# New Results on Baryon and Meson Production at SPS Energies

Nikolaos Davis[1]
for the NA61/SHINE collaboration

[1]H. Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences

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# Outline

1. $\phi$ meson production in proton-proton collisions (A. Marcinek)
2. Search for QCD critical point via intermittency analysis (N.D., N. Antoniou, F. Diakonos)
3. Electromagnetic effects in pion emission (A. Rybicki, A. Szczurek, M. Kiełbowicz)

# $\phi$ meson production — introduction

## Goal of the analysis

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

## Motivation

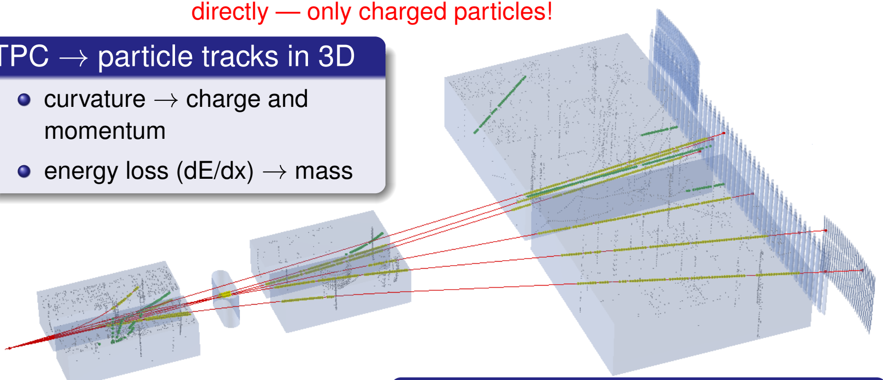
- To constrain hadron production models
  - $\rightarrow$ $\phi$ interesting due to its hidden strangeness ($s\bar{s}$)
- Reference data for Pb+Pb at the same energies

# NA61/SHINE detector

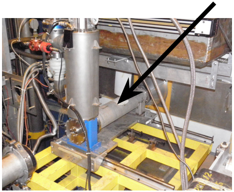
directly — only charged particles!

**TPC → particle tracks in 3D**

- curvature → charge and momentum
- energy loss (dE/dx) → mass



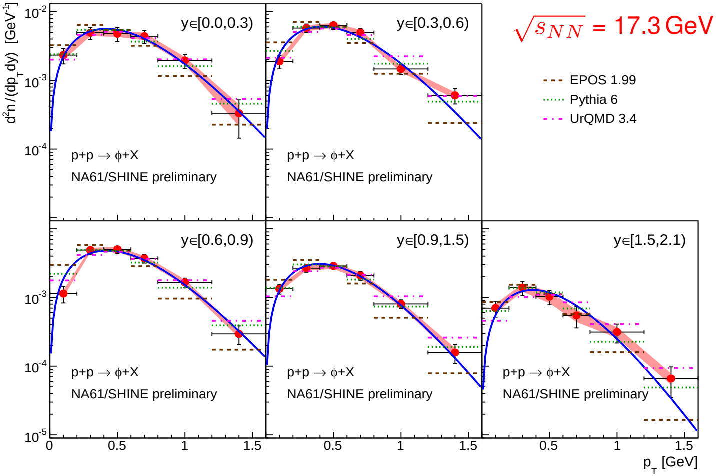
liquid $H_2$ target



**Performance**

- very good acceptance in the forward hemisphere of collision
- momentum resolution $\sigma(p)/p^2 \sim 10^{-4}\,\mathrm{GeV}^{-1}$
- track reconstruction efficiency $> 95\,\%$

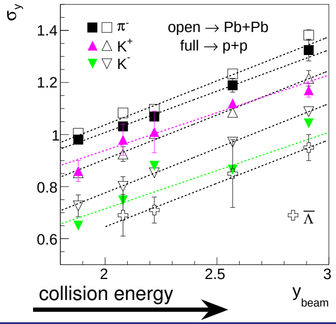
# Double differential $\phi$ meson spectra: p+p @ 158 GeV/c




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

# Reference data for Pb+Pb: $\sigma_y$ = width of $dn/dy$ distribution

NA49: PLB 491 (2000), PRC 66 (2002), PRL 93 (2004), PRC 77 (2008), PRC 78 (2008)




## 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

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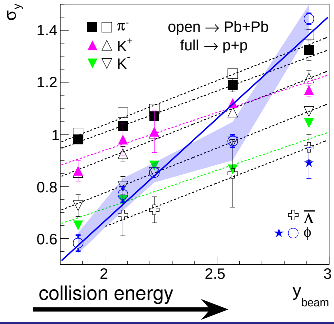


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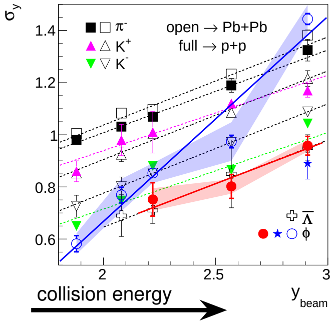


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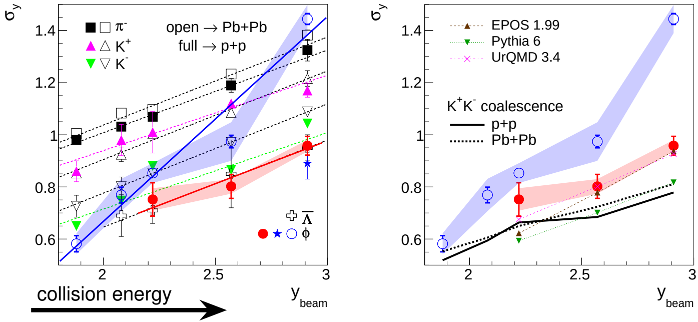


A. Marcinek, Ph.D. Thesis, UJ Kraków, 2016

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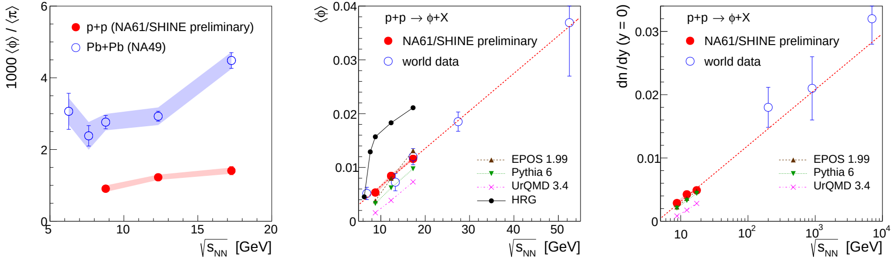
# Comparison with world data and models

NA49: PRC 66 (2002), PRC 77 (2008), PRC 78 (2008)

STAR: PRC 79 (2009), ALICE: EPJC 71 (2011), EPJC 72 (2012)




V. Blobel et al., PLB 59 (1975); ACCMOR, NPB 186 (1981)
D. Drijard et al., ZPC 9 (1981); LEBC-EHS, ZPC 50 (1991)
NA49, PLB 491 (2000); V. Vovchenko et al., PRC 93 (2016)

## p+p world data

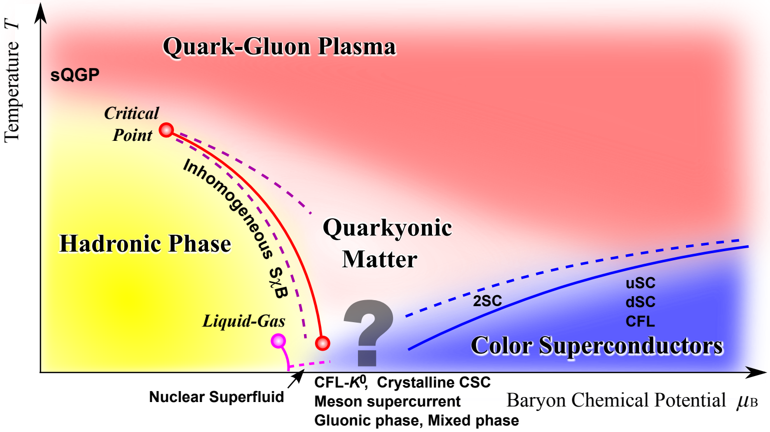
- Results consistent with world data, much more accurate

## 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

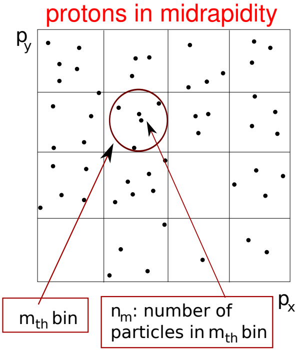
- Objective: Detection / existence of the QCD Critical Point (CP)




K. Fukushima, T. Hatsuda, Rept. Prog. Phys. 74, 014001 (2011)

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

# Intermittency analysis of factorial moments




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

where $\langle\ldots\rangle$ denotes averaging over events

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

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

- After subtracting non-critical background moments, the correlator:

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

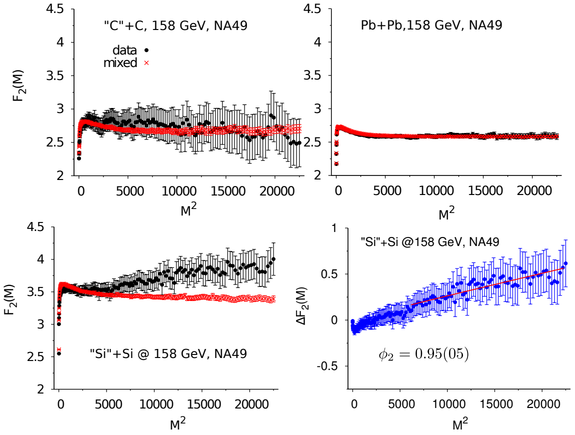
should scale according to a power-law for $M \gg 1$,

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

N. G. Antoniou et al., Phys. Rev. Lett. **97**, 032002 (2006)

# Intermittency analysis results – NA49 & NA61/SHINE

- Evidence for intermittency for protons in NA49 "Si"+Si. None detected in NA49 "C"+C and Pb+Pb datasets. T. Anticic et al., Eur. Phys. J. C 75, 587 (2015)



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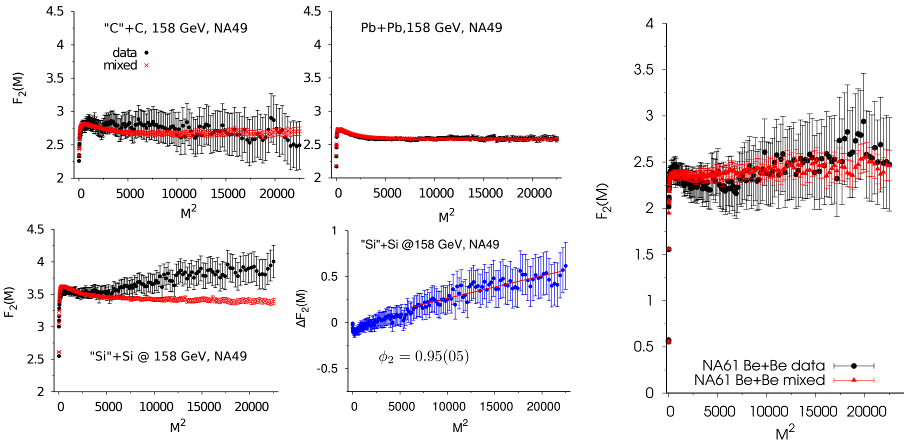
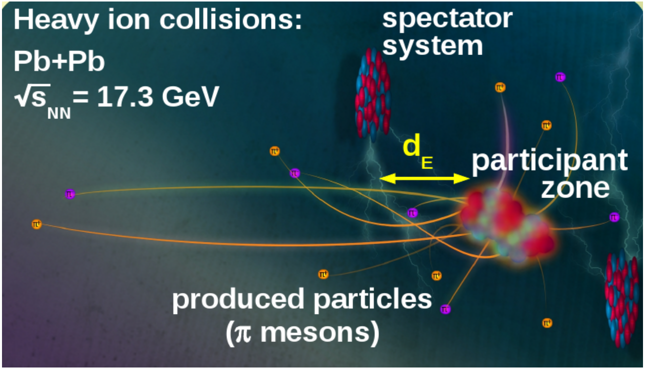



- No indication of intermittency in NA61/SHINE Be+Be @150 GeV/c
- Ar+Sc analysis ongoing

# Electromagnetic effects in pion emission — introduction



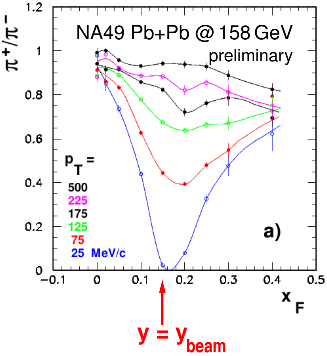

plot by I. Sputowska

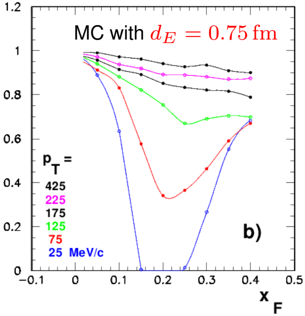
- Charged spectators in non-central collisions generate electromagnetic fields
- These modify the trajectories of final state charged particles
- By studying the resulting charge asymmetries in distributions of produced particles, we obtain information on the distance $d_E$

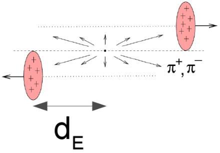
# Charge asymmetries from EM effects

A. Rybicki, Acta Phys. Polon. **B42**, 867 (2011)

A. Rybicki, A. Szczurek, Phys. Rev. C **75**, 054903 (2007)




$$x_F = \frac{2p_L \text{ (c.m.s.)}}{\sqrt{s_{NN}}}$$

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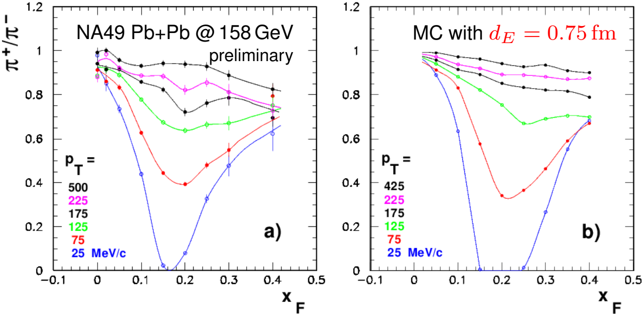


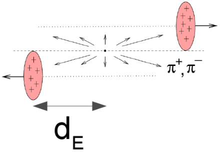


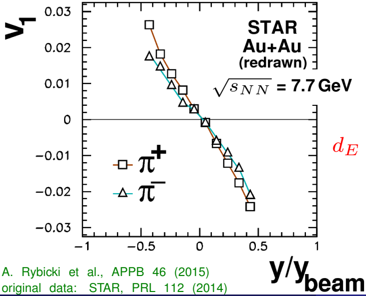


$d_E \approx 3$ fm

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

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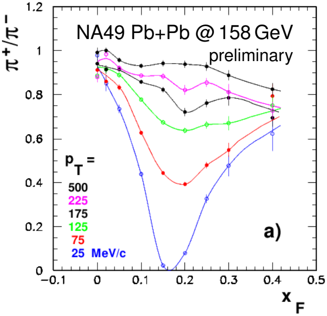


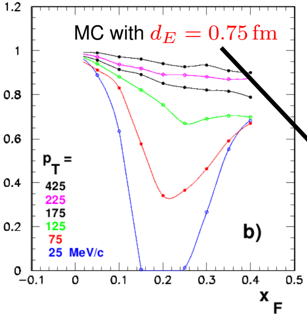


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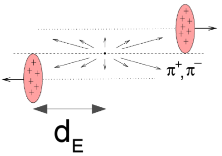
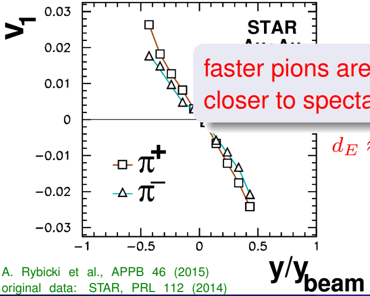
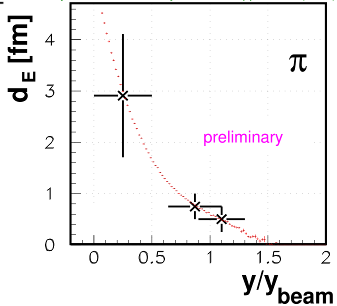



faster pions are produced
closer to spectator system

$d_E \approx 3$ fm

A. Rybicki et al., Acta Phys. Polon. Supp. 9, 303 (2016)

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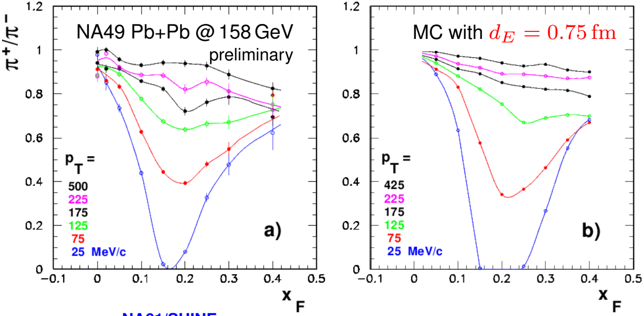


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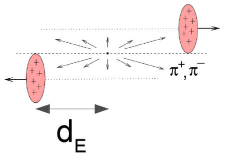
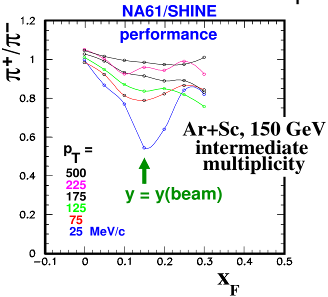
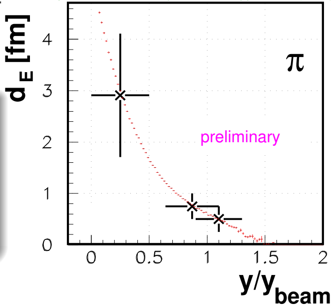



1[st] observation of spectator-induced E/M effects in Ar+Sc collisions at the SPS by NA61/SHINE

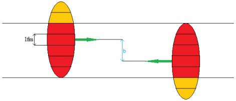
A. Rybicki et al., Acta Phys. Polon. Supp. 9, 303 (2016)



# Longitudinal evolution of the system

A. Szczurek, A. Rybicki, M. Kiełbowicz, Phys. Rev. C **95**, 024908 (2017)

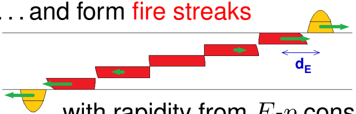
Bricks collide . . .




local energy-momentum conservation

W. D. Myers, Nucl. Phys. A **296**, 177 (1978)

. . . and form fire streaks




with rapidity from $E$-$p$ conservation

Each fire streak fragments independently in pions

$$\frac{\mathrm{d}n}{\mathrm{dy}} \sim A \cdot (E_{\mathsf{s}}^{*} - m_{\mathsf{s}}) \cdot \exp\left( - \frac{\left[ (\mathrm{y} - \mathrm{y}_{\mathsf{s}})^2 + \epsilon^2 \right]^{\frac{n}{2}}}{n \sigma_{\mathrm{y}}^{n}} \right)$$

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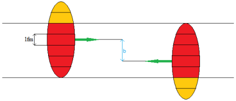


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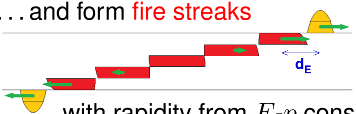


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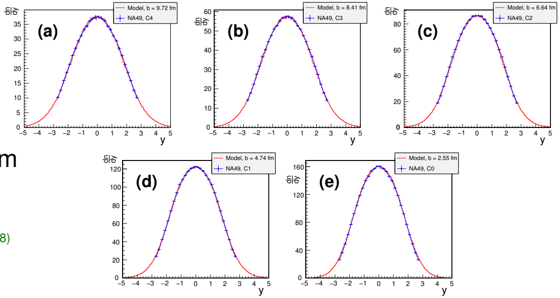
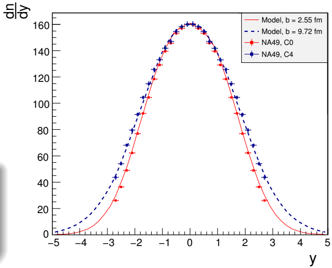



$\pi^-$ in NA49 Pb+Pb @ 158 GeV



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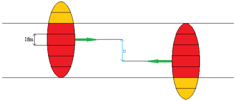
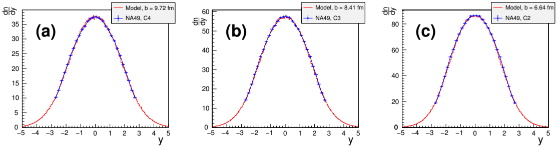
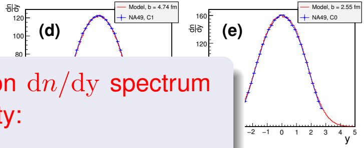



local energy-momentum conservation



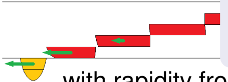

W. D. Myers, N

. . . and form fire strea

yield and shape of pion $\mathrm{d}n/\mathrm{d}y$ spectrum as function of centrality:

only from local $E$-$p$ conservation!

Pb+Pb @ 158 GeV



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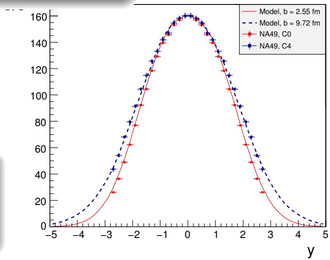


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# Summary

## $\phi$ meson production in p+p collision

- Differential ($\mathrm{y}$ and $p_T$) multiplicities at beam momenta 40 , 80 , 158 GeV/c
- Non-trivial system size dependence of width of rapidity distribution ($\sigma_\mathrm{y}$), contrasting with that of other mesons
- Failure of most microscopic and thermal models properties

## Critical Point via intermittency analysis

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

## EM effects in pion emission

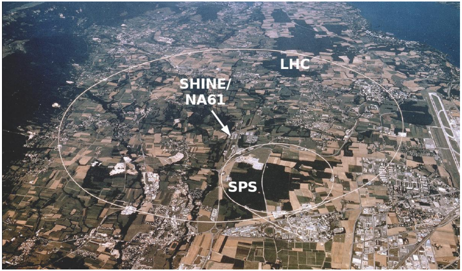
- Bring information on space-time position of pion formation zone, which is much closer to spectator for faster pions than for slower ones
- On that basis, longitudinal evolution of the system at SPS energies may be interpreted as pure consequence of energy-momentum conservation

# 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

# BACKUP

# NA61/SHINE experiment

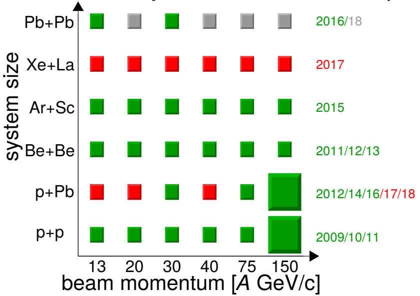



## General info

- Fixed target experiment in the North (experimental) Area of CERN SPS
- Successor of NA49
- Beams
  - hadrons (secondary)
  - ions (secondary and primary)
- $\sim$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, Miner$\nu$a, MINOS, NO$\nu$A, LBNE

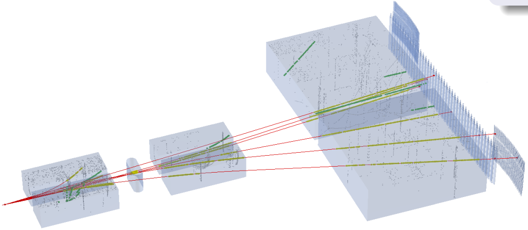
# Data selection

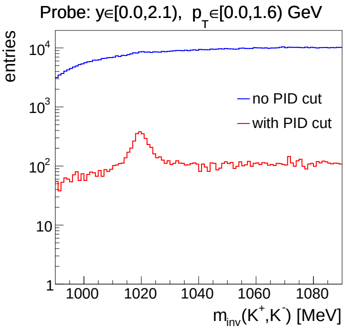
## Events

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

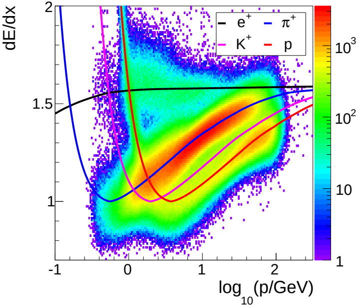
## TPC tracks

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





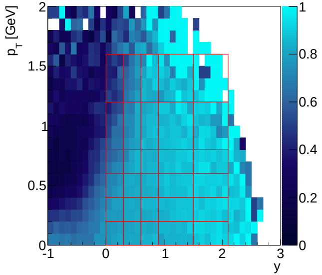
# Kaon candidate selection — PID cut

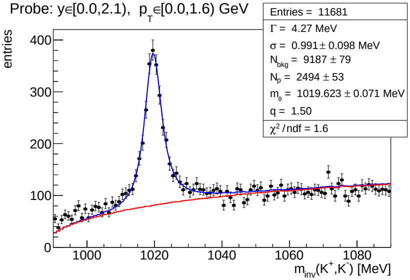



- Selection done with dE/dx
- Accept tracks in $\pm 5\,\%$ band around kaon Bethe-Bloch curve (area between black curves in right picture)
- Losses due to efficiency of this selection corrected with tag-and-probe method

# Signal extraction

## phase space binning, invariant mass spectrum



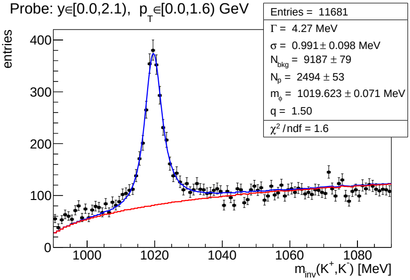
# Signal extraction

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 $f_{\text{qG}}(m_{\text{inv}}; \sigma, q)$ broadening due to detector resolution




## Background

Obtained with the event mixing method:

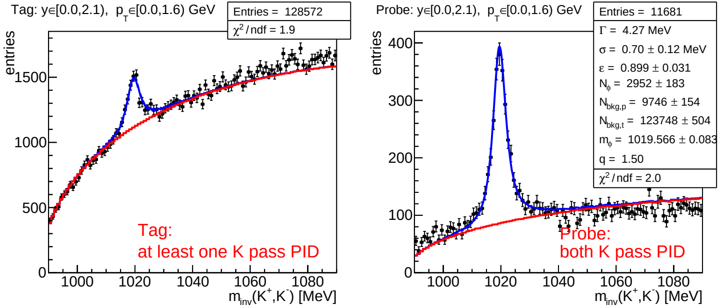
- Kaon candidate taken from the current event is combined with candidates from previous 500 events to create $\phi$ candidates in the mixed events spectrum

## Fitting function

$$f(m_{\text{inv}}) = N_{\text{p}} \cdot (f_{\text{relBW}} * f_{\text{qG}})(m_{\text{inv}}; m_\phi, \Gamma, \sigma, q) + N_{\text{bkg}} \cdot B(m_{\text{inv}})$$

# Signal extraction

tag-and-probe method → ATLAS, LHCb



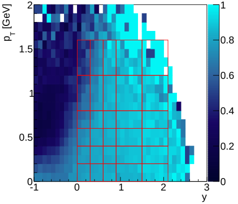

- Goal: to remove bias of $N_\phi$ due to PID cut efficiency $\varepsilon$
- Simultaneous fit of 2 spectra:
  - tag — at least one track in the pair passes PID cut

$$N_\text{t} = N_\phi \varepsilon (2 - \varepsilon)$$

  - probe — both tracks pass PID cut

$$N_\text{p} = N_\phi \varepsilon^2$$

# Normalization and corrections



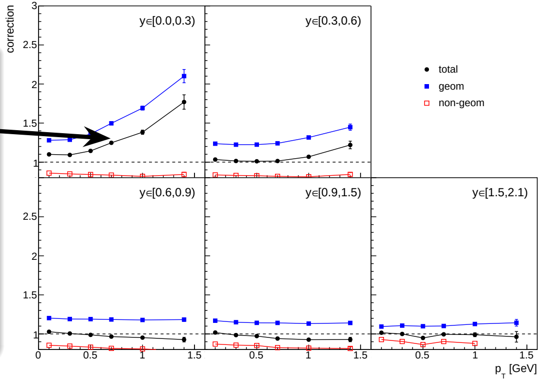

$$\frac{d^2 n}{dp_T\, dy} = \frac{N_\phi}{N_{ev}\, \Delta p_T\, \Delta y} \times \frac{c_\infty \cdot c_{bkg} \cdot c_{MC}}{\mathcal{BR}(\phi \to K^+K^-)}$$

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

## Monte Carlo correction

$$c_{MC} = \frac{N_\phi^{gen}}{N_{ev}^{gen}} \Big/ \frac{N_\phi^{sel}}{N_{ev}^{sel}}$$

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



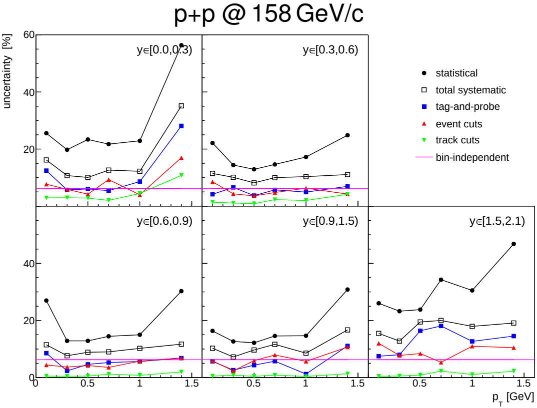
# Uncertainties

## Statistical

MINUIT/HESSE (symmetric)

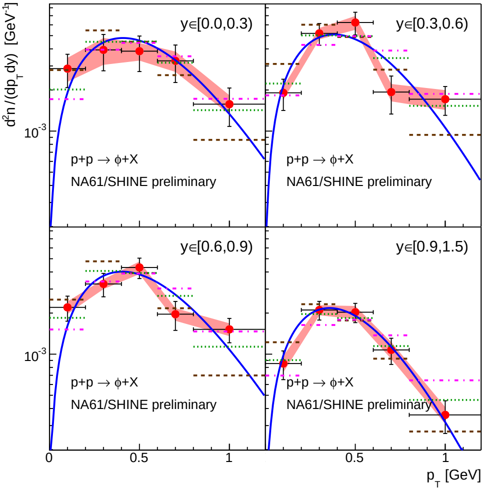
## Systematic bin-independent

| Source | value [%] |
|---|---|
| $\mathcal{BR}(\phi \to K^+K^-)$ | 1 |
| fitting constraints | 2 |
| resonance theory | 3 |
| background | 5 |
| Total (quadratic) | 6 |




- Total systematic uncertainty $= \sqrt{\sum \sigma_i^2}$
- For p+p @ 40 GeV/c additional bin-independent 3 % due to $c_{\text{MC}}$ averaging
- Statistical uncertainty dominates

# Double differential $\phi$ meson spectra: p+p @ 80 GeV/c

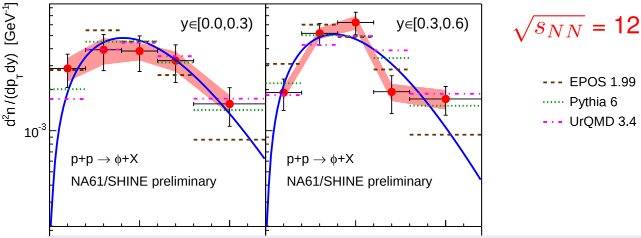



$\sqrt{s_{NN}}$ = 12.3 GeV

MC normalization:
$\int$ model $= \int$ data

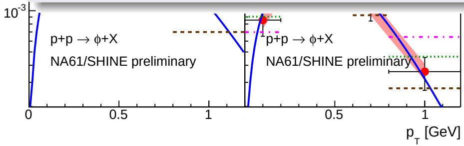
- Pythia describes spectra shapes best, UrQMD slightly too long tail, EPOS clearly too short tail
- Fit $p_T e^{-m_T/T}$ $\rightarrow$ extrapolation to $p_T = \infty \rightarrow$ tail $< 4\,\%$

# Double differential $\phi$ meson spectra: p+p @ 80 GeV/c




MC normalization:
$\int$ model $= \int$ data

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

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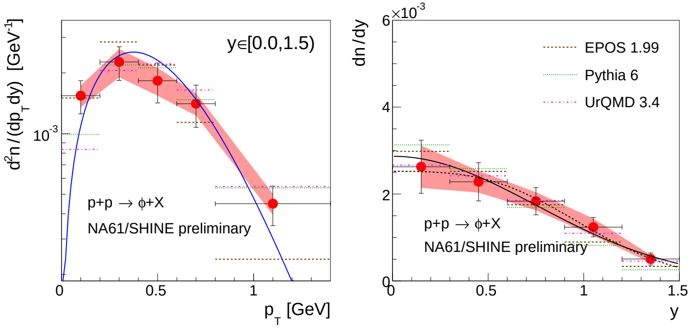
# Single differential spectra: p+p @ 40 GeV/c




$\sqrt{s_{NN}}$ = 8.8 GeV

MC normalization:
$\int$ model $= \int$ data

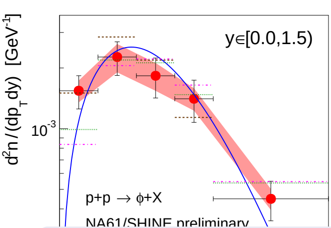
## $p_T$

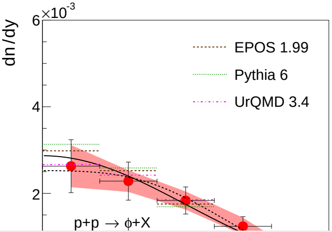
- Pythia agrees best, UrQMD similar, EPOS spectrum too short tail
- extrapolation tail $< 1\,\%$

## y

- UrQMD agrees with data, EPOS bit too narrow, Pythia even narrower
- extrapolation tail $5\,\%$

# Single differential spectra: p+p @ 40 GeV/c

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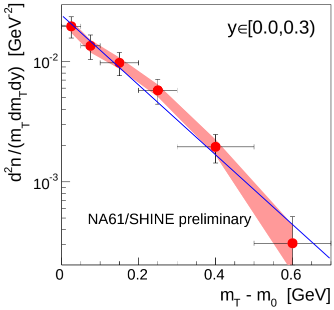
- UrQMD agrees with data, EPOS bit too narrow, Pythia even narrower
- extrapolation tail $5\,\%$

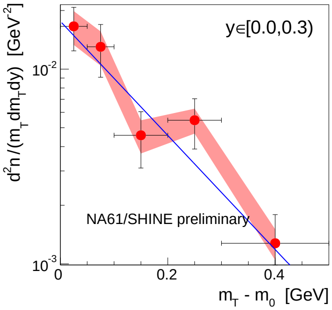
# Transverse mass spectra at midrapidity

p+p @ 158 GeV/c




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

p+p @ 80 GeV/c




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

## Thermal fit results

| $p_{\text{beam}}$ [GeV] | $T_\phi$ [MeV] | $T_{\pi^-}$ [MeV] |
|---|---|---|
| 158 | $150 \pm 14 \pm 8$ | $159.3 \pm 1.3 \pm 2.6$ |
| 80 | $148 \pm 30 \pm 17$ | $159.9 \pm 1.5 \pm 4.1$ |

# Observing power-law fluctuations

Experimental observation of local, power-law distributed fluctuations

$\Downarrow$

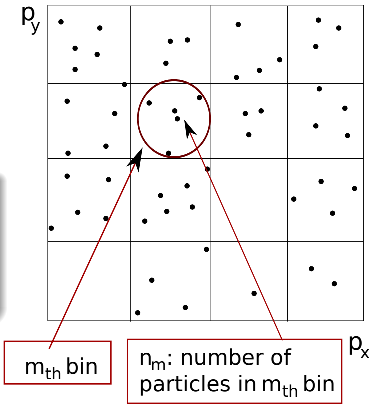
Intermittency in transverse momentum space (net protons at mid-rapidity)
(Critical opalescence in ion collisions)

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.



# Subtracting the background from factorial moments

- Experimental data is noisy $\Rightarrow$ 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

$$\langle n(n-1)\rangle = \underbrace{\langle n_c(n_c-1)\rangle}_{\text{critical}} + \underbrace{\langle n_b(n_b-1)\rangle}_{\text{background}} + \underbrace{2\,\langle n_b n_c\rangle}_{\text{mixed term}}$$

$$\underbrace{\Delta F_2(M)}_{\text{correlator}} = \underbrace{F_2^{(d)}(M)}_{\text{data}} - \lambda(M)^2\,\underbrace{F_2^{(b)}(M)}_{\text{background}} - 2\,\underbrace{\lambda(M)}_{\text{ratio } \frac{<n>_b}{<n>_d}}\,(1-\lambda(M))f_{bc}$$

- 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:

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

where $\varphi_2$ is the intermittency index.

## Theoretical predictions for $\varphi_2$

universality class, effective actions

$\varphi_{2,cr}^{(\sigma)} = \frac{2}{3}\ (0.66\ldots)$

sigmas (neutral isoscalar dipions)

N. G. Antoniou et al., Nucl. Phys. A **693**, 799 (2001)

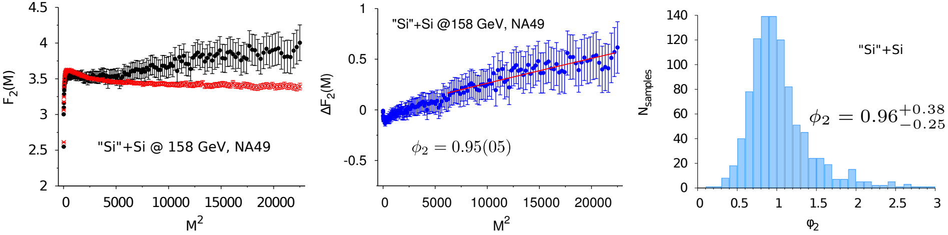
$\varphi_{2,cr}^{(p)} = \frac{5}{6}\ (0.833\ldots)$

net baryons (protons)

N. G. Antoniou et al., Phys. Rev. Lett. **97**, 032002 (2006)

# 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 $\Delta F_2^{(e)}(M\ ;\ \mathcal{C},\phi_2) = e^{\mathcal{C}} \cdot \left(M^2\right)^{\phi_2}$, 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)

# Finite-size scaling effect on intermittency

**Finite-size scaling**

$$\langle N_B \rangle \sim V^q \quad ; \quad q = \frac{d_F}{d},$$

$N_B$: baryon number

**Departing from the CEP:**

$\langle N_B \rangle \sim V^{\tilde{q}}$ with $\frac{3}{4} < \tilde{q} < 1$

$\Rightarrow$

Order parameter
self-similar fluctuations
even at large distances

$\Downarrow$

power-law correlations at small
(transverse) momentum differences

$\Downarrow$

Intermittency in (transverse)
momentum space

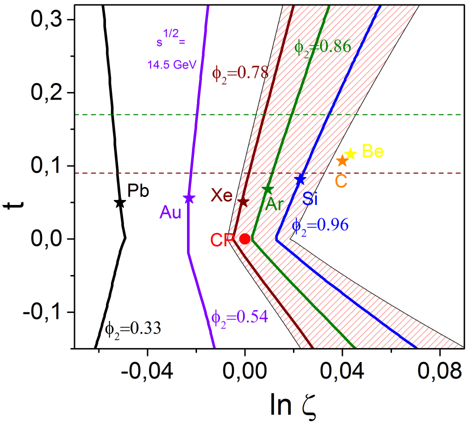
Intermittency index $\phi_2$ = $\tilde{q}$ (FSS exponent) $\Rightarrow$ $\tilde{q}$ is **measurable**

# FSS $\phi_2$ predictions

Accurate $(\mu, T, \phi_2)$ measurements $\Rightarrow$ **powerful tool**
from $(\mu, T, \phi_2)$ for Si + "Si" (neglecting errors)

$\Downarrow$ **Predictions:**

$(\mu, T, \phi_2)$ for Ar + Sc and Xe + La (freeze-out **very close** to CEP)




**critical region**

$\Downarrow$

**very narrow in**
$\ln\zeta$ $(\mu)$-direction

$\Delta\mu \approx \mathbf{5}$ MeV

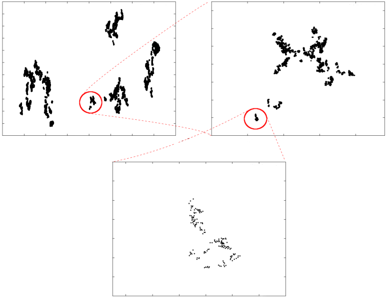
# Simulating a system of critical baryons

- Simplified version of CMC code:

  Antoniou et al., Phys. Rev. Lett. 97, 032002 (2006)

  - 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.

Lévy walk example

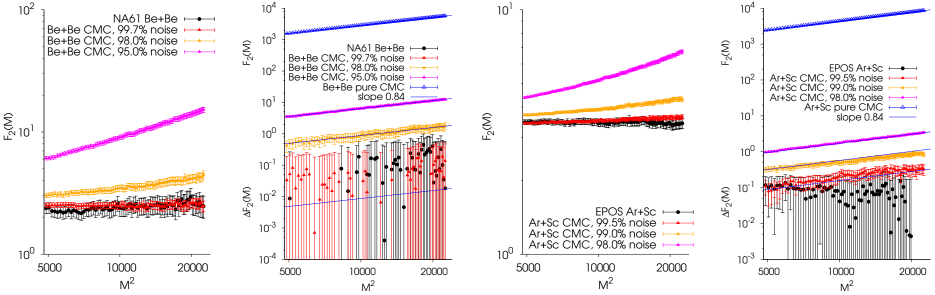


## Input parameters

| **Parameter** | $p_{\text{min}}$ [MeV] | $p_{\text{max}}$ [MeV] | $\lambda_{\text{Poisson}}$ | $T_c$ [MeV] |
|---|---|---|---|---|
| **Value** | 0.1 $\rightarrow$ 1 | 800 $\rightarrow$ 1200 | $\langle p \rangle$ | 163 |

# 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.

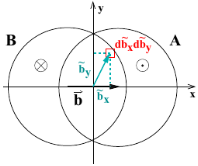



- A critical component as low as $0.5\%$ can be detectable through intermittency, provided a relatively high statistics and proton multiplicity at midrapidity!

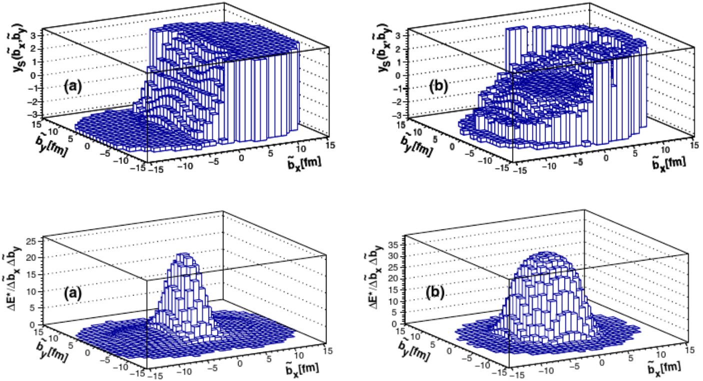
# Fire streaks' parameters

A. Szczurek, A. Rybicki, M. Kiełbowicz, Phys. Rev. C **95**, 024908 (2017)

Pb+Pb @ 158 GeV $\rightarrow \sqrt{s_{NN}}$ = 17.3 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