Charged hadron production in nucleus-nucleus collisions from NA61/SHINE at the CERN SPS

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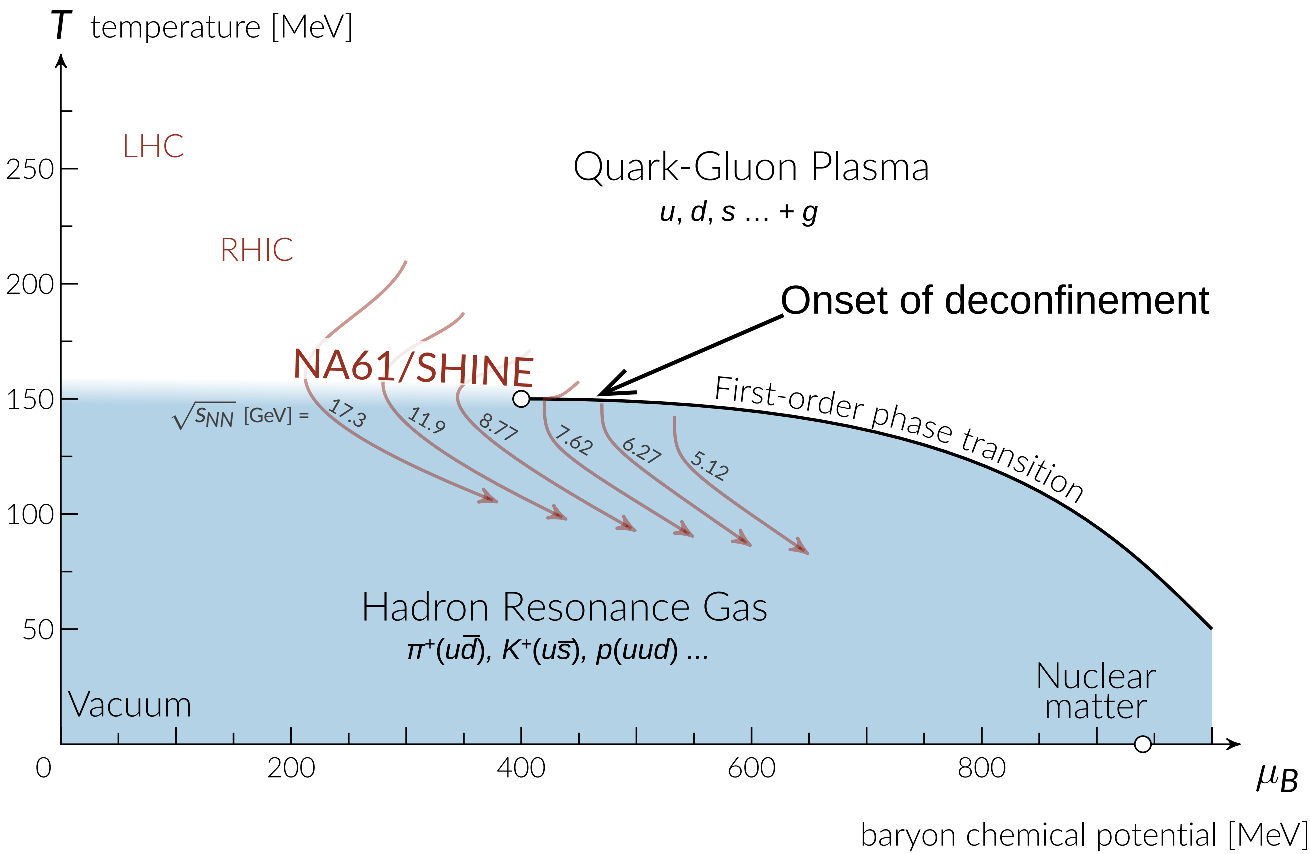
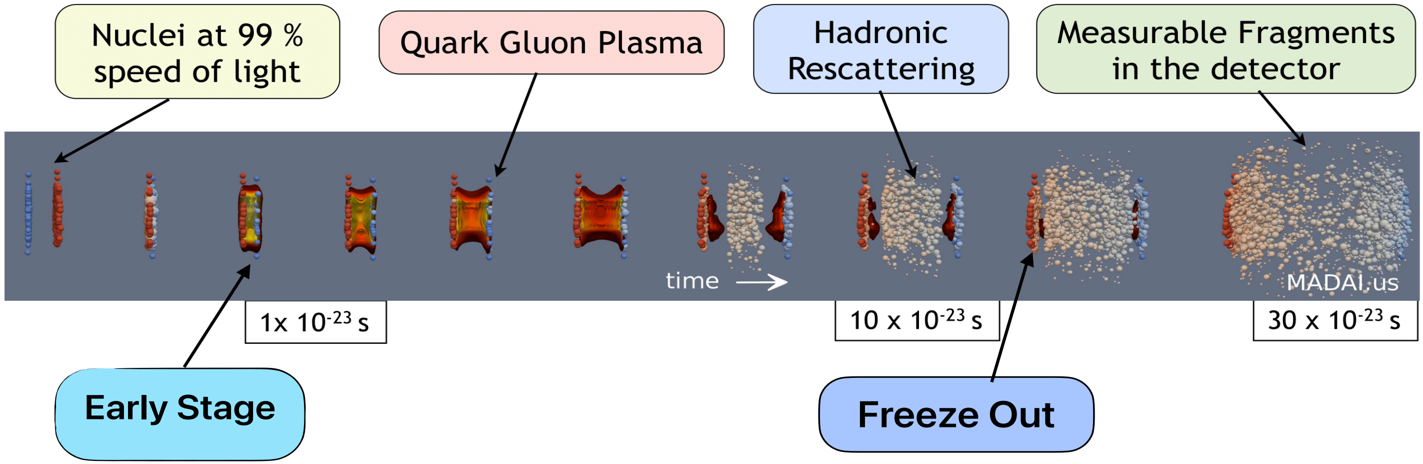
NO2 division seminar

May 18, 2026

Phase diagram of strongly interacting matter

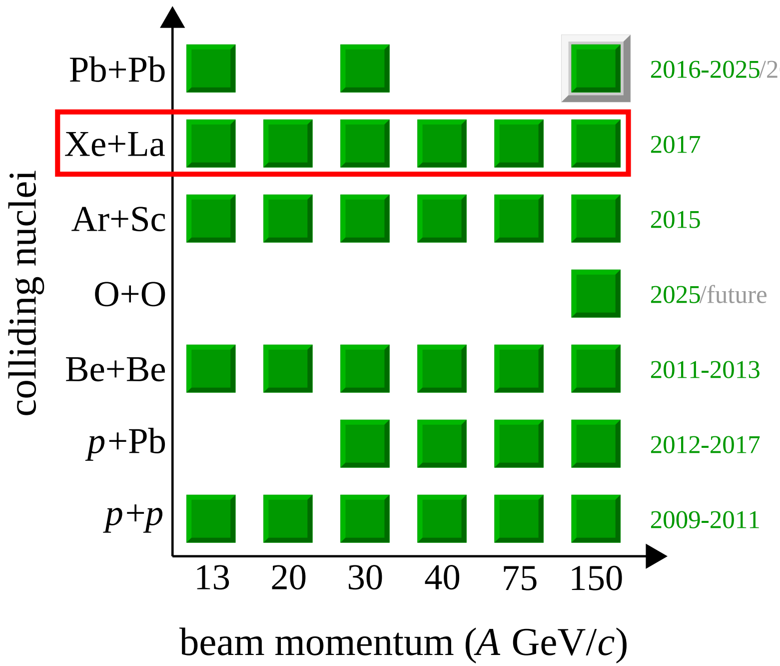


Heavy-ion collisions and QGP



NA61/SHINE physics program on strong interactions

- **Study of the properties of the onset of deconfinement**,
- search for the critical point of strongly interacting matter (Nikolaos Davis),
- direct measurement of open charm,
- study of violation of isospin symmetry in the kaonic sector of multiparticle production.

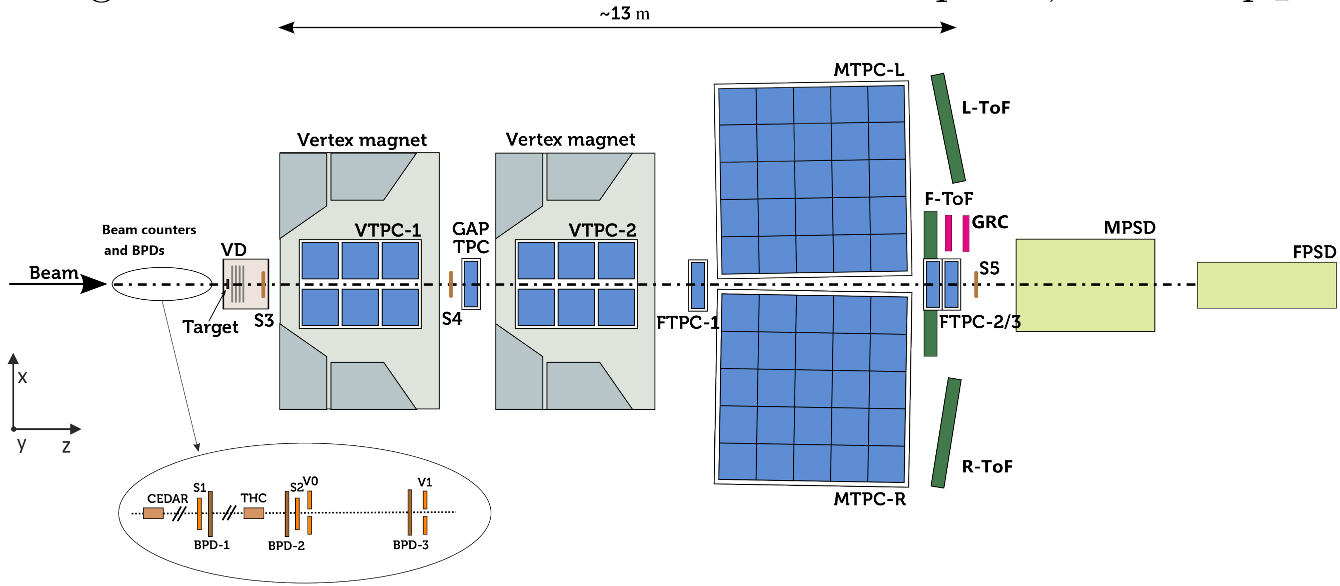


p_{beam} (GeV/c)	13A	19A	30A	40A	75A	150A
$\sqrt{s_{\text{NN}}}$ (GeV)	5.12	6.12	7.62	8.77	11.9	16.8

NA61/SHINE detector

Fixed-target experiment located at CERN SPS.

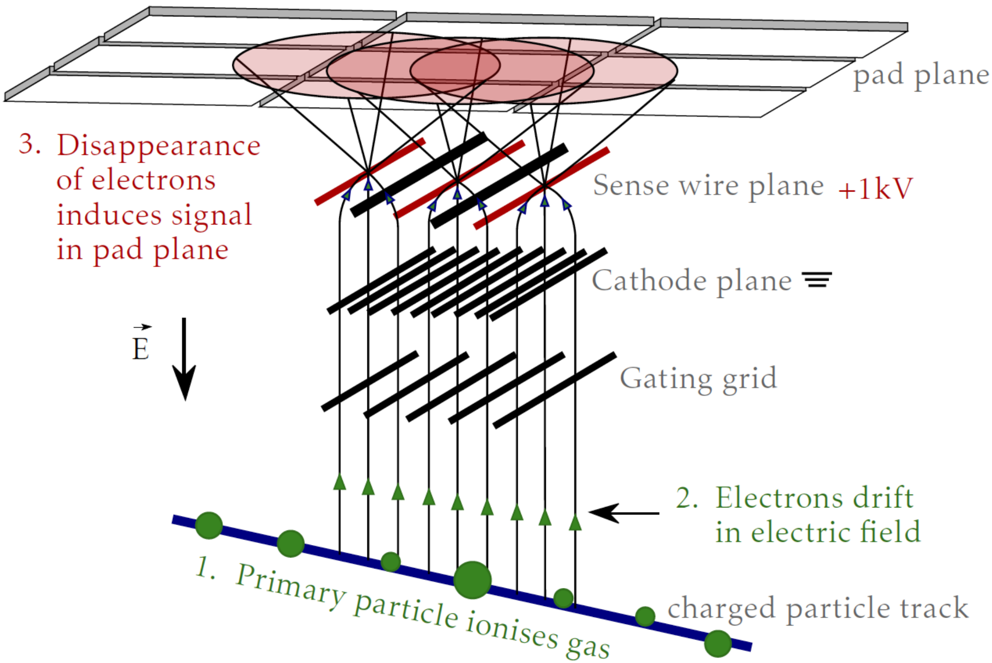
Coverage of the full forward center-of-mass hemisphere, down to $p_T = 0$.



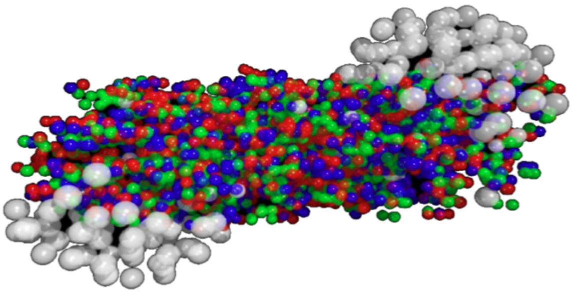
Beams:

- Ions (Be, O, Ar, Xe, Pb):
  $p_{\text{beam}} = 13A - 150A$ GeV$/c$, $\sqrt{s_{\text{NN}}} = 5.1 - 16.8$ GeV.
- Hadrons (π, K, p):
  $p_{\text{beam}} = 13 - 400$ GeV$/c$, $\sqrt{s_{\text{NN}}} = 5.1 - 27.4$ GeV.

How does TPC work?



Centrality selection



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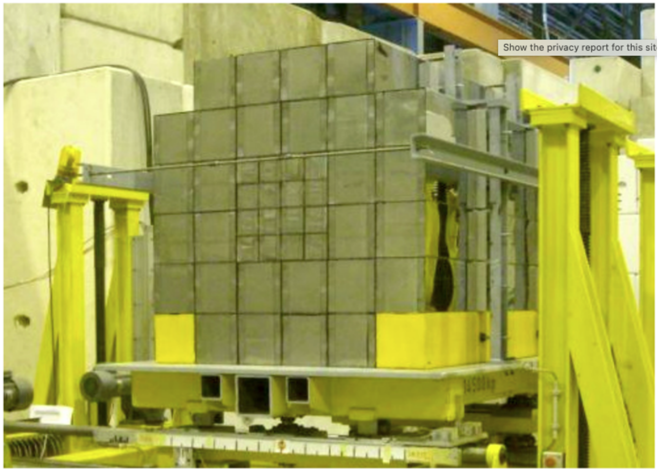
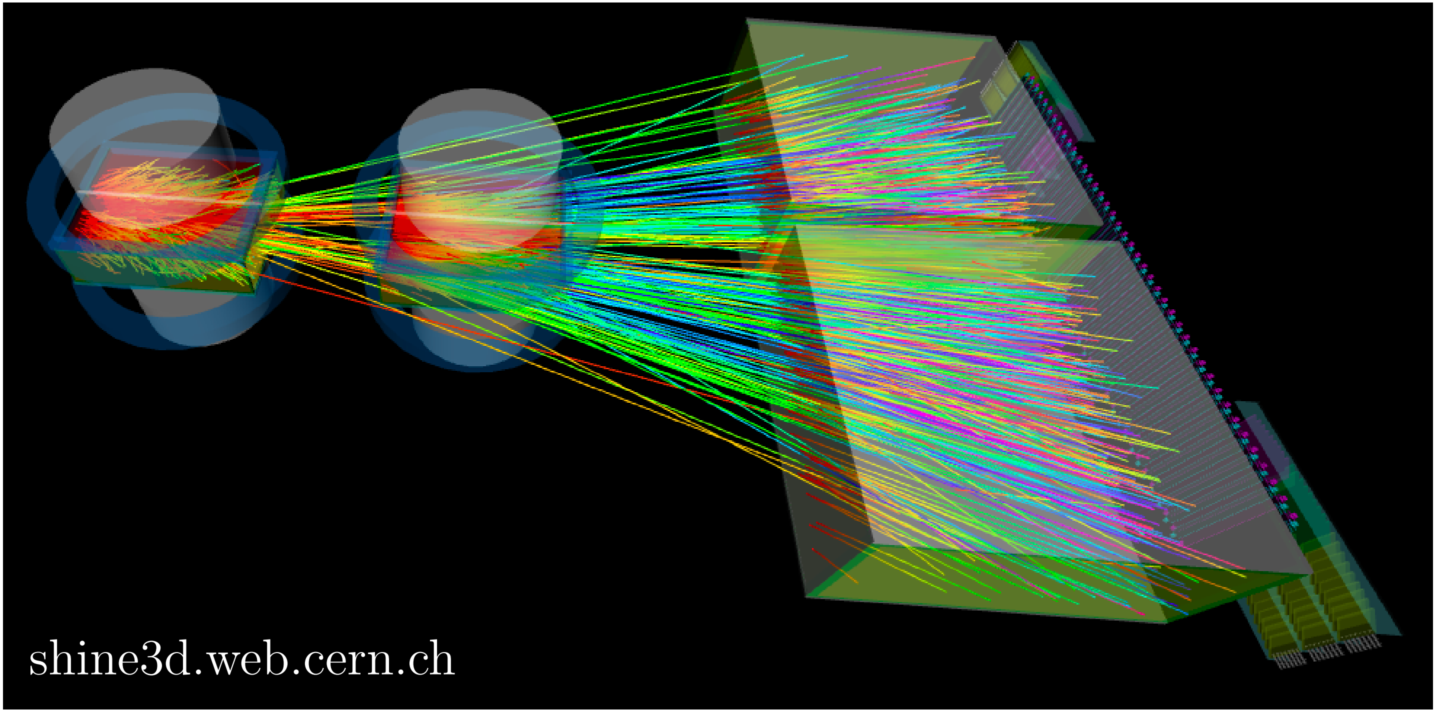


Centrality selection is based on the projectile spectator energy E_{F} measured by the Projectile Spectator Detector (PSD).

^{129}Xe + ^{139}La collision at 150A GeV/c



For each track, electric charge(q), momentum($\vec{p}$), and specific energy loss (dE/dx) are measured, which allows us to obtain the mass of the particle (particle identification – PID).

Methods of charged particle identification

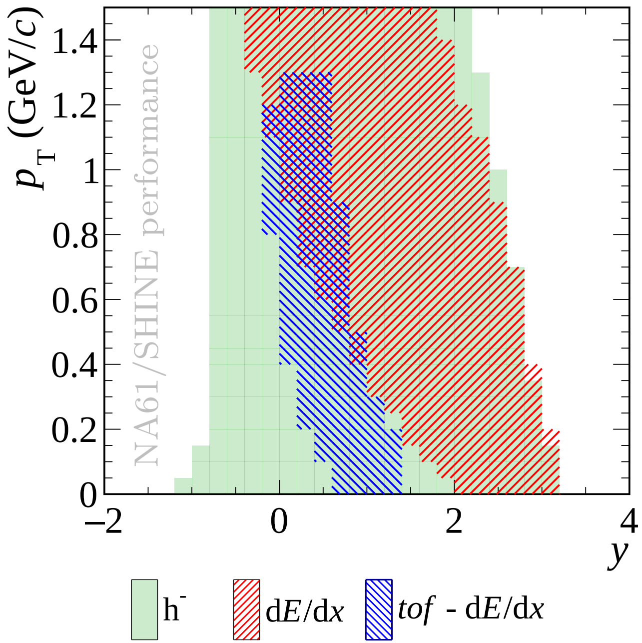
For charged hadrons:

- $\mathrm{d}E/\mathrm{d}x$:
  - ▶ based on ionization energy loss in TPCs,
  - ▶ $p_{\mathrm{lab}} \gtrsim 5$ GeV/c.
- $tof - \mathrm{d}E/\mathrm{d}x$:
  - ▶ based on the ionization energy loss + time of flight,
  - ▶ $1\ \mathrm{GeV}/c \lesssim p_{\mathrm{lab}} \lesssim 10\ \mathrm{GeV}/c$.

Additionally, the h^- method for π^-:

- ▶ $\approx 90\%$ of h^- are π^-,
- ▶ π^- are estimated from h^- using MC correction,
- ▶ the largest acceptance.

π^- at 40A GeV/c (Xe+La)

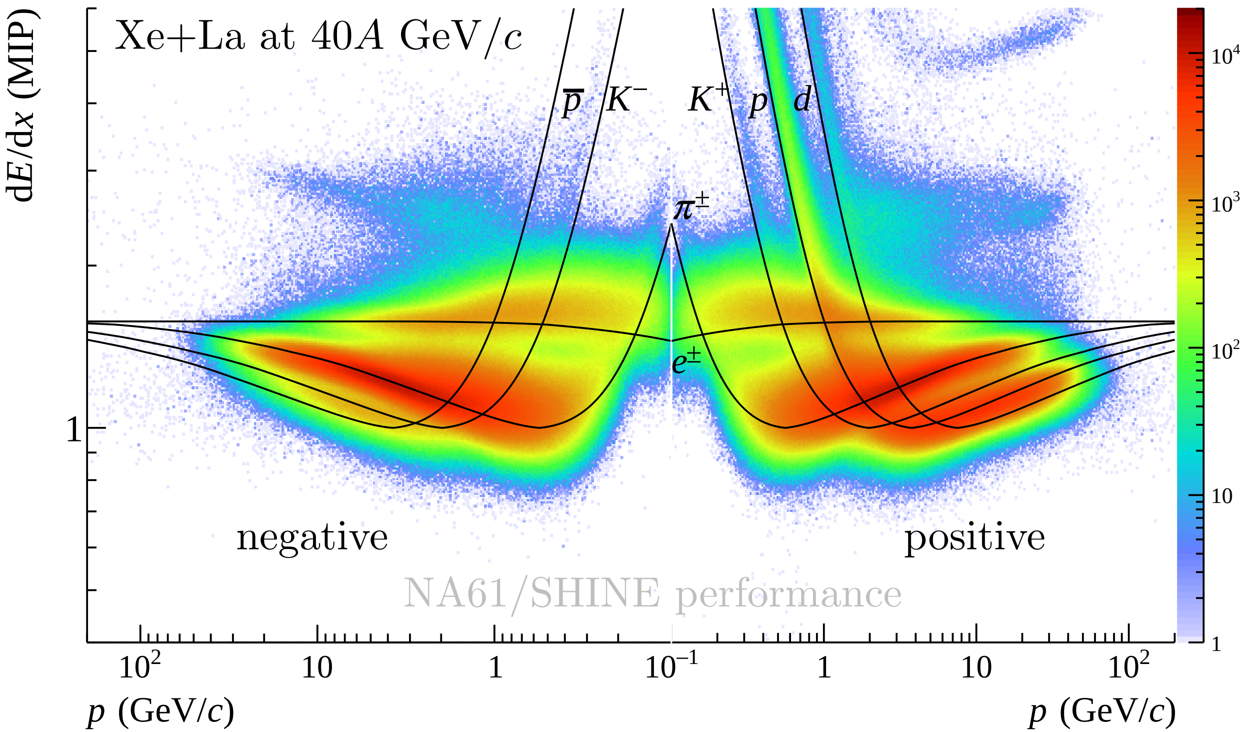


$y = \mathrm{arctanh}\frac{p_z}{E}$ – rapidity,

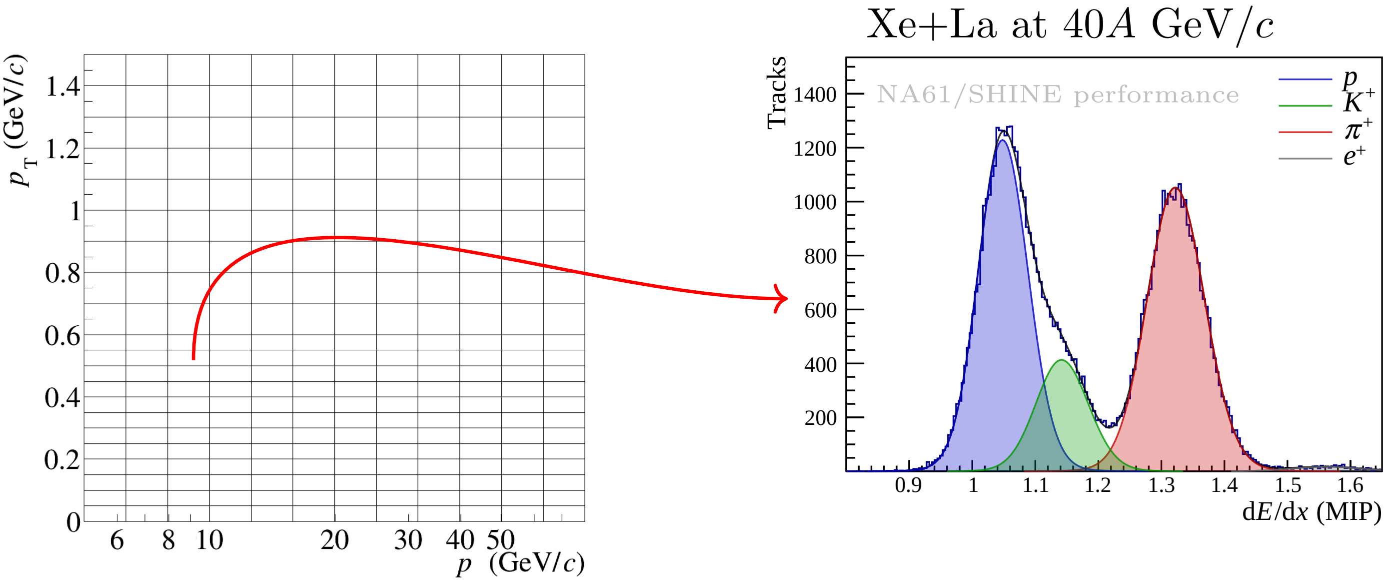
$p_{\mathrm{T}} = \sqrt{p_x^2 + p_y^2}$ – transverse momentum.

dE/dx method

Bethe-Bloch: $\left\langle -\frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = \frac{A}{\beta^2}\left[\ln B\beta^2\gamma^2 - 2\beta^2 - \delta(\beta\gamma)\right]$, $(0.1 \lesssim \beta\gamma \leq 1000)$.



dE/dx method

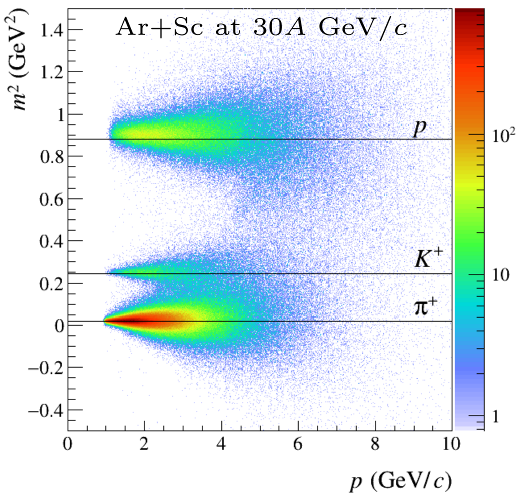


Fit with a dedicated function, which contains the precise knowledge of the detector response to the ionizing particle:

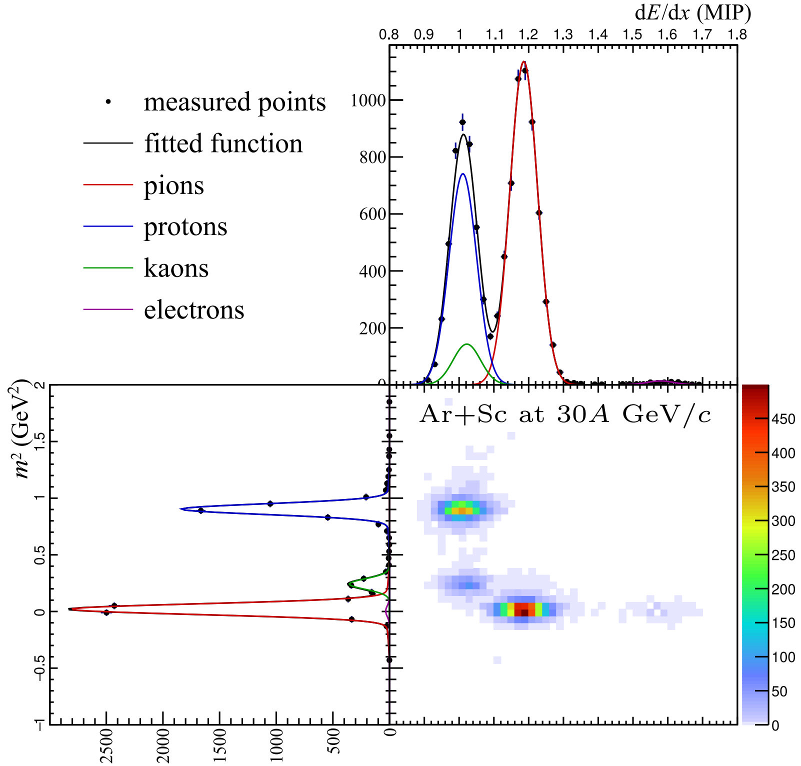
$$f\left(\mathrm{d}E/\mathrm{d}x\right) = \sum_{i=p,K,\pi,e,d} N_i \frac{1}{\sum_l n_l} \sum_l \frac{n_l}{\sqrt{2\pi}\sigma_{i,l}} \exp\left[-\frac{1}{2}\left(\frac{\mathrm{d}E/\mathrm{d}x - \langle \mathrm{d}E/\mathrm{d}x\rangle_i}{(1\pm\delta)\sigma_{i,l}}\right)^2\right].$$

$tof - \mathrm{d}E/\mathrm{d}x$ method

Based on $\mathrm{d}E/\mathrm{d}x$ and m^2 measurements.

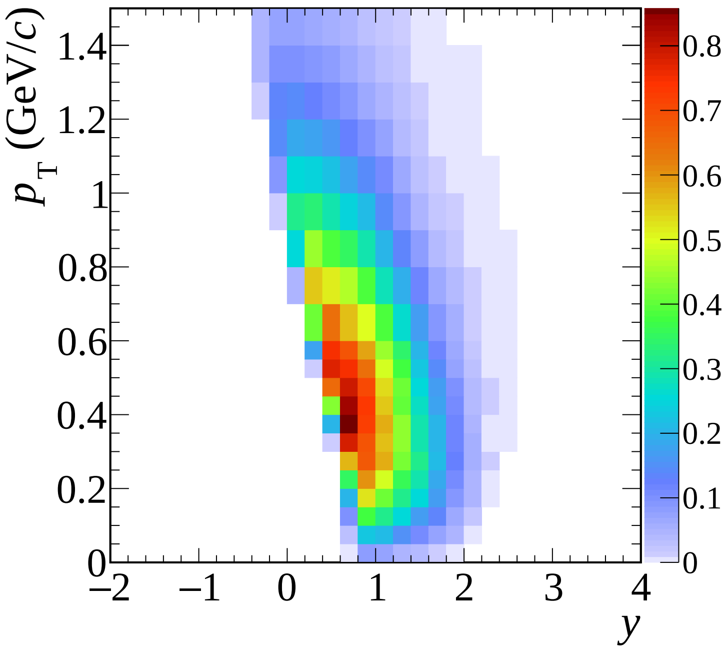


$$m^2 = p^2 \cdot \left[\frac{c^2 \cdot (tof)^2}{l^2} - 1 \right] .$$



NA61/SHINE: EPJC 84 (2024) 416

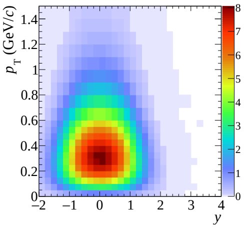
Raw $d^2n/dydp_T$ spectrum of K^- at 40A GeV/c



- Distribution is scaled by $1/(N_{\text{events}}\Delta y \Delta p_T)$.
- Spectrum is plotted in the center of mass system.
- $y = \text{arctanh}\frac{p_z}{E}$ – rapidity.
- $p_T = \sqrt{p_x^2 + p_y^2}$ – transverse momentum.

From raw to corrected data

K^- MC generated



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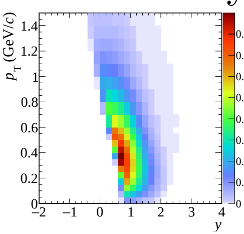
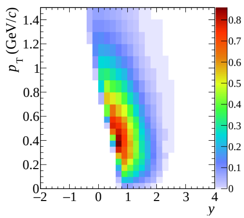
K^- MC sel not sec decay



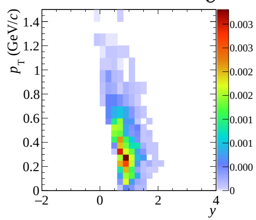
$\times$ (

K^- raw spectrum



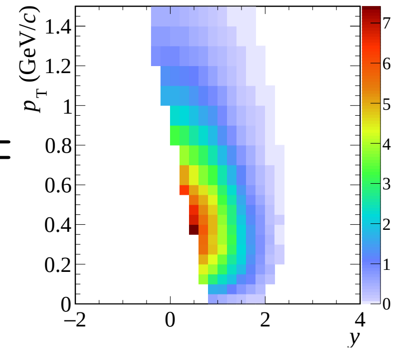
$-$

K^- MC sel sec decay



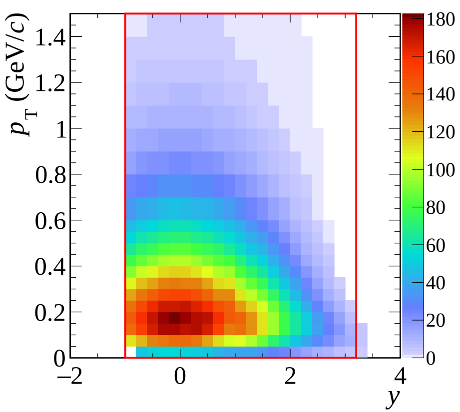
) $=$

K^- corrected spectrum



K^- MC sel sec decay – secondary K^- created in weak decays (tuned to data)

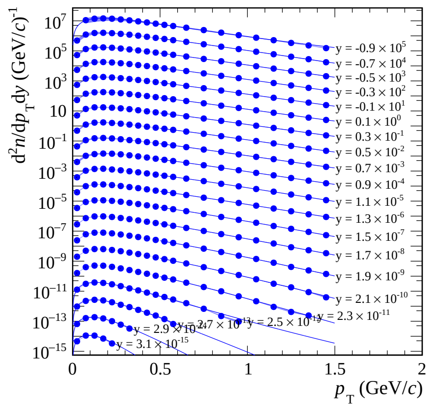
From 2D spectra to 1D spectra and mean multiplicities



Slicing

$\longrightarrow$

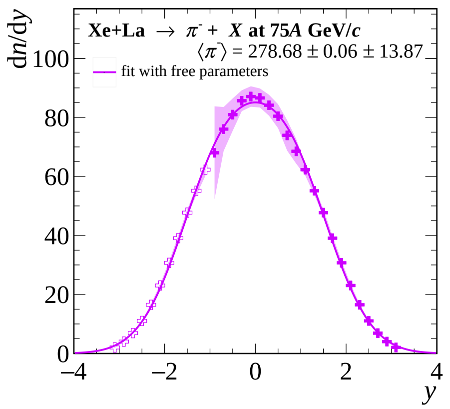
in y



Extrapolation

$\longrightarrow$

in p_T



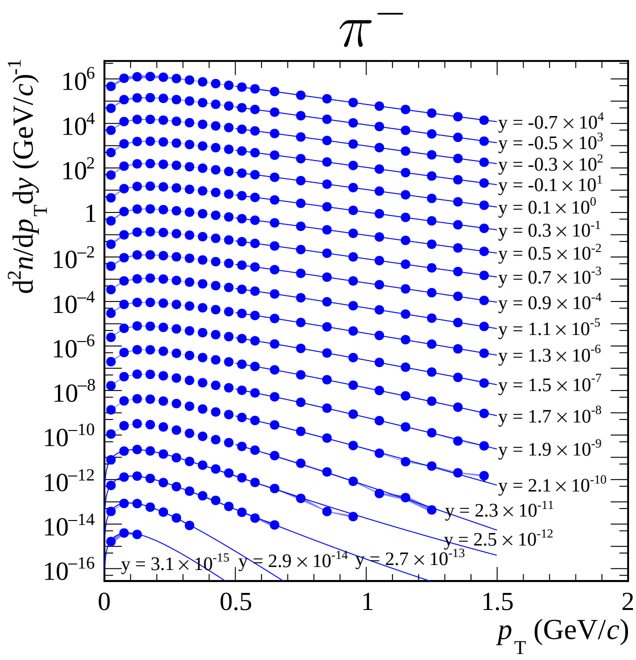
Extrapolation

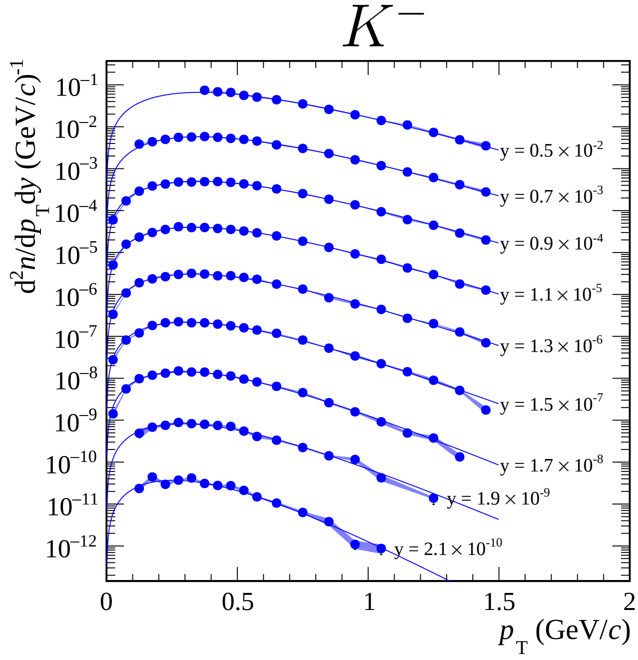
$\longrightarrow$

in y

$$\langle n \rangle$$

p_T distributions of π^- from h^- and K^- at 40A GeV/c

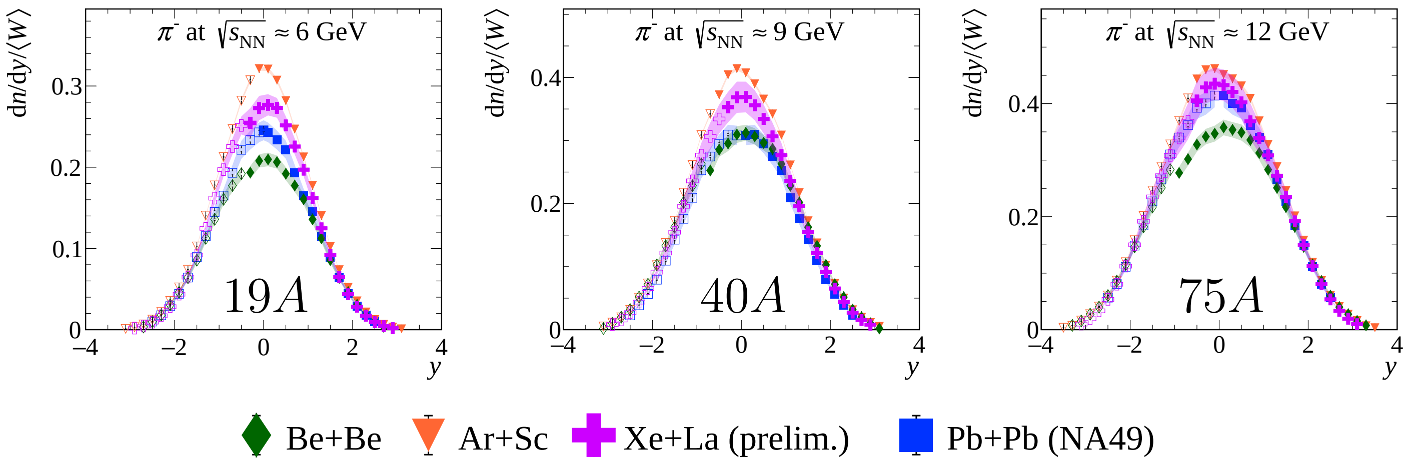




Coverage of full forward hemisphere for π^-.

Rapidity spectra of π^-

- Spectra are scaled by mean number of wounded nucleons ($\langle W \rangle^*$).
- Open points are reflected measured data points.



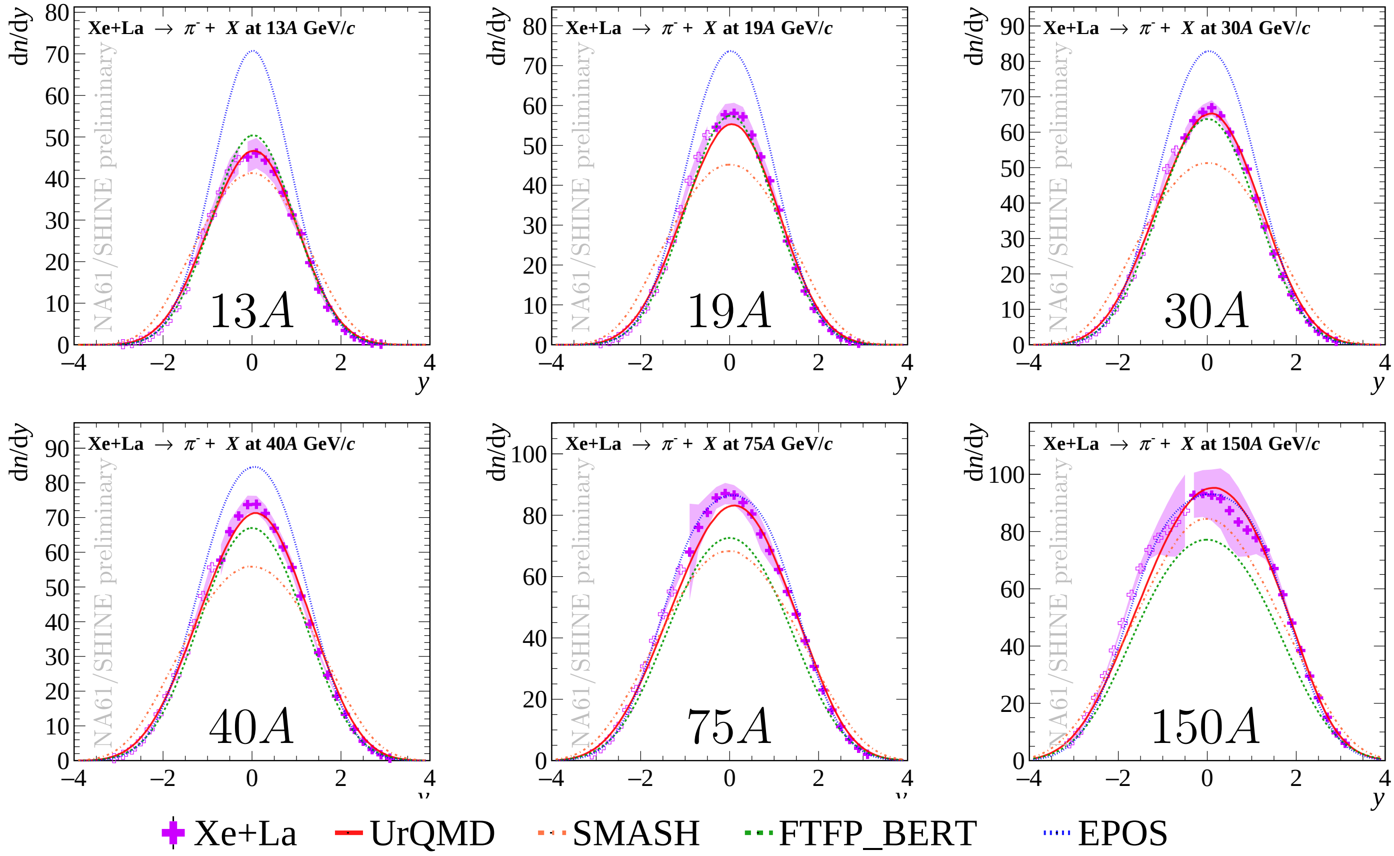
- Non-monotonic dependence of the $\mathrm{d}n/\mathrm{d}y/\langle W \rangle$ at $y \approx 0$ on the system size.

*For Be+Be and Ar+Sc, $\langle W \rangle$ estimated using EPOS; for Xe+La using `web-docs.gsi.de/~misko/overlap`; systematic uncertainty of $\langle W \rangle$ is not included.

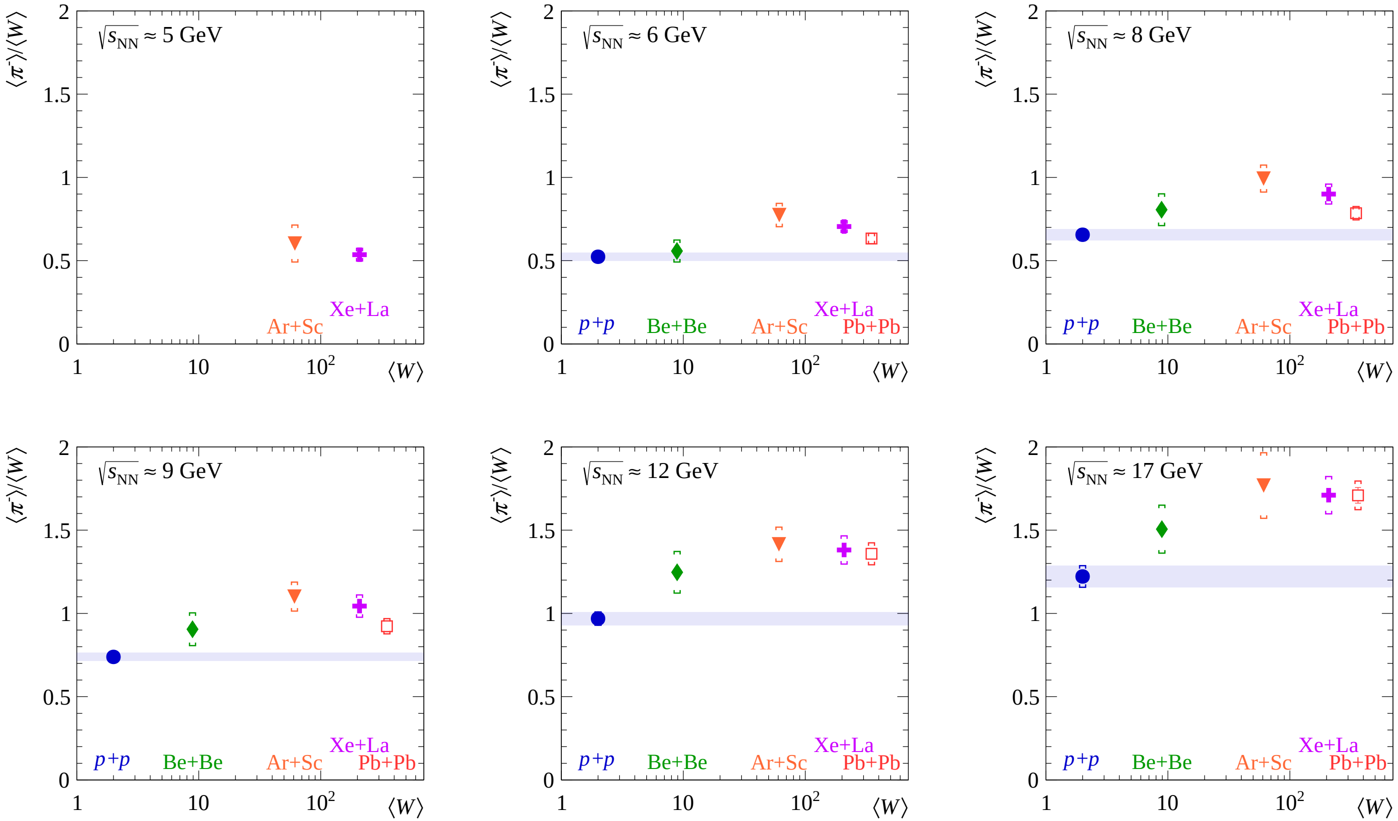
NA61/SHINE: EPJC 80 (2020) 961, EPJC 81 (2021) 397
NA49: PRC 66 (2002) 054902, PRC 77 (2008) 024903

Rapidity spectra of π^- in Xe+La collisions

Models' predictions



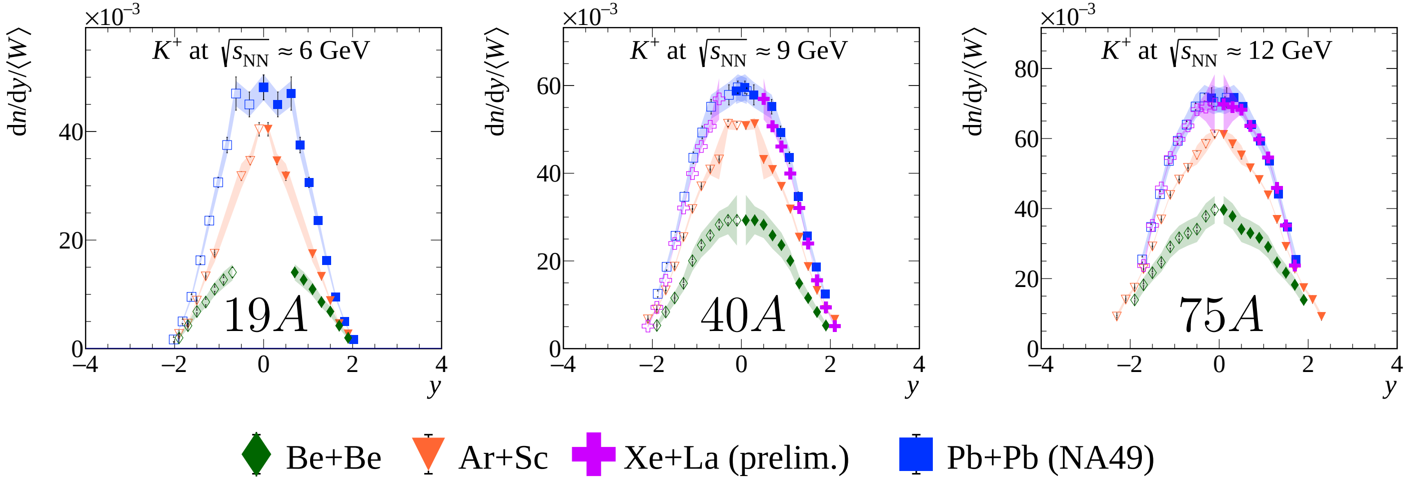
$\langle \pi^- \rangle / \langle W \rangle$ as function of system size



- Non-monotonic dependence of the $\langle \pi^- \rangle / \langle W \rangle$ on the system size.

Rapidity spectra of K^+

- Spectra are scaled by mean number of wounded nucleons ($\langle W \rangle$).
- Open points are reflected measured data points.



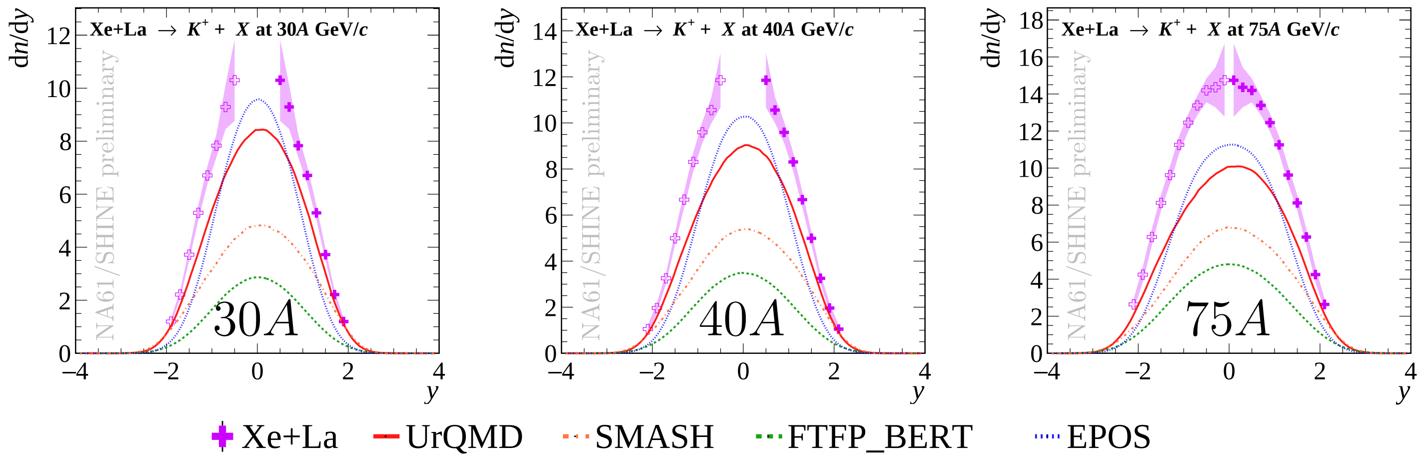
- Monotonic dependence of the $\mathrm{d}n/\mathrm{d}y/\langle W \rangle$ at $y \approx 0$ on the system size:

$$\text{Be+Be} \ll \text{Ar+Sc} < \text{Xe+La} \lesssim \text{Pb+Pb}.$$

NA61/SHINE: EPJC 81 (2021) 73, EPJC 84 (2024) 416
NA49: PRC 66 (2002) 054902, PRC 77 (2008) 024903

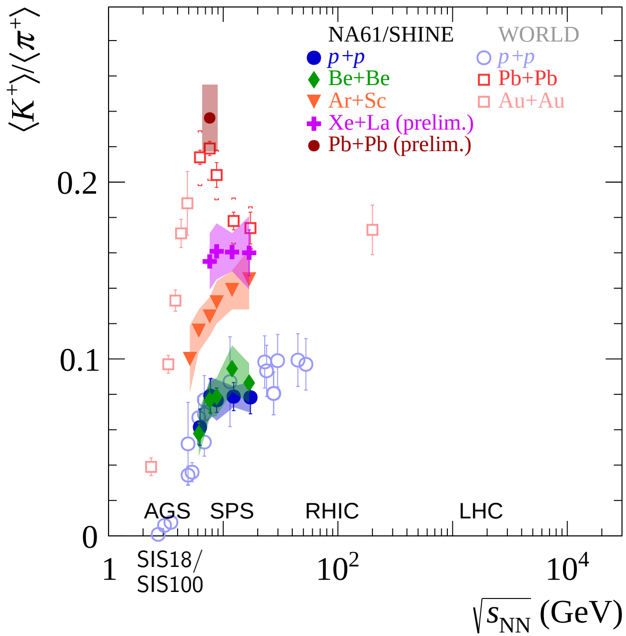
Rapidity spectra of K^+ in Xe+La collisions

Models' predictions



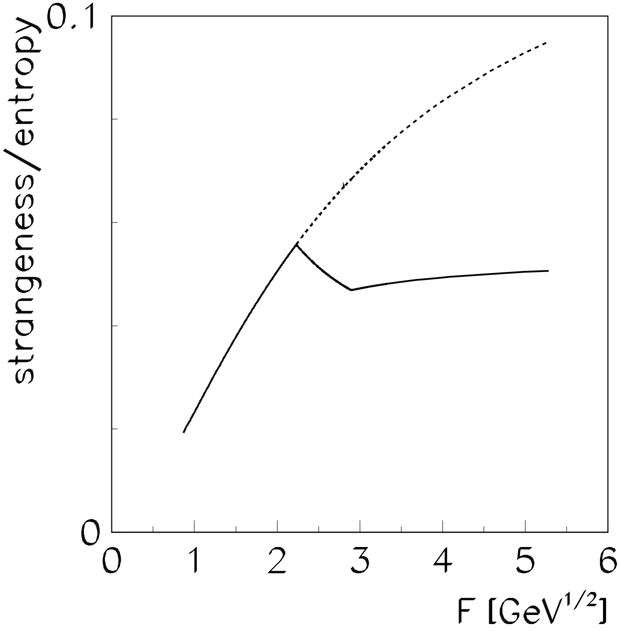
All models underestimate strangeness production.

Horn – $\langle K^+\rangle/\langle\pi^+\rangle$ as function of collision energy



- $\langle K^+\rangle/\langle\pi^+\rangle$ as a function of $\sqrt{s_{\mathrm{NN}}}$ has maximum ("horn") for heavy systems – Au+Au and Pb+Pb.

Horn – $\langle K^+\rangle/\langle\pi^+\rangle$ as function of collision energy



- Hadron gas:

$$\frac{\text{stangeness}}{\text{entropy}} \sim \frac{(M_K T)^{\frac{3}{2}}}{T^3} \exp^{-\frac{M_K}{T}}$$

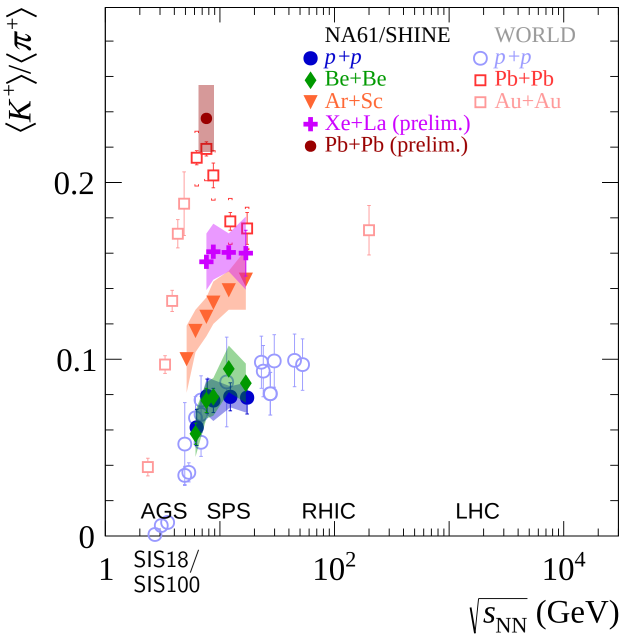
- Quark-gluon plasma:

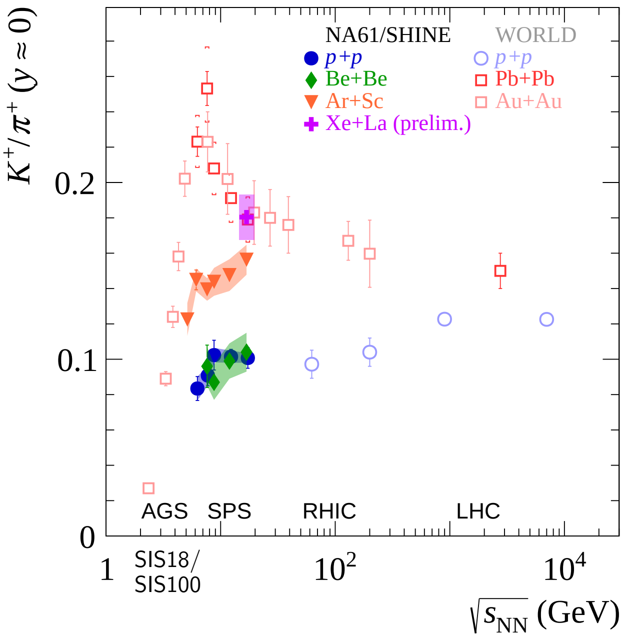
$$\frac{\text{stangeness}}{\text{entropy}} \sim \frac{T^3}{T^3} = \text{const}(T)$$

- $$\frac{\text{stangeness}}{\text{entropy}} \sim \frac{\langle K^+\rangle}{\langle\pi^+\rangle}$$

Gazdzicki, Gorenstein, Acta Phys. Pol. B 30, 2705 (1999)

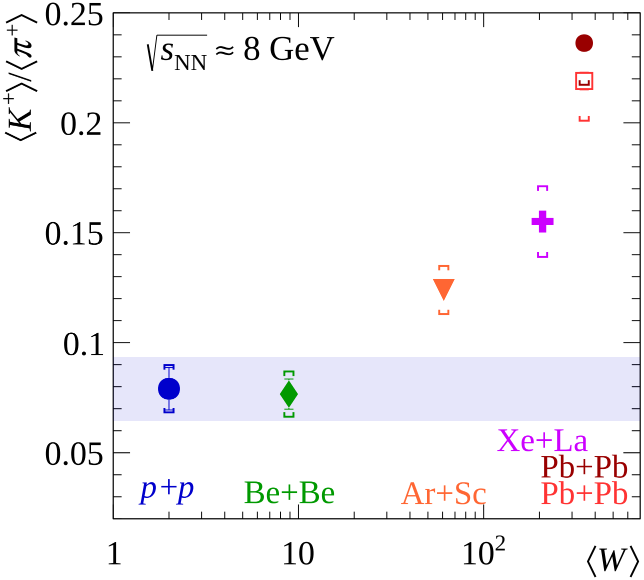
Horn: $\langle K^+\rangle/\langle\pi^+\rangle$ and $K^+/\pi^+{}_{(y\approx0)}$ as function of $\sqrt{s_{NN}}$

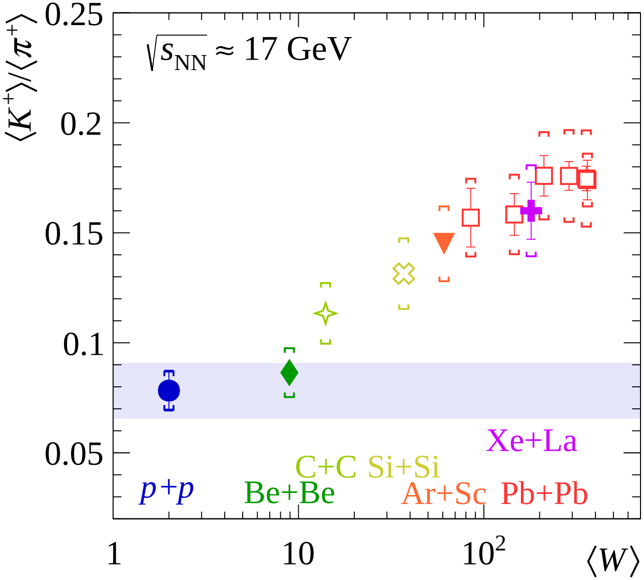




- Xe+La closely resembles Pb+Pb at the top SPS energies.
- Difference between light ($p + p$ and Be+Be) and heavy (Ar+Sc, Xe+La, Pb+Pb) systems.

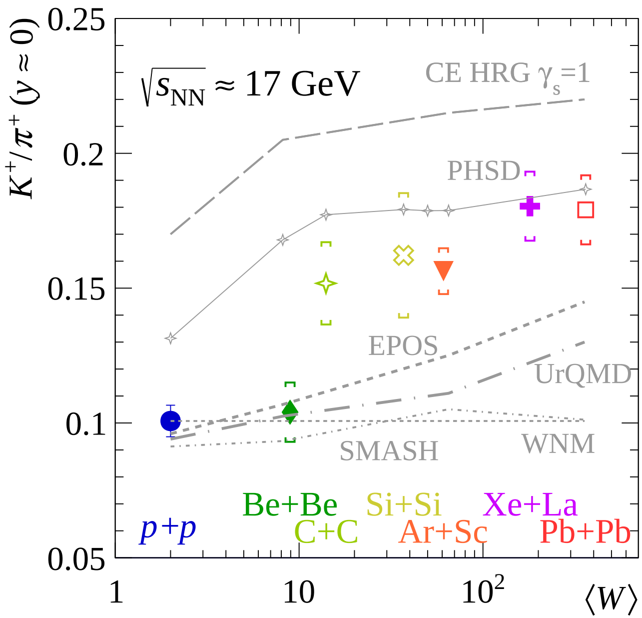
System size dependence of $\langle K^+ \rangle / \langle \pi^+ \rangle$





K^+/π^+ at $y \approx 0$ system size dependence

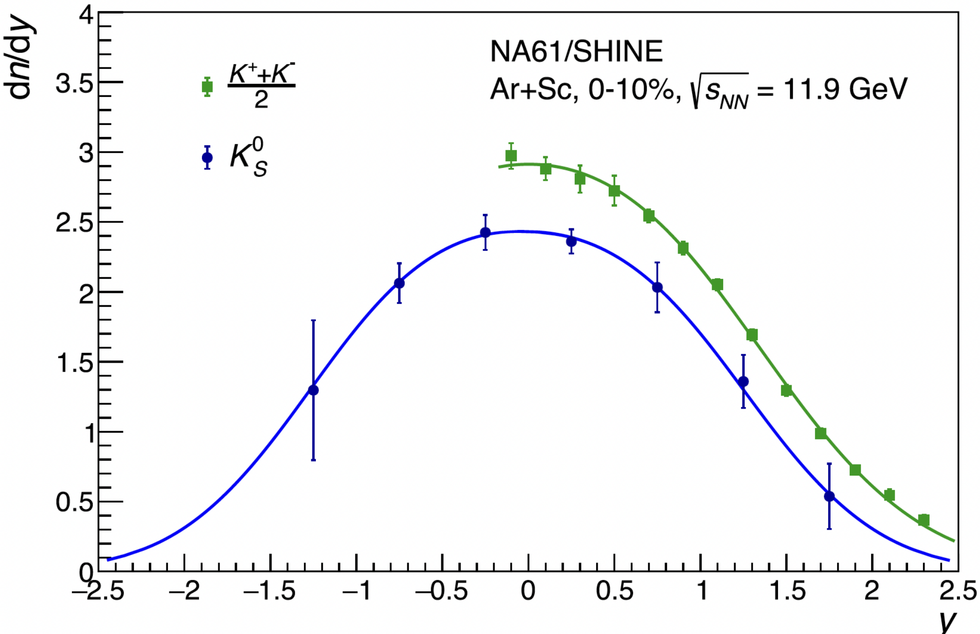
Comparison with models



- None of the models can describe data.

Large isospin symmetry violation in Ar+Sc

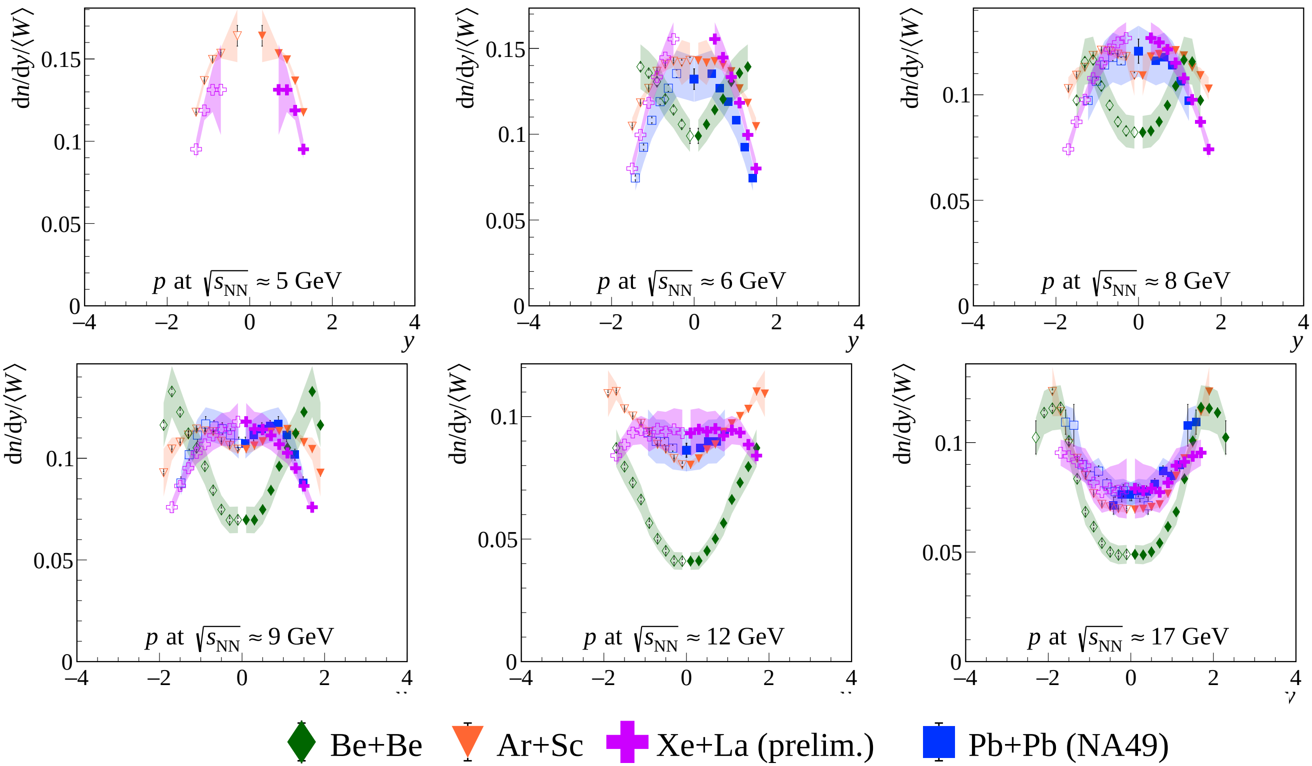
Nature Communications 16 (2025) 1, 2849
IFJ PAN Eurekalert, May 7th, 2025



- Not yet understood by known sources.
- Potentially very important for the understanding of strong interactions.
- Is there isospin symmetry violation in Xe+La?

Rapidity spectra of p

see also: M. Jeżabek *et al.* PLB816 (2021) 136200

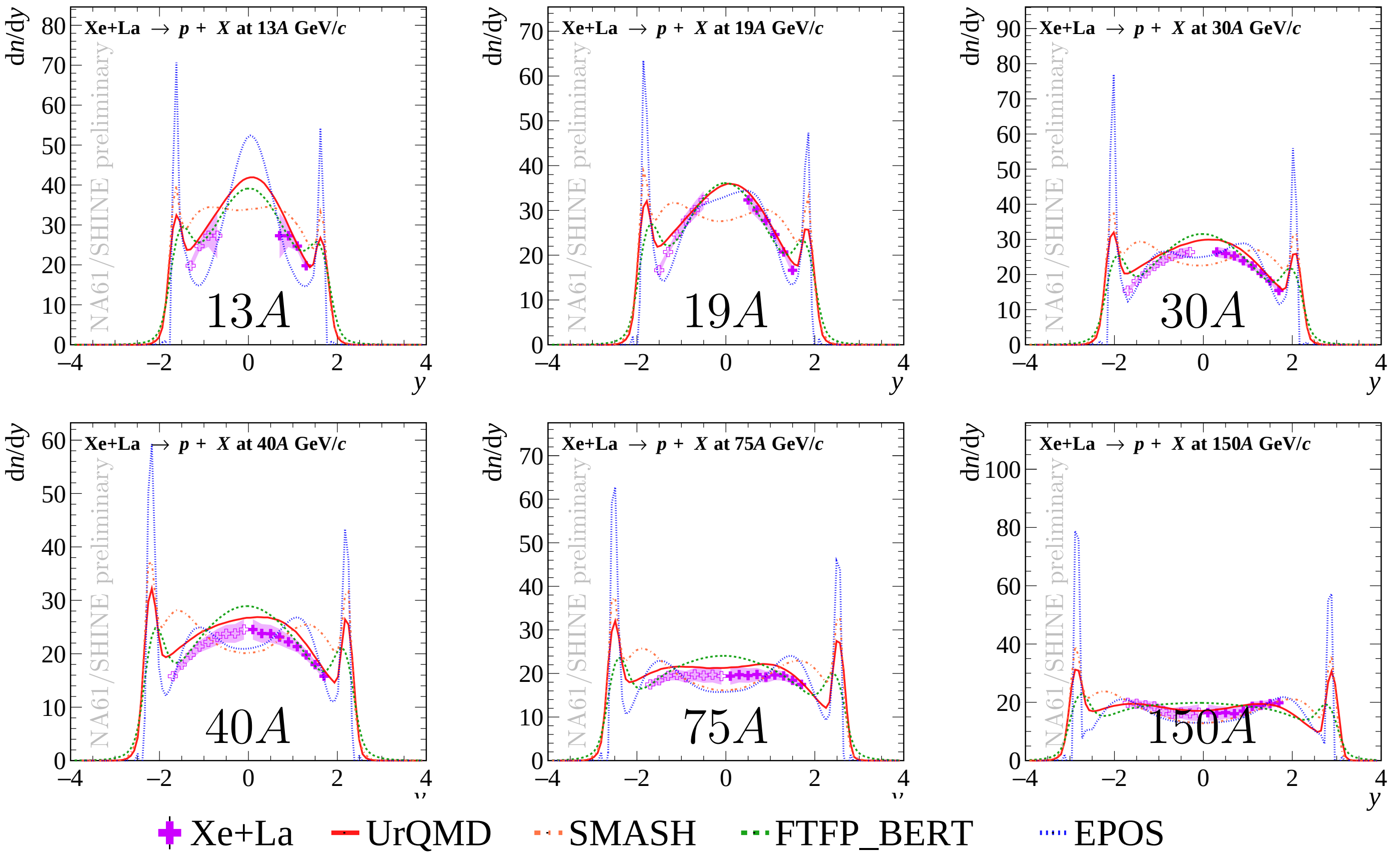


- Baryon density at $y \approx 0$ decreases with increasing energy (baryon transparency) but increases with increasing system size.

NA61/SHINE: EPJC 81 (2021) 73, EPJC 84 (2024) 416, preliminary

Rapidity spectra of p in Xe+La collisions

Models' predictions



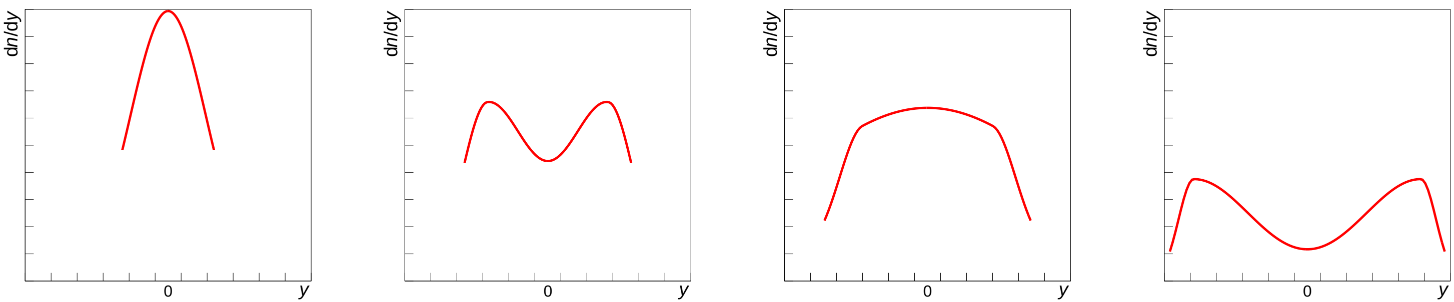
Peak-dip-peak-dip irregularity in p rapidity spectra

Reason of irregularity – onset of deconfinement!

For the EoS with a phase transition:

$\sqrt{s_{NN}}_1 < \sqrt{s_{NN}}_2 < \sqrt{s_{NN}}_3 < \sqrt{s_{NN}}_4$

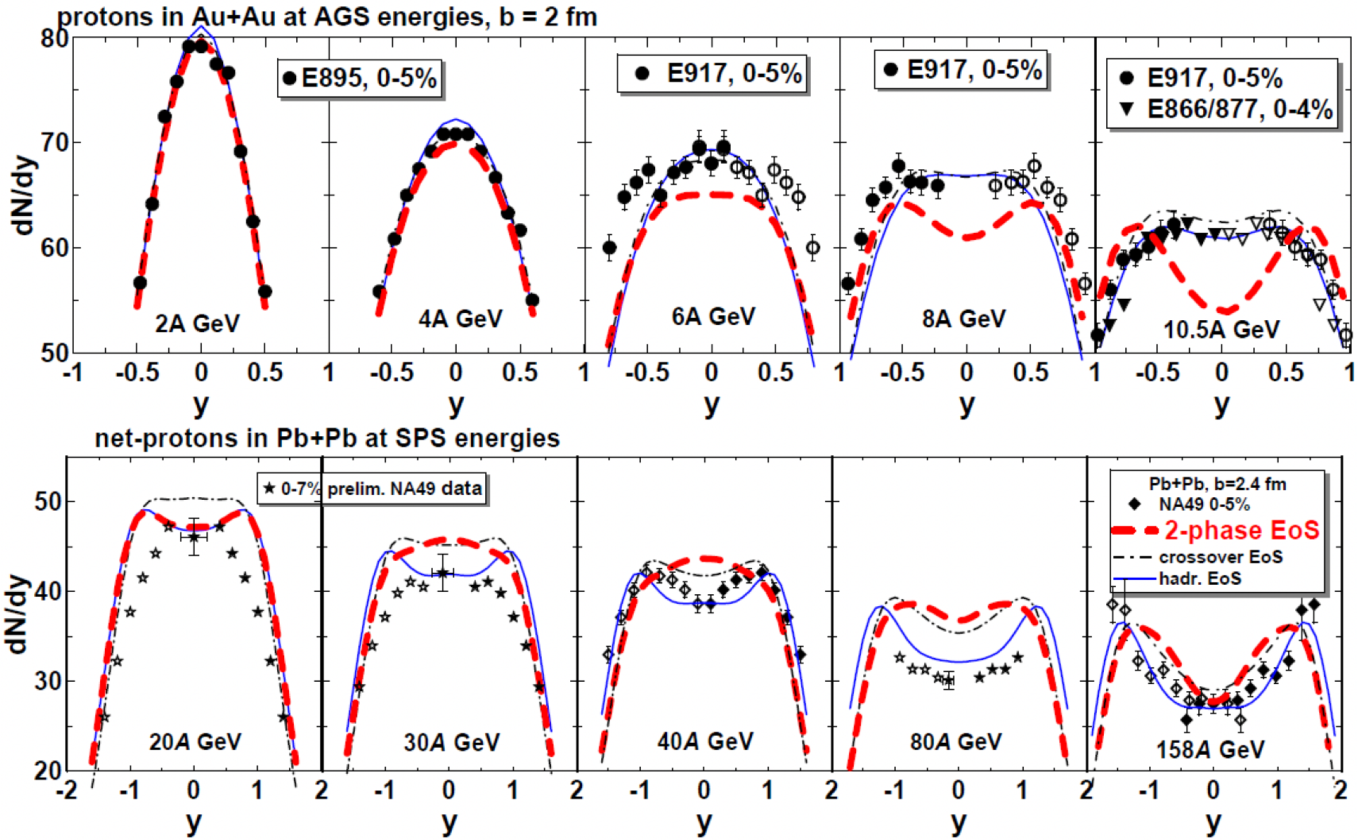
peak	dip	peak	dip



stiff EoS – spherical fireball	softest point region of the EoS – deformed fireball	stiffness of the EoS grows – less deformed fireball	kinetic pressure overcomes stiffness of the EoS – deformed fireball

Ivanov, Blaschke, EPJ A, 52, 237 (2016)

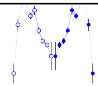
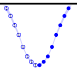
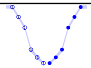
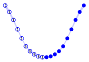
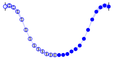
Peak-dip-peak-dip irregularity in p rapidity spectra



Peak-dip-peak-dip irregularity for experimental proton spectra.

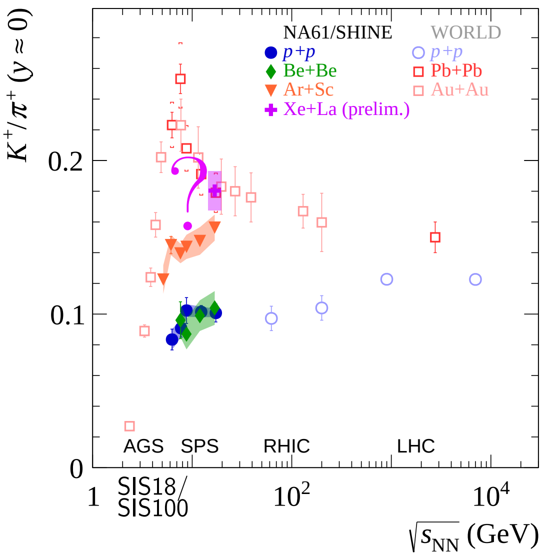
Ivanov, Blaschke, EPJ A (2016) 52: 237

Peak-dip-peak-dip irregularity in p rapidity spectra

p_{lab} (GeV/c)	$\sqrt{s_{NN}}$ (GeV)	NA61/SHINE				NA49
		p+p	Be+Be	Ar+Sc	Xe+La	Pb+Pb
19A	6.12					
30A	7.62					
40A	8.77					
75A	11.9					
150A	16.8					

- "Peak-dip" transition is observed for medium and heavy systems: Ar+Sc, Xe+La, and Pb+Pb within SPS energy range.
- No such transition for small systems: p+p and Be+Be.
- Data for lower energies are needed!

Summary



- Very violent effects in strangeness production as a function of system size and energy at the SPS,
  ... just between CBM and LHC experiments!
- These effects cannot be explained by a number of theoretical models.
- There is a horn, which was attributed to the onset of deconfinement – transition from hadronic matter to QGP.
- However, this transition seems to have a non-trivial dependence on system size.

Backup Slides

Data selection: Event cuts

Two types of cuts:

- upstream (not biasing):
  - only one beam particle,
  - well measured beam,
  - no detector malfunctioning.
- downstream (biasing):
  - 10% of the most central events,
  - main vertex present,
  - good quality of vertex fit,
  - fitted z-position of the main vertex is within 2 cm from the middle of the target.

Data selection: Vertex track cuts

- Tracks pointing to the main vertex,
- tracks with $q \cdot p_x > 0$,
- total number of measured clusters > 30 (maximum is 234, only for $\mathrm{d}E/\mathrm{d}x$),
- number of measured VTPC clusters > 15 (maximum is 144),
- azimutal angle $|\varphi| < 30^\circ$ (only for $\mathrm{d}E/\mathrm{d}x$).

Fitting

Simultaneous fit for positive and negative charges.

Sum of asymmetric Gaussians for p, K^+, π^+, e^+, d ($\bar{p}, K^-, \pi^-, e^- d$):

$$f(x) = \sum_{i=p,K,\pi,e,d} N_i \frac{1}{\sum_l n_l} \sum_l \frac{n_l}{\sqrt{2\pi}\sigma_{i,l}} \exp\left[-\frac{1}{2}\left(\frac{x - x_i'}{(1 \pm \delta)\sigma_{i,l}}\right)^2\right],$$

$x_i' = x_i - \frac{2}{\sqrt{2\pi}}\sigma_{i,l}\delta$ – mean dE/dx_i ($\approx$ peak position),
N_i – yields,
n_l – number of tracks with l number of clusters,
$\frac{1}{\sum_l n_l}\sum_l \ldots$ – weighted average of asymmetric Gaussians with widths

$$\sigma_{i,l} = \frac{\sigma_0}{\sqrt{l}}\left(\frac{x_i}{x_\pi}\right)^\alpha,$$

$\delta = \frac{\delta_0}{\sqrt{l}}$ – assymetry,
σ_0, δ_0 – common for all particle types,
$\alpha = 0.625$ – universal constant.

Parameters of fit for 25.12_31.62_0.45_0.50 histograms:

- σ_0, δ_0, σ_e, δ_e, α,
- π peak position,
- e peak position,
- p/π, K/π, d/π peak positions,
- N_π, N_K, N_p, N_d, N_e.

- red – fixed parameters,
- green – parameters different for − and + histograms,
- black – parameters common for − and + histograms.

Total number of Free parameters:
20 for both histograms (NFree),
13 for one histogram (NFree_1).

Distribution of strangeness between hadrons

$\bar{s}$ = s (net strangeness conservation)

$K^+(u\bar{s})$ $\approx$ $K^0(d\bar{s})$ (isospin symmetry)

$K^-(\bar{u}s)$ $\approx$ $\bar{K}^0(\bar{d}s)$ (isospin symmetry)

$K^+(u\bar{s}) \gg \bar{\Lambda}(\bar{u}\bar{d}\bar{s})$

$\bar{K}^0(\bar{d}s) \approx \Lambda(uds)$

$\bar{\Lambda}(\bar{u}\bar{d}\bar{s})$ $\ll$ $\Lambda(uds)$ (high baryon density)

(red) – sensitive to strangeness content only

(blue, green) – sensitive to strangeness content and baryon density

How to measure strangeness

$$2\langle N_{s\bar{s}}\rangle = \langle \Lambda + \bar{\Lambda}\rangle + \langle K^+ + K^- + K^0 + \bar{K}^0\rangle + ...$$

$$2\langle N_{s\bar{s}}\rangle \approx \langle \Lambda\rangle + \langle K^+ + K^- + K^0 + \bar{K}^0\rangle,$$

$$\langle N_{s\bar{s}}\rangle \approx \langle \Lambda\rangle + \langle K^- + \bar{K}^0\rangle \approx \langle K^+ + K^0\rangle \approx 2\langle K^+\rangle.$$

How to measure entropy

Entropy $\sim \langle \pi \rangle$

$$\langle \pi\rangle = \langle \pi^+ + \pi^0 + \pi^-\rangle \approx 3\langle \pi^+\rangle$$

Experimental measure of strangeness to entropy ratio

$$\frac{\text{strangeness}}{\text{entropy}} \sim \frac{\langle N_{s\bar{s}}\rangle}{\langle \pi\rangle} \approx \frac{2\langle K^+\rangle}{3\langle \pi^+\rangle}$$

Strangeness at phase transition

$$\langle N_i \rangle = \frac{gV}{(2\pi)^3} \int \mathrm{d}^3p \frac{1}{\exp\left(E/T\right) \pm 1}$$

confined matter

K-mesons

$g_K = 4$

$2M_K \approx 2 \times 500\text{MeV}$
heavy – $M_K > T_c$

Phase transition
$T_c \approx 150\text{MeV}$

quark-gluon plasma

s, $\bar{s}$ - quarks

$g_s = 12$

$2M_s \approx 2 \times 100\text{MeV}$
light – $M_s < T_c$

$$\langle N_K \rangle = g_K V \left(\frac{M_K T}{2\pi} \right)^{\frac{3}{2}} \exp\left(-M_K/T\right)$$

$$\langle N_s \rangle = g_s V \frac{2\pi^2}{4 \cdot 45} \cdot T^3$$

Strangeness production is sensitive to phase transition.

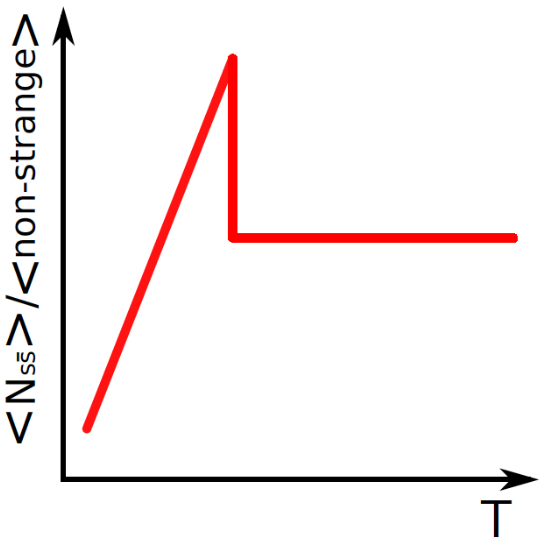
Strangeness/entropy at phase transition

hadron gas

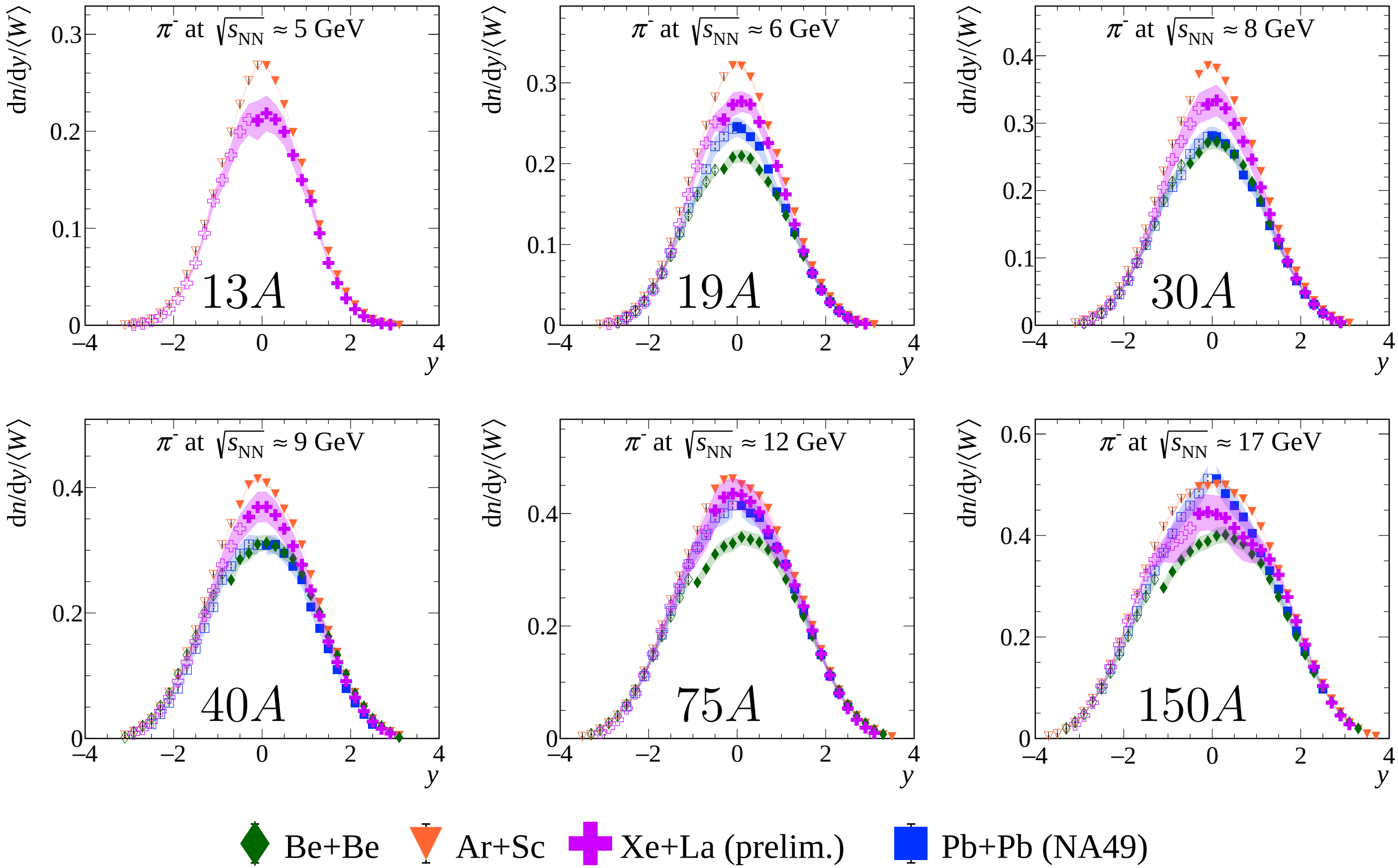
$$\frac{\langle K \rangle}{\langle \pi \rangle} \sim \frac{(M_K T)^{\frac{3}{2}}}{T^3} \exp^{-\frac{M_K}{T}}$$

quark-gluon plasma

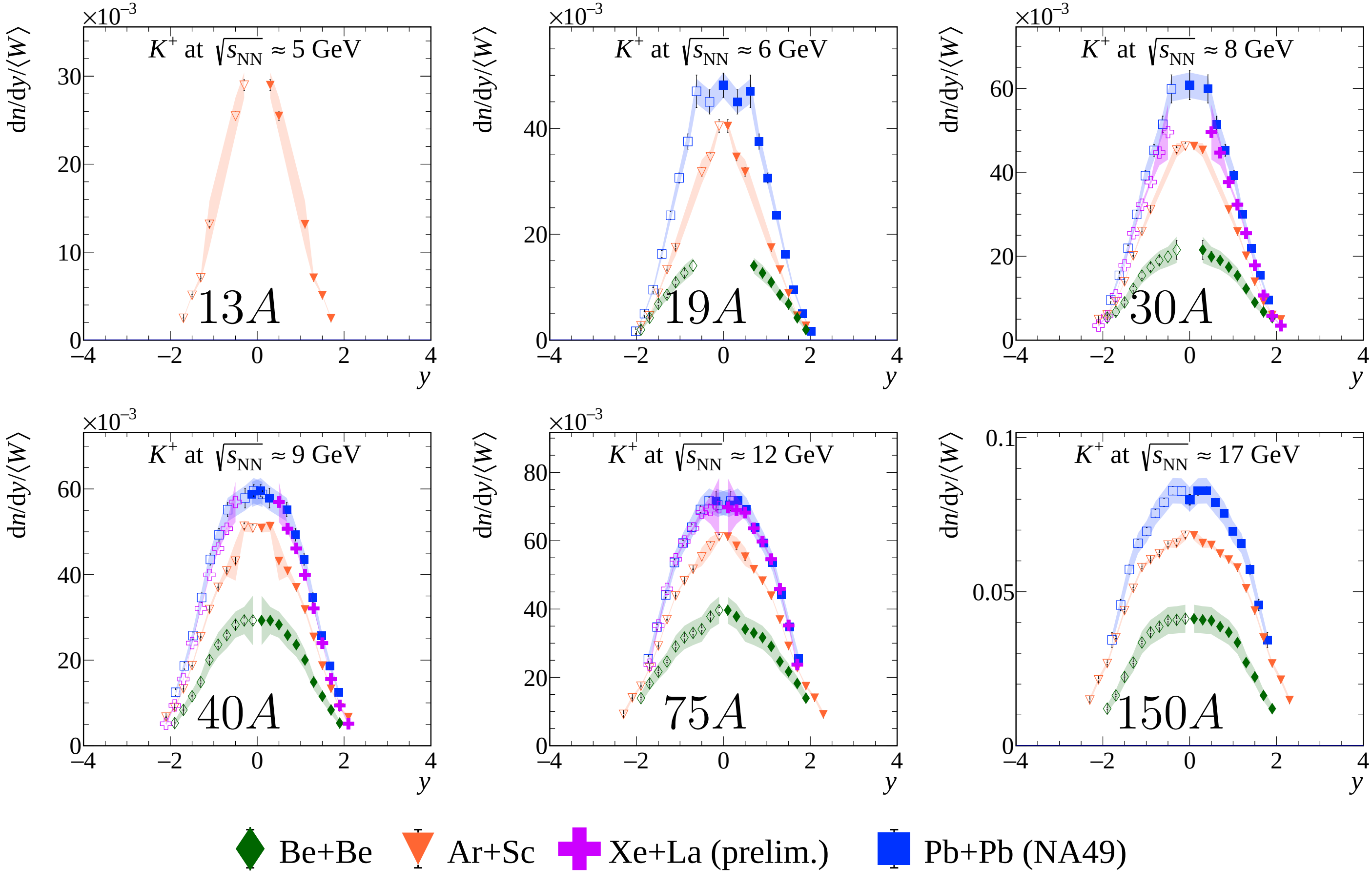
$$\frac{\langle s \rangle}{\langle u + d + g \rangle} \sim \frac{T^3}{T^3} = \text{const}(T)$$



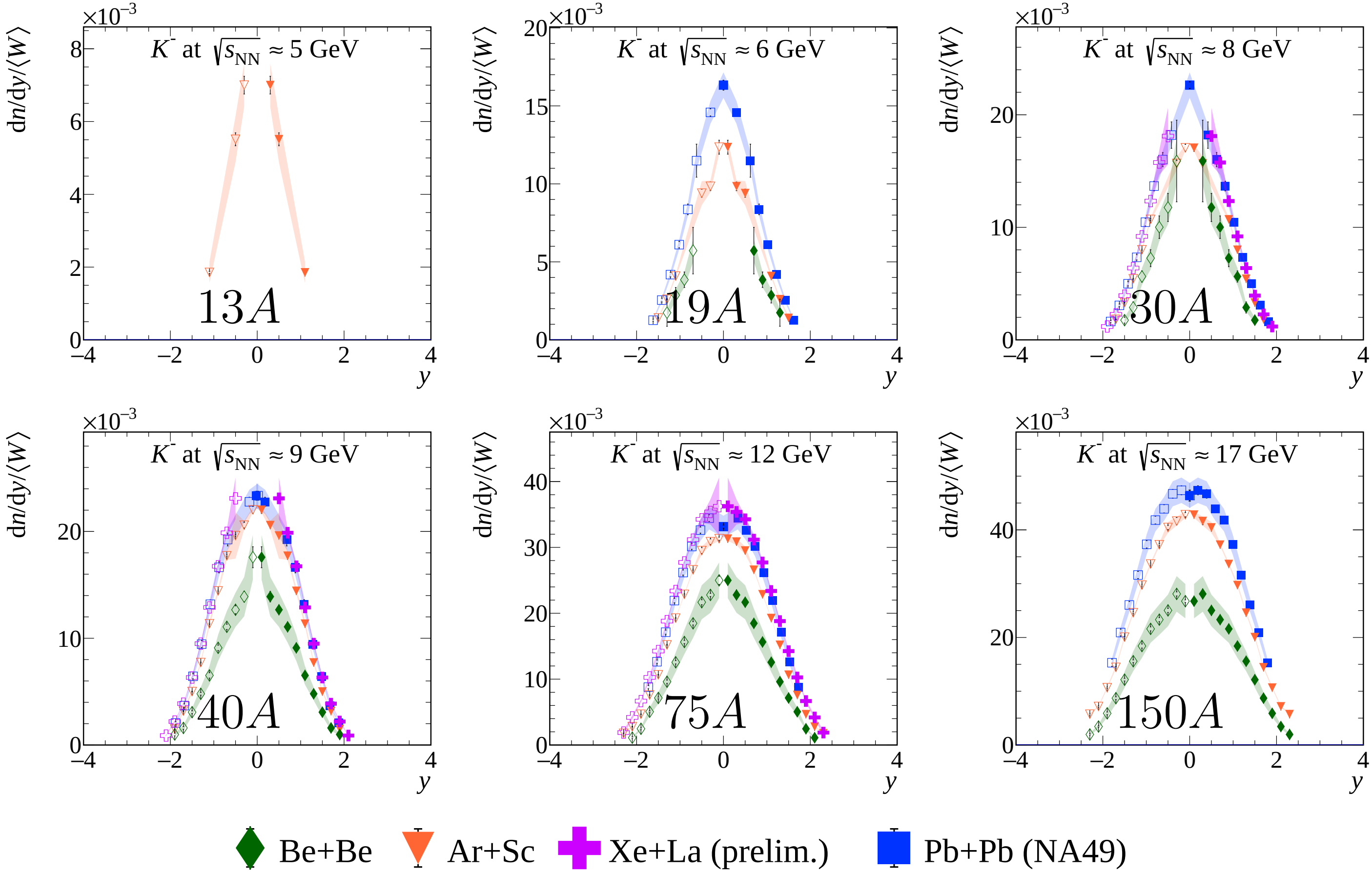
Rapidity spectra of π^- from h^-



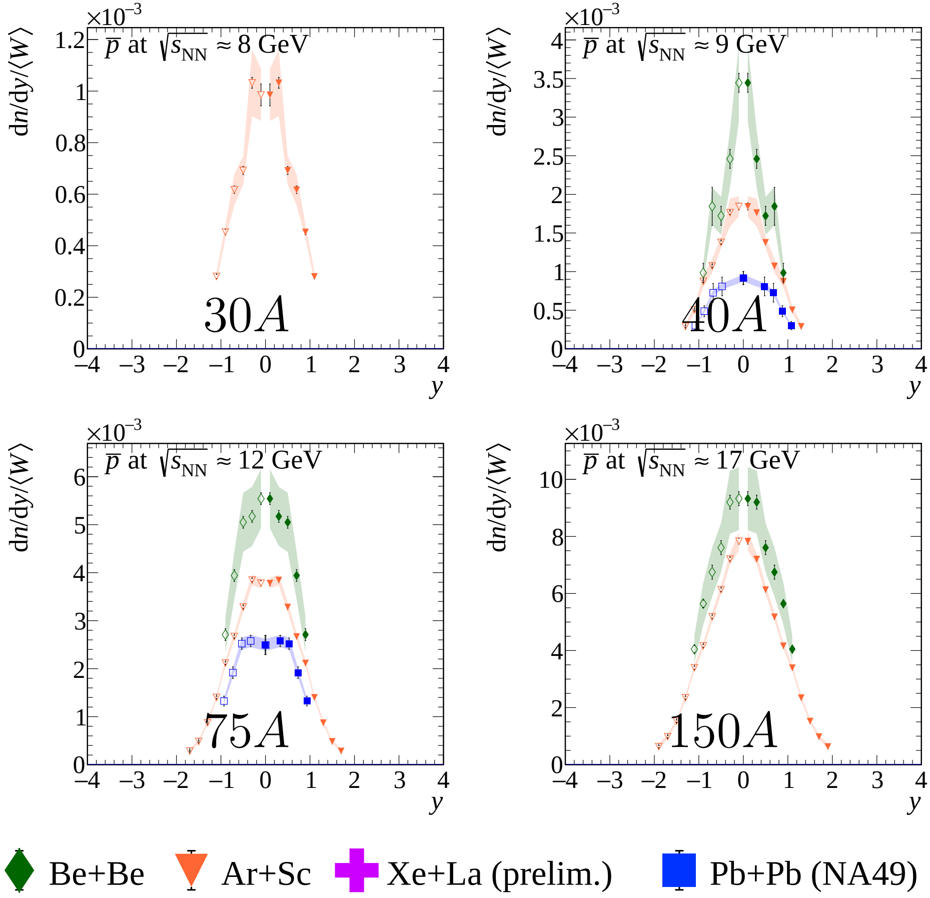
Rapidity spectra of K^+



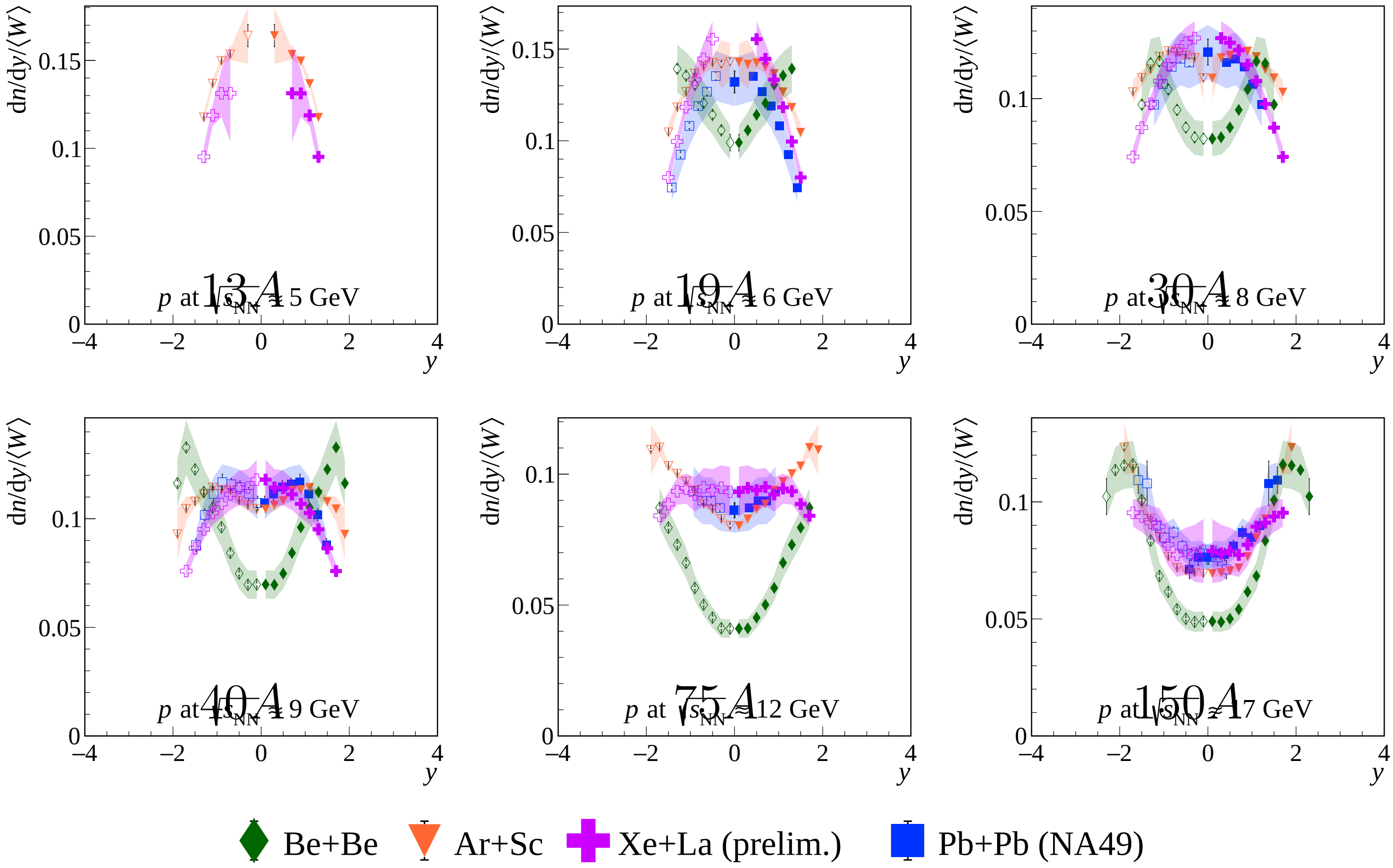
Rapidity spectra of K^-



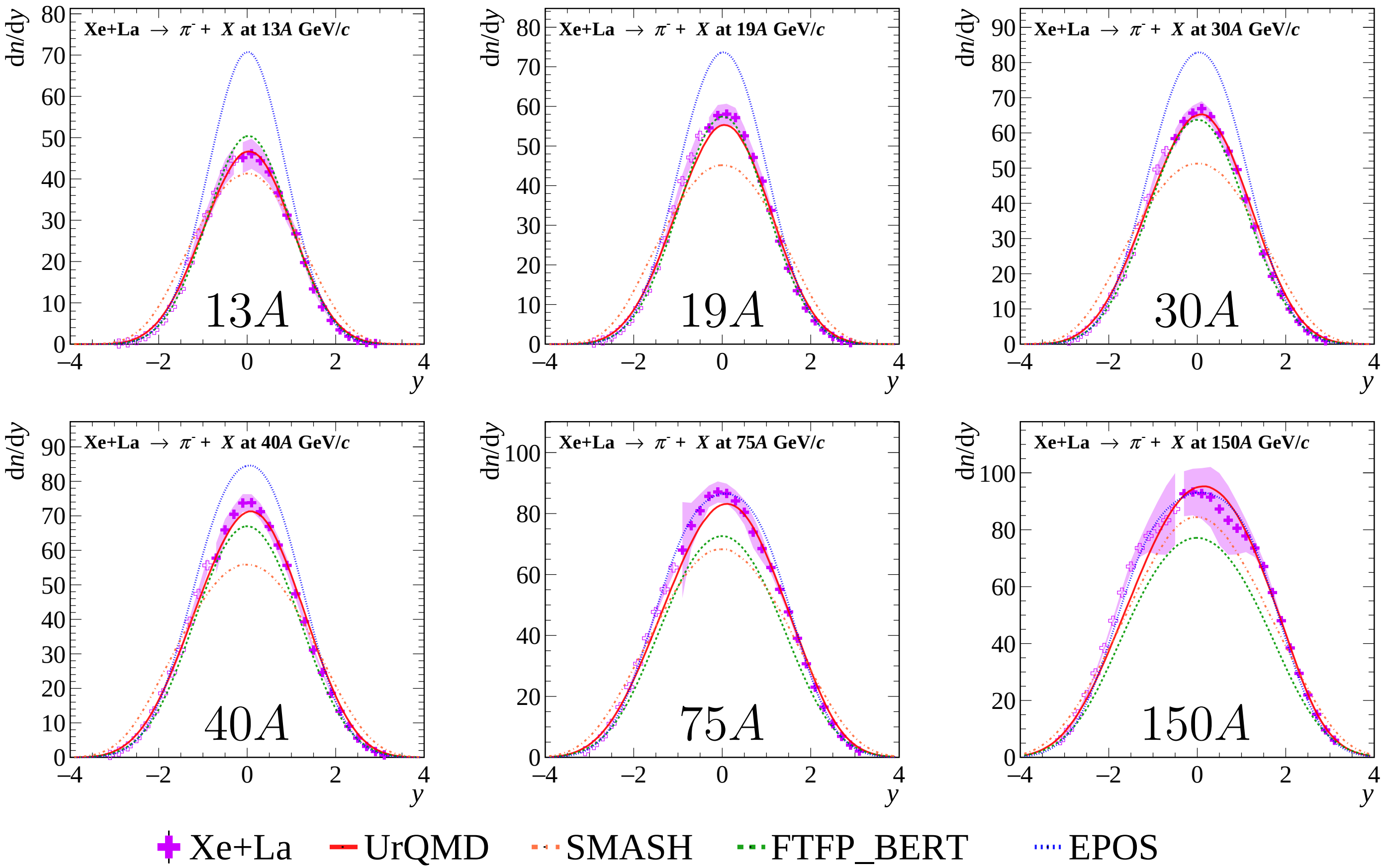
Rapidity spectra of $\bar{p}$



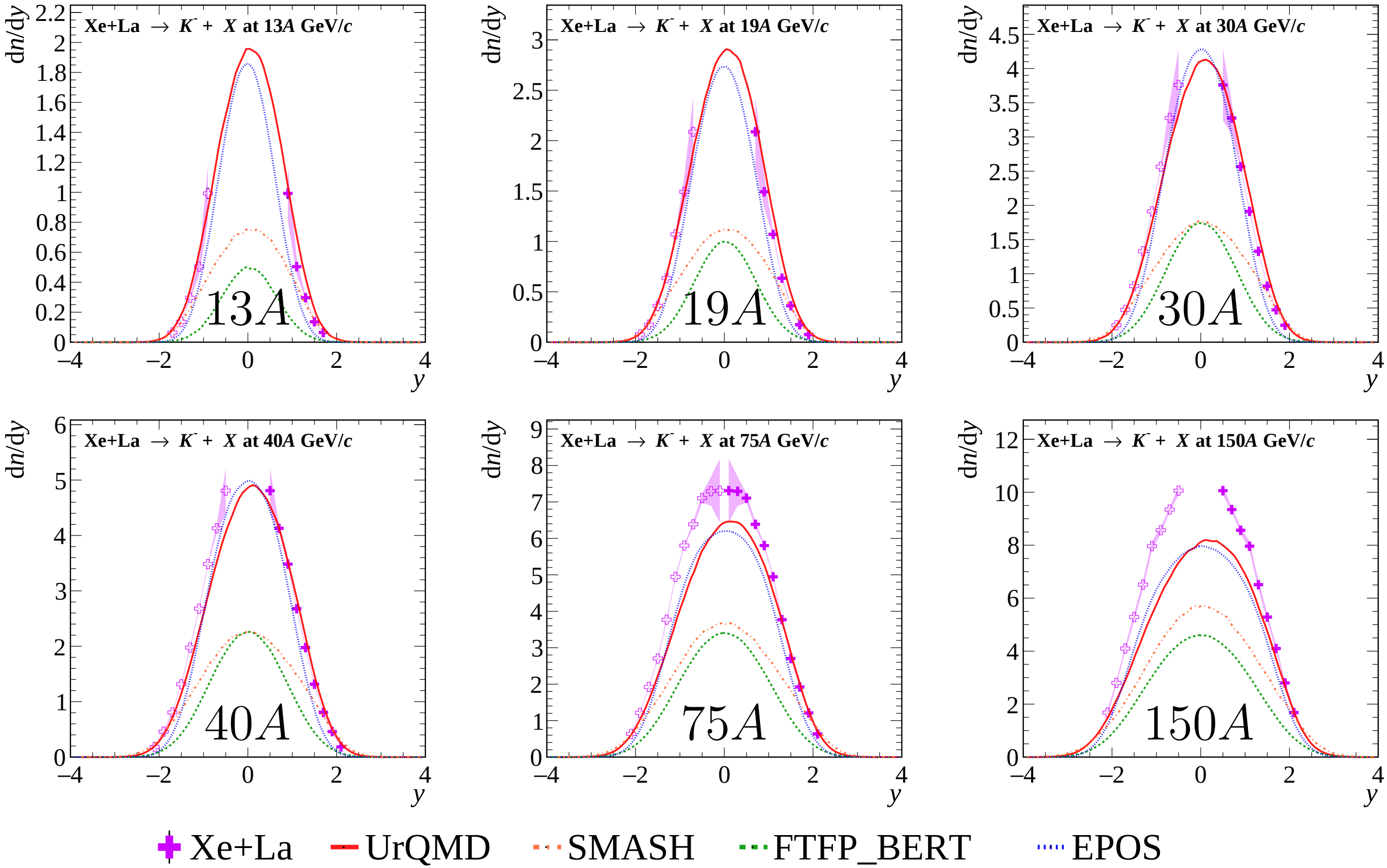
Rapidity spectra of p

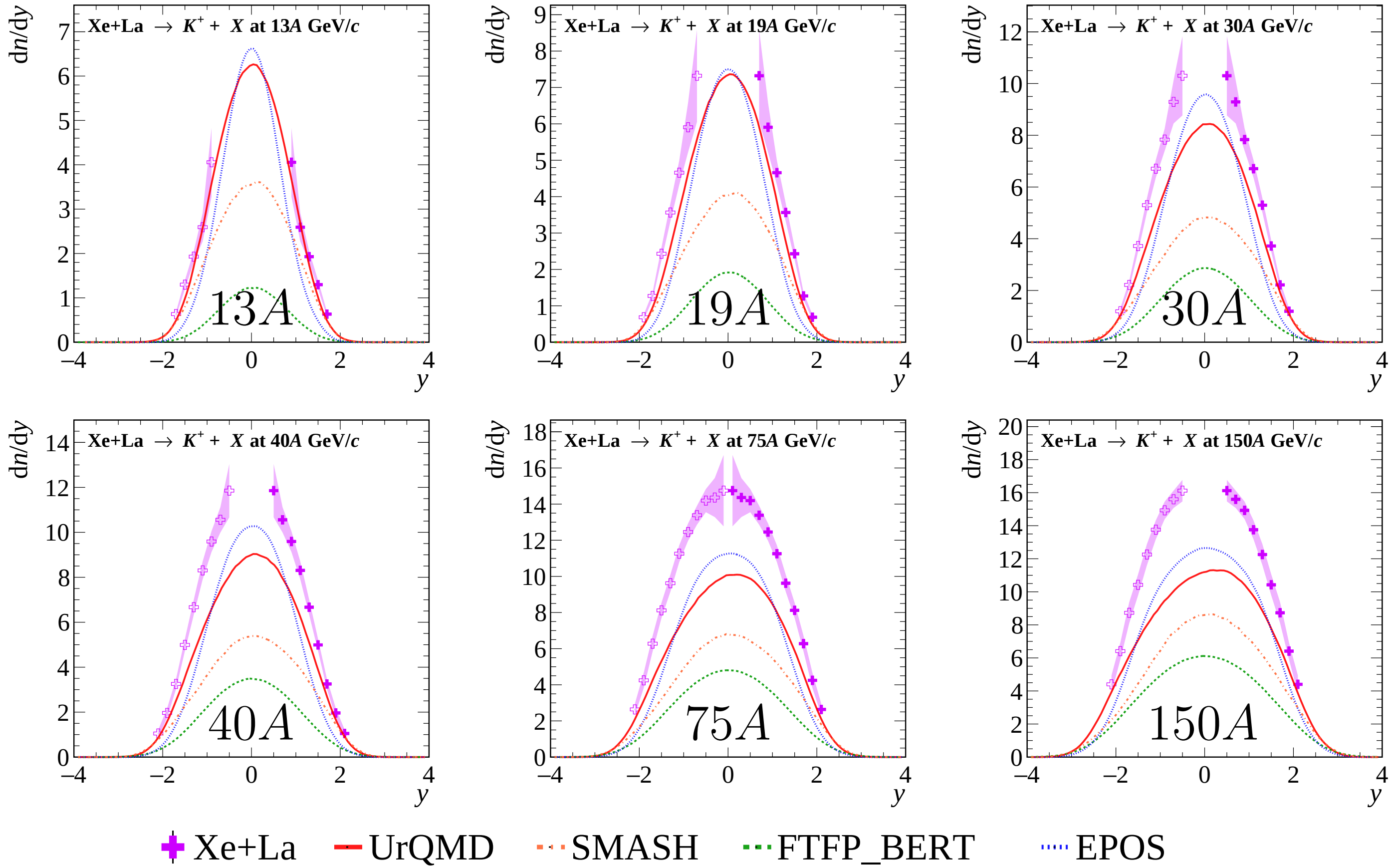


Rapidity spectra of π^- from h^-

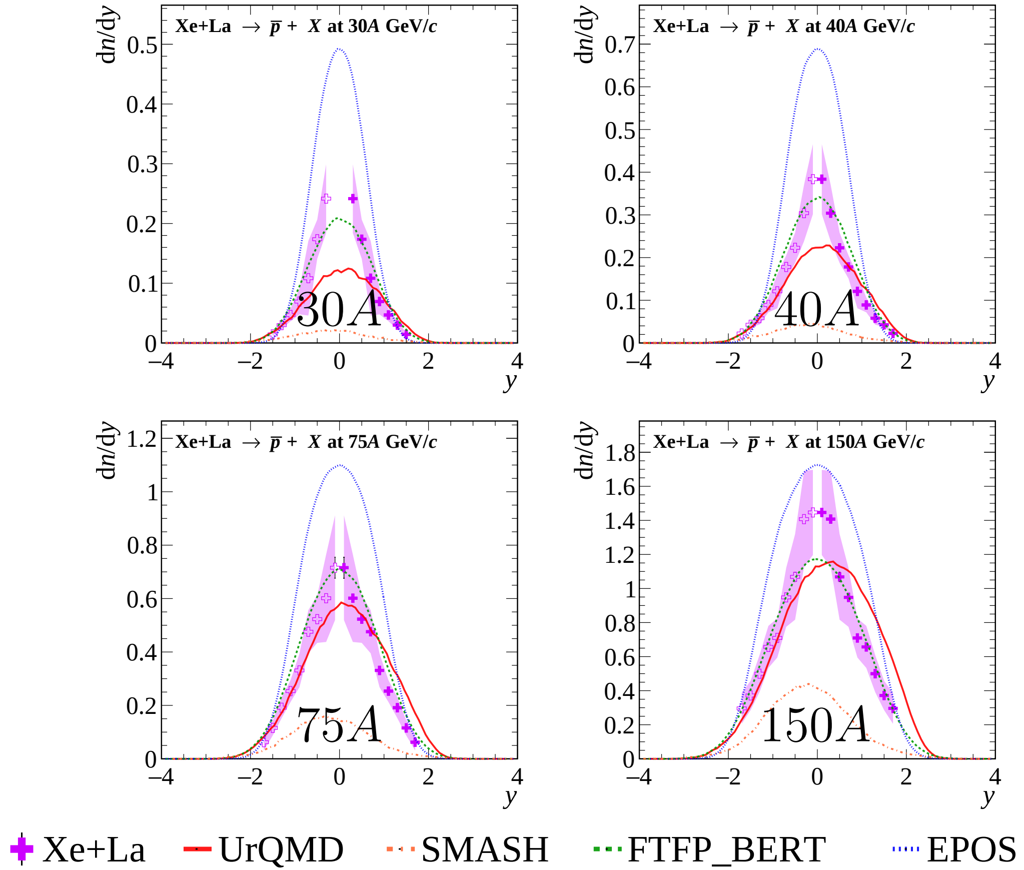


Rapidity spectra of K^-

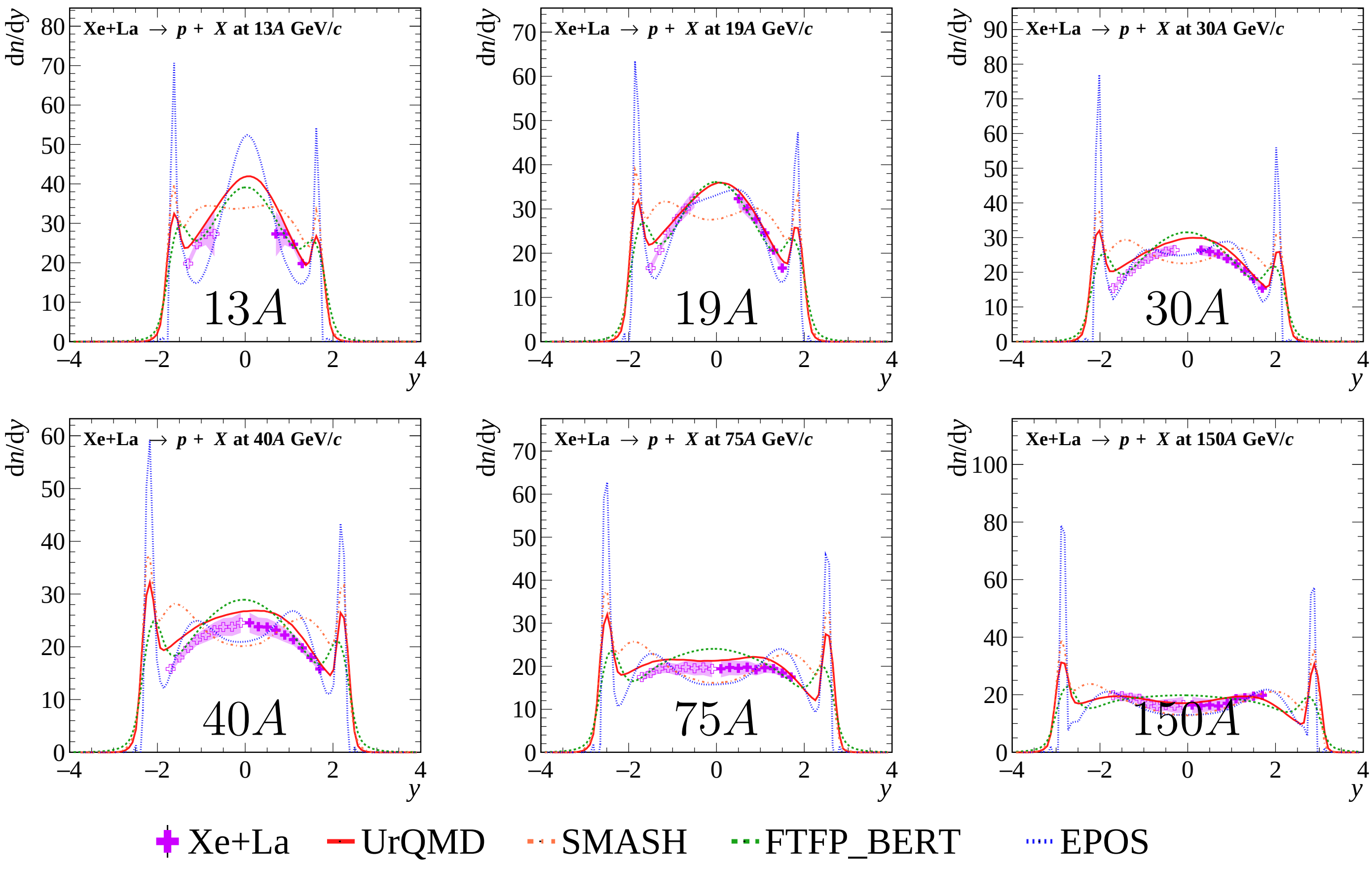




dn/dy
Xe+La → K+ + X at 13A GeV/c
13A
Xe+La → K+ + X at 19A GeV/c
19A
Xe+La → K+ + X at 30A GeV/c
30A
Xe+La → K+ + X at 40A GeV/c
40A
Xe+La → K+ + X at 75A GeV/c
75A
Xe+La → K+ + X at 150A GeV/c
150A
y
Xe+La
UrQMD
SMASH
FTFP_BERT
EPOS


Xe+La → p̄ + X at 30A GeV/c
30A
Xe+La → p̄ + X at 40A GeV/c
40A
Xe+La → p̄ + X at 75A GeV/c
75A
Xe+La → p̄ + X at 150A GeV/c
150A
dn/dy
y
Xe+La
UrQMD
SMASH
FTFP_BERT
EPOS

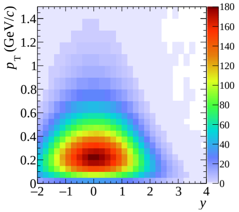
Rapidity spectra of p



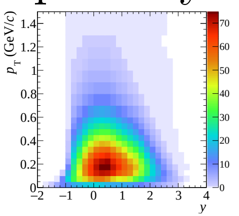
h^- method for π^-

h^- – all negatively charged hadrons ($\approx 90\%\ \pi^- + K^- + \bar{p} + ...$).

π^- MC generated

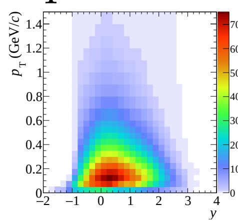


h^- MC sel primary



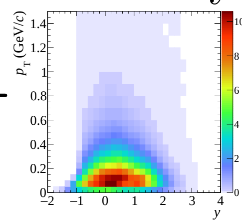
$\times$ (

h^- raw spectrum



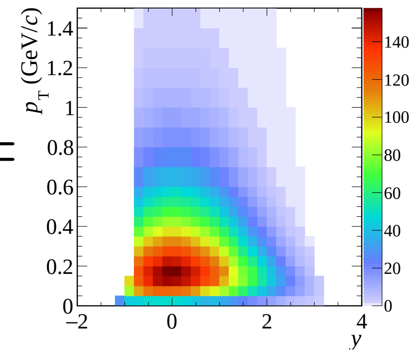
$-$

h^- MC sel secondary



) $=$

π^- corrected spectrum



$$n[\pi^-]^{\text{data}} = c_M \times (n[h^-]^{\text{data}}_{\text{raw}} - c_A),$$

$$c_M = \frac{n[\pi^-]^{\text{MC}}_{\text{gen}}}{(n[\pi^-, K^-, \bar{p}]^{\text{MC}}_{\text{sel}})_{\text{prim+sec\_not\_dec}}},\ c_A = (n[\pi^-, K^-, \bar{p}]^{\text{MC}}_{\text{sel}})_{\text{sec\_dec}} + n[other^-]^{\text{MC}}_{\text{sel}}.$$

Fitting of p_{T} distributions

- For π^+ and π^-, fit with Tsalis (q-exponential) function:

$$f(p_{\mathrm{T}}) = \frac{A \cdot p_{\mathrm{T}}}{T(T+m_\pi)} \left(1 + (1-q) \cdot \frac{(m_\pi - m_{\mathrm{T}})}{T}\right)^{1/(1-q)} .$$

- For K^+ and K^-, fit with exponential function:

$$f(p_{\mathrm{T}}) = \frac{A \cdot p_{\mathrm{T}}}{T(T+m_K)} \exp \frac{m_K - m_{\mathrm{T}}}{T} ,$$

- For p and $\bar{p}$, fit with Blast-wave function:

$$f(p_{\mathrm{T}}) = A \cdot p_{\mathrm{T}} \int_0^R r \,\mathrm{d}r \, m_{\mathrm{T}} \, I_0 \left(\frac{p_{\mathrm{T}} \sinh \rho}{T}\right) K_1 \left(\frac{m_{\mathrm{T}} \cosh \rho}{T}\right) .$$

where

$$\rho = \tanh^{-1} \beta_{\mathrm{T}}(r) , \quad \beta_{\mathrm{T}}(r) = \beta_s \left(\frac{r}{R}\right)^\alpha , \quad \langle \beta_{\mathrm{T}} \rangle = \frac{\beta_s}{\alpha/2 + 1} .$$

Calculation of dn/dy and $\langle n \rangle$

- To go from $\mathrm{d}^2n/\mathrm{d}y\mathrm{d}p_\mathrm{T}$ to $\mathrm{d}n/\mathrm{d}y$:

$$\frac{\mathrm{d}n}{\mathrm{d}y}(y) = \int_0^{p_\mathrm{T}^\mathrm{min}} f(p_\mathrm{T})dp_\mathrm{T} + \sum_{p_\mathrm{T}} \frac{\mathrm{d}^2n}{\mathrm{d}y\mathrm{d}p_\mathrm{T}}(y) \cdot \Delta p_\mathrm{T} + \int_{p_\mathrm{T}^\mathrm{max}}^{\infty} f(p_\mathrm{T})dp_\mathrm{T} \ .$$

- To go from $\mathrm{d}n/\mathrm{d}y$ to $\langle n \rangle$:

$$\langle n \rangle = \sum_y \frac{\mathrm{d}n}{\mathrm{d}y} \cdot \Delta y + \int_{-\infty}^{y^\mathrm{min}} f(y)\mathrm{d}y + \int_{y^\mathrm{max}}^{\infty} f(y)\mathrm{d}y \ ,$$

where

$$f(y) = \frac{A_0}{\sigma_0\sqrt{2\pi}} \exp\left(-\frac{(y-y_0)^2}{2\sigma_0^2}\right) + \frac{A_0}{\sigma_0\sqrt{2\pi}} \exp\left(-\frac{(y+y_0)^2}{2\sigma_0^2}\right) \ .$$