

Search for critical point in NA61/SHINE

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for the NA61/SHINE Collaboration



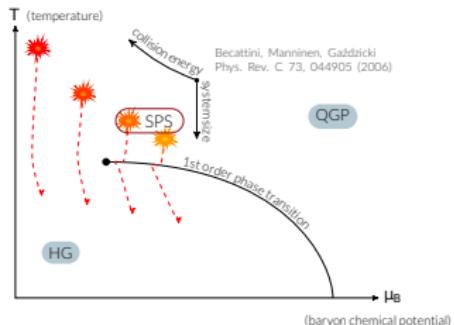
XVI Polish Workshop on Relativistic Heavy-Ion Collisions

Jan Kochanowski University, Kielce

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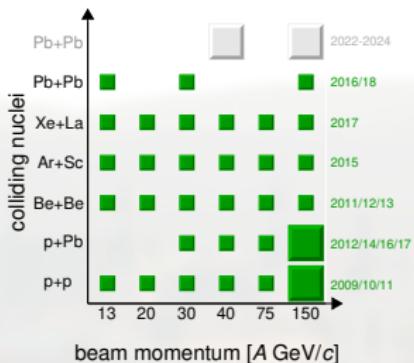
Strong interactions physics:

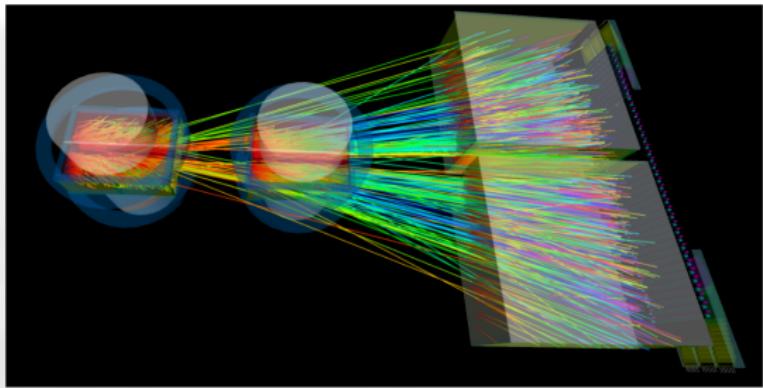
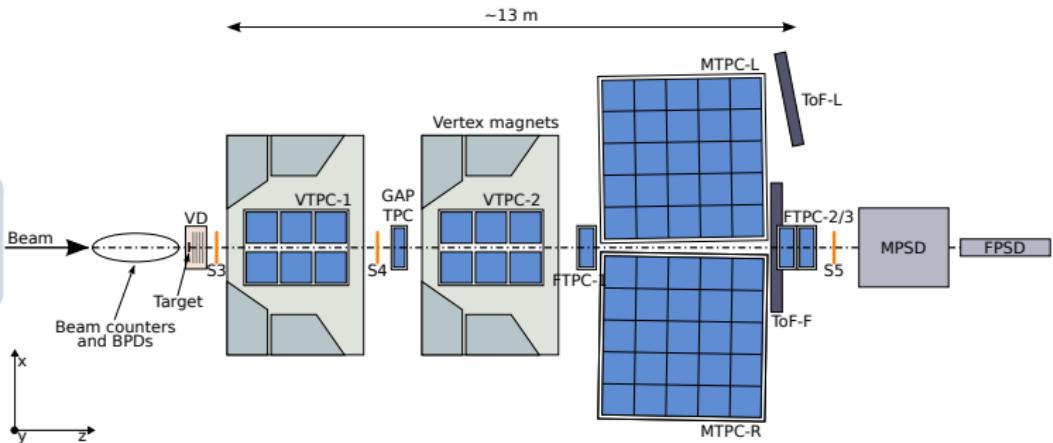
- search for the **critical point** of strongly interacting matter
- study the **diagram of high-energy nuclear collisions**
- direct measurement of **open charm**



And more:

- measurements for **neutrino programs** at J-PARC and Fermilab
- measurements of **nuclear fragmentation** cross section for cosmic rays physics





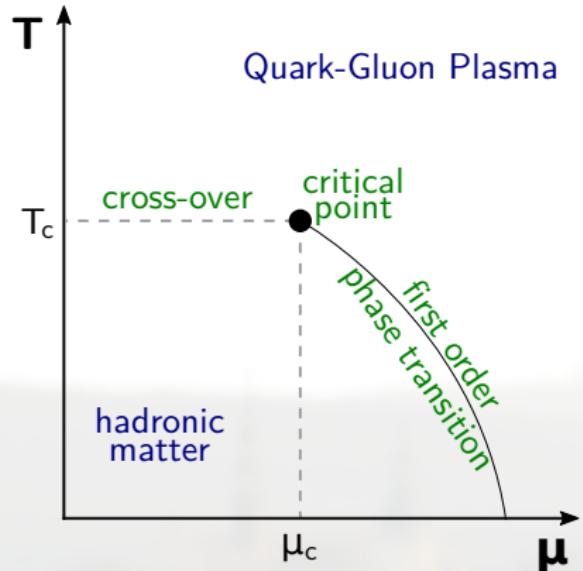
coverage up to 50% of produced charged particles starting from $p_T \approx 0$

$$p_{\text{beam}} = 13A - 150A \text{ GeV}/c$$

↓

$$\sqrt{s_{\text{NN}}} \approx 5 - 17 \text{ GeV}$$

Critical Point of QGP

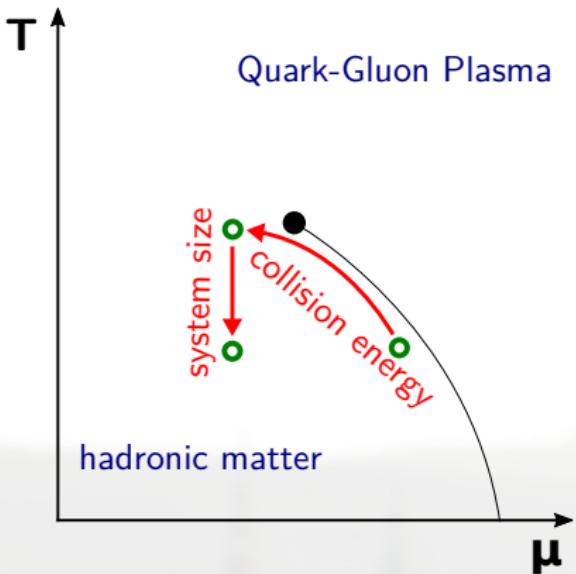


Critical point (CP) – a hypothetical end point of first order phase transition line (QGP-HM) that has properties of second order phase transition.

2nd order phase transition → scale invariance → power-law form of correlation function.

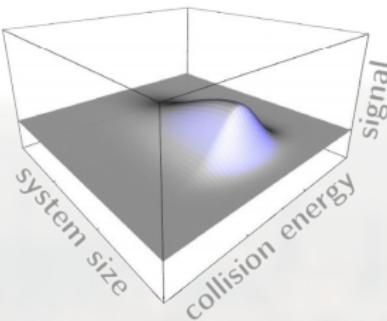
These expectations are for fluctuations and correlations in the configuration space which are expected to be projected to the momentum space via quantum statistics and/or collective flow.

Exploring the phase diagram with heavy-ion collisions

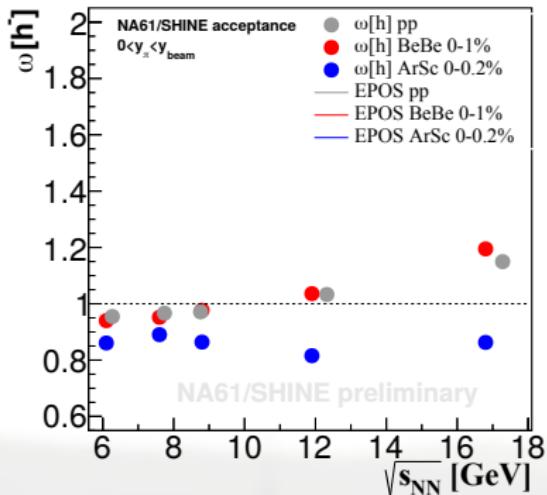


The experimental search for the critical point requires a two-dimensional scan in collision energy and size of the colliding nuclei (centrality).

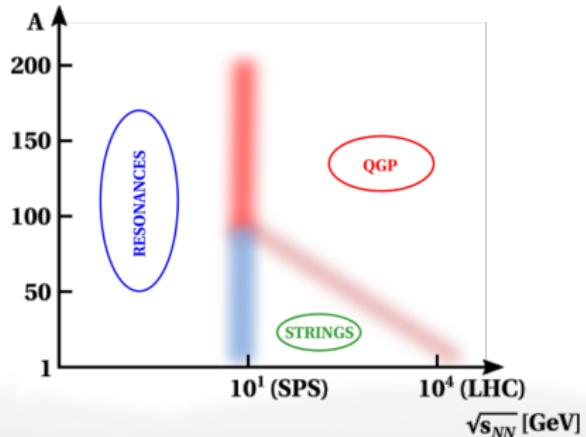
Search for the critical end point in heavy-ion collisions is performed by a scan in the parameters controlled in laboratory (collision energy and nuclear mass number, centrality). Conjecture is, that by changing them, we change freeze-out conditions (T, μ_B).



Multiplicity fluctuations

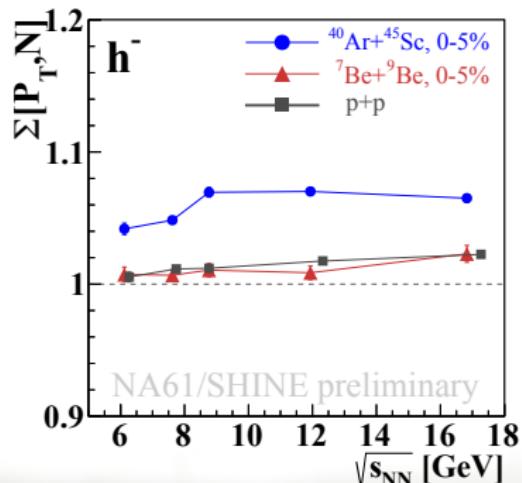


$$\omega[N] = \frac{\text{var}[N]}{\langle N \rangle}$$

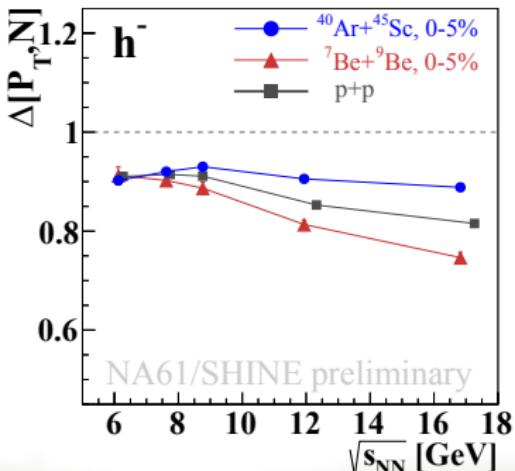


Be+Be similar to p+p, Ar+Sc different → onset of fireball (?).
No collision energy dependence that could be related to the critical point observed in Ar+Sc

Multiplicity-transverse momentum fluctuations



NA61/SHINE preliminary



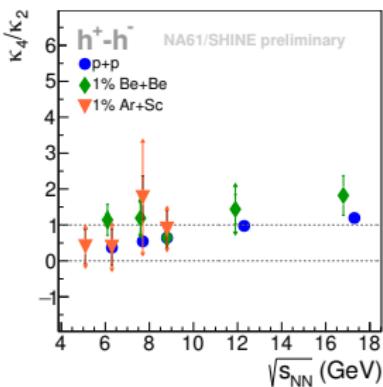
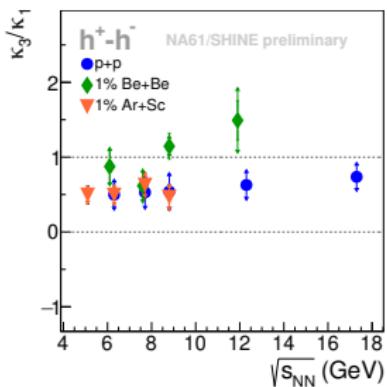
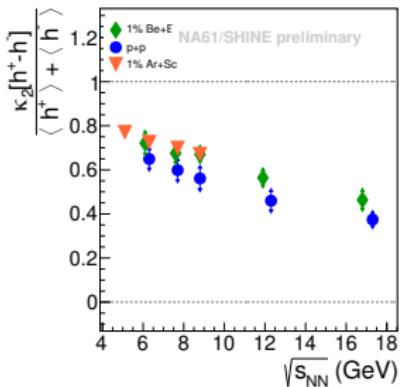
$$\Sigma[A, B] = \frac{1}{C_\Sigma} \left[\langle B \rangle \omega[A] + \langle A \rangle \omega[B] - 2 \left(\langle AB \rangle - \langle A \rangle \langle B \rangle \right) \right]$$

$$P_T = \sum_{i=1}^N p_{T,i}, \quad C_\Delta = C_\Sigma = \langle N \rangle \omega[p_T]$$

$$\Delta[A, B] = \frac{1}{C_\Delta} \left[\langle B \rangle \omega[A] - \langle A \rangle \omega[B] \right]$$

Be+Be similar to p+p, Ar+Sc different \rightarrow onset of fireball (?).
No collision energy dependence that could be related to the critical point observed in Ar+Sc

Net-charge fluctuations



$$\kappa_1 = \langle N \rangle$$

$$\kappa_2 = \langle (\delta N)^2 \rangle$$

$$\kappa_3 = \langle (\delta N)^3 \rangle$$

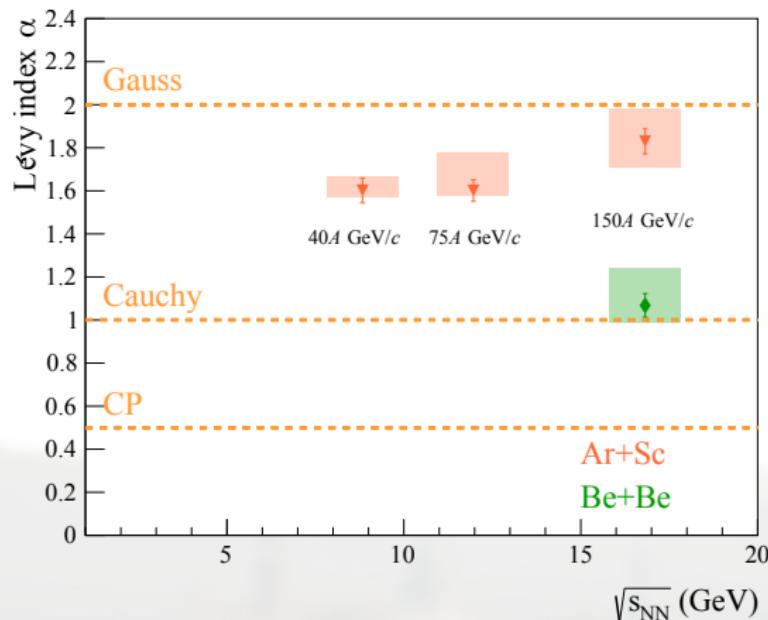
$$\kappa_4 = \langle (\delta N)^4 \rangle$$

$$\langle N_2 \rangle \sim \xi^2$$

$$\langle N_4 \rangle \sim \xi^7$$

No non-monotonic signal observed

Short-range correlations



Lévy-shaped source (1-D):

$$C(q) \cong 1 + \lambda \cdot e^{(-qR)^\alpha}$$

where $q = |\mathbf{p}_1 - \mathbf{p}_2|_{\text{LCMS}}$, λ describes correlation length, R determines the length of homogeneity and Lévy exponent α determines source shape:

- $\alpha = 2$: Gaussian, predicted from simple hydro
- $\alpha = 1$: Cauchy
- $\alpha = 0.5$: conjectured value at the critical point

No indication of the critical point so far

Fluctuations as a function of momentum bin size

Scaled factorial moments $F_r(M)$ of order r

$$F_r(M) = \frac{\left\langle \frac{1}{M} \sum_{i=1}^M n_i(n_i - 1)\dots(n_i - r + 1) \right\rangle}{\left\langle \frac{1}{M} \sum_{i=1}^M n_i \right\rangle^r}$$

M - number of subdivision intervals of the transverse momentum region Δ

n_i - number of particles in i -th bin

$\langle \dots \rangle$ - averaging over events

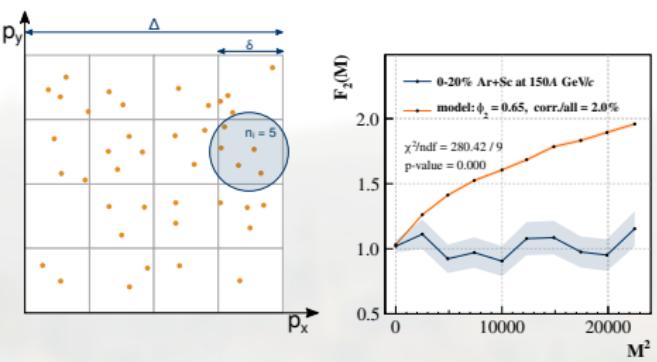
When the system is a simple fractal, $F_r(M)$ follows a power-law dependence:

$$F_r(M) = F_r(\Delta) \cdot (M^2)^{\varphi_r}.$$

Additionally, the exponent (intermittency index) φ_r obeys the relation:

$$\varphi_r = (r - 1)/2 \cdot d_r,$$

where the anomalous fractal dimension d_r is independent of r .



Bialas, Peschanski, NPB 273 (1986) 703

Wosiek, APPB 19 (1988) 863

Asakawa, Yazaki NPA 504 (1989) 668

Barducci, Casalbuoni, De Curtis, Gatto, Pettini, PLB 231 (1989) 463

Satz, NPB 326 (1989) 613

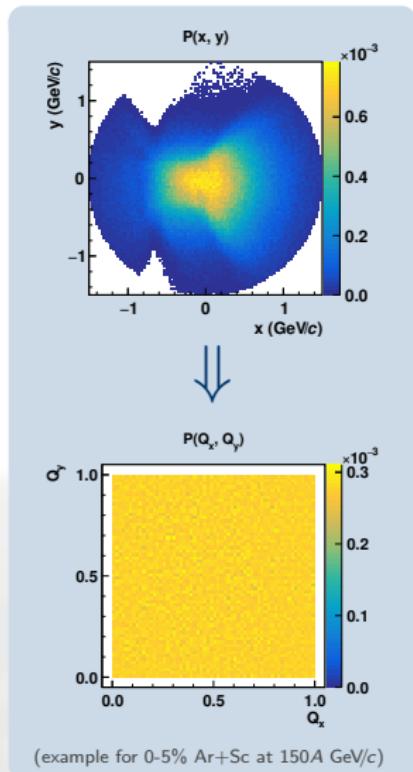
Cumulative transformation

Fluctuations as a function of momentum bin size

Instead of using p_x and p_y , one can use cumulative quantities:

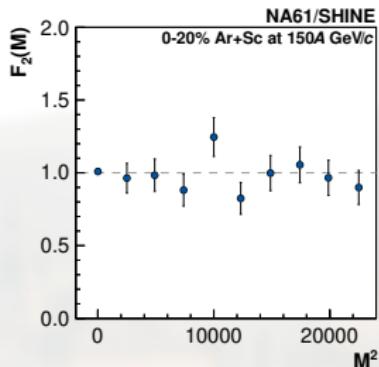
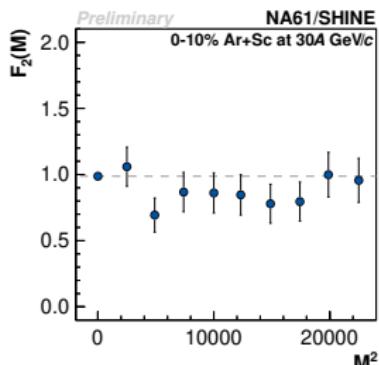
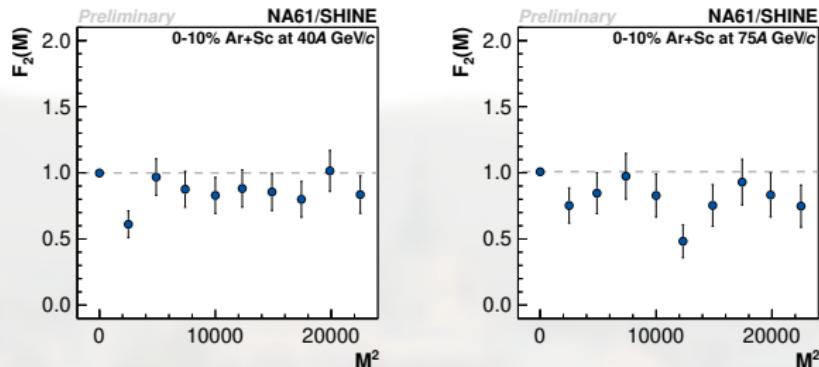
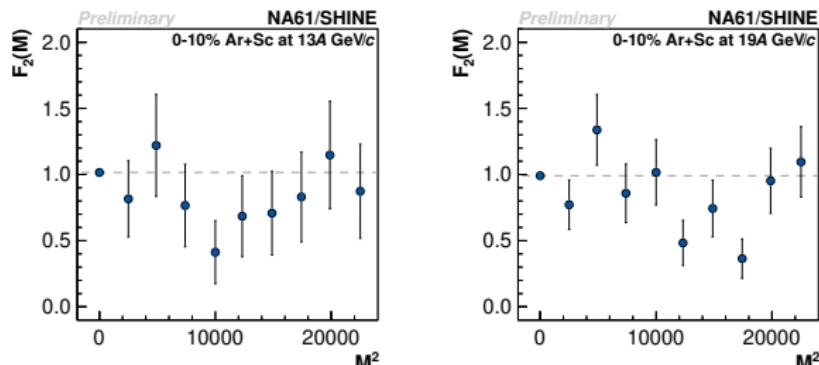
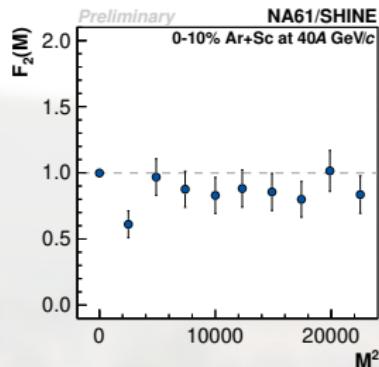
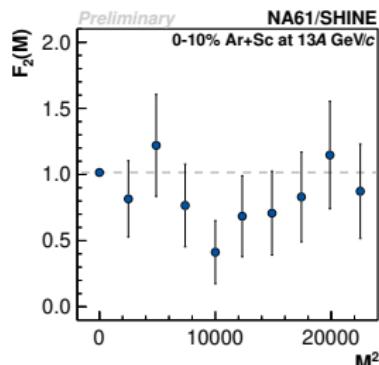
$$Q_x = \int_{\min}^x \rho(x) dx / \int_{\min}^{\max} \rho(x) dx \quad Q_y(x) = \int_{y_{\min}}^y P(x, y) dy / P(x)$$

- transform any distribution into uniform one (0,1)
- remove the dependence of F_2 on the shape of the single-particle distribution
- the intermittency index of an ideal power-law system described in two dimensions in momentum space was proven to remain approximately invariant after the transformation



Proton intermittency results for Ar+Sc

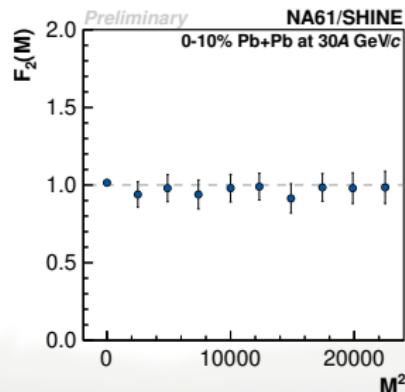
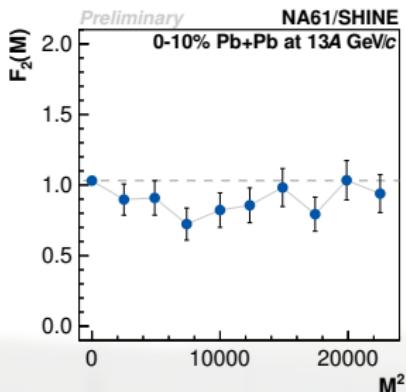
Fluctuations as a function of momentum bin size



No indication for power-law increase with bin size

Proton intermittency results for Pb+Pb

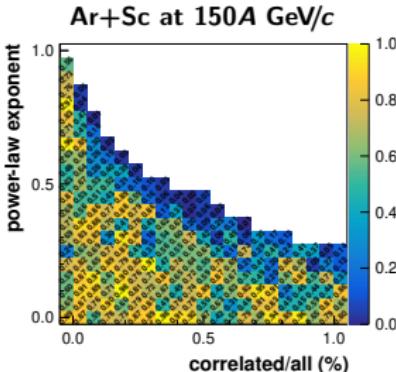
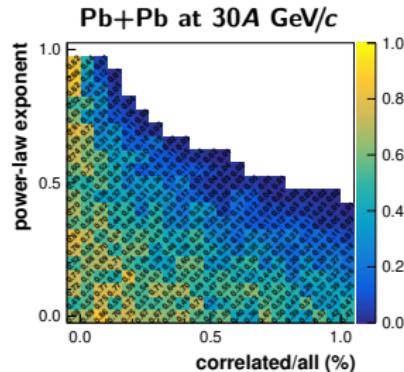
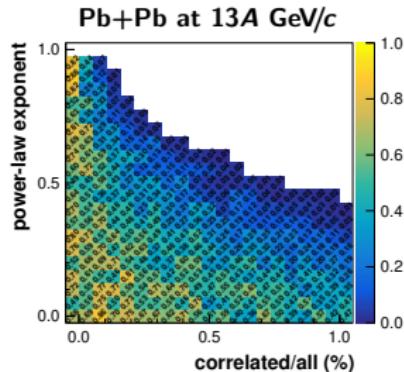
Fluctuations as a function of momentum bin size



No indication for power-law increase with bin size

Exclusion plots

Fluctuations as a function of momentum bin size



white area:
p-value < 0.01

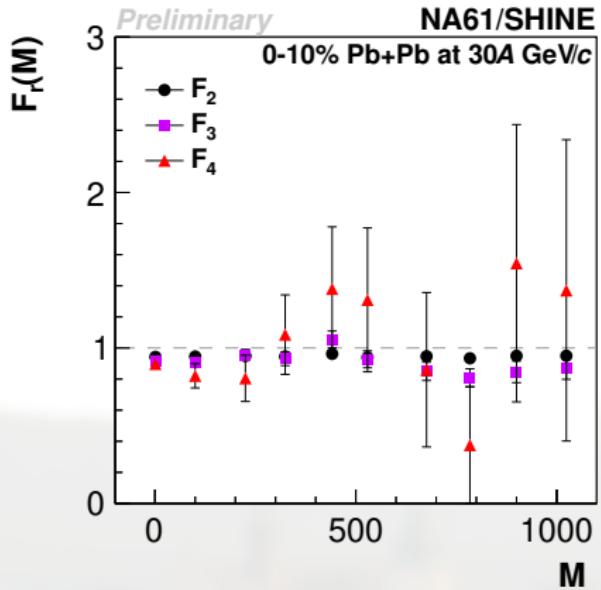
Exclusion plots for parameters of simple power-law model:

- power-law exponent ϕ in $|\Delta \vec{p}_T|$ correlation function $\rho(|\Delta \vec{p}_T|) = |\Delta \vec{p}_T|^{-\phi}$, $\varphi_2 = (\phi + 1)/2$,
- fraction of correlated particles

The intermittency index φ_2 for a system freezing out at the QCD critical endpoint is expected to be $\varphi_2 = 5/6$ assuming that the latter belongs to the 3-D Ising universality class.
This corresponds to the model power-law exponent equal $\phi = 2/3$

Negatively charged hadron intermittency analysis

Fluctuations as a function of momentum bin size



$$F_2(M) = \frac{2M}{\langle N \rangle^2} \langle N_2(M) \rangle$$

$$F_3(M) = \frac{6M^2}{\langle N \rangle^3} \langle N_3(M) \rangle$$

$$F_4(M) = \frac{24M^3}{\langle N \rangle^4} \langle N_4(M) \rangle$$

M - total number of 2D (p_x-p_y) bins

N - event multiplicity

$N_2(M)$ - total number of particle pairs in M bins in an event

$N_3(M)$ - total number of particle triplets in M bins in an event

$N_4(M)$ - total number of particle quadruplets in M bins in an event

$\langle \dots \rangle$ - averaging over events

Expected relationship between intermittency indices for higher order moments:

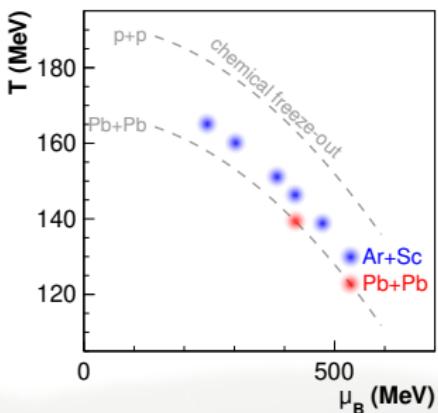
$$\varphi_2 = \frac{\varphi_3}{2} = \frac{\varphi_4}{3}$$

No indication for power-law increase with bin size

Summary

- Results on **net-charge fluctuations** in p+p, Ar+Sc and Ar+Sc energy scans show **no non-monotonic signal**
- Obtained exponents from the Lévy-shaped source fit in the **HBT analyses** of pions produced in Be+Be and Ar+Sc energy scans are **far from the values predicted for the critical point**
- Results on the dependence of **scaled factorial moments** of multiplicity distribution on cumulative momentum bin size, analyzed using independent data points for:
 - protons in Pb+Pb at 13A GeV/c ($\sqrt{s_{NN}} \approx 5.1$ GeV)
 - protons in Pb+Pb at 30A GeV/c ($\sqrt{s_{NN}} \approx 7.5$ GeV)
 - protons in Ar+Sc at 13A – 150A GeV/c ($\sqrt{s_{NN}} \approx 5 - 17$ GeV)
 - negatively charged hadrons in Pb+Pb at 30A GeV/c ($\sqrt{s_{NN}} \approx 7.5$ GeV)show **no indication of a power-law increase**
- **Exclusion plots** for parameters of a simple model (ratio of correlated to background particles and power-law exponent) were presented

Status of NA61/SHINE CP search via proton intermittency



Points indicate analyzed reactions with no evidence for CP. They are placed at $T-\mu_B$ values calculated from Becattini, Manninen, Gazdzicki, Phys. Rev. C73 2006

Thank You!

Additional slides

Cumulative transformation

1) normalization:

$$P(x, y) = \rho(x, y) / \int_{x, y} \rho(x, y) dx dy$$

2) projection on x:

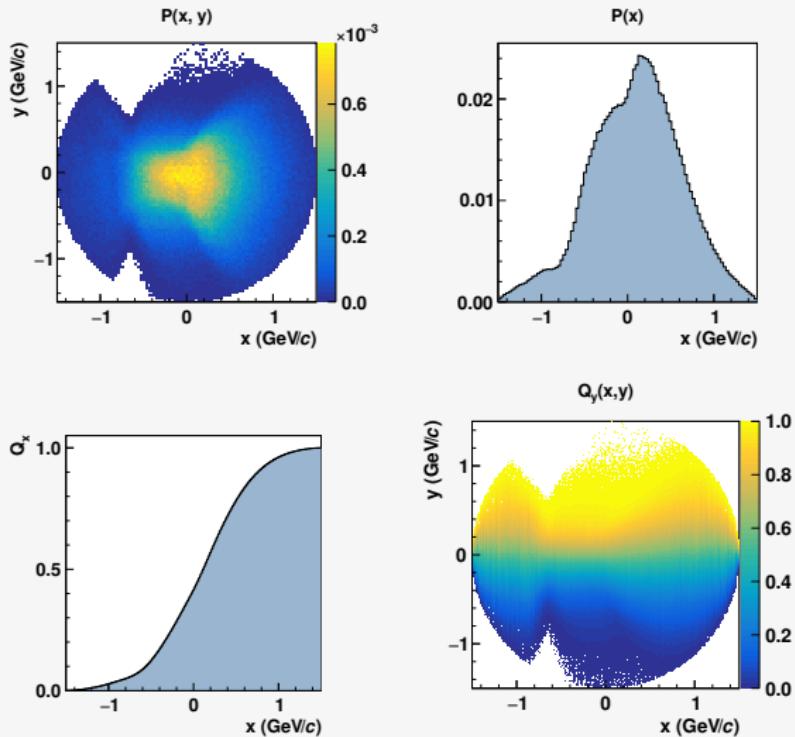
$$P(x) = \int_y P(x, y) dy$$

3) cumulative x:

$$Q_x = \int_{x_{\min}}^x P(x) dx$$

4) cumulative y:

$$Q_y(x) = \int_{y_{\min}}^y P(x, y) dy / P(x)$$



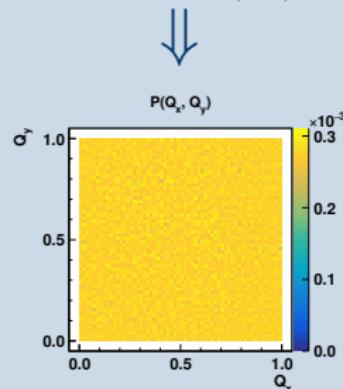
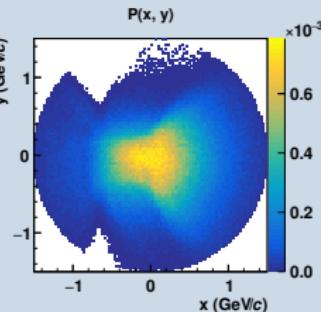
(examples for 0-5% Ar+Sc at 150A GeV/c, $x=p_x$, $y=p_y$)

Cumulative variables

Instead of using p_x and p_y , one can use cumulative quantities:

$$Q_x = \int_{\min}^x \rho(x) dx / \int_{\min}^{\max} \rho(x) dx \quad Q_y(x) = \int_{y_{\min}}^y P(x, y) dy / P(x)$$

- transform any distribution into uniform one (0,1)
- remove the dependence of F_2 on the shape of the single-particle distribution
- the intermittency index of an ideal power-law system described in two dimensions in momentum space was proven to remain approximately invariant after the transformation



(example for 0-5% Ar+Sc at 150A GeV/c)

Momentum-based Two-Track Distance cut

Time Projection Chambers do not allow to reconstruct tracks too close to each other.

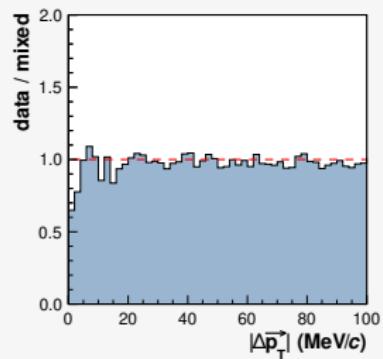
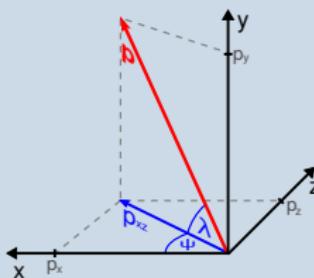
A momentum-based cut was introduced.

Parameters adjusted for Ar+Sc and Pb+Pb separately.

$$\begin{aligned}s_x &= p_x / p_{xz} = \cos(\psi) \\ s_y &= p_y / p_{xz} = \tan(\lambda) \\ \rho &= 1 / p_{xz}\end{aligned}$$

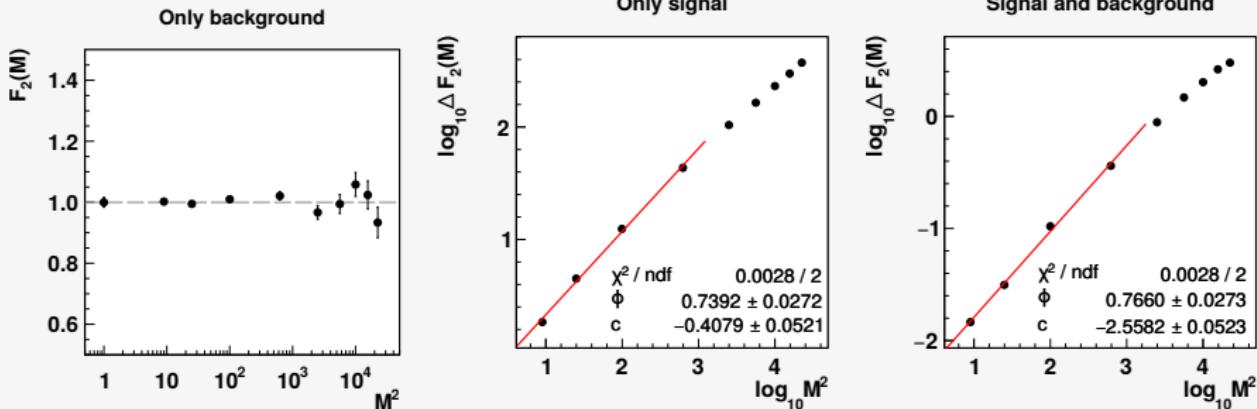
For pairs:

$$\begin{aligned}\Delta s_x &= s_{x,2} - s_{x,1} \\ \Delta s_y &= s_{y,2} - s_{y,1} \\ \Delta \rho &= \rho_2 - \rho_1\end{aligned}$$



Effect seen for $|\Delta \vec{p}_T| < 10 \text{ MeV}/c$

Simple power-law model results



Event and single-track selection

Ar+Sc at 150A GeV/c

- full 'good' target-inserted data set (029_17c_v1r8p1_pA_slc6_phys_PP)
- in total, 1.10M events with $\langle N_{\text{proton}} \rangle \approx 3.8$ left for analysis

Event selection

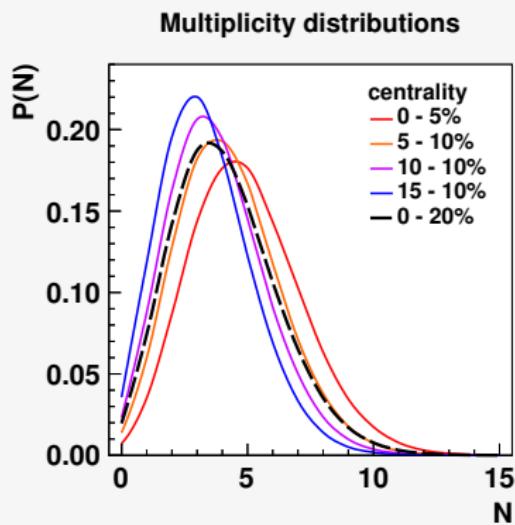
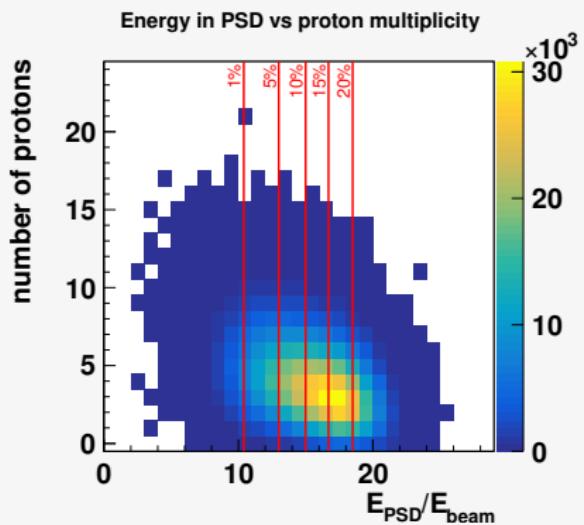
- WFA beam ($4 \mu\text{s}$)
- WFA interaction ($25 \mu\text{s}$)
- standard BPD cut
- trigger T2
- main vertex fit quality
- main vertex z-position ($\pm 10 \text{ cm}$ around target)
- energy in small PSD modules < 2800
- $800 < \text{energy in big PSD modules} < 5000$
- if number of tracks in fit < 50 , tracks in fit / all tracks > 0.25
- 'cloud no. 5'

Track selection

- good vertex track fit
- total number of measured clusters > 30
- $0.5 < \text{measured clusters} / \text{potential clusters} < 1.1$
- clusters in VTPCs > 15
- dE/dx clusters > 30
- $|b_x| < 2 \text{ cm}, |b_y| < 4 \text{ cm}$
- charge > 0
- $0.60 < \log_{10}(p / \text{GeV}/c) < 2.10$
- $0.5 < dE/dx < BB_p + 0.15(BB_K - BB_p)$
- $p_x < 1.5 \text{ GeV}/c, p_y < 1.5 \text{ GeV}/c$
- $|y_{\text{proton}}^{\text{CMS}}| < 0.75$
- acceptance map

Centrality selection

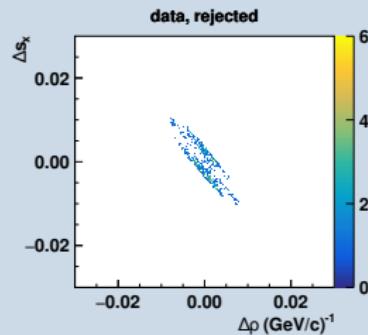
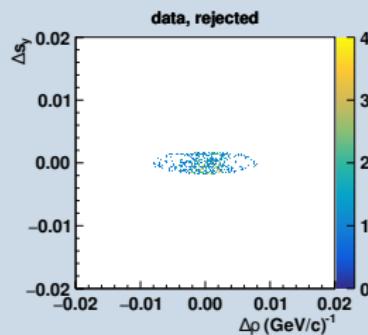
Ar+Sc at 150A GeV/c



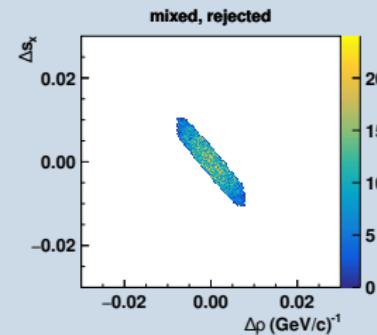
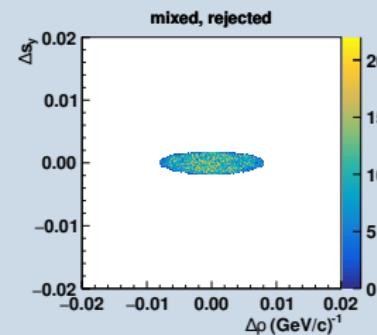
Two-Track Distance cut – rejected pairs

Ar+Sc at 150A GeV/c

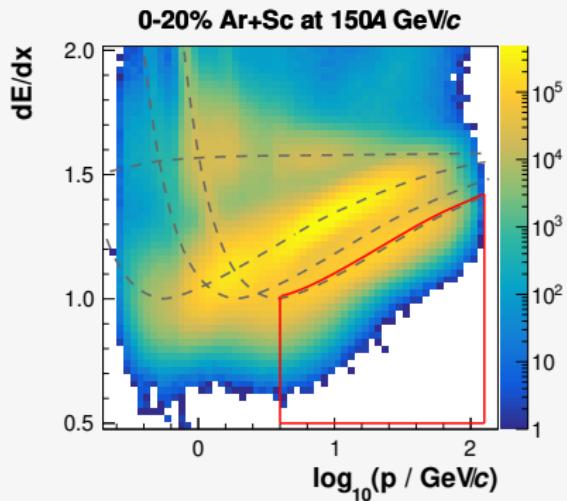
Momentum-based TTD cut



Momentum-based TTD cut



Momentum-based Two-Track Distance cut



Selection of protons is based on dE/dx measurements in TPCs:

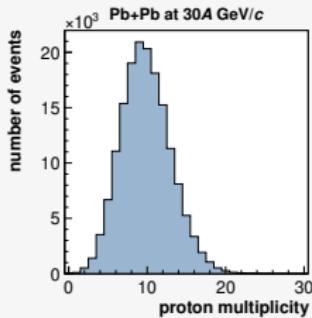
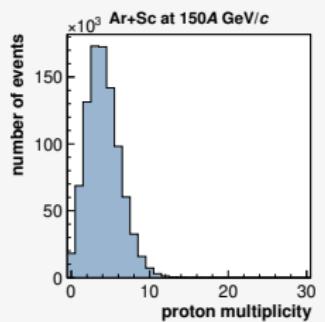
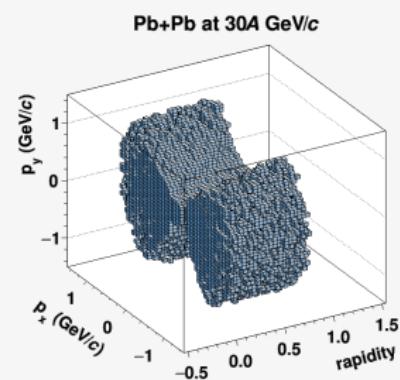
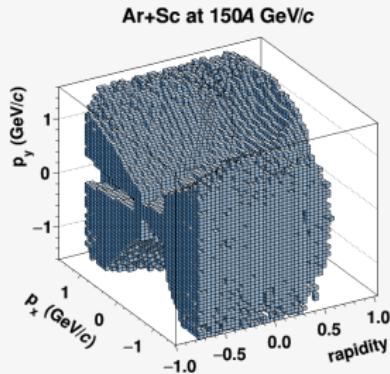
- $0.60 < \log_{10}(p / \text{GeV}/c) < 2.10$
- $0.5 < dE/dx < BB_p + 0.15(BB_K - BB_p)$

Within the selected range, the cut selects more than 50% of protons and a few percent kaons.

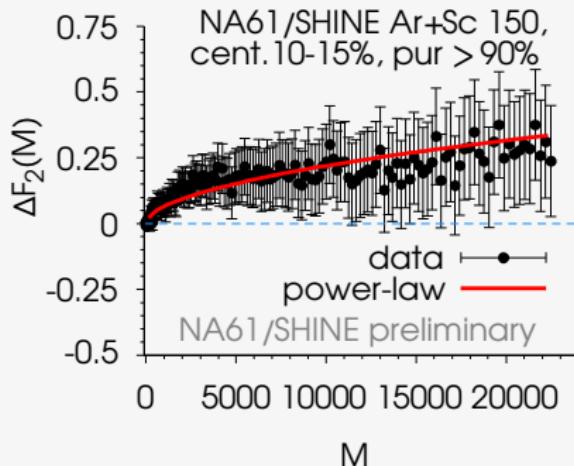
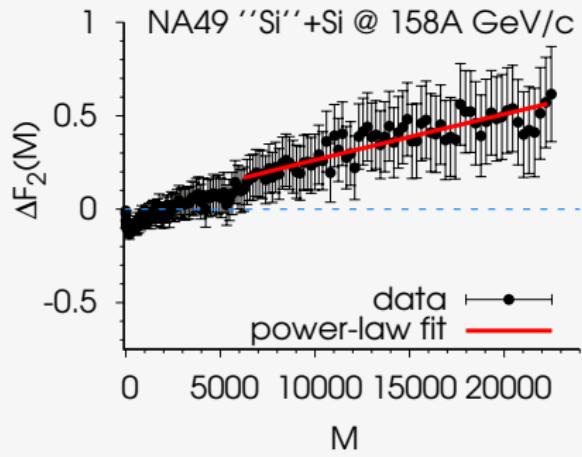
Analyses acceptance

$|p_x| < 1.5 \text{ GeV}/c$
 $|p_y| < 1.5 \text{ GeV}/c$

Ar+Sc: $-0.75 < \text{rapidity} < 0.75$
Pb+Pb: $0.00 < \text{rapidity} < 0.75$



CP search with proton intermittency in transverse momentum



A deviation of ΔF_2 ($\Delta F_2 = F_2^{\text{data}} - F_2^{\text{mixed}}$) from zero seems to be present in central Si+Si and mid-central Ar+Sc.

However, the data points are **correlated** which makes the interpretation difficult.

Results presented today were obtained with **statistically independent** points and **cumulative quantities**.

Simple power-law model

Comparison with simple power-law model

A simple model that generates momentum of particles for a given number of events with a given multiplicity distribution.

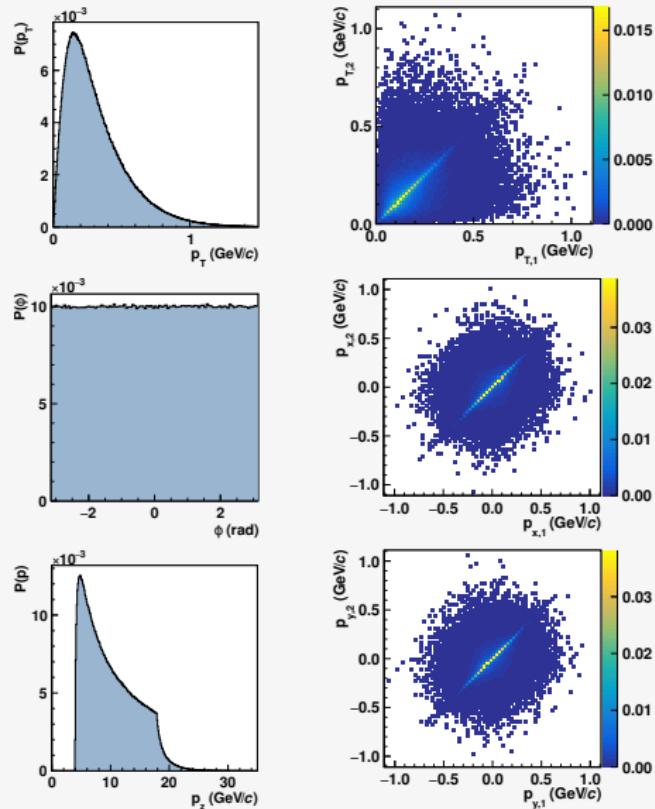
It has two main parameters:

- ratio of correlated to uncorrelated particles,
- power-law exponent.

Correlated pairs (signal)

$$\rho(|\Delta \vec{p}_T|) = |\Delta \vec{p}_T|^\phi$$

Examples for: $\phi = 0.80$
 $N_{\text{background}} = \text{Poisson}(30)$
 $N_{\text{signal}} = 2$



Examples of $F_2(M)$ results

Lots of model data sets generated:

- correlated-to-all ratio: vary from 0.0 to 4.0% (with 0.2% step)
- power-law exponent: vary from 0.00 to 1.00 (with 0.05 step)

and compared with the experimental data

For the construction of exclusion plots, statistical uncertainties were calculated using model with statistics corresponding to the data.

