Fluctuations and flow in nucleus-nucleus collisions at the LHC

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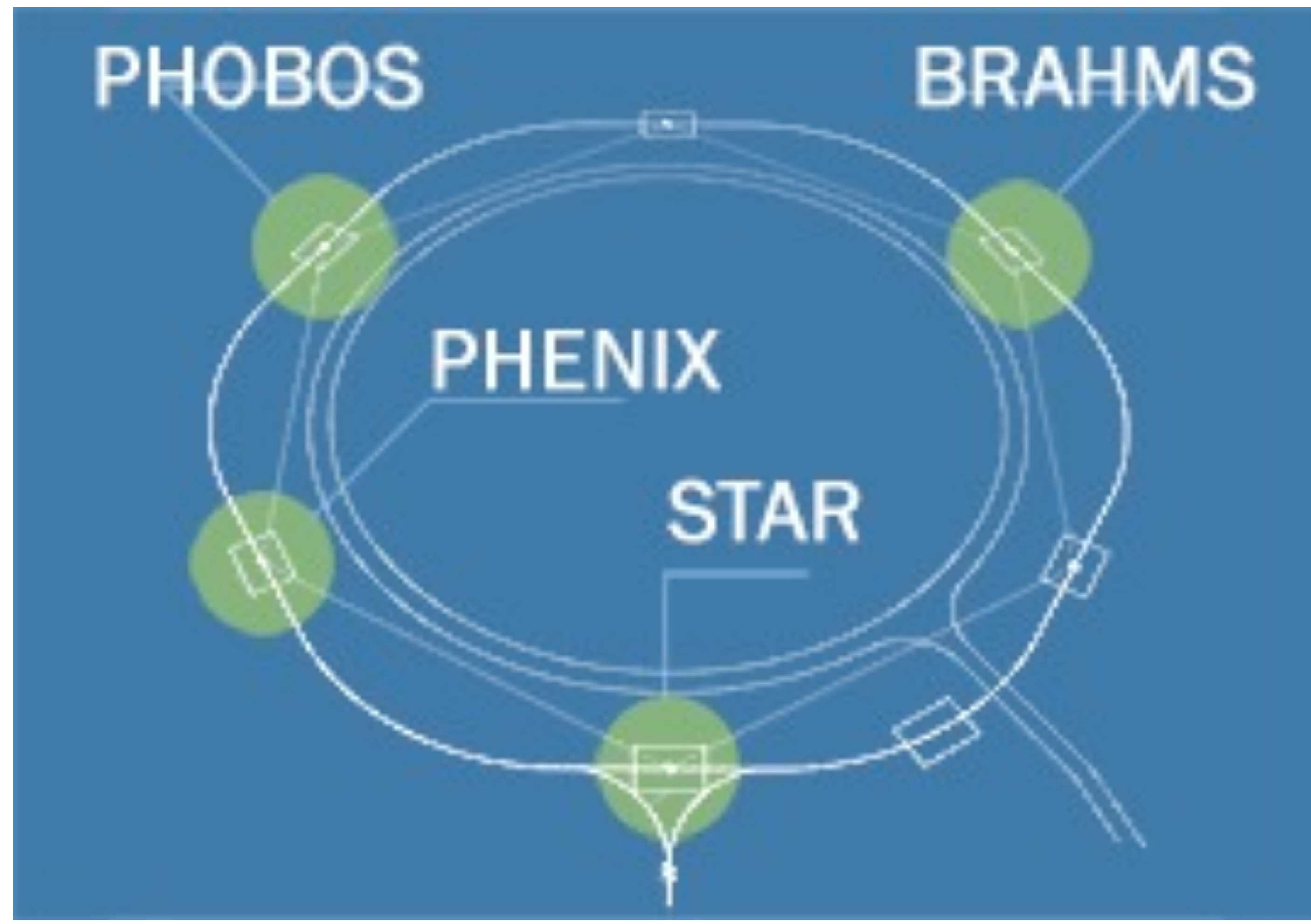
work in collaboration with Matt Luzum

LPC Clermont, November 25, 2011

RHIC (Brookhaven), since 2000

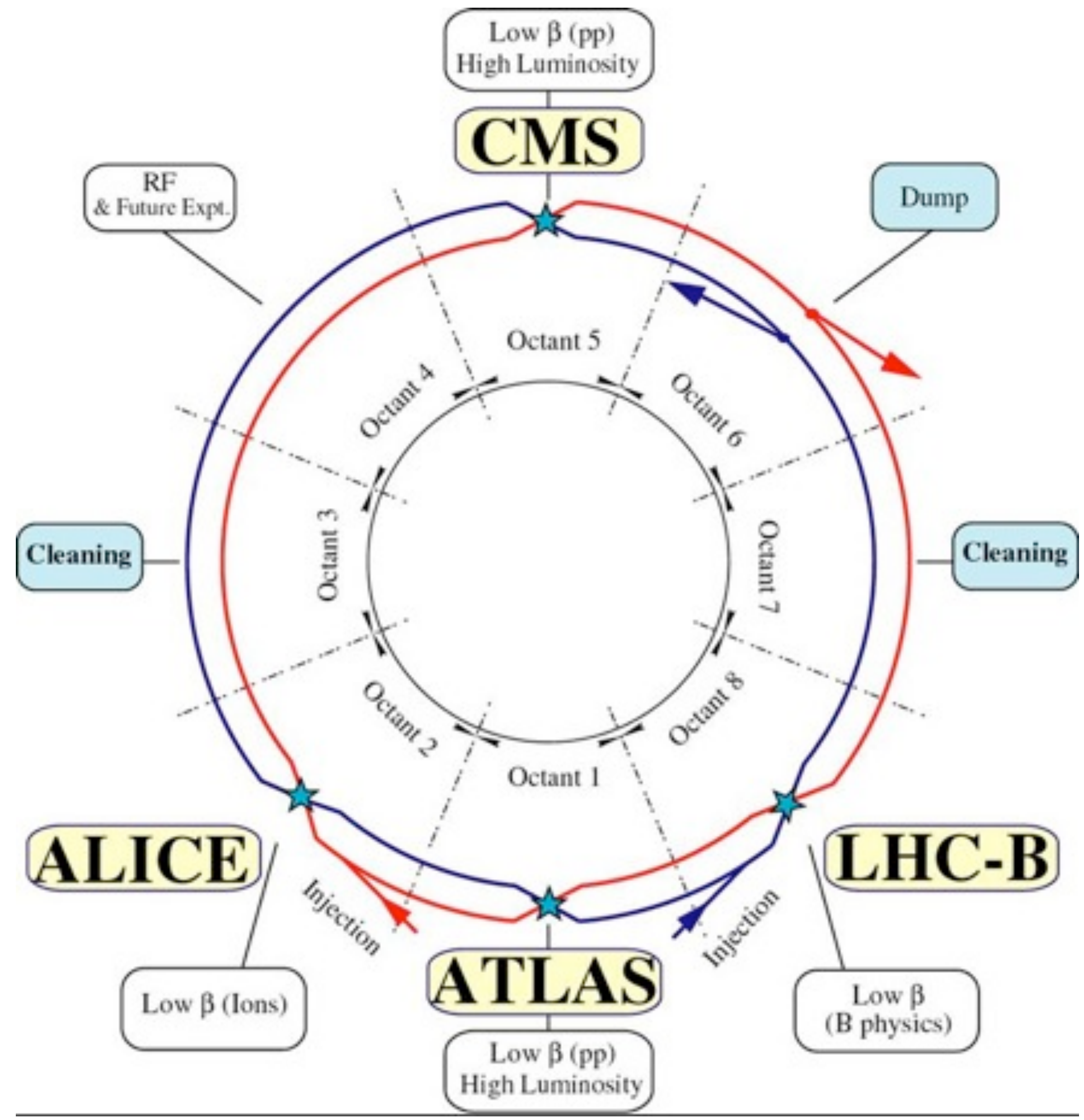
Au-Au collisions (mostly) up to 200 GeV/nucleon pair.

Theory breakthroughs until 2010, just in time for LHC



Heavy-ions at LHC

- First heavy-ion run at 2.76 TeV/nucleon pair (Pb-Pb): Nov. 2010.
- First detailed results (ALICE, CMS, ATLAS) presented at Quark Matter 2011, May 23-28, Annecy.



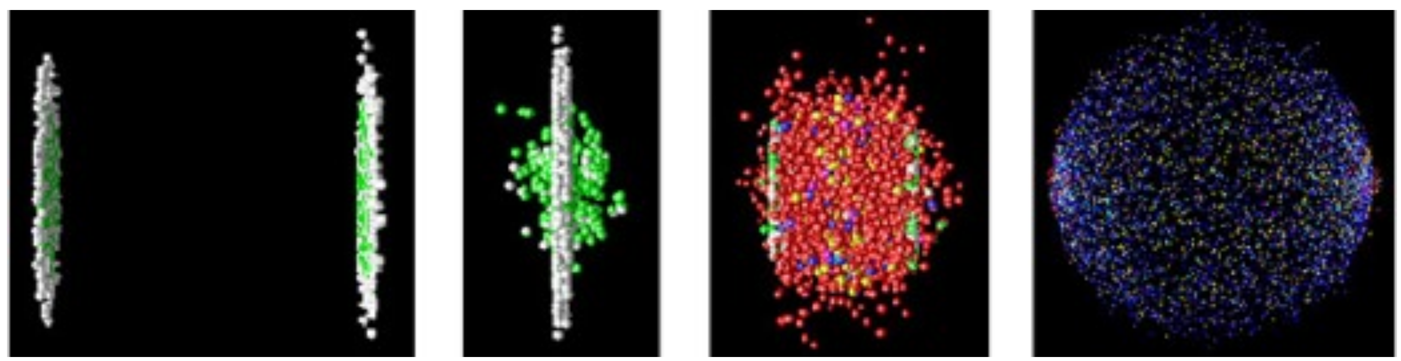
Outline

- Why heavy-ion collisions are special: correlations in proton-proton versus heavy-ion collisions
- The little bang: the old picture (2000) and the new picture (2010): qualitative ideas
- Quantitative prediction versus new LHC data (2011)
- Conclusions

Space-time picture of an ultrarelativistic heavy-ion collision

Thanks to the strong Lorentz contraction, clear separation of time scales -- and theory tasks

cartoon using the Monte-Carlo transport code UrQMD



Initial conditions

Expansion

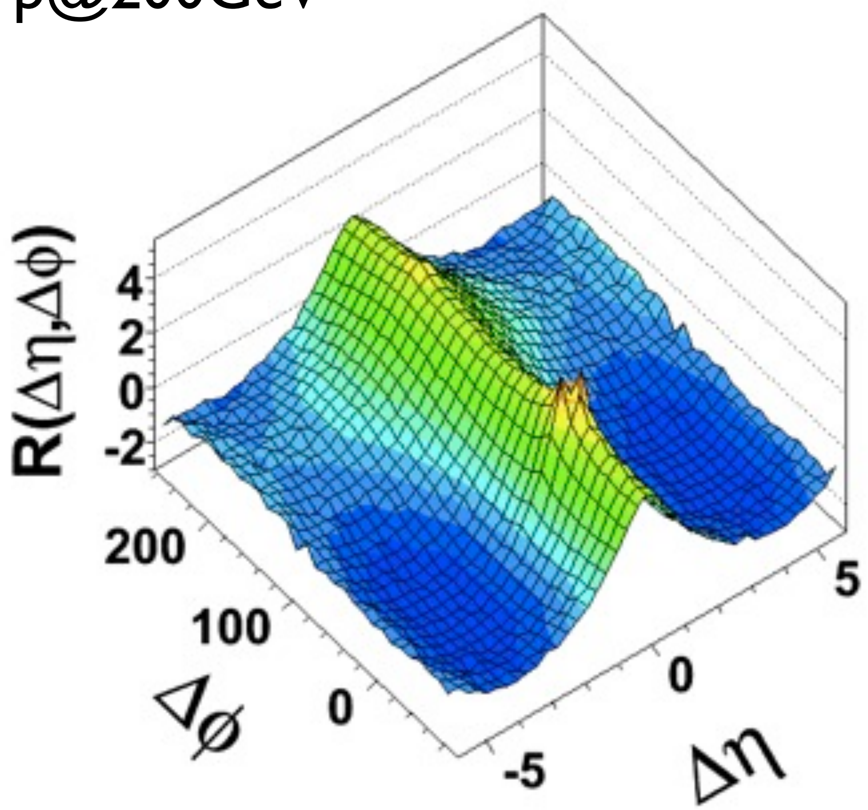
Hadronization and freeze-out

Two-particle correlations

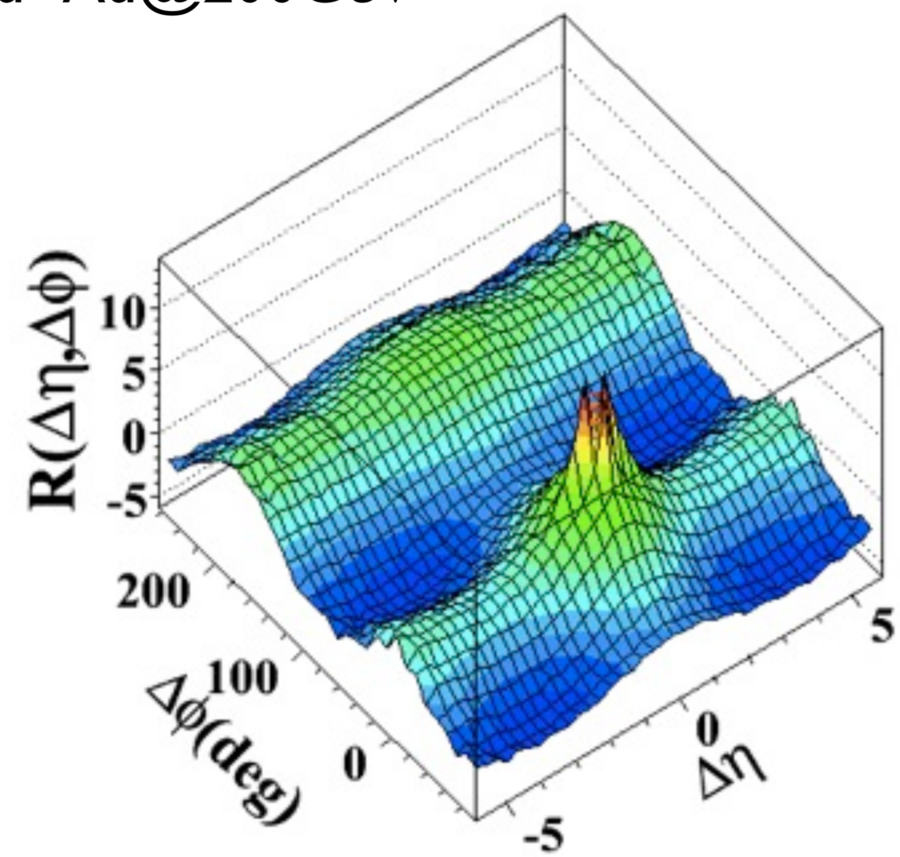
≈ number of particle pairs versus *relative* azimuthal angle ΔΦ and rapidity Δη

G. Stephans (PHOBOS), talk at QM'09

p+p@200GeV



Central Au+Au@200GeV



✓short range in rapidity
✓little azimuthal structure

✓long range in rapidity
✓specific azimuthal structure

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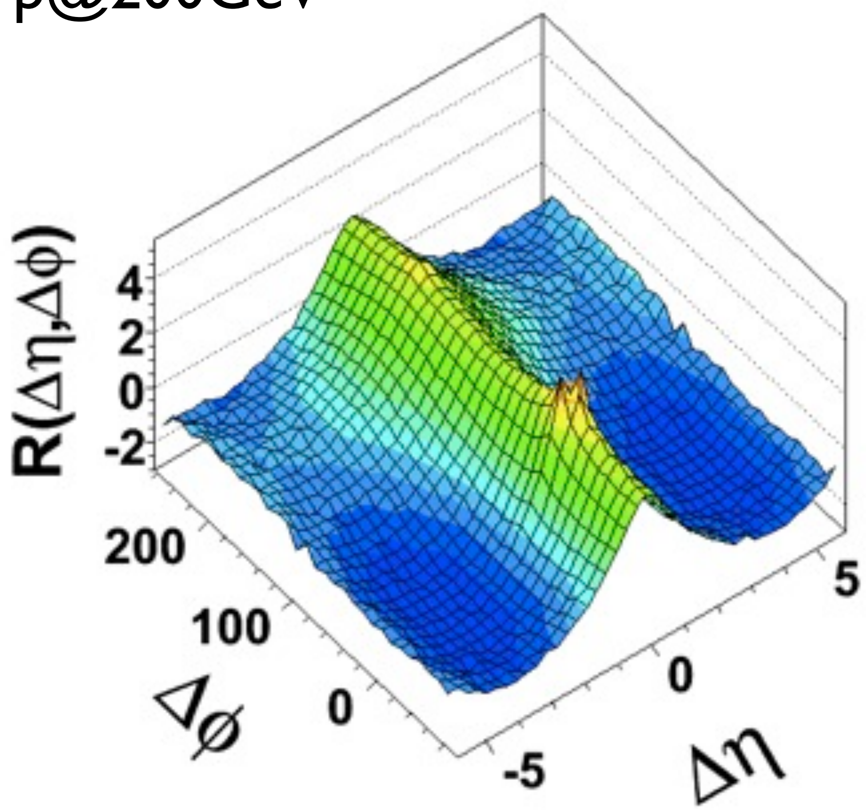

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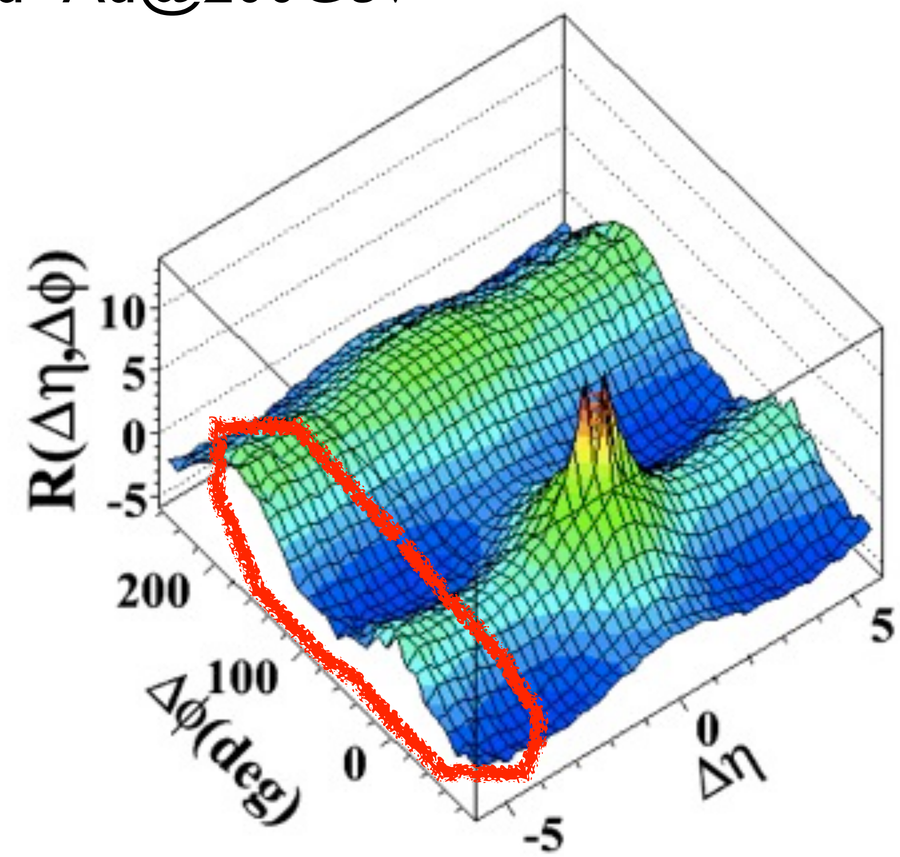

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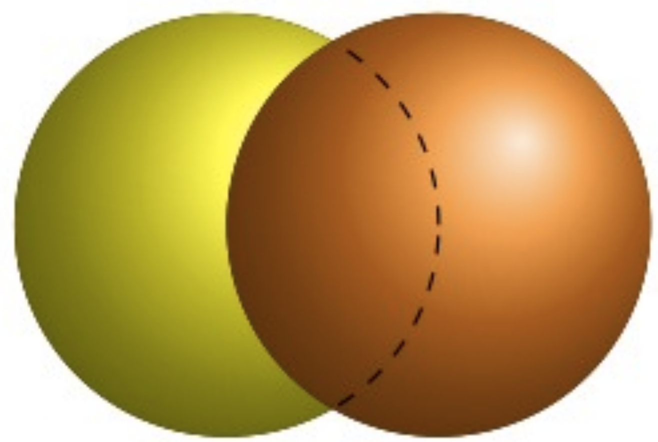
Collective flow: the old picture

(RHIC, 2000)



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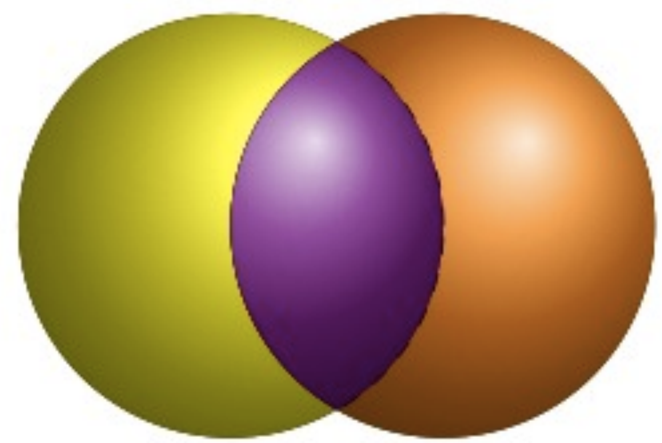
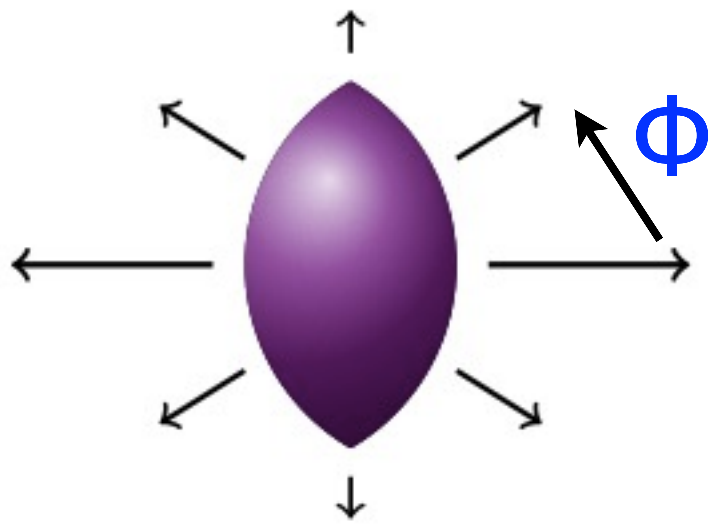


Collective flow: the old picture
(RHIC, 2000)

Collective flow: the old picture

(RHIC, 2000)



The system thermalizes and expands like a fluid

Collective flow: the old picture

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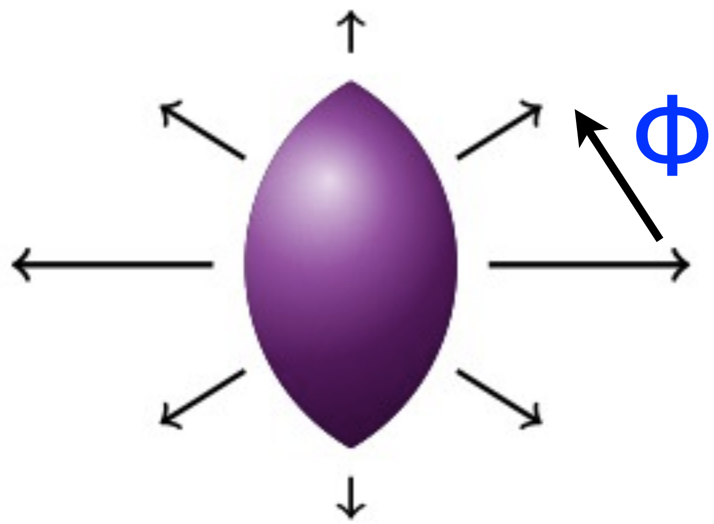


The system thermalizes and expands like a fluid

Particles are emitted independently in each event, with a ϕ-dependent distribution $dN/d\phi = (N/2\pi)[1+2v_2 \cos(2\phi)]$

v_2, elliptic flow, is a day 1 observable at RHIC and LHC

it depends weakly on rapidity

STAR nucl-ex/0009011, 445 citations

ALICE arXiv:1011.3914, 128 citations

Independent particles explain pair correlations

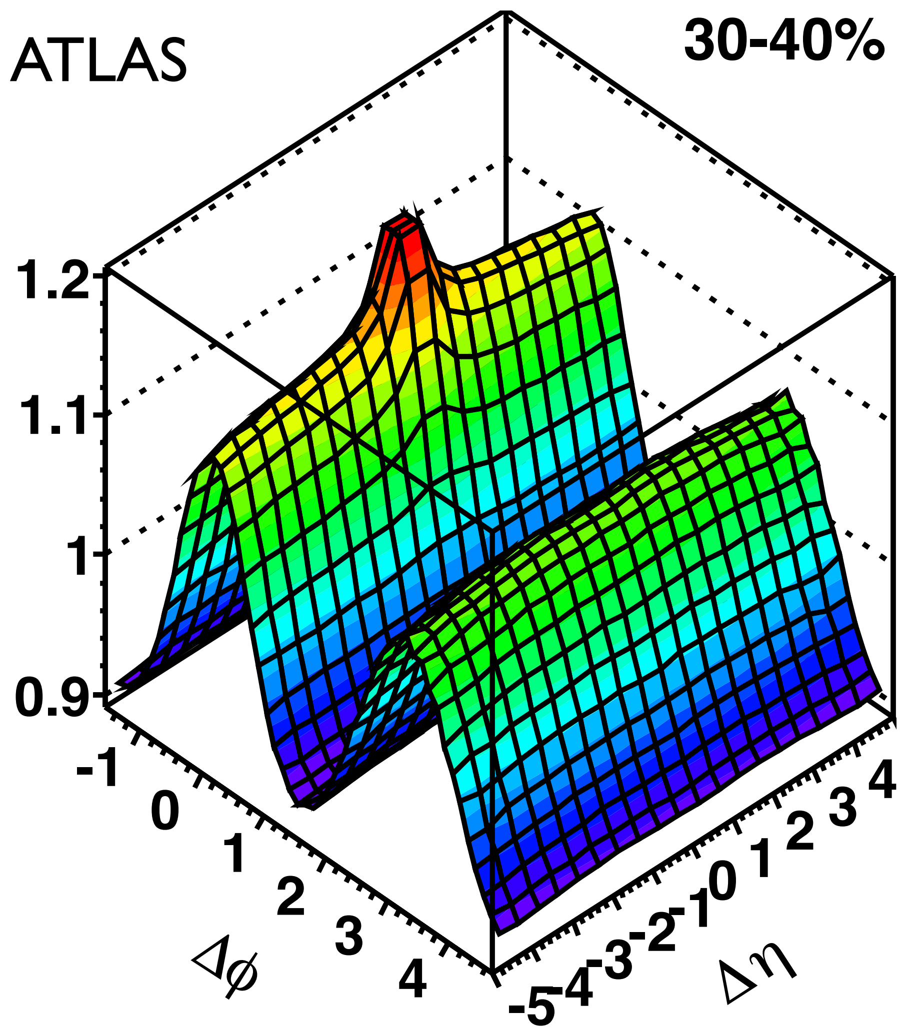
$v_2 = \langle e^{2i\phi} \rangle$ (reference direction $\phi=0$ changes event by event!)

$$\langle e^{2i\Delta\phi} \rangle = \langle e^{2i(\phi 1 - \phi 2)} \rangle = \langle e^{2i\phi 1} e^{-2i\phi 2} \rangle$$

$$= \langle e^{2i\phi 1} \rangle \langle e^{-2i\phi 2} \rangle = (v_2)^2$$

$$dN_{pair}/d\Delta\phi = (N_{pair}/2\pi)[1+2(v_2)^2\cos(2\Delta\phi)]$$

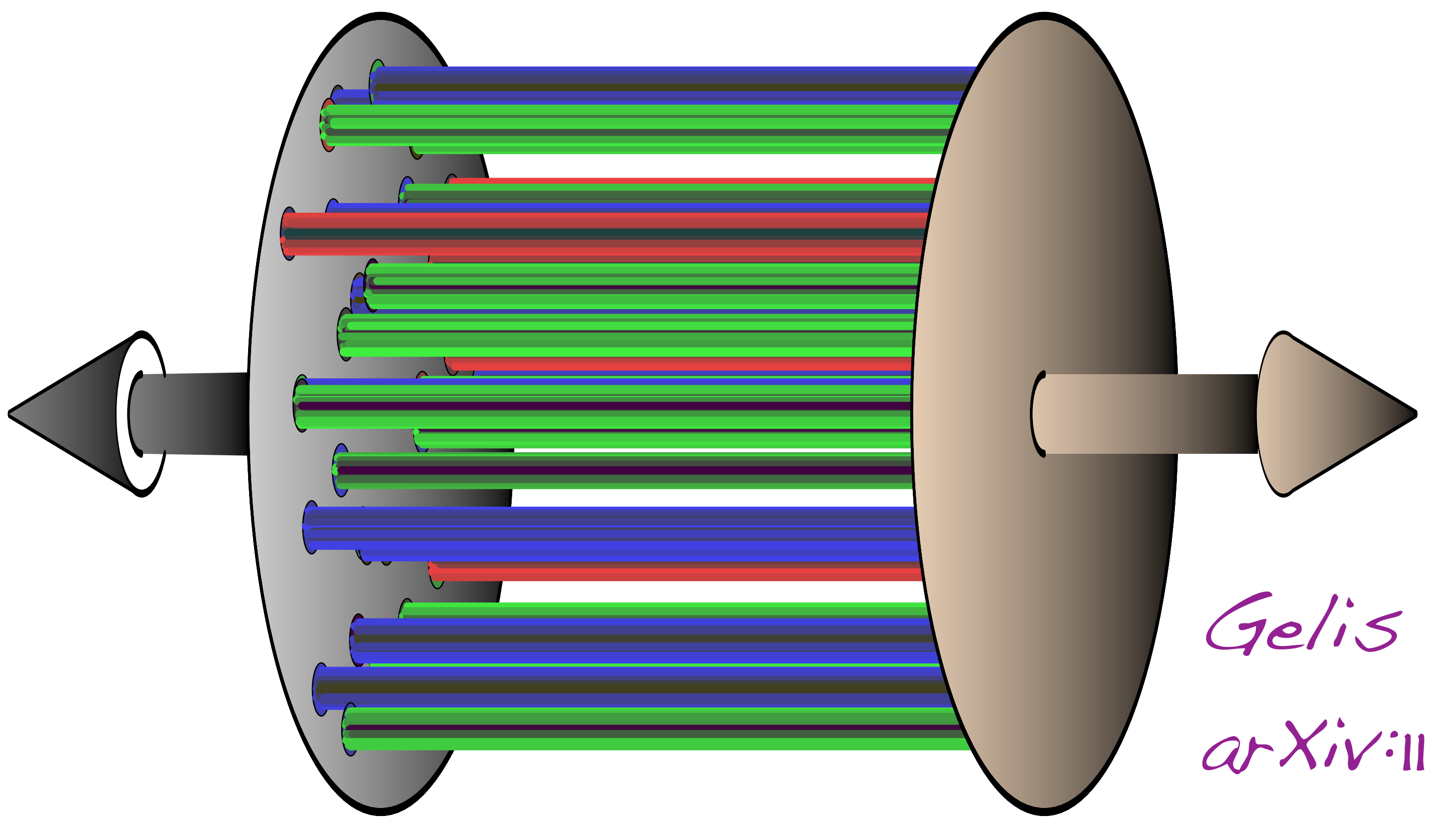
Is v_2 all we see at large $\Delta\eta$?



Correlation at large $\Delta\eta$ clearly dominated by a $\cos(2\Delta\phi)$ term but the peak at $\Delta\phi=0$ is narrower than that at $\Delta\phi=\pi$

this narrow, near-side ridge and this broad away-side structure have puzzled heavy ion physicists from 2005 to 2010.

Fluctuations



Gelis et al, arXiv:1102.0333

Each nucleus is made of a 208 nucleons.
The collision takes a snapshot of the nuclear wavefunction: initial density is lumpy in the transverse plane, but approximately independent of rapidity

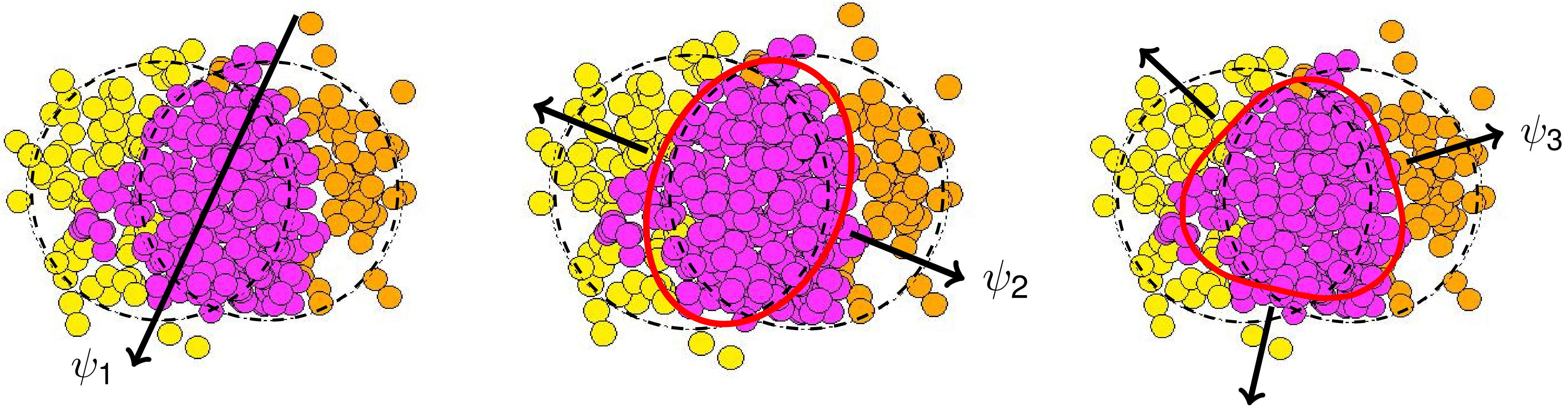
Fluctuations + flow

The initial state is no longer symmetric under $\Phi \to -\Phi$ and $\Phi \to \Phi + \pi$

The final Φ distribution in a single event is arbitrary:

$dN/d\Phi = (N/2\pi)[1 + 2 \sum_n v_n \cos(n(\phi - \psi_n))]$

both even and odd harmonics, each with its own direction ψ_n



From flow to correlations: the new picture (2010)

$v_n = \langle e^{in(\phi-\Psi n)} \rangle$ (v_n and reference directions ψ_n change event by event!)

$$\langle e^{in\Delta\phi} \rangle = \langle e^{in(\phi 1-\Psi n)} e^{-in(\phi 2-\Psi n)} \rangle$$

$$= \langle e^{in(\phi 1-\Psi n)} \rangle \quad \langle e^{-in(\phi 2-\Psi n)} \rangle \quad = (v_n)^2$$

$$dN_{pair}/d\Delta\phi = (N_{pair}/2\pi)[1+2\sum_n (v_n)^2 \cos(n\Delta\phi)]$$

this explains why near-side narrower than away-side!

independent particle emission explains data up to $p_t \approx 5$GeV

Alver Roland, "triangular flow" arXiv:1003.0194

Luzum arXiv:1011.5773, ALICE arXiv:1109.2501

Quantitative prediction for the LHC

- Goal: compute the single particle distribution (in particular, Φ distribution) in an event
- Model for initial state, including fluctuations
  (bottleneck: the only models available on the market are very crude)
- Evolve through relativistic viscous hydrodynamics
- Fluid eventually freezes into particles: compute spectra, elliptic flow, etc.
- We now have data from ALICE, CMS, ATLAS

Why hydrodynamics?

- The only theory describing the space-time history of a large, strongly-interacting system
- Can be formulated as a systematic gradient expansion = power expansion in 1/R, where R=nuclear radius

$$\partial_\mu((\varepsilon+P)u^\mu u^\nu - Pg^{\mu\nu}) + \eta\, \partial_\mu \partial_\rho \ldots + \partial_\mu \partial_\rho \partial_\sigma \ldots = 0$$

Infinite system: Ideal hydrodynamics

shear viscosity

1/R corrections
viscous hydrodynamics
relativistic Navier-Stokes

$1/R^2$ corrections
Israel-Stewart theories

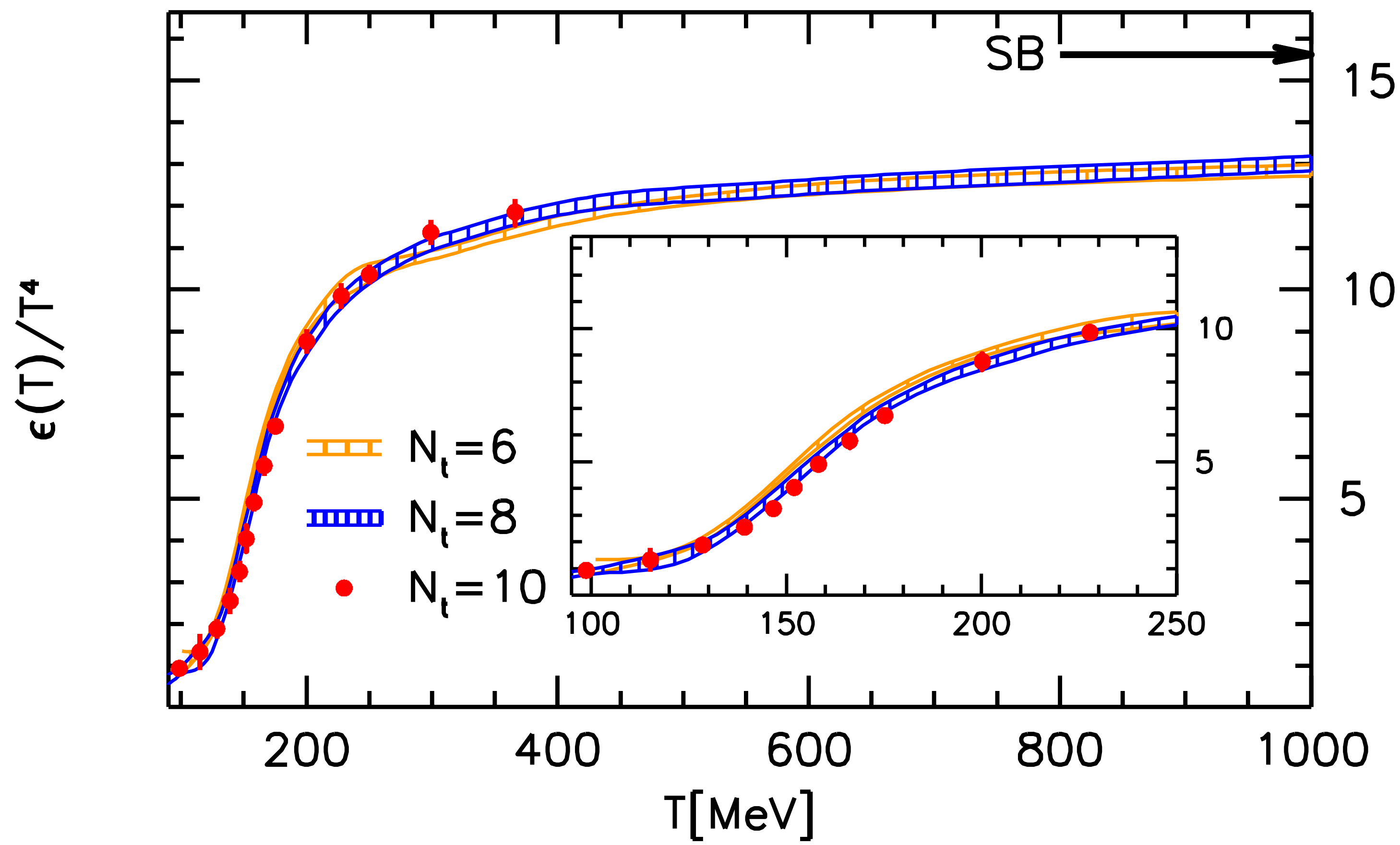
Is a nucleus large enough? is the viscosity small enough for hydro?

(some) Hydro groups

- Luzum & Romatschke, arXiv:0901.4588
- Shen, Heinz, Huovinen & Song arXiv:1105.3226
- Bozek, Chojnacki, Florkowski & Tomasik, arXiv:1007.2294
- Schenke, Jeon & Gale, arXiv:1009.3244
- Petersen et al, arXiv:0806.1695
- Takahashi et al, arXiv:0902:4870
- Hirano, Monnai, arXiv:0903.4436
- Chaudhuri, arXiv:0910.0979
- Holopainen et al, arXiv:1007.0368
- Werner et al, arXiv:1004.0805

Lattice QCD enters the precision era

Equation of state of hot QCD *(input of hydrodynamics)* now calculated with dynamical quarks and physical quark masses!



Borsanyi et al, arXiv:1007.2580

However, the viscosity η is not yet calculated: free parameter in hydro

Where heavy-ion physics meets string theory

- Stronger interactions imply lower viscosity
- One thus naturally expects that strong interactions in the nonperturbative, strong-coupling regime probed by heavy-ion collisions have a very low viscosity
- Using the AdS/CFT correspondence between string theory and gauge theories, one can compute exactly the viscosity to entropy ratio in strongly-coupled supersymmetric N=4 gauge theories (similar to QCD, with a few extra particles), and it has been postulated that the result is a universal lower bound (now known to be slightly violated)

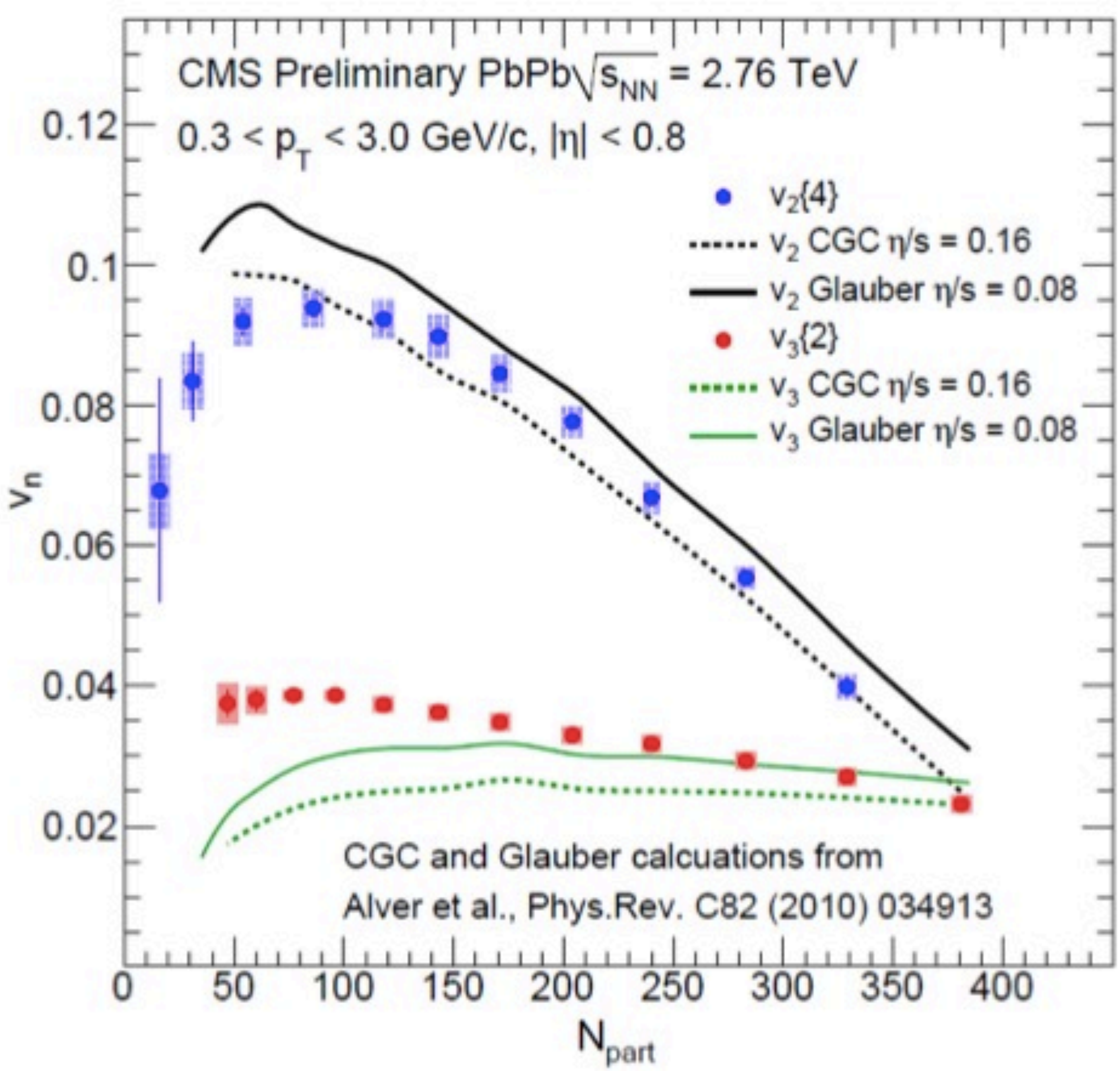
$\eta/s=\hbar/4\pi k_B \approx 0.08$ in natural units

Kovtun Son Starinets hep-th/0405231

Where is the model dependence in hydro calculations?

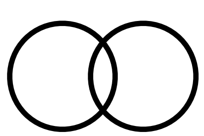
- Initial conditions: *We use two simple models called Glauber and CGC*
- Shear viscosity to entropy ratio η/s (assumed constant for simplicity): *For a given choice of initial conditions, it is tuned to fit RHIC data: 0.16 for CGC, 0.08 for Glauber*
- To a lesser extent, viscous corrections to the momentum distribution at freeeze-out

Hydro prediction (v_2 and v_3) versus 1st CMS data

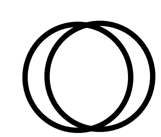


Julia Velkowska, plenary talk at QM2011

Luzum, arXiv:1011:5173

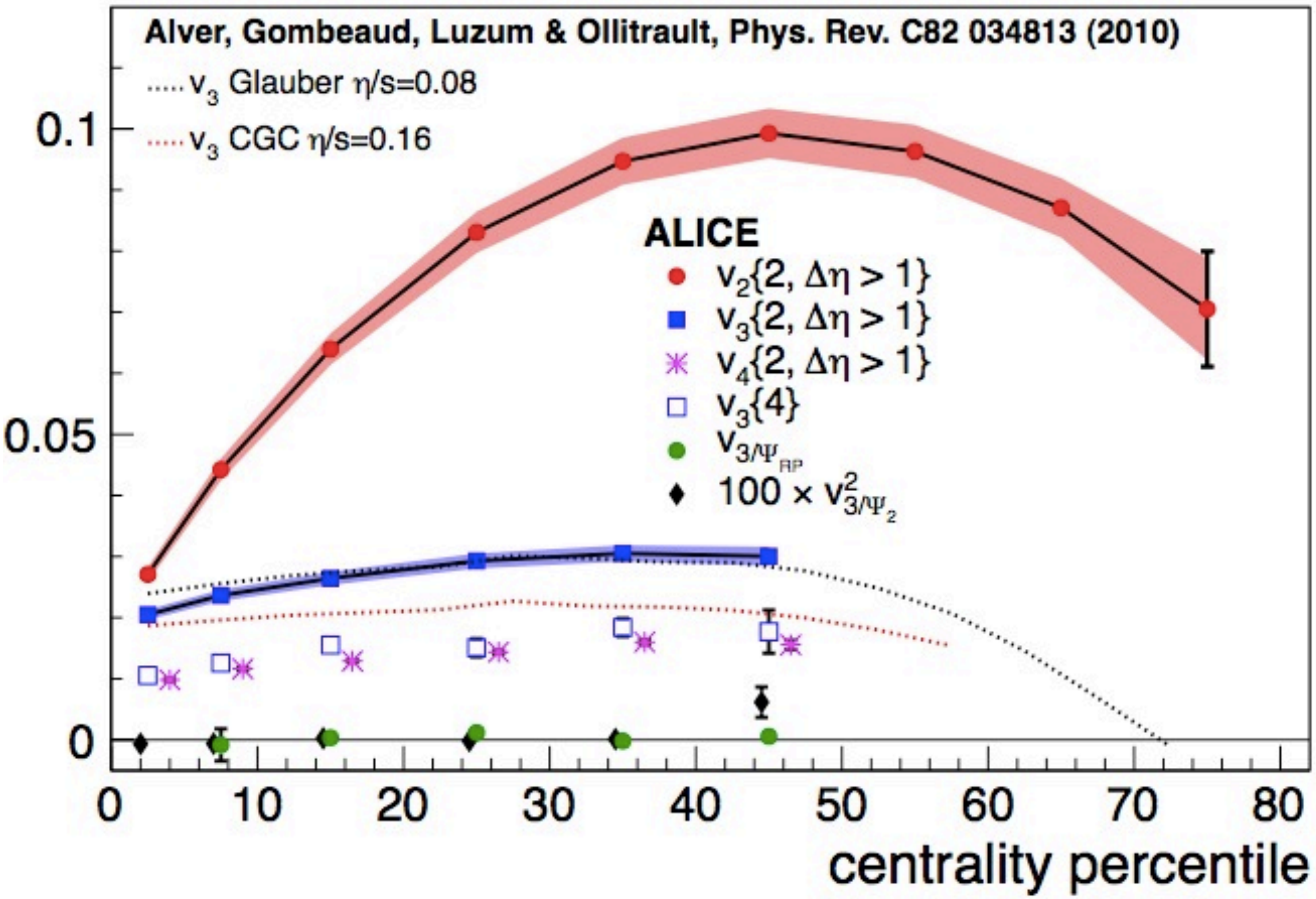


peripheral



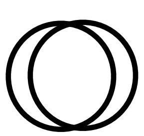
central

Hydro prediction for v_3 versus 1st ALICE data

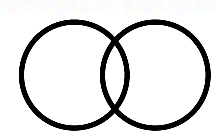


Raimond Snellings,
plenary talk
at QM2011

ALICE,
arXiv:1105.3865
[nucl-ex]

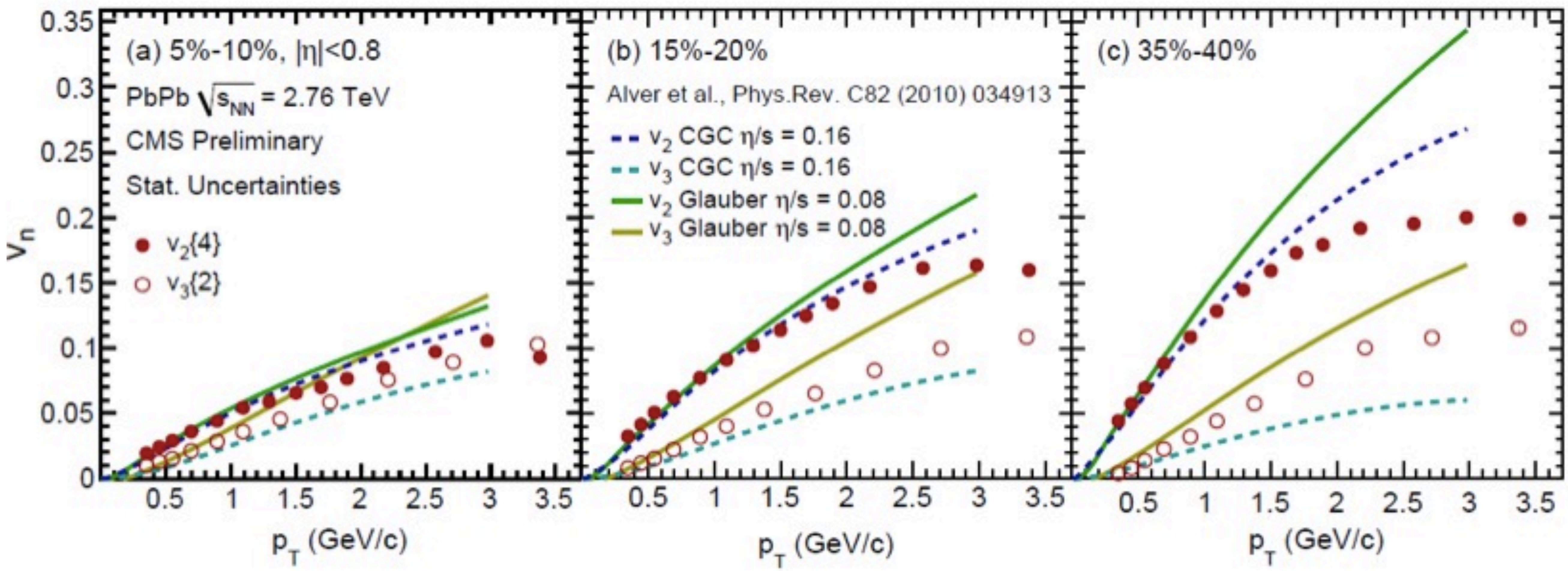


central



peripheral

More details: dependence on particle momentum



Julia Velkowska, plenary talk at QM2011

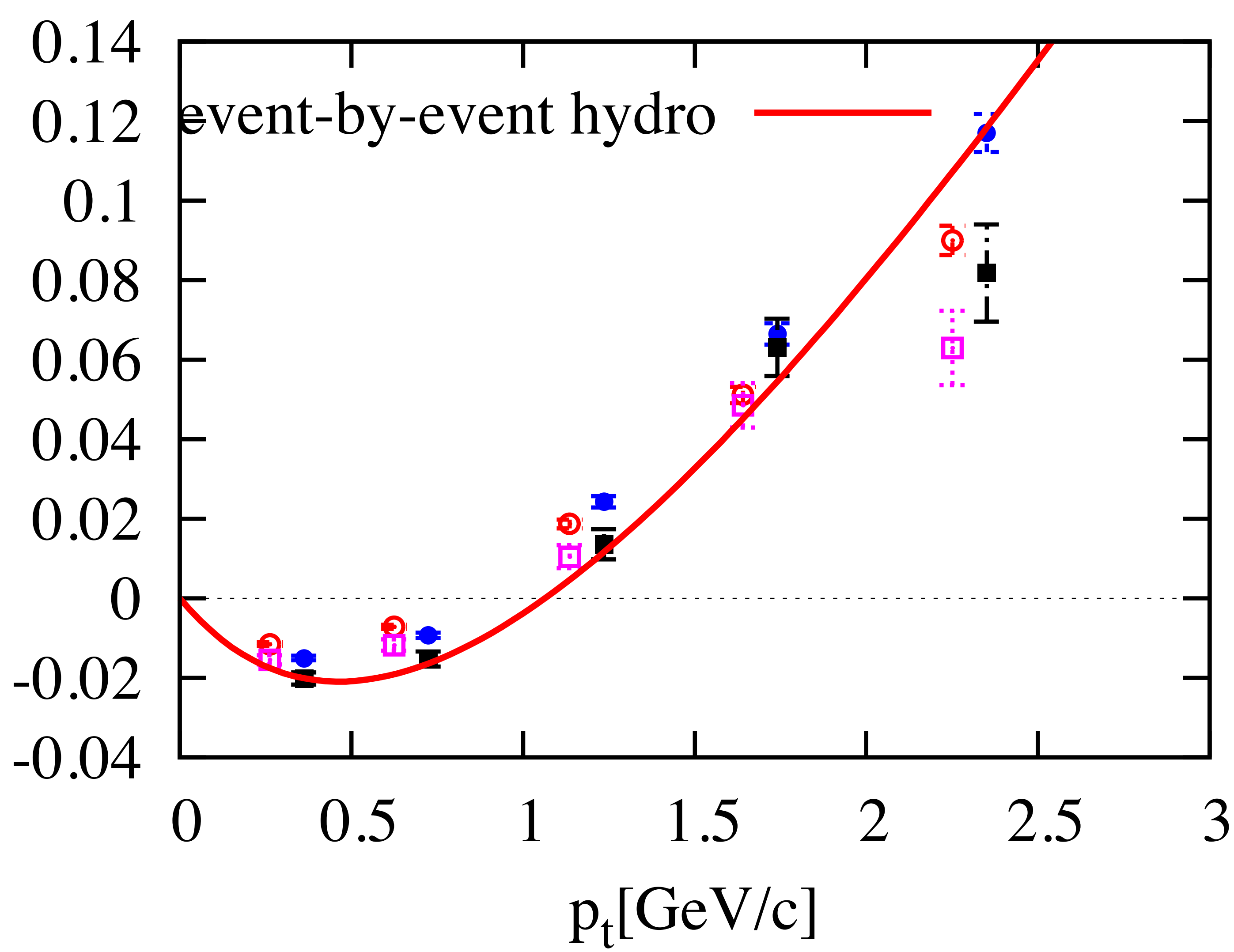
Hydrodynamics captures the magnitude, the centrality dependence and the momentum dependence of both elliptic and triangular flow.

v_1 from fluctuations not yet measured!

Extracted from 2-particle correlation data at RHIC

Luzum JYO, Phys. Rev. Lett. 106:102301 (2011)

STAR arXiv:1010.0690



Well reproduced by ideal hydrodynamics

Gardim Grassi Hama Luzum JYO

arXiv:1103.4605

Conclusions

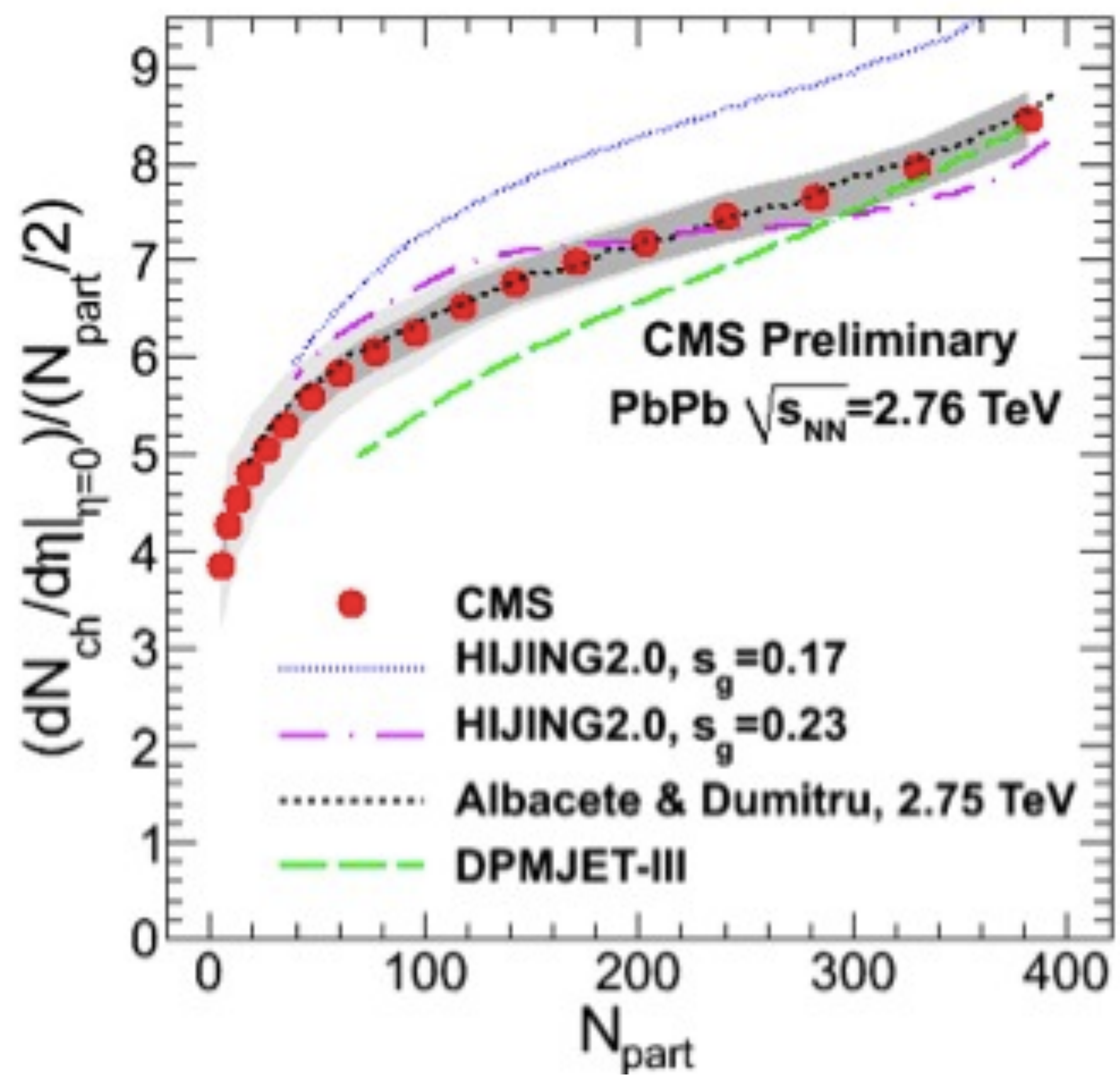
- Ultrarelativistic heavy-ion collisions produce a lump of fluid, with an extremely low viscosity/entropy, characteristic of a strongly-coupled plasma.
- Quantum fluctuations+flow+viscous damping generate the anisotropies observed in the little bang. This is very similar to the mechanism driving CMB (cosmic microwave background) anisotropies in big bang cosmology.
- Soft physics in heavy-ion collisions is largely understood from first principles. Room for progress in our understanding of "initial state" and fluctuations.

Backup slides

Models for the multiplicity

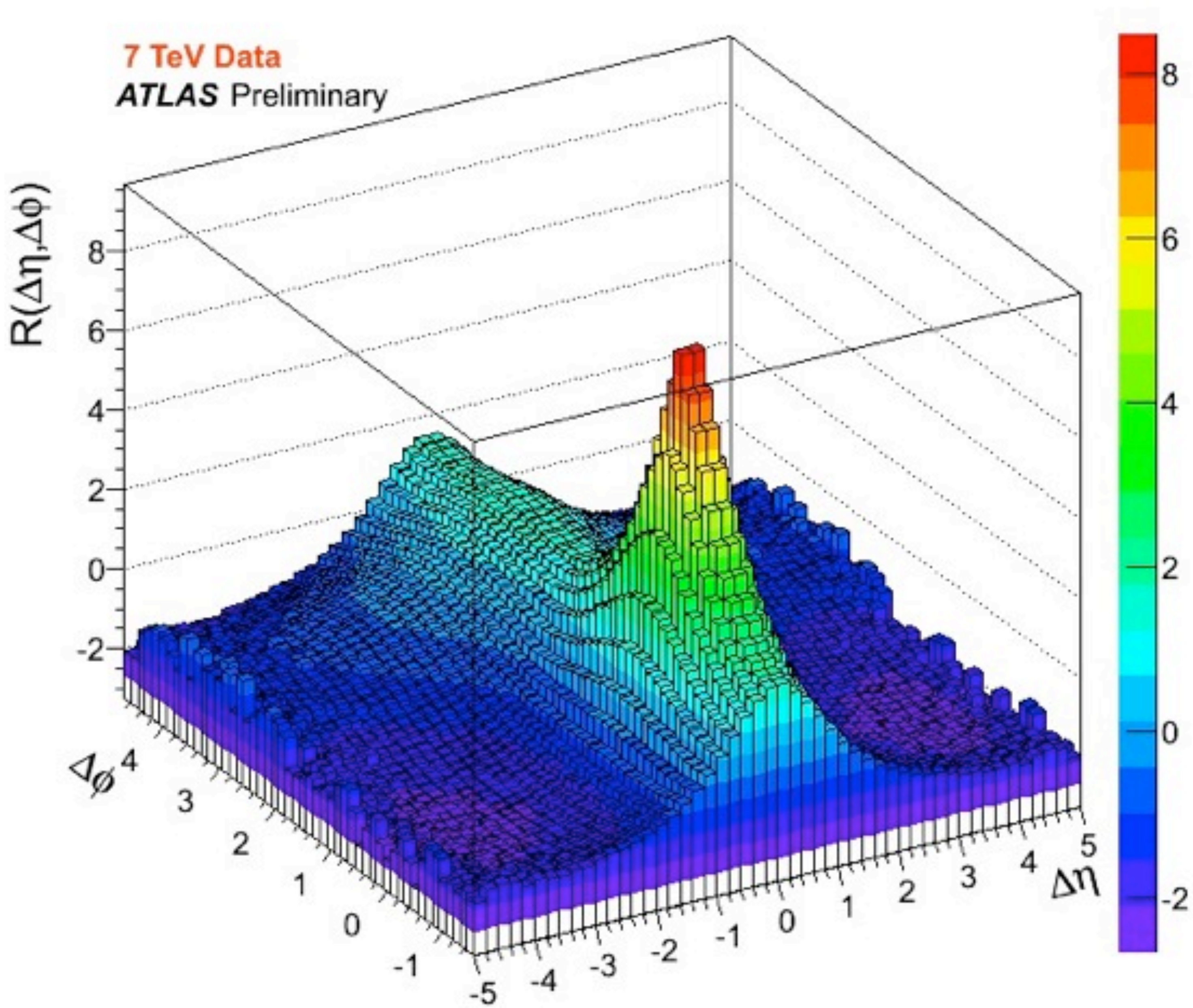
The increase of particle multiplicity from RHIC to LHC was accurately predicted using evolution equations from perturbative QCD (running coupling BK)

More generally, properties of the initial state can be studied within a perturbative framework, generally known as CGC (color glass condensate)

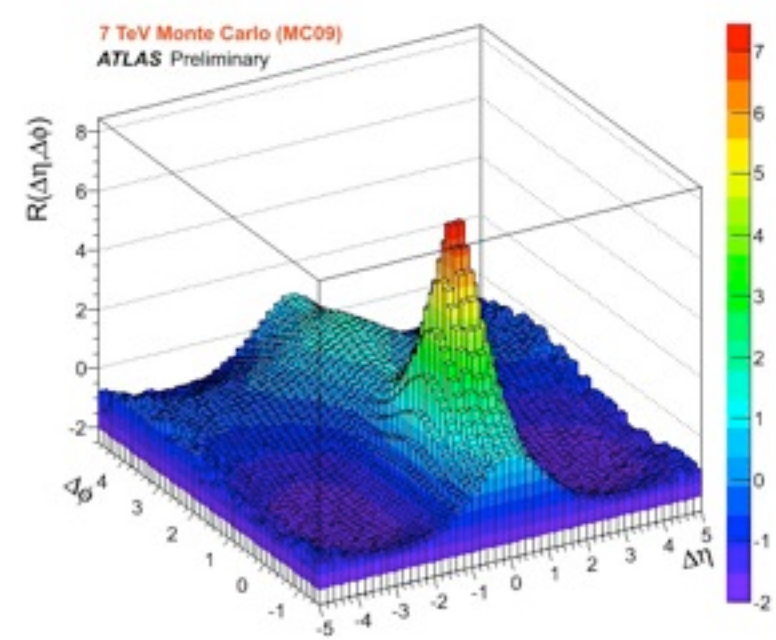


(B. Wyslouch, talk at Quark Mater 2011)

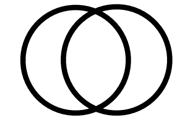
Correlations in pp @ LHC

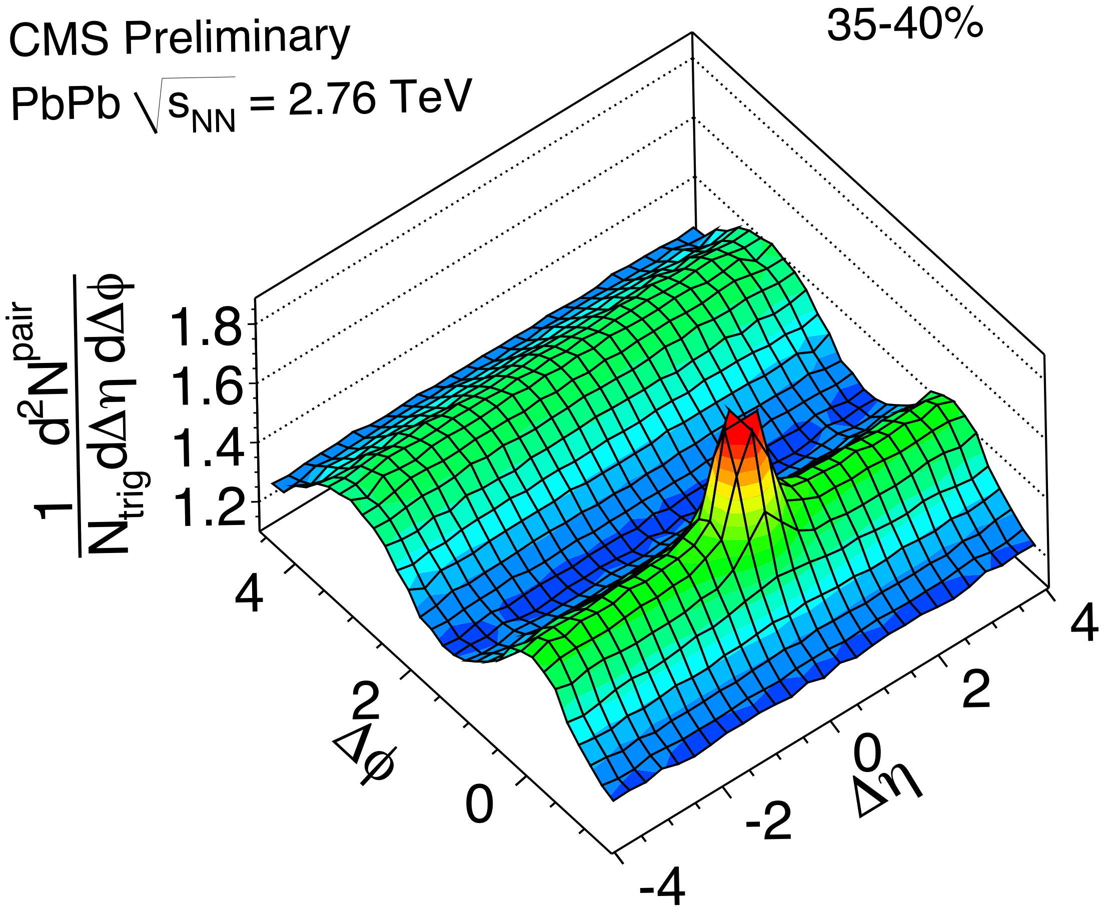


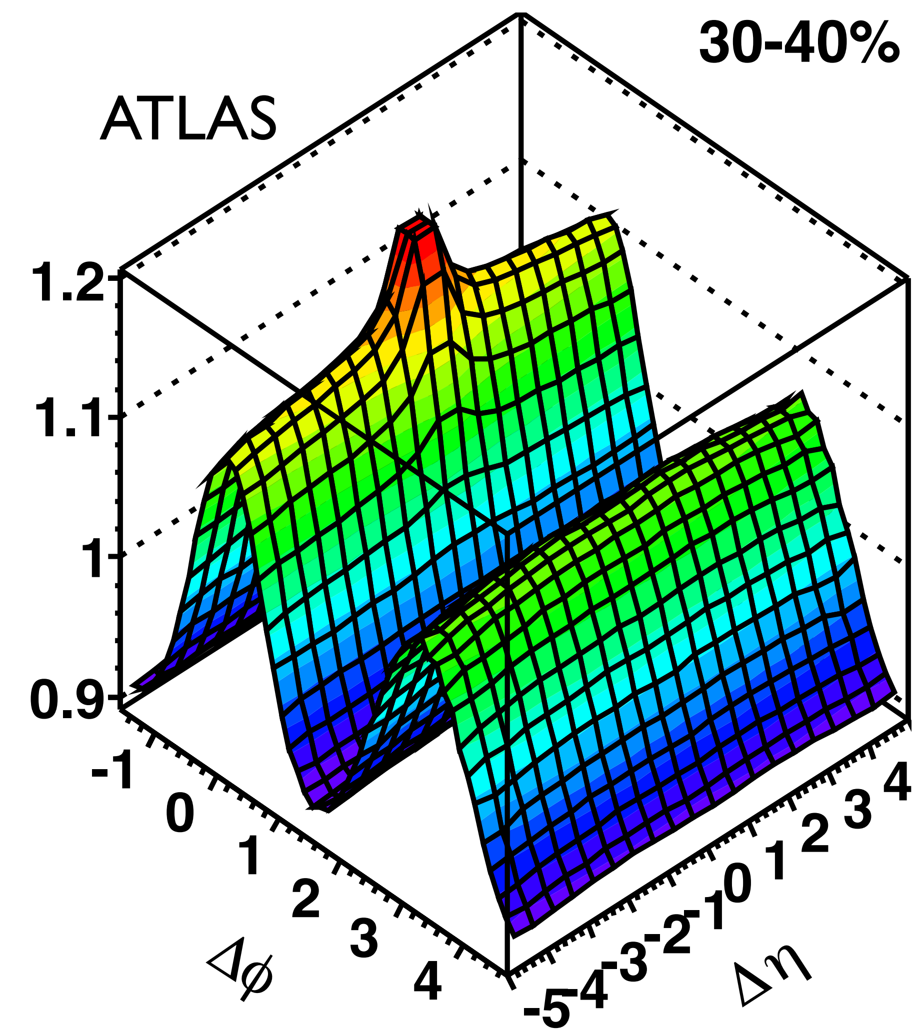
proton proton collisions at LHC:
all correlations are at small Δη
qualitatively reproduced by models (Pythia)



Correlations in Pb-Pb @ LHC

(semicentral) 



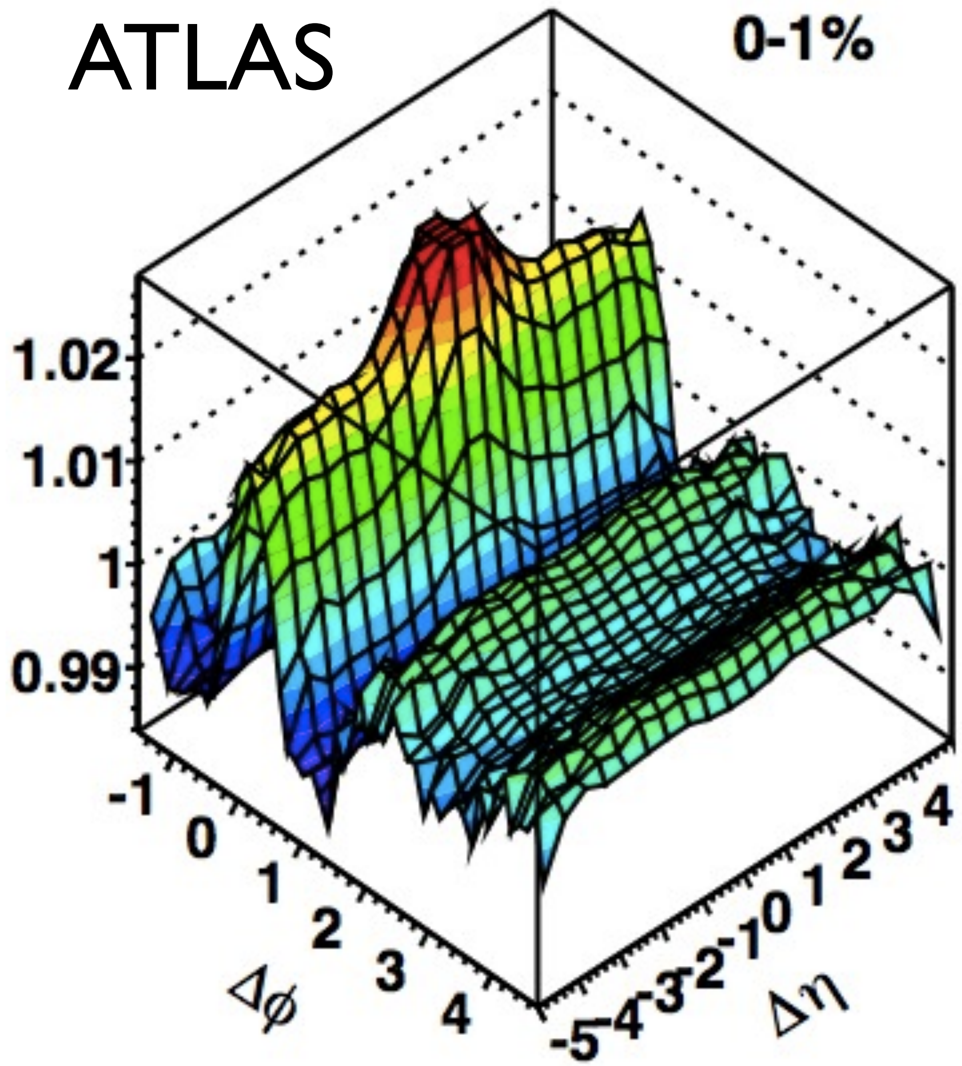


Additional correlation, independent of Δη

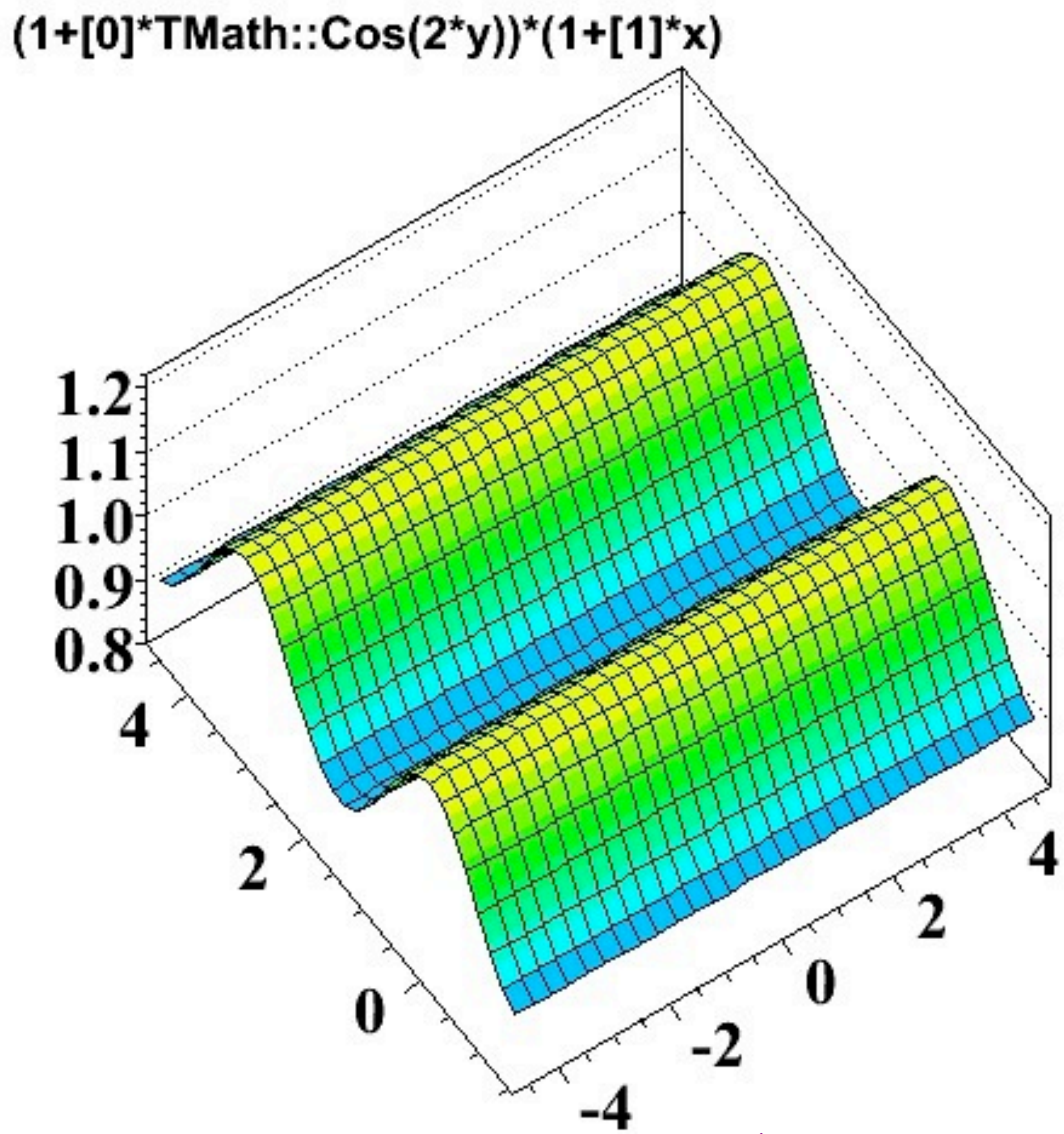
not quite apples-to-apples: restricted p_t interval here, [2,3] GeV for ATLAS and [2,4][4,6] CMS

Correlations in central Pb-Pb

central collisions are Φ symmetric, except for fluctuations!



Jia @ATLAS, talk at QM2011



Wei Li@CMS, talk at QM2011

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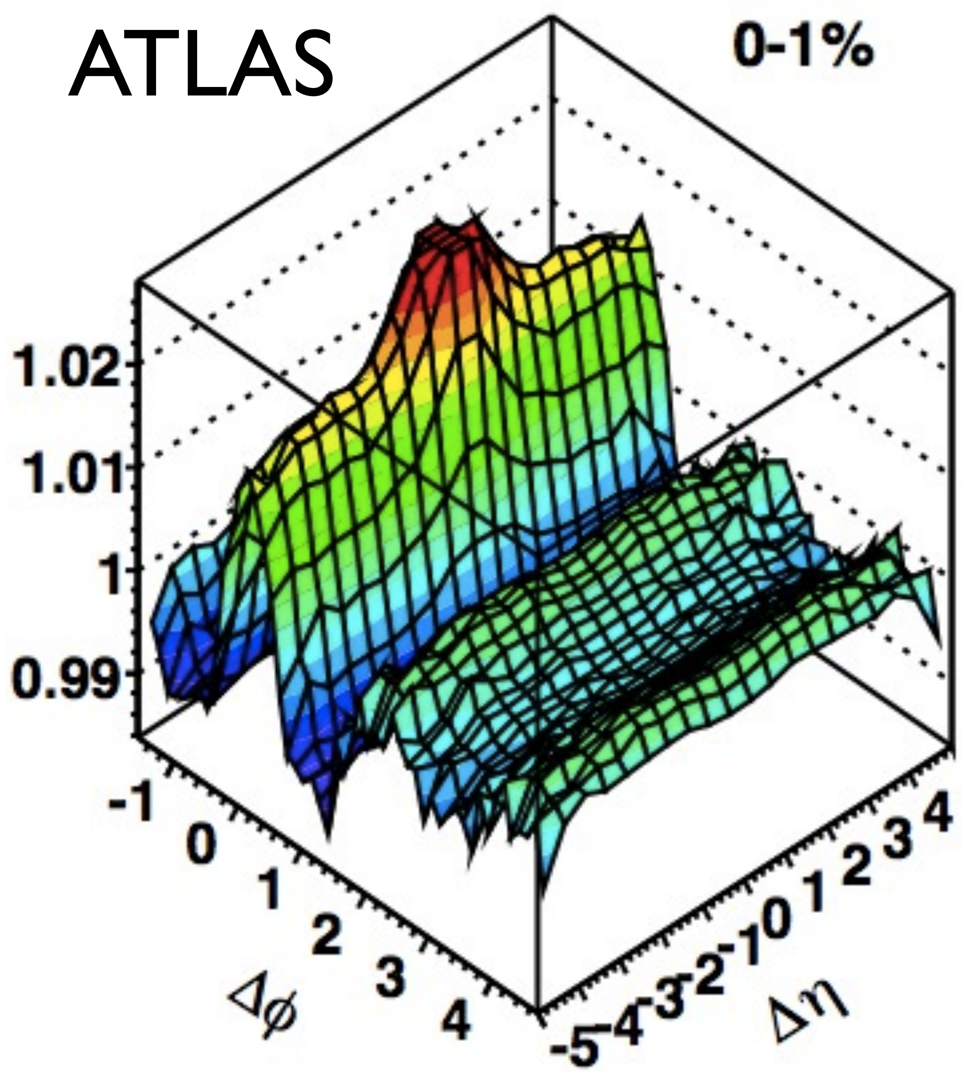

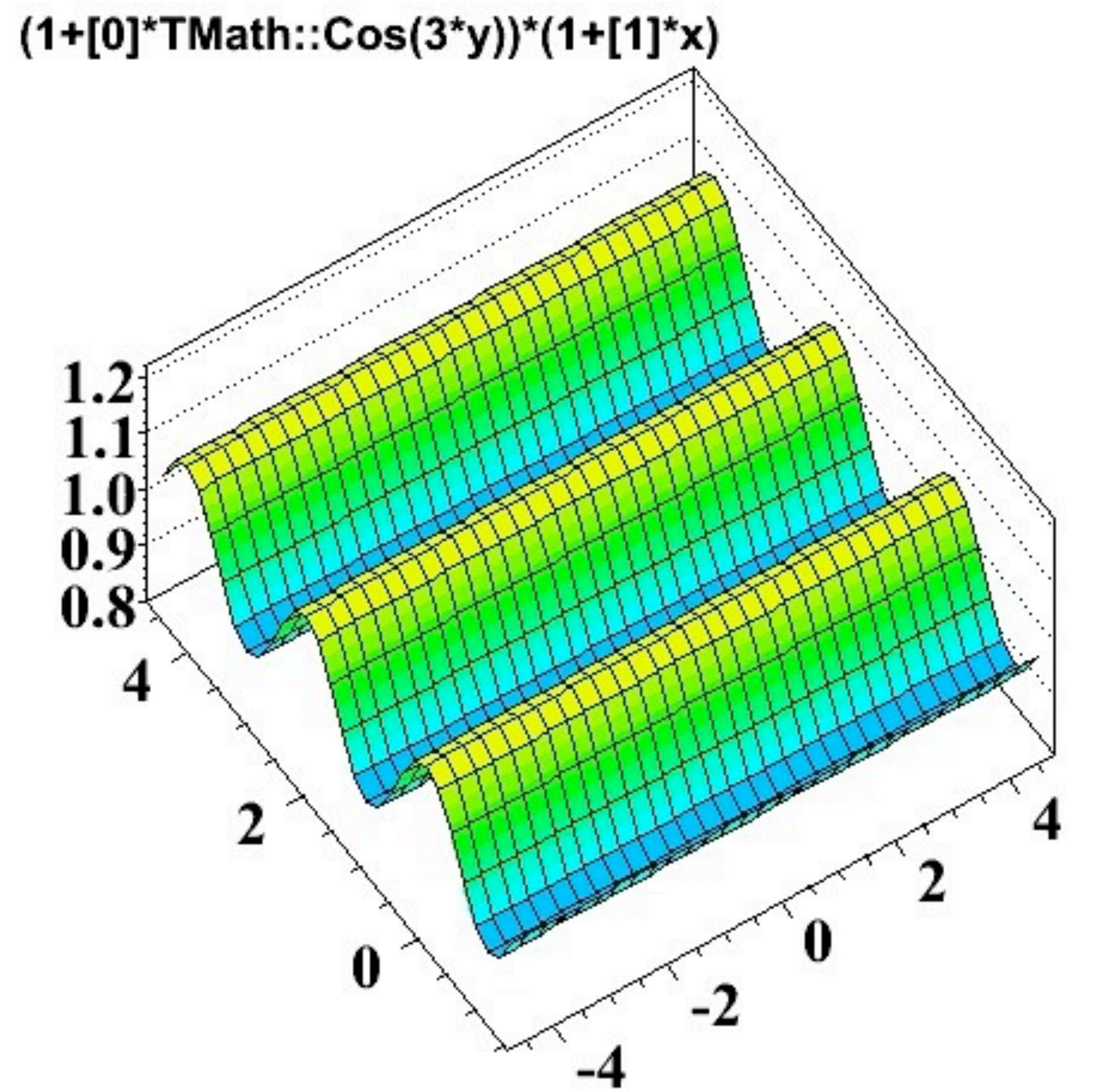

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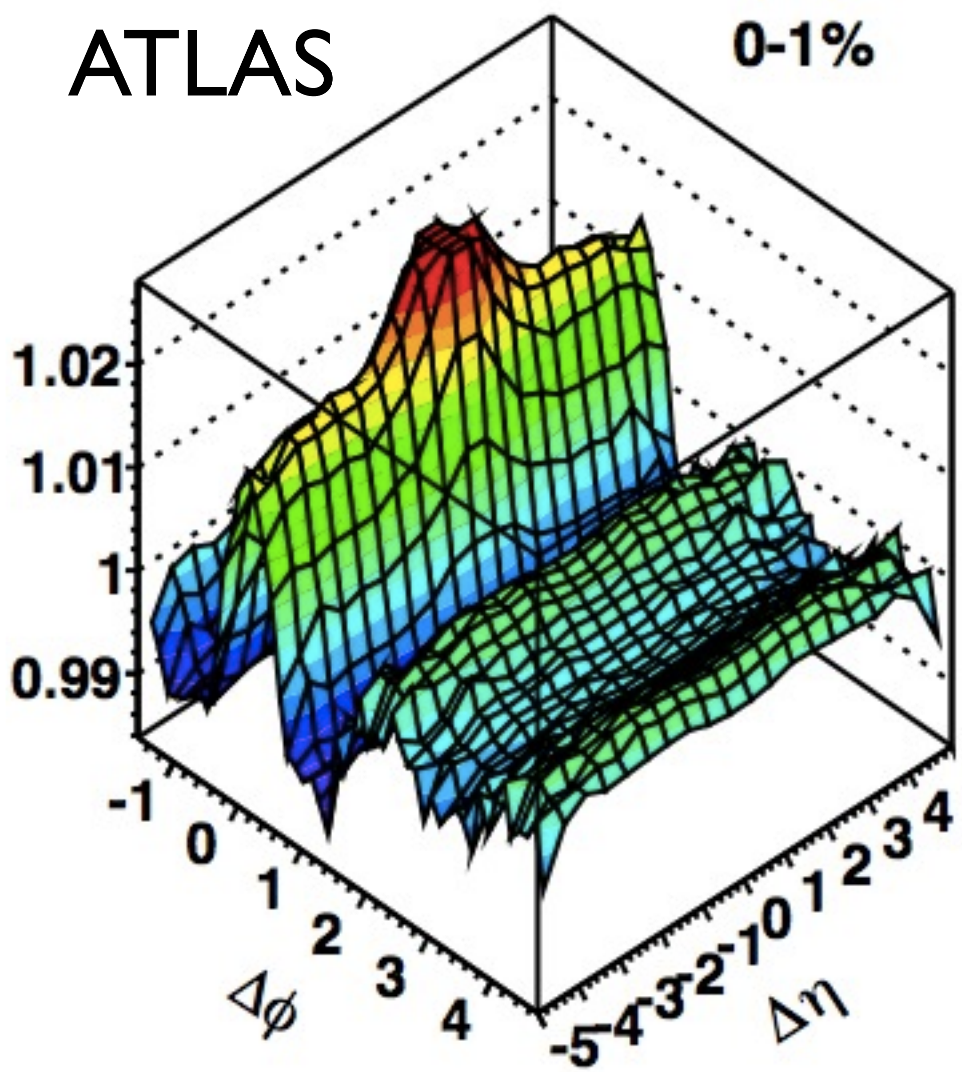

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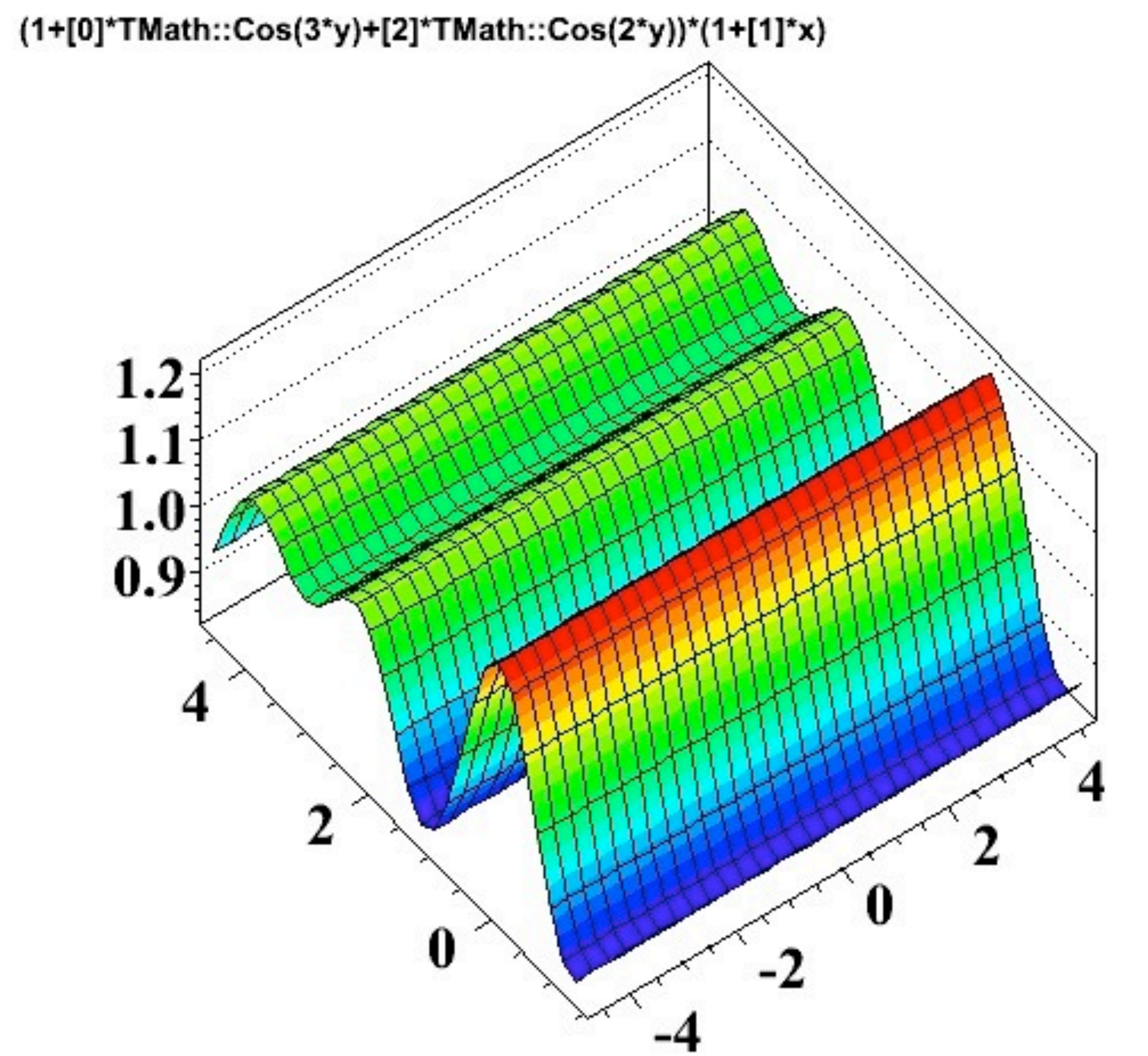
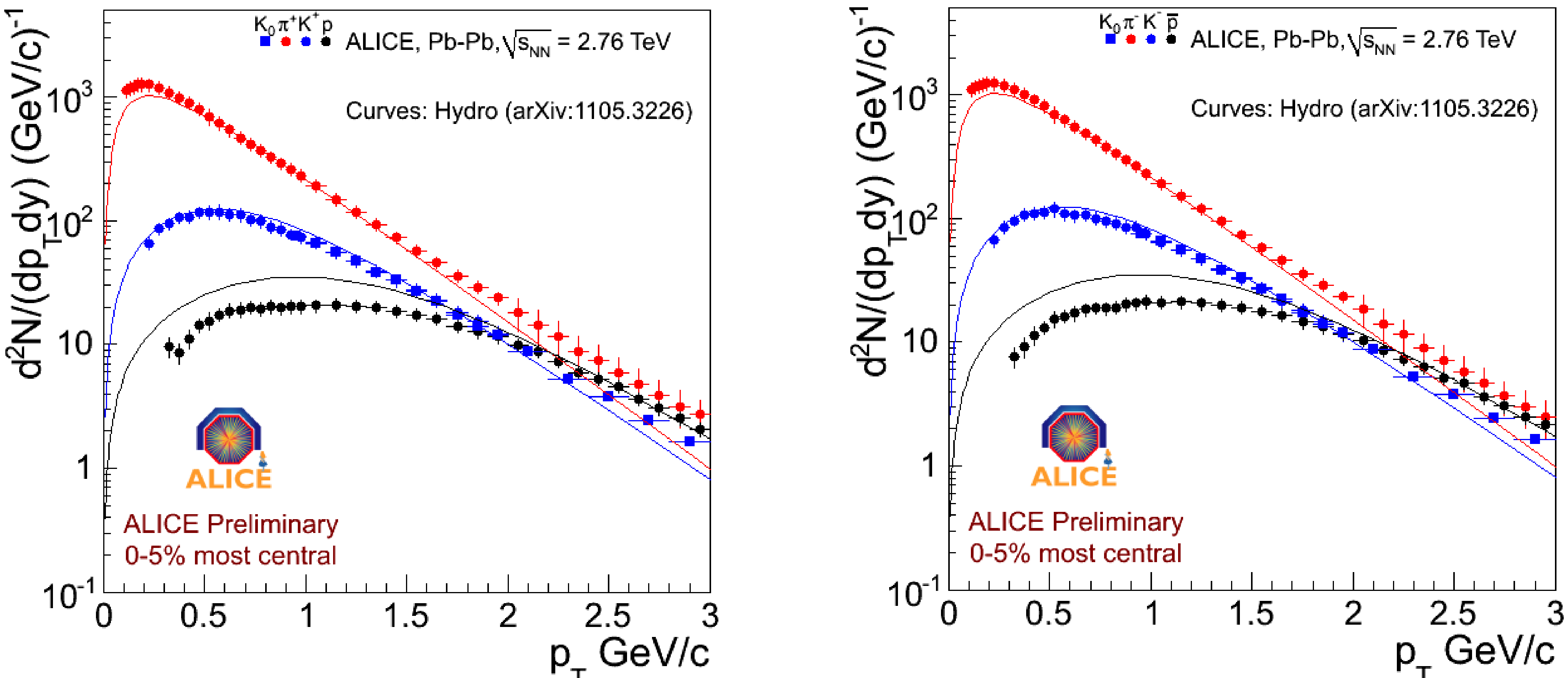


Wei Li@CMS, talk at QM2011

Identified particle spectra
(Michele Floris, talk at Quark Matter 2011)

positive | negative



At RHIC: STAR proton data generally not feed-down corrected.

Large feed down correction

➔ Consistent picture with feed-down corrected spectra

At LHC: ALICE spectra are feed-down corrected

- Harder spectra, flatter p at low pt
- Strong push on the p due to radial flow?

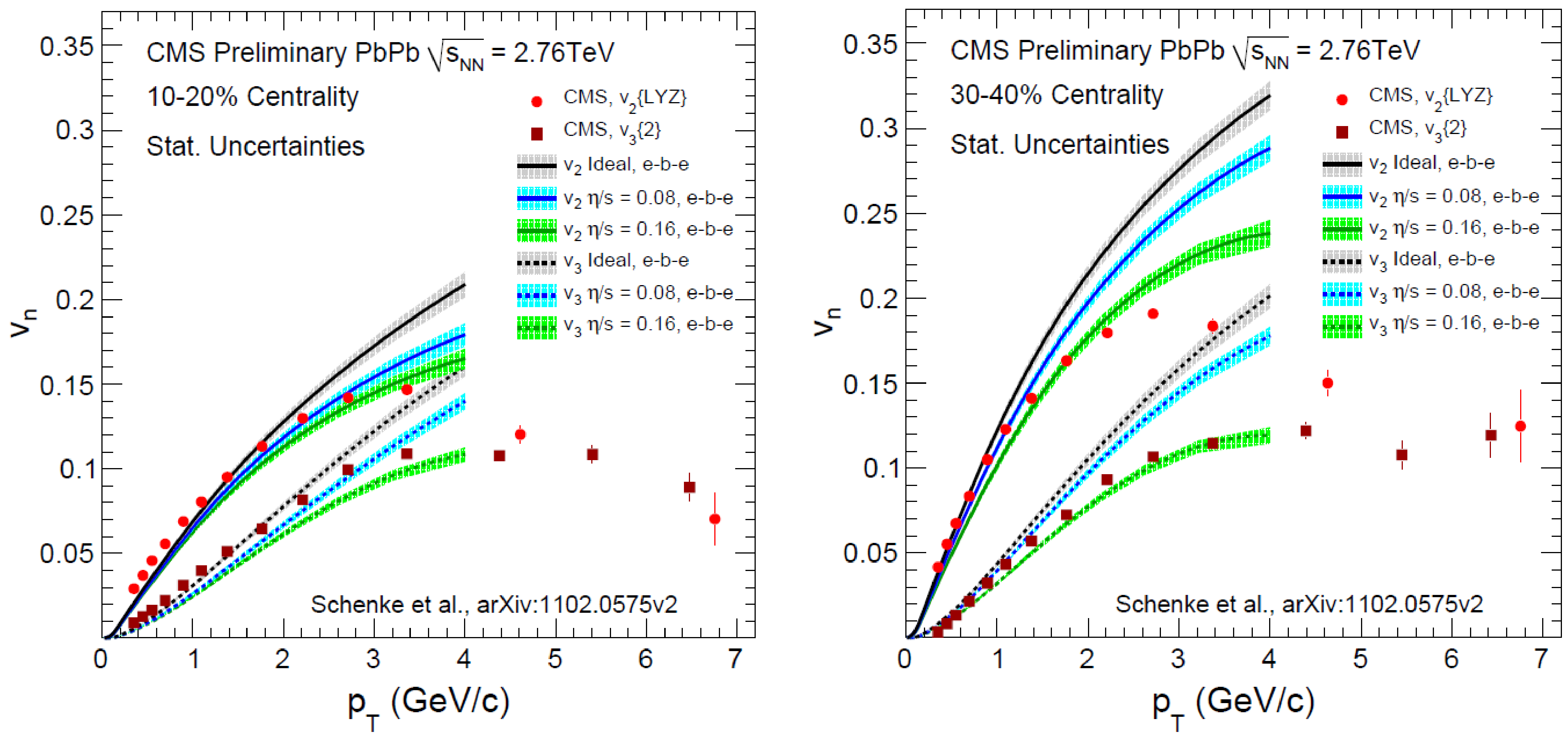
STAR, PRL97, 152301 (2006)

STAR, PRC 79 , 034909 (2009)

PHENIX, PRC69, 03409 (2004)

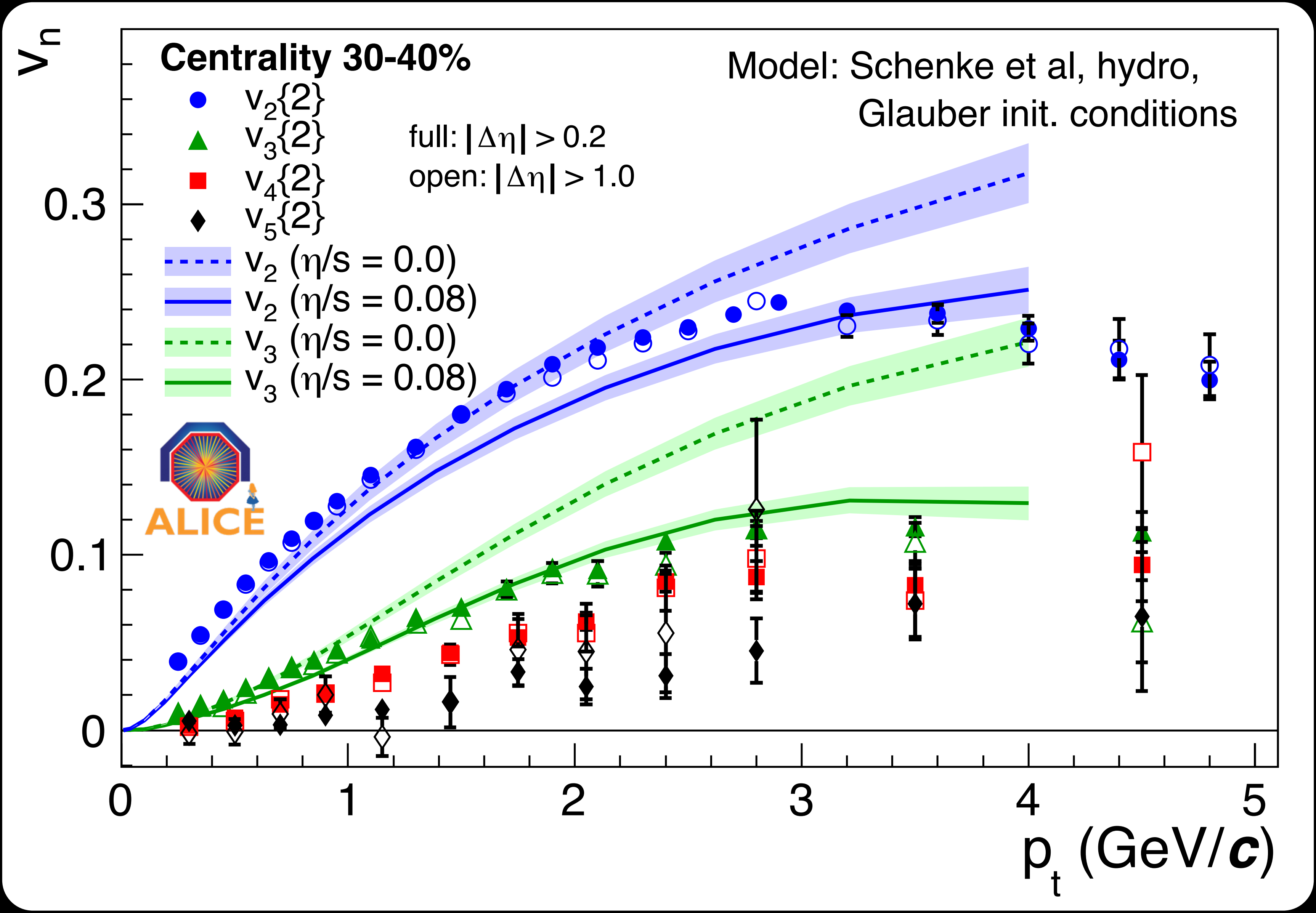
$v_2(p_T)$ and $v_3(p_T)$: sensitivity to η/s

Glauber initial conditions



- v_2 and v_3 together have better sensitivity
- The centrality dependence adds further constraints

Other Harmonics



ALICE Collaboration, arXiv:1105.3865

see presentation A. Bilandzic

The overall dependence of v_2 and v_3 is described

However there is no simultaneous description with a single η/s of v_2 and v_3 for Glauber initial conditions

Flow vs. non-flow correlations

Collective effects

Flow-related effects imply correlation through a plane of symmetry ψ_n.

Flow-dominated correlations should factorize:

$$\begin{aligned} \langle \cos n\Delta\varphi \rangle &= \langle \cos n(\varphi_{trig} - \varphi_{assoc}) \rangle \\ &= \langle \cos n(\varphi_{trig} - \psi_n) \rangle \langle \cos n(\varphi_{assoc} - \psi_n) \rangle \\ &= v_n(p_{Ttrig})\, v_n(p_{Tassoc}) \end{aligned}$$

Pair coefficients are just products of familiar single-particle v_ns.

Jet-related effects

A few energetic particles are highly correlated by fragmentation, but not directly through ψ_n.

Caveat: there can be indirect correlations, i.e. length-dependent quenching.
Would be largest w.r.t. ψ_2 since it reflects the collision geometry.

The collectivity relation

$$\langle \cos n\Delta\varphi \rangle \stackrel{?}{=} v_n(p_{Ttrig})\, v_n(p_{Tassoc})$$

is a quantitative hypothesis that can be tested!

Global fit of 2-particle Fourier moments

Find best $v_n(p_T)$

Fit <cos nΔφ> for all p_T bins simultaneously

Fit function: $V_{n\Delta} = v_n^t \, v_n^a$.

Fit breaks at high p_T, where jets dominate.

Key idea

If fit matches data

suggests flow-type correlations

If fit diverges

collective description less appropriate.

Transition between cases follows clear trends.