Correlation Signatures

of a Second Order QCD Phase Transition

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Introduction:

- **3 milestones in Au+Au collisions at RHIC**

Critical opalescence:

- **Experimental observation of a 2nd order phase transition**

Hard correlations:

- **Direct γ + hadron jet**
- **Critical opalescence and the disappearance of the punch-through jet**

Soft correlations:

- **Exact (i.e. not numerical) integrals of fluid dynamics**
  - **non-relativistic and relativistic solutions**
- **Lévy stable source distributions**

Measuring the critical exponent of the correlation function

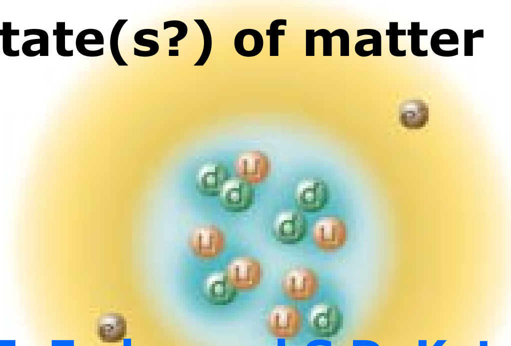
Lattice QCD: EoS of QCD Matter

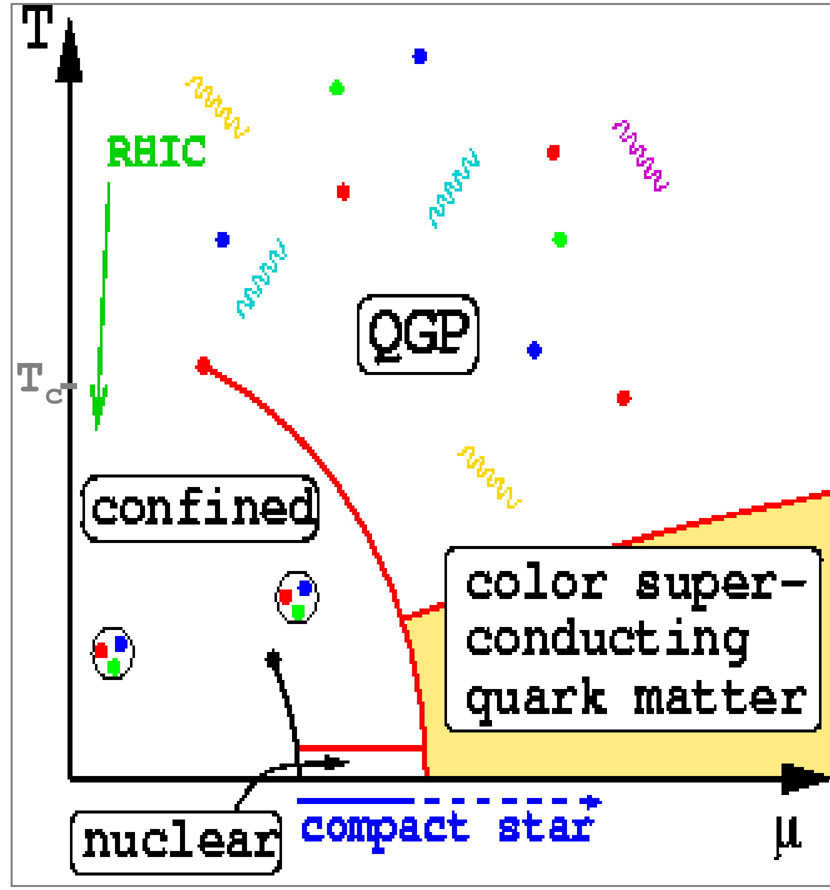
Old idea: Quark Gluon Plasma

"Ionize" nucleons with heat

"Compress" them with density

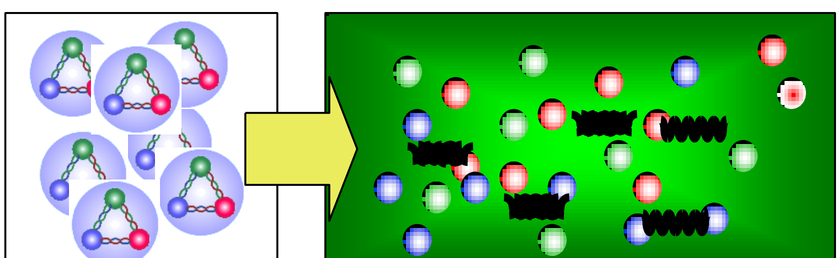
New state(s?) of matter





Z. Fodor and S.D. Katz:
critical end point of 1st order phase tr
even at finite baryon density,
cross over like transition.
(hep-lat/0106002, hep-lat/0402006)

T_c=176±3 MeV (~2 terakelvin)
(hep-ph/0511166)



General input for hydro: $p(\mu,T)$

LQCD for RHIC region: $p \sim p(T)$,

$$c_s^2 = \delta p/\delta e = c_s^2(T) = 1/\kappa(T)$$

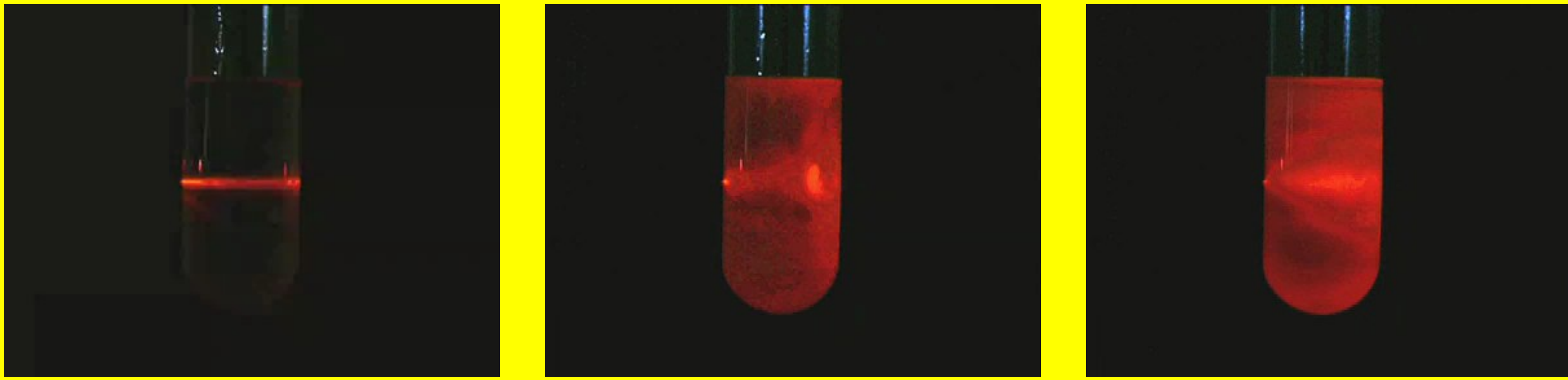
It's in the family analytic hydro solutions!

Critical Opalescence

Critical Opalescence: a laboratory method to observe a 2nd order PT

correlation length diverges, clusters on all scales appear incl. the wavelength of the penetrating (laser) probe

side view: http://www.msm.cam.ac.uk/doitpoms/tlplib/solidsolutions/videos/laser1.mov



front view: **matter becomes opaque at the critical point (CP)**

$T >> T_c$ **$T >\sim T_c$** **$T = T_c$**

Critical Opalescence

Suggests: the matter is most opaque at the critical point! (click on video)

observation of a penetrating probe with fixed trigger

(e.g. a trigger particle with high p_t > 5 GeV)

look for the broadening and disappearance of the punch-through jet

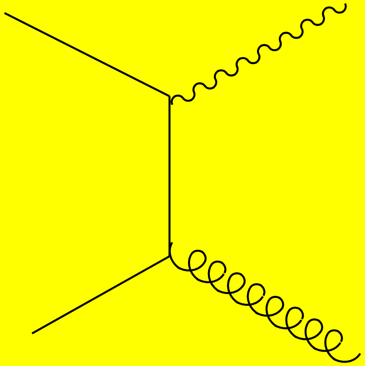
as a function of sqrt(s_{NN}): max effect corresponds to hitting T_c (CP)

Critical point: punch-through is hardest

Direct γ-hadron jet correlations

γ: yields the energy of the jet

penetrates matter



$$qg \rightarrow \gamma q$$

$$q\bar{q} \rightarrow \gamma g$$

hadron jet: punches through $T > T_c$

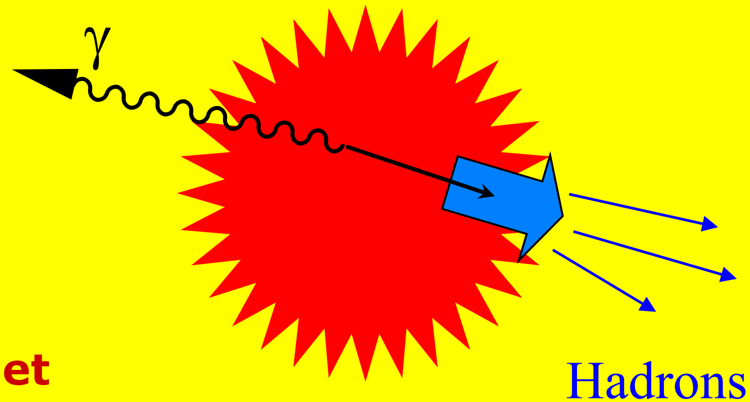
punches through $T < T_c$

disappears near T_c

running down RHIC provides a

unique

opportunity to measure



(γ , jet) correlation functions

disappearance of the punch-through jet

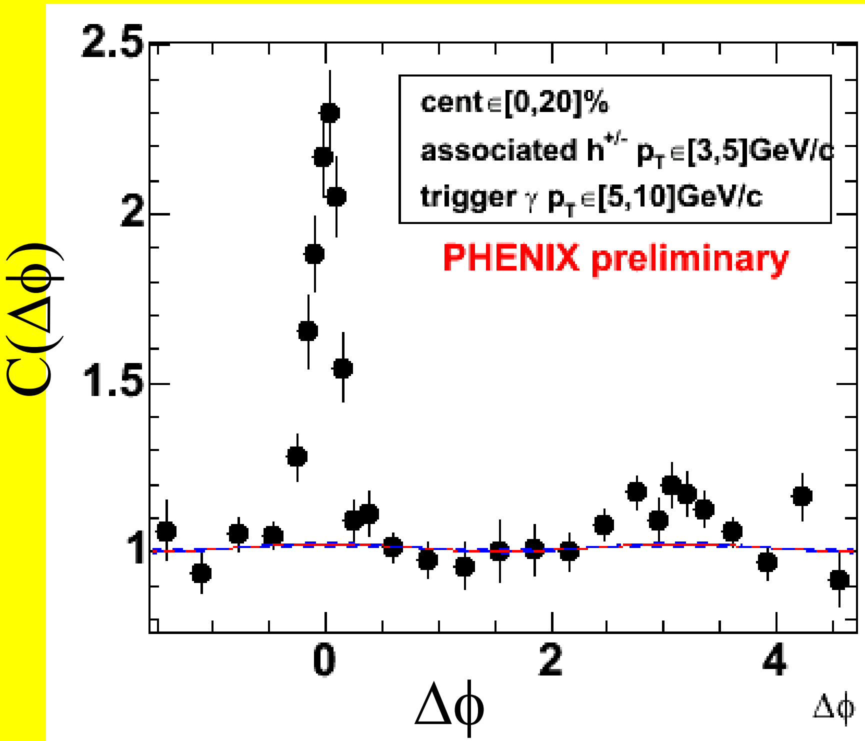
at the onset of the second order phase transition:

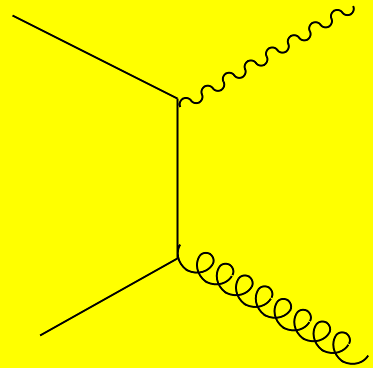
signal of critical opalescence.

(Minimum of R_{AA} is reached)

PHENIX preliminary: γ +jet correlations

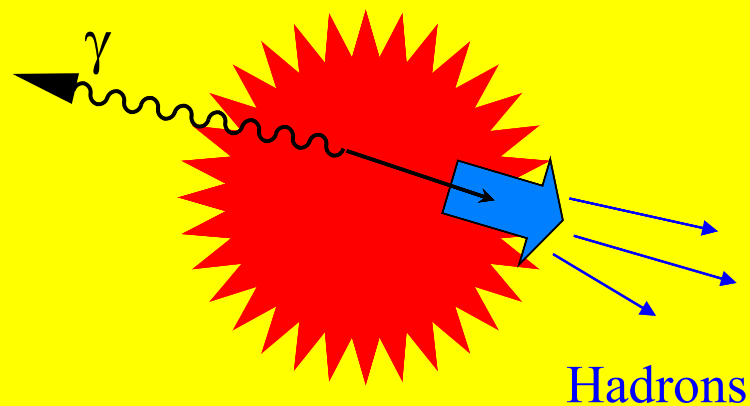
Direct γ-hadron jet correlations valuable tool to pin down the critical point of QCD!





$$qg \to \gamma q$$

$$q\bar{q} \to \gamma g$$



Comparison with π^0 triggered data necessary to extract direct photon correlations. (N. Grau for the PHENIX Collaboration, WWND 2006, San Diego)

Soft two-particle correlations

Single particle spectrum:

averages over space-time information

$$E\frac{dN}{d\mathbf{p}} = \int dx^4 S(x,\mathbf{p})$$

Correlations:

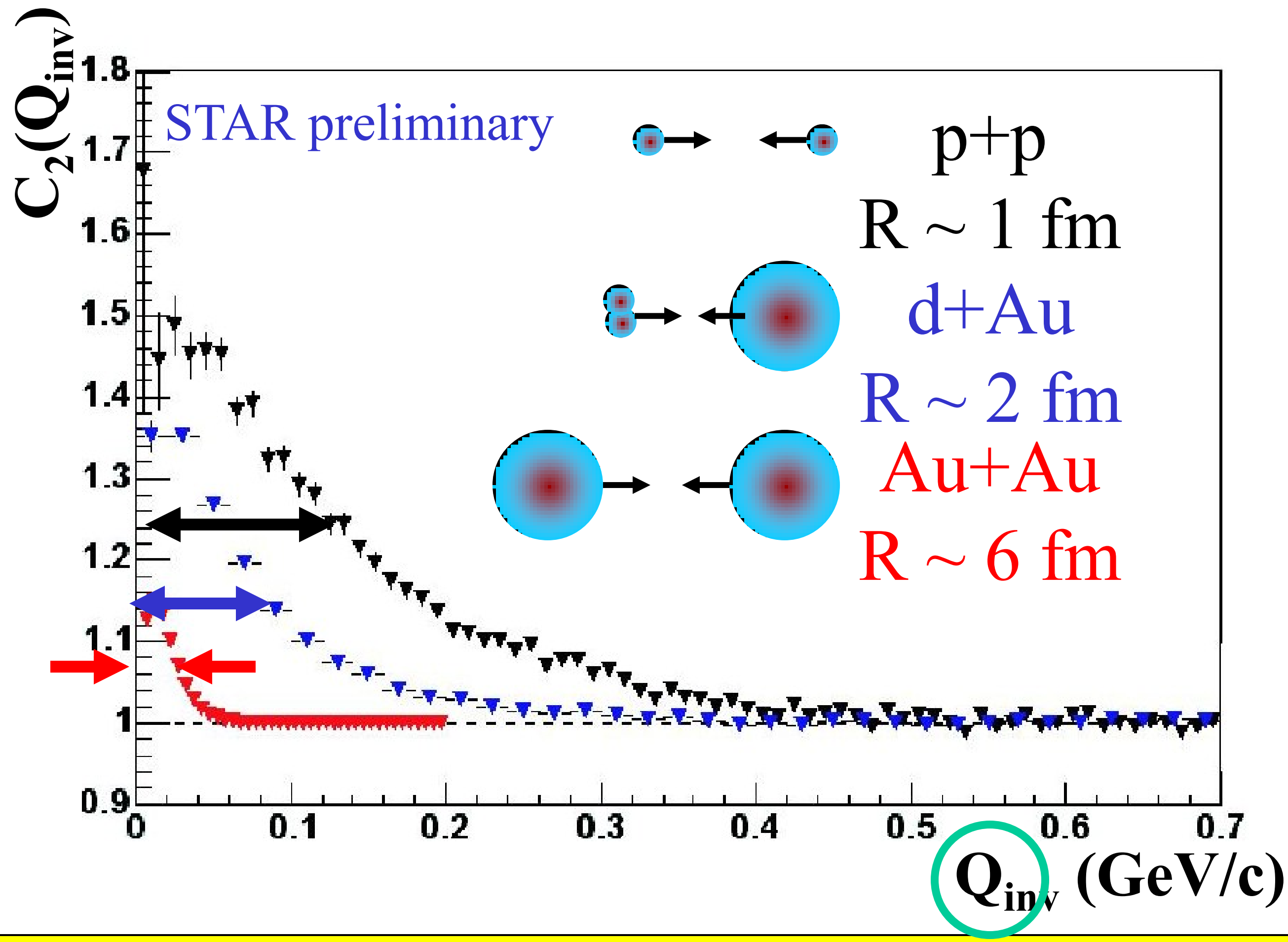
sensitivity to space-time information

$$C_2(\mathbf{q}) = \frac{dN_2 / d\mathbf{p}_1 d\mathbf{p}_2}{(dN_1 / d\mathbf{p}_1)(dN_1 / d\mathbf{p}_2)} \approx \int d\mathbf{r}\, |\Phi(\mathbf{r},\mathbf{q})|^2\, S(\mathbf{r},\mathbf{q})$$

FSI **Source function**

Intensity interferometry, HBT technique, femtoscopy ….

Correlation functions for various collisions



Correlations have more information (3d shape analysis)
Use advanced techniques & extract it (S. Panitkin, Moriond'05)

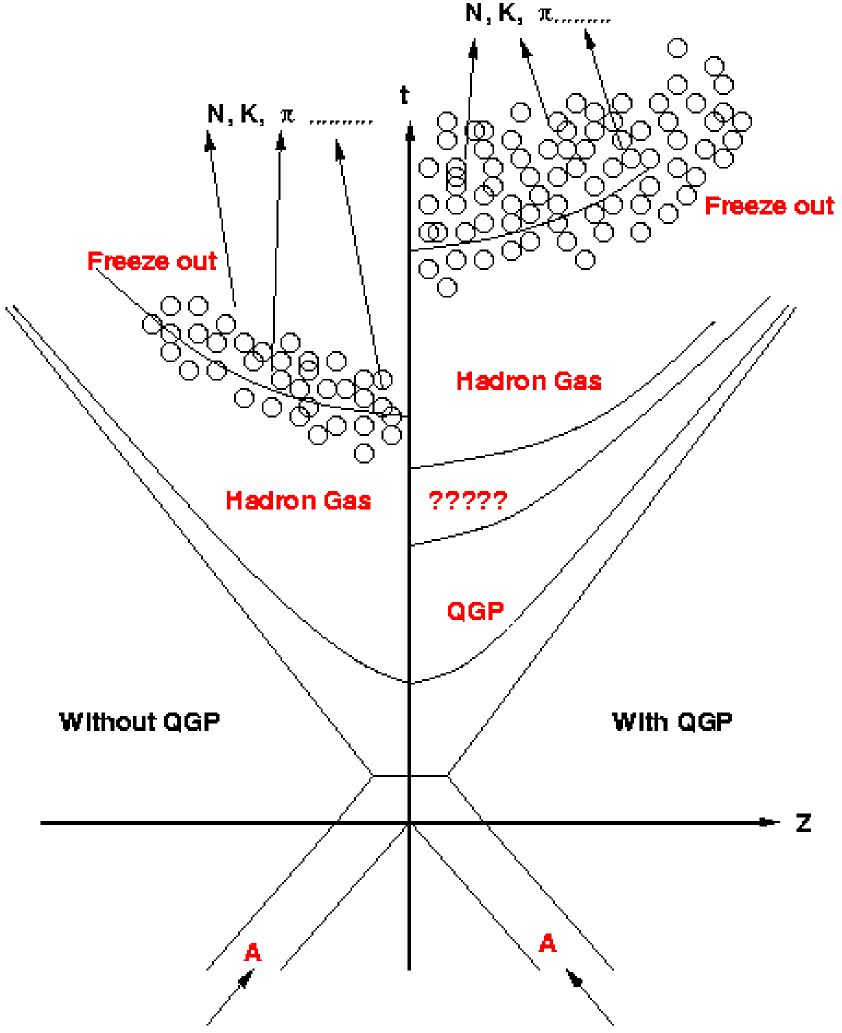
Search for a 1st order QCD phase transition

QGP has more degrees of freedom than pion gas

Entropy should be conserved during fireball evolution

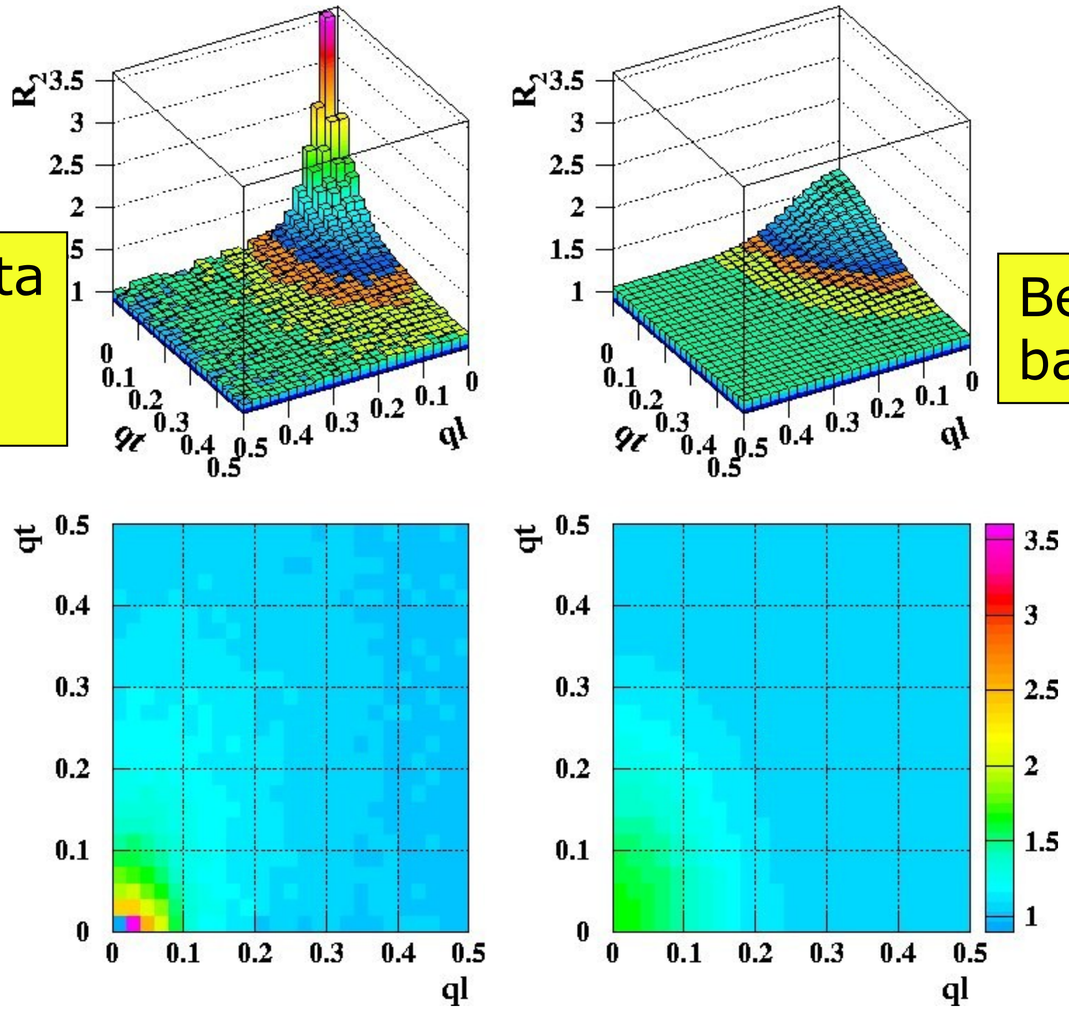
Hence:
Look in *hadronic* phase for signs of:
- **Large size,**
- **Large lifetime,**
- **Softest point of EOS**

signals of a 1st order (!) phase trans.



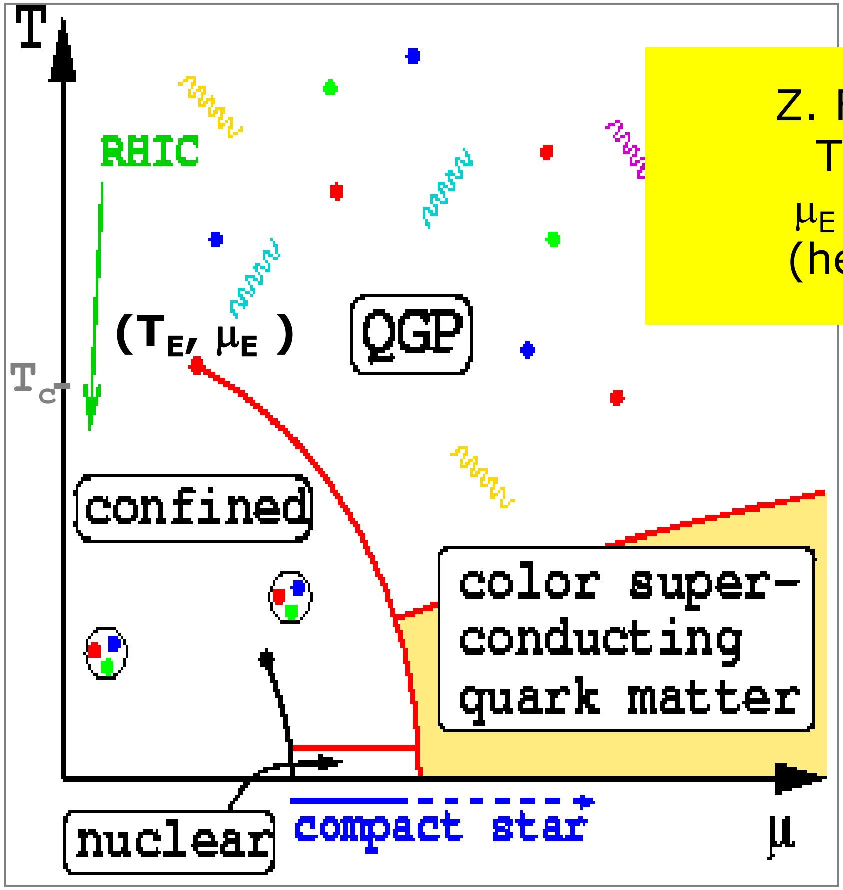
Non-Gaussian structures, 2d, UA1 data

UA1 (p+$\bar{p}$) data
B. Buschbeck
PLB (2006)



Best Gaussian
bad shape

Lattice QCD: EoS of QCD Matter



Z. Fodor, S.D. Katz:
T_E=162±2 MeV,
μ_E = 360±40 MeV
(hep-lat/0402006)

At the Critical End Point, the phase transition is of 2nd order.

Stepanov, Rajagopal,Shuryak:

Universality class of QCD -> 3d Ising model PRL 81 (1998) 4816

Critical phenomena

Order parameter of QCD - quark condensate: $c = \langle \bar{q} q \rangle$

Correlation function of quark condensate:

$$\rho(R) = \langle c(r+R)c(r) \rangle - \langle c \rangle^2$$

measures spatial correlations of pions,
it decreases for large distances as: $\rho(R) \propto R^{-(d-2+\eta)}$

d: dimension = 3
critical exponent of the correlation function η

For the d=3 Ising model (QCD @ CEP): $\eta(\text{3d Ising}) = 0.50 \pm 0.05$
(Rieger, Phys. Rev. B52 (1995) 6659)

Scale invariant (Lévy) sources

Fluctuations appear on many scales,
final position is a sum of many random shifts:

$$x = \sum_{i=1}^{n} x_i, \qquad f(x) = \int \Pi_{i=1}^{n} \mathrm{d}x_i \, \Pi_{j=1}^{n} f_j(x_j) \, \delta(x - \sum_{k=1}^{n} x_k).$$

correlation function measures a Fourier-transform,
that of an n-fold convolution:

$$\tilde{f}(q) = \int \mathrm{d}x \exp(iqx) f(x), \qquad \tilde{f}(q) = \prod_{i=1}^{n} \tilde{f}_i(q),$$

Lévy: generalized central limit theorems
adding one more step in the convolution does not change the shape

$$\tilde{f}_i(q) = \exp\left(iq\delta_i - |\gamma_i q|^{\alpha}\right), \qquad \prod_{i=1}^{n} \tilde{f}_i(q) = \exp\left(iq\delta - |\gamma q|^{\alpha}\right)$$

$$\gamma^{\alpha} = \sum_{i=1}^{n} \gamma_i^{\alpha}, \qquad \delta = \sum_{i=1}^{n} \delta_i.$$

Correlation functions for Lévy sources

Correlation funct of stable sources:

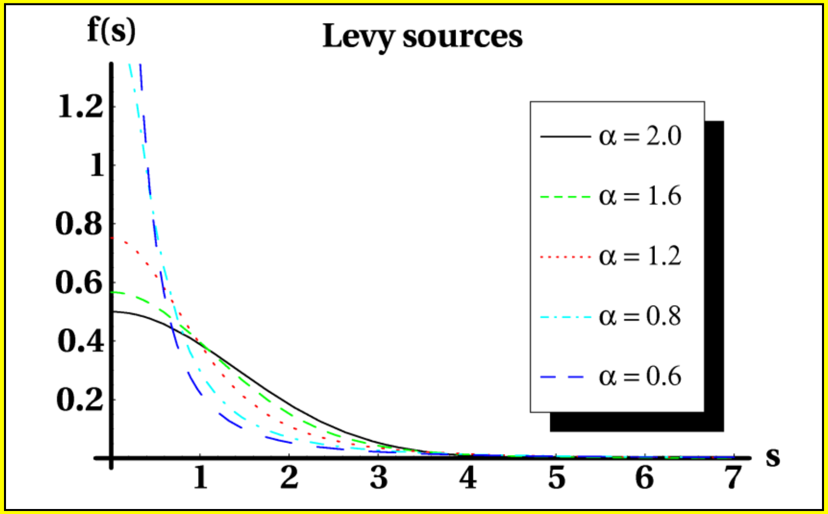
$$C(q;\alpha) = 1 + \lambda \exp\left(-|qR|^{\alpha}\right)$$

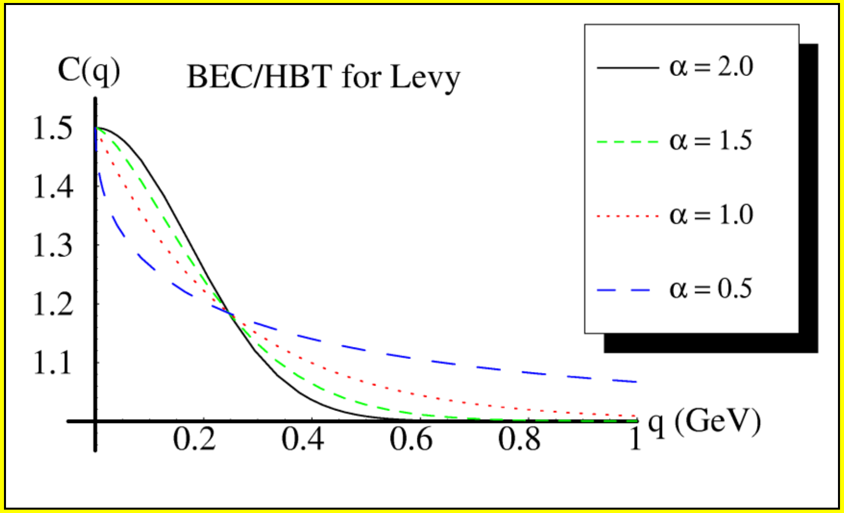
R: scale parameter

α: shape parameter or Lévy index of stability

$\alpha = 2$ Gaussian, $\alpha = 1$ Lorentzian sources

Further details: T. Cs, S. Hegyi and W. A. Zajc, EPJ C36 (2004) 67





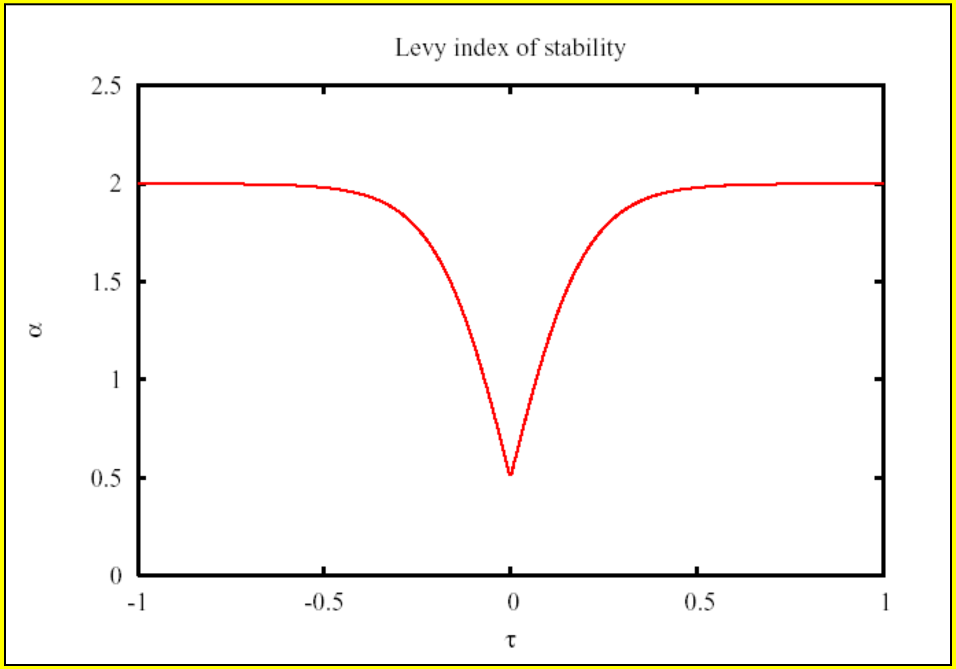
Correlation signal of the CEP

If the source distribution at CEP is a Lévy, it decays as:

$$\rho(R) \propto R^{-(1+\alpha)}$$

at CEP, the tail decreases as:

$$\rho(R) \propto R^{-(d-2+\eta)}$$



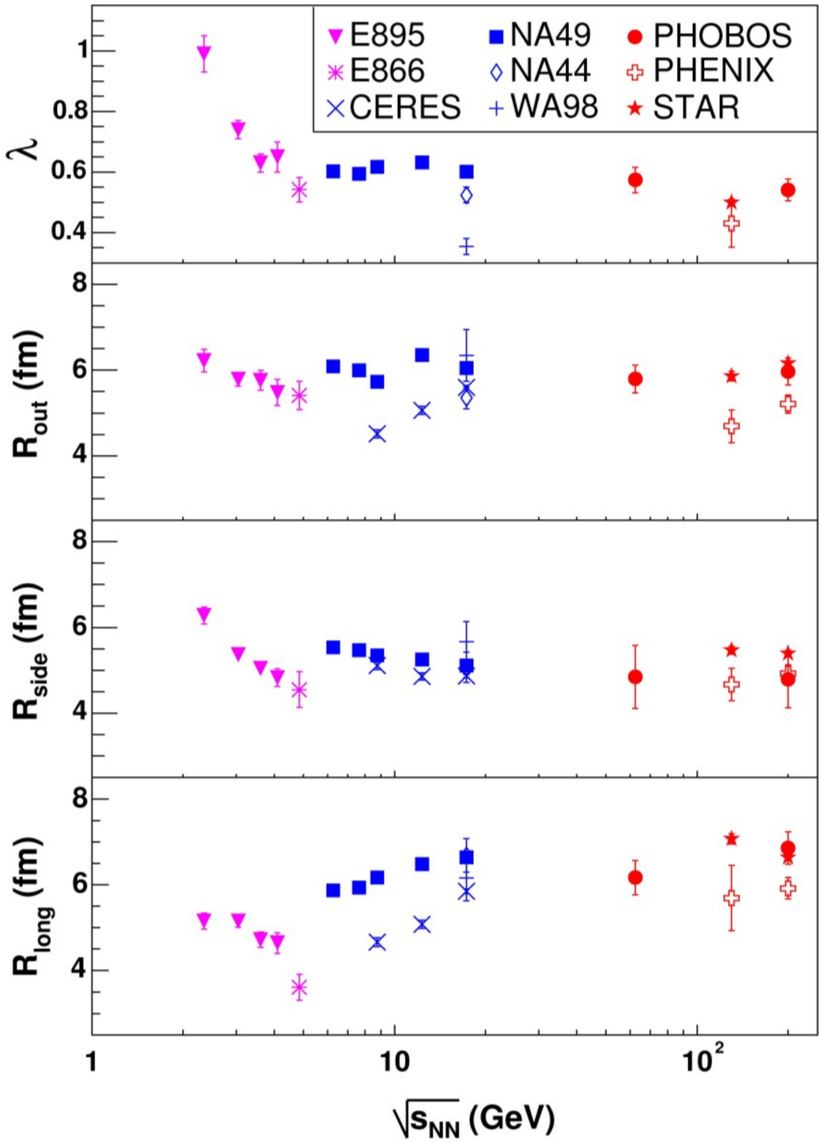
hence:

& excitation of α as a function of $\tau = | T - T_c| / T_c$

$$\alpha(\text{Lévy}) = \eta(\text{3d Ising}) = 0.50 \pm 0.05$$

T. Cs, S. Hegyi, T. Novák, W.A.Zajc, Acta Phys. Pol. B36 (2005) 329-337

Excitation of 3d Gaussian fit parameters



These data exclude:

1st order phase trans.
(assumed in many hydro codes)

For a second order PT:

excitation function of non-Gaussian parameter α

New analysis / new data are needed

Correlation signal, VARIOUS Quark Matters

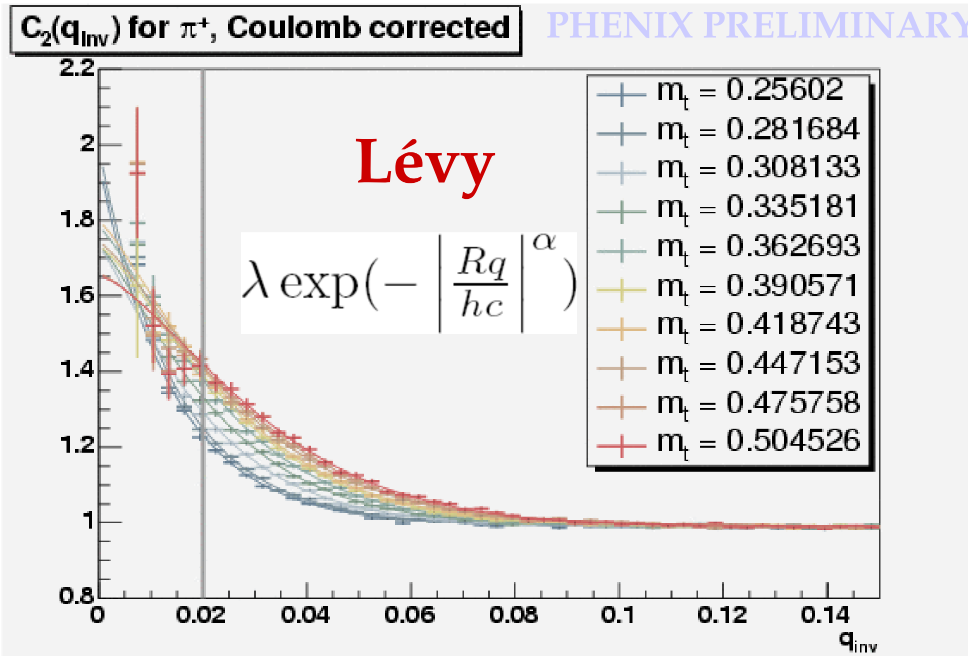
Transition to hadron gas may be:

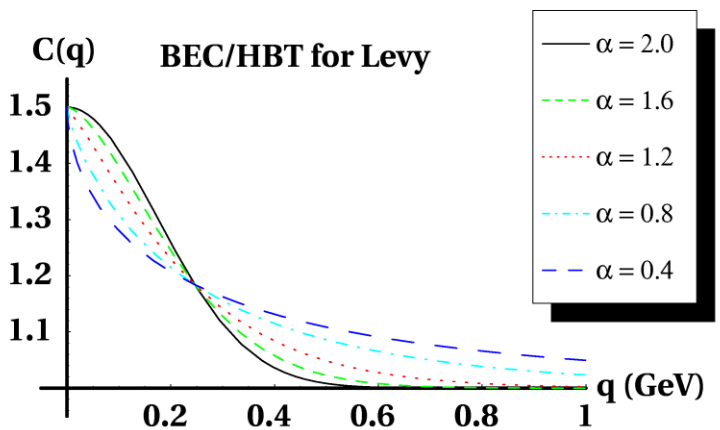
- (strong) 1st order
- second order (Critical Point, CP)
- cross-over
- from a supercooled state (scQGP)

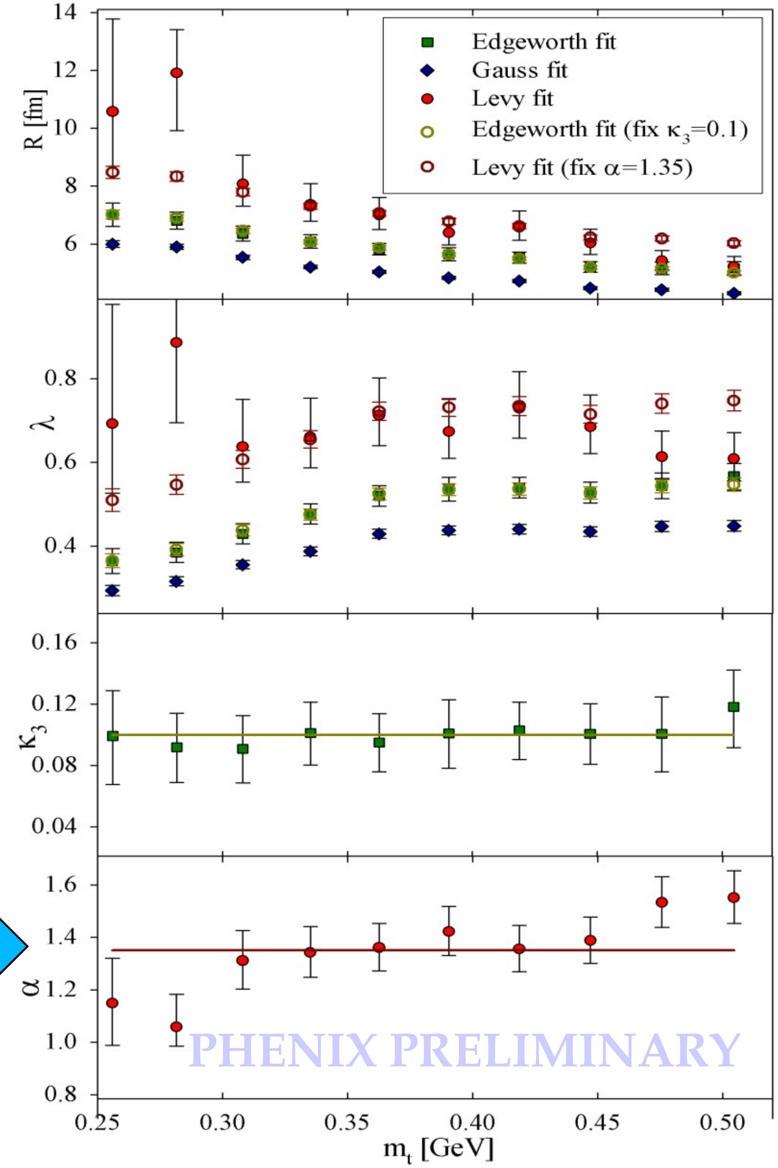
Type of phase transition:	its correlation signature:
Strong 1st order QCD phase transition: (Pratt, Bertsch, Rischke, Gyulassy)	$R_{out} >> R_{side}$
Second order QCD phase transition: (T. Cs, S. Hegyi, T. Novák, W.A. Zajc)	non-Gaussian shape α(Lévy) decreases to 0.5
Cross-over quark matter-hadron gas transition: (lattice QCD, Buda-Lund hydro fits)	hadrons appear from a region with $T > T_c$
Supercooled QGP (scQGP) -> hadrons: (T. Cs, L.P. Csernai)	pion flash ($R_{out} \sim R_{side}$) same freeze-out for all strangeness enhancement no mass-shift of ϕ

scQGP predicted in hep-ph/9406365 -
not inconsistent with RHIC Au+Au data in 2006 (!)

Lévy fits to prelim. Au+Au @ QM 2005







Summary

High transverse momentum γ + jet correlations:
maximal opalescence
promising signal for the critical end point

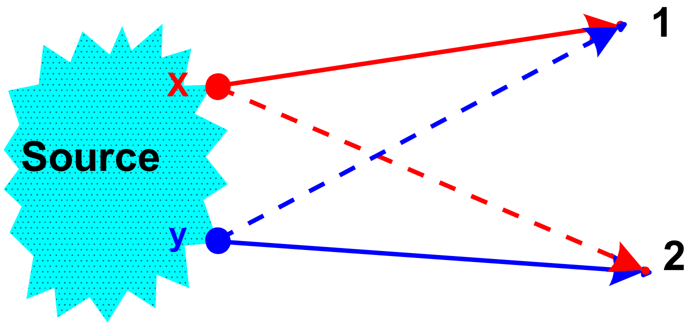
Soft Bose-Einstein correlations:
measure the excitation function of a
non-Gaussian parameter: Lévy index of stability, α
$\alpha = \eta$: critical exponent of the correlation function

Universality class argument:
α decreases from 2 (or 1.4) to 0.5 at the critical point
signals the 2nd order phase transition

Backup slides

Two particle Interferometry

for non-interacting identical bosons

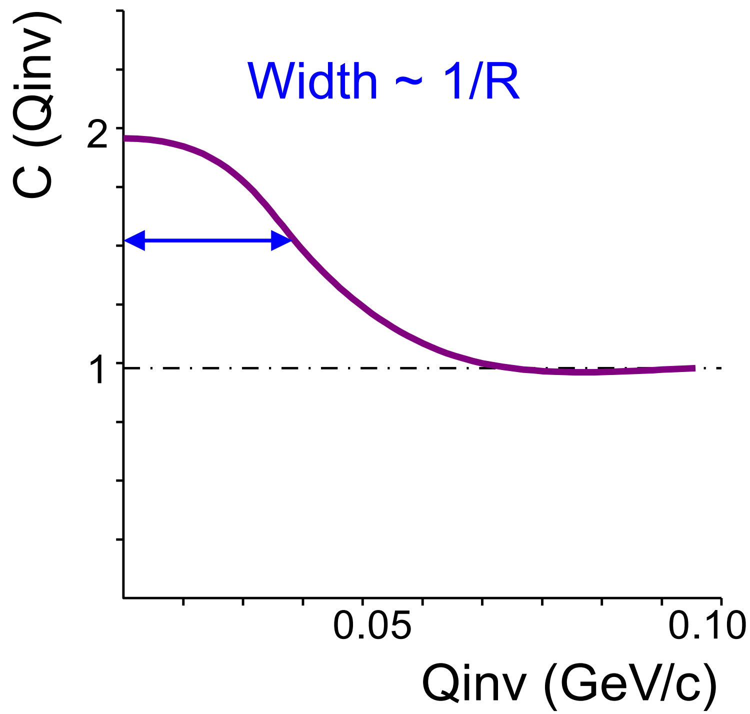


$$A_{12} = \frac{1}{\sqrt{2}}\left[e^{ip_1\cdot(r_1-x)}e^{ip_2\cdot(r_2-y)} + e^{ip_1\cdot(r_1-y)}e^{ip_2\cdot(r_2-x)}\right]$$

so that

$$\mathcal{P}_{12} = \int d^4x\, d^4y\, |A_{12}|^2 \rho(x)\rho(y) = 1 + |\tilde{\rho}(q)|^2 \equiv C_2(q)$$

emission function

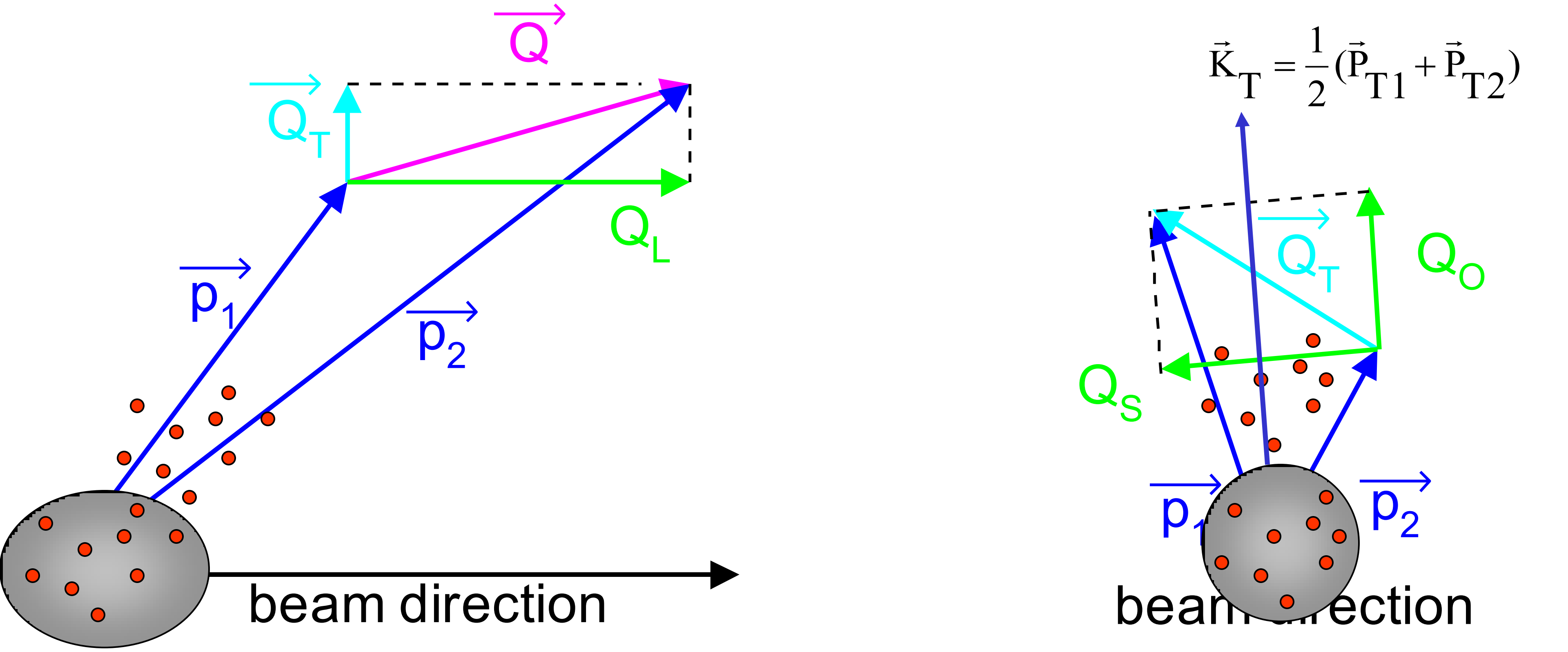


$$C(p_1,p_2) = 1 + \frac{\left|\int d^4x \cdot S(x,K) \cdot e^{iq\cdot x}\right|^2}{\left|\int d^4x \cdot S(x,K)\right|^2}$$

$$q = p_1 - p_2 \qquad K = \tfrac{1}{2}(p_1 + p_2)$$

Pratt-Bertsch coordinate system

$$C(\vec{q},\vec{k}) = 1 + \lambda(\vec{k})\, e^{-q_{\rm out}^2 R_{\rm out}^2 - q_{\rm side}^2 R_{\rm side}^2 - q_{\rm long}^2 R_{\rm long}^2}$$

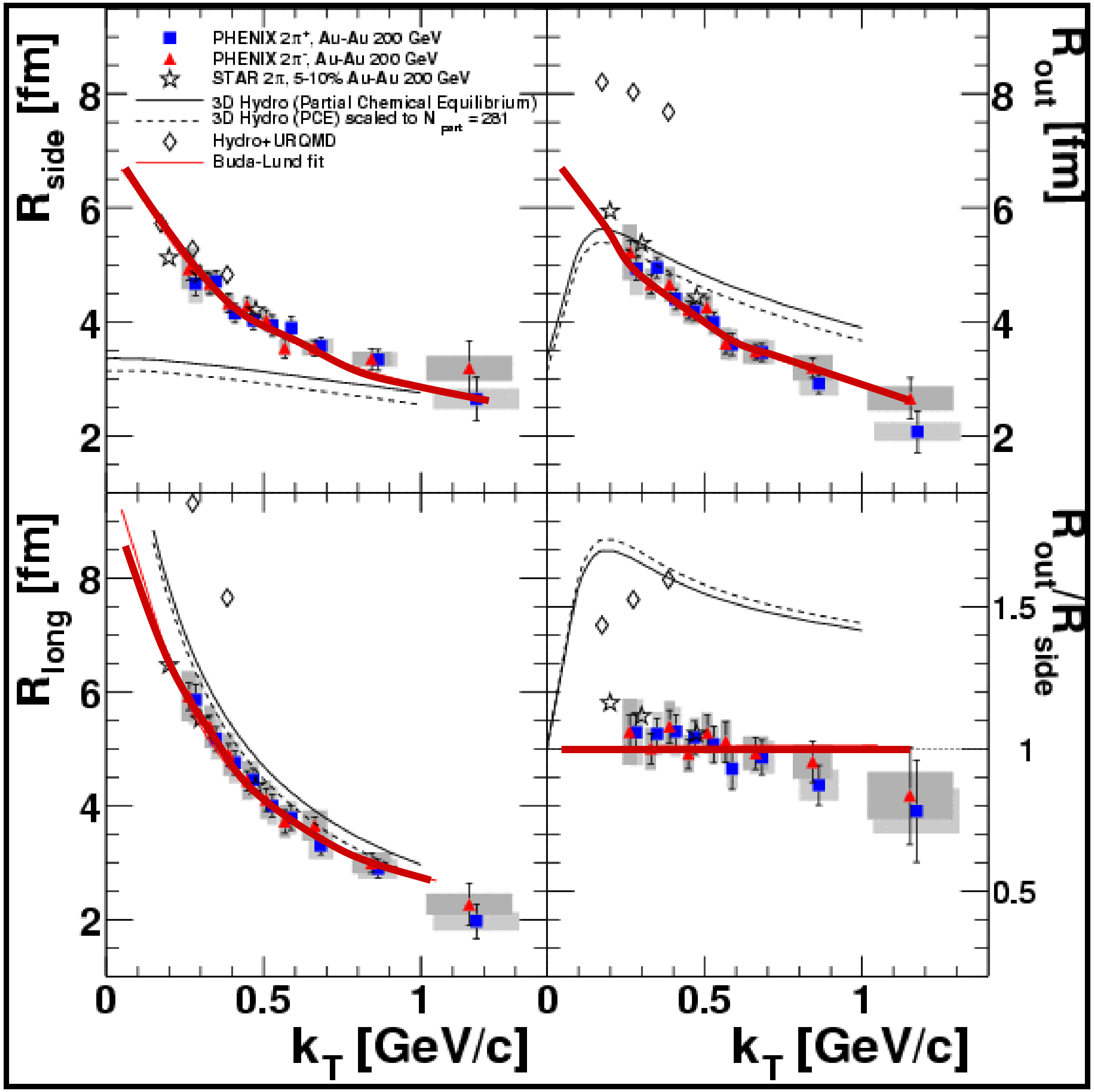


Femptoscopy signal of sudden hadronization

Buda-Lund hydro:
RHIC data follow the predicted (1994-96) scaling of HBT radii

T. Cs, L.P. Csernai hep-ph/9406365
T. Cs, B. Lörstad hep-ph/9509213

Hadrons with $T>T_c$:
1st order PT excluded
hint of a cross-over
M. Csanád, T. Cs, B. Lörstad and A. Ster, nucl-th/0403074



But are the correlation data Gaussian?

1 dimensional correlations:

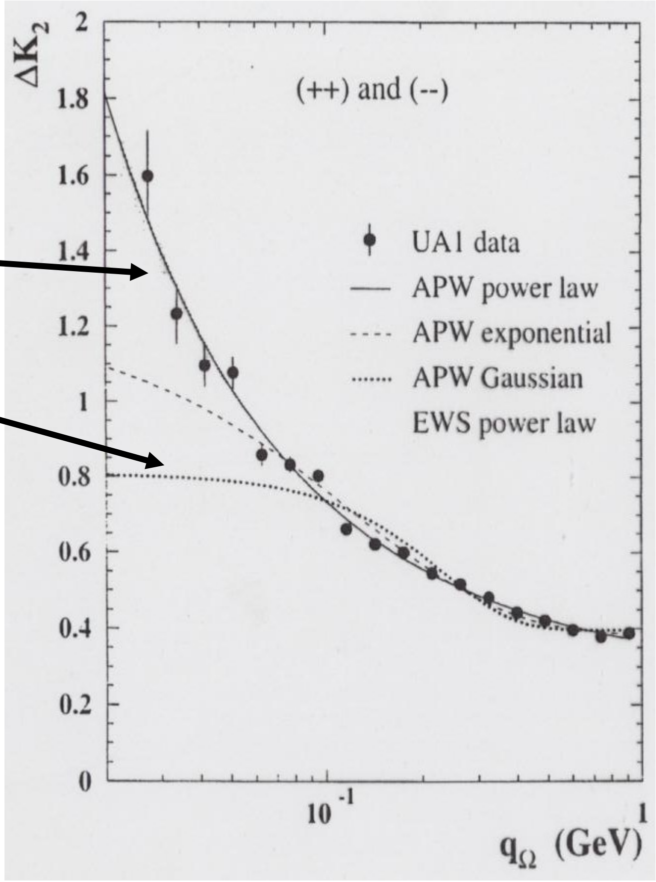
typically more peaked than a Gaussian

if a Gaussian fit does not describe the data

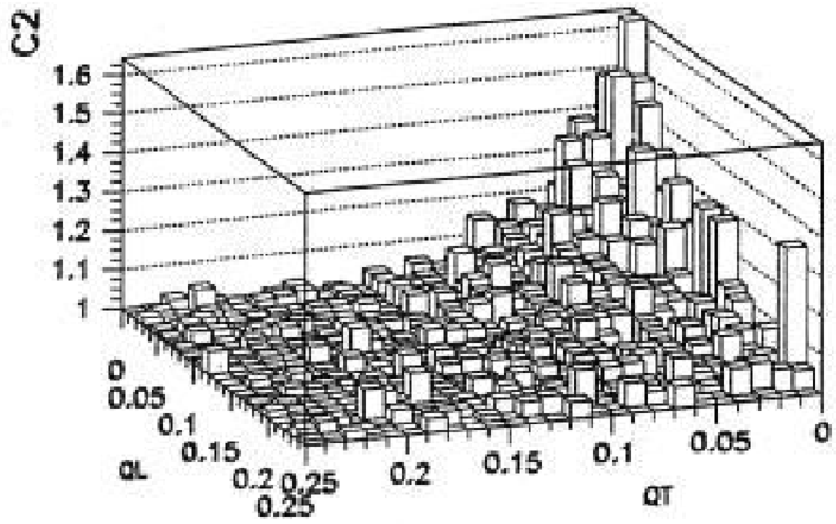
then have the parameters any meaning?

Example:
like sign correlation data of the UA1 collaboration

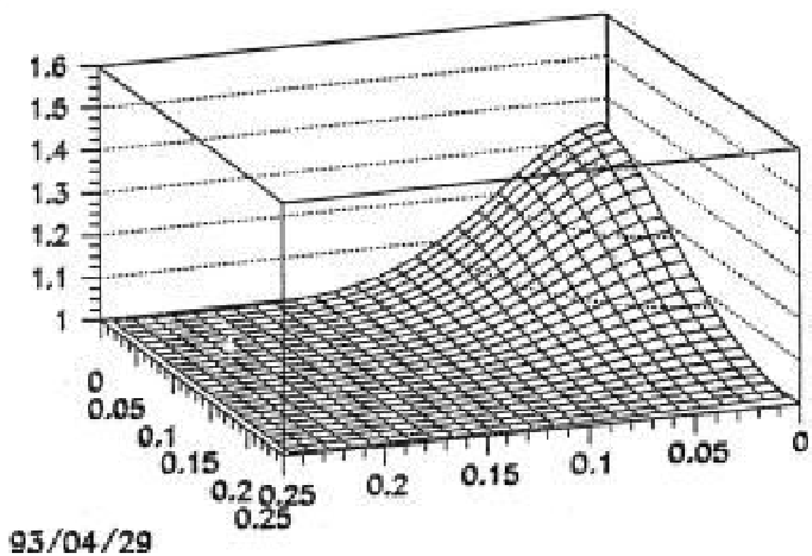
p + pbar @ E_{cms} = 630 GeV



Non-Gaussians, 2d E802 Si+Au data



E802 Si+Au data, sqrt(s_{NN}) = 5.4 GeV



Best Gaussian: bad shape