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Recent results from NA61/SHINE

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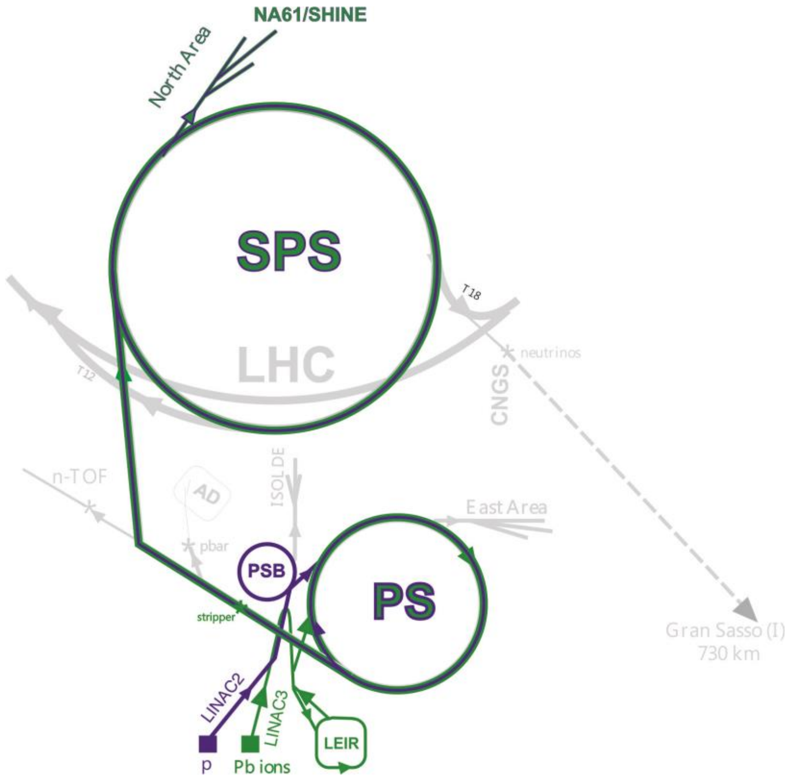
University of Silesia, Poland

NA61/SHINE - Physics program

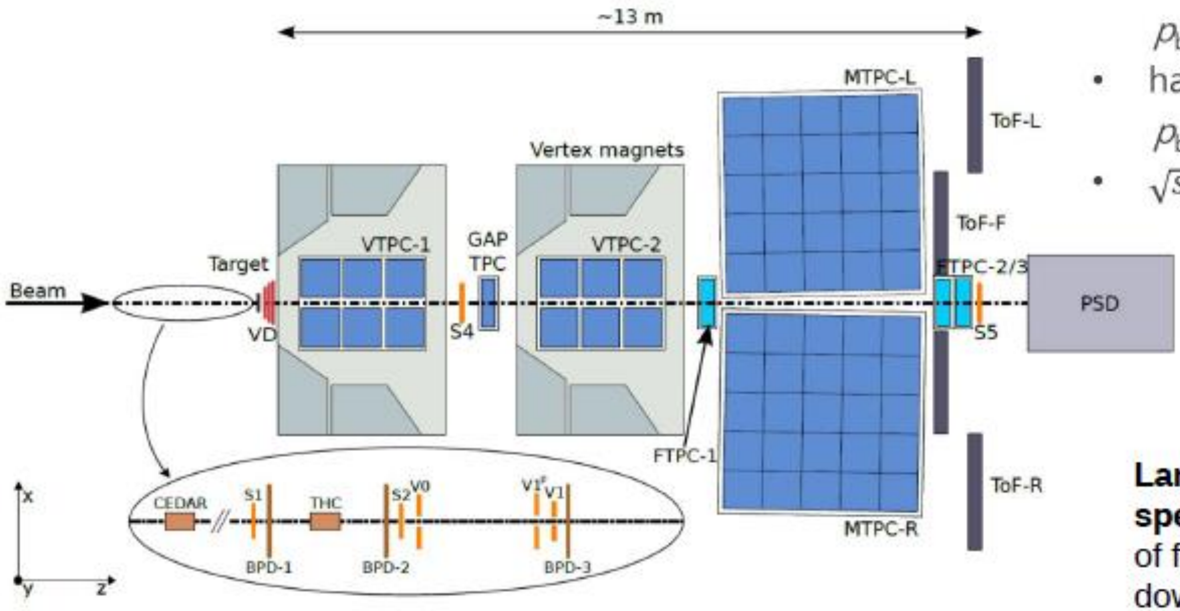
- **Strong interactions program**
  - **search for the critical point of strongly interacting matter**
  - **study of the properties of the onset of deconfinement**
  - **study high p_T particles production (energy dependence of nuclear modification factor)**
- Hadron-production measurements for neutrino 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



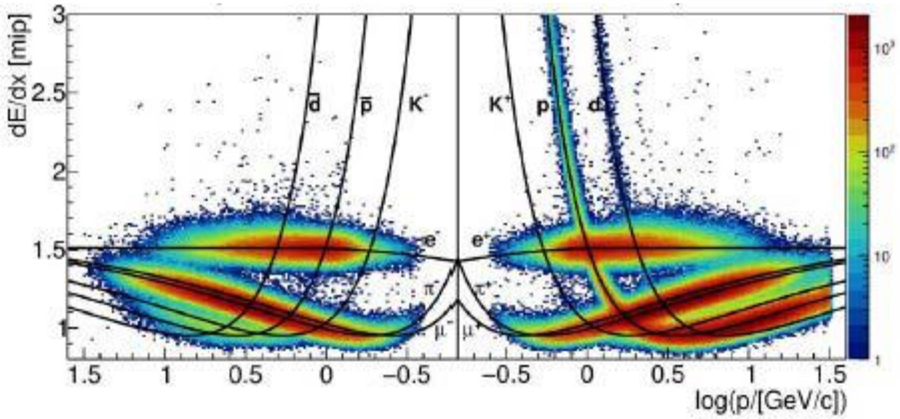
Beams:

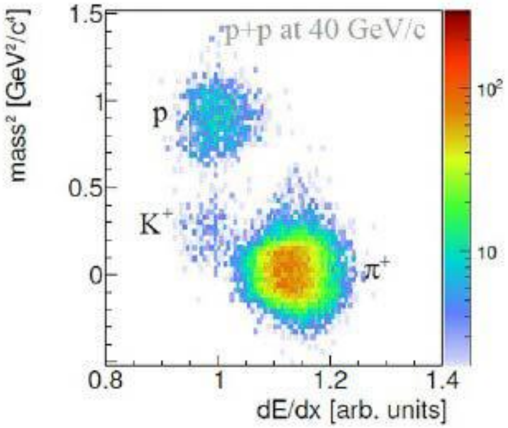
- ions (Be, Ar, Xe, Pb)
  p_{beam}=13*A*–150*A* GeV/*c*
- hadrons (π, K, p)
  p_{beam}=13–400 GeV/*c*
- $\sqrt{s_{NN}}$= 5.1–16.8 (27.4) GeV

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

NA61/SHINE Performance

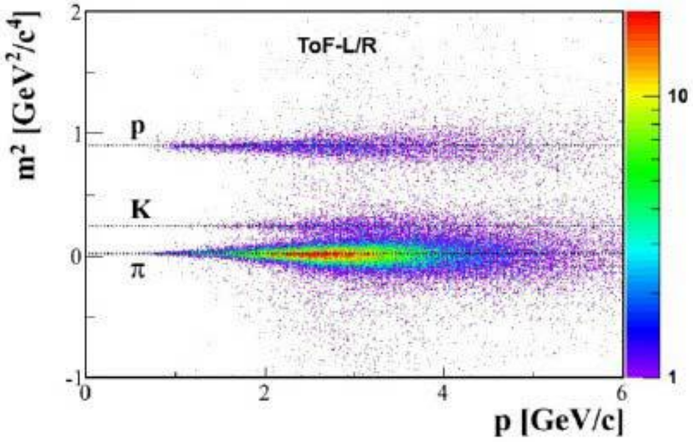




$$\sigma(p)/p^2 \approx 10^{-4}(GeV/c)^{-1}$$

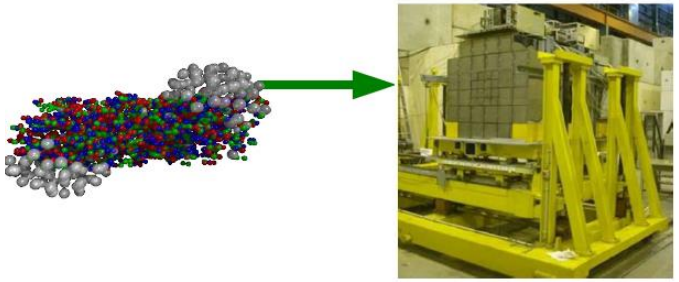
$$\sigma(dE/dx) \approx 4\%$$

$$\sigma(ToF) \approx 100\,ps$$

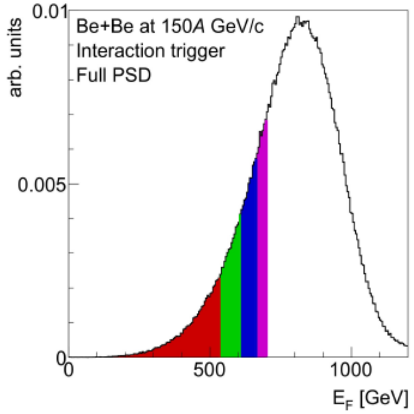


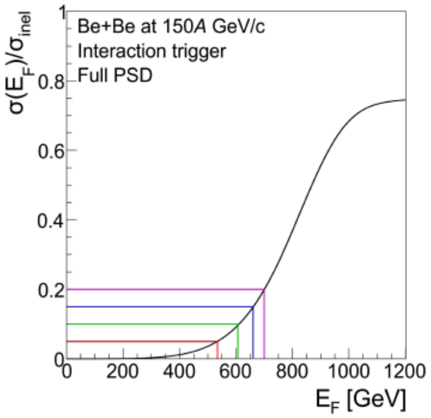
Centrality selection in ion collisions

- 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



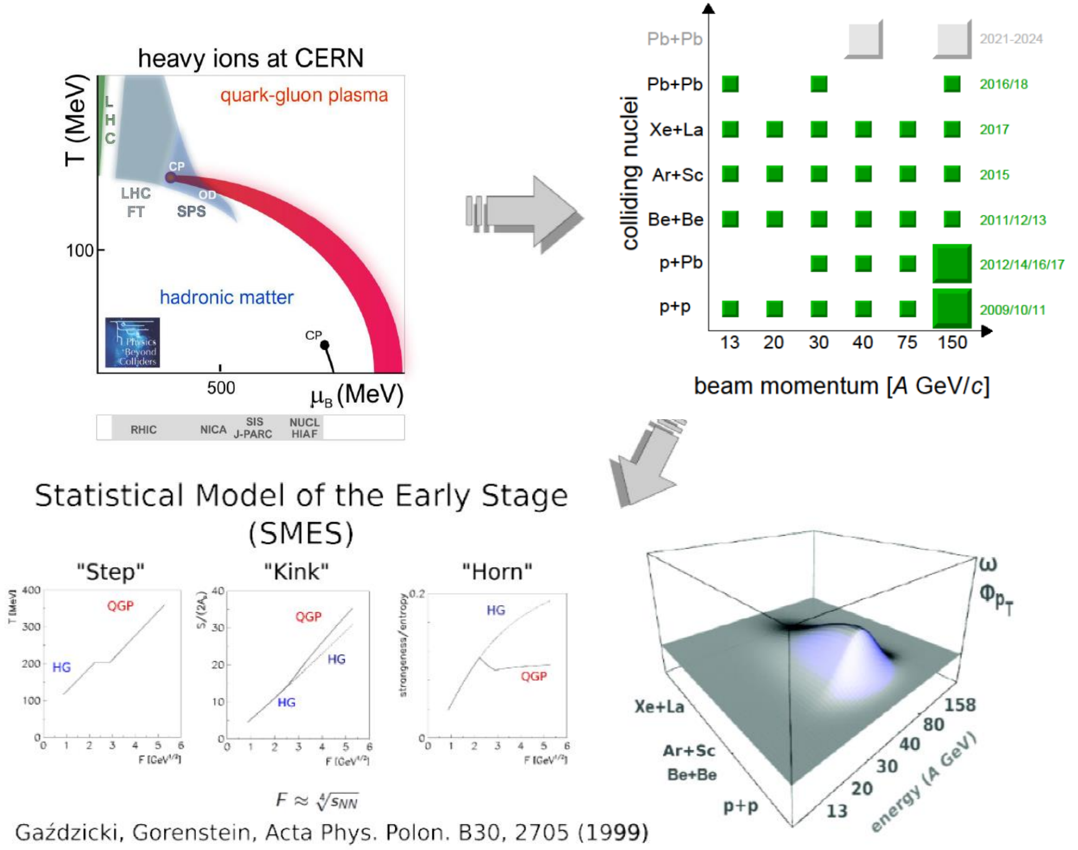
0 - 5% 5 - 10% 10 - 15% 15 – 20%





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



Study of the onset of deconfinement: Particle production properties

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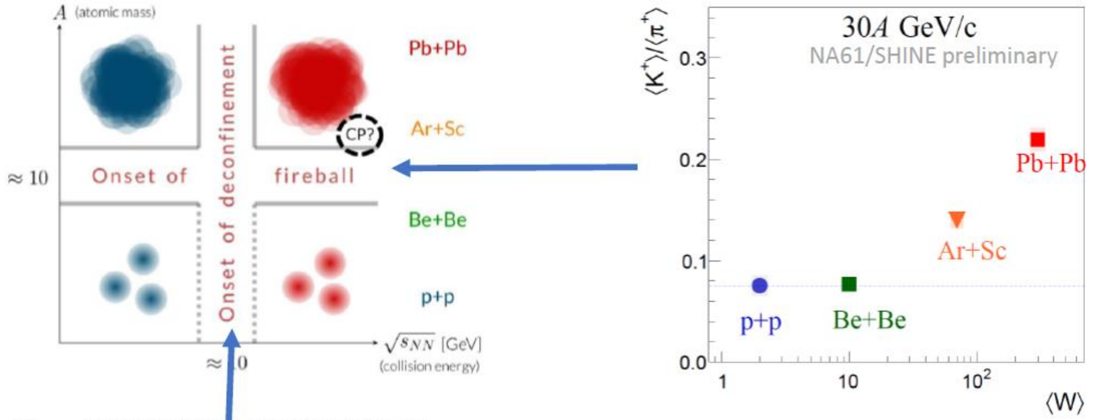
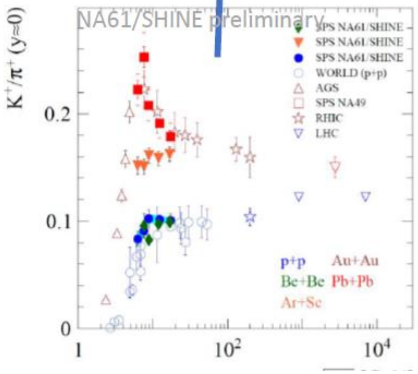
Uniqueness of heavy ion results from NA61/SHINE



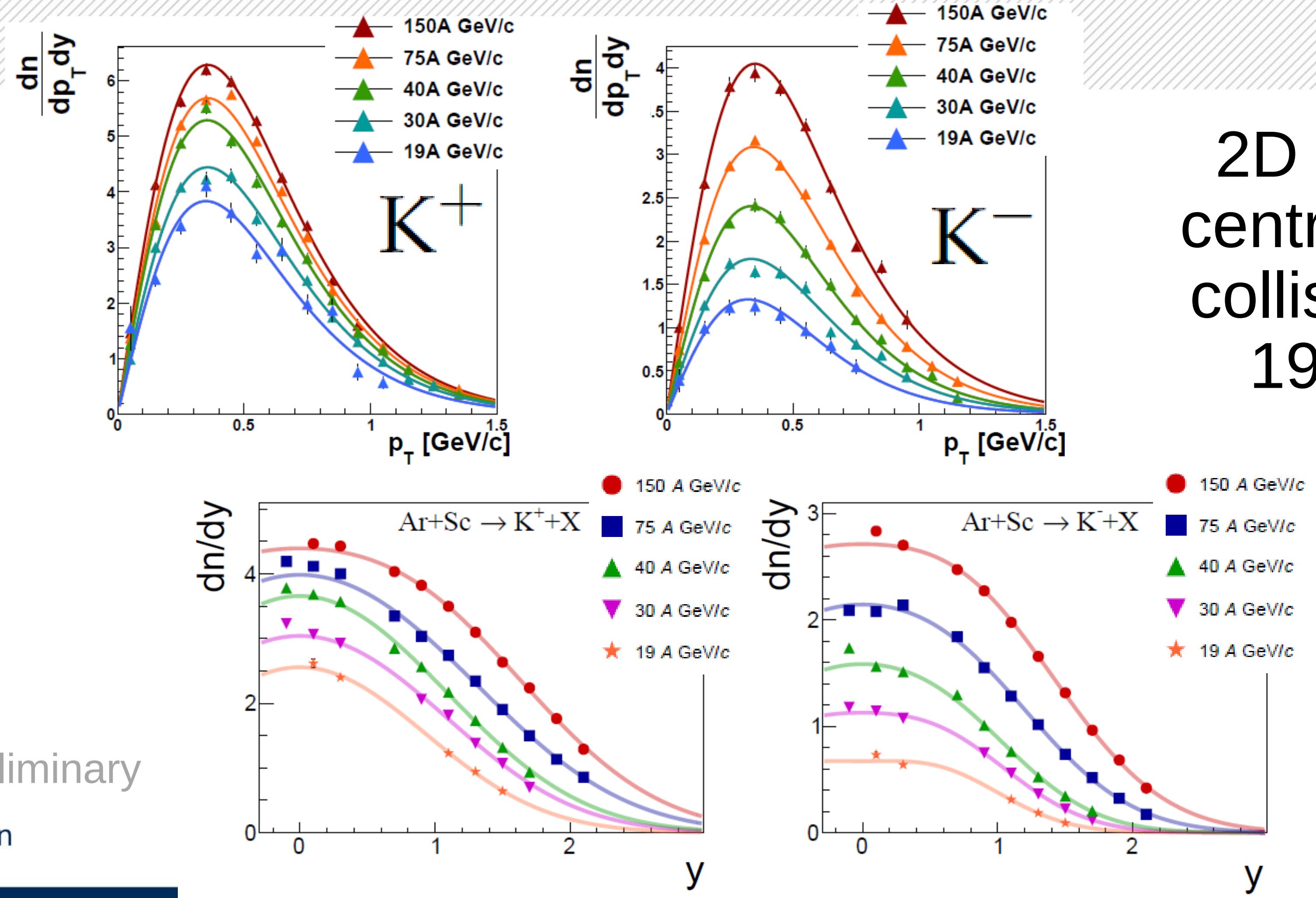


NA61/SHINE recorded unique data for:

- 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



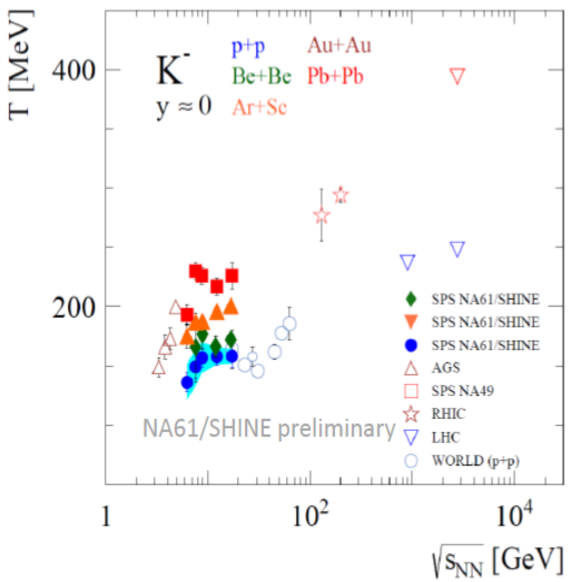
2D kaon spectra for central (0-10%) Ar+Sc collisions collisions at 19*A*–150*A* GeV/*c*

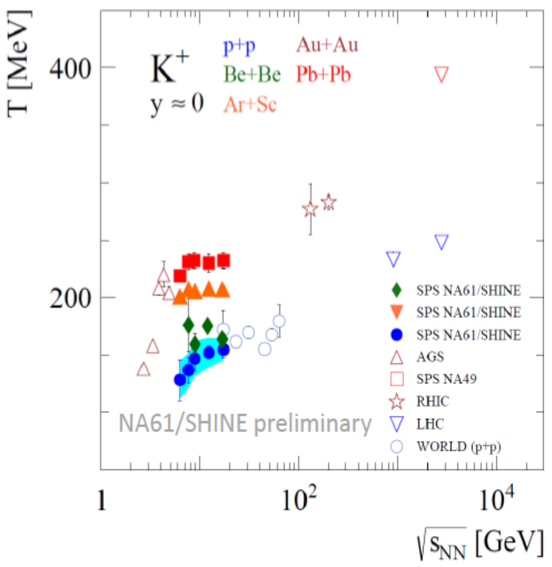
P. Podlaski, "Strangeness production at the CERN SPS energies," 2019. 18th International Conference on Strangeness in Quark Matter (SQM 2019), Bari, Italy.

NA61/SHINE preliminary

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).





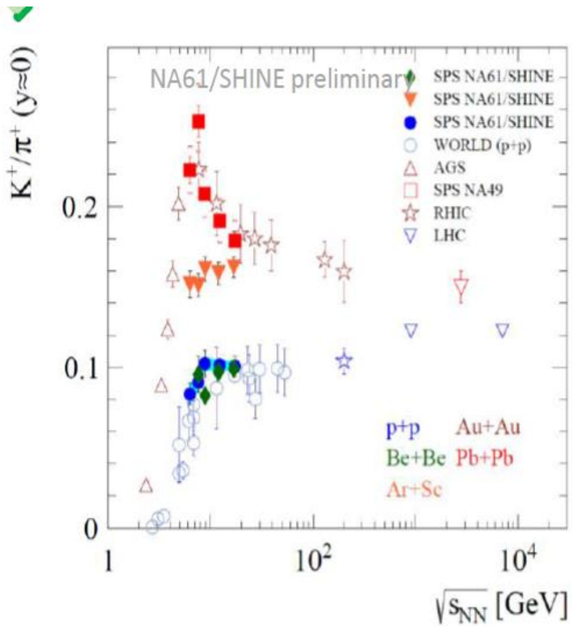
Qualitatively similar energy dependence is seen in p+p, Be+Be and Pb+Pb collisions

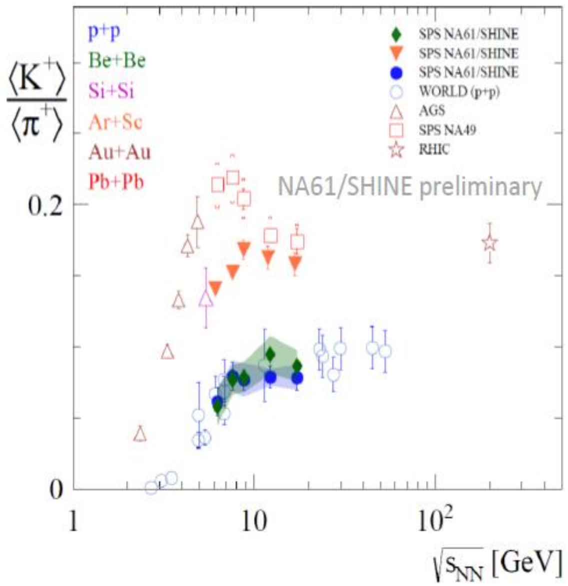
Magnitude of T in Be+Be slightly higher than in p+p

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)

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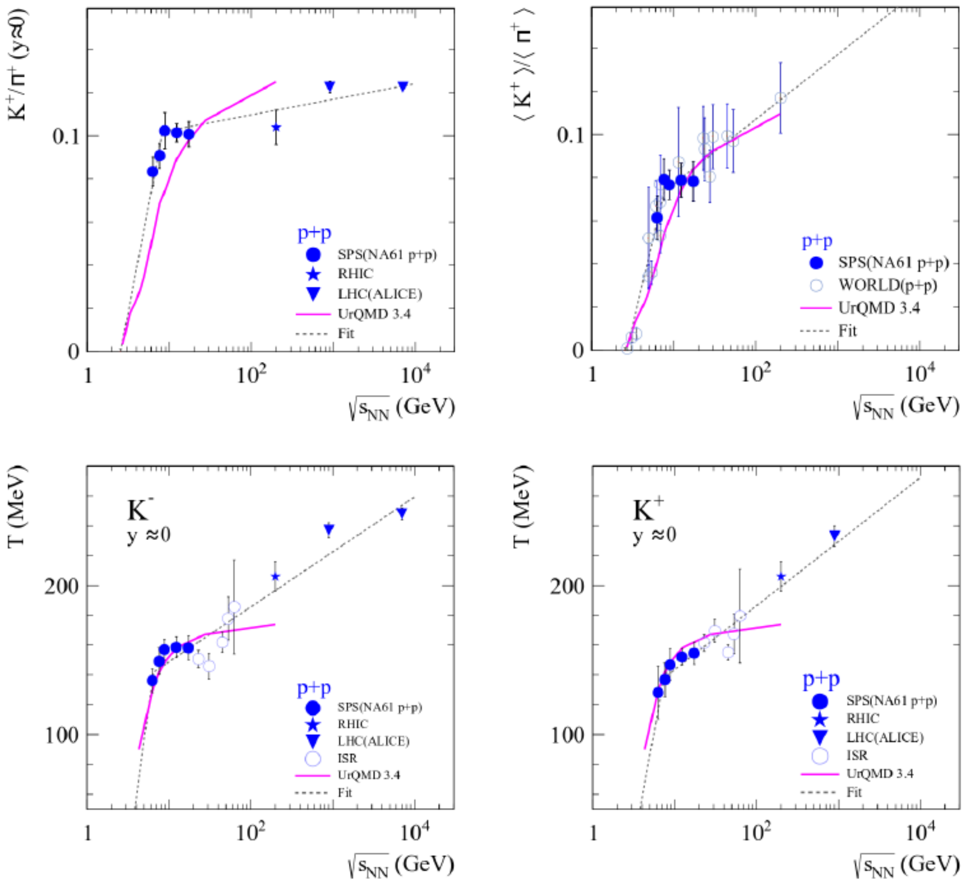
Onset of deconfinement: p+p data



- Rates of increase of K+/π+ 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.

PHYSICAL REVIEW C 102, 011901(R) (2020)

Study of the onset of fireball

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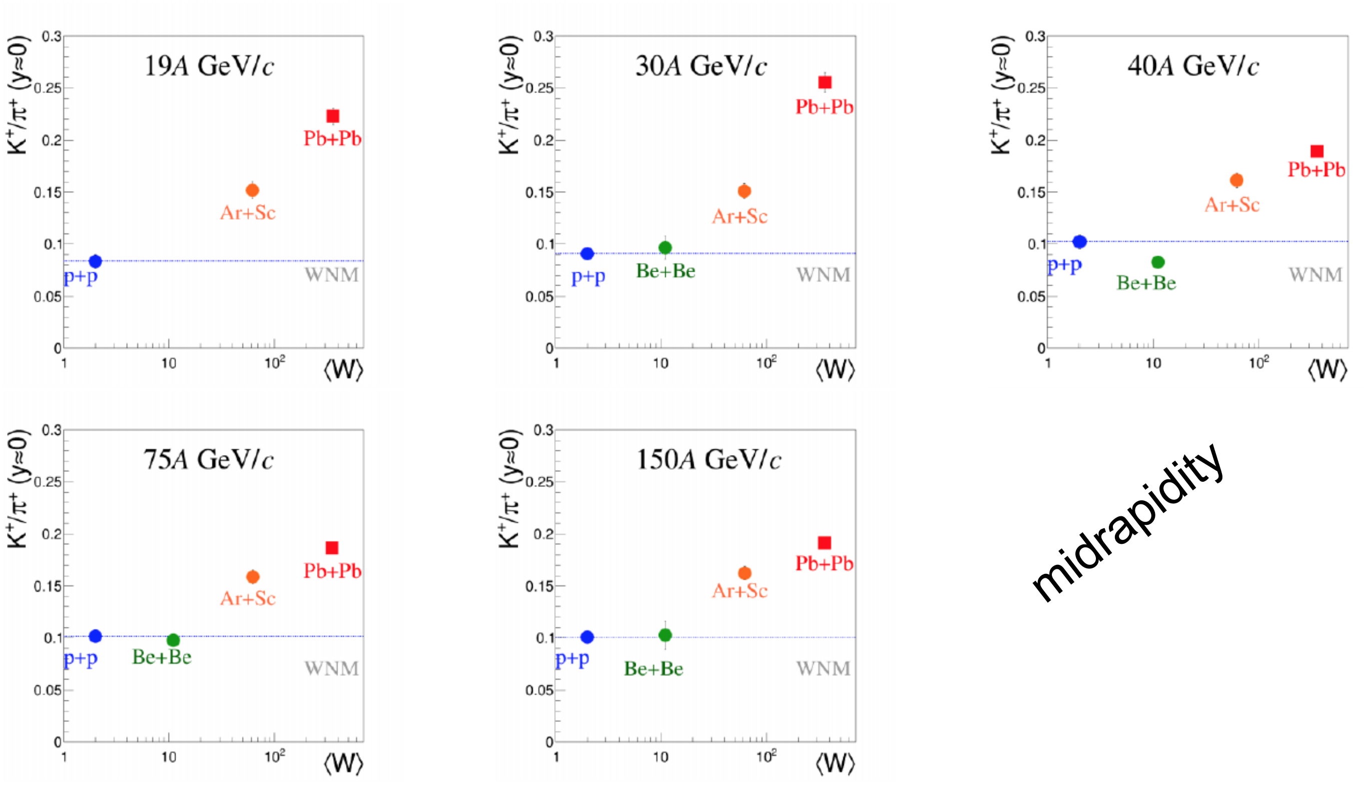
Onset of fireball: system size dependence

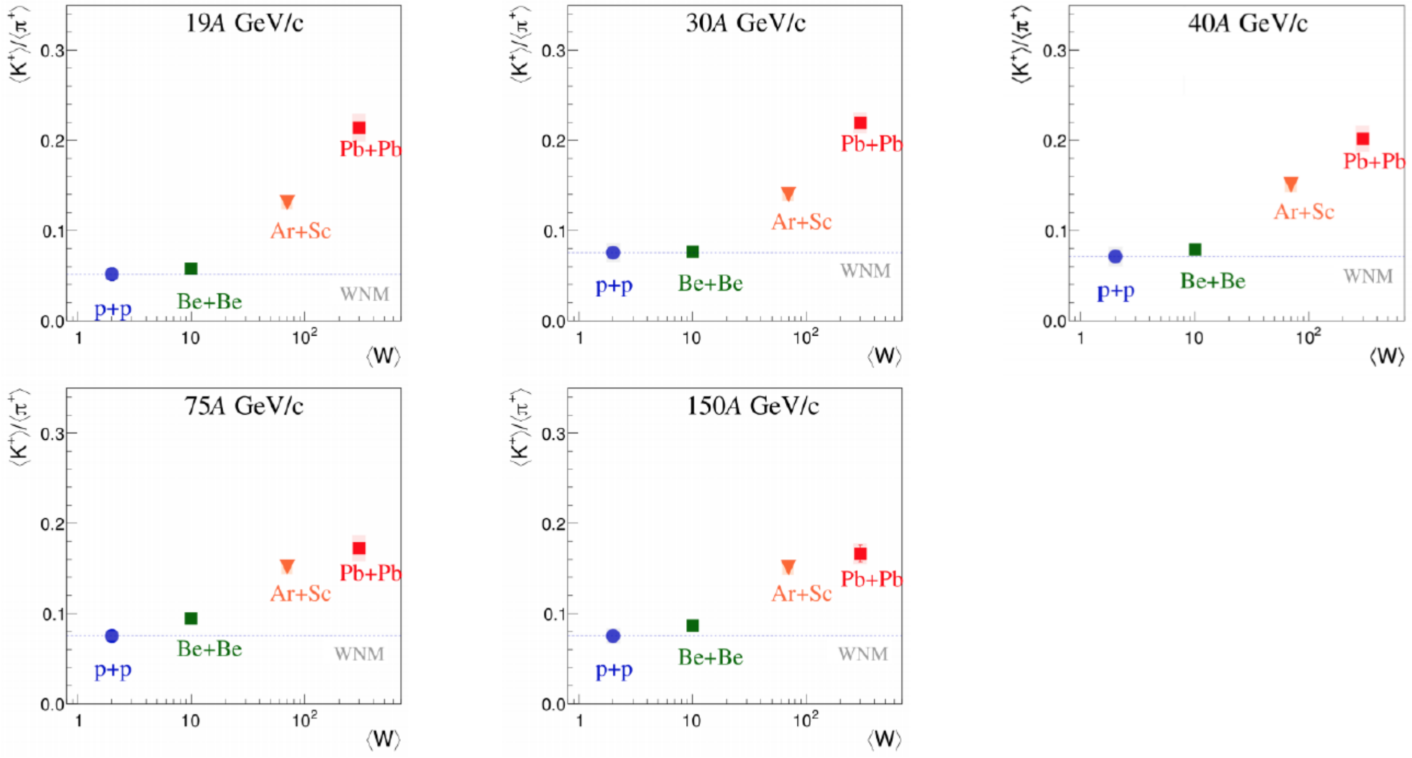


midrapidity

$$p + p \approx Be + Be \neq Ar + Sc \leq Pb + Pb$$

- Onset of fireball – beginning of creation of strongly interacting matter with increasing nuclear mass number
- Ar+Sc data are significantly higher than p+p~Be+Be results
- Ar+Sc is closer to Pb+Pb than to smaller systems
- Difference between Ar+Sc and Pb+Pb results is smaller for higher beam momenta

Onset of fireball: system size dependence



- Onset of fireball – beginning of creation of strongly interacting matter with increasing nuclear mass number
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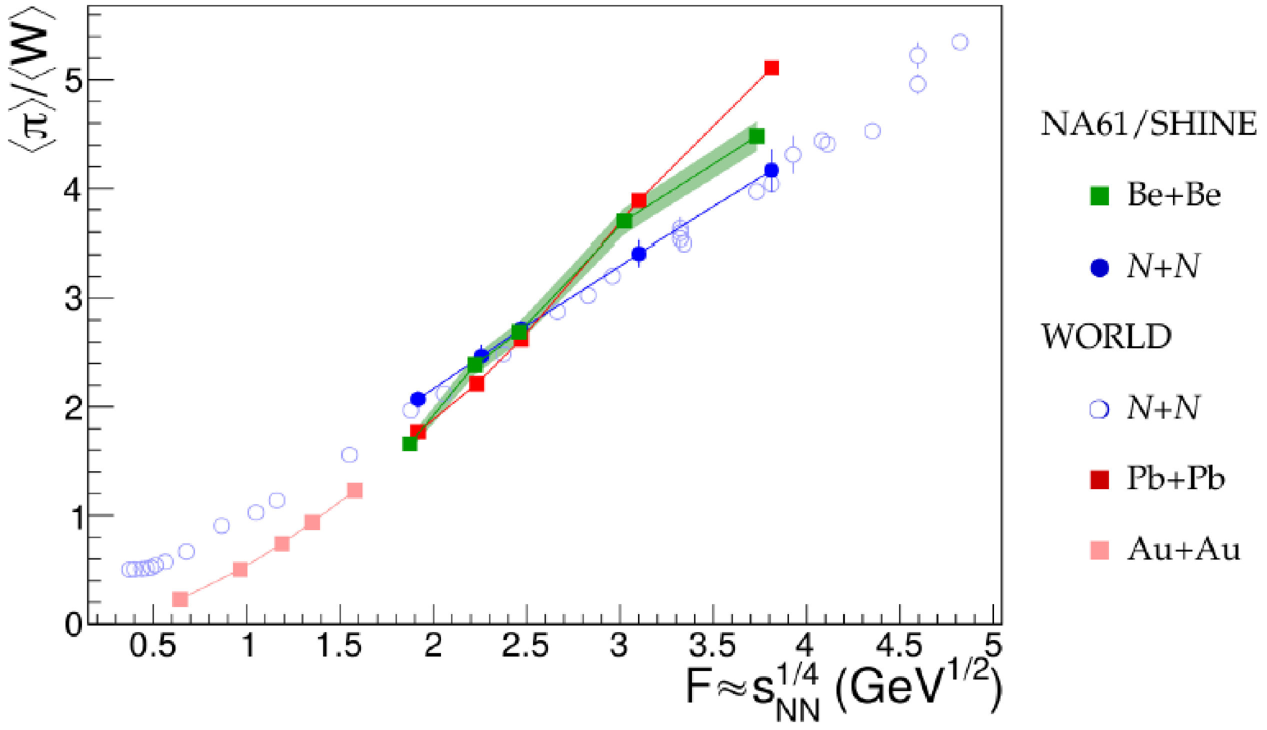
Pion production in Be+Be interactions



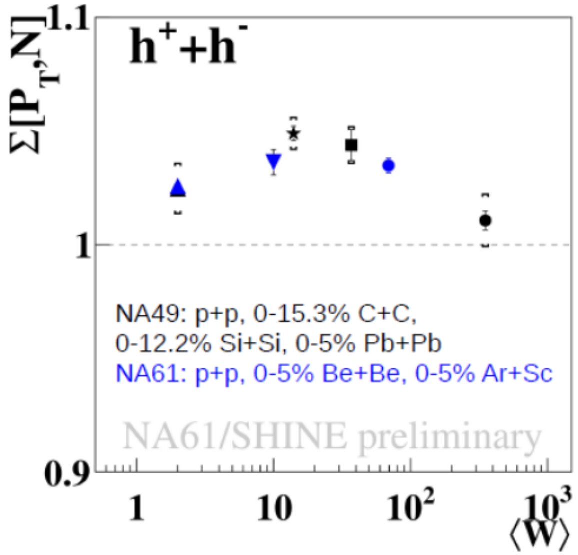
$\langle\pi\rangle\langle W\rangle$ in Be+Be interactions for low *F* follows Pb+Pb (Au+Au), while for top recorded collision energy it is close to *N*+*N*

arXiv:2008.06277v2 [nucl-ex] 9 Oct 2020

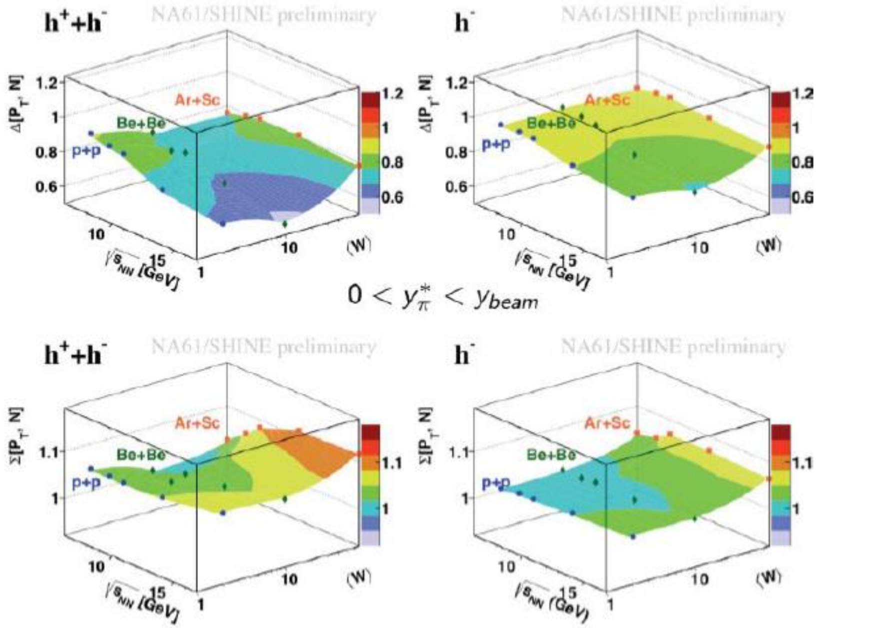
Search for critical point

Critical point: Strongly intensive measures $\Sigma[P_T,N]$

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

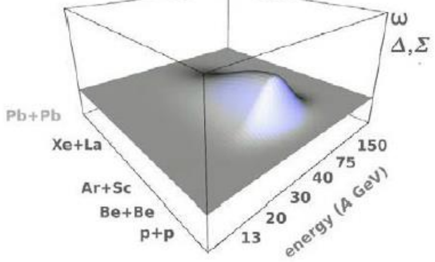


System size dependence of $\Sigma[P_T,N]$ at 150/158A GeV/c: NA49 and NA61/SHINE points show consistent trends



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

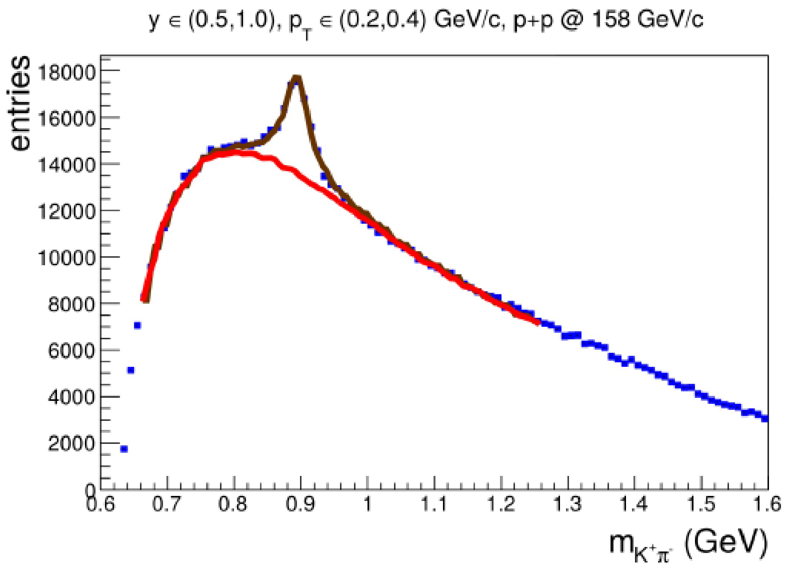


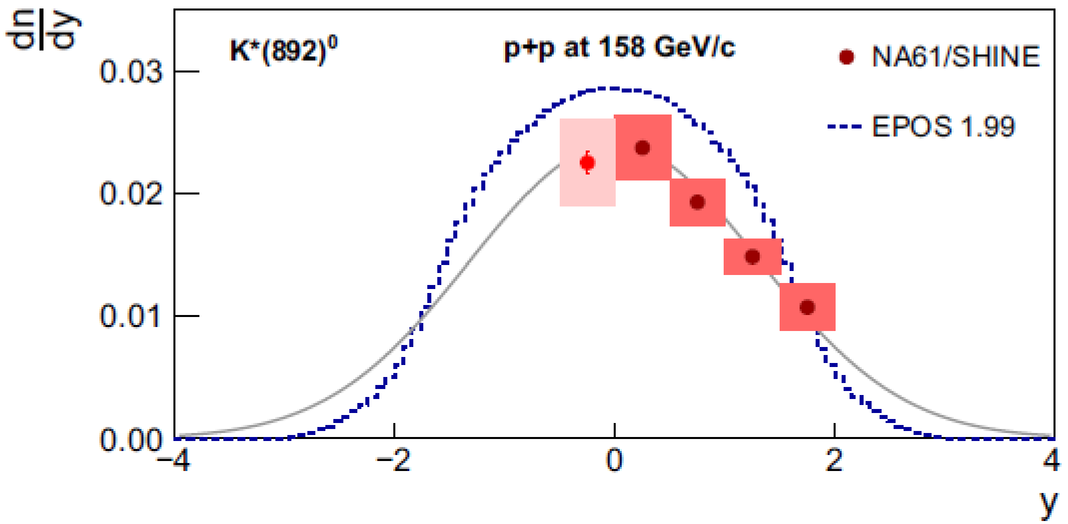
$$\Sigma[P_T,N] = \frac{1}{C_\Sigma}\left[\langle N\rangle\omega[P_T] + \langle P_T\rangle\omega[N] - 2\cdot(\langle P_T\cdot N\rangle - \langle P_T\rangle\langle N\rangle)\right]$$

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

Strangeness production in p+p at 158 GeV/c

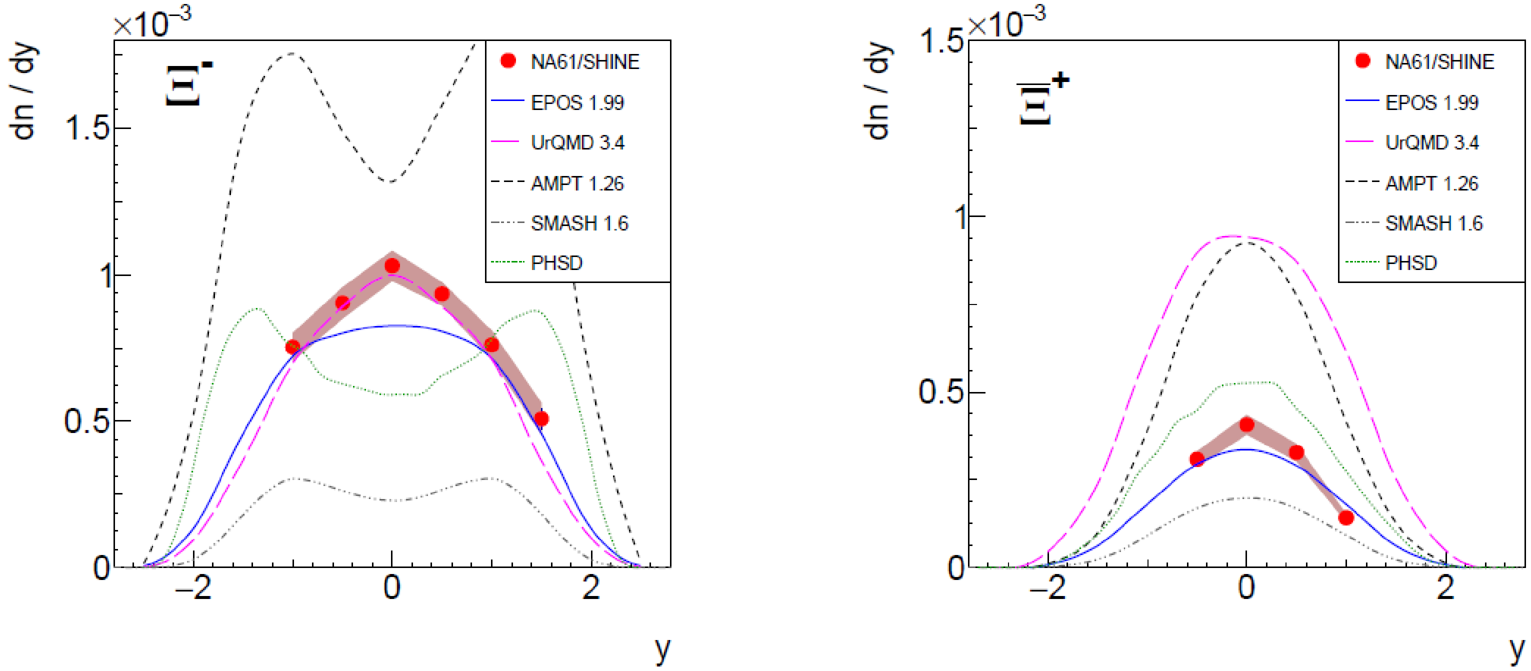
K*(892)^0 production in inelastic p+p collisions





Eur. Phys. J. C (2020) 80:460

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



Results on Ξ production obtained by the NA61/SHINE set a new baseline for calculation of strangeness enhancement factors in A+A collisions

Eur. Phys. J. C (2020) 80:199

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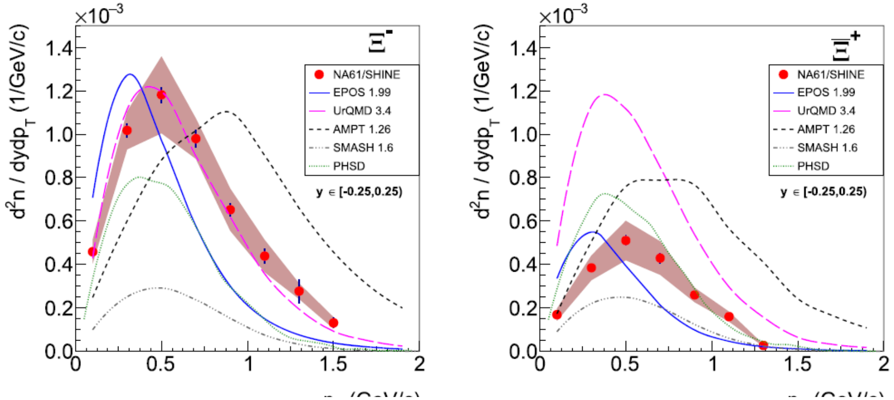
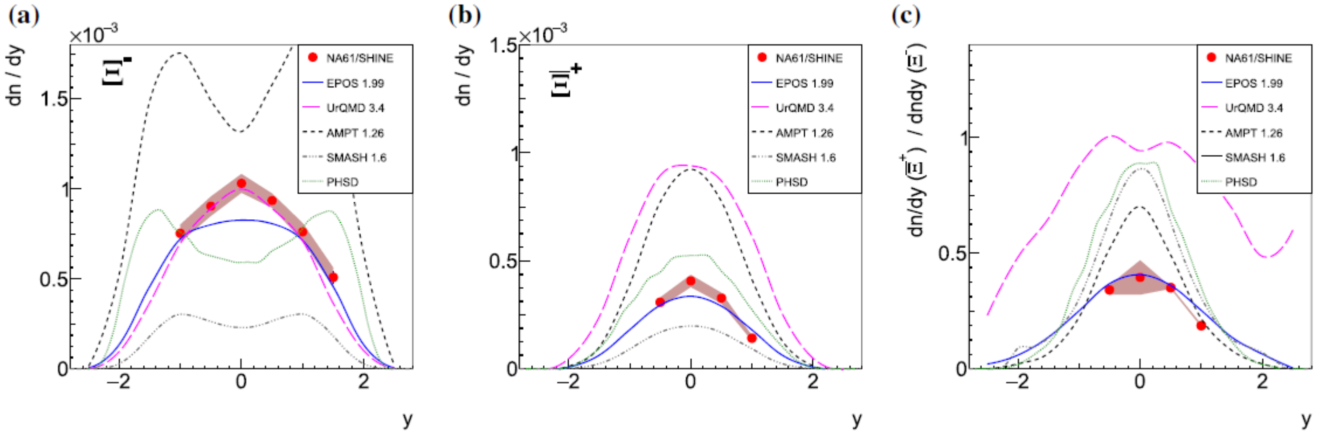
Ξ production in inelastic p+p collisions at 158 GeV/c

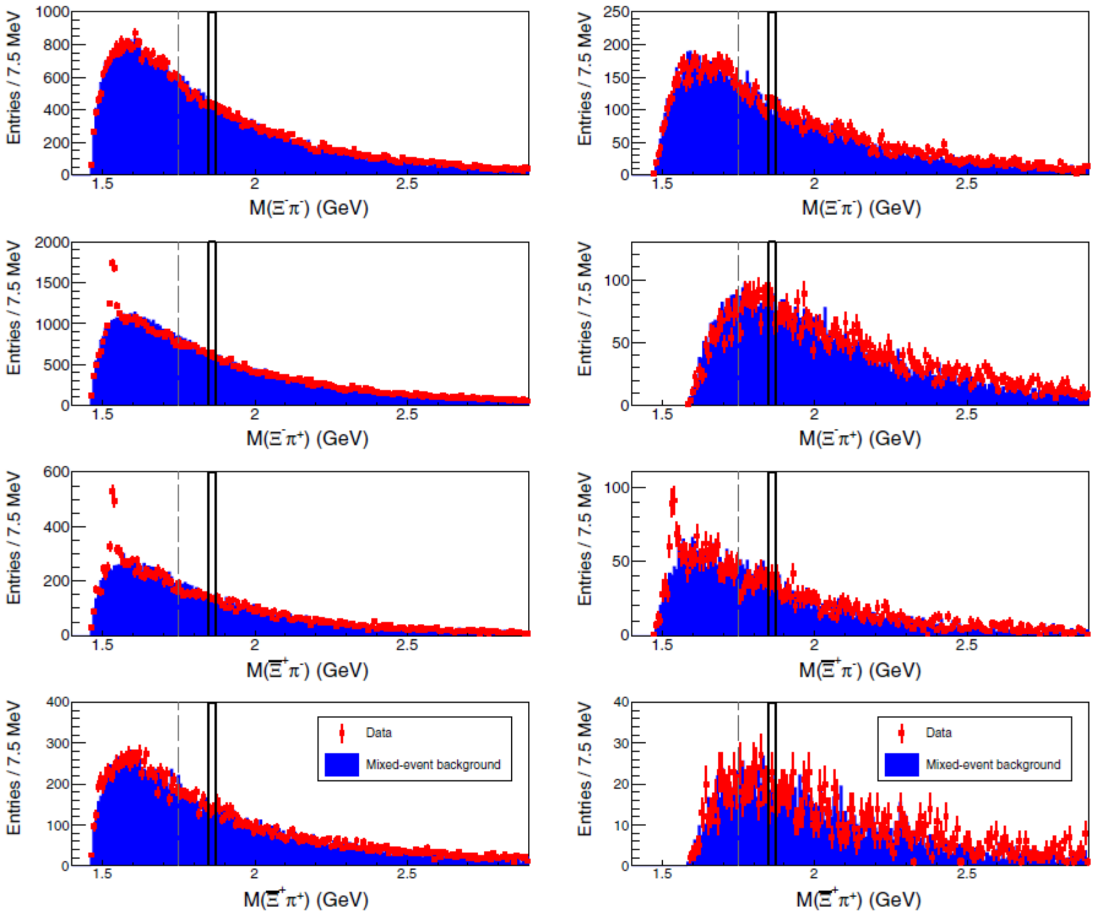




- UrQMD fails to describe ratio
- EPOS best description of the NA61/SHINE measurements

W'

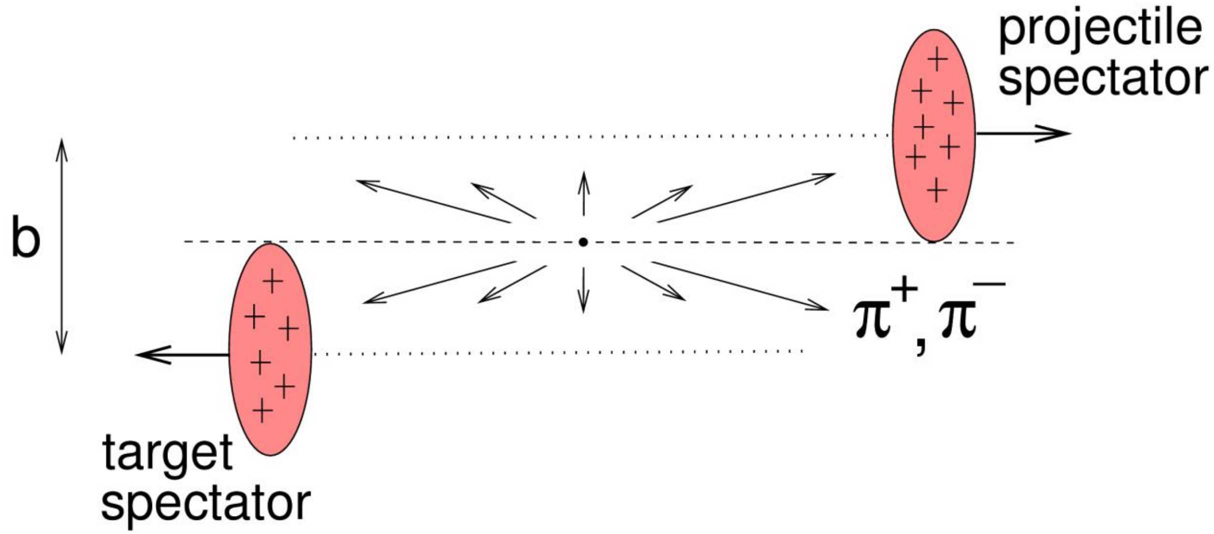
Ξ^{--}(1860) pentaquark search in NA61/SHINE



- 33M events
- No Ξ^{--}(1860) signal
- Ξ(1530) well visible

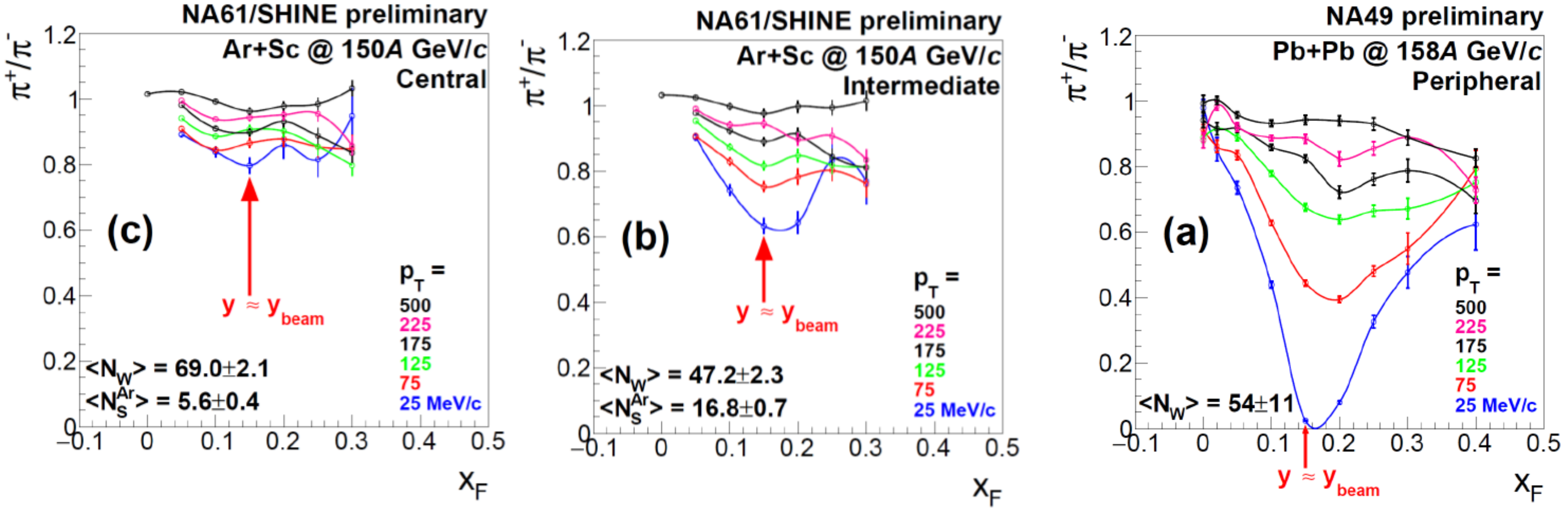
PHYS. REV. D 101, 051101 (2020)

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
- π+/π- 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

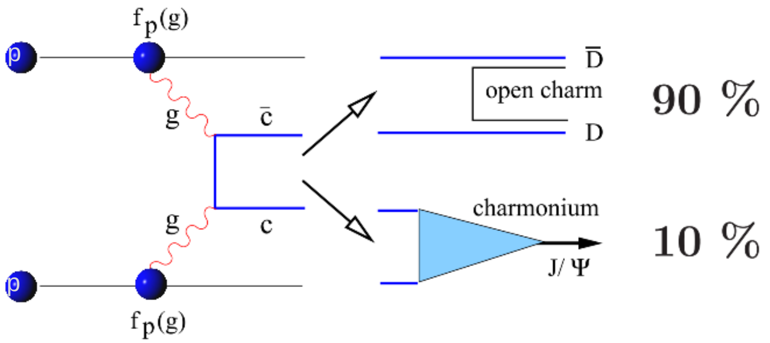
First observation of spectator induced EM effects in small systems at SPS

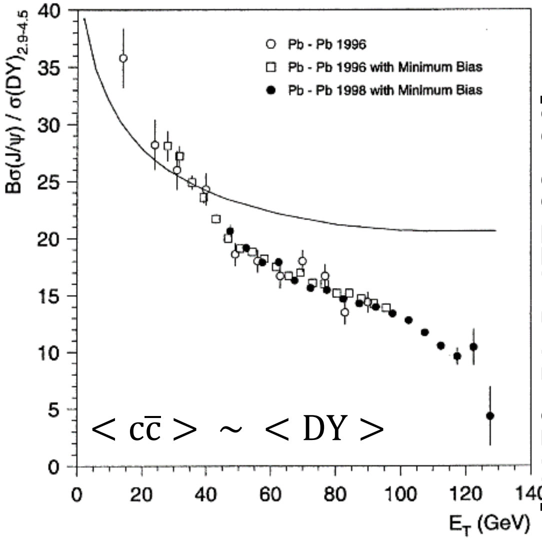
Similar effect seen in intermediate centrality Ar+Sc (NA61/SHINE) and peripheral Pb+Pb (NA49)

NA61/SHINE beyond 2020

J/ψ production as the signal of deconfinement

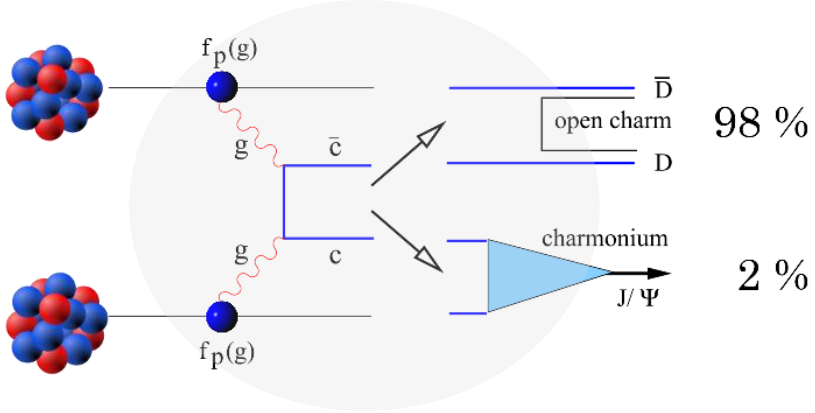
elementary p+p





[NA50, PL B 477 28–36]

Pb+Pb with QGP



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

Medium reduces probability of J/ψ production

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

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

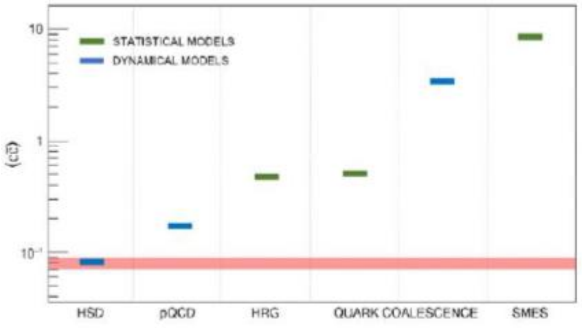
To answer these questions **mean number of charm quark pairs**, $c\bar{c}$ produced in A+A collisions has to be known. Up to now corresponding experimental data **does not exist** and **only NA61/SHINE can perform this measurement in the near future.**

NA61/SHINE program for 2021-2024

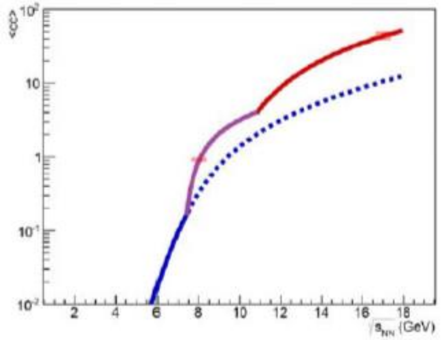
- What is the mechanism of open charm production?
- How does the onset of deconfinement impact open charm production?
- How does the formation of quark gluon plasma impact J/ψ production?

To answer these questions **mean number of charm quark pairs**, $c\bar{c}$ 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.**

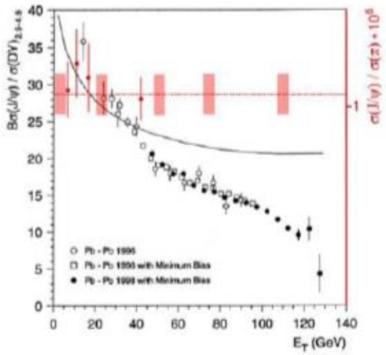
$\langle c\bar{c}\rangle$ and models



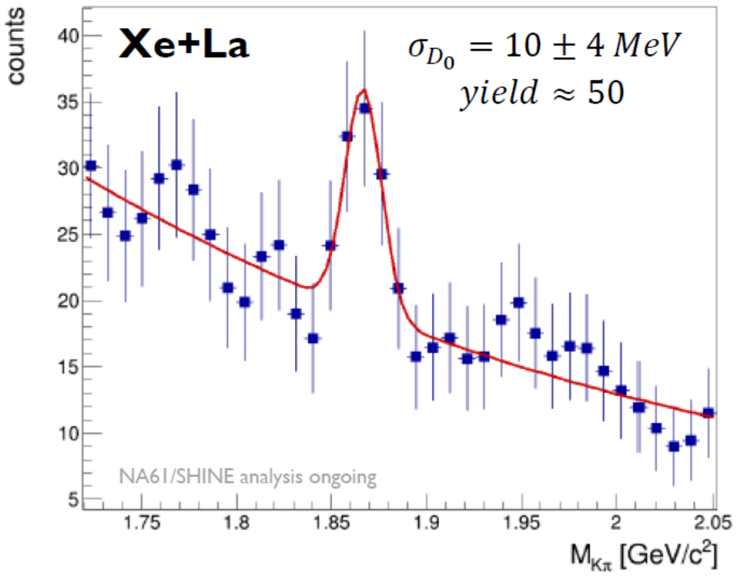
$\langle c\bar{c}\rangle$ and onset of deconfinement

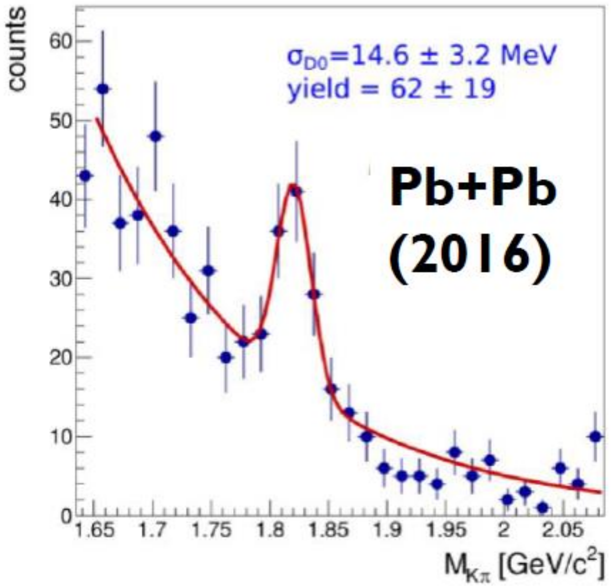


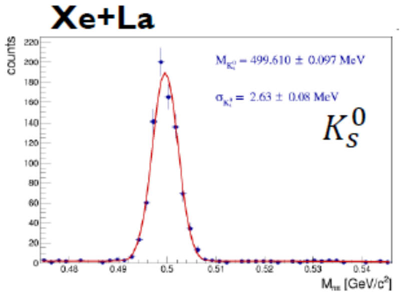
$\langle c\bar{c}\rangle$, $\langle J/\psi\rangle$ and QGP

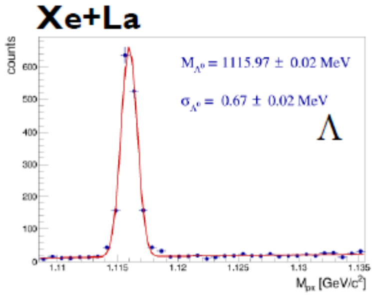


Test measurements - open charm signal in A+A at 150 A GeV/c

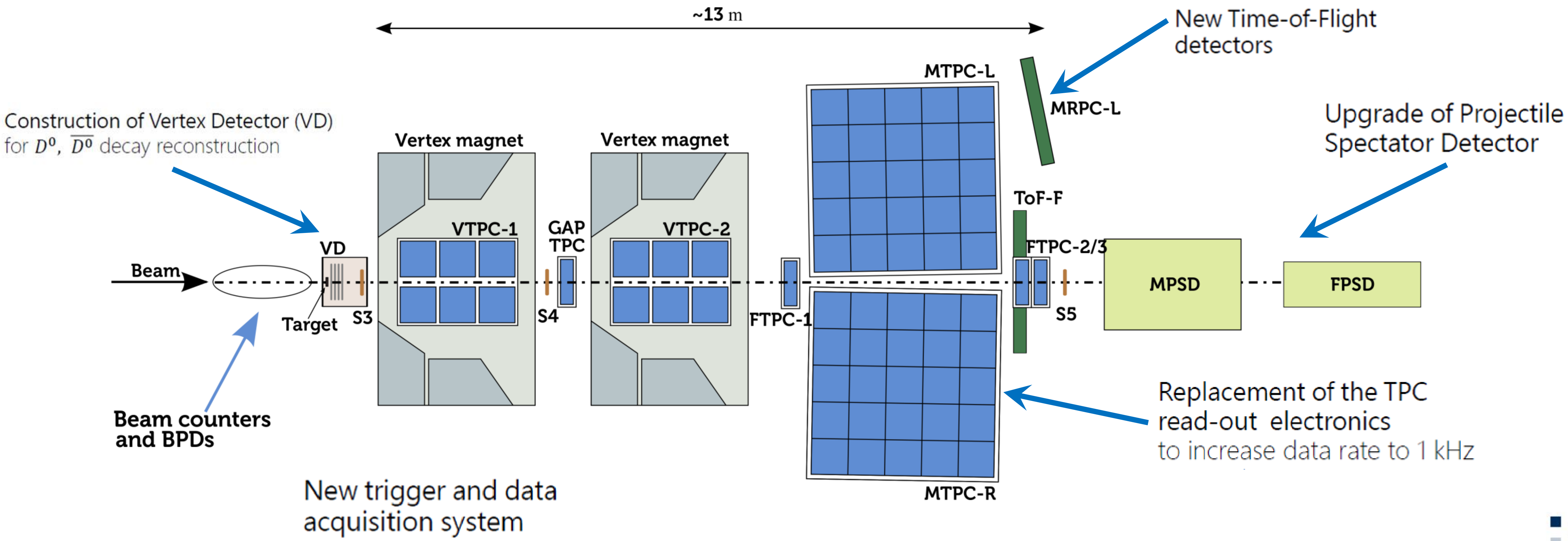






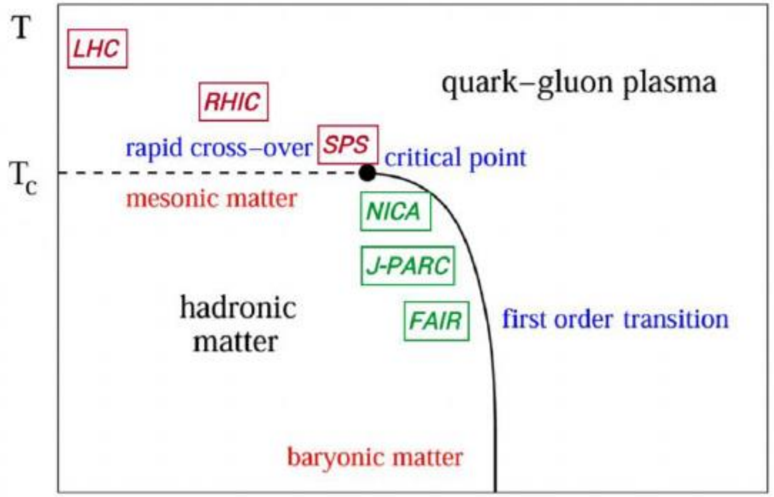


Detector upgrade during LS2



Uniqueness of NA61 open charm program

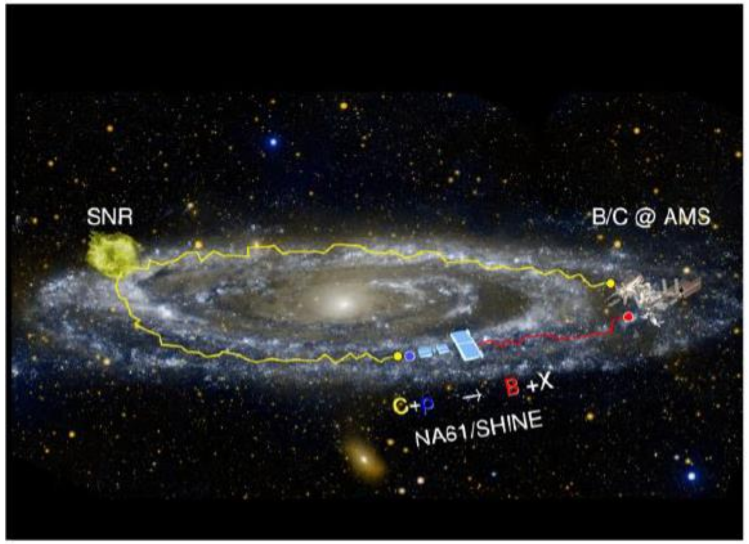
Landscape of present and future heavy ion experiments



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 at SIS-100
- NA61/SHINE planned in 2021 - 2024

Reference measurements: Nuclear fragmentation cross section for cosmic ray experiments



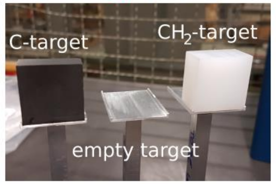
- Primary cosmic rays from supernova remnants
- Secondary cosmic rays from interactions with interstellar matter during propagation e.g.
  $^{12}C + p \stackrel{frag.}{\rightarrow} B + X$
  $^{12}C + p \stackrel{frag.}{\rightarrow} {}^{11}C + p \stackrel{decay}{\rightarrow} B + Y$
- Primary-to-secondary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

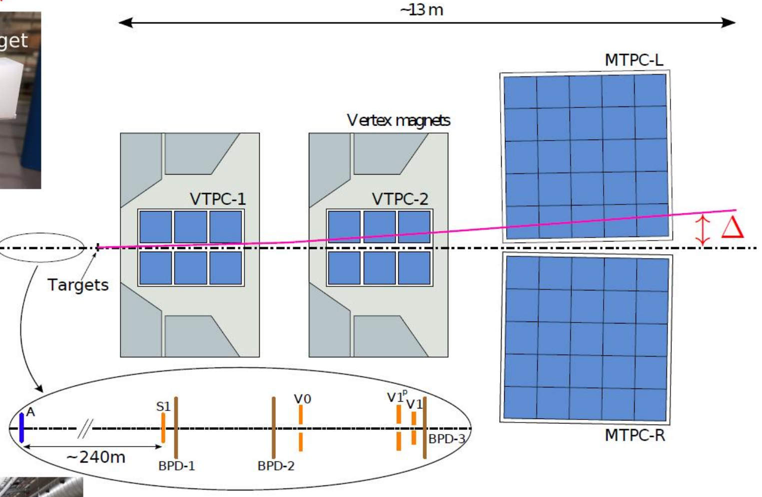
Understanding of cosmic ray propagation limited by uncertainties of fragmentation cross sections

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

Test measurement - nuclear fragmentation cross section

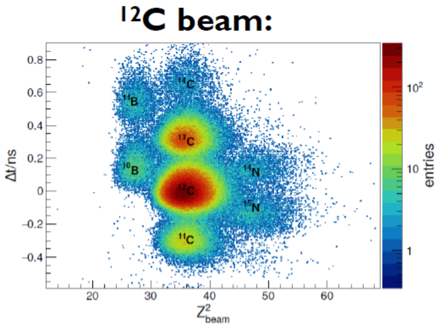
"C+p = (C+CH_2) - (C+C) - OUT"



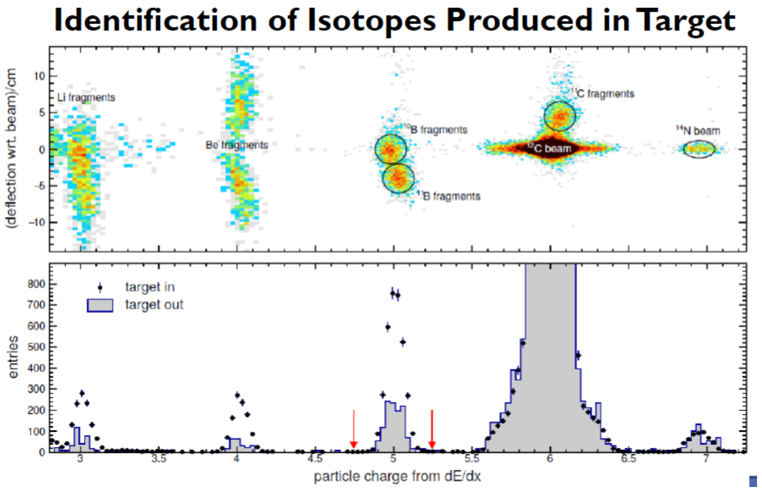


$\text{ToF(A to S1)} + dE/dx\text{(S1)} \rightarrow (A, Z^2)_{beam}$

$\Delta + dE/dx\text{(MTPC)} \rightarrow (A, Z^2)_{fragment}$



^{12}C purity: 99.2%
B contamination: < 0.1%



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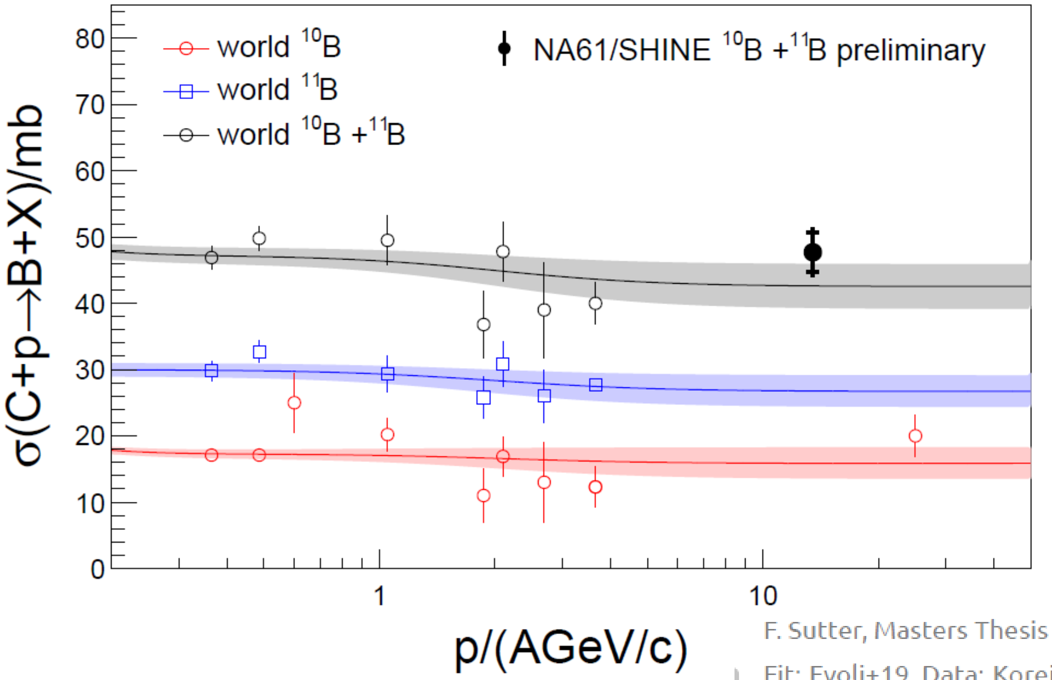
Direct ^{10}B + ^{11}B production (preliminary)

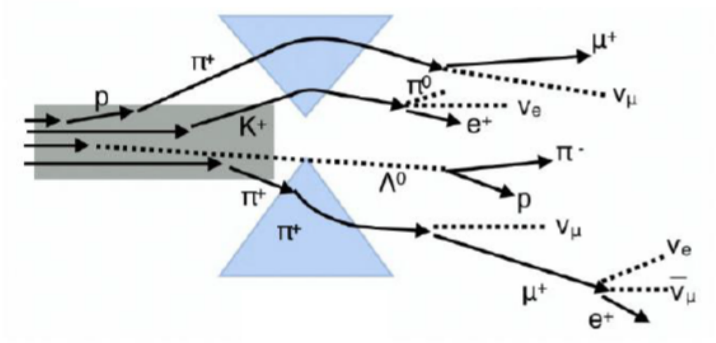
$$\sigma(^{12}\mathrm{C} + \mathrm{p} \rightarrow ^{10}\mathrm{B} + X) + \sigma(^{12}\mathrm{C} + \mathrm{p} \rightarrow ^{11}\mathrm{B} + \mathrm{X}) =$$
$$47.7 \pm 3.0\ \text{(stat.)} \pm 2.3\ \text{(syst.) mb}$$



F. Sutter, Masters Thesis KIT 2019; NA61/SHINE PoS(ICRC2019)446, arXiv:1909.07136

Fit: Evoli+19, Data: Korejwo+02, Korejwo+99, Webber+98, Webber90, Olson+83, Fontes+77

Reference measurements: Hadron production for neutrino experiments



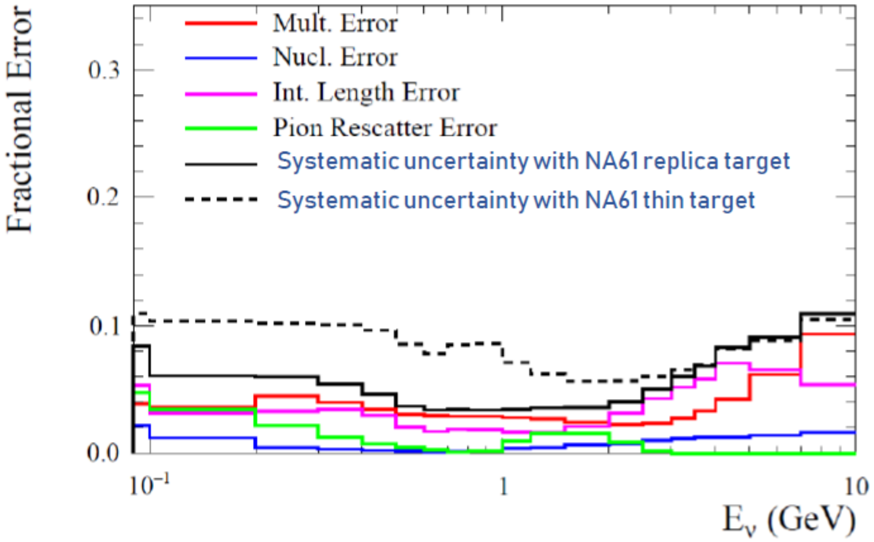
- Further improvement of the precision of measurements for the currently used T2K replica target,
- Measurements for a new target material (super-sialon) for T2K-II and Hyper-Kamiokande,
- Study of the possibility of measurements with beams <12 GeV/c for improved predictions of atmospheric and accelerator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

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Thank You

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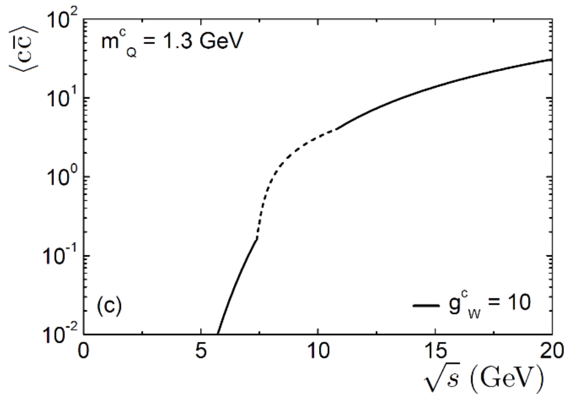
BACKUP

Open charm yield as the signal of deconfinement

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

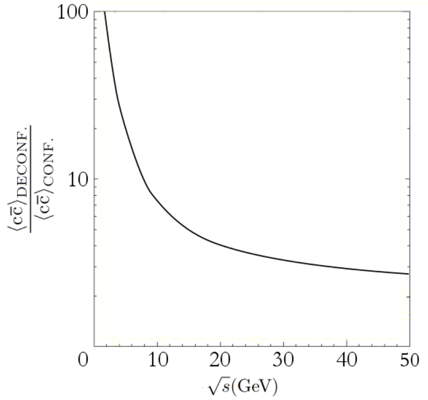
$$\mathrm{D\bar{D}\ mesons} \rightarrow \mathrm{charm\ quarks}$$
$$2m_{\mathrm{D}} = 3.7\ \mathrm{GeV} \rightarrow 2m_{\mathrm{c\bar{c}}} = 2.6\ \mathrm{GeV}$$
$$g_{\mathrm{D}} = 4 \rightarrow g_{\mathrm{c}} = 24$$

Statistical Model of the Early Stage



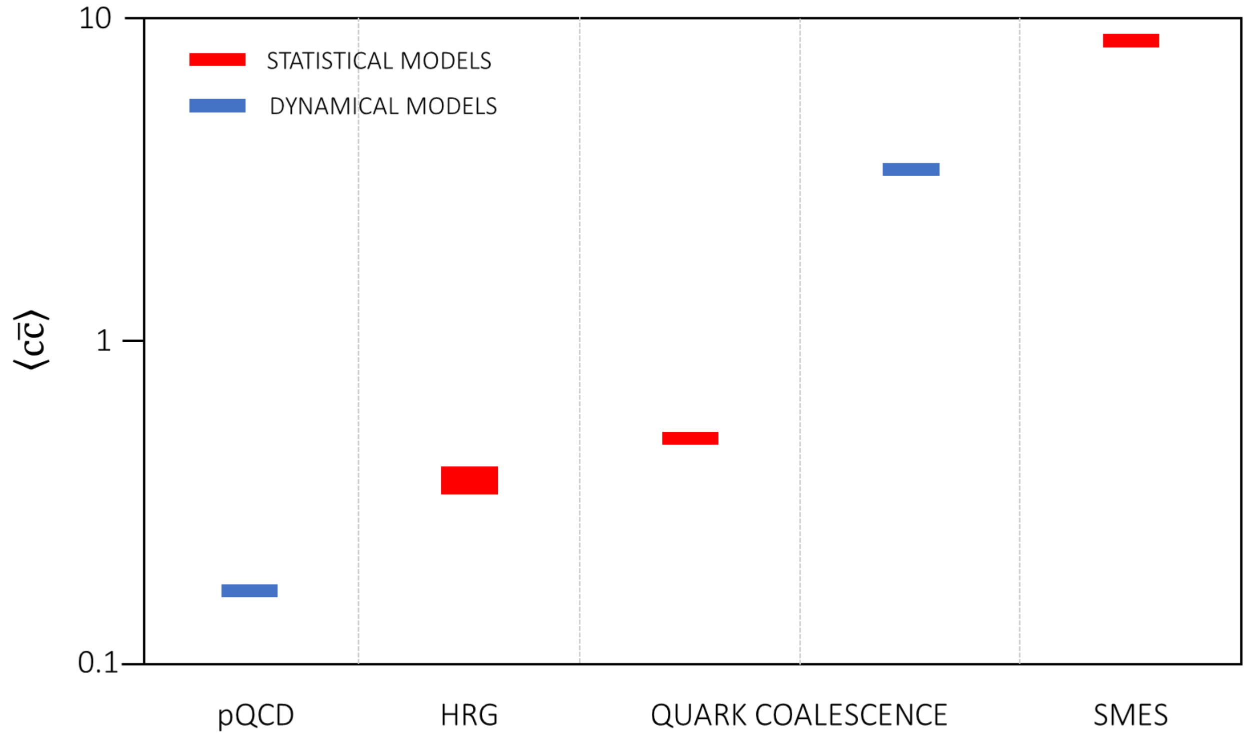
[Poberezhnyuk, Gazdzicki, Gorenstein, ACTA PHYS POL B 9 48(2017)]

QCD-inspired calculations



[Kostyuk, Gorenstein, Greiner, PL B519 207]

Mechanism of open charm and J/ψ production



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.

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

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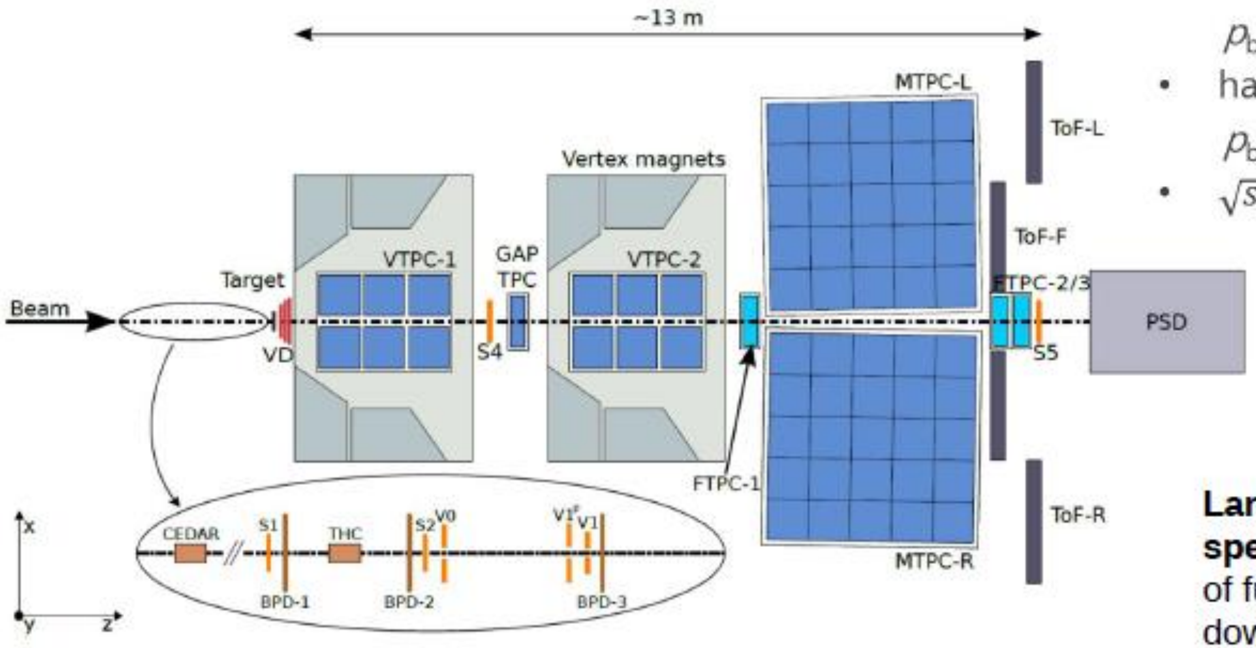
NA61/SHINE - Experimental layout

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}=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 $p_T = 0$

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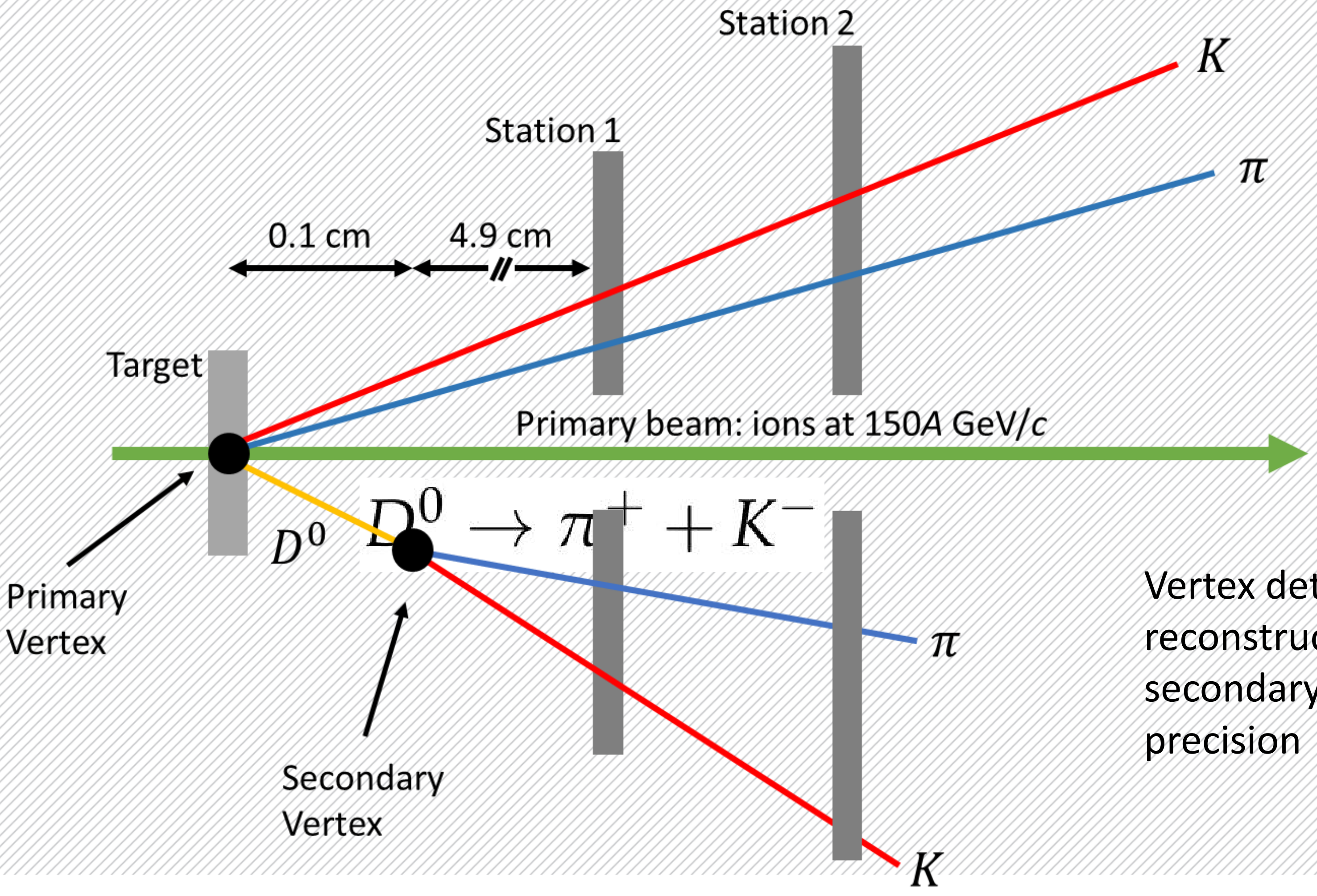
Feasibility studies of open charm measurements in NA61/SHINE

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

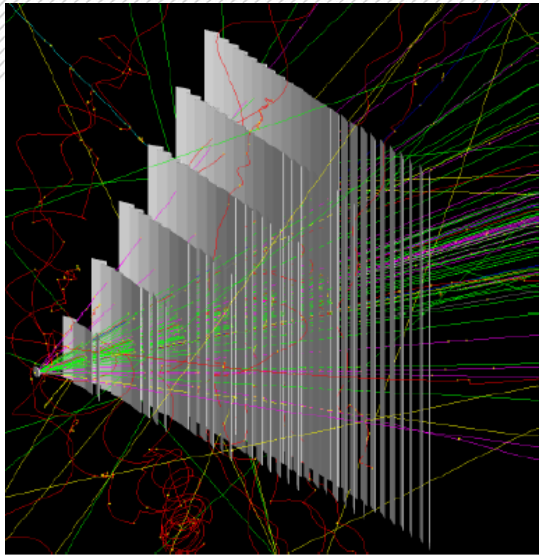
- 16 MIMOSA-26 sensors located on 2 horizontally movable arms
- Target holder integrated

Feasibility studies of open charm measurements in NA61/SHINE



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

Large Acceptance Vertex Detector



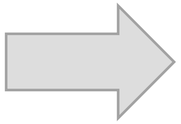
- General requirements:
  - Precise vertex measurement (at the level of better ~20-30μm for particles)
  - Fast detectors (< 30 μs) with high granularity
  - The low material budget
  - Large acceptance is desirable to accept 100% of the D^0s produced and to of NA61/SHINE
- LAVD is planned on technology 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
- 4 stations,

Replacement of the TPC electronics

Will increase the read-out rate by a factor of about 10 (up to 1 kHz)

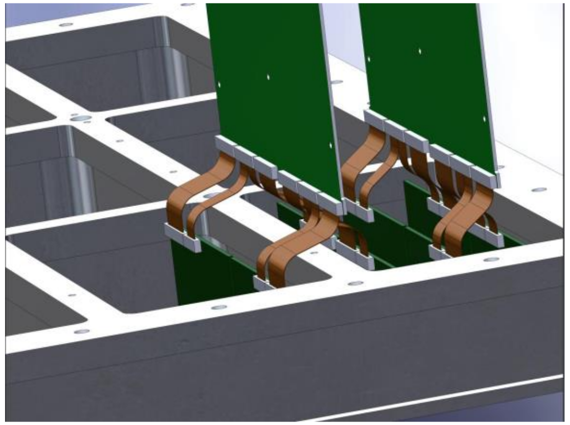
ALICE will transfer to NA61/SHINE its present TPC electronics that will be replaced during the long shutdown LS2

Present NA61
Front-End Card



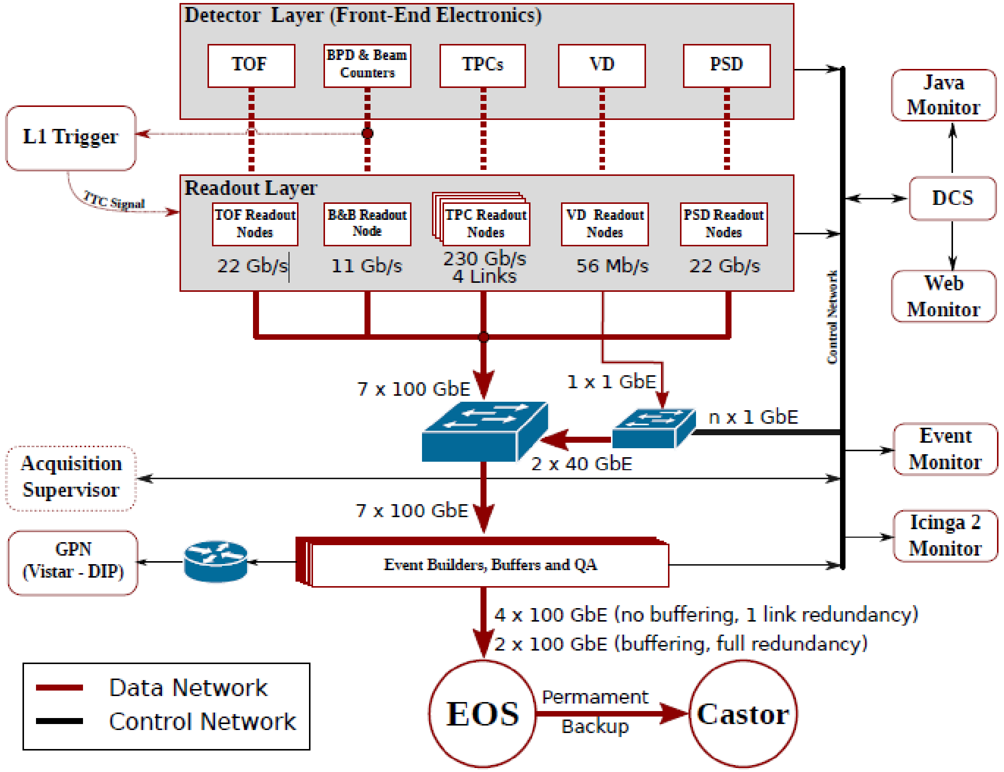
ALICE
Front-End Card

ALICE
Front-End Card on NA61 TPC



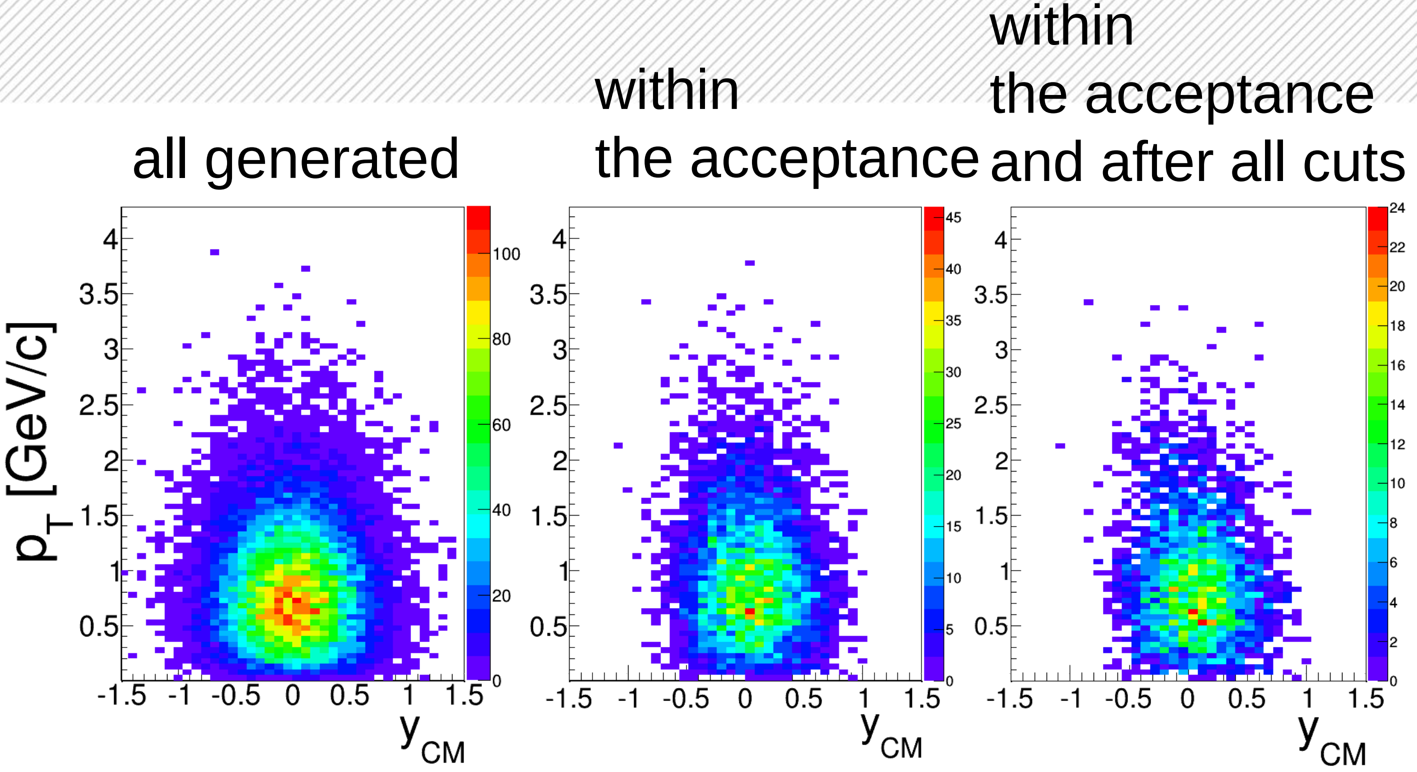
Upgrade of the trigger and data acquisition

- 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

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

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

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

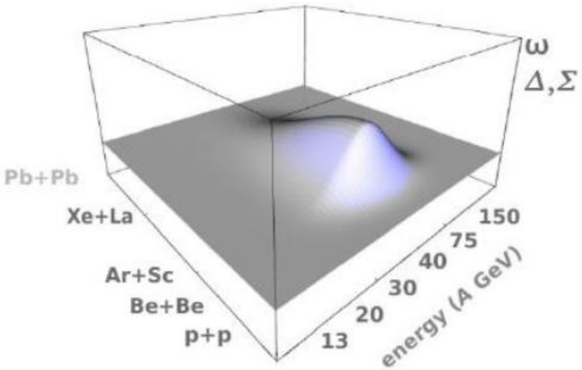
Δ = Σ = 0 for no fluctuations

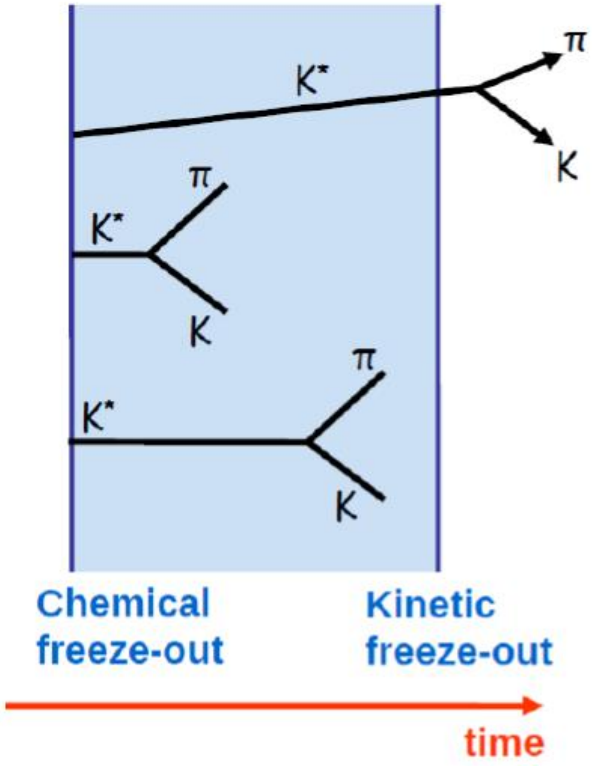
Δ = Σ = 1 for Independent Particle Model

- $\Delta[P_T, N]$ 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





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