Prospects for open heavy-flavour and quarkonium measurements with NA60+

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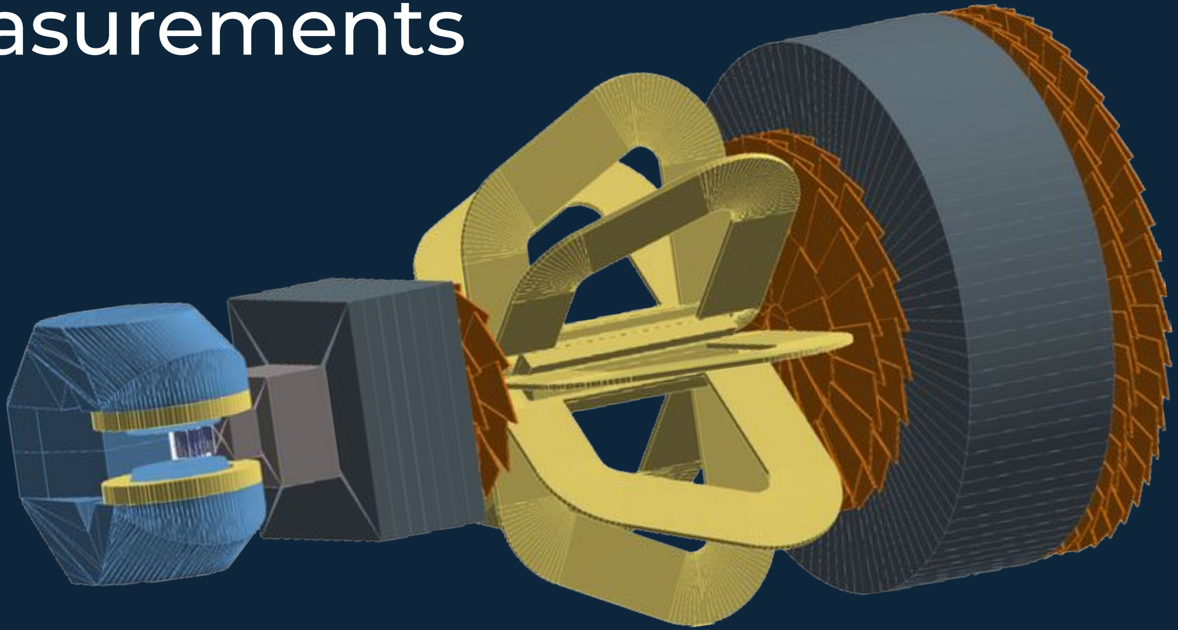
on behalf of the
NA60+ Collaboration



SQM2024

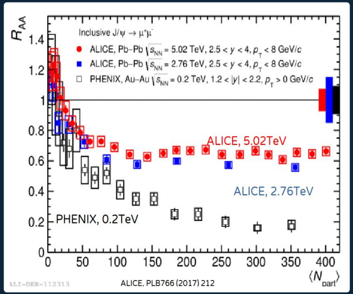
The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

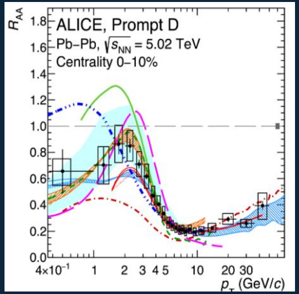
Open and hidden charm: from LHC to SPS

Open charm and quarkonia in nuclear collisions → probes of QGP

high energy: RHIC / LHC

Extensively measured
→ unprecedented insight on QGP properties at low μ_B





low energy: fixed target

open charm

very few results

- indirect open charm measurement by NA60 with 20% uncertainty ($1 < M_{\mu\mu} < 2.5$ GeV/c^2)
- upper limit on D^0 by NA49
- new NA61 result (Xe-La, $\sqrt{s_{NN}}$ = 16.8 GeV)

quarkonium

many results for J/ψ, ψ(2S) by NA50/60, but only at top SPS energy

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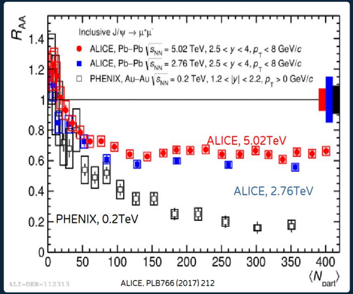

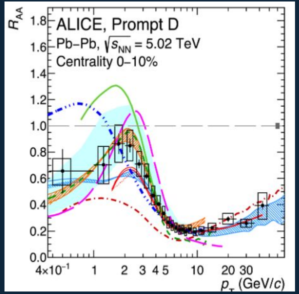

low energy: fixed target

NEW high precision open and hidden charm measurements would allow to

1) probe the medium at lower T wrt collider experiments
2) explore a non-zero μ_B region

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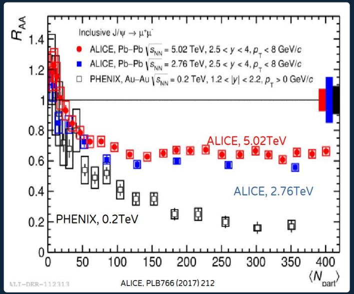

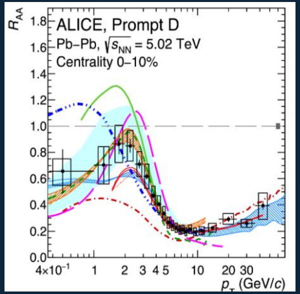

low energy: fixed target

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1) probe the medium at lower T wrt collider experiments
2) explore a non-zero μ_B region

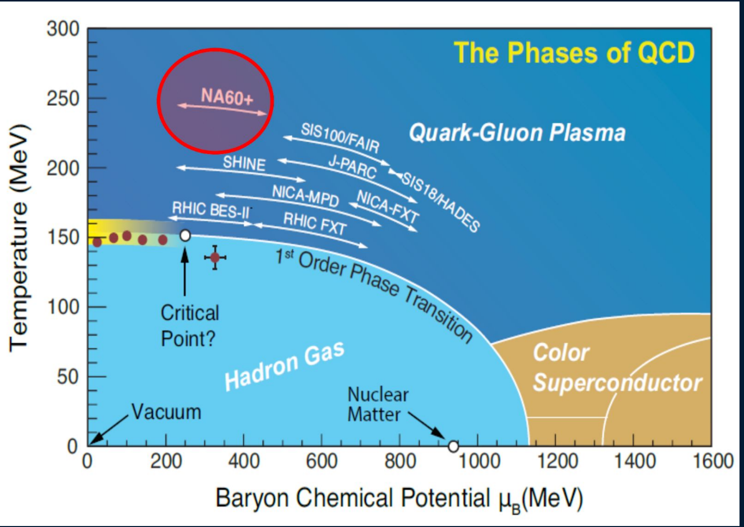
→ new experiment proposed at CERN SPS: **NA60+**

Sabyasachi Siddhanta, Tue June 4th
Piotr Podlaski, Fri June 7th

The NA60+ experiment at CERN SPS

NA60+ will explore the QCD phase diagram at high baryon chemical potential

- performing precision studies of hard and electromagnetic processes accessing
  - muon pair production from threshold up to $m_{\mu\mu} \sim 4$ GeV/c^2 (dilepton continuum, low mass resonances, quarkonia)
  - hadronic decays of strange and charm hadrons, hypernuclei



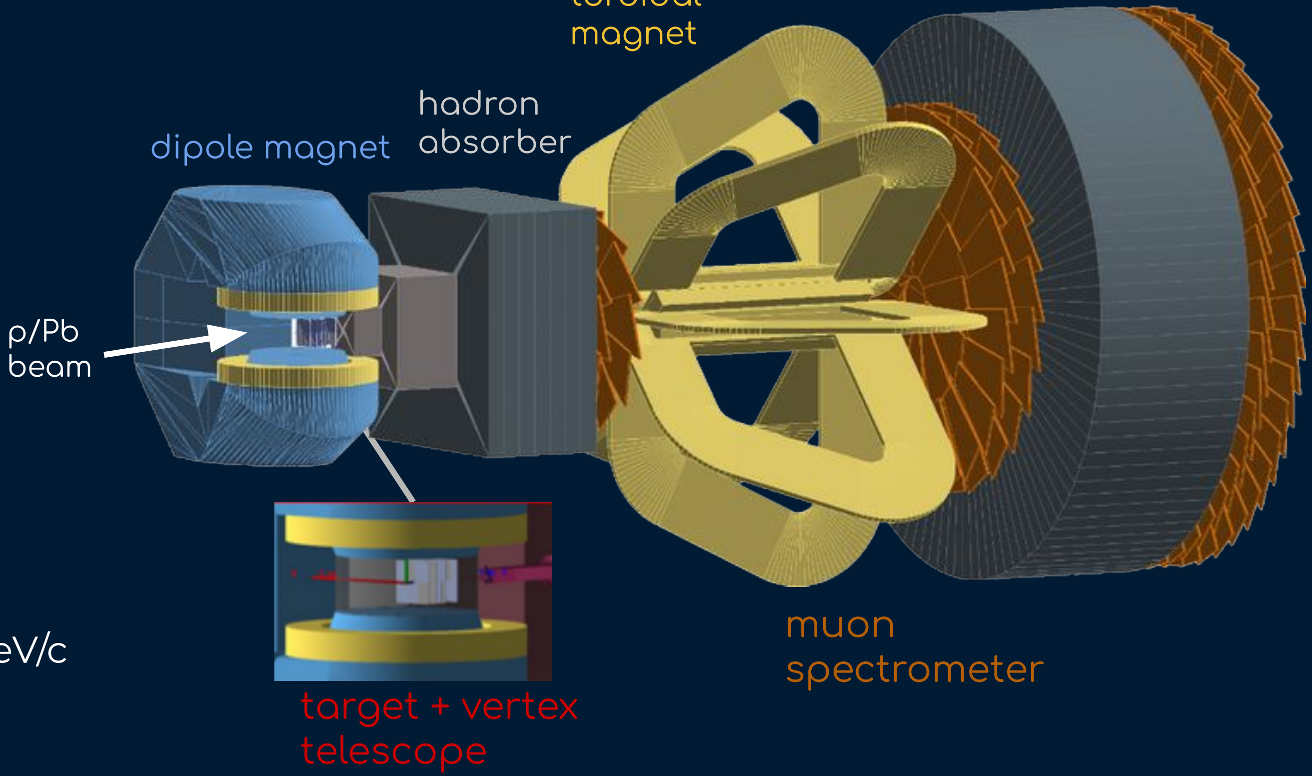
- via a beam energy scan between $\sqrt{s_{NN}} \sim 6$ - 17 GeV, exploring the μ_B range ~220 - 550 MeV

- exploiting large luminosities, needed for rare QGP probes studies
  - PbPb interactions rates > 10^5 Hz, reachable with 10^6 Pb/s in a fixed target environment

The NA60+ setup

Setup

- Muon spectrometer
- Vertex spectrometer



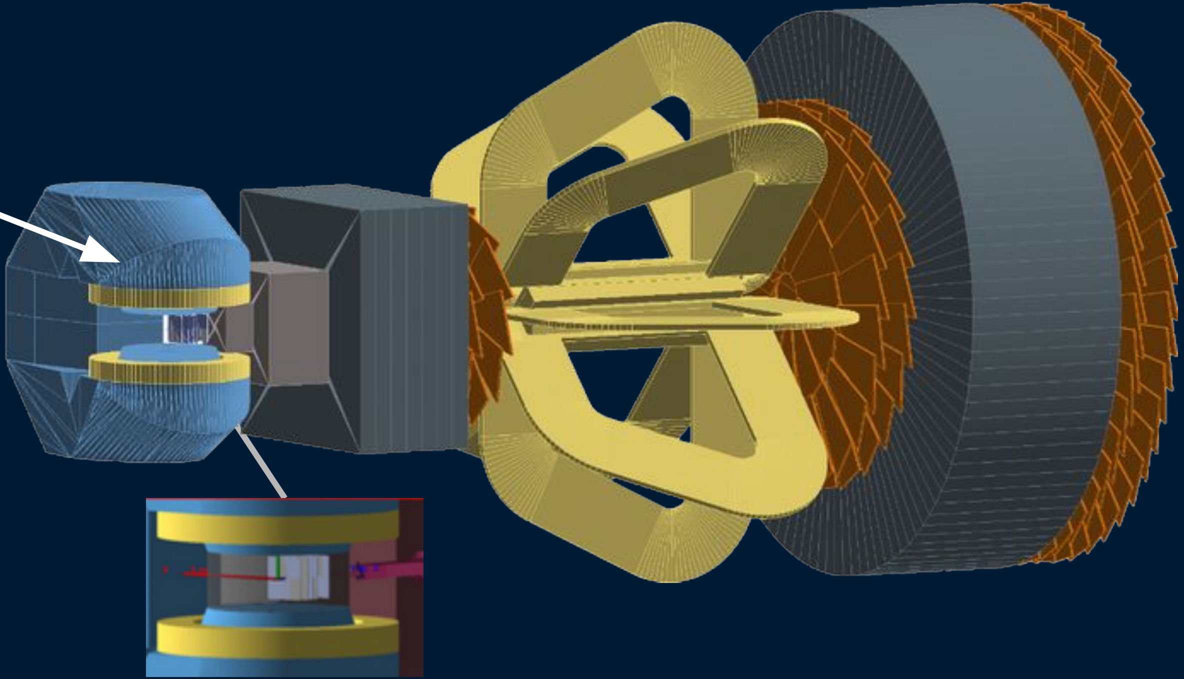
Energy/ systems

- 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 NA60+ setup

Dipole magnet:

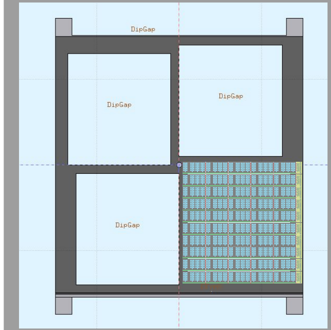
MEP48 (available at CERN), 1.5 T field over 400 mm gap

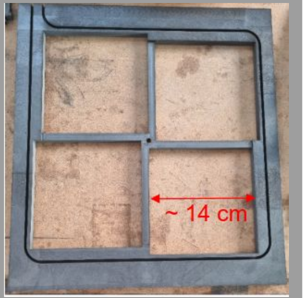


The NA60+ setup

Vertex spectrometer

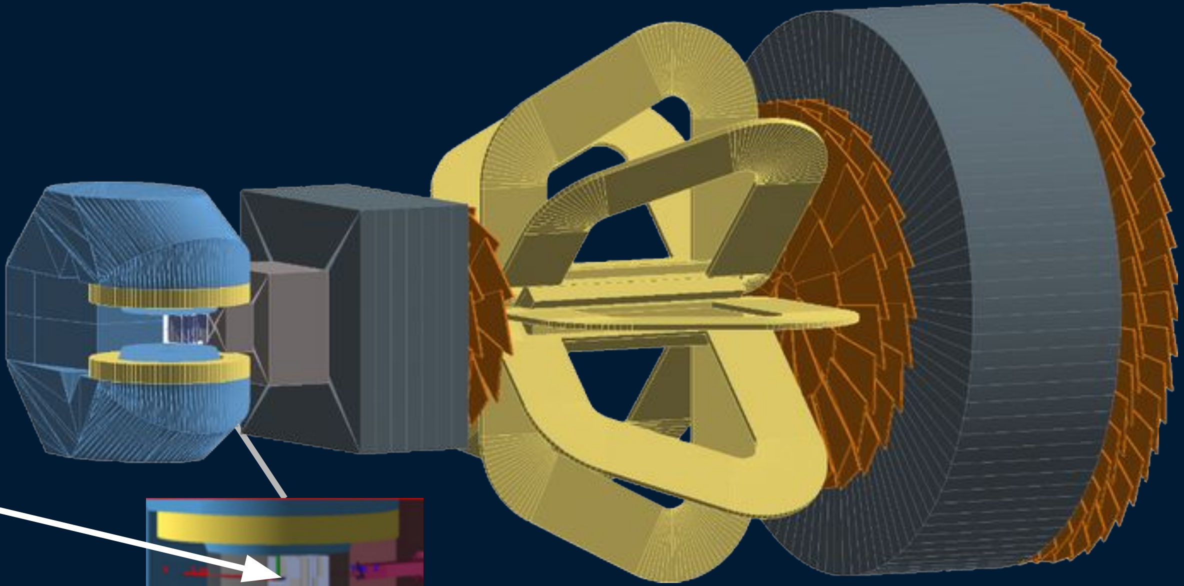
5 layers of MAPS detectors

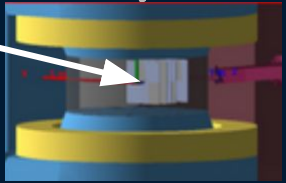




sensor based on 25 mm long units, replicated several times through stitching up to 15 cm length

synergy with ALICE ITS3 → first large area stitched sensor (MOSS) currently being tested

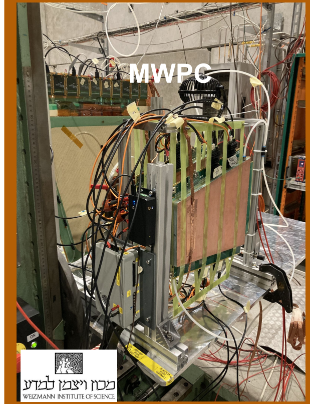


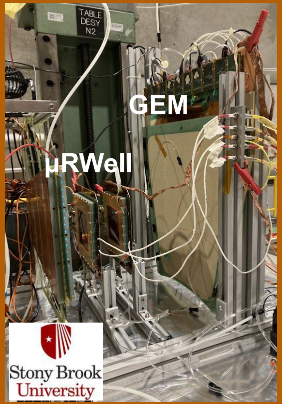


The NA60+ setup

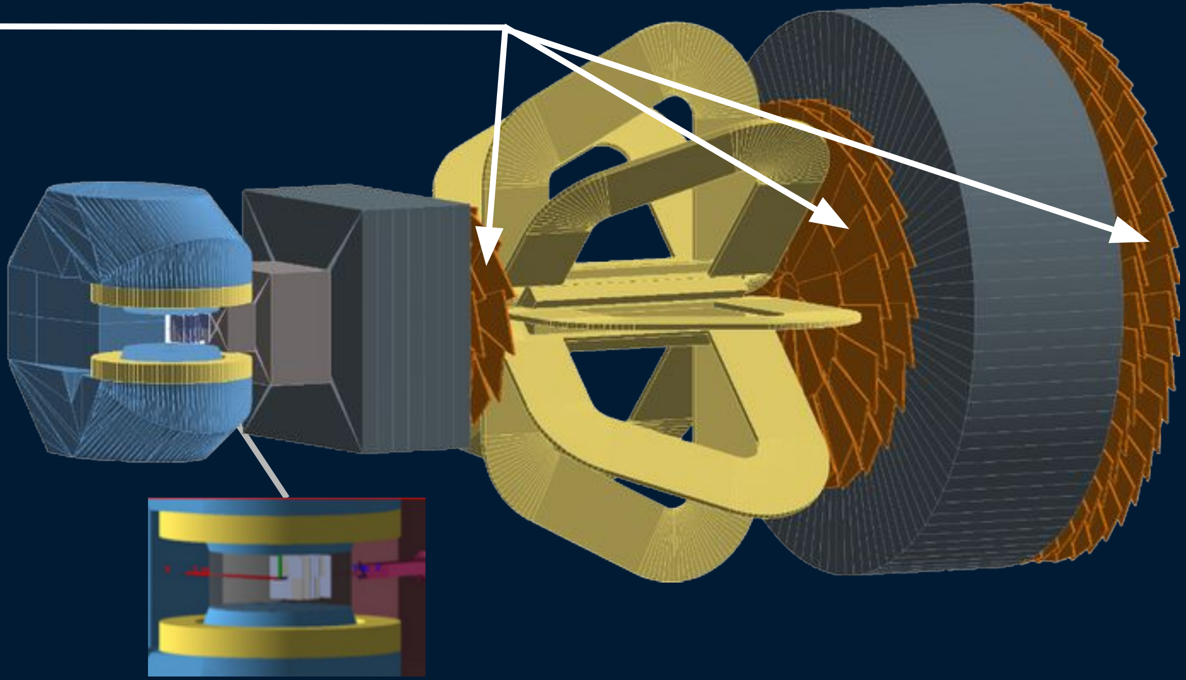
Muon spectrometer
position will be varied (rails), to cover mid-y at different √s

GEM or MWPC can match the expected rates (2 kHz/cm^2)





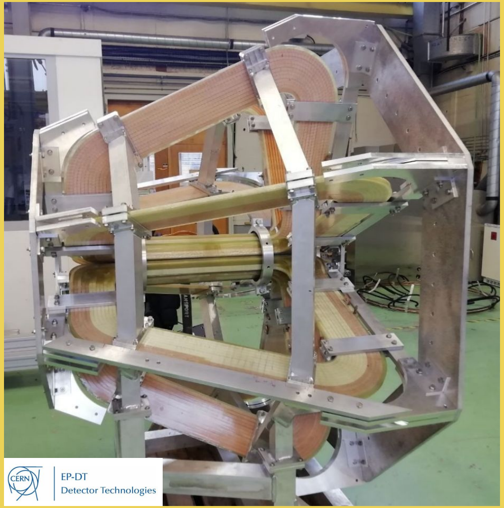
First prototypes characterised in Fall 23



The NA60+ setup

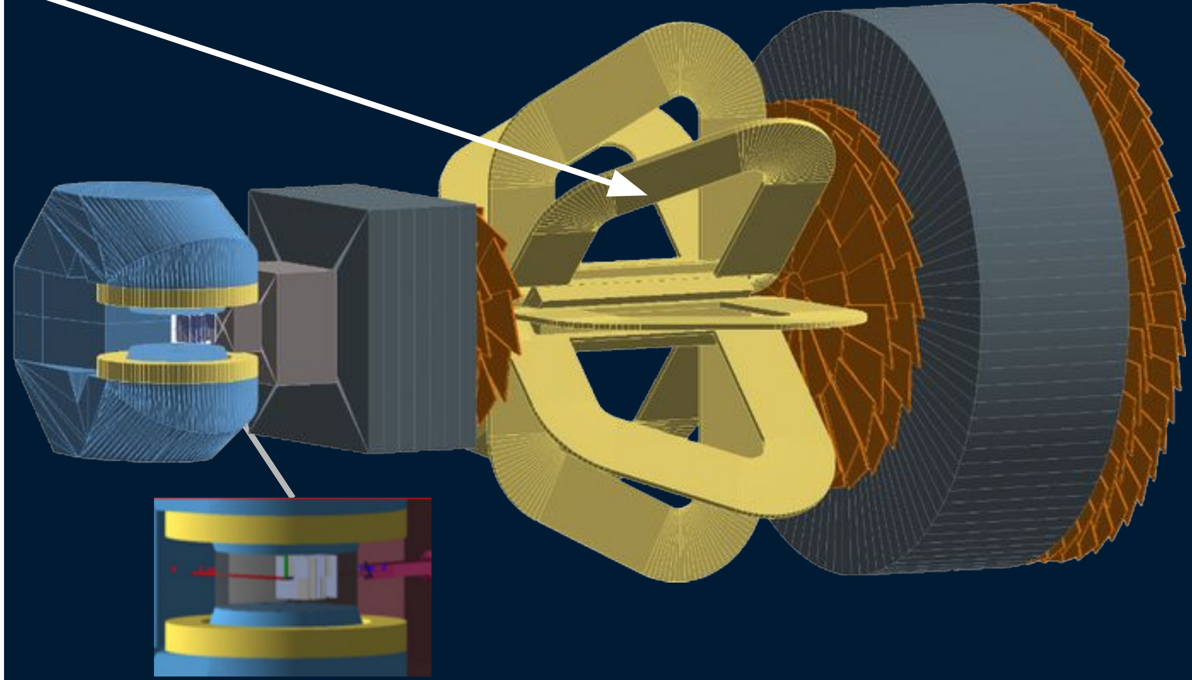
Warm toroid

- Eight sectors with 36 turns per coil
- Light design → **low material budget** in the acceptance area



Prototype (1:5 scale)

Prototype (1:5 scale) built and tested to check calculations and investigate mechanical solutions



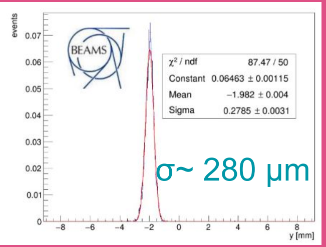
The NA60+ setup

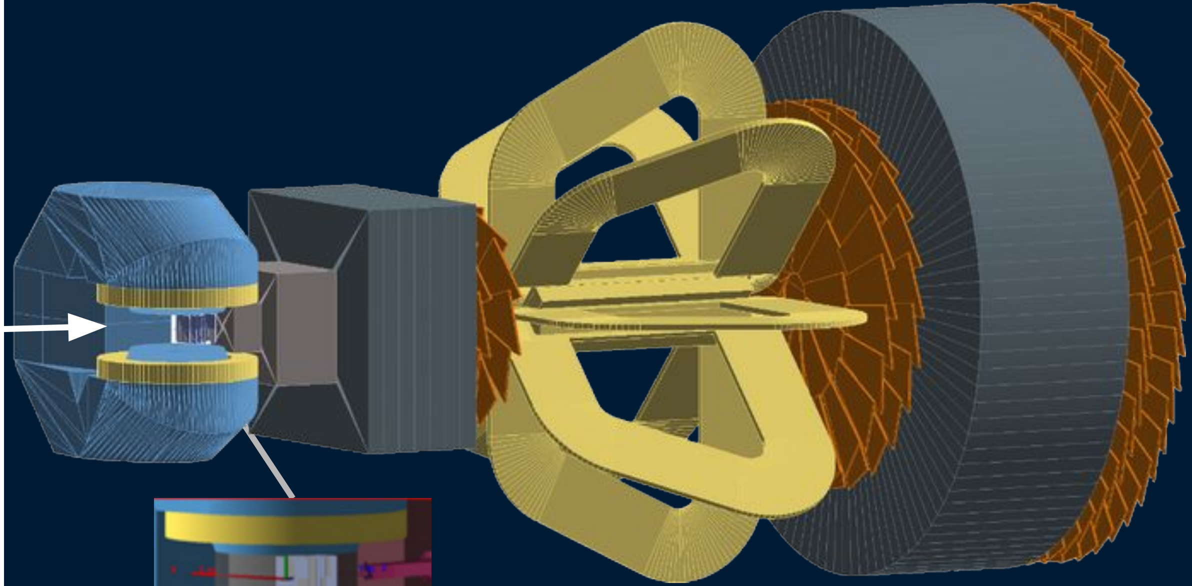
Beam studies

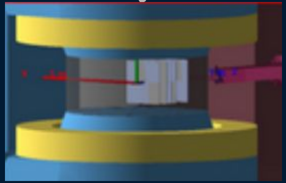
NA60+ will be installed in the CERN EHN1 - PPE138 area along the H8 beam line

very stringent beam requests at all energies

- high-intensity (10^7 Pb/spill)
- extremely focussed sub-mm beam (vertex spectrometer will have 6 mm hole)
- beam optics studies ongoing (up to 2.4 10^6 Pb/spill at 150 GeV)





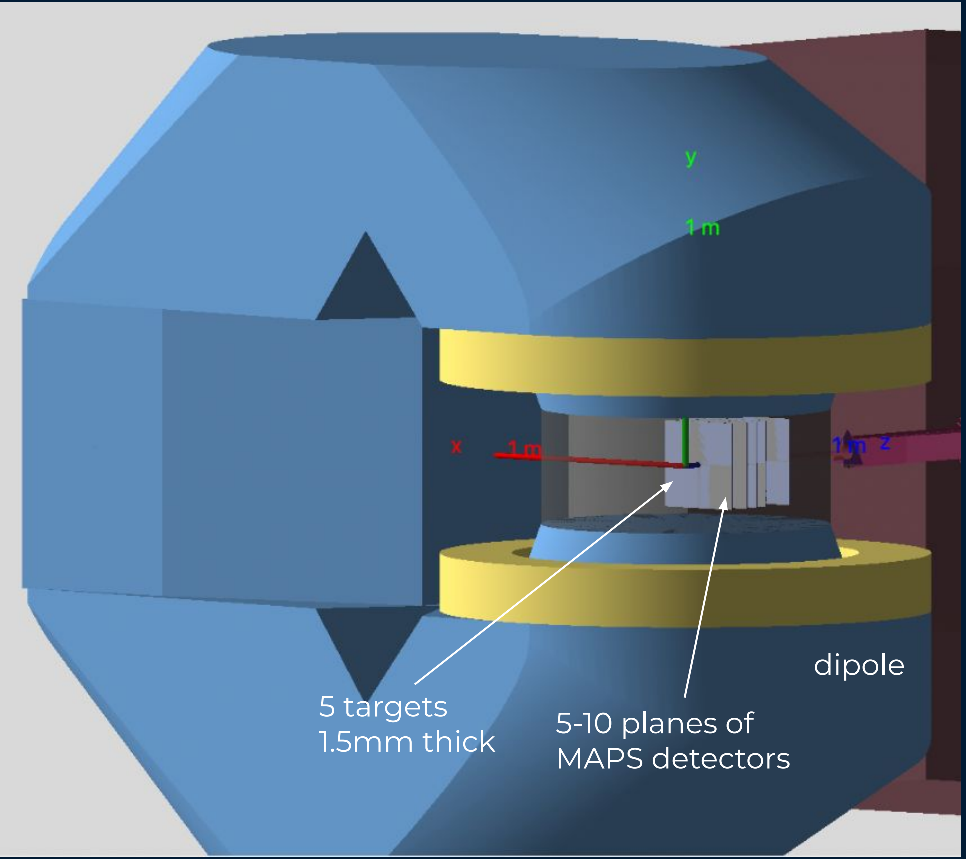


How to measure open charm in NA60+

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



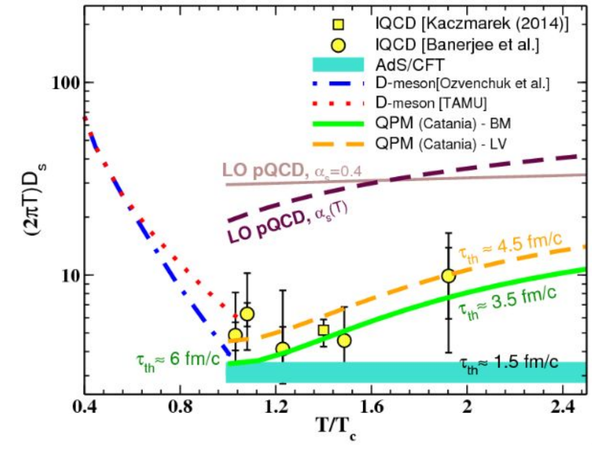
Open charm in AA at low √s

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

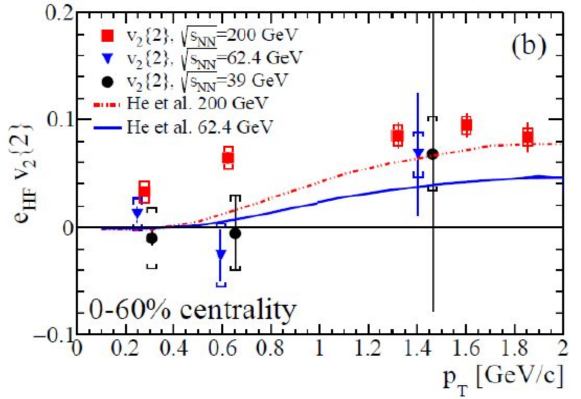


F. Scardina et al. PRC96, 2017 (044905)

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



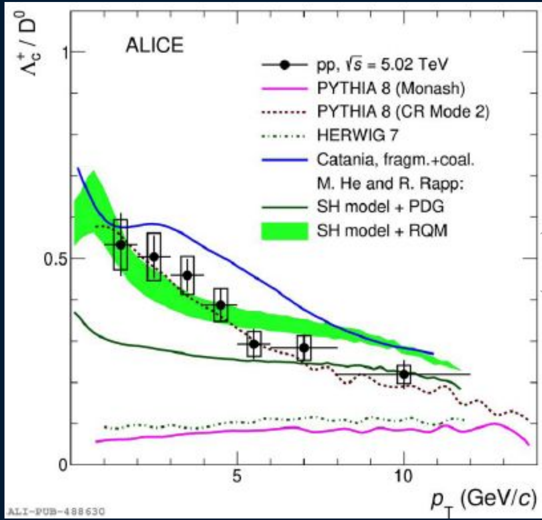
STAR, PRC95 (2017) 034907

Open charm in AA at low $\sqrt{s}$

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

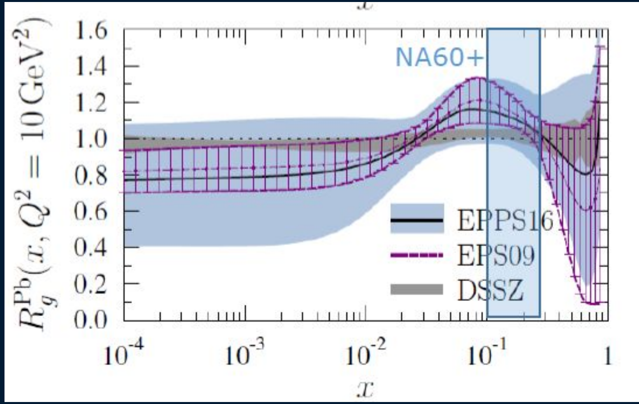
5 **nuclear PDFs via D meson production in pA**

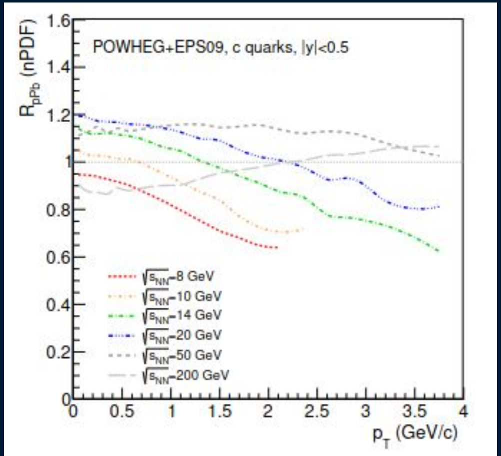
NA60+ will cover $0.1 < x_{Bj} < 0.3$ at $Q^2 \sim 10\text{-}40\ GeV^2$

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

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





D mesons performance studies

Fast simulation:

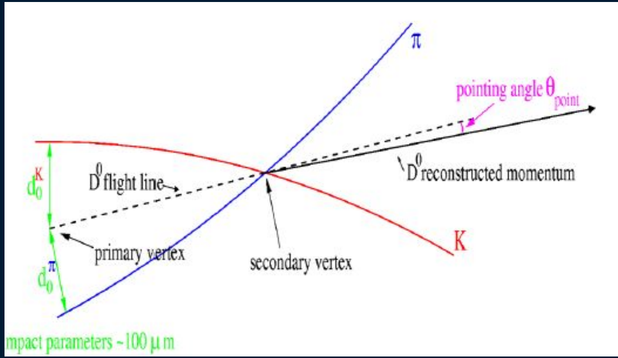
1. D-meson: signal simulated with p_T and y distributions from POWHEG-BOX + PYTHIA
Combinatorial background: π, K, p with multiplicity, p_T and y shapes from NA49

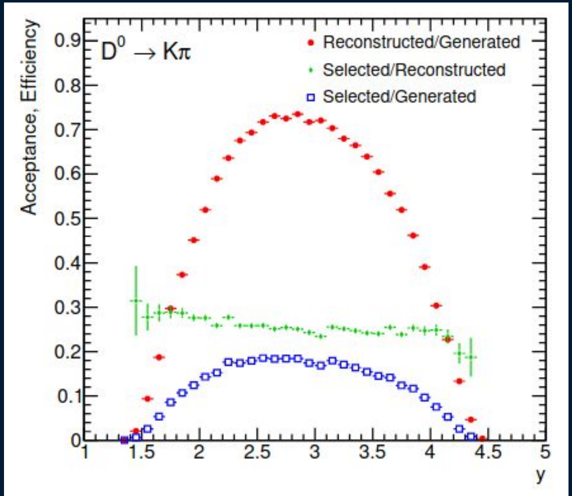
2. Particle transport: carried out in the VT, with parametrized simulation of its resolution
Track reconstruction: Kalman filter

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





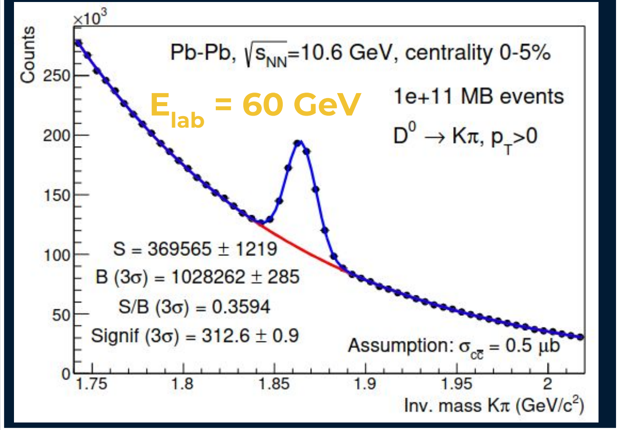
Charm hadrons performance studies

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

$D^0 \rightarrow K\pi$

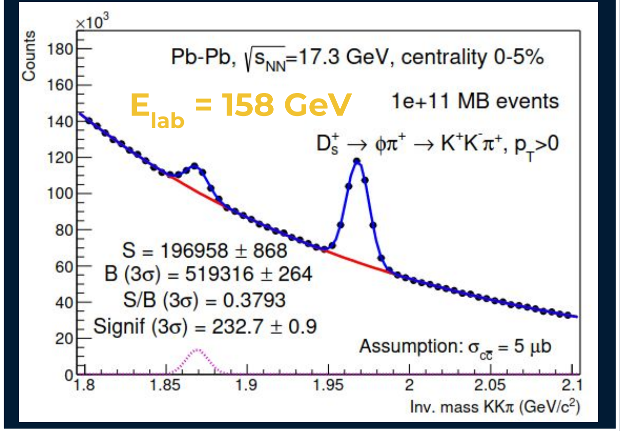
3 10^6 D^0, 0-5% PbPb, $\sqrt{s_{NN}}$=17.3 GeV
→ R_{AA} and v_2 vs p_T, y and centrality

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



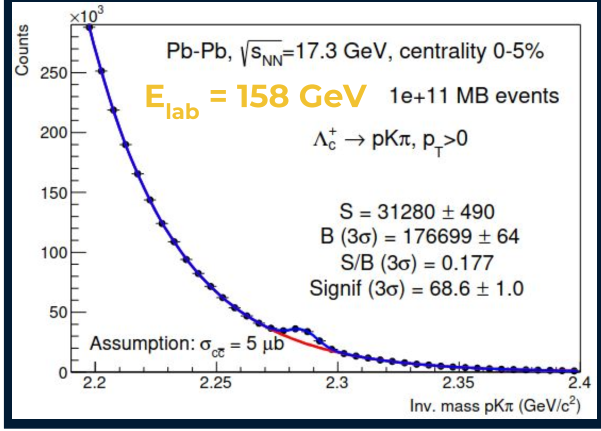
$D_s \rightarrow \phi\pi \rightarrow KK\pi$

measurement of yields feasible, statistical precision of few percent



$\Lambda_c \rightarrow pK\pi$

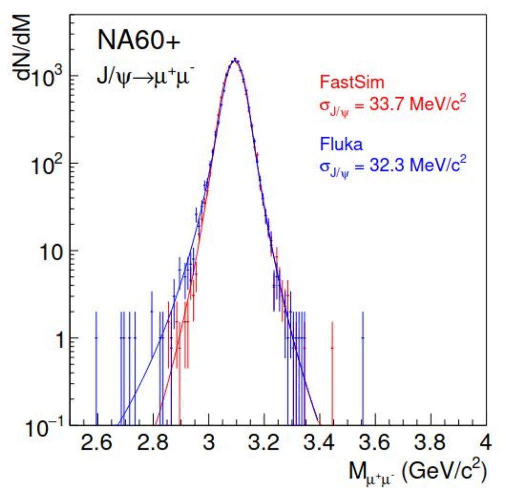
accessible, possible improvement with timing layers under study

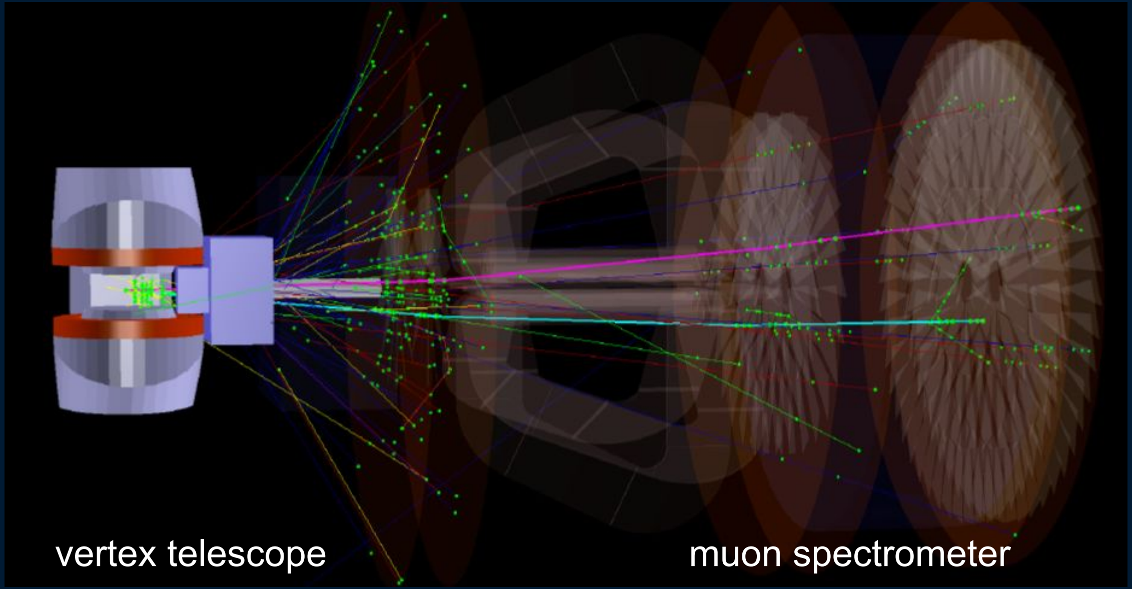


How to measure quarkonium in NA60+

Charmonium production studied via

- J/ψ and $\psi(2S)$ in the $\mu^+\mu^-$ decay channel
- $\chi_c \rightarrow J/\psi\ \gamma$, with γ measured via conversion in a lepton pair in the vertex telescope





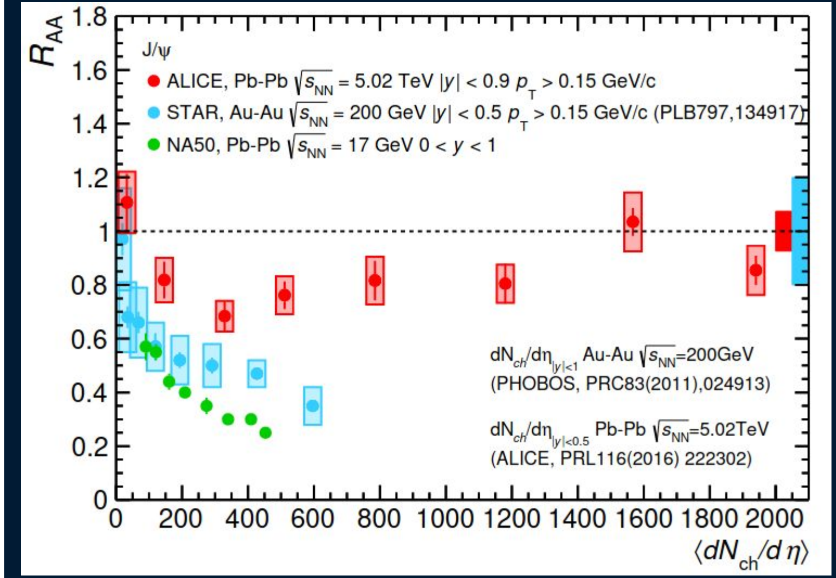
Muon tracks obtained matching tracks in vertex and muon spectrometer

→ very good mass resolution, ~30 MeV for the J/ψ

Quarkonium: high vs low √s

Different hot and cold nuclear effects at play:

RHIC / LHC	SPS
Hot matter effects suppression and regeneration	**Hot matter effects** suppression
Initial state effects mainly shadowing $10^{-5} < x_{BJ} < 10^{-2}$ for $-3 < y < 3$	**Initial state effects** (anti)shadowing $x_{BJ} \sim 10^{-1}$ for $y \sim 0$
Final CNM effects negligible, due to short crossing time $\tau = L/(\beta_z \gamma)$ $\sim 7\ 10^{-5}$ ($y\sim3$) - $4\ 10^{-2}$ ($y\sim-3$) fm/c	**Final CNM effects** sizable breakup in nuclear matter $\tau \sim 0.5$ fm/c for $y \sim 0$



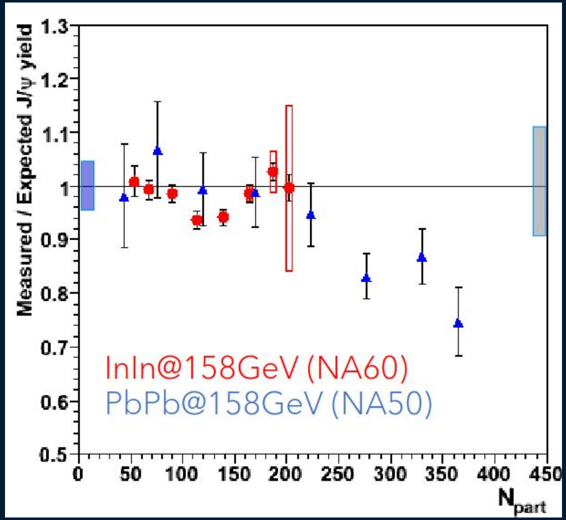
ALICE, arXiv:2211.04384

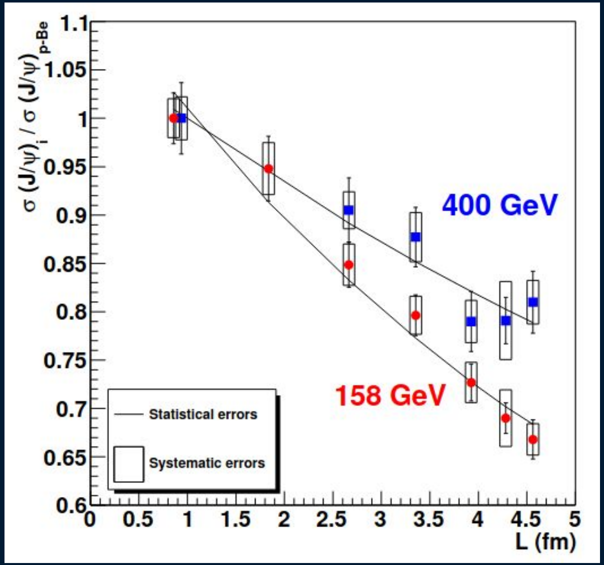
Quarkonium in pA and AA at low $\sqrt{s}$

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





pA:

precise measurement of CNM

- anti-shadowing contribution
- nuclear break-up dominant, stronger at lower $\sqrt{s}$

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...)

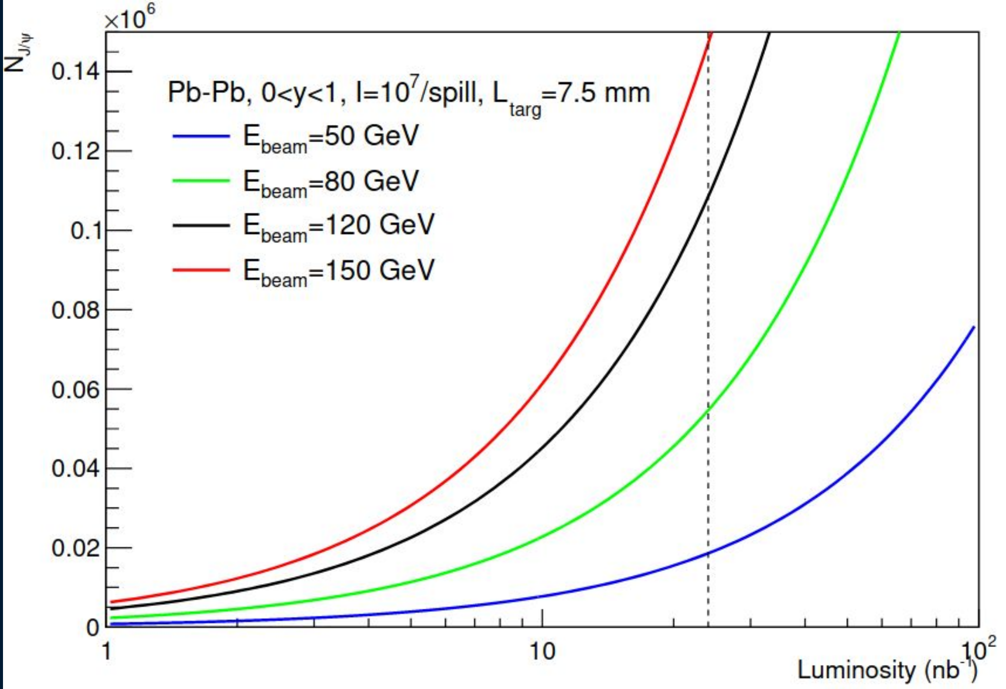
3 **pA: intrinsic charm**

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)

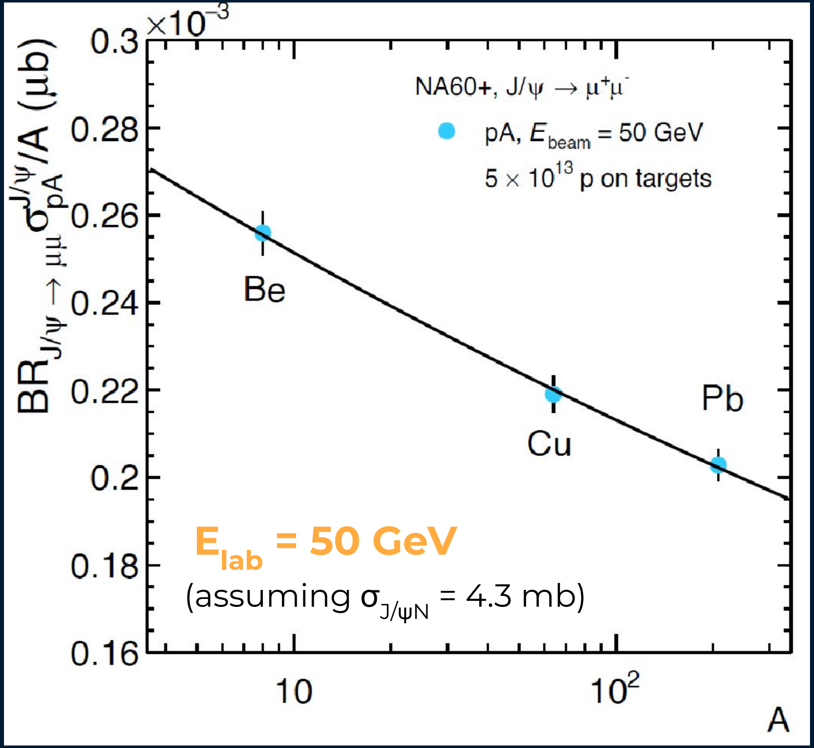
⇩

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:

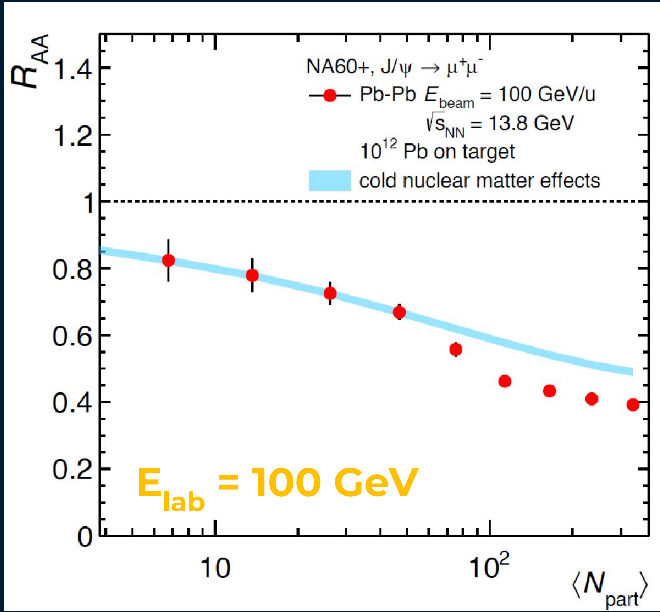
- I_{beam}~5 10^{13} p on target, target thickness 8.3 g/cm2

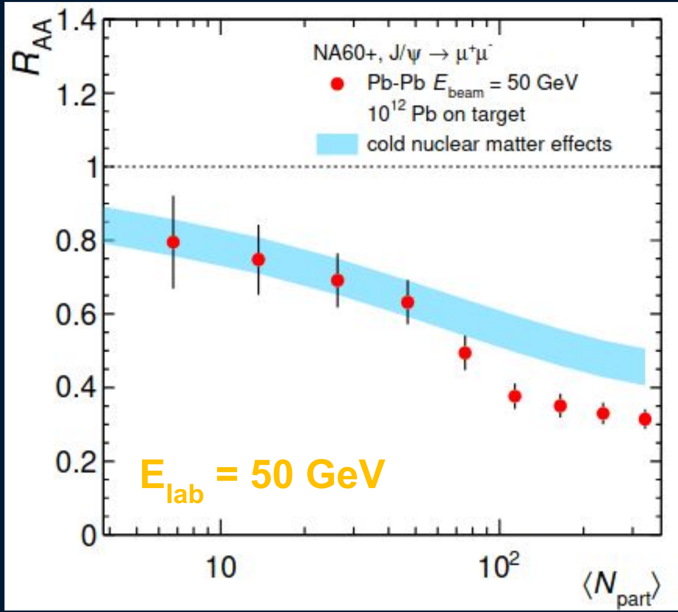
- NA60+ can aim at

  ~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

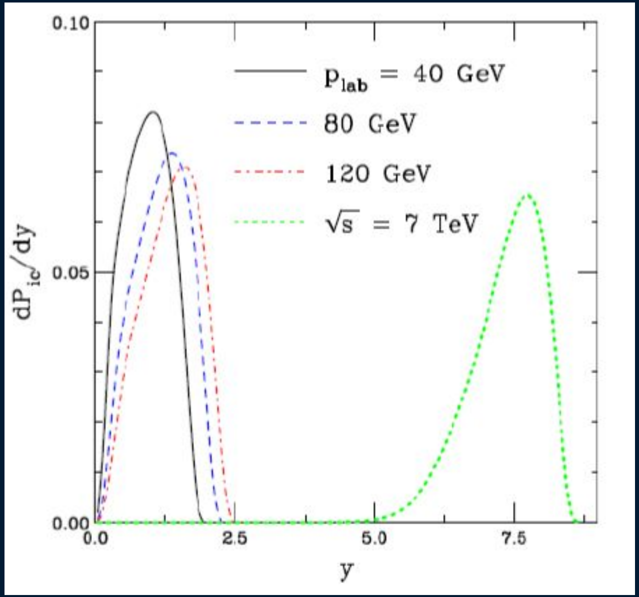
Precise evaluation of anomalous suppression within reach even at low energy

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

Intrinsic charm

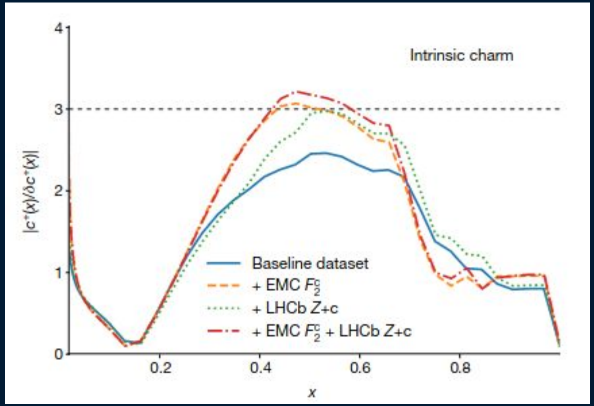
Intrinsic charm component of the hadron wave function |uudccbar>

enhanced charm production in the forward region



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

- 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))

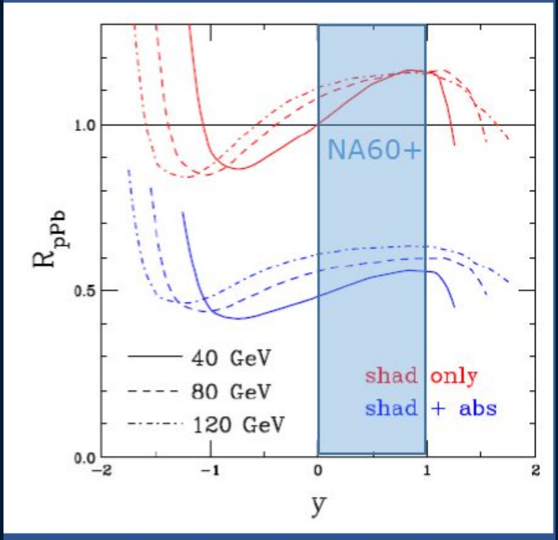


Intrinsic charm

p-Pb collisions:

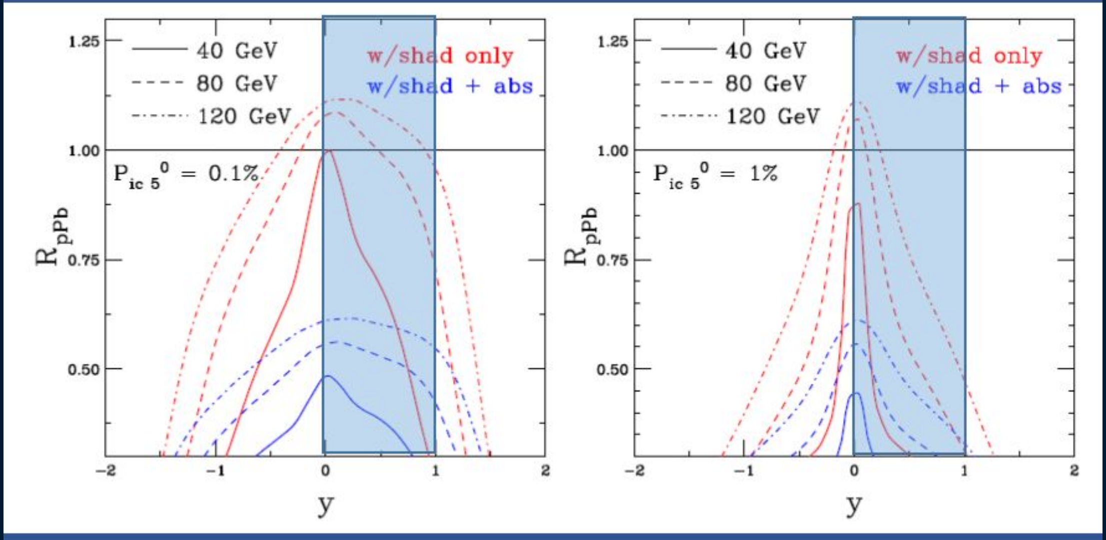
- EPPS16 shadowing
- σ_{abs} = 9, 10, 11 mb, E_{lab} = 120, 80, 40 GeV
- Intrinsic charm content P_{ic} varied between 0.1 and 1%

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%

Timeline of NA60+

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) and discussed with SPSC
- Expect proposal at the end of 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

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- 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

No results, so far, on open charm and charmonia below top SPS energy

Measurements from $\sqrt{s_{NN}}$ ~ 6 - 17 GeV/c extremely relevant to investigate

- QGP transport properties at high μ_B
- charm thermalization and hadronization
- intrinsic charm
- onset of charmonium anomalous suppression, correlation with temperature

NA60+: new experiment proposed at CERN SPS

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

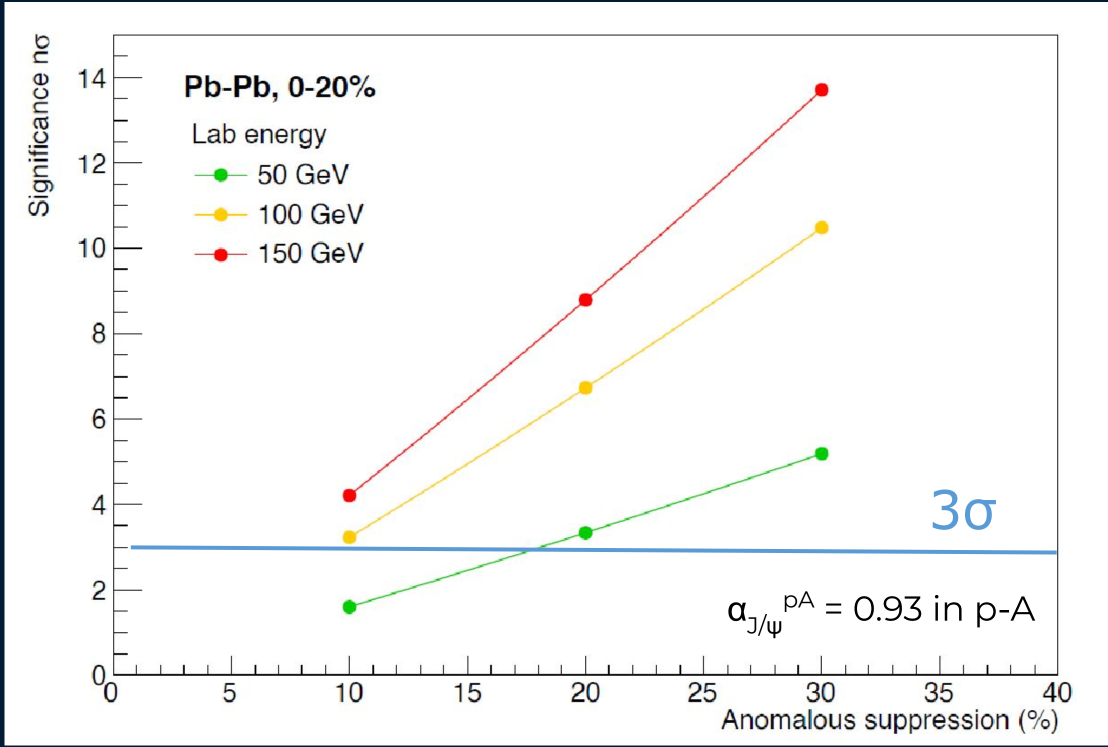
https://na60plus.ca.infn.it/

SQM2024

The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

Backup slides

charmonium R_{AA}



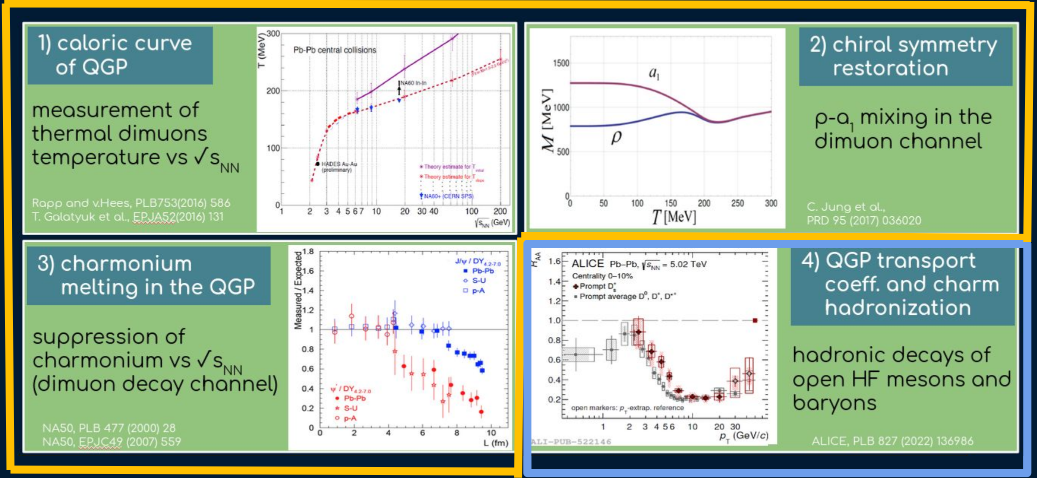
- 10% anomalous suppression signal detectable at 3σ for E_{lab}>100 AGeV
- 20% anomalous suppression signal detectable at 3σ for E_{lab}>50 GeV

Physics performances of NA60+

Collision systems

Forse questa slide
non serve

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



dimuons:

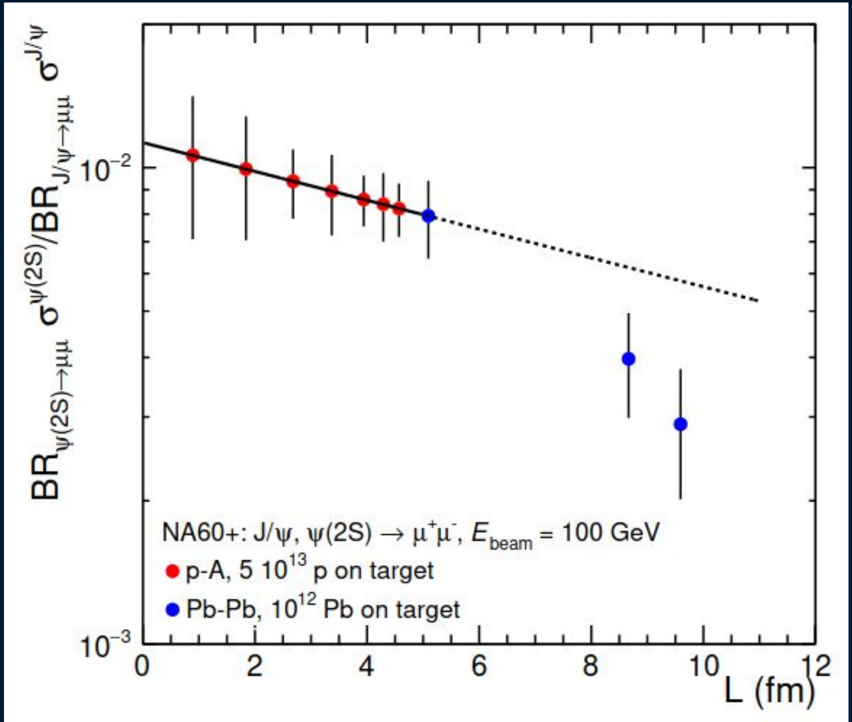
- vertex telescope
- muon spectrometer

charm hadrons

- vertex telescope

ψ(2S) in pA and AA

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



Assume

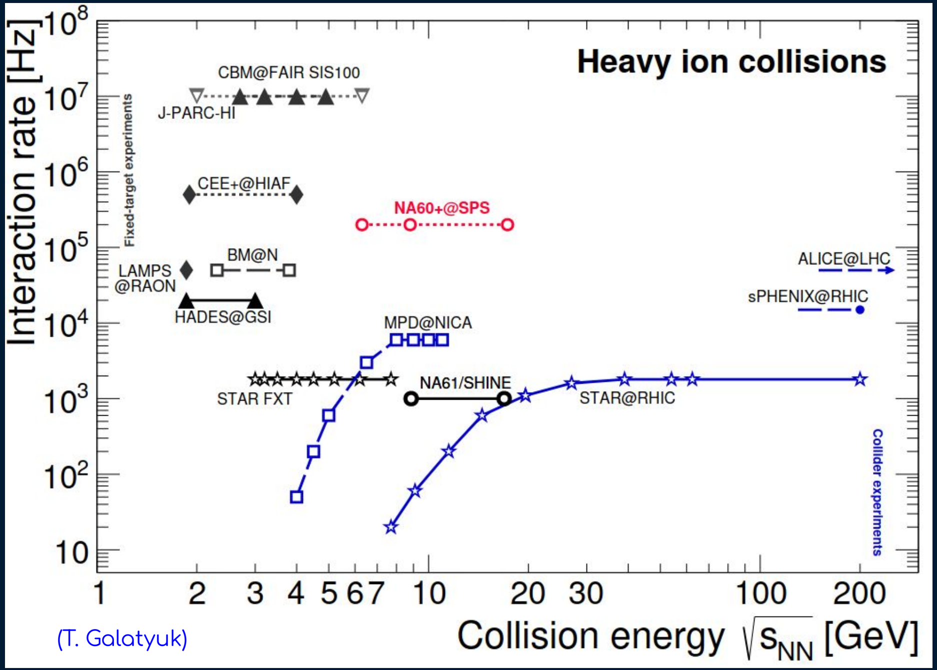
- stronger suppression for ψ(2S) than J/ψ

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

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

Uniqueness of NA60+

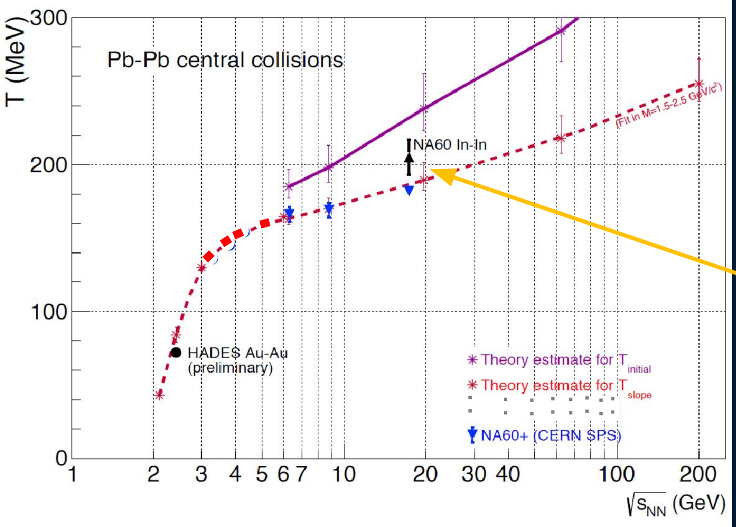
The NA60+ program needs a large luminosity to search for rare QGP probes



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)

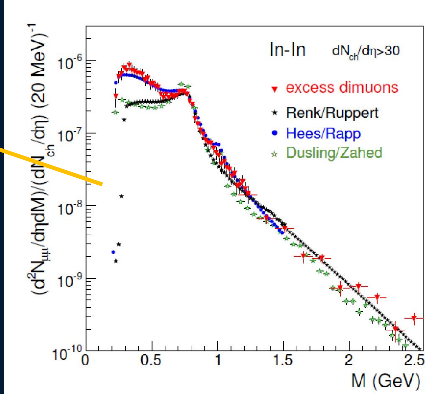
thermal dimuons



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

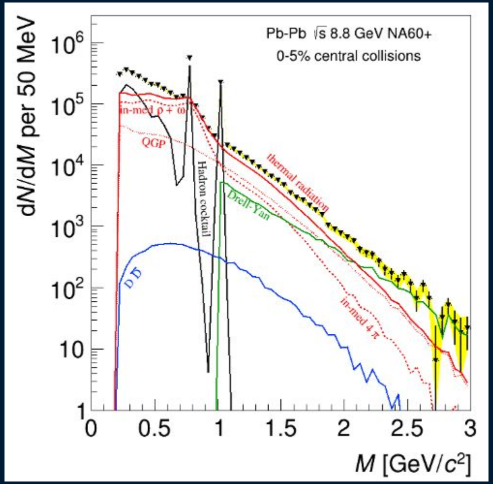
- accessible up to M= 2.5-3GeV/c^2
- dominated by ρ contribution at low mass

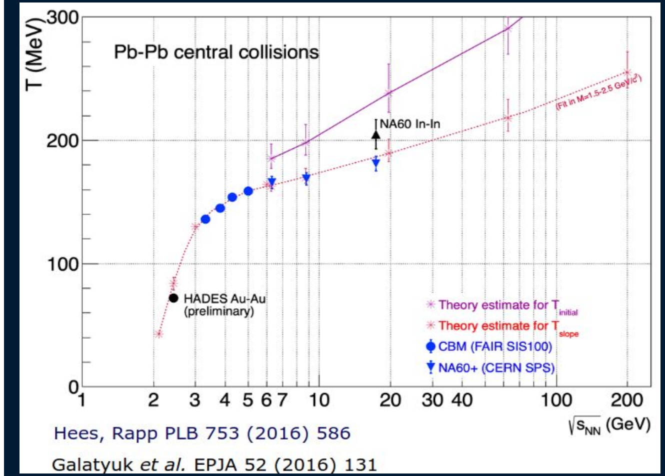
Drell-Yan contribution

- to be estimated via p-A measurements

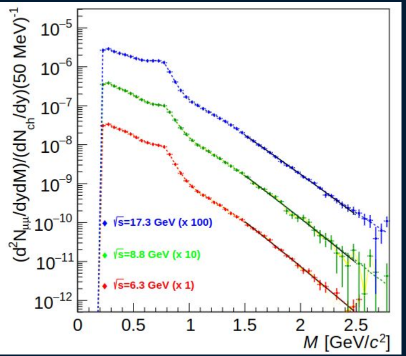
Open charm contribution

- 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

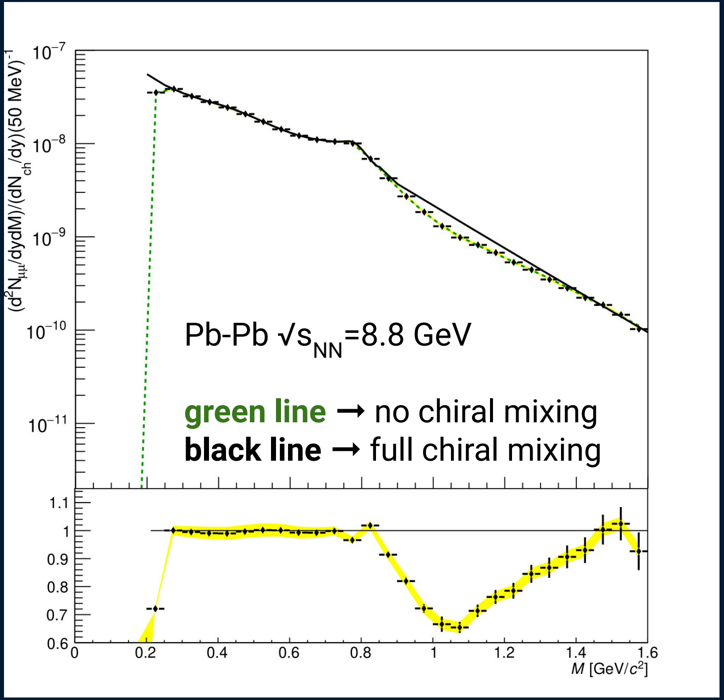
ρ-a_1 mixing in NA60+

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



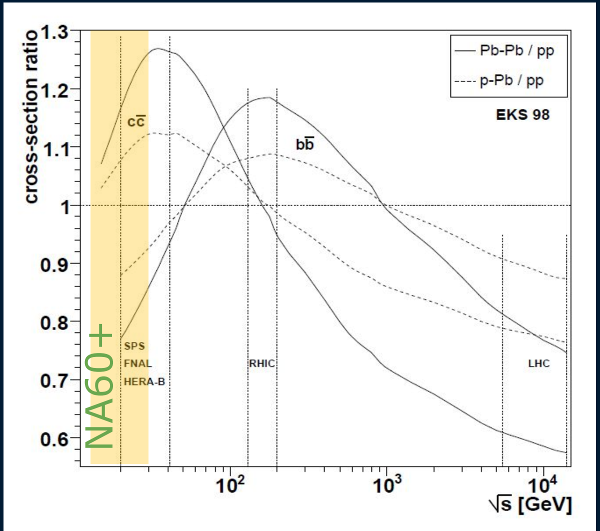
Open charm in pA at low √s

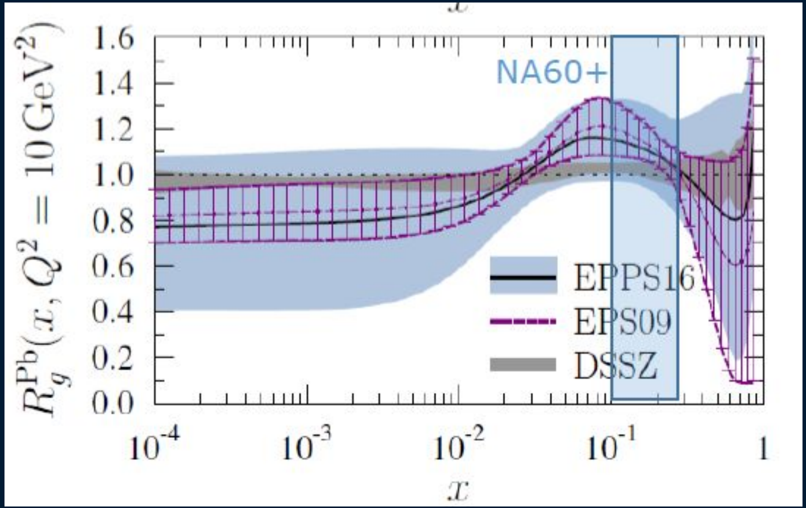
5 **nuclear PDFs via D meson production in pA**

⬇

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 at low $\sqrt{s}$

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 $\sqrt{s}$, vs y and p_T