New baryonic and mesonic observables from NA61/SHINE

Antoni Marcinek
for the NA49 and NA61/SHINE collaborations

H. Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences

6th International Conference on New Frontiers in Physics (ICNFP 2017),
24 August 2017, Crete
Outline

1. $\phi$ meson production in proton-proton collisions (A.M.)

2. Search for QCD critical point via intermittency analysis (N. Davis, N. Antoniou, F. Diakonos)

3. Electromagnetic effects in pion emission (A. Rybicki, A. Szczurek, M. Kiełbowicz)
**φ meson production — introduction**

**φ = s̅s meson according to PDG 2014**

- Mass \( m = (1019.461 \pm 0.019) \text{ MeV} \)
- Width \( \Gamma = (4.266 \pm 0.031) \text{ MeV} \)
- \( BR(\phi \rightarrow K^+K^-) = (48.9 \pm 0.5) \% \)

**Goal of the analysis**

- Differential \( \phi \) multiplicities in p+p collisions measured in NA61/SHINE
  - from invariant mass spectra fits in \( \phi \rightarrow K^+K^- \) decay channel
  - as function of rapidity \( y \) and transverse momentum \( p_T \)

**Motivation**

- To constrain hadron production models
  - \( \phi \) interesting due to its hidden strangeness \( (s\bar{s}) \)
- Reference data for Pb+Pb at the same energies
NA61/SHINE detector

directly — only charged particles!

TPC $\rightarrow$ particle tracks in 3D
- curvature $\rightarrow$ charge and momentum
- energy loss (dE/dx) $\rightarrow$ mass

Performance
- total acceptance $\sim 80\%$
- momentum resolution $\sigma(p)/p^2 \sim 10^{-4}$ GeV$^{-1}$
- track reconstruction efficiency $> 95\%$
Double differential spectra: p+p @ 158 GeV

$\sqrt{s_{NN}} = 17.3$ GeV

MC normalization: $\int_{\text{model}} = \int_{\text{data}}$

- Pythia describes spectra shapes best, UrQMD slightly too long tail, EPOS clearly too short tail
- Fit $p_T e^{-m_T/T} \rightarrow$ extrapolation to $p_T = \infty \rightarrow$ tail $< 1\%$
Double differential spectra: p+p @ 158 GeV

\[ \sqrt{s_{NN}} = 17.3 \text{ GeV} \]

- First 2D (\(y\) vs \(p_T\)) \(\phi\) production measurements for p+p @ 158 GeV
- First ever differential (2D) for p+p @ 80 GeV → \(\sqrt{s_{NN}} = 12.3 \text{ GeV}\)
- First ever differential (2×1D) for p+p @ 40 GeV → \(\sqrt{s_{NN}} = 8.8 \text{ GeV}\)

Pythia describes spectra shapes best, UrQMD slightly too long tail, EPOS clearly too short tail

\[ p_T e^{-m_T/T} \rightarrow \text{extrapolation to} \ p_T = \infty \rightarrow \text{tail} < 1\% \]
EPOS and UrQMD shape comparable to data, Pythia slightly narrower

Fit Gaussian $e^{-y^2/2\sigma_y^2}$ → extrapolation to $y = \infty$ →
tails: 3% for 158 GeV, 7% for 80 GeV, 5% for 40 GeV

NA61/SHINE consistent with NA49

Reference data for Pb+Pb: $\sigma_y = \text{width of } dn/dy$

Comparison of particles / reactions

- **All but $\phi$ in Pb+Pb:**
  - $\sigma_y$ proportional to $y_{\text{beam}}$ with the same rate of increase
  - two new $\phi$ points in p+p emphasize peculiarity of $\phi$ in Pb+Pb

Coalescence

- Not compatible with production through $K^+ K^-$ coalescence, but p+p closer
Reference data for Pb+Pb: $\sigma_y = \text{width of } dn/dy$

Comparison of particles / reactions

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  - two new $\phi$ points in p+p emphasize peculiarity of $\phi$ in Pb+Pb

Coalescence

- Not compatible with production through $K^+ K^-$ coalescence, but p+p closer
Reference data for Pb+Pb: \( \sigma_y = \text{width of } \frac{d n}{d y} \)

Comparison of particles / reactions

- All but \( \phi \) in Pb+Pb:
  \[ \sigma_y \text{ proportional to } y_{\text{beam}} \text{ with the same rate of increase} \]

- Two new \( \phi \) points in p+p emphasize peculiarity of \( \phi \) in Pb+Pb

Coalescence

- Not compatible with production through \( K^+ K^- \) coalescence, but p+p closer
**Reference data for Pb+Pb: \( \sigma_y \) = width of \( dn/dy \)**

\[
\sigma_y = \text{width of } dn/dy
\]

**Comparison of particles / reactions**

- All but \( \phi \) in Pb+Pb:
  - \( \sigma_y \) proportional to \( y_{\text{beam}} \) with the same rate of increase
  - two new \( \phi \) points in p+p emphasize peculiarity of \( \phi \) in Pb+Pb

**Coalescence**

- Not compatible with production through \( K^+ K^- \) coalescence, but p+p closer
Reference data for Pb+Pb: total yield


- $\phi/\pi$ ratio increases with collision energy
- Production enhancement in Pb+Pb about $3 \times$, independent of energy
- Enhancement systematically larger than for kaons, comparable to $K^+$
  - for $K^-$ consistent with strangeness enhancement in parton phase
    (square of $K^-$ enhancement)
Comparison with world data and models

Results consistent with world data, much more accurate

Models

- EPOS close to data, Pythia underestimates experimental data, UrQMD underestimates $\sim 2 \times$, HRG (thermal) overestimates $\sim 2 \times$
- EPOS rises too fast with $\sqrt{S_{NN}}$
Search for QCD critical point via intermittency analysis

- **Objective:** Detection / existence of the QCD Critical Point (CP)

Look for observables *tailored for the CP*; scan phase diagram by varying energy and size of collision system

Intermittency analysis of factorial moments

protons in midrapidity

We detect local, power-law fluctuations of baryon density by calculating the scaling of 2nd factorial moments $F_2(M)$ with cell size $\Leftrightarrow \#\text{cells } M$ in transverse momentum space (intermittency).

After subtracting non-critical background moments, the correlator:

$$\Delta F_2^{(e)}(M) = F_2^{\text{data}}(M) - F_2^{\text{mix}}(M)$$

should scale according to a power-law for $M \gg 1$,

$$\Delta F_2(M) \sim (M^2)^{\varphi_2}, \varphi_{2,cr} = 5/6$$

where $\langle \ldots \rangle$ denotes averaging over events.
**Evidence** for intermittency for protons in NA49 “Si”+Si. None detected in NA49 “C”+C and Pb+Pb datasets.  

- No indication of intermittency in NA61/SHINE Be+Be @ 150 GeV
- Ar+Sc analysis ongoing
Charged spectators in non-central collisions generate electromagnetic fields
These modify the trajectories of final state charged particles
By studying the resulting charge asymmetries in distributions of produced particles, we obtain information on the distance $d_E$
Charge asymmetries from EM effects


NA49 Pb+Pb @ 158 GeV
preliminary

MC with $d_E = 0.75$ fm

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New observables from NA61/SHINE
Charge asymmetries from EM effects


NA49 Pb+Pb @ 158 GeV
MC with $d_E = 0.75 \text{ fm}$

$p_T = 500$
$p_T = 225$
$p_T = 175$
$p_T = 125$
$p_T = 75$

$d_E \approx 3 \text{ fm}$

$\sqrt{s_{NN}} = 7.7 \text{ GeV}$

A. Rybicki et al., APPB 46 (2015)
original data: STAR, PRL 112 (2014)
Charge asymmetries from EM effects


NA49 Pb+Pb @ 158 GeV
preliminary

MC with $d_E = 0.75$ fm

faster pions are produced closer to spectator system!

A. Rybicki et al., APPB 46 (2015)
original data: STAR, PRL 112 (2014)

$√s_{NN} = 7.7$ GeV

$V_1$


New observables from NA61/SHINE
Longitudinal evolution of the system

Bricks collide . . .

local energy-momentum conservation

. . . and form fire streaks

with rapidity from $E$-$p$ conservation

Each fire streak fragments independently in pions

$$\frac{dn}{dy} \sim A \cdot (E_s^* - m_s) \cdot \exp \left( - \frac{\left[ (y - y_s)^2 + \epsilon^2 \right]^{n/2}}{n\sigma_y} \right)$$
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Longitudinal evolution of the system

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\( y \approx -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5 \)

local energy-momentum conservation

\( \frac{dn}{dy} \) spectrum as function of centrality:

\( y \approx -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5 \)

\( n \approx 0, 5, 10, 15, 20, 25, 30, 35 \)

\( \text{Model, } b = 9.72 \text{ fm} \)

\( \text{NA49, C4} \)

\( y \approx -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5 \)

\( n \approx 0, 5, 10, 15, 20, 25, 30, 35 \)

\( \text{Model, } b = 8.41 \text{ fm} \)

\( \text{NA49, C3} \)

\( y \approx -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5 \)

\( n \approx 0, 5, 10, 15, 20, 25, 30, 35 \)

\( \text{Model, } b = 6.64 \text{ fm} \)

\( \text{NA49, C2} \)

\( y \approx -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5 \)

\( n \approx 0, 5, 10, 15, 20, 25, 30, 35 \)

\( \text{Model, } b = 4.74 \text{ fm} \)

\( \text{NA49, C1} \)

\( y \approx -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5 \)

\( n \approx 0, 5, 10, 15, 20, 25, 30, 35 \)

\( \text{Model, } b = 2.55 \text{ fm} \)

\( \text{NA49, C0} \)

\( y \approx -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5 \)

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\( \text{NA49, C0} \)
Summary

**φ meson production in p+p collision**

- Differential \((y, p_T)\) multiplicities at beam energies 40 GeV, 80 GeV, 158 GeV
- Non-trivial system size dependence of width of rapidity distribution \((\sigma_y)\), contrasting with that of other mesons
- Failure of microscopic and thermal models properties

**Critical Point via intermittency analysis**

- Evidence for intermittency in NA49 Si+Si @ 158 GeV
- None detected in NA49 C+C, Pb+Pb @ 158 GeV, nor NA61/SHINE Be+Be @ 150 GeV

**EM effects in pion emission**

- Bring information on space-time position of pion formation zone, which is much closer to spectator for faster pions than for slower ones
- On that basis, longitudinal evolution of the system at SPS energies may be interpreted as pure consequence of energy-momentum conservation
Acknowledgements

This work was supported by the National Science Centre, Poland (grant numbers: 2014/14/E/ST2/00018, 2015/18/M/ST2/00125)
and the Foundation for Polish Science — MPD program, co-financed by the European Union within the European Regional Development Fund.
NA61/SHINE experiment

General info

- Fixed target experiment in the North (experimental) Area of CERN SPS
- Successor of NA49
- Beams
  - hadrons (secondary)
  - ions (secondary and primary)
- ~150 physicists
- Physics active since 2009
Physics programme

SHINE = SPS Heavy Ion and Neutrino Experiment

Heavy ion physics
- spectra, correlations, fluctuations
- critical point
- onset of deconfinement
- EM interactions with spectators

Cosmic rays and neutrinos
- precision measurements of spectra
- cosmic rays: Pierre Auger Observatory, KASCADE
- neutrinos: T2K, Minerv\(\nu\)a, MINOS, NO\(\nu\)A, LBNE

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New observables from NA61/SHINE
ICNFP 2017, August 24
Data selection

Events
- inelastic
- in the target
- with well measured main vertex

TPC tracks
- from main vertex
- well reconstructed
- number of points in TPCs → accurate dE/dx and momentum
- with dE/dx corresponding to kaons (PID cut)

Probe: $y \in [0.0, 0.21)$, $p_T \in [0.0, 1.6)$ GeV

- entries
- $10^3$
- $10^4$

$10^0$
$10^1$
$10^2$
$10^3$
$10^4$

$10^5$

$10^6$
$10^7$
$10^8$

$m_{inv}(K^+,K^-)$ [MeV]
Kaon candidate selection — PID cut

Selection done with dE/dx
Accept tracks in ±5% band around kaon Bethe-Bloch curve (area between black curves in right picture)
Losses due to efficiency of this selection corrected with tag-and-probe method
Signal extraction
phase space binning, invariant mass spectrum

Signal
Convolution of:
relativistic Breit-Wigner
\text{f_{relBW}}(m_{inv};m_{\phi},\Gamma)
resonance shape
q-Gaussian
\text{f_{qG}}(m_{inv};\sigma,q)
broadening
due to detector resolution

\begin{align*}
\text{Entries} &= 11681 \\
\Gamma &= 4.27 \text{ MeV} \\
\sigma &= 0.991 \pm 0.098 \text{ MeV} \\
N_{\text{bkg}} &= 9187 \pm 79 \\
N_{p} &= 2494 \pm 53 \\
m_{v} &= 1019.623 \pm 0.071 \text{ MeV} \\
q &= 1.50 \\
\chi^{2}/\text{ndf} &= 1.6
\end{align*}

Probe: \ y \in [0.0,2.1), \ p_{T} \in [0.0,1.6) \text{ GeV}

\begin{align*}
\text{Entries} &= 11681 \\
\Gamma &= 4.27 \text{ MeV} \\
\sigma &= 0.991 \pm 0.098 \text{ MeV} \\
N_{\text{bkg}} &= 9187 \pm 79 \\
N_{p} &= 2494 \pm 53 \\
m_{v} &= 1019.623 \pm 0.071 \text{ MeV} \\
q &= 1.50 \\
\chi^{2}/\text{ndf} &= 1.6
\end{align*}

Background
Obtained with the event mixing method:
Kaon candidate taken from the current event is combined with candidates from
previous 500 events to create \phi candidates in the mixed events spectrum

Fitting function
\text{f}(m_{inv}) = N_{p} \cdot (\text{f_{relBW}} \ast \text{f_{qG}})(m_{inv};m_{\phi},\Gamma,\sigma,q) + N_{bkg} \cdot B(m_{inv})
Signal extraction
phase space binning, invariant mass spectrum

Signal
Convolution of:
- relativistic Breit-Wigner
  \( f_{\text{relBW}}(m_{\text{inv}}; m_{\phi}, \Gamma) \) resonance shape
- q-Gaussian \( f_{qG}(m_{\text{inv}}; \sigma, q) \) broadening due to detector resolution

Background
Obtained with the event mixing method:
- Kaon candidate taken from the current event is combined with candidates from previous 500 events to create \( \phi \) candidates in the mixed events spectrum

Fitting function
\[
f(m_{\text{inv}}) = N_p \cdot (f_{\text{relBW}} \ast f_{qG})(m_{\text{inv}}; m_{\phi}, \Gamma, \sigma, q) + N_{\text{bkg}} \cdot B(m_{\text{inv}})
\]
Goal: to remove bias of \( N_\phi \) due to PID cut efficiency \( \varepsilon \)

Simultaneous fit of 2 spectra:

- **tag** — at least one track in the pair passes PID cut
  \[ N_t = N_\phi \varepsilon (2 - \varepsilon) \]

- **probe** — both tracks pass PID cut
  \[ N_p = N_\phi \varepsilon^2 \]
Monte Carlo correction

\[ c_{\text{MC}} = \frac{N_{\phi}^{\text{gen}}}{N_{\phi}^{\text{ev}}} \cdot \frac{N_{\phi}^{\text{sel}}}{N_{\phi}^{\text{ev}}} \]

- registration efficiency
- trigger bias
- losses due to vertex cuts
- reconstruction efficiency

\[ \frac{d^2n}{dp_T \ dy} = \frac{N_{\phi}}{N_{\phi}} \times \frac{c_{\infty} \cdot c_{\text{bkg}} \cdot c_{\text{MC}}}{\mathcal{B}} \]

- \( c_{\infty} \approx 1.06 \) — extrapolation of the resonance curve
- \( c_{\text{bkg}} = 1.05 \) — unaccounted-for effects in the background description by event mixing

Monte Carlo correction

\[ c_{\text{MC}} = \frac{N_{\phi}^{\text{gen}}}{N_{\phi}^{\text{ev}}} \cdot \frac{N_{\phi}^{\text{sel}}}{N_{\phi}^{\text{ev}}} \]

- registration efficiency
- trigger bias
- losses due to vertex cuts
- reconstruction efficiency

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New observables from NA61/SHINE

ICNFP 2017, August 24
# Uncertainties

## Statistical

MINUIT/HESSE (symmetric)

## Systematic bin-independent

<table>
<thead>
<tr>
<th>Source</th>
<th>value [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}\mathcal{R}(\phi \rightarrow K^+K^-)$</td>
<td>1</td>
</tr>
<tr>
<td>fitting constraints</td>
<td>2</td>
</tr>
<tr>
<td>resonance theory</td>
<td>3</td>
</tr>
<tr>
<td>background</td>
<td>5</td>
</tr>
<tr>
<td>Total (quadratic)</td>
<td>6</td>
</tr>
</tbody>
</table>

Total systematic uncertainty $= \sqrt{\sum \sigma_i^2}$

For p+p @ 40 GeV additional bin-independent 3 % due to $c_{MC}$ averaging

Statistical uncertainty dominates
Double differential spectra: p+p @ 80 GeV

\[ \frac{d^2N}{dp_T dy} \text{ [GeV]^{-1}} \]

\[ y \in [0.0,0.3) \]

\[ (dp_T/df_T) \text{ [GeV T]} \]

\[ y \in [0.3,0.6) \]

\[ y \in [0.6,0.9) \]

\[ y \in [0.9,1.5) \]

\[ \sqrt{s_{NN}} = 12.3 \text{ GeV} \]

MC normalization: \( \int \text{model} = \int \text{data} \)

- Pythia describes spectra shapes best, UrQMD slightly too long tail, EPOS clearly too short tail
- Fit \( p_T e^{-m_T/T} \rightarrow \text{extrapolation to } p_T = \infty \rightarrow \text{tail} < 4\% \)
Double differential spectra: p+p @ 80 GeV

- First $\phi$ production measurements for p+p @ 80 GeV

- Pythia describes spectra shapes best, UrQMD slightly too long tail, EPOS clearly too short tail

Fit $p_T e^{-m_T/T} \rightarrow$ extrapolation to $p_T = \infty \rightarrow$ tail $< 4\%$

$\sqrt{s_{NN}} = 12.3$ GeV

MC normalization: $\int_{model} = \int_{data}$

EPOS 1.99
Pythia 6
UrQMD 3.4

$\int_{model} = \int_{data}$

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New observables from NA61/SHINE

ICNFP 2017, August 24
Single differential spectra: \( p+p @ 40 \text{ GeV} \)

\[ \frac{d^2n}{dp_T \ dy} \ 	ext{[GeV]} \]

\[ y \in [0.0, 1.5) \]

\[ \sqrt{s_{NN}} = 8.8 \text{ GeV} \]

MC normalization: \( \int \text{model} = \int \text{data} \)

**\( p_T \)**
- Pythia agrees best, UrQMD similar, EPOS spectrum too short tail
- extrapolation tail < 1%

**\( y \)**
- UrQMD agrees with data, EPOS bit too narrow, Pythia even narrower
- extrapolation tail 5%
Single differential spectra: p+p @ 40 GeV

\[
\frac{d^2n}{dp_T dy} \ [\text{GeV}] \quad y\in[0.0,1.5)
\]

\[
\sqrt{s_{NN}} = 8.8 \text{ GeV}
\]

MC normalization: \( \int \text{model} = \int \text{data} \)

- First \( \phi \) production measurements for p+p @ 40 GeV

\( p_T \)
- Pythia agrees best, UrQMD similar, EPOS spectrum too short tail
- extrapolation tail < 1 %

\( y \)
- UrQMD agrees with data, EPOS bit too narrow, Pythia even narrower
- extrapolation tail 5 %
Transverse mass spectra at midrapidity

\[ p+p @ 158 \text{ GeV} \]

\[ p+p @ 80 \text{ GeV} \]

\[ \sqrt{s_{NN}} = 17.3 \text{ GeV} \]

\[ \sqrt{s_{NN}} = 12.3 \text{ GeV} \]

**Thermal fit results**

<table>
<thead>
<tr>
<th>( p_{\text{beam}} ) [GeV]</th>
<th>( T_{\phi} ) [MeV]</th>
<th>( T_{\pi^-} ) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>158</td>
<td>150 ± 14 ± 8</td>
<td>159.3 ± 1.3 ± 2.6</td>
</tr>
<tr>
<td>80</td>
<td>148 ± 30 ± 17</td>
<td>159.9 ± 1.5 ± 4.1</td>
</tr>
</tbody>
</table>
Observing power-law fluctuations

Experimental observation of local, power-law distributed fluctuations

\[ \text{Intermittency in transverse momentum space (net protons at mid-rapidity)} \]
\[ \text{(Critical opalescence in ion collisions)} \]

F. K. Diakonos et al., PoS (CPOD2006) 010, Florence

- Transverse momentum space is partitioned into \( M^2 \) cells
- Calculate second factorial moments \( F_2(M) \) as a function of cell size \( \Leftrightarrow \) number of cells \( M \):

\[ F_2(M) \equiv \frac{\sum_m \langle n_m(n_m - 1) \rangle}{\sum_m \langle n_m \rangle^2}, \]

where \( \langle \ldots \rangle \) denotes averaging over events.

\[ m_{\text{th}} \text{ bin} \quad \text{n}_m: \text{number of particles in} \quad m_{\text{th}} \text{ bin} \]
Subtracting the background from factorial moments

- Experimental data is noisy ⇒ a background of uncorrelated/non-critical pairs must be subtracted at the level of factorial moments.
- Intermittency will be revealed at the level of subtracted moments $\Delta F_2(M)$.

**Partitioning of pairs into critical/background**

\[
\langle n(n-1) \rangle = \langle n_c(n_c-1) \rangle + \langle n_b(n_b-1) \rangle + 2 \langle n_b n_c \rangle
\]

- \(\langle n(n-1) \rangle \) critical
- \(\langle n(n-1) \rangle \) background
- \(2 \langle n_b n_c \rangle \) mixed term

\[
\Delta F_2(M) = F_2^{(d)}(M) - \lambda(M)^2 F_2^{(b)}(M) - 2 \lambda(M) (1 - \lambda(M)) f_{bc}
\]

- \(F_2^{(d)}(M)\) correlator
- \(F_2^{(b)}(M)\) data
- \(\lambda(M)\) background
- \(1 - \lambda(M)\) ratio \(\frac{<n>_b}{<n>_d}\)

- The mixed term can be neglected for dominant background (non-trivial! Justified by CMC simulations)
Scaling of factorial moments – Subtracting mixed events

For $\lambda \lesssim 1$ (background domination), $\Delta F_2(M)$ can be approximated by:

$$\Delta F_2^{(e)}(M) = F_2^{\text{data}}(M) - F_2^{\text{mix}}(M)$$

For a critical system, $\Delta F_2$ scales with cell size (number of cells, $M$) as:

$$\Delta F_2(M) \sim (M^2)^{\varphi_2}$$

where $\varphi_2$ is the intermittency index.

<table>
<thead>
<tr>
<th>universality class, effective actions</th>
<th>$\varphi_{2,cr}^{(\sigma)} = \frac{2}{3} (0.66 \ldots)$</th>
<th>$\varphi_{2,cr}^{(p)} = \frac{5}{6} (0.833 \ldots)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>net baryons (protons)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Intermittency analysis results – NA49 “Si”+Si

- **Evidence** for intermittency in “Si”+Si – but **large statistical errors**.
- **No intermittency** detected in the “C”+C, Pb+Pb datasets.
- **Fit with** \( \Delta F_2^{(e)}(M \ ; \ C, \phi_2) = e^C \cdot (M^2)^{\phi_2} \), for \( M^2 \geq 6000 \)

- **Bootstrap distribution of** \( \phi_2 \) **values is highly asymmetric due to closeness of** \( F_2^{(d)}(M) \) **to** \( F_2^{(m)}(M) \).
- **The spread is partly artificial due to pathological fits** (negative \( \Delta F_2(M) \) values in some bootstrap samples)
Simulating a system of critical baryons

- **Simplified version of CMC code:**
  - Only protons produced
  - One cluster per event, produced by random Lévy walk:
    \[ \tilde{d}_F^{(B,2)} = 1/3 \Rightarrow \phi_2 = 5/6 \]
  - Lower / upper bounds of Lévy walks \( p_{\text{min, max}} \) plugged in.
  - Cluster center exponential in \( p_T \), slope adjusted by \( T_c \) parameter.
  - Poissonian proton multiplicity distribution.

---

**Input parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( p_{\text{min}} ) [MeV]</th>
<th>( p_{\text{max}} ) [MeV]</th>
<th>( \lambda_{\text{Poisson}} )</th>
<th>( T_c ) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.1 ( \rightarrow ) 1</td>
<td>800 ( \rightarrow ) 1200</td>
<td>( \langle p \rangle )</td>
<td>163</td>
</tr>
</tbody>
</table>
Critical Monte Carlo + background simulation of data

- Mixing CMC with random proton tracks (noise) allows us to estimate the fraction of critical protons in the analysed data sets.
- $F_2(M)$ levels of noisy CMC & data should match.

A critical component as low as 0.5% can be detectable through intermittency, provided a relatively high statistics and proton multiplicity at midrapidity!
Fire streaks’ parameters


\[ \text{Pb+Pb} \rightarrow \sqrt{s_{NN}} = 17.3 \text{ GeV}, \ y_{\text{beam}} = 2.9 \]

peripheral \( b = 9.72 \text{ fm} \)  
central \( b = 2.55 \text{ fm} \)

- Very narrow (if any) ‘stopped’ region in non-central collisions
- \( \Delta E^* \) is the streak’s energy in its own c.m.s. frame
- In peripheral collisions 2 spectator regions visible (with \( \Delta E^* = m \))
- Central collisions: broader ‘hot’ region, with higher excitation energies