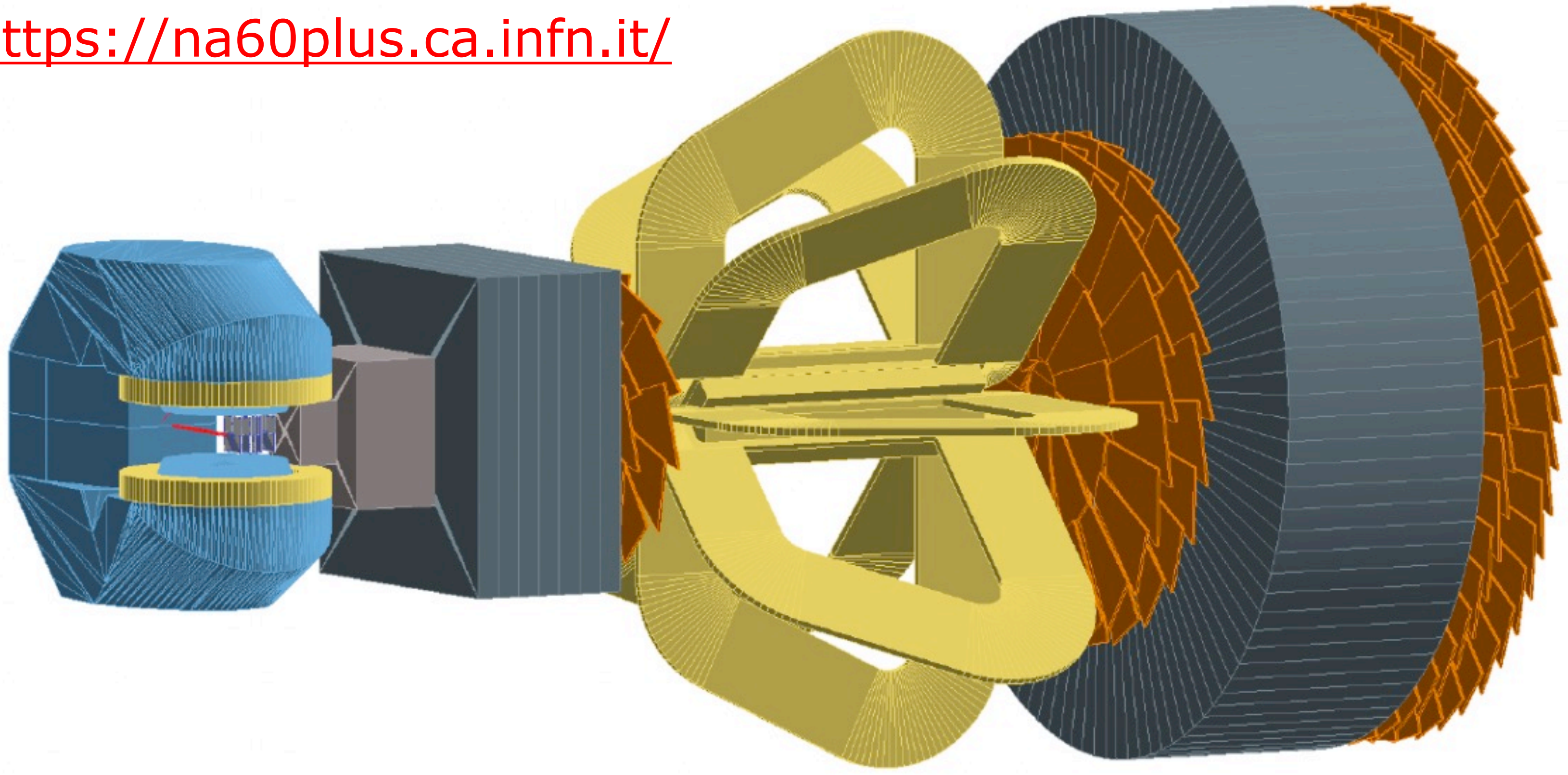
Measurement of a caloric curve and chiral symmetry restoration with the NA60+ experiment at the CERN SPS

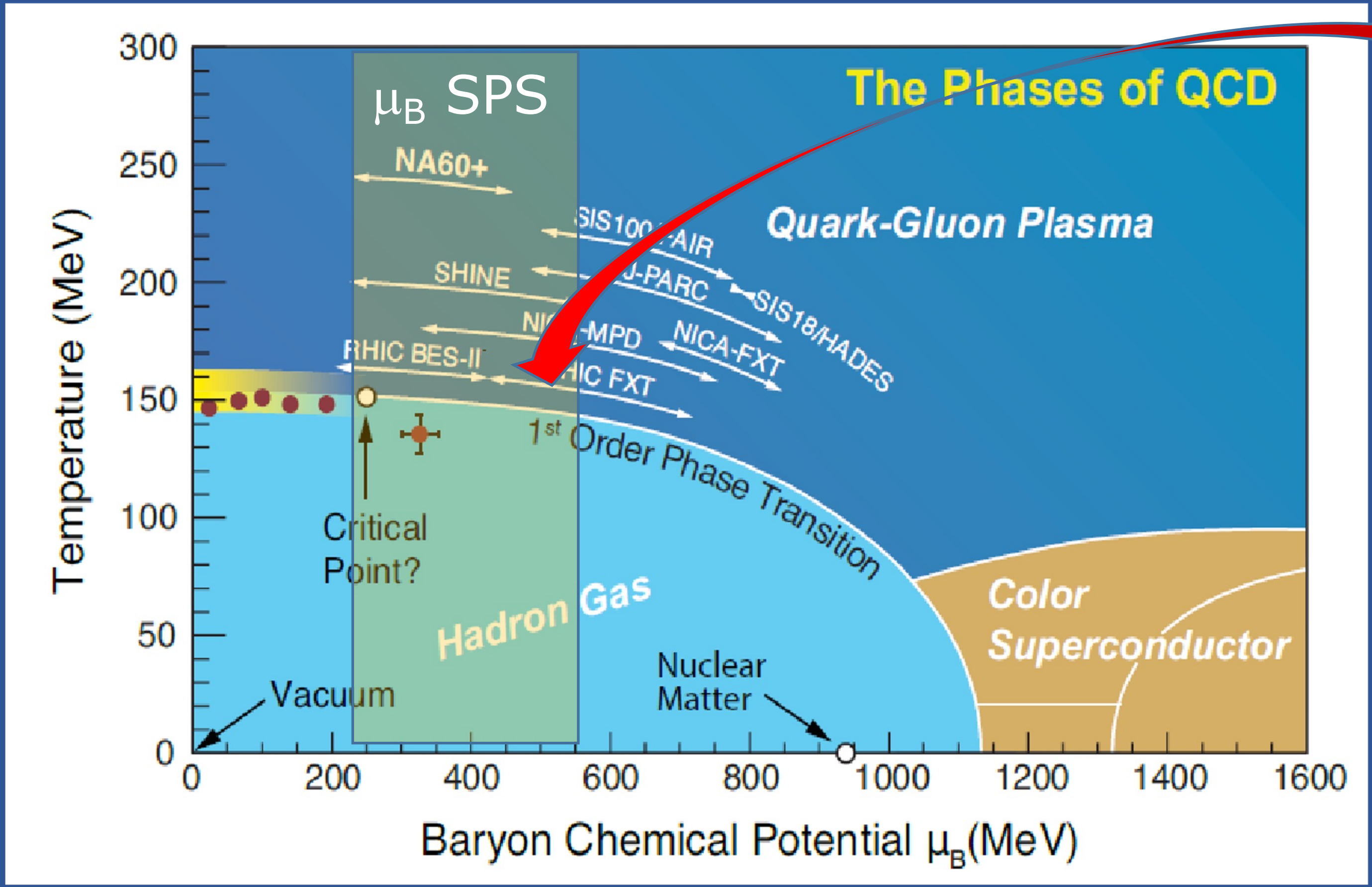
https://na60plus.ca.infn.it/

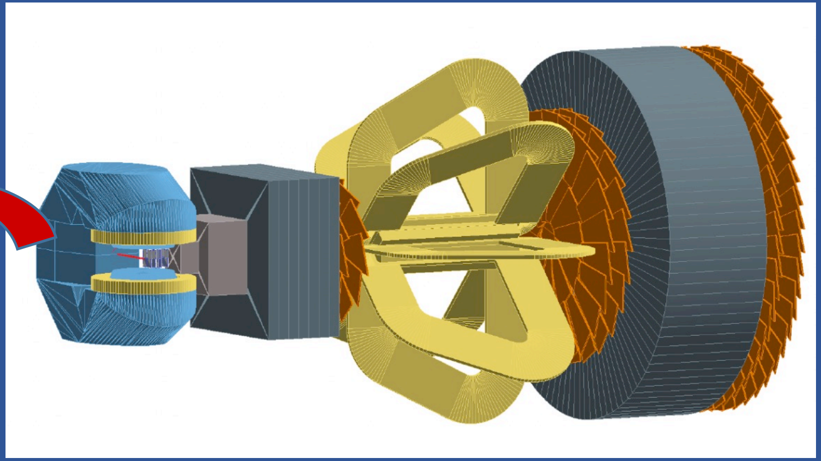


G. Usai
University of Cagliari and INFN, Italy

A new heavy-ion experiment at CERN: NA60+

NA60+: high-μ_B studies of hard and electromagnetic probes of the Quark-Gluon Plasma at SPS energies via a beam-energy scan





- Hard/e.m. probes:
  unexplored domain for observables in the SPS range $220<\mu_B<550$ MeV

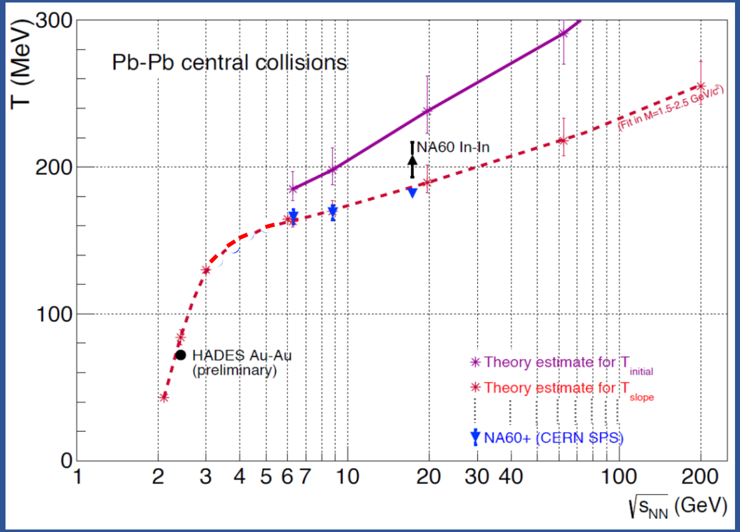
- Designed to measure:
  - Muon pairs (thermal, quarkonia)
  - Hadrons (open HF, strangeness)

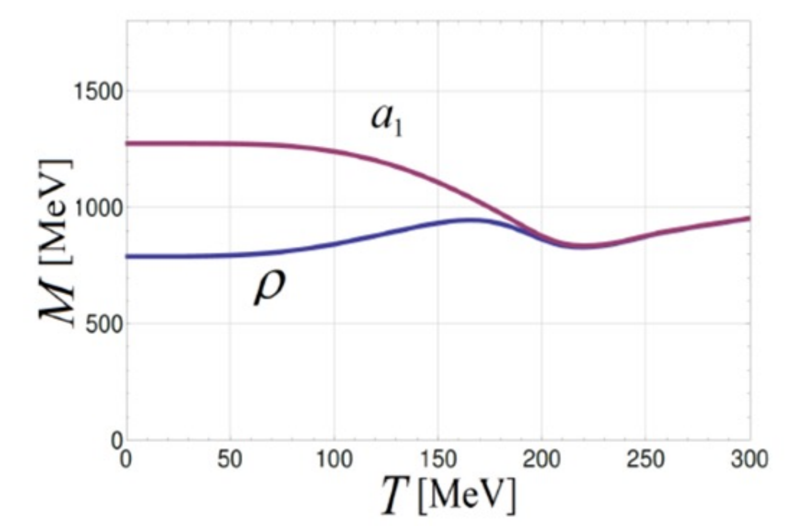
The pillars of the NA60+ physics program

Several **new and unique measurements** in the region $6<\sqrt{s_{NN}}<17$ GeV ($20<E_{lab}<160$ AGeV)

Caloric curve of QGP

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



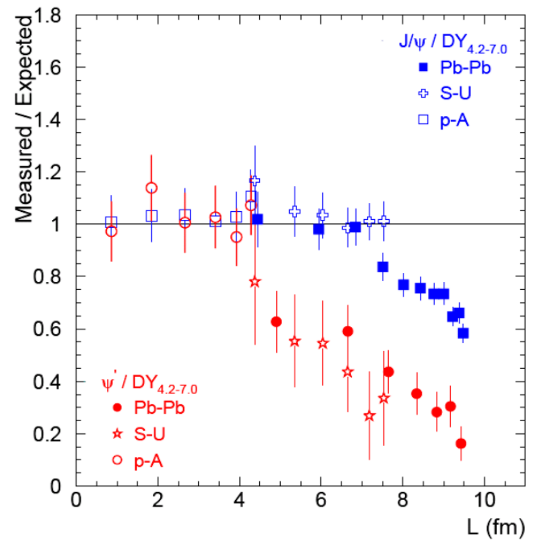


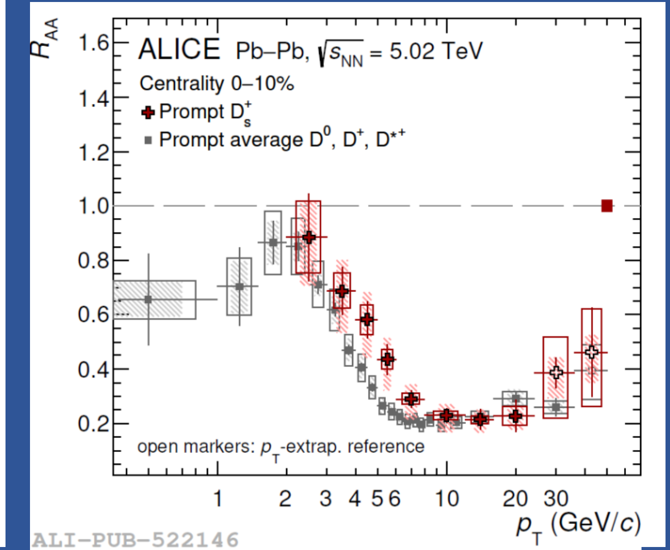
Chiral symmetry restoration

ρ-a_1 mixing in the dimuon channel

Charmonium melting in the QGP

Charmonium (J/ψ, $\psi(2S)$) suppression vs $\sqrt{s_{NN}}$ (dimuon decay channel)





QGP transport coefficients and charm hadronization

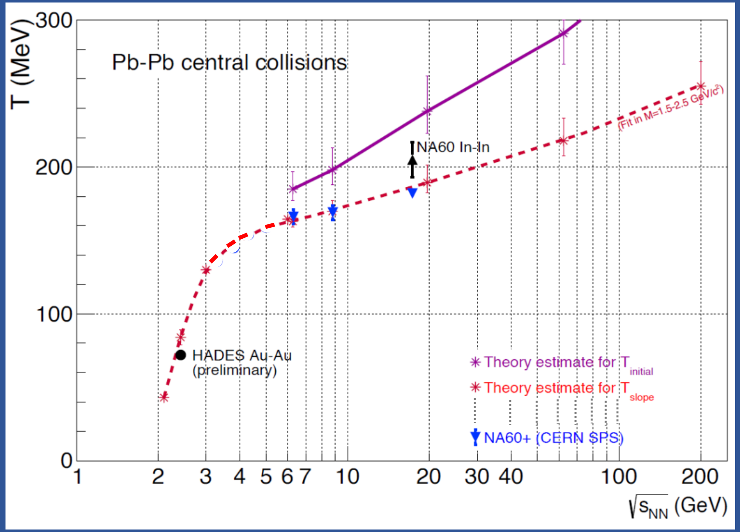
Hadronic decays of open HF mesons/baryons

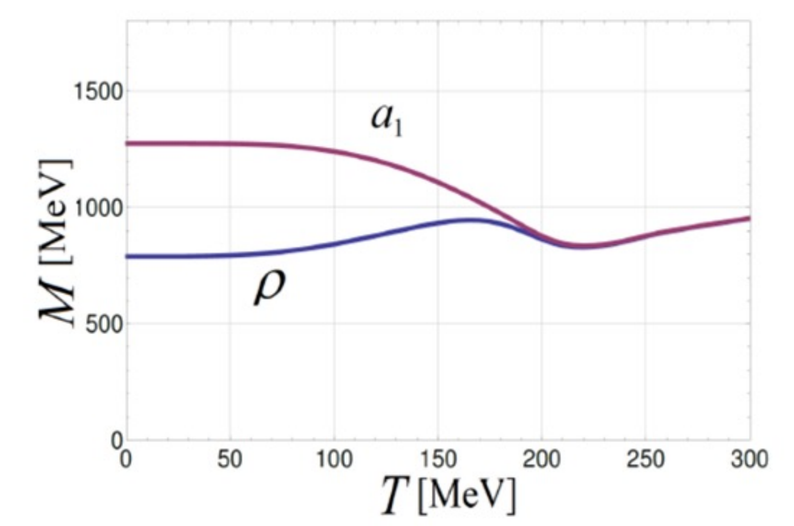
The NA60+ physics program

Several **new and unique measurements** in the region $6<\sqrt{s_{NN}}<17$ GeV ($20<E_{lab}<160$ AGeV)

Caloric curve of QGP

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





Chiral symmetry restoration

ρ-a_1 mixing in the dimuon channel

- ❑ This talk will cover the first 2 pillars with a detailed overview of the NA60+ apparatus

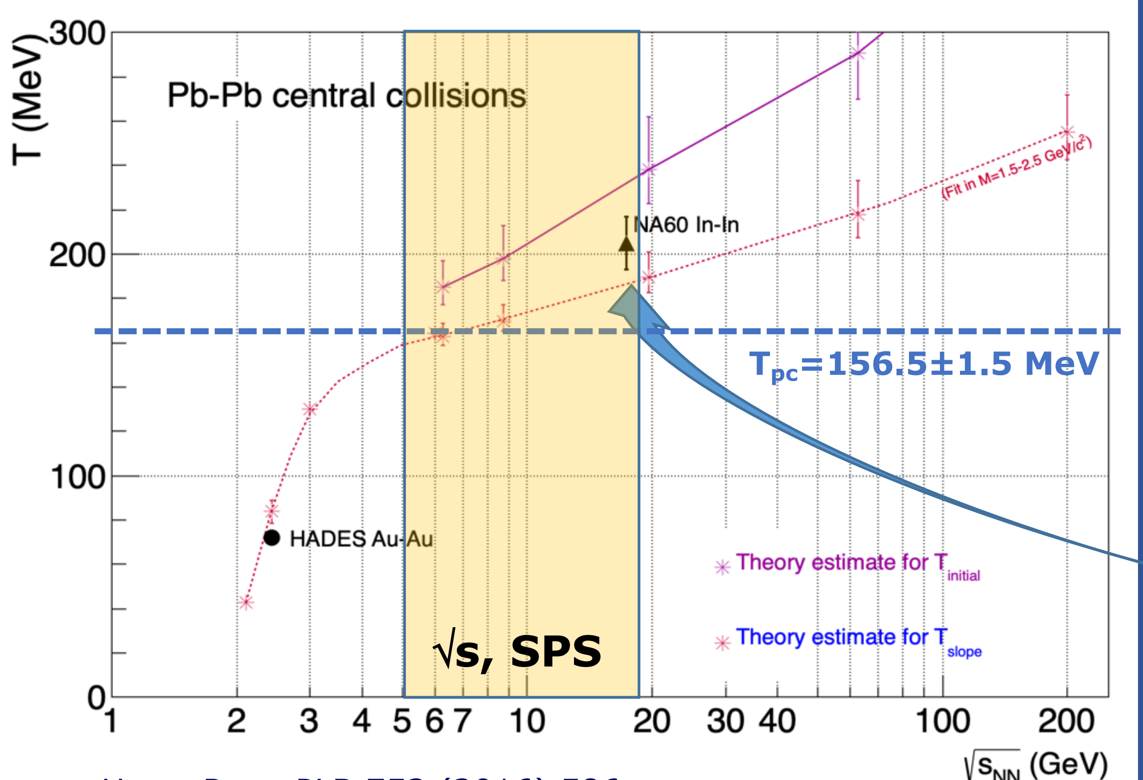
- ❑ Other talks covering NA60+ at HP2023:
  - Prospects for open heavy-flavor and quarkonium measurements with NA60+ R. Arnaldi Wednesday
  - Future facilities: SPS E. Scomparin Thursady

- ❑ More on the physics menu: strange mesons/baryons and hypernuclei

Caloric curve of QCD

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

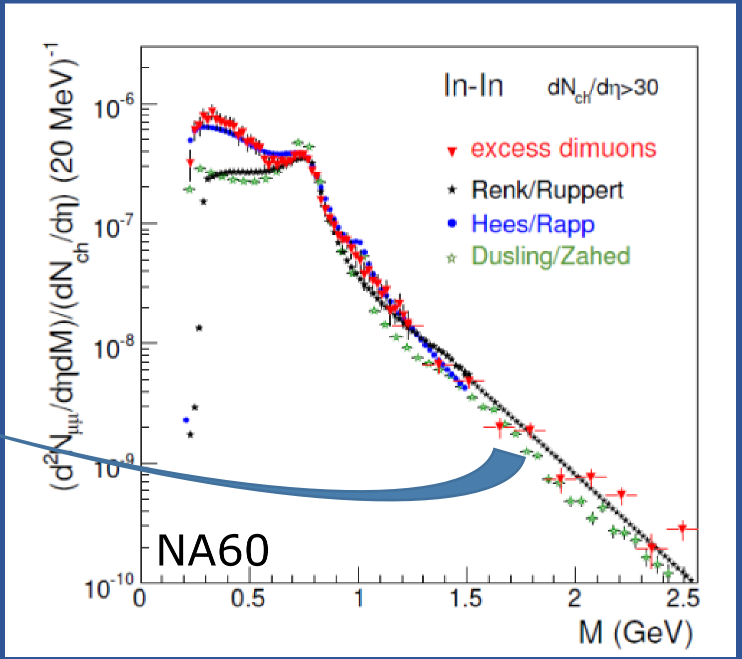
Only 2 precision measurements: top SPS energy (NA60) and very low energy (HADES)



Hees, Rapp PLB 753 (2016) 586

Galatyuk *et al.* EPJA 52 (2016) 131

HADES, Nature Phys. 15(2019) 1040
NA60, EPJC 61(2009) 711



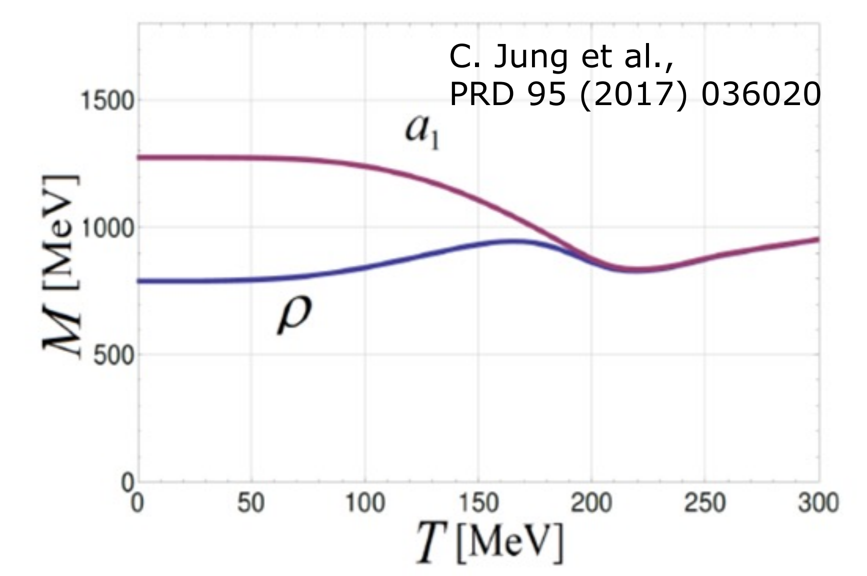
❑ Dilepton T_{slope} measurements → (average) **temperature of the early stage of the system**

❑ SPS energy → accurate information on the region close to the deconfinement transition temperature

→ possible signal of a **1st order phase transition**

Chiral symmetry restoration

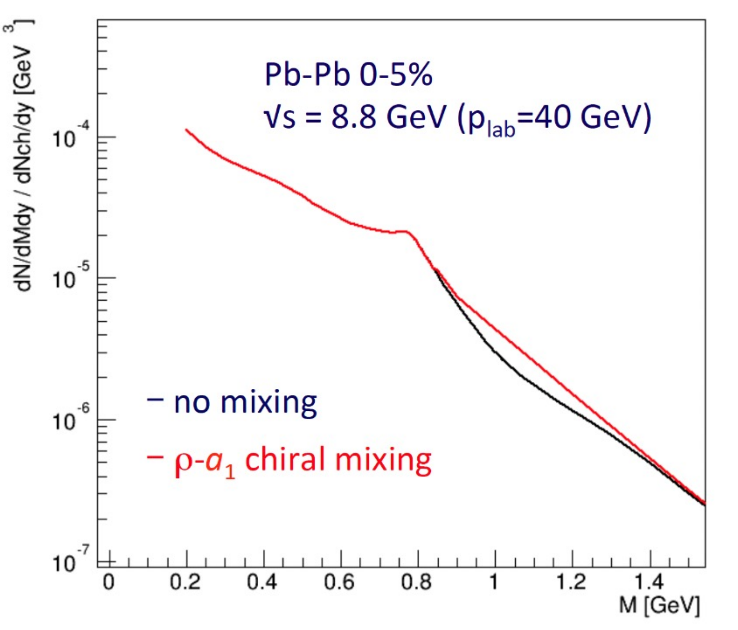
- Chiral restoration at the phase boundary: melting of ρ and a_1



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

- ρ meson measured with melting consistent with chiral restoration
- a_1 not measurable exclusively

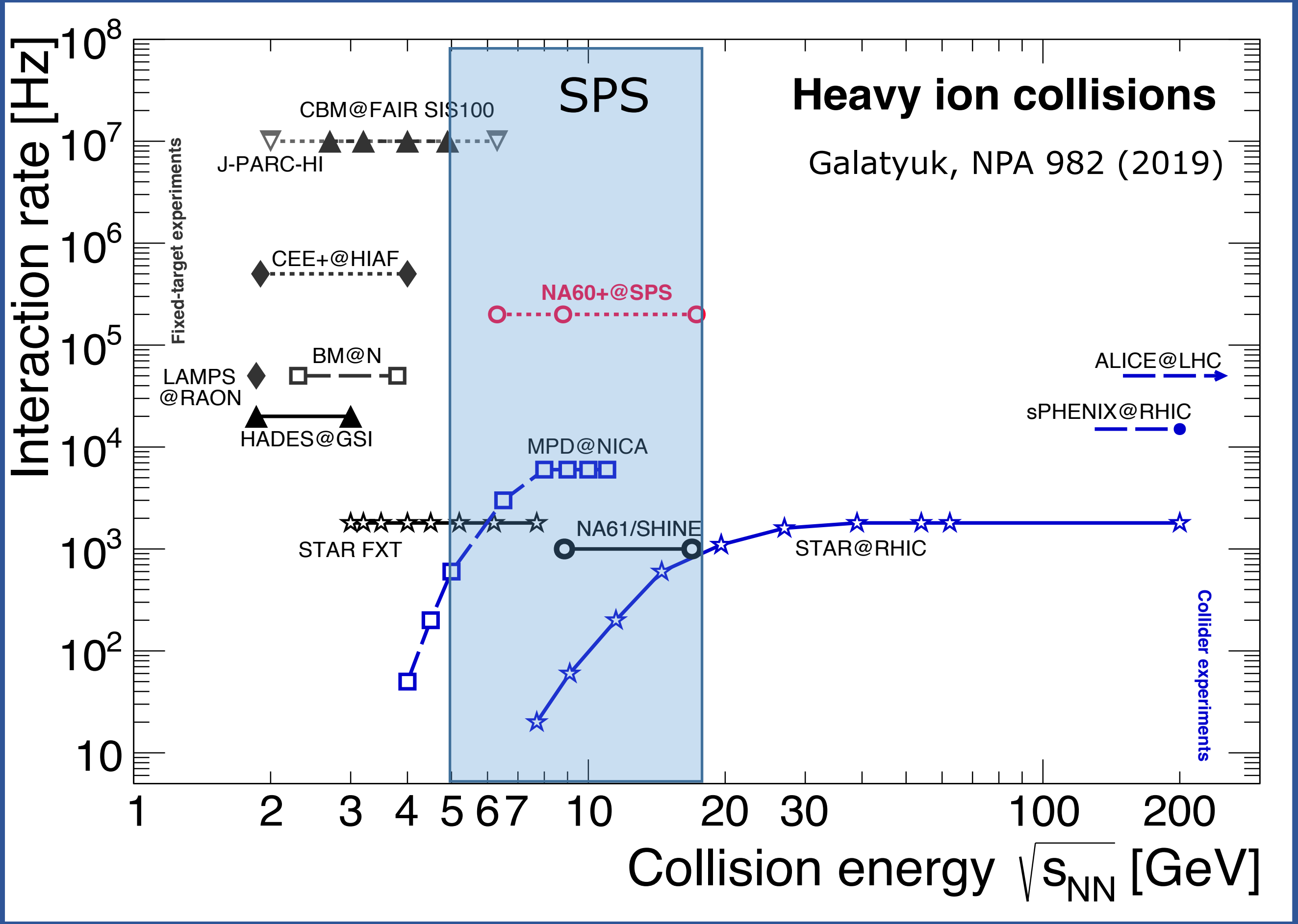
- Mixing of vector (V) and axial-vector (A) correlators → **dilepton enhancement** for $M_{\mu\mu} \sim 1\text{-}1.4\ \mathrm{GeV}/c^2$



R. Rapp and H. van Hees,PLB753 (2016) 586

- Measurement at low energy:
  → (Exponential) thermal dimuon yield from QGP becomes small
  → Contribution from open charm becomes relatively negligible

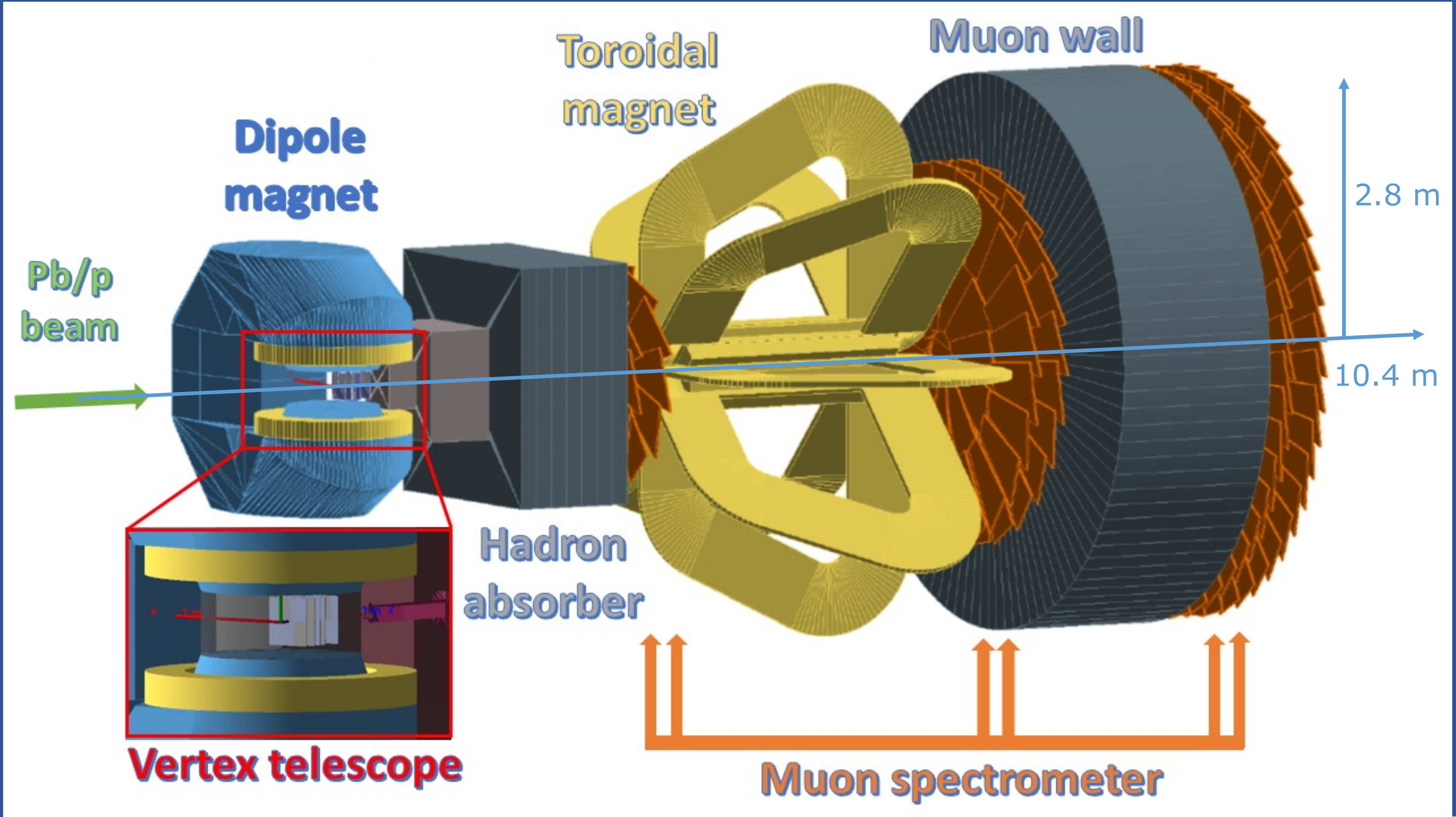
Uniqueness of NA60+ program



- ❑ The NA60+ physics program needs a large integrated luminosity
  → Measurement of **rare QGP probes**
- ❑ Such a luminosity can be obtained with **Pb-Pb interaction rates >10^5 Hz**, reachable with a ~10^6 s^{-1} beam intensity in a fixed-target environment
- ❑ In the SPS energy range, there **are no other existing/foreseen facilities/experiments** that can approach this kind of performance

- ❑ **Complementarity** with experiments accessing
  - ❑ different (hadronic) observables in the same energy range (STAR BES, NICA, NA61)
  - ❑ similar observables in a lower energy range (CBM at FAIR)

The NA60+ detector



Inspired by the **former NA60** detector (2002-2004)

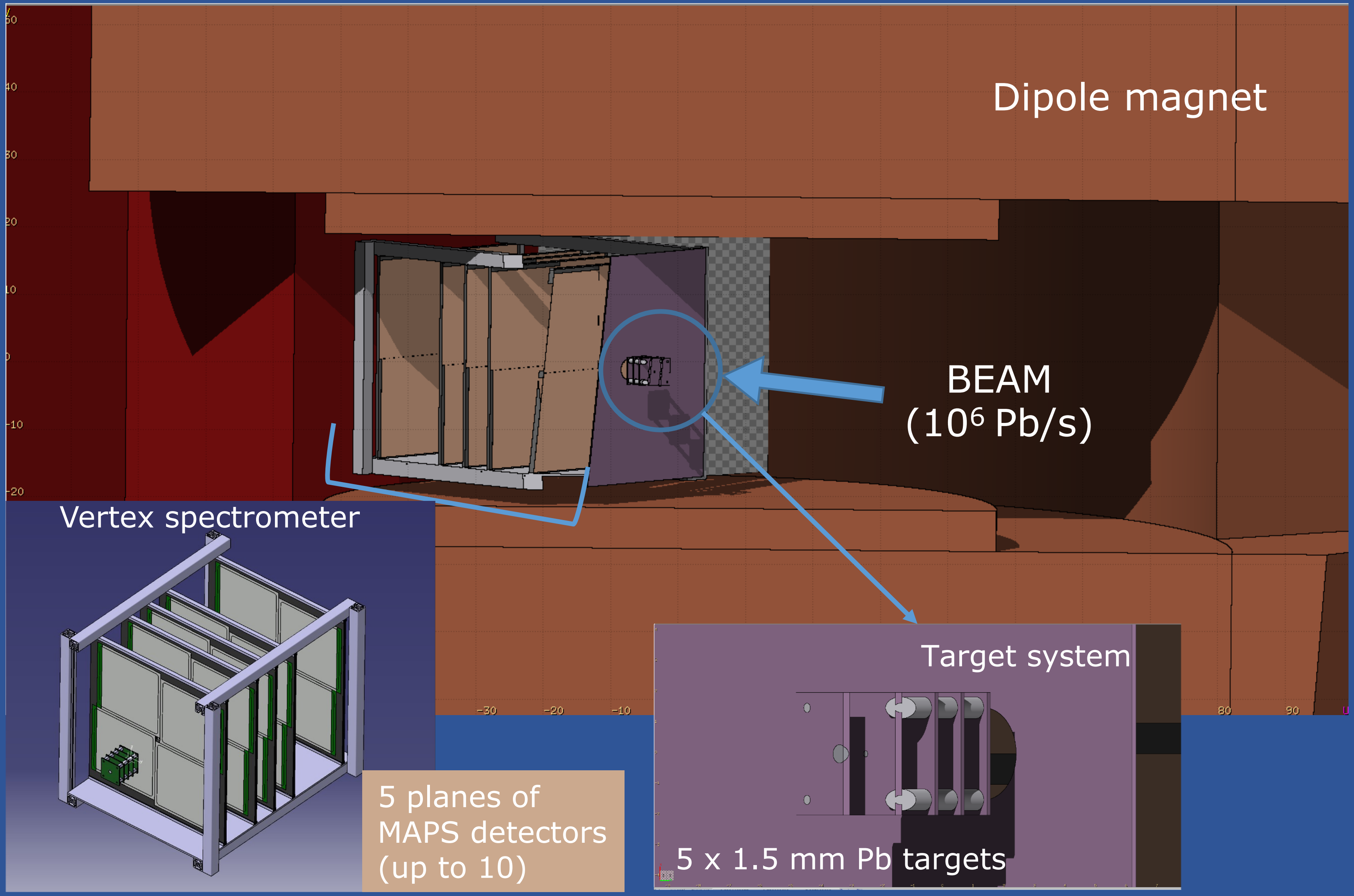
Measurement of **(di)muon** production and hadronic decays of **strange** and **charm** hadrons

SPS **energy scan**: vary z-position of the muon spectrometer and thickness of hadron absorber

The NA60+ vertex region

MEP48 dipole magnet
Field 1.5 T over a 400mm gap

Stored at **CERN,**
needs refurbishment



Dipole magnet

BEAM
(10^6 Pb/s)

Vertex spectrometer

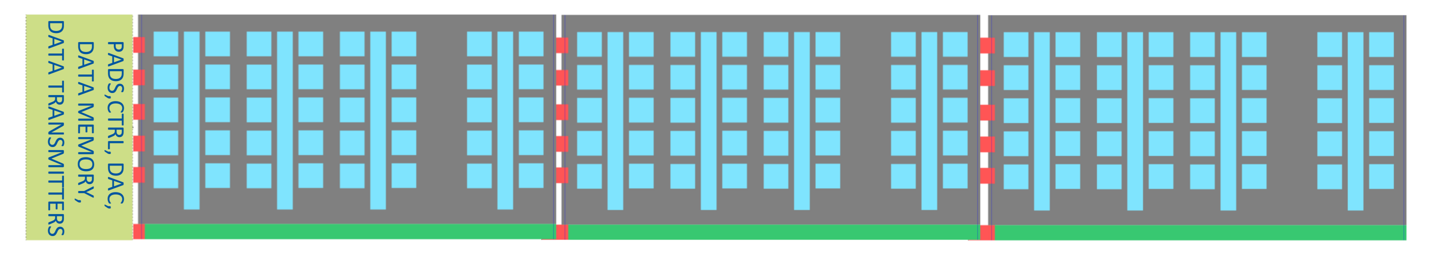
5 planes of
MAPS detectors
(up to 10)

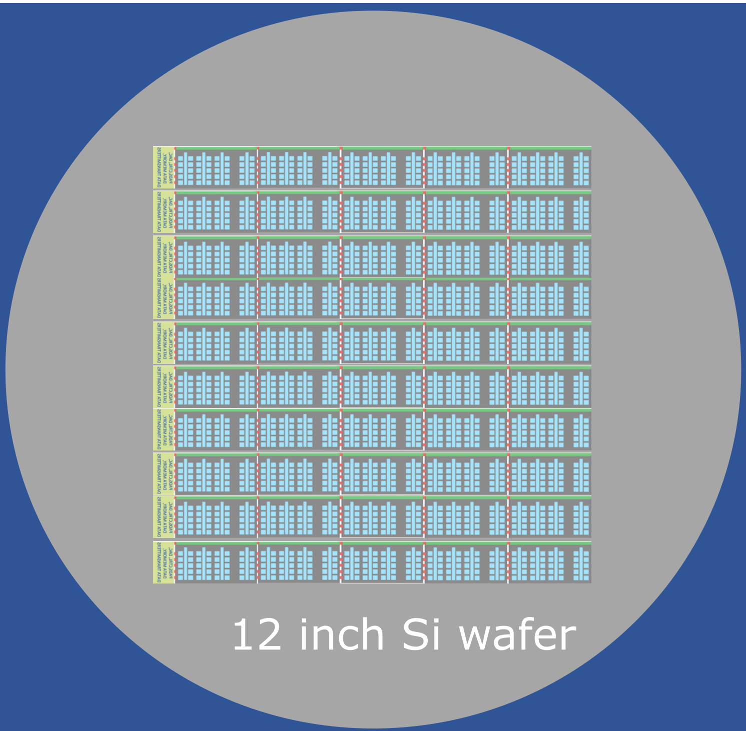
Target system

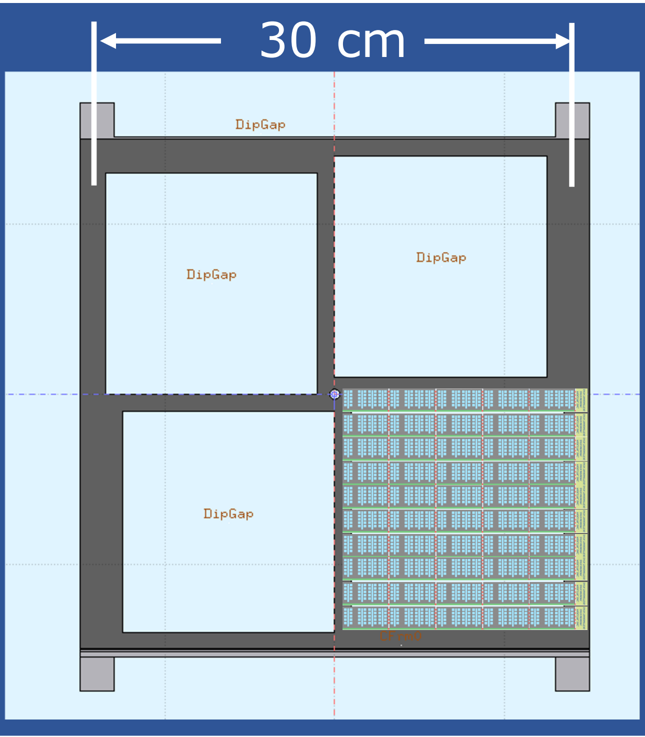
5 x 1.5 mm Pb targets

The NA60+ vertex telescope R&D

Sensor based on 25 mm long units, replicated several times through stitching
→ up to 15 cm length for NA60+







R&D in progress
Common development
ALICE ←→ NA60+
(same timeline!)

State-of-the-art imaging technology
TowerJazz 65 nm

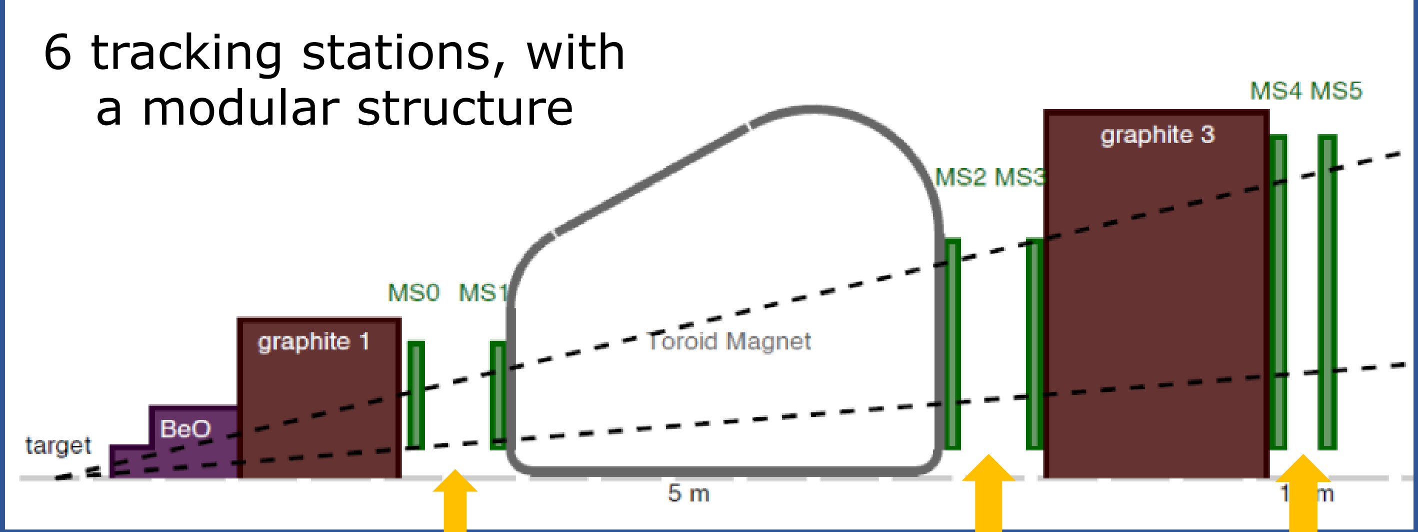
Sensor thickness:
few tens of microns of silicon
→ material budget **$<0.1\% X_0$**

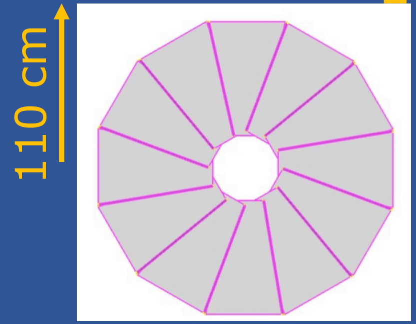
Spatial resolution $\leq$ **5 μm**

Cooling studies (NA60+ geometry)
→ **airflow+water**

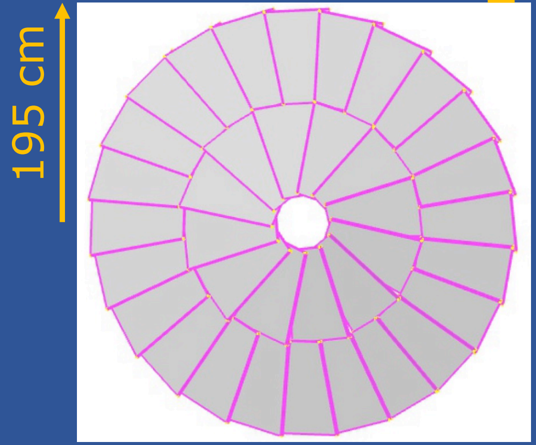
- ☐ Engineering run for a fully functional prototype
- ☐ Possibility of a second run if optimizations needed

The NA60+ muon spectrometer

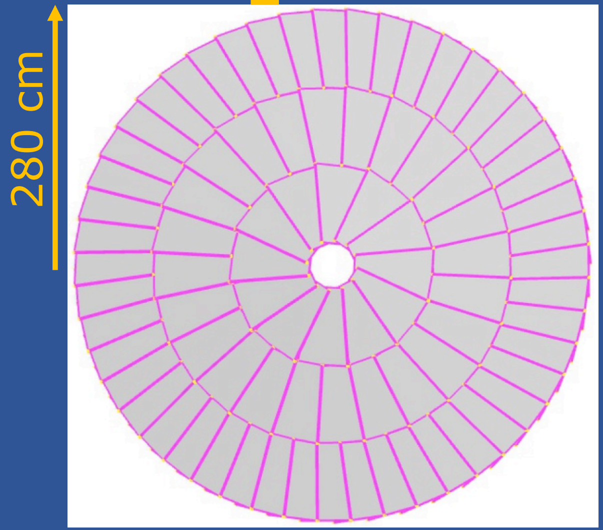

6 tracking stations, with
a modular structure



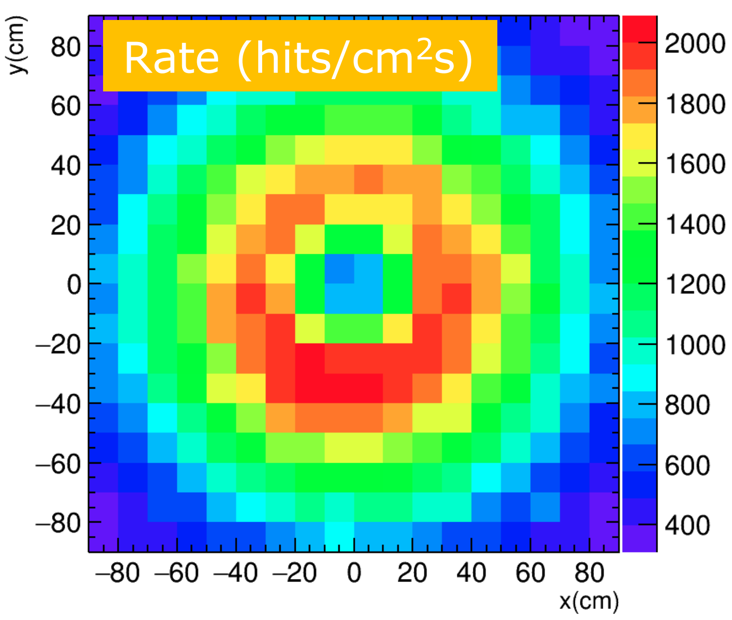
12x2 modules



36x2 modules



84x2 modules

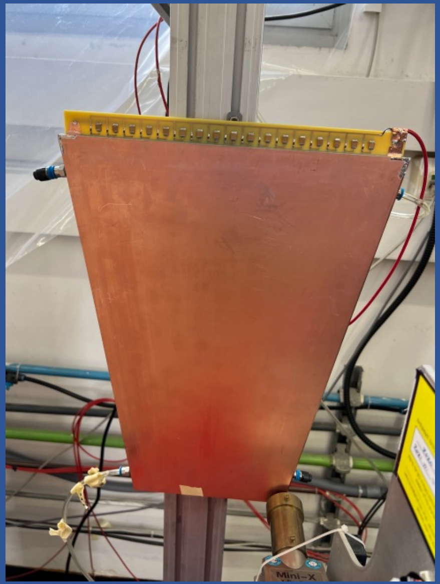


- Modest rates (FLUKA) already in the upstream stations, thanks to the thick absorber (235 cm BeO +C)
- For a 10^6 s^{-1} beam
  → charged particle rate ~2kHz/cm^2

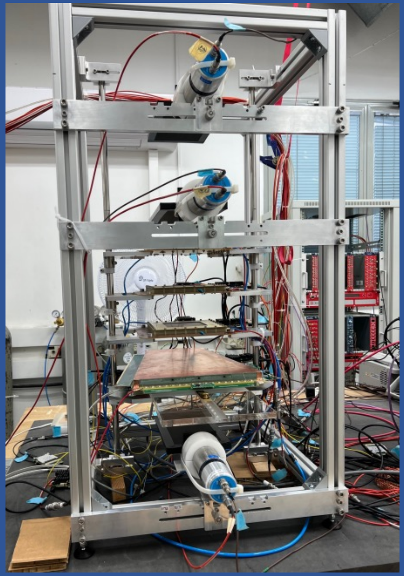
Can be matched by **GEM or MWPC** detectors

The NA60+ muon spectrometer R&D

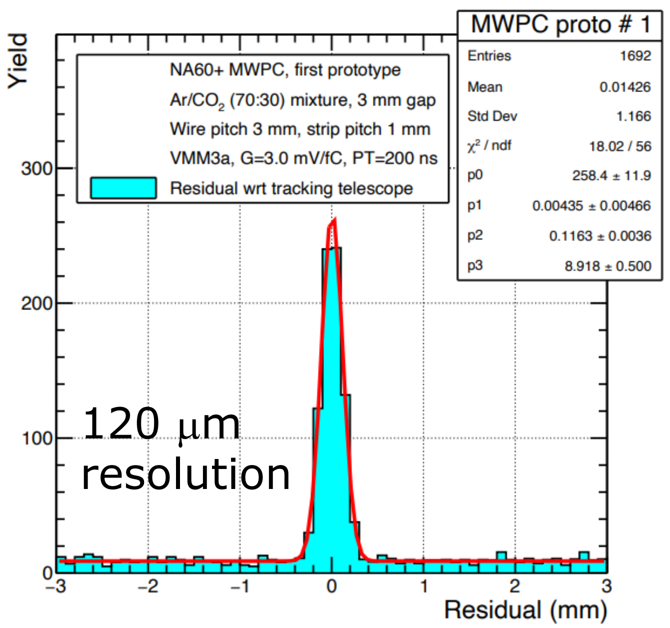
- First prototype of a **MWPC module built and tested in the lab**



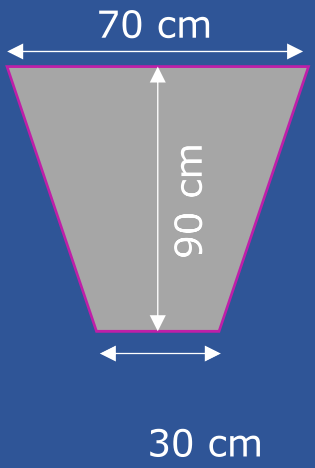
Prototype



Cosmic testbench



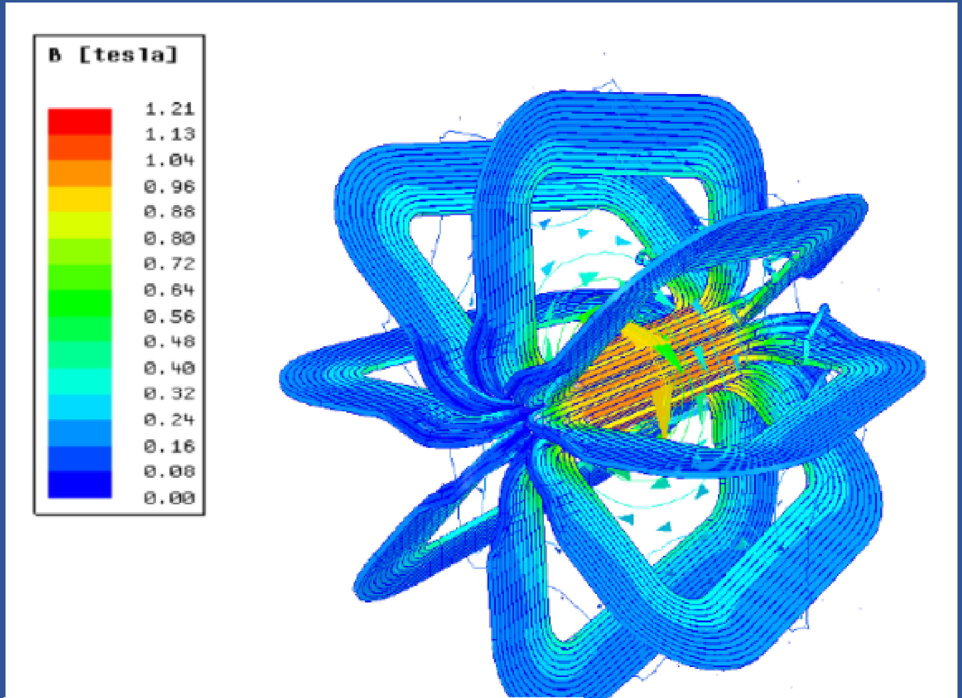
Collaborating institutes have availability of large facilities for **the production** of the detector modules for the NA60+ muon spectrometer



- Ongoing discussions on the final set-up of the spectrometer, various possible solutions, as
  - GEM technology for upstream stations (MS0-MS1)
  - MWPC technology for downstream stations (MS2-MS5)

R/O electronics likely to be based on the **VMM3a ASIC,** interface card to be designed

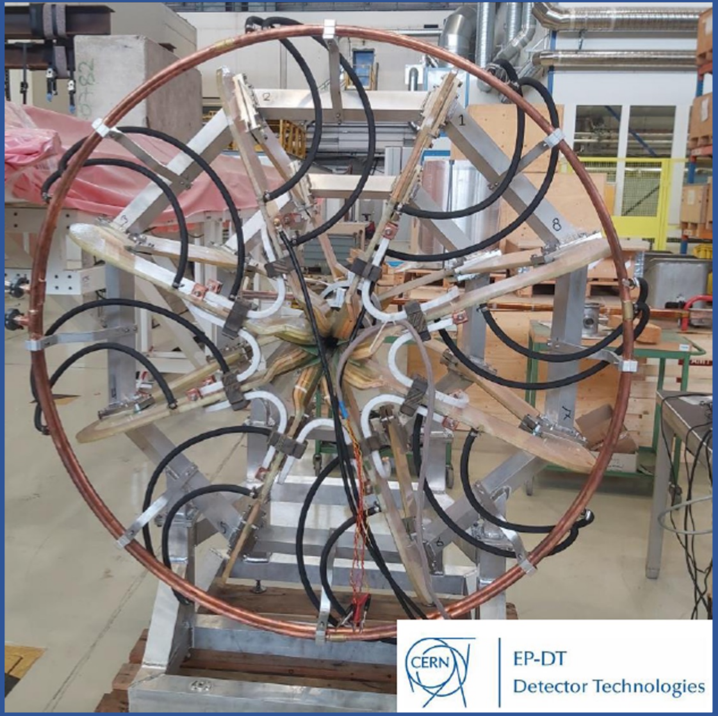
The NA60+ toroid



Warm magnet

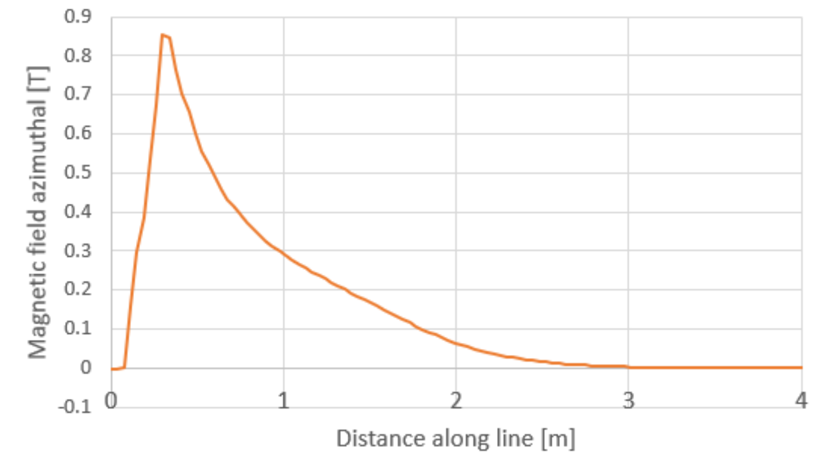
Eight sectors,
12 turns per coil

Conductor has a square copper section with a circular cooling channel in the centre



Prototype (1:5 scale)

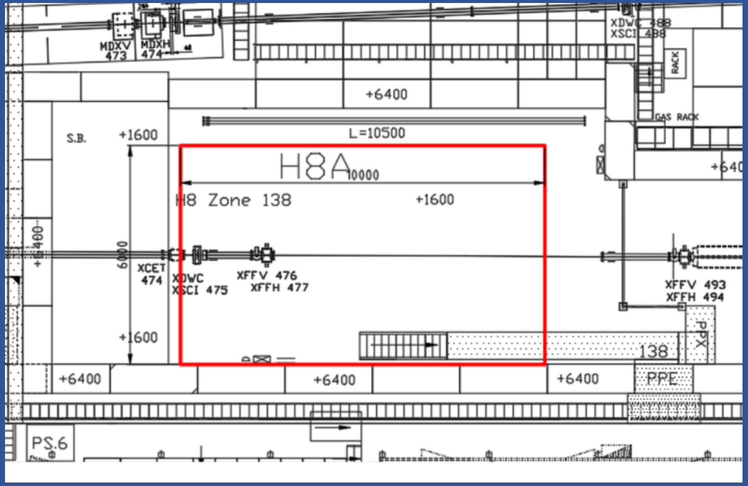
Operating Current [kA]	16.6
Amp-turns [kA]	199
Combined inductance [mH]	9.5
Resistivity Al 1100 @RT [μΩ.cm]	2.67
Length Conductor [m]	800
Total resistance [mΩ]	10.4
Dissipated power [MW]	2.8

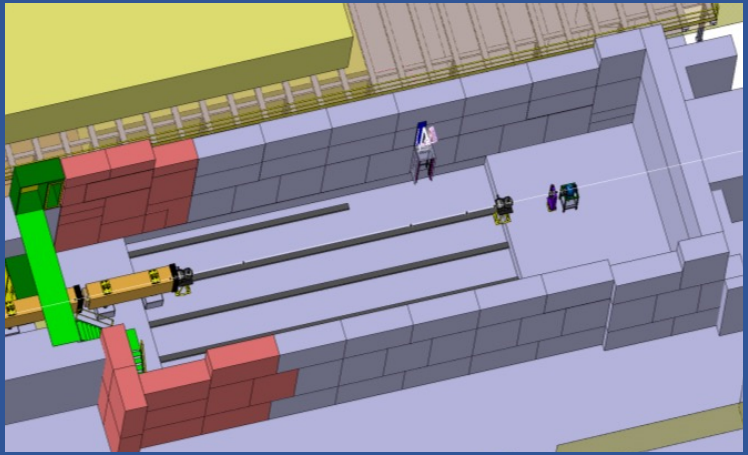


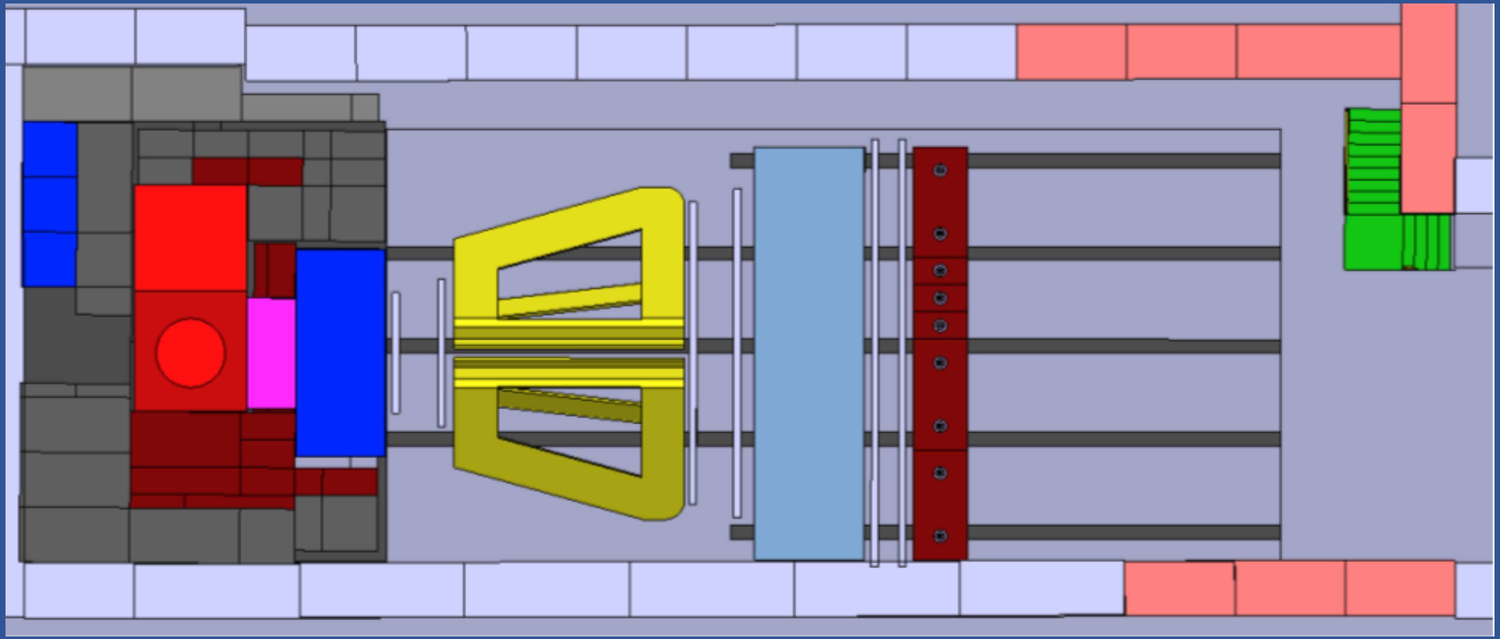
- Measurements of resistance, inductance, cooling performance and magnetic field were carried out
- B measurement
  → agreement with simulations by 3%
- Design of full scale magnet to be started

NA60+ installation in CERN EHN1 (north area)

- ❑ Thorough studies carried out in 2020/2021 thanks to **PBC support**, with the decisive help of the **CERN-BE-EA group**
  → integration feasible in the EHN1-PPE138 area on the H8 beam





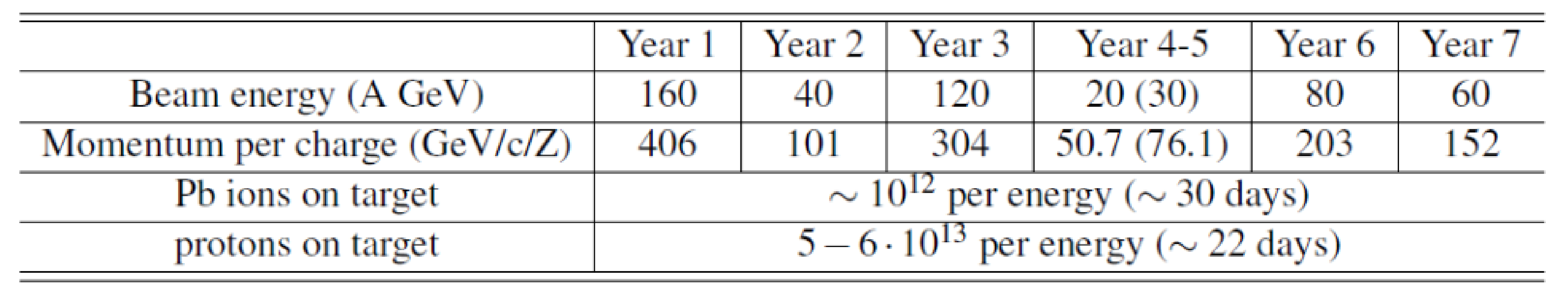


Need rail installation (muon spectrometer shifting) and a possible floor excavation due to the current vertical position of the beam line
Massive shielding for RP was studied by **CERN-HSE** group

NA60+, NIM A1047 (2023) 167887

NA60+: plan for beam energy scan

- run **~ 1month/year with Pb ions** at a different energy with a **~10^6 s^{-1} beam**
  - Tentatively 6 energy points
  - 20 A GeV: two months of data taking needed to fulfil the physics program



	Year 1	Year 2	Year 3	Year 4-5	Year 6	Year 7
Beam energy (A GeV)	160	40	120	20 (30)	80	60
Momentum per charge (GeV/c/Z)	406	101	304	50.7 (76.1)	203	152
Pb ions on target	$\sim 10^{12}$ per energy ($\sim$ 30 days)					
protons on target	$5-6 \cdot 10^{13}$ per energy ($\sim$ 22 days)					

- Corresponding periods with **proton beams** at the same energy are also needed
  - Reference for Pb-Pb results
  - Specific studies with p-A collisions
- Integrated luminosity per N-N collision similar for p-A and Pb-Pb
- Beam intensity ~8x10^8/spill, 3000 spills/day (preliminary estimate)

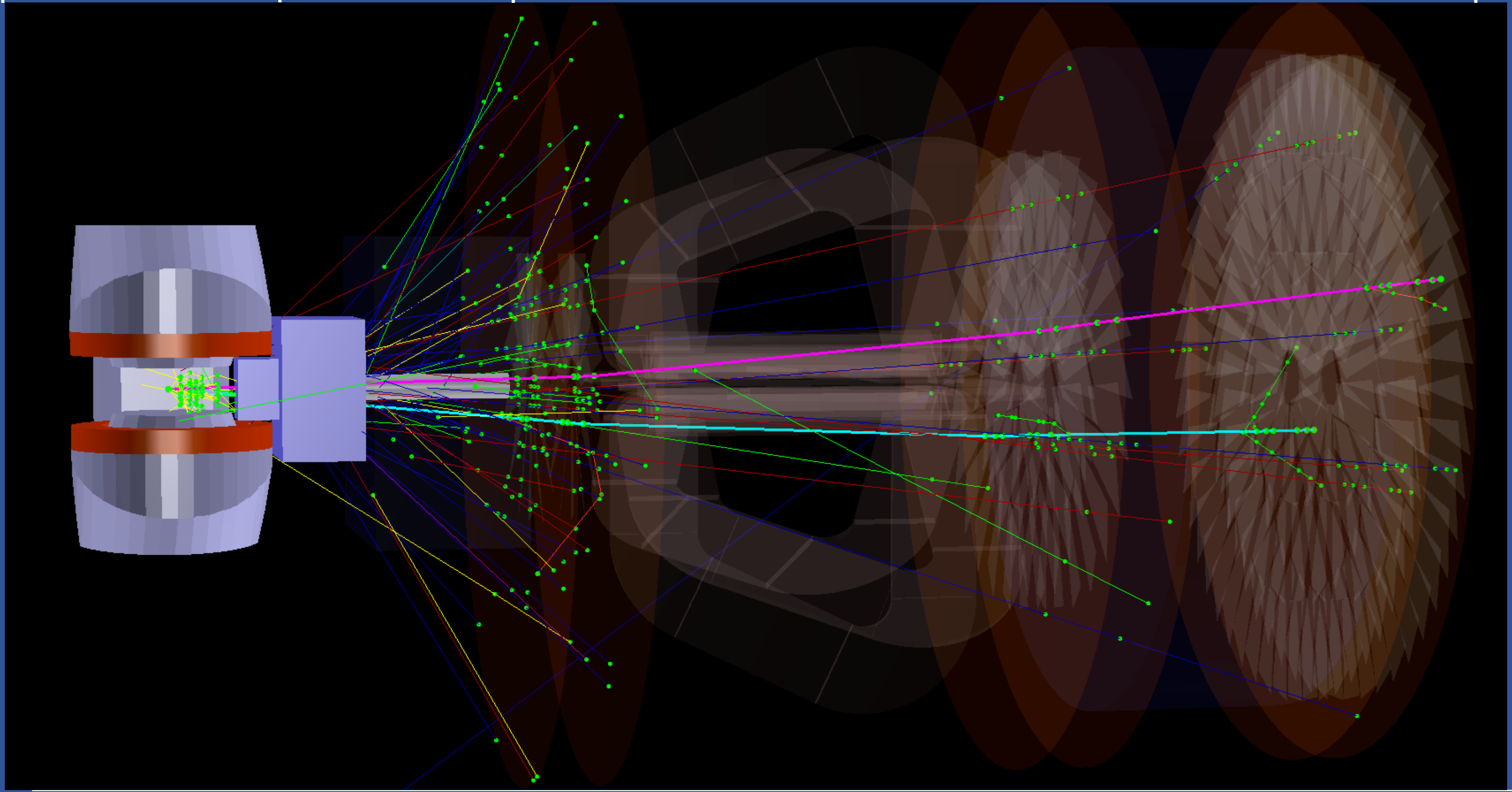
Physics performance: dimuons

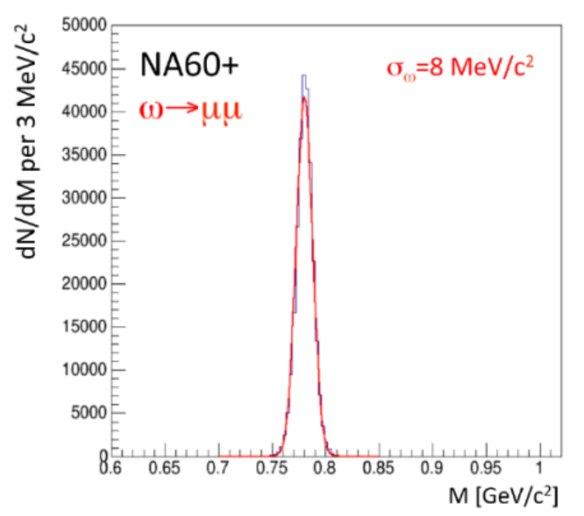
Track matching: measure muon kinematics before multiple scattering and energy loss

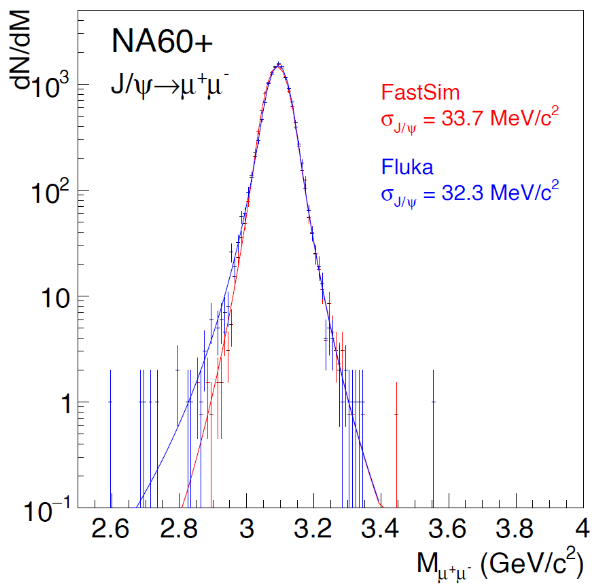
Vertex tracking (dipole field)

Track matching in position and momentum

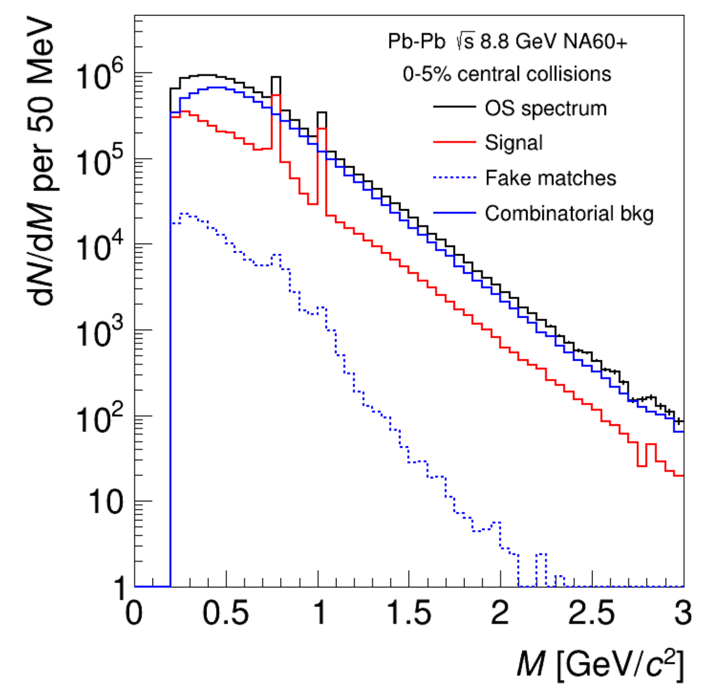
Muon identification in the spectrometer (toroidal field)

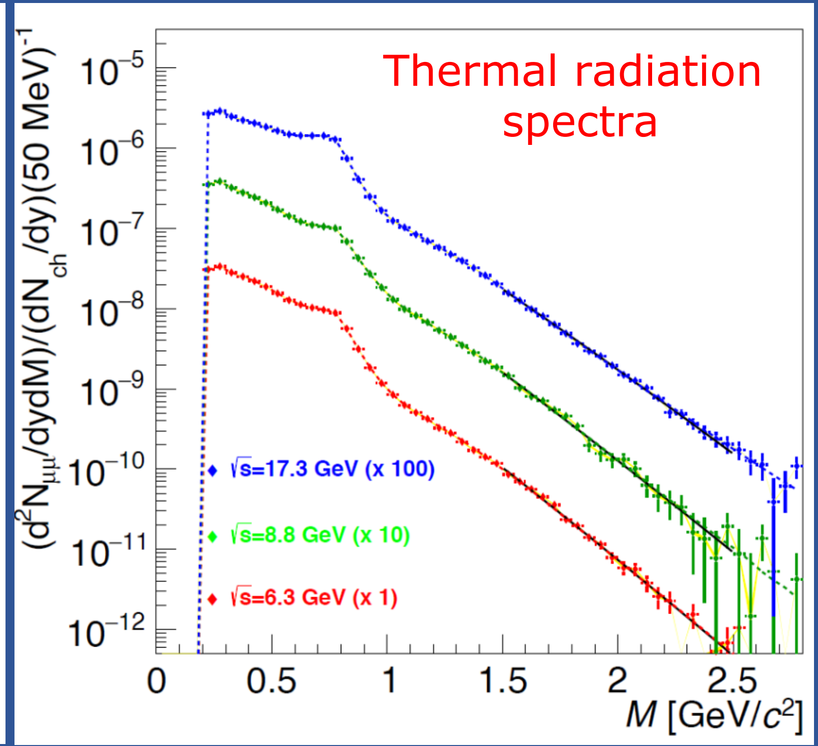






Physics performance: thermal radiation





- ☐ Thermal radiation yield
  - ☐ Dominated by ρ contribution at low mass
  - ☐ Accessible up to M=2.5-3 GeV/c²
- ☐ Drell-Yan contribution
  → to be also estimated via p-A measurements
- ☐ Open charm
  Negligible dimuon source

2 months → 6.3

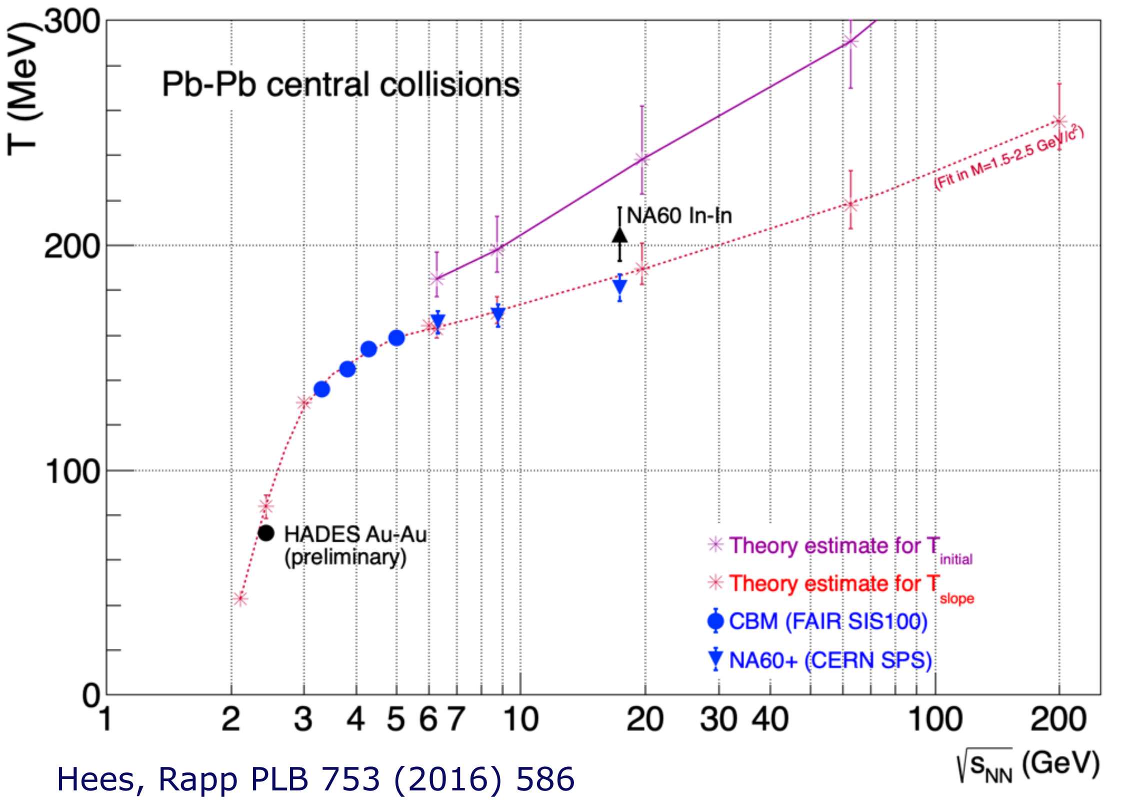
1 month → 8.8, 17.3

Energy (GeV)	Thermal pairs	T_{slope}
6.3	$3.52\cdot10^6$	$166\pm4.7\pm1$
8.8	$3.56\cdot10^6$	$169\pm4.4\pm1$
17.3	$9.70\cdot10^6$	$182\pm1.8\pm1$

(0-5% central Pb-Pb collisions)

~1-3% uncertainty on the evaluation of T_{slope}

Caloric curve and fireball lifetime



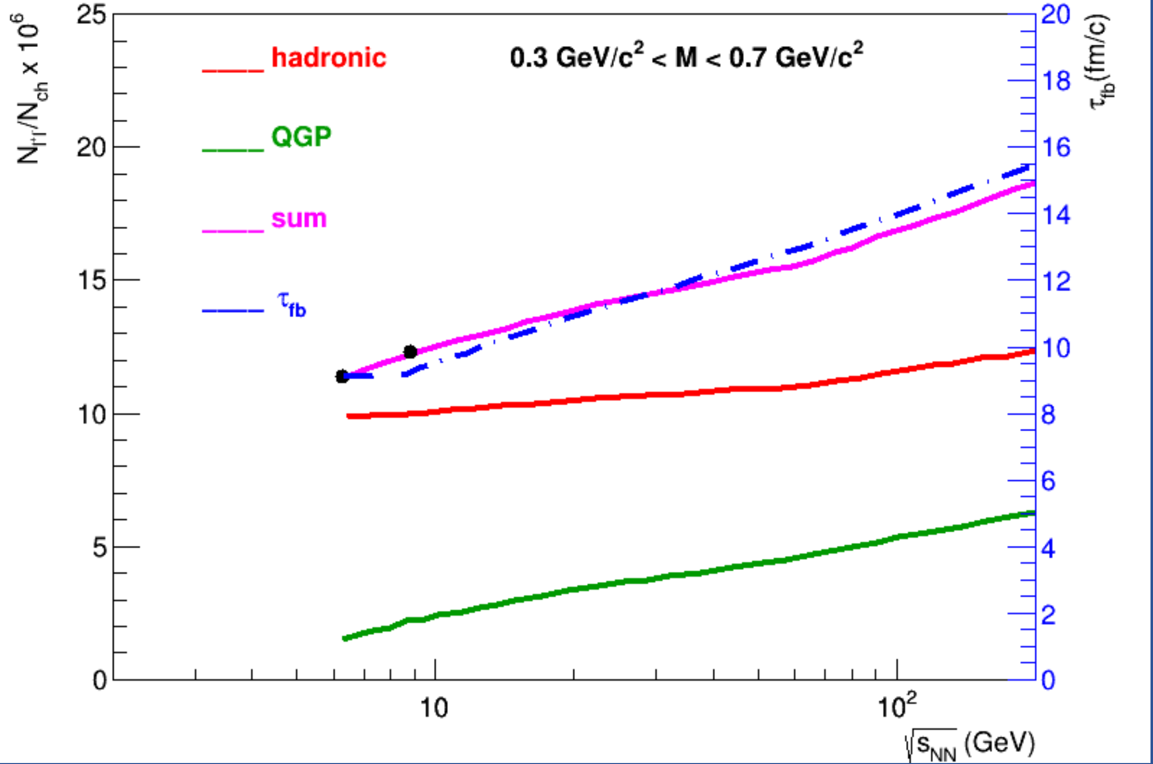
Hees, Rapp PLB 753 (2016) 586

Galatyuk *et al.* EPJA 52 (2016) 131

Accurate mapping of the region where T_{pc} is reached
→ Strong **sensitivity** to possible flattening due to
1st order transition

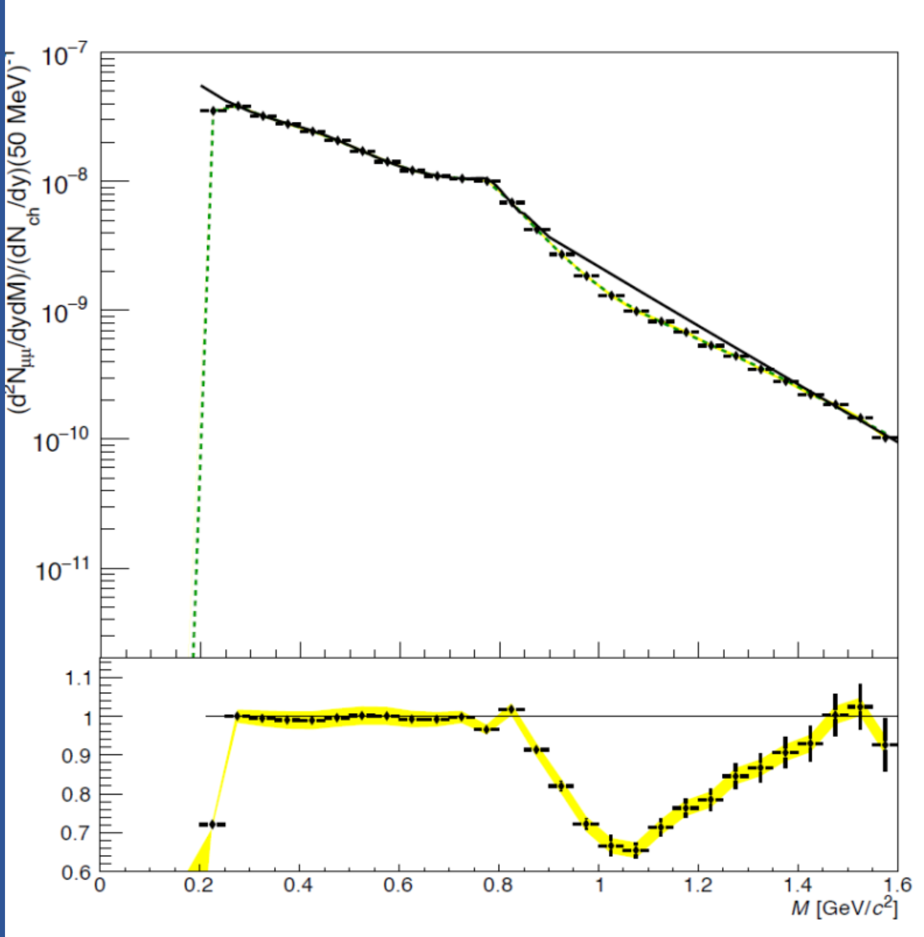
Precise measurement of thermal yield in
0.3<M<0.7 GeV **sensitive to the fireball lifetime**

Hees, Rapp, Phys. Lett. B 753 (2016) 586



Physics performance: chiral symmetry

- ☐ Detect **modification of continuum** in $1<M_{\mu\mu}<1.4$ GeV, related to chiral symmetry restoration

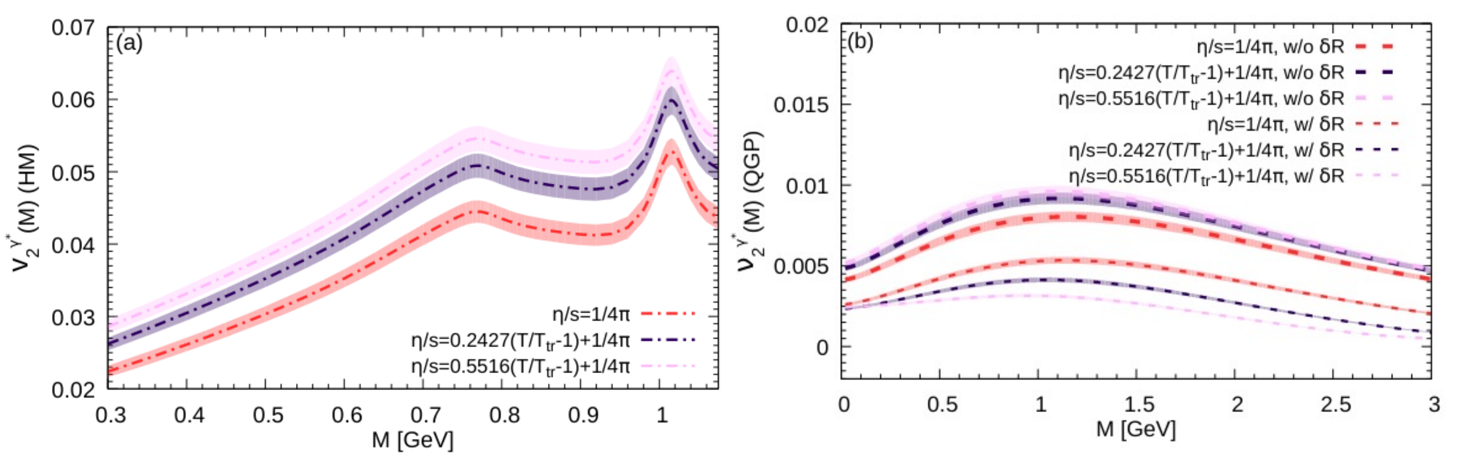


- ☐ Comparison of spectra ($\sqrt{s_{NN}}$ = 8.8 GeV), based on the assumption of no chiral mixing, with expectation of full chiral mixing

- ☐ Statistical and systematic uncertainty provide a very good sensitivity to an **increase of the yield due to chiral mixing of ~20–30%**

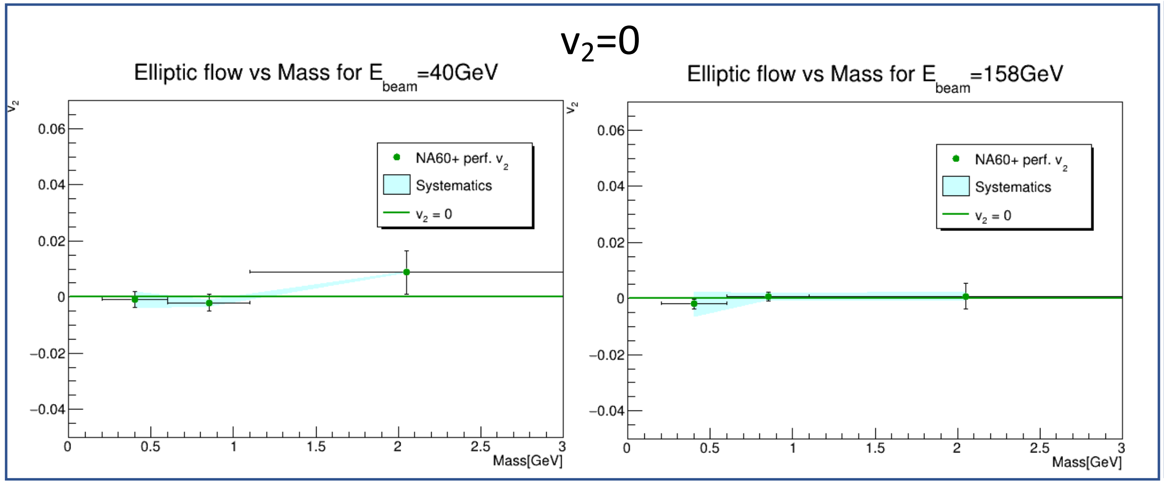
Physics performance: elliptic flow

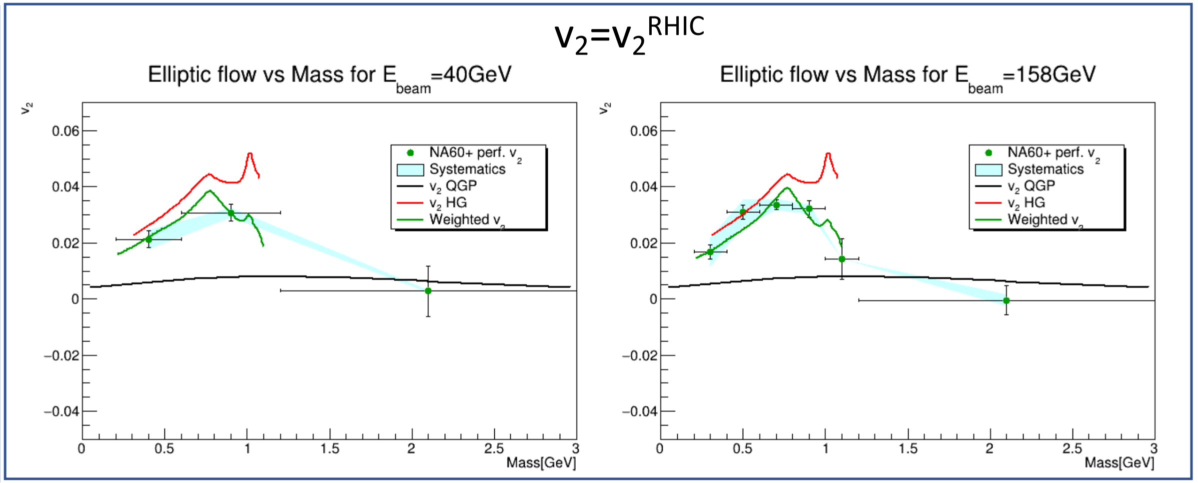
- No measurements at present
- Predictions at the RHIC energies
- LMR dominated by HG:
  almost linear increase of v_2 vs mass
- IMR dominated by QGP: small v_2



Vujanovic et al, Phys. Rev. C 98, 014902 (2018)

- No prediction at the SPS energies
  Two possible scenarios: $v_2=0$ → measurement with uncertainty between 0.003 and 0.008
  $v_2=v_2^{RHIC}$ → increase of v2 versus mass (HG) and a drop in the IMR (QGP)





Formal steps and timeline

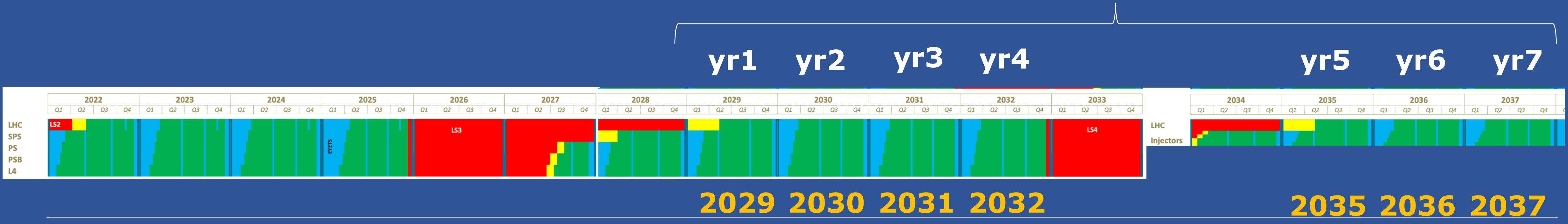
- ❑ Project followed by Physics Beyond Colliders at CERN since 2016
- ❑ EoI in 2019 https://cds.cern.ch/record/2673280
- ❑ LoI in 2022 CERN-SPSC-2022-036 ; SPSC-I-259
- ❑ Feb 2023: project discussed by SPSC

The SPSC **recognizes the fundamental interest of the measurements proposed by the NA60+ collaboration**, which are focused on electromagnetic and hard probes of the quark gluon plasma at high baryochemical potential. In order for the project to proceed with the suggested roadmap (starting construction in 2026 and data taking in 2029), **the SPSC would expect to start examining a proposal by 2024**

Our current plan is to have the experiment on the floor by the end of LS3 → **2029**

- ❑ Roadmap
  - ❑ Technical proposal: **2024-2025**
  - ❑ Construction and installation: **2026-2028**

NA60+ data taking



Summary

- ☐ The new heavy-ion experiment NA60+ at CERN is designed to perform **high precision measurements** of thermal dileptons, charmonium, open-heavy flavors **over a wide low-energy range** (also strangeness and hypernuclei are on the physics menu)

- ☐ Present stage: consolidation of collaboration and completion of R&D (pixel and muon detectors, magnet)

- ☐ We plan to submit to SPSC a proposal by 2024-25

- ☐ In our current timeline first data taking could occur in **2029**, after LS3

- ☐ **Further groups join the effort!** Still ample space for decisive contributions on all items: gas detectors, MAPS, magnet, trigger, DAQ,…
  → May represent an excellent testbench for detectors to be used at future facilities

Backup

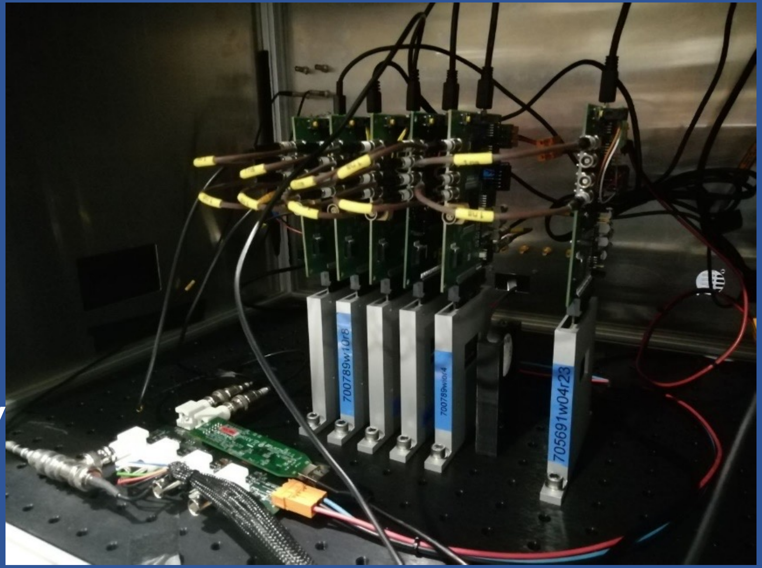
NA60+: beam studies R&D

- ☐ A **high-intensity Pb beam** (~10^6/s) is needed, from 20-30 A GeV to 160 A GeV
- ☐ Beam optics studies carried out to provide sub-mm beam all over the energy range

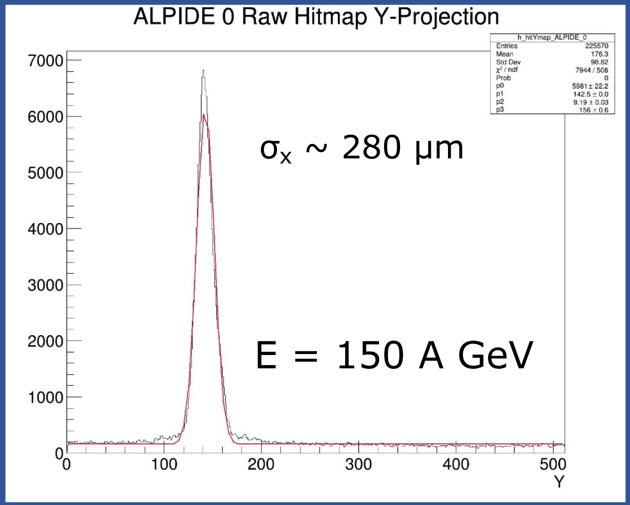
Goal

Parameter in zone 138	160 GeV/c	30 GeV/c
σ_x (mm)	0.19	0.33
σ_y (mm)	0.19	0.36
Transmission from T4 (%)	32.43	23.5

N.B.: Vertex spectrometer central hole, ∅ ~ 0.6 cm

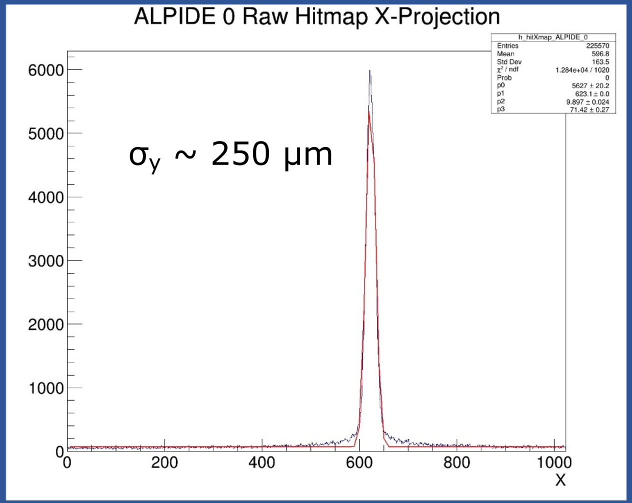


A first **test beam in PPE138** was carried out in November 2022, using a telescope of pixel sensors for a precise measurement



σ_x ~ 280 μm

E = 150 A GeV



σ_y ~ 250 μm

Result already promising, further tests needed
→ Lower beam energy
→ Higher beam intensity (now ~10^4 s^{-1})

Pb beam request submitted for fall 2023

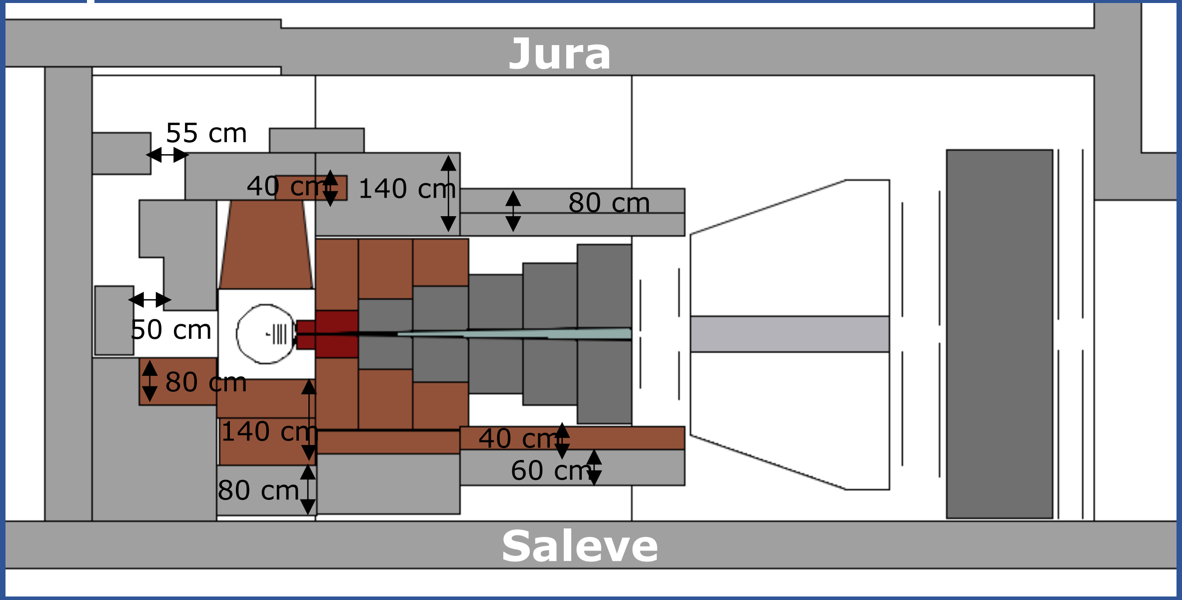
NA60+, NIM A1047 (2023) 167887

RP studies

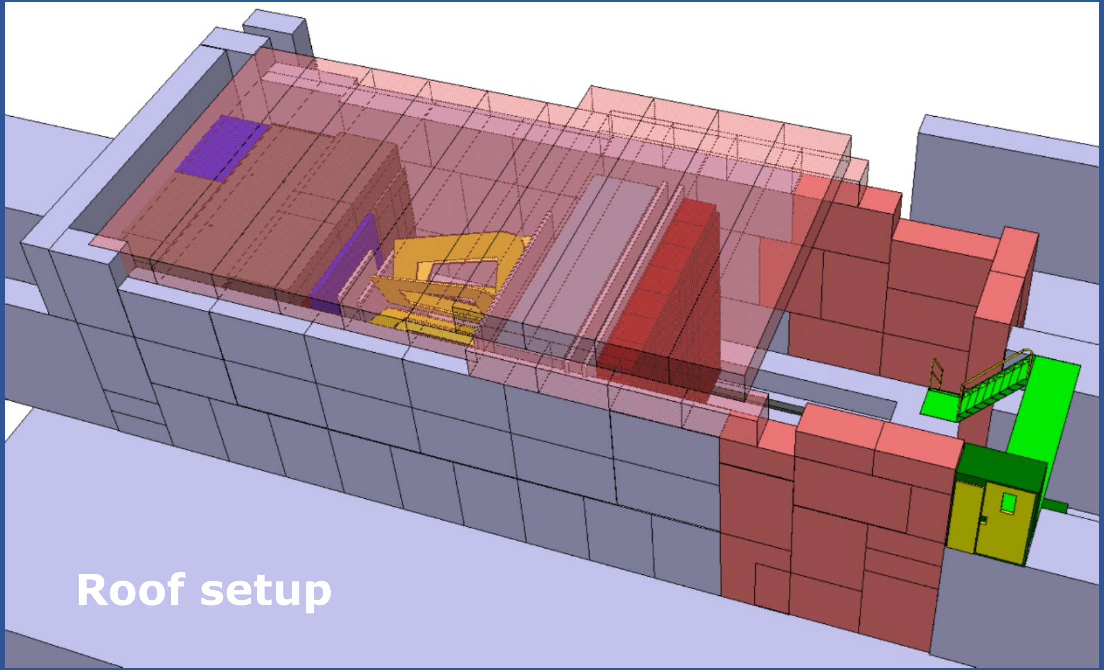
HSE
Occupational Health & Safety
and Environmental Protection unit

High-intensity beam in the EHN1 surface zone: non-negligible **radioprotection issues**
→ Thorough studies carried out by the **CERN-HSE** group

Top view



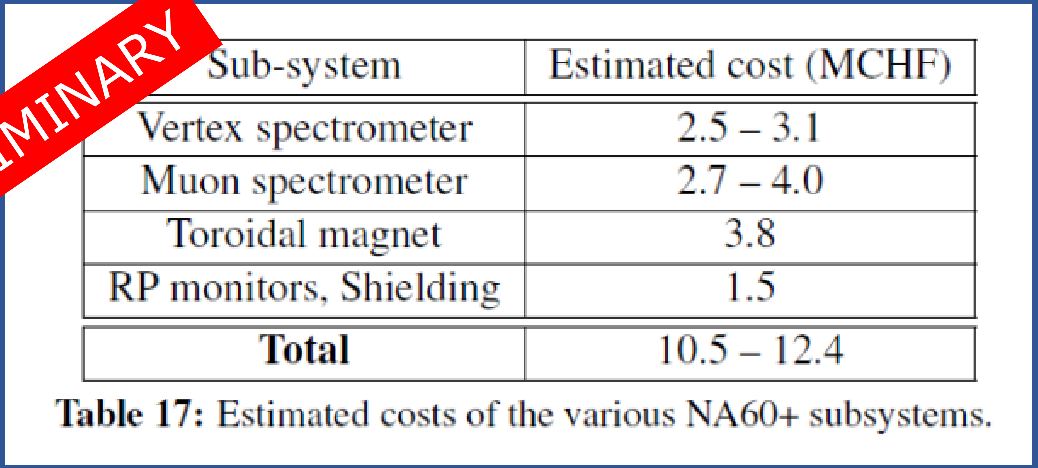
Prompt ambient dose, residual ambient dose, air activation and accidental beam loss scenarios studied in detail



A **massive shielding** around the absorber region, where the beam will be dumped, has been designed

Cost estimates

- ❑ Final definition of the set-up details still in progress
- ❑ Estimate of costs related to data acquistion, storage and computin is still in progress
- ❑ Current evaluation subject to oscillation in the cost of raw materials, electronic, etc.
- ❑ Assume 1 Euro ~ 1 CHF ~ 1 US$



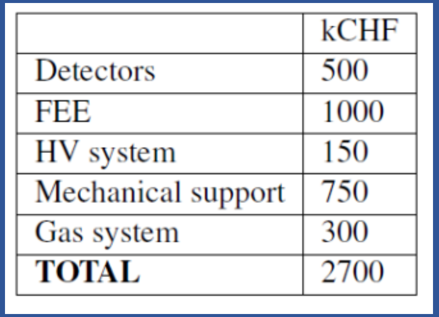
PRELIMINARY

Sub-system	Estimated cost (MCHF)
Vertex spectrometer	2.5 – 3.1
Muon spectrometer	2.7 – 4.0
Toroidal magnet	3.8
RP monitors, Shielding	1.5
Total	10.5 – 12.4

Table 17: Estimated costs of the various NA60+ subsystems.

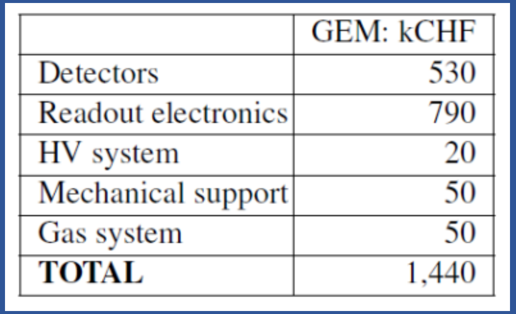
Muons

All MWPCs



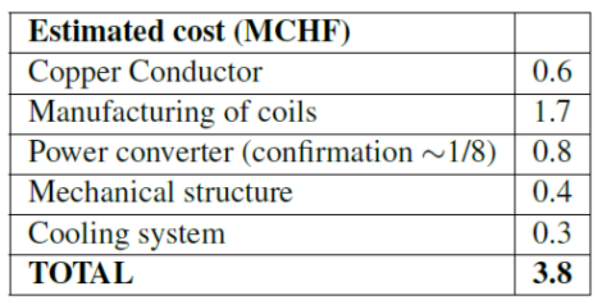
	kCHF
Detectors	500
FEE	1000
HV system	150
Mechanical support	750
Gas system	300
TOTAL	2700

MS0/1 GEMs

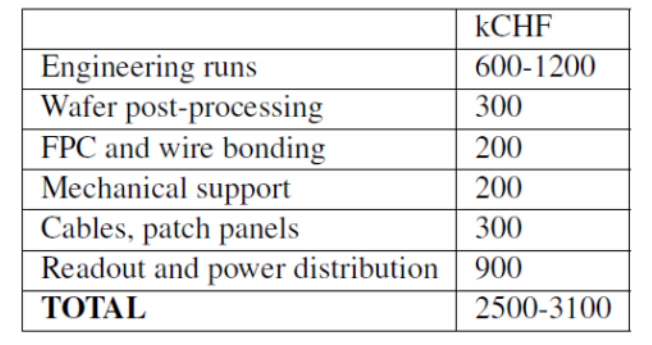


	GEM: kCHF
Detectors	530
Readout electronics	790
HV system	20
Mechanical support	50
Gas system	50
TOTAL	1,440

Toroid



Estimated cost (MCHF)	
Copper Conductor	0.6
Manufacturing of coils	1.7
Power converter (confirmation ~1/8)	0.8
Mechanical structure	0.4
Cooling system	0.3
TOTAL	**3.8**



	kCHF
Engineering runs	600-1200
Wafer post-processing	300
FPC and wire bonding	200
Mechanical support	200
Cables, patch panels	300
Readout and power distribution	900
TOTAL	2500-3100

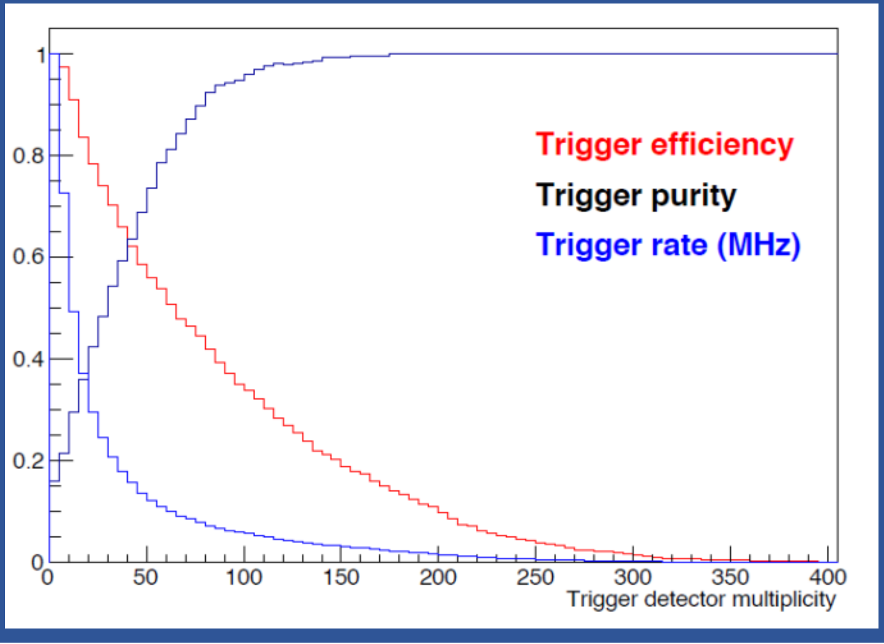
MAPS

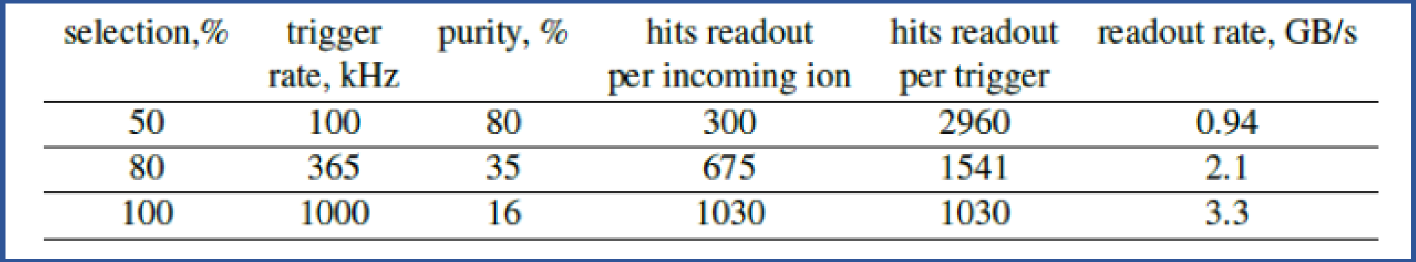
Trigger and DAQ

Data acquisition, processing, computing (1)

- **Data rate** dominated by the vertex telescope, for the assumed 10^6 ions/s Pb beam intensity,
  - → ~ **3.3 GB/s** data rate
  - → ~ 3.3 PB of data collected per year
- **δ-ray** production from non-interacting Pb ions (85% of the incident beam) significantly contribute to the data rate

- Consider to acquire data **triggered** by a fast scintillator close to the interaction region
  → increase purity at the price of discarding peripheral Pb-Pb events





selection,%	trigger rate, kHz	purity, %	hits readout per incoming ion	hits readout per trigger	readout rate, GB/s
50	100	80	300	2960	0.94
80	365	35	675	1541	2.1
100	1000	16	1030	1030	3.3

↑

Centrality selected

Data acquisition, processing, computing (2)

- ☐ **Offline data reconstruction**
  - ☐ → Use a modified version of the Cellular Automaton track finder developed for the ALICE ITS

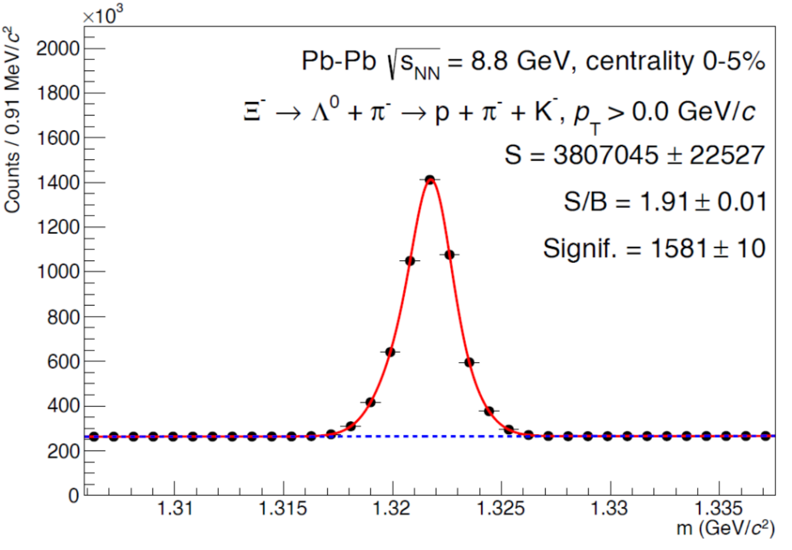
- ☐ **Data decoding and cluster-finding** require ~240 (~450) CPU seconds for 50% (80%) efficiency triggering scenarios, for 10^6 incoming ions ← preliminary!

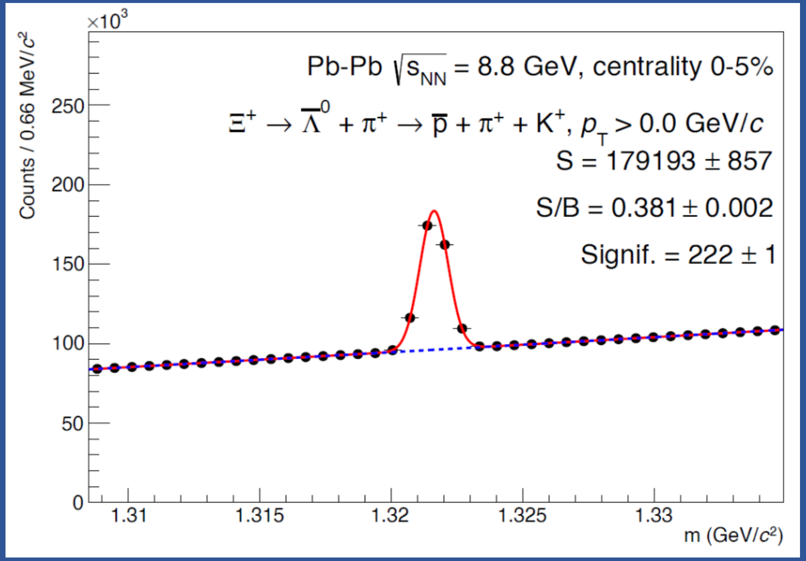
- ☐ Corresponding **track finding time** ~ 4200 CPU seconds (assume Intel i7-8700K @ 3.7 GHz processor)

- ☐ Data collected per heavy-ion run can be **fully processed in 2–3 months** by a farm of ~ 100 modern multicore processors or equivalent GRID jobs

Strangeness and hypernuclei

Strangeness measurements: hyperons





- Hyperon decays simulated with EVtGen, decay products propagated in the VT using the fast simulation of NA60+
- Background from hadron production → **NA49 results**

- Channels studied

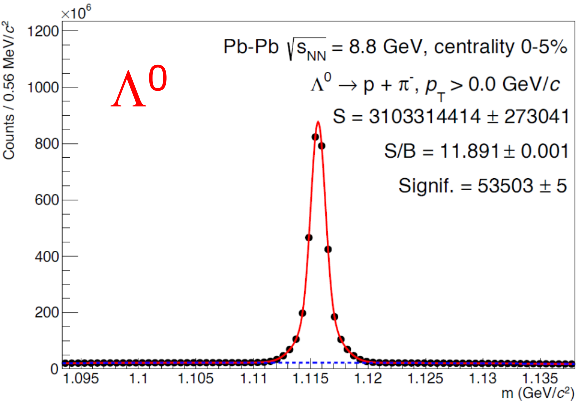
$\Lambda^0 \to p + \pi^-$ $\Xi^- \to \Lambda^0 + \pi^-$ $\Omega^- \to \Lambda^0 + K^-$

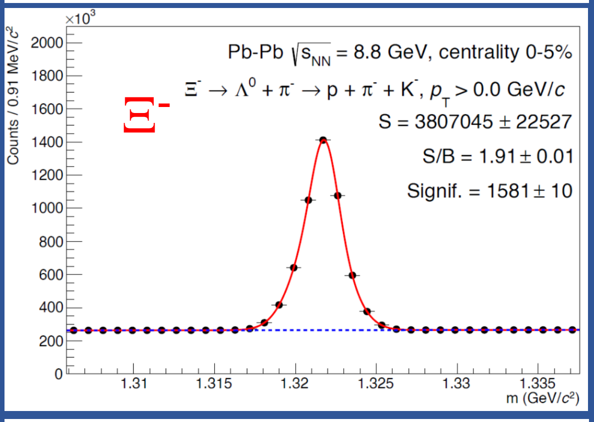
and charge conjugated

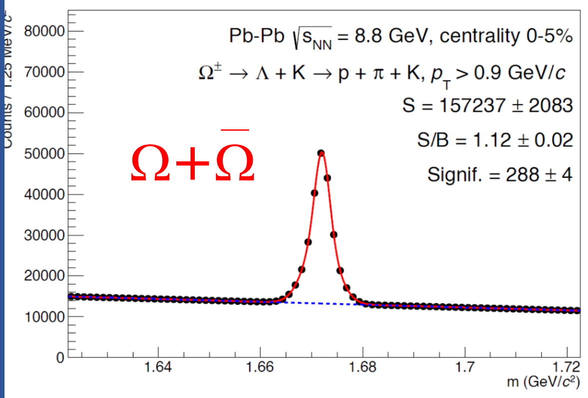
- **Topological selections** applied
- **BDT employed to enhance the significance of the signal**
- Among the variables:
  - Product of the impact parameter of decay tracks,
  - Distance of closest approac between the decay tracks
  - Decay length and the cosine of the pointing angle

- Also ϕ → KK and K_s → $\pi\pi$ were studied

Physics performance: strangeness and hypernuclei

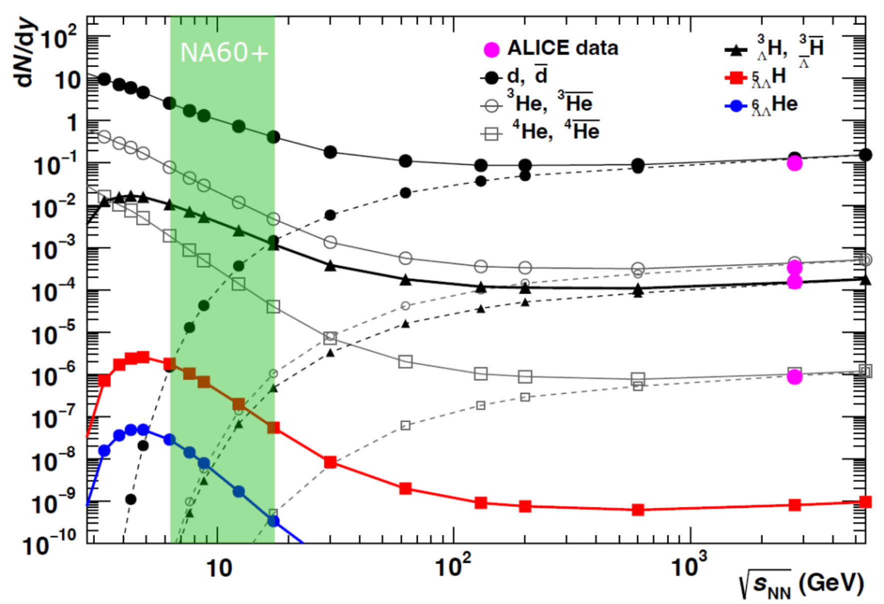




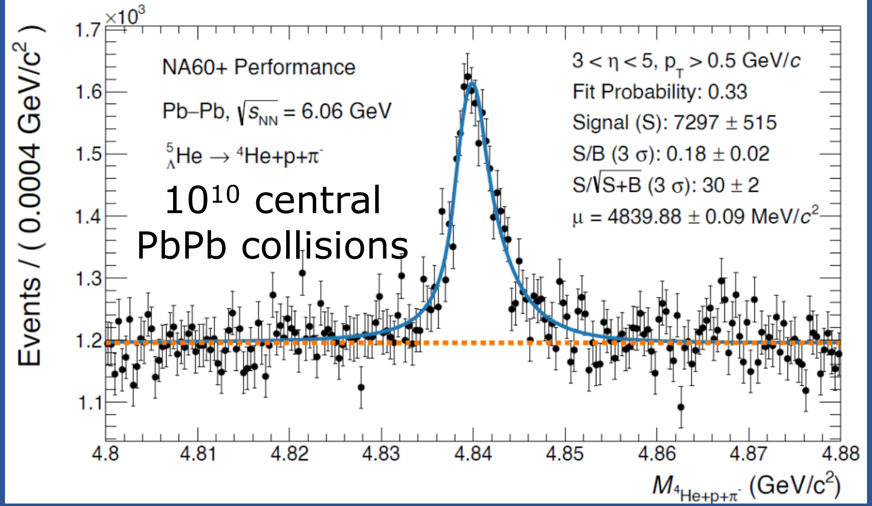


- **Topological selections with BDT** employed to **enhance the significance** of the signal
- Among the variables:
  - Product of the impact parameter of decay tracks
  - Distance of closest approach between the decay tracks
  - Decay length and the cosine of the pointing angle

- Also $\phi \rightarrow KK$ and $K_s \rightarrow \pi\pi$ have been studied



Low energy HI collisions → **high baryon density** favours the production of hypernuclear clusters

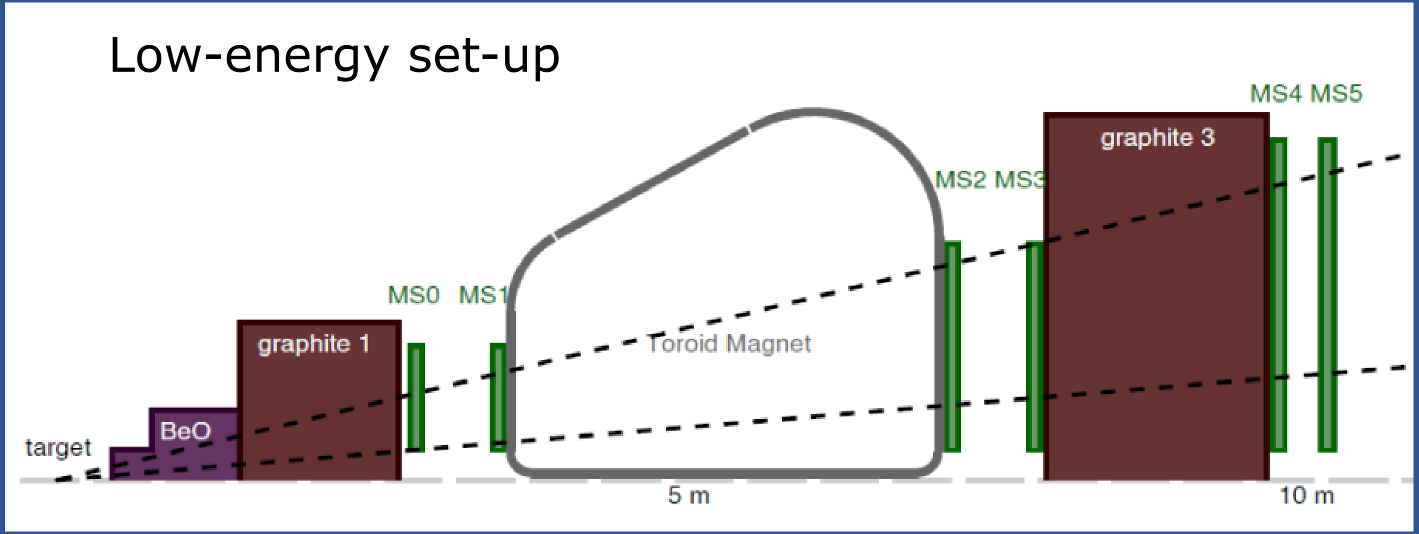


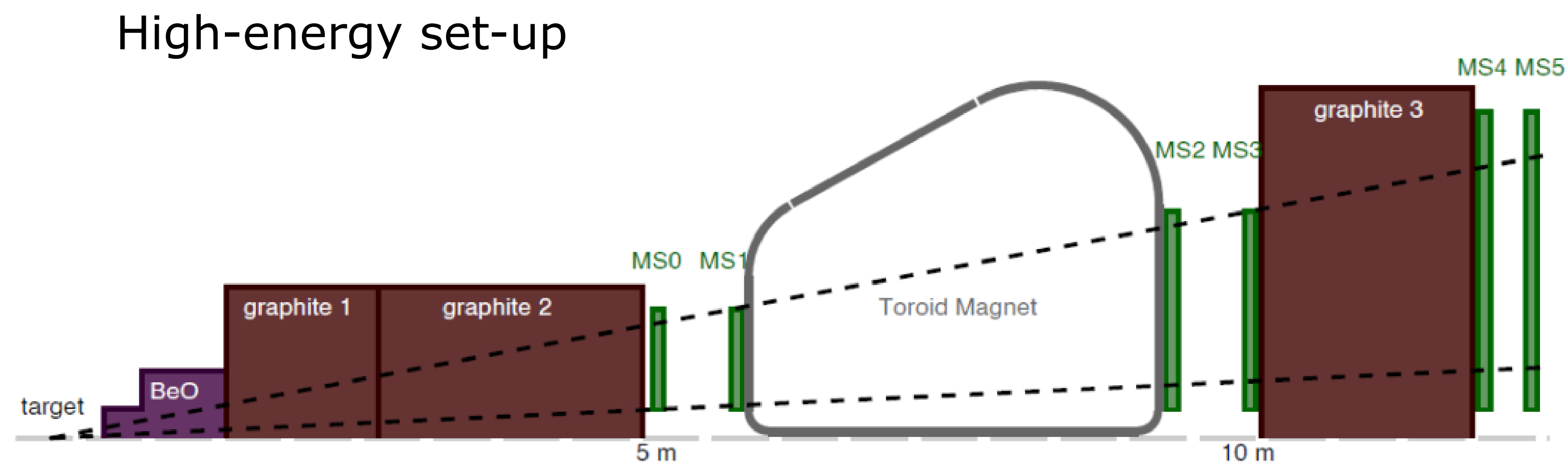
10^{10} central PbPb collisions

Separation of heavily ionising particles from ordinary hadrons → **size of the clusters** associated with the track

Muon spectrometer

The NA60+ muon spectrometer





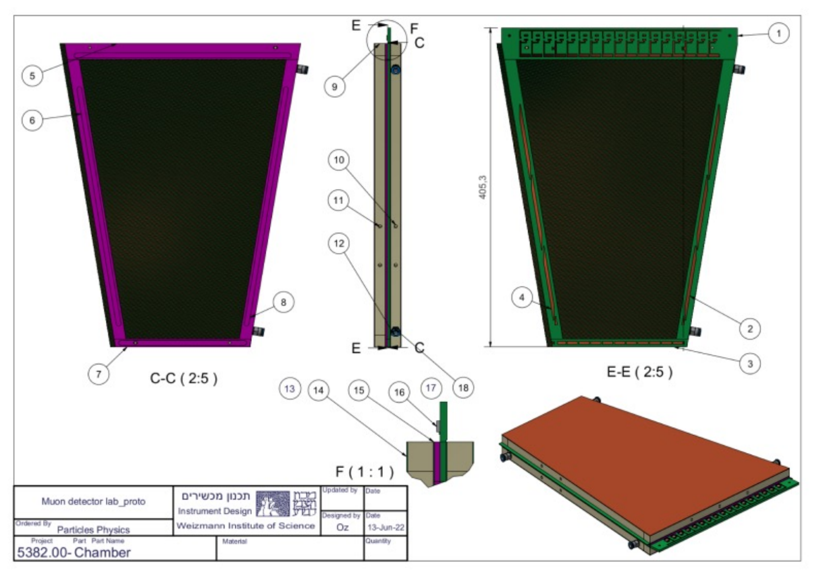
- ❑ (At least) two configurations of the muon spectrometer are foreseen

- ❑ **Low-energy set-up**
  →Thinner absorber
  →Smaller distance from target

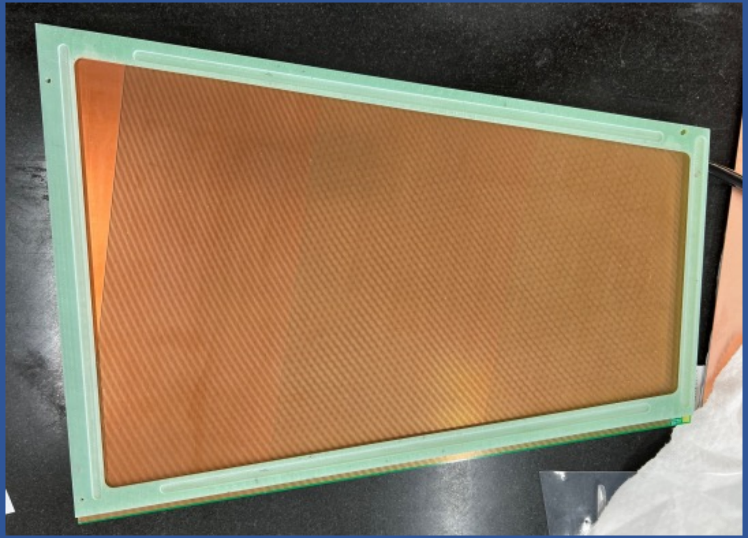
- ❑ **High-energy set-up**
  →Thicker absorber
  →Larger distance from target

Keep maximum acceptance around $y \sim y_{CM}$

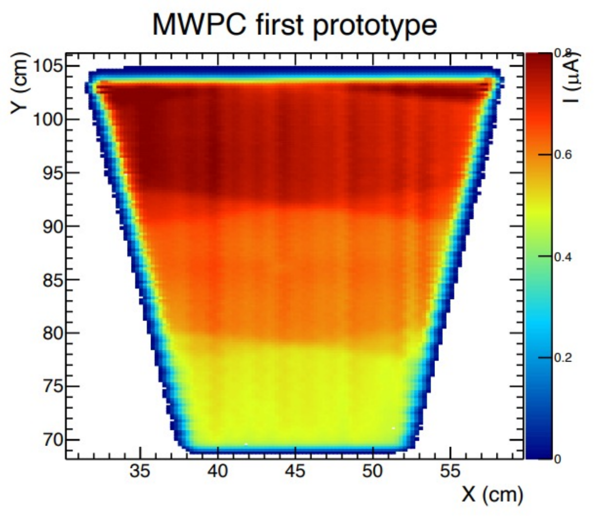
MWPC prototype tests

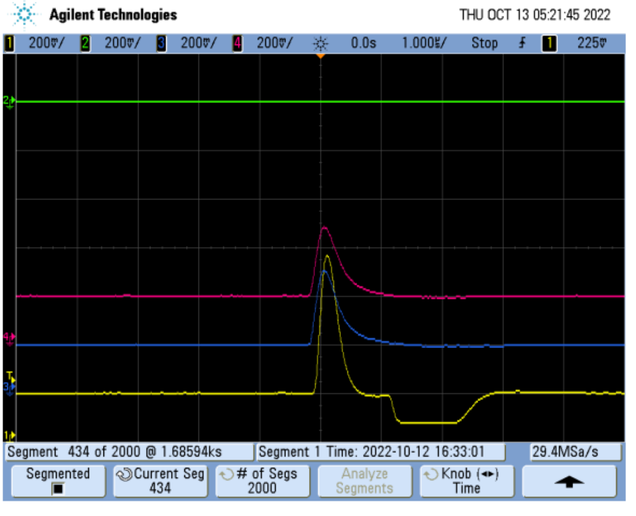


- ☐ Wire pitch: 3 mm
- ☐ Distance wire to cathode: 3 mm
- ☐ 1 mm strip pitch
- ☐ 2 cathodes with strips running in two different directions
  → Small angle stereo readout
- ☐ Readout electronics cards with VMM3a ASIC (128 ch each)

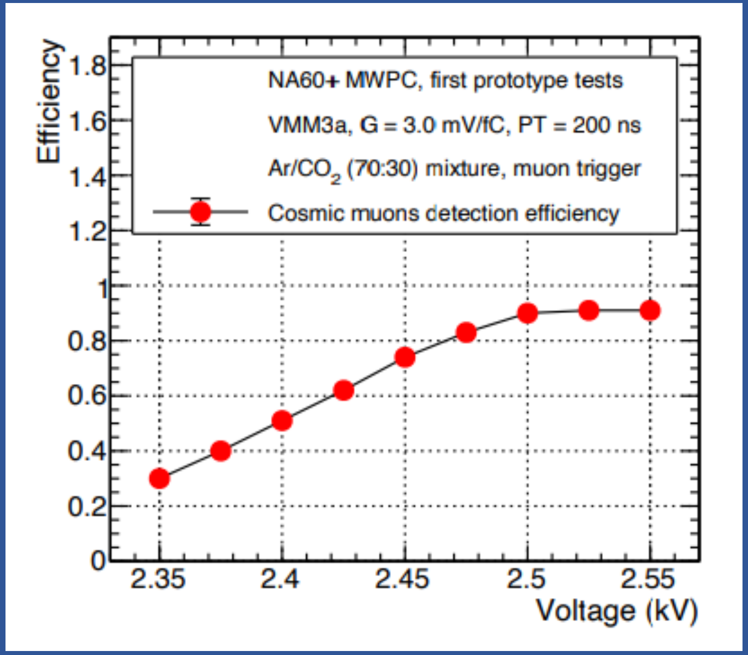


Detector tomography





Trigger and MWPC signals



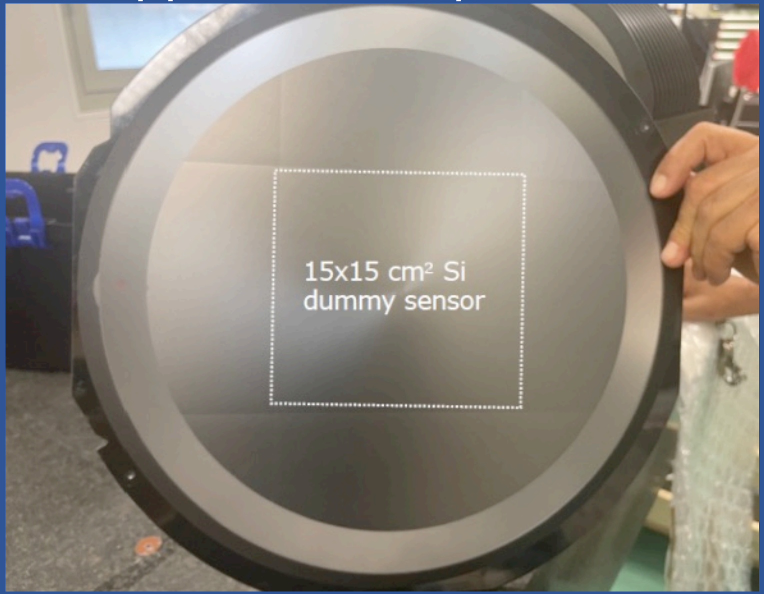
Vertex spectrometer

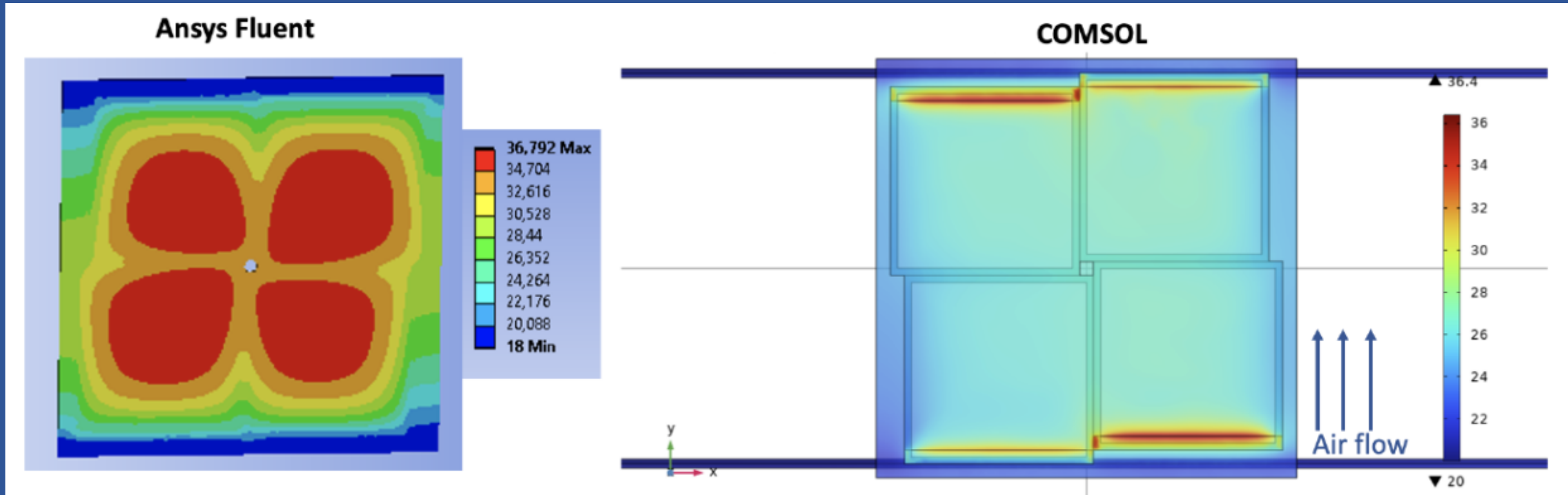
Ongoing R&D on vertex spectrometer

- Detector
  - Characterization of small-scale structures
  - Submission of first large area MAPS with the stitching technique (MOSS)
  - Development of test system for large area MAPS

- Mechanics
  - Positioning and gluing tests of (dummy) sensors on carbon foam/fiber supports with optical bench

- Cooling calculations
  → Mix air flow + water flow

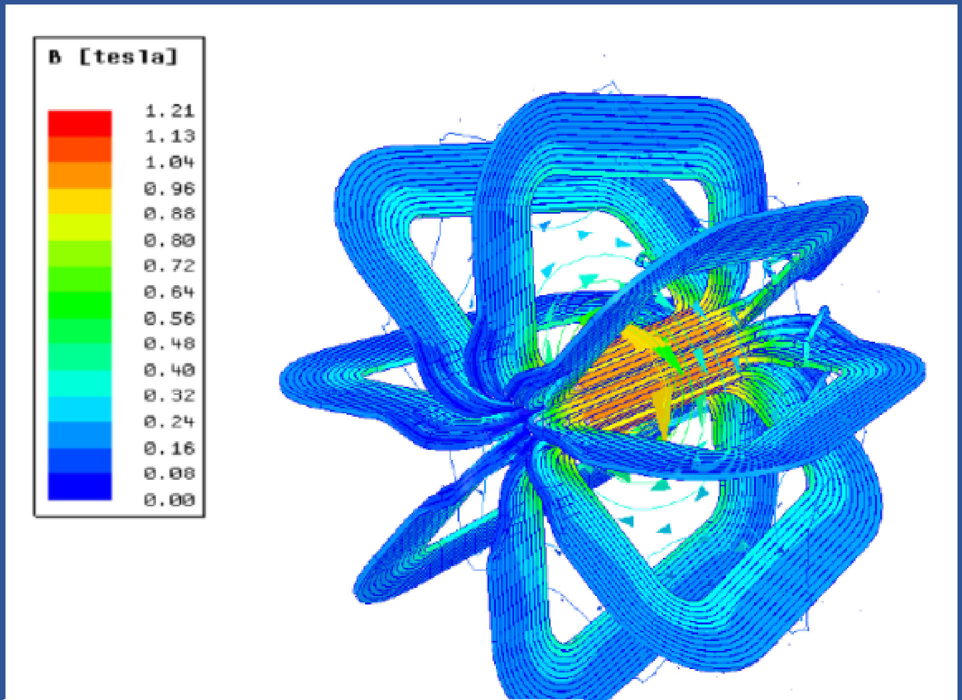




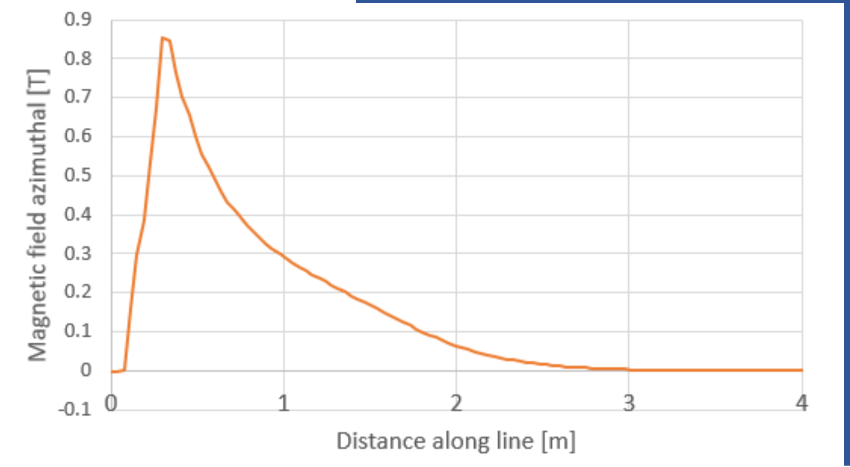
24°C ambient temperature
Air flow 1m/sec + water flow 0.5 l/min 18°C

Toroid

The NA60+ toroid



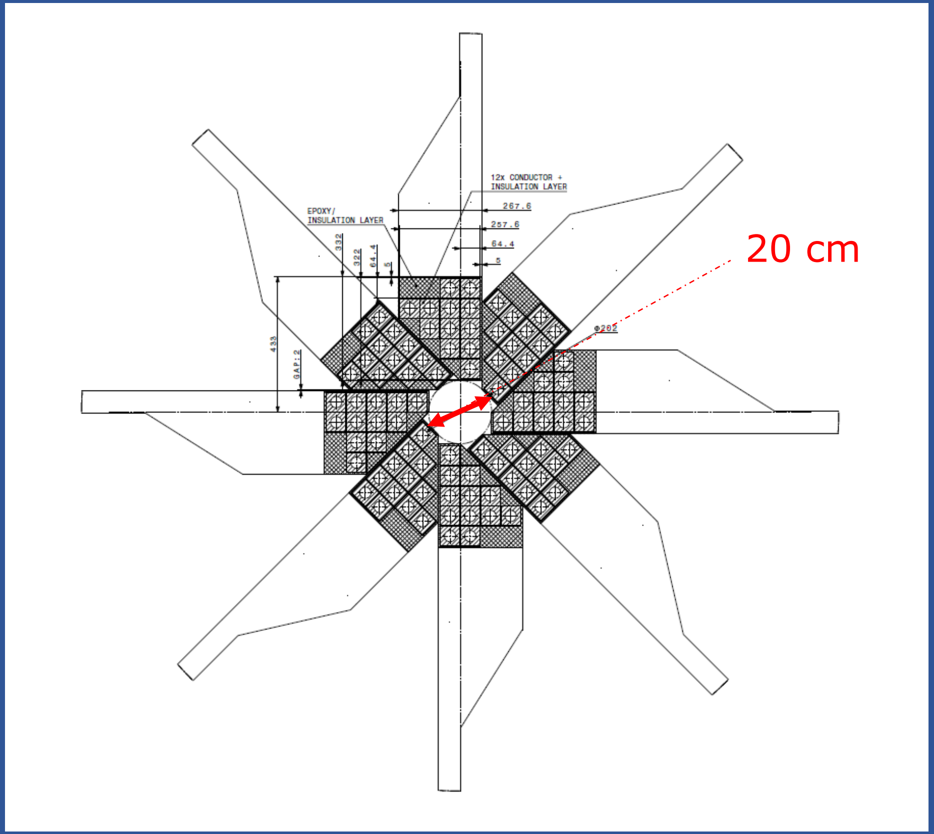
Operating Current [kA]	16.6
Amp-turns [kA]	199
Combined inductance [mH]	9.5
Resistivity Al 1100 @RT [μΩ.cm]	2.67
Length Conductor [m]	800
Total resistance [mΩ]	10.4
Dissipated power [MW]	2.8



Warm magnet

Eight sectors,
12 turns per coil

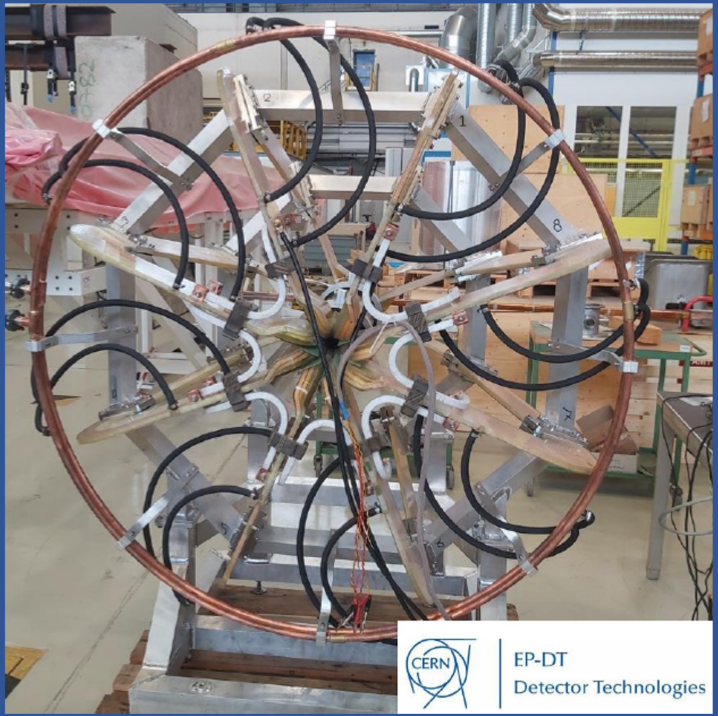
Conductor has a square copper section with a circular cooling channel in the centre

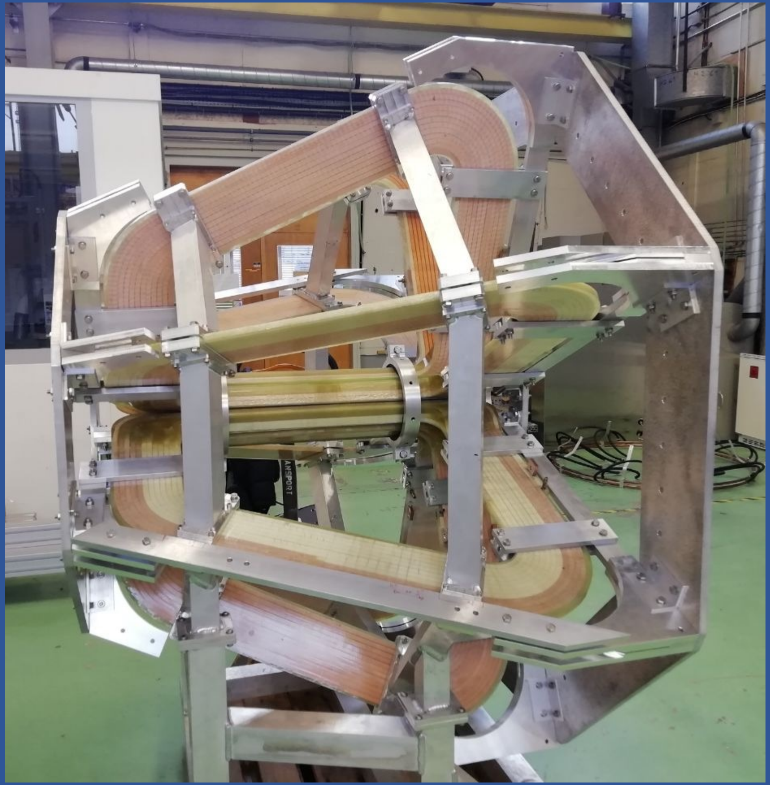


Complex arrangement of the coils close to the beam axis to reduce the ‘dead zone’ at forward y

Ongoing discussions on strategy for **reducing the dissipated power** (<2 month/yr, pulsed operation,…)

The NA60+ toroid R&D

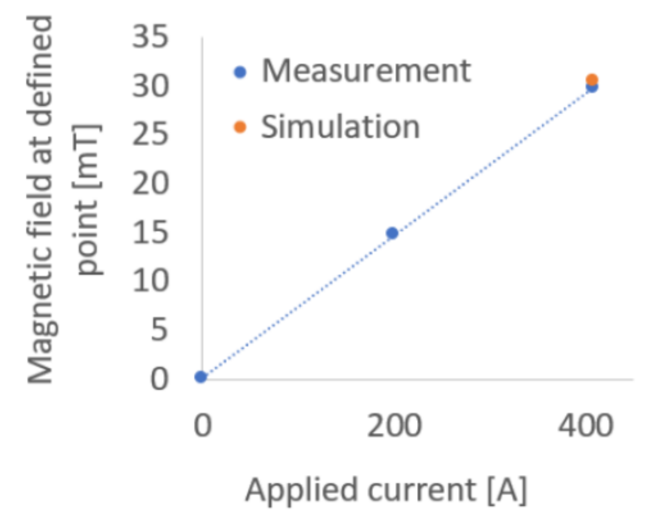




- ❑ A **prototype (1:5 scale)** was built and tested in 2020-2021 by the **CERN-EP-DT group**, to check calculations and investigate mechanical solutions, in view of the final object

→ **works correctly and as expected**

- ❑ Measurements of resistance, inductance, cooling performance and magnetic field were carried out



- ❑ B measurement
  → agreement with simulations by 3%

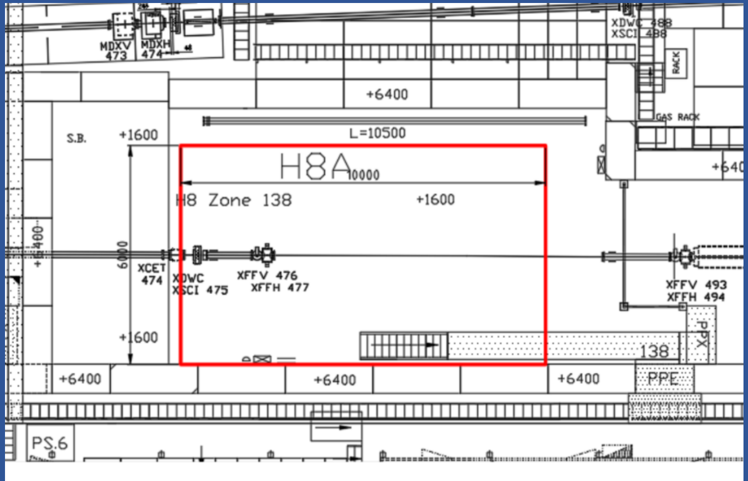
Support and participation of CERN in the design of the final toroid is very important

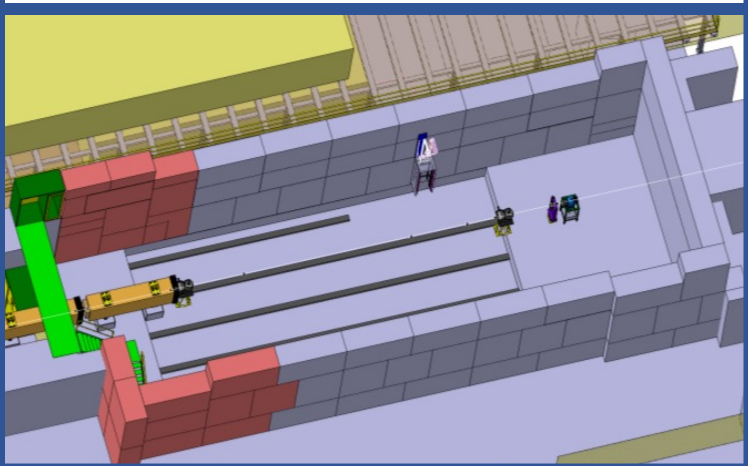
Integration, radioprotection, beam

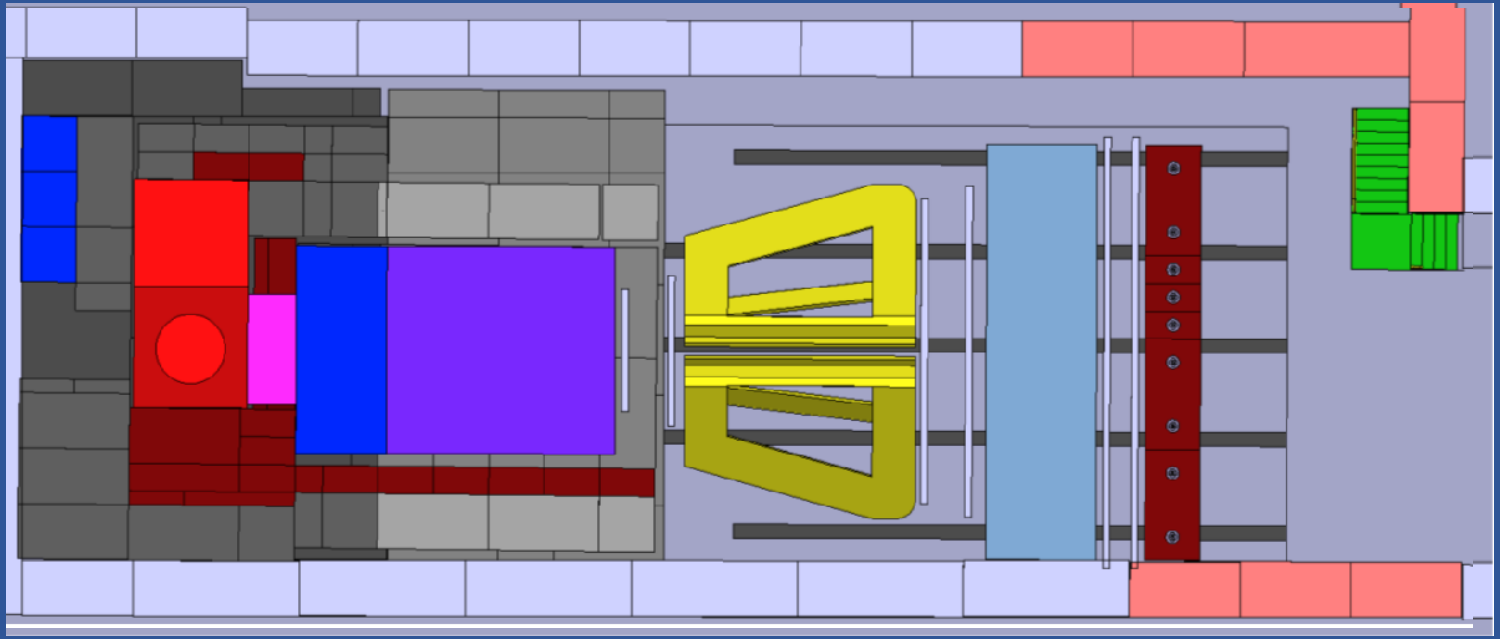
NA60+: where

Physics Beyond Colliders

- ☐ Thorough studies carried out in 2020/2021 thanks to **PBC support**, with the decisive help of the **CERN-BE-EA group**
  → integration feasible in the PPE138 area on the H8 beam







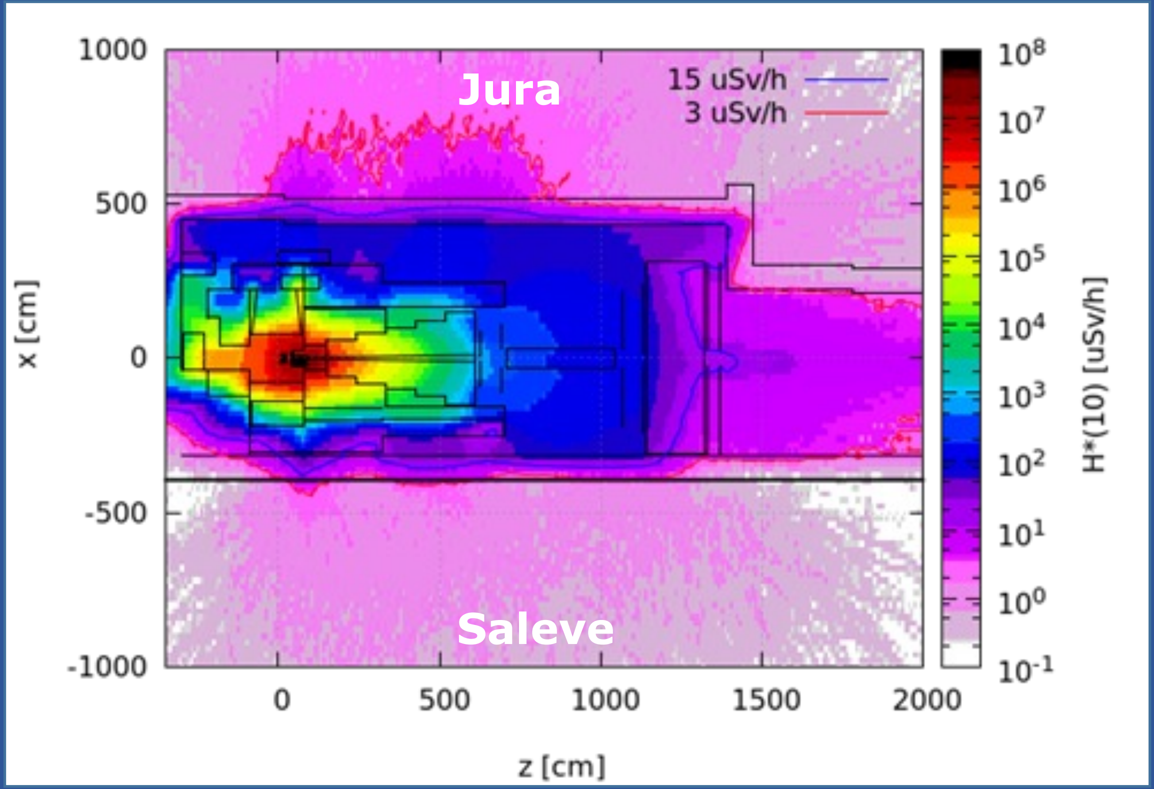
Need rail installation (muon spectrometer shifting) and a possible floor excavation due to the current vertical position of the beam line

High-energy setup

RP studies

HSE
Occupational Health & Safety
and Environmental Protection unit

Using a high-intensity beam in the EHN1 surface zone poses non-negligible **radioprotection issues**
→ Thorough studies carried out by the **CERN-HSE** group



Prompt ambient dose, residual ambient dose, air activation and accidental beam loss scenarios were studied

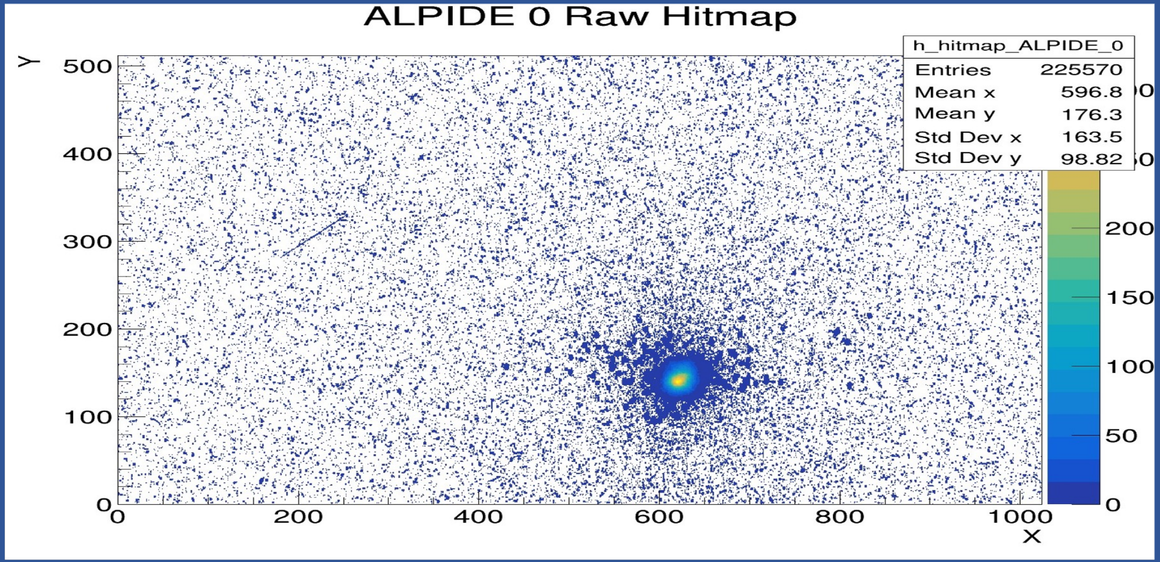
A **massive shielding** around the absorber region, where the beam will be dumped, has been designed

First test beam in the H8 experiment location

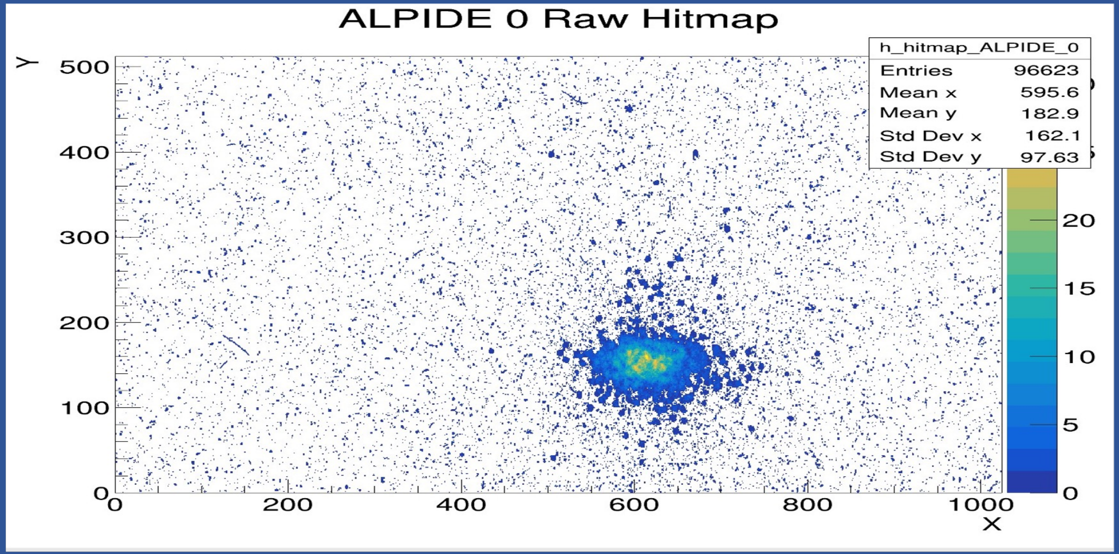
Focused optics

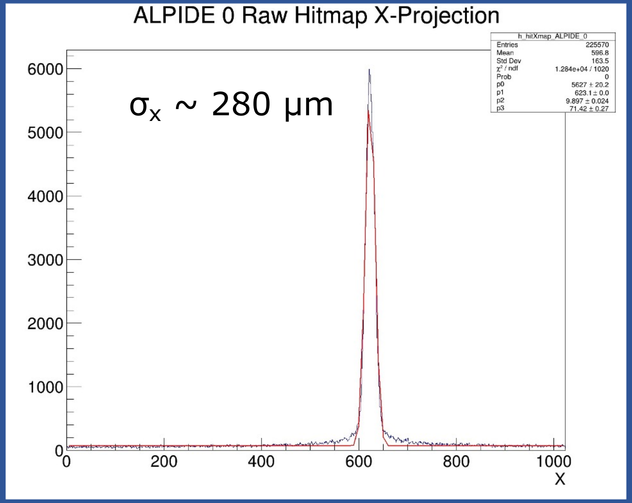
Max beam intensity
~ 2 10^5 /spill

Microcollimator

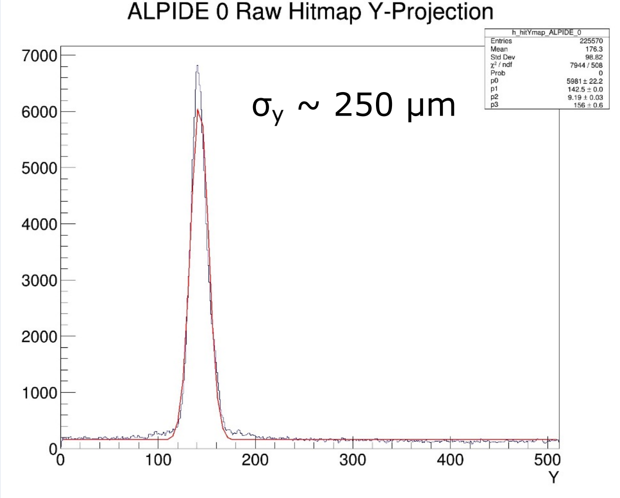


150
AGeV

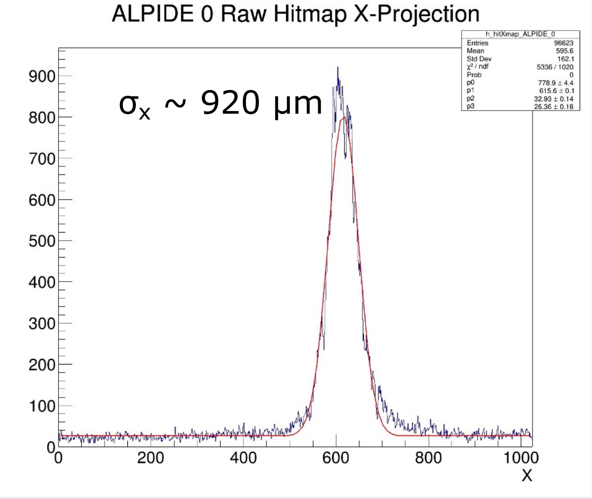




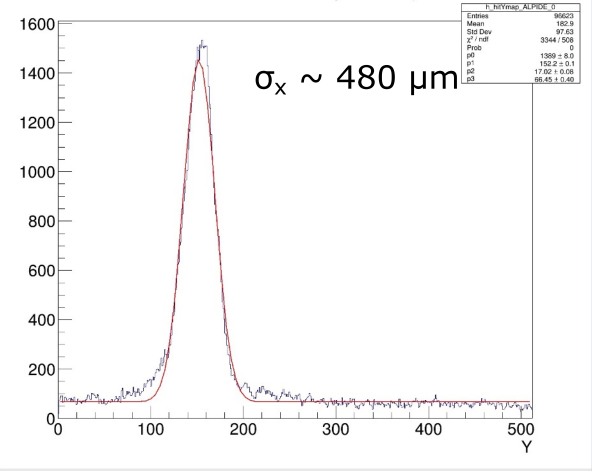
σ_x ~ 280 μm



σ_y ~ 250 μm



σ_x ~ 920 μm



σ_x ~ 480 μm