NA61/SHINE experiment at CERN SPS: Recent results, current status and perspectives

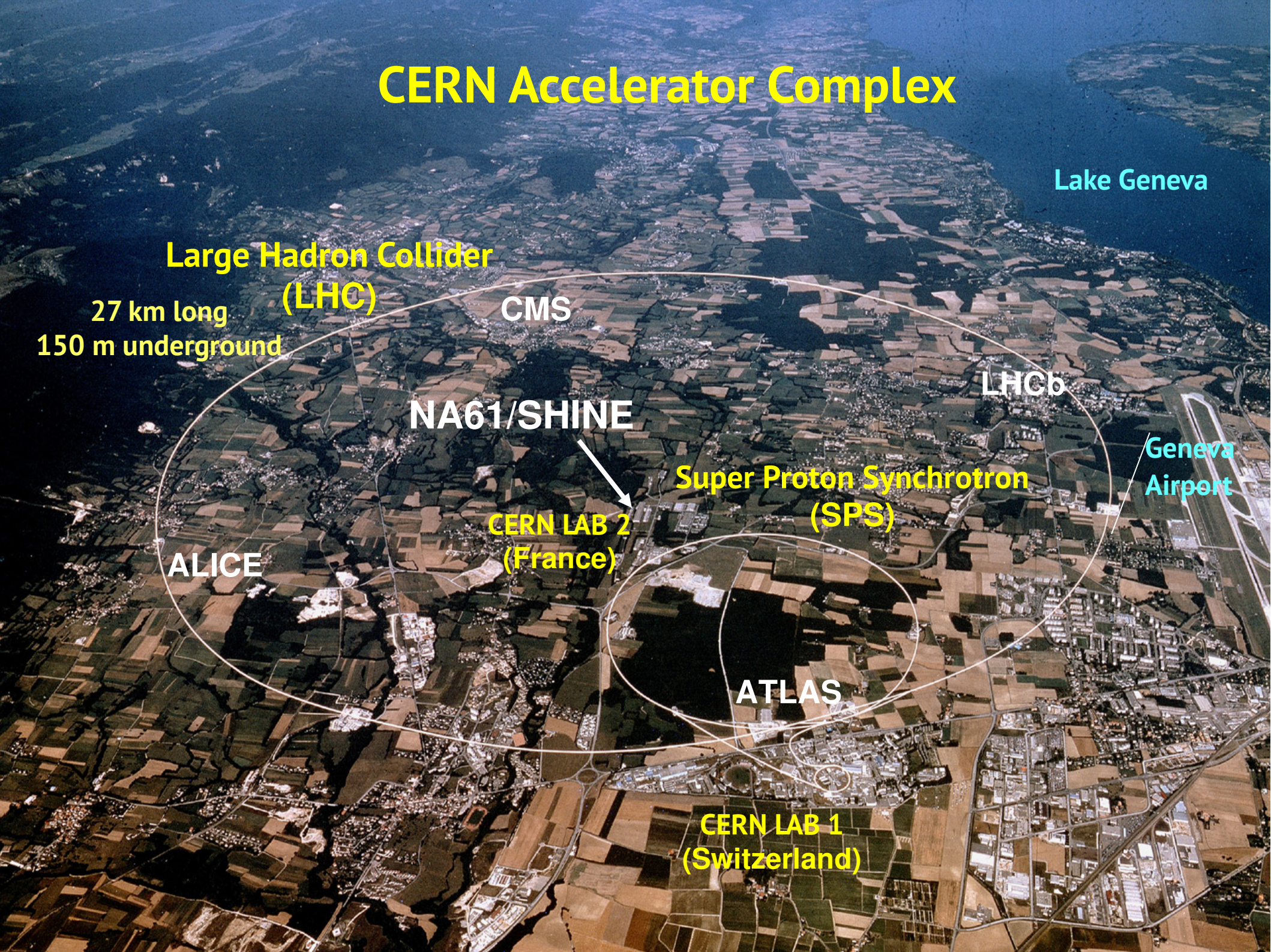
Janusz Brzychczyk

Jagiellonian University, Kraków, Poland

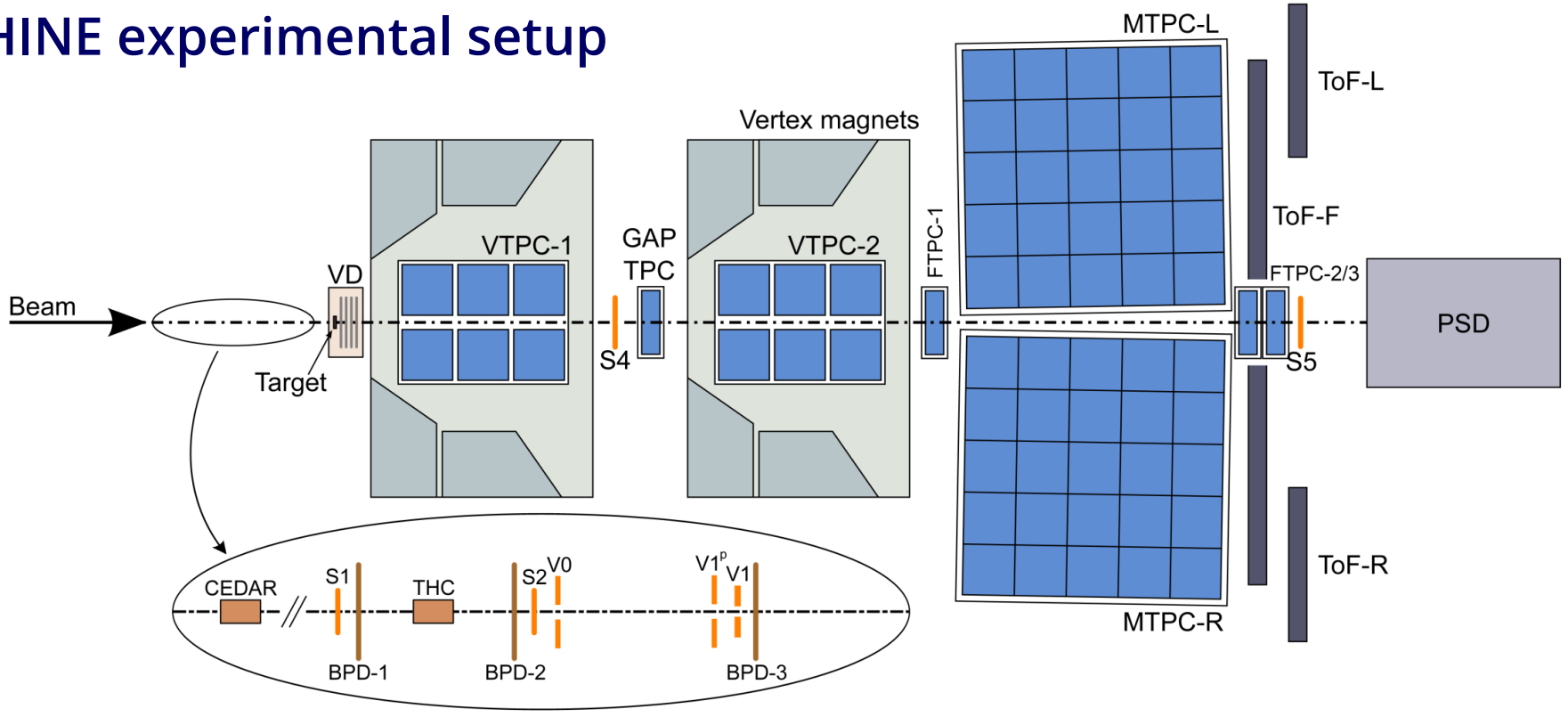
for the NA61/SHINE Collaboration

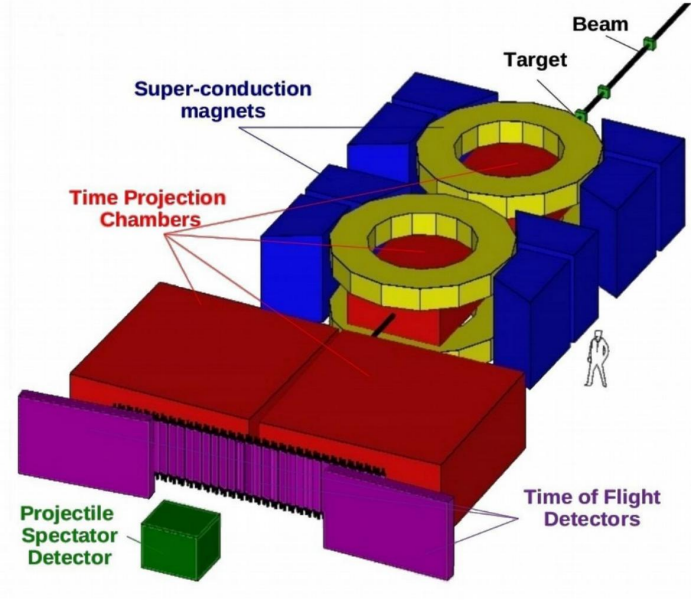
OUTLINE

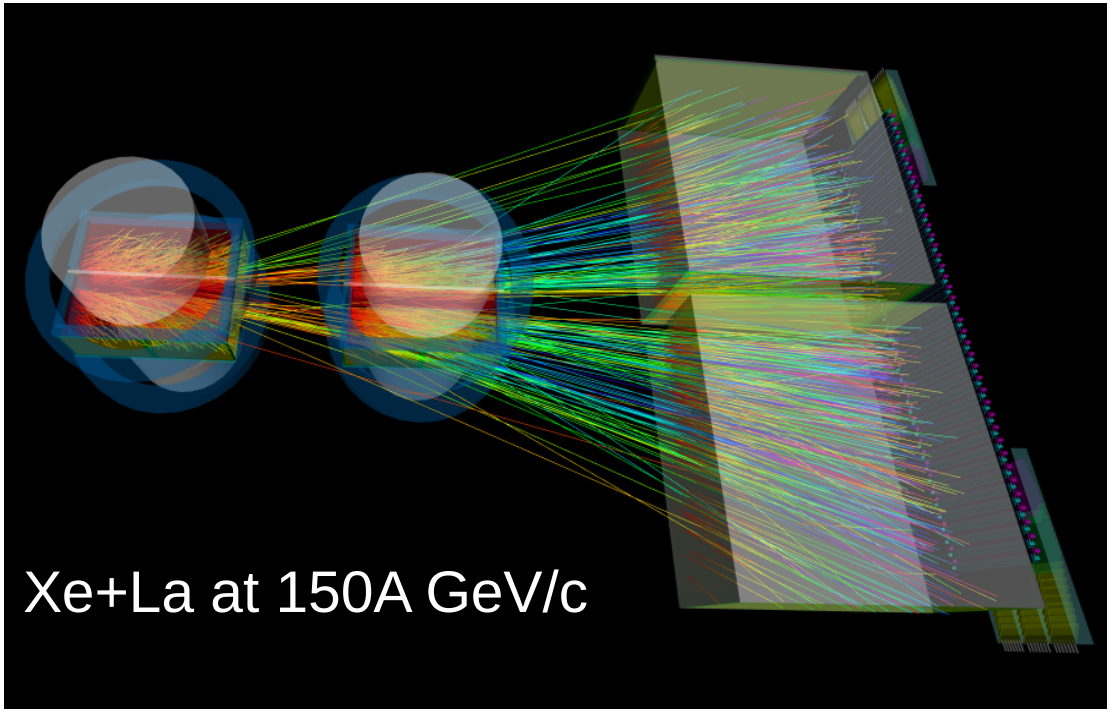
- Experimental setup
- Research program
- Recent results
  - Onset of deconfinement
  - Onset of fireball
  - Search for critical point
- Program for open charm measurements
  - Physics motivation
  - First measurements
- Physics program for 2021+
- Planned detector upgrades


CERN Accelerator Complex
Lake Geneva
Large Hadron Collider
(LHC)
27 km long
150 m underground
CMS
LHCb
NA61/SHINE
Super Proton Synchrotron
(SPS)
Geneva
Airport
CERN LAB 2
(France)
ALICE
ATLAS
CERN LAB 1
(Switzerland)

NA61/SHINE experimental setup



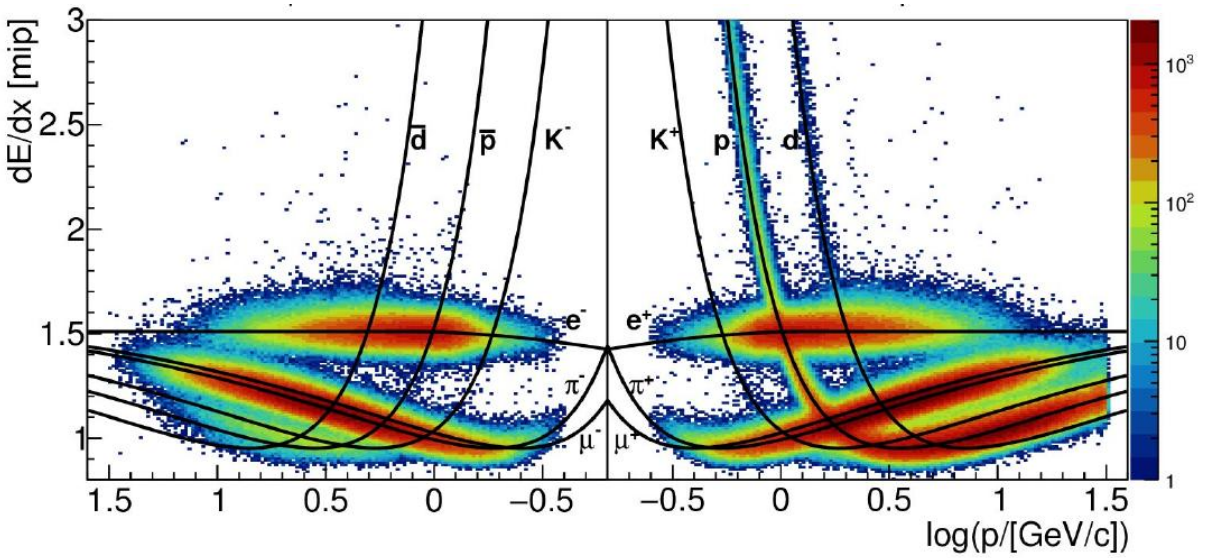




Beams

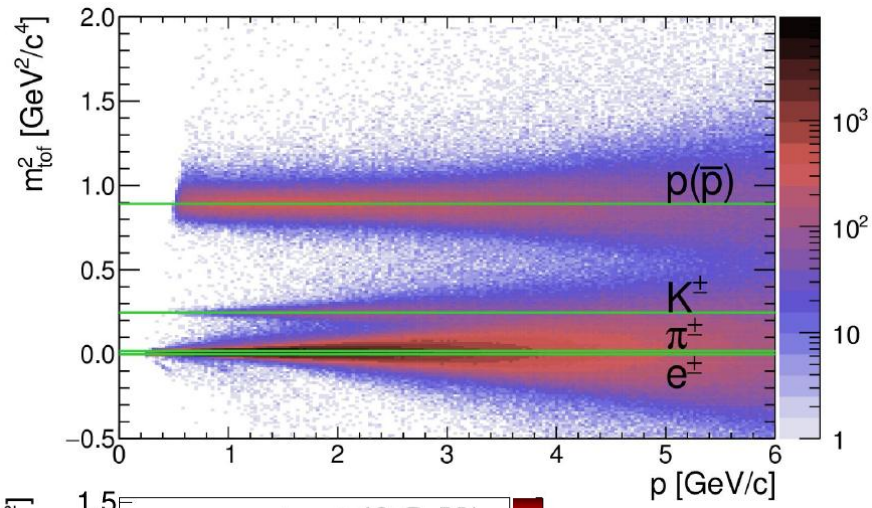
- **Hadron beams:**
  p (400 GeV/c)
  Secondary **π, K, p** (13–350 GeV/c)
- **Ion beams:**
  Ar, Xe, Pb (13–150A GeV/c)
  Secondary **Be** (13–150A GeV/c)
  (from Pb fragmentation)

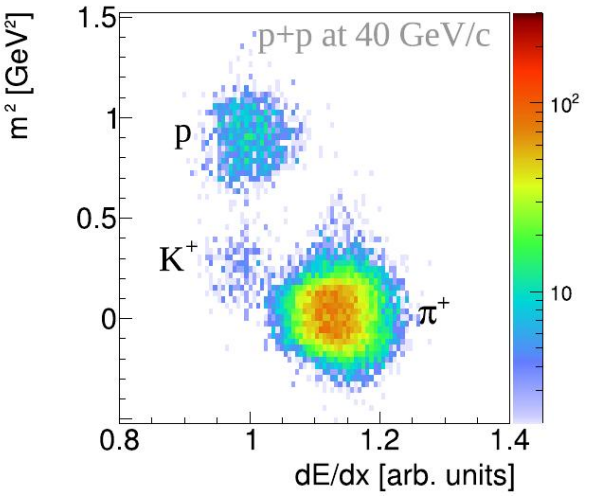
$\sqrt{s_{NN}}$ = 5.1–17.3(27.4) GeV



Detector

- **Large acceptance:**
  Full forward hemisphere coverage (down to p_T = 0)
- **High momentum resolution:**
  $\frac{\sigma(p)}{p^2} \approx 10^{-4}$ c/GeV
- **Good particle identification**
  $\sigma(TOF) \approx 80$ ps
  $\frac{\sigma(dE/dx)}{\langle dE/dx \rangle} \approx 0.04$
  $\sigma(m_{inv}) \approx 5$ MeV
- **Centrality selection** from projectile spectator measurements with PSD
- **Precise vertex determination:** ~15 μm
- **Tracking efficiency:** > 95%
- **Event rate:** ~ 80 events/s





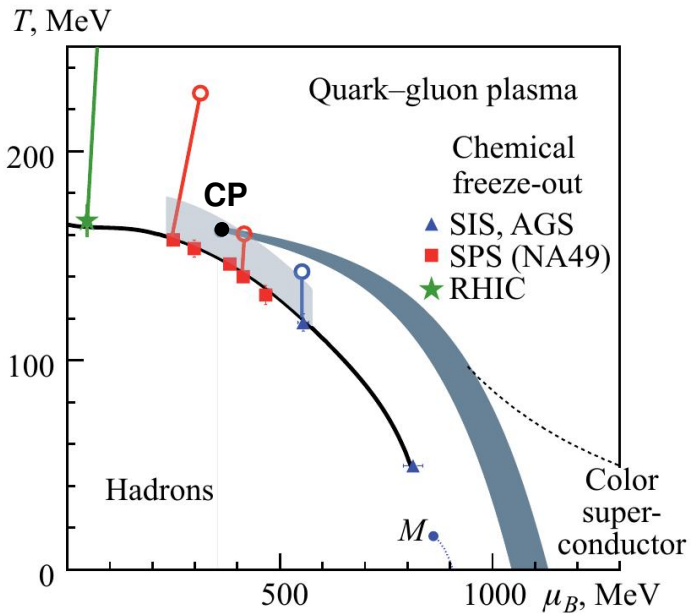
NA61/SHINE research program

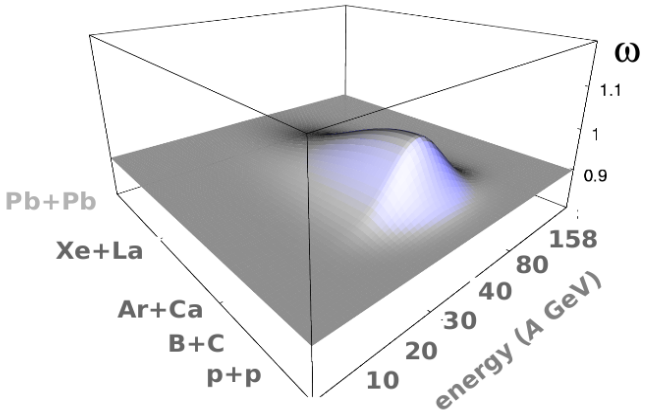
- Physics of strongly interacting matter
  - search for QCD critical point
  - study of the properties of the onset of deconfinement
  - collective flow
  - open charm production
  - EM interactions with spectators

- Hadron production measurements for neutrino experiments (T2K, J-PARC, FERMILAB) to improve neutrino beam flux predictions

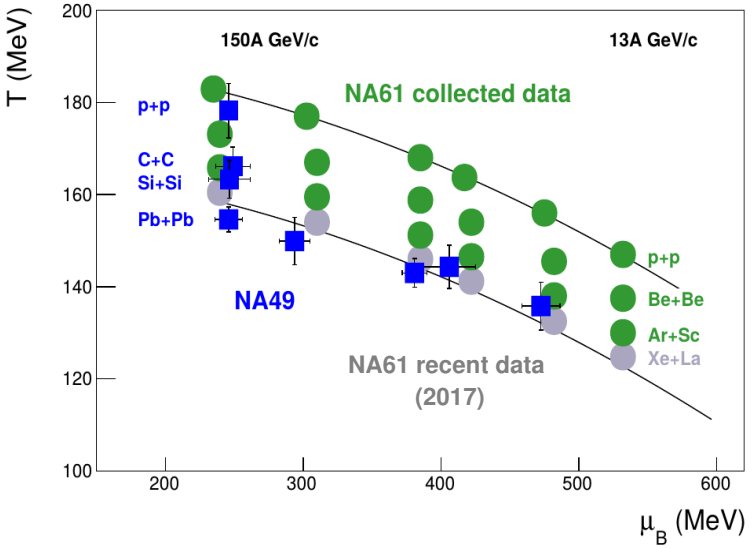
- Hadron production data for cosmic ray experiments (Pierre-Auger, KASKADE) to improve air-shower simulations

2D scan of phase diagram by varying collision energy and system size



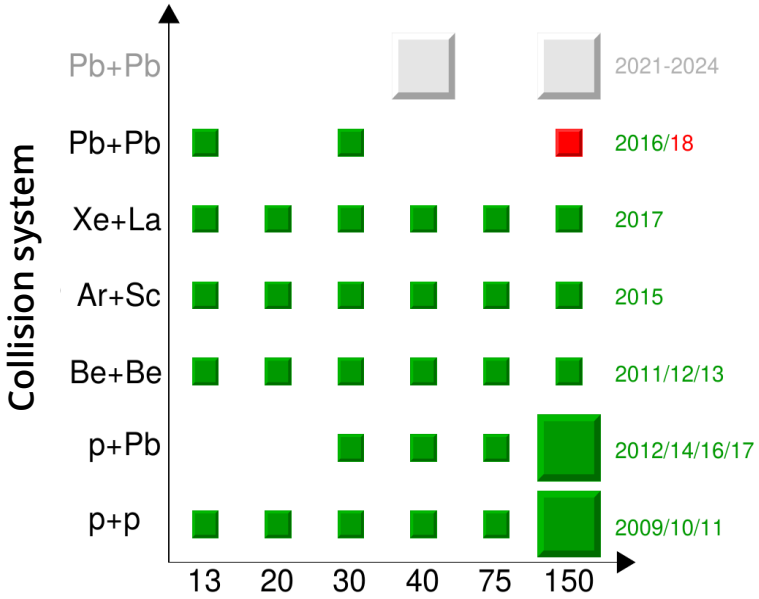


Increase of event-to-event multiplicity fluctuations is expected when a freeze-out point is close to the critical point

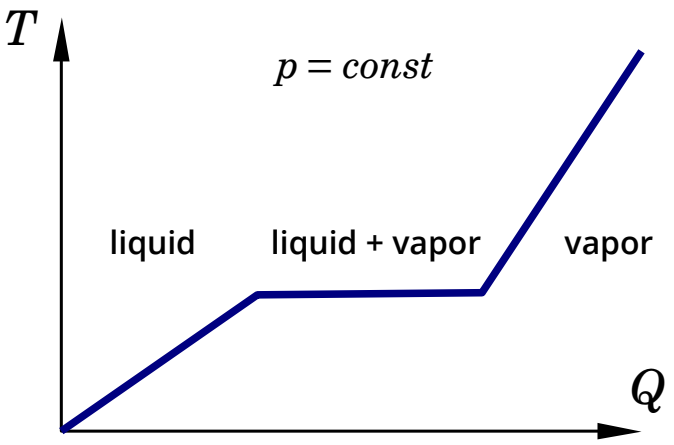


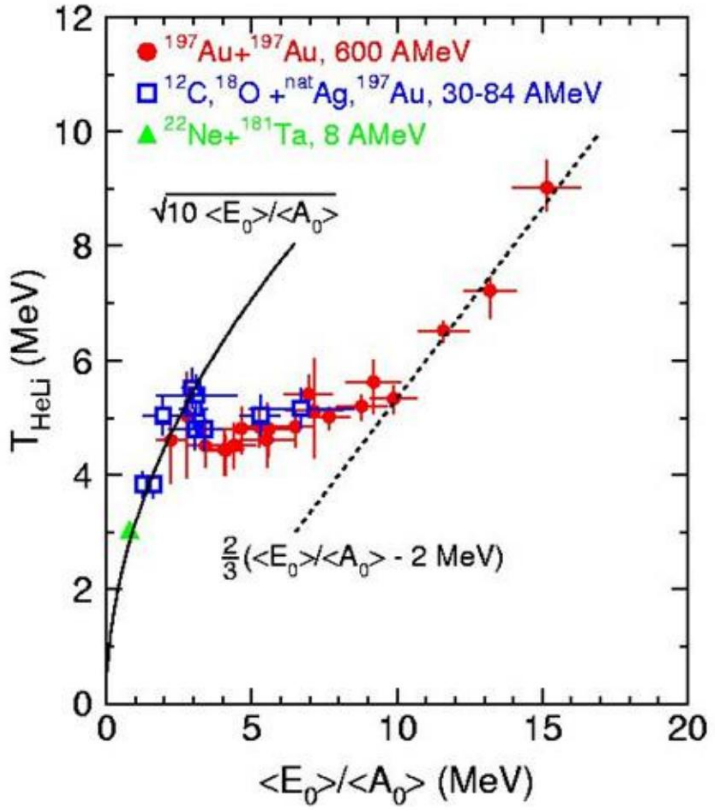
Location of the freeze-out point depends on the collision energy and the system size

Phys. Rev. C 73, 044905 (2006)



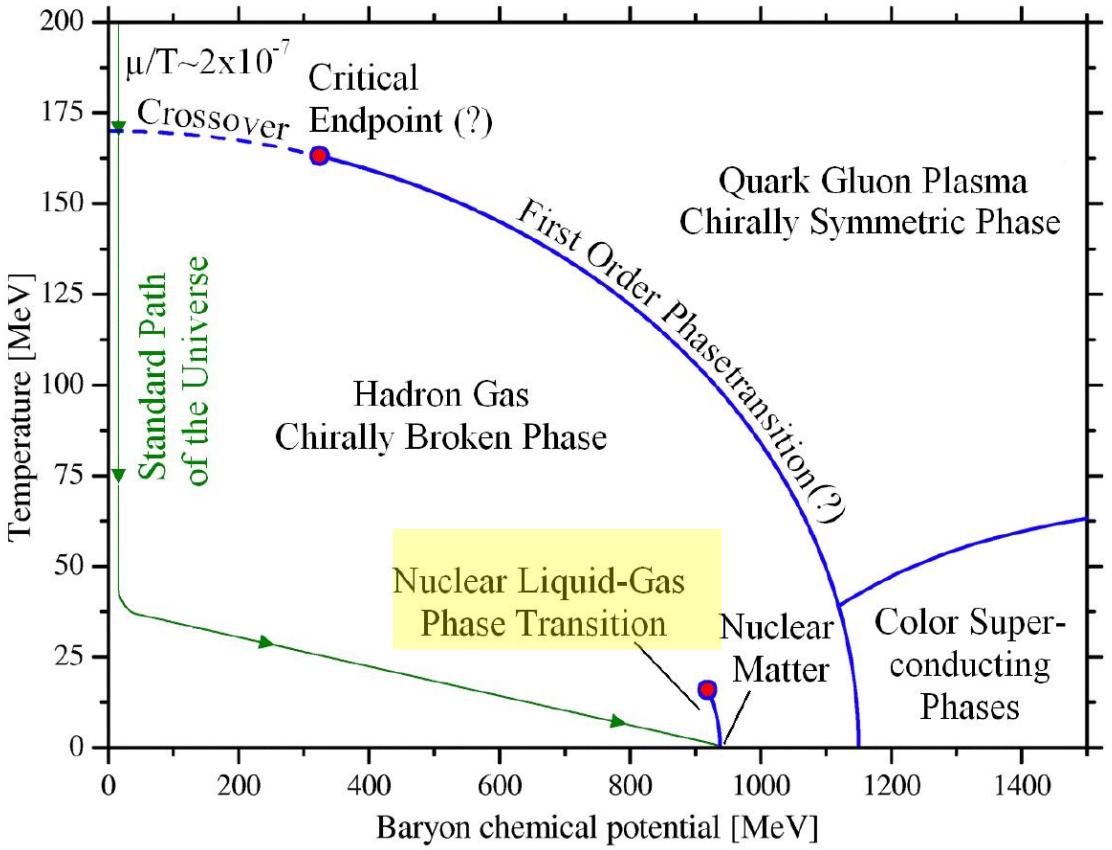
First-order phase transition: plateau in caloric curve

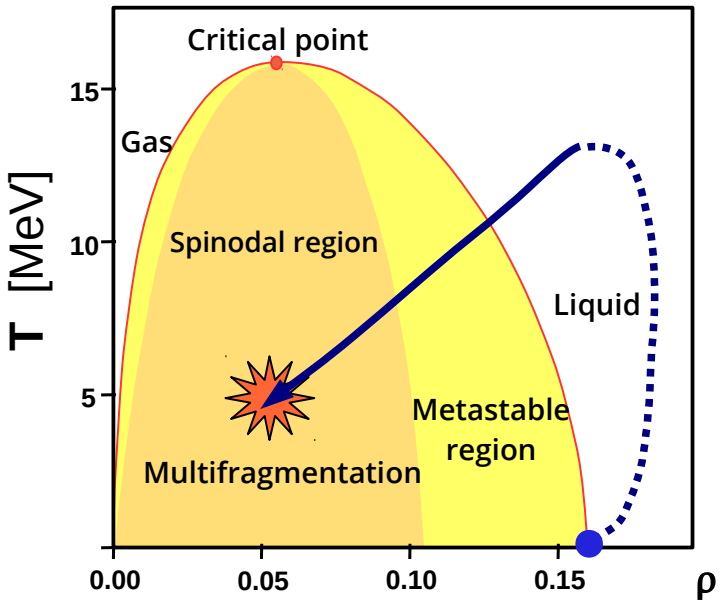




J. Pochodzalla et al., PRL 75 (1995) 1040

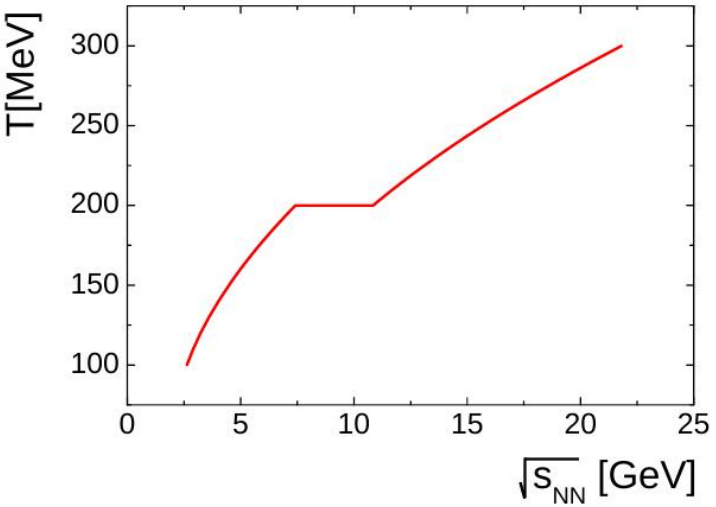
T. Boeckel, J. Schaffner-Bielich, PRD 85 (2012) 103506





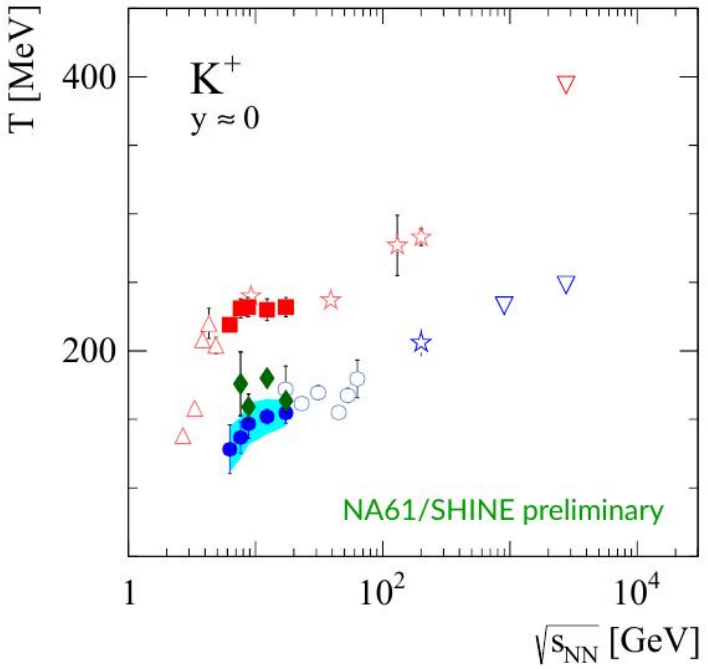
Nuclear liquid-gas phase transition probed with multifragmentation

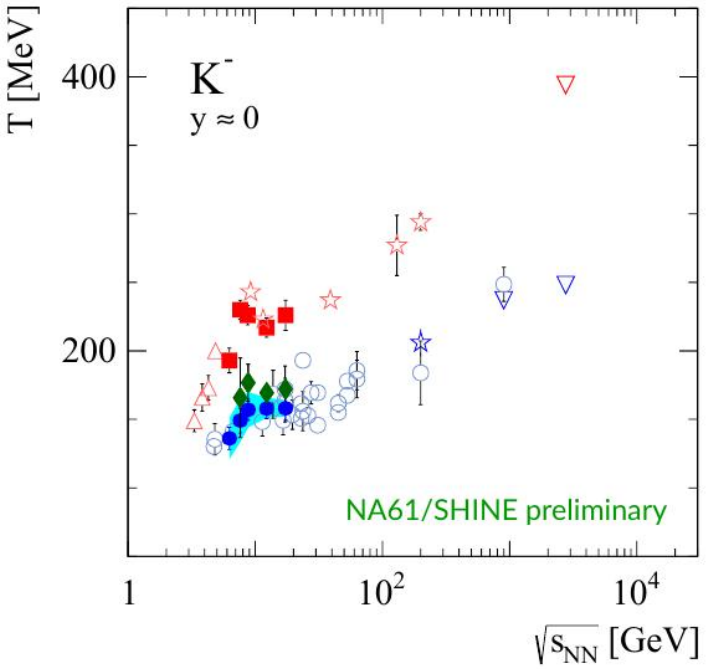
Transition to quark-gluon plasma – Onset of deconfinement

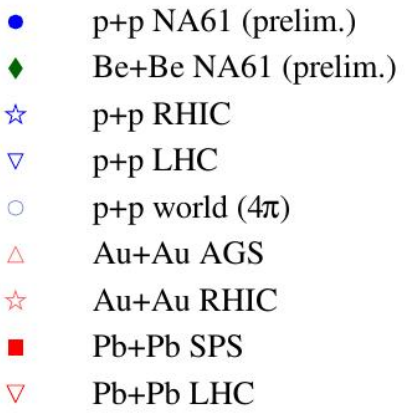


Prediction of Statistical Model of the Early Stage (SMES)

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





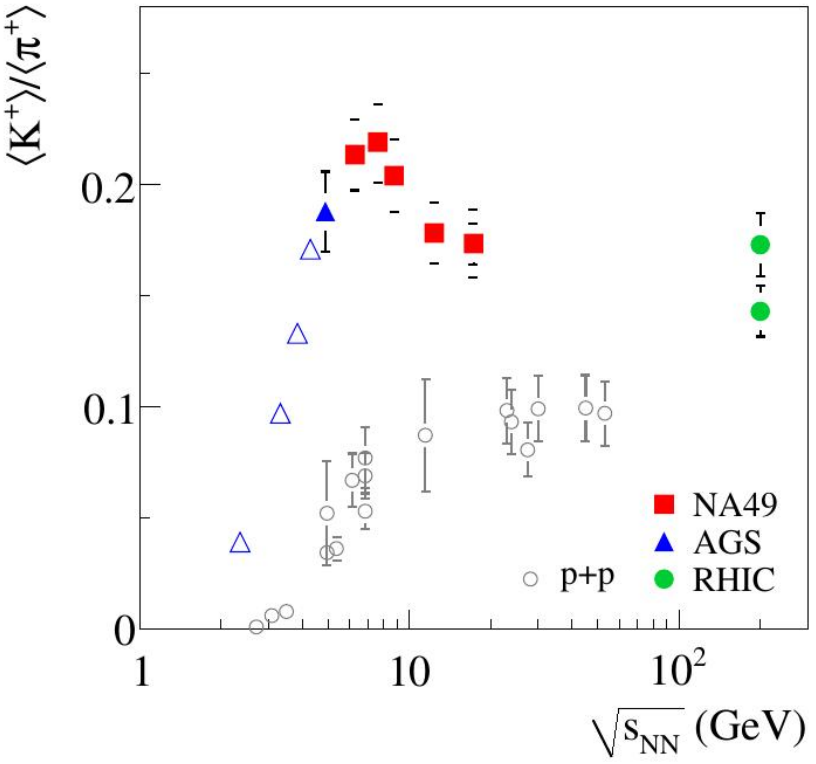


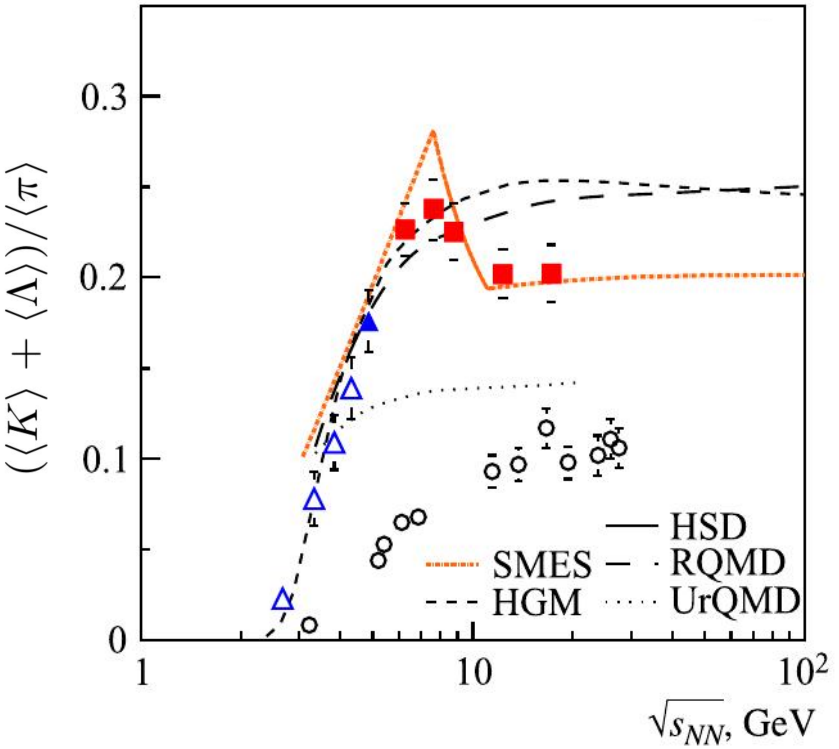
T – Inverse slope parameter of the invariant transverse mass distribution

(Kaon spectra weakly affected by hadron rescattering and resonance decays)

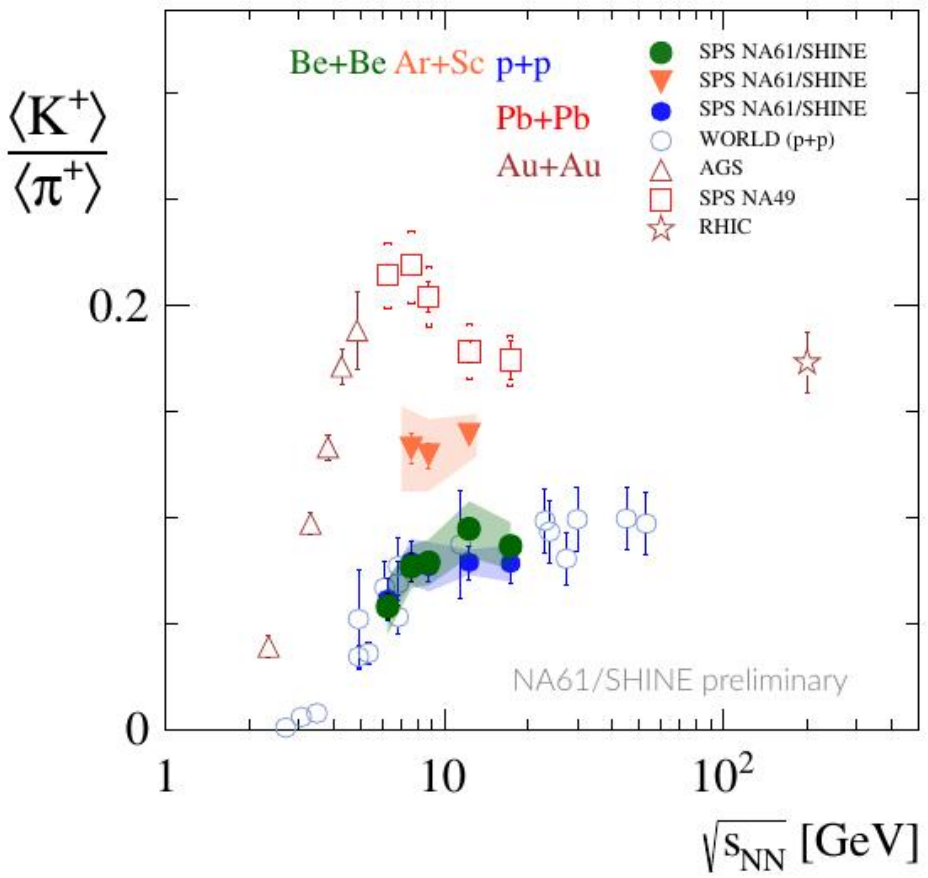
HORN in the excitation function of K^+/π^+ ratio

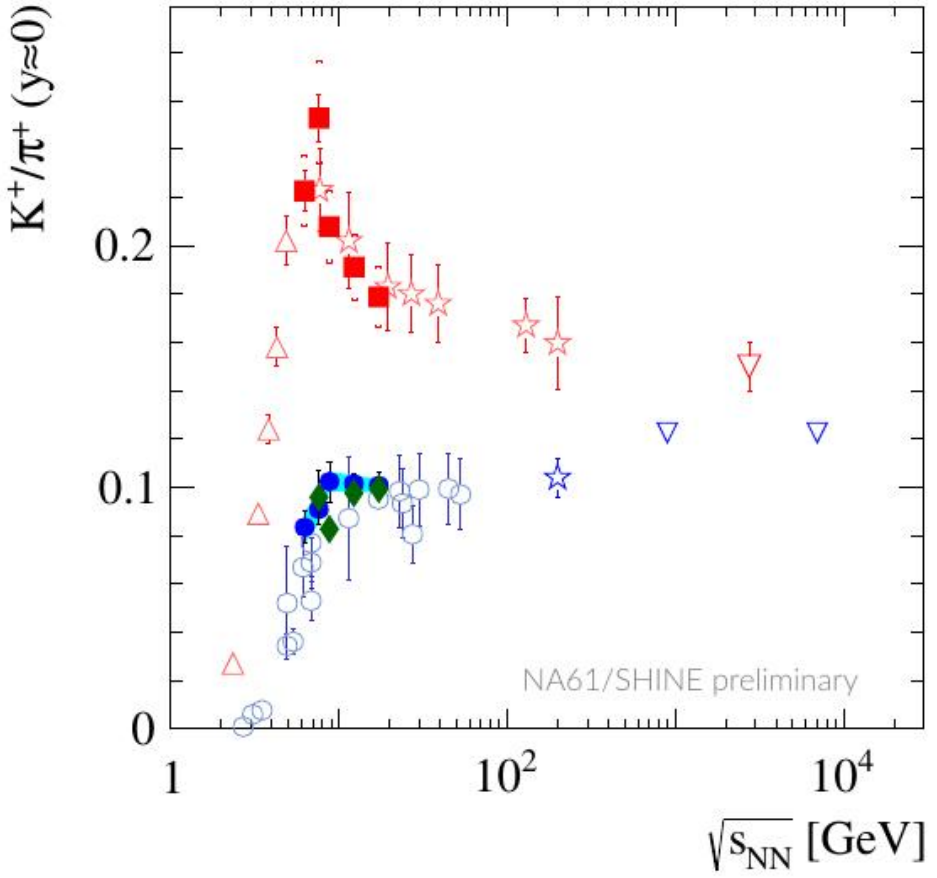
The horn structure observed by NA61 in Pb+Pb collisions was interpreted as a signature of onset of deconfinement based on SMES predictions





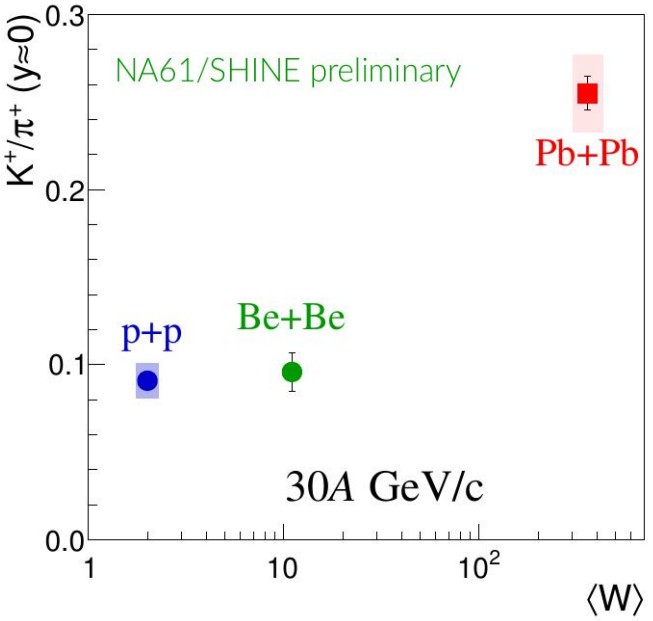
Recent NA61 results

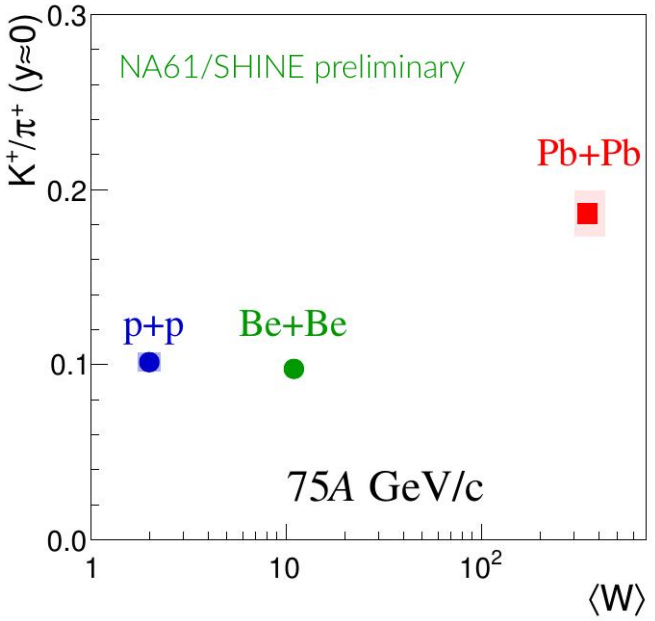


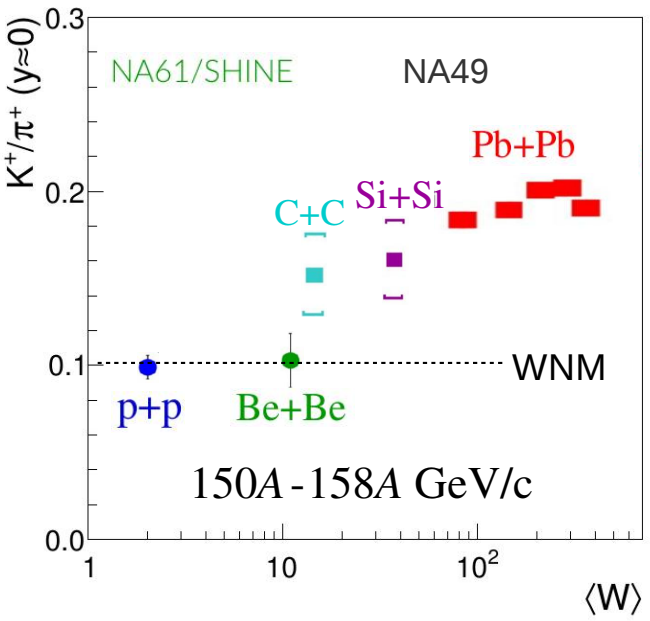


- Similar characteristics for p+p and Be+Be systems
- A shadow of the horn structure visible in these light systems
- $\langle K^+ \rangle / \langle \pi^+ \rangle$ for Ar+Sc in between p+p, Be+Be and Pb+Pb

System size dependence of K^+/π^+ ratio at midrapidity







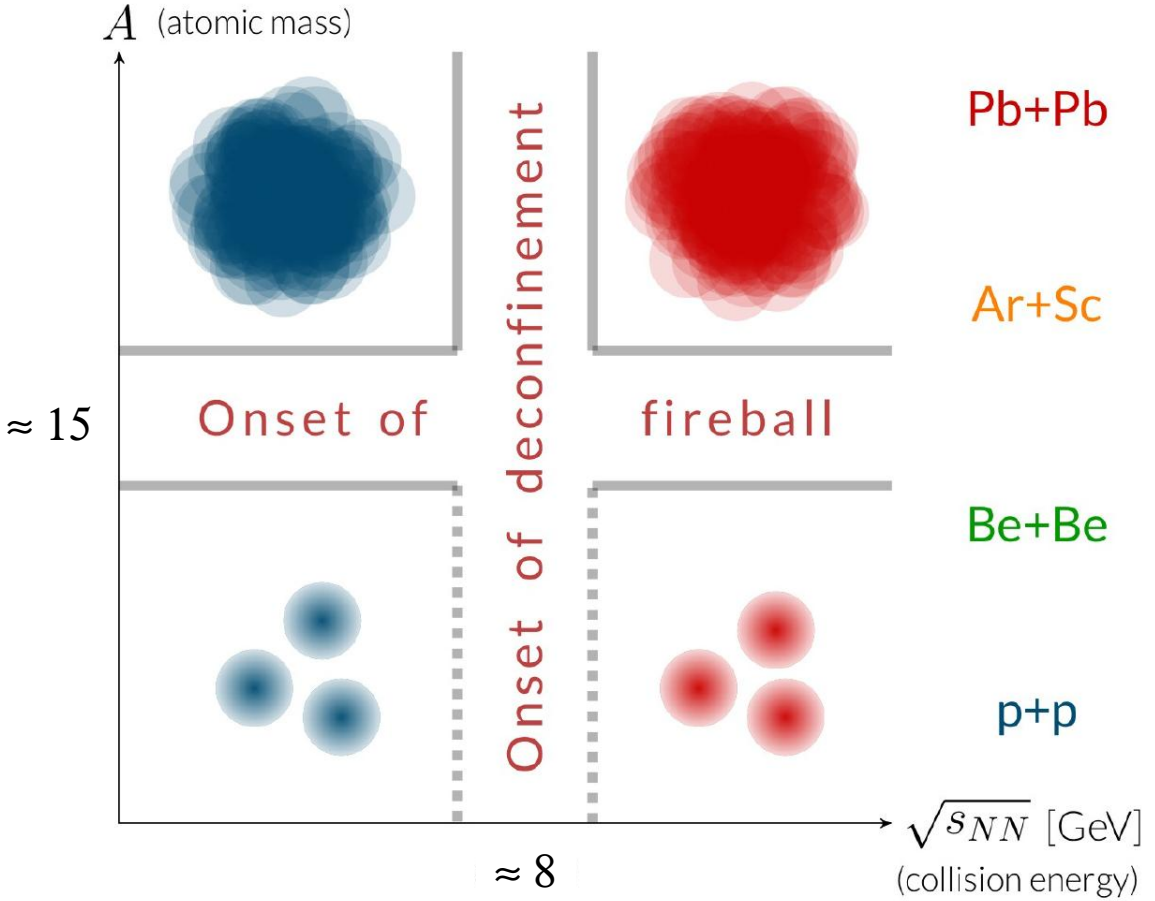
⟨W⟩ - the mean number of nucleons participating in the collision

- **Be+Be similar to p+p**
- **Rapid change when passing to heavier systems**

Proposed interpretation:
Begining of formation of a large thermalized cluster (fireball) decaying statistically

→ **Onset of fireball**

Tentative conclusions: Four domains of hadron production



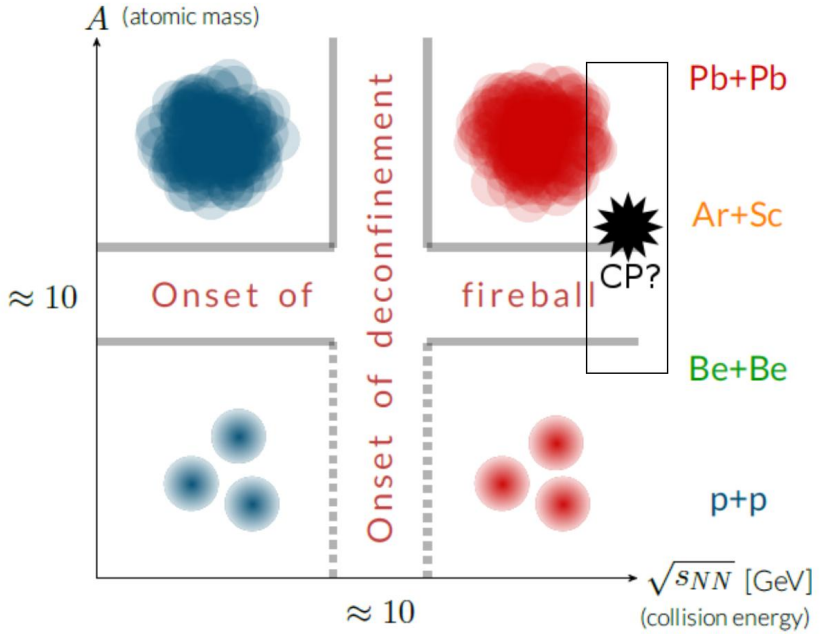
Anisotropic flow studies may be capable of shedding more light on the onset of deconfinement

→ Talks by: Oleg Golosov on Thursday at 18:05 in Alekseevskiy hall (NA49 data)
Evgeny Kashirin on Friday at 10:30 in Moskvorechye 1 hall (NA61 data)

Search for critical point

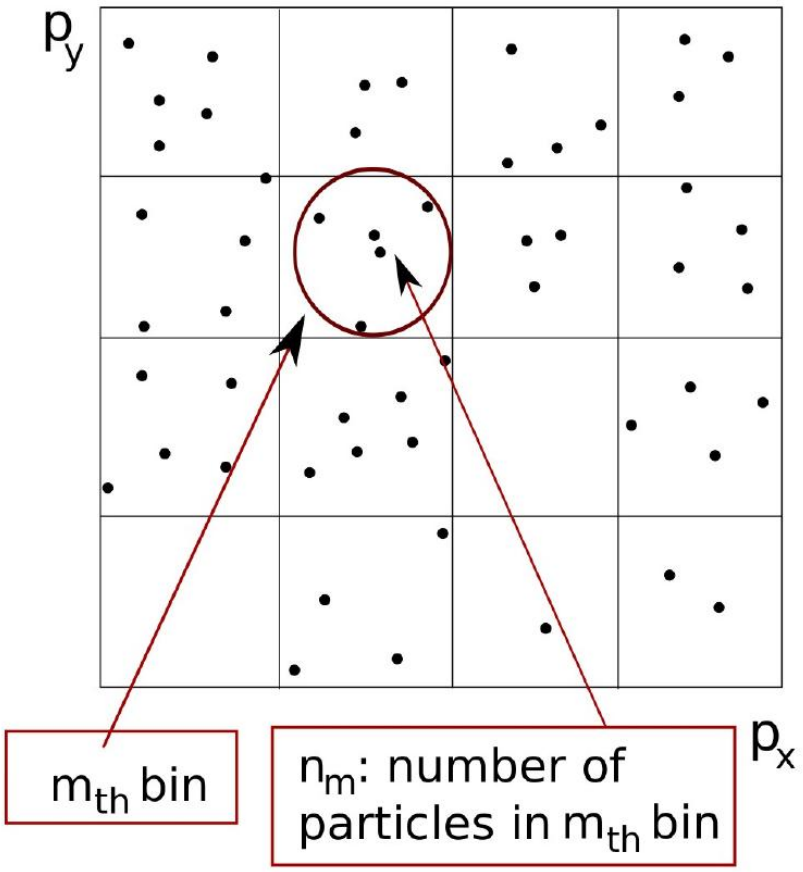
Ongoing data analysis:

- Particle multiplicity and transverse momentum event-to-event fluctuations
  - ➡ talk by Daria Prokhorova on Friday at 10:15 in Moskvorechye 1 hall
- Particle interferometry – Bose Einstein momentum correlations
- Intermittency analysis of proton density
  - ➡ First trace of critical behavior ?



Intermittency analysis of proton density

Transverse momentum distribution of protons at mid-rapidity in an event



Transverse momentum plane partitioned into M^2 bins

Second scaled factorial moment as a function of the bin size

$$F_2(M) = \left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i(n_i - 1) \right\rangle \Big/ \left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i \right\rangle^2 ,$$

$\langle \ldots \rangle$ - averaging over events

For critical events, one expects

$$F_2(M) \sim (M^2)^{\phi_{2,cr}} \quad , \quad \phi_{2,cr}^{(p)} = 5/6$$

N. Antoniou et al., PRL 97, 032002 (2006)

Occurrence of such power-law is examined in experimental data after the combinatorial background subtraction

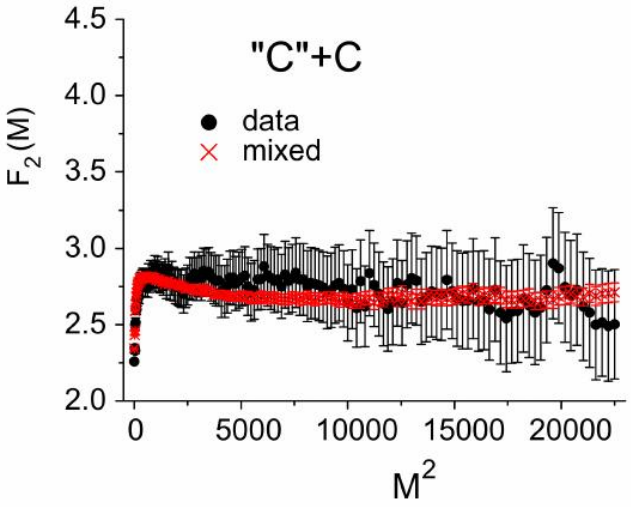
$$\Delta F_2(M) = F_2^{(d)}(M) - F_2^{(m)}(M)$$

calculated for mixed events

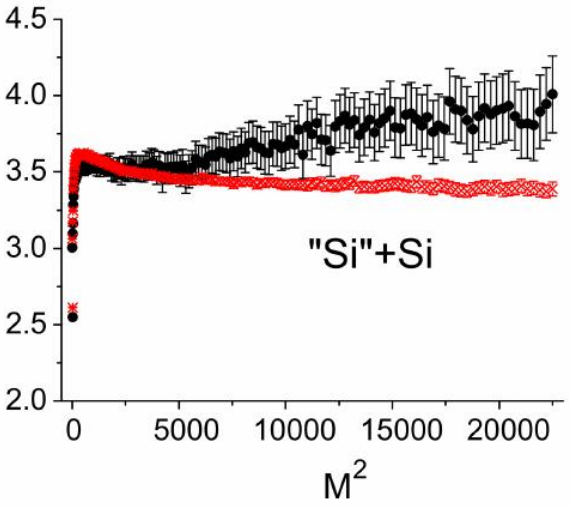
Proton intermittency results at 150/158*A* GeV/c

NA49

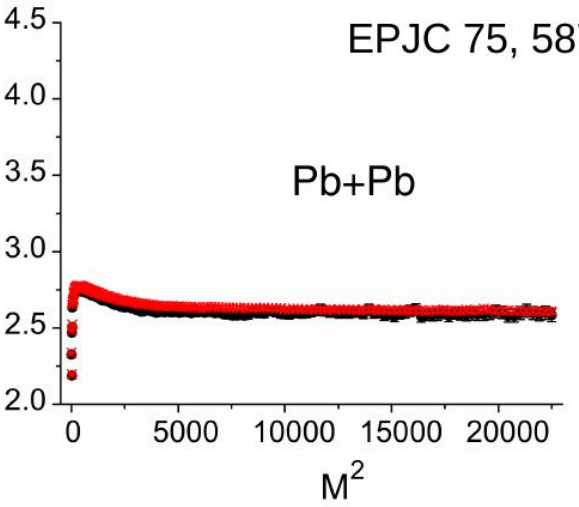
"C"+C, 0-12%



"Si"+Si, 0-12%

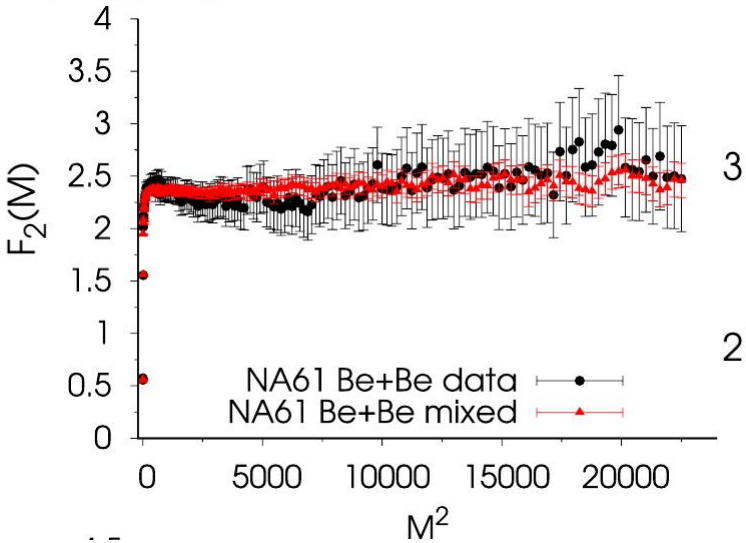


Pb+Pb, 0-10%

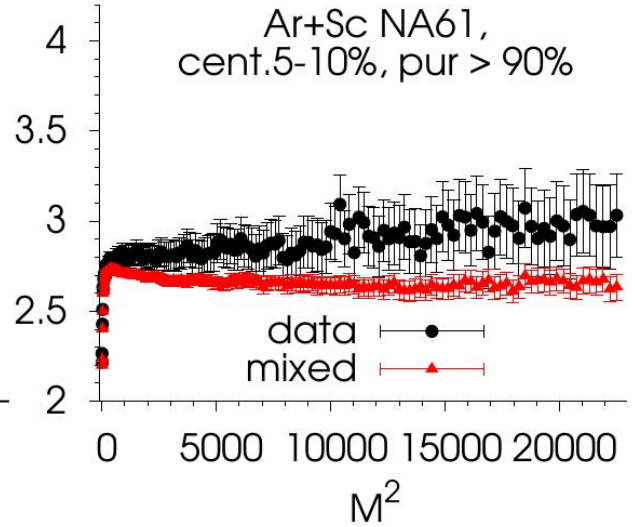


NA61

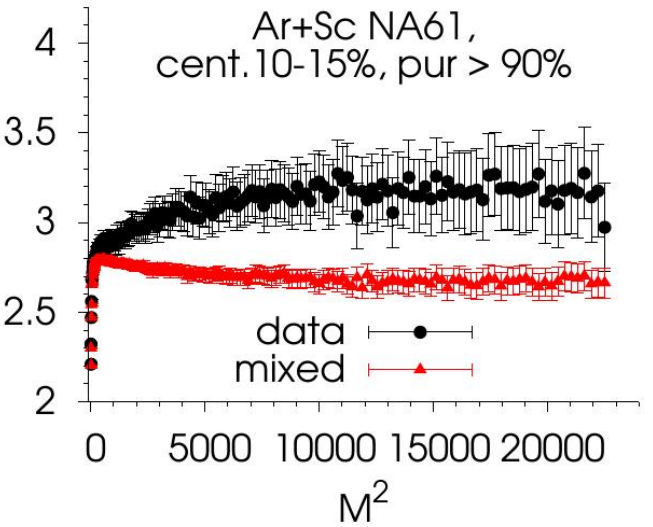
Be+Be, 0-12%



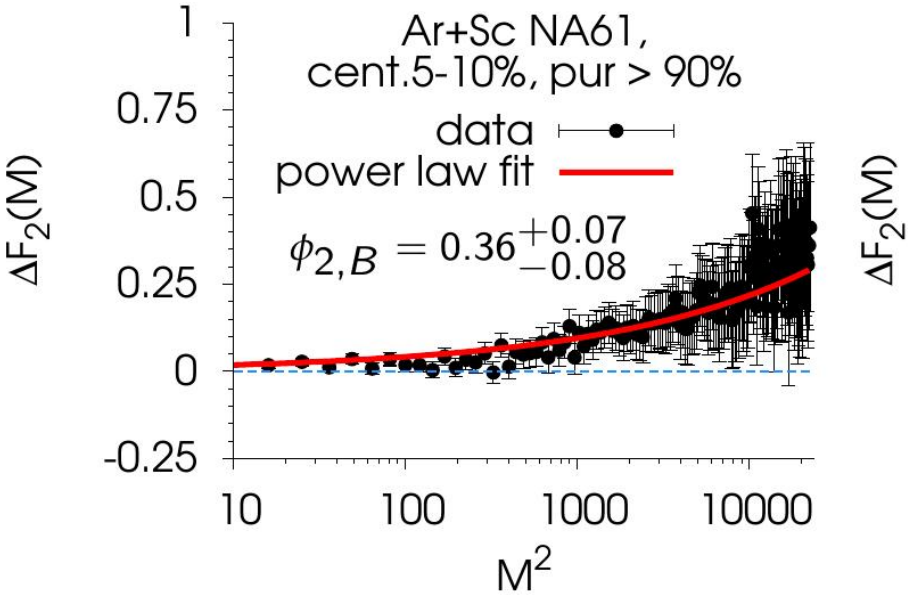
Ar+Sc, 5-10%

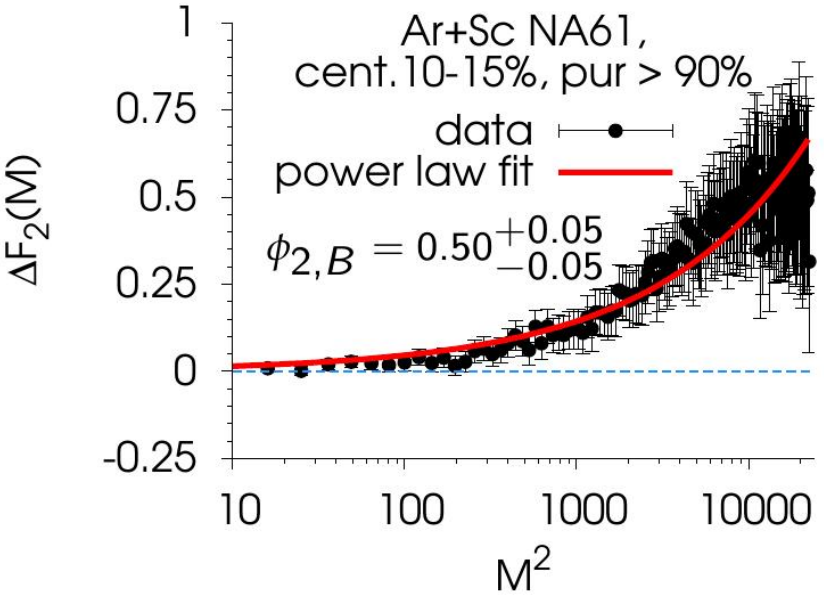


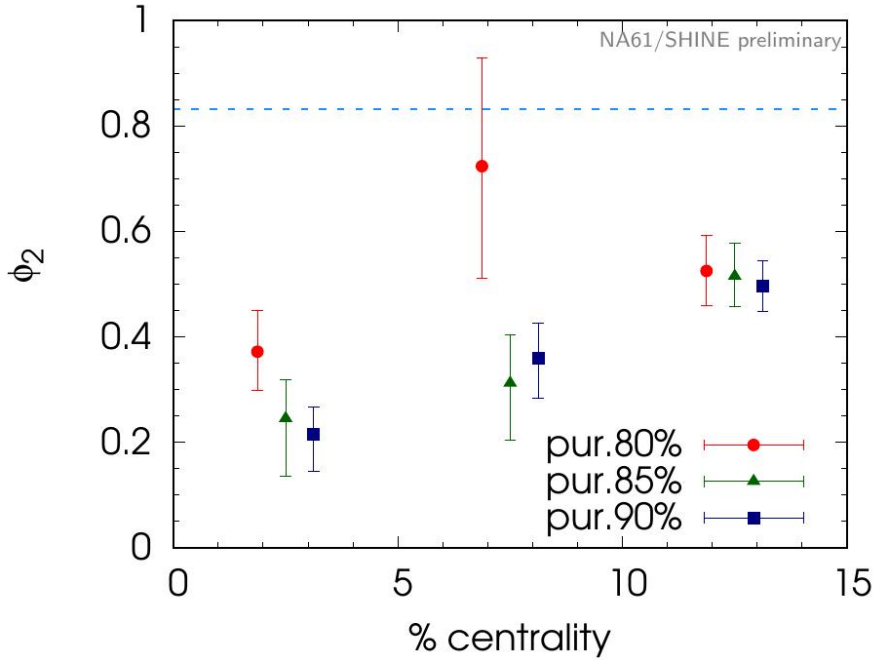
Ar+Sc, 10-15%



NA61: Intermittency signal in Ar+Sc at 150A GeV/c







NA49

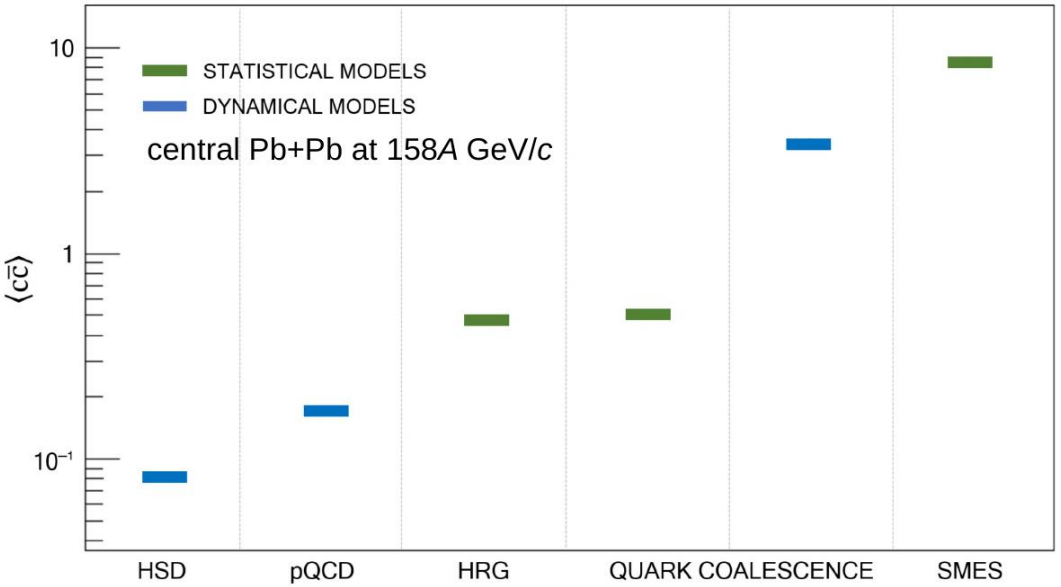
Estimated intermittency index for "Si"+Si at 158A GeV/c

$$\phi_{2,B} = 0.96^{+0.38}_{-0.25}(\text{stat.}) \pm 0.16(\text{syst.})$$

T. Anticic et al., EPJ C 75, 587 (2015)

Physics motivation for open charm measurements

Model predictions of $\langle c\bar{c} \rangle$ yield in central Pb+Pb at 150*A* GeV/*c*



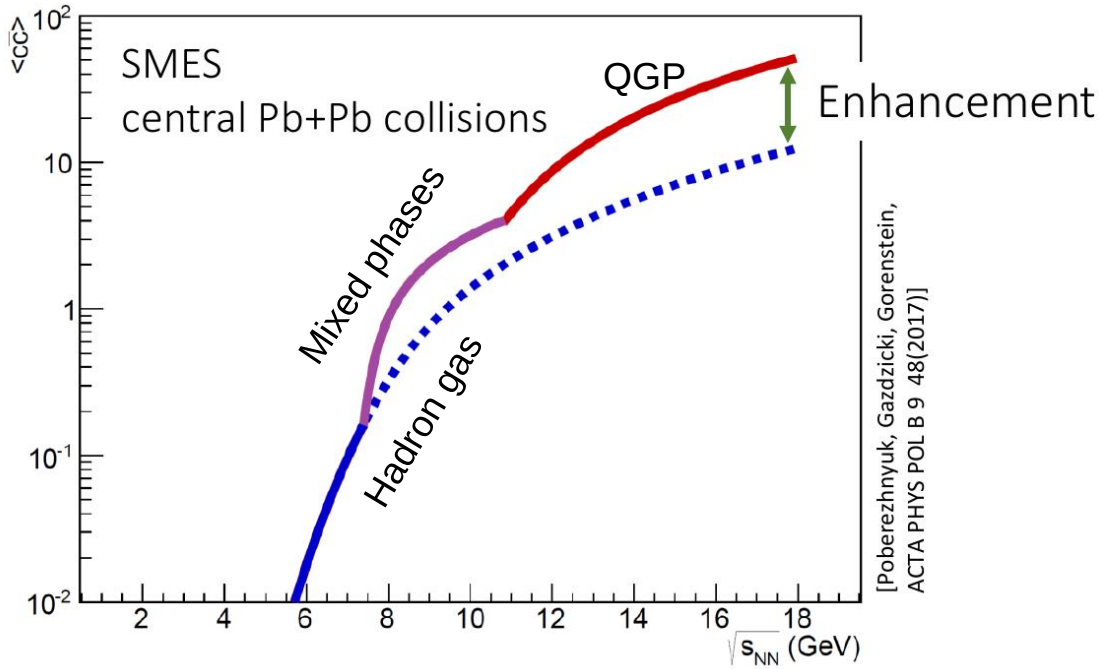
HSD
Linnyk, Bratkovskaya, Cassing, IJMP E17, 1367, 2008;
Song, private communication

pQCD
Gavai, et al., IJMP A10, 2999, 1995
Braun-Munzinger, Stachel, PL B490, 196, 2000

Quark Coalesc. Dyn.
Levai et al. JP G27, 703, 2001

HRG; Quark Coalesc. Stat.
Kostyuk et al. PL B531, 195, 2002

SMES
Gazdzicki, Gorenstein, APP B30, 2705, 1999



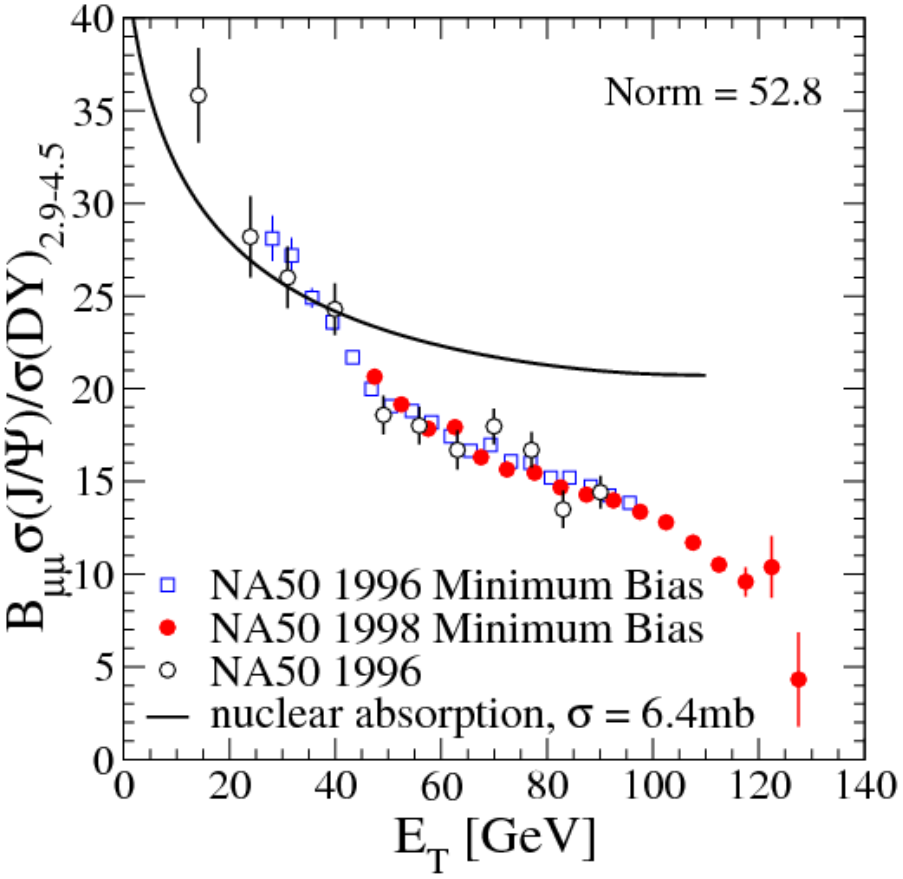
[Poberezhnyuk, Gazdzicki, Gorenstein, ACTA PHYS POL B 9 48(2017)]

Needed experimental constraints on the $\langle c\bar{c} \rangle$ yield in full phase space !

Anomalous J/ψ suppression as a signal of deconfinement

NA50: Pb+Pb at 158A GeV/c

(Eur. Phys. J. C39, 335, 2005)



QGP medium reduces probability of J/ψ production

(Matsui, Satz, PLB 178 (1986) 416)

$$P\left(c\bar{c} \to J/\psi\right) \equiv \frac{\langle J/\psi \rangle}{\langle c\bar{c} \rangle} \equiv \frac{\sigma_{J/\psi}}{\sigma_{c\bar{c}}}$$

The effect observed in NA38, NA50 and NA60 data assuming $\langle c\bar{c} \rangle$ ~ ⟨Drell-Yan pairs⟩

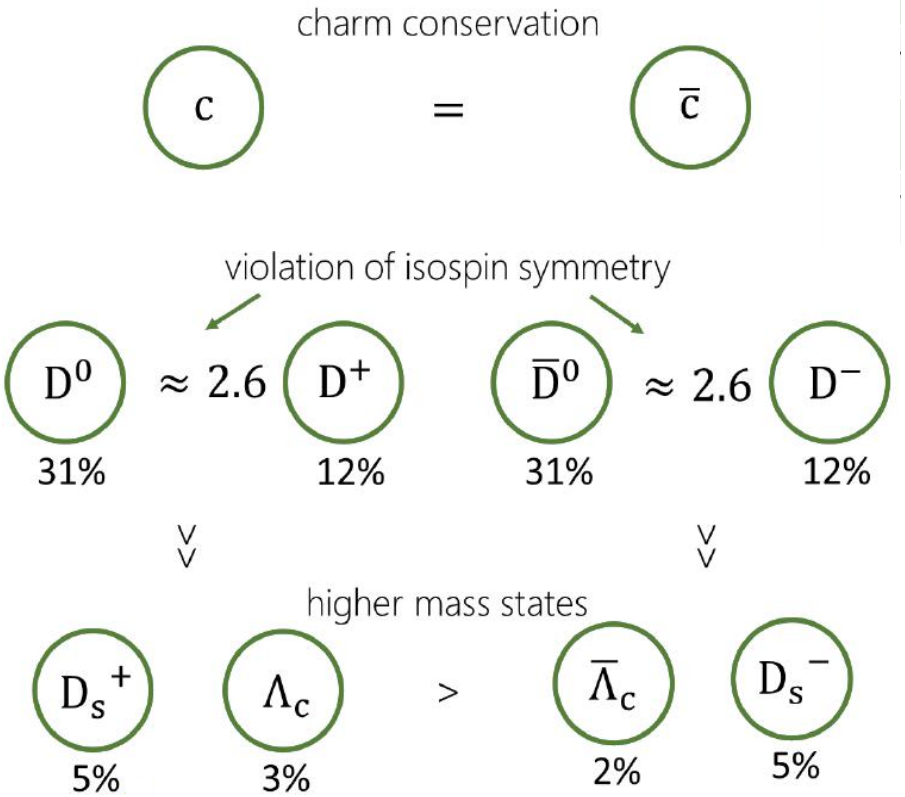
This assumption may be incorrect due to e.g. shadowing or parton energy loss

(H. Satz, Adv. High En. Phys. (2013) 2429)

Need for $\langle c\bar{c} \rangle$ measurements at SPS energies !

NA61 plans for measurements of $\langle c\bar{c} \rangle$

PHSD model predictions for
0-20% Pb+Pb at 150*A* GeV/*c*

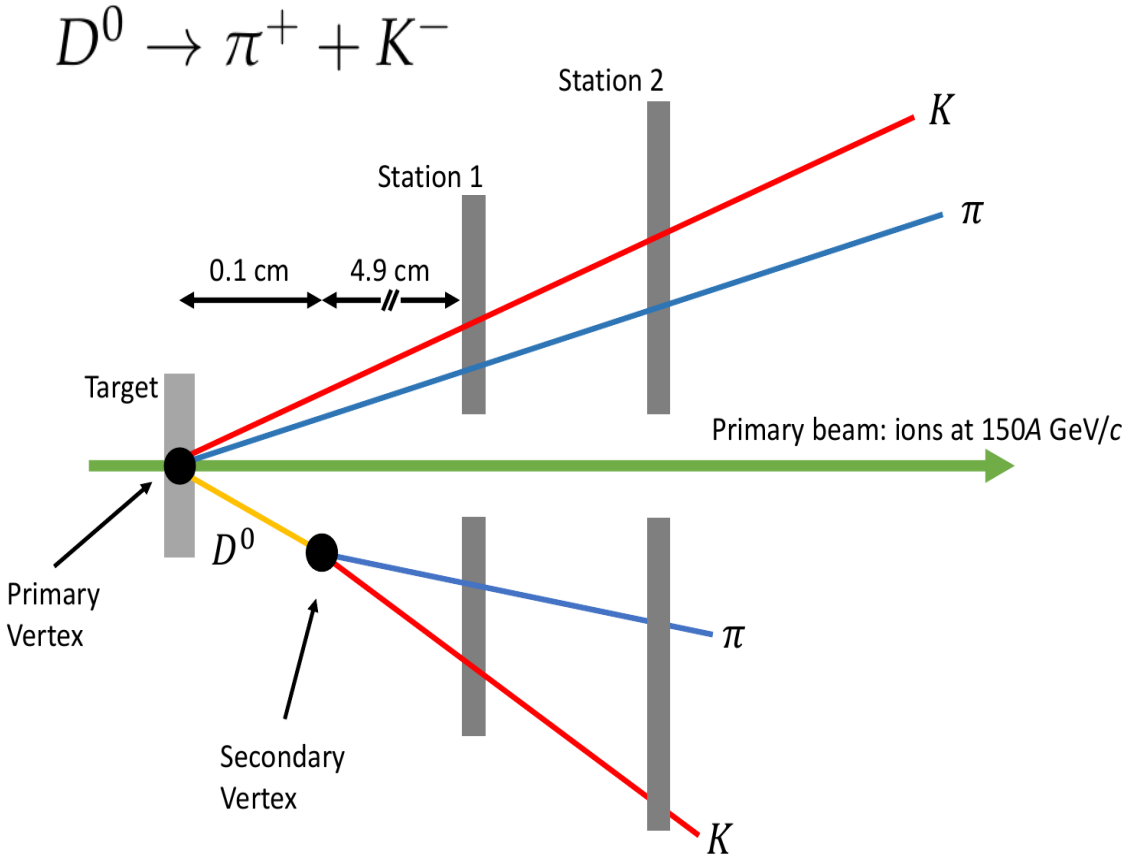


Measuring D^0, $\bar{D}^0$, D^+, D^- (~85%) provides a good total $\langle c\bar{c} \rangle$ estimate

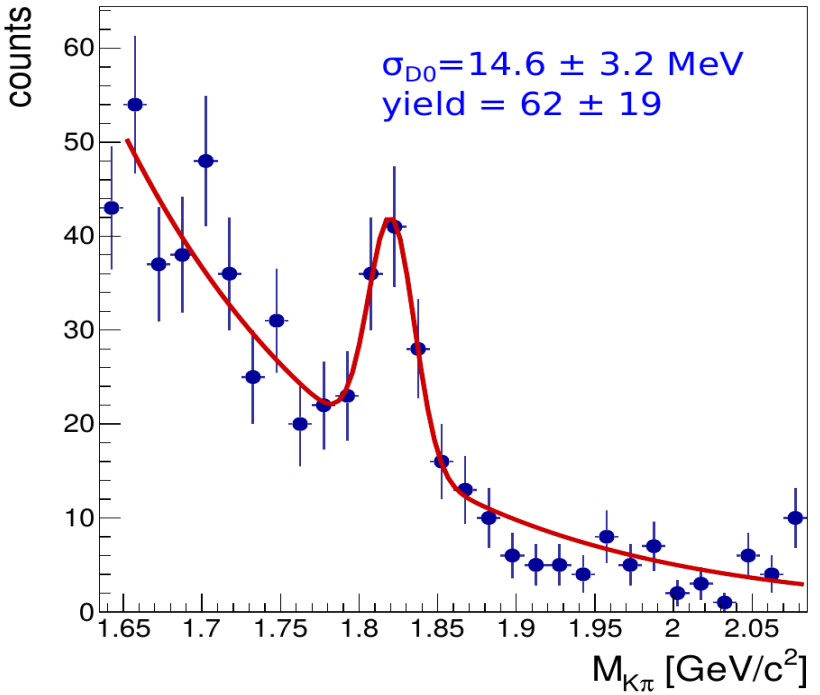
Hadrons containing charm considered for measurements:

Hadron	Decay channel	$c\bar{\tau}$ [μm]	BR
D^0	$\pi^+ + K^-$	123	3.89%
D^+	$\pi^+ + \pi^+ + K^-$	312	9.22%
D_S^+	$\pi^+ + K^- + K^+$	150	5.50%
Λ_c	$p + \pi^+ + K^-$	60	5.00%

First NA61/SHINE mesurements of D^0 mesons with Small Acceptance Vertex Detector (SAVD)



Result for 140k events of Pb+Pb at 150*A* GeV/c



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

NA61/SHINE program for 2021-2024

- Charm hadron production in Pb+Pb collisions for heavy ion physics
  - Mechanism of open charm production
  - Properties of the onset of deconfinement

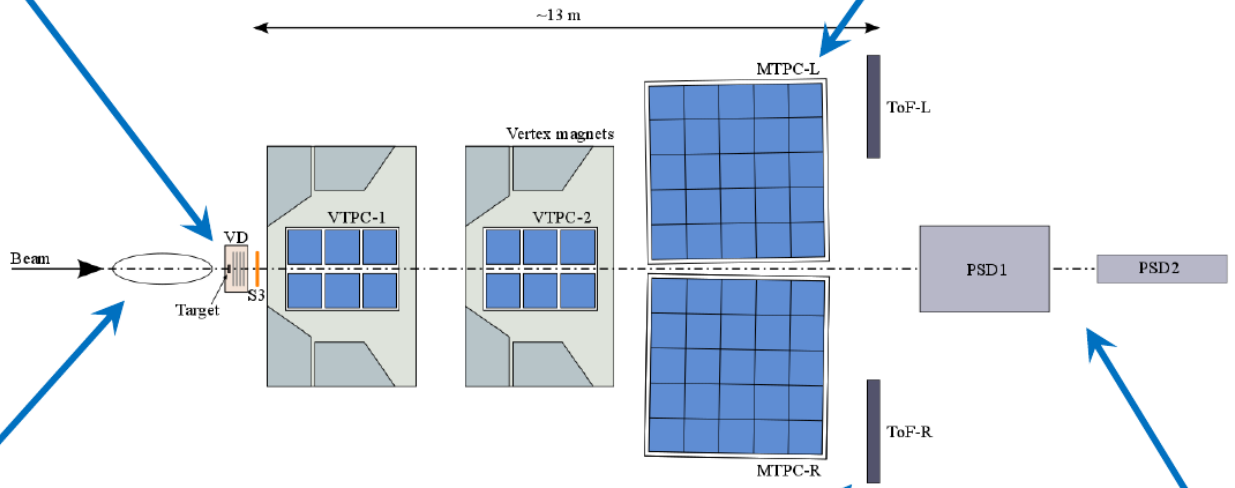
- Measurements for cosmic-ray physics
  - Nuclear fragmentation cross sections
  - (Anti-)deuteron production

- Hadron production induced by proton and kaon beams for neutrino experiments (T2K, T2K-II, Hyper-Kamiokande, DUNE)

Upgrades of NA61/SHINE detectors

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

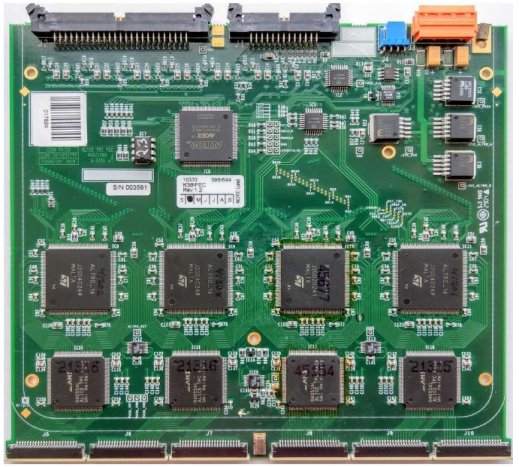
Replacement of TPC read-out electronics

- Necessary to increase the data rate from the current 80 Hz to 1 kHz

Present NA61 Front-End Card

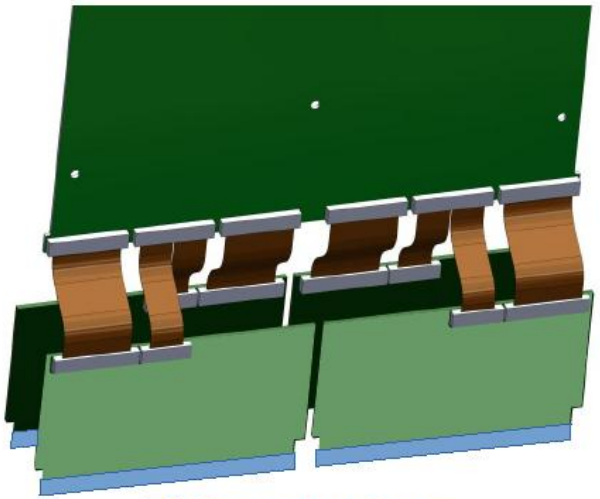
32 channels

ALICE Front-End Card



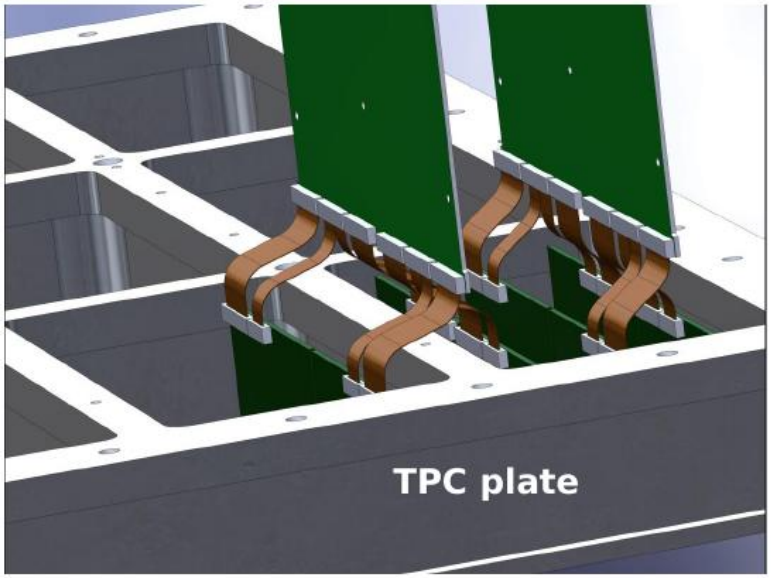
128 channels

ALICE Front-End Card



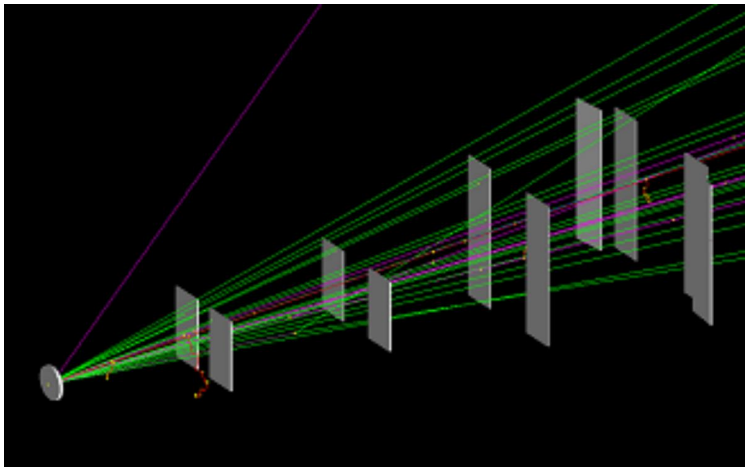
TPC connectors

+ Readout Control Units
+ Low Voltage
+ Cooling system

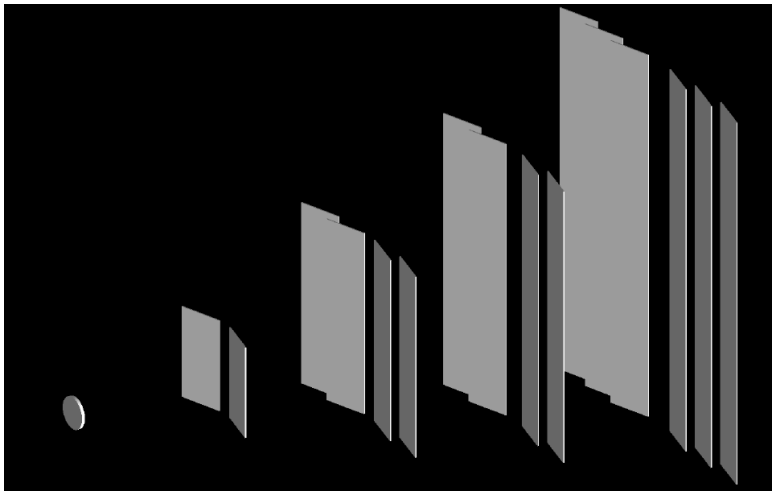


Upgrade of Vertex Detector

Small Acceptance Vertex Detector (SAVD)



Large Acceptance Vertex Detector (LAVD)



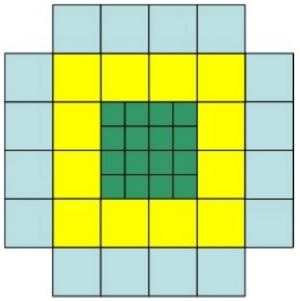
Mimosa 26AHR sensors will be replaced by ALPIDE sensors developed for ALICE-ITS

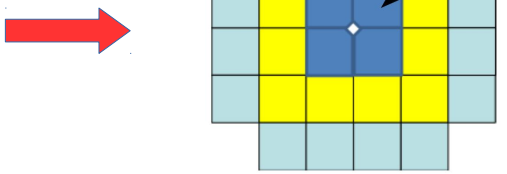
	SAVD	Future VD
Sensor	MIMOSA-26	ALPIDE
№ sensors	16	46
Active surface	$32cm^2$	$190cm^2$
Spatial resolution	$3.5\mu m$	$5\mu m$
Time resolution	$115.2\mu s$	$10\mu s$

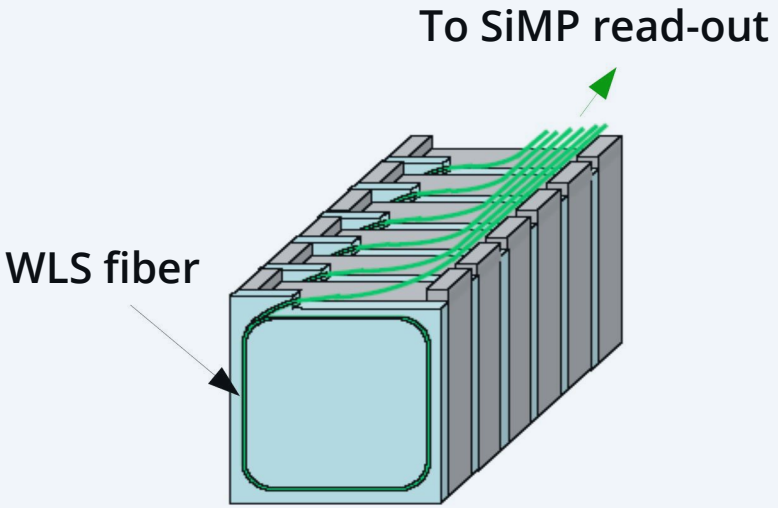
Upgrade of Projectile Spectator Detector (PSD)

Zero-degree calorimeter providing information on collision centrality and reaction plane orientation

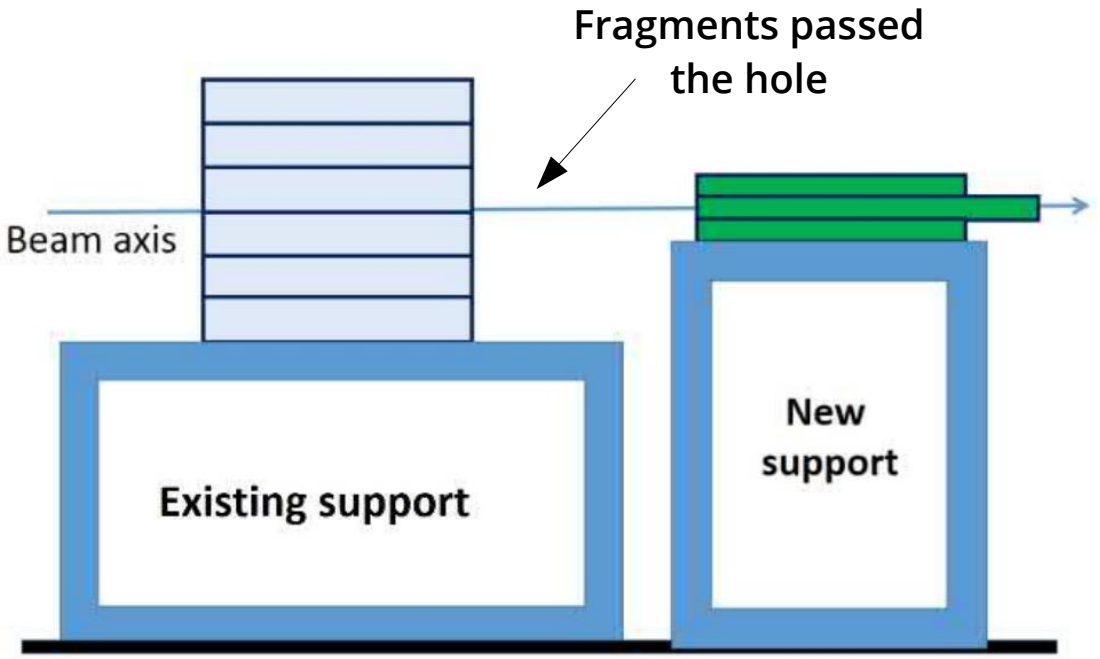
Front view of PSD







PSD module
- Pb/scintilator sandwiches

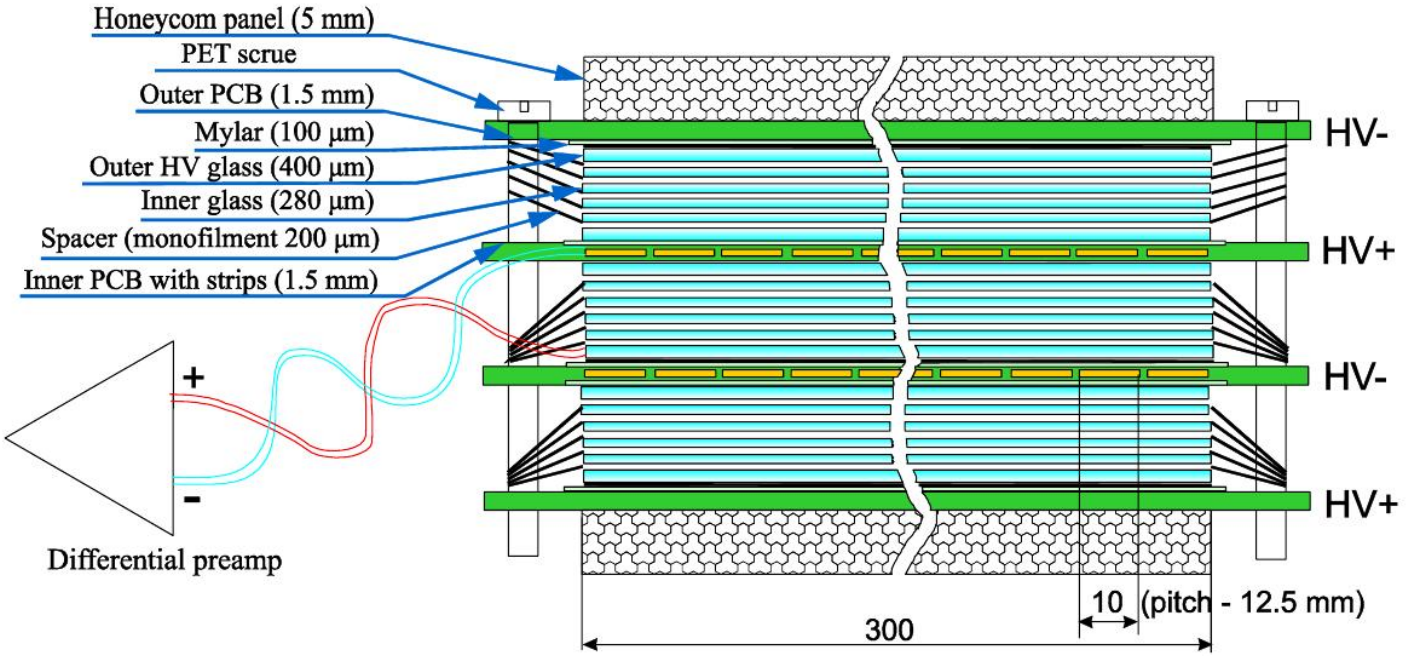


Side view

New Time of Flight system

New ToF detectors based on multi-gap resistive plate chambers (MRPC) are proposed as replacement of present ToF detector

(MPRCs are under construction for BM@N experiment at NICA facility)

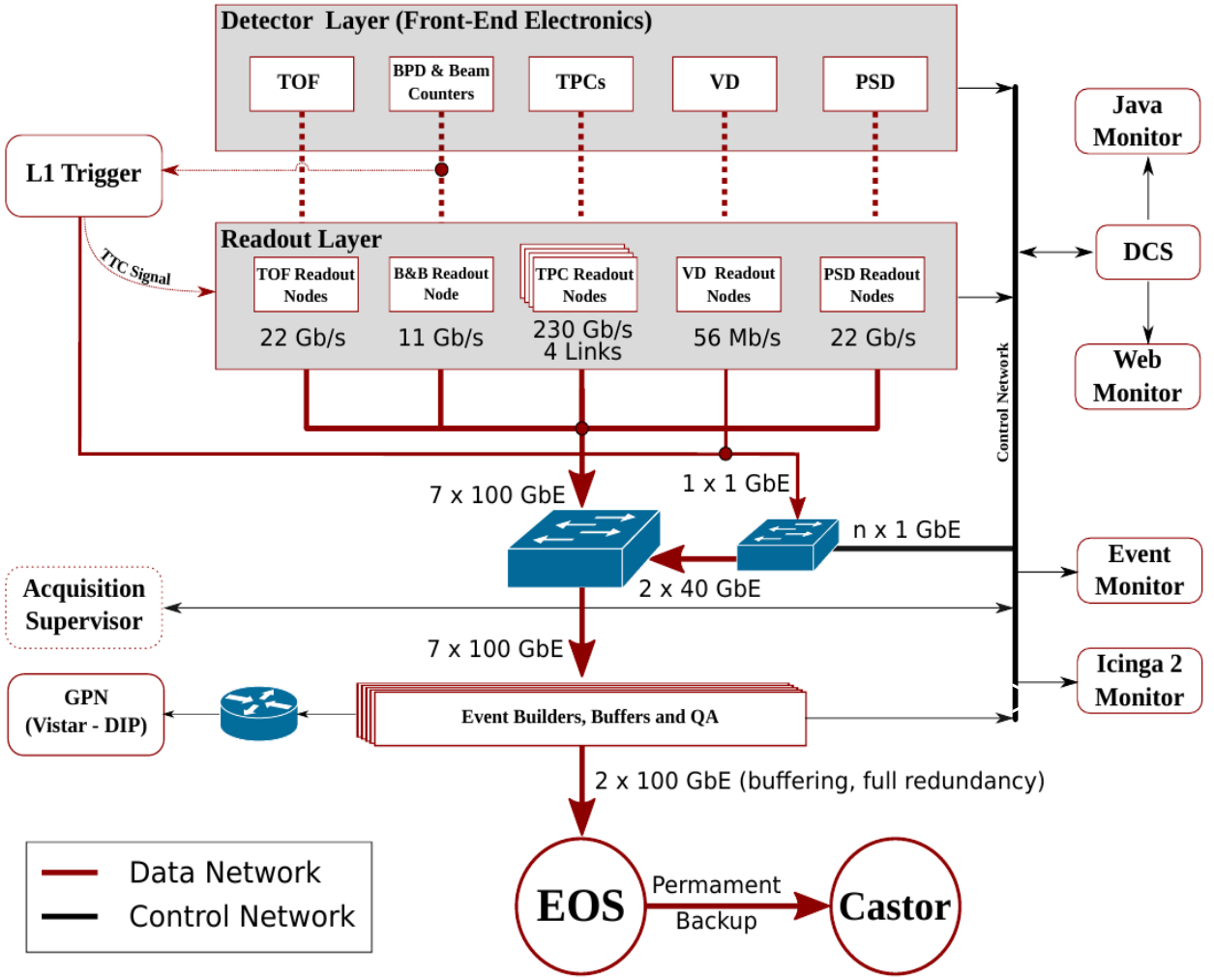


Cut view of the triple-stack MRPC

V. Babkin *et al. Nucl. Instrum. Meth.* **A824** (2016) 490–492.

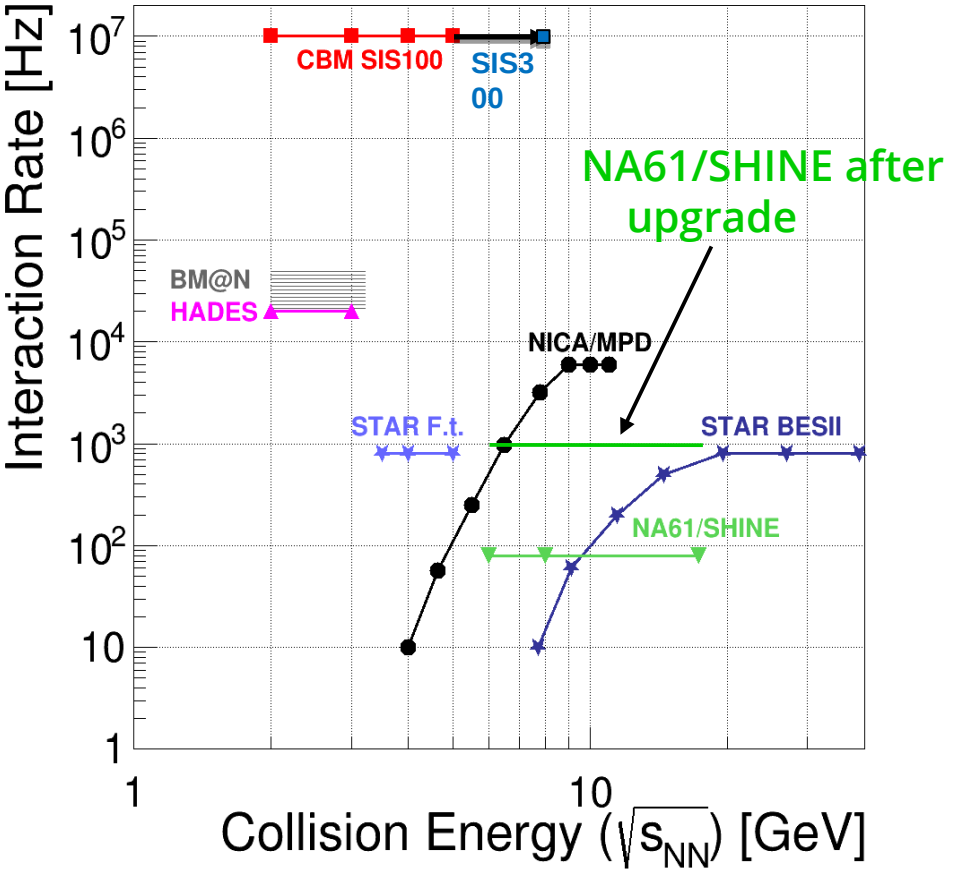
New Trigger and Data Acquisition system

- Inhomogeneous Nodes → flexible choice of sub-detector readout system
- Capable of 1 kHz read-out-rate
- Event aggregation from various nodes through Ethernet switches
- Homogeneous Core → data from all subsystems treated in the same way
- For 1 kHz expected data rate 160 Gb/s
- Based on Ethernet both for read-out and control
- On-line reconstruction to reduce data volumes



SUMMARY

- New results on system size dependence of hadron production
  - Traces of deconfinement in small systems ?
  - Onset of fireball
- Promising results of intermittency analysis
  - Signal of critical behavior ?
- First open charm measurements
- Rich physics program for 2021+
- Substantial detctor upgrades to increase data rate to 1 kHz



NA61/SHINE Collaboration

- 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

~150 physicists from ~30 institutes