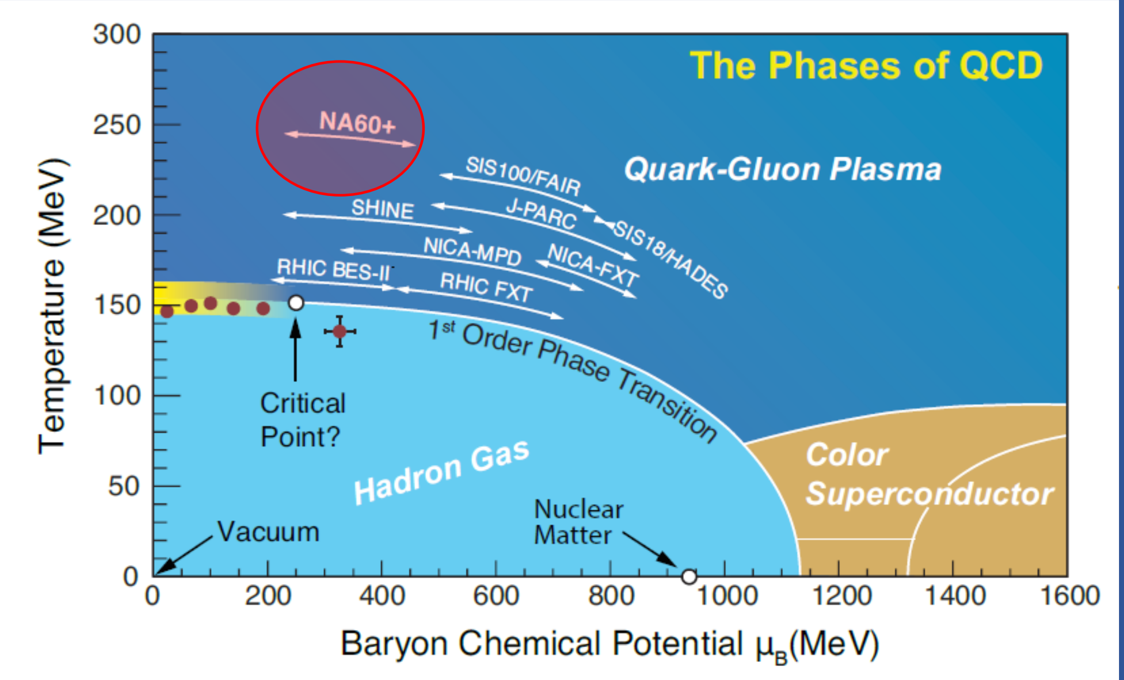
NA60+: status and next steps

Physics goal

Study of hard and electromagnetic processes at CERN-SPS energies: an investigation of the high-μ_B region of the QCD phase diagram



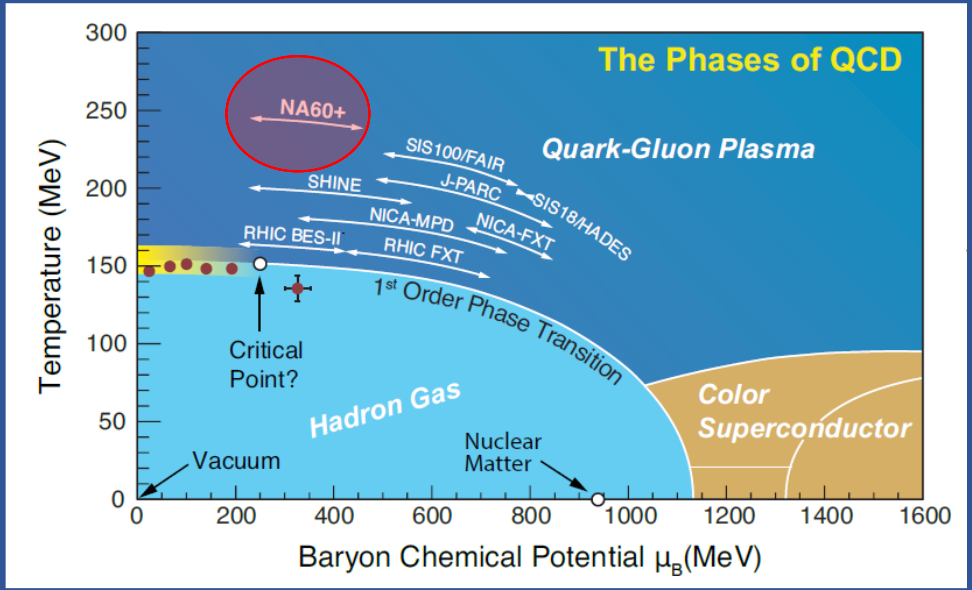
Hard processes: probe the Quark-Gluon Plasma and study its transport properties

Electromagnetic processes: information on the temperature of the system (QGP and/or hadronic), the nature of the phase transition and the approach to QCD chiral symmetry restoration

First studies carried out by NA60 (2003-2004), **only top SPS energy**

No results exist
below top SPS energy,
$\sqrt{s_{NN}}$=17.3 GeV for Pb-Pb collisions

Why going towards low SPS energy ?



Collider (top) energy for Pb-Pb (Au-Au) collisions
LHC → $\sqrt{s_{NN}}$=5.02 TeV
RHIC → $\sqrt{s_{NN}}$=0.2 TeV

- High energy density ($\varepsilon >> \varepsilon_c \sim$ 1 GeV/fm^3)
- Long-lived QGP phase
- QCD phase transition is a cross-over

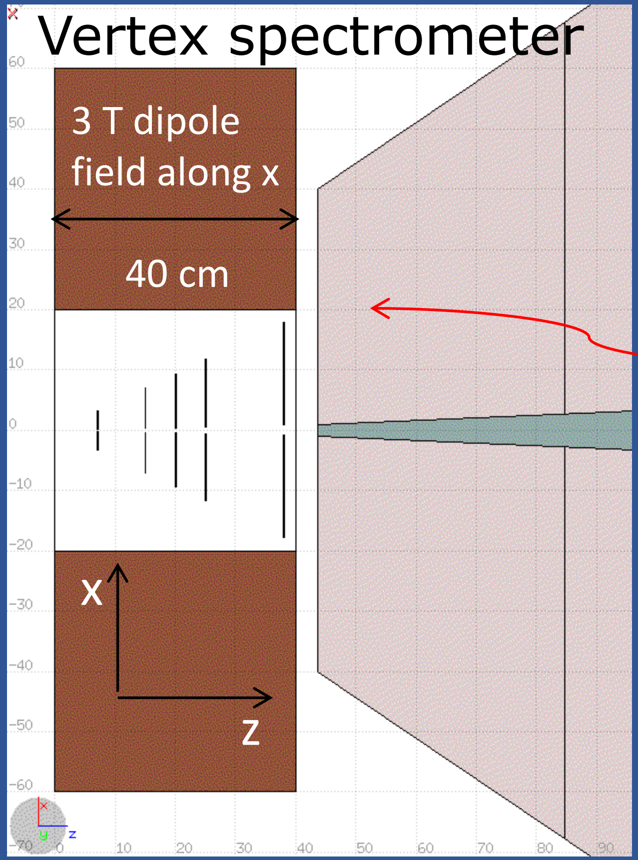
Up to now results **only on soft hadronic processes** (mainly NA49/NA61), also being explored in the RHIC Beam Energy Scan (BES I-II)

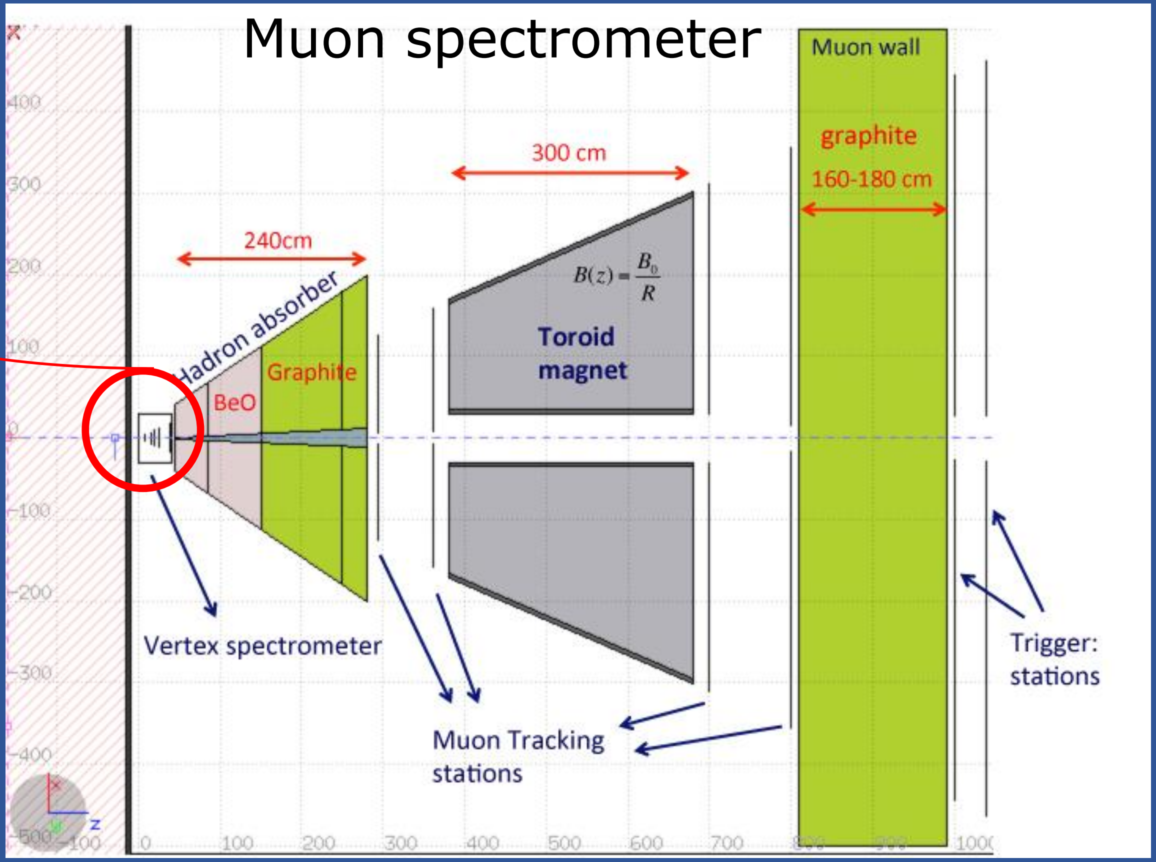
Low SPS energy ($\sqrt{s_{NN}}$>6.3 GeV)

- Energy density close to ε_c
- Explore the onset of deconfinement
- 1st order phase transition line, ending in a critical point

Strong physics case for a new experiment

NA60+: detector concept





Emphasis on
(di)muon production

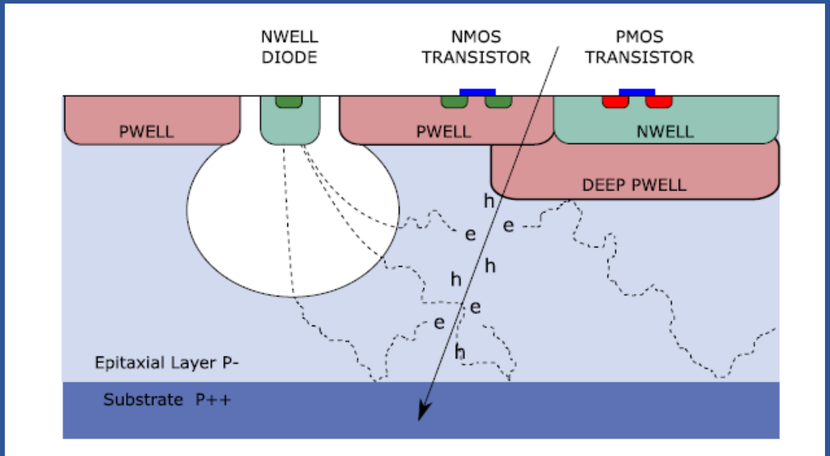
Crucial for measuring
- **Thermal dimuons** from QGP/hadronic phase
- **ρ-a_1 modifications** due to chiral symmetry restoration
- **Quarkonium suppression** as a signal of deconfinement

Accurate **vertex reconstruction**
Crucial for identification of
- **Prompt dimuon** signal
- **Hadronic decays of charmed mesons/baryons**

Muon spectrometer length needs to be varied, to **cover mid-rapidity at different collision energies**

Closing in on detector choices: vertex spectrometer

Default choice → **Monolithic Active Pixel Sensor (MAPS)**
Chosen for the upgrade of **ALICE Inner Tracker** (ALPIDE sensor)



Advantages

- Sensor and frontend electronics in the same silicon wafer
- NO Bump-bonding: pixel pitch: 30 μm, thickness down to 50 μm
- low power consumption ~3mW/mm²
- radiation tolerant technology

ALICE

Pixel chip developed for the ITS Upgrade

Parameter	Inner Barrel	Outer Barrel	ALPIDE
Silicon thickness	50μm	100μm	✔
Spatial resolution	5μm	10μm	~ 5μm
Chip dimension	15mm x 30mm		✔
Power density	< 300mW/cm^2	< 100mW/cm^2	< 40mW/cm^2
Event-time resolution	< 30μs		~ 2μs
Detection efficiency	> 99%		✔
Fake-hit rate *	< 10^{-6}/event/pixel		<<< 10^{-6}/event/pixel
NIEL radiation tolerance **	1.7x10^{13} 1MeV n$_{eq}$/cm^2	10^{12} 1MeV n$_{eq}$/cm^2	✔
TID radiation tolerance **	2.7Mrad	100krad	tested at 350krad

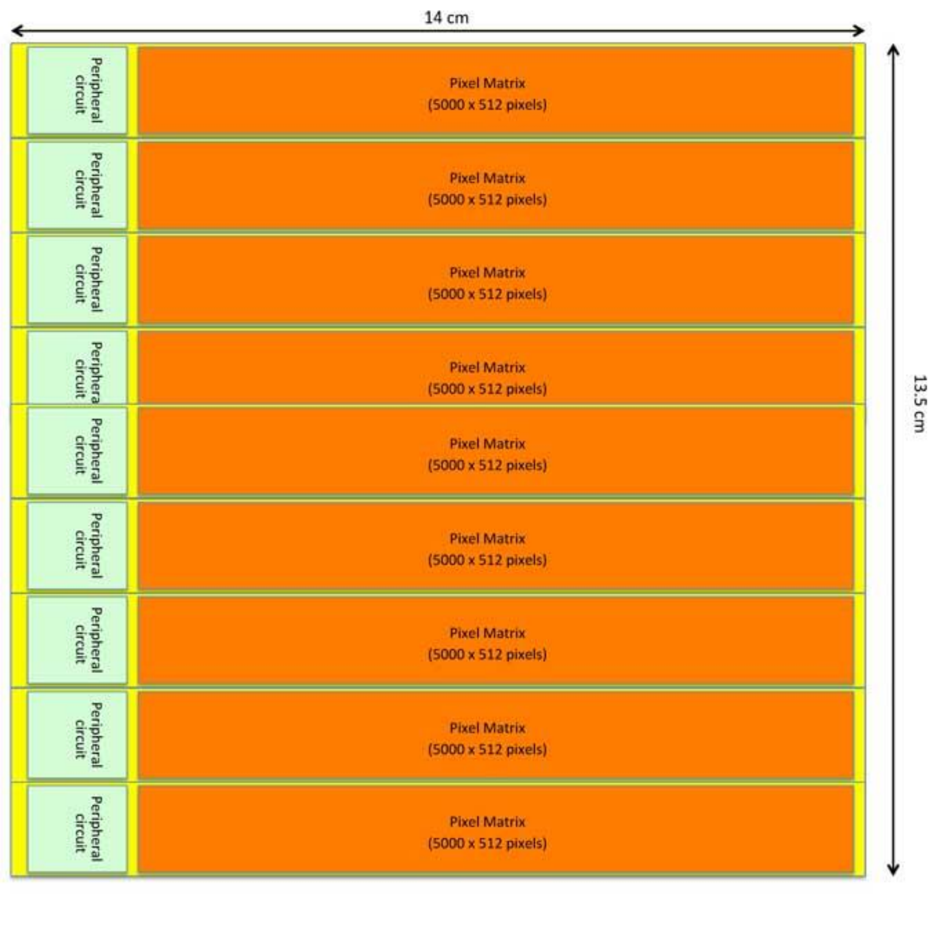
* revised numbers w.r.t. TDR
** including a safety factor of 10, revised numbers w.r.t. TDR

Requirements devised for ALICE should also fulfill NA60+ needs in terms of
- Material budget
- Particle and R/O rate
- Detector granularity

- Max particle rate ~ 100MHz /cm^2 (pile-up)
- Max readout rate ~ 10 MHz/cm^2 (bandwidth)

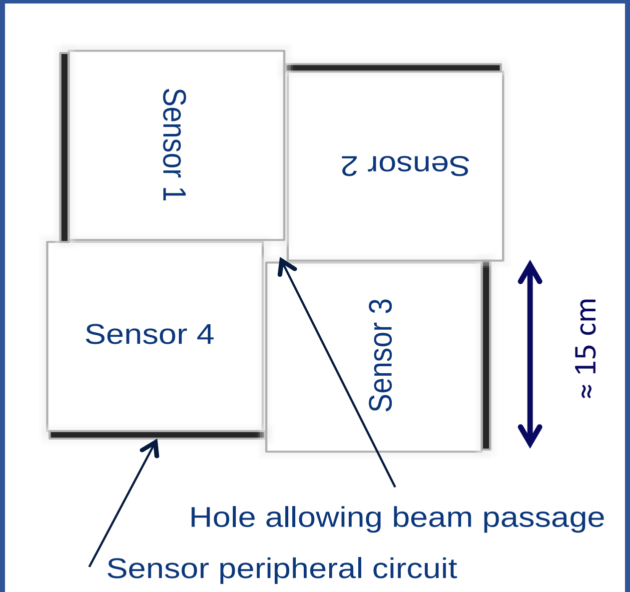
Closing in on detector choices: vertex spectrometer

Foreseen developments for LS3 in the frame of ALICE → **large area sensors with stitching**



Periphery contains the control logic, the interfaces for the configuration of the chip and the serial data transmitters

Mechanical support structures and cooling only on the borders, outside from acceptance



Opens up the possibility of producing

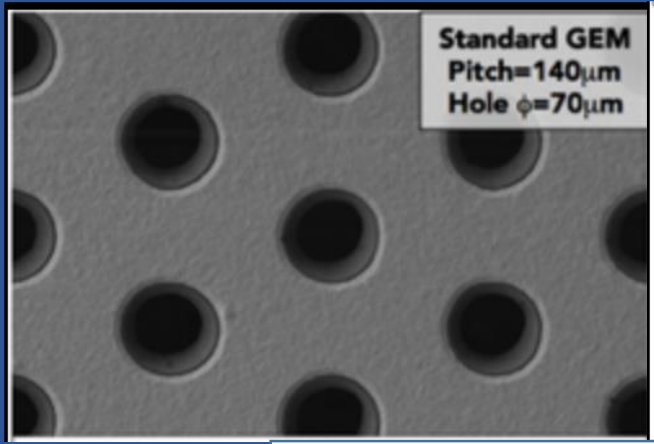
- **thin** (0.05 – 0.1% X_0)
- **large area** (~ 15 × 15 cm^2) sensors → ideal for NA60+ (5000 × 5000 pixels)
- **high granularity** (<5 μm resolution)

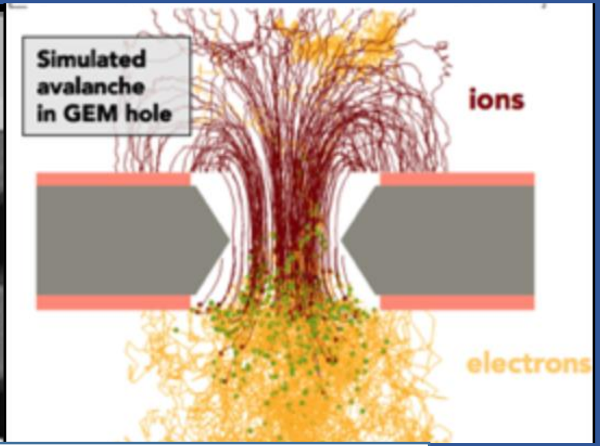
Closing in on detector choices: muon tracking

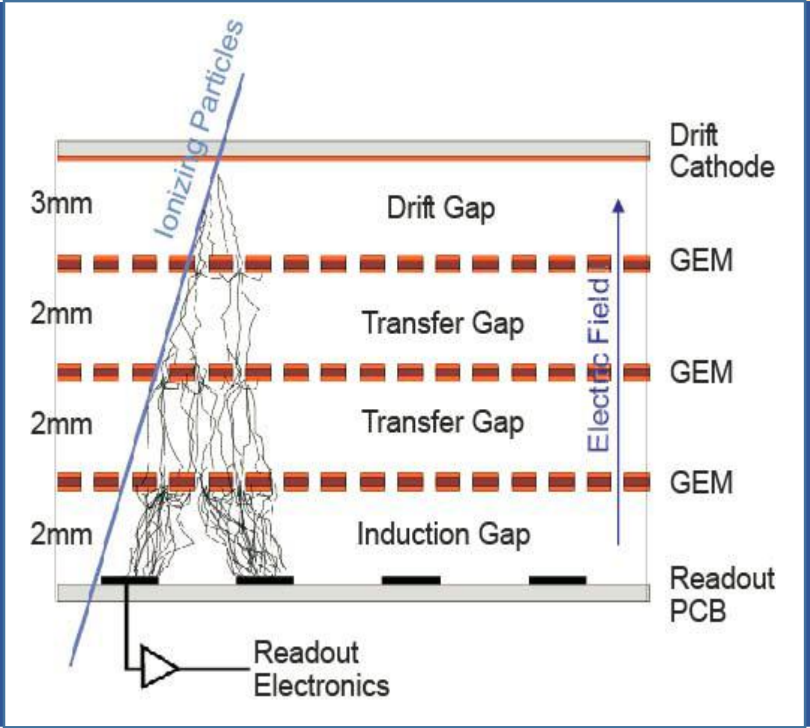
Default choice → **Gas Electron Multipliers (GEM)**

Typical GEM geometry:
- Inner/Outer hole diameter: 50/70 μm
- Pitch: 140 μm

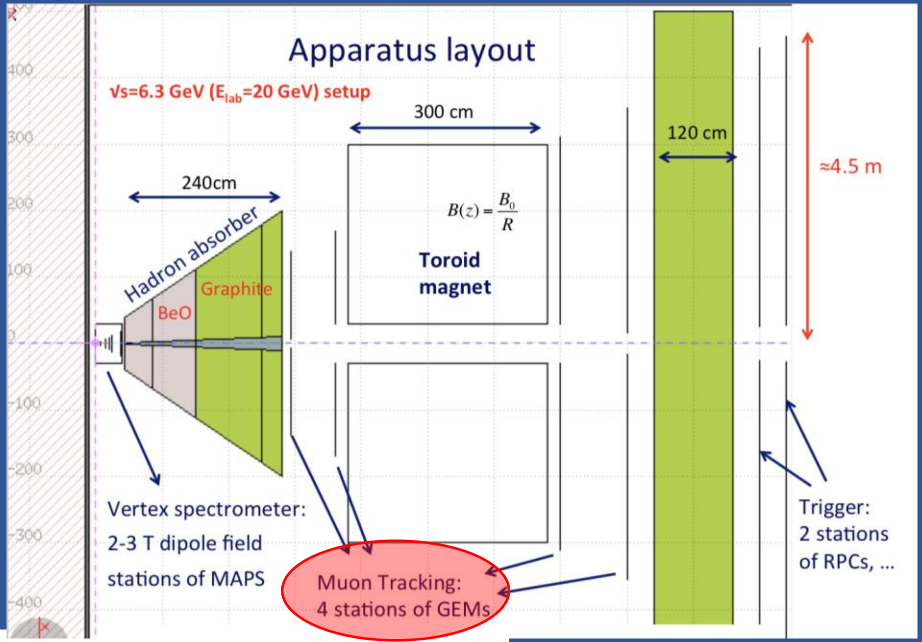
- **Position resolution < 100 μm**
- **Timing resolution < 10 ns**
- **High rate capabilities of O(1 MHz/cm^2)**
- **Radiation hardness**
- Can be stacked easily:
  - Higher gains (up to 10^5)
  - Improved stability against electrical discharges
- Used successfully in COMPASS, LHCb, TOTEM
- Solution chosen for **ALICE TPC Upgrade** and **CMS Muon Endcap Upgrade**







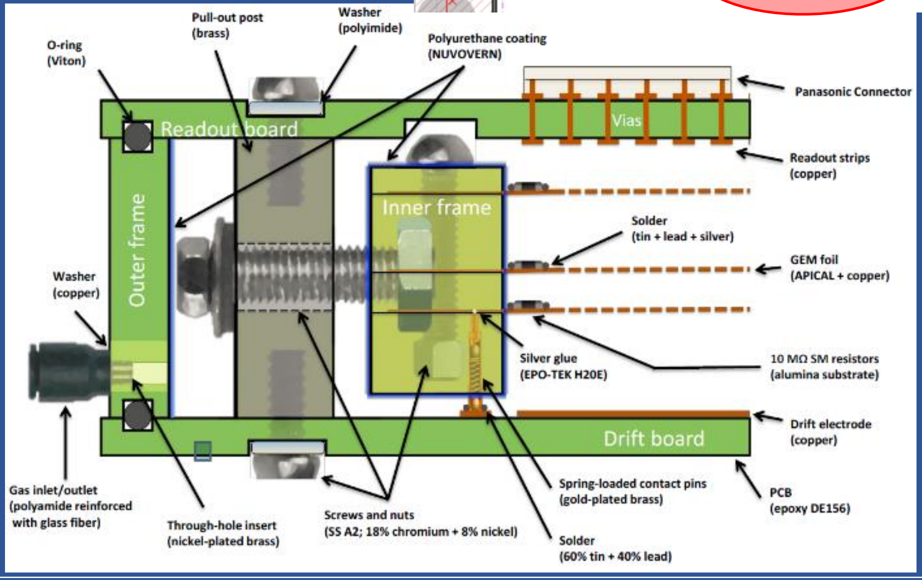
Closing in on detector choices: muon tracking



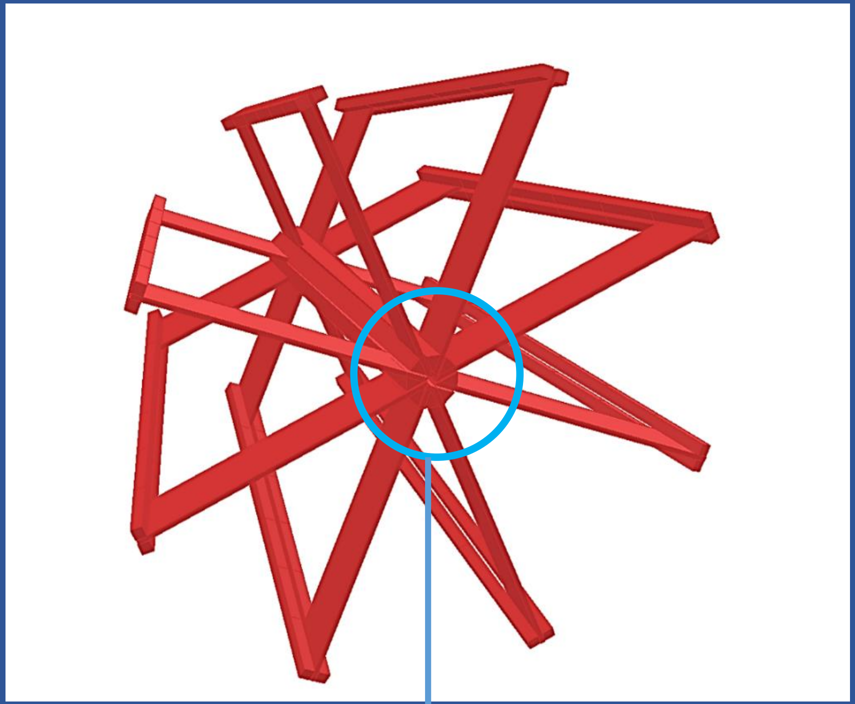
- 4 stations, behind the absorber, total area of 116 m^2
- Double 3-GEM modules with strip readout per station
- Single module: $50 \times 100\ cm^2$ - $50 \times 150\ cm^2$
- 310 - 464 chambers → 1000 - 1500 GEMs (with spares)
- NS2 system (like CMS) for faster chamber assembly (no gluing)
- Gas: $Ar\text{-}CO_2$ or $Ar\text{-}CO_2\text{-}CF_4$
  - Non flammable
  - No ageing effects observed

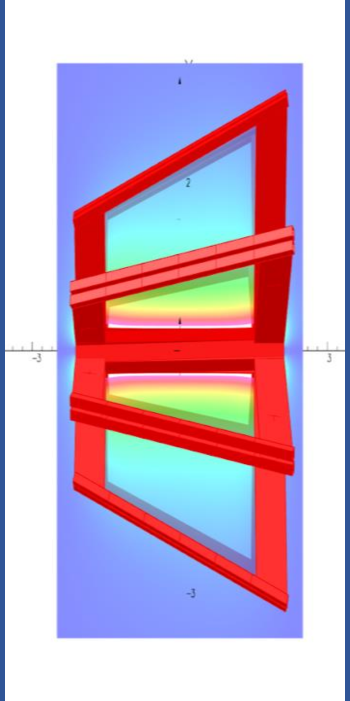
- 1-2 M electronic channels (1D or 2D strip R/O).
- Readout options: VFAT-3, VMM-3 chips

Needs a collaboration of several production institutes and optimized workflow



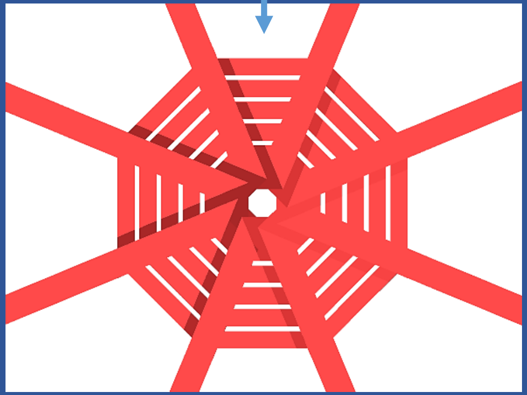
First studies on muon spectrometer magnet





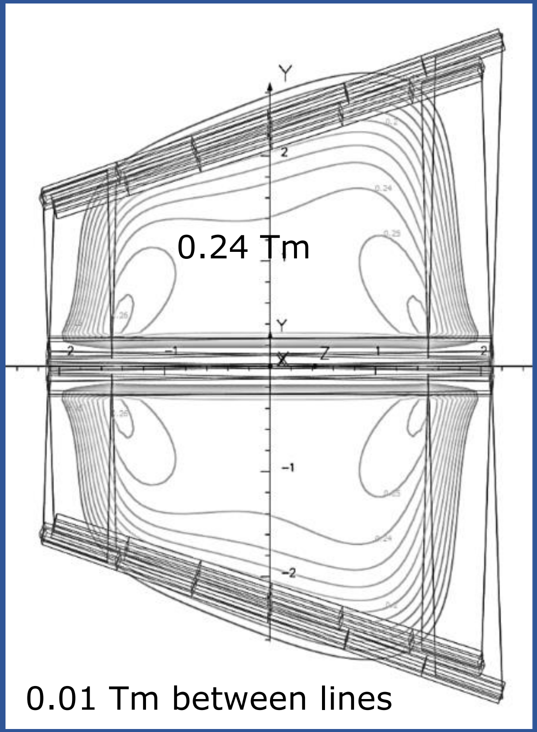
Open toroid with field circling the beam axis
L = 3m
0.3 < R < 1.65 m at entrance
0.3 < R < 2.95 m at exit
B · R ~ 0.2-0.25 Tm

Minimal design, easy to build and cheap
(F. Bergsma, P.A. Giudici, CERN-EP-DT-EF)

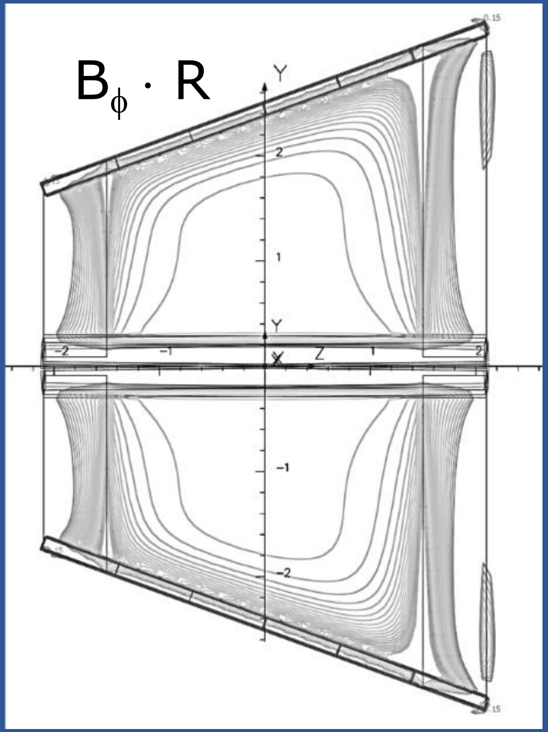


- **8 sectors**, tangentially displaced wrt cylinder axis
- Conductors made of **aluminium**
- Segments consist of a single winding, straight conductors joined by screws (Meccano-like)
- Possibility to add segments (same total current) to increase field homogeneity

First studies on muon spectrometer magnet



in between segments



in plane of segment

Physics performance studies to be **re-evaluated with realistic field** in order to finalize the design

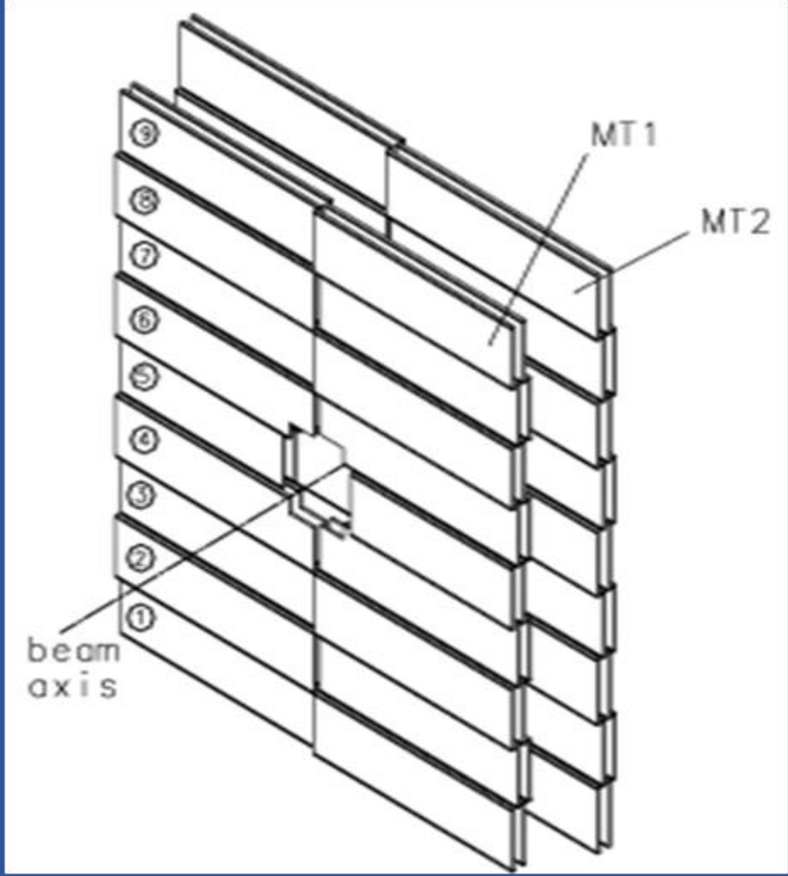
Default (and most economical) choice
→ **air cooling**
Central region is the most critical, dimensions limited by aperture constraints
→ Water cooling might be needed

Scaled models to be built to test the field quality in practice

Starting to define the characteristics of the **vertex spectrometer dipole magnet**
→ Gap dimension dictated by the transverse size of the pixel detector (<40 cm)
- A superconducting magnet might be needed

Closing in on detector choices: muon triggering

Default choice → **Resistive Plate Chambers (RPC)**



Maximum size of Bakelite electrodes → 300 × 180 cm^2

- Muon efficiency ≥ 95%
- Time resolution ≈ 1 ns
- Intrinsic spatial resolution ≈ mm
- Charge per hit ~100 pC
- Rate capability >50 Hz/cm^2
- Ageing-tested up to 50 mC/cm^2
- Low sensitivity to γ and n
- Low cost in proportion to the detection area

A set-up identical to the one adopted in ALICE is considered as the current baseline **(2 stations, 2 planes each), ask for a coincidence of 3 out of 4 planes**

Possible/foreseen improvements
FEE including an amplification stage, **better rate capability (>100 Hz/cm^2) and detector lifetime**
Use of non-flammable gas

Physics performance studies

- Carried out with a software package based on **ROOT/AliRoot**
- Simplified particle fast transport (**FLUKA** used for background studies)
- **Reconstruction** in the vertex/muon spectrometer and matching implemented
- Detector geometry still to be refined

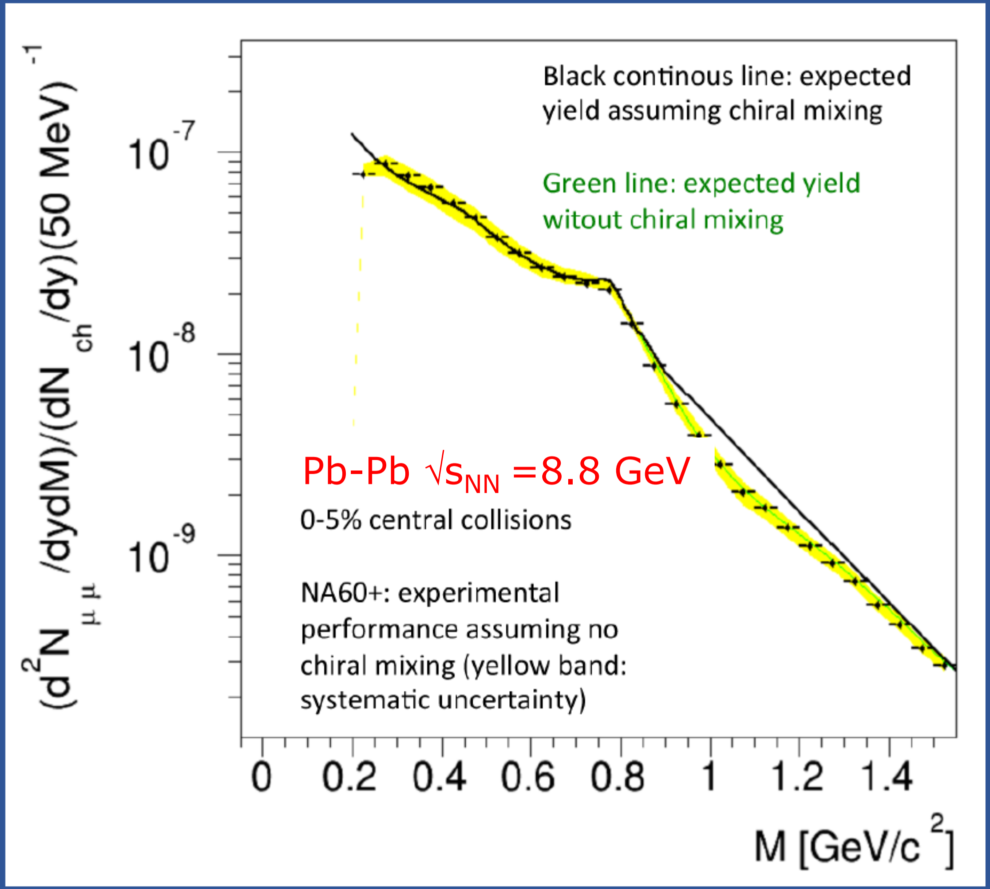
Large set of physics performance studies exist for most observables
Results for many of them already shown in previous PBC meetings

- Thermal radiation
  - Chiral symmetry restoration: measurement of ρ-a_1 chiral mixing **(X)**
  - Hadron-QGP phase transition: measure of caloric curve at high μ_B **(X)**
  - Thermal dilepton excitation function and fireball lifetime
- Quarkonium production **(X)**
- Open charm production **(X)**

(X) Results recently obtained/updated

Physics performance: ρ-a_1 mixing

- NA60 measured a **strong modification of the** ρ in nuclear collisions
- Signal of **chiral symmetry restoration ?** Information needed on the chiral partner, a_1



- No direct coupling of a_1 to dilepton channel, but chiral mixing ρ-a_1 via 4π states
  → leads to **yield enhancement in 1<M<1.5 GeV**

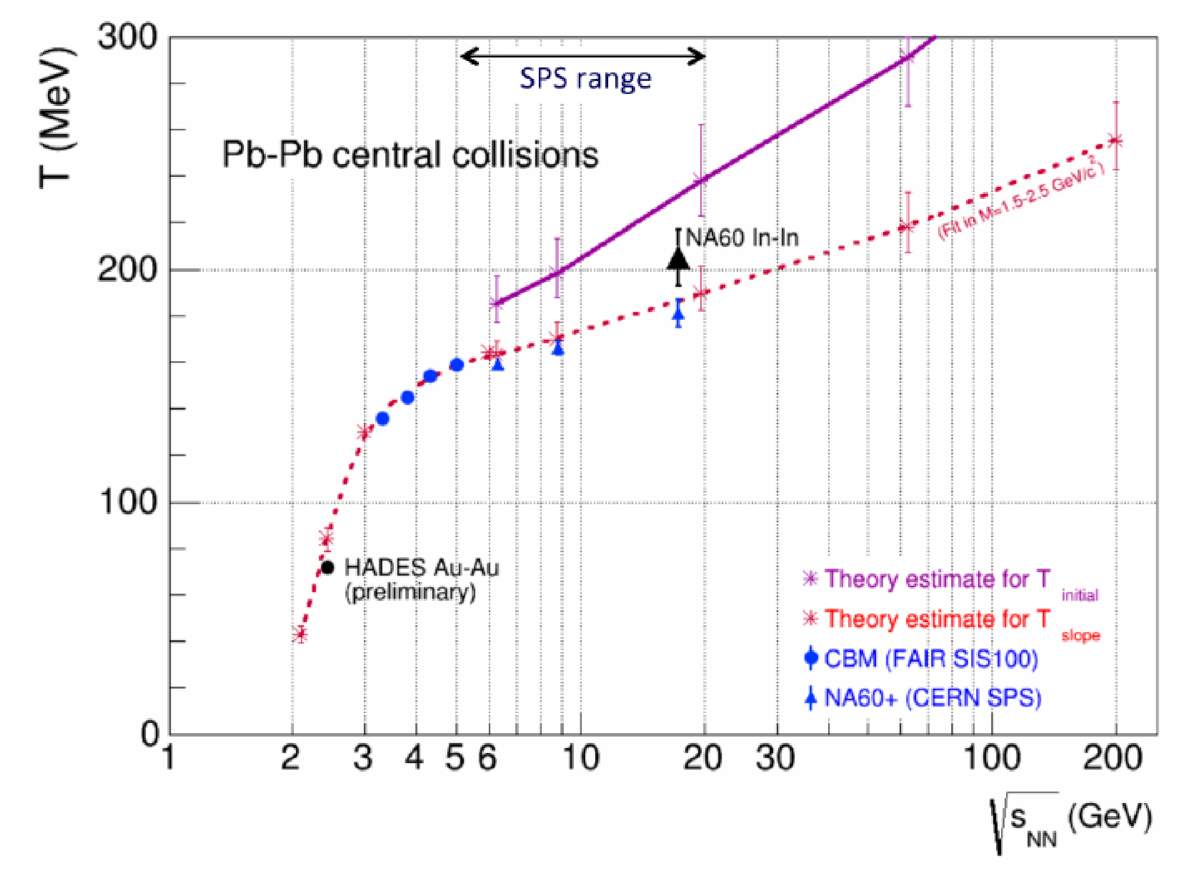
- Measurement challenging, but **sensitivity to enhancement! (~30% effect)**

- Signal optimized at low energy (QGP signal negligible)
- Need hadronic matter around T_c
- Sensitivity might improve further at √s=6.3 GeV (theoretical input needed)

Physics performance: nature of the phase transition

- Fit the dimuon spectrum for M>1.5 GeV
  ($dN/dM \propto M^{3/2} \exp(-M/T_s)$)

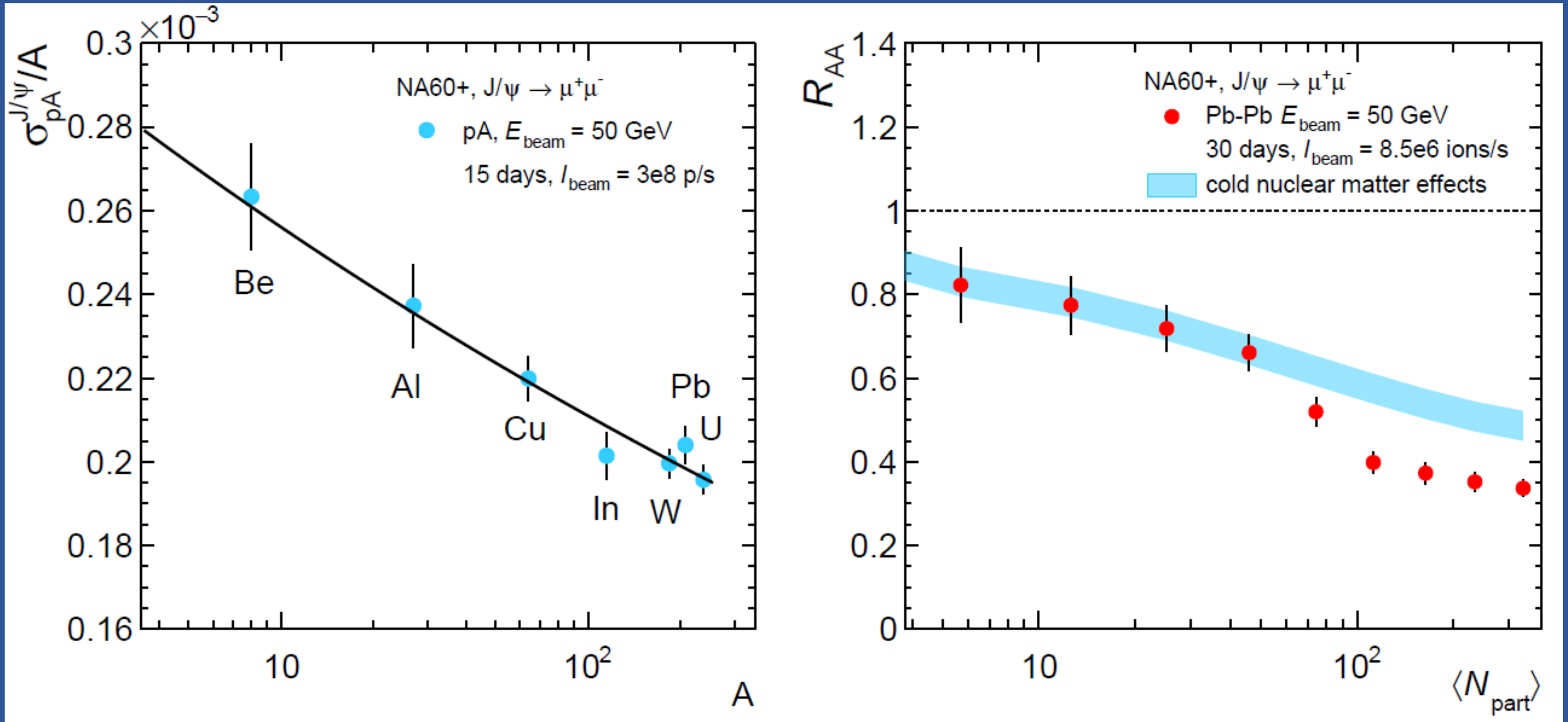
T_s → space-time average of the thermal temperature *T* over the fireball evolution
- NA60: T_s = 205 ± 12 MeV
- HADES: T_s = 72 ± 2 MeV (prelim.)



- Low SPS energy
  Map the evolution of T_s as a function of collision energy, with **a few MeV** resolution
  → strong sensitivity to a possible flattening, related to **1st order phase transition**

- Complementary to future measurement at FAIR energies

Physics performance: quarkonium production



J/ψ suppression observed from top SPS to LHC energy
→ Related to **color screening** in deconfined matter

Low SPS energy
→ Look for the **onset of the suppression**

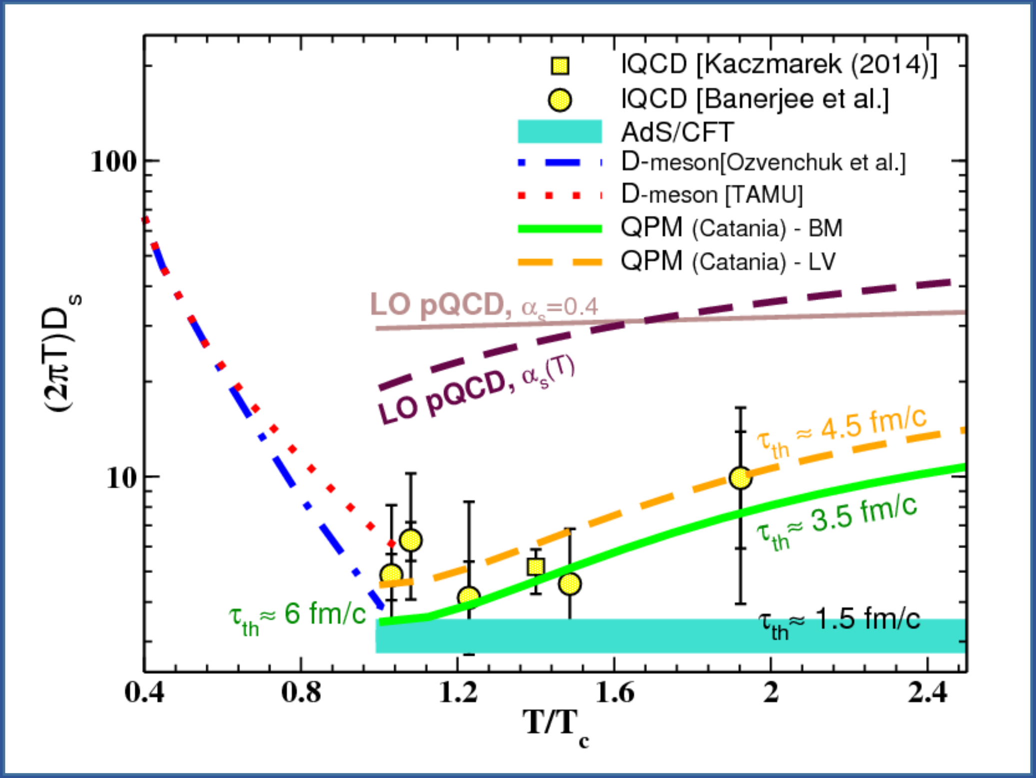
This measurement needs **high nuclear beam intensity (10^7 Pb/s)**
- low cross sections at small collision energy
- suppression increasingly small

A **measurement in p-A collisions is mandatory**, to calibrate cold matter effects

Measurement of **other quarkonium states** ($\psi(2S)$, χ_c) highly relevant → studies ongoing

Physics performance: open charm

- Measurement of **p_T distributions and azimuthal anisotropies of D mesons**
→ Extract fundamental **transport coefficients of QGP** (HQ diffusion coefficient)
- Measurement of **D_s and Λ_c** → hadronization mechanisms and quark recombination

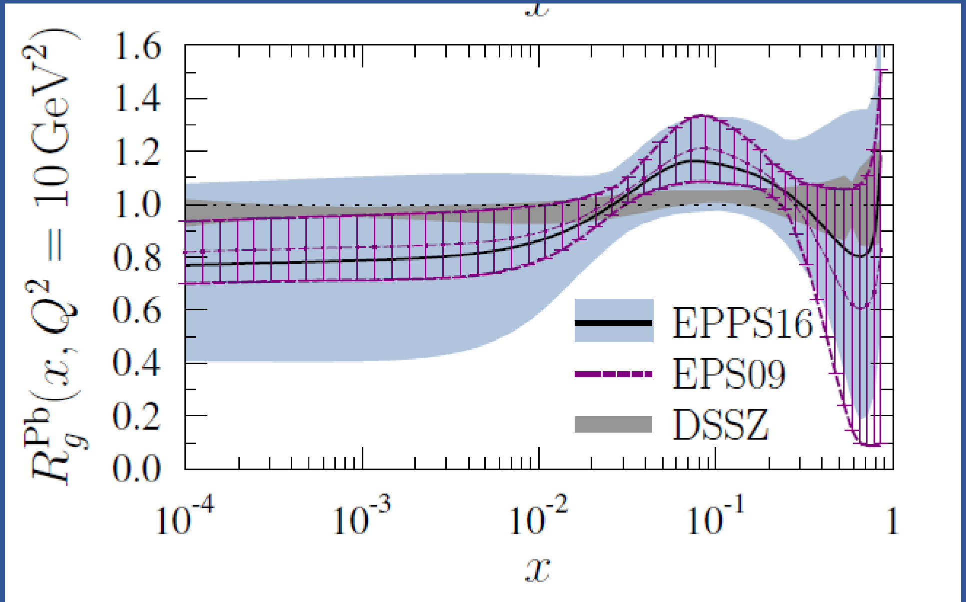


Phys. Rev. C96 (2017) 044905

Low energy Pb-Pb
→ Charm **diffusion coefficient larger in hadronic phase** than in a QGP around T_c
(measurement also important for precision estimates of diffusion coefficients at LHC!)
→ Observe a **strong enhancement of Λ_c/D**, thanks to large baryonic number in the fireball
→ Ideal **normalization for J/ψ** measurements
→ Possible **effects on the DD threshold** approaching chiral symmetry restoration

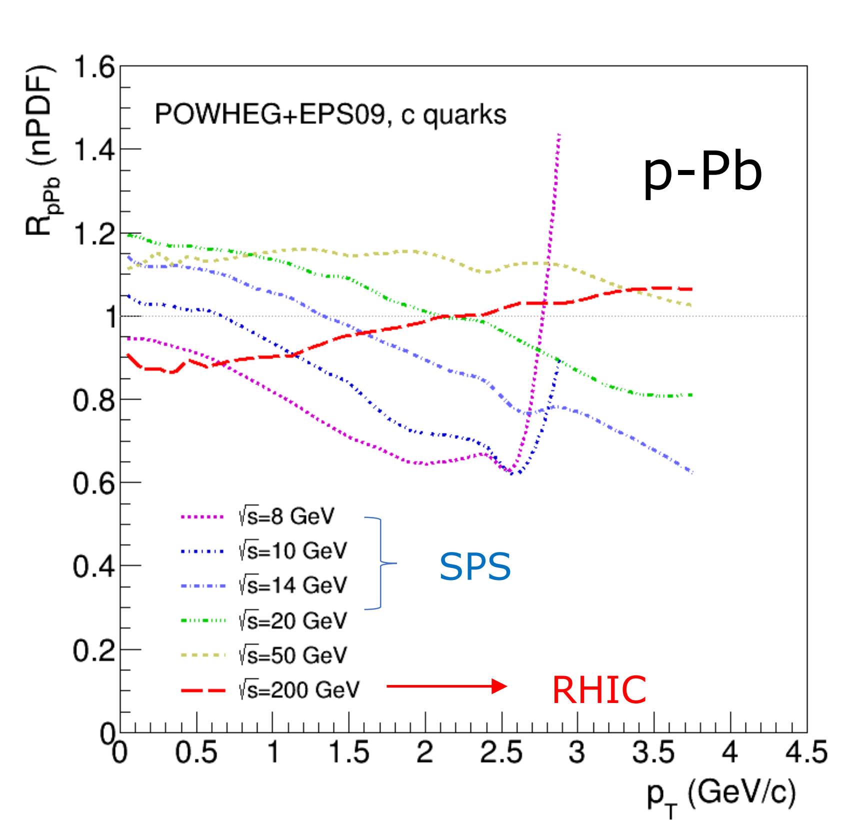
→ p-A : constraints to parameterizations of **nPDFs**
($x \sim 0.1$-0.3, $Q^2 \sim 10$-40 GeV^2)

Physics performance: open charm



K. Eskola et al, arXiv:1612.05741

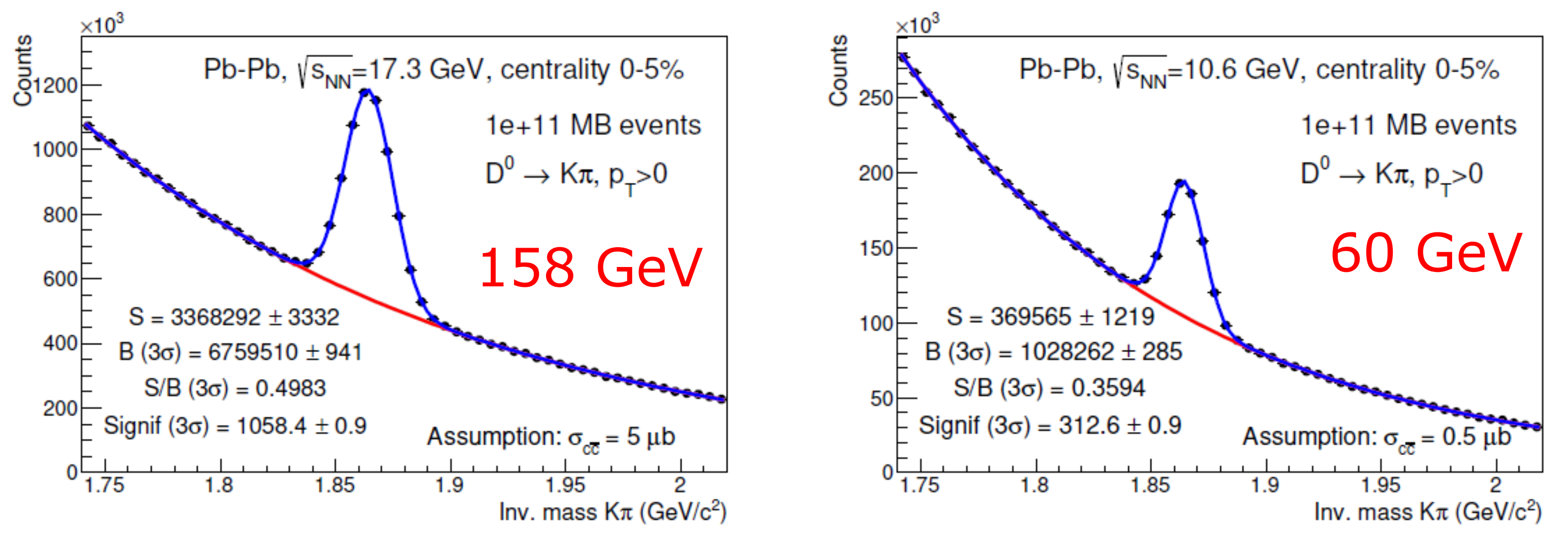
- **Large uncertainties on gluon nPDF**, over all the x_{Bj} range (especially in recent parameterization)
- NA60+ offers a unique opportunity to investigate the **large x_{Bj} region**



- Low energy → from antishadowing to EMC and Fermi motion region
- Perform measurement with **various nuclear targets** → also access A-dependence of nPDF
- High statistics measurement mandatory → **only accessible to NA60+**

Physics performance: open charm

- **$D^0 \rightarrow K\pi$** as benchmark (3 prong decay studies in progress), decay products reconstructed in the vertex spectrometer and various topological cuts applied
  N.B.: **S/B before selection is ~10^{-7}!**



Spatial resolution: 5 μm (MAPS)
Material budget per layer: 100 μm Si

Background: abundances, p_T and y distributions of π, K and p from NA49 results
Signal: p_T and y shapes from POWHEG-BOX+ PYTHIA6

Assume **10^{11} min.bias collisions** (1 month at 150 kHz)
Allows for **differential studies of yield and v_2 vs. p_T, centrality !**
More than 3 10^6 reconstructed D^0 at $\sqrt{s_{NN}}$=17.3 GeV

Document submitted to European Strategy

https://arxiv.org/abs/1812.07948

Study of hard and electromagnetic processes at CERN-SPS energies: an investigation of the high-μ_B region of the QCD phase diagram with NA60+

M. Agnello, F. Antinori, H. Appelshäuser, R. Arnaldi, R. Bailhache, L. Barioglio, S. Beole, A. Beraudo, A. Bianchi, L. Bianchi, E. Bruna, S. Bufalino, E. Casula, F. Catalano, S. Chattopadhyay, A. Chauvin, C. Cicalo, M. Concas, P. Cortese, T. Dahms, A. Dainese, A. Das, D. Das, D. Das, I. Das, L. Das Bose, A. De Falco, N. De Marco, S. Delsanto, A. Drees, L. Fabbietti, P. Fecchio, A. Ferretti, A. Feliciello, M. Gagliardi, P. Gasik, F. Geurts, P. Giubilato, V. Greco, F. Grosa, H. Hansen, J. Klein, W. Li, M. P. Lombardo, M. Masera, A. Masoni, L. Micheletti, L. Musa, M. Nardi, H. Onishi, C. Oppedisano, B. Paul, S. Plumari, F. Prino, M. Puccio, L. Ramello, R. Rapp, I. Ravasenga, A. Rossi, P. Roy, E. Scomparin, S. Siddhanta, R. Shahoyan, T. Sinha, M. Sitta, H. Specht, S. Trogolo, R. Turrisi, A. Uras, G. Usai, E. Vercellin, J. Wiechula

(Submitted on 19 Dec 2018)

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 ($\sqrt{s_{NN}} \sim$ 6-17 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. We propose in this document a new experiment, NA60+, that would address several observables which are fundamental for the understanding of the phase transition from hadronic matter towards 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 conclusive insights into the restoration of the chiral symmetry of QCD. In parallel, studies of heavy quark and quarkonium production would also be carried out, addressing the measurement of transport properties of the QGP and the investigation of the onset of the deconfinement transition. The document also 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 strong interaction physics. The document has been submitted as an input to the European Particle Physics Strategy Update 2018-2020 (this http URL).

Comments:	14 pages, 9 figures, submitted as an input to the European Particle Physics Strategy Update 2018-2020
Subjects:	**Nuclear Experiment (nucl-ex)**
Cite as:	arXiv:1812.07948 **[nucl-ex]**
	(or **arXiv:1812.07948v1 [nucl-ex]** for this version)

Observables

Requirements

Experimental layout

Detectors

Physics performances

Competition with Other measurements

Signed by 72 physicists from Germany, India, Italy, Japan, Switzerland, USA

Short and medium term plans

February 2019 → Submit an **Expression of Interest** for NA60+ to the SPSC
Based on the document submitted to the European Strategy, with minimal adjustments

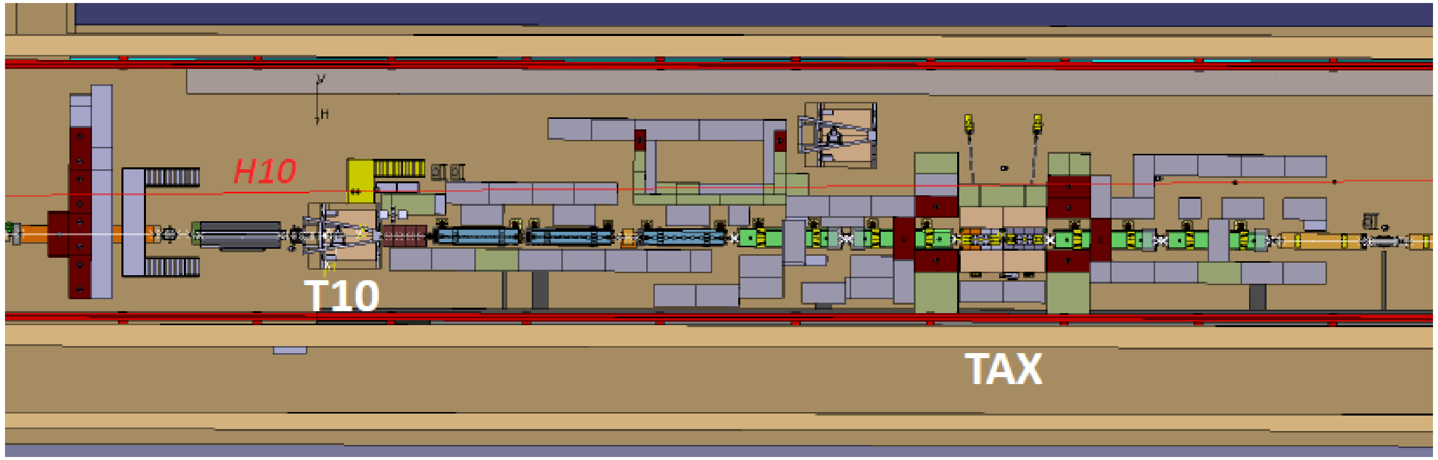
Summer 2019 → Submit a **Letter of Intent** for NA60+ to the SPSC
Physics performance studies only need minor adjustments
Detector studies: from conceptual design + detector options to a more realistic design, with preliminary sharing between groups

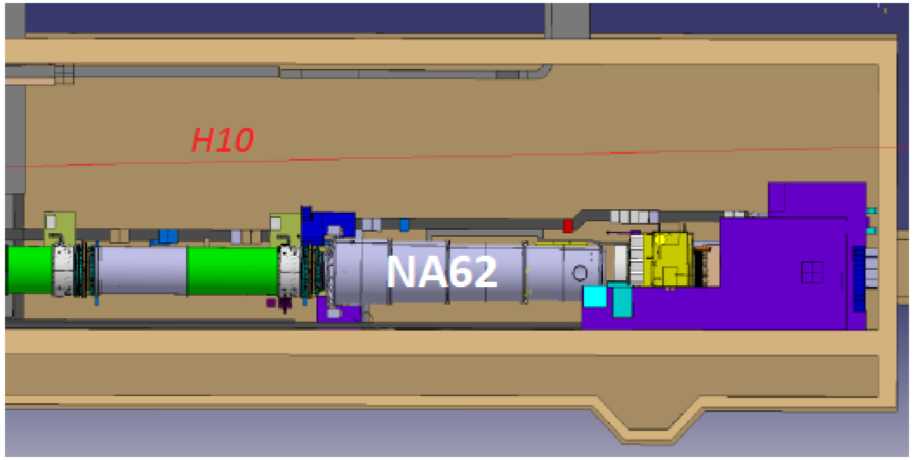
2019 → Present the NA60+ experiment to funding agencies, to obtain funding for starting activities (networking, manpower)

THE crucial item

- NA60+ needs a **high intensity ion beam** (~10^7/s), now only available in ECN3

- Requires **re-installation of the H10 beam line (beam optics existing and available)**
- According to Conventional Beam working group, no viable solution to have NA62 (or any other future experiment like KLEVER) in the same counting room





Some more thoughts

The heavy-ion community at large considers the physics that can be explored by NA60+ as **strategic for the field** in the next decade

> 2. *At lower center of mass energies where the highest baryon densities are reached, advances in accelerator and detector technologies provide opportunities for a new generation of precision measurements that address central questions about the QCD phase diagram.*
>
> …
>
> The Town Meeting also observed that the CERN SPS would be well-positioned to contribute decisively and at a competitive time scale to central open physics issues at large baryon density with proposals like NA60+. In particular, the CERN SPS will remain also in the future the only machine capable of delivering heavy ion beams with energies exceeding 30 GeV/nucleon, and the potential of investigating charm production and rare penetrating probes at this machine is attractive.

Conclusions of the Town Meeting: Relativistic Heavy Ion Collisions
https://indico.cern.ch/event/746182

We would like to ask CERN (through Physics Beyond Colliders initiative) to define a plan for the use and the development of the facilities of the laboratory, in such a way to allow both KLEVER and NA60+ to take data after LS3

Conclusions

- Recently submitted contribution to European Strategy, https://arxiv.org/abs/1812.07948 contains a summary of the present status of NA60+ related studies
- Proto-collaboration formed, regular meetings started (next one January 23)
- Expression of interest to be sent to the SPSC by February
- 2019 activities
  - From concept set-up to a realistic set of detectors → Preparation of a Letter of Intent
  - Consolidate (and extend!) the Collaboration
  - Start negotiations with funding agencies
- Availability of (an) experimental hall is the crucial item, default (ECN3) or alternative locations to be sorted out