# Spectator-induced electromagnetic effects in $^{40}$Ar+$^{45}$Sc collisions at 40$A$ GeV/$c$ beam momentum

23rd Zimányi School Winter Workshop on Heavy Ion Physics, Budapest, Hungary

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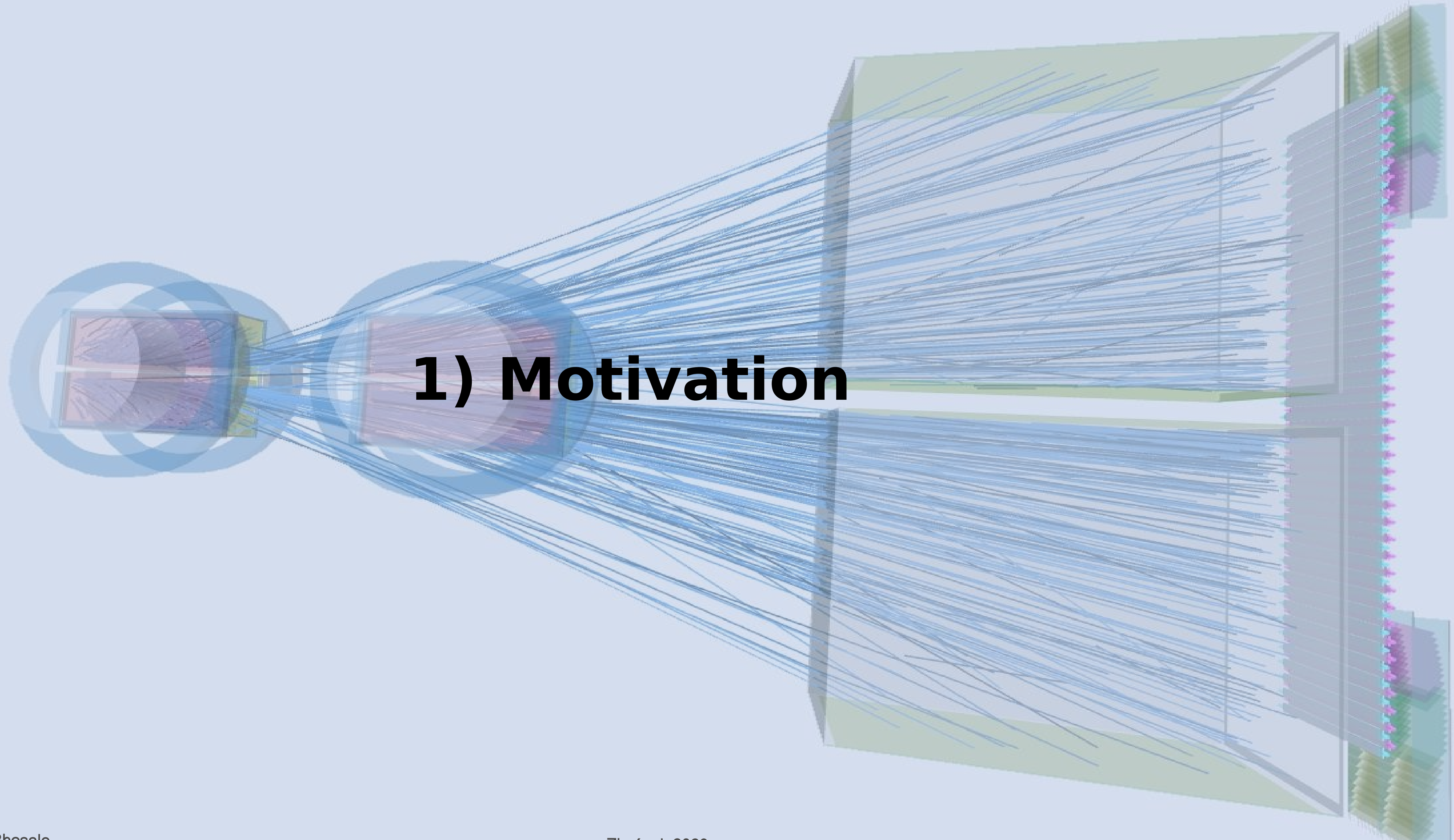
## Outline

- Motivation
- NA61/SHINE
- Particle identification
- Results
- Summary & conclusions



# 1) Motivation

# Spectator-induced electromagnetic (EM) effects:

1. Charged spectators generate EM fields, which modify the trajectories of $\pi^+$, $\pi^-$ mesons.

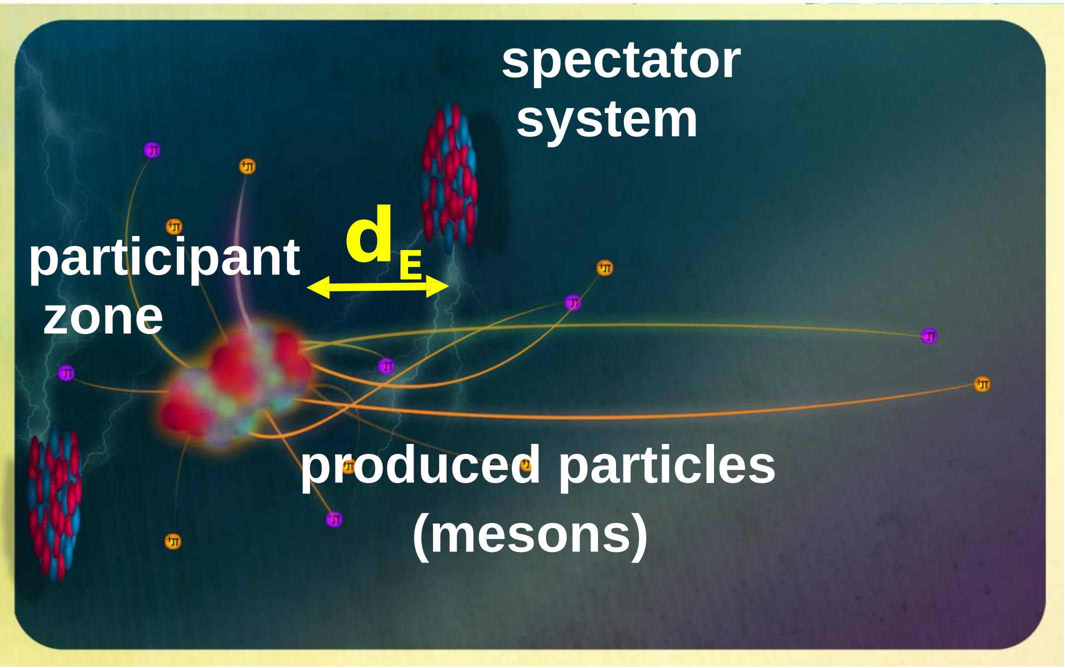
A. Rybicki, A. Szczurek, PRC 75 (2007), 054903
PRC 87(2013), 054909

→ they modify the double differential $\pi^+/\pi^-$ ratios, and result in charge splitting of directed flow.

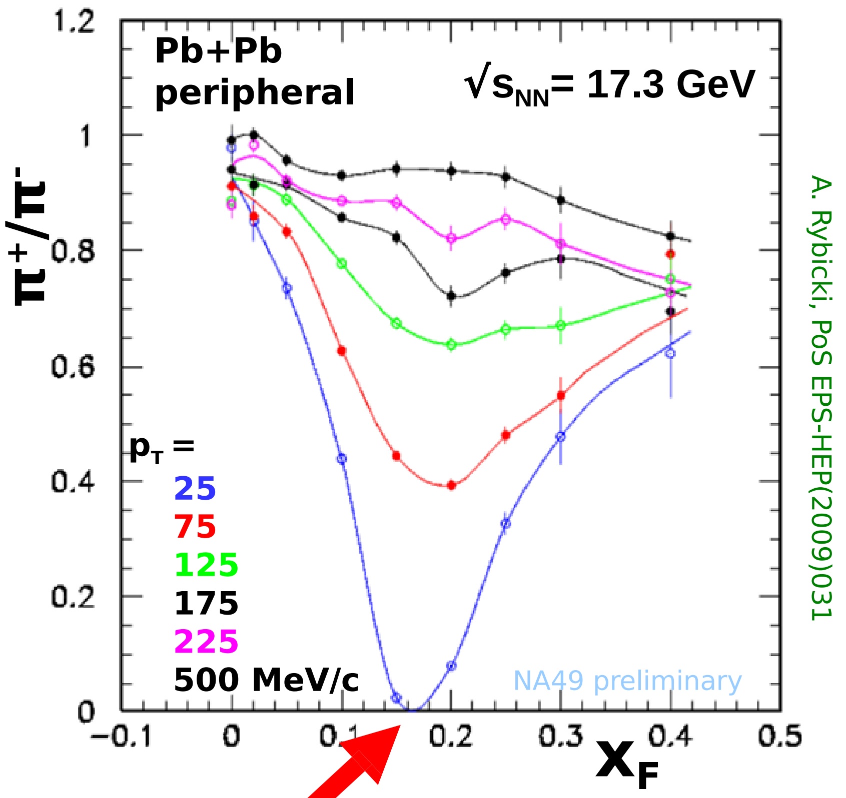
2. This EM distortion is sensitive to the distance $d_E$ between the pion formation zone and the spectator system.

→ new information on the space-time evolution of the system.

A. Rybicki, MESON 2016




S. Bhosale by I. Sputowska




Minimum at
$x_F = 0.15 = m_\pi/m_p$
(pions moving at spectator velocity)

spectator velocity

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

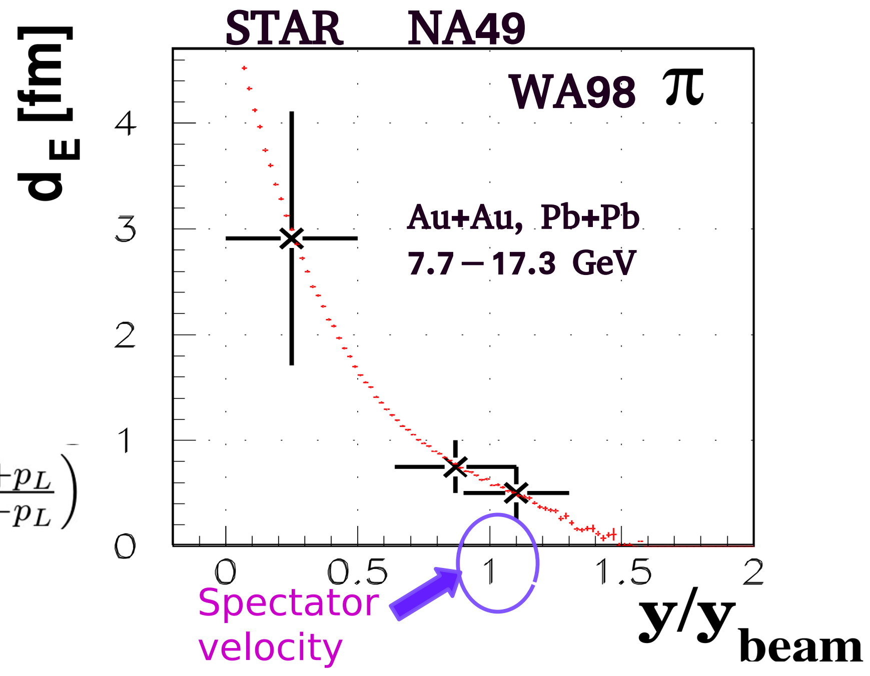
(c.m.s.)

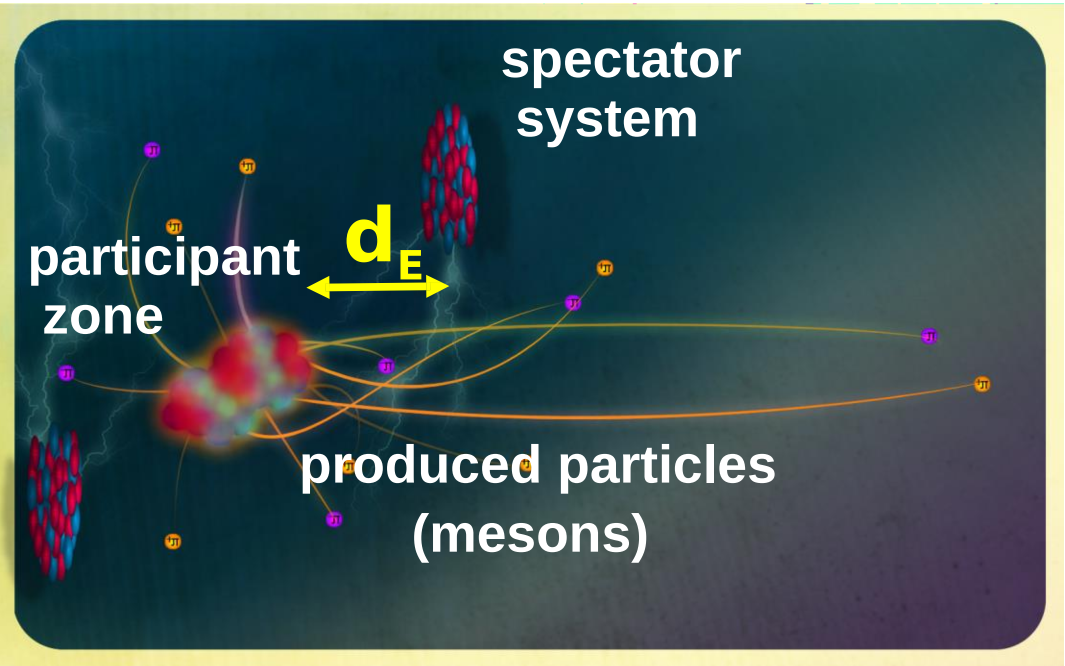
# Study of space-time evolution of the system from EM effects:

1. Introductory work- estimating $d_E$ as a function of pion rapidity: faster pions are produced closer to spectator system.

A. Rybicki, MESON 2016

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




by I. Sputowska

# Study of space-time evolution of the system from EM effects:

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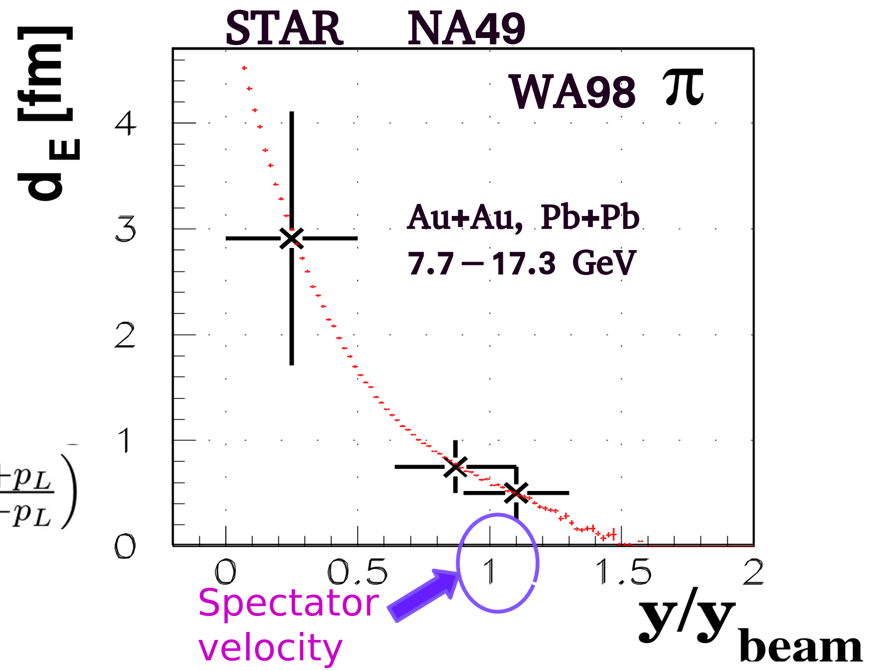


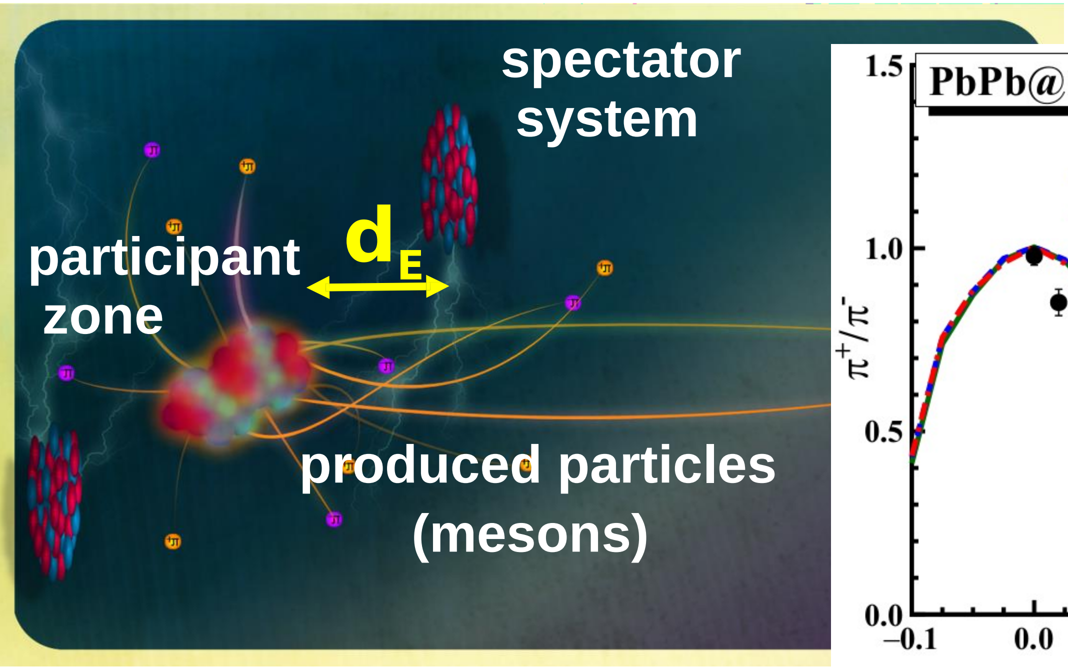

2. First realistic description of EM distortion of $\pi^+/\pi^-$ ratios.

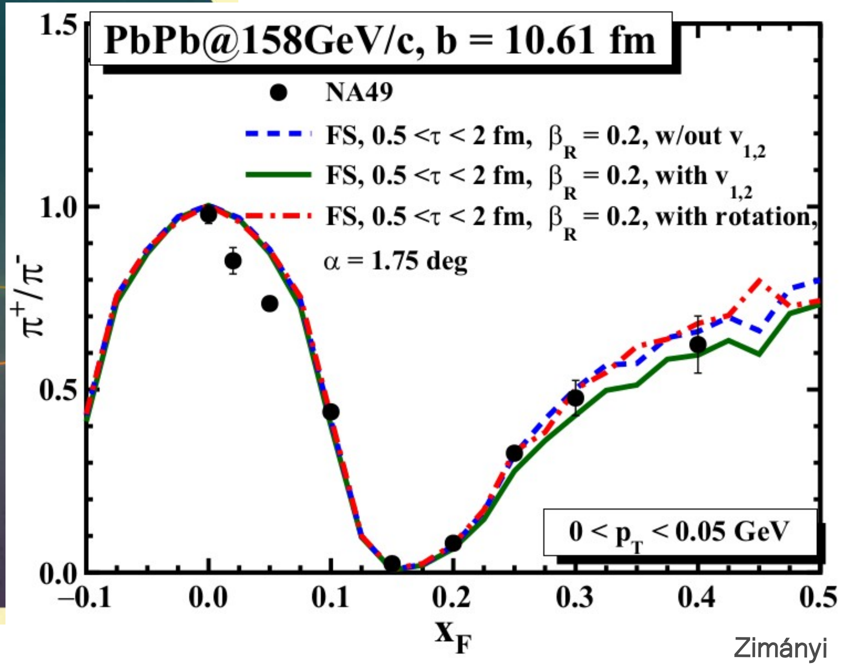
(1)collision geometry (2) longitudinal evolution, (3) $p_T$ spectra, (4) pion creation time, (5) isospin effects, (6) directed and elliptic flow, (7) transverse expansion, (8) vorticity,(9) spectator expansion, (10) relativistic effects on EM field.

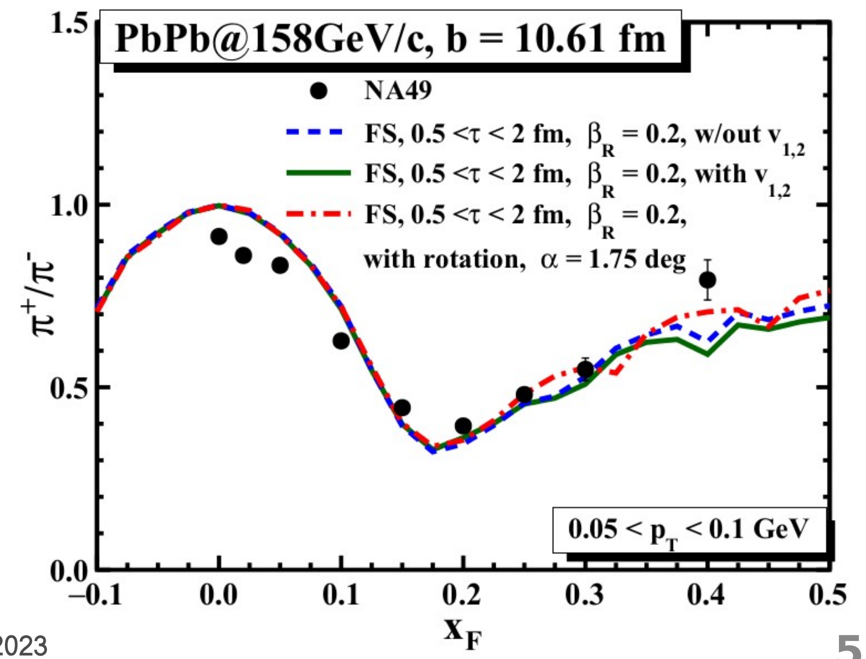
$$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$$

→Information on creation time scales for fast pions.

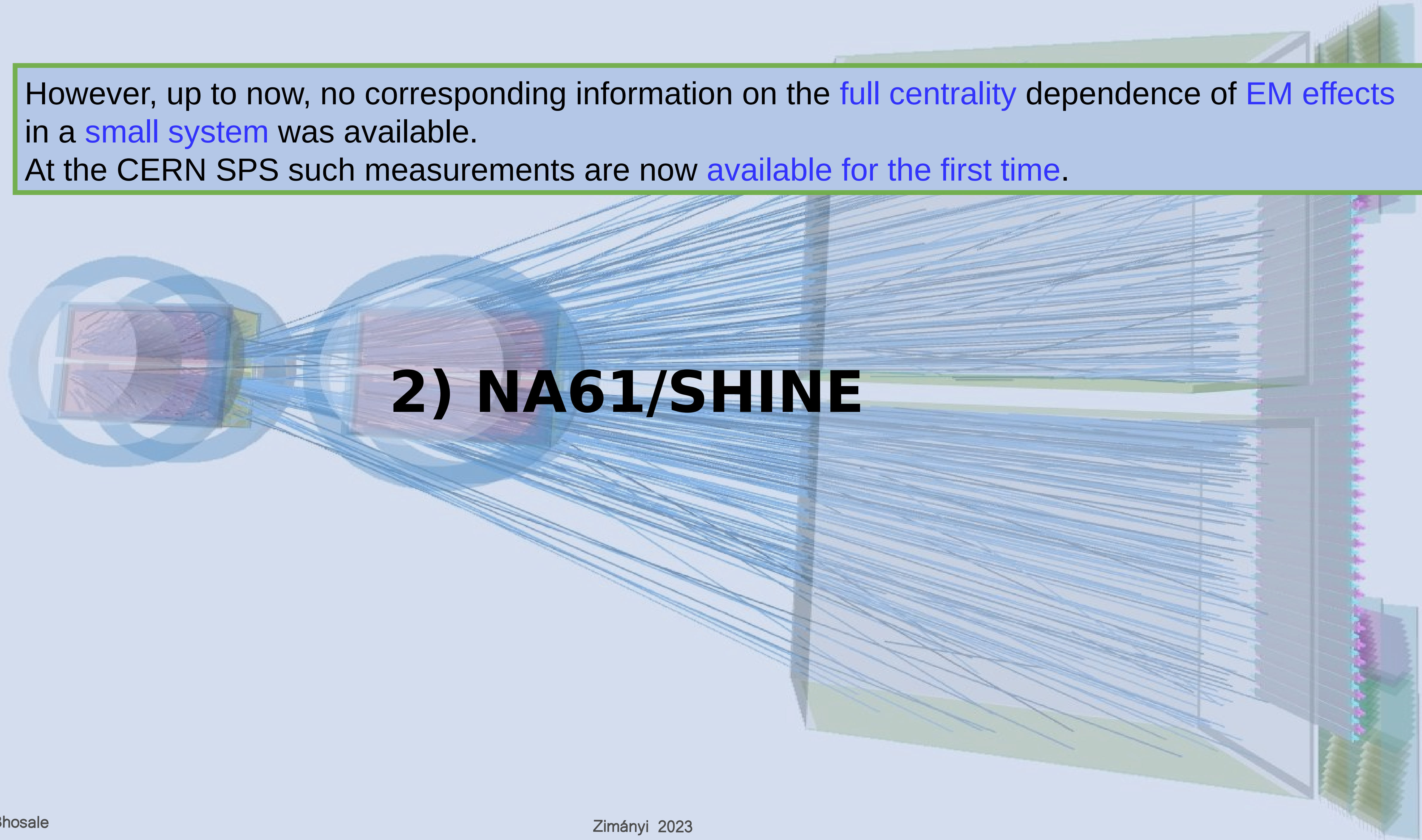
V. Ozvenchuk et al., Phys.Rev. C 102 (2020) 1, 014901



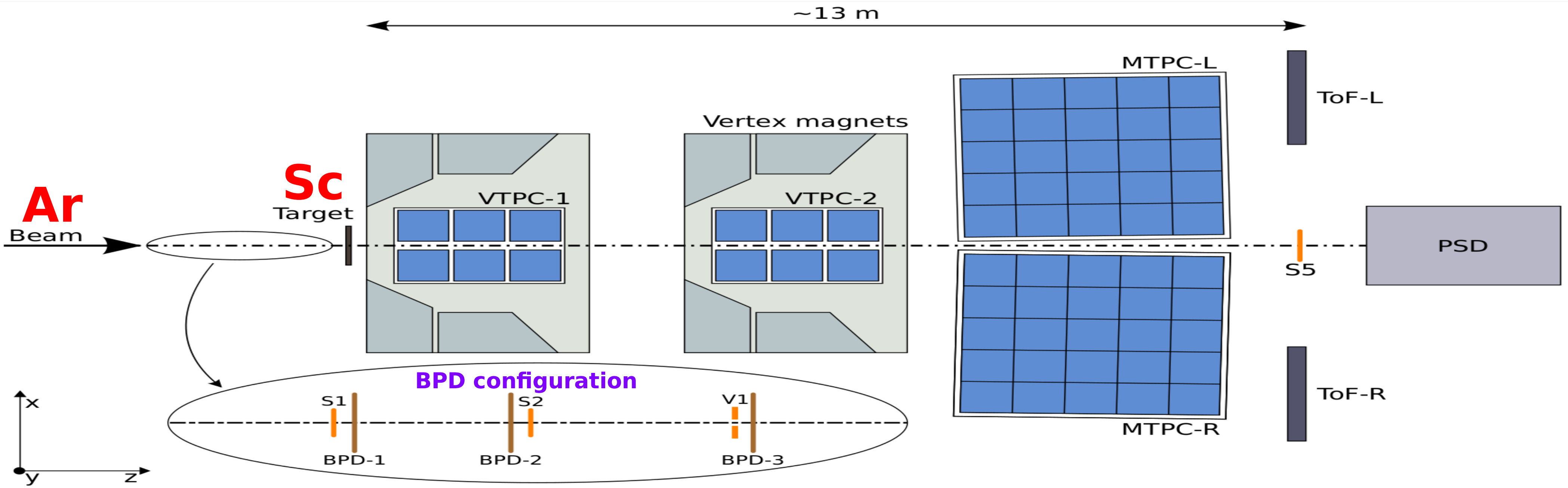



However, up to now, no corresponding information on the full centrality dependence of EM effects in a small system was available.
At the CERN SPS such measurements are now available for the first time.



# 2) NA61/SHINE

# About NA61/SHINE:

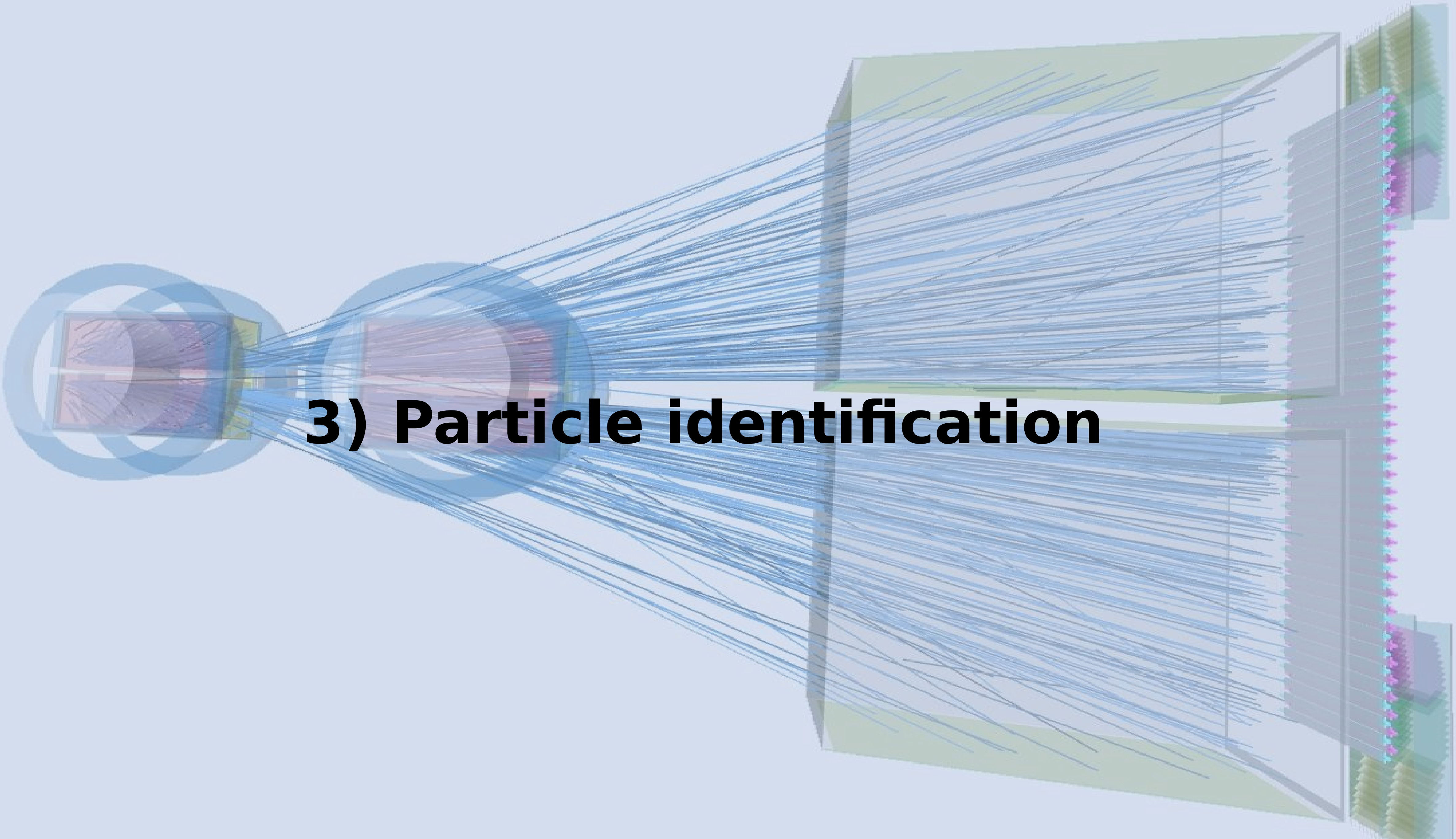



- VTPC-1 and VTPC-2 are placed in the magnetic field.
- TPC system: track reconstruction and particle identification based on ionization energy loss.
- Projectile Spectator Detector (PSD): hadronic calorimeter, measures projectile spectators energy.

  → strongly asymmetric, projectile oriented. .....Different from collider experiments!!

  → this method is particularly good for my study, as it is focused on projectile spectator charge and its influence on particle emission in the forward hemisphere.
- S5 : scintillator counter, crucial to define the minimum-bias interaction trigger (T4). $S1 \cdot S2 \cdot \overline{V1} \cdot \overline{S5}$

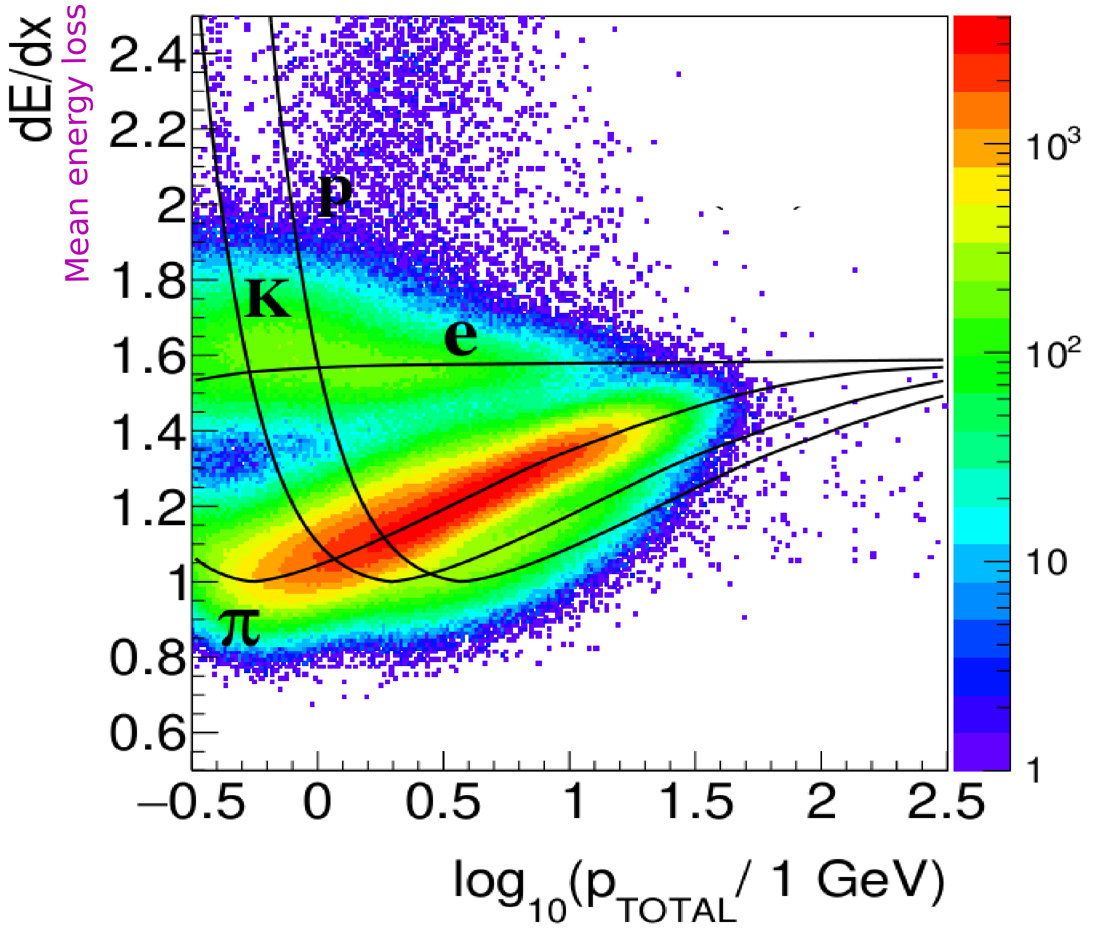
  → the S5 signal below the beam ion signal is associated with the beam interacting with the target.



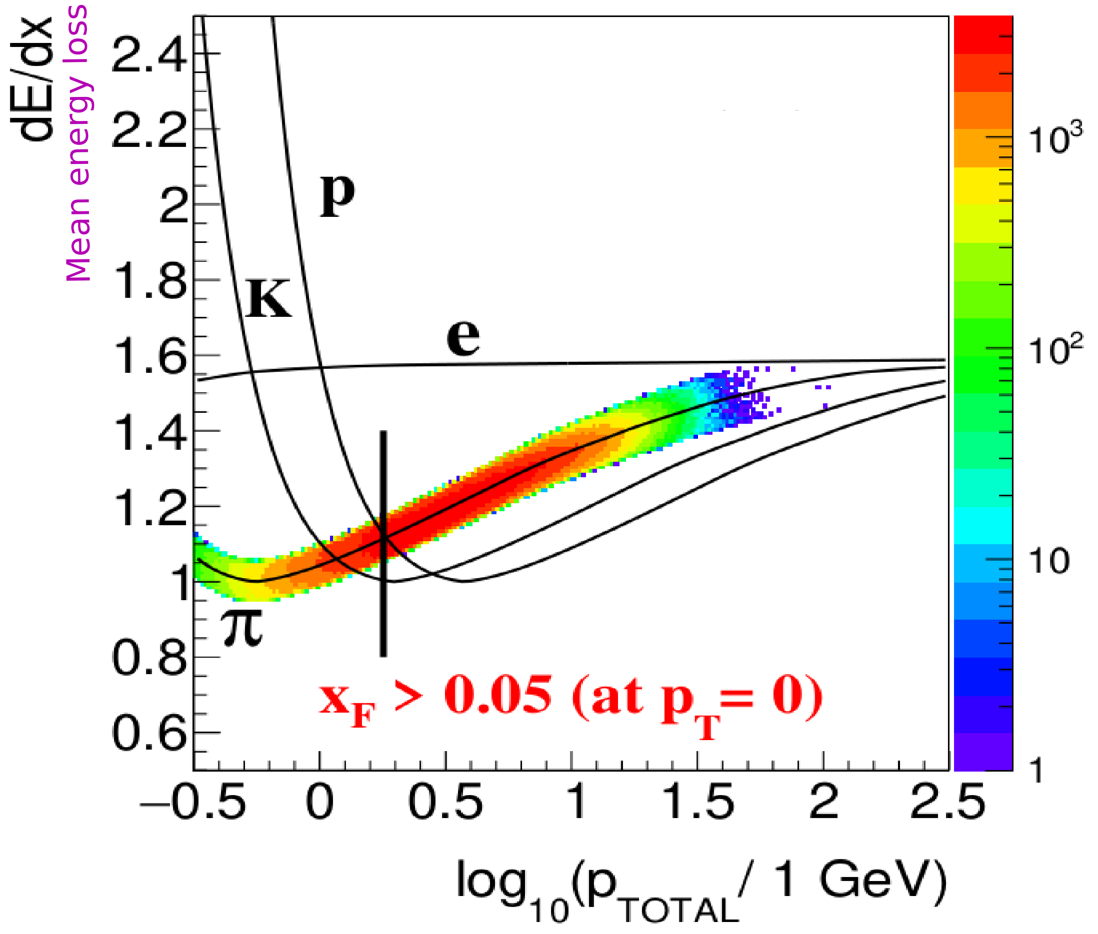
# 3) Particle identification

# Particle Identification:

* the case of negative particles is shown

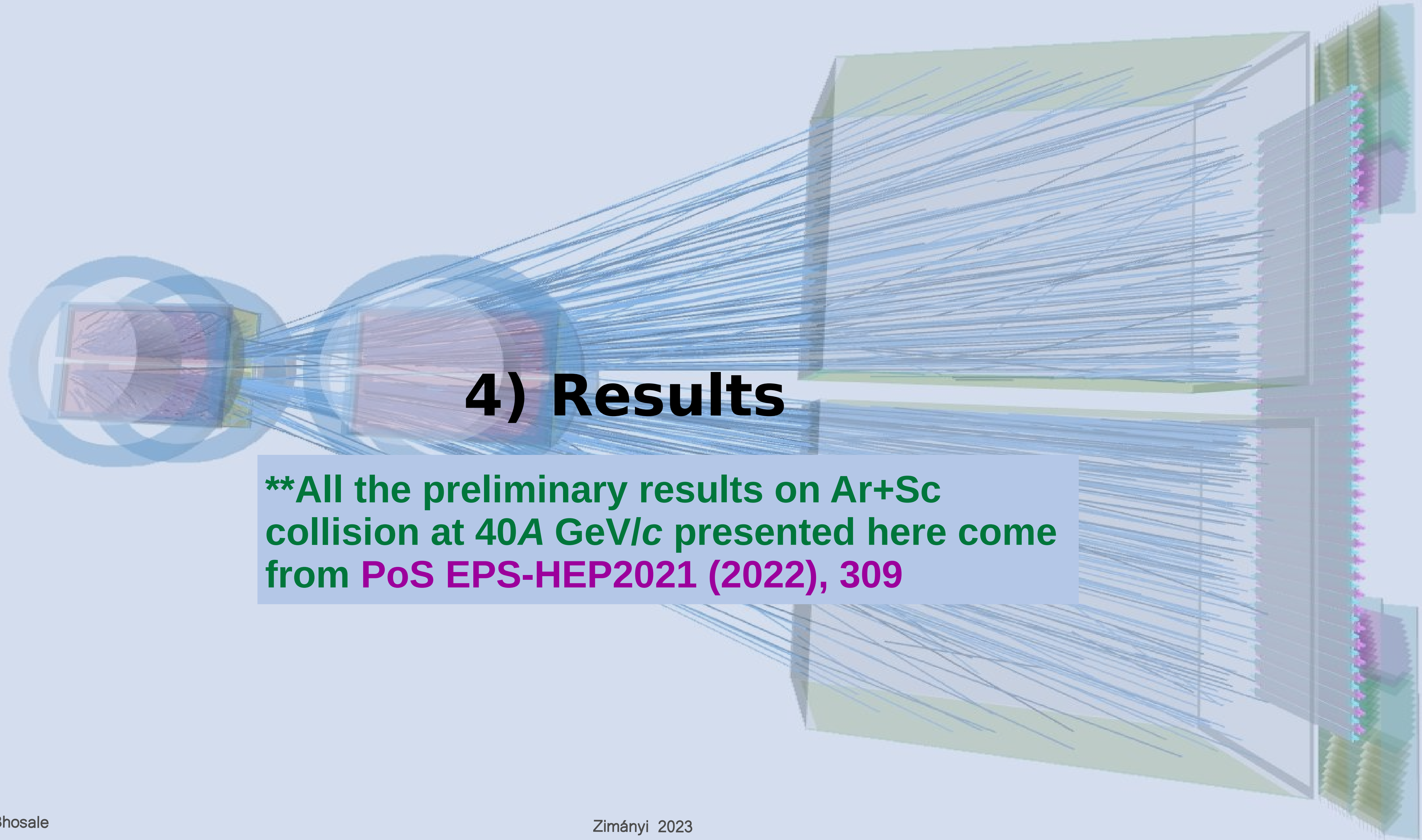



dE/dx ±5% around pion Bethe-Bloch




Note: this identification method can be readily used for measuring the $\pi^+/\pi^-$ ratio (the imposed trivial biases largly cancel out, and the remaining can be estimated by simple methods).

**All the preliminary results on Ar+Sc collisions at 40*A* GeV/*c* presented here come from PoS EPS-HEP2021 (2022),309



# 4) Results

****All the preliminary results on Ar+Sc collision at 40*A* GeV/*c* presented here come from PoS EPS-HEP2021 (2022), 309**

# $\pi^+/\pi^-$ ratio at three different centralities:

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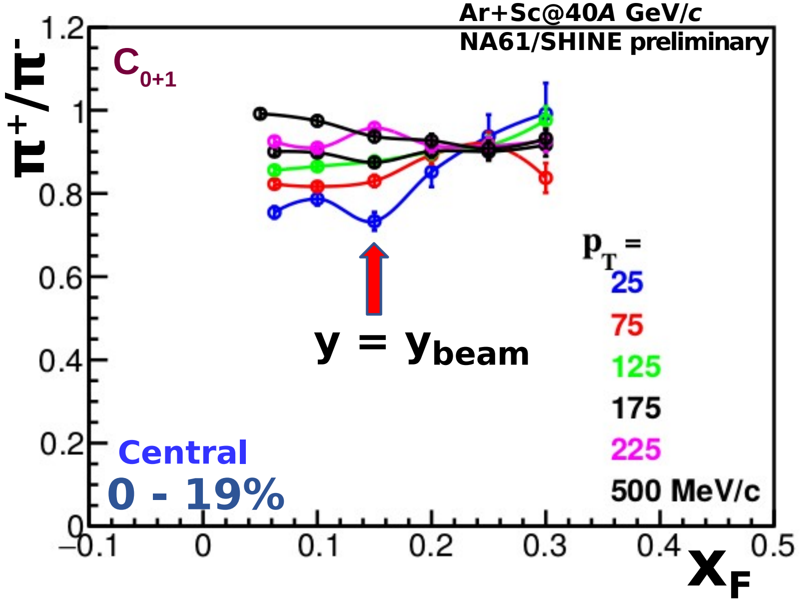
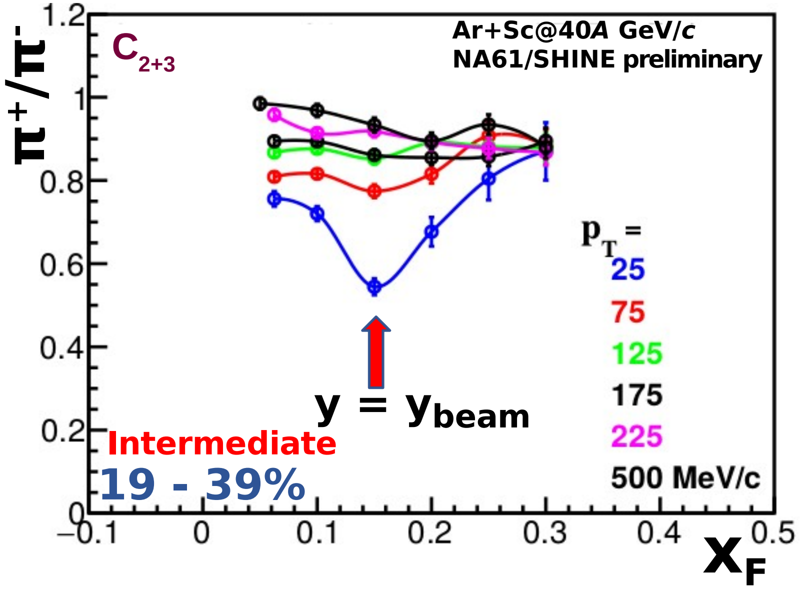
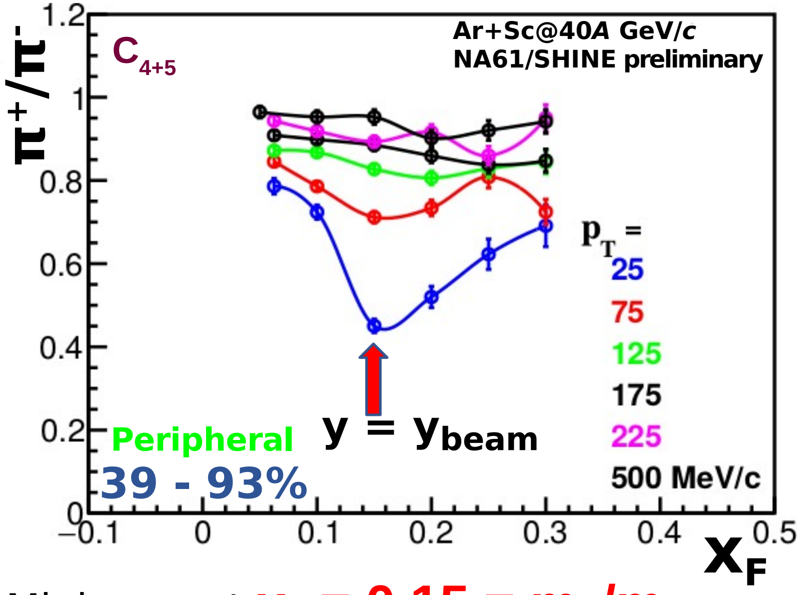


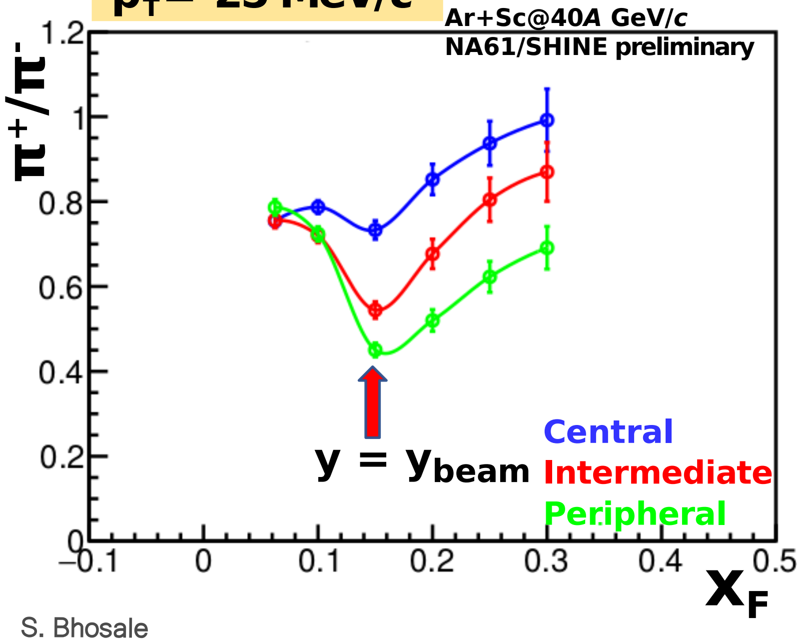




Minimum at $x_F = 0.15 = m_\pi/m_p$

(pions moving at spectator velocity)

$p_T$ = 25 MeV/*c*




1. EM effect is strong enough to break isospin symmetry (p/n =0.82)

2. Spectator-induced EM effects are present in small colliding systems, in spite of small spectator charge (*);

(*) peripheral Pb+Pb: Q~70
Ar+Sc: Q from 4 to 17.

3. Slow decrease of the effect with increasing centrality.

# $\pi^+/\pi^-$ ratio at six different centralities:

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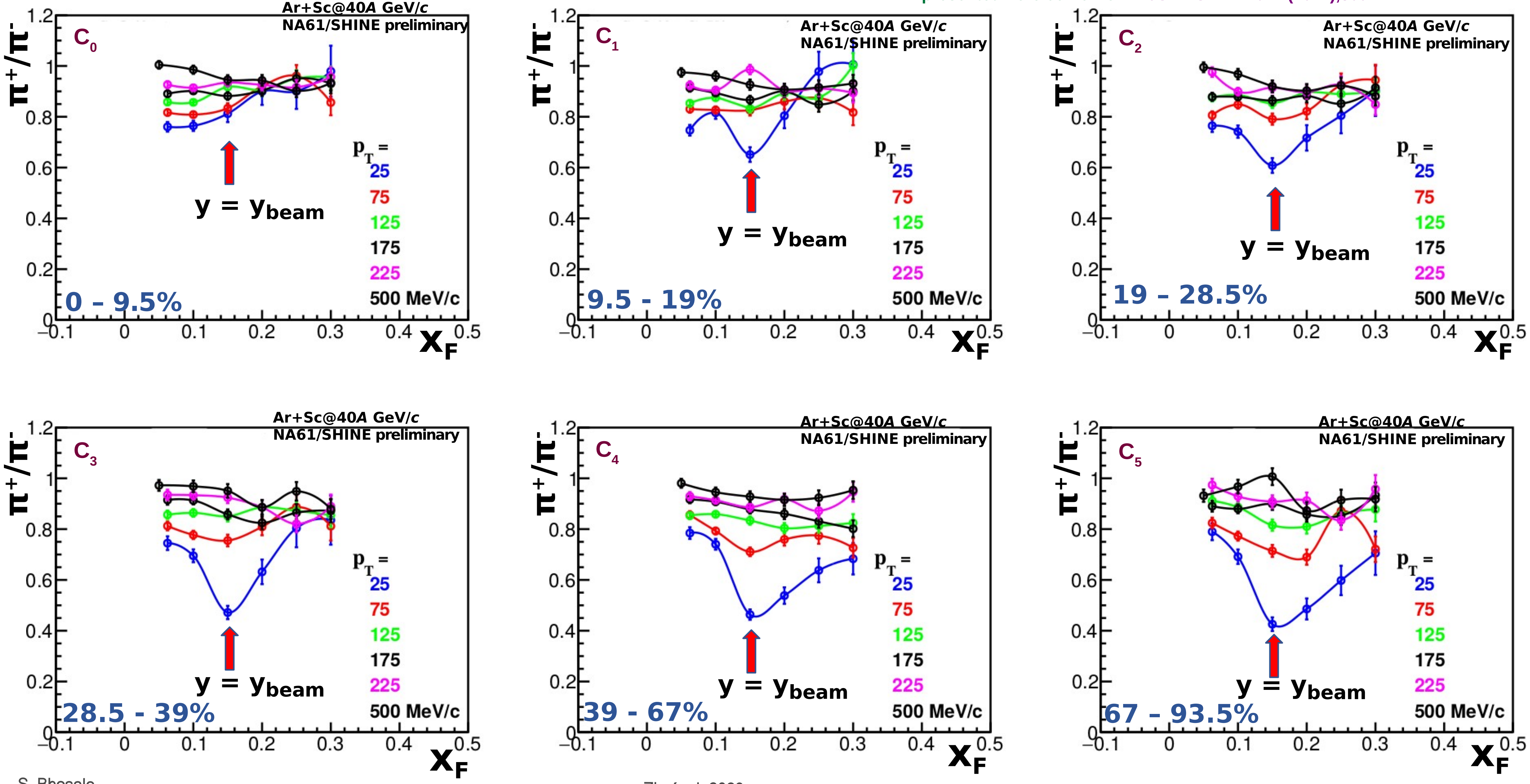
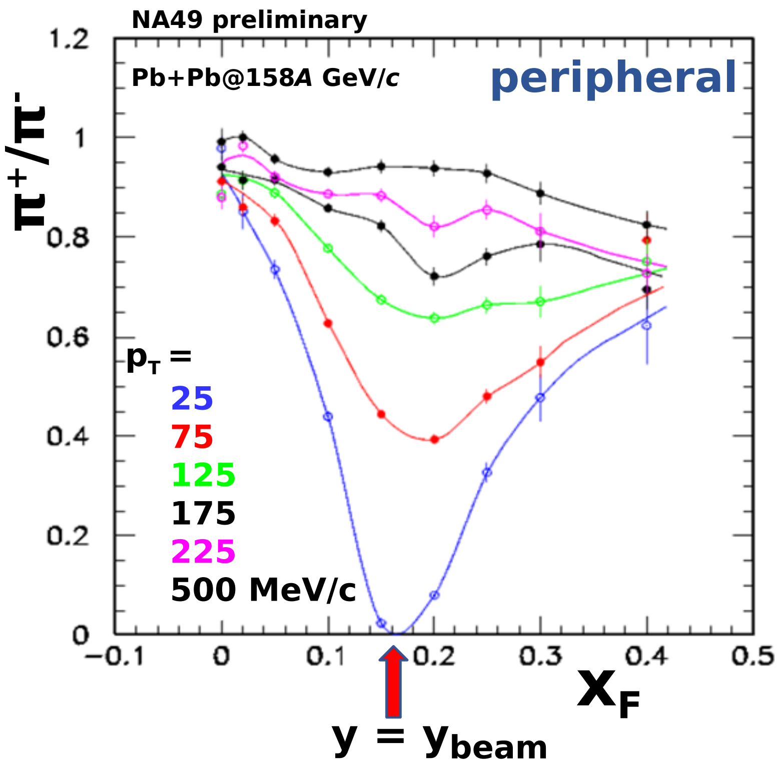
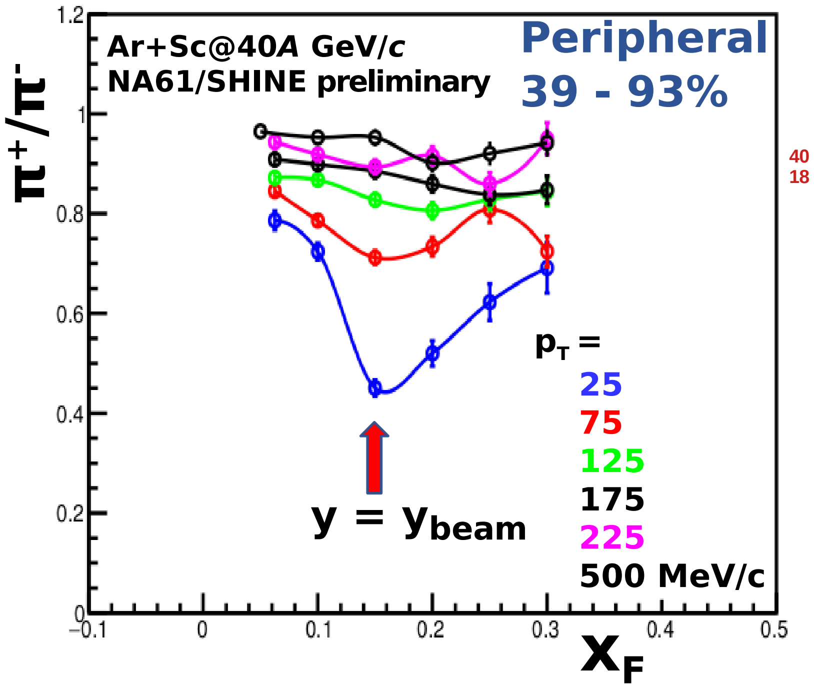


# Comparison between Ar+Sc and Pb+Pb reactions:

$$\text{Ar+Sc} \approx \frac{1}{5} \cdot \text{Pb+Pb}$$

$^{208}_{82}$Pb nucleus
protons 82
neutrons 126
p/n =0.65




$^{40}_{18}$Ar nucleus
protons 18
neutrons 22
p/n = 0.82

- the overall EM effect is similar, $\frac{1}{2}$ of the effect is observed in Ar+Sc as compared to Pb+Pb
- isospin effects are visible in the values of the $\pi^+/\pi^-$ ratio at higher values of $p_T$ (≥125 Mev/*c*)

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# The model:

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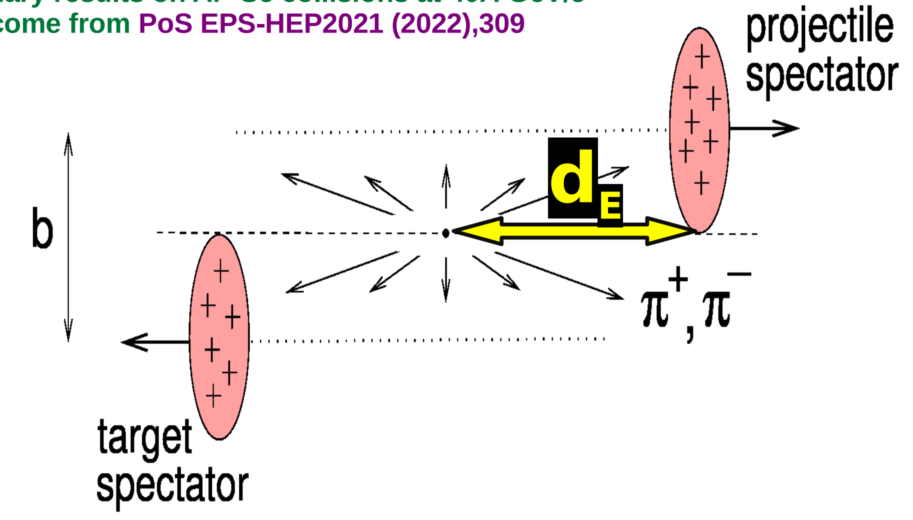



- The initial geometry of the collision is obtained using Glauber simulation (impact parameter and spectator charge corresponds to the experimental centrality selection).
- The final state pion emission takes place from the hypothetical interaction point after a given emission time, $t_{delay}$.

  Note: account taken that the spectator velocity is very close to speed of light, the numerical value of $d_E$ in fm is nearly identical to the numerical value of $t_{delay}$ in fm/*c* ( $d_E \approx t_{delay}$ ).

- spectator spheres expand radially with surface velocity β.

  In spectator c.m.s.

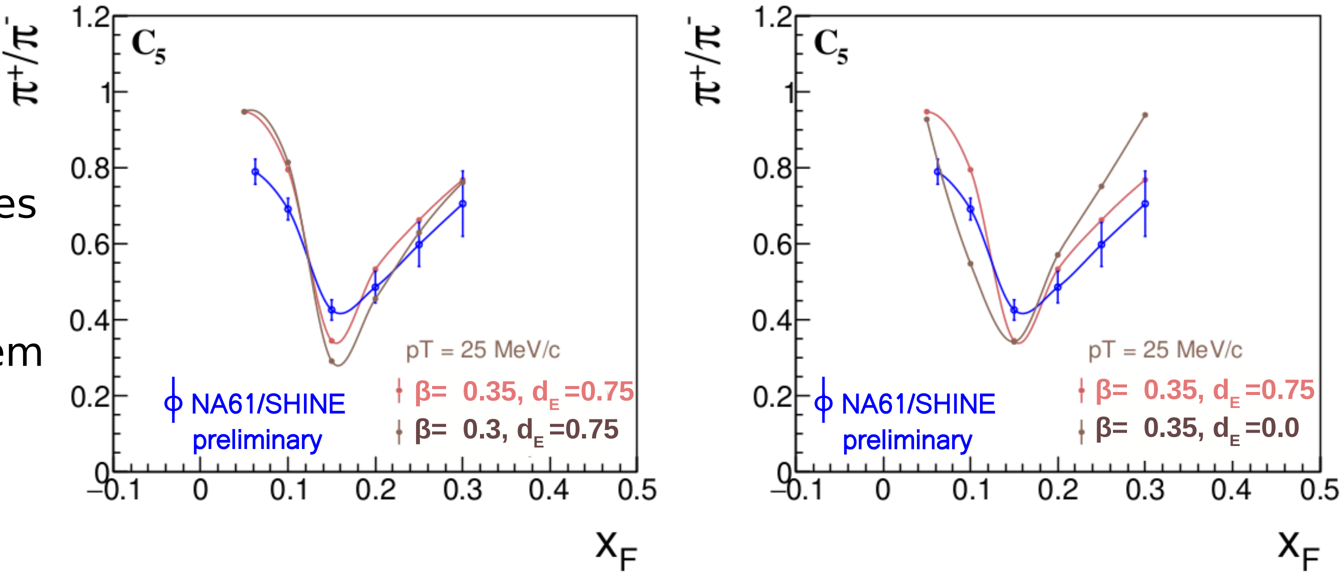
- the initial 2D $x_F$, $p_T$ distribution of the emitted pions is assumed similar (in shape) to nucleon-nucleon collisions at 40*A* GeV/*c* (parametrized from NA61/SHINE p+p data)

  parametrization by Ł. Rozpłochowski, 2021

1. A reasonably high sensitivity of the modeled EM effect to the expansion of the spectator system
2. Change of $d_E$ by less than 1 fm significantly changes the overall shape of the EM distortion
3. Sensitivity to the space-time evolution of the system

   (A. Rybicki, A. Szczurek, 2007)

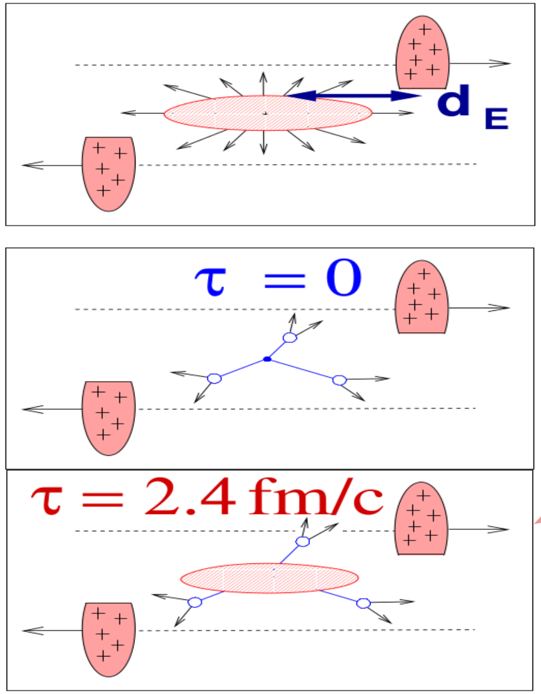
4. We can obtain estimates for the pion emission distance $d_E$ by adjusting the model to the data.




A. Szczurek et al 2007 J. Phys. G: Nucl. Part. Phys. 34 S827

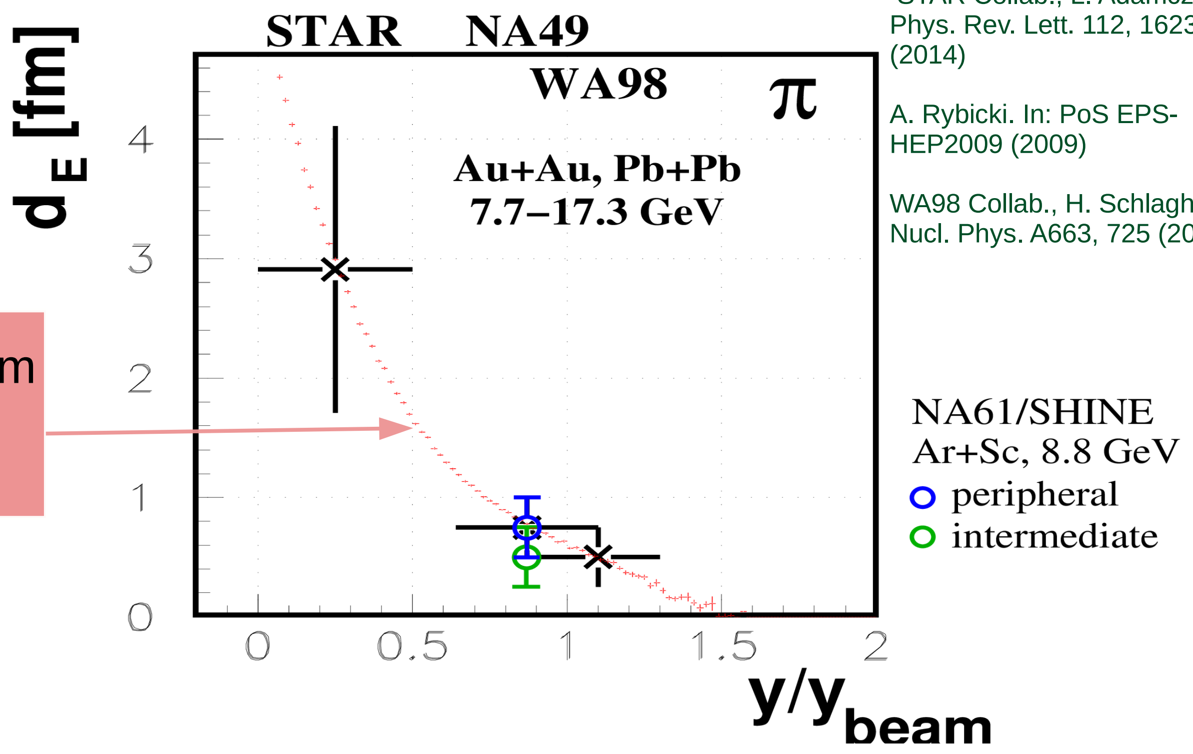
** the additional influence of participant charge, as well as the strong final state interactions are neglected.

# The importance of this analysis:




WA98 (see A. Rybicki, Acta Phys.Polon.Supp. 9 (2016) 303)

Intermediate system prior to resonance formation




STAR Collab., L. Adamczyk et al. Phys. Rev. Lett. 112, 162301 (2014)

A. Rybicki. In: PoS EPS-HEP2009 (2009)

WA98 Collab., H. Schlagheck, Nucl. Phys. A663, 725 (2000).

Distribution of the distance $d_E$ between the pion formation zone and the spectator system as a function of pion rapidity. The black "x" symbols correspond to values estimated on the basis of pion data from STAR, NA49 and WA98. Very tiny red crosses correspond to a Monte Carlo model simulation of pion production by resonances emitted from an intermediate system.

→ The decrease of $d_E$ with increase in $y/y_{beam}$ and the non-zero value of $d_E$ at beam rapidity ($y/y_{beam}$= 1) can be understood as a direct consequence of pion production from resonances emitted from an intermediate system (fireball, QGP?).

# 5) Summary & conclusions:

- New data on spectator-induced electromagnetic effects in Ar+Sc collisions at 40 A GeV/c beam momentum ( $\sqrt{s_{NN}}$ = 8.76 GeV) is the first ever data on the full centrality dependence of these effects in small systems at the CERN SPS (and first analysis of peripheral small systems in NA61/SHINE)

  → the $\pi^+/\pi^-$ ratio goes down to about 0.4 which is far below the lower limit estimated from a pure strong interaction, preserving isospin symmetry (0.82)

- Spectator-induced EM effects are present in small systems (in spite of the small spectator charge)

  → no EM effect was seen in the most central collisions (0-10% of the total Ar+Sc cross-section)

- The new experimental results on Ar+Sc collisions have been compared with the existing data on the peripheral Pb+Pb reactions

  → a qualitative similarity in the $x_F$, $p_T$ dependence of the EM effect

# 5) Summary & conclusions:

- A simulation based on a simple theoretical model was performed

  → the bulk of the centrality dependence of the EM effect in Ar+Sc reactions is described reasonably well by the simple approach used

  → comparison between model predictions and experimental data at higher $p_T$ suggests that our description of isospin effects can be considered oversimplified

  → velocities β characterizing the fragmentation of the projectile spectator system adjusted to the exp. data are quite large (in some way connected to the expansion of the participant system?)

  → the values of the pion emission distance $d_E$ between the pion formation zone and the spectator system agree with the overall trend obtained for heavy ion collisions on the basis of STAR, WA98 and NA49 data

Thank you so much!

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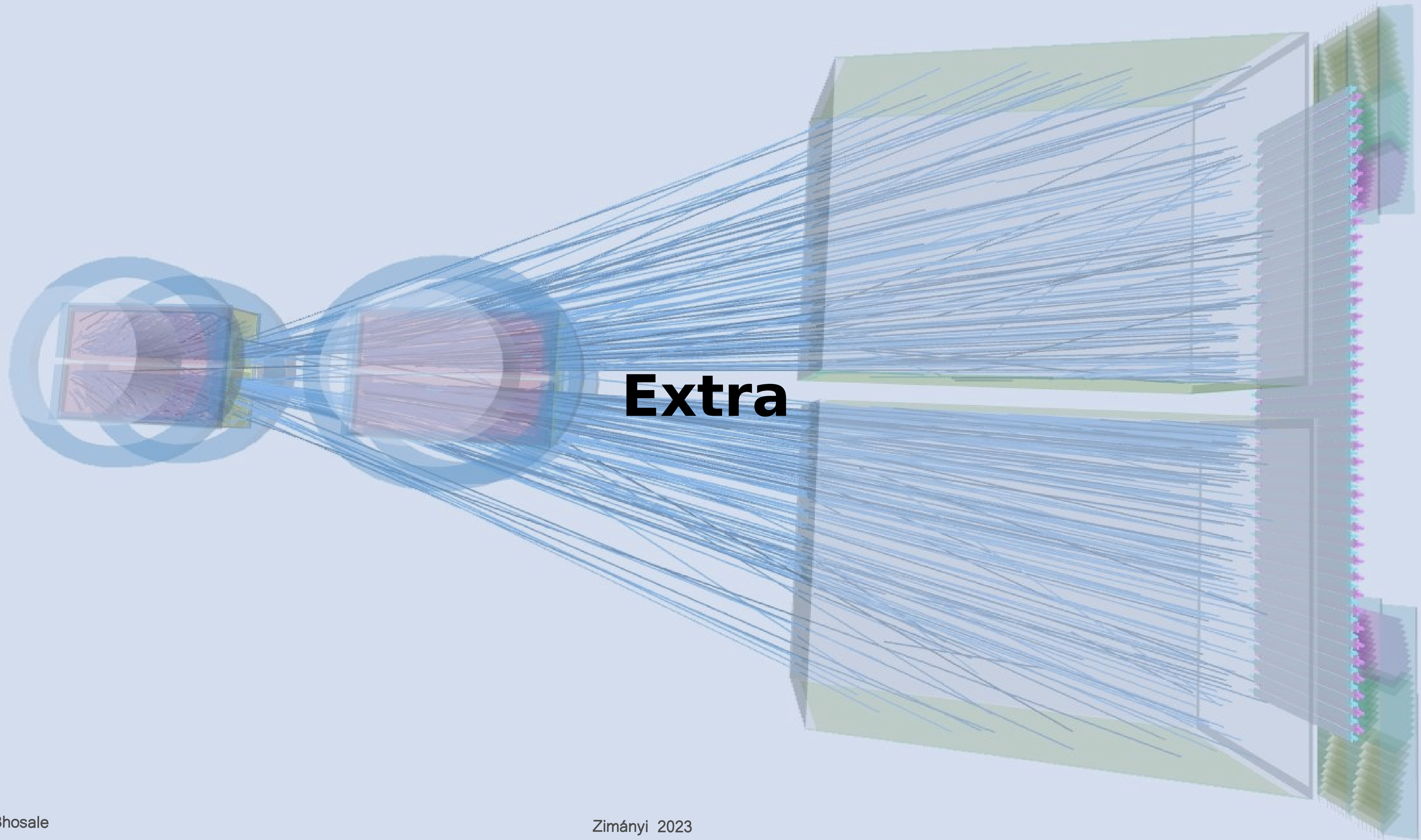
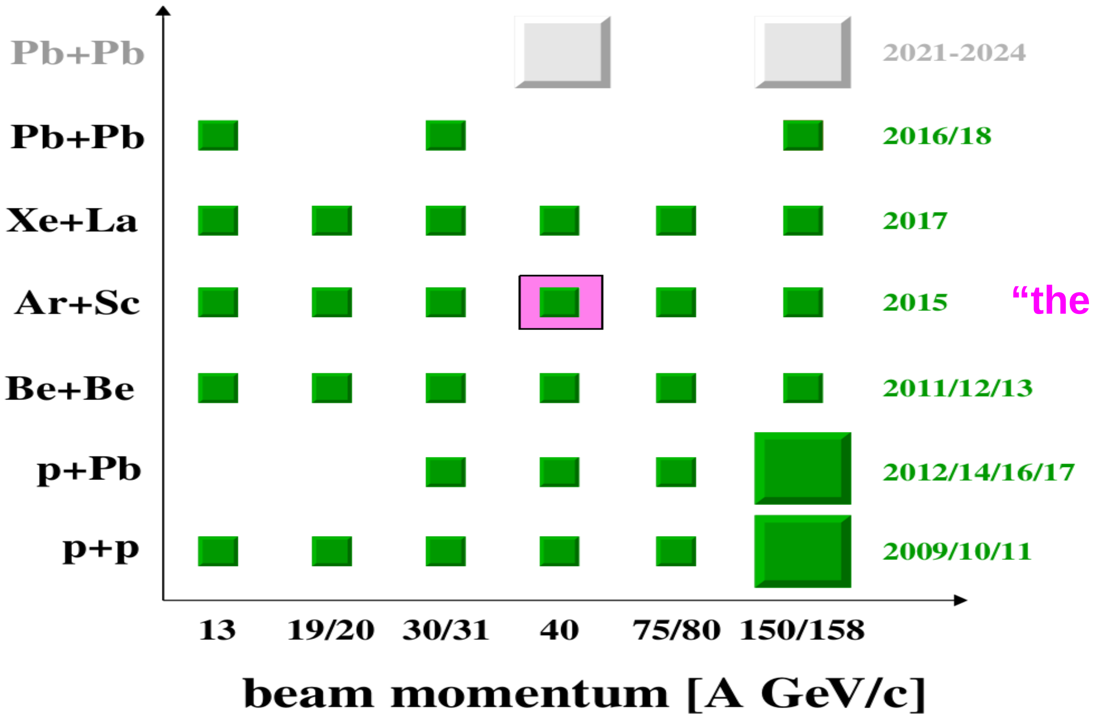
# Extra



# Ar+Sc :




What was missing ??
1. System size dependence
2. Centrality dependence

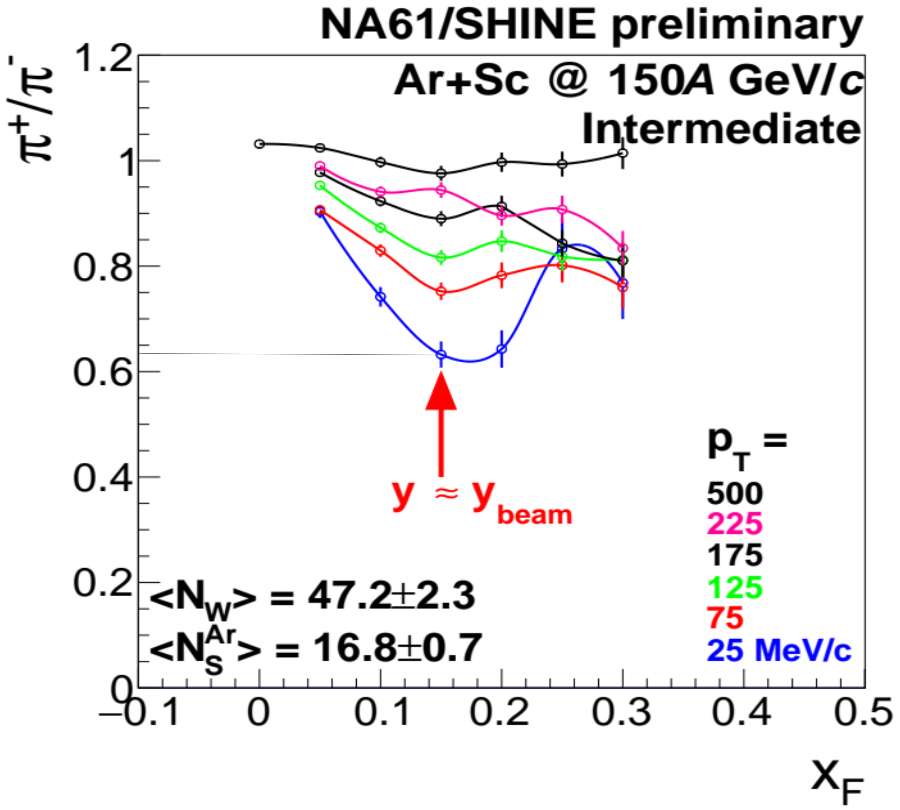
"the Ar+Sc colliding system is 5 times smaller than Pb+Pb"

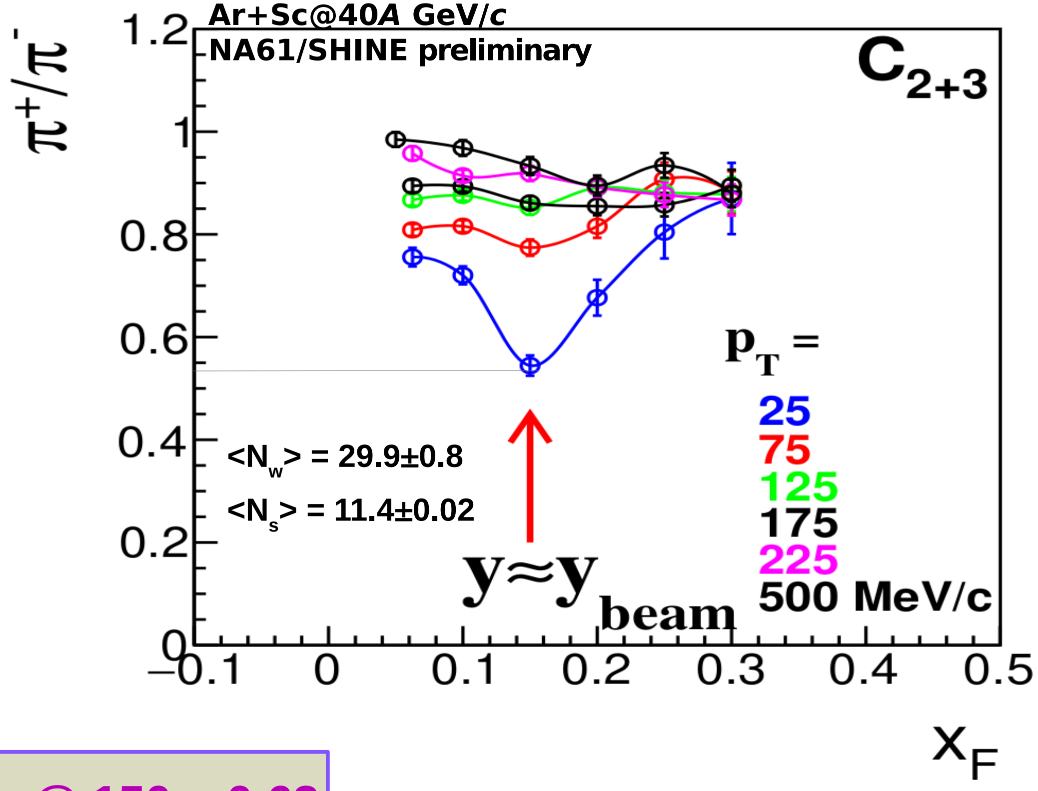
**Advantages of this study :**
1. EM effects in a small system in the full range of centrality, from very central to peripheral collisions (first-ever at the SPS).
2. Centrality dependence of the space-time evolution of pion production for fast pions.
3. Possibility to verify existing models describing EM, isospin, and other effects.

# Comparison between Ar+Sc 40*A* GeV/*c* and 150*A* GeV/*c*:

$^{40}_{18}$Ar nucleus: protons 18
neutrons 22
p/n = 0.82

M. Kiełbowicz [NA61/SHINE], Acta Phys. Polon. Supp. 12 (2019), 353, see also:
A. Marcinek [NA61/SHINE], Acta Phys. Polon. B 50 (2019), 1127




Ar+Sc @ 150 ~ 0.63
Ar+Sc @ 40 ~ 0.54

****All the preliminary results on Ar+Sc collisions at 40*A* GeV/*c* presented here come from PoS EPS-HEP2021 (2022),309**

# Centrality parameters:

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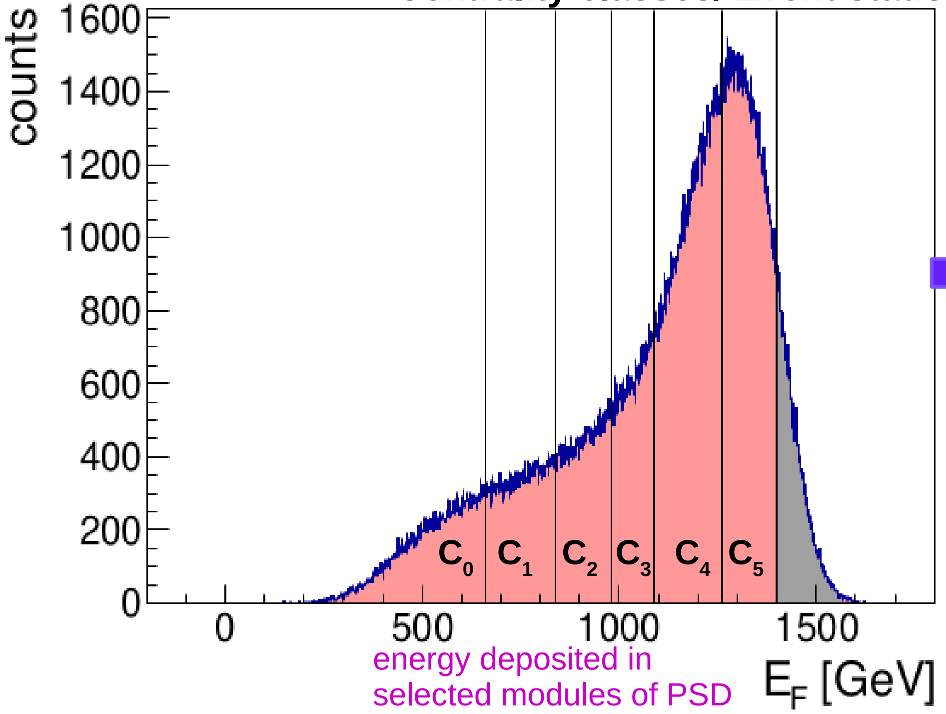
**Centrality classes/ Event statistics after cuts:**



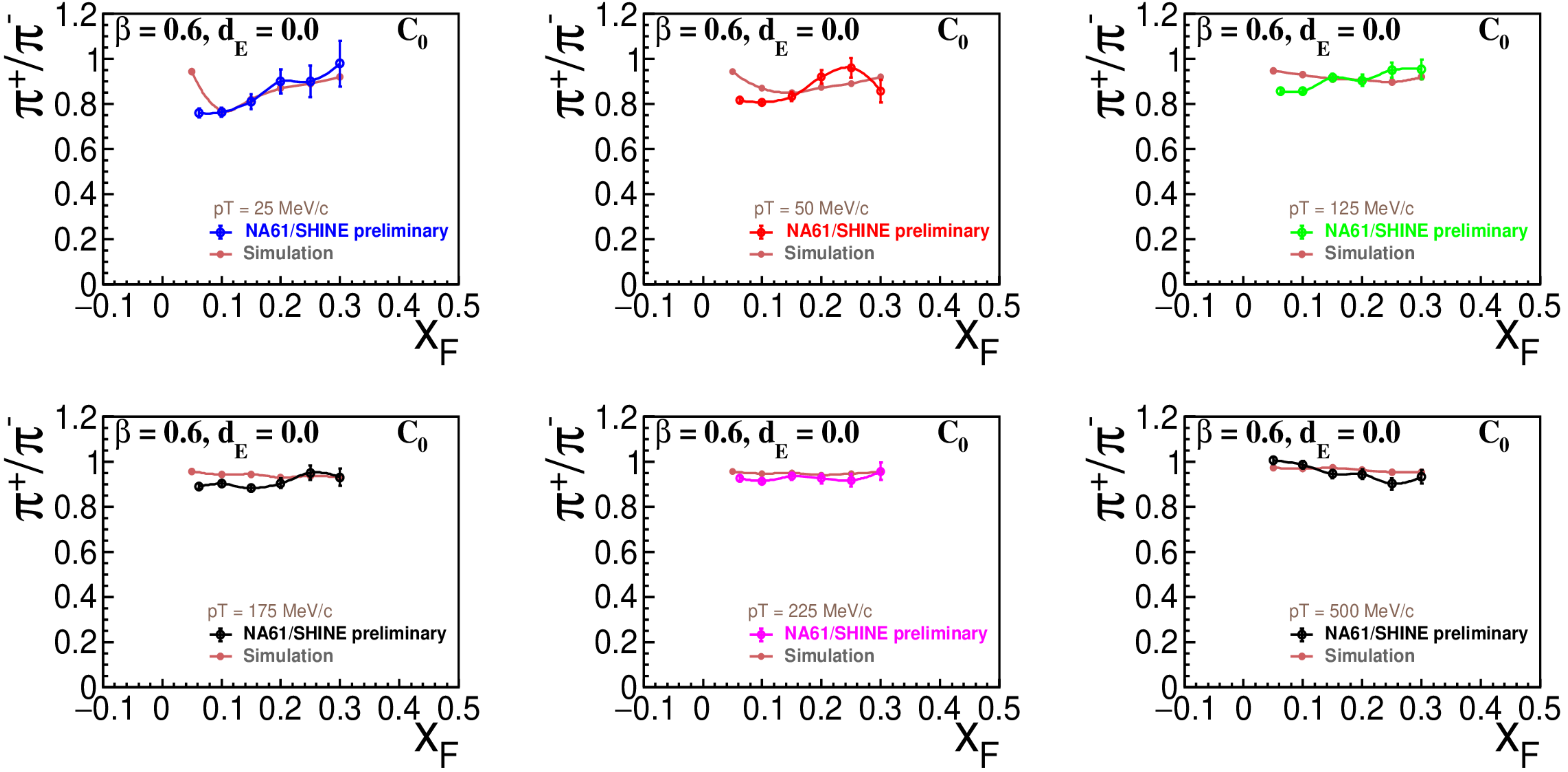

| Class | $E_F$ selection | Centrality percentiles (%) | Total events |
|---|---|---|---|
| $C_0$ | $0 < E_F < 660$ | 0-9.5 | 61k |
| $C_1$ | $660 < E_F < 840$ | 9.5-19 | 61k |
| $C_2$ | $840 < E_F < 980$ | 19-28.5 | 60k |
| $C_3$ | $980 < E_F < 1090$ | 28.5-39 | 65k |
| $C_4$ | $1090 < E_F < 1260$ | 39-67 | 171k |
| $C_5$ | $1260 < E_F < 1400$ | 67-93.5 | 144k |
| $C_{0+1}$ | $0 < E_F < 840$ | 0-19 | 121k |
| $C_{2+3}$ | $840 < E_F < 1090$ | 19-39 | 126k |
| $C_{4+5}$ | $1090 < E_F < 1400$ | 39-93 | 314k |

| Class | <b> [fm] | $\langle N_W \rangle$ | <QsAr> |
|---|---|---|---|
| $C_0$ | $1.94 \pm 0.18$ | $61.9 \pm 1.7$ | $4.2 \pm 0.4$ |
| $C_1$ | $3.32 \pm 0.06$ | $46.5 \pm 0.6$ | $7.6 \pm 0.1$ |
| $C_2$ | $4.23 \pm 0.10$ | $35.0 \pm 0.6$ | $10.2 \pm 0.1$ |
| $C_3$ | $5.04 \pm 0.17$ | $25.2 \pm 0.9$ | $12.4 \pm 0.2$ |
| $C_4$ | $6.34 \pm 0.26$ | $12.9 \pm 0.8$ | $15.2 \pm 0.2$ |
| $C_5$ | $7.78 \pm 0.44$ | $4.9 \pm 0.1$ | $17.0 \pm 0.5$ |
| $C_{0+1}$ | $2.62 \pm 0.12$ | $54.4 \pm 1.1$ | $5.8 \pm 0.2$ |
| $C_{2+3}$ | $4.65 \pm 0.15$ | $29.9 \pm 0.8$ | $11.4 \pm 0.2$ |
| $C_{4+5}$ | $6.91 \pm 0.33$ | $9.8 \pm 1.4$ | $15.9 \pm 0.3$ |

Estimates and their uncertainties have been obtained using three models:

- Dedicated simple geometrical "Glauber" simulation with selection of centrality by the number of Ar spectator nucleons.
- EPOS 1.99 with its implementation of the Wounded Nucleon Model, with selection of centrality by the number of Ar spectator nucleons.
- same version of EPOS, with centrality selection by the $E_F$ from a GEANT 4 simulation of PSD

# Comparison between experimental data and model simulations:

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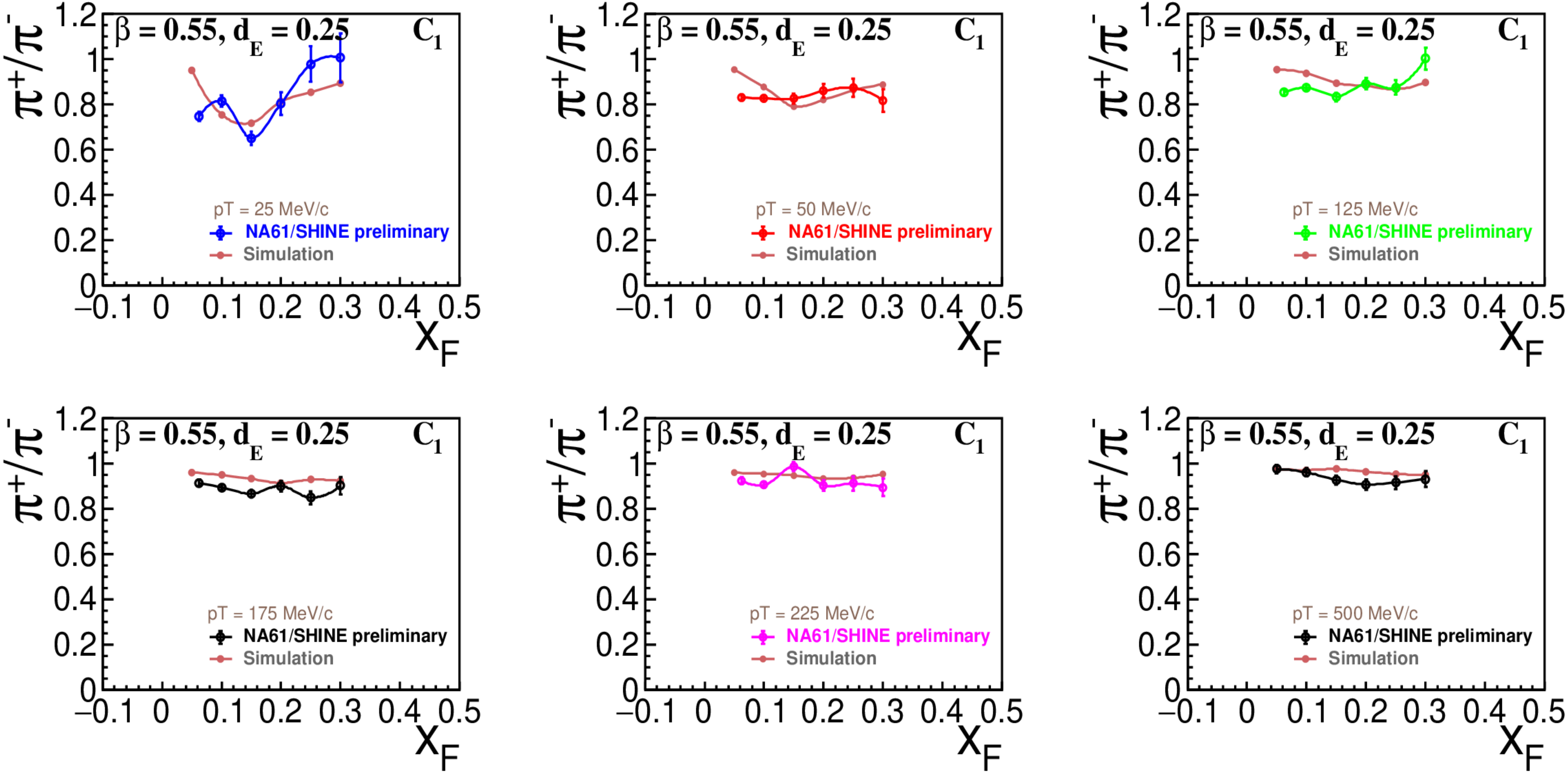


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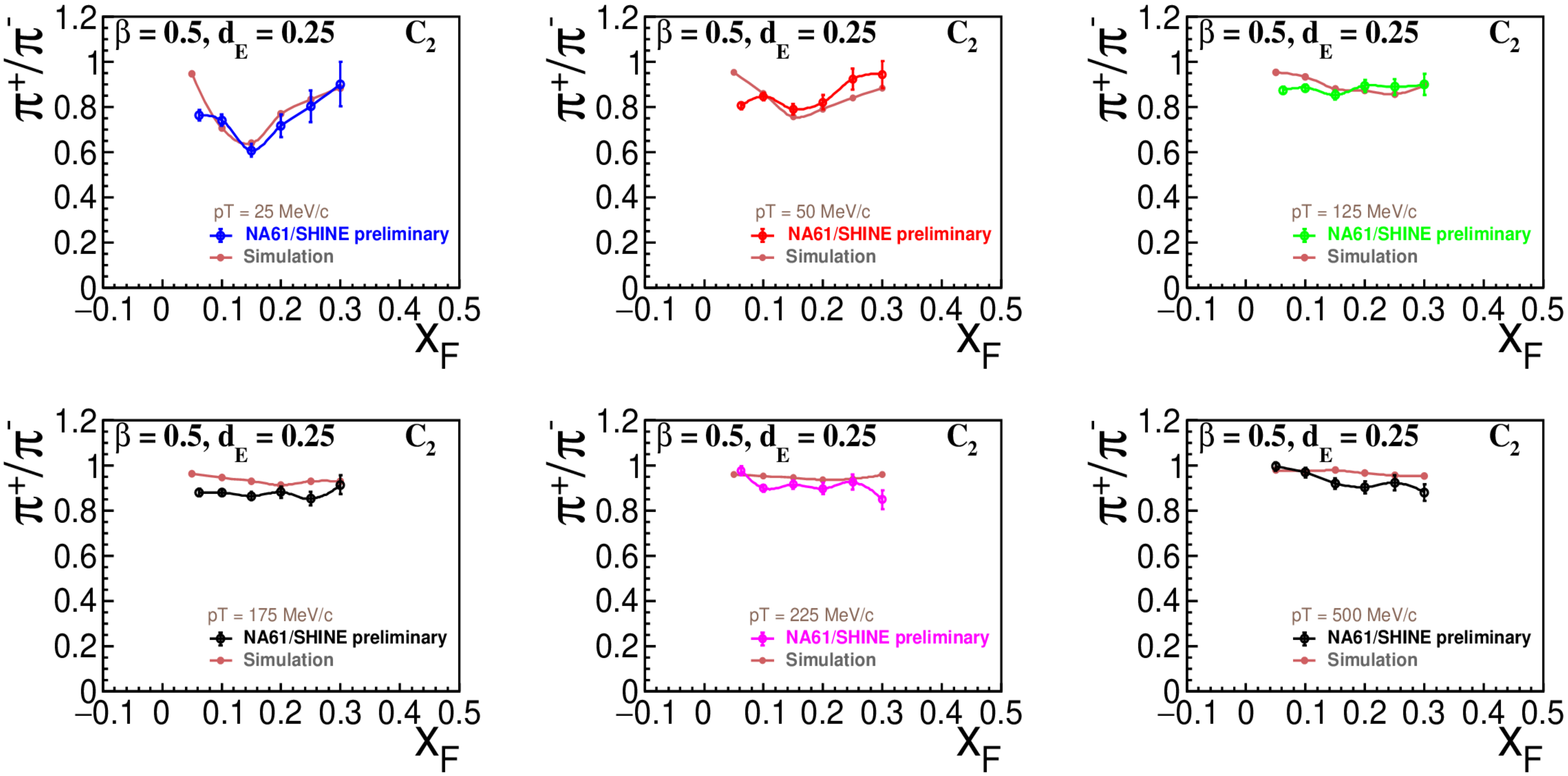


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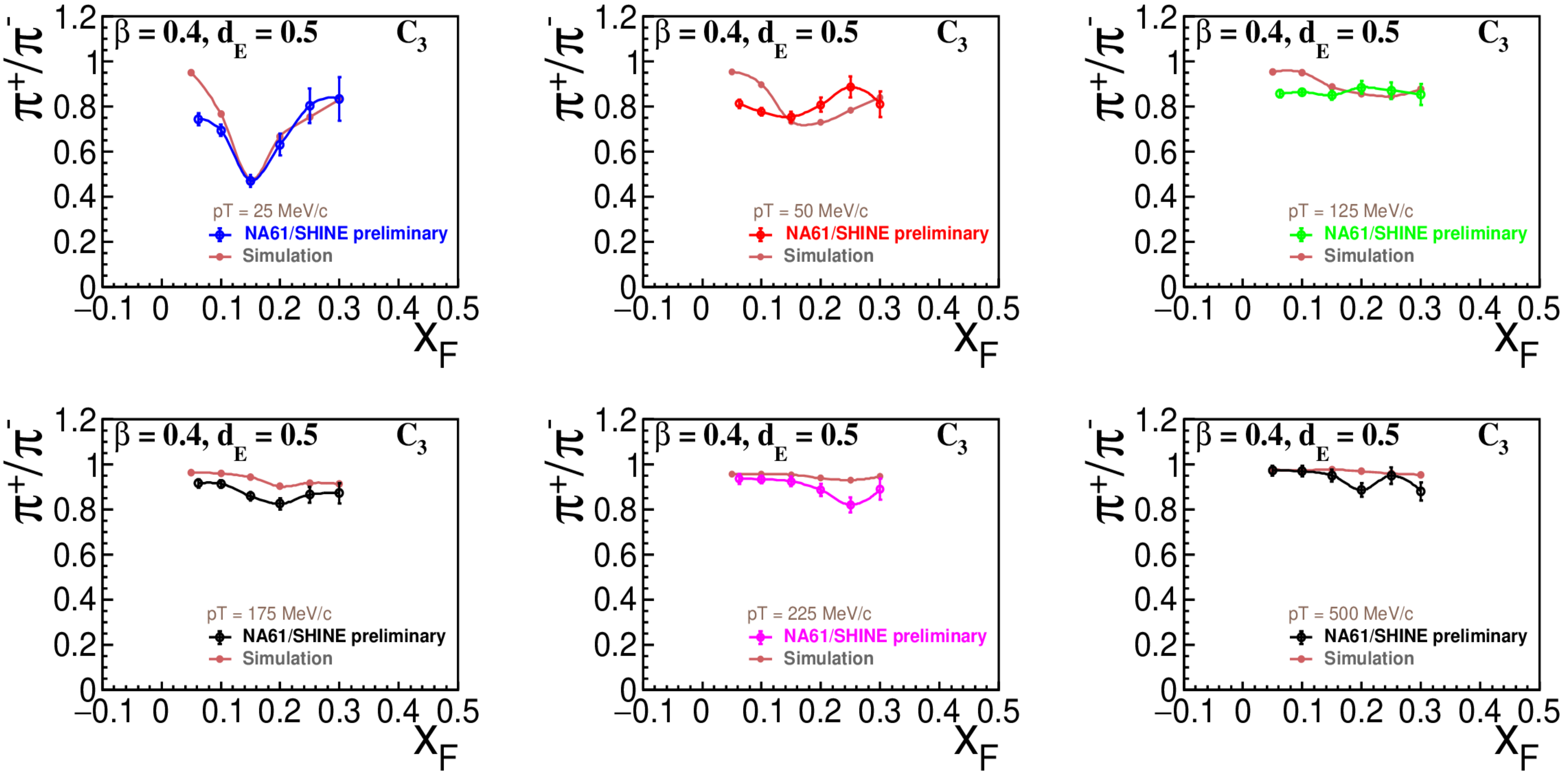


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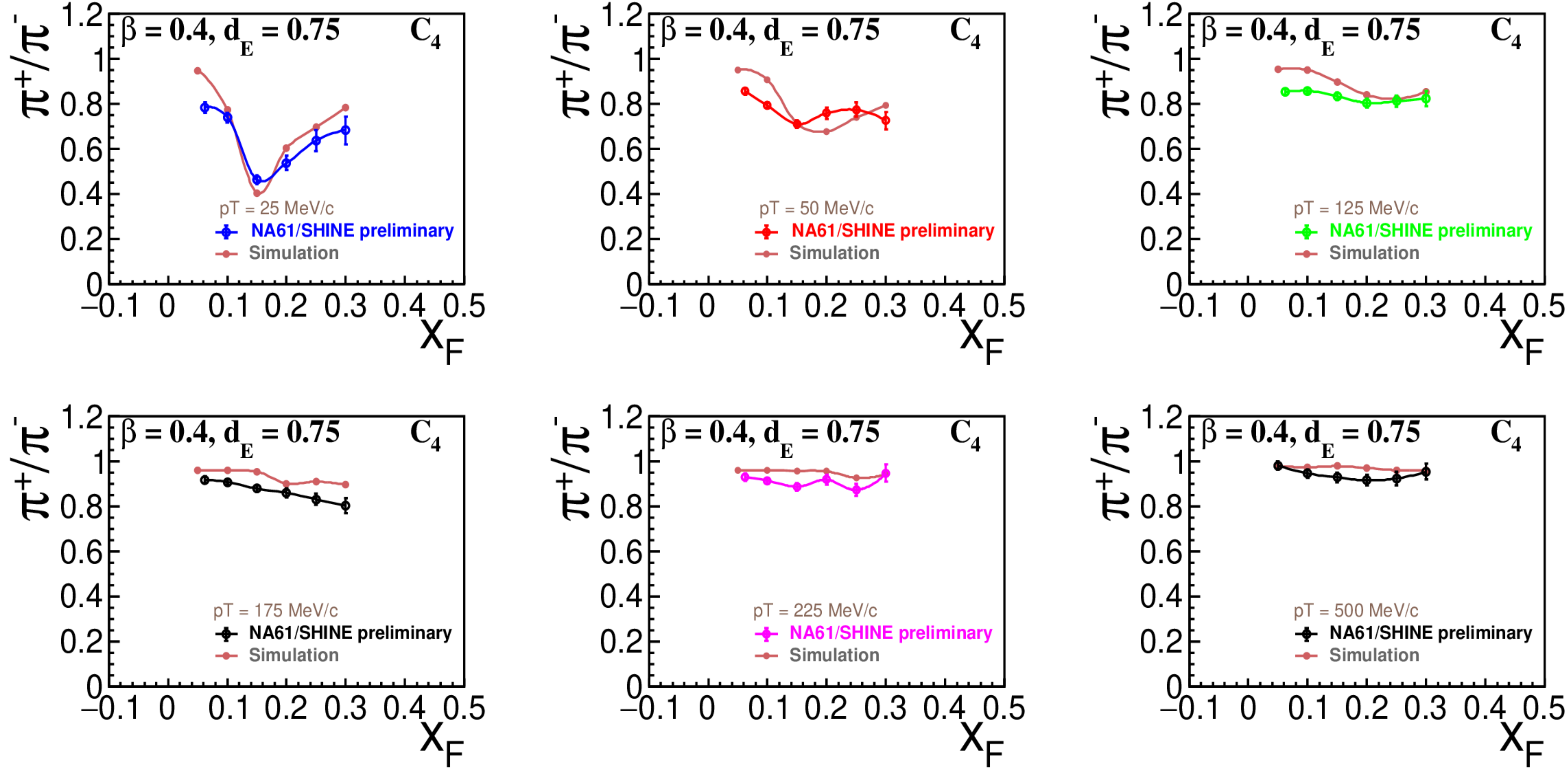


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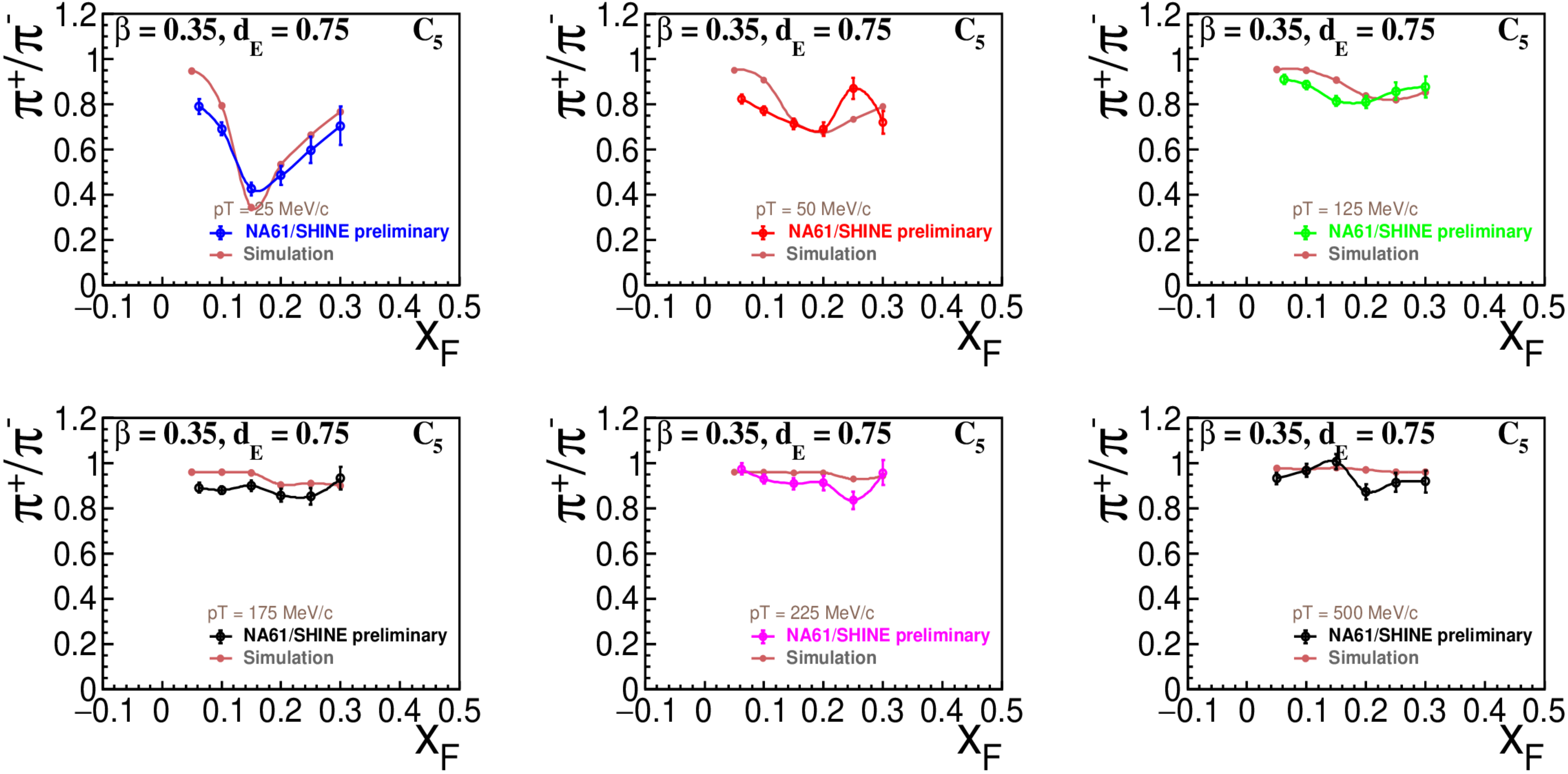


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