Rapidity distributions of pions in p+p and Pb+Pb collisions at CERN SPS energies

Antoni Marcinek
Andrzej Rybicki, A. Szczurek, M. Kiełbowicz, V. Ozvenchuk, Ł. Rozpłochowski, I. Sputowska, N. Davis

Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland

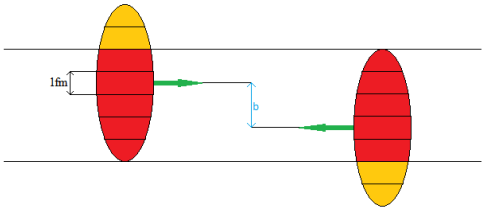
The European Physical Society Conference on High Energy Physics,
11 July 2019, Ghent, Belgium

Largely based on A. Rybicki et al., Phys. Rev. C **99**, 024908 (2019)

Introduction — fire streaks in Pb+Pb

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

Bricks collide . . .



R. Hagedorn, CERN-71-12 (1971)
W. D. Myers, Nucl. Phys. A **296**, 177 (1978)

(Re)invented by A. Szczurek

. . . and form fire streaks

with E^*_{s} and $\mathrm{y_s}$ from local E-p conservation

Each fire streak fragments independently into pions

$$\frac{\mathrm{d}n}{\mathrm{d}\mathrm{y}} = \sum_{\mathrm{s}} A(E^*_{\mathrm{s}} - m_{\mathrm{s}}) \exp\left(- \frac{\left[(\mathrm{y} - \mathrm{y_s})^2 + \epsilon^2 \right]^{\frac{r}{2}}}{r \sigma^r_{\mathrm{y}}} \right)$$

Motivated by observations from spectator-induced EM effects
$\rightarrow$ see talk by I. Sputowska

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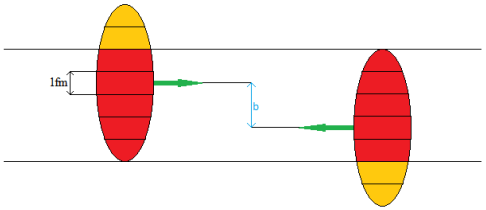

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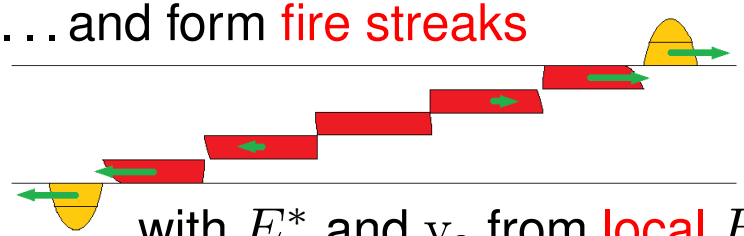

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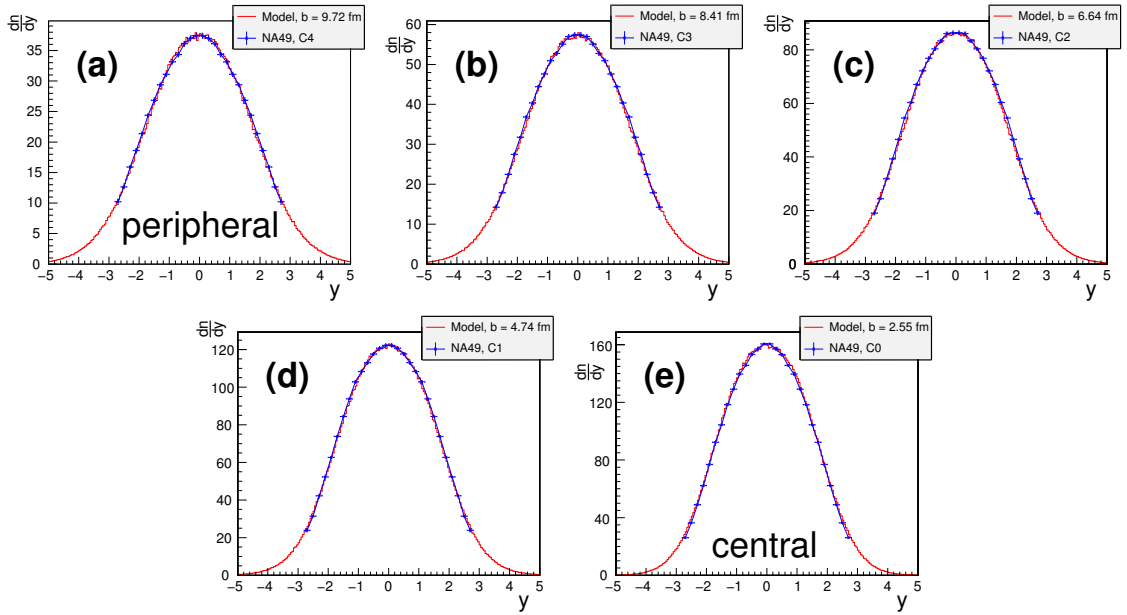
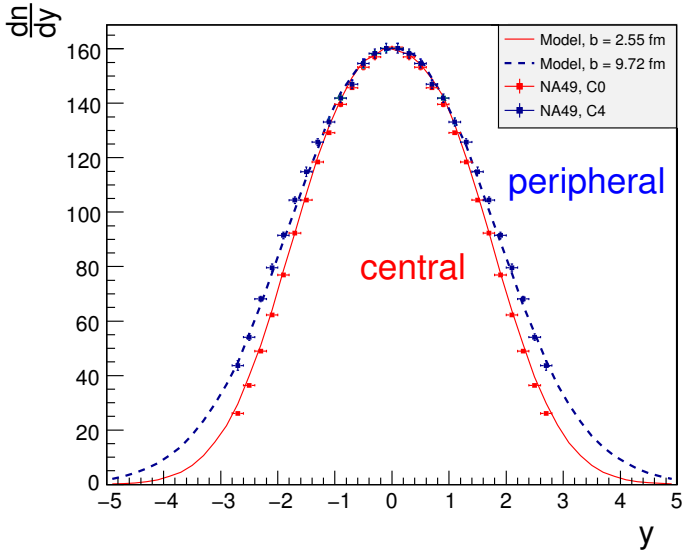


π^- in NA49 Pb+Pb @158A GeV



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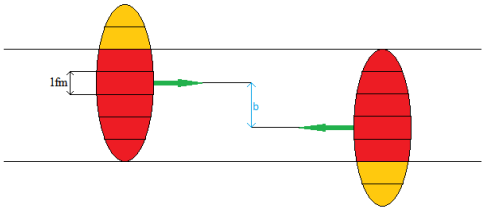

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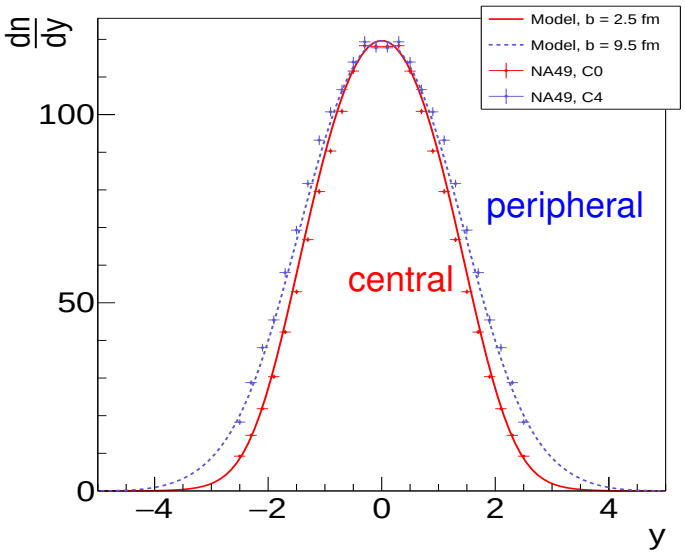

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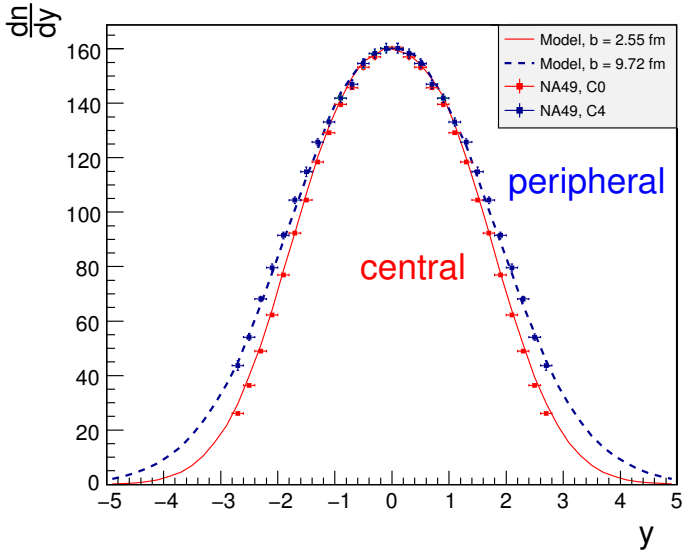

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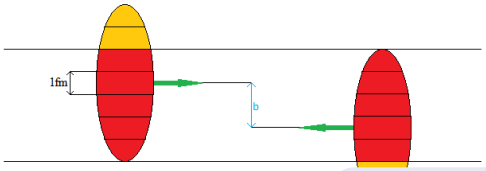

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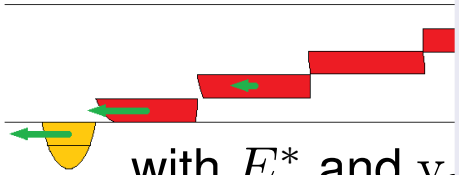

with E_s^* and y_s

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Our simple model explains
the whole centrality dependence
of the pion $\mathrm{d}n/\mathrm{d}y$ spectrum

↓

only from local E-p conservation and
collision geometry!

Valid in some extended energy range,
$\sqrt{s_{NN}} = 9$–17 GeV at least

A. Rybicki et al., Phys. Rev. C **99**, 024908 (2019)

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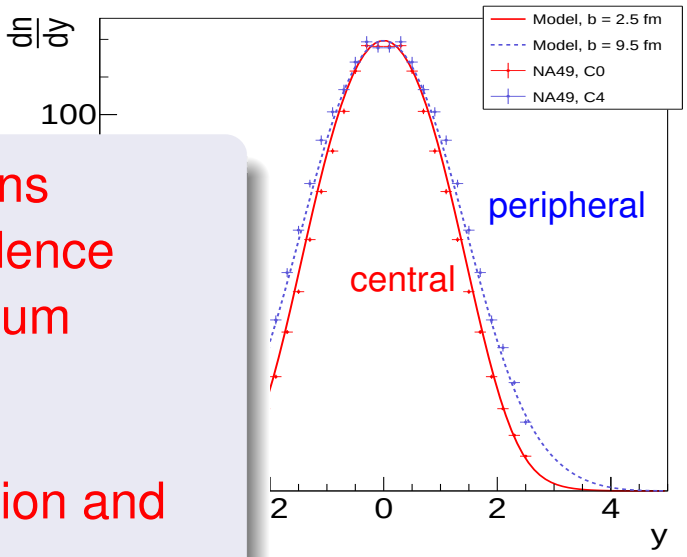

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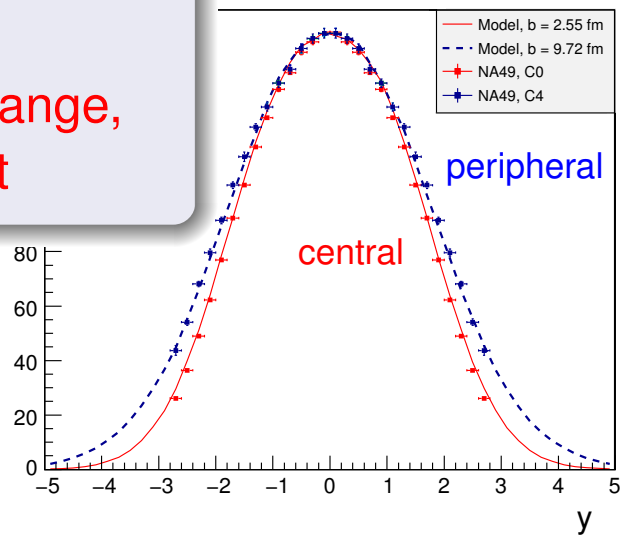
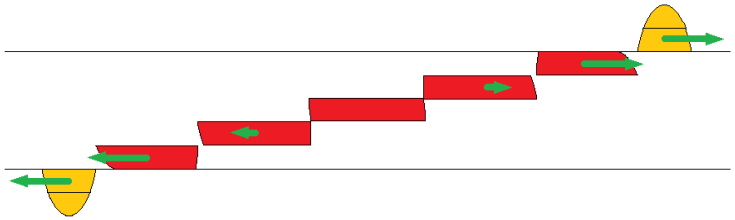


Pion production from one fire streak

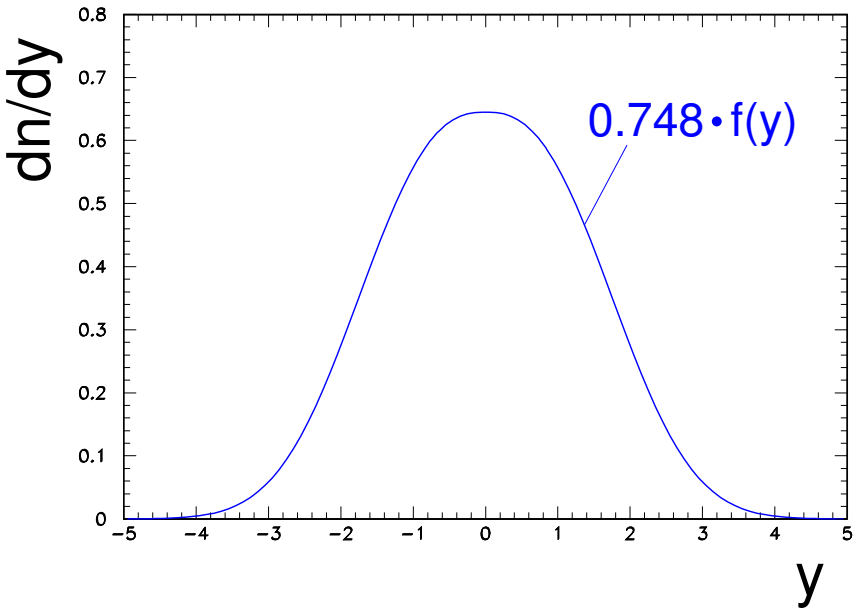
Let's take:

- single fire streak with $E^* = \sqrt{s_{NN}}$, $m_\mathrm{s} = 2m_\mathrm{N}$, $\mathrm{y_s} = 0$
- fire streak fragmentation function fitted to Pb+Pb at $\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$



$$f(\mathrm{y}) = A(E^*_\mathrm{s} - m_\mathrm{s}) \exp\left(-\frac{\left[(\mathrm{y}-\mathrm{y_s})^2 + \epsilon^2\right]^{\frac{r}{2}}}{r\sigma^r_\mathrm{y}} \right)$$

We get pion production from this one fire streak:



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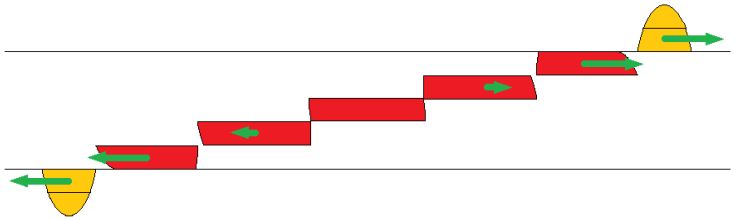

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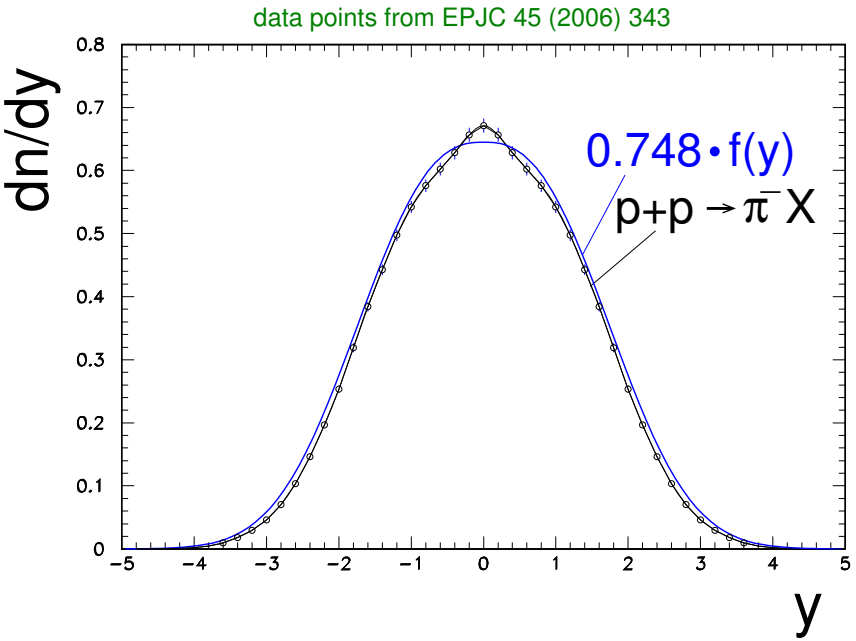

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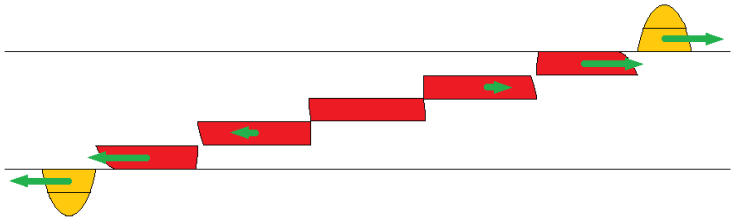

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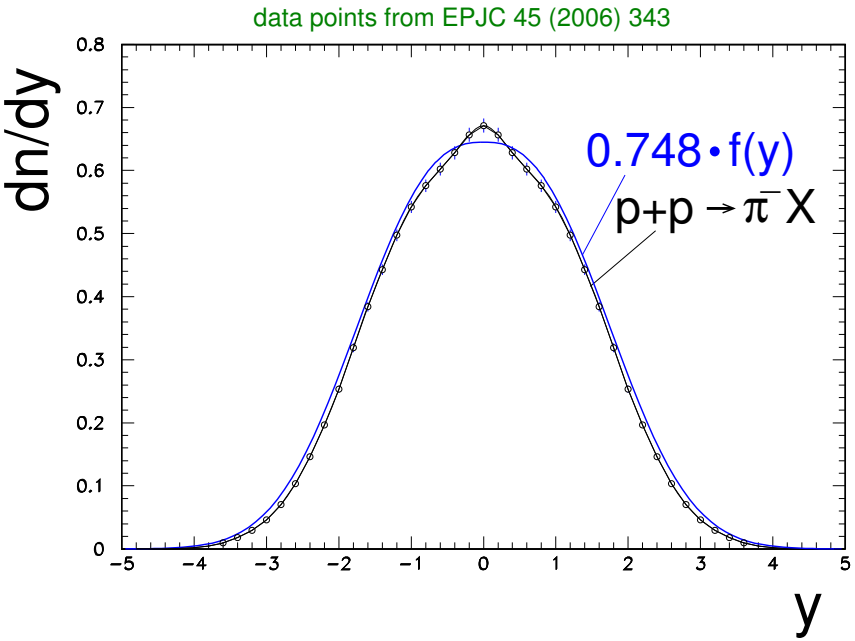

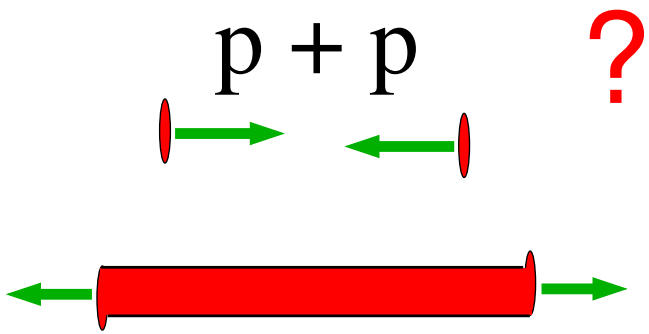

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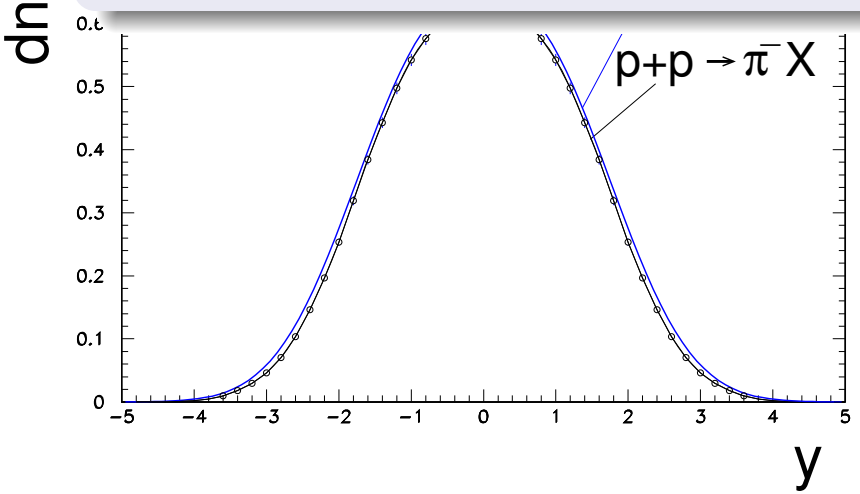
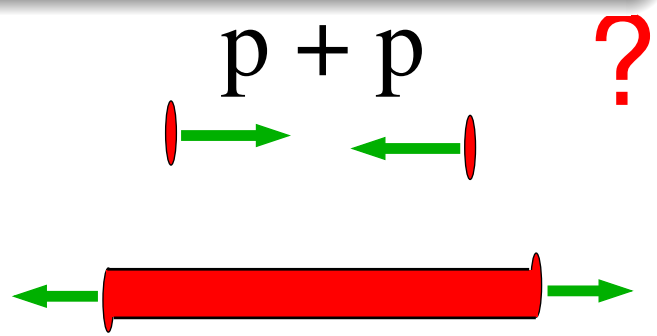
We

- The pion rapidity distribution from one fire streak in Pb+Pb collisions $\sim$ the experimental pion rapidity spectrum in p+p collisions
- Significant difference in absolute normalization: 0.748
- This can be understood by a different energy repartition in p+p and Pb+Pb reactions.



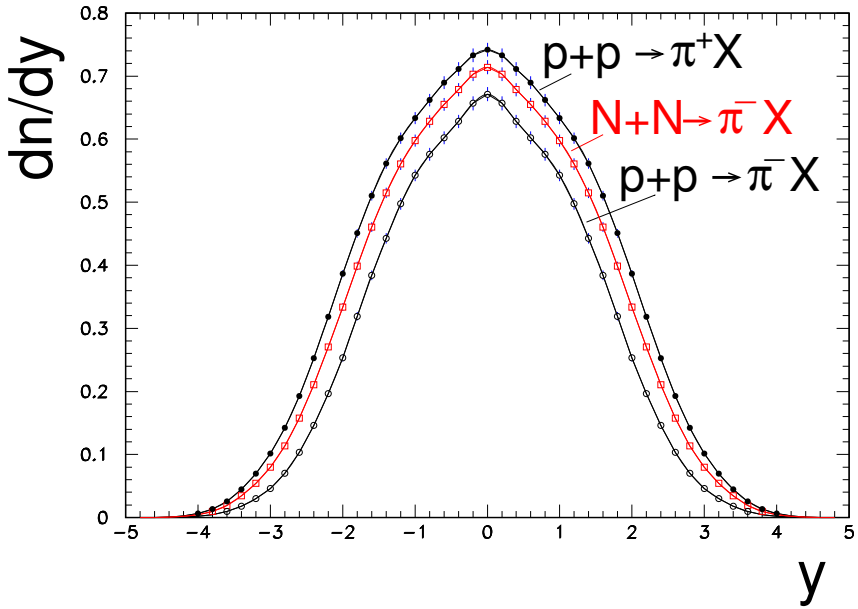


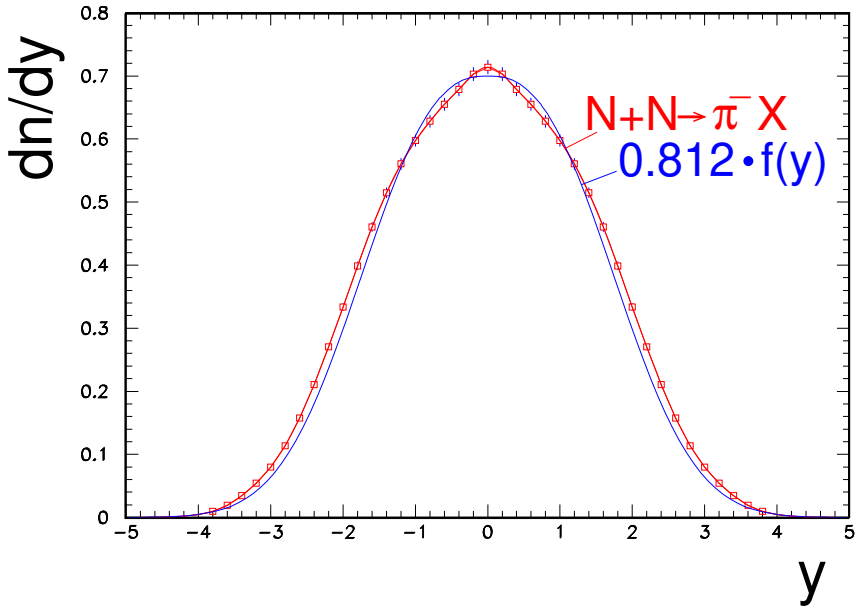
Isospin

- Pb+Pb collision: 40 % protons, 60 % neutrons
- p+p $\to \pi^- X$ is not directly comparable to Pb+Pb $\to \pi^- X$
- isospin symmetry: $\frac{\mathrm{d}n}{\mathrm{dy}}(n \to \pi^-) = \frac{\mathrm{d}n}{\mathrm{dy}}(p \to \pi^+)$
- isospin-averaged π^- distribution:

$$\frac{\mathrm{d}n}{\mathrm{dy}}(N+N \to \pi^- X) = \frac{Z}{A} \cdot \frac{\mathrm{d}n}{\mathrm{dy}}(p+p \to \pi^- X) + \left(1 - \frac{Z}{A}\right) \cdot \frac{\mathrm{d}n}{\mathrm{dy}}(p+p \to \pi^+ X)$$

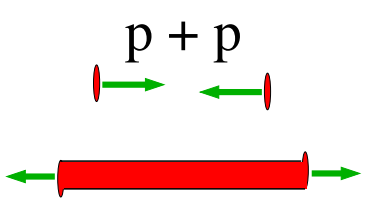
data points from EPJC 45 (2006) 343

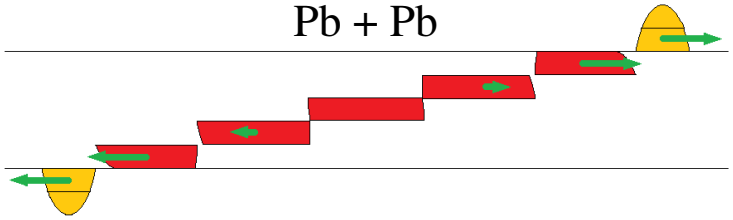




Once isospin is taken into account, the difference in absolute normalization between p+p and Pb+Pb collisions changes from 0.748 to 0.812.

Energy balance in p+p and Pb+Pb collisions





(Fire streak energy) $\approx$ (baryon energy) + (pion energy) + (kaon energy)

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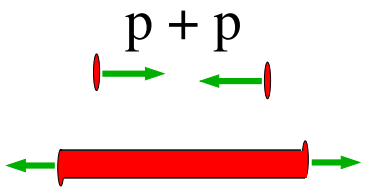
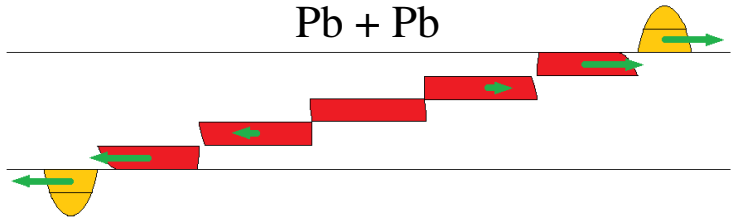
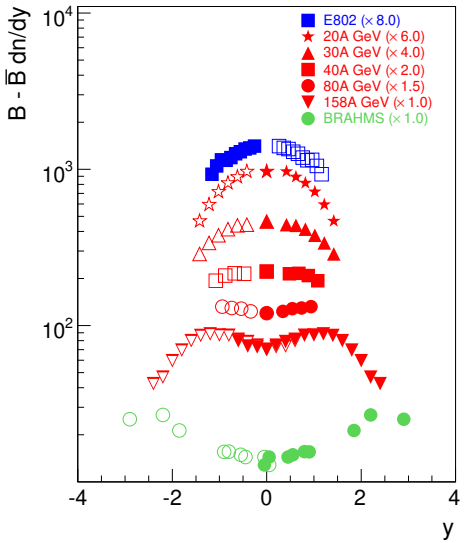




(Fire streak energy) ≈ (baryon energy) + (pion energy) + (kaon energy)

baryon stopping
(inelasticity)

C. Blume, NA49,
J.Phys. G34 (2007) 951,
and references therein



K. Grebieszkow, NA61/SHINE,
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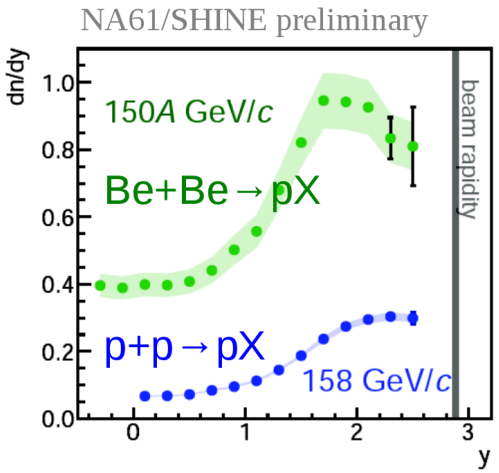

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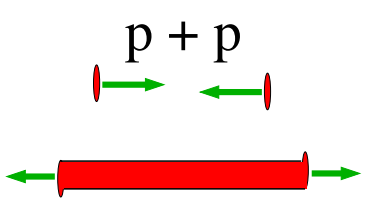

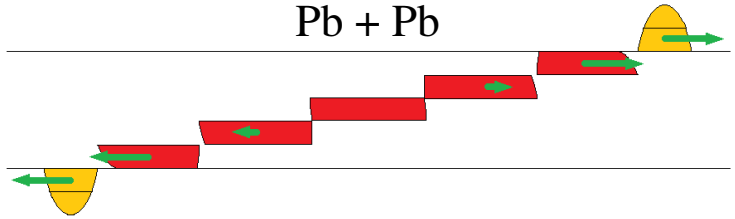

(Fire streak energy) ≈ (baryon energy) + (pion energy) + (kaon energy)

baryon stopping
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strangeness
enhancement

C. Blume, NA49,
J.Phys. G34 (2007) 951,
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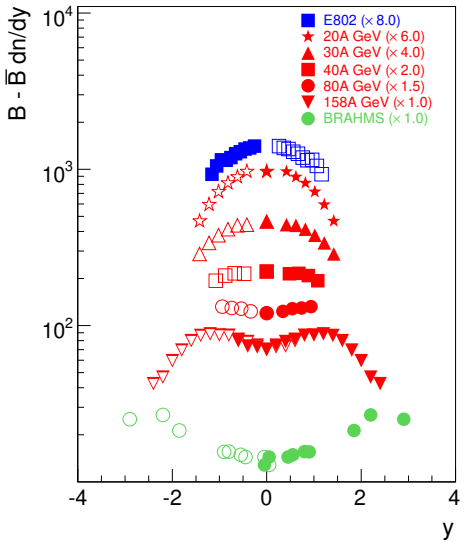

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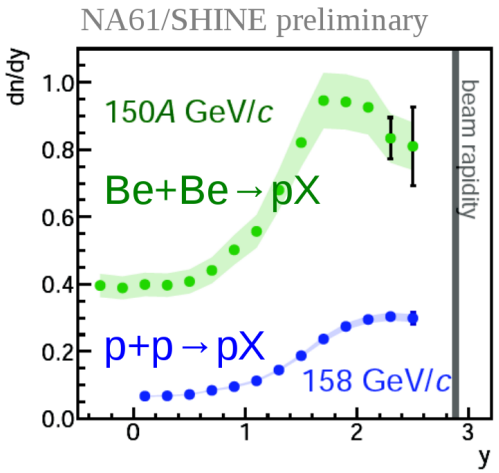

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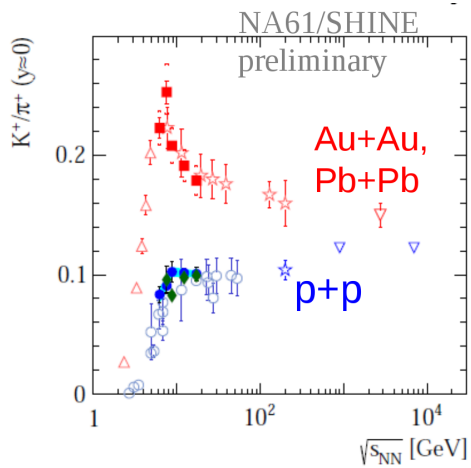
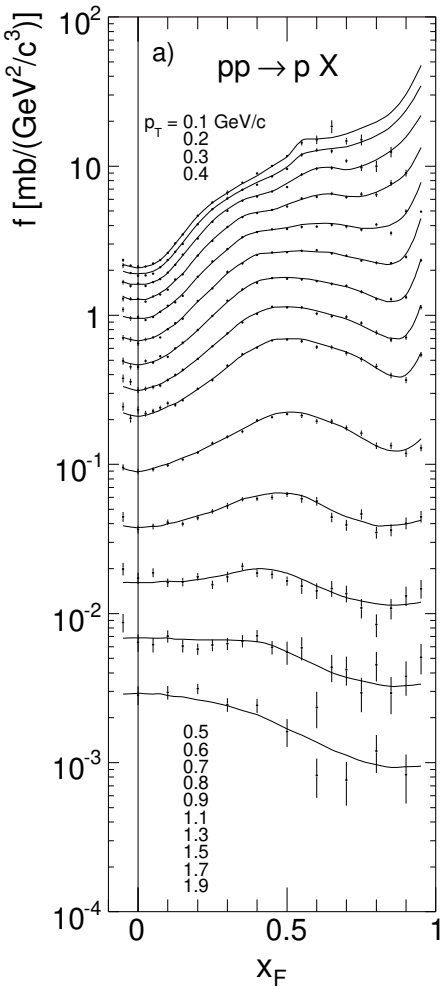
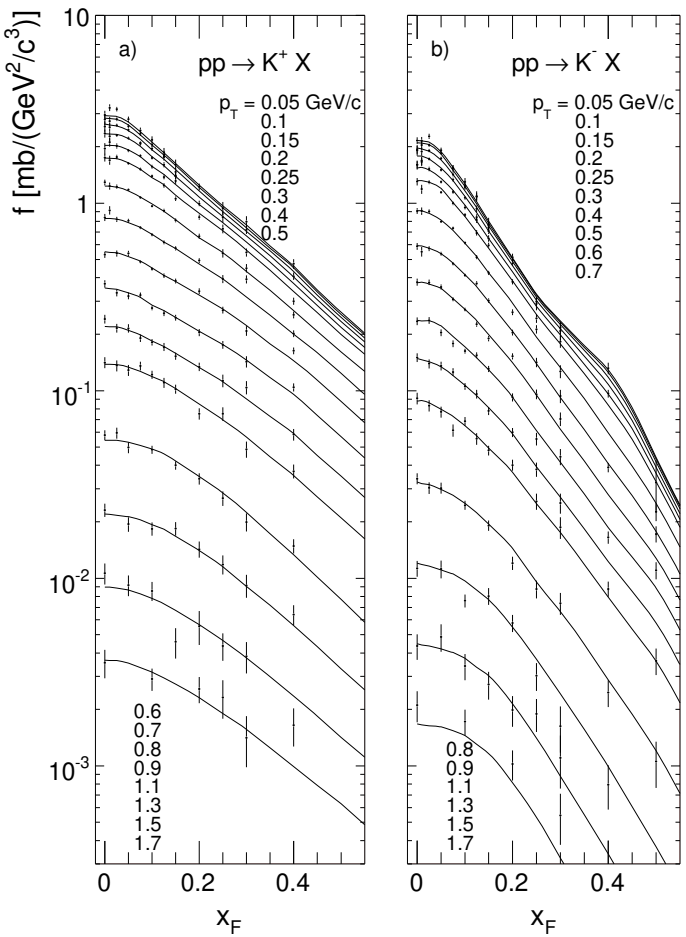


Interpolated data on p+p collisions

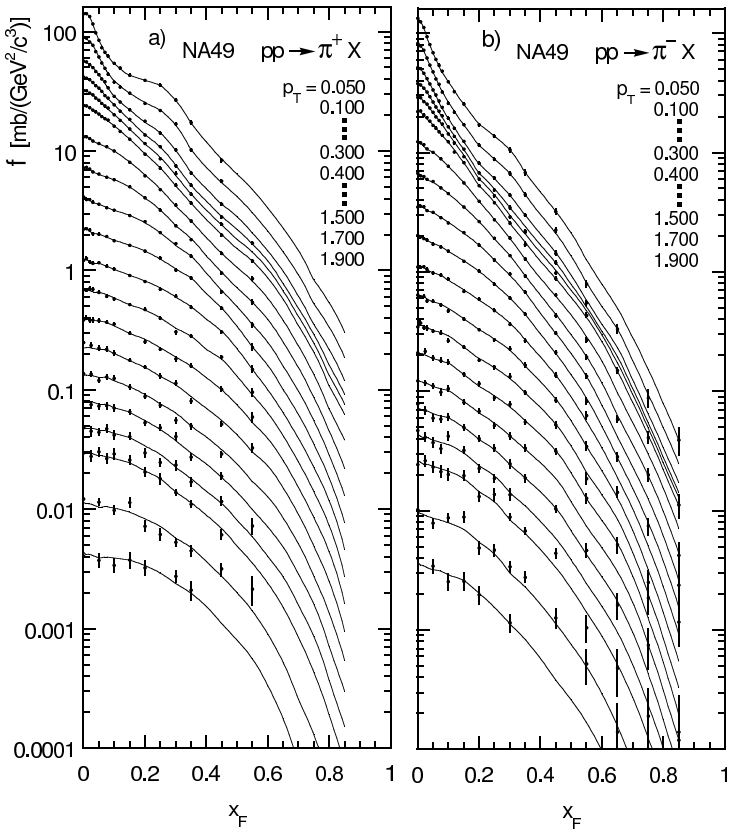
EPJC 65 (2010) 9, arXiv:0904.2708



EPJC 68 (2010) 1, arXiv:1004.1889



EPJC 45 (2006) 343, arXiv:hep-ex/0510009



$$x_F = \frac{p_L}{p_{\text{beam}}}\text{(c.m.s.)}$$

Mean energy spent on particle i — p, $\bar{p}$, $\pi^{\pm}$, $K^{\pm}$:

$$\langle E_i \rangle = \frac{\int_0^1 \int_0^{p_T(\max)} E_i(x_F, p_T) \left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_F \mathrm{d}p_T}\right)_i \mathrm{d}p_T \mathrm{d}x_F}{\int_0^1 \int_0^{p_T(\max)} \left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_F \mathrm{d}p_T}\right)_i \mathrm{d}p_T \mathrm{d}x_F}$$

← model independent calculation

Calculation of energy balance (simplified)

p+p:

- (pion energy) = $\langle \pi \rangle \cdot \langle E_\pi \rangle$ = 6862 MeV
- (kaon energy) = $\langle K \rangle \cdot \langle E_K \rangle$ = 918 MeV
- (baryon energy) $\rightarrow$ baryon inelasticity K = 0.547:

$$K = \frac{2E_{\text{inel}}}{\sqrt{s} - 2m_p}, \qquad E_{\text{inel}} = \frac{\sqrt{s}}{2} - \langle E_{\text{net proton}} \rangle$$

Pb+Pb: the relation between (baryon energy), (pion energy) and (kaon energy) is evaluated on the basis of:

- baryon inelasticity in Pb+Pb, K $\approx$ 0.78 C. Blume, NA49, J.Phys. G34 (2007) 951, and references therein
- the change in K/π ratios between p+p and Pb+Pb ($\sim$2)

Finally, we get (per unit of total collision energy):

$$\frac{\text{Energy spent on pions in p+p}}{\text{Energy spent on pions in Pb+Pb}} = \frac{0.547/(1+0.13378)}{0.78/(1+0.26333)} = 0.781$$

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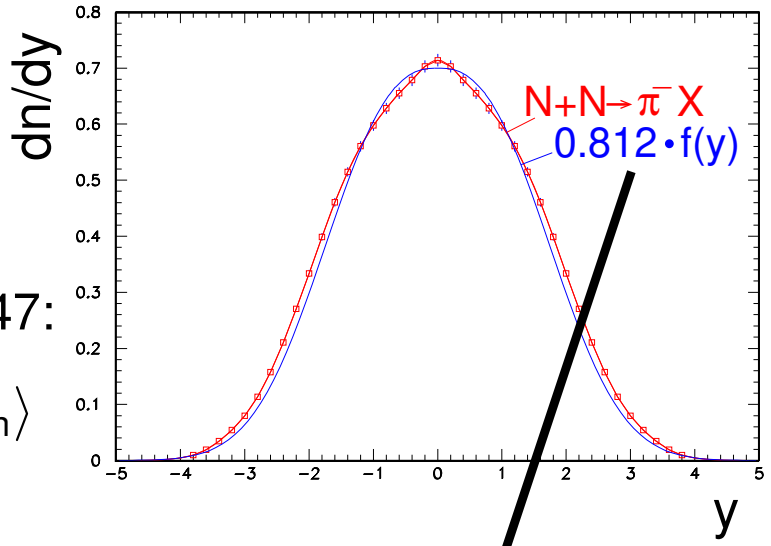
- (baryon energy) $\rightarrow$ baryon inelasticity K = 0.547:

$$K = \frac{2E_{\text{inel}}}{\sqrt{s} - 2m_p}, \qquad E_{\text{inel}} = \frac{\sqrt{s}}{2} - \langle E_{\text{net proton}} \rangle$$



Pb+Pb: the relation between (baryon energy), (pion energy) and (kaon energy) is evaluated on the basis of:

- baryon inelasticity in Pb+Pb, K $\approx$ 0.78 C. Blume, NA49, J.Phys. G34 (2007) 951, and references therein
- the change in K/π ratios between p+p and Pb+Pb ($\sim$2)

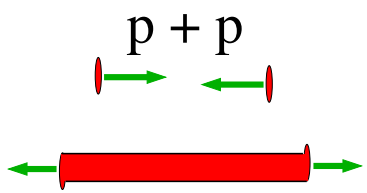
agreement within 4 %

Finally, we get (per unit of total collision energy):

$$\frac{\text{Energy spent on pions in p+p}}{\text{Energy spent on pions in Pb+Pb}} = \frac{0.547/(1+0.13378)}{0.78/(1+0.26333)} = 0.781$$

Relation between $\mathrm{d}n/\mathrm{dy}$ spectra in p+p and Pb+Pb

- The pion rapidity distribution from one fire streak in Pb+Pb collisions reproduces the pion rapidity spectrum in p+p collisions...
- ...with a difference in absolute normalization which is a direct reflection of the different energy repartition in the two reactions.
- Thus, a correspondence exists between $\mathrm{d}n/\mathrm{dy}$ spectra in p+p and Pb+Pb collisions:



pion $\mathrm{d}n/\mathrm{dy}$ distribution in p+p collisions

$\Downarrow$

correction for isospin

$\Downarrow$

isospin corrected pion $\mathrm{d}n/\mathrm{dy}$ distribution in p+p

$\Downarrow$

correction for change in baryon inelasticity and strangeness enhancement

$\Downarrow$

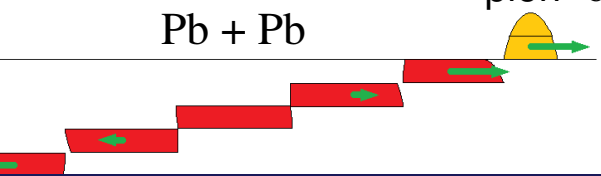
fire-streak fragmentation function in Pb+Pb

$\Downarrow$

collision geometry + local $E - \vec{p}$ conservation

$\Downarrow$

pion $\mathrm{d}n/\mathrm{dy}$ distributions in Pb+Pb as a function of centrality



This may be followed 'up' or 'down'.

THE END

Summary

- Our simple model explains the whole centrality dependence of the pion rapidity distribution in Pb+Pb collisions.
- It is valid in some extended collision energy range (at least $\sqrt{s_{NN}} = 9$–$17\,\mathrm{GeV}$).
- Now the study is extended to p+p reactions.
- The pion rapidity distribution from one fire streak in Pb+Pb collisions reproduces the pion rapidity spectrum in p+p collisions. . .
  - . . . with a difference in absolute normalization which directly results from the different energy repartition in the two reactions.
  - This can indicate that one fire streak is formed in the p+p collision.
- As a result, an interesting correspondence emerges between pion distributions in p+p and Pb+Pb reactions.

Acknowledgements

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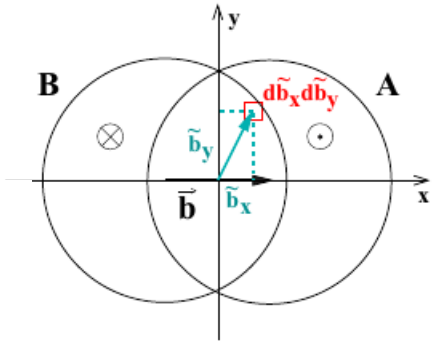
BACKUP

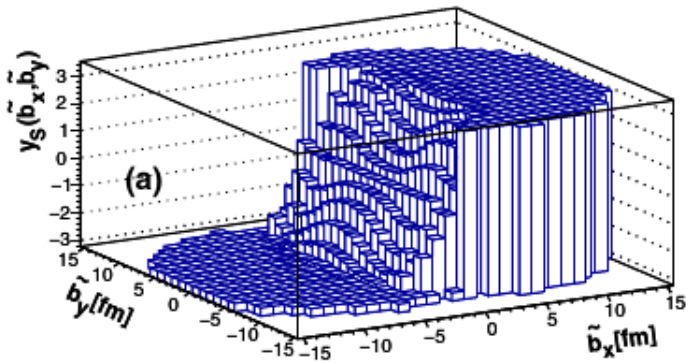
Fire streaks' parameters

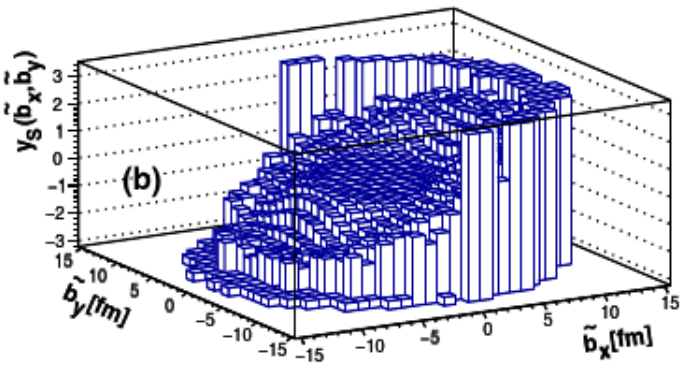
A. Szczurek, A. Rybicki, M. Kiełbowicz, Phys. Rev. C **95**, 024908 (2017)

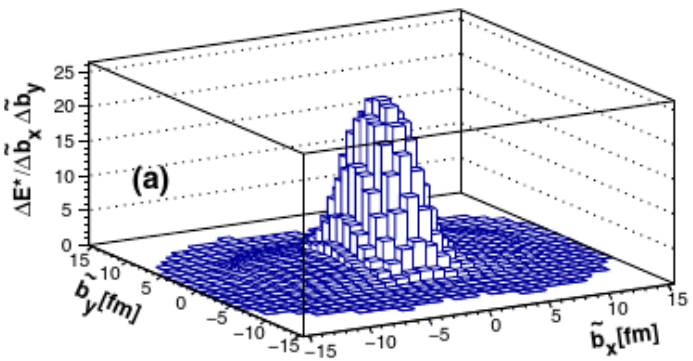
Pb+Pb @158A GeV/c $\rightarrow$ $\sqrt{s_{NN}}$ = 17.3 GeV, $y_{\text{beam}} = 2.9$

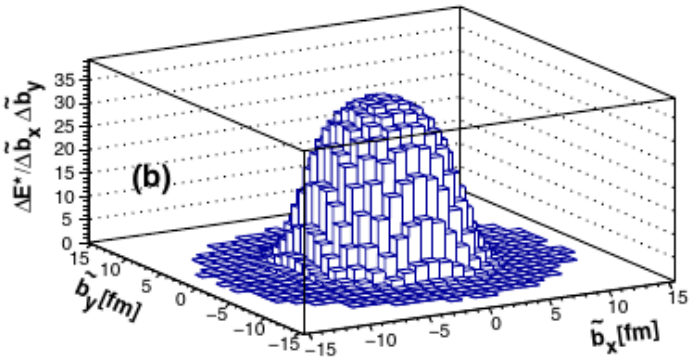
peripheral $b = 9.72\,\text{fm}$ central $b = 2.55\,\text{fm}$











- Very narrow (if any) 'stopped' region in non-central collisions
- ΔE^* 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

Energy dependence of the fragmentation function

A. Rybicki et al., Phys. Rev. C **99**, 024908 (2019)