The physics program of the NA60+ experiment at the CERN SPS

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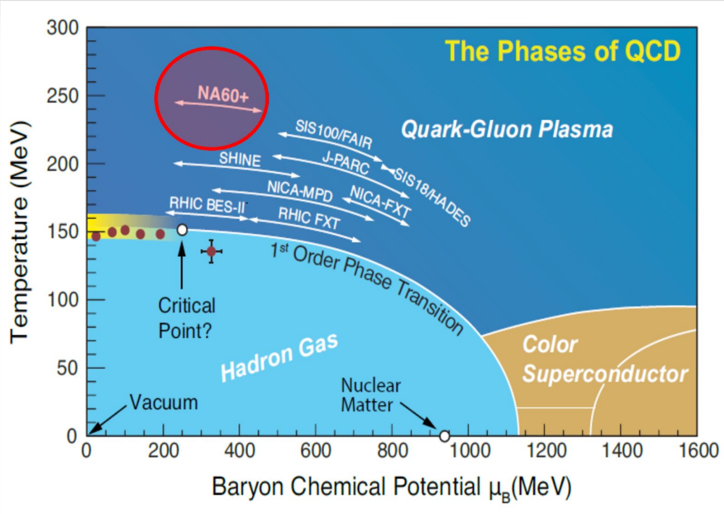
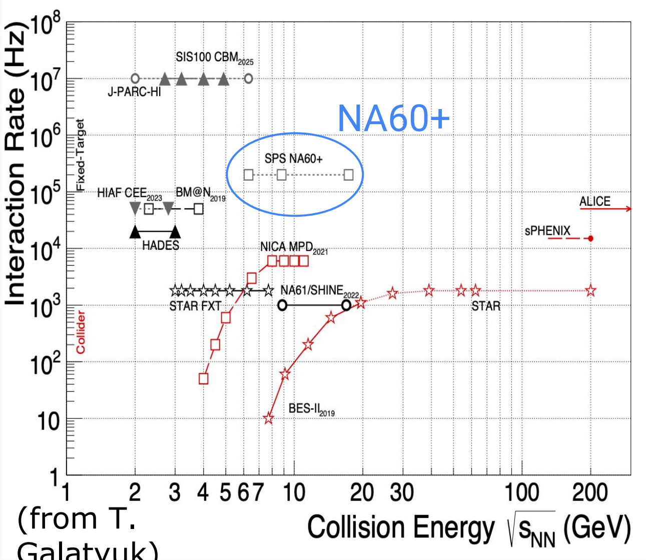
Quinto incontro nazionale di fisica nucleare INFN 2022 09/05/22

- NA60+ is a proposed experiment at the CERN SPS:
  - **explore the Quantum ChromoDynamic phase diagram** at large baryochemical potential (μ_B)

- NA60+ will perform a beam **energy scan in the range $\sqrt{s_{NN}}$ ~ 5-17 GeV** with an **high interaction rates** (~100 kHz)



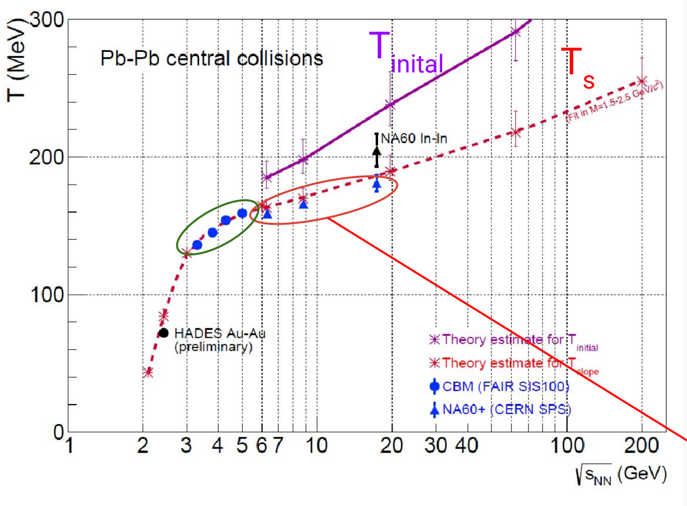


(from T. Galatyuk)

- **Main topics:**
  - Presence of a critical point?
  - First order phase transition at large μ_B?
  - Restoration of the chiral symmetry?
  - Properties of the QGP at large μ_B
- Ongoing studies at RHIC and NA61/SHINE, but the results are mostly on soft processes. NA60+ higher rates allow the study of hard and em processes:
  - **Hard processes**
  - **Electromagnetic processes**

NA60+: physics motivation

- Measure:
  - **Thermal dimuons from QGP/hadronic phase: caloric curve for first order transition**
  - **ρ-a_1 modifications: chiral symmetry restoration**

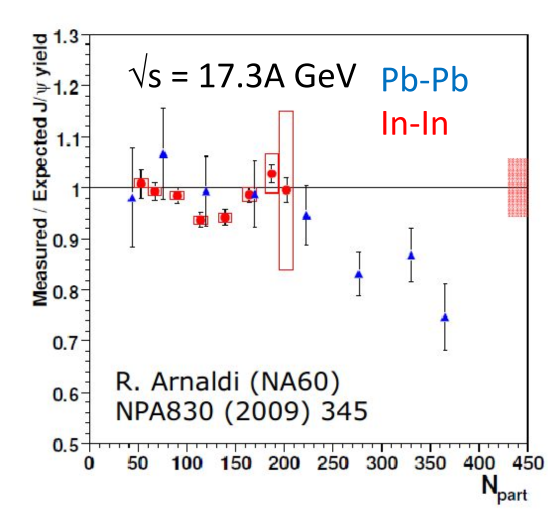


Compilation T. Galatyuk, QM2018
Hades,Nature Phys, 15(2019) 1040
√s>6 GeV, R. Rapp, PLB 753 (2016) 586
√s<6 GeV, T. Galatyuk, EPJA 52 (2016) 131

- **Extract temperature via fit** the dimuon mass:
  - $dN/dM \propto M^{3/2}\exp(-M/T_s)$
  - Possible flattening in √s-dependence of T_s
- Reach T at which the chiral symmetry may be restored:
  - observation of **ρ-a_1 mixing**

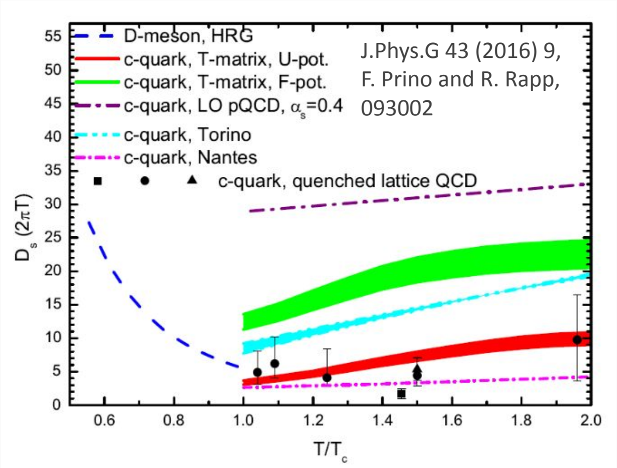
$\sqrt{s_{NN}}$ range covered by NA60+
→ complementarity with **CBM**

- Measure:
  - **Quarkonium suppression: signal of deconfinement**
  - **Hadronic decays of charmed hadrons: QGP transport coefficients**



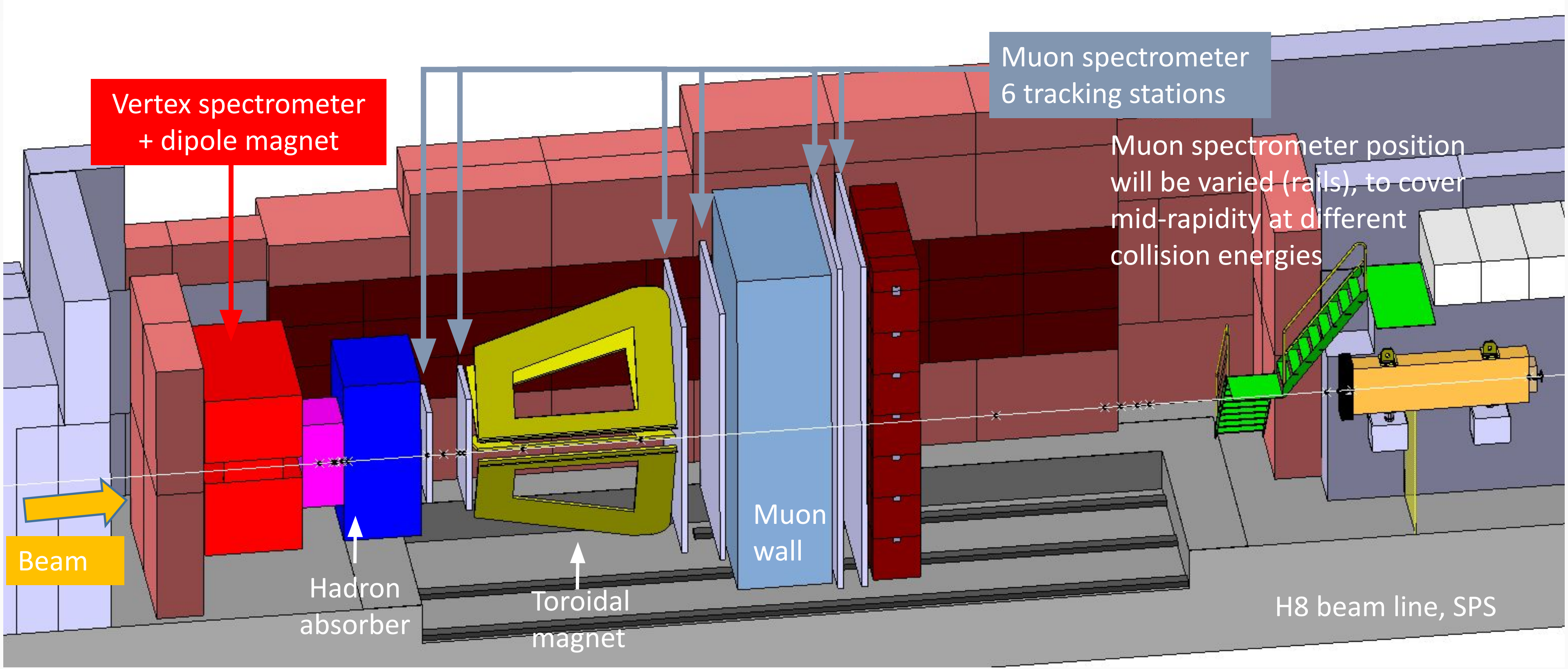
- NA50/NA60 experiments detected an **anomalous J/ψ suppression** ➞ not explainable by cold nuclear matter effects
  - NA60+ can explore the centrality dependence of **J/ψ suppression vs √s**

- Measure 2 and 3 prong decays of charmed mesons and baryons:
  - R_{AA}, v_2 : **transport coefficients**
  - Λ_c, D, D_s : study **hadronization mechanisms**



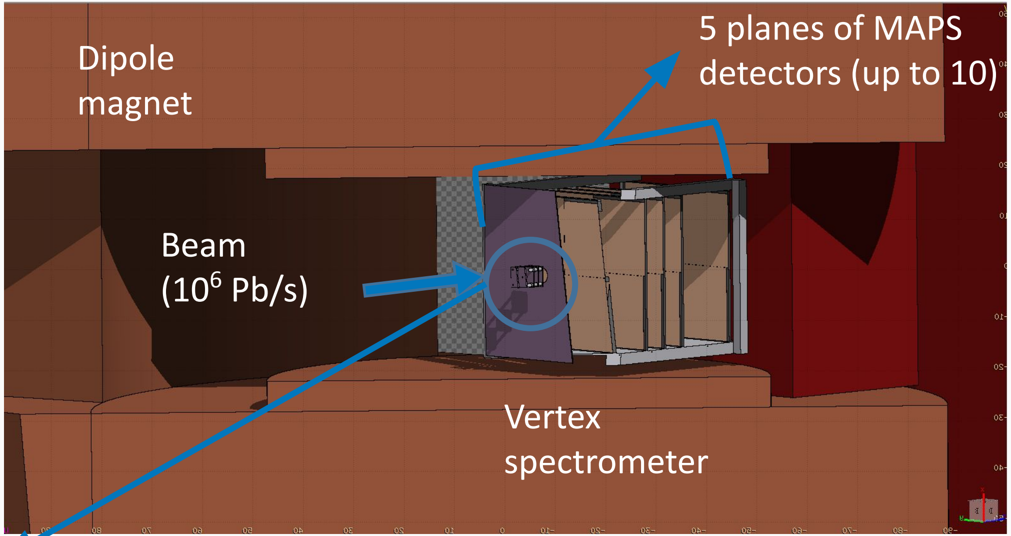
Also study strangeness production and hadronic decays of K^0_s, ϕ, and hyperons

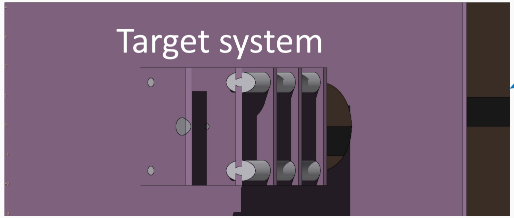
NA60+: experimental setup



NA60+: vertex region

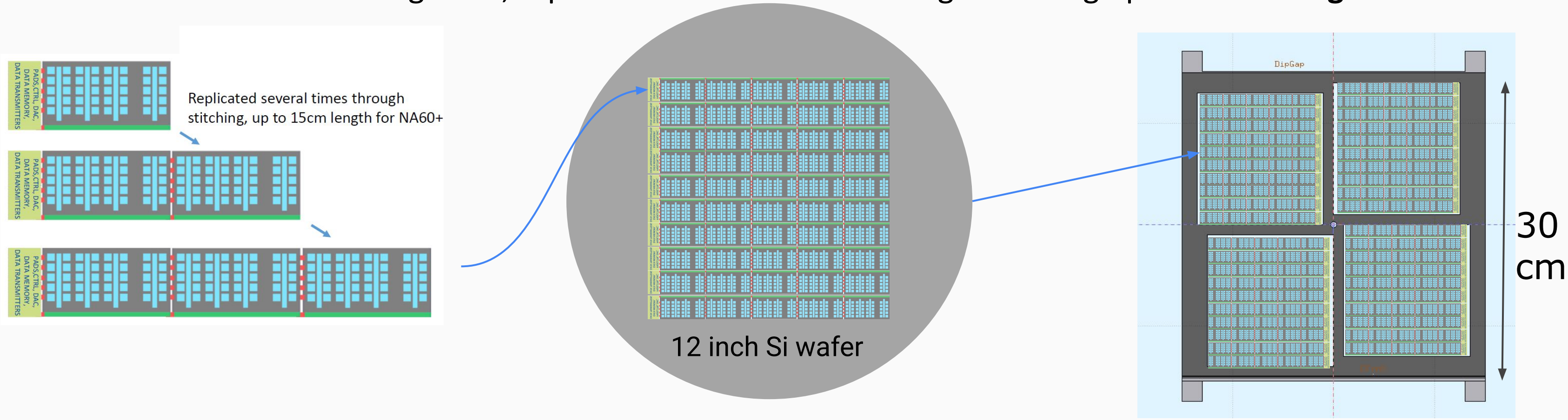
- Target system: 5 plates of 1.5 mm thick Pb
- Vertex spectrometer: from 5 to 10 layers of large area pixel sensors
- Vertex spectrometer embedded in a 1.5 T Magnetic field ➞ MEP48 is already available at CERN





NA60+: vertex spectrometer

- High charged particle multiplicity in Pb-Pb collisions (up to $dN_{ch}/dy = 450$) requires:
  - High granularity, fast and radiation hard detectors in the vertex region
- Use of **state-of-the-art Monolithic Active Pixel Sensors**
- Synergy with **ALICE ITS3**
- Sensor based on 25 mm long units, replicated several times through stitching up to **15 cm length** for NA60+

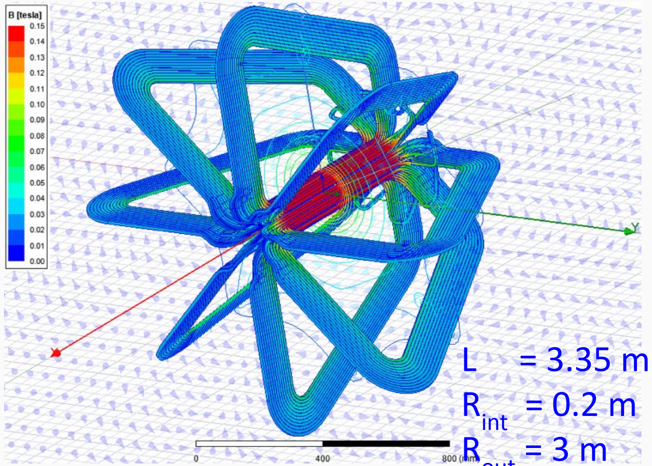


4 sensors per station

- Few tens of microns of silicon ➞ material budget **< 0.1% X_0**
- Spatial resolution **≲ 5 µm**

R&D: toroidal magnet

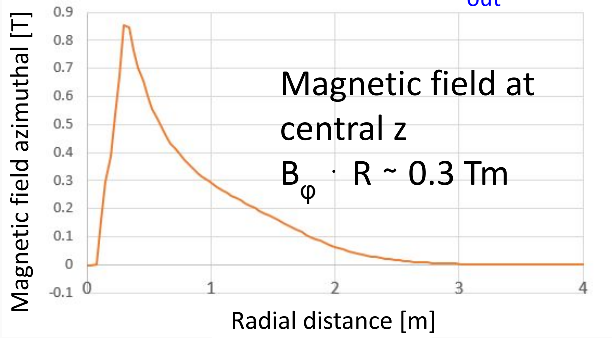
- Eight sectors with 12 turns per coil
- Light design ➞ **low material budget** in the acceptance area



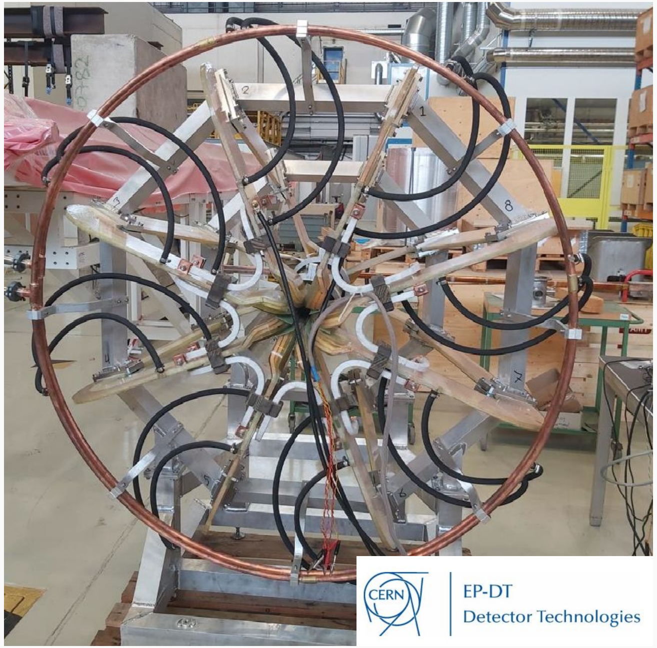
$L = 3.35$ m

$R_{int} = 0.2$ m

$R_{out} = 3$ m

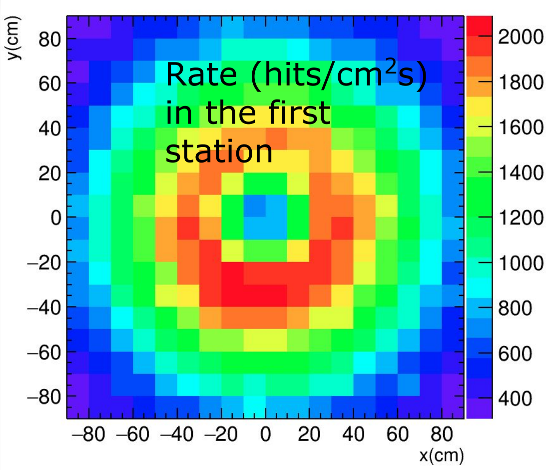


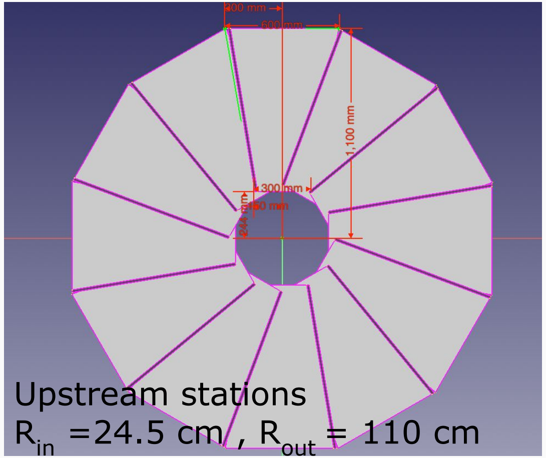
Operating Current [kA]	16.6
Amp-turns [kA]	199
Combined inductance [mH]	9.5
Resistivity Al 1100 @RT [μΩ.cm]	2.67
Length Conductor [m]	800
Total resistance [mΩ]	10.4
Dissipated power [MW]	2.8



- **Prototype (1:5 scale)** built and tested in 2020-2021 to check calculations and investigate mechanical solutions ➞ **works as expected**
- Magnet mechanical support designed in collaboration with INFN

- Thick hadron absorber (235 cm of BeO + C) ➞ rates in the upstream stations are modest (simulated with FLUKA)
  - Requirements can be matched by GEM or MWPC detectors
  - Discussion on technology choice in progress
- With a 10^6 Ions/s beam ➞ charged particle rate ~$2kHz/cm^2$





Stony Brook University

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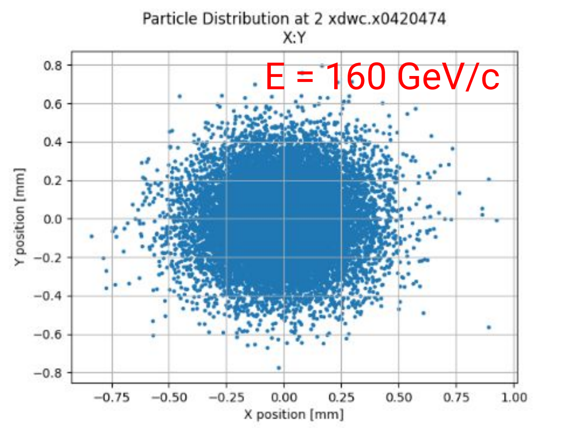
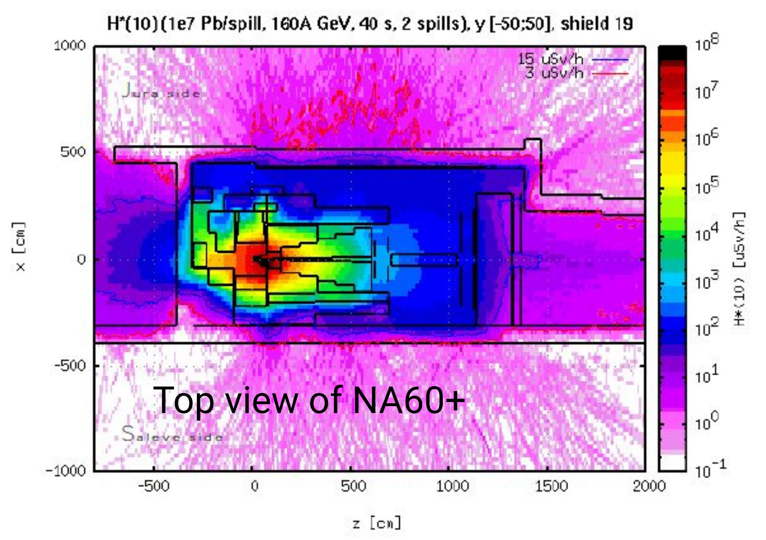
- **GEM:**
  - Triple GEM chambers with 2D strip readout
- **MWPC:**
  - MWPC with 3 mm wire pitch and 3 mm gap from anode wire to cathode
  - SPS beam test of first prototype in October/November

Beam and Radioprotection studies

- Need for :
  - **High-intensity** (10^7/spill) ➞ can be provided by the H8 beam line at EH1N hall
  - **Collimated** (σ < 1mm) beam ➞ a fully re-designed optics will be tested at SPS in November 2022

Parameter in zone 138	160 GeV/c	30 GeV/c
σ_x (mm)	0.19	0.33
σ_y (mm)	0.19	0.36



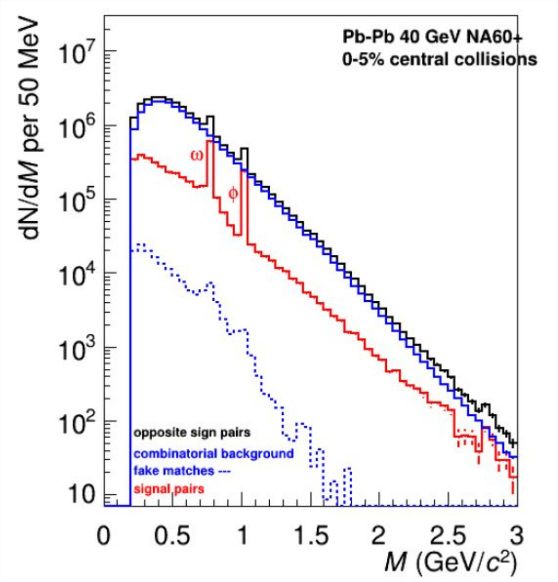


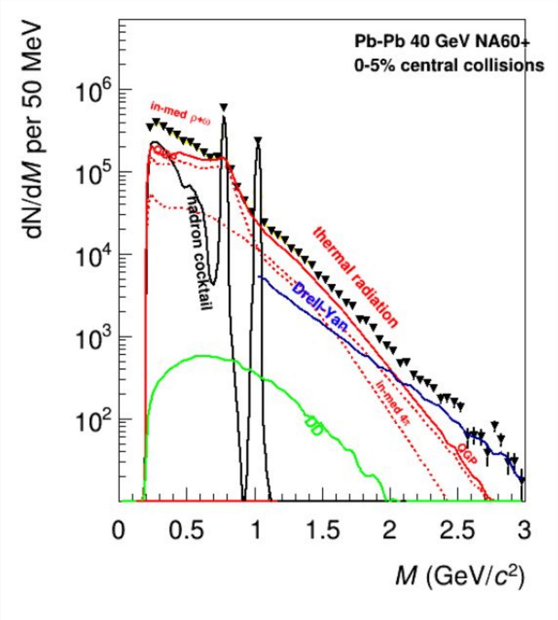
- **Heavy shielding** is needed
  - Iron and concrete shielding was designed:
  - Dose below 3 µSv/h externally to the experiment
- Integration studies for detector and infrastructure were performed

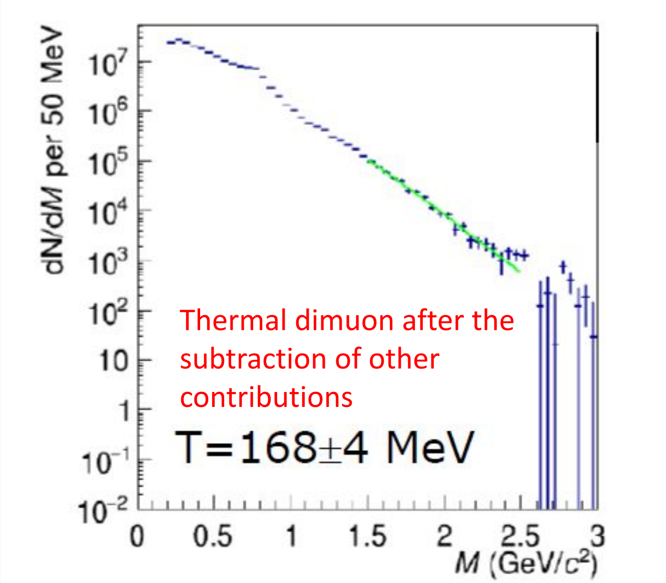
Physics performance

Dimuon mass distribution

- $4 \cdot 10^6$ reconstructed dimuon pair in central Pb-Pb in 1 month data taking at ~200 kHz ➞ 20 times with respect to NA60
- Thermal radiation yield accessible up to M = 2.5-3 GeV/c^2



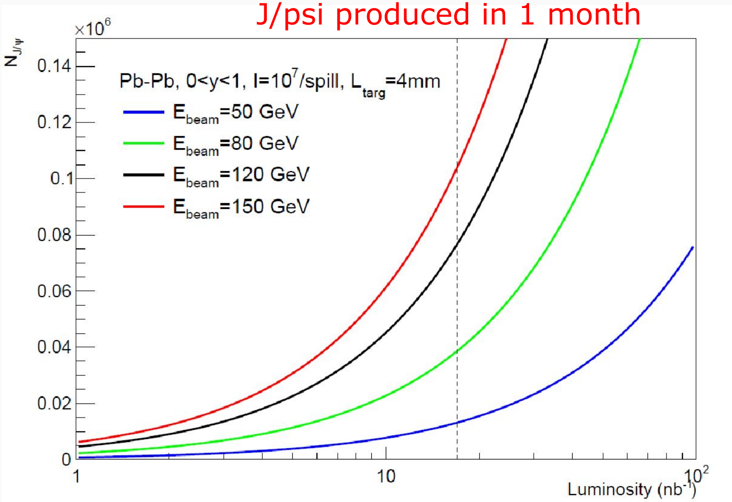


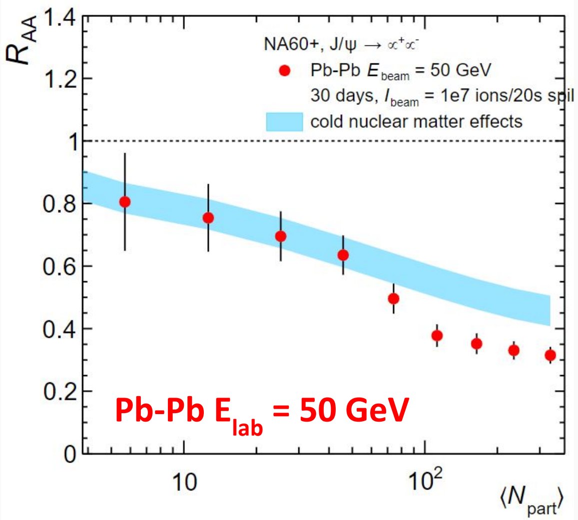


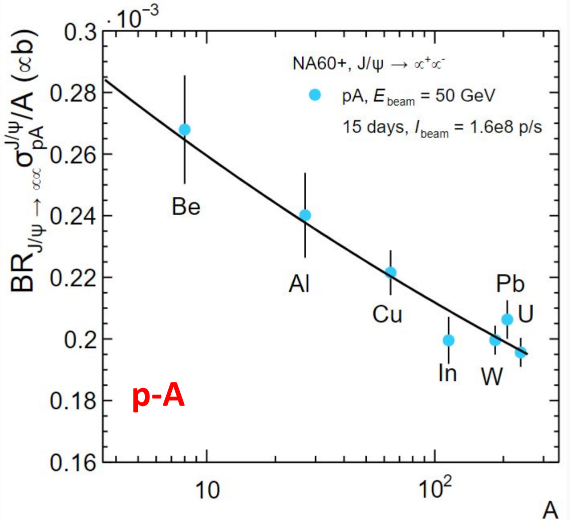
- ~2% uncertainty on the T_{slope} measurement:
  - Allows an **accurate mapping of the √s-dependence of T_{slope}** around T_c

- **Quarkonium measurements** in the dimuon channel

J/psi produced in 1 month





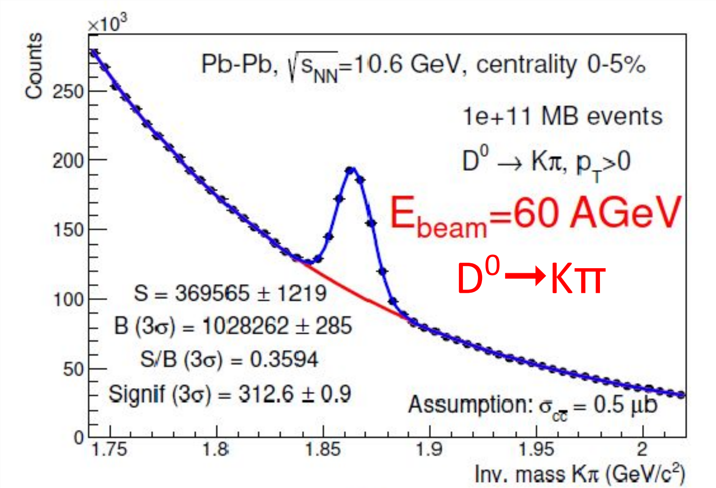


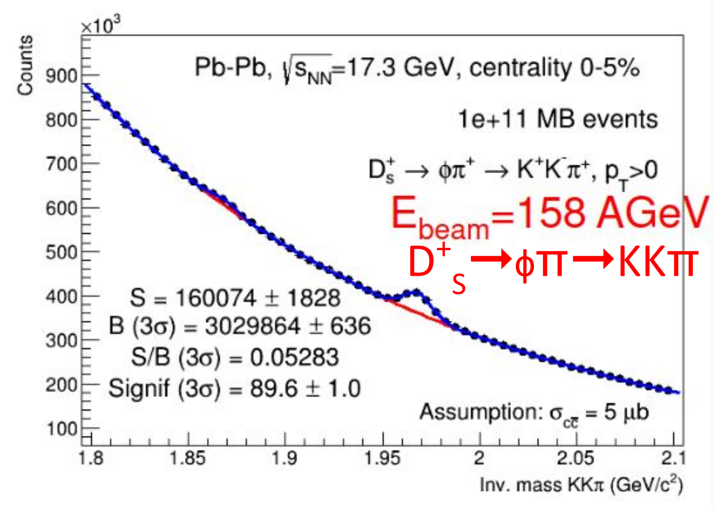
- NA60+ aims at:
  - **~O(10^4) J/ψ at 50 GeV**
  - **~O(10^5) J/ψ at 158 GeV**
- ψ(2S) within reach down to E_{beam}=100-120 GeV

- Allows detection of onset of anomalous suppression effects down to low SPS energy
- Need to calibrate Cold Nuclear Matter effects ➞ p-A data taking (few weeks/year)

Open charm

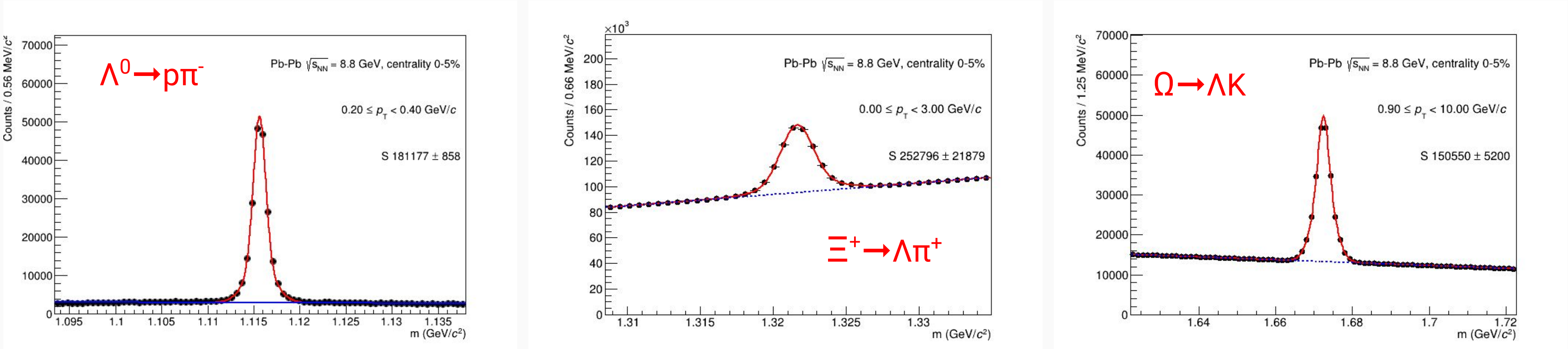
- Decay products reconstructed in the vertex spectrometer
- Geometrical selections on the displaced decay-vertex topology (cτ ~60-300 mm) to enhance the S/B
- All simulations based on 10^{11} minimum bias events in Pb-Pb collisions (~1 month data taking)





- Allows for differential studies of yield and v_2 vs p_T, y and centrality

- Decay products reconstructed in the vertex spectrometer
- Geometrical selections on the displaced decay-vertex topology (cτ ~ 2-3 cm) to enhance the S/B (except for the ϕ)
- All simulations based on 10^{11} minimum bias events in Pb-Pb collisions (~1 month data taking)



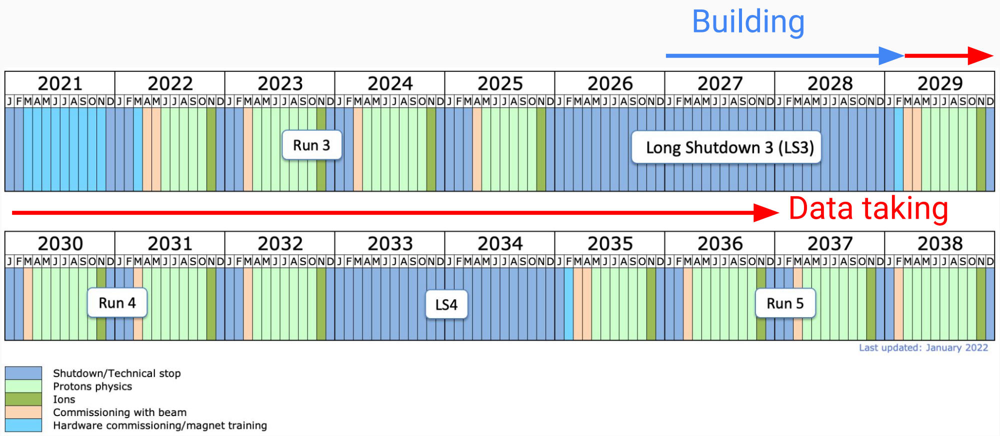
- Excellent performance for strange hadrons
- Very large statistical significance for K^0_S, Λ^0, ϕ, Ξ and Ω hyperons:
  - **Large improvement in their measurement w.r.t. the NA49 and NA57 measurements**

- The project is part of the **Physics Beyond Colliders** CERN initiative since 2016 (QCD study group) and receives a substantial support on several technical aspects, including integration, RP and beam studies, and the project of the toroidal magnet

- An **Expression of Interest** (https://cds.cern.ch/record/2673280) was submitted in 2019 to the CERN SPSC

- A **Letter of Intent** is currently in (advanced) preparation → to be submitted in 2022

- Goal:
  - Obtain the CERN approval and build the experiment for data taking not later than the **end of LHC Long Shutdown 3** (2029)
  - Foresee **at least 5-6 yrs** of data taking (one energy point per year with p-A and Pb-Pb)



Conclusion

- Precision studies of **electromagnetic and hard probes** in the region $6<\sqrt{s_{NN}}< 17$ GeV are currently lacking
- The CERN NA60 experiment had obtained measurements with unsurpassed precision in the study of dilepton production at top SPS energy ($\sqrt{s_{NN}}$ =17.3 GeV)
- **NA60+: a new dimuon experiment** with a similar concept but based on state-of-the-art technology choices may collect a factor ~20 larger statistics for several collision energies at the SPS
- Expected physics performance ➞ possible **breakthrough** on several hot topics
- From **design to realization**: R&D studies ongoing, CERN test beam periods from 2022

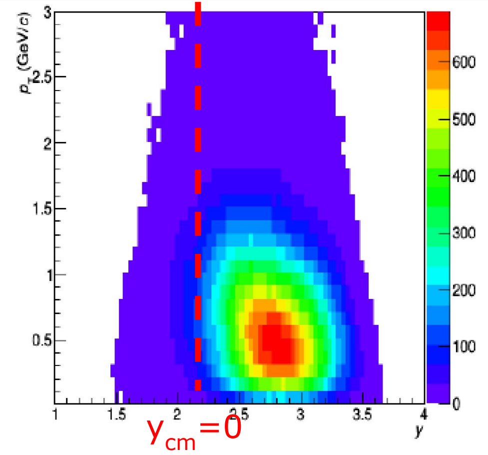
A Collaboration is being built and still needs to be strengthened in order to bring the project to approval ➞ you are welcome to contact us for discussions!

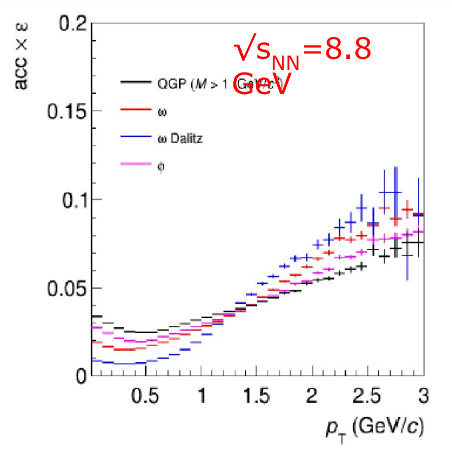
Backup

(Di)muon detection performance

- Detector performance studies:
  - based on a **simulation framework** with a semi-analytical tracking algorithm (Kalman filter)
  - **FLUKA** for background studies

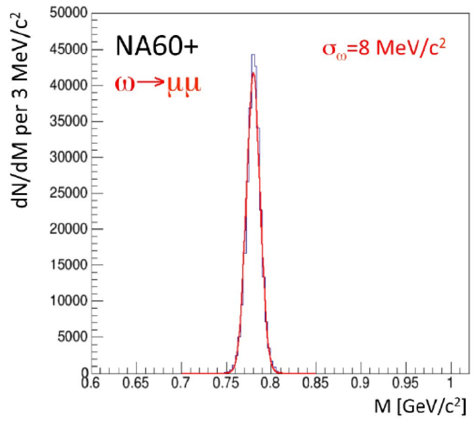
QGP (m>1 GeV/c^2)

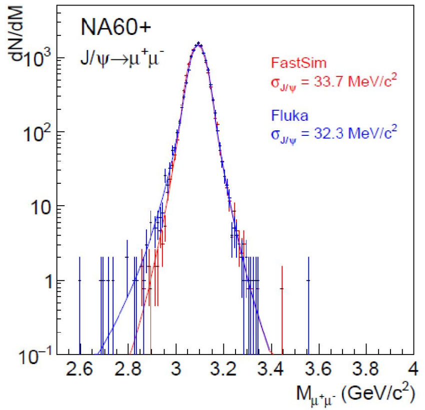




- Full phase-space acceptance at dimuon low and intermediate masses ⟶ >1%
- Good coverage down to midrapidity AND zero p_T, realized at all energies by displacing the muon spectrometer

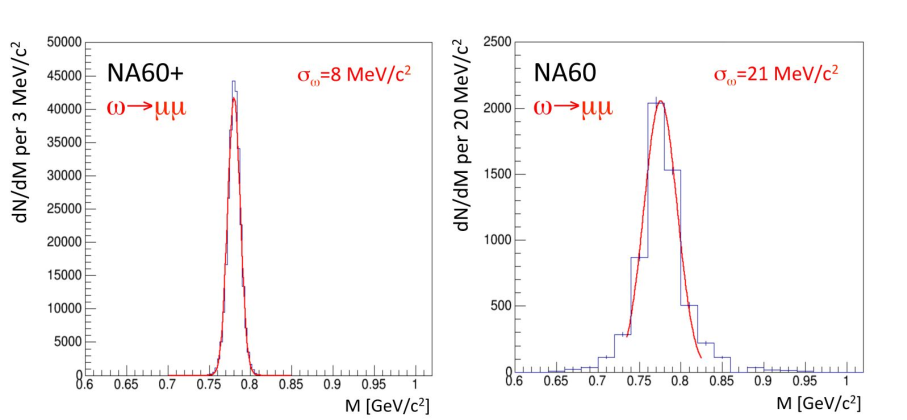
- The mass resolution for resonances varies from < 10 MeV (ω) to ~30 MeV (J/ψ):
  - Factor >2 improvement with respect to NA60



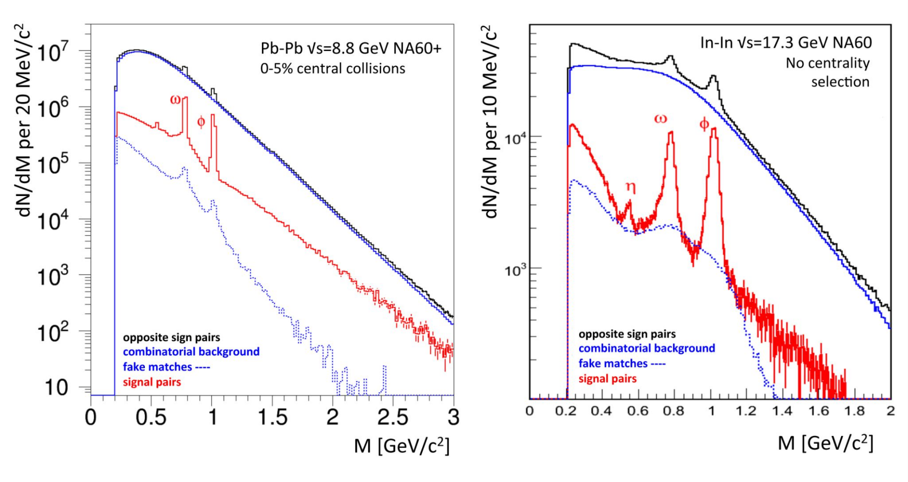


Dimuon detection performance: NA60 vs NA60+

- Detector performance studies:
    - Simulation framework tested simulating NA60 ➞ results in according to what was obtained by NA60



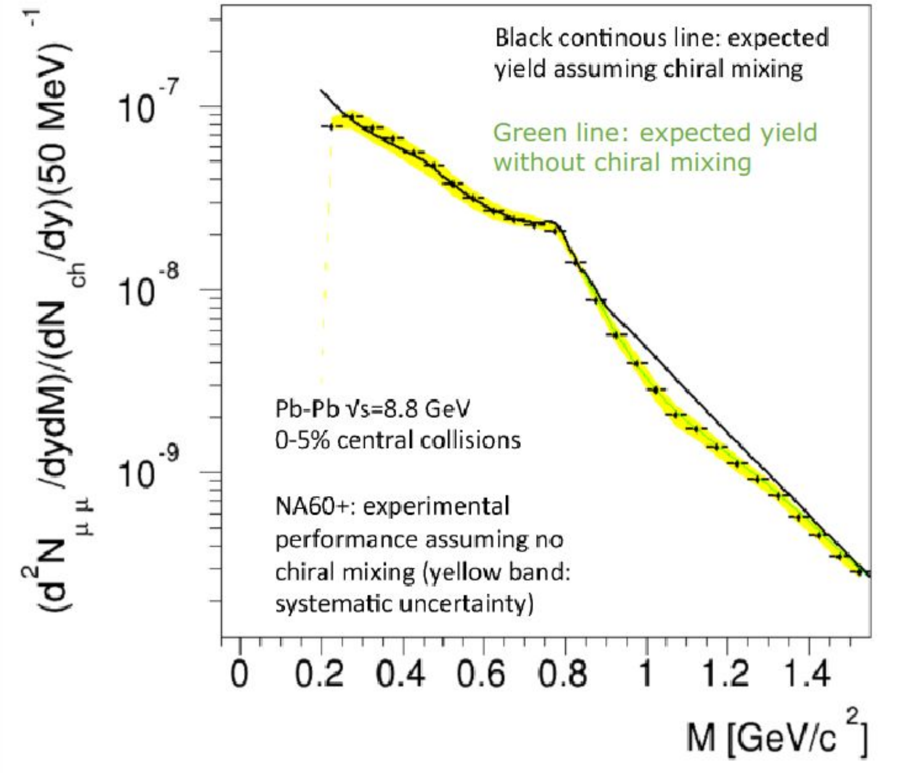
- The mass resolution for resonances varies from < 10 MeV/c^2 (ω) to ~30 MeV/c^2 (J/ψ):
    - Factor >2 improvement with respect to NA60 (21 MeV/c^2)



- Dimuon spectrum comparison ➞ similar signal-to-background ratio but:
    - Higher statistics
    - Better resolution
    - Centrality selection (0-5%)

Chiral symmetry restoration

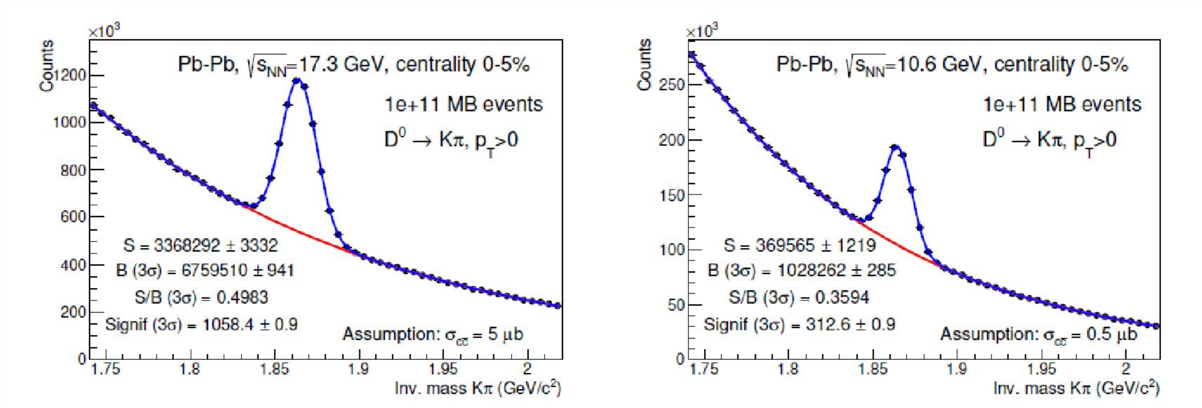
Thermal dimuon after the subtraction of other contributions



- Simulations carried out by considering:
  - **No chiral mixing** (dip in 1<M<1.4 GeV/c^2)
  - **Full ρ-a_1 chiral mixing** ➞ a 20-30% enhancement is expected
- Studies modeled from Rapp, vanHees, PLB753 (2016) 586
- NA60+ could clearly detect the signal of chiral symmetry restoration

Open charm simulations

- Hadronic decays of charmed particles can be reconstructed in the vertex spectrometer (no PID)



(equivalent to 30 days data taking at 150 kHz)

- $D^0 \to K^+\pi^-$ (POWHEG-BOX+PYTHIA6):
  - Background from NA49 light hadron production data
- 0-5% Pb-Pb, $\sqrt{s_{NN}}$=17.3 GeV :
  - 1200 p,K,π per event
  - 8×10^3 candidates in $m_D \pm 60$ MeV
  - S/B~10^{-7}, enhanced with kinematic and geometric selections

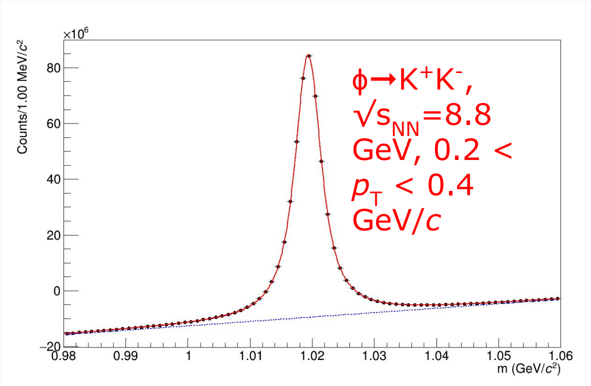
- Measurement for $\Lambda_c \to pK\pi$ more challenging 3-particle decay, S/B~ 10^{-10}
- Alternatively, $\Lambda_c \to pK^0_S$ $K^0_S \to \pi\pi$ (lower BR, lower background)
- Measurement of $D^+_S \to KK\pi$

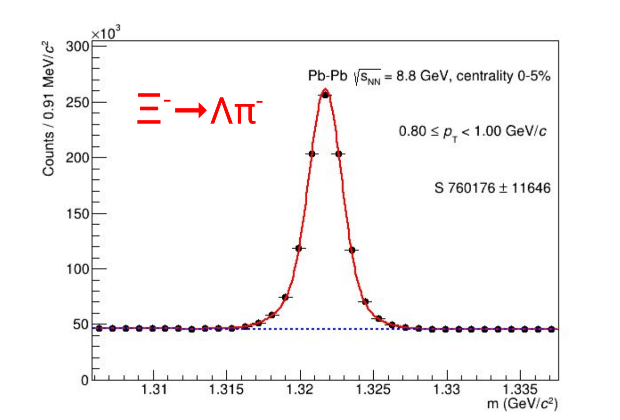
} in progress

Good prospects for a first low-energy measurement of charm in nuclear collisions!

Strangeness simulations

- Hadronic decays of strange particles can be reconstructed in the vertex spectrometer (no PID)

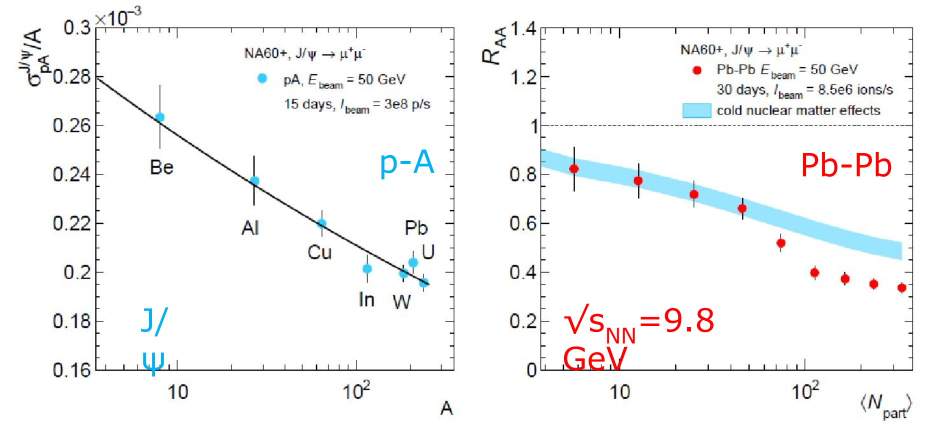




- 0-5% Pb-Pb, $\sqrt{s_{NN}}$= 8.8 GeV :
  - Background and signal from NA49 light hadron production data
  - Analysis performed using Boosted Decision Trees (except for the ϕ)
  - ϕ signal extracted subtracting the background with the event mixing

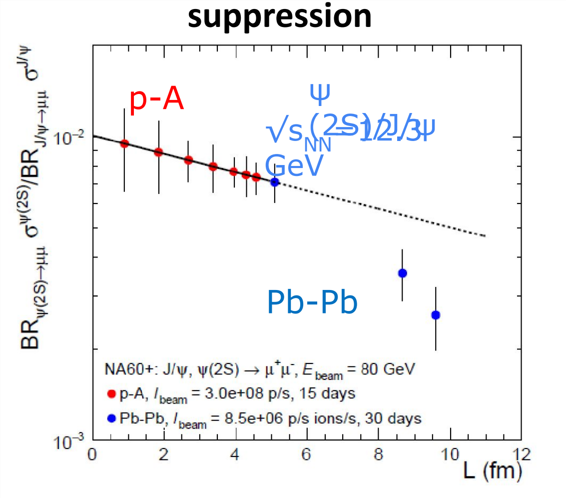
(equivalent to 30 days data taking at 75 kHz)

- K^0_S, Λ^0, ϕ, Ξ^-: very low statistical uncertainties for p_T and rapidity spectra measurements ➞ dominated by the systematic uncertainties
- Ξ^+,Ω : very good prospects
- Improvements respect to the NA49 measurements



- $\psi(2S)$:
  - pA ➞ assume stronger suppression for $\psi(2S)$ relative to J/ψ (as measured by NA50 at $\sqrt{s_{NN}}$=29 GeV)
  - Pb-Pb ➞ simulation assuming factor 2 stronger suppression for $\psi(2S)$

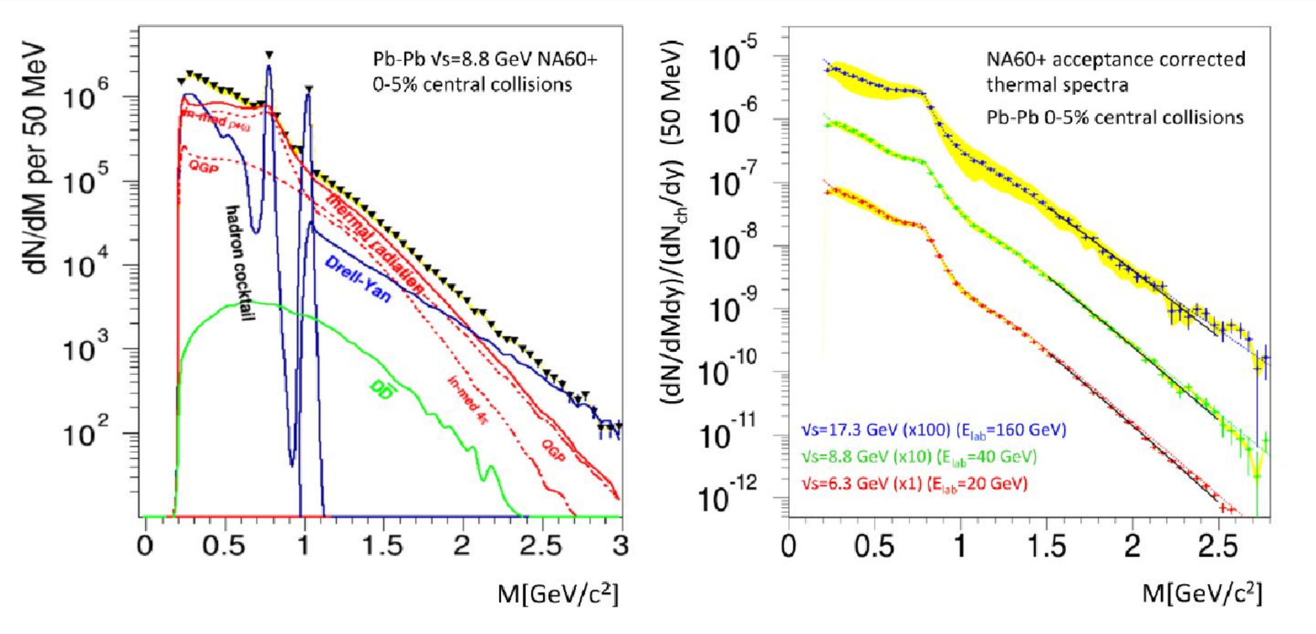
Look for the onset of $\psi(2S)$ suppression



- p-A measurement calibrate CNM effects (assume same effect as measured by NA60 at $\sqrt{s_{NN}}$=17.3 GeV)
- Extrapolate CNM effect to Pb-Pb and compare with a scenario where anomalous suppression sets in at N_{part} ~50 and reaches 20% (was ~30% at $\sqrt{s_{NN}}$=17.3 GeV)
- Assume 30 days of Pb beam and ~10^7 Pb/s

Good sensitivity to J/ψ suppression onset

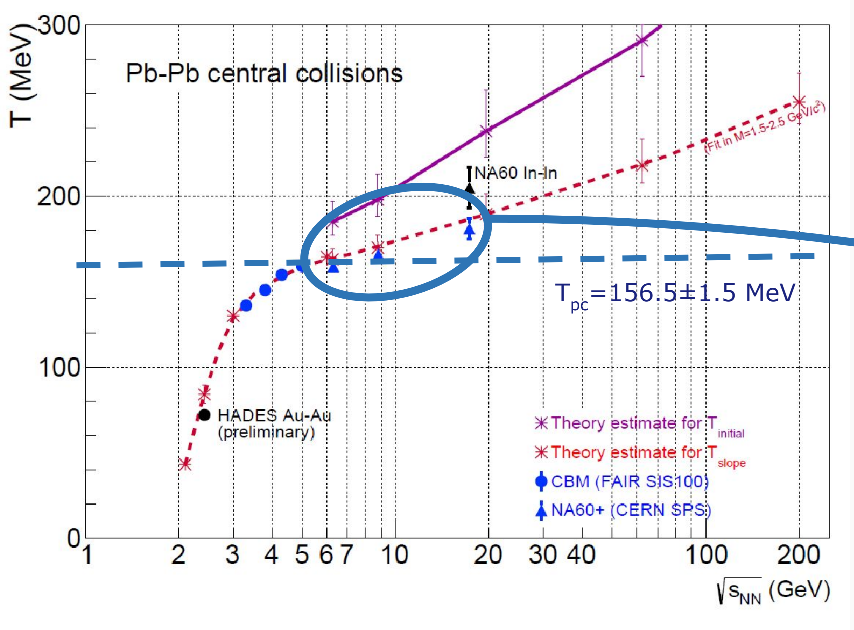
Tslope measurement



- Thermal radiation yield
  - Dominated by ρ contribution at low mass
- Accessible up to M=2.5-3 GeV/c^2
  - Drell-Yan contribution to be also estimated via p-A measurements

- Acceptance-corrected signal spectra fitted with $dN/dM=M^{3/2}\exp(-M/T_s)$ in the interval 1.5<M<2.5 GeV/c^2

Tslope measurement



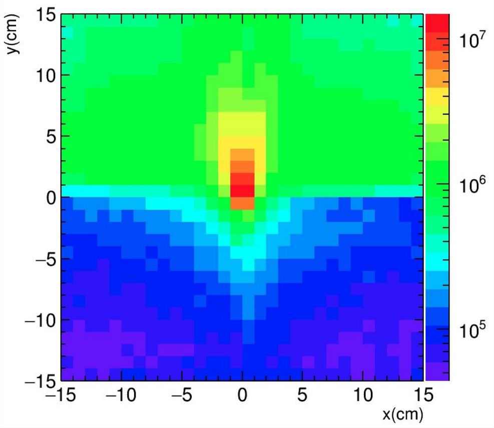
T_{slope} values from thermal yields in 1.5<M<2.5 GeV/c^2

Theory √s>6 GeV, R. Rapp, PLB 753 (2016) 586
√s<6 GeV, T. Galatyuk, EPJA 52 (2016) 131

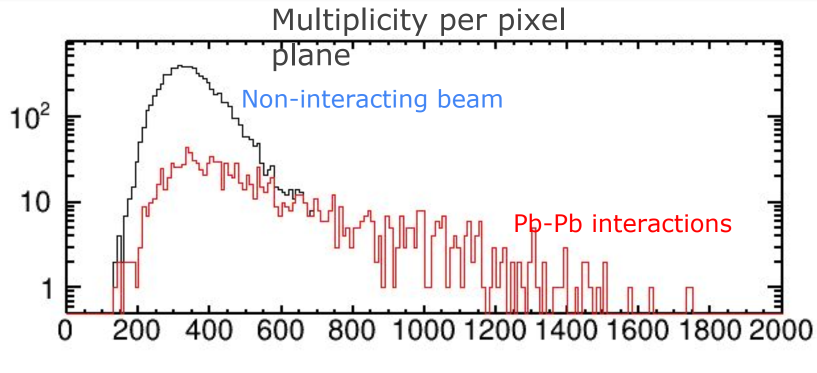
A few MeV accuracy can be reached (1.4 to 5 MeV for $\sqrt{s_{NN}}$ to 6.3 to 17.3 MeV) on T_{slope}

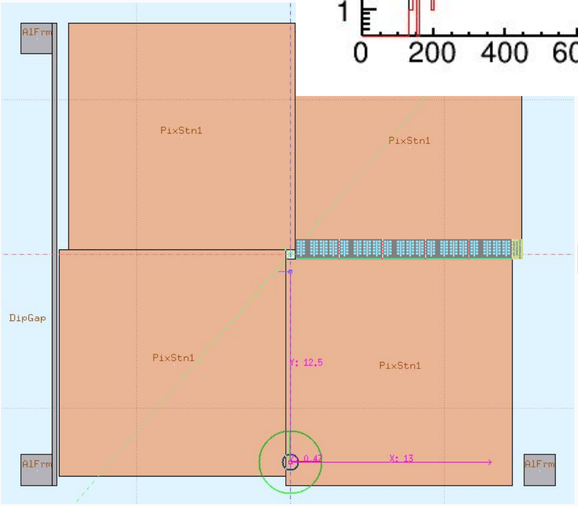
- Accurate mapping of the region where the pseudocritical temperature is reached
- Sensitive to potential effects expected in case of 1st order phase transition

- Based on **FLUKA simulations** implementing a detailed experiment geometry
- 40 A GeV Pb beam on 5 Pb targets, 10^6 Pb/s



Upstream MAPS plane
(7.1 cm from last target)



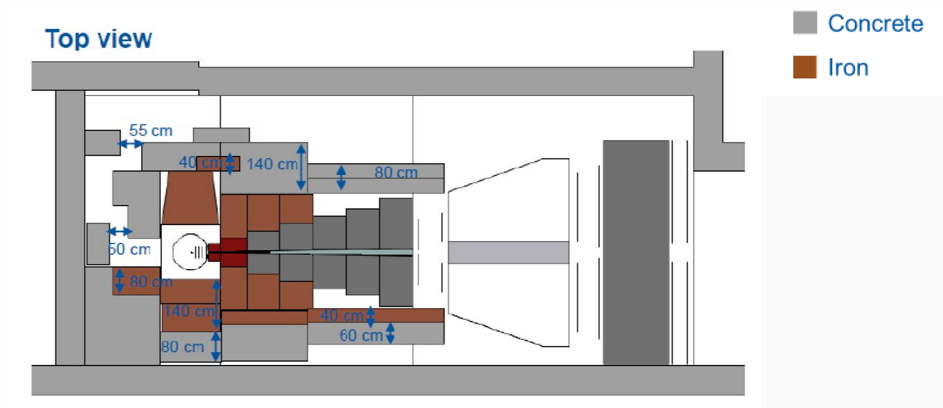


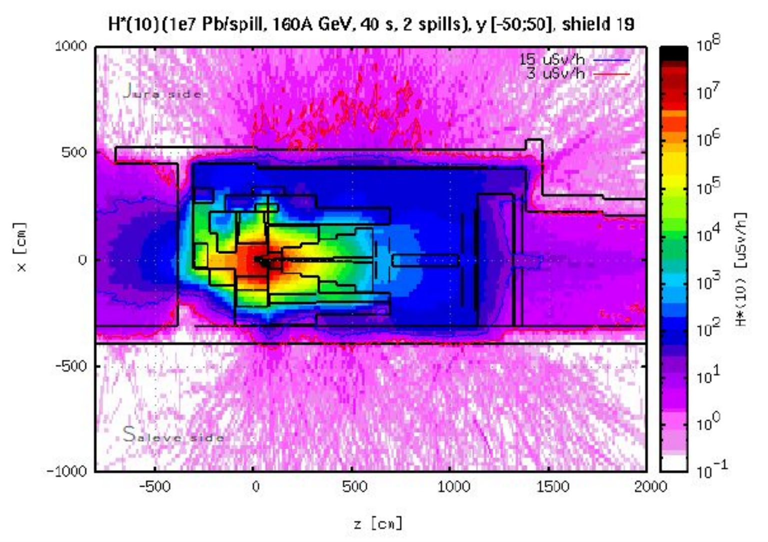
Fluences up to 10^7/s close to the beam axis

Significant contribution from δ-ray production (upward bent by dipole magnet)

Most “exposed” sensors get a 10-15 MHz rate
 20-30 MB/s data throughput

- Studies based on FLUKA geometry of the NA60+ set-up



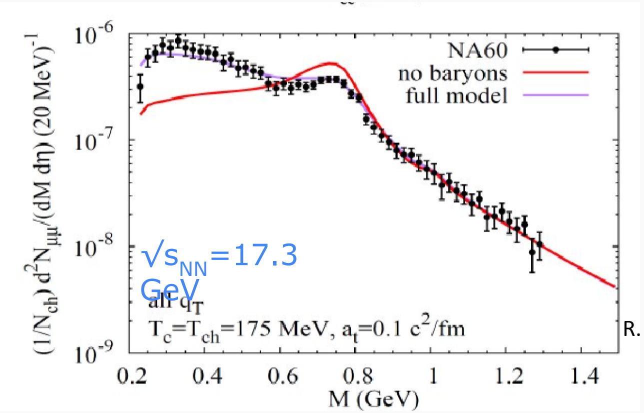


- Installation on a surface zone implies strict requirements on radiation safety
- Dose has to be:
  - <3 µSv/h in permanent workplaces external to the experimental hall
  - <15 µSv/h in low occupancy region ➞ A thick shielding is necessary!

5. Conclusions: Feasibility Evaluation and Cost Estimation

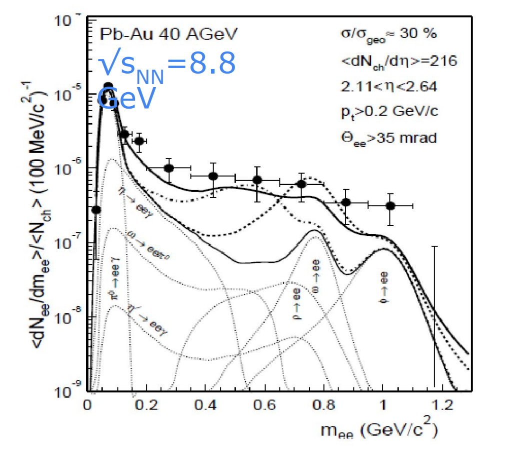
The potential integration of the NA60+ experiment in user zone PPE138 of EHN1 has been examined concerning beam physics requirements (Chapter 2), the infrastructure integration (Chapter 3) and radiation protection (Chapter 4). **The experiment is deemed to be feasible** with regard to these aspects. The aspects of general infrastructure, detector design, data acquisition and analysis as well as the physics reach have not been evaluated.

Dilepton studies at CERN SPS energy



R. Arnaldi et al. (NA60), EPJC 61(2009) 711

- NA60 : low and intermediate-mass dileptons at top SPS energy
- First precision measurement of:
  - in-medium ρ modifications
  - Temperature via thermal dimuons in $1.5<m_{\mu\mu}<2.5$ GeV/c^2



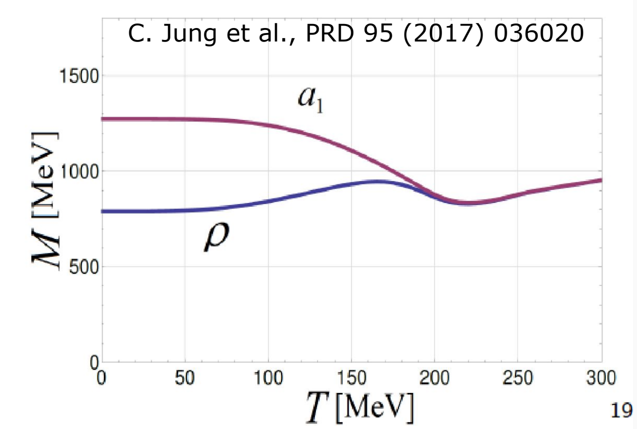
Region below top SPS energy almost unexplored

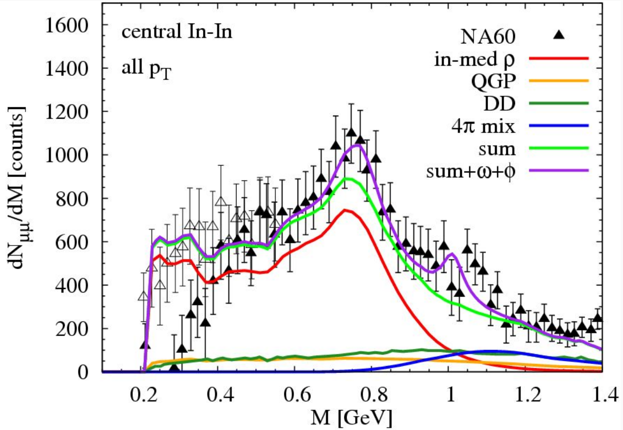
- Only a CERES measurement (low-mass dileptons at $\sqrt{s_{NN}}$=8.8 GeV):
  - **Dielectron excess** (central Pb-Au)
  - Indication (1.8 σ) for excess due to in-medium modifications of ρ spectral function

D. Adamova et al. (CERES), PRL91 (2003)042301

Dilepton spectrum and chiral symmetry restoration

- NA60 observed a broadening of ρ-meson spectral function ➞ qualitatively consistent with chiral symmetry restoration need to investigate the chiral partner a_1





R. Rapp et al., arXiv:0901.3289

- No direct coupling of axial states to the dilepton channel ➞ in vacuum the (e^+e^-➞ hadrons) cross section has a dip in the a_1 mass range
- Chiral symmetry restoration ➞ mixing of vector and axial-vector (A) correlators enhancement of the dilepton rate for $m_{\mu\mu}$~1-1.4 GeV/c^2
- Low-energy measurement expected to be more sensitive to chiral restoration effects:
  - The thermal dimuon yield from QGP becomes smaller
  - Contribution from open charm becomes relatively negligible

NA60+ expression of interest

https://na60plus.ca.infn.it/

Signed by 82 physicists from France, Germany, India, Italy, Japan, Switzerland, USA

The NA60+ Collaboration

M. Agnello[14,16], F. Antinori[12], H. Appelshäuser[2], M. Arba[7], R. Arnaldi[14], R. Bailhache[2], L. Barioglio[17,14], S. Beole[17,14], A. Beraudo[14], F. Bergsma[20], A. Bianchi[17,14], L. Bianchi[17,14], E. Botta[17,14], E. Bruna[14], S. Bufalino[16,14], E. Casula[7,8], F. Catalano[16,14], S. Chattopadhyay[6], A. Chauvin[7], C. Cicalo[7], M. Concas[15,14], P. Cortese[18,14], T. Dahms[4,5,i], A. Dainese[12], A. Das[6], D. Das[6], D. Das[6], I. Das[6], L. Das Bose[6], A. De Falco[7,8], N. De Marco[14], S. Delsanto[17,14], A. Drees[22], L. Fabbietti[5], P. Fecchio[16,14], A. Ferretti[17,14], A. Feliciello[14], M. Gagliardi[17,14], P. Gasik[5], F. Geurts[21], P. Giubilato[12,13], P.A. Giudici[20], V. Greco[9], F. Grosa[16,14], H. Hansen[1], J. Klein[14], W. Li[21], M.P. Lombardo[11] D. Marras[7], M. Masera[17,14], A. Masoni[7], P. Mereu[14], L. Micheletti[17,14], A. Mulliri[7,8], L. Musa[20], M. Nardi[14], H. Onishi[19], C. Oppedisano[14], B. Paul[7,8], S. Plumari[10], F. Prino[14], M. Puccio[17,14], L. Ramello[18,14], R. Rapp[23], I. Ravasenga[16,14], A. Rossi[12,13], P. Roy[6], B. Schmidt[20], E. Scomparin[14,i], S. Siddhanta[7], R. Shahoyan[20], T. Sinha[6], M. Sitta[18,14], H. Specht[3], S. Trogolo[17,14], R. Turrisi[12], M. Tuveri[7], A. Uras[1], G. Usai[7,8,i,ii], E. Vercellin[17,14], J. Wiechula[2], S. Winkler[5]

- Observables
- Requirements
- Experimental layout
- Detectors
- Physics performances
- Competition with other measurements

http://cds.cern.ch/record/2673280

CERN-SPSC-2019-017 / SPSC-EOI-019
03/05/2019

Expression of Interest for a new experiment at the CERN SPS: NA60+

NA60+ Collaboration

Abstract

The exploration of the phase diagram of Quantum ChromoDynamics (QCD) is carried out by studying ultrarelativistic heavy-ion collisions. The energy range covered by the CERN SPS ($\sqrt{s_{NN}} \sim$ 5–17 GeV) is ideal for the investigation of the region of the phase diagram corresponding to finite baryochemical potential (μ_B), and has been little explored up to now. In this Expression of Interest, we describe the physics motivations and the exploratory studies for a new experiment, NA60+, that would address several observables which are fundamental for the understanding of the phase transition between hadronic matter and a Quark–Gluon Plasma (QGP) at SPS energies. In particular, we propose to study, as a function of the collision energy, the production of thermal dimuons from the created system, from which one would obtain a caloric curve of the QCD phase diagram that is sensitive to the order of the phase transition. In addition, the measurement of a ρ–a_1 mixing contribution would provide crucial insights into the restoration of the chiral symmetry of QCD. In parallel, studies of heavy quark and quarkonium production would also be carried out, providing sensitivity for transport properties of the QGP and the investigation of the onset of the deconfinement transition. The document defines an experimental set-up which couples a vertex telescope based on monolithic active pixel sensors (MAPS) to a muon spectrometer with tracking (GEM) and triggering (RPC) detectors within a large acceptance toroidal magnet. Results of physics performance studies for most observables accessible to NA60+ are discussed, showing that the results of the experiment would lead to a significant advance of our understanding of (non-perturbative) strong interaction physics. It is also shown that beam intensities of the order of 10^7 lead ions/s are required in order to obtain meaningful results on the various physics topics. Such intensities can presently be reached only in the ECN3 underground hall of the SPS. In addition, the support and engagement of CERN for the development, construction and operation of the toroidal magnet is considered crucial for the success of the project.

May 3, 2019