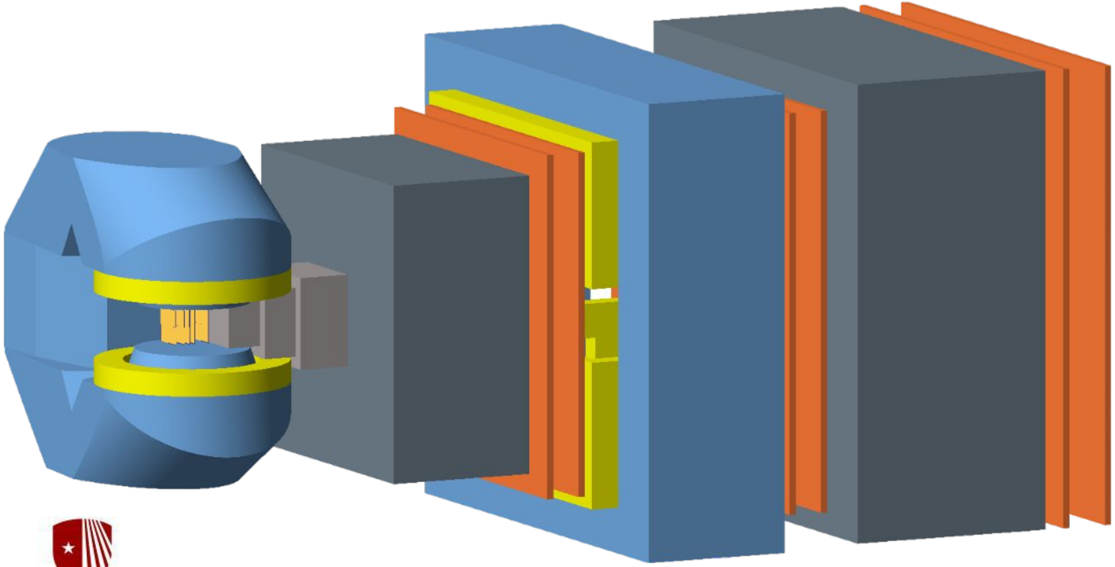
# Prospects for open heavy-flavour and quarkonium measurements with NA60+



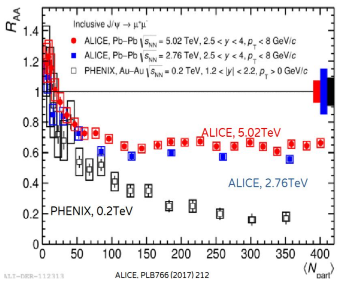
**Giacomo Alocco, University & INFN Torino (Italy)**
**on behalf of the NA60+ Collaboration**

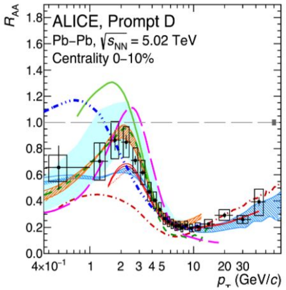
# Open and hidden charm: from LHC to SPS

Open charm and quarkonia in nuclear collisions ➞ probes of QGP

## High energy: RHIC / LHC

Extensively measured ➞ unprecedented insight on QGP properties at low $\mu_B$




## Low energy: fixed target

### Open charm

Very few results *Eur. Phys. J. C59 (2009) 607*

- 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 *Phys. Rev. C73 (2006) 034910*
- Preliminary 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

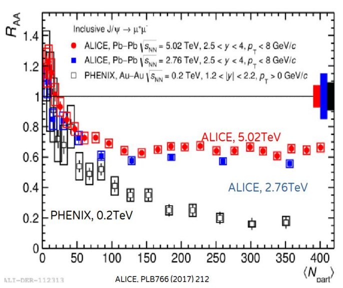
*Eur. Phys. J. C39 (2005) 335*
*Phys. Rev. Lett. 99 (2007)*

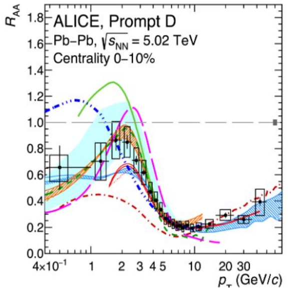
# Open and hidden charm: from LHC to SPS

Open charm and quarkonia in nuclear collisions ➞ probes of QGP

## High energy: RHIC / LHC

Extensively measured ➞ unprecedented insight on QGP properties at low $\mu_B$




## Low energy: fixed target

**NEW high precision** open and hidden charm measurements would allow to:

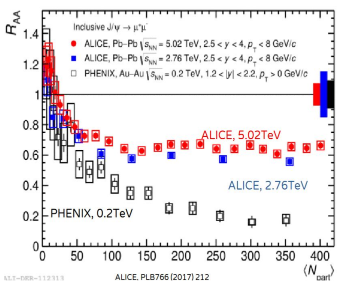
1) Probe the medium at lower T w.r.t. collider experiments
2) Explore a non-zero $\mu_B$ region

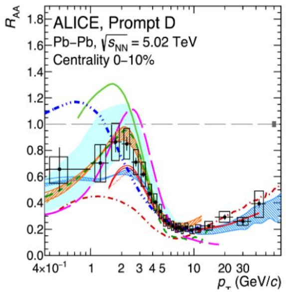
# Open and hidden charm: from LHC to SPS

Open charm and quarkonia in nuclear collisions ➞ probes of QGP

## High energy: RHIC / LHC

Extensively measured ➞ unprecedented insight on QGP properties at low $\mu_B$




## Low energy: fixed target

**NEW high precision** open and hidden charm measurements would allow to:

1) Probe the medium at lower T w.r.t. collider experiments
2) Explore a non-zero $\mu_B$ region

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

# The NA60+ experiment at CERN SPS

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

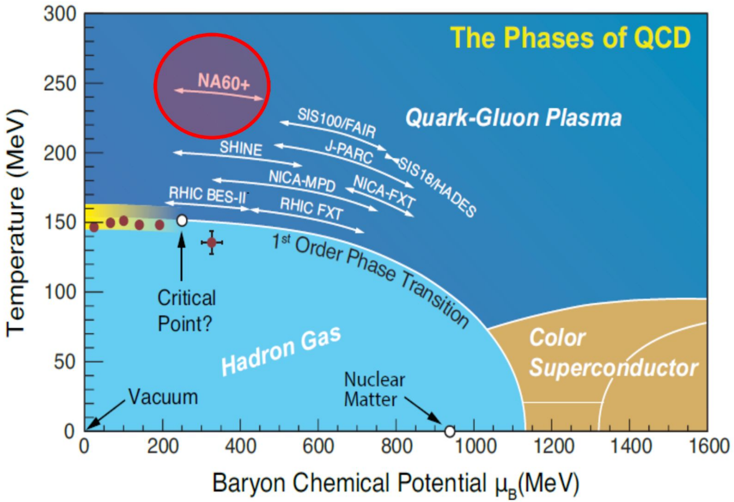
Performing precision studies of **hard and electromagnetic processes** accessing:

- 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, and hypernuclei

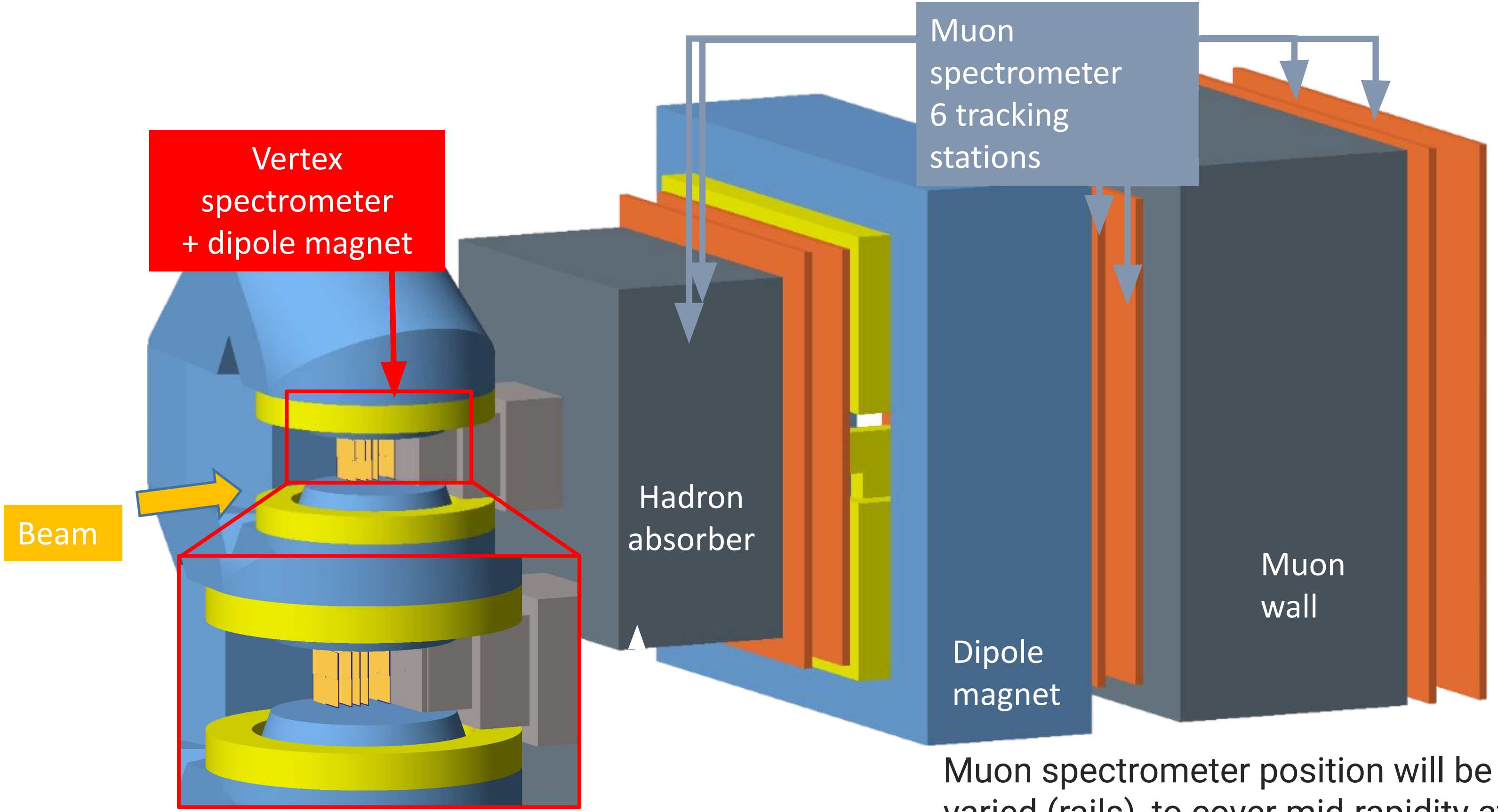
**Beam energy scan** between $\sqrt{s_{NN}} \sim 6 - 17$ GeV, exploring the $\mu_B$ range ~220 - 550 MeV

**Large luminosities** are needed for rare QGP probes studies:

- PbPb interactions rates > $10^5$ Hz, reachable with $10^6$ Pb/s in a fixed target environment



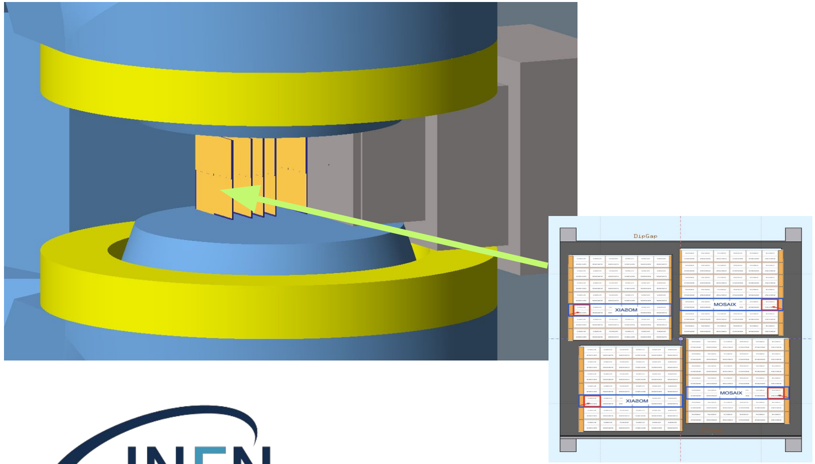
# The NA60+ setup

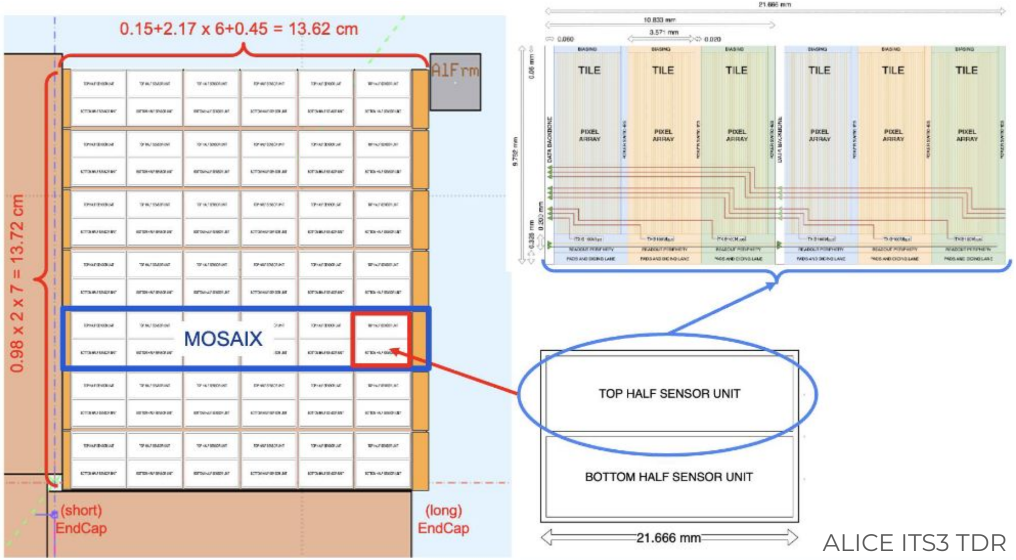



Muon spectrometer position will be varied (rails), to cover mid-rapidity at different collision energies

# The vertex telescope

5 planes of MAPS detectors
VT inside a 1.5 T dipole magnetic field provided by MEP48 (already available at CERN)





ALICE ITS3 TDR

**Synergy with ALICE ITS3** → first large area stitched sensor (MOSS) tested

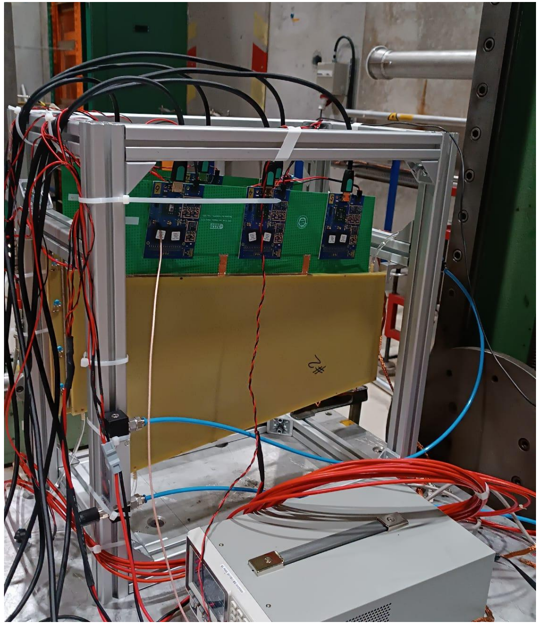
**Realistic sensor floorplan available** (13.6 x 13.7 $cm^2$)

- MOSAIX with 6 stitched RSU (21.7 x 19.5 $mm^2$ units)
- 7 MOSAIX replicated vertically

(almost) final sensor prototype expected in 2025

# The Muon Spectrometer chambers

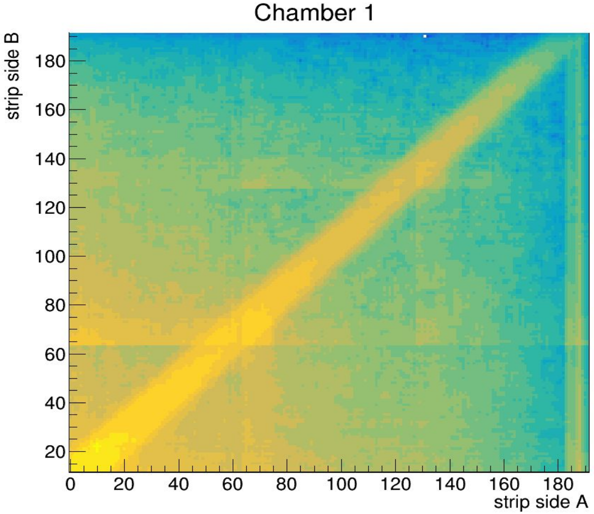
GEM or MWPC ➡ can match the expected rates of charged particles (2 kHz/cm$^2$)



A first prototype was tested in Fall 2023

**A new prototype in was tested last week in a test beam at CERN:**

- New strip readout pattern 2D strips at 10° crossing angle
- Electronics based on VMM3a chip made by USTC, planned to be used in final detector



# The dipole magnet MNP33

A new opportunity: the NA62 dipole **MNP33** will become available in LS3 (the previous plan was to build a new toroidal magnet)

**MNP33 looks very promising:**

- Potential significant simplification of integration of NA60+ in H8
  - more compact setup
- Cost reduction of NA60+ project by ~ 3M€ w.r.t. building the toroidal magnet
- Detailed simulations to assess the physics performances on-going

Magnet specifics:

- Iron yokes: 2.40 m x 3.20 m
- Integrated field: 0.864 T m, similar to that of the toroid

# The beam

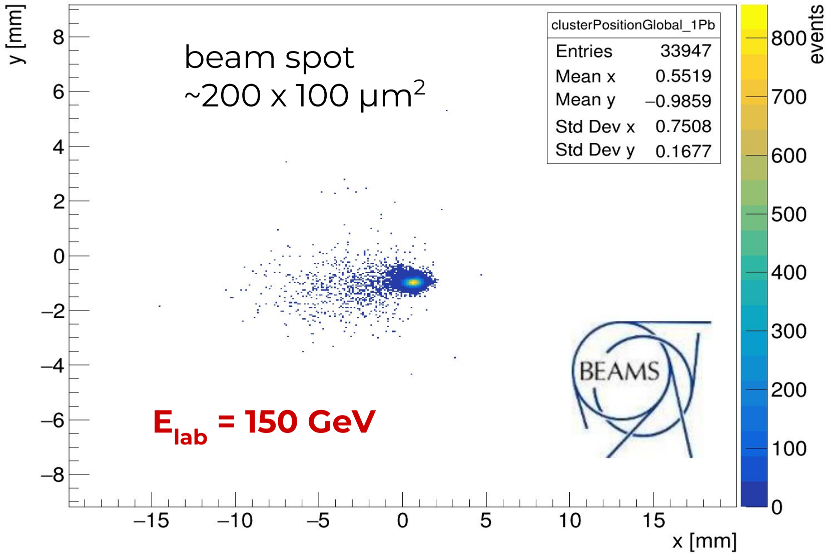
**Planning of HI and p beams quickly converging** →
- to achieve $10^{12}$ Pb on target, in 1 month at all energies
- to collect pA at the same energy (~5-6 x $10^8$ p/spill)

**Very stringent beam requests at all energies** →
- high-intensity ($10^7$ Pb/spill)
- very focussed sub-mm beam (vertex spectrometer has 6 mm hole)

**Test beam finished last week!**

**Reached the target intensity:**
1.2 $10^6$ Pb/s at 150 GeV with a very narrow beam spot

**Optics tested also at 13.5 GeV**: Promising results, reached 5 $10^5$ Pb/s and a 1200 x 750 $\mu m^2$

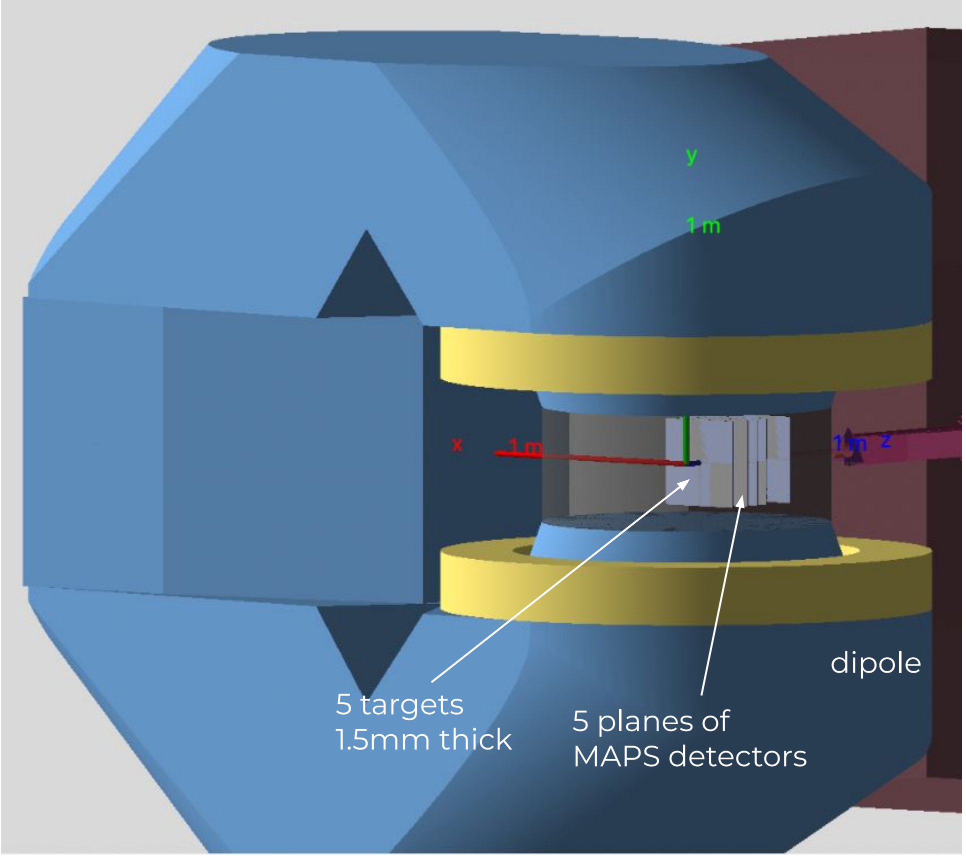


# How to measure open charm in NA60+

**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% |
| $\Lambda_c$ | 2285 | 60 | $pK^-\pi^+$<br>$pK^0_s$<br>$\Lambda\pi^+$ | 6.28%<br>1.59%<br>1.30% |

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



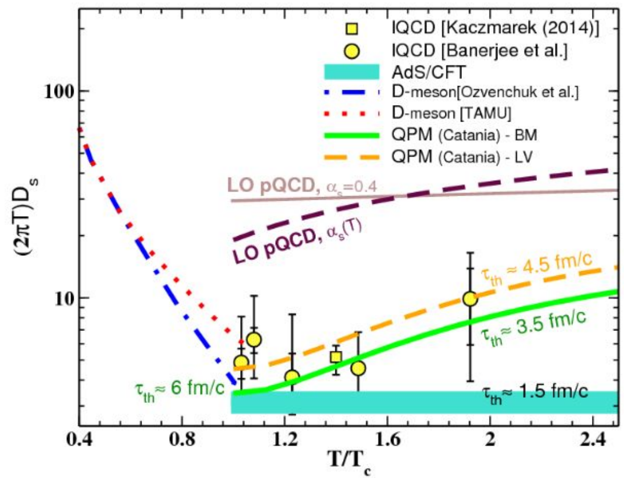
# Open charm in AA at low √s

## 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

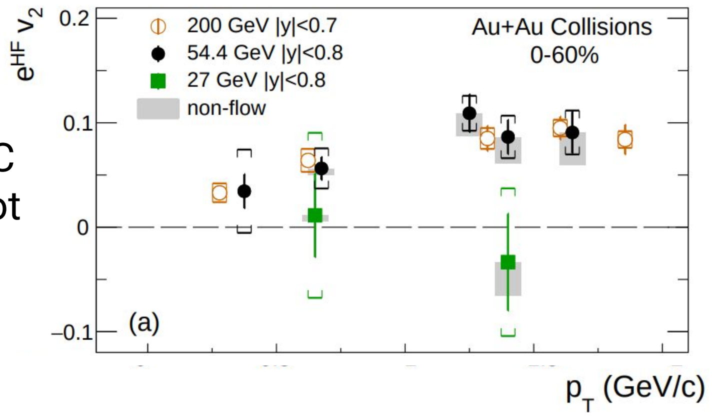



F. Scardina et al. PRC96, 2017 (044905)

## Charm thermalization

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

- Current measurements on HF-decay electron $v_2$ at RHIC $\sqrt{s_{NN}}$= 27 show small $v_2$ w.r.t. 54.4 GeV and 200 GeV, not conclusive on $v_2$> 0




Phys. Lett. B 844 (2023) 138071

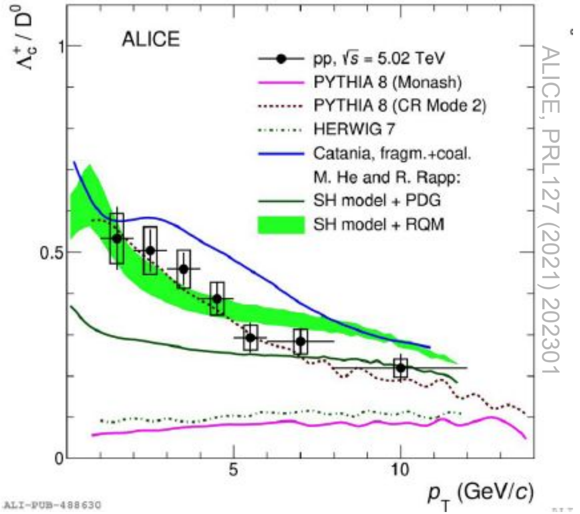
# Open charm in AA at low √s

## Hadronization mechanisms

Measure the relative abundances of charm-hadrons
($D^0$, $D^+$, $D^+_s$ mesons and $\Lambda_c$ baryons) in a high $\mu_B$ environment

- Strange/non-strange meson ratio ($D_s/D^0$)
  - Enhanced in AA due to recombination in the strangeness rich QGP

- Baryon/meson ratio ($\Lambda_c$ /D)
  - Enhanced in AA in case of hadronization via coalescence
  - Interesting also in pp and pA, as observed at LHC




ALICE, PRL127 (2021) 202301

## 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

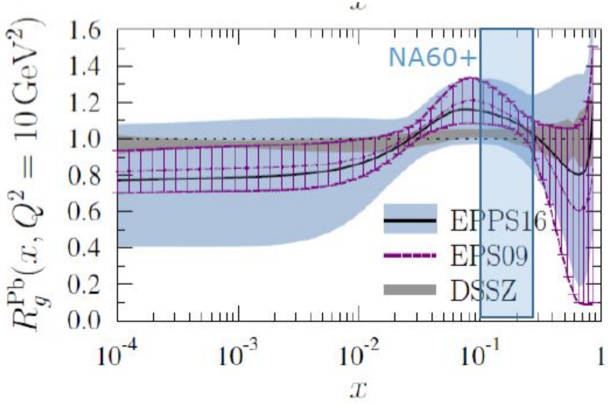
# Open charm in pA at low √s

**Nuclear PDFs via D meson production in pA**

⬇

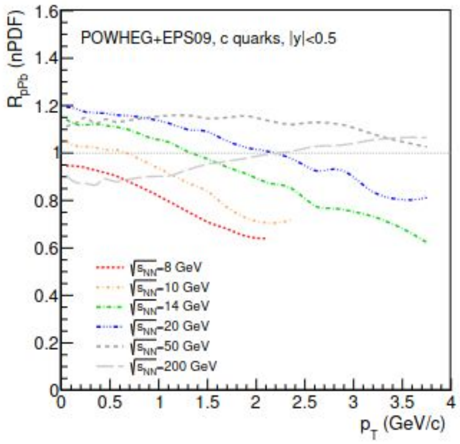
NA60+ will cover $0.1 < x_{Bj} < 0.3$ at $Q^2 \sim 10\text{-}40\ GeV^2$

- 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 $p_T$



# 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

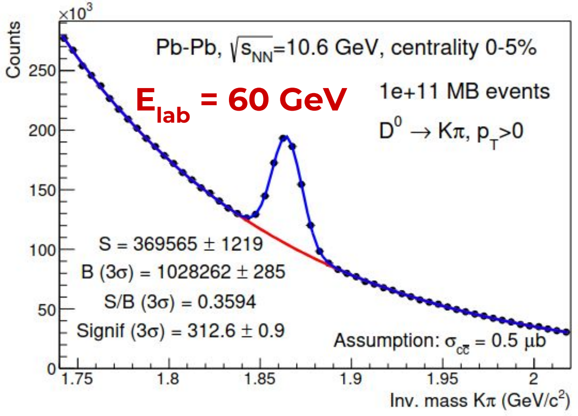
Accessible also at lower $\sqrt{s_{NN}}$ with ~1% statistical precision

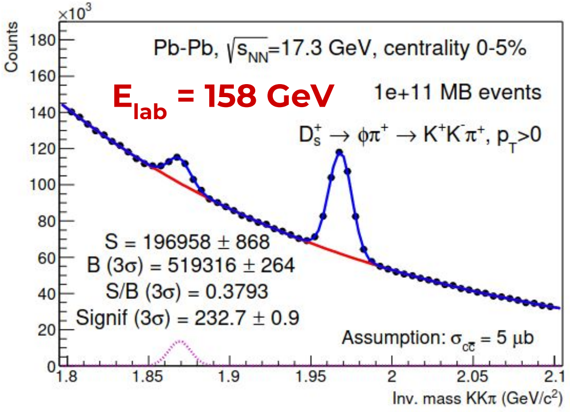
$D^+_s \rightarrow \phi\pi \rightarrow KK\pi$

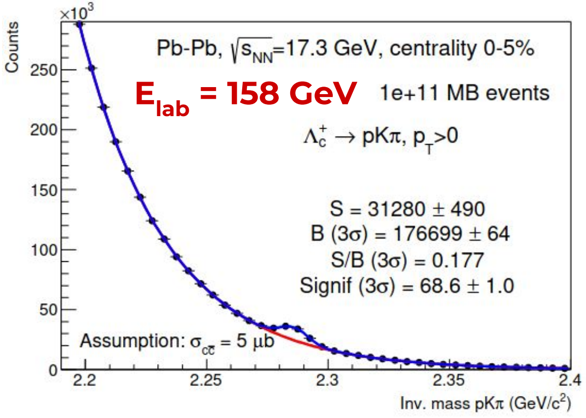
Measurement of yields feasible, statistical precision of few percent

$\Lambda^+_c \rightarrow pK\pi$

Accessible, possible improvement with timing layers under study



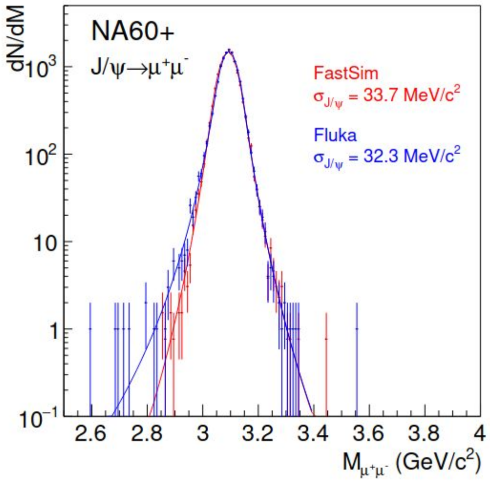



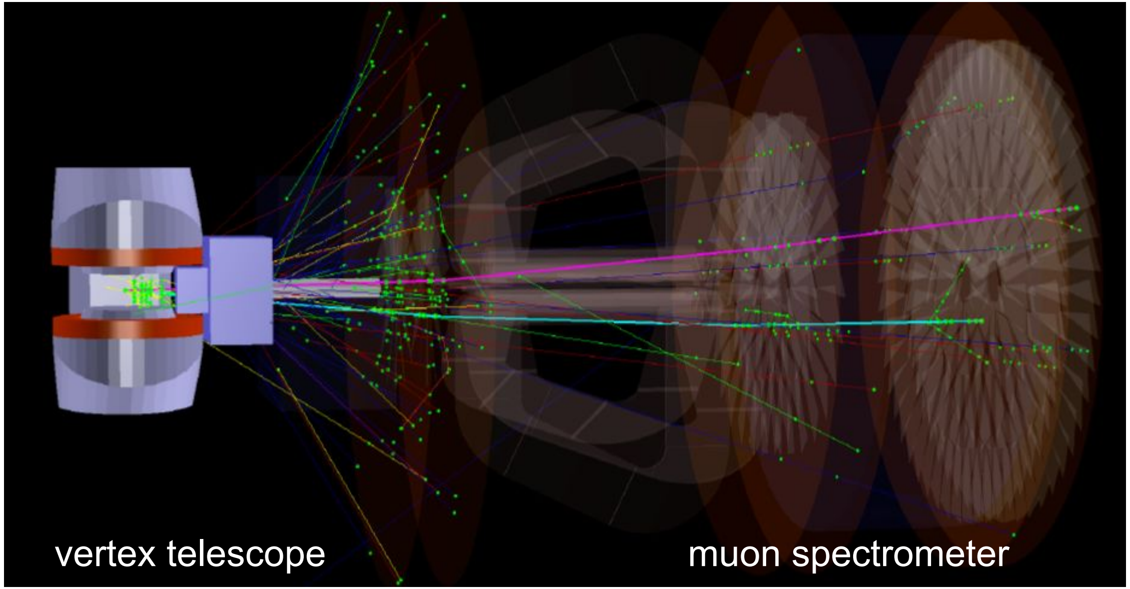



# How to measure quarkonium in NA60+

Charmonium production studied via

- J/ψ and ψ(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



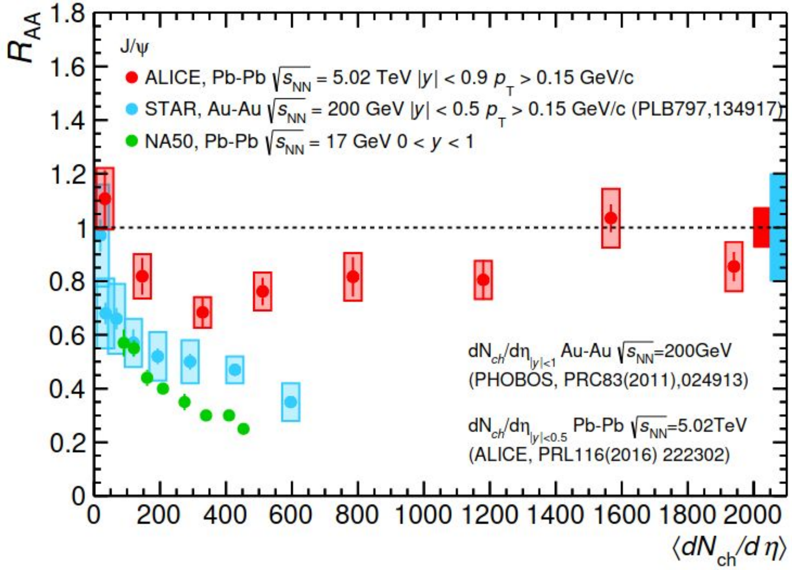




Muon tracks obtained matching tracks in vertex and muon spectrometer ➞ very good mass resolution, ~30 MeV for the J/ψ

# Quarkonium: high vs low √s

Different hot and cold nuclear effects at play:

| RHIC / LHC | SPS |
|---|---|
| **Hot matter effects**<br>suppression and regeneration | **Hot matter effects**<br>suppression |
| **Initial state effects**<br>mainly shadowing<br>$10^{-5} < x_{BJ} < 10^{-2}$ for $-3 < y < 3$ | **Initial state effects**<br>(anti)shadowing<br>$x_{BJ} \sim 10^{-1}$ for $y \sim 0$ |
| **Final CNM effects**<br>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**<br>sizable breakup in nuclear matter<br>$\tau \sim 0.5$ fm/c for $y \sim 0$ |

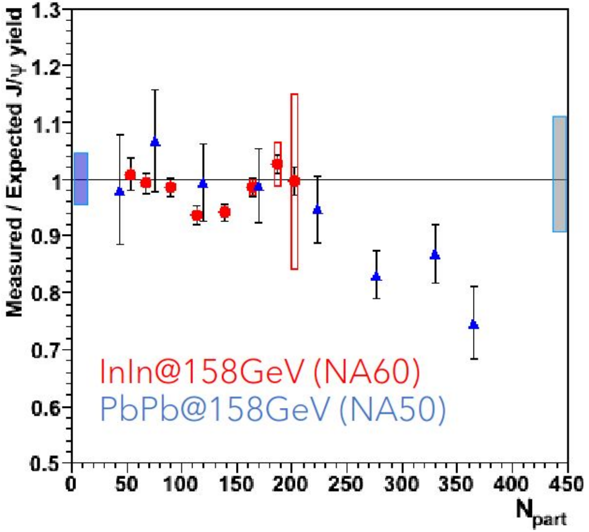


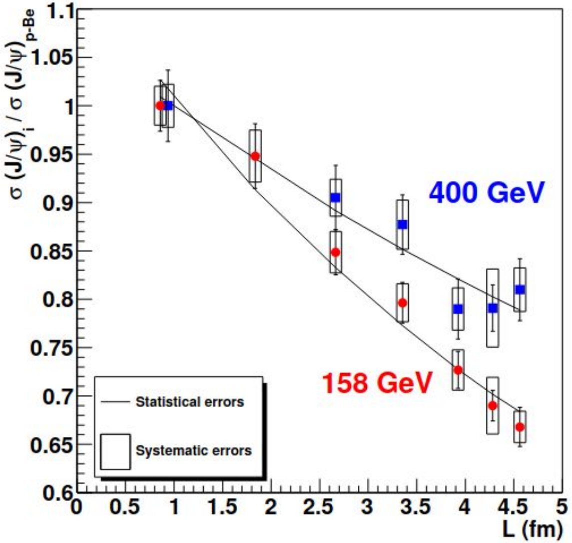
ALICE, arXiv:2211.04384

# Quarkonium in pA and AA at low √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 $\chi_c$ feed-down
- significant contribution from CNM effects




**pA:** measurement of CNM

- Anti-shadowing contribution
- Nuclear break-up dominant, stronger at lower √s

# Charmonium in NA60+

Quarkonium never studied below top SPS energies

## 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

## 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…)

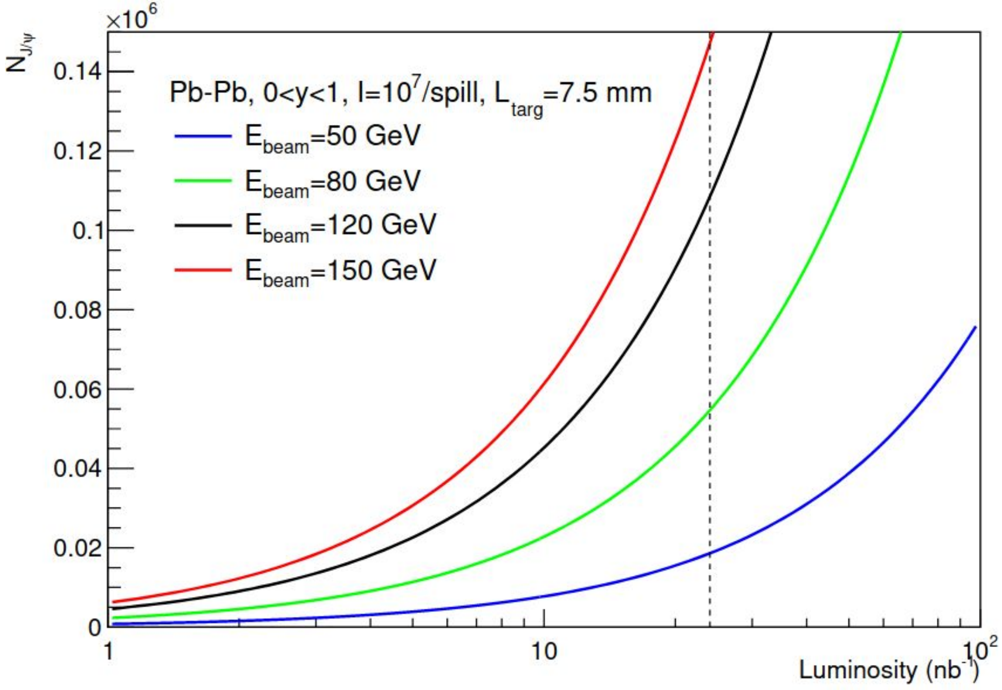
## pA: intrinsic charm:

Expected enhanced charm production at large $x_F=2m_T/\sqrt{s}\sinh(y)$

- 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 of data taking→ $L_{int}$~24 $nb^{-1}$
- A factor 3 overall suppression (CNM+QGP)

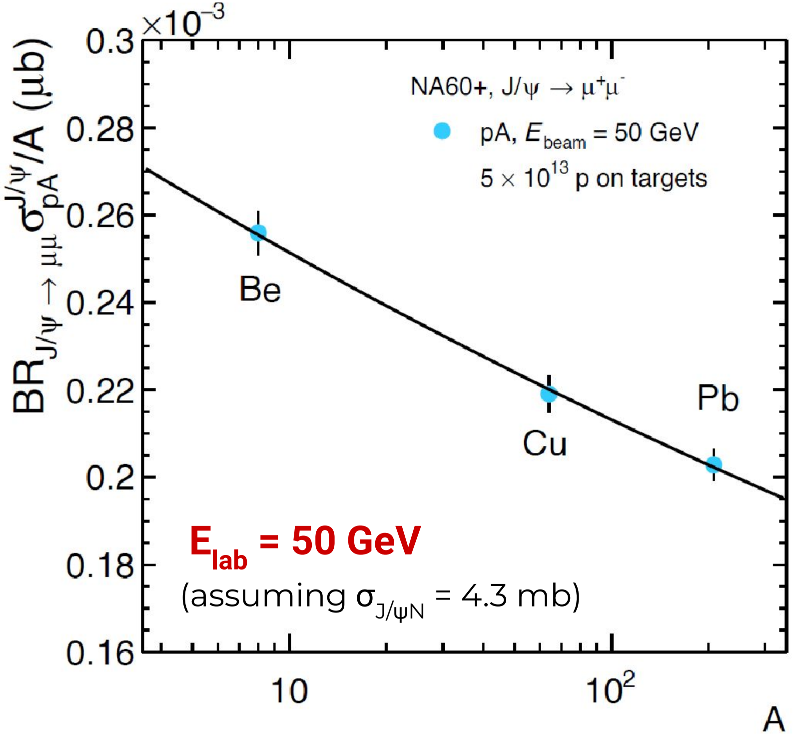
⬇

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/cm$^2$

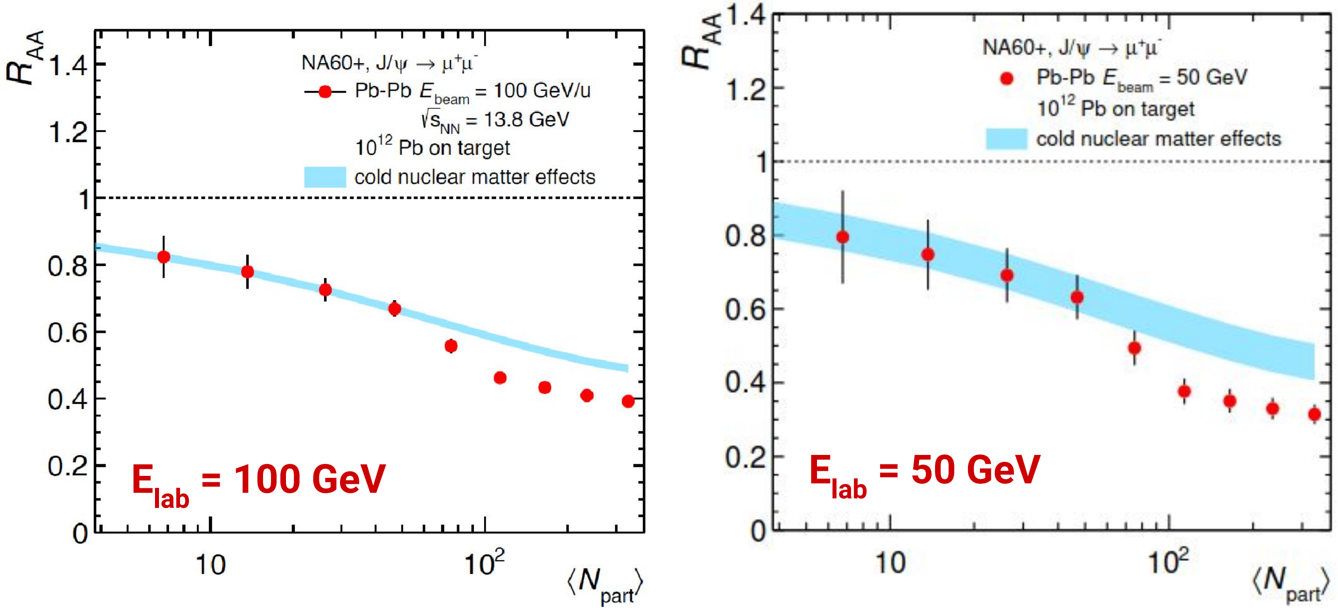
⬇

- 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 $\sigma_{pp}$, 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

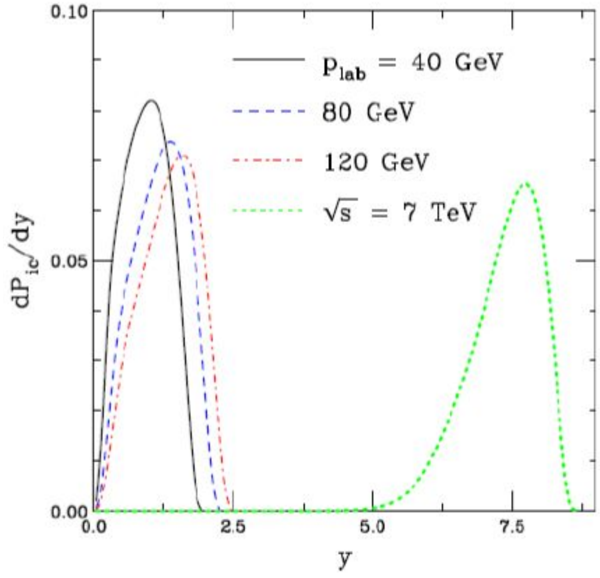
Precise evaluation of anomalous suppression within reach even at low energy

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

# Intrinsic charm

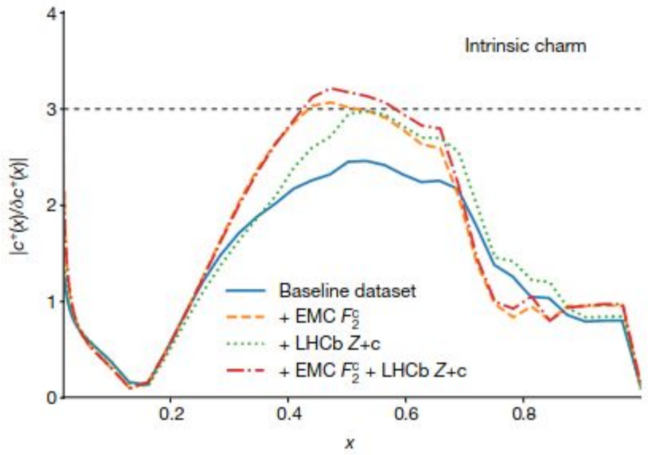
Intrinsic charm component of the hadron wave function |uudccbar>

**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))

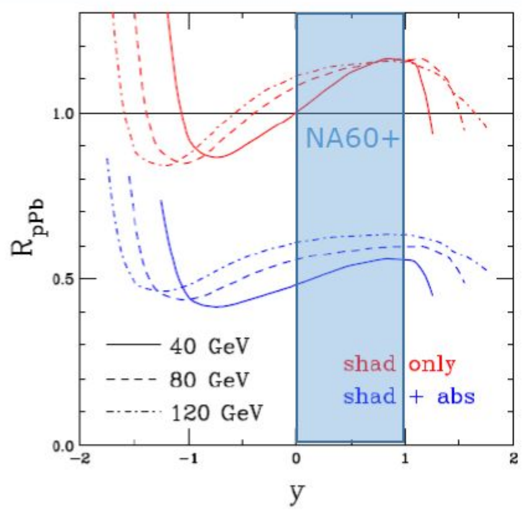


# Intrinsic charm

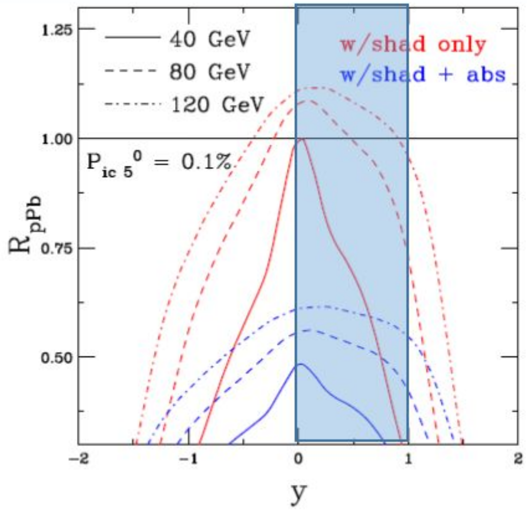
p-Pb collisions:

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

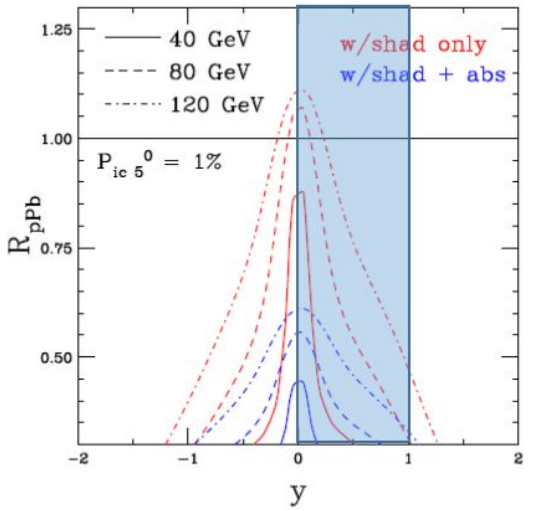
without intrinsic charm




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 → **2025** Technical proposal → **2026-2028/29** Construction → **2029/30-2036/37** 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
- Technical proposal will be submitted in May 2025
- Aim is taking data in 2029/30 after LHC LS3
  - 7-years running with Pb beam (one beam energy per year)
  - proton beams for reference and dedicated p-A studies

# 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 $\mu_B$
- 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/

# The NA60+ Collaboration

C. Ahdida[1], G. Alocco[2,3], F. Antinori[4], M. Arba[3], M. Aresti[2,3], R. Arnaldi[5], A. Baratto Roldan[1], S. Beolè[6,5], A. Beraudo[5], J. Bernhard[1], L. Bianchi[6,5], M. Borysova[7,8], S. Bressler[7], S. Bufalino[9,5], E. Casula[2,3], C. Cicalò[3], S. Coli[5], P. Cortese[10,5], A. Dainese[4], H. Danielsson[1], A. De Falco[2,3], K. Dehmelt[11], A. Drees[11], A. Ferretti[6,5], F. Fionda[2,3], M. Gagliardi[6,5], A. Gerbershagen[12], F. Geurts[13], V. Greco[14,15], W. Li[13], M.P. Lombardo[16], D. Marras[3], M. Masera[6,5], A. Masoni[3], L. Micheletti[1], L. Mirasola[2,3], F. Mazzaschi[1,6], M. Mentink[1], P. Mereu[5], A. Milov[7], A. Mulliri[2,3], L. Musa[1], C. Oppedisano[5], B. Paul[2,3], M. Pennisi[6,5], S. Plumari[14], F. Prino[5], M. Puccio[1], C. Puggioni[3], R. Rapp[17], I. Ravinovich[7], A. Rossi[4], V. Sarritzu[2,3], B. Schmidt[1], E. Scomparin[5], S. Siddhanta[3], R. Shahoyan[1], M. Tuveri[3], A. Uras[18], G. Usai[2,3], H. Vincke[1], I. Vorobyev[1]

1 .European Organization for Nuclear Research (CERN), Geneva, Switzerland
2 .Dipartimento di Fisica dell'Università di Cagliari, Cagliari, Italy
3 .INFN, Sezione di Cagliari, Cagliari, Italy
4 .INFN, Sezione di Padova, Padova, Italy
5 .INFN, Sezione di Torino, Turin, Italy
6 .Dipartimento di Fisica dell Università di Torino, Turin, Italy
7 .Department of Particle Physics and Astrophysics, Weizmann Insitute of Science, Rehovot, Israel
8 .Kyiv Institute for Nuclear Research (KINR), Natl. Acad. of Sci. of Ukraine (NASU)
9 .Dipartimento DISAT del Politecnico di Torino, Turin, Italy
10 .Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale, Alessandria, Italy
11 .Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, New York, USA
12 .Department of Radiation Oncology, University of Groningen, Groningen, The Netherlands
13 .Department of Physics and Astronomy, Rice University, Houston, Texas, USA
14 .Dipartimento di Fisica e Astronomia dell'Università di Catania, Catania, Italy
15 .INFN, Laboratori Nazionali del Sud, Catania, Italy
16 .INFN, Laboratori Nazionali di Frascati, Frascati, Italy
17 .Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, Texas, USA
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

# Backup slides

# D mesons performance studies

**Fast simulation:**

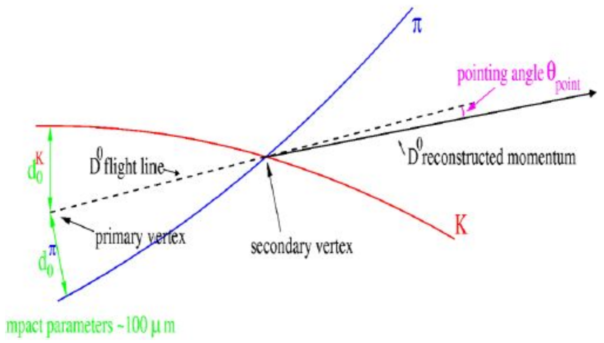
- D-meson: signal simulated with $p_T$ and y distributions from POWHEG-BOX + PYTHIA
  Combinatorial background: π, K, p with multiplicity, $p_T$ and y shapes from NA49

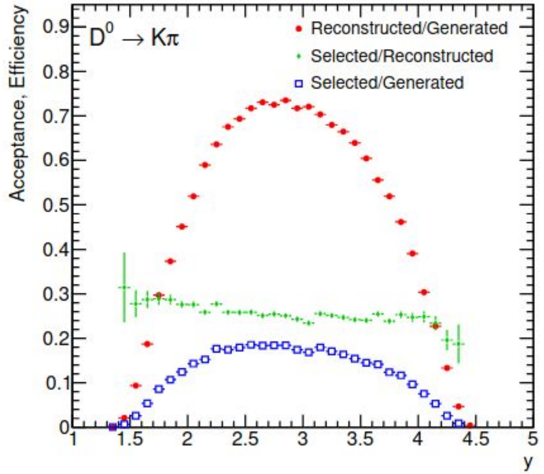
- Particle transport: carried out in the VT, with parameterized simulation of its resolution
  Track reconstruction:  Kalman filter

- D-meson vertex reconstructed from decay tracks ➞ geometrical selections based on decay vertex topology

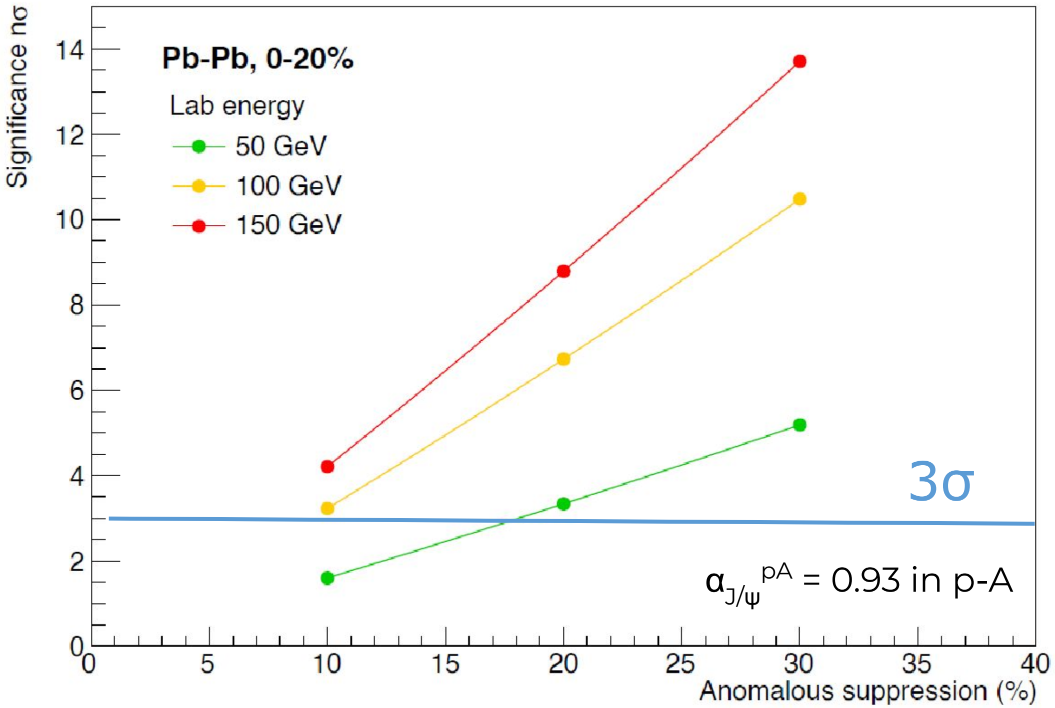
$D^0$ in central PbPb:

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



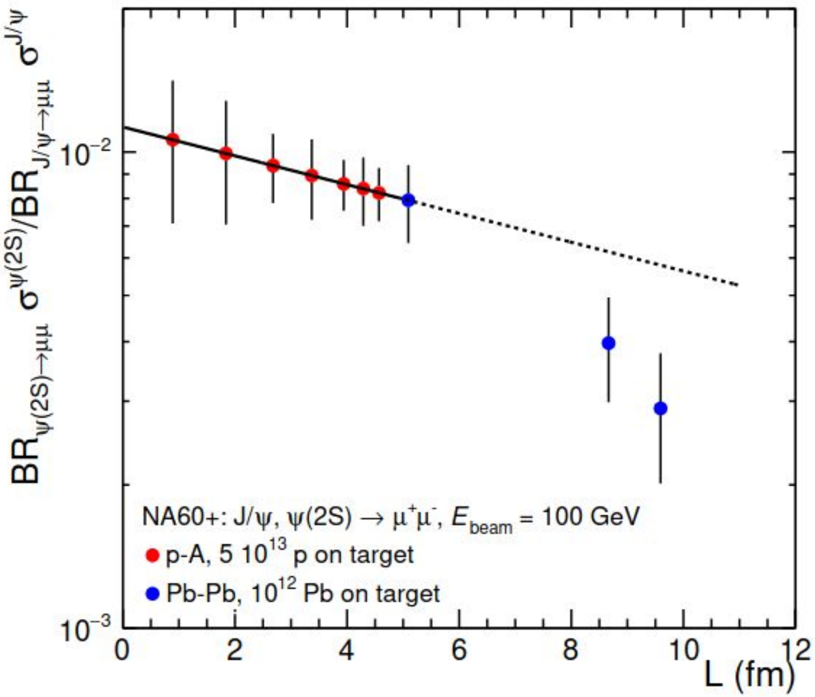
# Charmonium $R_{AA}$




- 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 and AA

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




Assume

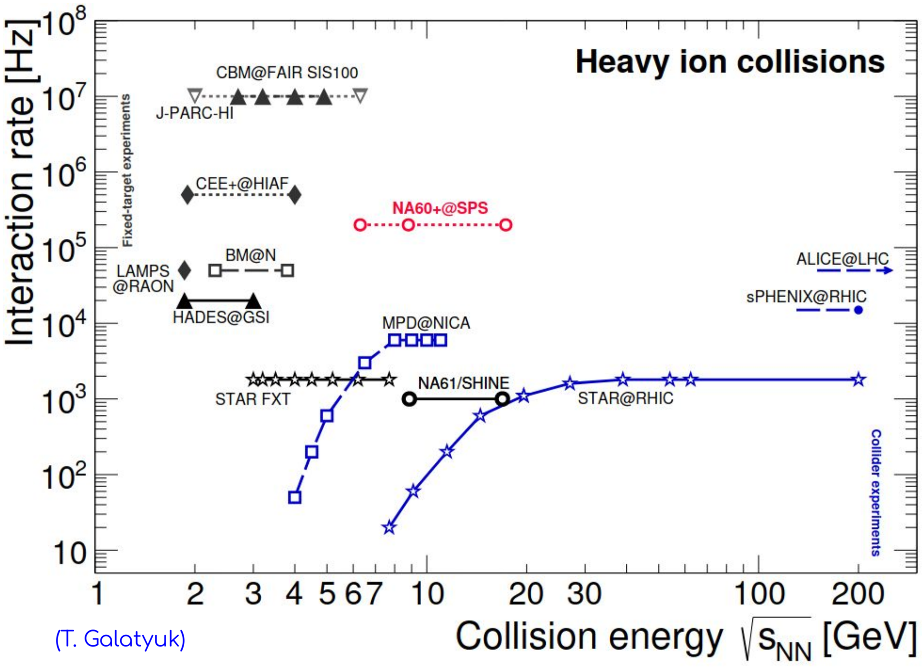
- stronger suppression for ψ(2S) than J/ψ

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**

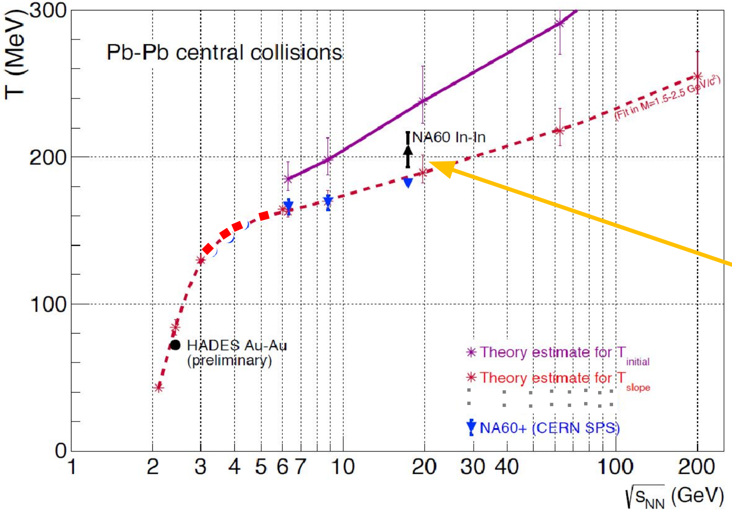



(T. Galatyuk)

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

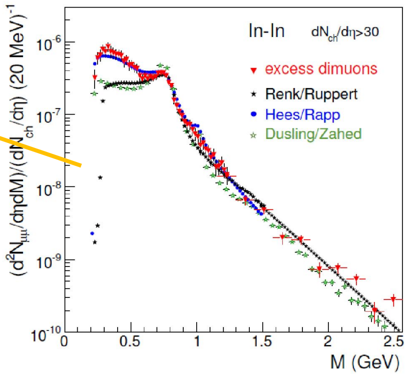



Caloric curve of the QGP

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 1$^{st}$ order phase transition

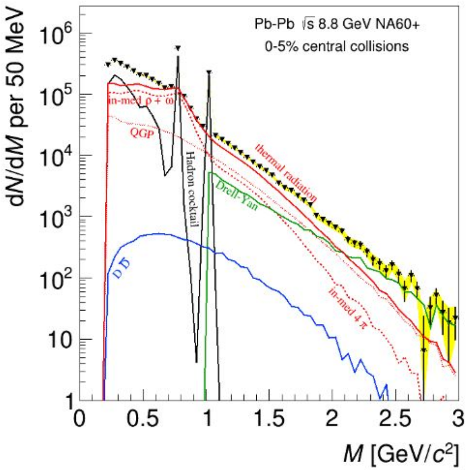
# Thermal dimuons in NA60+

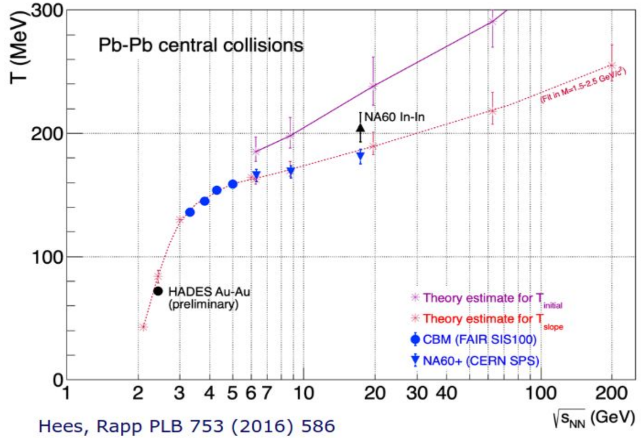
Thermal radiation yield:

- Accessible up to M= 2.5-3 GeV/$c^2$
- Dominated by ρ contribution at low mass

Drell-Yan contribution to be estimated via p-A measurements

Open charm contribution negligible dimuon source

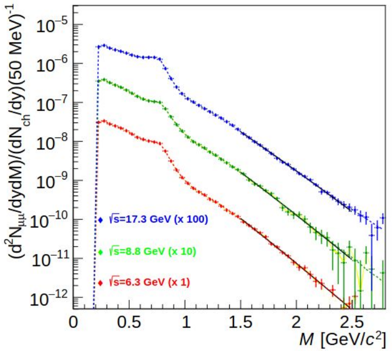



Hees, Rapp PLB 753 (2016) 586

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

$T_{slope}$ 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