Recent results from NA61/SHINE

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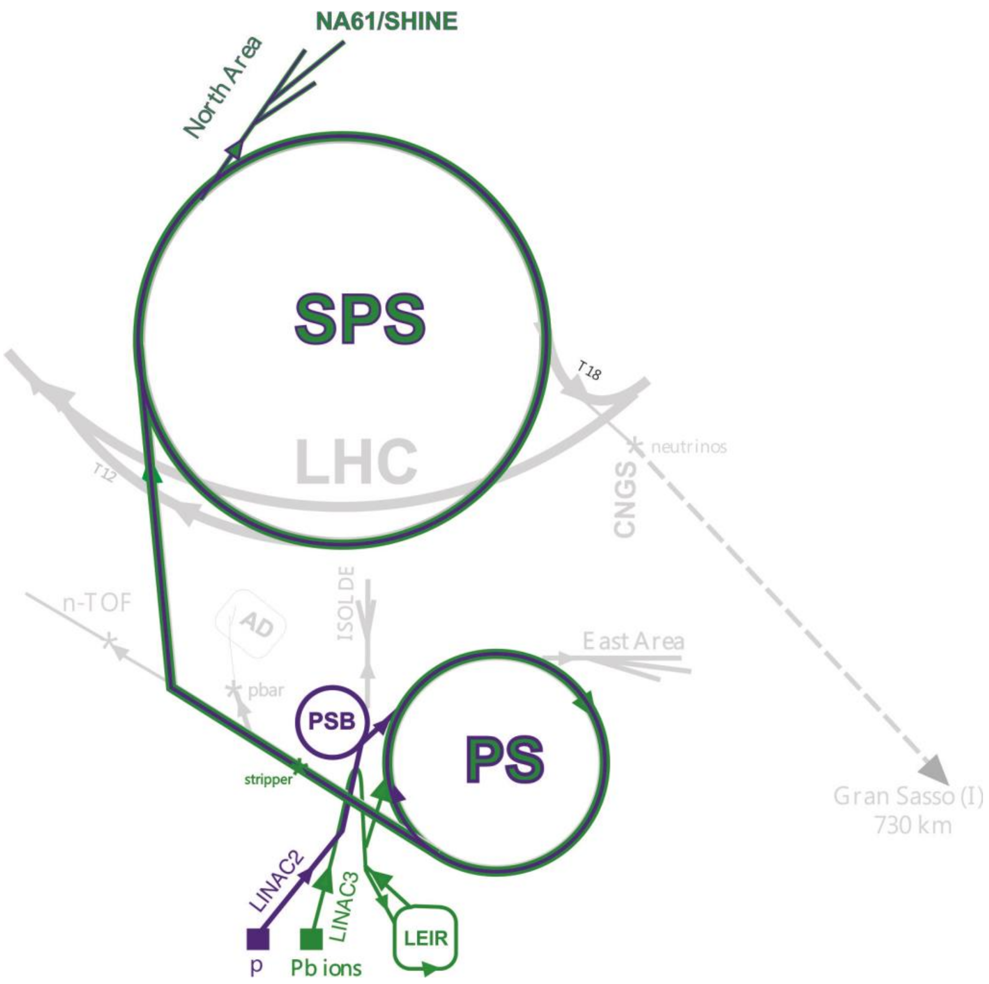
NA61/SHINE - Physics program

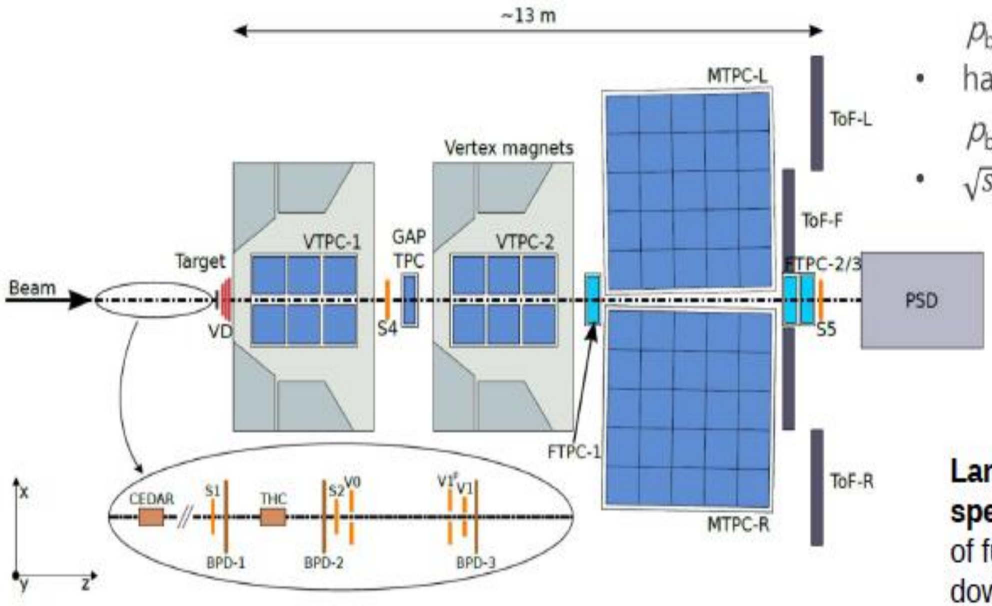
- **Strong interactions program**
  - **search for the critical point of strongly interacting matter**
  - **study of the properties of the onset of deconfinement**
  - **study high p_T particles production (energy dependence of nuclear modification factor)**
- Hadron-production measurements for neutrino experiments
  - reference measurements for the neutrino experiment for computing initial neutrino fluxes at J-PARC, FERMILAB
- Hadron-production measurements for cosmic ray experiments
  - reference measurements of p+C, p+p, π+C, and K+C interactions for cosmic-ray physics (Pierre-Auger, KASCADE) for improving air shower simulations
  - measurement of Nuclear Fragmentation Cross Sections of intermediate mass nuclei needed to understand the propagation of cosmic rays in our Galaxy (background for dark matter searches with space-based experiments as AMS)

NA61/SHINE - Acceleration chain



- Primary beams:
  - Protons at 400 GeV/c
  - Ions (Ar, Xe, Pb) at 13A – 150A GeV/c
- Secondary beams:
  - Hadrons ($\pi^{+/-}$, $K^{+/-}$, anty-p) at 13 - 400 GeV/c
  - Ions (Be) at 13A - 150A GeV/c

NA61/SHINE - Experimental layout



Beams:

- ions (Be, Ar, Xe, Pb)
  p_{beam}=13*A*–150*A* GeV/c
- hadrons (π, K, p)
  p_{beam}=13–400 GeV/c
- $\sqrt{s_{NN}}$= 5.1–16.8 (27.4) GeV

Large acceptance hadron spectrometer – coverage of full forward hemisphere, down to $p_T = 0$

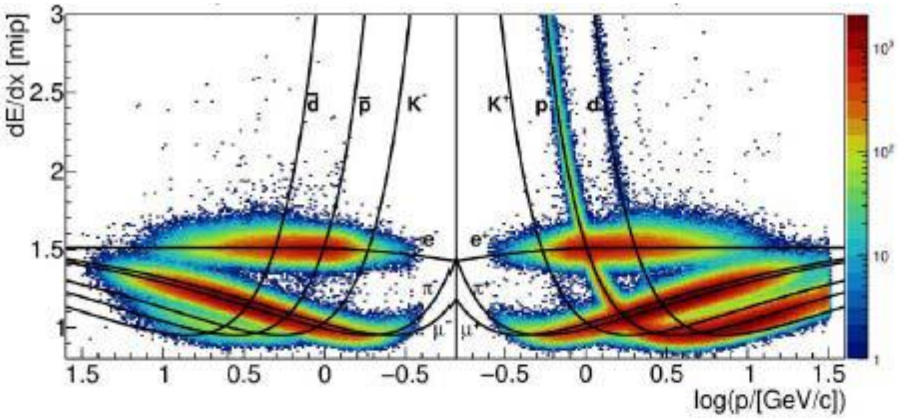
Large acceptance hadron spectrometer

- **Beam particles measured in set of counters and position detectors**
- **Tracks of charged particles measured in set of TPCs: measurement of q, p and identification by energy loss measurement**
- **3 Time of Flight Walls: identification via time of flight measurement**
- **Projectile Spectator Detector measures the forward energy which characterizes centrality of collision**

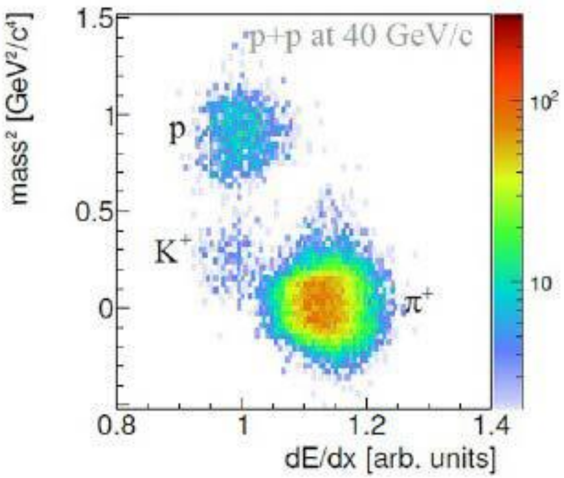
Recent upgrades:

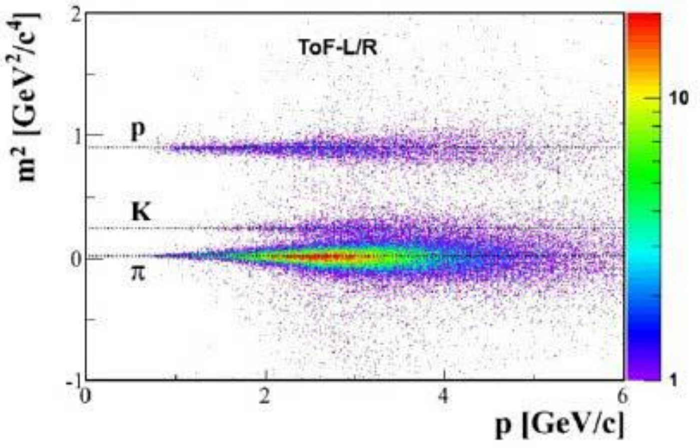
- **Vertex Detector (open charm measurements)**
- **FTPC-1/2/3**

NA61/SHINE Performance



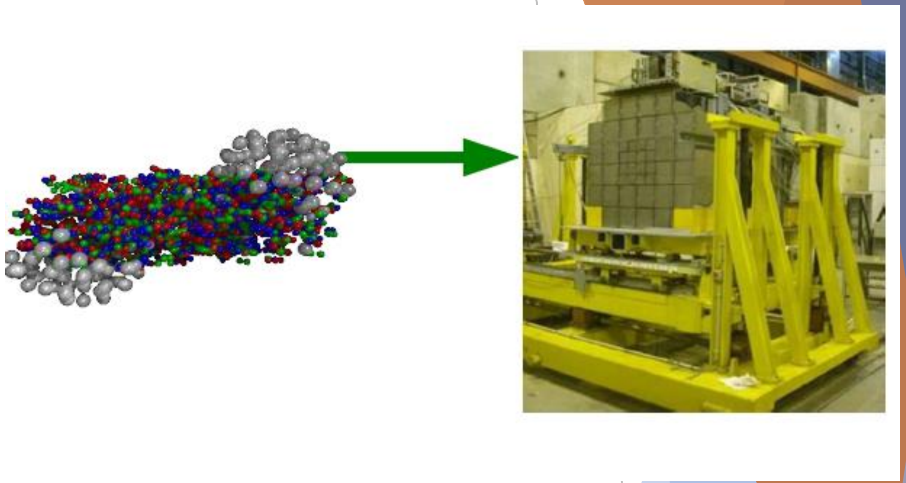
$$\sigma(p)/p^2 \approx 10^{-4}(GeV/c)^{-1}$$
$$\sigma(dE/dx) \approx 4\%$$
$$\sigma(ToF) \approx 100\,ps$$



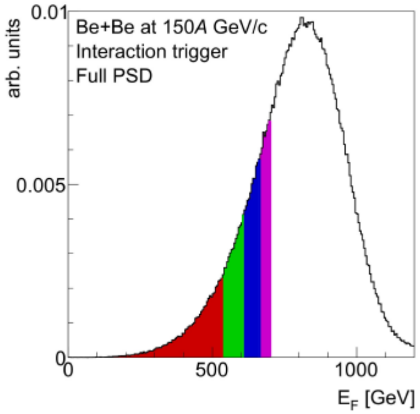


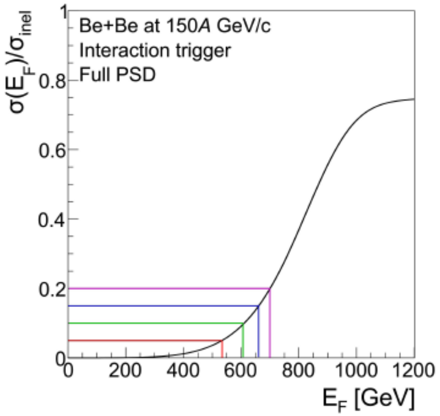
Centrality selection in ion collisions

- Centrality is measured using Projectile Spectator Detector (PSD)
- PSD is located on the beam axis and measures the forward energy E_F related to the non-interacting nucleons of the beam nucleus
- Intervals in E_F allow to select different centrality classes



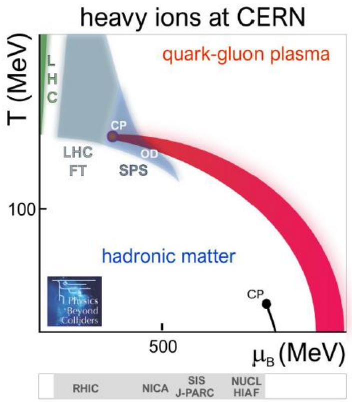
0 - 5% 5 - 10% 10 - 15% 15 – 20%

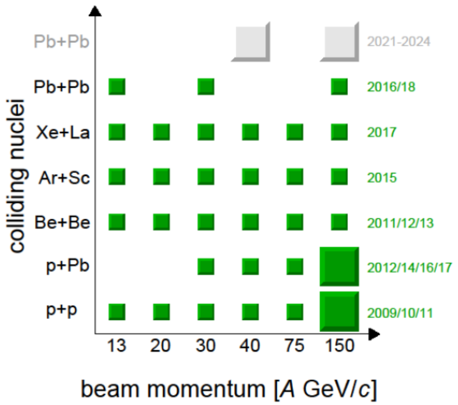




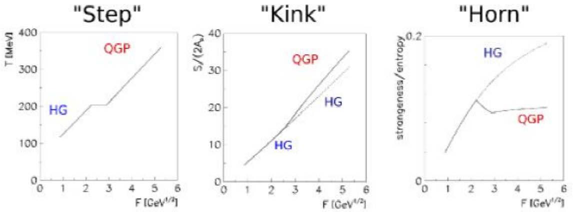
NA61/SHINE 2-dimensional scan

NA61/SHINE performerd the 2D scan in **collision energy and system size** to study the phase diagram of strongly interacting matter



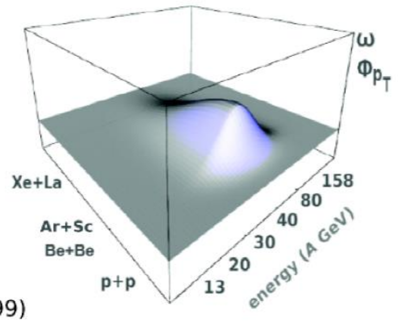


Statistical Model of the Early Stage (SMES)



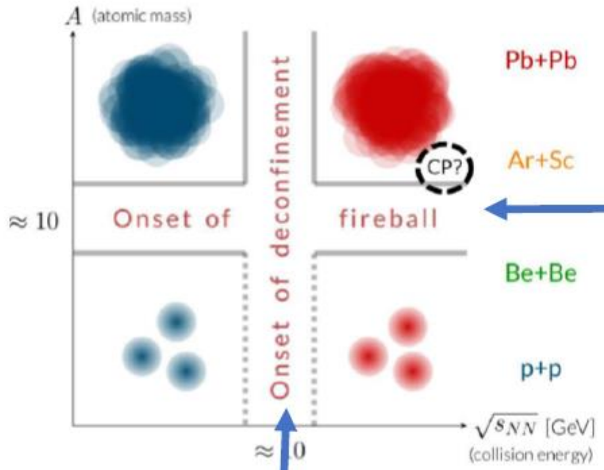
$F \approx \sqrt[4]{s_{NN}}$

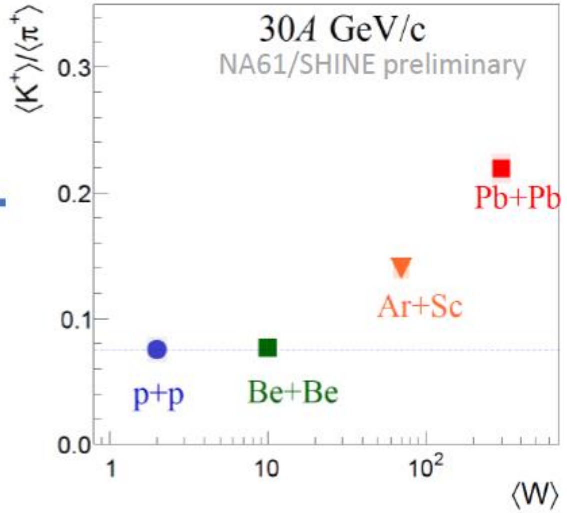
Gaździcki, Gorenstein, Acta Phys. Polon. B30, 2705 (1999)

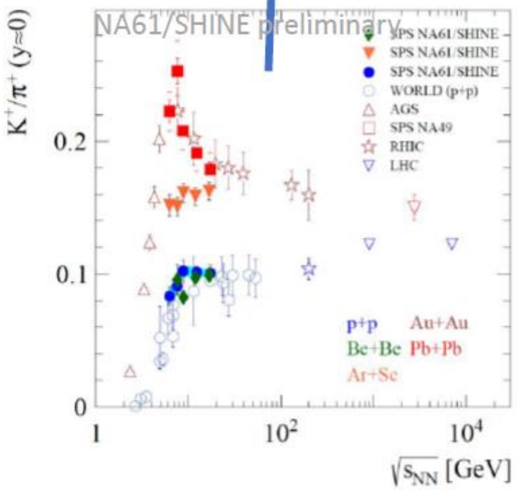


Study of the onset of deconfinement: Particle production properties

Uniqueness of heavy ion results from NA61/SHINE







NA61/SHINE recorded unique data for:

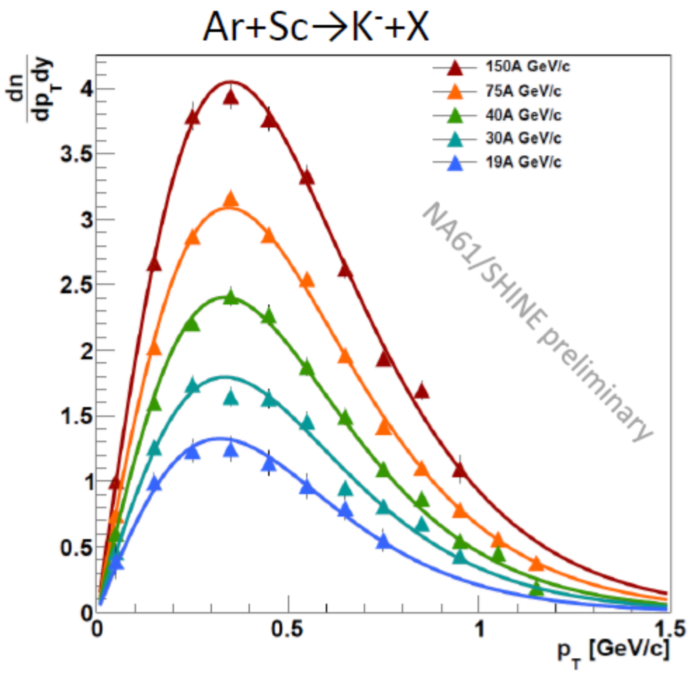
- Onset of deconfinement
- Onset of fireball
- Critical point?

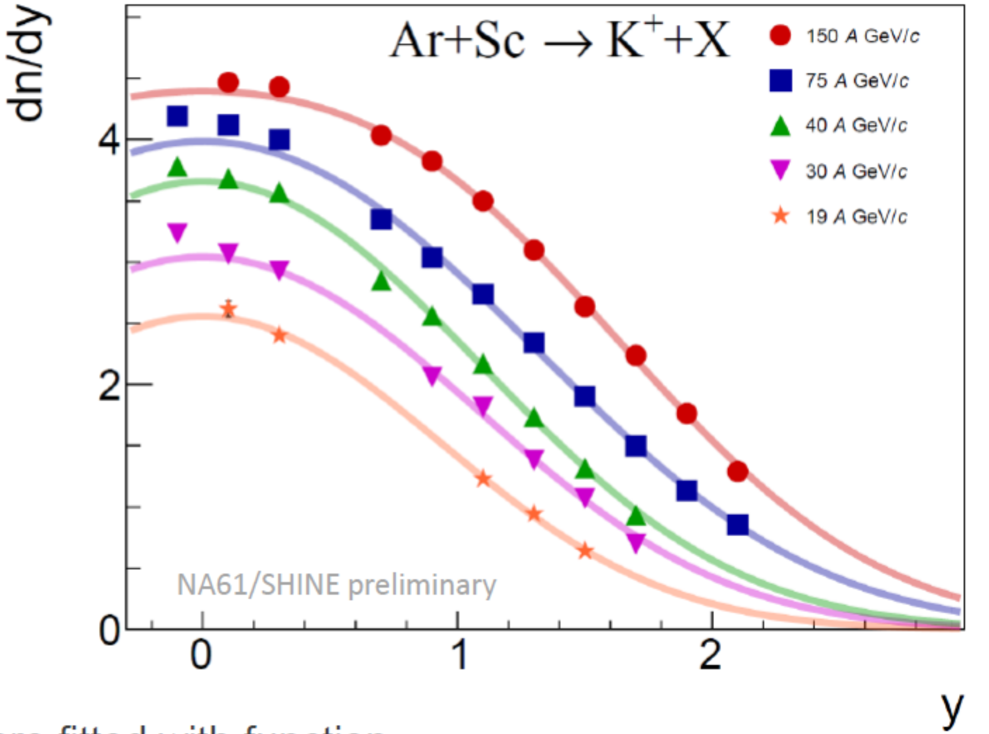
Two onsets in nucleus-nucleus collisions

- **Onset of deconfinement - beginning of QGP formation**
- **Onset of fireball - beginning of formation of a large cluster which decays statistically**

Onset of deconfinement: step and horn

2D kaon specra for central (0-10%) Ar+Sc collisions



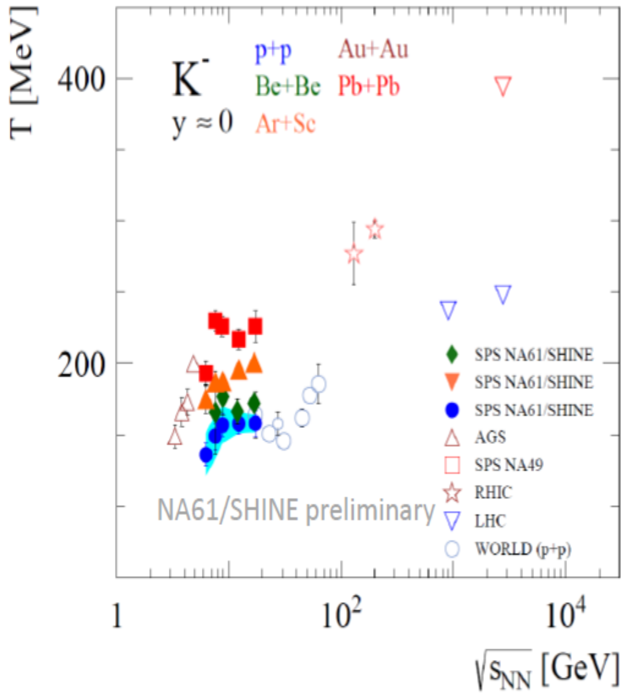


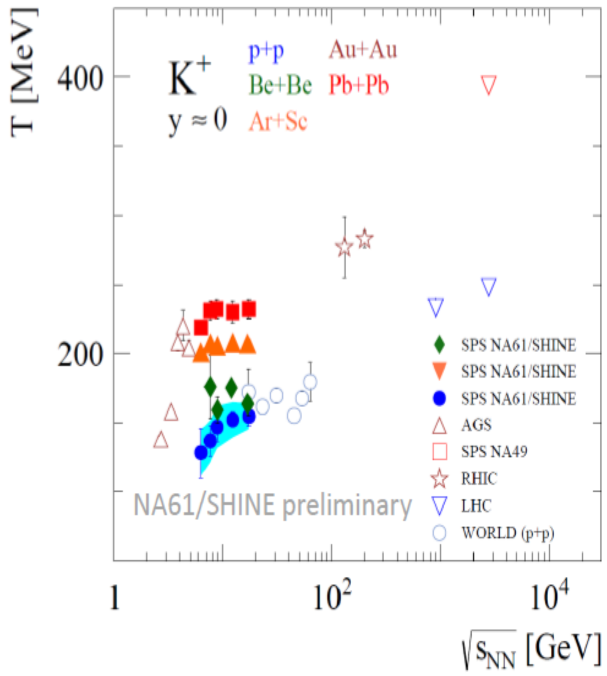
$K^{\pm}$ spectra in p_T are fitted with function

$$\frac{d^2 n}{dp_T\,dy} = \frac{S\ p_T}{T^2 + T\ m_K}\ exp\left(-\frac{\sqrt{p_T^2 + m_K^2} - m_K}{T}\right)$$

Onset of deconfinement: step

Plateau – **STEP** – in the inverse slope parameter T of m_T spectra in Pb+Pb collisions observed at SPS energies. This is expected for the onset of deconfinement due to mixed phase of HRG and QGP (SMES).





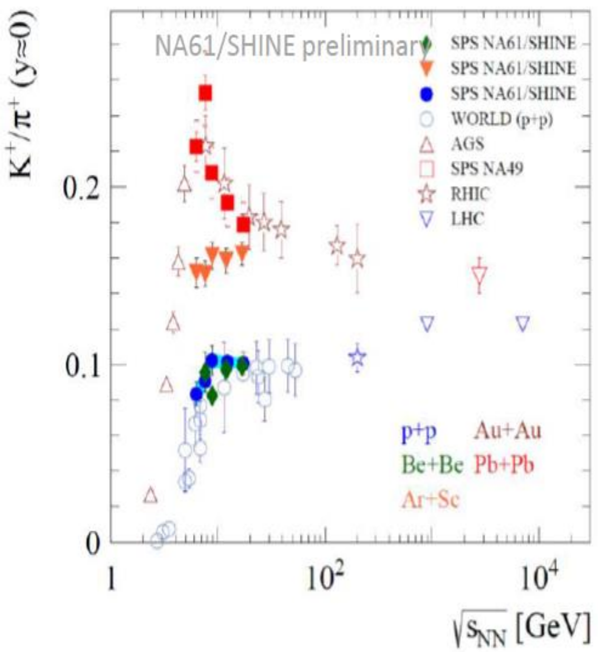
Qualitatively similar energy dependence is seen in p+p, Be+Be and Pb+Pb collisions

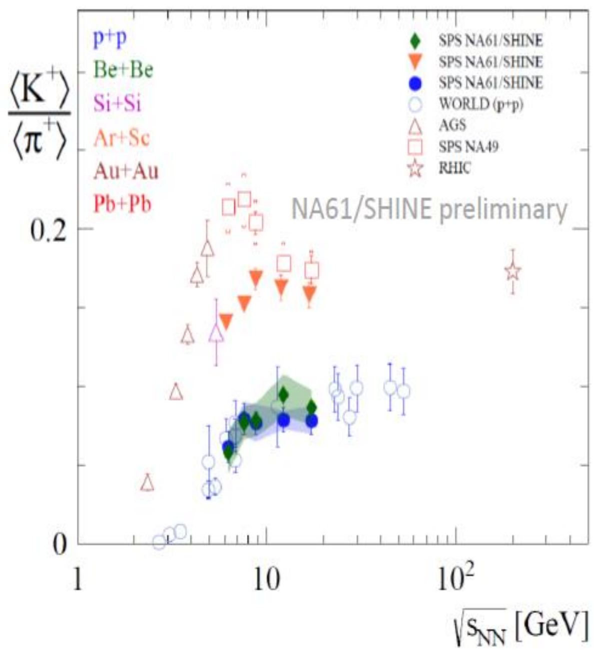
Magnitude of T in Be+Be slightly higher than in p+p

Ar+Sc results between p+p/Be+Be and Pb+Pb

Onset of deconfinement: horn

Rapid changes in K^+/π^+ – **HORN** – were observed in Pb+Pb collisions at SPS energies. This was predicted (SMES) as a signature of onset of deconfinement.



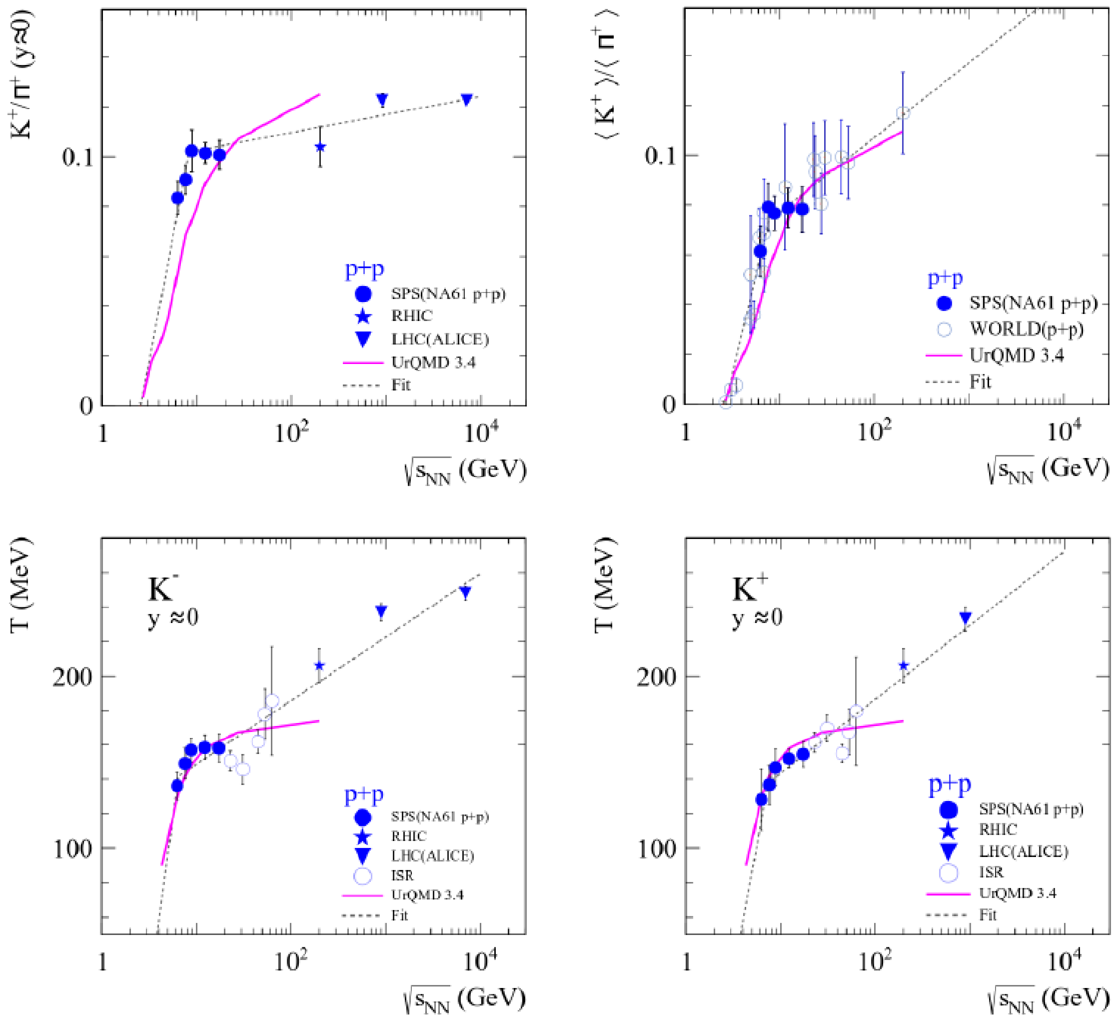


Plateau like structure visible in p+p

Be+Be close to p+p

Ar+Sc is higher than p+p but for of energy dependence is similar to p+p (no horn)

Onset of deconfinement: p+p data



Rates of increase of $K+/\pi+$ and T change sharply in p+p collisions at SPS energies .

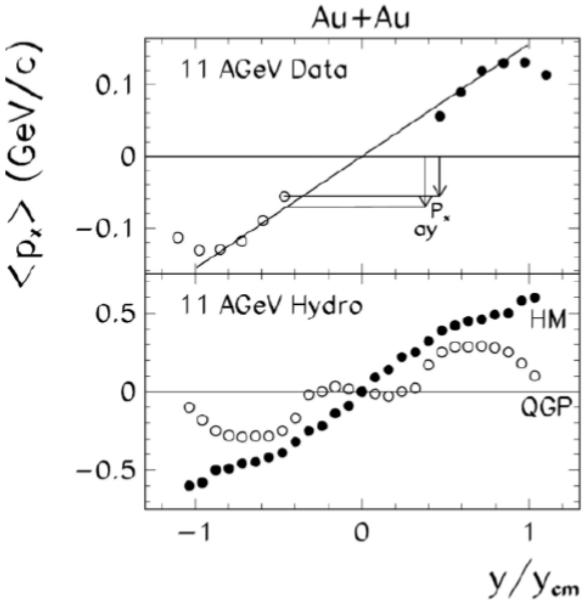
The fitted change energy is ≈7 GeV - close to the energy of the onset of deconfinement ≈8 GeV.

Study of the onset of deconfinement: Flow

Directed flow and the onset of deconfinement

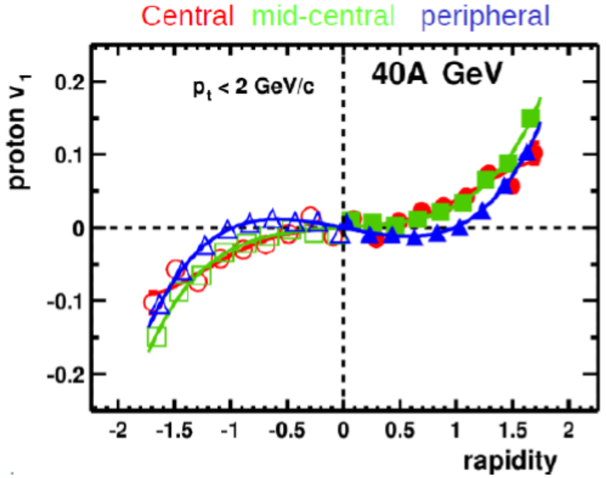
Directed flow v1 is considered to be **sensitive to 1st order phase transition** (softening of EOS). Expected: **non-monotonic behavior** (positive→negative→positive) **of proton dv_1 /dy as a function of beam energy** -"collapse of proton flow"

Predictions of hydrodynamical model:



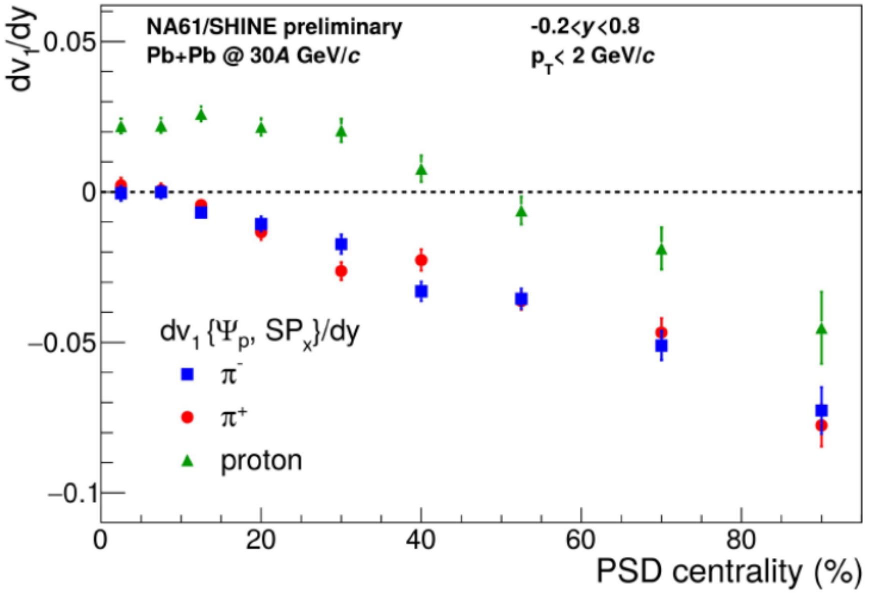
$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$$

Directed flow measured by NA49 at middle SPS energy ("anti-flow" of protons at mid-rapidity):



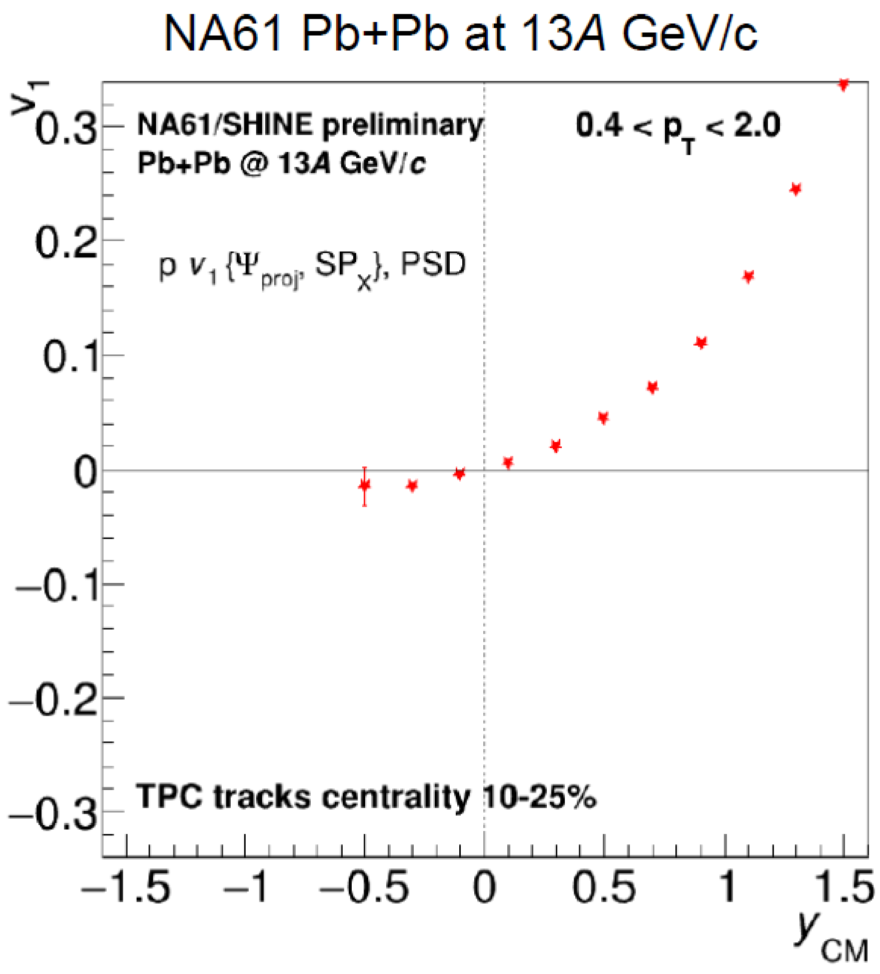
Centrality dependence of dv_1 /dy in Pb+Pb at $\sqrt{s_{NN}}$= 7.6 GeV

- NA61/SHINE fixed target setup → tracking and particle identification over wide rapidity range
- Flow coefficients are measured relative to the **spectator plane estimated with Projectile Spectator Detector** (PSD) → unique for NA61/SHINE



Close to mid-rapidity(-0.2 < y < 0.8)
Slope of pion v_1 is always negative
Slope of proton v_1 changes sign at centrality of about 50%

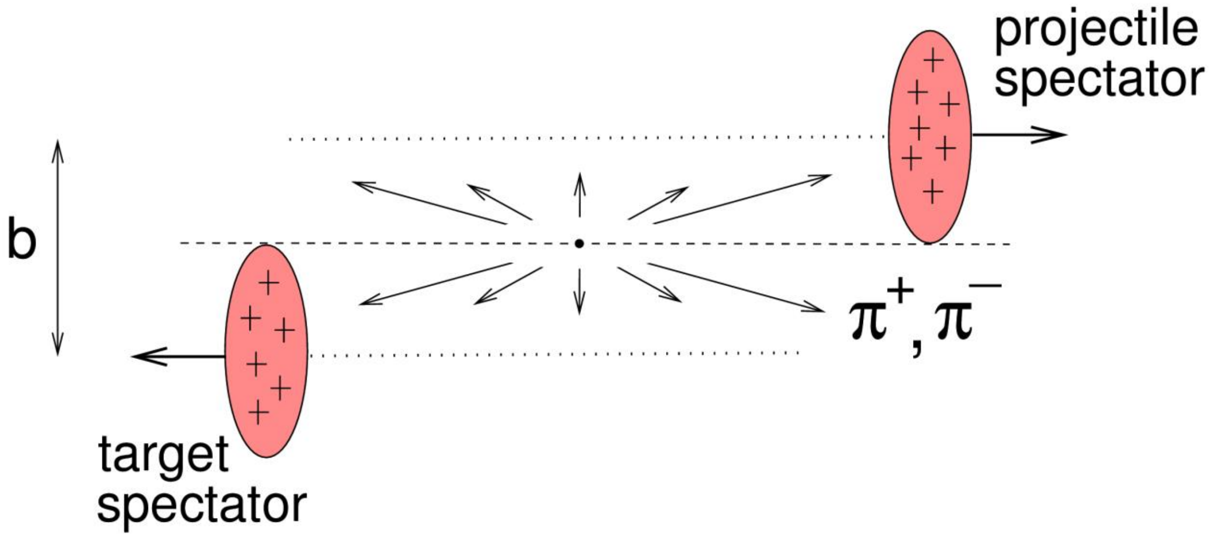
Proton directed flow vs rapidity



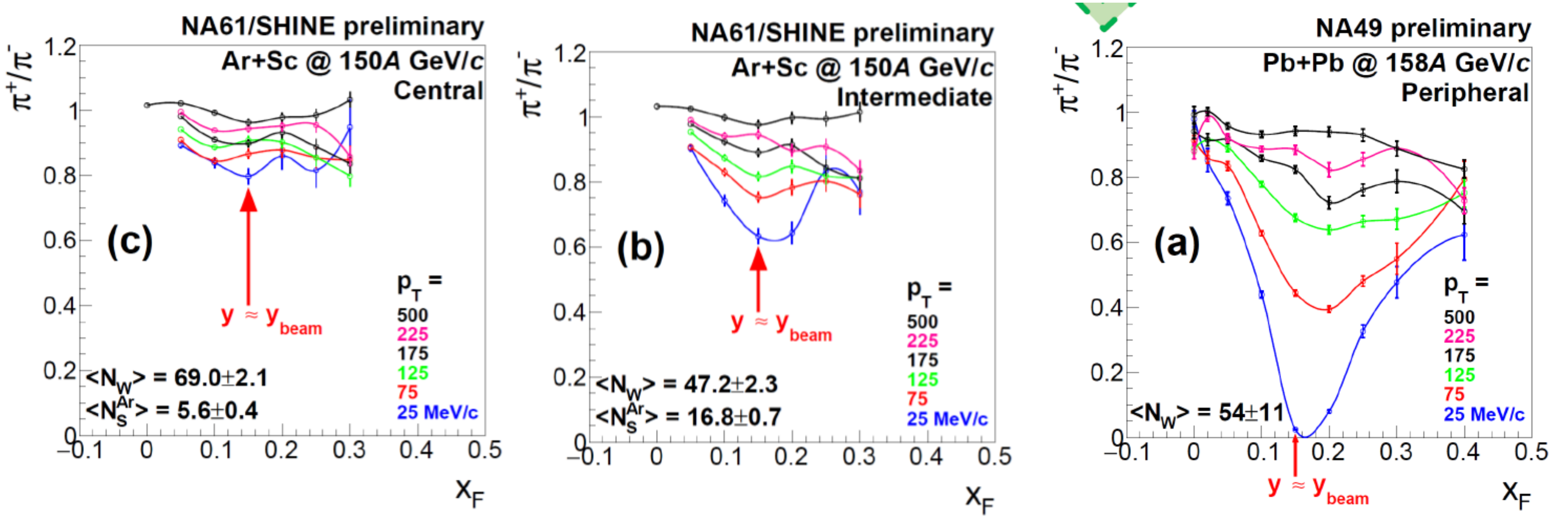
No evidence for the collapse of proton directed flow in Pb+Pb at 13*A*GeV/c

π^+/π^- ratio and spectator-induced electromagnetic effects

- Spectators (in non-central collisions) follow their initial path with unchanged momenta; charged spectators generate electromagnetic fields
- Charged pion trajectories can be modified by electromagnetic interactions (repulsion for π^+ and attraction for π^-) with the spectators → the effect is sensitive to the space-time evolution the system
- $\pi+/\pi-$ ratio allows to study spectator-induced electromagnetic effects → new information on the space and time evolution of the particle production process



Spectator-induced electromagnetic effects



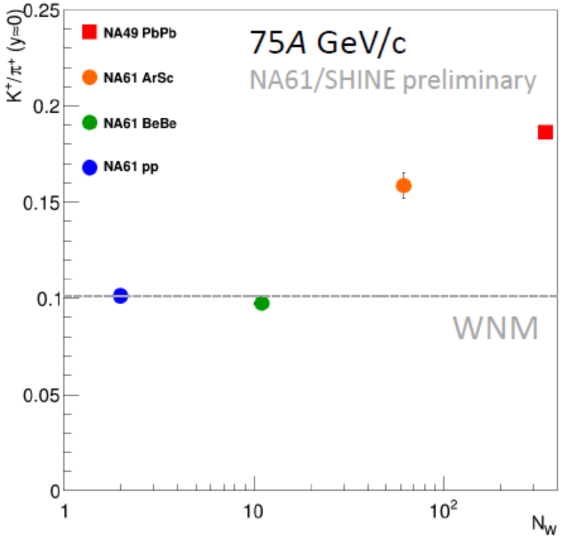
EM-repulsion of π^+ and attraction π^- of is the strongest for pions with rapidities close to spectator (beam) rapidity and with low p_T

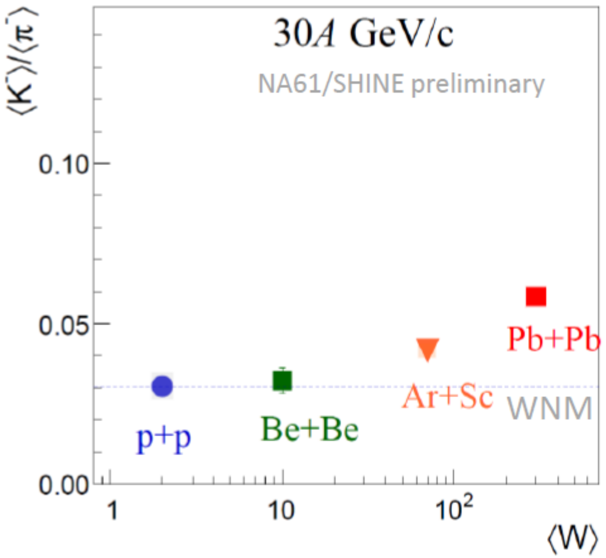
First observation of spectator induced EM effects in small systems at SPS

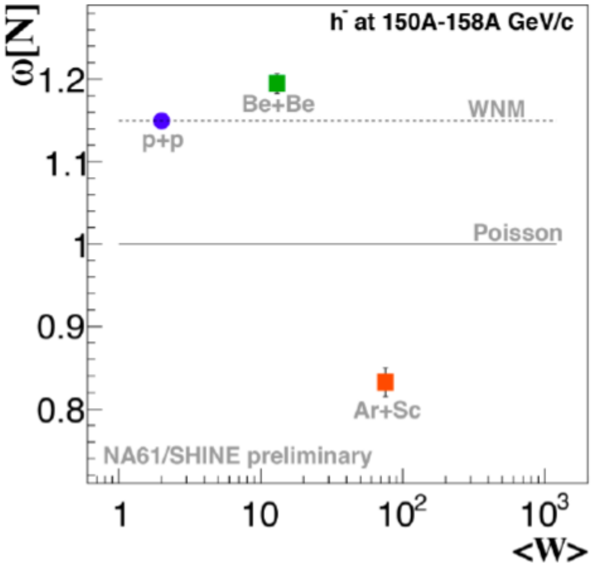
Similar effect seen in intermediate centrality Ar+Sc (NA61/SHINE) and peripheral Pb+Pb (NA49)

Study of the onset of fireball

Onset of fireball: system size dependence







Change between

p+p ≈ Be+Be and Ar+Sc, Pb+Pb results

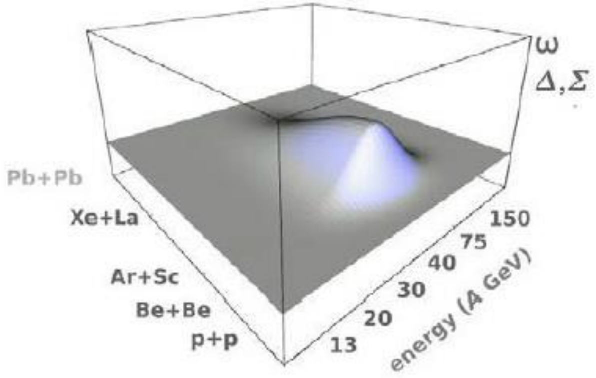
- p+p data are corrected for experimental biases, systematic uncertainty ~0.1 [EPJ.C76:635]
- 0-1% Be+Be data is uncorrected, experimental bias is ~10-15%
- 0-0.2% Ar+Sc data is uncorrected, experimental bias is ~5-7%

$$\omega[N] = \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle}$$

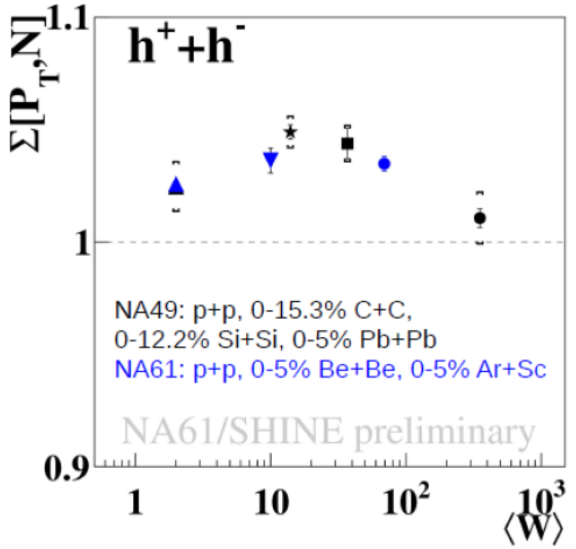
Scaled variance of multiplicity distributions

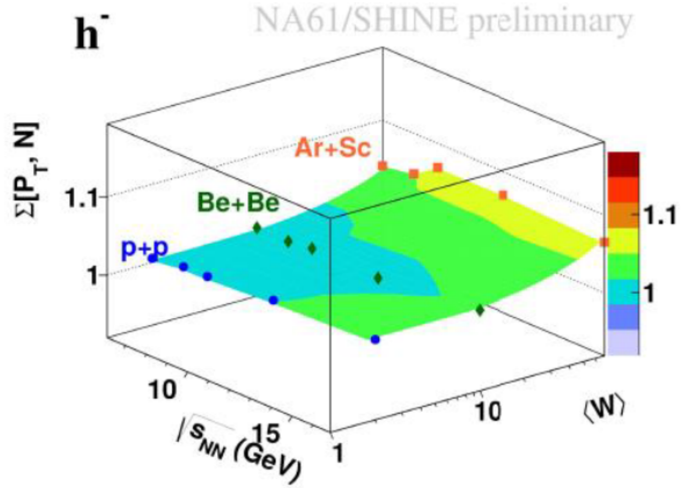
Search for critical point

Critical point: Strongly intensive measures Σ[PT,N]



Comparison to NA49 *A+A* at 158*A* GeV/*c* within NA49 two different acceptances





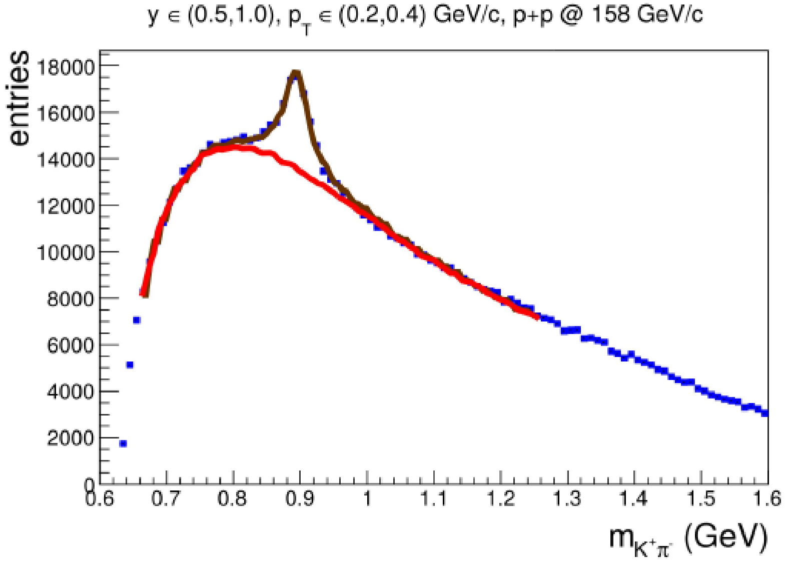
System size dependence of $\Sigma[P_T,N]$ at 150/158A GeV/c: NA49 and NA61/SHINE points show consistent trends

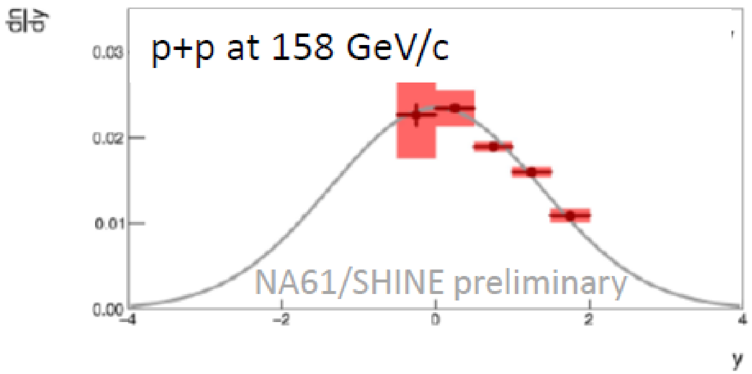
So far there are no prominent structures which could be related to critical point

Eur.Phys.J. C77 (2017) no.2, 59,
CERN-SPSC-2018-029

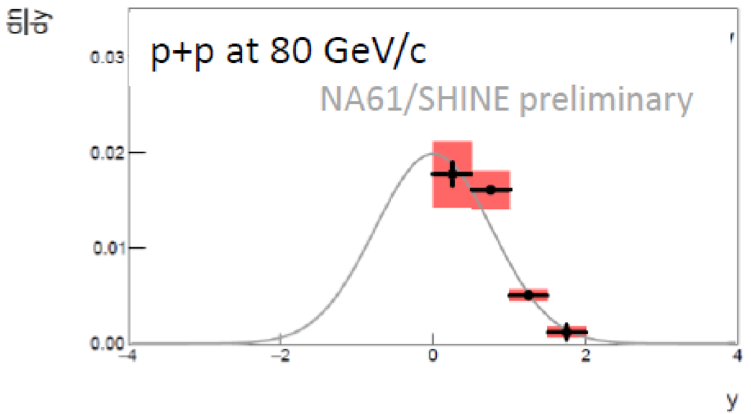
Strangeness production in p+p at 158 GeV/c

K*(892)^0 production in inelastic p+p collisions



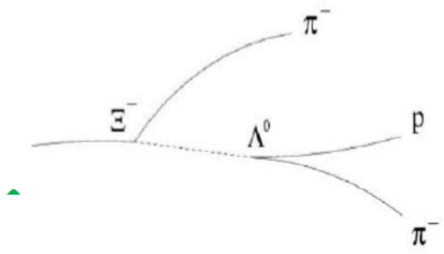


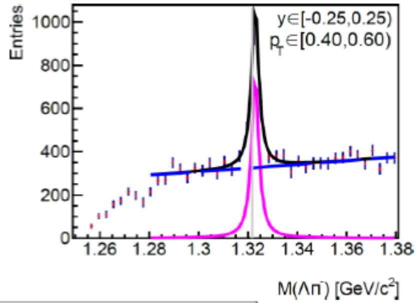
<K*(892)>=0.08058 ± 0.00059 ± 0.0026

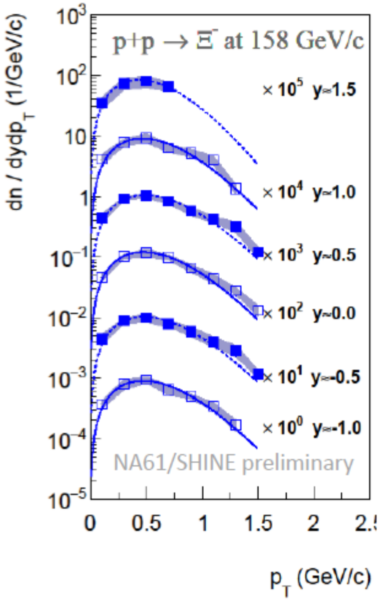


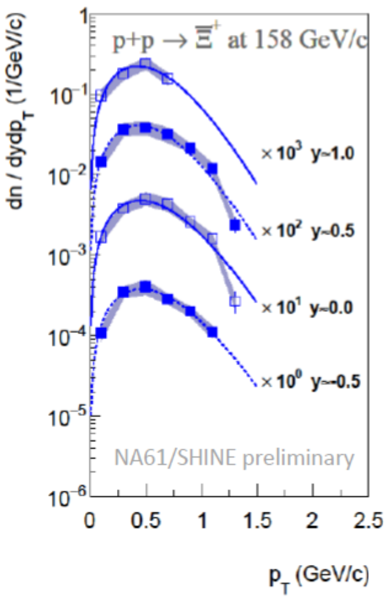
<K*(892)>=0.03812 ± 0.00538 ± 0.00372

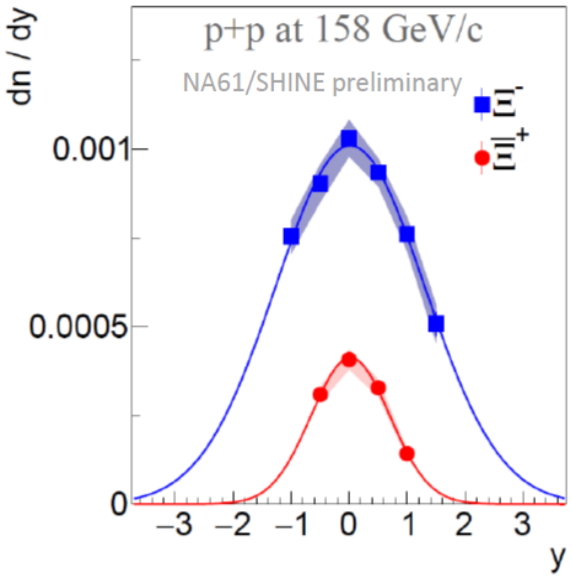
Ξ production in inelastic p+p collisions at 158 GeV/c





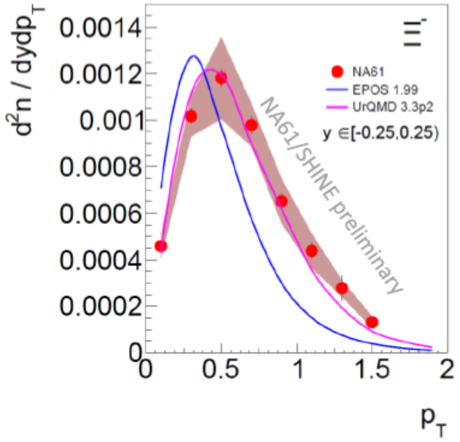


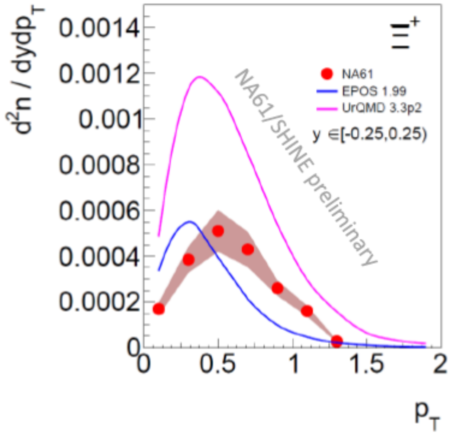


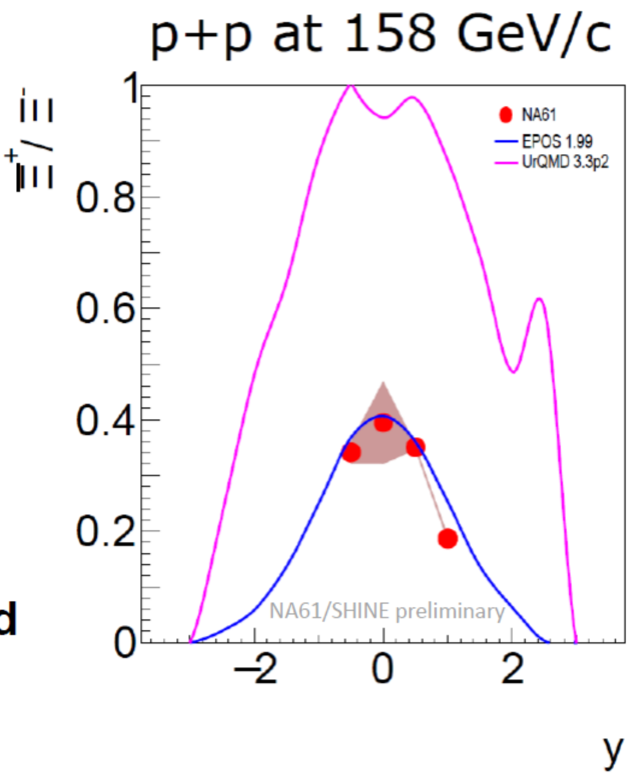


$$\langle \bar{\Xi}^+ \rangle = 0.00079 \pm 0.00002 \pm 0.00010$$
$$\langle \Xi^- \rangle = 0.0033 \pm 0.0001 \pm 0.0006$$

Ξ production in inelastic p+p collisions at 158 GeV/c







UrQMD fails to describe $\overline{\Xi}^+/\Xi^-$ ratio – known problem of string models.

EPOS describes rapidity distributions of $\overline{\Xi}^+, \Xi^-$ and their ratio, but not shape of transverse momentum distributions.

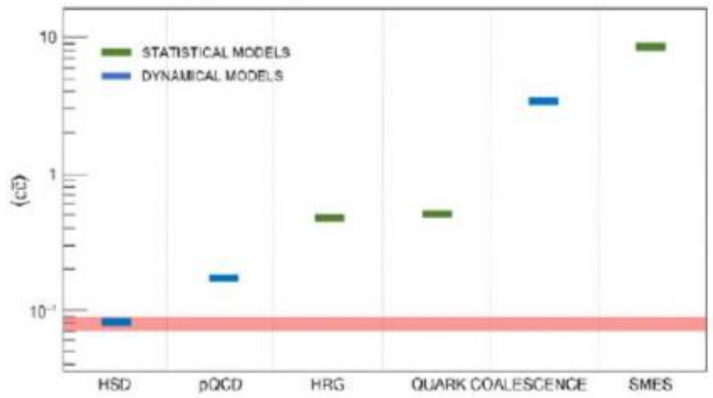
NA61/SHINE beyond 2020

NA61/SHINE program for 2021-2024

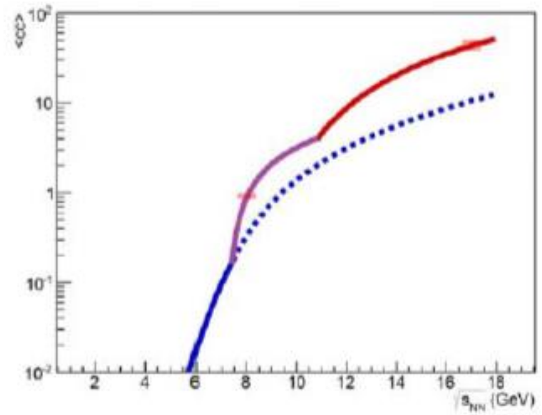
- What is the mechanism of open charm production?
- How does the onset of deconfinement impact open charm production?
- How does the formation of quark gluon plasma impact J/ψ production?

To answer these questions **mean number of charm quark pairs,** $\langle c\bar{c}\rangle$
,
produced in A+A collisions has to be known. Up to now corresponding experimental data **does not exist** and
only NA61/SHINE can perform this measurement in the near future.

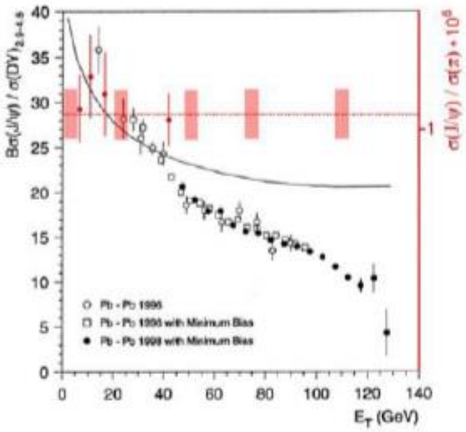
⟨cc̄⟩ and models



⟨cc̄⟩ and onset of deconfinement



⟨cc̄⟩, ⟨J/ψ⟩ and QGP

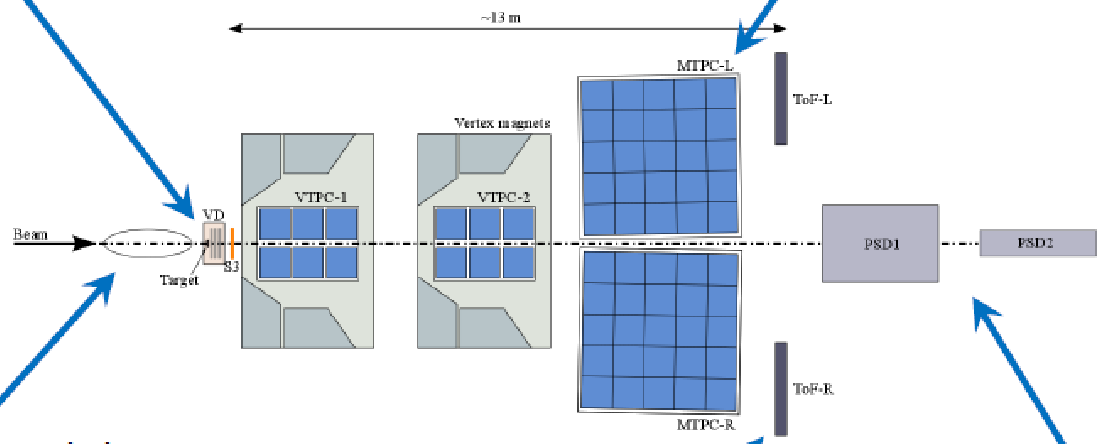


Foreseen NA61/SHINE resolution is sufficient to answer addressed questions

Detector upgrade during LS2

Construction of Vertex Detector (VD)
for D^0, $\overline{D^0}$ decay reconstruction

Replacement of the TPC
read-out electronics
to increase data rate to 1 kHz



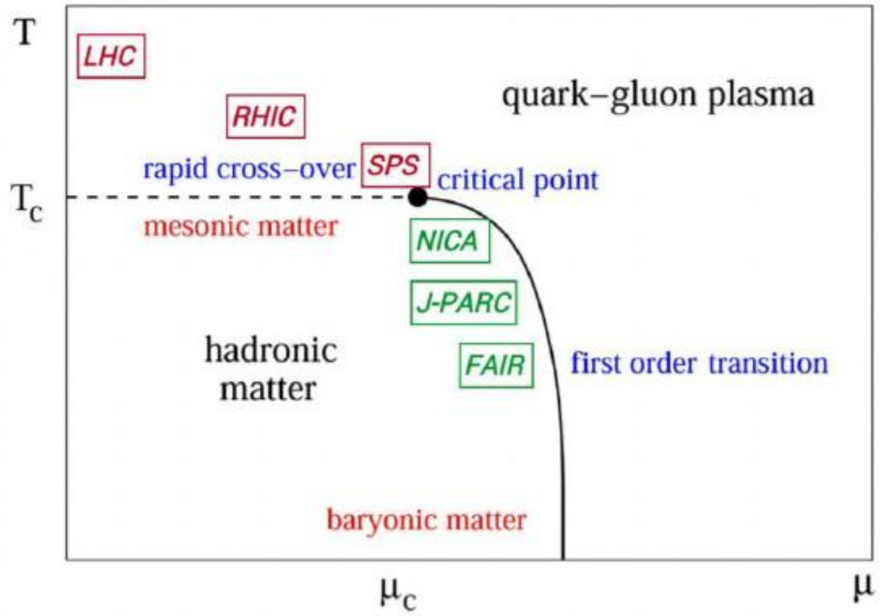
New trigger and data
acquisition system

New Time-of-Flight
detectors

Upgrade of Projectile
Spectator Detector

Uniqueness of NA61 open charm program

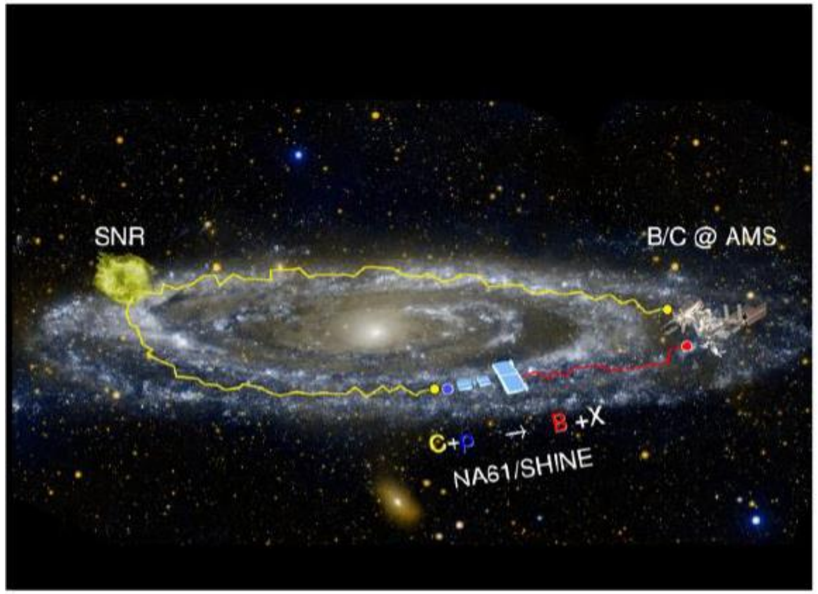
Landscape of present and future heavy ion experiments



Only NA61/SHINE is able to measure open charm production in heavy ion collisions in full phase space in the near future

- LHC and RHIC at high energies: measurements in small phase space due to collider geometry
- RHIC BES collider: measurement not possible due to collider topology
- RHIC BES fixed-target: measurement require dedicated setup, not under consideration
- NICA (< 80AGeV/c): measurement during stage 2 under consideration
- J-PARC (< 20AGeV/c): maybe possible after 2025
- FAIR (< 10AGeV/c): not possible

Reference measurements: Nuclear fragmentation cross section for cosmic ray experiments



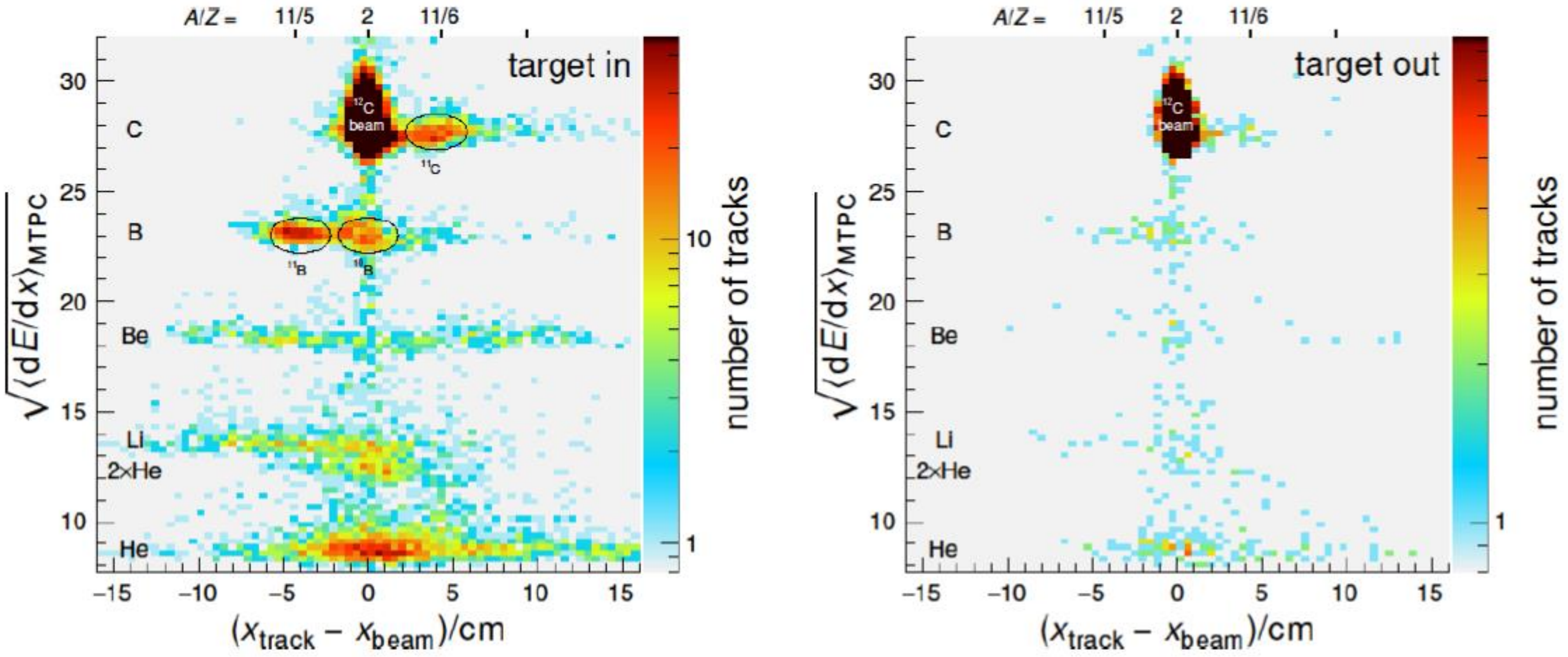
- Primary cosmic rays from supernova remnants
- Secondary cosmic rays from interactions with interstellar matter during propagation e.g.
  $^{12}\mathrm{C} + \mathrm{p} \xrightarrow{\text{frag.}} \mathrm{B} + \mathrm{X}$
  $^{12}\mathrm{C} + \mathrm{p} \xrightarrow{\text{frag.}} {}^{11}\mathrm{C} + \mathrm{p} \xrightarrow{\text{decay}} \mathrm{B} + \mathrm{Y}$
- Primary-to-secondary ratios (e.g. B/C)
  → traversed mass density
- Unstable-to-stable ratios (e.g. $^{10}\mathrm{Be}/^{9}\mathrm{Be}$)
  → traversed distance
- Important for the understanding of origin of Galactic cosmic rays and backgrounds for DM searches

Understanding of cosmic ray propagation limited by uncertainties of fragmentation cross sections

NA61/SHINE will significantly reduce the uncertainties
(from 20% to 0.5%)

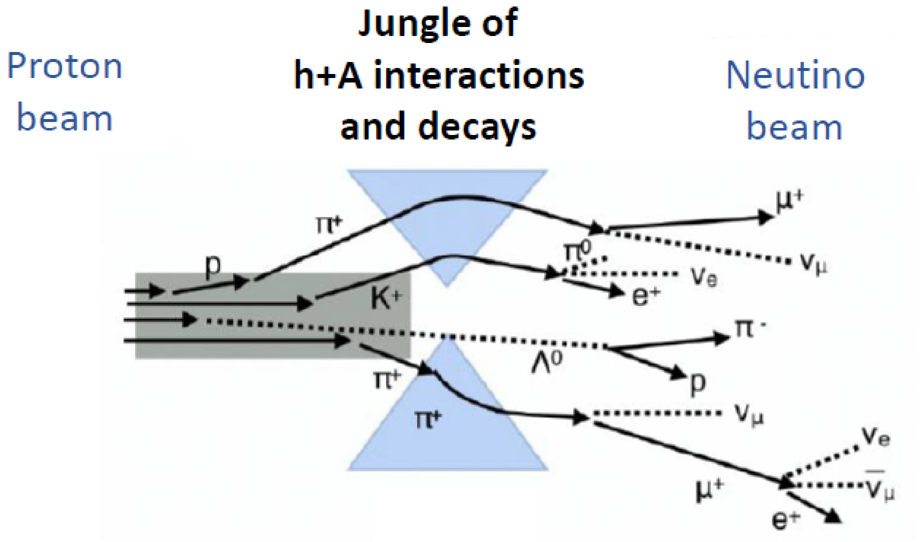
First look on 2018 test Fragmentation cross sections

Pb at 13.5*A* GeV/c→ Secondary fragments with A/Z=1/2 at 13*A* GeV/c



NA61/SHINE setup allows to determine fragmentation cross section

Reference measurements: Hadron production for neutrino experiments



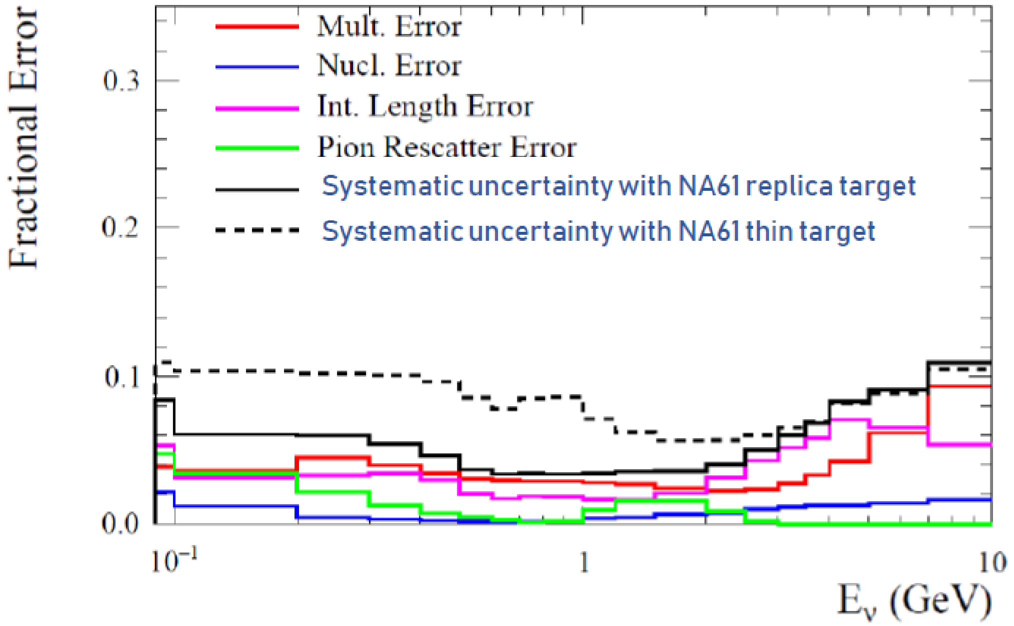
- Further improvement of the precision of measurements for the currently used T2K replica target,
- Measurements for a new target material (super-sialon) for T2K-II and Hyper-Kamiokande,
- Study of the possibility of measurements with beams <12 GeV/c for improved predictions of atmospheric and accelerator ν fluxes,
- Ultimate hadron production measurements with prototypes of Hyper-Kamiokande and DUNE targets.

NA61/SHINE will decrease systematic uncertainties on neutrino fluxes (for T2K-II, Hyper-K from 10% to 3%)

Neutrino-related accomplishments from NA61/SHINE first phase

NA61/SHINE took thin and thick target data with 31 GeV/c protons specifically for T2K in 2007, 2009 and 2010

T2K flux predictions (Phys.ReV.D87 2013 no.1, 012001) currently uses thin target data and incorporation of thick target data is in progress



2016/17 data collection:

- Thin target measurements with p and π beams at C, Be, Al targets at 30, 60 and 120 GeV/c

2018 data collection:

- 120 GeV/c p on NOvA replica target provided by Fermilab
- 18M events recorded

Summary

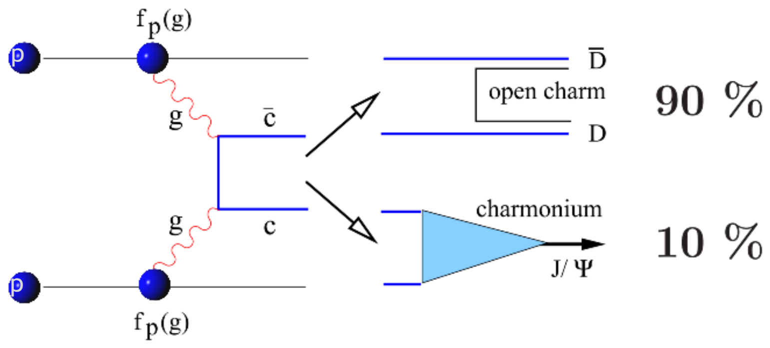
- 2D scan in system size and collision energy was completed in 2017 with Xe+La data
- Analysis ongoing for p+p, Be+Be Ar+Sc , Xe+La and Pb+Pb data
- No horn in Ar+Sc collisions
- Unexpected system size dependence : (p+p Be+Be) ≠ (Ar+Sc ≠ Pb+Pb)
- No convincing indication of CP
- Plans to extend NA61/SHINE program with measurements of open charm production in 2021 2024

BACKUP

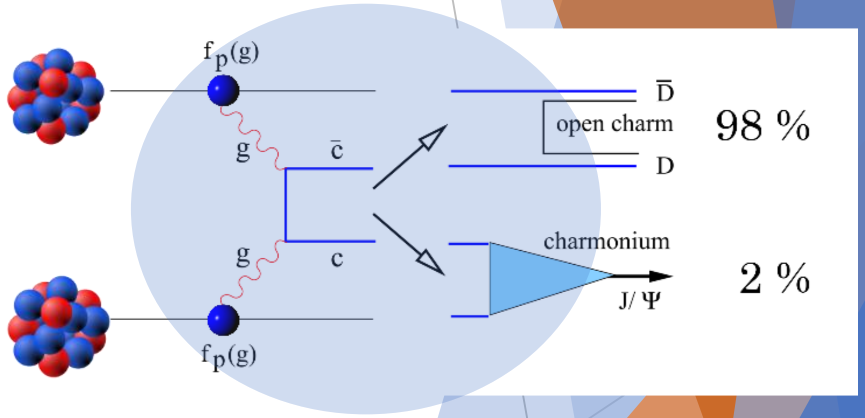
J/ψ production as the signal of deconfinement

Open charm and J/ψ production within Matsui-Satz model
[PL B178 416]

vacuum



medium



$$P(c\bar{c} \to J/\psi) \equiv \frac{< J/\psi >}{< c\bar{c} >} \equiv \frac{\sigma_{J/\psi}}{\sigma_{c\bar{c}}}$$

$$P_{\text{vacuum}}(c\bar{c} \to J/\psi) \quad > \quad P_{\text{medium}}(c\bar{c} \to J/\psi)$$

Medium reduces probability of J/ψ production

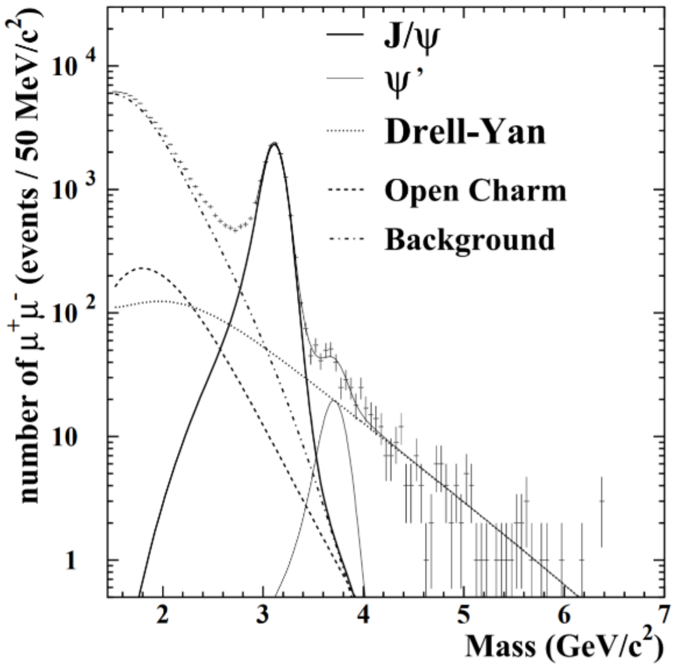
J/ψ production as the signal of deconfinement

Calculation of $P(c\bar{c} \rightarrow J/\psi)$ requires data on:

- J/ψ – at SPS precise data by NA38, NA50, NA60
- $c\bar{c}$ – at SPS not available up to now, NA61 has just started the corresponding measurements

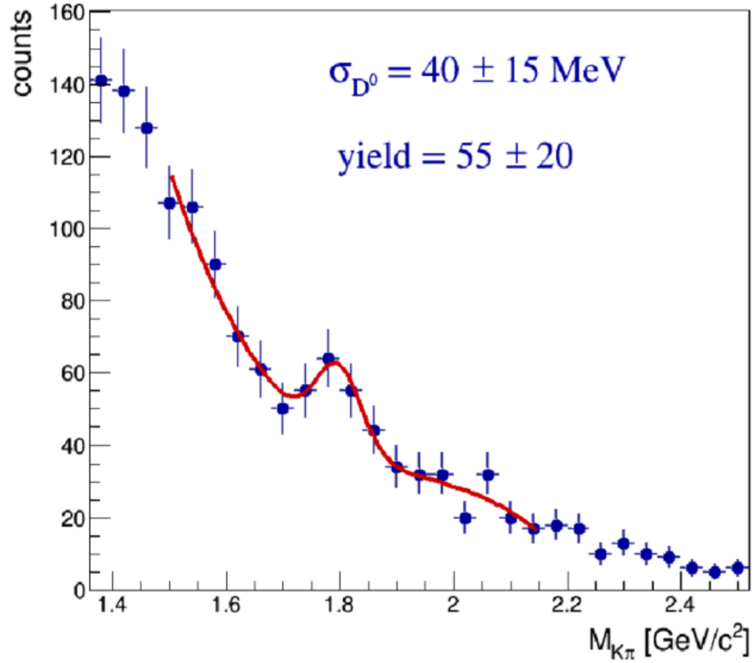
central Pb+Pb at 150-158A GeV/c

NA50



[NA50, arXiv:hep-ex/0412036v1]

NA61



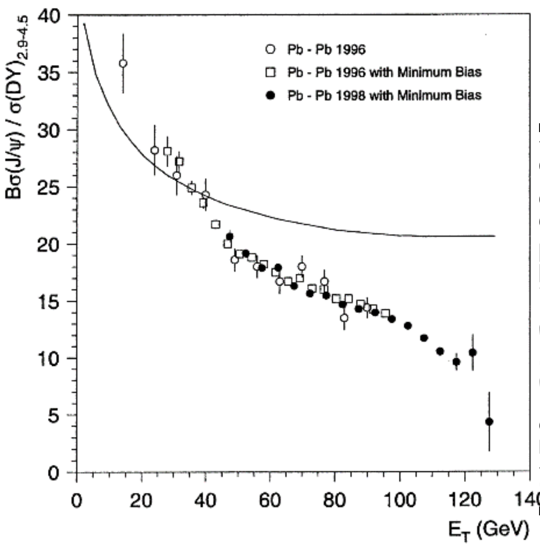
[CERN-SPSC-2017-038]

J/ψ production as the signal of deconfinement

Data on J/ψ production has been normalized by:

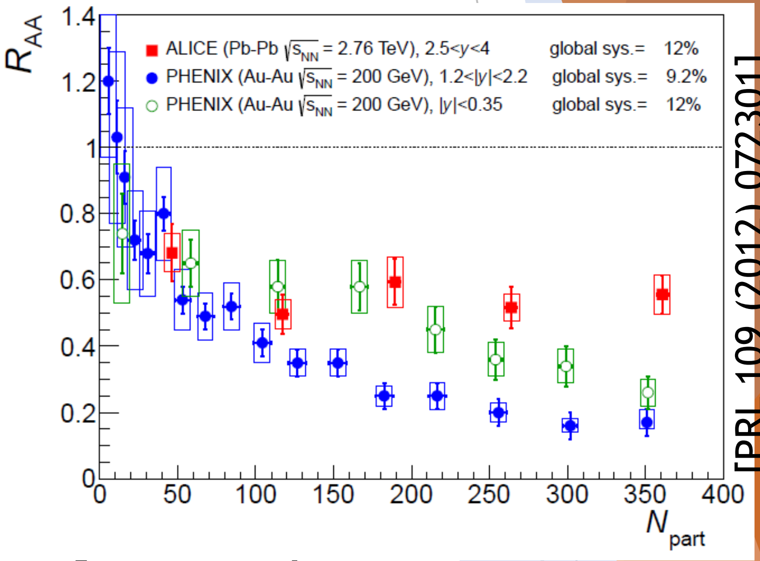
$$R_{AA} = \frac{\sigma_{AA}}{N_{coll}\sigma_{pp}}$$

at SPS by DY



[NA50, PL B 477 28-36]

at LHC/RHIC by N_{coll}



[PRL 109 (2012) 072301]

Interpreting these results one frequently assumes:

$< c\bar{c} > \sim < DY >$ or $< c\bar{c} > \sim < N_{coll} >$

This assumptions may be incorrect due to many effects: shadowing, parton energy losses, etc.

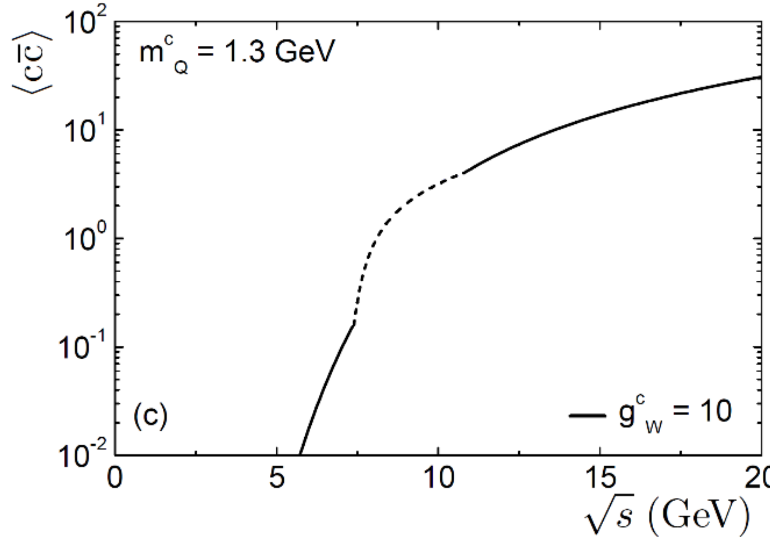
Note: LHC/RHIC results refer to a narrow acceptance

Open charm yield as the signal of deconfinement

$$\textbf{confined matter} \quad \rightarrow \quad \textbf{deconfined matter}$$

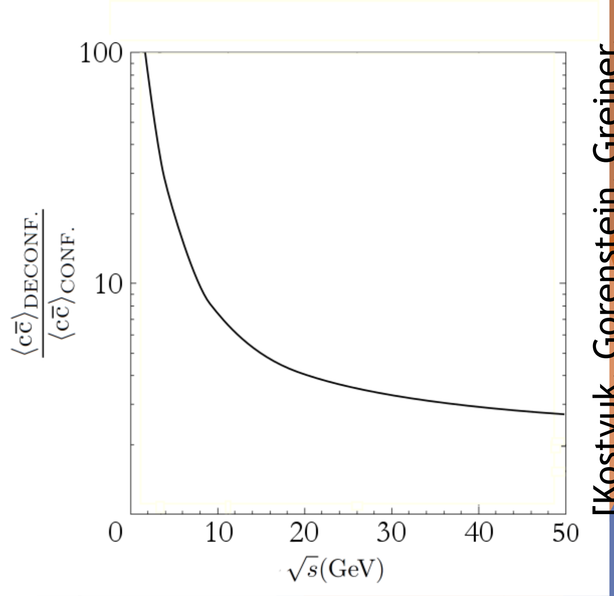
$$\mathrm{D\bar{D}}\ \text{mesons} \quad \rightarrow \quad \text{charm quarks}$$
$$2m_{\mathrm{D}} = 3.7\ \text{GeV} \quad \rightarrow \quad 2m_{\mathrm{c\bar{c}}} = 2.6\ \text{GeV}$$
$$g_{\mathrm{D}} = 4 \quad \rightarrow \quad g_{\mathrm{c}} = 24$$

Statistical Model of the Early Stage



[Poberezhnyuk, Gazdzicki, Gorenstein, ACTA PHYS POL B 9 48(2017)]

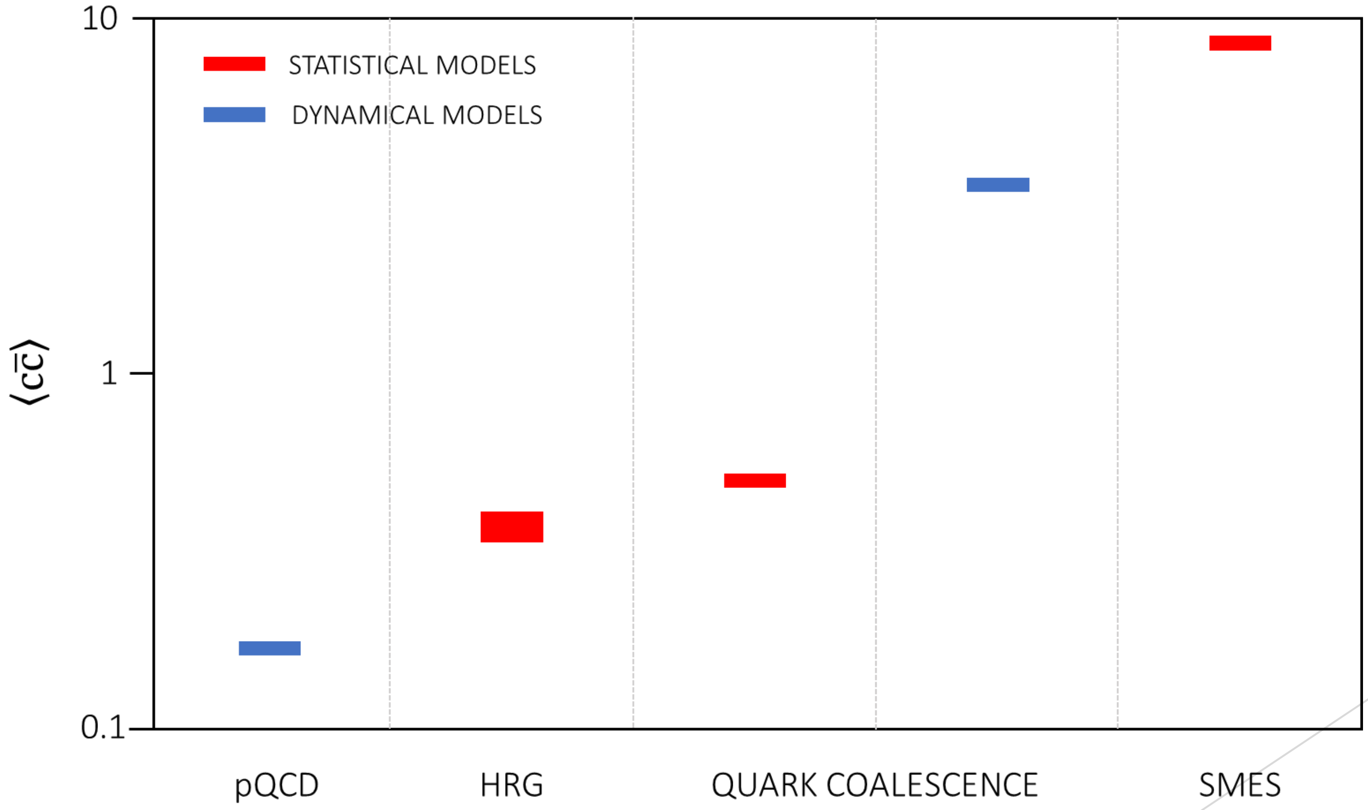
QCD-inspired calculations



[Kostyuk, Gorenstein, Greiner, PL B519 207]

Mechanism of open charm and J/ψ production

Predictions for $< c\bar{c} >$ in central Pb+Pb at 158A GeV/c differ by a factor of about **50**.



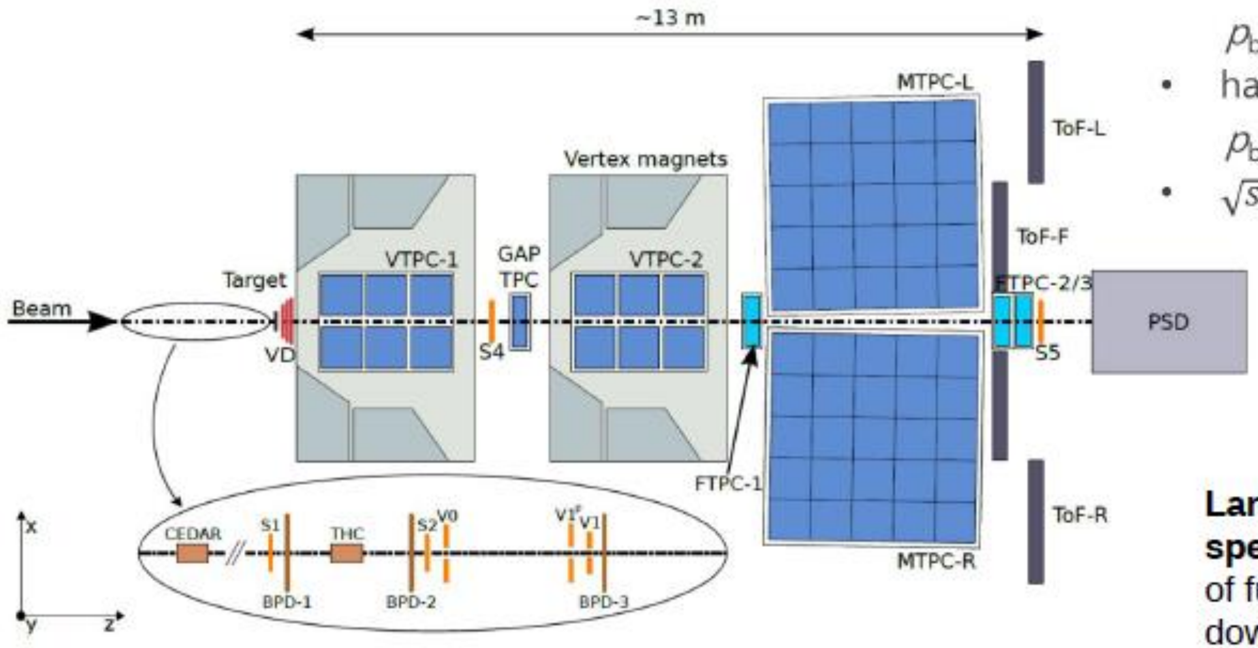
pQCD
Gavai *et al*. IJMP A 10 2999.
Braun-Munzinger, J. Stachel, PL B 490, 196.
HRG, Quark Coalesc. Stat.
Gorenstein, Kostyuk, Stoecker, Greiner, PL B 509, 277.
Quark Coalesc. Dyn.
Levai, Biro, Csizmadia, Csorgo, Zimanyi, JP G 27, 703
SMES
Gazdzicki, Gorenstein, APP B30, 2705.

- The important questions:
  - How does the formation of quark gluon plasma impact J/ψ production?
  - How does the onset of deconfinement impact open charm production?
  - What is the mechanism of open charm and J/ψ production?

can be answer by NA61/SHINE
in the near future (2021-2024)

NA61/SHINE - Experimental layout

Unique, multi-purpose facility to study hadron production in hadron-proton, hadron-nucleus and nucleus-nucleus collisions at the CERN SPS



Beams:

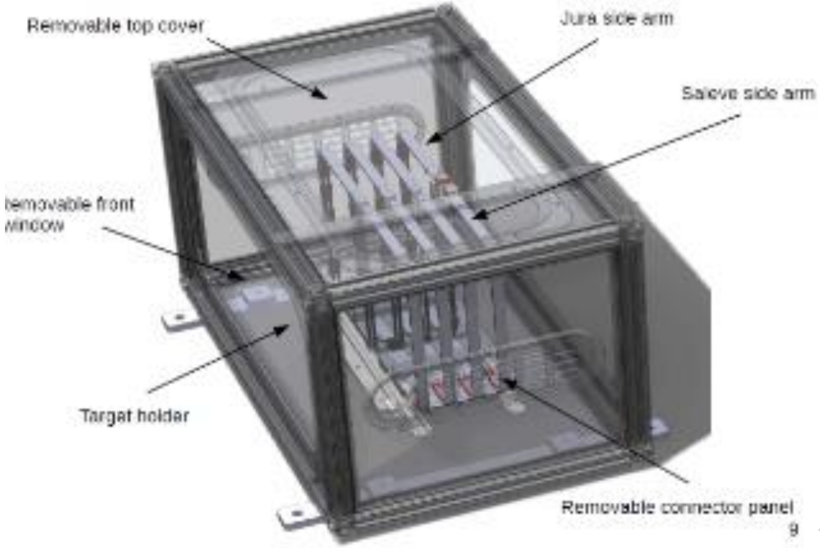
- ions (Be, Ar, Xe, Pb) p_{beam}=13A–150A GeV/c
- hadrons (π, K, p) p_{beam}=13–400 GeV/c
- $\sqrt{s_{NN}}$= 5.1–16.8 (27.4) GeV

Large acceptance hadron spectrometer – coverage of full forward hemisphere, down to $p_T = 0$

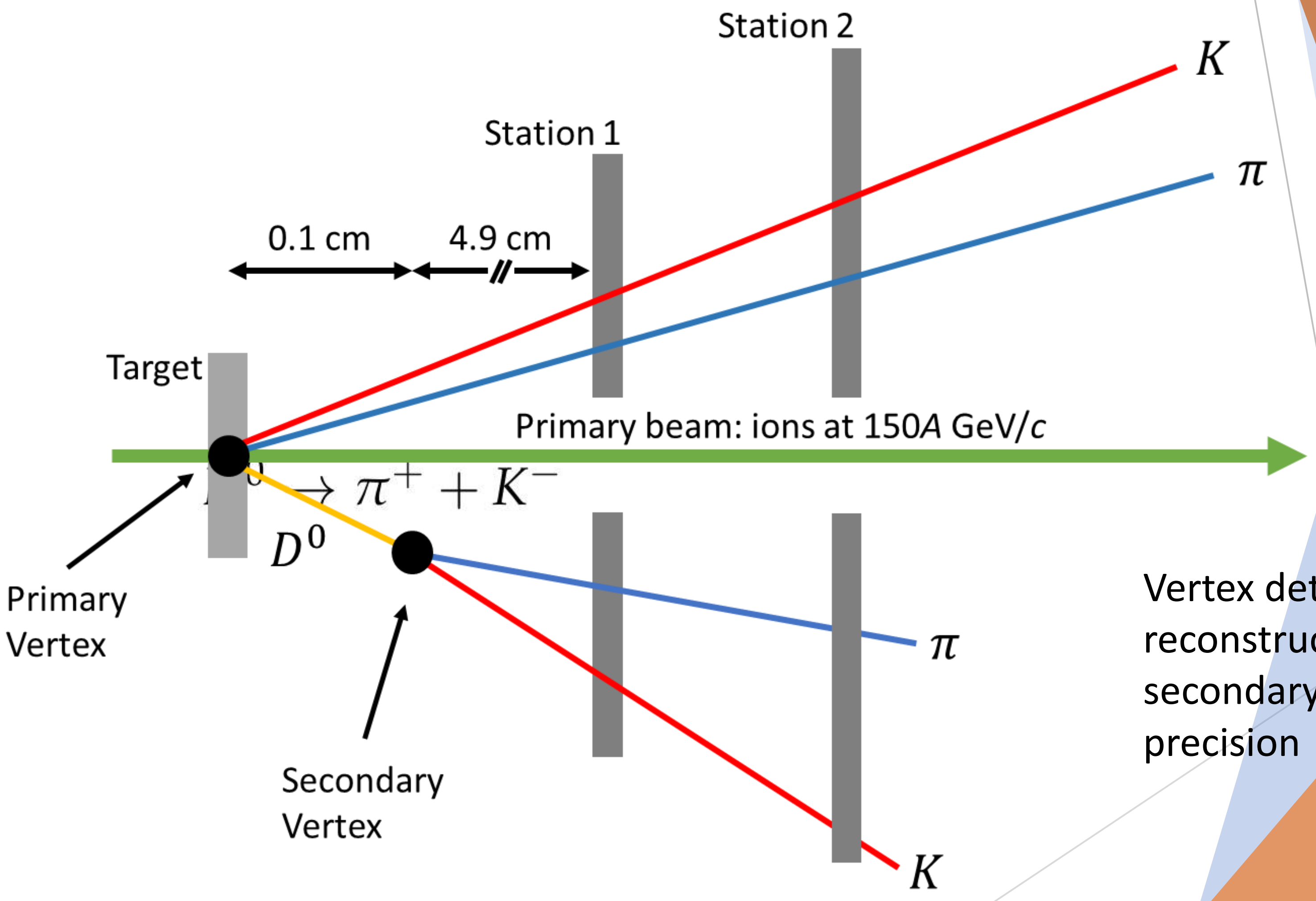
Feasibility studies of open charm measurements in NA61/SHINE

In 2016 **S**mall **A**cceptance **V**ertex **D**etector was introduce to NA61/SHINE detector system:

- 16 MIMOSA-26 sensors located on 2 horizontally movable arms
- Target holder integrated



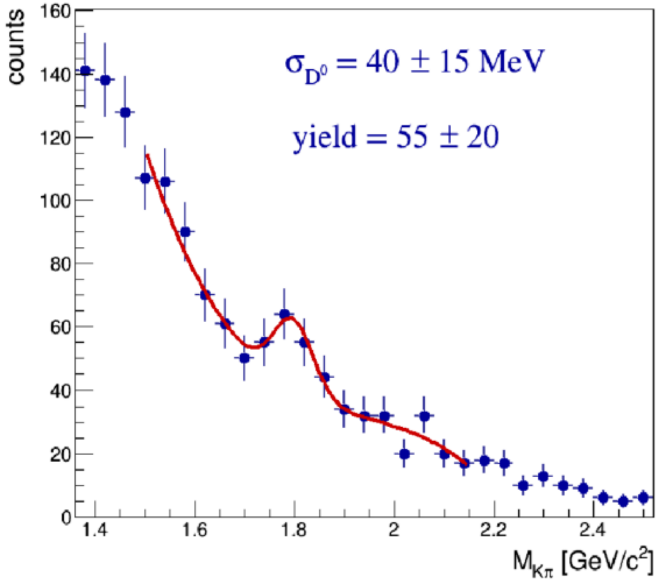
Feasibility studies of open charm measurements in NA61/SHINE



Vertex detector is needed to reconstruct primary vertex and secondary vertexes with high precision

Search for D^0

First results using simplified reconstruction
(200k 0-20% central Pb+Pb at 150 AGeV/c in 2016)

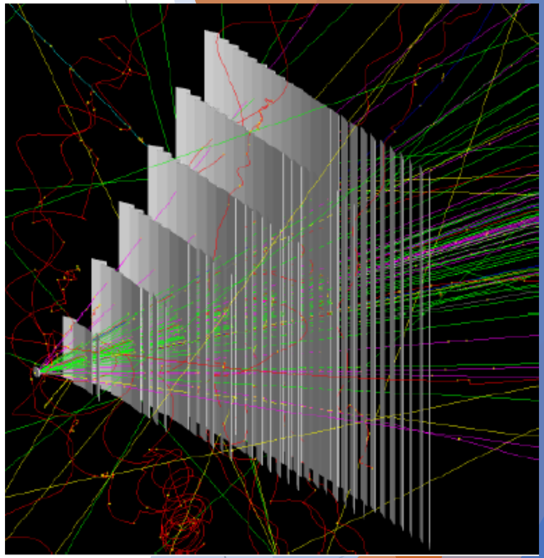


With background suppression

- First indication of D^0 signal in heavy ion collision at the CERN SPS
- Significant NA61/SHINE detector upgrades are need for a precise open charm measurements

Large Acceptance Vertex Detector

- General requirements:
  - Precise vertex measurement (at the level of better ~20-30μm for particles)
  - Fast detectors (< 30 μs) with high granularity
  - The low material budget
  - Large acceptance is desirable to accept 100% of the D^0s produced and to match the VTPC-1 of NA61/SHINE
- LAVD is planned on technology develop for ALICE ITS and MFT:
  - CMOS ALPIDE pixel sensors
    - Sensor size 15 mm x 30 mm.
    - Pixel pitch 29 μm x 27 μm.
  - Carbon fiber support structure
  - Read-out electronics
- 6 stations, 220 sensors



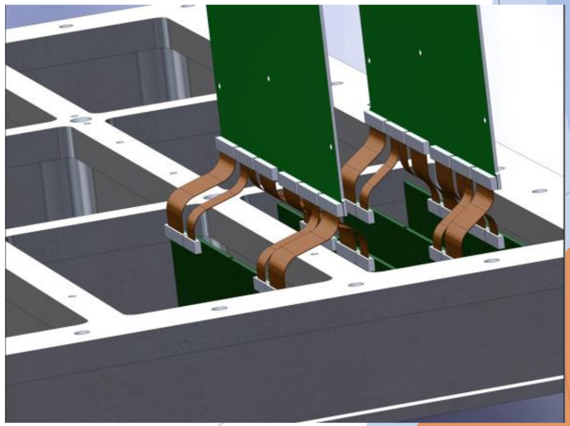
Replacement of the TPC electronics

- Will increase the read-out rate by a factor of about 10 (up to 1 kHz)
  - ALICE will transfer to NA61/SHINE its present TPC electronics that will be replaced during the long shutdown LS2

Present NA61
Front-End Card

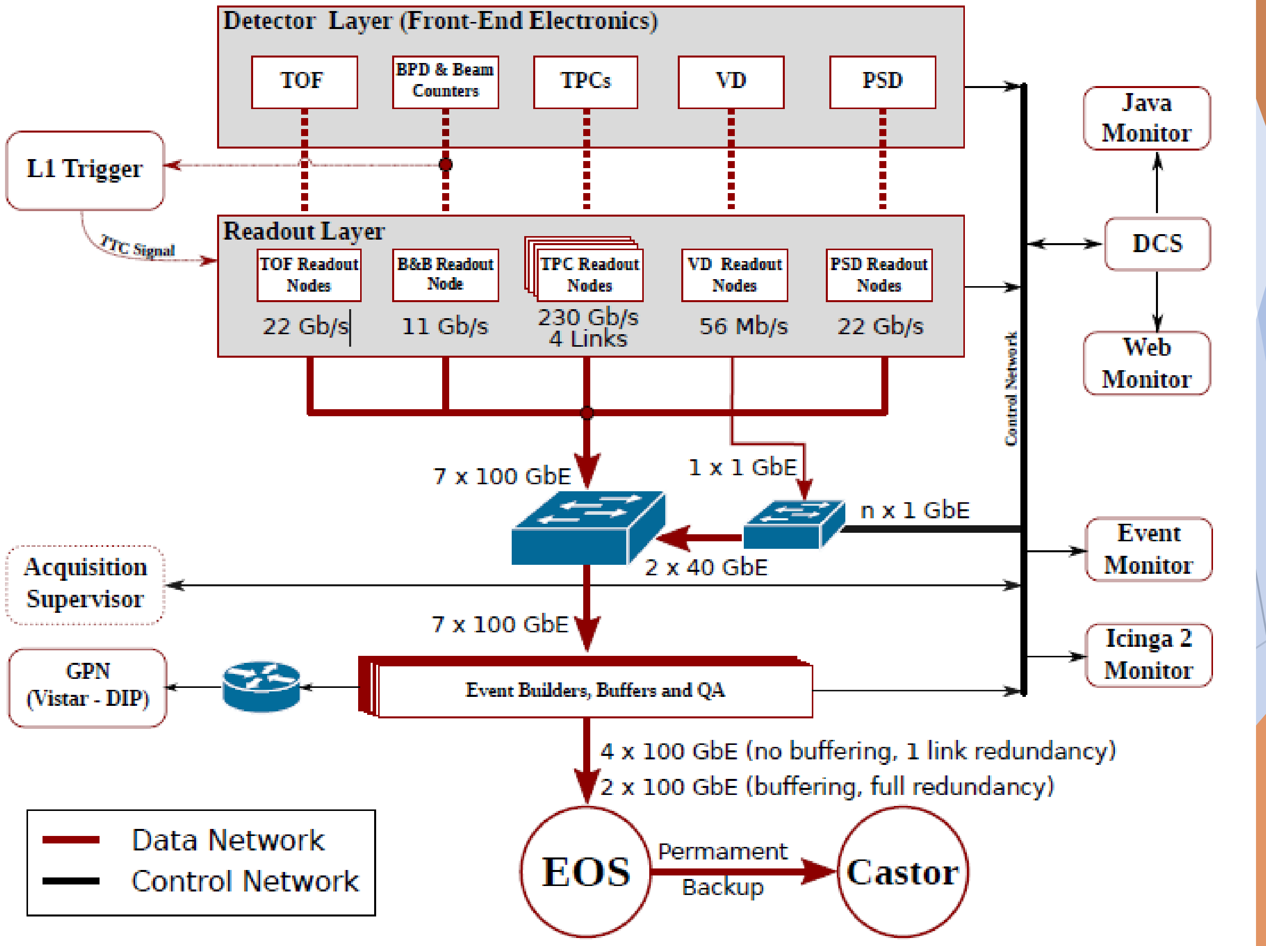
ALICE
Front-End Card

ALICE
Front-End Card on NA61 TPC



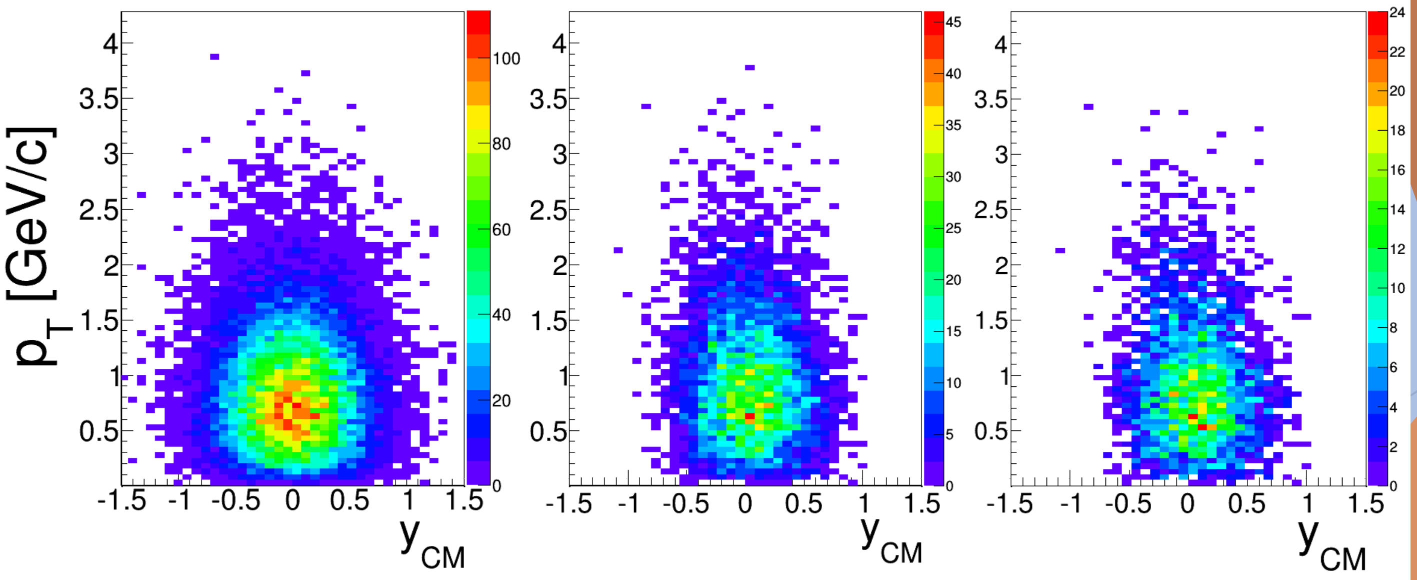
Upgrade of the trigger and data acquisition

- Need for 1kHz readout frequency,



Open charm measurements after detector upgrade

10 days in 2021 (1kHz + LAVD) ≈ **40000 D^0 in 40 M events**



Results are plotted for the 0-20 % most central Pb+Pb collisions at 150A GeV/c and correspond to 4 million events. – 1 day of data taking

Critical point: Strongly intensive measures Δ and Σ

$$\Delta[P_T, N] = \frac{1}{\omega[p_T]\langle N\rangle}\left[\langle N\rangle\omega[P_T] - \langle P_T\rangle\omega[N]\right] \qquad P_T = \sum_{i=1}^{N} p_{T\,i}$$

$$\Sigma[P_T, N] = \frac{1}{\omega[p_T]\langle N\rangle}\left[\langle N\rangle\omega[P_T] + \langle P_T\rangle\omega[N] - 2(\langle P_T N\rangle - \langle P_T\rangle\langle N\rangle)\right]$$

$$\omega[P_T] = \frac{\langle P_T^2\rangle - \langle P_T\rangle^2}{\langle P_T\rangle} \qquad \omega[p_T] = \frac{\overline{p_T^2} - \overline{p_T}^2}{\overline{p_T}} \qquad \omega[N] = \frac{\langle N^2\rangle - \langle N\rangle^2}{\langle N\rangle}$$

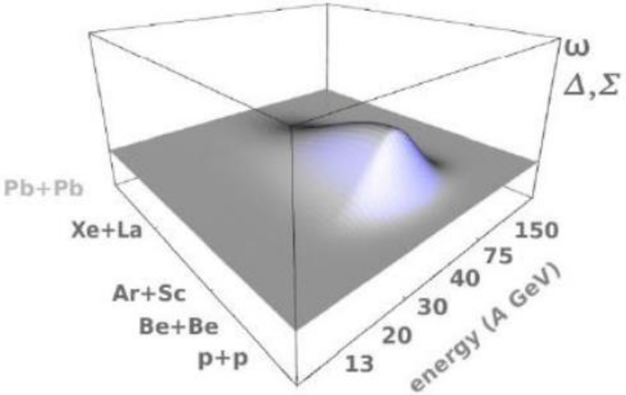
Δ = Σ = 0 for no fluctuations

Δ = Σ = 1 for Independent Particle Model

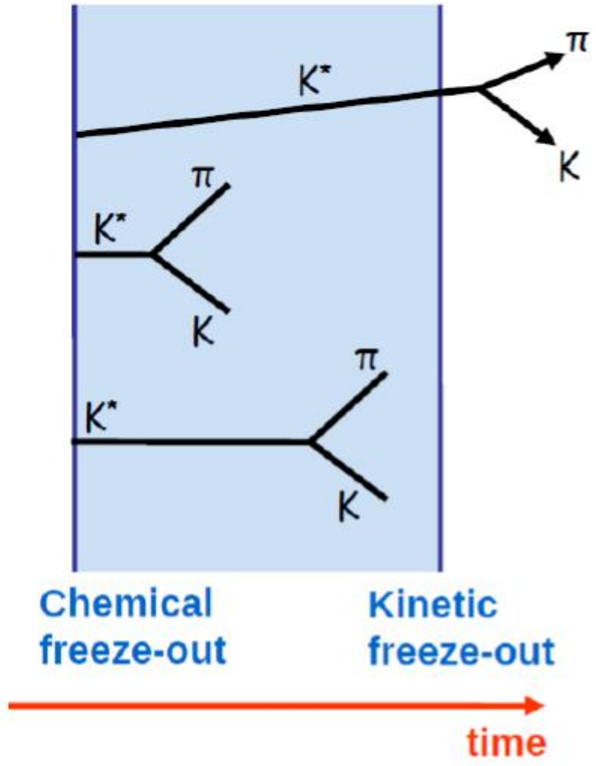
- $\Delta[P_T, N]$ uses only first two moments: $\langle N\rangle$, $\langle P_T\rangle$, $\langle P_T^2\rangle$, $\langle N^2\rangle$
- $\Sigma[P_T, N]$ uses also correlation term: $\langle P_T N\rangle - \langle P_T\rangle\langle N\rangle$

thus Δ and Σ can be sensitive to several physics effects in different ways

Expected: non-monotonic behavior of CP signatures



Motivation of K* measurement



The picture assumes that conditions at chemical freeze-out of p+p and Pb+Pb are the same

K* lifetime (≈ 4 fm/c) comparable with time between freeze-outs →

Some **resonances may decay inside fireball**; momenta of their decay products can be modified due to elastic scatterings → problems with experimental reconstruction of resonance via invariant mass →

Suppression of observed K* yield

Assuming no regeneration processes (Fig.) time between freeze-outs can be determined from (STAR, PR C71, 064902, 2005):

$$\frac{K^*}{K}(\text{kinetic}) = \frac{K^*}{K}(\text{chemical}) \cdot e^{\frac{-\Delta t}{\tau}}$$

use Pb+Pb or Au+Au ratio

use p+p ratio

Δt – time between kinetic and chemical freeze-outs

τ – K*(892)⁰ lifetime = 4.17 fm/c; PDG, PR D98, 030001, 2018