SPS upgrades and prospects

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FACULTY OF PHYSICS
UNIVERSITY OF WARSAW

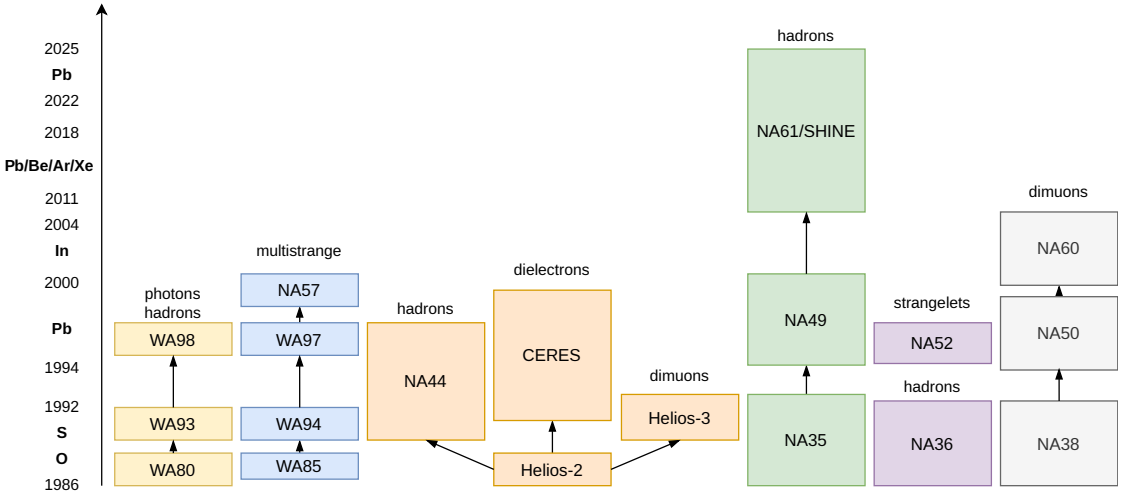
SQM 2024

Heavy ions at the CERN SPS

Brief history

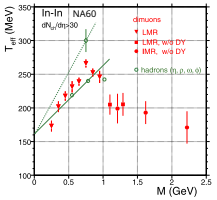
- CERN Super Proton Synchrotron started operation in 1976
- 10 years later, in 1986, the first heavy ion beams were delivered to fixed target experiments
- Since then, SPS provided many different ion species to experimental facilities in North and West Areas, yielding many important physics results

Heavy ion experiments at CERN SPS: history

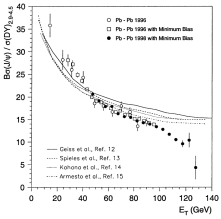


Selected signatures of QGP - early 2000s

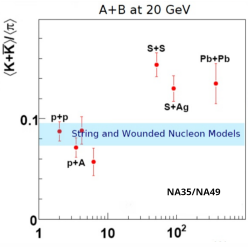
$T \approx 200$ MeV

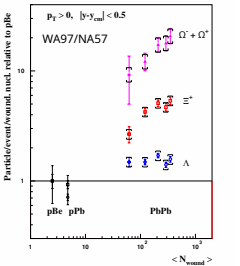


J/ψ melting

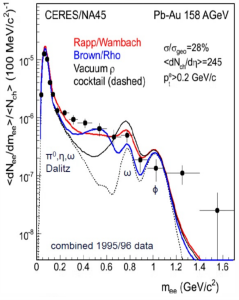


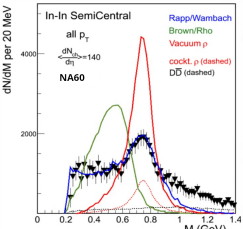
strangeness/multi-strange enhancement





modification of vector boson properties





CERN is announcing QGP discovery

C

SPECIAL SEMINAR

TITLE : A New State of Matter:
Results from the CERN Lead-Beam Programme
TIME : Thursday 10 February at 09.30 hrs
PLACE : Council Chamber, bldg 503

ABSTRACT

This special seminar aims at an assessment of the results from the heavy ion programme with lead ion beams at CERN which was started in 1994. A series of talks will cover the essential experimental findings and their interpretation in terms of the creation of a new state of matter at about 20 times the energy density inside atomic nuclei. The data provide evidence for colour deconfinement in the early collision stage and for a collective explosion of the collision fireball in its late stages. The new state of matter exhibits many of the characteristic features of the theoretically predicted Quark-Gluon Plasma.

Ulrich Heinz (CERN)
Making Quark-Gluon Matter in Relativistic Nuclear Collisions

Louis Kluberg (IN^{2}P^3)
The J/ψ suppression pattern observed in Pb-Pb collisions ions: a signature for the production of a new state of matter.

Johanna Stachel (University of Heidelberg)
Virtual and real photons radiated by the cooling and hadronizing fireball.

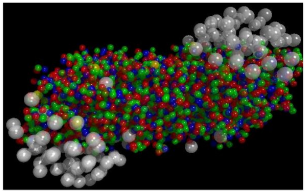
Reinhard Stock (University of Frankfurt)
Hadron Signals of the Little Bang.

Emanuele Quercigh (CERN)
Strange signals of a new state of matter from nuclear collisions at SPS.

Luciano Maiani (Director General, CERN)
Summary.

New State of Matter created at CERN

10 FEBRUARY, 2000



Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN[1]'s Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN[1]'s Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

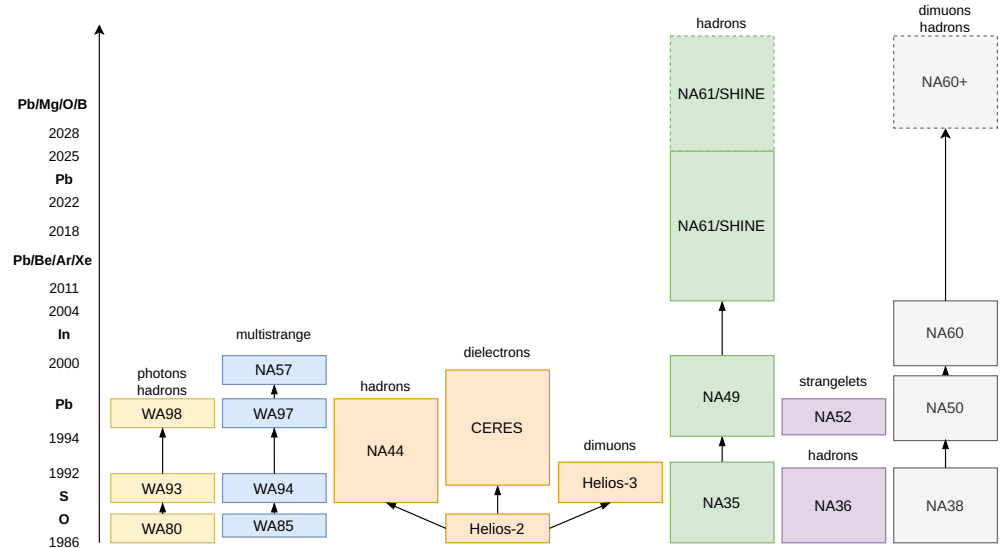
Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.

Professor Luciano Maiani, CERN Director General, said *"The combined data coming from the seven experiments on CERN's Heavy Ion programme have given a clear picture of a new state of matter. This result verifies an important prediction of the present theory of fundamental forces between quarks. It is also an important step forward in the understanding of the early evolution of the universe. We now have evidence of a new state of matter where quarks and gluons are not confined. There is still an entirely new territory to be explored concerning the physical properties of quark-gluon matter. The challenge now passes to the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory and later to CERN's Large Hadron Collider."*

Additional resources:

- Recording of the QGP announcement seminar: Part 1 Part 2
- CERN press release
- 40 years SPS NA Physics
- 30 Years of Heavy Ions: what next?

Heavy ion experiments at CERN SPS: future



Future of heavy ions at CERN SPS

- Currently two experiments are planning to run with heavy ions at the CERN SPS beyond LS3
- NA61/SHINE:
  - energy scan with light and medium mass ions to study the diagram of high-energy nuclear collisions
  - large statistics, high rate hadron production in Pb+Pb interactions to study locality of charm creation via correlations
- NA60+:
  - performing precision studies of hard and electromagnetic processes accessing:
    - muon pair production from threshold up to $m_{\mu\mu} \sim 4$ GeV/c^2 (dilepton continuum, low mass resonances, quarkonia)
    - hadronic decays of strange and charm hadrons, hypernuclei
  - Studies of: the caloric curve of the QGP at high μ_B, thermal dimuons and order of the phase transition, charm hadronization and thermalisation, onset of anomalous charmonium suppression

NA61/SHINE:
Physics, detector and upgrades

Motivation: indications of the onset of fireball

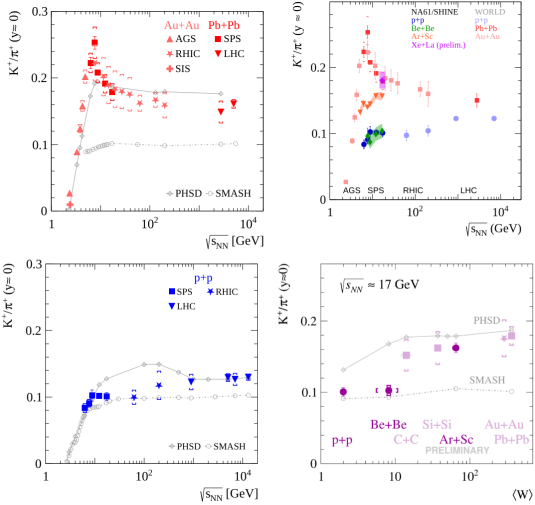
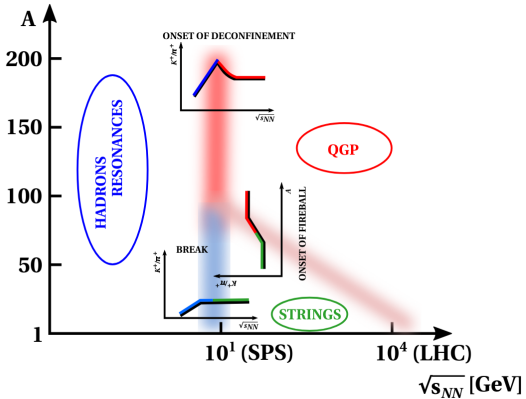
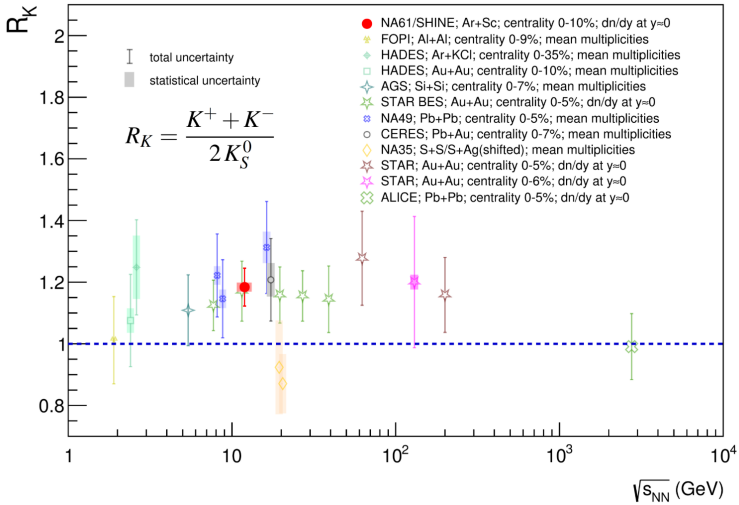


Diagram of high-energy nuclear collisions



M. Kuich et al., Universe 9 (2023) 2, 106

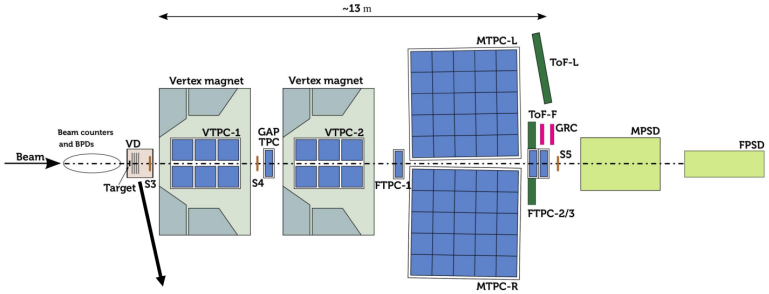
Motivation: excess of charged over neutral kaons



- Unexpected excess of charged over neutral kaon production in A+A collisions
- Up to now, not understood by known effects → **violation of isospin symmetry beyond known effects**
- For additional insight to NA61/SHINE results and their interpretation see:
  - Talk by T. Šuša (12:00 Wed.)
  - Talk by F. Giacosa (8:50 Tue.)

Future *Phase I*: Detector

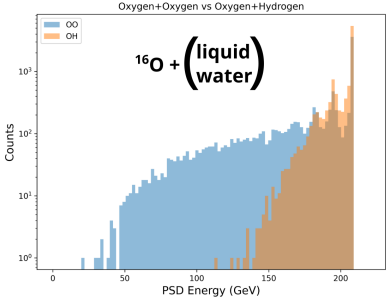
Significantly upgraded during LS2, the detector was successfully used in 2022 & 2023 data taking. No additional upgrades are needed for post-LS3 light-ion measurements



Cluster distribution in four planes of the new Vertex Detector

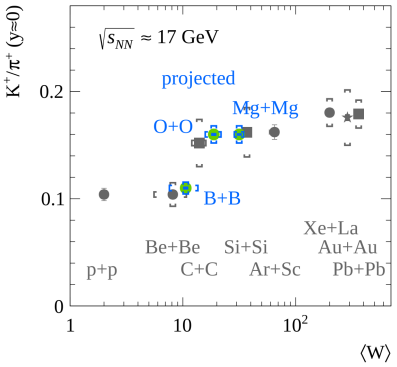
Future *Phase I*: Beams and targets

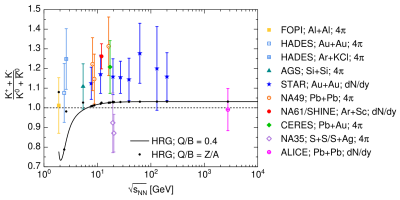
- Data taking with ^{24}Mg, ^{16}O and ^{10}B beams at 13A, 30A and 150A GeV/c is planned
- One beam species per year
- One week of running per beam momentum
- Isospin-symmetric (N=Z) reactions are planned to be recorded
- Short targets will be used, enabling tracking with Vertex Detector



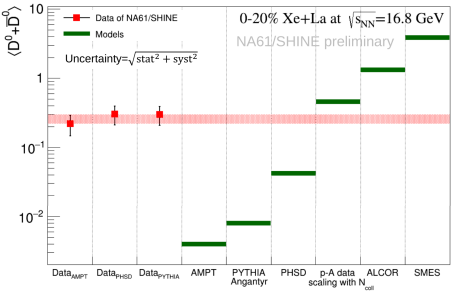
Future *Phase I*: Physics performance

- Considerable difference between light and heavy systems: **the onset of fireball**
  - Systematic studies in low-intermediate ion mass region
  - Essential to quantify and understand this region of the diagram
- Charged/neutral kaon puzzle:
  - Assuming collisions of N = Z nuclei and the exact isospin symmetry one gets $R_K = 1$
  - The proposed post-LS3 runs with O+O and Mg+Mg collisions post-LS3 may allow verification of the hypothesis of the isospin symmetry violation in kaon production beyond known effects





Future *Phase II*: Motivation - open charm in HI collisions



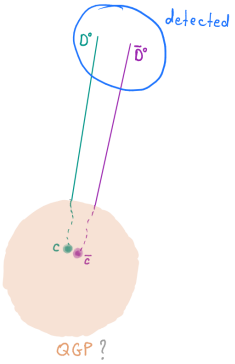
- First results on $\langle D^0 + \bar{D}^0 \rangle$ in heavy-ion collisions reported at SQM2024. See talk by A. Merzlaya (10:40 Tue.)

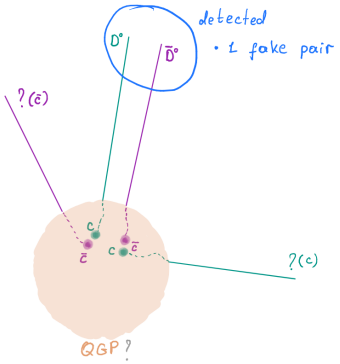
- High-statistics Pb+Pb measurement for open charm studies are ongoing (2022-2025)
- NA61/SHINE expects to provide a precise measurement of $\langle D^0 + \bar{D}^0 \rangle$ yield in Pb+Pb collisions and its dependence on collision centrality
- First estimate: $\langle c\bar{c} \rangle \approx 1$ in central Pb+Pb collisions at the top SPS energies
- What if we go one step further and look at two charm hadrons simultaneously? **Charm correlations at SPS**

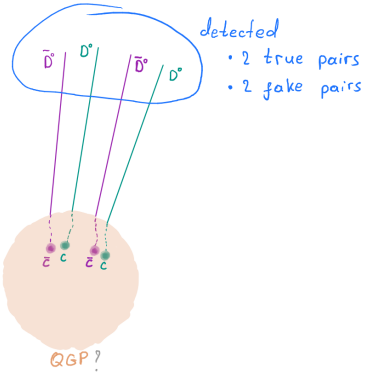
Future *Phase II*: Charm correlations

Measuring correlations of c and $\bar{c}$ quarks from the same pair forces one to seek events with only a single $c\bar{c}$-pair.

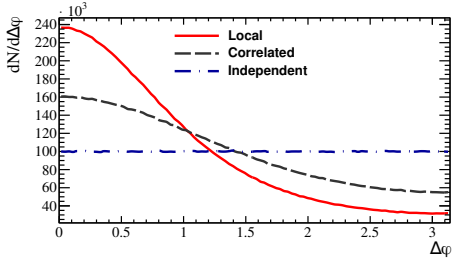
$$\langle c\bar{c} \rangle \lesssim 1$$



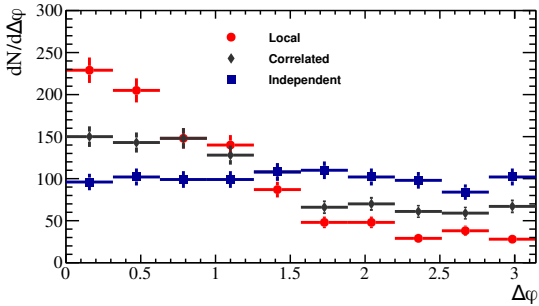




Future *Phase II*: Charm correlations



- Correlation in azimuthal angle $\Delta\varphi$ give access to probing locality of charm production
- Recording $N = 1000(D^0\bar{D}^0)$ pairs allows for obtaining measurable signal



arXiv:2305.00212

Future *Phase II*: Charm correlations

Statistics needed for 1000 $D^0\bar{D}^0$-pairs

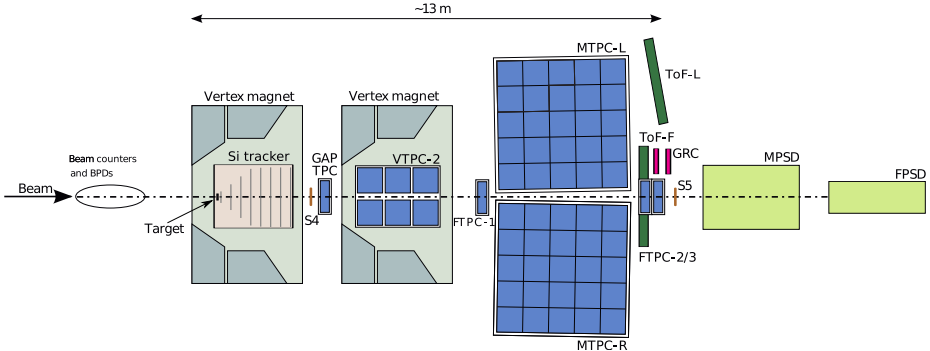
- $\langle D^0\bar{D}^0\rangle_{rec} \approx \langle c\bar{c}\rangle \cdot 1.2 \cdot 10^{-6}$
- Event selection cuts usually accept about 35% of events
- One would need about $1000/(0.35 \cdot \langle D^0\bar{D}^0\rangle_{rec}) \approx 2.4 \cdot 10^9/\langle c\bar{c}\rangle$

And, finally, we can estimate the time needed to accumulate this statistics (taking into account duty cycles, i.e. data-taking takes 30% of an actual run-time):

	$\langle c\bar{c}\rangle = 0.1$	$\langle c\bar{c}\rangle = 0.2$	$\langle c\bar{c}\rangle = 0.5$	$\langle c\bar{c}\rangle = 1$
1 kHz	$\sim$ 1000 days	$\sim$ 500 days	$\sim$ 200 days	$\sim$ 100 days
10 kHz	$\sim$ 100 days	$\sim$ 50 days	$\sim$ 20 days	$\sim$ 10 days
100 kHz	$\sim$ 10 days	$\sim$ 5 days	$\sim$ 2 days	$\sim$ 1 day

Future *Phase II*: Detector

- Replace one of the VTPCs with a fast Si tracker, at least a 10-fold increase of the readout speed
- Complement Si detectors with other tracking walls (MPGD?) to gain tracking performance at reasonable cost



Status and timeline

- *Phase I*:
  - Addendum with light-ion scan and extension of the NA61/SHINE program beyond LS3 submitted to SPSC (SPSC-P-330-ADD-14)
  - All ions are selected in close collaboration with CERN BE
  - Detector is ready and operational, no upgrades are needed
  - A short test with ^{16}O beam scheduled in 2025
- *Phase II*:
  - Feasibility study for the large acceptance Si tracker in the magnetic field started

NA60+:
Physics and detector

NA60+ will explore the QCD phase diagram at high baryon chemical potential:

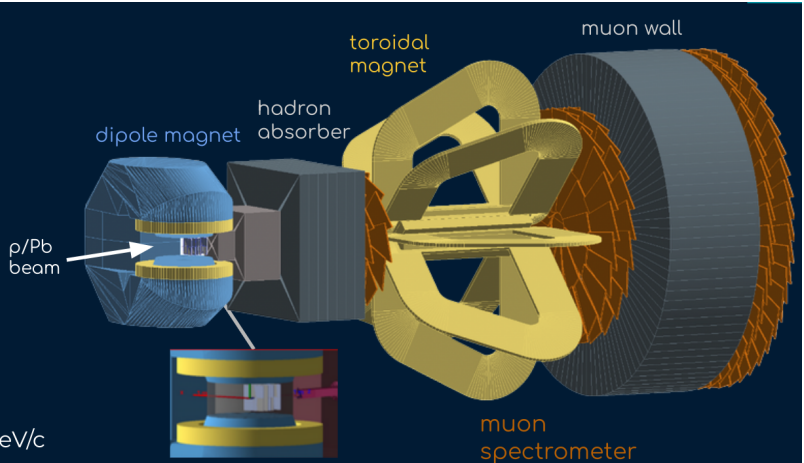
- Beam energy scan for $\sqrt{s_{NN}} = 6 - 17$ GeV with Pb and p beams
- High luminosities to study rare QGP probes - beam rates of up to 10^6 Pb ions per second
- Precise measurements of open and hidden charm in heavy ion collisions

Detector setup

NA60+

Setup

- Muon spectrometer
- Vertex spectrometer



Energy/ systems

- Pb-Pb and p-A collisions
- energy scan 6 < $\sqrt{s}$ < 17 GeV/c (20 < E_{lab} < 158 GeV/c)
- high luminosity ~10^6 Pb/s

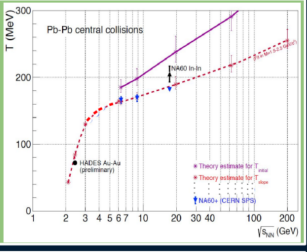
Talk by S. Siddhanta (14:00 Tue.)

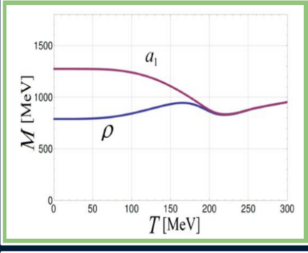
Talk by R. Arnaldi (12:00 Wed.)

1) caloric curve of QGP

measurement of thermal dimuons temperature vs $\sqrt{s_{NN}}$

Rapp and v.Hees, PLB753(2016) 586
T. Galatyuk et al., EPJA52(2016) 131





2) chiral symmetry restoration

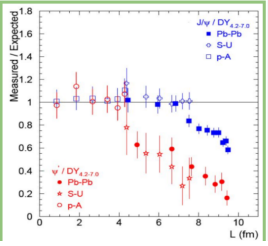
ρ-a_1 mixing in the dimuon channel

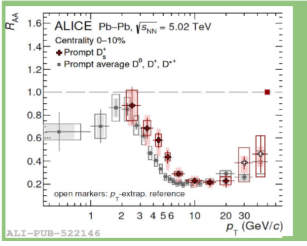
C. Jung et al.,
PRD 95 (2017) 036020

3) charmonium melting in the QGP

suppression of charmonium vs $\sqrt{s_{NN}}$ (dimuon decay channel)

NA50, PLB 477 (2000) 28
NA50, EPJC49 (2007) 559





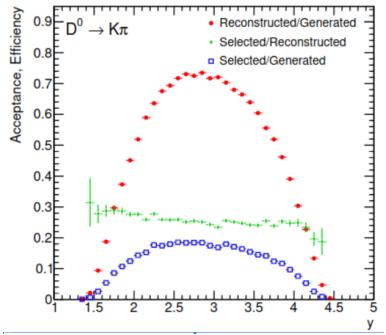
4) QGP transport coeff. and charm hadronization

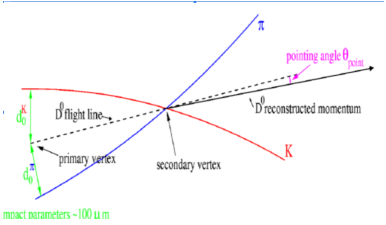
hadronic decays of open HF mesons and baryons

ALICE, PLB 827 (2022) 136986

Talk by R. Arnaldi (12:00 Wed.)

Open charm measurements

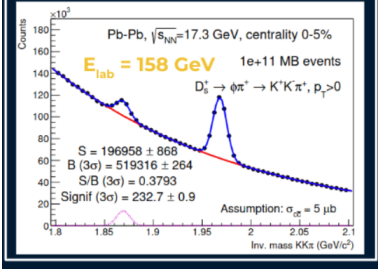




With 10^{11} MB Pb+Pb events (∼1 month of data):

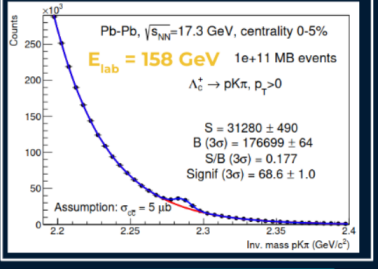
$D_s \to \phi\pi \to KK\pi$

measurement of yields feasible, statistical precision of few percent



$\Lambda_c \to pK\pi$

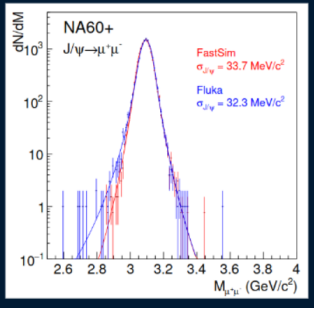
accessible, possible improvement with timing layers under study

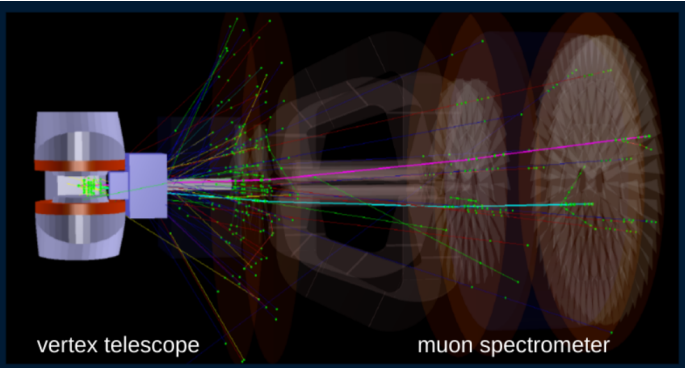


Talk by R. Arnaldi (12:00 Wed.)

Charmonium production studied via

- J/ψ and ψ(2S) in the $\mu^+\mu^-$ decay channel
- $\chi_c \rightarrow J/\psi\,\gamma$, with γ measured via conversion in a lepton pair in the vertex telescope





Muon tracks obtained matching tracks in vertex and muon spectrometer

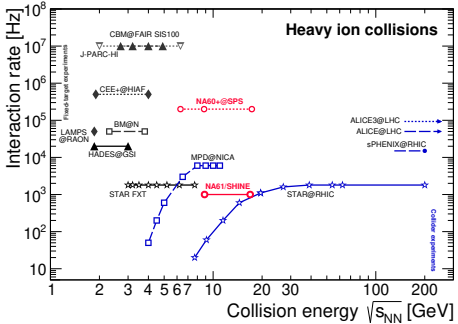
→ very good mass resolution, ~30 MeV for the J/ψ

Talk by R. Arnaldi (12:00 Wed.)

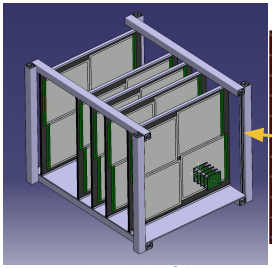
High intensity, focused Pb beam

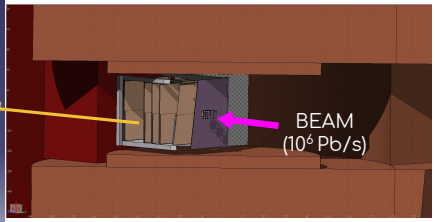
Very stringent beam requests at all energies:

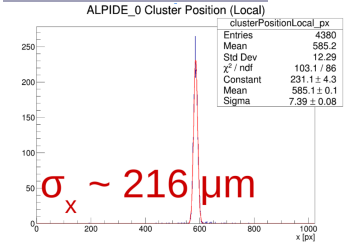
- high-intensity (10^7 Pb/spill)
- extremely focused sub-mm (vertex spectrometer will have 6 mm hole)
- beam optics studies ongoing (up to $2.4 \cdot 10^6$ Pb/spill at 150A GeV/c)

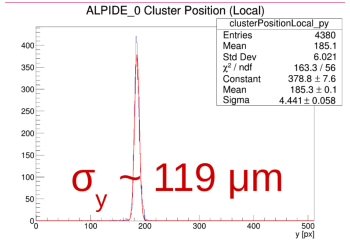


T. Galatyuk, NPA 982 (2019), update 2024









Talk by R. Arnaldi (12:00 Wed.)

NA61/SHINE and NA60+: synergy

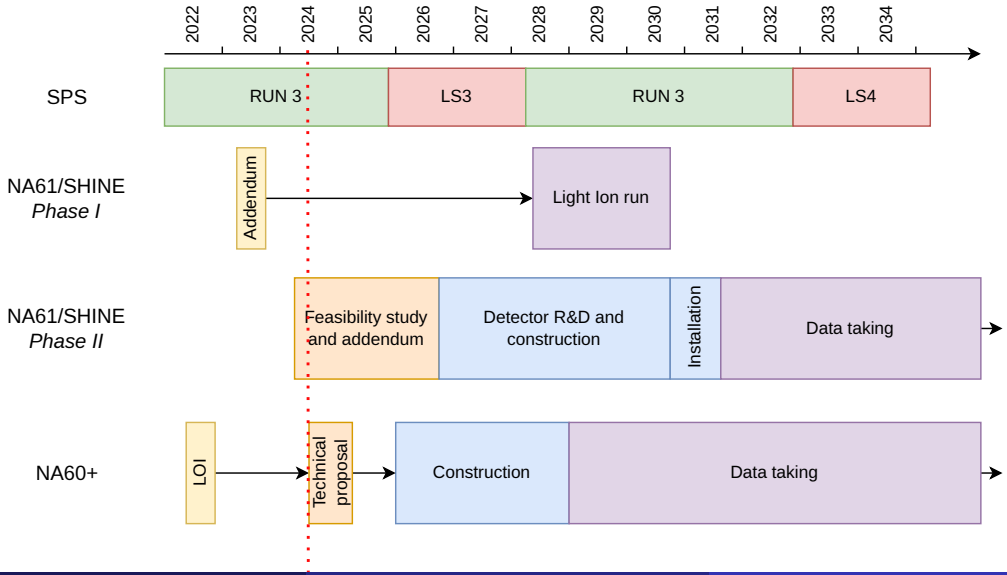
NA61/SHINE:

- Measurements of open charm mesons at the top SPS energy ongoing
- Extended plan to continue studies of diagram of high energy nuclear collisions and fundamental symmetries with light ion collisions
- Well-defined plans to measure charm correlations in HI collisions at SPS
- *Phase I* detector ready
- R&D needed for the *Phase II* upgrade

NA60+:

- High statistics open charm mesons and baryons measurements planned
- Extensive plans for dimuon and quarkonia measurements
- Studies of thermal dileptons and chiral symmetry restoration
- Detector R&D ongoing
- Strict beam requirements - challenging for lower momenta beams at the CERN NA

NA61/SHINE and NA60+: timeline



NA61/SHINE and NA60+: beams

p_{beam} [AGeV/c]	$\sqrt{s_{NN}}$ [GeV]	^{10}B	^{16}O	^{24}Mg	^{208}Pb	p
13	5.1					
30	7.6					
40	8.8					
60	10.7					
80	12.3					
120	15.1					
150	16.8					

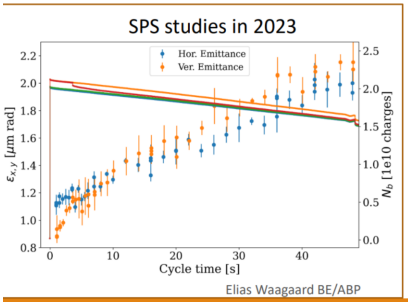
Beams requested by:

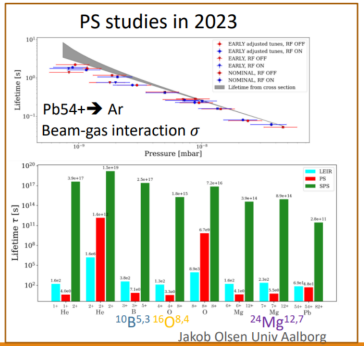
NA61/SHINE **NA60+** **NA61/SHINE and NA60+**

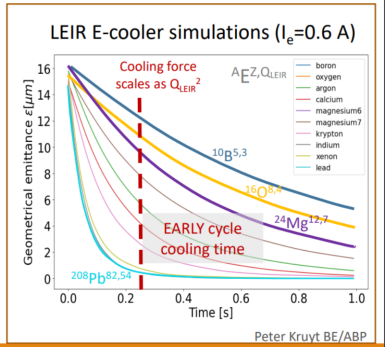
Development of new light ion beams at CERN

Light ions R&D at CERN

- **The challenge**: performance reach of ion beams limited by space charge (SC), intra-beam scattering (IBS), beam-gas interactions (BG) and electron cooling (EC) performance??
- **The goal: develop simulation** models; **benchmark** with data; **predict performance** for future ions





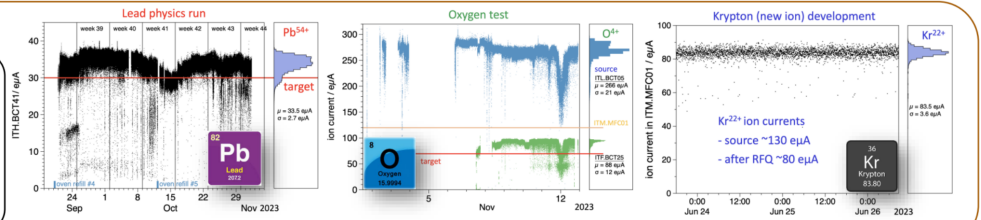


Talk by R. Alemany Fernandez at 2024 Annual PBC Workshop

Light ions R&D at CERN

2023

For the first time **three species** produced in the **same year**!



2024

2025

Talk by R. Alemany Fernandez at 2024 Annual PBC Workshop

Summary

Summary

- Long history of heavy ions at the CERN SPS
- Future is bright: Big interest to continue studies of diagram of high energy nuclear collisions in fixed target experiments at the CERN SPS
- Two projects plan long-term future:
  - NA61/SHINE - diagram, fundamental symmetries and charm locality
  - NA60+ - precise open charm and quarkonia measurements
- Big overlap and synergies between the two projects
- Close cooperation with CERN BE and participation in the Physics Beyond Colliders working groups

References

- Recording of the QGP announcement seminar: Part 1 Part 2
- CERN press release announcing QGP discovery
- 30 Years of Heavy Ions: what next?
- 40 years SPS NA Physics
- NA60+ LOI
- NA61/SHINE Addendum on physics with light ions
- 2024 Physics Beyond Colliders Annual Workshop
- NA61/SHINE website
- NA60+ website

Thank you