Searching for the QCD critical point in C+C collisions at the SPS

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Cern, March 2003

Critical properties in the isoscalar (sigma) sector

- Density fluctuations of pion pairs ($\pi^+\pi^-$) at threshold ($2m_\pi$) simulate the sigma-field fluctuations $\langle\sigma^2\rangle$ at (T_c, μ_c)

- Critical clusters in transverse space with $d_F = \frac{2(\delta-1)}{\delta+1}$ ($\delta \approx 5$) leading to: $\langle\sigma^2\rangle \sim |\vec{x}_\perp|^{-\frac{4}{\delta+1}}$ (correlation length $\xi = 6\ fm$)

- Critical fluctuations in transverse momentum space obey: $\langle\sigma^2\rangle \sim |\vec{p}_\perp|^{-\frac{2(\delta-1)}{\delta+1}}$ leading to the intermittent behaviour:

$$F_2(M) \sim \left(M^2\right)^{\frac{\delta-1}{\delta+1}} \qquad \left(\frac{\delta-1}{\delta+1} \approx \frac{2}{3}\right)$$

- Scaling properties of the net-baryon density in rapidity (order parameter) translate the QCD phase diagram in terms of experimentally accessible quantities

$$\Downarrow$$

<u>Theoretical Claim:</u>

The process $C + C$ at the SPS freezes out close to the critical point, closer than the $Pb + Pb$ system at the same energy $(158 GeV/n)$.

Note: The size of the C+C system (central collisions) is larger than ξ ($R_\perp > 3\ fm$)

CMC generator for critical events

All the above properties are incorporated in the **Critical Monte Carlo** (CMC) event generator with two parts:

1) Generation of:

momenta of σ-particles organized in		
fixed number of clusters		Strong intermittency effects
with fixed size	$\Rightarrow$	$F_2(M) \sim M^{4/3}$
and prescribed fractal		in transverse momentum
geometry		factorial moments

2) Generation of:

momenta of pions determined by		Intermittency effects
the decay of the sigma-particles	$\Rightarrow$	suppressed due to
through pure kinematics		kinematical disortion
		when $p_\sigma^2 > 4m_\pi^2$

Use the CMC events as a guide for an algorithm reconstructing the σ-sector (critical fluctuations)

Reconstructing the critical isoscalar sector

(i) Combinatorics: In each CMC event

- Use: $\vec{p}_\sigma = \vec{p}_{\pi^+} + \vec{p}_{\pi^-}$ to obtain the σ-momenta
- Choose only pairs (π^+, π^-) fulfilling:

$$(2m_\pi)^2 \leq (p_{\pi^+} + p_{\pi^-})^2 \leq (2m_\pi + \epsilon)^2$$

with $\epsilon \ll 2m_\pi$

Each pion can in principle have more than one partners

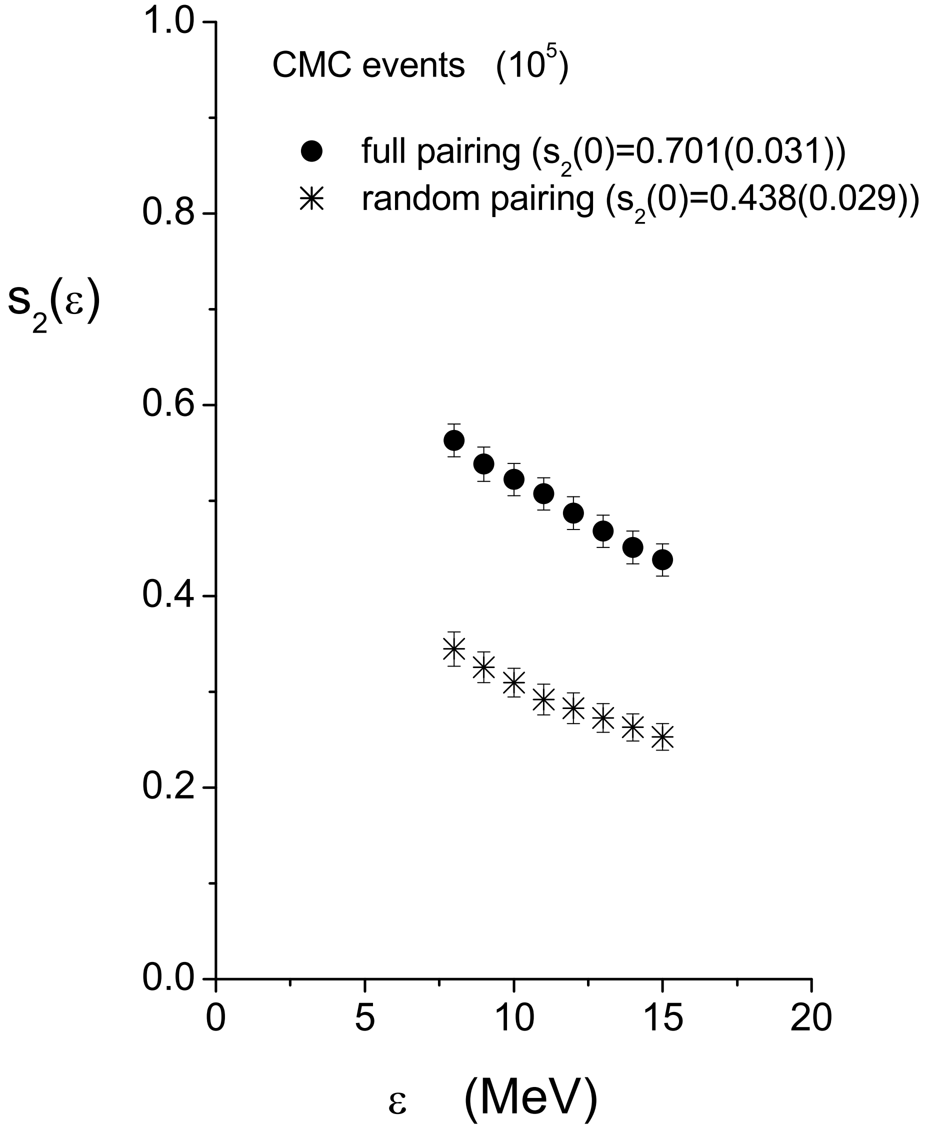
fulfilling the above criterion

$$\Downarrow$$

Use two ways of (π^+, π^-) pairing: (1) random (one-to-one)

(2) full pairing

Perform factorial moment analysis (transverse momentum space) in the events of reconstructed sigmas (different sets for different ϵ-values) obtained using both ways of pairing



Expected behaviour: $s_2(0) \approx \frac{2}{3} \Rightarrow$ **full pairing is prefered**

(ii) Correlated part of the sigma sector - Mixing

- Factorial moments explore fluctuations (intermittency) **not** correlations
- Intermittency in factorial moments is **neccessary** but **not sufficient** condition for **critical** fluctuations
- Need for a tool revealing the **correlated** part in a set with nontrivial fluctuations

$$\Downarrow$$

- Use a set of mixed events obtained from the CMC events to determine the uncorrelated part of the isoscalar sector
- Perform mixing in the transverse momenta of the charged pions (energy conservation respected)
- Introduce the correlator $G(M)$ as a measure of **both** correlations and fluctuations in the data set

The correlator $G(M)$

Use the two particle density:

$$\rho_c(1,2;\ \epsilon) = \rho(1, 2 \cap A) - \rho_m(1, 2 \cap A)$$

$1, 2$ refer to sigmas, m refers to the mixed events and A is the condition that $p_1^2, p_2^2 \in [4m_\pi^2, 4(m_\pi + \epsilon)^2]$ in an event with at least n_o sigmas. Using conditional probabilities:

$$\rho(1, 2 \cap A) = \rho(1, 2|A)p(A)$$

$p(A) = \frac{N(A)}{N_{ev}}$ is the probability that condition A is true. $N(A) =$ number of events fulfilling A and $N_{ev} =$ total number of events.

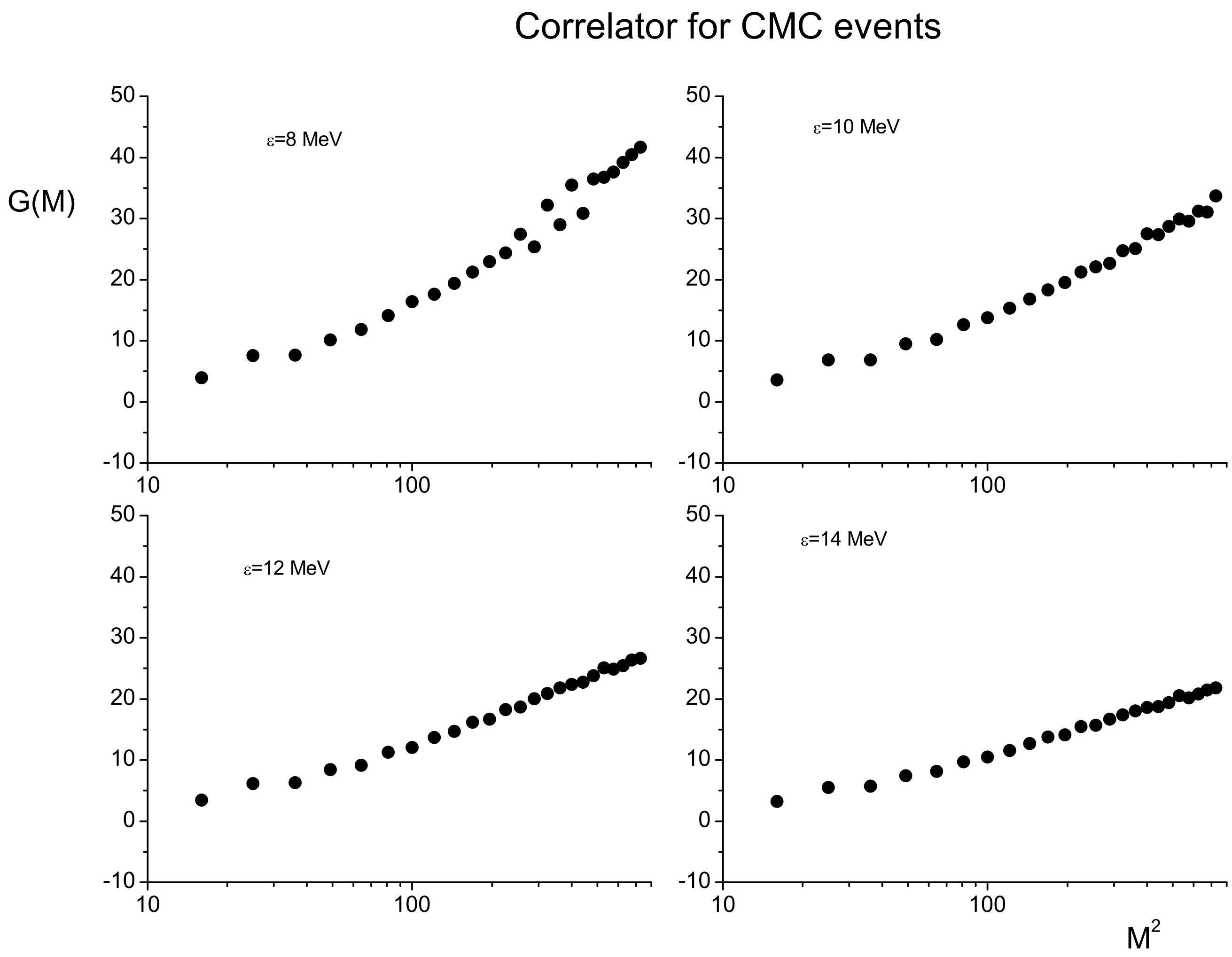
$$\rho_c(1,2;\ \epsilon) = \frac{N(A)}{N_{ev}} \left(\rho(1,2|A) - \frac{N_m(A)}{N(A)} \rho_m(1,2|A) \right)$$

The correlator $G(M)$ is defined as:

$$G(M, \epsilon) \equiv \frac{\int \int_{\Delta\Omega} \rho_c(1, 2;\ \epsilon) dp_1\, dp_2}{< n_\sigma(\epsilon) >^2}$$

leading after a little algebra to:

$$G(M, \epsilon) \sim F_2(M, \epsilon) - \underbrace{\left(\frac{N_m(A) < n_{\sigma,m} >^2}{N(A) < n_\sigma >^2} \right)}_{W(\epsilon)} F_{2,m}(M, \epsilon)$$


Correlator for CMC events
G(M)
ε=8 MeV
ε=10 MeV
ε=12 MeV
ε=14 MeV
50
40
30
20
10
0
-10
10
100
M2

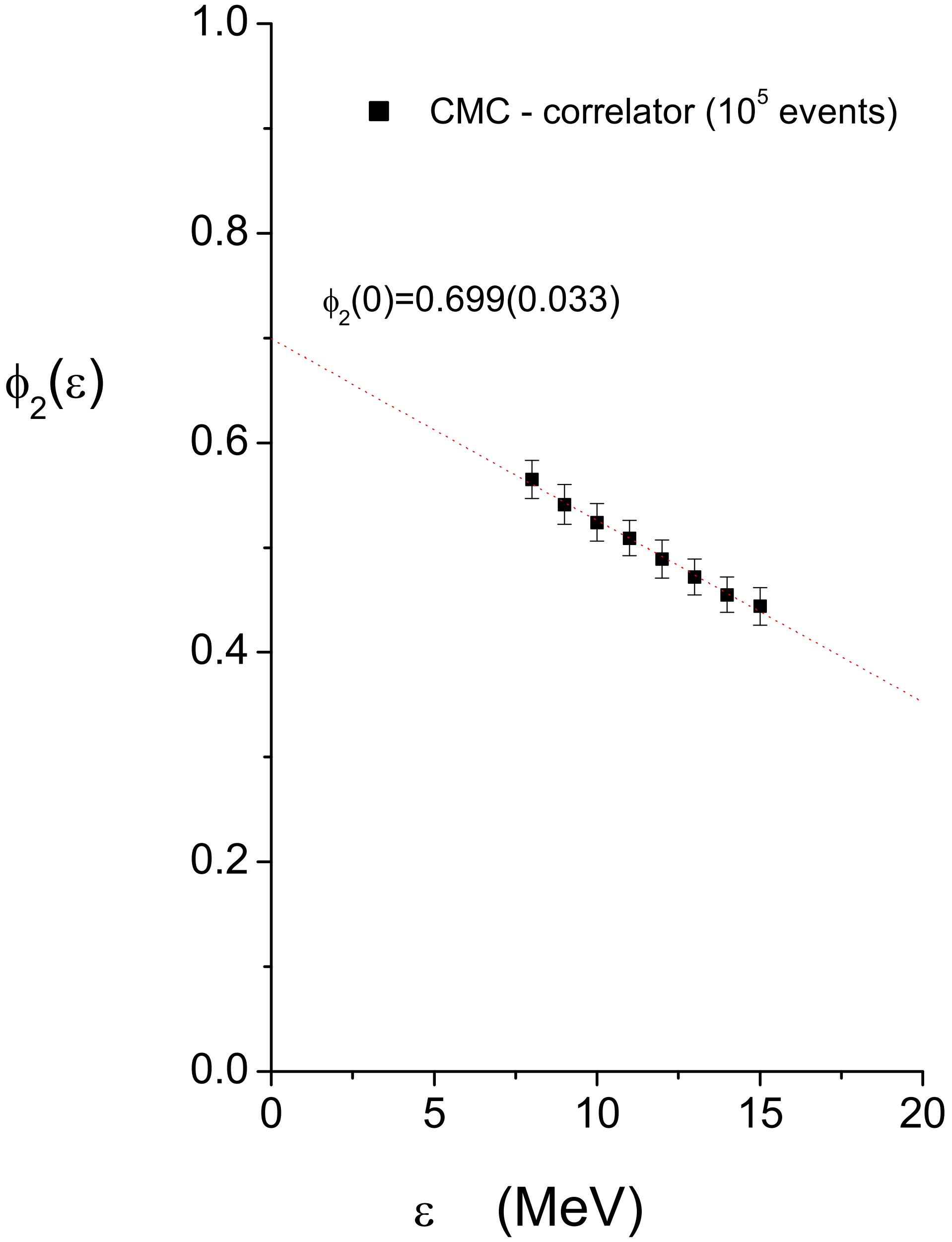
(iii) Extrapolation to the two-pion threshold:

Critical isoscalar fluctuations imply:

$$G(M) \sim (M^2)^{\phi_2} \text{ with } \phi_2 \approx \tfrac{2}{3}$$

holding at $\epsilon = 0$ (two-pion threshold).

Therefore calclulate $\phi_2(\epsilon)$ and extrapolate to $\epsilon = 0$.



Analysis of the $C + C$-data at the SPS

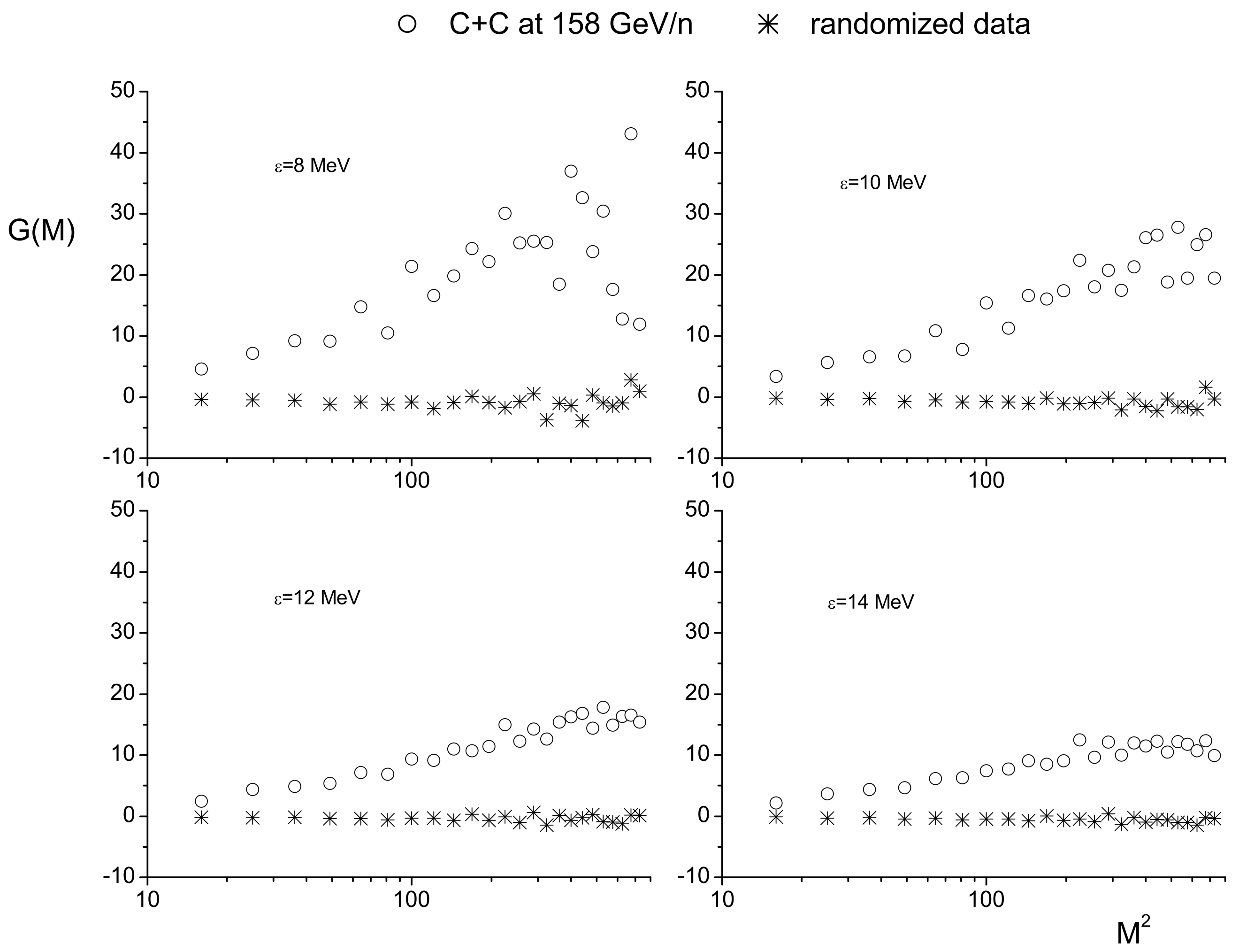
Reconstruction of the isoscalar sector

- Construct the sigma-momenta as discussed. Prefer the full pairing

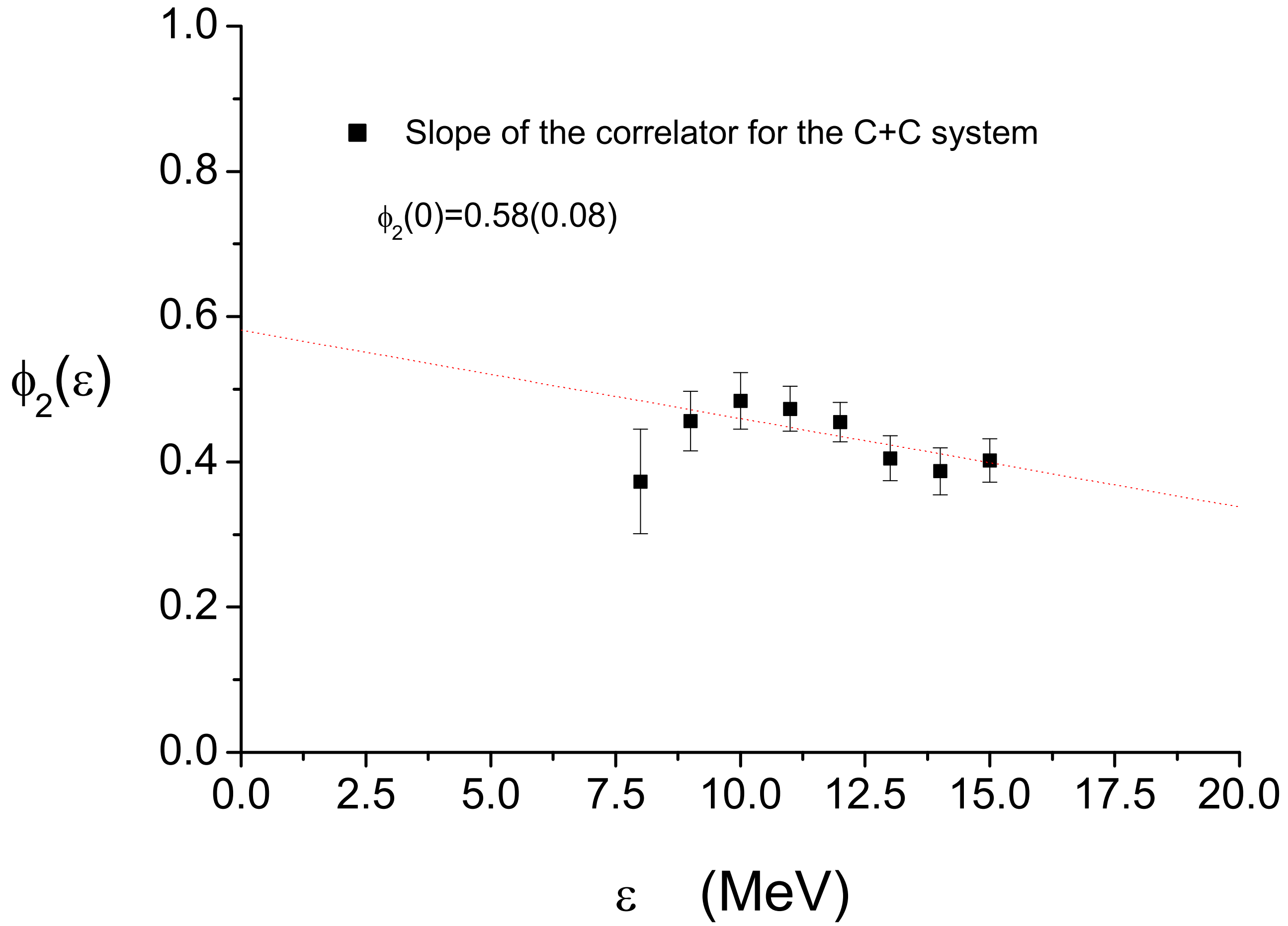
- Calculate the correlator $G(M, \epsilon)$ for various values of ϵ. To avoid the competition of Coulomb effects use $\epsilon > 4\ MeV$

- Find $\phi_2(\epsilon_i)$ for several ϵ_i and extrapolate to $\epsilon = 0$

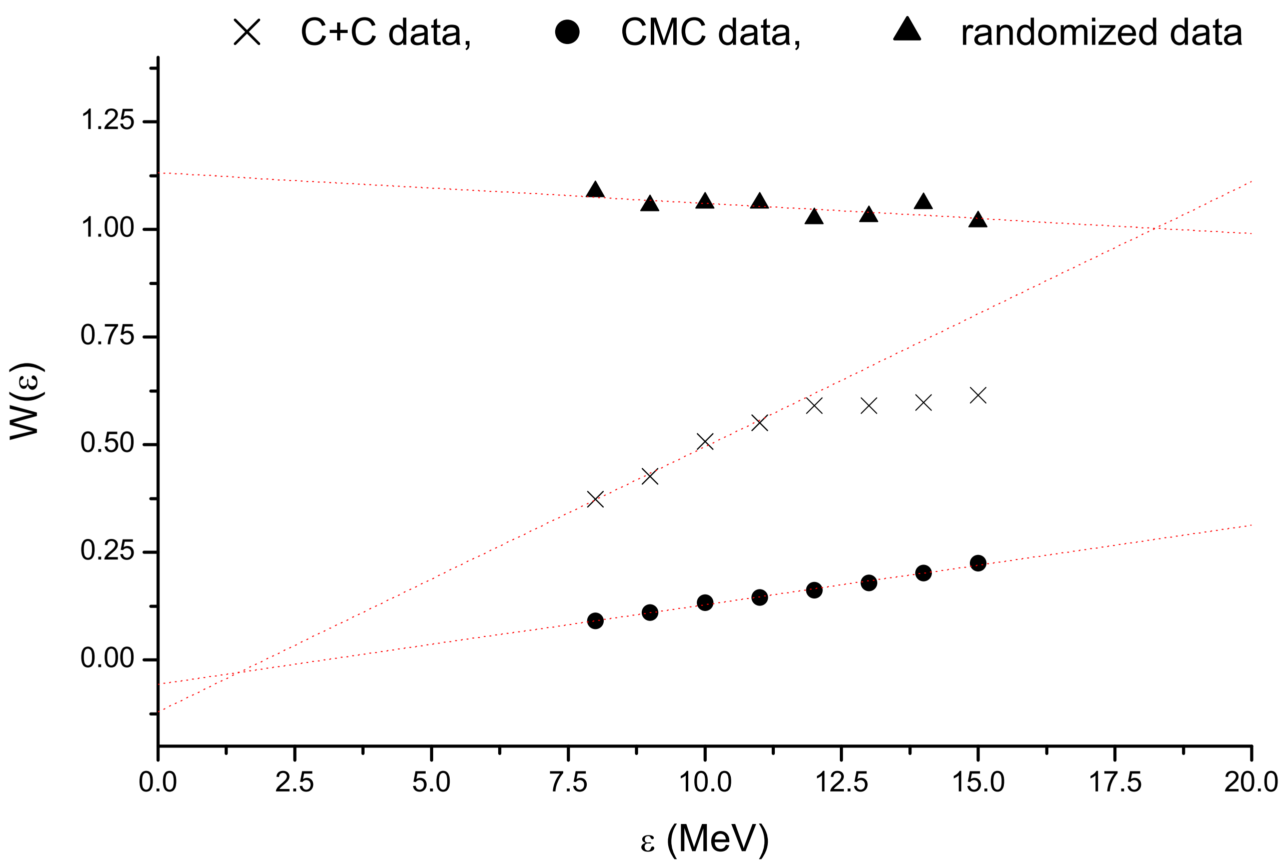
We use a data-set produced from the $C+C$ data through randomization for a comparison. Remember that the correlator $G(M)$ for mixed events is per definition zero.



C+C at 158 GeV/n
randomized data
G(M)
ε=8 MeV
ε=10 MeV
ε=12 MeV
ε=14 MeV
M²



Slope of the correlator for the C+C system
φ2(0)=0.58(0.08)
φ2(ε)
ε (MeV)
1.0
0.8
0.6
0.4
0.2
0.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0



C+C data,
CMC data,
randomized data
W(ε)
1.25
1.00
0.75
0.50
0.25
0.00
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
ε (MeV)

Conclusions

- Guided by the properties of the CMC generator for production of critical events we develop an algorithm able to detect critical (correlated) fluctuations in the isoscalar hadronic sector (sigmas).

- The algorithm has 3 stages: (i) the reconstruction of the momenta of the sigmas with invariant mass $\in [2m_\pi, 2m_\pi + \epsilon]$, (ii) the determination of the correlated subset of sigmas (correlator $G(M)$) and (iii) the determination of the underlying geometry of the correlated set of sigmas at the two-pion threshold

- Applying this algorithm to the $C+C$-SPS data we find a clear signal for the presence of critical fluctuations in the isoscalar hadronic sector of this system confirming theoretical predictions