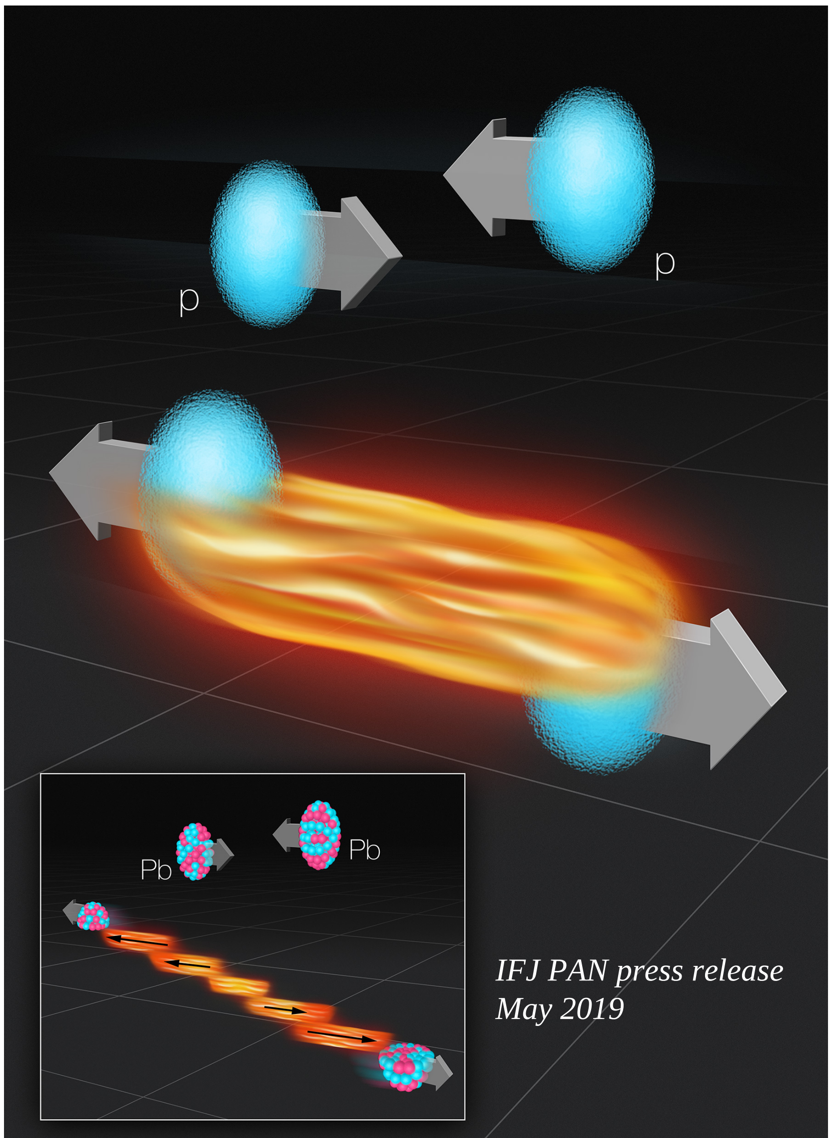
Comments on the space-time evolution of the system created in the nucleus-nucleus collision at high energy



By Dual Color™

Andrzej Rybicki

H. Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences

Work done with
A. Szczurek, V. Ozvenchuk, A. Marcinek, M. Kiełbowicz, Ł. Rozpłochowski, N. Davis, S. Bhosale, M. Kłusek-Gawenda

See also:
1) PRC 99 (2019) 024908,
2) arXiv: 1910.04544

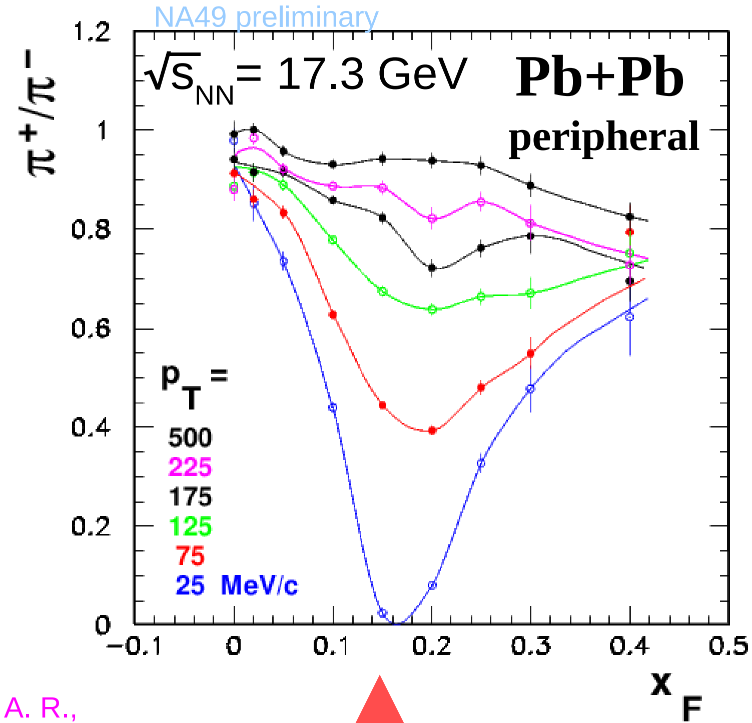
1. The idea;

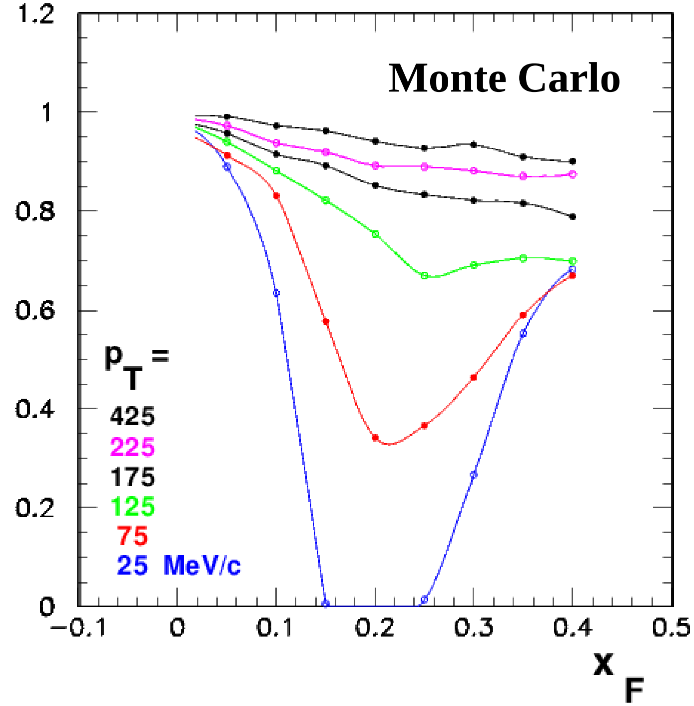
2. Getting information from EM effects ;

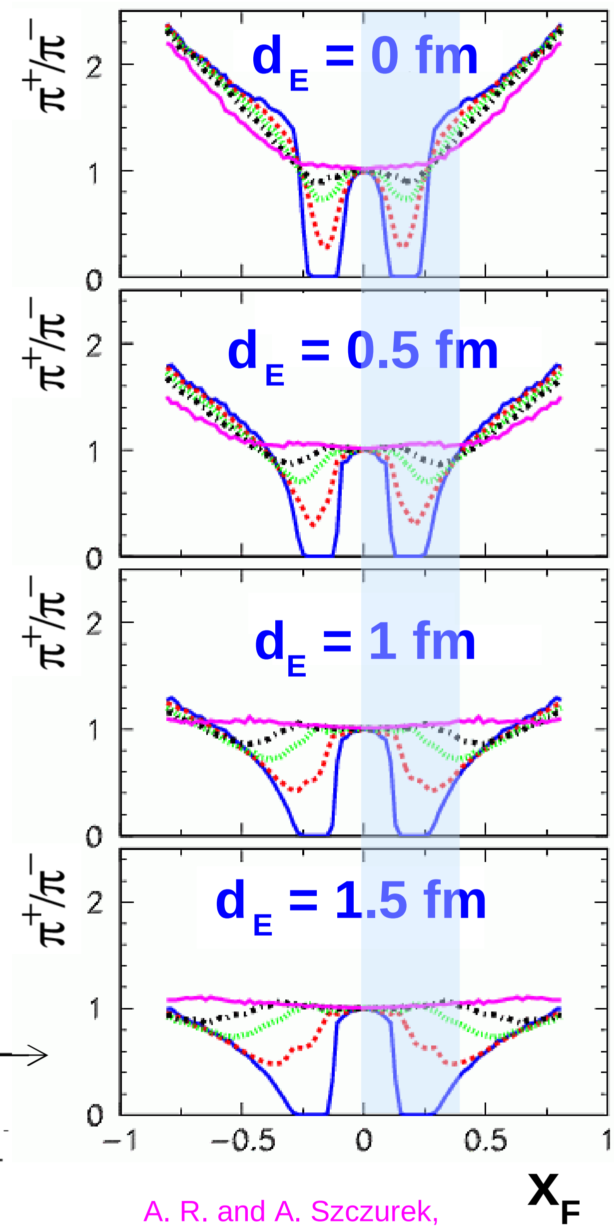
3. Space-time evolution of forward pion production ;

4. Summary.

1)
The idea







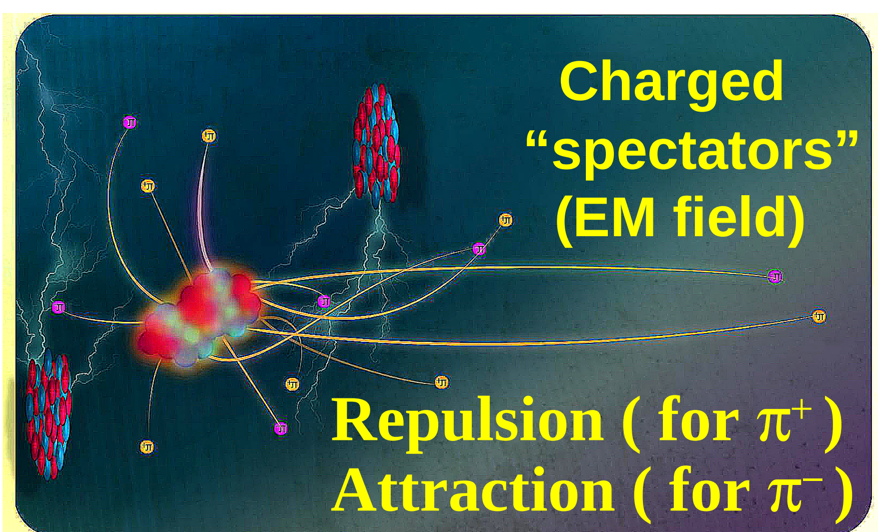
A. R., Acta Phys. Polon. B42 (2011) 867

spectator velocity
$y = y_{beam}$

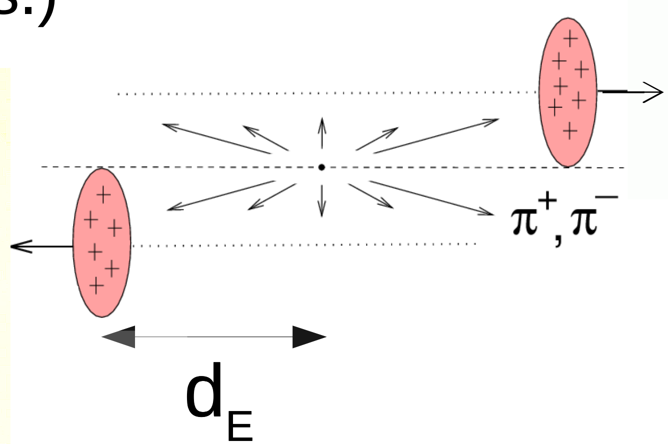
$$x_F = \frac{p_L}{p_L^{beam}}$$

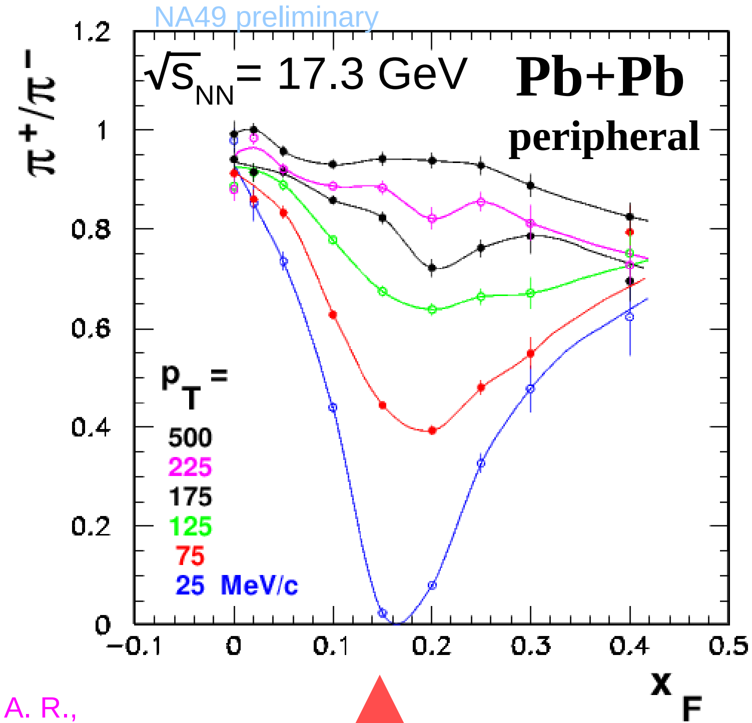
(c.m.s.)

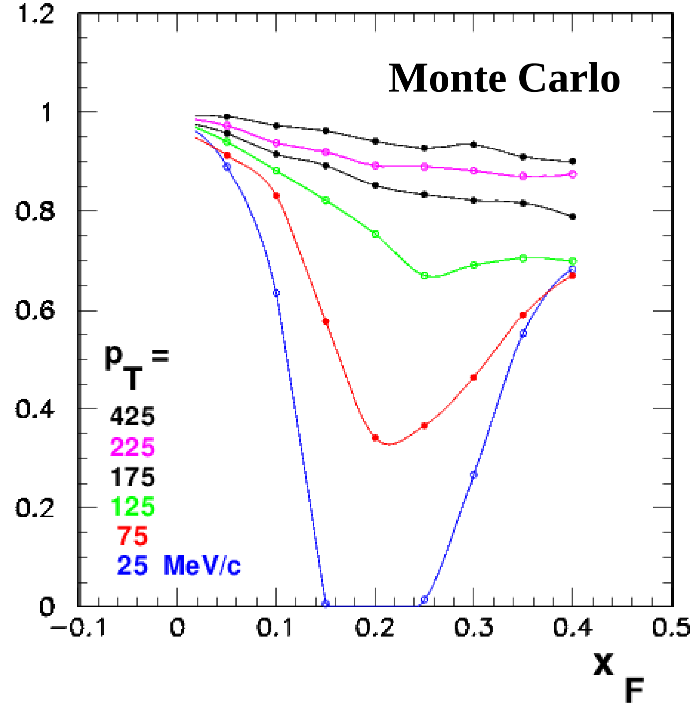
A. R. and A. Szczurek, Phys. Rev. C75 (2007) 054903

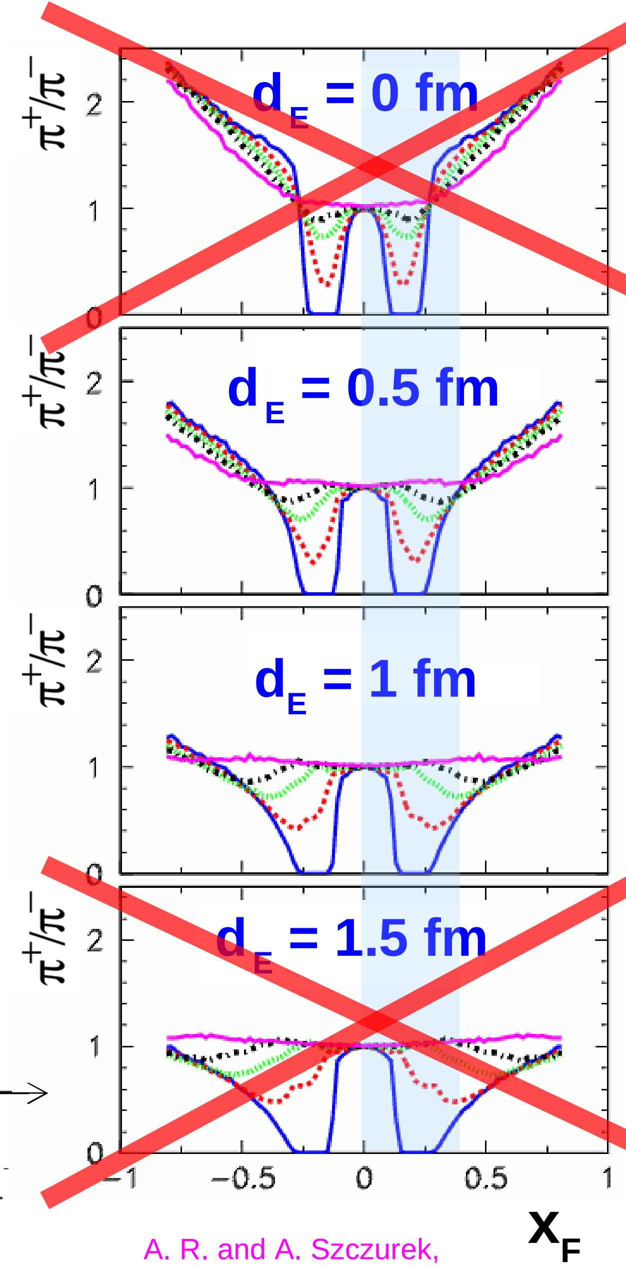


by I. Sputowska









A. R., Acta Phys. Polon. B42 (2011) 867

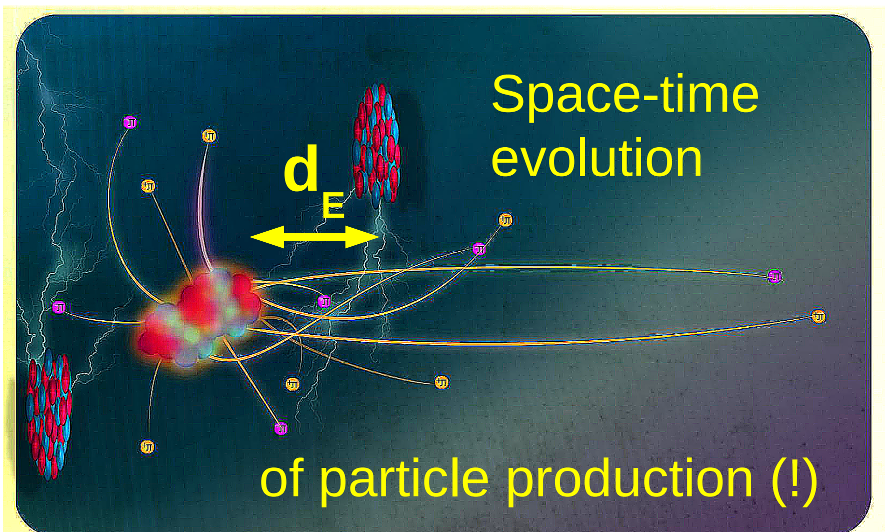
spectator velocity
$y = y_{beam}$

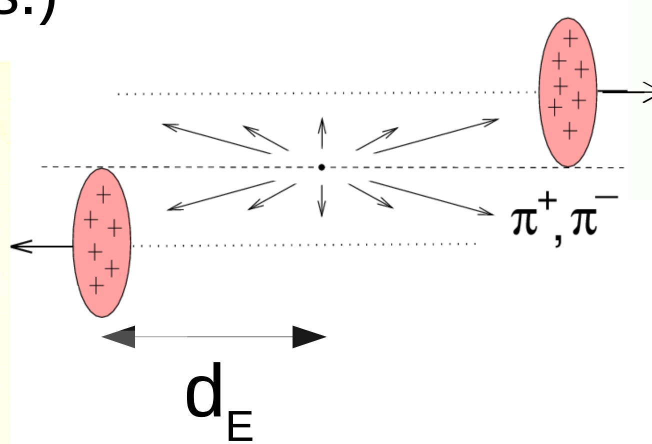
$$x_F = \frac{p_L}{p_L^{beam}}$$

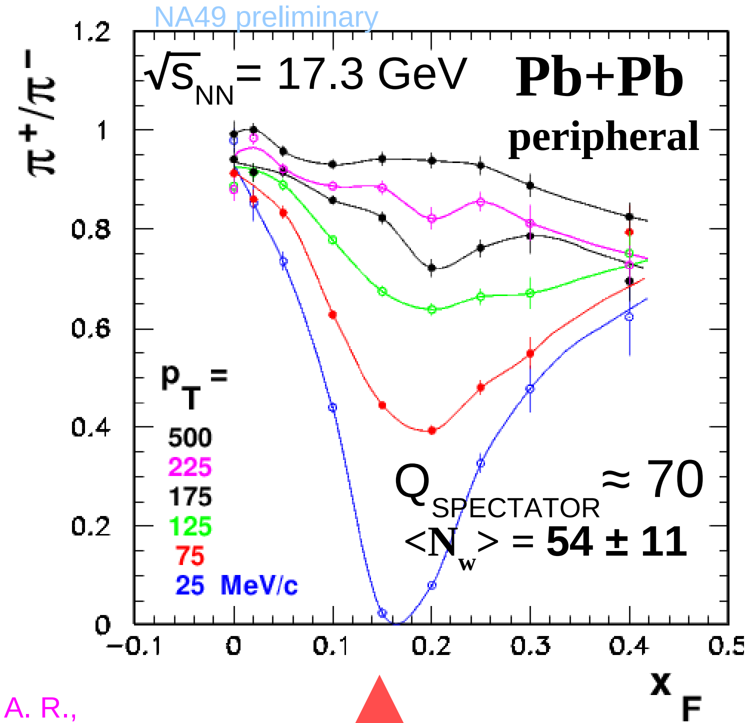
(c.m.s.)

$d_E \approx 0.75$ fm

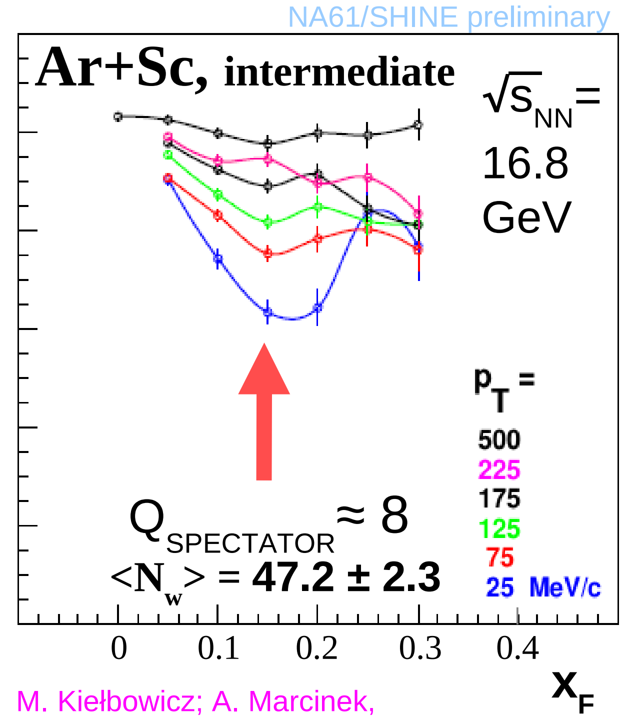
A. R. and A. Szczurek, Phys. Rev. C75 (2007) 054903



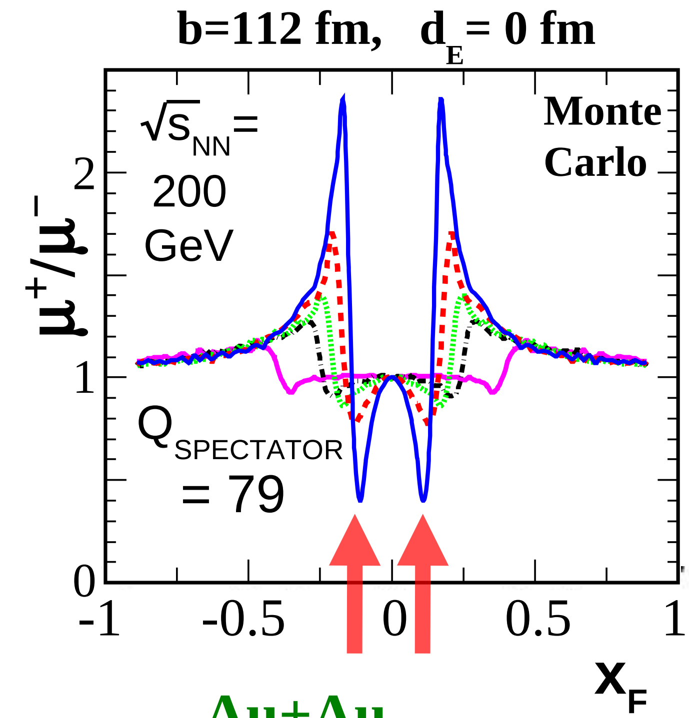




A. R.,
Acta Phys. Polon.
B42 (2011) 867



M. Kiełbowicz; A. Marcinek,
Acta Phys. Polon. B50 (2019) 1127

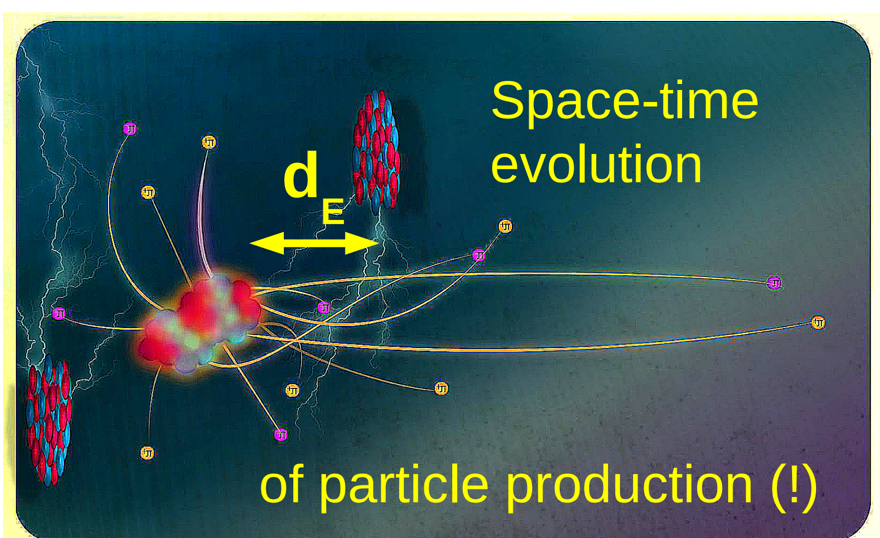


spectator velocity
$y = y_{beam}$

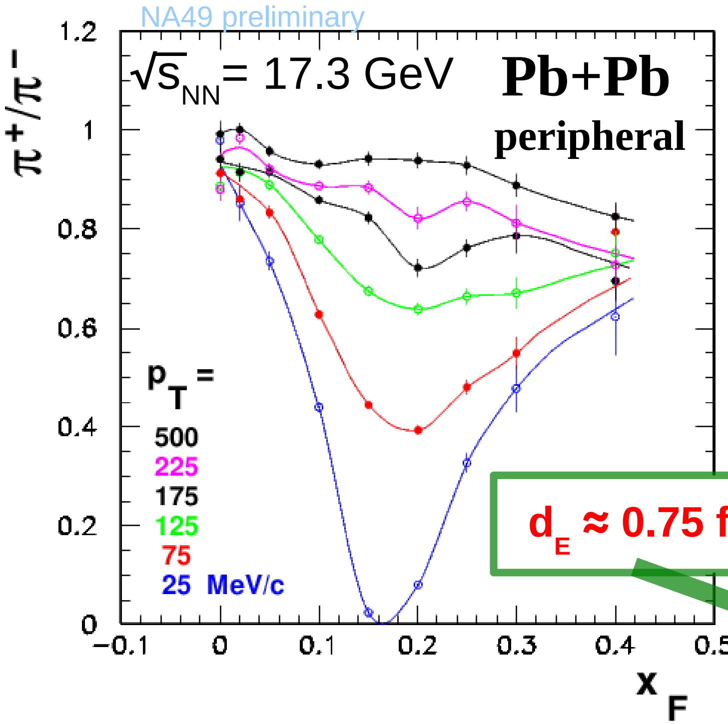
$$x_F = \frac{p_L}{p_L^{beam}}$$

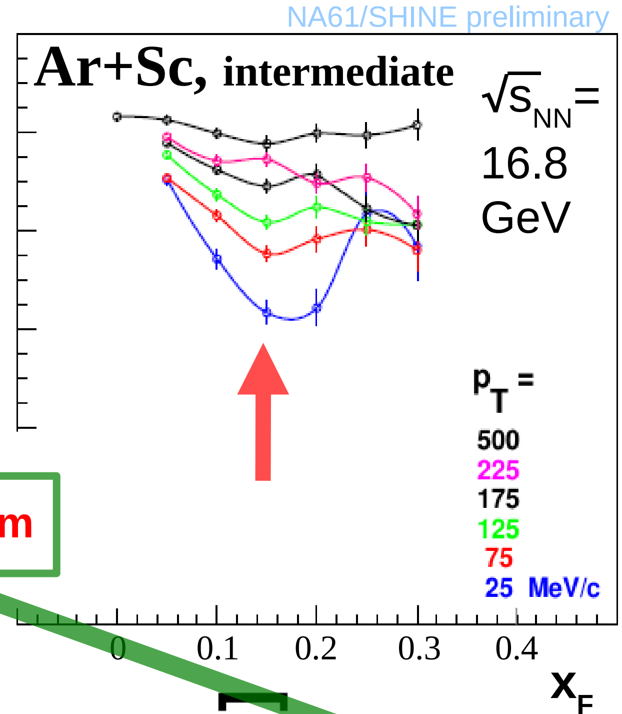
(c.m.s.)

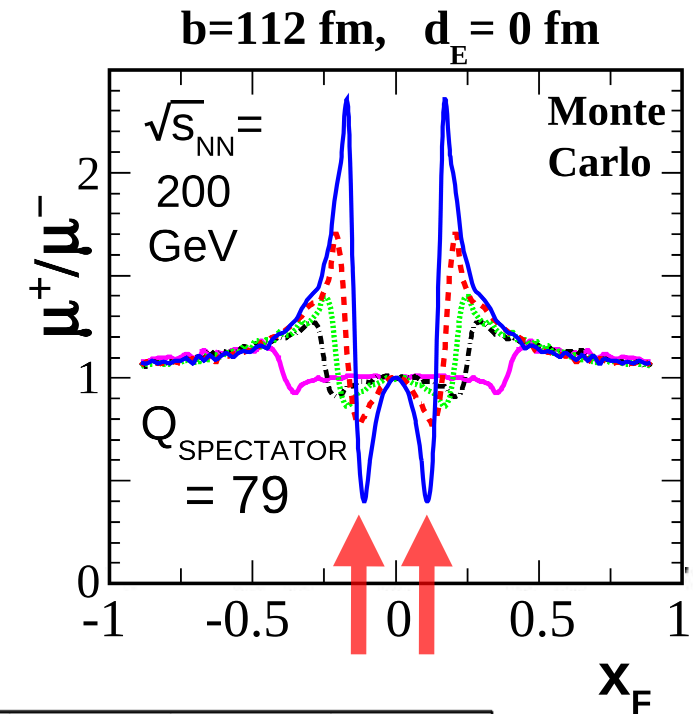
Au+Au,
ultra-peripheral,
$(\gamma\gamma \rightarrow \mu^+\mu^-)$



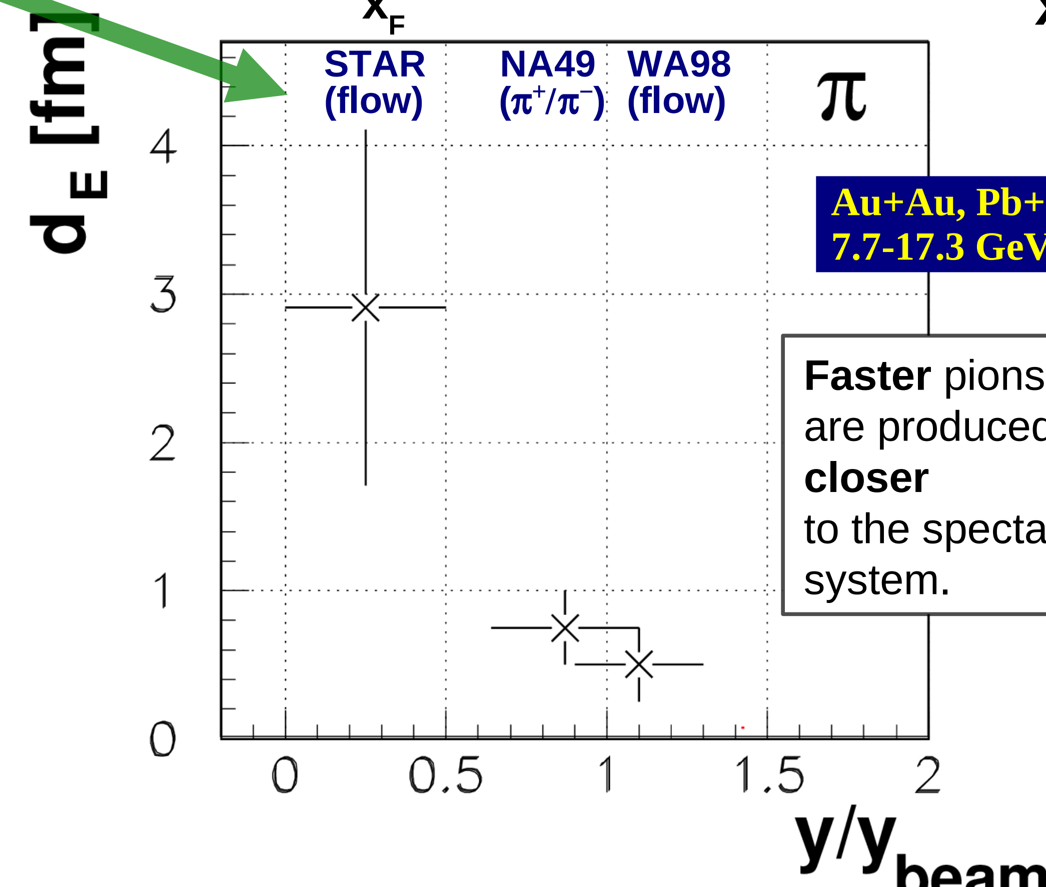
2) Getting information from EM effects

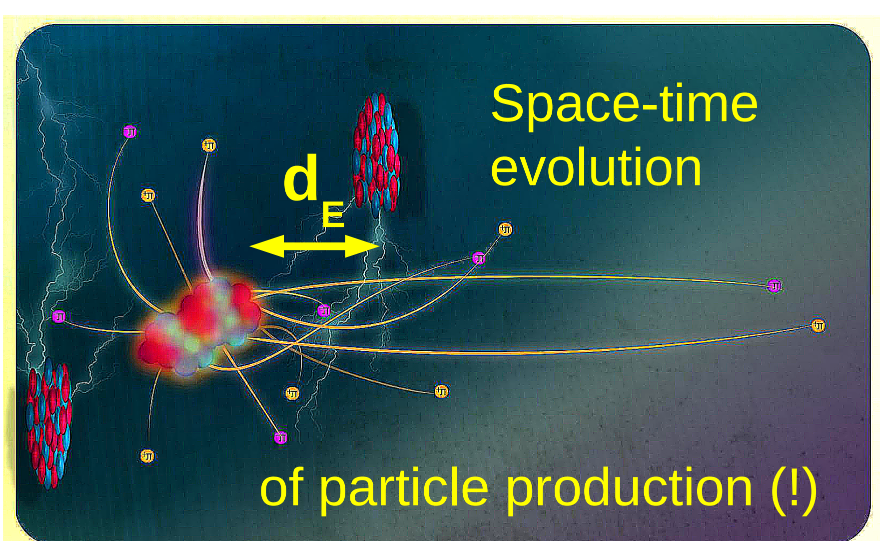


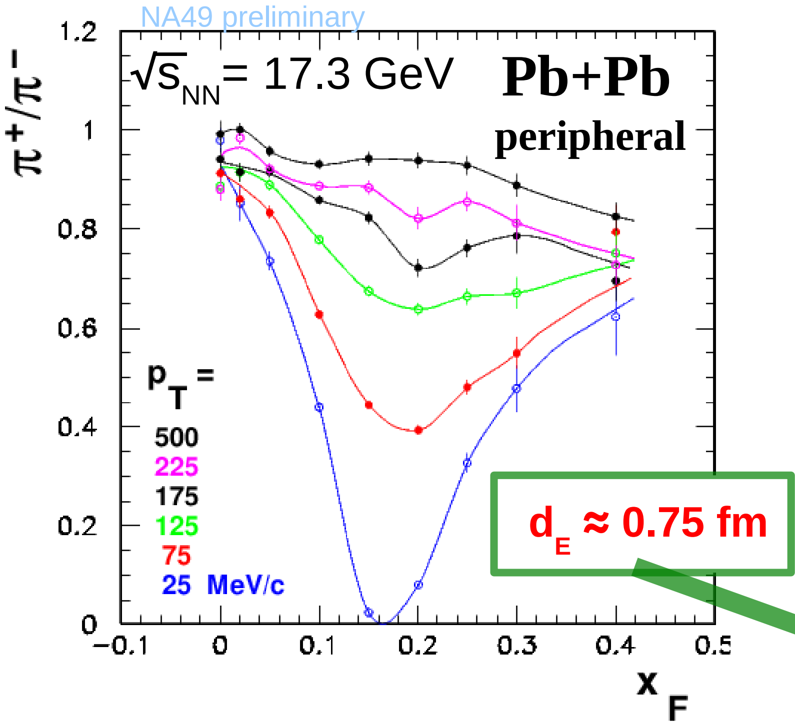


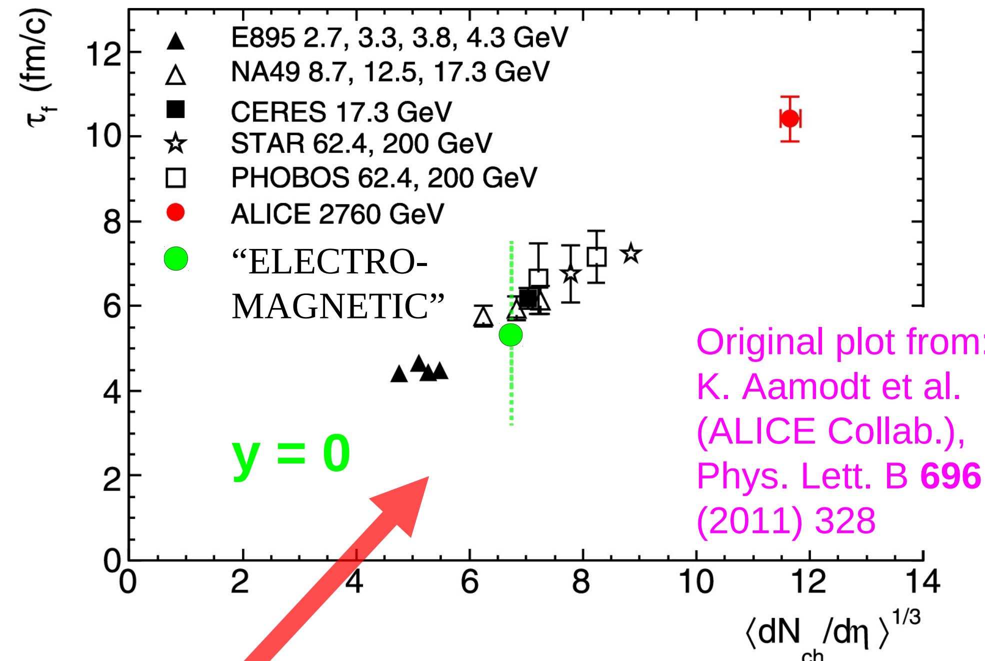


Note: the remaining points in the right plot are deduced from EM effects on azimuthal anisotropies (flow).
Data: L. Adamczyk et al., STAR, PRL 112, 2014, 725,
H. Schlagheck et al., WA98, NPA 663, 2000, 725.
See also: A. R. et al., APPB 46 (2015) 3, 737.

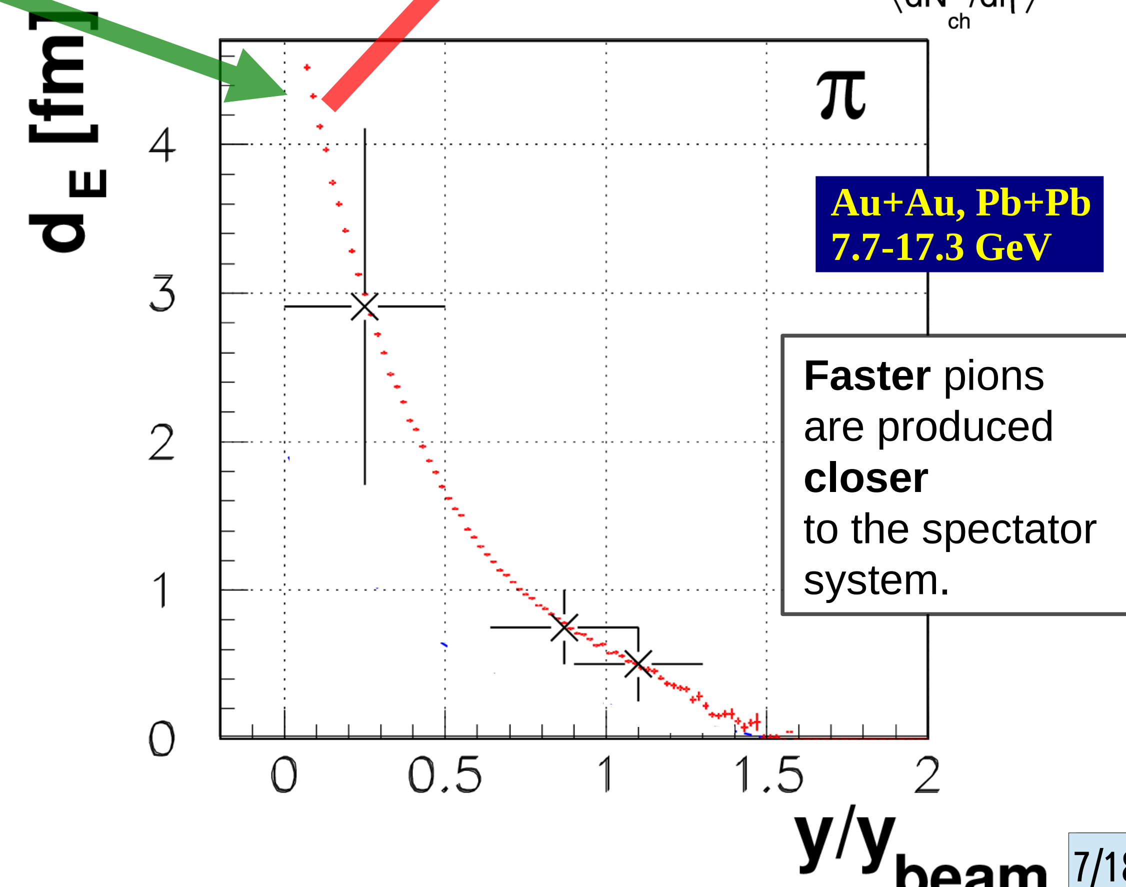


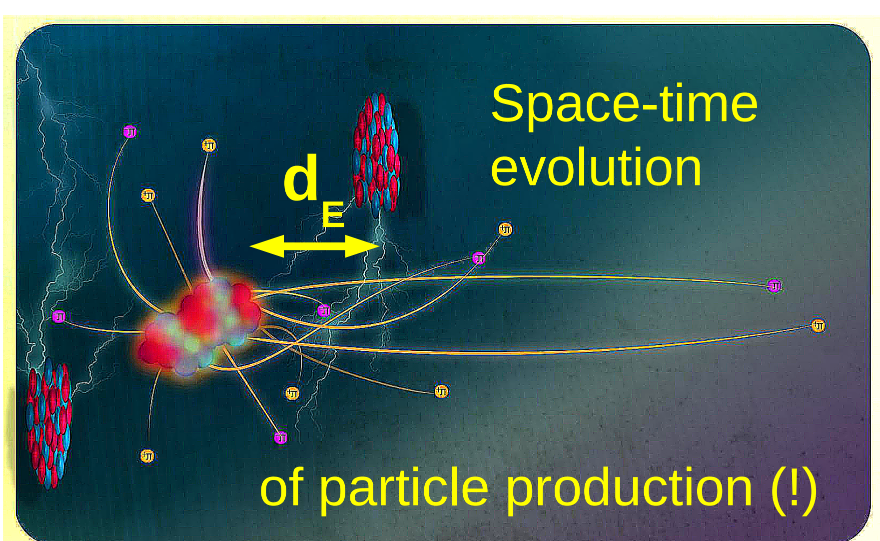




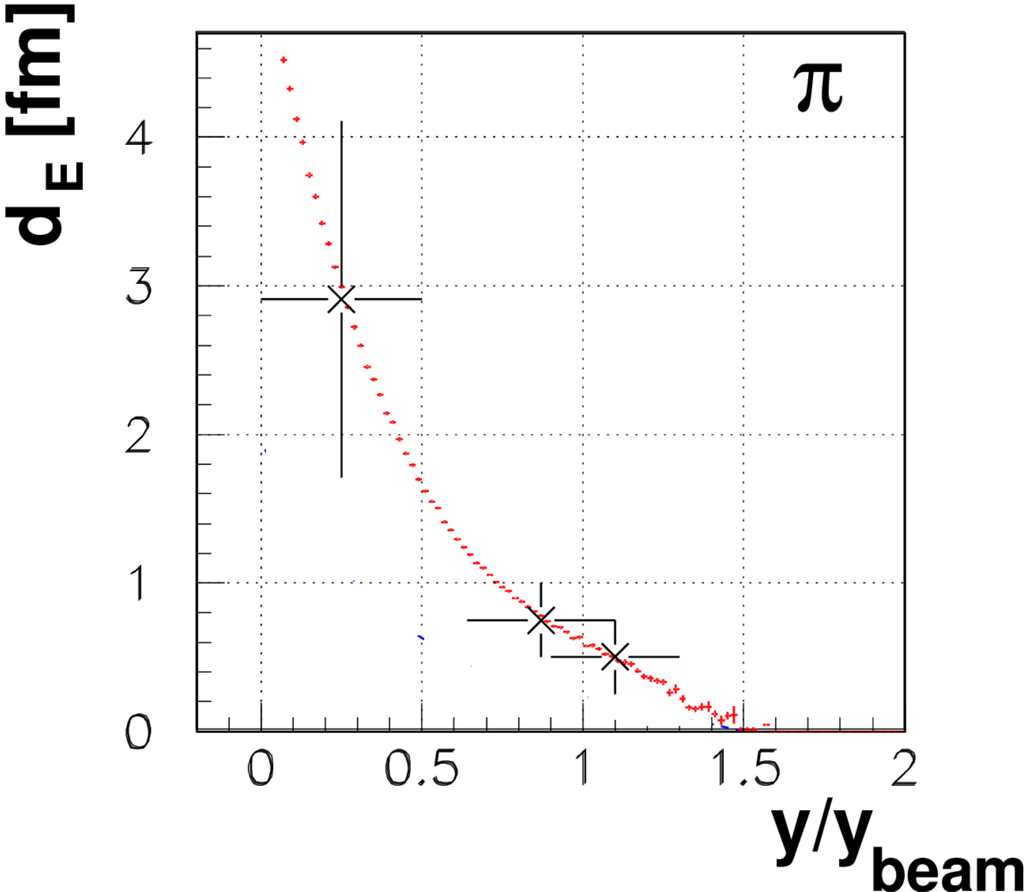


• EM effects **their own estimate** for the time of pion creation, at y=0.

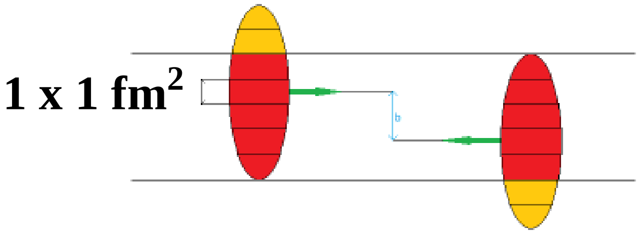




3)
Space-time evolution of forward pion production

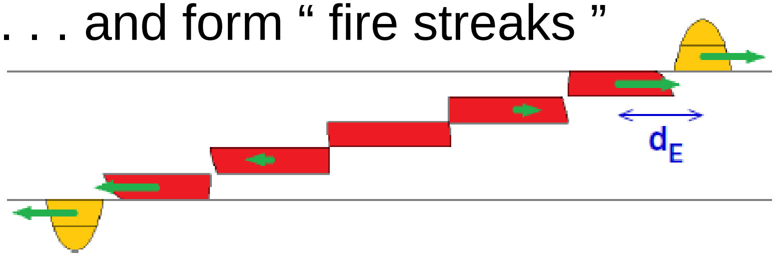


Bricks collide . . .



PRC 95 (2017) 024908
Idea by A. Szczurek,
See also:
R. Hagedorn, CERN-71-12
W.D. Myers, NPA 296, 1978, 177

. . . and form “ fire streaks ”



Each fire streak fragments independently into pions

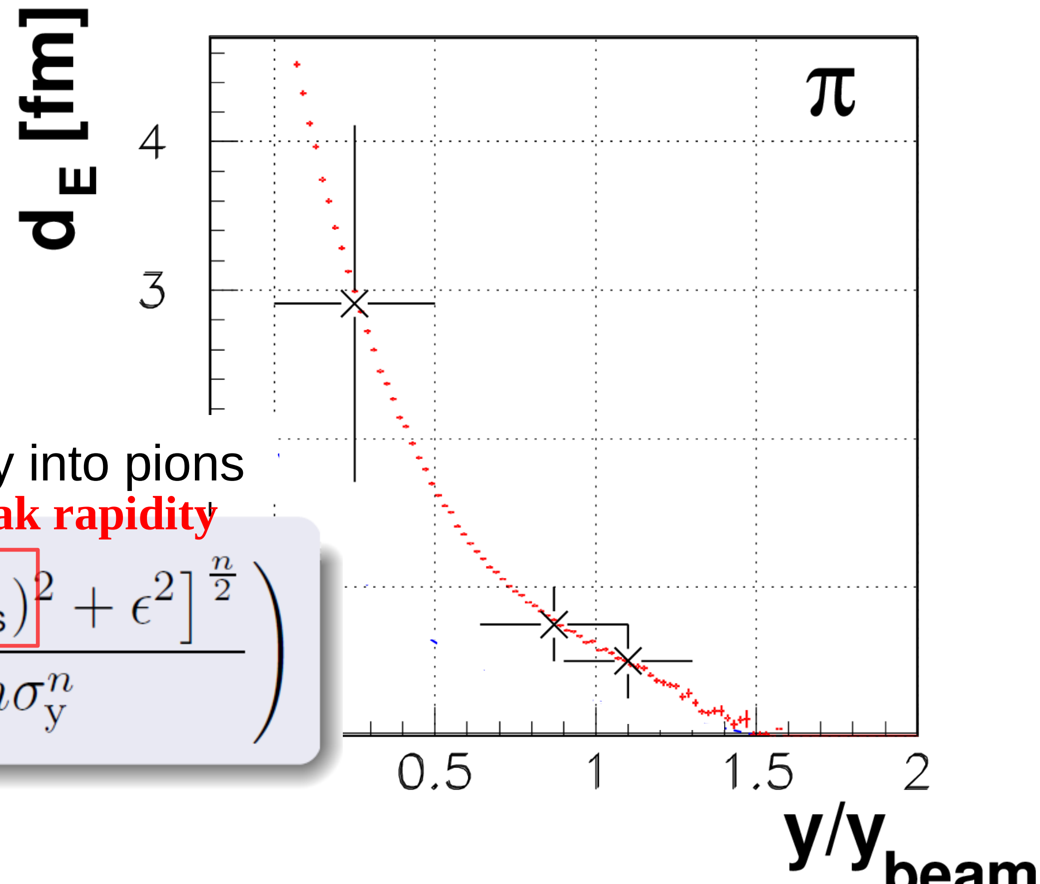
$$\frac{dn}{dy} = A \cdot (E_s^* - m_s) \cdot \exp\left(- \frac{\left[(y - y_s)^2 + \epsilon^2 \right]^{\frac{n}{2}}}{n \sigma_y^n} \right)$$

available energy ($E_s^* - m_s$)

fire streak rapidity (y_s)

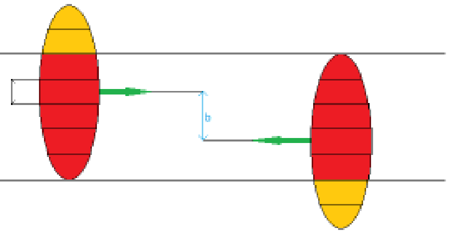
total fire streak energy (E_s^*)

sum of brick masses (m_s)



NA49, π^-, Pb+Pb, $\sqrt{s_{NN}}$ = 17.3 GeV

Bricks collide . . .



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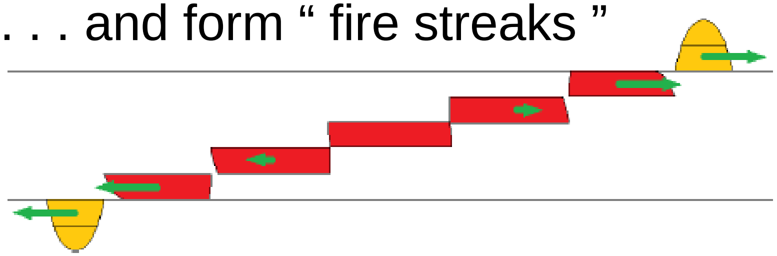


Each fire streak fragments independently into pions

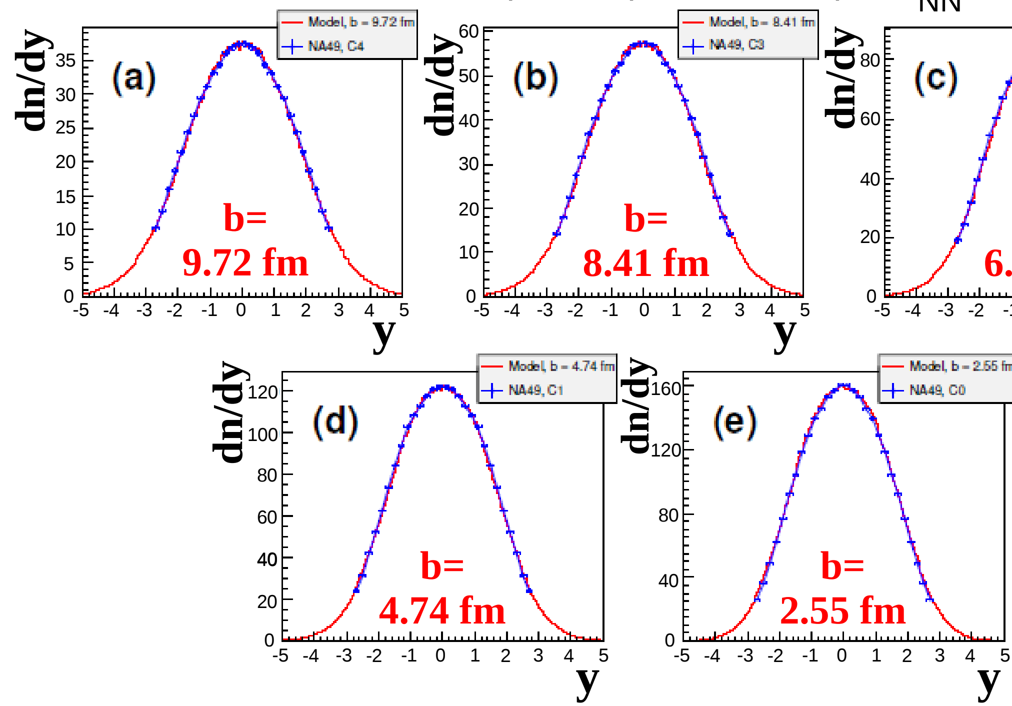
available energy

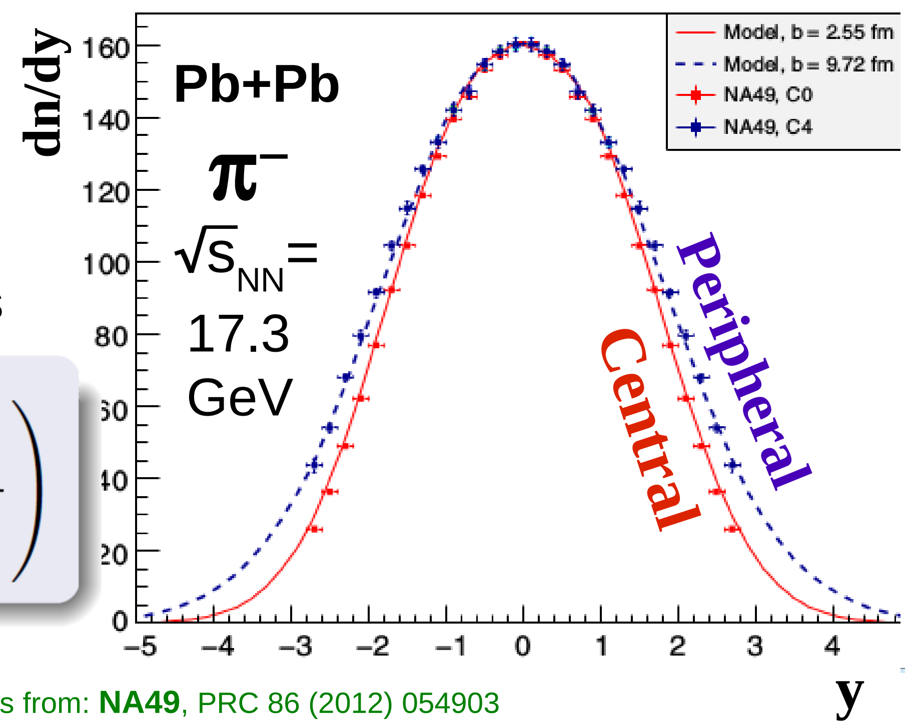
fire streak rapidity

$$\frac{dn}{dy} = A \cdot (E^*_s - m_s) \cdot \exp\left(- \frac{[(y - y_s)^2 + \epsilon^2]^{\frac{n}{2}}}{n \sigma_y^n} \right)$$

total fire streak energy

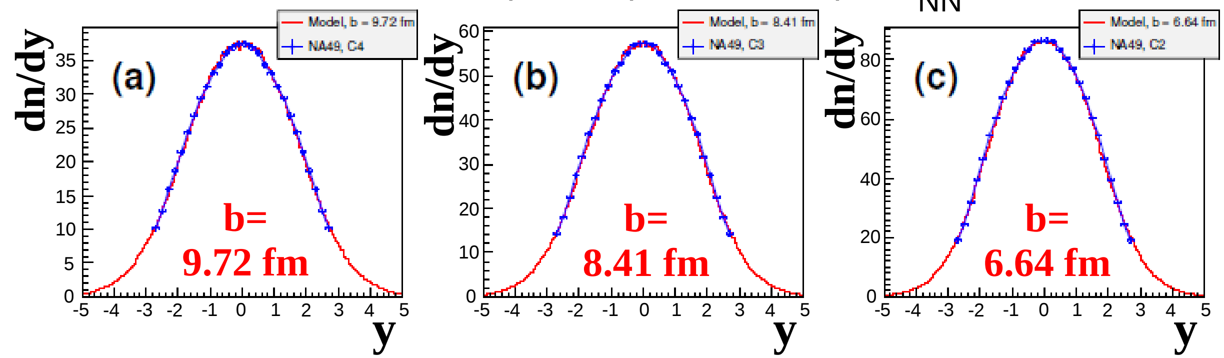
sum of brick masses

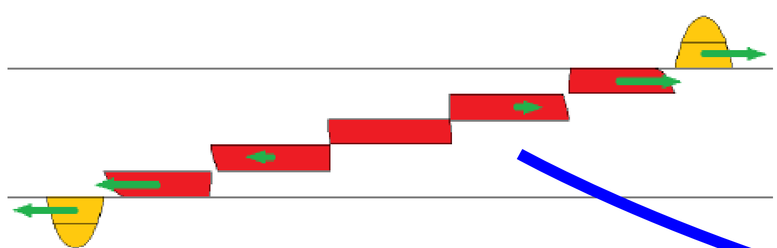


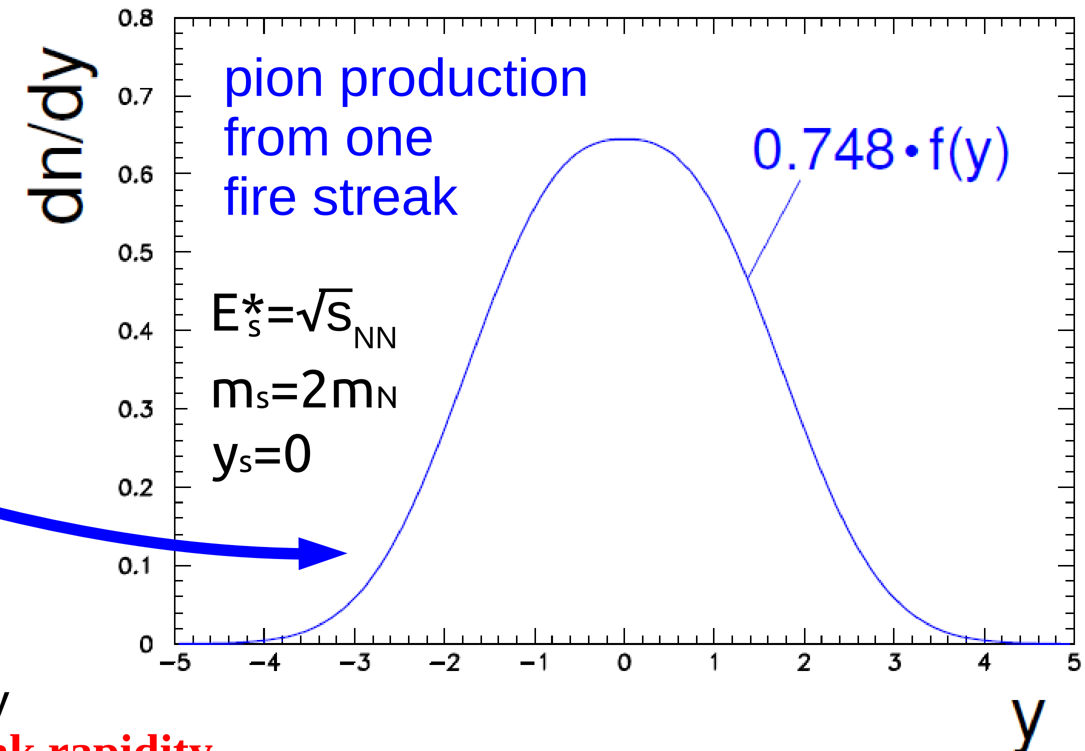


data points from: **NA49**, PRC 86 (2012) 054903

NA49, π^-, Pb+Pb, $\sqrt{s_{NN}}$ = 17.3 GeV







Each fire streak fragments independently

available energy — **fire streak rapidity**

$$f(y) = A \cdot (E_s^* - m_s) \cdot \exp\left(- \frac{\left[(y - y_s)^2 + \epsilon^2\right]^{\frac{n}{2}}}{n\sigma_y^n} \right)$$

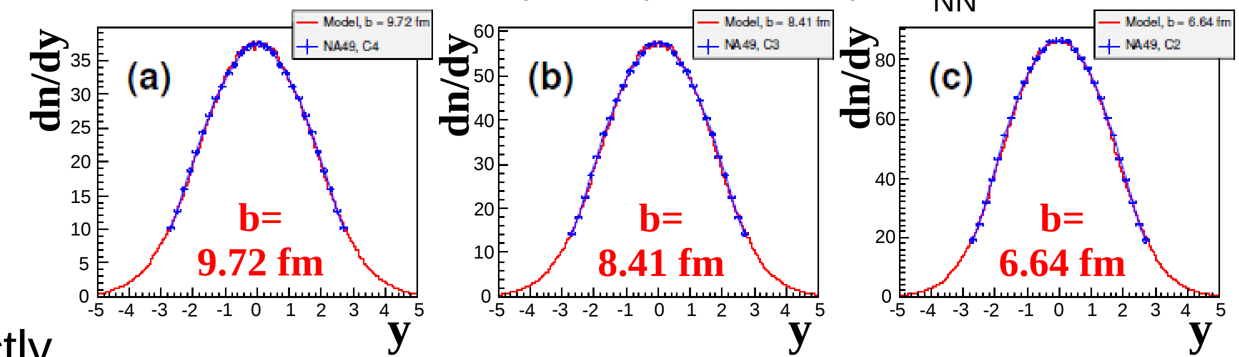
E_s^*: total fire streak energy

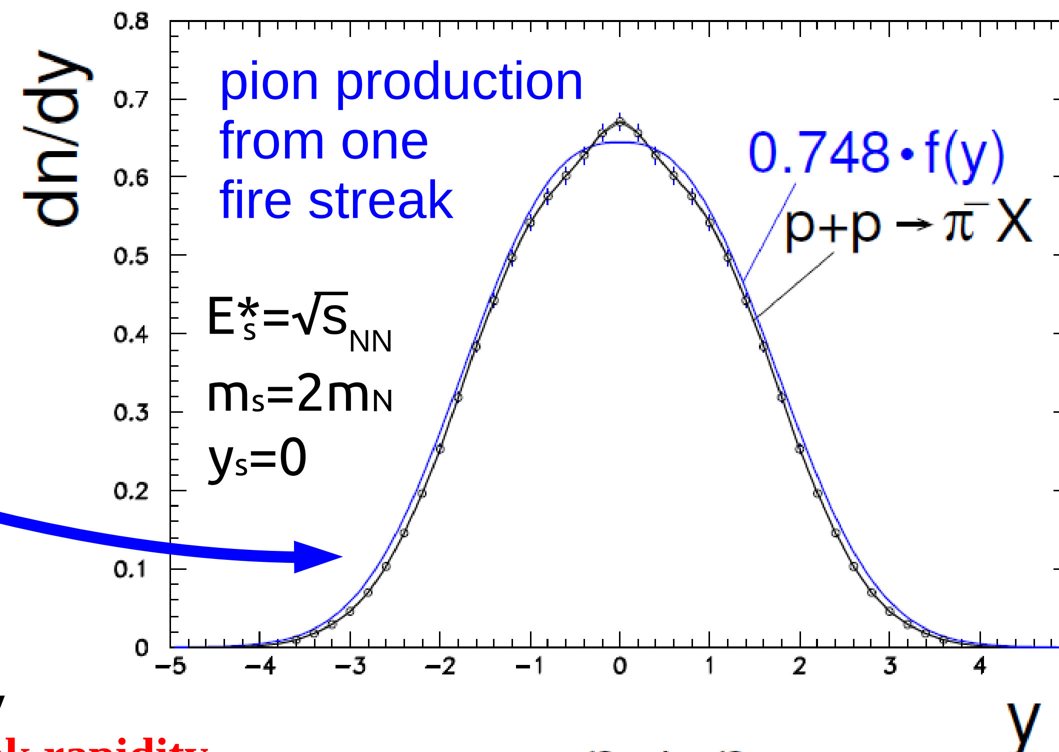
m_s: sum of brick masses

data points from: **NA49**, PRC 86 (2012) 054903

- The pion rapidity distribution from **one fire streak** in Pb+Pb collisions is **similar** to the pion rapidity distribution in **p+p** reactions ;
- The difference in absolute normalization (**0.748**) can be directly obtained from the different energy repartition in **p+p** and **Pb+Pb** reactions (see PRC 99 (2019) 024908).

NA49, π^-, Pb+Pb, $\sqrt{s_{NN}}$ = 17.3 GeV





Each fire streak fragments independently

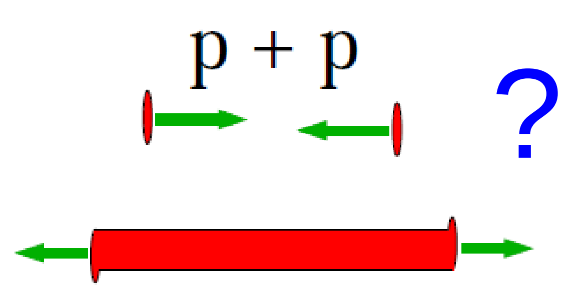
$$f(y) = A \cdot (E^*_s - m_s) \cdot \exp\left(- \frac{\left[(y - y_s)^2 + \epsilon^2 \right]^{\frac{n}{2}}}{n \sigma_y^n} \right)$$

available energy

fire streak rapidity

total fire streak energy

sum of brick masses



data points from: **NA49**, PRC 86 (2012) 054903, EPJC 45 (2006) 343

- The pion rapidity distribution from **one fire streak** in Pb+Pb collisions is **similar** to the pion rapidity distribution in **p+p** reactions ;
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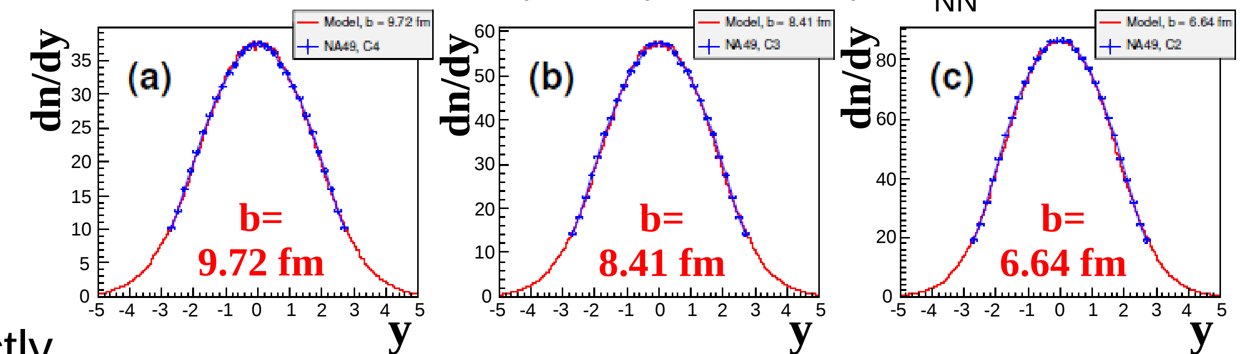
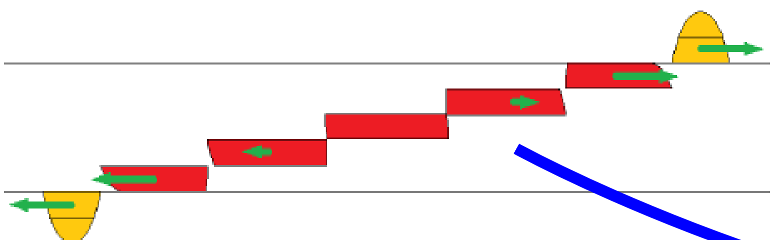
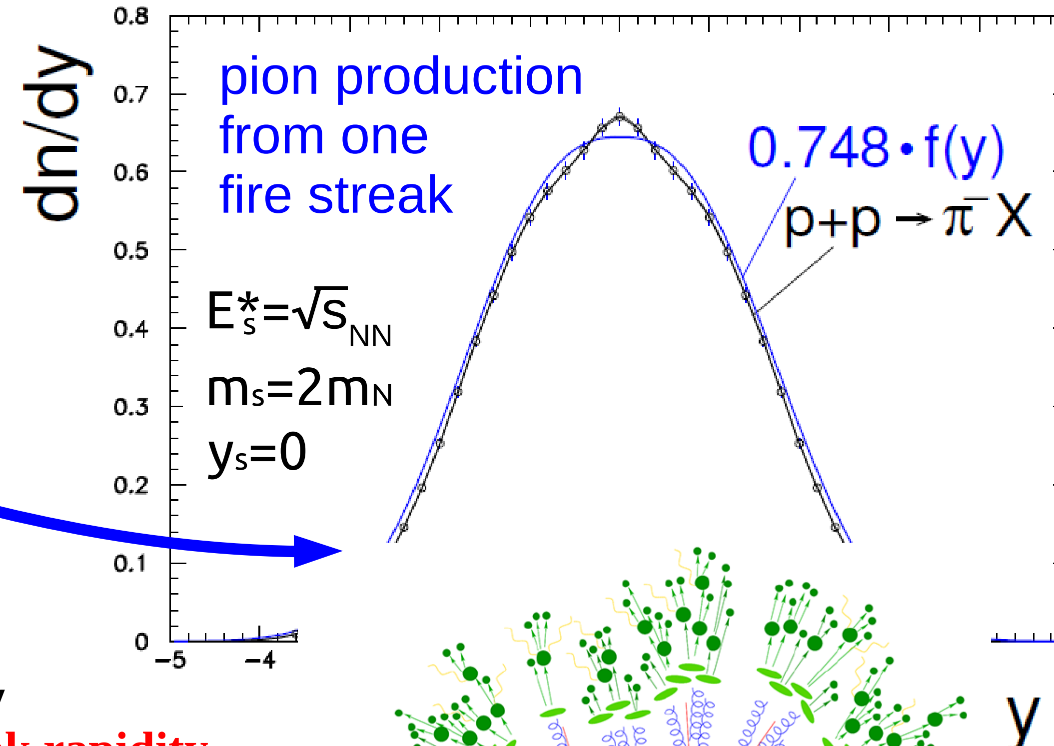
NA49, π^-, Pb+Pb, $\sqrt{s_{NN}}$= 17.3 GeV





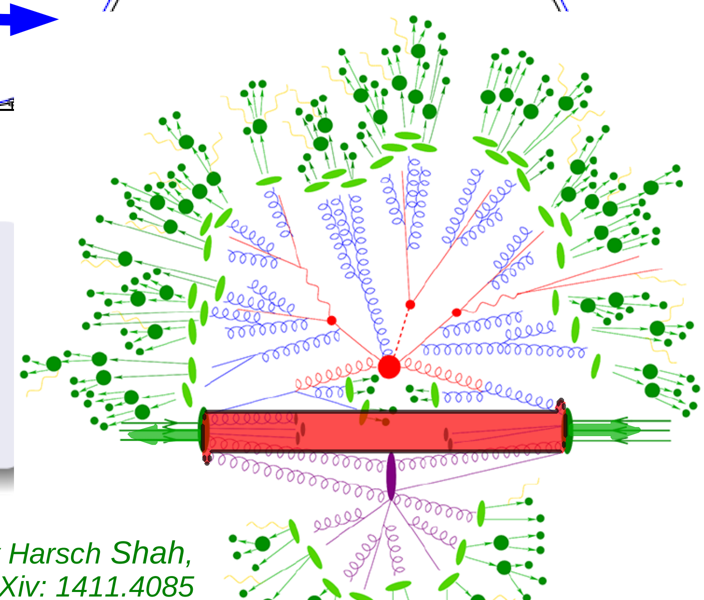


Each fire streak fragments independently

$$f(y) = A \cdot (E^*_s - m_s) \cdot \exp\left(- \frac{[(y - y_s)^2 + \epsilon^2]^{\frac{n}{2}}}{n\sigma_y^n} \right)$$

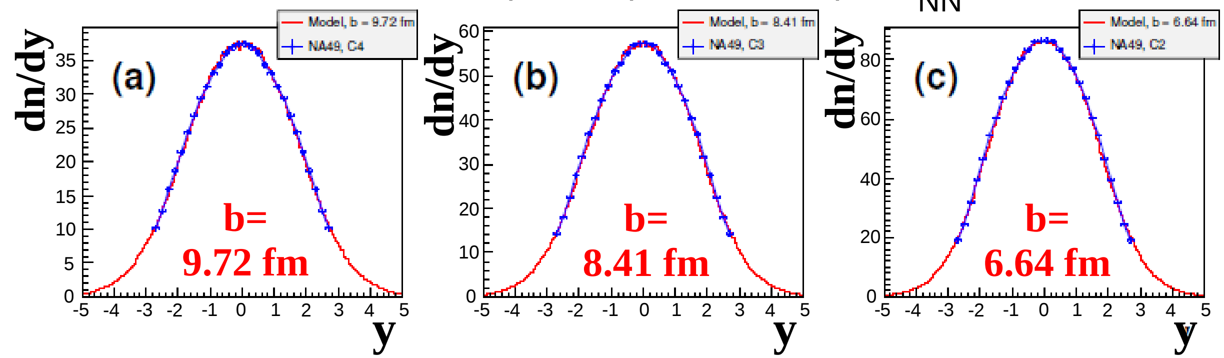
available energy — fire streak rapidity

total fire streak energy — sum of brick masses

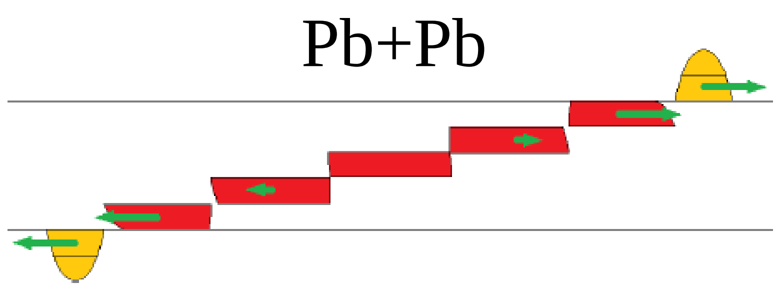


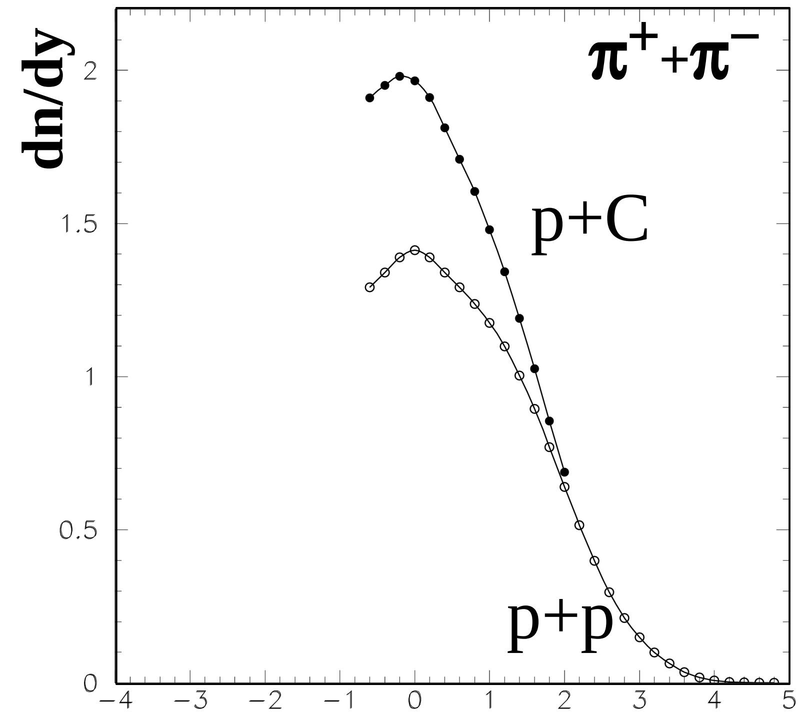
Courtesy by Harsch Shah, S.Hoche, arXiv: 1411.4085

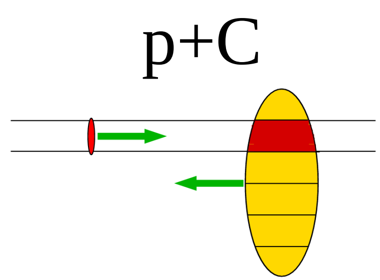
NA49, π^-, Pb+Pb, $\sqrt{s_{NN}}$ = 17.3 GeV

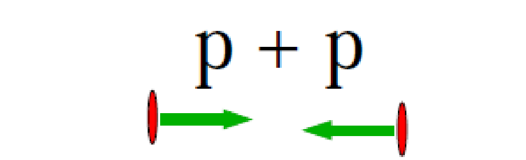


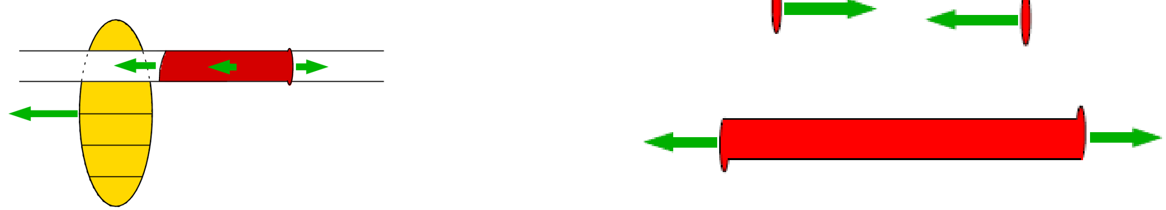
- Link between p+p, p+A, and A+A collisions.





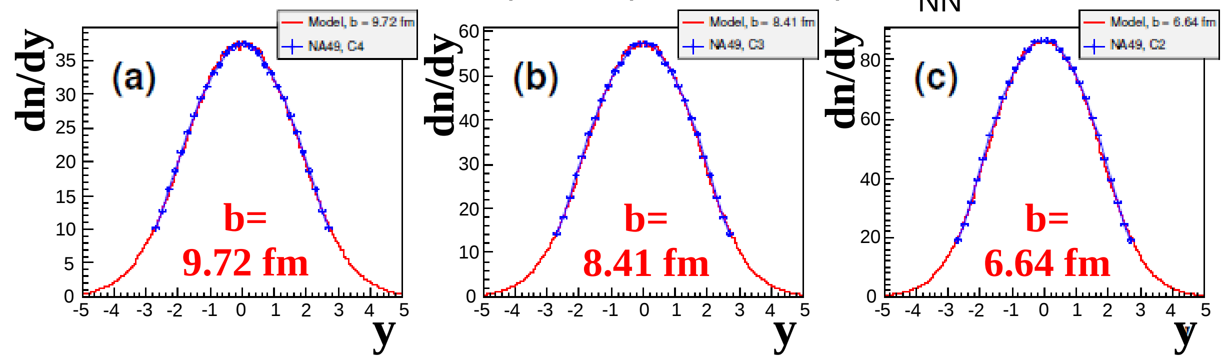




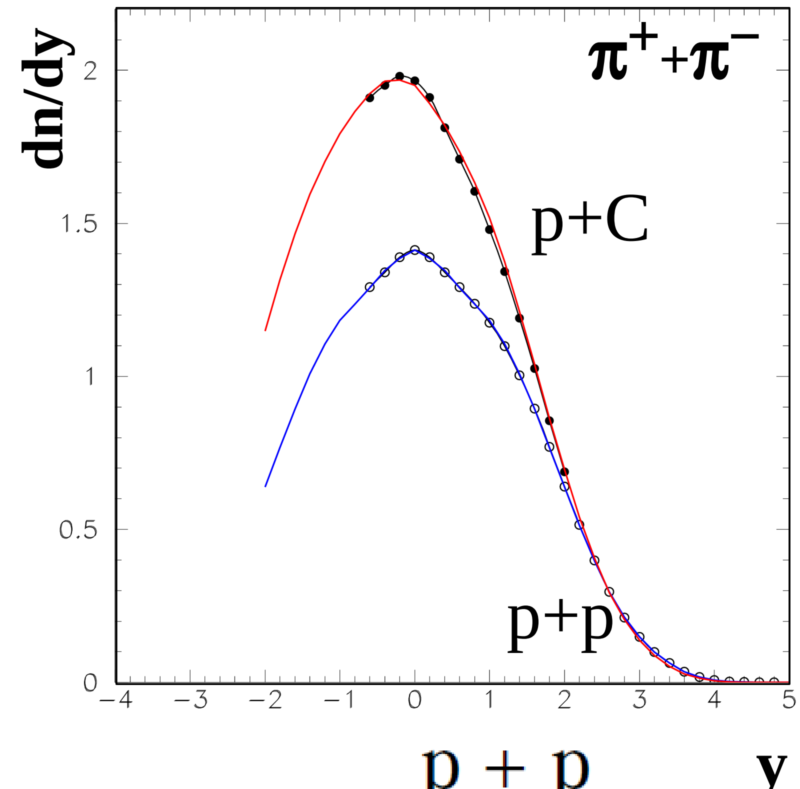


data points from: **NA49**, PRC 86 (2012) 054903, EPJC 45 (2006) 343, EPJC 49 (2007) 919

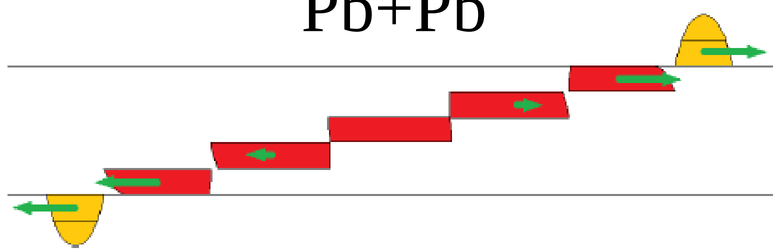
NA49, π^-, Pb+Pb, $\sqrt{s_{NN}}$= 17.3 GeV



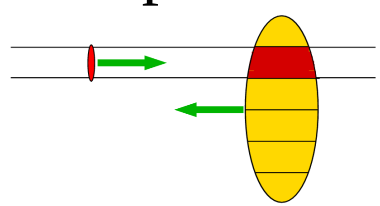
- Link between p+p, p+A, and A+A collisions.

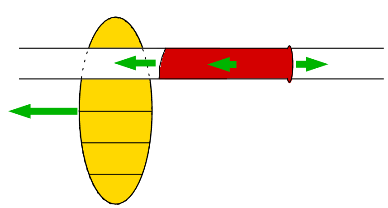


Pb+Pb

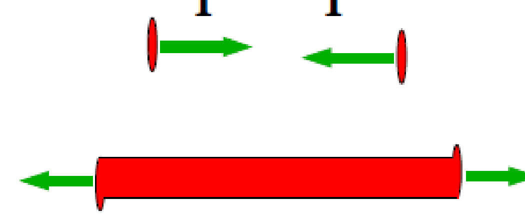


p+C

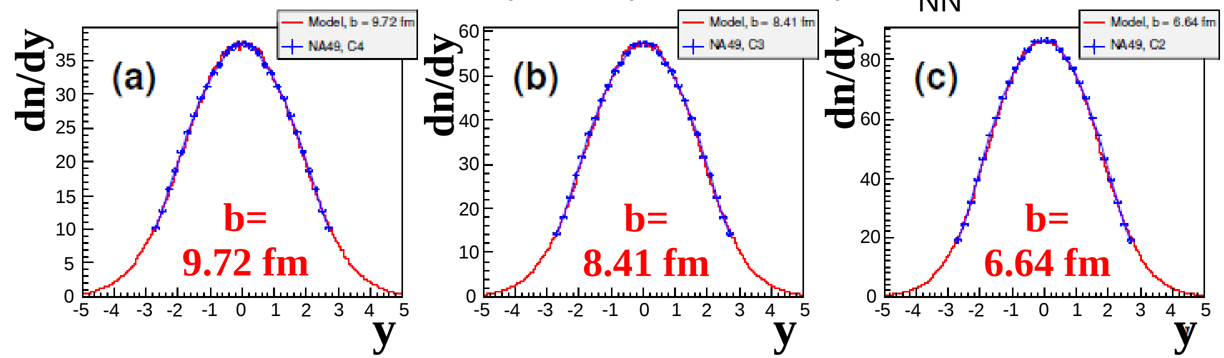




p + p

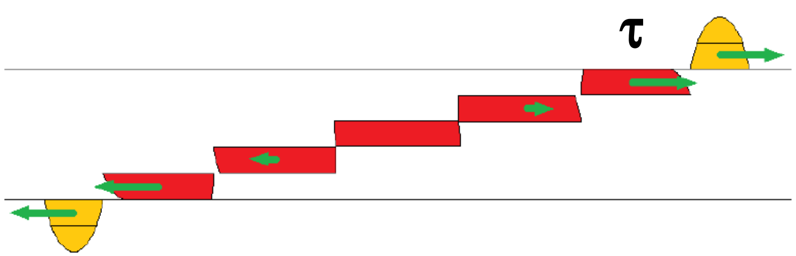


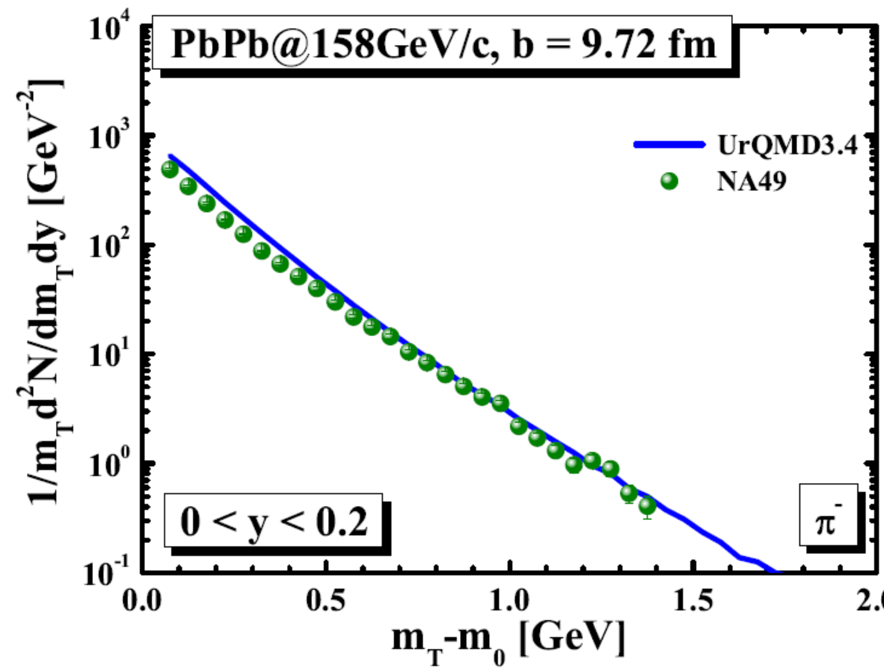
NA49, π^-, Pb+Pb, $\sqrt{s_{NN}}$ = 17.3 GeV



Implementation of our model for studies of EM effects:

- Initial longitudinal evolution of the system → from our model ;
- Initial (before the action of the EM field) rapidity distribution of pions → from our model ;





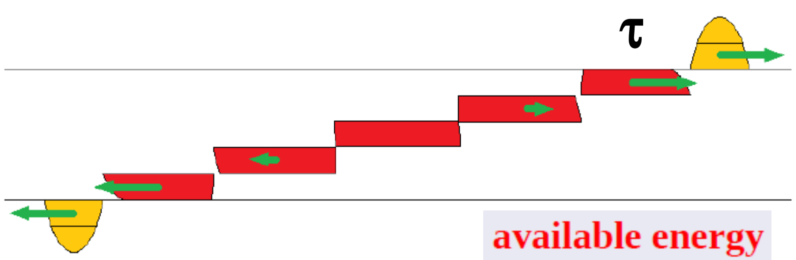
- Initial p_T distribution of pions → from UrQMD v3.4 ;
- The pion creation time τ (taken in the fire streak c.m.s.) → taken as free parameter ;
- Isospin effects between π^+ and π^- → included → PRC 99 (2019) 024908 ;
- Fragmentation (expansion) of the spectator charge → included optionally;
- Azimuthal anisotropies (“flow”) → included optionally.

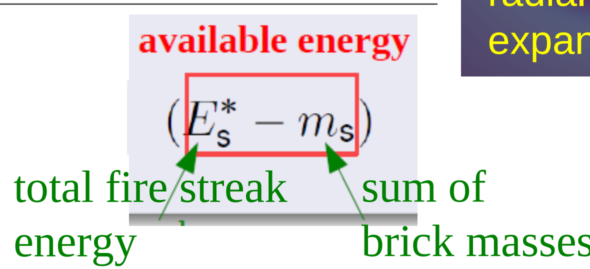
data points from: **NA49**, PRC 86 (2012) 054903

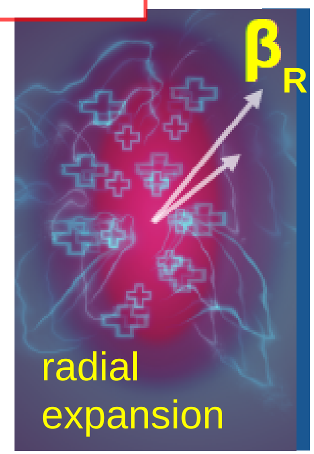
Implementation of our model for studies of EM effects, <u>state of the art:</u>

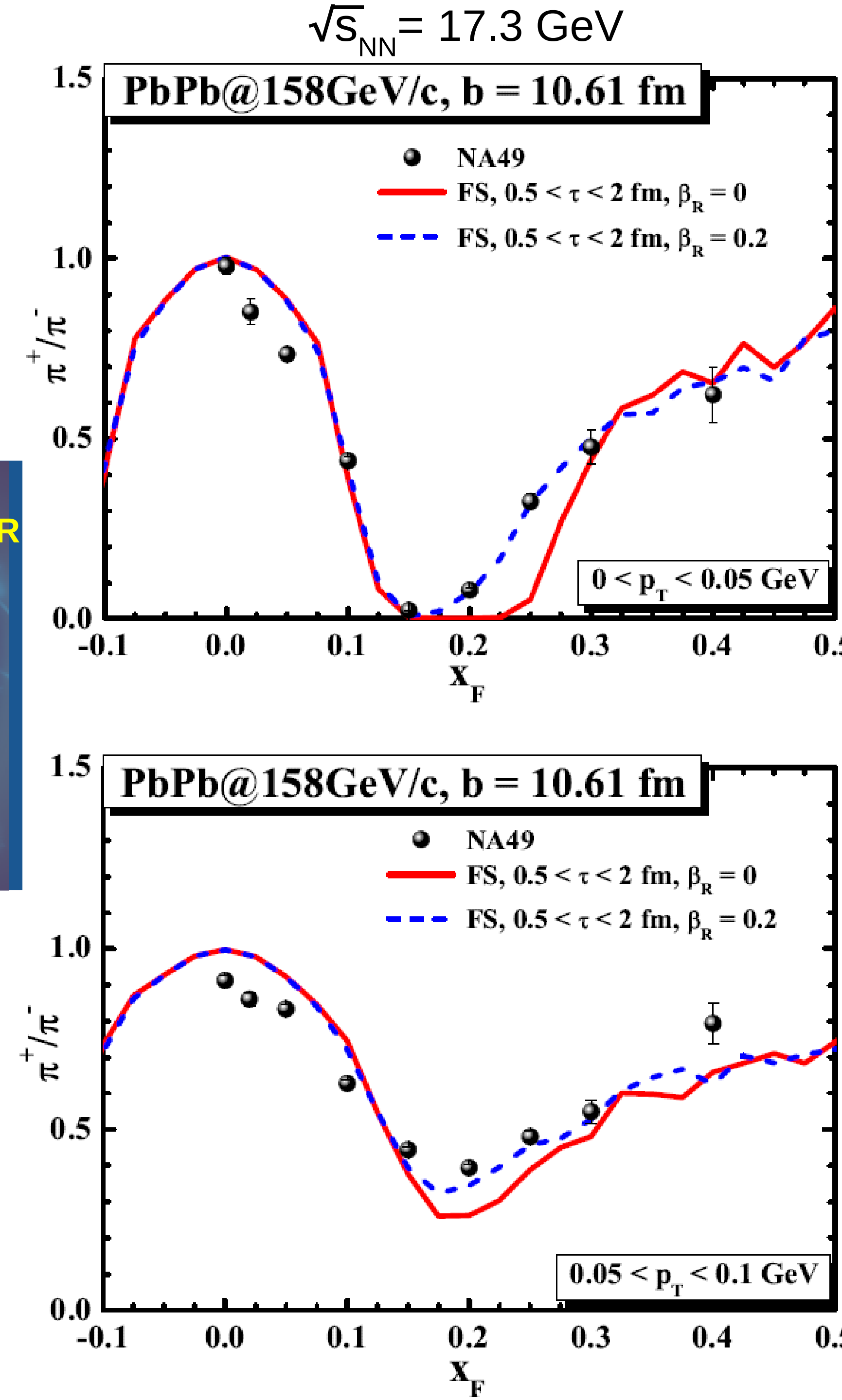
$a \approx 0.08$
$\tau_0 = 0.5 \text{ fm}/c$

- Simple parametrization of pion creation time : $\tau = a(E_s^* - m_s) + \tau_0$
- Radial expansion assumed for spectator system.









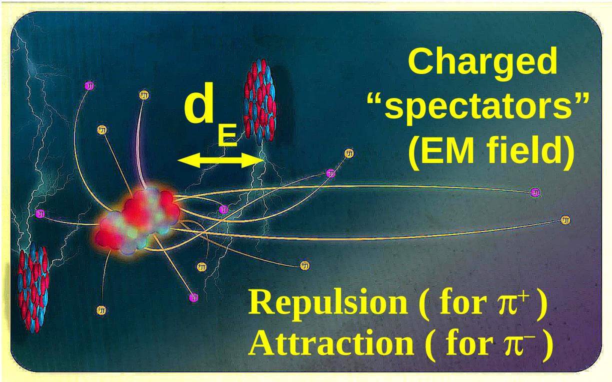
Exp. data: A. R., APPB 42 (2011) 867

➔ Reasonable agreement with data for $x_F \geq 0.1$.

➔ Inclusion of spectator expansion improves the description ;

➔ **Short pion creation times** (0.5 < τ < 2 fm/*c*, to be compared with ~ 5.5 fm/*c* at y=0).

4) Summary



Spectator-induced electromagnetic (EM) effects can be used to study the **space-time evolution of particle production**.

Our studies have shown that in high energy nucleus-nucleus collisions, **faster** pions are produced **closer** to the spectator system, and provided an **independent estimate** for the time of pion creation, at y=0.

On that basis, we built a simple phenomenological model with realistic initial conditions (incidentally we found that it **works** for all the three reaction types). This we used to study the space-time evolution of the system w.r.t. forward production of **fast (x_F>0.1) pions**.

This study gives an indication that relatively **short** pion production time scales (proper pion creation times τ) are needed to describe the experimental data.

Thank you !

Acknowledgments.

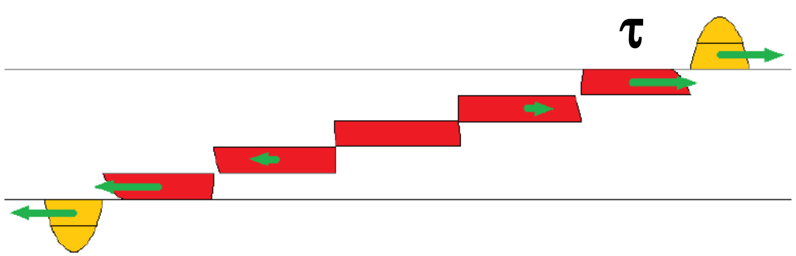
This work was supported by the National Science Centre, Poland

(grant no. 2014/14/E/ST2/00018).

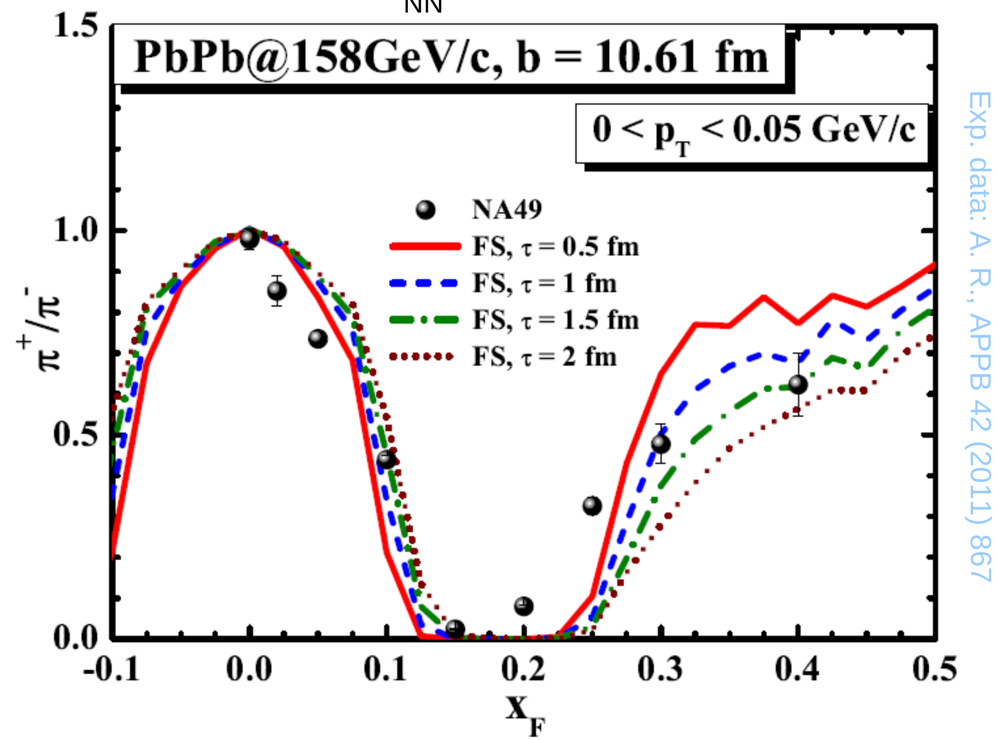
Extra slides

Implementation of our model for studies of EM effects, first results:

- Fixed pion creation time τ (in fire streak rest frame) ;
- No spectator fragmentation.



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

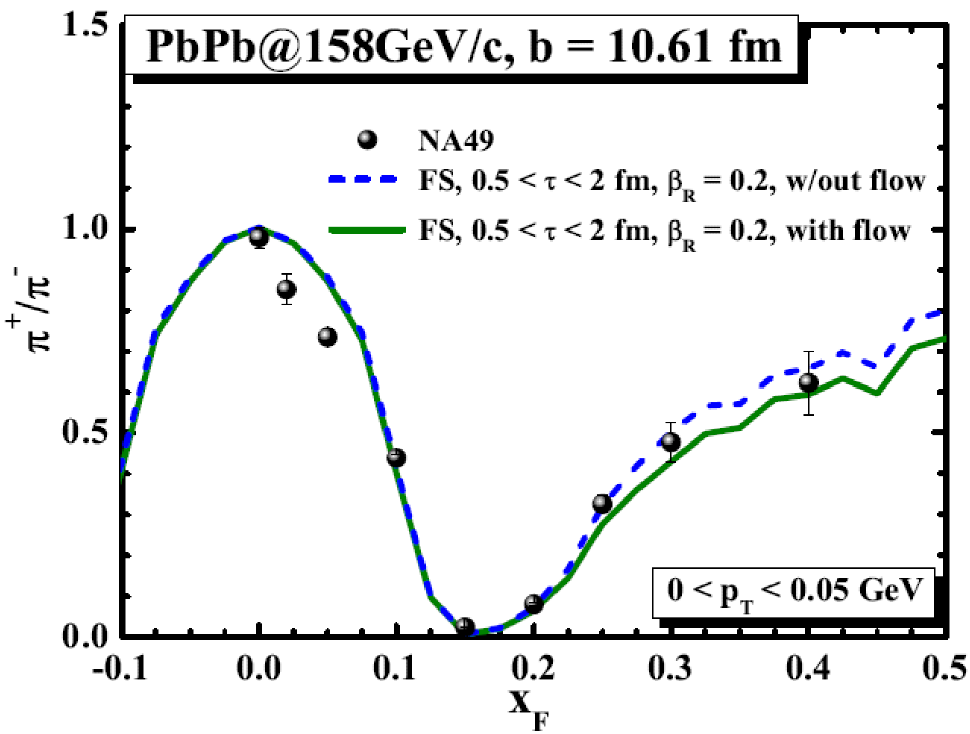


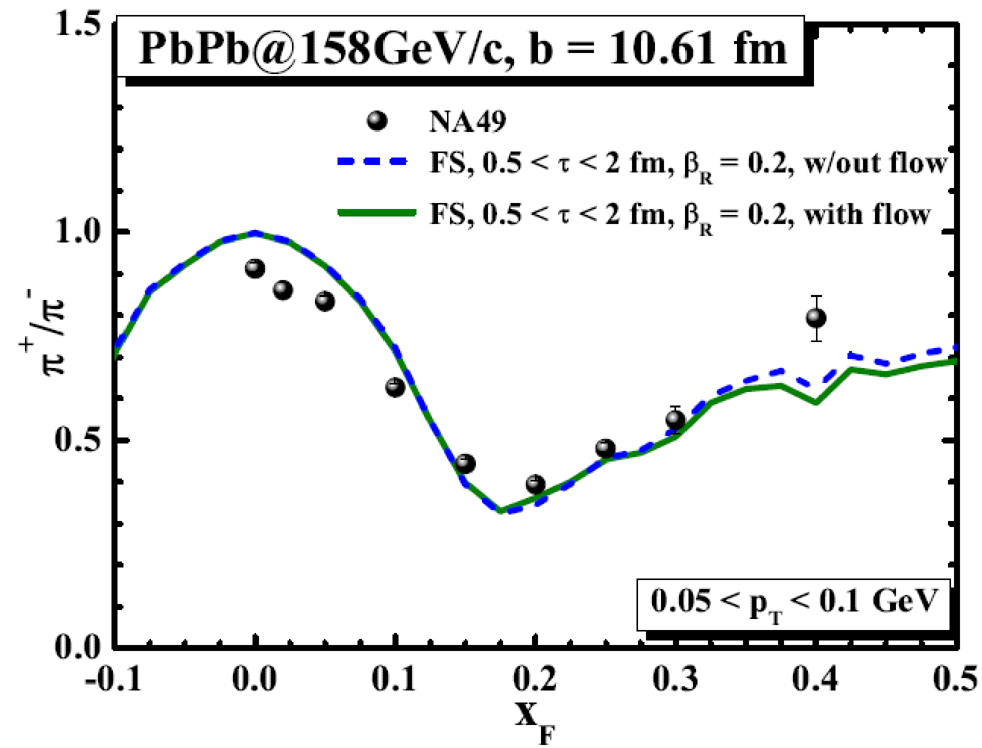
➔ Relatively **short pion creation times** are suggested by the exp. data (τ ~ 0.5 - 1.5 fm/*c*, to be compared with ~ 5.5 fm/*c* at y=0) ;

➔ Impossible to fit the data with **one single value** of τ ;

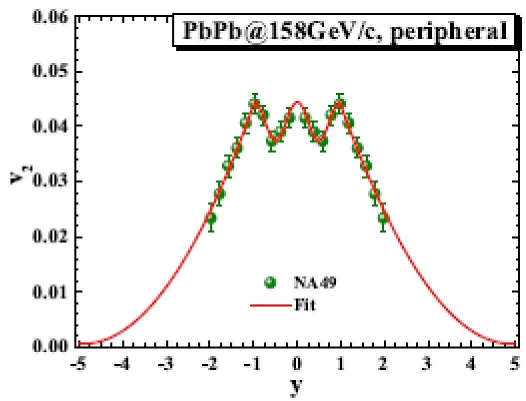
➔ Evident **problem** at x_F= 0.2 - 0.25.

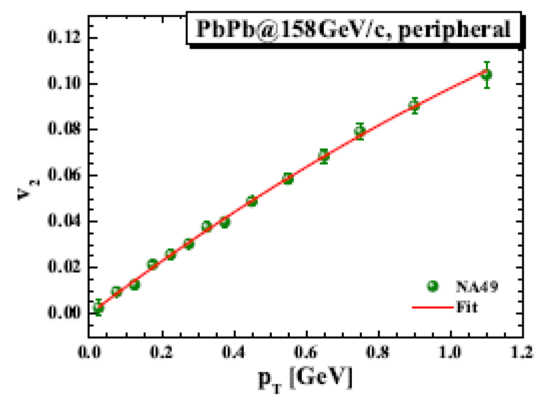
Influence of asimuthal anisotropies (flow) on π^+/π^- ratios

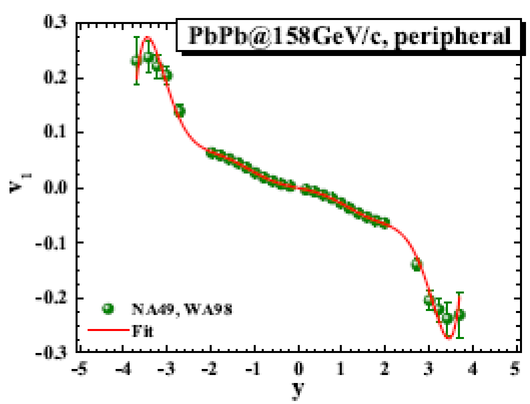


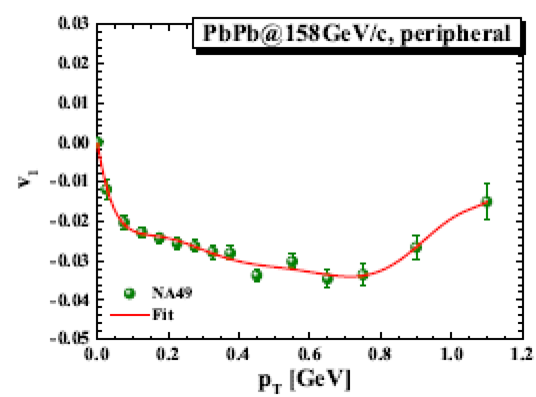


Inclusion of asimuthal anisotropies (flow) in the model

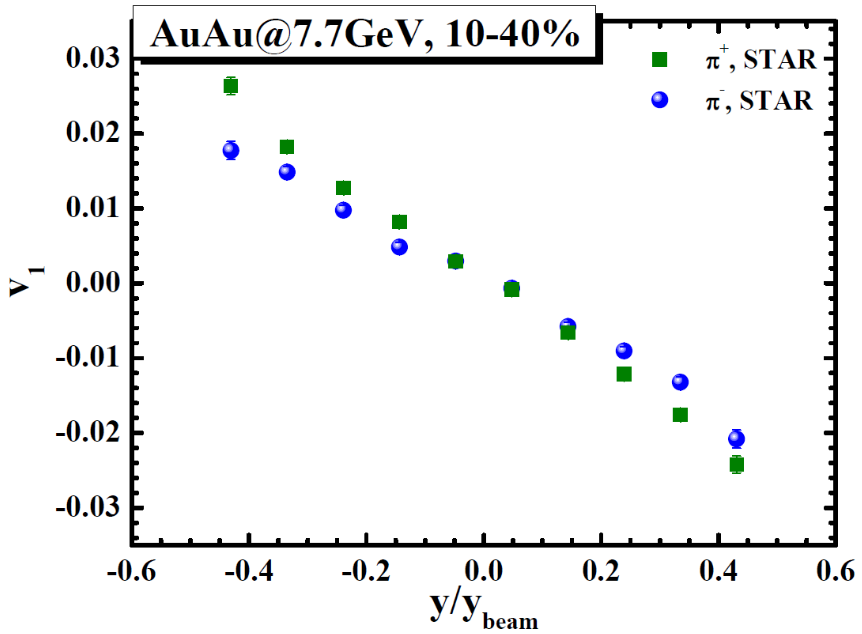


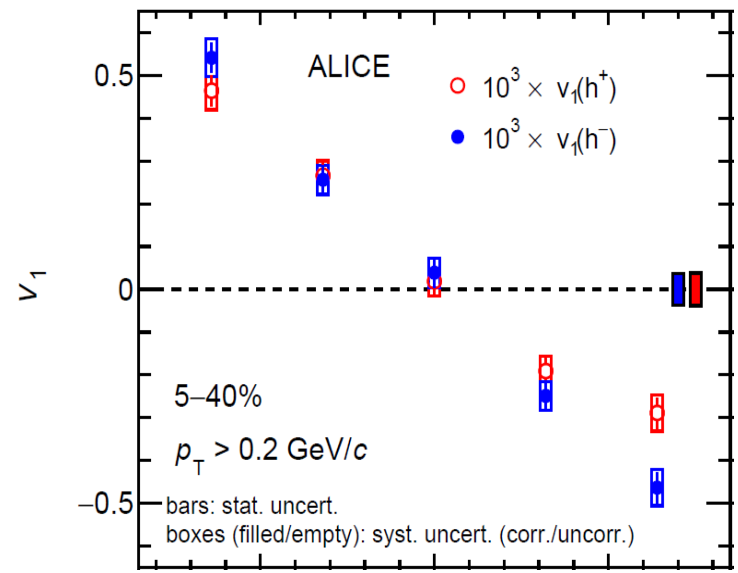


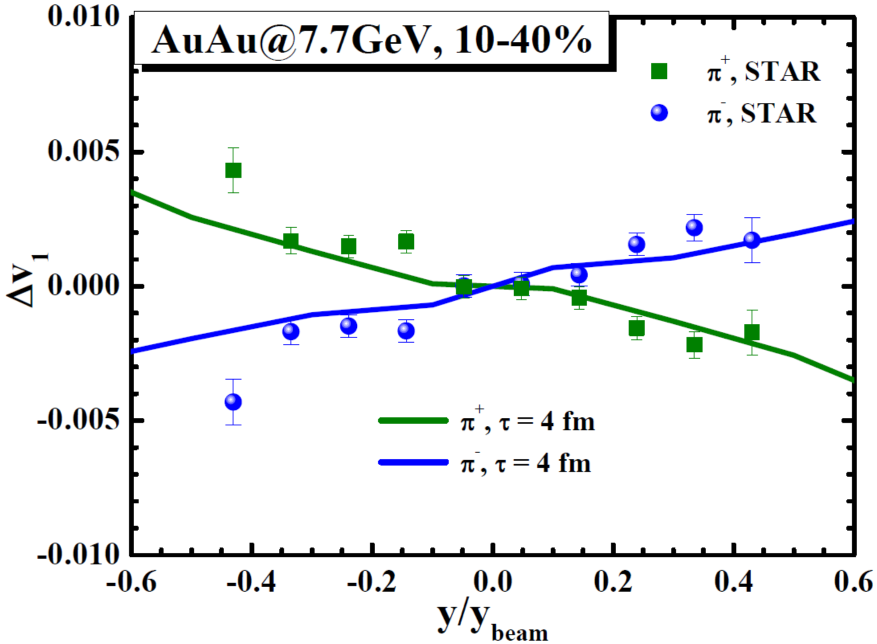




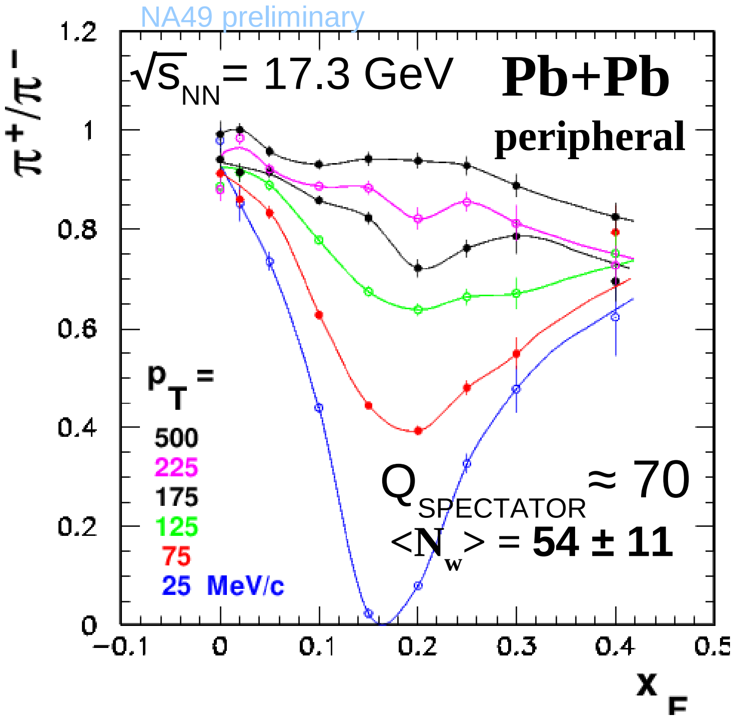
More on asimuthal anisotropies (flow)

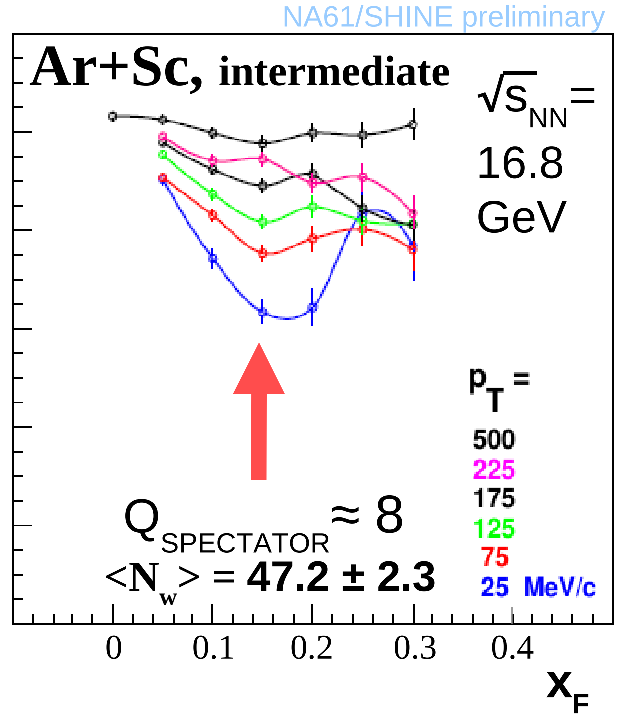


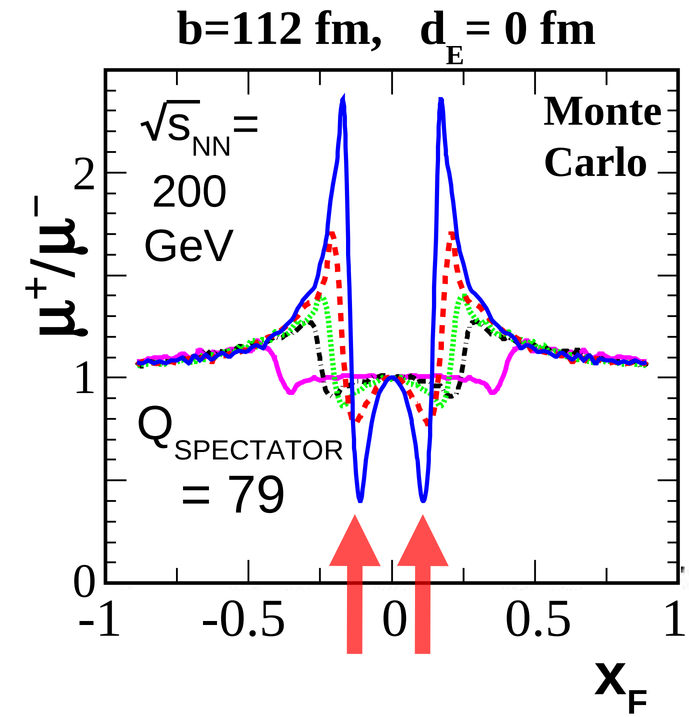


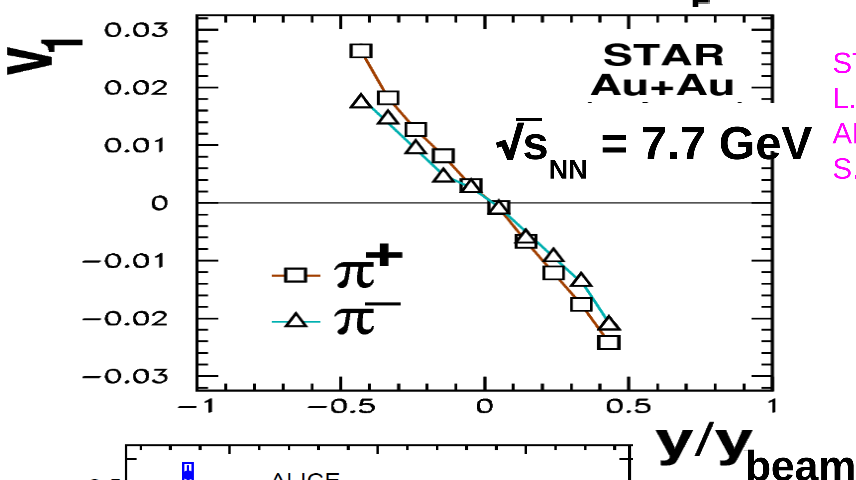


STAR:
L. Adamczyk et al., PRL 112 (2014) 162301
ALICE:
S. Acharya et al., arXiv:1910.14406 [nucl-ex]

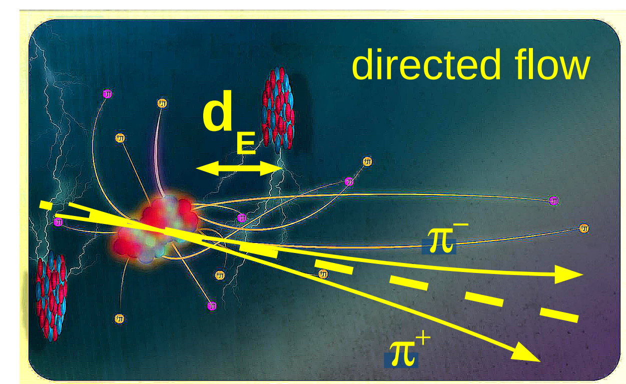


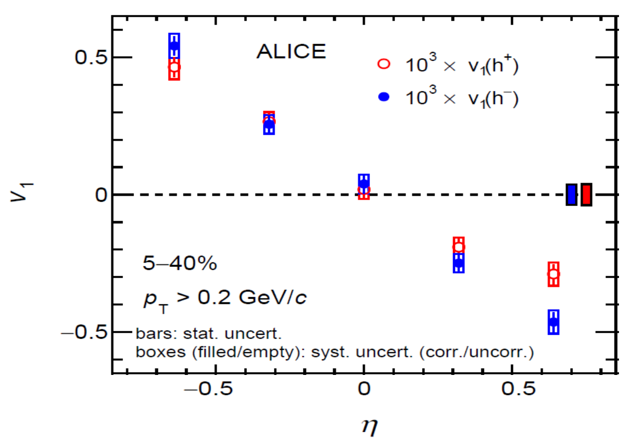






STAR:
L. Adamczyk et al., PRL 112 (2014) 162301
ALICE:
S. Acharya et al., arXiv:1910.14406 [nucl-ex]

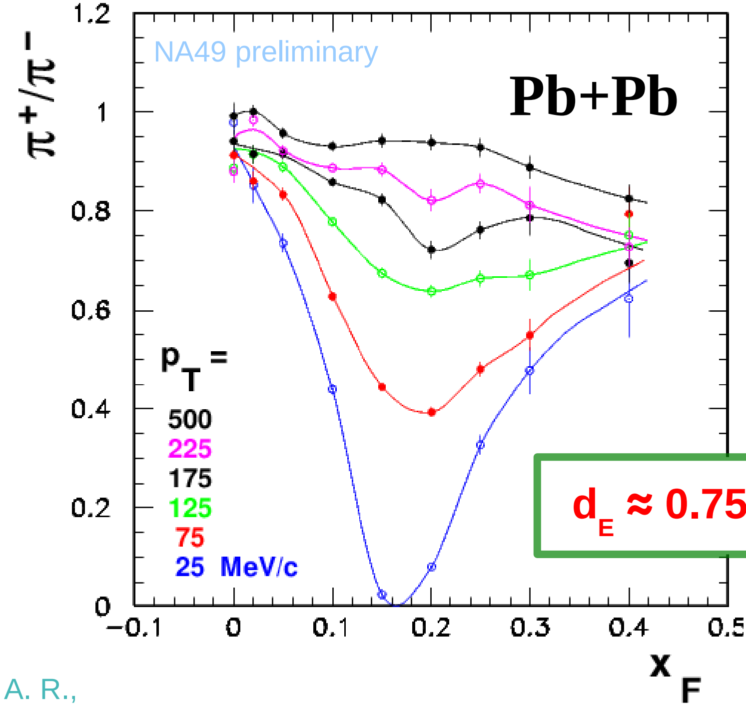


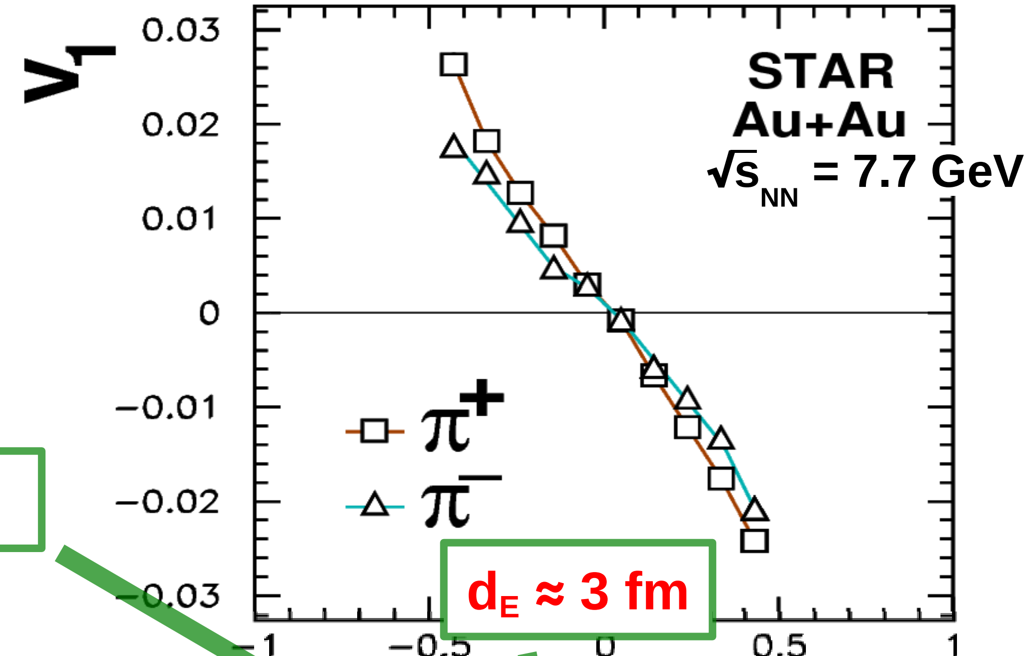


- v_1 ("directed flow") is the sidewards deflection of pions in the reaction plane :

  $v_1 \equiv < \cos(\varphi_{\text{w.r.t. reaction plane}}) >$

- the spectator charge induces *charge splitting* of v_1 .

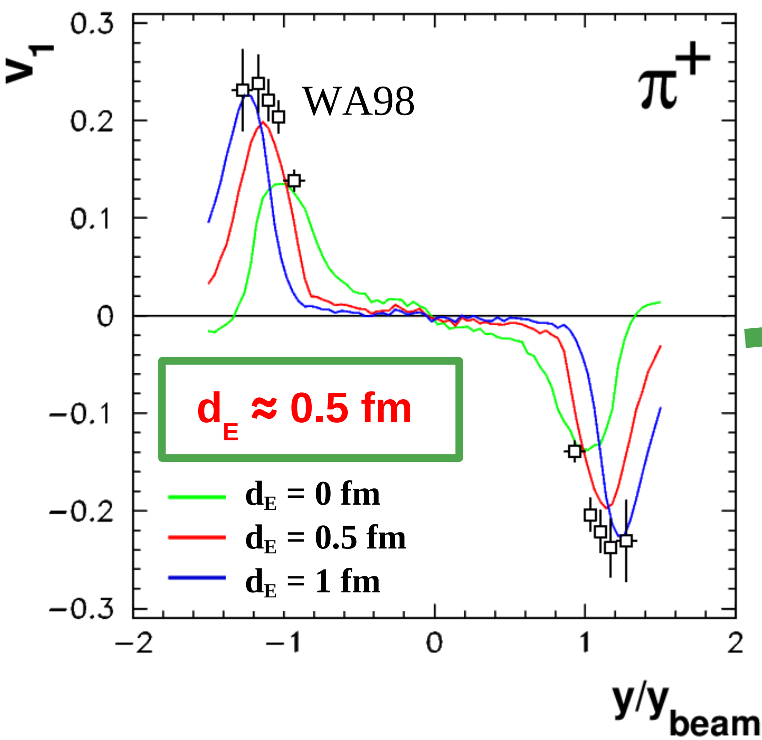




$d_E \approx 0.75$ fm

$d_E \approx 3$ fm

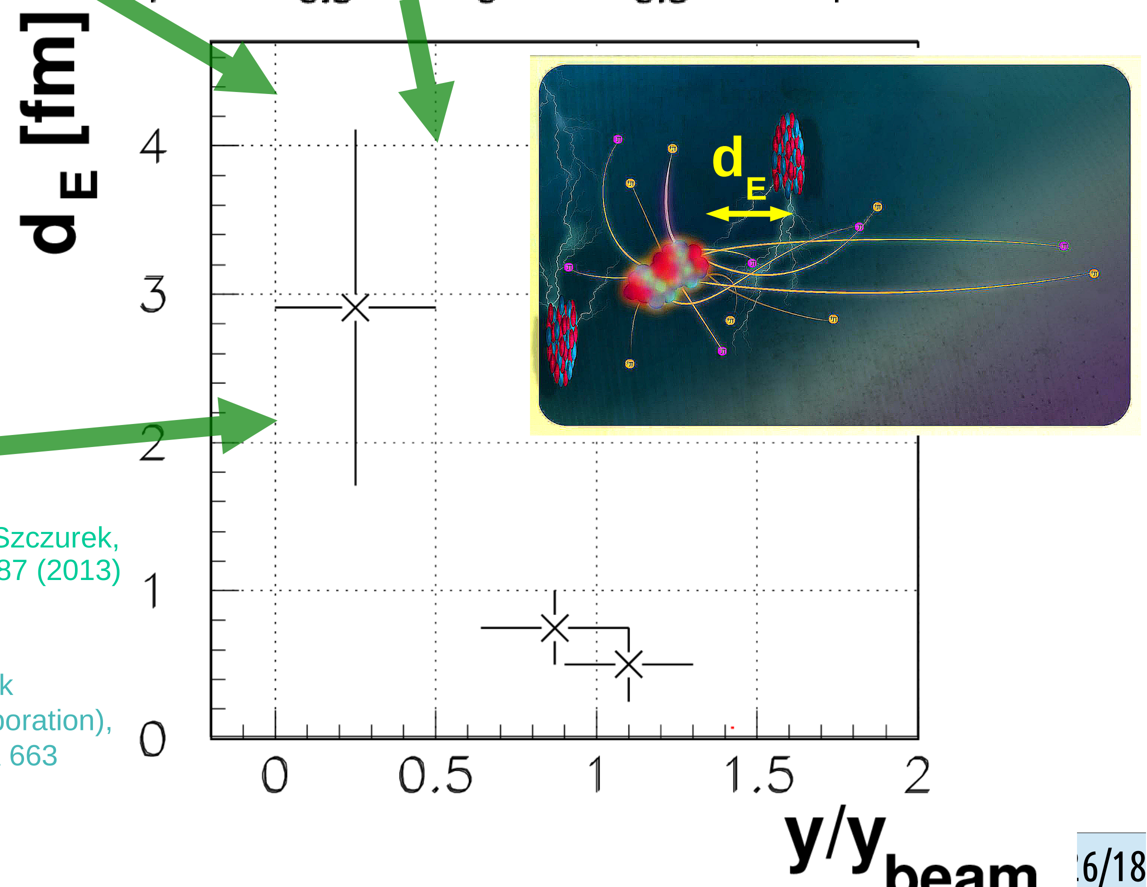
A. R.,
Acta Phys. Polon.
B42 (2011) 867



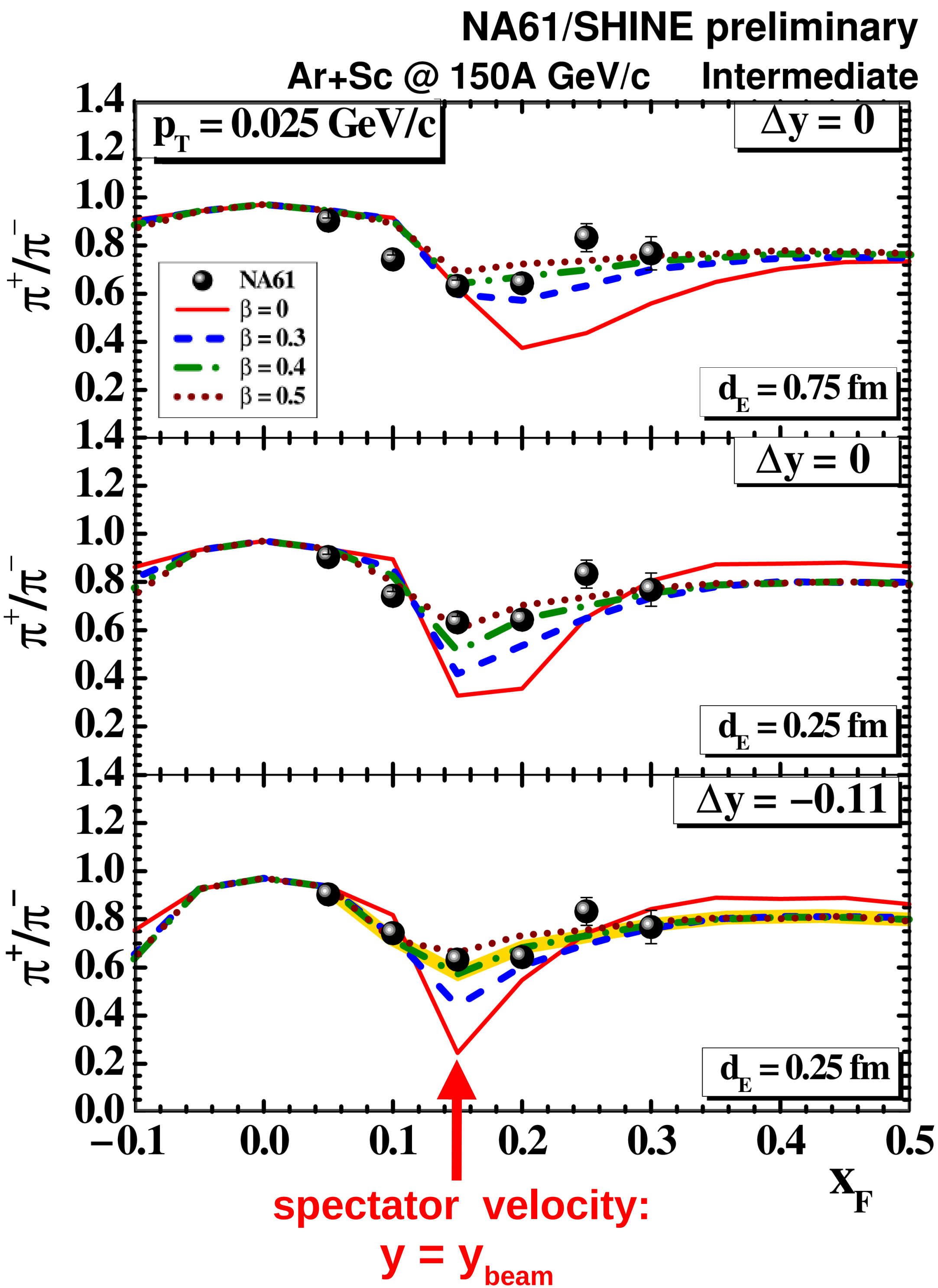
$d_E \approx 0.5$ fm

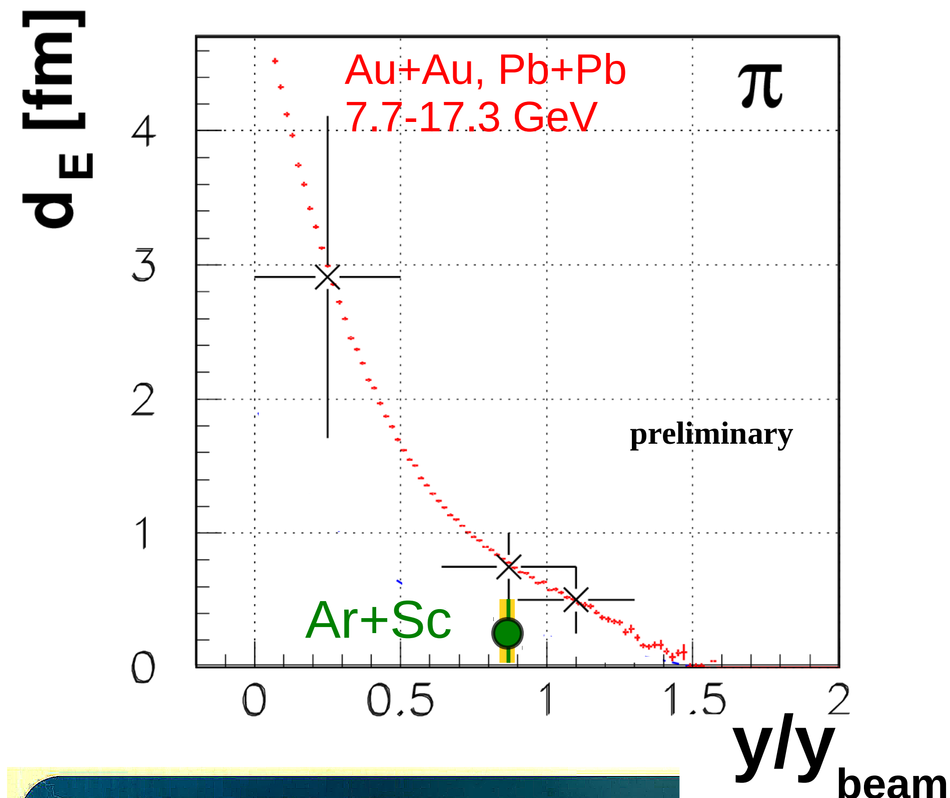
A. R. and A. Szczurek,
Phys. Rev. C87 (2013)
054909.

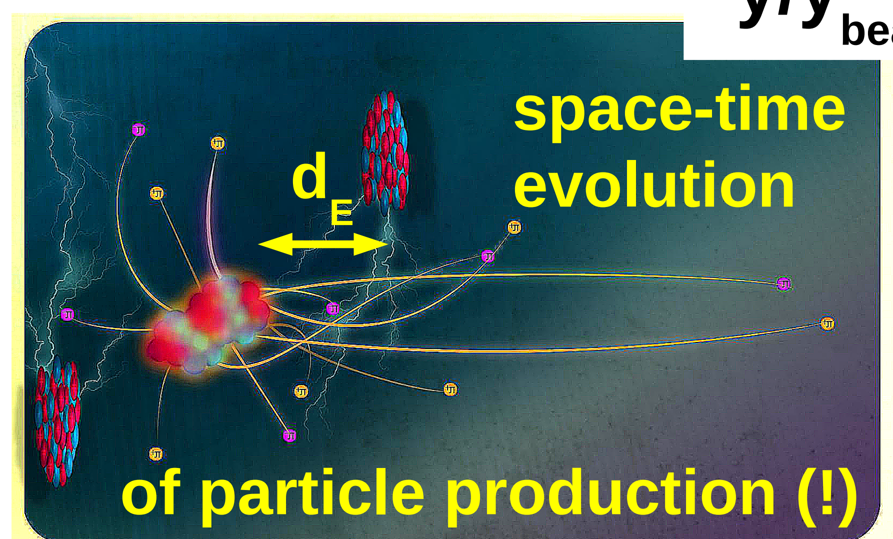
H. Schlagheck
(WA98 Collaboration),
Nucl. Phys. A 663
(2000) 725.



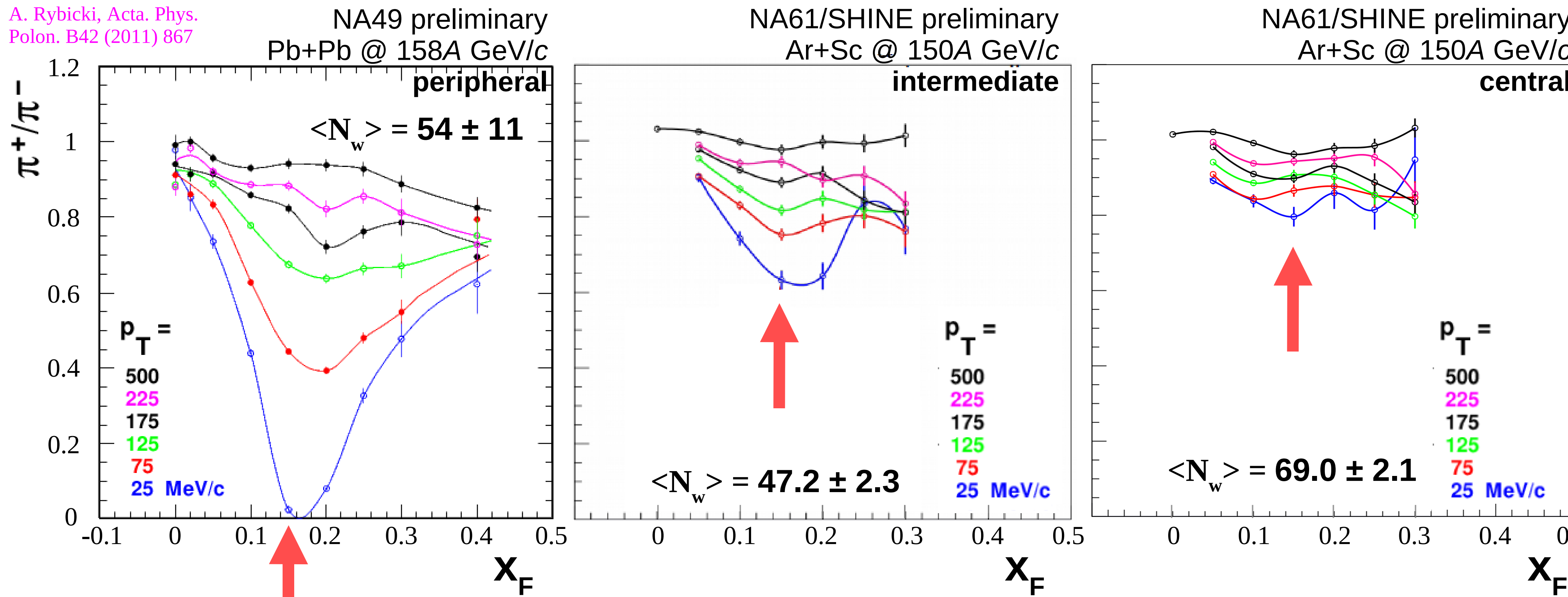
EM effects from NA61/SHINE







A. Marcinek,
Acta Phys. Polon. B50 (2019) 1127



spectator velocity:
$y = y_{beam}$

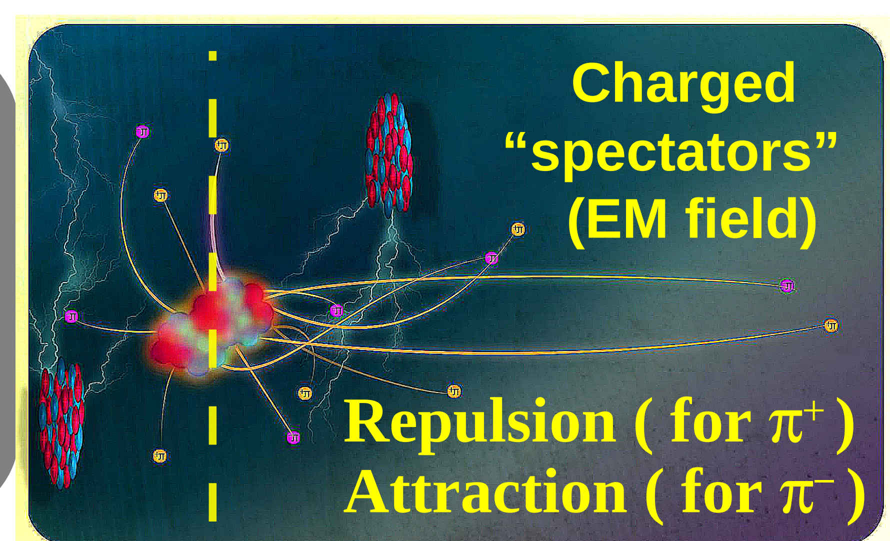
$$x_F = \frac{p_L}{p_L^{beam}}$$ (c.m.s.)

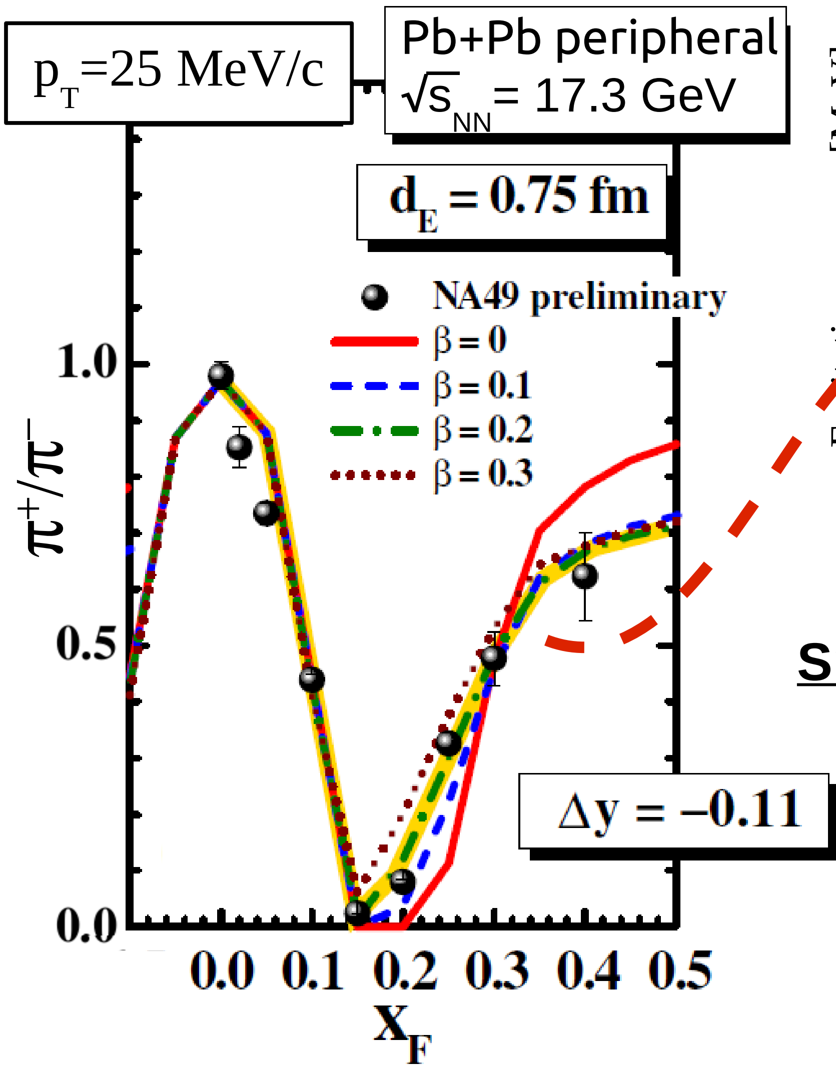
A. Marcinek,
Acta Phys. Polon. B50 (2019) 1127

(a) Peripheral Pb+Pb ($Q_{SPECTATOR} \approx 70$)
→ large EM effect, $\pi^+/\pi^- \approx 0$.

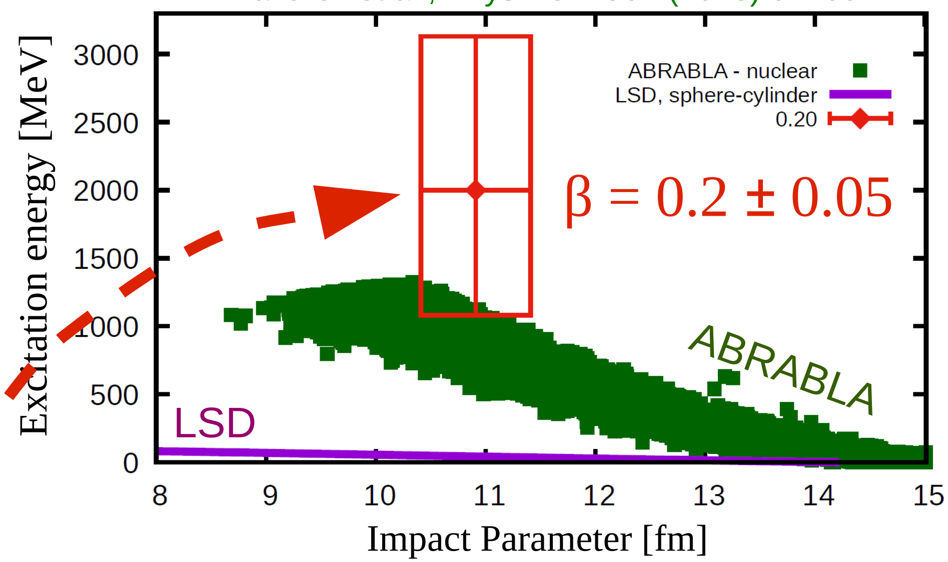
(b) Intermediate Ar+Sc ($Q_{SPECTATOR} \approx 8$)
→ visible EM effect, breaks isospin symmetry.

(c) Central Ar+Sc ($Q_{SPECTATOR} \approx 3$)
→ still visible shadow of EM effect.

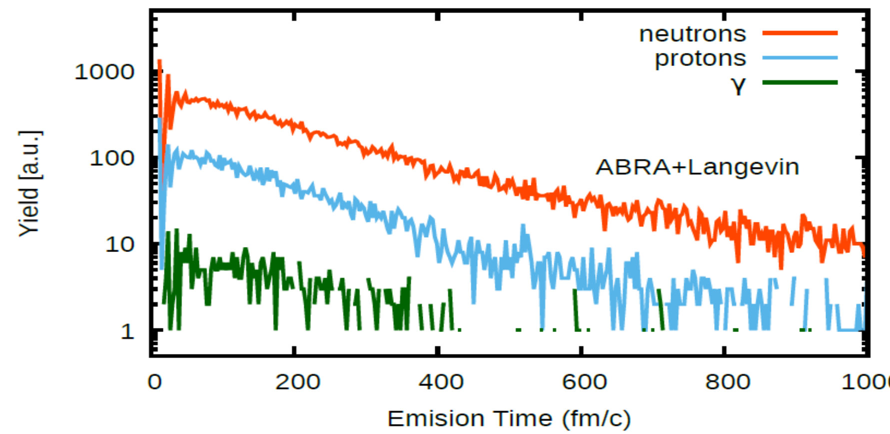


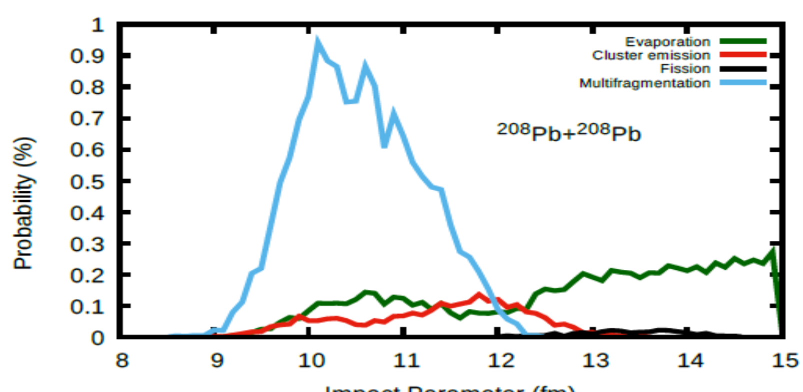


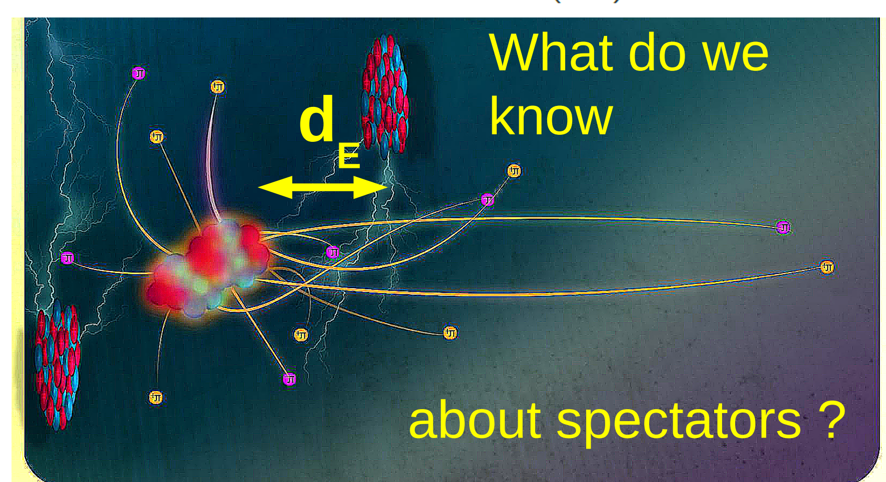
K. Mazurek et al., Phys.Rev. C97 (2018) 024604



Spectators





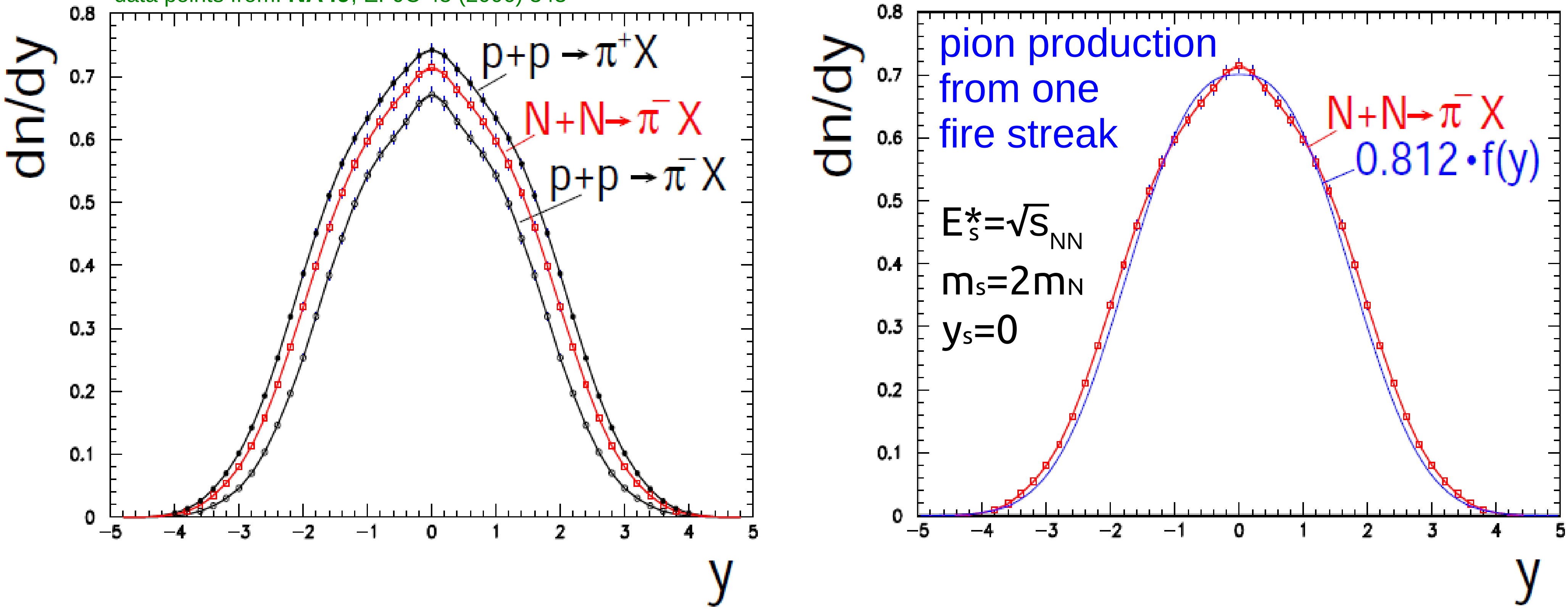


Isospin effects

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

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

data points from: **NA49**, EPJC 45 (2006) 343



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

Includes:

- characteristics of “fire streaks”

- computation of energy balance

- energy dependence

- auxiliary information on proton-nucleus

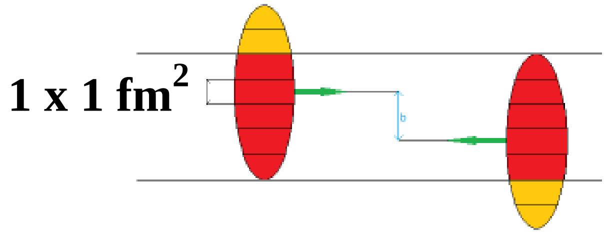
More on our simple model

For a more extended description including formulae, numerical values, tables and plots, please see PRC 99 (2019) 024908

A. S., A. R., M. K., Phys. Rev. C **95**, 024908 (2017)

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

Bricks collide . . .

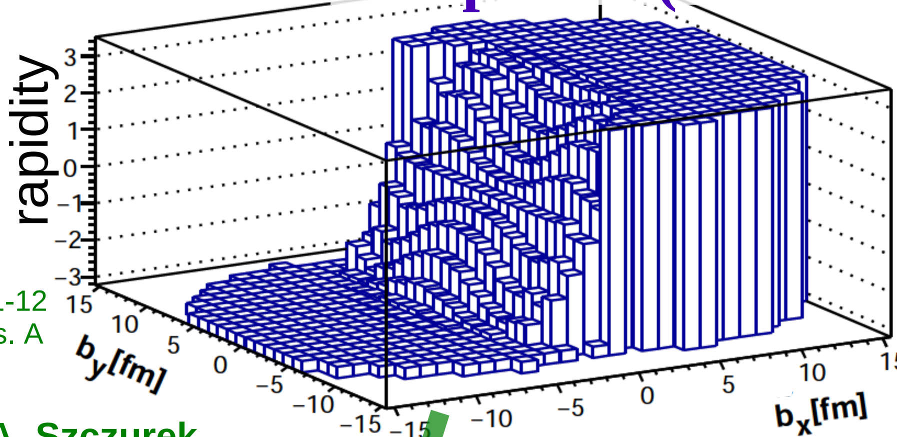


R. Hagedorn, CERN-71-12
W.D. Myers, Nucl. Phys. A

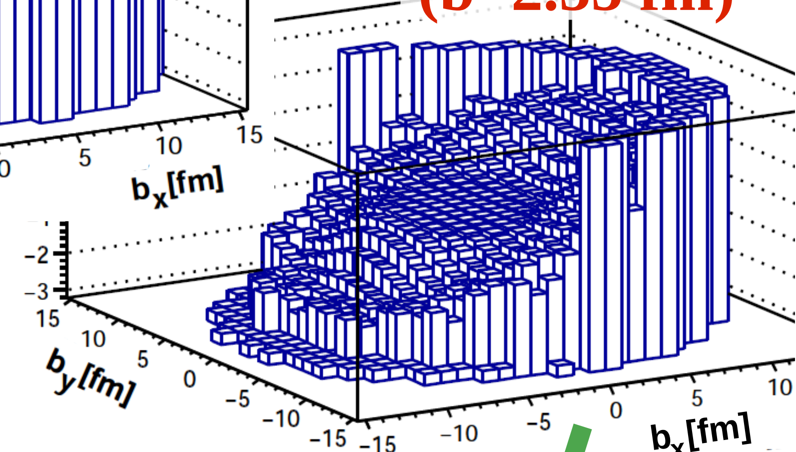
(Re)invented by A. Szczurek

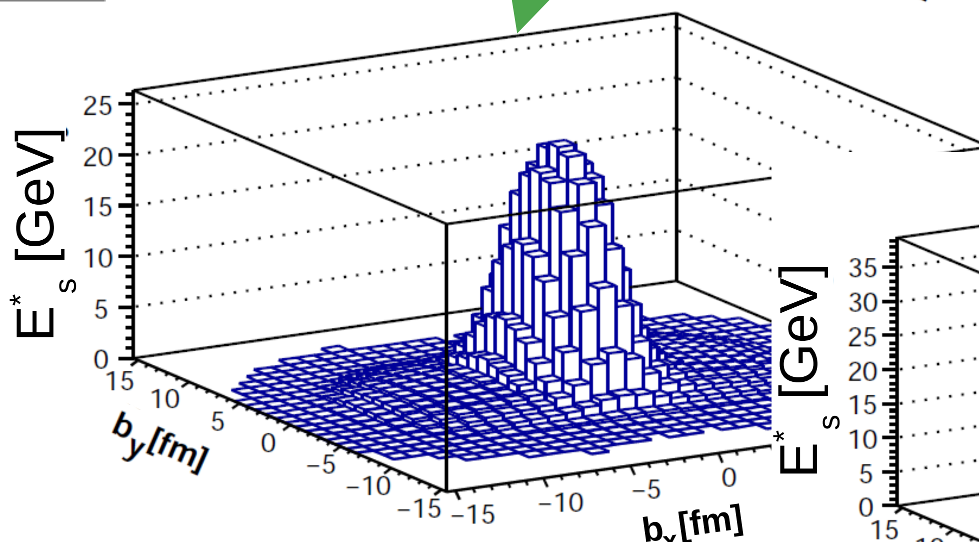
. . . and form fire streaks

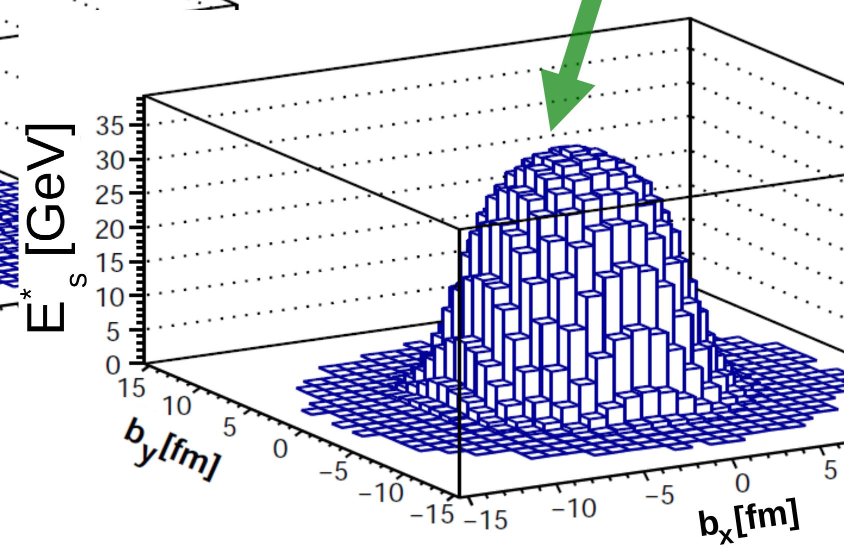
Peripheral (b=9.72 fm)



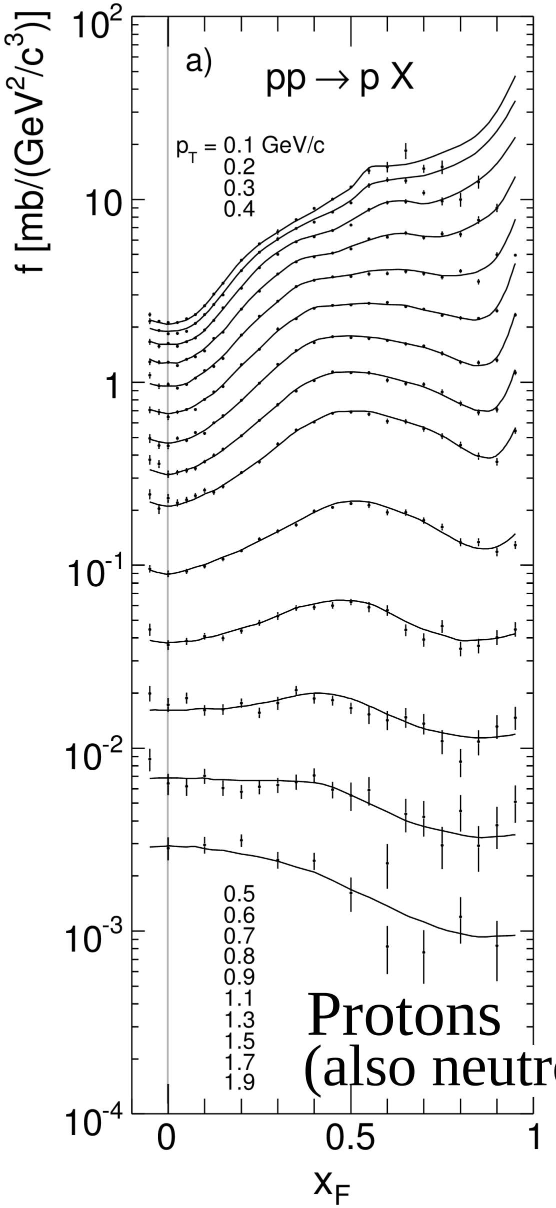
Central (b=2.55 fm)

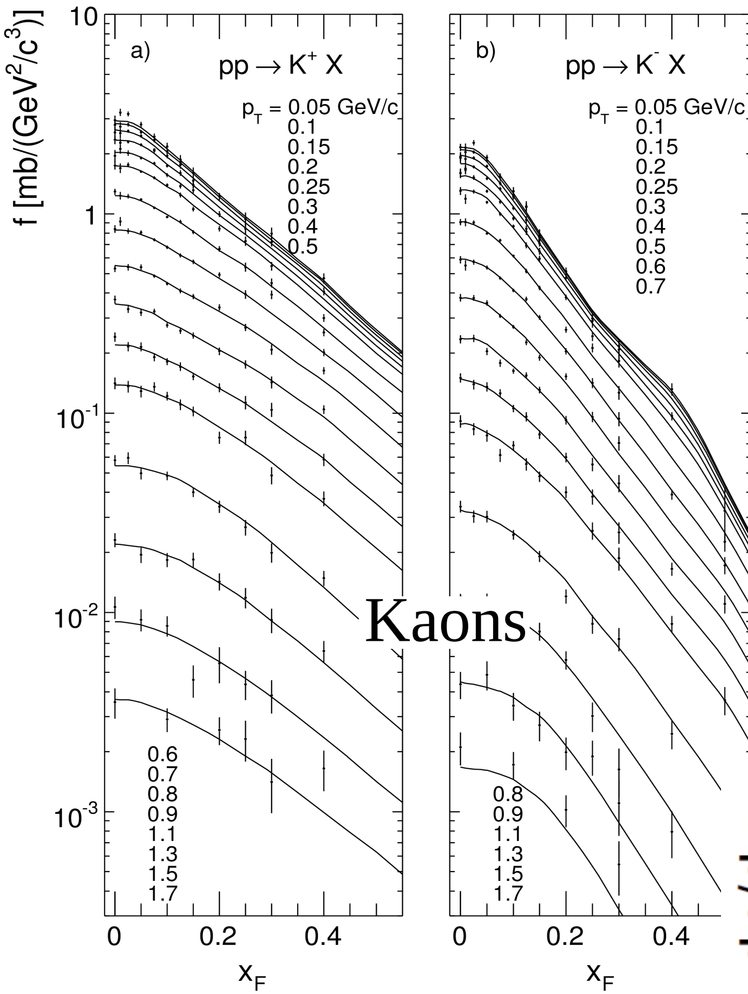


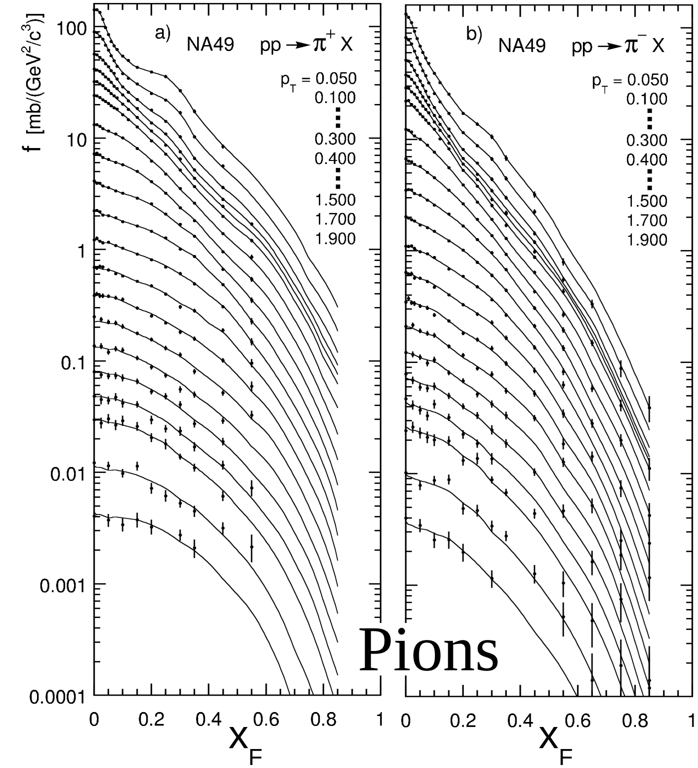




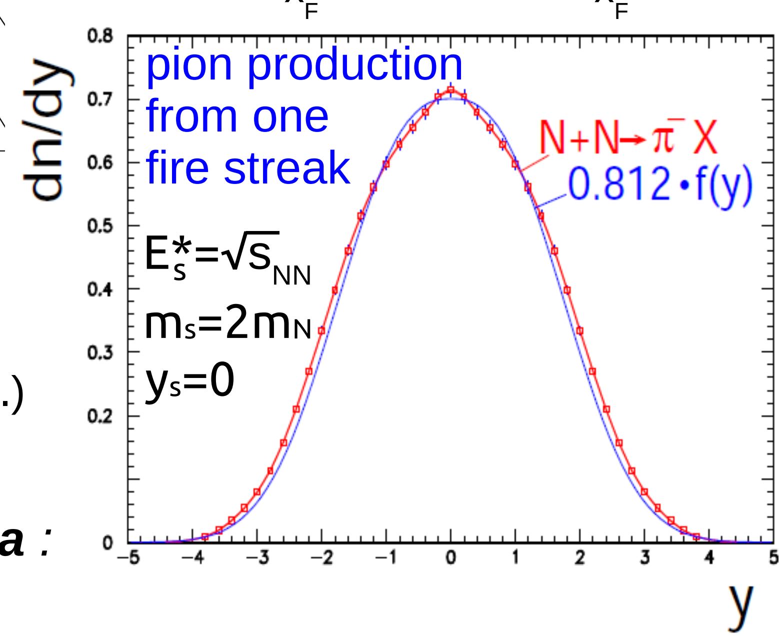
<u>**Characteristics of “fire streaks”**</u>







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



*In **p+p** collisions, the average energies of pions, kaons and protons can be computed **directly from their spectra** :*

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

i – *proton*, π^+, π^-, K^+, K^-, ...

NA49, EPJC 65 (2010) 9, EPJC 68 (2010) 1, EPJC 45 (2006) 343
arXiv:hep-ex/0510009, 0904.2708 [hep-ex], 1004.1889 [hep-ex]

Calculation of energy balance (simplified):

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

p+p: (pion energy) = **6862 MeV** ;
(kaon energy) = **918 MeV** ;
(baryon energy) → baryon inelasticity **K = 0.547**.

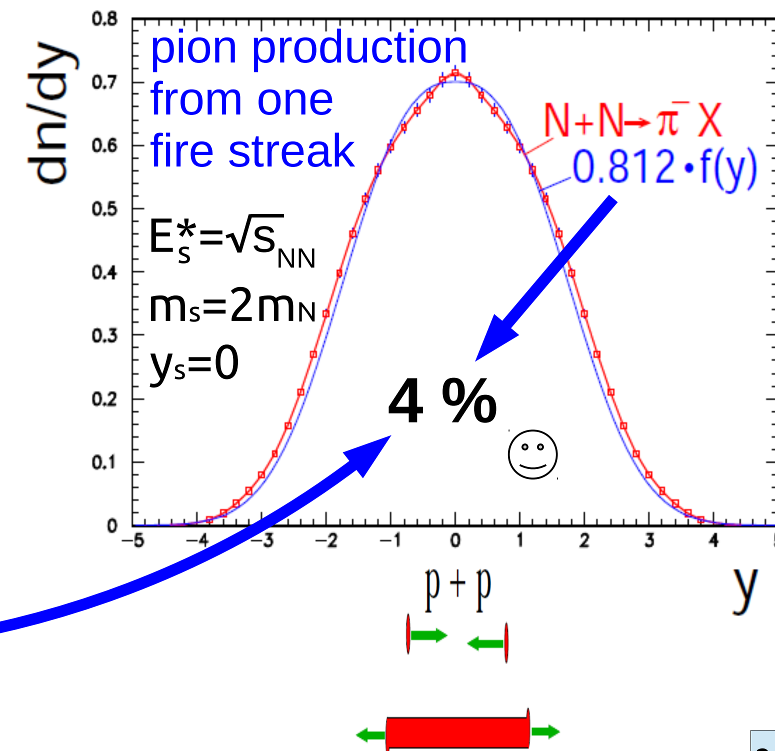
$$K = \frac{2 \cdot E_{inel}}{\sqrt{s} - 2m_p}$$

The relation between (baryon energy), (pion energy) and (kaon energy) in **Pb+Pb** collisions is calculated on the basis of:

→ baryon inelasticity in Pb+Pb, **K ≈ 0.78** ; → C.Blume, **NA49**, J.Phys. G34 (2007) 951, and refs therein.

→ the change in ***<K>/<π>*** ratios between p+p and Pb+Pb (**~2**).

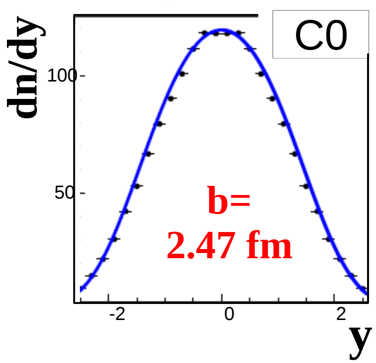
From:
NA49, EPJC 65 (2010) 9, EPJC 68 (2010) 1, EPJC 45 (2006) 343, PRC 86 (2012) 054903, and references therein.
NA49, compilation of numerical results, http://na49info.web.cern.ch/na49info/na49.

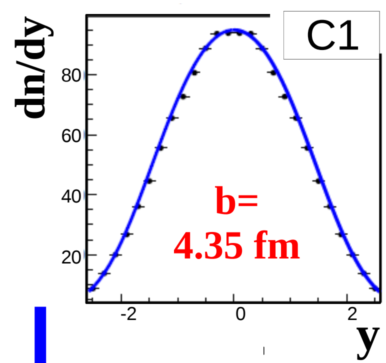


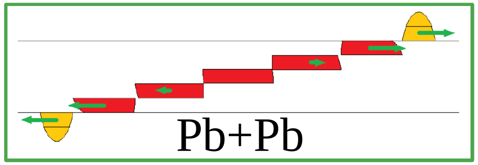
In this way we get (per unit of total collision energy):

$$\frac{\textit{Energy spent on pions in p+p}}{\textit{Energy spent on pions in Pb+Pb}} = 0.781$$

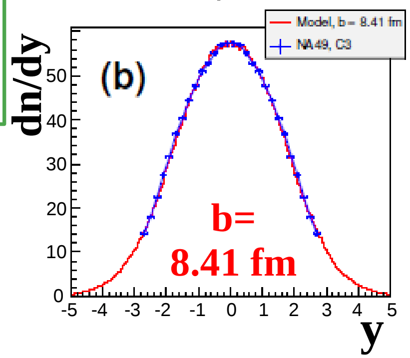
π^-, Pb+Pb, $\sqrt{s_{NN}}$= 8.8 GeV

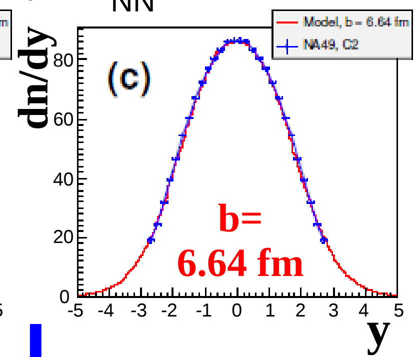






π^-, Pb+Pb, $\sqrt{s_{NN}}$= 17.3 GeV



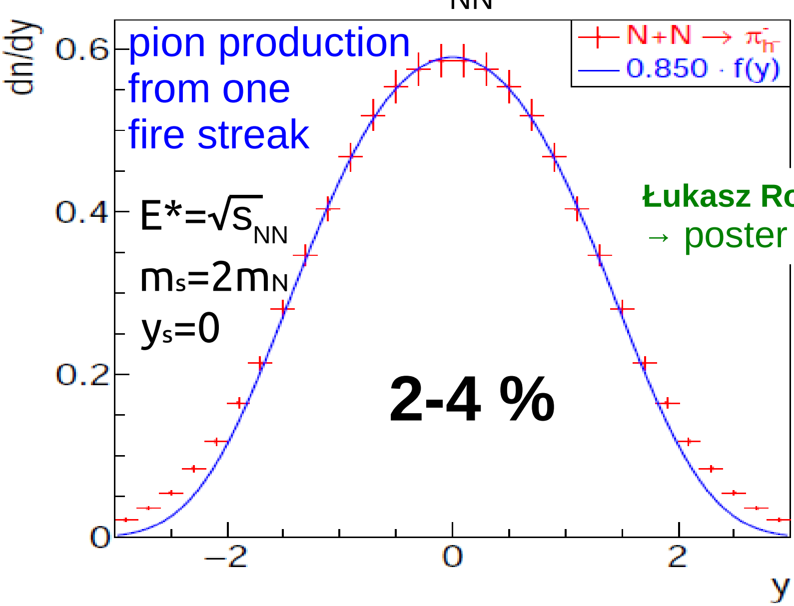


Valid for

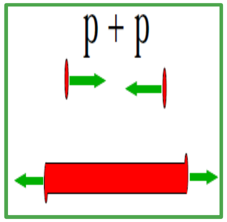
8.8 GeV ≤ $\sqrt{s_{NN}}$ ≤ 17.3 GeV

(or better)

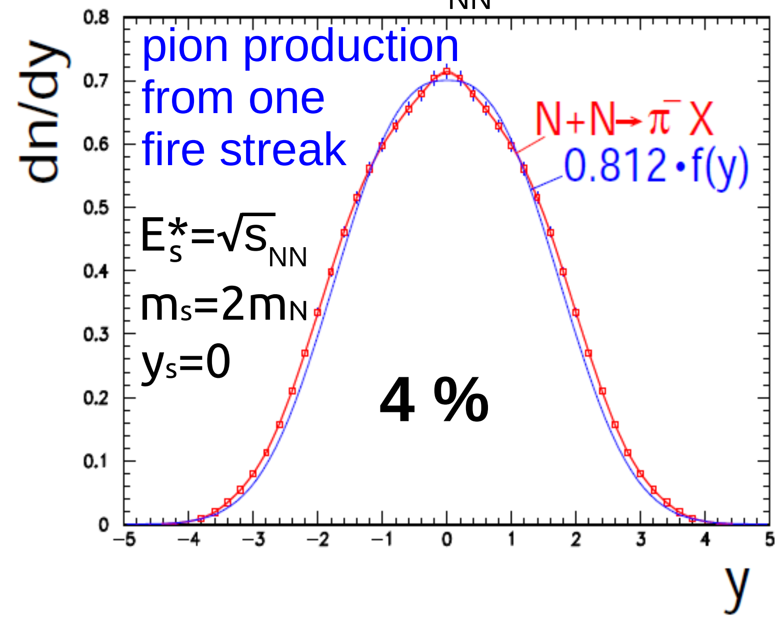
π^-, N+N, $\sqrt{s_{NN}}$= 8.8 GeV



Łukasz Rozpłochowski
→ poster **67**



π^-, N+N, $\sqrt{s_{NN}}$= 17.3 GeV



Experimental data: **NA61/SHINE**, EPJC 74 (2014) 2794, EPJC 77 (2017) 671

The energy dependence of the fire streak fragmentation function
(PRC 99 (2019) 024908, Appendix B)

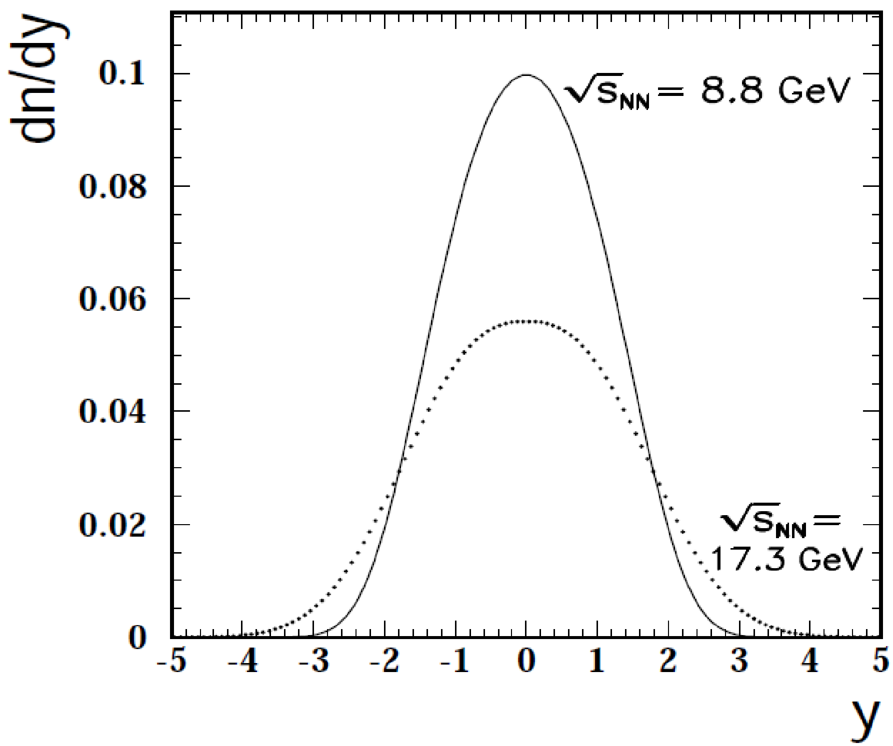
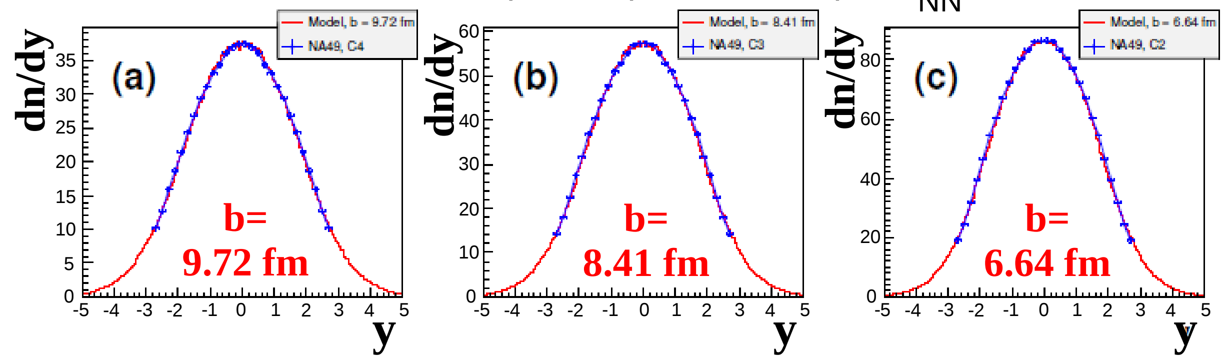


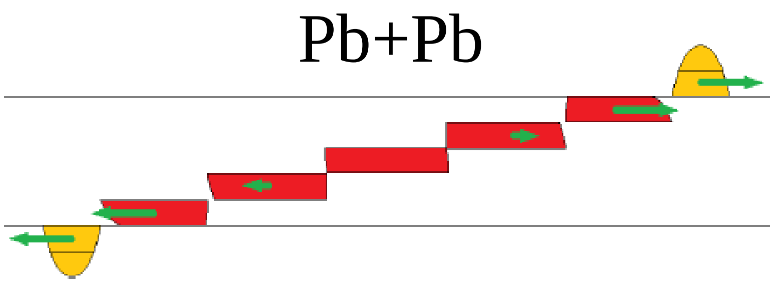
FIG. 7:

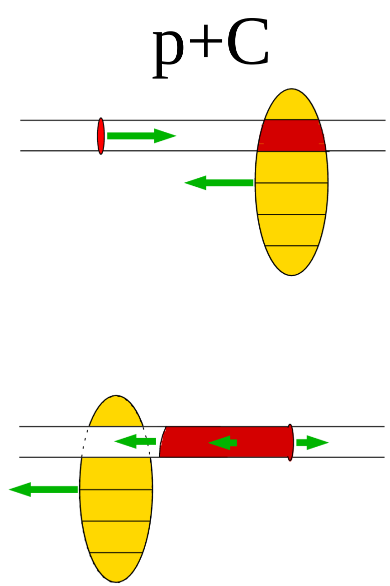
Comparison of single fire-streak fragmentation functions used for the description of π^- rapidity distributions in Pb+Pb collisions at $\sqrt{s_{NN}} = 8.8$ GeV (solid) and at $\sqrt{s_{NN}} = 17.3$ GeV (dotted). The two presented functions are given by Eq. (2.1) with $(E_s^* - m_s) \equiv 1$ GeV. The numerical values of the function parameters are given in the text.

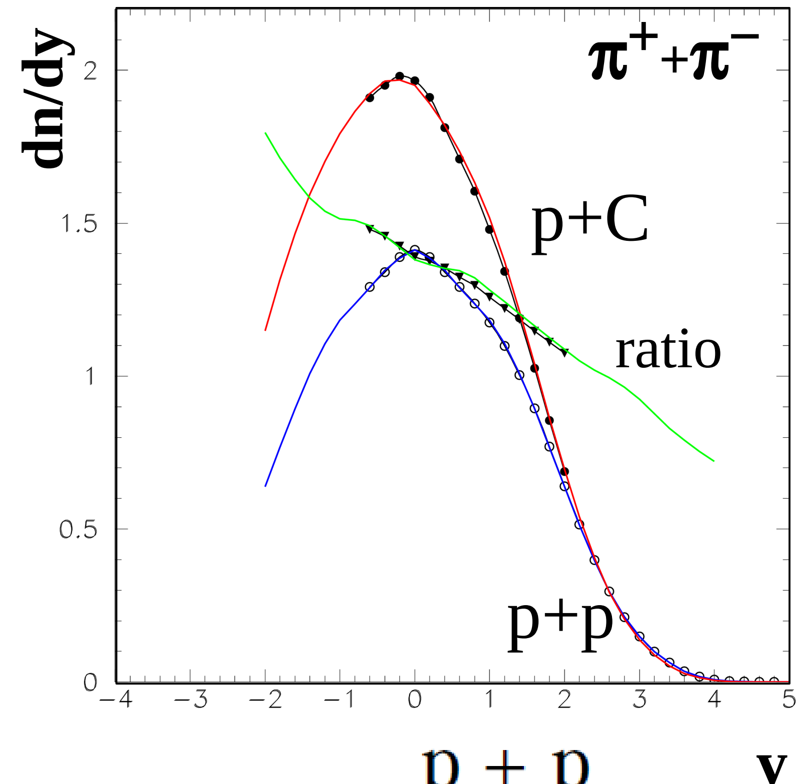
NA49, π^-, Pb+Pb, $\sqrt{s_{NN}}$ = 17.3 GeV

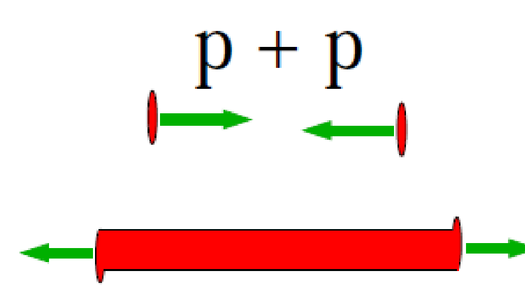


- Link between p+p, p+A, and A+A collisions.



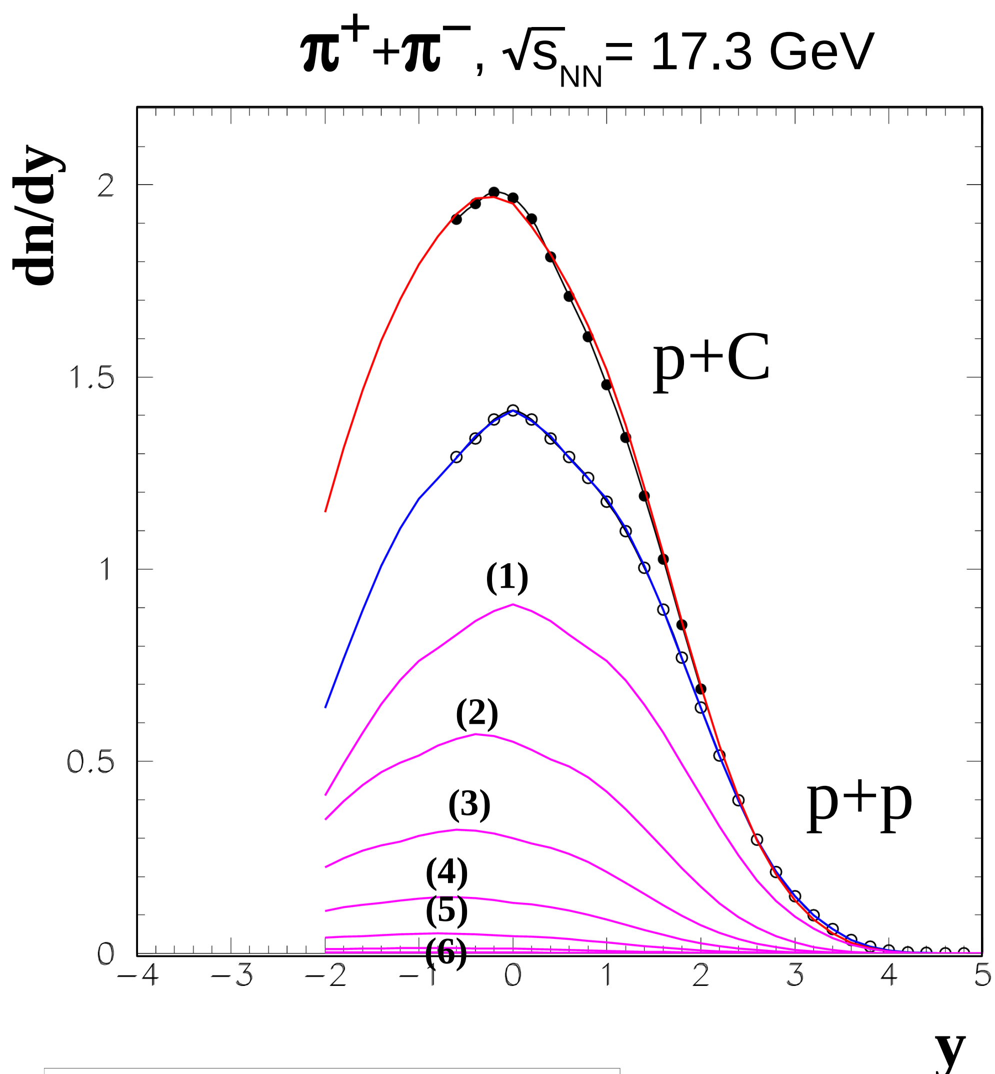


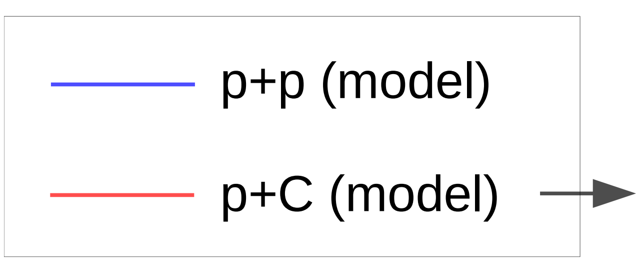


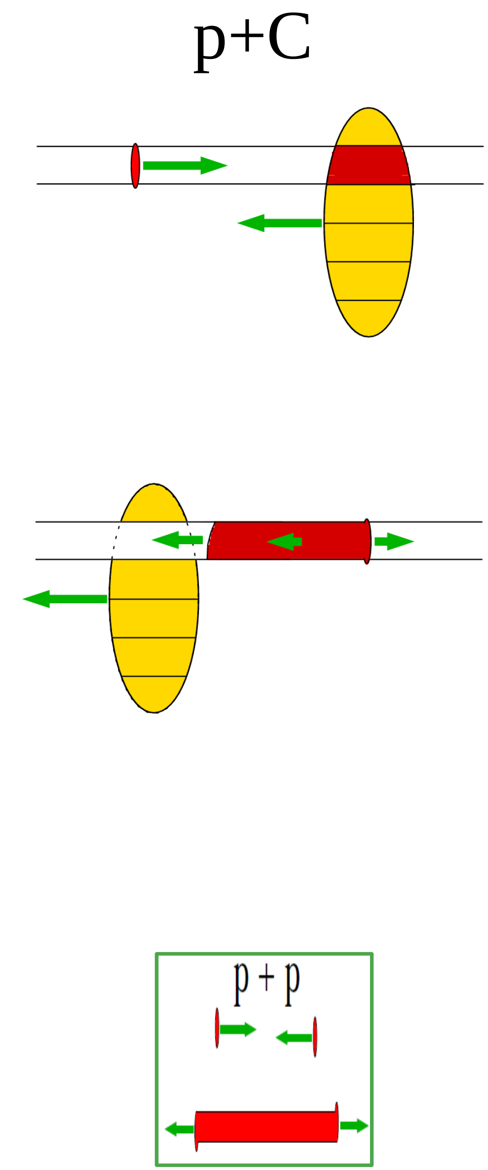


- Calibration of the model with p+p/p+A/A+A rapidity spectra... done!

Experimental data points from: **NA49**, EPJC 45 (2006) 343, EPJC 49 (2007) 919







Energy balance:
change in energy spent on pions by **+13 %** w.r.t. p+p, can be explained by baryon stopping.