Collective effects at the LHC

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Disclaimer - talk is based on the listed below papers:

- On the ridge-like structures in the nuclear and hadronic reactions: S.M. Troshin & N.E. Tyurin. [arXiv:1009.5229] (Sep 2010)
- Unitarity: confinement and collective effects in hadron interactions: S.M. Troshin & N.E. Tyurin. [arXiv:1005.1731] (May 2010)
- Energy dependence of average transverse momentum in hadron production due to collective effects: S.M. Troshin & N.E. Tyurin. Mod.Phys.Lett. A25: 1315-1324, 2010

Plan of the talk

- Reflective scattering and possible existence of hadronic liquid state at high temperatures (relevant for the LHC energies)
- Third vacuum state and strongly interacting transient state in proton collisions
- Rotation of transient matter: average transverse momentum and the ridge structures in proton-proton collisions.

- Reflective scattering and possible existence of hadronic liquid state at high temperatures (relevant for the LHC energies)

Elastic scattering (pure imaginary case)

- In impact parameter representation (2->2)

$$S(s,b)=(1-U(s,b))/(1+U(s,b))$$

- Physical interpretation for U can be provided as a quantity related somehow to the scattering dynamics of the confined objects

Reflective elastic scattering

- Models and experiment: U(s,b) increases with energy (like power) and decreases with impact parameter (like exponent).
- From relation of S with U: at very high energies (small b) S(s,b)<0 – it is treated as a reflective scattering (by analogy with optics)
- Reflective scattering starts to appear at the energy s_R

$$U(s_R, b=0) = 1$$

Unitarity relation in terms of U(s,b)

- Amplitude of elastic scattering f(s,b):

$$S(s,b) = 1 + 2if(s,b)$$

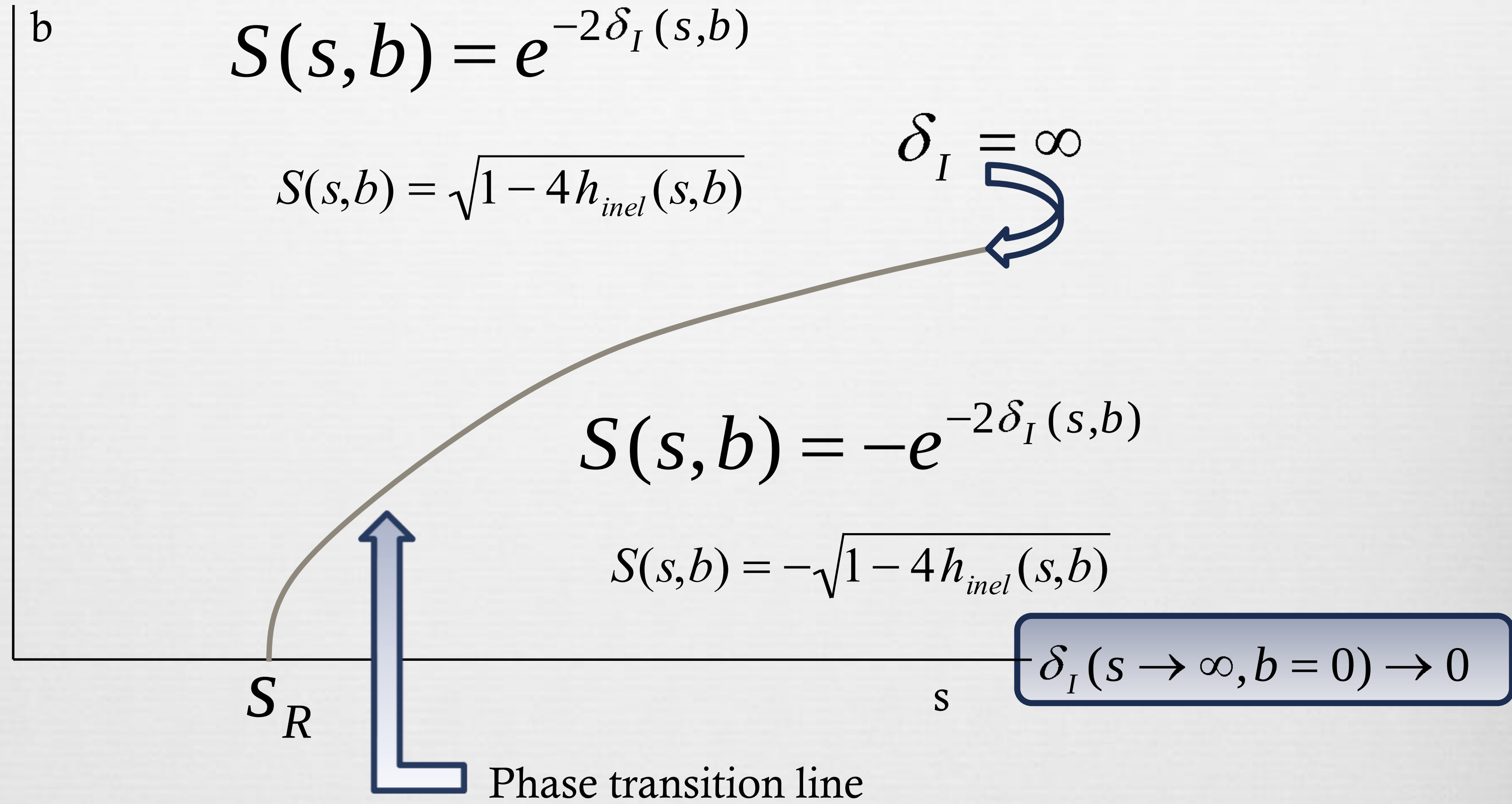
$$\operatorname{Im} f(s,b) = h_{el}(s,b) + h_{inel}(s,b)$$

$$h_{inel}(s,b) = U(s,b)/(1+U(s,b))^2$$

$$h_{el}(s,b) = U^2(s,b)/(1+U(s,b))^2$$

Horizon of reflective elastic scattering

- At the energy values $s > s_R$ $S(s,b) = 0$ has solution at $b = R(s)$ - equation for the horizon of reflective elastic scattering
- The probability of reflective elastic scattering is equal to zero at $b \geq R(s)$
- Logarithmic dependence of R(s)



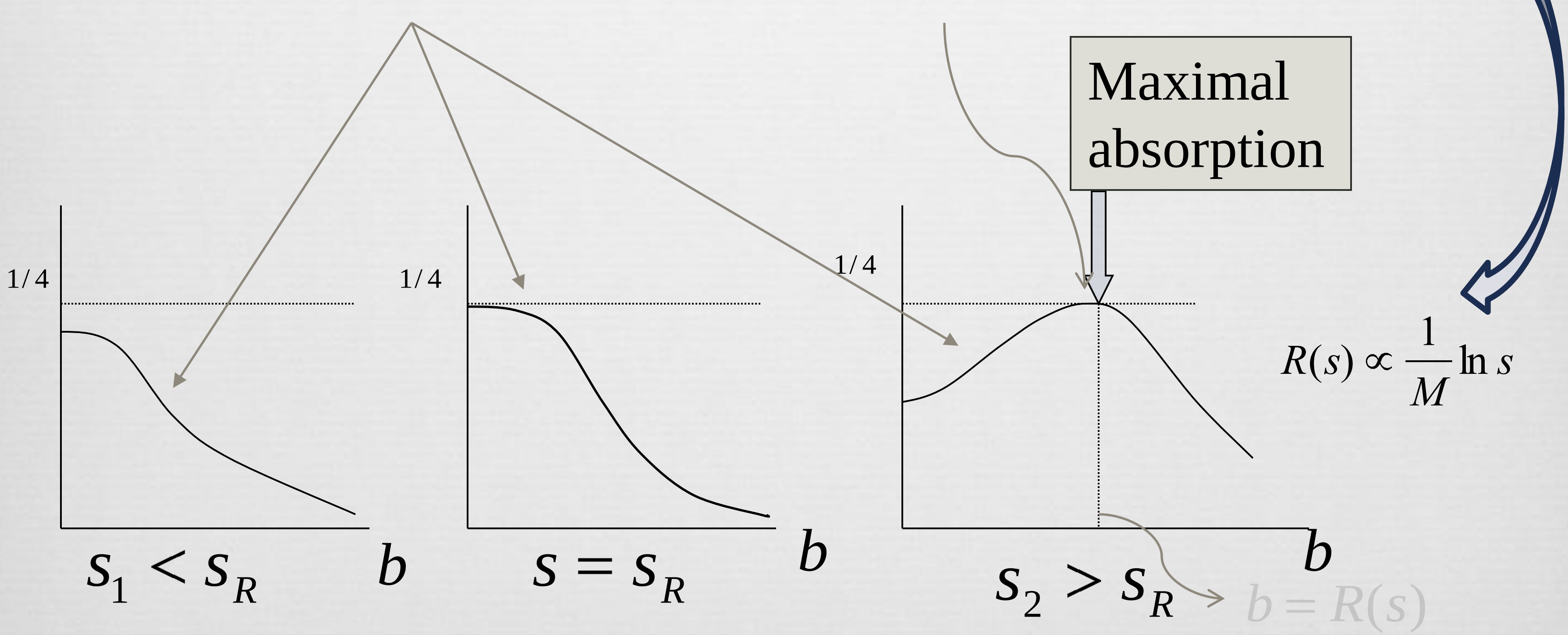
b
$S(s,b) = e^{-2\delta_I(s,b)}$
$S(s,b) = \sqrt{1-4h_{inel}(s,b)}$
$\delta_I = \infty$
$S(s,b) = -e^{-2\delta_I(s,b)}$
$S(s,b) = -\sqrt{1-4h_{inel}(s,b)}$
$\delta_I(s\to\infty, b=0)\to 0$
s_R
s
Phase transition line

$$h_{inel}(s,b) \equiv \frac{1}{4\pi}\frac{d\sigma_{inel}}{db^2}$$

$$U(s, b = R(s)) = 1$$

$$\Downarrow$$

$$h_{inel}(s, b = R(s)) = 1/4$$



Reflective scattering and hadronic liquid

- Presence of reflective scattering can be accounted for by the van der Waals method
- Reflective scattering simulates a presence of repulsive cores and acts in the opposite direction to deconfinement
- Hadron liquid density:

$$n_R(T,\mu) = n(T,\mu)/(1+\kappa(s)n(T,\mu))$$

$$n_R(T,\mu) \approx 1/\kappa(s) \approx M^3/\ln^3 s$$

- Third vacuum state and strongly interacting transient state in proton collisons

Microscopic mechanism and third vacuum state

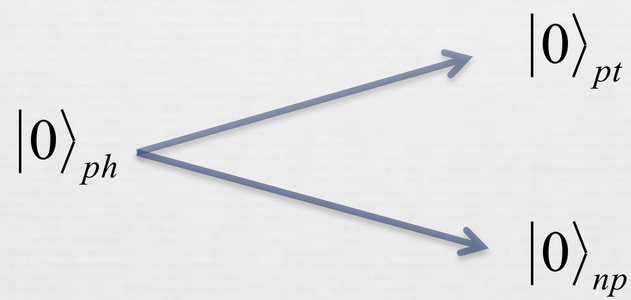
- The same scale of confinement-deconfinement transition and restoration of chiral symmetry?
- Another situation might be realized and it assumes different scales mentioned above, it implies- nonperturbative vacuum in the hadron interior
- Generation of masses of quarks: effective degrees of freedom – constituent quarks and Goldstone bosons

Quark-pion hadron structure

- At short distances vacuum is perturbative $|0\rangle_{pt}$ and current quarks and gluons are the relevant degrees of freedom
- Outside hadrons vacuum is physical with ordinary hadrons as degrees of freedom
- Constituent quarks and Goldstone bosons (pions) are the degrees of freedom in hadron (probed not at too short distances)

Deconfinement at RHIC

- What kind of transition occur at RHIC ?
- Where physical vacuum goes to ?



- Crossover form of deconfinement implies transition from the physical to the nonperturbative vacuum

What should occur at the LHC energies?

- Should transition to perturbative vacuum finally take place or might be another additional options?
- At high temperatures confinement mechanism could be triggered on again – finite probabilities to form colorless clusters again
- It would correspond to unitarity saturation (kind of a loop transition of vacuum)

$$|0\rangle_{ph}(Hadron\ gas) \to |0\rangle_{np}(Quark - pion\ liquid) \to |0\rangle_{ph}(Hadron\ liquid)$$

White clusters in colored gas

- The reflective scattering always accompanied by absorptive scattering at moderate and large impact parameters
- It implies transition of nonperturbative to the perturbative vacuum
- It should be fog instead of liquid (white clusters of hadrons inside of colored gas of quarks and gluons)

- Rotation of transient matter: average transverse momentum and the ridge structures in proton-proton collisions

Average transverse momentum at the LHC

- How could all what was said above be confronted with experimental data?
- Elastic scattering dominance at the LHC energies due to reflective scattering
- Now global characteristics (some of them) are available for the multiparticle production at the LHC energies
- Average transverse momentum of secondary particles at 7 TeV, its energy and multiplicity dependencies
- Ridge-like structure in pp-collisons

Model for U-matrix

- U(s,b) is constructed in the framework of the model which uses above notions:

$$U(s,b) = \prod_{i=1}^{N=n_1+n_2} \left\langle f_{Q_i} \right\rangle (s,b)$$

- Quasi-independent scattering in the mean field is assumed for constituent quarks

Some features of the model

- Number of scatterers

$$\tilde{N}(s,b) \approx \frac{(1-\langle k_Q \rangle)\sqrt{s}}{m_Q} D_c^{h_1} \otimes D_c^{h_2} \equiv N_0(s) D_C(b)$$

- Mean multiplicity $\langle n \rangle (s,b) = \alpha N_0(s) D_C(b)$

- Orbital angular momentum $L(s,b) \propto b \frac{\sqrt{s}}{2} D_C(b)$

Inclusive cross-section

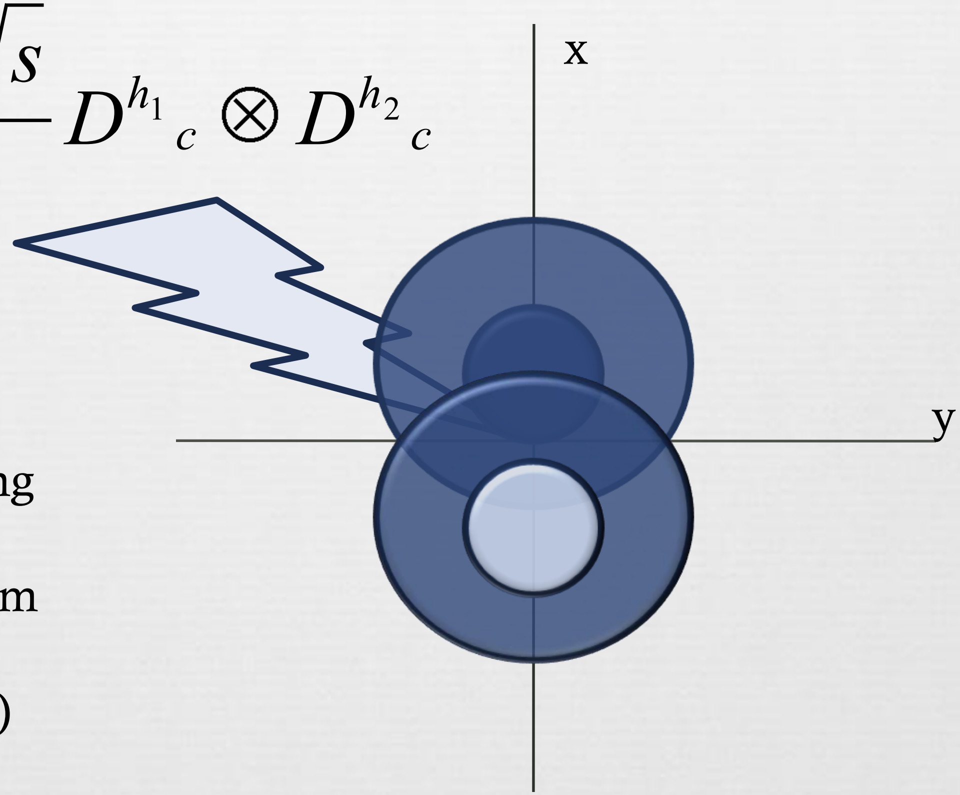
- Unitarization

$$\frac{d\sigma}{d\xi} = 8\pi \int_0^\infty bdb \frac{I(s,b,\xi)}{|1-iU(s,b)|^2}$$

$$I(s,\mathbf{b},y,\mathbf{p}_\perp) = \frac{1}{2\pi} I_0(s,b,y,p_\perp)[1+\sum_{n=1}^{\infty} 2\bar{v}_n(s,b,y,p_\perp)\cos n\phi]$$

Overlap region

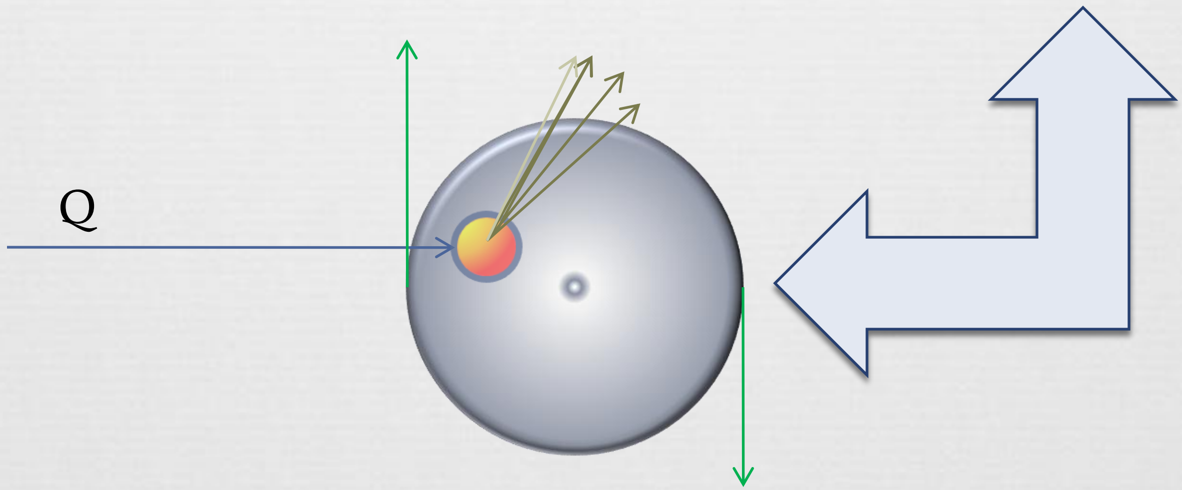
$$\tilde{N}(s,b) \propto \frac{(1-\langle k_Q \rangle)\sqrt{s}}{m_Q} D^{h_1}{}_c \otimes D^{h_2}{}_c$$



Due to strongly interacting transient state the large orbital angular momentum in the initial state of collision (with nonzero b) will lead to the coherent rotation of the quark-pion liquid in the transient state

Rotation and average transverse momentum

Particle production mechanism at moderate transverse momenta is an excitation of a part of the rotating transient state of massive constituent quarks (interacting by pion exchanges) by the one of the valence constituent quarks with subsequent hadronization of the quark-pion liquid droplets .



Average transverse momentum

- Coherent rotation of quark-pion liquid in the transient state and relation with transverse momentum

$$\langle p_T \rangle(s,b) = \kappa L(s,b)$$

- Average transverse momentum

$$\langle p_T \rangle(s) = \frac{\int_0^\infty bdb \langle p_T \rangle(s,b) \langle n \rangle(s,b) h_{inel}(s,b)}{\int_0^\infty bdb \langle n \rangle(s,b) h_{inel}(s,b)}$$

Energy dependence

$$\langle n \rangle (s) = g s^{\delta}$$

$$\delta = \frac{1}{2}\left(1 - \frac{\xi}{m_Q R_C}\right)$$

$$\delta \approx 0.2$$

$$\langle p_T \rangle (s) = a + c s^{\delta}$$

Multiplicity is correlated with transverse momentum

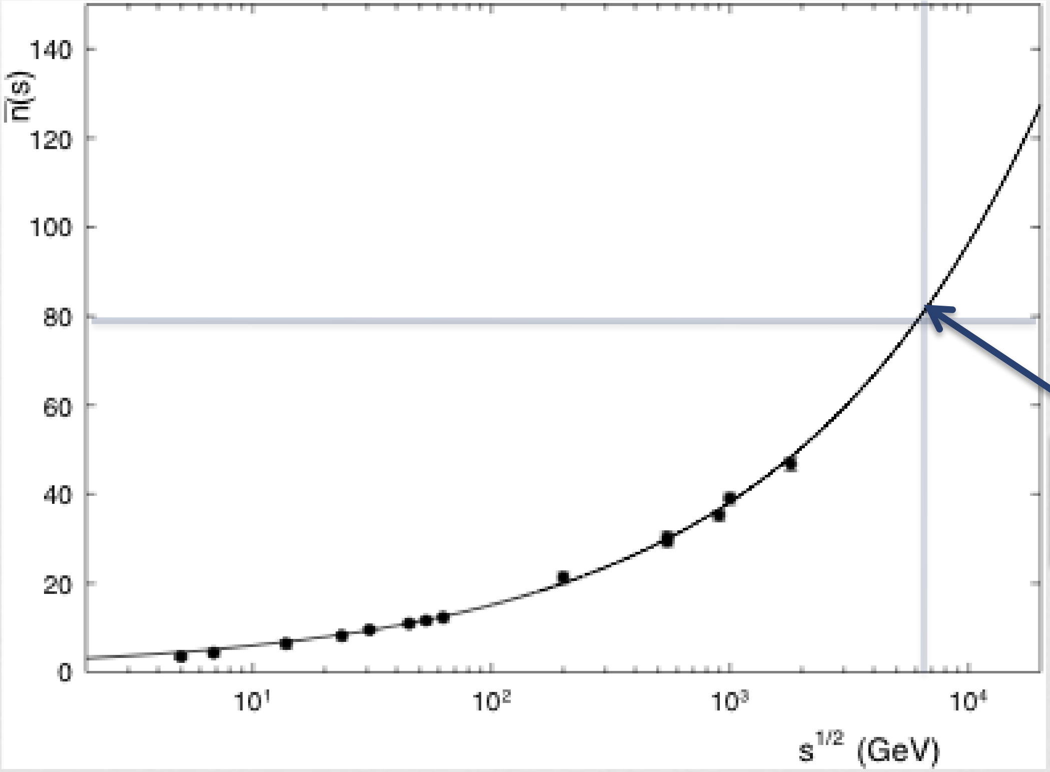
$$\langle p_T \rangle (s) = a + \gamma \langle n \rangle (s)$$

liquid state keeps its identity at super high energies

$$\langle p_T \rangle (s) / \langle n \rangle (s) \to const$$

$$s \to \infty$$

Mean multiplicity at 7 TeV



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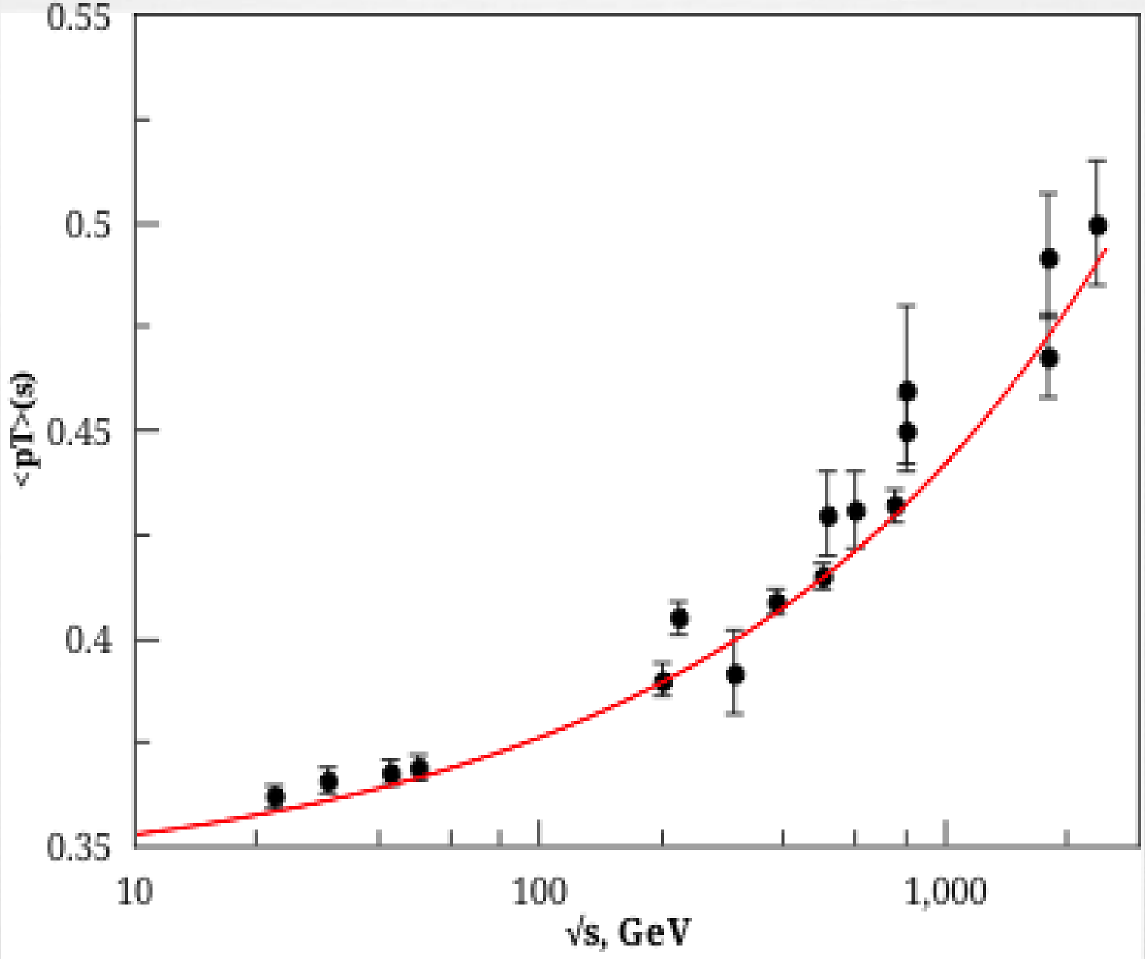
Comparison with data



Other rotation effects

- Rise of the average transverse momentum with associated multiplicity
- Rising dependence of mean multiplicity with transverse momentum
- Qualitative agreement with preliminary data of ATLAS

Two-particle correlations (R)

Charged two-particle correlation function

Signal distribution

$$R(\Delta\eta,\Delta\phi)=\left\langle (\langle N\rangle -1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)}-1\right)\right\rangle_{bins}$$

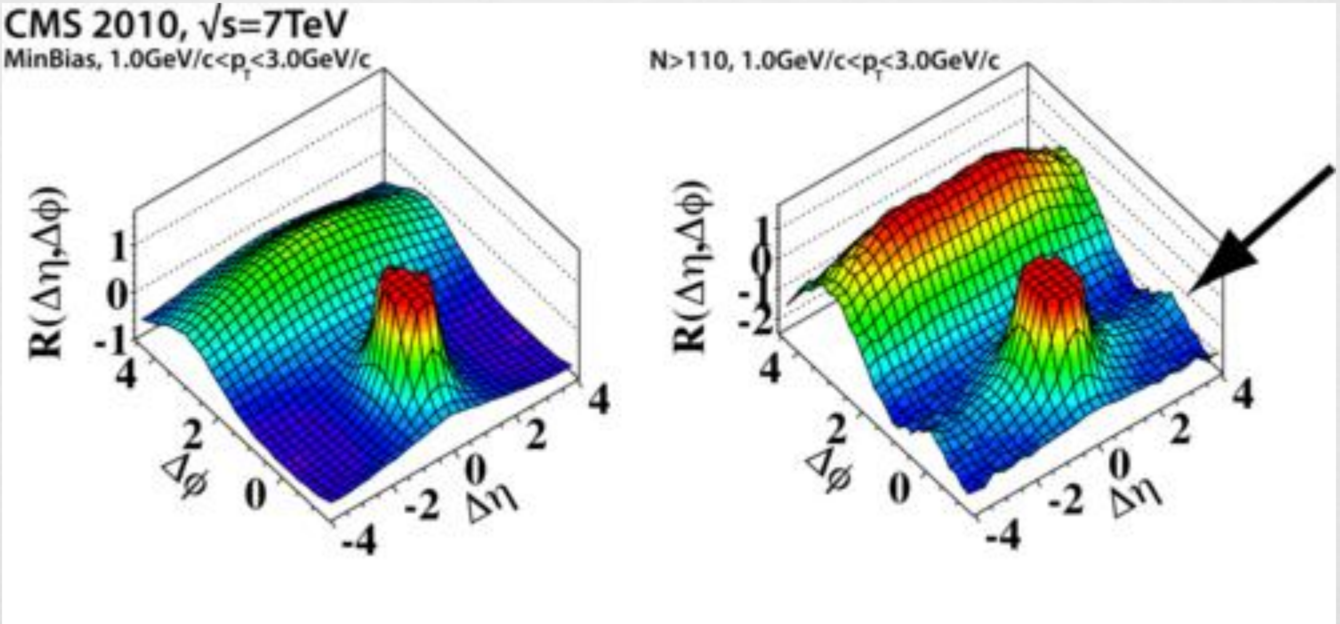
The differences in pseudorapidity and azimuthal angles between the two particles

Background distribution

Number of tracks per event averaged over the multiplicity bin

Ridge-like structures

- Observed at RHIC in nuclear reactions (AuAu) in the two-particles correlation function and in pp-collisions at the LHC.



Ridge phenomenon - recent interpretations

- Explosion of strings in their central part, relation of explosion as such with high multiplicity events (E. Shuryak, arXiv 1009.4635)
- Color-glass condensate and glasma formation dynamics (gluon saturation) (A. Dimitriu et al. arXiv 1009.5295)
- Coplanarity of incoming and outcoming partons in the parton model, increase of coplanarity with energy (I.M. Dremin, V.T. Kim, arXiv 1010.0918)
- QGP formation in pp-collisions, anticipated long time ago (M. Tannenbaum, R.M. Weiner, arXiv 1010.0964)

Rotation, ridge and anisotropic flows

- Small spread of correlations over azimuthal angle can reflect rotation plane of transient matter
- Directed flow can be another result of rotation
- Rotation of transient matter affect also elliptic flow
- Peripheral nature of pp-collisions is the effect of the reflective scattering (next slide)

Reflective (antishadowing) scattering at 7 TeV

- Inelastic collisions are mainly peripheral at this energy
- Main contribution to the multiplicity is due to peripheral collisions
- Hence, large impact parameters are presented in the majority of the inelastic events in pp-collisions

Specific conclusions

- Presence of the orbital angular momentum in the initial state lead to collective rotation in the transient state
- Orbital angular momentum increases with energy and leads therefore to increasing average transverse momentum
- Collective, coherent, liquid transient state in hadron collision
- Average transverse momentum, ridge-like structures, directed and elliptic flows might be associated with transient matter rotation

General lessons

- pp-scattering is not a kind of "elementary process" for heavy-ion collisions; AA and pp are the processes with the similar dynamics
- pp-scattering cannot be used, therefore, as a reference process in QGP searches in AA collisions
- This fact was anticipated long time ago (theoretically), experimentally confirmed now (long-range correlations were observed at ISR, but they were isotropical in asimuthal angle)
- Dynamics of pp-interactions at 7 TeV is nonperturbative at least at high multiplicities
- Event generators need revisions now, at least should be revised those which do not reproduce ridge structure in pp-collisons
- Start of paradigm change in hadron interactions