Prospects on fixed-target heavy ion physics opportunities at CERN

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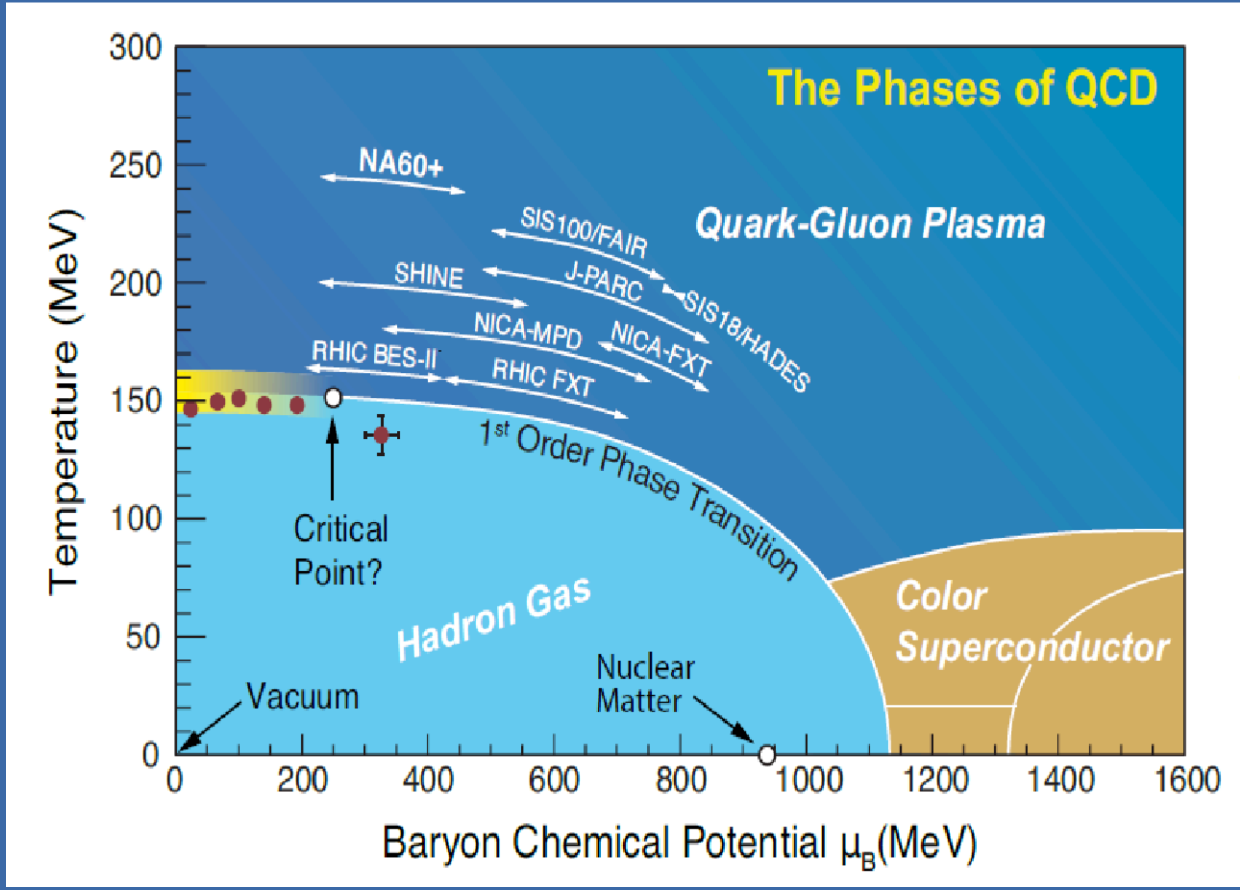
The phase diagram of QCD at low baryonic density

Phase diagram of QCD:
temperature vs net baryonic density μ_B



Explored at collider energy
RHIC (Au-Au) $\sqrt{s_{NN}}$=0.2 TeV
LHC (Pb-Pb) $\sqrt{s_{NN}}$=5.02 TeV

Main results

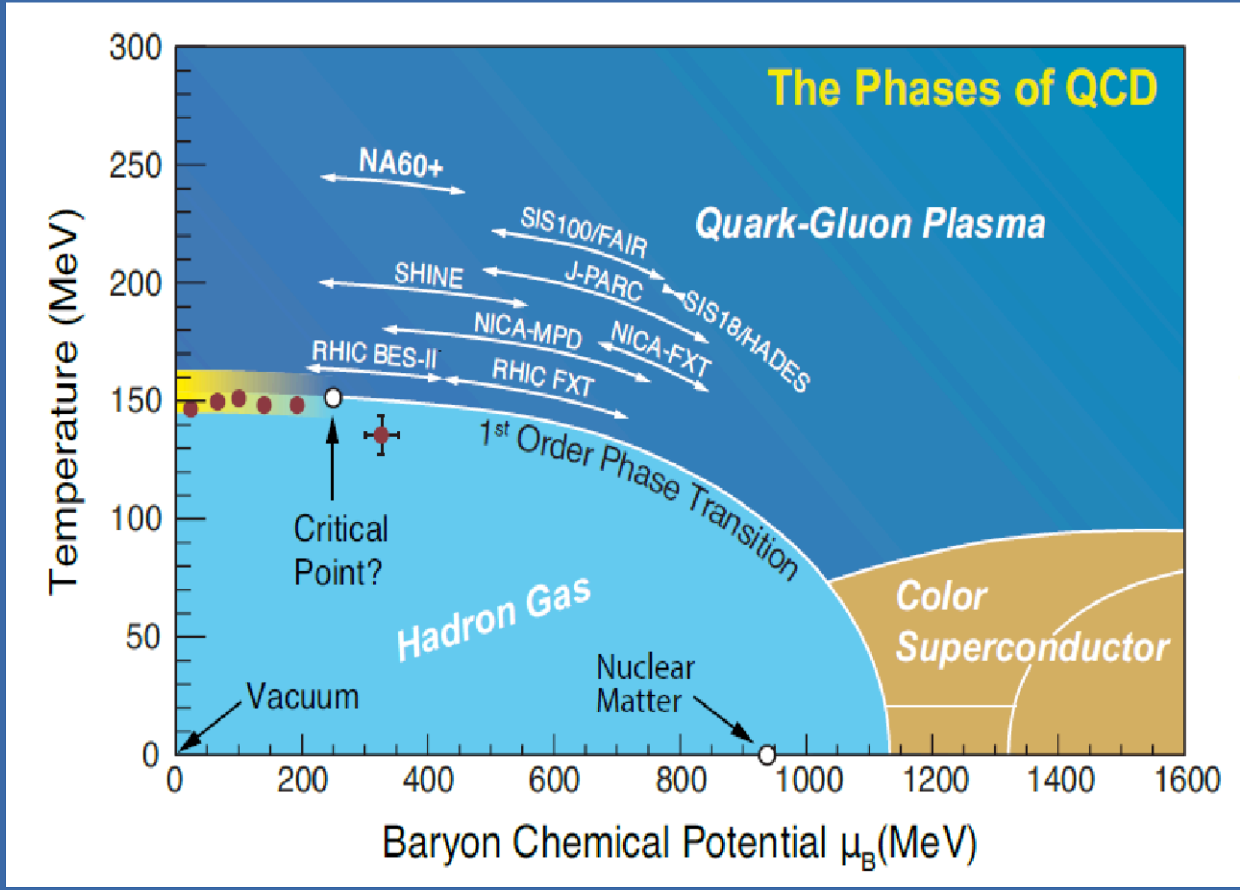
- High energy density QGP formed ($\varepsilon >> \varepsilon_c \sim$ 1 GeV/fm^3)
- Long-lived QGP phase (perfect fluid)

- Smooth cross-over between hadronic matter and QGP (no latent heat)

But we still do not now if QCD has a true phase transition

The phase diagram of QCD at high baryonic density

Phase diagram of QCD:
temperature vs net baryonic density μ_B



Many effective models suggest **1st order phase transition ending with a critical point (CP)**

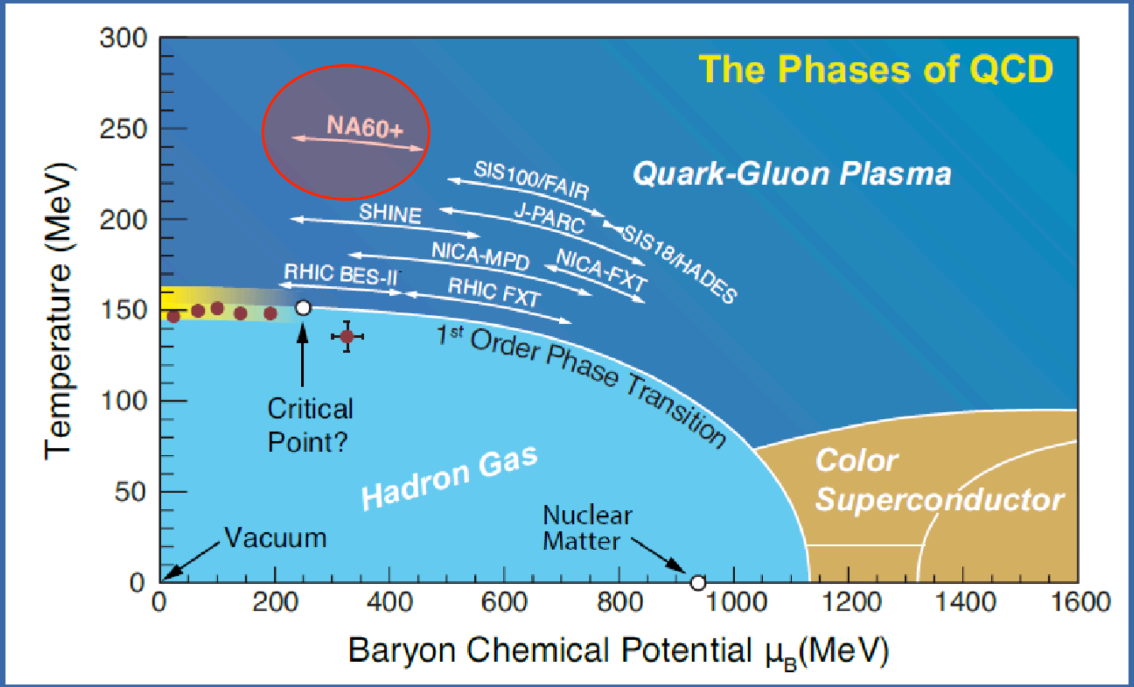
High μ_B accessible at lower collision energy ($\sqrt{s_{NN}}$<~20 GeV)

CP main motivation of RHIC BES:

- some intriguing results from phase 1, but statistically limited

A new experiment at the CERN SPS: NA60+

Investigation of the QCD phase transition at high-μ_B by precision measurements of hard and electromagnetic processes



Electromagnetic processes

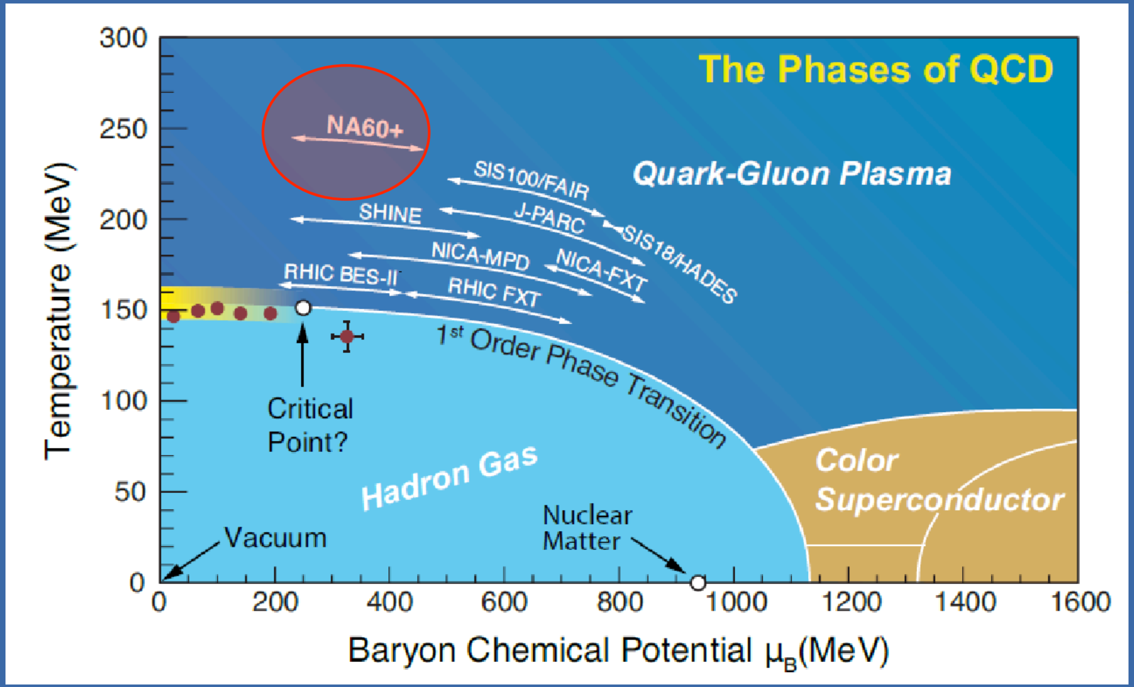
- temperature of the system (QGP and/or Hadronic) → nature of the phase transition
- approach to QCD chiral symmetry restoration

Hard QCD processes

- probe Quark-Gluon Plasma and its transport properties

A new experiment at the CERN SPS: NA60+

Investigation of the QCD phase transition at high-μ_B by precision measurements of hard and electromagnetic processes



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

Proposal: study Pb-Pb collisions at lower SPS energies, down to $\sqrt{s_{NN}}$=4.9 GeV for Pb-Pb, **via an energy scan**

Strong physics case: QCD phase transition if it exists, is likely the only one involving fundamental degrees of freedom of standard model accessible to laboratory experiments

Uniqueness of CERN SPS/NA60+

NA60+ is part of a considerable effort of the community for the study of the high μ_B region of the phase diagram → **Several facilities and experiments planned in the next decade**

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

CERN SPS/NA60+ is central and unique:

- Coverage of a **very wide μ_B region**
- **Precision physics**: possibility of reaching **very high interaction rates** (>MHz)

Energy range complementary to FAIR/GSI

Ideal mapping of a large region of the QCD phase diagram with rare processes

NA60+: physics observables

Emphasis on **(di)muon production**

Experimental apparatus: based on a **muon spectrometer,** coupled to a **vertex detector**, which provides accurate information on the primary and secondary vertices

Optimized to measure:

- **Thermal dimuons from QGP/hadronic phase**: **caloric curve for first order transition**
- **ρ-a_1 modifications: chiral symmetry restoration**
- **Quarkonium suppression: signal of deconfinement**

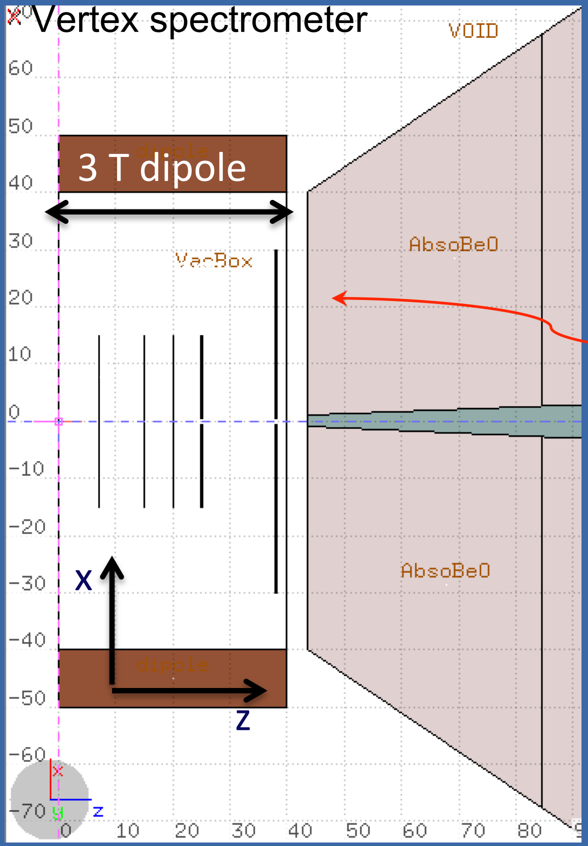
With the same experiment one can also address

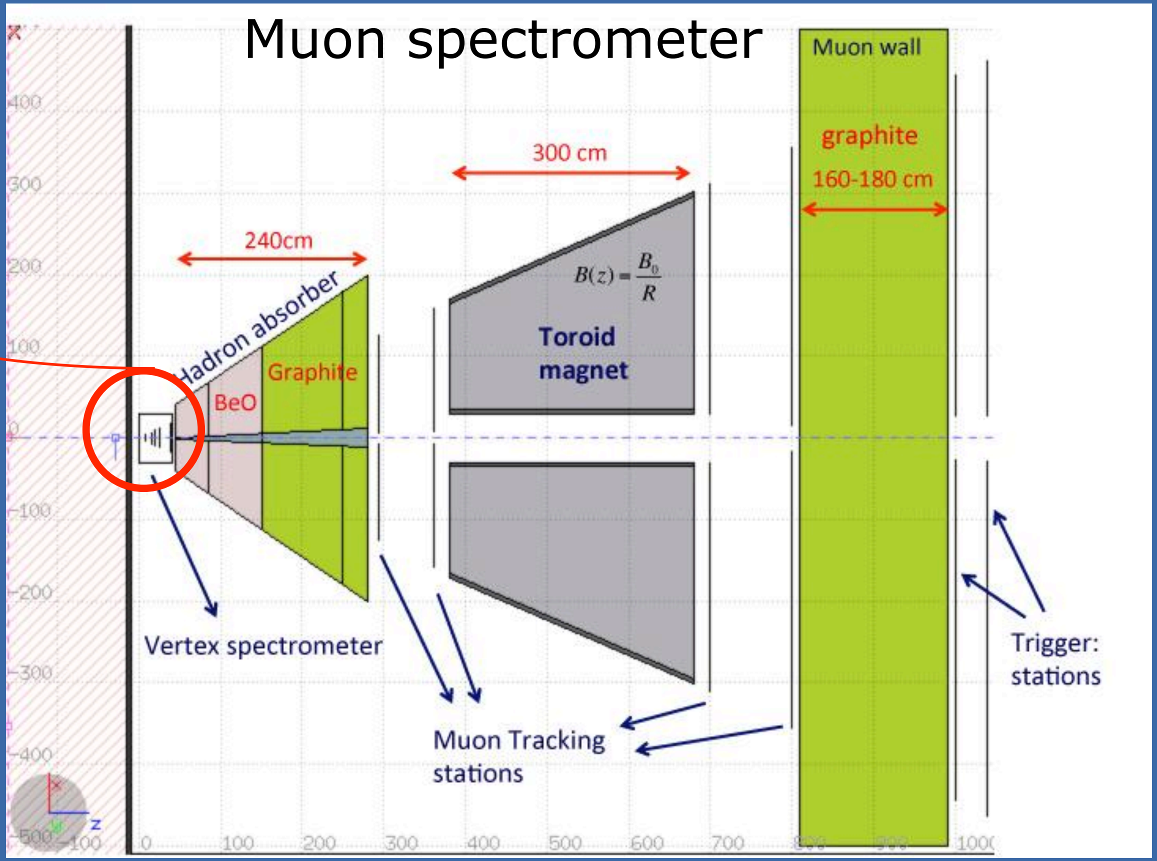
- **Hadronic decays of charmed mesons/baryons: QGP transport coefficients**

Study of these physics topics: high intensity Pb beams (> 10^7 ions/s)

p-A also mandatory, to calibrate cold matter effects

NA60+: detector concept

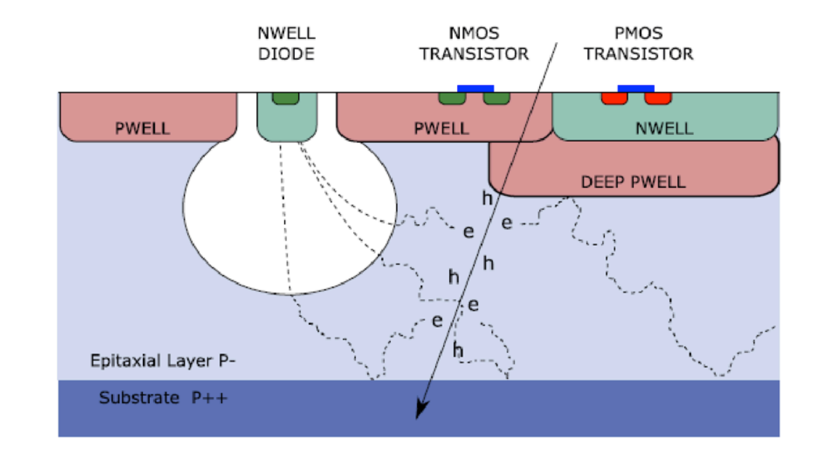


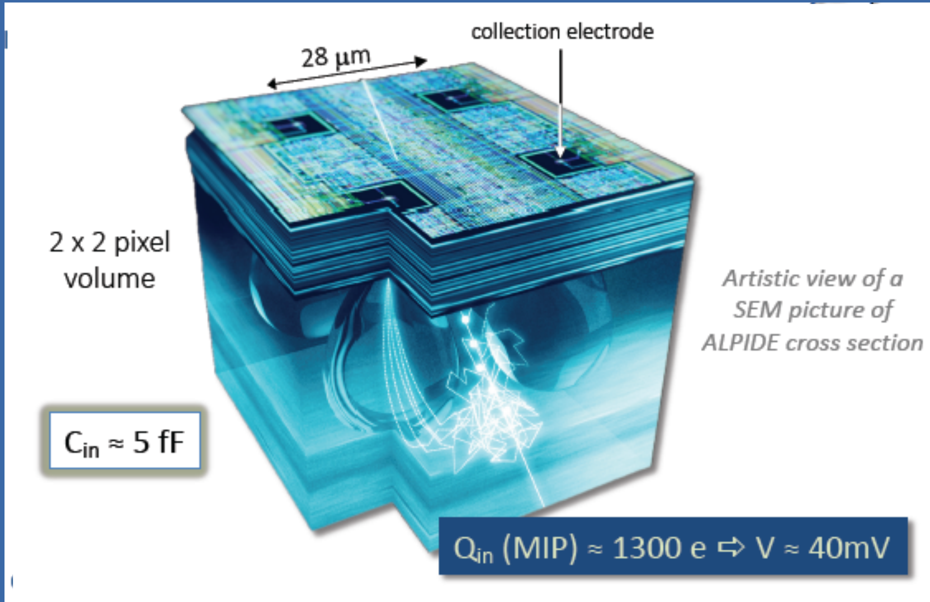


Energy scan at SPS energy → Muon spectrometer length needs to be scaled, to keep the same center of mass coverage at the various collision energies

Vertex spectrometer: technology choice

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





Advantages over hybrid pixel sensors

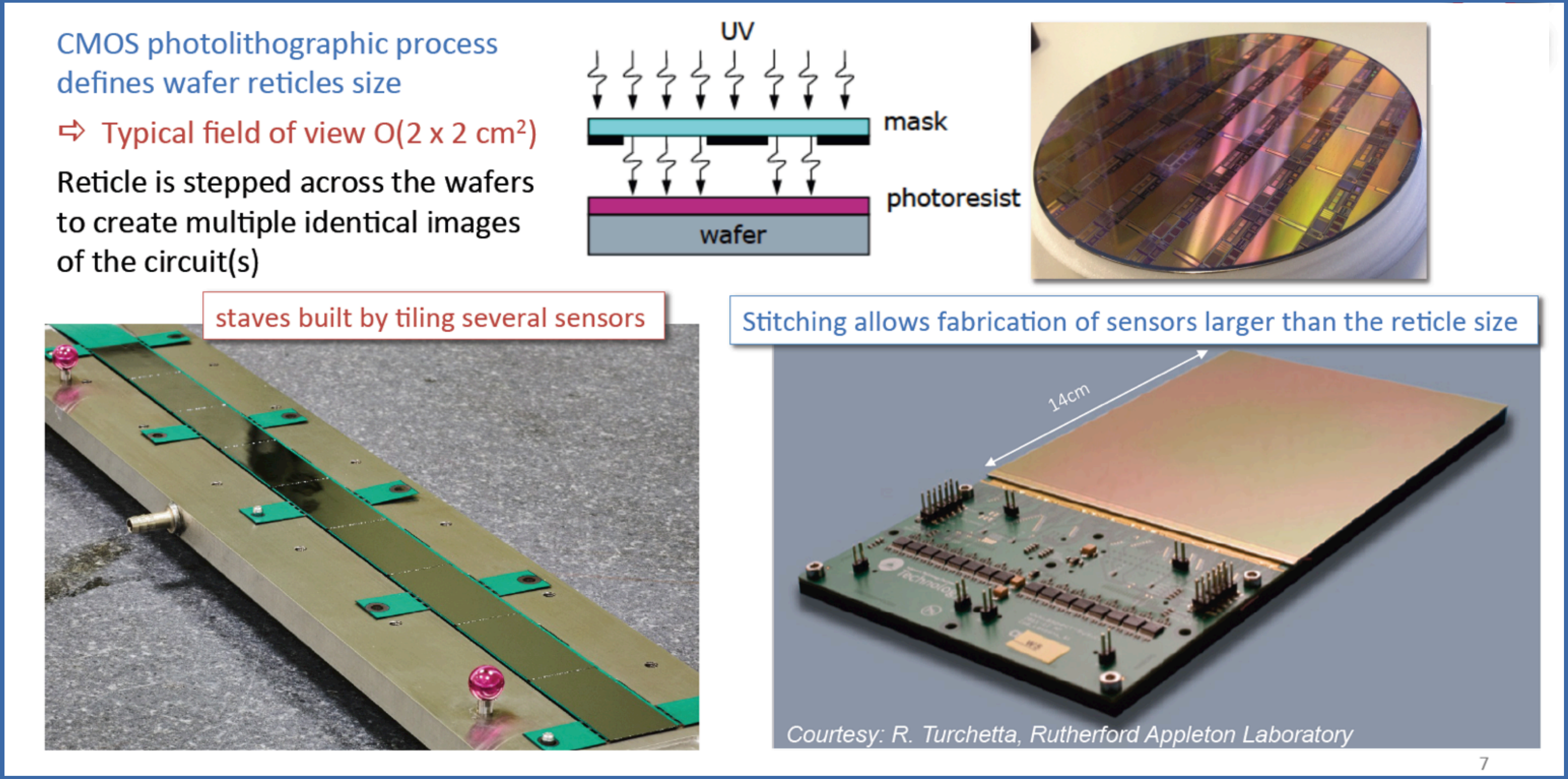
- Sensor and frontend electronics in the same silicon wafer with NO Bump-bonding: factor 2 cost reduction
- pixel pitch of 30 μm: factor 3 better resolution (5 μm)
- Material budget of 50 μm thickness: factor 10 smaller X_0

NA60: profit of new development with TowerJazz process 65 nm

Significantly improved performance:

- Pixel pitch < 20 μm
- Large area (wafer-scale) with stitching
- radiation tolerance: $O(10^{15})$ n_{eq}/cm^2
- data rate: 100 MHz/cm^2
- Event time resolution: 200 ns

Stitching: wafer-scale MAPS



These days, **stitching** is widely applied in the digital imaging industry (e.g. large flat panels for **medical and dental X-rays**)

Stitched-MAPS: new R&D for a wafer-scale MAPS

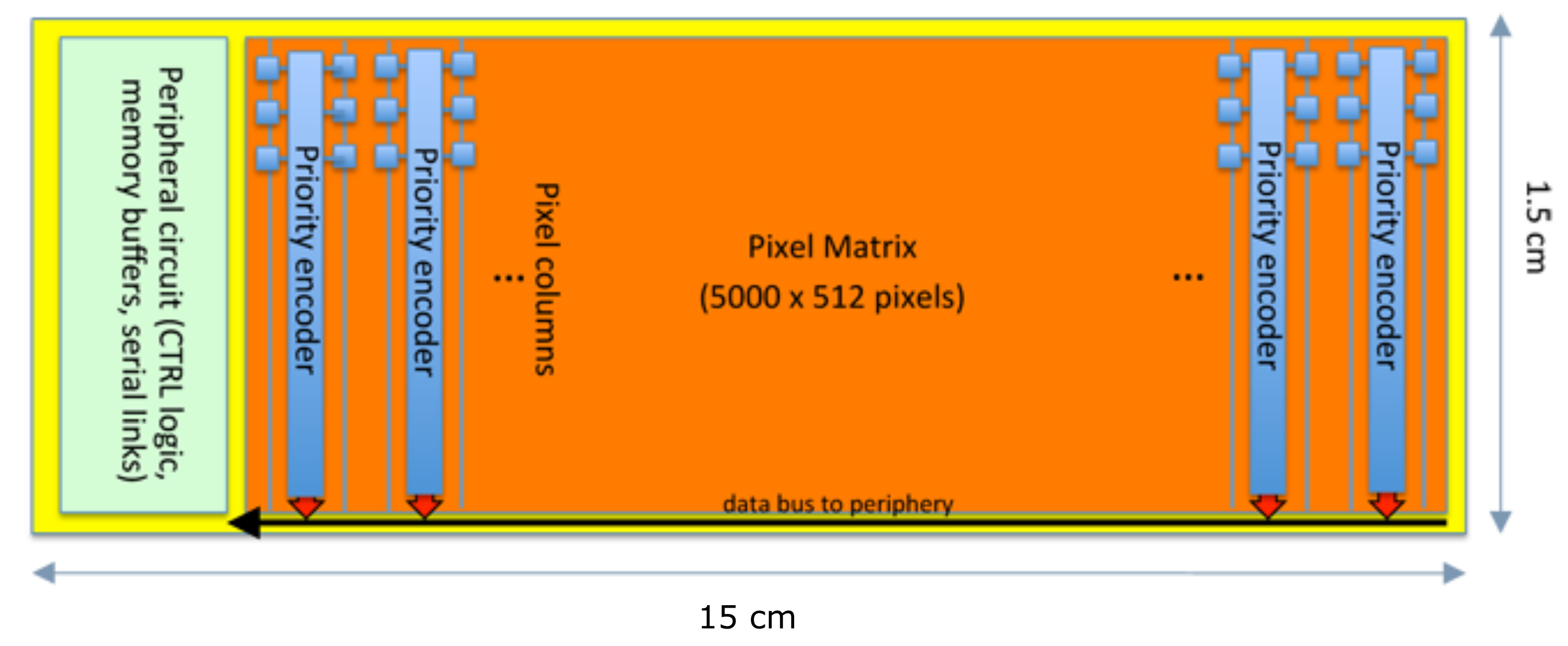
A novel large area, fast, radiation-tolerant monolithic active pixel sensor for tracking devices of unprecedented precision

- **Funded project with 1 MEuro** (starting September 2019)
- **Cagliari University, Bari University and Politecnico, INFN** (G. Usai et al.)

Common R&D effort together with CERN and other labs

New sensor suitable for different applications:

- NA60+
- ALICE LS3 upgrade
- CLIC vertex detector
- Proton computer tomography scan for hadron therapy

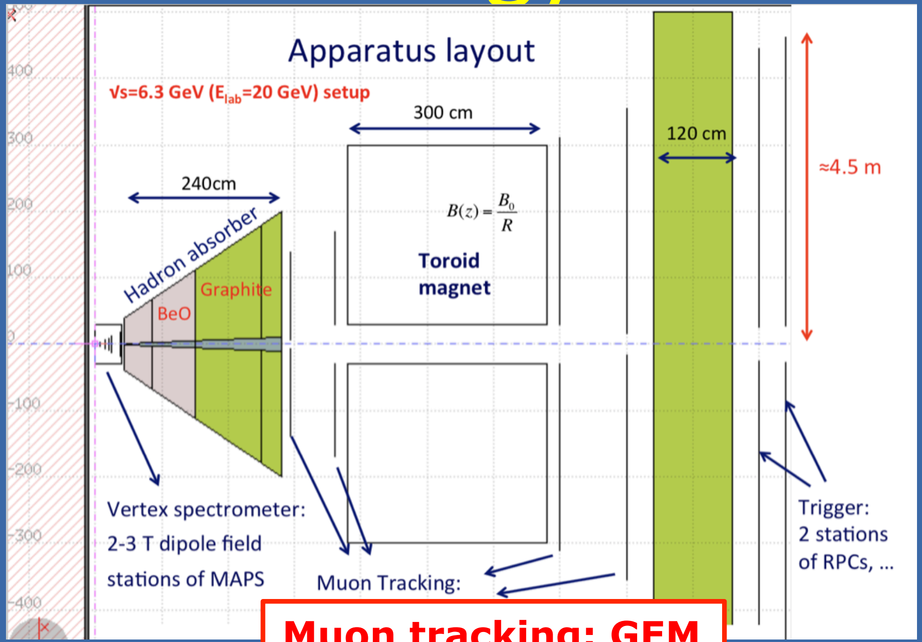


Migration of the design to Tower 65 nm →<20 μm pixel pitch

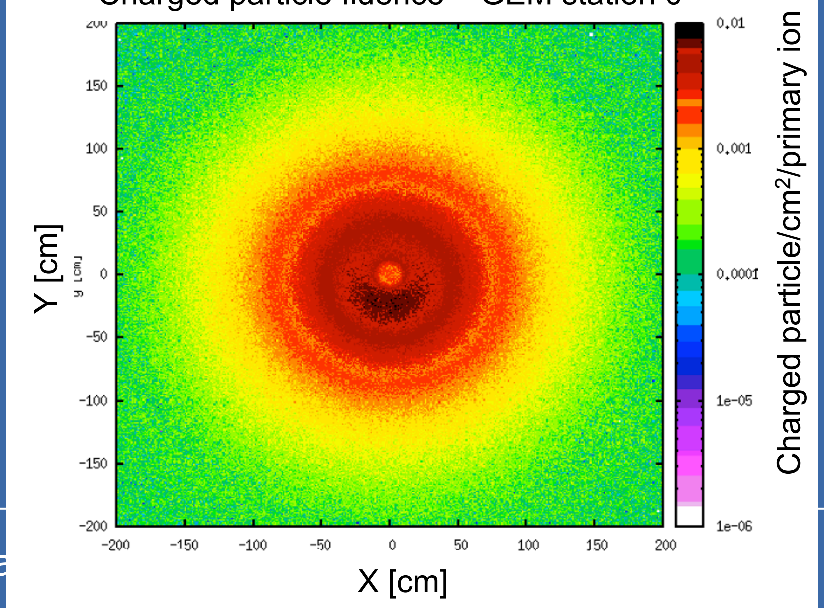
Muon tracking: choice of detector technology

Gas Electron Multipliers (GEM)

- **- Position resolution < 100 μm**
- **- Timing resolution < 10 ns**
- **- High rate capabilities of O(1 MHz/cm²)**
- **- Radiation hardness**
- - Can be stacked easily:
  - – Higher gains (up to 10^5)
  - – Improved stability against electrical discharges
- - Solution chosen for **ALICE TPC Upgrade** and **CMS Muon Endcap Upgrade**



Muon tracking: GEM



NA60+: 4 stations, behind the absorber, total area 116 m²

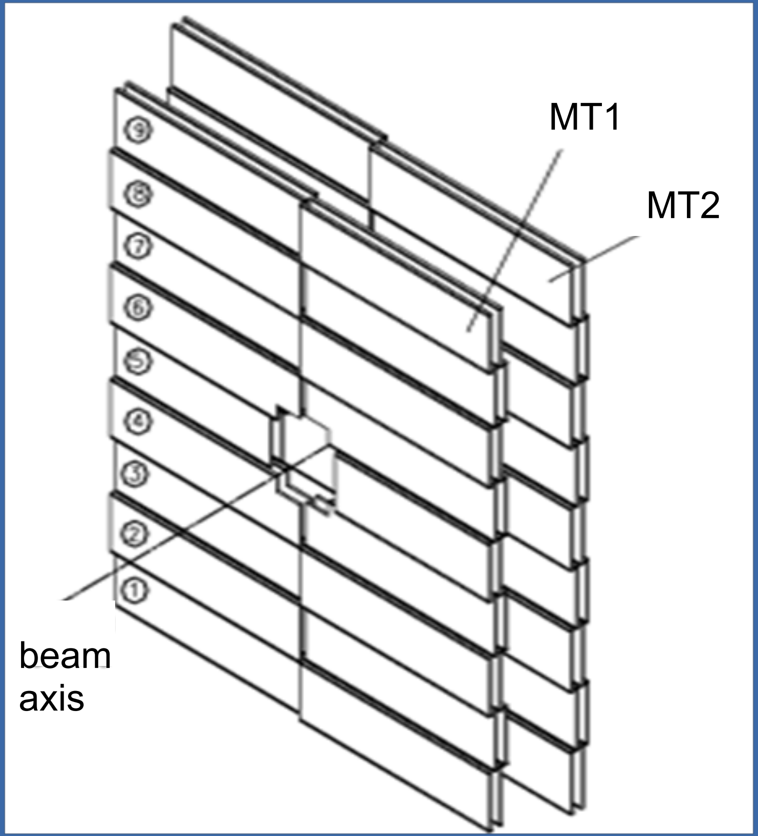
Max. fluence/ion = **50 kHz/cm² in innermost region**

Still factor **10 lower** than inner LHCb chambers!

Closing in on detector choices: muon selection

Muon selection: RPC

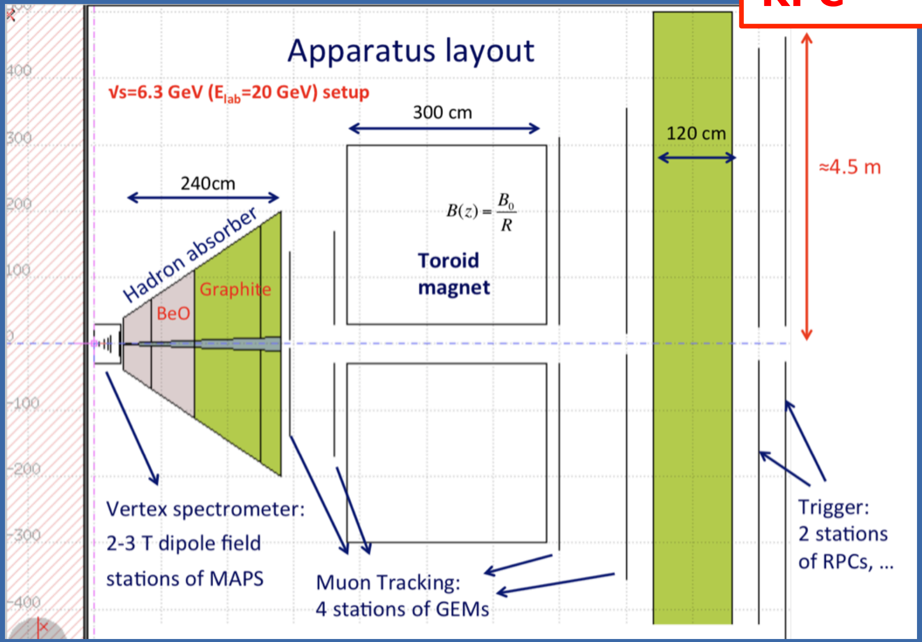
Default choice → **Resistive Plate Chambers (RPC)**



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

Set-up identical to ALICE:

- 2 stations, 2 planes each



Under discussion:

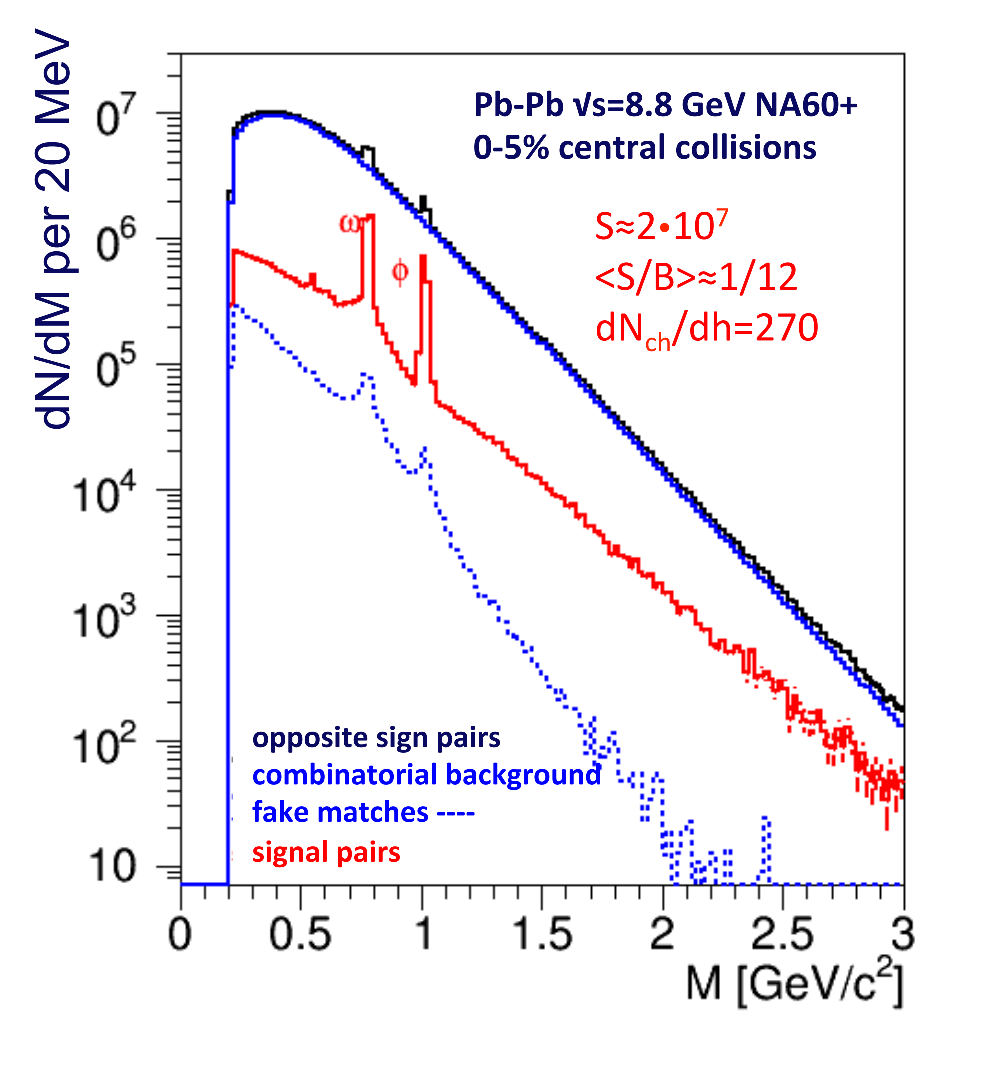
- Muon triggering (50 kHz dimuon signal):

- ask for a coincidence of 3 out of 4 planes

- Triggerless readout:

- All collisions are readout; RPCs used for muon identification

Dimuon spectra with NA60+



Statistics goal:

- $2 \cdot 10^7$ reconstructed signal pairs in 0-5% central events - factor 100 over NA60
- Similar data sets at several different energies in $6 < \sqrt{s} < 17$ GeV

Physics Goal:

- **Thermal spectrum (QGP+hadronic), J/ψ**

Requires:

- subraction of background
- Subtraction of η, ω, ϕ, DD and Drell-Yan
- Acceptance correction

Exploring the QCD phase transition

→Caloric curve:

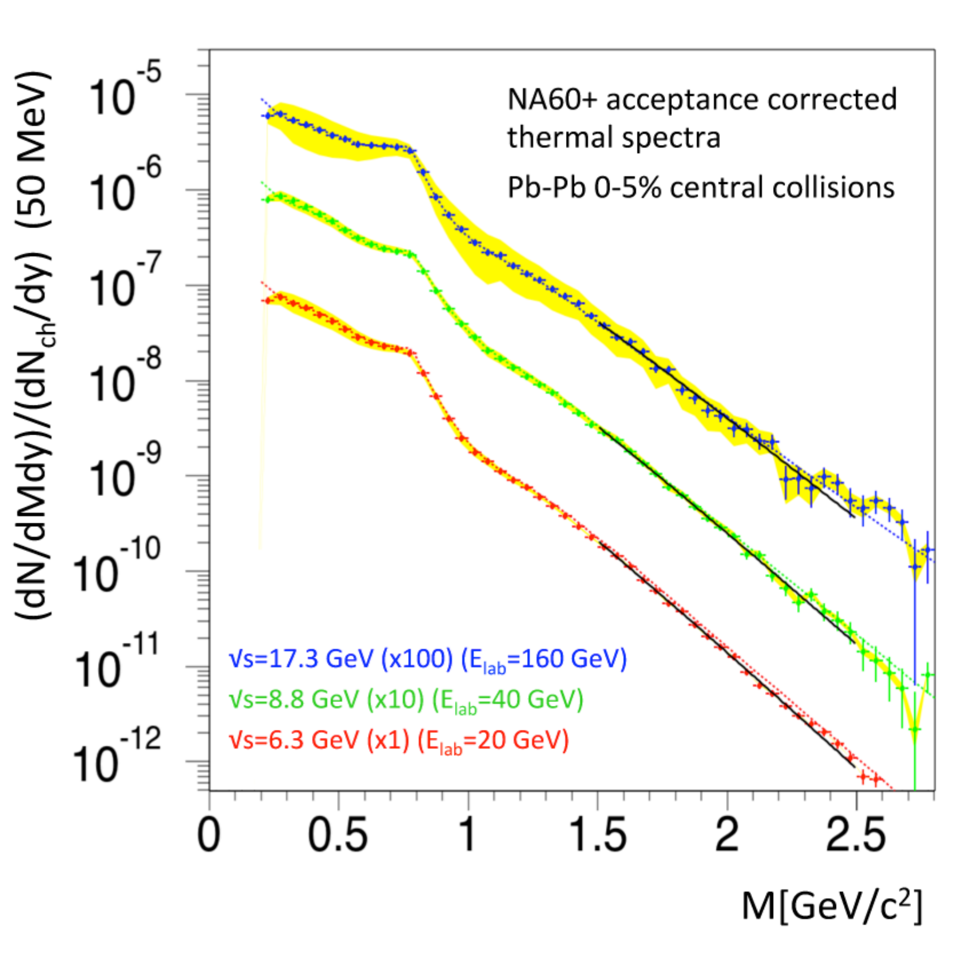
- Map the evolution of T vs collision energy

- 1st order transition: plateau in a caloric curve

- T measurement from dimuon spectrum of thermal radiation for M>1.5 GeV: fit with

$$dN/dM \propto M^{3/2} \exp(-M/T_s)$$

- T_s → **space-time average of thermal T over fireball evolution**
- **Beam energy scan to vary collision energy**



Thermal spectrum (QGP+hadronic) after subraction of η, ω, ϕ, DD and Drell-Yan

Physics performance: nature of the phase transition

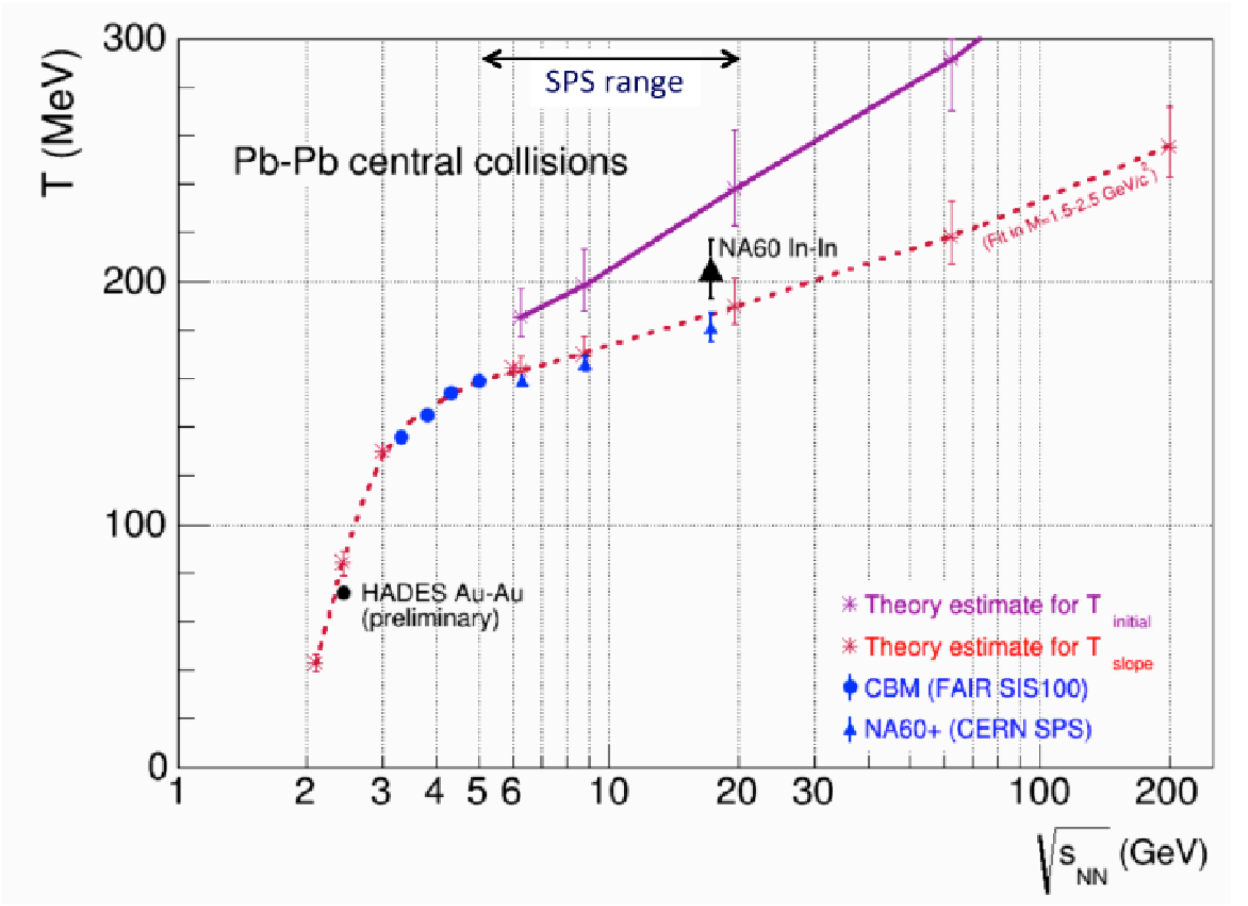
Measurement of medium T from thermal dimuons → Caloric curve:

- Map the evolution of T vs collision energy with **MeV precision**
- **1st order transition: plateau in a caloric curve**

Only two measurements at present:
- NA60: T_s = 205 ± 12 MeV
- HADES: T_s = 72 ± 2 MeV (prelim.)

No other experiment able to measure T in the wide SPS energy range

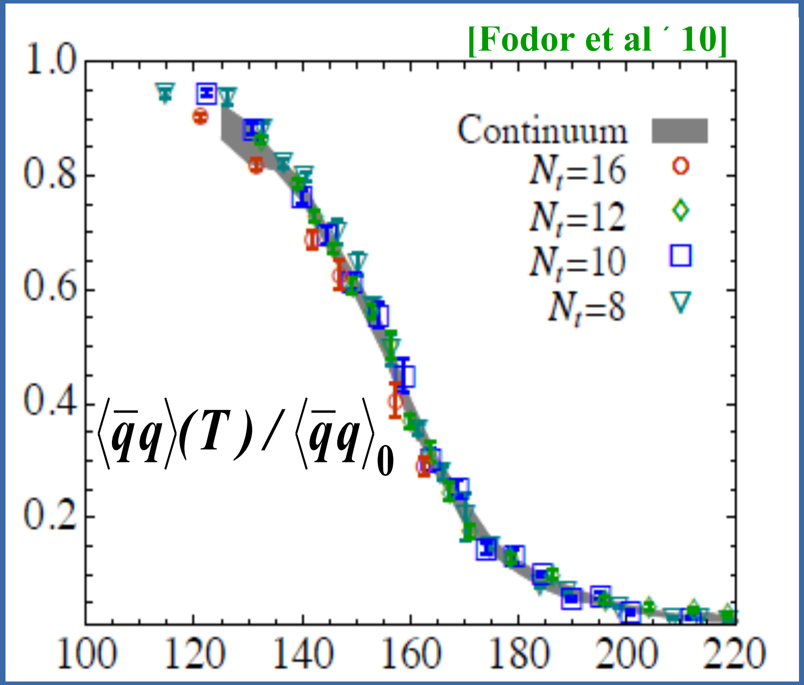
Complementary to future measurement at FAIR energies

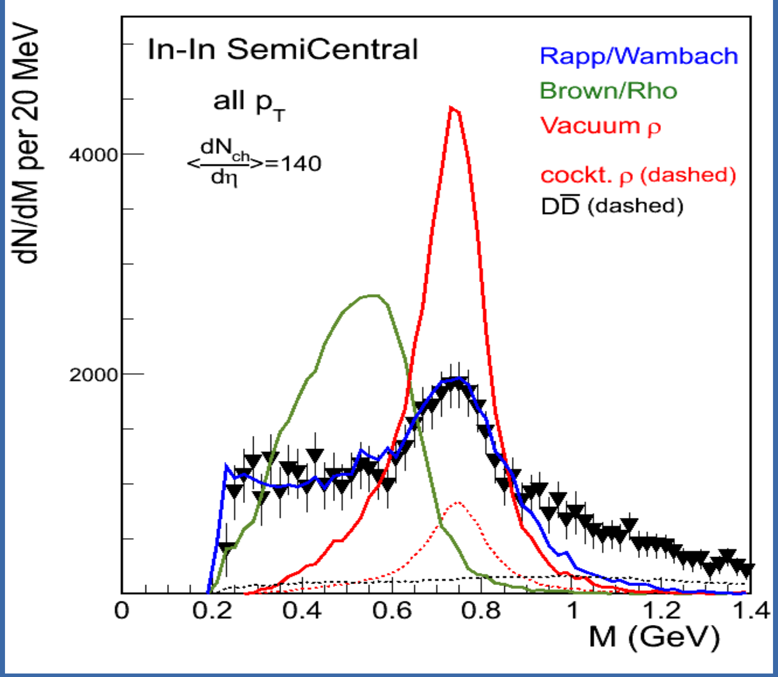


Chiral symmetry restoration in heavy ion collisions

Chiral symmetry: fundamental property of QCD and standard model

Lattice QCD: melting of the chiral condensate at the phase boundary



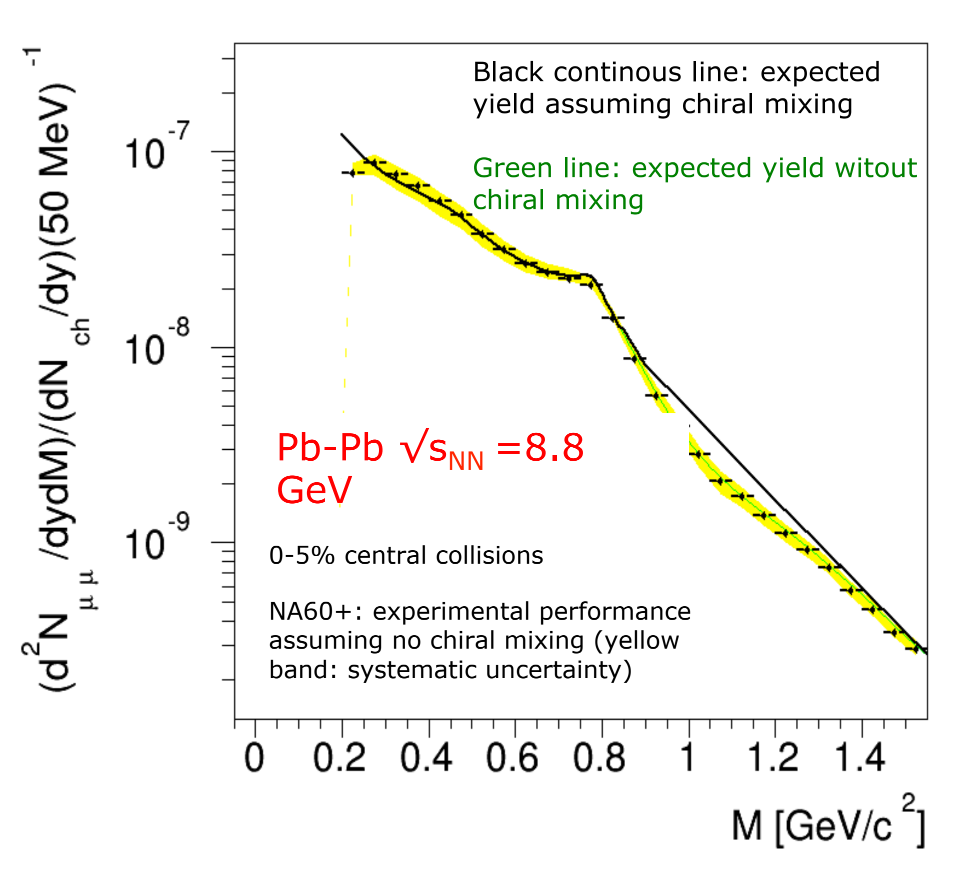


ρ meson in In-In collisions (NA60):

- **strong broadening** observed (no mass shift) → 'hadron melting'
- **indirect evidence** of chiral symmetry restoration

No direct measurement of chiral restoration: requires access to chiral partner a_1

Direct measurement of chiral restoration: ρ-a_1 mixing



- 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**

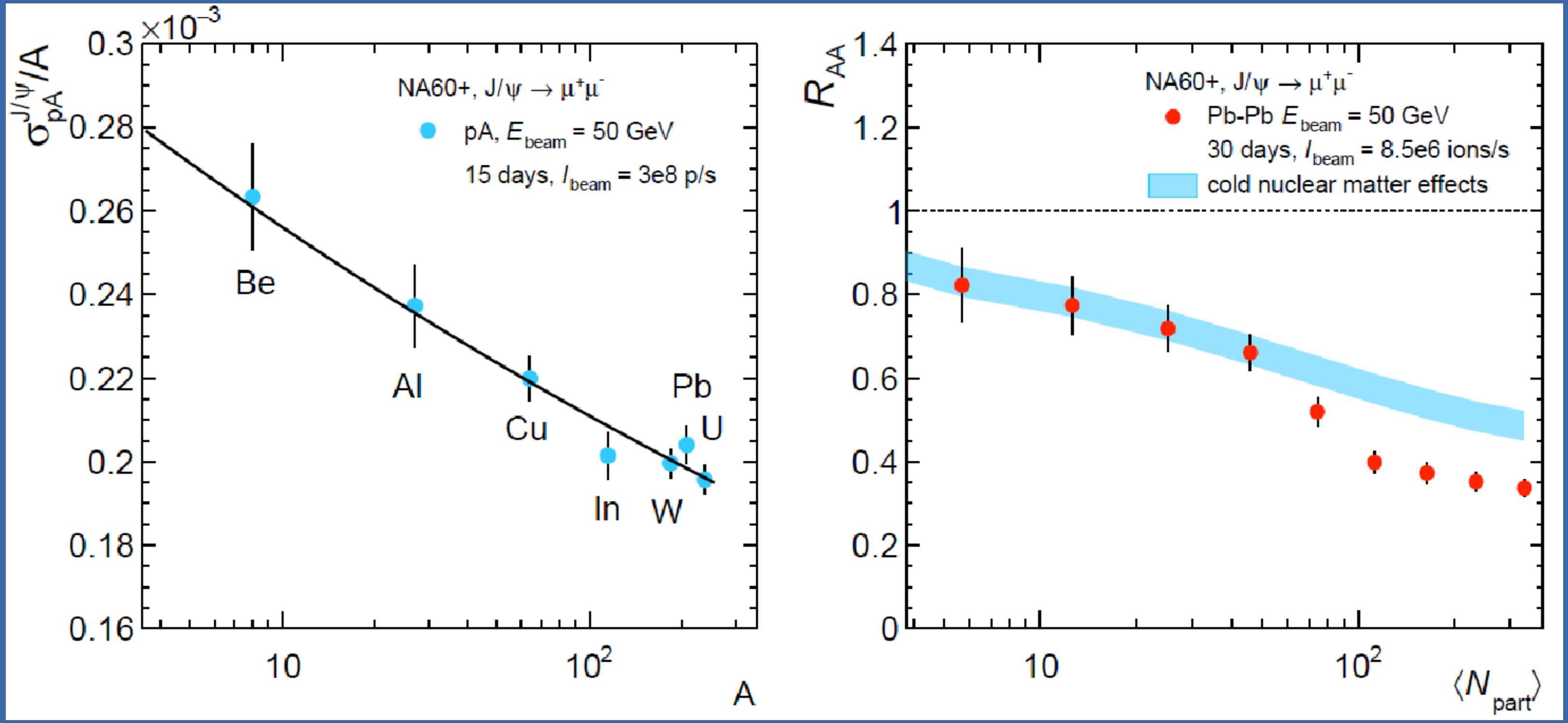
- Measurement challenging, but **sensitivity to enhancement! (~30% effect)**

Signal optimized at low energy (QGP negligible)

- Very difficult if/not impossible to measure at RHIC/LHC energies
- Sensitivity might improve further at √s=6.3 GeV (theoretical input needed)

Quarkonium production at low energies

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



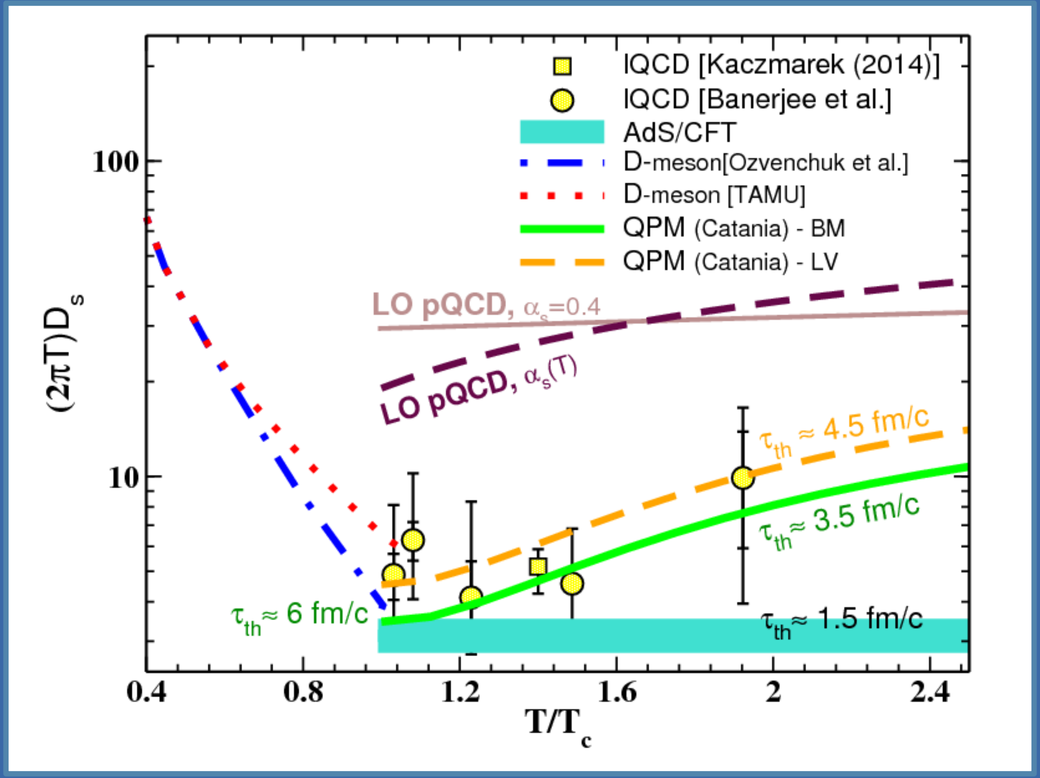
Look for the **onset of J/ψ suppression** due to melting of X_c and ψ(2S) and corresponding disapperance of their decay J/ψ (direct J/ψ likely not melting at SPS energy)

No existing data below $\sqrt{s_{NN}}$=17.3 GeV

High precision measurements possible down to **$\sqrt{s_{NN}}$=10 GeV** and **no other experiment** able to do the measurement

Measurement of **other quarkonium states** (ψ(2S), χ_c) → studies ongoing

Open charm at low energies



Phys. Rev. C96 (2017) 044905

Charm **diffusion coefficient larger in hadronic phase** than in a QGP around T_c (measurement also important for LHC!)

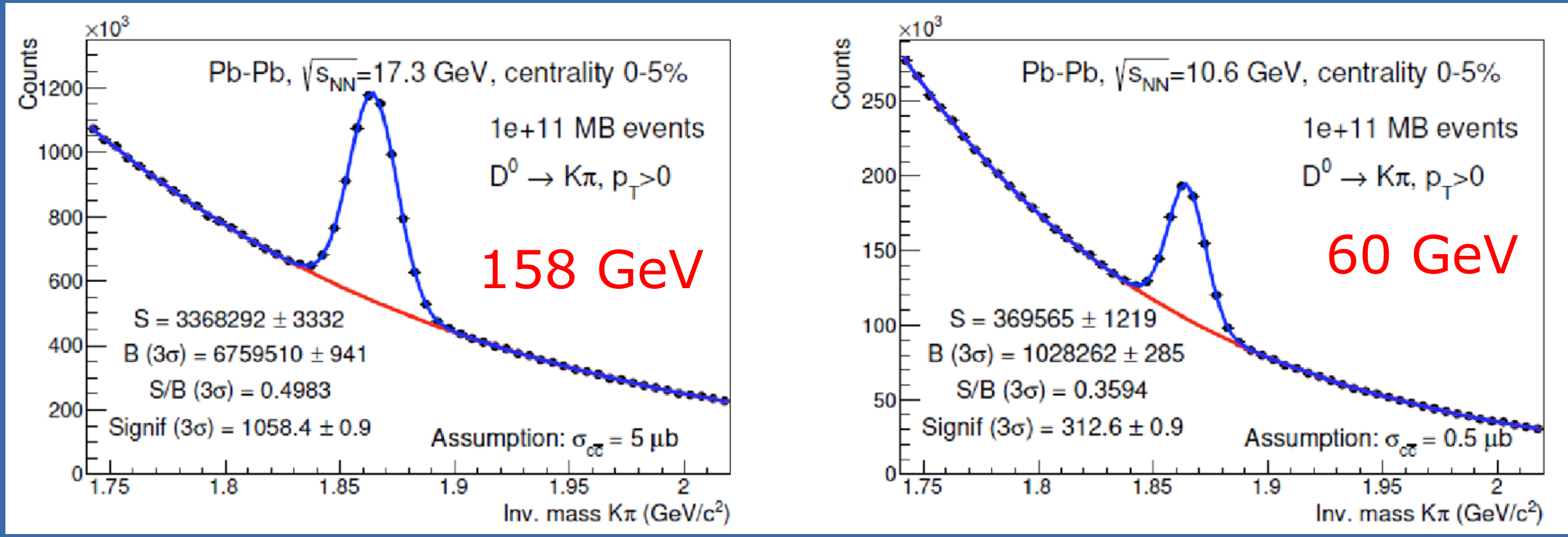
Ideal **normalization for J/ψ** measurements

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: D mesons

$D^0 \rightarrow K\pi$ as benchmark (3 prong decay studies in progress)
N.B.: **S/B before selection is ~10^{-7}!**



High precision data:
- More than 3×10^6 D^0 at $\sqrt{s_{NN}}$=17.3 GeV
- Systematics at different energies

Unique simultaneous measurement of hidden and open-charm

Measurement of **other states** (D_s, Λ_c) highly relevant → studies ongoing

NA60+ Expression of Interest

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

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

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]

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

Outlook

CERN SPS/NA60+: unique opportunity for investigating fundamental aspects of QCD phase diagram

- Presently discussed within CERN Physics Beyond Colliders and European Particle Physics Strategy Upgrade (EPPSU)

Timeline

- 2019-22 → formation of collaboration; detector R&D (pixels, toroid magnet starting now)
- 2020/21 → after EPPSU output CERN decision about approval
- 2023-25 → construction

Data taking

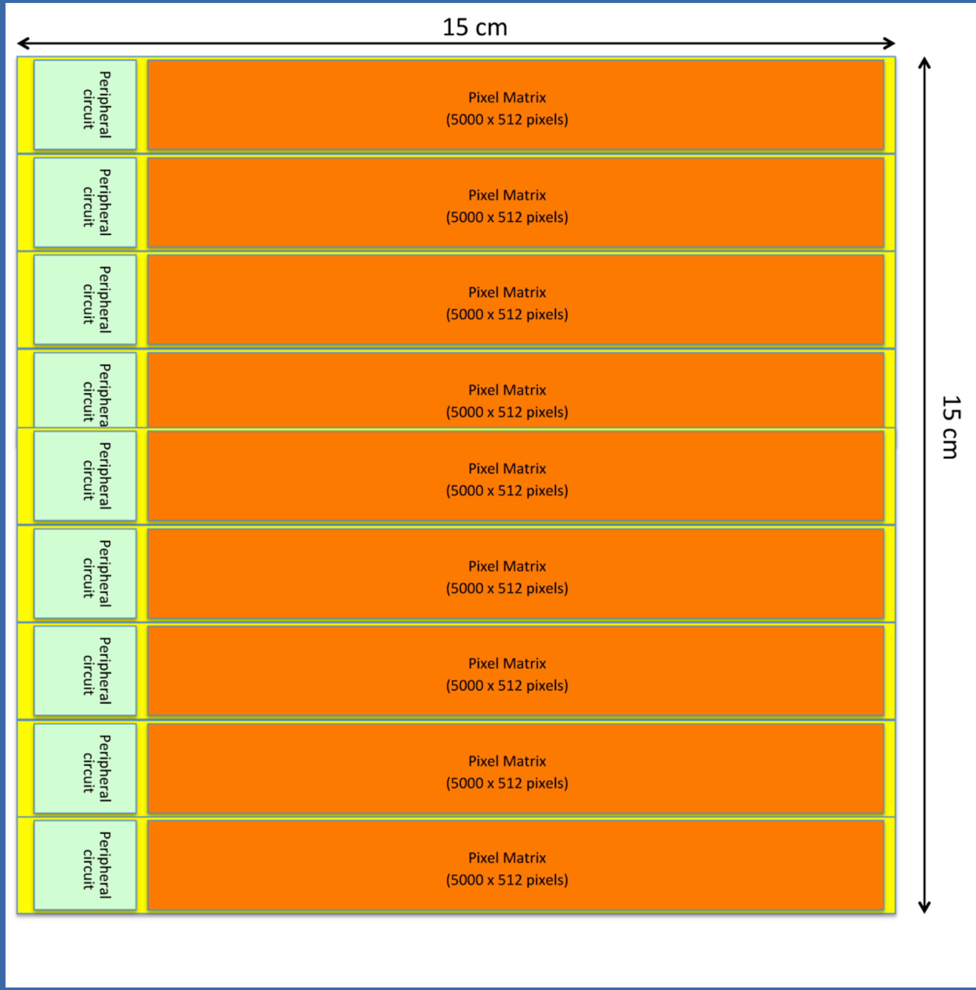
- From 2026 → in parallel with LHC run 4

Dedicated workshop at ECT* - Trento on the NA60+ physics:

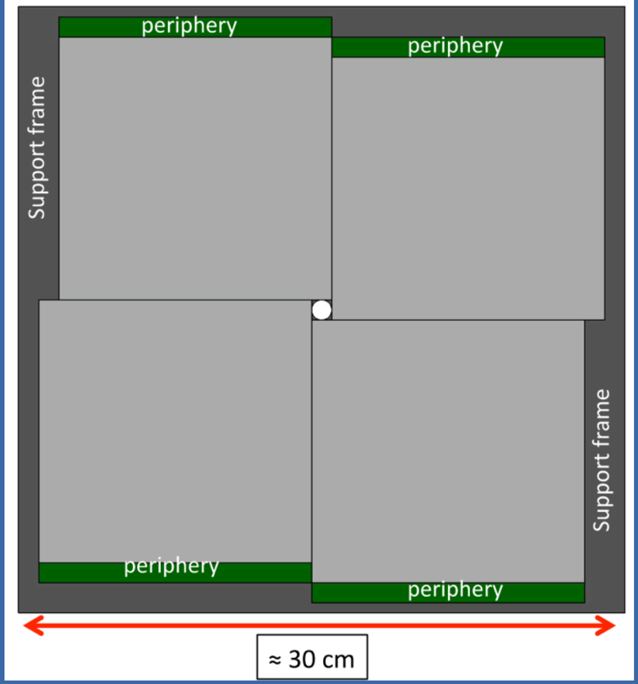
- Exploring high-μ_B matter with rare probes – 21-25 september 2020

Backup

Silicon tracking stations



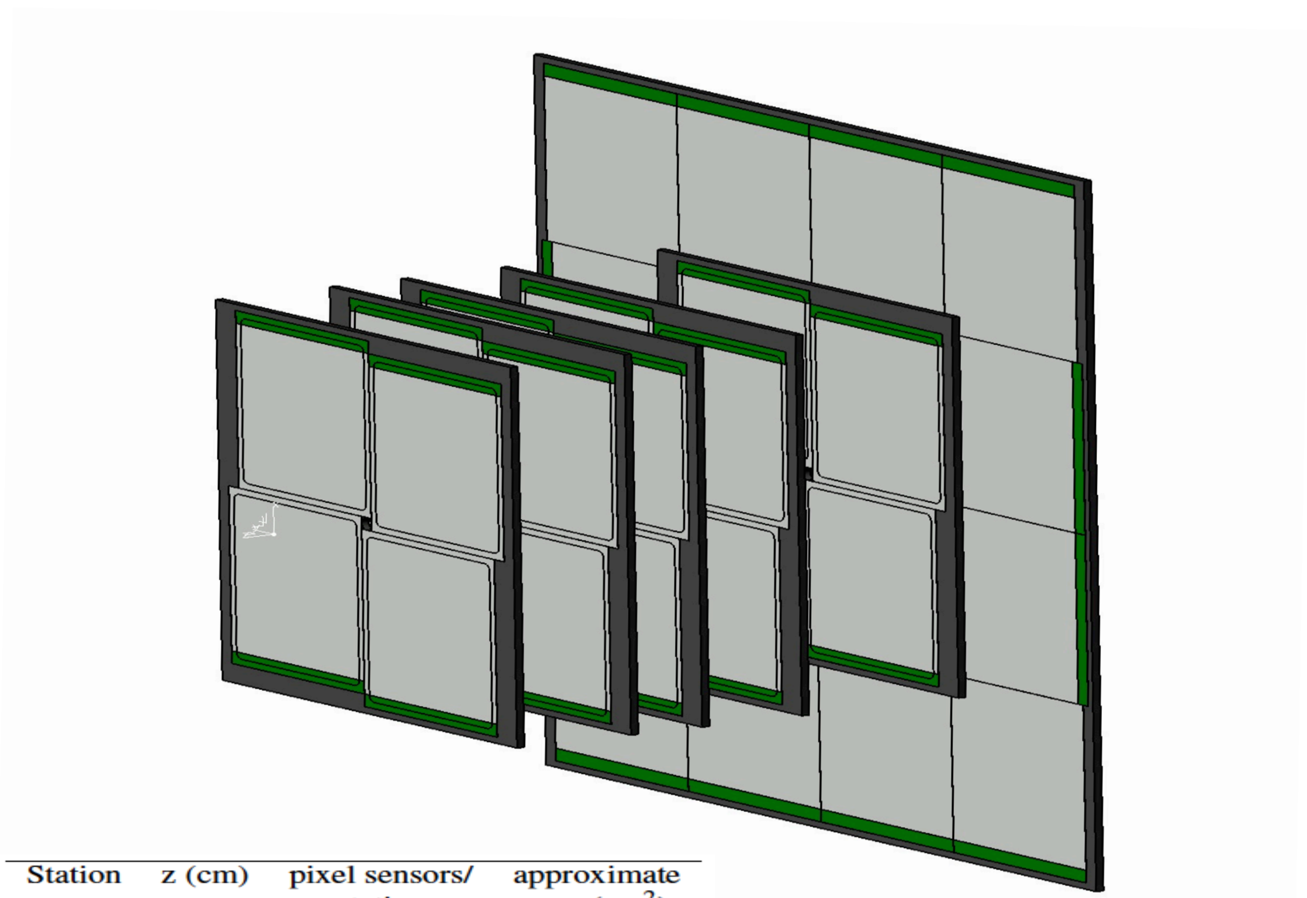
Sensor periphery contains the control logic, the interfaces for the configuration of the chip and the serial data transmitters



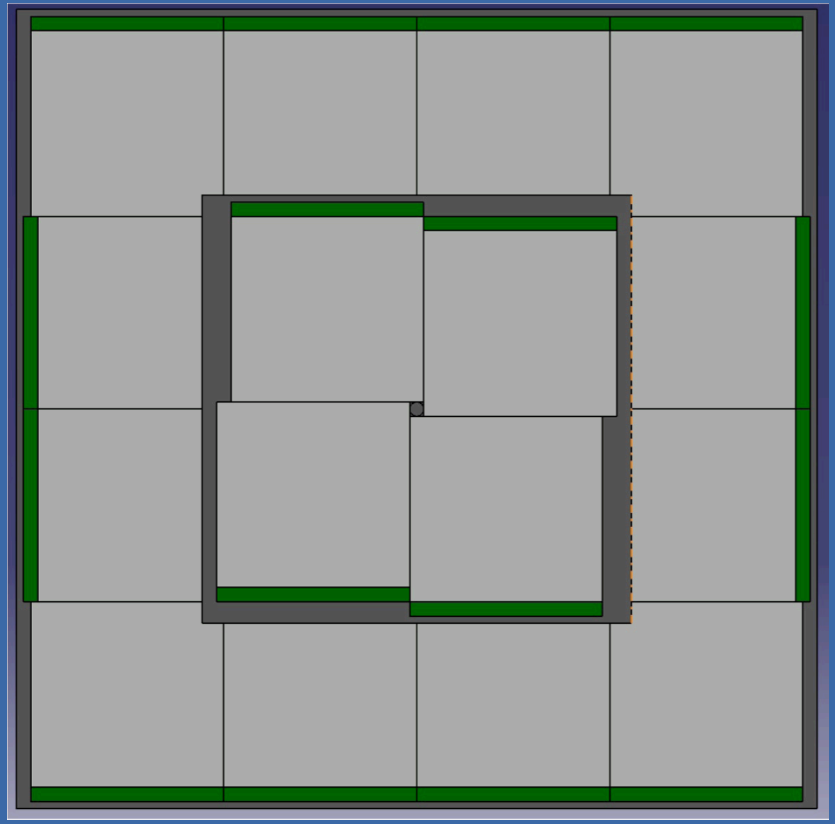
Mechanical support structures and cooling only on the borders, outside from acceptance

Opens up the possibility of producing
- **thin** (0.05 – 0.1% X_0)
- **large area** (~ 15 × 15 cm^2) sensors → ideal for NA60+
- **high granularity** (<5 μm resolution)

Silicon tracking stations for NA60+

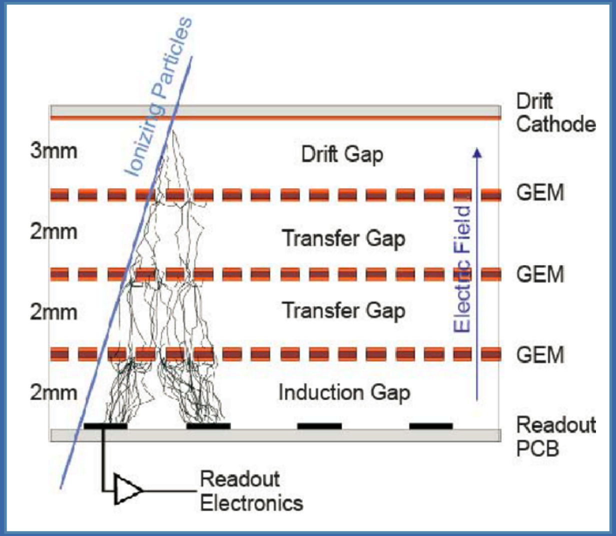


Station	z (cm)	pixel sensors/ station	approximate area (cm^2)
S0	7.0	4	30x30
S1	15.0	4	30x30
S2	20.0	4	30x30
S3	27.0	4	30x30
S4	38.0	16	60x60



60x60 cm^2 station: based on a 15x15 cm^2 station surrounded by a ring of 12 sensors

GEM modules

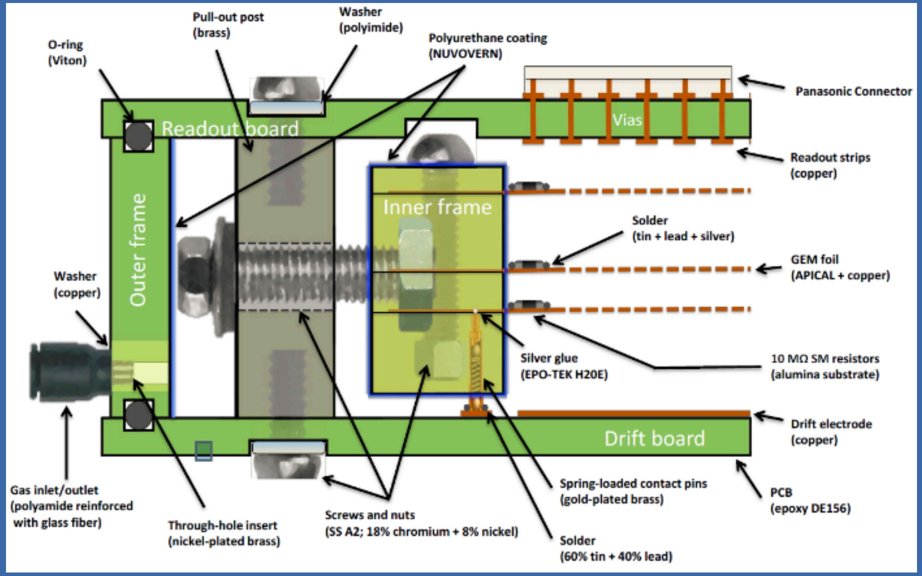


Double 3-GEM modules with 2D strip readout

- module size: 50 × 110 cm^2
- 300 chambers → 1000 GEMs (with spares)
- NS2 system (like CMS) for faster chamber assembly (no gluing)
- Gas: Ar-CO_2 or Ar-CO_2-CF_4
  - Non flammable
  - No ageing effects observed

- 1 M electronic channels
- Readout options: VFAT-3, VMM-3 chips

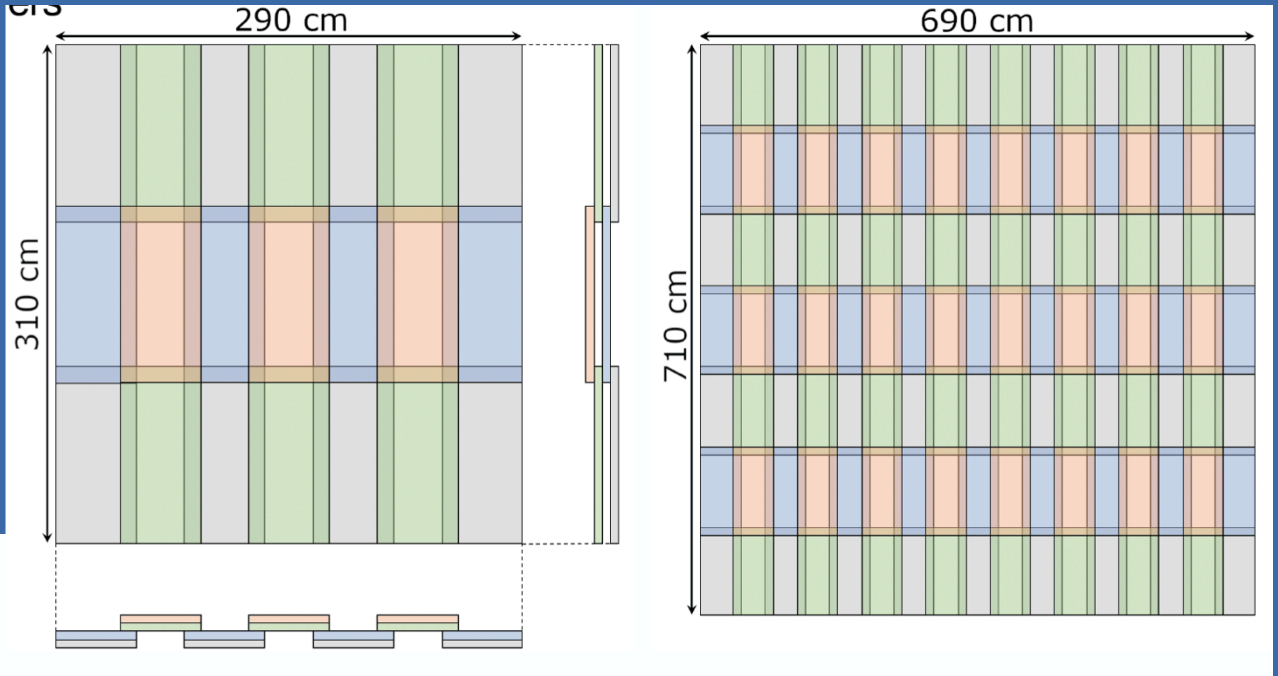
Needs a collaboration of several production institutes and optimized workflow

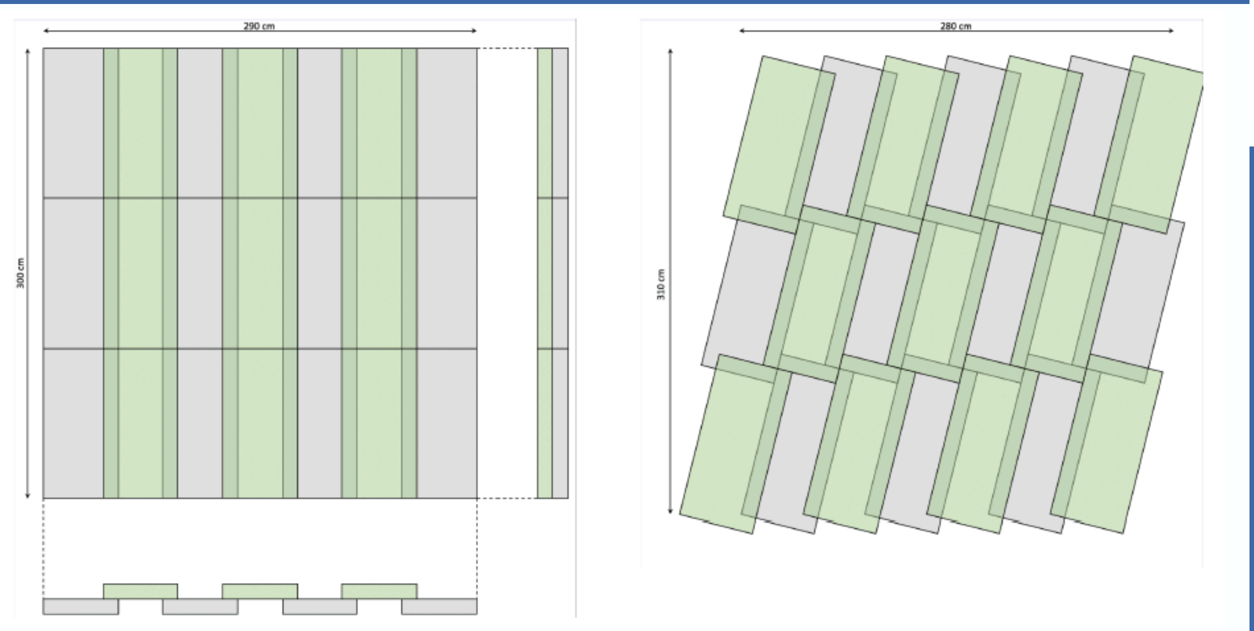


Muon tracker stations: layout

Stations with triple GEM modules:

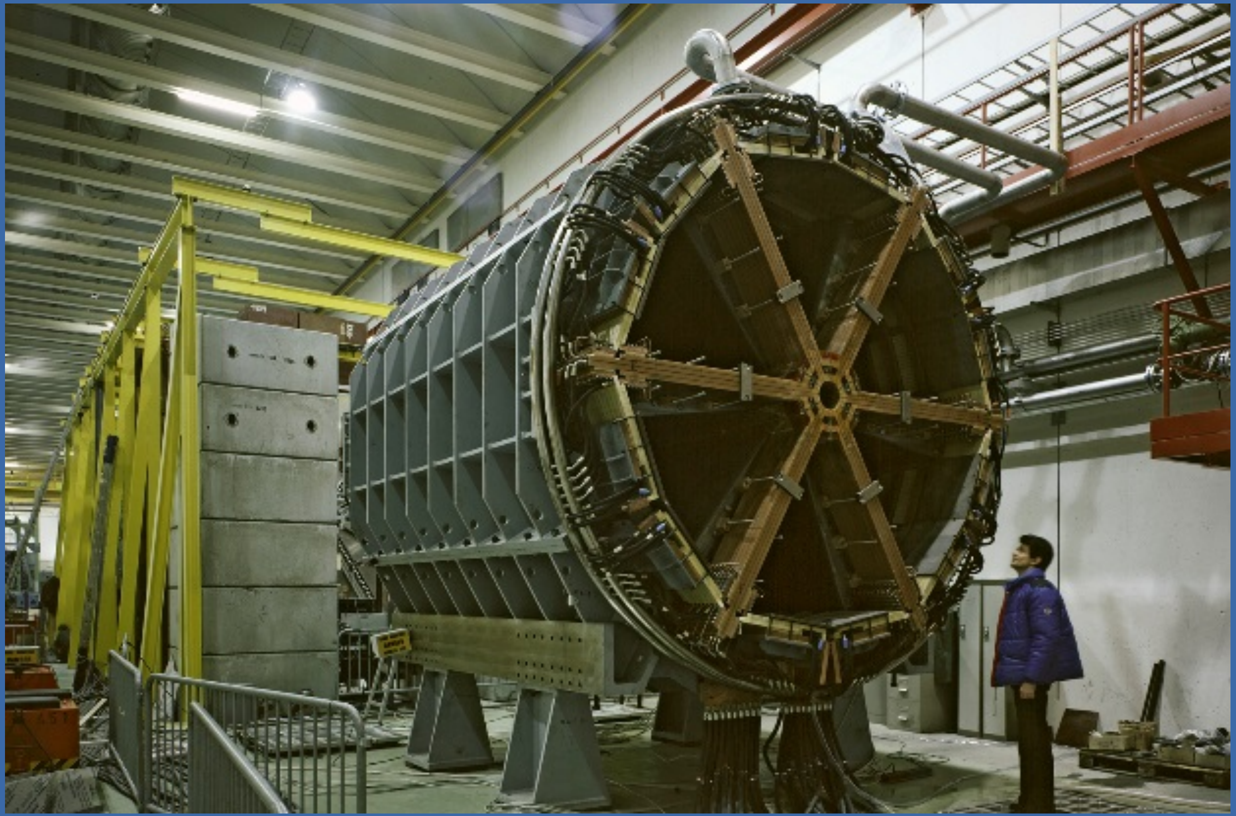
- module size: 50 × 110 cm^2
- Modules staggering: ~10 cm overlap in each direction
- Up to ~20 cm shift in z between the layers





More complicated designs also possible, but presumably not really needed

Toroidal magnet for the muon spectrometer



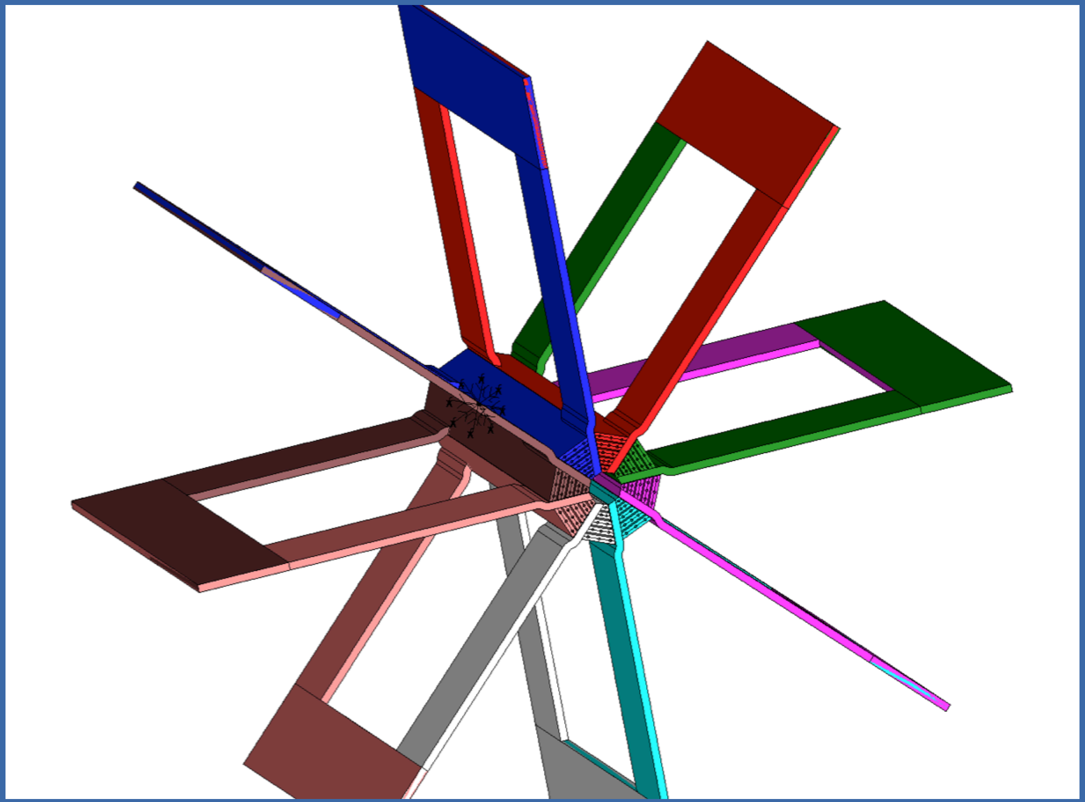
NA60 used the ACM, an open toroid with field circling the beam-axis with an excellent field quality

Not suited for NA60+, which requires a **larger angular coverage**

Construction of a new ACM-like magnet

- Windings arranged in a very complicated way:
  - difficult to build
  - Very expensive: > 5 MCHF

CERN-EP-DT-EF: a new general-purpose toroid

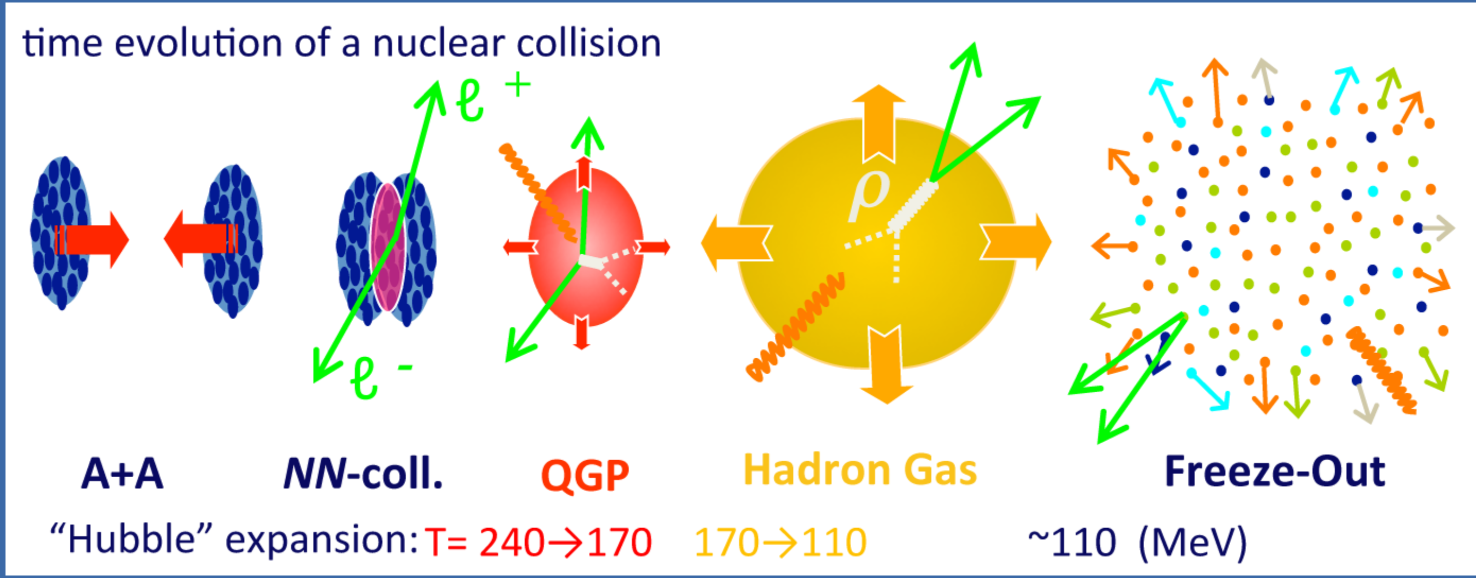


Open toroid for NA60+
- Field circling the beam axis
- L = 3m
- 0.3 < R < 1.65 m at entrance
- 0.3 < R < 2.95 m at exit
- B · R ~ 0.2-0.25 Tm

Minimal design:
- Concept put forward by F. Bergsma, P.A. Giudici (CERN-EP-DT-EF)
- **Easy to build**
- **Much cheaper than ACM**

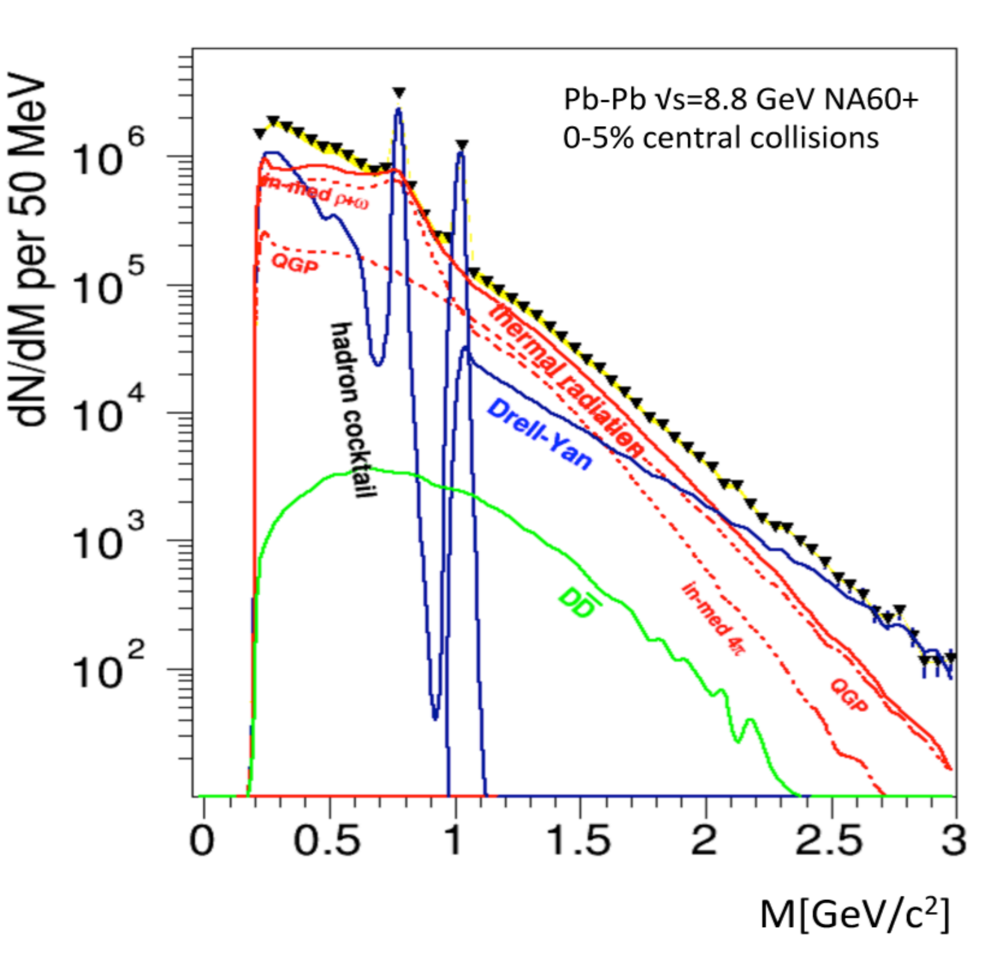
- **8 sectors (octants)**, tangentially displaced wrt cylinder axis
- Conductors made of **aluminium**
- Segments consist of a single winding, straight conductors joined by screws (Meccano-like)

Experimental dimuon spectrum



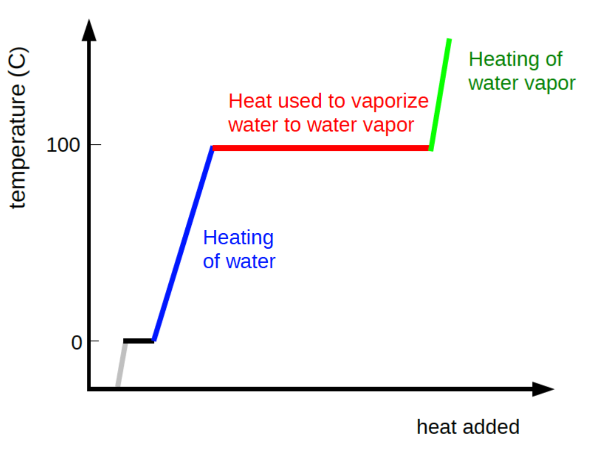
Dimuon spectrum: superposition of

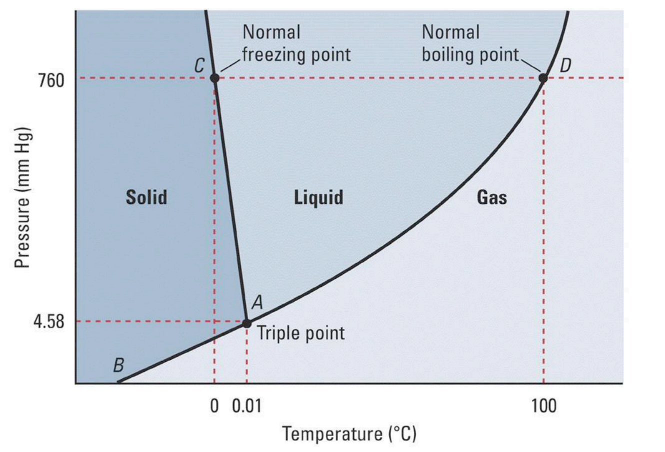
- Drell-Yan and DD pairs (NN-coll.)
- Cocktail of hadronic resonance decays (M<1 GeV) (freeze-out)
- **Thermal radiation (QGP+hadronic)**



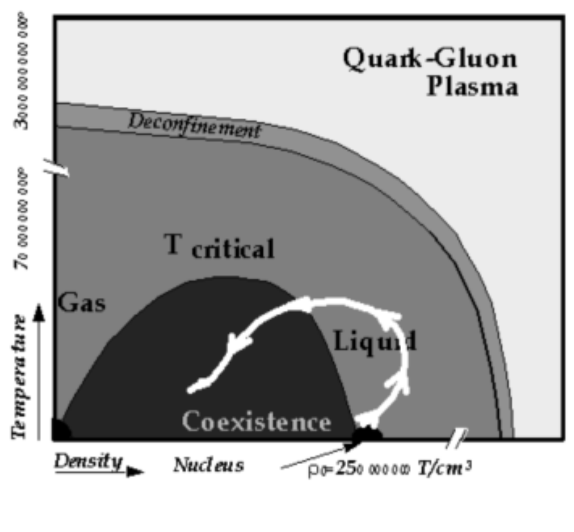
Phase transitions and caloric curves

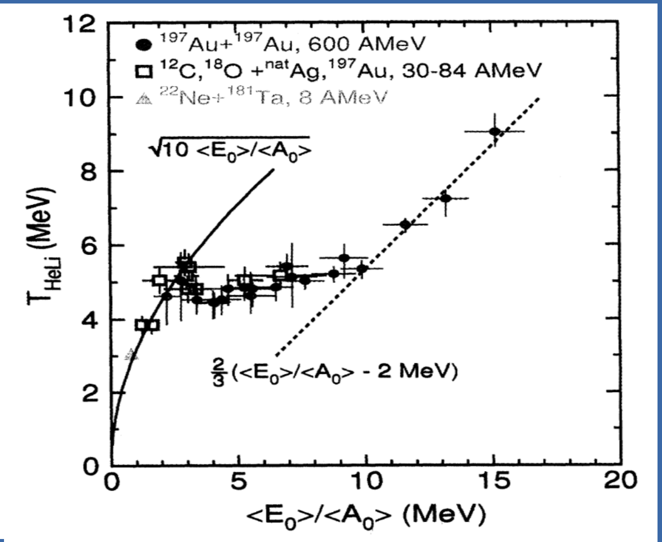
- Caloric curve and phase diagram of water



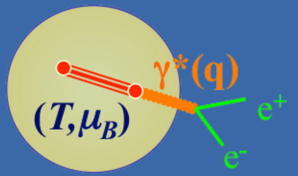


- Caloric curve for liquid-hadron gas phase transition in nuclear matter (Pochodzalla et al., Phys. Rev. Lett. 75 (1995), D'Agostonio et al., Nucl. Phys. A749 (2005) 55–64)



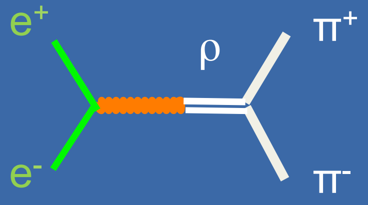


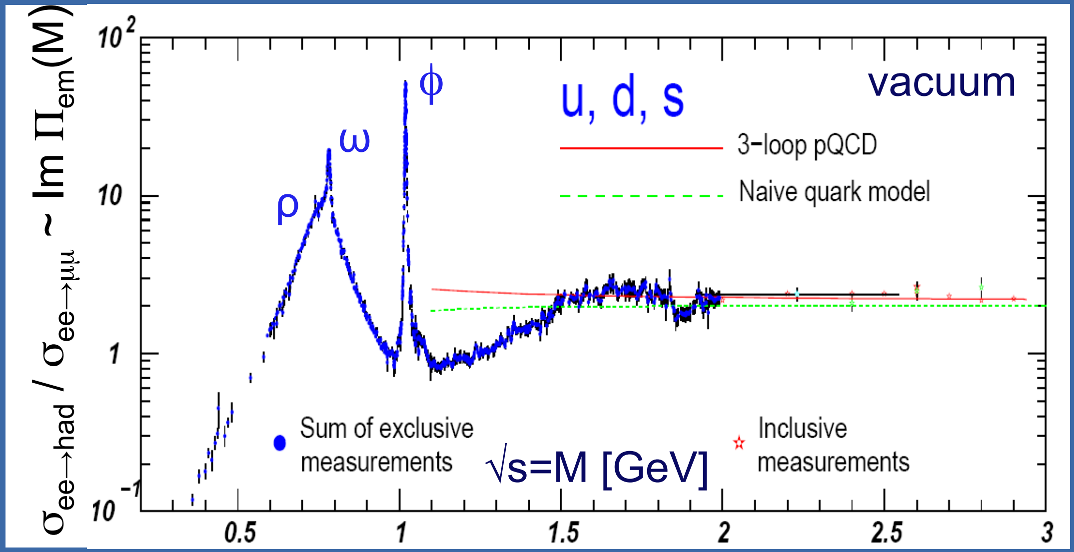
Thermal dilepton rate and medium temperature

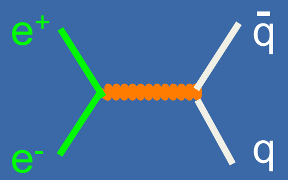


$$\frac{dN_{ee}}{d^4x\,d^4q} = \frac{-\alpha_{em}^2}{\pi^3 M^2} f^B(q_0,T) \times \mathrm{Im}\,\Pi_{em}(M,q;\mu_B,T)$$

e.m. spectral function







Flat spectral function for M>1.5 GeV ➔mass spectrum after integration over momenta and emission 4-volume:

$$dN_{\mu\mu}/dM \propto M^{3/2} \times \langle \exp(-M/T) \rangle$$

non-perturbative

in-medium spectral function(s)

$\mathrm{Im}\Pi_{em} \sim \mathrm{Im}\, D_\rho + \ldots$

$\mathrm{Im}\,\Pi_{em} \sim N_c \sum (e_q)^2$

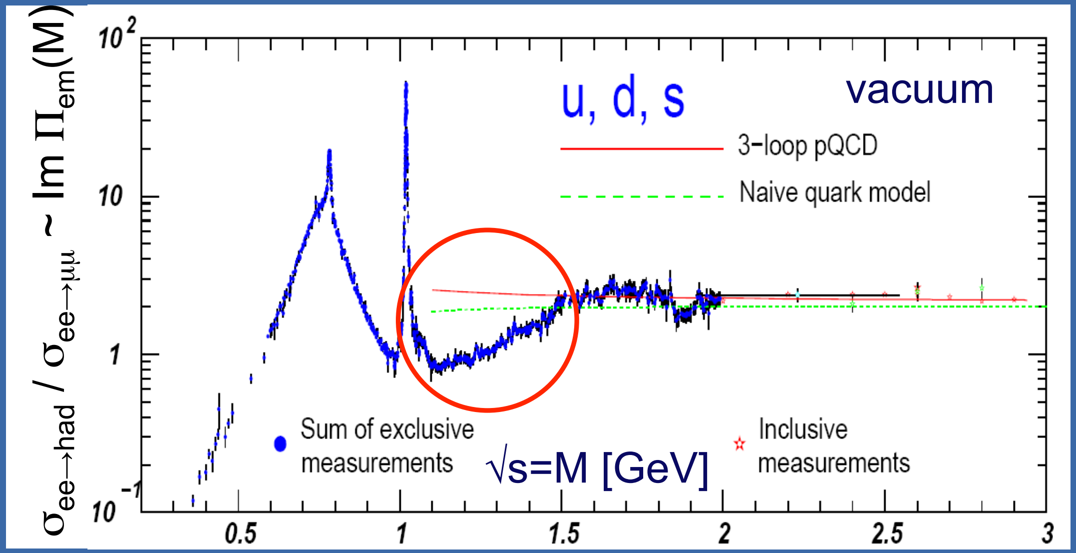
perturbative

hadron-parton duality (flat SF)

T from dilepton spectrum: average temperature which tracks initial temperature (dominant contribution from early stages)

Fit of mass spectrum for M>1.5 GeV → thermometer!

a_1 and dileptons : vacuum vs medium



Axial states don't couple to virtual photons

In vacuum (left) dip the region M=1-1.5 GeV: significant depletion

In the medium: chiral mixing
To lowest order in T, pion induced mixing of vector and axial-vector correlators:

$$\Pi_V(T) = (1-\varepsilon)\Pi_V(T=0) + \varepsilon\Pi_A(T=0)$$

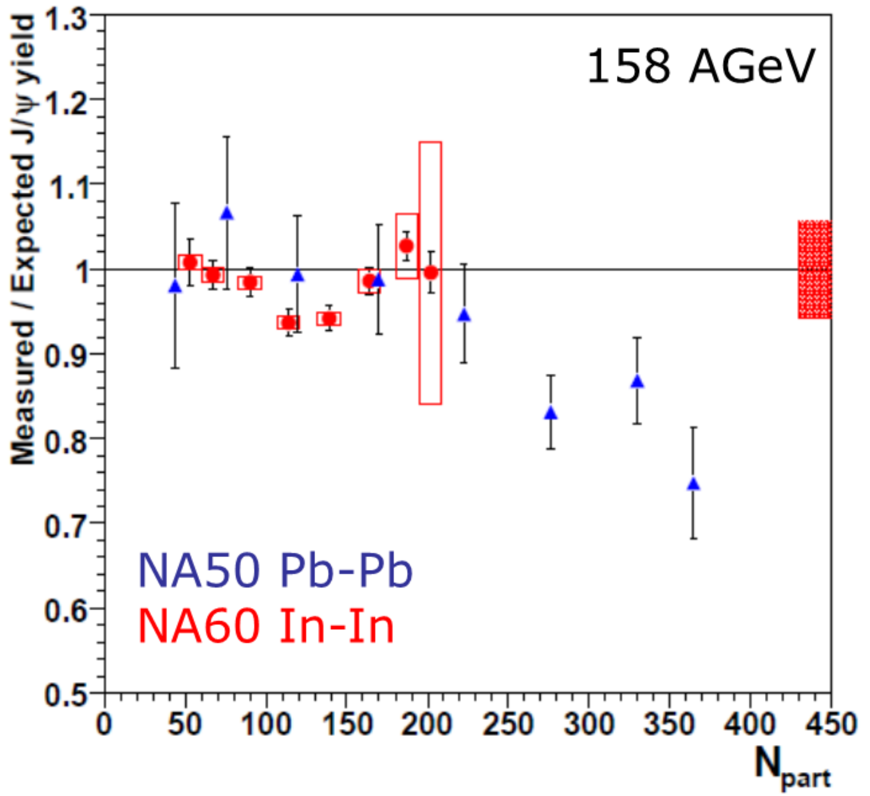
$\varepsilon = T^2/6f^2_\pi$

The admixture of the a_1 resonance, via the axial-vector correlator, thus entails an enhancement of the dilepton rate for M ~ 1 – 1.4 GeV

Low-SPS energy charmonium production

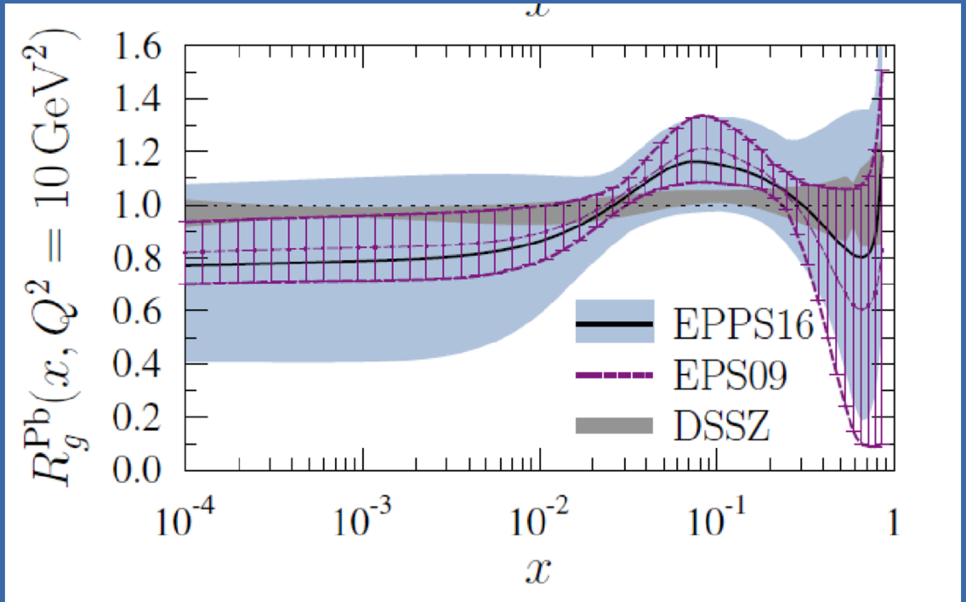
- Extract information of the fundamental in-medium QCD force in the region of finite μ_B and at energy densities smaller than in the collider energy range

- Possible observables:
  - Top SPS energy: J/ψ suppression compatible with feed-down effects from χ_c and $\psi(2S)$
    → do direct J/ψ continue to survive at high baryon density?
  - Can a sequential suppression be established (similarly to what done at LHC for the Υ)?
  - Study interaction of charmonia in confined matter via p-A collisions
    → separate hot and cold matter effects
    → investigate inelastic reaction rates in hadronic matter (small for J/ψ, possibly significant for χ_c and $\psi(2S)$)



NA60, NPA830 (2009) 345c

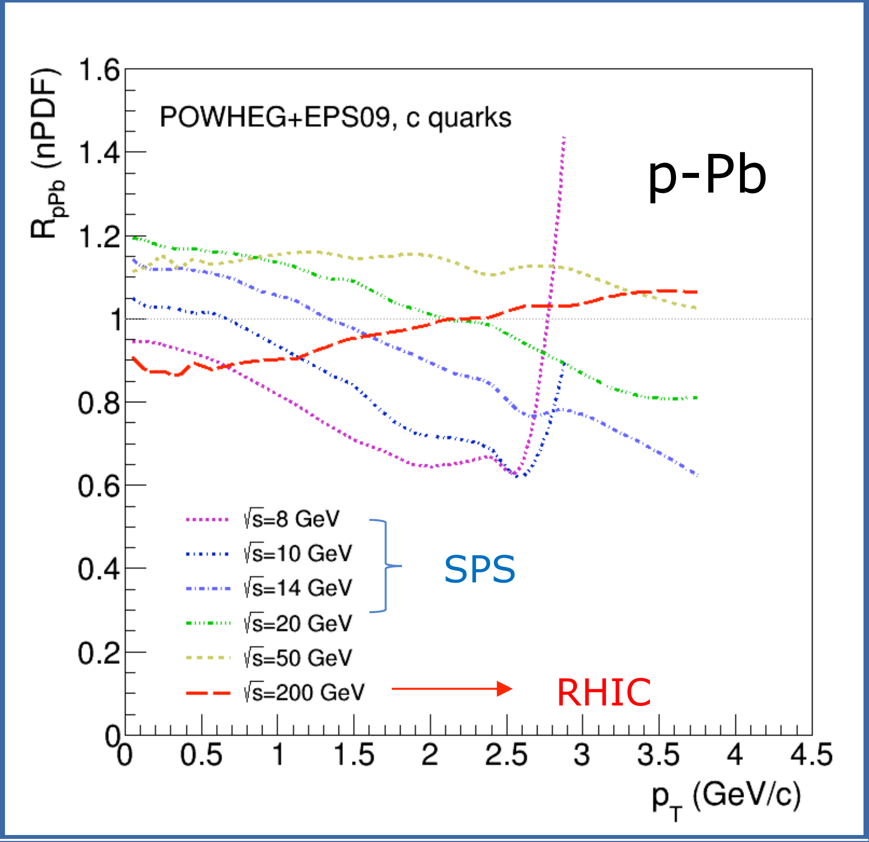
Physics performance: open charm



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+**

NA60+ project: present status

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 at the CERN Town Meeting 2018: Relativistic Heavy Ion Collisions
https://indico.cern.ch/event/746182/

Project discussed within CERN Physics Beyond Colliders
QCD Working Group Report arXiv:1901.04482

An (HL-HE-)LHC/FCC based AA/pA/fixed-target program is unique and provides essential science at the frontline towards a profound understanding of particle physics.

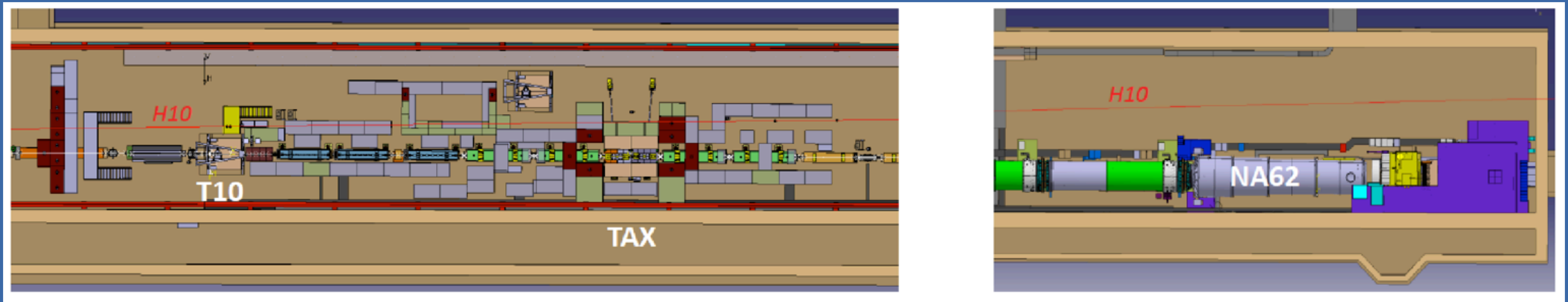
A coherent and complementary "hot & dense QCD program" at the SPS brings valuable and unique contributions in the exploration of the QCD phase diagram.

NA60+ presented at at the EPPSU (European Strategy for Particle Physics) symposium (Granada 2019) for Hot & Dense QCD

Installation site: discussions ongoing

- 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



We asked CERN (through the 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**