Prospects with NA60+

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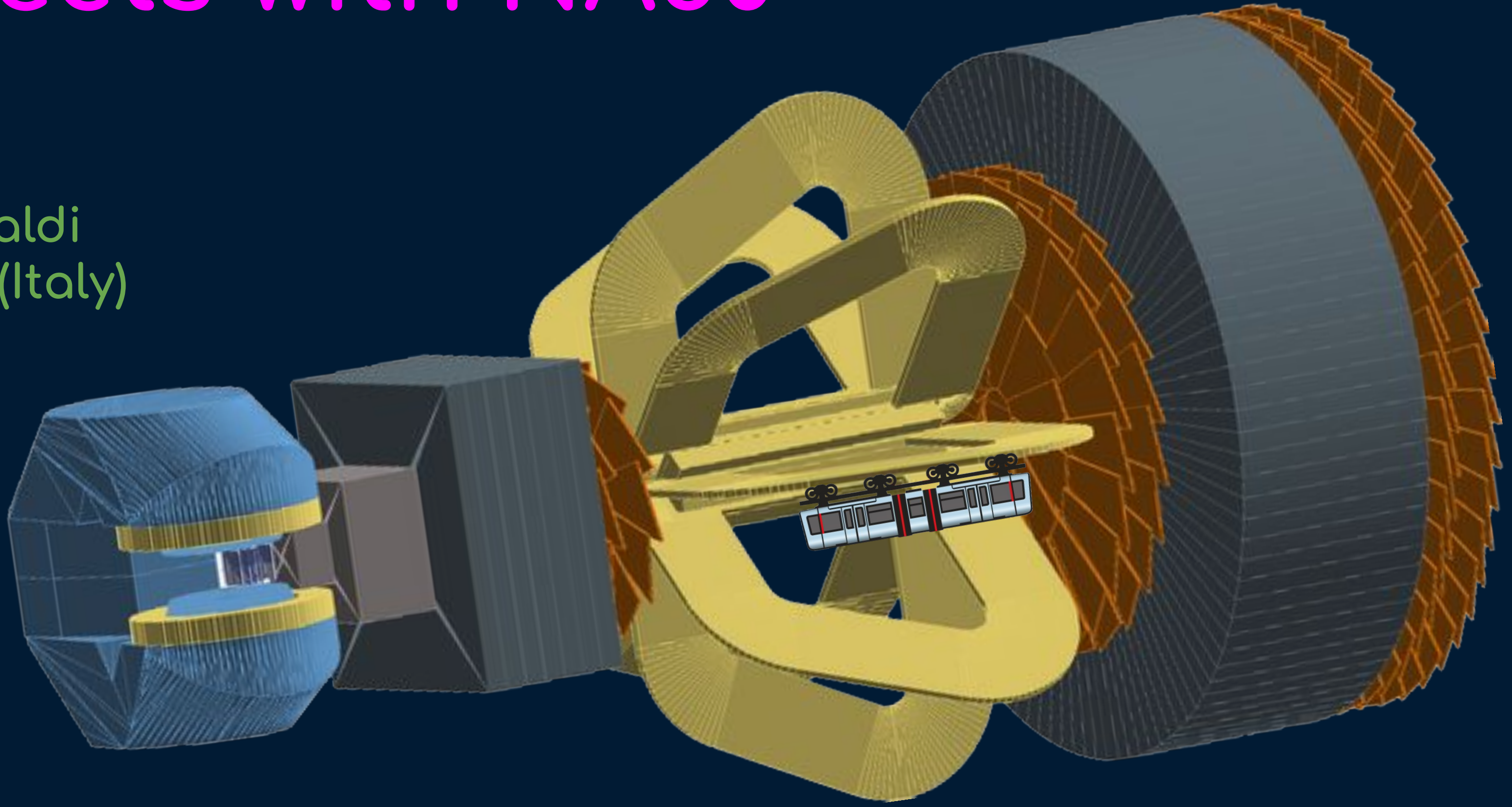


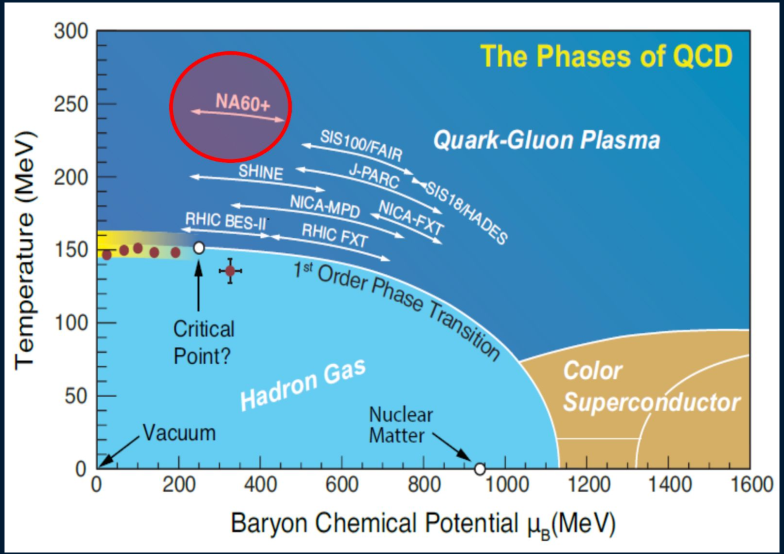
Physics opportunities with proton beams at SIS100, Wuppertal, 6-9 February 2024

the NA60+ project

- New experiment at the CERN SPS to explore the QCD phase diagram at high baryon chemical potential (μ_B)

- NA60+ will perform precision studies of hard and electromagnetic processes
    - accessing muon pair production from threshold up to $m_{\mu\mu}$ ~ 4 GeV/c^2 (dilepton continuum + quarkonia)
    - measuring hadronic decays of strange and charm hadrons

- A beam energy scan between $\sqrt{s_{NN}}$ ~ 6 - 17 GeV will allow us to access the μ_B region ~220 - 550 MeV



T. Ulrich

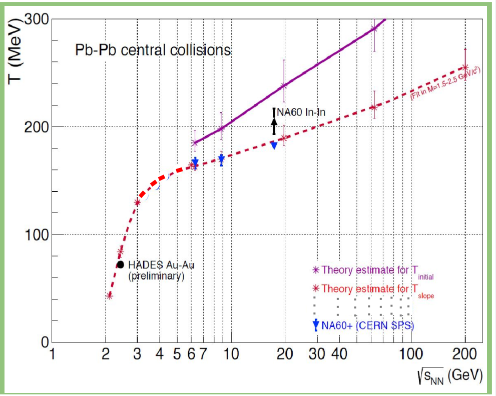
the NA60+ physics program

Several new and unique measurements

1) caloric curve of QGP

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

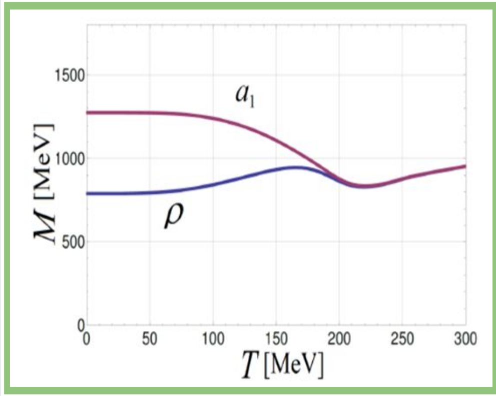
Rapp and v.Hees, PLB753(2016) 586
T. Galatyuk et al., EPJA52(2016) 131



2) chiral symmetry restoration

ρ-a_1 mixing in the dimuon channel

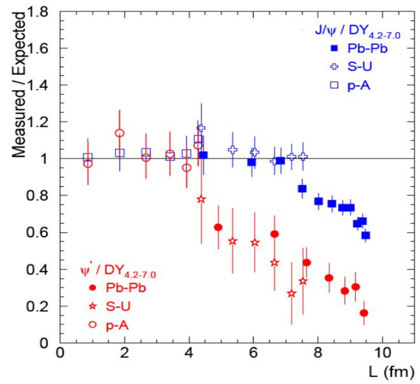
C. Jung et al., PRD 95 (2017) 036020



3) charmonium melting in the QGP

suppression of charmonium vs $\sqrt{s_{NN}}$ (dimuon decay channel)

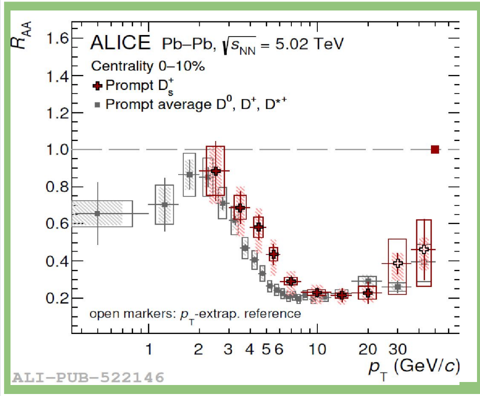
NA50, PLB 477 (2000) 28
NA50, EPJC49 (2007) 559



4) QGP transport coeff. and charm hadronization

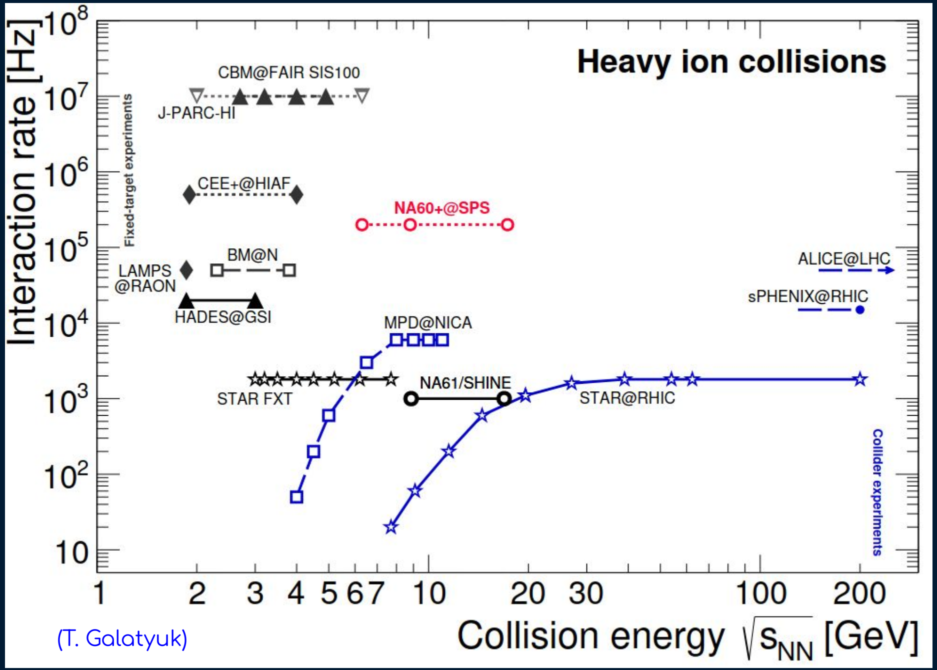
hadronic decays of open HF mesons and baryons

ALICE, PLB 827 (2022) 136986



uniqueness of NA60+

The NA60+ program needs a large luminosity to search for rare QGP probes



This luminosity can be collected with PbPb interactions rates > 10^5 Hz, reachable with 10^6 s^{-1} beam intensity in a fixed target environment

- NA60+ is unique, for energy coverage AND interaction rate, in the heavy-ion landscape
- NA60+ is complementary to experiments accessing:
  - different (hadronic) observables in the same energy range (STAR BES, NICA, NA61)
  - similar observables in a lower energy range (CBM)

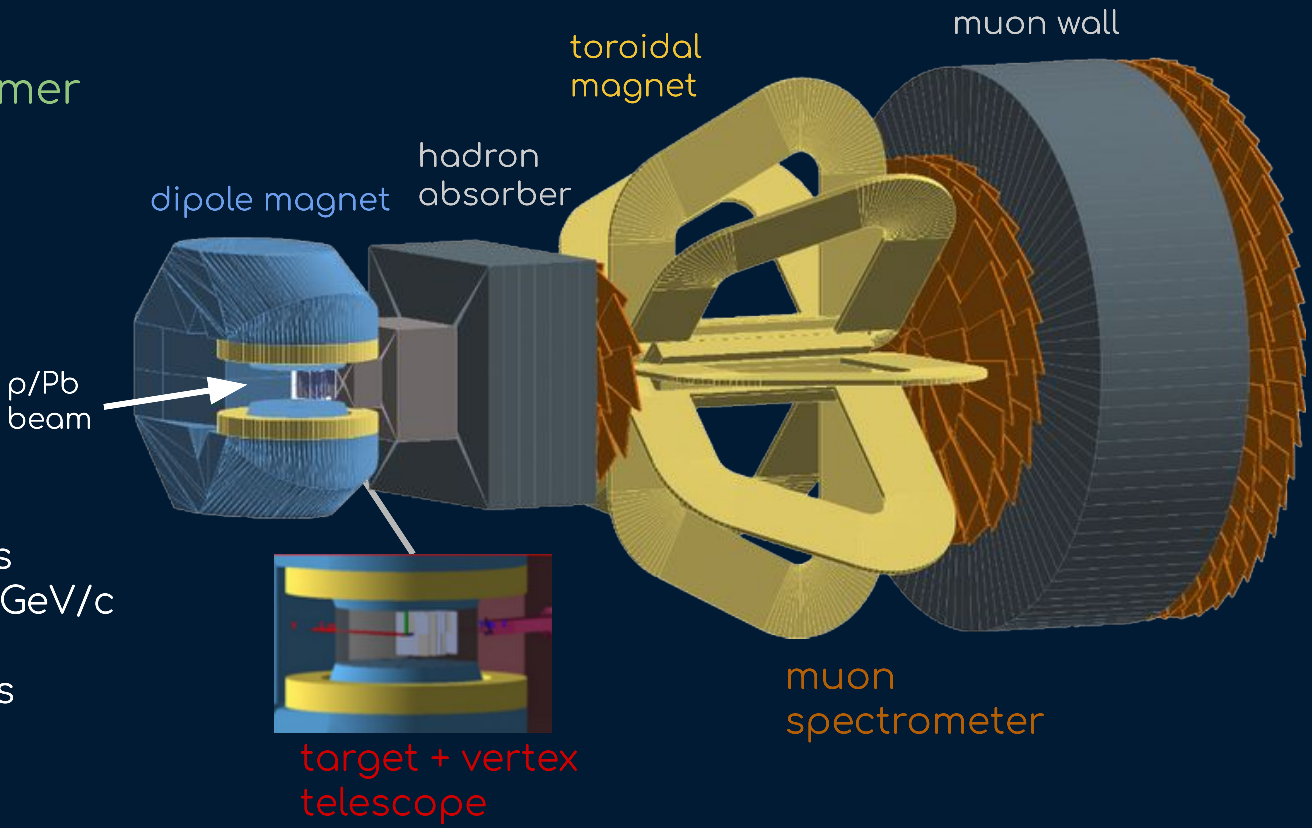
the NA60+ detector

Setup inspired by the former NA60 detector:

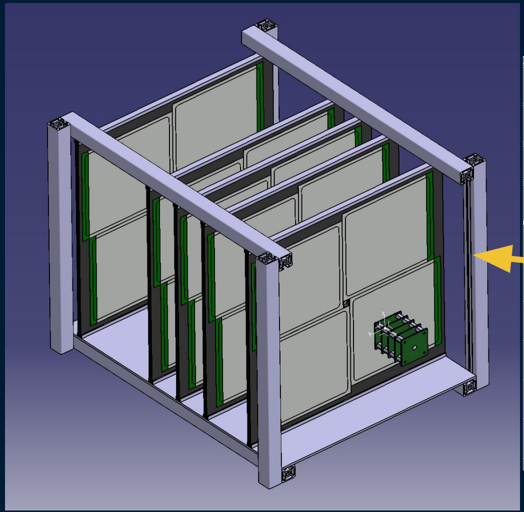
- Muon spectrometer
- Vertex spectrometer

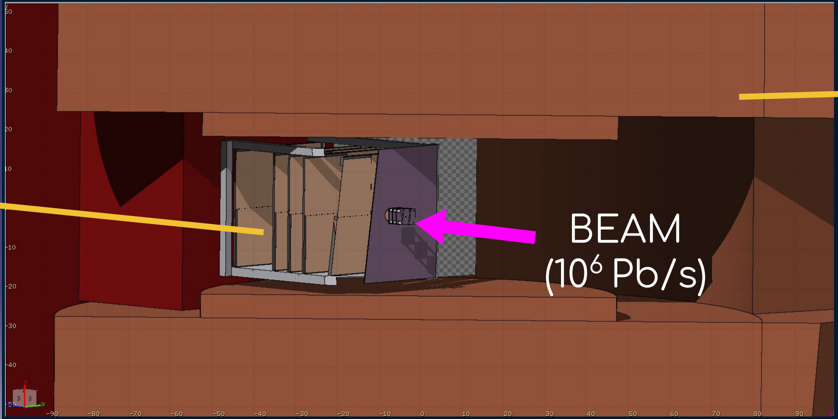
Energy/systems:

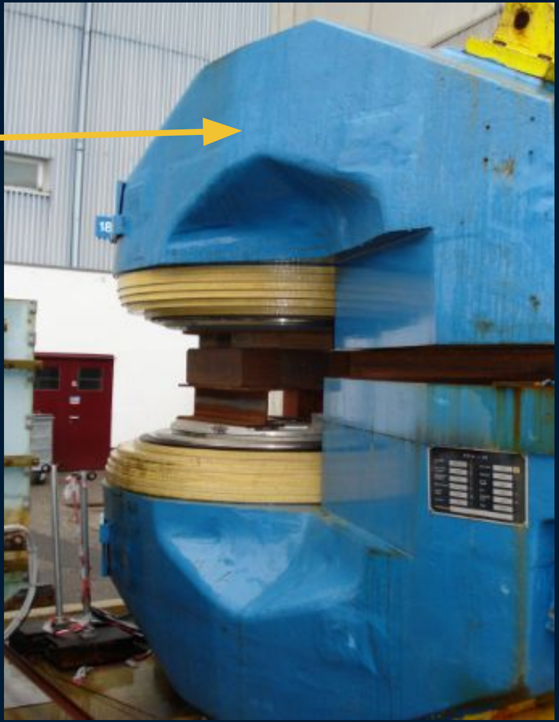
- Pb-Pb and p-A collisions
- energy scan: $6 < \sqrt{s} < 17$ GeV/c ($20 < E_{lab} < 158$ GeV/c)
- high luminosity ~10^6 Pb/s



the vertex region







- Dipole magnet:
  MEP48 (available at CERN), 1.5 T field over 400 mm gap
- Vertex spectrometer:
  5 layers of MAPS detectors
- Target system:
  - AA: 5 Pb sub-targets, 1.5 mm thick each
  - pA: several sub-targets (e.g. Be, Cu, In, W, Pb) simultaneously exposed to the beam

the vertex telescope R&D

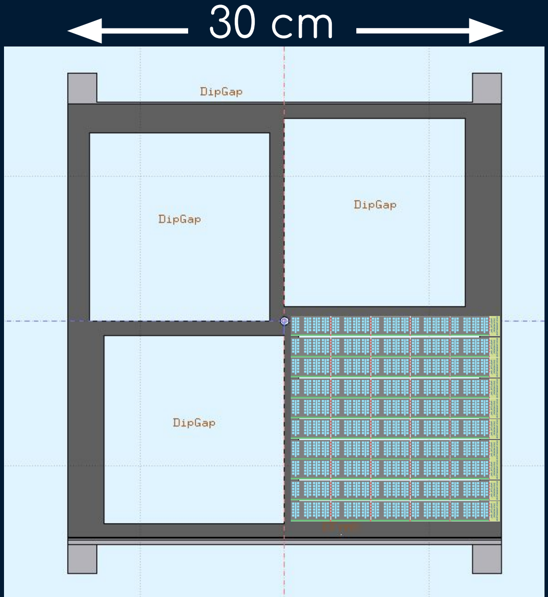
High charged particle multiplicity in Pb-Pb collisions (up to $dN_{ch}/dy = 450$)

→ high granularity, fast and radiation hard detectors in the vertex region

Use of state-of-the-art Monolithic Active Pixel Sensors

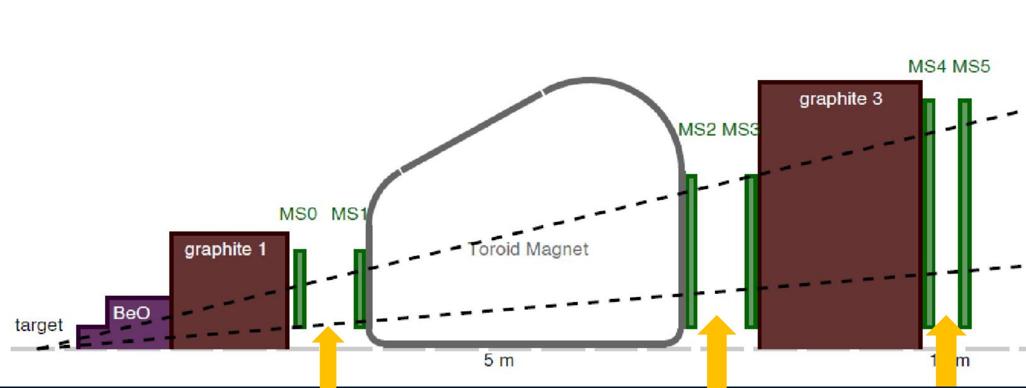
- synergy with ALICE ITS3 → first large area stitched sensor (MOSS) is currently being tested
- sensor based on 25 mm long units, replicated several times through stitching up to 15 cm length for NA60+

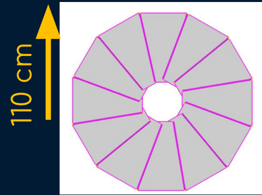
- few tens of microns of Si → material budget < 0.1% X_0
- spatial resolution ≤ 5 µm
- cooling with airflow and water



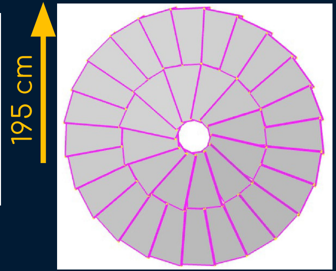
the muon spectrometer

6 tracking stations, with a modular structure

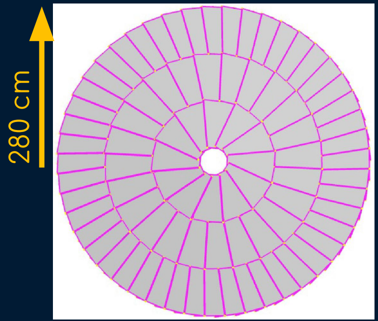




12x2 modules



36x2 modules

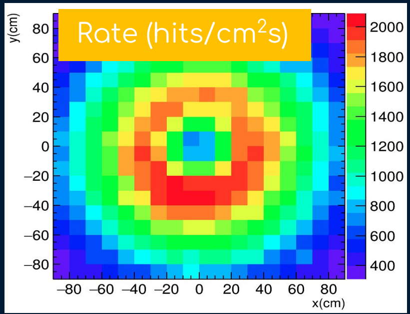


84x2 modules

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

Thick absorber (235 cm BeO +C)
→ modest rates (FLUKA) already in the upstream stations

for 10^6 ions/s beam, rate of charged particle ~2 kHz/cm^2



➡ **GEM or MWPC detectors can match these rates**

the muon spectrometer R&D

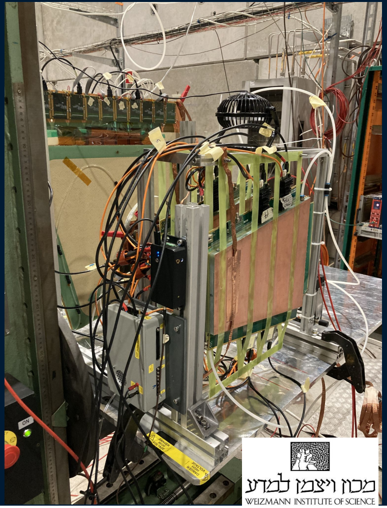
Ongoing discussions on the final spectrometer set-up, various possible solutions, as

- GEM for upstream stations (MS0-MS1)
- MWPC for downstream stations (MS2-MS5)

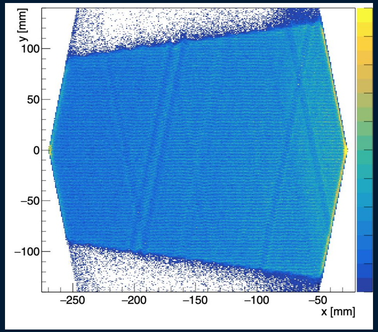
First prototypes modules characterised in a Pb test beam at CERN (Fall 23)

MWPC

Good performances of the MWPC (1 mm readout strips)

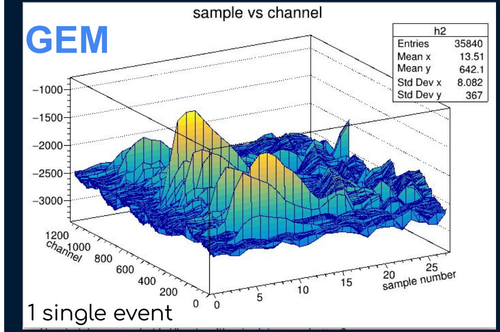


First rough evaluation of resolution ~100 μm

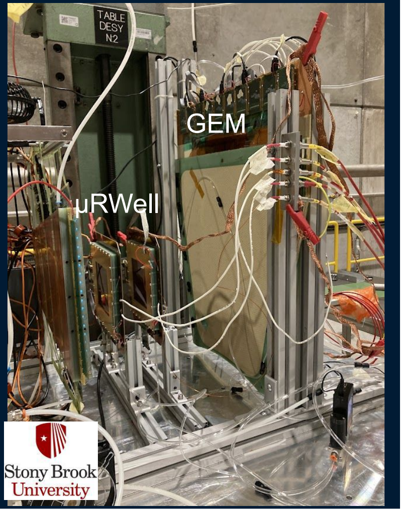


GEM

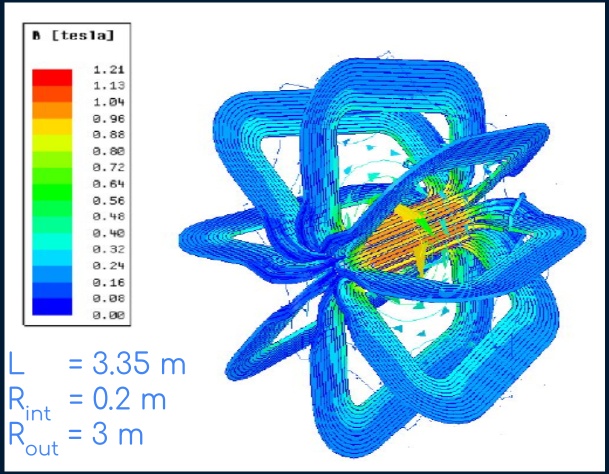
Good performances of GEM

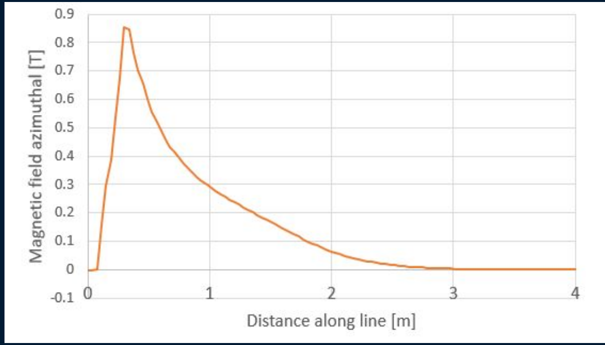


(channel corresponds to readout strips, sample number to 25 ns time samples, z axis is ADC)



the toroidal magnet R&D





Warm magnet

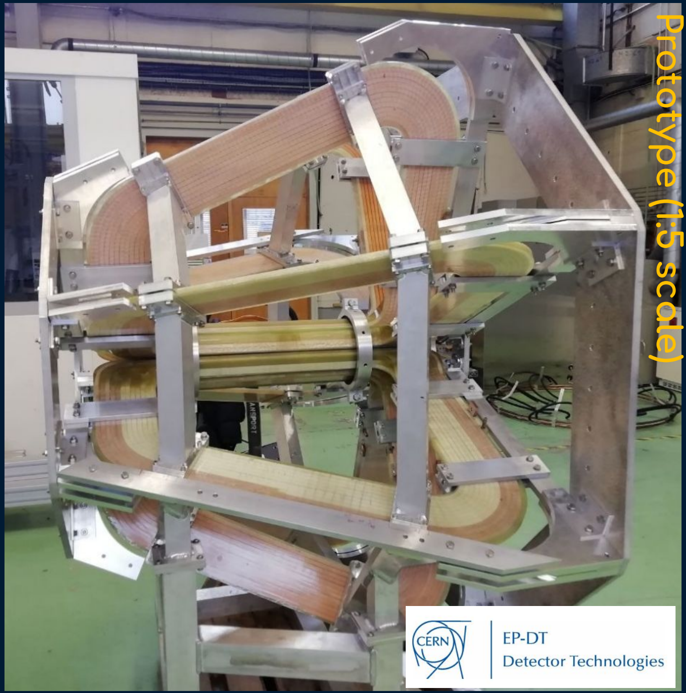
- Eight sectors with 12 turns per coil
- Light design → **low material budget** in the acceptance area

Prototype (1:5 scale)

built and tested to check calculations and investigate mechanical solutions

⬇

B measurement □ agreement with simulations by 3%

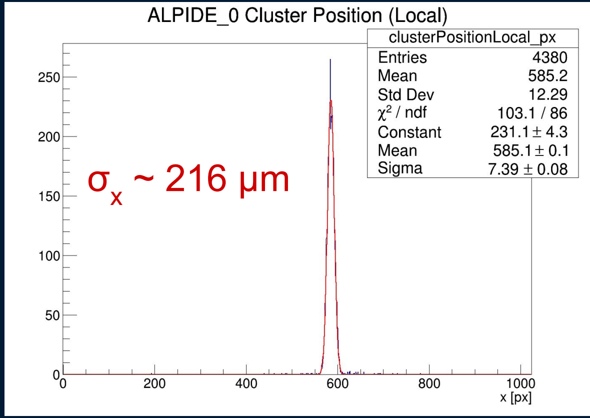


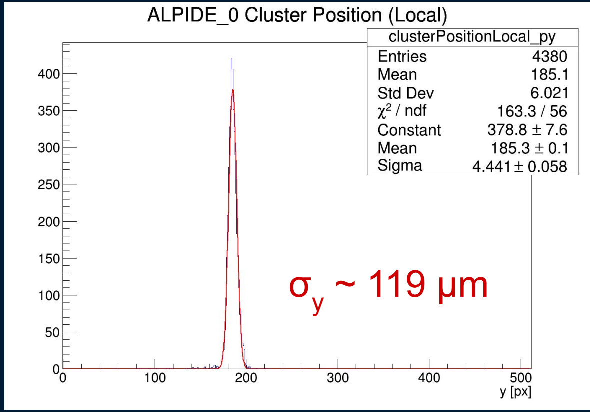
Prototype (1:5 scale)

beam for NA60+

- NA60+ will be installed in the CERN EHN1 - PPE138 area along the H8 beam line
- very stringent beam requests at all energies (from 20-30 A GeV to 160 A GeV)
  - high-intensity (10^7 Pb/spill)
  - extremely focussed sub-mm beam (vertex spectrometer will have 6 mm hole)

➡
- ongoing beam optics studies
- promising results from high intensity tests (up to 2.4 10^6 Pb/spill at 150 GeV) at SPS in 2022 and 2023





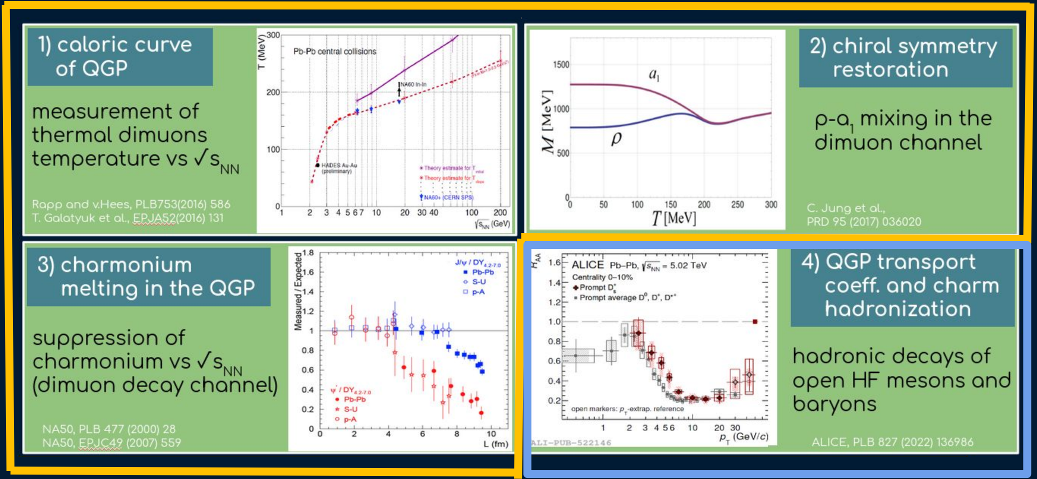
physics performances of NA60+

Collision systems

- PbPb
  → data taking: 1 month per year
- pA
  → data taking at the same energies as AA collisions, with similar integrated luminosity

dimuons:

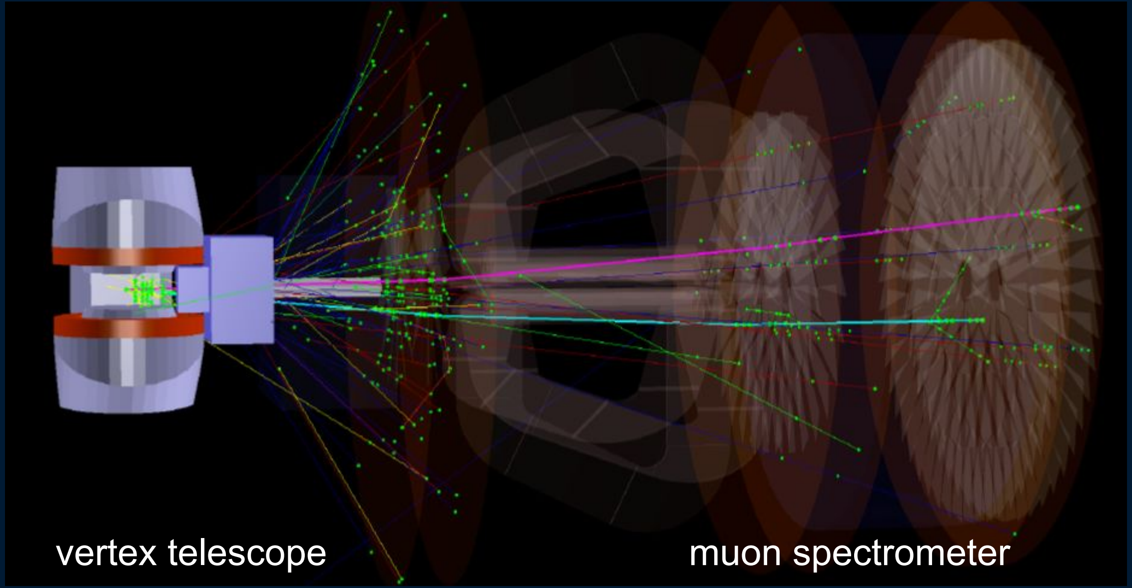
- vertex telescope
- muon spectrometer



charm hadrons

- vertex telescope

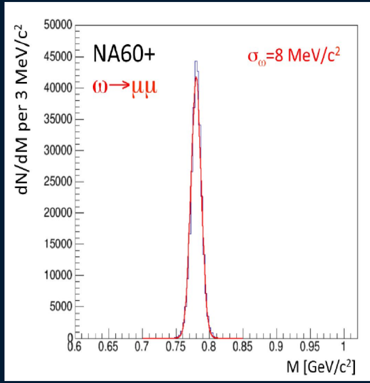
dimuons in NA60+

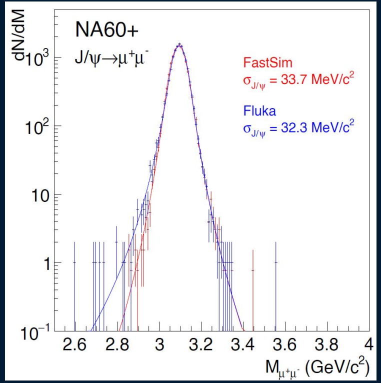


Muon tracks

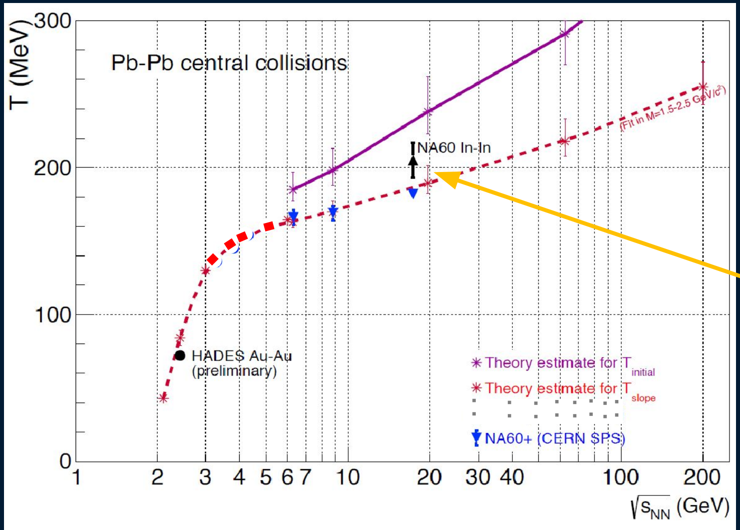
- matching (in coordinates and momentum space) of tracks in vertex and muon spectrometer
- measure muon kinematics before multiple scattering and energy loss

very good mass resolution





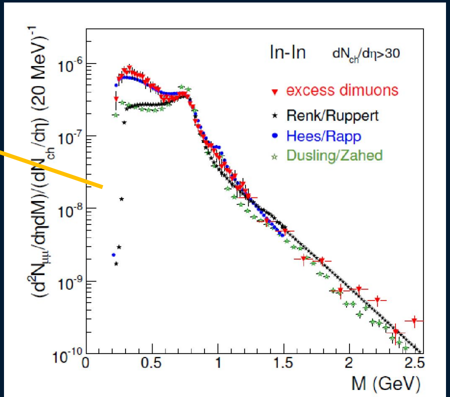
thermal dimuons



Caloric curve of the QGP

Measurements only at top SPS energy and at very low energy

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



dilepton T_{slope} measurement □ (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

thermal dimuons in NA60+

Thermal radiation yield

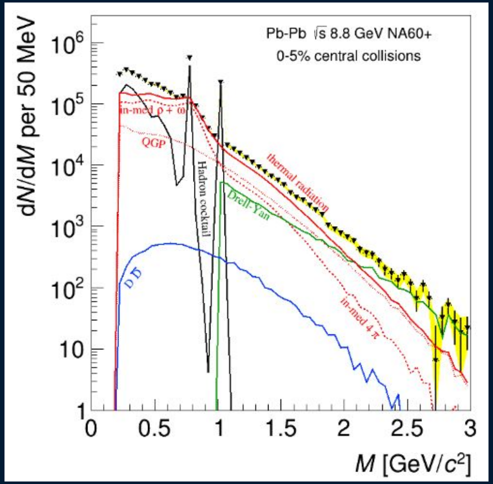
- accessible up to M= 2.5-3GeV/c^2
- dominated by ρ contribution at low mass

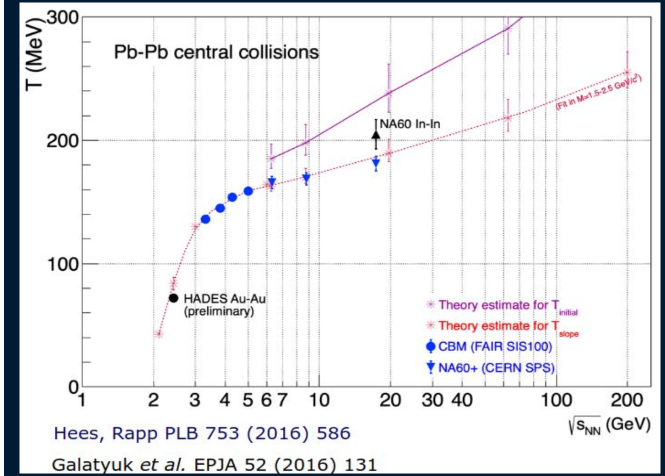
Drell-Yan contribution

- to be estimated via p-A measurements

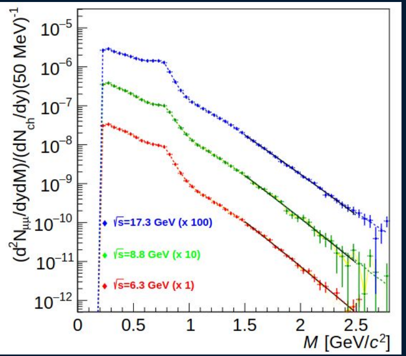
Open charm contribution

- negligible dimuon source





T_{slope} extracted fitting
1.5 < M < 2.5 GeV/c^2



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

- accurate mapping of T_s **√s-dependence** around T_{pc}
- strong **sensitivity** to possible flattening of the caloric curve due to 1st order transition

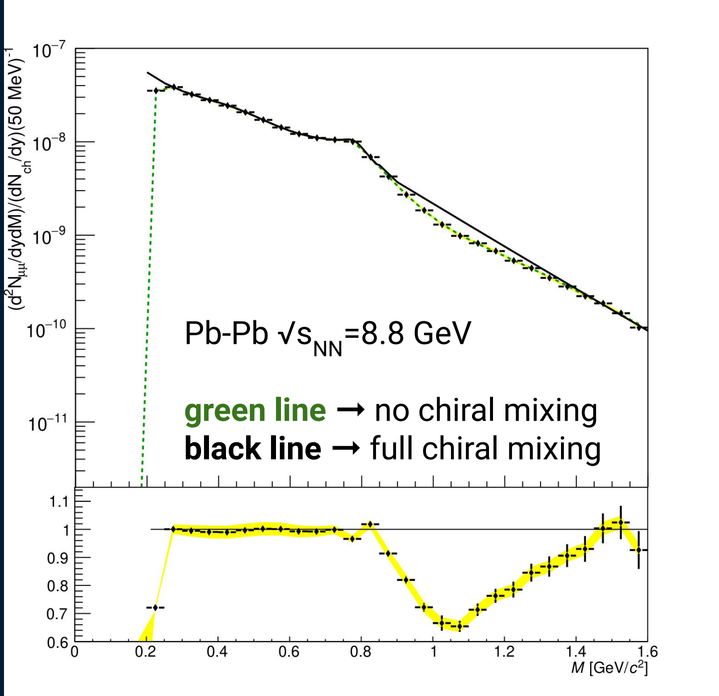
ρ-a_1 mixing in NA60+

Chiral symmetry restoration investigated with the measurement of the ρ-a_1 mixing

Full ρ-a_1 chiral mixing detected studying the modification of the dimuon continuum

➞ a 20-30% enhancement is expected in the region 0.8 < M < 1.5 GeV/c^2 w.r.t. no mixing

NA60+ could clearly detect a signal of chiral symmetry restoration



charmonium at low √s

SPS

hot matter effects
suppression

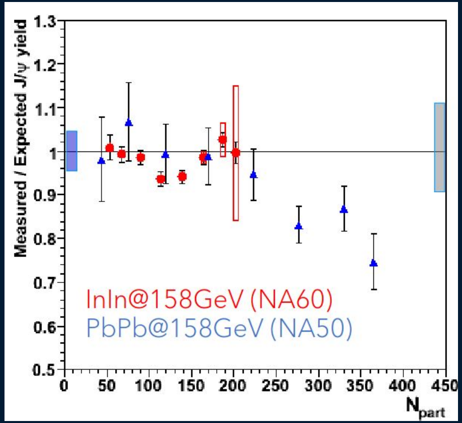
initial state effects
(anti)shadowing
$x_{BJ} \sim 10^{-1}$ for y~0

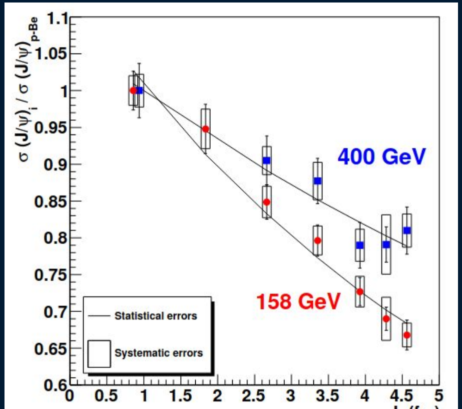
final CNM effects
sizable breakup in nuclear matter
τ~0.5 fm/c for y~0

AA:

accurate measurements from NA50/NA60 at top SPS energy

- ~30% J/ψ anomalous suppression in central PbPb, beyond CNM
- consistent with J/ψ suppression from ψ(2S) and χ_c feed-down
- significant contribution from CNM effects





NA60, PLB706 (2012) 263

pA:

precise measurement of CNM

- anti-shadowing contribution
- nuclear break-up dominant, stronger at lower √s

charmonium in NA60+

Quarkonium never studied below top SPS energies

1

AA: onset of charmonium suppression

accessible via energy scan

- evaluate the threshold temperature of the charmonium melting correlating the onset with T measured via thermal dimuons

2

pA: cold nuclear matter effects

CNM effects increase at low $\sqrt{s}$

- mandatory (at the same $\sqrt{s}$ as AA) for a correct evaluation of hot matter effects
- disentangle the various contributions (shadowing, nuclear breakup...)

3

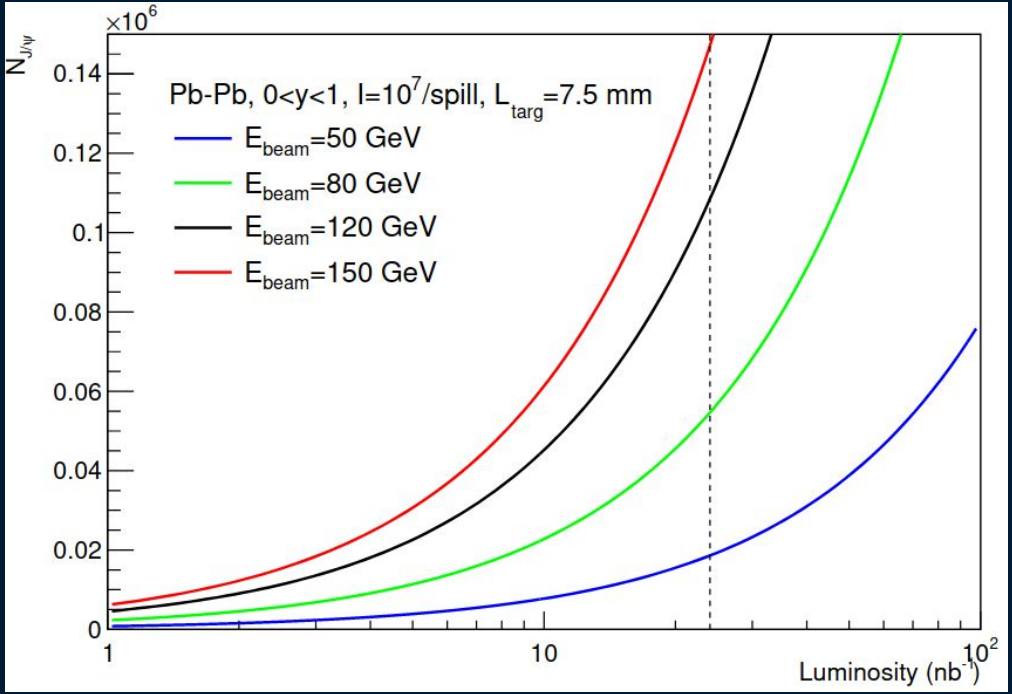
pA: intrinsic charm

expected enhanced charm production at large x_F

- fixed target is the ideal configuration → enhancement is expected closer to mid-y
- dominant effect even with 0.1% probab. of intrinsic charm contribution in the proton (R. Vogt. PRC 103 (2021)3, 035204)

charmonium in AA

High luminosity is needed to cope with the low production cross sections at low √s



Assuming:

- I_{beam}~10^7 Pb/spill, 7.5 mm target, 1 month data taking→ L_{int}~24 nb^{-1}
- a factor 3 overall suppression (CNM+ QGP)

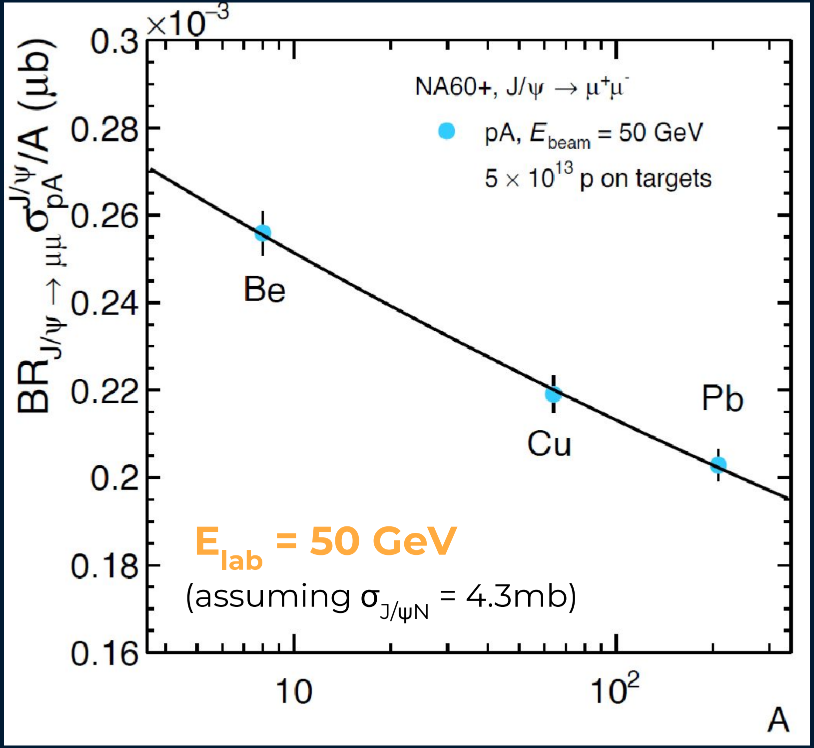
⬇

NA60+ can aim at

~O(10^4) J/ψ at 50 GeV
~O(10^5) J/ψ at 158 GeV

charmonium in pA

p-A data taking mandatory to calibrate CNM effects



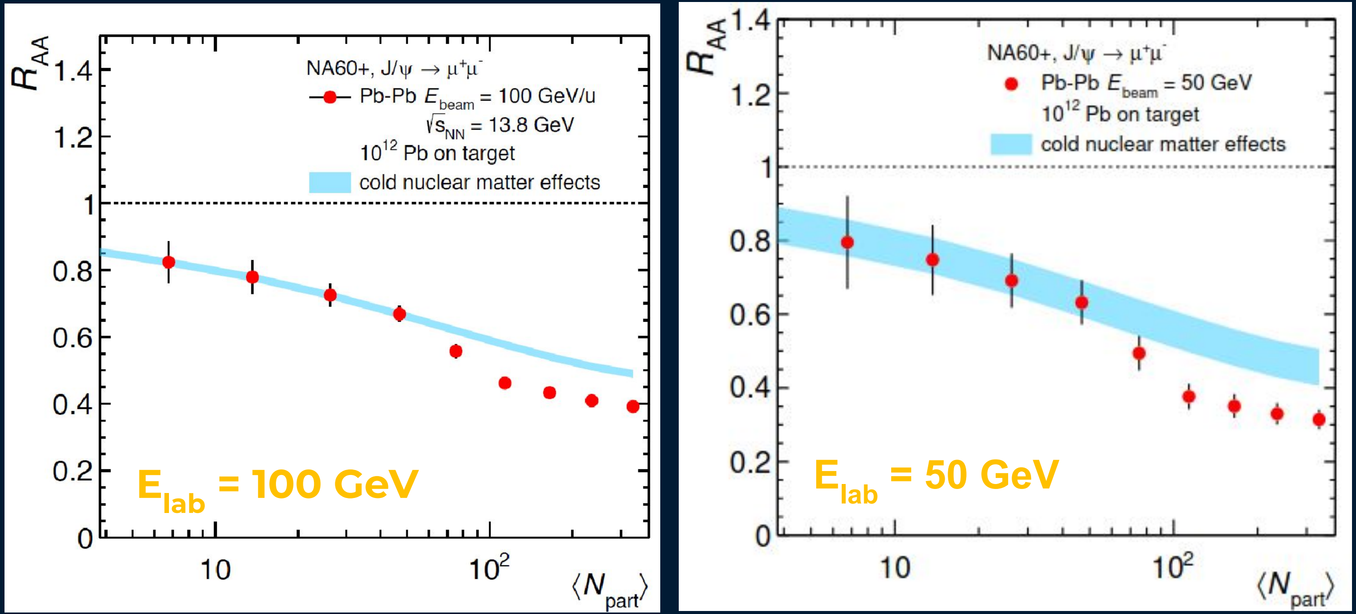
Assuming:

- I_{beam}~5 10^{13} p on target, target thickness 8.3 g/cm2
- NA60+ can aim at

  ~8000 J/ψ at 50 GeV
  ~60000 J/ψ at 158 GeV

- pA data will provide an estimate of CNM effects
- extrapolating the pA measurements down to A = 1, we can estimate σ_{pp}, to be used in the R_{AA} evaluation

charmonium R_{AA}



Based on

- 10^{12} Pb ions, 8.5 g cm^{-2} target
- 5 x 10^{13} protons, 8.3 g cm^{-2} target

Assume

- CNM effects for N_{part}<50
- CNM effects + 20% QGP suppression for N_{part}>50

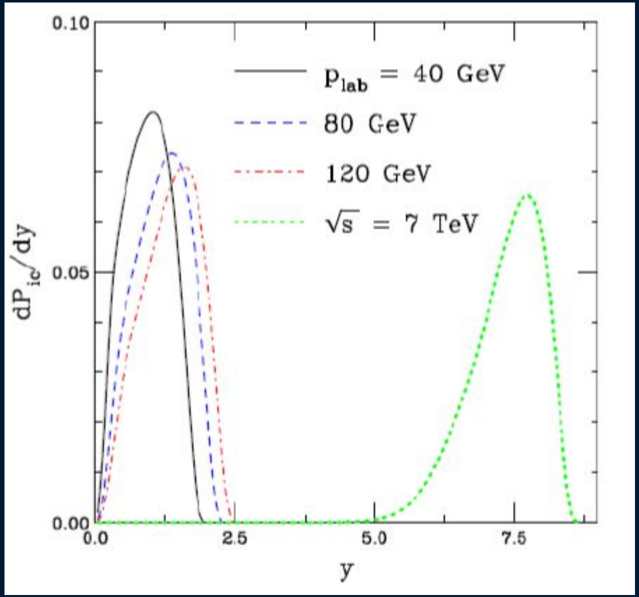
Precise evaluation of anomalous suppression within reach even at low energy

Uncertainties on CNM (σ_{abs}) are ~6 - 15% at 158 and 50 GeV, respectively

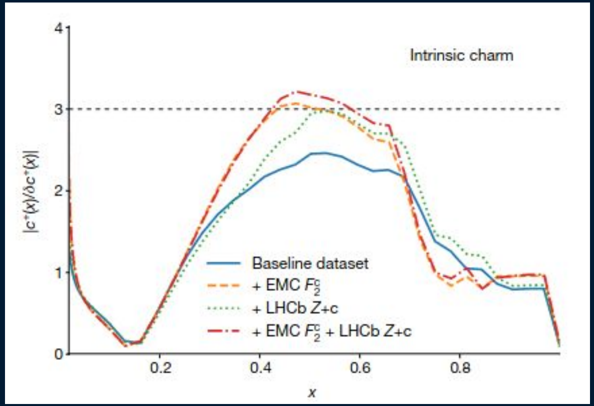
intrinsic charm

Intrinsic charm component of the hadron wave function |uudccbar>

➡ enhanced charm production in the forward region



- at collider energies, the region where the IC effects can be observed is at very large y
- for fixed-target , low √s, the enhancement is closer to mid-y
- first evidence recently claimed by NNPDF group based on LHCb data (Nature 608,483(2022)



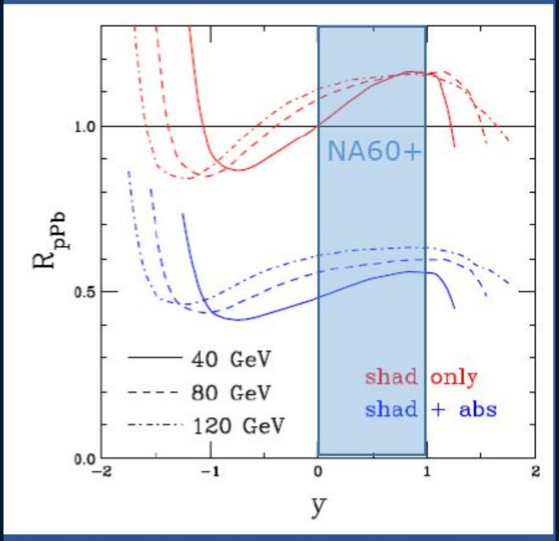
R. Vogt PRC 103, 035204 (2021)
R. Vogt arXiv:2207.04347

intrinsic charm

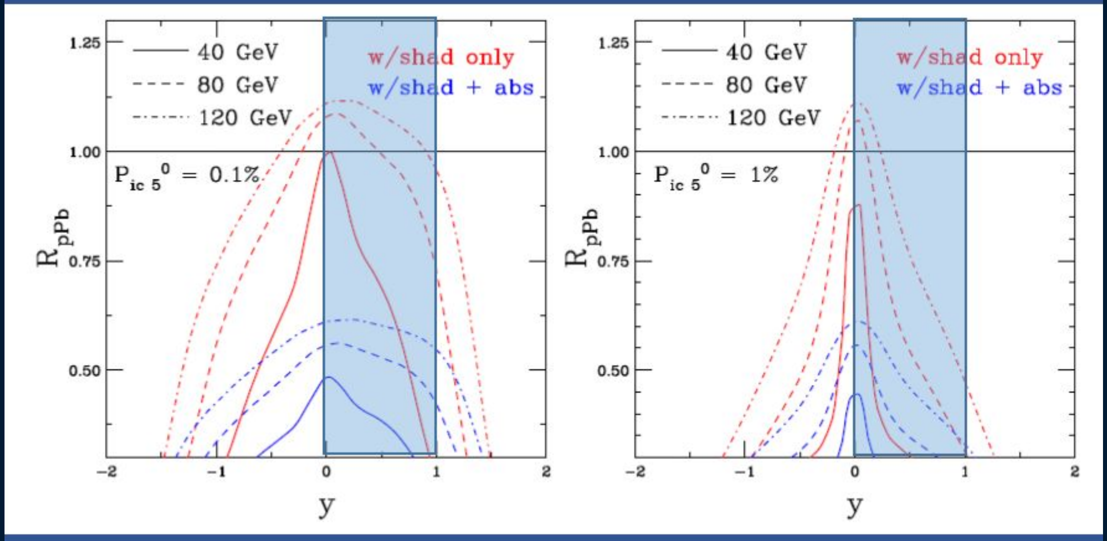
p-Pb collisions:

- EPPS16 shadowing
- σ_{abs} = 9, 10, 11 mb, E_{lab} = 120, 80, 40 GeV
- Intrinsic charm content P_{ic} varied between 0.1 and 1%

without intrinsic charm



with P_{IC} = 0.1% with P_{IC} = 1%



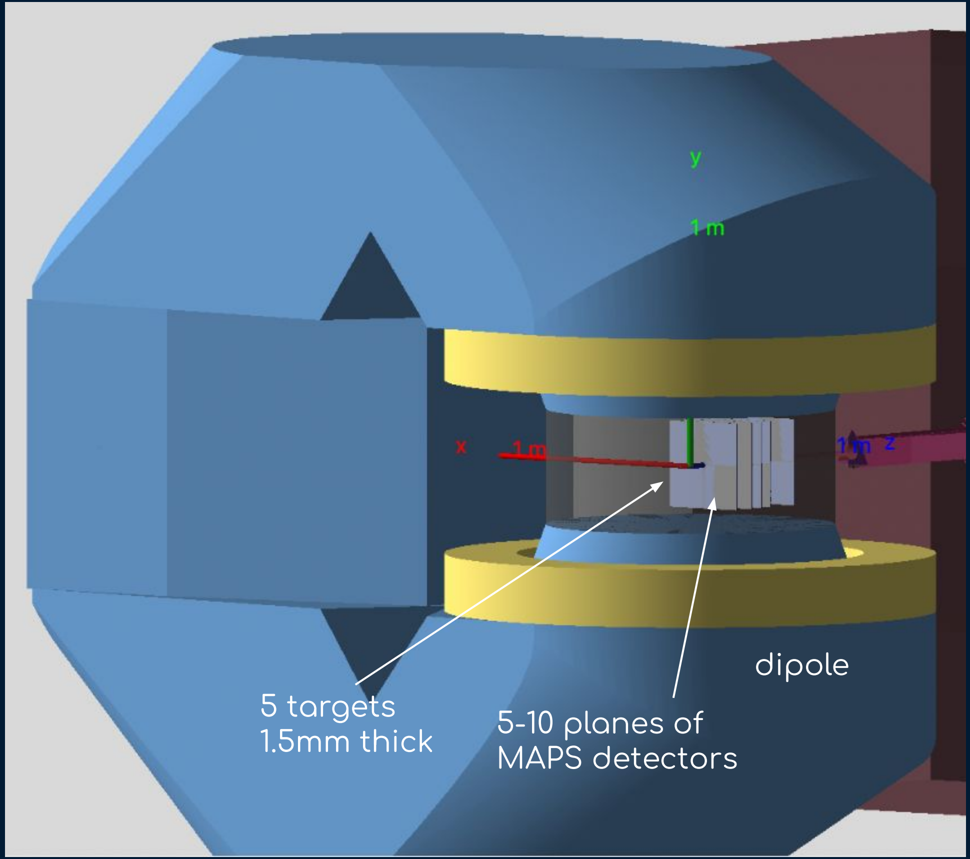
R_{pPb} shape is dominated by intrinsic charm already with P_{ic} = 0.1%

open charm in NA60+

Measurement performed through hadronic decays reconstructed in the vertex telescope

	Mass (MeV)	cτ (μm)	decay	BR
D^0	1865	123	$K^-\pi^+$	3.95%
D^+	1869	312	$K^-\pi^+\pi^+$	9.38%
D^+_s	1968	147	$\phi\pi^+$	2.24%
Λ_c	2285	60	$pK^-\pi^+$ pK^0_s $\Lambda\pi^+$	6.28% 1.59% 1.30%

Combinatorial background reduced via geometrical selection on the displaced decay-vertex topology



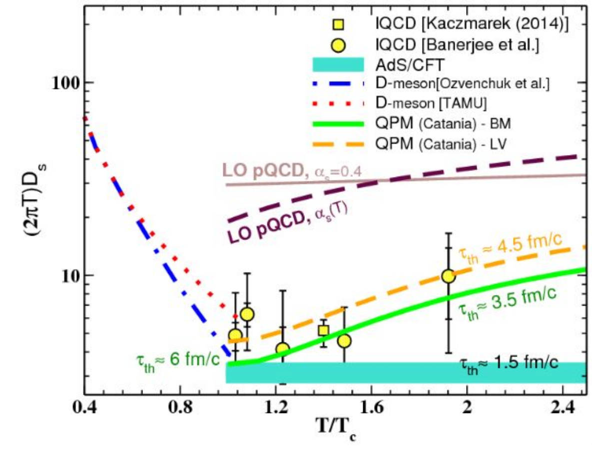
open charm in AA at low √s

1 QGP transport properties

Charm diffusion coefficient depends on the medium T, being larger in the hadronic than in QGP phases

At SPS

- temperatures closer to T_{PC} can be explored
- hadronic phase is a large part of the collision evolution
  → sensitivity to hadronic interactions
  → input for precision measurements at LHC

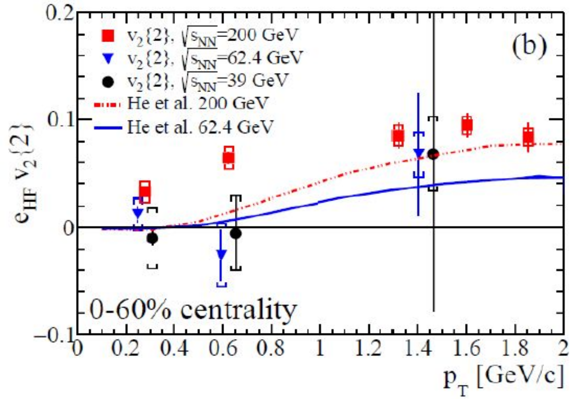


F. Scardina et al. PRC96, 2017 (044905)

2 charm thermalization

Impact on charm of a shorter-lived medium can be explored

- current measurements on HF-decay electron v_2 at RHIC $\sqrt{s_{NN}}$= 39 and 62 GeV/c show small v_2 wrt 200 GeV, not conclusive on v_2>0



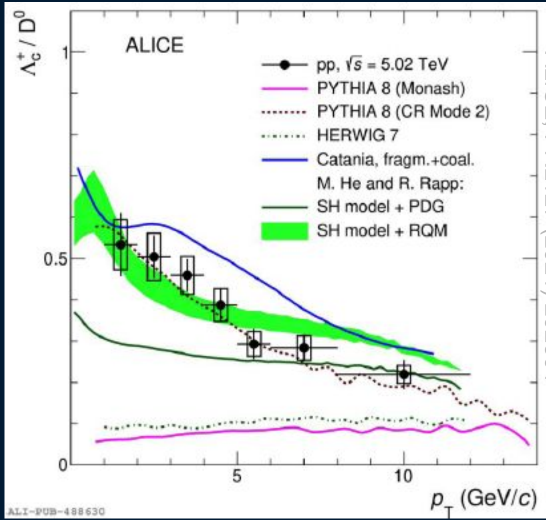
STAR, PRC95 (2017) 034907

open charm in AA at low √s

3 hadronisation mechanisms

Measure the relative abundances of charm-hadrons (D^0, D^+, D^+_s mesons and Λ_c baryons) in a high μ_B environment

- Strange/non-strange meson ratio (D_s/D^0)
  - enhanced in AA due to recombination in the strangeness rich QGP
- Baryon/meson ratio (Λ_c /D)
  - enhanced in AA in case of hadronisation via coalescence
  - interesting also in pp and pA, as observed at LHC



ALICE, PRL127 (2021) 202301

4 total charm cross section

Limited measurements so far (NA60,NA49) because of low yields

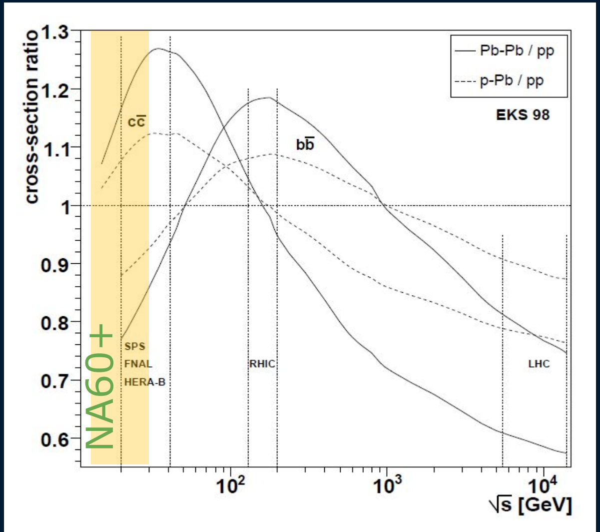
- precise measurement requires to reconstructs mesons and baryons ground states
- ideal reference for charmonia

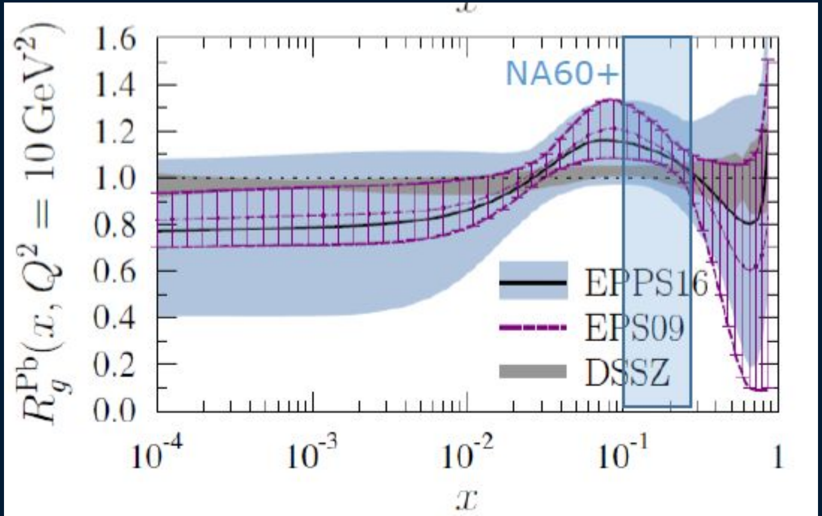
open charm in pA at low √s

5 nuclear PDFs via D meson production in pA

NA60+ will cover the range $0.1 < x_{Bj} < 0.3$ at $Q^2 \sim 10\text{-}40$ GeV^2

- EMC and anti-shadowing regions accessible,
- PDFs poorly constrained by existing data



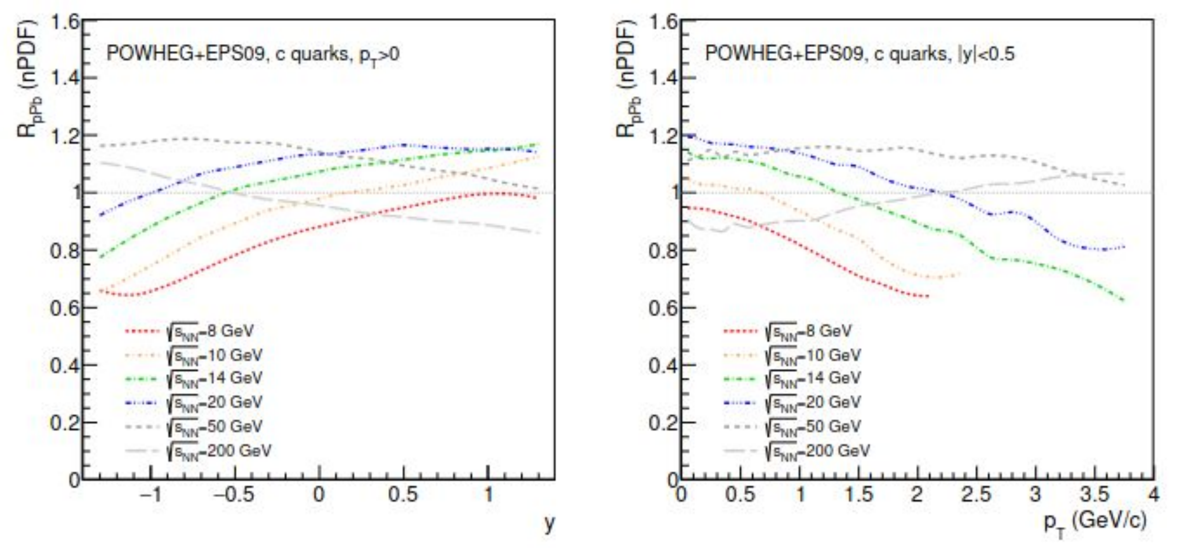


open charm in pA in NA60+

5 nuclear PDFs via D meson production in pA

NA60+ will use several nuclear targets, from Be to Pb

- access to the A-dependence of nPDF
- precise inputs to nPDF from D production ratios pA/pBe at different √s, vs y and p_T



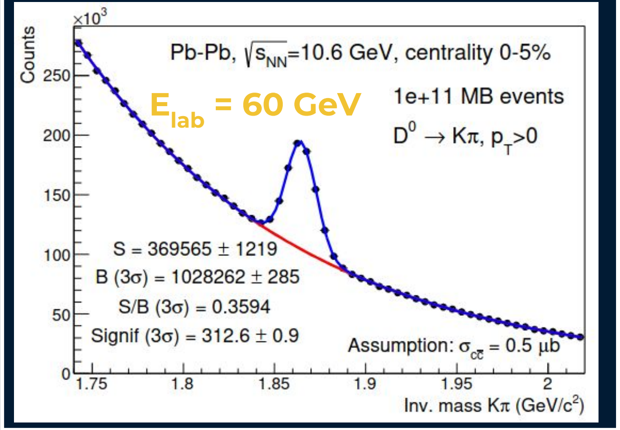
charm-hadrons in NA60+

with 10^{11} MB Pb-Pb collisions (1 month of data taking)

$D^0 \to K\pi$

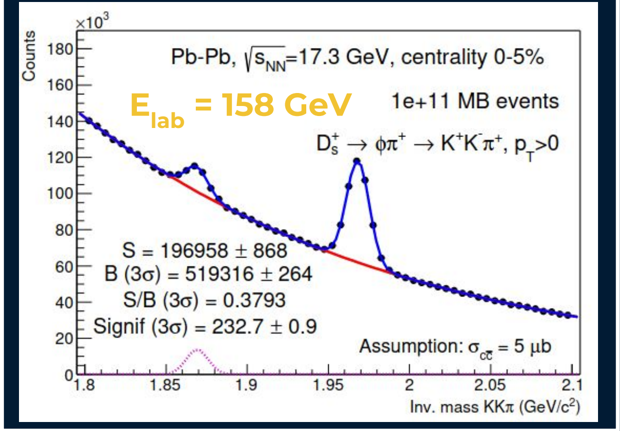
3 10^6 D^0, 0-5% PbPb, $\sqrt{s_{NN}}$=17.3 GeV
→ R_{AA} and v_2 vs p_T, y and centrality

accessible also at lower $\sqrt{s_{NN}}$ with ~1% statistical precision



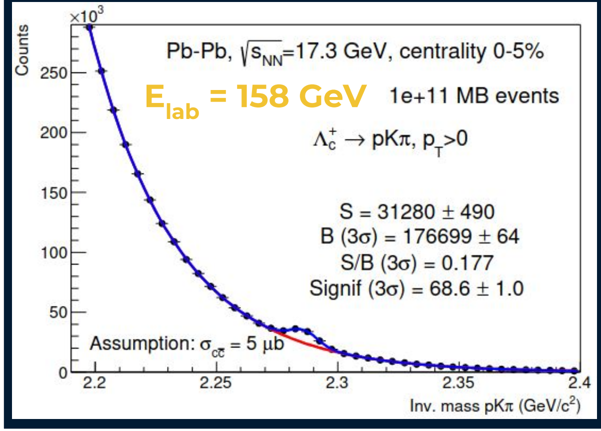
$D_s \to \phi\pi \to KK\pi$

measurement of yields feasible, statistical precision of few percent



$\Lambda_c \to pK\pi$

accessible, possible improvement with timing layers under study



the NA60+ timeline

2022 LOI	2024 Technical proposal	2026-2028 Construction	2029-2036 Data taking

- Project is part of CERN Physics Beyond Collider Initiative
- LOI released at the end of 2022 (arXiv:2212.14452)
- Expect proposal in 2024
- Aim is taking data in 2029, after LHC LS3
  - 7-years running with Pb beam (one beam energy per year)
  - proton beams for reference and dedicated p-A studies

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

the NA60+ collaboration

Letter of Intent: the NA60+ experiment

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18 .Institut de Physique des 2 Infinis de Lyon, Université de Lyon, CNRS/IN2P3, Lyon, France

- the LoI was signed by 62 physicists, engineers, technicians
- support also from members of the QGP theory community

- funding for the R&D phase since 2020 allowed us to complete the LoI preparation
- ongoing contacts to strengthen the Collaboration

conclusions

Precision studies of **em and hard probes** in the range $6 < \sqrt{s_{NN}} < 17$ GeV are currently lacking

NA60+: new heavy-ion experiment proposed at CERN SPS

- designed for high precision measurements of thermal dileptons, charmonium, open-heavy flavors

- project is part of CERN Physics Beyond Collider Initiative
- technical proposal expected in 2024, data taking in 2029
- present stage: consolidation of collaboration and completion of R&D

Feedback on physics program and participation to the NA60+ realization is welcome!

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

backup slides

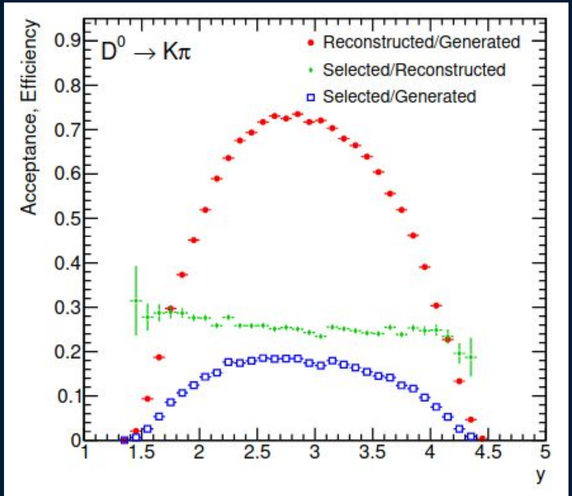
Example: D-mesons performance studies

Fast simulation:

1 D-meson: signal simulated with p_T and y distributions from POWHEG-BOX + PYTHIA
Combinatorial background: π, K, p with multiplicity, p_T and y shapes from NA49

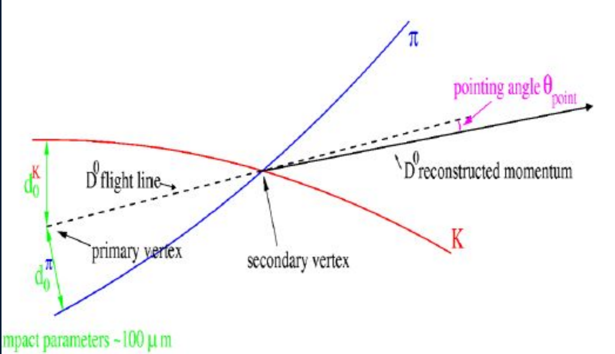
2 Particle transport: carried out in the VT, with parametrized simulation of its resolution
Track reconstruction: Kalman filter

3 D-meson vertex reconstructed from decay tracks
Geometrical selections based on decay vertex topology

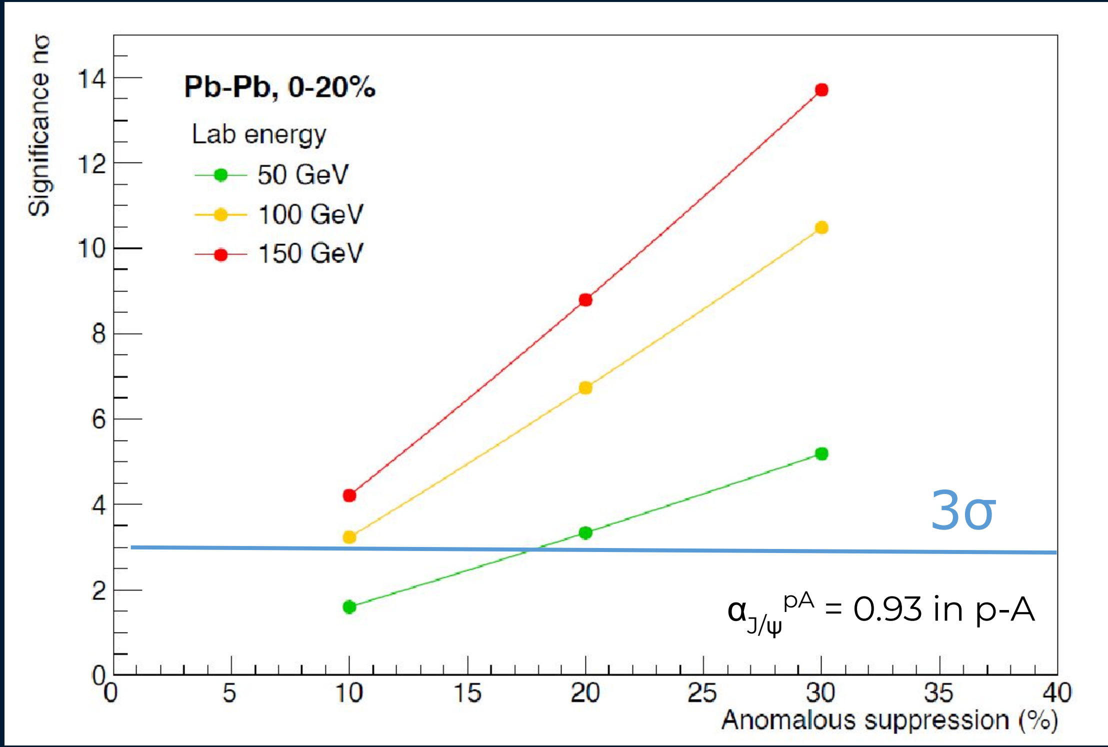


D^0 in central PbPb:

- initial S/B ~10^{-7}
- after selections S/B ~0.5



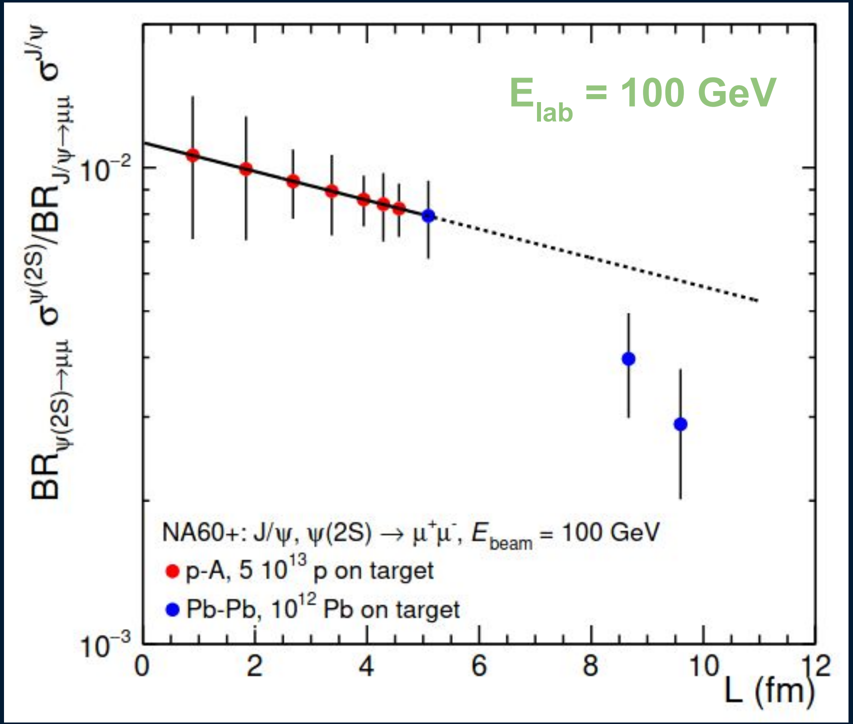
charmonium R_{AA}



- 10% anomalous suppression signal detectable at 3σ for E_{lab}>100 AGeV
- 20% anomalous suppression signal detectable at 3σ for E_{lab}>50 GeV

ψ(2S) in pA+AA

Good charmonium resolution (30 MeV for J/ψ) will help ψ(2S) measurements:



Assume

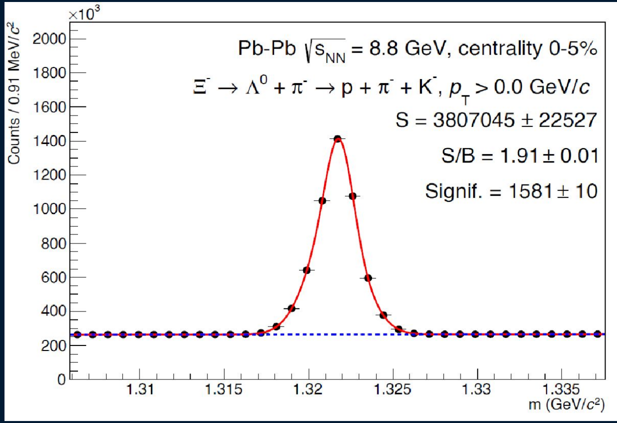
- stronger suppression for ψ(2S) than J/ψ

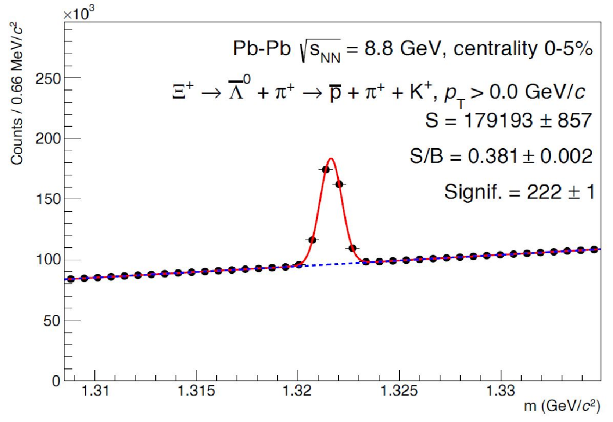
⬇

ψ(2S)/ψ measurement feasible down to E_{lab} ~ 100 GeV

Lower E_{lab} would require larger beam intensities/longer running times

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

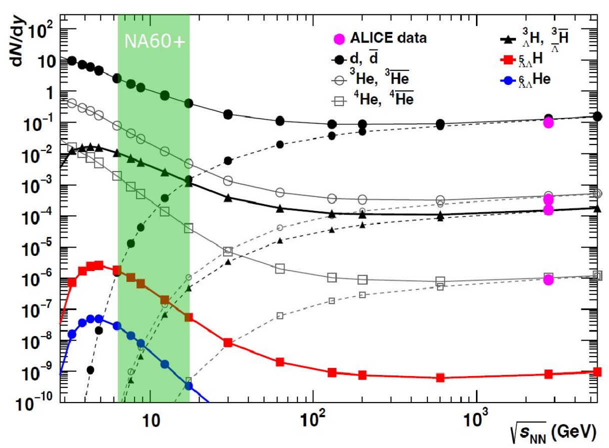
$\Lambda^0 \rightarrow p + \pi^-$ $\quad \Xi^- \rightarrow \Lambda^0 + \pi^-$ $\quad \Omega^- \rightarrow \Lambda^0 + K^-$

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 approach between the decay track
  - ❑ Decay length and the cosine of the pointing angle

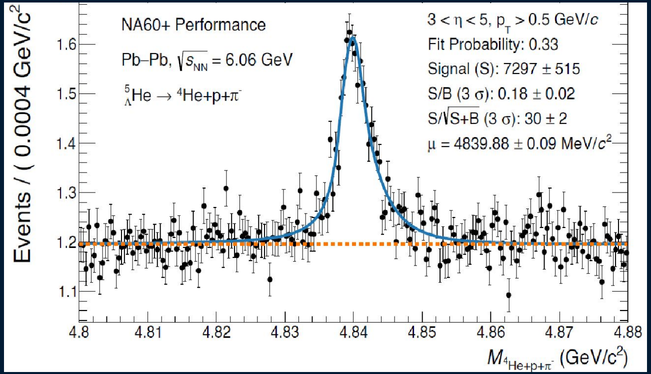
- ❑ Also ϕ □ KK and K_s □ ππ were studied

hyperons



Low energy HI collisions

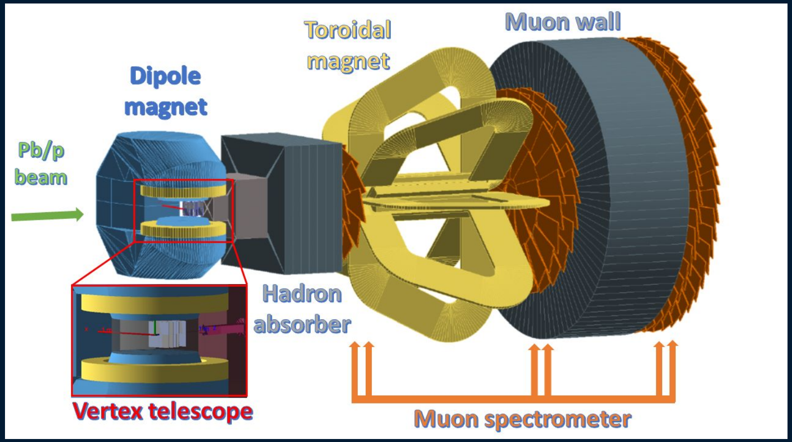
- **high baryon density** favours the production of hypernuclear clusters

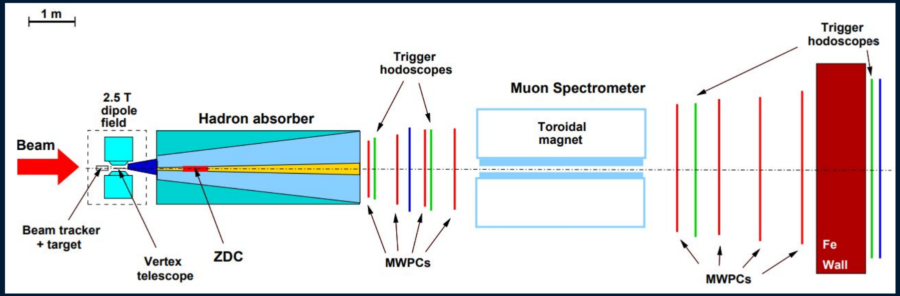


Separation of heavily ionising particles from ordinary hadrons

- **size of the clusters** associated with the track

NA60+ vs NA60





Some important improvements:

Physics program extended to lower energy

- Fundamental to explore rare probes in high-μ_B region

Larger angular acceptance

- cope with lab rapidity shift when varying energy down to low SPS energy

Access new observables (open charm etc.)

NA60: (di)muon trigger ~ 5 kHz
NA60+: MB trigger (>100 kHz)

State-of-the art detectors

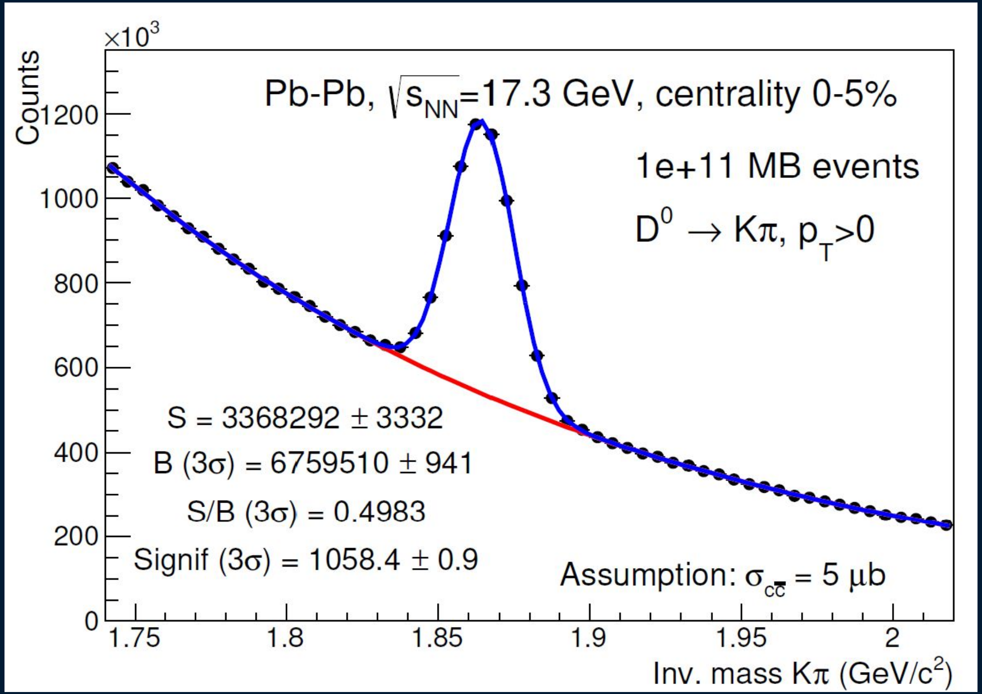
Pixel size: from 50x425 μm^2(NA60) to 30x30 μm^2(NA60+
sensors (from 2% to 0.1% X_0)
improved resolution and signal over background
from 21 to 8 MeV at the ω mass
from 70 to 30 MeV at the J/ψ mass

NA60+ vs NA61

NA61

Year	Beam	#days	#events	#($D^0 + \overline{D^0}$)	#($D^+ + D^-$)
2022	Pb at 150*A* GeV/*c*	42	250M	38k	23k
2023	Pb at 150*A* GeV/*c*	42	250M	38k	23k
2024	Pb at 40*A* GeV/*c*	42	250M	3.6k	2.1k

NA60+



N.B.: different assumptions for open charm cross section