NA60+ overview

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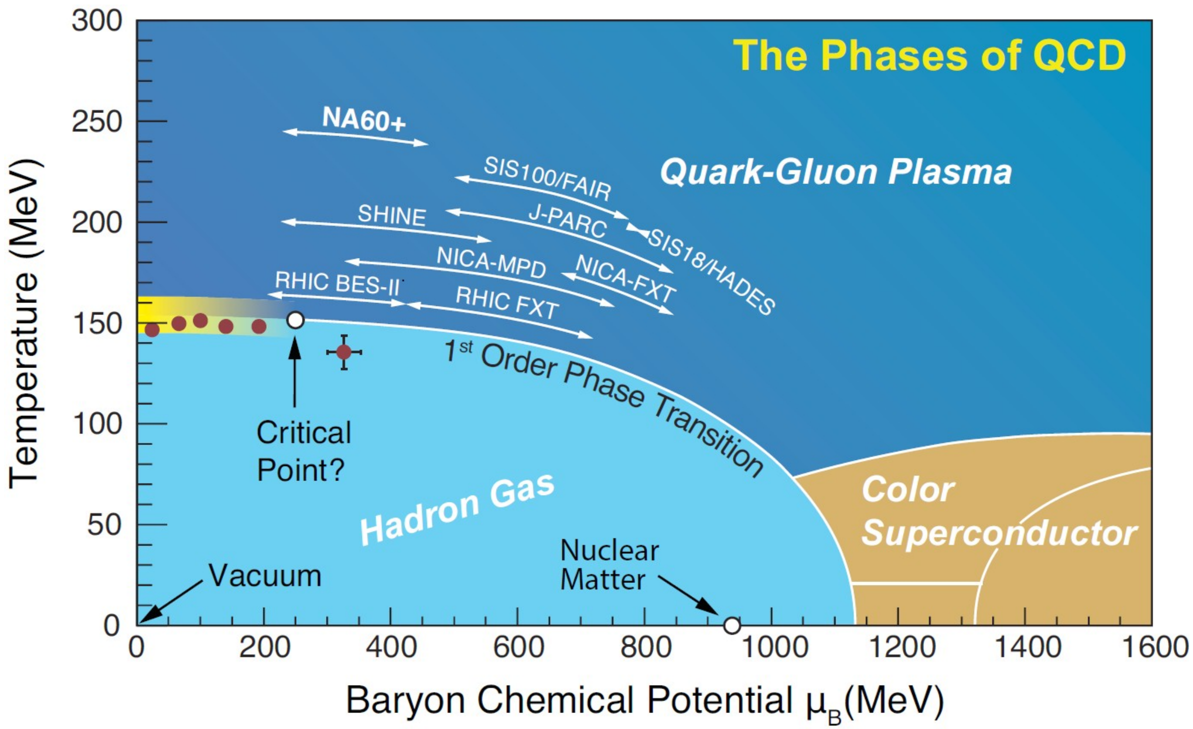
for the NA60+ Collaboration

Exploring high-μ_B matter with rare probes
Trento, 11-15 / 10 / 2021

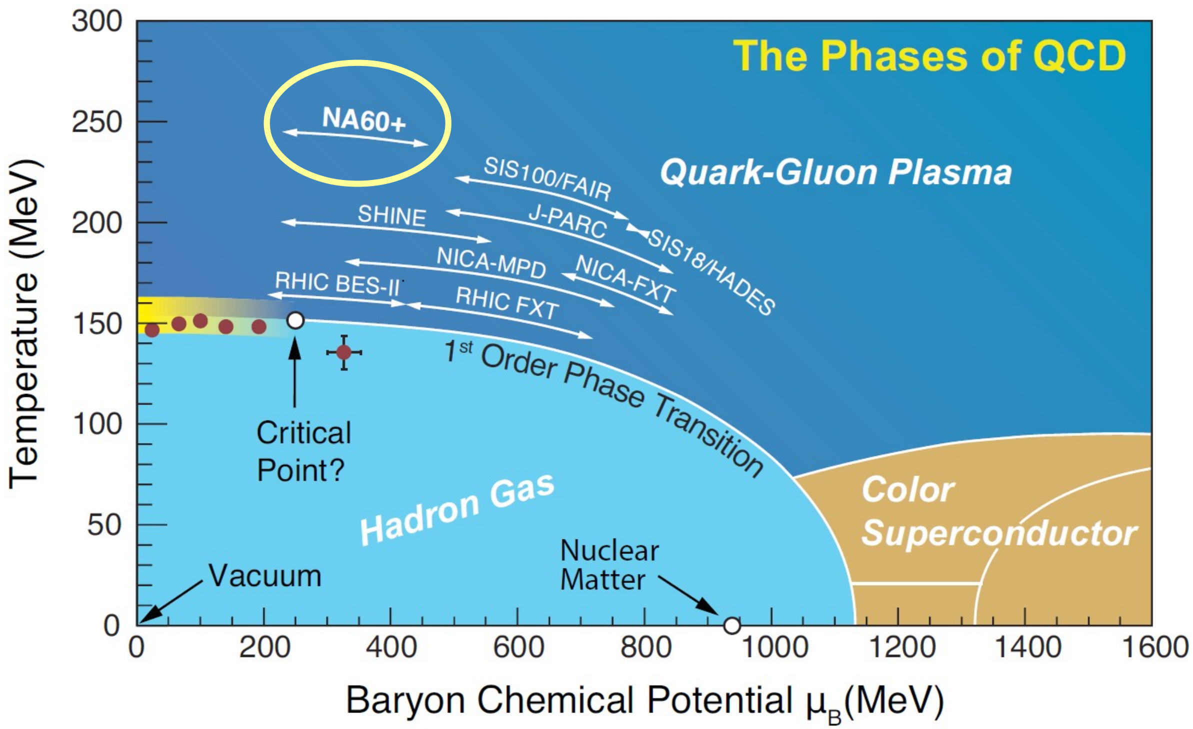
Exploring the QCD phase diagram at large μ_B

- Heavy ion collisions at low $\sqrt{s}$: probe the QCD phase diagram at large μ_B
  - Search for the critical point
  - Establish if the phase transition is of first order at large μ_B
  - Search for chiral symmetry restoration effects
  - Search for the onset of deconfinement
  - Study the properties of the QGP at large μ_B



The goal of the NA60+ experiment

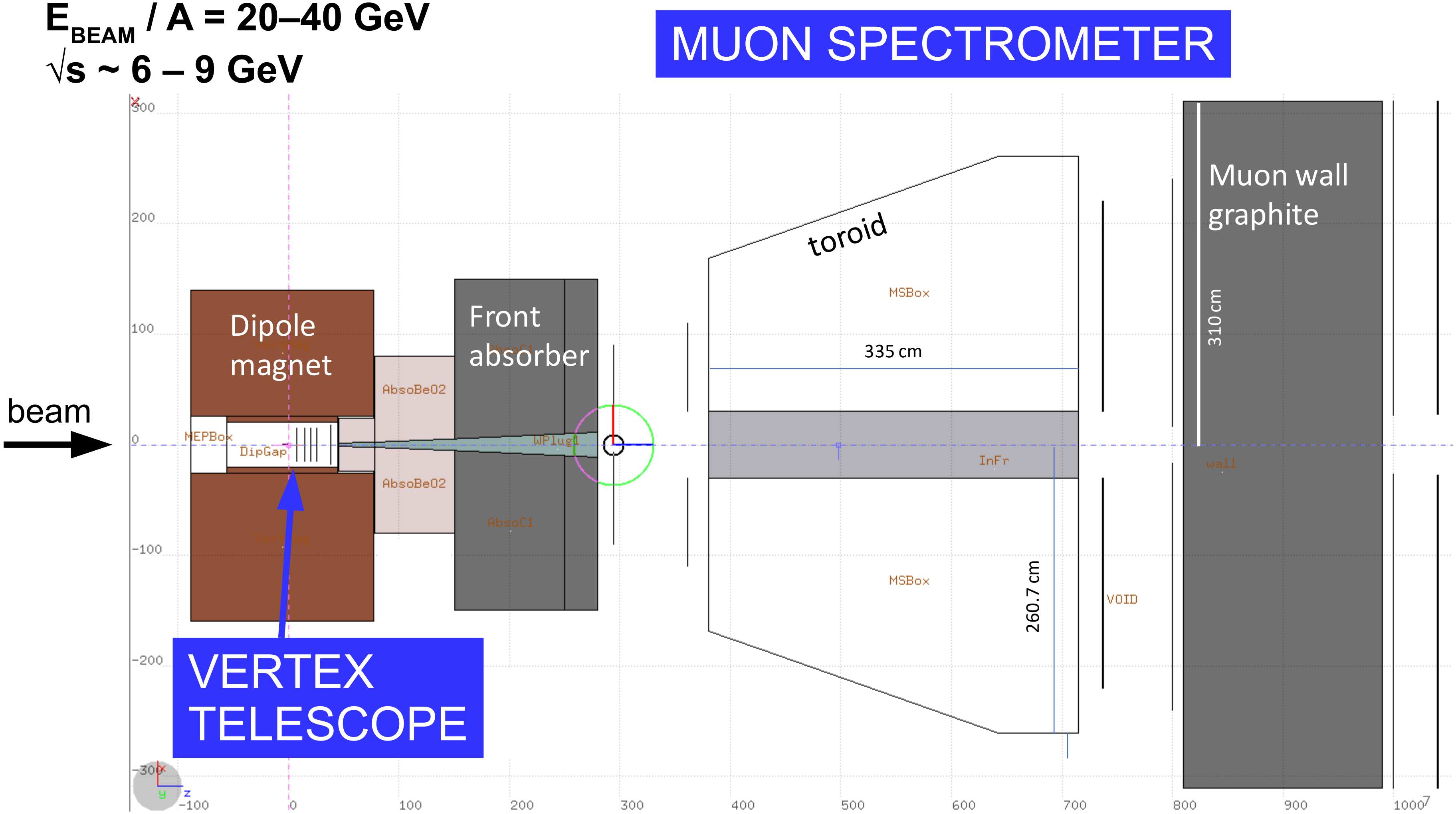
- Investigate the large μ_B region of the QCD phase diagram through the study of hard and electromagnetic probes at the CERN SPS
  - Hard probes: onset of deconfinement, transport properties of the medium
  - E.M. probes: insights on
    - temperature of the system
    - chiral symmetry restoration
    - order of the phase transition



The NA60+ detector at low energy

- Detecor concept: muon spectrometer → dimuon measurements + vertex telescope → reconstruct tracks close to the IP
- Setup changes with beam energy to cover the region around midrapidity

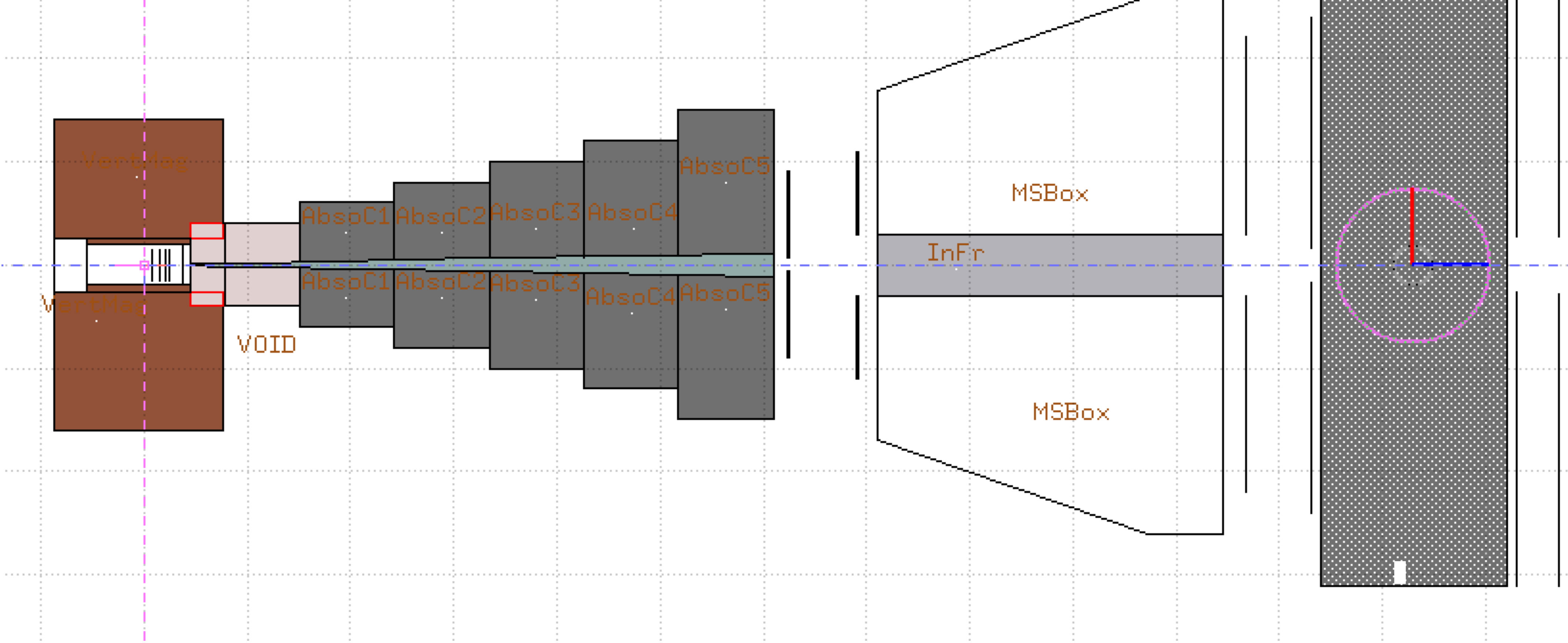
Low-energy setup
E_{BEAM} / A = 20–40 GeV
$\sqrt{s}$ ~ 6 – 9 GeV



The NA60+ detector at high energy

- Muon spectrometer will be moved on rails by 3.3 m in the high energy setup
- Thicker front absorber (4.6 m thick graphite)

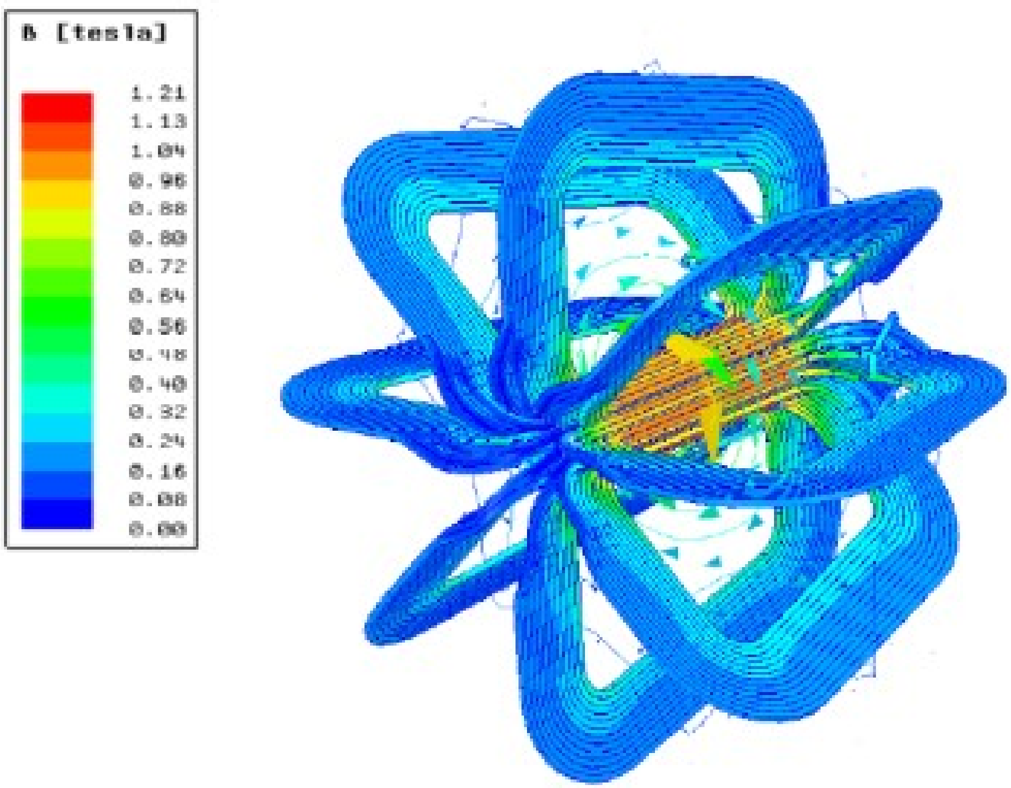
High-energy setup
E_{BEAM} / A = 160 GeV
$\sqrt{s}$ ~ 17 GeV



Muon spectrometer: toroidal magnet

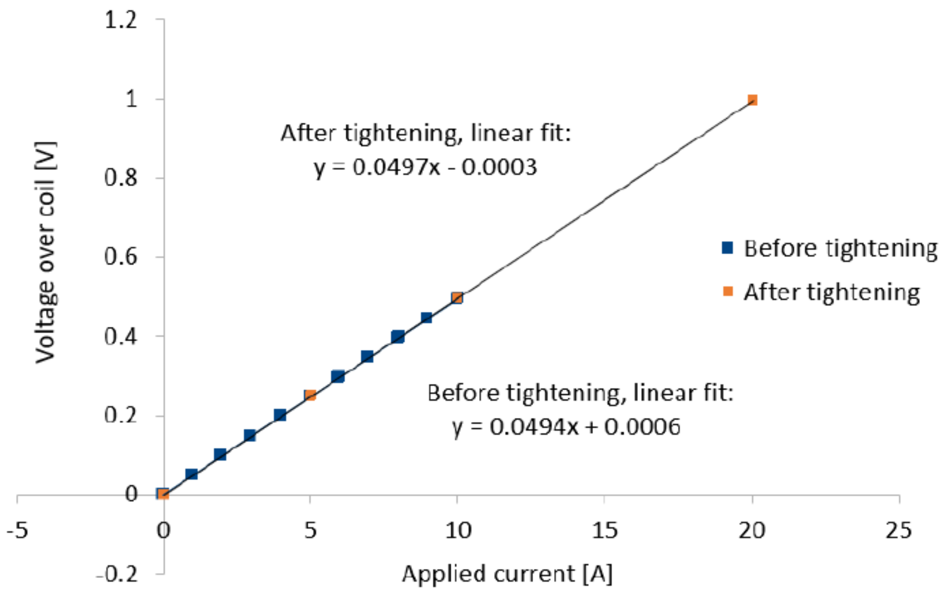
- Collaboration with CERN EP-DT for the design of a new toroidal magnet
- Preliminary characterization (Electrical properties, Cooling, Forces)
- Construction of a small-scale prototype (INFN+CERN)

$$B \cdot R \sim 0.2 - 0.5\,\mathrm{Tm}$$



Toroidal magnet: status

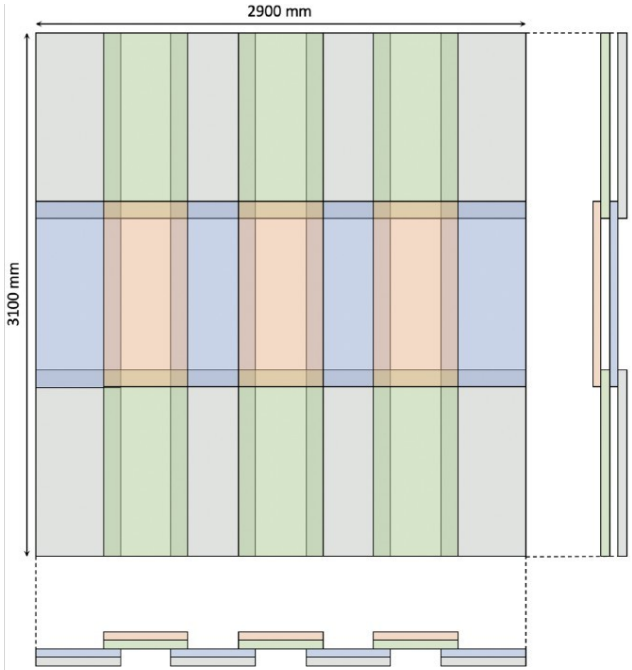
- Completion of the prototype construction (scale 1:5)
- First tests carried out (low current)
- Discussion on choices for full scale object started



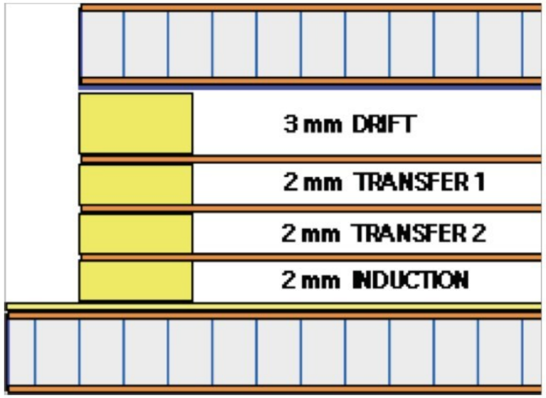
- Resistances:
  - All coil resistances = (6.110 ± 0.023) mΩ
  - All busbar resistances = (0.0375 ± 0.0044) mΩ
  - Joints = (0.073 ± 0.072) mΩ

Muon Spectrometer: tracking chambers

- Tracking stations based on GEM modules
  - ~ 330 modules,each 50 x 110 cm^2 → 130 m^2
  - One tracking layer per station
  - Overlap of ~ 10 cm in both coordinates



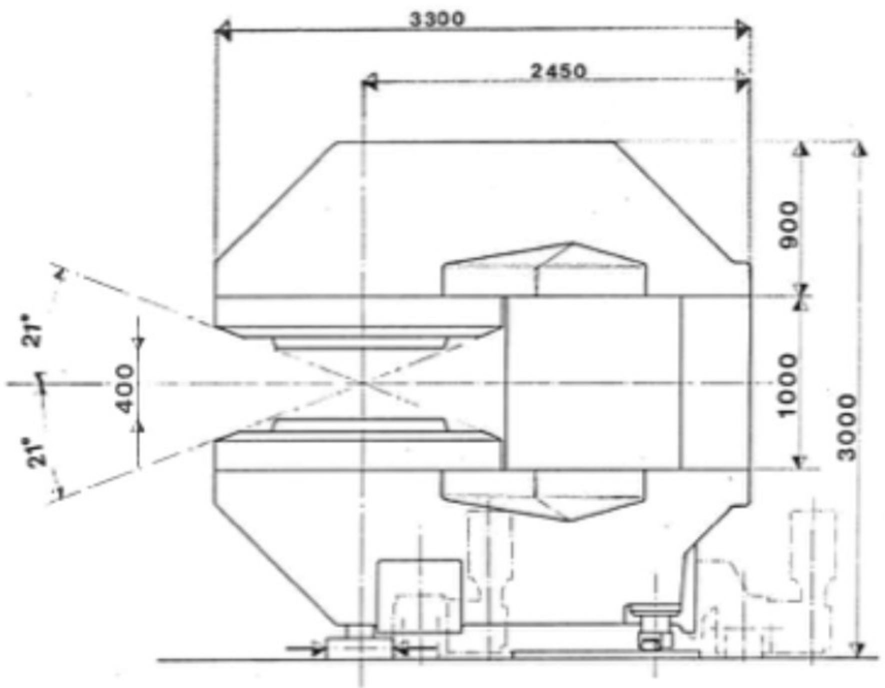
- Design: triple GEM chambers
  - Profit from experience in LHC experiments (ALICE, CMS)
  - 2D-strip readout
  - Resolution ~200 μm

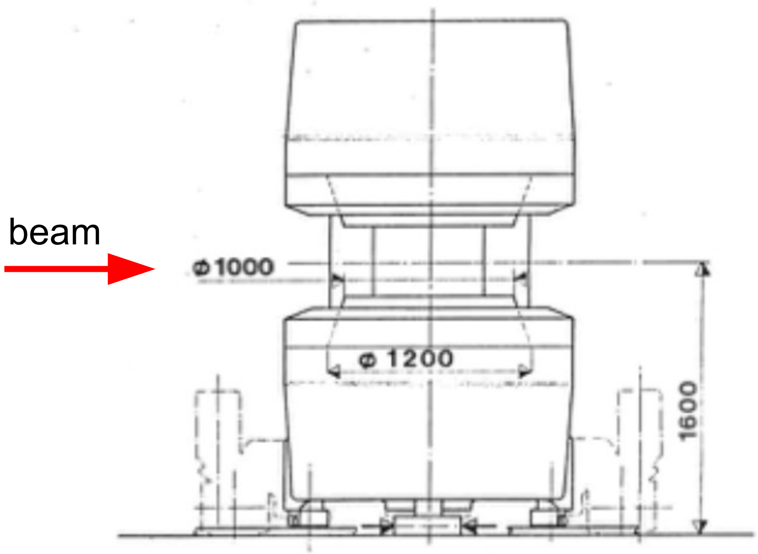


- Big effort: collaboration needs to be strenghtened

The vertex telescope: dipole magnet

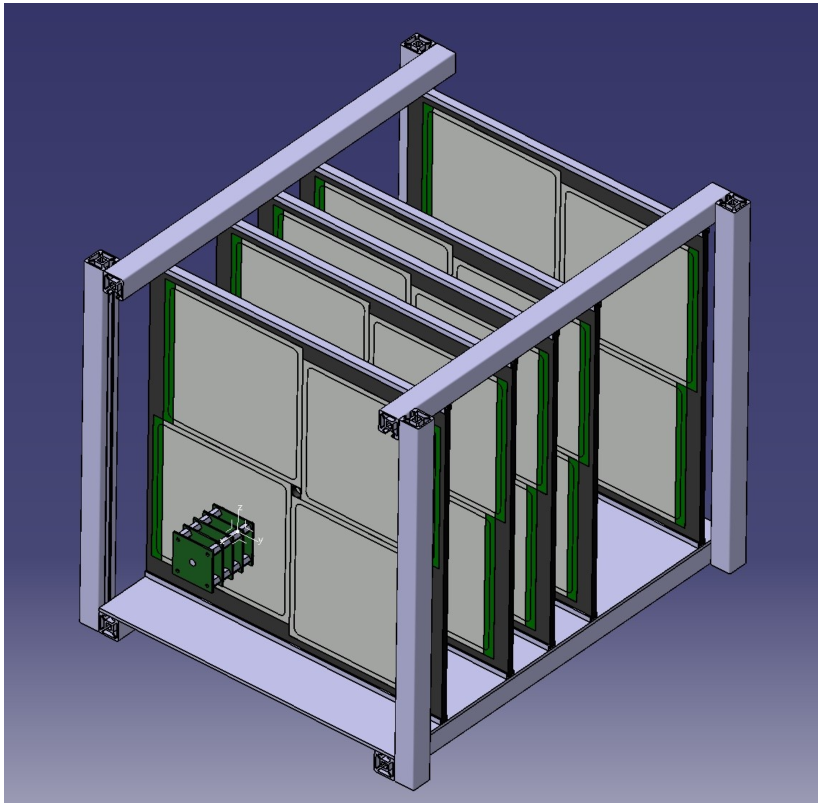
- CERN MEP48 dipole magnet
- B = 1.47 T at max current
- Up to 21^0 polar angle coverage

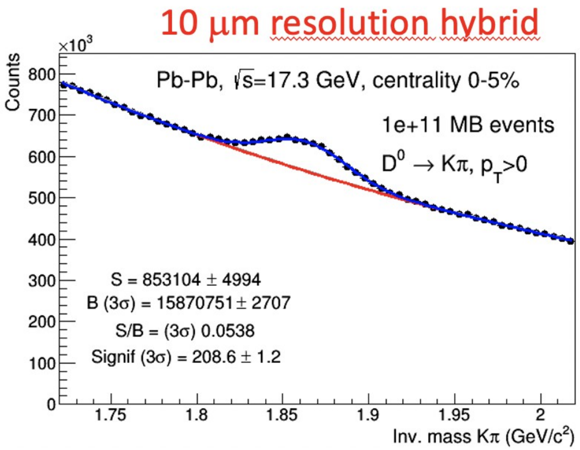


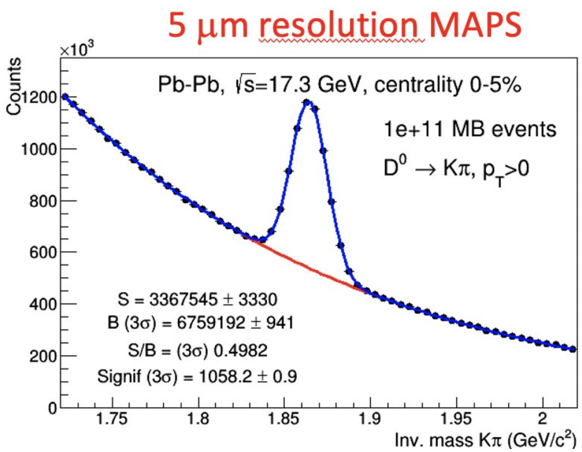


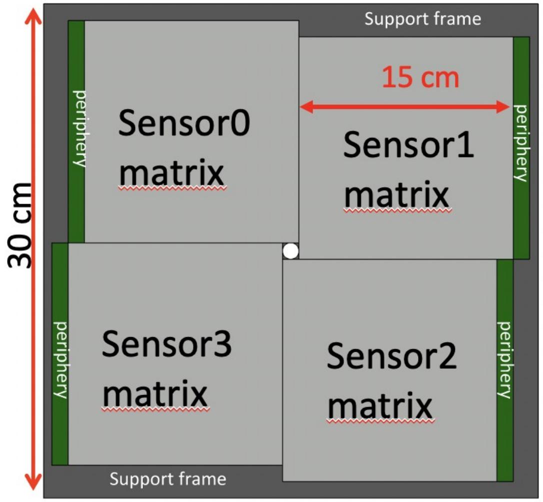
The silicon vertex telescope

- 5 to 10 silicon stations
- Large area MAPS with stitching technology
- Thickness: O(20 μm)
- Pixel size: O(15 x 15 μm^2)
- No mechanical support/cooling in the sensitive area → material budget < 0.1% X_0
- Spatial resolution: 5μm or better



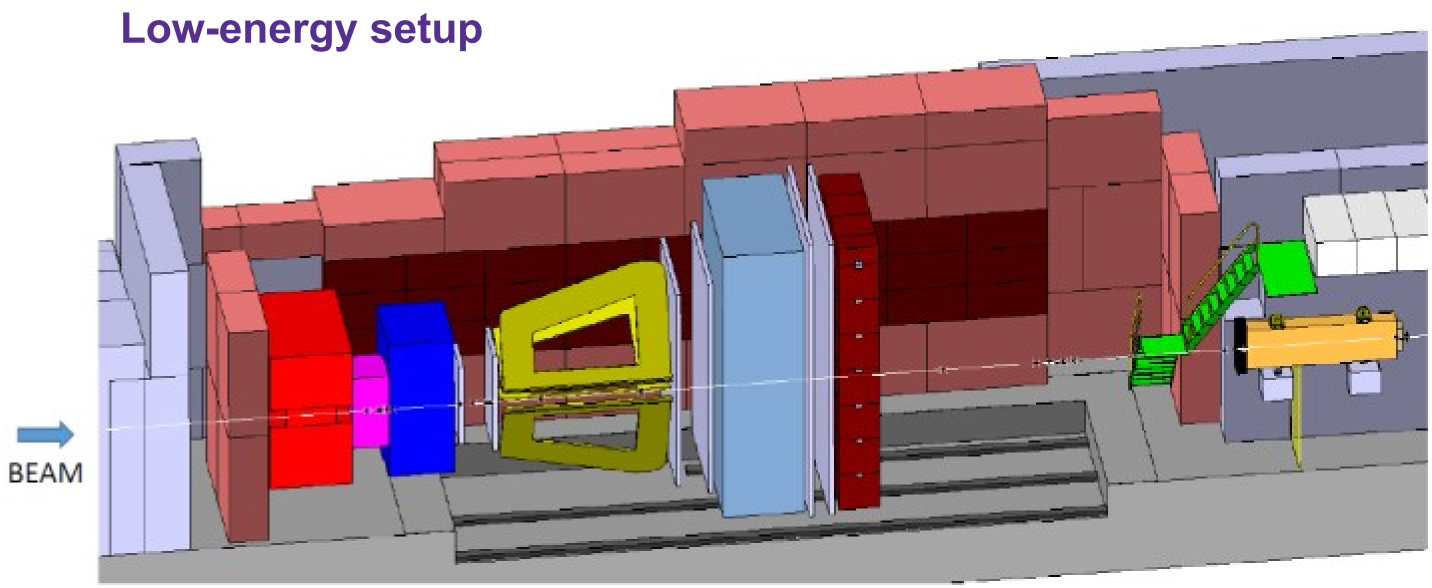


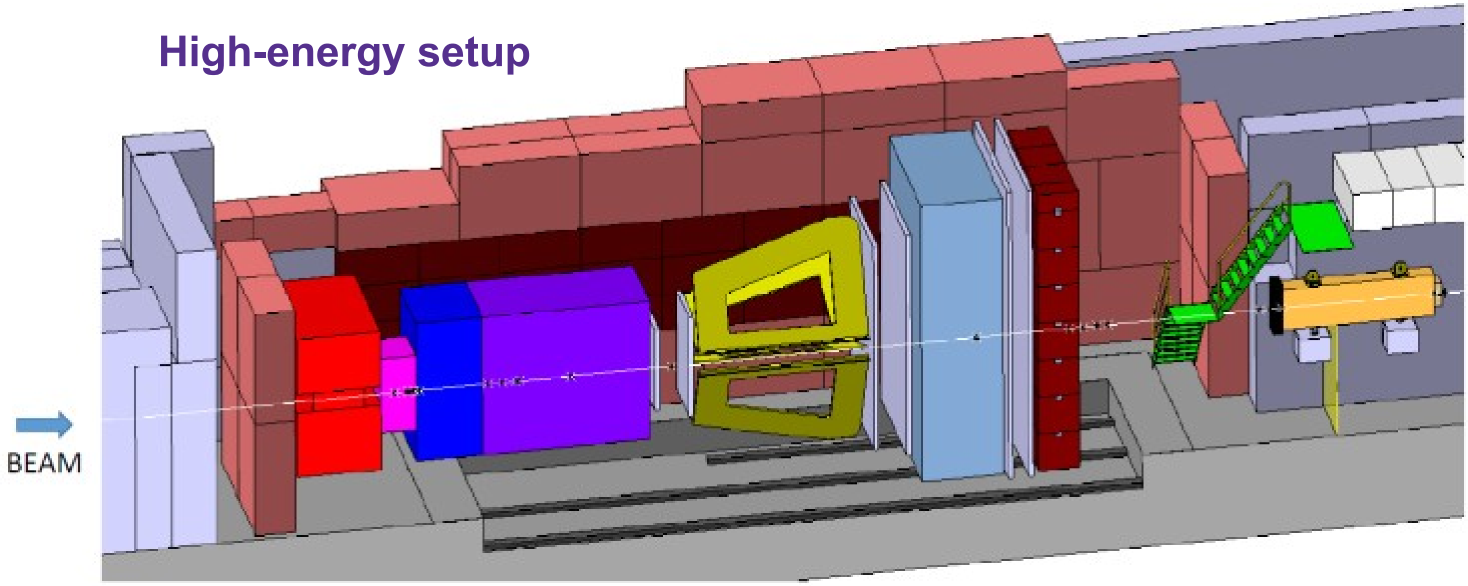




Integration at the CERN North Area

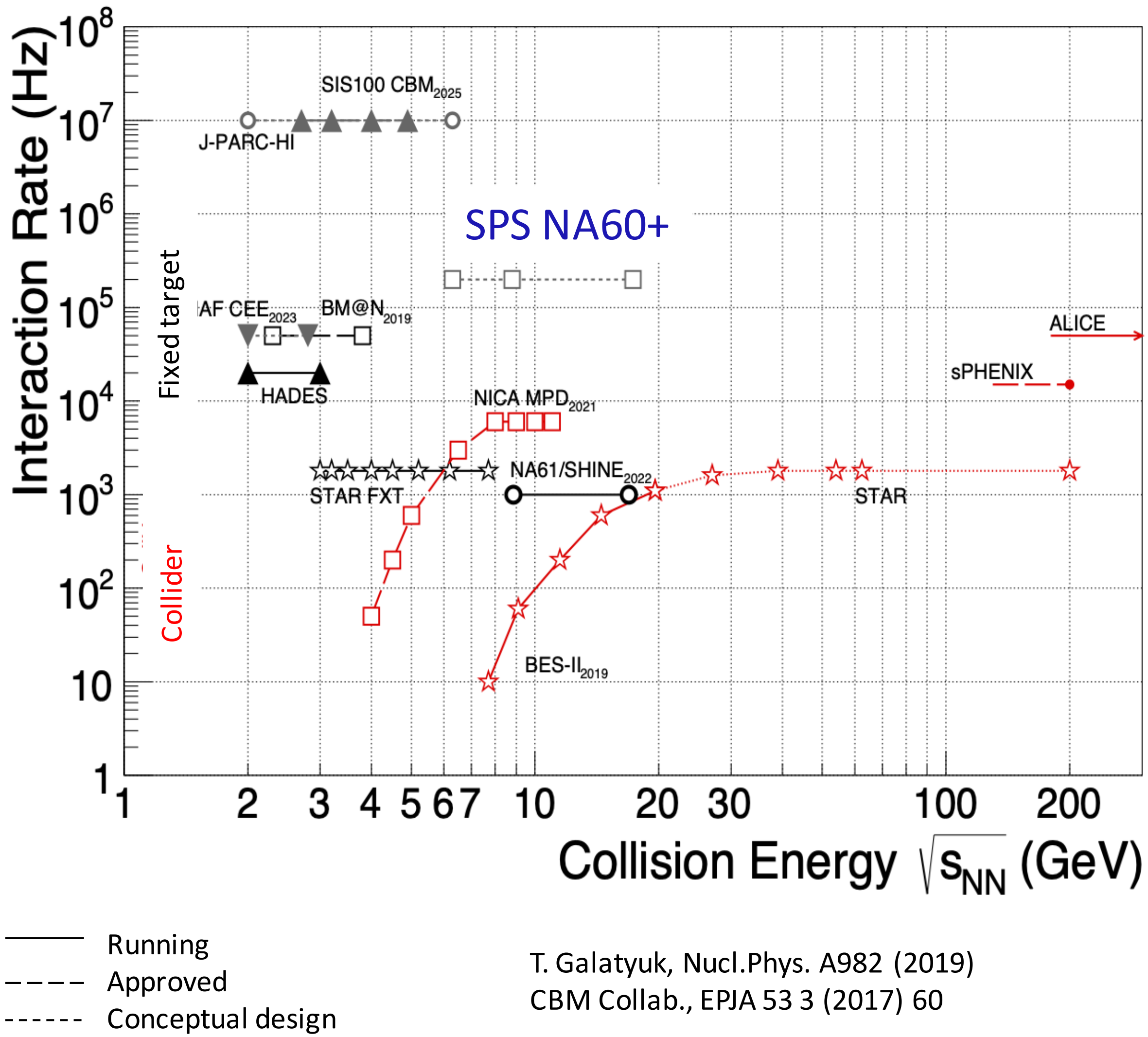
- Installation foreseen at the CERN-SPS, EHN1 hall, H8 beam line
- Intensity: 10^7 Pb ions/20 s spill (radioprotection studies ongoing)
- High energy: muon spectrometer shifted by 3.3 m
- Goal: start data taking with LHC run 4, in 2027





Statistics reach

- Very significant statistics at each energy
  - Thermal dimuons: 10^7 etvs (~20 times NA60)
  - J/ψ: $O(10^4)$ (energy down to E_{lab}=50 GeV)
  - D^0: ~ 3 10^6, central evts, highest energy (factor 10 lower at low energy)
  - Run time: 1 month per energy
  - 10 times (or more) higher interaction rate wrt other experiments in the same μ_B range
  - Complementary to CBM

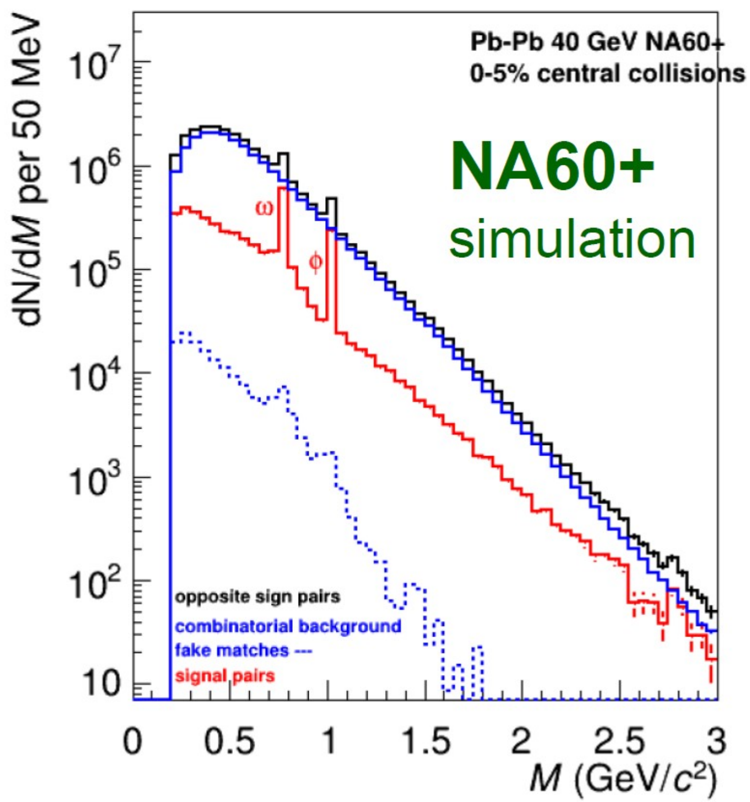


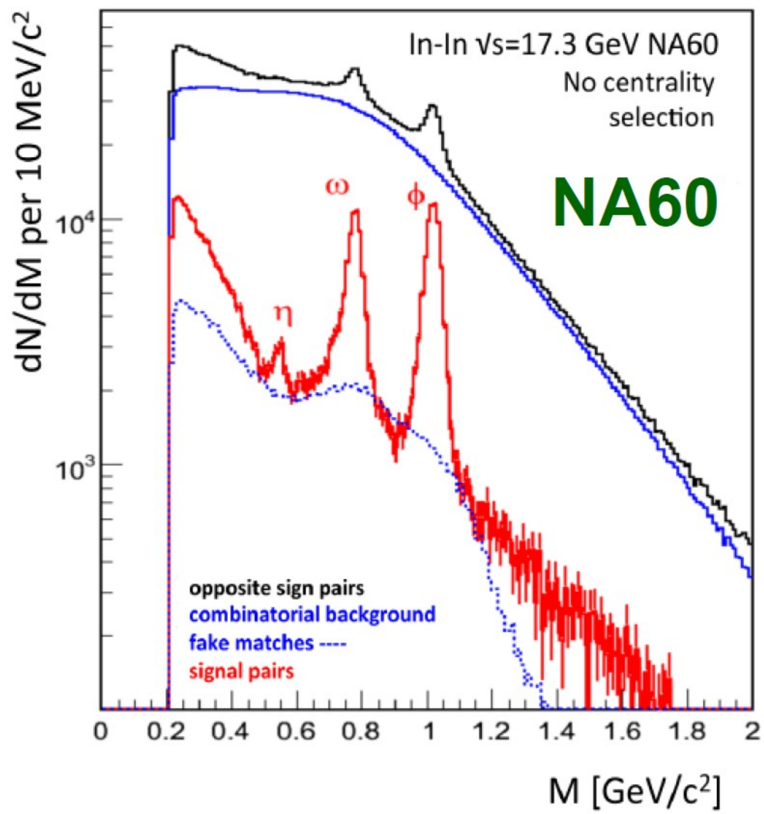
T. Galatyuk, Nucl.Phys. A982 (2019)
CBM Collab., EPJA 53 3 (2017) 60

Dimuon measurements

Dimuon simulation

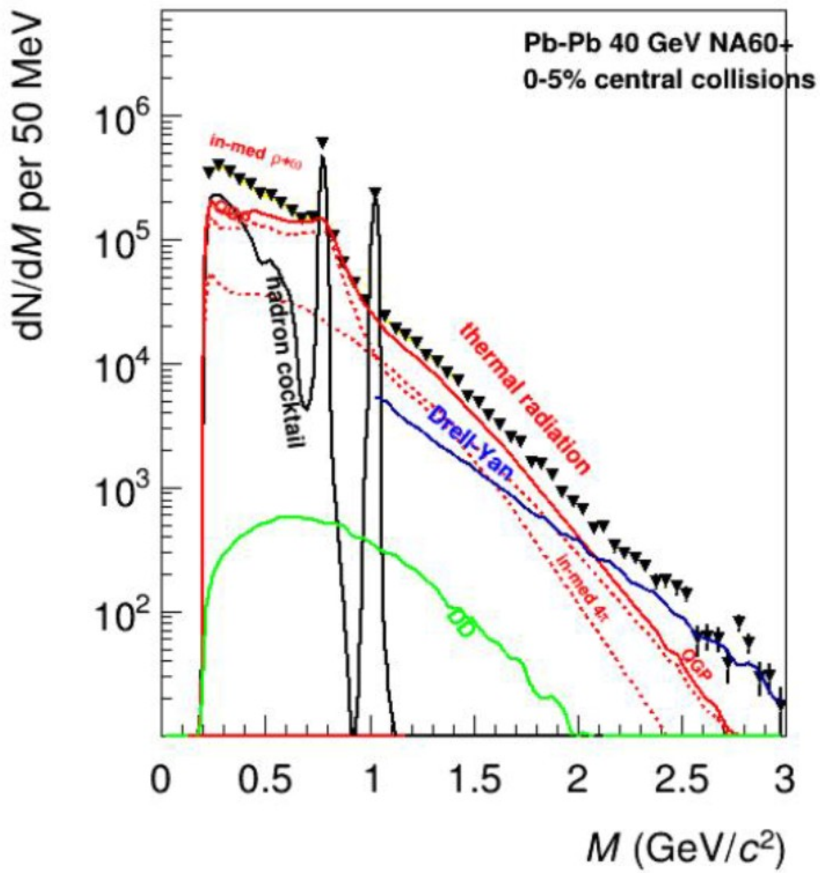
- Signal: fast simulation with semi-analytical tracking (Kalman filter)
- Background: FLUKA
- Matching between muon tracks reconstructed in the muon spectrometer and tracks in the vertex telescope
- Mass resolution: ~7 MeV at the ω, 30 MeV at the J/ψ
- Combinatorial background and fake matches to be subtracted





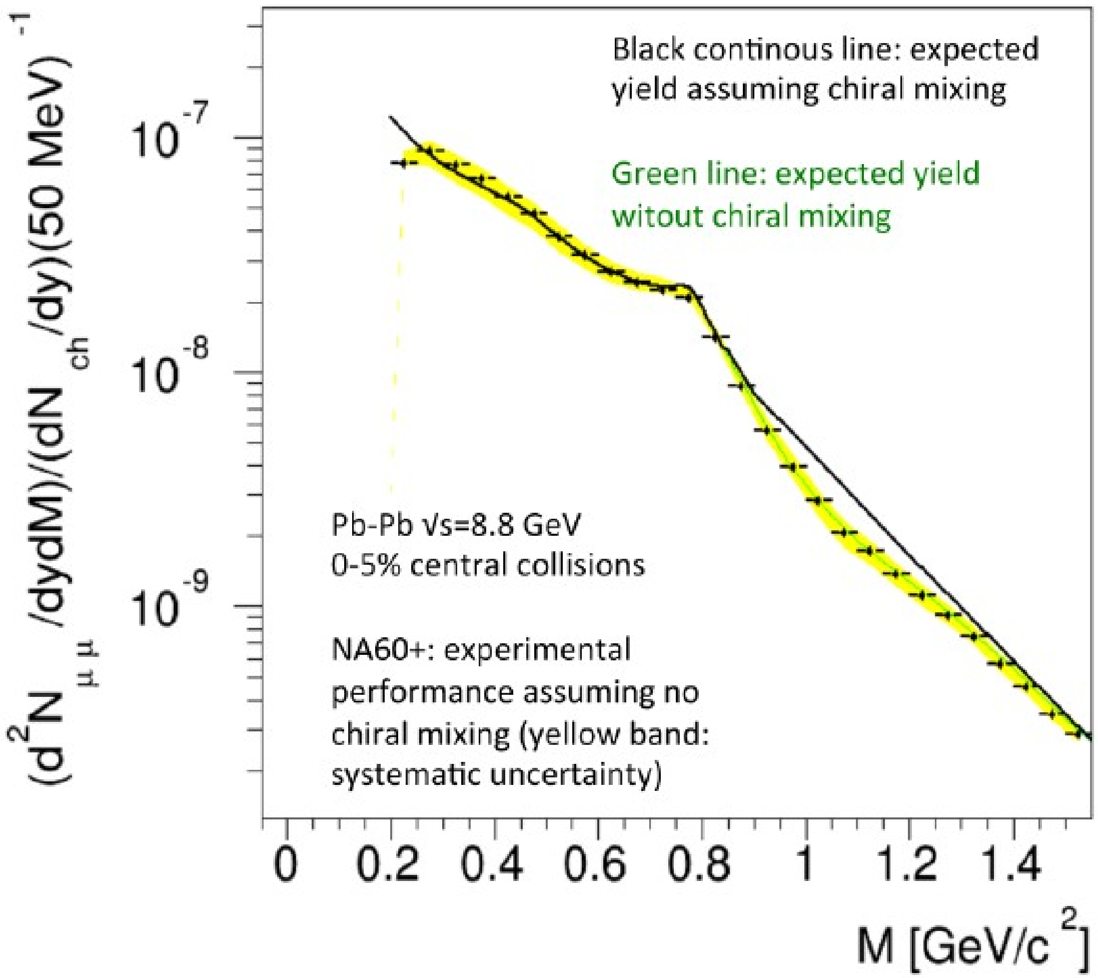
Low and intermediate mass dimuons

- Low mass dimuons (M<1.5 GeV/c^2) dominated by the hadronic cocktail
- Precision measurements of ρ spectral function



ρ-a_1 mixing: expected performances

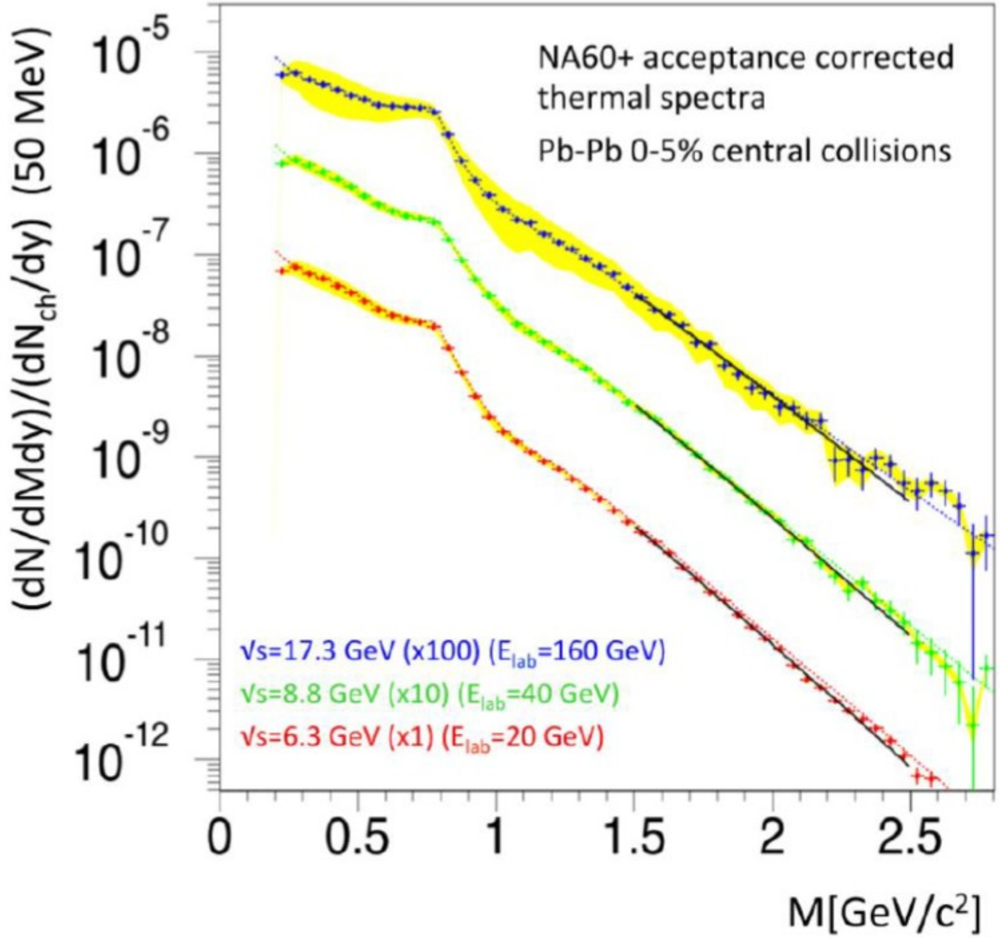
- Chiral mixing ρ-a_1 via 4π states
- Dimuon enhancement in $1<M<1.5$ GeV/c^2
- 20-30% enhancement expected in case of full mixing



Low and intermediate mass dimuons

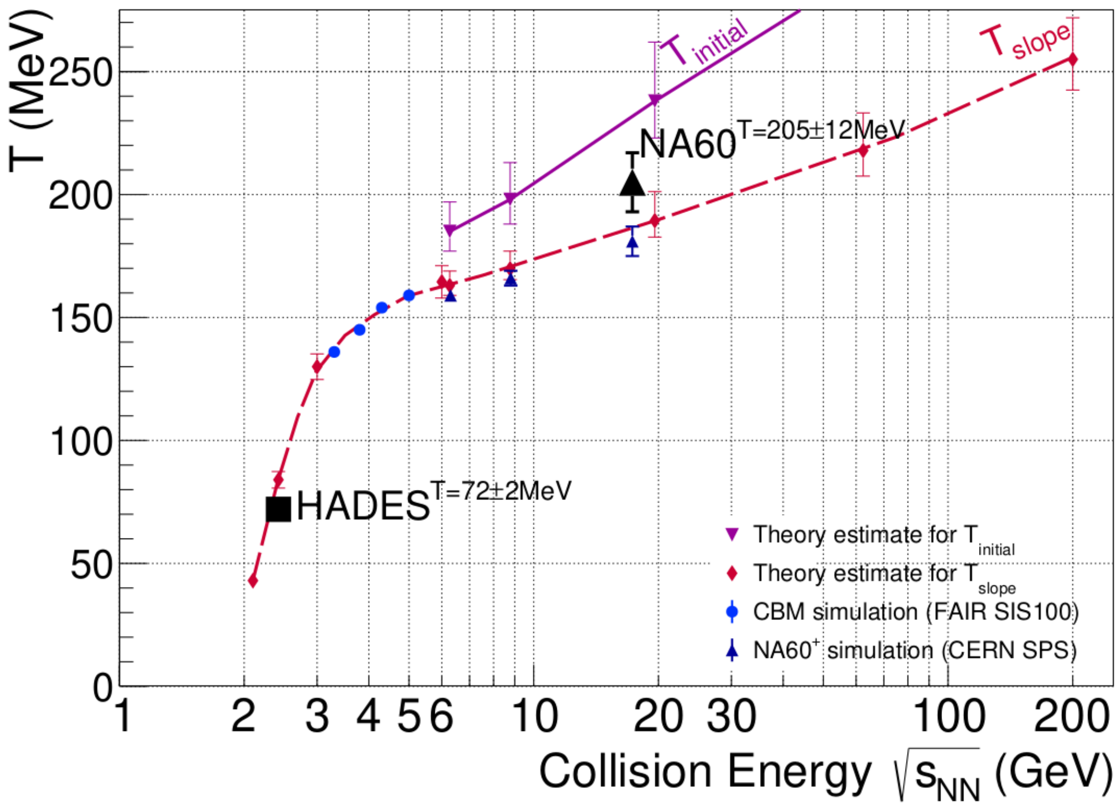
- For M > 2 GeV/c², thermal dimuons (after DY and open charm subtraction)
- T measured within few MeV via a fit to the mass spectrum

$$dN/dM \propto M^{-3/2} e^{-M/T_{slope}}$$



Caloric curve

- T_{slope} from the fit: space-time average over the fireball evolution
- Dimuon T_{slope} close to initial temperature
- Flattening of the caloric curve expected for first order transition in the region where the pseudocritical temperature is reached
- Strong sensitivity to this flattening
- Complementary to future measurements at FAIR



Compilation T. Galatyuk,
Quark Matter 2018

NA60, EPJC 61 (2009) 711

HADES, Nature Phys. 15 (2019) 1040

$\sqrt{s_{NN}} > 6$ GeV
R. Rapp and H. v. Hess,
PLB 753 (2016) 586

$\sqrt{s_{NN}} < 6$ GeV
T. Galatyuk et al., EPJA 52 (2016) 131

Hard probes and strangeness

- J/ψ suppression: covered in the talk by Roberta Arnaldi
- Open charm and strangeness: covered in the talk by Francesco Prino

Summary

- NA60+ can carry out precision measurements at large μ_B on
  - low mass dimuons
  - charmonia
  - open charm
- Strong physics case for beam energy scan
- Expression of Interest submitted in May 2019
  (82 physicists from France, Germany, India, Italy, Japan, Switzerland,USA)
- Letter of Intent under preparation
- Expression of Interest: http://cds.cern.ch/record/2673280

The NA60+ Collaboration

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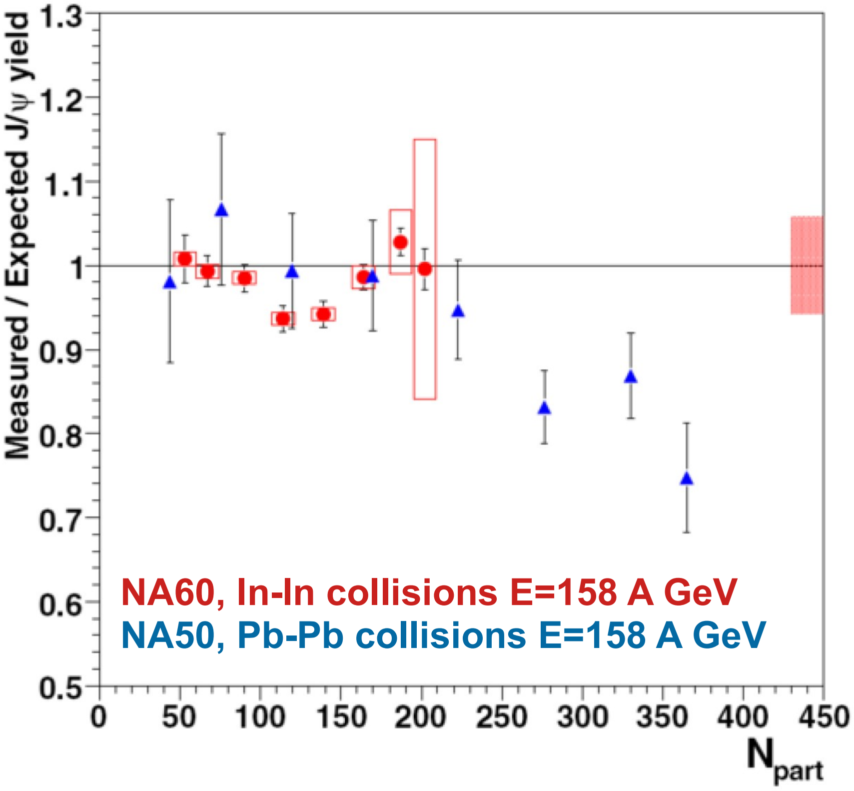
Backup slides

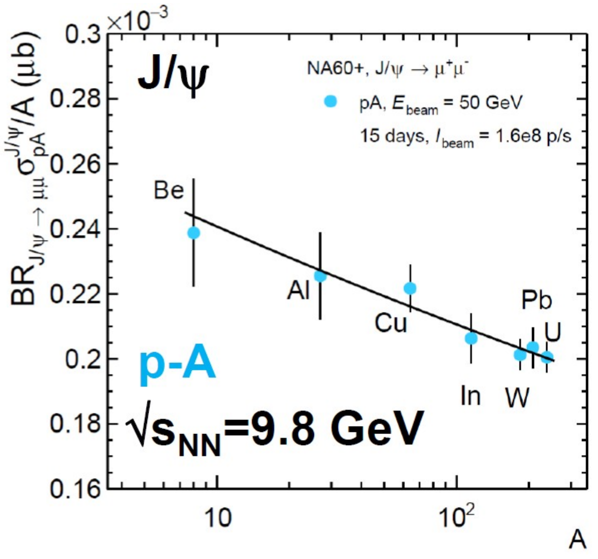
J/ψ suppression

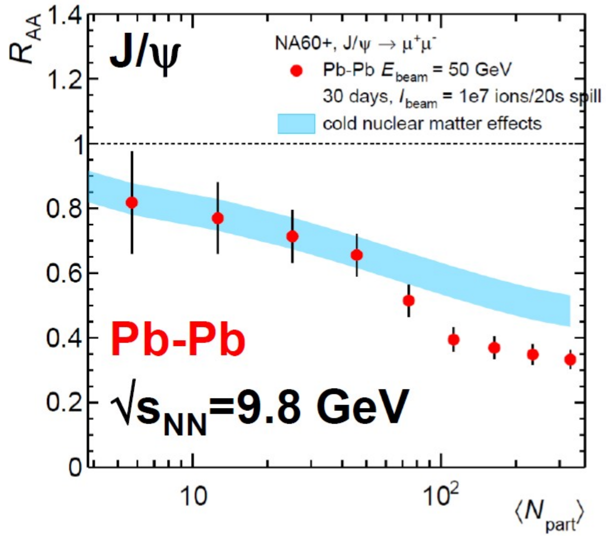
- SPS measurements: J/ψ suppressed by up to 30% wrt CNM
- Qualitatively consistent with χ_c and ψ(2S) melting in a deconfined medium
- NA60+ target: extend measurements to lower energy
  - Search for the onset of deconfinement
  - Correlate with temperature obtained from thermal dimuons
  - Measure χ_c and ψ(2S)

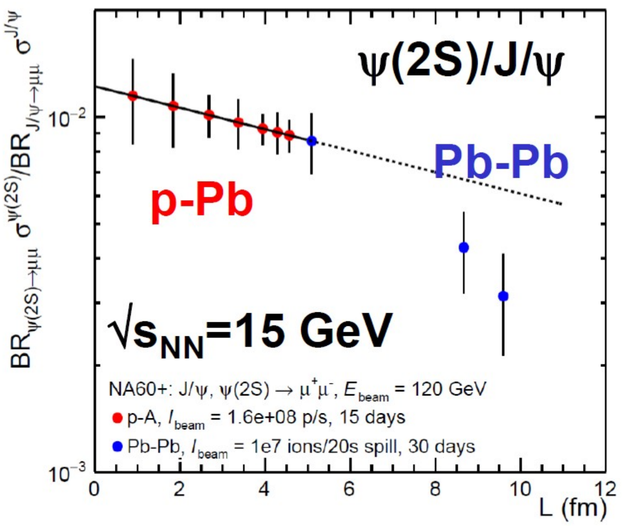


NA60+ physics performances for charmonia

- One month data taking with Pb beams at 5 10^5 ions/s
- 1.5 – 20 · 10^4 reconstructed J/ψ (depending on beam energy)
- Cold nuclear matter effects: p-A measurements at different energies

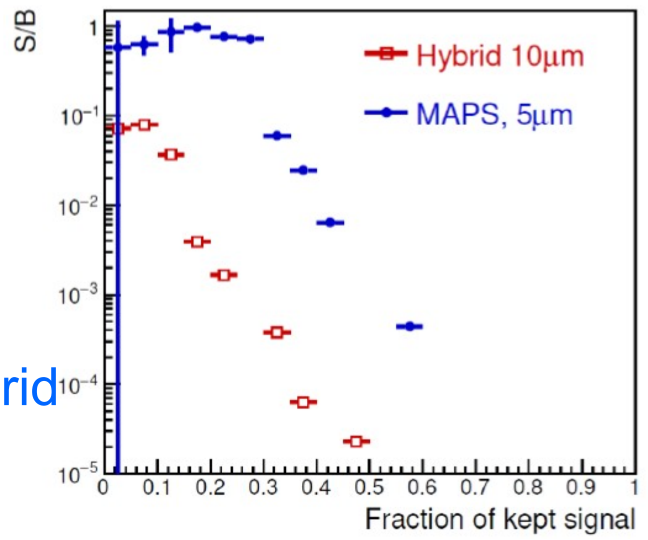




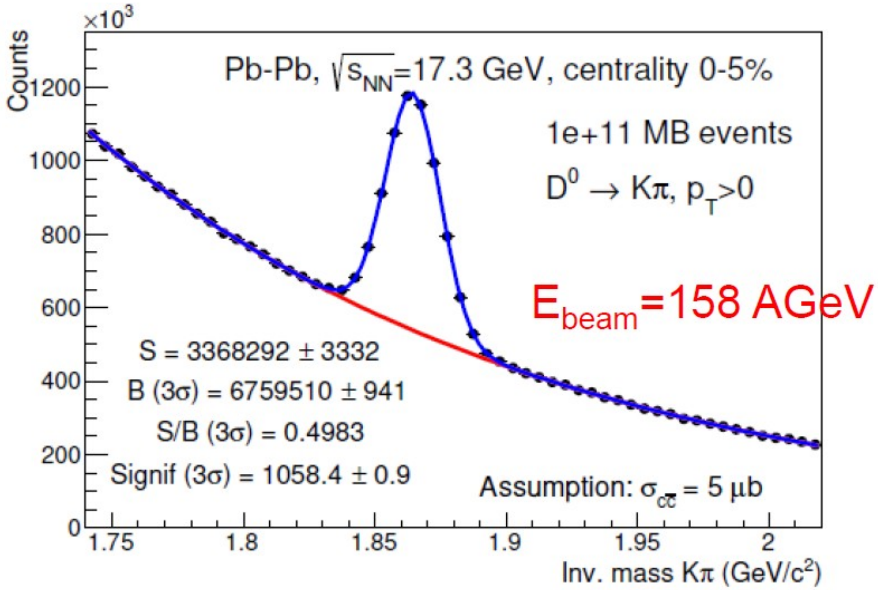


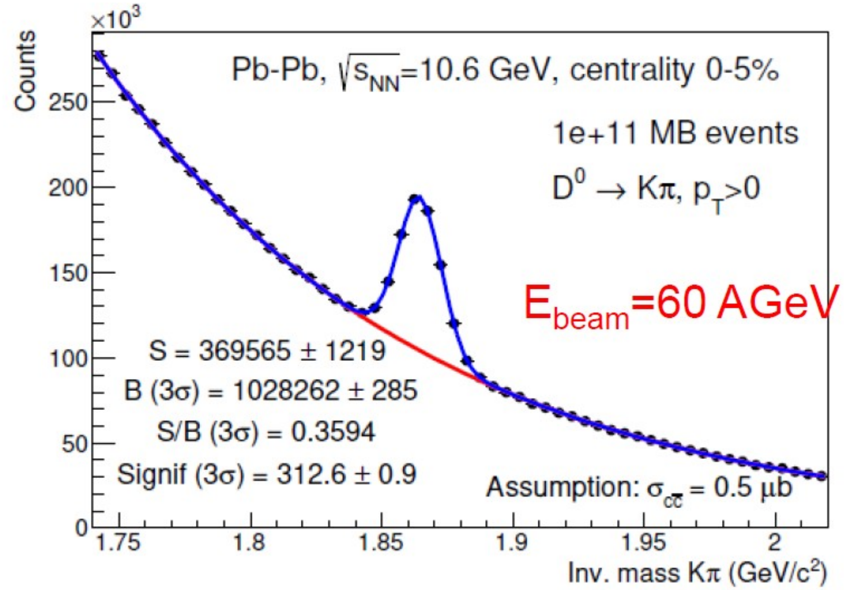
Open charm measurements

- Charmed hadrons reconstructed in the vertex telescope via decay into charged hadrons
- Selection on decay vertex topology (cτ~60–300 μm)
  - need for high resolution on vertex reconstruction
  - MAPS technology: S/B ~ 10 times better than with hybrid



- No measurement below top SPS energy
- In one month data taking more than 3 10^6 D^0 reconstructed in central collisions at top SPS energy → yield and v_2 vs p_t, y, centrality
- Measurement feasible at lower √s with statistical precision of $O(10^{-2})$





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

NA60+ Collaboration

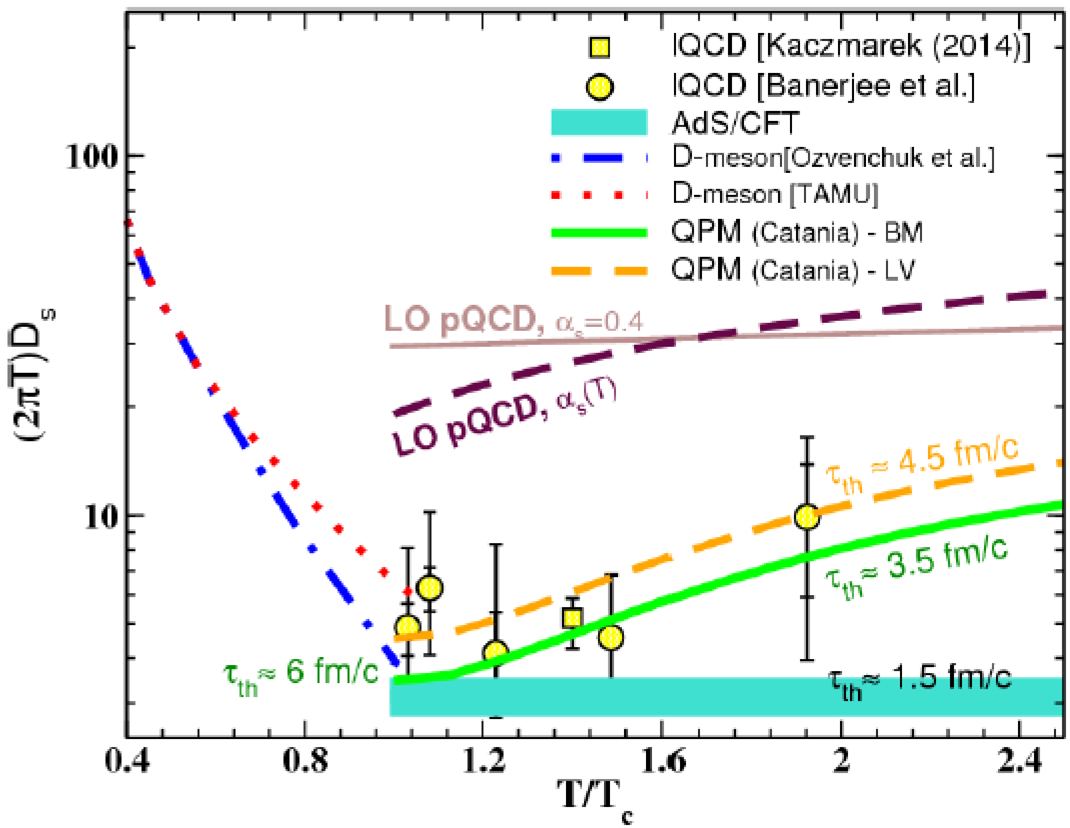
Abstract

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.

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

May 3, 2019

Theoretical calculations for charm-quark diffusion coefficient



F. Scardina, S. K. Das, V. Minissale, S. Plumari, and V. Greco, "Estimating the charm quark diffusion coefficient and thermalization time from D meson spectra at energies available at the BNL Relativistic Heavy Ion Collider and the CERN Large Hadron Collider," *Phys. Rev.* **C96** (2017) 044905, `arXiv:1707.05452 [nucl-th]`.

Stitched MAPS vs ALPIDE

Table 1: Parameters of the stitched MAPS for NA60+ and comparison to present ALPIDE.

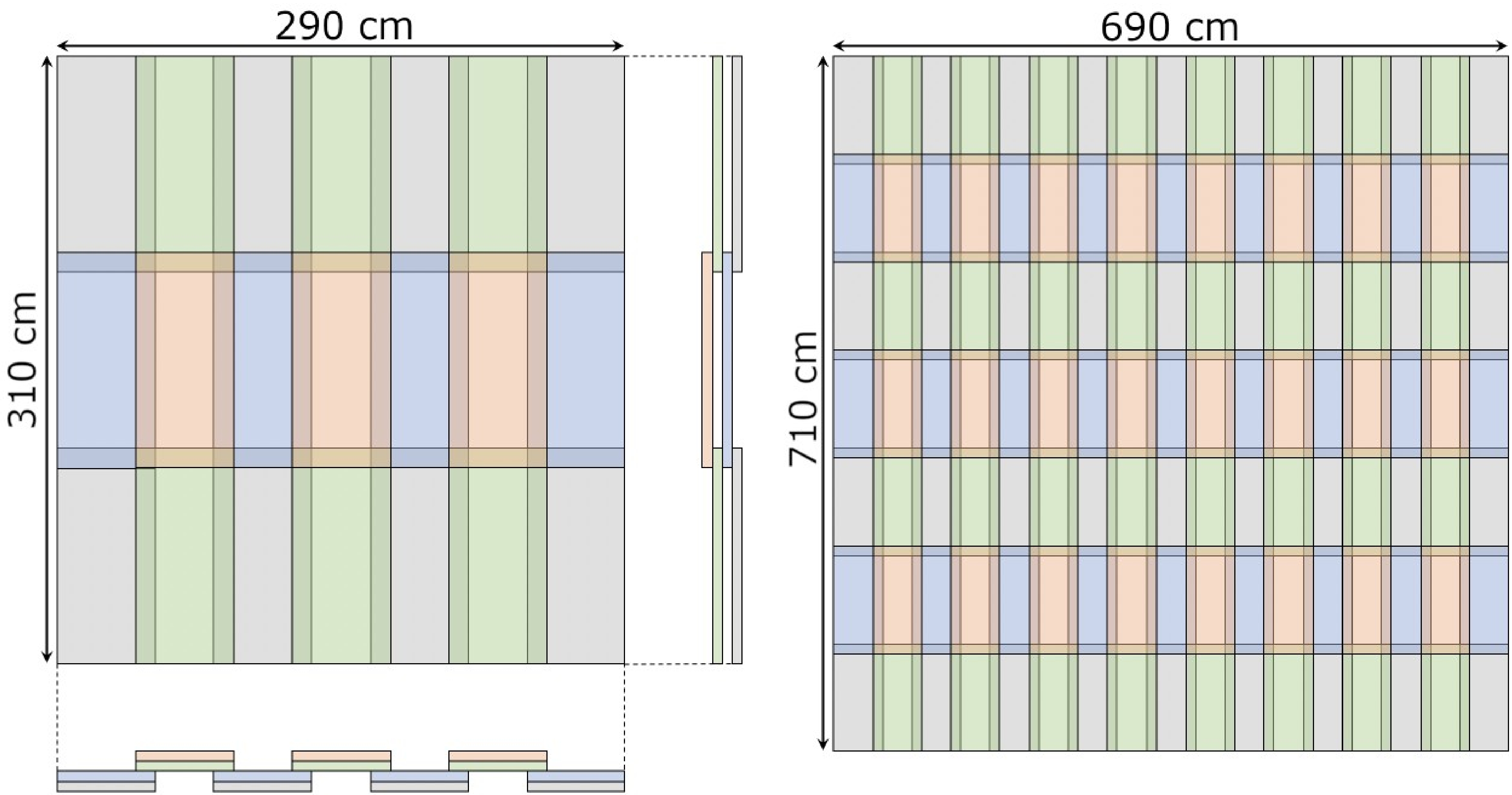
Parameter	ALPIDE	Stitched MAPS (NA60+)
Technology	Tower 180 nm	Tower 180 nm or 65 nm
Silicon thickness	50 µm	50 µm
Pixel size	$27 \times 29\ \mu m^2$	$\mathcal{O}(30 \times 30\ \mu m^2)$
Chip dimension	$15 \times 30\ mm^2$	scalable up to $140 \times 140\ mm^2$
Event-time resolution	~2 µs (ALICE operation)	~200 ns
Max. particle fluence	$\sim 100\ MHz/cm^2$	$\sim 300\ MHz/cm^2$
Max. data rate	$10\ MHz/cm^2$	$\sim 20–30\ MHz/cm^2$ (~2–300 kHz R/O rate)
Detection efficiency	$> 99\%$	$> 99\%$
Fake hit rate	$\ll 10^{-6}$ /event/pixel	$\ll 10^{-6}$ /event/pixel
NIEL radiation tolerance	$1.7 \times 10^{13}\ n_{eq}/cm^2$	5×10^{14} to $\sim 10^{15}\ n_{eq}/cm^2$

Pixel sensors cost estimates

Table 2: Cost estimate for the sensor R&D and production.

Item	R&D (kCHF)	Construction kCHF)	Total Cost kCHF)
Pixel CMOS sensors	700	700	1400
Sensor test	100	150	250
Thinning/dicing	200	300	500
Total	**1000**	**1150**	**2050**

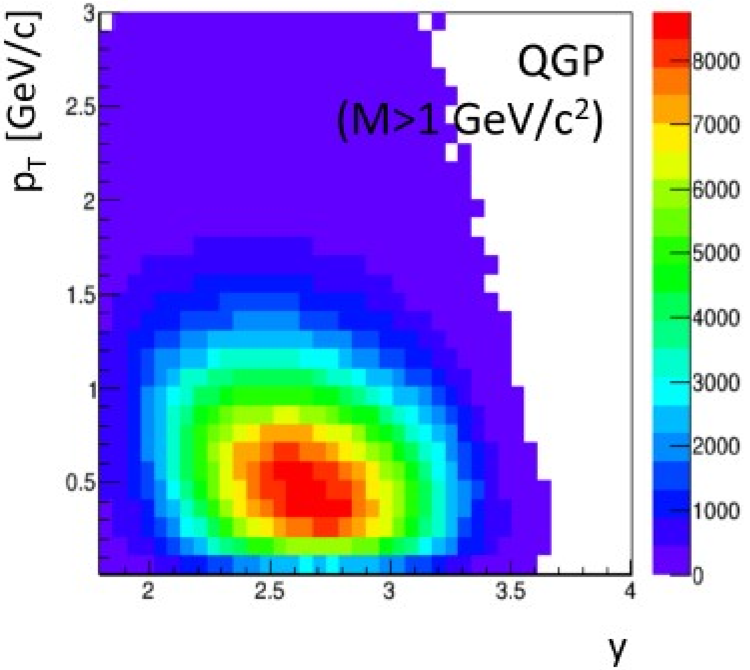
GEM chambers layout

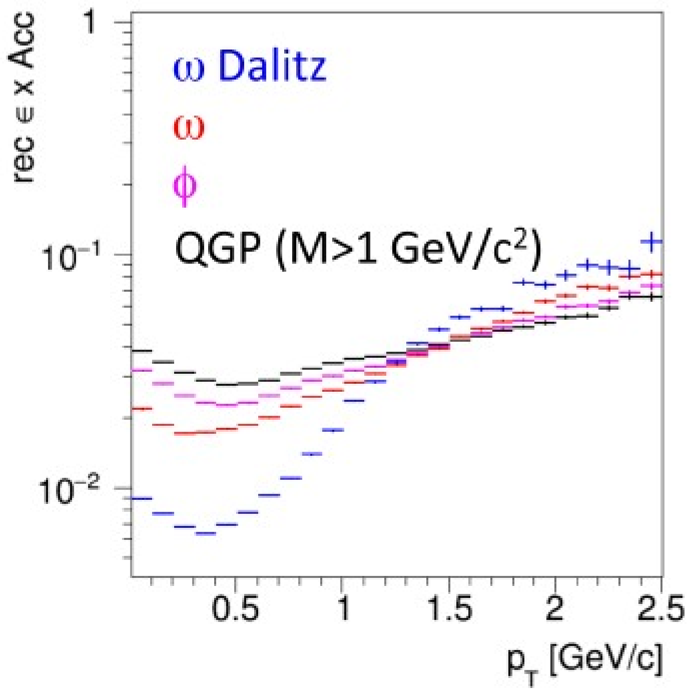


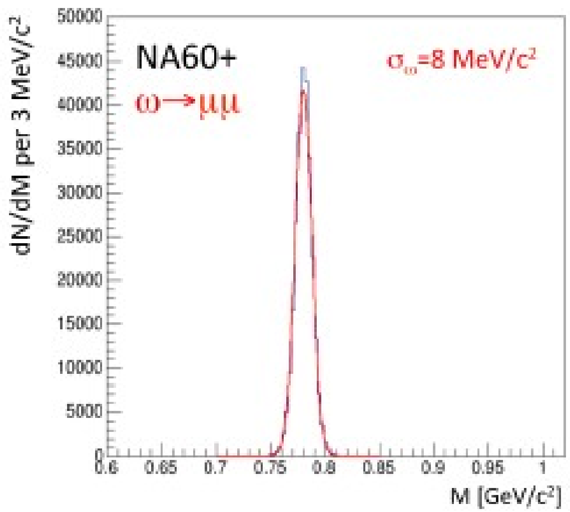
Cost estimate for GEMs

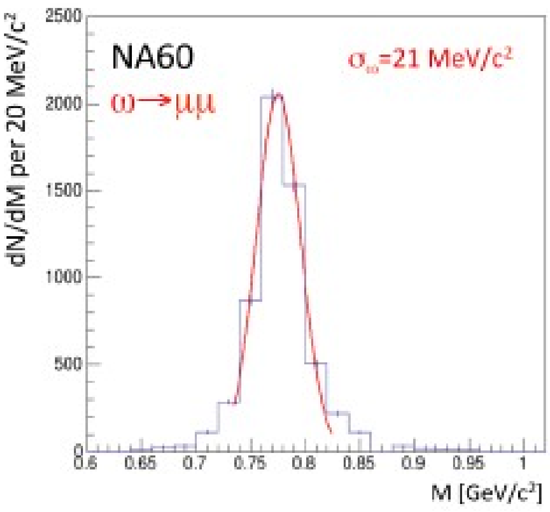
	Baseline 4 stations (kCHF)	Expanded 6 stations (kCHF)
GEM foils	1000	1500
NS2 frames	400	600
Drift + Readout	250	375
FEE	2800	4200
HV system	100	150
Mechanical support	500	750
Gas system	200	300
TOTAL	**5250**	**7875**

A*ε and resolution at low masses





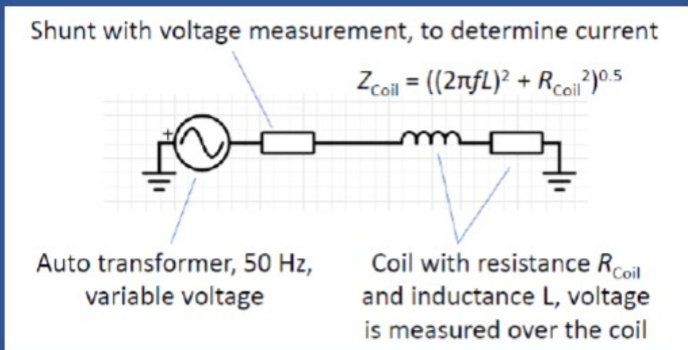




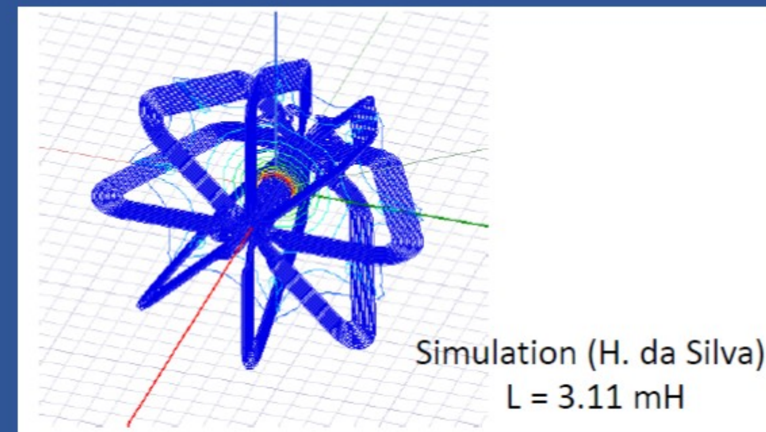
Competition with future experiments

Facility/ Experiment	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Interaction rate	Dileptons	Charm	Ref.
SPS NA60+	~6–17.3	440–220	>MHz	yes	yes	
SPS NA61/SHINE	~5–17.3	540–220	5 kHz	no	yes	[82, 83]
SIS100 CBM, HADES	2.7–5.5	740–510	>MHz	yes	yes	[84, 85]
RHIC STAR	3–19.6	710–200	~1 kHz	yes	yes	[86, 87]
NICA MPD	4–11	620–320	~7 kHz	yes	yes	[88, 89]
Nuclotron BM@N	2.3–3.5	800–660	20–50 kHz	(yes)	no	[90, 91]
J-PARC-HI DHS, D2S	2–6.2	840–480	>MHz	yes	(yes)	[92, 93]

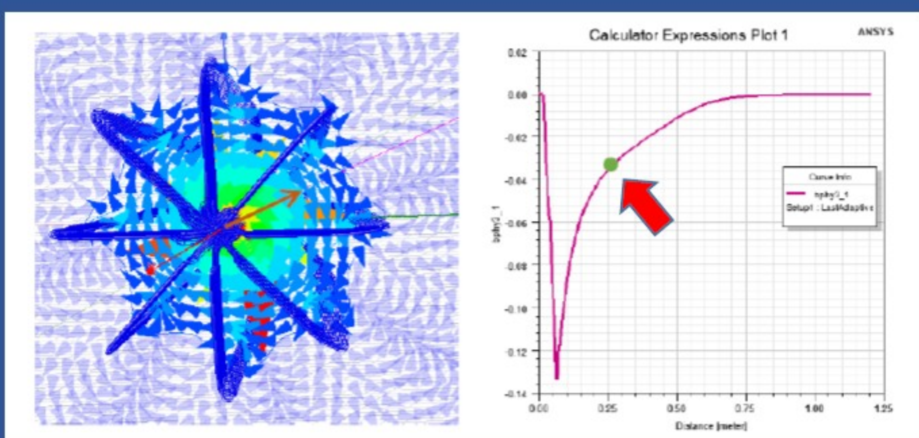
Toroidal magnet prototype, first measurement



Measured inductance:
3.083 mH
in agreement with
simulation within ~1%



Magnetic field

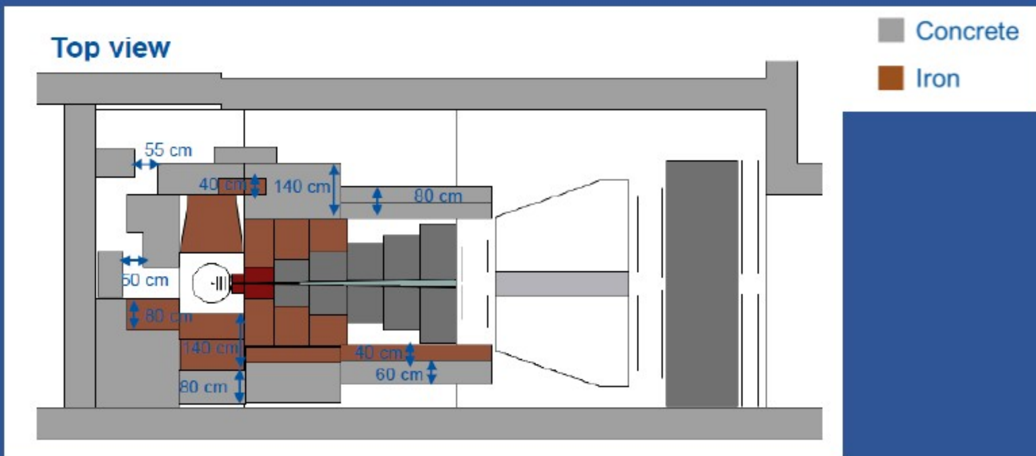


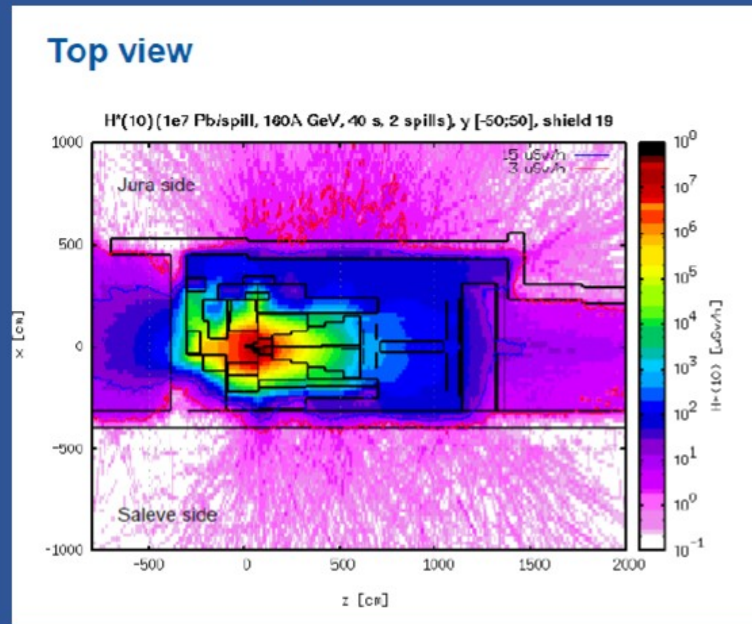
Magnetic field measured with I=20A, in the middle between coils → B = (1.3 ± 0.1) mT

Extrapolation to 500 A gives (32.5 ± 0.1) mT, consistent with simulation within uncertainties

Radiation protection

- ❑ Studies of HSE-RP group, 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 regions

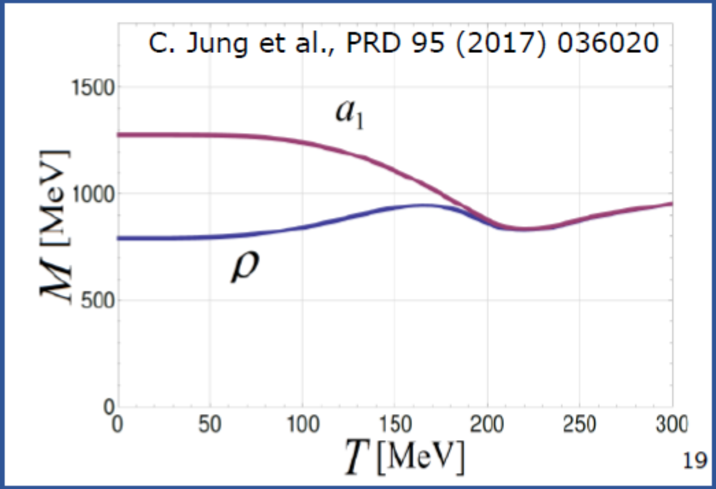
→ A thick shielding is necessary!

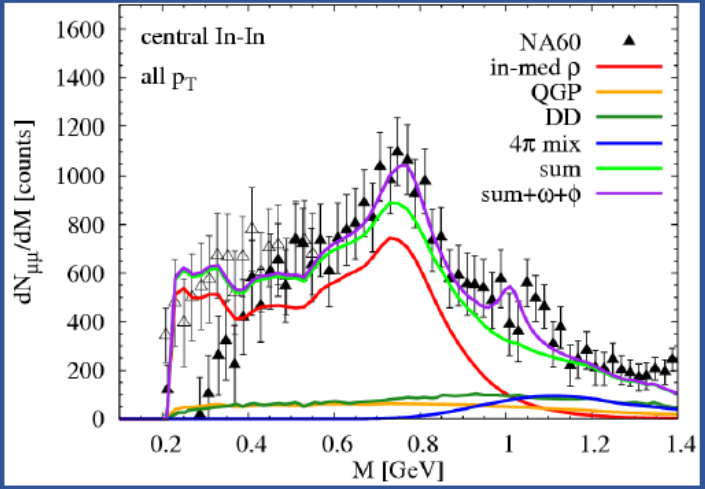
5. Conclusions: Feasibility Evaluation and Cost Estimation

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 spectrum and chiral symmetry restoration

- Broadening of ρ-meson spectral function is qualitatively consistent with chiral symmetry restoration → need to investigate the chiral partner a_1



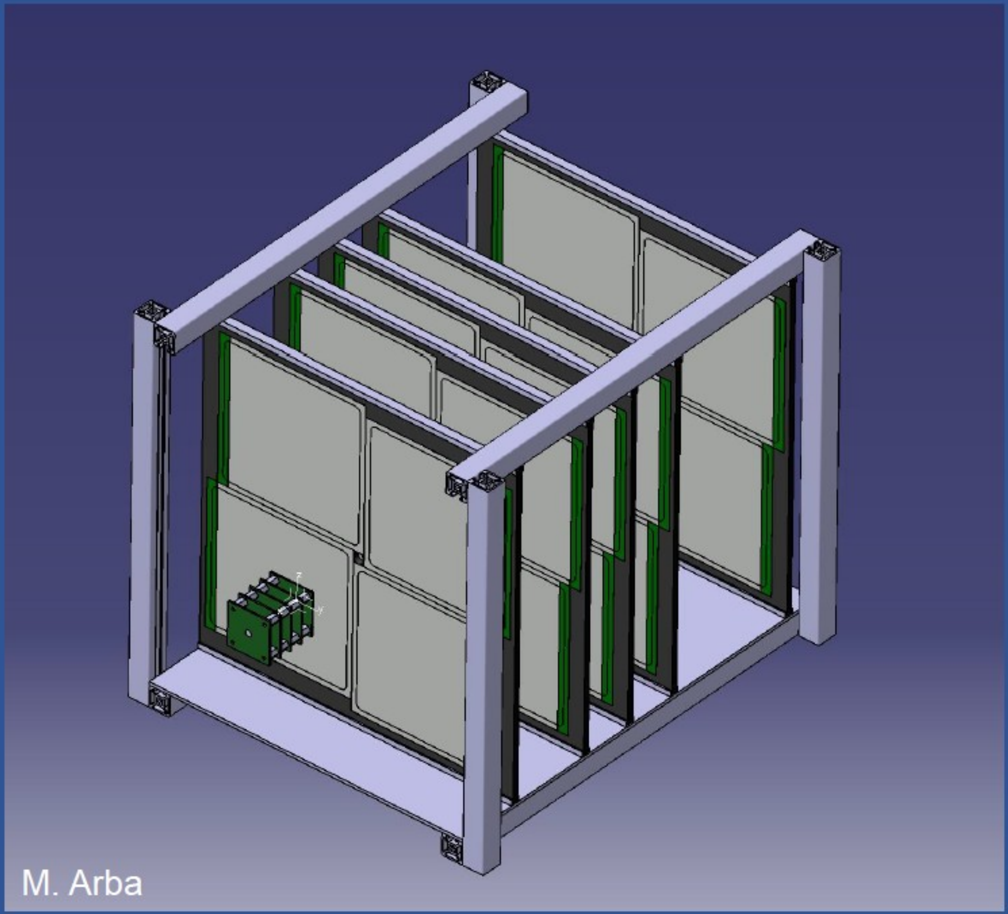


R. Rapp et al., arXiv:0901.3289

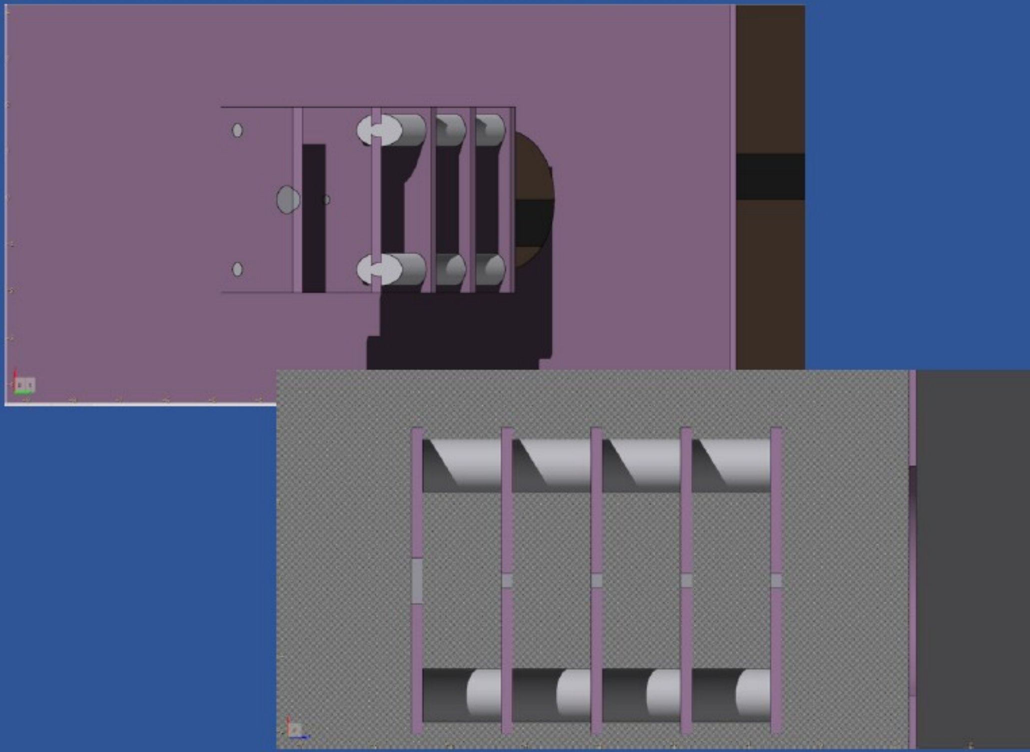
- No direct coupling of axial states to the dilepton channel
  → in vacuum the ($e^+ e^- \rightarrow$ hadrons) cross section has a dip in the a_1 mass range

- Chiral symmetry restoration → mixing of vector (V) and axial-vector (A) correlators
  → enhancement of the dilepton rate for $m_{\mu\mu} \sim 1\text{-}1.4$ GeV/c^2
- Low-energy measurement expected to be more sensitive to chiral restoration effects
  → (Exponential) thermal dimuon yield from QGP becomes smaller
  → Contribution from open charm becomes relatively negligible

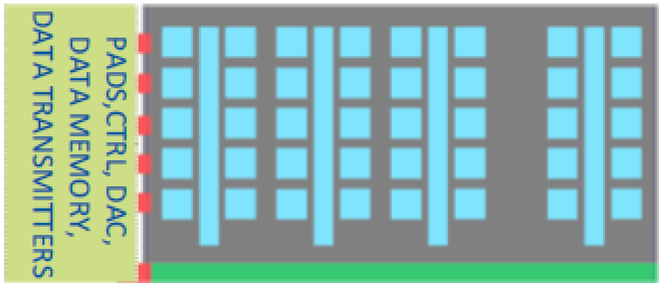
Target box and pixel telescope



- Each Pb target fixed at the center of an FR4 panel
- The panels are connected by aluminum bolts
- The target box will be fixed to an FR4 panel which is placed in front of the vertex telescope frame (detail still missing in the design)



Also consider targets suspended to wires and/or target block movable along z



Basic subsensor unit 25 mm long,
Replicated several times through stitching, up to 15cm length for NA60+