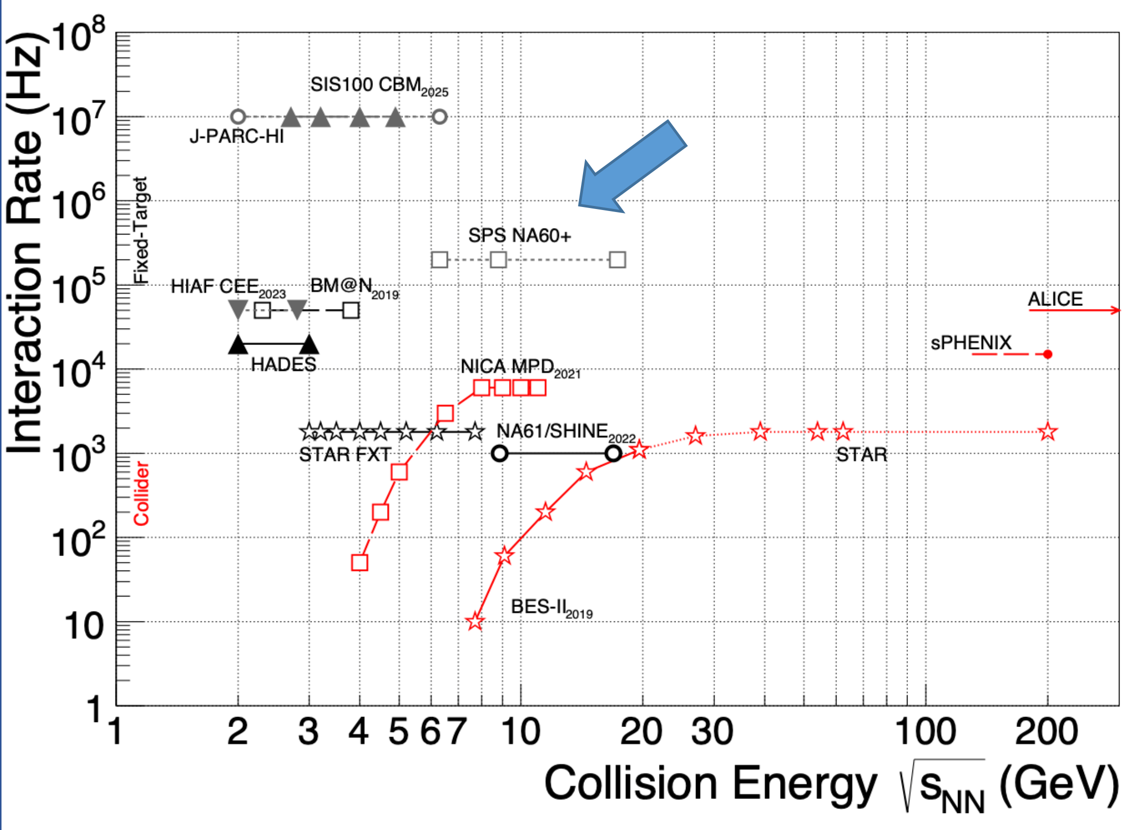
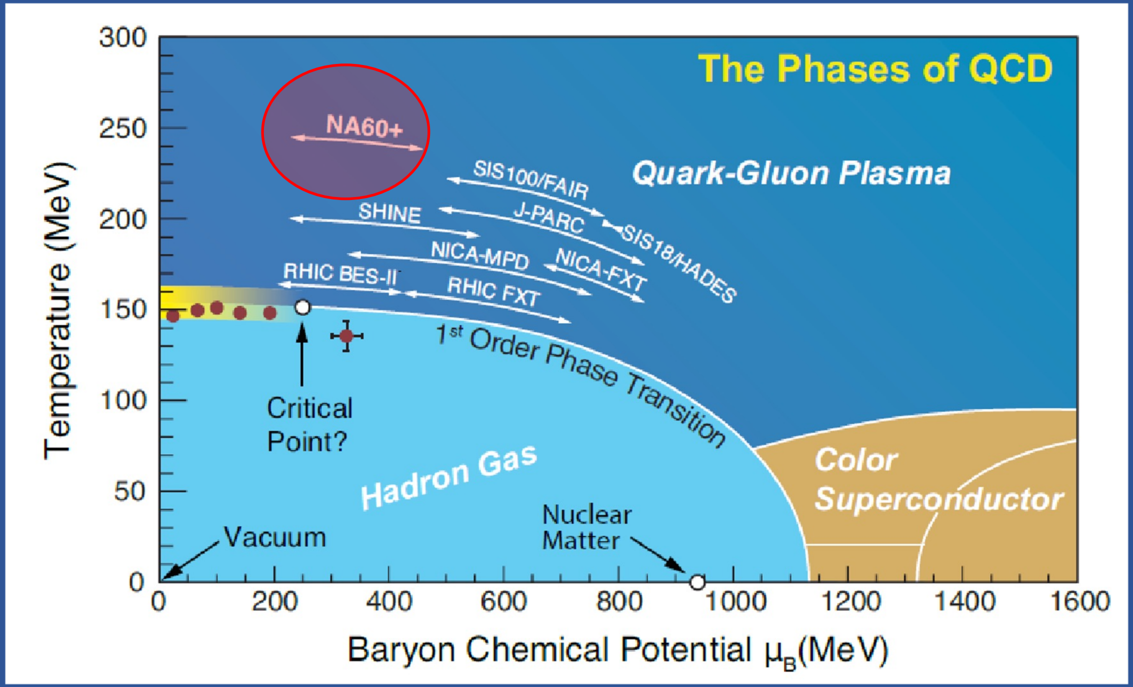
NA60+ status report

G. Usai (INFN Cagliari) for the NA60+ collaboration

- Hard and electromagnetic processes at the CERN-SPS: an investigation of the high-μ_B region of the QCD phase diagram via an **energy scan** ($\sqrt{s_{NN}}$=6 to 17 GeV)



(from T. Galatyuk)



- Main features
  - Coverage of a **wide μ_B region**
  - Precision physics: possibility of reaching **high interaction rates** (hundreds kHz)
  - Complete physics reach for **dimuons and charm**
  - Energy range complementary to FAIR/GSI (and J-PARC)

Aim at significant improvement (and extension) of the physics reach wrt the former NA60 experiment

Status of the project

Beam optics and integration studies

→ Paper submitted to NIM https://arxiv.org/abs/2210.17527

→ New optics prepared down to low SPS energy (to be tested with Pb beam this month)

Vertex spectrometer R&D (MAPS) in progress

→ Characterization of small pixel arrays and first prototype of large area MAPS

→ Assembly station for testing of mechanics/cooling of NA60+ vertex spectrometer

Muon tracker

→ Preparation of prototypes for muon tracking chambers, to be tested at SPS in 2023

→ Muon station geometry with MWPC and geometry implementation in Geant4

Prototype of the toroid magnet finalized and tested

→ Results in agreement with simulation studies

Physics performance: all studies updated to H8 conditions

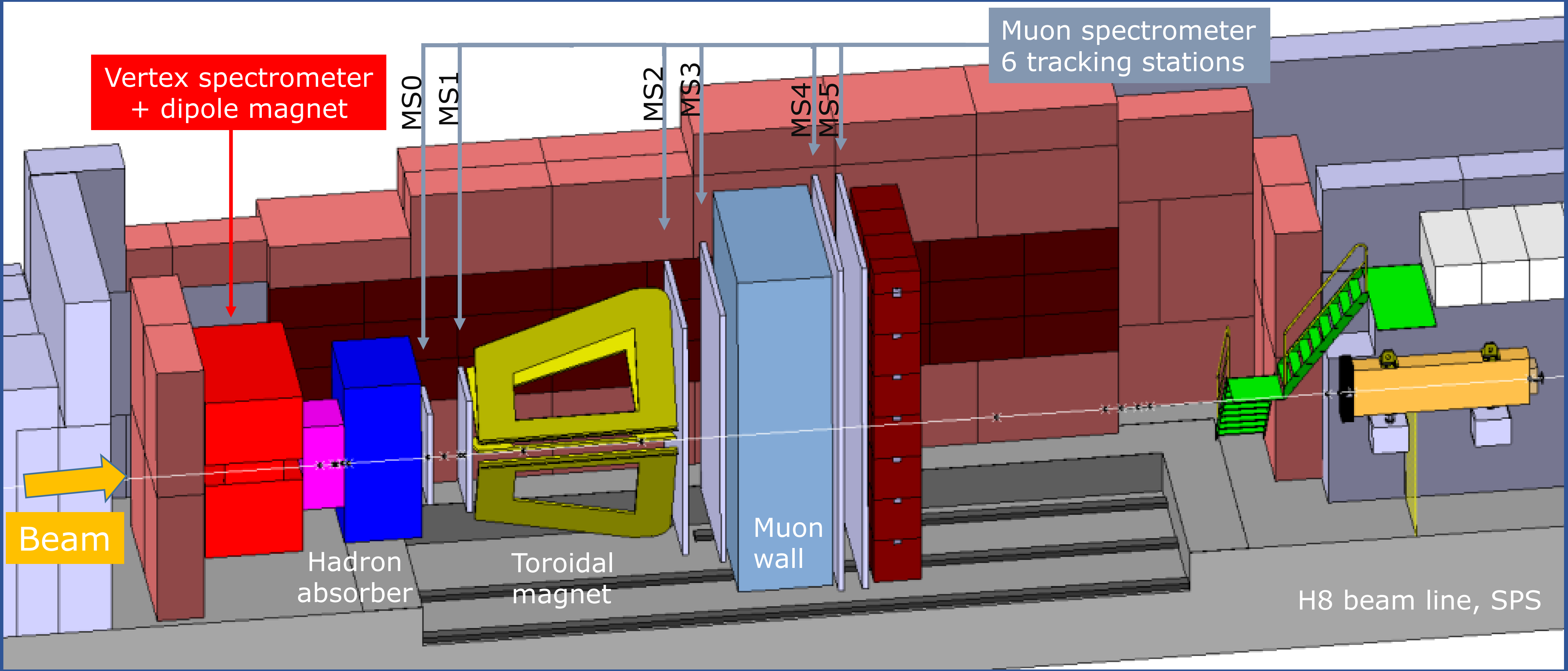
→ New physics chapters: dilepton elliptic flow, hypernuclei

Letter of intent: finalization

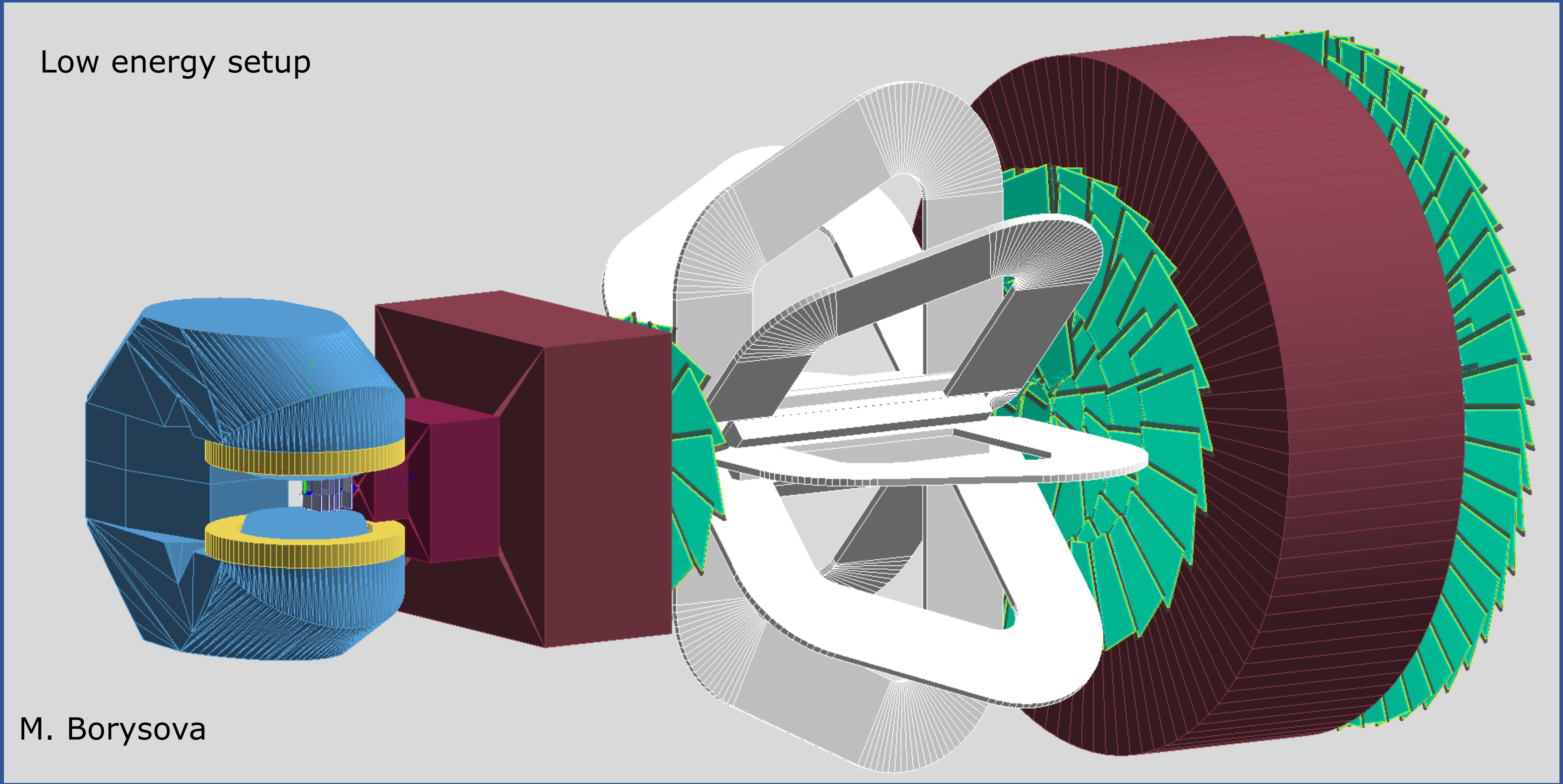
NA60+ set-up in H8

CERN support to the project through Physics Beyond Colliders

Muon spectrometer position will be varied (rails), to cover mid-rapidity at different collision energies



Overview of the setup in Geant4



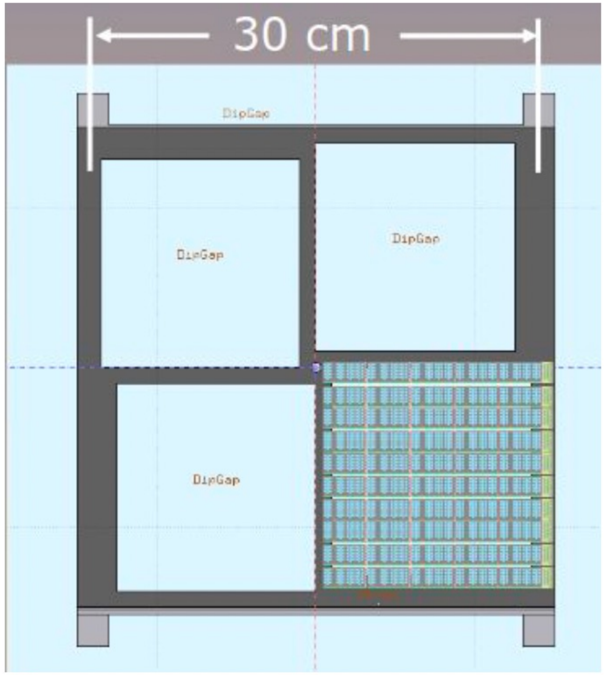
Beam energy scan (tentative plan)

- Beam energy scan with high(est) intensity Pb beam (~1-2x10^7 ions/spill)
- Data taking at low energy (20GeV) may have to span over two years, if ion beam stays at 1 month/year
- Complementary proton runs at corresponding energies (reference for charmonia and thermal dimuon measurements)

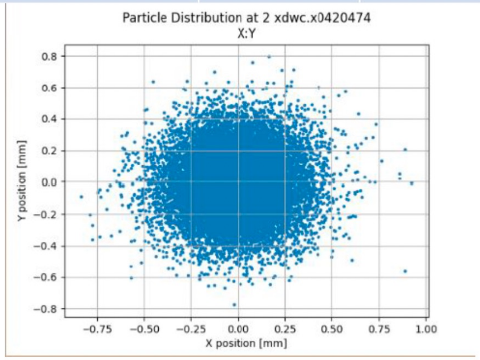
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Beam energy (A GeV)	158	40	120	20 (30)	80	100
$\sqrt{s}$	17.3	8.8	15.1	6.3 (7.6)	12.3	13.8
Pb ions on target	$\sim 10^{12}$ per energy ($\sim$1 month)					
protons on target	$5-6\cdot10^{13}$ per energy ($\sim$ 22 days)					

PBC Report - Post-LS3 North Area Experiments ion beam requirements

Pb beam characteristics

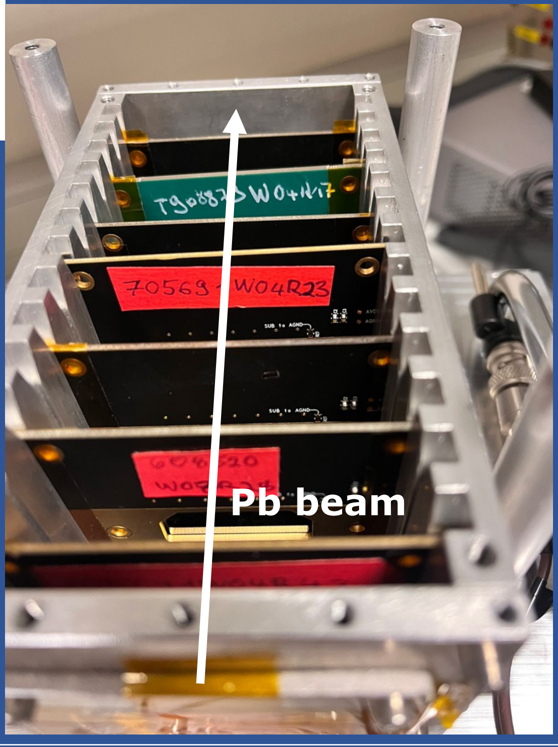


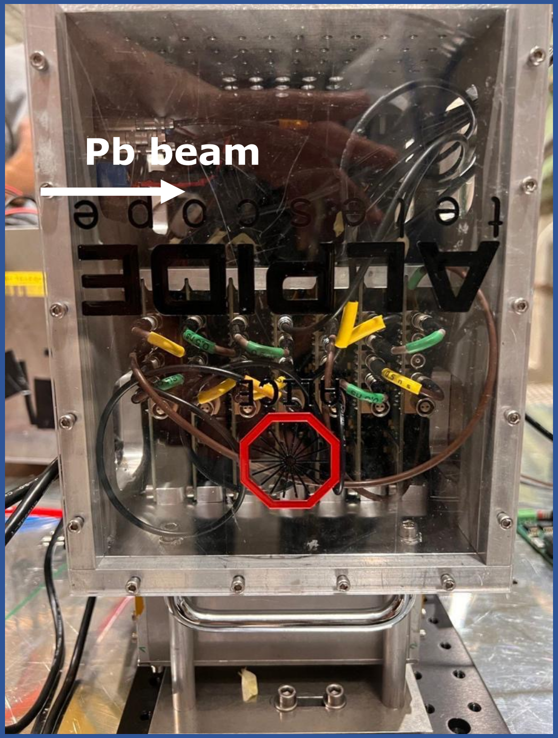
Parameter in zone 138	160 GeV/c	30 GeV/c
σ_x (mm)	0.19	0.33
σ_y (mm)	0.19	0.36
Transmission from T4 (%)	32.43	23.5



Central "hole" defined by the sensors of the vertex spectrometer →~6 mm diameter
Defines acceptance at forward y
→$y_{lab, max}$ ~ 3.9 if upstream MAPS plane at 7.12 cm
(y_{CMS}=2.92 at top SPS energy)

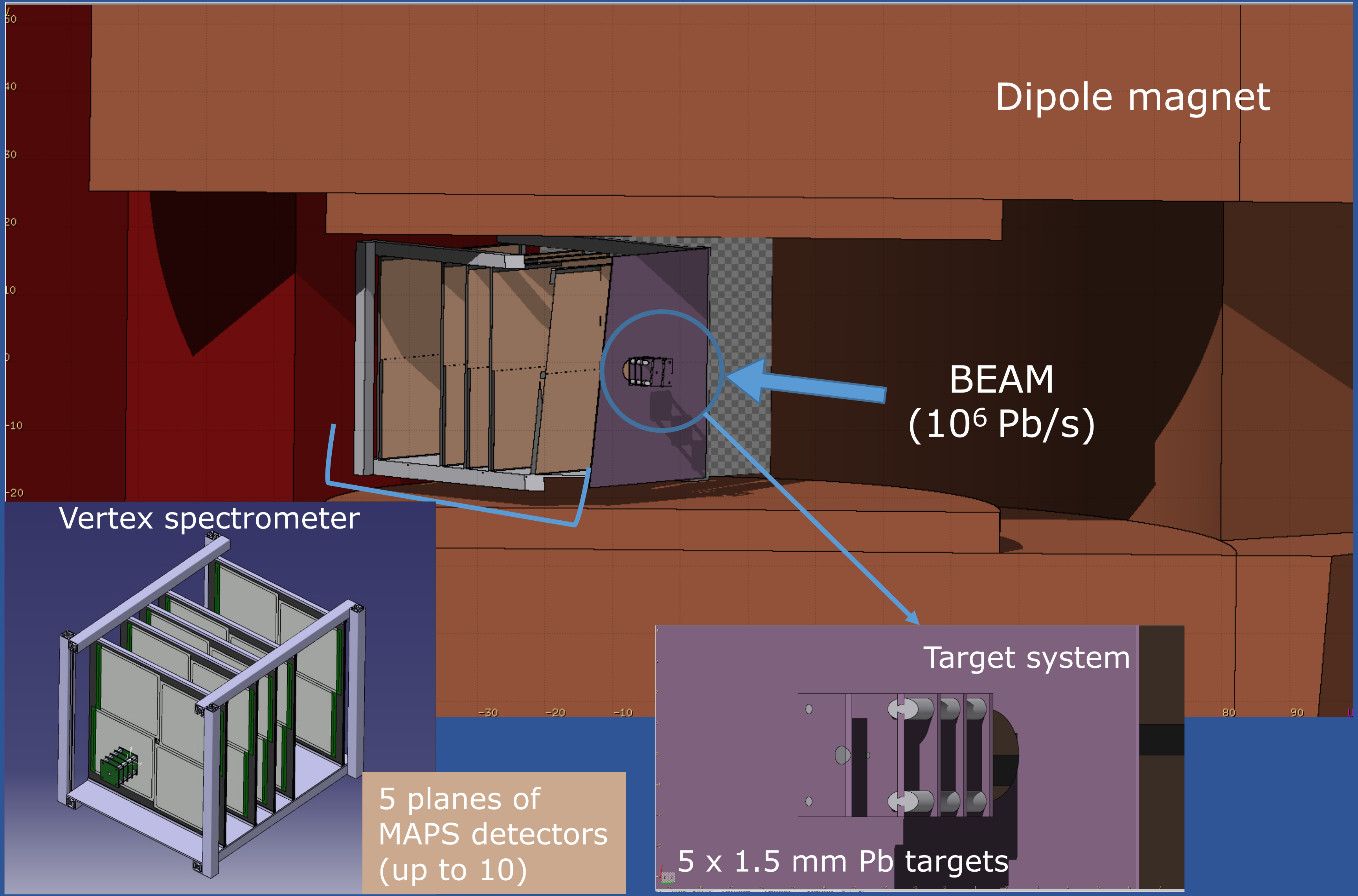
- Pb test beam on week 47 (end of November)
- Silicon Pb beam tracker:
  - Telescope with ALPIDE MAPS sensors (synergy with ALICE)





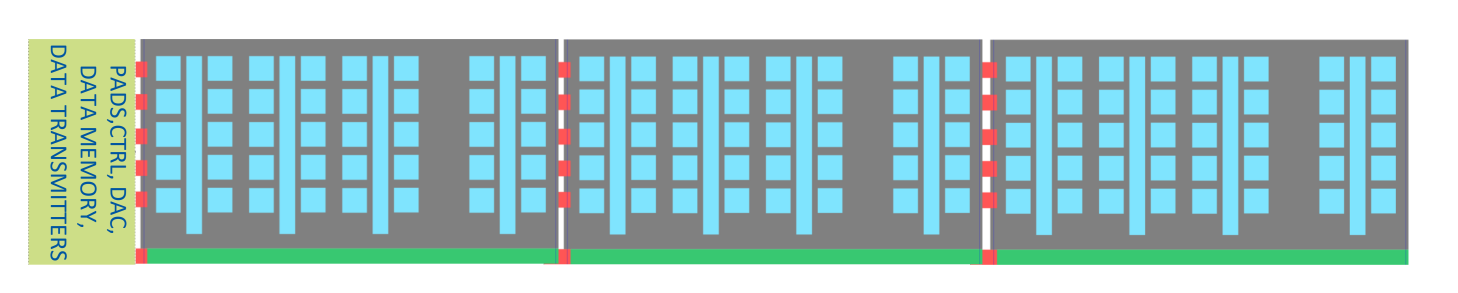
NA60+ set-up: vertex region

MEP48 dipole magnet
Field: 1.5 T over a 400mm gap



R&D: vertex spectrometer

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



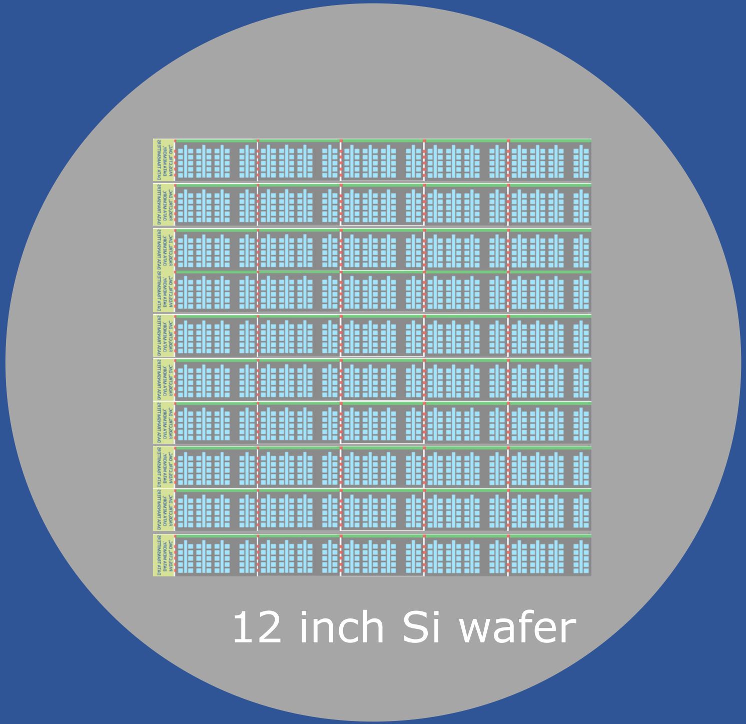
R&D in progress
Common development
ALICE ←→ NA60+

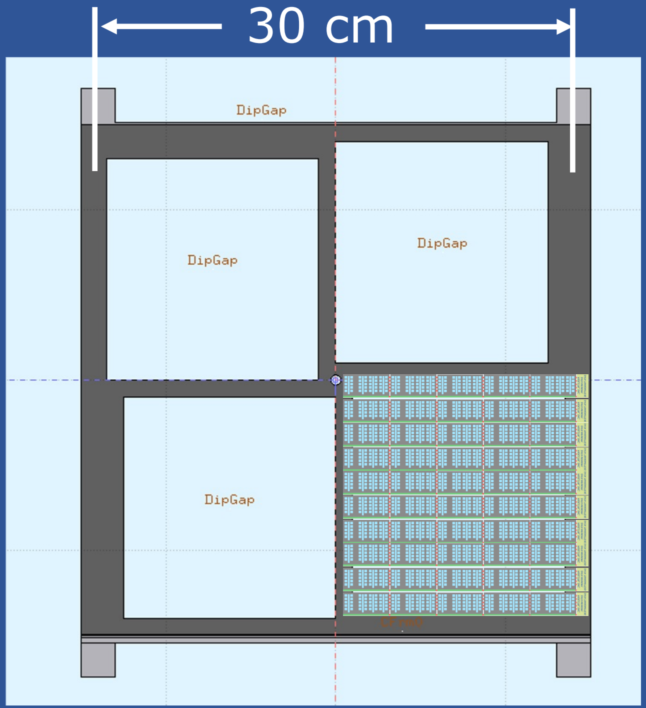
State-of-the-art imaging technology
TowerJazz 65 nm

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

Spatial resolution ≤ **5 μm**

Cooling studies (NA60+ geometry)
in progress





Complete NA60+ station → 4 sensors

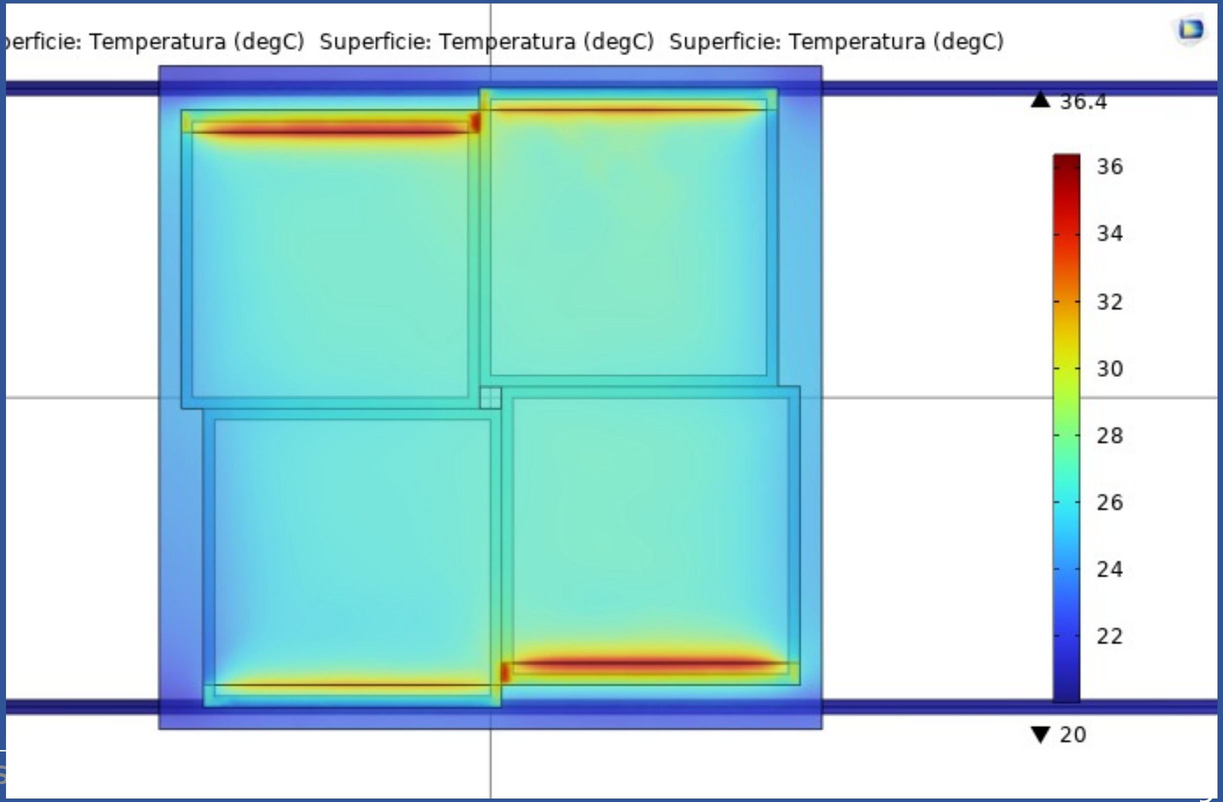
Ongoing R&D

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 R/D of NA60+ silicon stations:

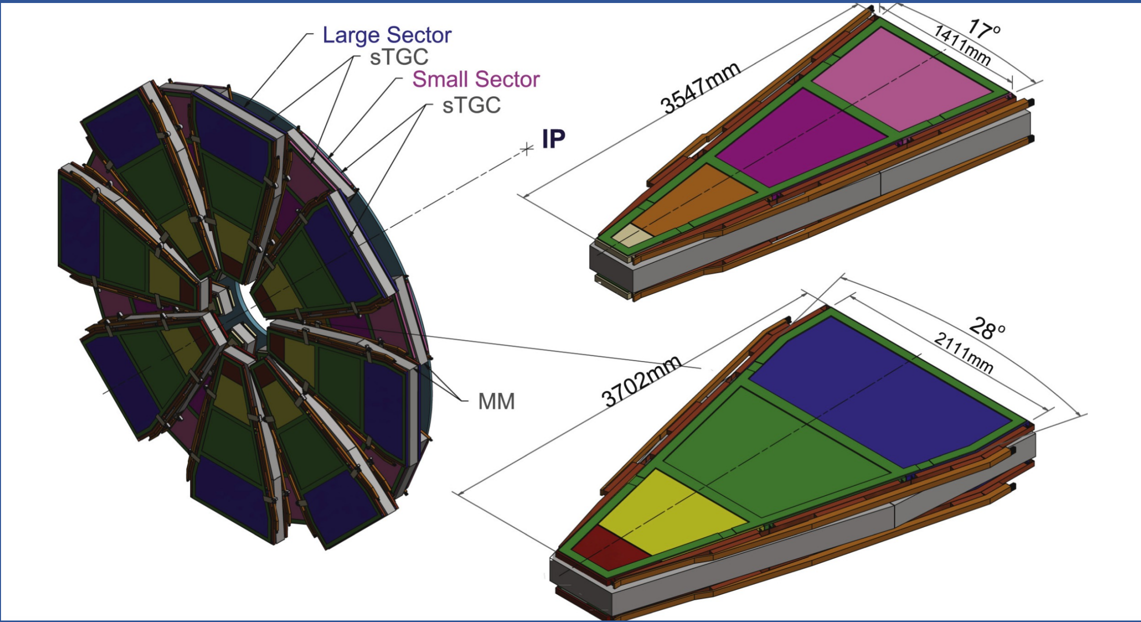
→ Positioning and gluing tests of (dummy) sensors on carbon foam/fiber supports with optical bench

Cooling with with air-flow and water
Next step: experimental measurements

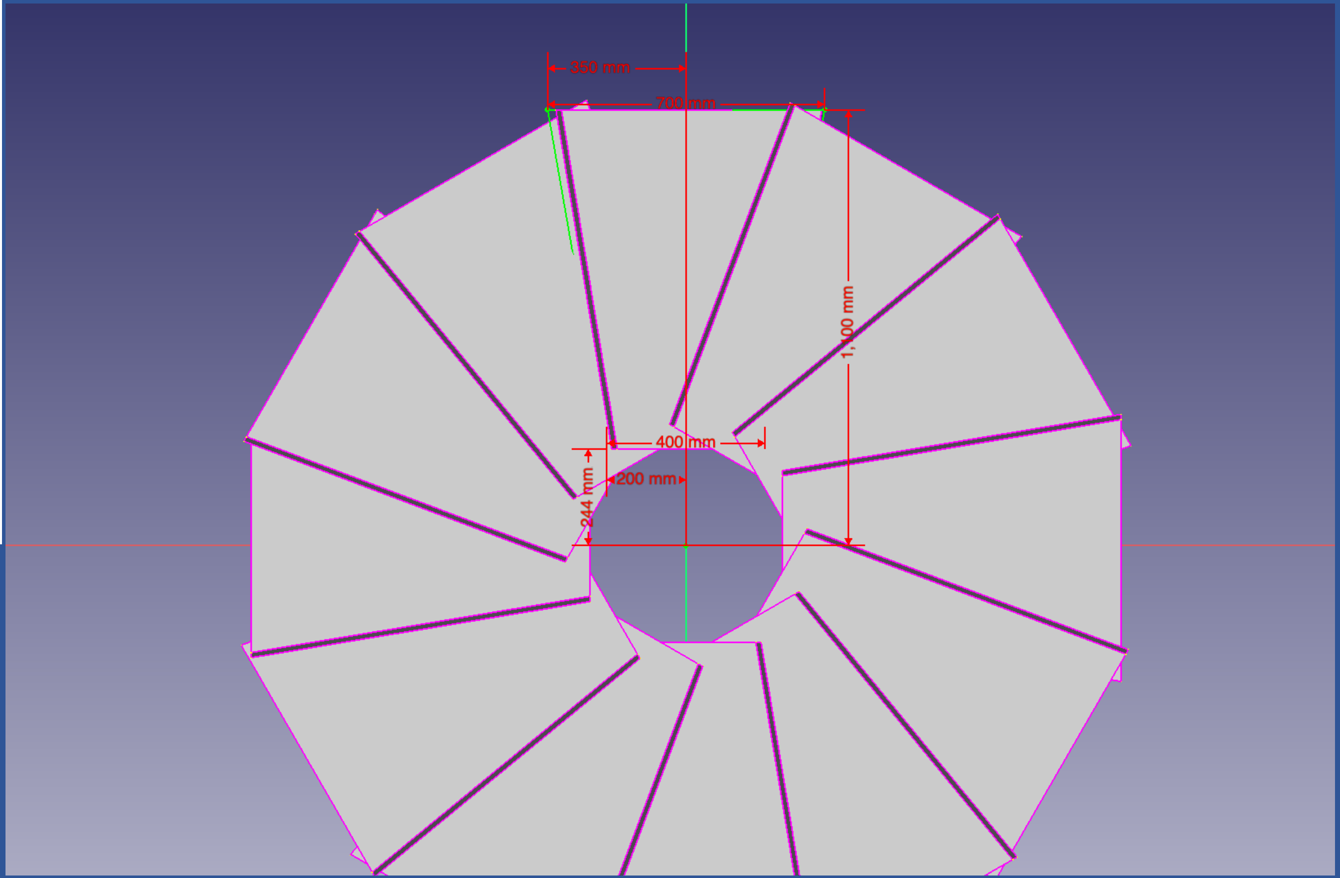


NA60+ muon stations with MWPC modules

Schematic diagram of the small and large sectors that make up the New Small Wheel



view of the first wheel of muon spectrometer built of 12 trapezoidal 30° sectors

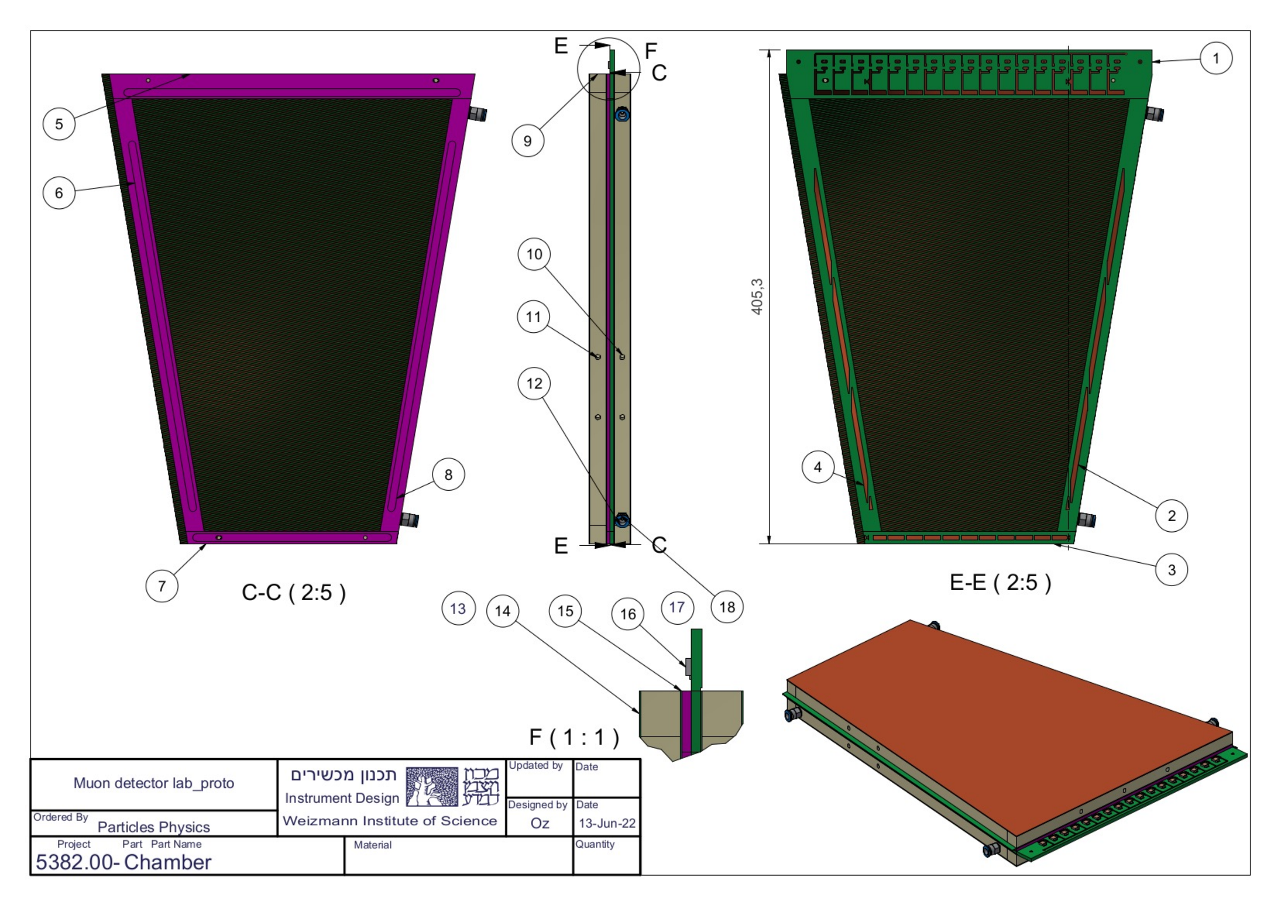


- ❑ Technologies under discussion:
  - ❑ GEM, MWPC
- ❑ Weizman Institute, Stony Brook

MWPC prototype: design

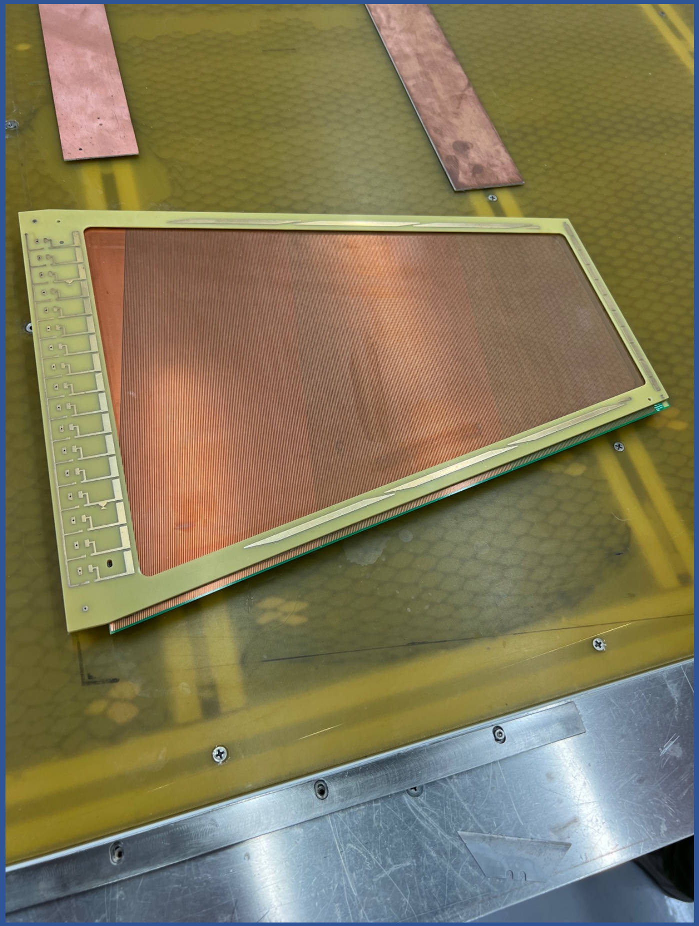
First Prototype assembled at Weizmann institute

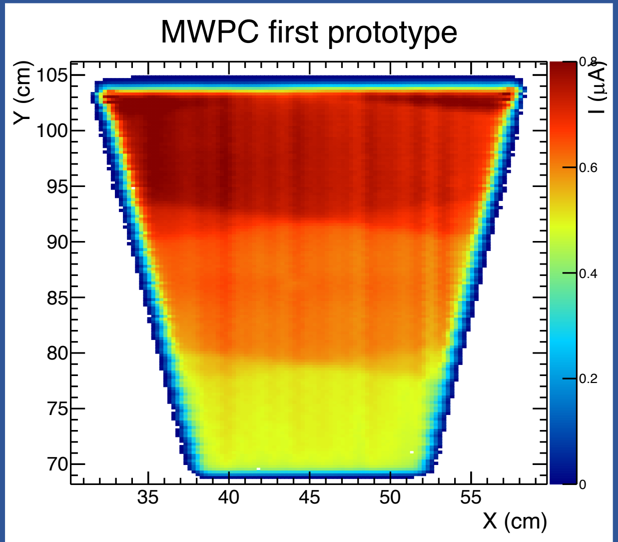
- ❑Two strip cathode boards, each made out of honeycomb sandwich – 1 mm strip pitch
- ❑The strips on each cathode are running on a different direction, providing a small angle stereo readout
- ❑ 3 mm cathode-wire distance
- ❑ 3 mm wire pitch
- ❑ Readout via VMM3a ASIC



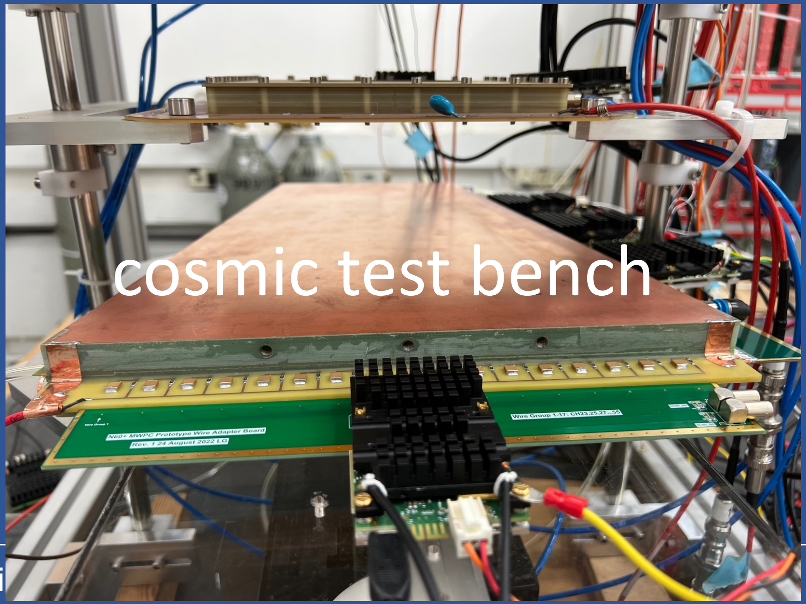
I. Ravinovich

MWPC prototype: construction and lab tests

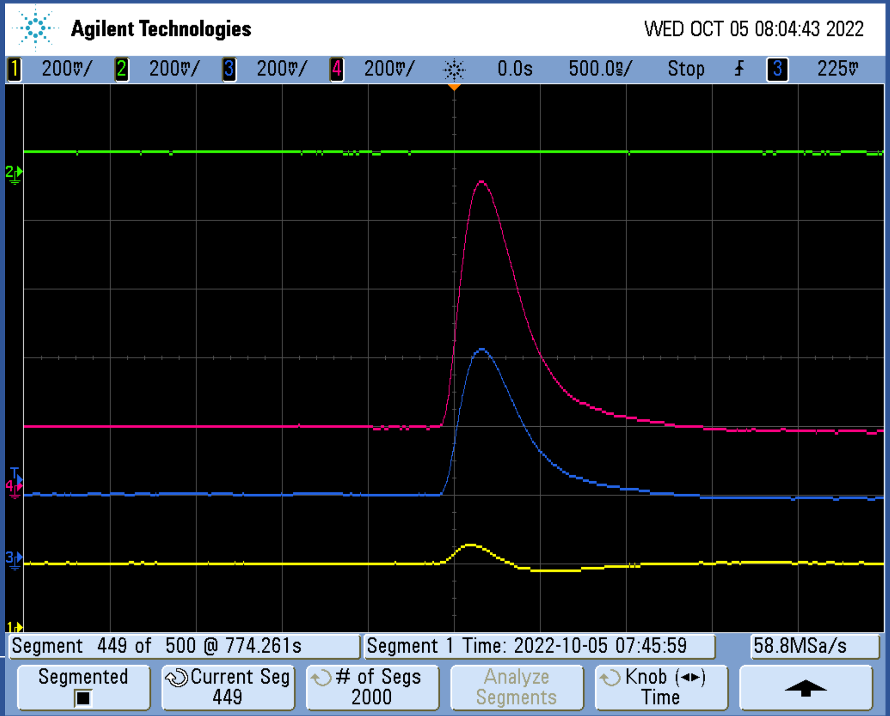




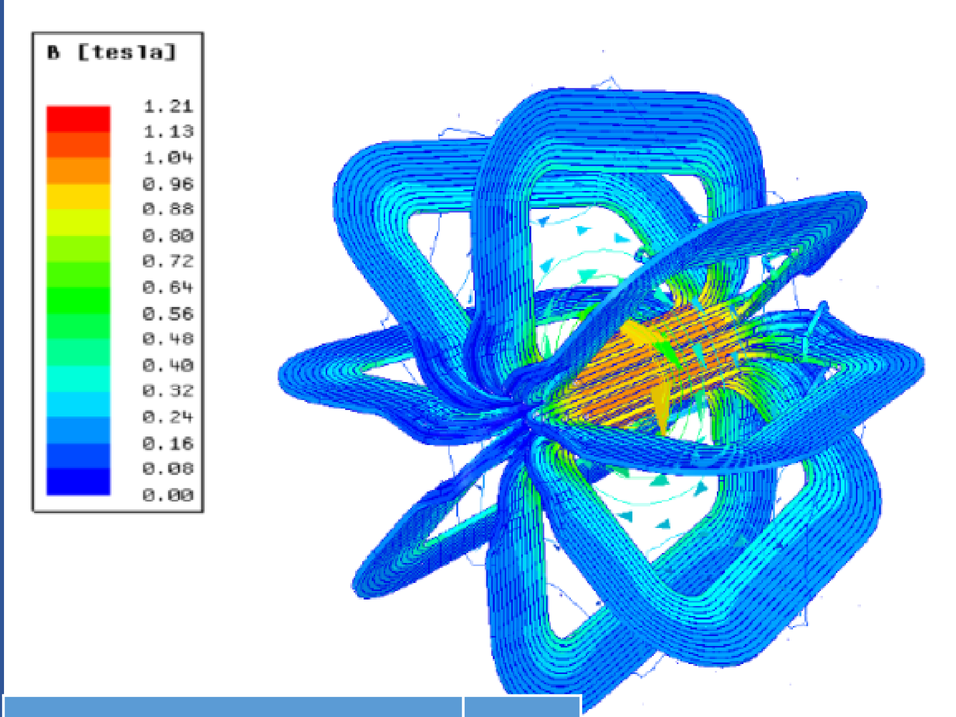
X-ray tomography



First muon signals



R&D: toroidal magnet

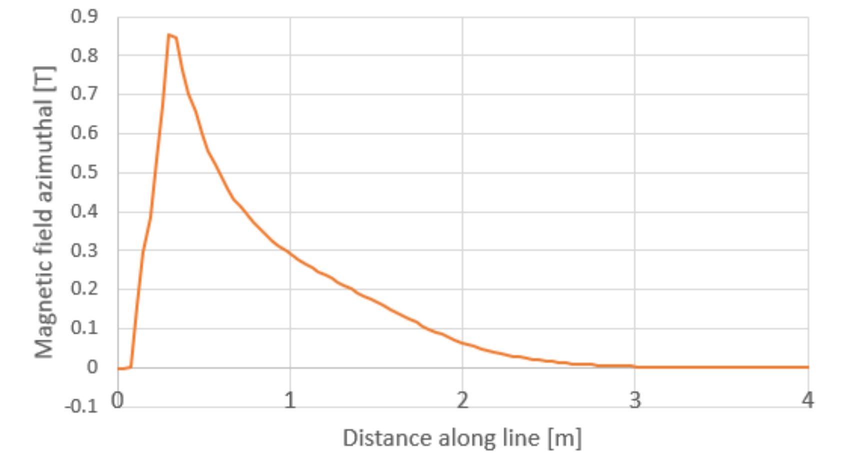


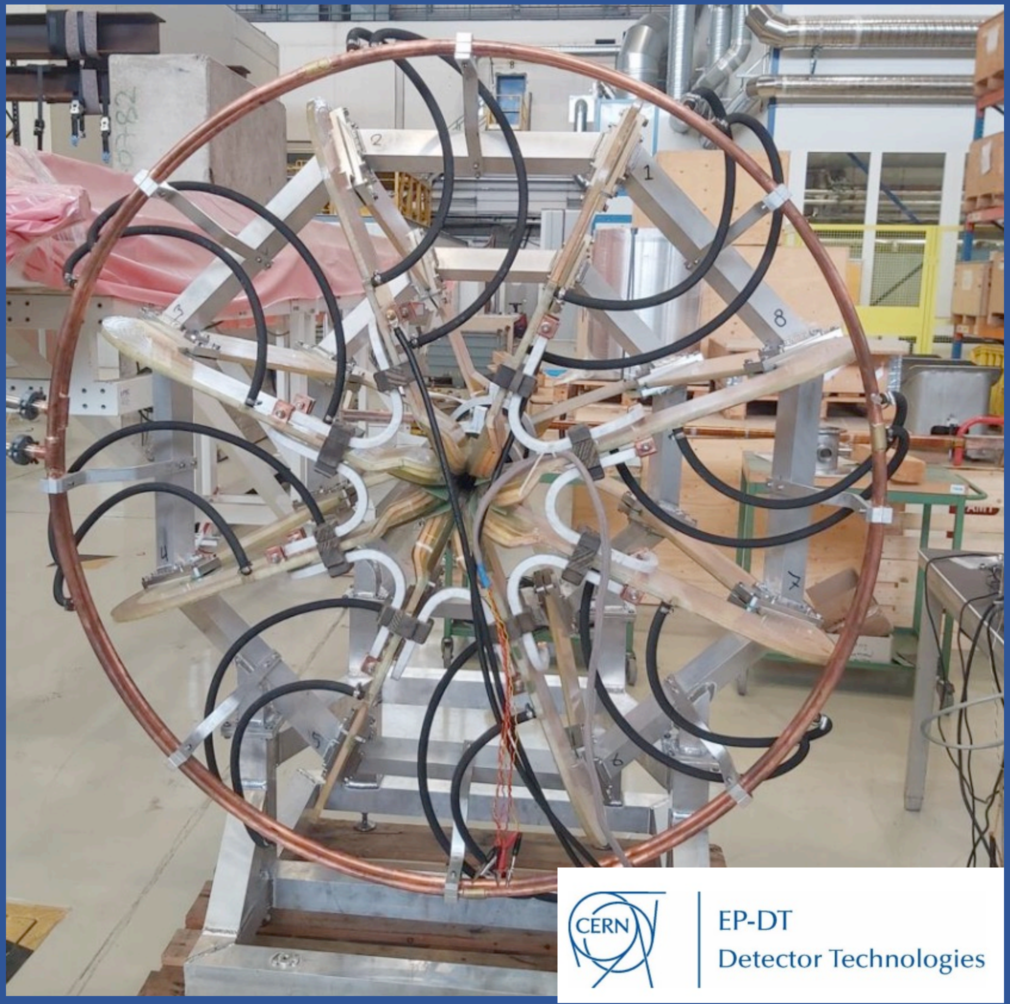
CERN EP-DT design

Eight sectors, 12 turns per coil

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

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



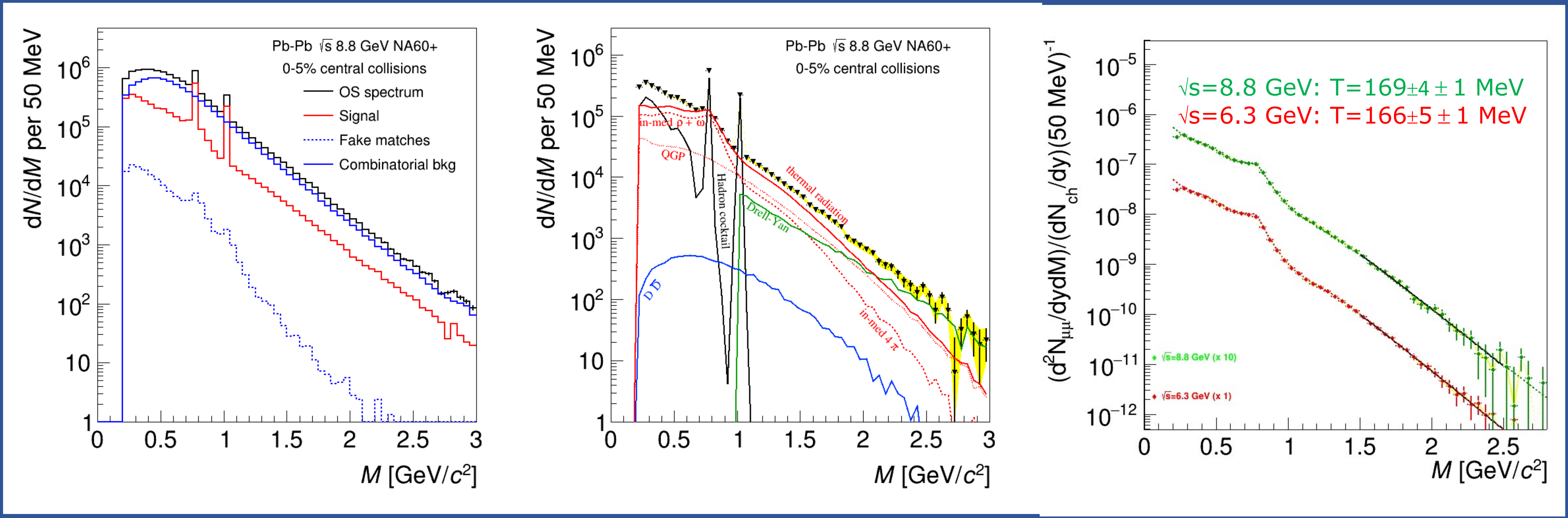


- **Prototype (1:5 scale)** was built and tested in 2020-2021, to check calculations and investigate mechanical solutions, in view of the final object

→ **works correctly and as expected**

Dimuon thermal spectra, temperature (new for H8)

~$3.5 \cdot 10^6$ reconstructed dimuon pairs in central Pb-Pb at $\sqrt{s}$=6.3, 8.8 GeV

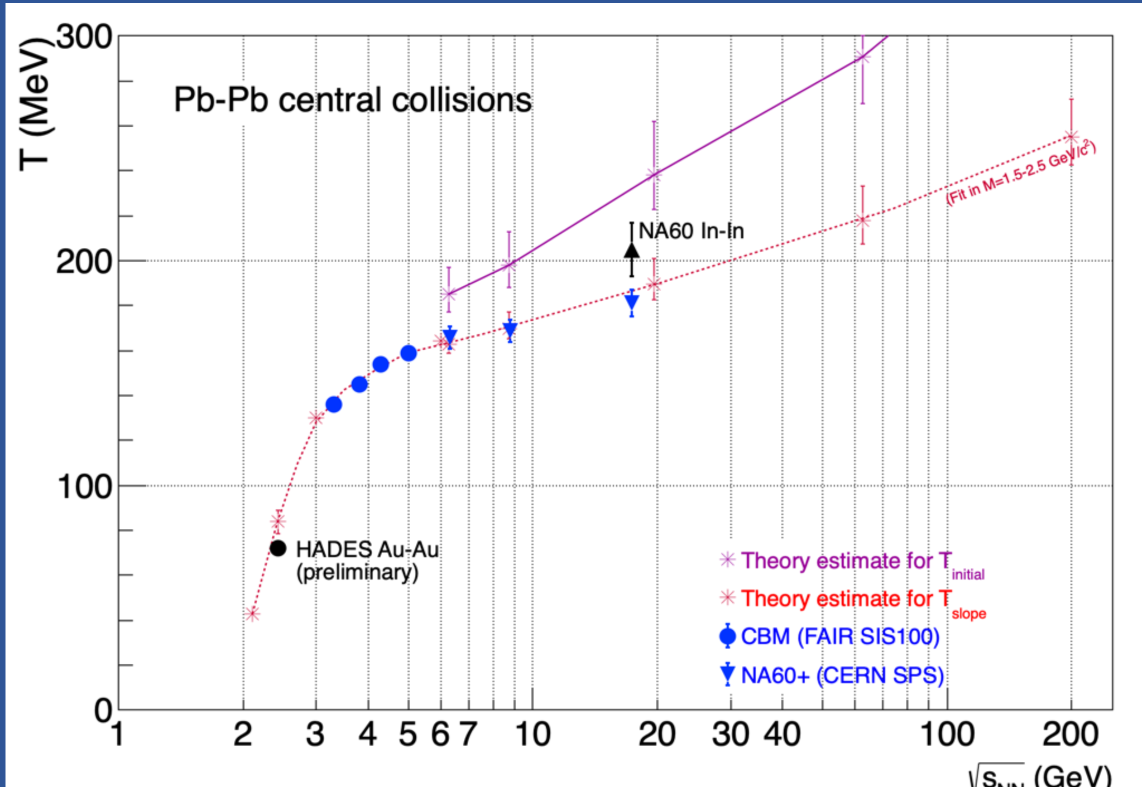


Total dimuon spectrum

Dimuon signal spectrum

Thermal dimuon spectra and temperature (T_{slope}) fits

Caloric curve and fireball lifetime (new for H8)



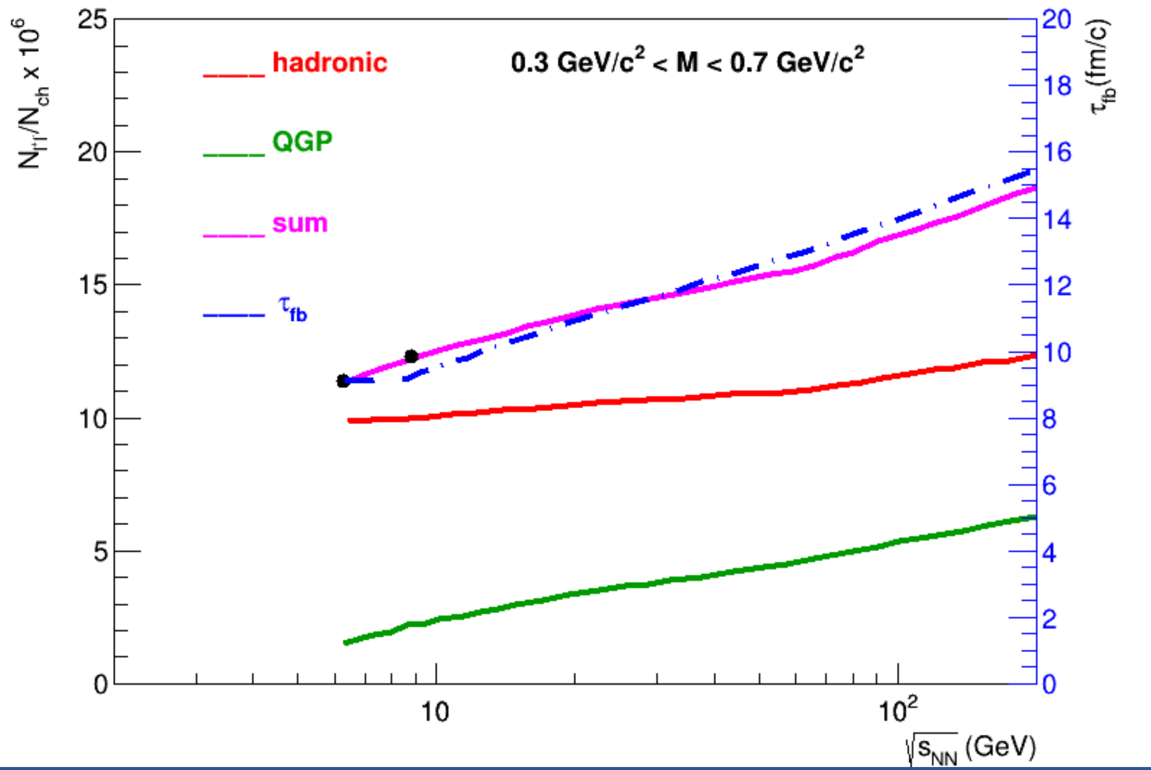
Hees, Rapp PLB 753 (2016) 586

~3% uncertainty on the T_{slope} measurement:

- Allows an **accurate mapping** of the √s-dependence of T_{slope} around T_c

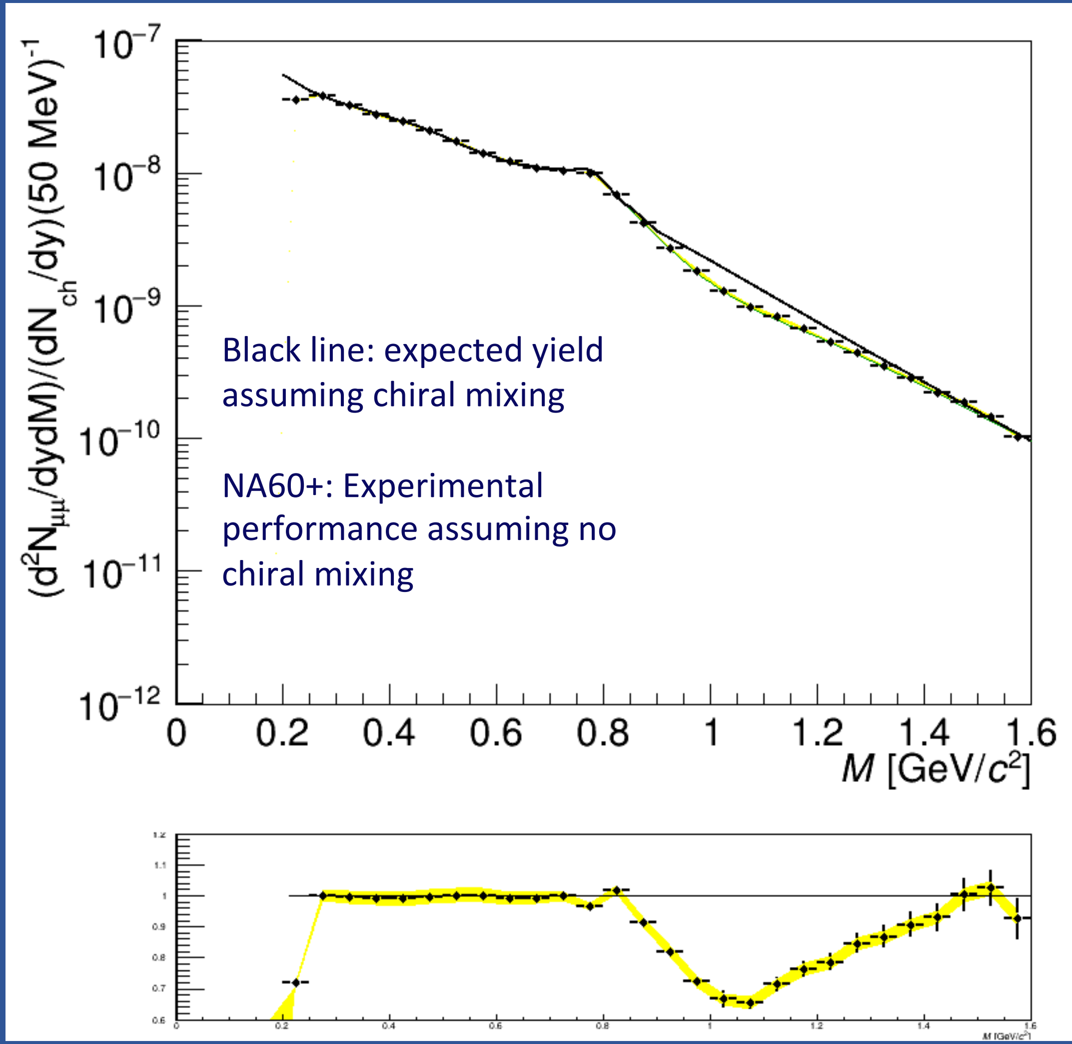
Precise measurement of thermal yield in 0.3<M<0.7 GeV **sensitive to the fireball lifetime**

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



ρ-a_1 chiral mixing (new for H8)

Pb-Pb √s=8.8 GeV 0-5% central collisions



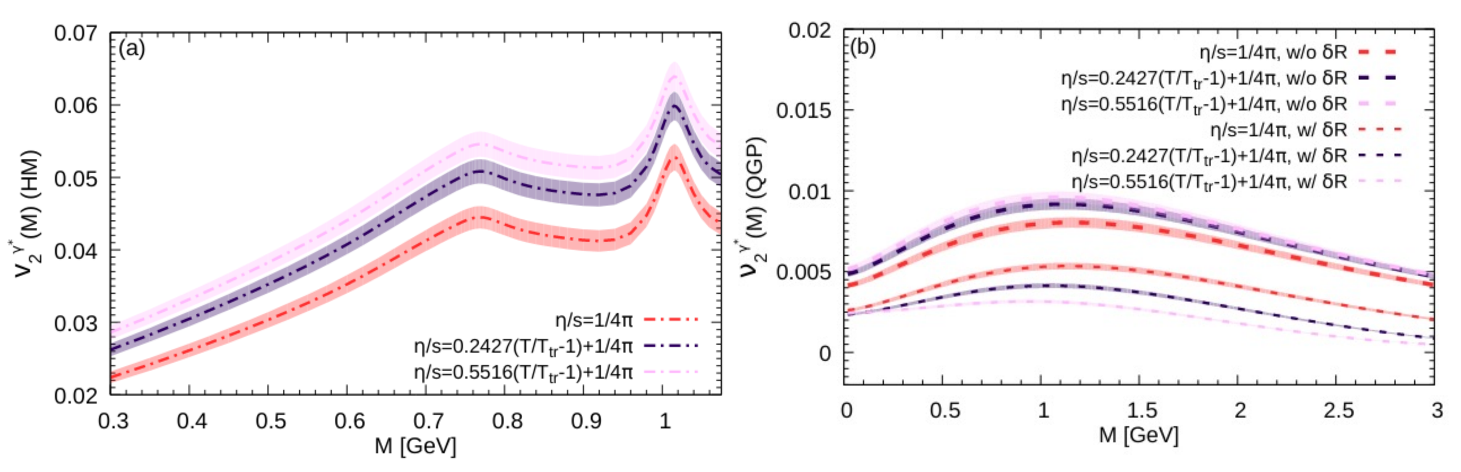
ρ-a_1 chiral mixing:
yield enhancement in 1<M<1.5 GeV

Measurement challenging, but
sensitivity to enhancement!

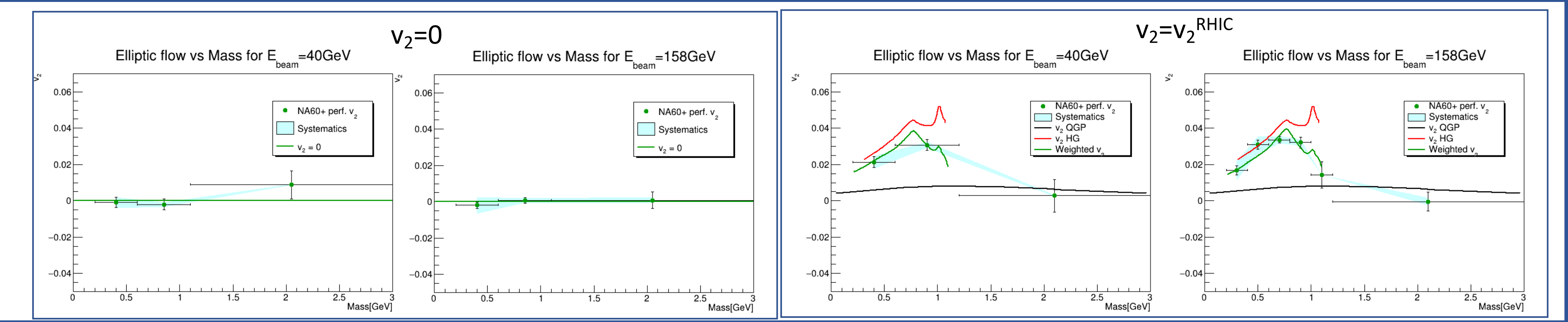
Elliptic flow of thermal dimuons (new for H8)

- 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

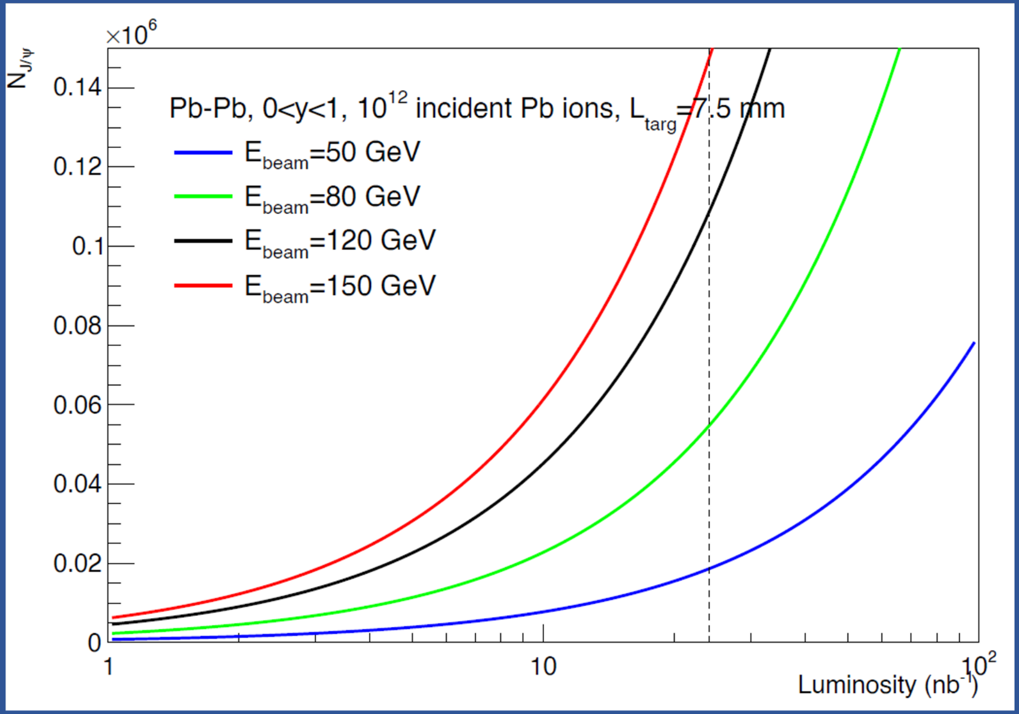
Vujanovic et al, Phys. Rev. C 98, 014902 (2018)



- 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)



Charmonium measurement (new for H8)



With 10^{12} incident Pb ions on a 7.5 mm Pb target → $\mathbf{L_{int}}$ **~24 nb^{-1}**

NA60+ can aim at

~O(10^4) J/ψ at 50 GeV

~O(10^5) J/ψ at 158 GeV

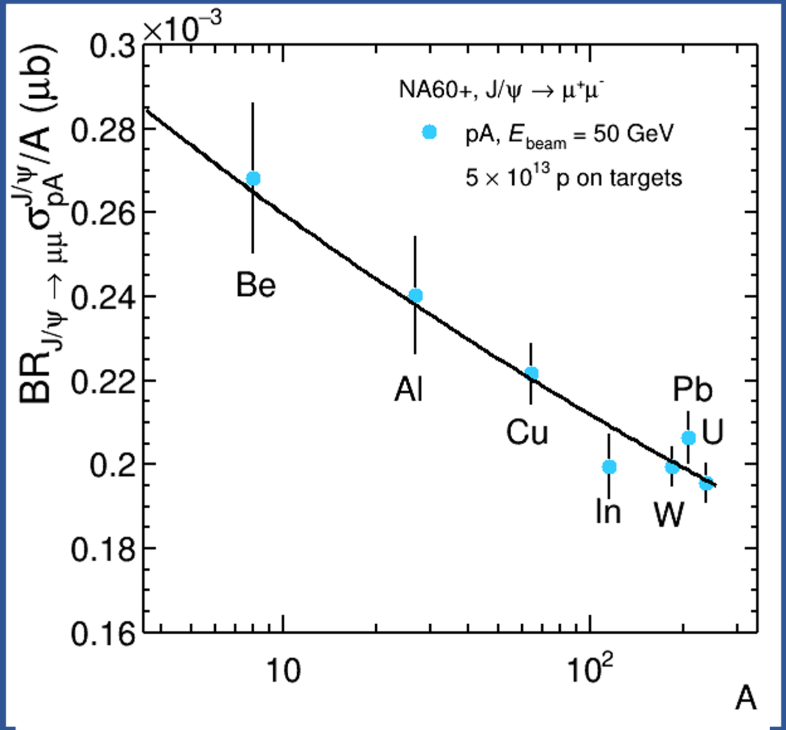
pA

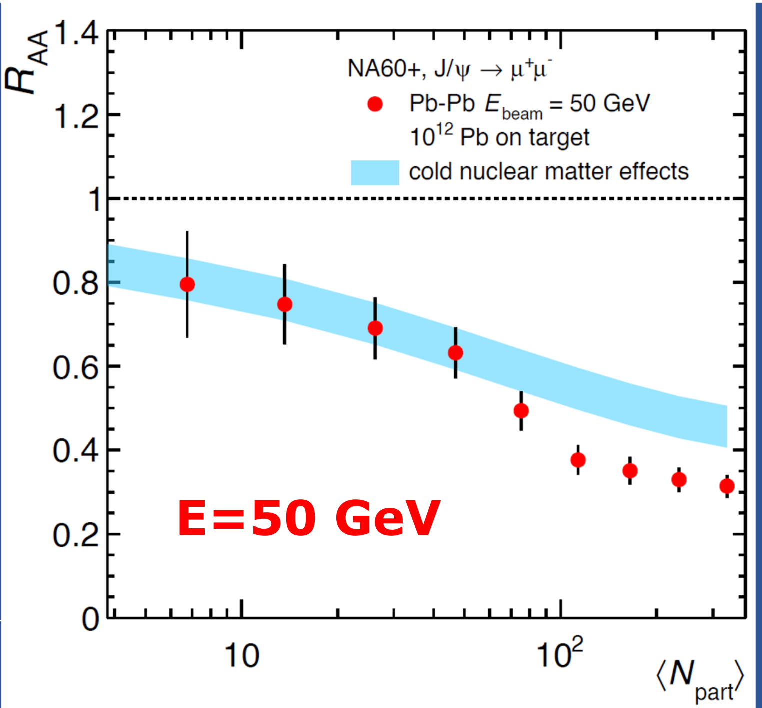
Use a system of various nuclear targets and extrapolate cross sections to pp

→ reference for R_{AA} measurement

Pb-Pb

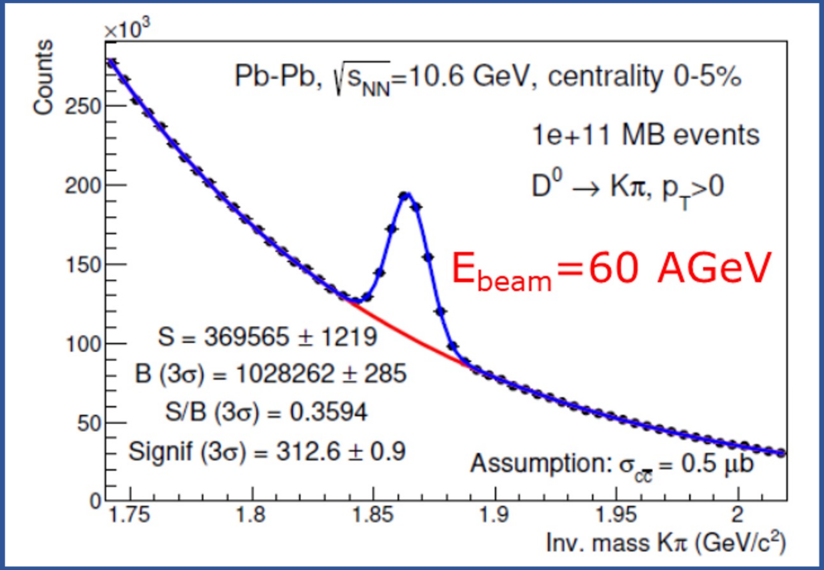
Assume only CNM effects, extrapolated from p-A, for N_{part}<50 and 20% "anomalous" suppression for N_{part}>50



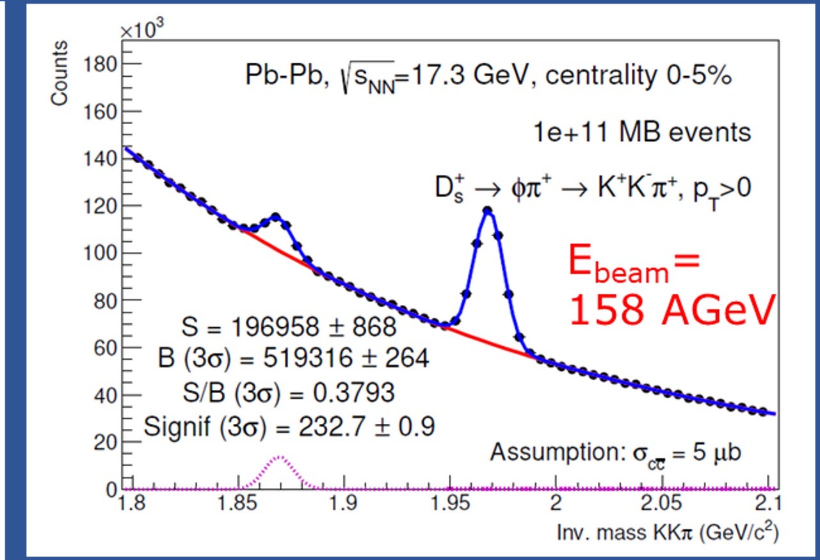


Open charm measurement (new for H8)

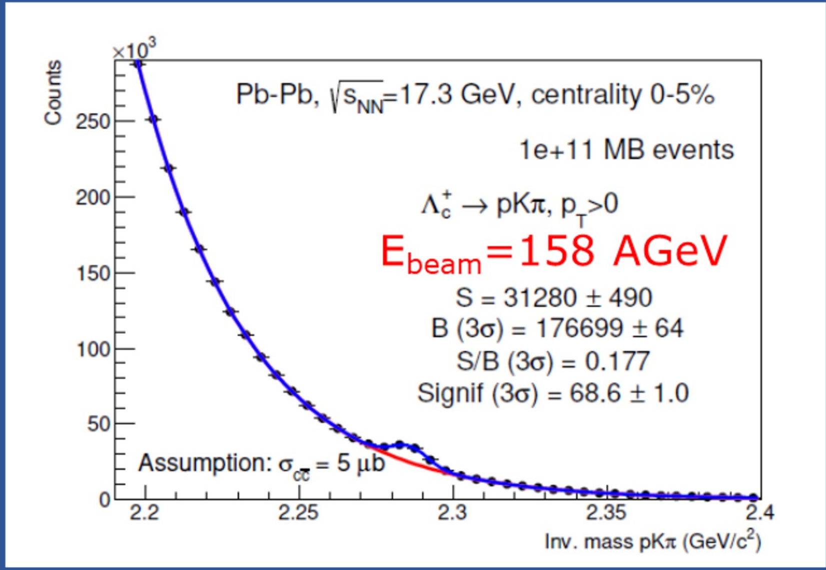
- With **~10^{11} minimum bias Pb-Pb collisions** (1 month of data taking)
  - More than $3\cdot10^6$ reconstructed D^0 in central Pb-Pb collisions at $\sqrt{s_{NN}}$=17.3 GeV
  - Allows for differential studies of yield and v_2 vs. p_T, y and centrality
  - D^0 at lower collision energies with statistical precision at the percent level
  - Measurement of D_s yield feasible with statistical precision of few percent
  - Λ_c baryon also accessible



$D^0 \rightarrow K\pi$



$D_s^+ \rightarrow \Phi\pi \rightarrow KK\pi$

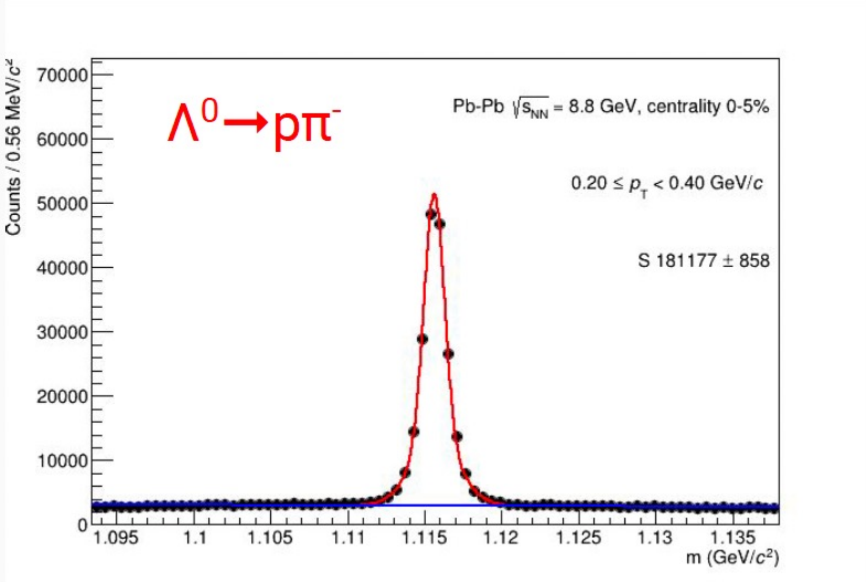


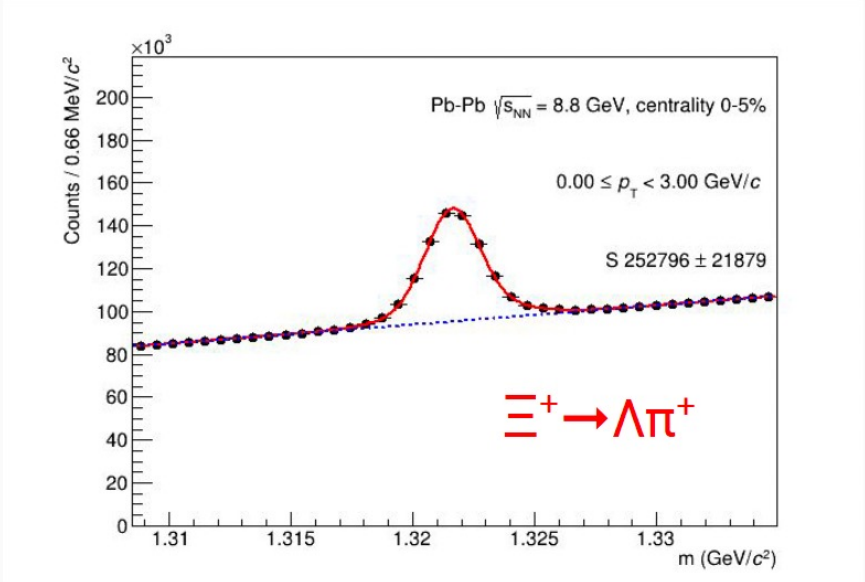
$\Lambda_c^+ \rightarrow pK\pi$

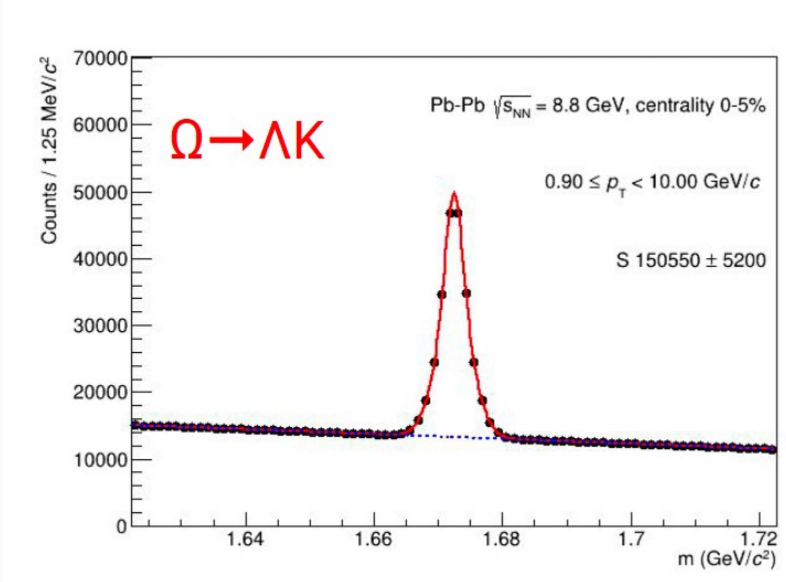
Strangeness (new for H8)

Decay products reconstructed in the vertex spectrometer

- Geometrical selections on the displaced decay-vertex topology ($c\tau \sim$ 2-3 cm) to enhance the S/B (except for the ϕ)



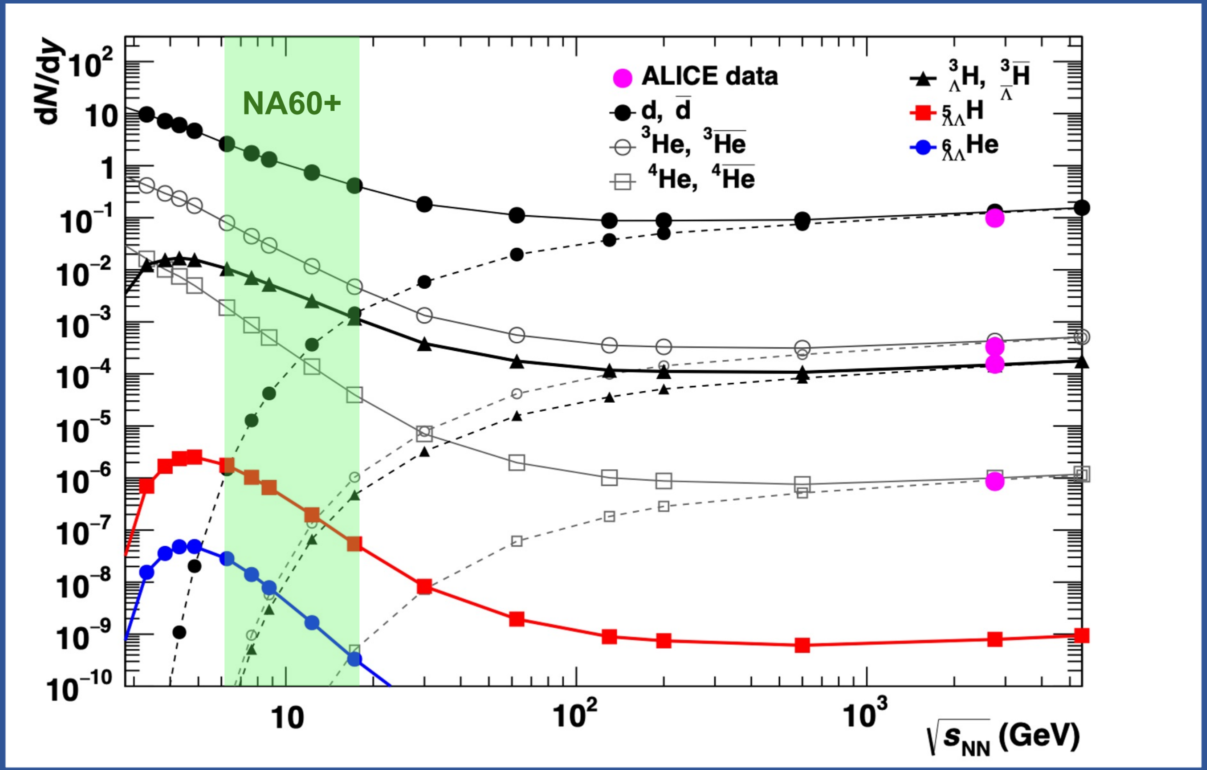




Very large statistical significance for K^0_S, Λ^0, φ, Ξ and Ω hyperons:

- Large improvement in their measurement w.r.t. to past SPS measurements
- **Elliptic flow**

A hypernuclear factory at CERN



In the Statistical Hadronisation Model:
→ hypernuclei yield **peaks at low $\sqrt{s_{NN}}$**

In 1.5×10^{10} central Pb-Pb $\sqrt{s_{NN}}=7$ GeV events

3.3×10^4 $_{\Lambda\Lambda}{}^5$H	10^3 $_{\Lambda}{}^6$He
3.3×10^2 $_{\Lambda\Lambda}{}^6$He	10^3 $_{\Lambda}{}^6$H
3.3×10^4 $_{\Xi}{}^5$H	20 $_{\Lambda}{}^7$He

*N.B. detectable decay channels have O(50%) B.R.

- Refined SHM predictions soon to be published

Heavy hypernuclei: statistics at different energies can be integrated

→Systematic study of properties and production of hypernuclei up to A=6 is well in reach!

Letter of intent

- ❑ Editing in final stage
- ❑ Editorial team:
  - ❑ INFN Cagliari, Torino
  - ❑ Weizmann
  - ❑ Stony Brook
  - ❑ CERN EP-AIP, EP-DT, BE-EA*, HSE
- ❑ To be finalized in the next few weeks

*A. Gerbershagen now at Groningen University

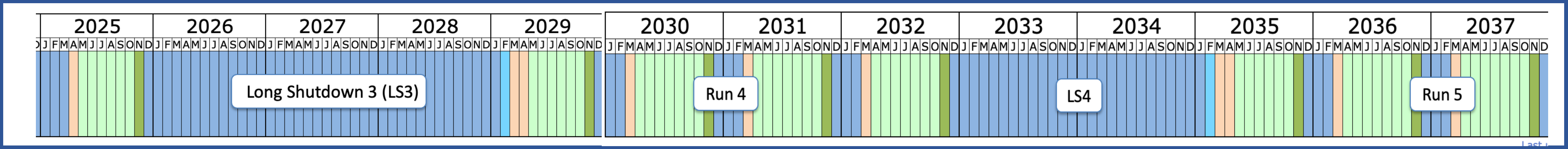
Contents

Timeline and cost-estimate

- 2022 → Letter of Intent
- 2024-25 → Proposal
- 2025-2028 → Construction
- From 2029 → Data taking

Preliminary cost estimate

Sub-system	Estimated cost (MCHF)
Vertex spectrometer	2-3
Muon spectrometer	3
Toroidal magnet	4
RP monitors, Shielding	1.5



- Foresee **at least 6 yrs** of data taking (one energy point per year with p-A and Pb-Pb)

Summary and outlook

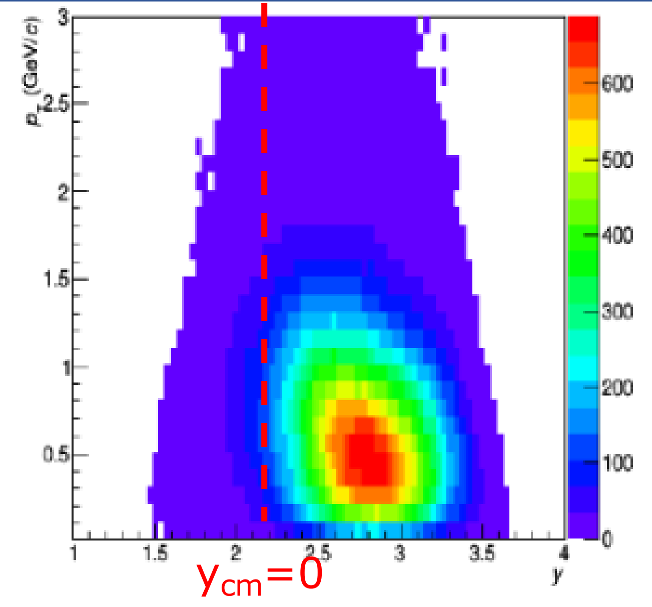
- Very rich physics case → discovery potential for QCD phase diagram at high μ_B
- R&D on several detector system is progressing well
- Fundamental steps in 2023 after release of LOI:
  - Consolidation of detectors R&D:
    - pixel tracker → release and test of first stitched sensor for ALICE ITS3
    - muon chambers → test beam for MWPC prototypes; GEM prototypes
    - toroidal magnet → design of full scale magnet
    - interaction trigger → various options under study
  - Consolidation of collaboration
  - Discussion with funding agencies

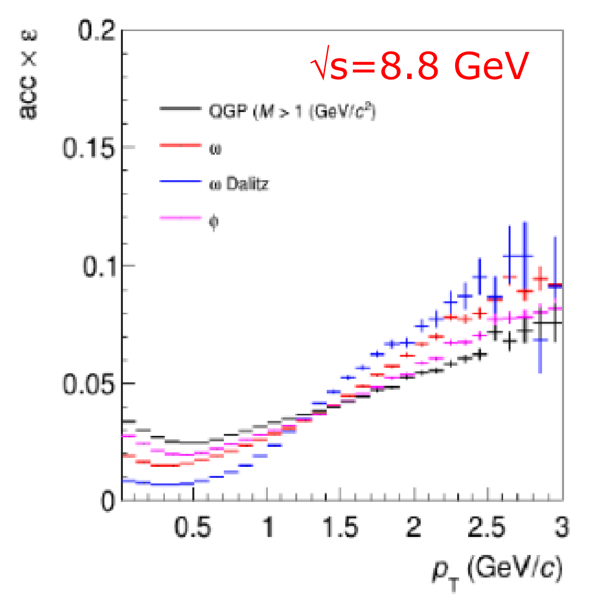
Backup

(Di)muon detection performance

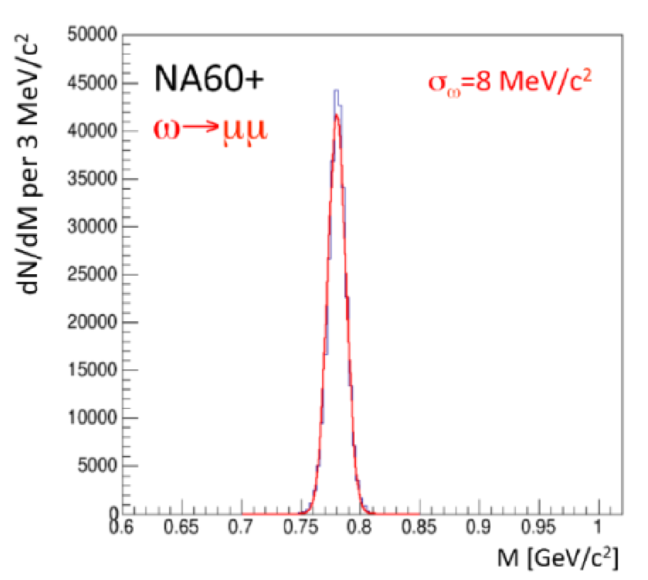
Detector performance studies → based on a **simulation framework** with a semi-analytical tracking algorithm (Kalman filter)
FLUKA for background studies

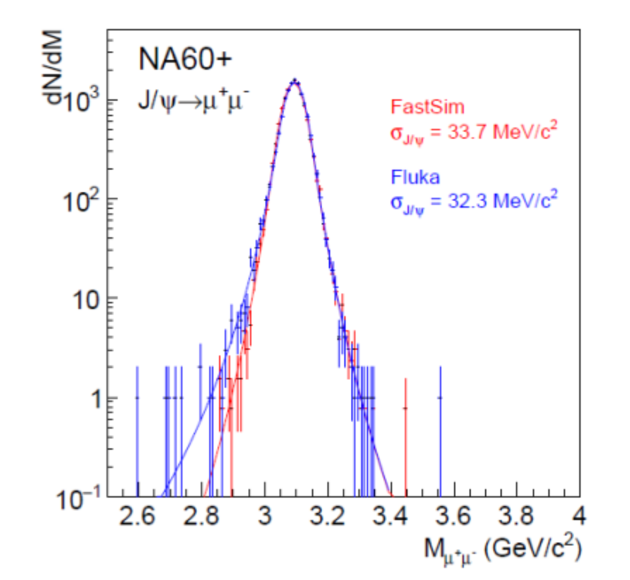
QGP ($M>1$ GeV/c^2)





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

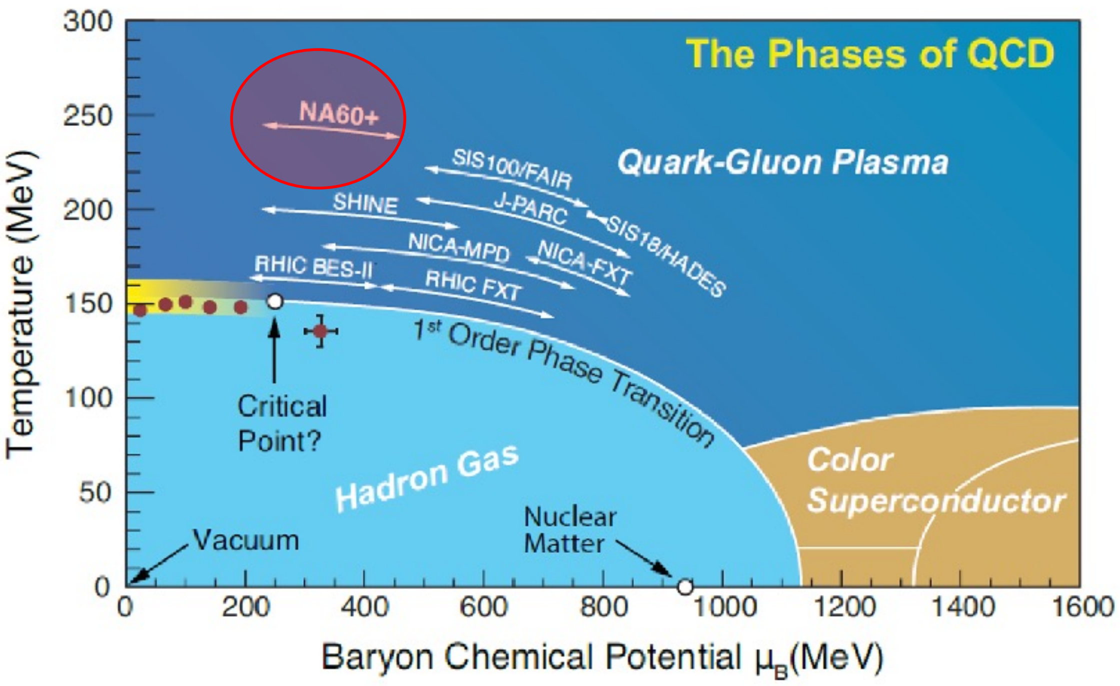




The mass resolution for resonances varies from <10 MeV (ω) to ~30 MeV (J/ψ)

(factor >2 improvement with respect to NA60)

Thermal dimuons in NA60+: motivation



- QCD phase diagram:
  - Existence of critical point and first order phase transition put forward

  Additional chiral phase transition:
  - Exploration of changes in the hadron spectrum

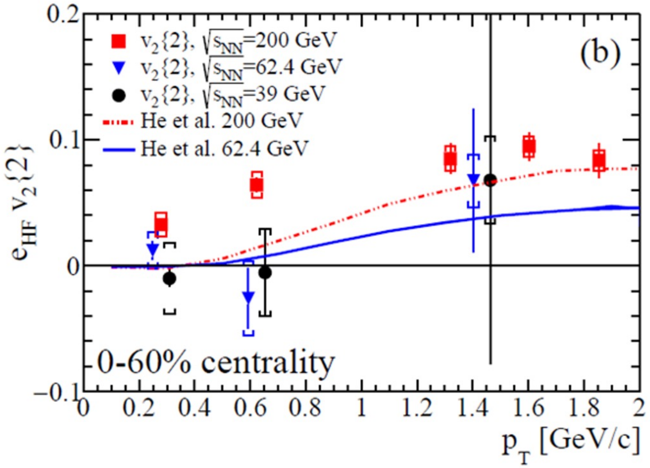
- Aims at precision measurements of thermal dimuon mass spectra in beam energy scan at high μ_B:
  - Measurement of temeperature (M>1.5 GeV) → **Caloric curve**
  - Measurement of yield (0.3<M<0.7) → **Fireball lifetime**
  - Measurement of yield (0.9<M<1.4 GeV) → **ρ-a_1 chiral mixing**

- Additional measurement of dimuon elliptic flow:
  - Measurement of elliptic flow (v_2) vs mass and p_T → **further insight into phase transition**

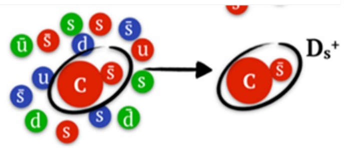
Open charm measurement in NA60+: motivation

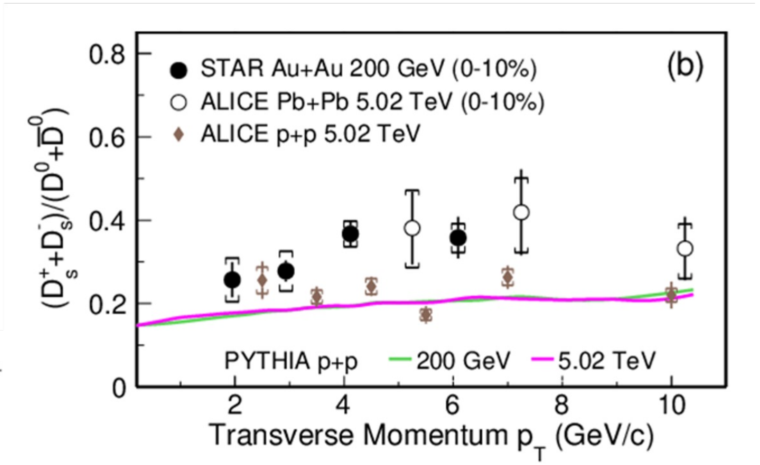
- No results at SPS energies (only indirect measurements at top SPS energy, NA60 and NA49)
- Aims at precision measurements of nuclear modification factor and elliptic flow for BOTH meson (D^0,D^+,D_s) and baryon (Λ_c) states
  - Insight into **QGP transport properties**
  - Study of **charm thermalization at low √s**
  - Insight into **hadronization mechanism** (via ratios D_s/D^0 and Λ_c/D^0)
  - Use **total charm cross section** as a reference for charmonium studies

Complements results at collider energies! Different "weight" of QGP and hadronic phase



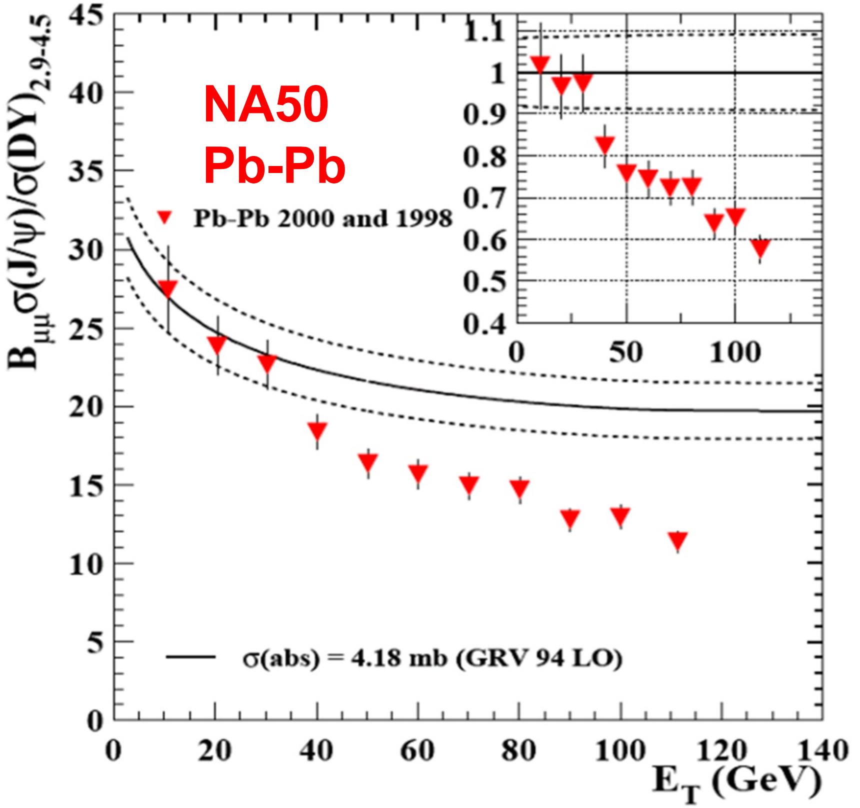
D-meson elliptic flow and charm thermalization vanishes at low energy?





D_s enhancement due to quark recombination

Charmonium measurement in NA60+: motivation



J/ψ production not studied below top SPS energies!

Perform an energy scan in

E_{lab} = 20 – 158 GeV

- ❑ Decreasing √s:
  - ❑ **Onset of charmonium melting** to be correlated to T measurement via thermal dimuons
  - ❑ **Stronger CNM effects** to be accounted for with pA data taking at the same √s

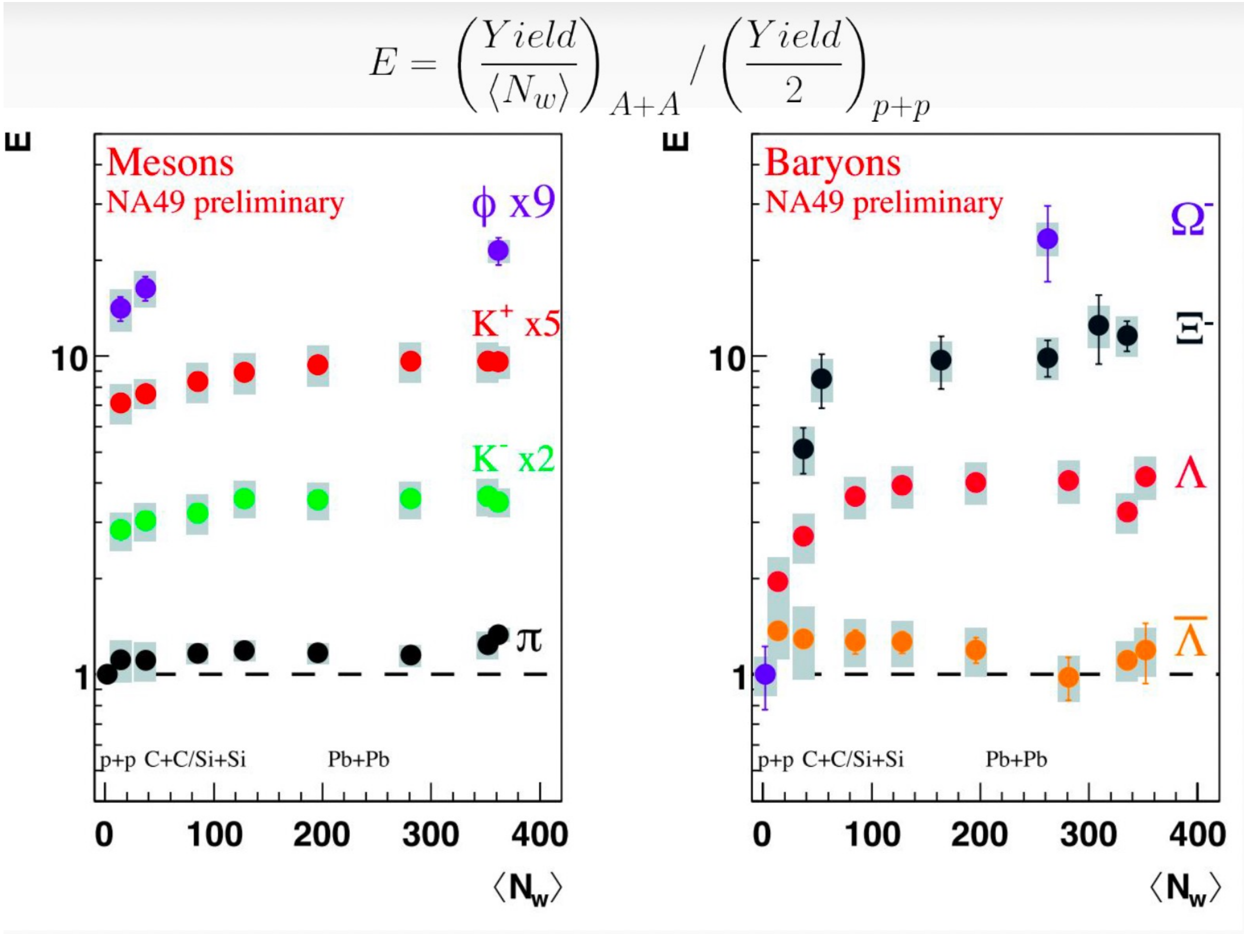
- ❑ Accurate studies were performed at √s=17.3 GeV (NA50, NA60)
- ❑ QGP-induced suppression evaluated with respect to a cold nuclear matter reference obtained with systematic p-A studies
- ❑ **~30-40% anomalous suppression effect** possibly due to disappearance of feed-down from χ_c and ψ(2S)

Strangeness measurement in NA60+: motivation

- Pb-Pb and p-Pb(Be) interactions at low $\sqrt{s_{NN}}$ probe multiplicity region around 10-100 particles at mid rapidity → **overlaps to high-multiplicity pp and MB p-Pb collision at the LHC**

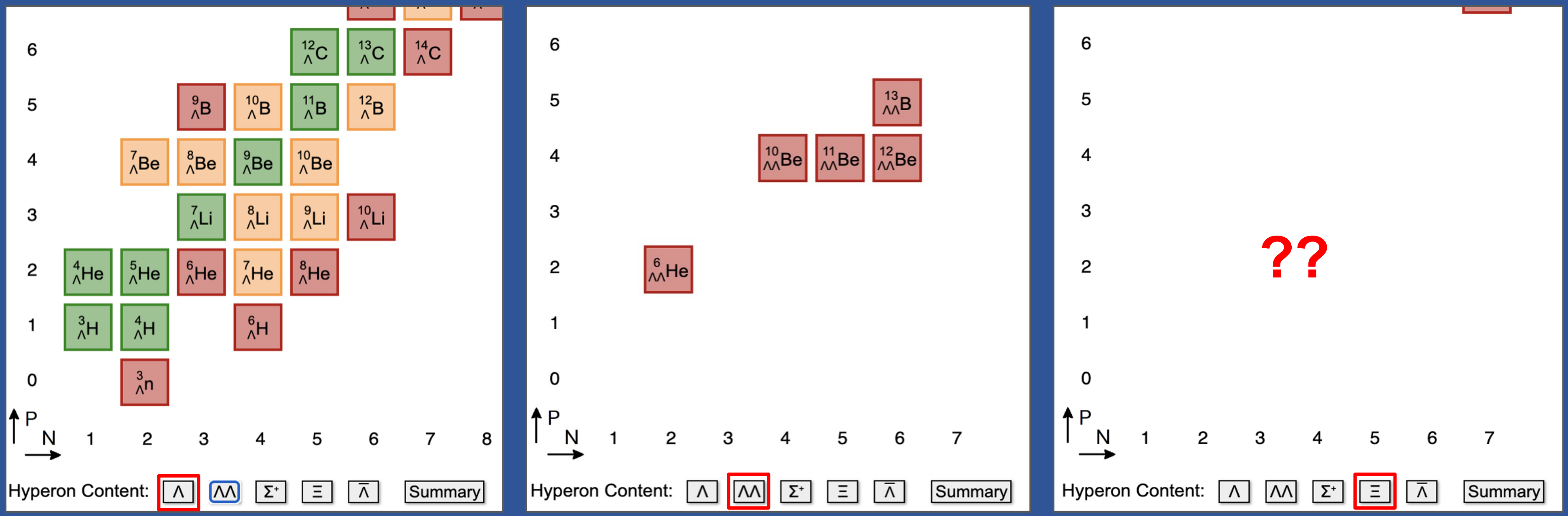
- Matter/anti-matter imbalance rate would allow a **precise determination of the baryochemical potential** → probe production probabilities in an energy region where baryon number conservation depletes anti-particle yields

- NA60+: complete the measurement of the strangeness enhancement carried by NA49, NA57 with precise measurements of K^0_S, ϕ, $\Xi^{\pm}$, and $\Omega^{\pm}$ **including elliptic flow**



Hypernuclei: the knowns, the unknowns and discoveries potential

From the Mainz hypernuclei database, July 2022



- Open points in hypernuclear physics that can be addressed with NA60+:
  - Precise characterisation of known states: properties of Λ hypernuclei
  - Properties and confirmation of poorly known/unknown hypernuclei: A=6, light ΛΛ hypernuclei
  - Discovery of light Ξ and Σ hypernuclei bound according to theory [1,2] (e.g. NNNΞ)

[1] E. Hiyama et al. *Phys. Rev. Lett.* 124, 092501
[2] H. Le et al. *Eur. Phys. J. A* (2021) 57: 339