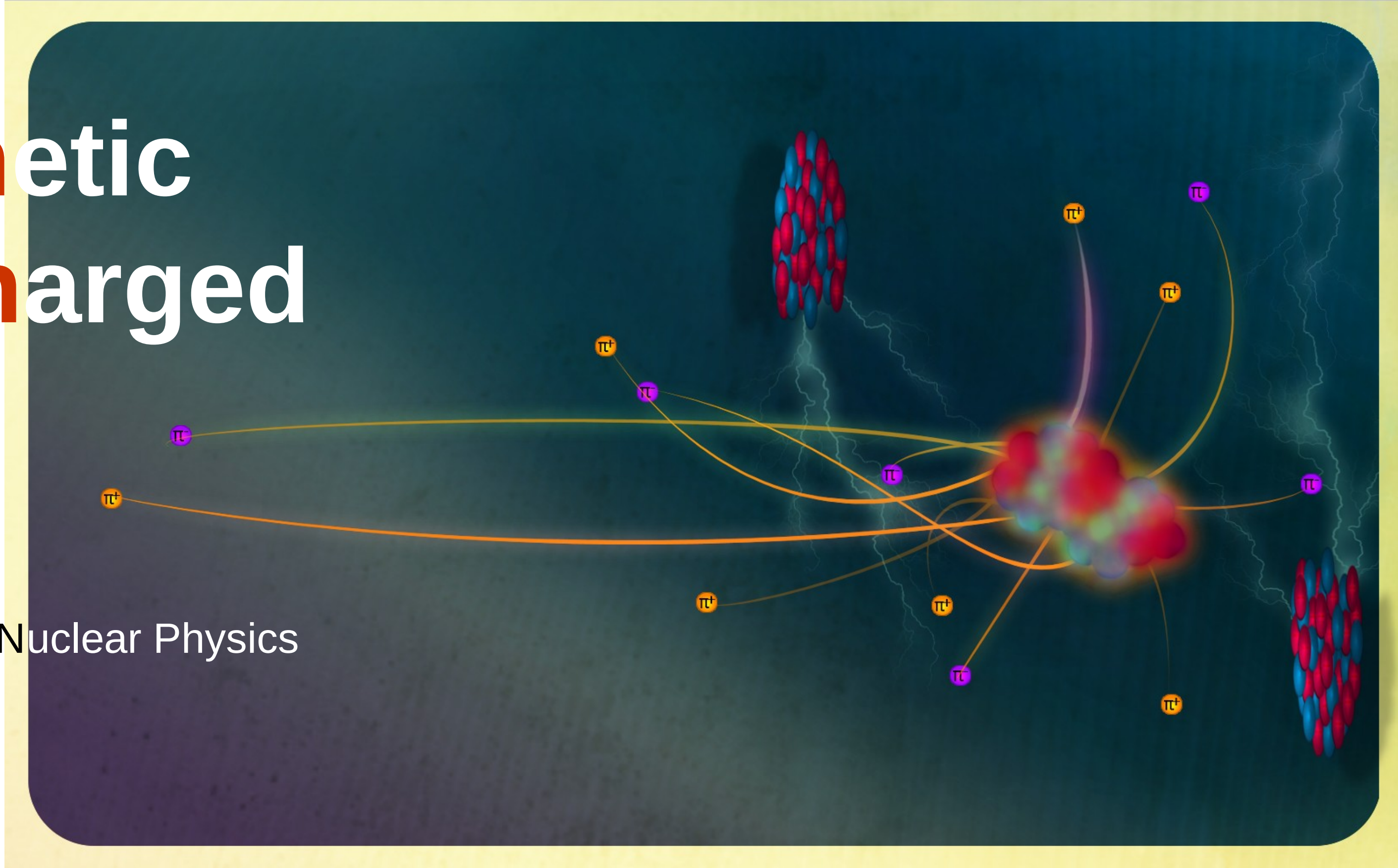
Electromagnetic effects on charged particles

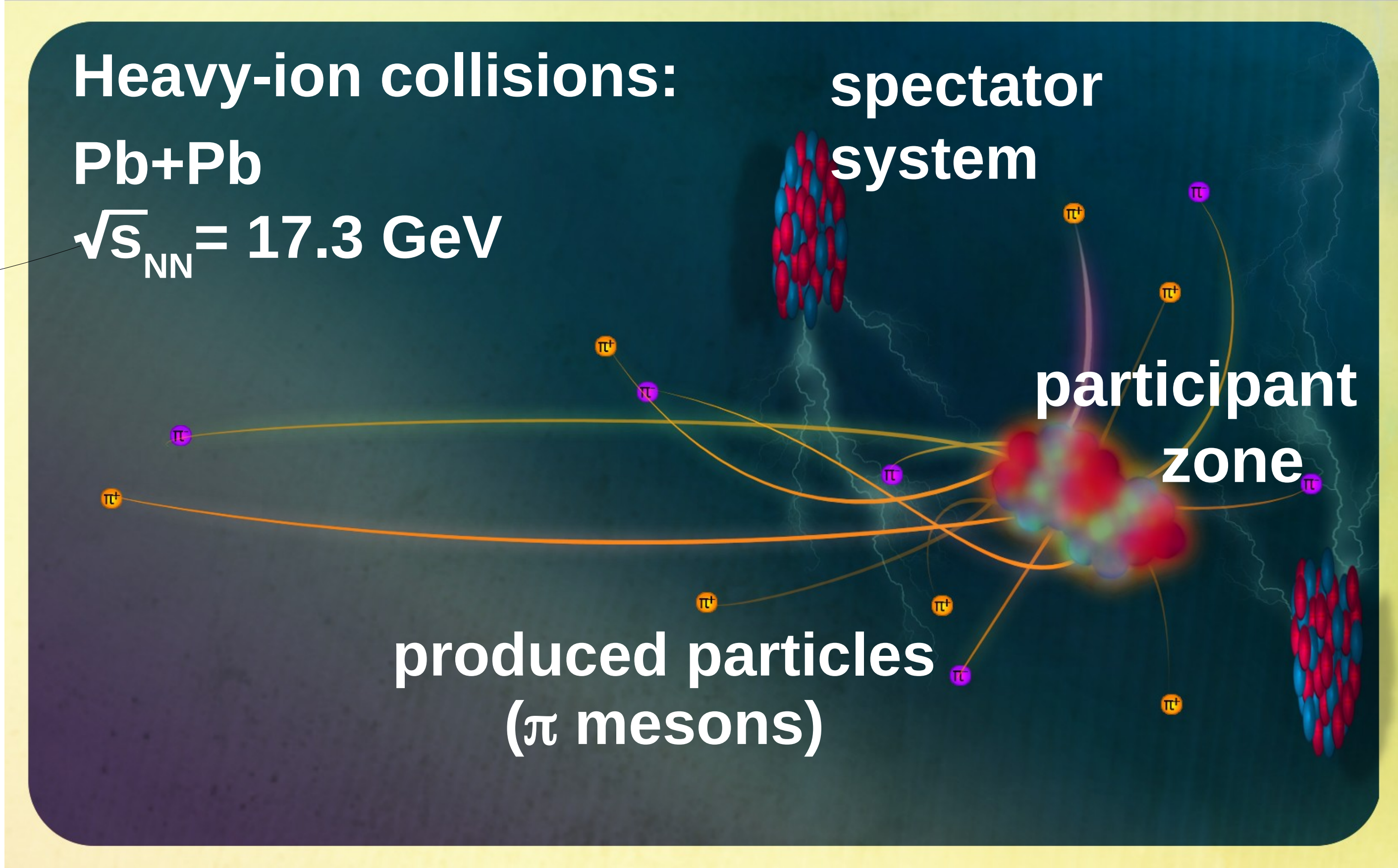


by I. Sputowska

Andrzej Rybicki
H. Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences

1) **Prologue ;**
2) **Do never agree with your boss ;**
3) **EM effects on charged particles ;**
4) **Space-time evolution of the system ;**
5) **EM effects in small systems ;**
6) **UPC's ?**
7) **<u>No</u> epilogue.**

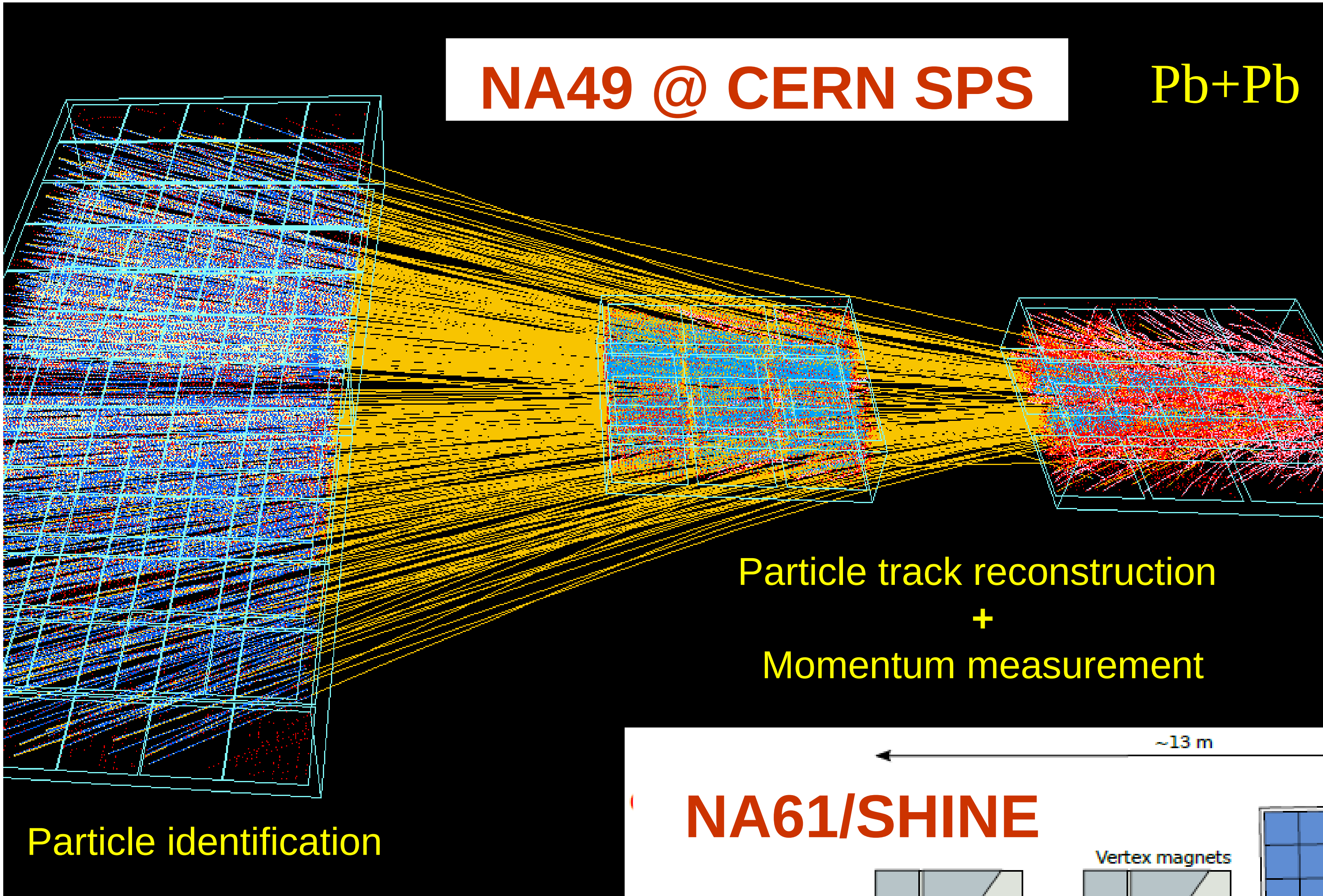
Collision energy in the c.m.s. (center-of-mass system), per one pair of colliding nucleons.



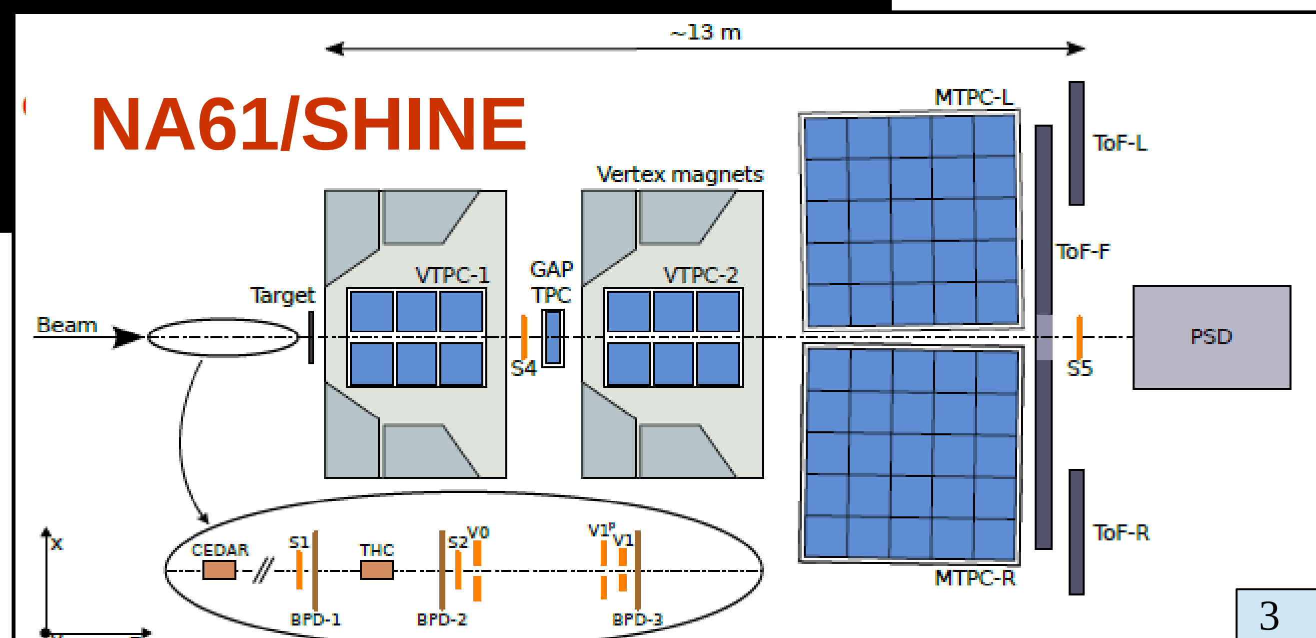
by I. Sputowska

1) Prologue

- Charged spectators generate electromagnetic fields.
- These modify charged pion spectra in the final state.
- We use this effect as a new source of information on the space-time evolution of the system.



Pb beam
E = 158 GeV/N

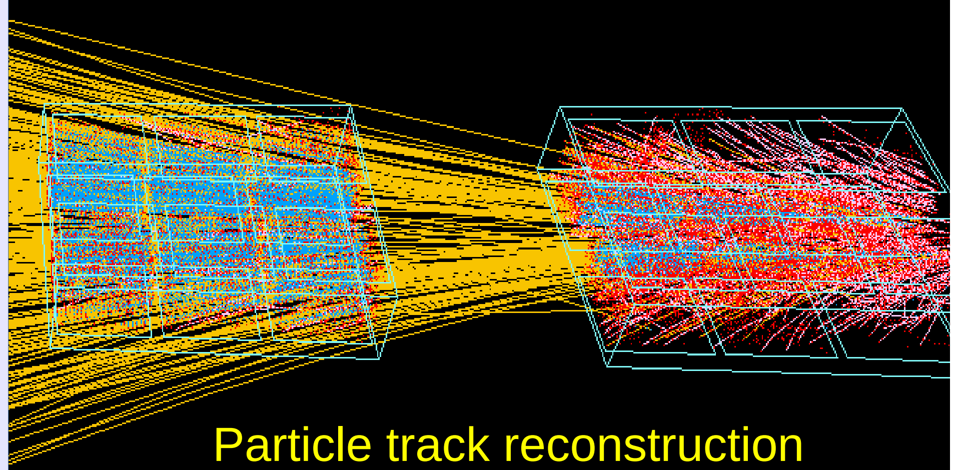


Please note:
advantages of fixed-target w.r.t. collider experiments:

- typically better coverage of kinematically available phase-space (p_x,p_y,p_z) : "forward" hemisphere of the collision.
- Full coverage of low transverse momentum starting from p_T=0 ; ($p_T=\sqrt{p_x^2+p_y^2}$)
- Easier to develop (add new subdetectors) ;
- Cheaper (?)

NA49 @ CERN SPS

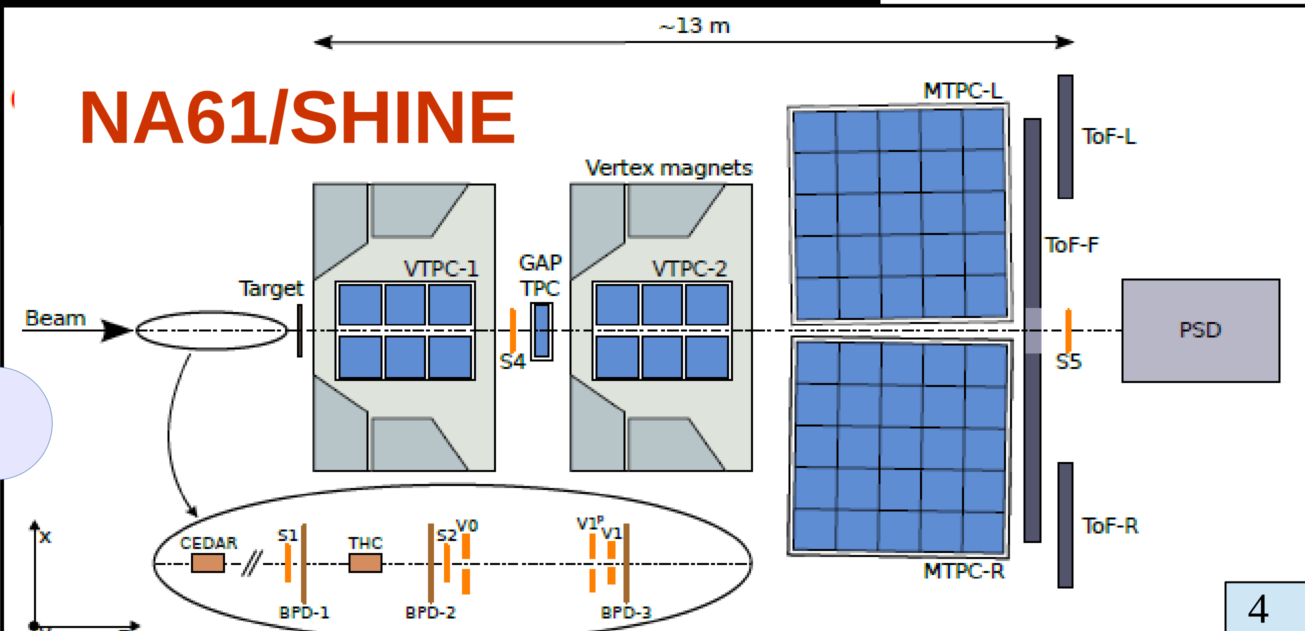
Pb+Pb



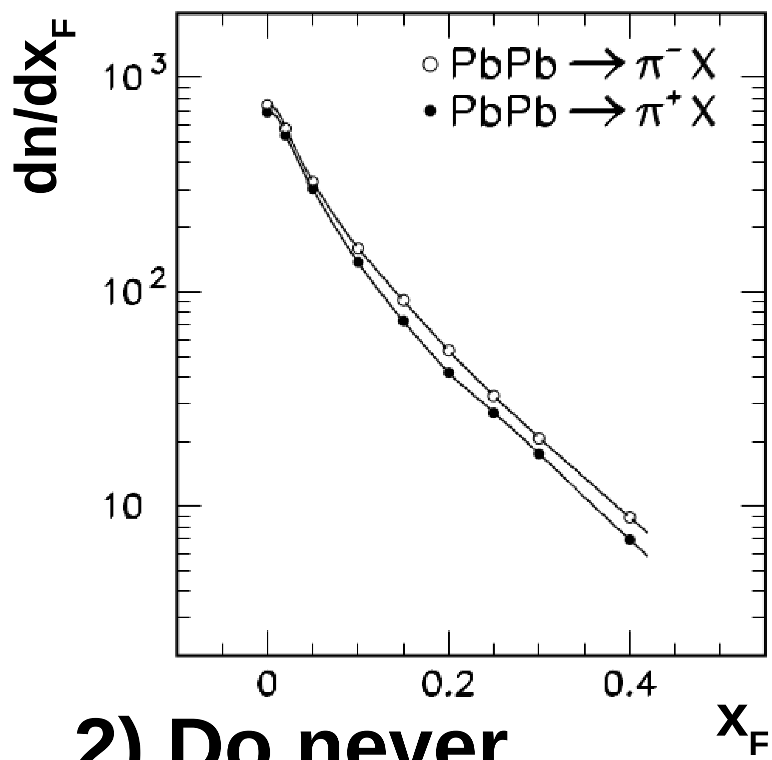
Pb beam
E = 158 GeV/N

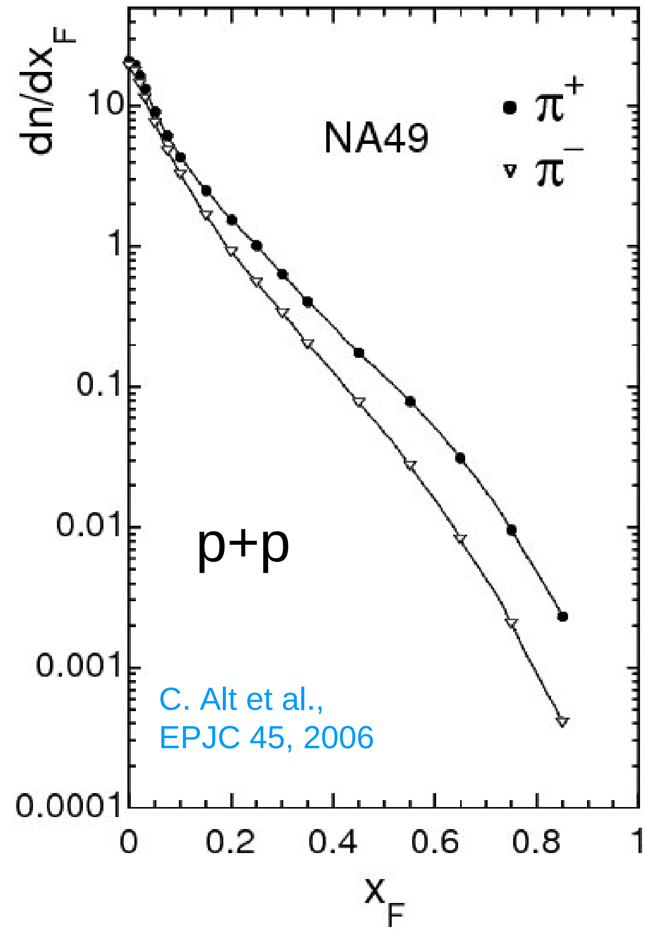
Particle track reconstruction
+
Momentum measurement

NA61/SHINE



NA49 preliminary





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

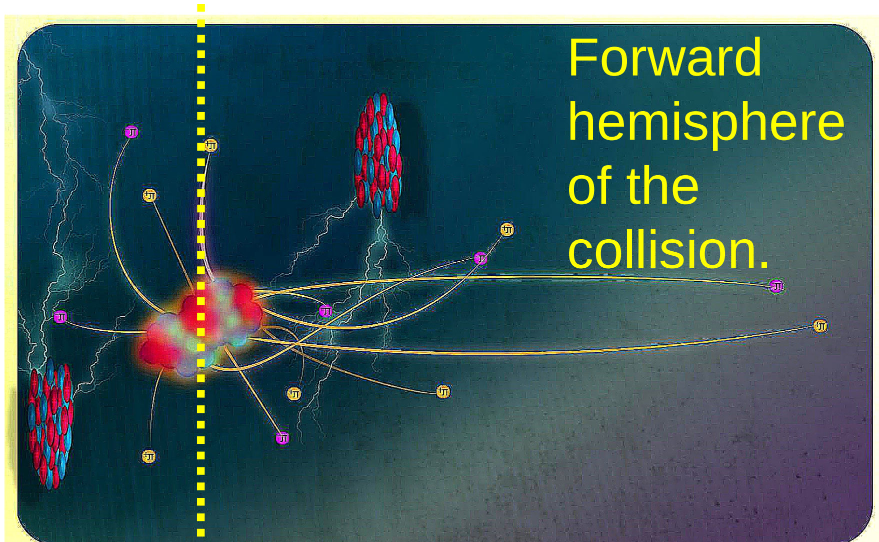
(c.m.s.)

2) Do never agree with your boss (*)

A historical (?) question:

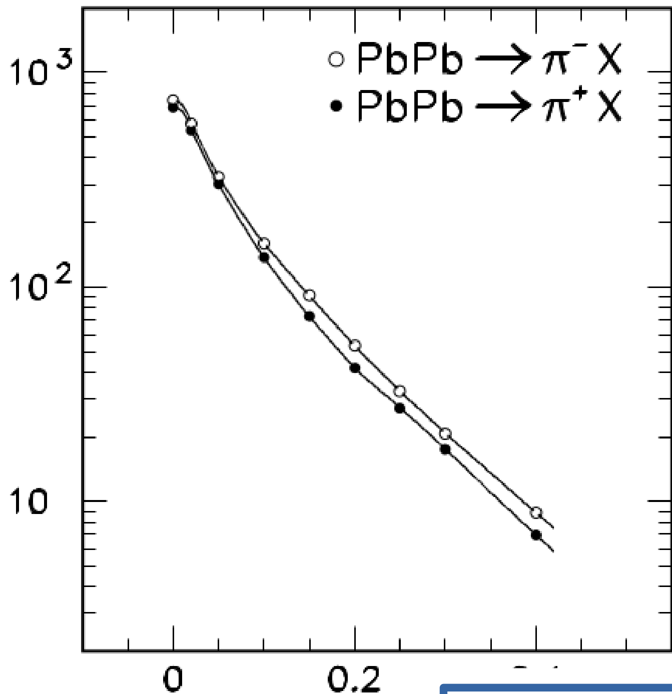
- what is a heavy-ion collision?

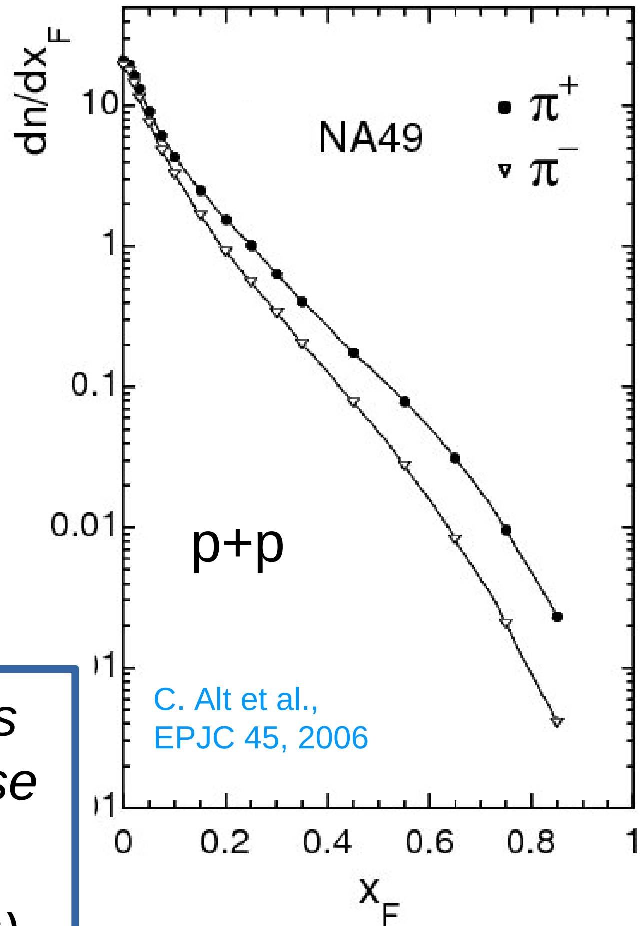
A simple consequence of nucleon-nucleon processes? “New” physics? Both?



(*) unless present in this room

NA49 preliminary





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

(c.m.s.)

2) Do never agree with y boss (*)

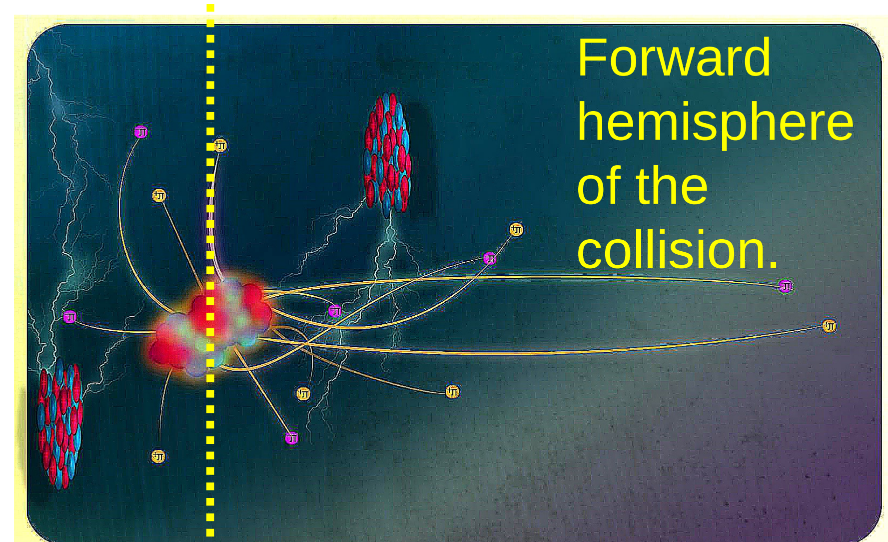
*Now I will discuss the **ratios** of these distributions:*

$$\pi^+/\pi^- = \frac{dn/dx_F(\pi^+)}{dn/dx_F(\pi^-)}$$

A historical (?) qu

- what is a heavy-ion collision?

A simple consequence of nucleon-nucleon processes? “New” physics? Both?

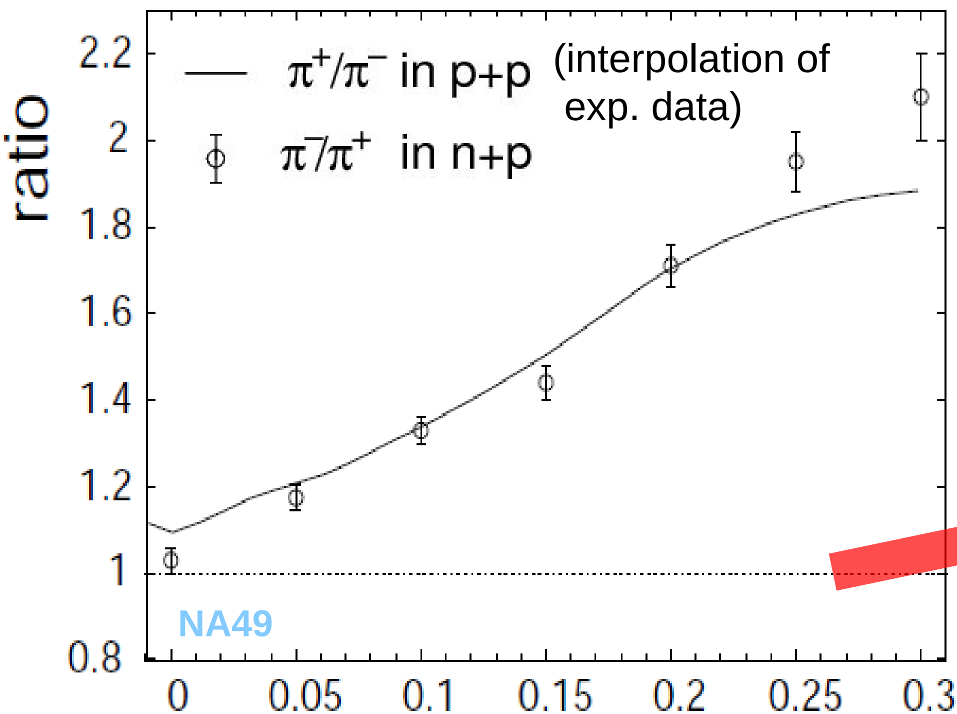


(*) unless present in this room

π^+/π^- ratios in Pb+Pb @ $\sqrt{s_{NN}}$= 17.3 GeV

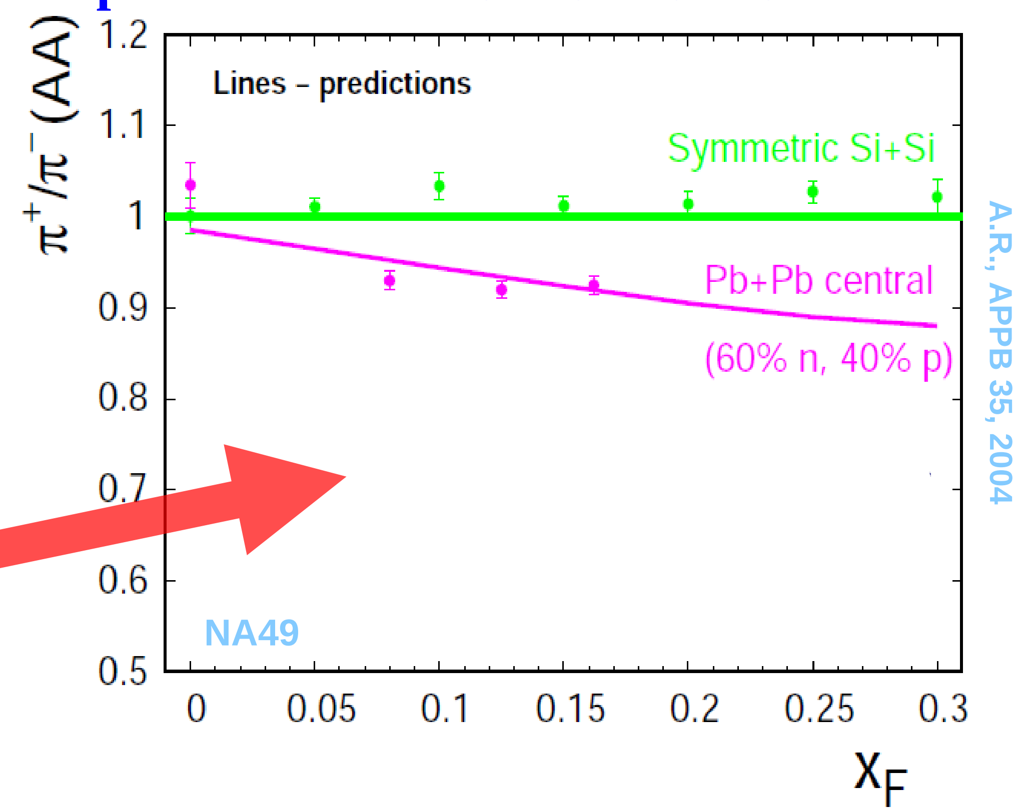
- simple superposition of proton and neutron collisions?

p+p, n+p collisions



C. Alt et al., EPJC 45, 2006
O. Chvala, EPJC 33, 2004

predictions for nucleus-nucleus reactions



π^+/π^- ratios remember the structure (*p/n* content) of the nucleus...

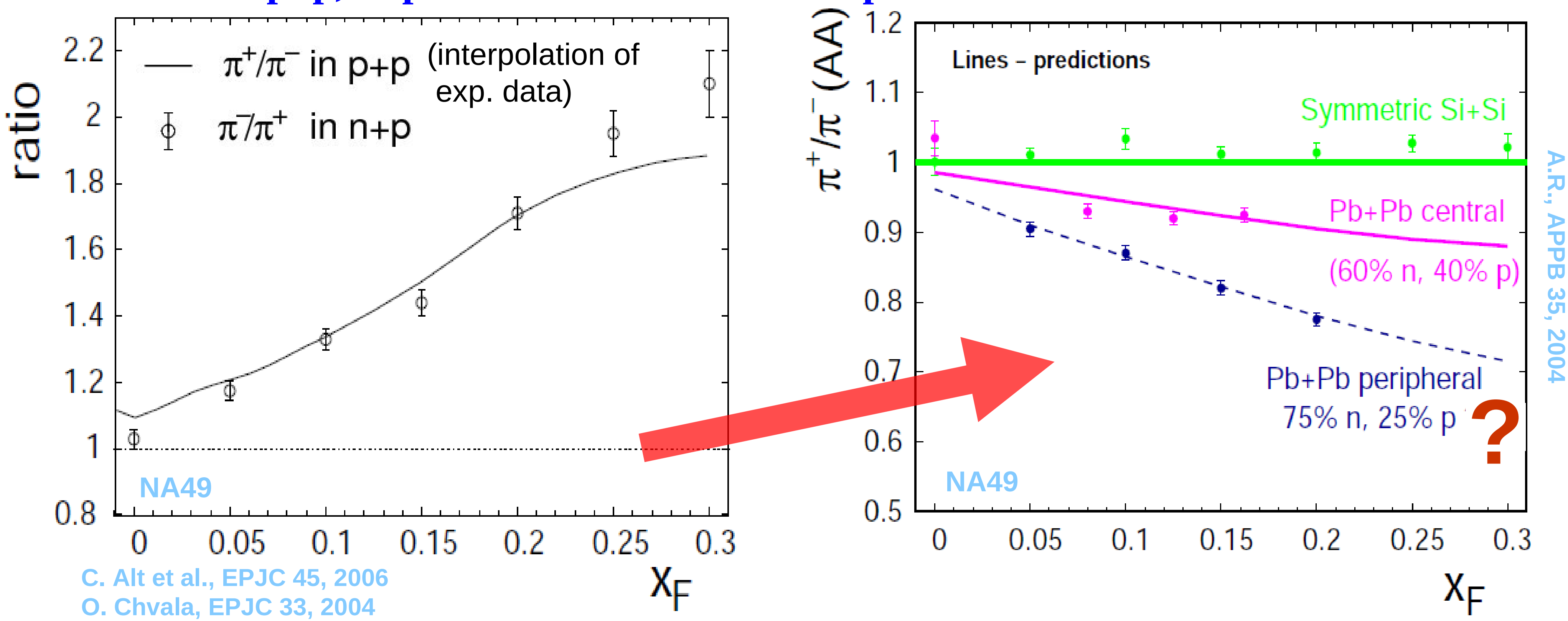
$$x_F = \frac{p_L}{p_L^{beam}}$$

(c.m.s.)

π^+/π^- ratios in Pb+Pb @ $\sqrt{s}_{NN}$= 17.3 GeV

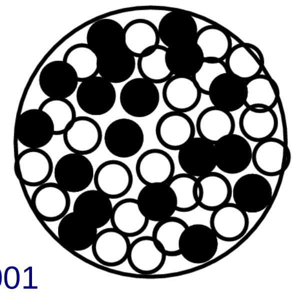
- simple superposition of proton and neutron collisions?

p+p, n+p collisions | **predictions for nucleus-nucleus reactions**



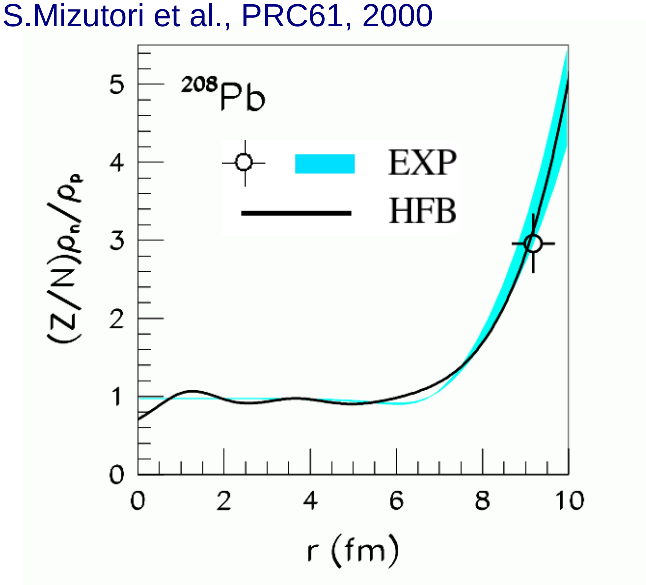
π^+/π^- ratios remember the structure (*p/n* content) of the nucleus...

... but what is happening in the *peripheral* Pb+Pb collision **?**

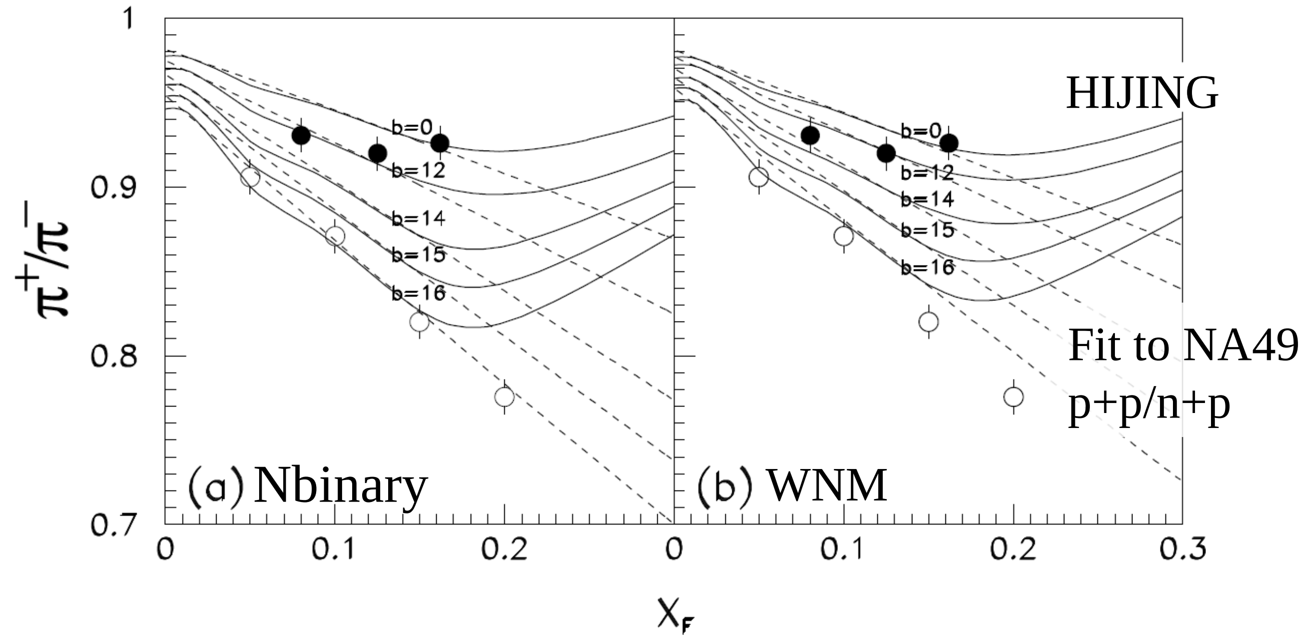


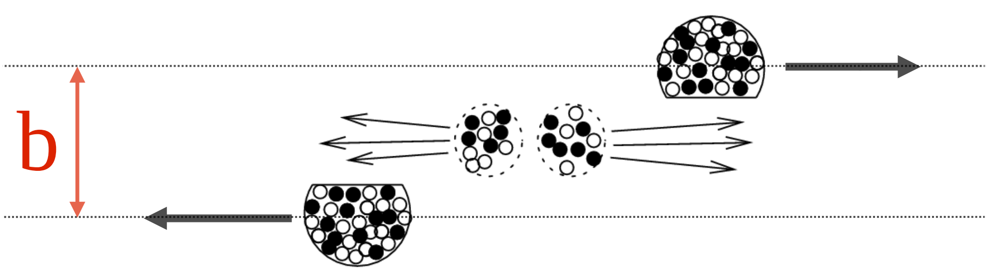
Hypothesis no. 1: the “neutron halo” ?

A.Trzcińska et al., PRL87, 2001
R.Schmidt et al., PRC67, 2003
S.Mizutori et al., PRC61, 2000

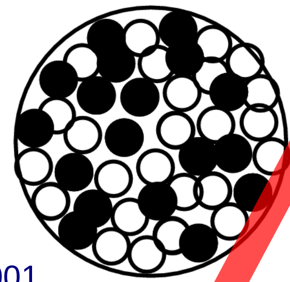


P.Pawłowski, A.Szczurek, PRC70, 2004



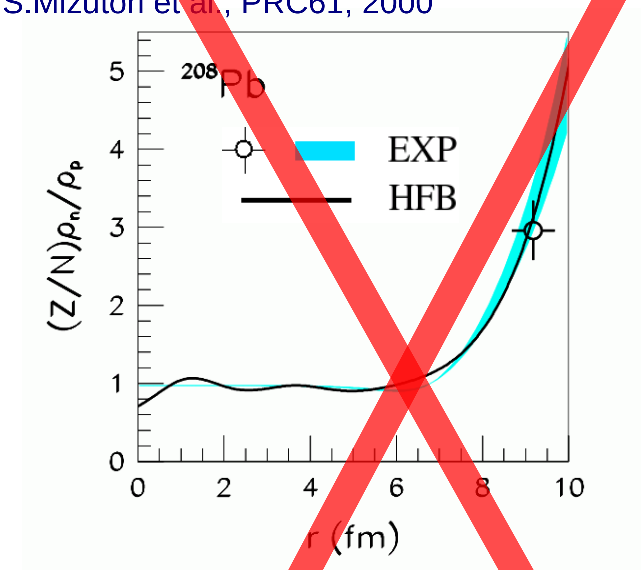


- **Analysis of collision geometry:** **b = 10.9 ± 0.5 fm**
- **Not possible to obtain 75% n, 25 % p**

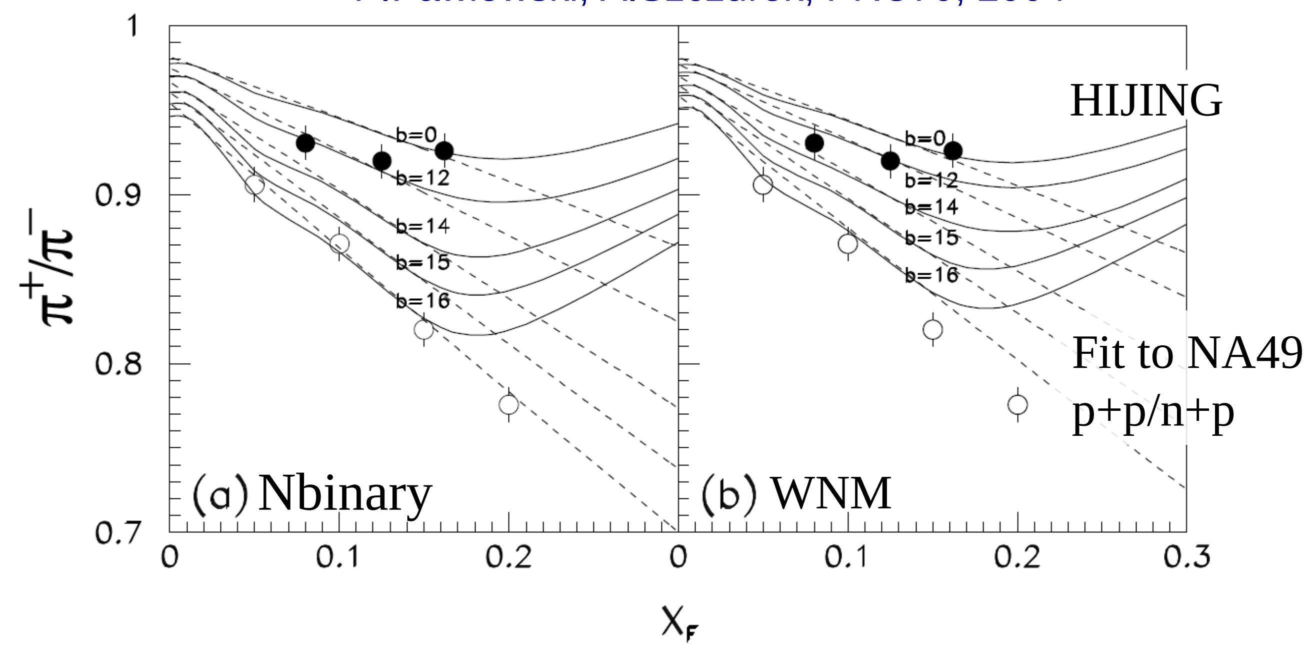


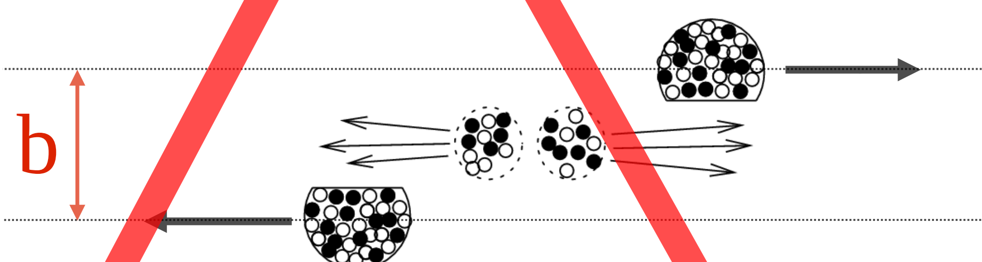
Hypothesis no. 1: the "neutron halo" ?

A.Trzcińska et al., PRL87, 2001
R.Schmidt et al., PRC67, 2003
S.Mizutori et al., PRC61, 2000



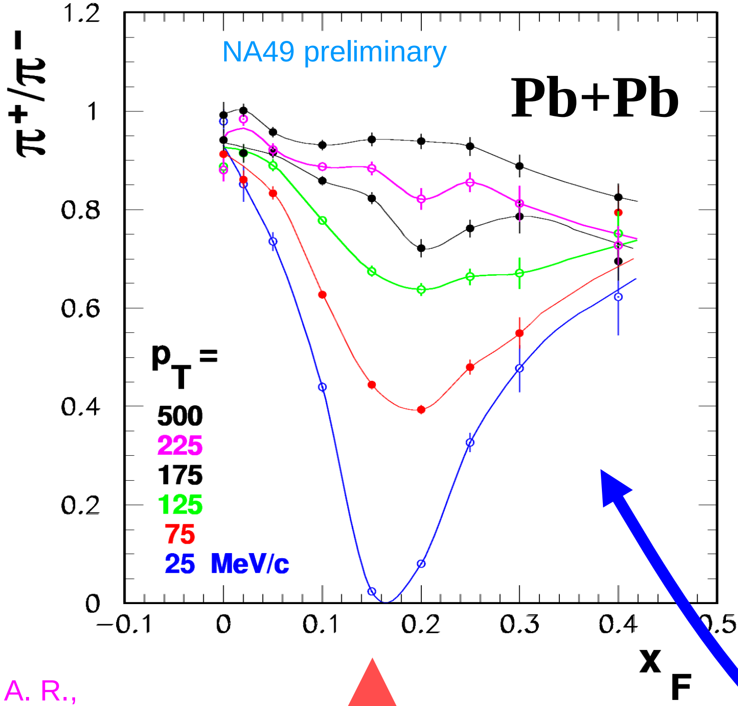
P.Pawłowski, A.Szczurek, PRC70, 2004





- **Analysis of collision geometry:** **b = 10.9 ± 0.5 fm**
- **Not possible to obtain 75% n, 25 % p**

3) EM effects



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

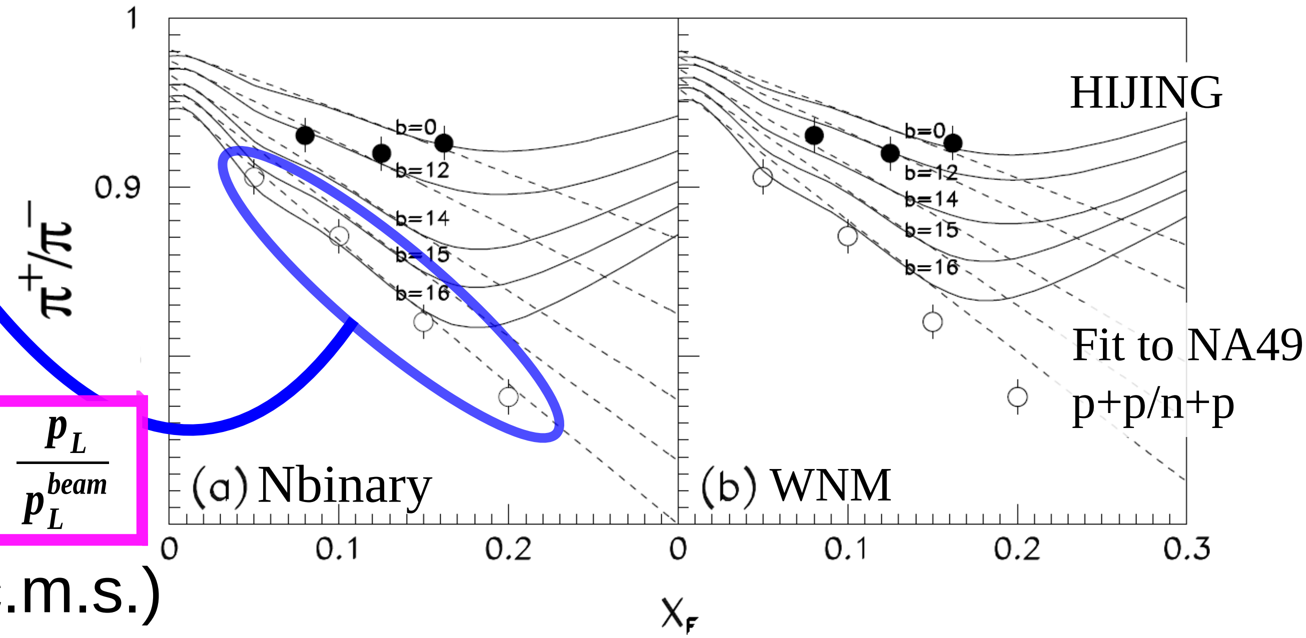
spectator velocity:

$$x_F = 0.15 = m_\pi / m_p$$

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

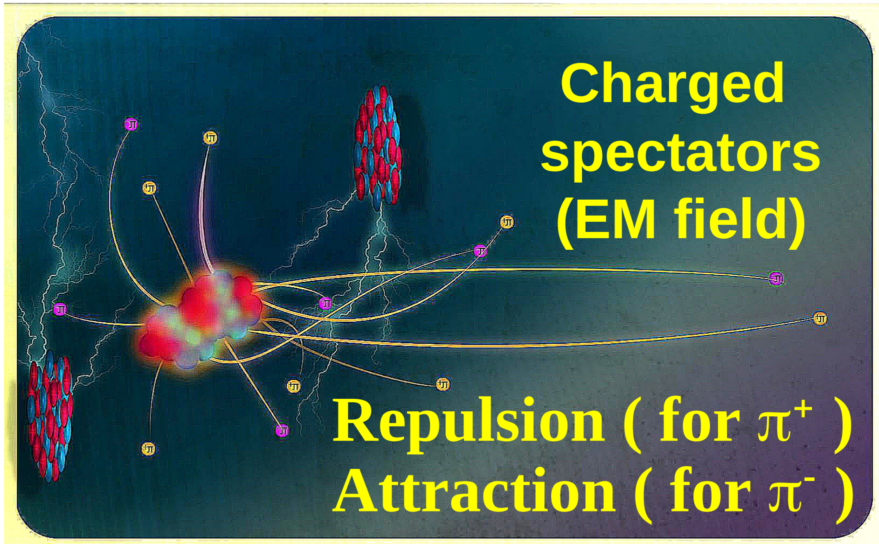
(c.m.s.)

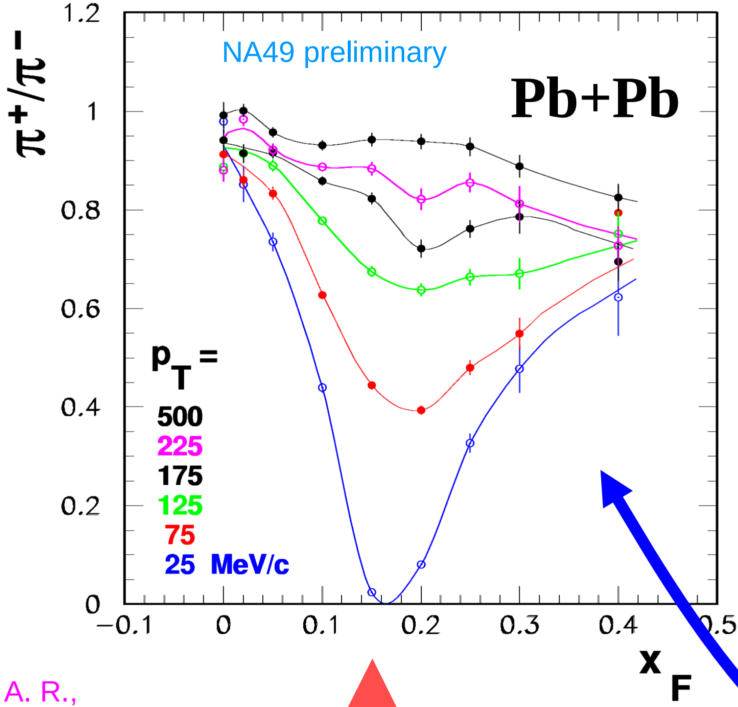
P.Pawłowski, A.Szczurek, PRC70, 2004



$$x_F = \frac{p_L}{p_L^{beam}} = \frac{m_\pi \ \gamma \ \beta}{m_p \ \gamma \ \beta} = \frac{m_\pi}{m_p} = 0.15$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} , \quad \beta = \frac{v}{c}$$





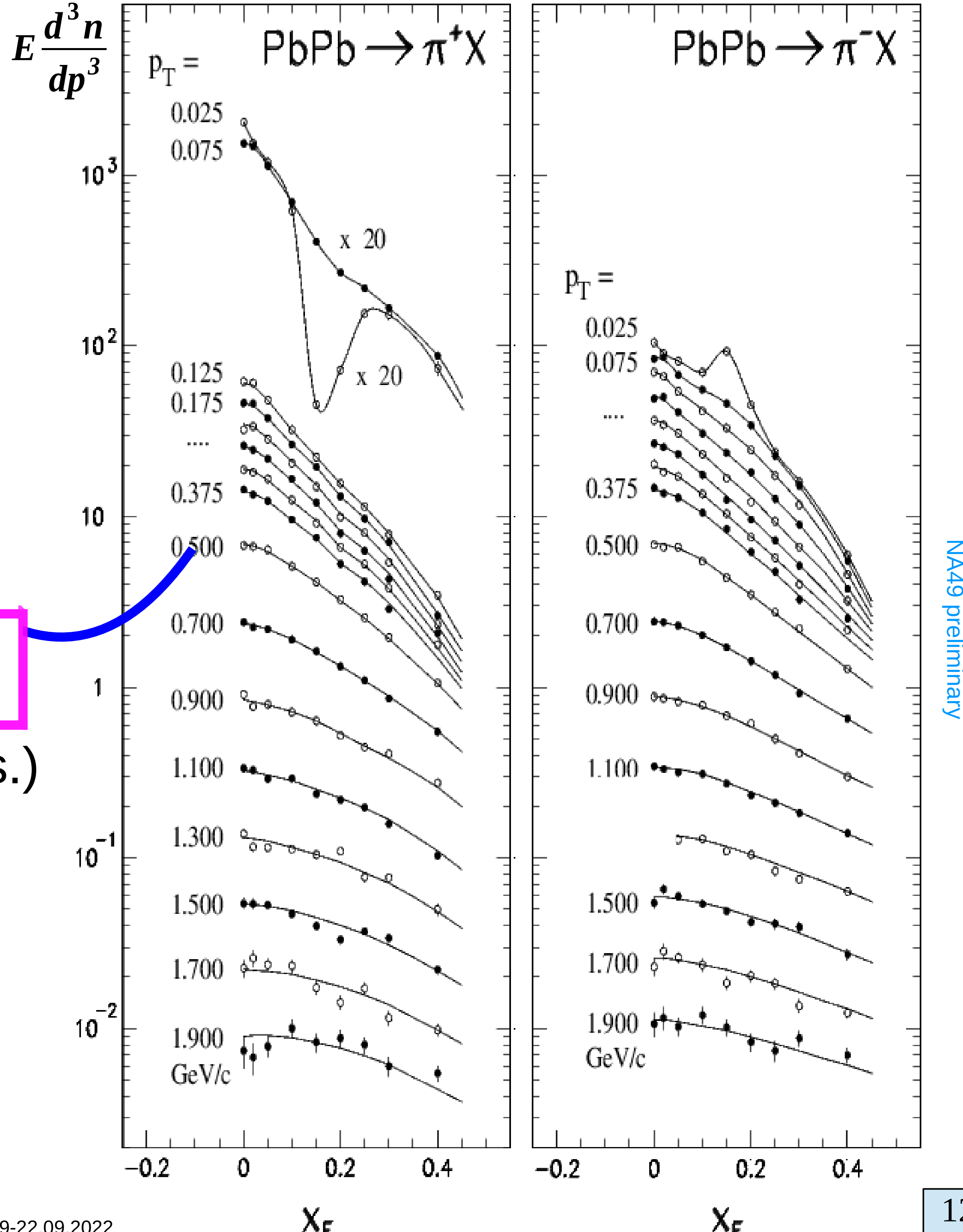
A. R.,
Acta Phys. Polon.
B42 (2011) 867

spectator velocity:

$x_F = 0.15 = m_\pi / m_p$

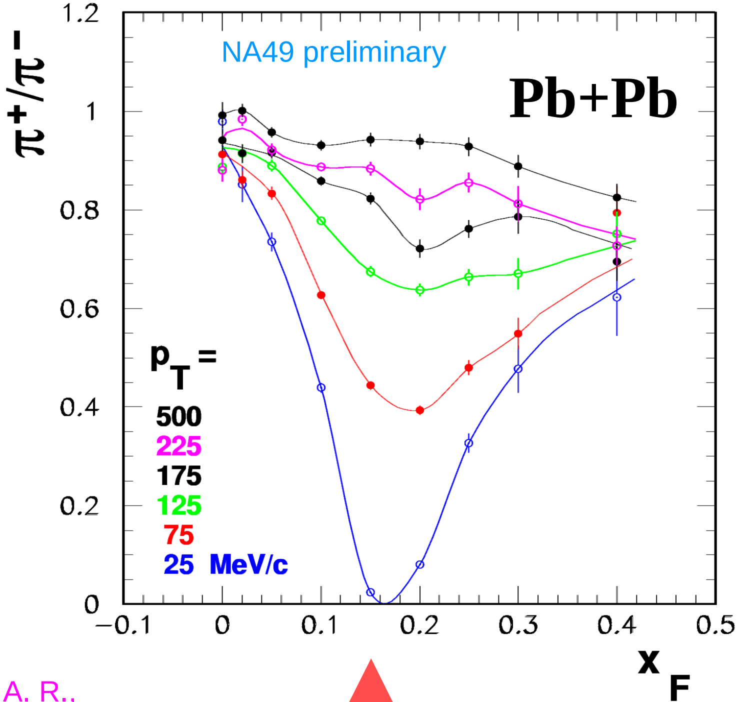
$$x_F = \frac{p_L}{p_L^{beam}}$$

(c.m.s.)

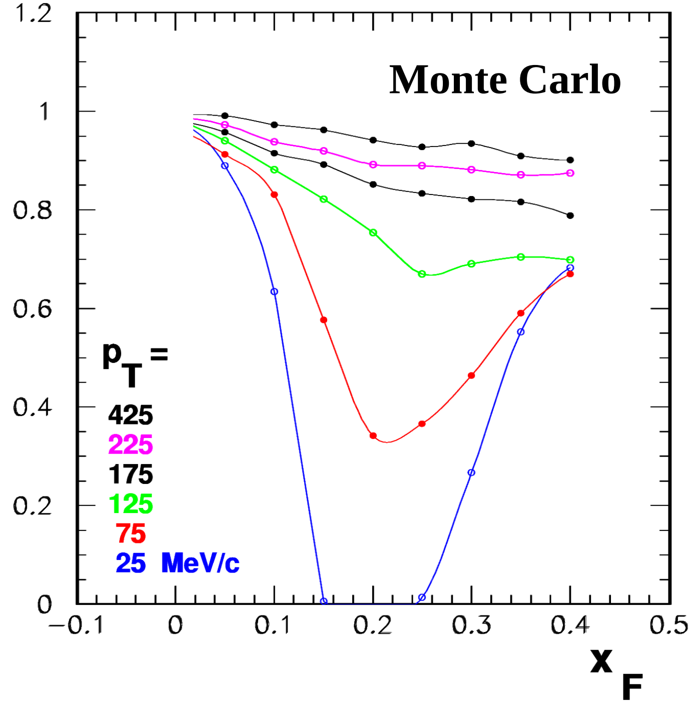


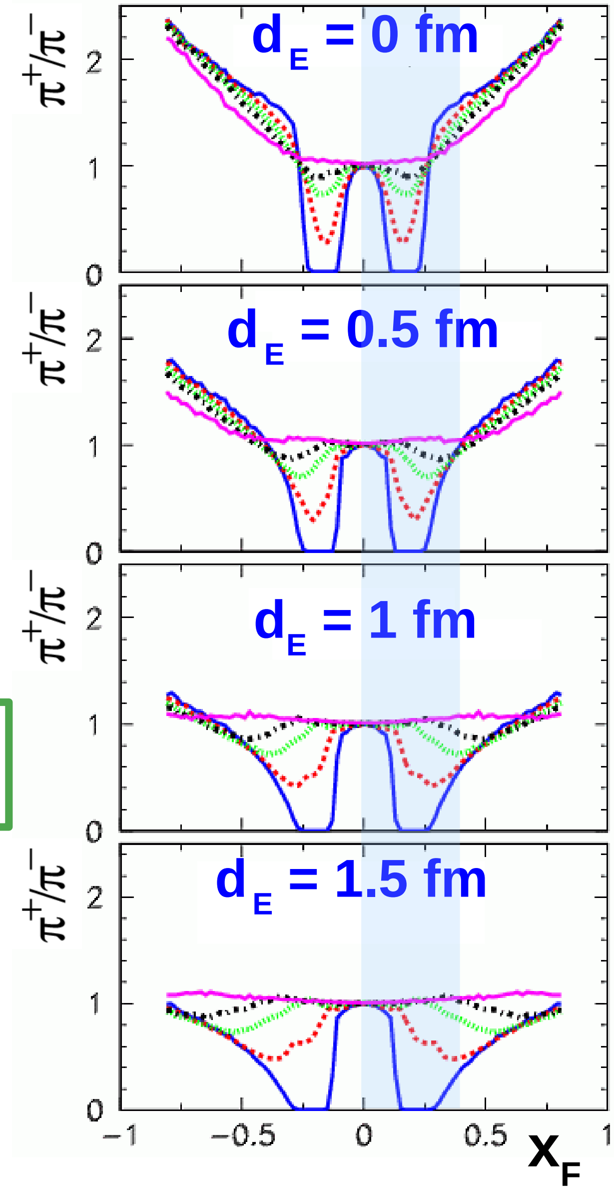
$$x_F = \frac{p_L}{p_L^{beam}} = \frac{m_\pi \ \gamma \ \beta}{m_p \ \gamma \ \beta} = \frac{m_\pi}{m_p} = 0.15$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} , \quad \beta = \frac{v}{c}$$



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





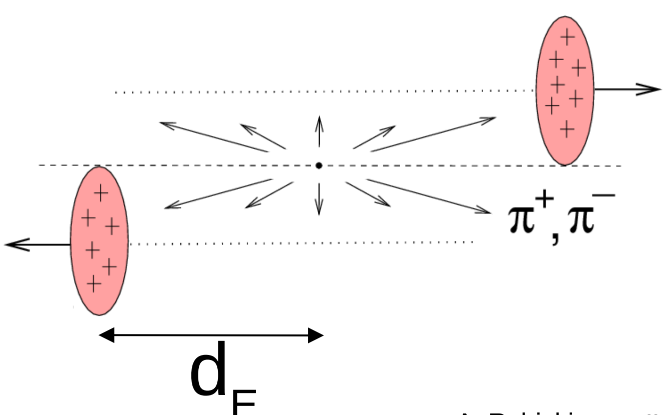
A. R. and A. Szczurek.,
Phys. Rev. **C75** (2007)
054903

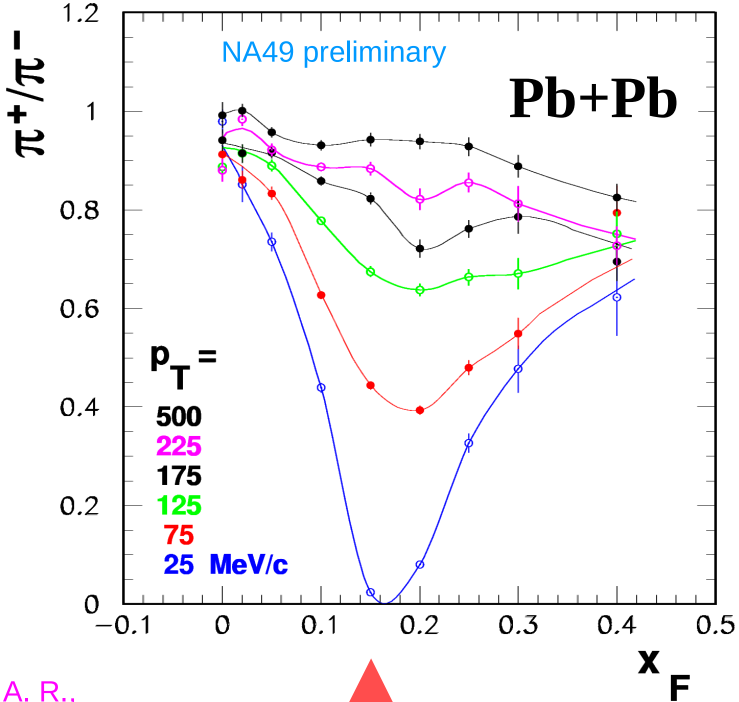
$d_E \approx 0.75$ fm !

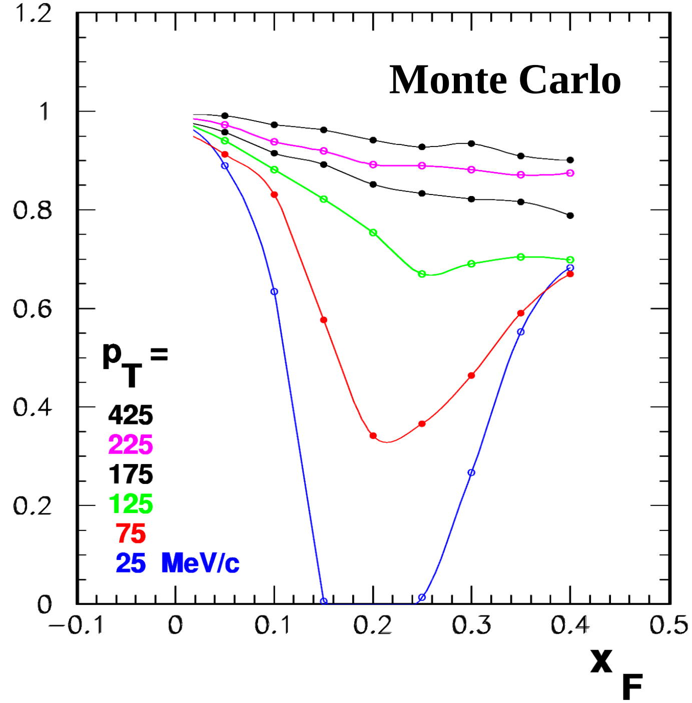
spectator velocity:
$x_F = 0.15 = m_\pi/m_N$

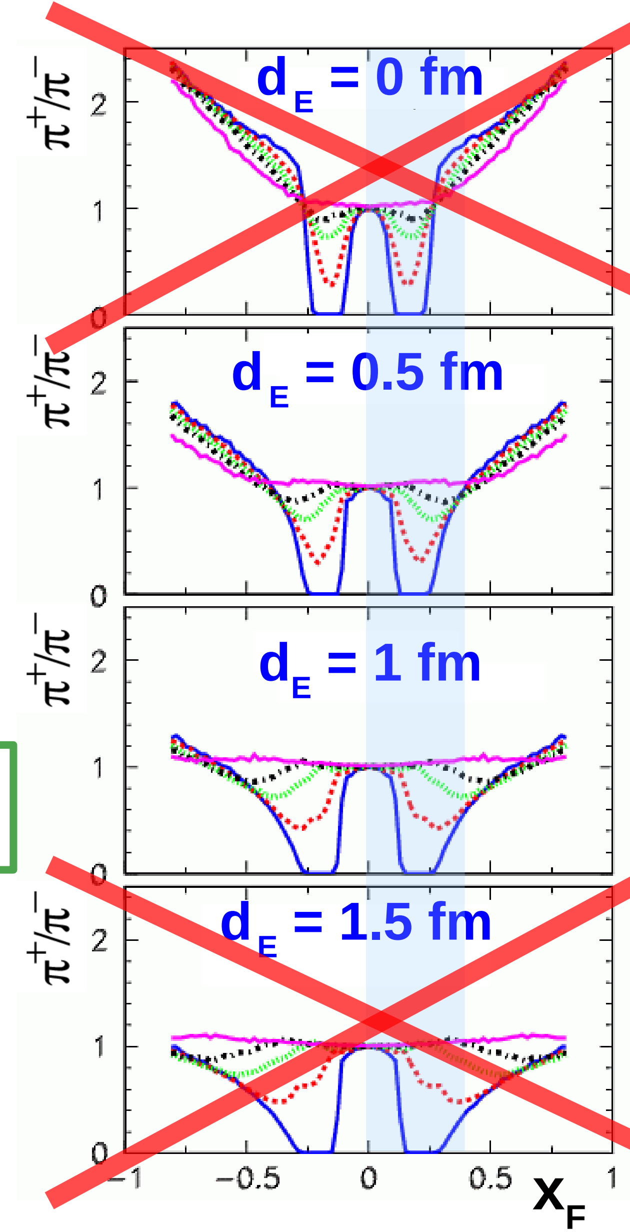
$$x_F = \frac{p_L}{p_L^{beam}}$$

(c.m.s.)









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

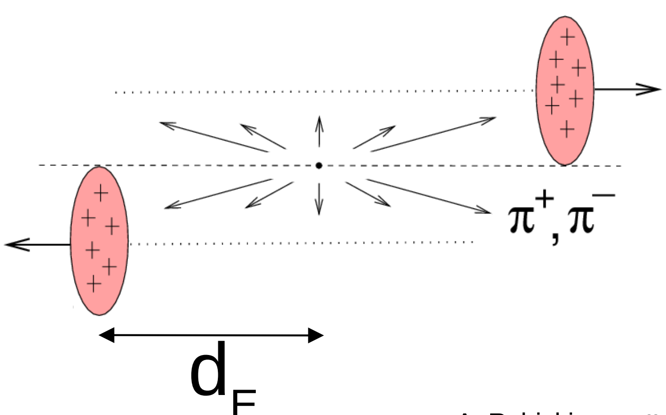
spectator velocity:
x_F= 0.15 = m_π/m_N

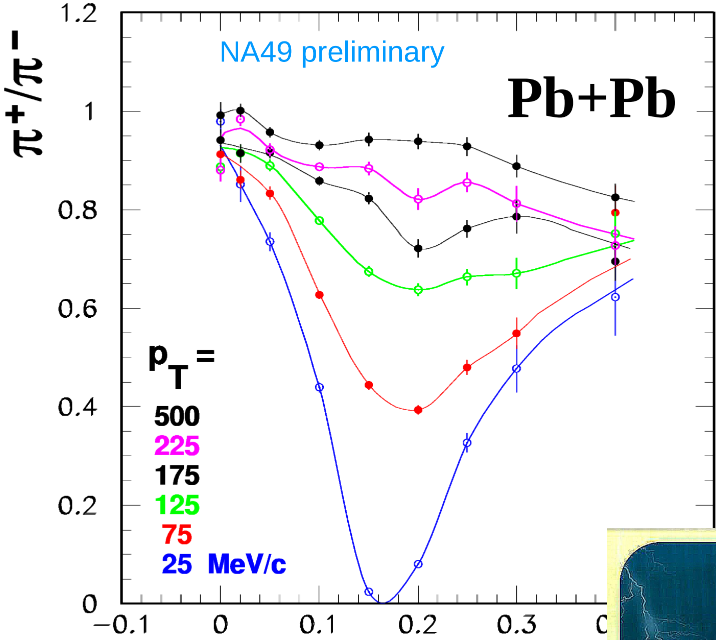
$$x_F = \frac{p_L}{p_L^{beam}}$$

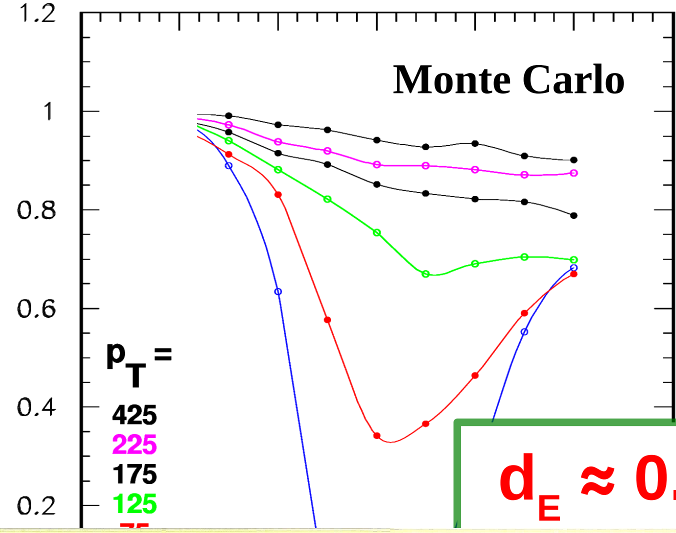
(c.m.s.)

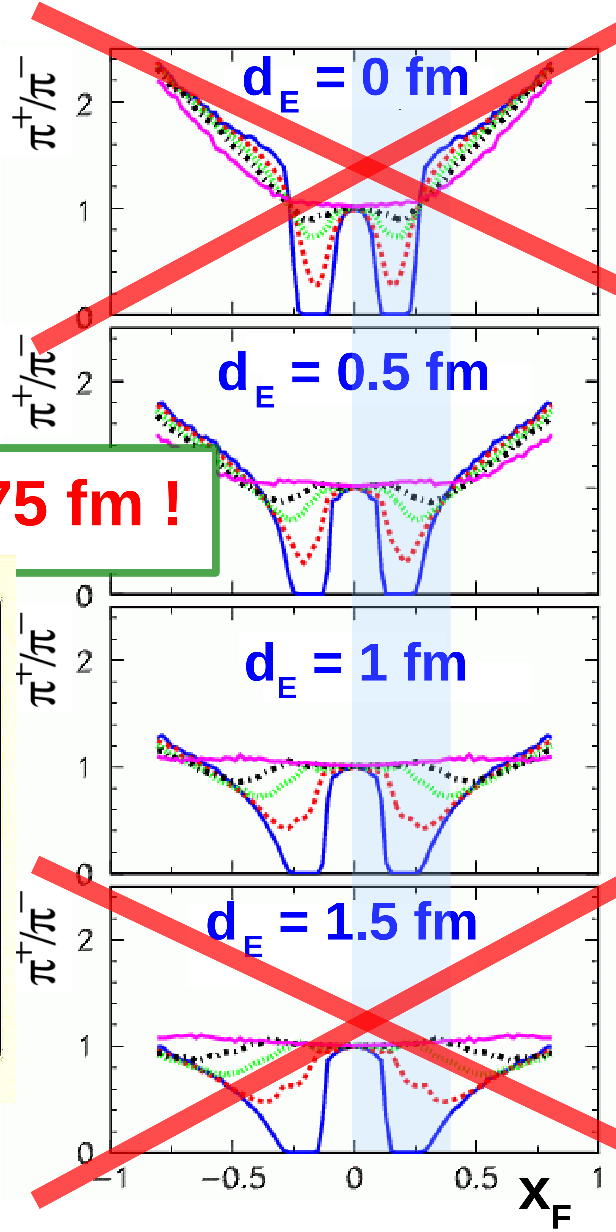
$d_E \approx$ 0.75 fm !

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





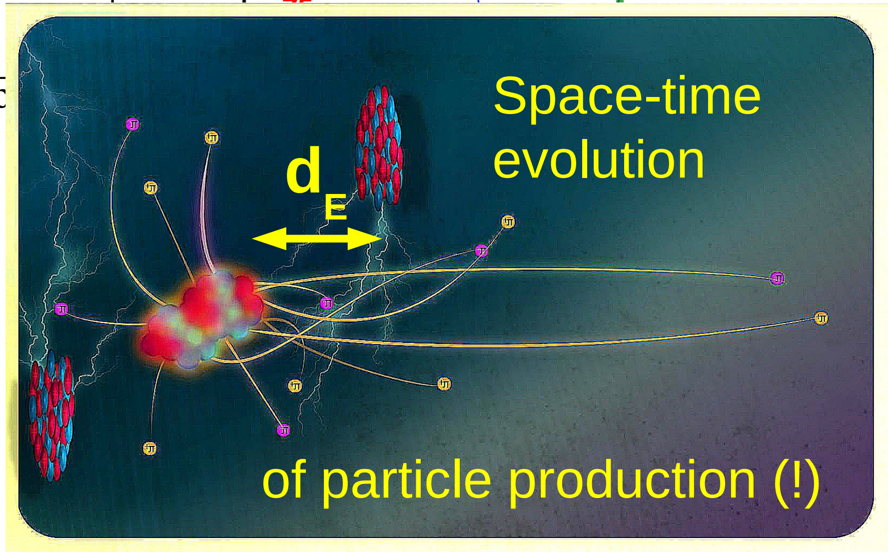


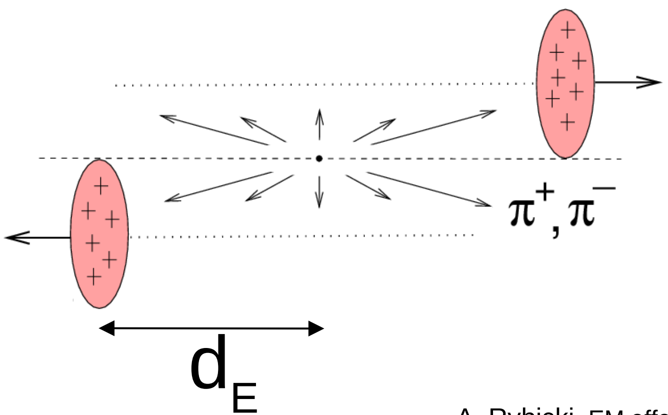


$d_E \approx 0.75$ fm !

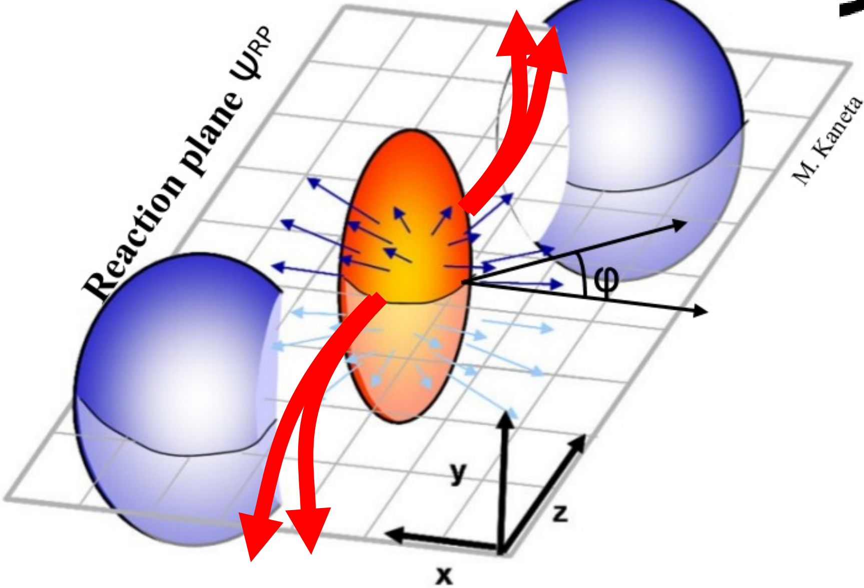
A. R.,
Acta Phys. Polon. **B42** (2011) 867

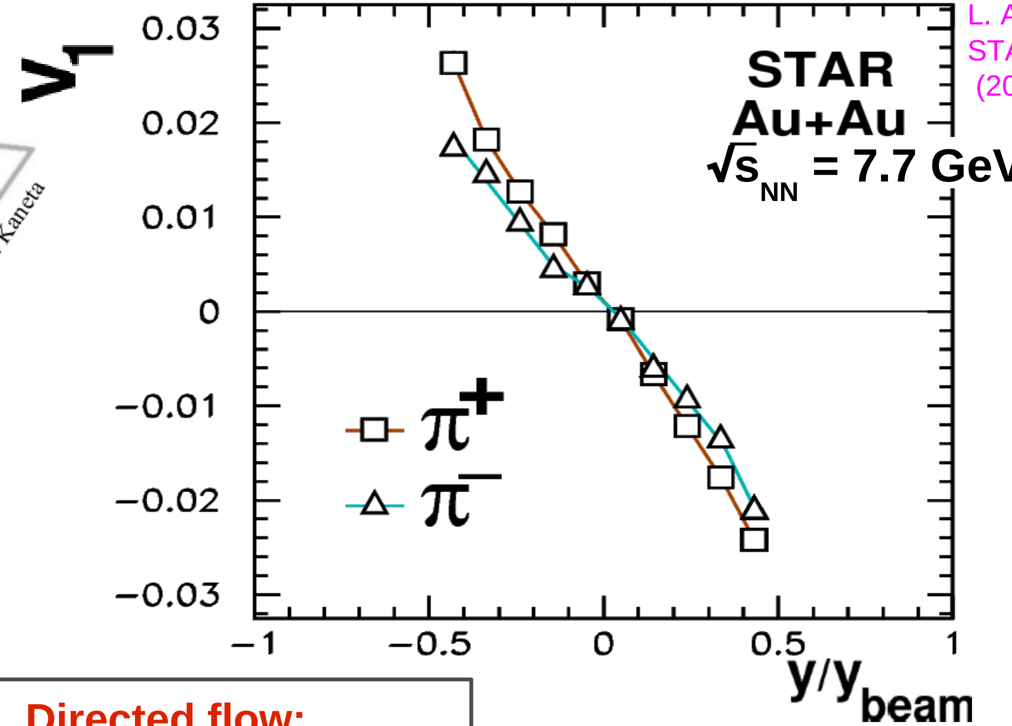
spectator velocity:
$x_F = 0.15 = m_\pi/m_N$





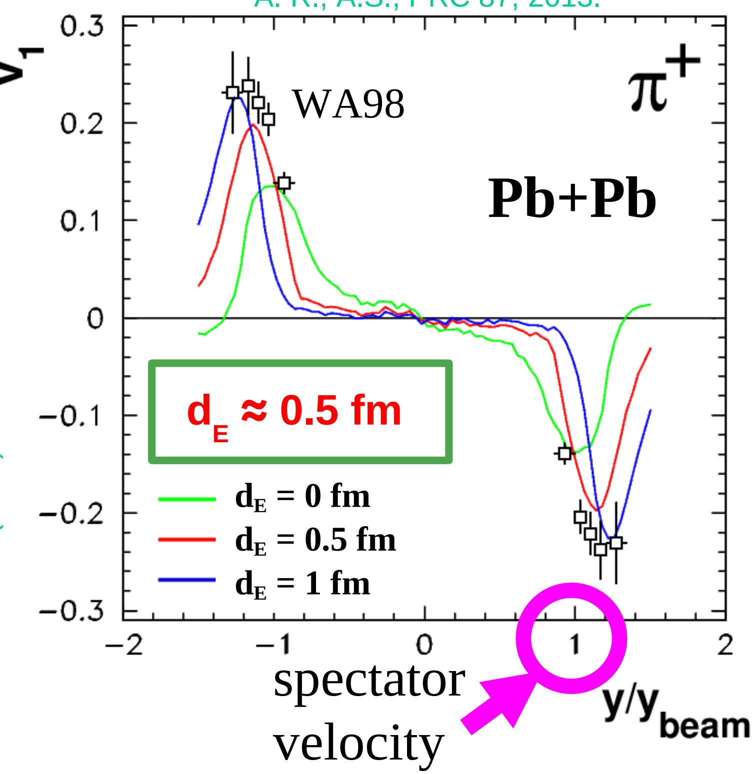
A. R. and A. Szczurek.,
Phys. Rev. **C75** (2007) 054903





L. Adamczyk et al. STAR, PRL 112, (2014) 162301.

A. R., A.S., PRC 87, 2013.



WA98: NPA 663 (2000) 725

Directed flow:

$v_1 = \langle \cos(\phi - \Psi_{RP}) \rangle$

reflects sidewards collective motion of emitted particles.

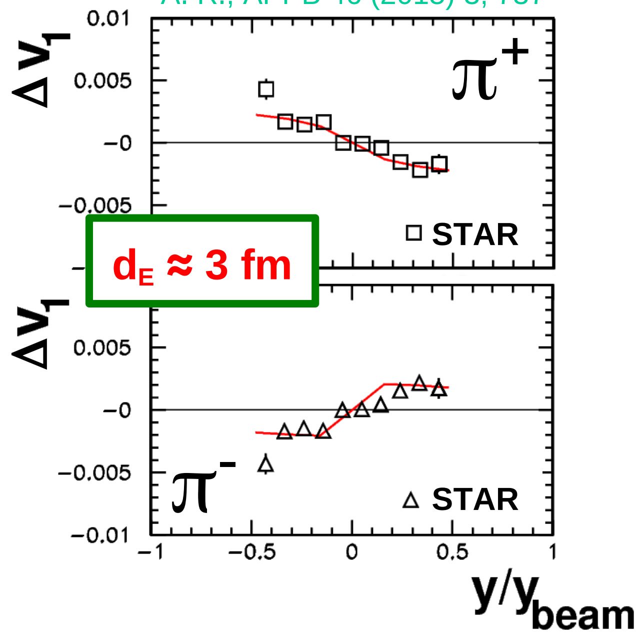
EM effects induce charge splitting of directed flow.

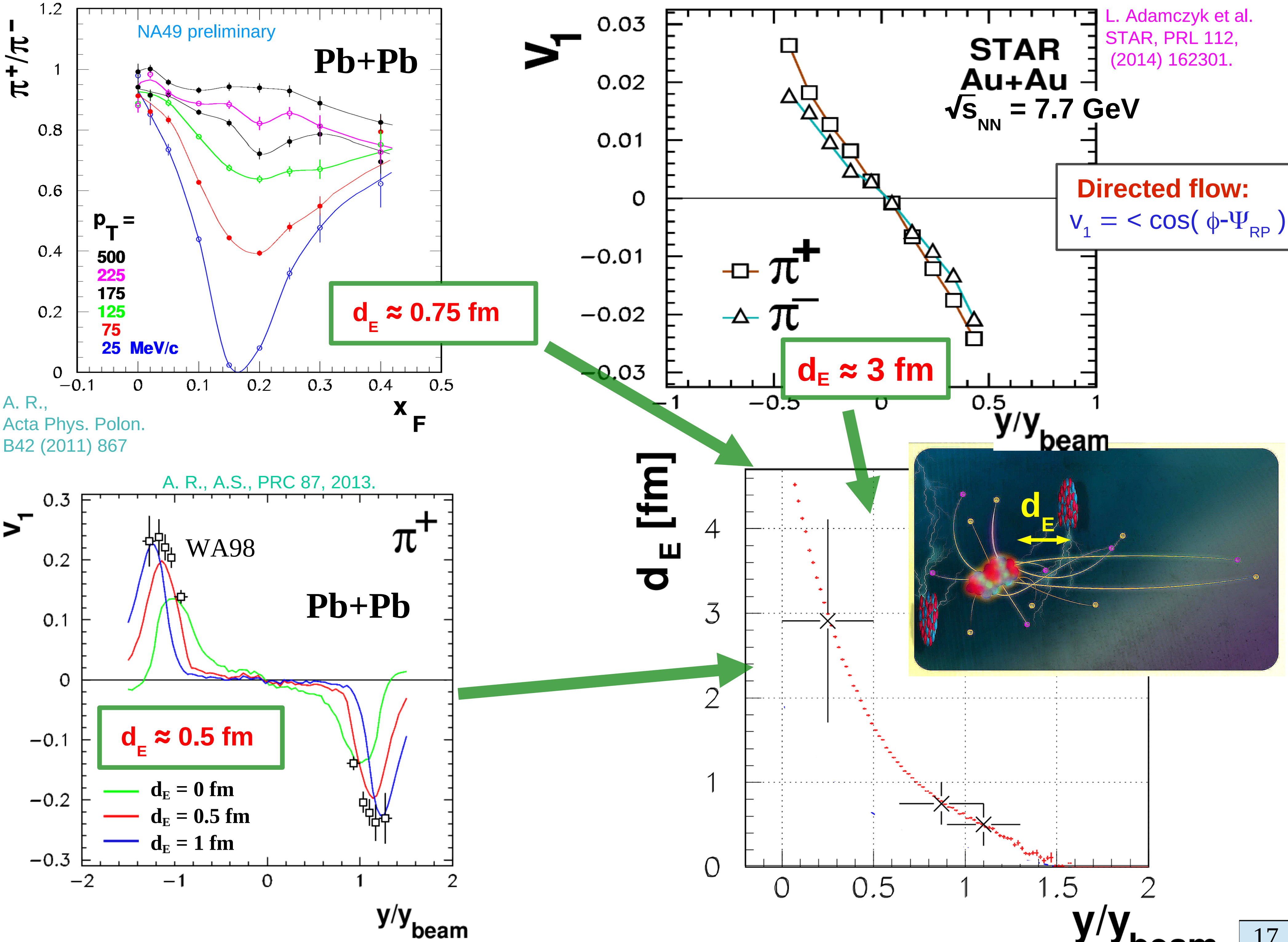
(A.R., A.S., PRC 87,2013)

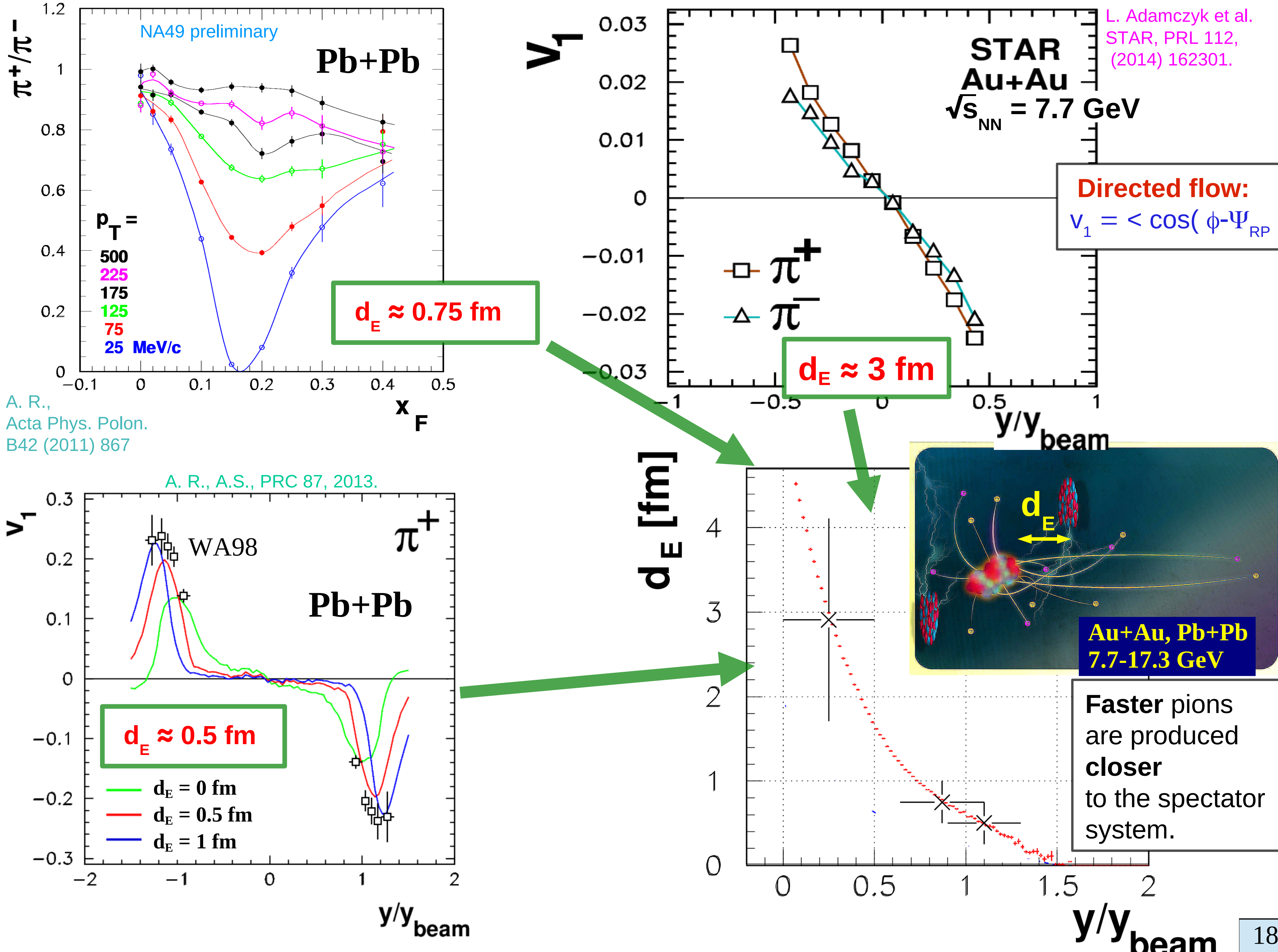
$$y = \frac{1}{2} \ln \left(\frac{E+pz}{E-pz} \right)$$

$$y = \tanh^{-1}(v_z/c)$$

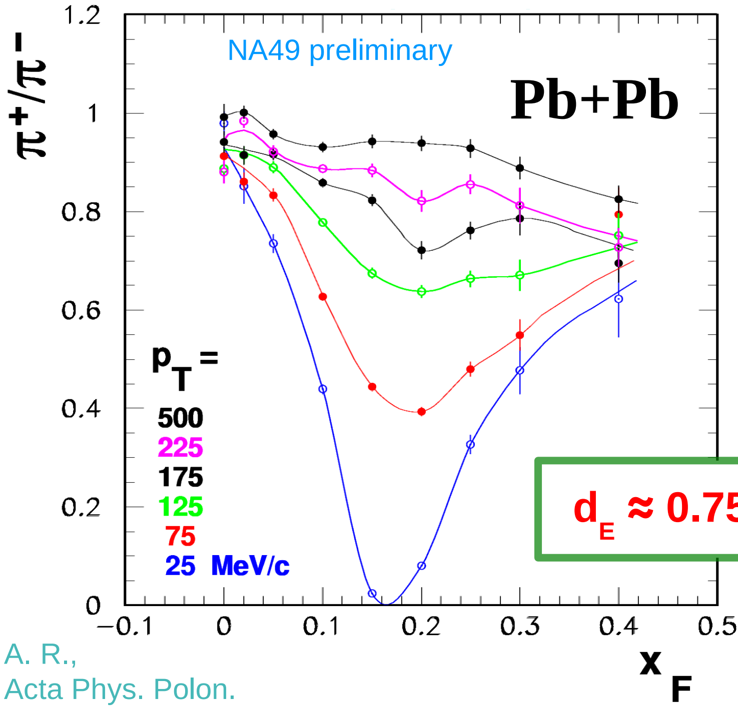
A. R., APPB 46 (2015) 3, 737



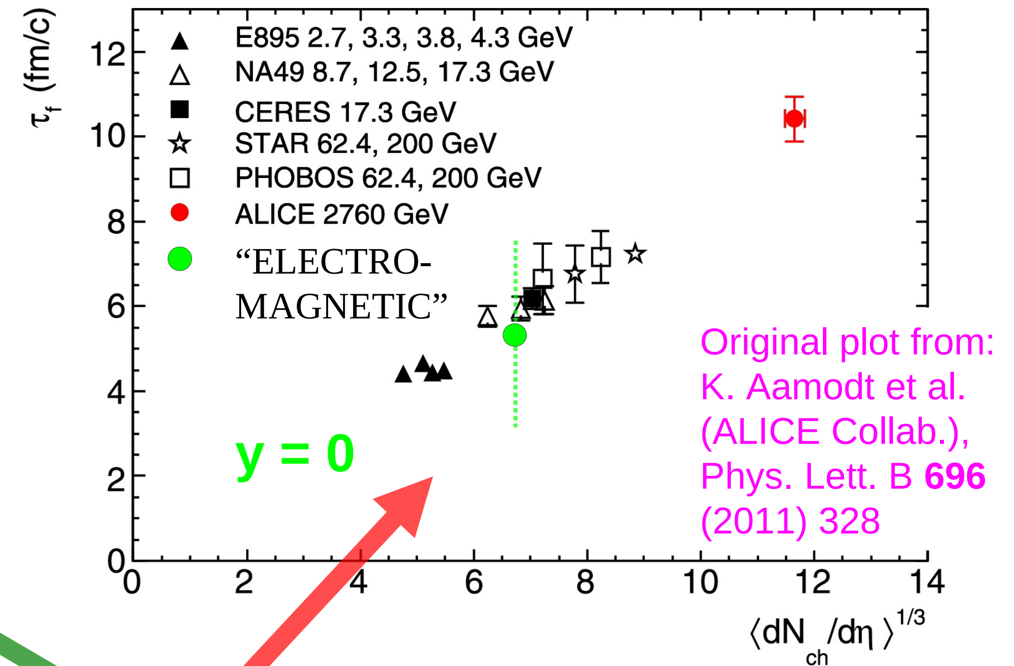

NA49 preliminary
Pb+Pb
π+/π−
pT =
500
225
175
125
75
25 MeV/c
xF
A. R.,
Acta Phys. Polon.
B42 (2011) 867
dE ≈ 0.75 fm
L. Adamczyk et al.
STAR, PRL 112,
(2014) 162301.
STAR
Au+Au
√sNN = 7.7 GeV
v1
π+
π−
y/ybeam
dE ≈ 3 fm
Directed flow:
v1 = < cos(ϕ-ΨRP)
A. R., A.S., PRC 87, 2013.
WA98
π+
Pb+Pb
dE ≈ 0.5 fm
dE = 0 fm
dE = 0.5 fm
dE = 1 fm
y/ybeam
dE [fm]
dE
y/ybeam

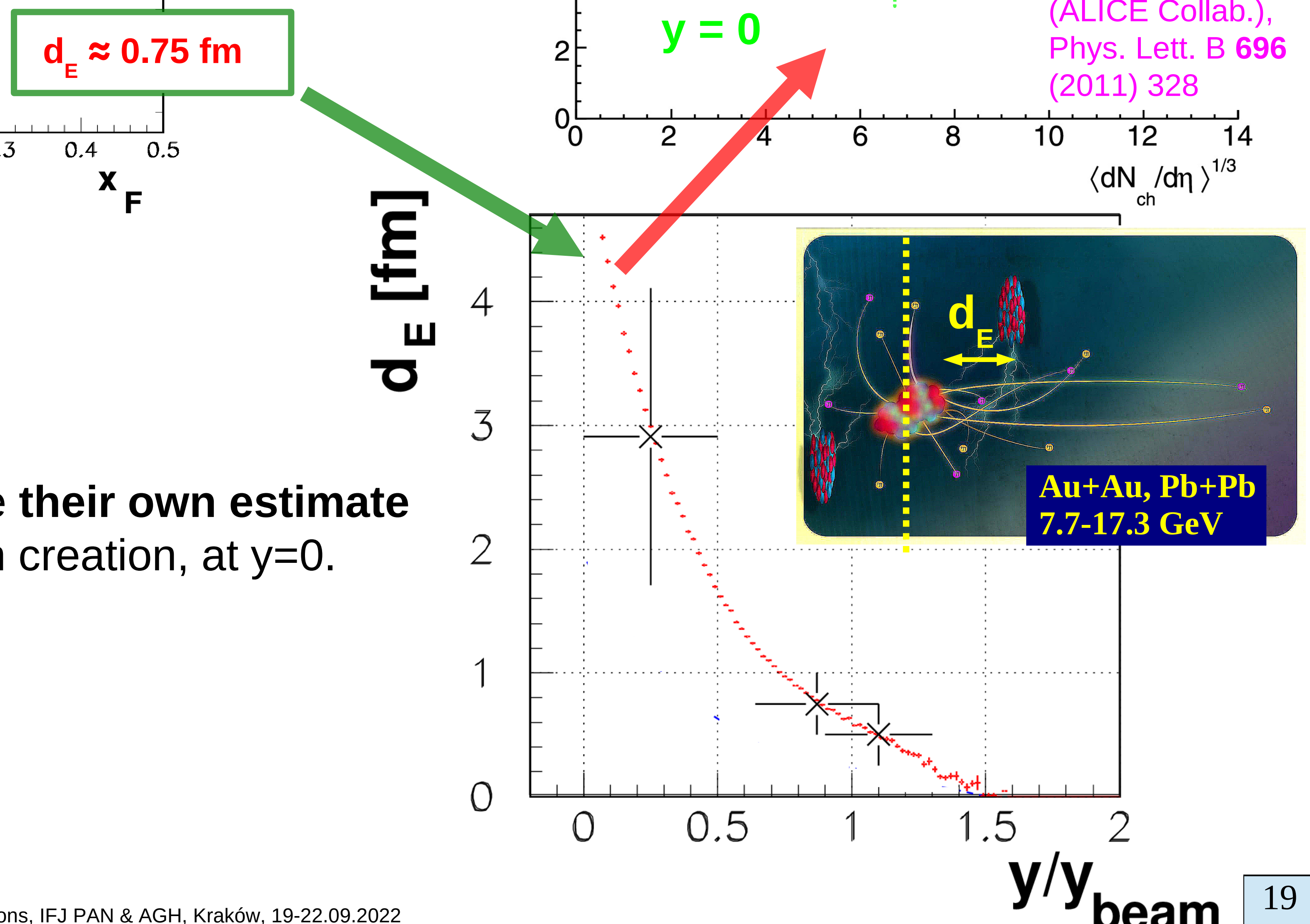


NA49 preliminary
Pb+Pb
π+/π−
pT =
500
225
175
125
75
25 MeV/c
xF
A. R.,
Acta Phys. Polon.
B42 (2011) 867
dE ≈ 0.75 fm
v1
STAR
Au+Au
√sNN = 7.7 GeV
L. Adamczyk et al.
STAR, PRL 112,
(2014) 162301.
Directed flow:
v1 = < cos(ϕ-ΨRP)
π+
π−
dE ≈ 3 fm
y/ybeam
A. R., A.S., PRC 87, 2013.
WA98
π+
Pb+Pb
dE ≈ 0.5 fm
dE = 0 fm
dE = 0.5 fm
dE = 1 fm
y/ybeam
dE [fm]
dE
Au+Au, Pb+Pb
7.7-17.3 GeV
Faster pions
are produced
closer
to the spectator
system.
y/ybeam



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





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

4)
Space-time evolution of forward pion production

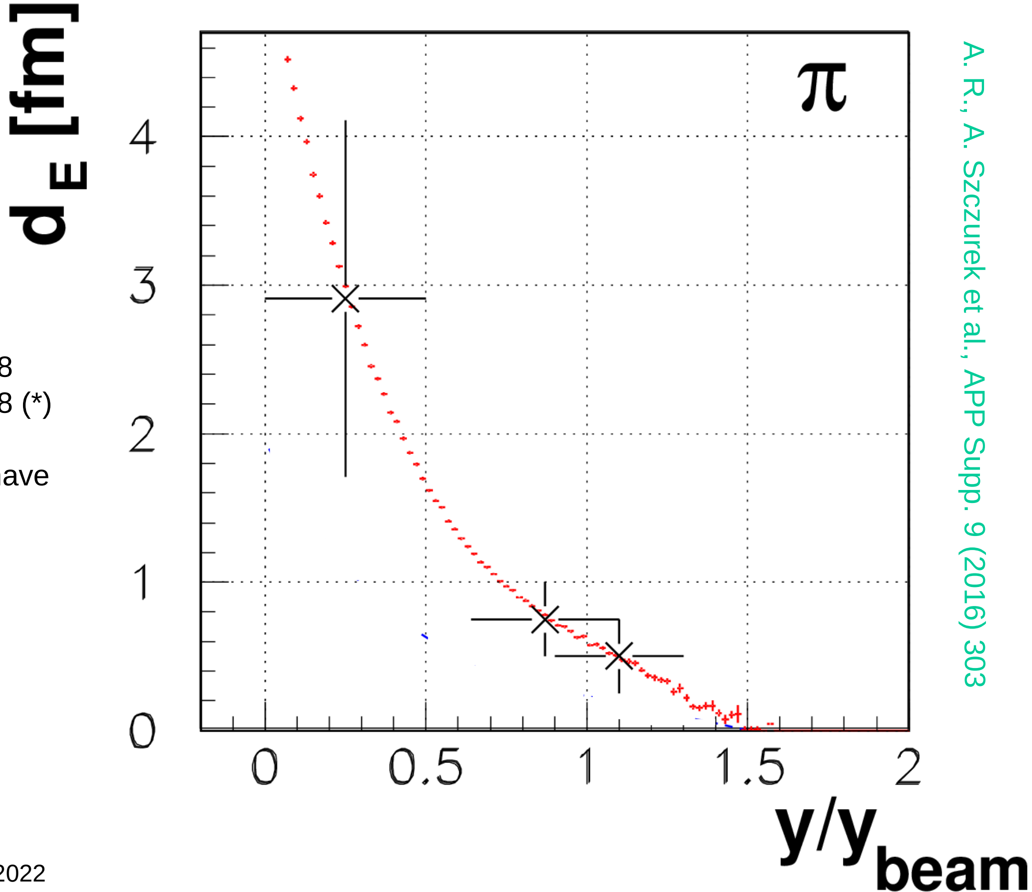
Plan:

- Formulation of a simple model ;
- Validation with exp. data on rapidity distributions ;
- Application to EM effects.

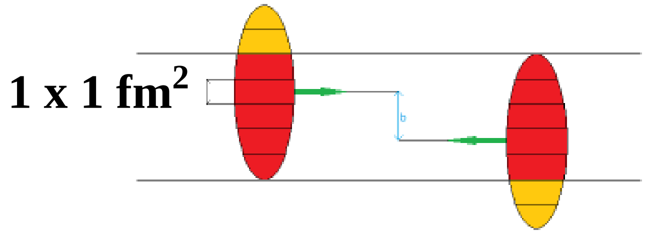
PRC 95 (2017) 024908
PRC 99 (2019) 024908 (*)

(*) Yes, both papers have page no. 024908

PRC102 (2020) 014901

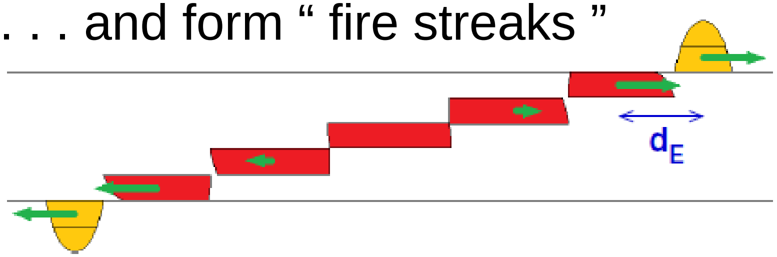


Bricks collide . . .



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

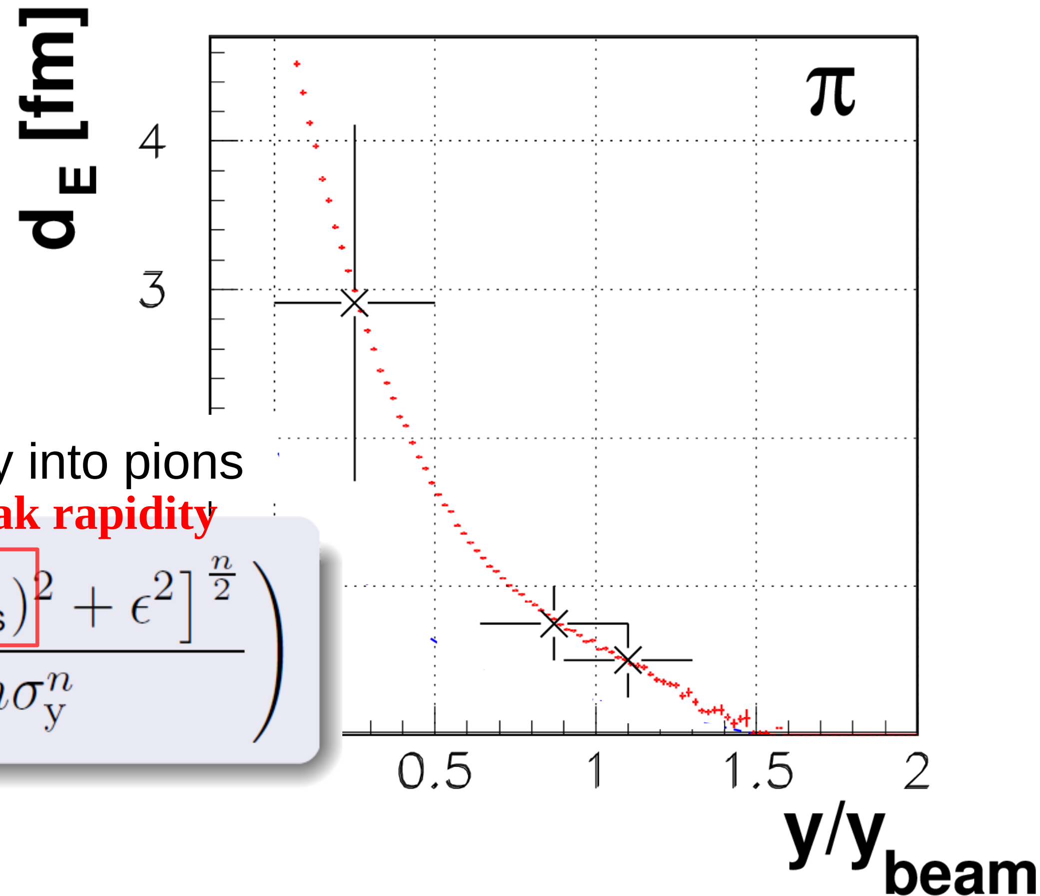
available energy

fire streak rapidity

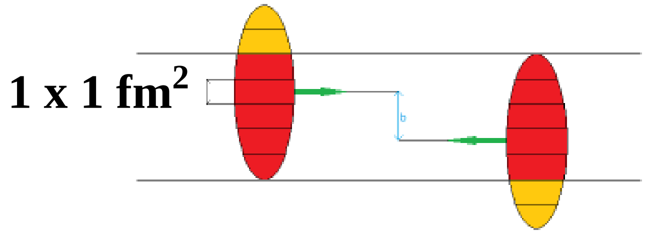
$$\frac{dn}{dy} = A \cdot (E_s^* - m_s) \cdot \exp\left(- \frac{\left[(y - y_s)^2 + \epsilon^2\right]^{\frac{n}{2}}}{n\sigma_y^n} \right)$$

total fire streak energy

sum of brick masses

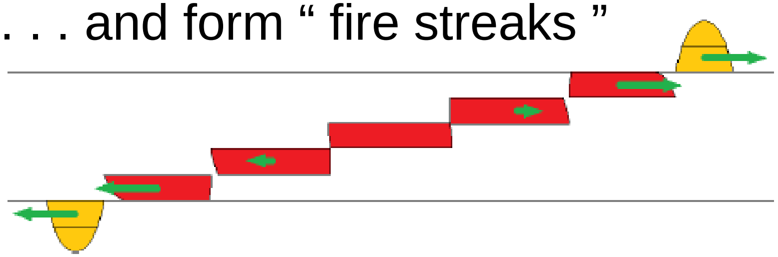


Bricks collide . . .



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

available energy

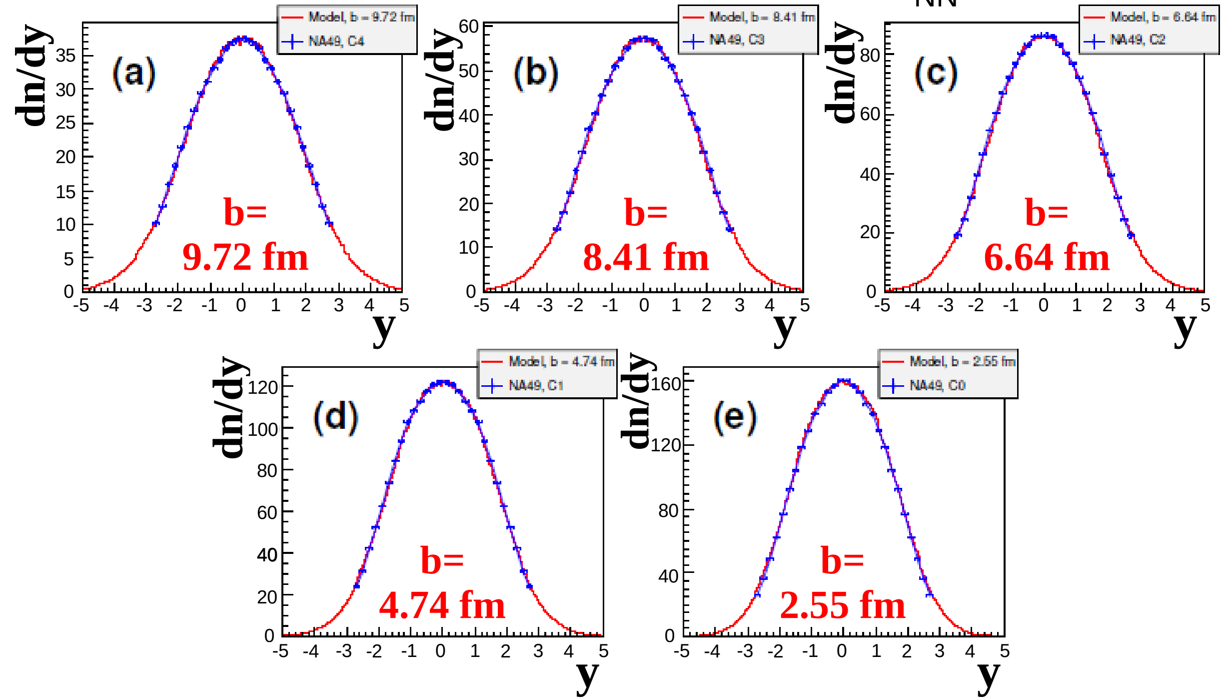
fire streak rapidity

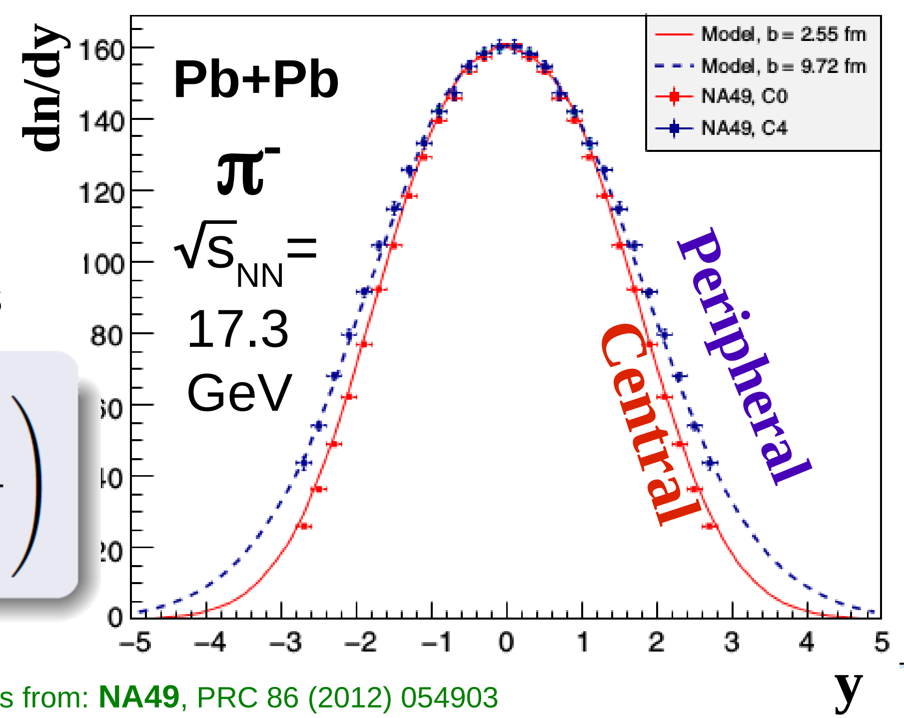
$$\frac{dn}{dy} = A \cdot (E^*_s - m_s) \cdot \exp\left(- \frac{\left[(y - y_s)^2 + \epsilon^2\right]^{\frac{n}{2}}}{n \sigma_y^n} \right)$$

total fire streak energy

sum of brick masses

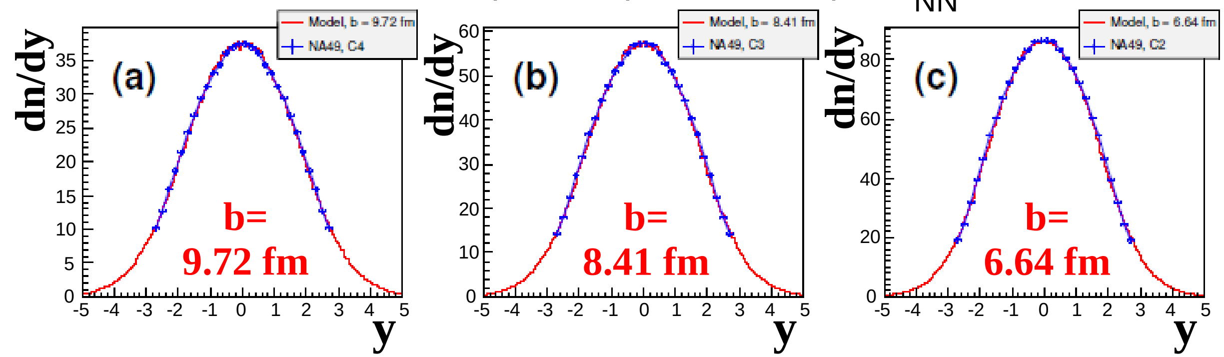
NA49, π^-, Pb+Pb, $\sqrt{s_{NN}}$ = 17.3 GeV

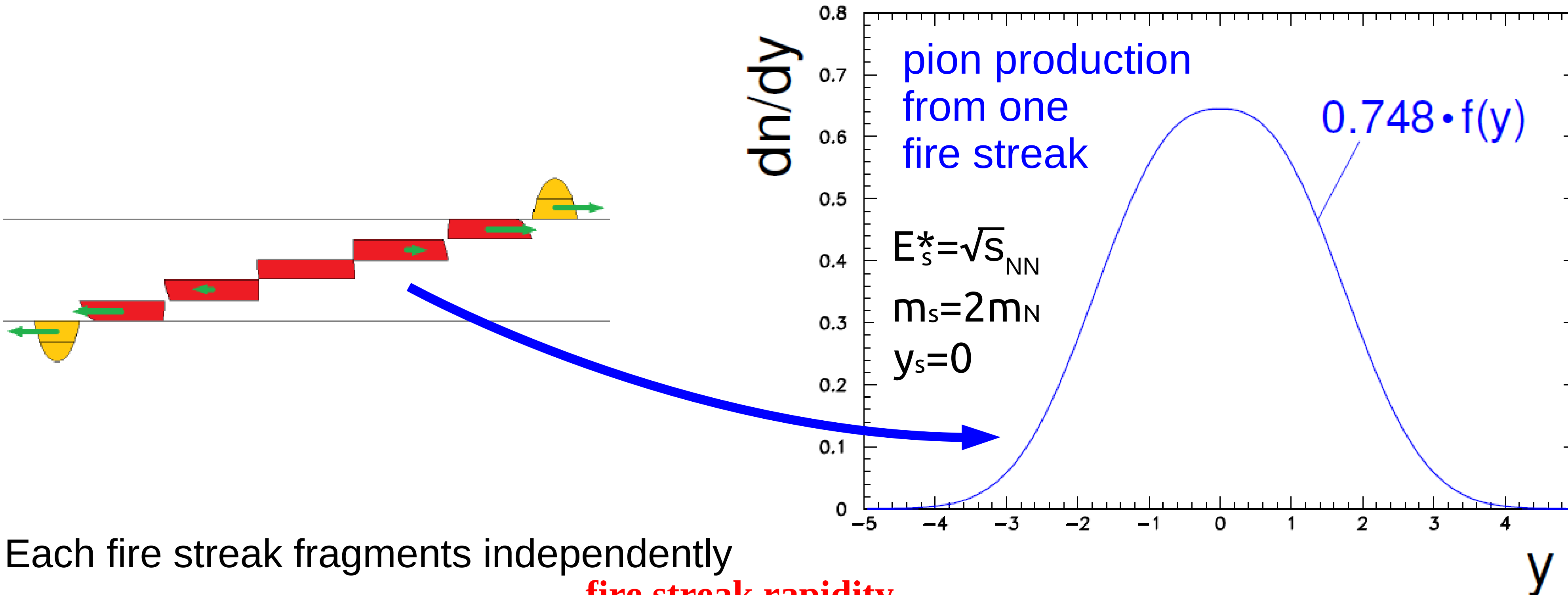




data points from: **NA49**, PRC 86 (2012) 054903

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





Each fire streak fragments independently

fire streak rapidity

available energy

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

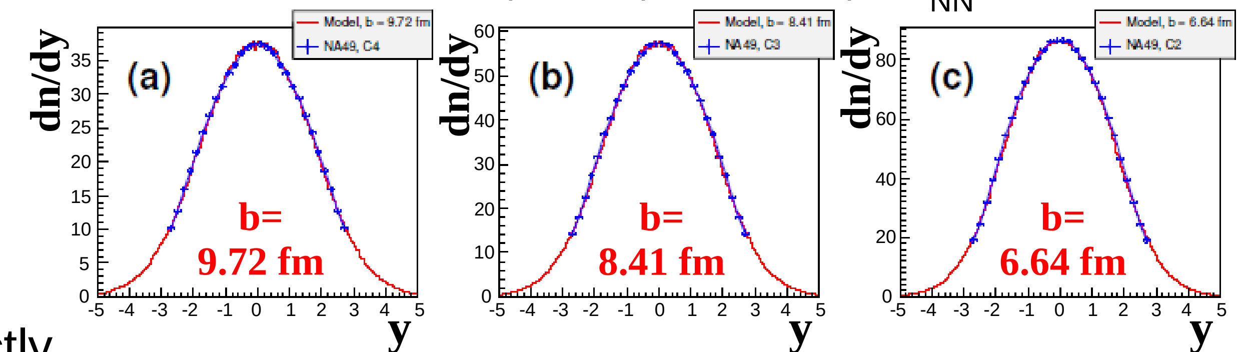
total fire streak energy

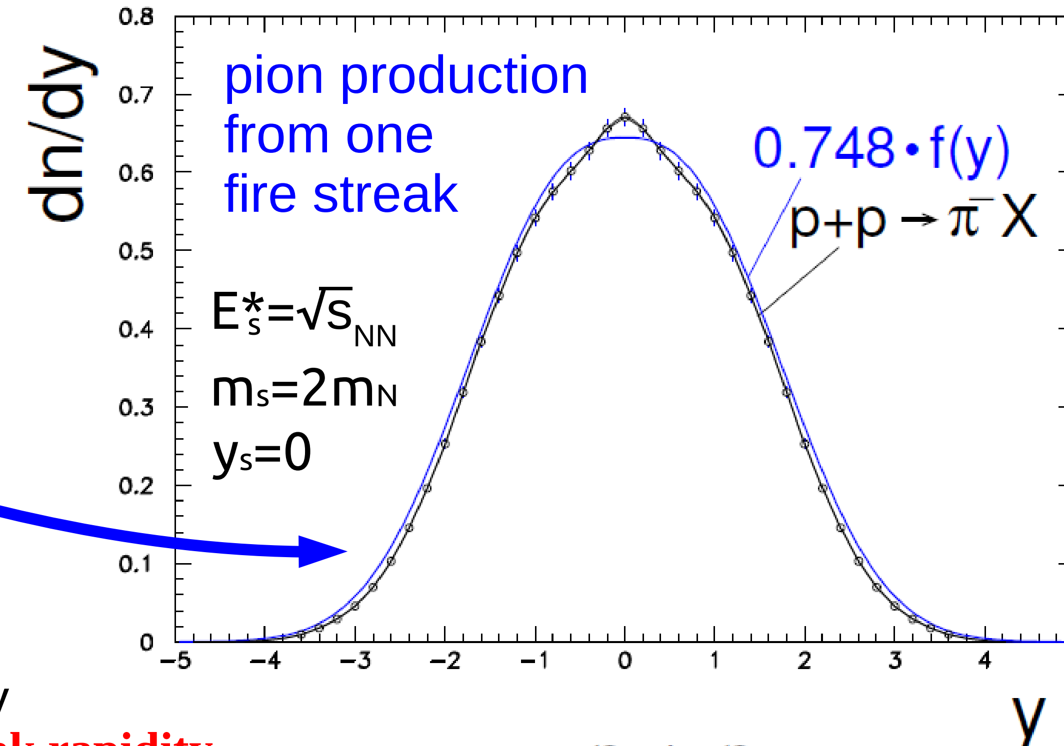
sum of brick masses

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



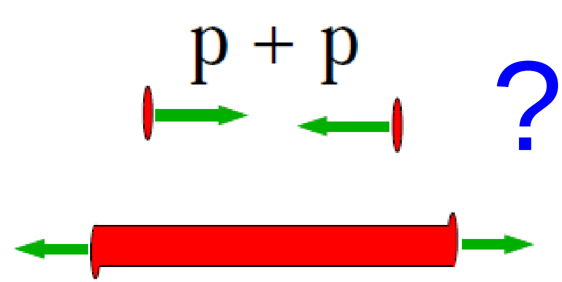


Each fire streak fragments independently

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

available energy ($E_s^* - m_s$); fire streak rapidity (y_s)

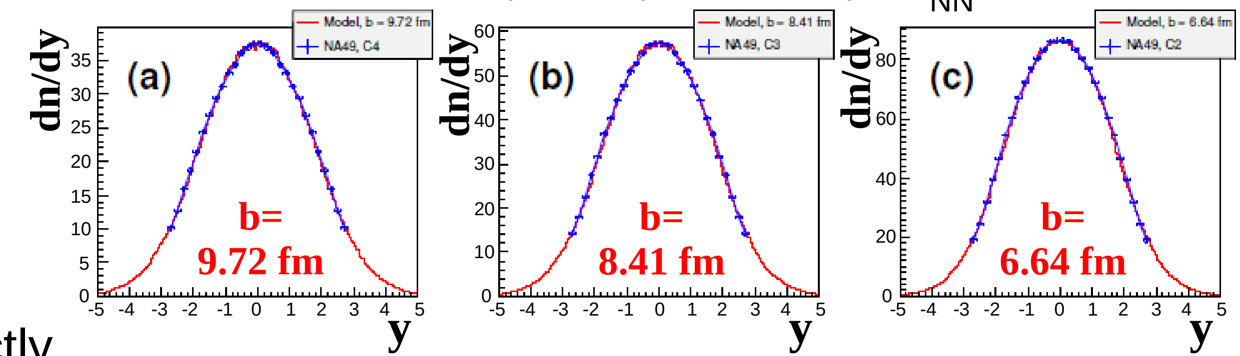
total fire streak energy (E_s^*); sum of brick masses (m_s)

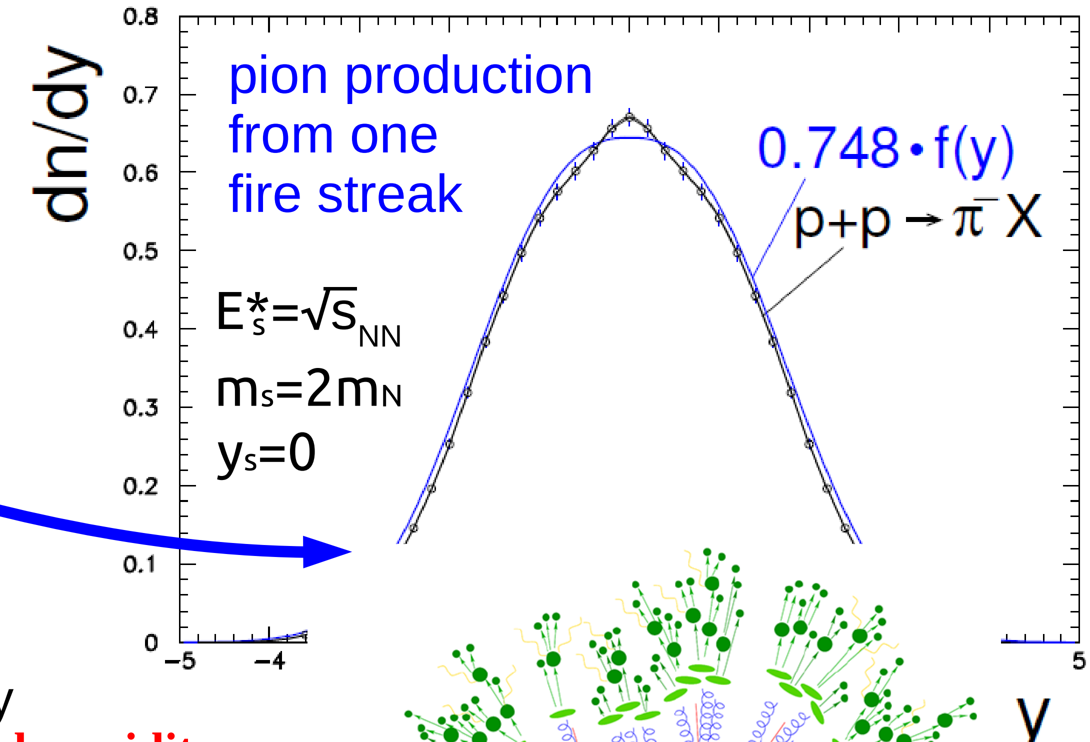


data points from: **NA49**, PRC 86 (2012) 054903, EPJC 45 (2006) 343

- The pion rapidity distribution from **one fire streak** in Pb+Pb collisions is **similar** to the pion rapidity distribution in **p+p** reactions ;
- 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





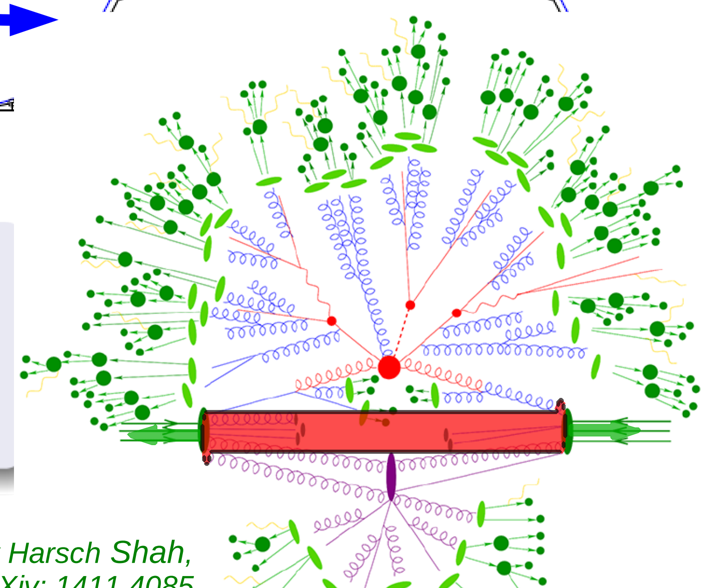
Each fire streak fragments independently

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

available energy (around $E_s^* - m_s$); fire streak rapidity (around y_s)

total fire streak energy (E_s^*)

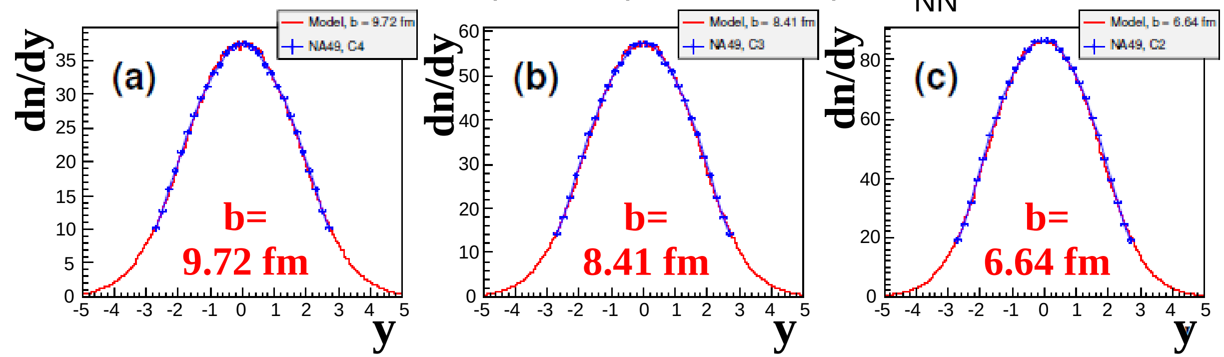
sum of brick masses (m_s)



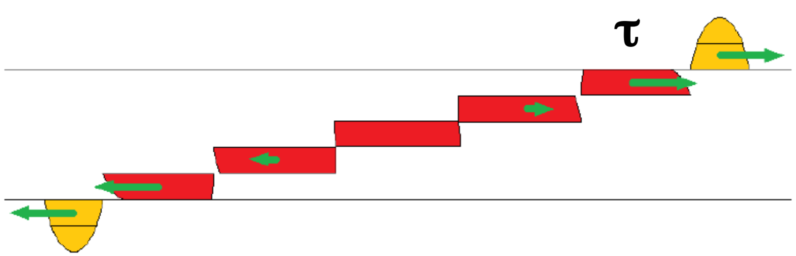
Courtesy by Harsch Shah, S.Hoche, arXiv: 1411.4085

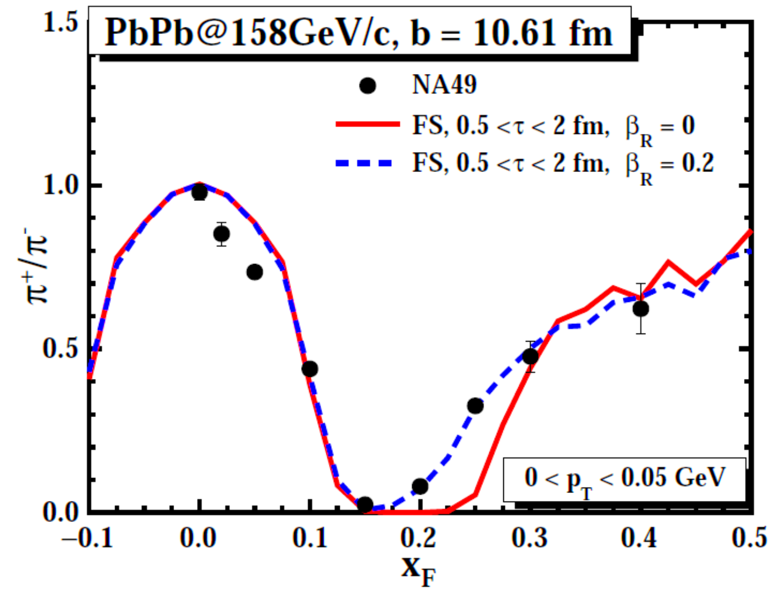
Application to EM effects

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

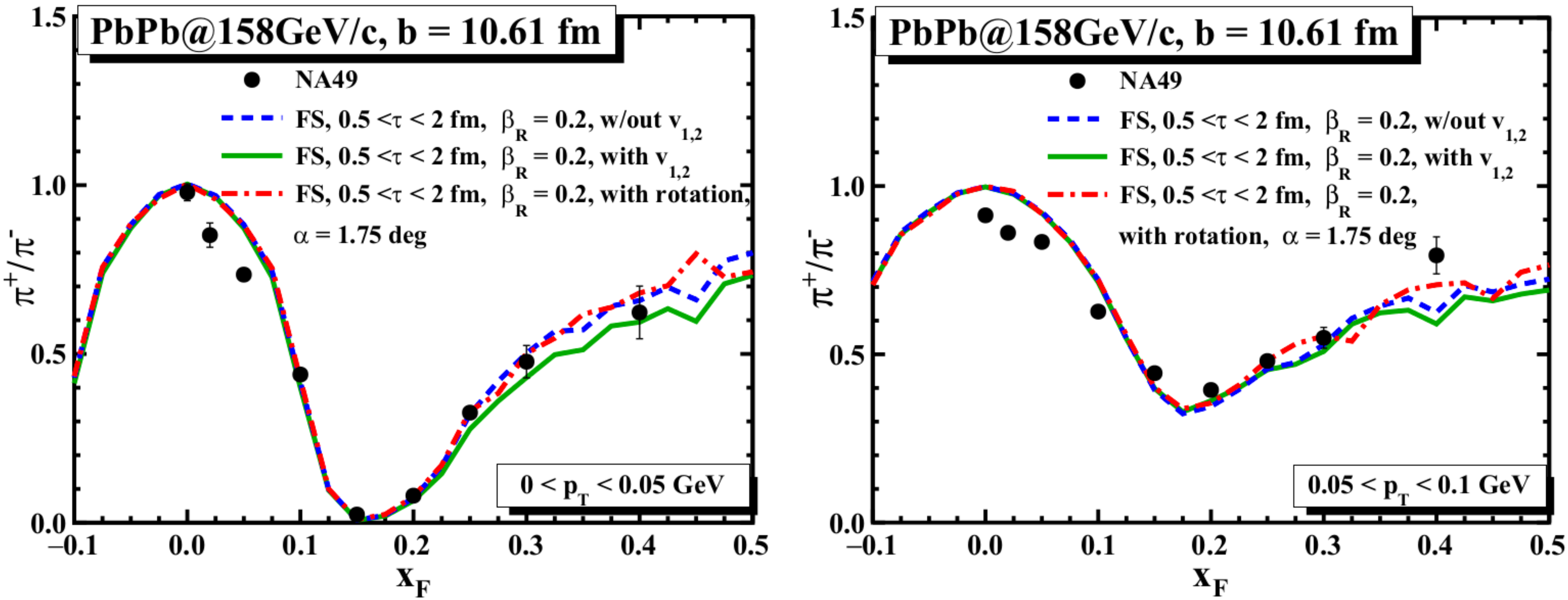


- Longitudinal evolution of the system → from our model ;
- Initial (before the action of the EM field) rapidity distribution of pions from our model ;





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

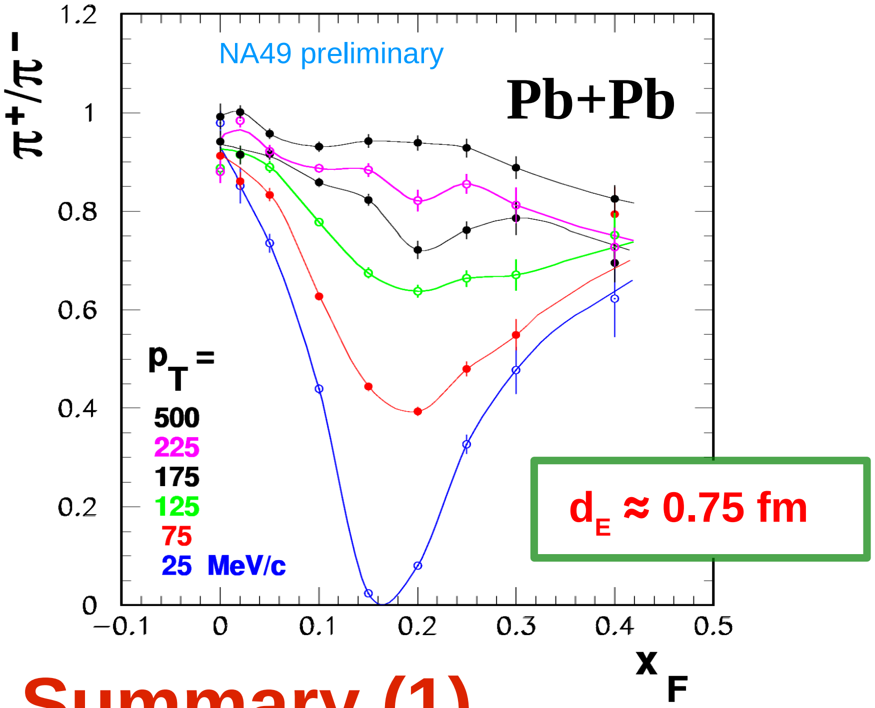


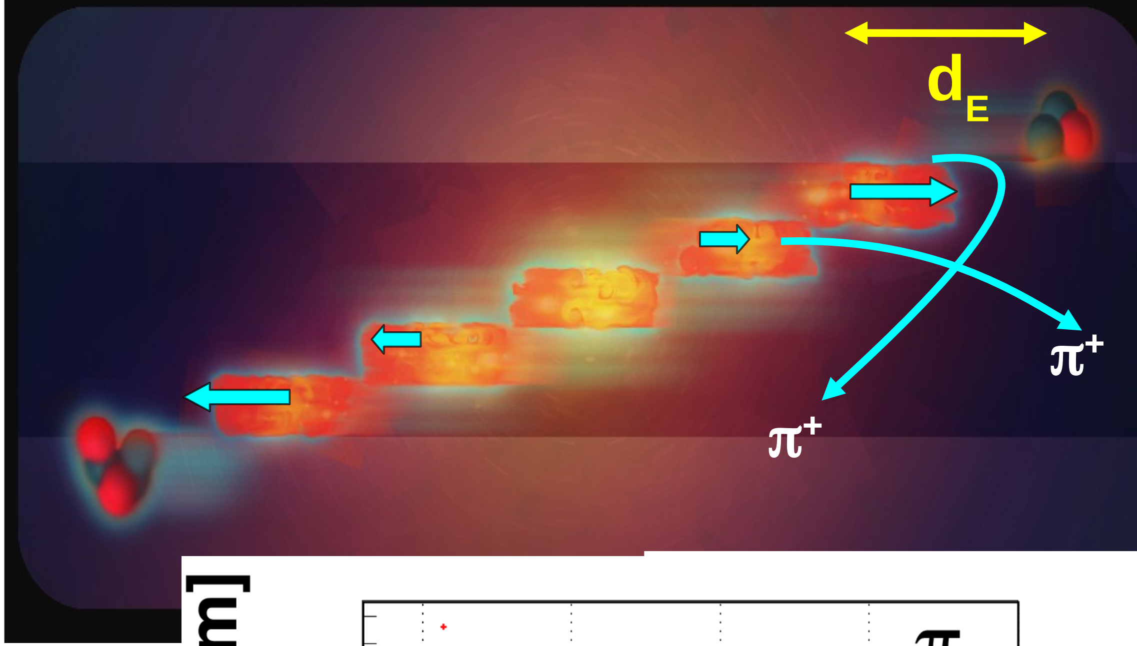
***First quantitative description** of the electromagnetic distortion of π^+/π^- ratios in Pb+Pb collisions at 158 GeV/nucleon beam energy ($\sqrt{s_{NN}}$=17.3 GeV)* [PRC102 (2020) 014901].

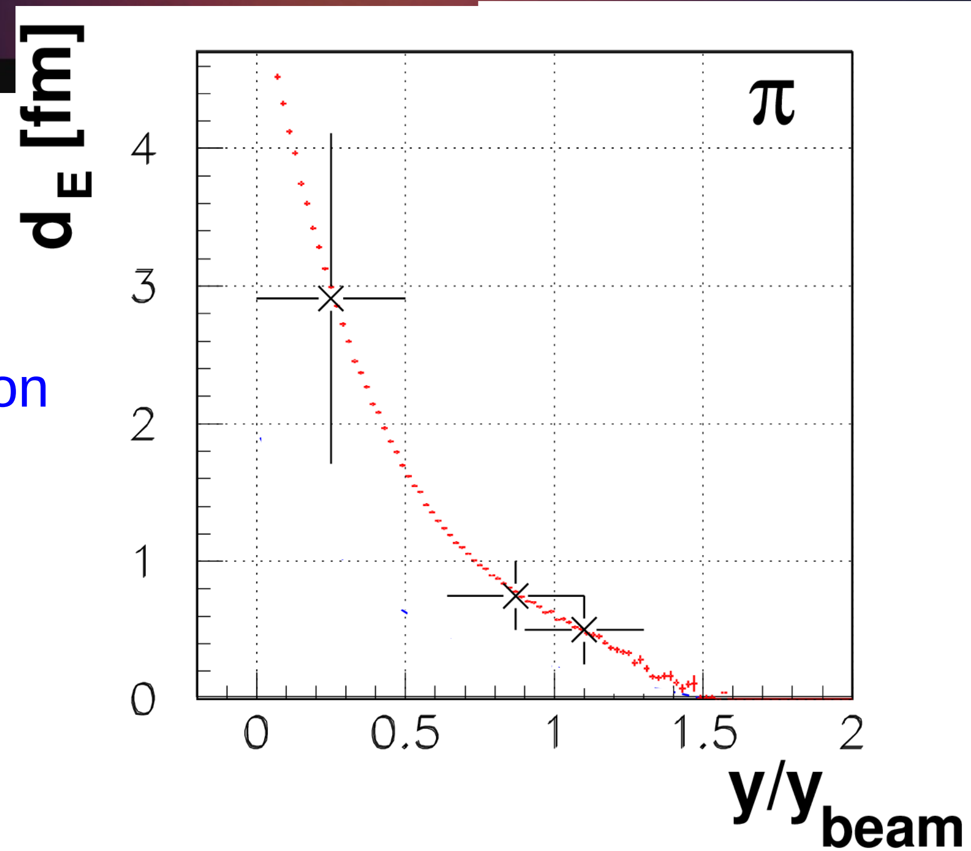
➔ Reasonable agreement with experimental data for $x_F \geq 0.1$;

➔ Inclusion of spectator expansion improves the description of exp. data ;

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







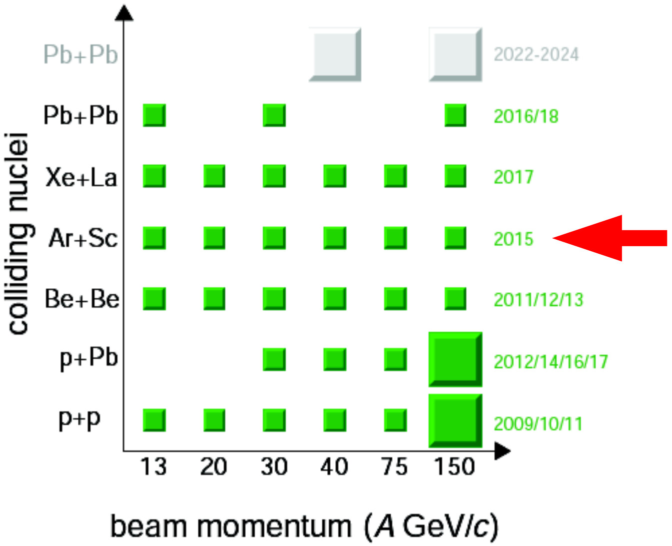
Summary (1)

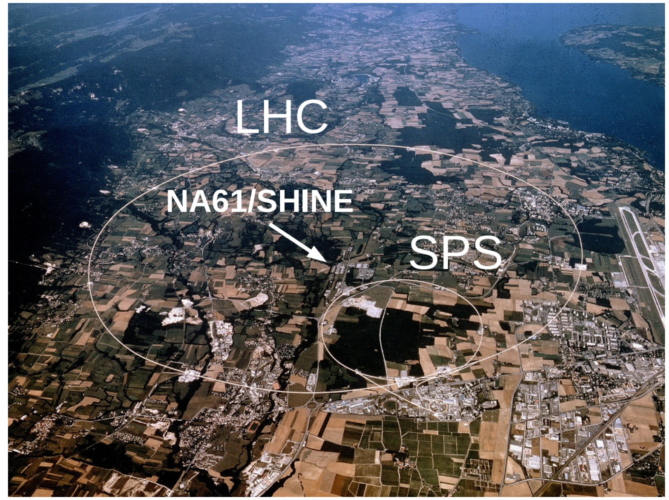
- EM effects induced by spectators bring new information on the space-time evolution of the process of (fast) pion production ;
- We obtained this information and used it ;
- Results look reasonable.

➔ **Small systems ;**

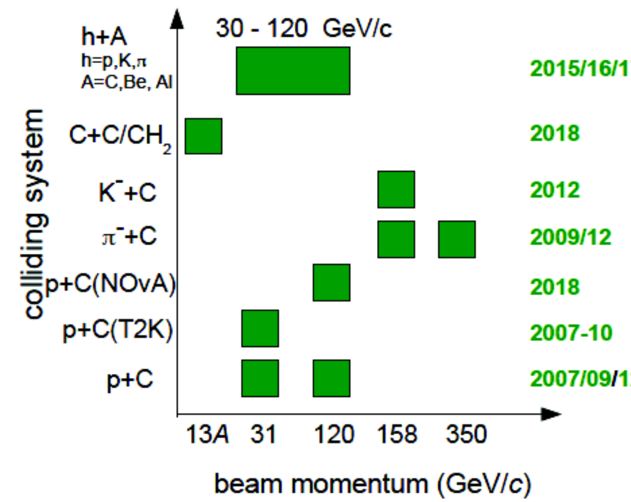
➔ **UPC (gamma-gamma) .**

SHINE = SPS Heavy Ion and Neutrino Experiment





$\sqrt{s_{NN}}$ = 5.1–17.3(27.4) GeV

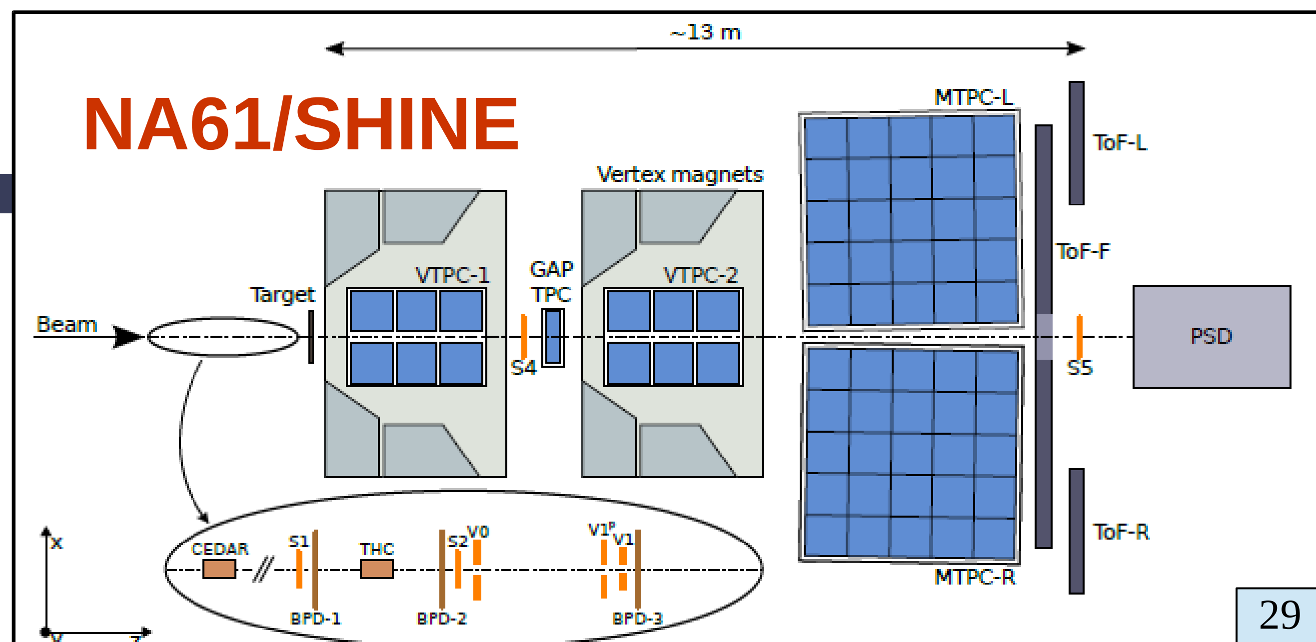


Strong interactions

- study the onset of deconfinement
- search for the critical point

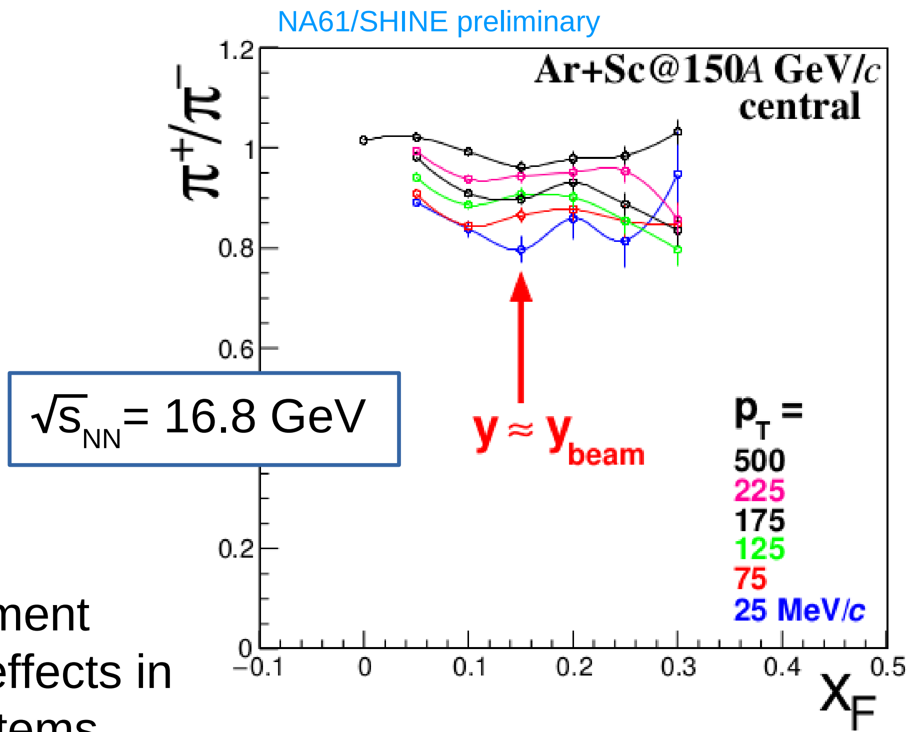
Cosmic rays and neutrinos

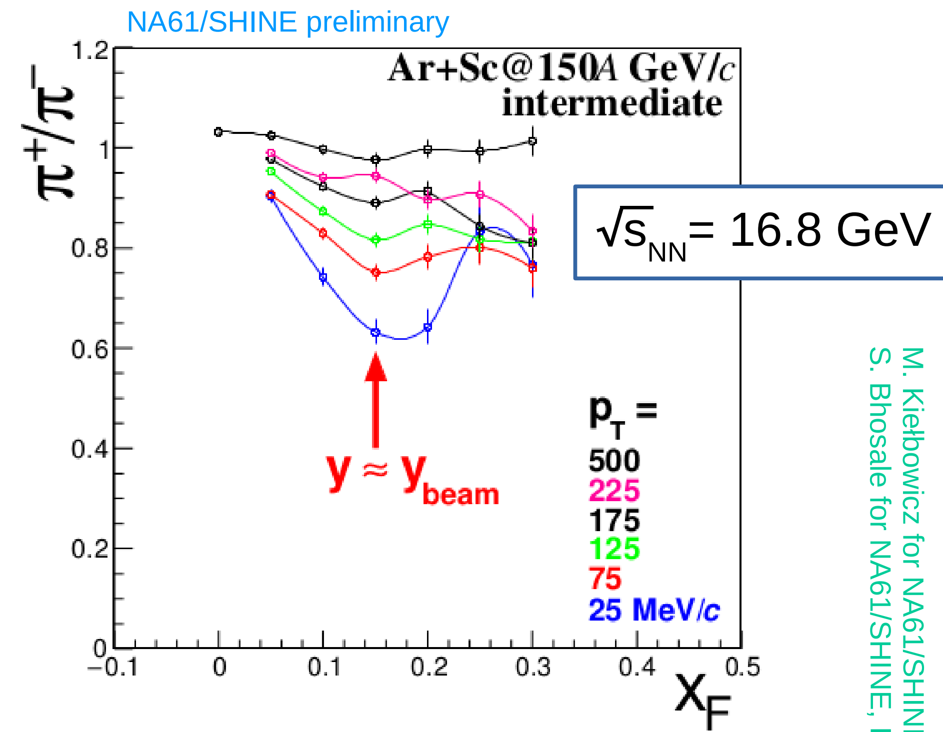
Adapted from Antoni Marcinek, QM22

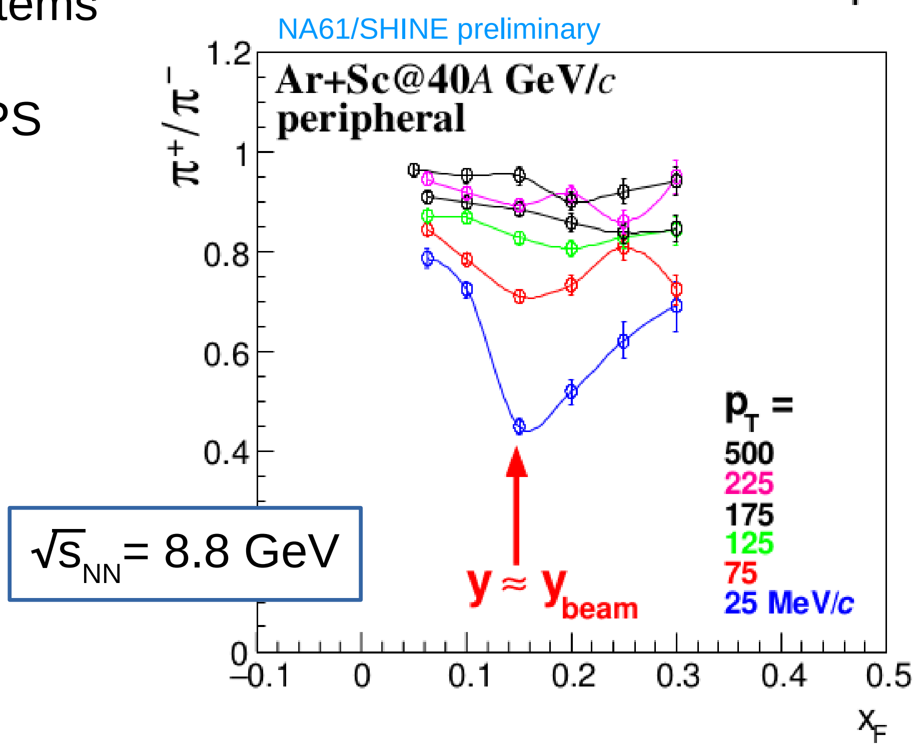


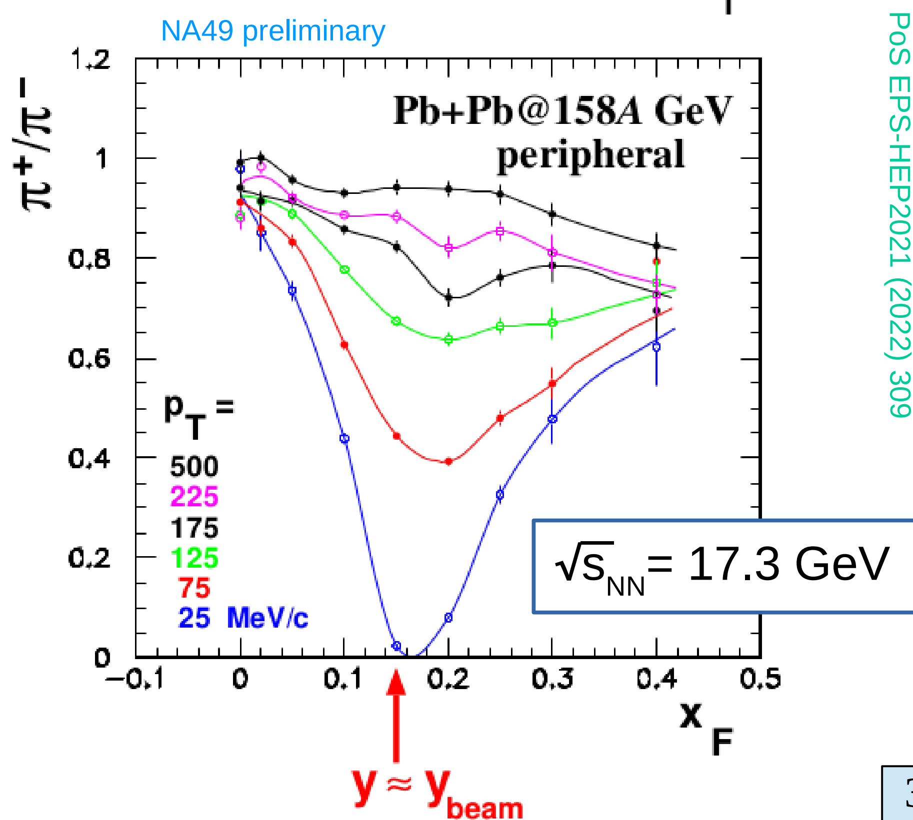
5)
Small systems

First ever measurement of these effects in small systems at the CERN SPS



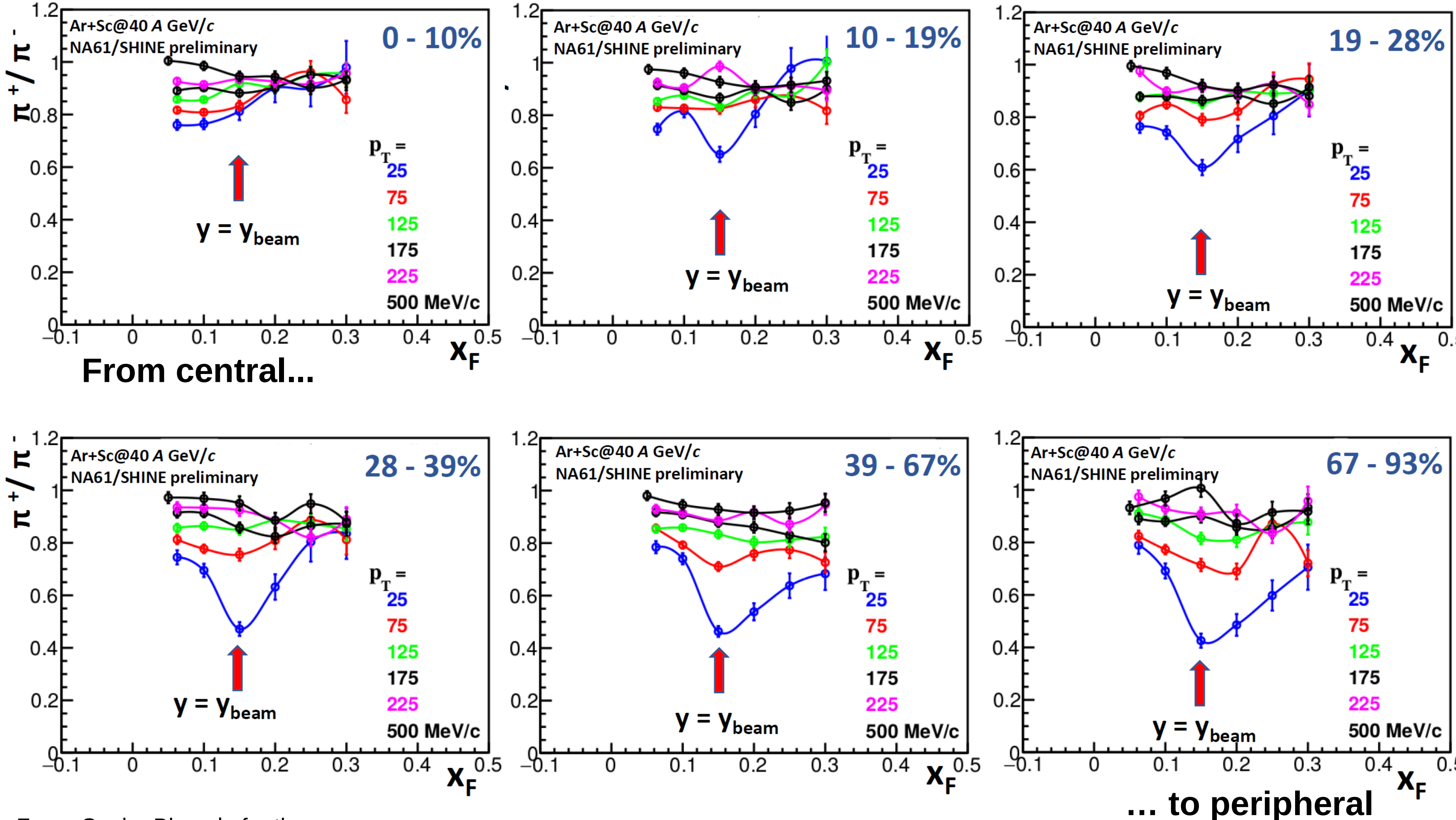






M. Kiełbowicz for NA61/SHINE, APP Supp. 12 (2019) 353
S. Bhosale for NA61/SHINE, PoS EPS-HEP2021 (2022) 309

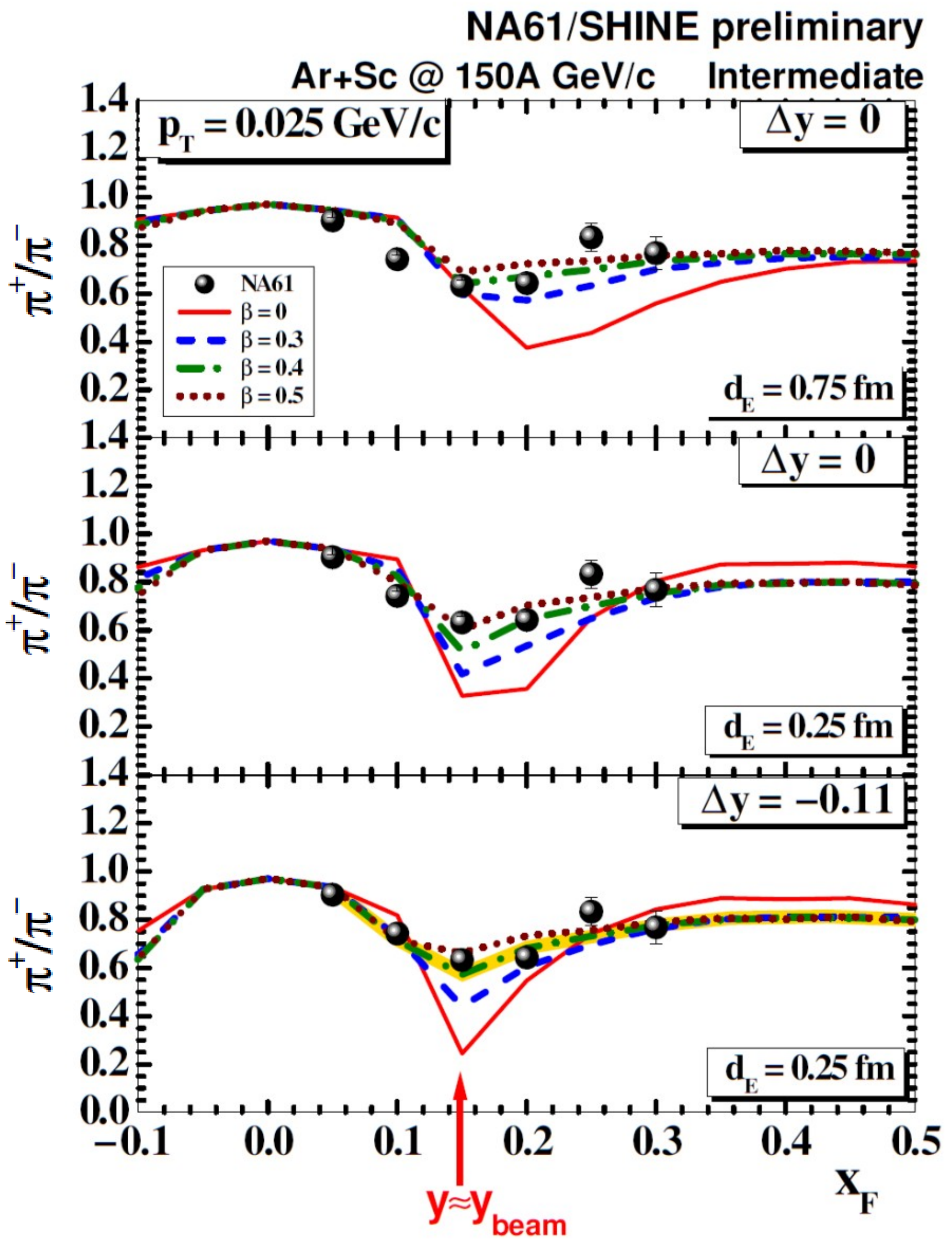
$\sqrt{s_{NN}}$= 8.8 GeV



From: Sneha Bhosale for the NA61/SHINE collaboration, MESON2021, 18 May 2021

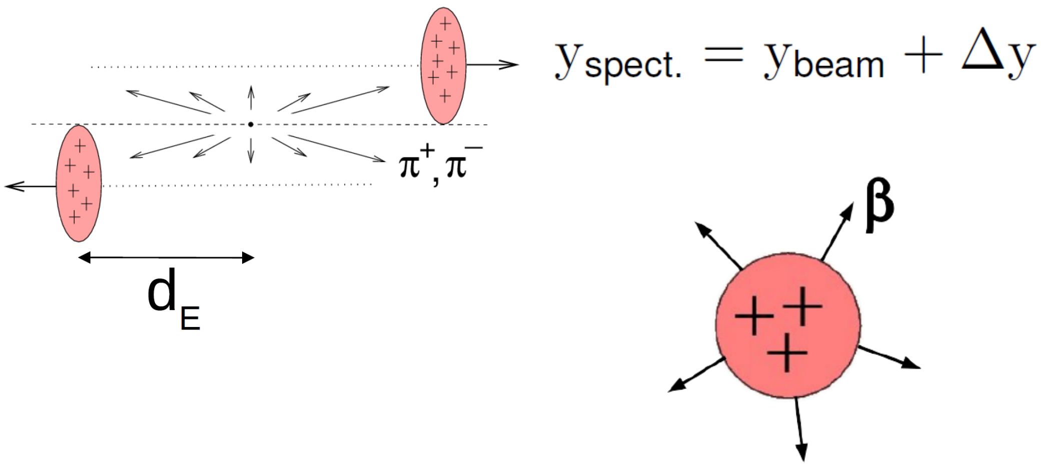
See also e.g.: A. Marcinek for NA61/SHINE, QM22

Modelling EM effects in new Ar+Sc data



APPB 50 (2019), 1127

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

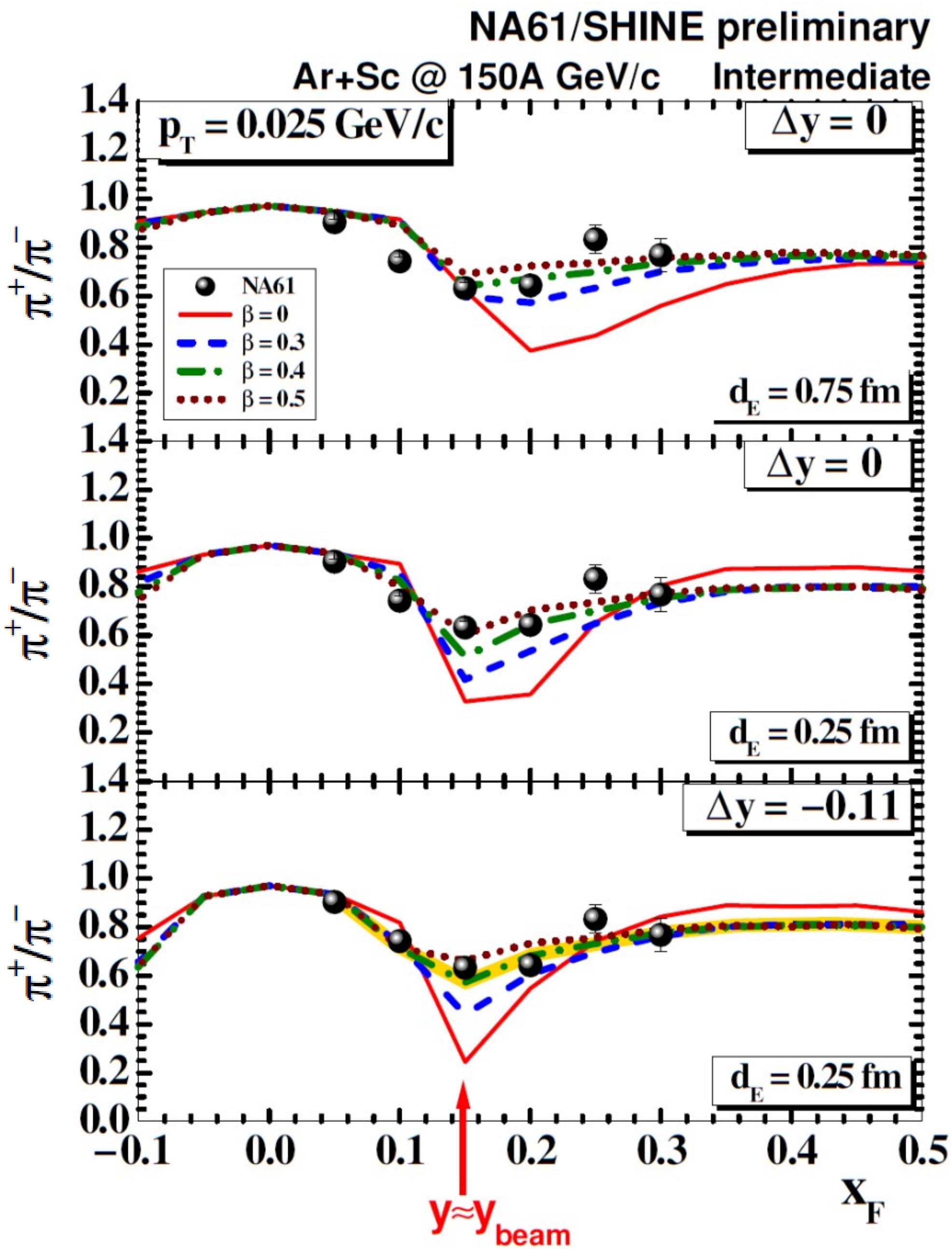


- Non-expanding spectator system cannot describe data (contrary to Pb+Pb, see A. Rybicki et al., APPB 46,737 (2015))

  ↓

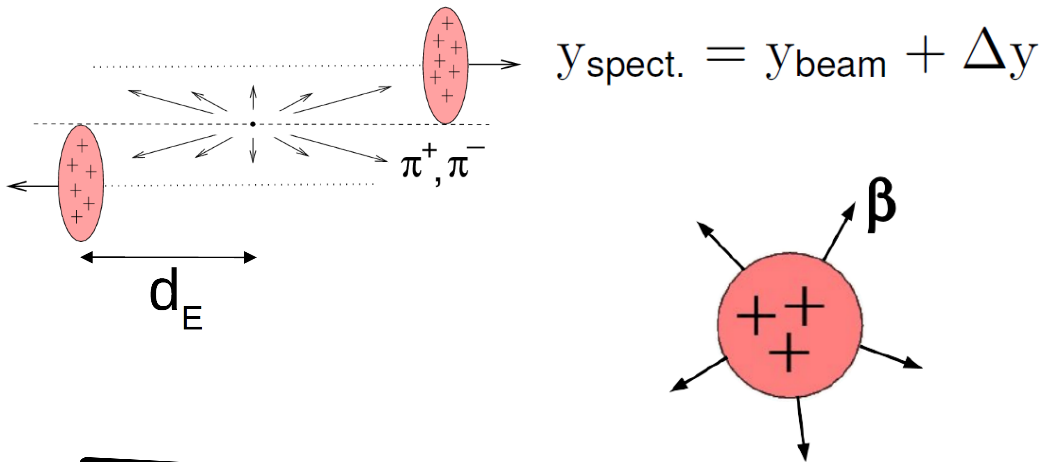
  need significant expansion velocity β of the charge cloud
- Optimal description: charge cloud moves slower than spectator system → presence of participant charge?

Modelling EM effects in new Ar+Sc data



APPB 50 (2019), 1127

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



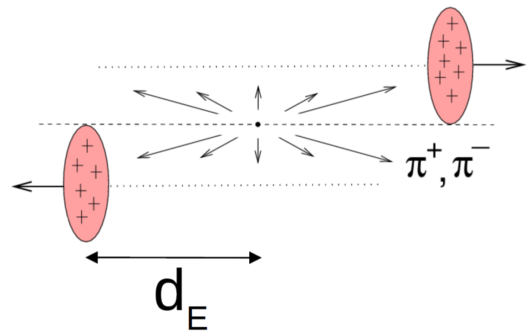
Entangled interplay of several phenomena: EM effects induced by the (small) spectator charge, these induced by the participant charge, isospin effects, spectator fragmentation, and others.

Further experimental guidance is needed.

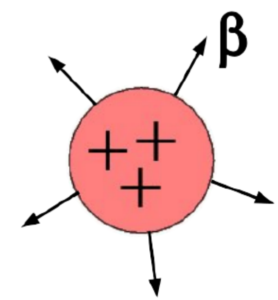
Xe+La ?

Modelling EM effects in new Ar+Sc data

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



$$y_{spect.} = y_{beam} + \Delta y$$



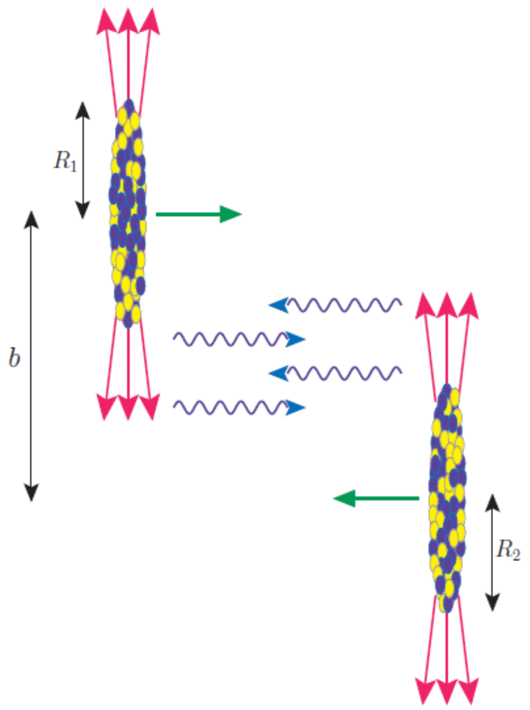
NA61/SHINE

Entangled interplay of several phenomena: EM effects induced by the (small) spectator charge, these induced by the participant charge, isospin effects, spectator fragmentation, and others.

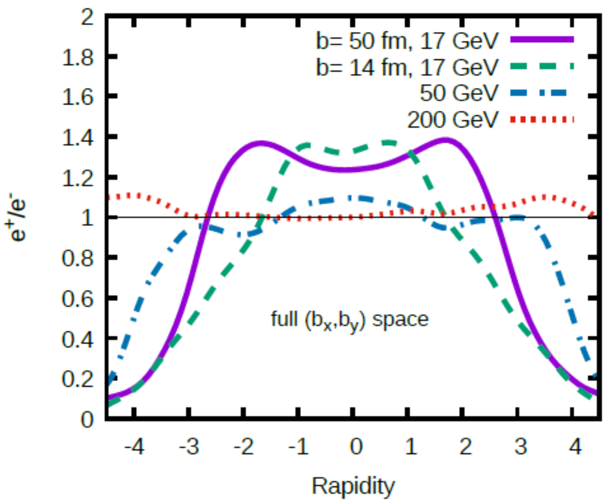
Further experimental guidance is needed.

Xe+La ?

6) Comment: how about gamma-gamma processes in ultra-peripheral collisions ?



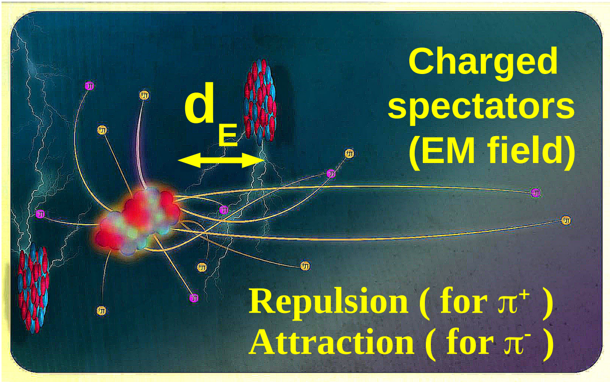
- Think about **Pb+Pb (γ γ) → e^+e^-** ;
- What happens to leptons once created ?
- Subject of long discussions (here in Kraków) ;
- Conceptual difficulties ;
- Never measured.



See talk by
Kasia Mazurek
(Tuesday).

2107.13239

6) No epilogue



The electromagnetic (EM) fields resulting from the presence of charged spectators induce distortions in spectra of charged particles, and result in charge splitting of directed flow.

These spectator-induced EM effects can be used to study the space-time evolution of particle production.

Such studies have shown that in high energy heavy-ion collisions, faster pions are produced closer to the spectator system. They also provided an independent estimate for the time of pion creation, at y=0.

A first quantitative description of the EM distortion of charge ratios (π^+/π^-) of fast pions produced in Pb+Pb collisions at $\sqrt{s_{NN}}$=17.3 GeV has been obtained. This gives an indication of significantly shorter pion production time scales (shorter proper times τ) w.r.t. what was obtained at central rapidity.

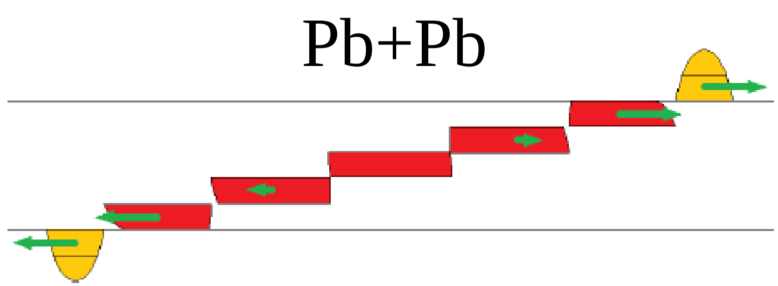
First ever measurements of these effects in small systems at the CERN SPS are now available from NA61/SHINE.

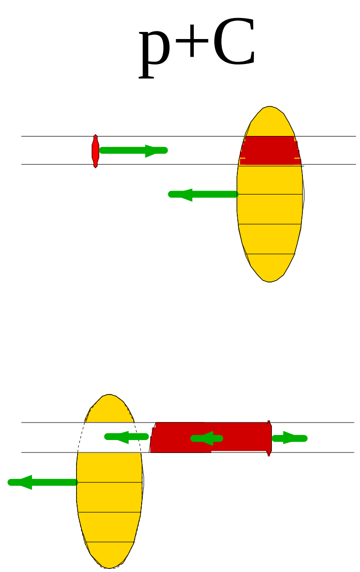
Thank you !

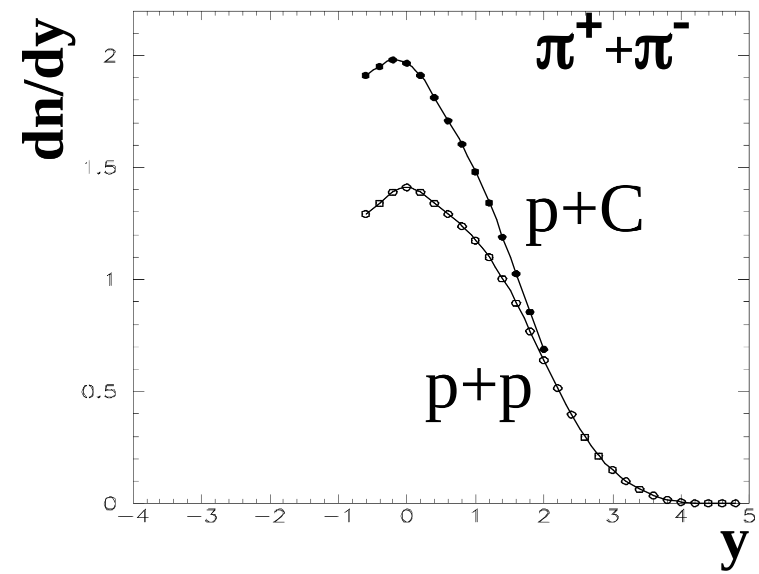
Extra slides

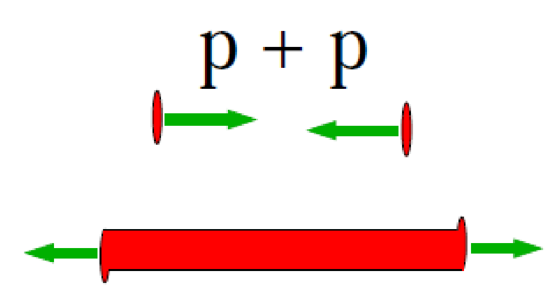
$\sqrt{s_{NN}}$= 17.3 GeV

- p+A collisions with our model from Sec. 4.





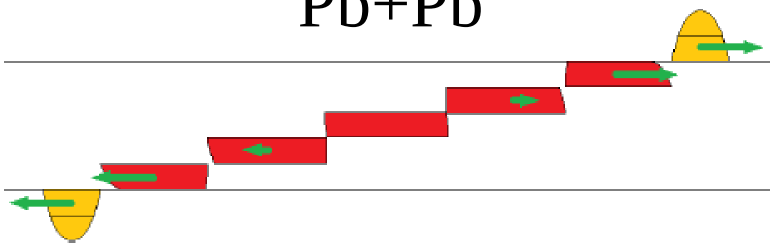




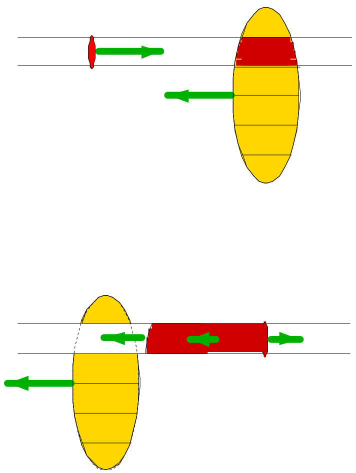
data points from: **NA49**, EPJC 45 (2006) 343, EPJC 49 (2007) 919

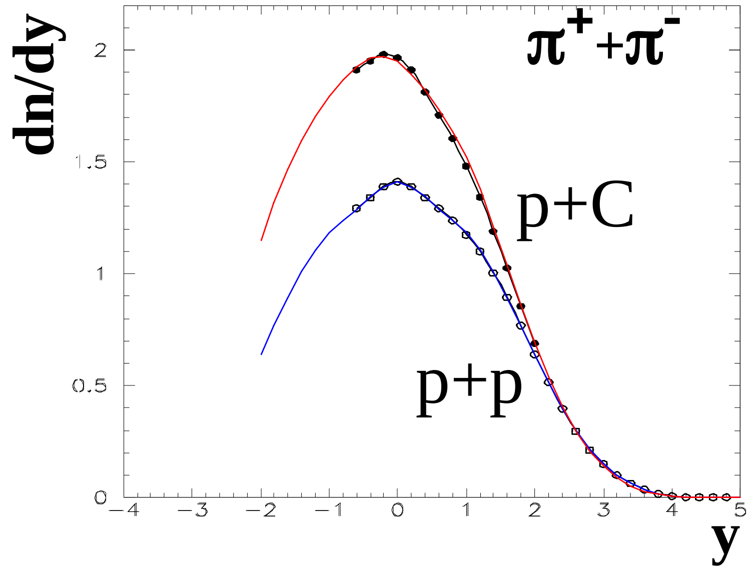
- p+A collisions with our model from Sec. 4.

Pb+Pb

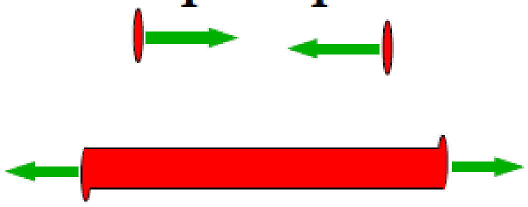


p+C



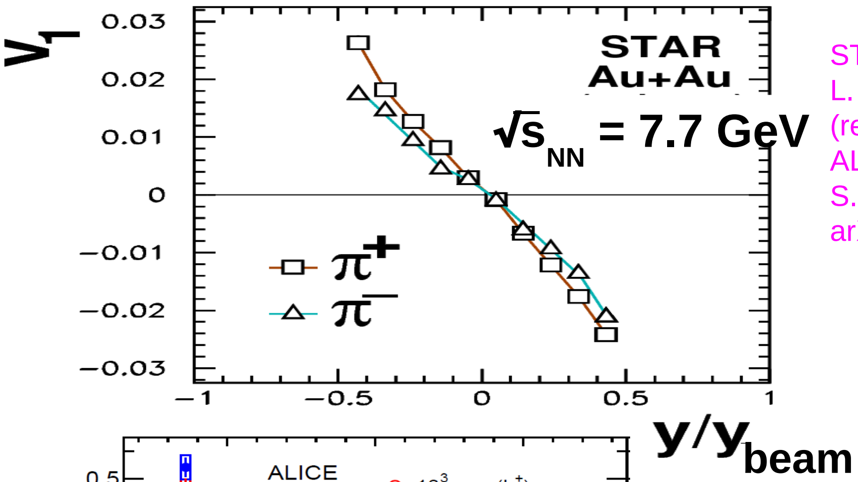


p + p

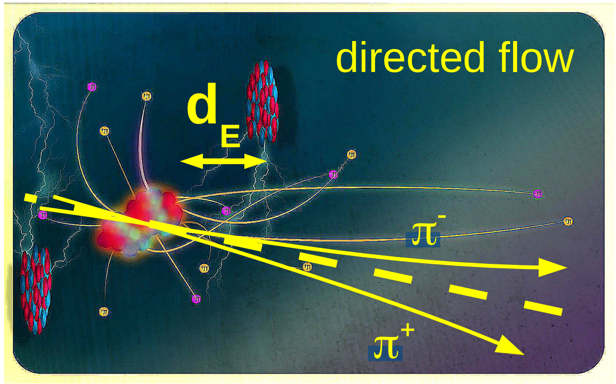


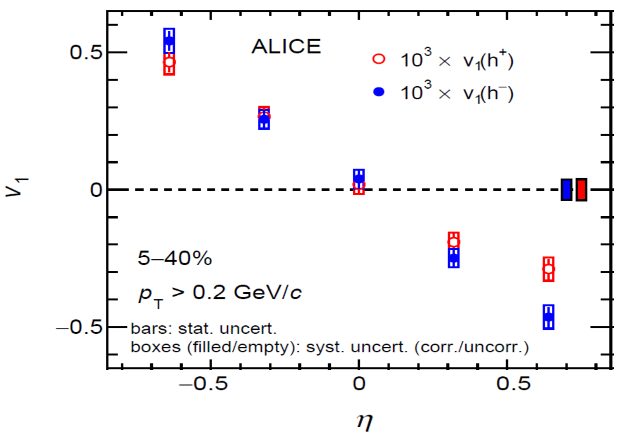
data points from: **NA49**, EPJC 45 (2006) 343, EPJC 49 (2007) 919

- More on directed flow.



STAR:
L. Adamczyk et al., PRL 112 (2014) 162301 (redrawn)
ALICE:
S. Acharya et al., PRL 125 (2020) 2, 022301, arXiv:1910.14406 [nucl-ex]





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

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

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