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

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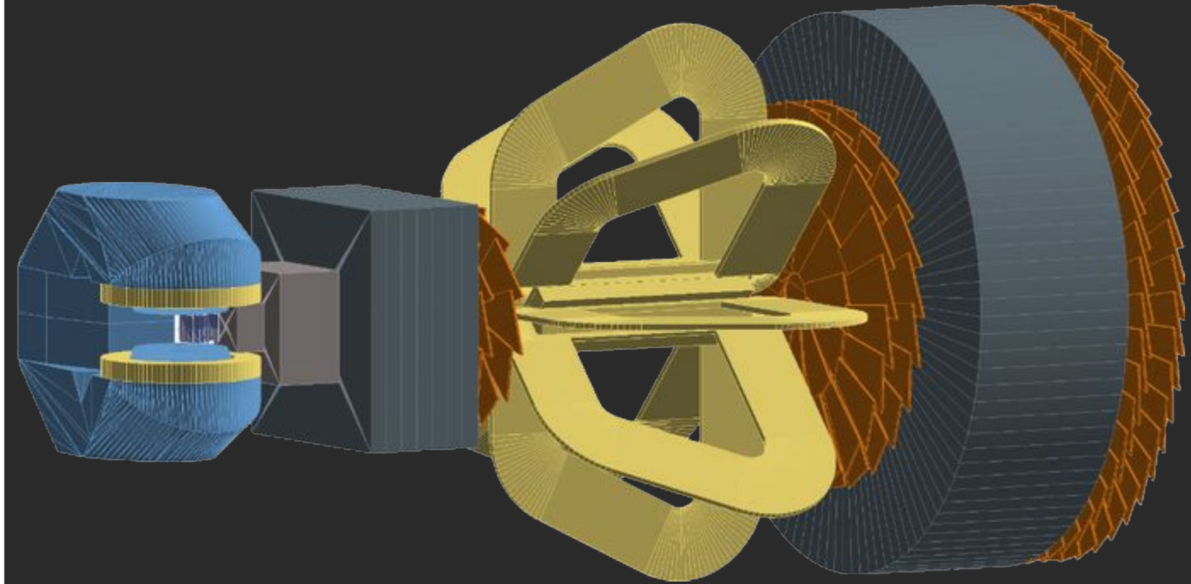


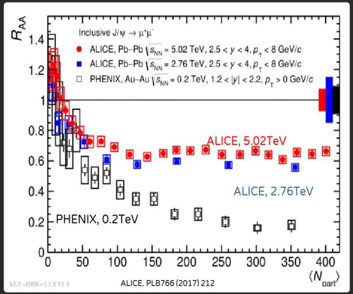
Hard Probes 2023, 29 March 2023

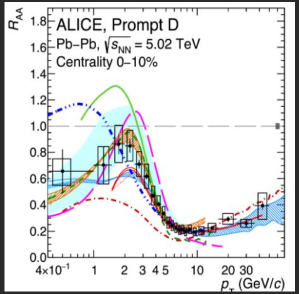
Open and hidden charm: from LHC to SPS

Open charm and quarkonia in nuclear collisions →probes of QGP

HI at high energy: RHIC / LHC

Extensively measured
→ unprecedented insight on QGP properties at low μ_B





HI at 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

quarkonium

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

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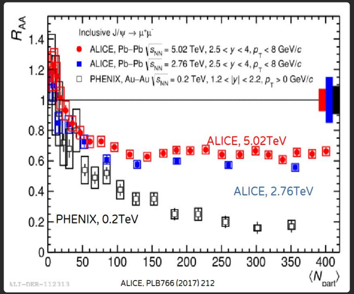

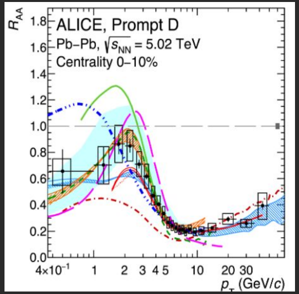

HI at low energy: fixed target

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

Open and hidden charm: from LHC to SPS

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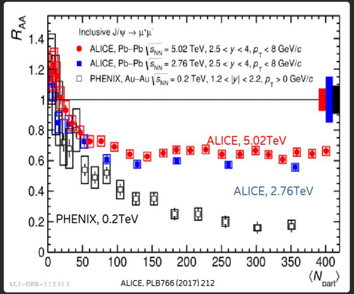
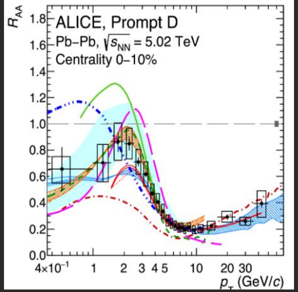




HI at low energy: fixed target

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

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

E. Scomparin, Plenary Thur. 30
G. Usai, Future exp. Session, Tue 28

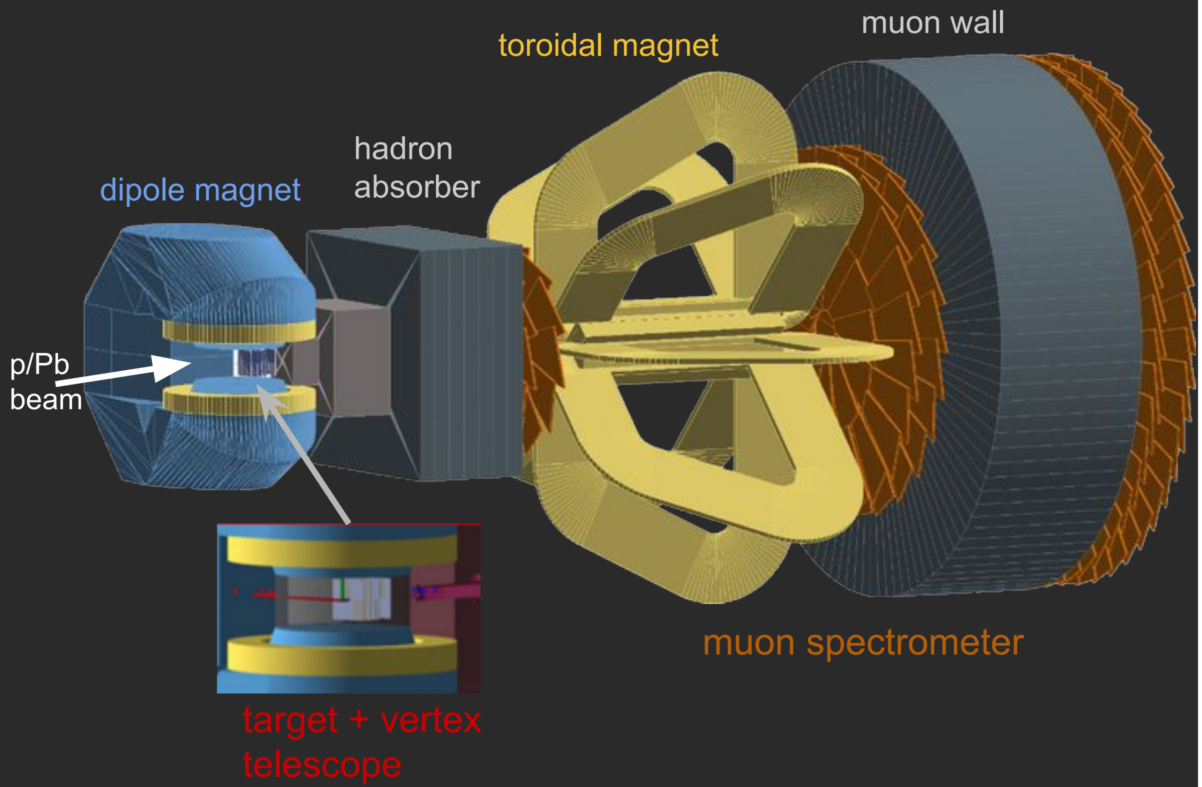
The NA60+ experiment at CERN SPS

Goal

high precision measurements of
- dimuon spectrum from threshold to the charmonium mass region
- hadronic decays of charm and strange hadrons

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 $\sim 10^6$ Pb/s

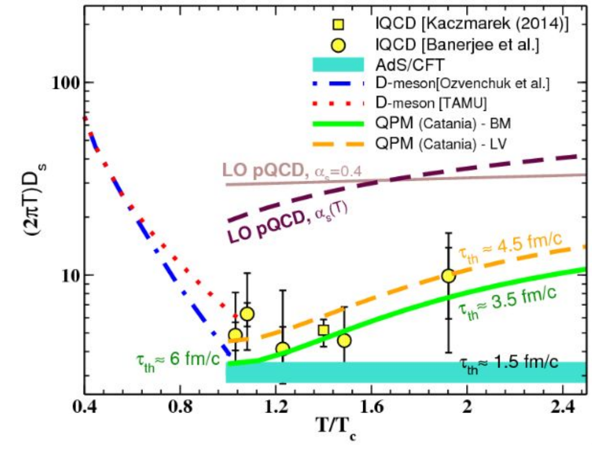


Open charm in AA at low √s

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

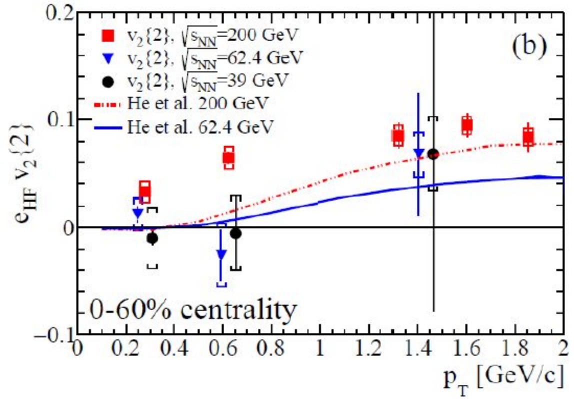


F. Scardina et al. PRC96, 2017 (044905)

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



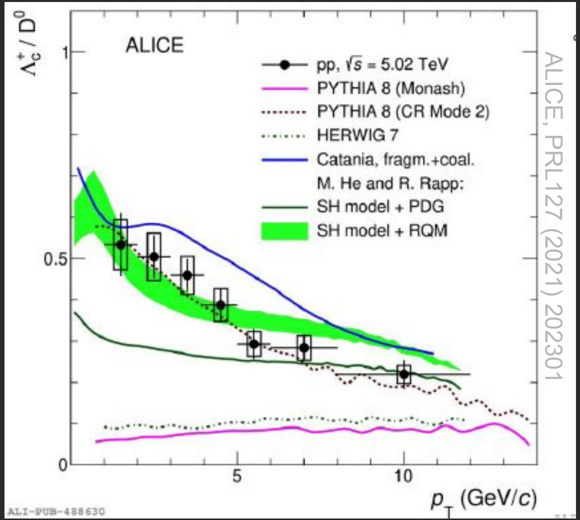
STAR, PRC95 (2017) 034907

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



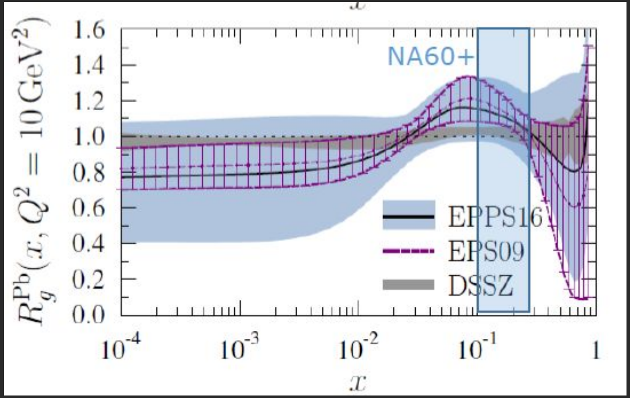
4 total charm cross section

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

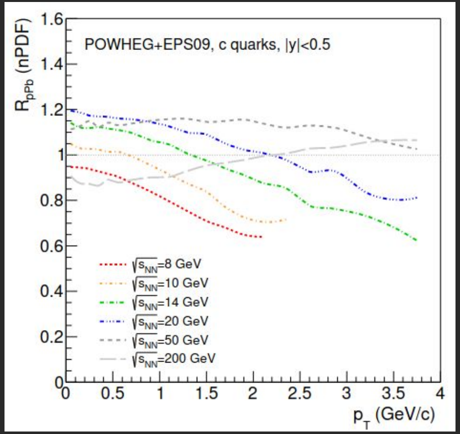


NA60+ will cover the range $0.1 < x_{Bj} < 0.3$ at Q^2~10-40 GeV^2

- EMC and anti-shadowing regions accessible

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

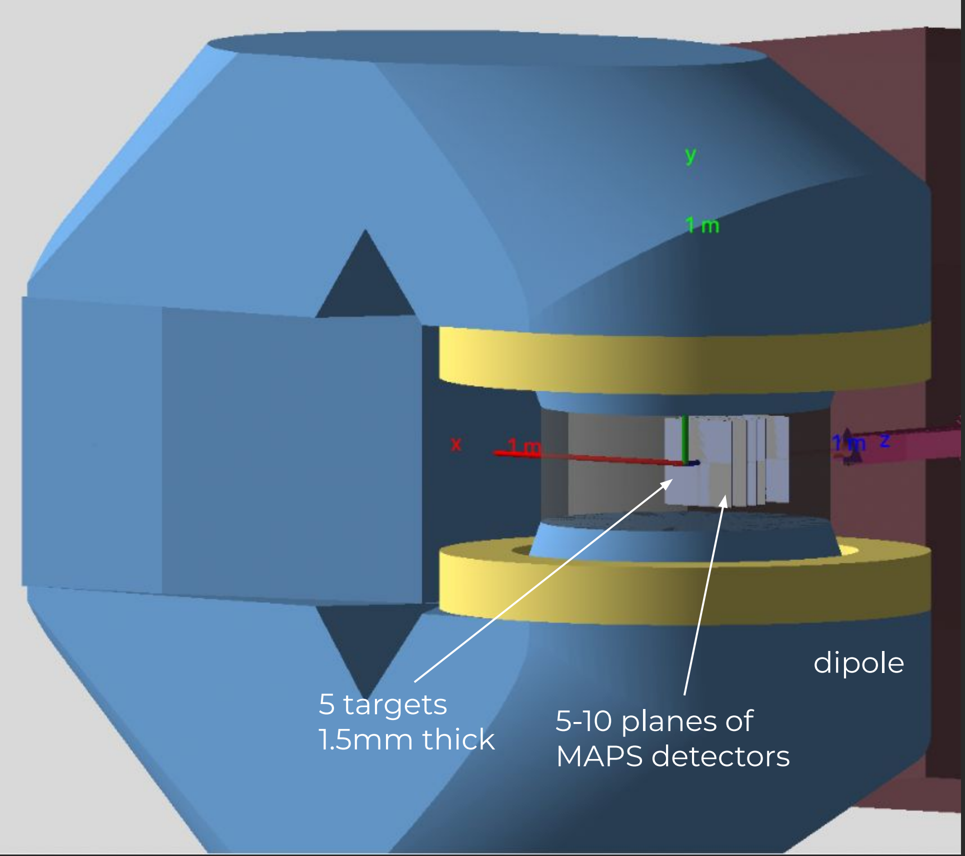


How to measure charm in NA60+

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



Example: D-mesons performance studies

Fast simulation:

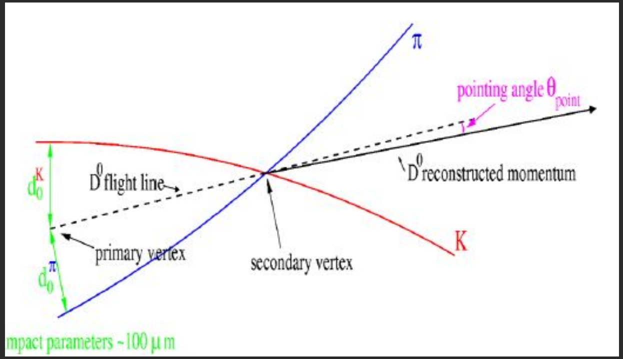
1. D-meson: signal simulated with p_T and y distributions from POWHEG-BOX + PYTHIA
   Combinatorial background: π, K, p with multiplicity, p_T and y shapes from NA49

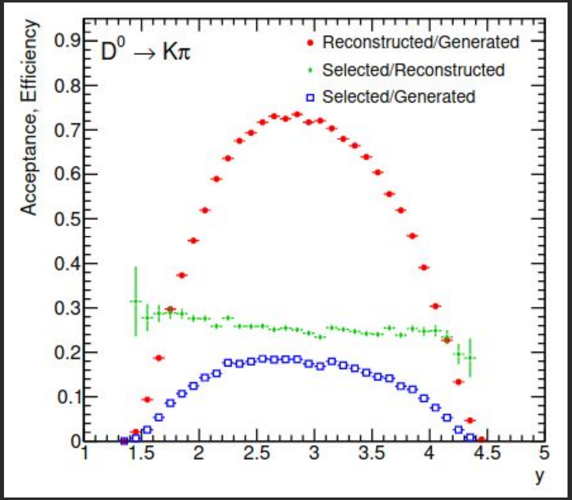
2. Particle transport: carried out in the VT, with parametrized simulation of its resolution
   Track reconstruction: Kalman filter

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





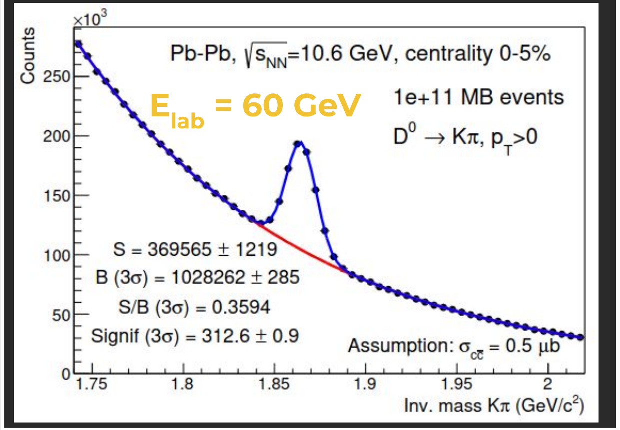
Charm-hadrons: performance studies

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

$D^0 \rightarrow K\pi$

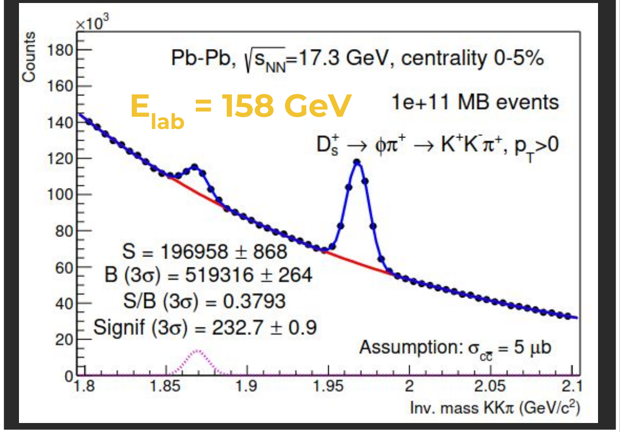
$3\ 10^6$ D^0, 0-5% PbPb, $\sqrt{s_{NN}}$=17.3 GeV
→ R_{AA} and v_2 vs p_T, y and centrality

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



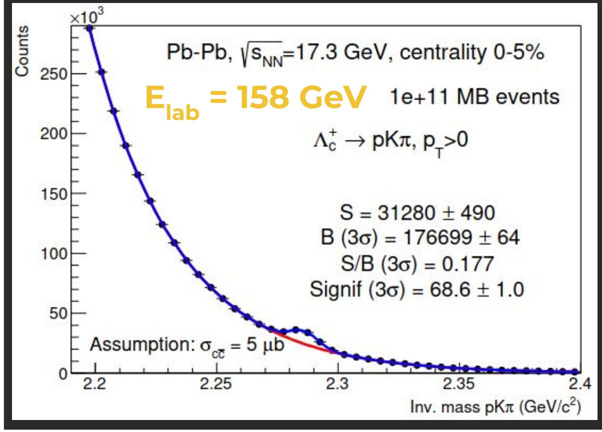
$D_s \rightarrow \phi\pi \rightarrow KK\pi$

measurement of yields feasible, statistical precision of few percent



$\Lambda_c \rightarrow pK\pi$

accessible, possible improvement with timing layers under study



Quarkonium: high vs low $\sqrt{s}$

Different hot and cold nuclear effects at play:

RHIC / LHC

Hot matter effects
suppression and regeneration

Initial state effects
mainly shadowing
$10^{-5} < x_{BJ} < 10^{-2}$ for $-3 < y < 3$

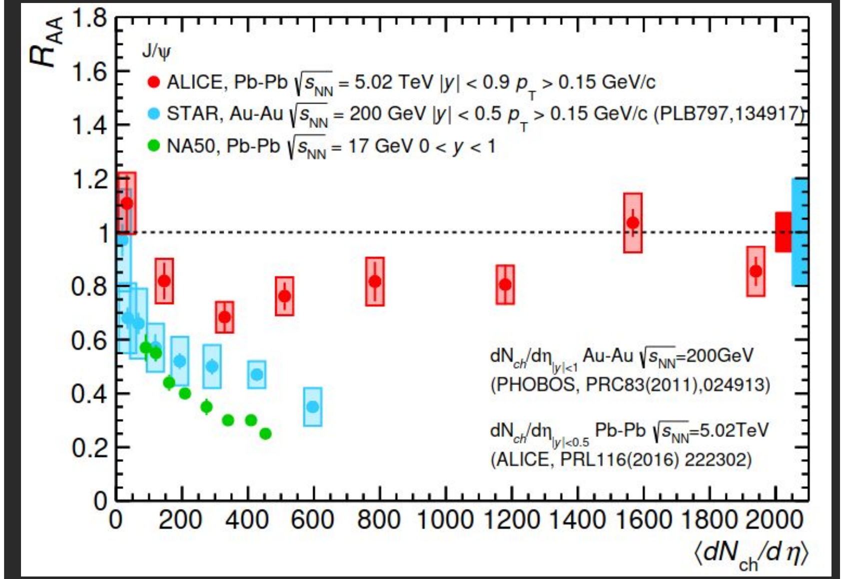
Final CNM effects
negligible, due to short crossing time $\tau = L/(\beta_z\gamma)$
~$7\,10^{-5}$ (y~3) - $4\,10^{-2}$ (y~-3) fm/c

SPS

Hot matter effects
suppression

Initial state effects
(anti)shadowing
x_{BJ} ~ 10^{-1} for y~0

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



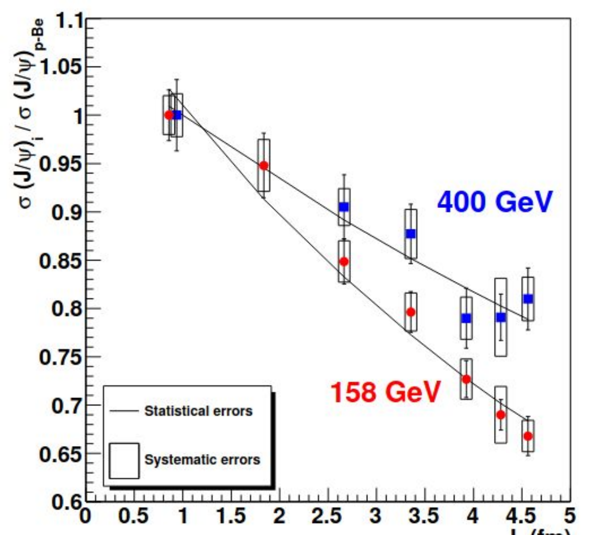
ALICE, arXiv:2211.04384

Quarkonium in pA and AA at low √s

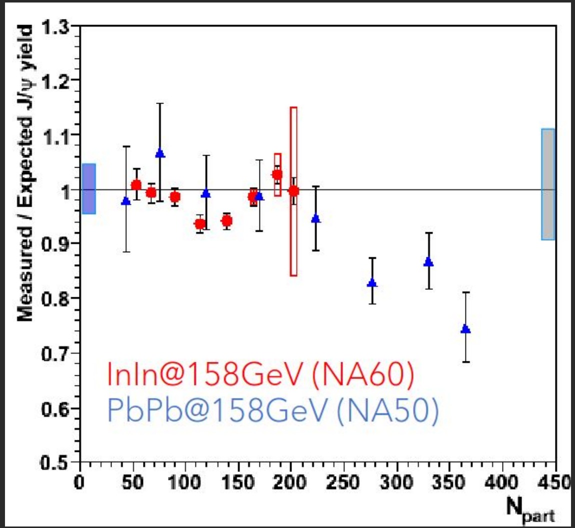
AA:

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 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

Quarkonium 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

G. Usai, Future exp. session, Tue 28

Quarkonium in NA60+

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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

G. Usai, Future exp. session, Tue 28

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…)

Quarkonium in NA60+

Quarkonium never studied below top SPS energies

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accessible via energy scan

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

G. Usai, Future exp. session, Tue 28

2

pA: cold nuclear matter effects

CNM effects increase at low √s

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

3

pA: intrinsic charm

- should lead to an 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)

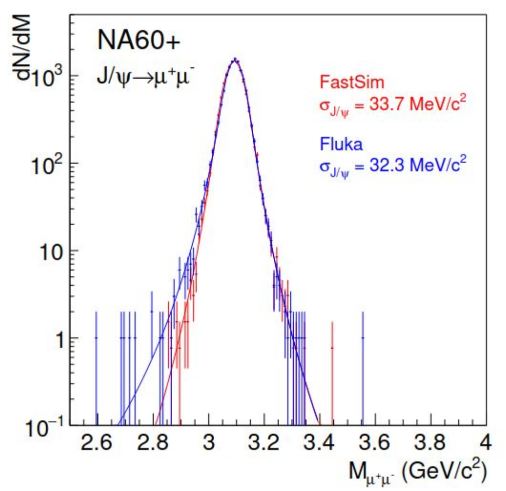
R. Vogt, HF session, Tue 28

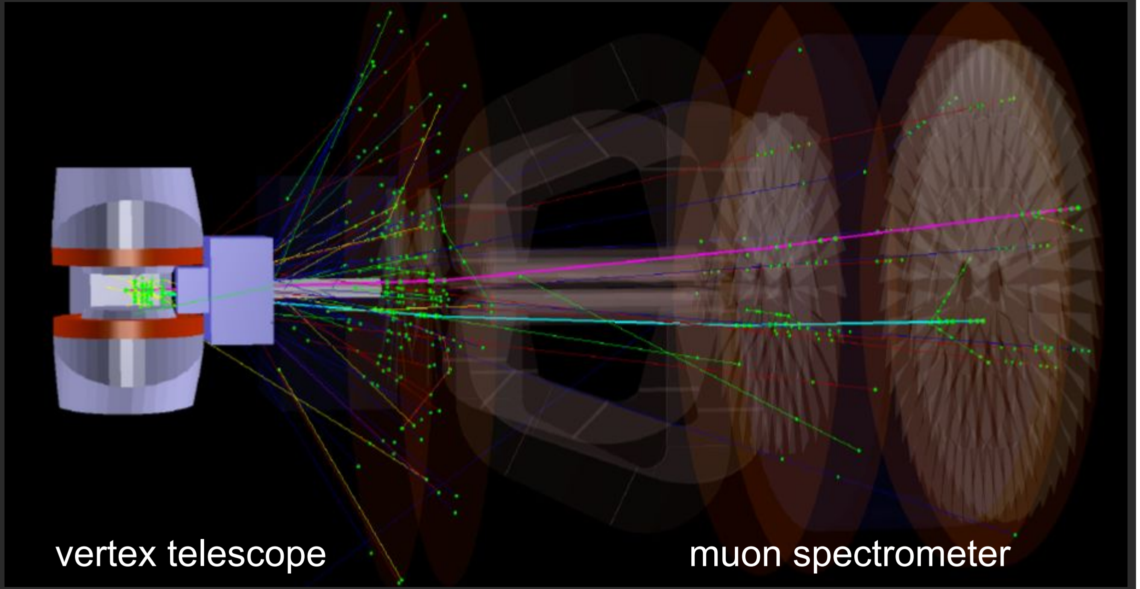
- first evidence recently claimed by NNPDF group based on LHCb data (Nature 608,483(2022))

How to measure quarkonium in NA60+

Charmonium production studied via

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



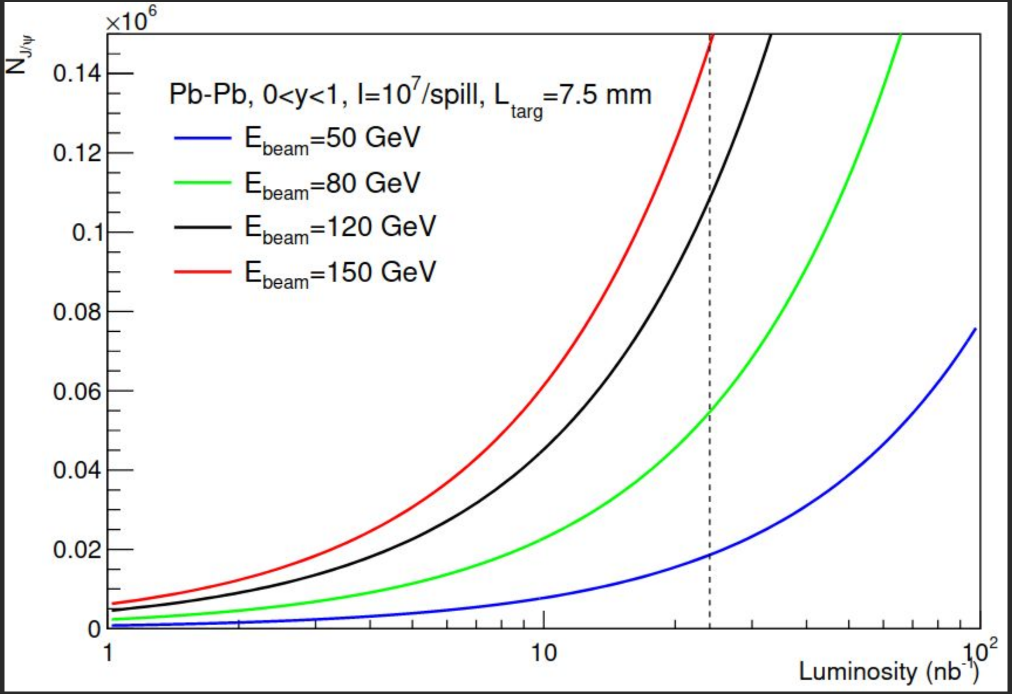


Muon tracks obtained matching tracks in vertex and muon spectrometer

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

J/ψ performance study in Pb-Pb

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



Assuming:

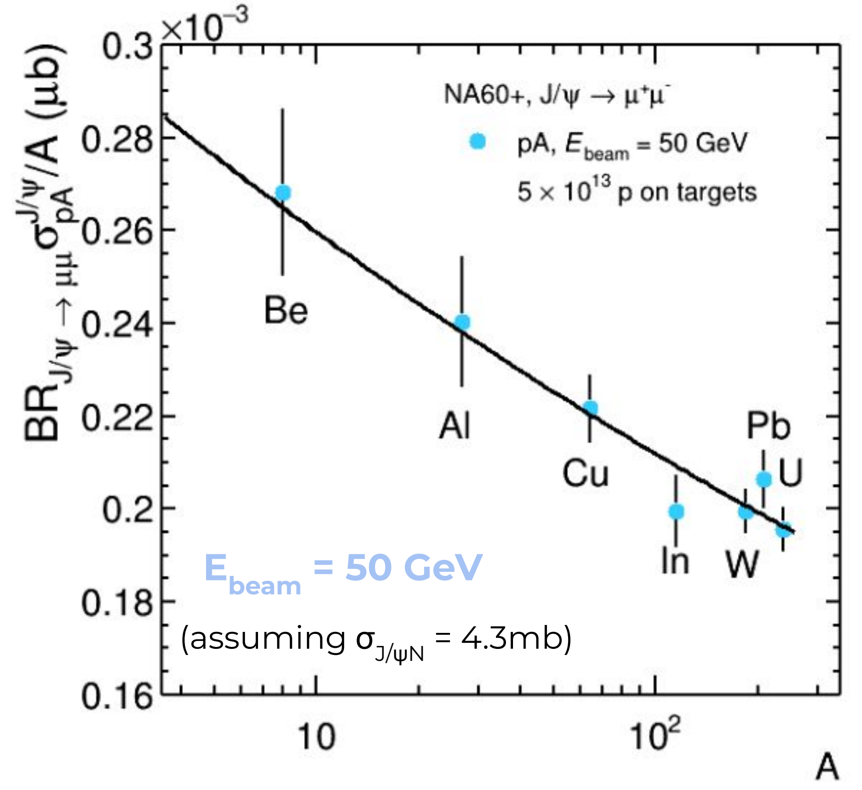
- I_{beam}~10^7 Pb/spill, 7.5 mm target, 1 month data taking→ L_{int}~24 nb^{-1}
- a factor 3 overall suppression (CNM+ QGP)

⇩

NA60+ can aim at

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

J/ψ performance study in pA



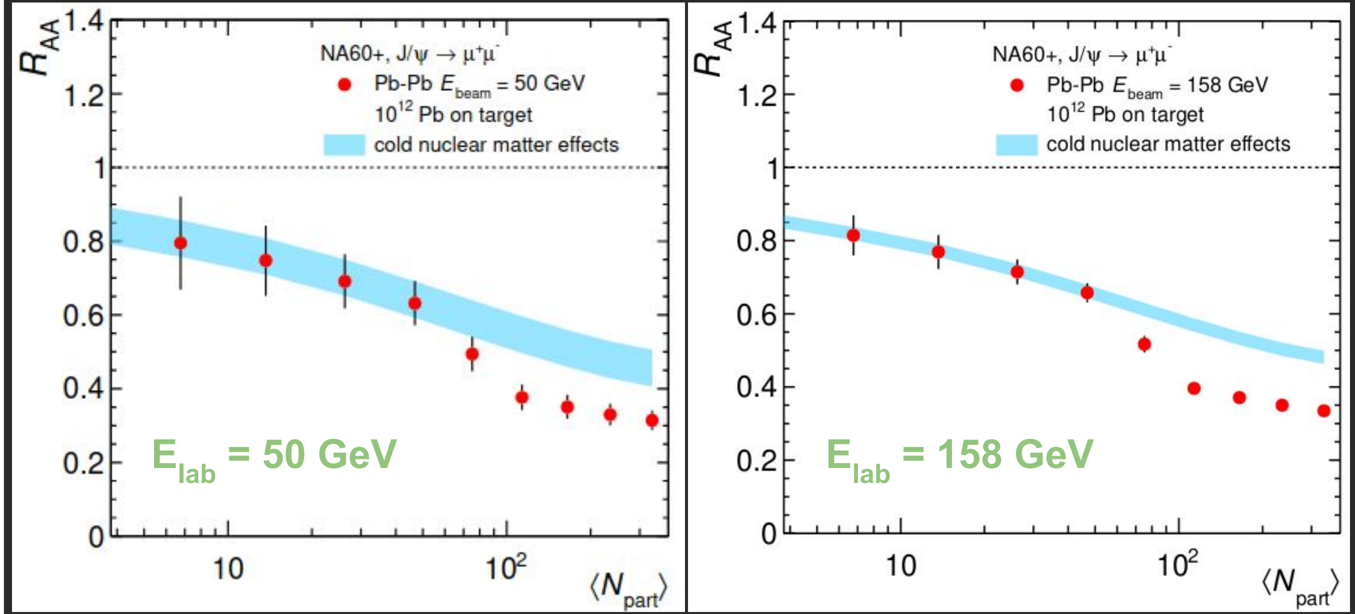
Assuming:

I_{beam}~8 10^8 p/spill, 7 targets (10% λ_I in total)

NA60+ can aim at

~6000 J/ψ at 50 GeV
~50000 J/ψ at 158 GeV

J/ψ R_{AA} estimate



Based on

- 30 days in PbPb, I_{beam} = 1e^7/spill
- 15 days in pp, I_{beam} = 8e^8/spill

Assume

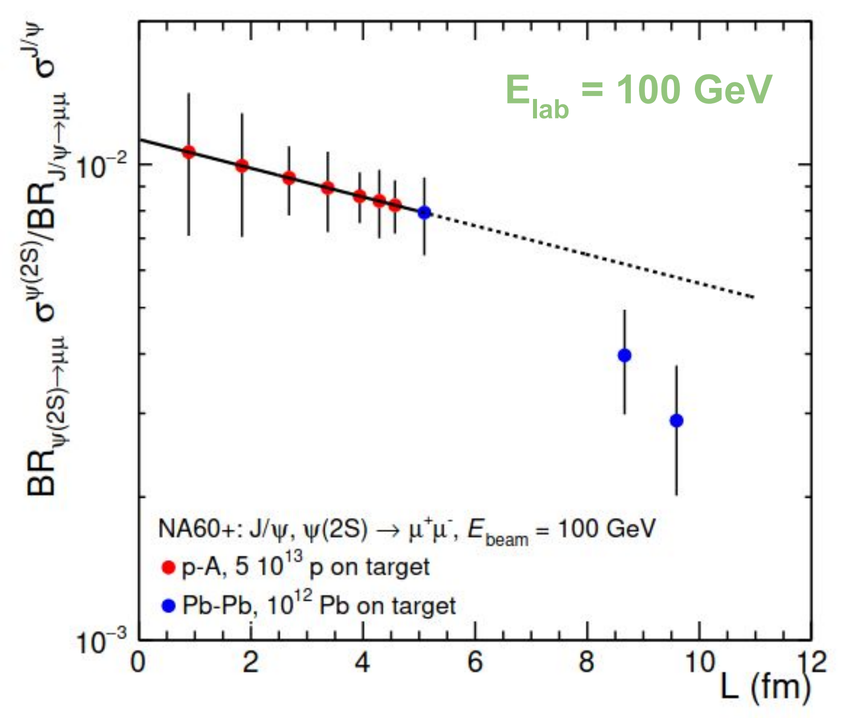
- CNM effects for N_{part}<50
- CNM effects + 20% QGP suppression for N_{part}>50

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

ψ(2S)

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

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

- 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 long shutdown 3

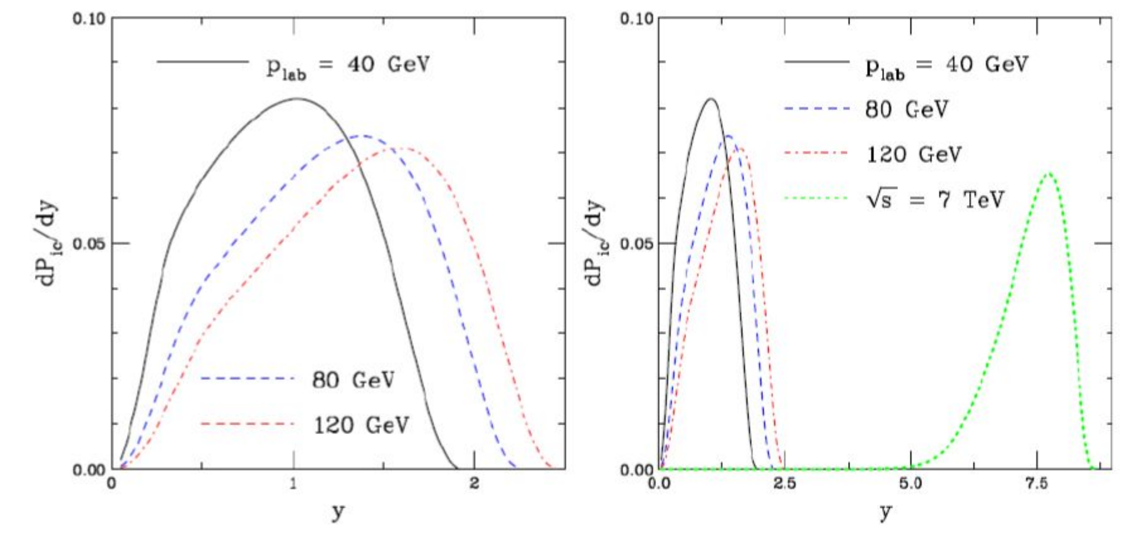
Feedback on physics program and participation to the NA60+ realization is welcome!

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

Backup

Intrinsic charm

Intrinsic charm component of the hadron wave function |uudccbar>
Leads to enhanced charm production in the forward region



Assumed intrinsic charm content varied between 0.1% and 1%

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

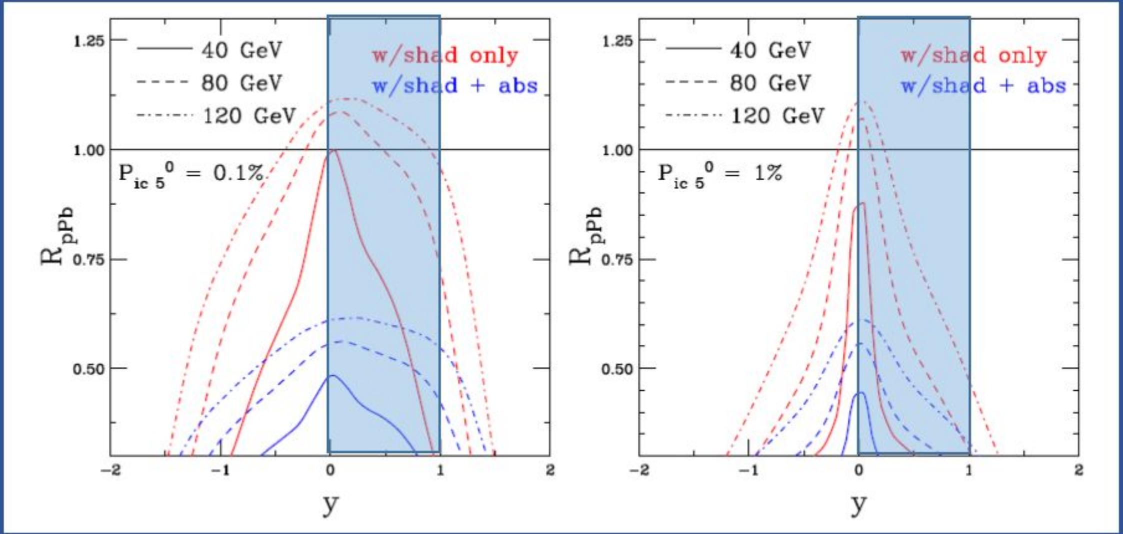
Intrinsic charm

p-Pb collisions:

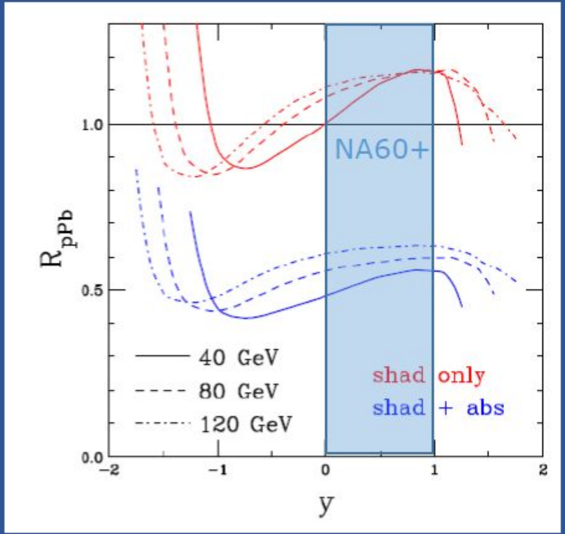
EPPS16 shadowing

σ_{abs} = 9, 10, 11 mb, E_{lab} = 120, 80, 40 GeV

P_{ic} varied between 0.1 and 1%

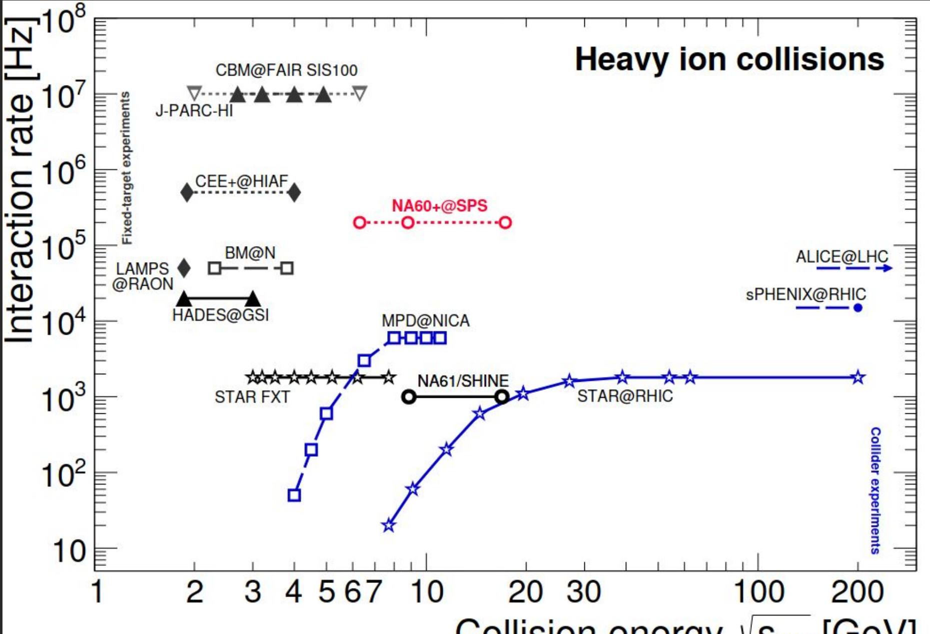


without intrinsic charm



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

Uniqueness of NA60+



T. Galatyuk, NPA 982 (2019)

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

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

In the SPS energy range, no other existing/foreseen facilities that can approach this level of performance

Complementarity with experiments accessing:

- Different (hadronic) observables in the same energy range (STAR BES, NICA, NA61)
- Similar observables in a lower energy range (CBM)