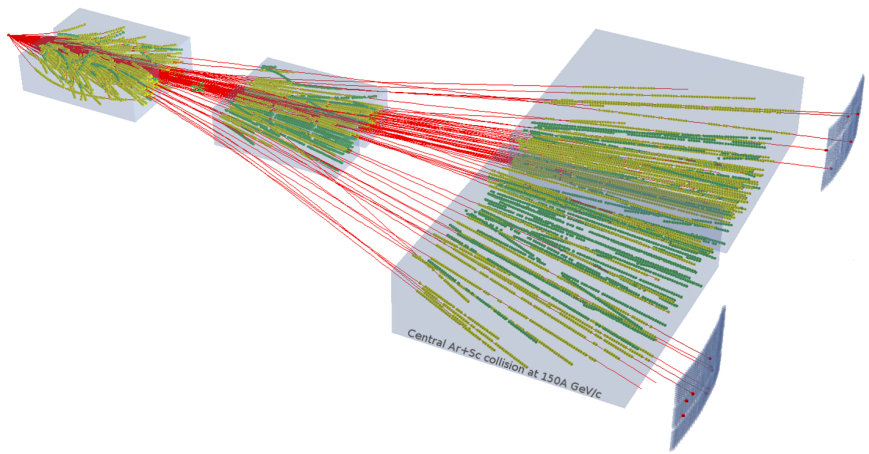
News on spectra from NA61/SHINE at CERN SPS

Magdalena Kuich

for the NA61/SHINE collaboration



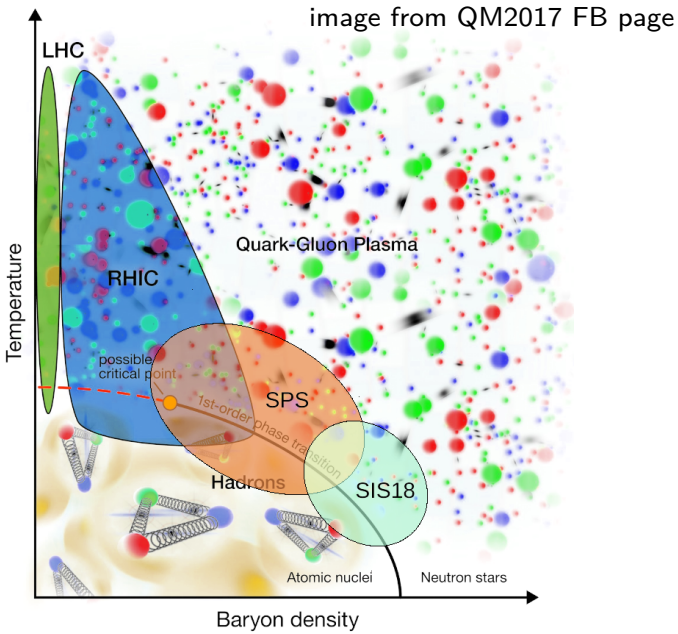
European Physical Society Conference on High Energy Physics

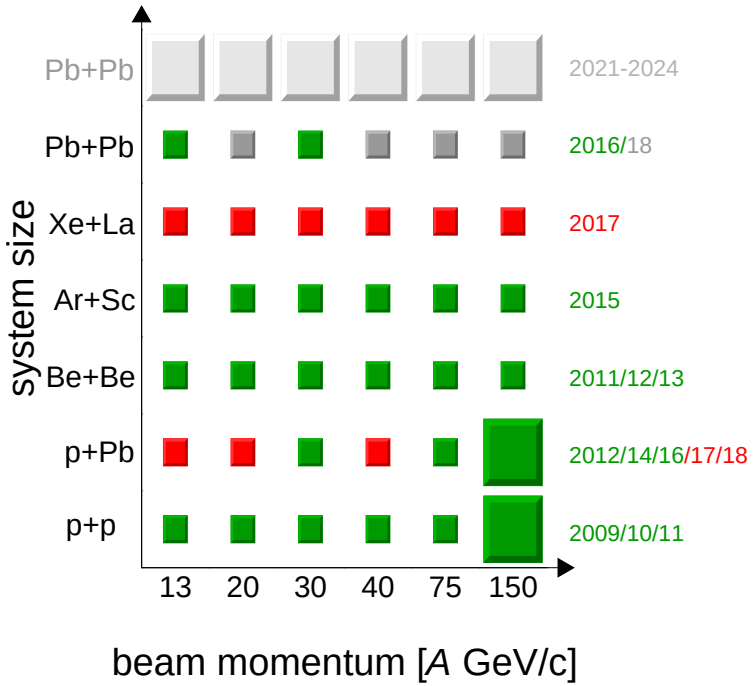
Venice, Italy, July 5-12 2017

2D phase space scan by NA61/SHINE

NA61/SHINE experiment performs 2D scan in **collision energy and system size** to study the phase diagram of strongly interacting matter in **baryon density and temperature**

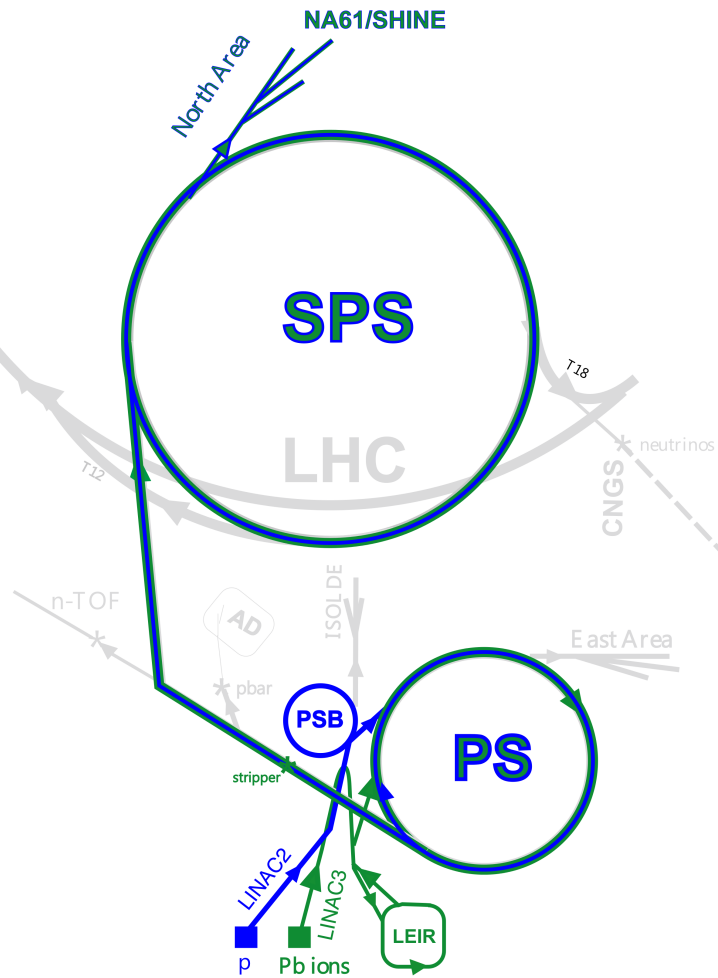
Research was motivated by NA49 results on onset of deconfinement

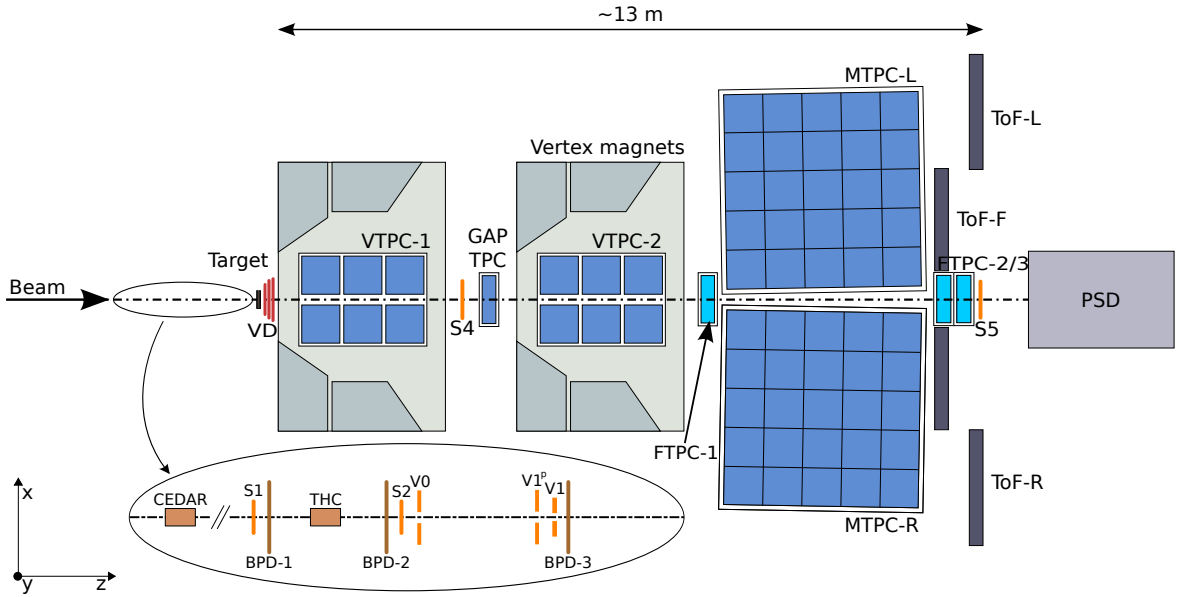




- Particle spectra → study of **onset of deconfinement** (this talk)
- Fluctuations → search for the **critical point** (talk by K. Grebieszkow tomorrow)

NA61/SHINE spectrometer

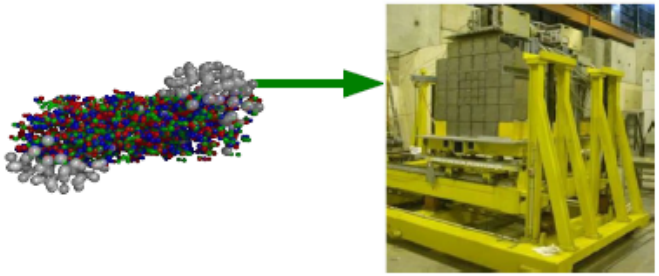


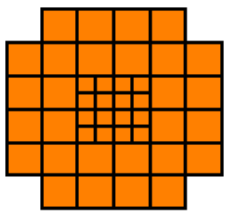


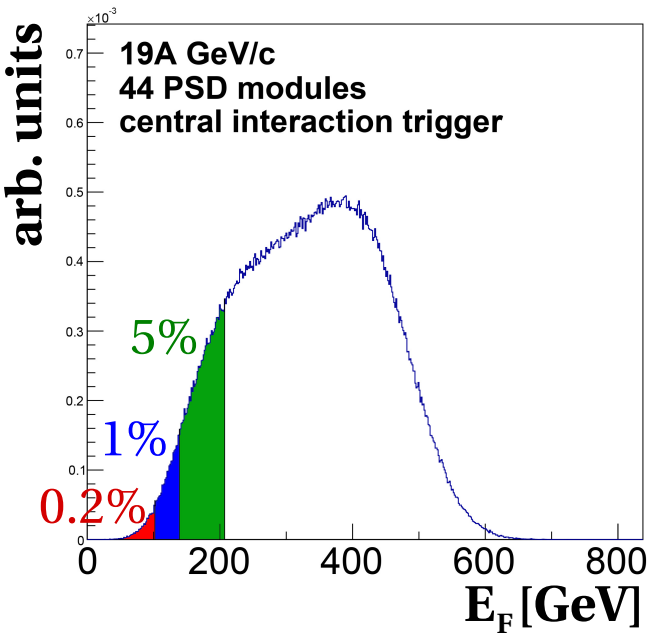
- **Fixed target experiment located at the SPS accelerator**
- Beams:
  ions (Be, Ar, Xe, Pb) $p_{\text{beam}} = 13A - 150A$ GeV/c
  hadrons (π, K, p) $p_{\text{beam}} = 13 - 400$ GeV/c
  $\sqrt{s_{\text{NN}}} = 5.1$–$16.8$ (27.4) GeV
- **Large acceptance hadron spectrometer** – coverage of the full forward hemisphere, down to $p_{\text{T}} = 0$
- **Centrality** selection based on **forward energy** (projectile spectators) measured in PSD

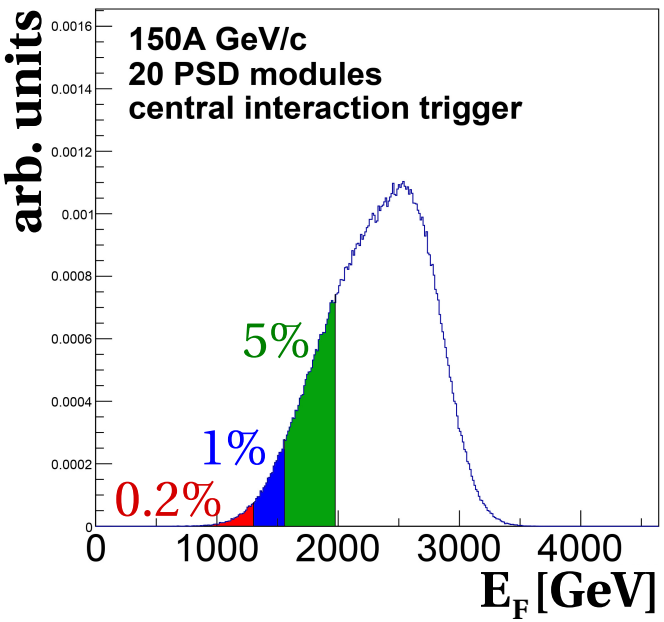
Event selection based on forward energy measurements

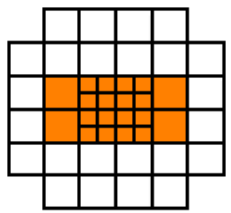
- **Event (centrality) selection** is done using **the forward energy**(E_F) dominated by energy of projectile spectators
- Due to different magnetic field setting and PSD position for various beam momenta, selection of PSD modules for E_F calculation depends on reaction
- The module selection is based on correlation between energy deposit in a module and track multiplicity
- Examples of event selection using E_F for Ar+Sc:





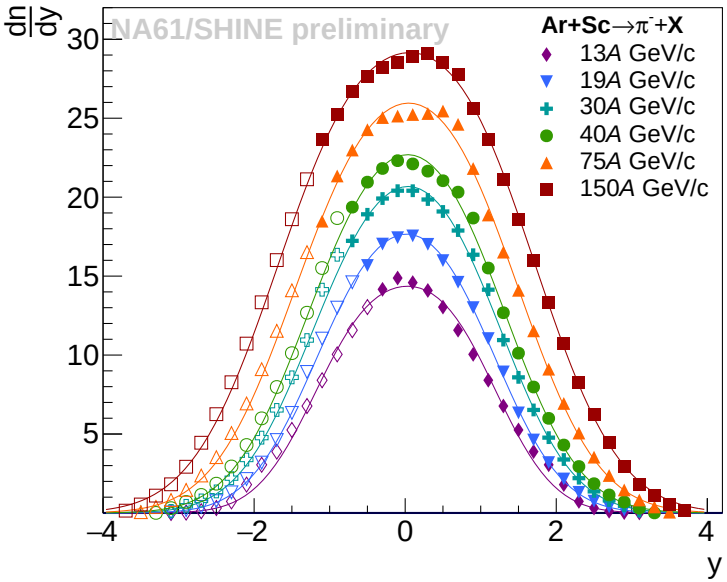




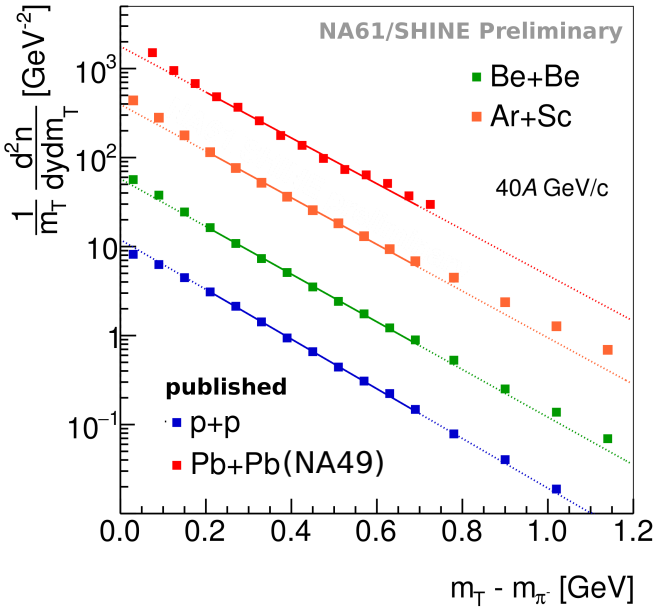


π^- spectra from the two-dimensional scan

Collision energy dependence



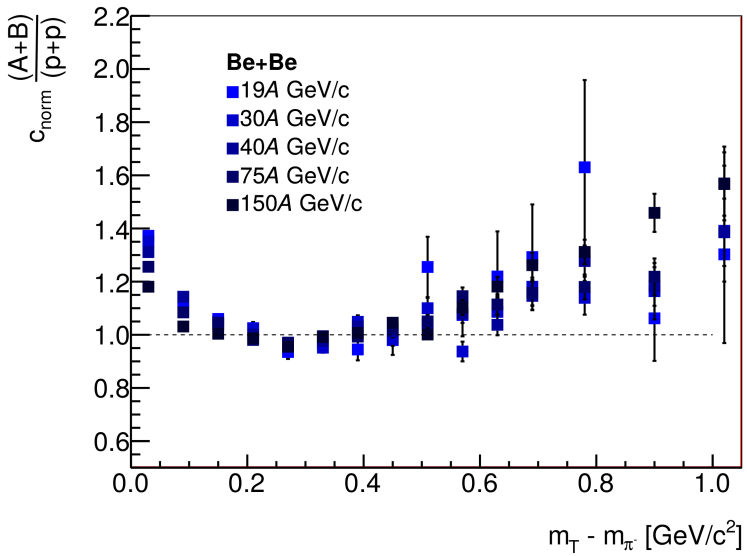
System size dependence

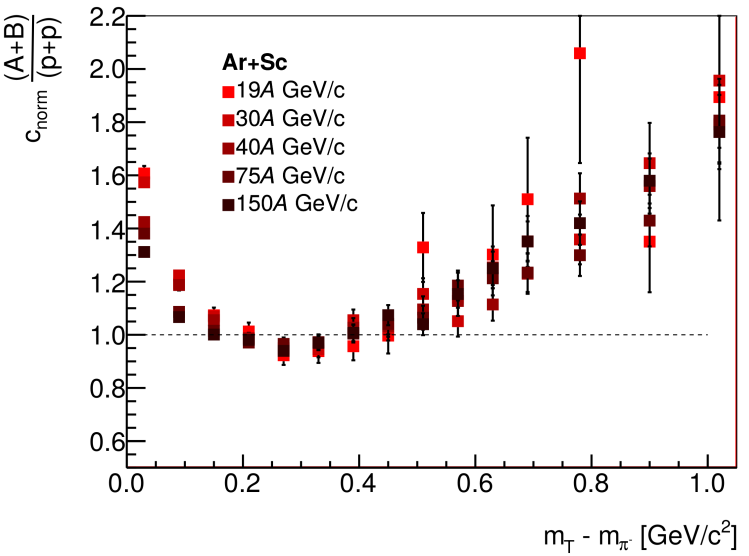


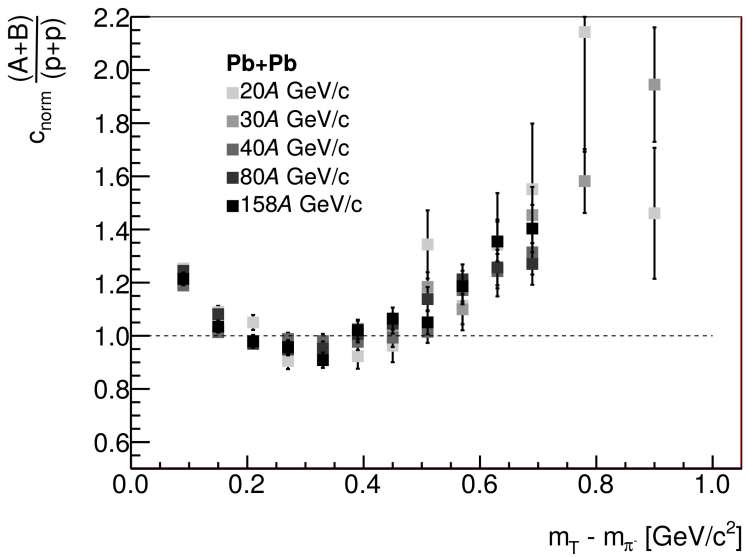
- π^- spectra measured in large acceptance: p_T down to 0, in full forward hemisphere
- Rapidity spectra approximately gaussian, independently of the collision energy
- Large detector acceptance allows to obtain 4π pion multiplicity from the data and extrapolation (for details see arXiv:1612.01334)
- m_T spectra in p+p $\approx$ exponential
- m_T spectra in larger systems (central collisions) deviate from the exponential shape

Only statistical uncertainties shown

Energy and system size dependence of m_T spectra

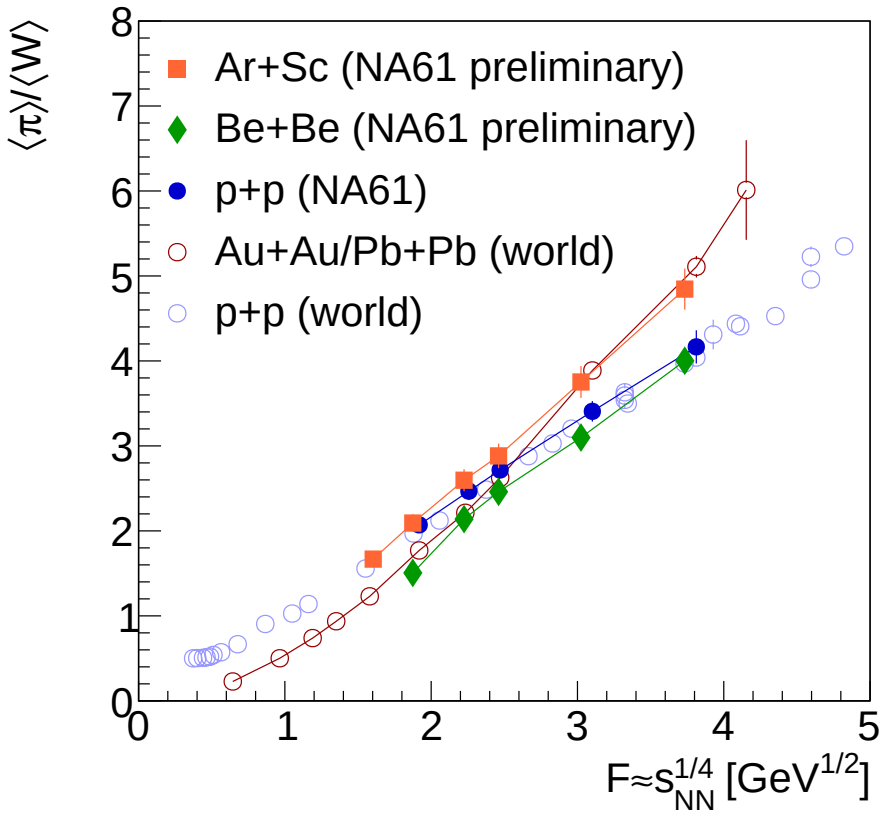






- m_T shape differs significantly between p+p and A+A
  - clear system size dependence
  - small energy dependence
  - the effect associated to transverse collective flow

Study of the onset of deconfinement: kink



$\langle\pi\rangle$ – mean π multiplicity in full acceptance

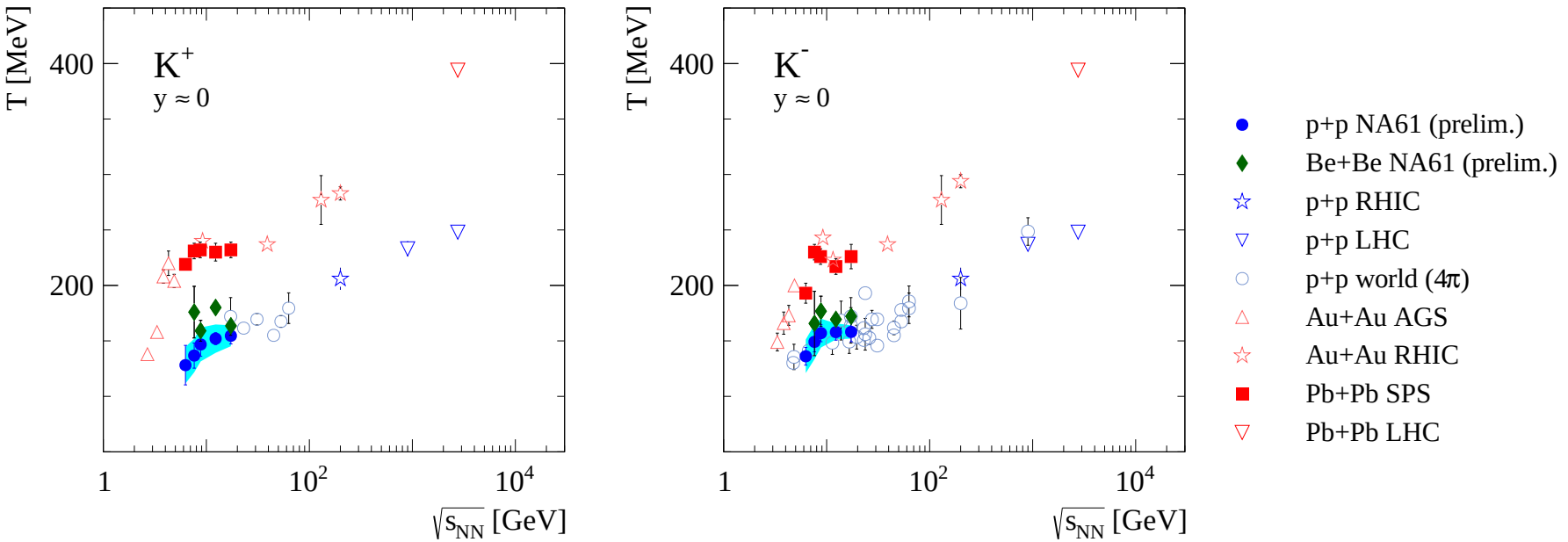
$\langle W\rangle$ – mean number of wounded nucleons

$$F \equiv \left[\frac{(\sqrt{s_{NN}}-2m_N)^3}{\sqrt{s_{NN}}}\right]^{1/4} \approx s_{NN}^{1/4}$$

- The slope of energy dependence for heavier systems is larger than for lighter systems at high SPS energies
- Statistical model with phase transition (SMES[a]) predicts increase of the slope – **KINK** – of $\langle\pi\rangle/\langle W\rangle$ in QGP due to the larger number of degrees of freedom in comparison to HRG

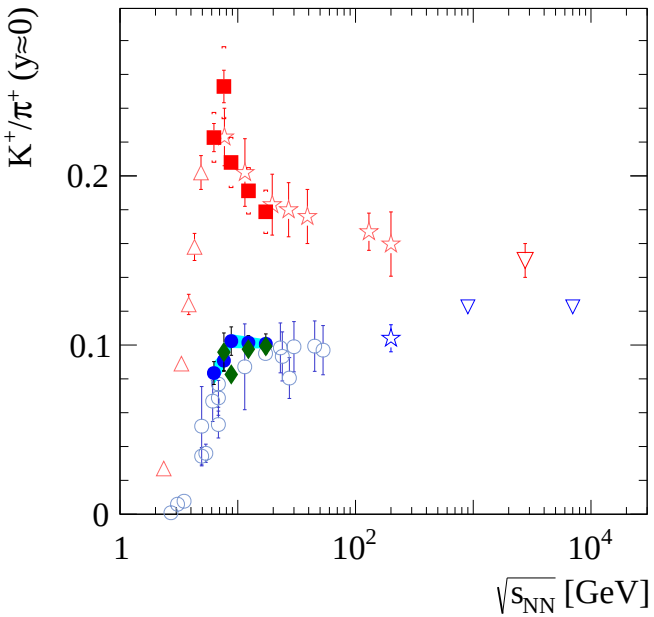
[a] Acta Phys. Pol. B30 (1999) 2705

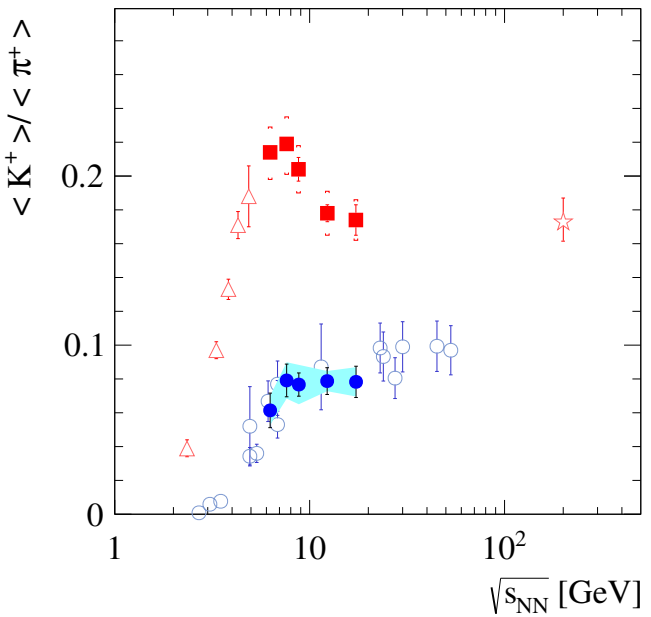
Study of onset of deconfinement: step

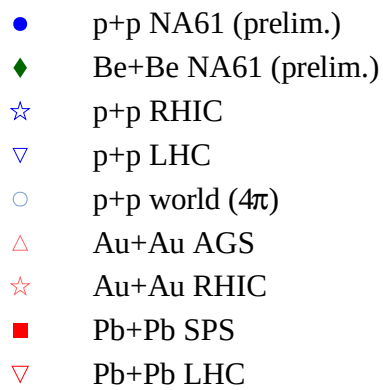


- Plateau – **STEP** – in the inverse slope parameter of m_T spectra in Pb+Pb collisions observed. It is expected for the onset of deconfinement due to mixed phase of HRG and QGP (SMES)
- Qualitatively similar structure is visible in p+p (mixed phase in p+p?)
- Be+Be is consistent with step structure and slightly above p+p

Study of onset of deconfinement: horn

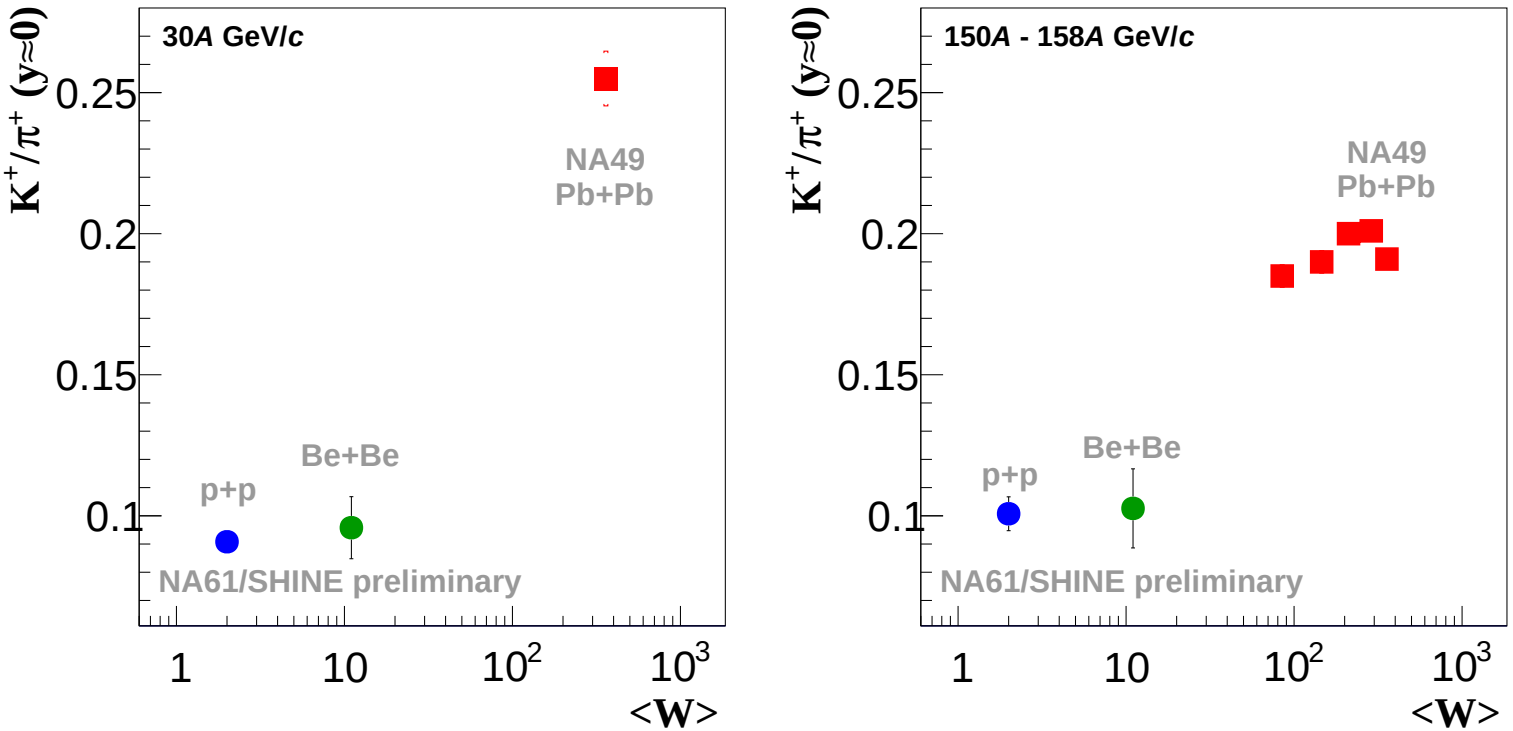






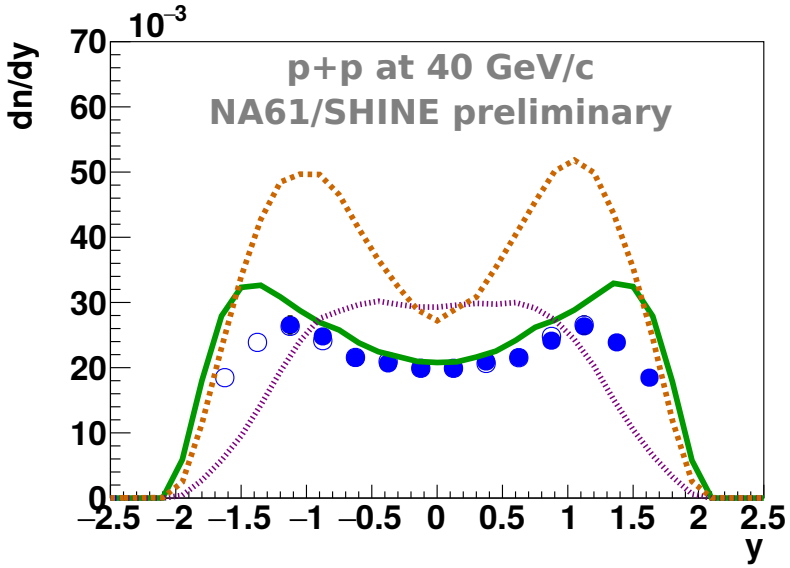
- Rapid changes in K^+/π^+ – **HORN** – were observed in Pb+Pb collisions. It was predicted (SMES) as a signature of onset of deconfinement too
- Plateau like structure (shadow of horn structure in p+p?) visible in p+p in mid-rapidity as well as in 4π acceptance
- Be+Be very close to p+p

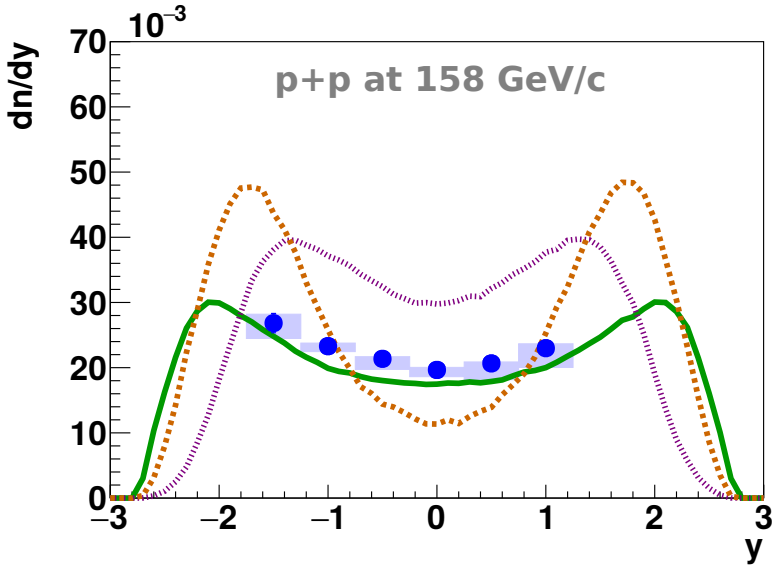
Closer look at the system size dependence



- Surprisingly Be+Be results are very close to p+p independent of collision energy
- Significant jump between light systems and a heavy system
- Waiting on the edge of my sit for Ar+Sc results!

Λ production in p+p

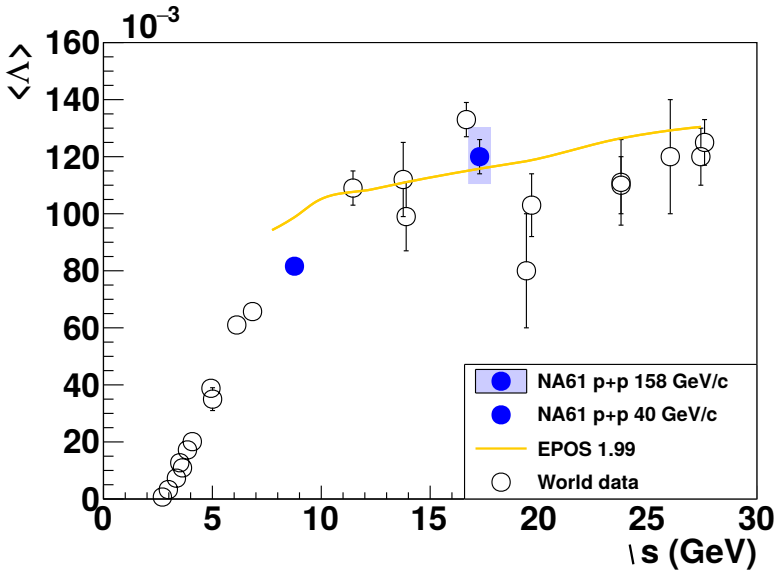


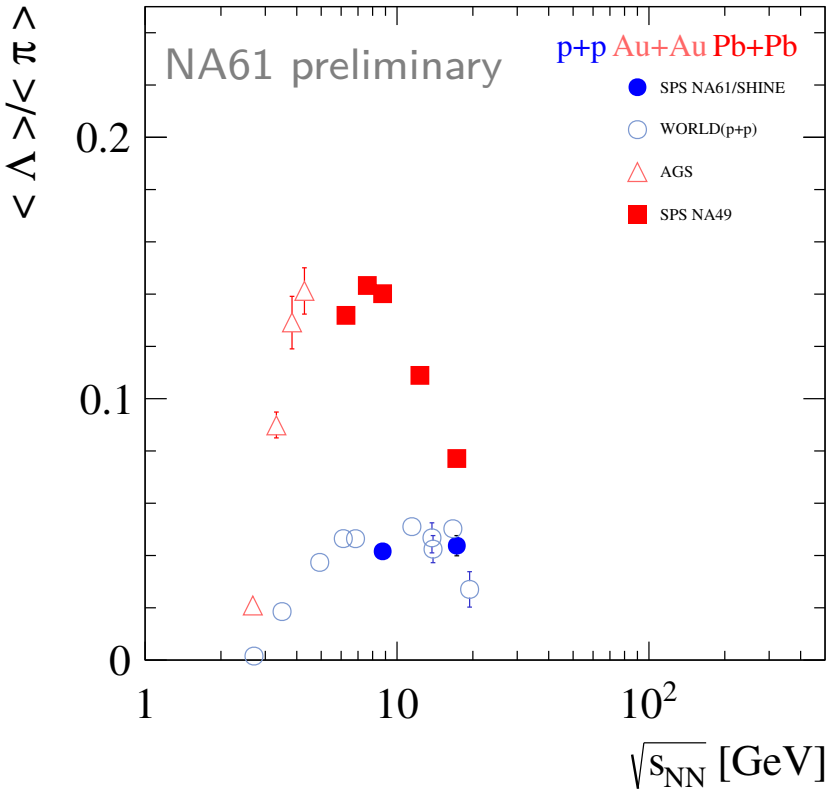


- EPOS close to data, slightly overestimates Λ in high y region
- FRITIOF overestimates $\sim 1.5\times$ at high y region for both momenta, overestimates 40 GeV/c spectrum and underestimates 158 GeV/c spectrum at $y \approx 0$
- UrQMD overestimates $\sim 1.5\times$ at $y \approx 0$ and underestimates spectra at high y region

NA61
EPOS 1.99
FRITIOF 7.02
UrQMD 3.4

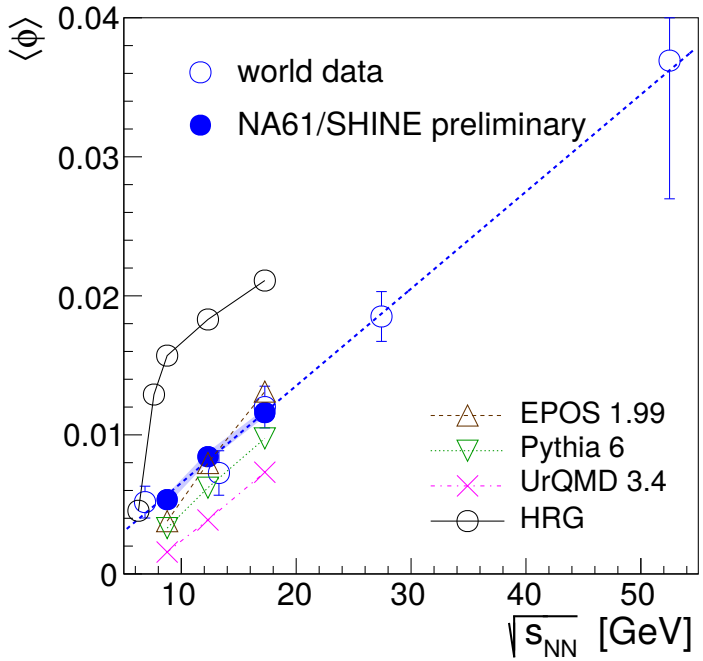
Energy dependence of Λ production and $\frac{\Lambda}{\pi}$ ratio

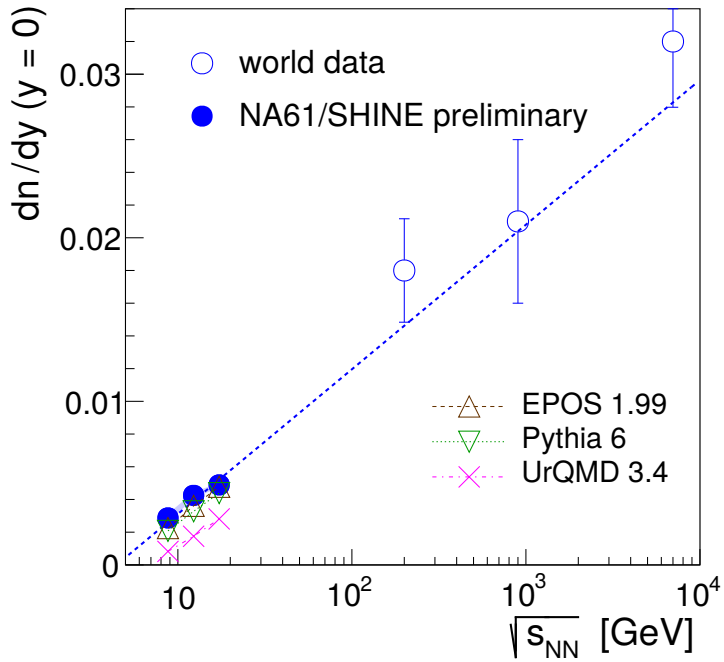




- Results are consistent with world data.
- Smooth energy dependence of Λ production
- EPOS estimates of $\langle\Lambda\rangle$ for 158 GeV/c but overestimates for 40 GeV/c
- $\langle\Lambda\rangle/\langle\pi\rangle$ in p+p reaches a plateau at the SPS energies in contrast to Pb+Pb

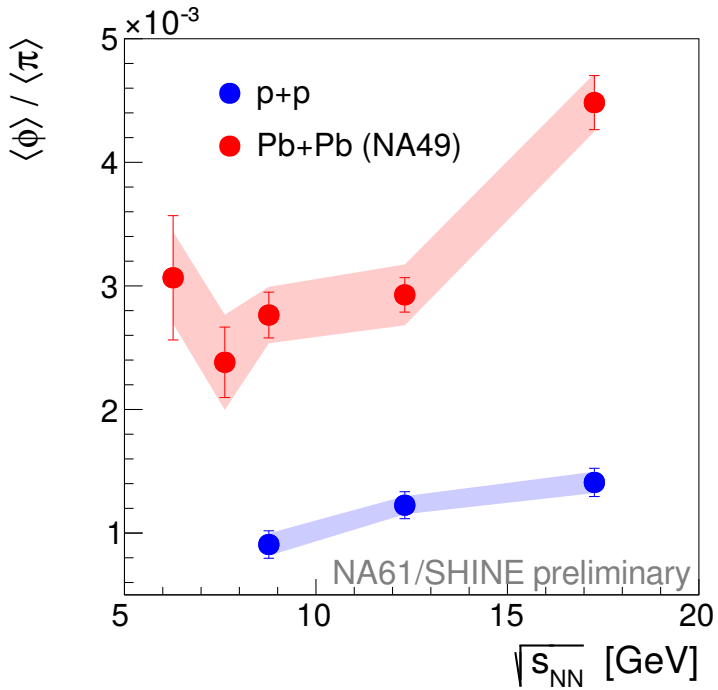
Energy dependence of ϕ production in p+p

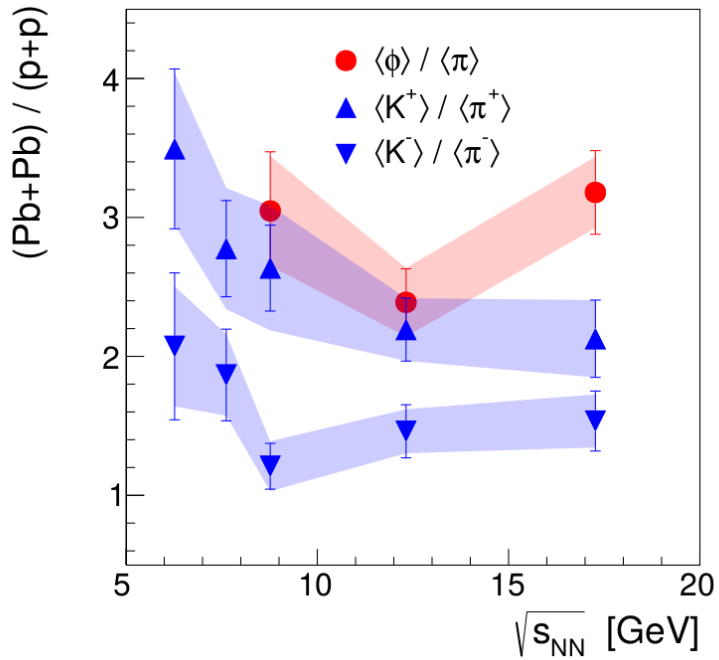




- Results consistent with world data
- EPOS close to data, Pythia underestimates experimental data, UrQMD underestimates $\sim 2\times$, HRG (thermal) overestimates $\sim 2\times$
- EPOS rises too fast with interaction energy

Energy dependence of $\frac{\phi}{\pi}$ ratio

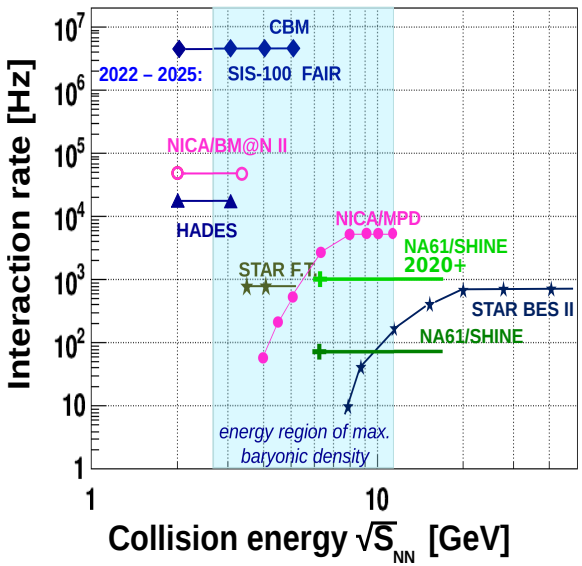


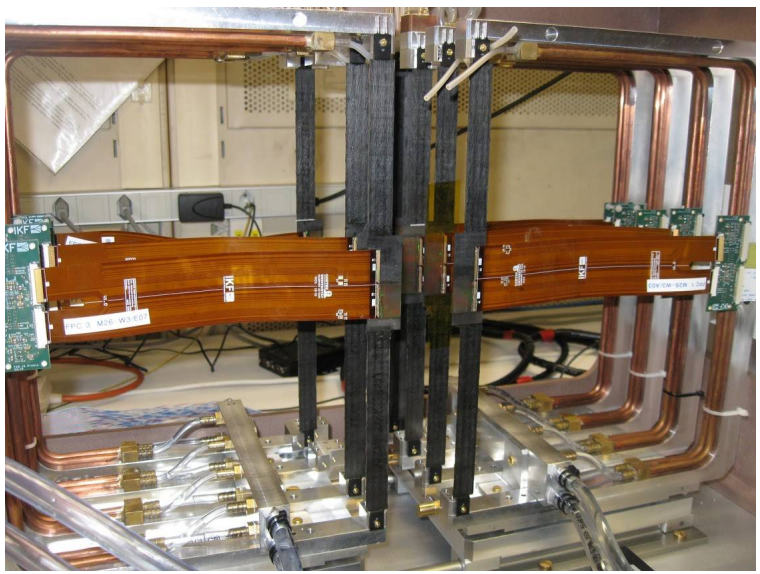


- $\langle\phi\rangle/\langle\pi\rangle$ increases with $\sqrt{s_{NN}}$
- production of $\langle\phi\rangle/\langle\pi\rangle$ in Pb+Pb collisions about 3× larger independently of interaction energy
- Enhancement of $\langle\phi\rangle/\langle\pi\rangle$ is systematically larger than for $\langle K^-\rangle/\langle\pi^-\rangle$ and comparable with $\langle K^+\rangle/\langle\pi^+\rangle$

Summary and outlook

- NA61/SHINE unique system size vs energy scan will be completed with **Xe+La** in 2017 and **Pb+Pb** in 2018
- Recent results of **NA61/SHINE** and **LHC** suggest similarities between **p+p** and **Pb+Pb** hadron production (onset of deconfinement in p+p?)
- Unexpected system size dependence in particle yields ratios and fluctuations (see talk by K. Grebieszkow tomorrow) observed





- **High statistics** beam momentum scan with **Pb+Pb** collisions for precise measurements of **open charm** and **multi-strange hyperon** production as well as **fluctuations**, **event plane** and **collective effects**
- Detector upgrades during Long Shutdown in 2019–2020: **1 kHz readout**, **Large Acceptance Vertex Detector**, ToF, PSD

Backup

NA61/SHINE Collaboration ∼150 physicists from ∼30 institutes

- Azerbaijan
  - National Nuclear Research Center, Baku
- Bulgaria
  - University of Sofia, Sofia
- Croatia
  - IRB, Zagreb
- France
  - LPNHE, Paris
- Germany
  - KIT, Karlsruhe
  - Fachhochschule Frankfurt, Frankfurt
  - University of Frankfurt, Frankfurt
- Greece
  - University of Athens, Athens
- Hungary
  - Wigner RCP, Budapest
- Japan
  - KEK Tsukuba, Tsukuba
- Norway
  - University of Bergen, Bergen
- Poland
  - UJK, Kielce
  - NCBJ, Warsaw
  - University of Warsaw, Warsaw
  - WUT, Warsaw
  - Jagiellonian University, Kraków
  - IFJ PAN, Kraków
  - AGH, Kraków
  - University of Silesia, Katowice
  - University of Wrocław, Wrocław
- Russia
  - INR Moscow, Moscow
  - JINR Dubna, Dubna
  - SPBU, St.Petersburg
  - MEPhI, Moscow
- Serbia
  - University of Belgrade, Belgrade
- Switzerland
  - ETH Zürich, Zürich
  - University of Bern, Bern
  - University of Geneva, Geneva
- USA
  - University of Colorado Boulder, Boulder
  - LANL, Los Alamos
  - University of Pittsburgh, Pittsburgh
  - FNAL, Batavia
  - University of Hawaii, Manoa

Publications from the NA61/SHINE two-dimensional scan

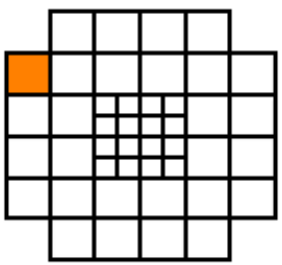
1. p+p collisions at 13, 20, 31, 40, 80, and 158 GeV/c
   - 1.1 π^- production in p+p at 20–158 GeV/c; based on h^- method [1]
   - 1.2 $\pi^\pm$, $K^\pm$, $\bar{p}$ production in p+p at 20–158 GeV/c; based on information from dE/dx and *tof*-dE/dx [2]; see also Ref. [3] for identified particle multiplicities in 4π
   - 1.3 Λ production in p+p at 40 [4] and 158 GeV/c [5]
   - 1.4 Transverse momentum and multiplicity fluctuations of non-identified hadrons in p+p at 20–158 GeV/c [6]; a new set of preliminary results for p+p in a slightly different acceptance was shown in Refs. [7, 8]
   - 1.5 Two-particle correlations of non-identified hadrons in azimuthal angle and pseudo-rapidity in p+p at 20–158 GeV/c [9, 10]
   - 1.6 Multiplicity fluctuations of identified particles (chemical fluctuations) in p+p at 31–158 GeV/c [11]; additional preliminary results on $\pi^+\pi^-$ fluctuations were shown in Refs. [12, 13]
   - 1.7 Higher order moments of multiplicity and net-charge fluctuations in p+p at 31–158 GeV/c [7, 14]
2. Be+Be collisions at 13A, 19A, 30A, 40A, 75A, and 150A GeV/c
   - 2.1 π^- production in Be+Be at 20–150A GeV/c; based on h^- method [15, 16]
   - 2.2 Cross-section in Be+Be at 13–150A GeV/c [15, 7] (Ref. [7] shows updated results and for all energies)
   - 2.3 $K^\pm$ spectra at mid-rapidity in Be+Be at 30–150A GeV/c (Ref: [17])
   - 2.4 Transverse momentum and multiplicity fluctuations of non-identified hadrons in Be+Be at 19–150A GeV/c [18, 7] (those two references show results in slightly different acceptances)
   - 2.5 Long-range correlations (in multiplicities and mean transverse momenta) in Be+Be at 150A GeV/c [19]
   - 2.6 Long-range fluctuations (in electric charge) in Be+Be at 150A GeV/c [20]

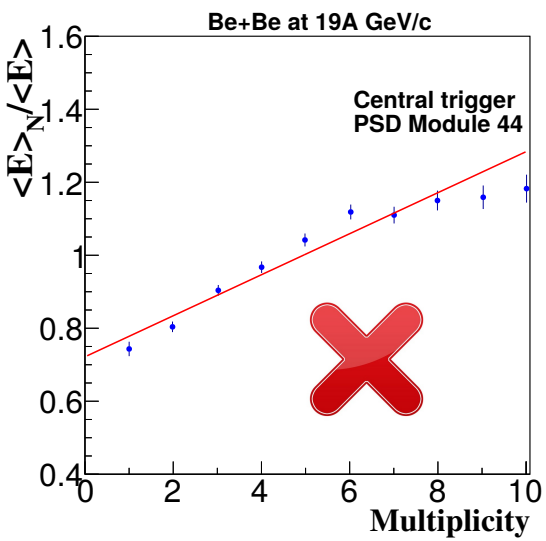
Publications from the NA61/SHINE two-dimensional scan

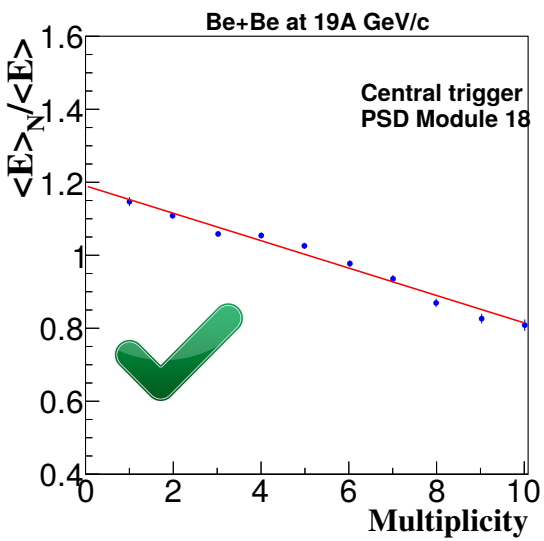
3. Ar+Sc collisions at 13A, 19A, 30A, 40A, 75A, and 150A GeV/c
   - 3.1 π^- production in Ar+Sc at 13–150A GeV/c; based on h$^-$ method [21, 22, 7]
   - 3.2 Transverse momentum and multiplicity fluctuations of non-identified hadrons in Ar+Sc at 19–150A GeV/c [8, 7]
   - 3.3 Multiplicity and multiplicity-forward energy fluctuations in Ar+Sc at 19–150A GeV/c [23, 7]

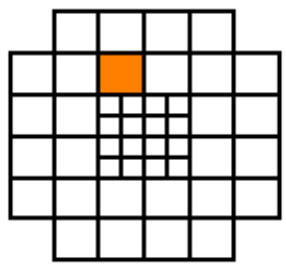
Event selection based on E_F measurements

- Due to different magnetic field setting and PSD position for various beam momenta, selection of PSD modules for E_F calculation depends on reaction
- The module selection is based on correlation between energy deposit in a module and track multiplicity in TPC
- Negative correlation implies dominance of spectators hitting the module

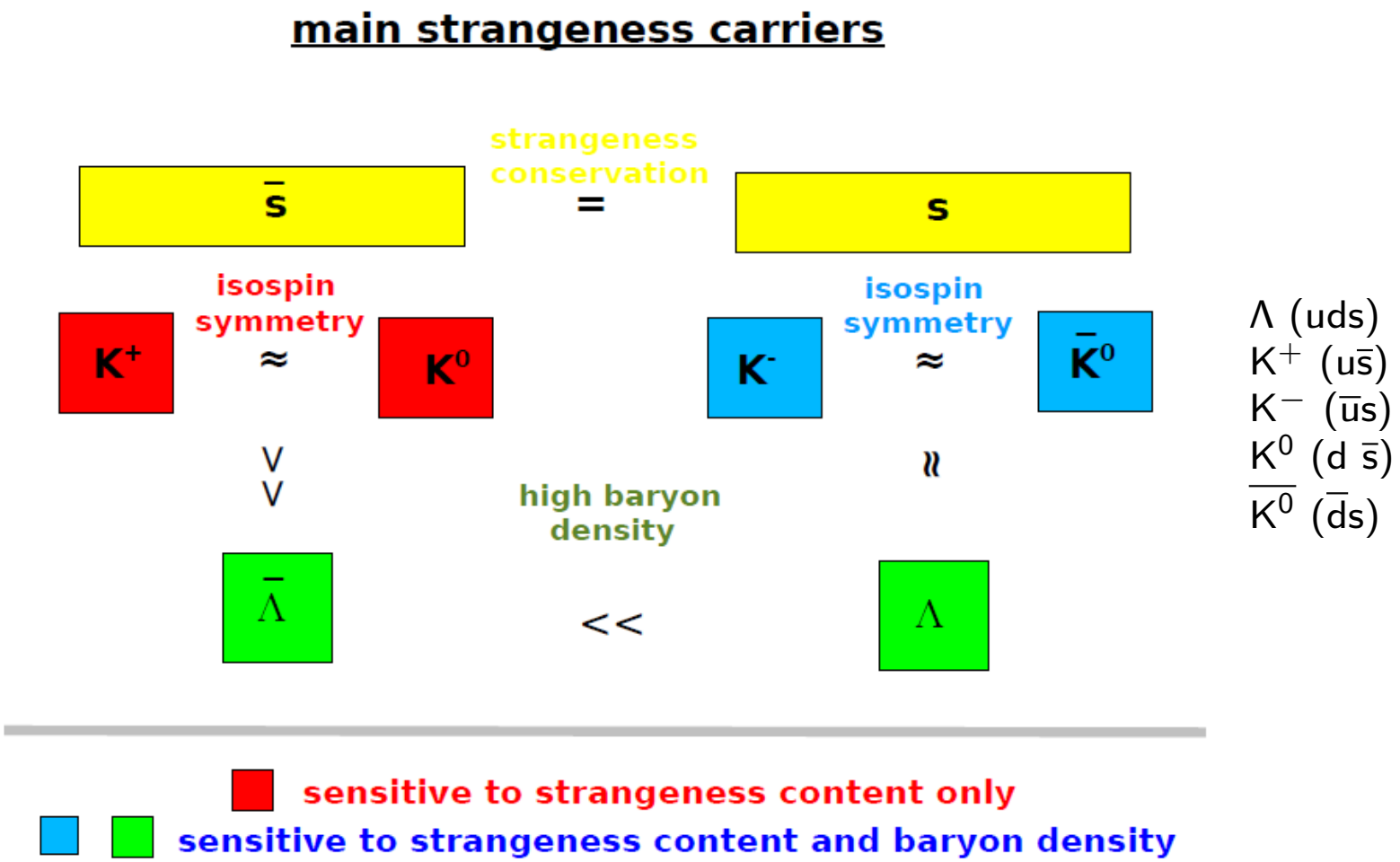








Examples of correlation between energy in a PSD module and track multiplicity in TPC for ^{7}Be+^{9}Be collisions 19A GeV/c

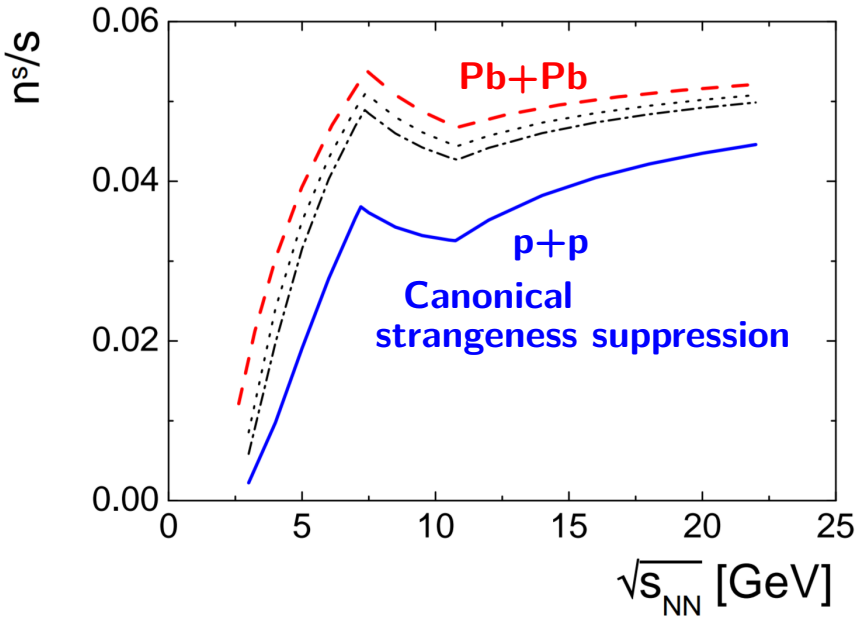


Λ (uds)
K^+ ($u\bar{s}$)
K^- ($\bar{u}s$)
K^0 ($d\ \bar{s}$)
$\overline{K^0}$ ($\bar{d}s$)

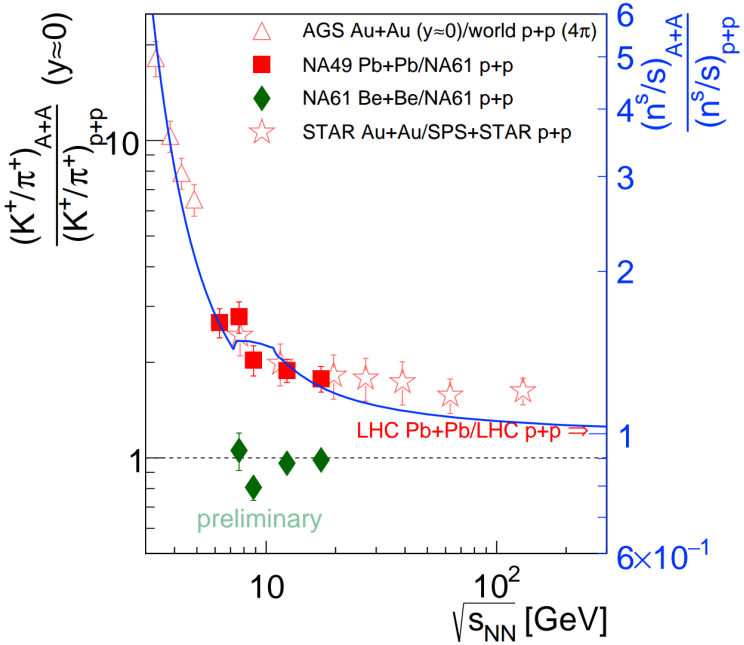
Difference in $\langle K^+ \rangle$ and $\langle K^- \rangle$ production due to different sensitivity to baryon density. At SPS energies lambdas have significant influence on total strangeness production ($\overline{\Lambda}$ not).

Study of the onset of deconfinement in p+p interactions

Statistical Model with phase transition (SMES):



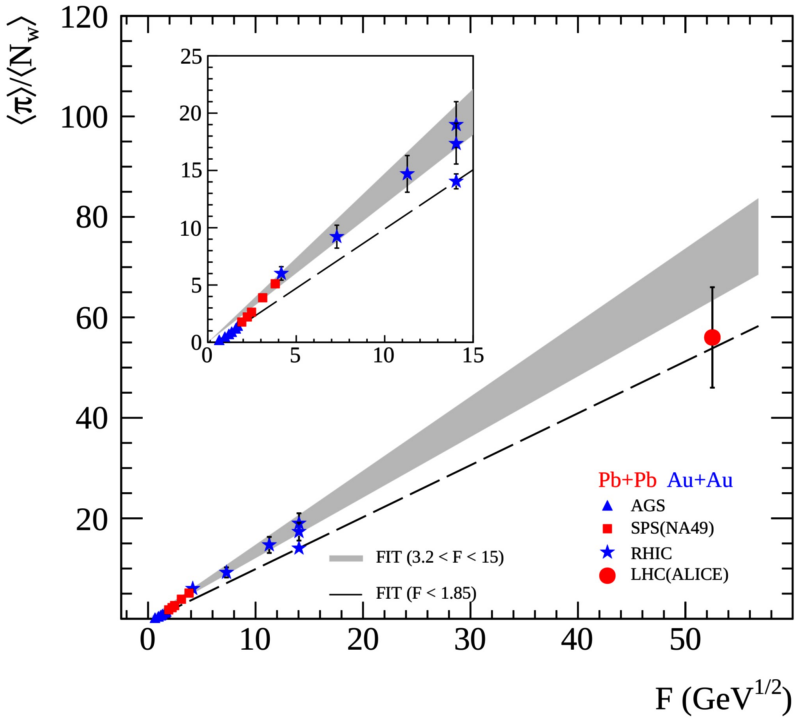
RVP, MG and MG, APP B46, 1991 (2015)



assumption: $K^+/\pi^+ = a(n_s/s) + b$

- Recent results of NA61/SHINE and LHC clearly suggest that p+p and Pb+Pb are qualitatively similar, e.g. rapid change of K^+/π^+ ratio at SPS energies and collective flow at LHC energies in p+p
- Be+Be interactions are very close to p+p

KINK in LCH energy range



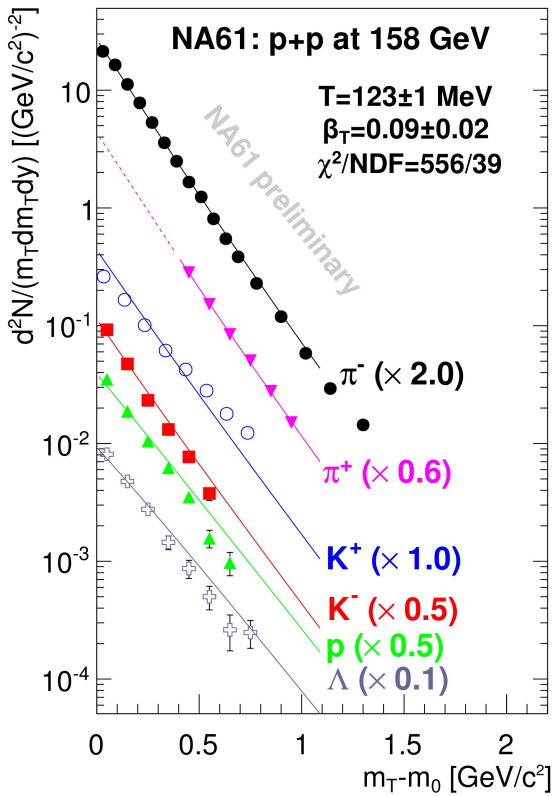
- Kink: increased entropy
- Pions measure early stage entropy.
- In SMES
  $< \pi > / < W > \sim (ndf)^{\frac{1}{4}}$
- Change of slope around $30A$ GeV$/c$
- No change of slope in p+p data (not shown)
- $< \pi >$ at LHC was estimated based on ALICE N_{ch} measurement

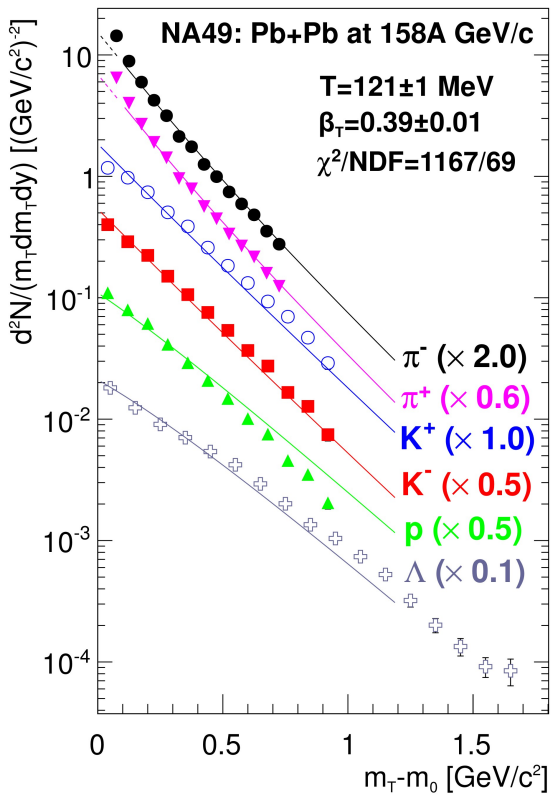
m_T spectra in p+p described with Blast Wave model

$$\frac{dN_i}{m_T dm_T dy} = A_i m_T K_1\left(\frac{m_T \cosh\rho}{T}\right) I_0\left(\frac{p_T \sinh\rho}{T}\right)$$

PR C48, 2462 (1993)

$$\rho = \text{atanh}\beta_T$$



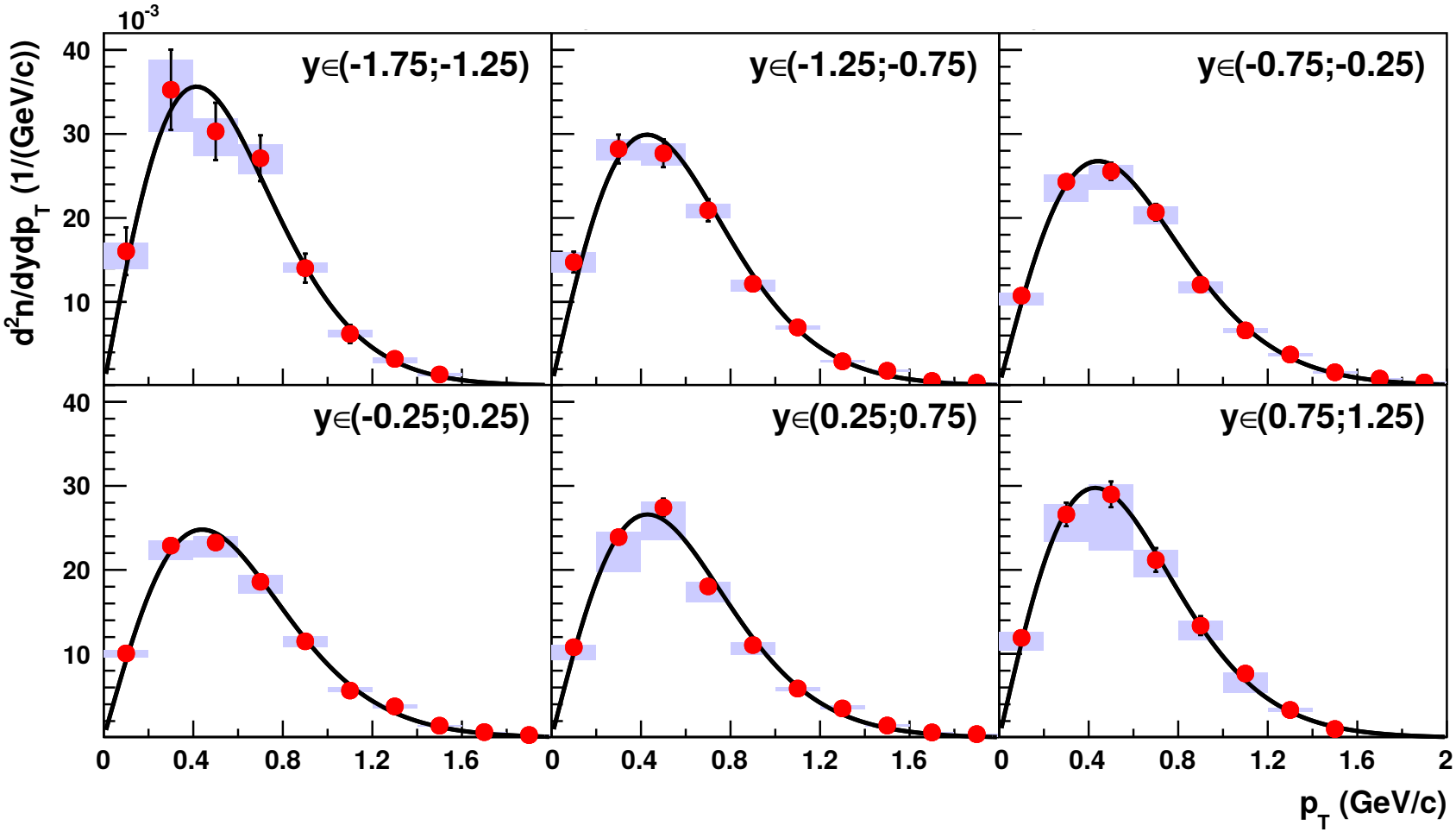


NA61/Shine
SPSC report 2014
and
arXiv:1510.00674

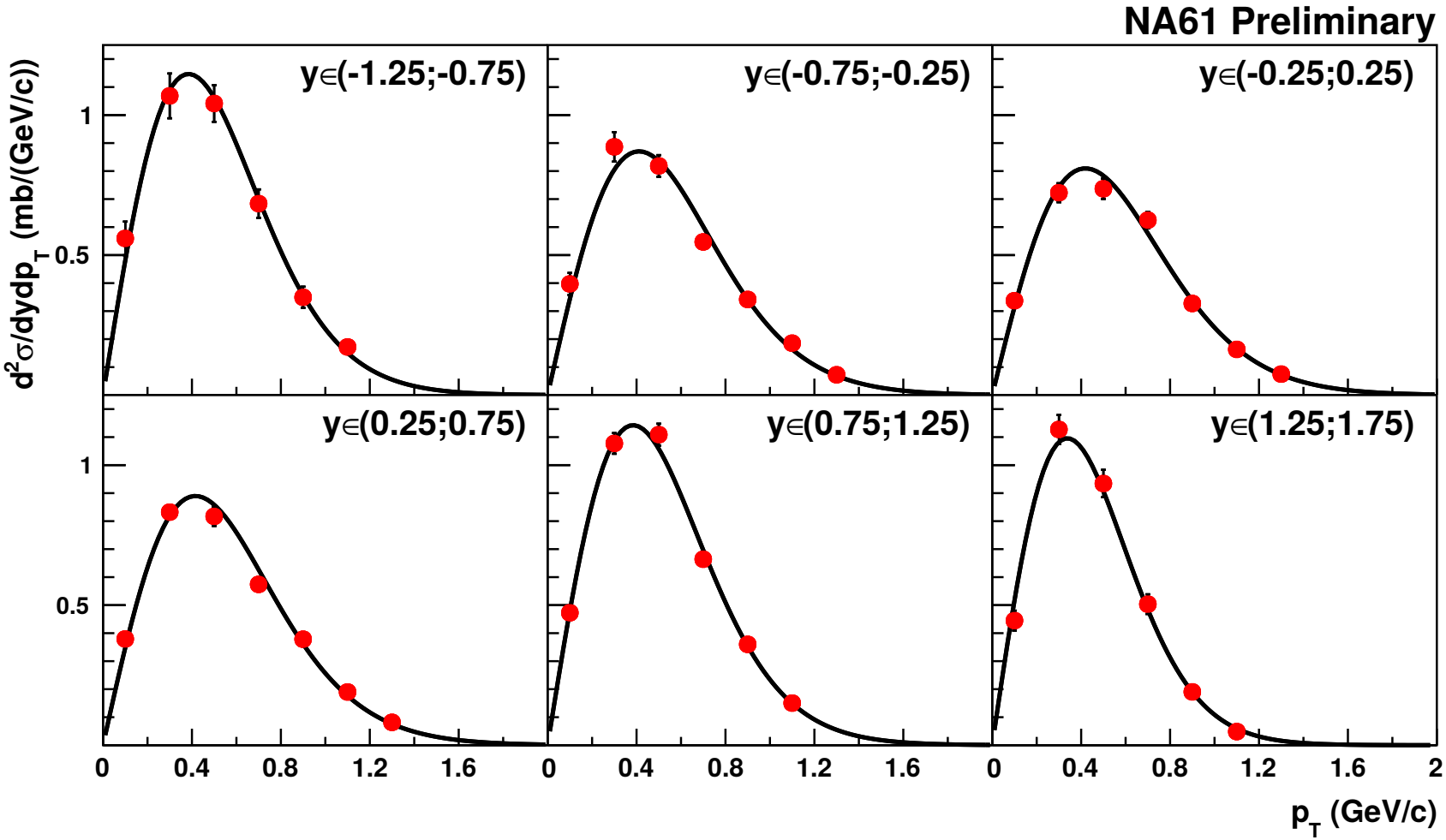
$$\frac{1}{p_T}\frac{dN}{dp_T} = \frac{1}{m_T}\frac{dN}{dm_T}$$

- Transverse mass spectra are approximately exponential

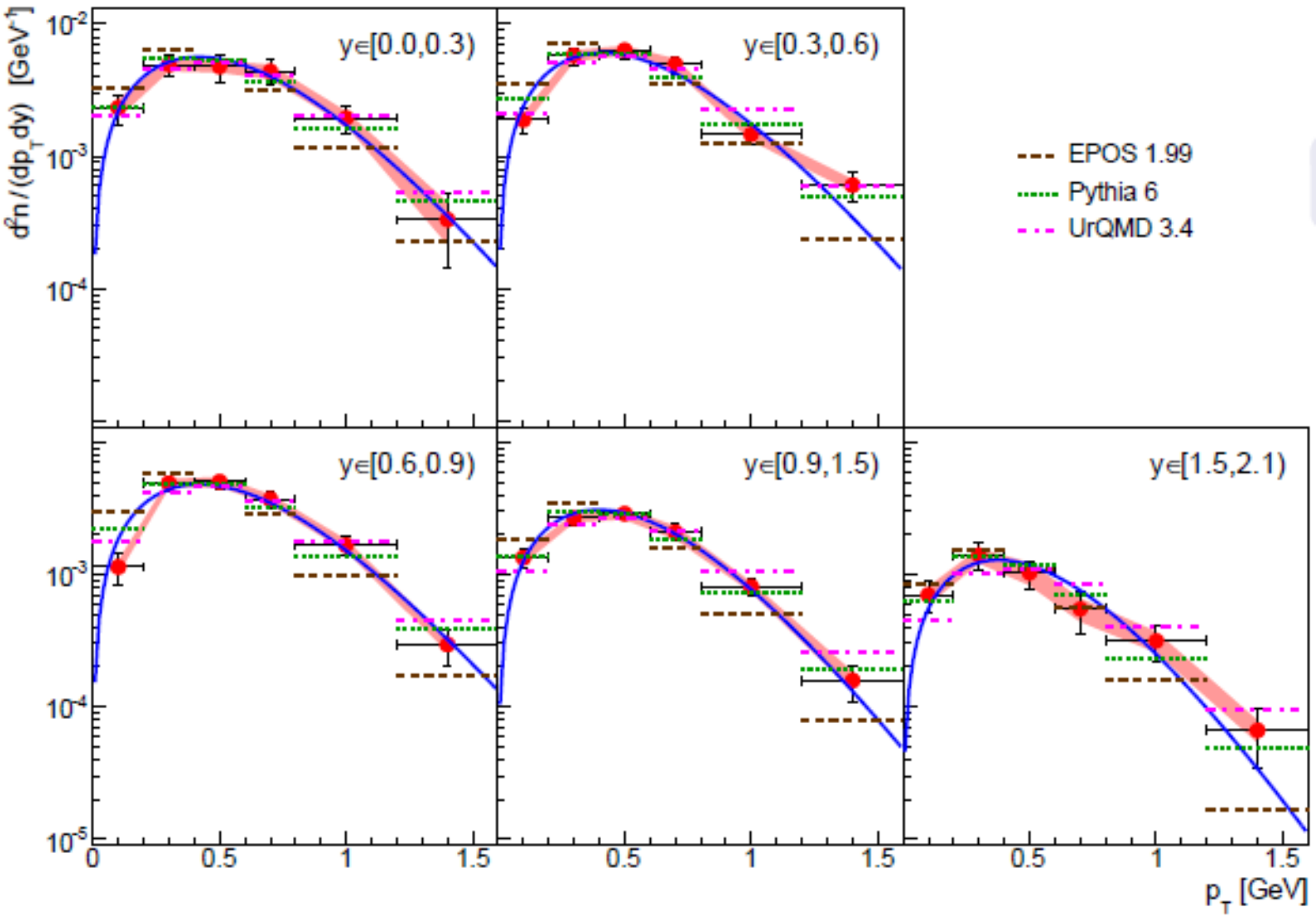
Λ p_T spectra at 158 GeV/c



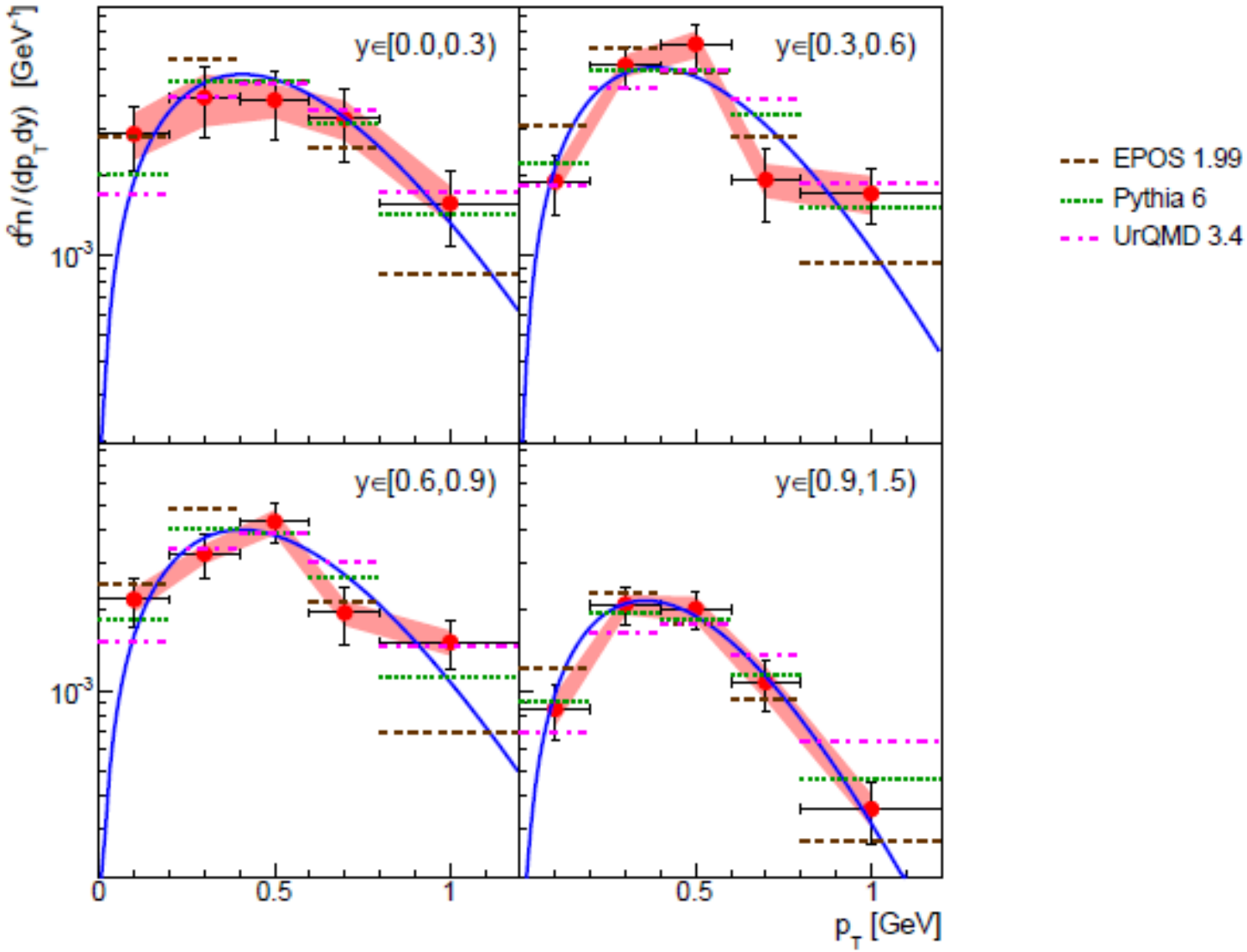
Λ p_T spectra at 40 GeV/c



ϕ spectra at 158 GeV/c

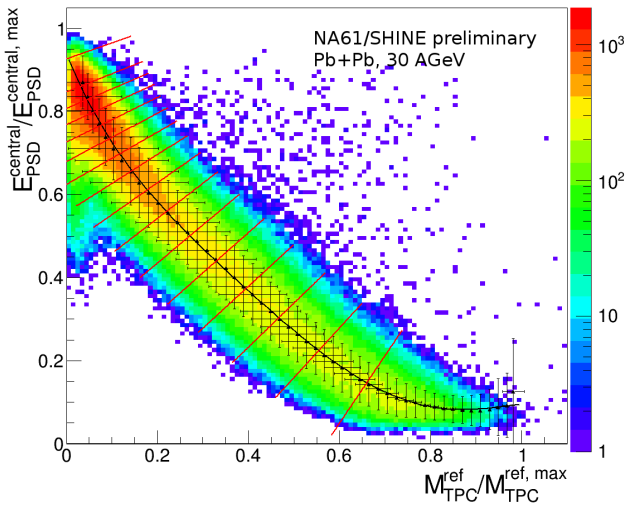


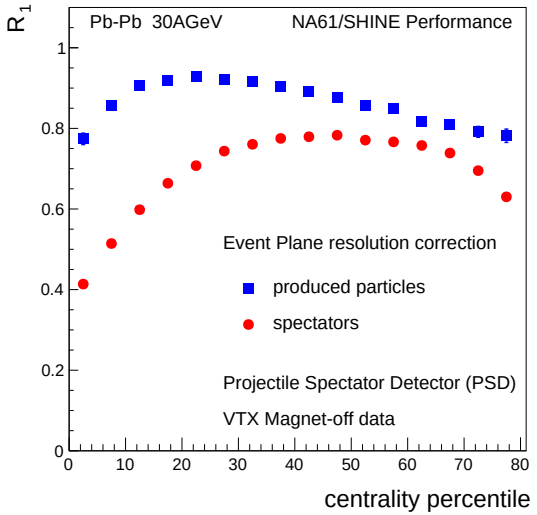
ϕ spectra at 80 GeV/c



Event plane

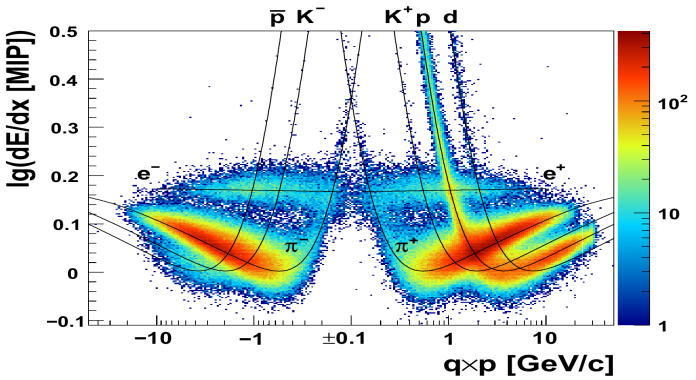
- NA61/SHINE attempts to measure **event plane** as well as direct flow

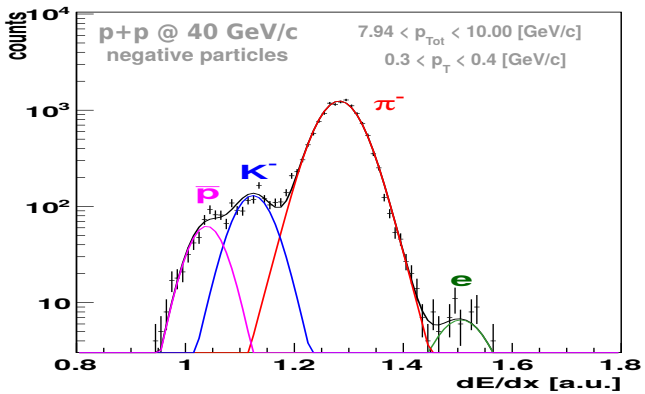


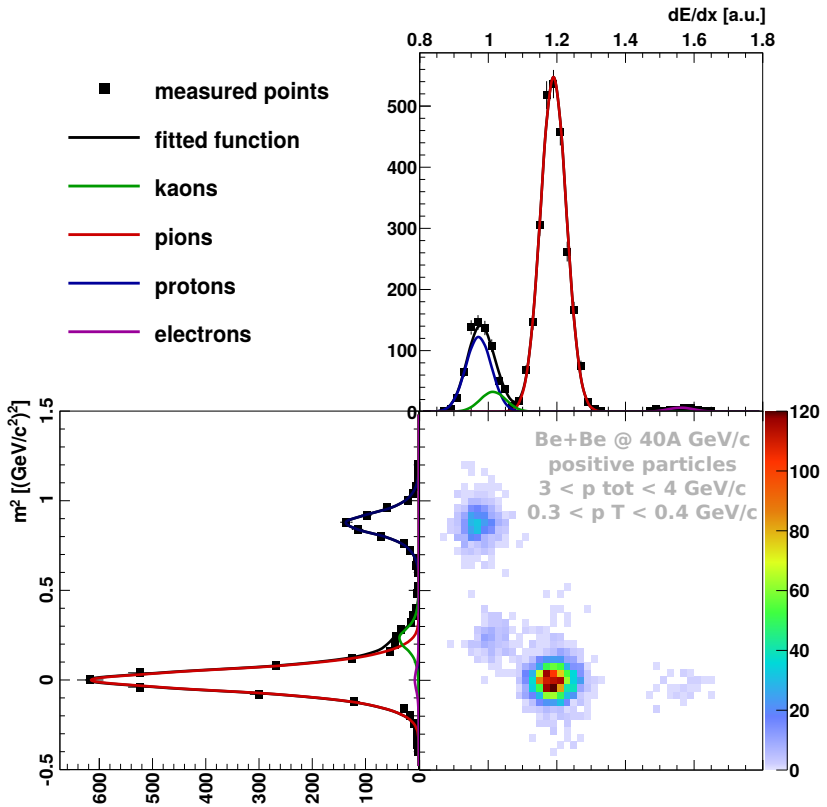


- Inspite of the **non-uniform azimuthal acceptance** measurements will benefit from **transversal and longitunal granularity of the forward calorimeter**

Particle identification

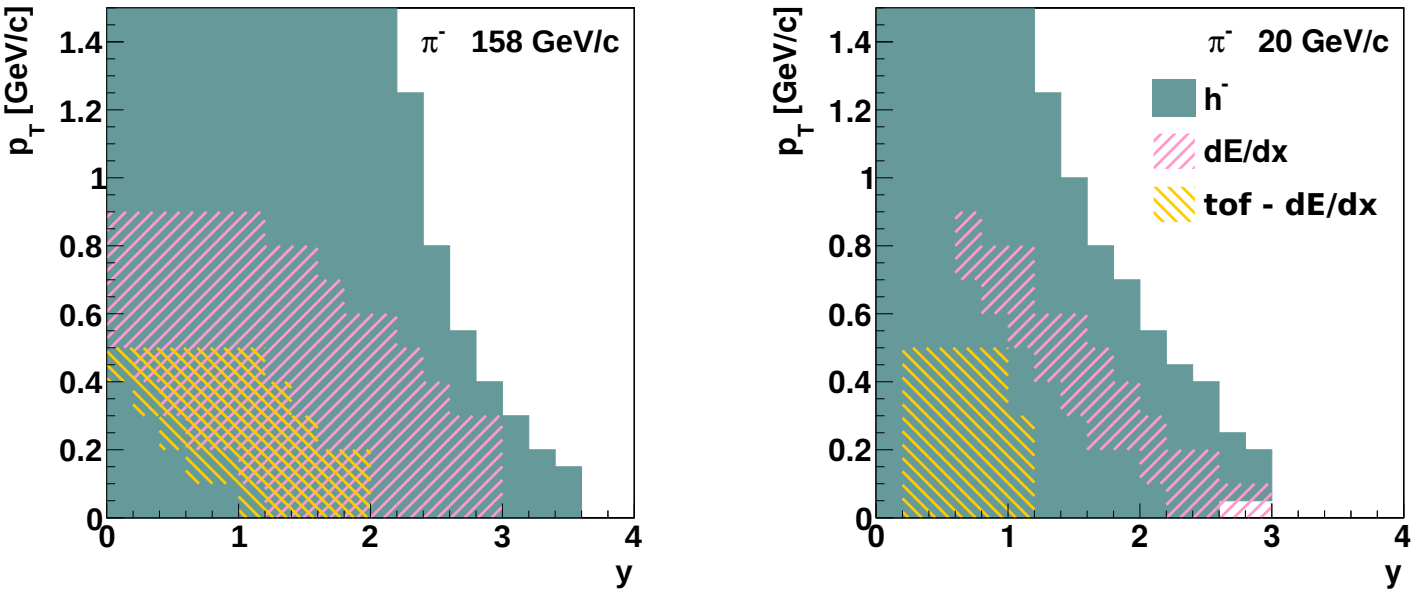






- *dE/dx* method estimates number of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ using an energy loss measurement
- *tof-dE/dx* method estimates number of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ using an energy loss and a particle time of flight measurements

Particle identification



- h^- method estimates number of π^- in large phase space based on fact that majority of negatively charged particles produced in p+p and A+A collisions are π^-
- Non–π^- contamination is corrected for by models (typically EPOS 1.99)
- All methods are complementary, allow for cross check and covering the large part of the phase space
- Final results stand for primary particles produced in strong and electromagnetic processes, they are corrected for detector geometrical acceptance and reconstruction efficiency as well as weak decays and secondary interactions

Bibliography I

[1] N. Abgrall *et al.*, [NA61/SHINE Collab.] *Eur.Phys.J.* **C74** (2014) 2794, arXiv:1310.2417 [hep-ex].

[2] S. Pulawski, [NA61 Collab.] *PoS* **CPOD2014** (2015) 010, arXiv:1502.07916 [nucl-ex].

[3] A. Aduszkiewicz, [NA61/SHINE Collab.], "Report from the NA61/SHINE experiment at the CERN SPS," Oct, 2015. http://cds.cern.ch/record/2059310.

[4] H. Stroebele, [NA61/SHINE Collab.], "New(s) from NA61: Λ in p+p and π^- in Ar+Sc," 2016. talk at the 16th International Conference on Strangeness in Quark Matter (SQM 2016) Berkeley, USA, June 27-July 1, 2016 (proceedings to be published), https://indico.cern.ch/event/403913/contributions/2142033/attachments/1300036/1940346/1000_HS-SQM16_final.pdf .

[5] A. Aduszkiewicz *et al.*, [NA61/SHINE Collab.] *Eur. Phys. J.* **C76** no. 4, (2016) 198, arXiv:1510.03720 [hep-ex].

[6] A. Aduszkiewicz *et al.*, [NA61/SHINE Collab.] *Eur. Phys. J.* **C76** (2016) 635, arXiv:1510.00163 [hep-ex].

[7] K. Grebieszkow, [NA61/SHINE Collab.], "News from strong interactions program of the NA61/SHINE experiment," in *10th International Workshop on Critical Point and Onset of Deconfinement (CPOD 2016) Wroclaw, Poland, May 30-June 4, 2016*. 2016. arXiv:1608.01538 [nucl-ex]. http://inspirehep.net/record/1479456/files/arXiv:1608.01538.pdf.

[8] E. Andronov, [NA61/SHINE Collab.], "Transverse momentum and multiplicity fluctuations in Ar+Sc collisions at CERN SPS from NA61/SHINE," 2016. talk at 10th International Workshop on Critical Point and Onset of Deconfinement (CPOD 2016) Wroclaw, Poland, May 30-June 4, 2016 (proceedings to be published), https://indico.cern.ch/event/449173/contributions/2167165/attachments/1280888/1902801/EA_cpod.pdf .

[9] B. Maksiak, [NA61/SHINE Collab.] *PoS* **CPOD2014** (2015) 055, arXiv:1503.02470 [nucl-ex].

[10] A. Aduszkiewicz *et al.*, [NA61/SHINE Collab.] *Eur. Phys. J.* **C77** no. 2, (2016) 59, arXiv:1610.00482 [nucl-ex].

[11] M. Mackowiak-Pawlowska, [NA61/SHINE Collab.] *PoS* **CPOD2013** (2013) 048.

[12] N. Abgrall, [NA61/SHINE Collab.], "Report from the NA61/SHINE experiment at the CERN SPS," Oct, 2014. http://cds.cern.ch/record/1955138.

Bibliography II

[13] M. Mackowiak-Pawlowska, [NA61/SHINE Collab.], "Fluctuations and correlations from the energy scan in p+p and Be+Be interactions at the SPS energies," 2015.
talk at the XI Polish Workshop on Relativistic Heavy-Ion Collisions,
https://indico.cern.ch/event/348749/contributions/1754804/attachments/688461/945511/pwhir.pdf .

[14] M. Mackowiak-Pawlowska, [NA61/SHINE Collab.], "Higher order moments of net-charge and multiplicity distributions in p+p interactions at SPS energies from NA61/SHINE," 2016.
talk at 10th International Workshop on Critical Point and Onset of Deconfinement (CPOD 2016) Wroclaw, Poland, May 30-June 4, 2016 (proceedings to be published),
https://indico.cern.ch/event/449173/contributions/2167176/attachments/1284531/1909796/cpod2016_mmp.pdf .

[15] E. Kaptur, [NA61/SHINE Collab.] *PoS* **CPOD2014** (2015) 053.

[16] S. Pulawski, [NA61/SHINE Collab.] *Acta Phys. Polon.* **B46** no. 11, (2015) 2381, arXiv:1510.07794 [nucl-ex].

[17] A. Aduszkiewicz, [NA61/SHINE Collab.], "Recent results from NA61/SHINE,"
2017.
arXiv:1704.08071 [hep-ex].
http://inspirehep.net/record/1596898/files/arXiv:1704.08071.pdf.

[18] T. Czopowicz, [NA61/SHINE Collab.] *PoS* **CPOD2014** (2015) 054, arXiv:1503.01619 [nucl-ex].

[19] A. Seryakov, [NA61/SHINE Collab.] *J. Phys. Conf. Ser.* **668** no. 1, (2016) 012077, arXiv:1510.00847 [nucl-ex].

[20] E. Andronov, [NA61/SHINE Collab.] *J. Phys. Conf. Ser.* **668** no. 1, (2016) 012036, arXiv:1510.00174 [nucl-ex].

[21] M. Naskret, [NA61/SHINE Collab.], "Mean pion multiplicities in Ar+Sc collisions," 2016.
talk at 10th International Workshop on Critical Point and Onset of Deconfinement (CPOD 2016) Wroclaw, Poland, May 30-June 4, 2016 (proceedings to be published),
https://indico.cern.ch/event/449173/contributions/2175377/attachments/1280844/1902710/05_25_16.pdf .

[22] M. Lewicki, [NA61/SHINE Collab.], "Pion spectra in Ar+Sc interactions," 2016.
talk at 10th International Workshop on Critical Point and Onset of Deconfinement (CPOD 2016) Wroclaw, Poland, May 30-June 4, 2016 (proceedings to be published),
https://indico.cern.ch/event/449173/contributions/2176292/attachments/1285437/1911664/cpod_draft.pdf .

Bibliography III

[23] A. Seryakov, [NA61/SHINE Collab.], "Centrality determination and multiplicity fluctuations in Ar+Sc collisions at CERN SPS from NA61/SHINE," 2016.
talk at 10th International Workshop on Critical Point and Onset of Deconfinement (CPOD 2016) Wroclaw, Poland, May 30-June 4, 2016 (proceedings to be published),
https://indico.cern.ch/event/449173/contributions/2176683/attachments/1281405/1903798/Seryakov_CPOD_2016_v4.pdf .