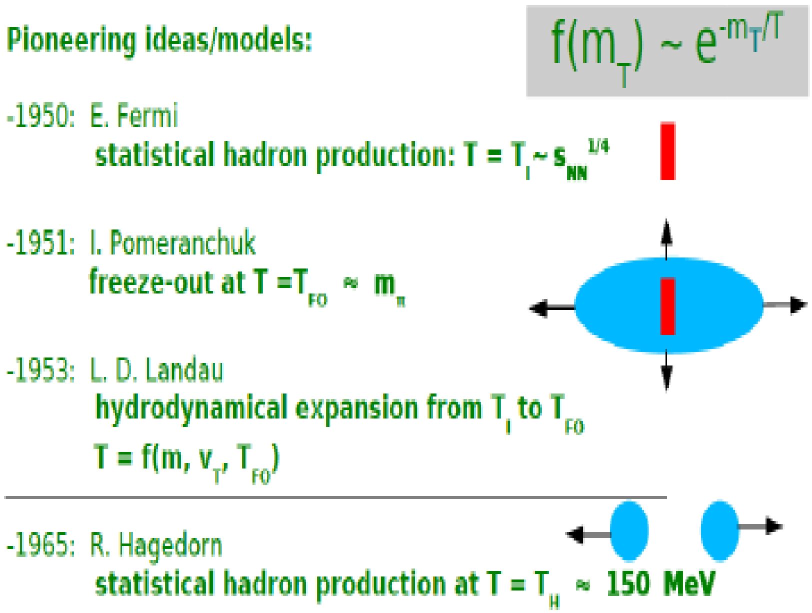
Event structure of multiparticle production in nucleus-nucleus collisions

RogachevskyOleg

LHEP

NICA/JINR-FAIRBilateralWorkshop
3.04.2012

The statistical and hydrodynamical models predict an approximately exponential form of particle transverse momentum spectra



(Thanks to M,Gazdzicki)

A fireball is
**... a statistical equilibrium of an undetermined number of all kinds of fireballs, each of which in turn is considered to be...*

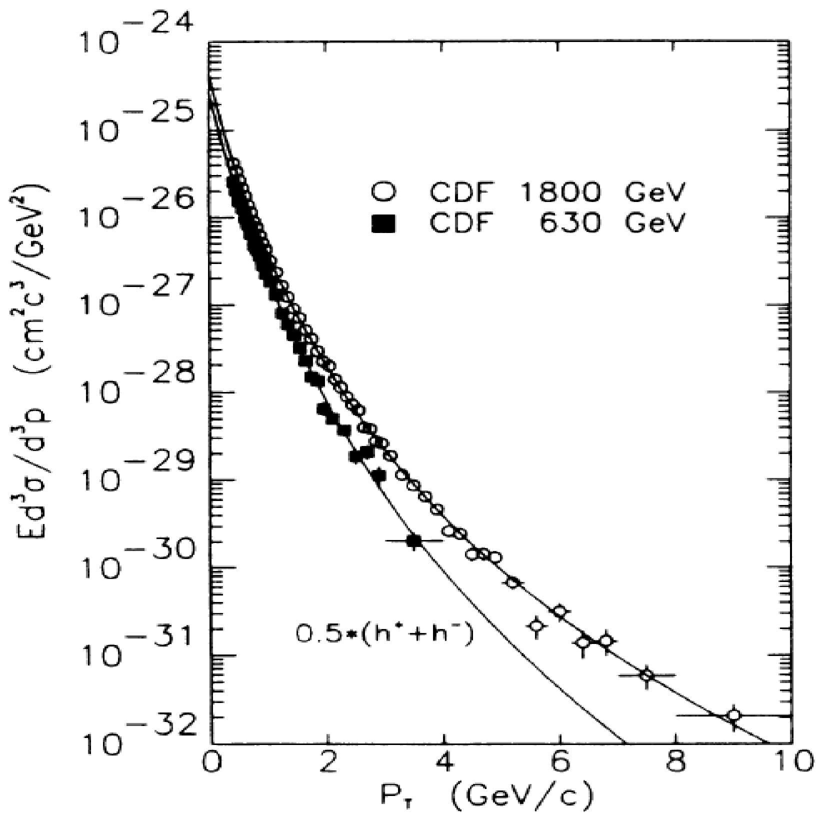
R.Hagedorn

(selfsimilarity)

The Fractal geometry of nature
B.B. Mandelbrot Science 155, 636 (1967)

The Non-extensive statistical mechanics
C. Tsallis, J. Stat. Phys. 52, 479 (1988)

PPbar collisions



Abe F. et al 1988 Phys. Rev. Lett. 61 1819

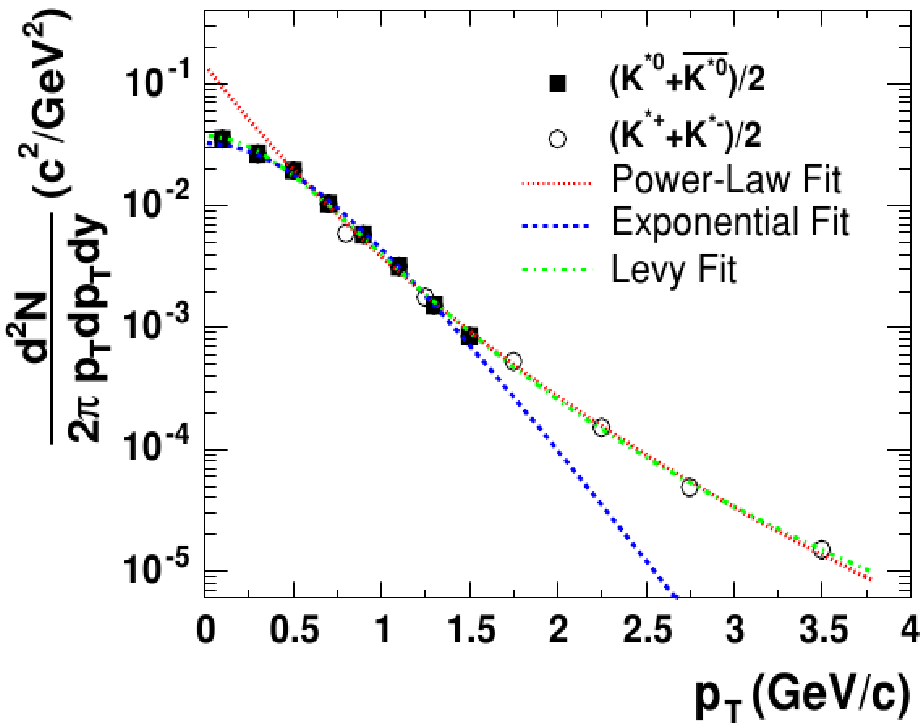
ppbar → h + X

$$E\frac{d^3\sigma}{d^3p} = \frac{Ap_0^n}{(p_T + p_0)^n}$$

Inclusive cross sections for rapidity |y| < 1.0
and fitted curves with p_0 fixed at 1.3 GeV/c.

Levy function

STAR collaboration
Phys. Rev. C 71, 064902 (2005)



exp

$$\frac{1}{2\pi m_T}\frac{d^2N}{dy\,dm_T} = \frac{dN}{dy}\frac{1}{2\pi T(m_0+T)}\exp\left(\frac{-(m_T-m_0)}{T}\right)$$

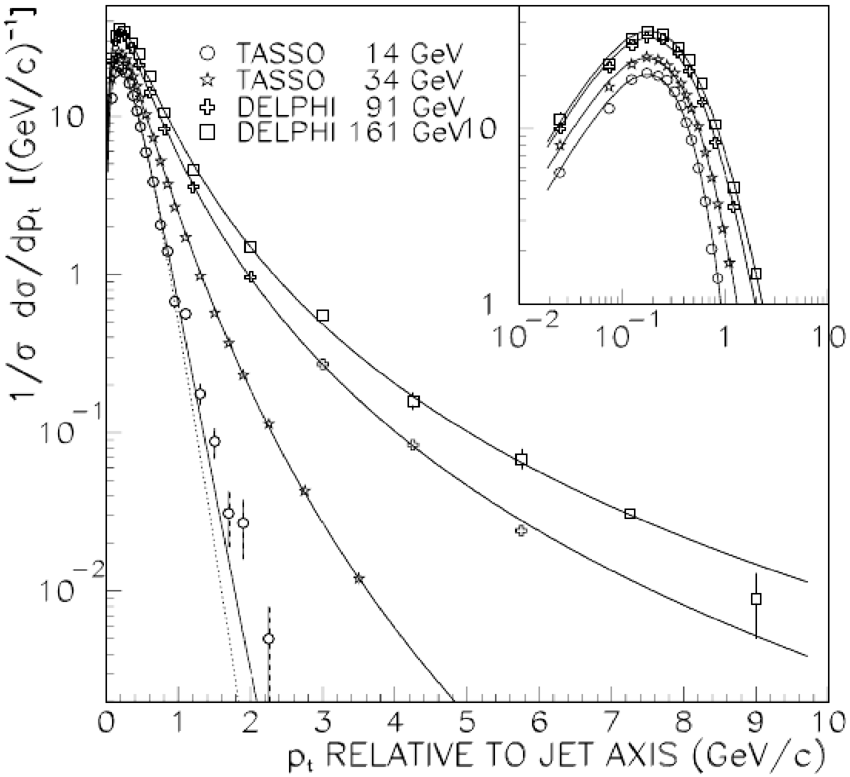
Power law

$$\frac{1}{2\pi p_T}\frac{d^2N}{dy\,dp_T} = \frac{dN}{dy}\frac{2(n-1)(n-2)}{\pi(n-3)^2\langle p_T\rangle^2} \times \left(1+\frac{p_T}{\langle p_T\rangle(n-3)/2}\right)^{-n}$$

Levy

$$\frac{1}{2\pi p_T}\frac{d^2N}{dy dp_T} = \frac{dN}{dy}\frac{(n-1)(n-2)}{2\pi nT[nT+m_0(n-2)]} \times \left(1+\frac{\sqrt{p_T^2+m_0^2}-m_0}{nT}\right)^{-n}$$

The invariant yields for both (K ∗0 + K ∗0)/2 and (K ∗+ + K ∗−)/2 as a function of pT for |y| < 0.5 in minimum bias p + p interactions. The dotted curve is the fit to the power-law function for pT > 0.5 GeV/c and extended to lower values of pT . The dashed curve is the K ∗0 spectrum fit to the exponential function and extended to higher values of pT . The dashed-dotted curve is the fit to the Levy function for pT < 4 GeV/c. Errors are statistical only.



Bediaga I, Curado EMF and Miranda J.

A non-extensive thermodynamical equilibrium approach in e(+) e(-)→ hadrons

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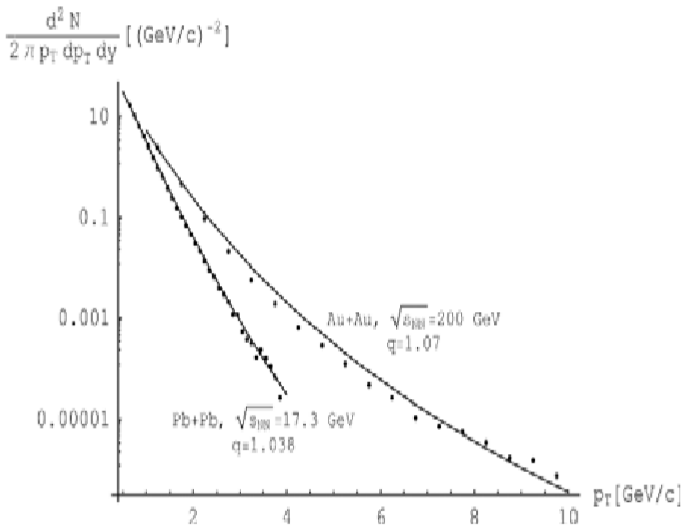
Physica A 286: 156-163 2000.

The transverse momentum pt of charged hadrons with respect to jet axis is sketched for four different experiments, whose center-of-mass energies vary from 14 and 34 GeV (TASSO) up to 91 and 161 GeV (DELPHI).

$$\frac{1}{\sigma}\frac{d\sigma}{dp_t} = c\,p_t \int_0^\infty dp_l \left[1 - \frac{1-q}{T_0}\sqrt{p_l^2+\mu^2}\right]^{q/(1-q)}$$

PbPb & AuAu collisions

Eur. Phys. J. A 40, 313 (2009)

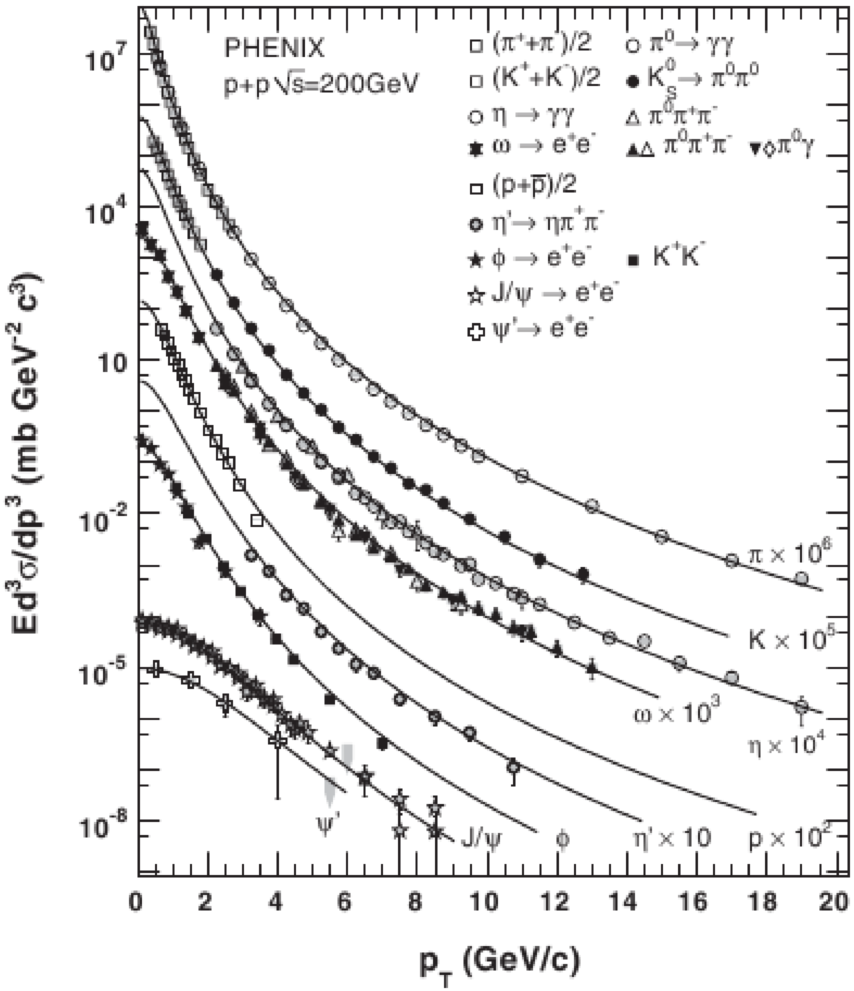


Experimental neutral pion invariant yields in central Pb+Pb collisions at $\sqrt{s_{NN}}$ = 17.3 GeV and in central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV compared with the modified thermal distribution shape by using non-extensive statistics

(q = 1.038 for Pb+Pb and q = 1.07 for Au+Au collisions.)

$$\frac{\mathrm{d}^2 N}{2\pi p_\perp \mathrm{d}p_\perp \mathrm{d}y} = C\, m_\perp \left[1-(1-q)\frac{m_\perp}{T}\right]^{1/(1-q)}$$

PHENIX collaboration
PRD 83, 052004 (2011)



Tsallis distribution

$$G_q(E) = C_q\left(1 - (1-q)\frac{E}{T}\right)^{1/(1-q)},$$

$$n = -\frac{1}{1-q}.$$

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{2\pi}\frac{d\sigma}{dy}\frac{(n-1)(n-2)}{(nT+m_0(n-1))(nT+m_0)}\left(\frac{nT+m_T}{nT+m_0}\right)^{-n}$$

Invariant differential cross sections of different particles measured in p + p collisions at √s = 200 GeV in various decay modes.

Charged particle transverse momentum spectra in pp

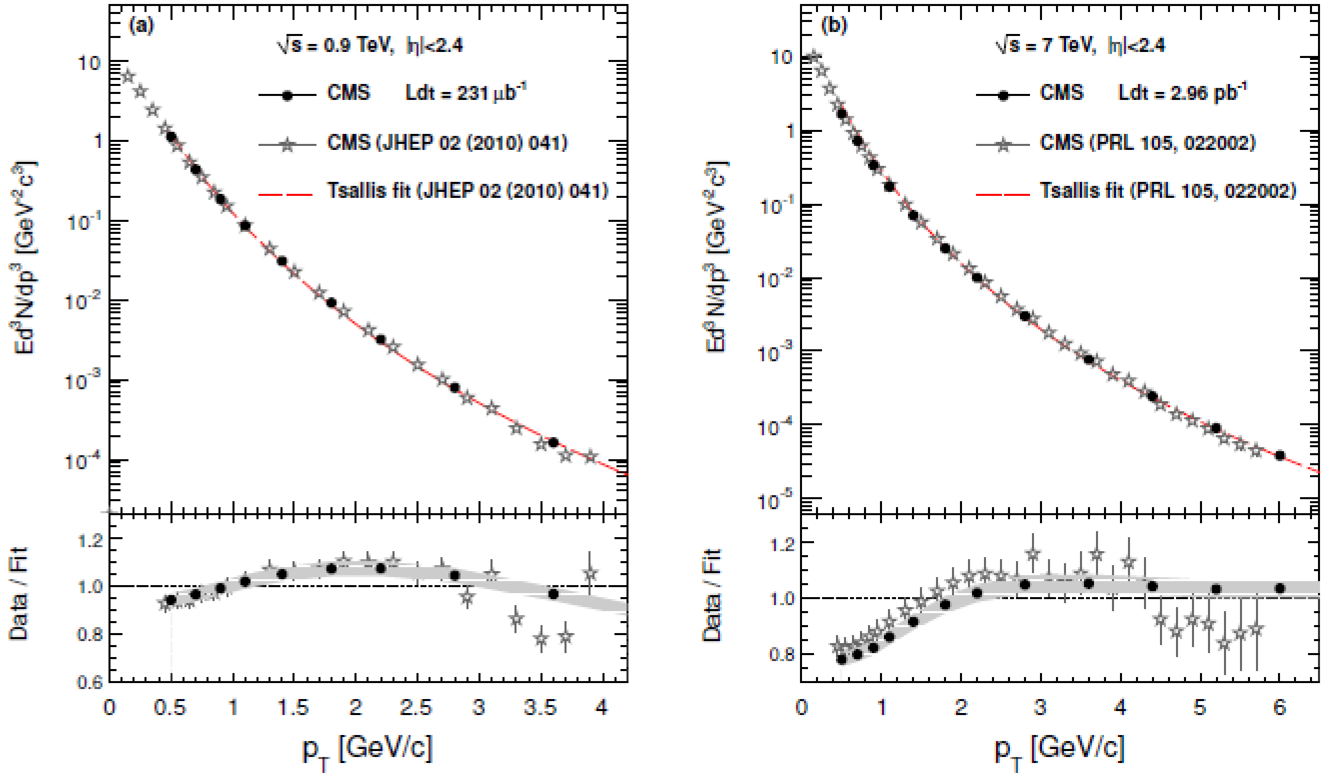


Figure 4. (a) Upper panel: the invariant charged particle differential yield from the present analysis (solid circles) and the previous CMS measurements at $\sqrt{s} = 0.9\,\mathrm{TeV}$ (stars) over the limited p_T range of the earlier result. Lower panel: the ratio of the new (solid circles) and previous (stars) CMS results to a Tsallis fit of the earlier measurement. Error bars on the earlier measurement are the statistical plus systematic uncertainties added in quadrature. The systematic uncertainty band around the new measurement consists of all contributions, except for the common event selection uncertainty. (b) The same for $\sqrt{s} = 7\,\mathrm{TeV}$.

Tsallis distribution

- Transverse-Momentum and Pseudorapidity Distributions of Charged Hadrons in Collisions at $\sqrt{s}$=7 TeV

  Physical Review Letters 105, 022002 (2010)
- Transverse momentum spectra of charged particles in proton–proton collisions at vs = 900 GeV with ALICE at the LHC

  Physics Letters B 693 53–68 (2010)
- Measurement of neutral mesons in p+p collisions at $\sqrt{s}$ = 200 GeV and scaling properties of hadron production

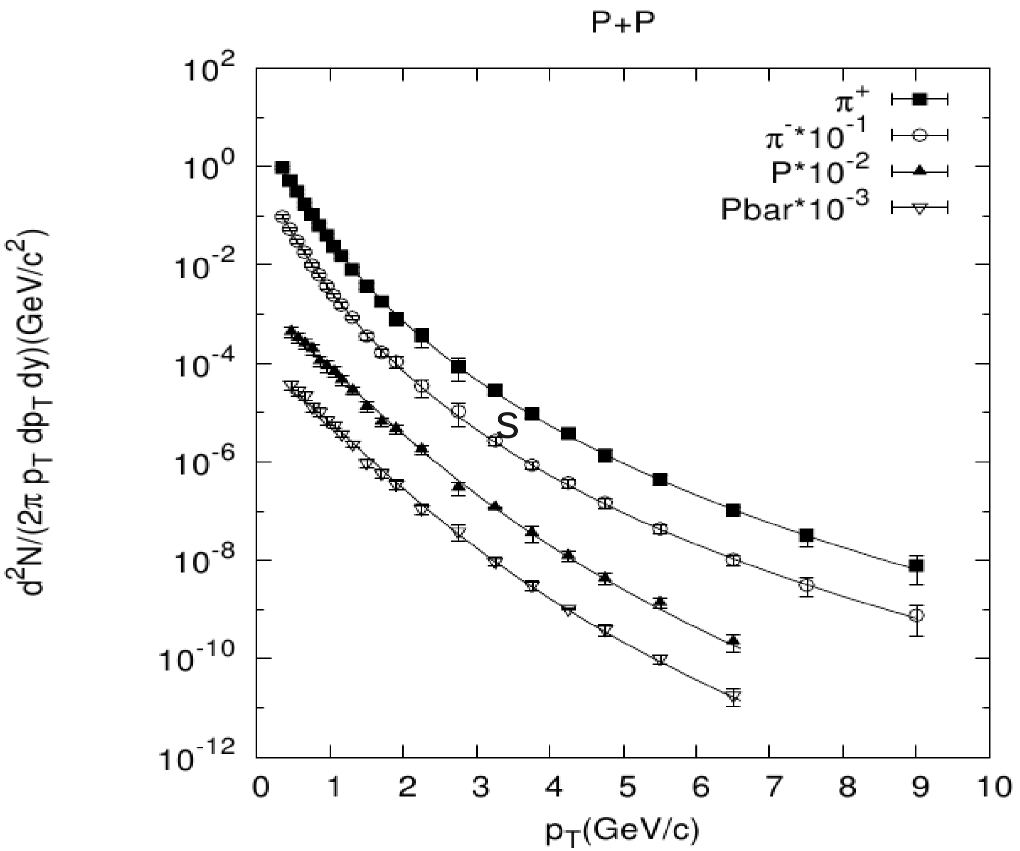
  Physical Review D 83, 052004 (2011)
- Nuclear modification factors of φ mesons in d + Au, Cu + Cu, and Au + Au collisions at$\sqrt{s_{NN}}$ = 200 GeV

  Physical Review C 83, 024909 (2011)
- Strange particle production in proton–proton collisions at $\sqrt{s}$ = 0.9 TeV with ALICE at the LHC

  The European Physical Journal C 71, 1594(2011)
- Production of pions, kaons and protons in pp collisions at $\sqrt{s}$ = 900 GeV with ALICE at the LHC

  The European Physical Journal C 71, 1655(2011)
- Charged-particle multiplicities in pp interactions measured with the ATLAS detector at the LHC

  New Journal of Physics 13, 053033 (2011)



Bhaskar De
S. Bhattacharyya
Goutam Sau
S. K. Biswas

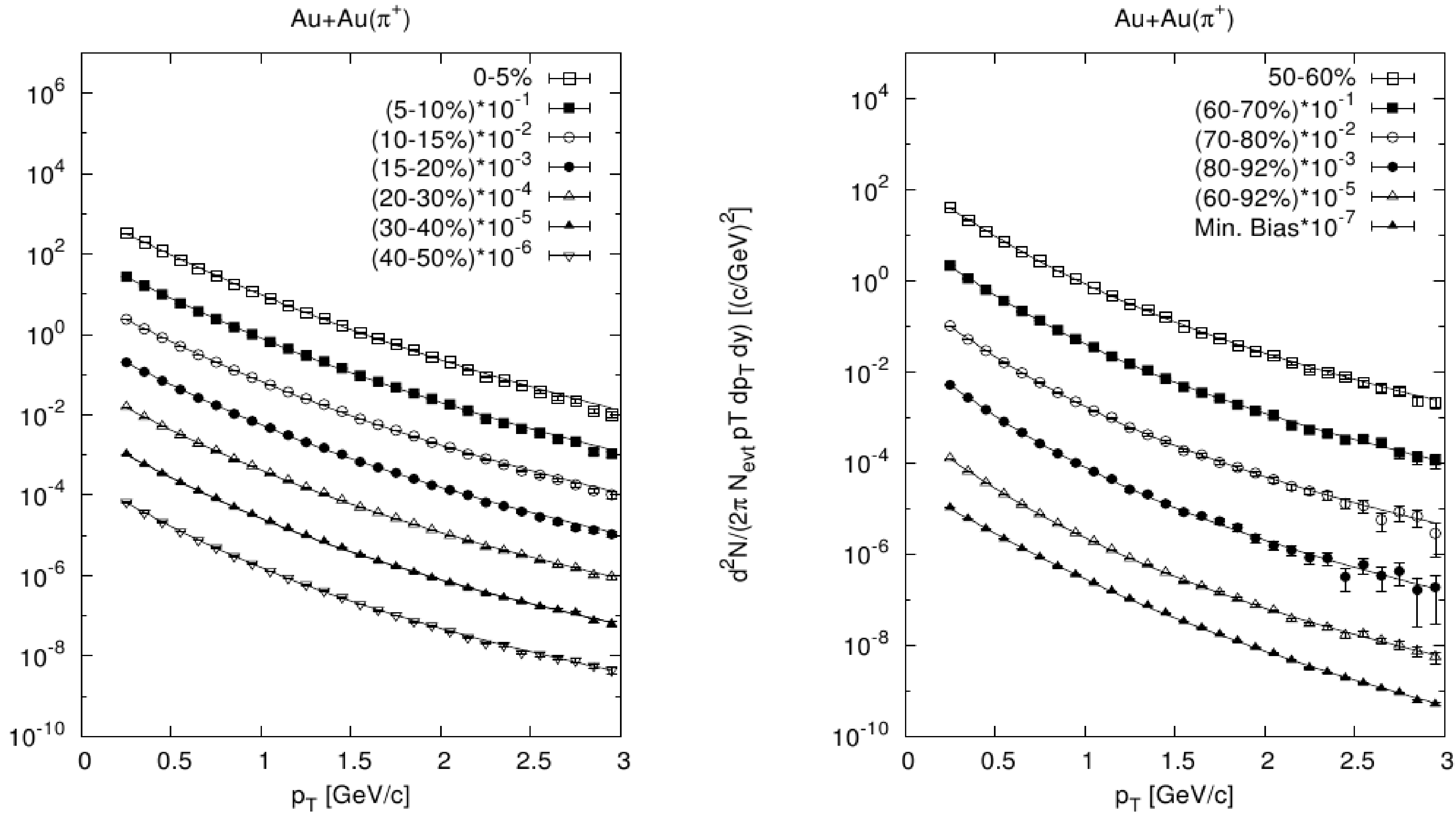
IJMP E Vol. 16, No. 6 (2007) 1687

STAR & PHENIX
$\sqrt{s}$ = 200 GeV

$$\frac{1}{\sigma}\frac{d\sigma}{dp_T} \approx \quad c p_T \int_0^\infty dp_L \left(1 + (q-1)\beta\sqrt{p_T^2 + p_L^2 + m_0^2}\right)^{-q/(q-1)}$$

Tsallis statistics (2)

Ibid.

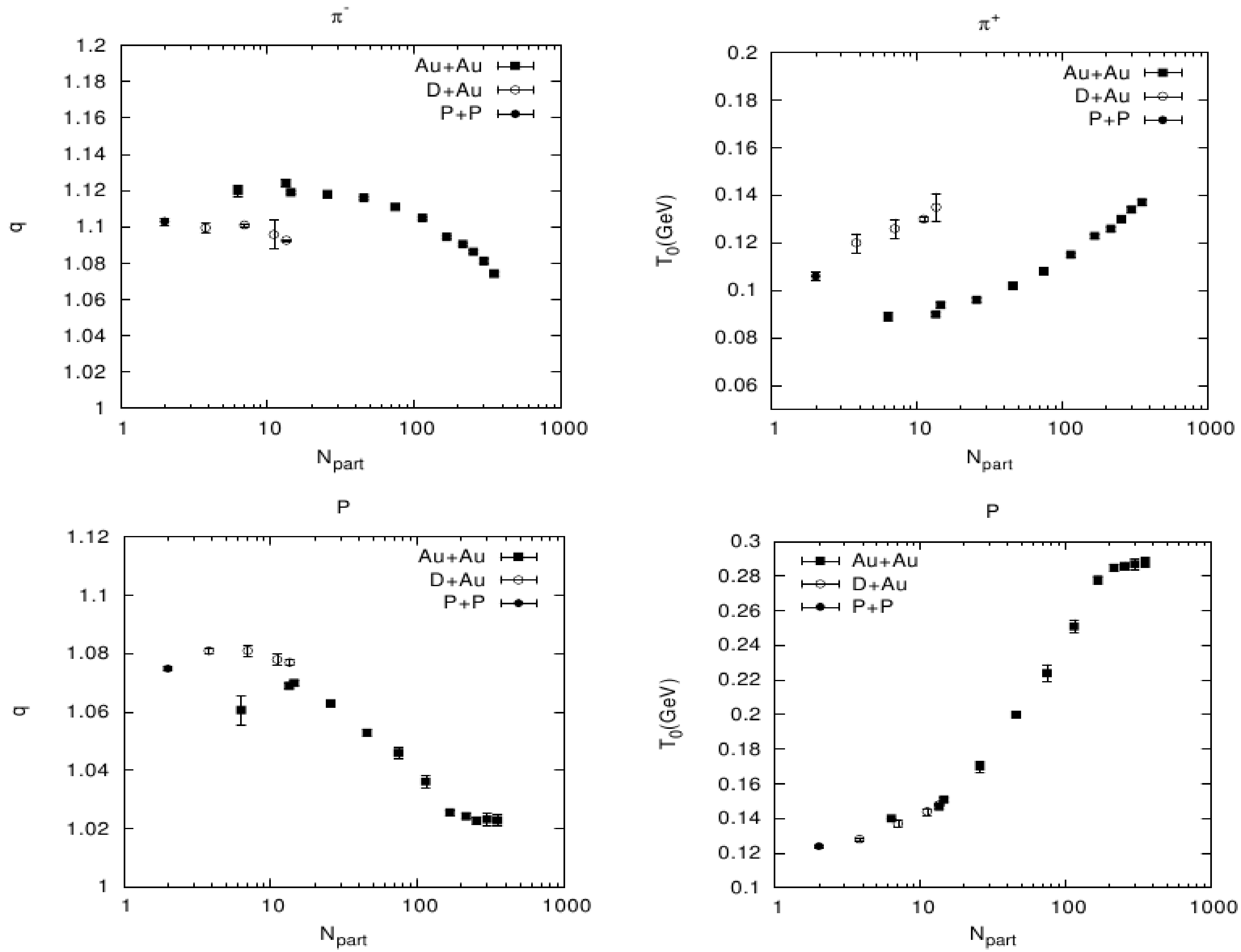


Oleg Rogachevsky

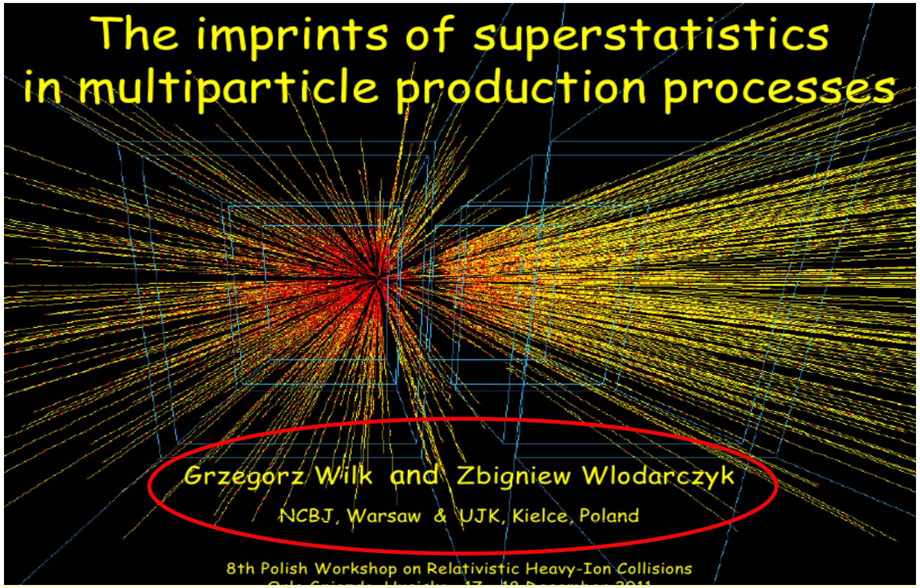
Table 1. Values of fitted parameters with respect to experimental data on π^+-spectra at different centralities of $Au + Au$, $D + Au$ and $P + P$ collisions at RHIC.

	Centrality	C	q	T_0(GeV)	χ^2/ndf
$Au + Au$	0–5	7963 ± 198	1.080 ± 0.002	0.137 ± 0.001	35.180/25
	5–10	7000 ± 180	1.084 ± 0.002	0.134 ± 0.001	33.758/25
	10–15	6500 ± 170	1.090 ± 0.002	0.130 ± 0.001	28.543/25
	15–20	6010 ± 160	1.095 ± 0.002	0.126 ± 0.001	27.543/25
	20–30	4915 ± 123	1.099 ± 0.002	0.123 ± 0.001	28.704/25
	30–40	3873 ± 114	1.107 ± 0.002	0.115 ± 0.001	31.913/25
	40–50	2918 ± 53	1.114 ± 0.001	0.108 ± 0.001	21.123/25
	50–60	2089 ± 45	1.118 ± 0.001	0.102 ± 0.001	22.208/25
	60–70	1324 ± 40	1.122 ± 0.002	0.096 ± 0.001	24.902/25
	70–80	769 ± 32	1.125 ± 0.003	0.090 ± 0.001	19.718/25
	80–92	408 ± 23	1.119 ± 0.003	0.089 ± 0.002	14.443/25
	60–92	815 ± 24	1.121 ± 0.001	0.094 ± 0.001	12.717/25
	Min. Bias	3003 ± 36	1.091 ± 0.001	0.128 ± 0.001	24.140/25
$D + Au$	0–20	259 ± 51	1.092 ± 0.003	0.135 ± 0.006	5.682/21
	20–40	196 ± 4	1.096 ± 0.001	0.130 ± 0.001	7.505/21
	40–100	107 ± 13	1.099 ± 0.002	0.120 ± 0.004	5.022/21
	Min. Bias	145 ± 21	1.099 ± 0.002	0.126 ± 0.004	5.077/21
$P + P$	—	81 ± 6	1.102 ± 0.002	0.106 ± 0.002	2.813/20

Tsallis statistics parameters



q interpretations



Tsallis distribution

C. Tsallis, J.Stat.Phys. **52** (1988) 479

$$f(E) = \frac{2-q}{T}\left[1-(1-q)\frac{E}{T}\right]^{\frac{1}{1-q}}$$

$q \to 1$ — meaning of q ?

BG

R. Hagedorn (1965)

$$f(E) = \frac{1}{T}\exp\left(-\frac{E}{T}\right)$$

3

Tsallis statistics as Superstatistics

C. Beck et al., Physica A322 (2003) 267

Superstatistics is a superposition of two different statistics relevant to system under consideration
with a stationary state
and intensive parameter fluctuations

$$h(E/T) = \int_0^\infty f(E/T)\, g(1/T)\, d(1/T)$$

G. Wilk, Z. Włodarczyk, Phys. Rev. Lett. 84, 2770 (2000); Physica A376(2007)279 PRC79(2009)054903; EPJA40(2009)299; JPG38(2011)065101; Physica A390(2011)3566 G. Wilk, Z. Włodarczyk, W.Wolak, APPB(2011)1277

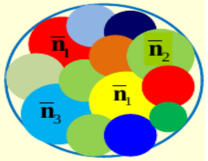
M. Biyajima et al., EPJC40(2005)243 and C48(2006)593 (p_T fits).
T. Osada et al.. PRC77(2008)044903; PTPSuppl.174(2008)168 (2008); CEJP7(2009)432; IJP85(2011)825 (q-hydrodynamics)

4

In full phase space q measures dynamical fluctuations in P(N)

(*) Experiment: P(N) is adequately described by NBD depending on <N> and k (k≥1) affecting its width:

$$\frac{1}{k} = \frac{\sigma^2(N)}{\langle N\rangle^2} - \frac{1}{\langle N\rangle}$$



(*) If 1/k is understood as a measure of fluctuations of <N>, then

$$P(N) = \int_0^\infty d\bar{n}\, \frac{\bar{n}^n \exp(-\bar{n})}{n!} \cdot \frac{\gamma^k \bar{n}^{k-1}\exp(-\gamma\bar{n})}{\Gamma(k)}$$

$$= \frac{\Gamma(k+n)}{\Gamma(1+n)\Gamma)\Gamma(} \cdot \frac{\gamma^k}{(\gamma+1)^{k+n}} \quad \text{with} \quad \gamma = \frac{k}{\langle\bar{n}\rangle}$$

(P.Carruthers, C.C.Shih, Int.J.Phys. A4 (1989)5587)

$$\frac{1}{k} = D(\bar{n}) = \frac{\sigma^2(\bar{n})}{\langle\bar{n}\rangle^2} = q-1$$

(*) → one expects: q=1+1/k what indeed is observed

G.Wilk, Z.Włodarczyk, EPJA40(2009)299; F.Navarra, O.Utyuzh, WW, PRD67(2003)114002

8

q interpretations

Tsallis Distribution in High-Energy Collisions

(arXiv:1101.3023, accepted in EPL)

Gergely Gábor Barnaföldi
KFKI RMKI of the HAS
in collaboration
T.S. Biró, G. Kalmár, K. Ürmössy, P. Ván

High-pT Physics for the LHC 2011, Utrecht 4-7 April 2011

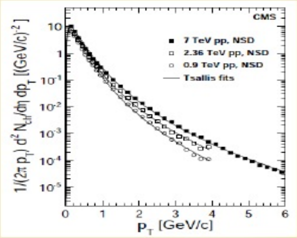
MOTIVATION

- New LHC pp data (CMS)

  CMS: JHEP 1002:041(2010)

  fitted Tsallis distribution for p_T spectra:

$$E\frac{d^3N_{ch}}{dp^3} = \frac{1}{2\pi p_T}\frac{E}{p}\frac{d^2N_{ch}}{d\eta dp_T} = C(n,T,m)\frac{dN_{ch}}{dy}\left(1+\frac{E_T}{nT}\right)^{-n}$$



  Parameters:

  0.9 TeV T= 130 MeV, q=1.13

  2.36 TeV T= 140 MeV, q=1.15 $n := (q-1)^{-1}$

- RHIC analysis on AuAu data (y=0)

  Cooper-Frye model: K. Ürmössy, T.S. Bíró: PL B689 14 (2010)

  Parameters: $f(E) = A[1+(q-1)E/T]^{-1/(q-1)}$

  200 GeV T= 51 MeV, q= 1.062 (fit for p_T < 6 GeV/c)

Basics of non-extensive thermodynamics

Non-extensive thermodynamics (Based on: T.S. Biró: EPL84, 56003,2008)
associative composition rule, (non-additive) :

$$h(h(x,y),z) = h(x,h(y,z))$$

Then should exist a strict monotonic function, X(x) 'generalised logarithm' (an entropy-like quantity), for which:

$$h(x,y) = X^{-1}(X(x)+X(y)) \qquad X(h(x,y)) = X(x)+X(y).$$

Examples: (i) Classical Boltzmann-Gibbs thermodynamics:

$$f(E) = e^{-\beta E}/Z \qquad h(x,y) = x+y.$$

(ii) Tsallis-Pareto-like distribution with $a = q-1$:

$$f(E) = \frac{1}{Z}e^{-\frac{\beta}{a}\ln(1+aE)} = \frac{1}{Z}(1+aE)^{-\beta/a} \qquad h(x,y) = x+y+axy$$

$$S = \int f\frac{e^{-a\ln(f)}-1}{a} = \frac{1}{a}\int(f^{1-a}-f).$$

Hadronization via non-extensive way

Our program:

i) Search and fit Tsallis distribution to data from AA, pp, ee.

ii) Test: can a BFKL / DGLAP-like evolution equation be obtained?

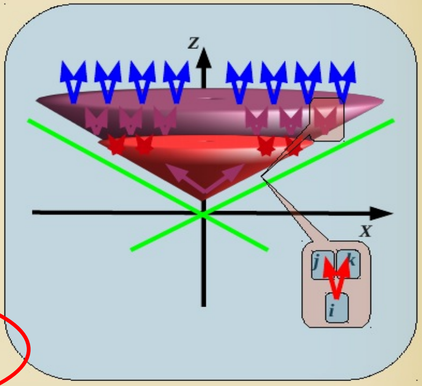
  $D(x,Q^2) \sim f(E,T,q) * f(\ln(Q^2))$

  $D(x,Q^2) \sim f(E,T(\ln(Q^2)),q(\ln(Q^2)))$

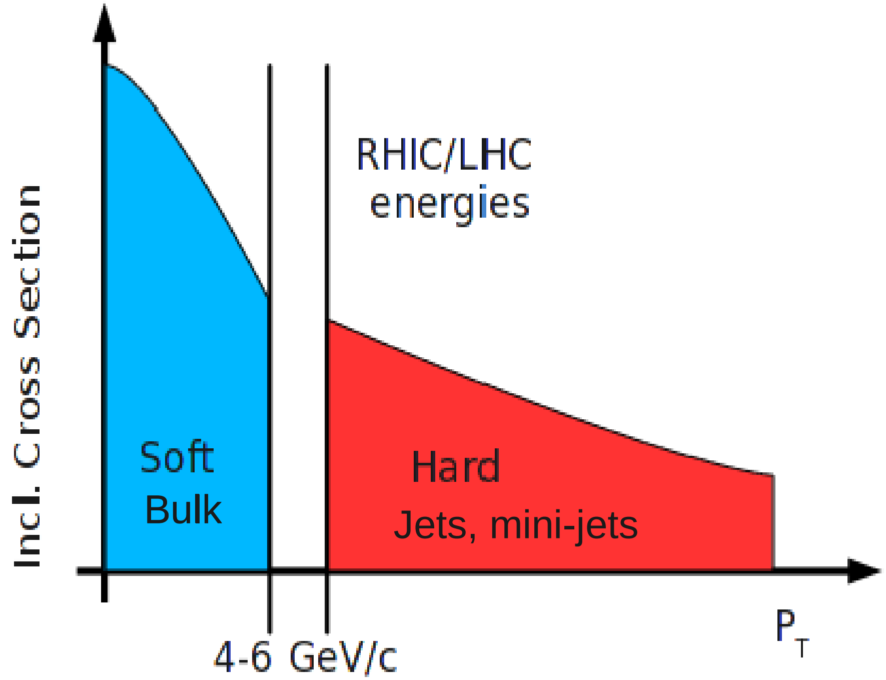
iii) Build up a simple theory to test.

iv) Search for physical meaning of T and q parameters.

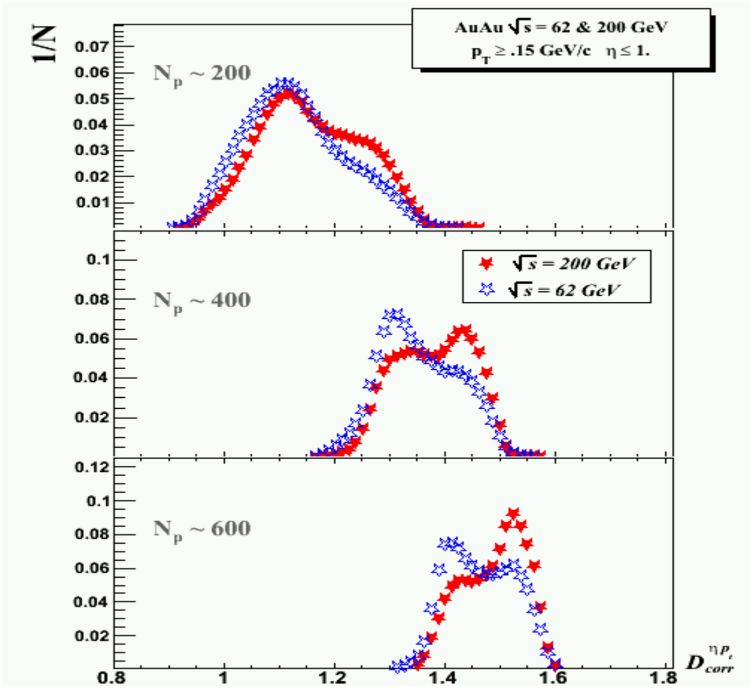
  → This is a hard thing...



Interpretation ?



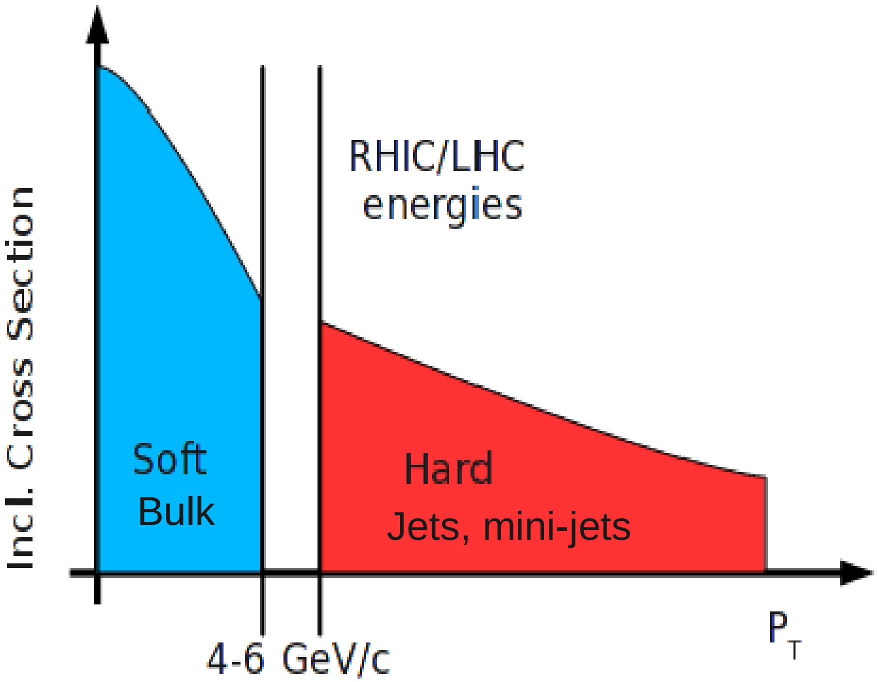
R.O. ICHEP 2006

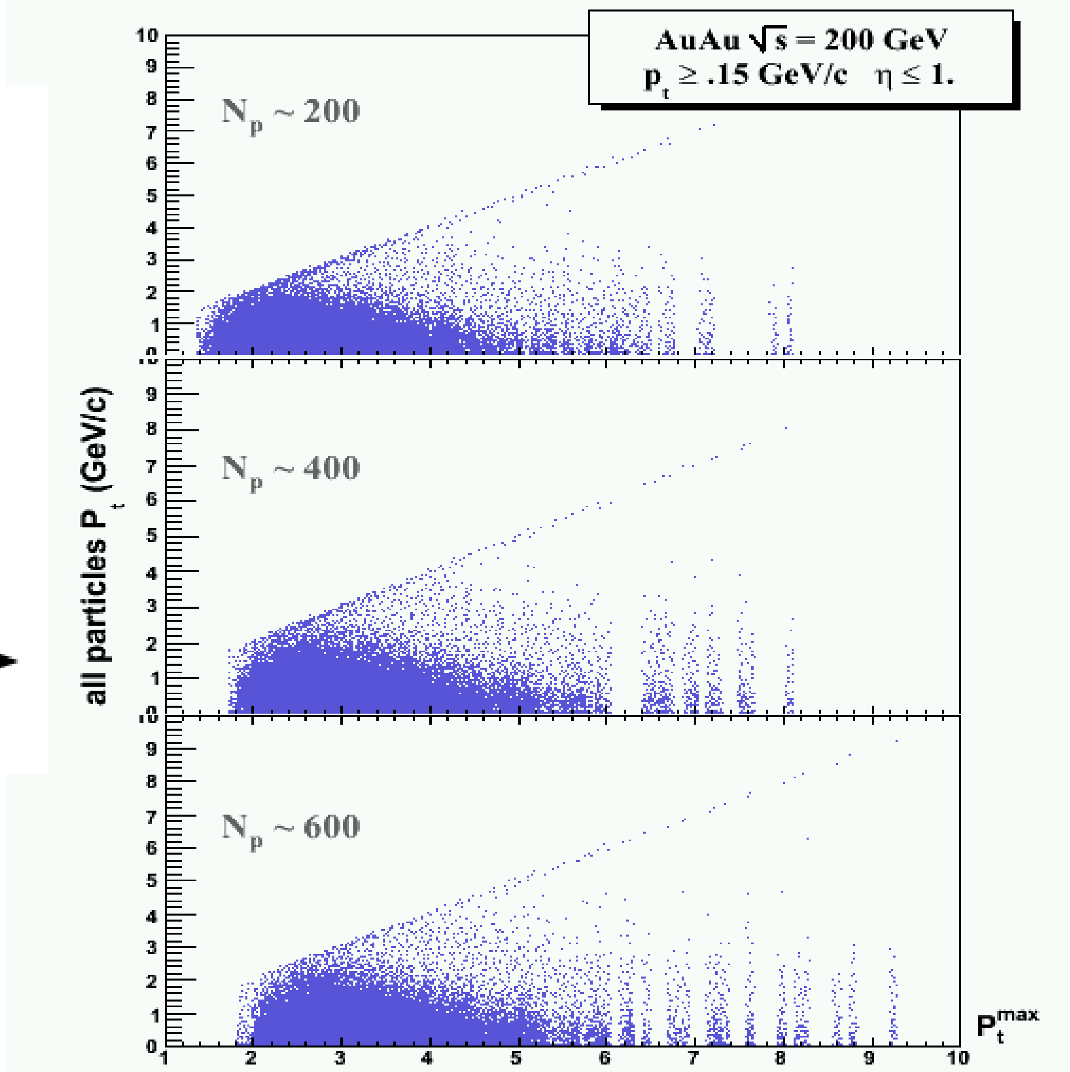


Fractal dimensions of events in rapidity-transverse momentum space

Event fractal dimensions

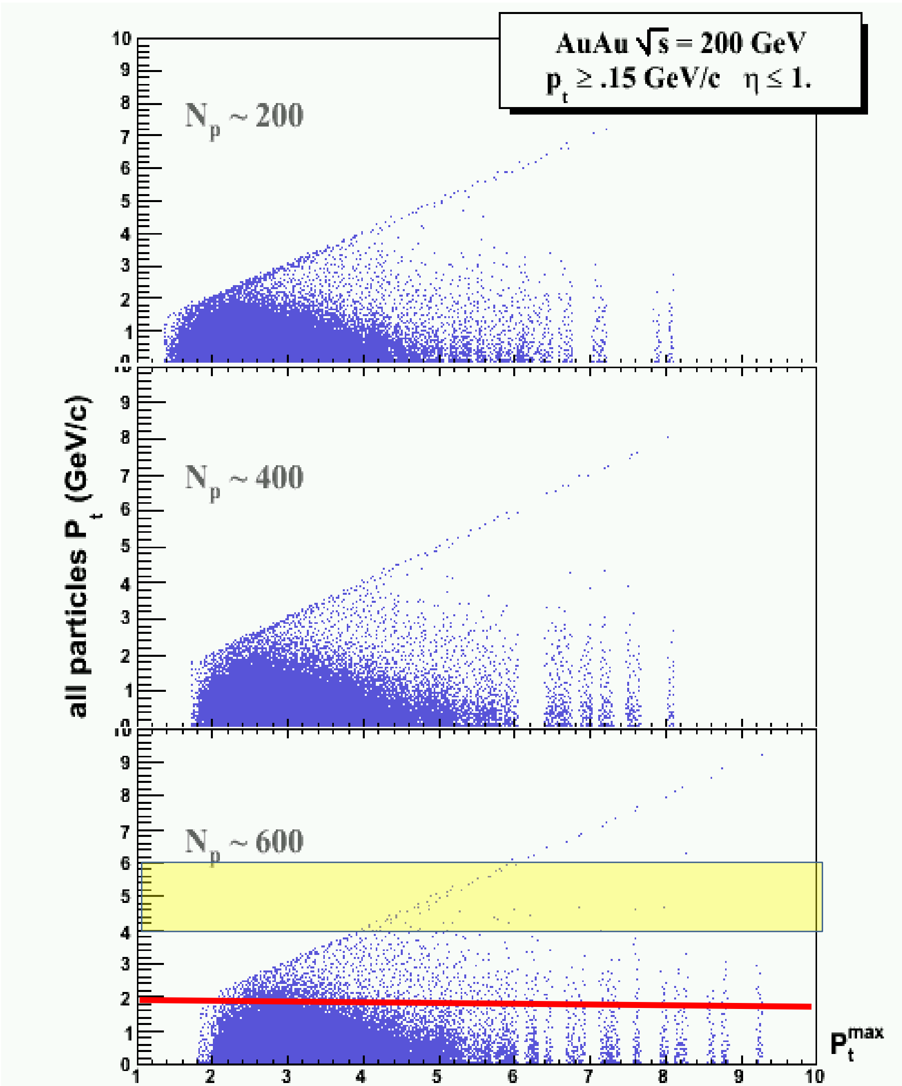
R.O. ICHEP 2006



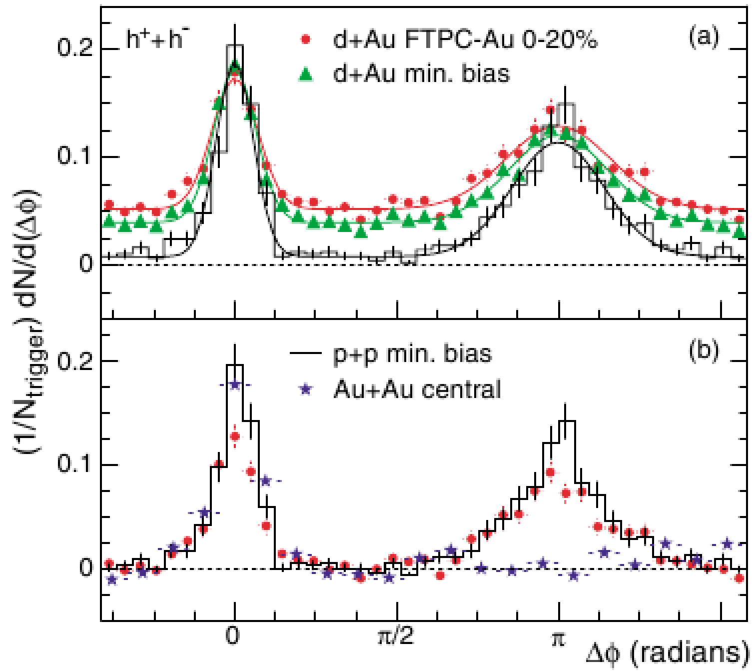


p_T^{max} – maximum transverse momentum of a particle in the event

Disappearance of away side jet



Phys. Rev. Lett. 91, 072304 (2003).

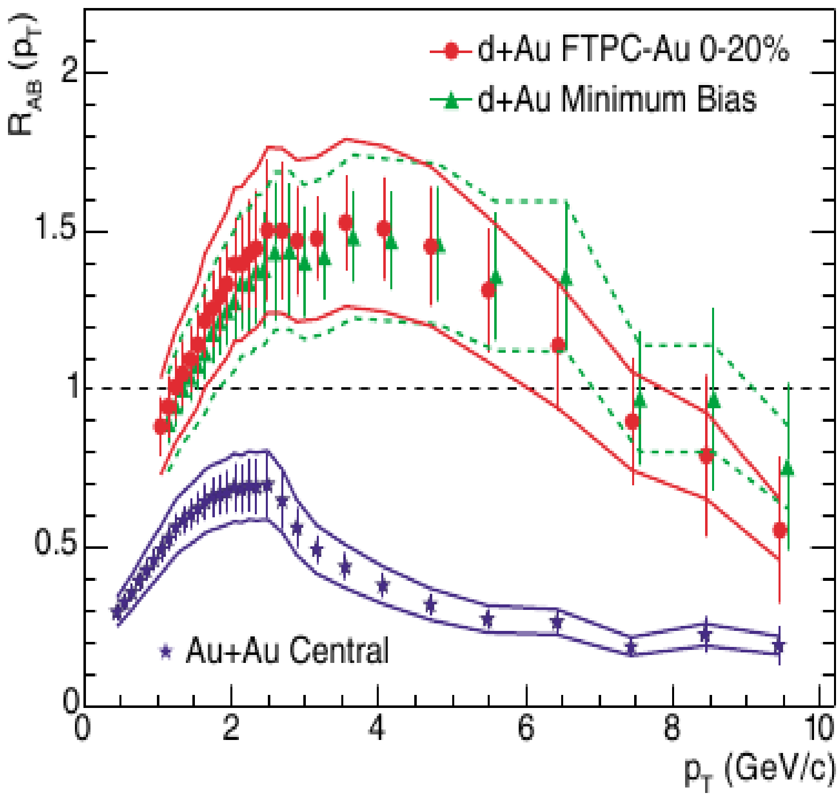


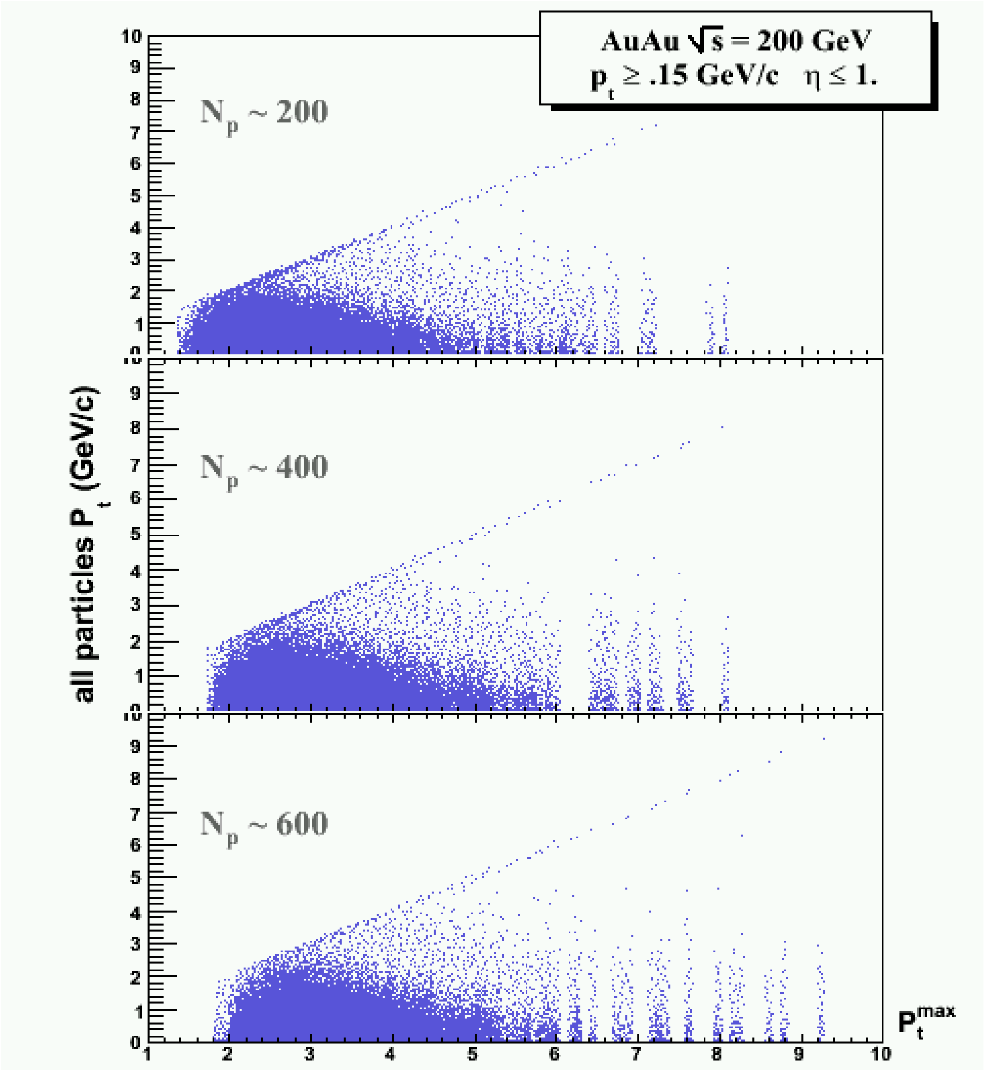
$$D(\Delta\phi) \equiv \frac{1}{N_{\rm trigger}} \frac{1}{\epsilon} \frac{dN}{d(\Delta\phi)}$$

. Only particles within |η|<0:7 are included in the analysis. $N_{triggers}$ is the number of particles within 4 < p_T (trig) < 6 GeV/c, referred to as trigger particles. The distribution results from the correlation of each trigger particle with all associated particles in the same event having 2 < p_T < p_T (trig), where ε is the tracking efficiency of the associated particles.

High p_T suppression

Phys. Rev. Lett. 91, 072304 (2003).

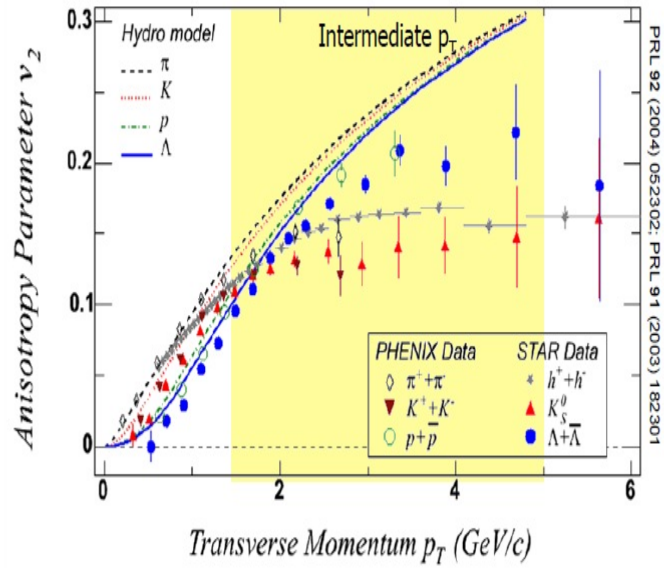




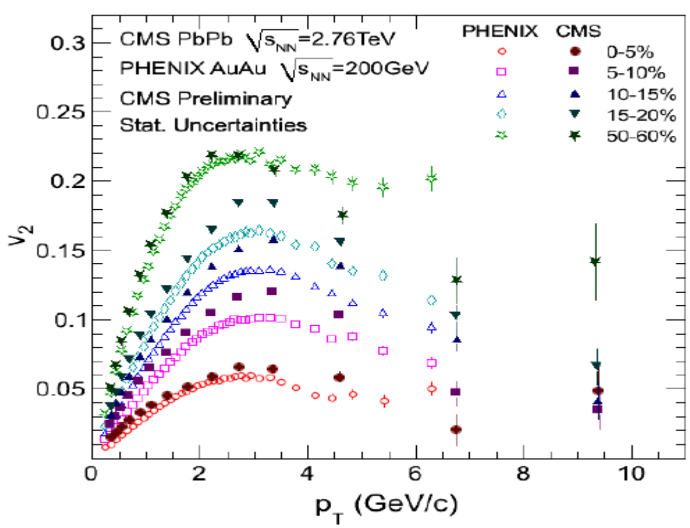
$$R_{AB}(p_T) = \frac{d^2N/dp_T d\eta}{T_{AB} d^2\sigma^{pp}/dp_T d\eta}$$

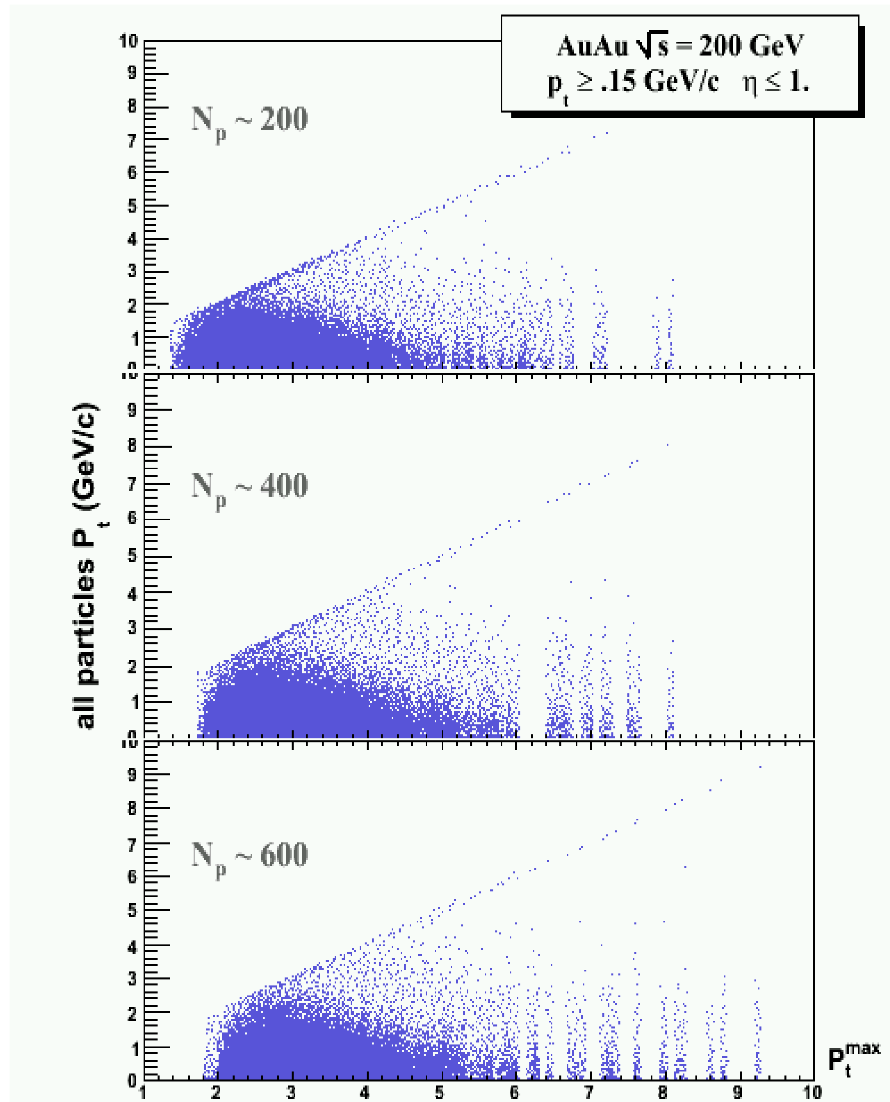
Azimutal anisotropy

RHIC



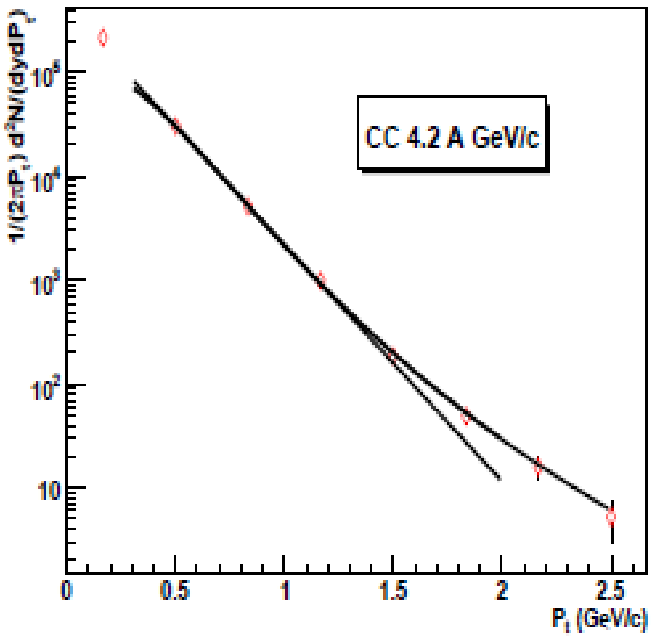
LHC



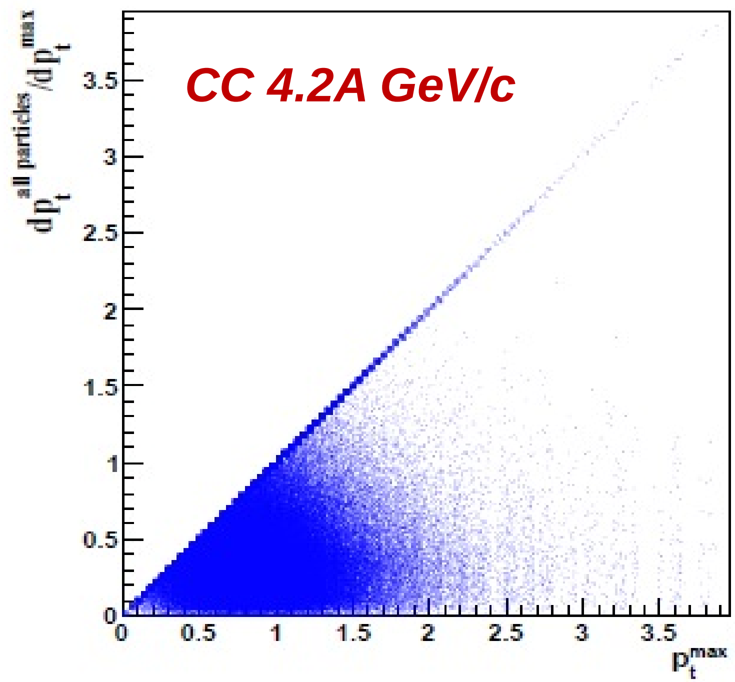


pC dC aC CC @ 4.2A GeV/c

Interaction	Number of events
pC	5722
dC	3826
αC	9643
CC	15842

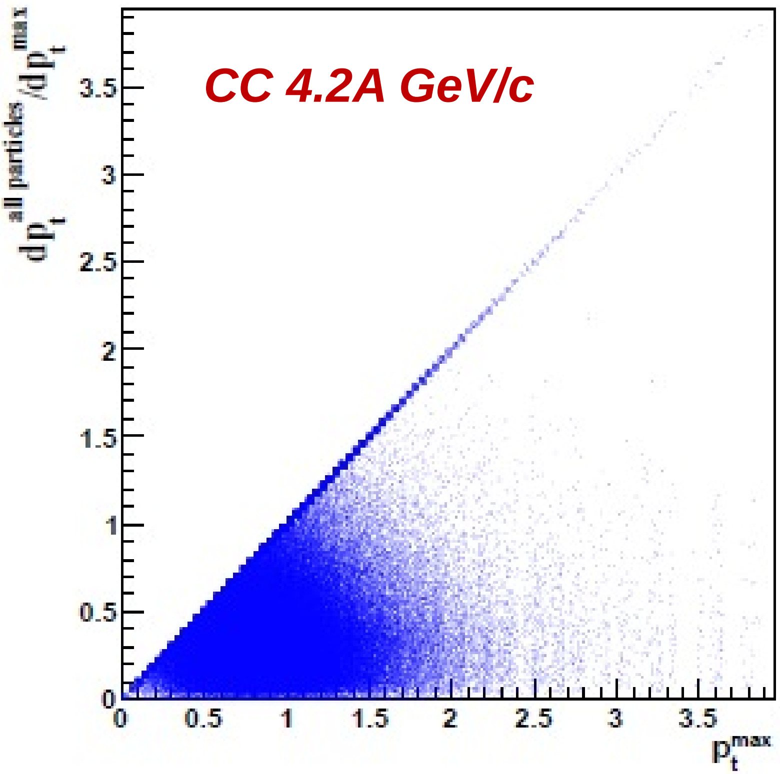


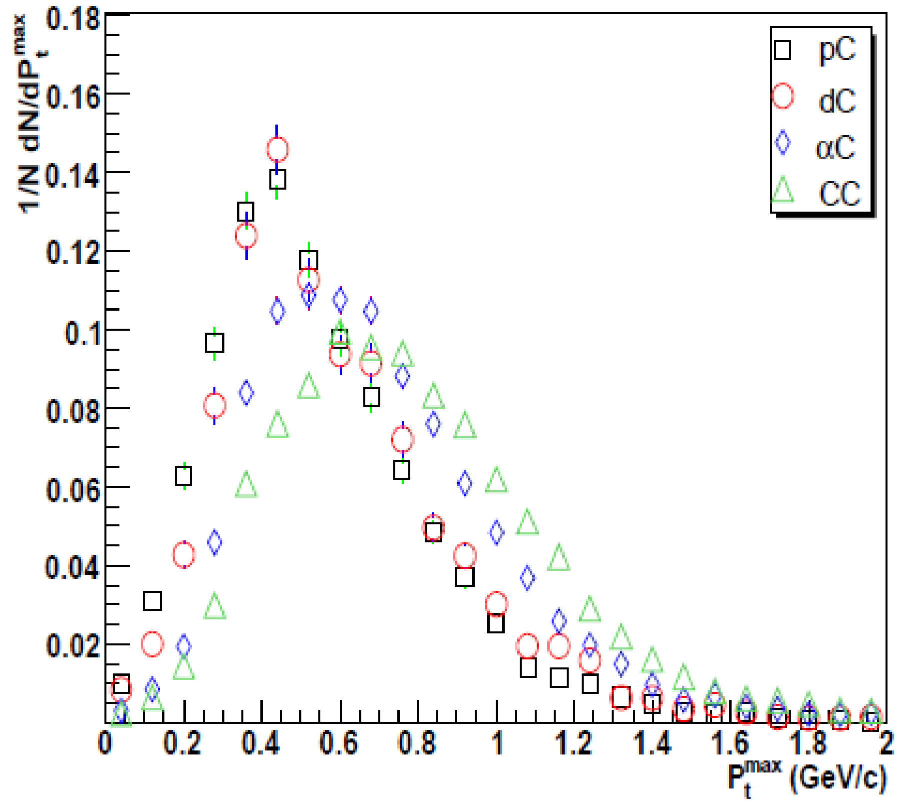
Levy distribution fit



	parameter value			
	n	T	B	χ^2/ndf
pC	7.45 ± 1.22	6.86e-02 ± 6.04e-03	2.29e+04 ± 2.40e+03	0.19
dC	6.68 ± 1.10	6.63e-02 ± 6.78e-03	1.85e+04 ± 2.31e+03	0.19
αC	6.59 ± 0.57	7.08e-02 ± 3.66e-03	6.10e+04 ± 3.70e+03	1.20
CC	6.84 ± 0.39	7.69e-02 ± 2.39e-03	1.30e+05 ± 4.55e+03	3.20

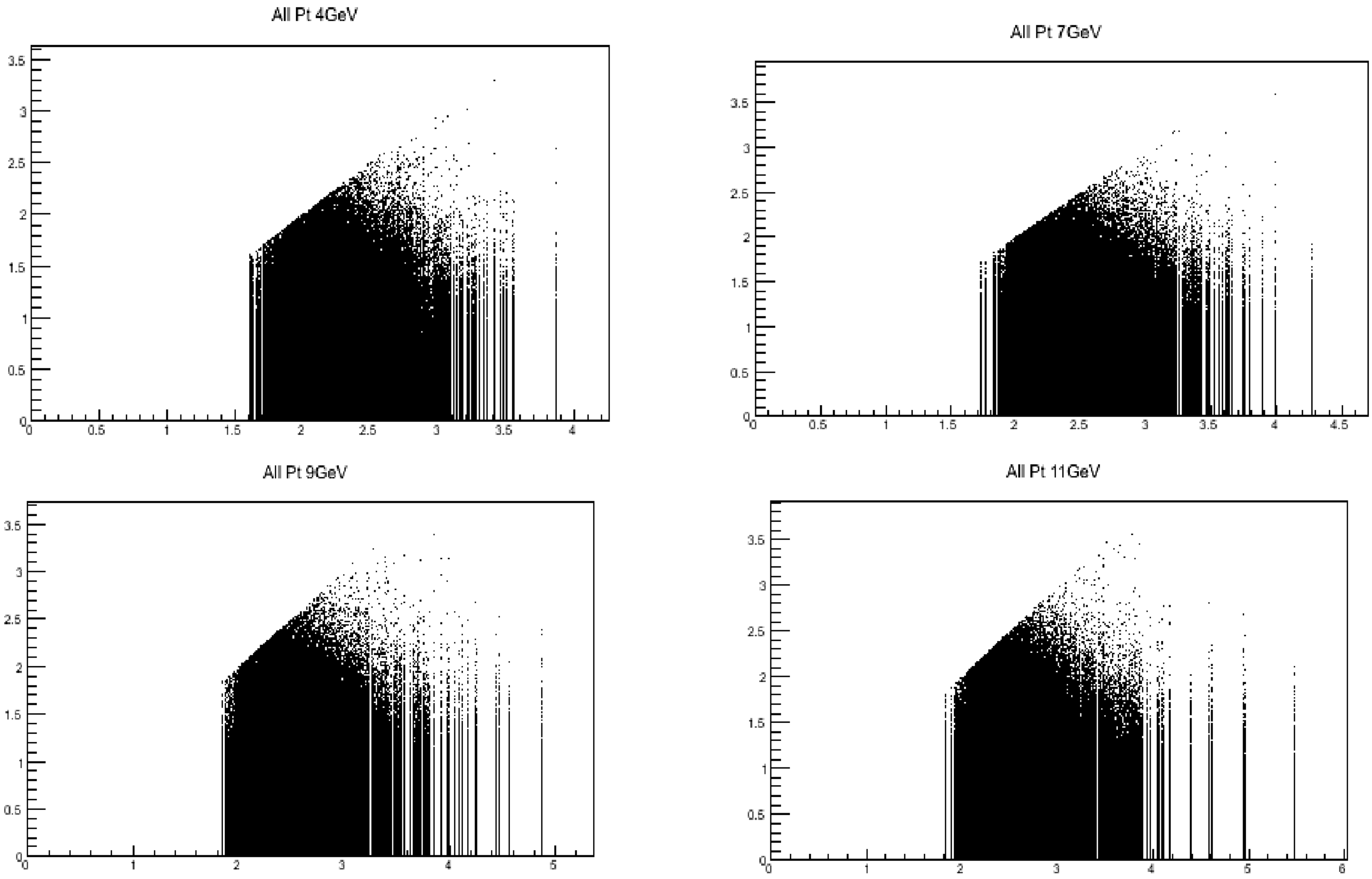
Transition region @4.2 GeV/c





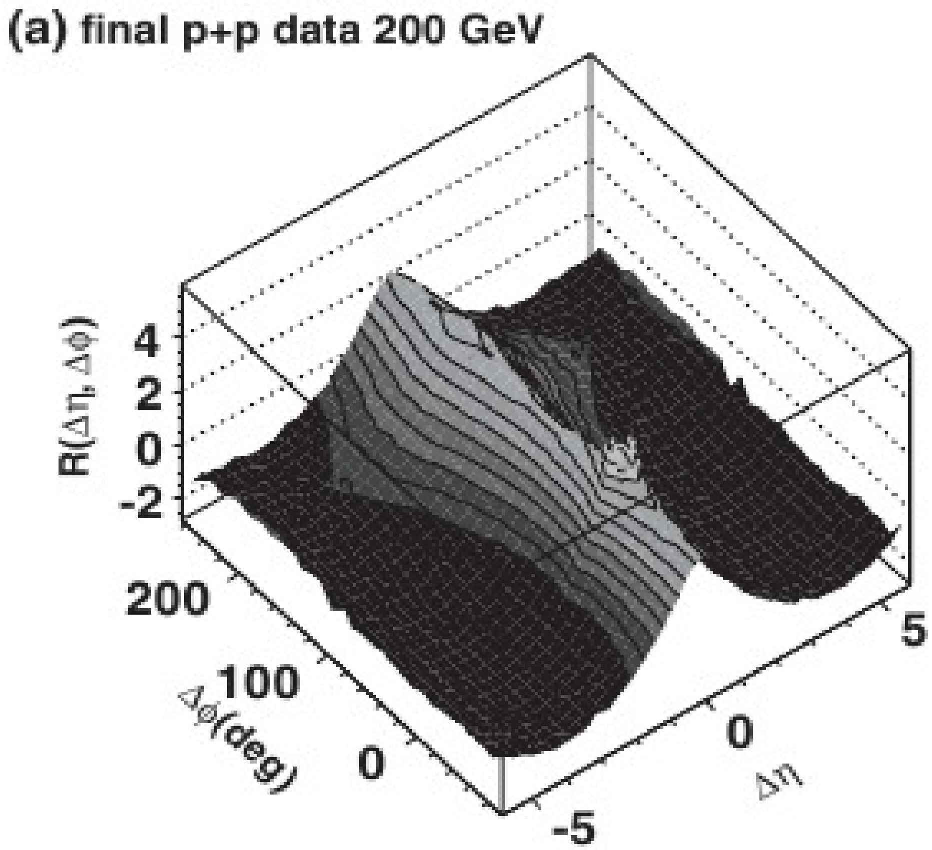
- Shifts with A
- Broadening with A

UrQMD AuAu & NICA energies

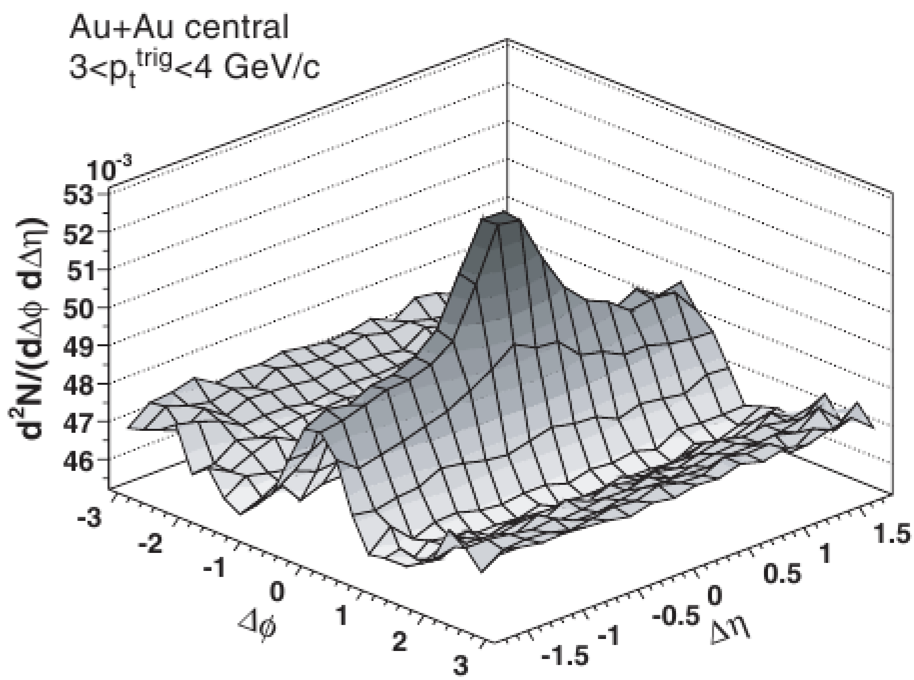


Ridge @ RHIC

PHYSICAL REVIEW C **75**, 054913 (2007)



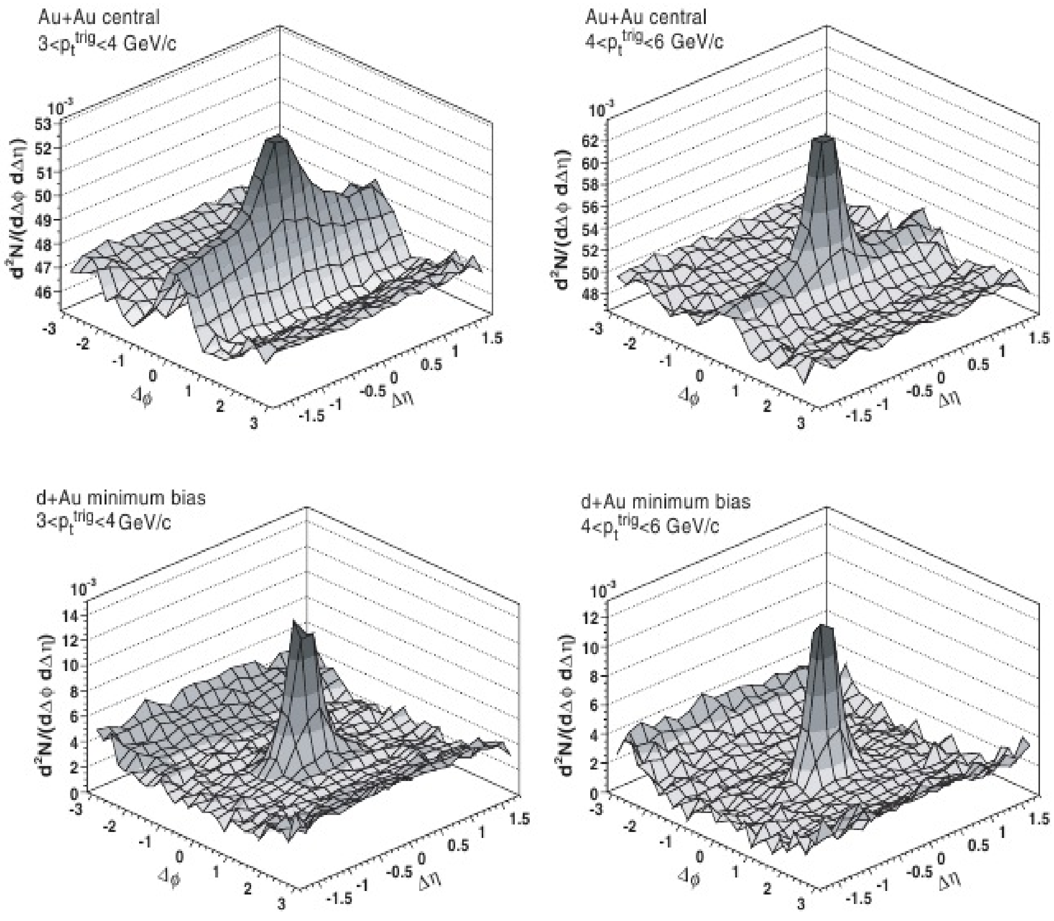
PHYSICAL REVIEW C **80**, 064912 (2009)



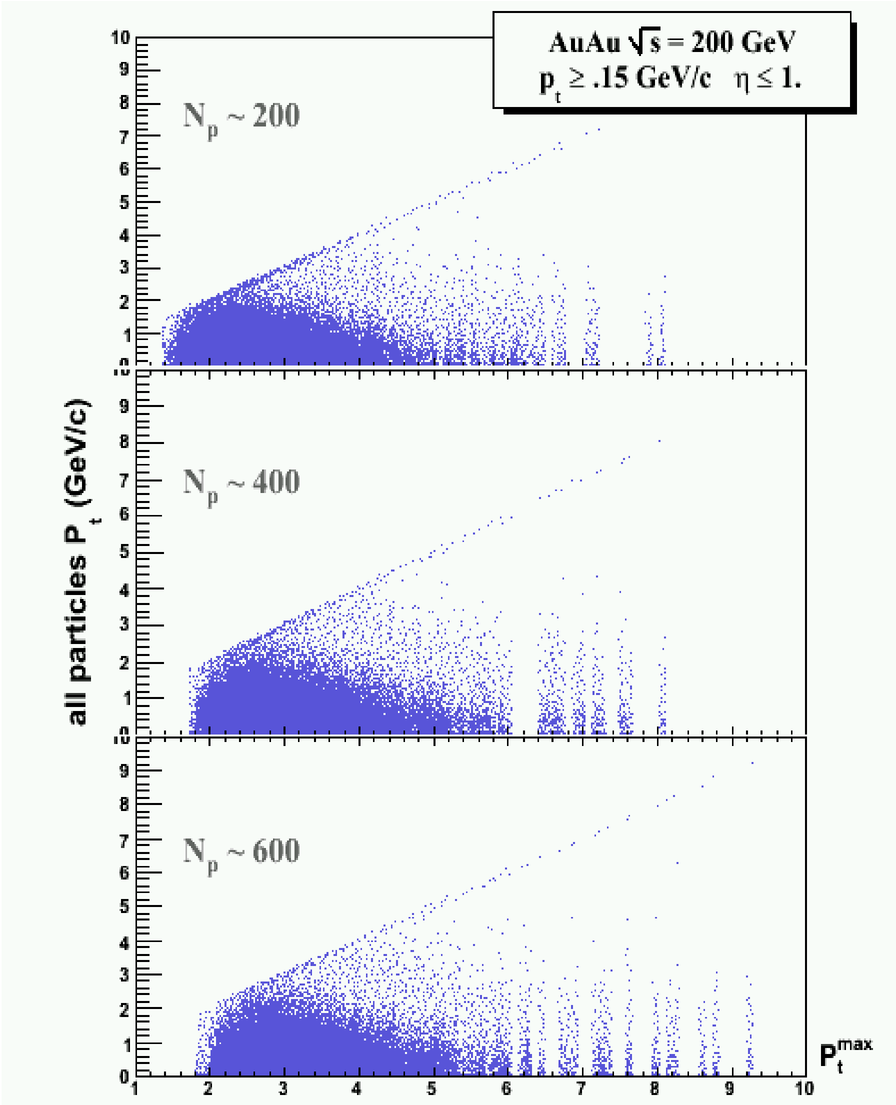
$2\ \mathrm{GeV/c} < p_T^{assoc} < p_T^{trig}$

They cover an acceptance of 3 < |η| < 4.5 and −180◦ < φ < 180◦ . About 5 × 105 200-GeV and 8 × 105 410-GeV p+p events were selected for further analysis by requiring that the main collision vertex fell within |zvtx | < 10 cm along the beam axis.

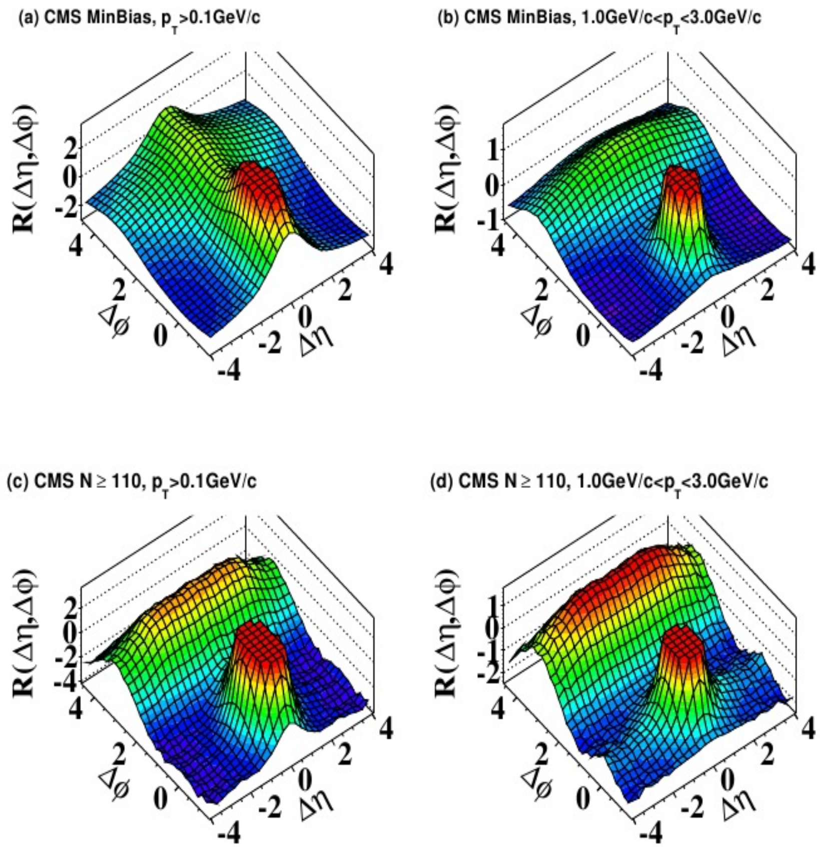
Ridge dAu vs AuAu

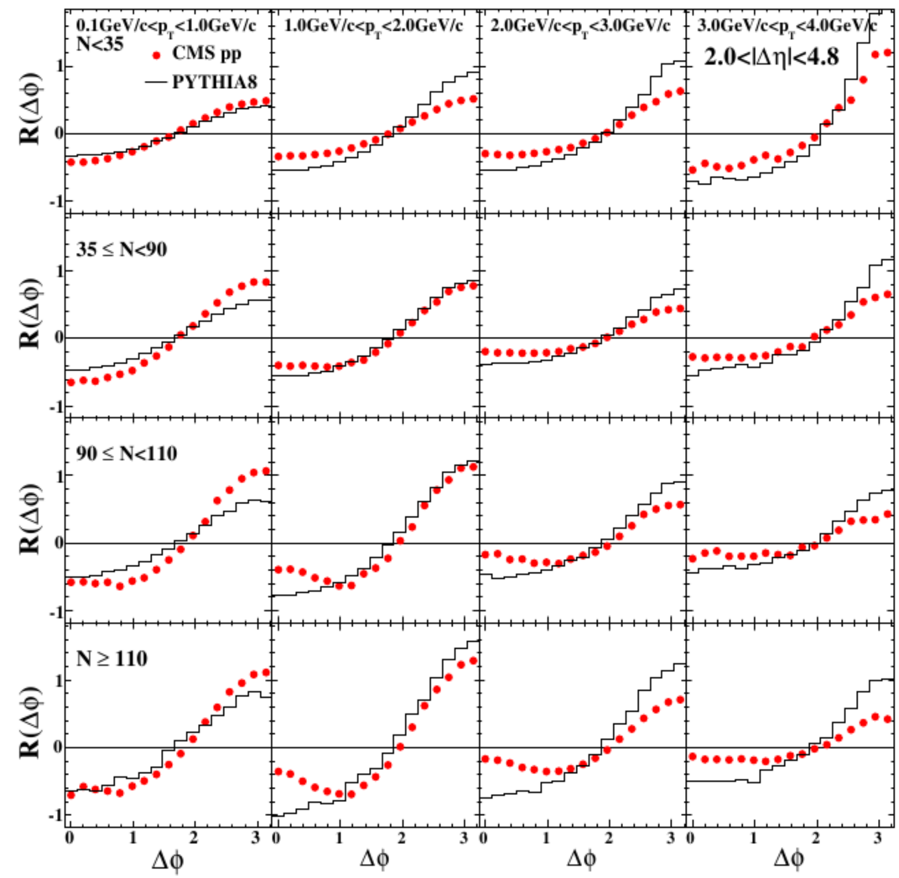


$2\ \mathrm{GeV}/c < p_T^{assoc} < p_T^{trig}$

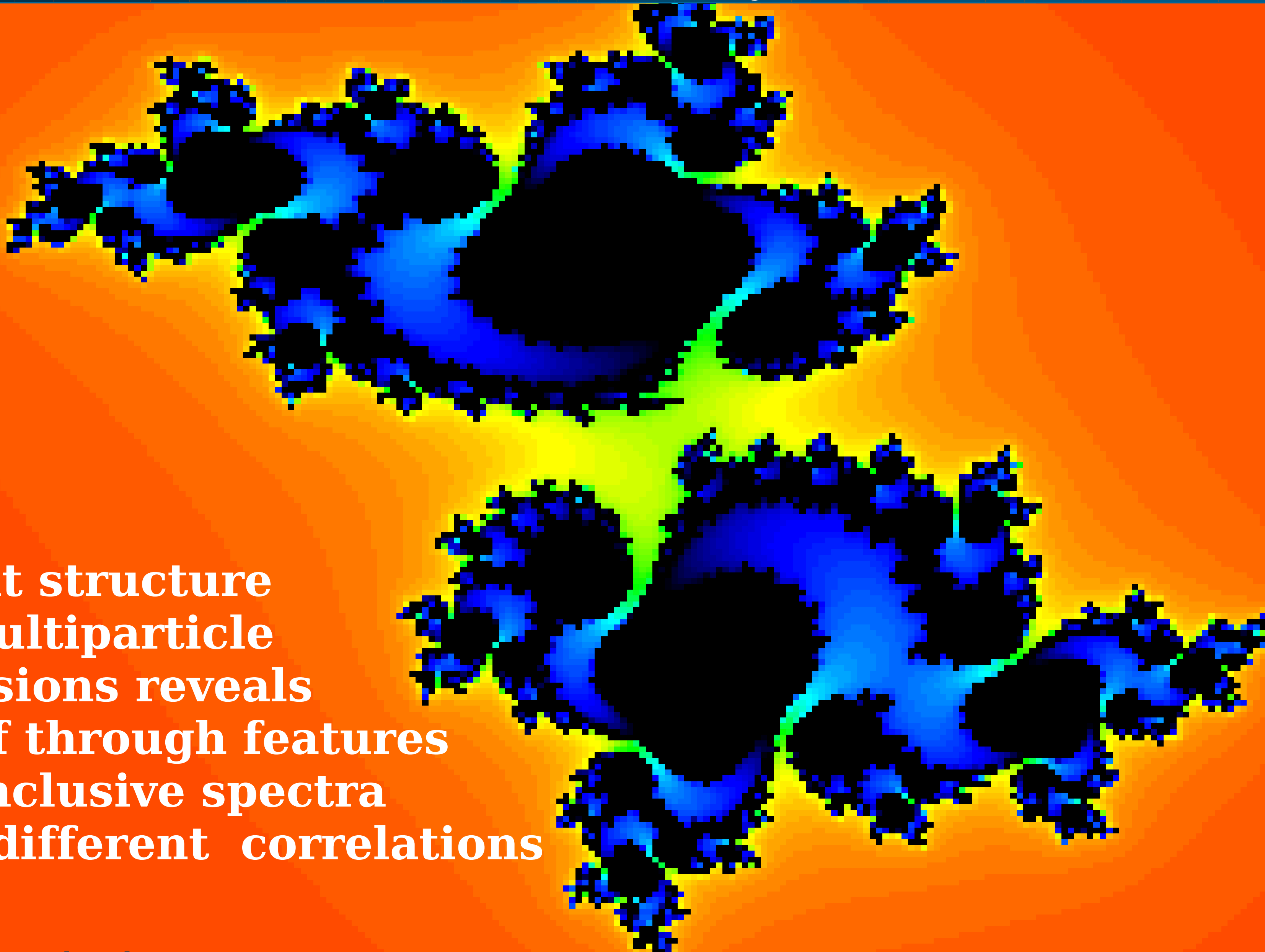


pp @ 7 TeV


(a) CMS MinBias, p_T>0.1GeV/c
(b) CMS MinBias, 1.0GeV/c<p_T<3.0GeV/c
(c) CMS N ≥ 110, p_T>0.1GeV/c
(d) CMS N ≥ 110, 1.0GeV/c<p_T<3.0GeV/c
R(Δη,Δϕ)
Δϕ
Δη


0.1GeV/c<p_T<1.0GeV/c
1.0GeV/c<p_T<2.0GeV/c
2.0GeV/c<p_T<3.0GeV/c
3.0GeV/c<p_T<4.0GeV/c
N<35
CMS pp
PYTHIA8
2.0<|Δη|<4.8
35 ≤ N<90
90 ≤ N<110
N ≥ 110
R(Δϕ)
Δϕ

Summary

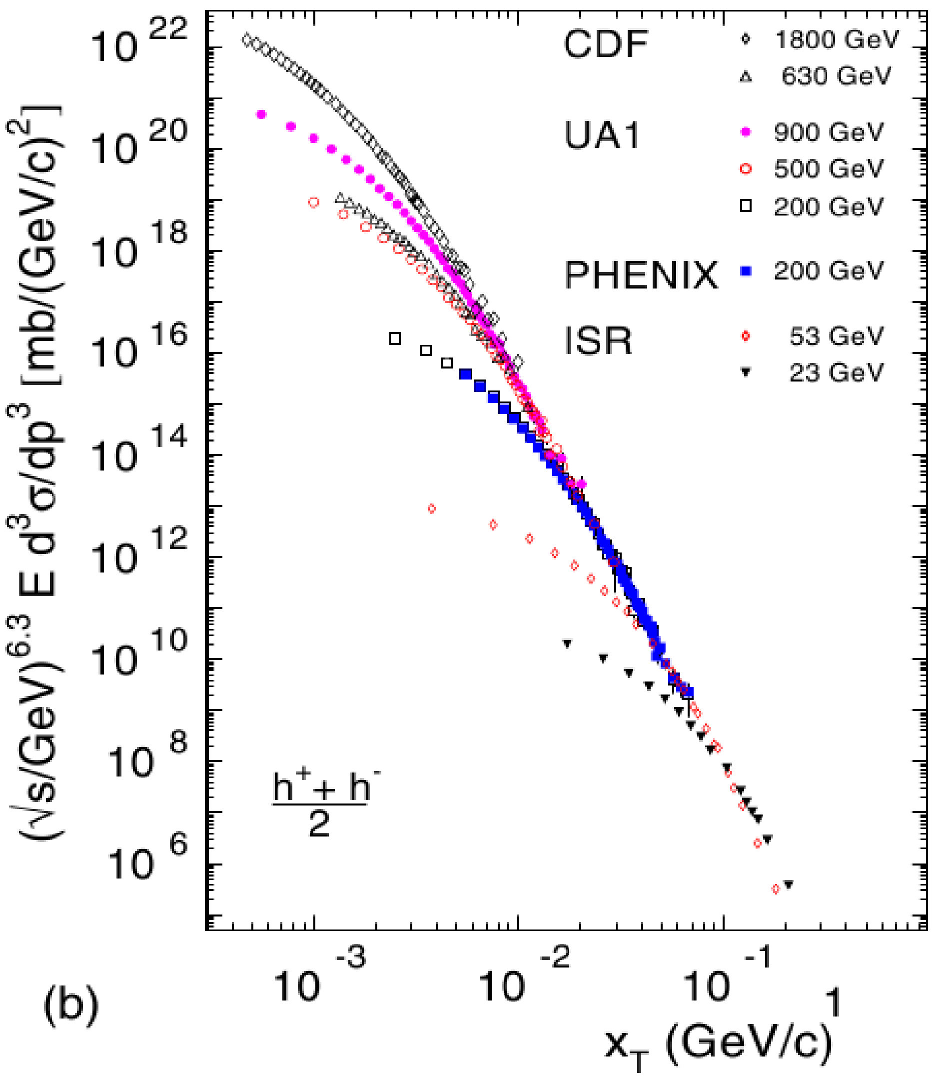


Event structure
of multiparticle
collisions reveals
itself through features
in inclusive spectra
and different correlations

Thanks for your attention

X_T scaling

Adcox K et al PHENIX Collaboration 2005 Nucl. Phys. A 757 184–283



$\sqrt{s}(\text{GeV})^{6.3} \times Ed^3\sigma/d^3p$ vs. $x_T = 2p_T/\sqrt{s}$

First LHC data on charged hadron production

pp collisions at low p_T

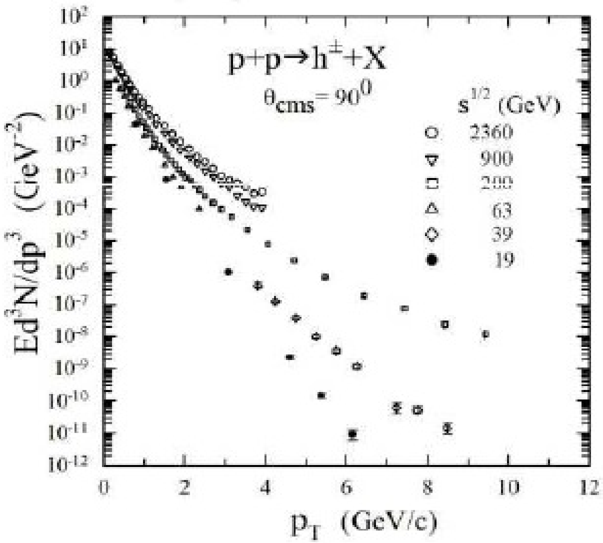
MT & I.Zborovsky
J. Phys.G: Nucl.Part.Phys. 37,085008(2010)

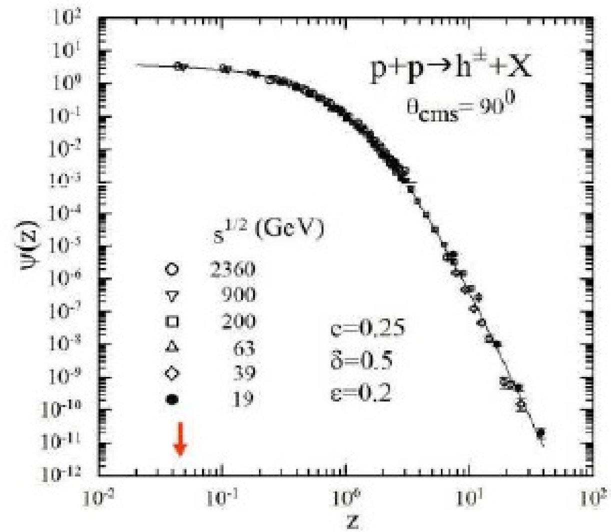
FNAL (fixed target)
PRD 19 (1979) 764
PRD 40 (1989) 2777

ISR: BS Coll.
Nucl.Phys. B 100 (2007) 237

RHIC: STAR Coll.
PRL 91 (2003) 172302

LHC: CMS Coll.
JHEP02(2010) 041





- Energy independence at low p_T
- CMS data confirm onset of saturation for $z < 0.1$

122

M.Tokarev