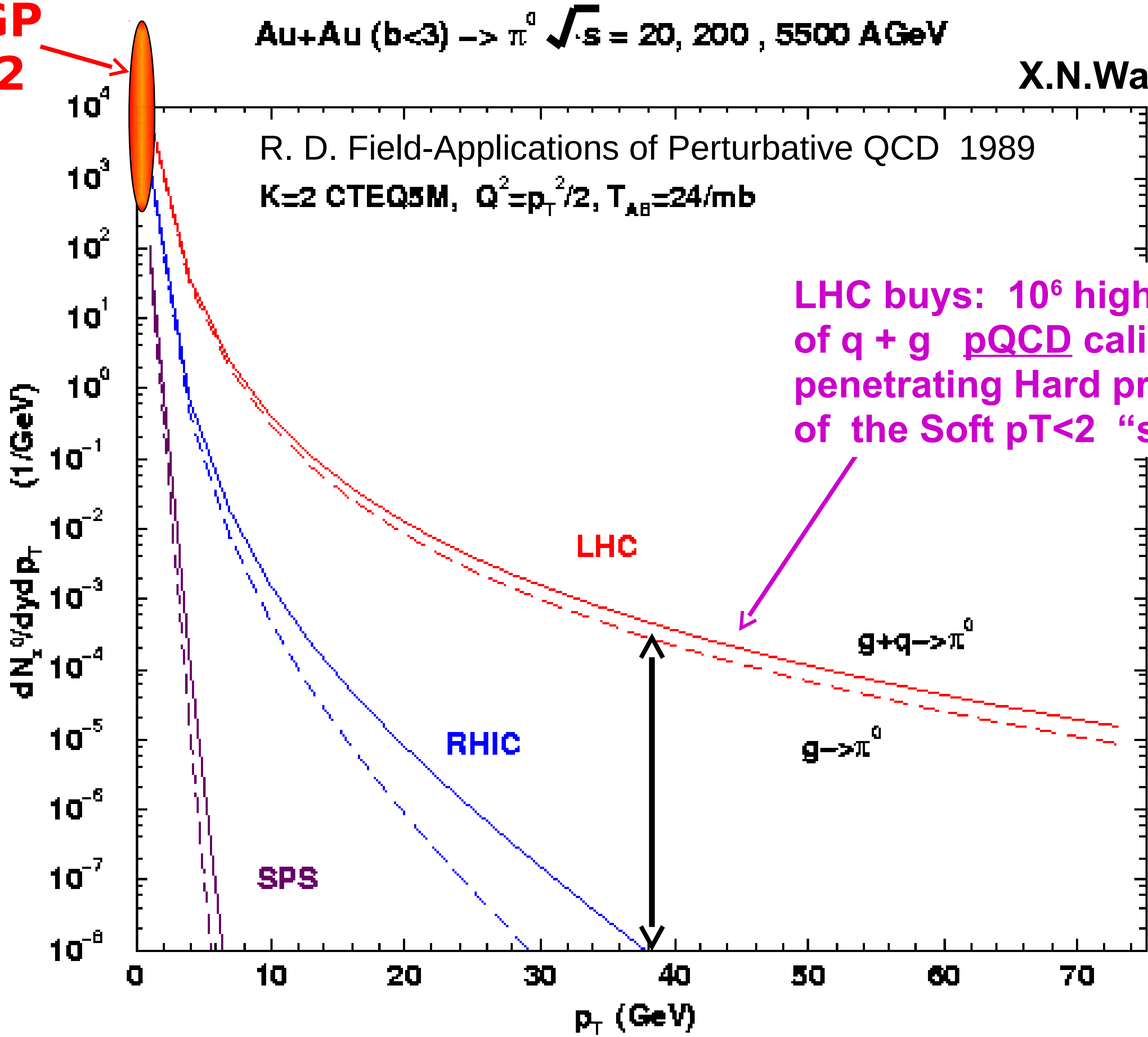
S.Bass's Iconic Cartoon



How to propagate *theoretical* systematic uncertainties after each step?

Can we de-convolute the tsunami of data at RHIC and LHC to distinguish and test each step?

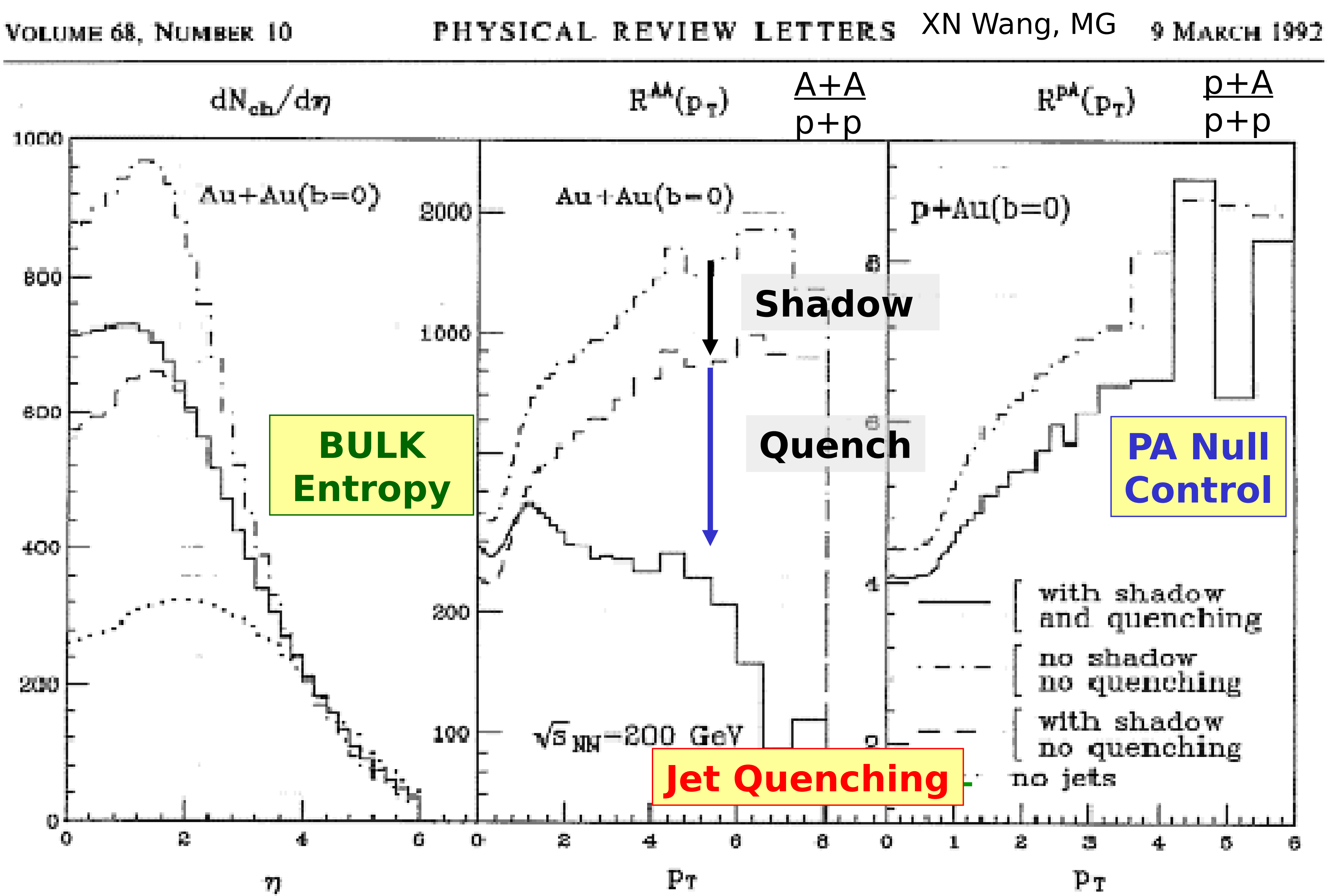
sQGP
$p_T<2$



X.N.Wang,I.Vitev,MG

LHC buys: 10^6 higher flux of q + g <u>pQCD</u> calibrated penetrating Hard probes of the Soft pT<2 "sQGP"

High pT "hard" observables probe the "soft" sQGP fluid

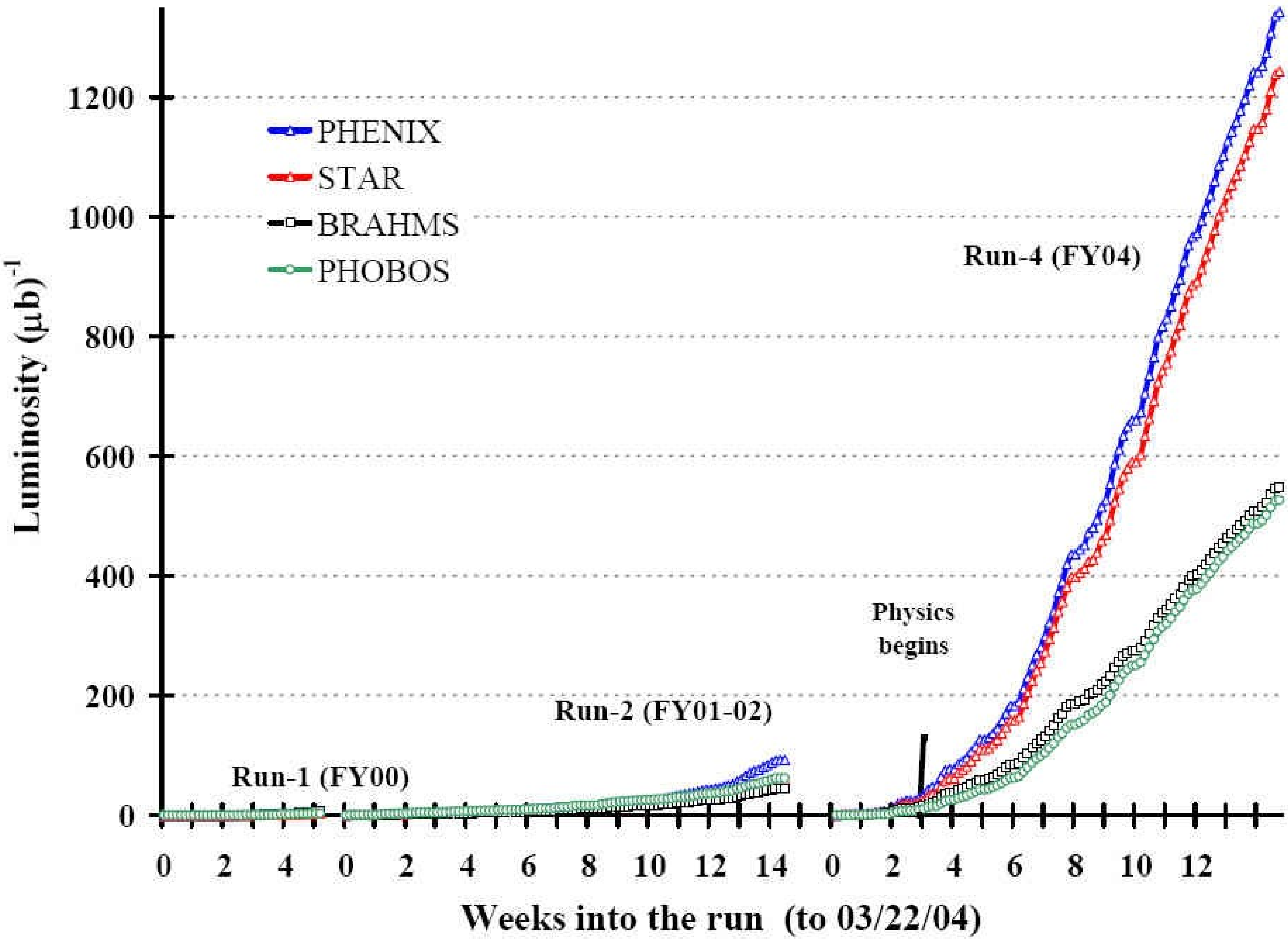


HIJING = multi minijets + strings Monte Carlo
Predictions for RHIC at 200 AGeV cm

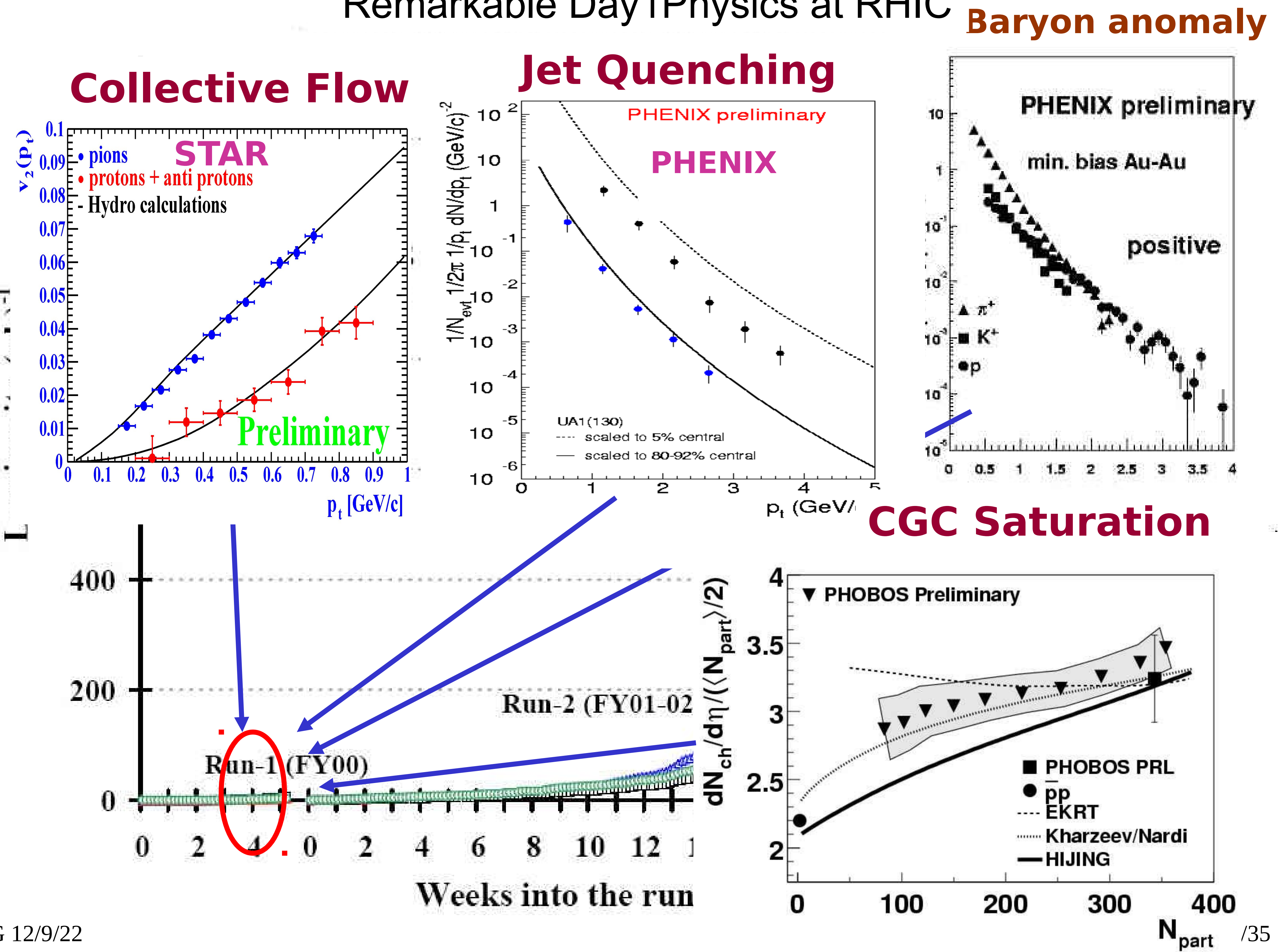
Four detectors

1200 Physicists 50 Countries 2000 Publications

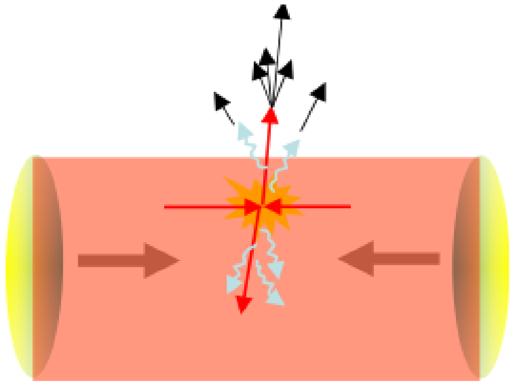
RHIC Delivered Au-Au Luminosity



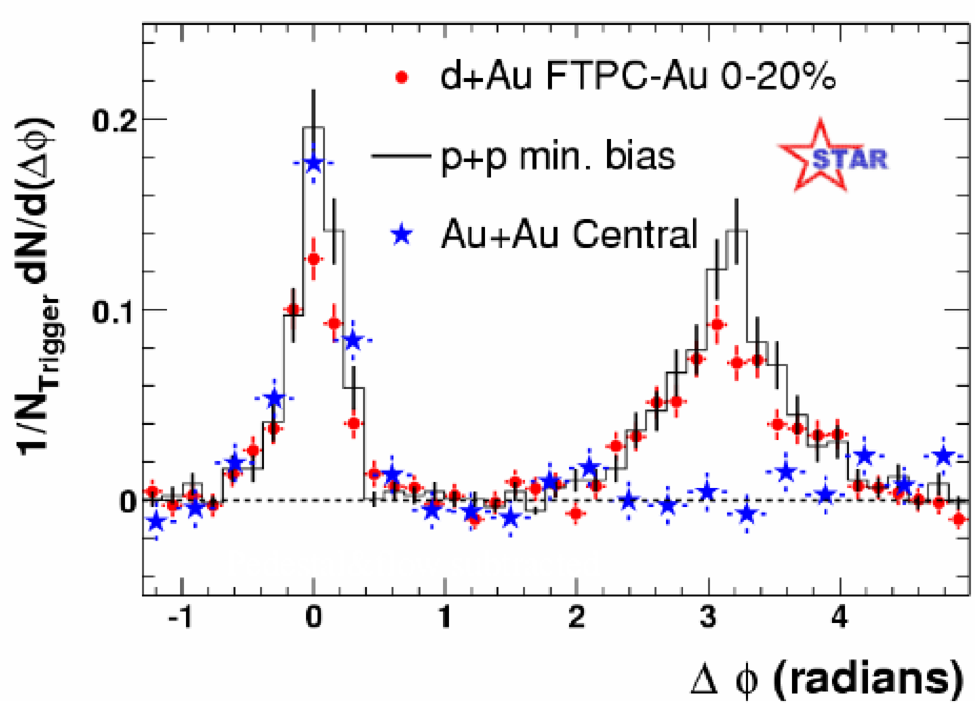
Remarkable Day1Physics at RHIC



Hard (pT>2) jets and dijets jet fragments quenched



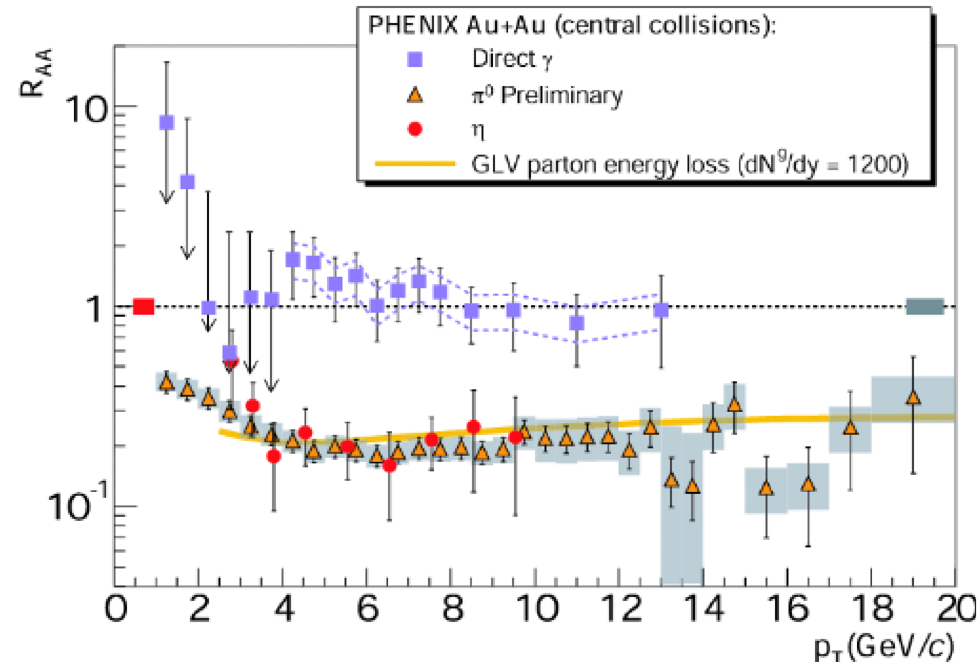
"Return of the Jeti" P.Jacob's baby



Away side suppression ***Only*** in AA

$4 < p_T(trig) < 6$ GeV/c

$p_T(assoc) > 2$ GeV/c

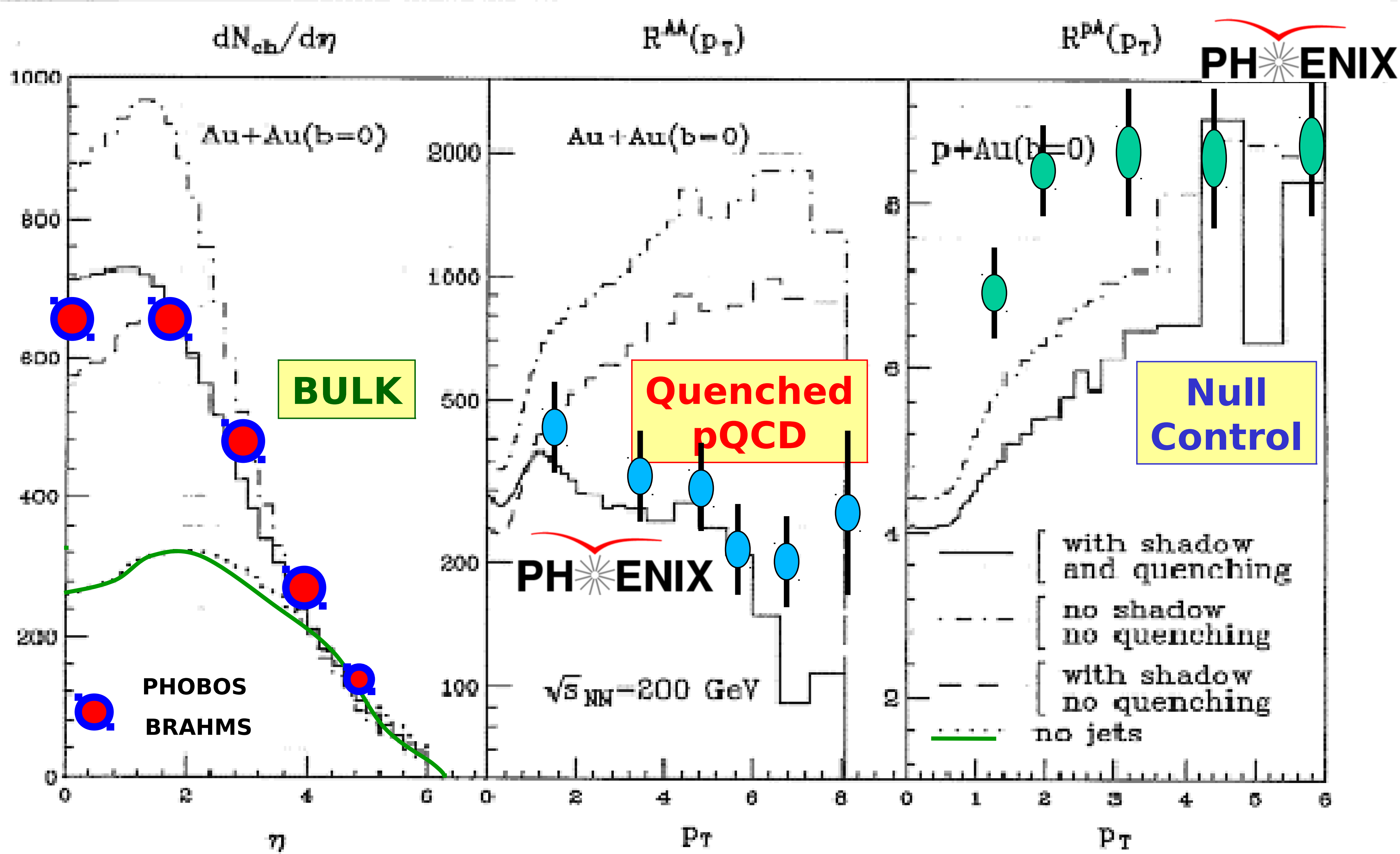


direct photons ***NOT*** Quenched
But hadronic jet fragments frag
quenched as predicted via GLV

PHENIX

HIJING three home runs around these bases in 2003

VOLUME 68, NUMBER 10 PHYSICAL REVIEW LETTERS XN Wang, MG 9 MARCH 1992



Our HIJING predictions could explain the Hard jet fragment data,
But it had nothing to say about the Soft collective flow data!

P.F. Kolb, U.W. Heinz, P. Huovinen, K.J. Eskola, K. Tuominen, NPA 696 (2001) 197
D. Teaney, J. Lauret, E.V. Shuryak, Phys. Rev. C 68 (2003) 034913; ...

Fig. 8 shows the striking ***Soft*** collectivity elliptic flow signature of QGP formation at RHIC. Unlike at SPS and lower energies, the observed large elliptic deformation $((1+2v_2)/(1-2v_2) \sim 1.5)$ of the final transverse momentum distribution agrees for the first time with non-viscous hydrodynamic predictions [48–60] at least up to about $p_T < 2$

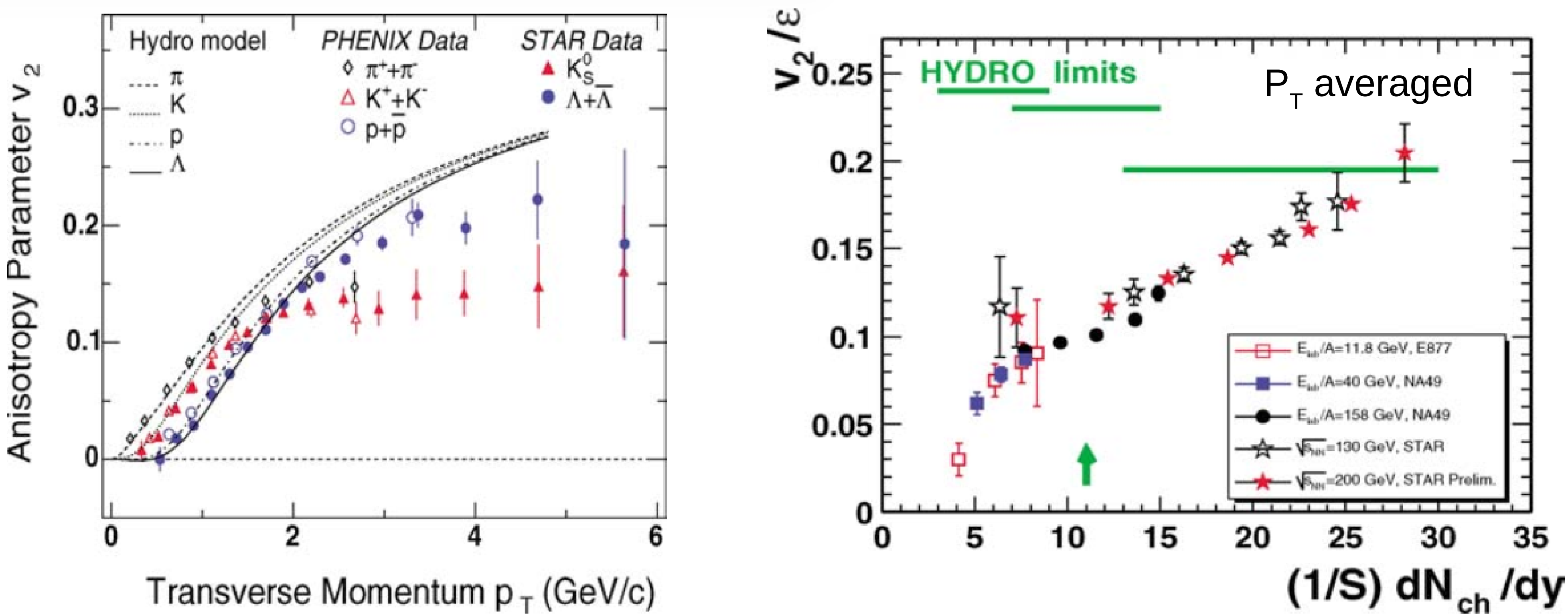


Fig. 8. First line of evidence: bulk collective flow is the barometric signature of QGP production. Left figure combines STAR [43–46] and PHENIX [47] measurements of the azimuthal elliptic flow ($v_2(p_T)$) of π, K, p, Λ in Au + Au at 200 A GeV. The predicted hydrodynamic flow pattern from [48–52] agrees well with observations

see **"New forms of QCD matter discovered at RHIC"**, M. Gyulassy, L. McLerran NPA 750 (2005) 30

Three Lines of Empirical Evidence in 2004 converged to sQGP Discovery

QGP $= P_{QCD}$ + pQCD + dA = v_2 + $(R+I)_{AA}$ + $(R+I)_{DA}$

Unique long wavelength collective properties

Elliptic flow ⬄ P_{QCD}

Unique short wavelength dynamical properties

Jet Quenching ⬄ pQCD

Conclusive Null Control with D+Au

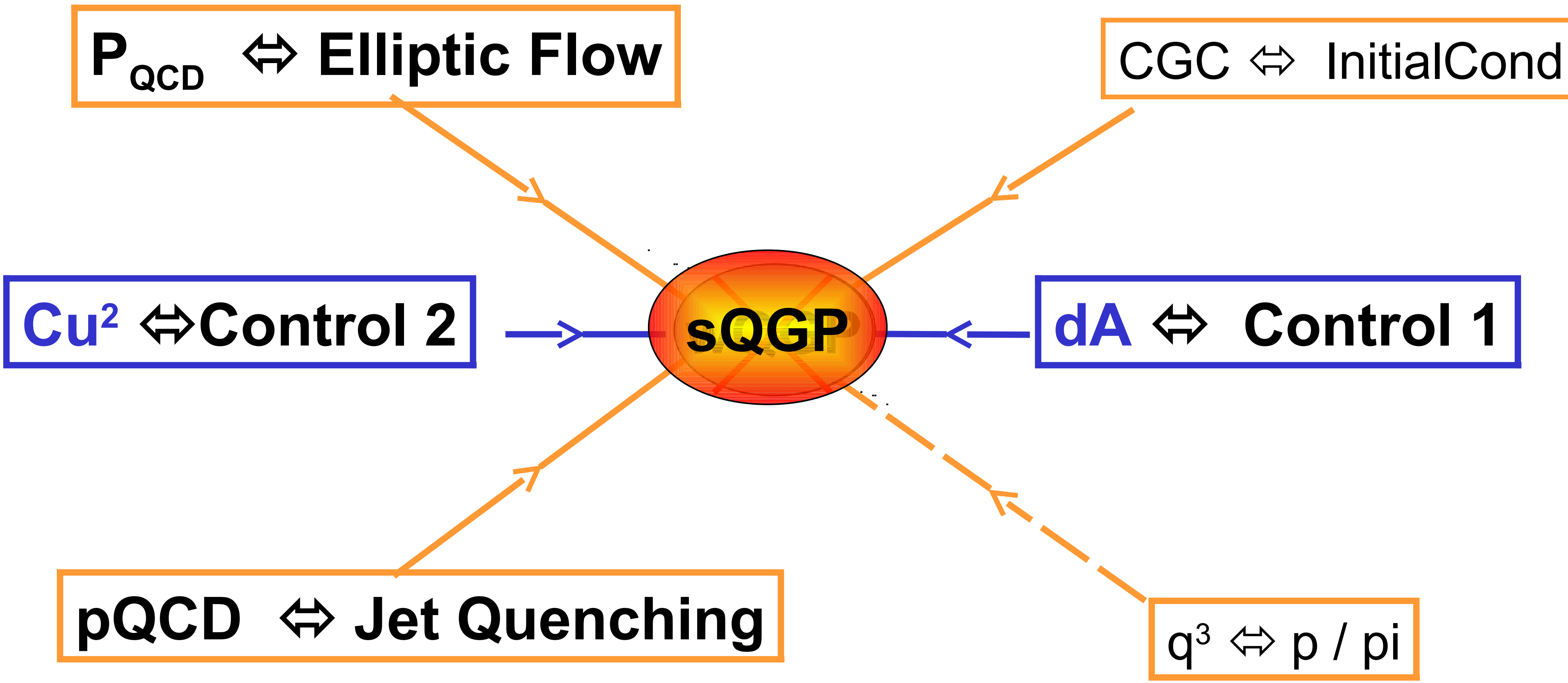
RHIC QGP = sQGP ≠ wQGP

"New forms of QCD matter discovered at RHIC", M. Gyulassy, L. McLerran NPA 750 (2005) 30

"**What RHIC experiments and theory tell us about properties of quark-gluon plasma?"**, E.V.Shuryak,ibid p64

2006 Update of
2004 MG, LMc

Empirical Evidence at RHIC for sQGP and CGC

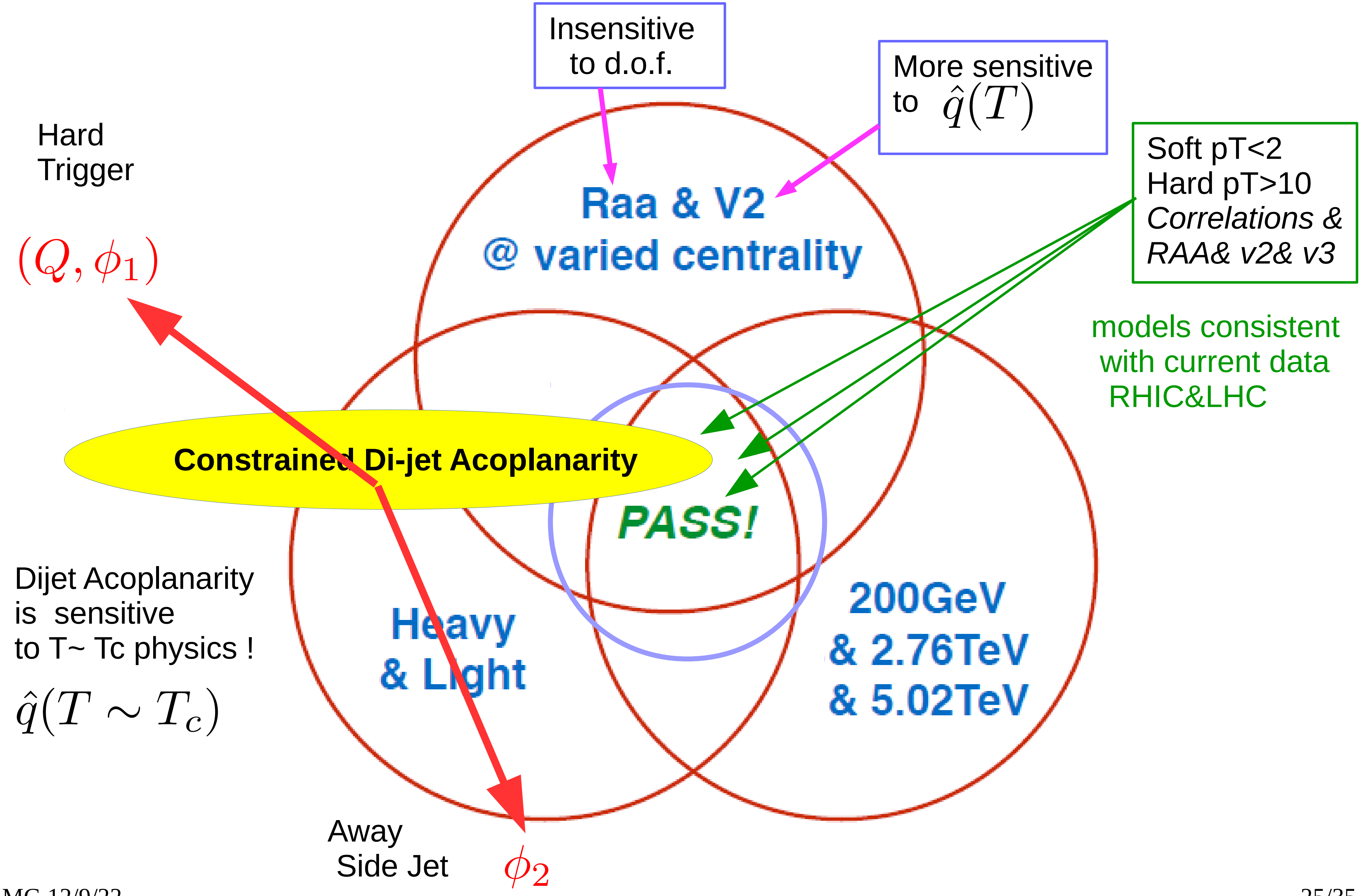


$$sQGP = P_{QCD} + pQCD + dA + Q_s + q^3 + \ldots$$

$$CGC = Q_s(y,A)$$

Summary Cartoon of Tasks ahead

RAA&v2 *Constrained* Dijet Acoplanarity Tomography can help to falsify competing models of the color d.o.f. in perfect QCD fluids produced at RHIC and LHC



Lattice QCD “data” constrained thermodynamics P(T), L(T), $\chi^u(T)$, μ_{E},(T), $\mu_M(T)$

“Fast deconfinement”

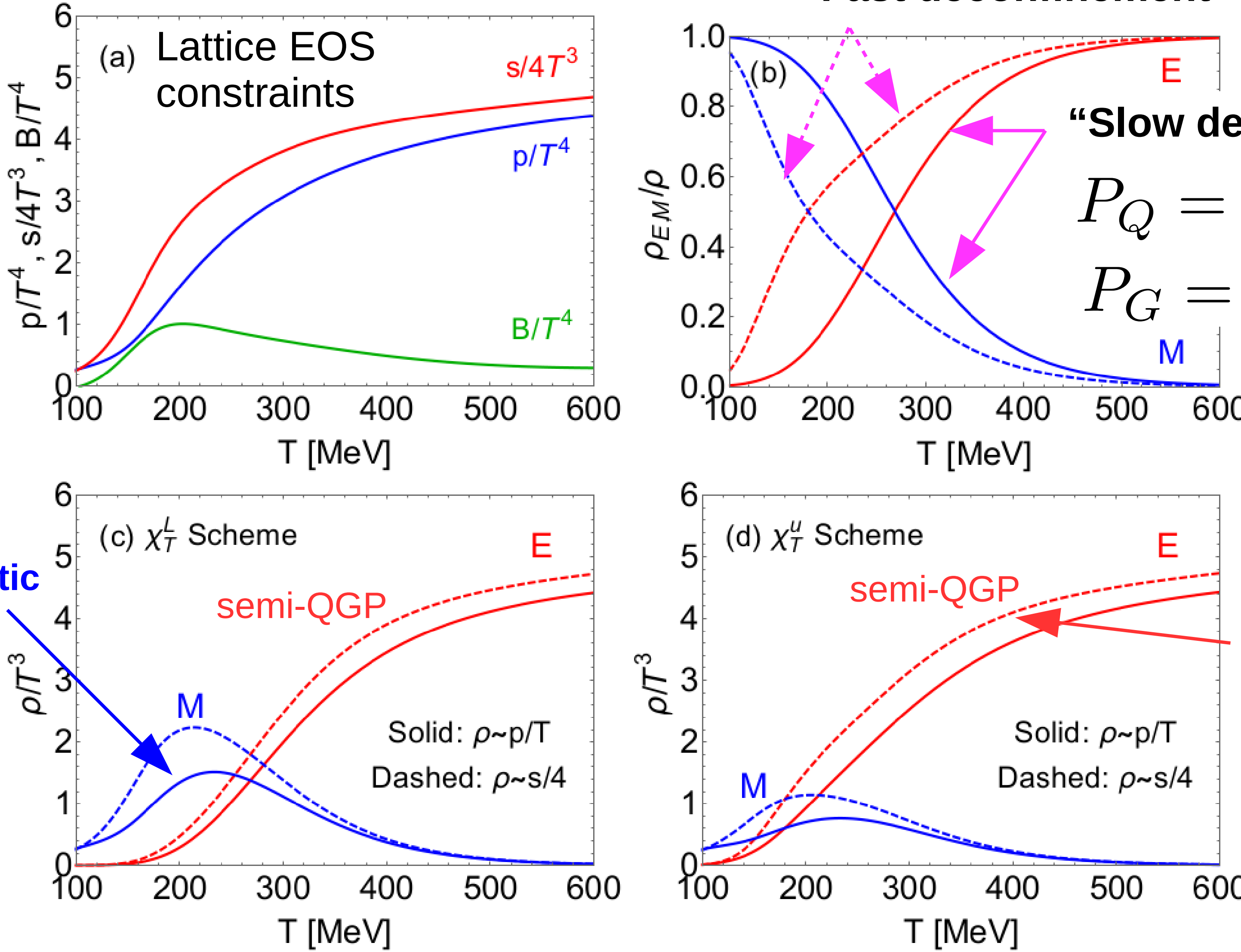
“Slow deconfinement”

$$P_Q = P_Q^{SB} L(T)$$

$$P_G = P_G^{SB} L^2(T)$$

Emergent
Color Magnetic Monopole d.o.f.
Shuryak, Liao (2007)

Suppressed Color Electric “<u>semi</u>-QGP”
Hidaka,Pisarski

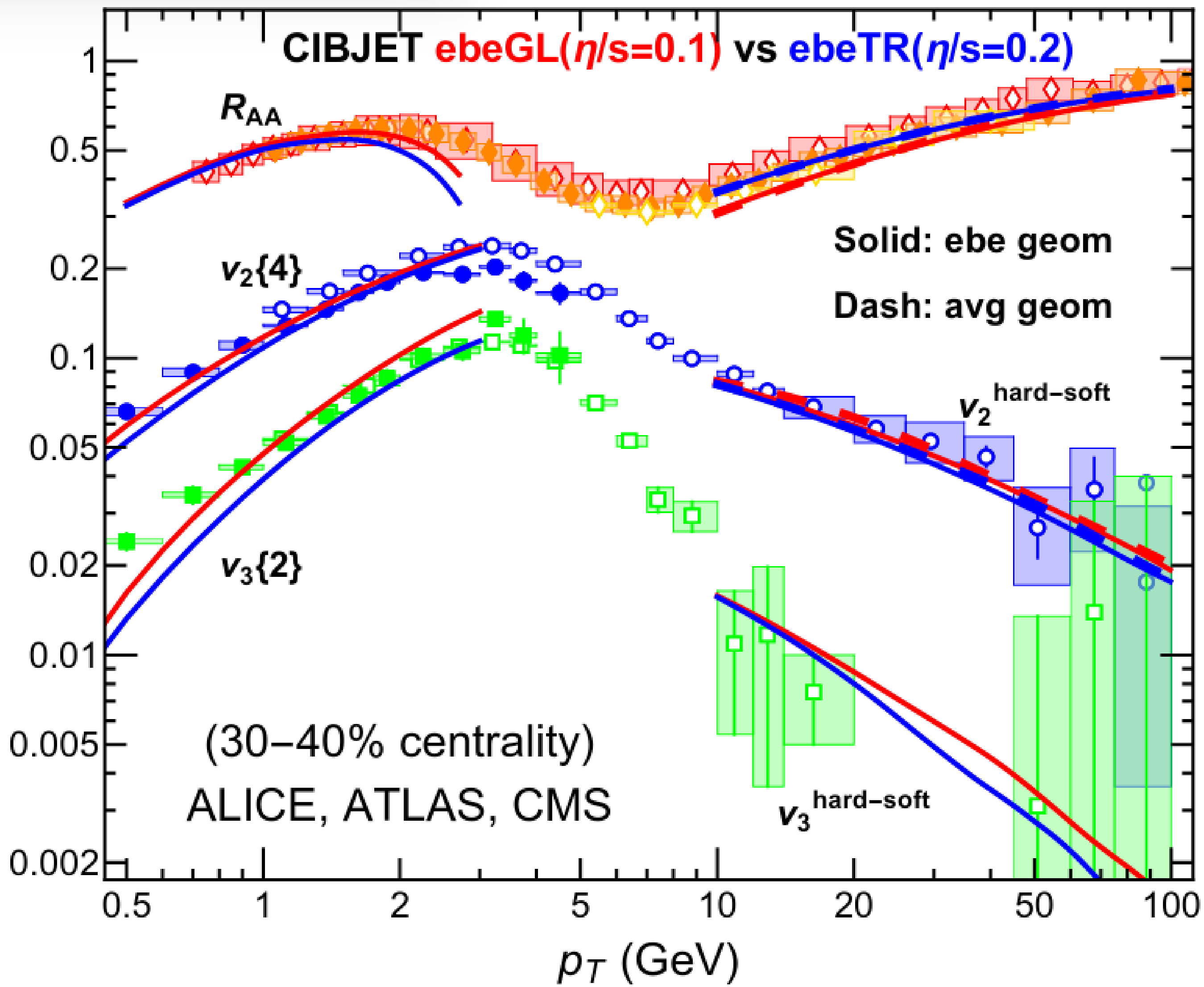


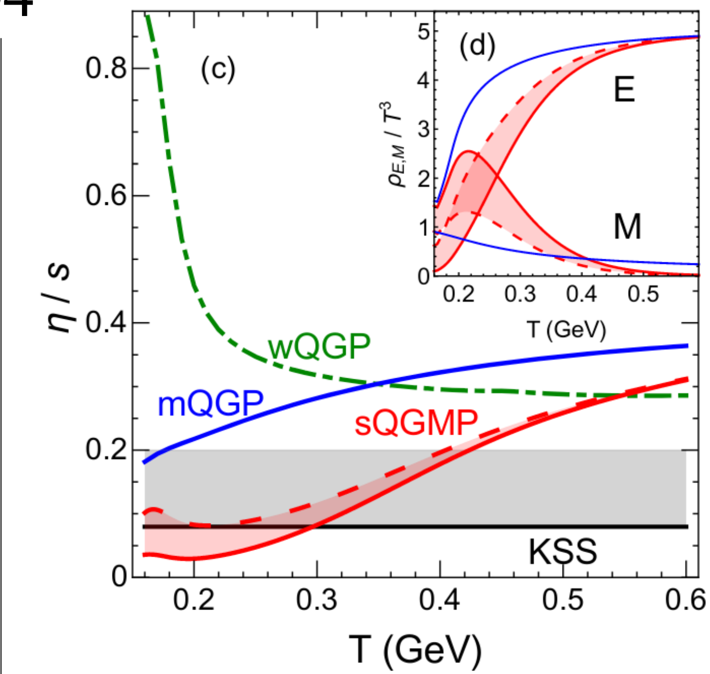
“sQGMP” is a lattice QCD constrained model of the 1974 suggestion by **t’Hooft, Polyakov and Mandelstam** that emergent color magnetic monopole d.o.f. may play an important role in confining color electric q and g d.o.f. at T<Tc

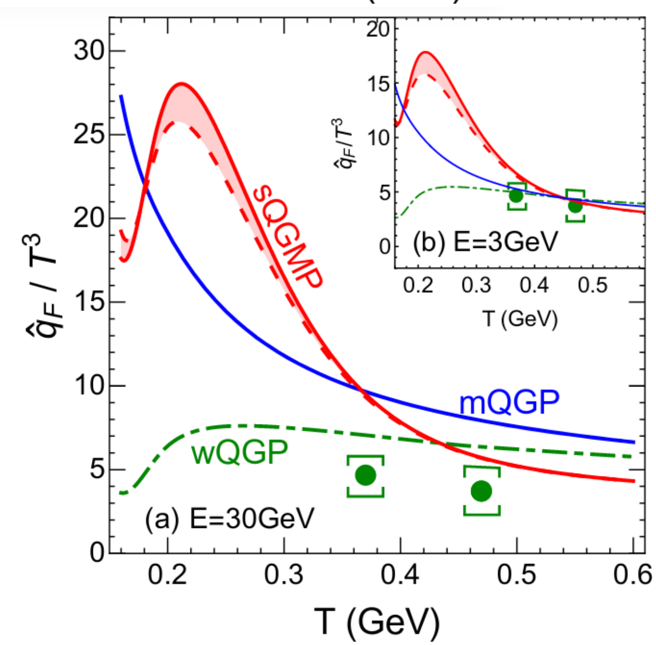
(See also B.Zakharov:1412.6287; Ramamurti, Shuryak, Zahed, 1802.10509)

Probing the Color Structure of the Perfect QCD Fluids via Soft-Hard-Event-by-Event Azimuthal Correlations

S.Shi, J.Liao. MG, Chin.Phys.C 42 (2018) 10, 104104







Art etal Practice on Bevalac and AGS waves

Art enjoyed waves and tried to ride them
All with over 1000 other exp colleagues

More serious waves and competitors at SPS

Alas he found perfect waves at RHIC and LHC

STAR,PHENIX,ALICE,CMS,ATLAS

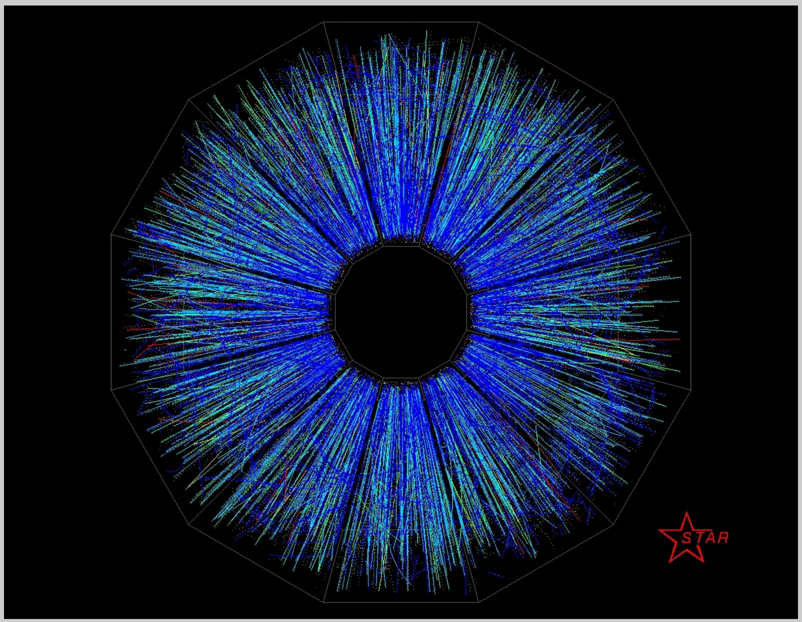
Physicists do have more fun. Thanks Art and LBNL to our half century of exciting physics.

We will never forget you

Appendix : 5th dimension overtime slides

that Art was certainly never fond of

Does Consistency of Soft Bulk Flow *and* Hard Jet Tomography force us to jump into a gedanken 5D AdS Black Hole to describe sQGP ?



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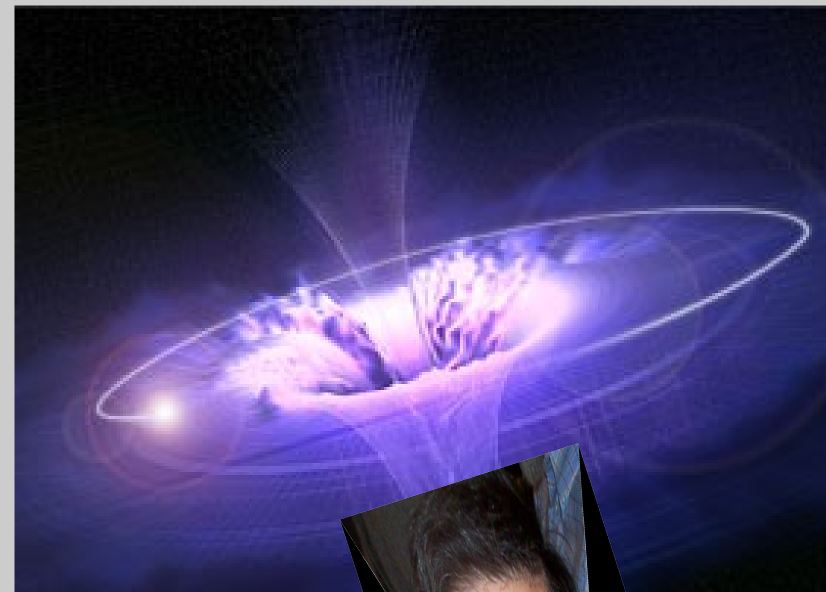


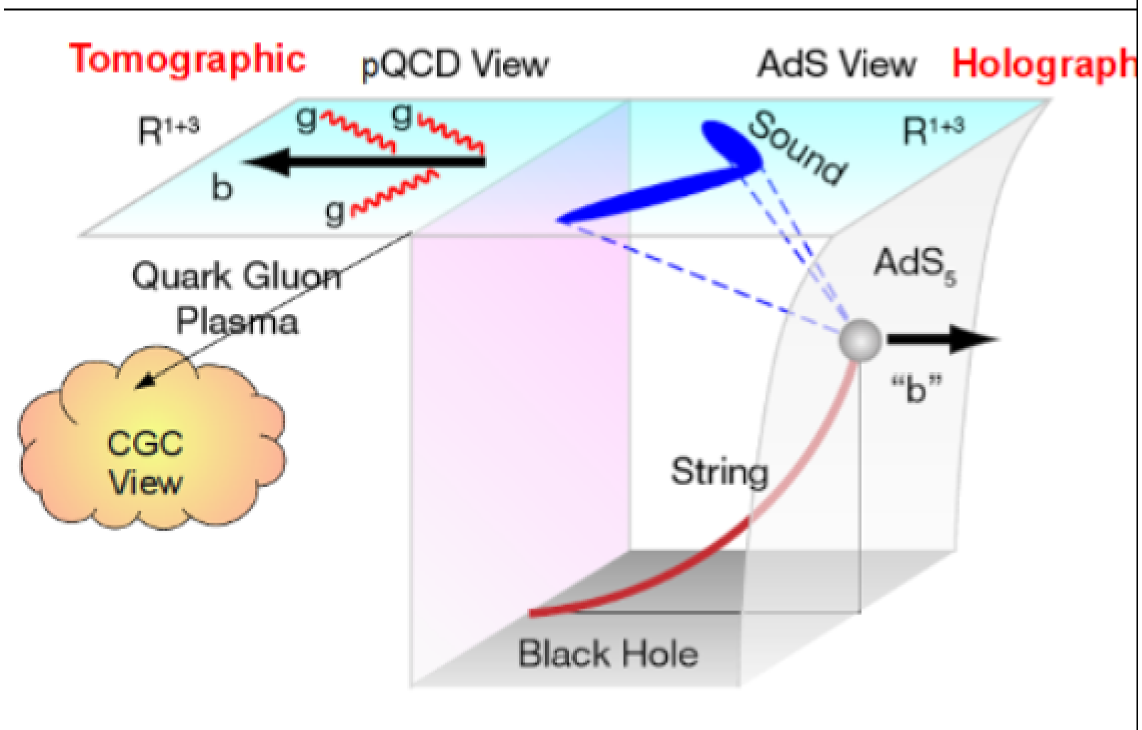
Ed

RHIC and LHC provide critical consistency tests of the competing dynamical models

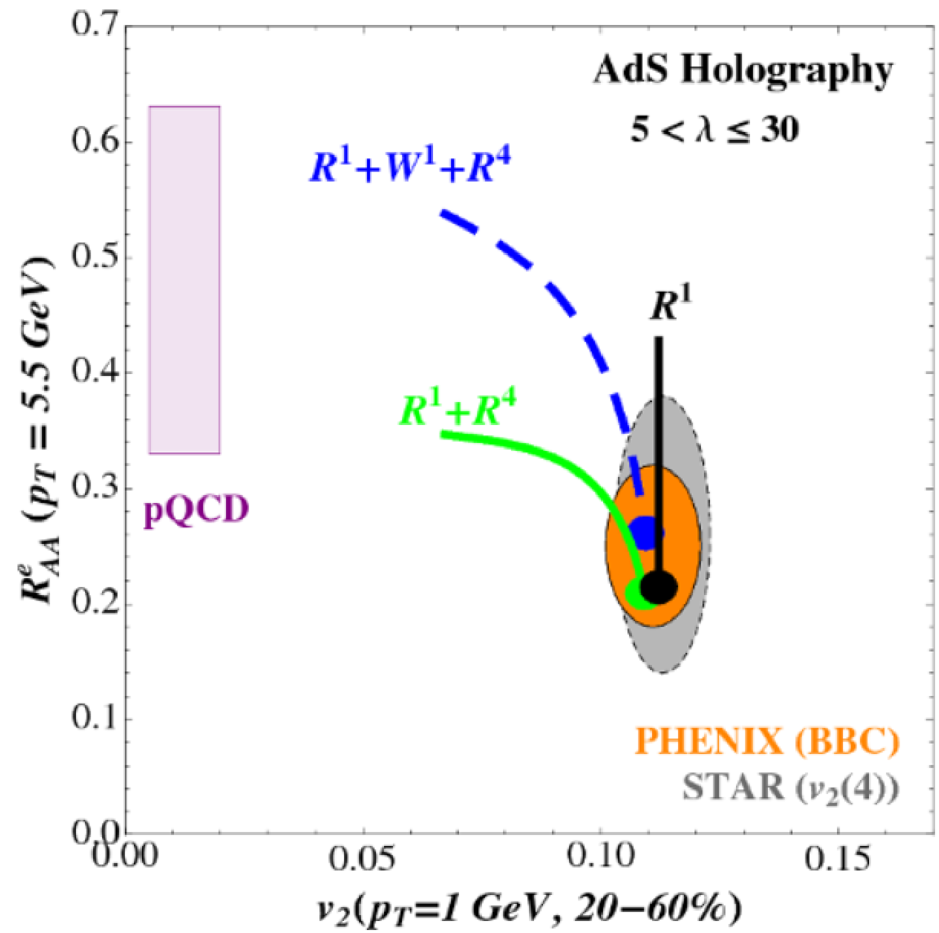
Jet Tomography versus Holography at RHIC and LHC

M. Gyulassy[a], A. Buzzatti, A. Ficnar, J. Noronha, and G. Torrieri

EPJ Web of Conferences ,13,01001 (2011)



Quench of e from c+b jets vs elliptic flow



Consistency between Hard (RAA) and Soft (v2) Observables is essential to falsify
Competing dynamical model assumptions

Heavy quarks quenching is problematic in Ads string drag picture and requires deforming Ads geom with extra dilaton field (A.Ficnar,J.Noronha, MG,J.Phys.G 38 (2011))

Gubser, Klebanov, Tseytlin (98)
Gubser, PRD74 (06)
Buchel, Myers, Sinha, Paulos (08,09)

Kats, Petrov 07
Brigante 08
Maldacena Hoffman 08

The *Lure* of 5D AdS Black Holes

Hard & Soft Phenomena @ RHIC

J. Noronha, M. Gyulassy, G. Torrieri, hep-ph: 0906.4099

The idea is to use both $R^2 \propto \lambda_{GB} \sim 1/N_c$ *and* $R^4 \propto \lambda^{-3/2}$ *pertubations* to R^1 (AdS_5)

(2) $$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 - 4\lambda_{GB} + 15\frac{\zeta(3)}{\lambda^{3/2}}\right)$$

(1) $$\frac{s}{s_{SB}} = \frac{3}{4}\left(1 + \lambda_{GB} + \frac{15}{8}\frac{\zeta(3)}{\lambda^{3/2}}\right)$$

Heavy quark energy loss

(3) $$\frac{dp}{dt} = -\frac{\sqrt{\lambda}\pi T^2}{2M_Q}\left(1 + \frac{3}{2}\lambda_{GB} + \frac{15}{16}\frac{\zeta(3)}{\lambda^{3/2}}\right)$$

To compute

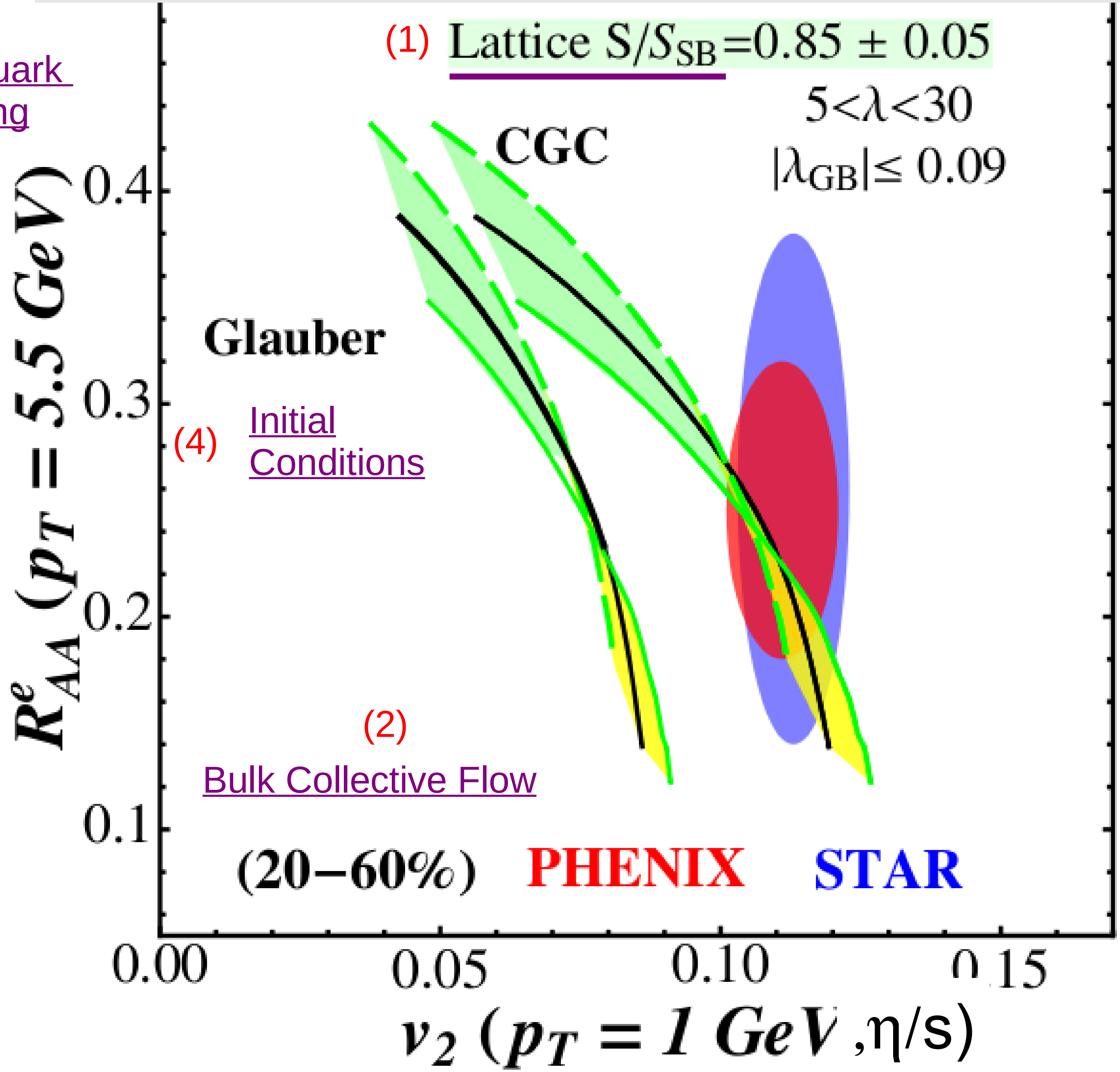
$$R^e_{AA} \times v_2$$

*Predicts *analytic* correlations between soft thermo, transport, *and* hard nonequilib dynamics for the first time !

5 Fold AA correlations! described by the sQGP ~ AdS BH paradigm

J. Noronha, MG, G. Torrieri, hep-ph: 0906.4099

(3) Heavy quark Jet quenching



(5) Heavy quark Jet induced collective flow

The Future

Heavy quark jet tomography of Pb + Pb at LHC: AdS/CFT drag or pQCD energy loss?

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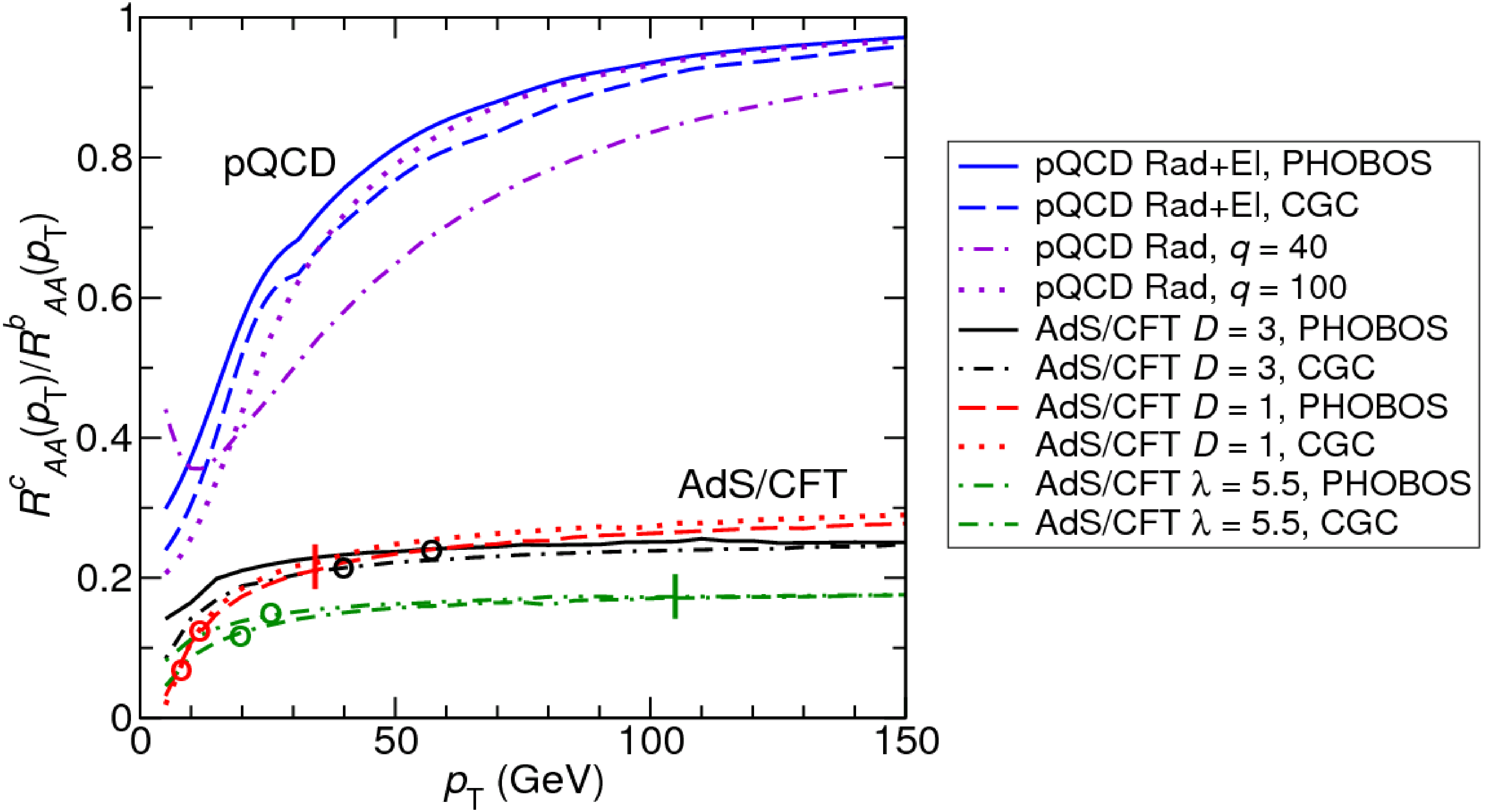

Robust yes/no exp at LHC to help discriminate paradigms

Current data strongly favors pQCD over this particular AdS scenario