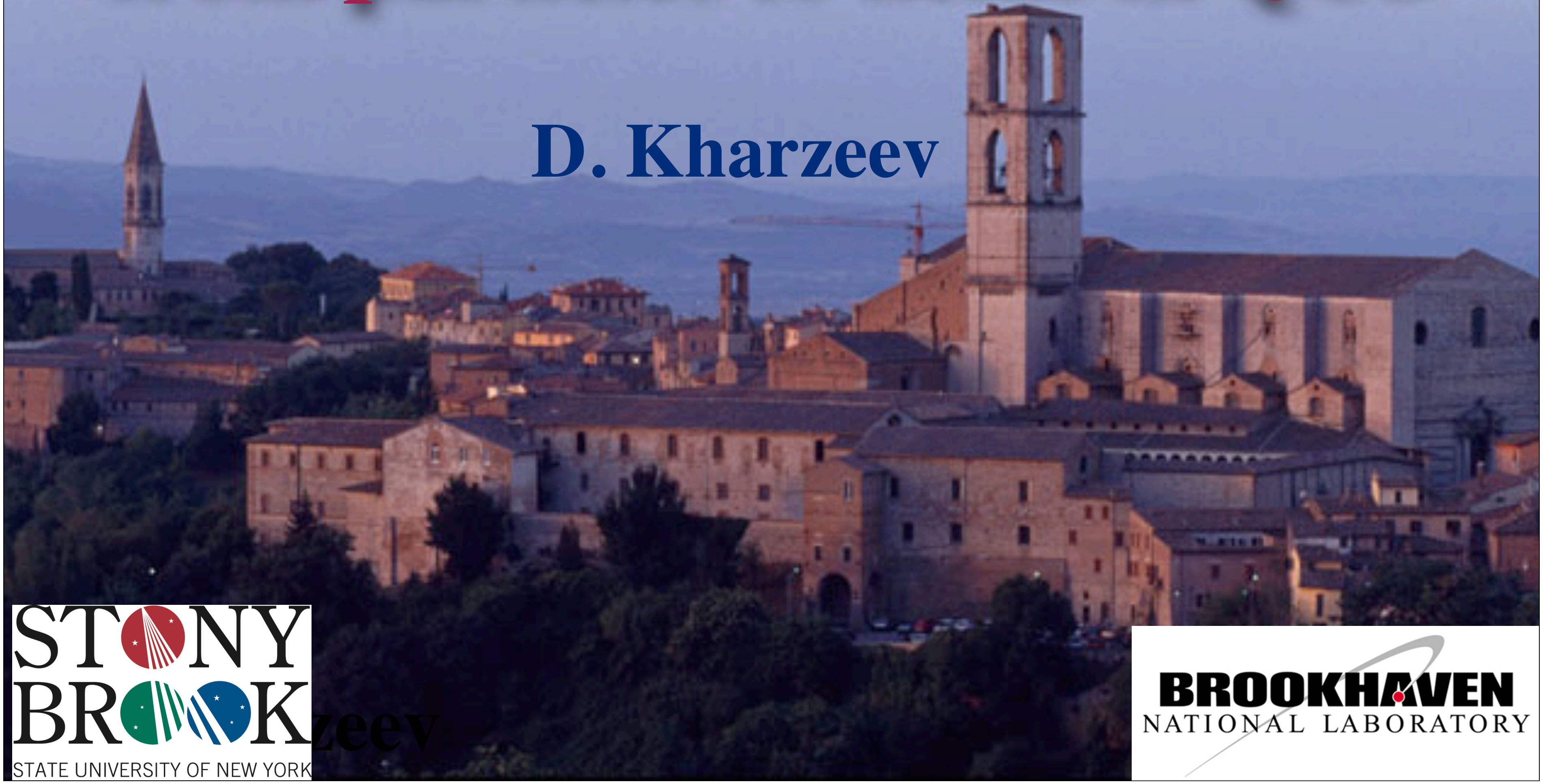
Physics at LHC, Perugia, Italy, June 6-11, 2011

Heavy ion physics: from particles to fields in QCD

D. Kharzeev



STONY BROOK
STATE UNIVERSITY OF NEW YORK

BROOKHAVEN
NATIONAL LABORATORY

A theorist's review of the field driven by the experiment;

therefore, the emphasis in the talk will be not on the answers, but on the **questions**

Disclaimer: not a systematic review of heavy ion theory

see talk by N. Borghini

Understanding QCD

QCD = quarks + geometry

(local gauge invariance,

gluon fields)

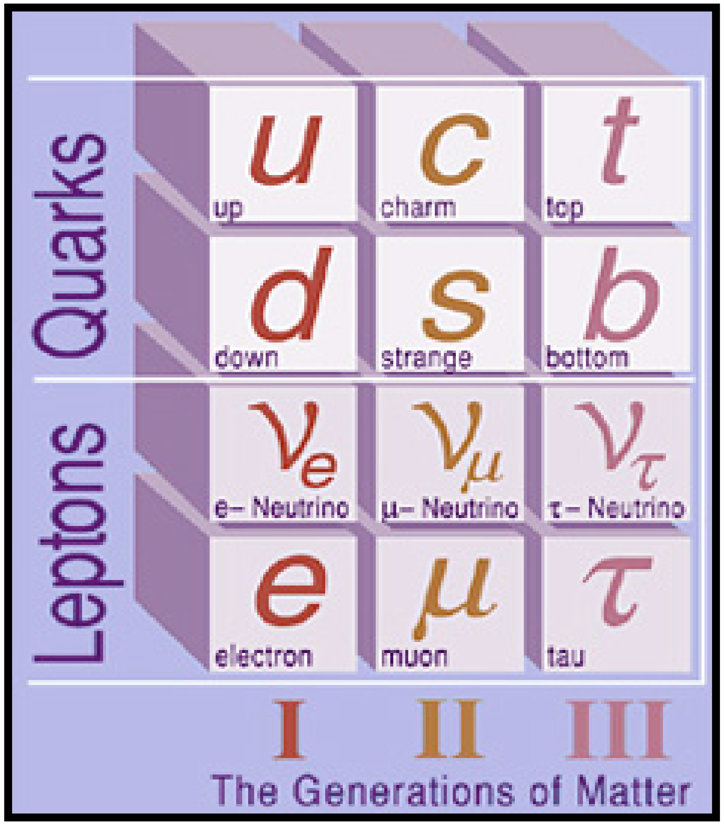
$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_f \bar{q}^a_f (i\gamma_\mu D_\mu - m_f) q^a_f;$$

$$D_\mu = \partial_\mu - igA^a_\mu t^a$$

Elegant, consistent, and correct theory

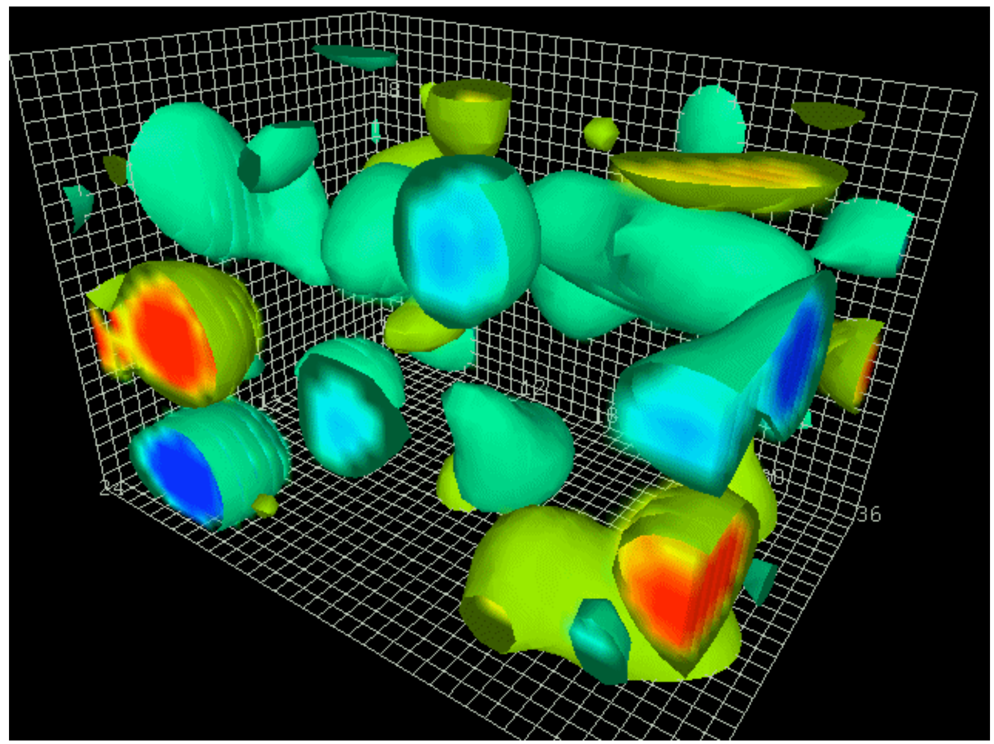
From particles to fields in QCD

Particles

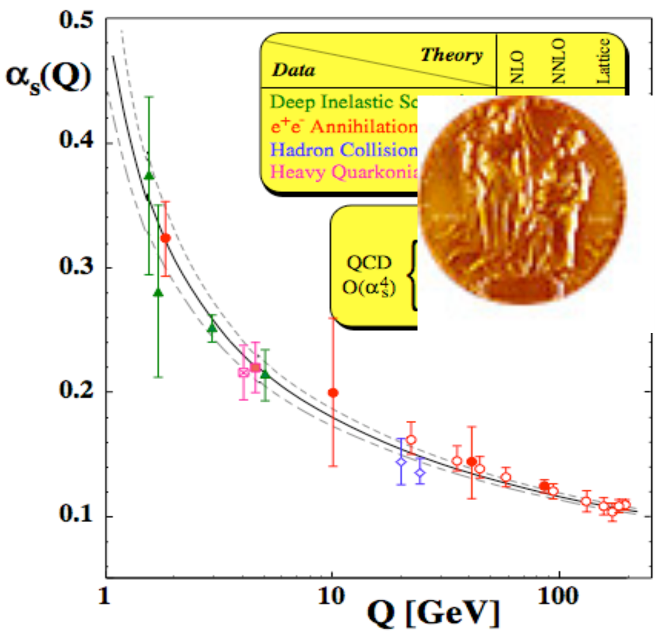


Fields

(Geometry)



Asymptotic Freedom: particles of QCD revealed



At short distances,
the strong force becomes weak
(anti-screening) -
one can access the "asymptotically free" regime in hard processes

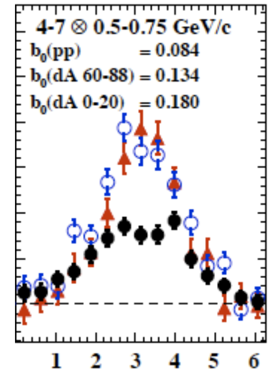
and in super-dense matter
(inter-particle distances ~ 1/T)

$$\alpha_s(Q) \simeq \frac{4\pi}{b \ln(Q^2/\Lambda^2)}$$

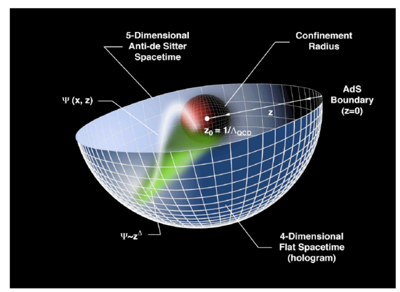
But: Strong confining interaction at large distances -
must understand dynamics of fields!

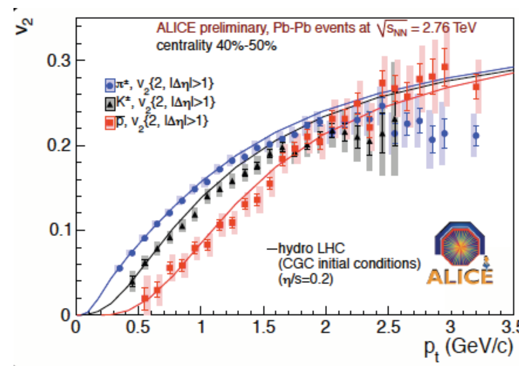
From particles to fields: collective phenomena as the essence of QCD

- From partons to strong color fields: nuclear wave functions at small x

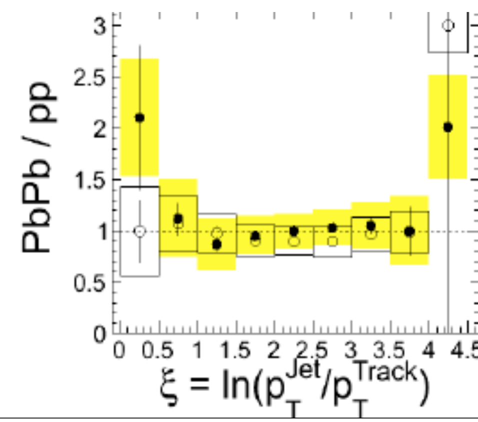


- Hydrodynamics: the other (low-energy) TOE; AdS/CFT; phase diagram; anomalies and chiral magnetic effect





- Jets:the flow of energy and momentum in QCD



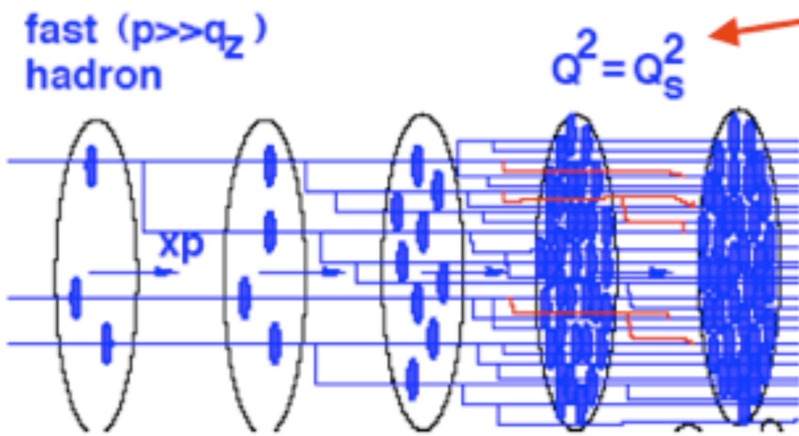
- The probes: heavy quarks, dileptons, ..

Building up strong color fields: small x (high energy) and large A (heavy nuclei)

Bjorken x : the fraction of hadron's momentum carried by a parton; high energies s open access to small $x = Q^2/s$

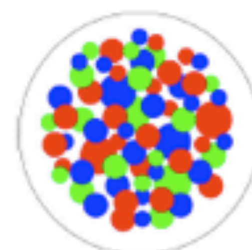
the boundary of non-linear regime: partons of size $1/Q > 1/Q_s$ overlap

Large x



Color Glass Condensate

small x

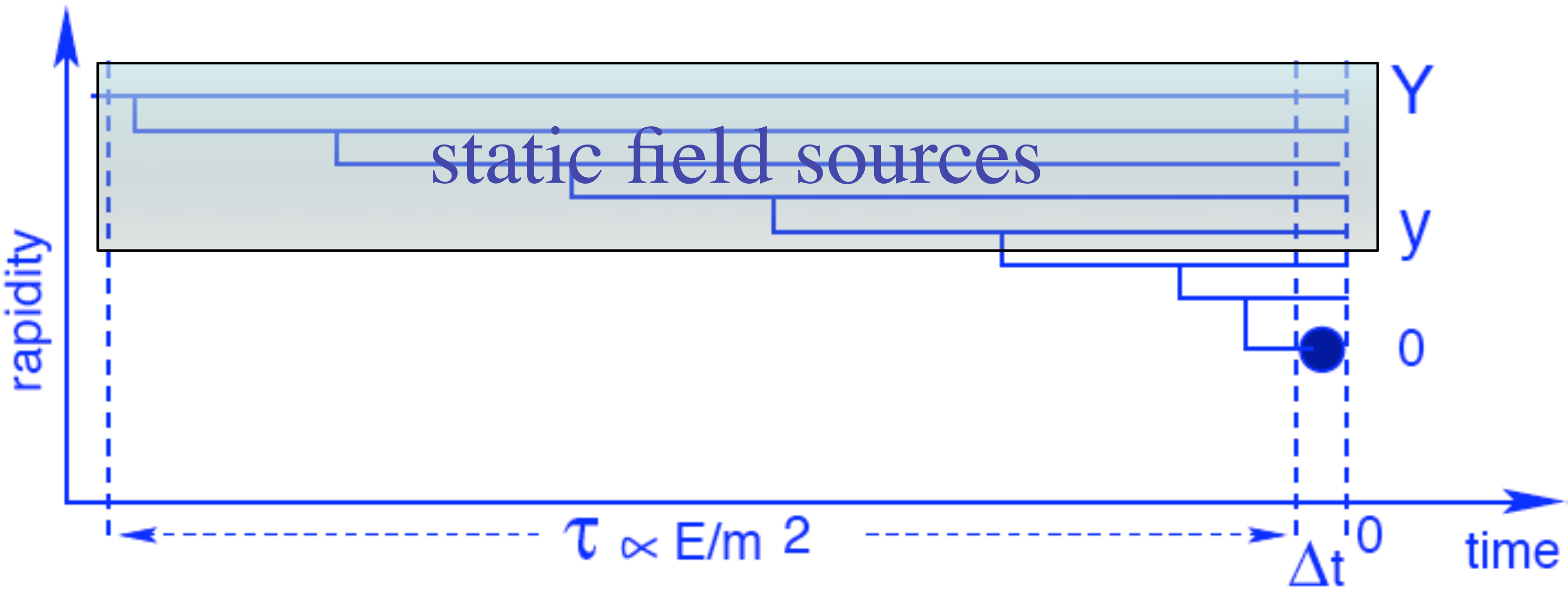


Because the probability to emit an extra gluon is $\sim \alpha_s \ln(1/x) \sim 1$, the number of gluons at small x grows; the transverse area is limited

$\rightarrow$ transverse density becomes large

The origin of classical background field

Coherent field with occupation number $\sim \dfrac{1}{\alpha_s(Q_s)}$
suppression of hard processes at small x;
depletion of back-to-back (quantum) correlations

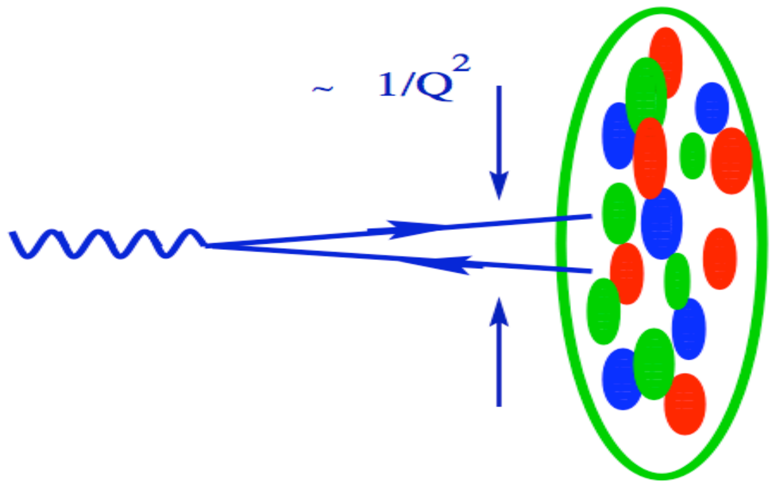


Gluons with large rapidity and large occupation number
act as a background field for the production of slower gluons

"Color Glass Condensate"

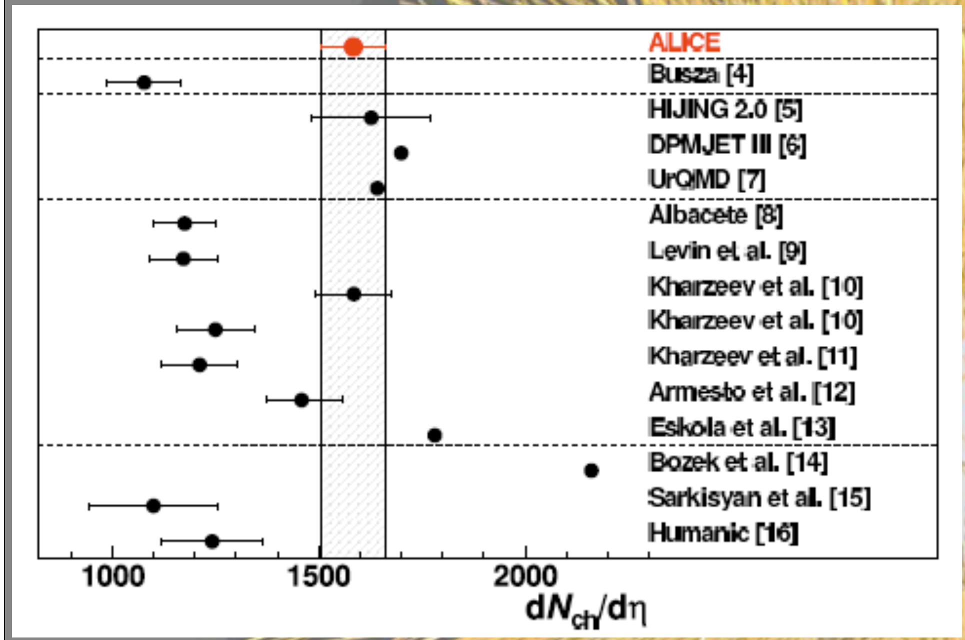
Coherent interactions - from partons to fields at small x

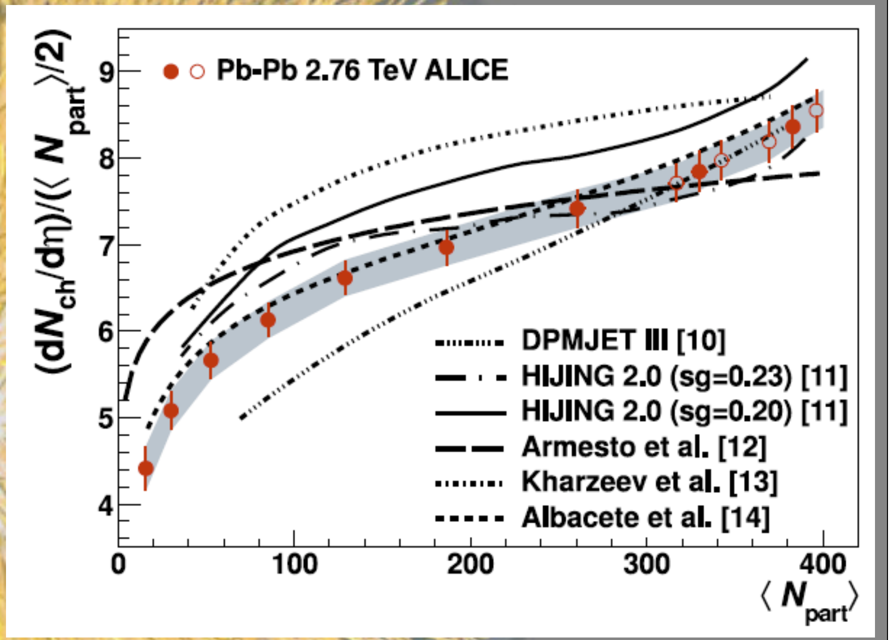
At small Bjorken x, hard processes develop over large longitudinal distances $$l_c \sim \frac{2\omega}{Q^2} = \frac{1}{mx}$$



At small x, when these distances exceed the size of the nucleus, **parton interactions become coherent**

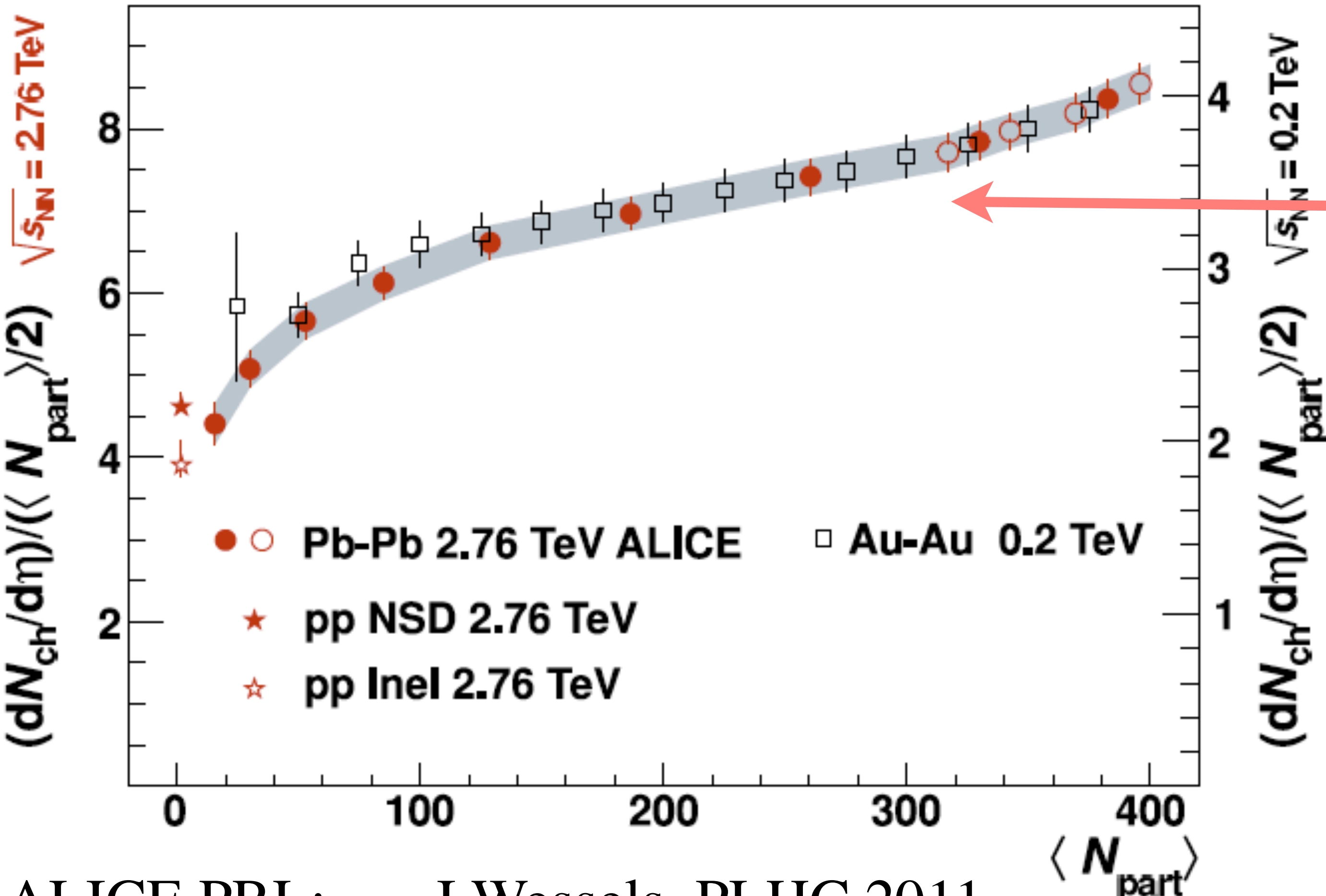
Breaking the coherence in nuclear collisions





Coherence of gluon fields inside the nuclei tames hadron multiplicities

The scaling in the centrality dependence of hadron multiplicity at RHIC and LHC



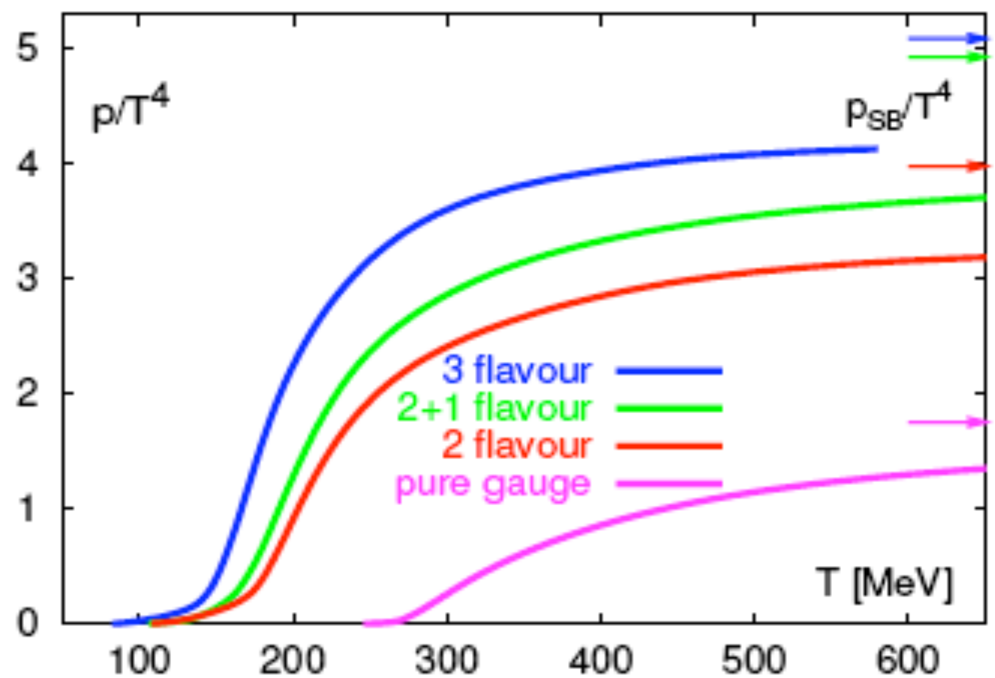
The origin of scaling within the parton saturation picture:

$$\sim \frac{1}{\alpha_s(Q_s)}$$

(KLN)

ALICE PRL; J.Wessels, PLHC 2011

QCD at high energy density: gauge fields with boundary conditions (horizons)



Phase transitions:

deconfinement

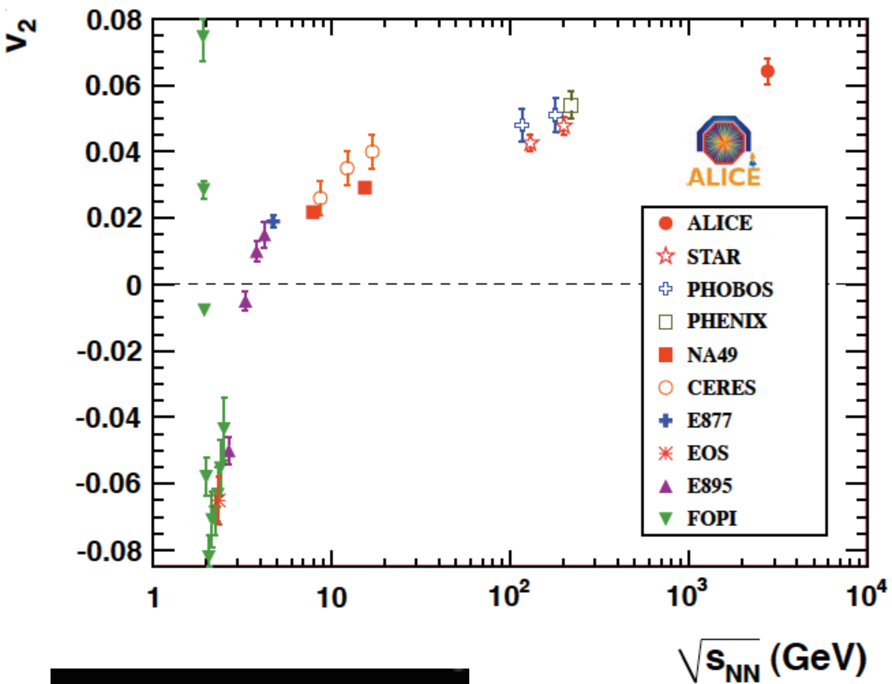
Chiral symmetry restoration

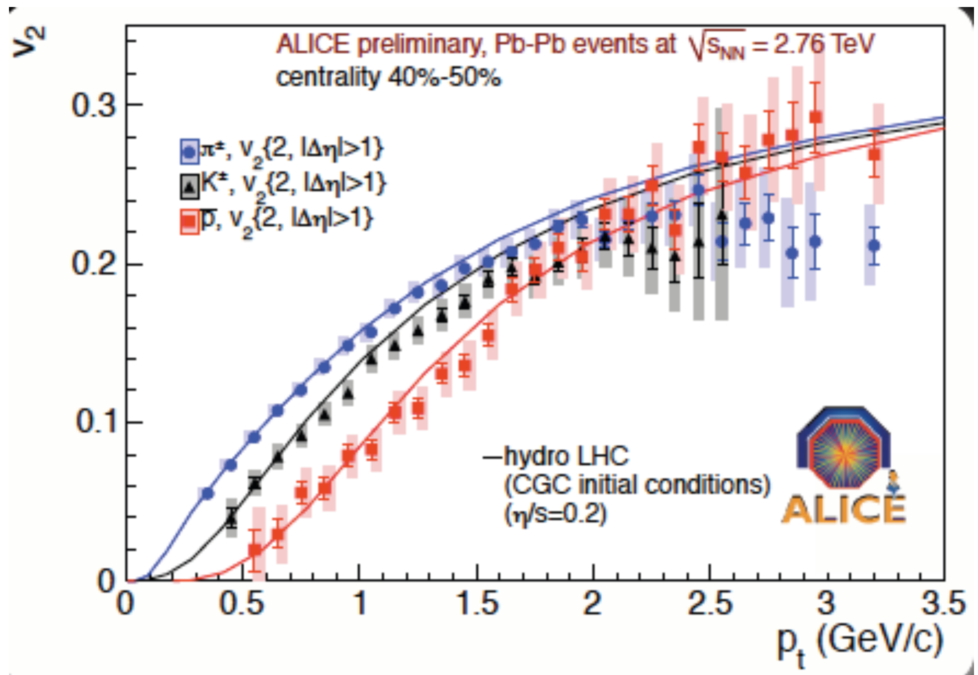
$U_A(1)$ restoration

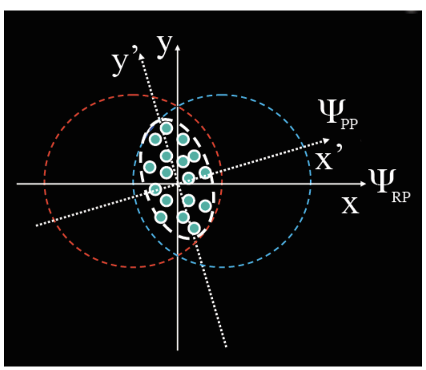
Data from lattice QCD simulations F. Karsch et al

Is T~200 MeV "hot" or "cold"? The answer depends on the strength of interactions and gauge field dynamics

How does the produced matter evolve?
The remarkable success of hydrodynamics



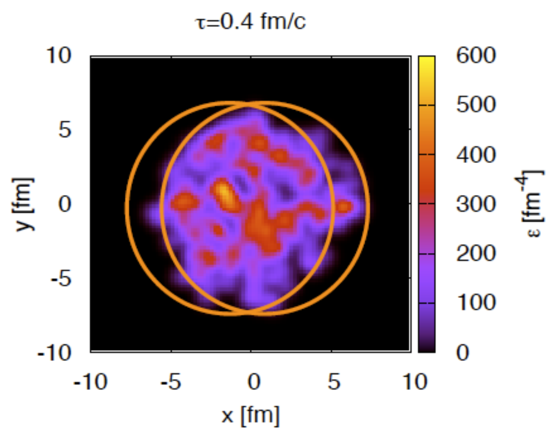




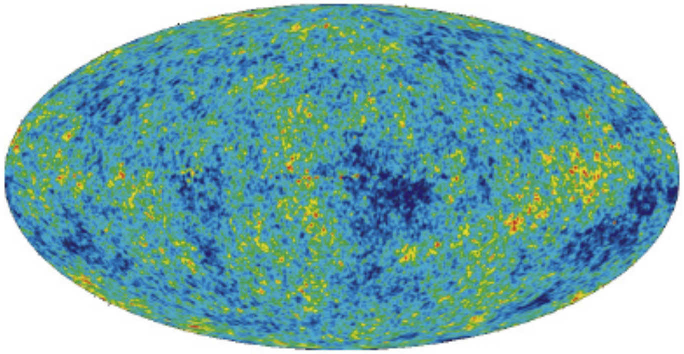
R. Snellings [ALICE Coll.] Talk at QM2011

Hydrodynamics: an effective low-energy Theory **O**f **E**verything (**TOE**)

- Hydrodynamics states that the response of the fluid to slowly varying perturbations is completely determined by conservation laws (energy, momentum, charge, ...)



Little Bang

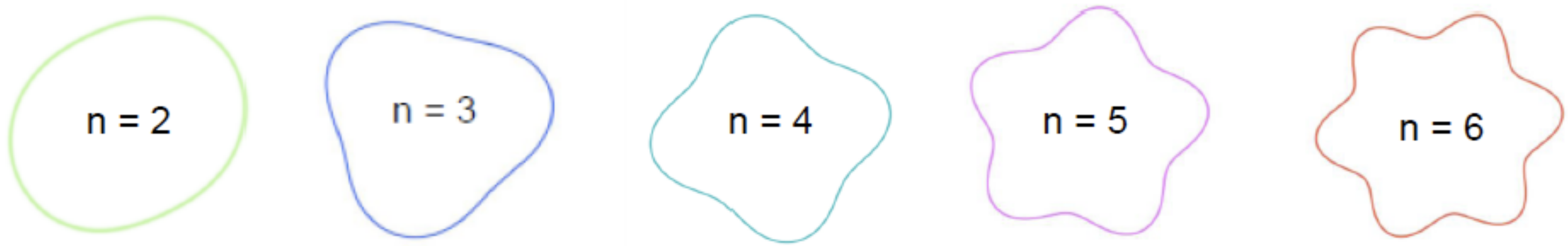


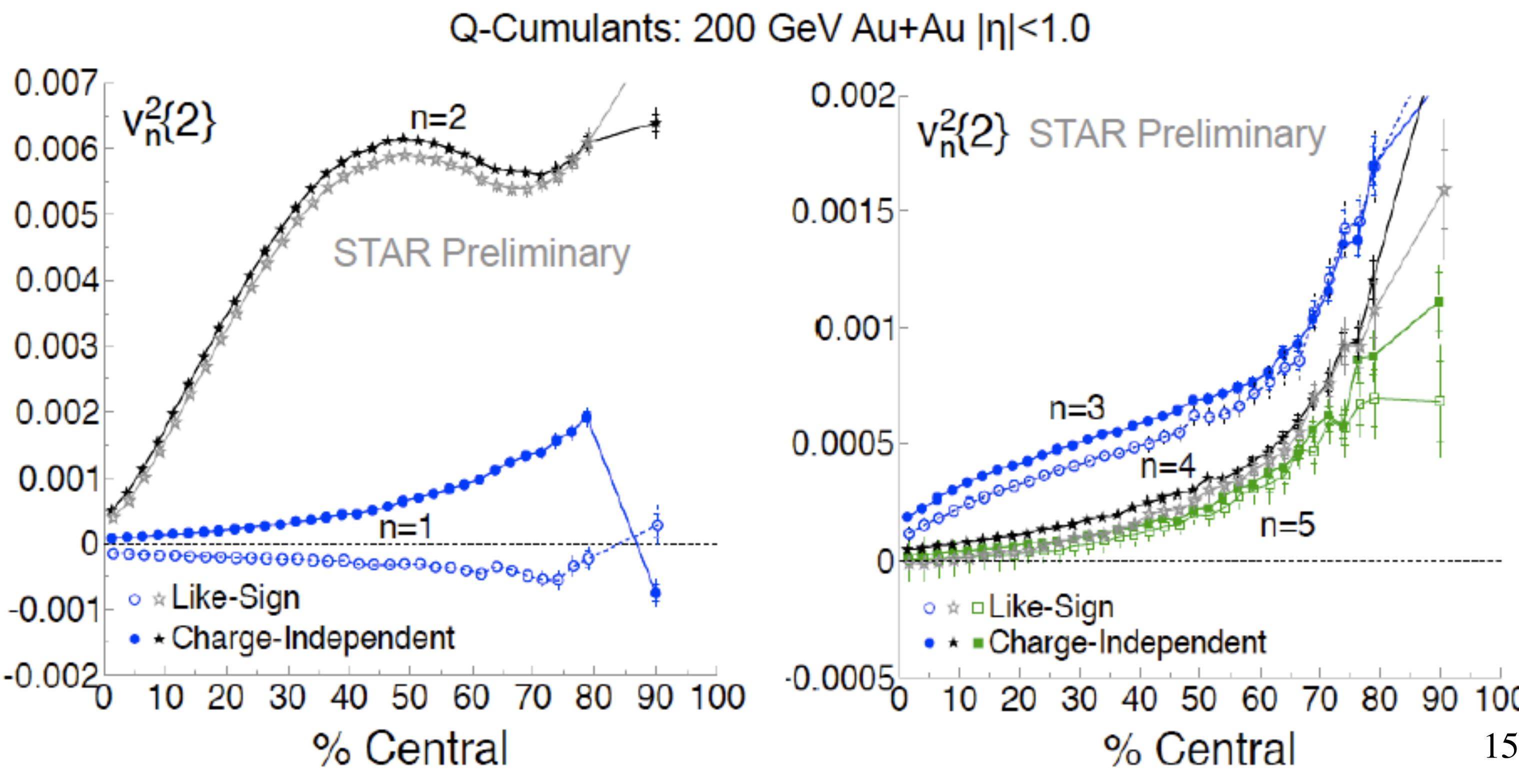
WMAP, Astrophys.J.Suppl.170:288,2007

Big Bang

Hydrodynamics

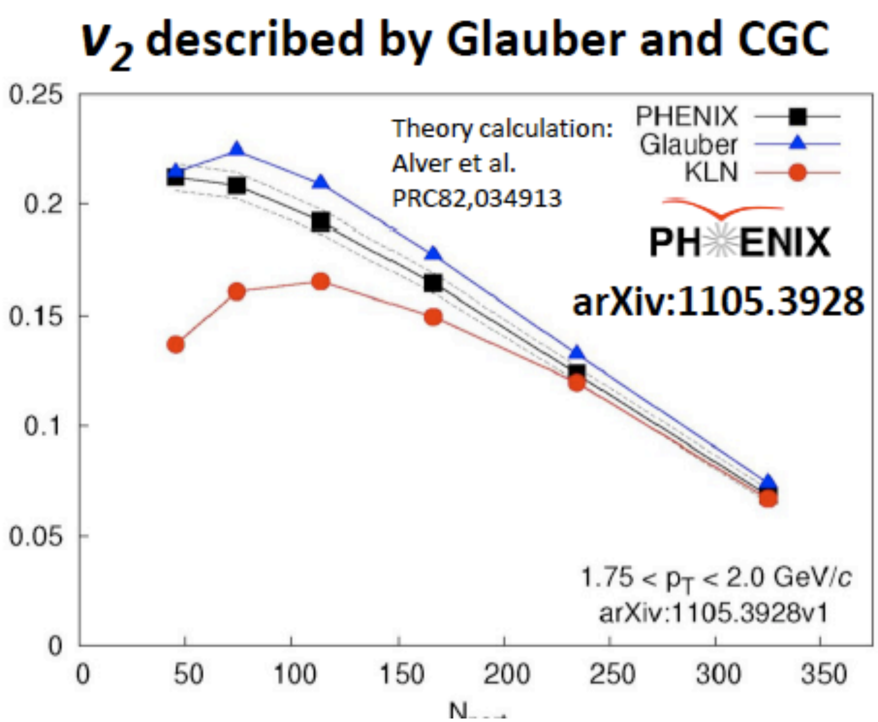
$$N_{pairs} \propto 1 + 2v_1^2 \cos\Delta\varphi + 2v_2^2 \cos 2\Delta\varphi + 2v_3^2 \cos 3\Delta\varphi + 2v_4^2 \cos 4\Delta\varphi + \ldots$$

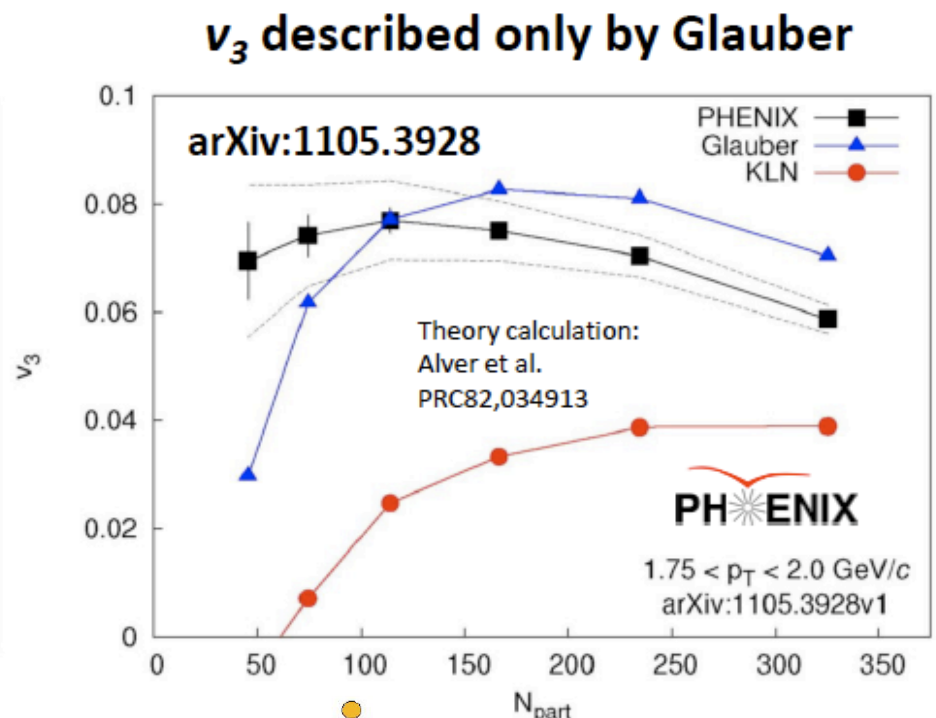




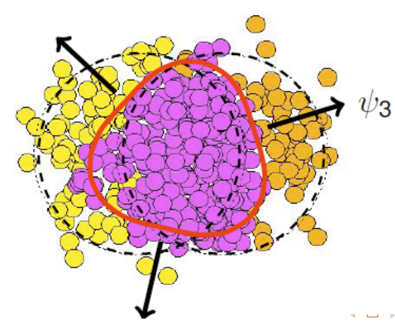
P. Sorensen
[STAR]
QM 2011

Promise to discriminate between various initial conditions using higher harmonics:

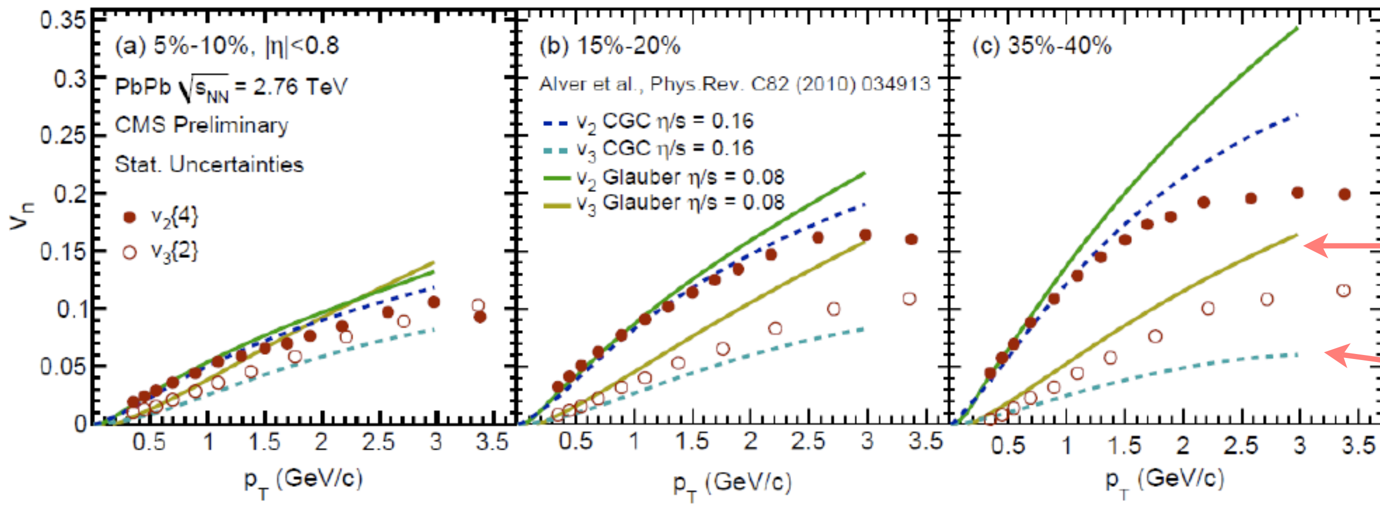




S. Bathe [PHENIX Coll] QM 2011



But more work is needed to realize it:

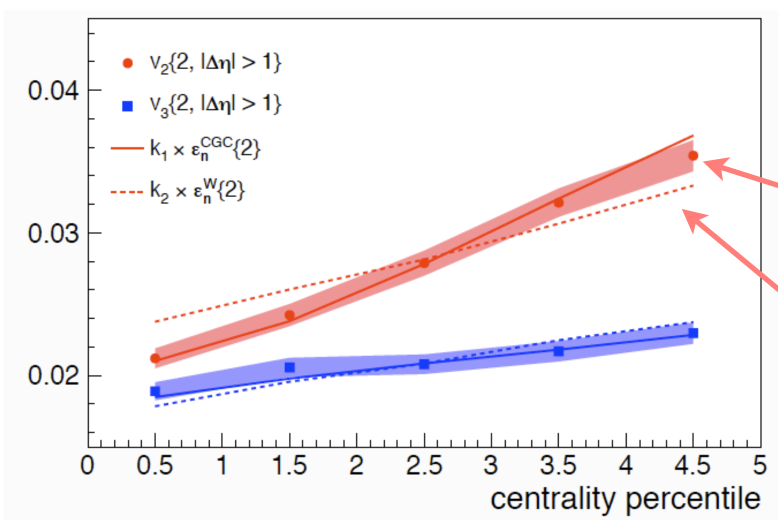


Glauber

Color Glass (KLN)

J. Velkovska [CMS Coll] QM 2011

ALICE, arXiv:1105.3865



M. Luzum, QM 2011

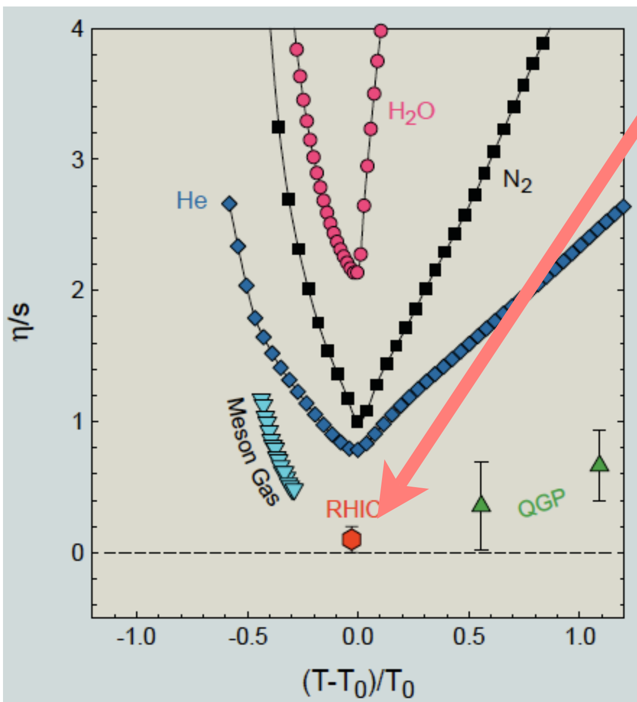
Color Glass (KLN)

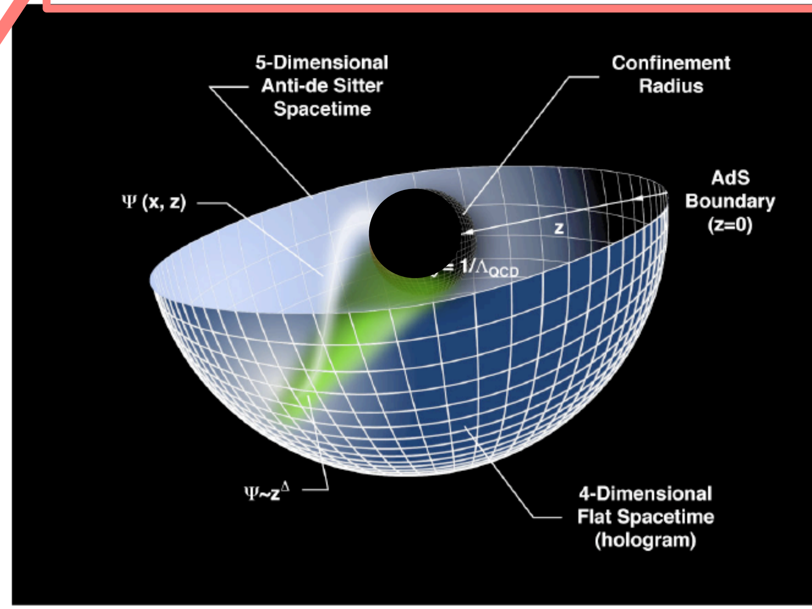
Glauber

Quantifying the transport properties of QCD matter

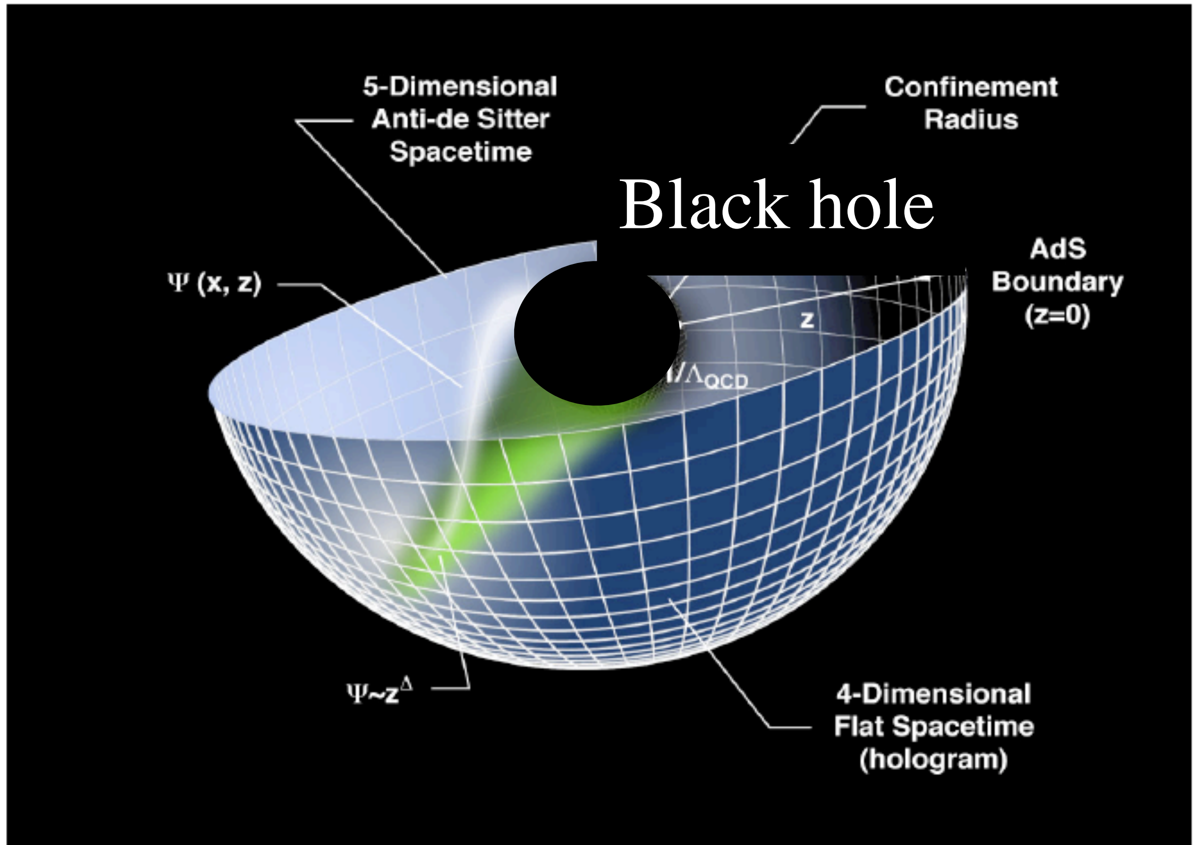
- Hydrodynamics:
  an effective low-energy theory, expansion in the ratio of thermal length 1/T to the typical variation scale L, $\epsilon \equiv \frac{1}{LT}$
- Each term in this derivative expansion is multiplied by an appropriate transport coefficient

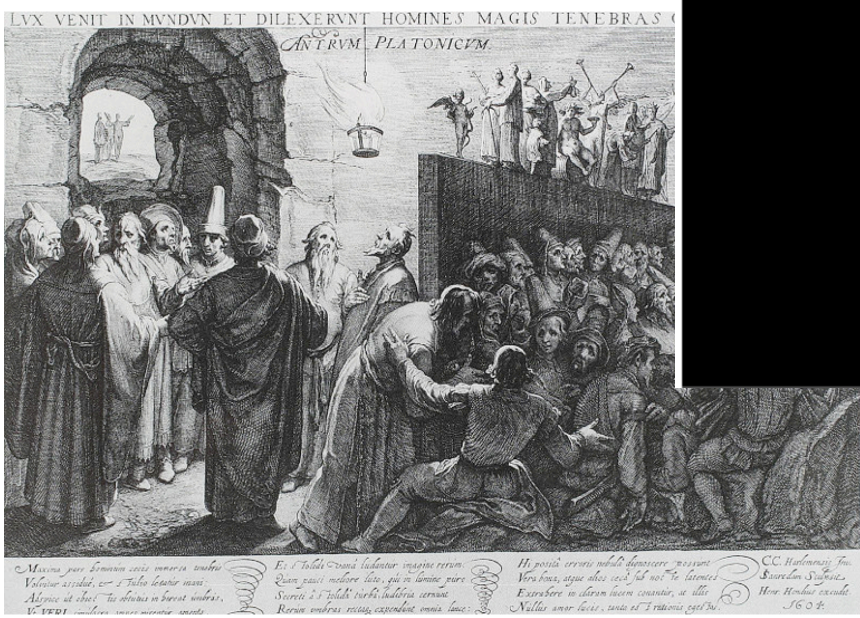
very small shear viscosity - "perfect liquid"; strong coupling!





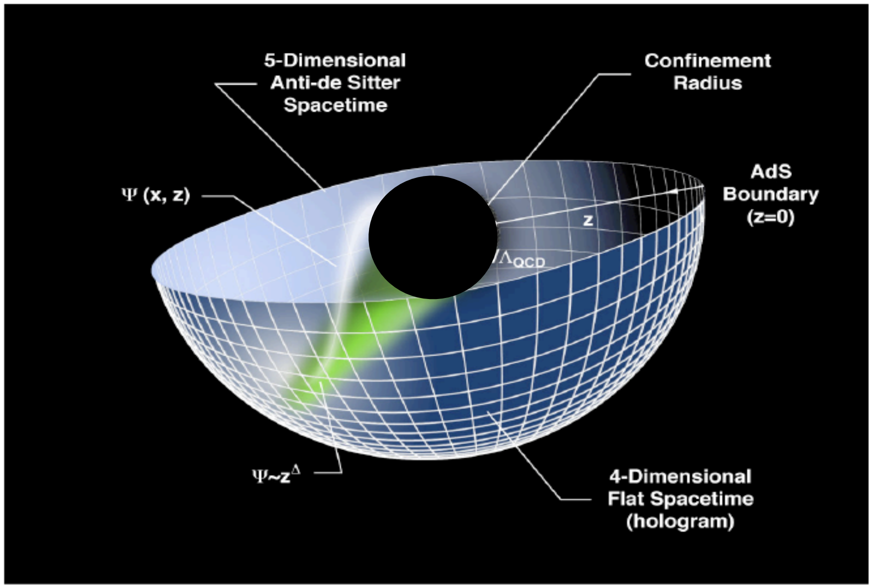
The metaphor of the cave, 2010 A.D.





“The prisoners would take the shadows to be real things and the echoes to be real sounds, not just reflections of reality, since they are all they had ever seen or heard.”

Low-energy effective ToE: hydrodynamics



Holographic view:

Particle contents of supergravity: **gravitons, dilatons, axions**

Caveman's view:

- Shear viscosity
- Bulk viscosity
- Rate of topological transitions

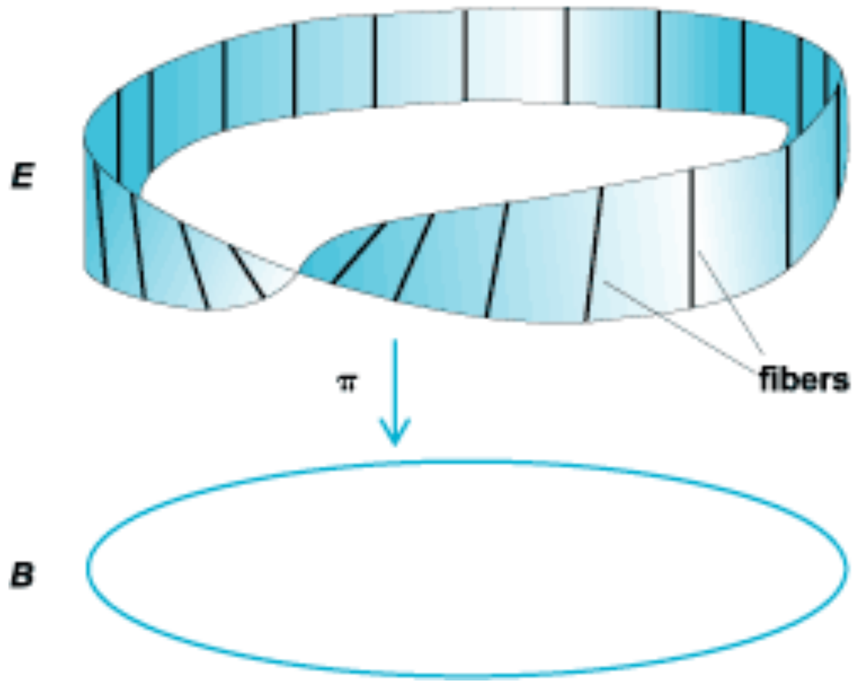
AdS_5 "Reality":

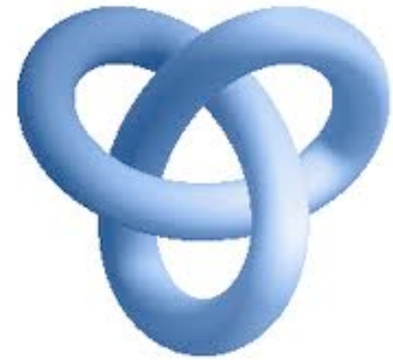
- Graviton propagation
- Dilaton propagation
- Axion propagation

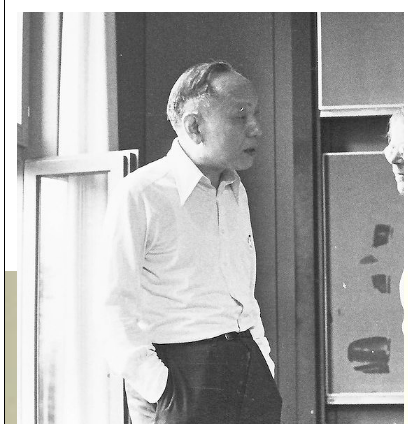
Relativistic hydrodynamics and quantum anomalies

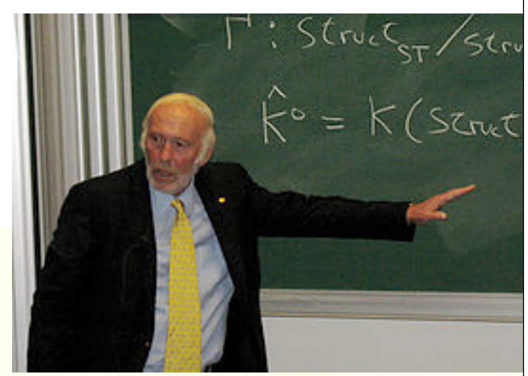
- Hydrodynamics: an effective low-energy TOE. States that the response of the fluid to slowly varying perturbations is completely determined by conservation laws (energy, momentum, charge, ...)
- Conservation laws are a consequence of symmetries of the underlying theory
- What happens to hydrodynamics when these symmetries are broken by quantum effects (anomalies of QCD and QED)?

Anomalies and topology of gauge fields









CHARACTERISTIC FORMS

$$TP_1(\theta) = \frac{1}{4\pi^2}\{\theta_{12} \wedge \theta_{13} \wedge \theta_{23} + \theta_{12} \wedge \Omega_{12} + \theta_{13} \wedge \Omega_{13} + \theta_{23} \wedge \Omega_{23}\} \; . \qquad (6.1)$$

Chiral Magnetic Effect in a chirally imbalanced plasma

Fukushima, DK, Warringa, PRD'08

Chiral chemical potential is formally equivalent to a background chiral gauge field: $\mu_5 = A_5^0$

In this background, vector e.m. current is not conserved:

$$\partial_\mu J^\mu = \frac{e^2}{16\pi^2} \left(F_L^{\mu\nu} \tilde{F}_{L,\mu\nu} - F_R^{\mu\nu} \tilde{F}_{R,\mu\nu} \right)$$

Compute the current through

$$J^\mu = \frac{\partial \log Z[A_\mu, A_\mu^5]}{\partial A_\mu(x)}$$

The result:

$$\boxed{\vec{J} = \frac{e^2}{2\pi^2} \, \mu_5 \, \vec{B}}$$

Coefficient is fixed by the axial anomaly, no corrections

Chiral magnetic conductivity: discrete symmetries

$$\vec{J} = \boxed{\frac{e^2}{2\pi^2}\,\mu_5}\,\vec{B}$$

P-odd
T-odd

P-even
T-odd

P-odd

<u>P-odd effect!</u>

T-even

<u>Non-dissipative current!</u>

(quantum computing etc)

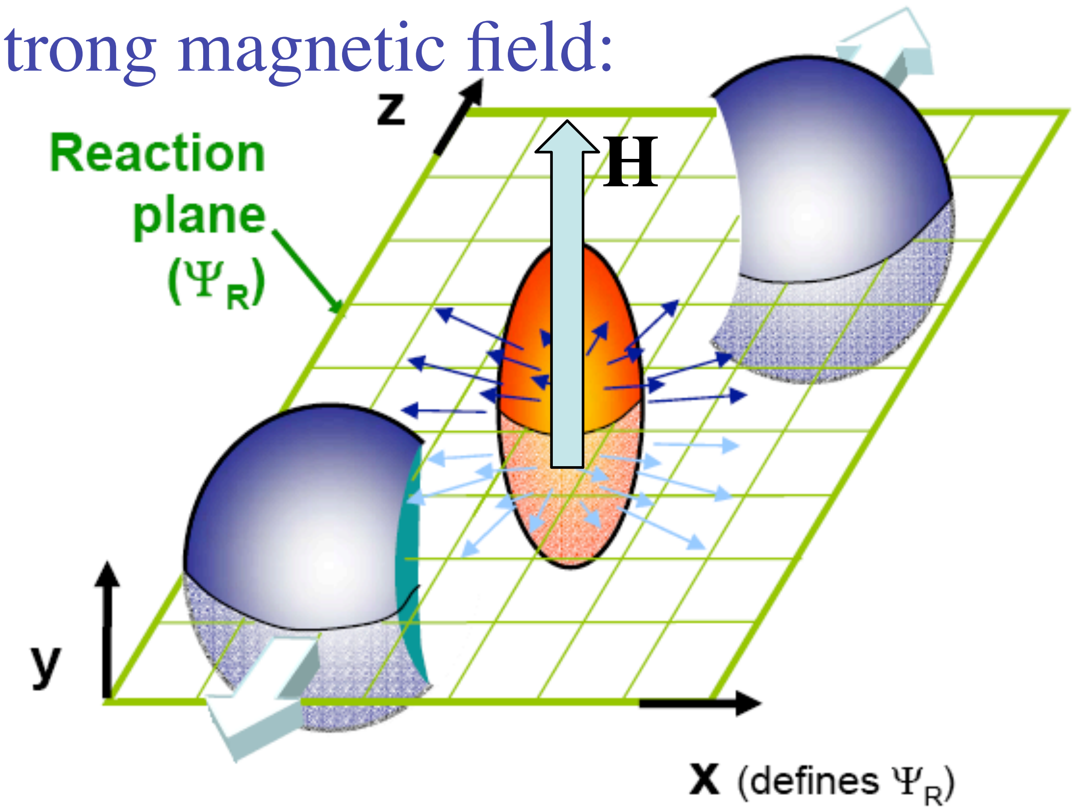
cf Ohmic conductivity:

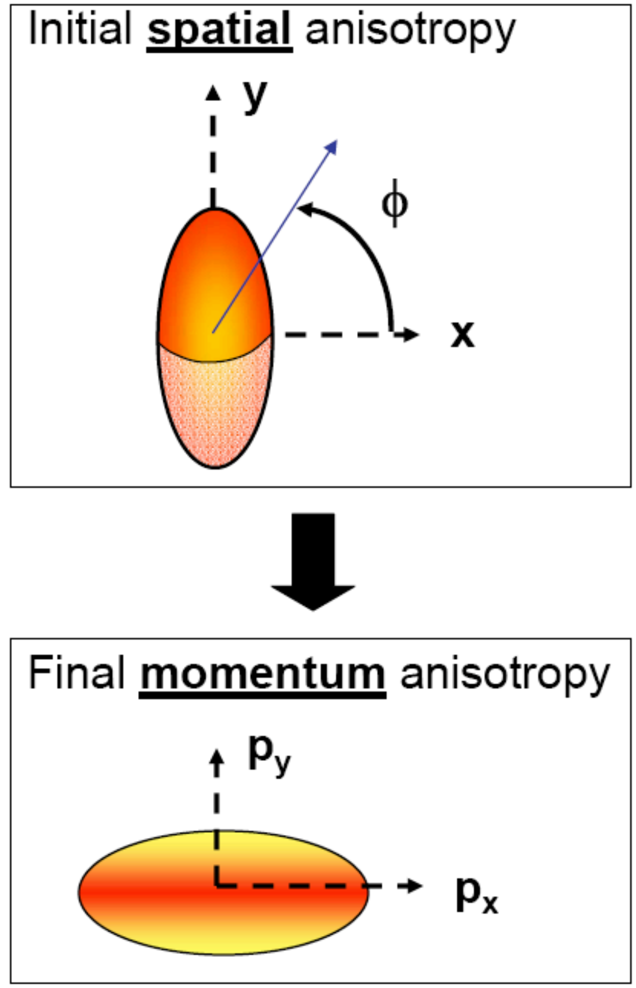
$$\vec{J} = \sigma\vec{E}$$

T-odd, dissipative

Is there a way to observe topological charge fluctuations in experiment?

Relativistic ions create a strong magnetic field:



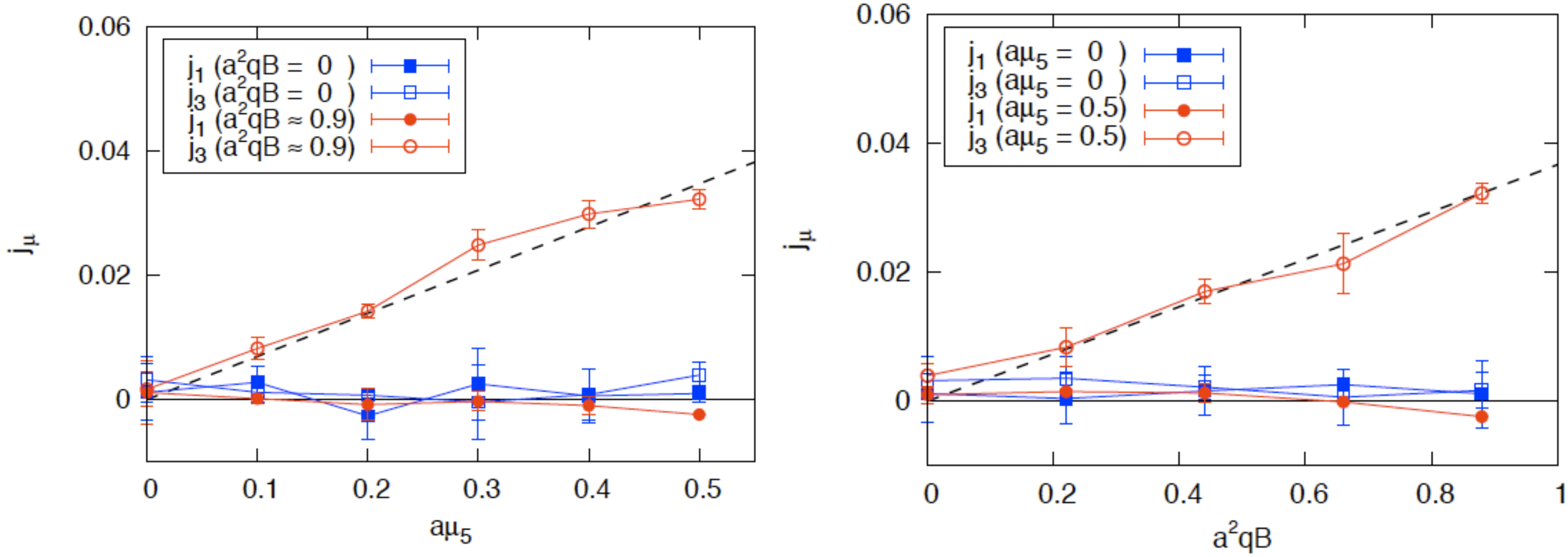


arXiv:1105.0385 May 3, 2011

Chiral magnetic effect in lattice QCD with chiral chemical potential

Arata Yamamoto
Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan
(Dated: May 3, 2011)

We perform a first lattice QCD simulation including two-flavor dynamical fermion with chiral chemical potential. Because the chiral chemical potential gives rise to no sign problem, we can exactly analyze a chirally asymmetric QCD matter by the Monte Carlo simulation. By applying an external magnetic field to this system, we obtain a finite induced current along the magnetic field, which corresponds to the chiral magnetic effect. The obtained induced current is proportional to the magnetic field and to the chiral chemical potential, which is consistent with an analytical prediction.



Chiral MagnetoHydroDynamics (CMHD) - relativistic hydrodynamics with triangle anomalies and external electromagnetic fields

First order (in the derivative expansion) formulation:
D. Son and P. Surowka, arXiv:0906.5044

Constraining the new anomalous transport coefficients:
positivity of the entropy production rate, $\partial_\mu s^\mu \geq 0$

$$\nu^\mu = -\sigma T P^{\mu\nu}\partial_\nu \left(\frac{\mu}{T}\right) + \sigma E^\mu + \xi\omega^\mu + \xi_B B^\mu,$$

CME
(for chirally imbalanced matter)

$$s^\mu = su^\mu - \frac{\mu}{T}\nu^\mu + D\omega^\mu + D_B B^\mu,$$

$$\xi = C\left(\mu^2 - \frac{2}{3}\frac{n\mu^3}{\epsilon + P}\right), \quad \xi_B = C\left(\mu - \frac{1}{2}\frac{n\mu^2}{\epsilon + P}\right).$$

Chiral MagnetoHydroDynamics (CMHD) - relativistic hydrodynamics with triangle anomalies and external electromagnetic fields

First order hydrodynamics has problems with causality and is numerically unstable, so second order formulation is necessary;

Complete second order formulation of CMHD:
DK and H.-U. Yee, 1105.6360 (June 1)

Many new transport coefficients - use conformal/Weyl invariance;
still 18 independent transport coefficients related to the anomaly.
15 that are specific to 2nd order; 13 are computed

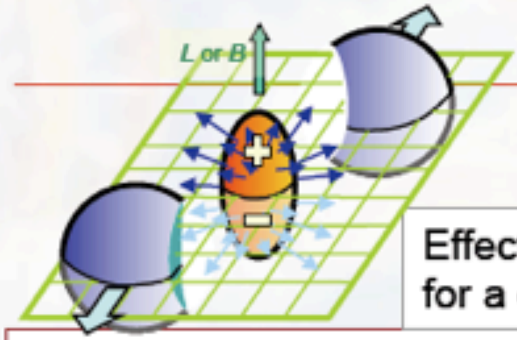
$$\sigma^{\mu\nu}\mathcal{D}_\nu\bar{\mu}\ ,\ \omega^{\mu\nu}\mathcal{D}_\nu\bar{\mu}\ ,\ \Delta^{\mu\nu}\mathcal{D}^\alpha\sigma_{\nu\alpha}\ ,\ \Delta^{\mu\nu}\mathcal{D}^\alpha\omega_{\nu\alpha}\ ,\ \sigma^{\mu\nu}\omega_\nu\ ,$$
$$\sigma^{\mu\nu}E_\nu\ ,\ \sigma^{\mu\nu}B_\nu\ ,\ \omega^{\mu\nu}E_\nu\ ,\ \omega^{\mu\nu}B_\nu\ ,u^\nu\mathcal{D}_\nu E^\mu\ , \tag{2.60}$$
$$\epsilon^{\mu\nu\alpha\beta}u_\nu E_\alpha\mathcal{D}_\beta\bar{\mu}\ ,\ \epsilon^{\mu\nu\alpha\beta}u_\nu B_\alpha\mathcal{D}_\beta\bar{\mu}\ ,\ \epsilon^{\mu\nu\alpha\beta}u_\nu E_\alpha B_\beta\ ,\ \epsilon^{\mu\nu\alpha\beta}u_\nu\mathcal{D}_\alpha E_\beta\ ,\ \epsilon^{\mu\nu\alpha\beta}u_\nu\mathcal{D}_\alpha B_\beta\ .$$

new

Many new anomaly-induced phenomena!

Observable

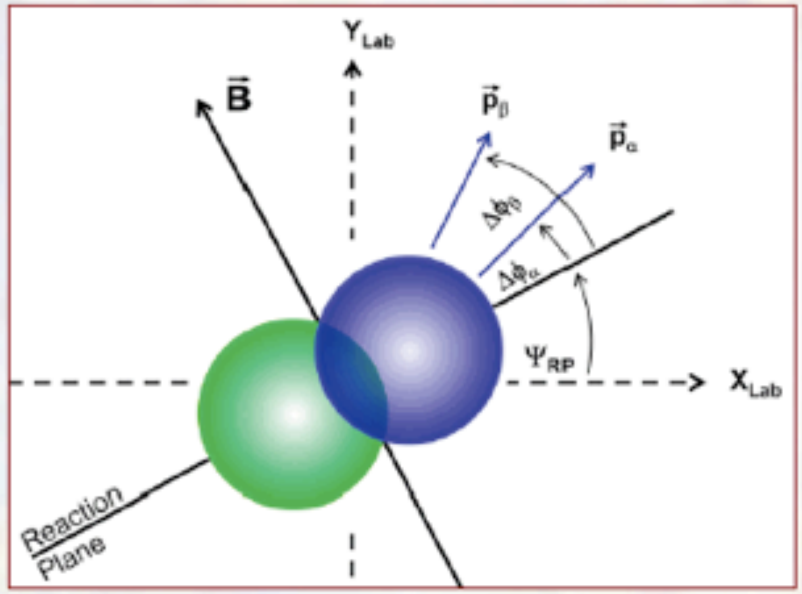
S.A. Voloshin, Phys. Rev. C 70 (2004) 057901



Effective particle distribution for a certain Q.

$$\frac{dN_\alpha}{d\phi} \propto 1 + 2v_{1,\alpha}\cos(\Delta\phi) + 2\,v_{2,\alpha}\cos(2\Delta\phi) + \ldots$$
$$+\ 2a_{1,\alpha}\sin(\Delta\phi) + 2\,a_{2,\alpha}\sin(2\Delta\phi) + \ldots,$$

$$\Delta\phi = (\phi - \Psi_{RP})$$



- The effect is too small to observe in a single event
- The sign of Q varies and $\langle a \rangle = 0$ (we consider only the leading, first harmonic) ➔ one has to measure correlations, $\langle a_\alpha a_\beta \rangle$, $\mathcal{P}$-even quantity (!)
- $\langle a_\alpha a_\beta \rangle$ is expected to be ~ 10^{-4}
- $\langle a_\alpha a_\beta \rangle$ can not be measured as $\langle \sin\varphi_\alpha \sin\varphi_\beta \rangle$ due to large contribution from effects not related to the orientation of the reaction plane
  ➔ study the difference in corr's in- and out-of-plane

Slide from S. Voloshin

$$\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle =$$
$$= \langle\cos\Delta\phi_\alpha\,\cos\Delta\phi_\beta\rangle - \langle\sin\Delta\phi_\alpha\,\sin\Delta\phi_\beta\rangle$$
$$= [\langle v_{1,\alpha}v_{1,\beta}\rangle + B^{in}] - [\boxed{\langle a_\alpha a_\beta\rangle} + B^{out}].$$

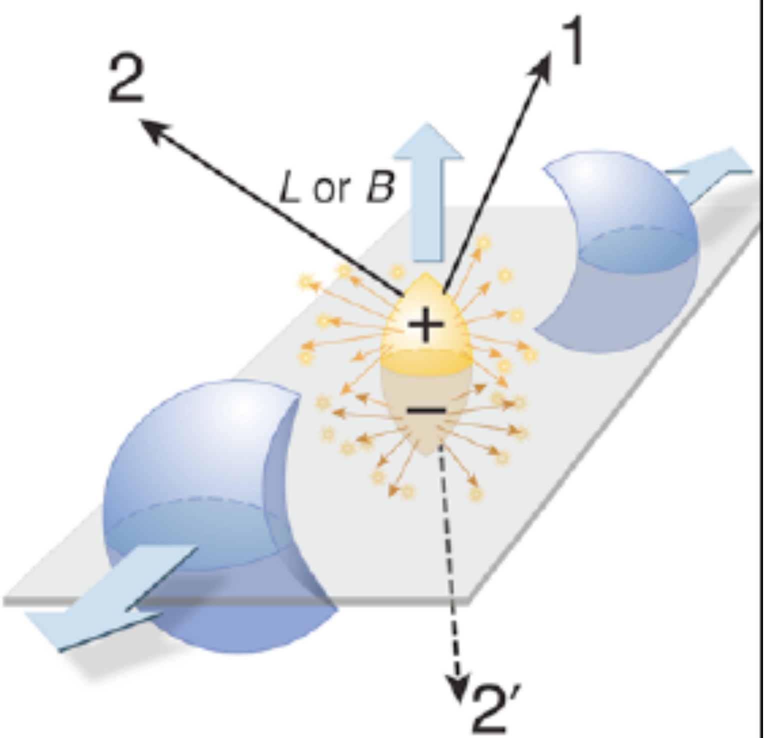
$$B^{in} \approx B^{out}, \quad v_1 = 0$$

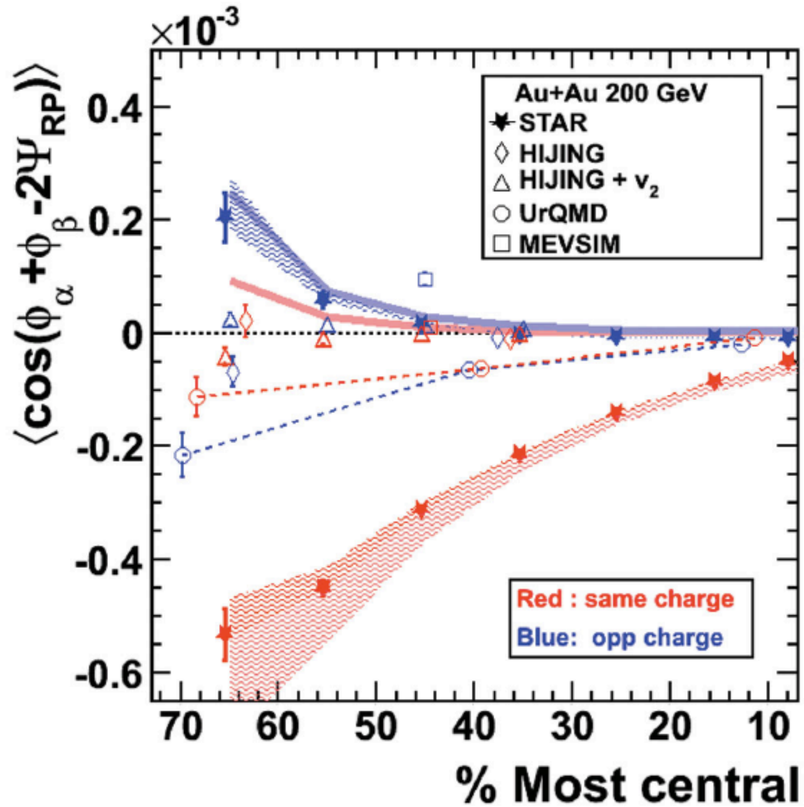
A practical approach: three particle correlations: $\langle\cos(\phi_a + \phi_\beta - 2\phi_c)\rangle = \langle\cos(\phi_a + \phi_\beta - 2\Psi_{RP})\rangle\, v_{2,c}$

Selected for a Viewpoint in *Physics*
PRL **103,** 251601 (2009) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

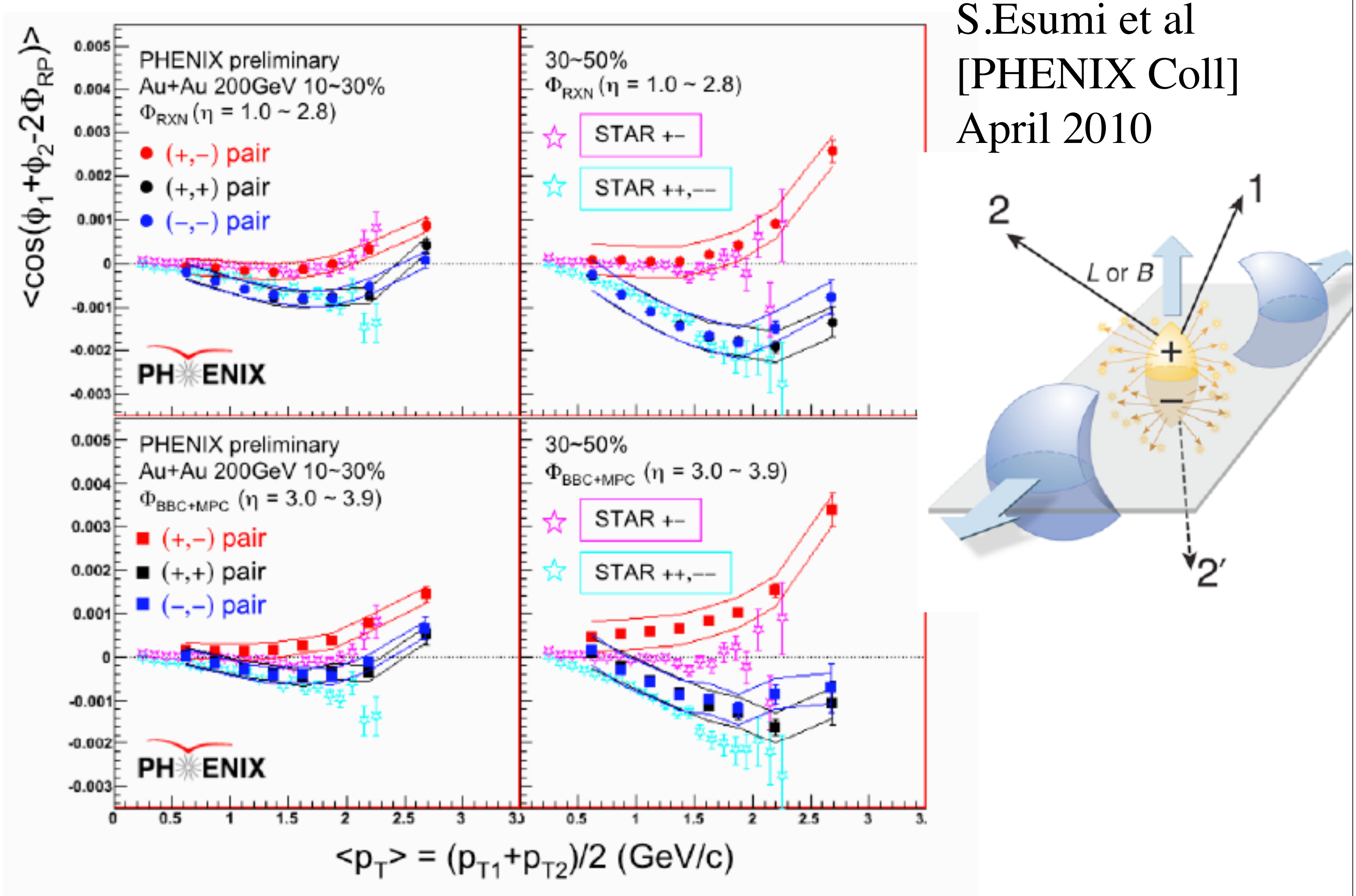
(STAR Collaboration)





NB: P-even quantity (strength of P-odd fluctuations); consistent with the measured balance functions (dynamical charge correlations) - Talk by G. Westfal; ongoing work

S.Esumi et al
[PHENIX Coll]
April 2010



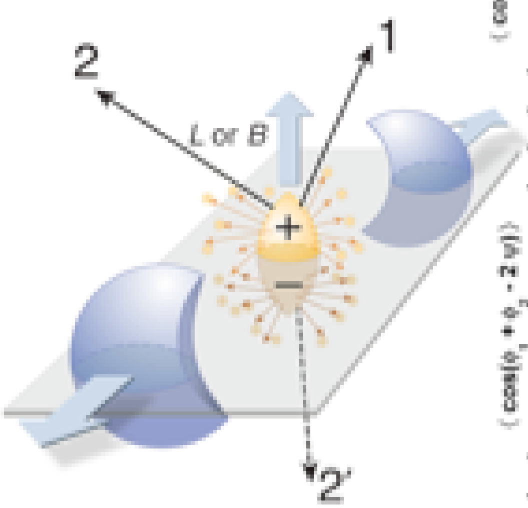
Relatively good agreement between PHENIX & STAR

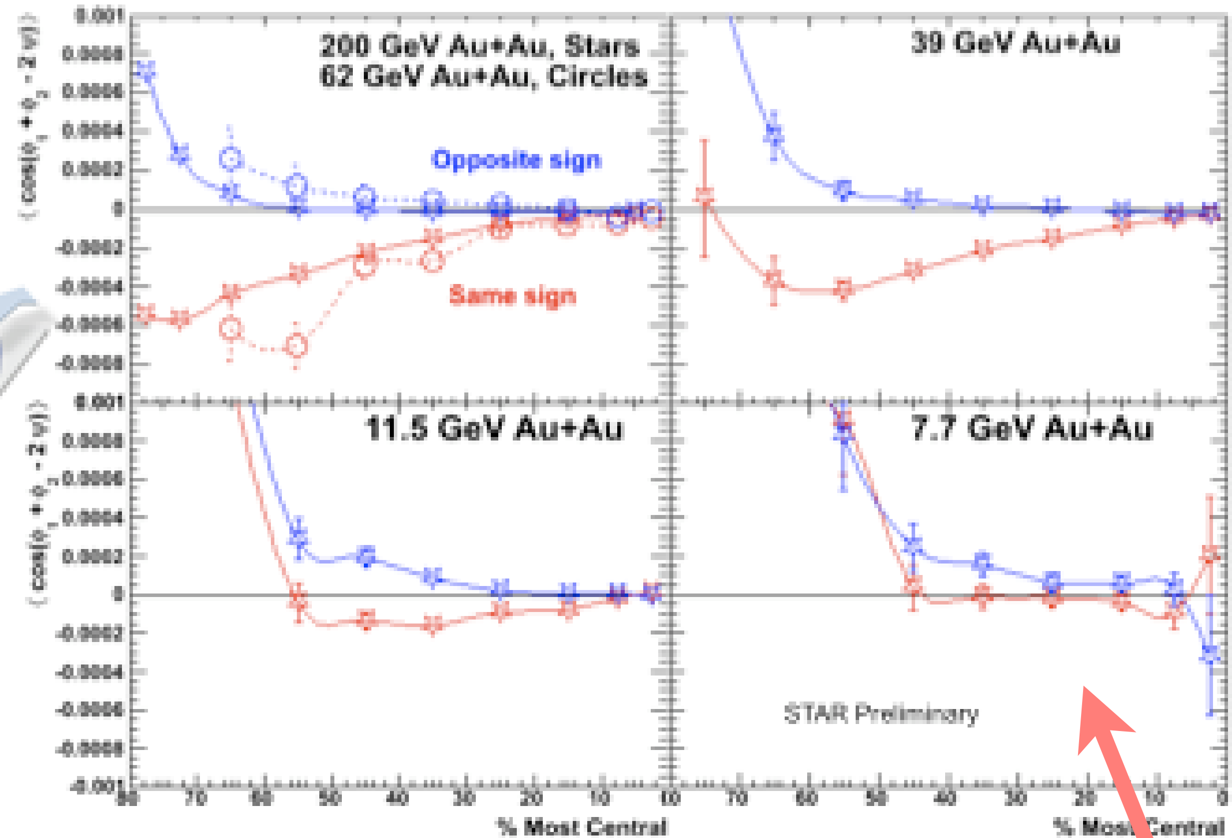
B. Mohanty [STAR Coll] QM 2011

Dynamical Charge Correlations

Observations:

Measurement of charge correlations with respect to event plane

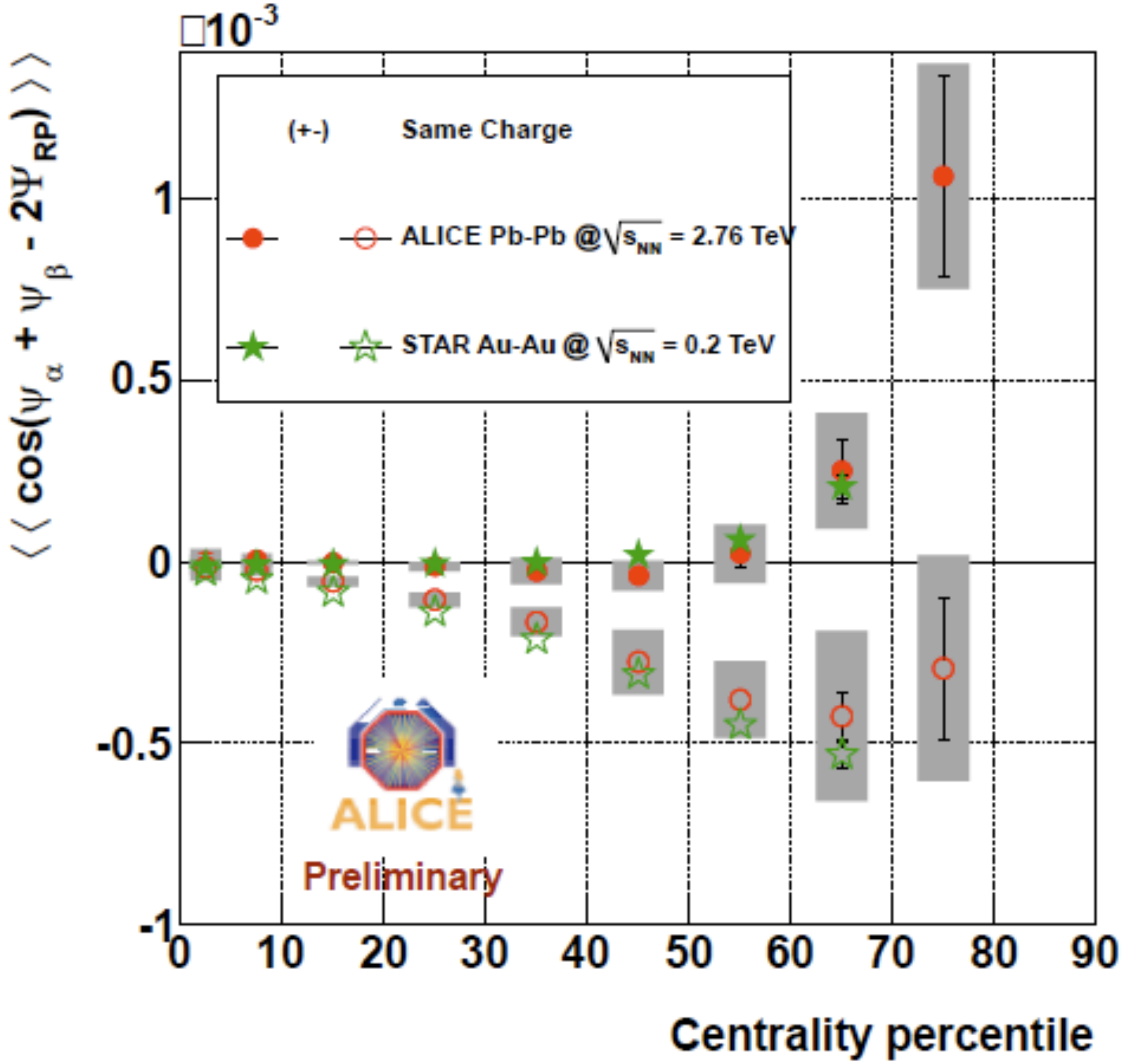




Difference between same sign and opposite sign charge correlations decreases as beam energy decreases.
Same sign charge correlations become positive at 7.7 GeV.

Signal disappears

CME studies at the LHC

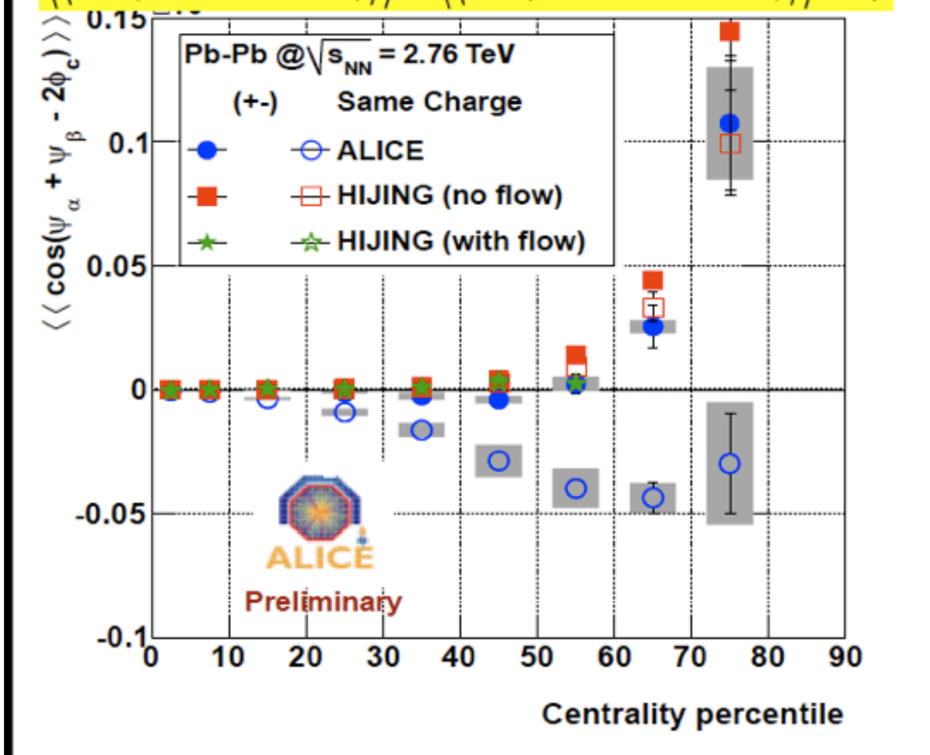


P. Cristakoglou, J. Schukraft [ALICE Coll] Talks at QM 2011

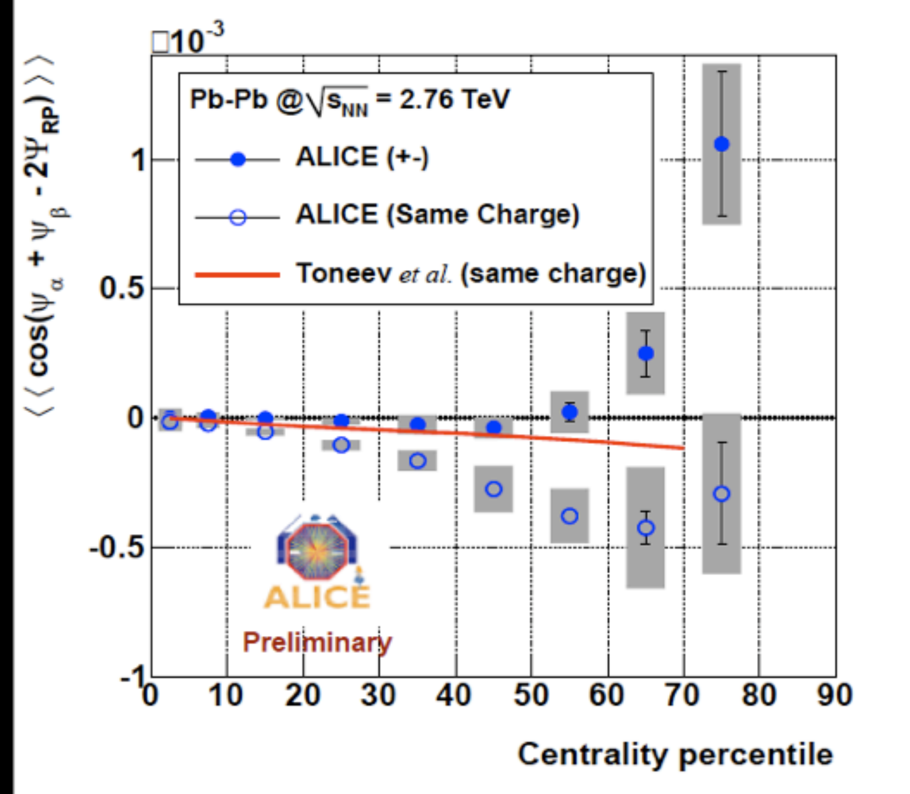
Comparison with models

S. A. Voloshin, Phys. Rev. C **70**, 057901 (2004).

$$\langle\langle\cos(\psi_a+\psi_b-2\phi_c)\rangle\rangle = \langle\langle\cos(\psi_a+\psi_b-2\Psi_{RP})\rangle\rangle \square v_{2,c}$$



V.D. Toneev and V. Voronyuk, arXiv:1012.1508v1 [nucl-th]



P. Cristakoglou [ALICE Coll] Talk at QM 2011

A new test: baryon asymmetry

DK, D.T.Son
arXiv:1010.0038; PRL

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}]$$

CME

Vorticity-induced
"Chiral Vortical Effect"

$$J_E^{CME} \sim \frac{2}{3} \;\; (N_f = 3) \;\; \text{or} \;\; \frac{5}{9} \;\; (N_f = 2)$$

$$J_B^{CME} = 0 \;\; (N_f = 3) \;\; \text{or} \;\; \sim \frac{1}{9} \;\; (N_f = 2).$$

CME:
(almost) only
electric charge

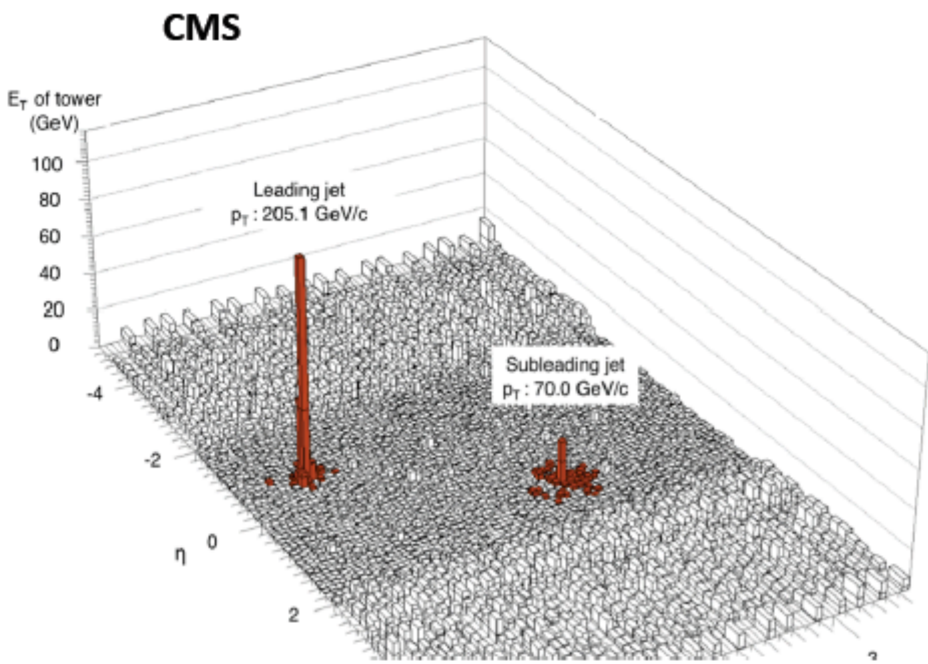
$$J_E^{CVE} = 0 \;\; (N_f = 3) \;\; \text{or} \;\; \sim \frac{1}{3} \;\; (N_f = 2);$$

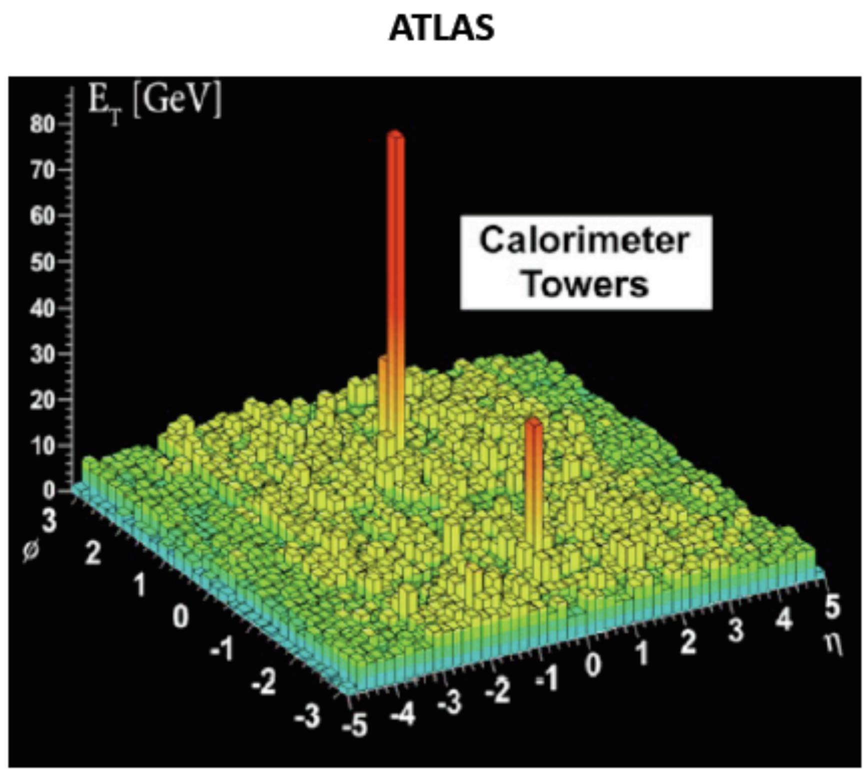
CVE:
(almost) only
baryon charge

$$J_B^{CVE} \sim 1 \;\; (N_f = 3) \;\; \text{or} \;\; \sim \frac{2}{3} \;\; (N_f = 2).$$

There has to be a positive correlation between
electric charge and baryon number! mixed correlators - e.g. $\Lambda \;\; \pi^+$

Response of QCD matter to fast collimated perturbations (**jets**)

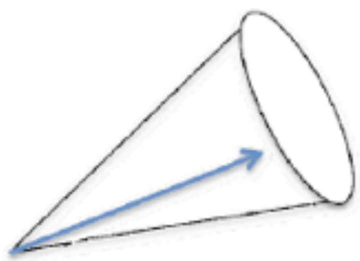




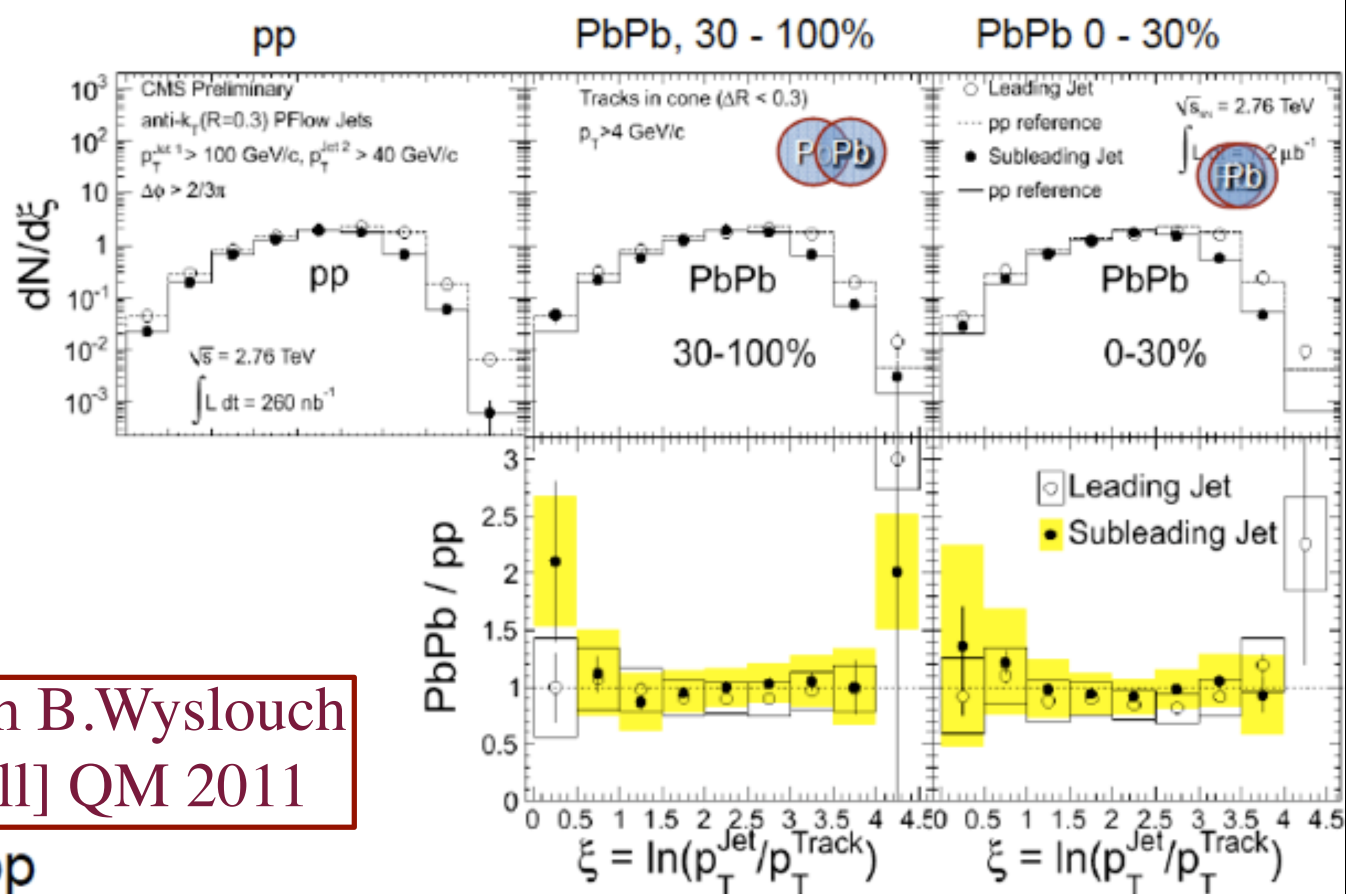
Jets in QCD matter: suppressed, but shape unmodified?

Updated jet algorithm: Particle Flow, Anti-k_T, R=0.3

Charged tracks, p_T^{Track} >4 GeV/c, jets with p_T^{Jet} =40-300 GeV/c



$$\xi = \ln\left(\frac{p_T^{Jet}}{p_T^{Track}}\right)$$



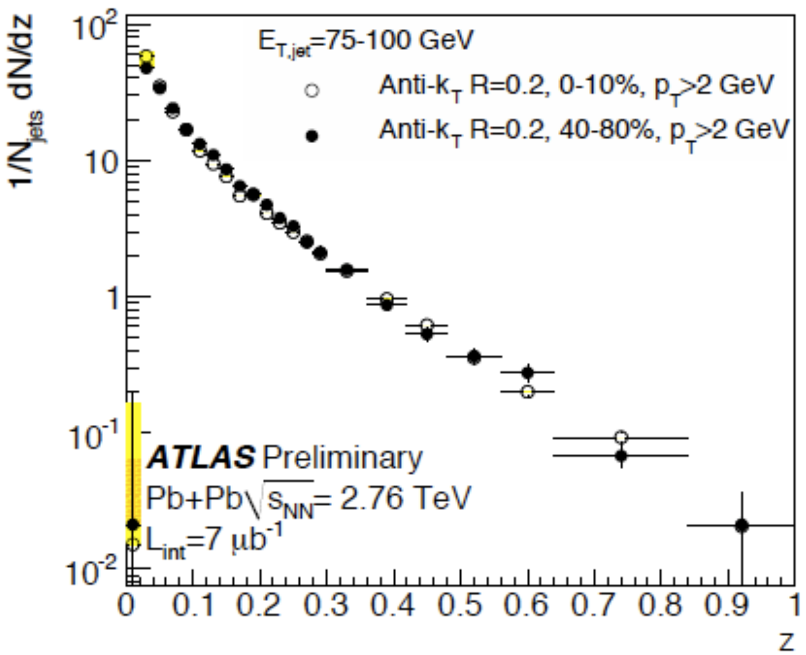
Slide from B.Wyslouch [CMS Coll] QM 2011

Compare PbPb to pp

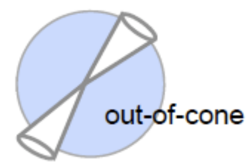
– Fragmentation function similar between PbPb and pp

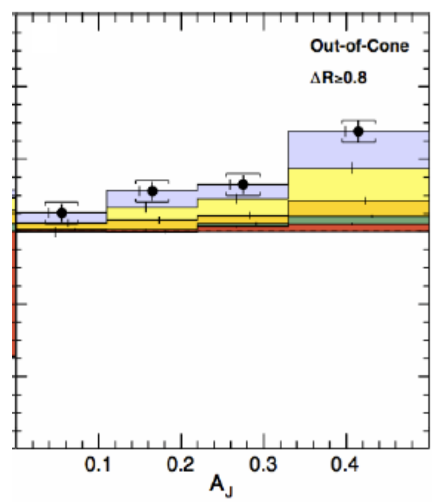
Jets in QCD matter: suppressed, but shape unmodified?

No change in shape between central and peripheral collisions



P.Steinberg [ATLAS Coll] QM 2011





Out-off-cone low p_T particles balance the complete event

B. Wyslouch [CMS Coll] QM 2011

L. Pontecorvo [ATLAS Coll] PLHC 2011

G. Tonelli [CMS Coll] PLHC 2011

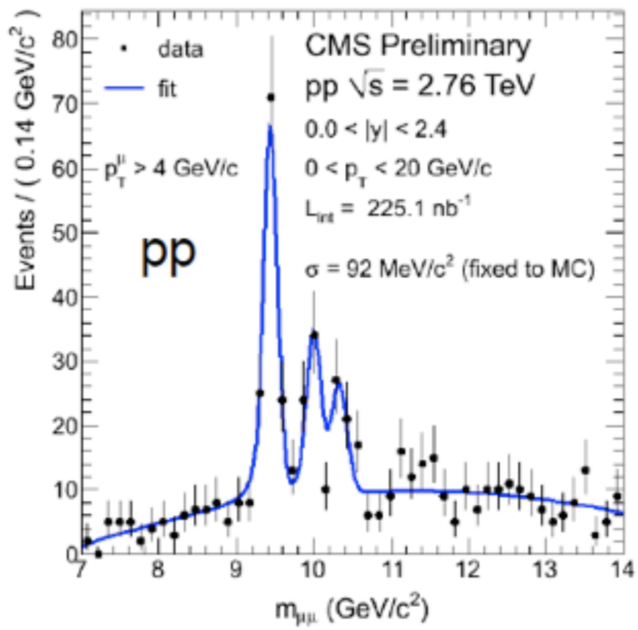
Formation time of gluon radiation

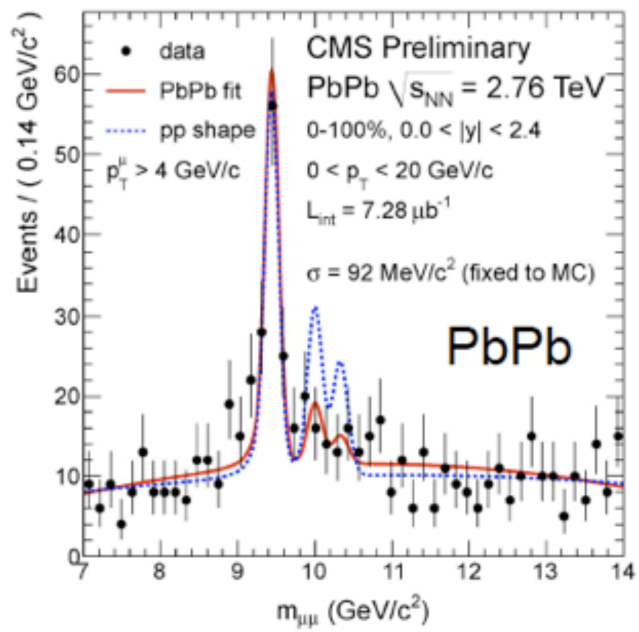
$$t_f \sim \frac{\omega}{k_\perp^2} \sim \frac{1}{k_\perp}\frac{1}{\theta}$$

- do not expect modification at small angle, large z; but: surprise at small z, large angles

The plasma thermometer: quarkonium suppression

Suppression of excited Υ states





$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$

$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$

Slide from B.Wyslouch [CMS Coll] QM 2011

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- Excited states Υ(2S,3S) relative to Υ(1S) are suppressed

Understanding the dynamics of gauge fields with heavy ions

Problem		Measurements
Weak/vacuum fields	⟷	Jets, parton fragmentation
Strong static fields	⟷	Small x distributions in nuclei
Real-time dynamics	⟷	EM probes, jets, heavy quarks
Gauge fields with boundary conditions/ event horizons	⟷	Bulk behavior, soft photons and dileptons
Low-energy effective Theory of Everything: hydrodynamics	⟷	Transport properties: shear and bulk viscosities, vorticity
Topology of gauge fields; Chiral MagnetoHydroDynamics	⟷	Chiral magnetic effect

Summary

Heavy ions at LHC and RHIC offer a unique window into the dynamics of Quantum ChromoDynamics under extreme conditions

New results with broad significance not limited to nuclear/particle physics