Understanding nucleus-nucleus collisions at the LHC

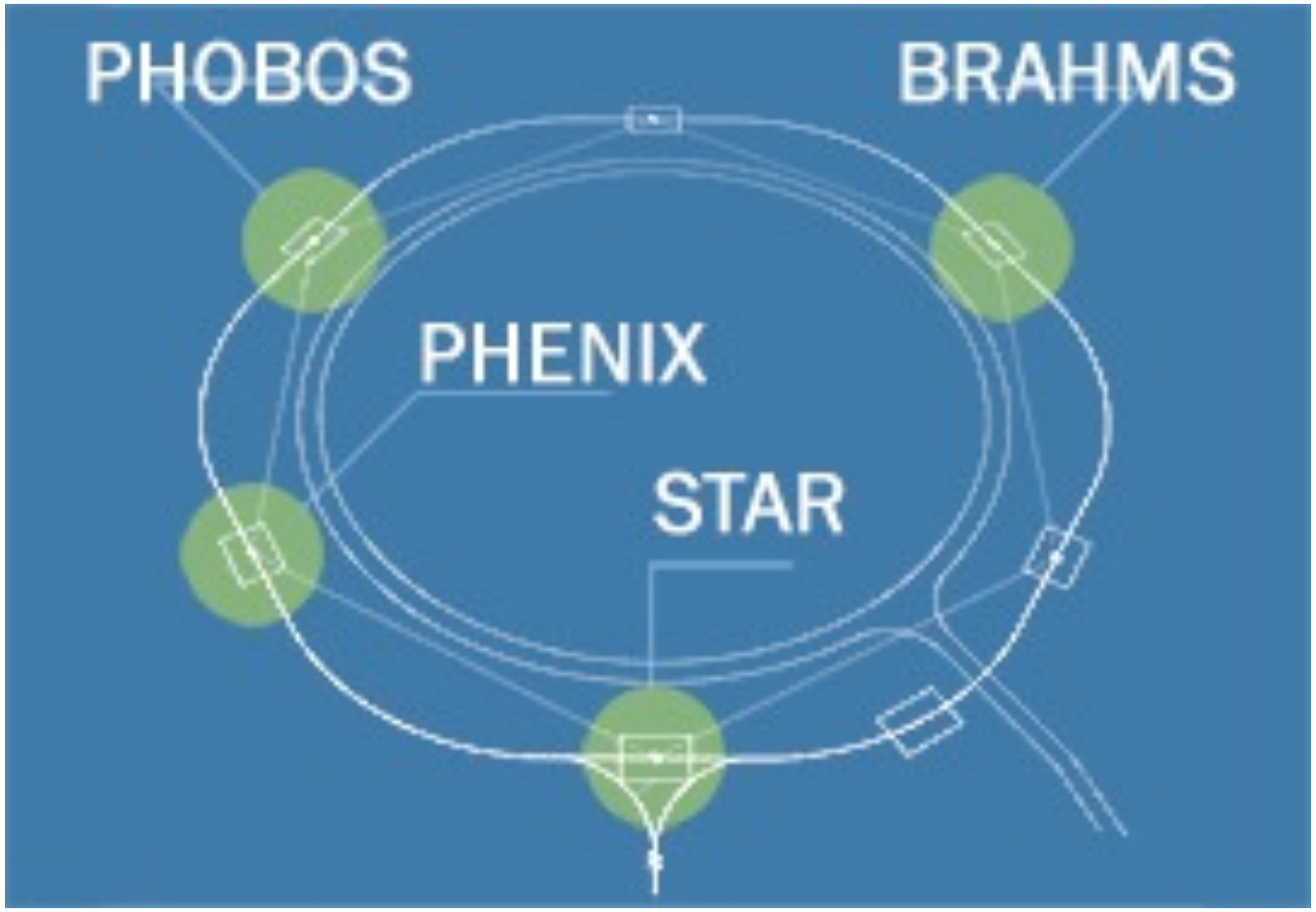
Jean-Yves Ollitrault, IPhT

Seminar, IRFU/SPP, April 10th, 2012

RHIC (Brookhaven), since 2000

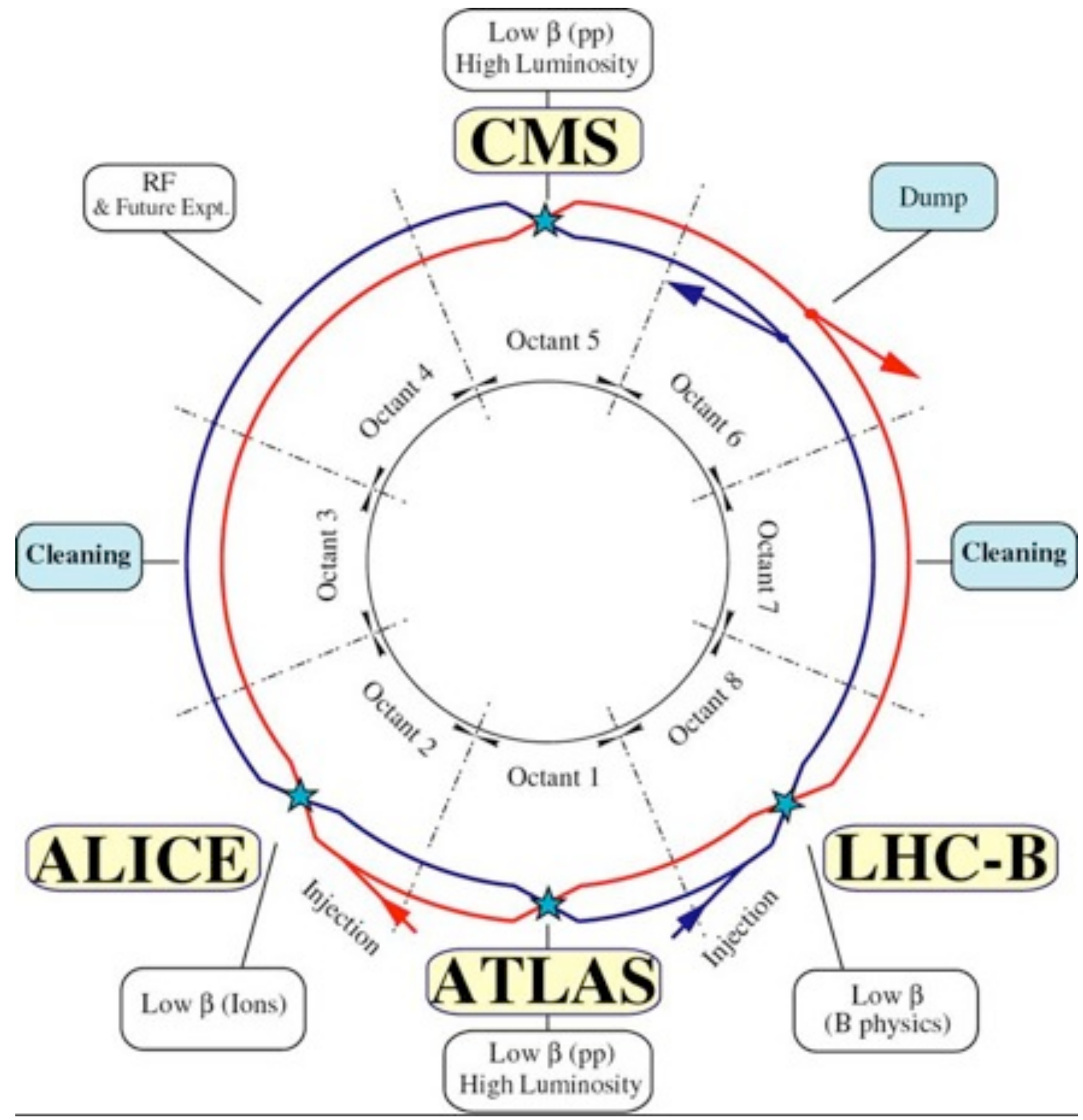
Au-Au collisions (mostly) up to 200 GeV/nucleon pair, now lower energies.

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.



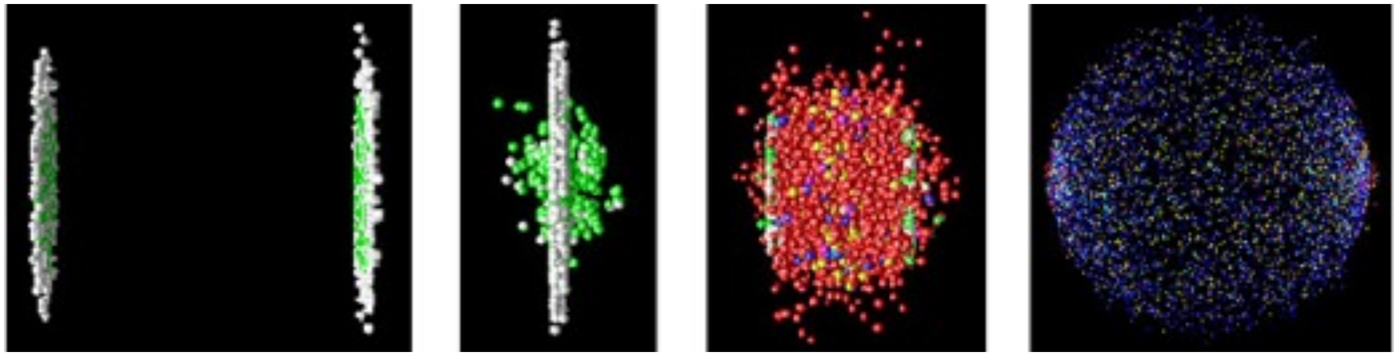
Outline

- Soft probes
  - Why heavy-ion collisions are special: why we are interested in soft physics
  - pair correlations: 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)
- Hard probes
  - from p-p to Pb-Pb collisions: weakly-interacting versus strongly-interacting probes
  - Jet quenching : from leading particles to fully-reconstructed jets
- 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

Hadronization and freeze-out

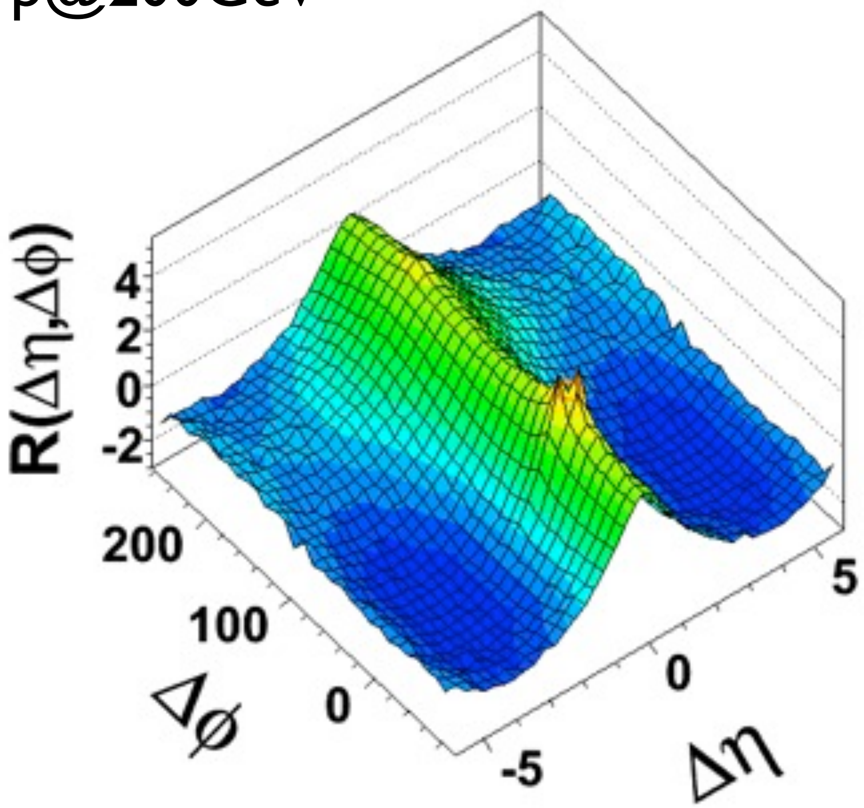
Expansion

Two-particle correlations at RHIC

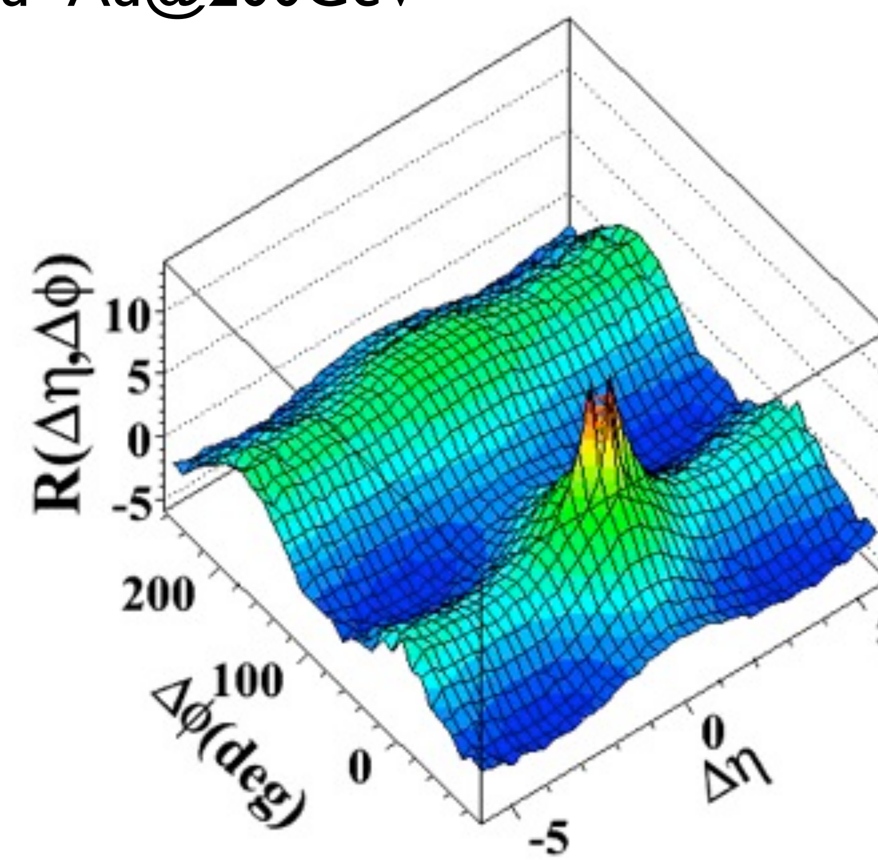
≈ number of particle pairs versus *relative* azimuthal angle ΔΦ and rapidity Δη

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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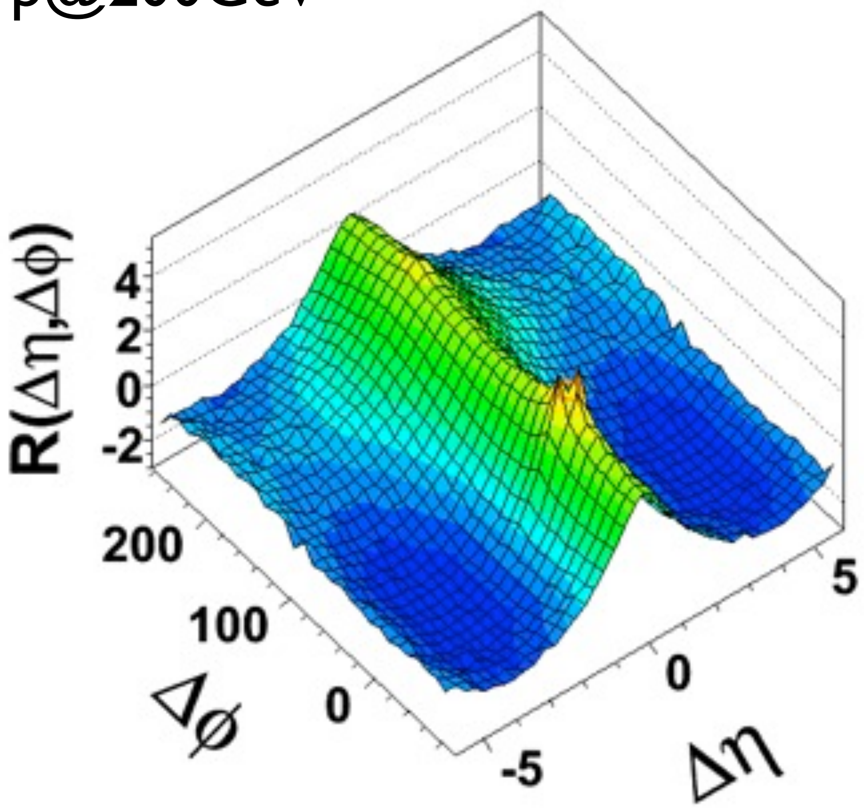

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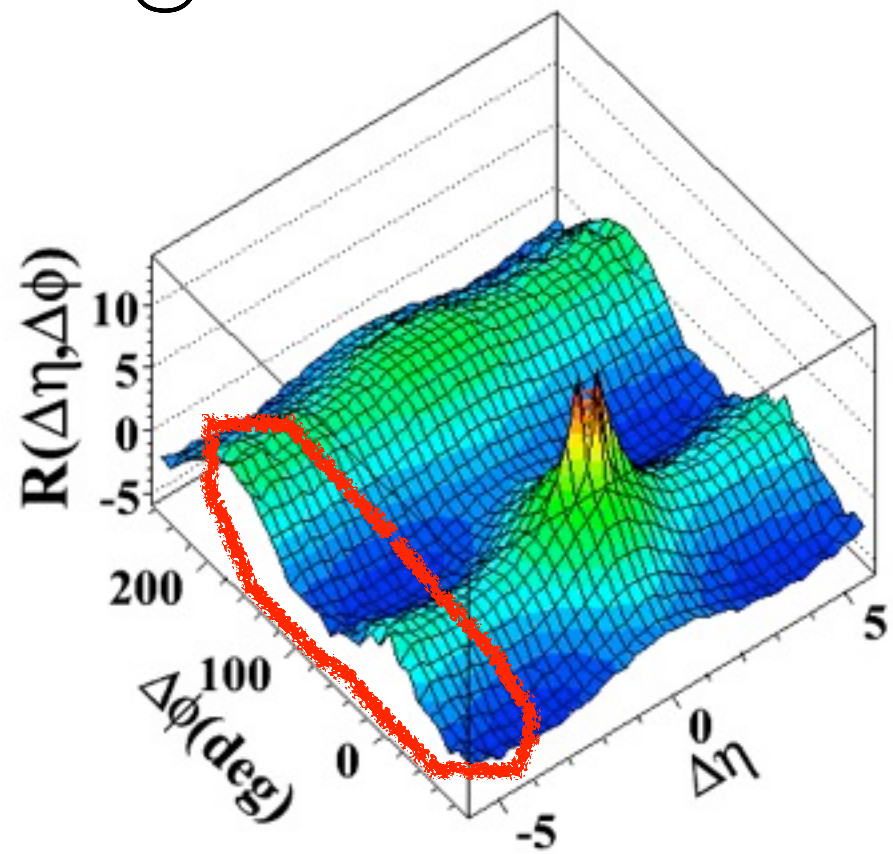

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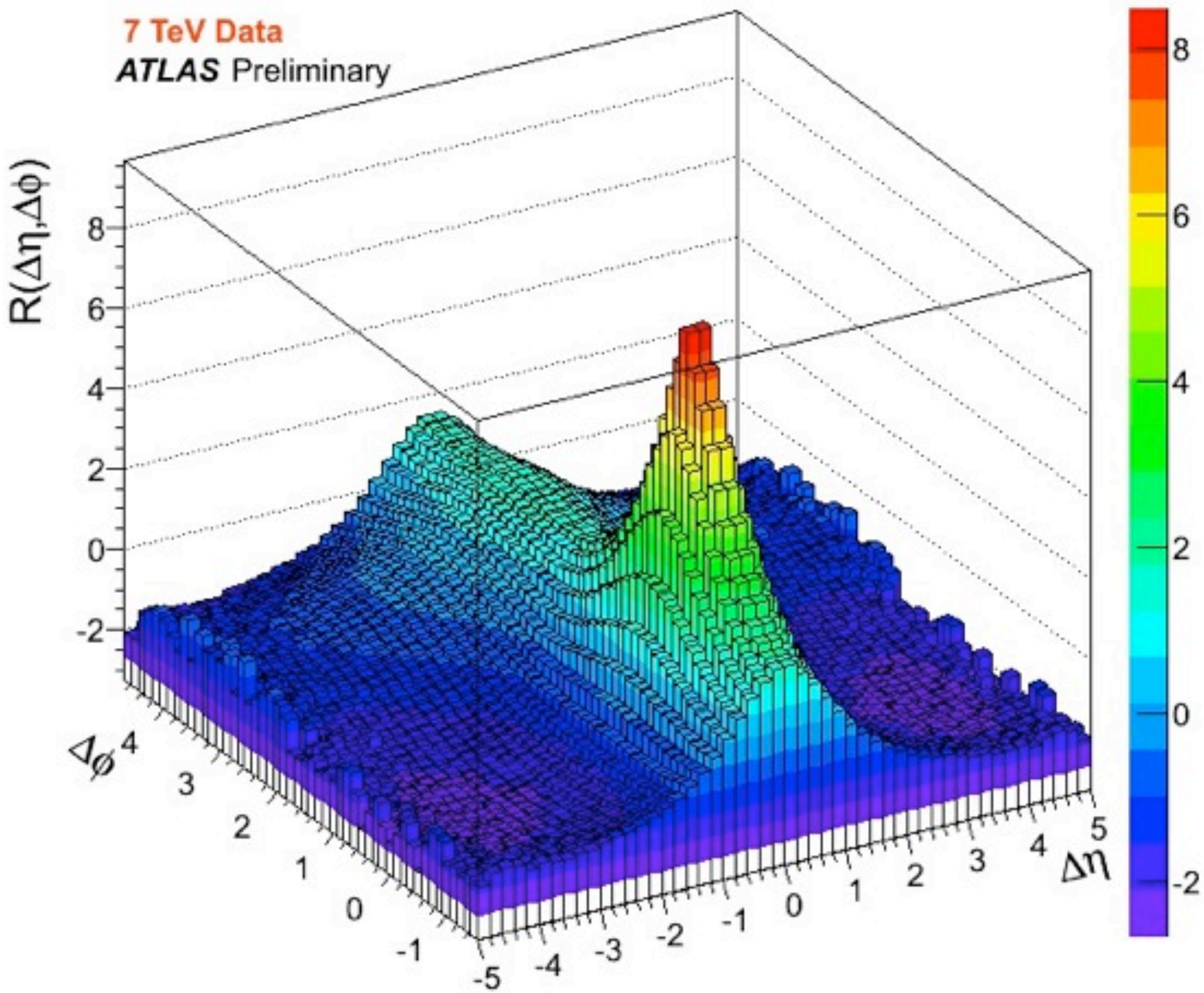
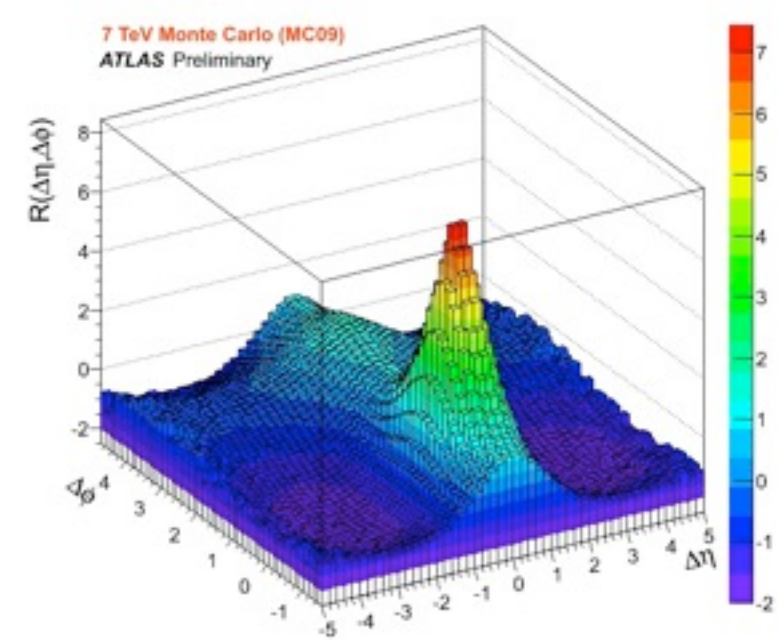
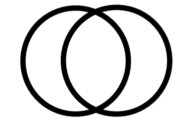
Correlations in pp @ LHC

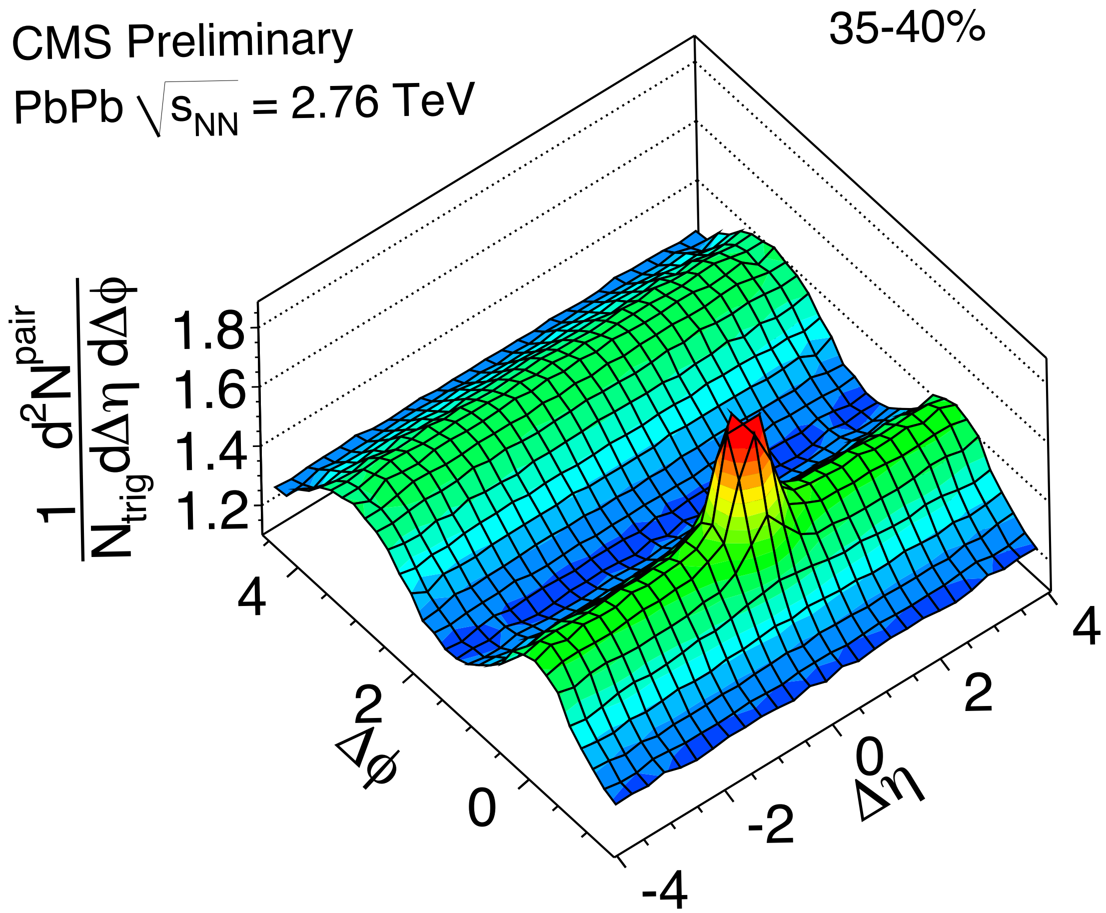


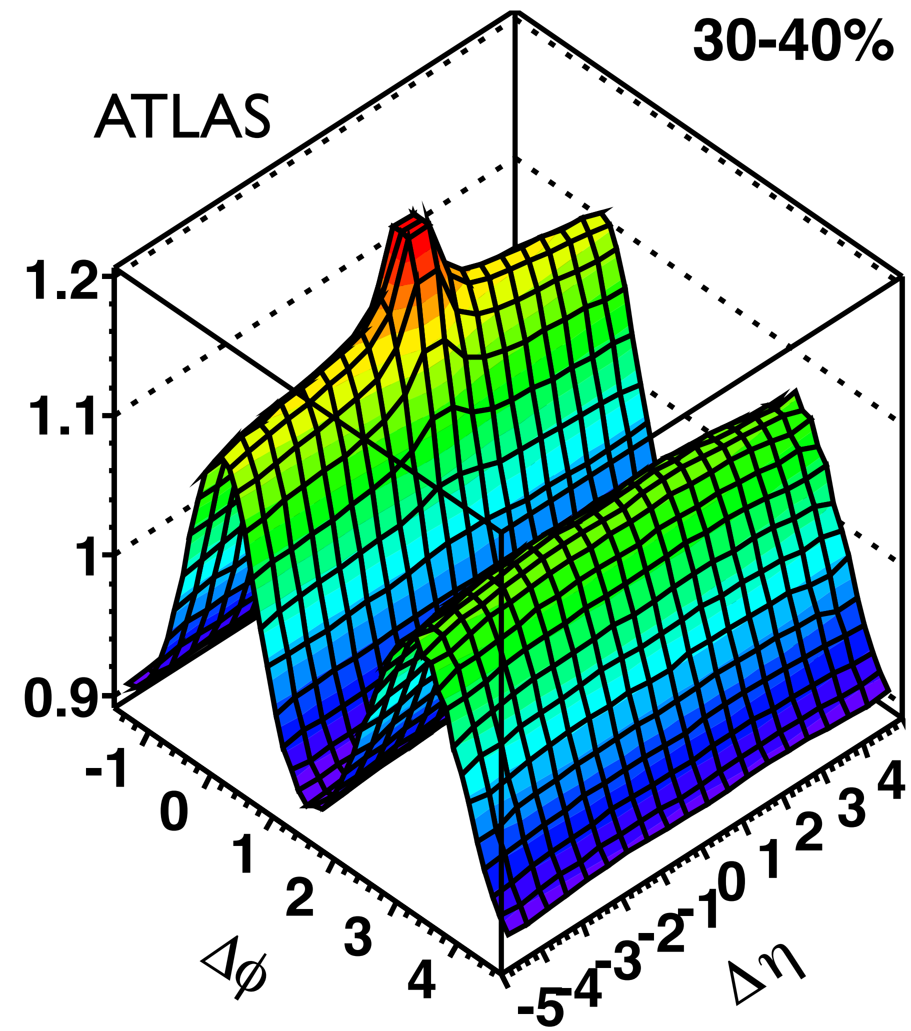
proton proton collisions at LHC:
again, all correlations are at small Δη
qualitatively reproduced by models (Pythia)



Correlations in Pb-Pb @ LHC

(semicentral) 



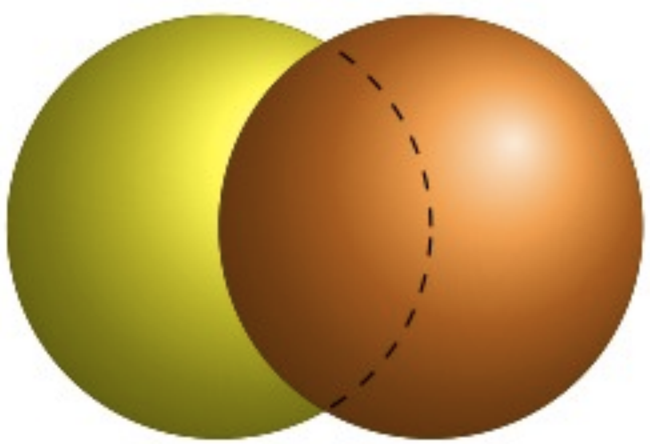


Additional correlation, independent of $\Delta\eta$

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

Collective flow: the old picture

(RHIC, 2000)



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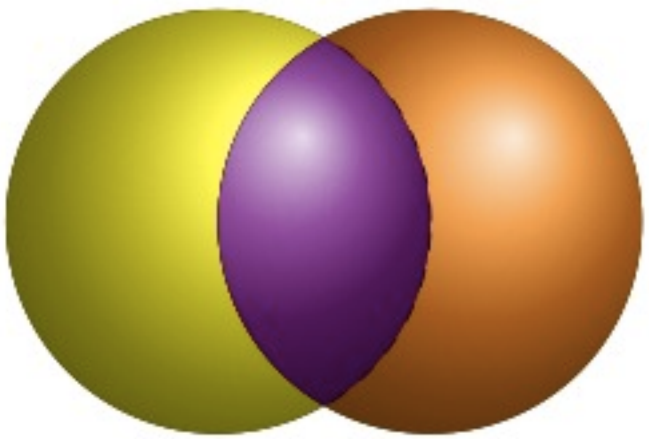

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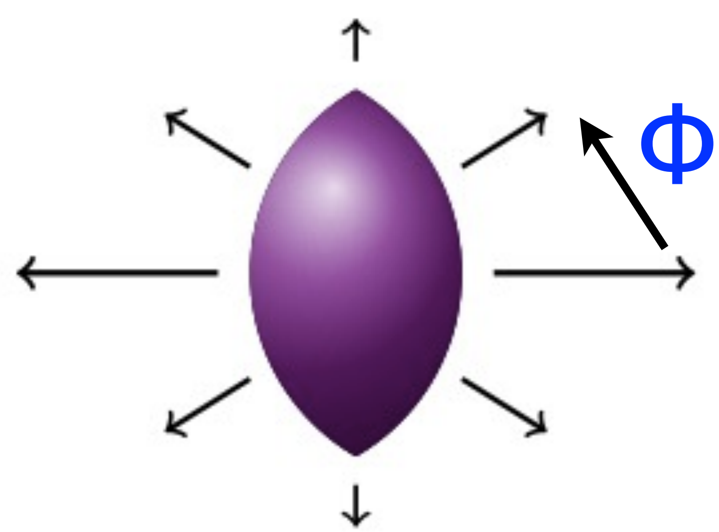

The system thermalizes and expands like a fluid

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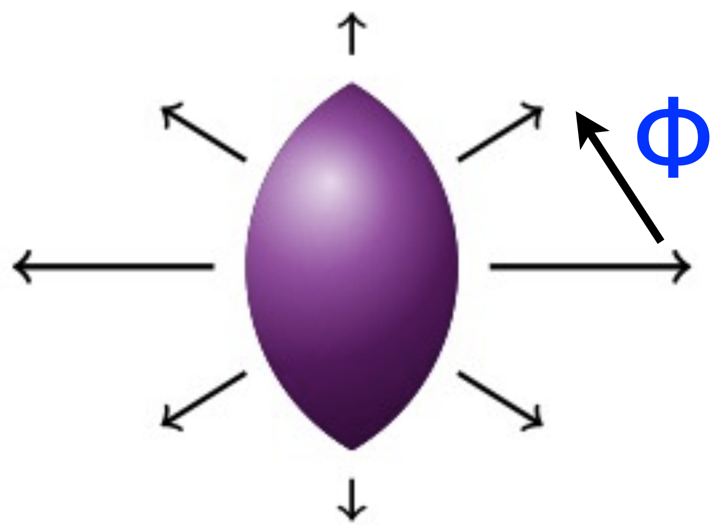


The system thermalizes and expands like a fluid

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, 458 citations

ALICE arXiv:1011.3914, 174 citations

Independent particles explain pair correlations

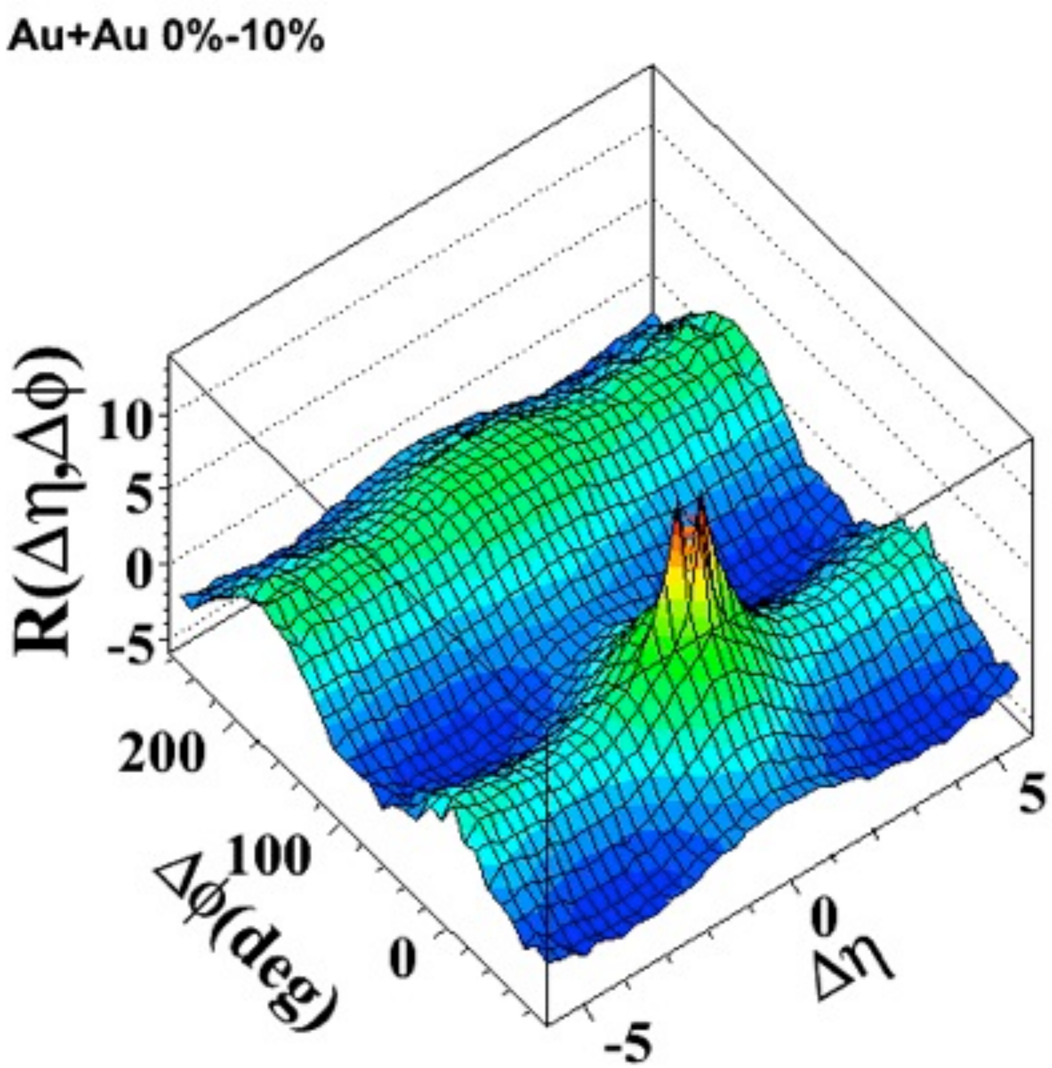
$v_2 = \langle e^{2i\phi} \rangle$ (reference direction $\phi=0$ changes event by event!)

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

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

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

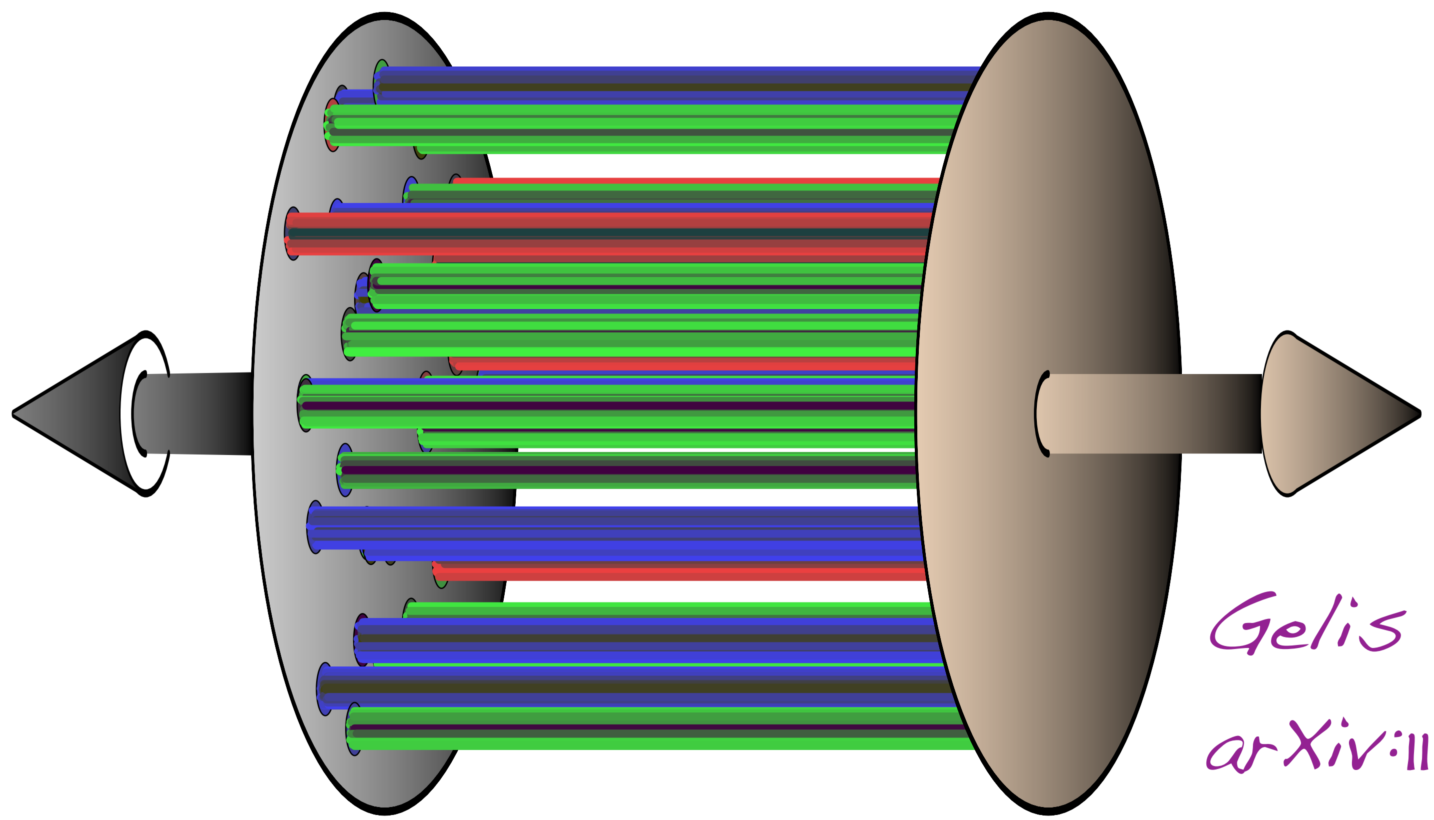
Is v_2 all we see at large $\Delta\eta$?



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

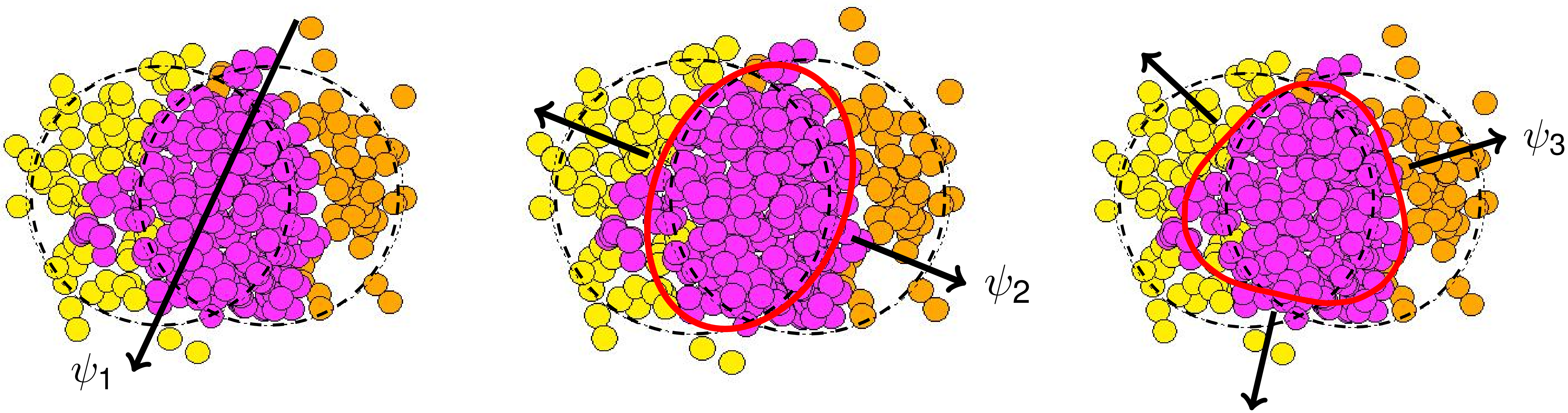
Fluctuations + flow

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 low p_t physics

- 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

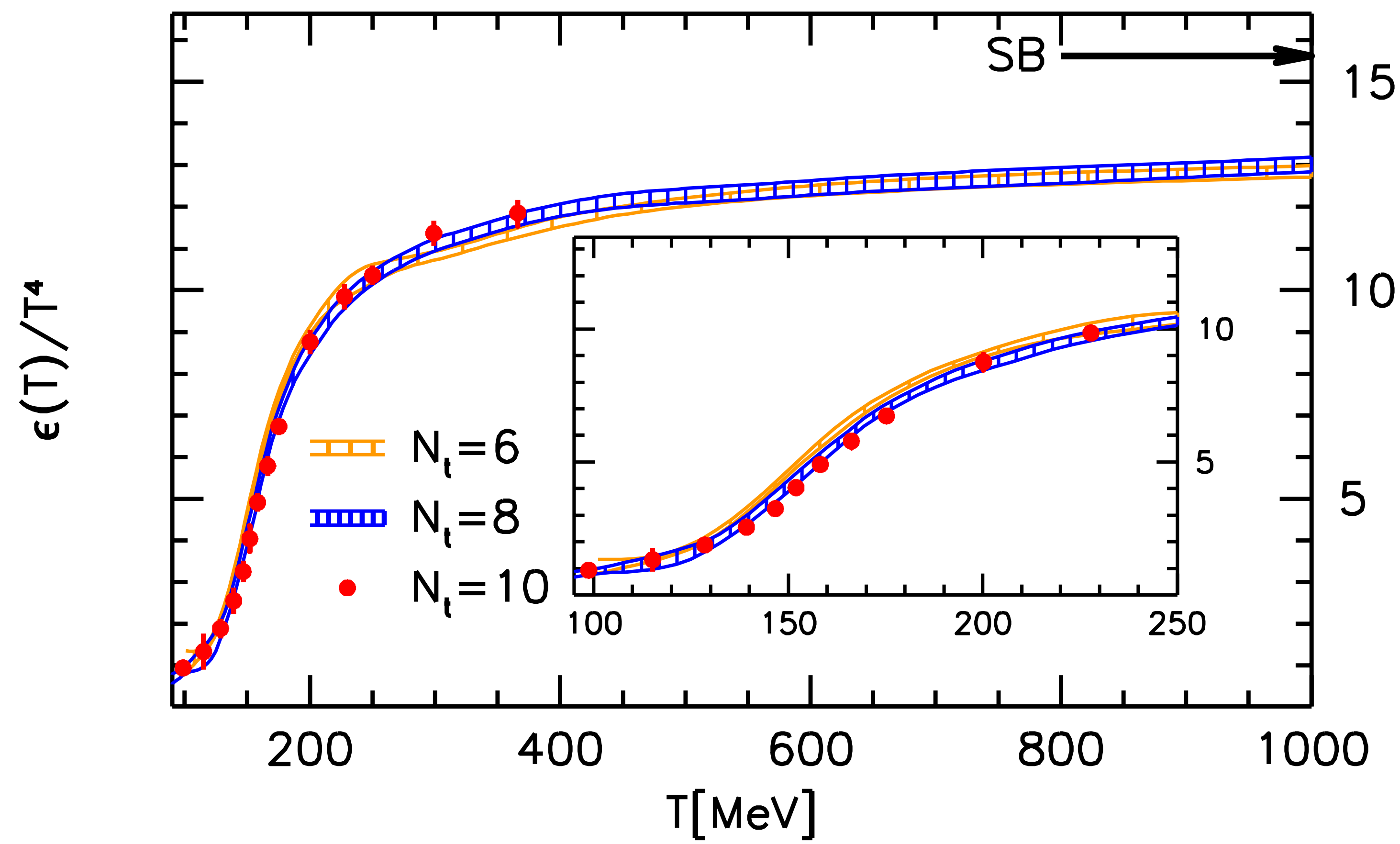
Is a nucleus large enough? is the viscosity small enough for hydro?

(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

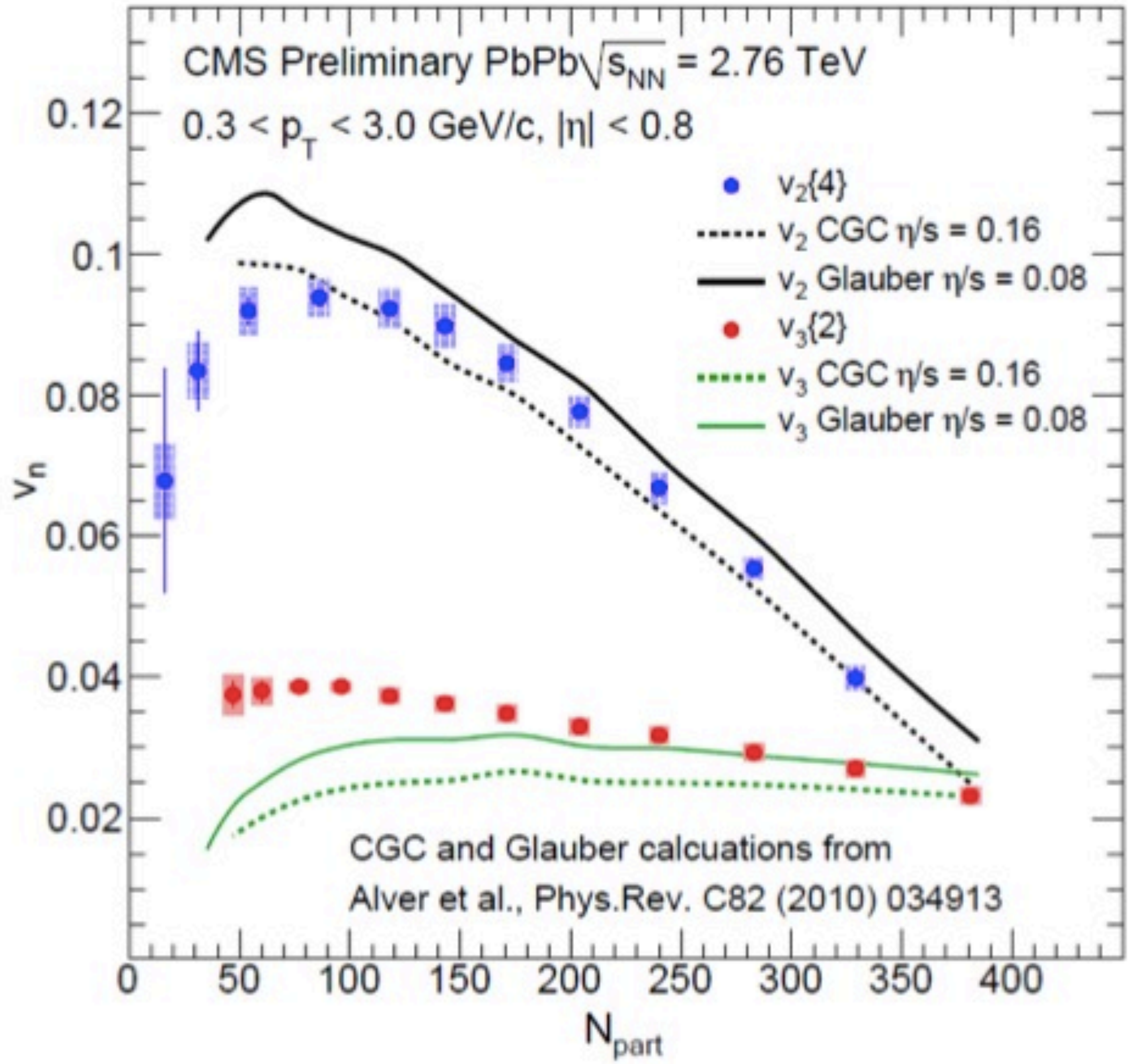
Equation of state of hot QCD *(input of hydrodynamics)* now calculated with dynamical quarks and physical quark masses!



Borsanyi et al, arXiv:1007.2580

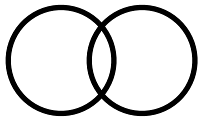
However, the viscosity η is not yet calculated: free parameter in hydro

Hydro prediction versus 1st LHC data

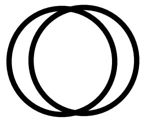


Julia Velkowska,
plenary talk
at QM2011

Luzum,
arXiv:1011:5173

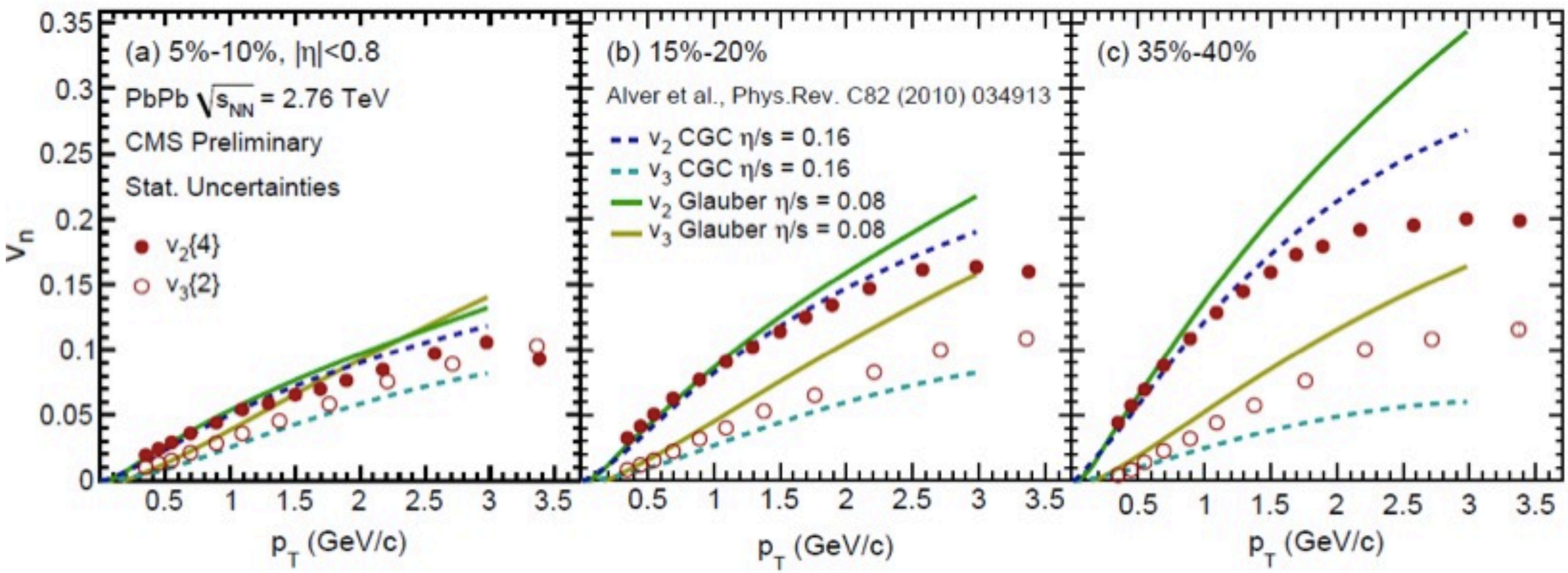


peripheral



central

More details: dependence on particle momentum



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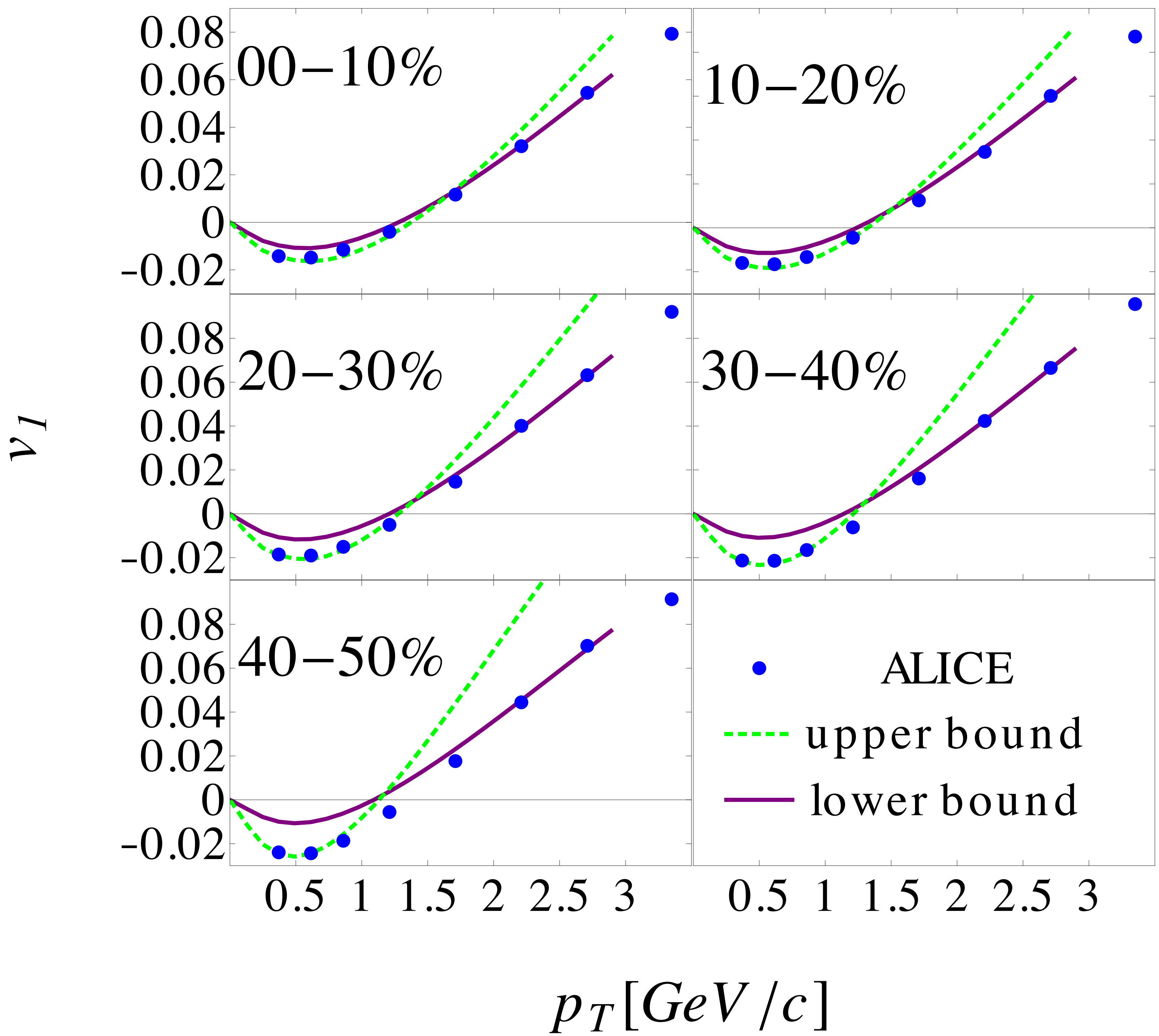
Hydrodynamics captures the magnitude, the centrality dependence and the momentum dependence of both elliptic and triangular flow.

First measurement of v_1 at LHC + first viscous hydro calculation of v_1



Retinskaya, Luzum, JYO, arxiv:1203.0931 (using ALICE data)

ATLAS, arXiv:1203.3087

Hard probes : testing pQCD in Pb-Pb collisions

(from Lamia Benhabib, talk at HCP2011)

Z boson

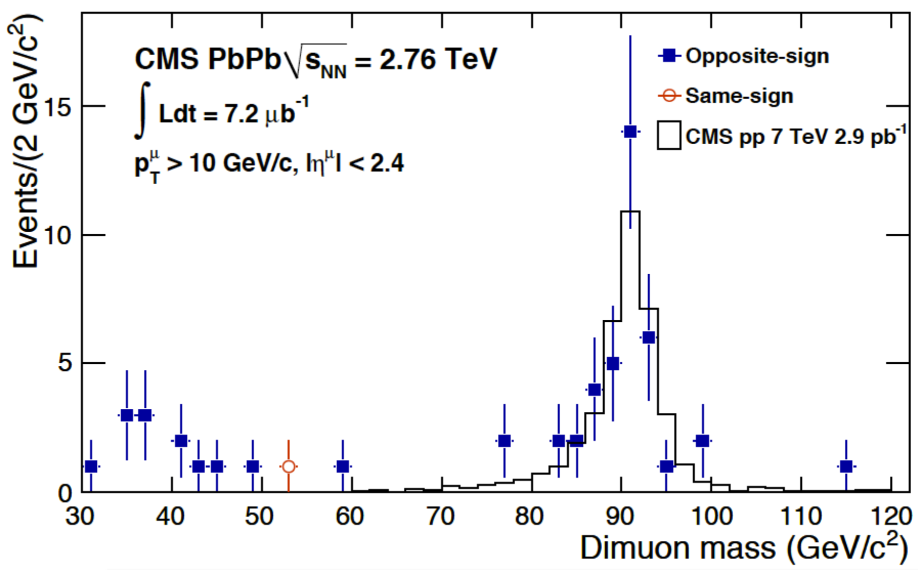
- Around 40 Z candidates in both ATLAS Phys. Lett. B **697** (2011) 294-312 CMS PRL 106, 212301 (2011)
  - Almost background free (one like sign count only)
- Z production scales with the number of NN collisions
- Comparaison to different theoretical predictions
- Using POWHEG cross-section:

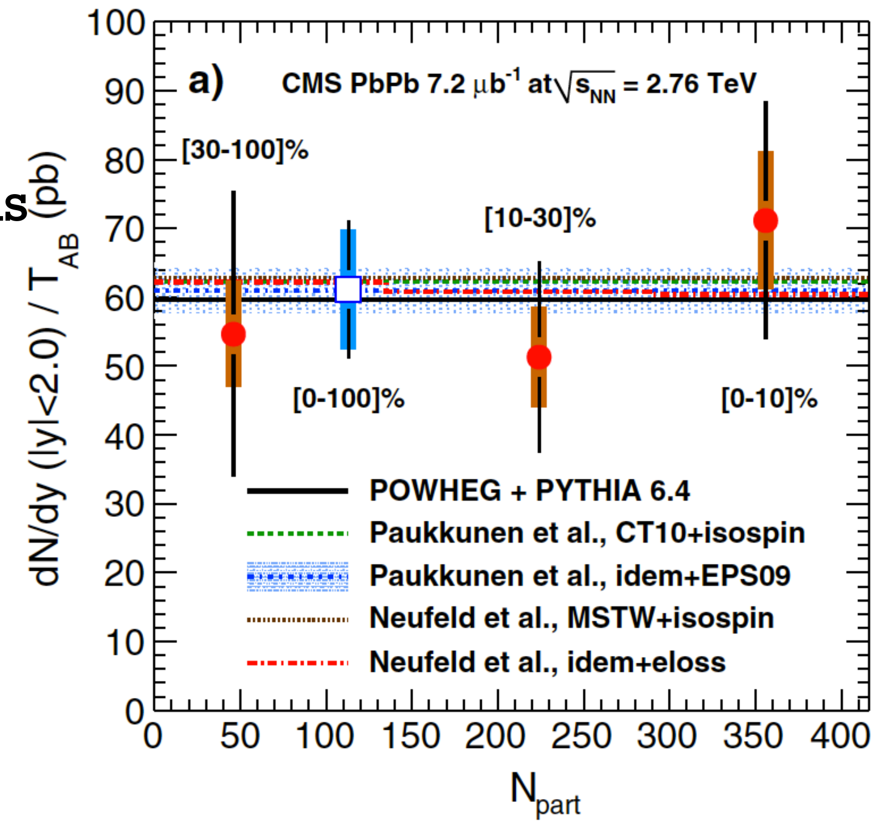
- $d\sigma_{pp}/dy = 59.6$pb in $|y|<2$

The resulting R_{AA} is: $dN_{AA}/(T_{AB}\, d\sigma_{pp})$

$= 1.00 \pm 0.16 \pm 0.14$

Heavy ion run @2.76 TeV





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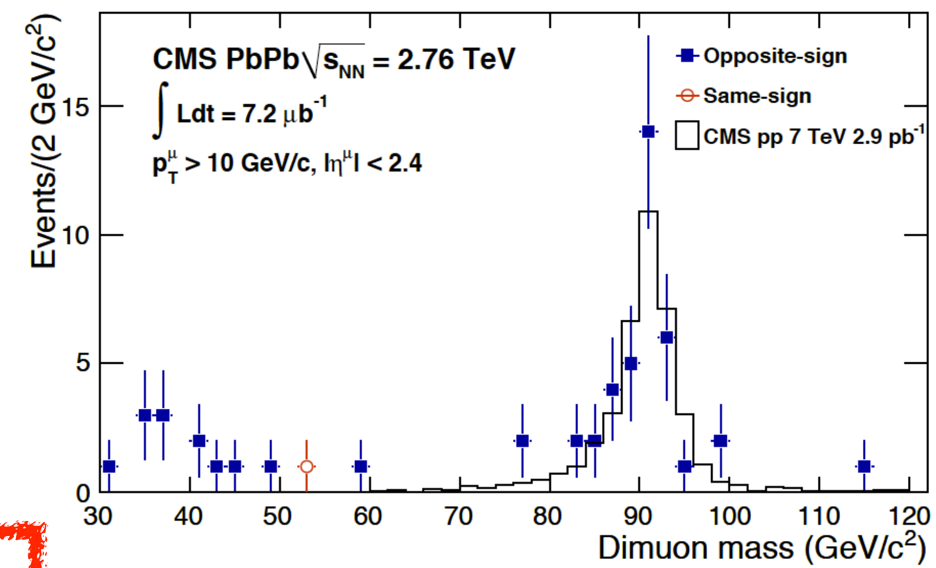

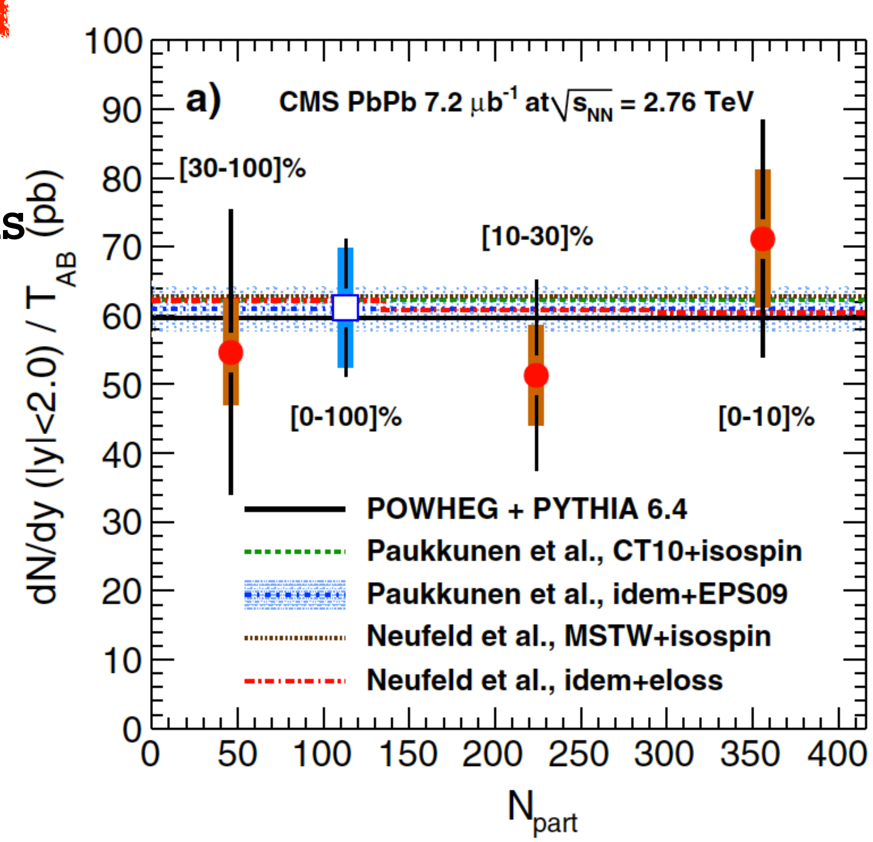

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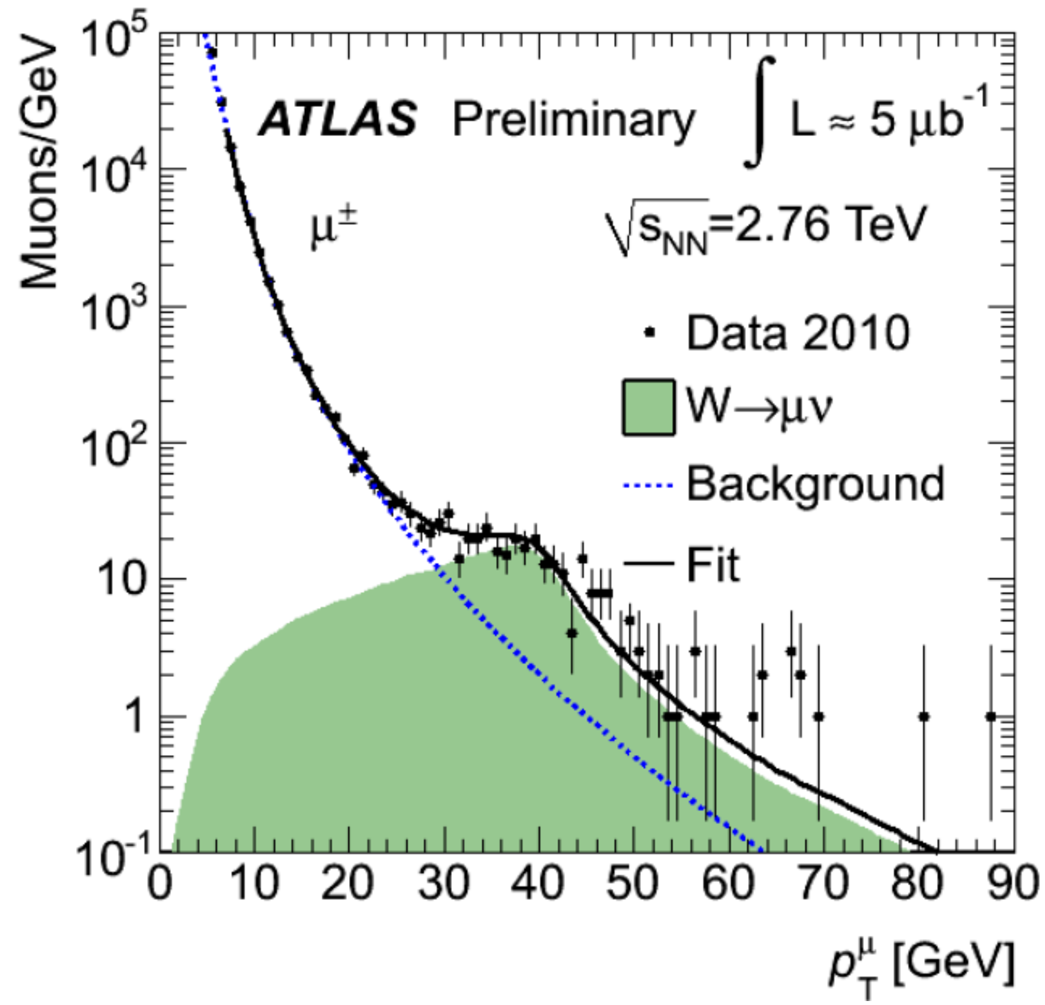
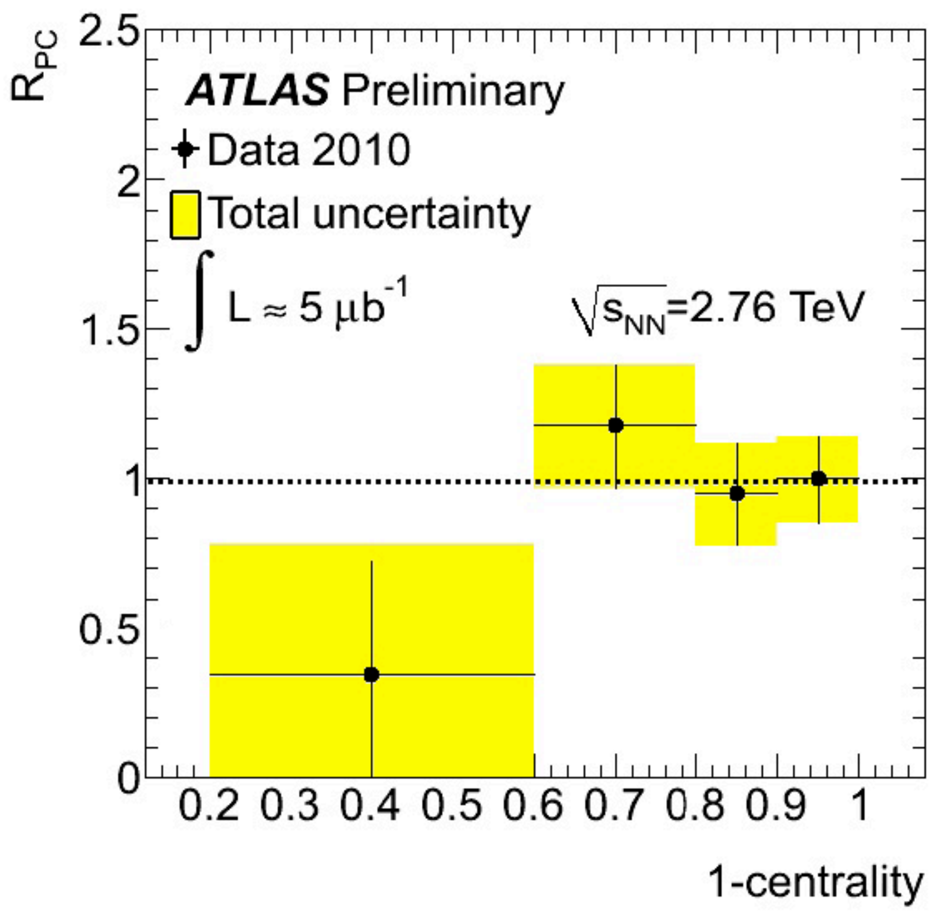
Hard probes : testing pQCD in Pb-Pb collisions

(from Lamia Benhabib, talk at HCP2011)

+ W boson

- W signal: built a template from W →μν decays
  - Use MC @ √s = 2.76TeV
- Use a function to describe background and find the best estimate of number of W with fitting signal + background to data





The results are consistent with no suppression

$R_{W/Z}$ =10.5 ± 2.3 : in agreement with standard model prediction

J. Phys.G: Nucl. Part. Phys. 38 124133

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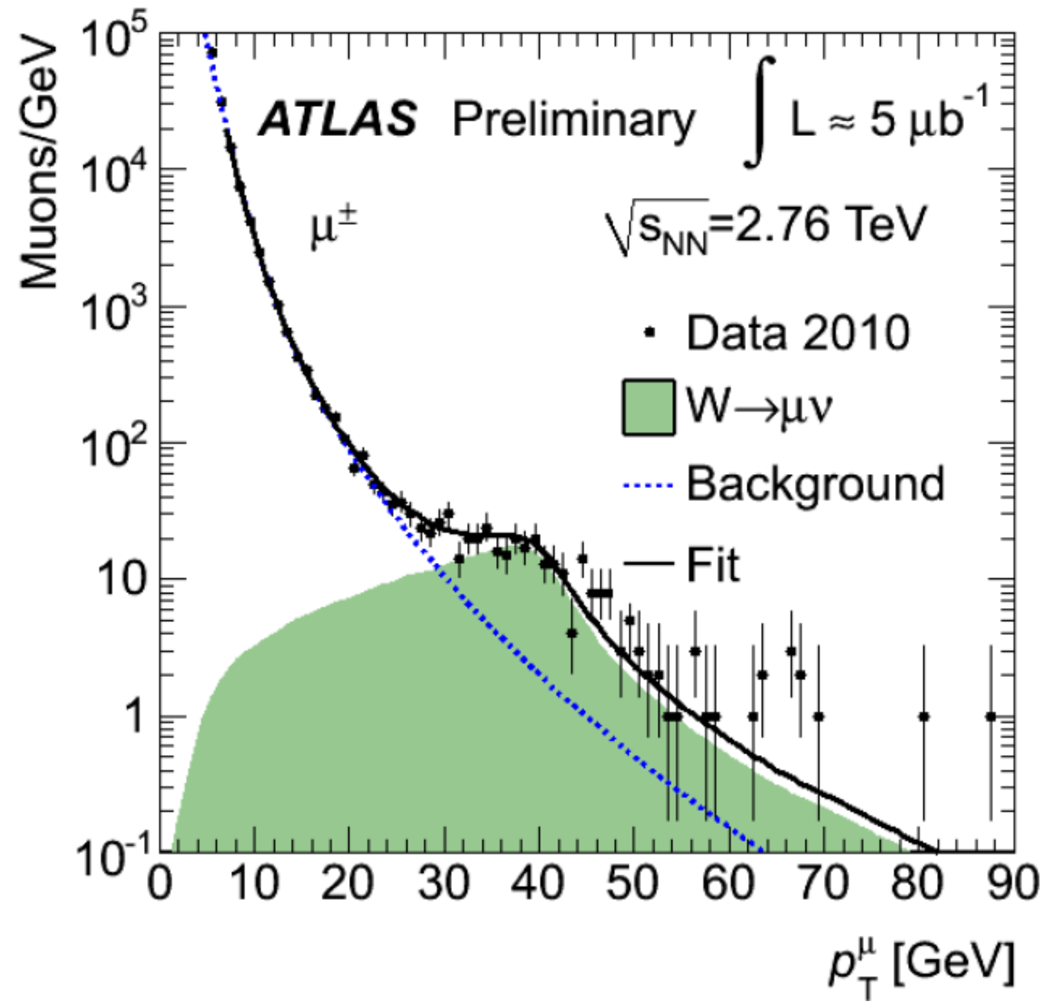

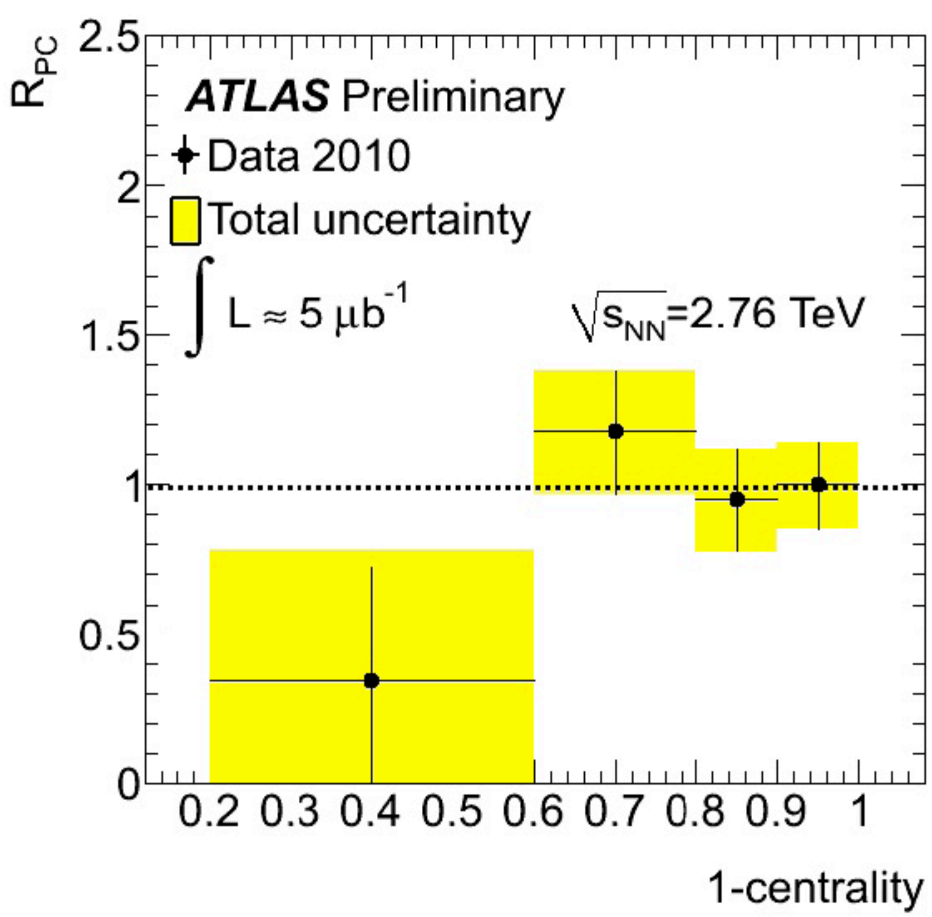

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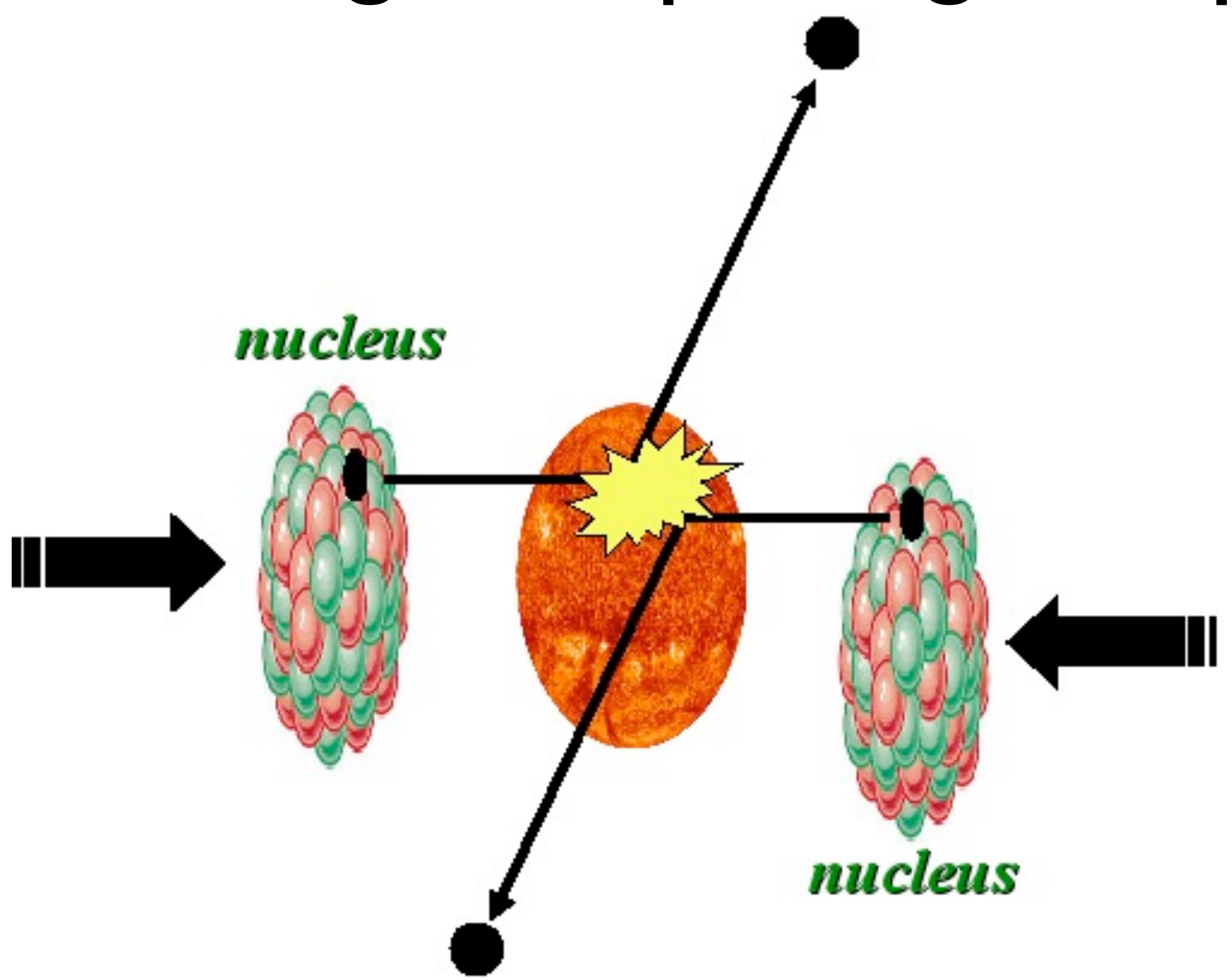
Strongly-interacting hard probes: jet quenching in a quark-gluon plasma



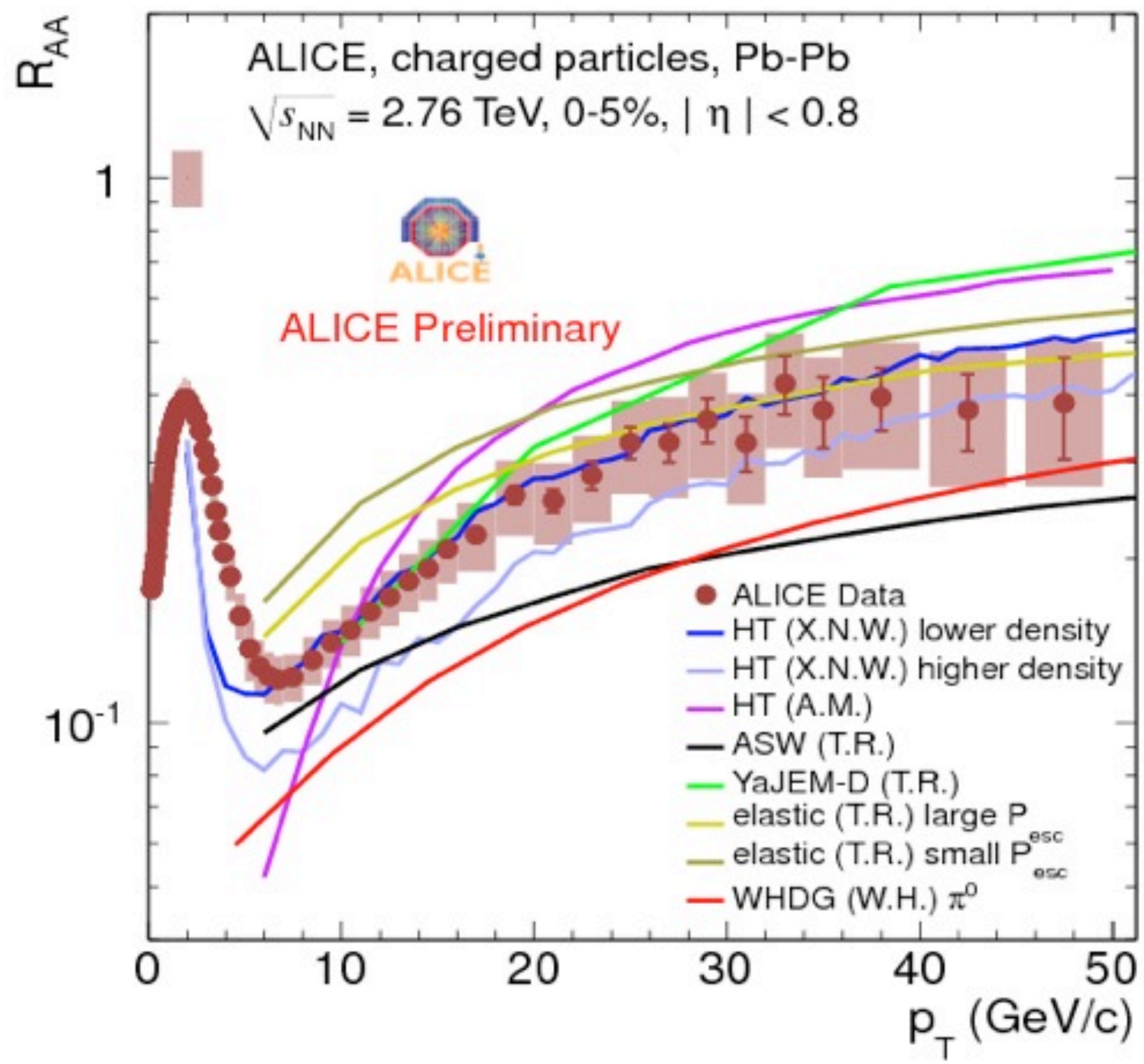
- Supression of high pt hadrons (leading particles)
- One jet loses more energy : dijet asymmetry

Early observations of jet quenching: suppression of high-pt particles

HT: X-N Wang et al, arXiv:1102.5614 (PRC)
HT: Majumder, Shen, arXiv:1103.0809
TR: T. Renk et al, arXiv:1103.5308 (PRC)
WHDG: Horowitz and Gyulassy, arXiv:1104.4958

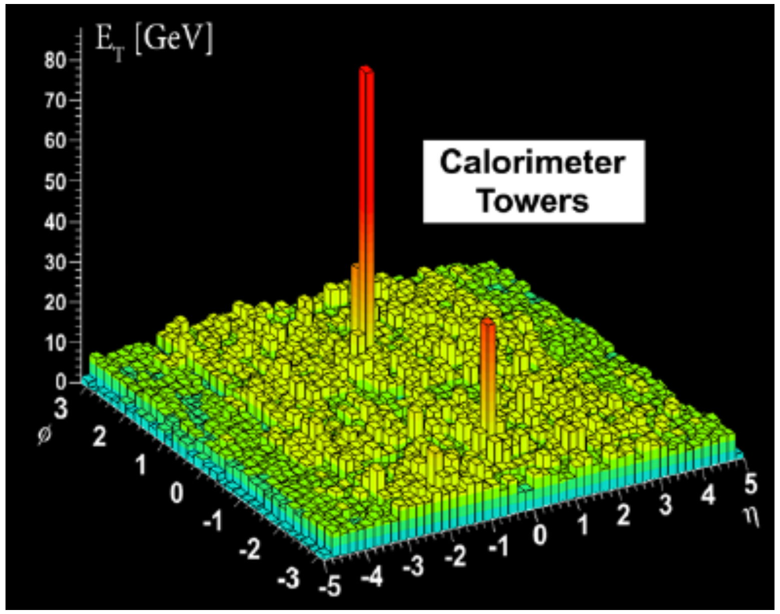
R_{AA}
= ratio Pb-Pb/pp,
divided by number of binary collisions
= observed/perturbative

(from M. van Leeuwen, talk at HCP2011)



Studying quenching with fully reconstructed jets
(from Lamia Benhabib, talk at HCP2011)

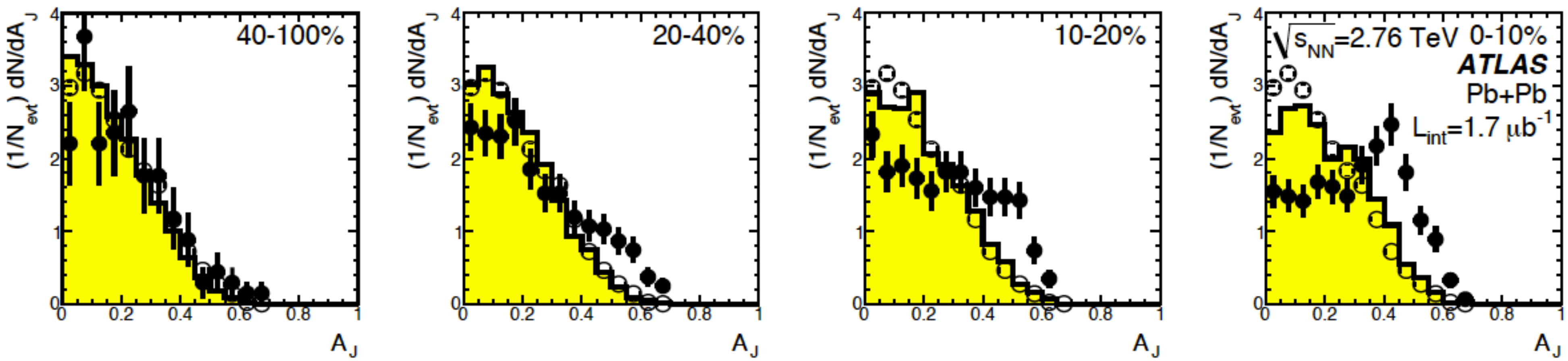
+ Dijet imbalance



- Dijet selection
  - Leading jet p_T > 100 GeV/c
  - Subleading jet p_T > 25 GeV/c
- Quantify dijet imbalance by asymmetry ratio

$$A_j = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

ATLAS, Phys. Rev. Lett **105** (2010) 252303



- Larger imbalance in central collisions, but not in peripheral collisions, with respect to pp reference
- Parton energy loss is observed as pronounced energy imbalance in reconstructed dijets

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Conclusions

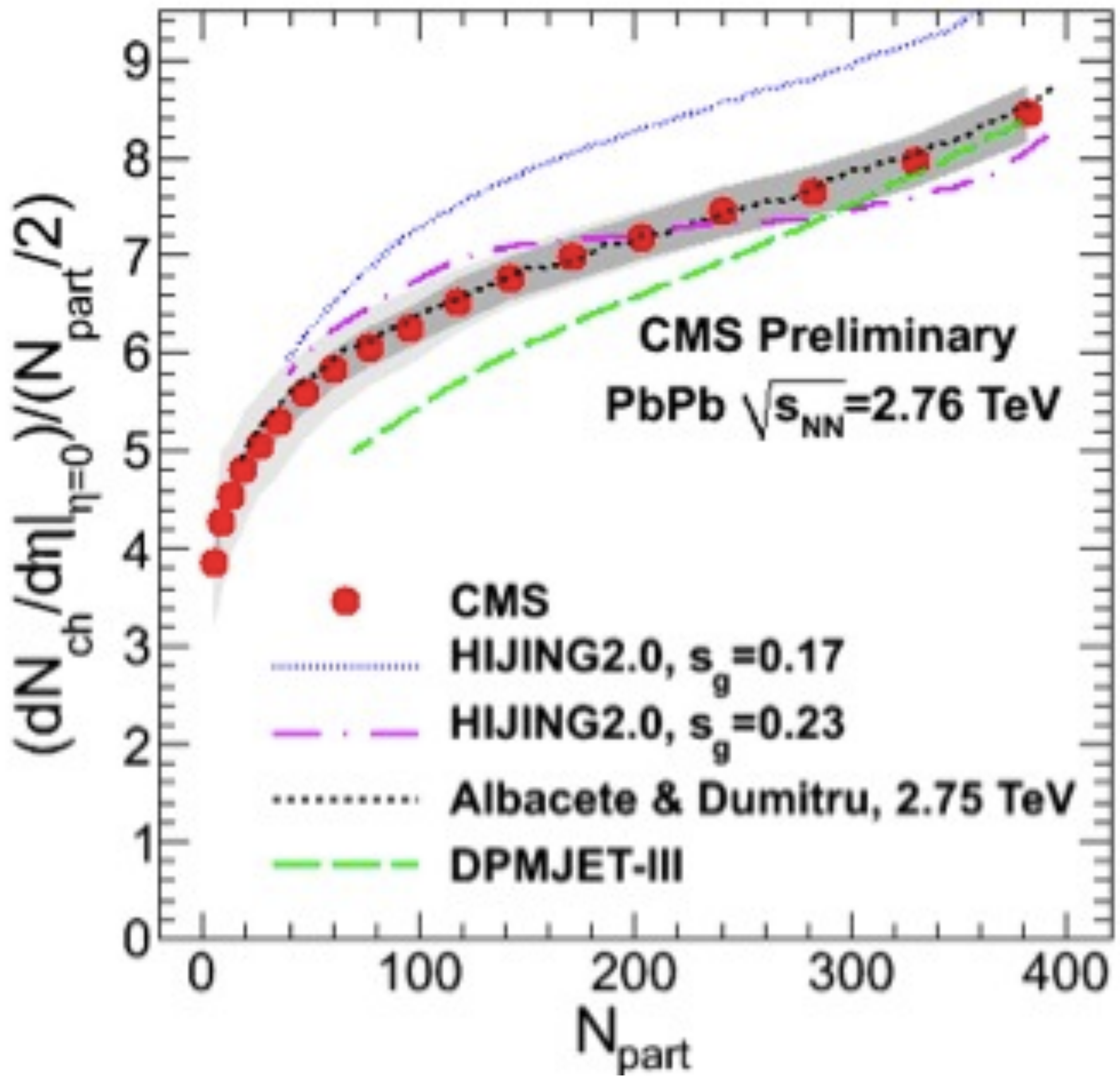
- Ultrarelativistic heavy-ion collisions produce a lump of fluid, with an extremely low viscosity/entropy, characteristic of a strongly-coupled plasma.
- Quantum fluctuations+flow+viscous damping generate the anisotropies observed in the little bang. This is very similar to the mechanism driving CMB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

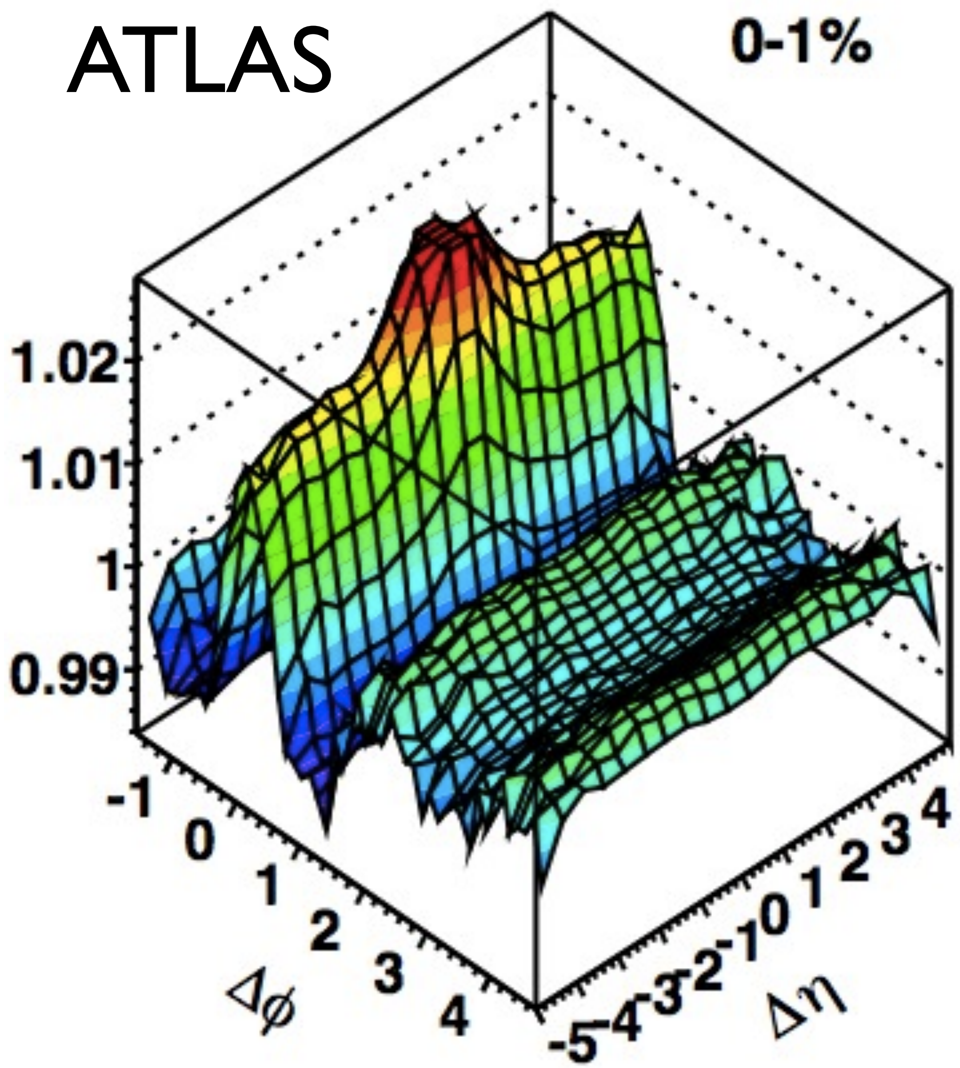
More generally, properties of the initial state can be studied within a perturbative framework, generally known as CGC (color glass condensate)



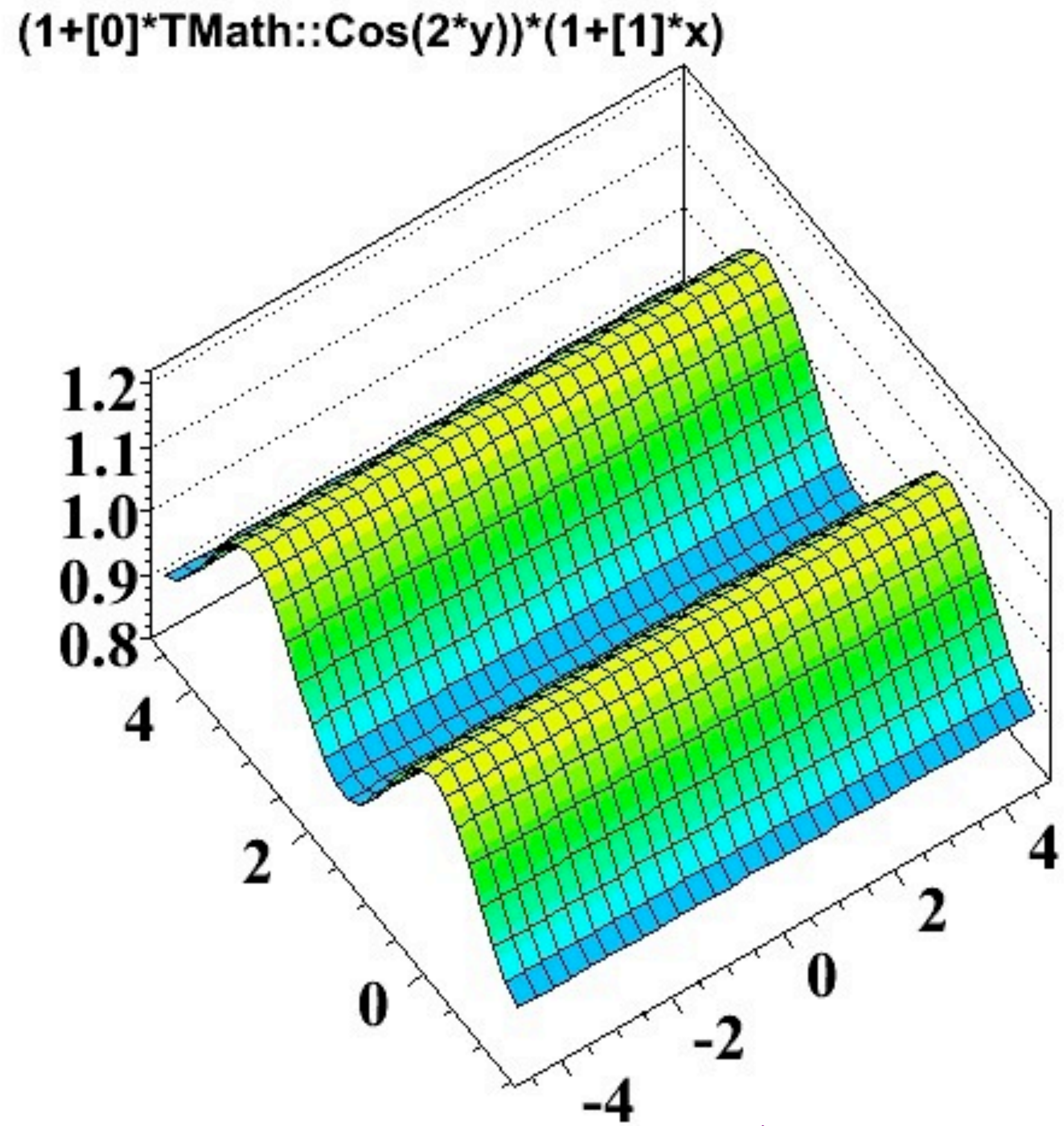
(B. Wyslouch, talk at Quark Mater 2011)

Correlations in 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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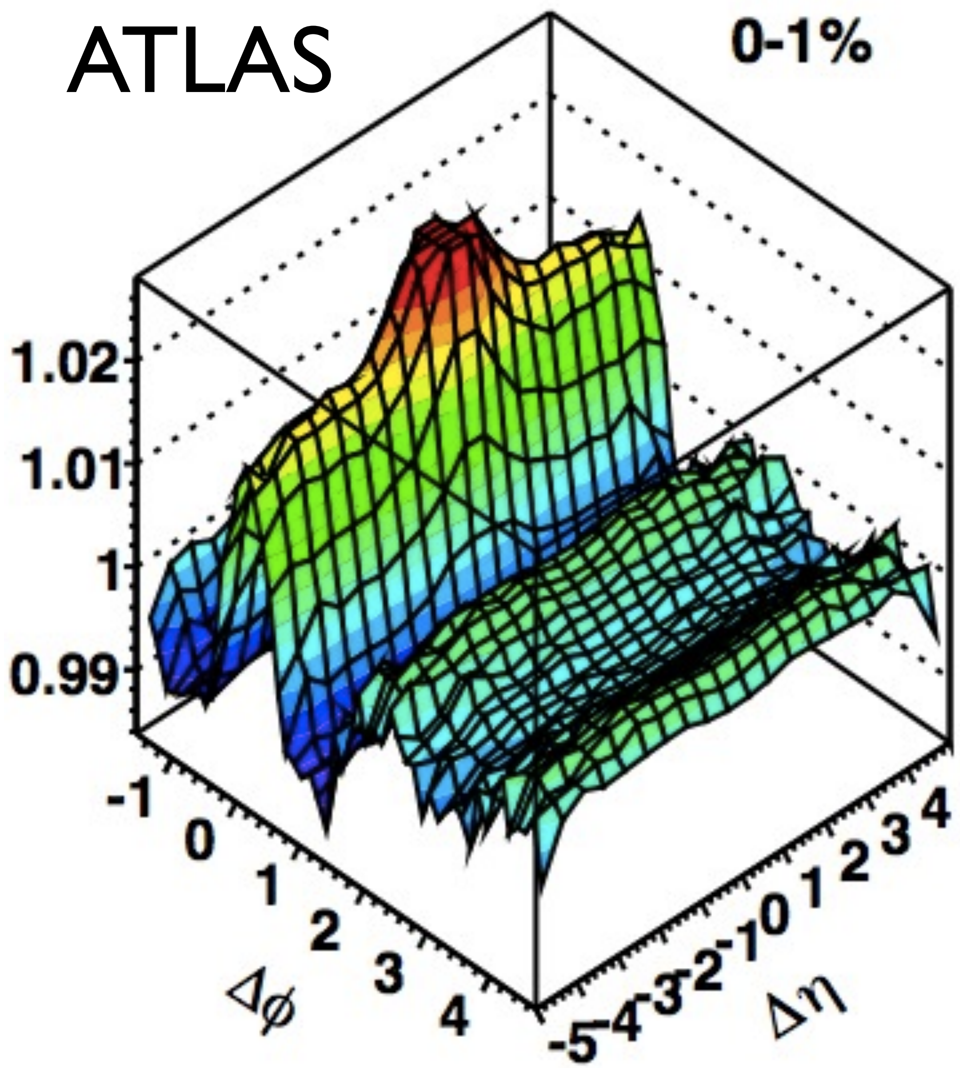

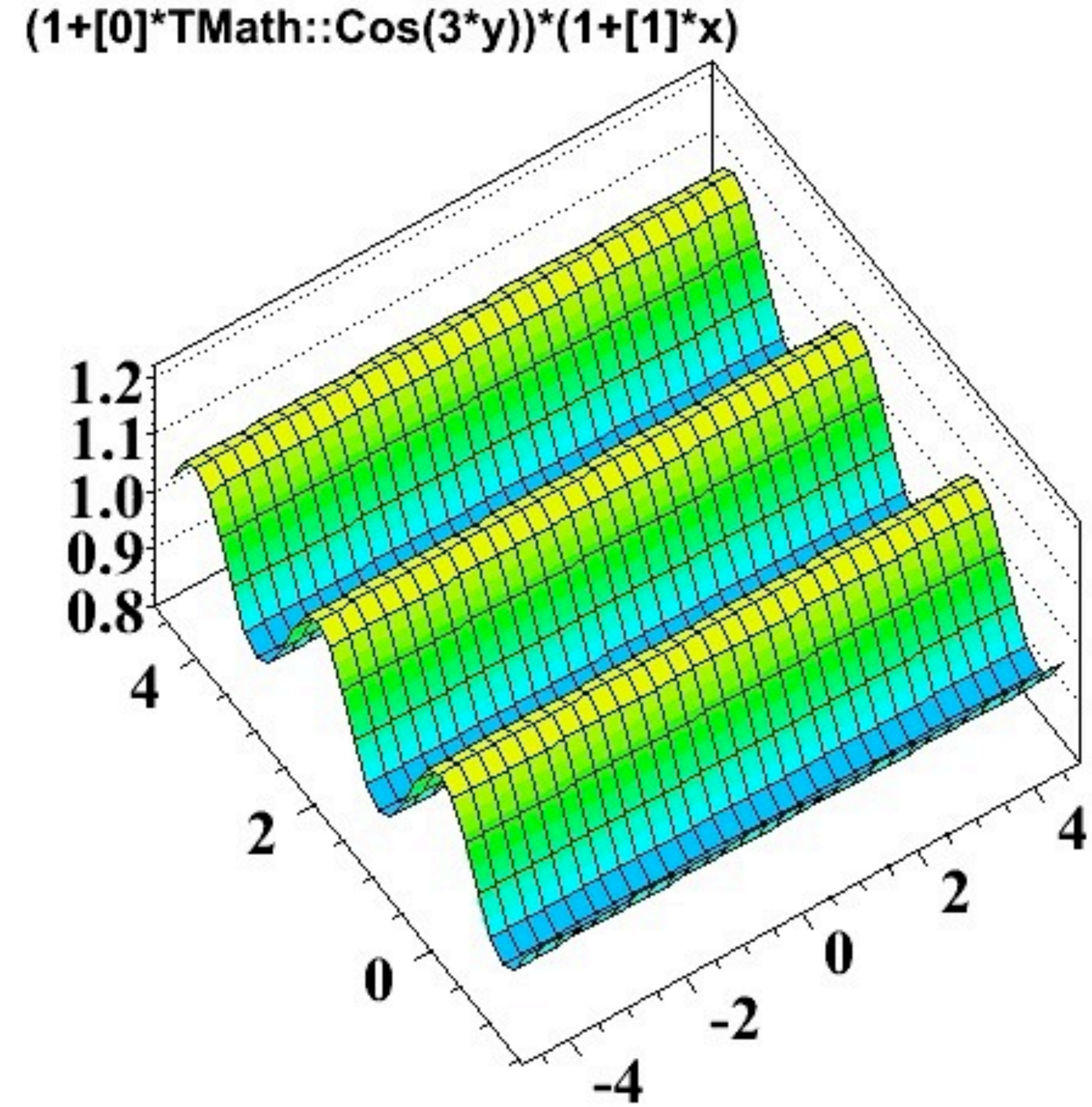

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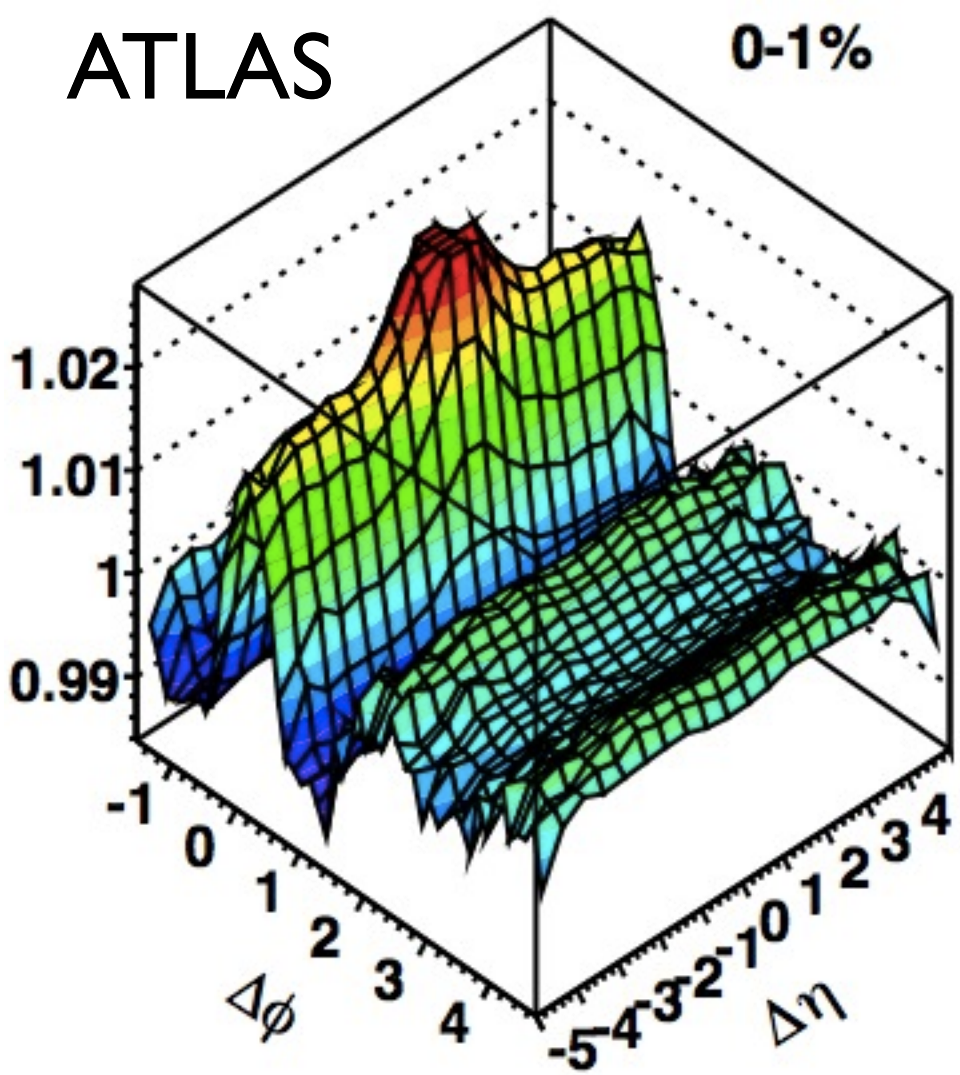
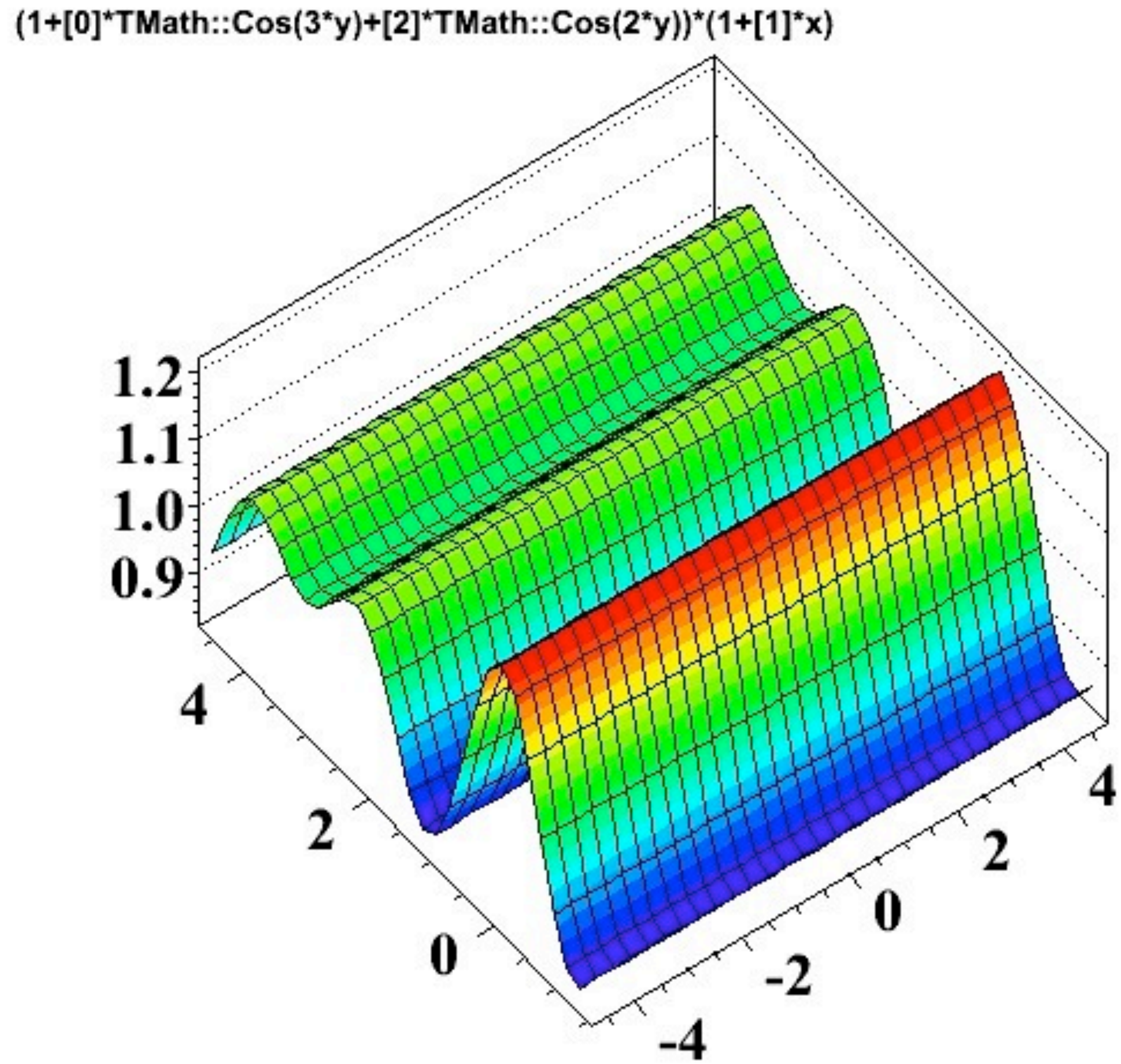


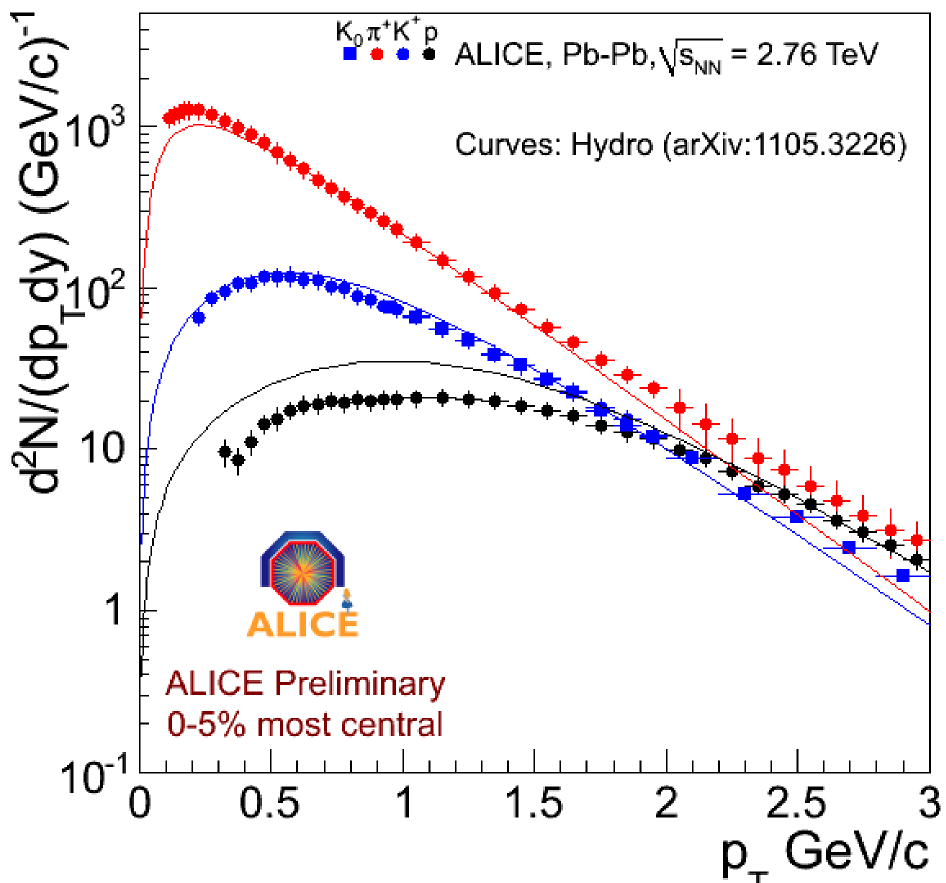


Jia @ATLAS, talk at QM2011

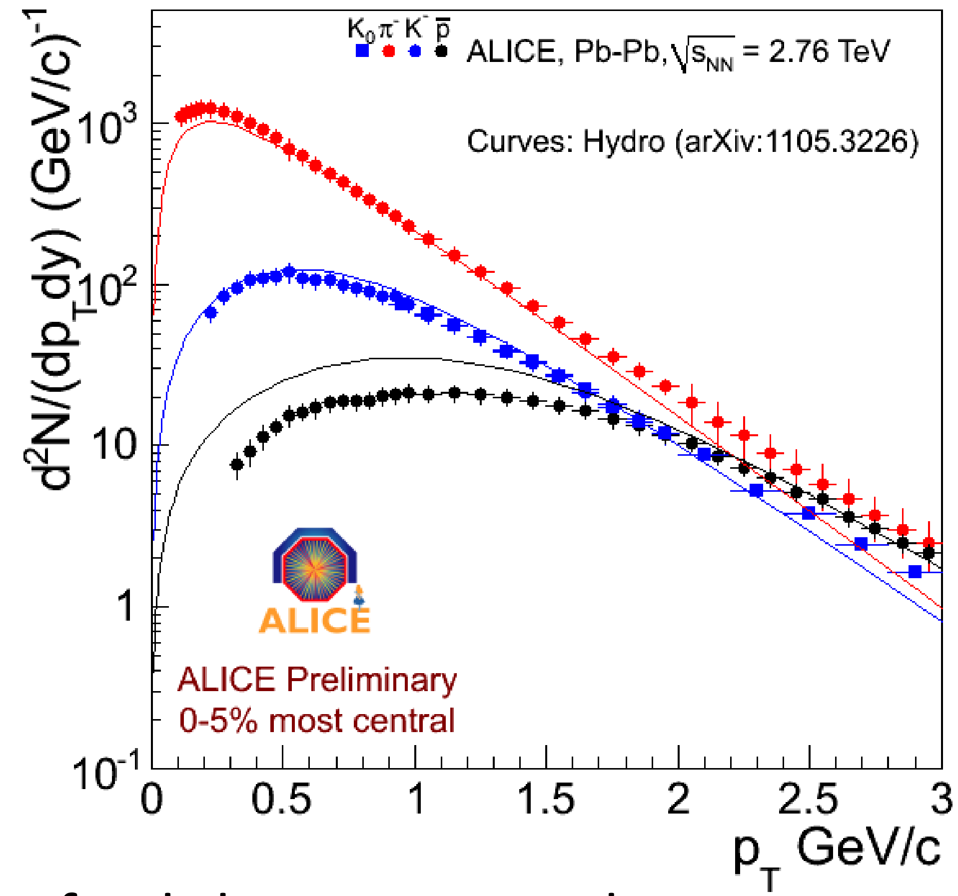
Wei Li@CMS, talk at QM2011

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

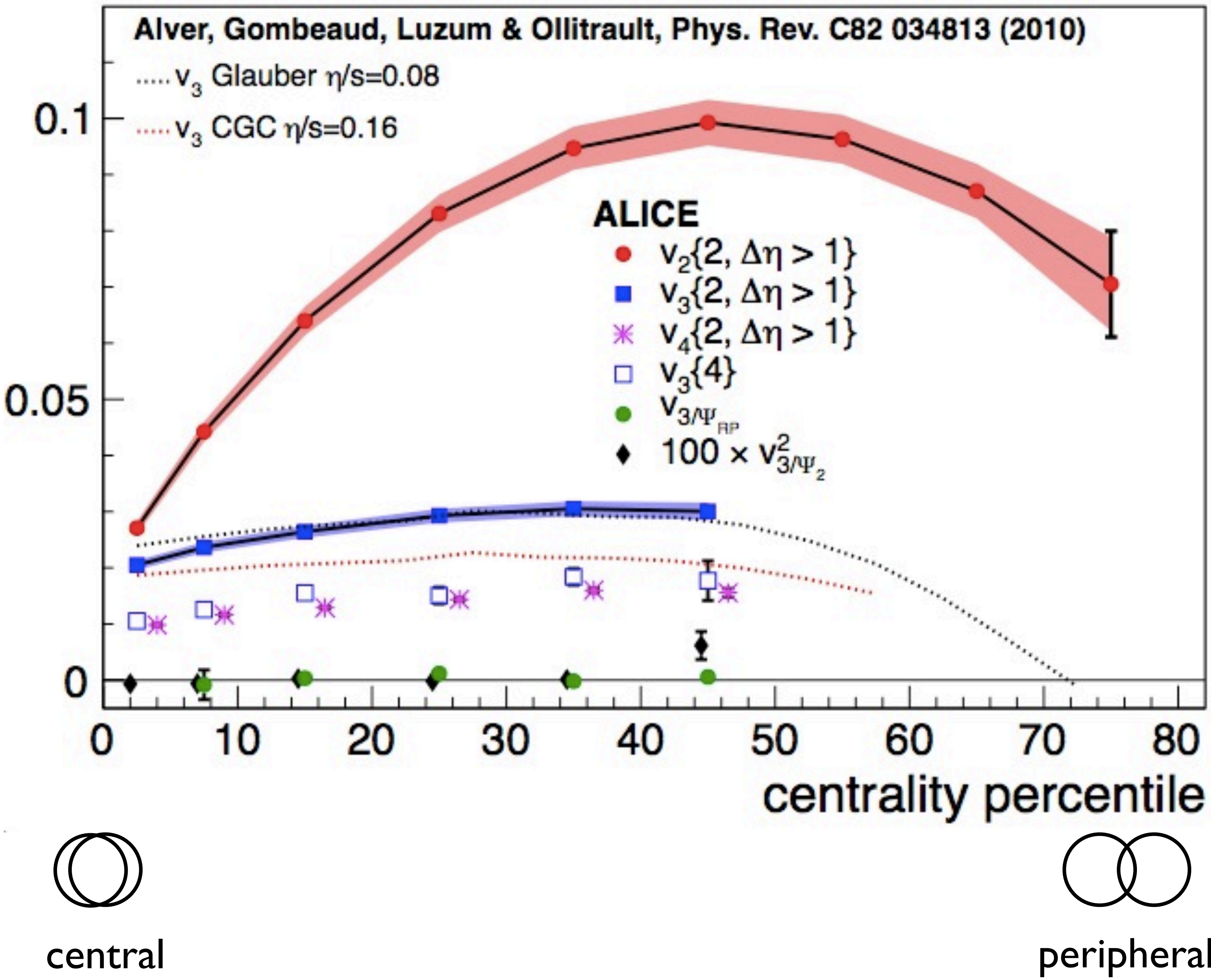
➔ Consistent picture with feed-down corrected spectra

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)

Hydro prediction versus 1st LHC data

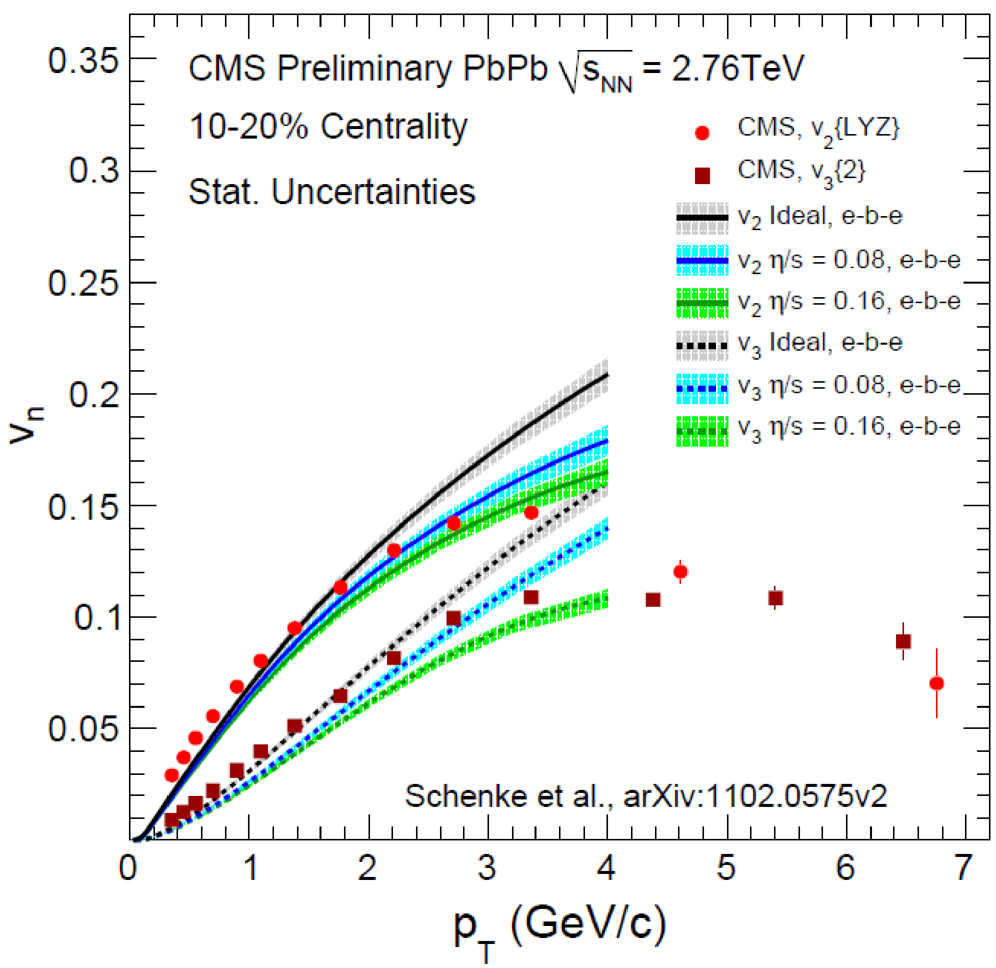


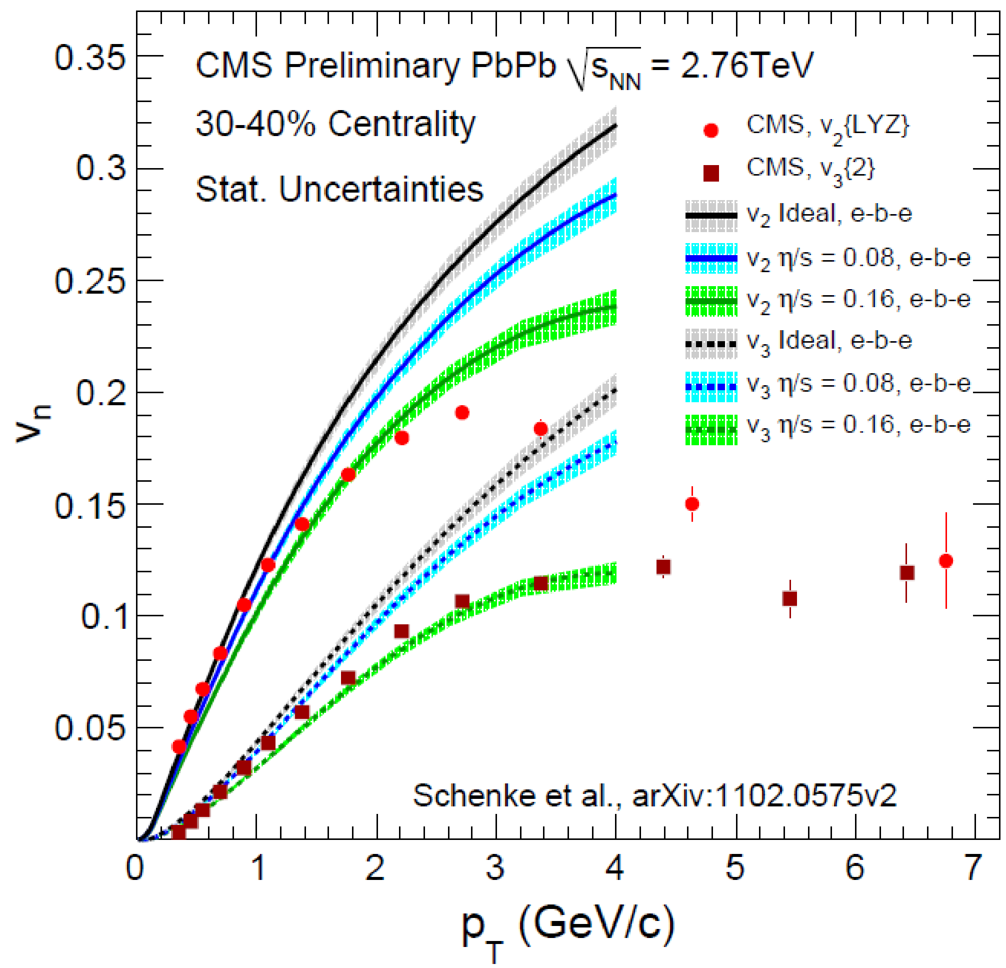
Raimond Snellings,
plenary talk
at QM2011

ALICE,
arXiv:1105.3865
[nucl-ex]

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

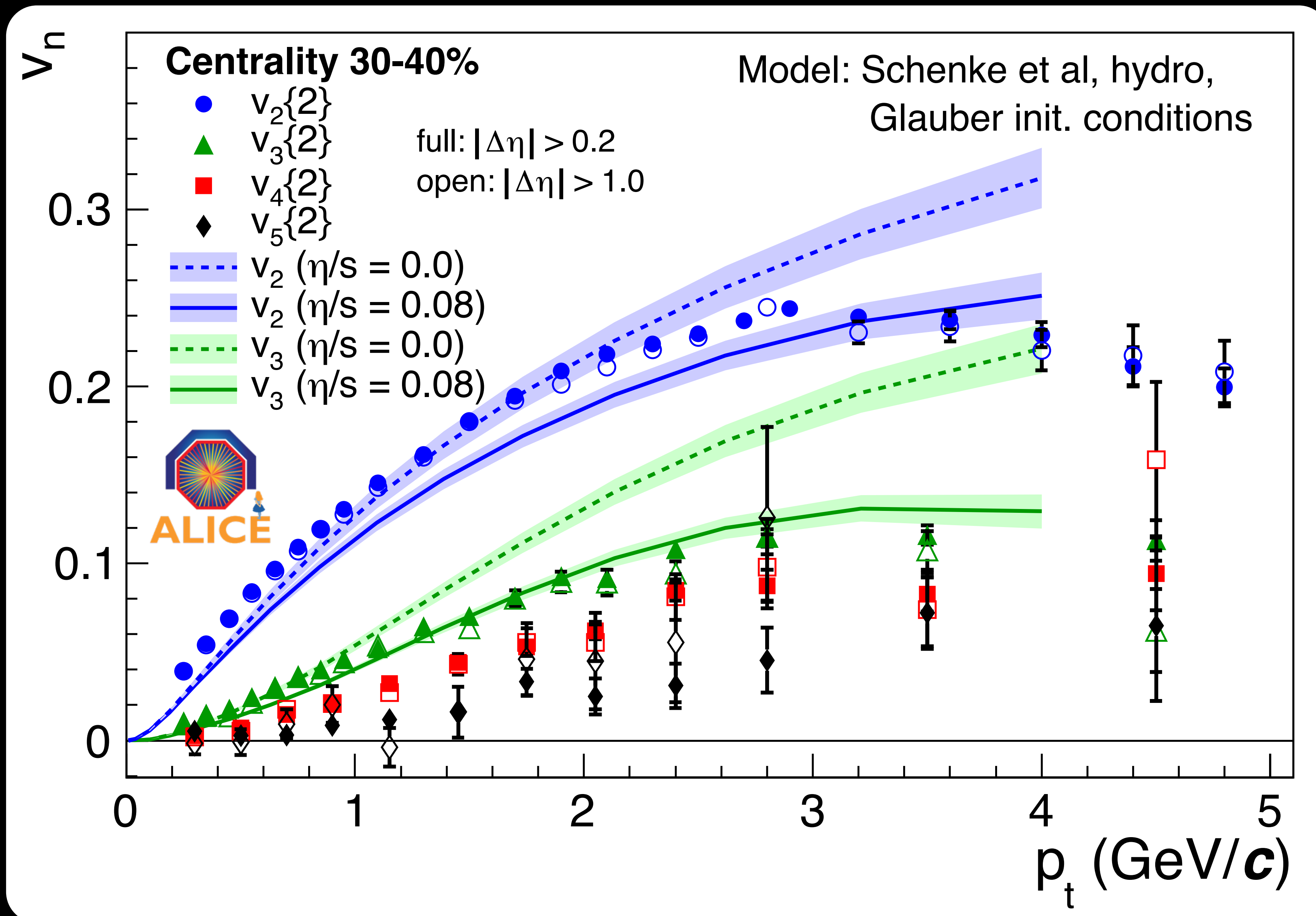
Glauber initial conditions





- 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

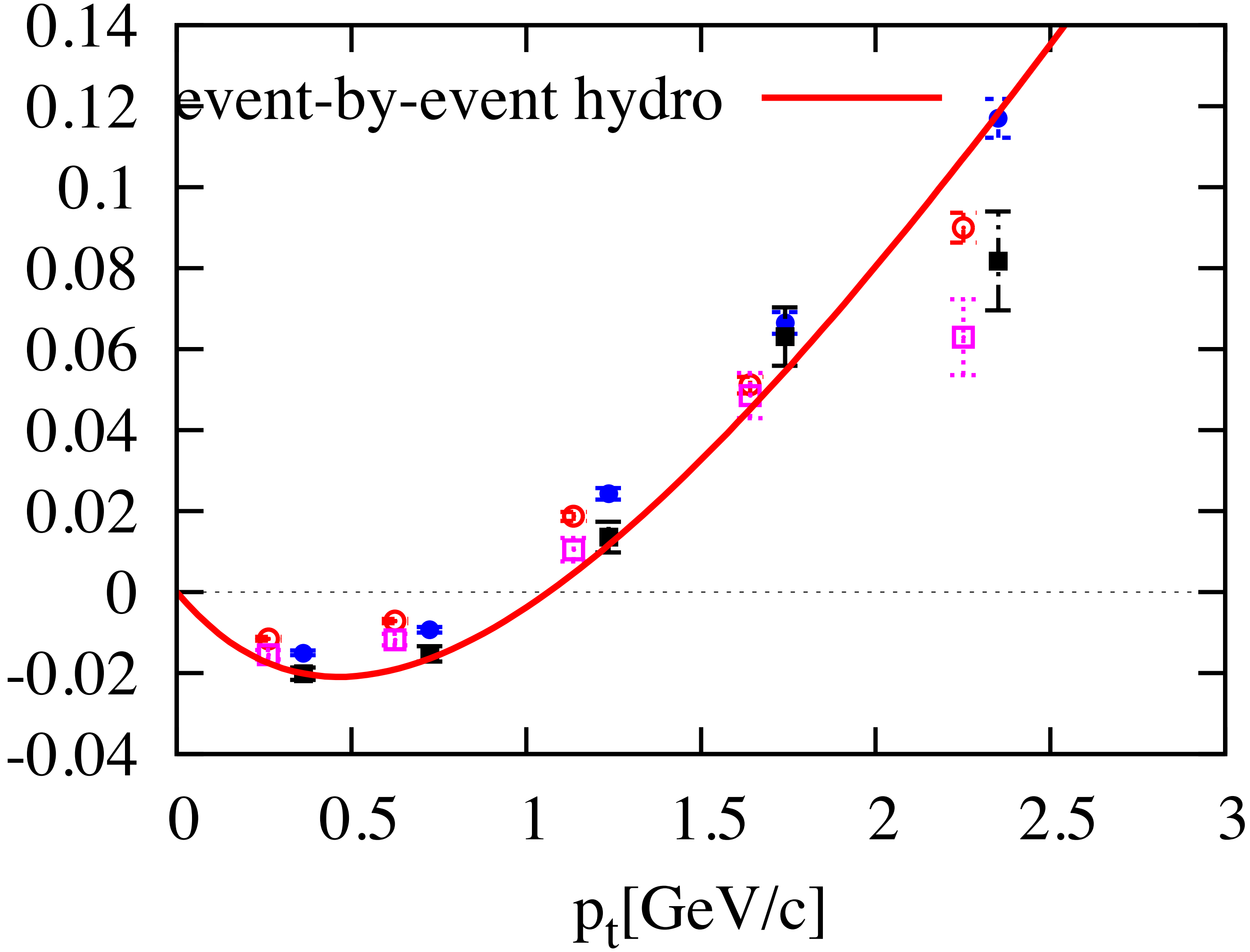
However there is no simultaneous description with a single η/s of v_2 and v_3 for Glauber initial conditions

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

lundi 9 avril 2012

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.