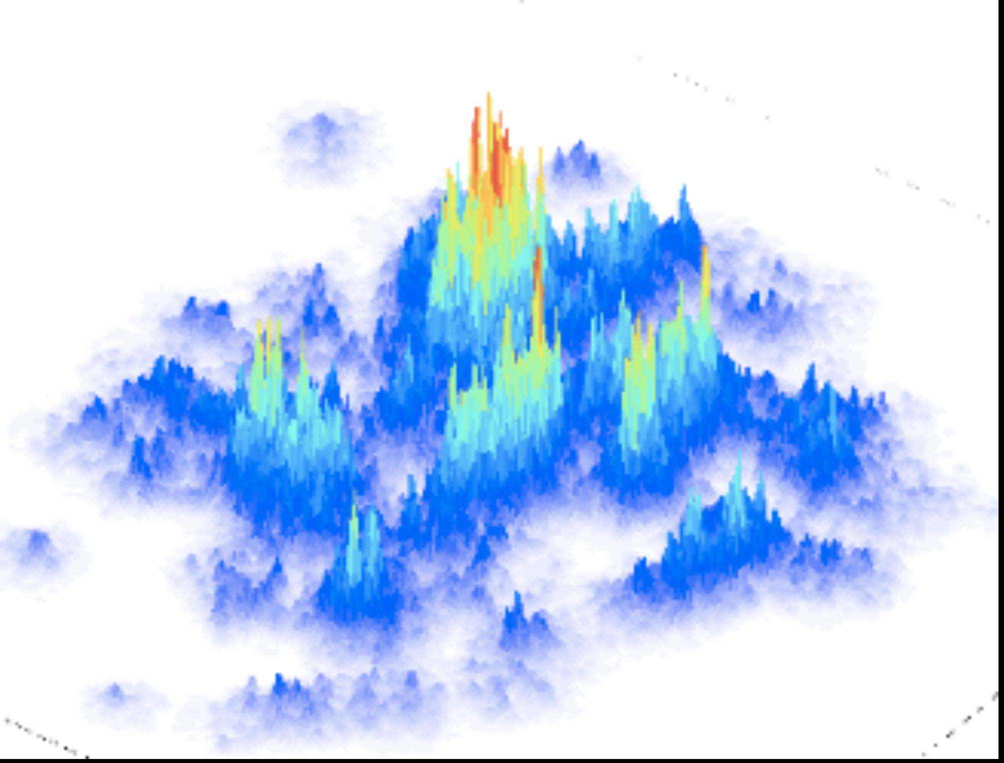
Initial State Fluctuations and Final State Correlations



Gunther Roland

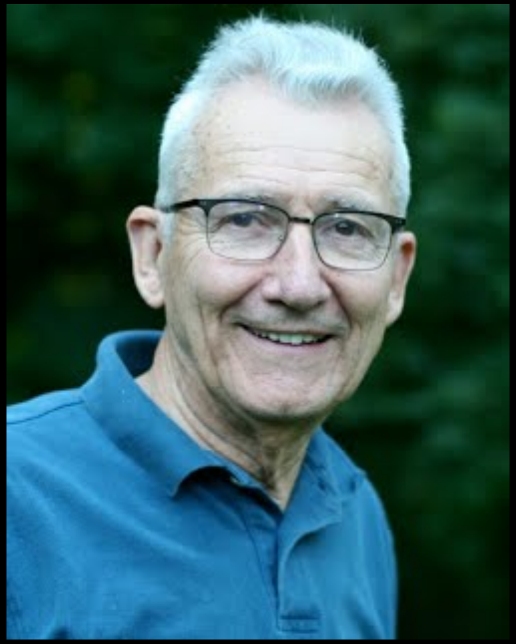
Berkeley School of Collective Dynamics 2014

Organization

- Two lectures
  - Geometry, geometry fluctuations and hydrodynamic flow in nucleus-nucleus collisions
  - Correlations in pp, pA and dA collisions

Organization

As this is a workshop in honor of Wit Busza, I decided to provide a *historical* overview of the developments in our understanding of flow and correlations over the last 15 years



This will naturally highlight contributions made under Wit's leadership in PHOBOS and the MIT heavy-ion group

I will mostly focus on experimental/conceptual developments

Historical note

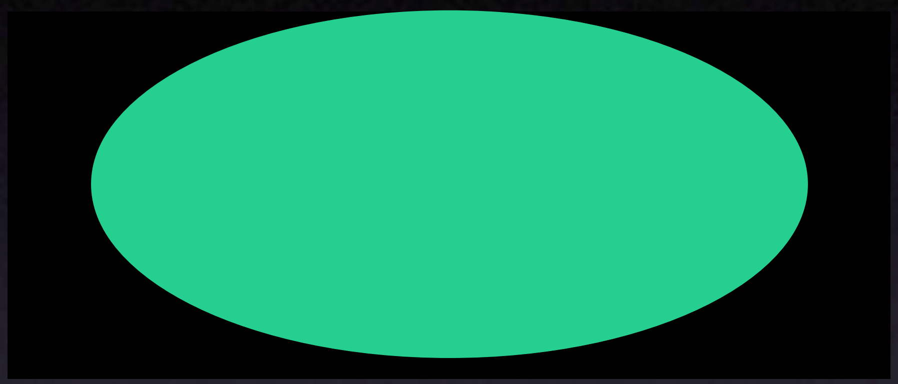
In NA49 I worked on some of the earliest studies of event-by-event fluctuations in transverse momentum and particle ratios, or more generally, particle correlations

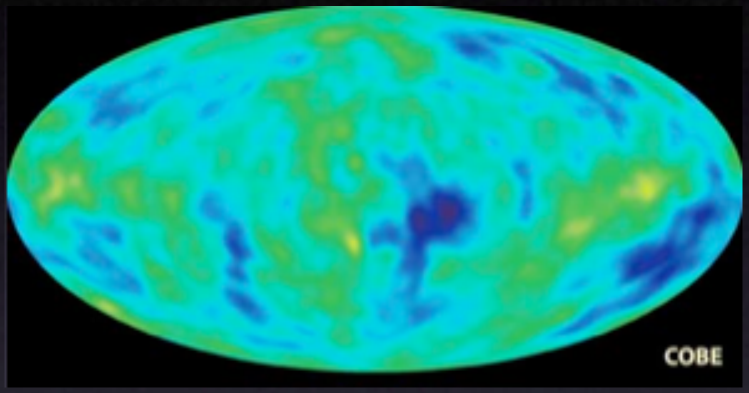
Whenever the subject of correlations and in particular correlation functions came up in our meetings at MIT, Wit would ask:

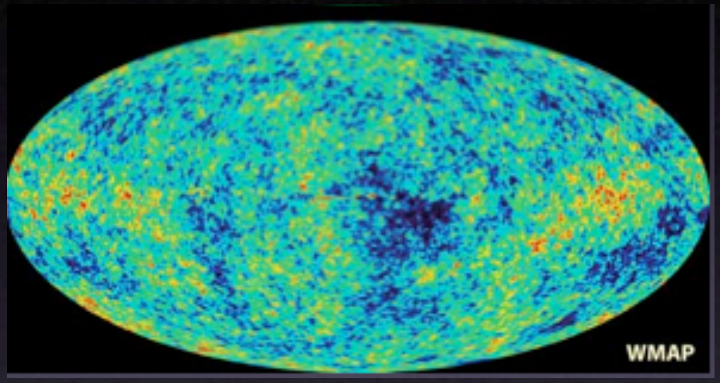
Is there anything that we have learned from correlation measurements?

Analogy: Cosmic Microwave Background

Cosmic microwave background







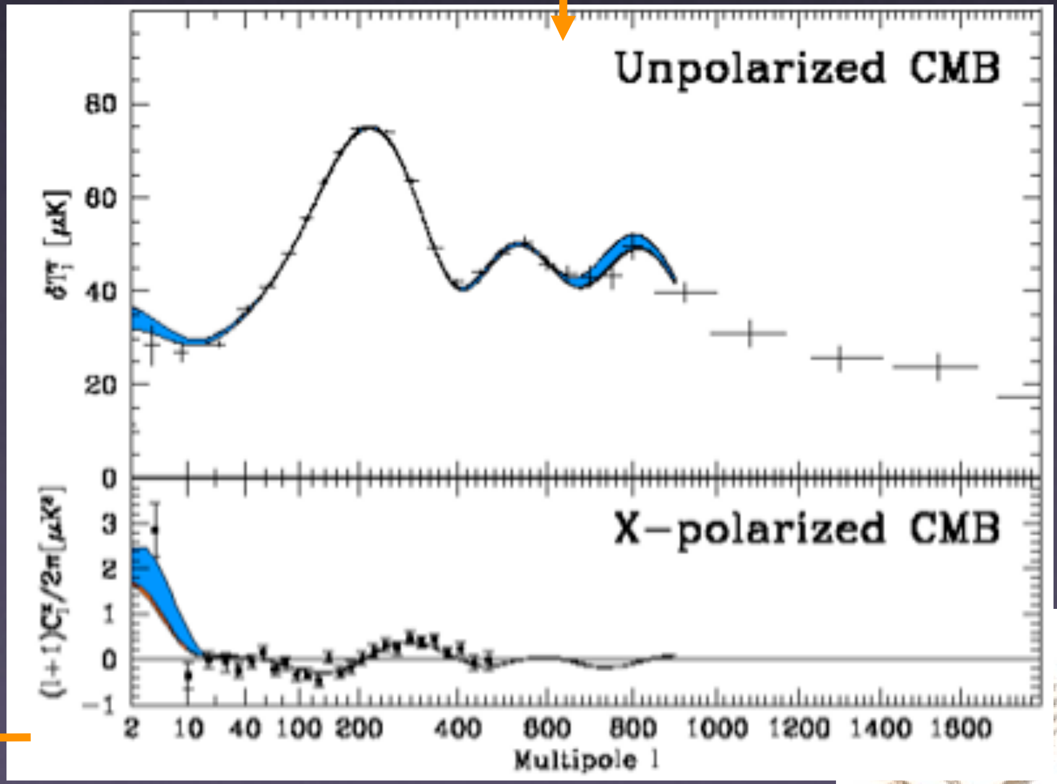
Penzias, Wilson 1964

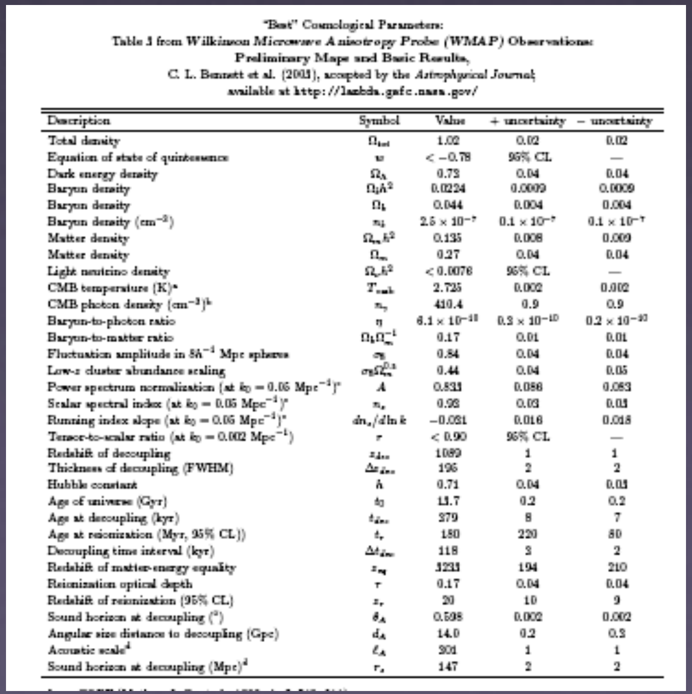
$<T>=3K$

COBE 1992

$\Delta T/T \sim 10^{-5}$

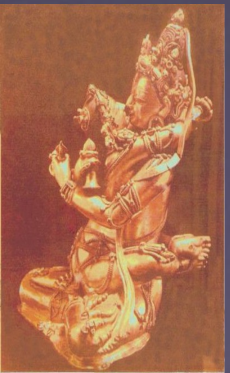
WMAP et al. 2003





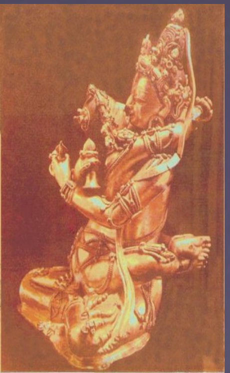
"Best" Cosmological Parameters:
Table 3 from *Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Preliminary Maps and Basic Results*,
C. L. Bennett et al. (2003), accepted by the *Astrophysical Journal*;
available at http://lambda.gsfc.nasa.gov/

Description	Symbol	Value	+ uncertainty	− uncertainty
Total density	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< -0.78	95% CL	—
Dark energy density	Ω_Λ	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.009
Matter density	Ω_m	0.27	0.04	0.04
Light neutrino density	$\Omega_\nu h^2$	< 0.0076	95% CL	—
CMB temperature (K)[a]	T_{cmb}	2.725	0.002	0.002
CMB photon density (cm^{-3})[b]	n_γ	410.4	0.9	0.9
Baryon-to-photon ratio	η	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}
Baryon-to-matter ratio	$\Omega_b \Omega_m^{-1}$	0.17	0.01	0.01
Fluctuation amplitude in $8h^{-1}$ Mpc spheres	σ_8	0.84	0.04	0.04
Low-z cluster abundance scaling	$\sigma_8 \Omega_m^{0.5}$	0.44	0.04	0.05
Power spectrum normalization (at $k_0 = 0.05$ Mpc^{-1})[c]	A	0.833	0.086	0.083
Scalar spectral index (at $k_0 = 0.05$ Mpc^{-1})[c]	n_s	0.93	0.03	0.03
Running index slope (at $k_0 = 0.05$ Mpc^{-1})[c]	$dn_s/d\ln k$	-0.031	0.016	0.018
Tensor-to-scalar ratio (at $k_0 = 0.002$ Mpc^{-1})	r	< 0.90	95% CL	—
Redshift of decoupling	z_{dec}	1089	1	1
Thickness of decoupling (FWHM)	Δz_{dec}	195	2	2
Hubble constant	h	0.71	0.04	0.03
Age of universe (Gyr)	t_0	13.7	0.2	0.2
Age at decoupling (kyr)	t_{dec}	379	8	7
Age at reionization (Myr, 95% CL))	t_r	180	220	80
Decoupling time interval (kyr)	Δt_{dec}	118	3	2
Redshift of matter-energy equality	z_{eq}	3233	194	210
Reionization optical depth	τ	0.17	0.04	0.04
Redshift of reionization (95% CL)	z_r	20	10	9
Sound horizon at decoupling (°)	θ_A	0.598	0.002	0.002
Angular size distance to decoupling (Gpc)	d_A	14.0	0.2	0.3
Acoustic scale[d]	ℓ_A	301	1	1
Sound horizon at decoupling (Mpc)[d]	r_s	147	2	2



Correlations and Fluctuations

- Correlations/fluctuations induced by interaction of perturbations with medium
  - Essential for understanding the nature of medium and of perturbations
- Need to interface experiment/theory and experiment/experiment
  - Find a representation of correlation content, i.e. our ‘Power spectrum’



Workshop on Correlations and Fluctuations in
Relativistic Heavy Ion Collisions
MIT, 4/21 to 4/23 2005
Organizers T. Trainor, G.Roland

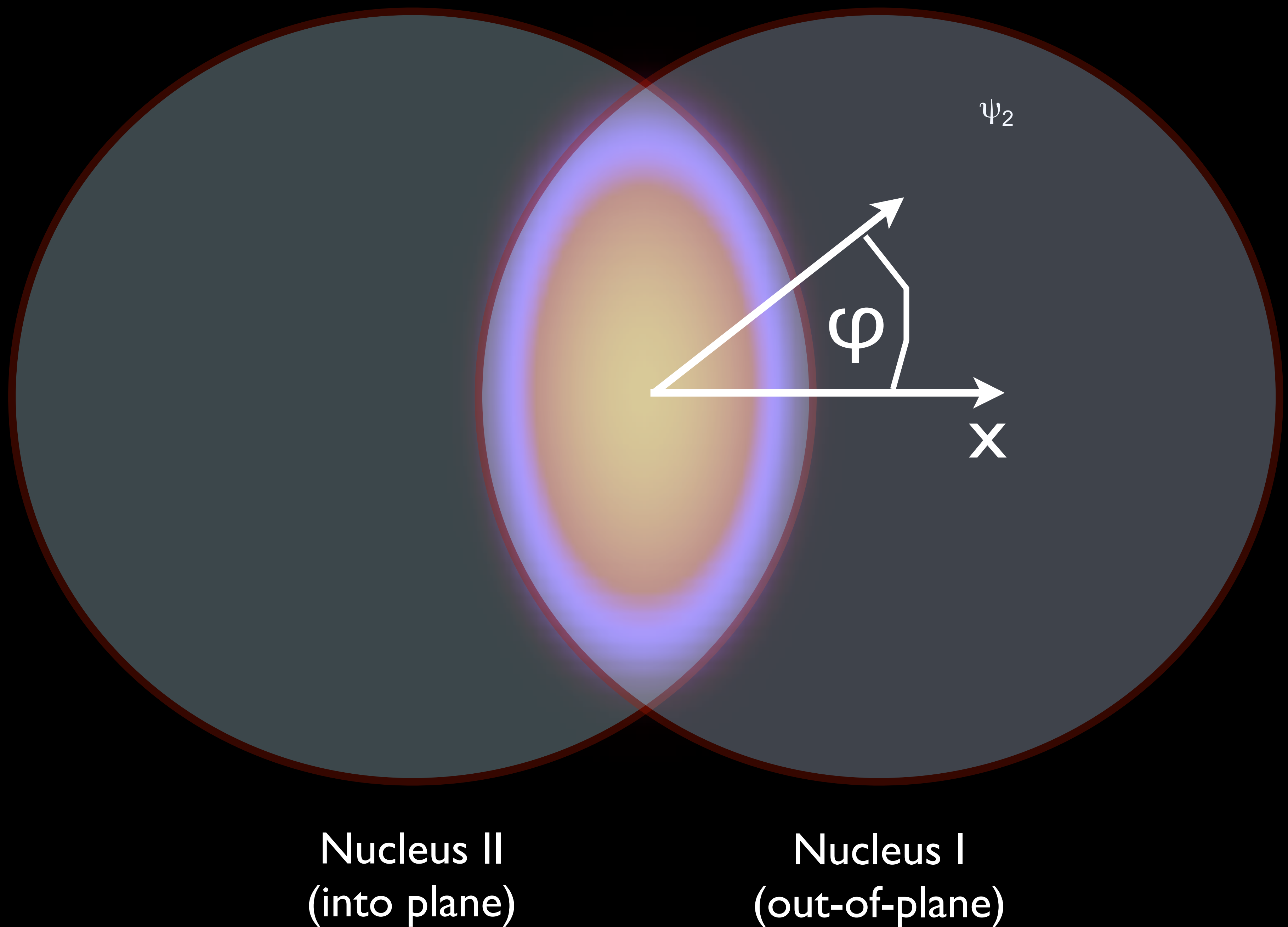
A brief history of correlations in HIC

Is there anything that we have learned from correlation measurements?

2002 2006 2010 2014

Anisotropic initial state

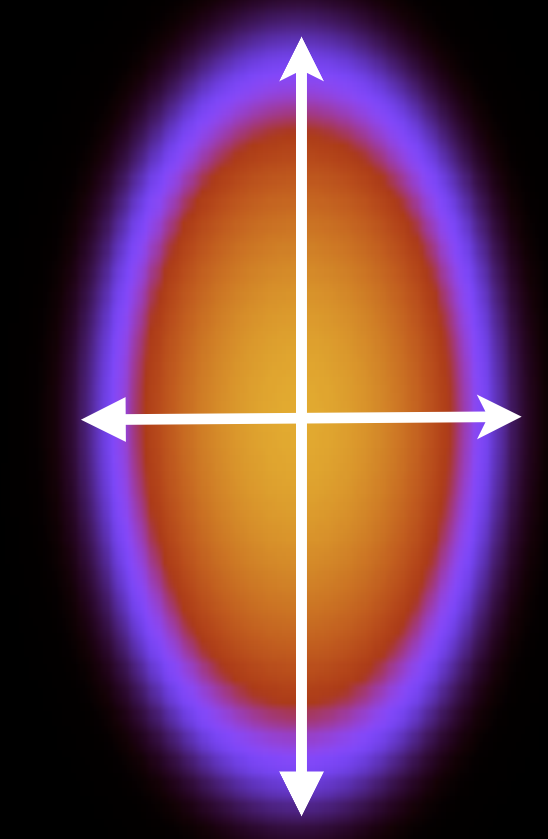
Non-central collision (Transverse plane)



Initial overlap in transverse plane
is asymetric in azimuth φ

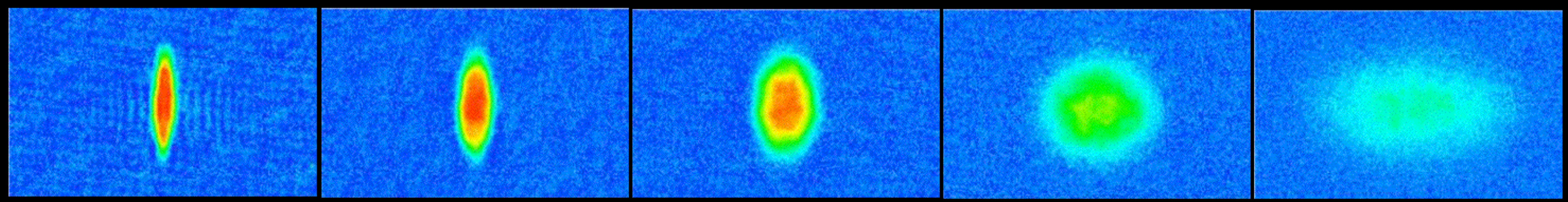
Anisotropic initial state

Small pressure gradient



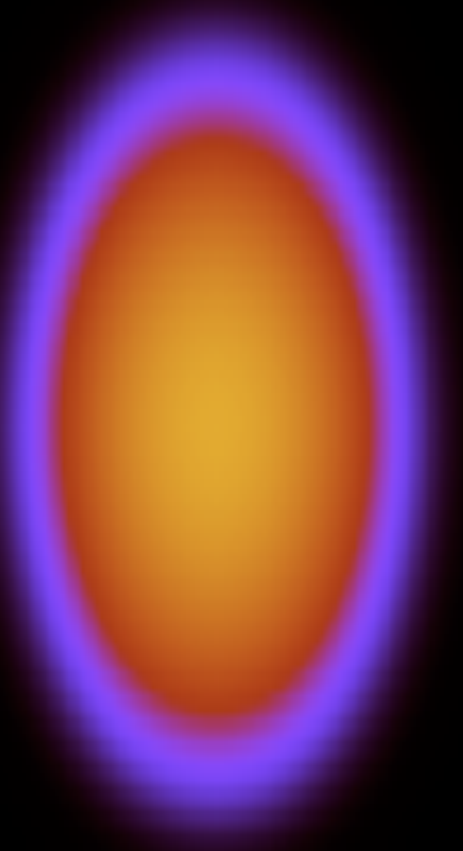
Large pressure gradient

Time →



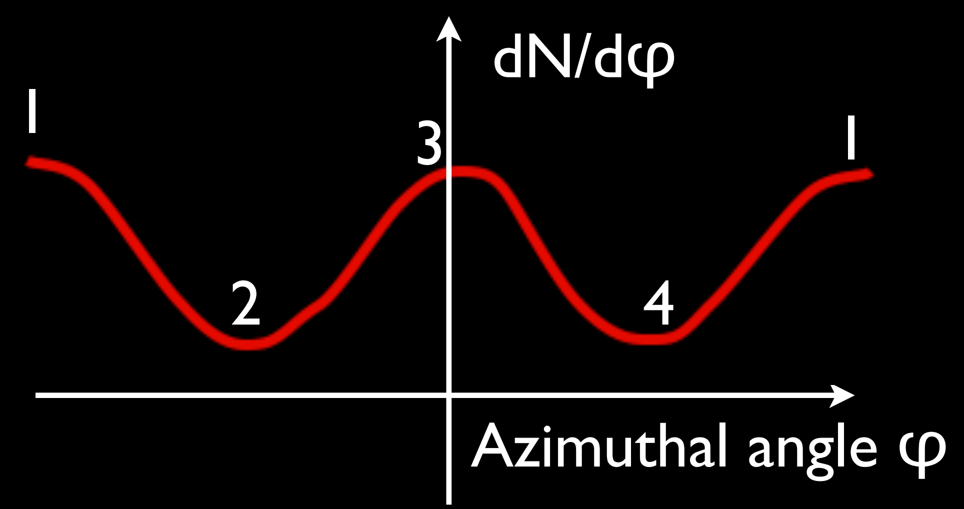
n.b. picture shows expansion of
ultracold atoms released from trap

“Elliptic Flow”

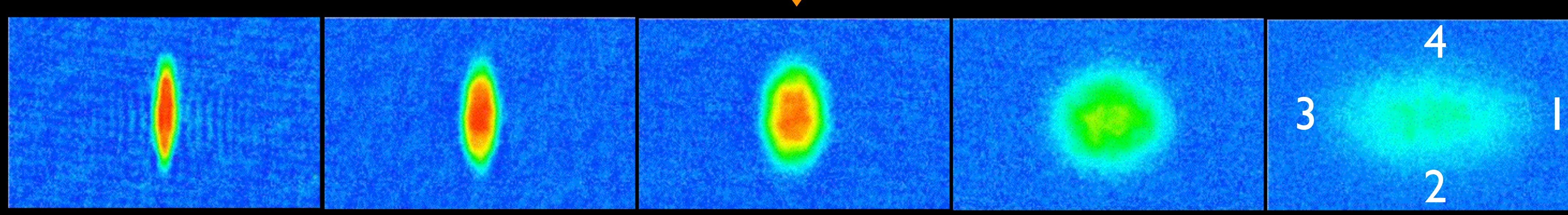


Shape information transformed into momentum space

cos(2 φ) modulation of azimuthal distribution



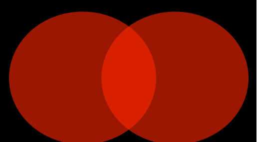
Time →

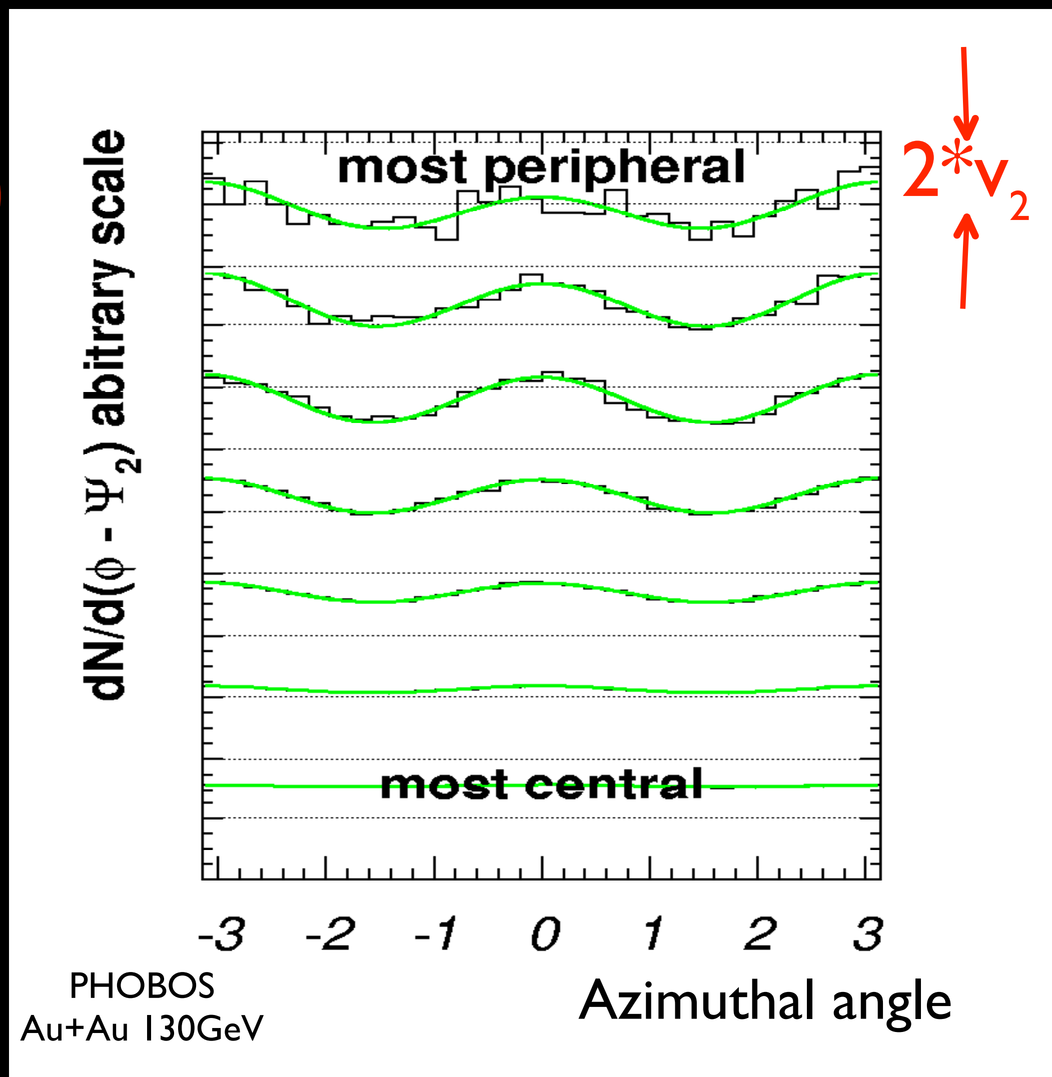


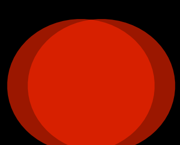
Pressure driven *hydrodynamic* expansion

First results from RHIC in 2000

Azimuthal distribution
$dN/d\varphi = 1 + 2\, v_2 \cos(2(\varphi - \varphi 0))$



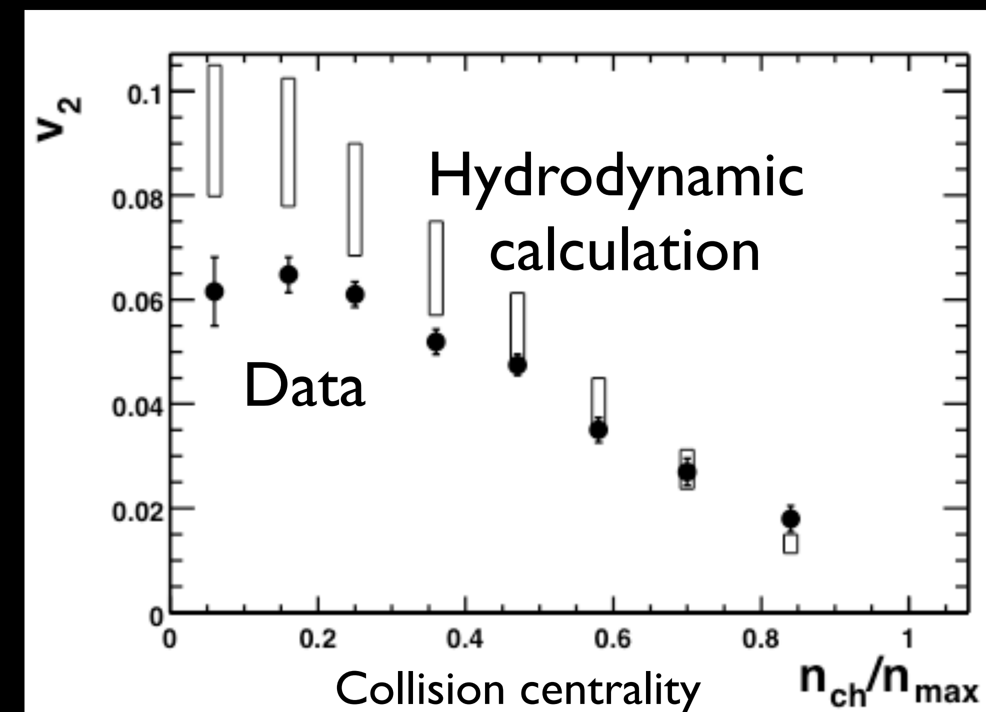




“Elliptic Flow”
is clearly seen

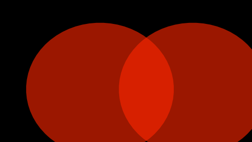
“Elliptic Flow”

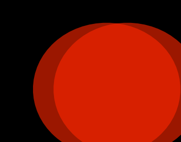
STAR PRL 2000



Peripheral collisions

central collisions





Close to “ideal hydrodynamics”

Hydrodynamics

Hydrodynamics: conservation laws for long wavelength modes

$$\partial_\mu T^{\mu\nu} = 0$$

Generally:

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \pi^{\mu\nu}.$$

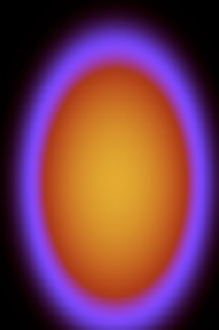
First order Navier Stokes theory:

$$\pi^{\mu\nu} = \pi^{\mu\nu}_{(1)} = \eta(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \tfrac{2}{3}\Delta^{\mu\nu}\nabla_\alpha u^\alpha).$$

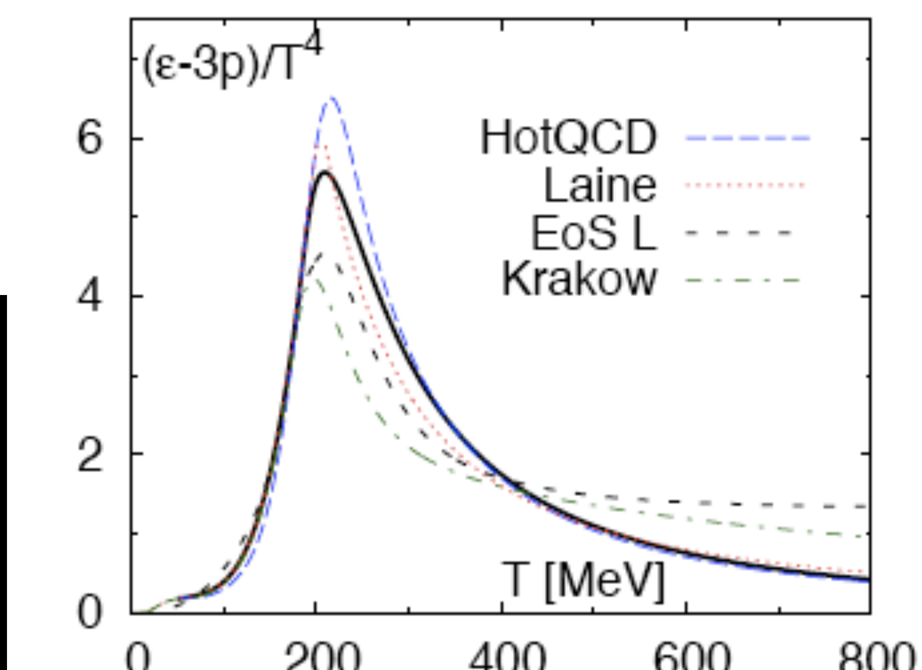
$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$

η: Shear viscosity
Large shear viscosity → transport of momentum across fluid layers

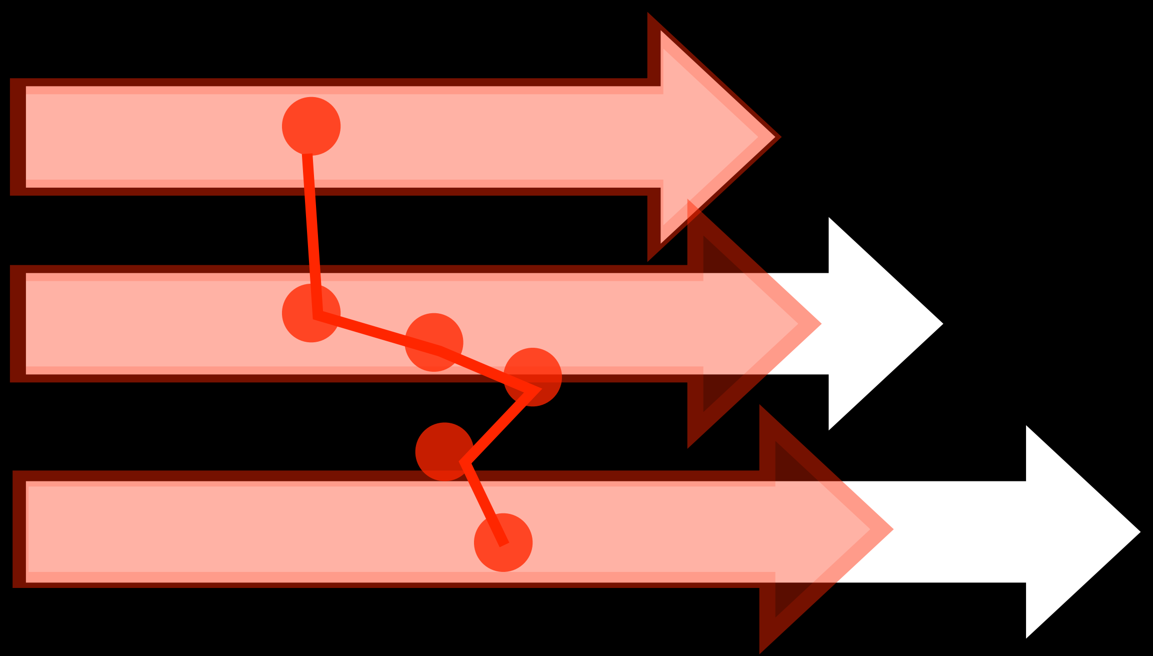
+ initial conditions



+ Equation of State



Shear Viscosity

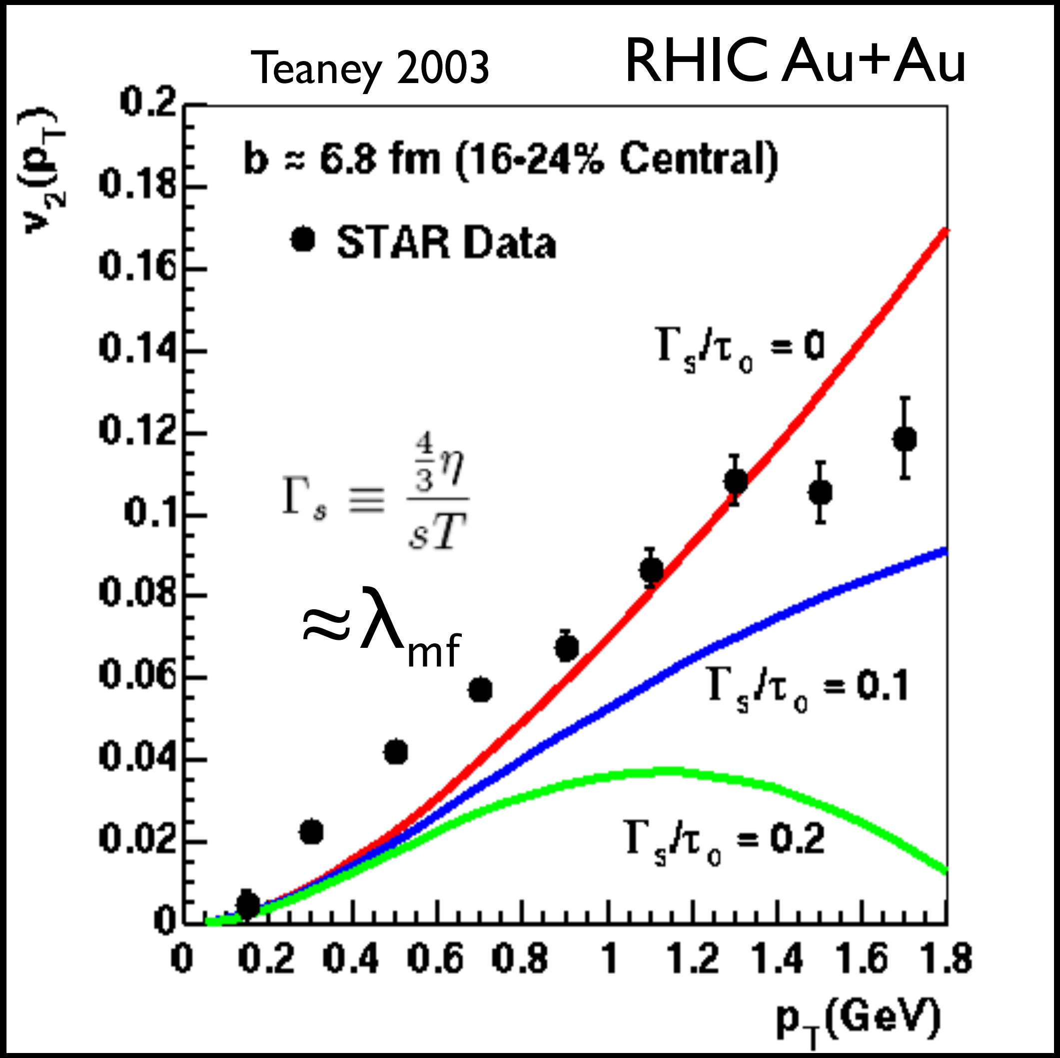


Shear viscosity: Momentum transport across fluid reduces gradients → less elliptic flow

To compare systems: Divide by entropy density → η/s
("η"for QGP is very large, but "s" is even larger...)

Weakly interacting gas: Large η/s

The importance of shear viscosity

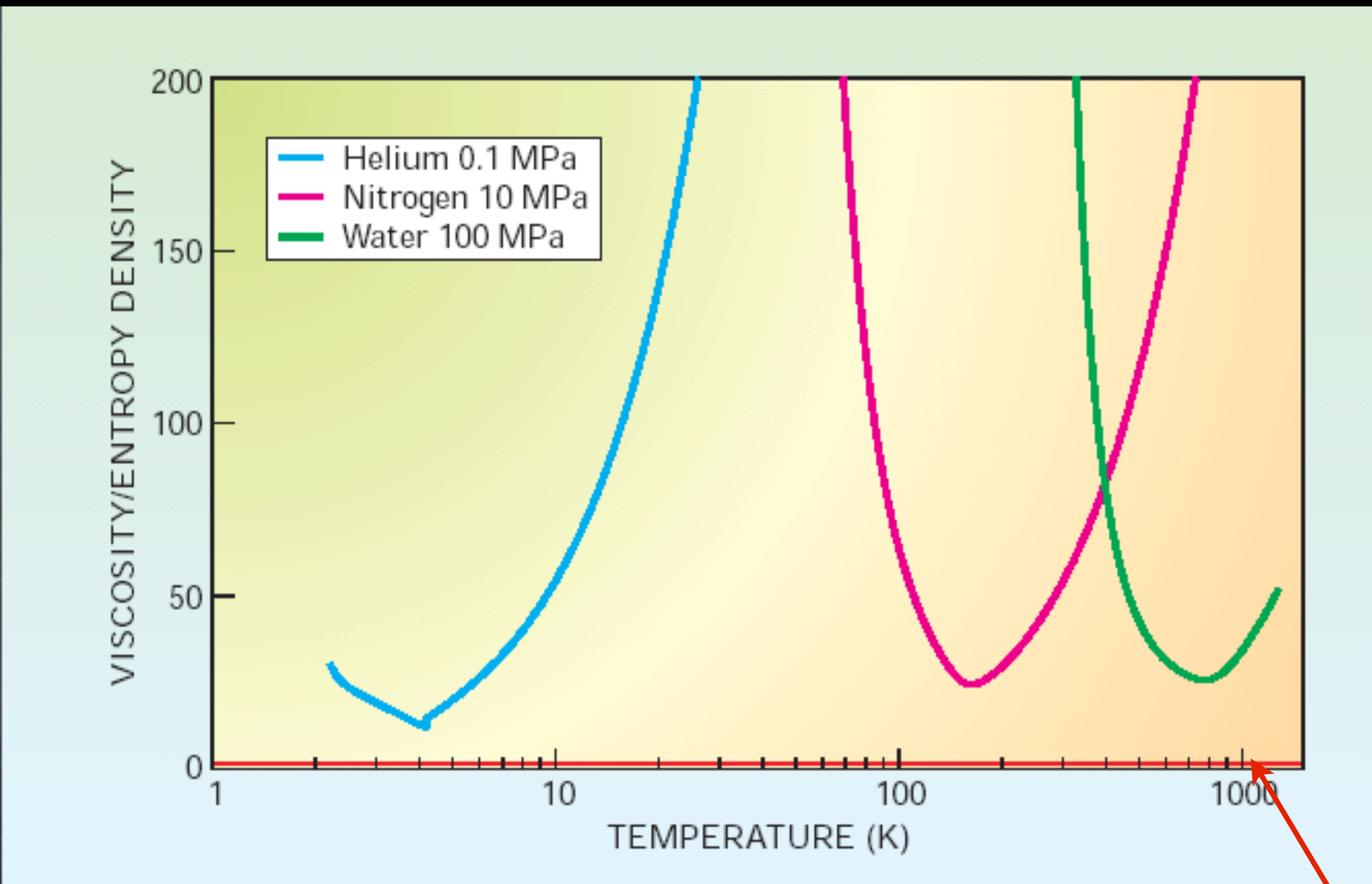


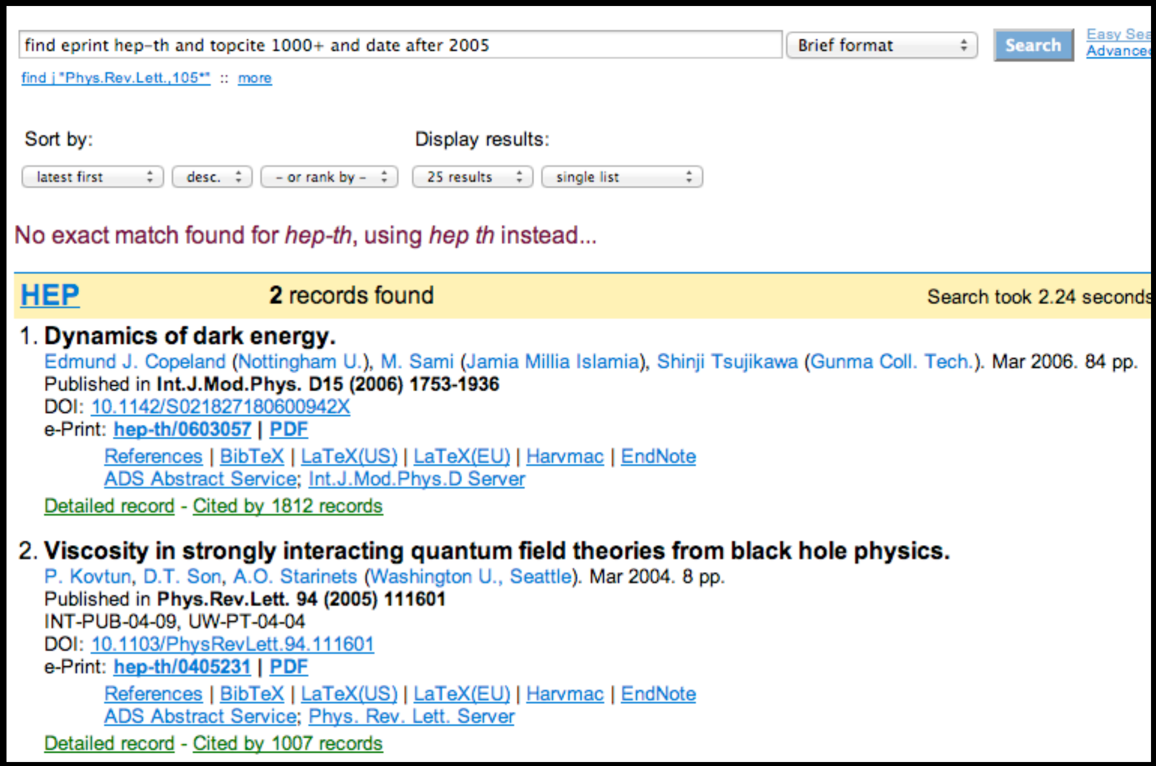
Phys.Rev. C68 (2003) 034913

First estimate of viscous corrections: Magnitude of v_2 changes rapidly with η/s

The observed elliptic flow places a constraint on the shear viscosity. Indeed, unless Γ_s/τ_o is less than 0.1, v_2 as a function of p_T falls well below the ideal curve by $p_T \approx 1.0\,\mathrm{GeV}$. For the blast wave model, the viscous corrections to elliptic observables become large *before* the corresponding corrections to the transverse momentum spectra.

η/s << 1 makes QGP unique





find eprint hep-th and topcite 1000+ and date after 2005 | Brief format | Search

find j "Phys.Rev.Lett.,105*" :: more

Sort by: latest first | desc. | - or rank by - Display results: 25 results | single list

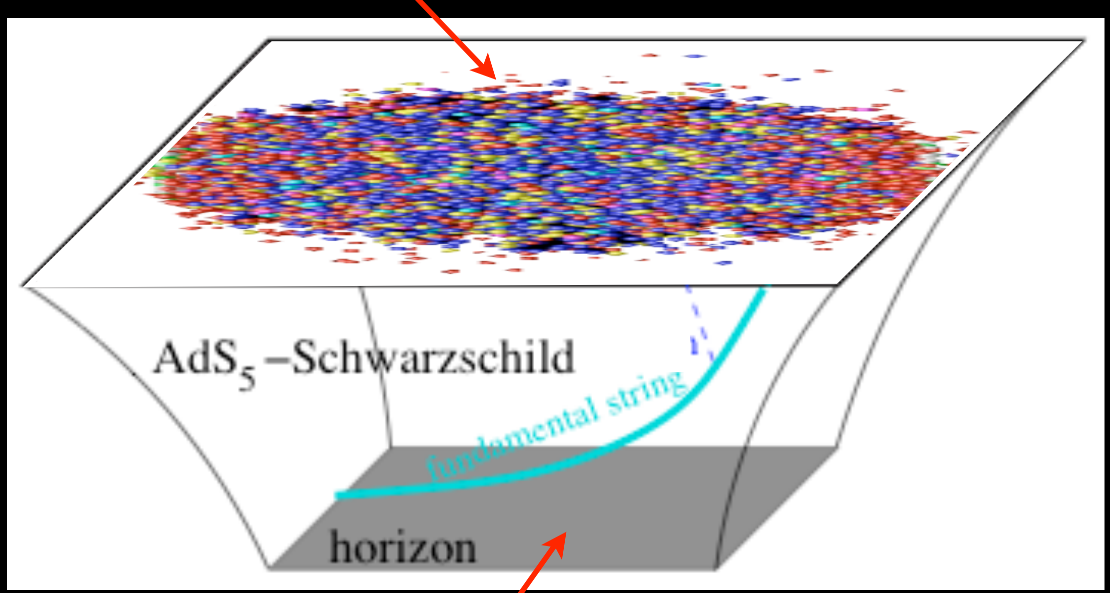
No exact match found for *hep-th*, using *hep th* instead...

HEP **2 records found** Search took 2.24 seconds

1. **Dynamics of dark energy.**
Edmund J. Copeland (Nottingham U.), M. Sami (Jamia Millia Islamia), Shinji Tsujikawa (Gunma Coll. Tech.). Mar 2006. 84 pp.
Published in **Int.J.Mod.Phys. D15 (2006) 1753-1936**
DOI: 10.1142/S021827180600942X
e-Print: **hep-th/0603057** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Int.J.Mod.Phys.D Server
Detailed record - Cited by 1812 records

2. **Viscosity in strongly interacting quantum field theories from black hole physics.**
P. Kovtun, D.T. Son, A.O. Starinets (Washington U., Seattle). Mar 2004. 8 pp.
Published in **Phys.Rev.Lett. 94 (2005) 111601**
INT-PUB-04-09, UW-PT-04-04
DOI: 10.1103/PhysRevLett.94.111601
e-Print: **hep-th/0405231** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Phys. Rev. Lett. Server
Detailed record - Cited by 1007 records

Thermal Field Theory (distant cousin of QCD...)



Black hole horizon

$$\frac{\eta}{s} = \frac{\hbar}{4\pi}$$

Viscosity in CFT

Graviton absorption by black hole

Shear viscosity in *N*=4 supersymmetric Yang-Mills in strong coupling, large N limit related to absorption cross-section of graviton on black three-brane in 10D classical gravity, using AdS/CFT

Kovtun, Son, Starinets hep-th/0405231
Policastro, Son, Starinets hep-th/0104066

AIP Top Physics Story, Dec 2005

1931-2006
AMERICAN INSTITUTE OF PHYSICS
75 Years of Service

SEARC

Physics News Update
The AIP Bulletin of Physics News

Article Tools
Enlarge text
Shrink text
Print
E-mail

Subscribe
E-mail alert
RSS feed RSS

Save and Share
Digg this
Del.icio.us

Number 757 #1, December 7, 2005 by Phil Schewe and Ben Stein

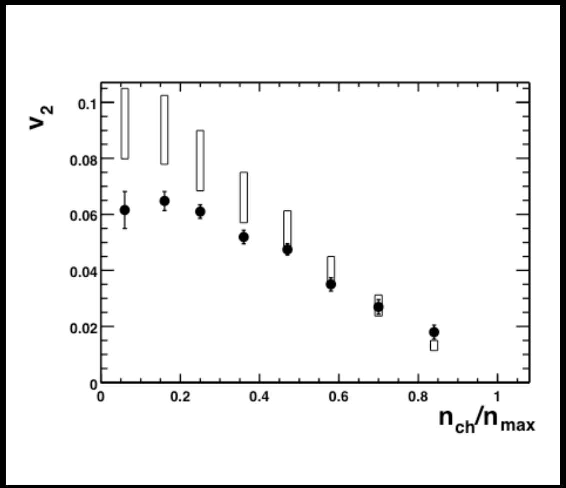
The Top Physics Stories for 2005

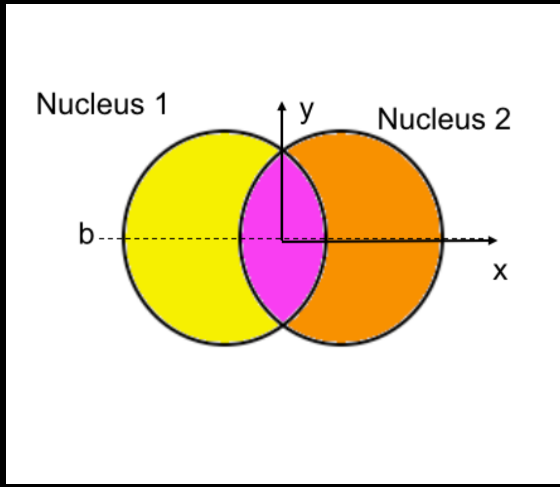
At the Relativistic Heavy Ion Collider (RHIC) on Long Island, the four large detector groups agreed, for the first time, on a consensus interpretation of several year's worth of high-energy ion collisions: the fireball made in these collisions -- a sort of stand-in for the primordial universe only a few microseconds after the big bang -- was not a gas of weakly interacting quarks and gluons as earlier expected, but something more like a liquid of strongly interacting quarks and gluons (PNU 728).

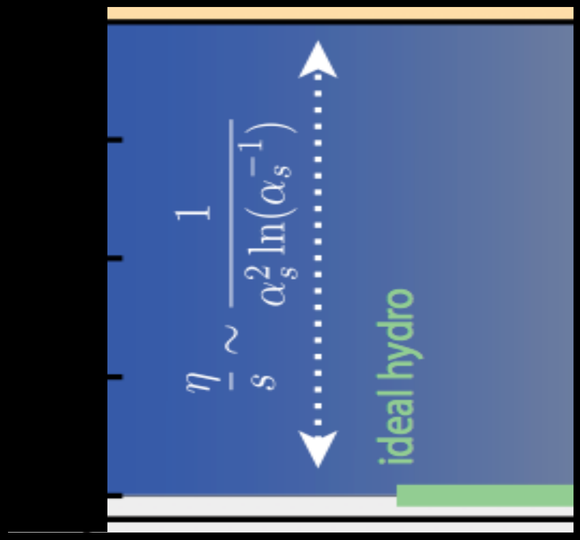
"...the fireball made in these [heavy-ion] collisions...was not a gas of weakly interacting quarks and gluons as earlier expected, but something more like a liquid..."

based on Whitepapers by BRAHMS, PHENIX, PHOBOS and STAR collaborations at RHIC

A brief history of correlations in HIC

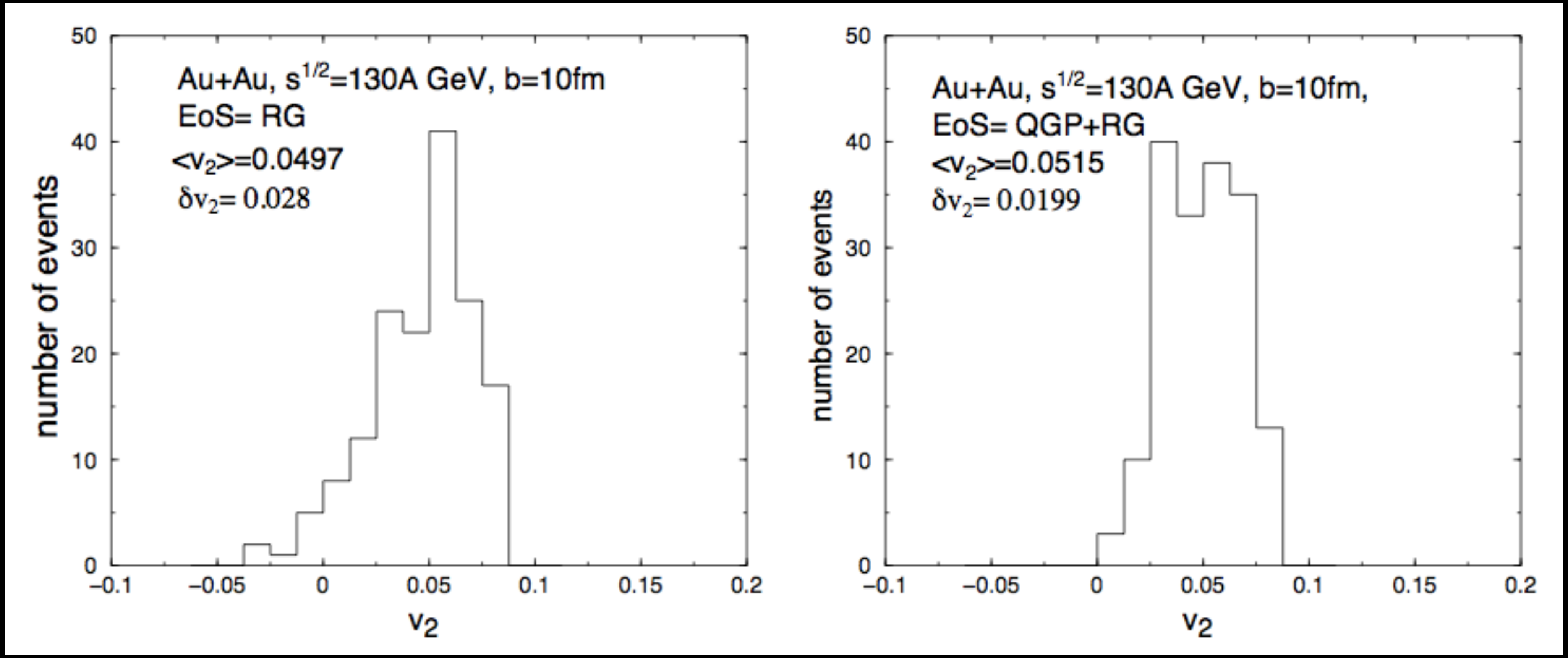


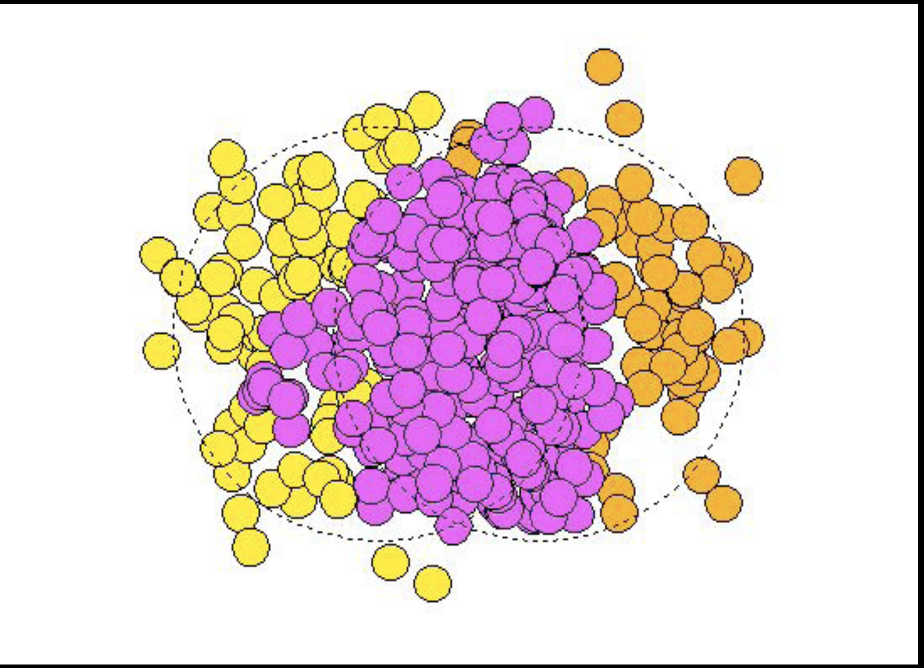




2002 2006 2010 2014

Importance of Geometry Fluctuations





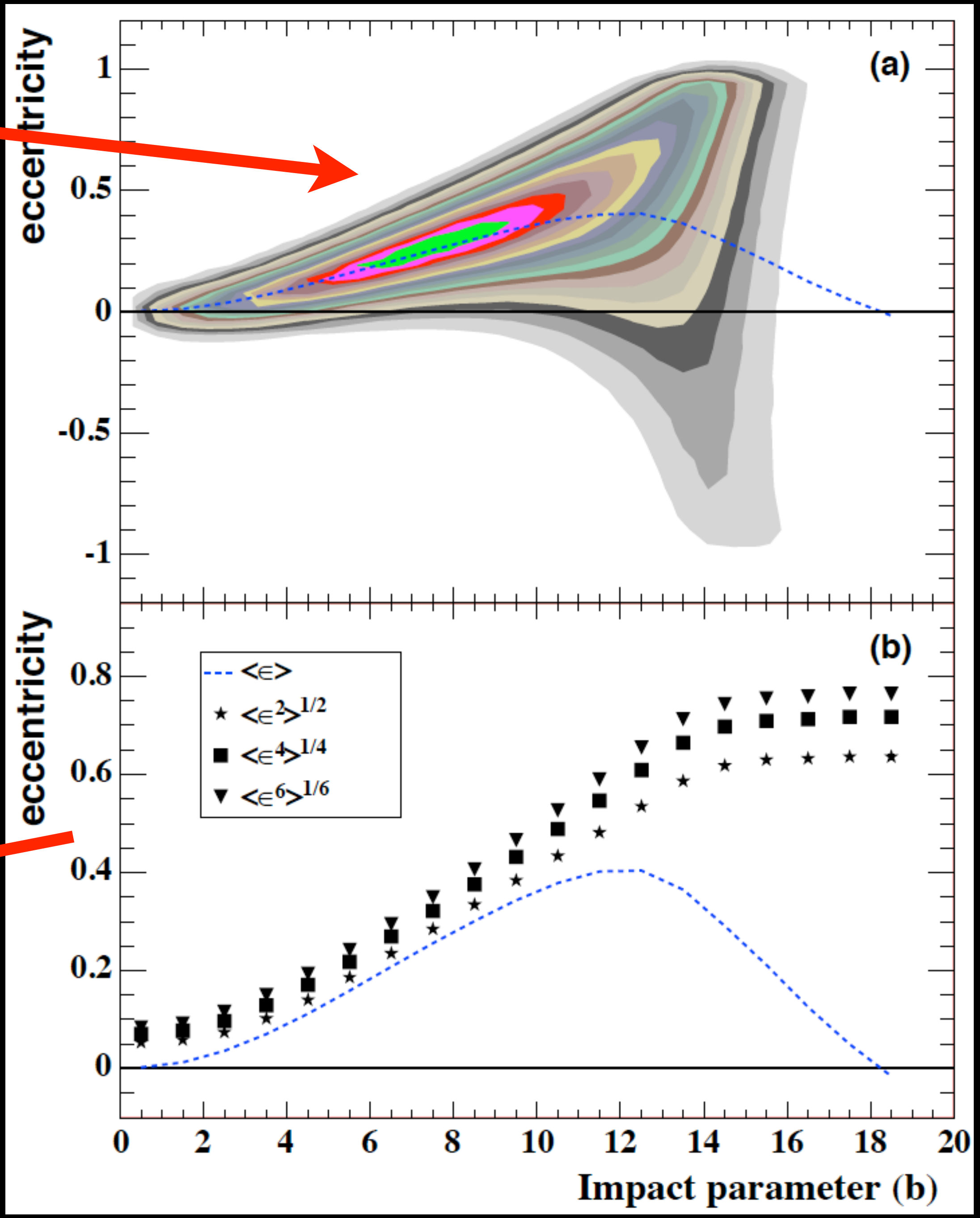
Aguiar, Hama et al
Nucl.Phys.A698 (2002) 639-642

Using NeXus (K. Werner) MC
Glauber initial conditions

Importance of Geometry Fluctuations

MC Glauber eccentricity fluctuations relative to the reaction plane

Miller, Snellings
nucl-ex/0312008



In summary, experimental measurements of elliptic flow (v_2) might be affected by fluctuations.

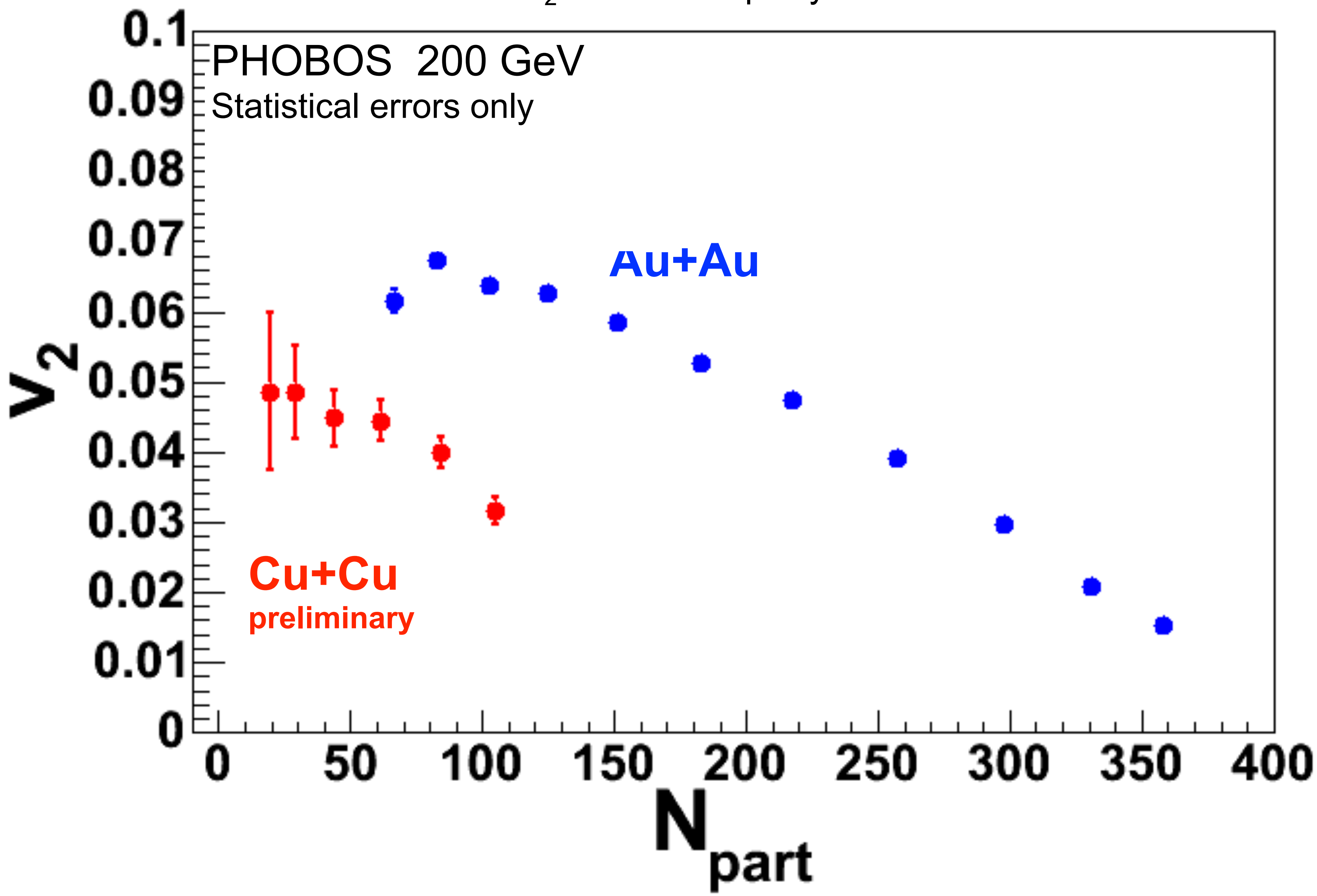
Geometry fluctuations still treated as a perturbation of reaction plane eccentricity

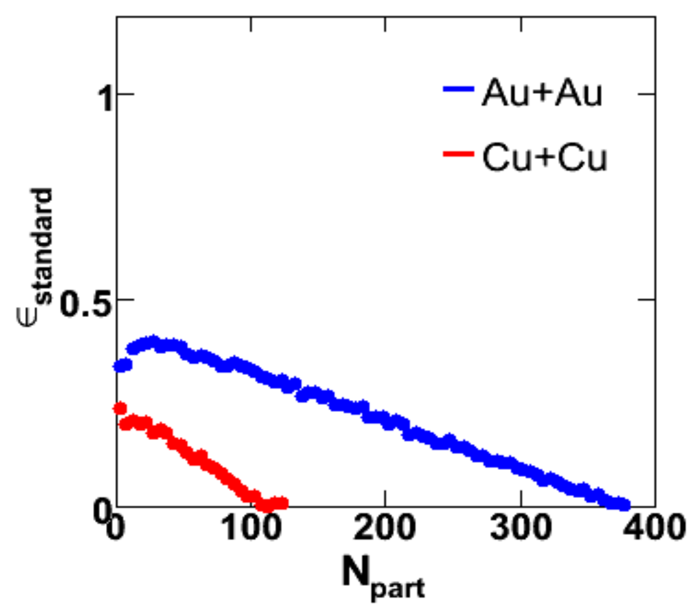
Elliptic Flow, Geometry & Density

Q: How does elliptic flow scale with geometry and density?

Elliptic Flow vs N_{part}

v_2 near mid-rapidity

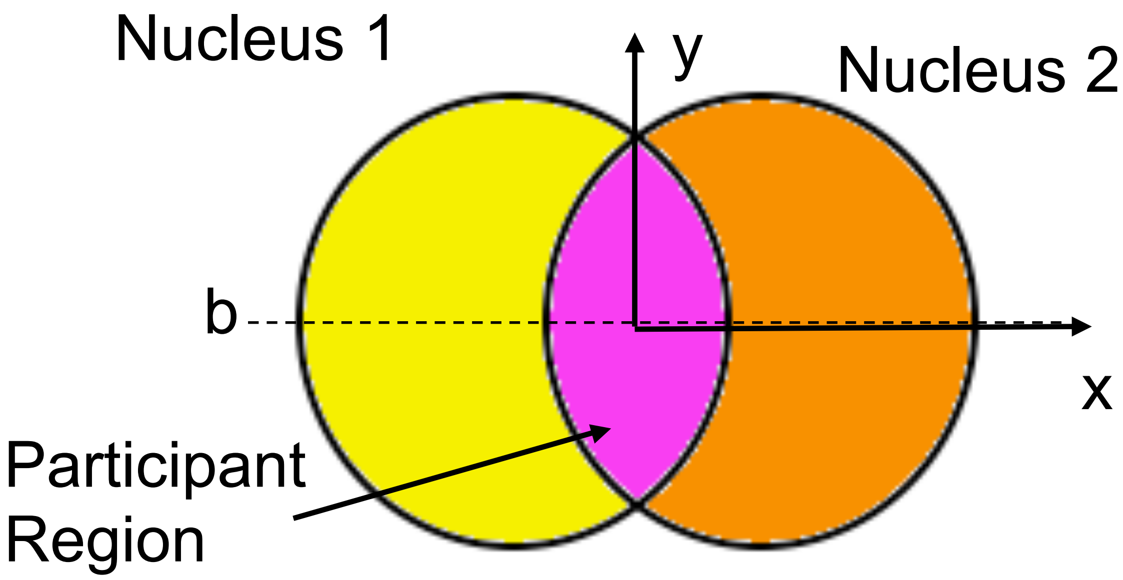


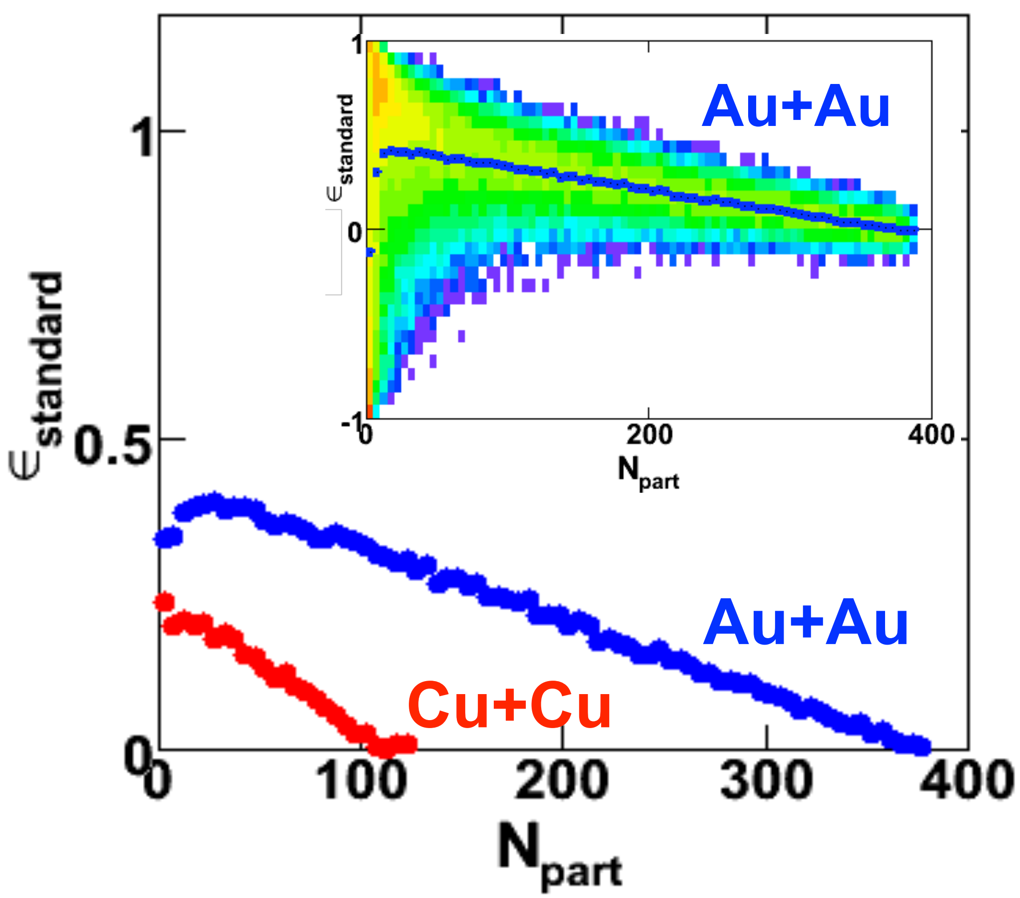


Substantial v_2 even for most central bin in Cu+Cu

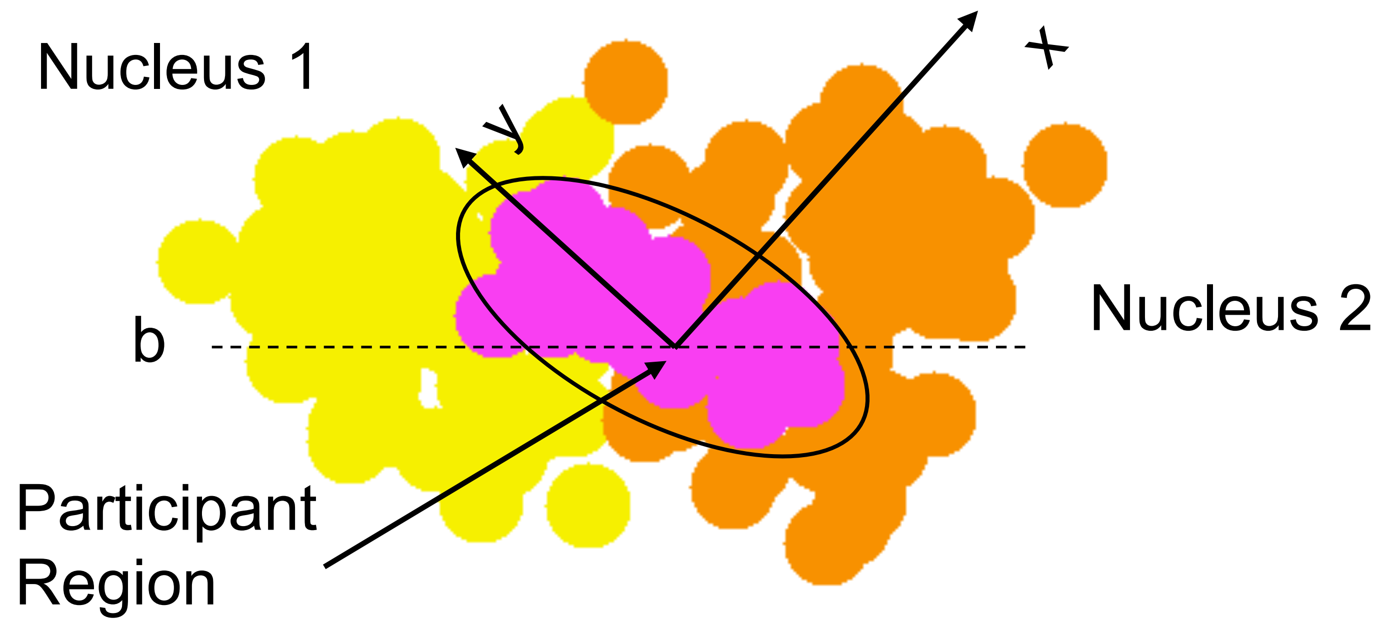
Eccentricity Calculation

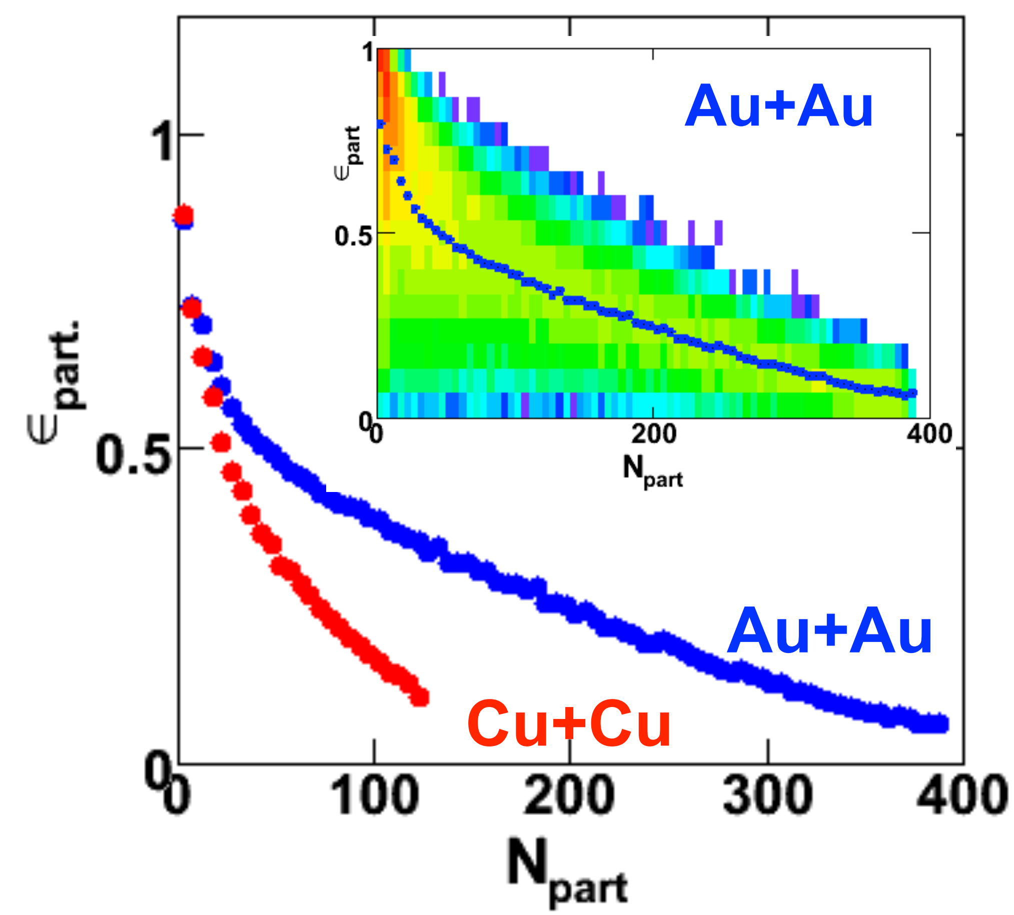
Standard Eccentricity





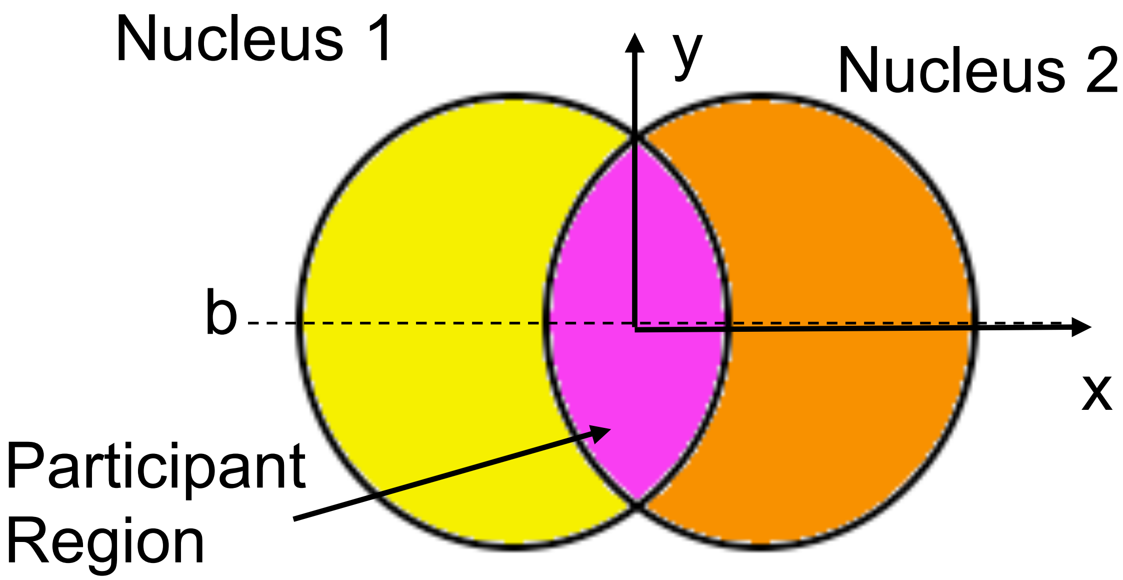
Participant Eccentricity



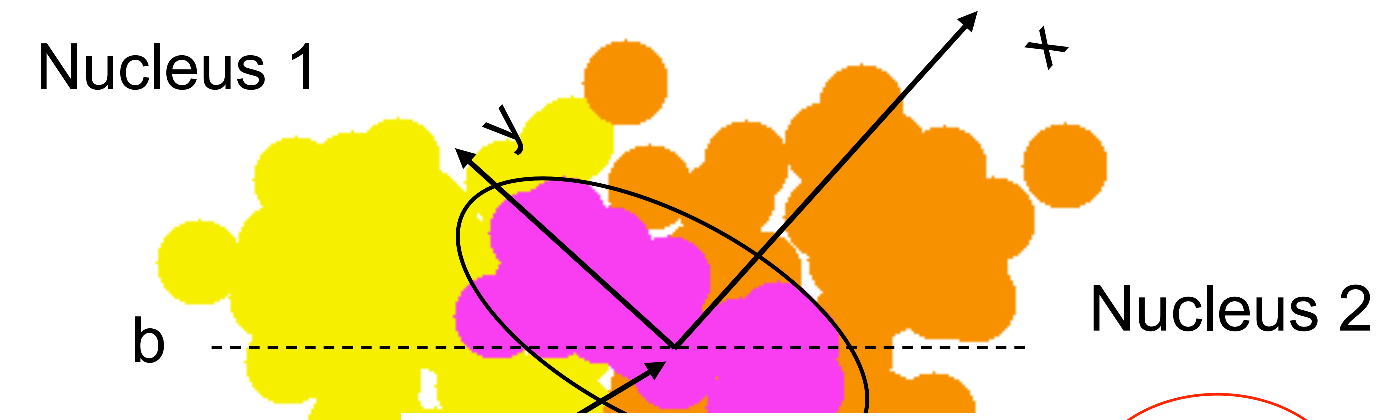


Eccentricity Calculation

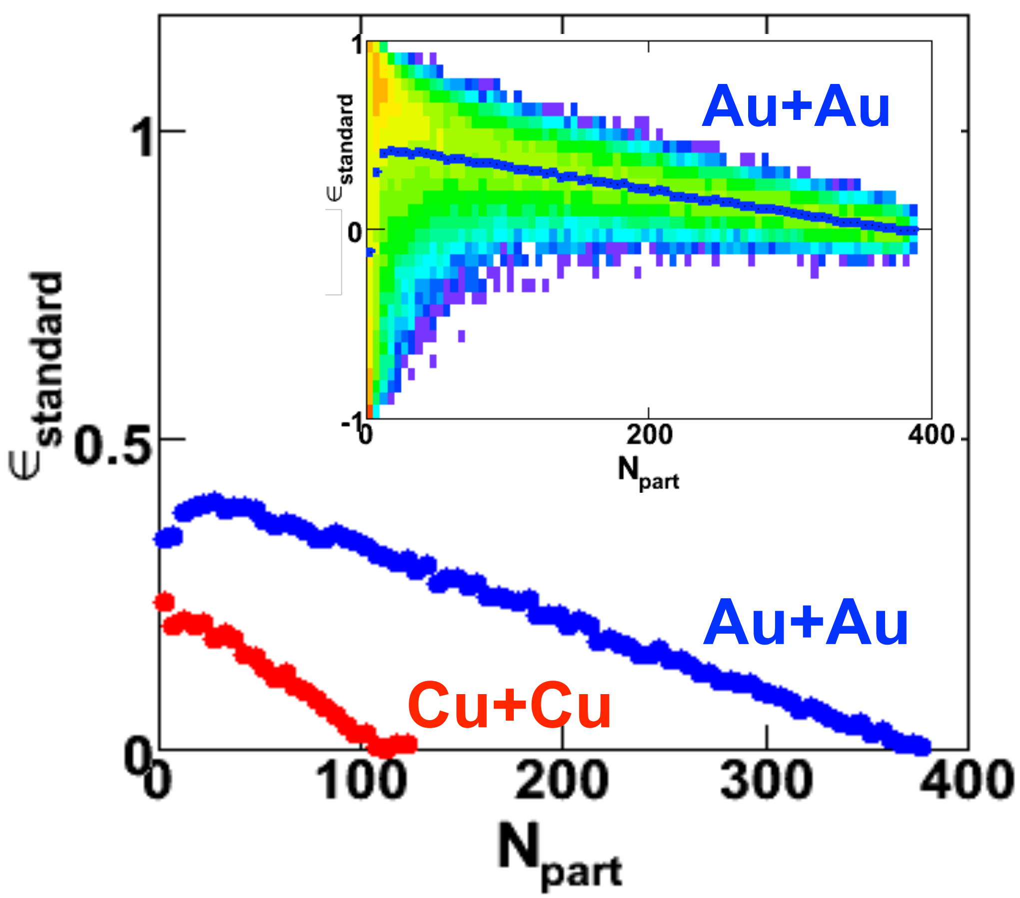
Standard Eccentricity

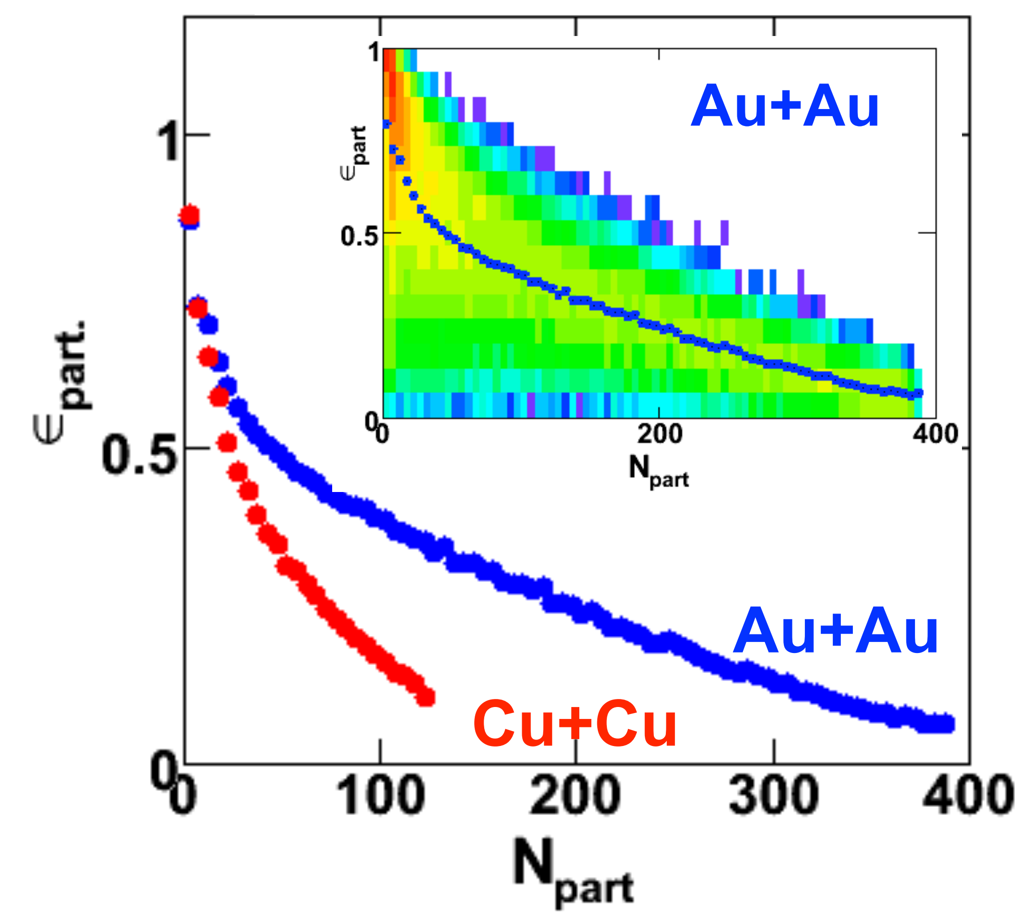


Participant Eccentricity



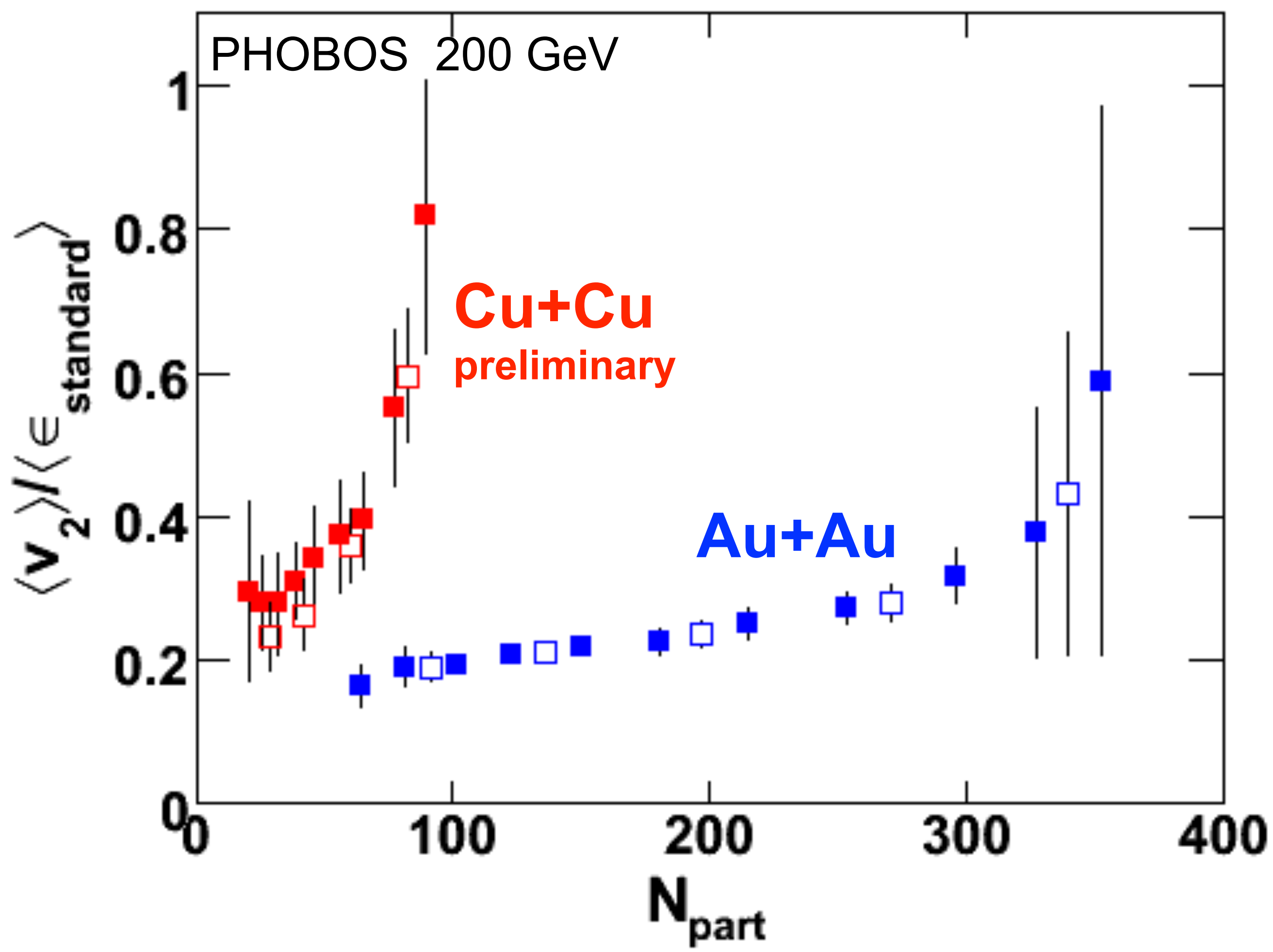
$$\epsilon_{\mathrm{part}} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$



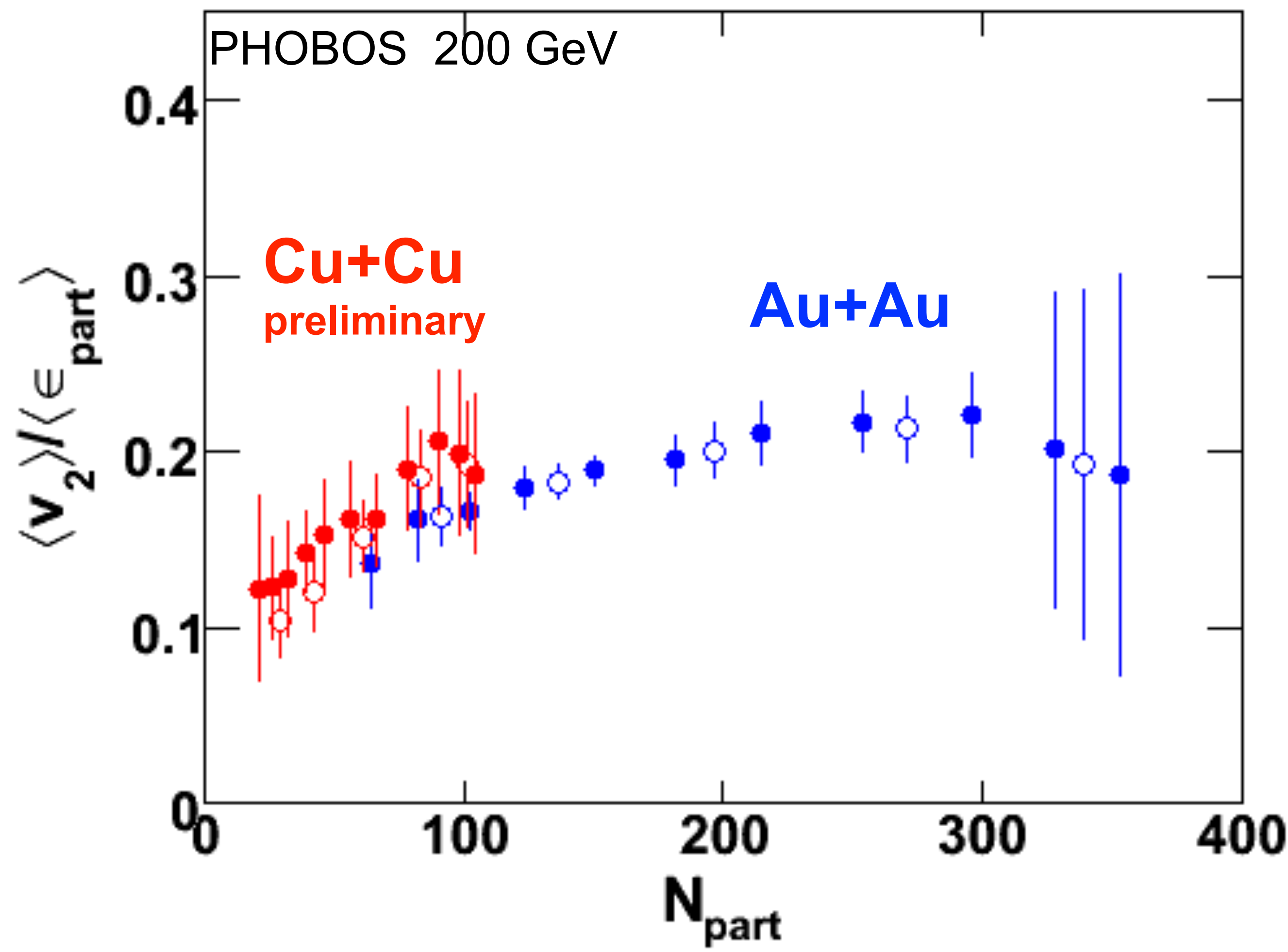


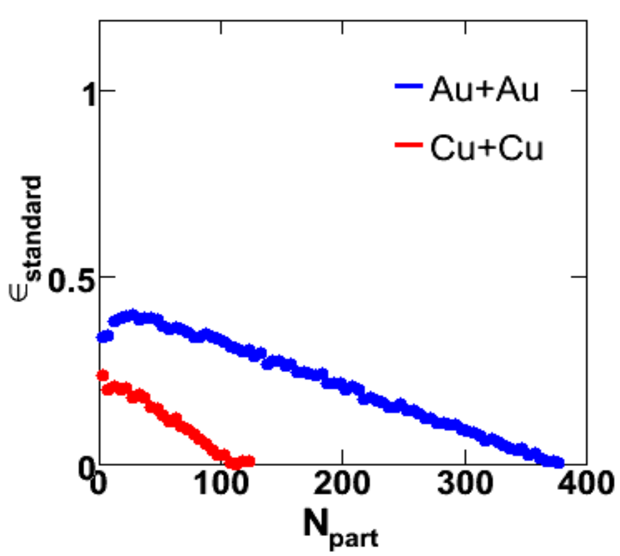
Elliptic Flow vs N_{part}, II

Standard Eccentricity

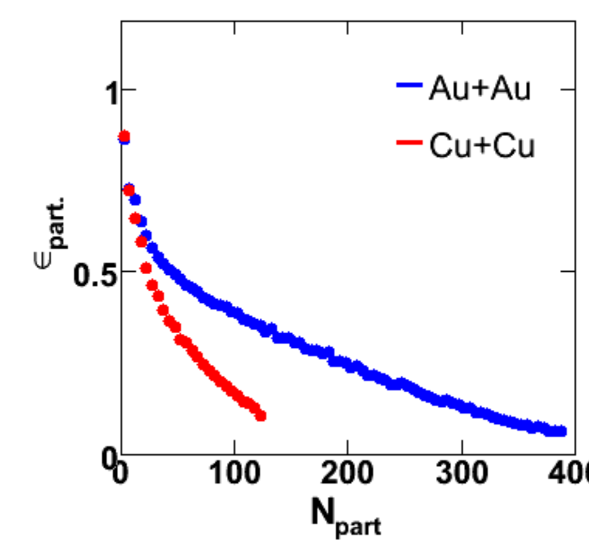


Participant Eccentricity



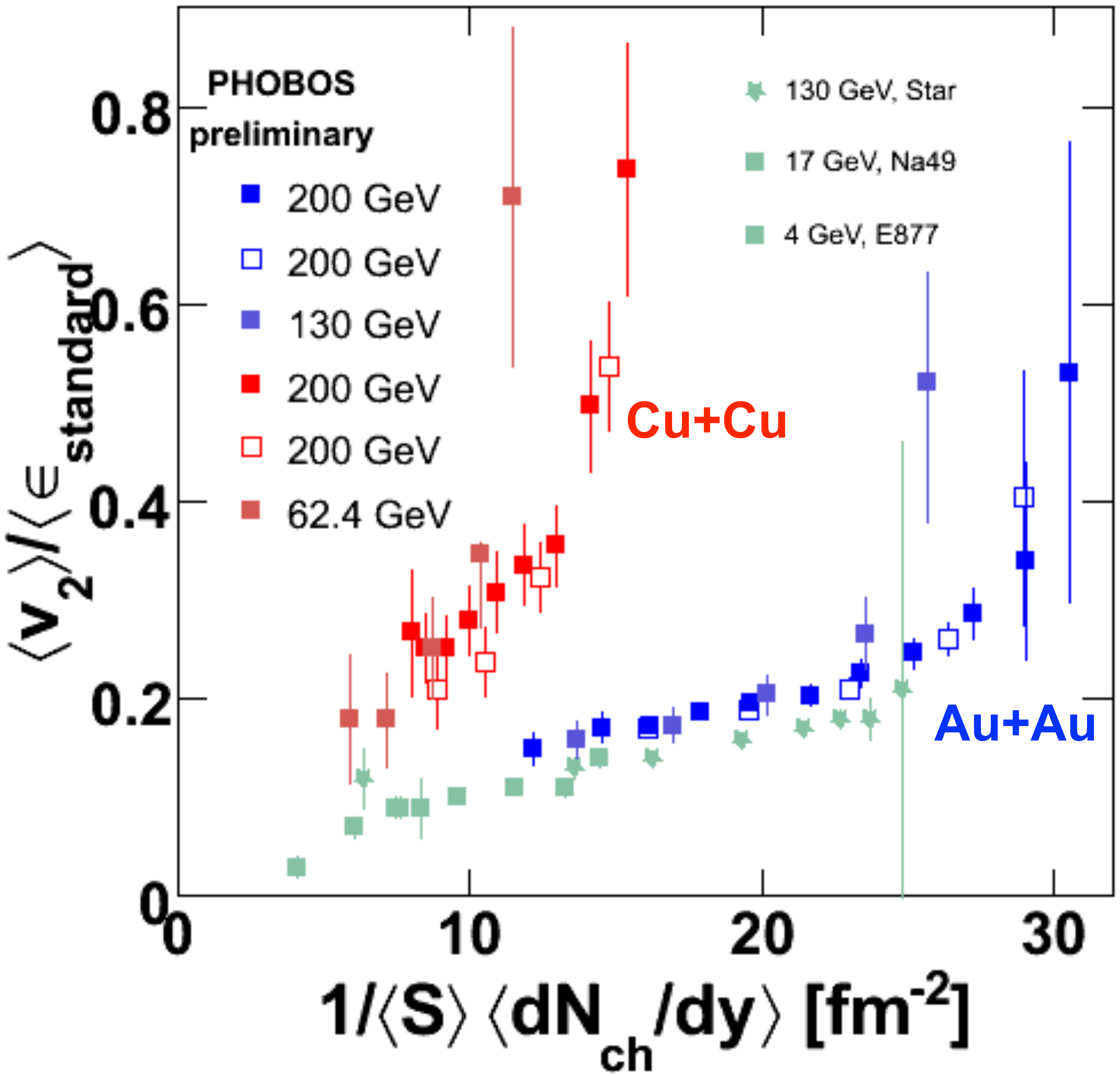


"Participant Eccentricity" allows v_2 scaling from Cu+Cu to Au+Au

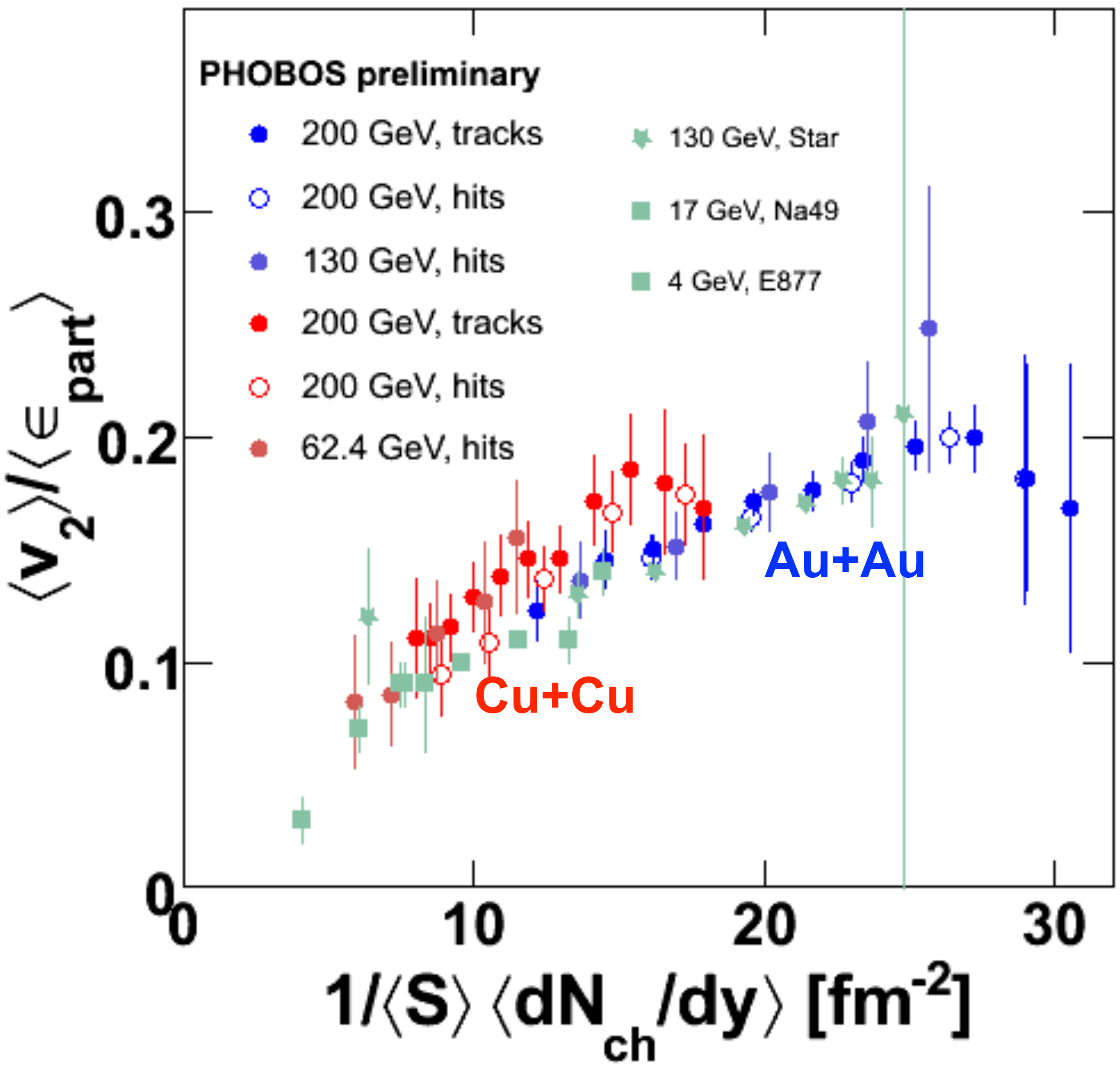


'Low Density Limit'-Scaling

Standard Eccentricity



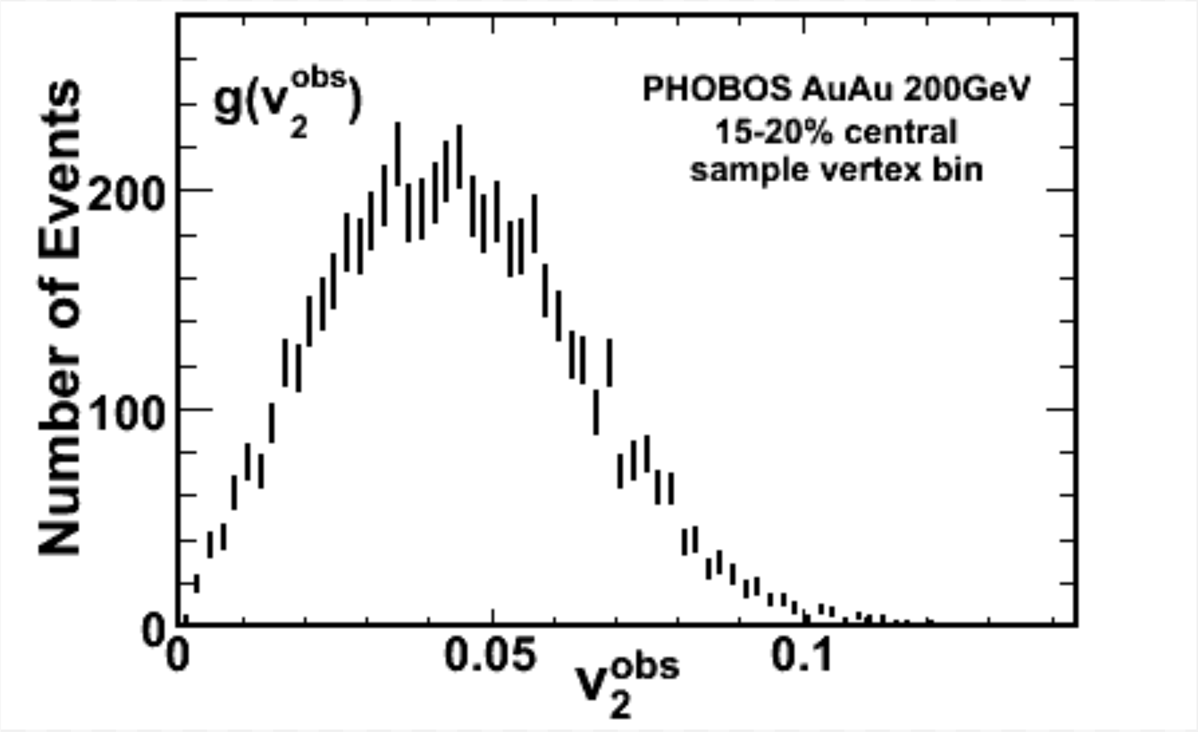
Participant Eccentricity



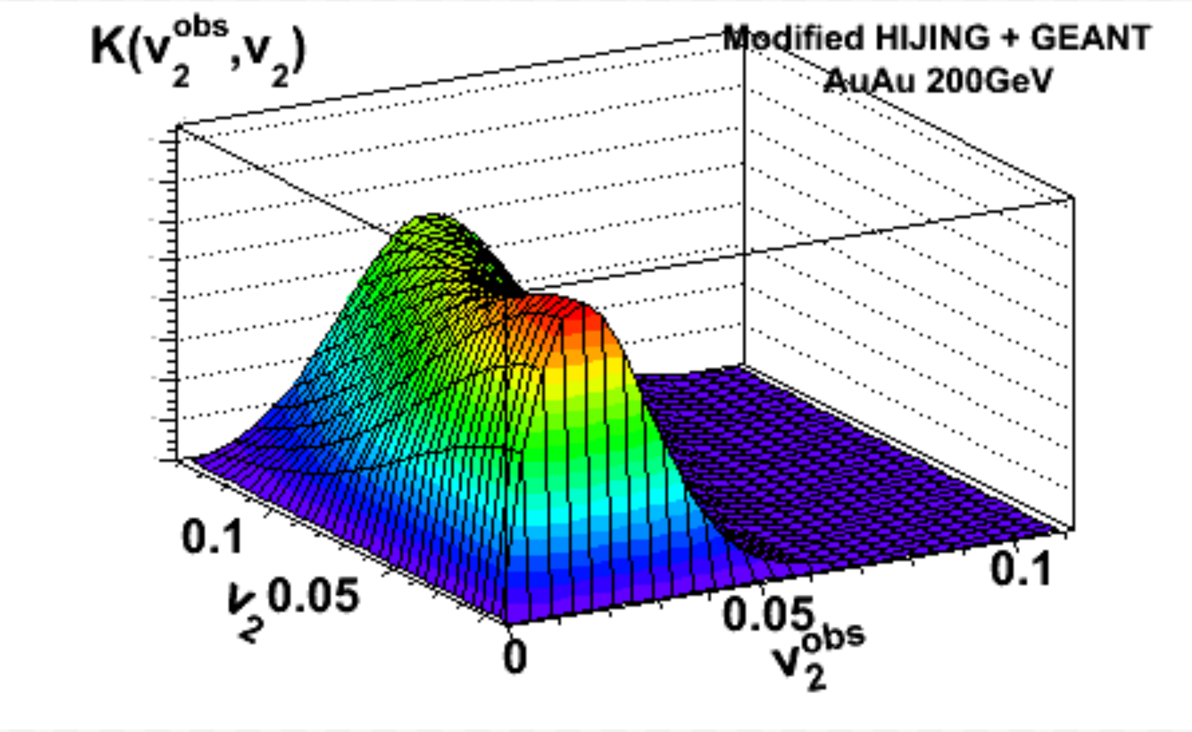
Low Density Limit:
STAR, PRC 66 034904 (2002)
Voloshin, Poskanzer, PLB 474 27 (2000)
Heiselberg, Levy, PRC 59 2716, (1999)

Quark Matter 2006

v_2^{obs} distribution in "data"



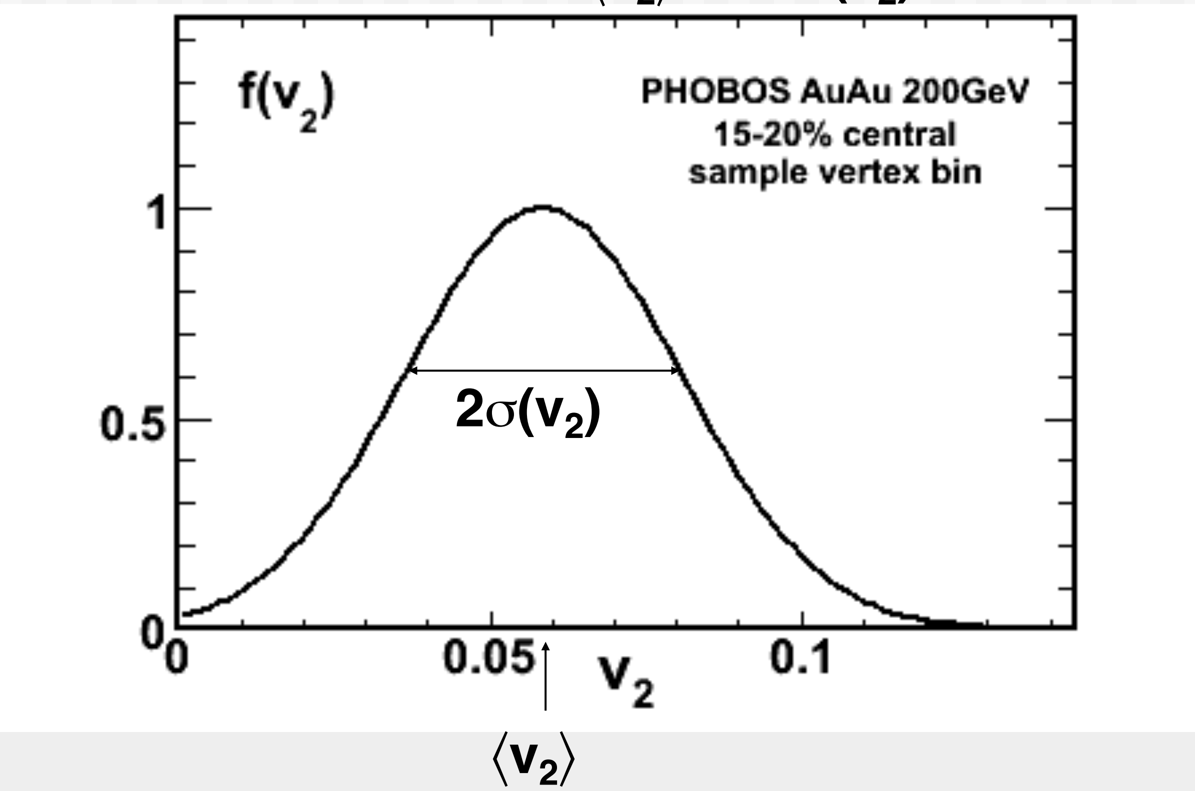
Kernel – Response Function



- Event-by-event measurement
- Determination of response in MC
- Extraction of true $\langle v_2 \rangle$ and $\sigma(v_2)$

$$g(v_2^{obs}) = \int K(v_2^{obs}, v_2) f(v_2) dv_2$$

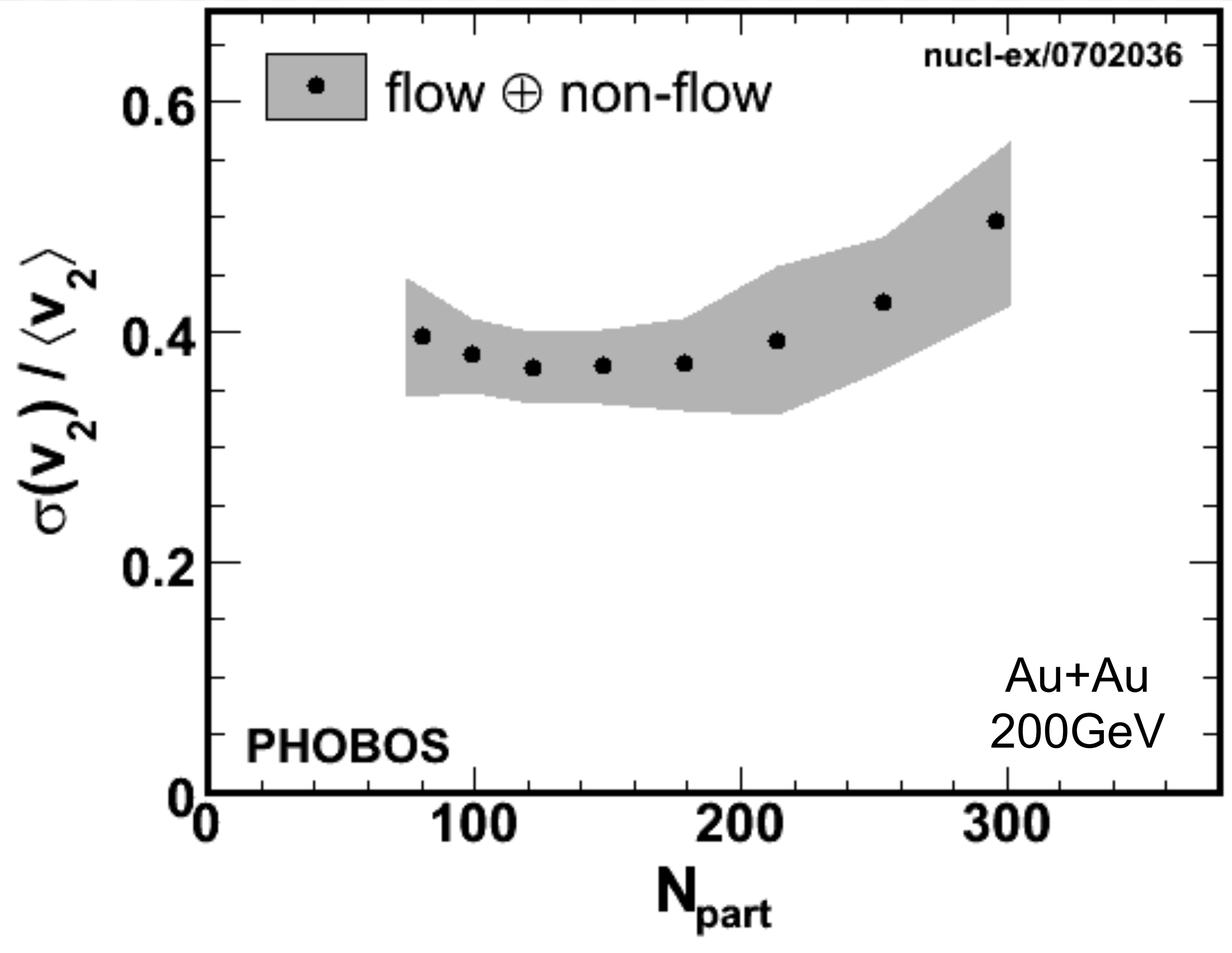
Extracted true $\langle v_2 \rangle$ and $\sigma(v_2)$



arXiv:nucl-ex/0702036

Quark Matter 2006

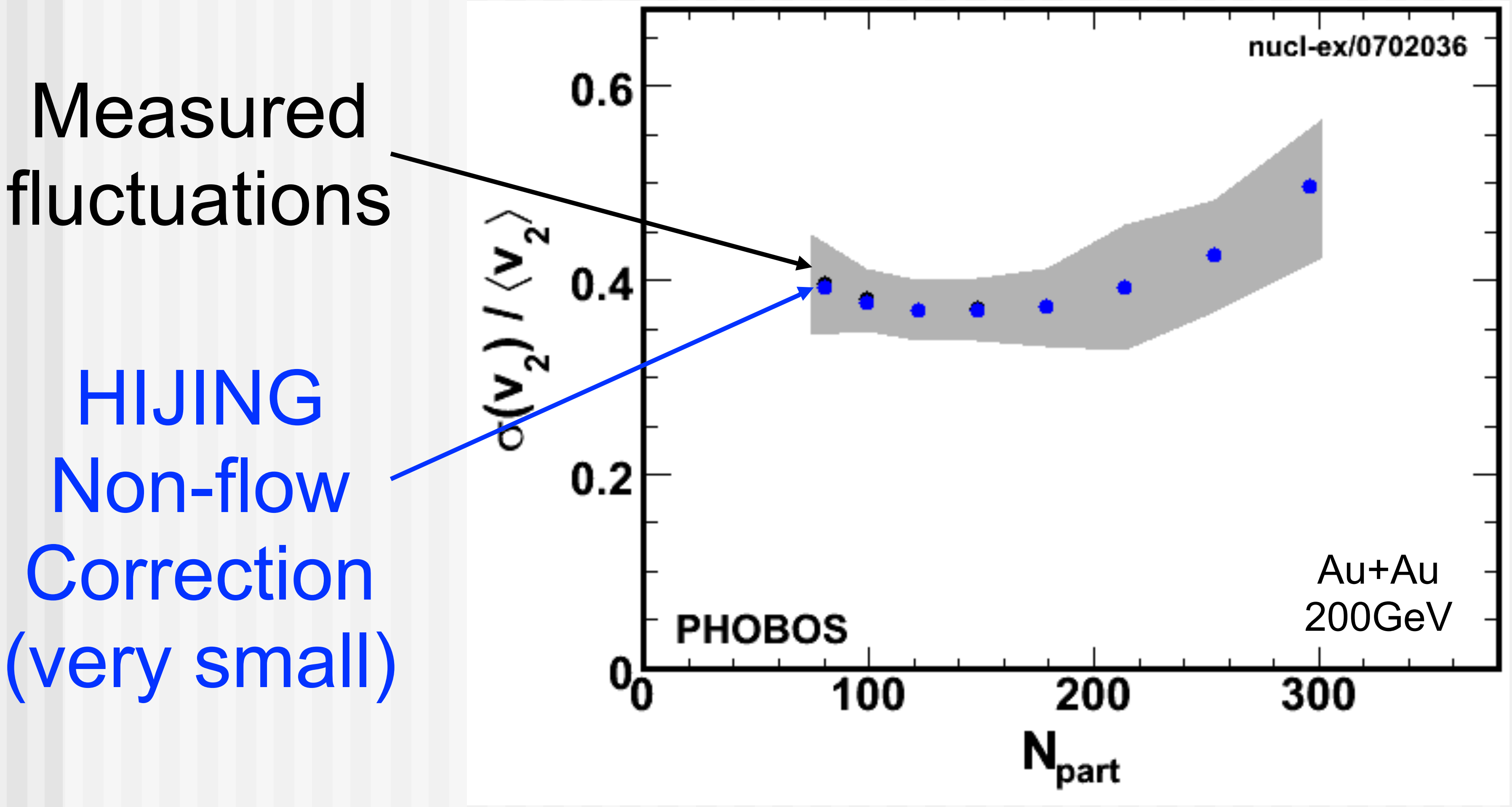
- Relative v_2 fluctuations of approximately 40%



- Correlated particle production (non-flow correlations) can broaden the v_2^{obs} distribution and affect the fluctuation measurement.

Quark Matter 2006

- Estimate non-flow contribution with HIJING

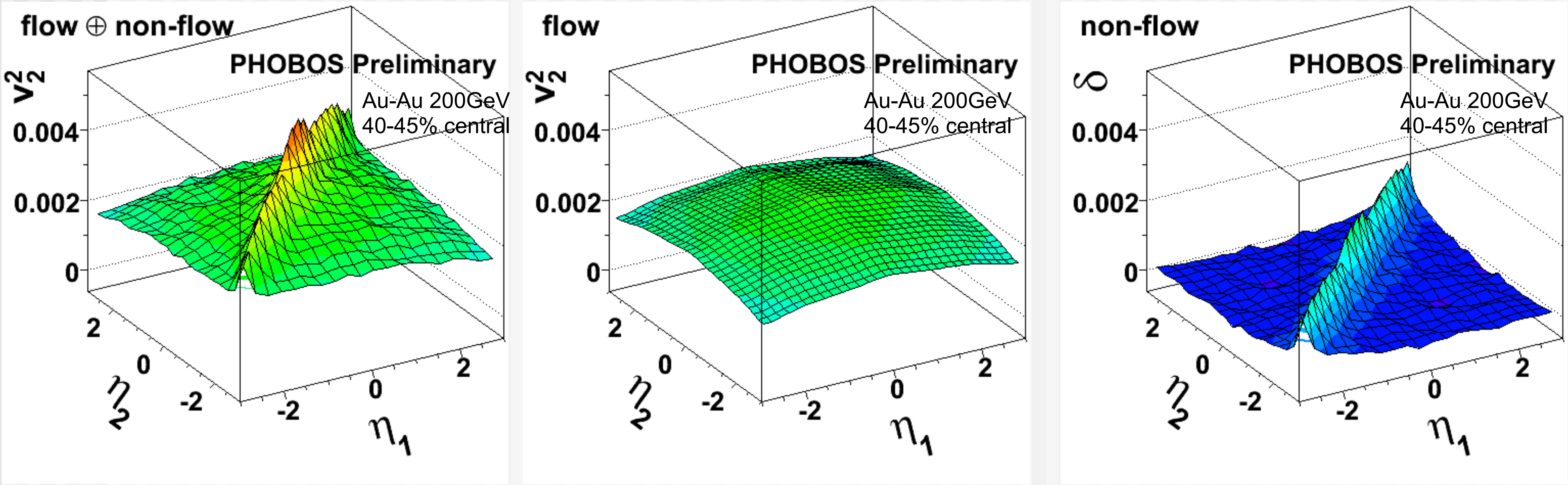


- We used response function calculated from HIJING with correlations preserved to estimate non-flow effect.

Separating flow and non-flow

- Subtract to find $\delta(\eta_1,\eta_2)$ at all ranges:

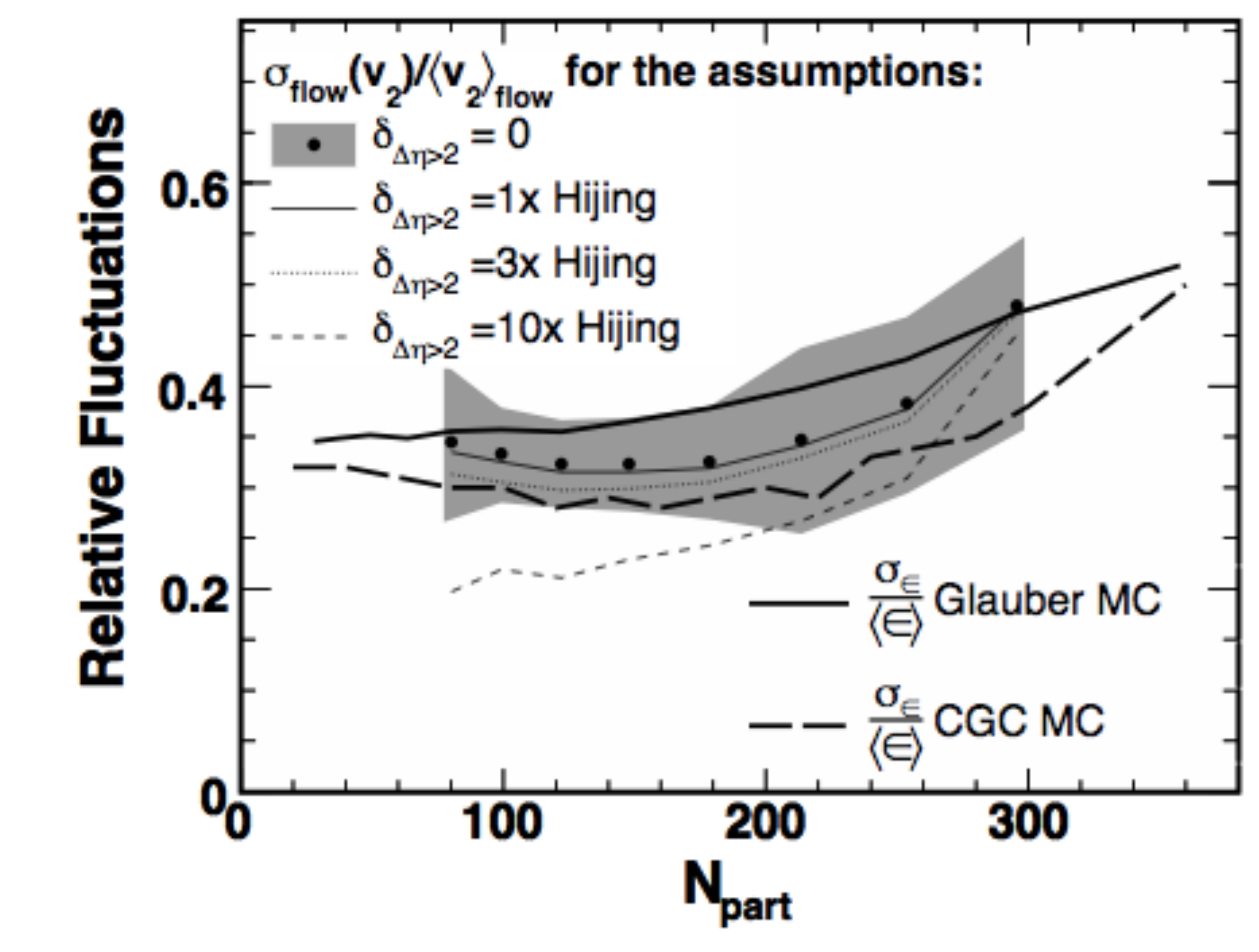
$$\delta(\eta_1,\eta_2) = v_2^2(\eta_1,\eta_2) - v_2(\eta_1) \times v_2(\eta_2)$$



flow⊕non-flow | flow | non-flow

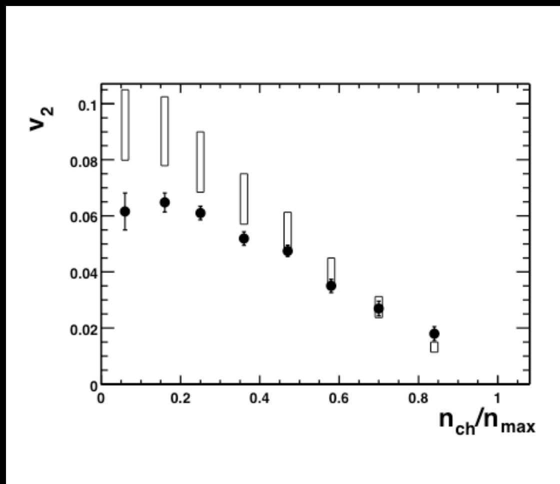
Elliptic Flow Fluctuations in Au+Au

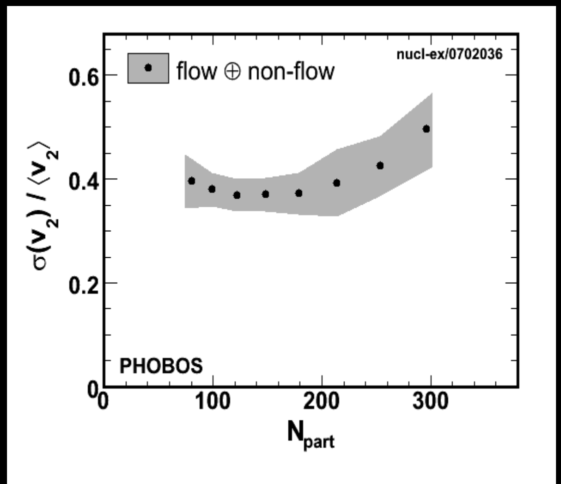
PHOBOS Phys.Rev. C81 (2010) 034915

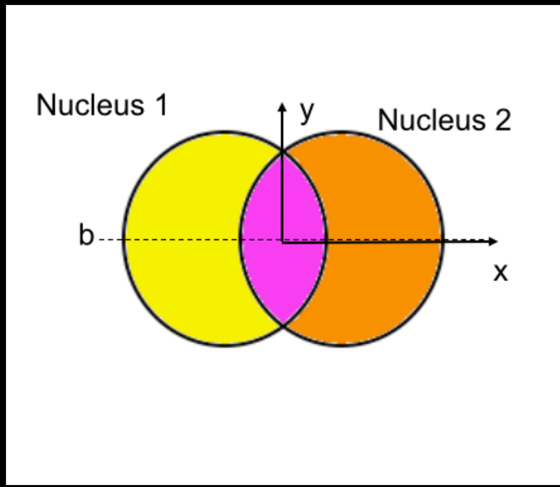


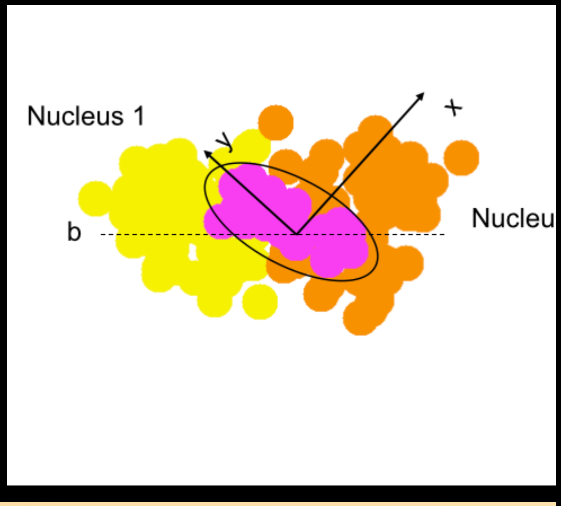
Elliptic flow fluctuations for different non-flow assumptions
(constrained by long-range pseudo-rapidity factorization)

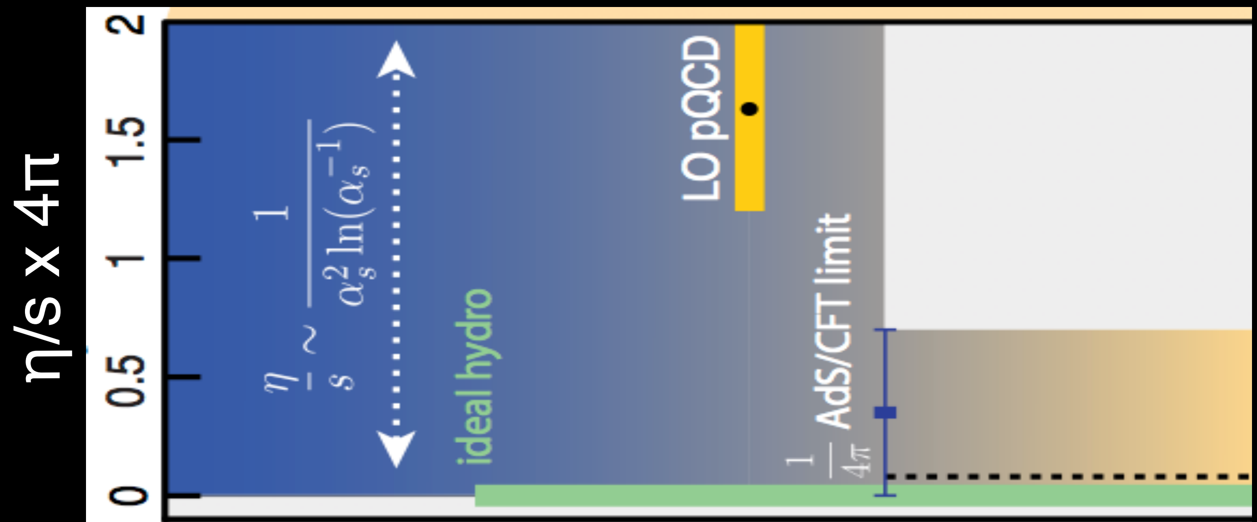
A brief history of correlations in HIC





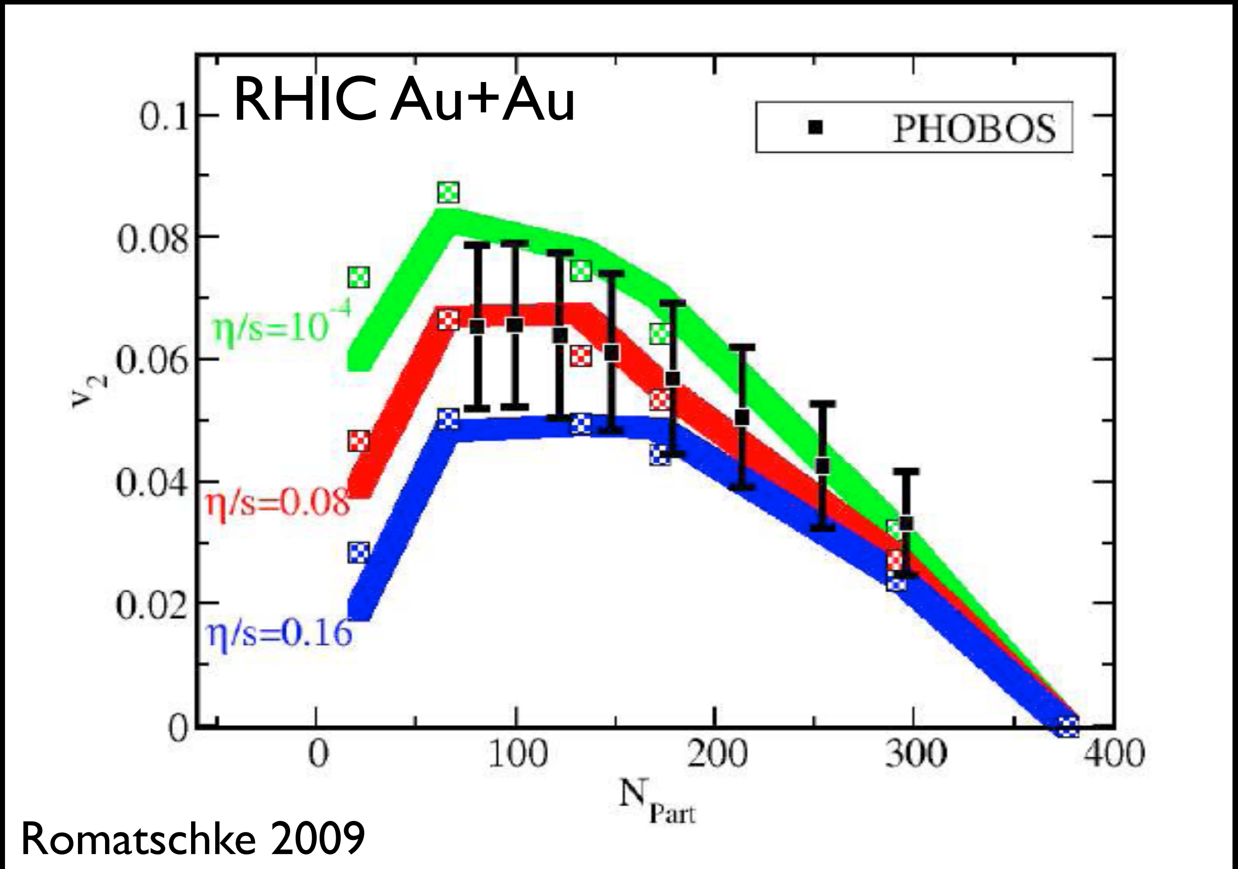






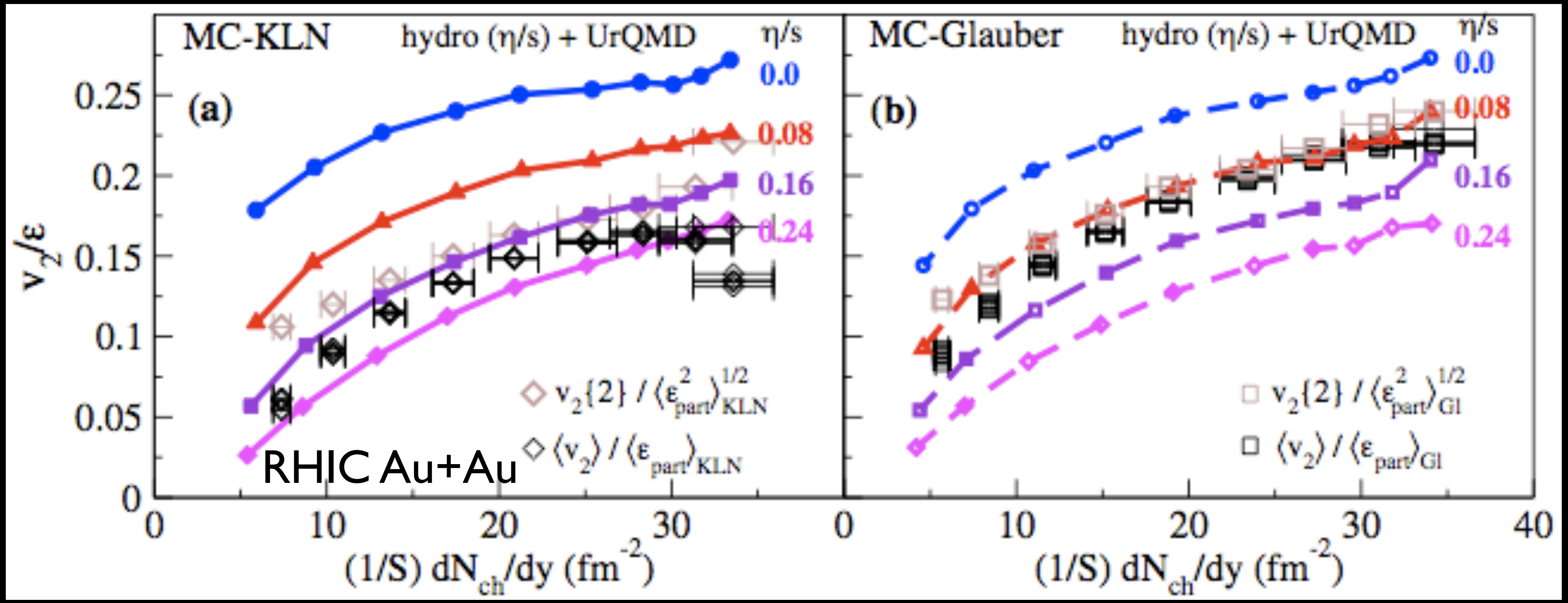
2002 2006 2010 2014

Development of viscous hydrodynamics



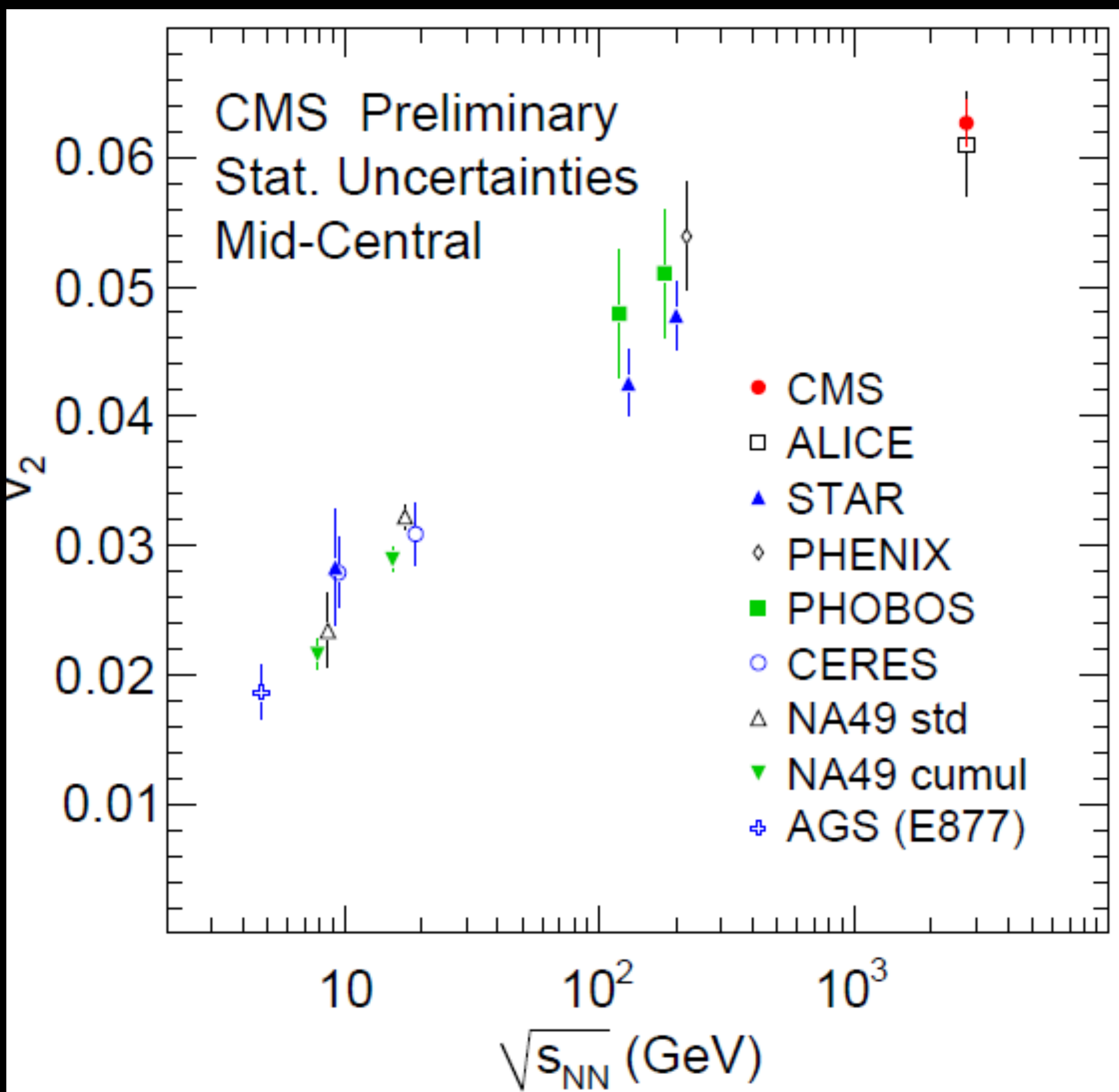
0.1 < η/s < 0.3

Large contribution to uncertainty from initial geometry

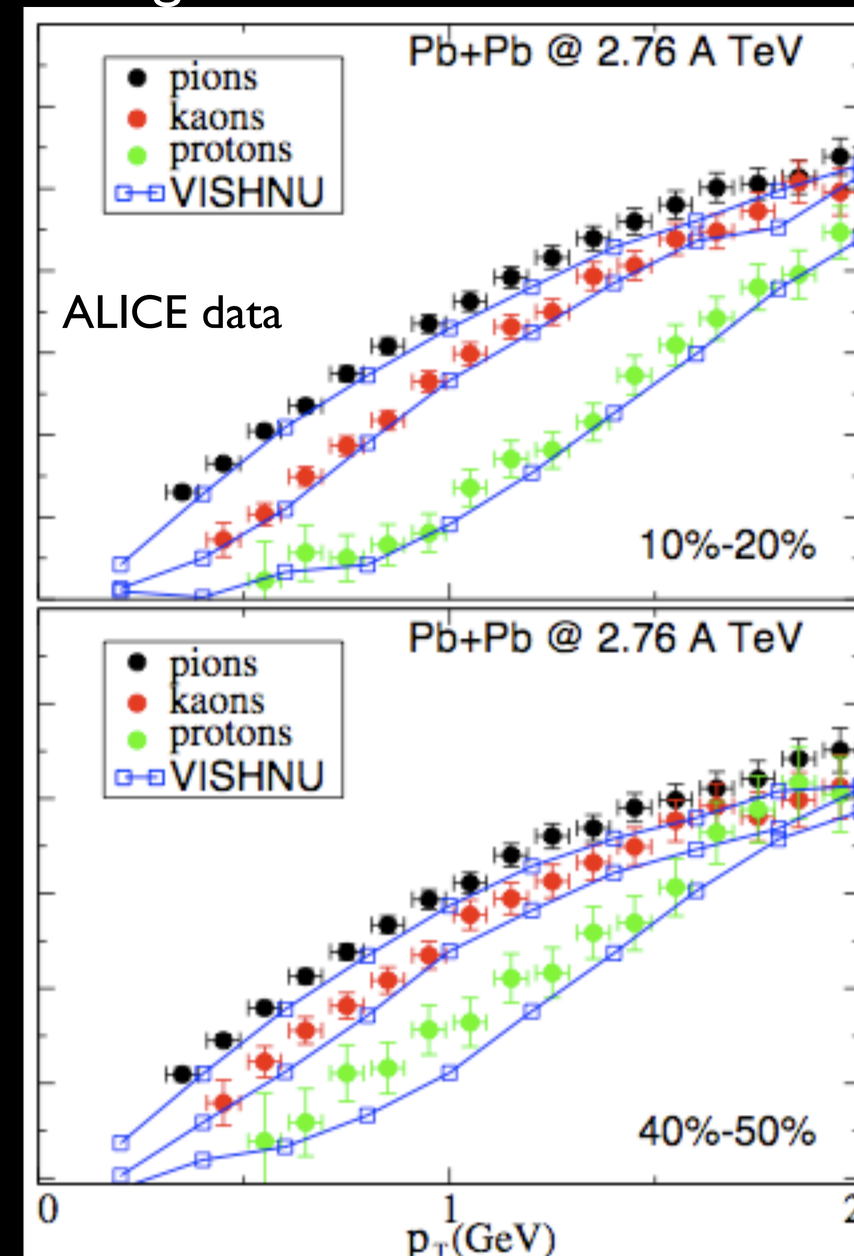


Heinz et al, 2011

What about the LHC?



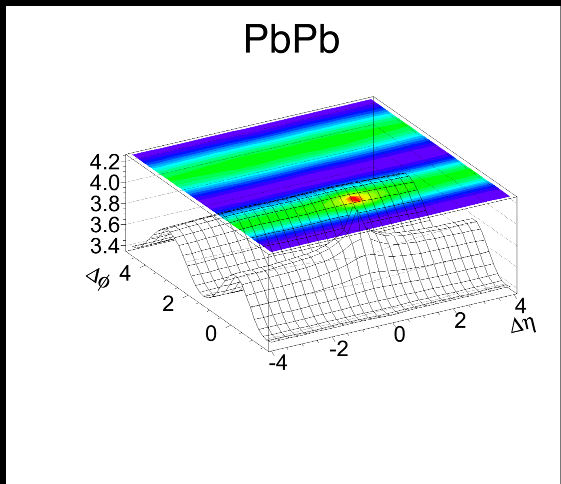
Song, Heinz et al, PANIC 2011

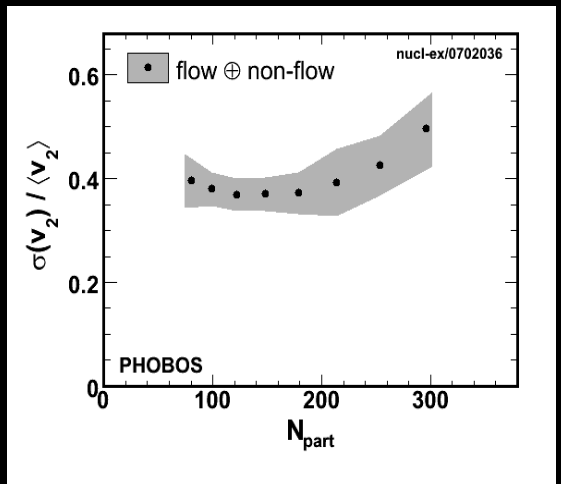


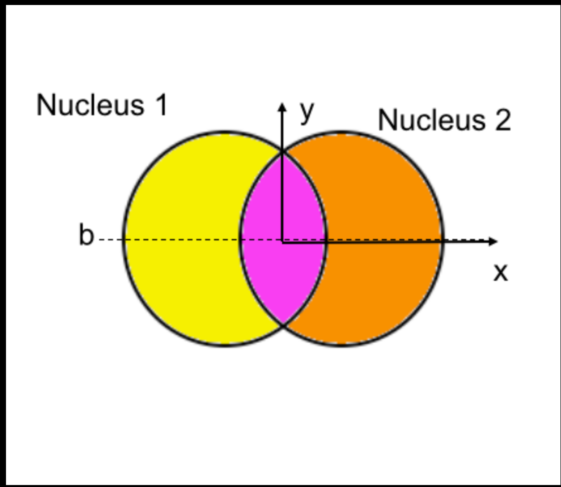
Elliptic flow 10% larger at LHC: Stronger initial push due to higher density

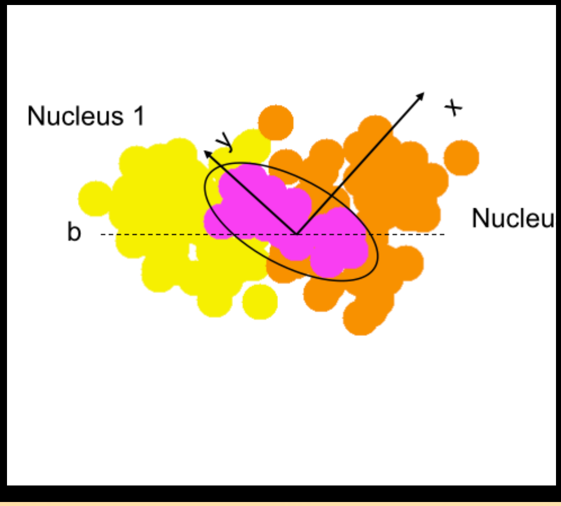
Comparison to state-of-the-art hydro calculations suggests: $\eta/s_{(LHC)} \sim \eta/s_{(RHIC)}$

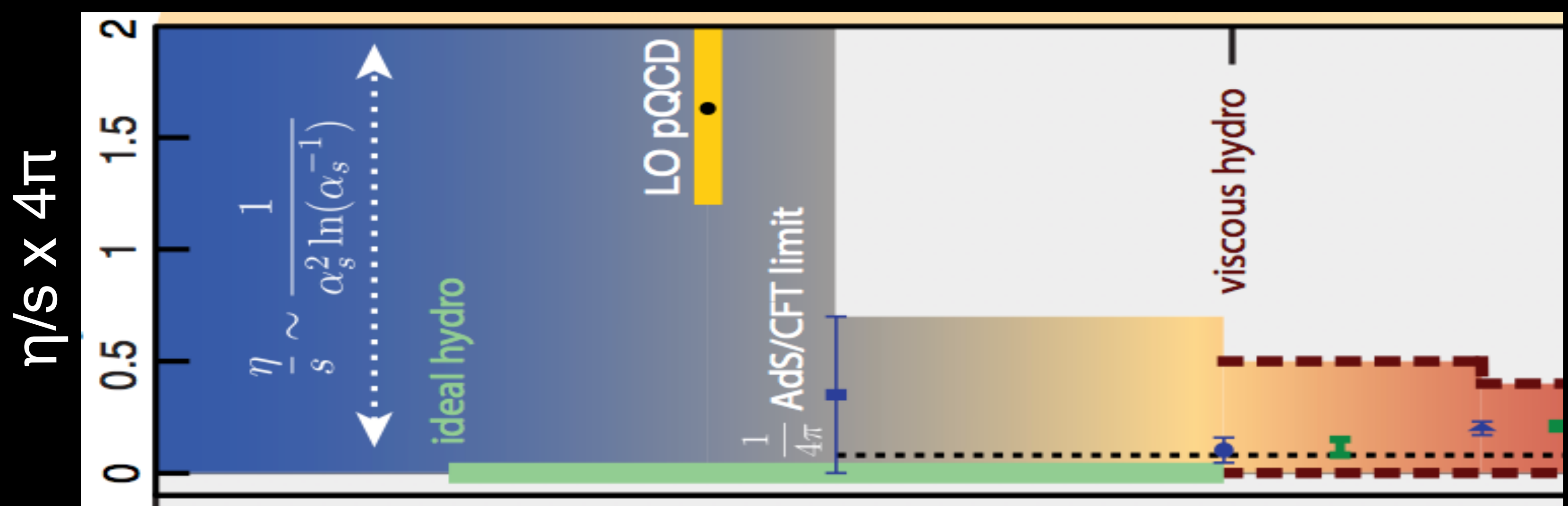
A brief history of correlations in HIC





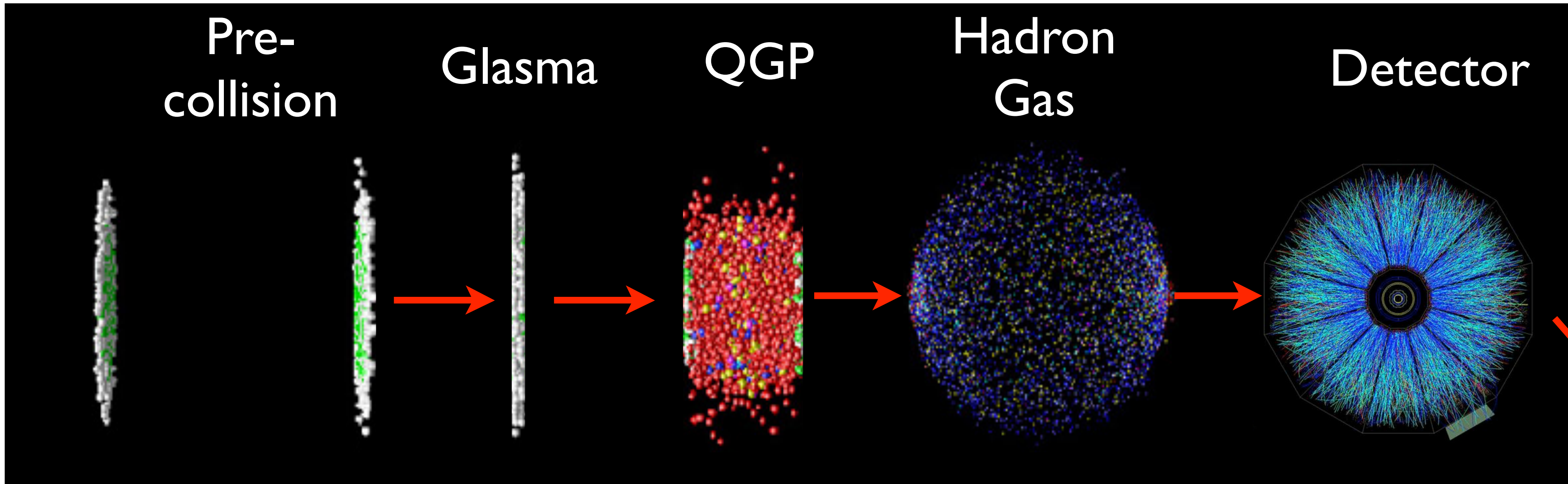




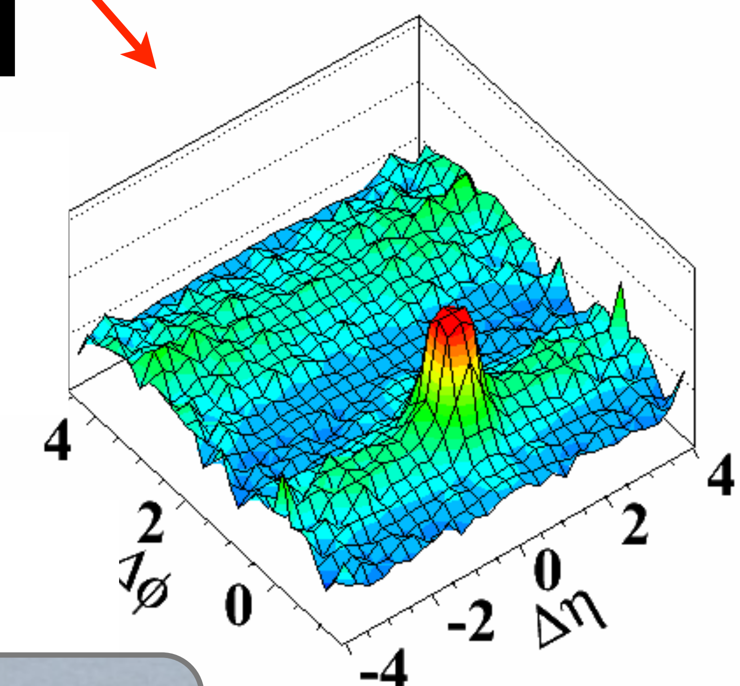


2002 2006 2010 2014

High p_T Correlations



Two-hadron
Correlation Function



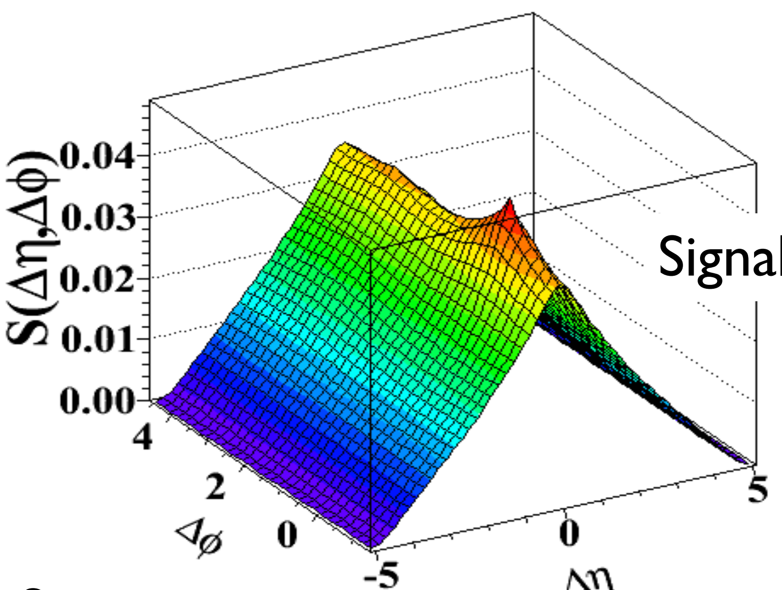
Initial State Correlations $\otimes$ Hydrodynamic Flow =

Jets
Glasma Flux Tubes
Hot Spots
Glauber Fluctuations

Key Physics Topics:

- Jet energy loss
- Jet-medium interactions
- Transport properties of the medium

Angular Correlation Functions

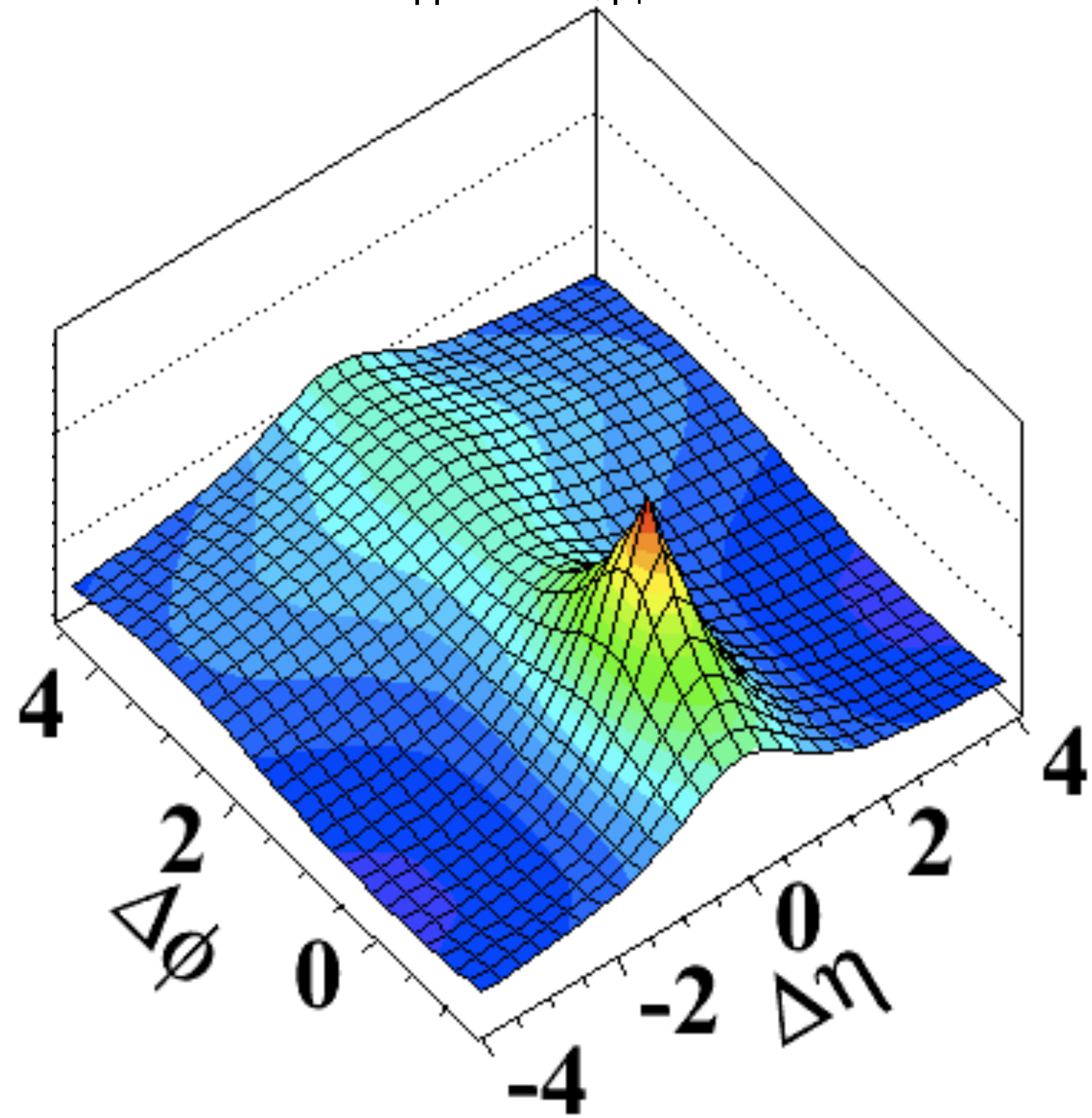


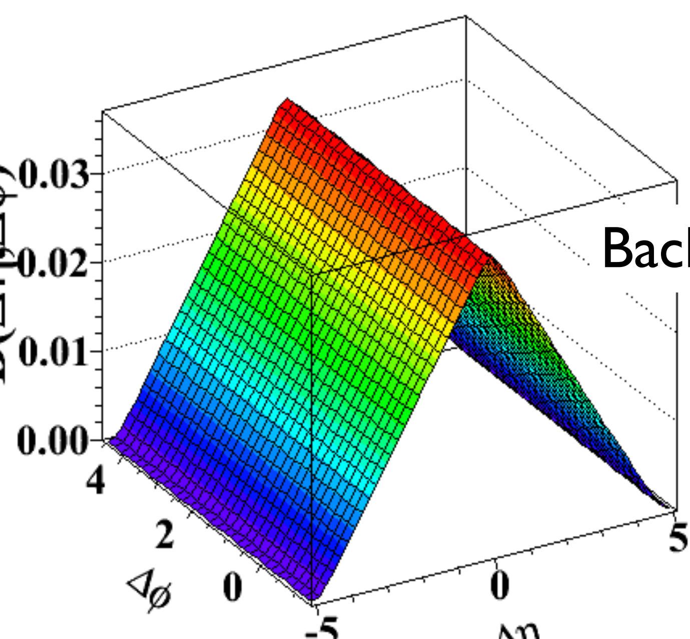
Signal distribution

Same event pairs

Ratio
Signal/Background

CMS 7TeV pp min bias, p_T > 0.1 GeV/c





Background distribution:

Mixed event pairs

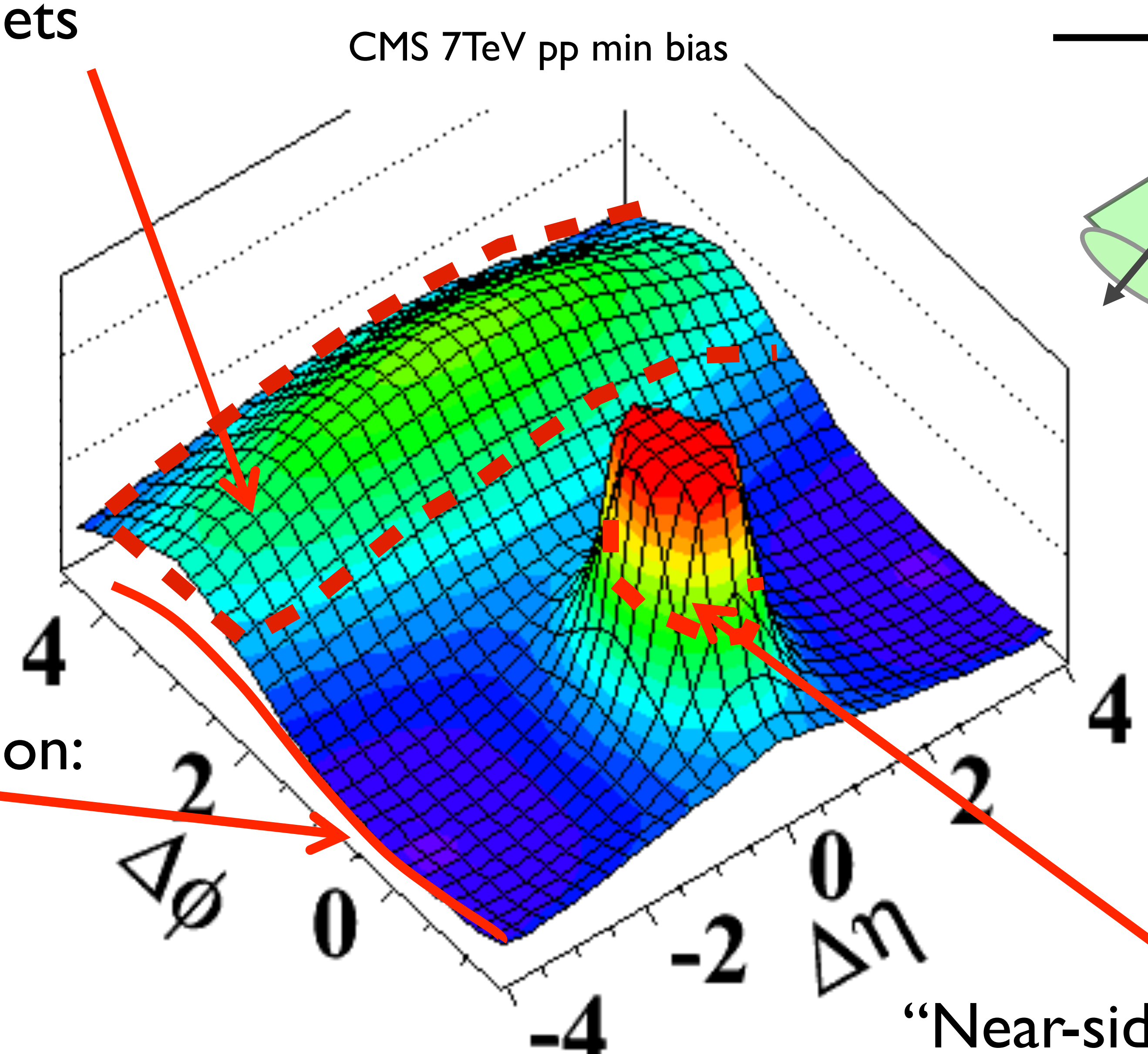
$$\Delta\eta = \eta_1 - \eta_2$$

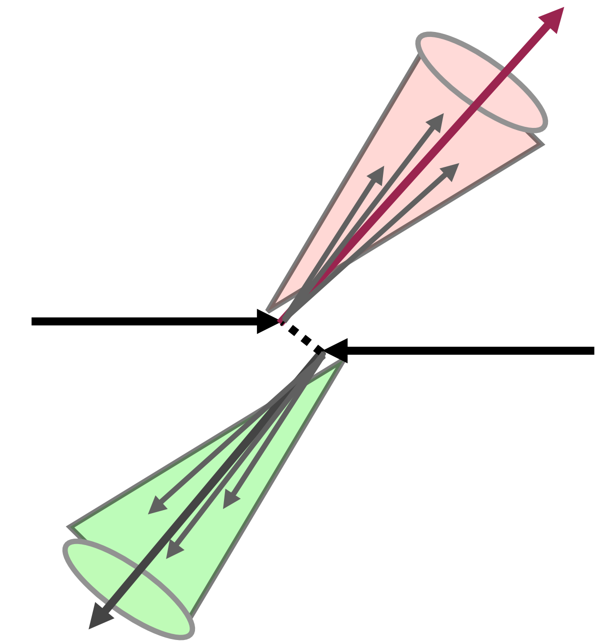
$$\Delta\varphi = \varphi_1 - \varphi_2$$

p_T-inclusive two-particle
angular correlation function

High(er) p_T Correlations in pp

"Away-side" ($\Delta\phi \sim \pi$) jet correlations:
Correlation of particles between back-to-back jets





Momentum conservation:
$\sim -\cos(\Delta\phi)$

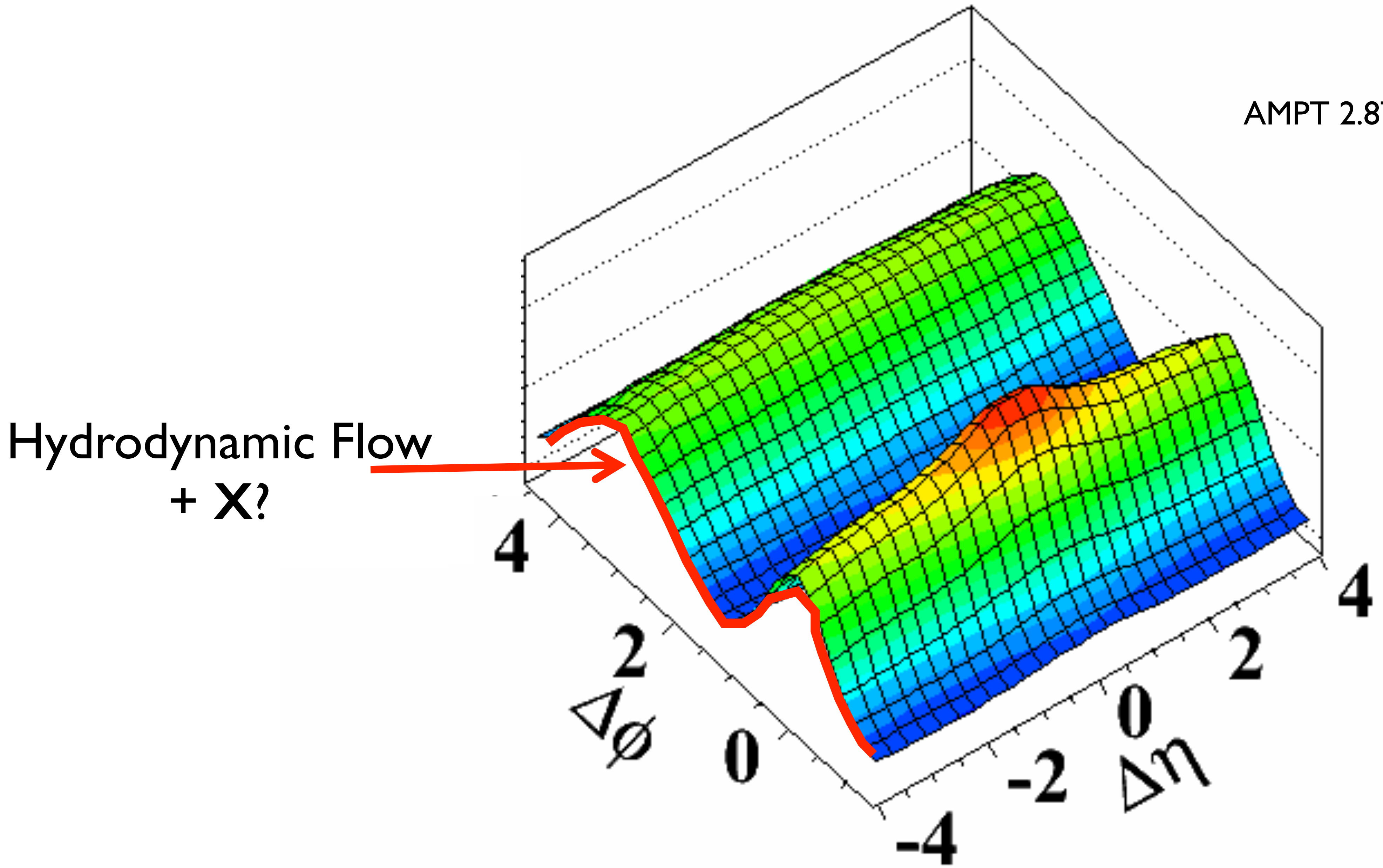
"Near-side" ($\Delta\phi \sim 0$) jet peak:
Correlation of particles within a single jet

$1 < p_T < 3$ GeV/c

Dominated by jet-like correlations

High(er) p_T Correlations in PbPb

AMPT 2.8TeV PbPb min bias



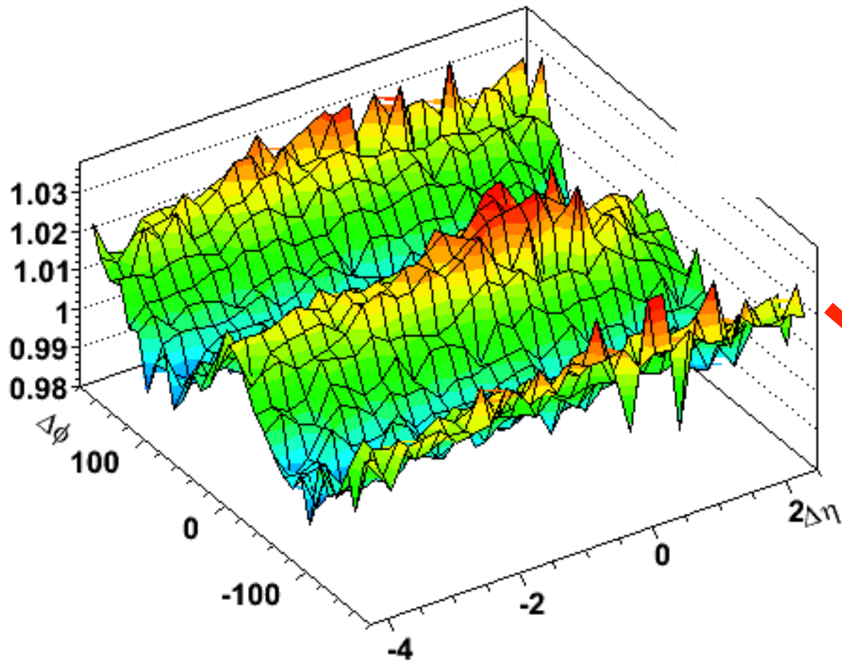
PbPb correlations, $1 < p_T < 3$ GeV/c

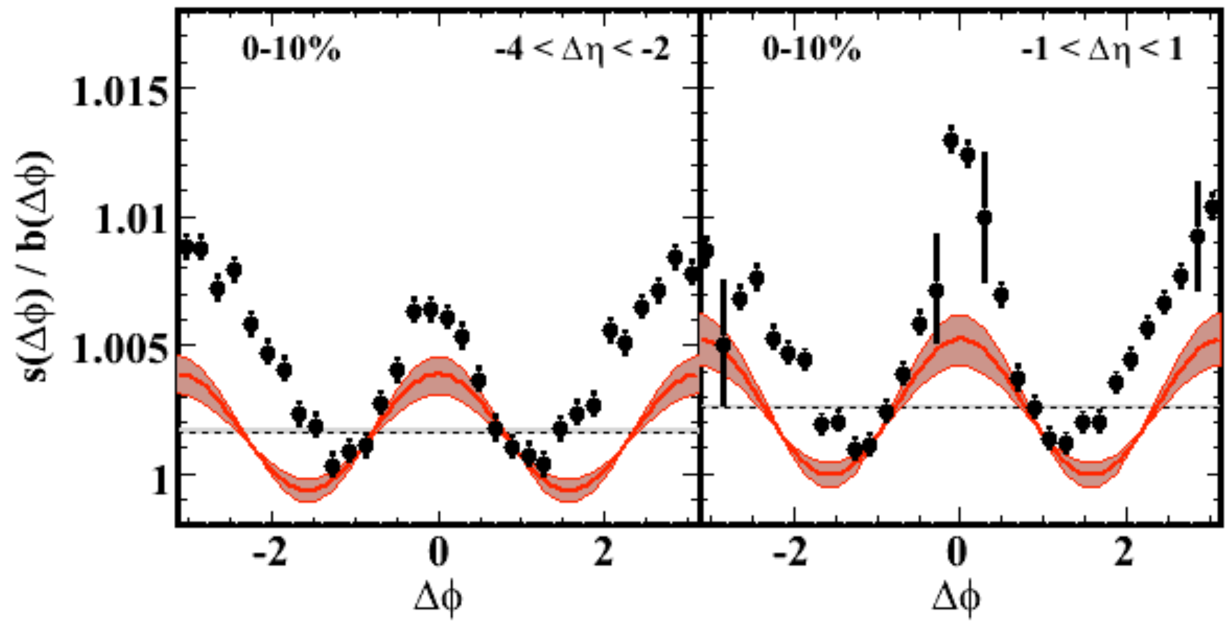
Large v2 term from elliptic flow dominates correlations

Note: flow modulation in correlation function is $\propto v_N^2$

"Flow subtraction"

"Raw" correlation function

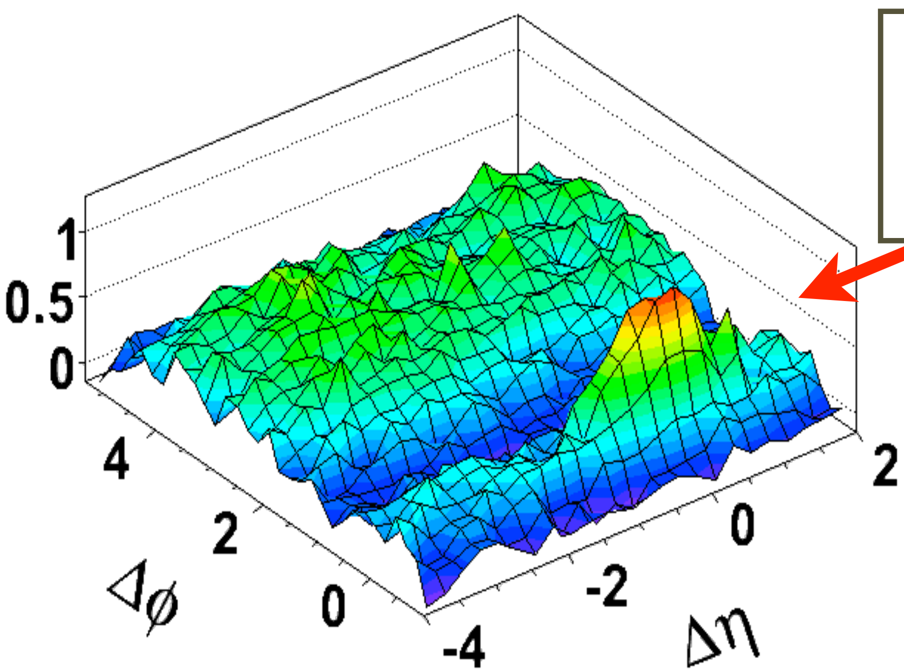




"ZYAM" (zero yield at minimum): assume that one component of the correlations (jets) gives zero contribution at some $\Delta\phi$; match v_2 flow at that $\Delta\phi$ and subtract

$$\frac{1}{N_{trig}}\frac{d^2N_{ch}}{d\Delta\phi\, d\Delta\eta} = B(\Delta\eta)\left\{ \frac{s(\Delta\phi,\Delta\eta)}{b(\Delta\phi,\Delta\eta)} - a(\Delta\eta)\; 1 + 2V(\Delta\eta)\cos(2\Delta\phi) \right]$$

for some measurements: also v_4

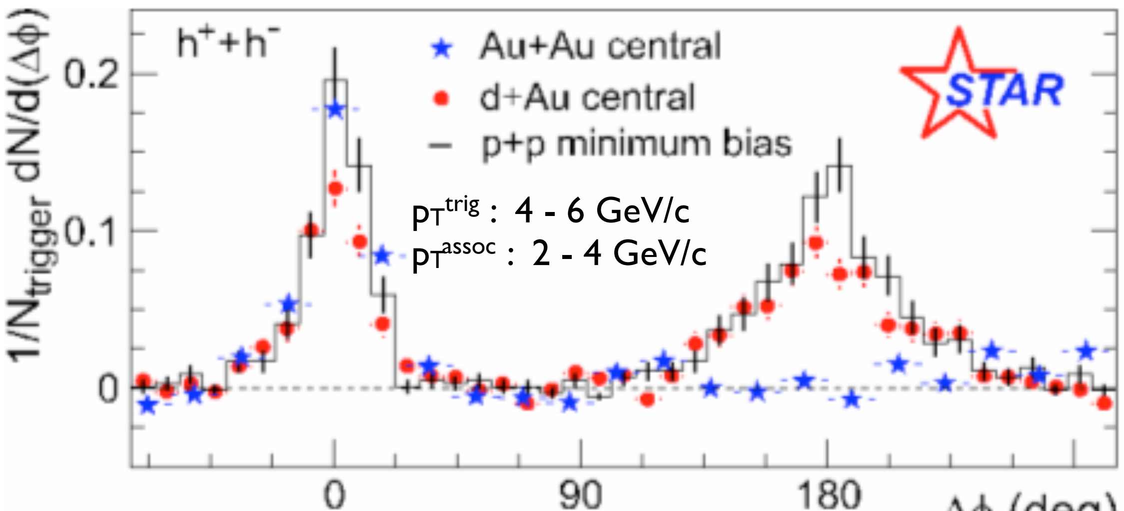


v_2 subtracted "associated yield"

Normalization term to go from correlation amplitude to yield per trigger particle

Selected Results

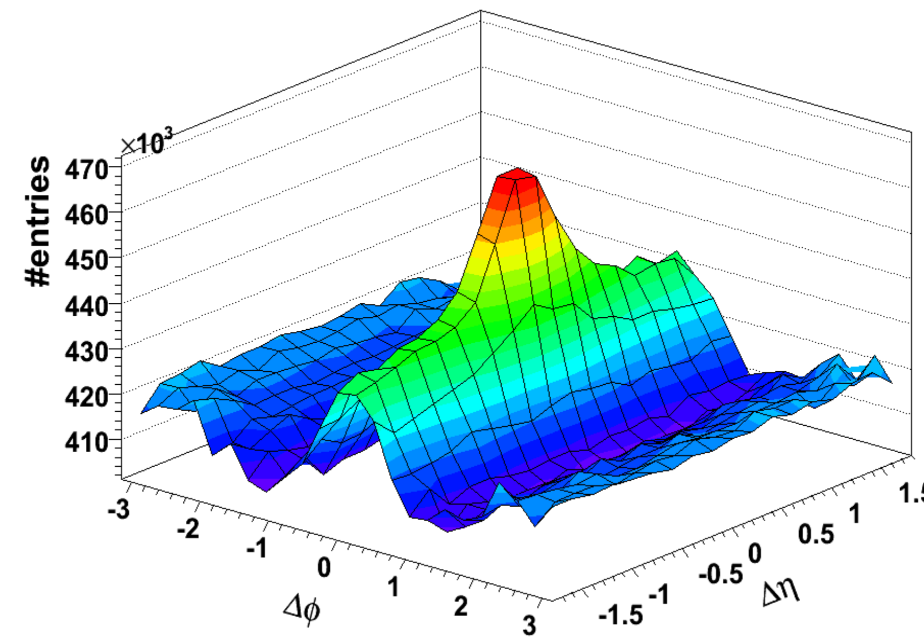
"Disappearance" of away-side jet correlations in central AuAu



STAR, PRL **91**, 072304 (2003)

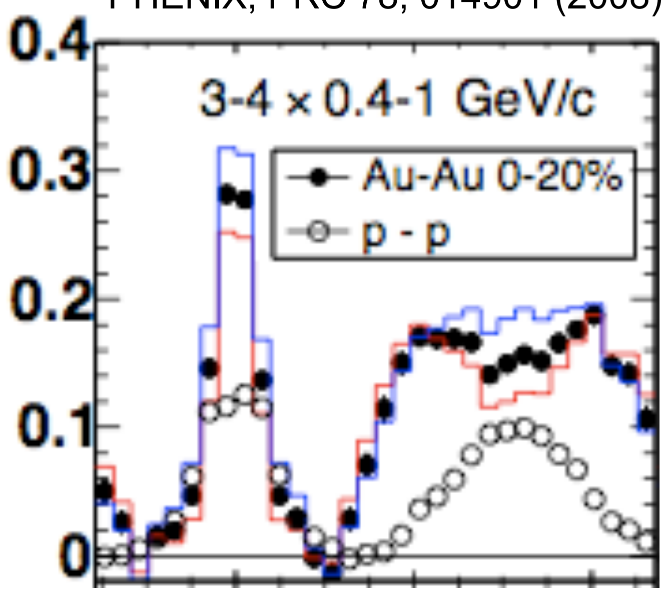
p_T^{trig} : 3-4 , p_T^{assoc} : >2 GeV/c

STAR, J.Phys.G34:S679-684,2007



p_T^{trig} : 3-4 , p_T^{assoc} : 0.4-1 GeV/c

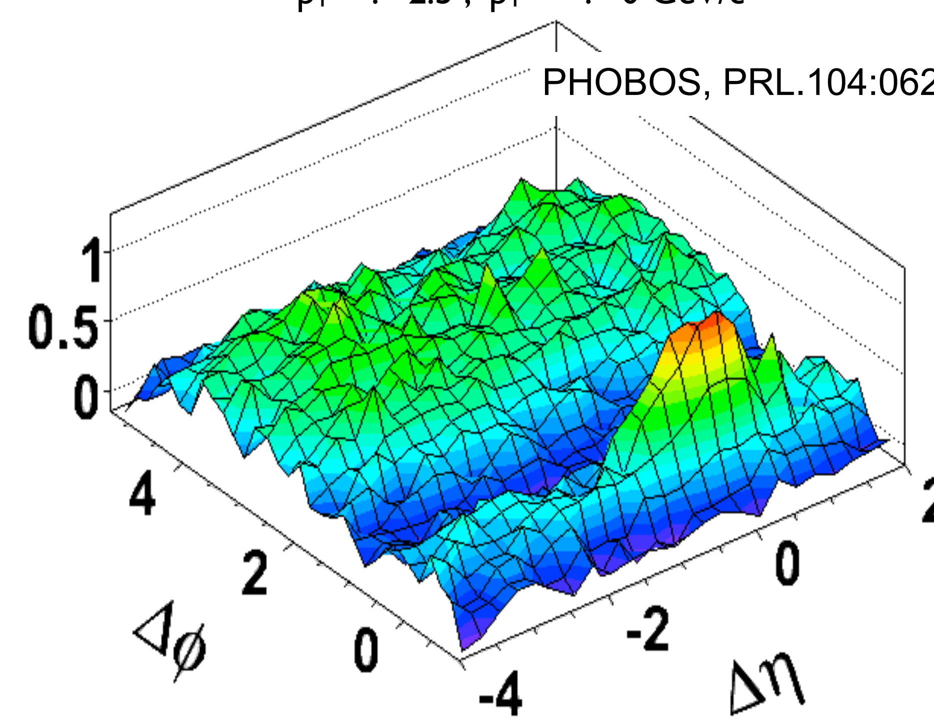
PHENIX, PRC 78, 014901 (2008)



Emergence of long-range near-side correlations in AuAu: Ridge

p_T^{trig} : >2.5 , p_T^{assoc} : >0 GeV/c

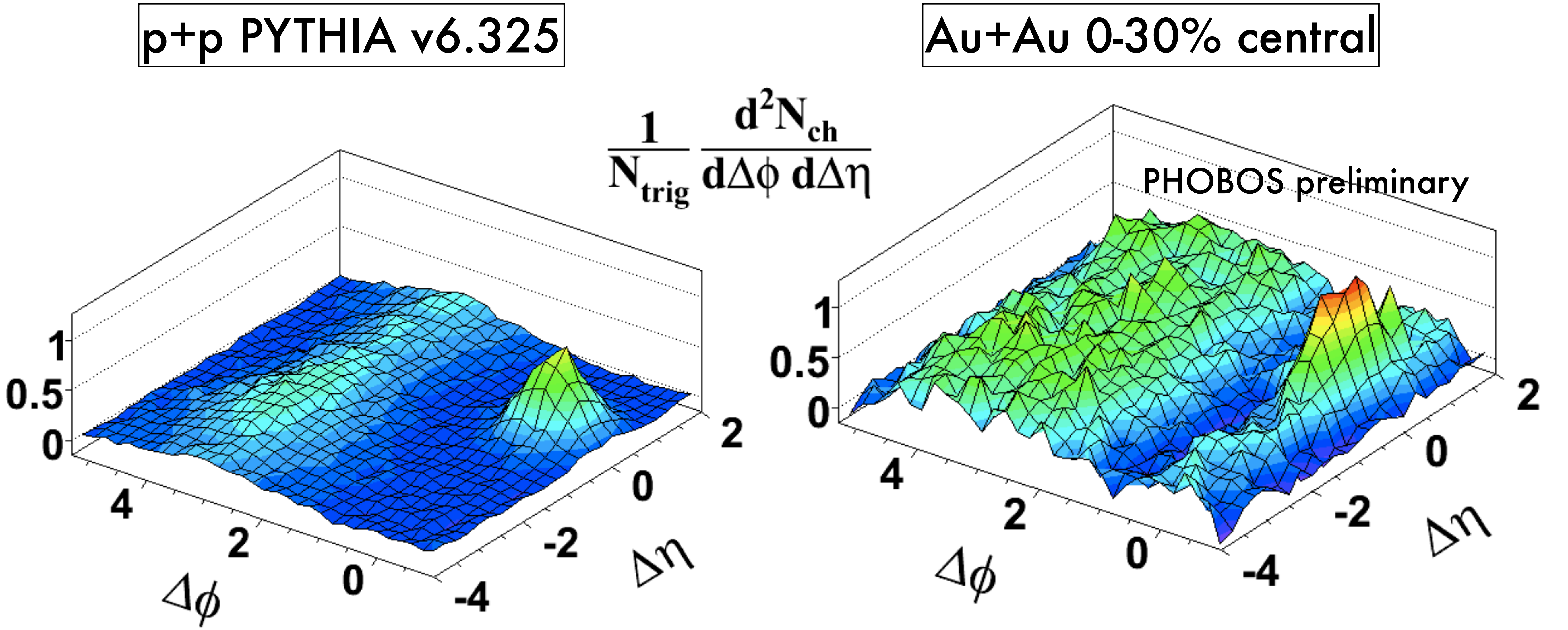
PHOBOS, PRL.104:062301 (2010)



Broadening of away-side jet correlations in central AuAu: Conical emission?

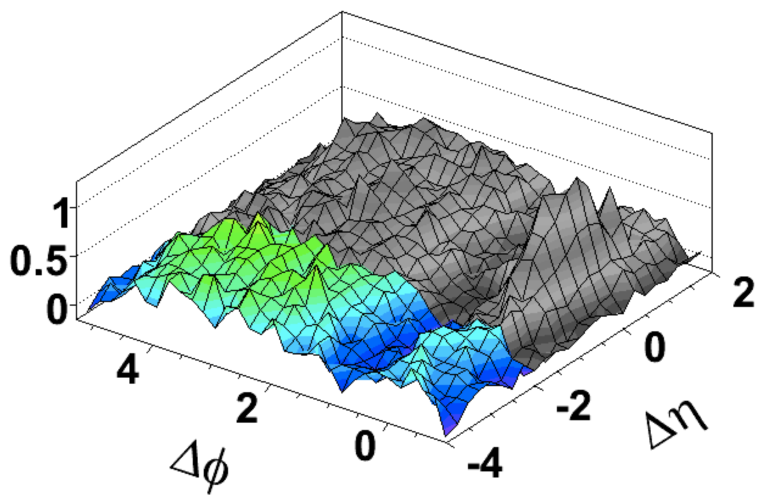
Results

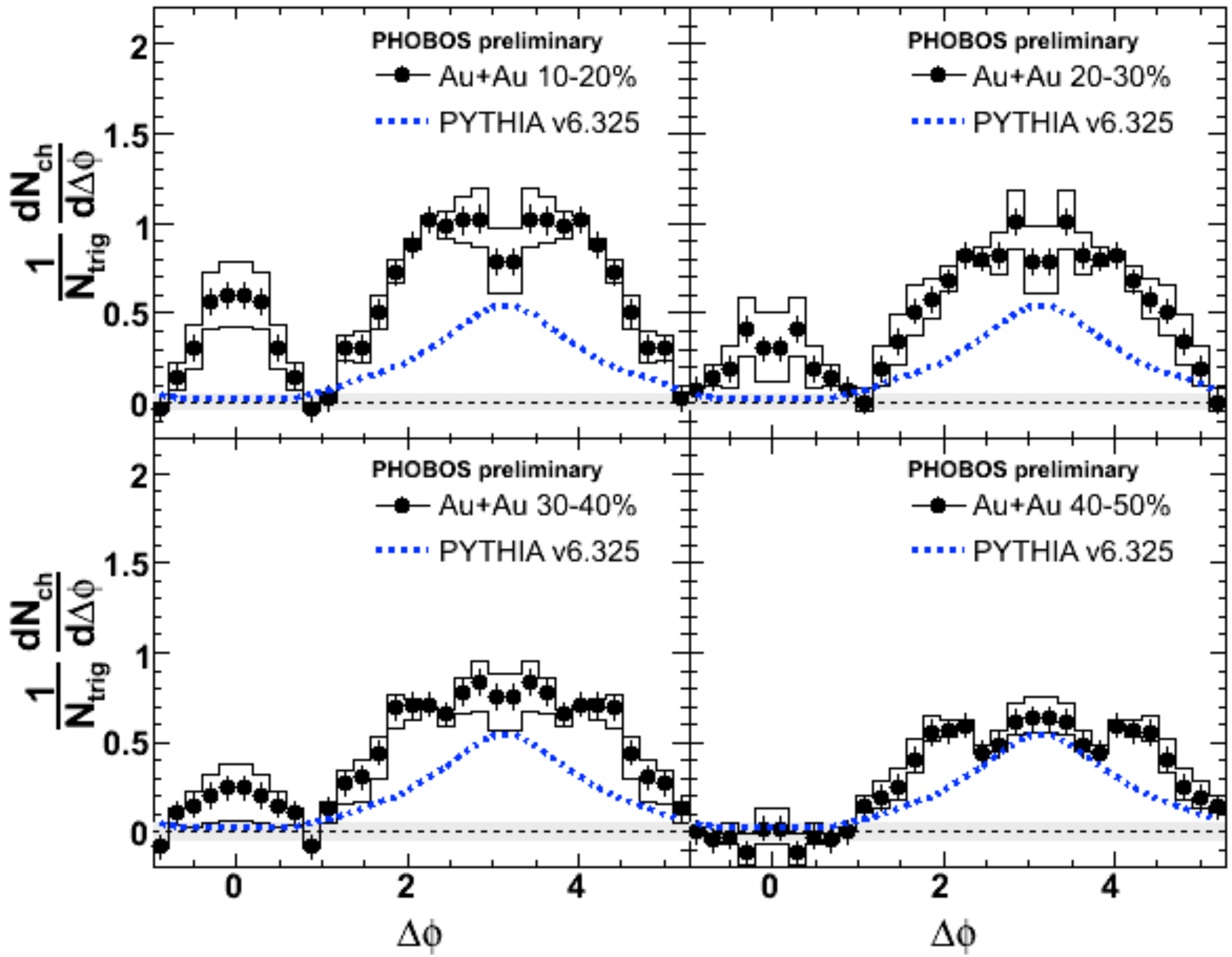
$p_T^{trig} > 2.5$ GeV/c
$p_T^{assoc} \gtrsim 20$ MeV/c



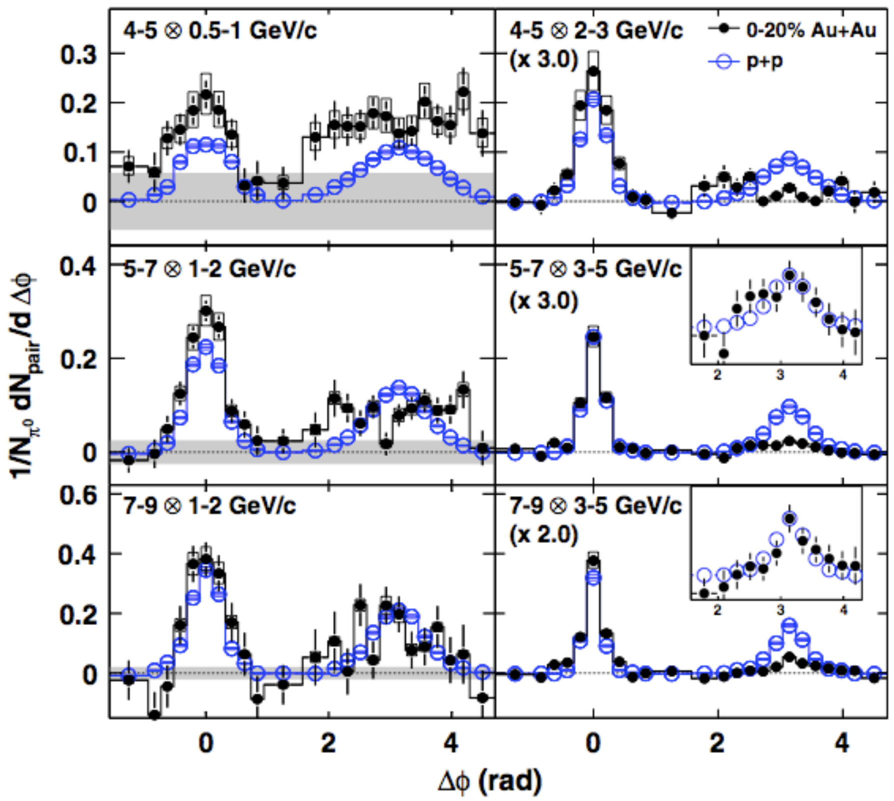
Long-Range Centrality Dependence

$-4 < \Delta\eta < -2$

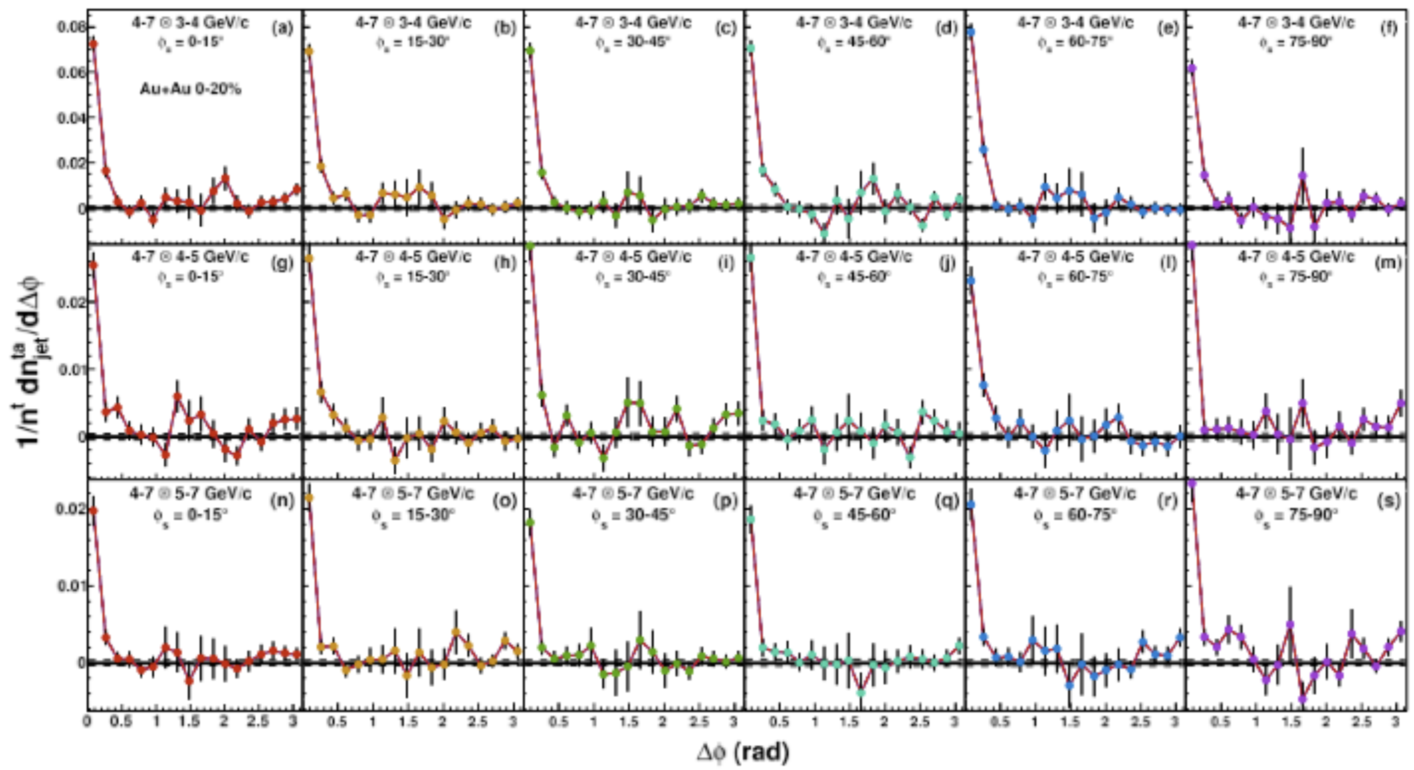




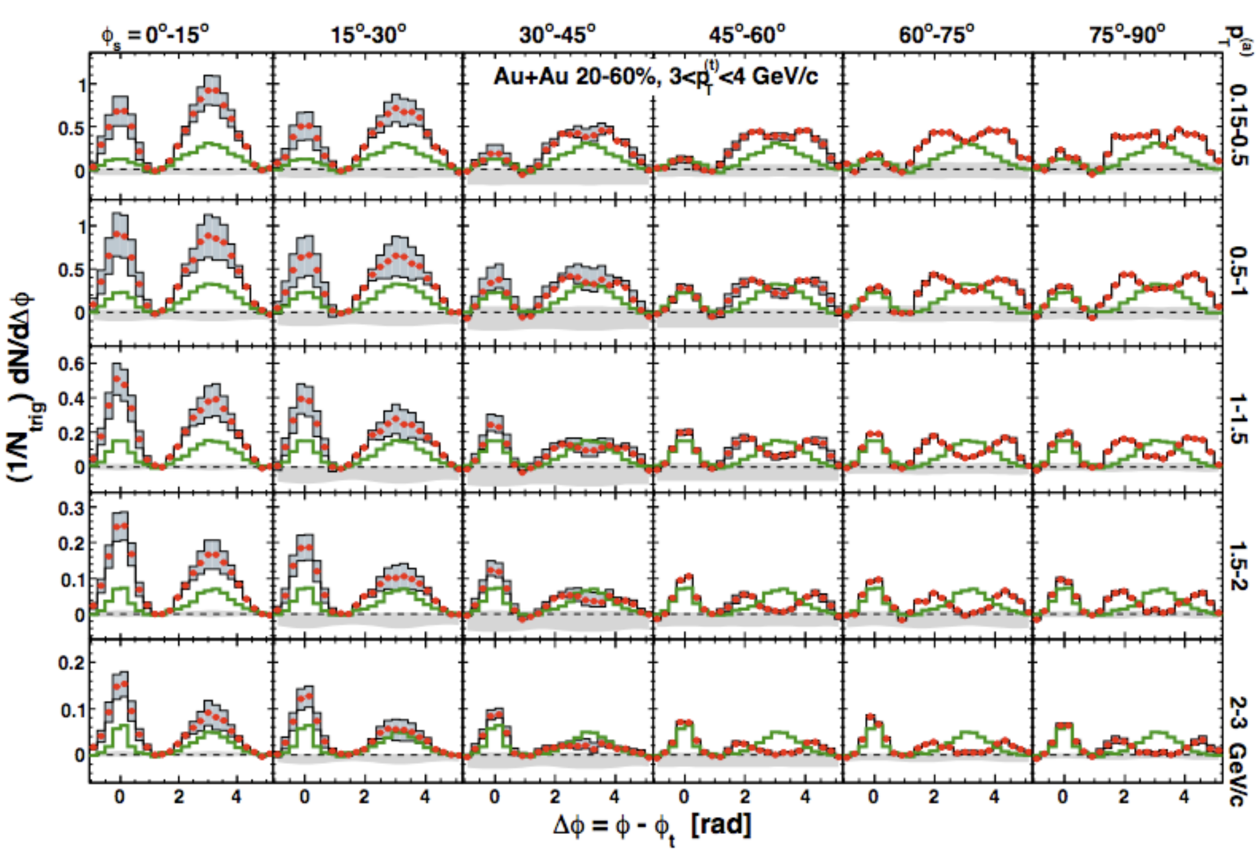
This Talk: Selected Recent Results



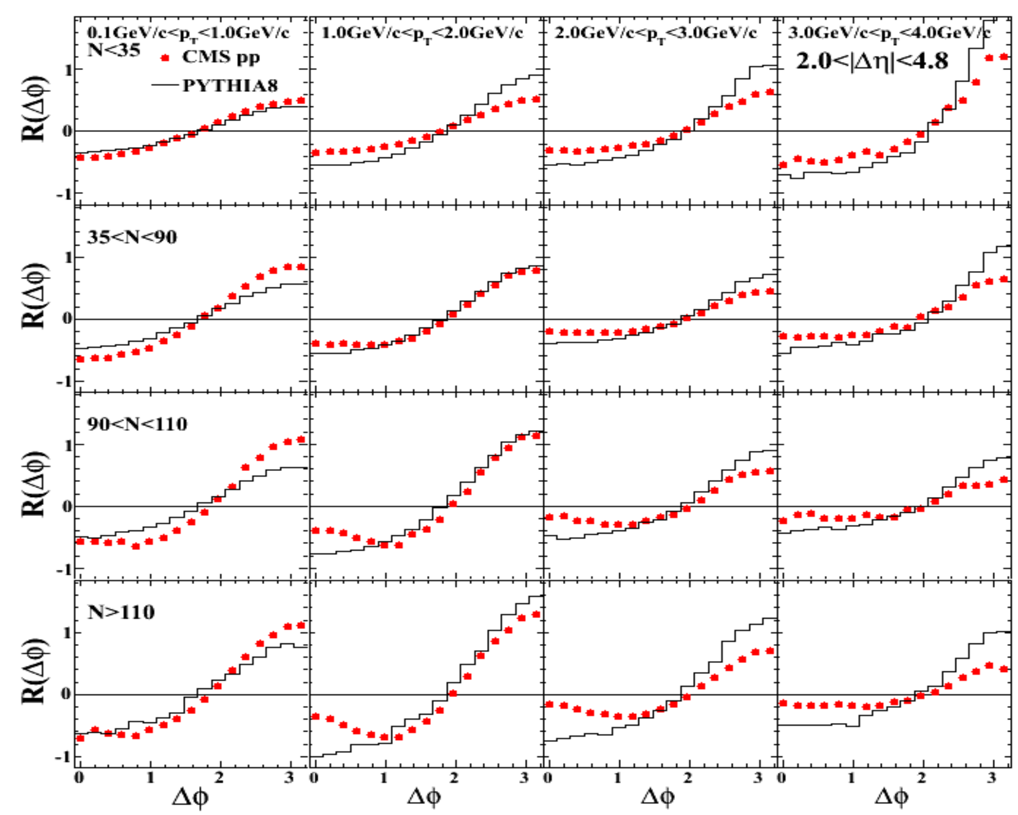
PHENIX arXiv:1002.1077



PHENIX arXiv:1010.1521



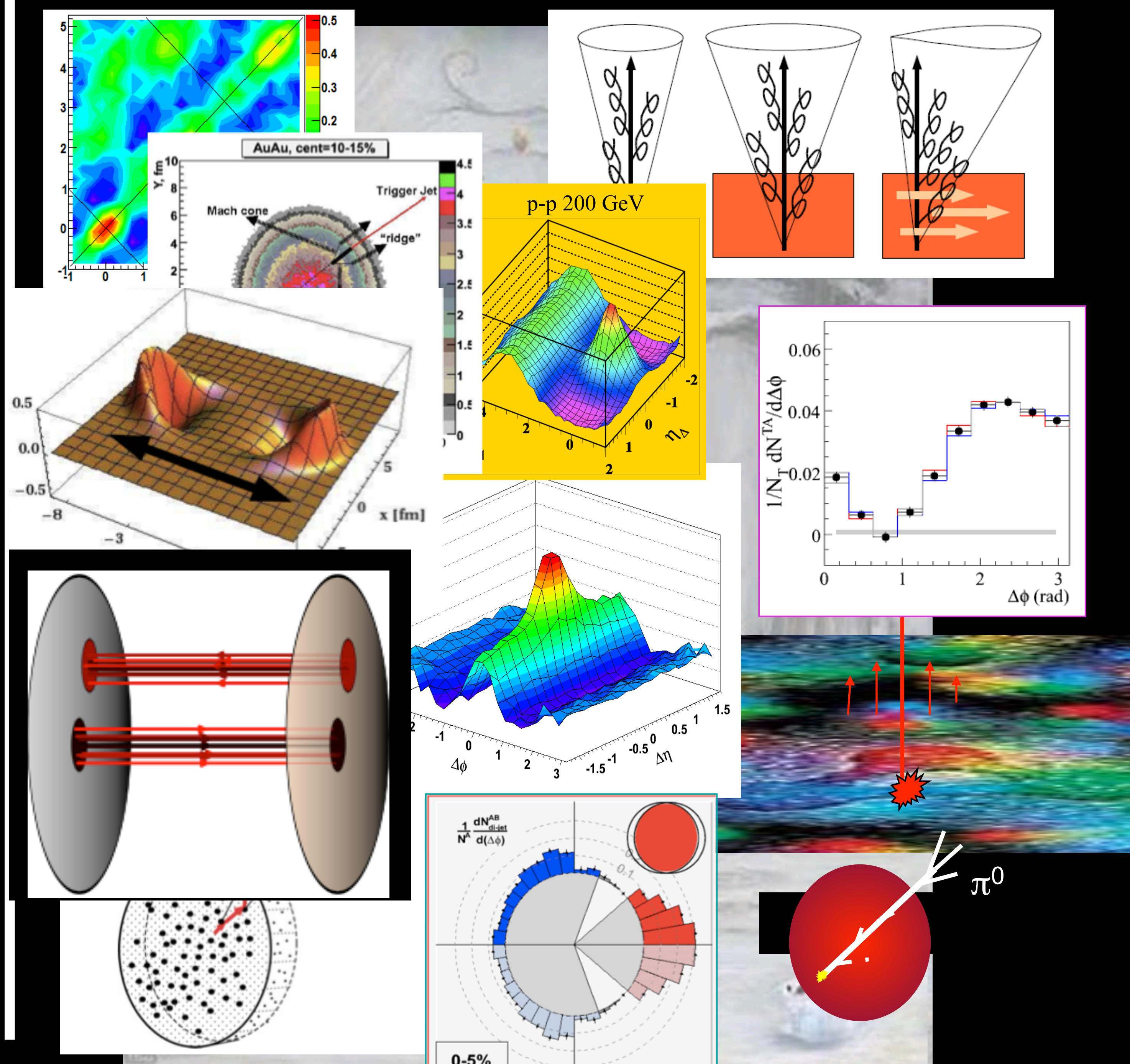
STAR arXiv:1010.0690



CMS arXiv:1009.4122

Ridge, Bulk, and Medium Response

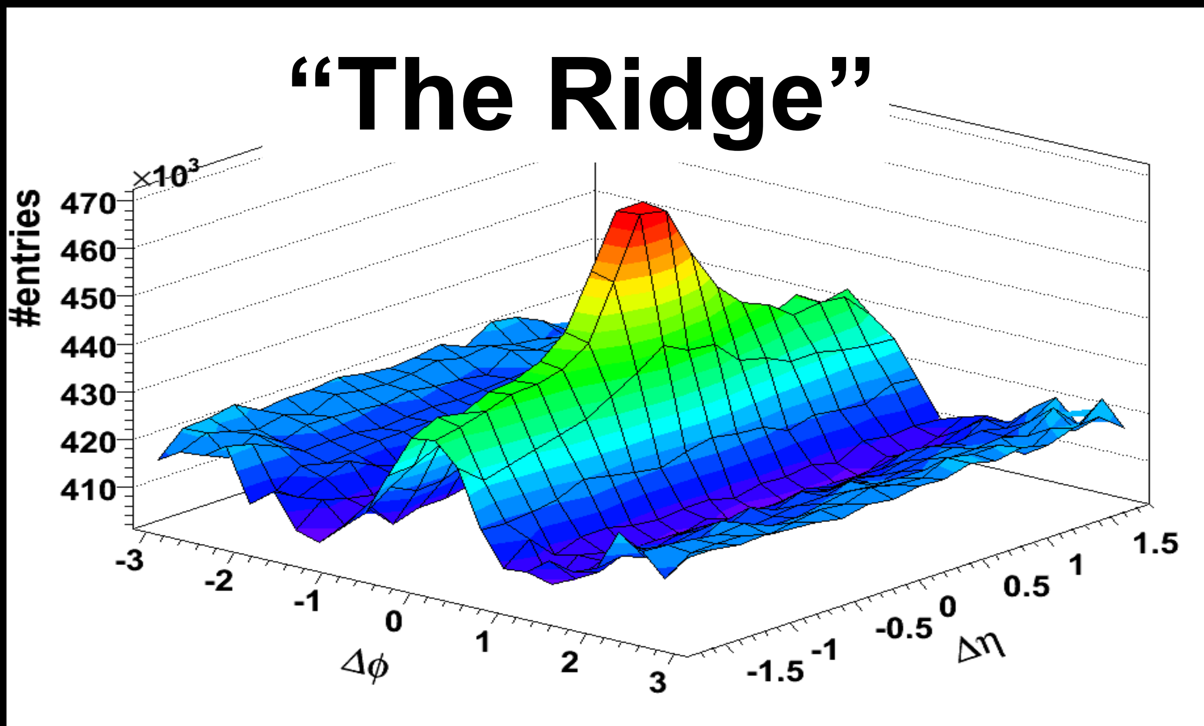
How to Kill Models and Learn Something in the Process

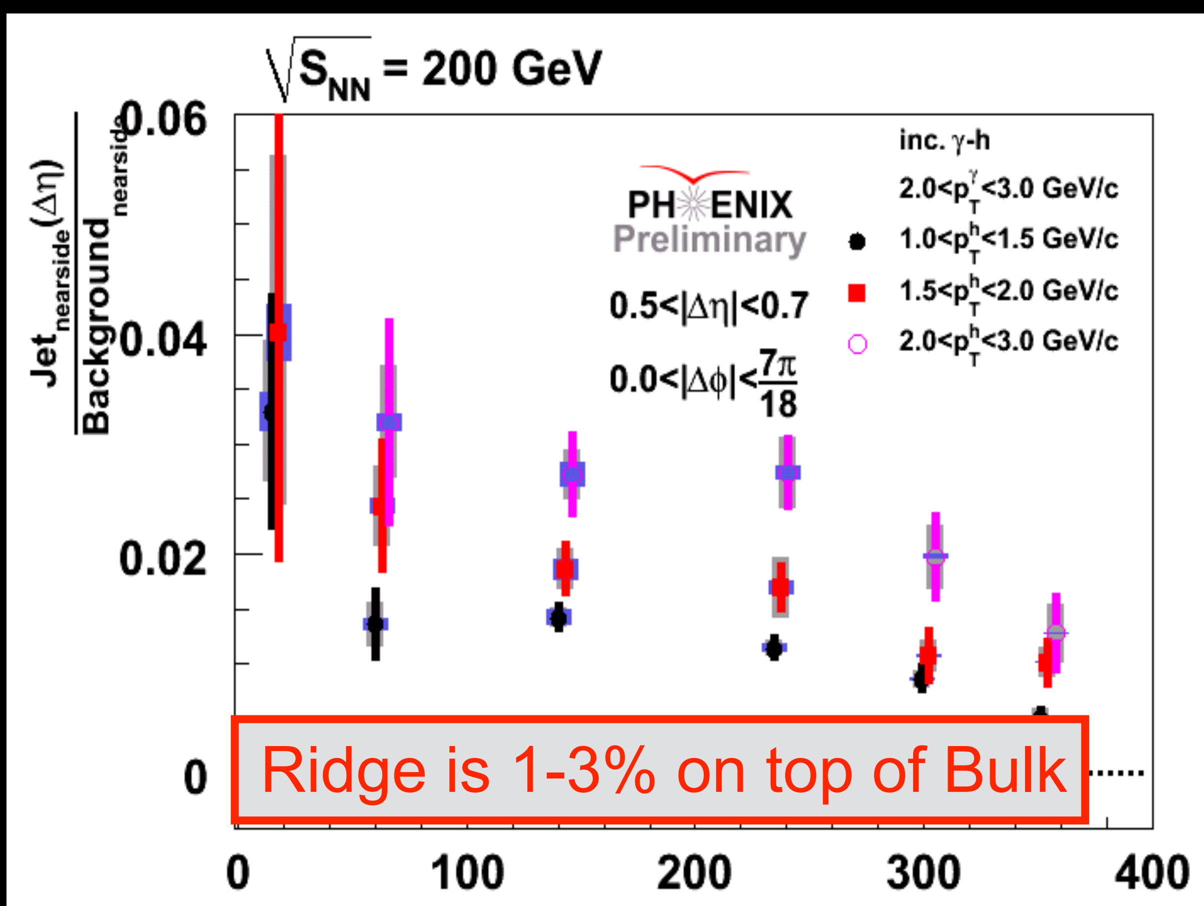


Jamie Nagle
University of Colorado at Boulder

QM 2009

Medium Response? QM 2009





See talk by J. Chen

Basic Properties:

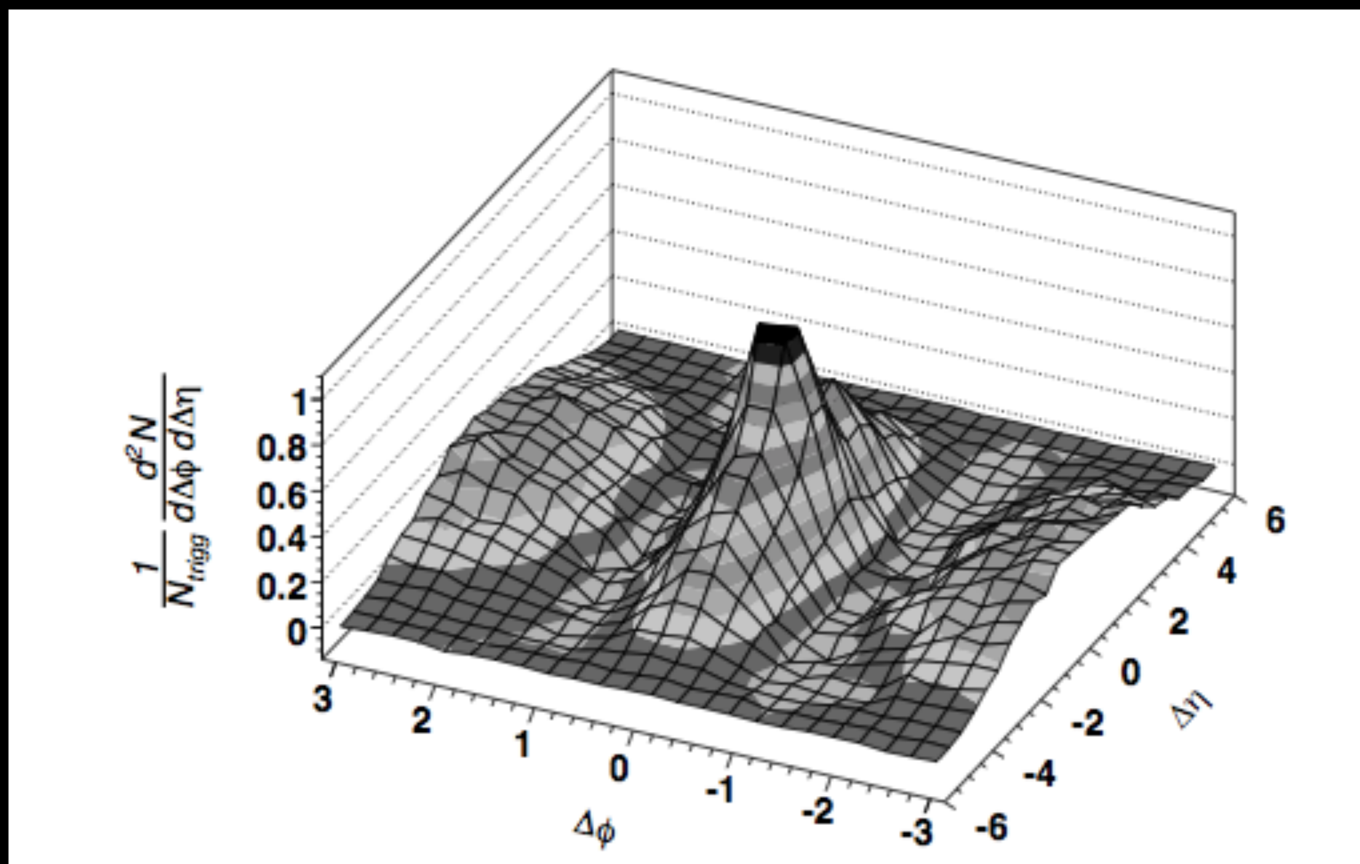
1. p_T spectra similar to bulk (or slightly harder)
2. baryon/meson enhancement similar to bulk
3. Scales per trigger like Npart similar to bulk

"Theoretical Free-For-All"

Paul Stankus

"Theorists, help us Kill your model."

Brian Cole QM08



Takahashi et al, arXiv:0902.4870
Phys.Rev.Lett. 103 (2009) 242301

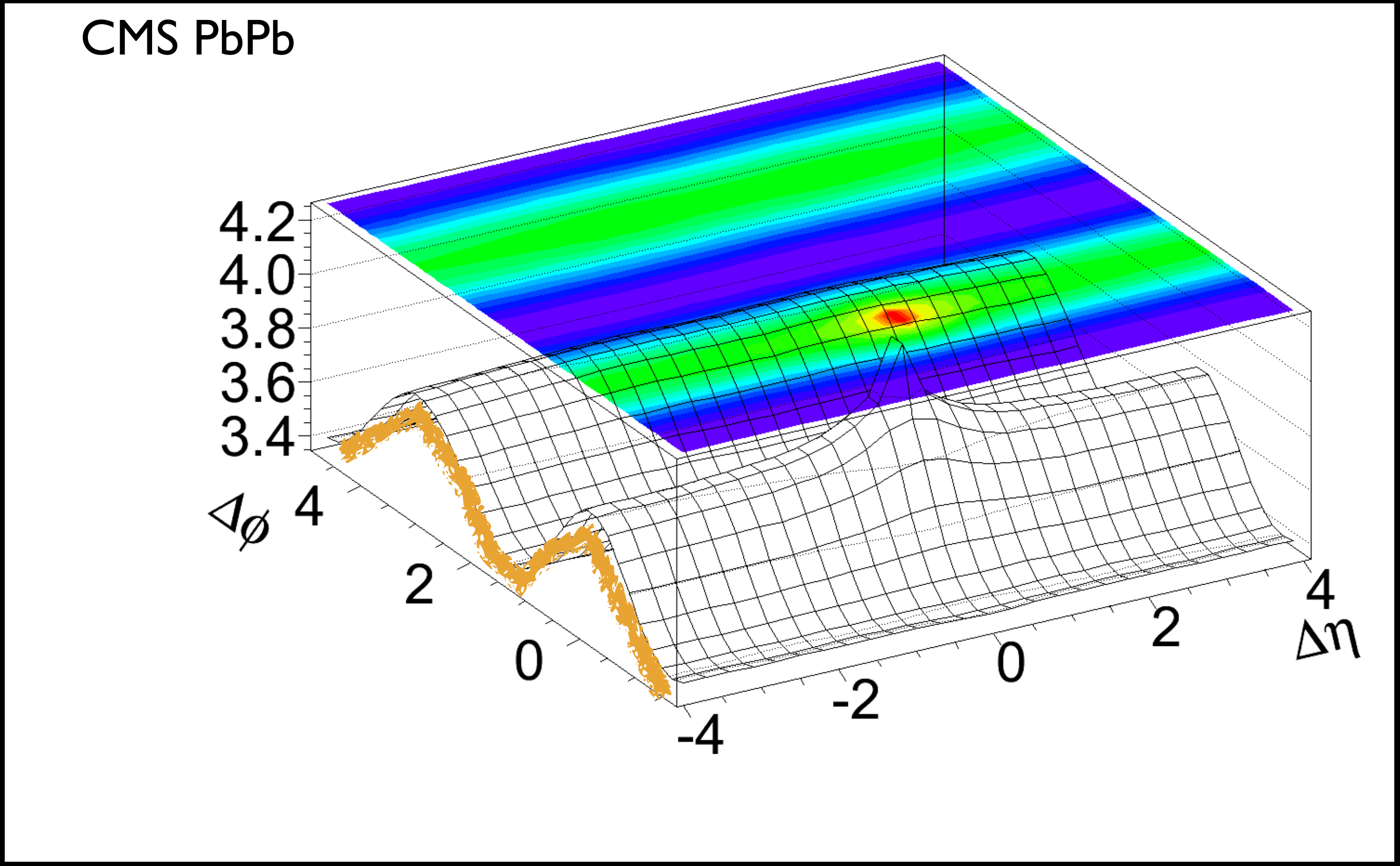
Hydro with MC Glauber initial conditions

3.5. Ridge effect

Another effect, which is produced naturally by the longitudinal baton structure of IC, as shown in Fig.1, is the so-called *ridge phenomenon* which has been experimentally seen in high-p_T nearside correlations [12]. Since

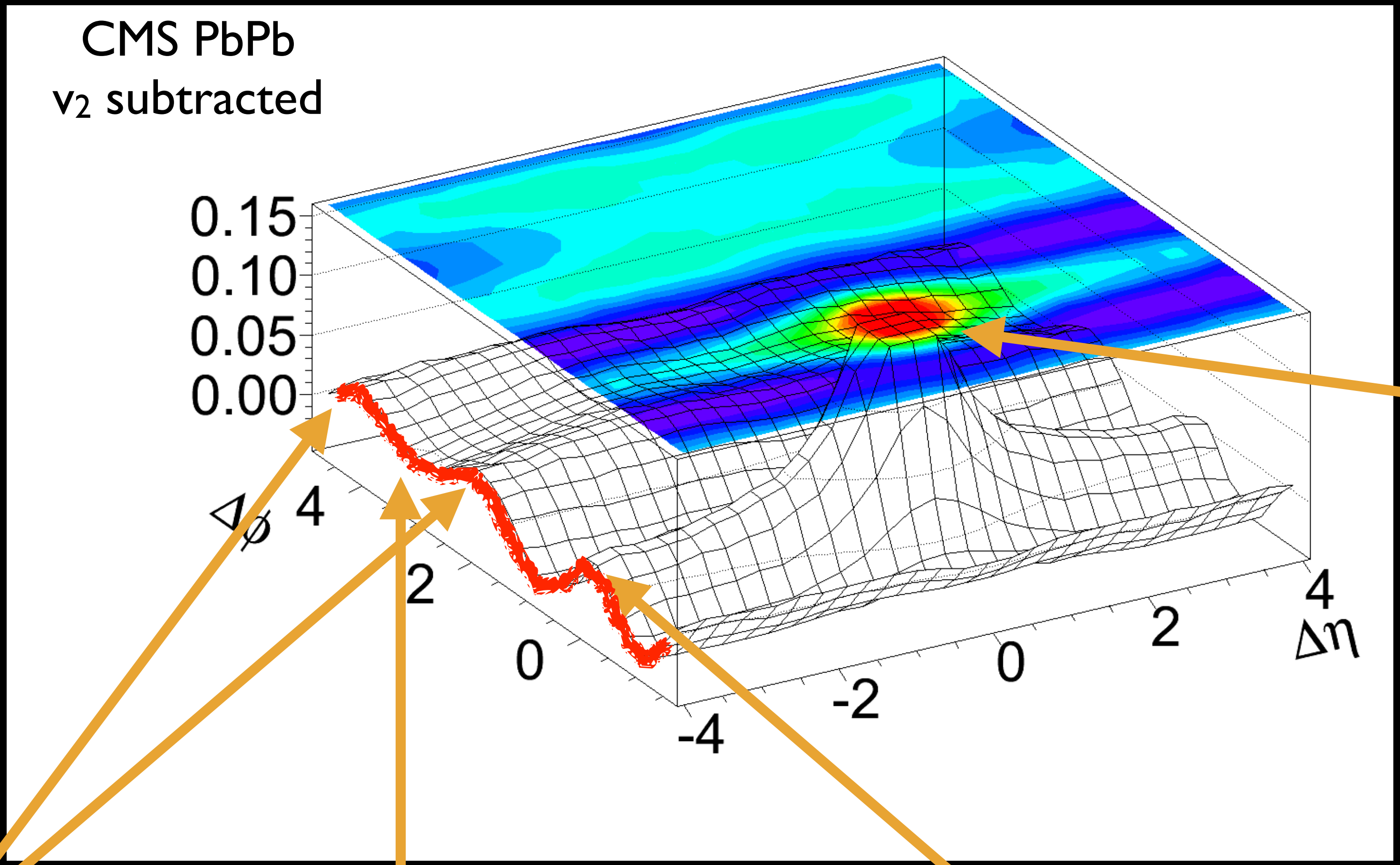
Beyond elliptic flow

Subtract or suppress elliptic flow:
Complex remnant correlation structure



Beyond elliptic flow

Subtract or suppress elliptic flow:
Complex remnant correlation structure



Jet correlations

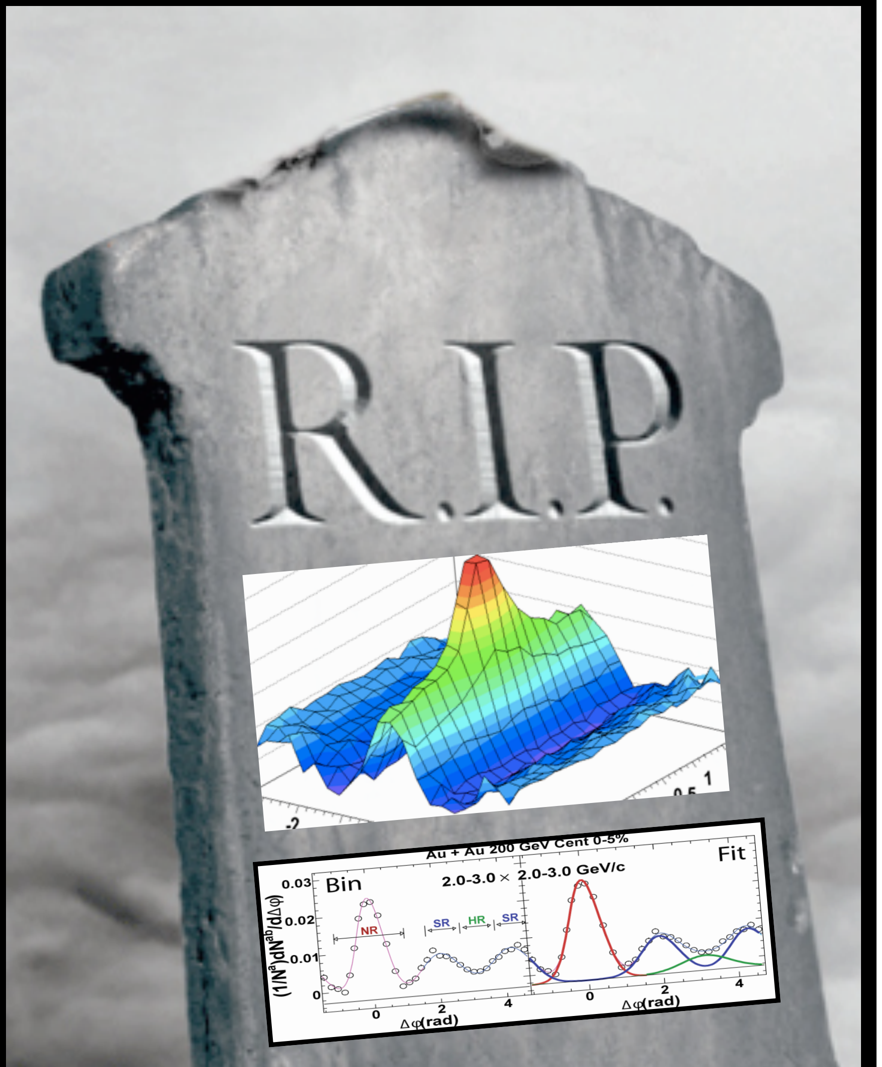
"Shoulder"
"Mach cones"
PHENIX (2005)
STAR (2010)

"Head"
"π region"
PHENIX (2005)
STAR (2010)

"Ridge"
STAR (2006)
PHOBOS (2008)

2005-2010:
Extensive literature (100's of papers) on each of these features

Demise of Ridge and Mach Cones



Geometry fluctuations and final state correlations:

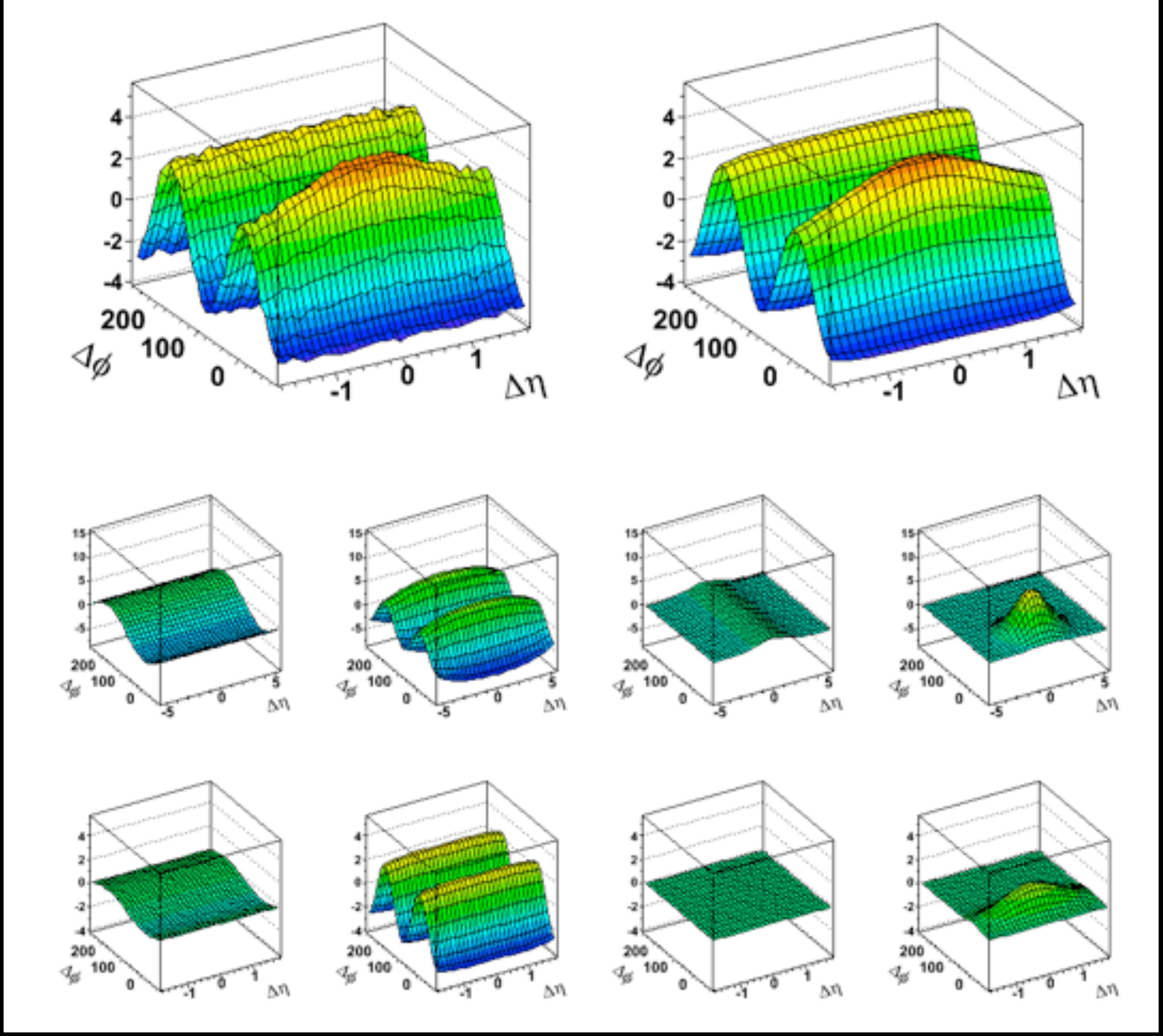
Mishra et al arXiv:0711.1323
Takahashi et al, arXiv:0902.4870
Sorensen, arXiv:1002.4878

"Triangular flow"
and
"Participant triangularity"

No ridge, no mach cone, just flow

Burak Alver
Mithig meeting
10/13/2009

PHOBOS dead ends… (2009)

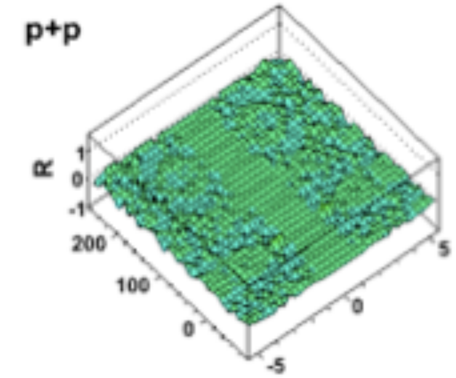


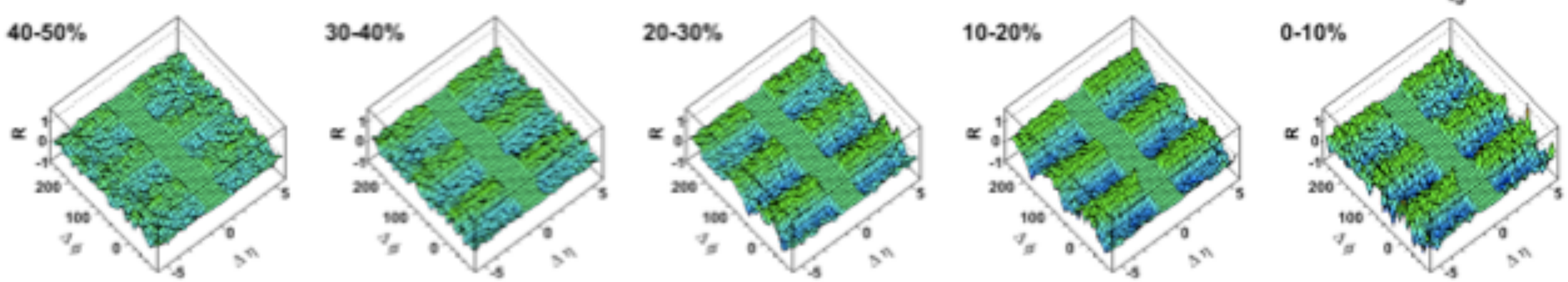
Decomposing CFs à la STAR

Decomposing CF at large Δη

Let's look at "non-flow"

- Flow subtraction is tricky
  - Let's just take out all First and Second FC
- Normalize in bins of $\Delta\eta$ (a la $\Delta\eta$ of ZYAM)
- Hide $\Delta\eta<1$

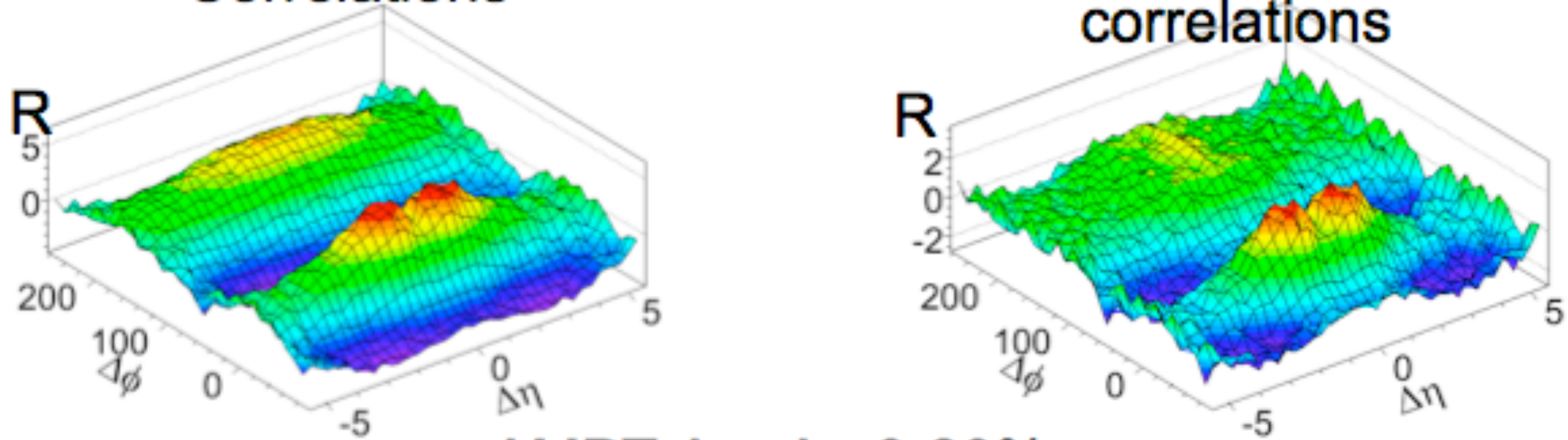




AMPT and Correlations

AMPT model: Glauber initial conditions, collective flow

Correlations　　　　Elliptic flow subtracted correlations



AMPT Au+Au 0-20%

AMPT model also produces similar correlation structures that extend out to long range in Δη.

Lin et. al. nucl-th/0411110

Putting everything together...

"Triangular flow"
and
"Participant triangularity"

No ridge, no mach cone, just flow

Burak Alver

Mithig meeting

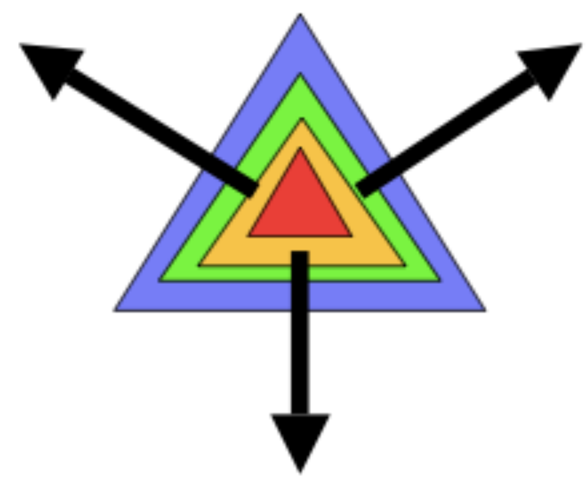
10/13/2009

Triangularity...

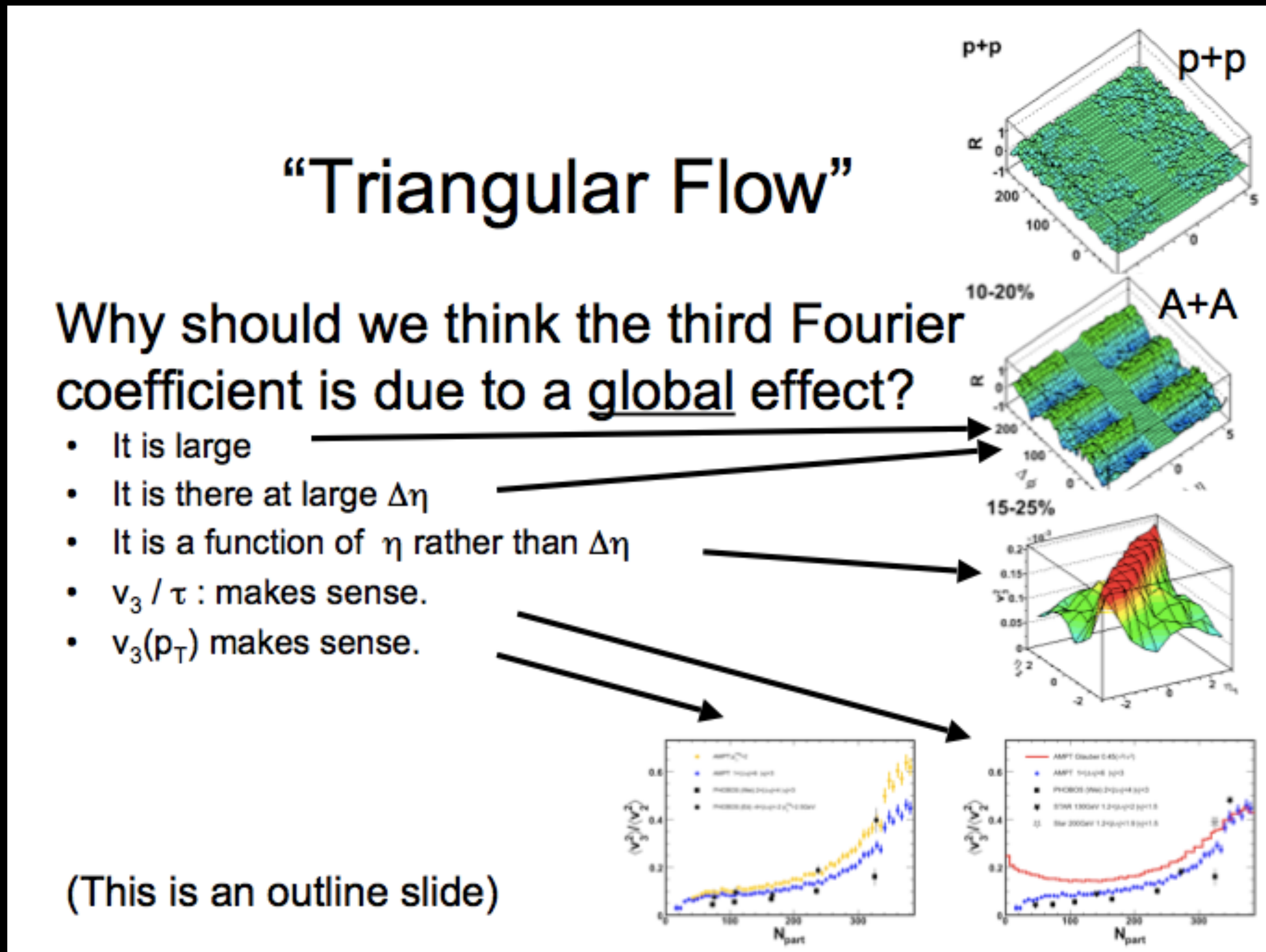
“Participant Triangularity” τ

If the initial geometry were a triangle, then we would expect global v_3

Define
<u>participant triangularity τ</u>
analogous to
<u>participant eccentricity ε</u>



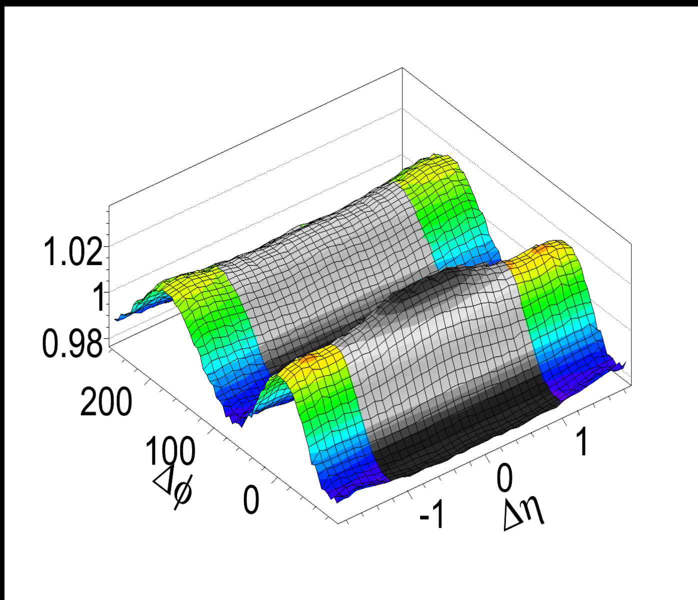
Triangular Flow



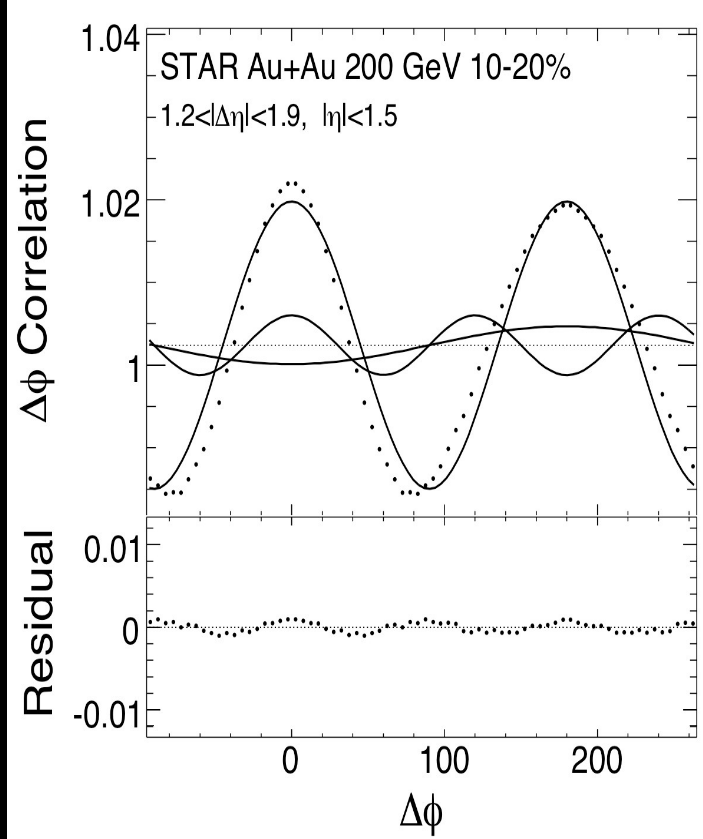
Comparison to published data

Burak Alver, GR, arXiv:1003.0194 (PRC in press)

Inclusive correlations

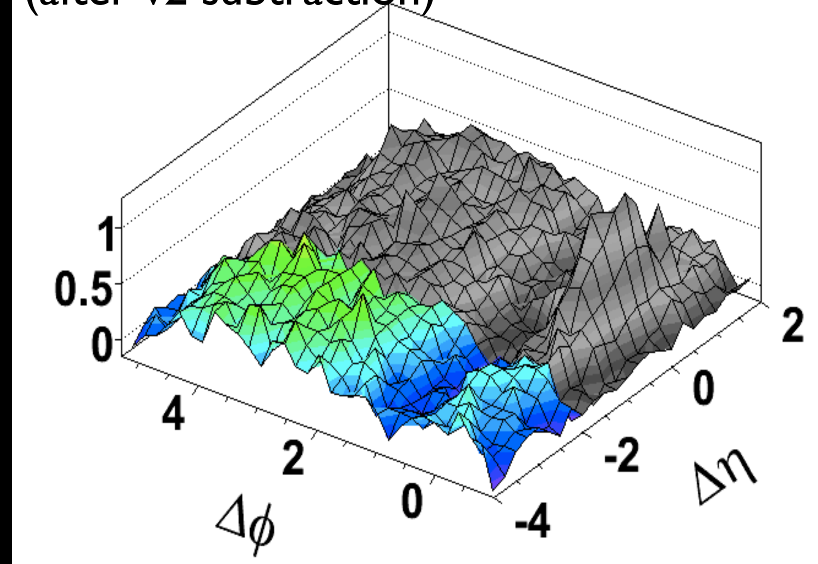


arXiv:0806.0513

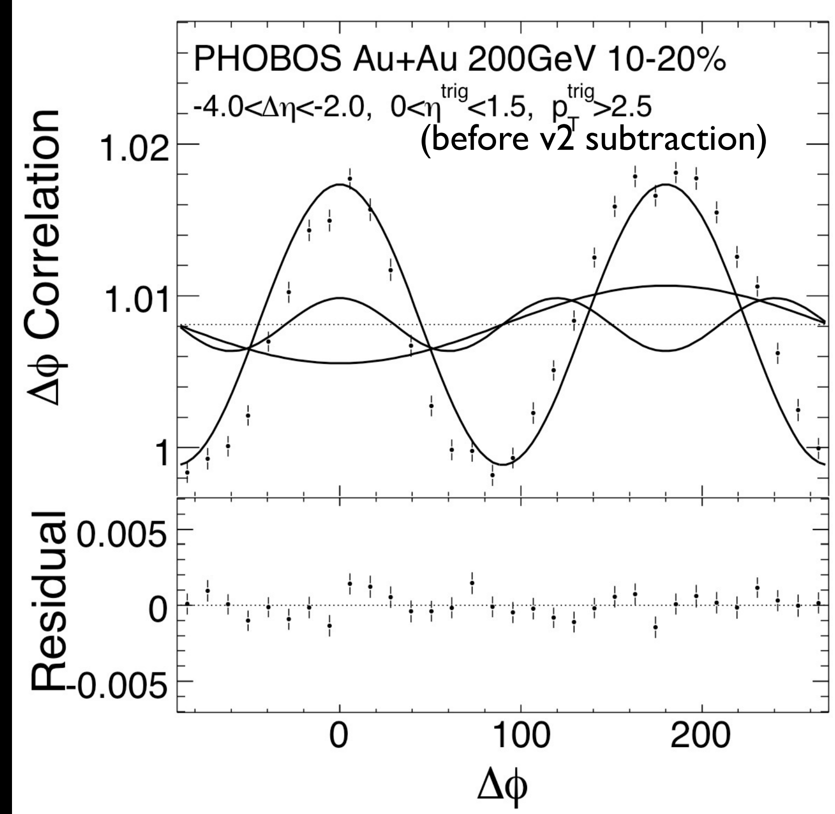


Triggered correlations

(after v2 subtraction)



PRL 104, 06230 (2010)



Published correlation data (STAR, PHOBOS) show v_3 component!

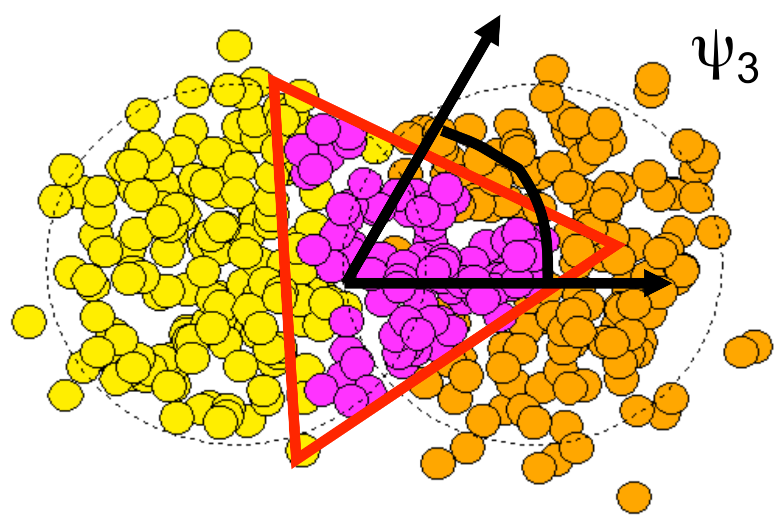
Flow contribution to long-range "ridge" and "broad away-side"

This is purely a fluctuation effect - no fluctuations, no v_3!

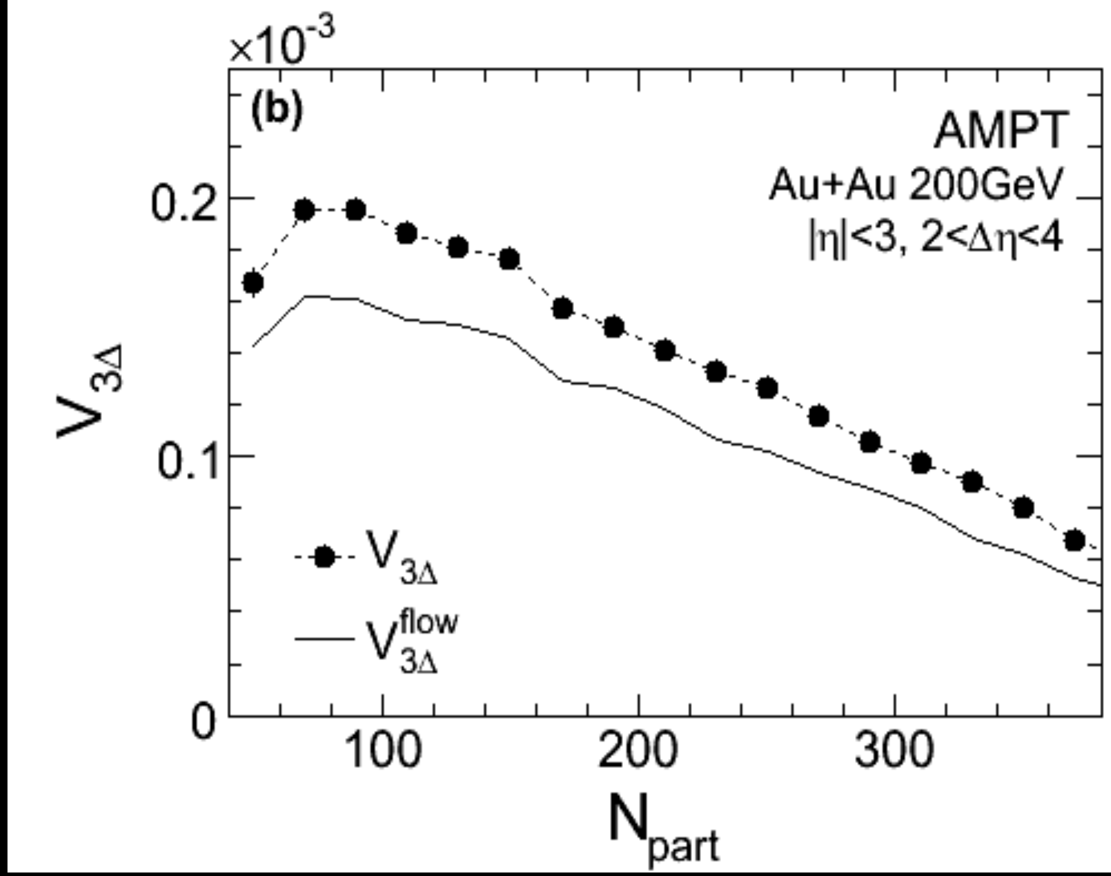
n.b. Ψ2 and Ψ3 are uncorrelated - triangular flow is not visible in v_2 event plane analysis

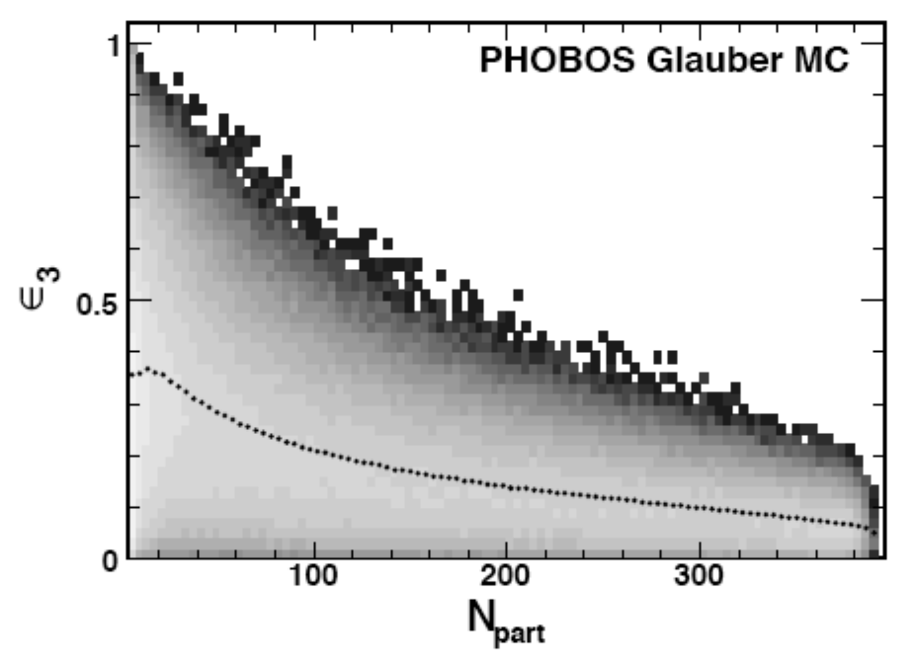
Shape Fluctuations

Participant Triangularity



$$\varepsilon_3 = \frac{\sqrt{\left\langle \left(r^2 \cos(3\phi) \right) \right\rangle^2 + \left\langle \left(r^2 \sin(3\phi) \right) \right\rangle^2}}{\left\langle r^2 \right\rangle}$$

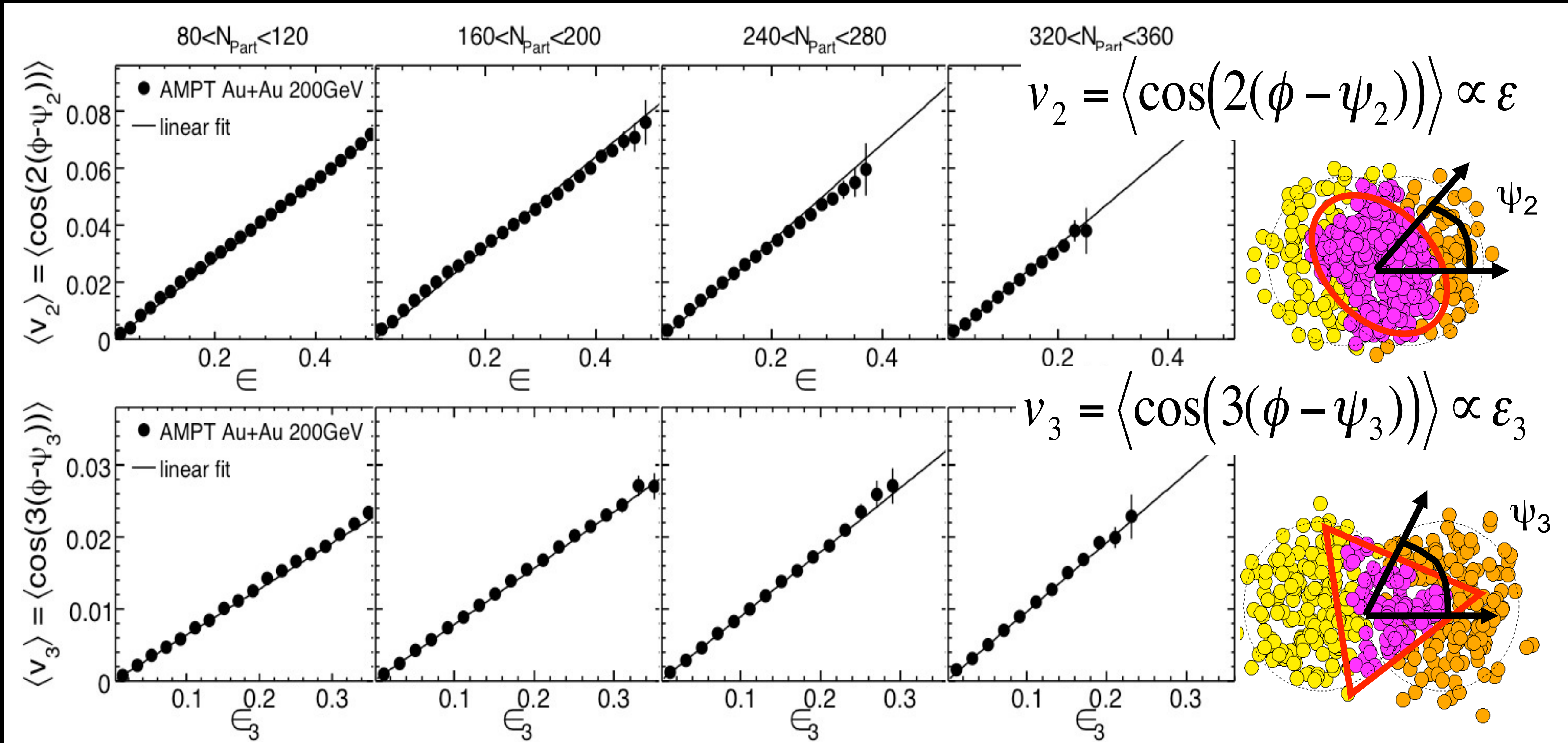




Just like elliptic flow reflects event-by-event eccentricity, "triangular flow" (v_3) reflects event-by-event "triangularity" (ε_3)

Burak Alver, GR, arXiv:1003.0194

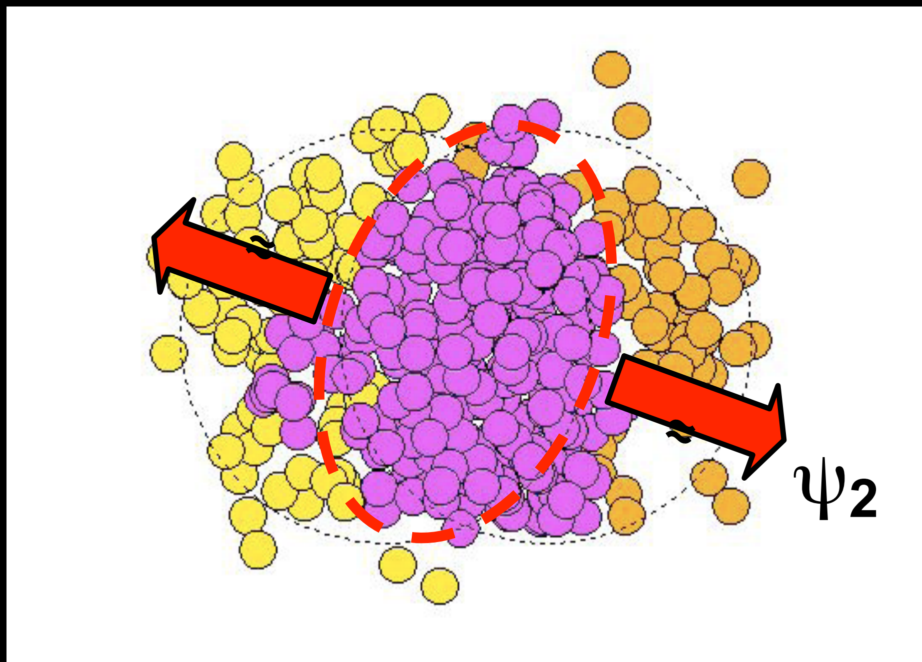
Elliptic and triangular flow

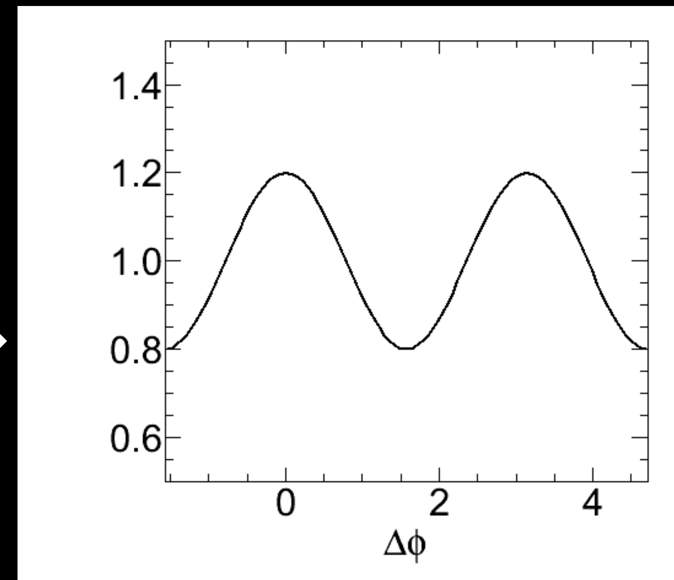


Burak Alver, GR, arXiv:1003.0194

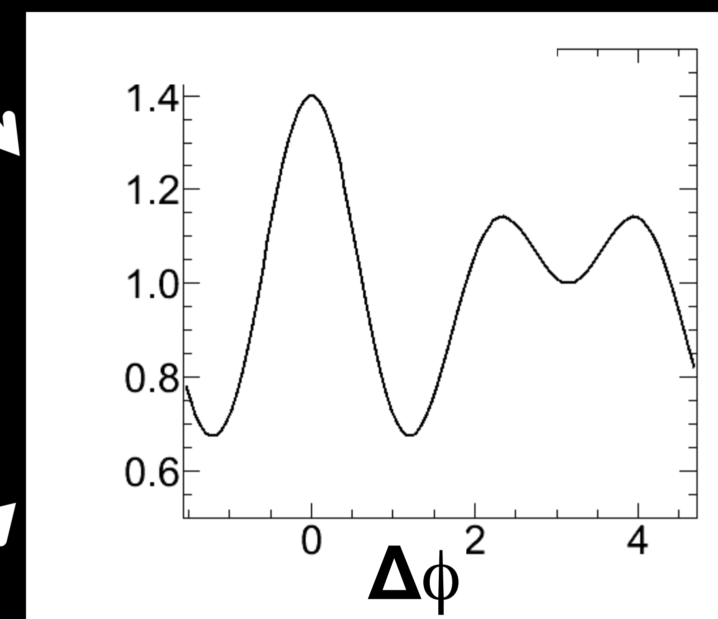
“No ridge, no mach cone, just flow”

Elliptic flow (v_2)

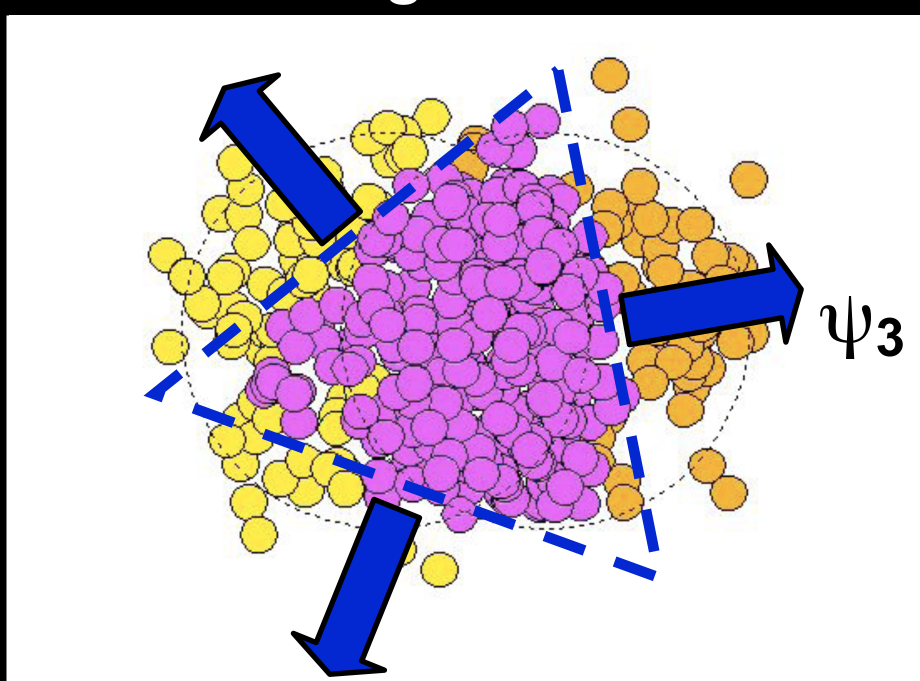




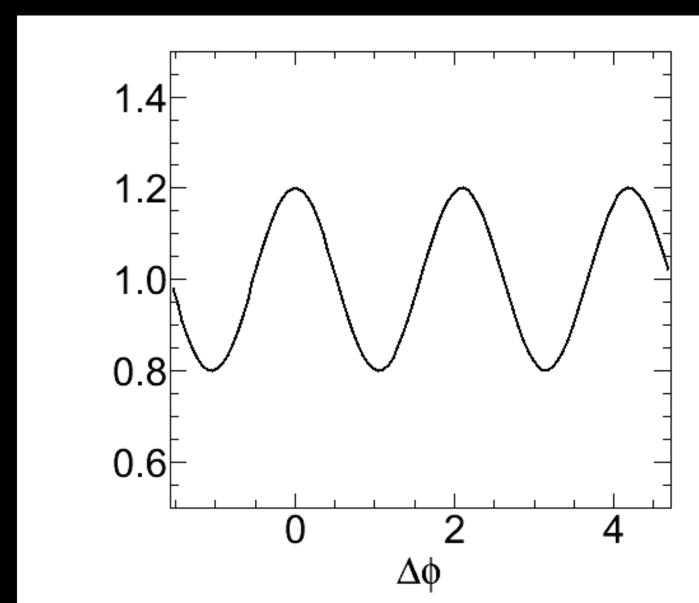
Add v_2^2 and v_3^2

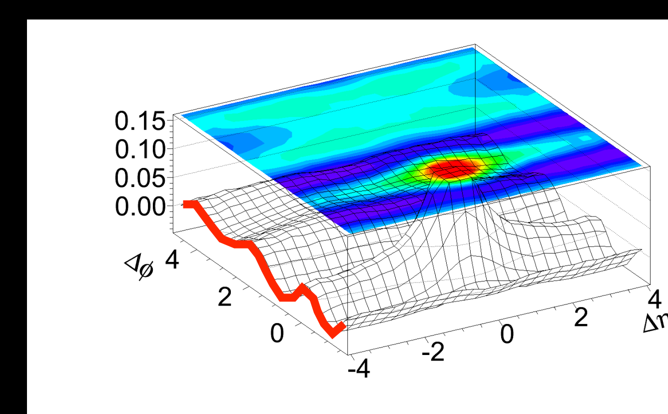


Triangular flow (v_3) from fluctuating initial condition



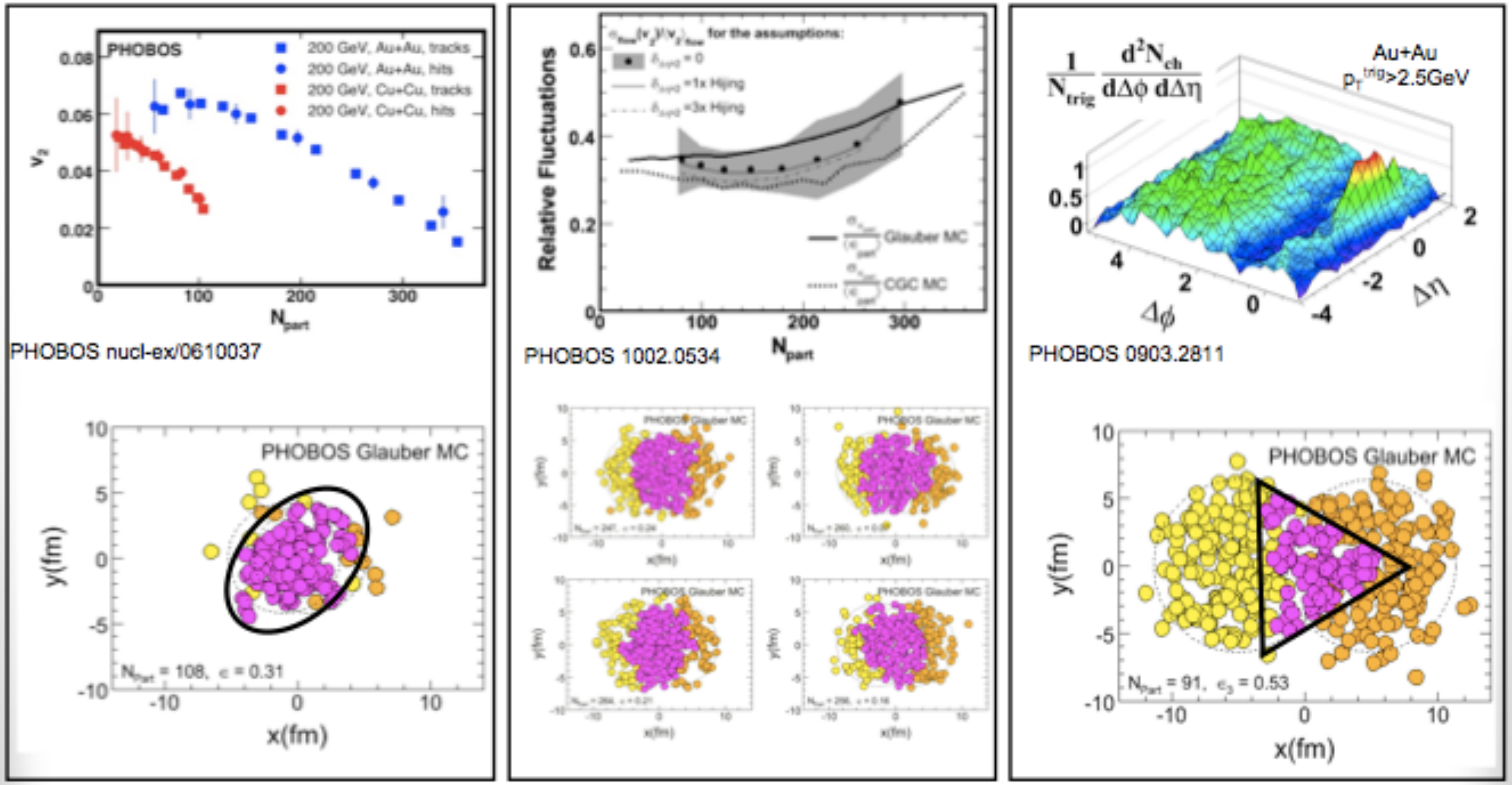
2-particle correlation functions



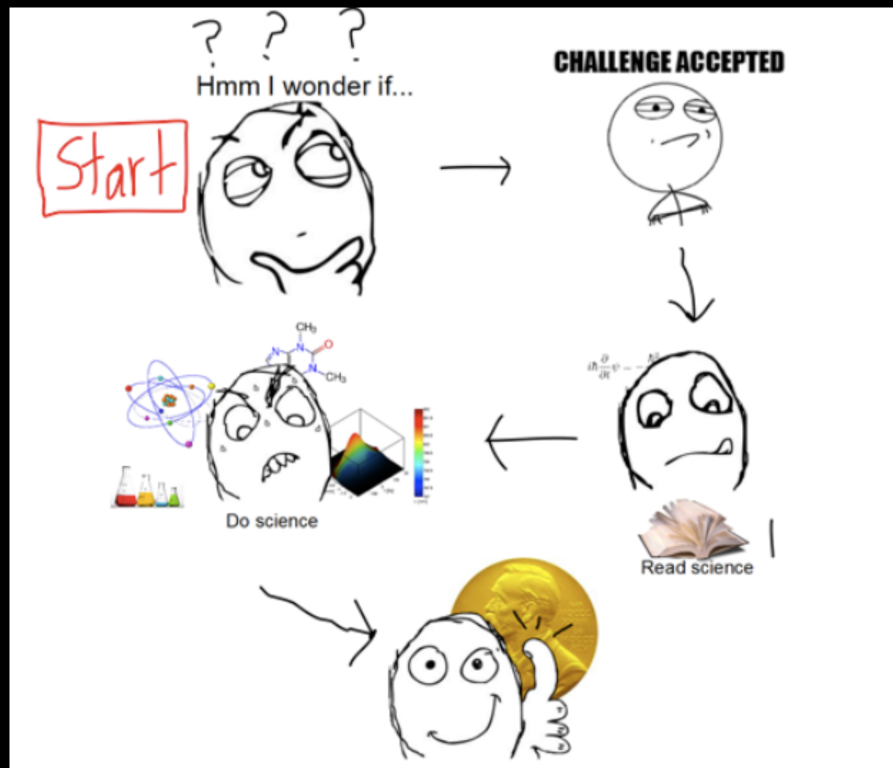


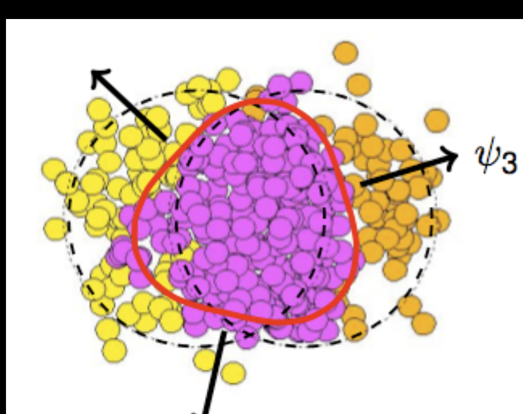
Initial geometry fluctuations

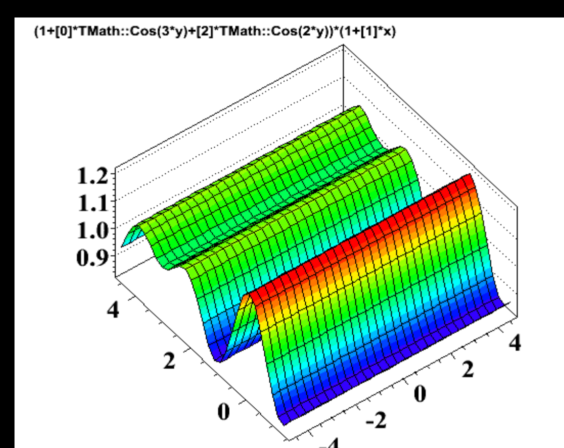
A consistent picture



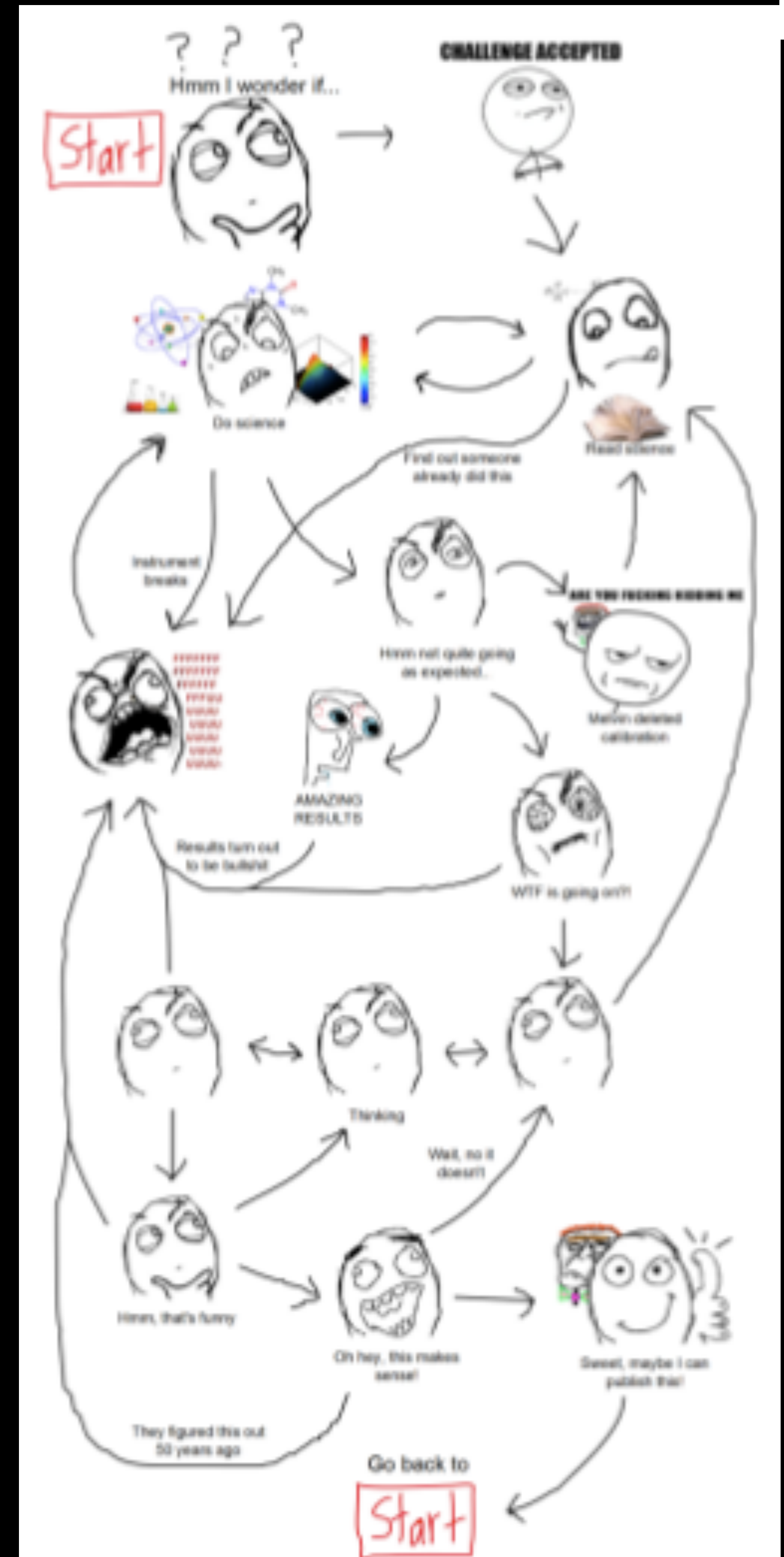
Romantic notion of science



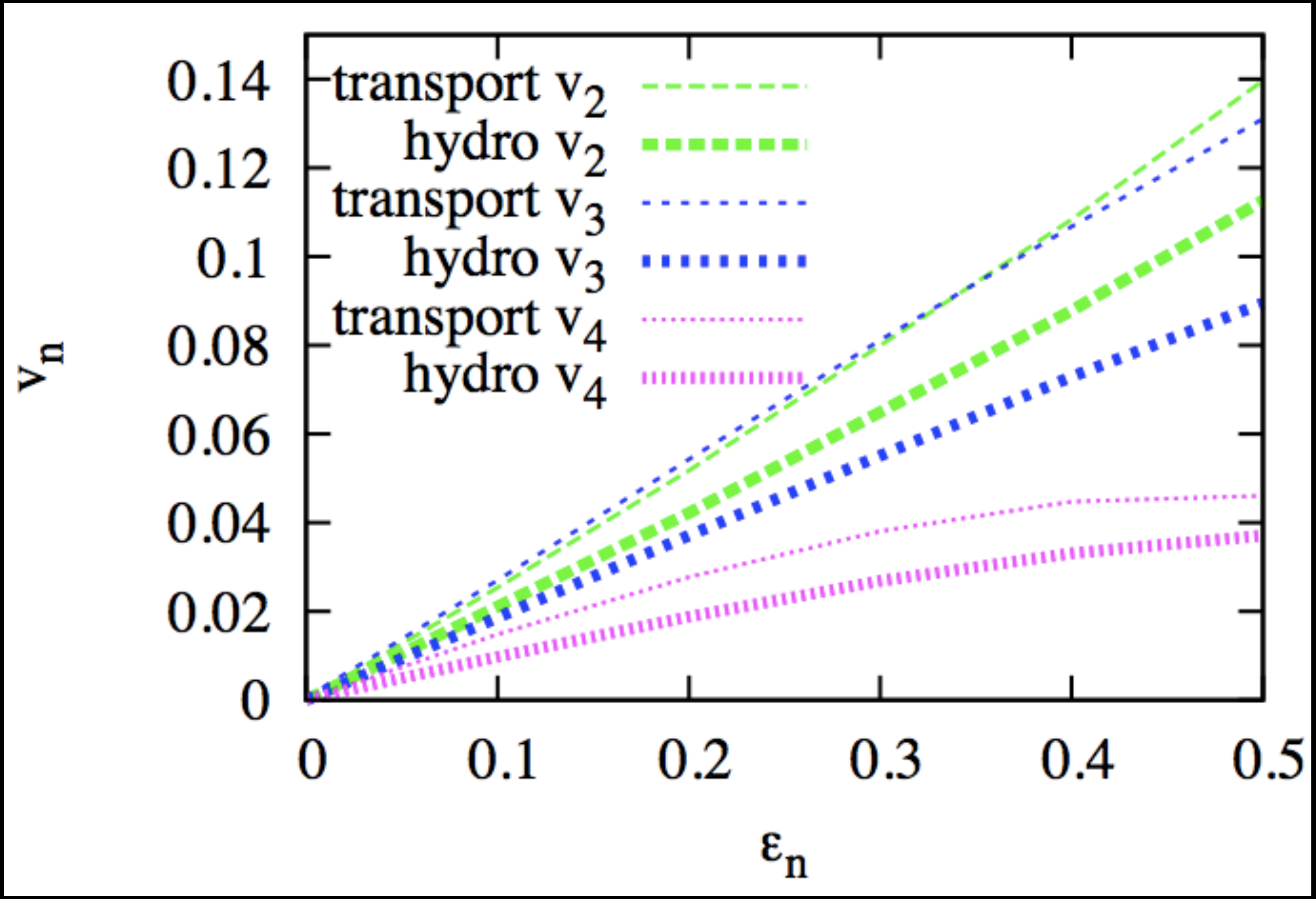




Science in real life

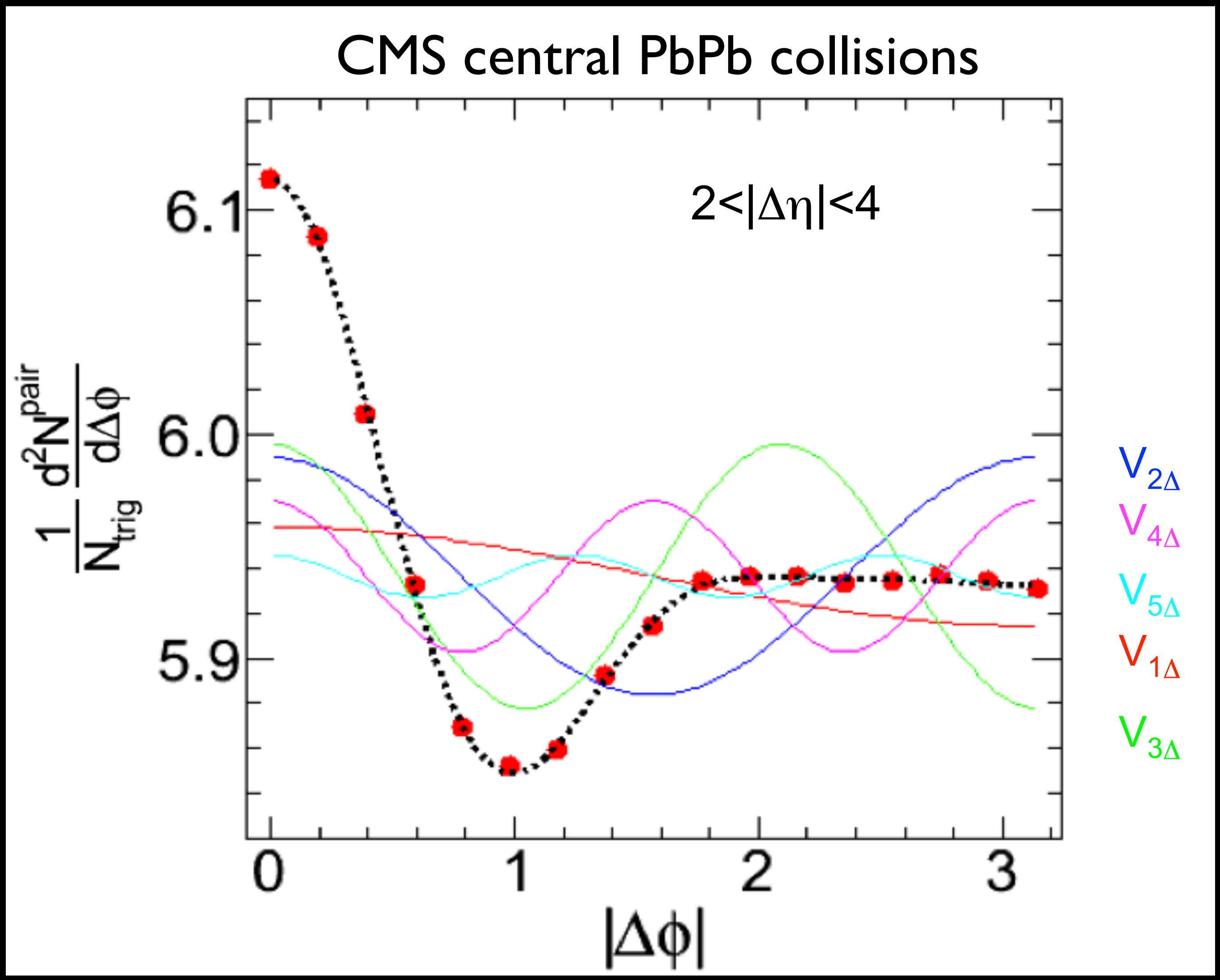


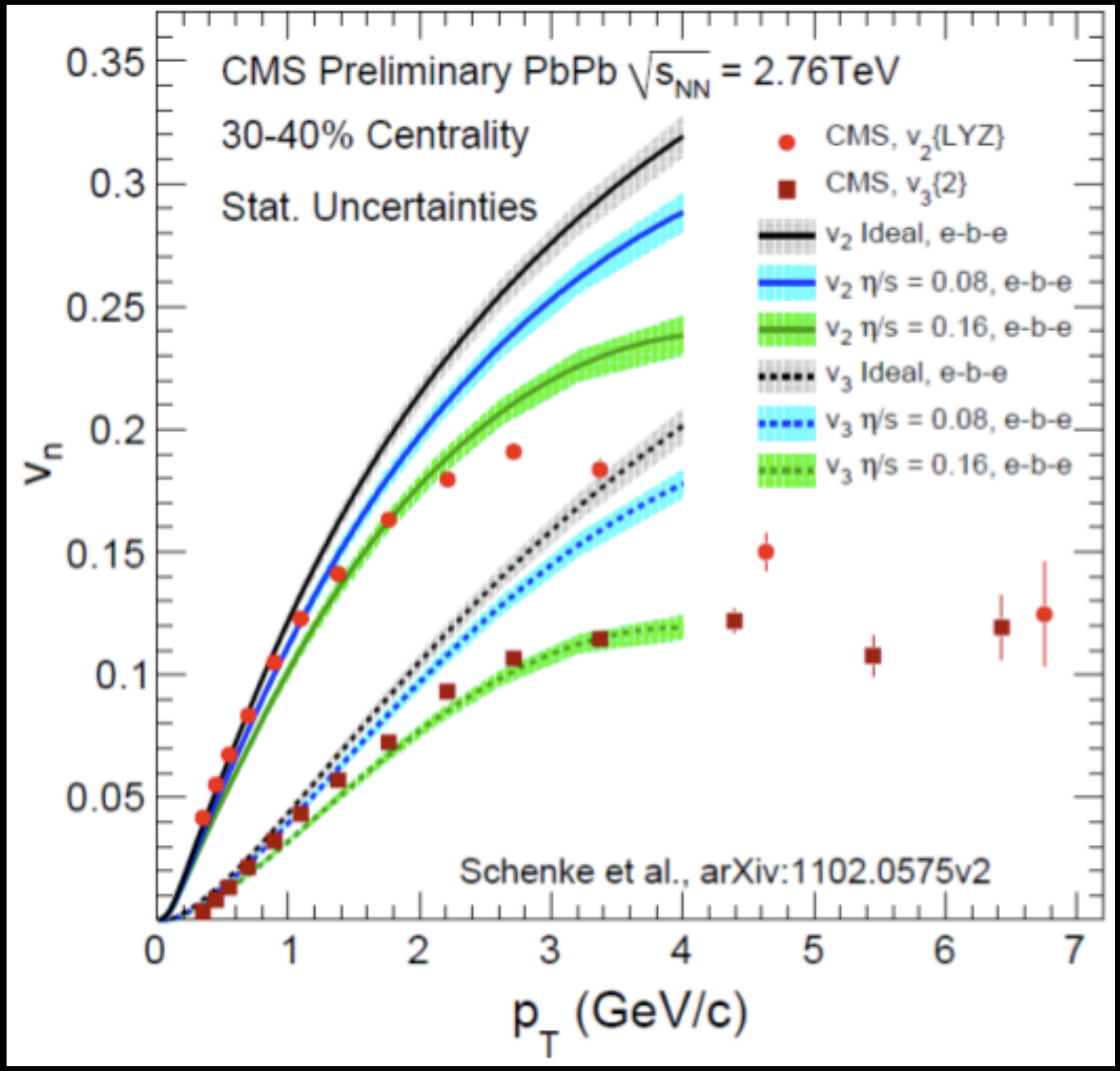
Confirmation in real hydro



Alver, Gombeaud, Luzum, Ollitrault 1007.5496

Confirmation at the LHC

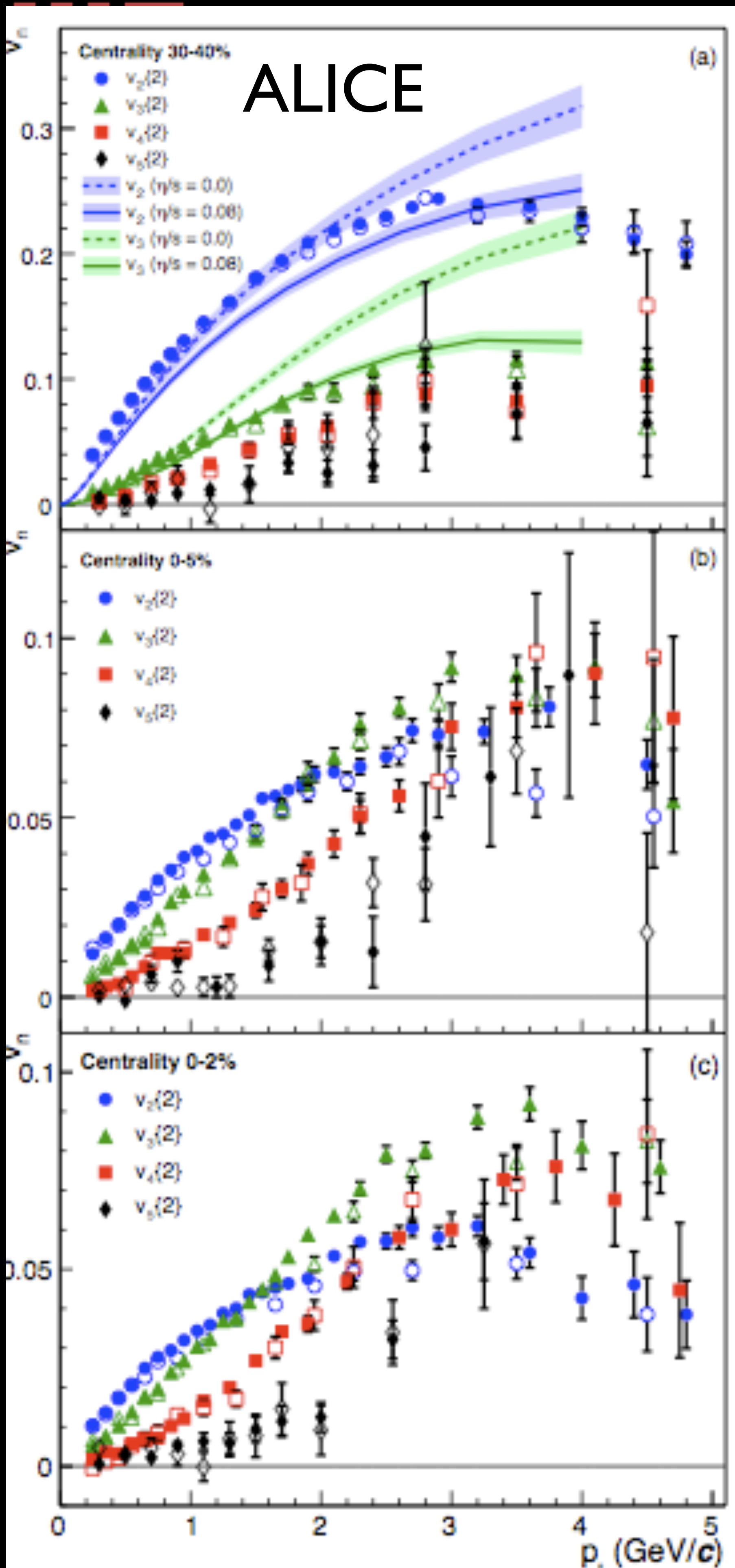


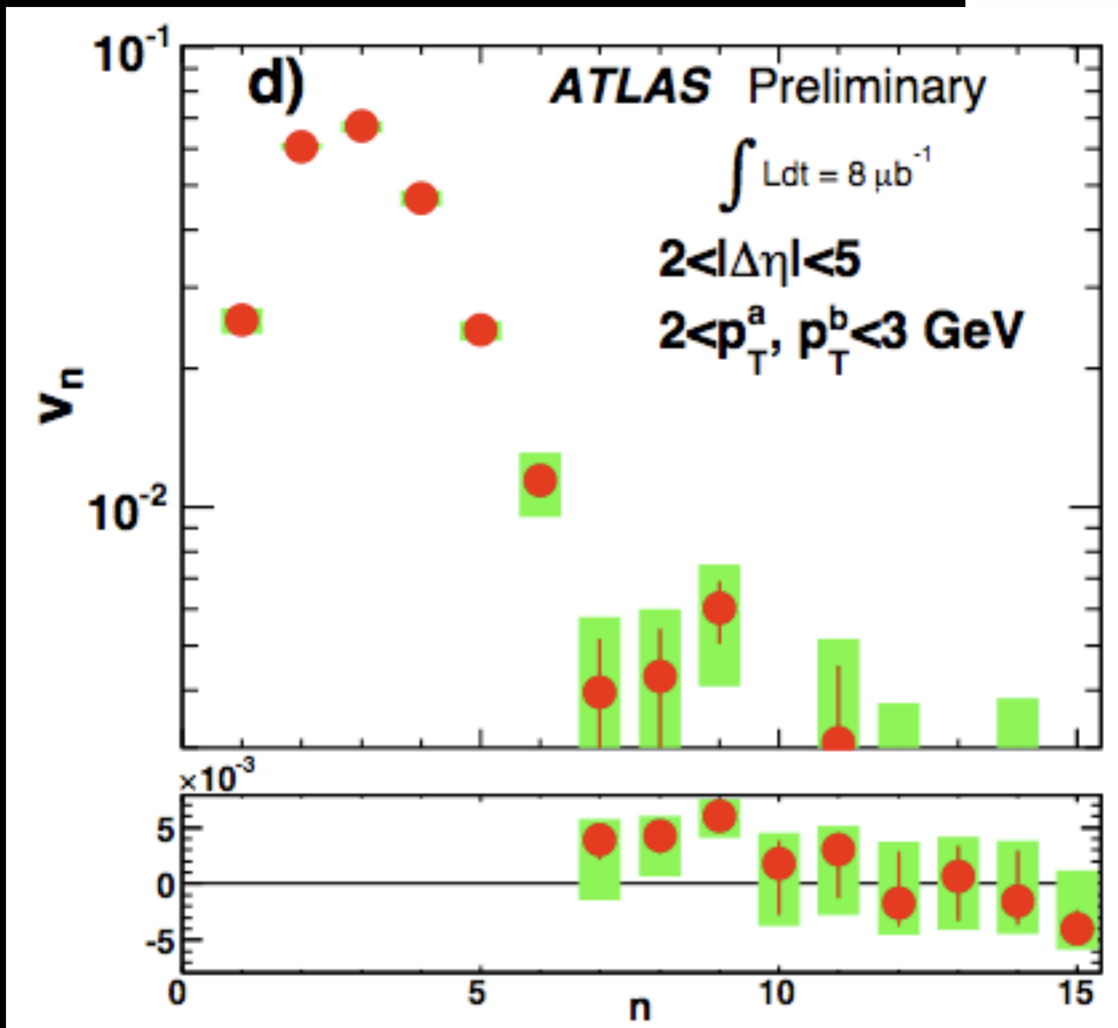


Azimuthal correlations for central collisions (driven by shape fluctuations) show higher order Fourier components

Proof is in the pudding: Full e-by-e viscous hydro calculations can describe v_3

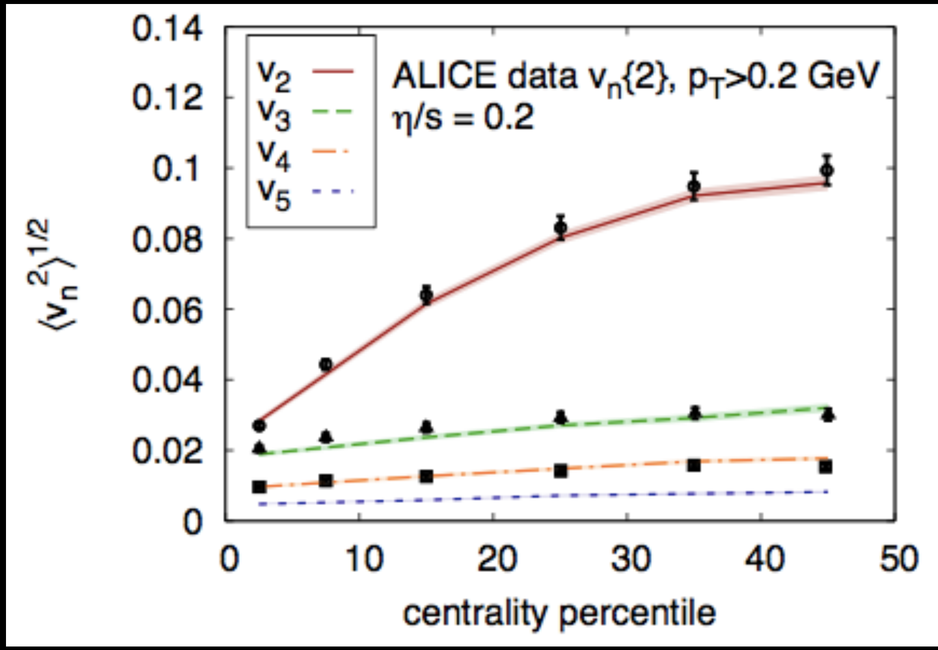
(but many functions can be Fourier-decomposed...)

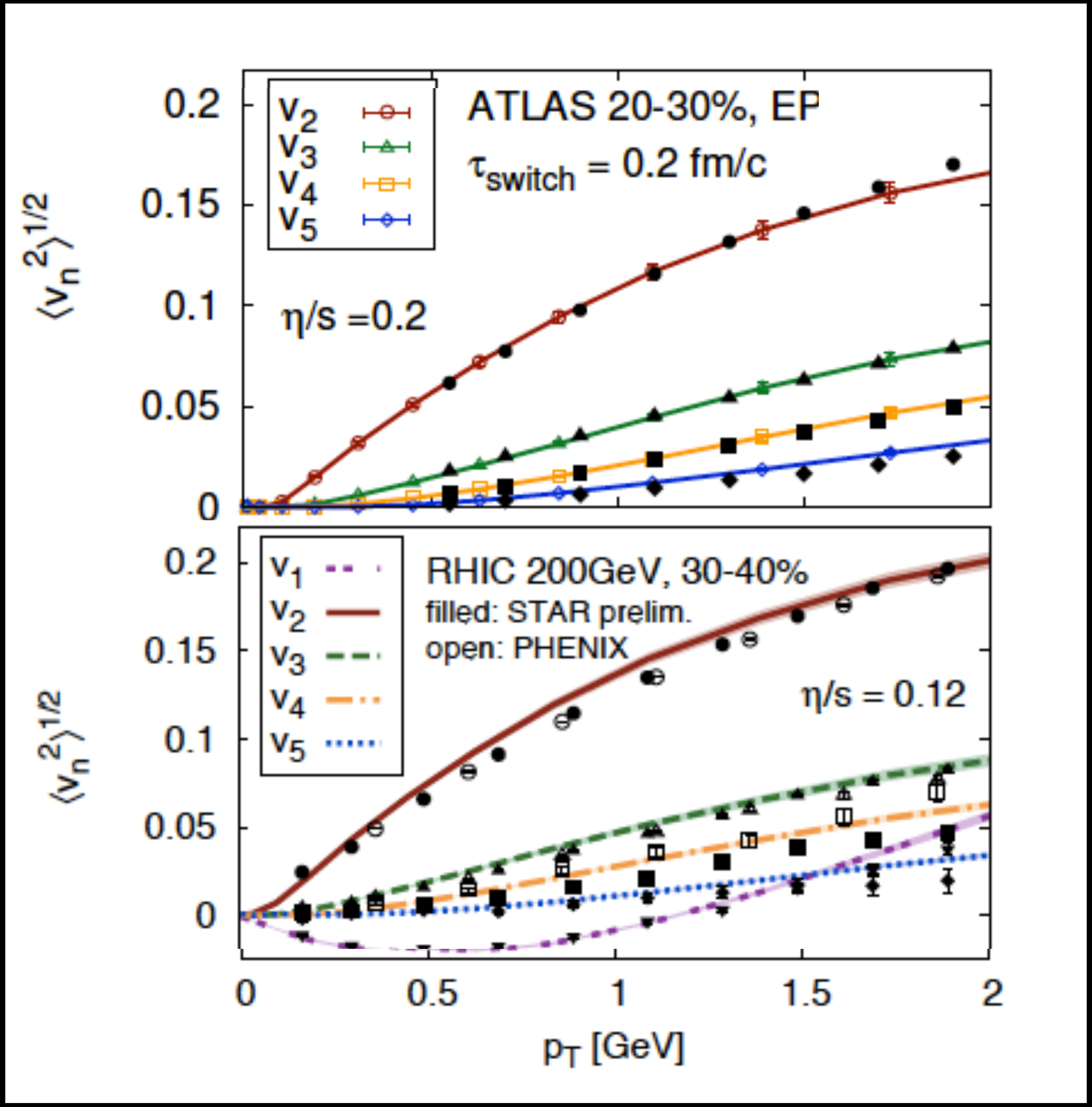


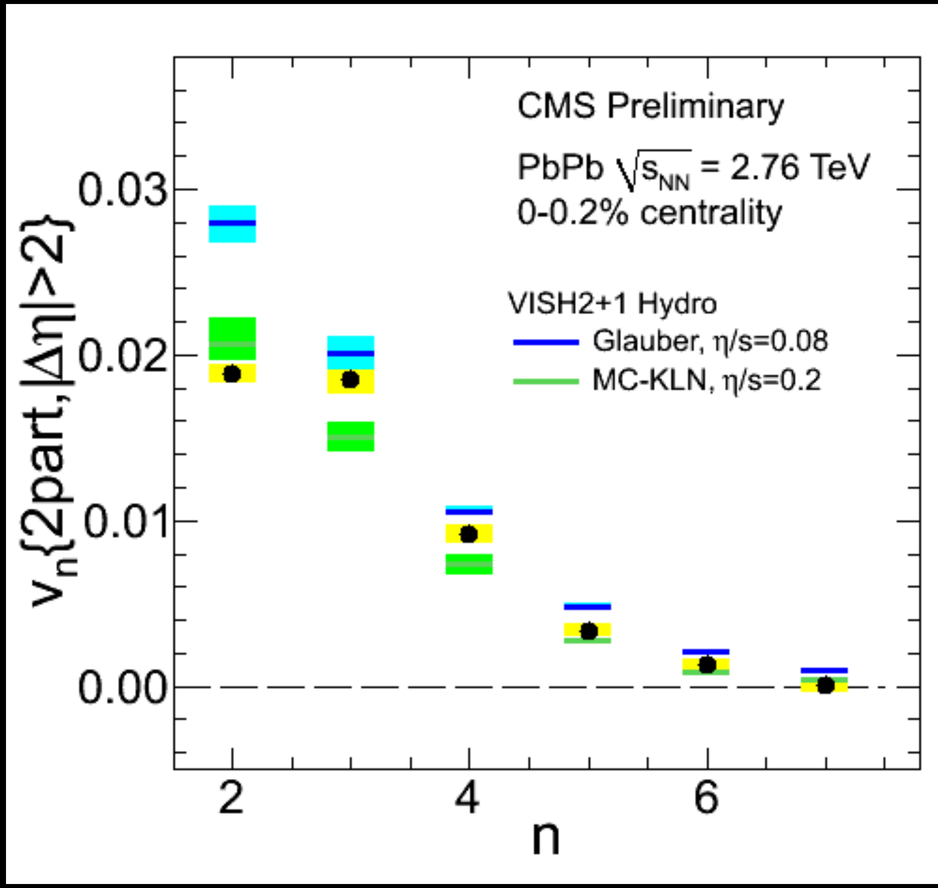


Fourier coefficients for central PbPb

Viscous hydro calculations vs data

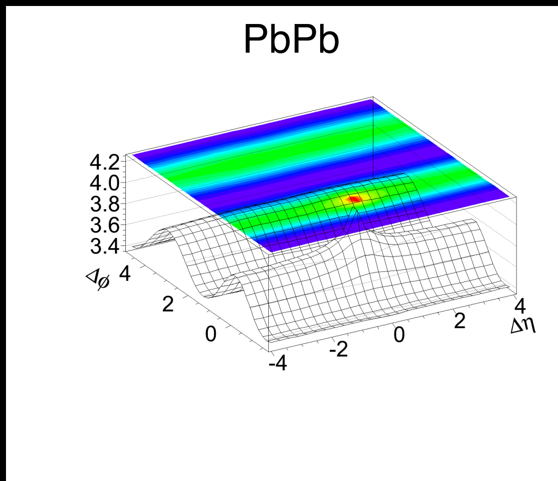


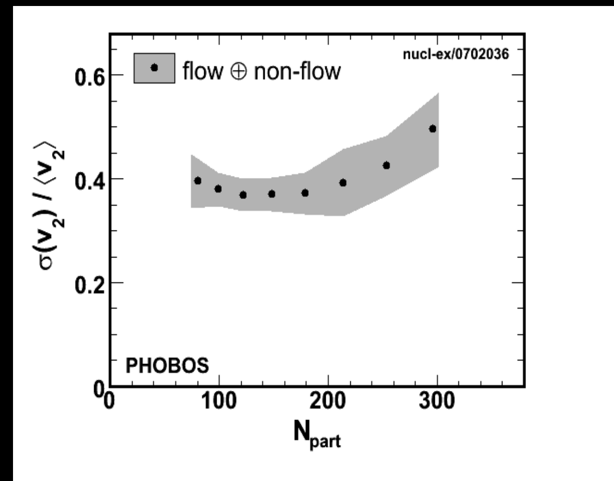


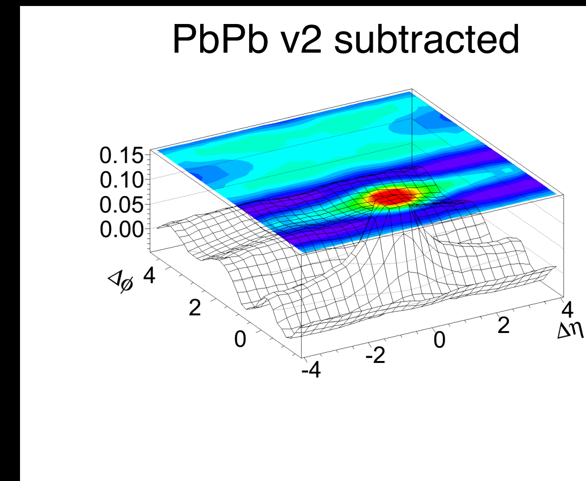


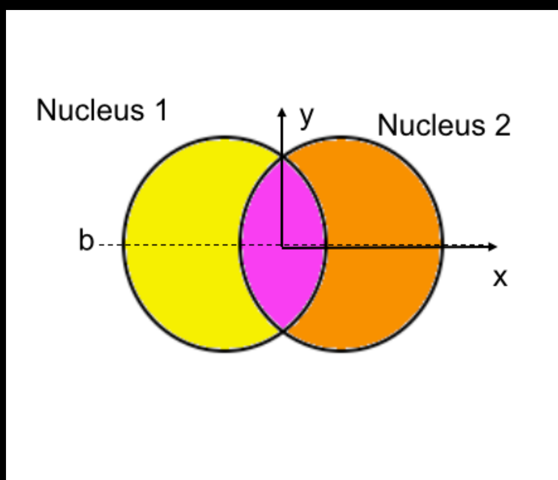
Existing hydro calculations were able to describe the new flow components

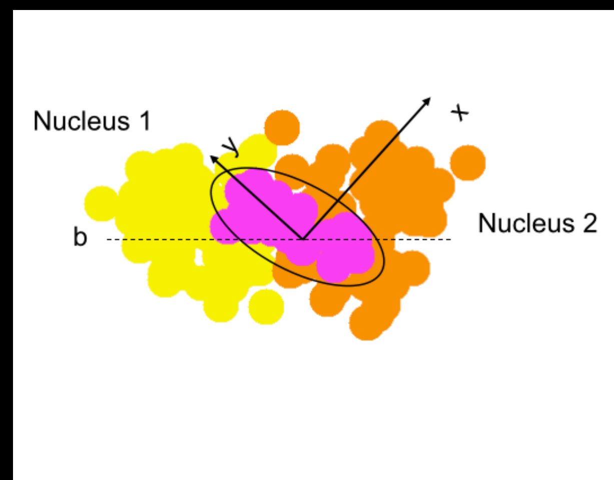
A brief history of correlations in HIC

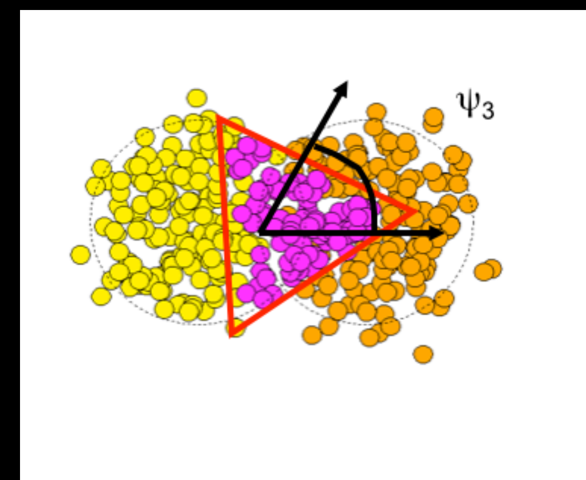


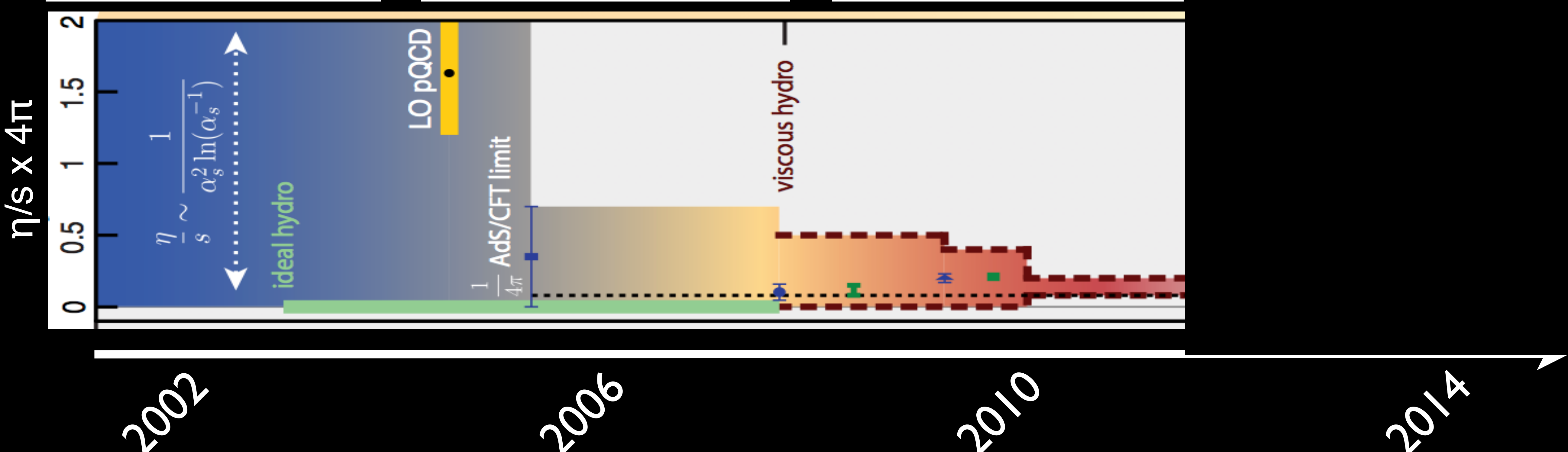


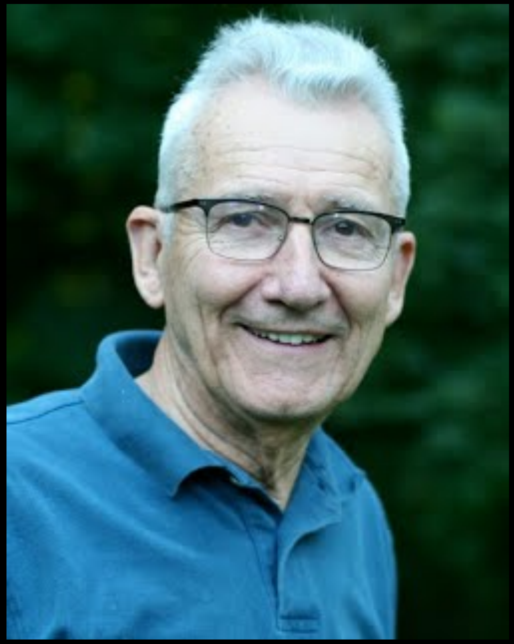






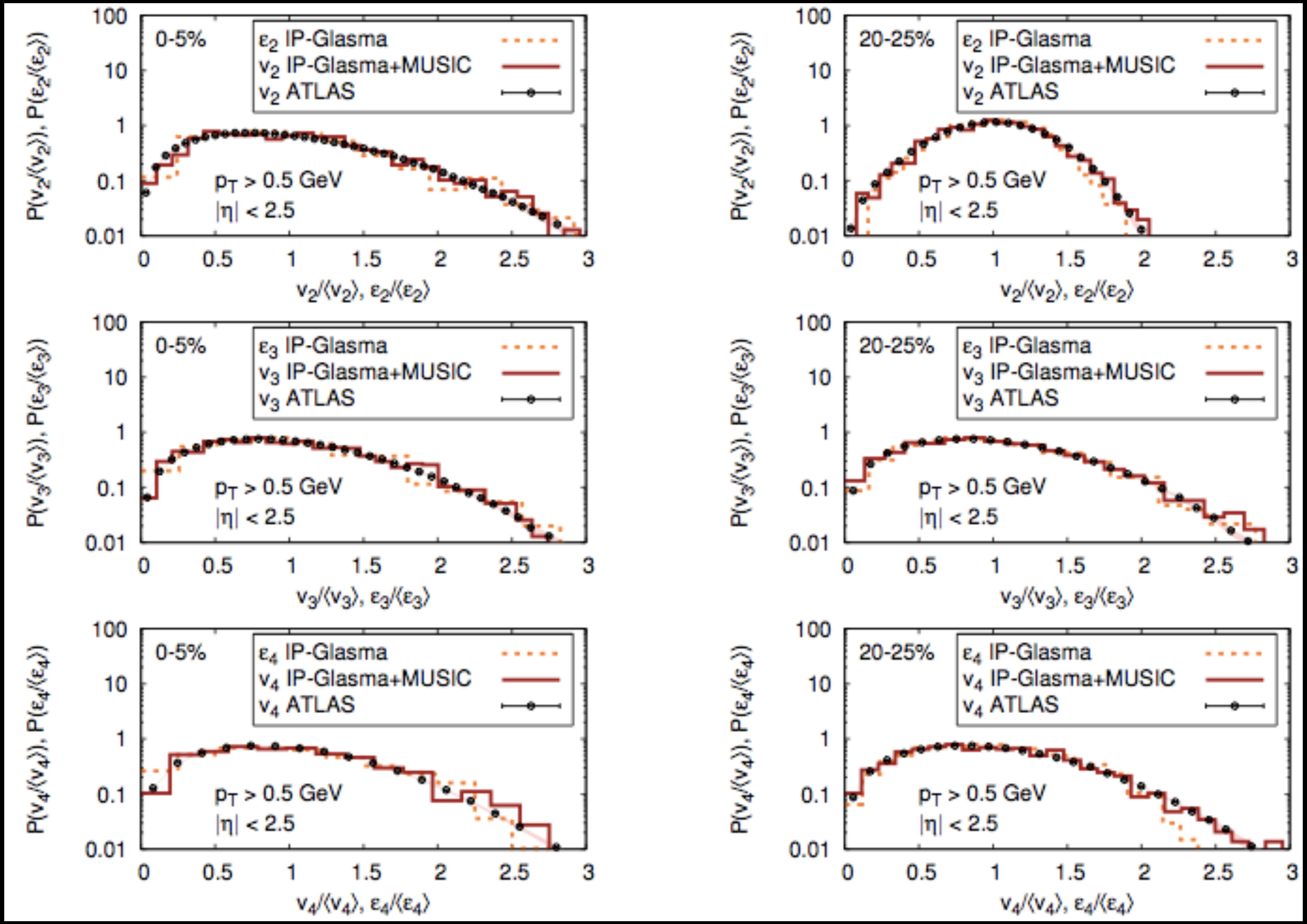






Has hydrodynamics ever predicted anything?

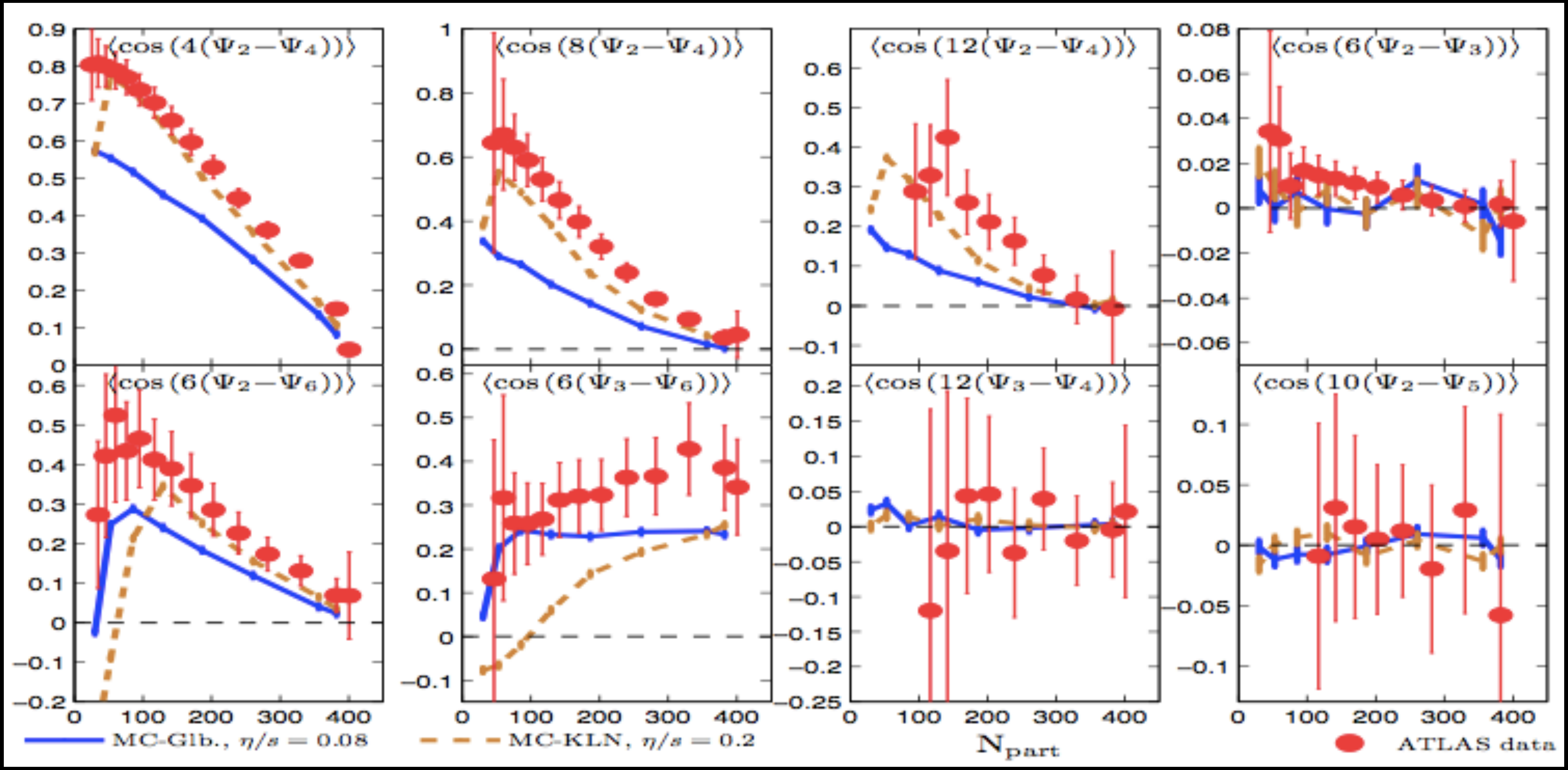
Beyond average v_n



Information content per HI collision is obviously much lower than for CMB
But we have billions of events: Study event-by-event fluctuations

Event-plane angle correlations

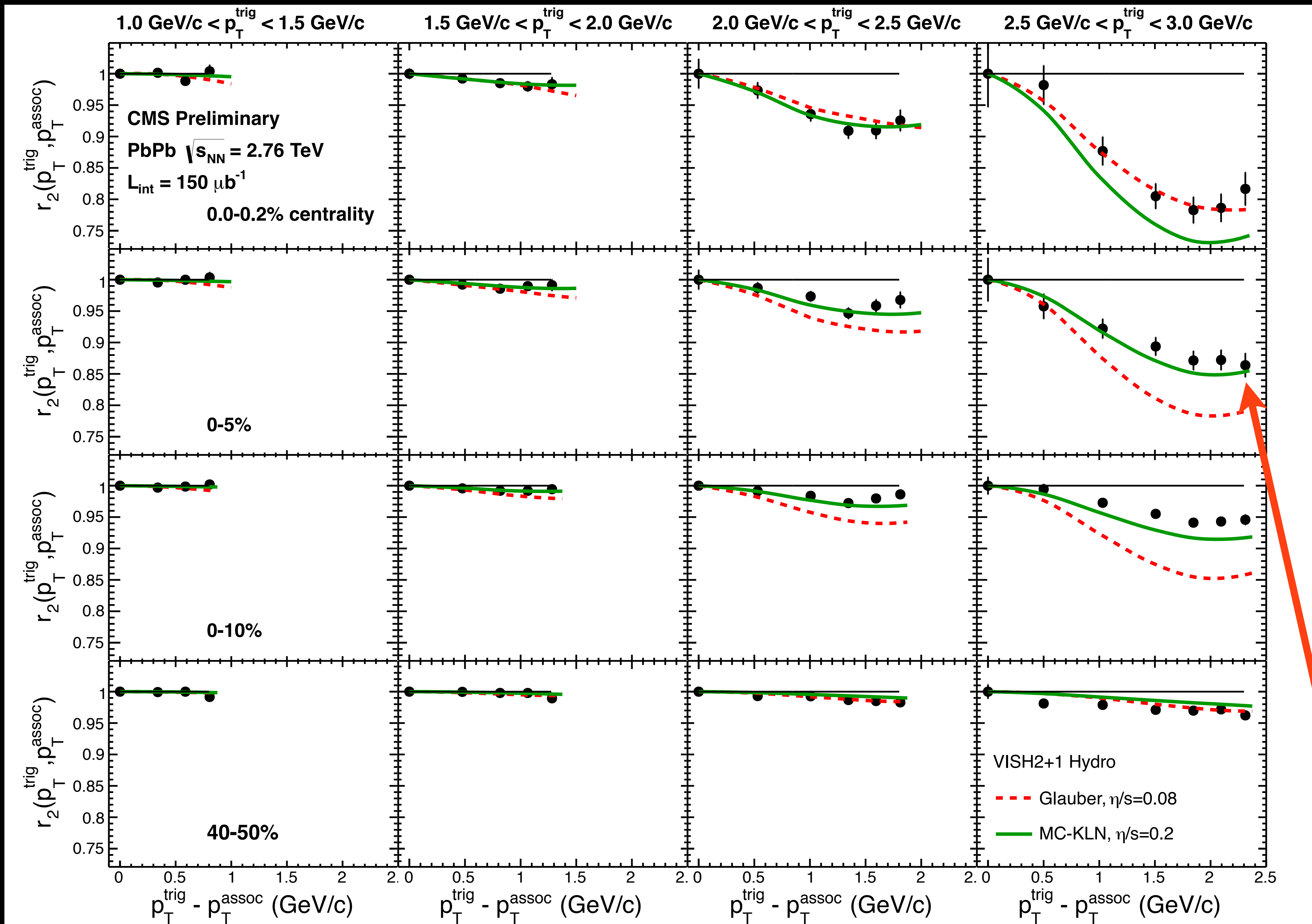
Calculations: Heinz et al.,



Fluctuations + hydro evolution lead to specific correlations of different order event plane angles

Factorization breakdown

Calculations: Heinz et al., PRC 87, 034913 (2013)



$$r_n \equiv \frac{V_{n\Delta}(p_T^{trig}, p_T^{assoc})}{\sqrt{V_{n\Delta}(p_T^{trig}, p_T^{trig})}\sqrt{V_{n\Delta}(p_T^{assoc}, p_T^{assoc})}}$$

Factorization is broken as fluctuations lead to p_T dependent event-plane angle

QCD-inspired models

- **MC-KLN**: k_T factorization, positions of the nucleons fluctuate

  Drescher and Nara, Phys. Rev. C 76, 041903 (2007), Albacete and Dumitru, arXiv:1011.5161

- **MCrcBK**: + fluctuations added to match multiplicity distribution in pp collisions

  Dumitru and Nara, Phys. Rev. C 85, 034907 (2012)

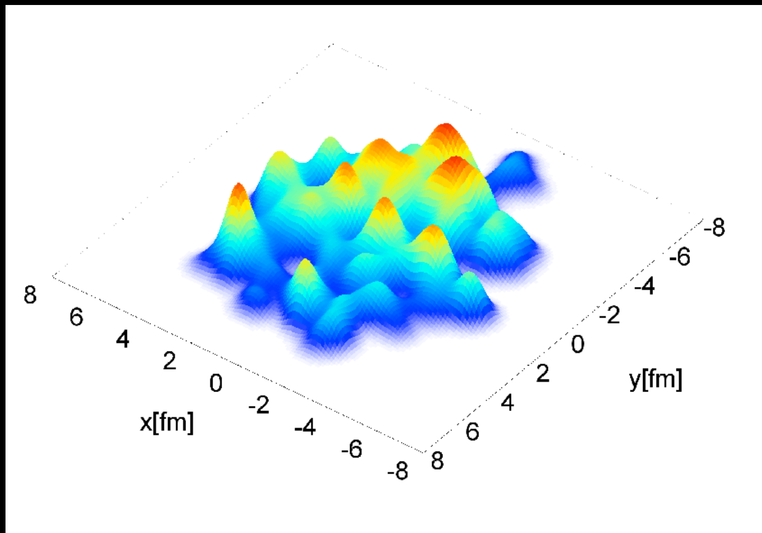
- **DIPSY**: +multiple gluon cascade

  Flensburg, arXiv:1108.4862

- **IP Glasma**: no k_T factorization, non-linearities, fluctuations of color charges within a nucleon

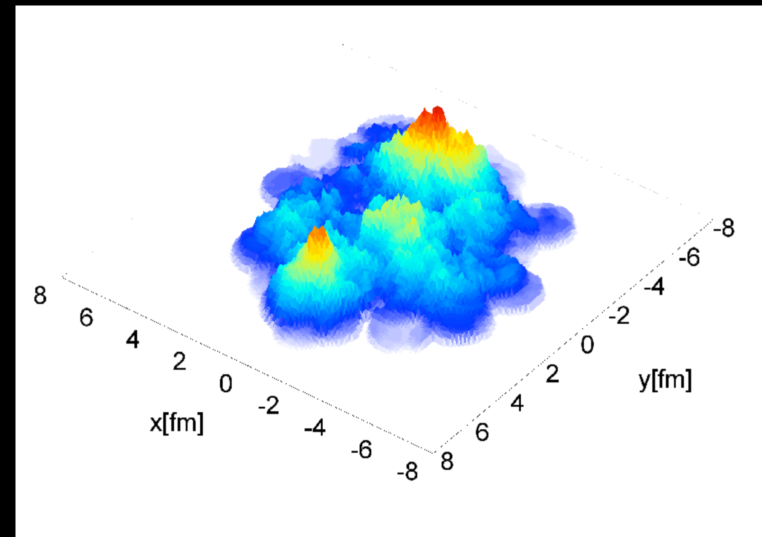
  Schenke, Tribedy, Venugopolan: PRL108 (2012), 252301

Zooming in on Geometry



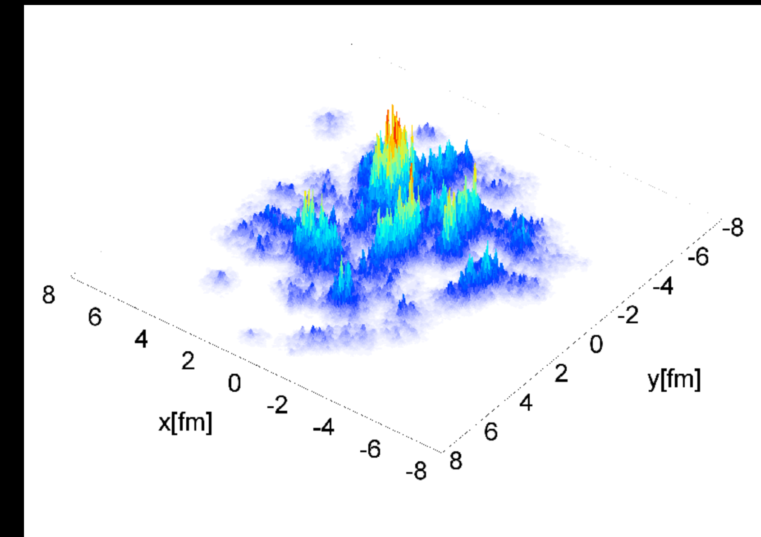
MC Glauber

(Billiard-ball nucleons)



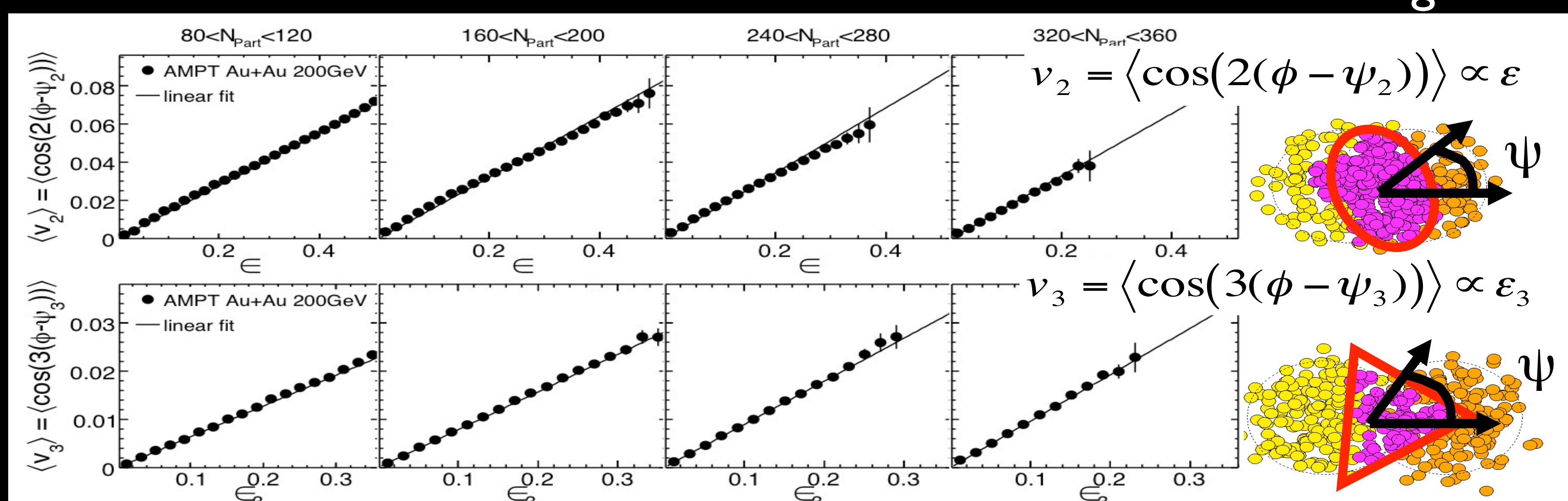
MC KLN

Nucleonic fluctuations
+ saturation effects



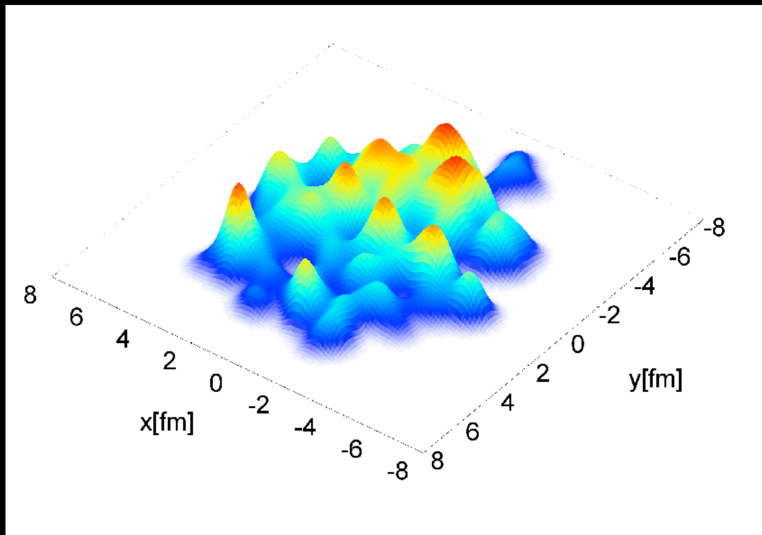
IPGlasma

Nucleonic fluctuations
+ quantum fluctuations of
gluon fields



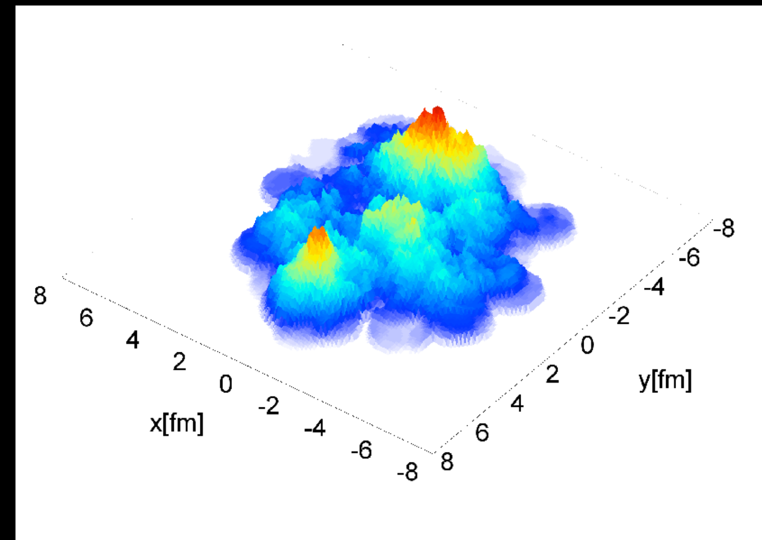
Recall: Linear response of elliptic (v_2) and triangular flow (v_3) to initial eccentricities ε_2 and ε_3

Zooming in on Geometry

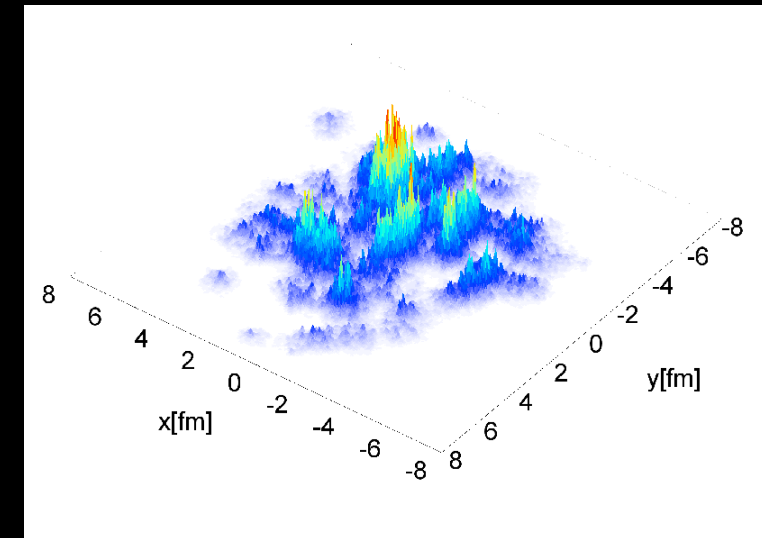


MC Glauber

(Billiard-ball nucleons)



MC KLN

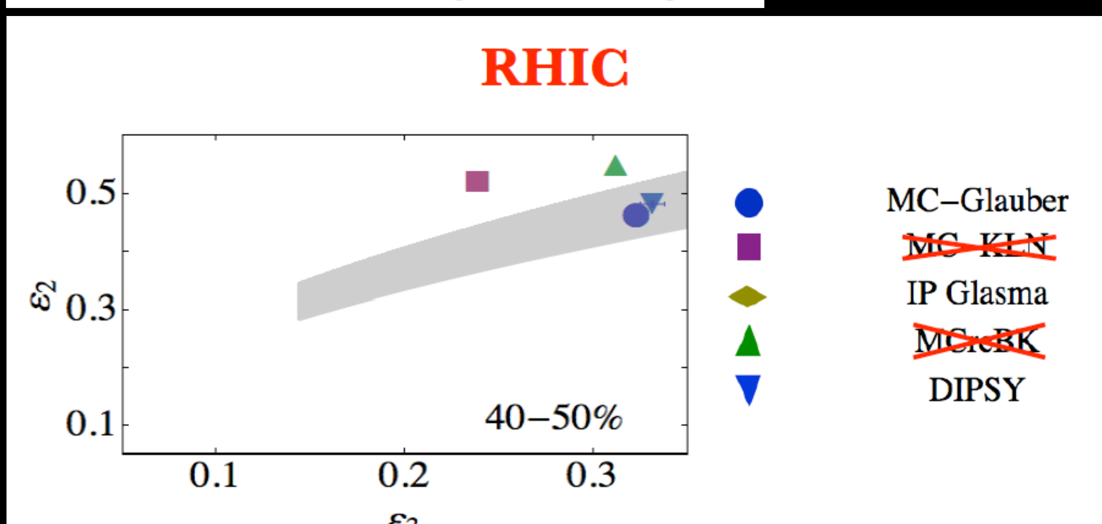


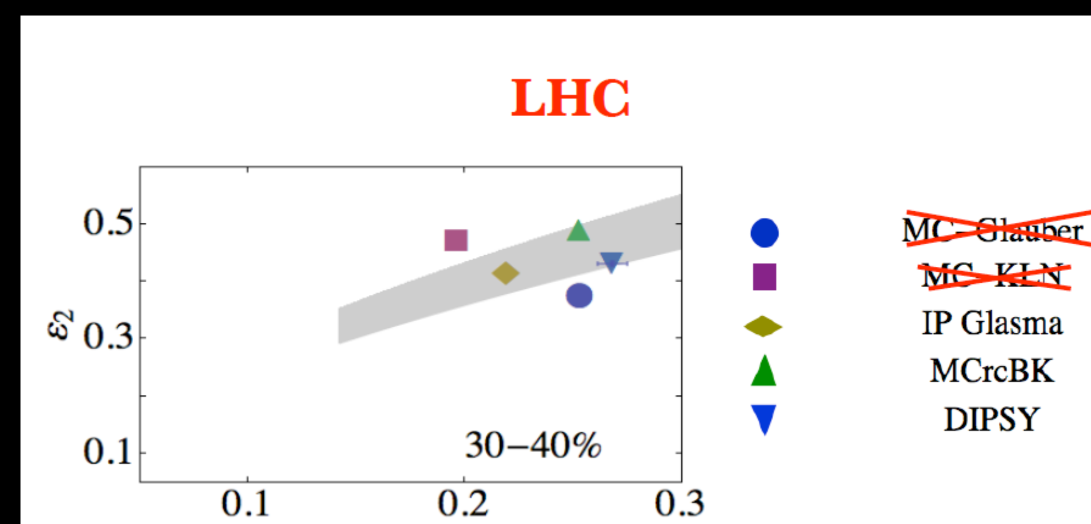
IPGlasma

Nucleonic fluctuations
+ quantum fluctuations of
gluon fields

$$\sqrt{\langle \varepsilon_2^2 \rangle} = C \left(\sqrt{\langle \varepsilon_3^2 \rangle} \right)^k$$

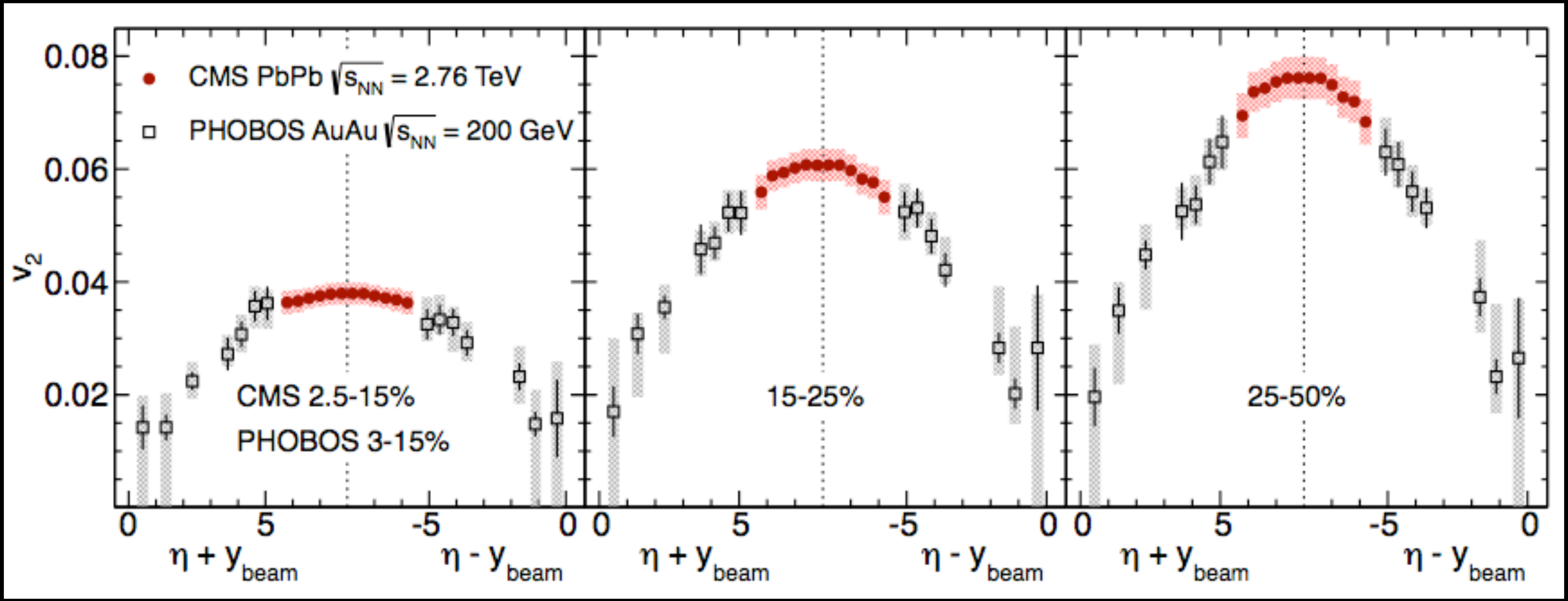
Parametrized
hydro response





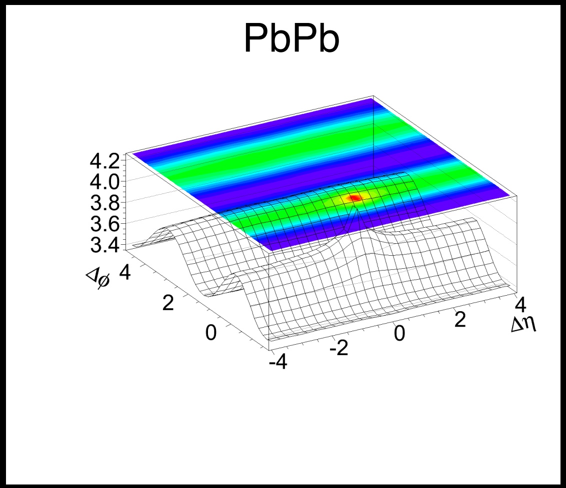
Luzum, Ollitrault, Retinskaya, IS2013 conference (1311.5339)

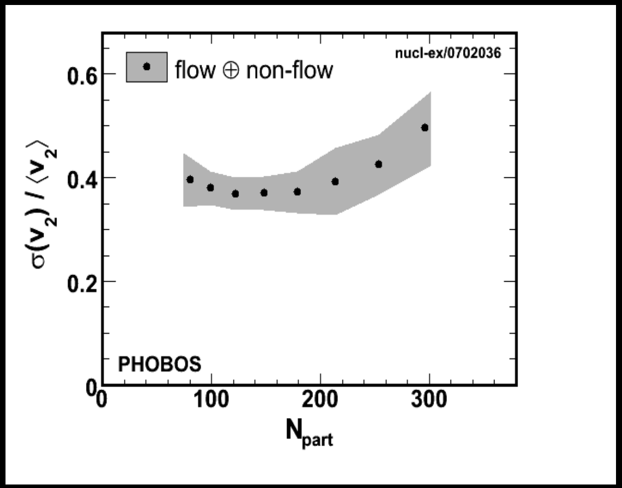
What about the longitudinal direction?

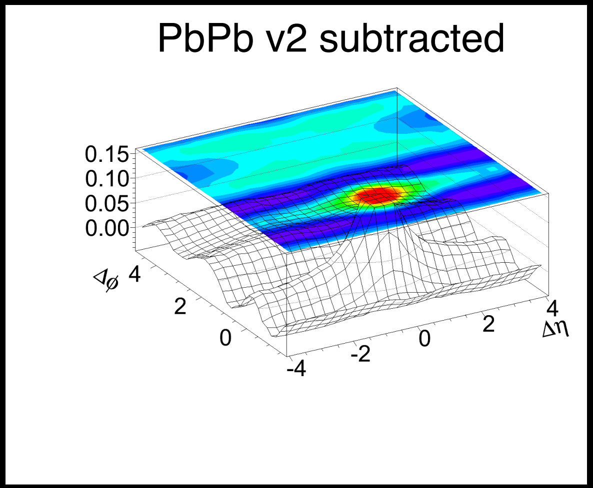


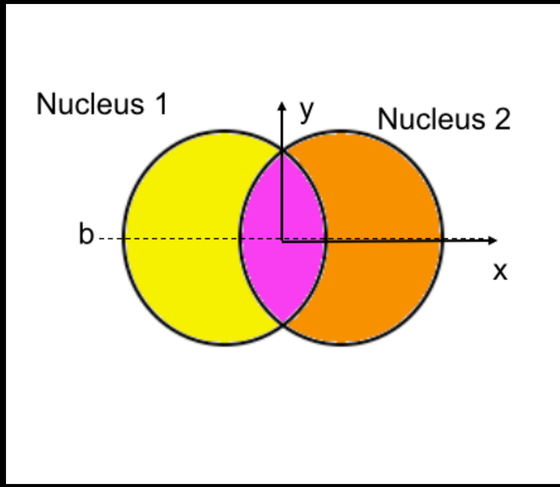
Profound questions remain, e.g. what is the longitudinal structure of the source?

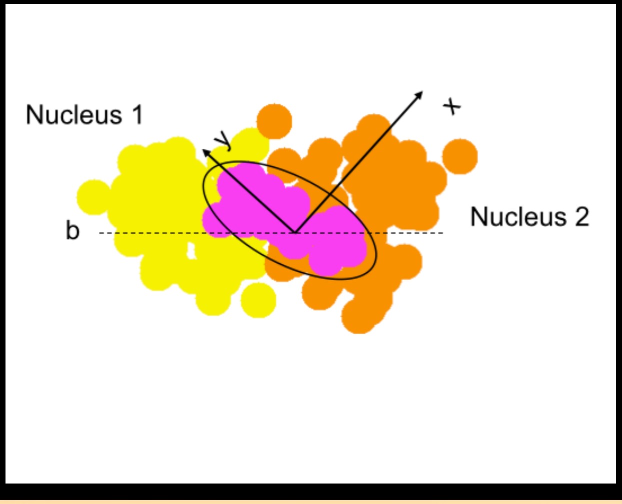
A brief history of correlations in HIC

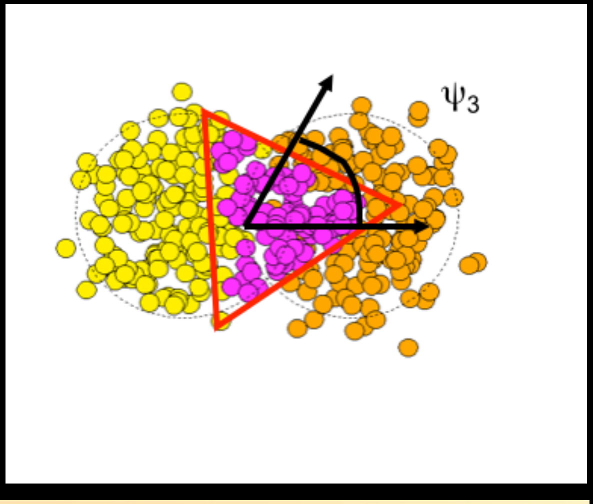


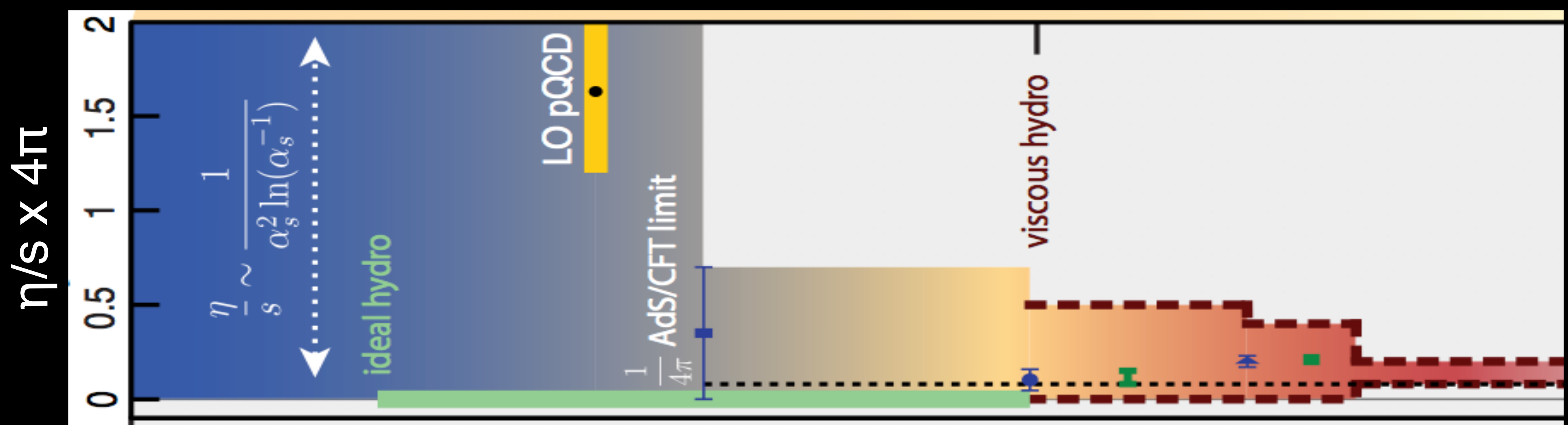








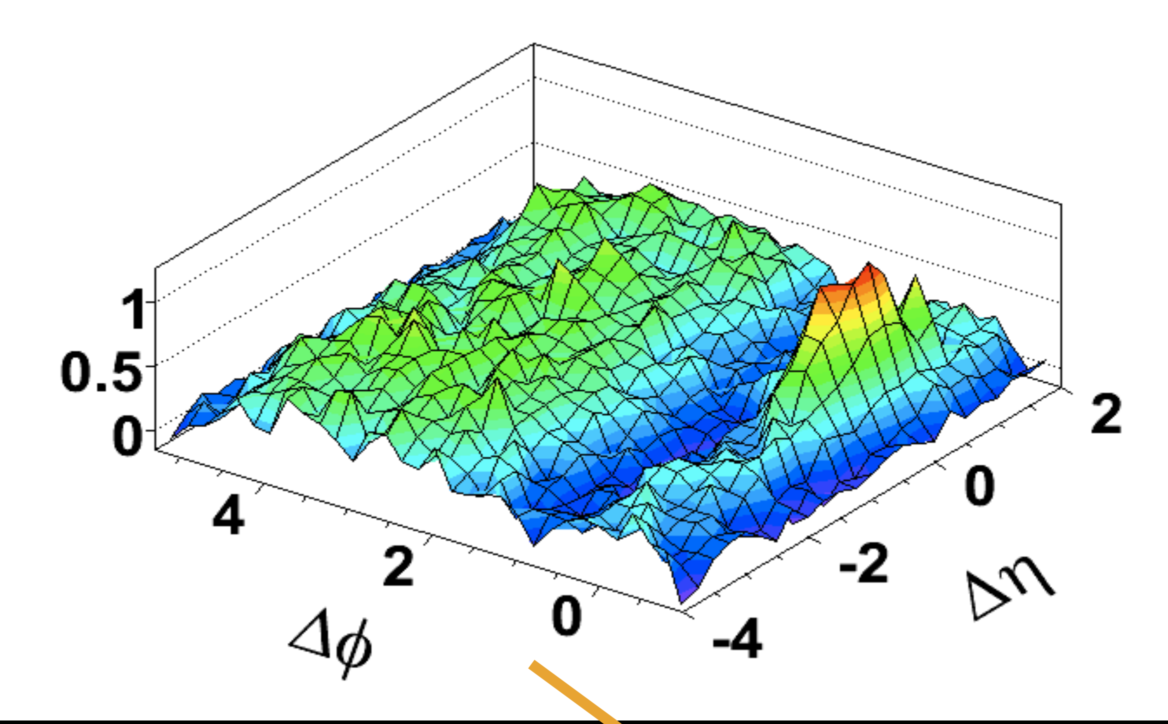




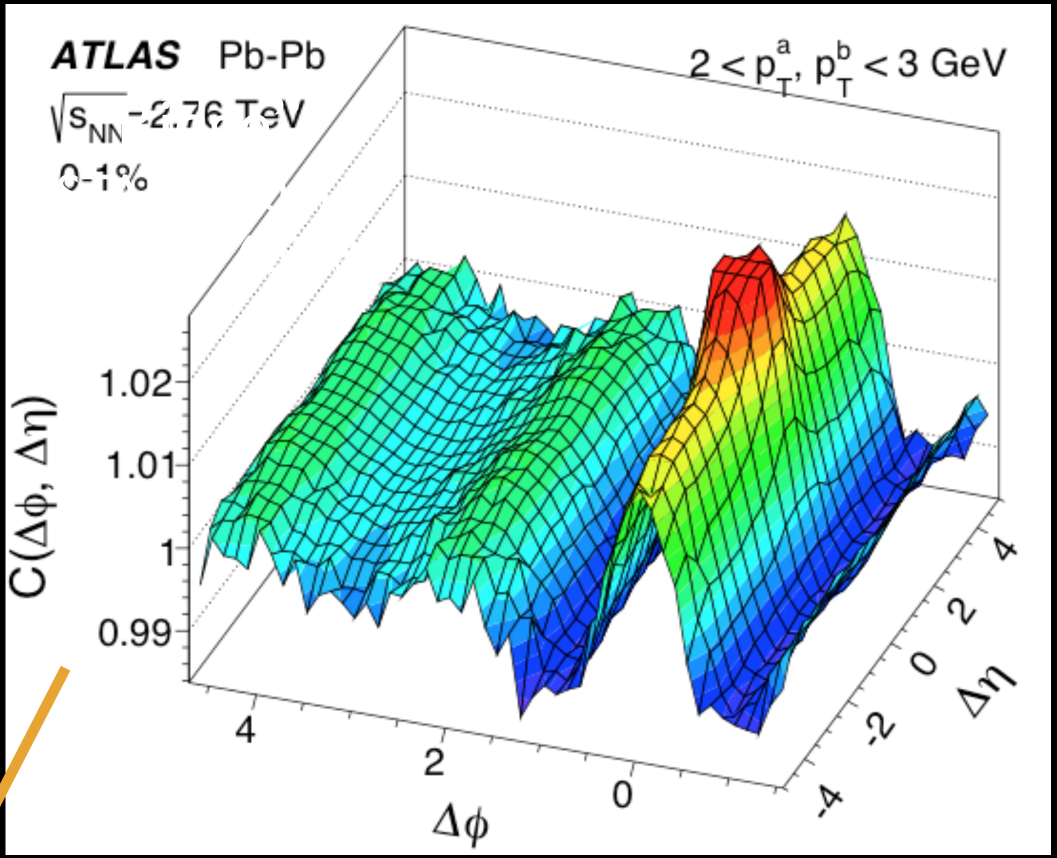
2002 2006 2010 2014

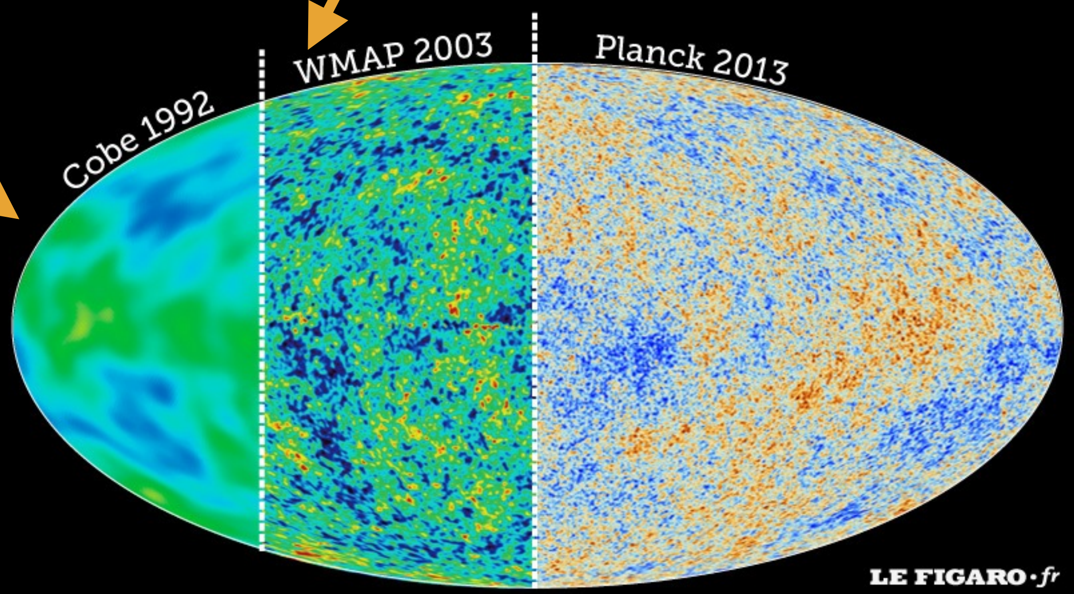
Beyond elliptic flow

PHENIX/PHOBOS/STAR
Au+Au 200 GeV
2006-2010



ALICE/ATLAS/CMS
PbPb 2.76TeV
Nov 2010-Mar 2011





?