Fire streaks, electromagnetic effects, directed flow and lifetime of the plasma at SPS energies

Vitalii Ozvenchuk,

in collaboration with

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<u>Our model</u>: PRC 95 (2017) 2, 024908; PRC 99 (2019) 2, 024908;
<u>EM part</u>: PRC 102 (2020) 1, 014901

Outline

- Introduction & Motivation
- The model
- Electromagnetic effects in peripheral Pb+Pb collisions:
  - Initial conditions
  - Results
- Summary & Outlook

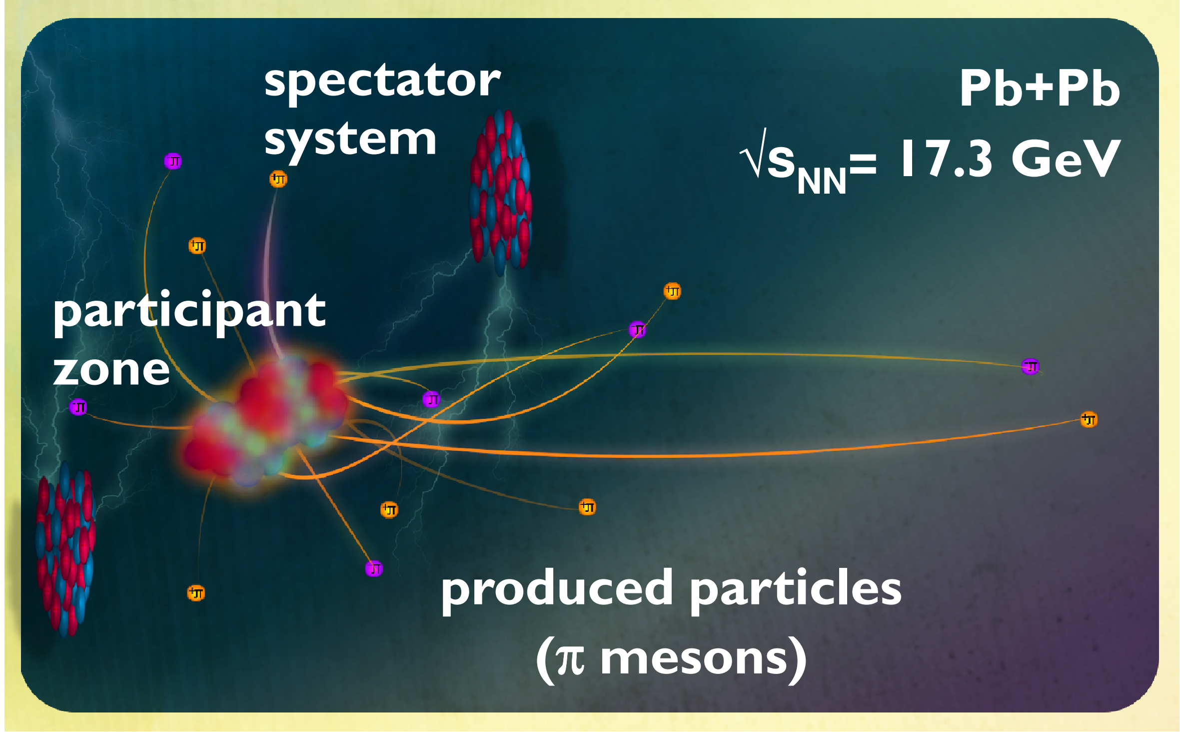
Introduction & Motivation

- We study the electromagnetic effects in heavy-ion collisions

- Charged spectators generate electromagnetic fields

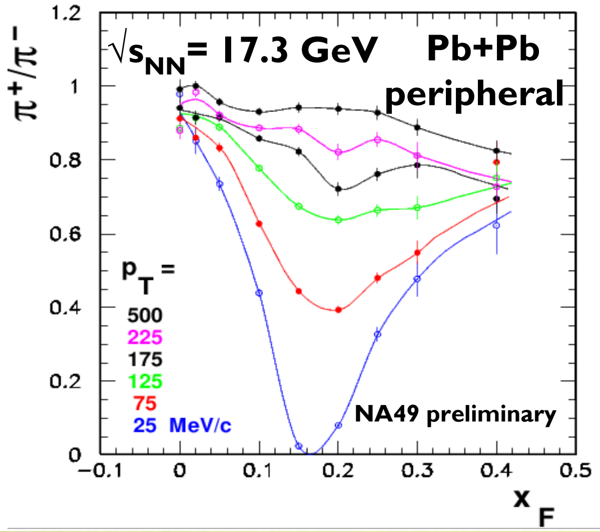
- These modify the trajectories of charged pions

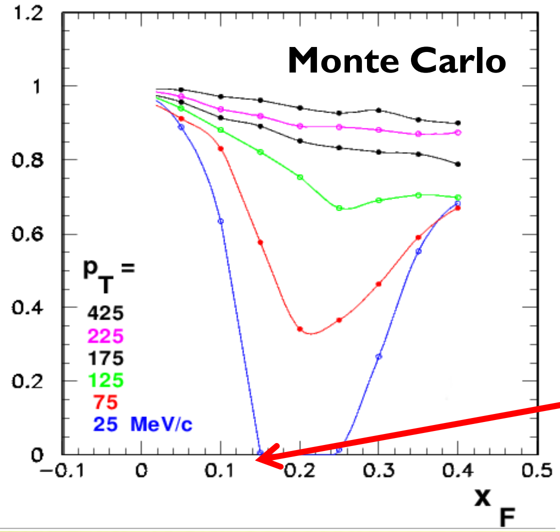
- We use this effect as a new source of the information on the space-time evolution of the system



by I. Sputowska

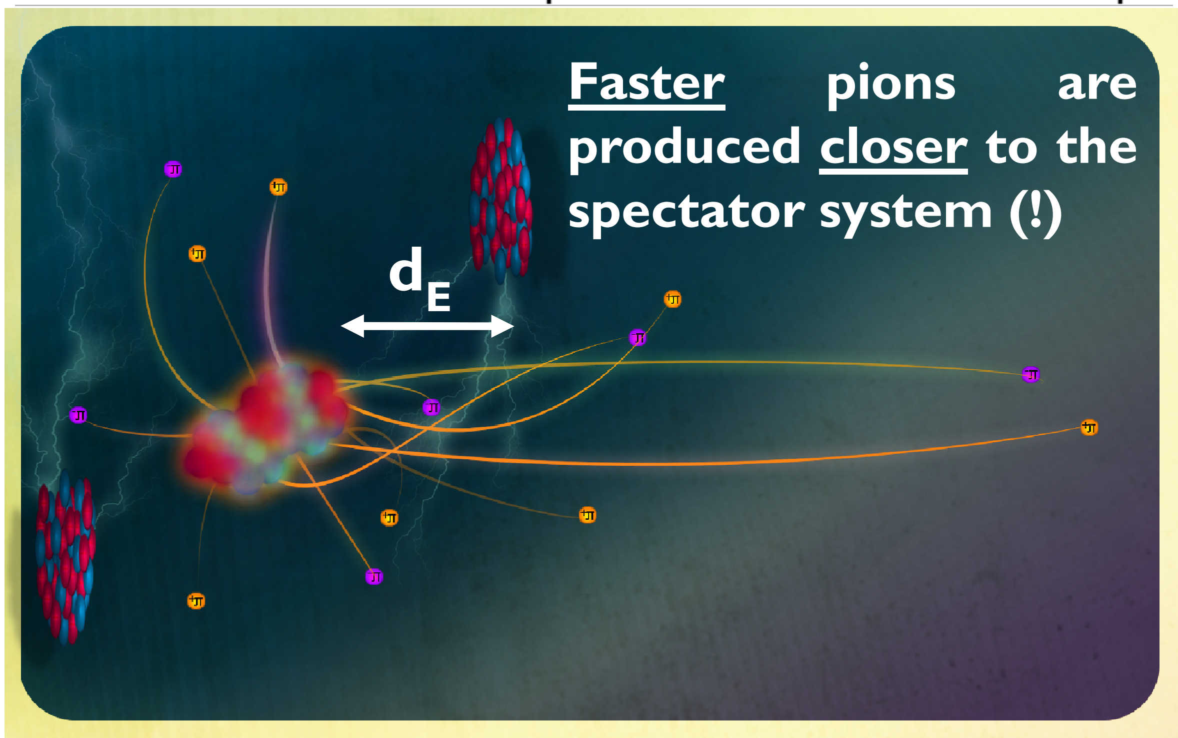
Introduction & Motivation

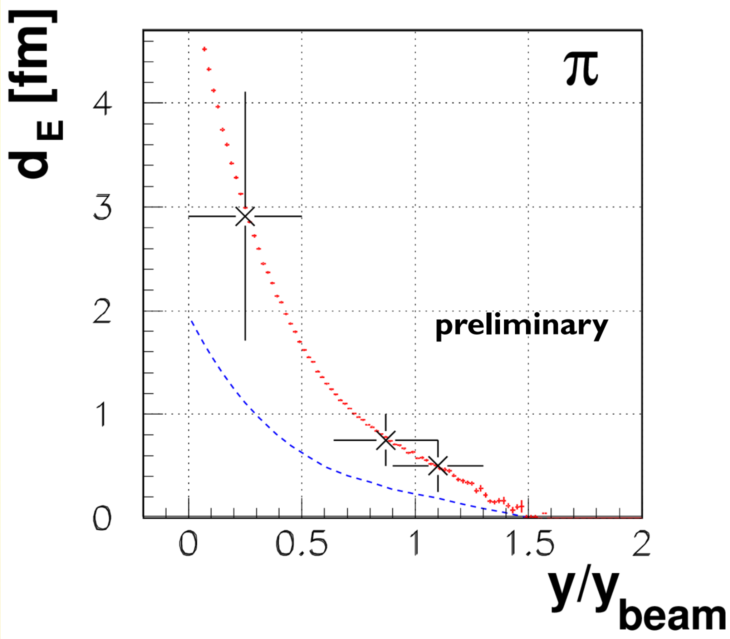




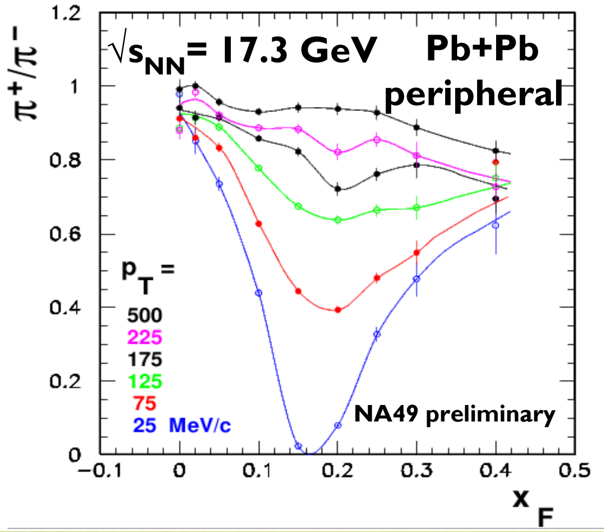
spectator velocity

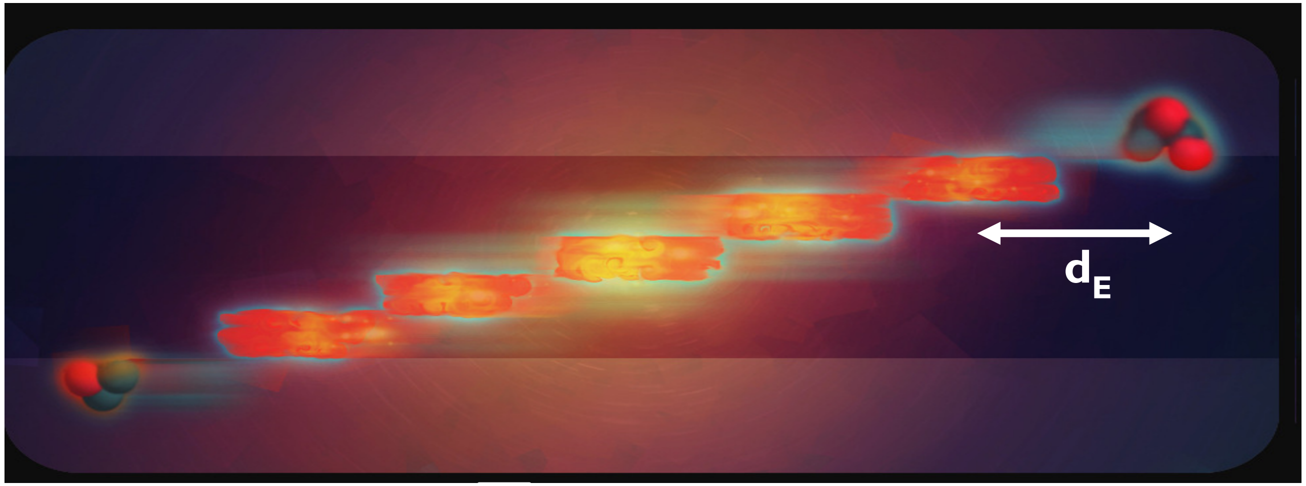
See also: A. Rybicki *et al.*, APP Supp. **9**, 303 (2016)



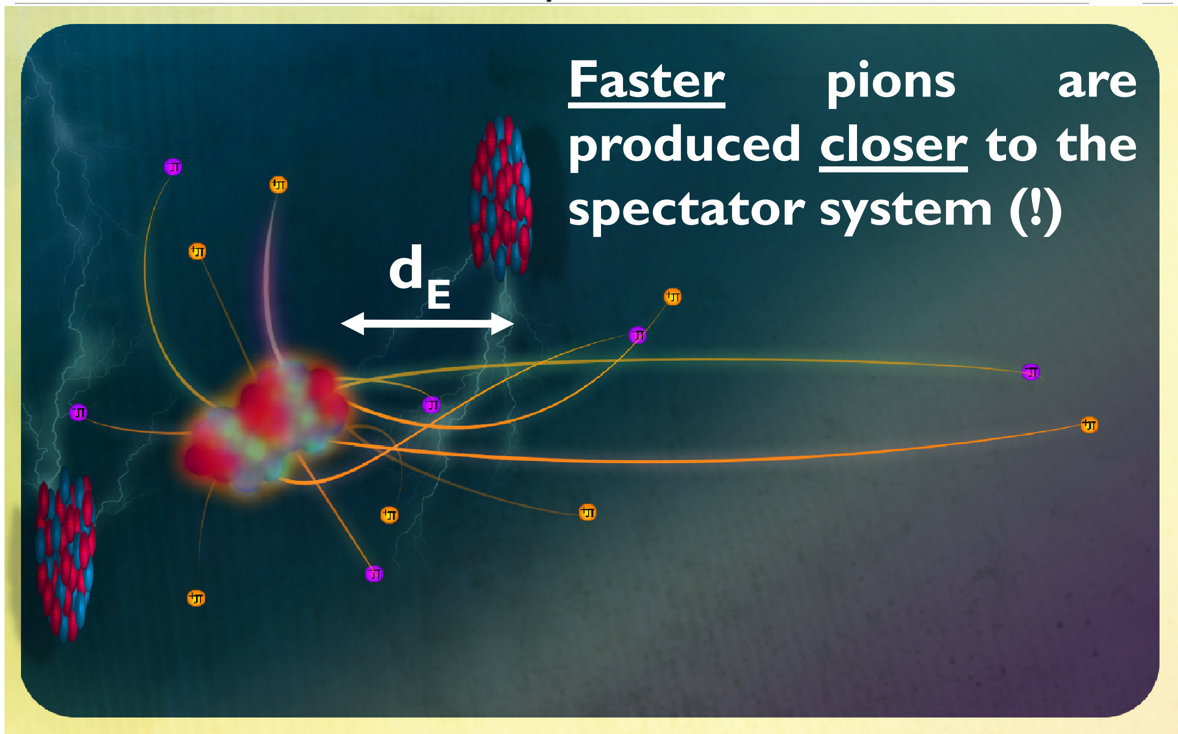


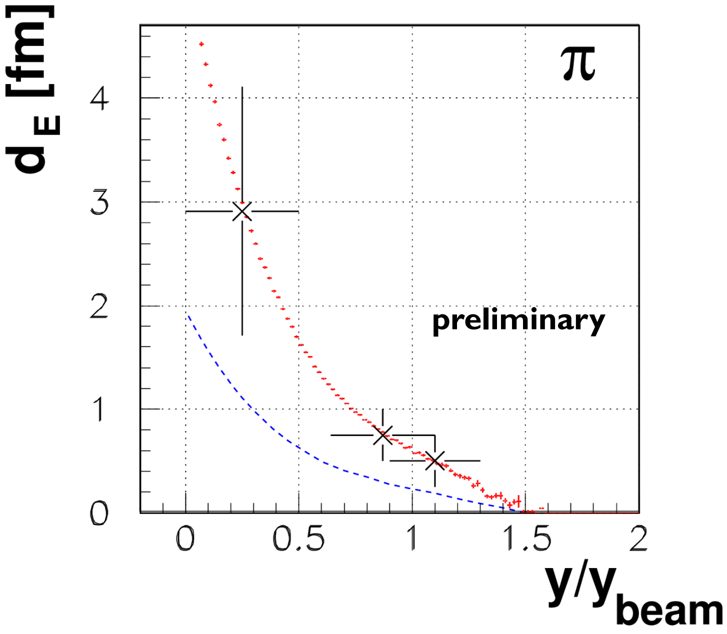
Introduction & Motivation





See also: A. Rybicki *et al.*, APP Supp. **9**, 303 (2016)



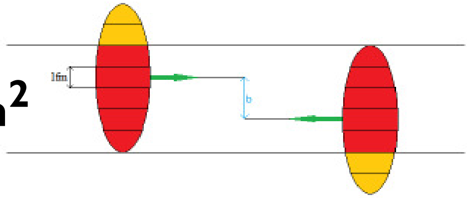


The model

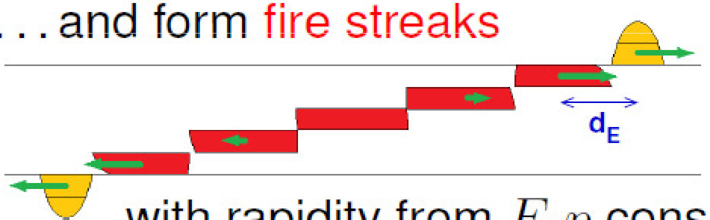
Bricks collide . . .

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

1x1 fm^2



. . . and form fire streaks



with rapidity from E-p conservation

Each fire streak fragments independently in pions

available energy **fire streak rapidity**

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

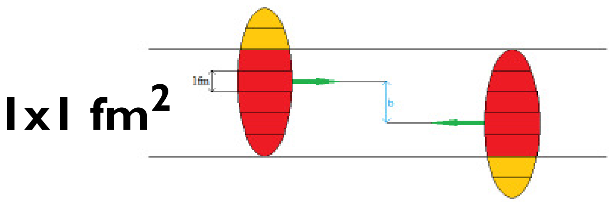
total fire streak energy sum of brick masses

- **Idea by A. Szczurek**
- **See also:**

  R. Hagedorn, CERN-71-12 (1971)
  W. D. Myers, NPA 296, 177 (1978)

The pion rapidity distribution in Pb+Pb collisions

Bricks collide . . .



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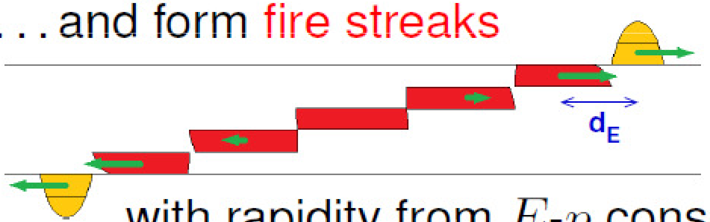

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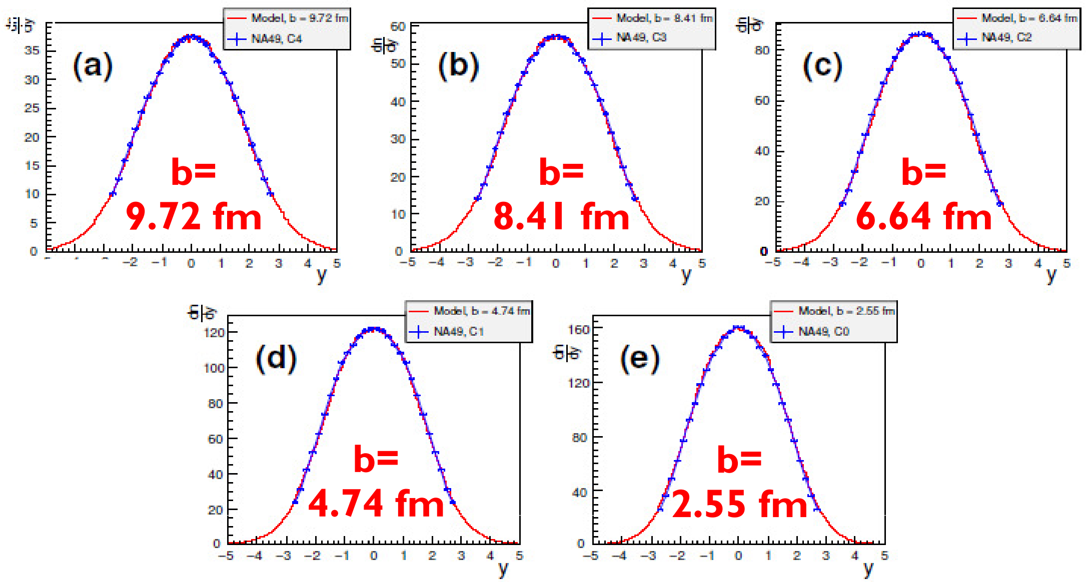
Each fire streak fragments independently in pions

available energy   fire streak rapidity

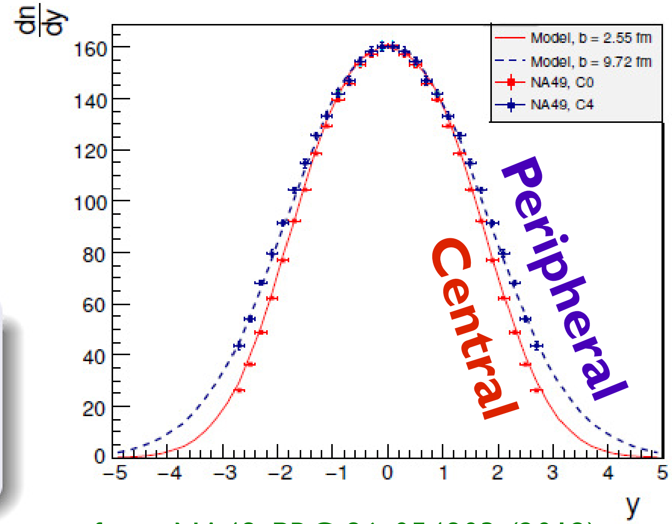
$$\frac{\mathrm{d}n}{\mathrm{d}y} \sim A \cdot \boxed{(E_{\mathrm{s}}^{*} - m_{\mathrm{s}})} \cdot \exp\left(- \frac{\left[(\mathrm{y} - \boxed{\mathrm{y_s}})^2 + \epsilon^2\right]^{\frac{n}{2}}}{n\sigma_{\mathrm{y}}^{n}} \right)$$

total fire streak energy   sum of brick masses

data points from: T. Anticic et al., Phys. Rev. C **86**, 054903 (2012)



π^- in NA49 Pb+Pb @ 158 GeV



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

Spectator induced electromagnetic effects

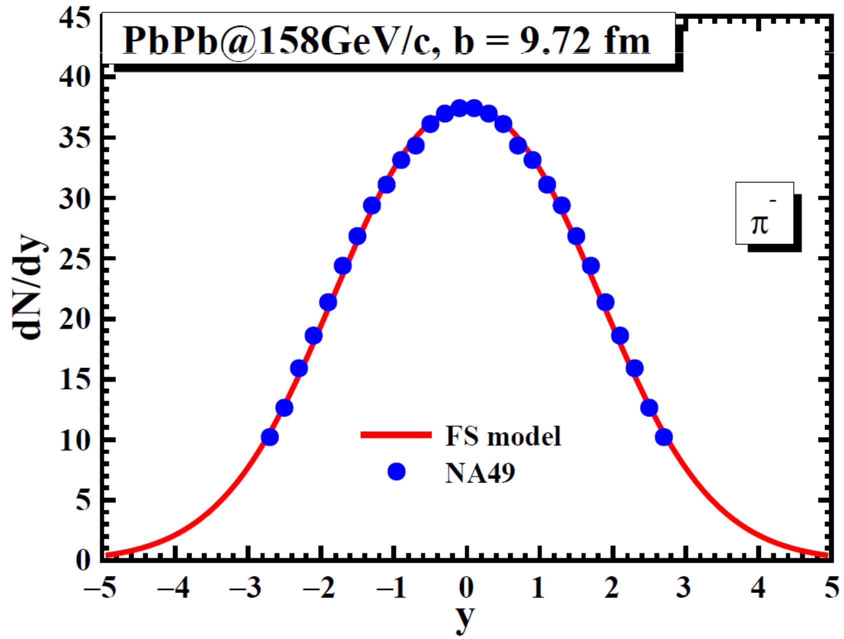
Pion rapidity and transverse-momentum spectra

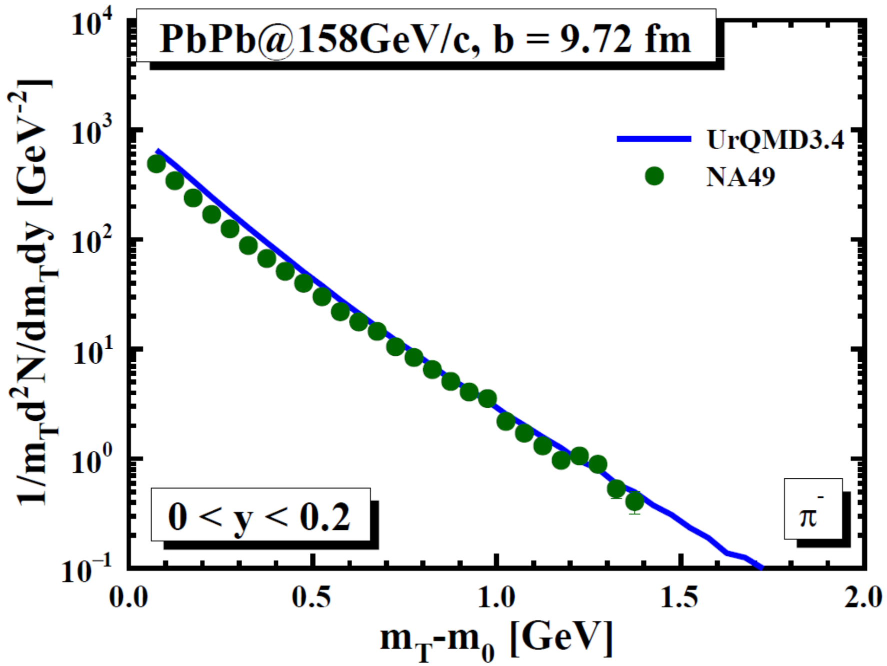
- **We use the initial (without electromagnetic effects included) rapidity distribution of negative pions obtained from our model**

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

- **For the initial transverse-momentum distribution of pions we choose one obtained from UrQMD 3.4 model**

S.A.Bass *et al.,* Prog. Part. Nucl. Phys. 41 (1998) 225; M.Bleicher *et al.,* J. Phys. G 25 (1999) 1859



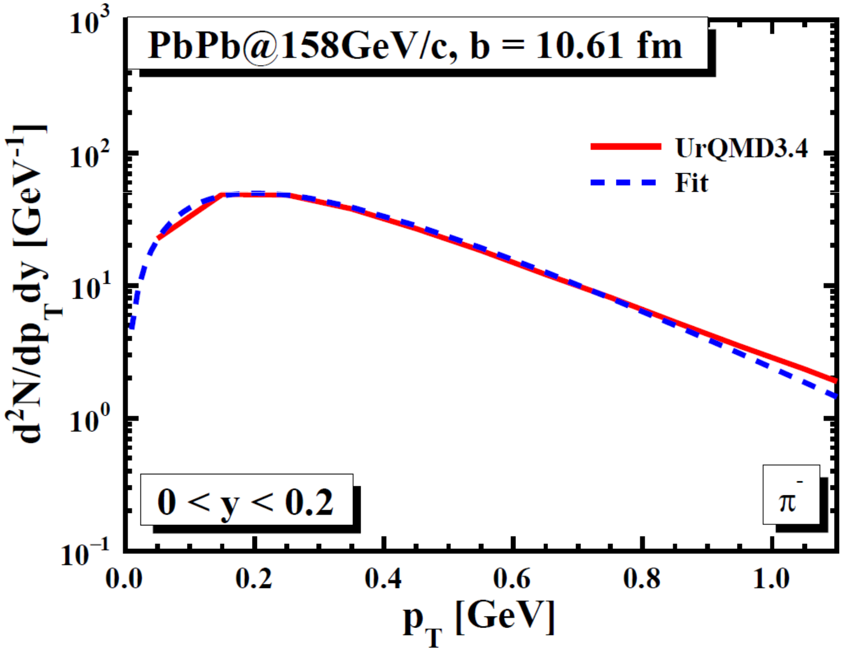


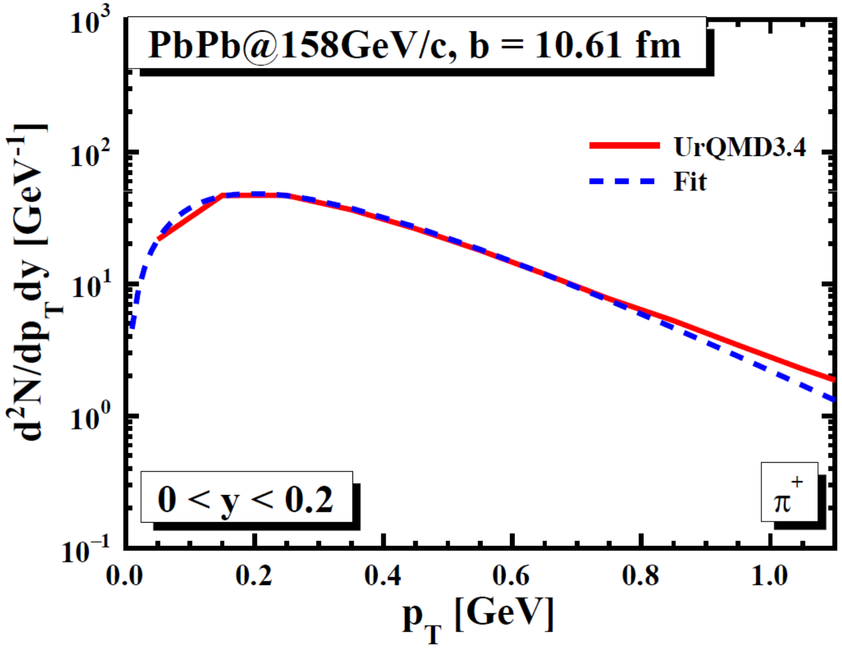
data: T. Anticic *et al.,* NA49, Phys. Rev. C 86, 054903 (2012)

Fitting of pion transverse-momentum spectra

❑ **The resulting UrQMD predictions for transverse-momentum distribution of pions at midrapidity we parametrize by the exponential function:**

$$\boxed{\frac{dN}{dp_T} = \frac{Sp_T}{T^2 + mT} \exp\left[-(m_T - m)/T\right]}$$





❑ **It gives:** $T_{\pi^-} = 165 \text{ MeV}$ **and** $T_{\pi^+} = 163 \text{ MeV}$

❑ **In general,** $T = T(y)$

Pion emission time

- We fix the pion emission time from the fire streaks and initial position of the pion relative to the spectator

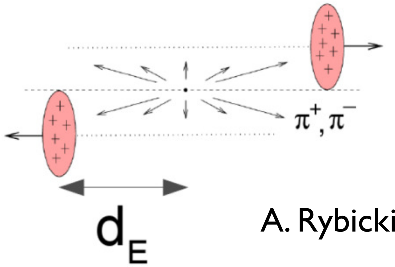
- We assume the pion emission time in the fire streak rest frame; up to this time the fire streaks (plasma) evolves in longitudinal direction

- We calculate the actual position of pion creation in z for each (i,j) fire streak in nucleus-nucleus cms frame by Lorentz transformation

$$\boxed{\tau \to t_{i,j}}$$

- The transformation depends on a velocity of the given fire streak in cms which in our model depends on its position in the impact parameter space (b_x, b_y)

Comparison to the previous study

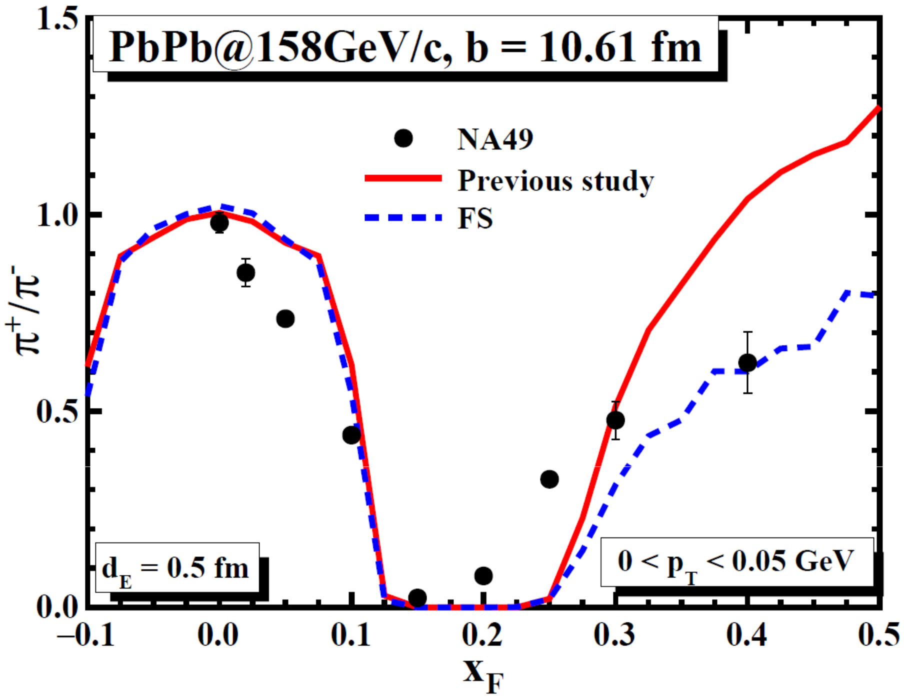


❑ Red (previous study)

A. Rybicki, A. Szczurek, Phys. Rev. C 75, 054903 (20(

➢ emission region is reduced to a single point

➢ initial pion two-dimensional (x_F, p_T) distribution is similar to p+p collisions



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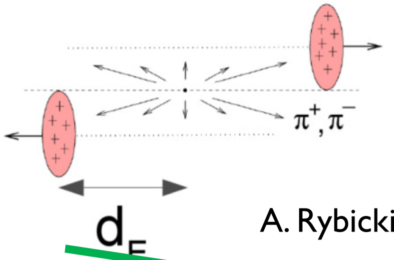

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A. Rybicki, A. Szczurek, Phys. Rev. C 75, 054903 (200

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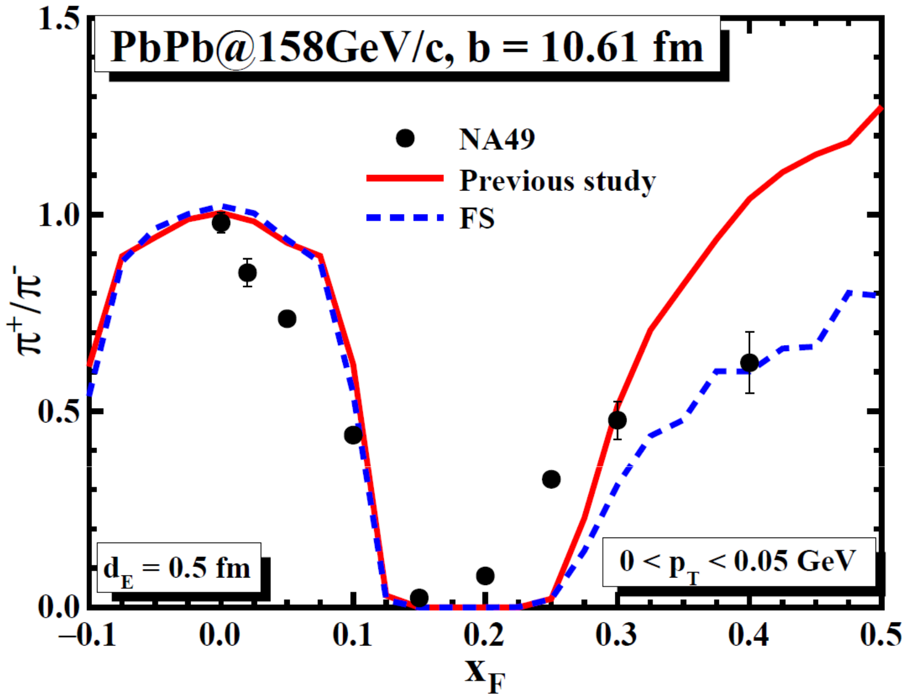
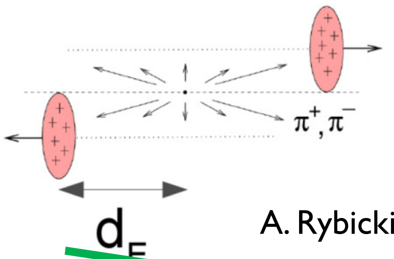


❑ **Blue** (current study):

➢ initial transverse positions of fire streak obtained by collision geometry

Comparison to the previous study



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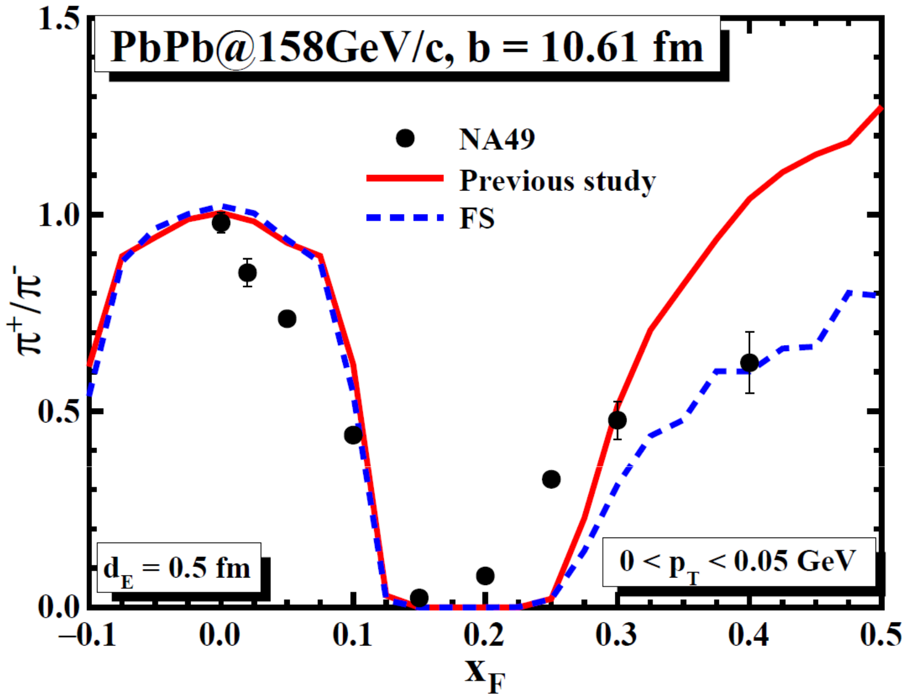
➢ rapidity distribution taken from our model, transverse-momentum spectrum from the UrQMD model



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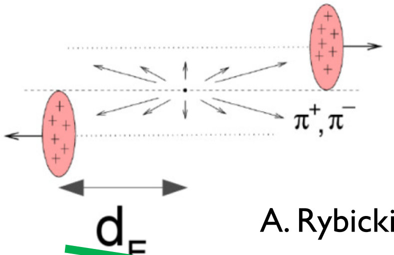

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A. Rybicki, A. Szczurek, Phys. Rev. C 75, 054903 (20(

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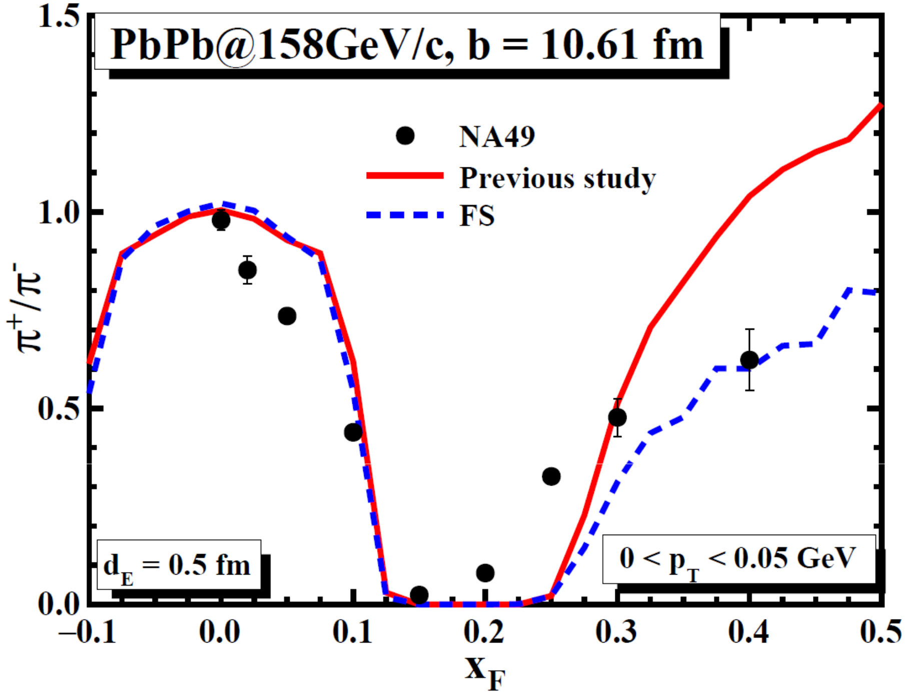


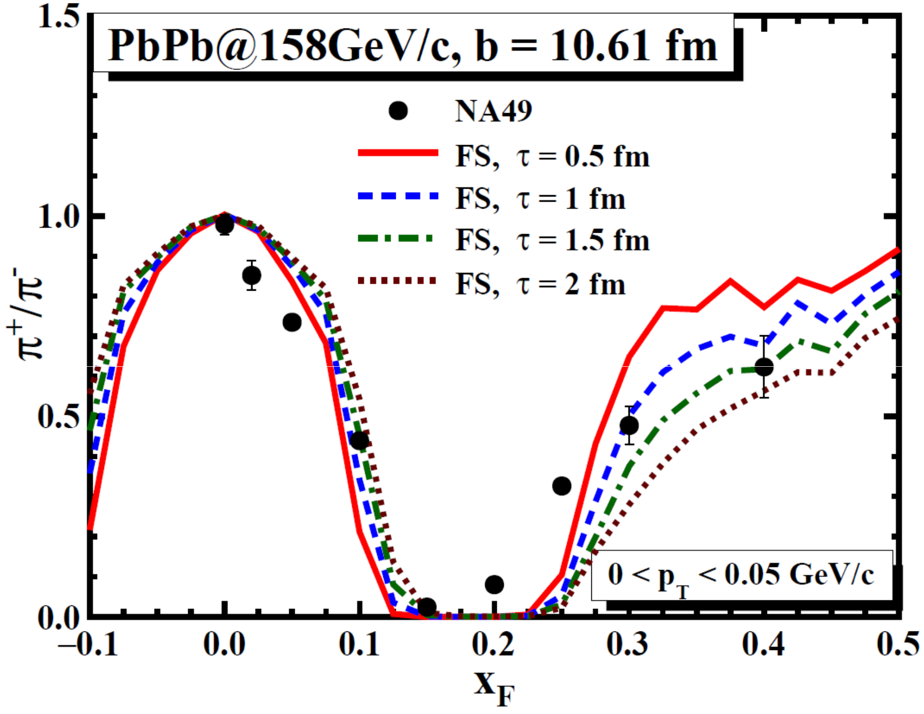
- **Blue (current study):**

- initial transverse positions of fire streak obtained by collision geometry
- rapidity distribution taken from our model, transverse-momentum spectrum from the UrQMD model

- **In both cases, the emission time/distance is d_E = 0.5fm**

Fixed pion emission time

- We introduce pion creation time for each fire streak
- We perform simulations for various values of tau: tau = 0.5, 1, 1.5, 2 fm
- The values are in the rest frames of the individual fire streak
- Note the values of pion creation time in nucleus-nucleus cms are different due to the different velocities of fire streaks

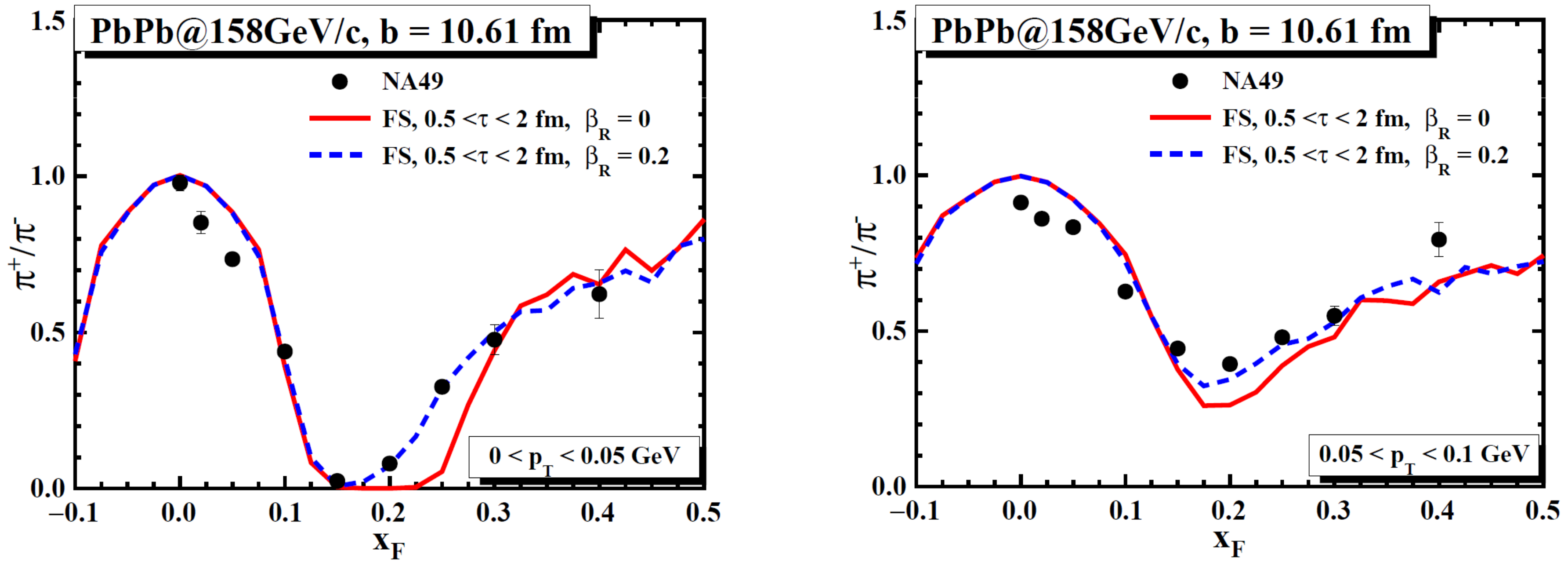


Results

- We assume that the pion creation time is linearly proportional to the excitation energy of the fire streak, i.e.

$$\boxed{\tau = a(E_s^* - m_s) + \tau_0}$$

with $\tau_0 = \tau_{min} = 0.5\ \mathrm{fm}$ and τ_{max} is set to 2 fm, which gives us $a \approx 0.08$



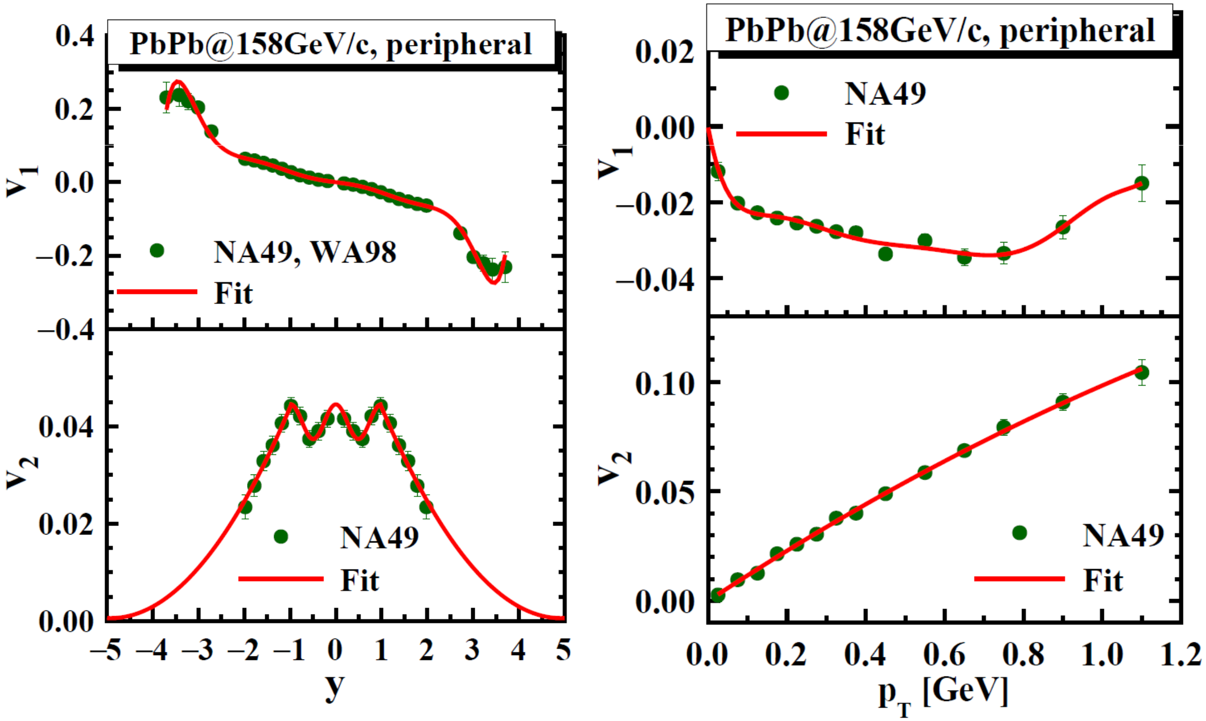
- The configuration with the expanding spectator (β_R = 0.2) gives the best description K.Mazurek, A.Szczurek *et al.*, PRC 97, 024604 (2018)

Particle flow

- The **particle flow** is quantified in terms of the **Fourier decomposition**:

$$\frac{dN(y,p_T,\phi)}{dp_T d\phi} = \frac{dN(y,p_T)}{dp_T}(1 + 2v_1(y,p_T)cos(\phi) + 2v_2(y,p_T)cos(2\phi) + ...)$$

- We fit **NA49** and **WA98** experimental data



- **We assume:**

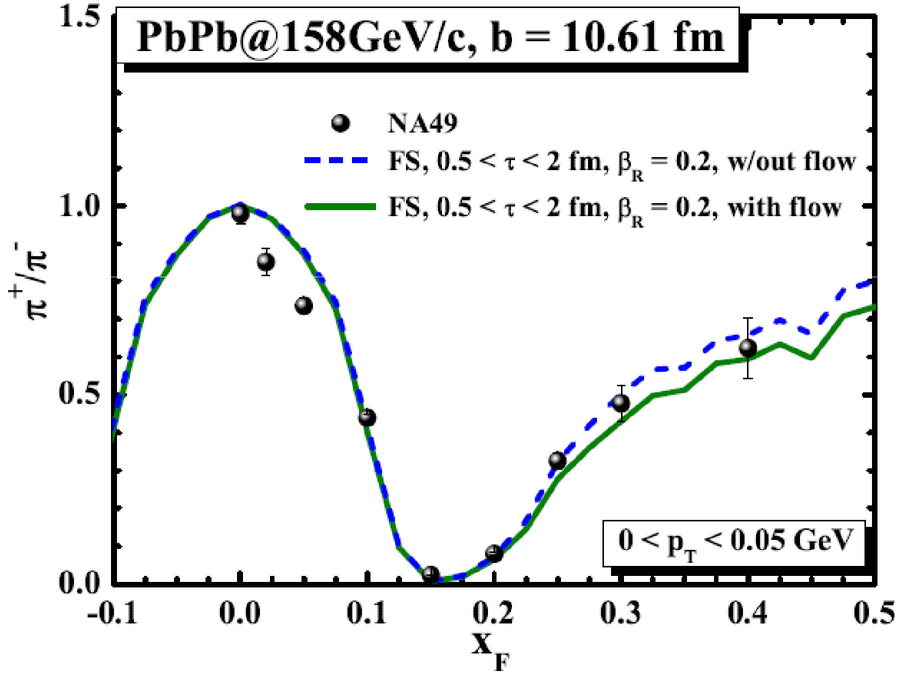
$$v_{1,2}(y,p_T) = v_{1,2}(y) \times v_{1,2}(p_T)/v_{1,2}^{eff}$$

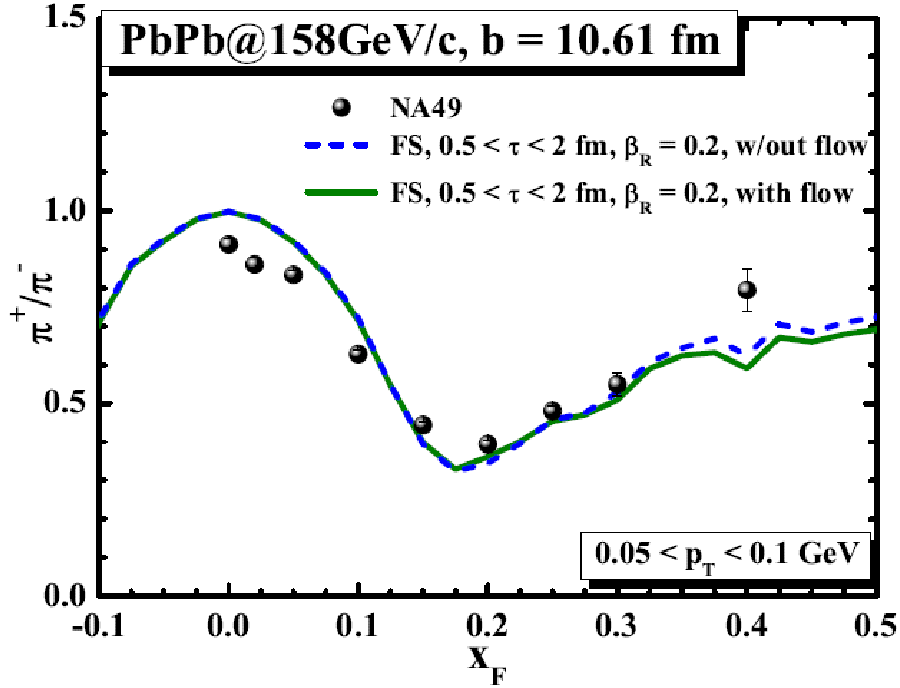
NA49 data:
C.Alt *et al.*, PRC 68, 034903 (2003)

WA98 data:
H.Schlagheck, NPA 663, 75 (2000)

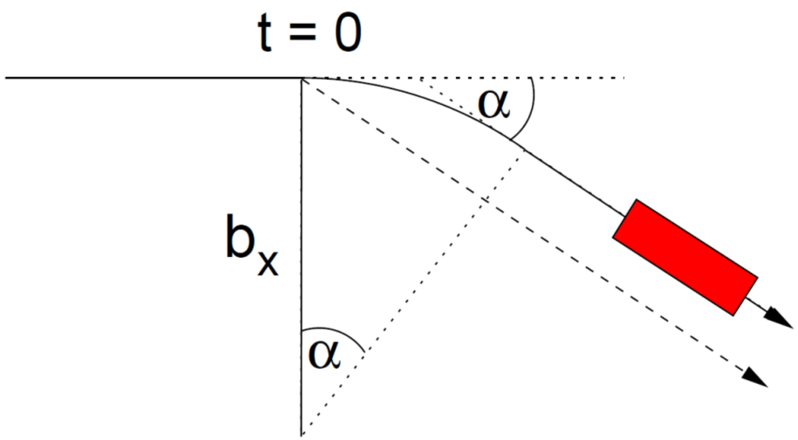
Particle flow (results)

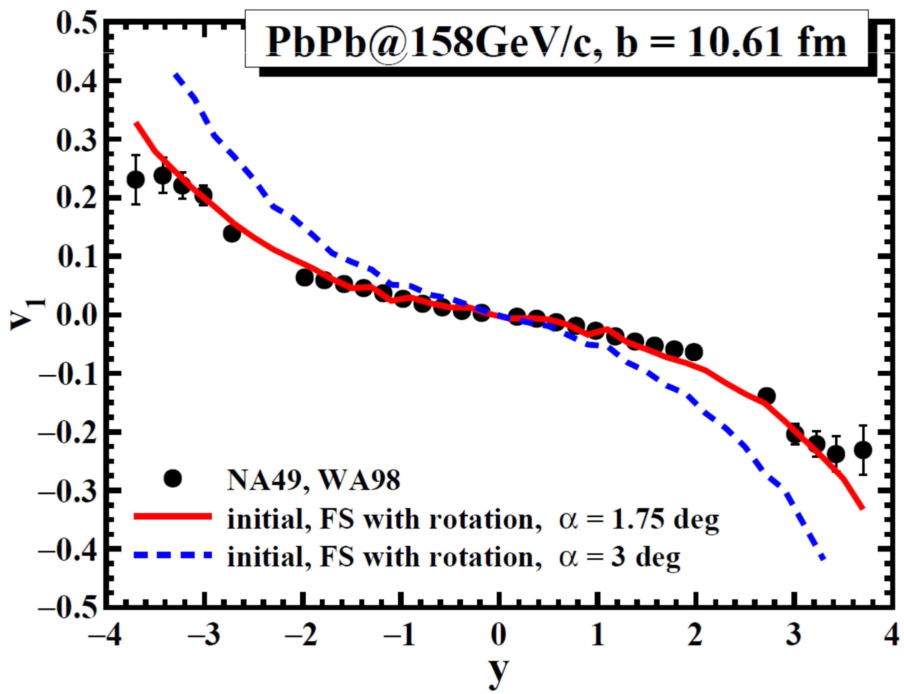
- We find no effect for v2 but a non-negligible effect for v1:





Vorticity of fire streaks



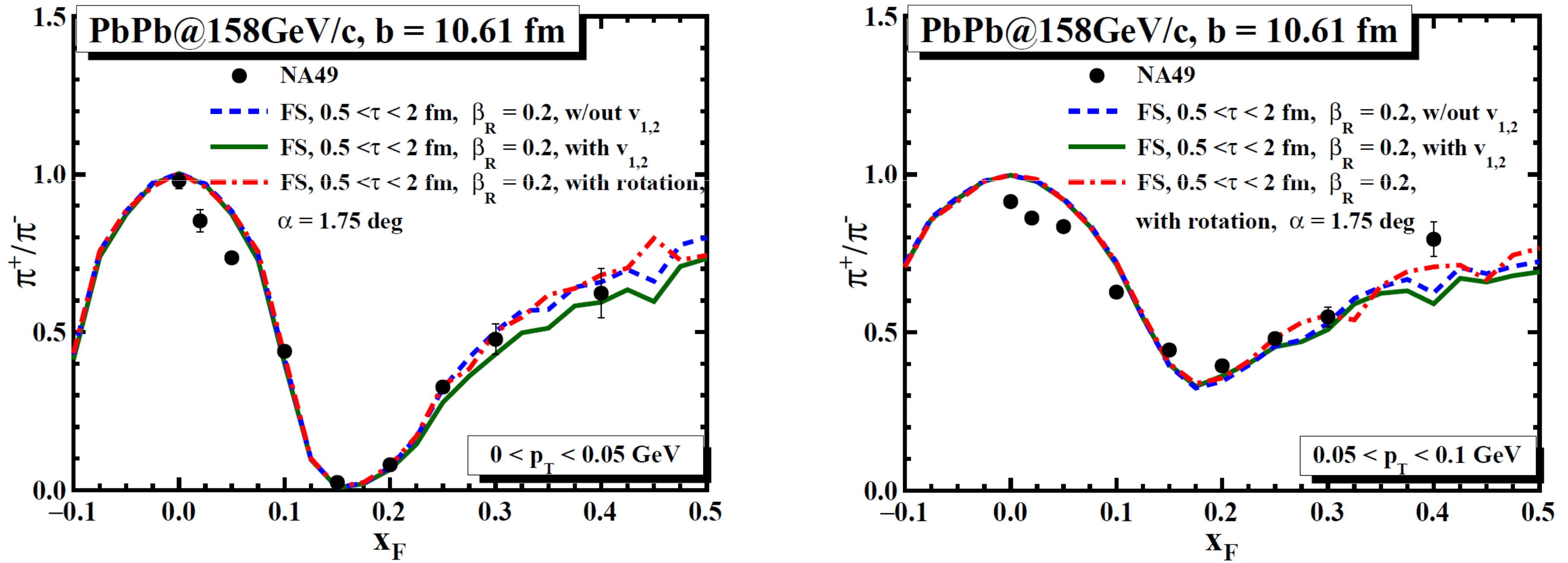


- **Fire streak rotates for a given small angle α**
- **After rotation the fire streak follows its modified trajectory until pions are emitted from the fire streak**
- **The pion emission point is shifted in transverse and longitudinal direction with respect to the case with no rotation**
- **The size of the shift increases with increasing α and τ**
- **Rotation by α = 1.75 deg gives a good description of the experimental data on v_1 (!)**

Vorticity (results)

- **No significant change** is visible with respect to the case with no rotation

- **Due to the small angle allowed by the experimental data = small displacement of the pion emission points**



- **Difference between the case with rotation and explicit parametrization of v_1 is due to the imperfect description of the p_T-dependence of v_1 by our model with rotation**

Summary

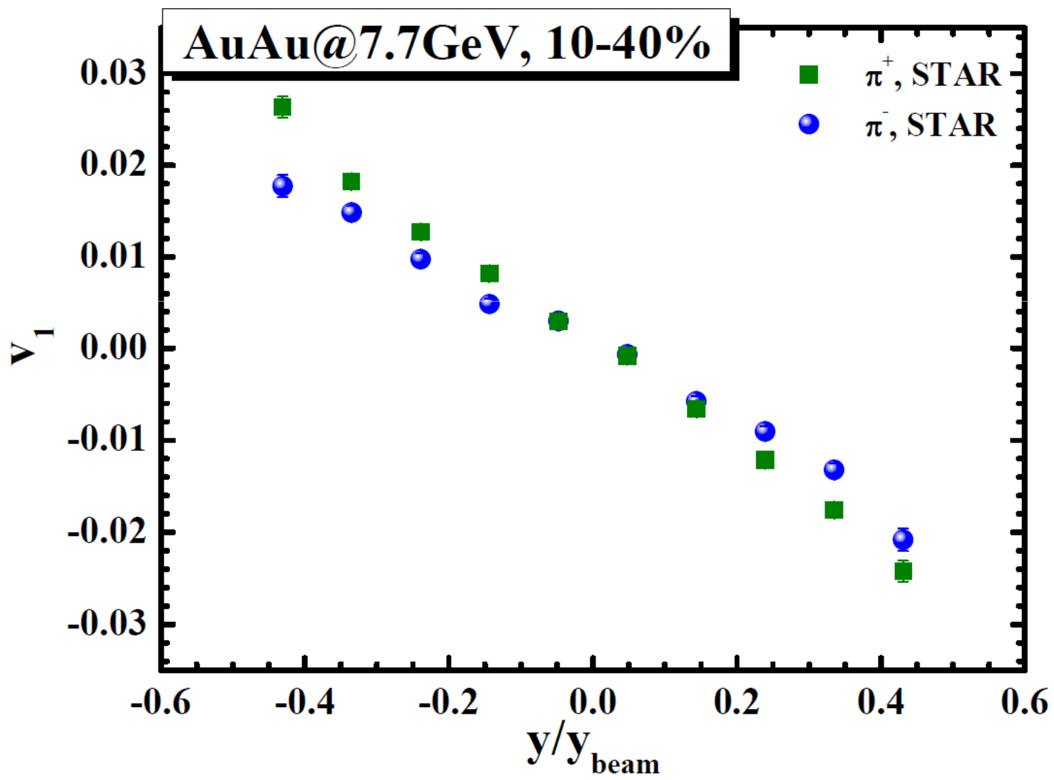
- **We introduced the model of the longitudinal evolution of the system, which**
  - **explains the centrality dependence of pion yields and rapidity spectra in Pb+Pb collisions**
  - **links pion rapidity spectra in p+p and Pb+Pb collisions**

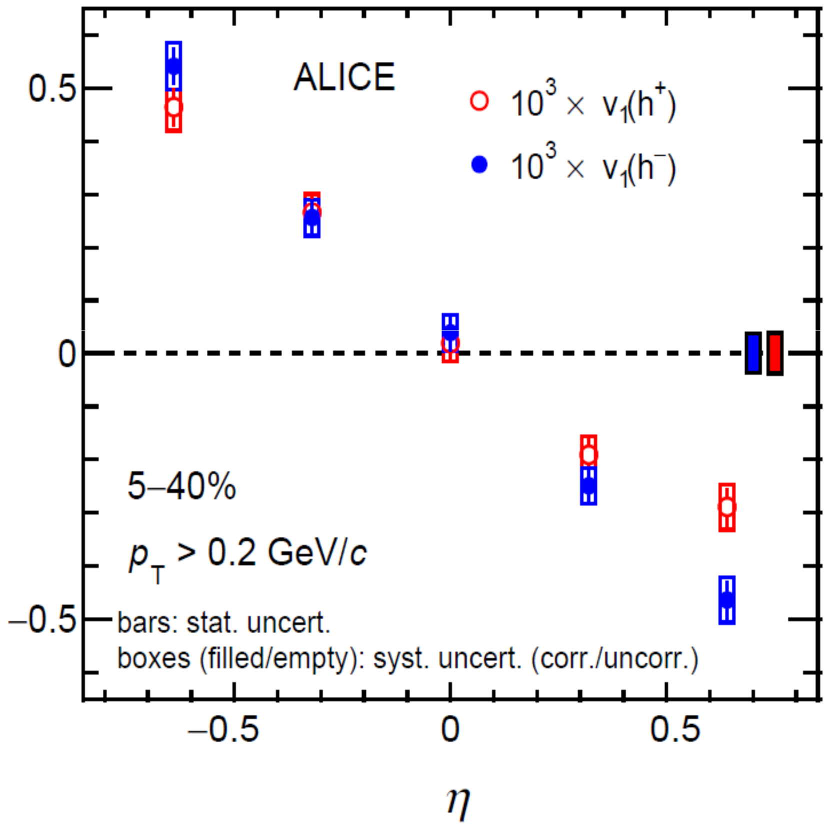
- **We implemented the initial conditions for pion production provided by our model to study the electromagnetic effects in peripheral Pb+Pb collisions**
  - **rather small pion creation times have been necessary to describe the data on electromagnetic effects, which concern faster pions ($0.5<\tau<2$ fm)**
  - **configuration with the expanding spectators gives the best description of the data**
  - **inclusion of directed flow gives a non-negligible effect, whereas elliptic flow shows no effect**
  - **rotation of fire streaks results in the presence of directed flow**
  - **small angle, smaller than 2 deg., is needed to describe the data**

Outlook

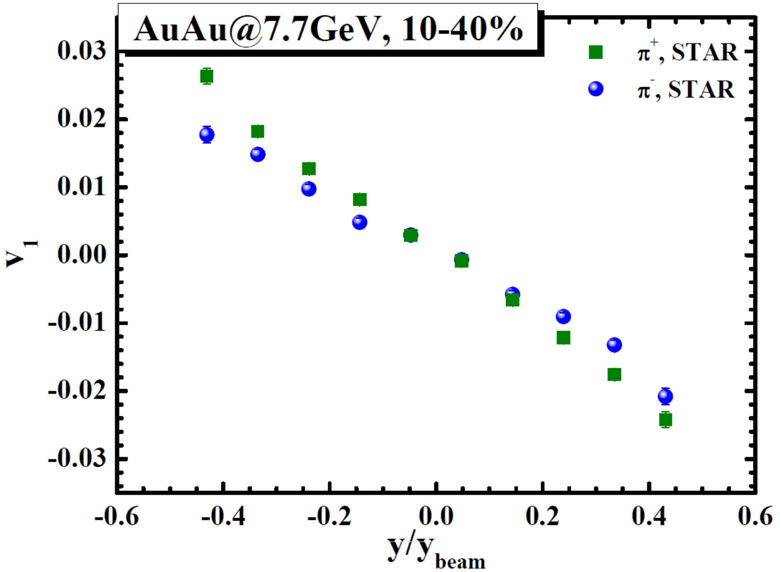
STAR data: L. Adamczyk *et al.*, PRL 112, 162301 (2014)

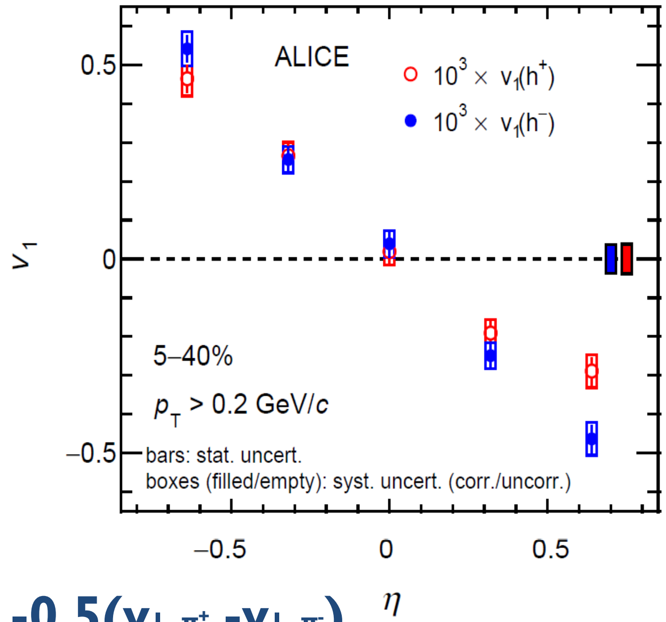
ALICE data: S. Acharya *et al.*, arXiv:1910.14406 [nucl-ex]





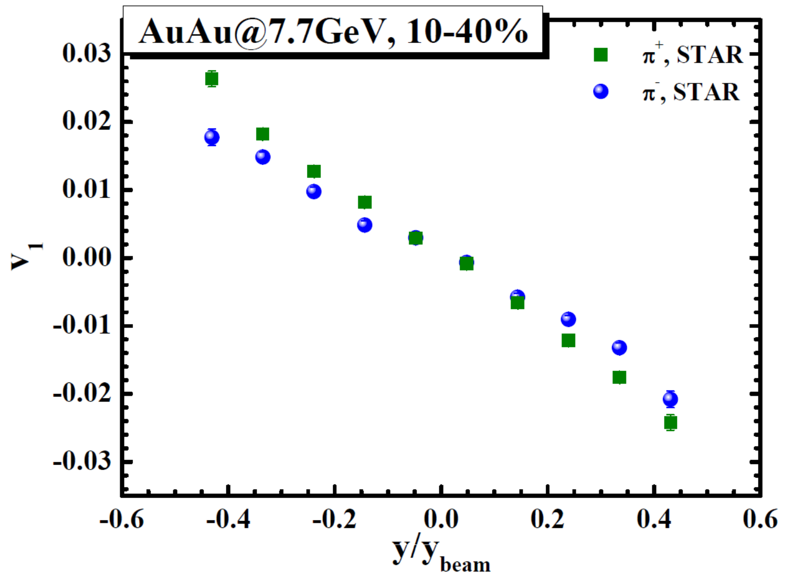
Outlook

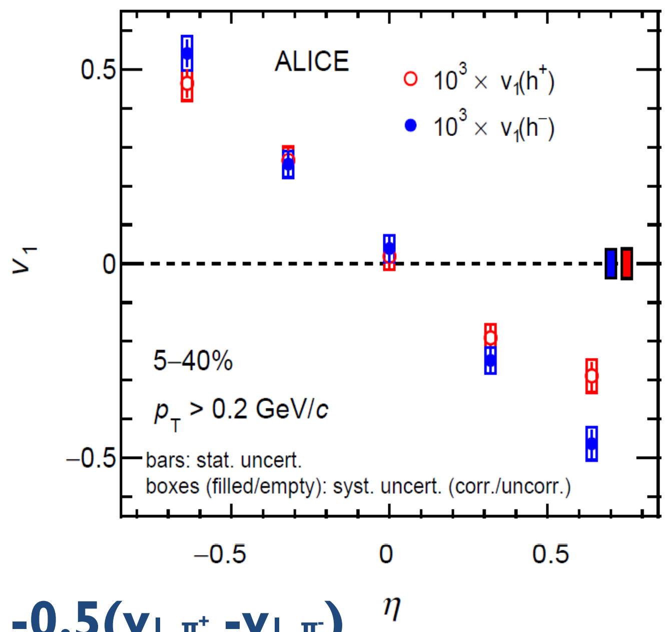




$\Delta v_{1,\pi^+} = 0.5(v_{1,\pi^+} - v_{1,\pi^-})$ **and** $\Delta v_{1,\pi^-} = -0.5(v_{1,\pi^+} - v_{1,\pi^-})$

Outlook





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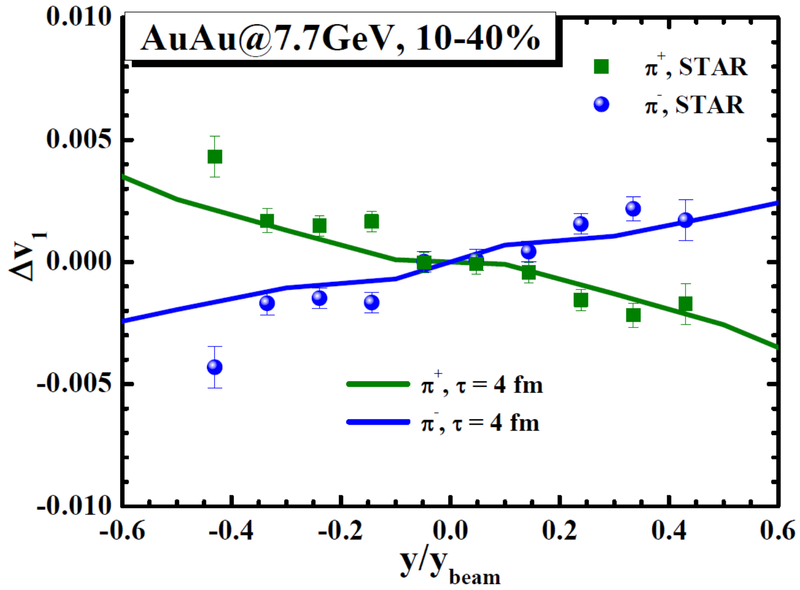

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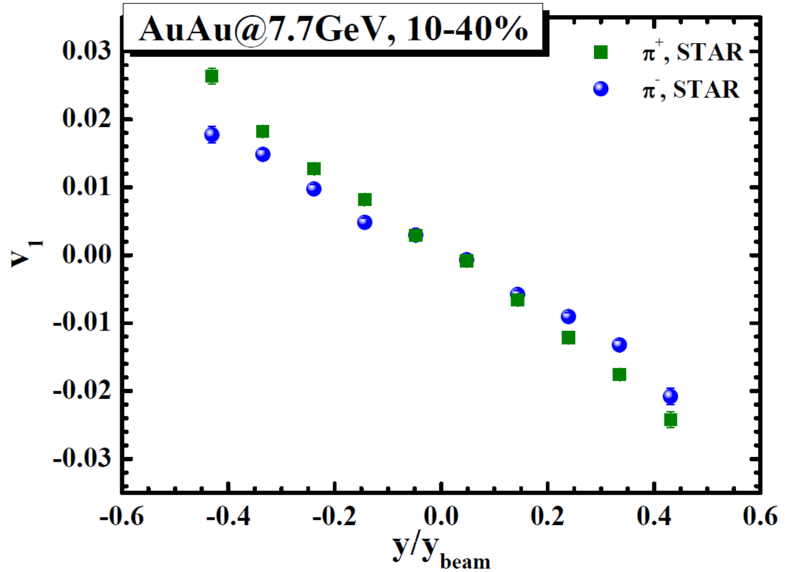

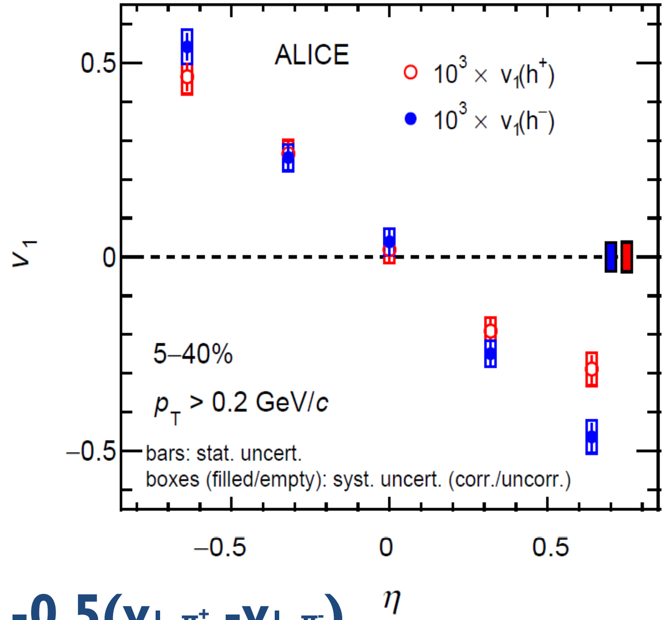

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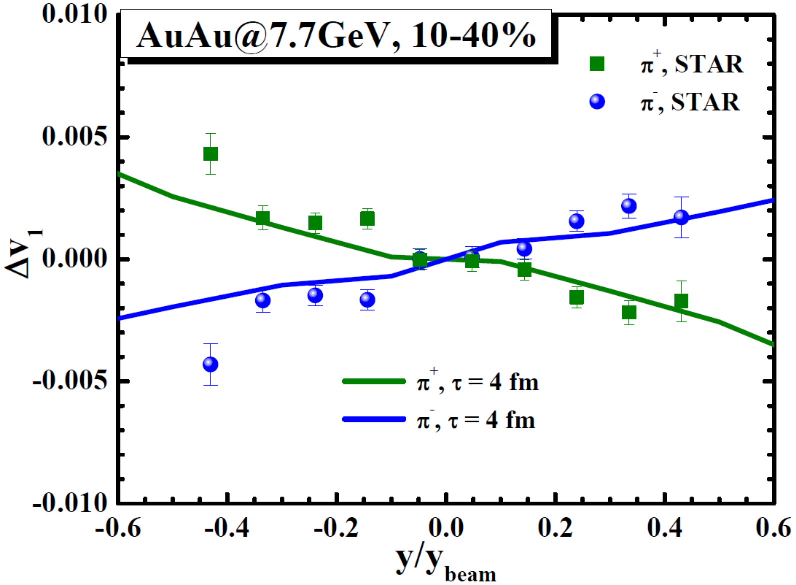

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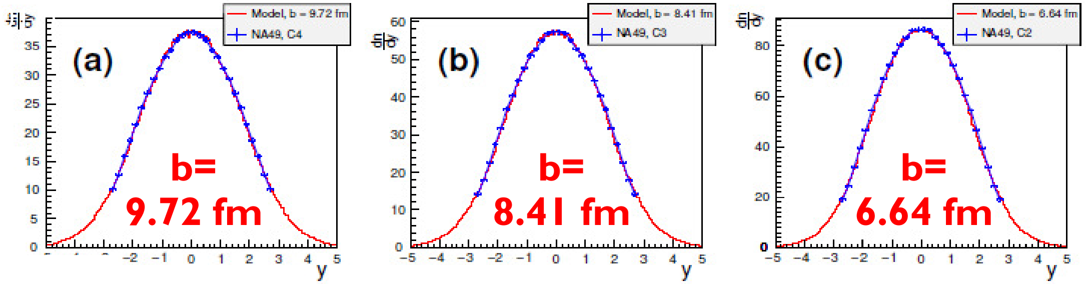
Thank you!

Acknowledgments:
This work was supported by the National Science Centre, Poland under grant no. 2014/14/E/ST2/00018

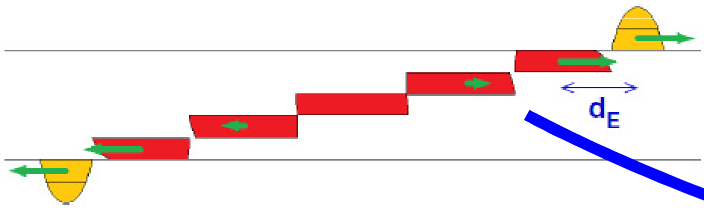
Back up

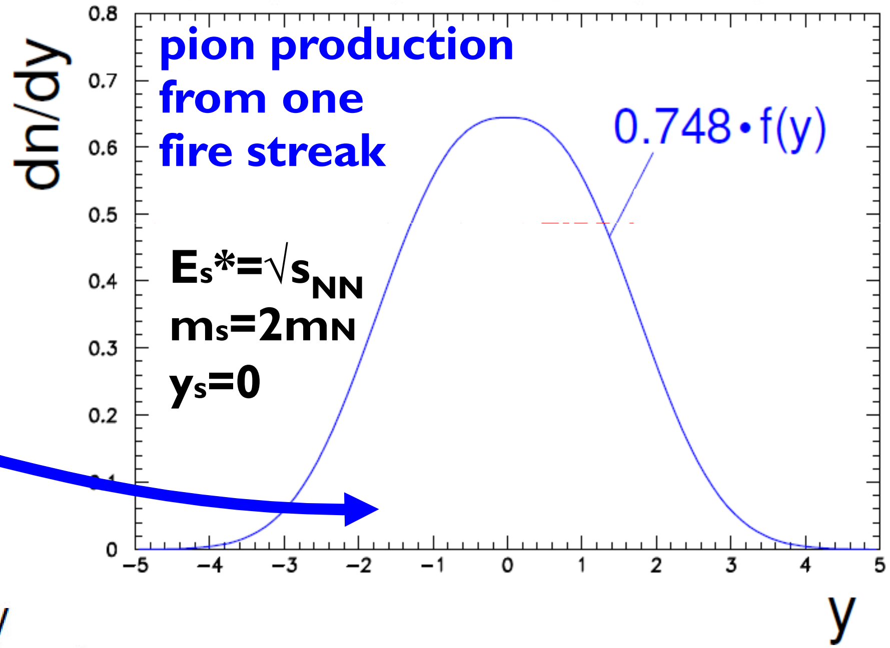
The pion rapidity distribution in p+p collisions

data points from: T. Anticic et al., Phys. Rev. C **86**, 054903 (2012)



- **From now on: $\sqrt{s_{NN}}$= 17.3 GeV**





Each fire streak fragments independently

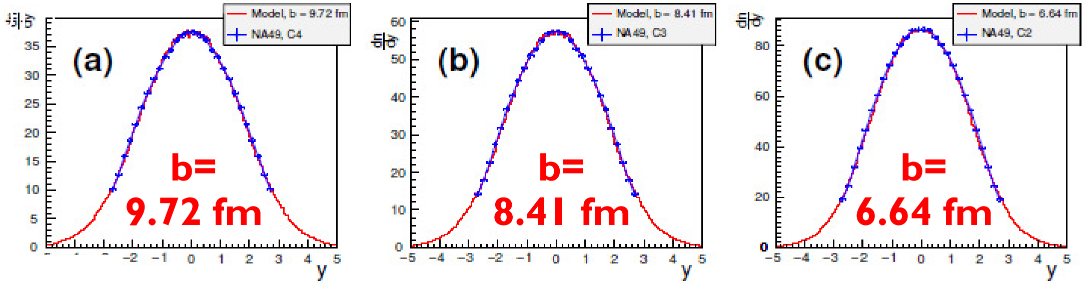
available energy **fire streak rapidity**

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

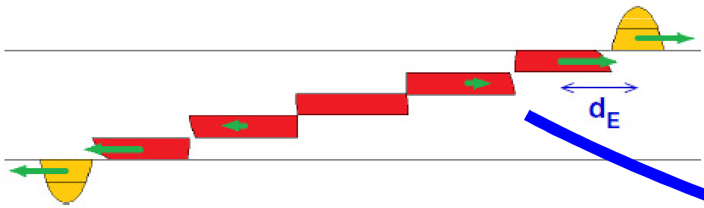
total fire streak energy sum of brick masses

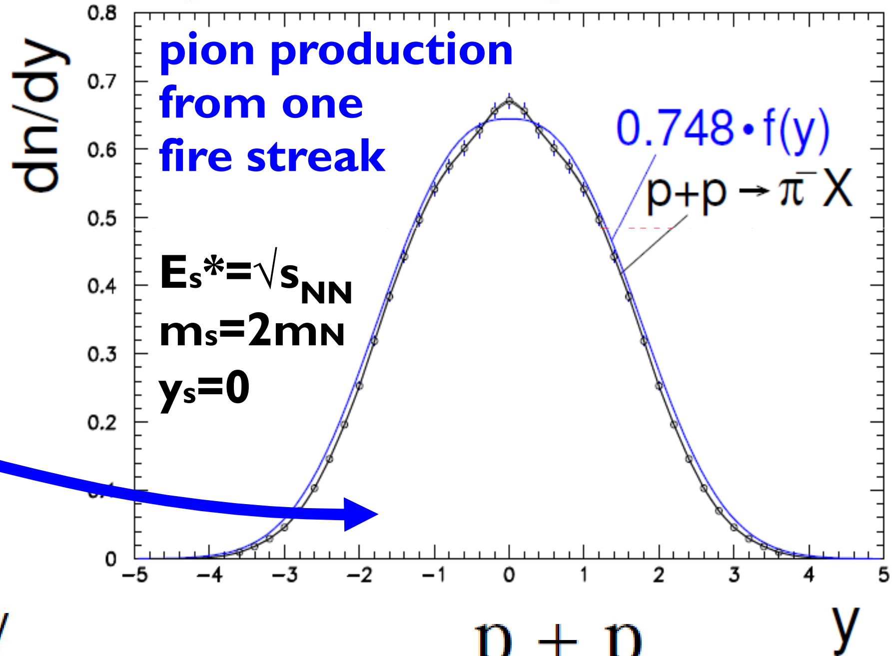
The pion rapidity distribution in p+p collisions

data points from: T. Anticic et al., Phys. Rev. C **86**, 054903 (2012)



- From now on: $\sqrt{s_{NN}}$= 17.3 GeV





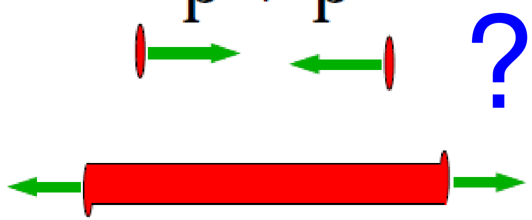
Each fire streak fragments independently

available energy

fire streak rapidity

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

total fire streak energy sum of brick masses

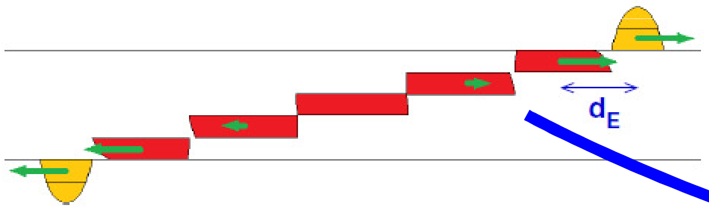


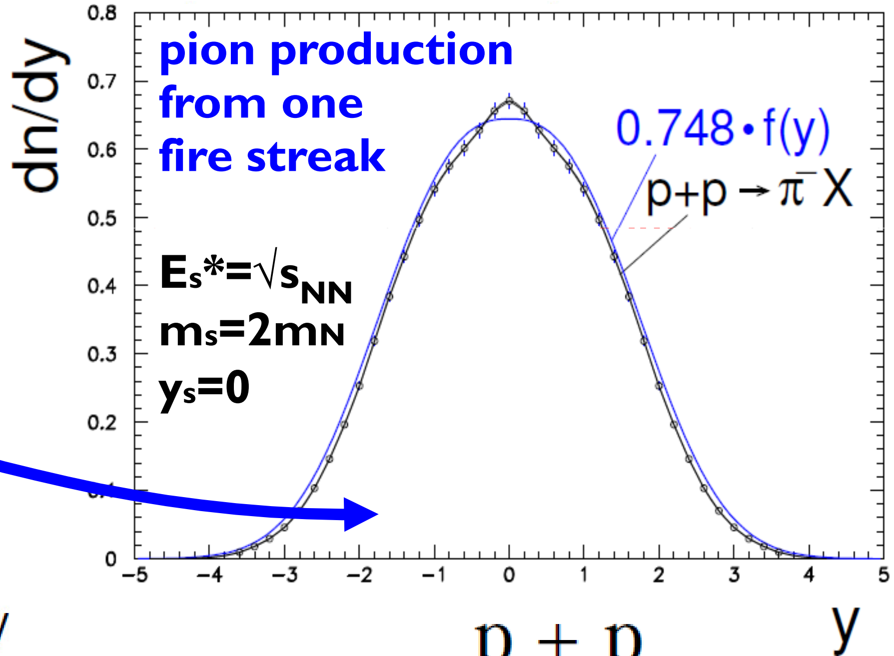
data points from: NA49, PRC 86, 054903 (2012)

The pion rapidity distribution in p+p collisions

- The pion rapidity distribution from one fire streak in Pb+Pb collisions resembles the pion rapidity distribution in p+p reactions
- There is a difference in absolute normalization: 0.748
- This difference can be understood by a different energy repartition in p+p and Pb+Pb collisions

A. Rybicki, *et al.*, Phys. Rev. C 99, 024908 (2019)
A. Rybicki's talk at "XLV Congress of Polish Physicists"



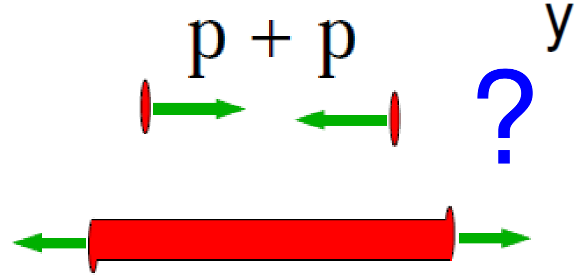


Each fire streak fragments independently

available energy | fire streak rapidity

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

total fire streak energy | sum of brick masses

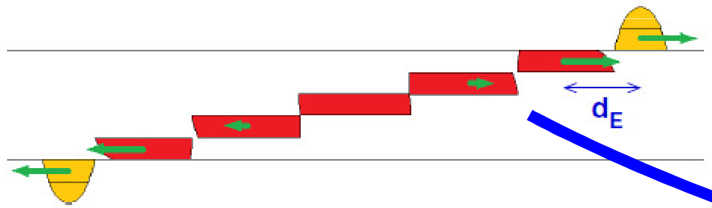


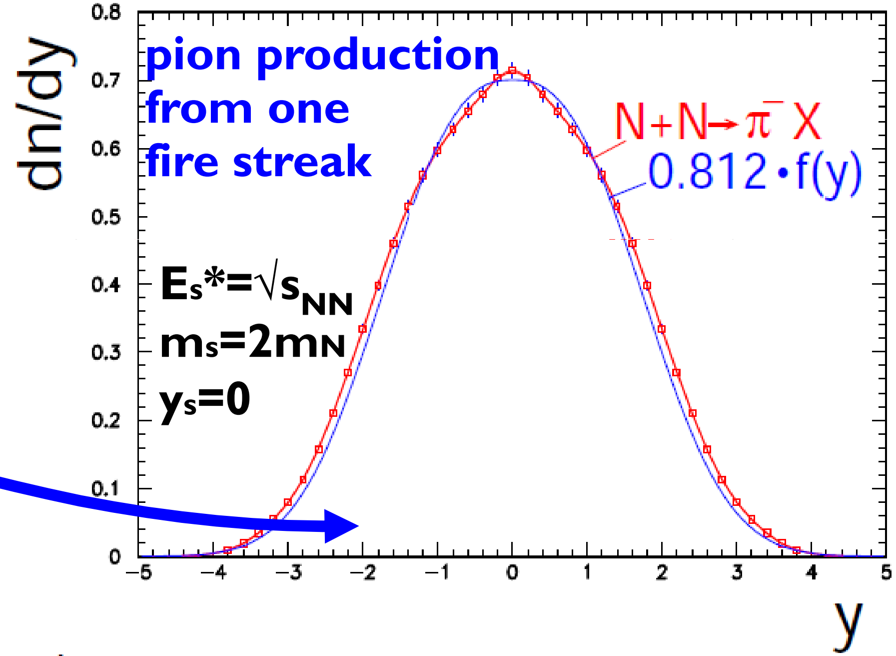
data points from: NA49, PRC 86, 054903 (2012)

The pion rapidity distribution in p+p collisions

- The pion rapidity distribution from **one fire streak** in Pb+Pb collisions **resembles** the pion rapidity distribution in p+p reactions
- There is a difference in absolute normalization: **0.812 – isospin correction**
- This difference can be understood by a **different energy repartition** in **p+p** and **Pb+Pb** collisions

A. Rybicki, *et al.*, Phys. Rev. C 99, 024908 (2019)
A. Rybicki's talk at "XLV Congress of Polish Physicists"



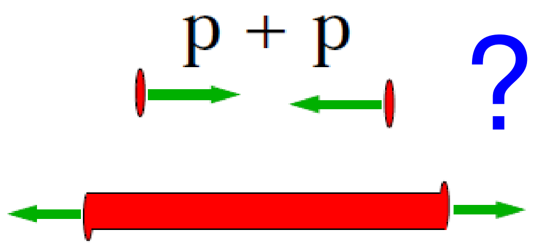


Each fire streak fragments independently

available energy — fire streak rapidity

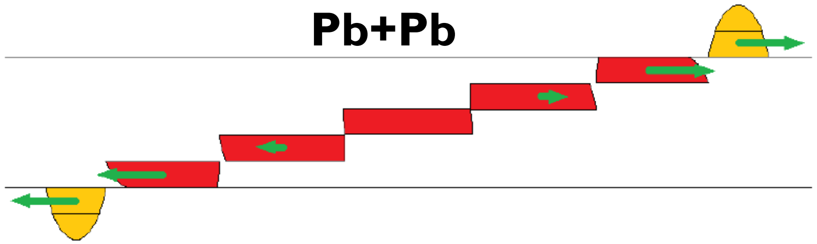
$$\frac{dn}{dy} \sim A \cdot \boxed{(E_s^* - m_s)} \cdot \exp\left(- \frac{\left[(y - \boxed{y_s})^2 + \epsilon^2 \right]^{\frac{n}{2}}}{n \sigma_y^n} \right)$$

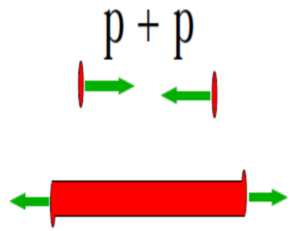
total fire streak energy — sum of brick masses



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

The energy balance in p+p and Pb+Pb collisions





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

p+p: (Fire streak energy) = $\sqrt{s}$ ≈ (baryon energy) + (pion energy) + (kaon energy)

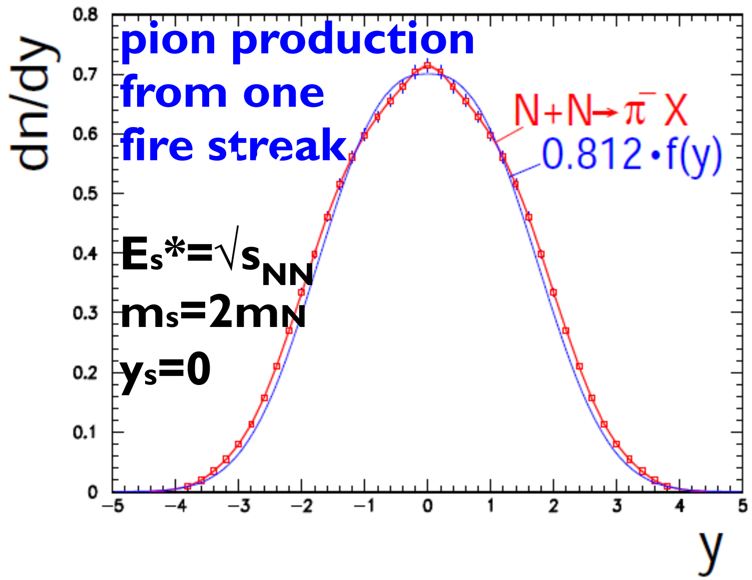
- **After calculation the differences in the overall energy balance between p+p and Pb+Pb collisions we get:**

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

accuracy within 4%

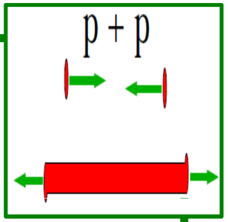
- **For more details:**

A. Rybicki, *et al.*, Phys. Rev. C 99, 024908 (2019)
A. Rybicki's talk at "XLV Congress of Polish Physicists"



Description of pion spectra in Pb+Pb from p+p

- 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 comes from the different energy repartition in the two reactions
- Thus, a correspondence exists between dn/dy spectra in p+p and Pb+Pb collisions



pion dn/dy distribution in p+p

↓

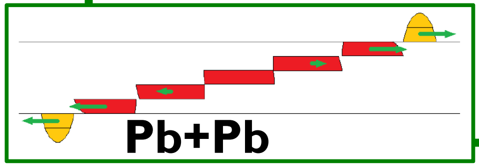
correction for isospin,
baryon inelasticity and strangeness enhancement

↓

collision geometry + local E-p conservation

↓

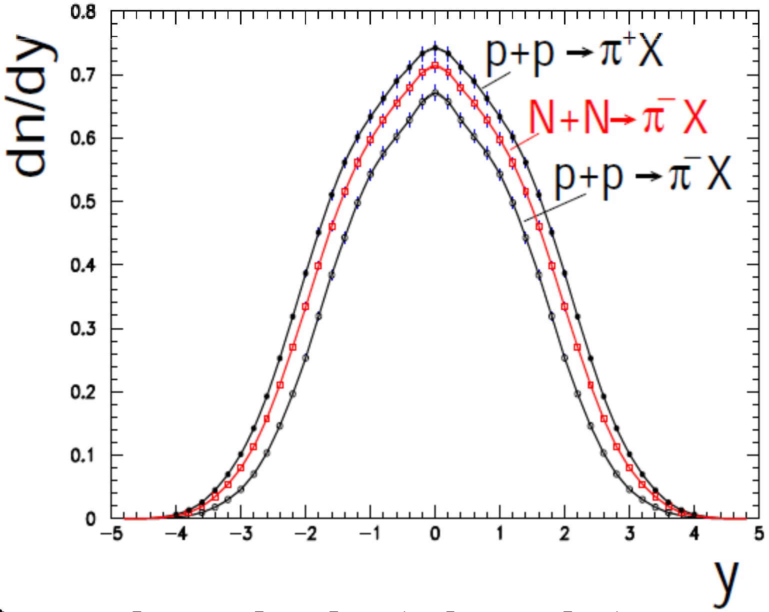
pion dn/dy distributions in Pb+Pb, as a function of centrality

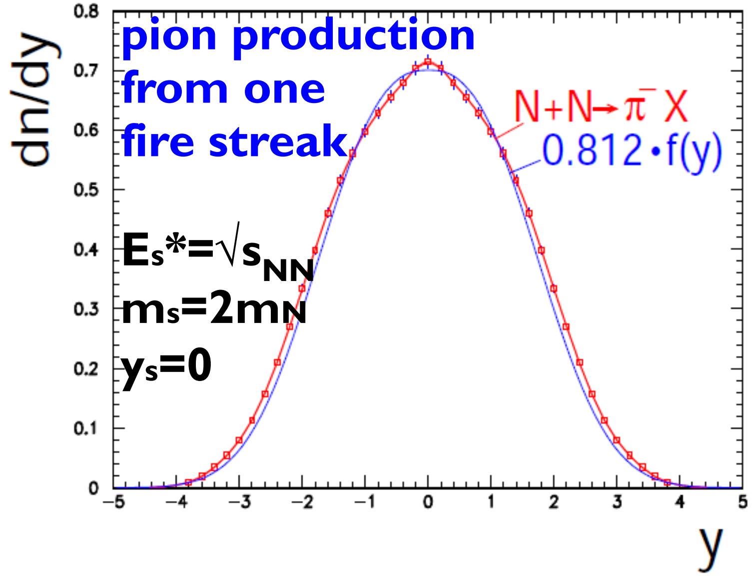


Isospin correction

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

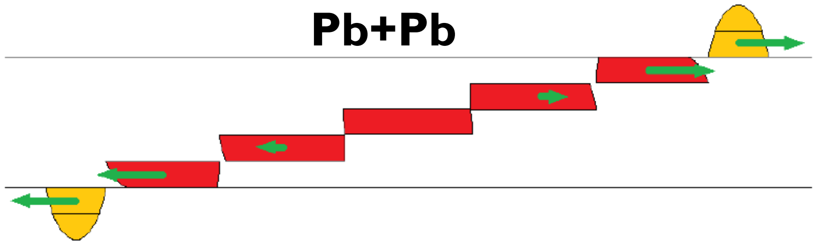
$$\boxed{\frac{dn}{dy}(N+N \to \pi^- X) = \left(\frac{Z}{A}\right) \cdot \frac{dn}{dy}(p+p \to \pi^- X) + \left(1 - \frac{Z}{A}\right) \cdot \frac{dn}{dy}(p+p \to \pi^+ X)}$$

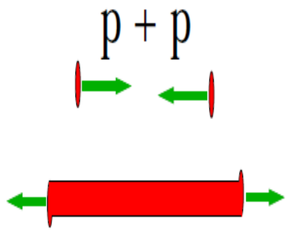




- **Once isospin is taken into account, the difference in absolute scaling between p+p and Pb+Pb collisions changes from 0.748 to 0.812**

The energy balance in p+p and Pb+Pb collisions

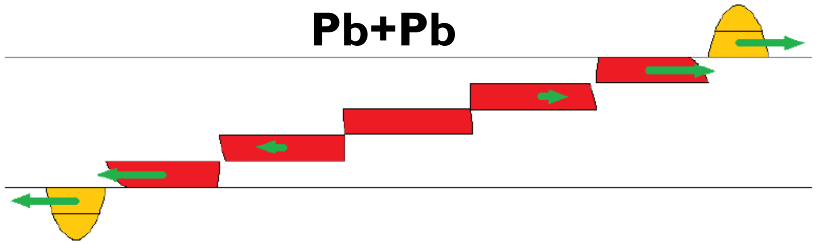


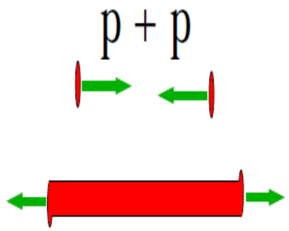


Pb+Pb: **(Fire streak energy) ≈ (baryon energy) + (pion energy) + (kaon energy)**

p+p: **(Fire streak energy) = $\sqrt{s}$ ≈ (baryon energy) + (pion energy) + (kaon energy)**

The energy balance in p+p and Pb+Pb collisions



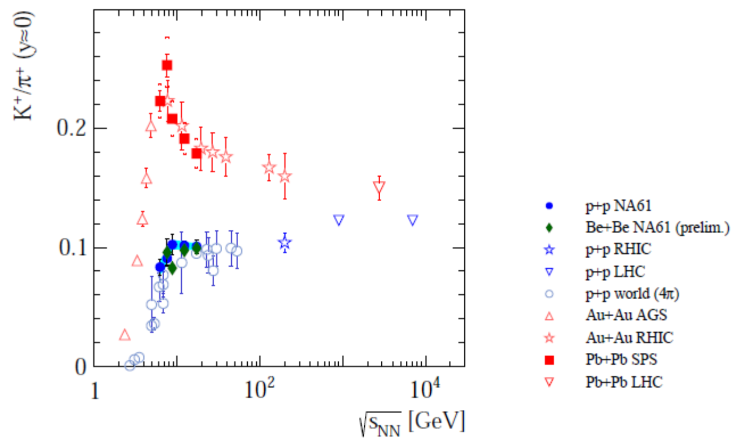


Pb+Pb: (Fire streak energy) ≈ (baryon energy) + (pion energy) + (kaon energy)

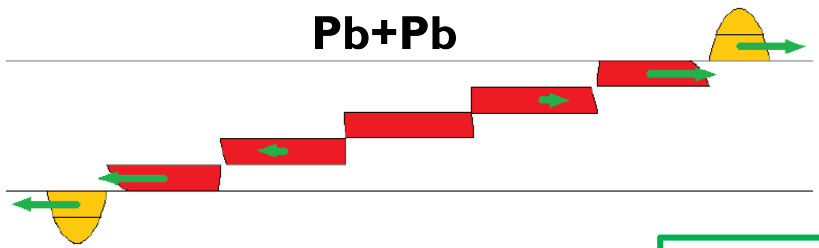
>

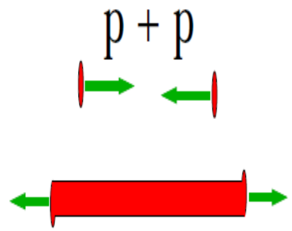
p+p: (Fire streak energy) = $\sqrt{s}$ ≈ (baryon energy) + (pion energy) + (kaon energy)

strangeness enhancement



The energy balance in p+p and Pb+Pb collisions





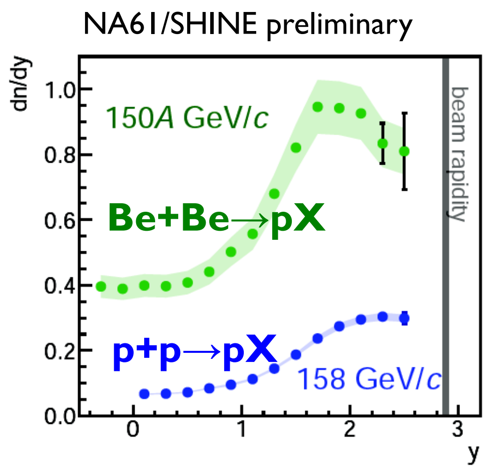
Pb+Pb: (Fire streak energy) ≈ (baryon energy) + (pion energy) + (kaon energy)

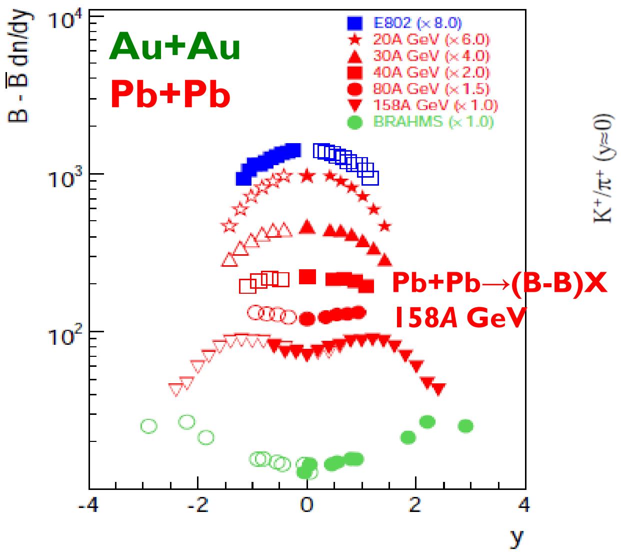
$<$ (baryon energy) $>$ (kaon energy)

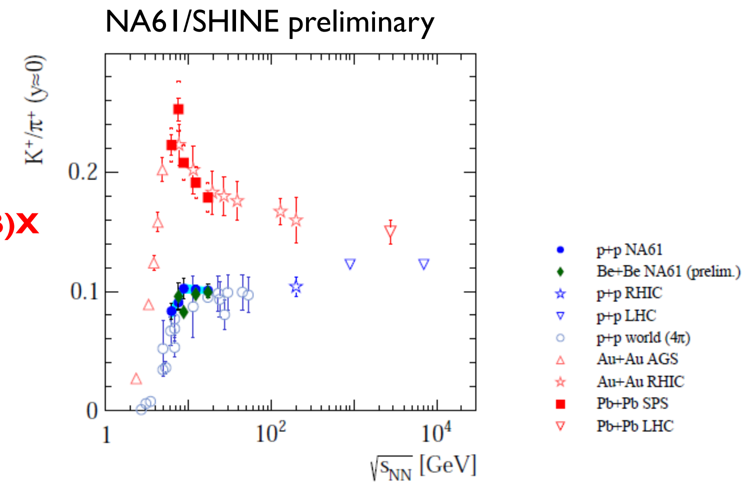
p+p: (Fire streak energy) = $\sqrt{s}$ ≈ (baryon energy) + (pion energy) + (kaon energy)

baryon stopping (inelasticity)

strangeness enhancement



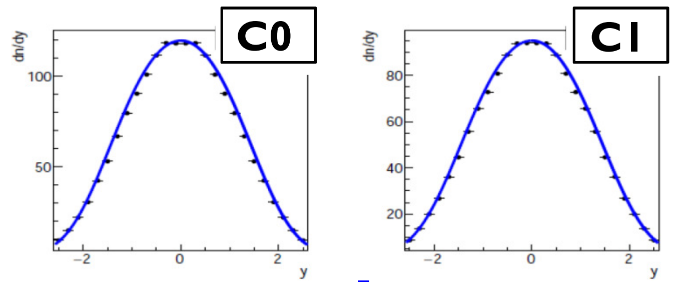


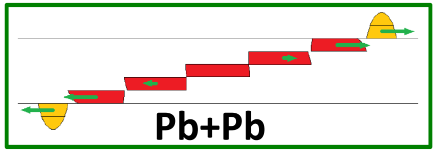


C. Blume, NA49, J.Phys.G34, 951 (2007)

The model at 40GeV/c

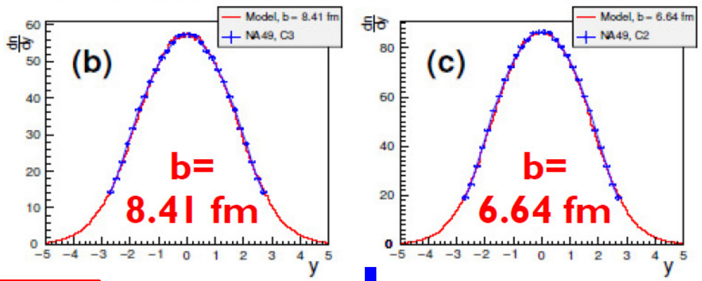
π-, Pb+Pb, $\sqrt{s_{NN}}$= 8.8 GeV





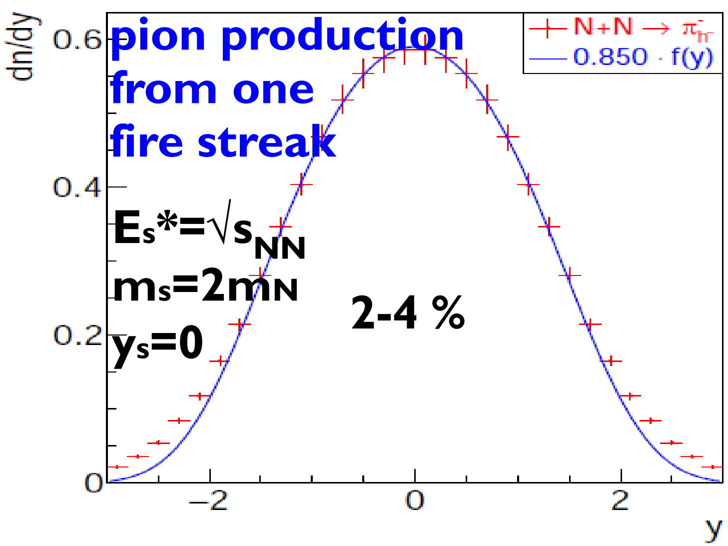
π-, Pb+Pb, $\sqrt{s_{NN}}$= 17.3 GeV

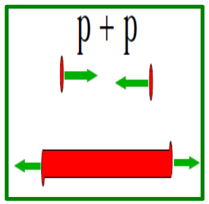
data points from: T. Anticic et al., Phys. Rev. C **86**, 054903 (2012)



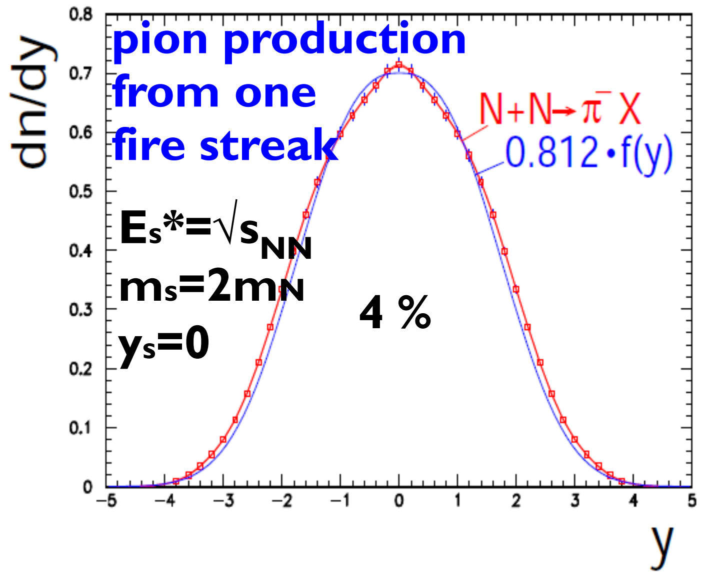
Valid for
8.8 GeV ≤ $\sqrt{s_{NN}}$ ≤ 17.3 GeV
(or better)

π-, N+N, $\sqrt{s_{NN}}$= 8.8 GeV





π-, N+N, $\sqrt{s_{NN}}$= 17.3 GeV



The model at 40GeV/c

π-, Pb+Pb, $\sqrt{s_{NN}}$= 8.8 GeV

π-, Pb+Pb, $\sqrt{s_{NN}}$= 17.3 GeV

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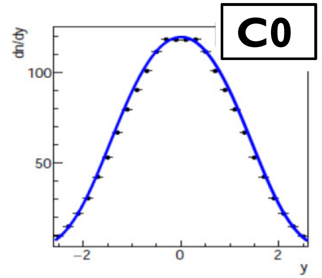
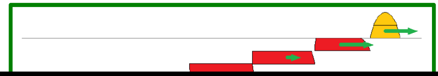
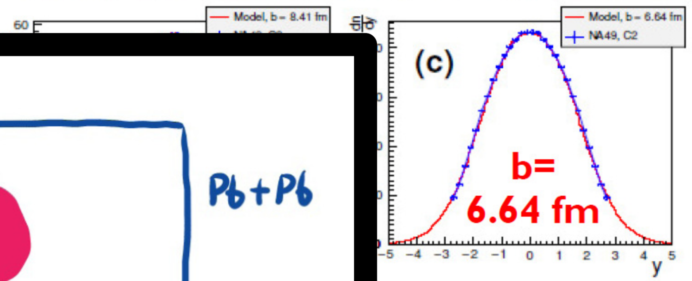
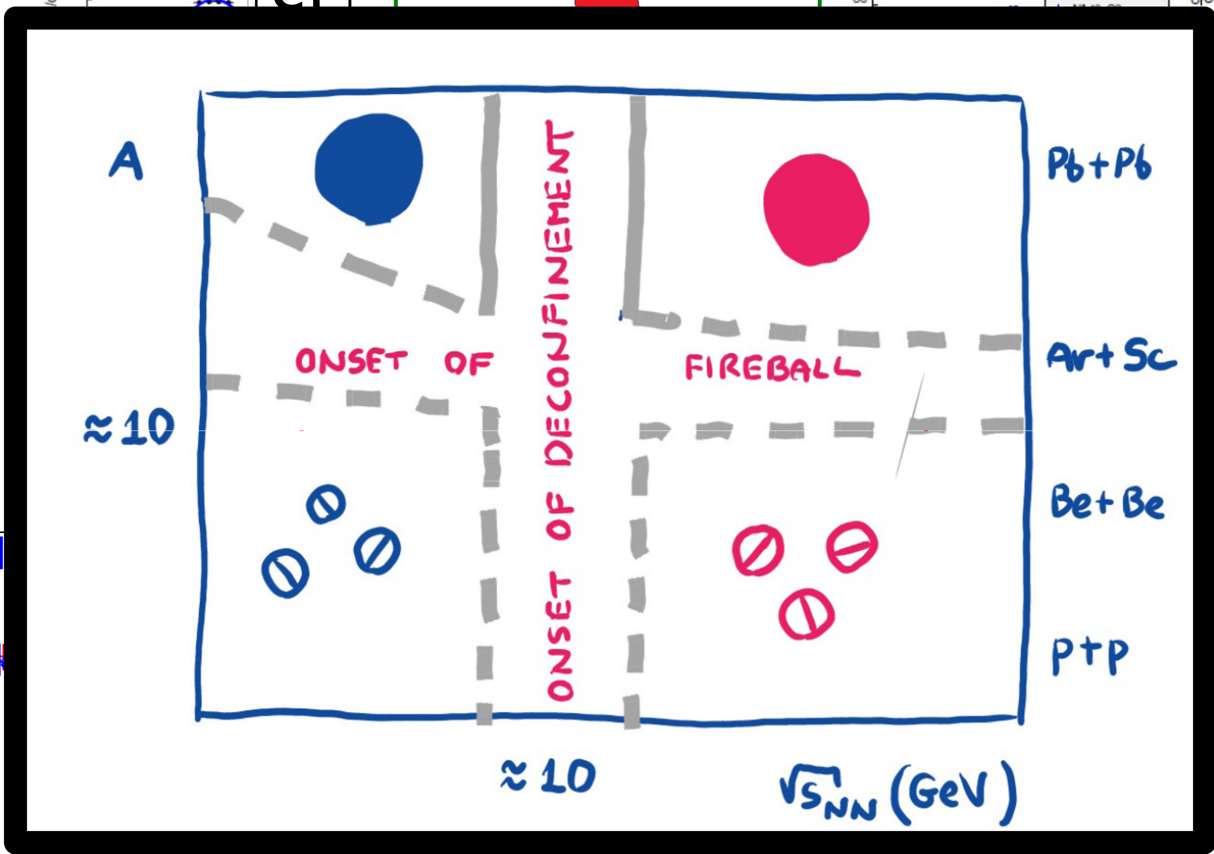


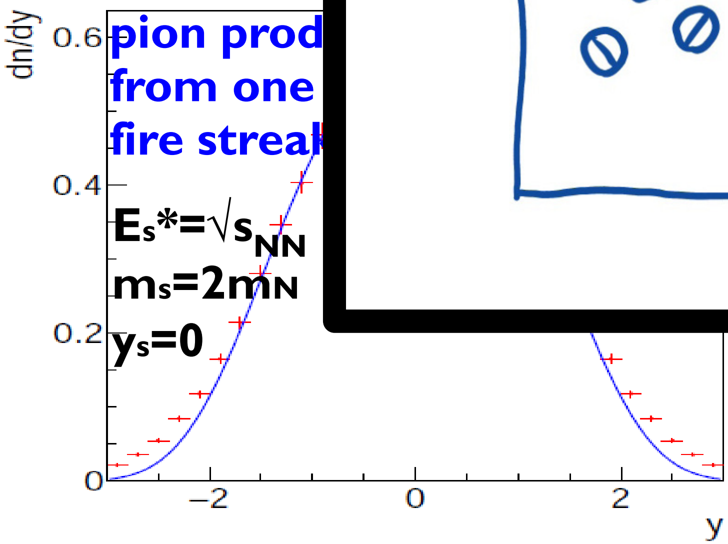


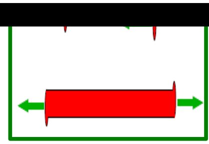


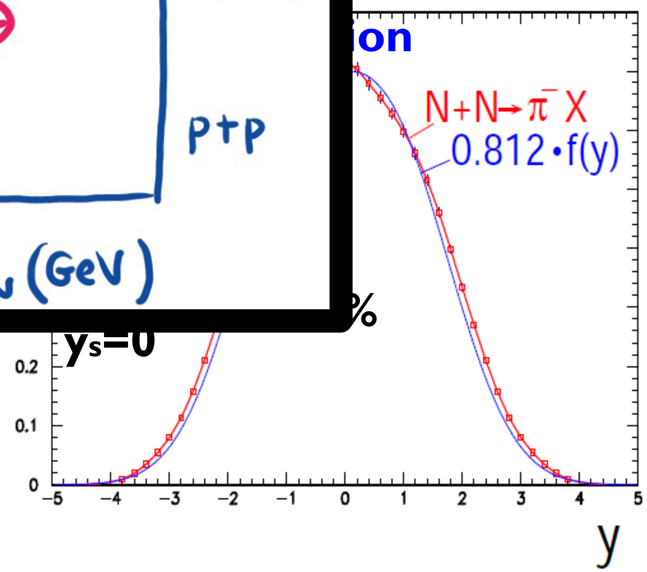


π-, N+N, $\sqrt{s_{NN}}$=

17.3 GeV



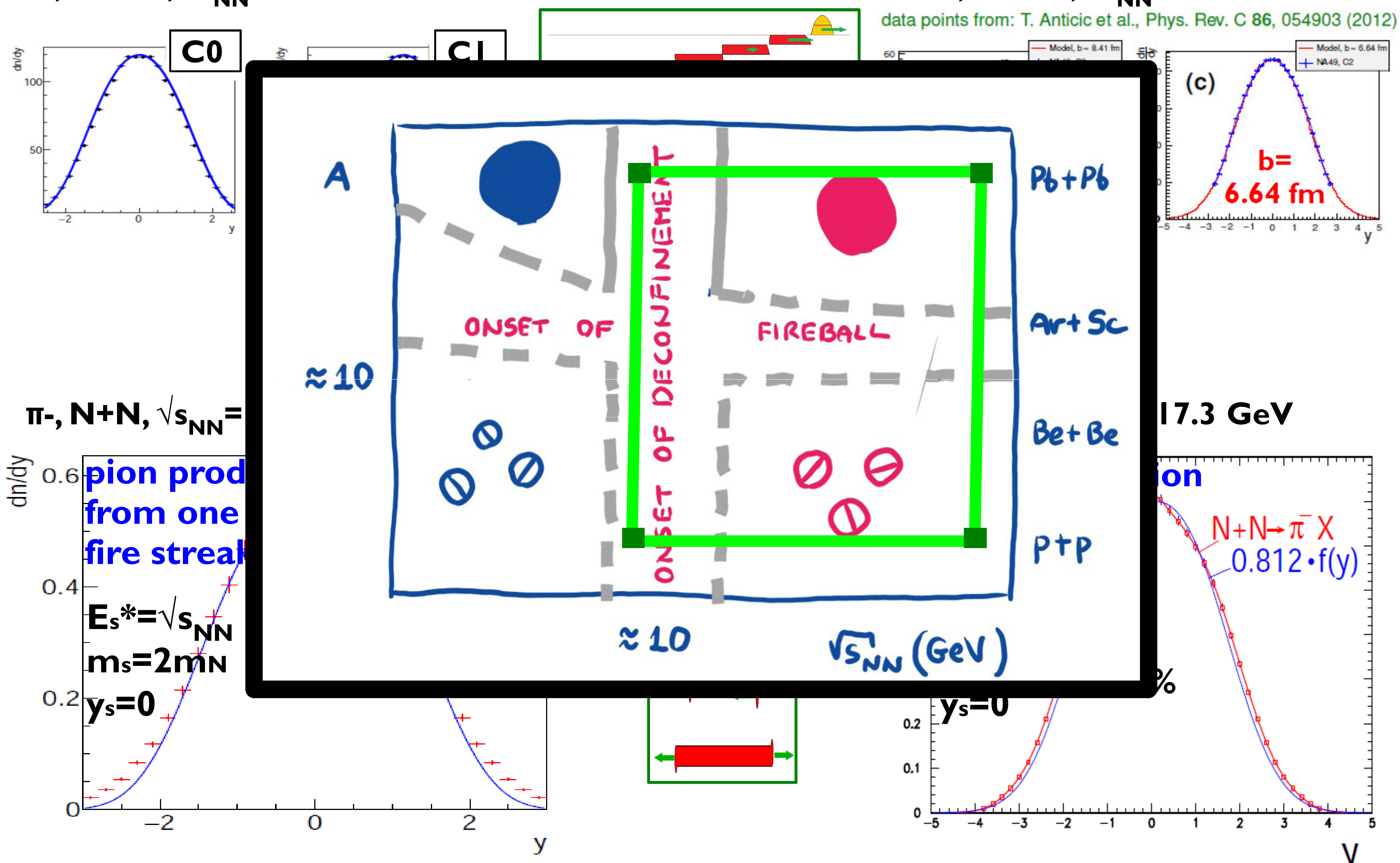




The model at 40GeV/c

π-, Pb+Pb, √s$_{NN}$= 8.8 GeV

π-, Pb+Pb, √s$_{NN}$= 17.3 GeV



Isospin correction

- **Isospin symmetry:** $\boxed{\frac{\mathrm{d}n}{dy}(n \rightarrow \pi^-) = \frac{\mathrm{d}n}{dy}(p \rightarrow \pi^+)}$

- **Isospin-averaged π⁻ and π⁺ distributions:**

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

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

Isospin correction

- **Isospin symmetry:** $\boxed{\frac{\mathrm{d}n}{dy}(n \to \pi^-) = \frac{\mathrm{d}n}{dy}(p \to \pi^+)}$

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

Isospin correction

- **Isospin symmetry:** $\boxed{\frac{\mathrm{d}n}{dy}(n \to \pi^-) = \frac{\mathrm{d}n}{dy}(p \to \pi^+)}$

- **Isospin-averaged π⁻ and π⁺ distributions:**

from FS model

$$\boxed{\frac{dn}{dy}(PbPb \to \pi^- X)} = \boxed{\left(\frac{Z}{A}\right)\frac{dn}{dy}(pp \to \pi^- X) + \left(1 - \frac{Z}{A}\right)\frac{dn}{dy}(pp \to \pi^+ X)}$$

$$\frac{dn}{dy}(PbPb \to \pi^+ X) = \boxed{\left(\frac{Z}{A}\right)\frac{dn}{dy}(pp \to \pi^+ X) + \left(1 - \frac{Z}{A}\right)\frac{dn}{dy}(pp \to \pi^- X)}$$

from NA49 experimental data

Isospin correction

- **Isospin symmetry:** $\boxed{\frac{dn}{dy}(n \to \pi^-) = \frac{dn}{dy}(p \to \pi^+)}$

- **Isospin-averaged π⁻ and π⁺ distributions:**

from FS model

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

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

from NA49 experimental data