Search for the QCD Critical Point in Nuclear Collisions at the CERN SPS*

N. Davis
University of Athens

*Publication: PRC81, 064907 (2010).
(NA49 Collaboration, N.G. Antoniou, F.K. Diakonos and G. Mavromanolakis)

Outline

1. The QCD critical point

2. Critical opalescence in QCD matter – Intermittency

3. Sigma fluctuations in a medium

4. Observables and reconstruction of critical σ-fluctuations

5. Data analysis of four $A+A$ systems at maximum SPS energy

6. Results / Future Plans

7. Summary and conclusions

The QCD critical point

High Energy Heavy Ion collisions can probe the boundary of quark-hadron phase transition in the QCD phase diagram and detect the Critical Point.

Relevance and characteristics

- Chiral symmetry breaking $\Rightarrow$ Mass generation in the visible world

  [F. Wilczek, hep-ph/0003183; M. A. Stephanov, Int. J. Mod. Phys. A**20**, 4387 (2005); R. Casalbuoni POS **CPOD2006** 001]

- Order parameters:
  - isoscalar (sigma) field: $\sigma(\vec{x}) = \langle \bar{\psi}\psi \rangle$
  - baryon density: $n_B(\vec{x}) = \langle \bar{\psi}\gamma^0\psi \rangle$

- Universality class: 3D-Ising $\Rightarrow$ $\delta \simeq 5$, $\eta \simeq 0$*

*[See discussion in: N. G. Antoniou, F. K. Diakonos and A. S. Kapoyannis, PRC**81**, 011901R, 2010]

Critical Opalescence – Intermittency

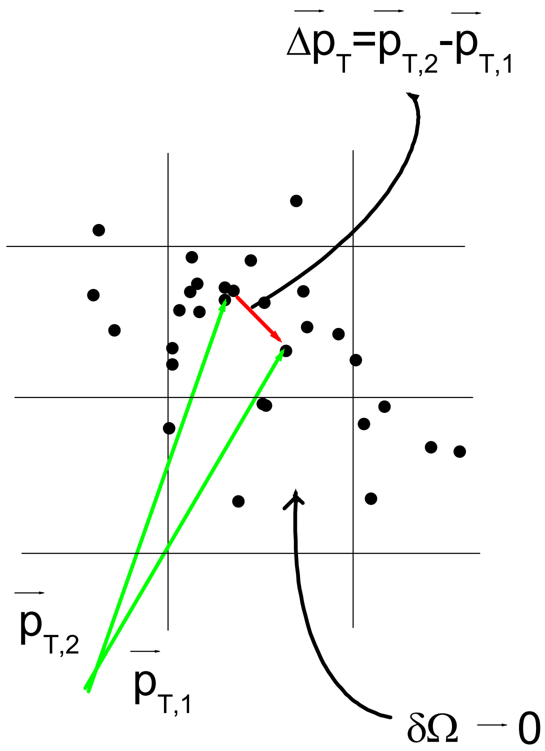
- **Power-law fluctuations** of the σ-field can be observed in **transverse momentum space**
- Critical opalescence: Power-law singularity of long-wavelength scattering $\Rightarrow$ experimental signature of a **critical point**

  [H. E. Stanley, *Introduction to Phase Transitions and Critical Phenomena*]
- Correlator in momentum space: $\langle n_{\vec{p}}\, n_{\vec{p}+\vec{k}} \rangle \sim \left|\vec{k}\right|^{-d_F}$ for small $\vec{k}$
- Power-law singularity $\Rightarrow$ Intermittency: factorial moments $F_p(M)$ scale with momentum cell size $\delta\Omega \Leftrightarrow$ total number of cells M for large M:

  $F_p(M) \sim M^{2\phi_2(p-1)}$, $\phi_2 = \frac{\delta-1}{\delta+1}$

  $\Rightarrow$ indicates **self-similar fluctuations** in transverse momenta

  [N. G. Antoniou et al., Nucl.Phys. A**693**,799 (2001); Nucl.Phys. A**761**,149 (2005)]



Sigma fluctuations in a medium

- Sigmas are unstable $\Rightarrow$ favored decay mode: $\sigma \to \pi^+\pi^-$
- Sigma decay cross section:

$$\frac{d^3N}{dp^3} \sim g^2_{\sigma\pi\pi} \cdot \rho_\sigma(m_{\pi^+\pi^-})$$

  where $g_{\sigma\pi\pi}$ is the coupling constant, ρ_σ the spectral density of decaying sigmas and $m_{\pi^+\pi^-}$ is the dipion invariant mass.

- **Threshold singularity** $(2m_\pi)$ of spectral density $\rho_\sigma(m_{\pi^+\pi^-})$ near the critical point:

$$\rho_\sigma(m_{\pi^+\pi^-}) \sim \left(1 - \frac{4m_\pi^2}{m^2_{\pi^+\pi^-}}\right)^{-\frac{1}{2}}$$

  [T. Hatsuda, T. Kunihiro and H. Shimizu, PRL **82**,2840(1999); T. Hatsuda and T. Kunihiro, PRL **247**,221(1994); S. Chiku and T. Hatsuda, PRD **58**,076001(1998)]

- **Partial restoration** of **chiral symmetry** at $\rho_B > 0$.
- Singularity $\Rightarrow$ smooth maximum when departing from critical point.

Observables – Reconstruction of σ-fluctuations

- σ **not** directly observable, but **fluctuations** can be detected by **dipion reconstruction**, as shown using critical events generated by the CMC code. [Antoniou et al., NPA **761**, 149 (2005)]
- Most suitable observables: 2D scaled factorial moments of the reconstructed sigmas (opposite charged dipions) in transverse momentum space:

$$F_p(M) \equiv \frac{\left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i(n_i-1)\cdots(n_i-p+1) \right\rangle}{\left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i \right\rangle^p} \sim M^{2\phi_2(p-1)}, (M \gg 1)$$

- Event-by-event filtering of dipions ($\pi^+\pi^-$ pairs) satisfying the condition:
$(2m_\pi + \varepsilon_1)^2 \leq (p_{\pi^+} + p_{\pi^-})^2 \leq (2m_\pi + \varepsilon_2)^2, \quad \varepsilon_{1,2} \ll 2m_\pi$

- Due to "fake" $\pi^+\pi^-$ pairs, a combinatorial background is introduced that hides the threshold enhancement.

- Because of threshold enhancement, a narrow window $\Delta\varepsilon = \varepsilon_2 - \varepsilon_1$ near the threshold **enhances** the ratio of real/fake pairs. However, **statistics** suffers when $\Delta\varepsilon \to 0 \Rightarrow$ a compromise is in order.

- $\varepsilon_1 \geq 5$ MeV avoids Coulomb correlations.

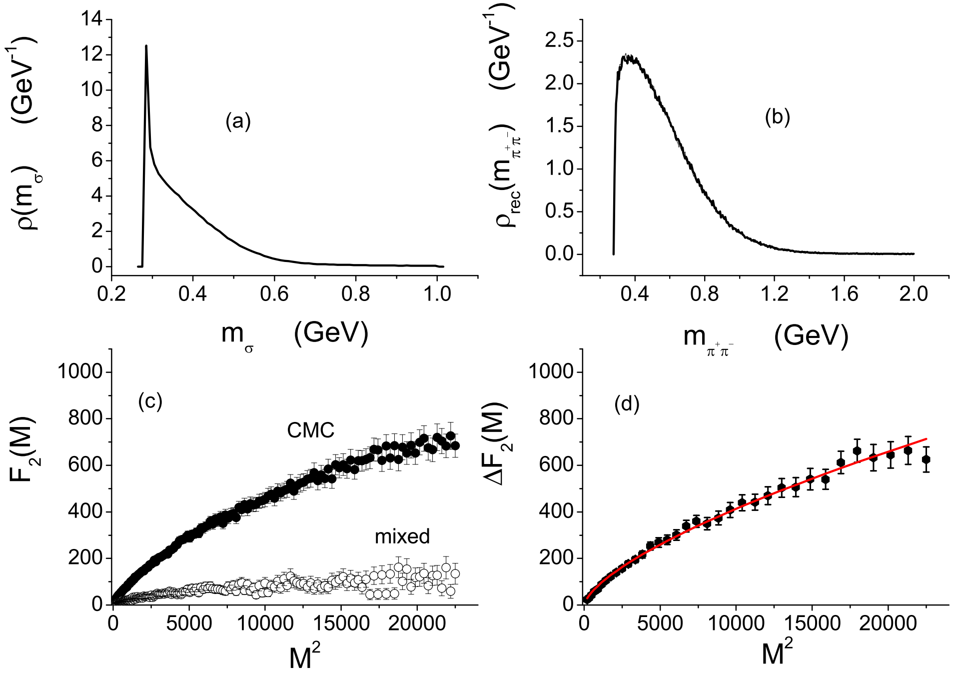
- **Mixed events** can be used to remove – at the level of F_2 – the combinatorial background of fake sigmas:

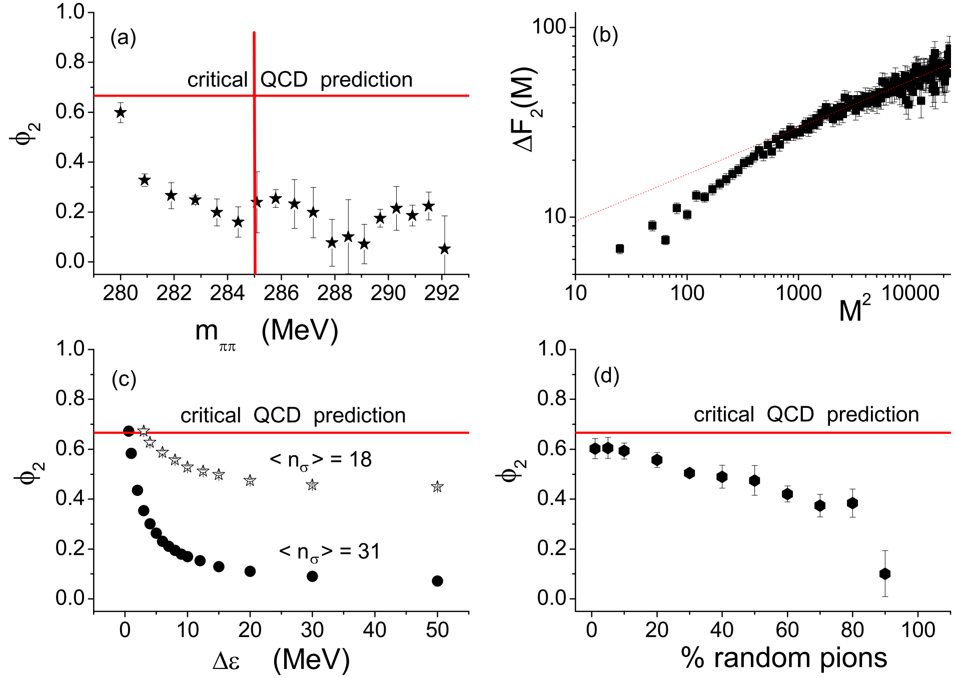
$$\Delta F_2(M) = F_2(M) - x_M^2\ F_2^{(m)}(M) - 2x_M(1-x_M), \quad x_M = \frac{\langle n^{(m)} \rangle_M}{\langle n \rangle_M}$$

- A scan is performed to find the choice for $\varepsilon_{1,2}$ that gives strongest power-law fluctuations. **Criteria**: maximize critical index ϕ_2, coefficient of determination R^2, minimize χ^2/dof. Also, $\Delta\varepsilon$ must be $\geq$ **experimental resolution**!

Reconstruction algorithm applied to CMC data

- Dipions reconstructed from CMC data show intermittent factorial moments ΔF_2. Best window gives: $\phi_2 = 0.67 \pm 0.01$





- Intermittency index ϕ_2 drops with $\Delta\varepsilon$ increase, as well as the introduction of random (noncritical) pions to the simulation.

NA49 Data Analysis

- Four different $A + A$ datasets were analyzed: A = p, C, Si, Pb, at 158 A GeV

- For A = Si, C, 12% most central events were taken. For Pb+Pb, 5% most central

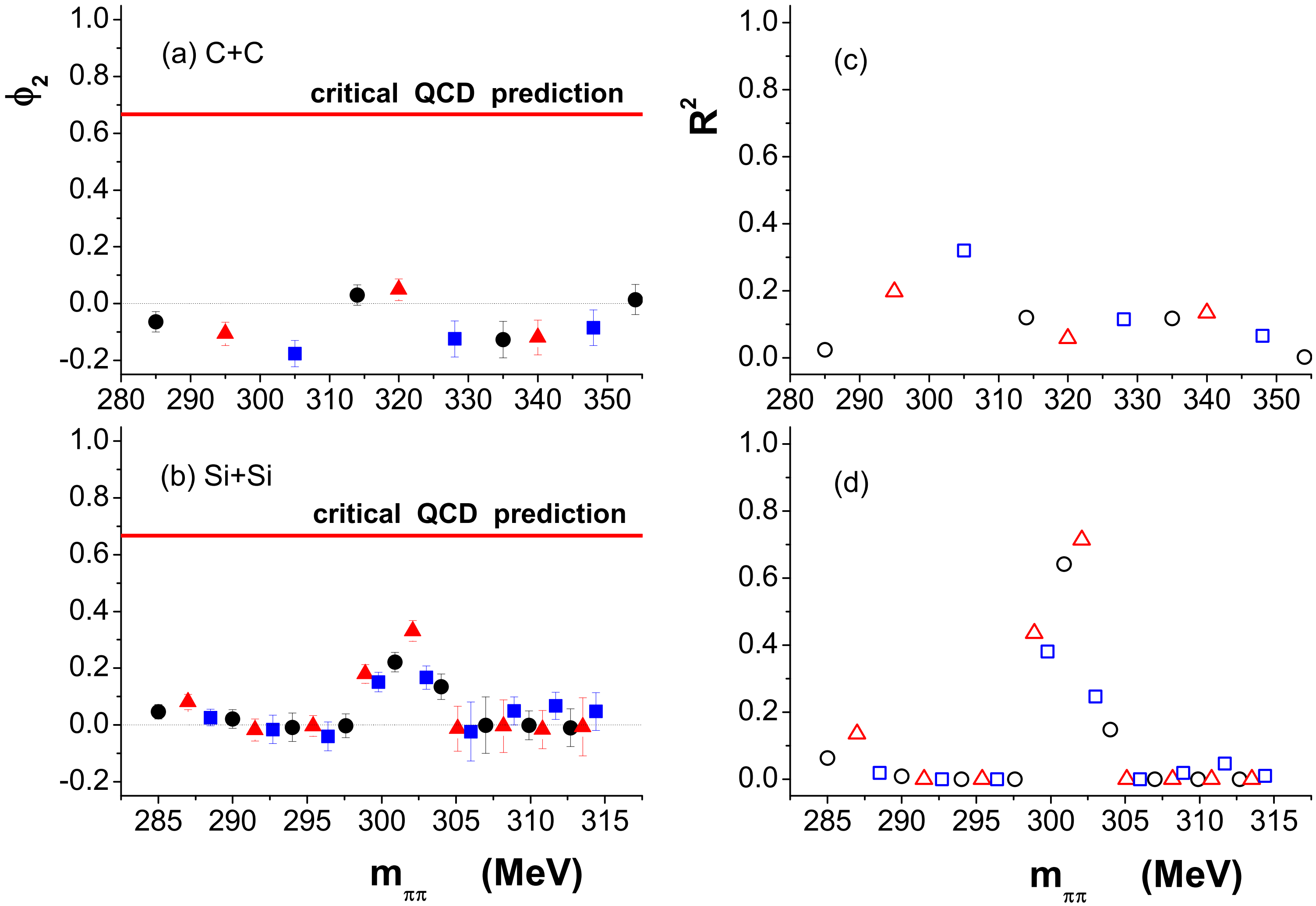
A	Number of events	run period
p	408708	1998
C	33689	1998
Si	17053	1998
Pb	30000	1996

- All the appropriate vertex and track quality cuts were applied for events. dE/dx cuts were used for particle identification.

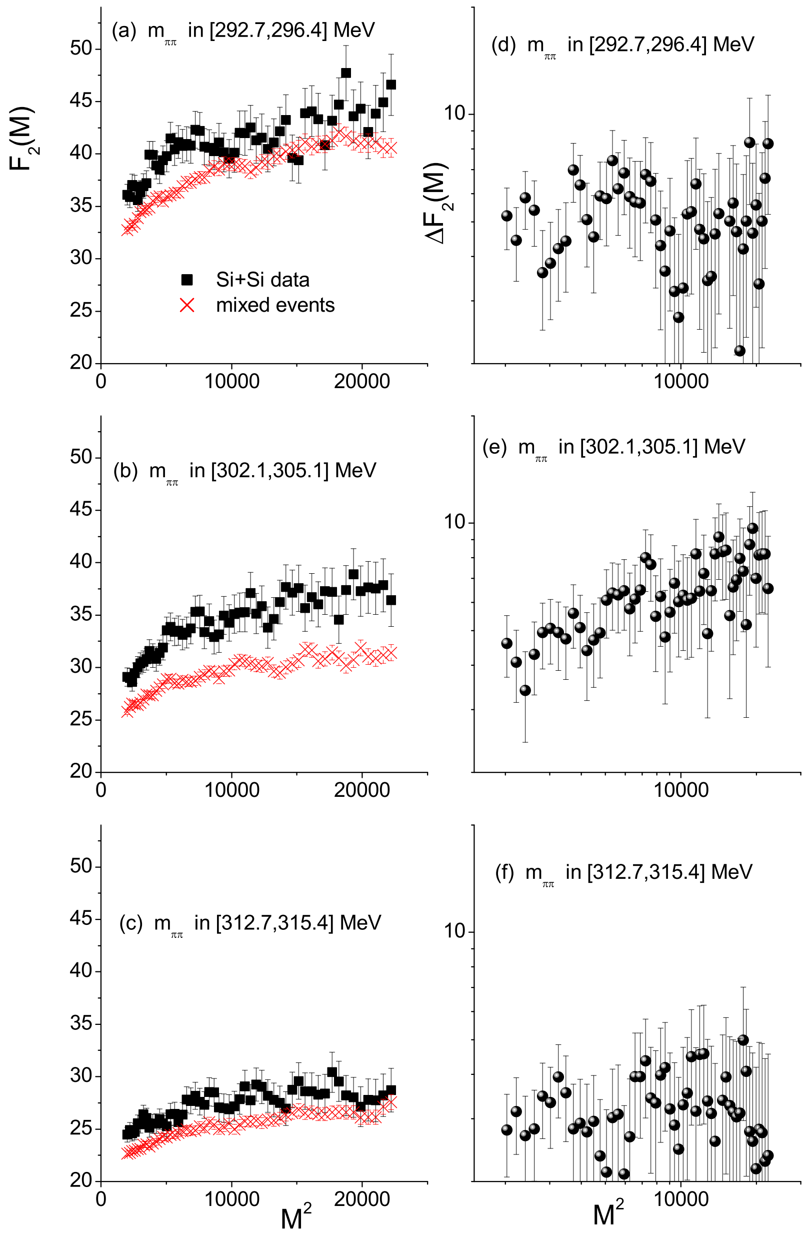
Summary of $m_{\pi\pi}$ window scans and results

A	$m_{\pi\pi}$ window range (MeV)	# of windows	ϕ_{2max}	R^2	χ^2/dof	$\langle n_{\pi^+\pi^-}\rangle_{\Delta\varepsilon}$
p	[285,575]	1	~ 0	~ 0	large	~ 4
C	[285,350]	3 sets (ε_1 = 5,15,25 MeV)	~ 0	~ 0	large	~ 4
Si	[285,320]	3 sets (ε_1 = 5,7,8.5 MeV)	0.33 $\pm$ 0.04 ($m_{\pi\pi}$=302 MeV)	0.71	~ 0.3	~ 4
Pb	[285,286]	1, ε_1=5 MeV, $\Delta\varepsilon$=1 MeV	$\sim 0.04 \pm 0.02$	0.07	large	~ 20

$m_{\pi\pi}$ window scans for C+C, Si+Si systems

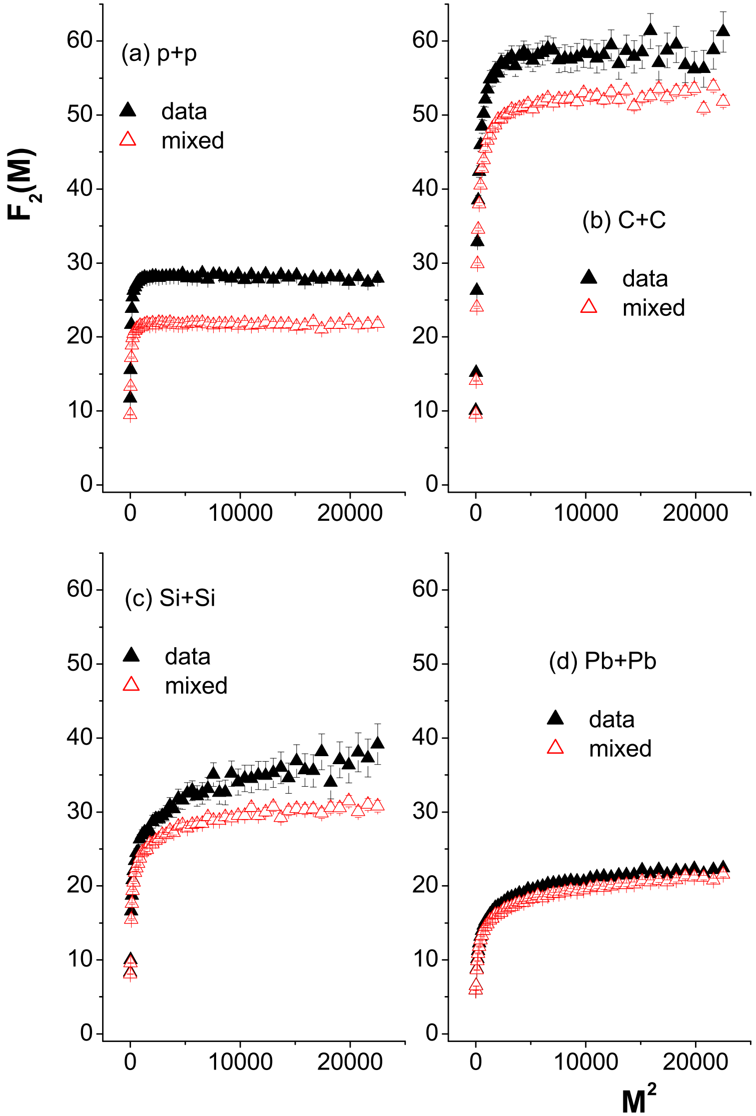


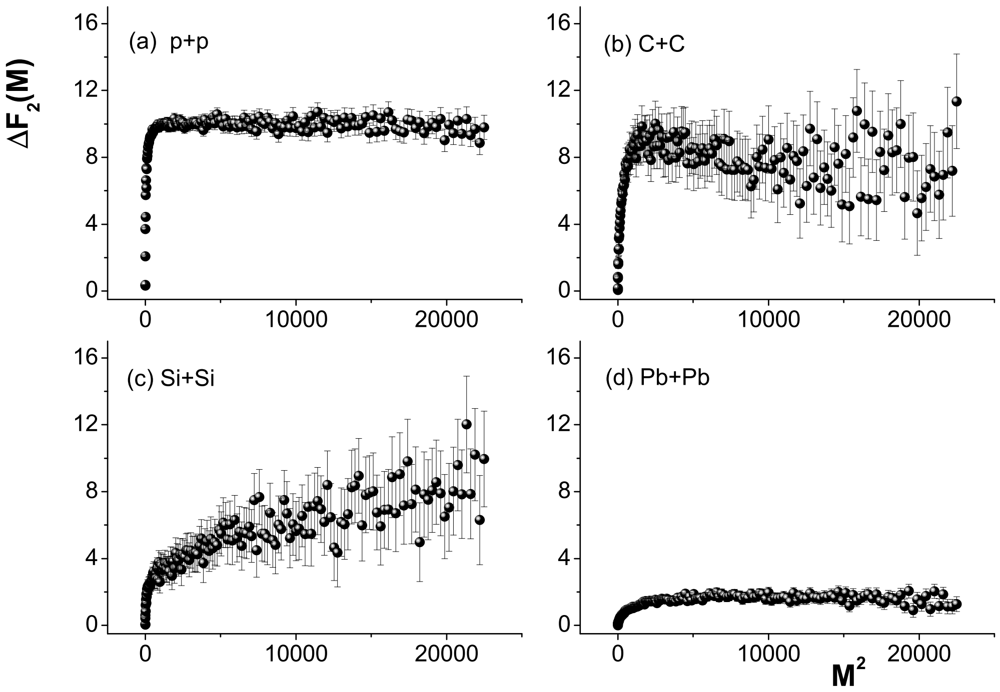
- Maxima locations of ϕ_2, R^2 are consistent with each other $\Rightarrow$ evidence for critical behaviour in Si+Si, but not in C+C



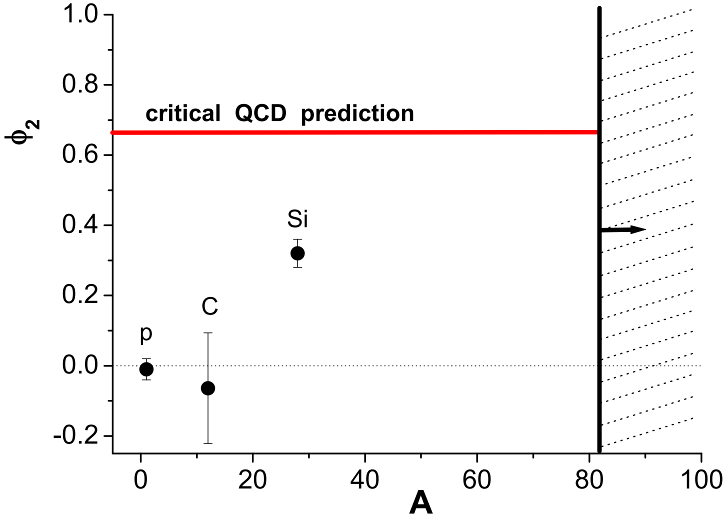
- $F_2, F_2^{(m)}$ differ considerably near the ϕ_{2max} window.
- At a distance from the maximum, F_2 and $F_2^{(m)}$ overlap $\Rightarrow$ ϕ_2 decreases, R^2: bad quality.

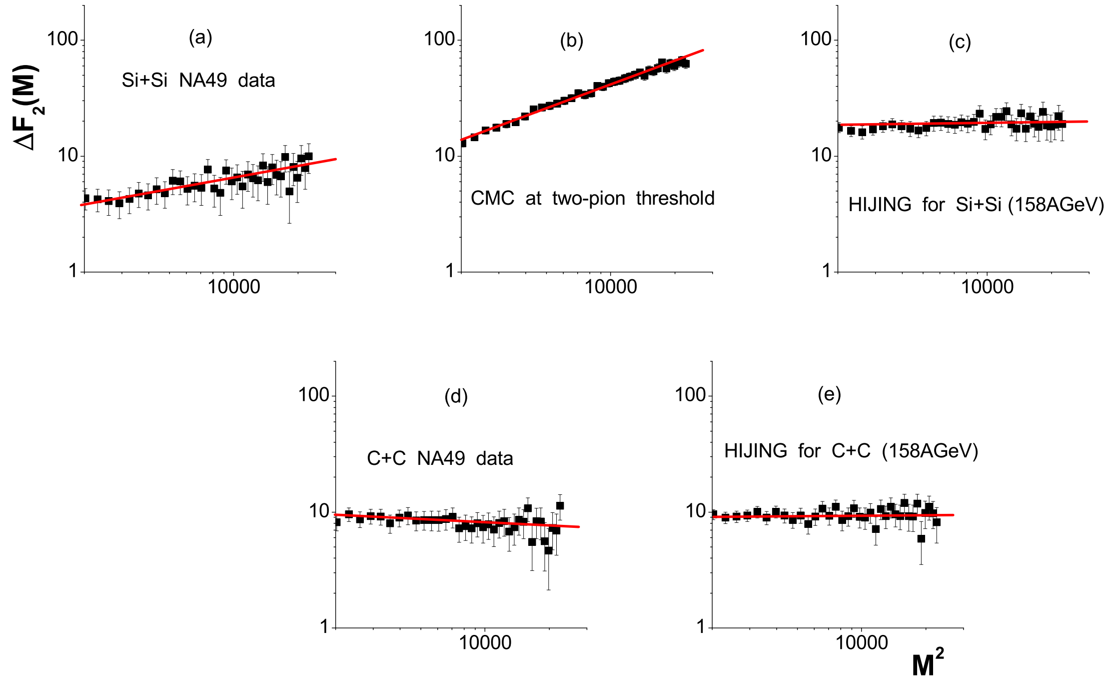
Comparison of $F_2, \Delta F_2$ for all systems





- Self-similar fluctuations observed only in Si+Si system





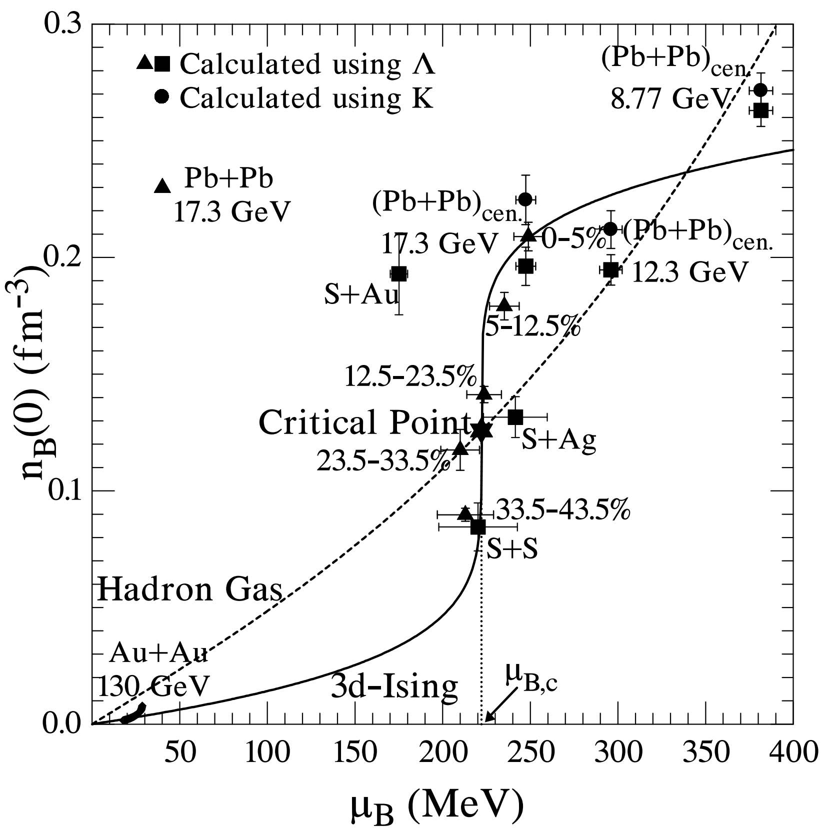
- Same detector acceptance / $m_{\pi\pi}$ window in HIJING as in NA49 analysis.
- For HIJING: $R^2, \phi_2 \to 0 \Rightarrow$ no critical fluctuations.

Plans for future analysis

- Analysis of events in different peripherality ranges is expected to shed light on systems for which current intermittency analysis fails. Specifically, for large systems like Pb+Pb, there is some evidence that the 12.5% → 33.5% peripherality range may lie close enough to the critical point to exhibit intermittency.

  [N. G. Antoniou, F. K. Diakonos and A. S. Kapoyannis, PRC **81**, 011901(R) (2010)]

  Futhermore, more peripheral events have lower multiplicities ⇒ may be possible to select small $\Delta\varepsilon$ window with desired (low) dipion multiplicity.



Plans for future analysis

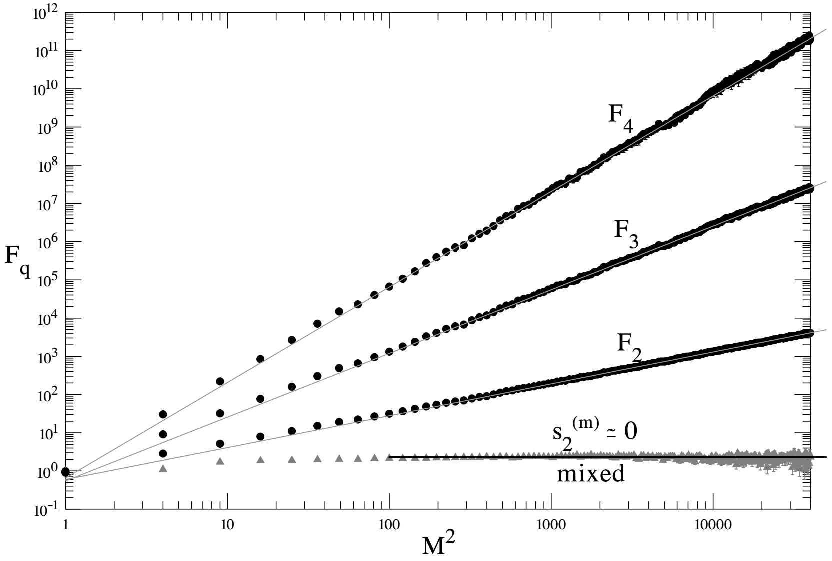
- The baryonic sector should also exhibit critical behaviour if the freeze-out state of the A+A system considered is close to the critical point.

  [D. Bower and S. Gavin, PRC **64**, 051902(R) (2001)]

- There is theoretical evidence that intermittency analysis of baryons in transverse momentum space will show power-law scaling.

  [N. G. Antoniou et al, PRL **97**, 032002 (2006)]

- Baryons are expected to scale with a **different intermittency index** than sigmas: $\phi_2^B = 5/6 \Leftrightarrow \phi_2^\sigma = 2/3$



Conclusions

- Pion pairs produced near the $2m_\pi$ threshold at CERN SPS have a **strong component** in the σ-mode and are sensitive to the order parameter of the QCD Critical Point.

- Density fluctuations with power-law behaviour can be observed, provided the system freezes out close enough to the CEP.

- CMC simulation indicates that $\phi_{2max} \to 2/3$ when moving towards the $2m_\pi$ threshold $\Rightarrow$ indicator for existence of CEP and partial chiral symmetry restoration.

- Scaled factorial moment analysis in small domains of transverse momentum space exhibits intermittency and is a suitable observable for detecting proximity to the CEP.

- Large, unconventional power-law fluctuations are observed in Si+Si, 158 AGeV. Pb+Pb system remains to be resolved.

Backup slides

Phenomenology of the Critical Point

- **Density fluctuations** of order parameter (for example) $\sigma(\vec{x})$ in transverse space obey **power law** at the CEP:

  $$(\delta\sigma)^2 \simeq \langle\sigma^2\rangle \sim |\vec{x}_\perp|^{d_F-2} \quad , \quad d_F = 2\left(\frac{\delta-1}{\delta+1}\right)$$

  [N.G. Antoniou et al., Nucl. Phys. A693, 799(2001); *ibid.* 761, 149(2005)]

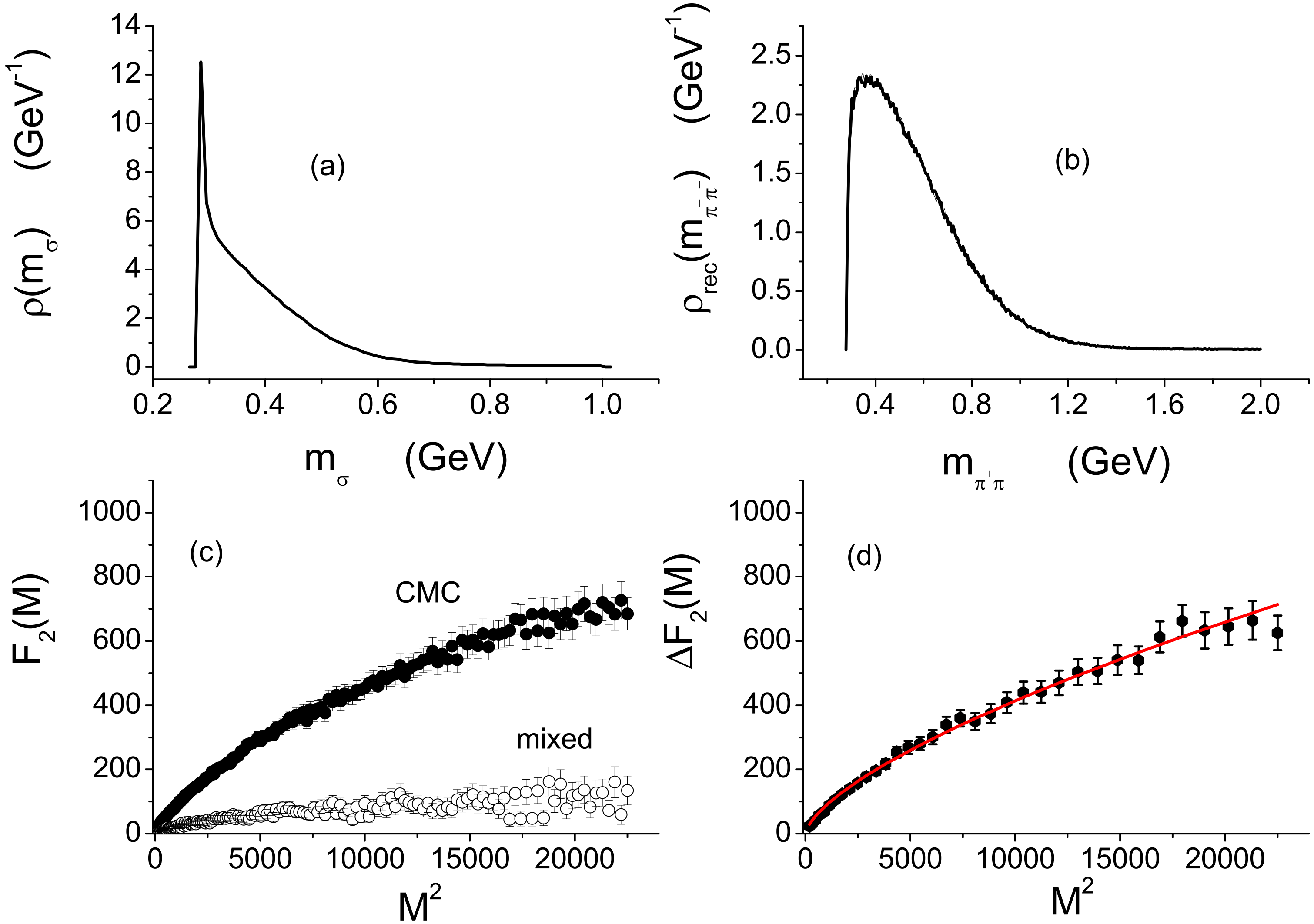
- Second order transition $\Rightarrow$ **infinite correlation length** ξ*
  Singular baryon number susceptibility: $\frac{\partial n_B}{\partial \mu_B} \sim \xi^{2-\eta}$

- Universality class: 3D-Ising $\Rightarrow \delta \simeq 5$, $\eta \simeq 0$*

*[See discussion in: N. G. Antoniou, F. K. Diakonos and A. S. Kapoyannis, PRC**81**, 011901R, 2010]

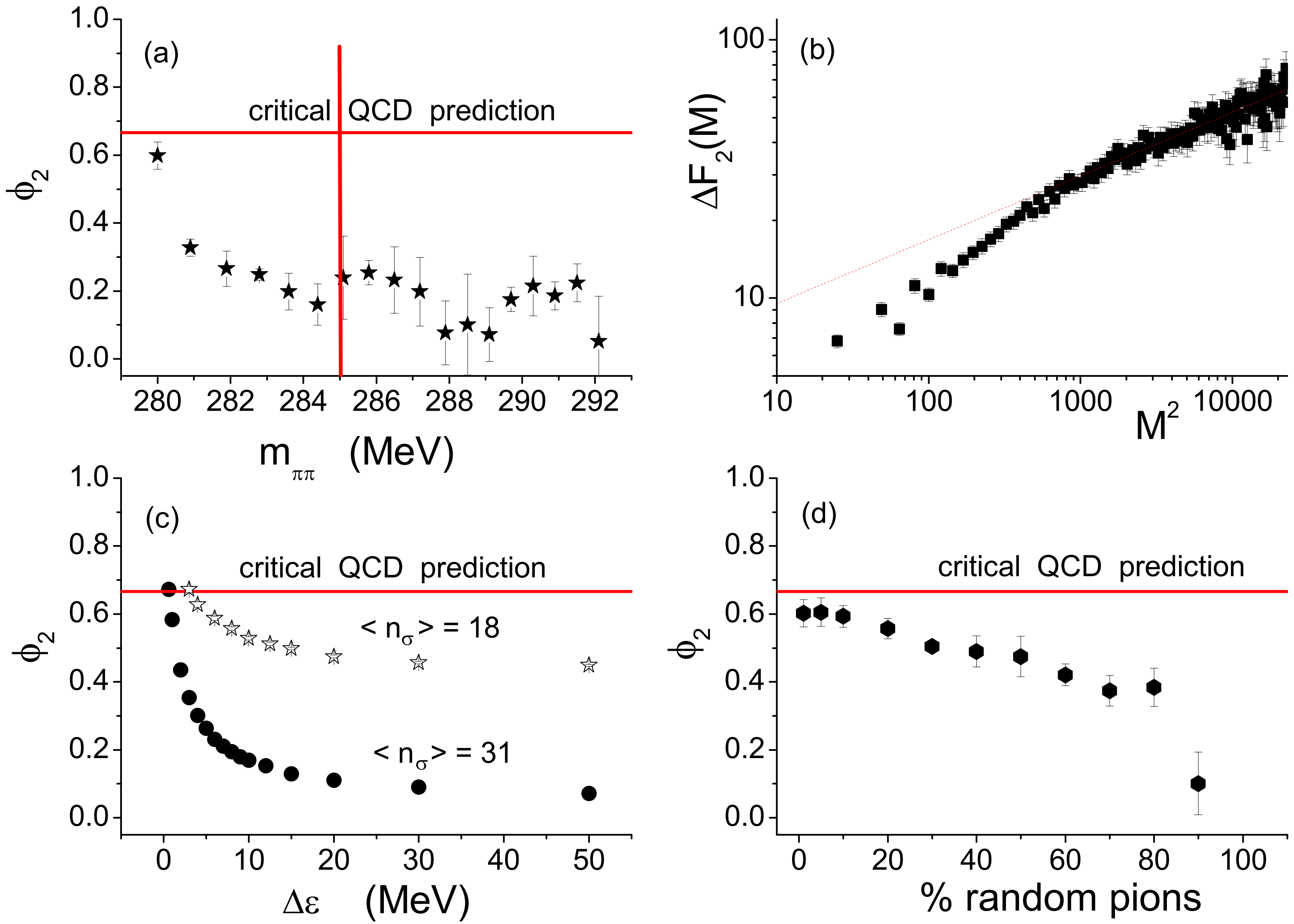
Reconstruction algorithm applied to CMC data

- Dipions reconstructed from CMC data show intermittent factorial moments ΔF_2. Best window gives: $\phi_2 = 0.67 \pm 0.01$



Reconstruction algorithm applied to CMC data

- Intermittency index ϕ_2 drops with $\Delta\varepsilon$ increase, as well as the introduction of random (noncritical) pions to the simulation.



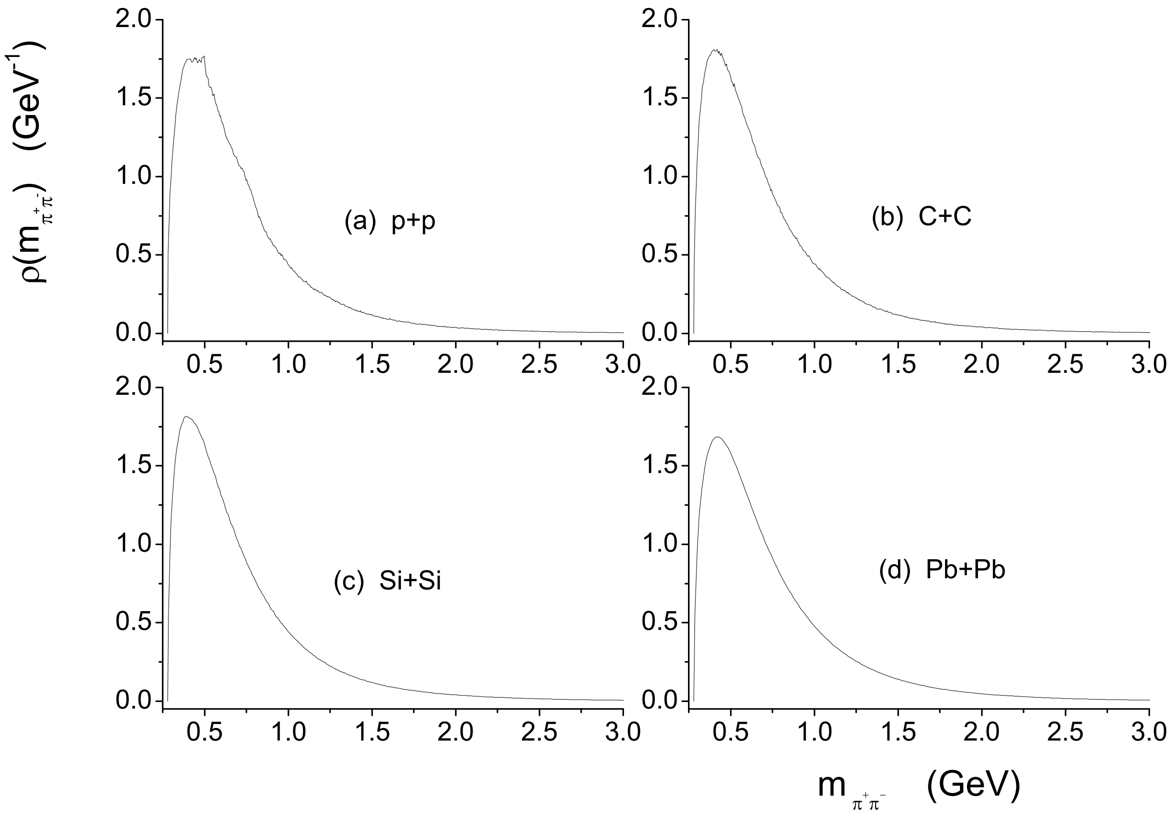
Results of Analysis & Future plans

- For each $A + A$ system (A = p, C, Si, Pb), we determine $\Delta\varepsilon$ such that: $\langle n_{\pi^+\pi^-}\rangle_{\Delta\varepsilon} \simeq 4 \Rightarrow$ **good compromise** between **signal / statistics**.
- $\varepsilon_1 \geq 5MeV$ to avoid Coulomb correlations.
- Must take experimental resolution $\delta\varepsilon$ into account $\Leftarrow$ calculated from momentum transfer:

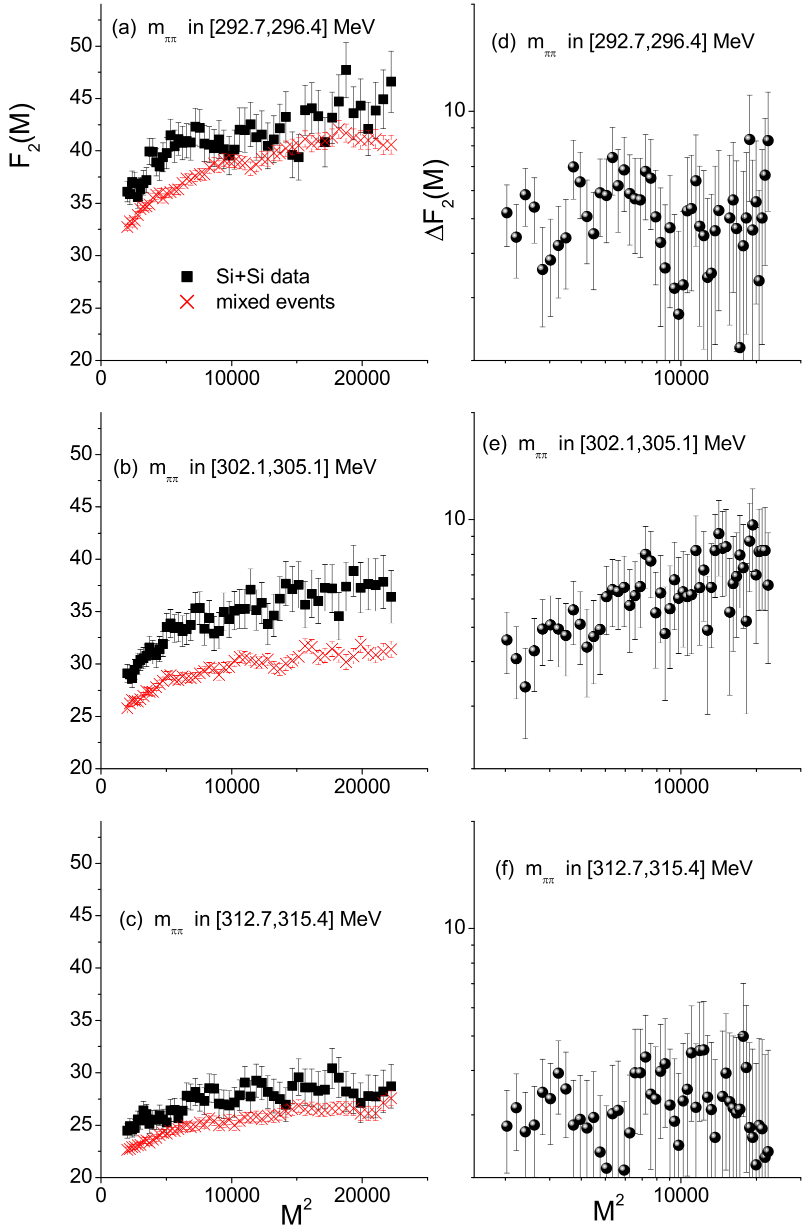
$$Q = \sqrt{-(p_\pi^+ - p_\pi^-)^2}$$

  where we assume constant resolution $\delta Q \simeq 5MeV$.
- C+C satisfies the constraint $\Delta\varepsilon \geq \delta\varepsilon$ for the desired multiplicity. Si+Si is restricted in $m_{\pi^+\pi^-}$ window range. Pb+Pb cannot satisfy the constraint due to large event multiplicity.
- CMC simulation for Pb-like system, near threshold and in the experimental window, indicates that reconstruction for large systems in dipion sector is not possible with the method used. Signal is found only in threshold window, precluded in experimental analysis by Coulomb threshold.

Invariant mass distributions



- Distributions are similar to CMC simulated dipion events
- Maximum for C+C: $m_{\pi\pi} \sim 421\ MeV$
- Maximum for Si+Si: $m_{\pi\pi} \sim 386\ MeV$
- Activity of critical sigmas in the freeze-out **not evident** in invariant mass distribution alone ⇒ study of fluctuations necessary.



- $F_2, F_2^{(m)}$ differ considerably near the ϕ_{2max} window.
- At a distance from the maximum, F_2 and $F_2^{(m)}$ overlap $\Rightarrow$ ϕ_2 decreases, R^2: bad quality.
- The error of F_2 is validated by splitting C+C and Si+Si events into 4 datasets and performing independent moment analysis $\Rightarrow$ variation of ϕ_2 between subsets is consistent with $\delta\phi_2$ of fit.