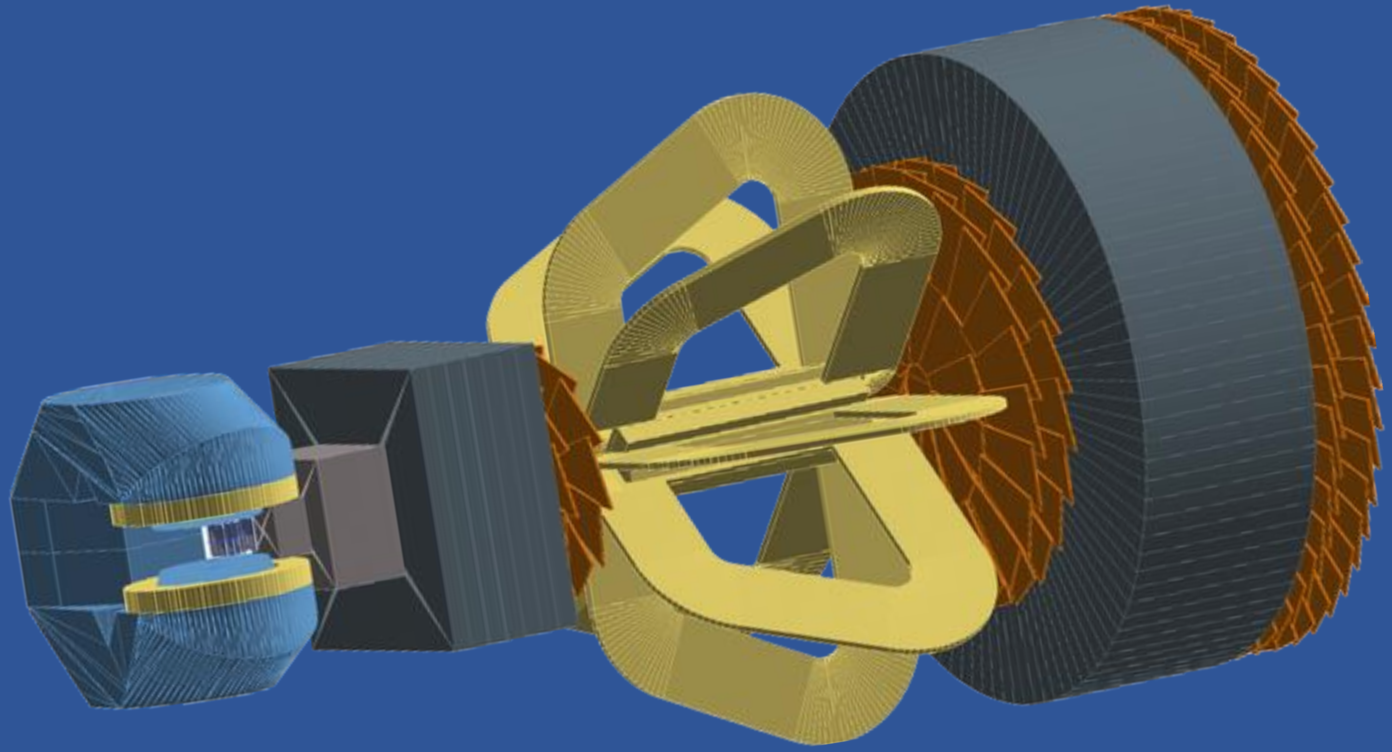
Measuring open/hidden charm at SPS energy in the NA60+ experiment

E. Scomparin – INFN Torino (Italy)



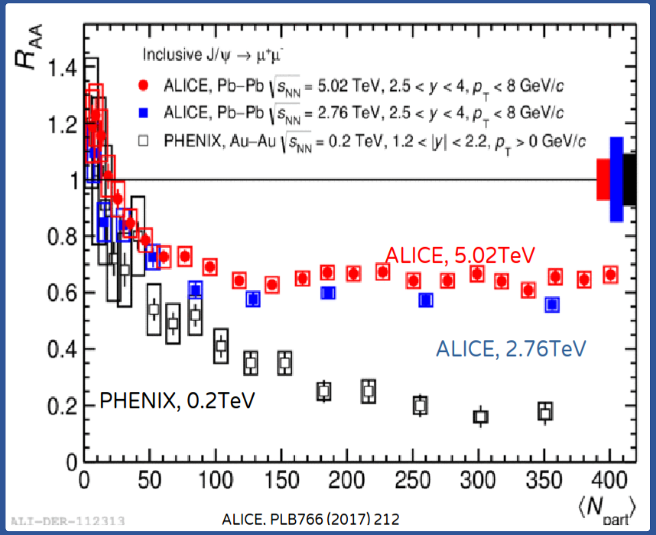
EXPLORING QUARK-GLUON PLASMA THROUGH SOFT AND HARD PROBES

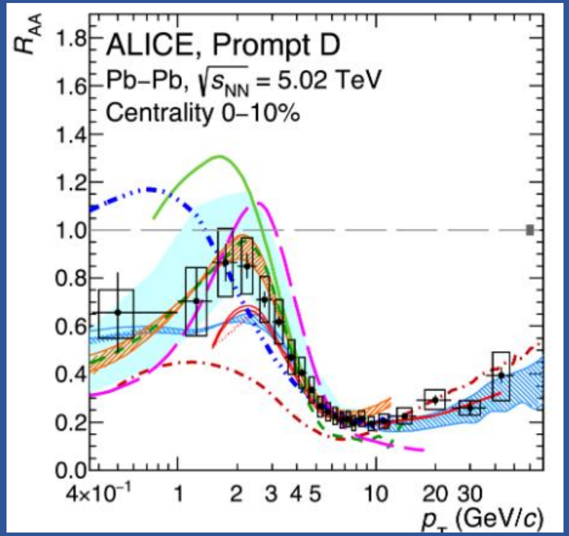
MAY 29-31, 2023

BELGRADE (SERBIA)

Introduction

- ❑ **Open charm and charmonia** in nuclear collisions → probe QGP
- ❑ Extensive information available at collider energy





- ❑ At **fixed target energies**
  - ❑ **Few results on open charm** production at top SPS energy
    → Indirect measurement from NA60 (IMR dilepton spectrum)
    → Upper limit on D^0 by NA49
  - ❑ **Many results on charmonia, only** at top SPS energy → J/ψ, ψ(2S)
  - ❑ Is it meaningful/relevant to revive these studies and **extend them to lower energy ?**
  - ❑ An experiment is being proposed with this aim → **NA60+ at CERN SPS** (also focuses on electromagnetic probes!)

It is crucial to sharpen the physics program in this area, your feedback is important!

A new experiment at the CERN SPS

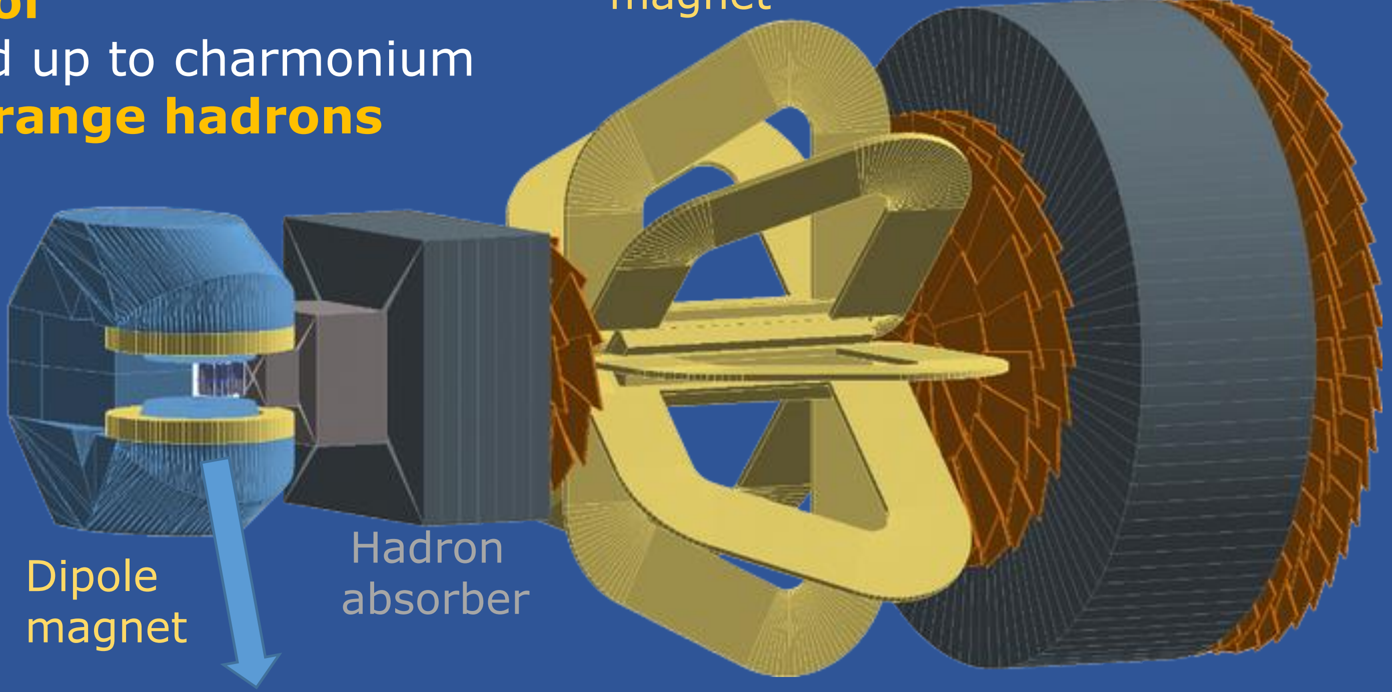
- Goal: **high precision measurements of**
  - **dimuon spectrum** from threshold up to charmonium
  - hadronic decays of **charm and strange hadrons**

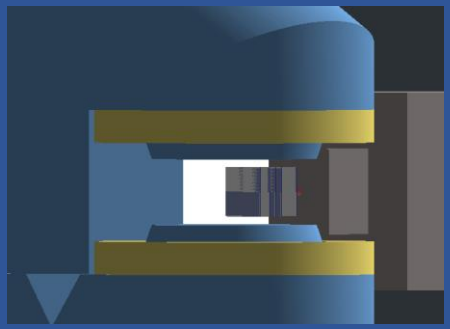
- **Energy scan** with a Pb beam
  → $6<\sqrt{s_{NN}}<17$ GeV

- Based on a
  - **muon** spectrometer (toroid field)
  - **vertex** spectrometer (dipole field)

- High luminosity, to access rare probes of QGP
  → $\sim 10^{6}\ s^{-1}$ Pb ions/s

- **p-A program**
  - Reference for Pb-Pb
  - Specific items (nPDF, Drell-Yan,…)





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

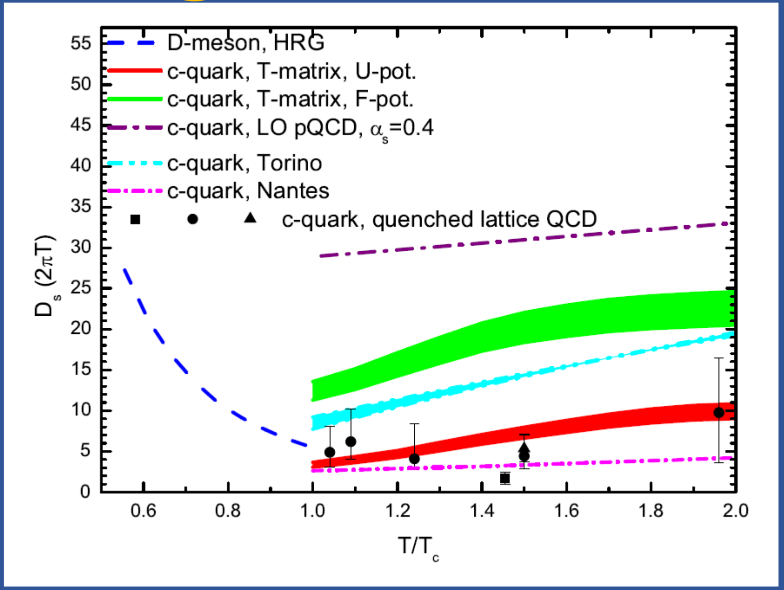
Open charm in AA collisions – fixed target

QGP transport properties

- Charm diffusion coefficient depends on the medium temperature, larger in the hadronic phase

- 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

Prino, Rapp, JPG43 (2016) 093002

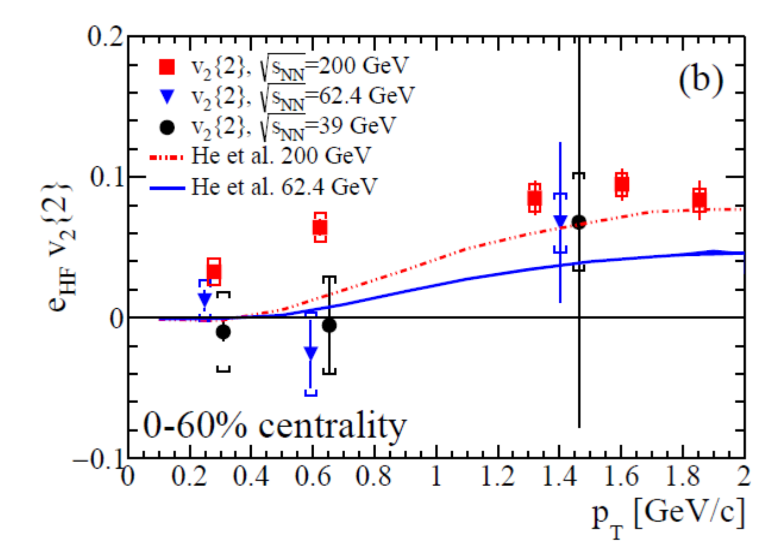


Charm thermalization

- 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, PRC 95 (2017) 034907

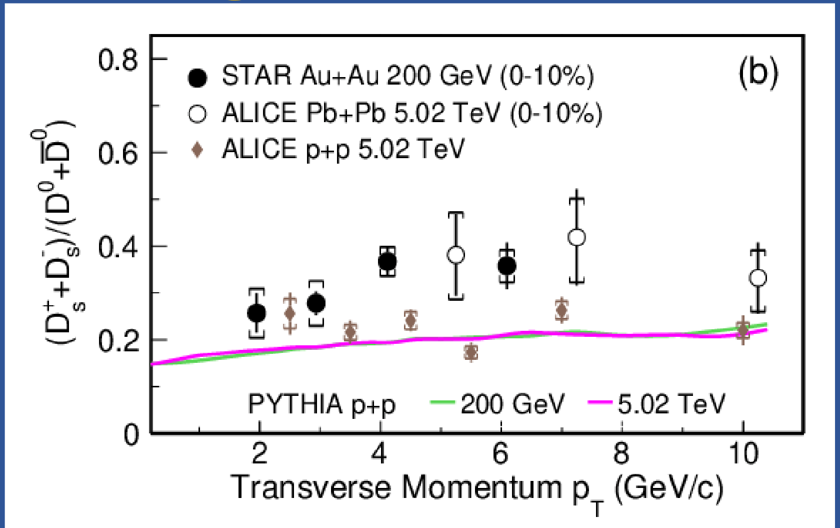


Open charm in AA collisions – fixed target

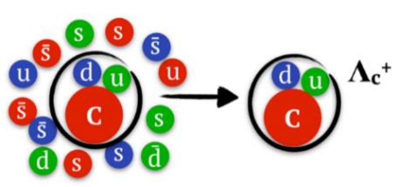
Hadronization mechanisms

- ❑ Strange/non-strange meson ratio (D_s/D)
- ❑ D_s/D enhancement expected in A-A collisions
  → **recombination** in the strangeness rich QGP

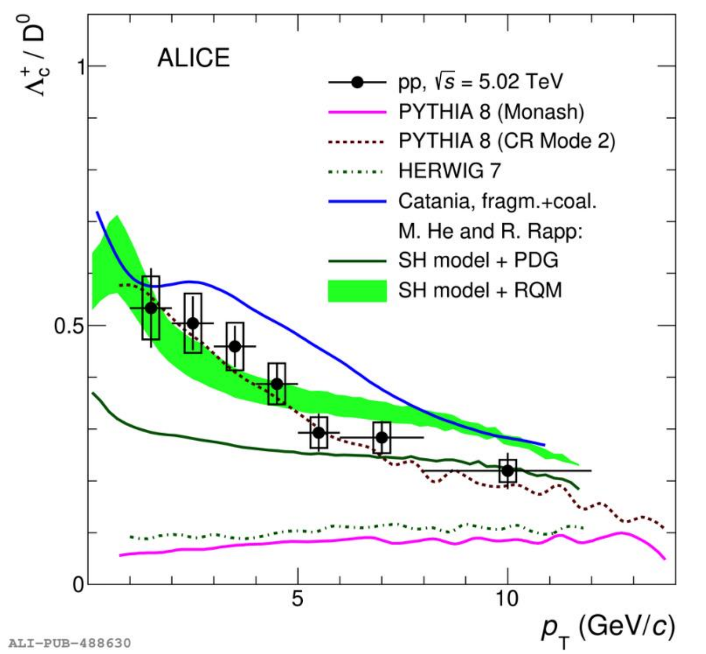
STAR, PRL 127 (2021) 092301
ALICE, PLB827 (2022) 136986



- ❑ Baryon/meson ratios (Λ_c/D)
- ❑ Expected to be enhanced in A-A
  → hadronisation via coalescence
- ❑ Interesting also in p-A since Λ_c/D^0 in pp (p-Pb) at LHC is higher than in e^+e^-



ALICE, PRL127 (2021) 202301



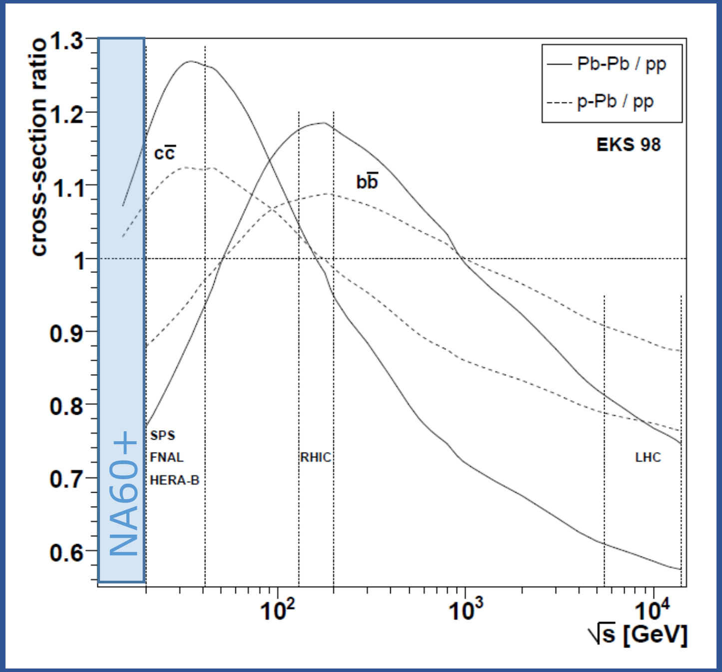
Total charm cross section

- ❑ Limited measurements so far (NA60,NA49) because of low yields
- ❑ Precise measurement
  → reconstruct mesons and baryons ground states
- ❑ Ideal reference for charmonia

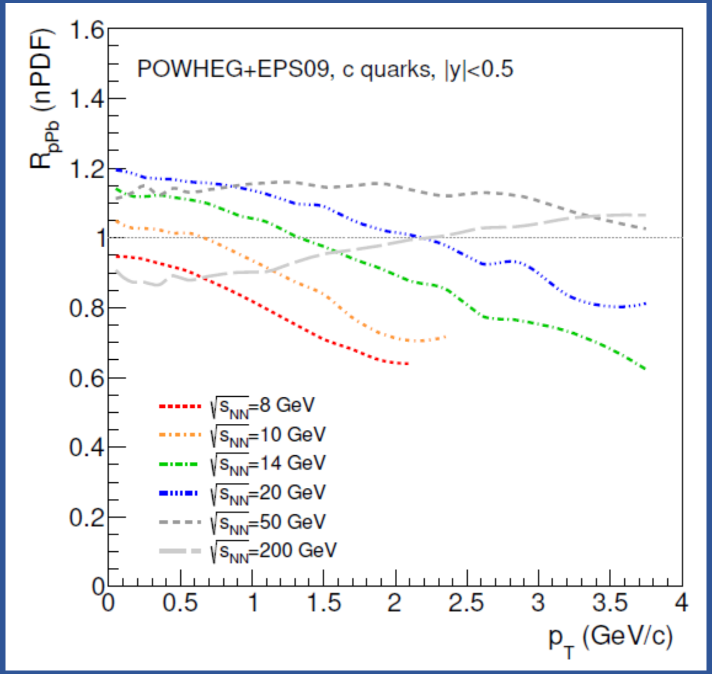
Open charm pA collisions: fixed target

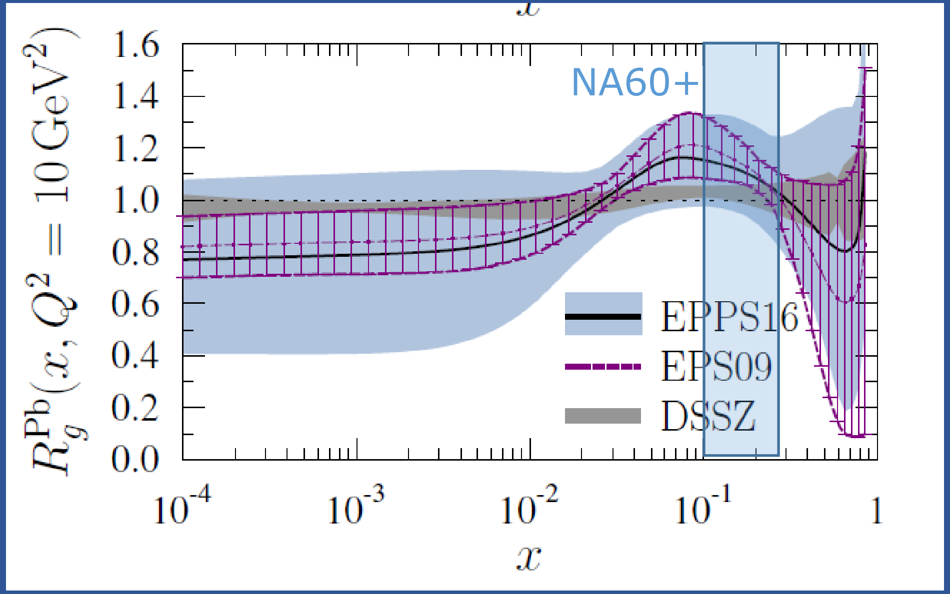
Nuclear PDFs via D-meson production in p-A

- Perform measurements with various nuclear targets to access the A-dependence of nPDF
- NA60+ offers a unique opportunity to investigate the **large x_{Bj} region** (study ratio to pA/pBe)
  - → EMC and anti-shadowing effects, $0.1<x_{Bj}<0.3$ at $Q^2\sim10\text{-}40$ GeV^2



Lourenco, Wohri,
Phys.Rept.433 (2006) 127



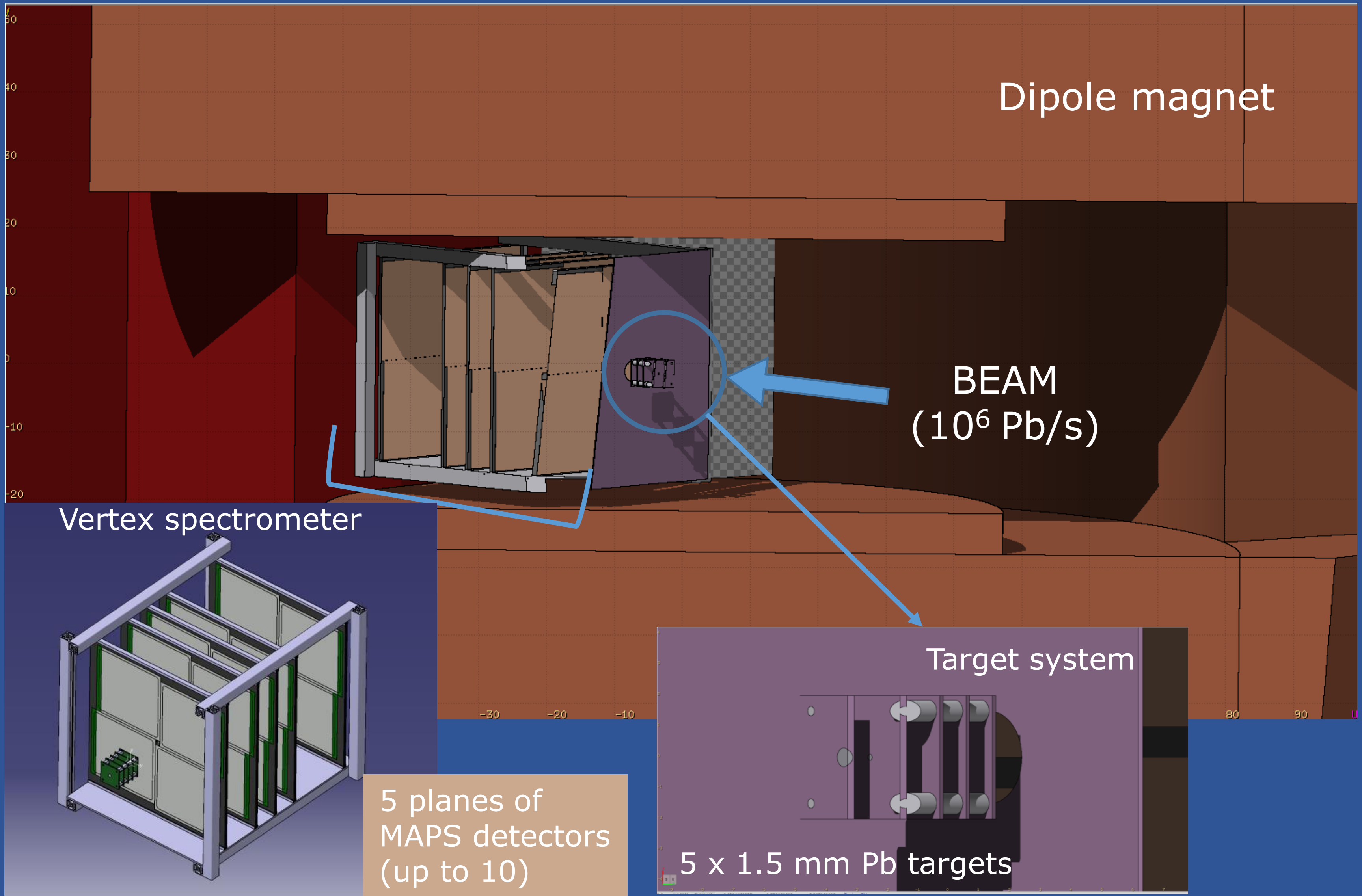


Eskola et al. , EPJ C77 (2017) 13

Towards a precise measurement of open charm at SPS energy

A measurement of **hadronic decays** is required

	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%

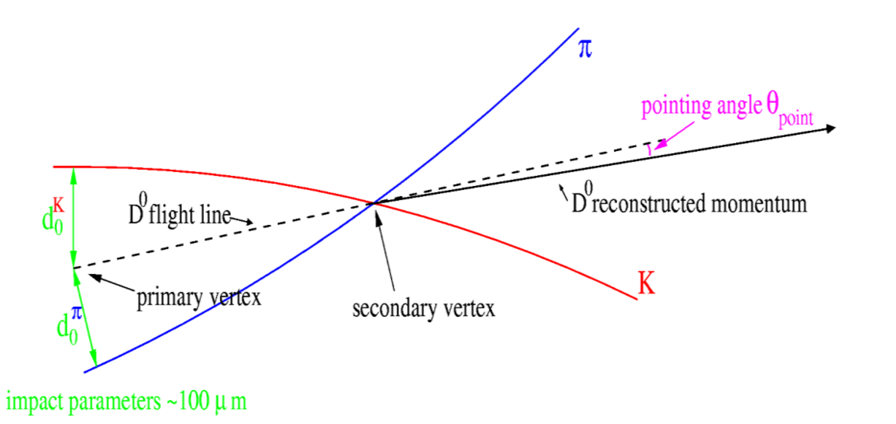


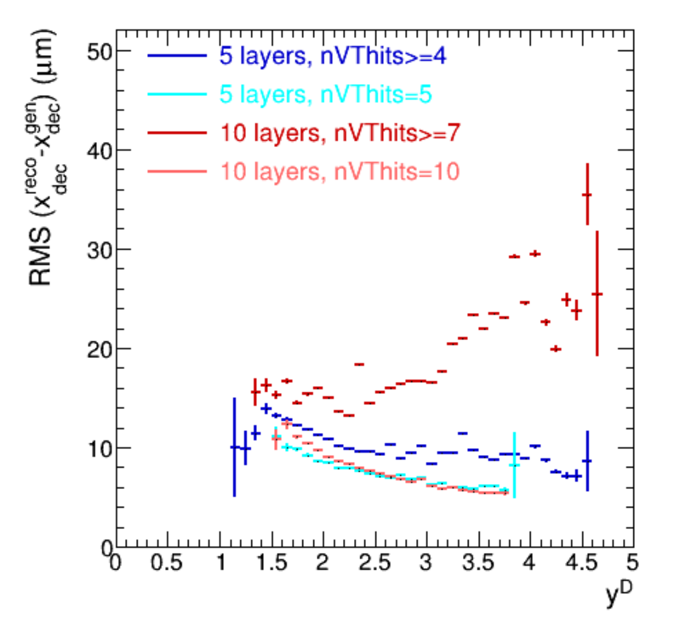
D-meson performance studies

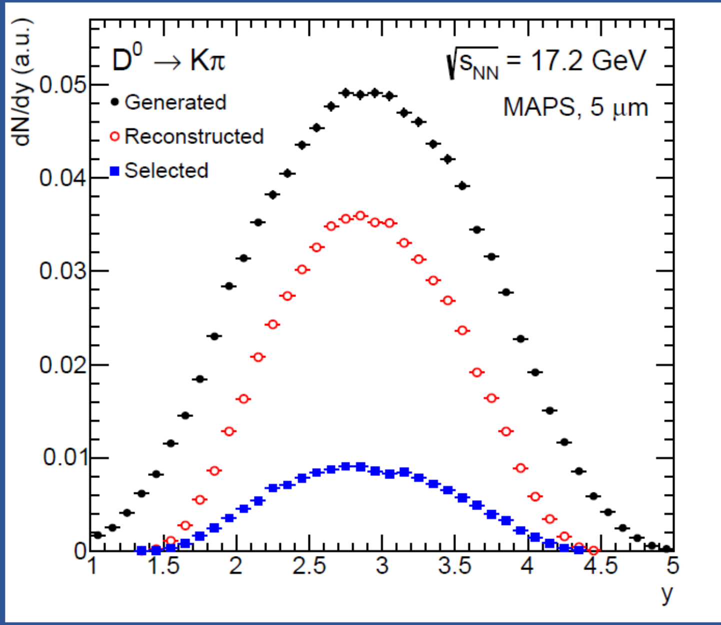
- **Fast simulation** for central Pb-Pb collisions:
  - D-meson signal simulation: p_T and y distributions from POWHEG-BOX+PYTHIA
  - Combinatorial background: dN/dp_T and dN/dy of p, K and p from NA49

  - Parametrized simulation of VT detector resolution + track reconstruction with Kalman filter

  - Reconstruct D-meson decay vertex from decay tracks
  - Geometrical selections based on displaced decay vertex topology
    - For D^0 in central Pb-Pb:
      - initial S/B ~10^{-7}
      - → after selections S/B ~0.5

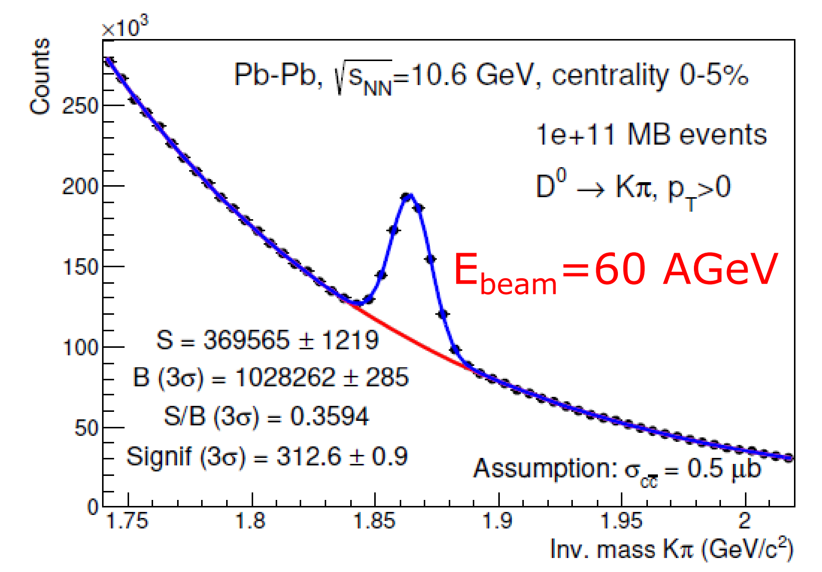




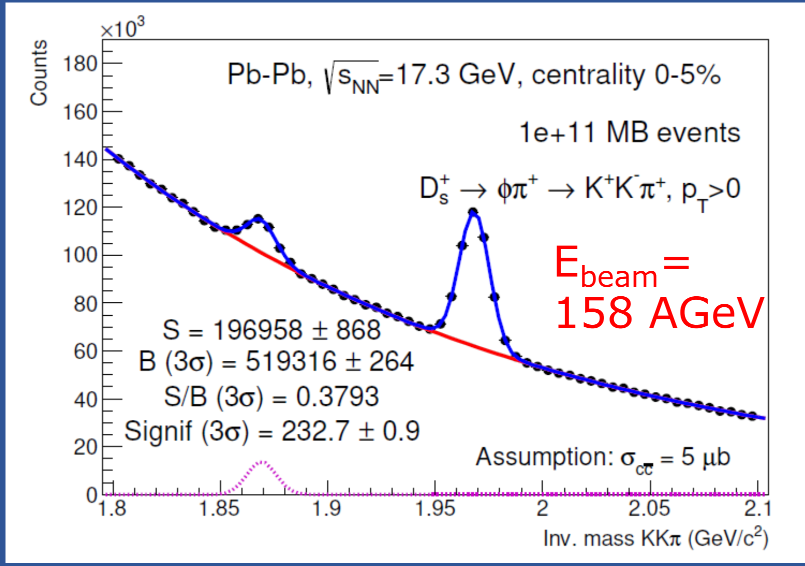


Charm hadrons: performance plots

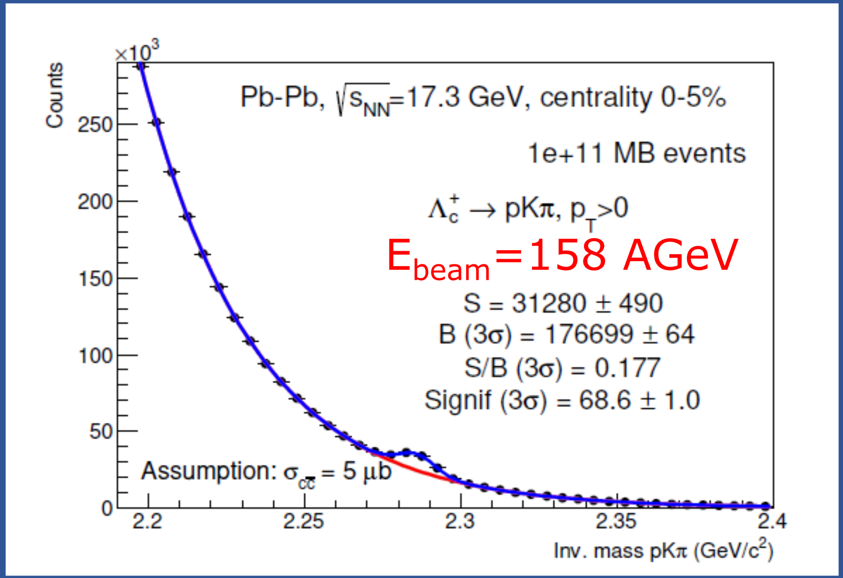
- With 10^{11} minimum bias Pb-Pb collisions (1 month of data taking)
  - More than $3 \cdot 10^6$ reconstructed **D^0** in central Pb-Pb collisions at $\sqrt{s_{NN}}$=17.3 GeV
    - Allows for differential studies of yield and v_2 vs. p_T, y and centrality
  - D^0 accessible also at lower collision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



$D^0 \rightarrow K\pi$



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



$\Lambda_c^+ \rightarrow pK\pi$

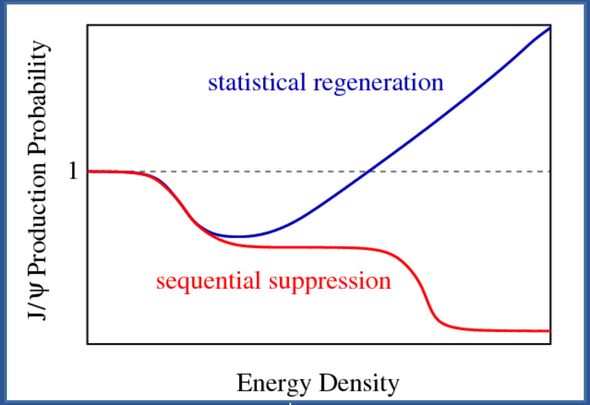
Charmonia: high vs low √s

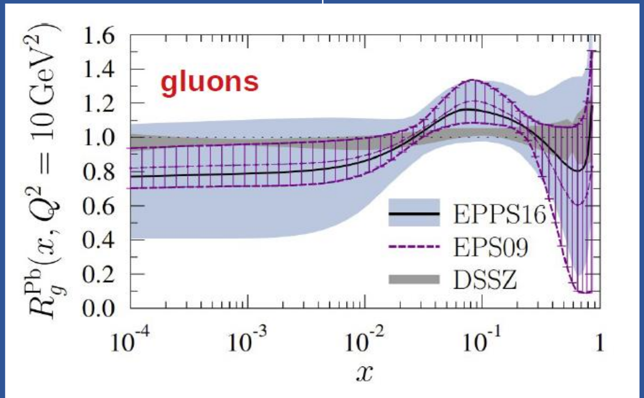
Collider

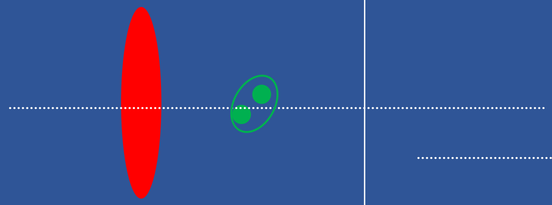
Hot matter effects: regeneration counterbalances (overcomes) suppression

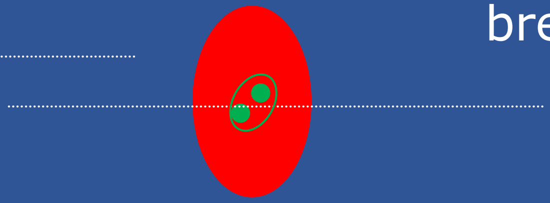
Initial state effects:
shadowing
$x \sim 10^{-5}$ ($y \sim 3$),
$x \sim 10^{-3}$ ($y = 0$),
$x \sim 10^{-2}$ ($y \sim -3$)

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









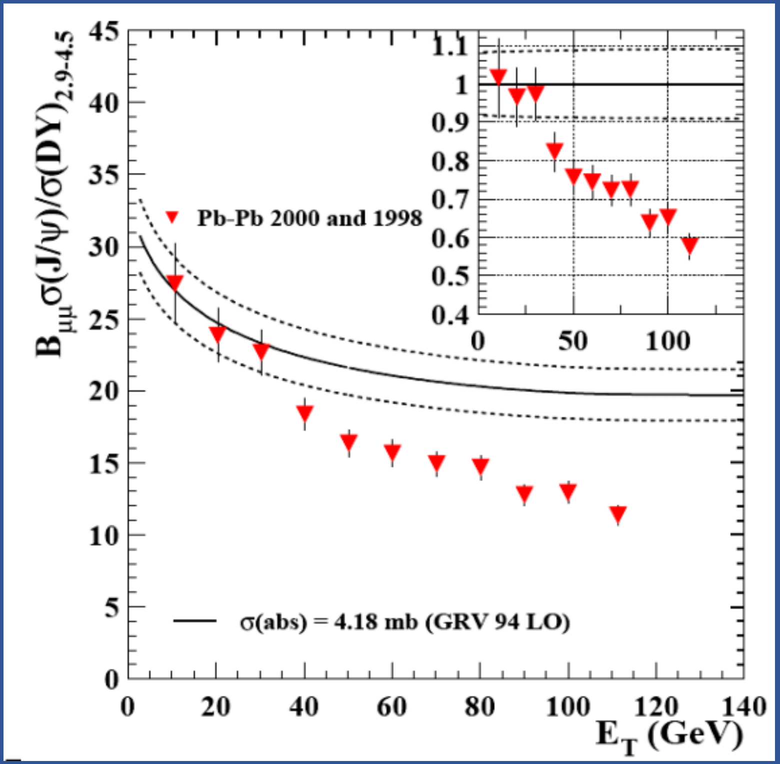
Fixed target

Hot matter effects:
suppression effects (if existing) dominate

Initial state effects:
moderate anti-shadowing
$x \sim 10^{-1}$ ($y = 0$)

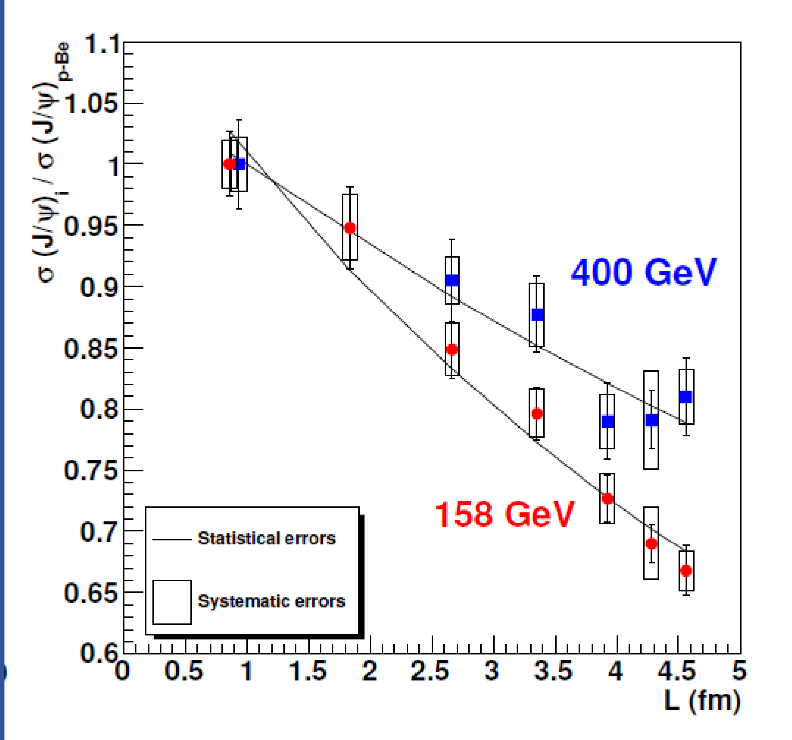
(Final state) CNM effects:
break-up in nuclear matter can be sizeable
$\tau = L/(\beta_z\gamma) \sim 0.5$ fm/c($y = 0$)

J/ψ suppression: Pb-Pb at top SPS energy



- Contrary to open charm, accurate studies were performed at √s=17.3 GeV (NA50, NA60)
- J/ψ yields normalized to Drell-Yan reference
- QGP-induced suppression evaluated with respect to a CNM reference obtained with systematic p-A studies

~30-40% anomalous suppression effect
possibly due to disappearance of feed-downfrom χ_c and ψ(2S)



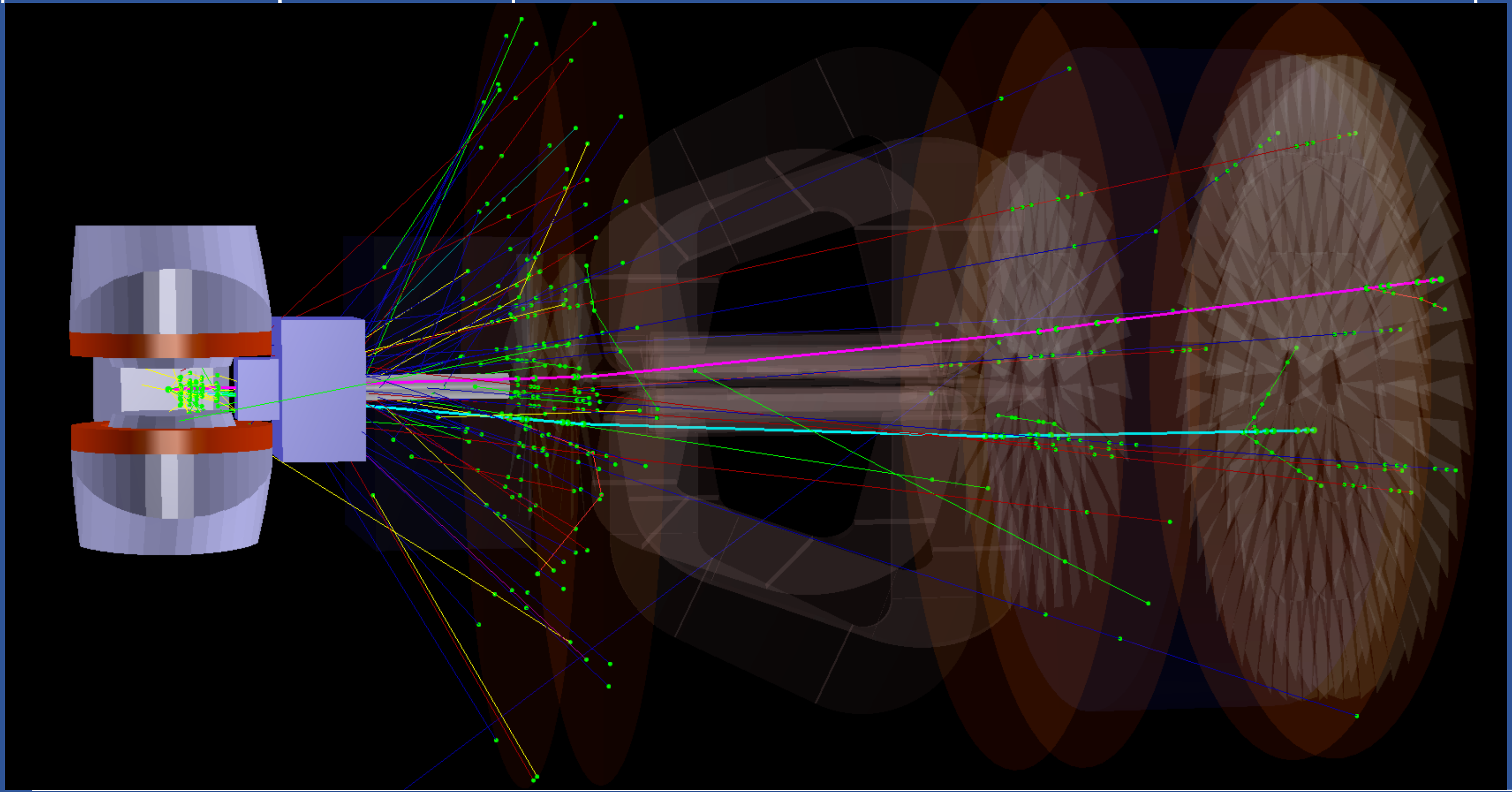
- p-A
- Shadowing effects are moderate
- Dominated by nuclear absorption
- **Strong √s-dependence**
  → CNM-induced suppression may become the dominant effect at low energy

Charmonia below top SPS energy

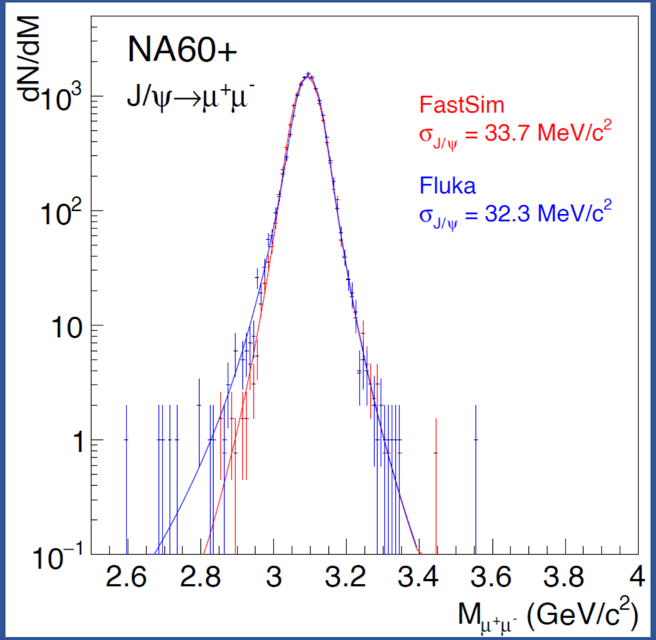
Track matching

Vertex tracking (dipole field)

Muon identification in a spectrometer (toroidal field)



Track matching: measure muon kinematics before multiple scattering and energy loss



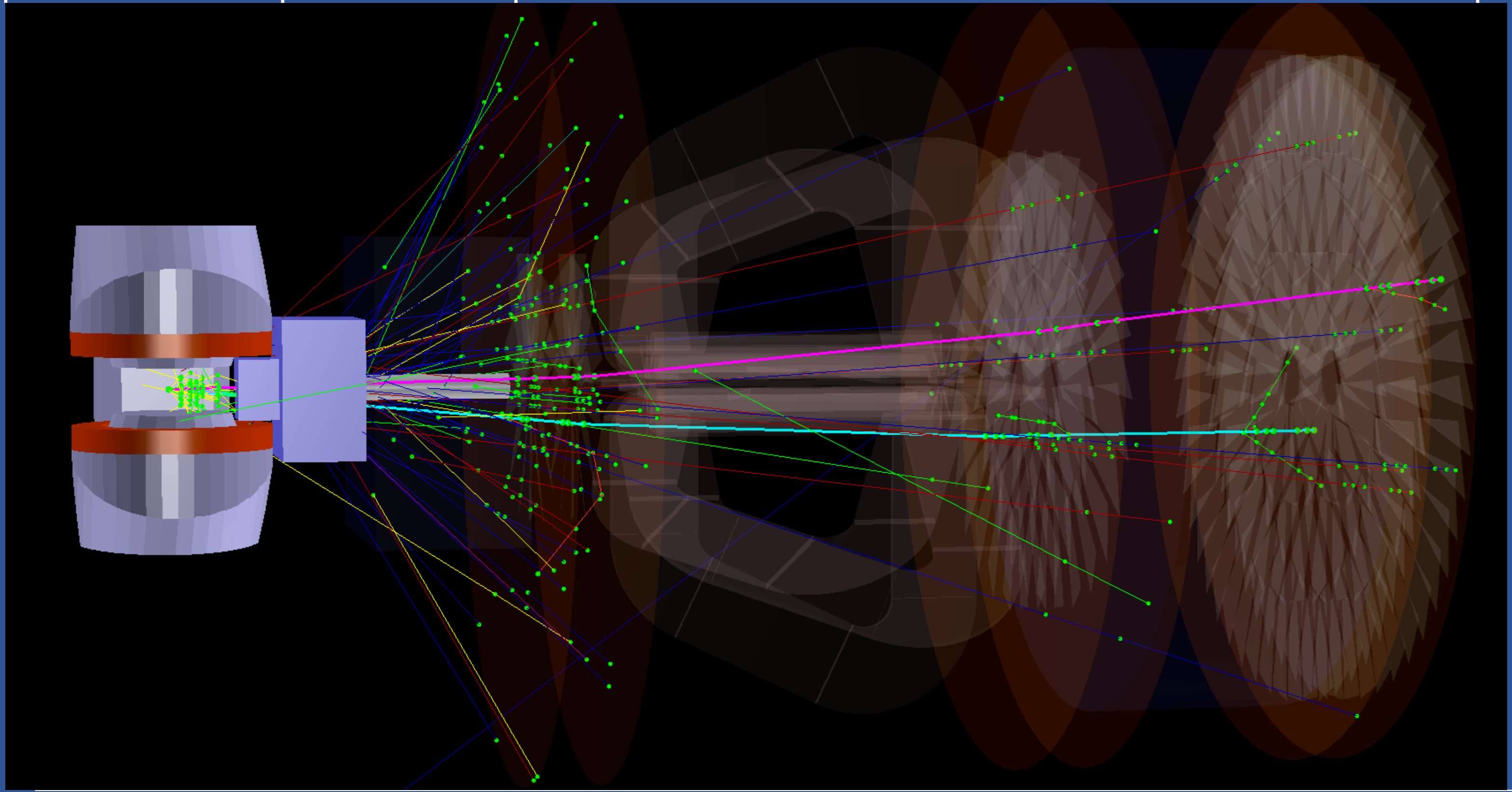
- ❑ J/ψ and $\psi(2S)$ in the $\mu^+\mu^-$ decay channel
- ❑ $\chi_c \rightarrow J/\psi\ \gamma$, with γ measured via conversion in a lepton pair in the vertex telescope

Charmonia below top SPS energy

Track matching

Vertex tracking (dipole field)

Muon identification in a spectrometer (toroidal field)

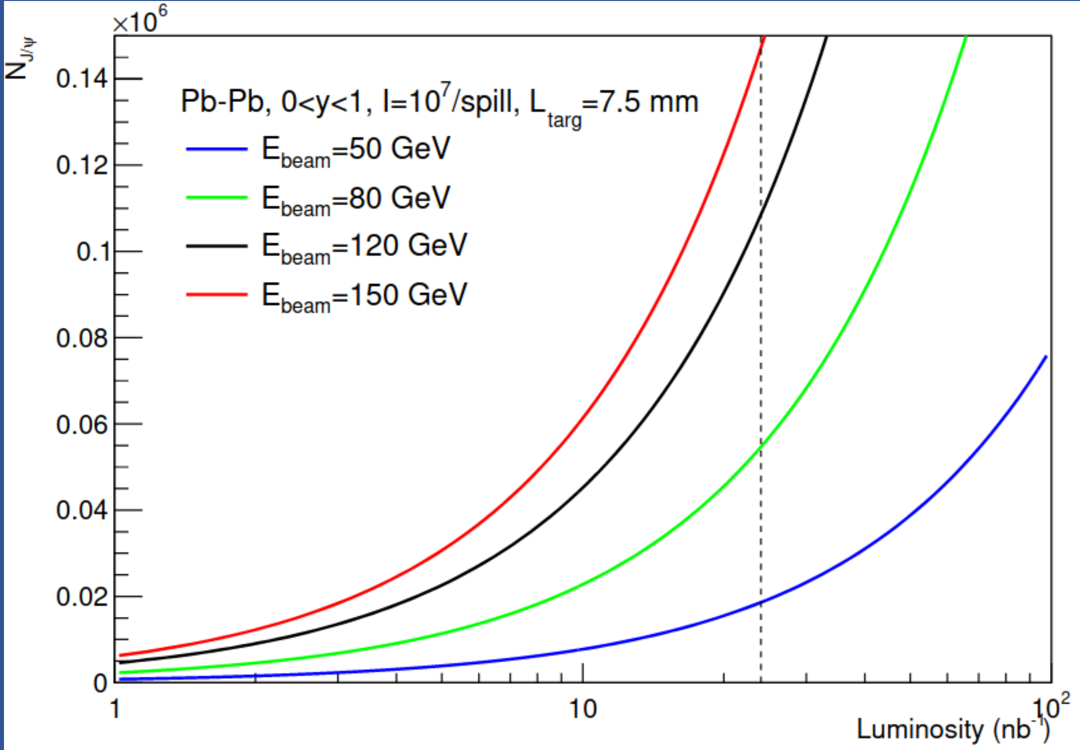


Quarkonium production not studied below top SPS energies!

Perform an energy scan in **E_{lab} = 20 – 158 GeV**

- ❑ Decreasing √s:
  - ❑ **Onset of χ_c and $\psi(2S)$ melting**
    → to be correlated to T measurement via thermal dimuons

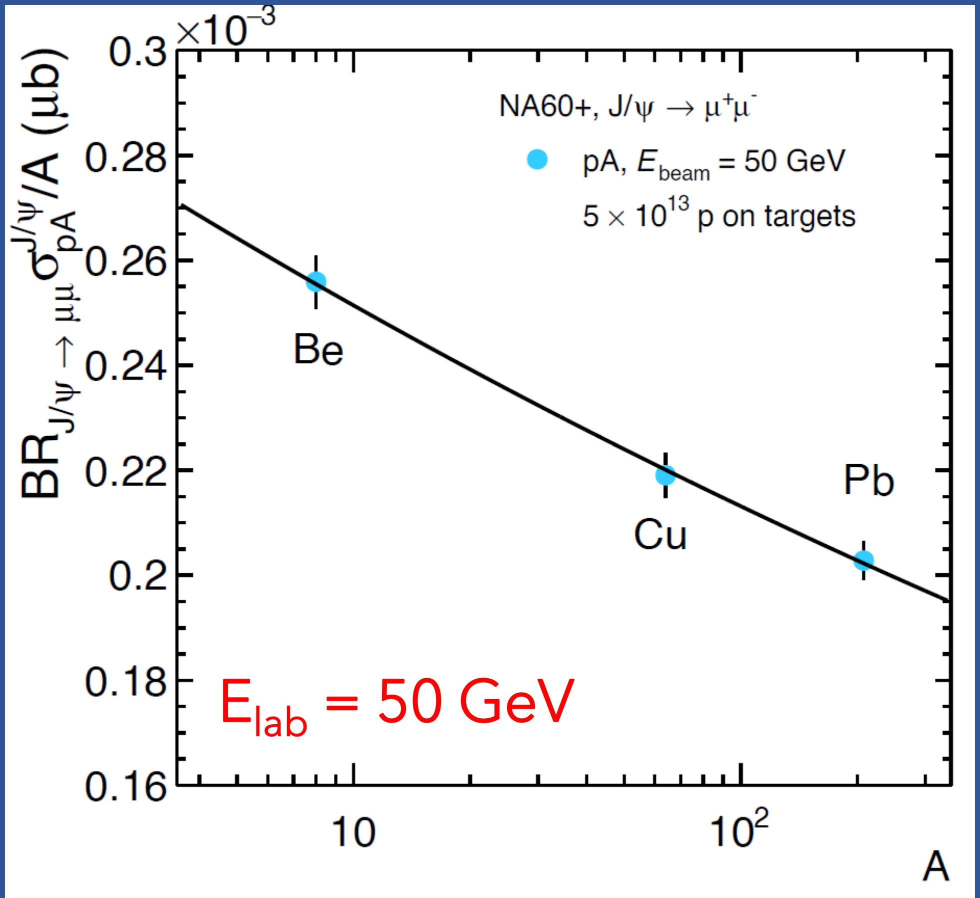
Pb-Pb collisions: expected statistics



- With I_{beam}~10^6 Pb/s, 7.5 mm Pb target (8.5 g cm^{-2}) and 1 month of data taking → **L_{int} ~24 nb^{-1}** NA60+ can aim at
  - **~O(10^4) J/ψ at 50 GeV**
  - **~O(10^5) J/ψ at 158 GeV**

- N.B.: a factor 3 overall suppression (CNM + QGP) is assumed in these estimates

p-A collisions: performance



Assume $\alpha_{J/\psi}^{pA} = 0.93$
(as measured at E_{lab} = 400 GeV)

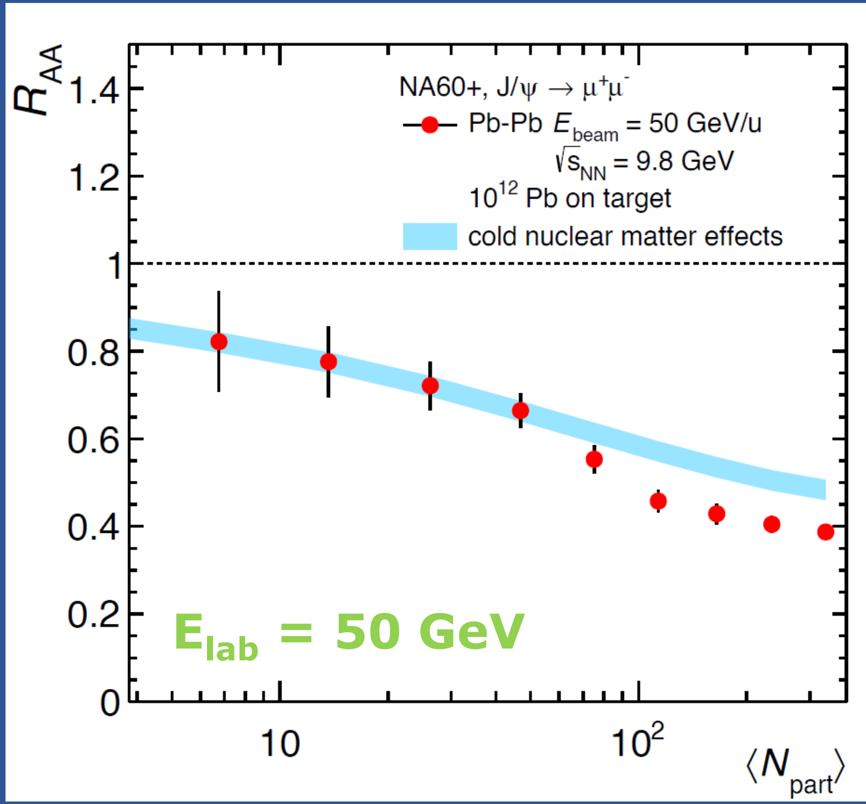
A possible choice: total thickness 8.3 g cm^{-2}

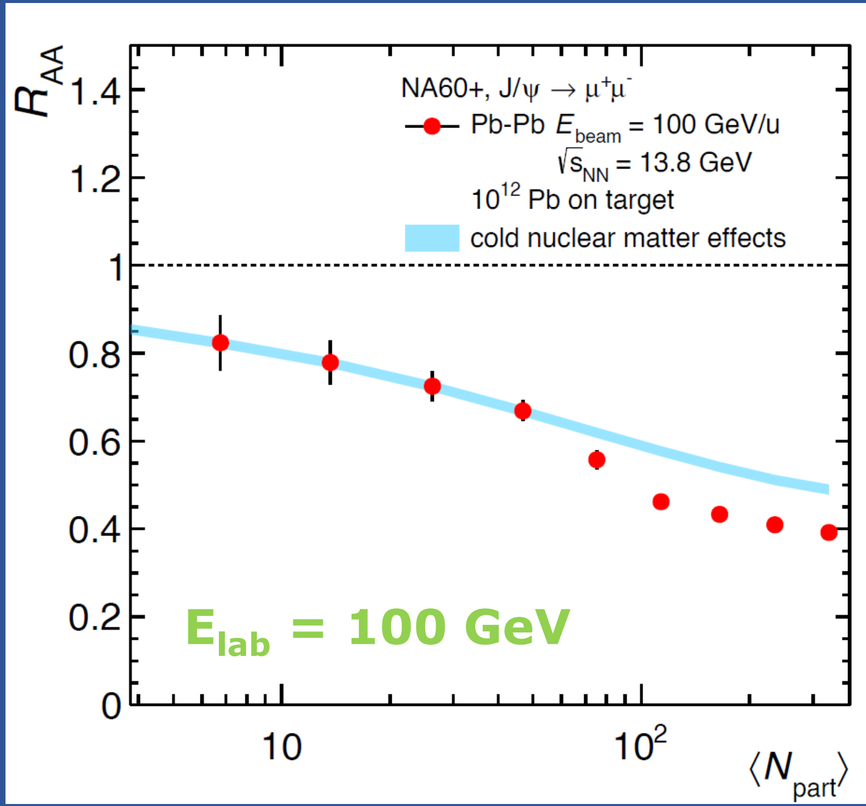
A	Be	Al	Cu	In	W	Pb	U
Thickness (cm)	1.2	0.	0.3	0.	0.	0.3	0.

- 3 nuclear species
- Optimize lever arm of the fit to get σ_{pp}

- With 5 x 10^{13} protons on target the expected statistics in pA is
  - **~8000 J/ψ at 50 GeV**
  - **~60000 J/ψ at 150 GeV**

NA60+, R_{AA} estimate





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

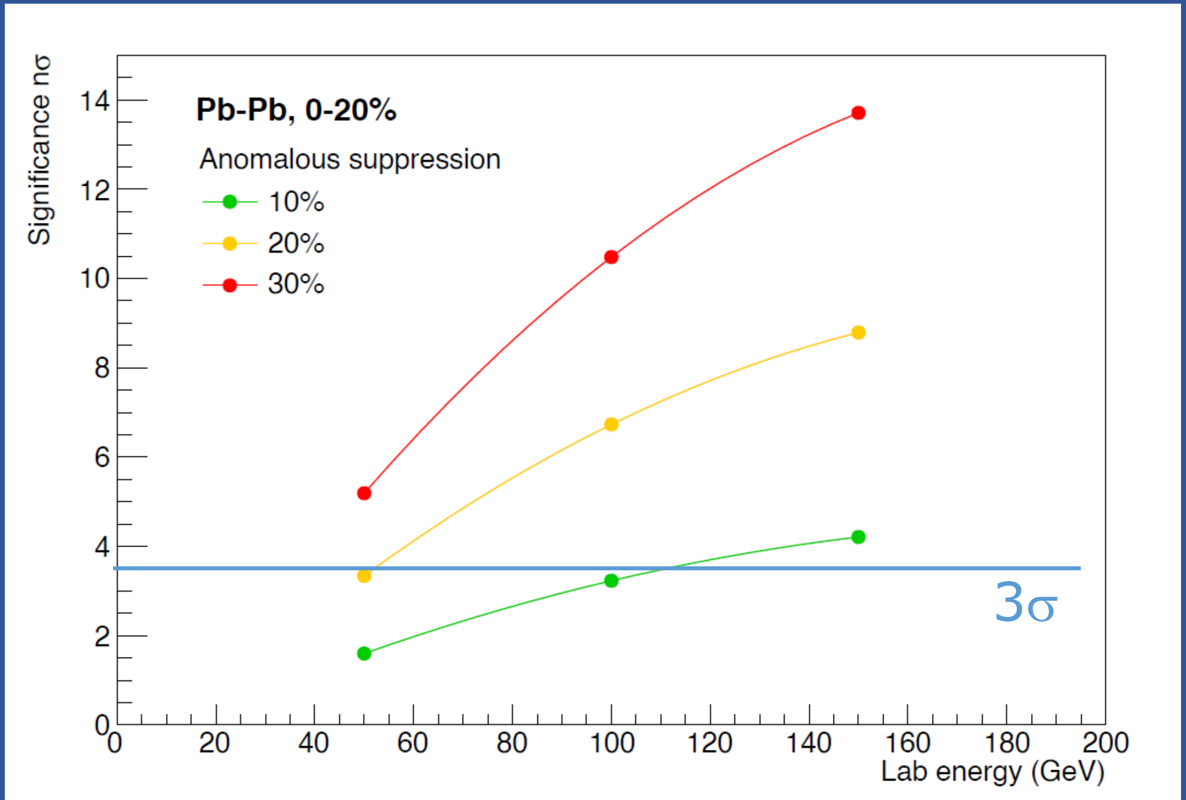
Assume only CNM effects for N_{part}<50 and 20% extra suppression in Pb-Pb for N_{part}>50

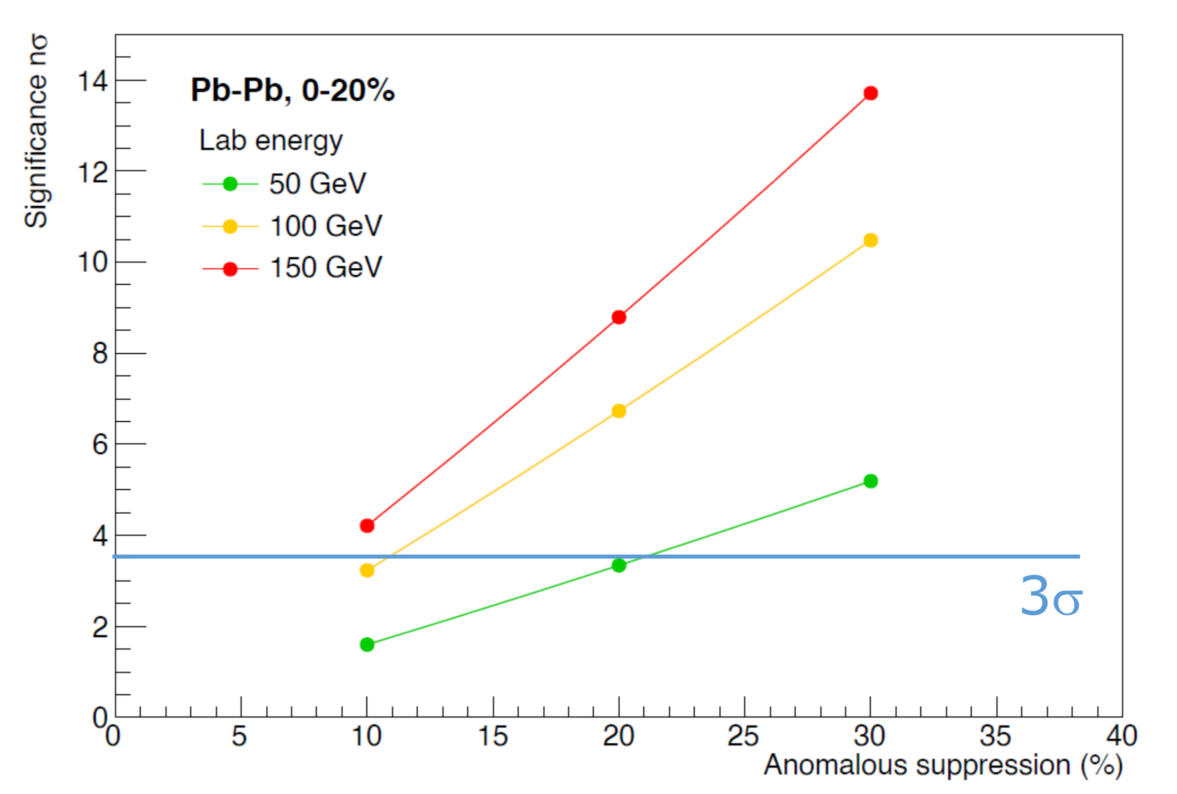
→ **Precise evaluation of anomalous suppression within reach even at low energy**

N.B.: statistical uncertainties only
Assume $\alpha_{J/\psi}^{pA}$ = 0.93 in p-A

NA60+, significance of suppression signal

N.B.: statistical uncertainties only



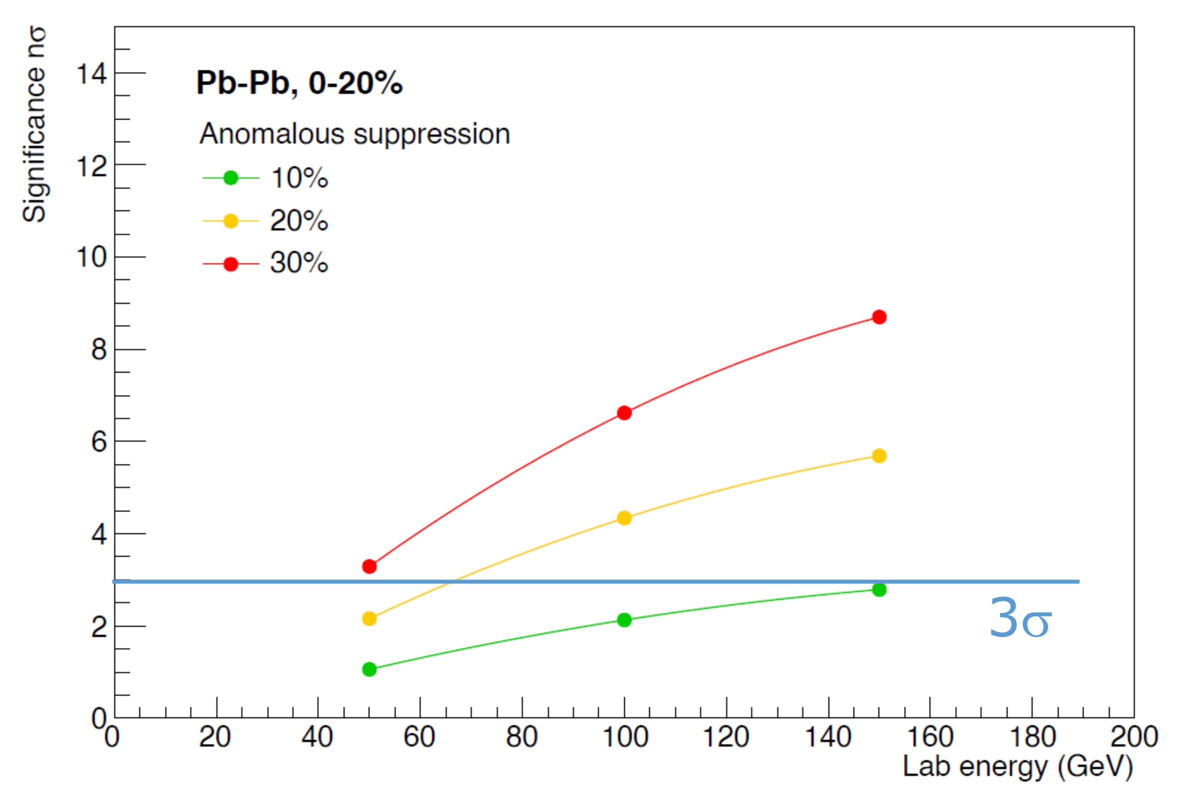


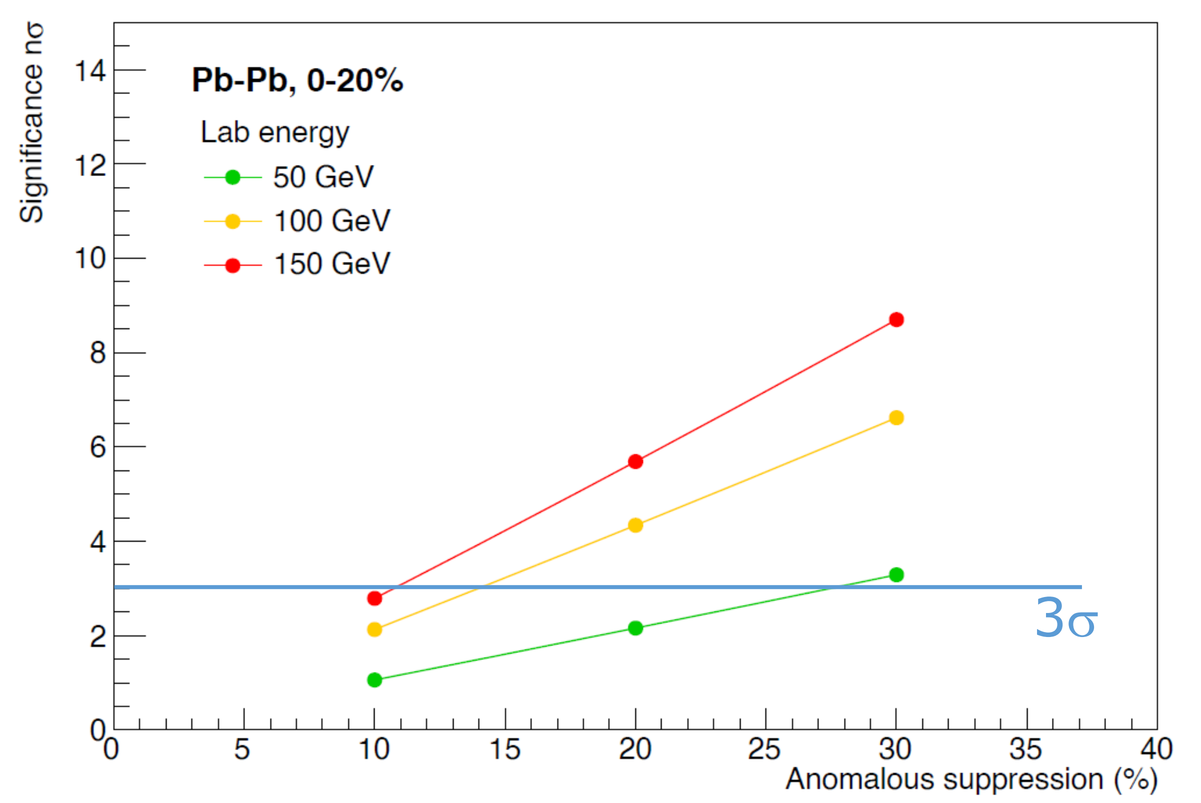
- **10% anomalous suppression** signal detectable at 3σ for E_{lab}>100 AGeV ($\sqrt{s_{NN}}$=13.8 GeV)
- **20% anomalous suppression** signal detectable at 3σ for E_{lab}>50 GeV ($\sqrt{s_{NN}}$=9.8 GeV)

Assume $\alpha_{J/\psi}^{pA}$ = 0.93 in p-A

NA60+, significance of suppression signal

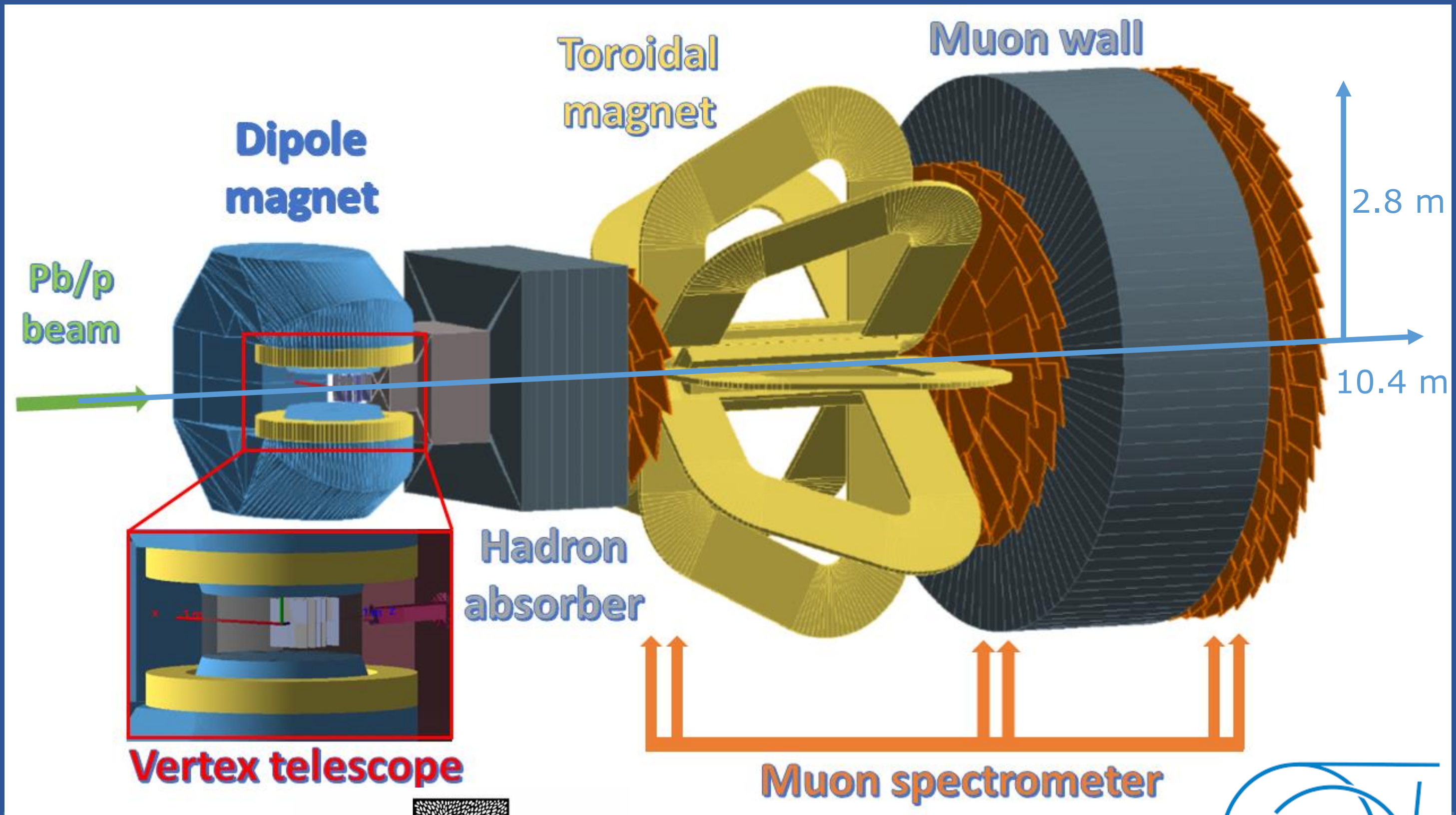
Significance **depends** on strength of p-A suppression: here moving from $\alpha_{J/\psi}^{pA} = 0.93$ to $\alpha_{J/\psi}^{pA} = 0.88$





- ❑ **20% anomalous suppression** signal detectable at 3σ for E_{lab}>60 AGeV ($\sqrt{s_{NN}}$=10.7 GeV)
- ❑ **30% anomalous suppression** signal detectable at 3σ for E_{lab}>50 GeV ($\sqrt{s_{NN}}$=9.8 GeV)

From design to reality



- **Letter of Intent** submitted in 2022
  http://arxiv.org/abs/arXiv:2212.14452
  SPSC encouraged technical proposal
- Submission of **technical proposal** by **2024**
- Construction starts: **2026** (during LS3)
- First data taking: **2029** (together with LHC run 4)
- 7-year running with **Pb beam** (one beam energy per year, from 20 to 150 A GeV)

Conclusions

- **Open charm and charmonia** in nuclear collisions → no results below top SPS energy

- A **new experiment at the CERN SPS** has been designed for precise measurements of heavy-quark production → **NA60+**
- Couples state-of-the-art and well-known detection techniques

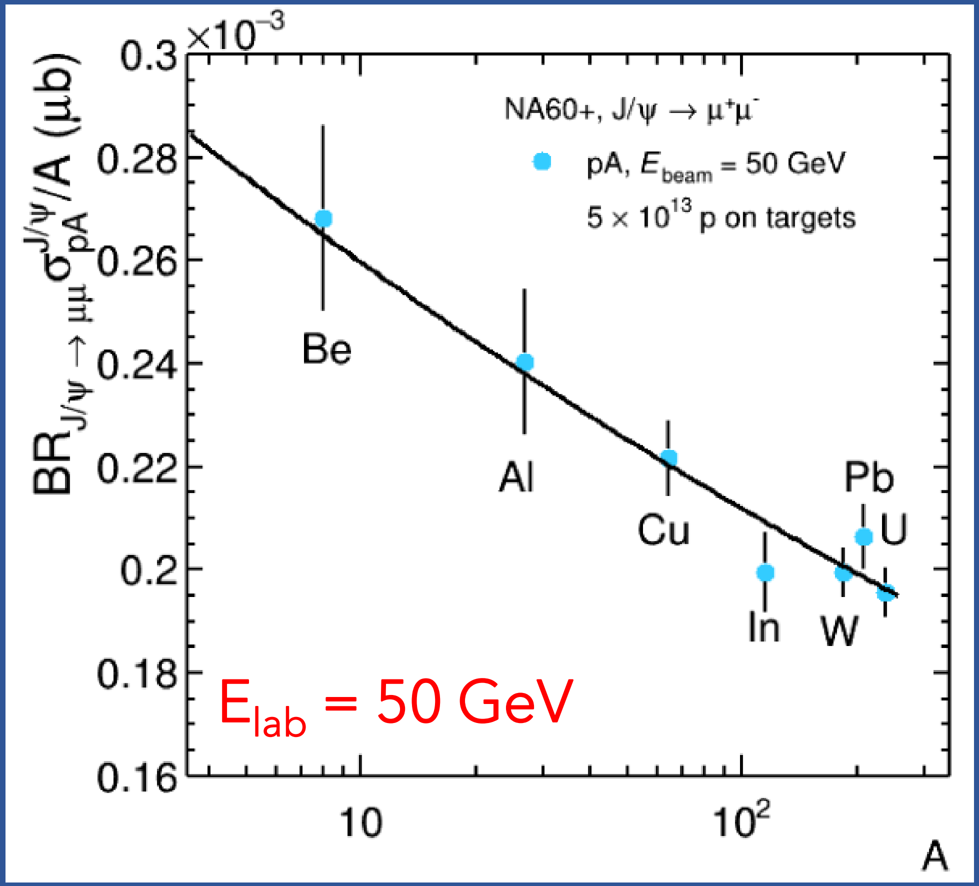
- Measurements from $\sqrt{s_{NN}} \sim 6$ to 17 GeV
  - QGP transport properties at high μ_B
  - Charm thermalization and hadronization
  - Intrinsic charm
  - Onset of charmonium anomalous suppression (and correlation with temperature)

- **Specific theory predictions** lacking for most observables!
  → Would be extremely useful to finalize realistic physics performance studies

- **Further experimental groups to join!** Still ample space for decisive contributions on all items → gas tracking detectors, MAPS, magnet, trigger, DAQ,…

Backup

p-A collisions: choices and performance

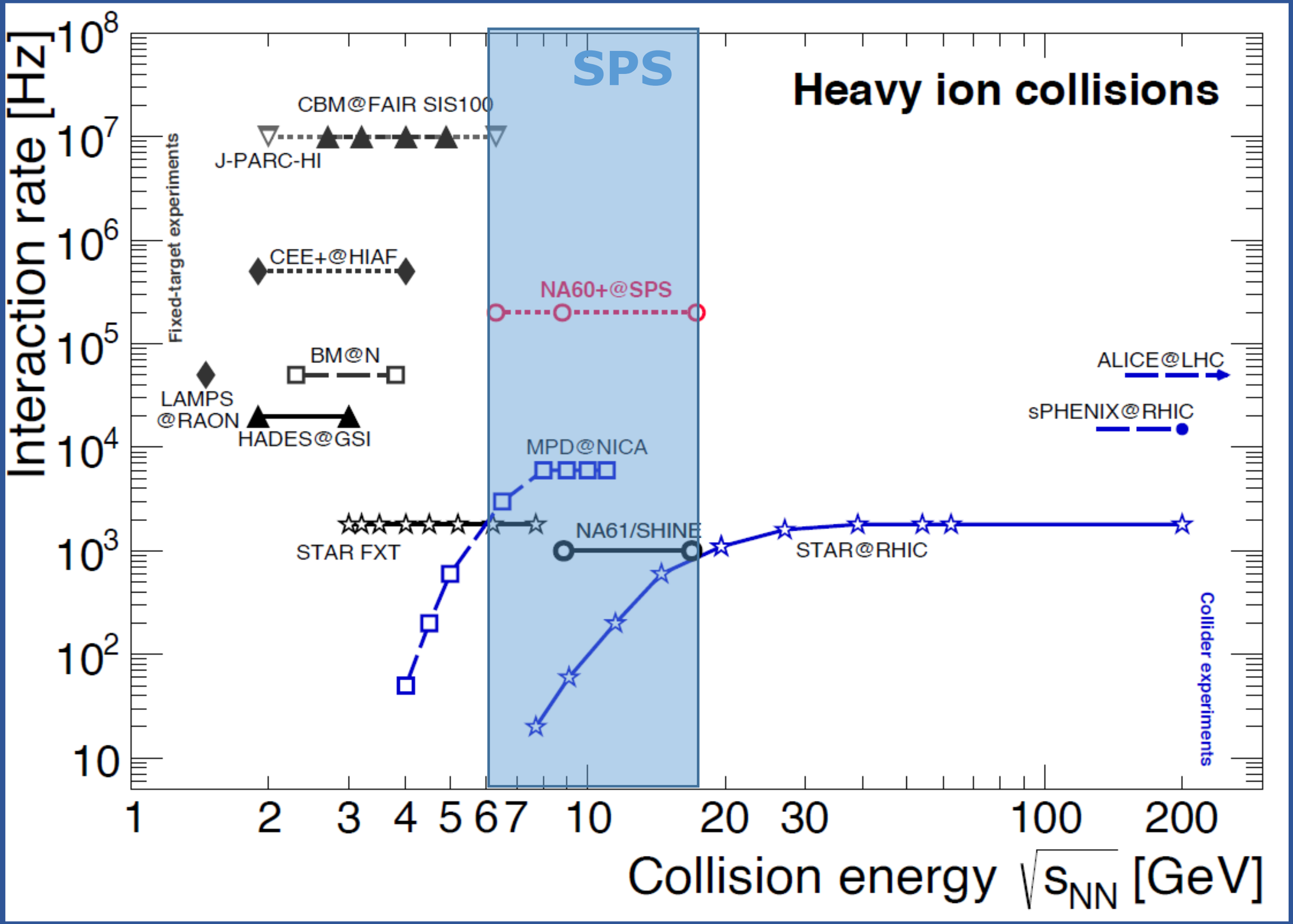


Default choice (LoI): total thickness 7.0 g cm^{-2}

A	Be	Al	Cu	In	W	Pb	U
Thickness (cm)	0.1	0.1	0.1	0.1	0.1	0.1	0.1

- ❑ Maximizes number of nuclear species
- ❑ Does not optimize lever arm of the fit to get σ_{pp}

Uniqueness of NA60+ program



- The NA60+ physics program needs a large integrated luminosity
  → Measurement of **rare QGP probes**

- Such a luminosity can be obtained with **Pb-Pb interaction rates >10^5 Hz**, reachable with a ~10^6 s^{-1} beam intensity in a fixed-target environment

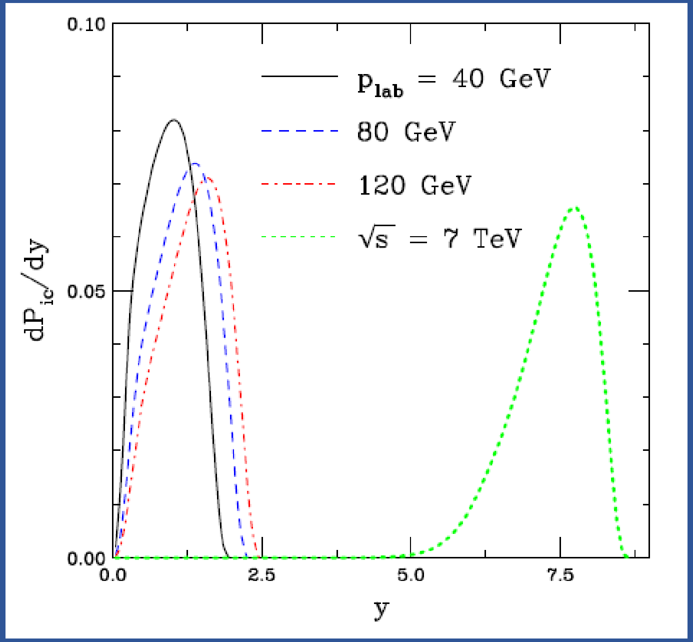
- In the SPS energy range, there **are no other existing/foreseen facilities/experiments** that can approach this kind of performance

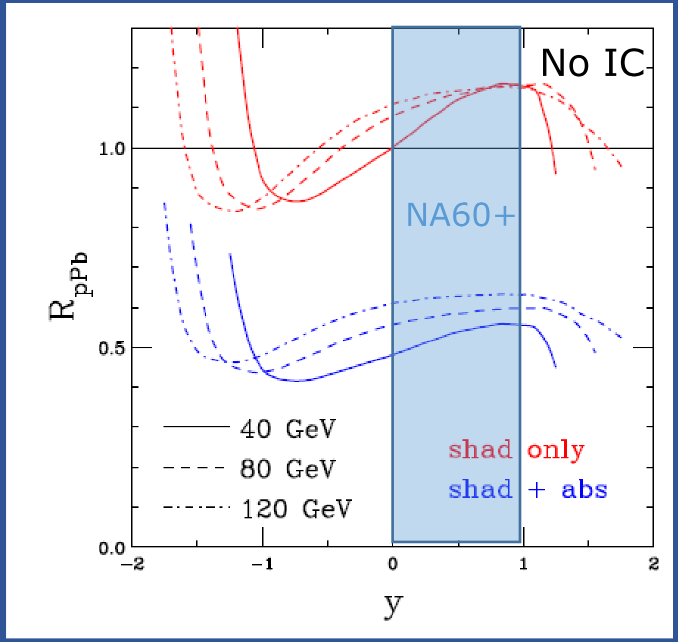
- **Complementarity** with experiments accessing
  - different (hadronic) observables in the same energy range (STAR BES, NICA, NA61)
  - similar observables in a lower energy range (CBM at FAIR)

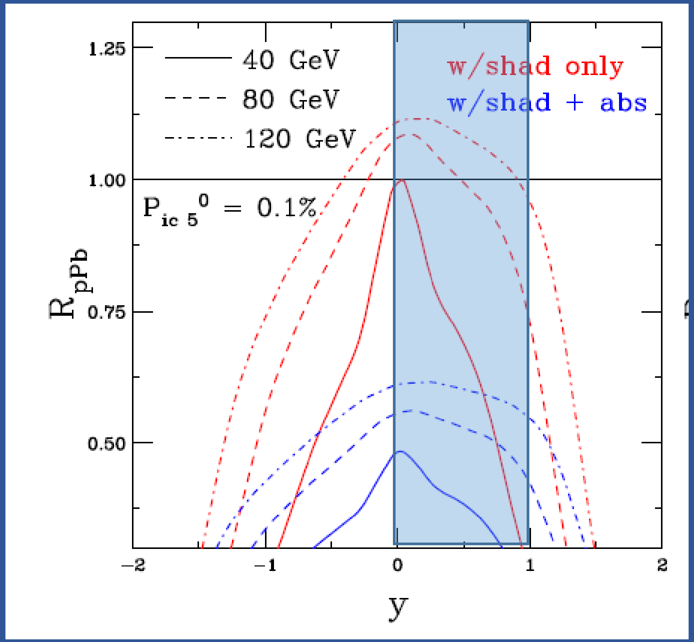
Low-√s J/ψ: studying intrinsic charm

- Intrinsic charm component of the hadron wavefunction **|uudc$\bar{c}$>**
- Leads to **enhanced charm production** in the forward region

- **Hints** from several experiments
- First **evidence** recently claimed by NNPDF group based on LHCb data (Nature 608,483(2022))
- Fixed-target configurations more appropriate for these studies → signal not far from midrapidity



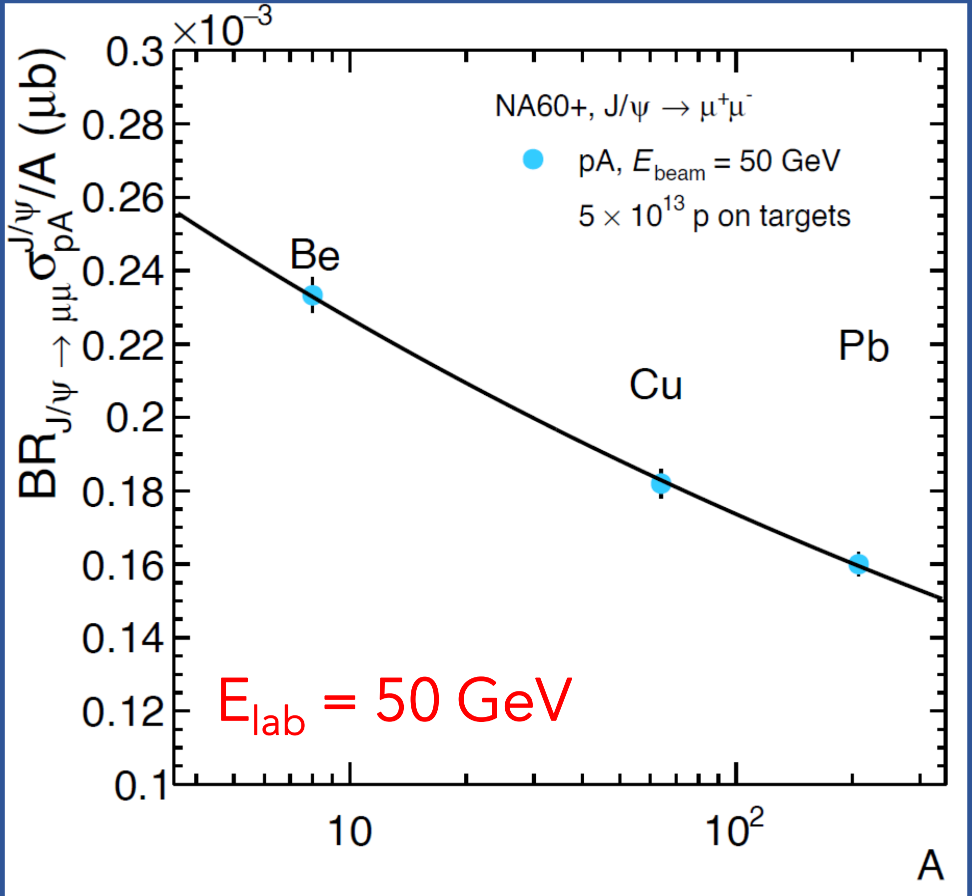




R. Vogt, PRC 103, 035204 (2021)
R. Vogt, arXiv:2207.04347

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

p-A collisions: choices and performance



Assume $\alpha_{J/\psi}$ **= 0.88**
(as measured at E_{lab} = 158 GeV)

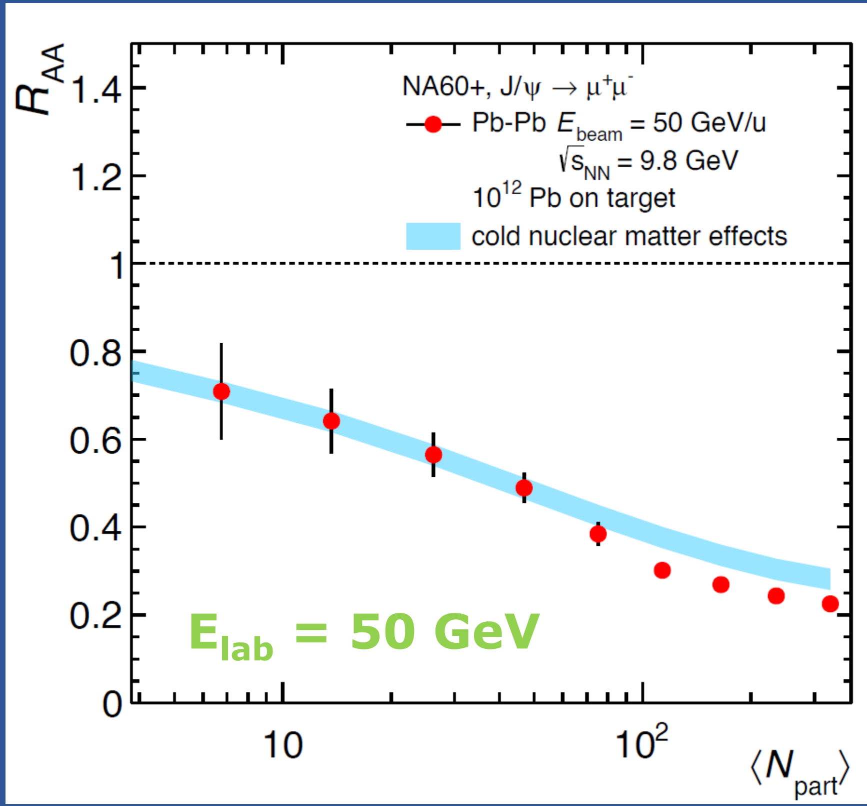
Alternative choice (LoI): total thickness 8.3 g cm^{-2}

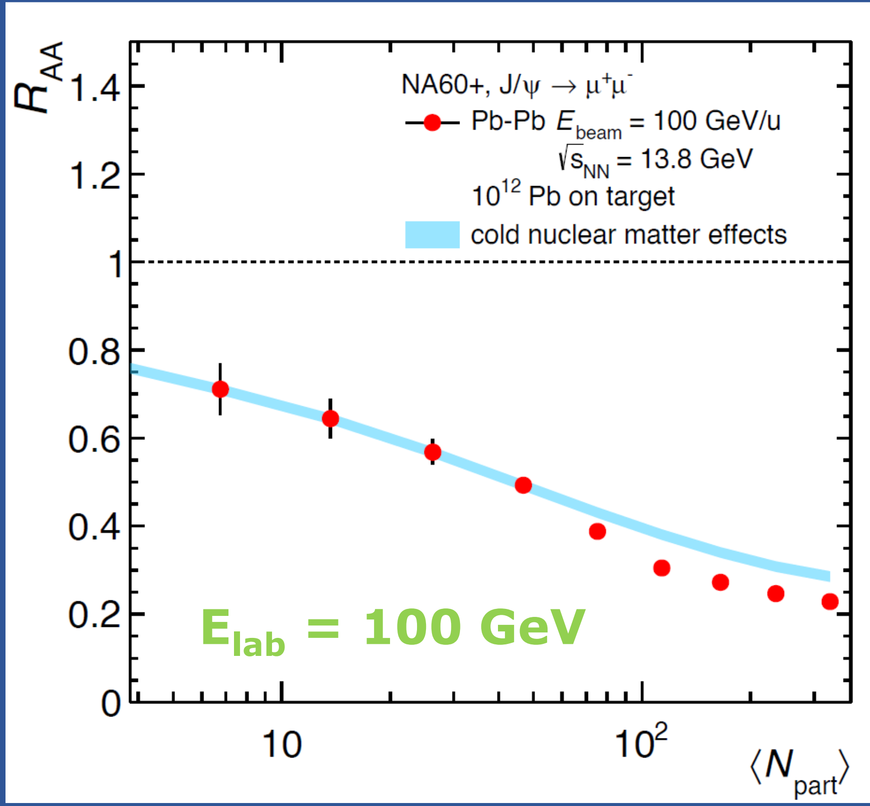
A	Be	Al	Cu	In	W	Pb	U
Thickness (cm)	1.2	0.	0.3	0.	0.	0.3	0.

- ❑ Smaller number of nuclear species
- ❑ Optimizes lever arm of the fit to get σ_{pp} → ~factor 2 smaller uncertainties

- ❑ With 5 x 10^{13} protons on target the expected statistics in pA ia
  - ❑ **~7000 J/ψ at 50 GeV**
  - ❑ **~50000 J/ψ at 150 GeV**

NA60+, R_{AA} estimate





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

Assume only CNM effects for N_{part}<50 and 20% extra suppression in Pb-Pb for N_{part}>50

→ **Precise evaluation of anomalous suppression within reach even at low energy**

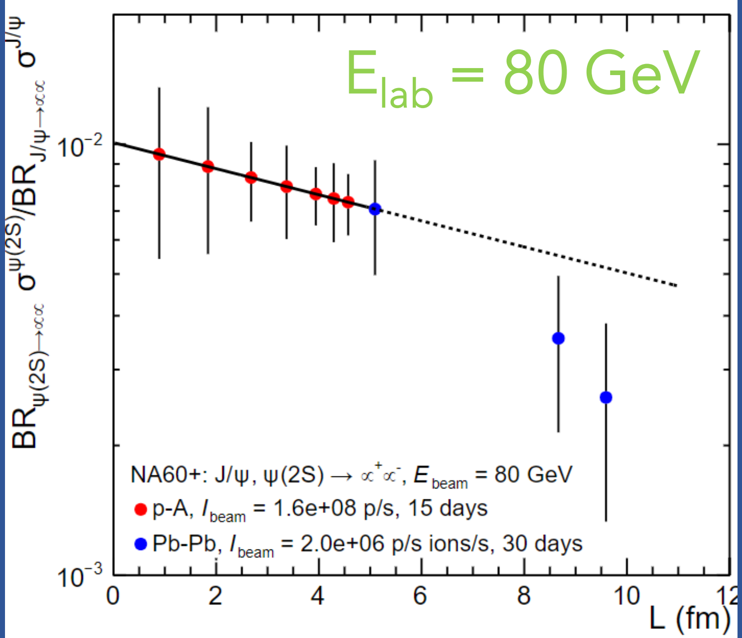
N.B.: statistical uncertainties only
Assume $\alpha_{J/\psi}$ **= 0.88**

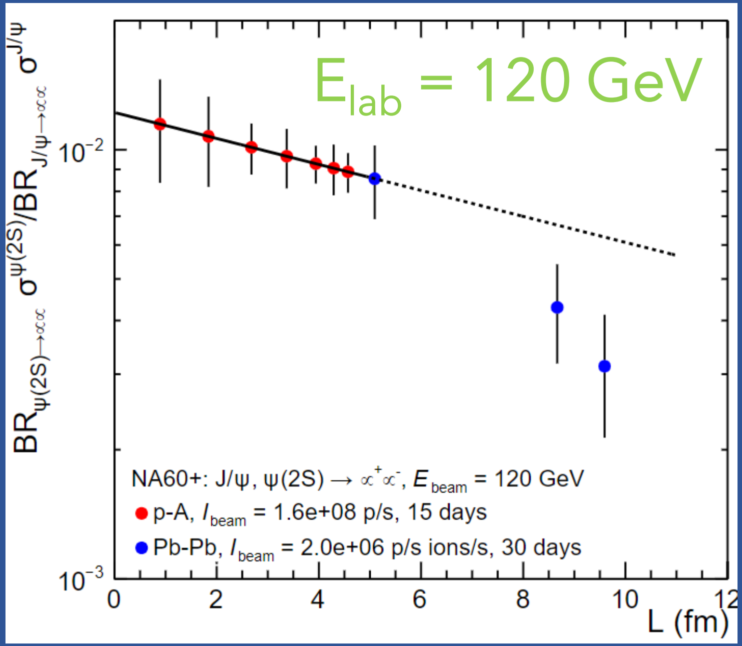
Prospects for ψ(2S) measurements at low √s

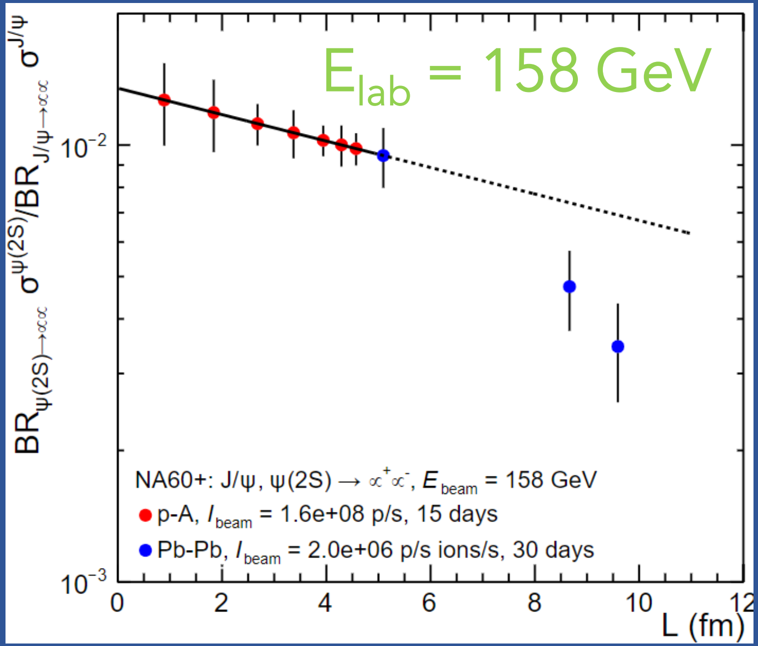
Good charmonium resolution (~30 MeV for the J/ψ) will help ψ(2S) measurements

Expectations based on
- 30 days PbPb, I_{beam} = 1e7 ions/spill
- 15 days pA, I_{beam} = 8e8 p/spill

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

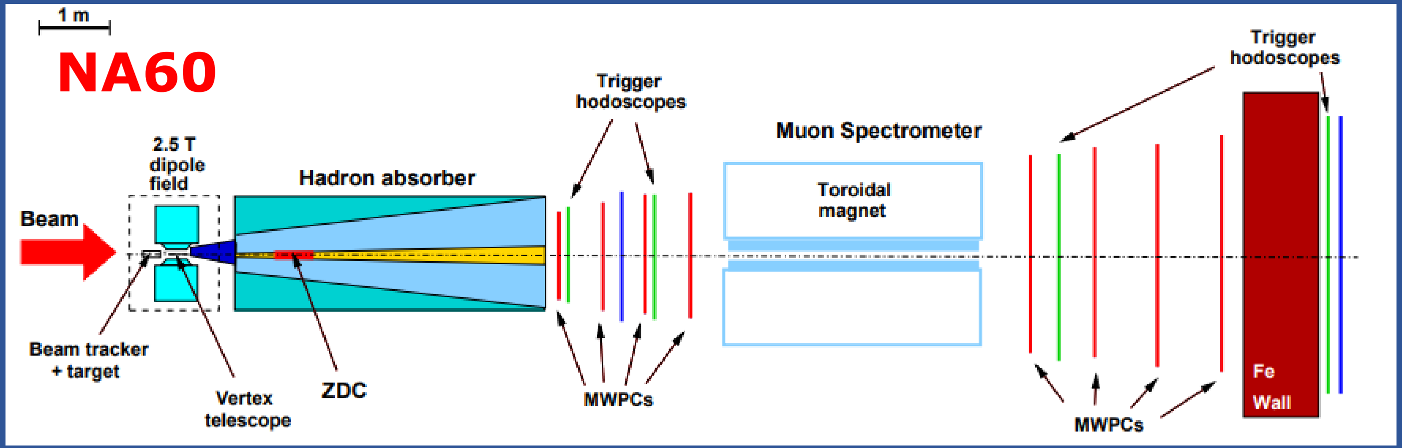




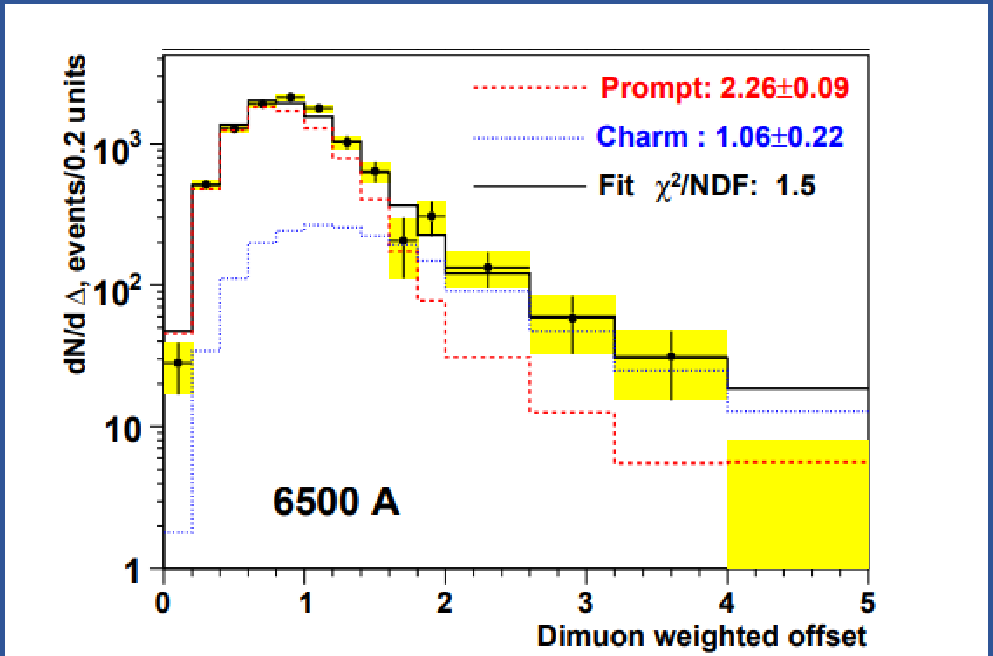


- ❑ **ψ(2S)/ψ measurement looks feasible down to E_{lab} = 120 GeV**
- ❑ Lower E_{lab} would require larger beam intensites/longer running times

Existing open charm results at SPS energy



- ❑ Match track(s) in a muon spectrometer to tracks in a vertex spectrometer
- → Excellent resolution on the muon kinematics
- → Separate prompt (DY+thermal) from nonprompt sources (open charm)



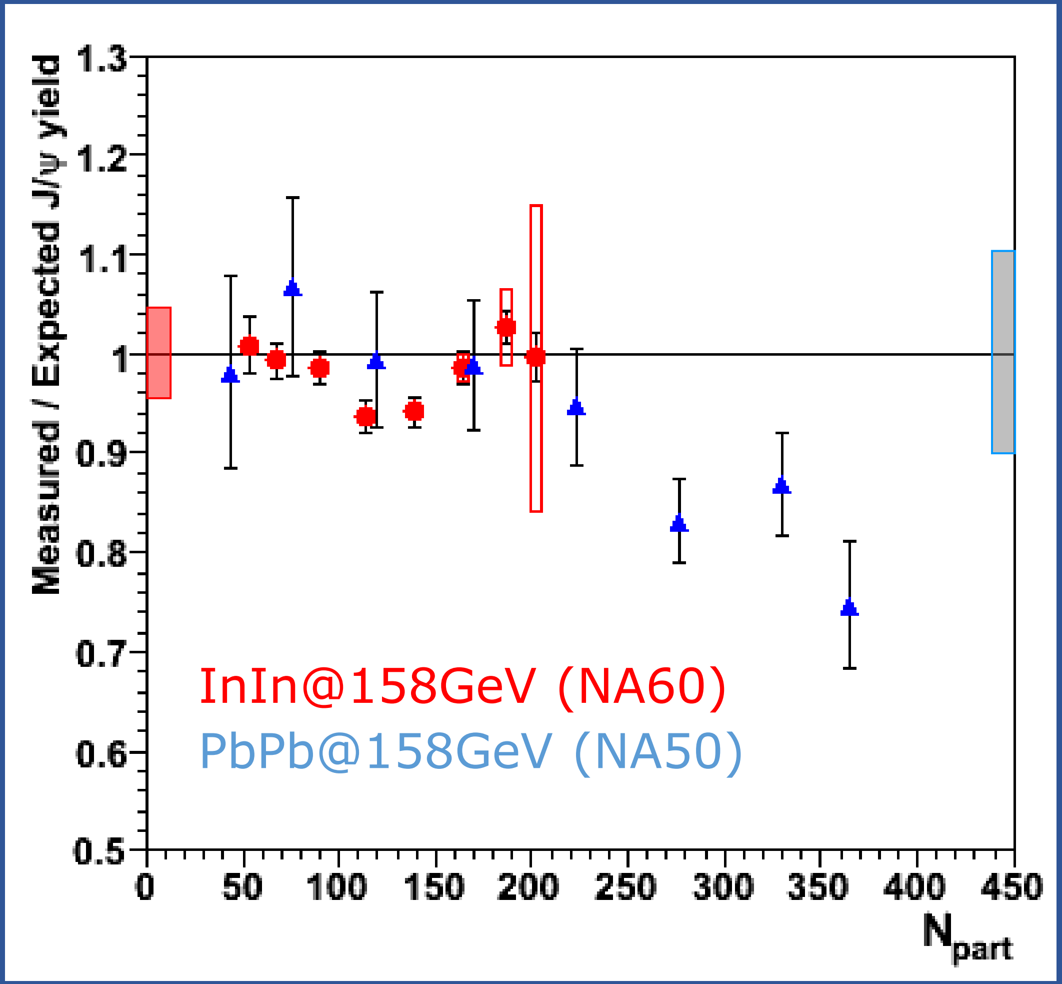
NA60, EPJ C59 (2009) 607

- ❑ Analysis of open charm contribution (semileptonic decays of charm hadron pairs) leads, for In-In collisions at $\sqrt{s_{NN}}$=17.3 GeV, to σ_{cc}= 9.5±1.3(stat.)±1.4(syst.) μb assuming kinematic distribution as in PYTHIA6

- → Compatible with corresponding p-A measurements by NA50 and supporting the hypothesis of N_{coll} scaling

No other results available below top SPS energy

"Summary" J/ψ plot



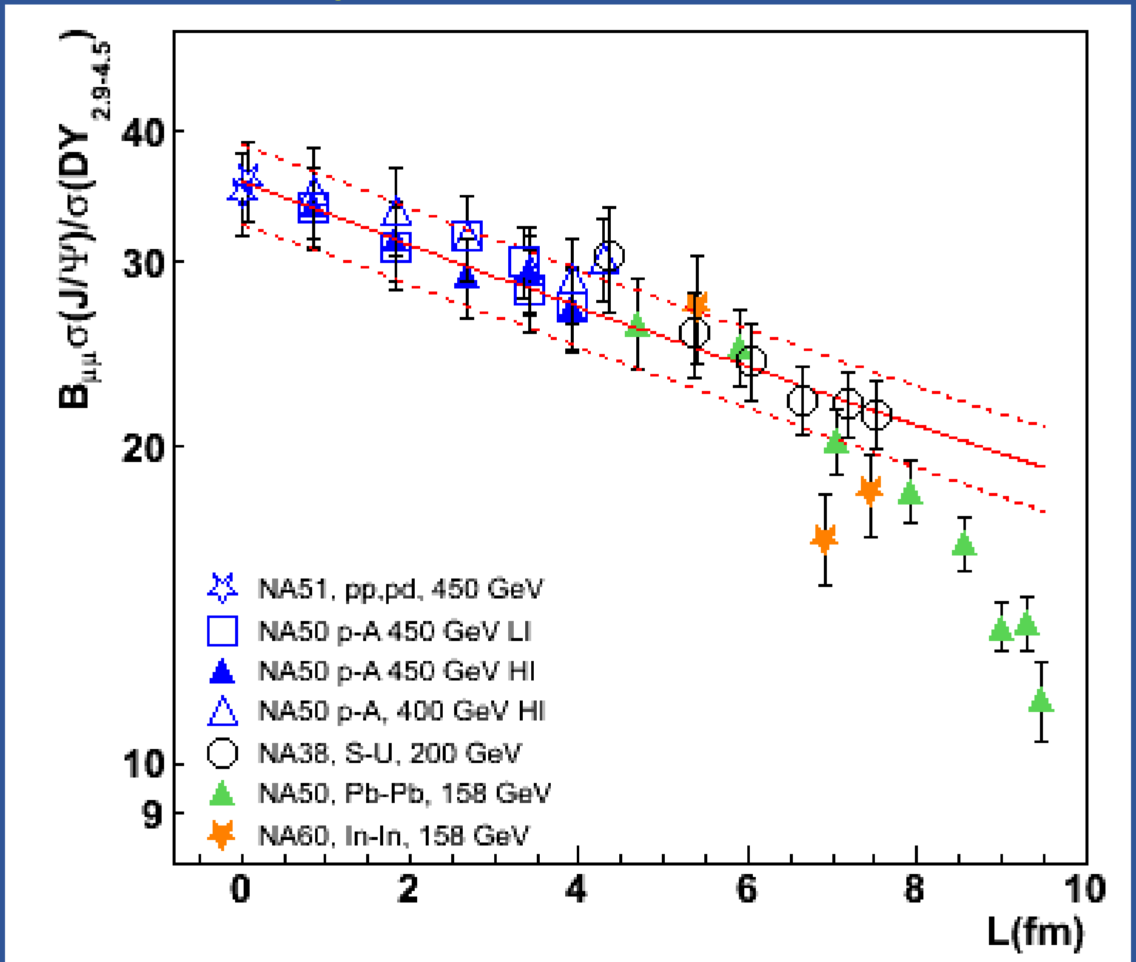
NA50, EPJC39 (2005) 335

NA60, Nucl. Phys. A830 (2009) 345

R.Arnaldi, P. Cortese, E. Scomparin Phys. Rev. C 81, 014903

- Expressed in terms of **measured J/ψ yield, normalized to an extrapolation of CNM effects**, evaluated starting from p-A results
- **Drell-Yan** reference used to extract results
- **Suppression** effects beyond CNM reach **~30%** in central Pb-Pb collision
- Qualitatively consistent with **suppression of feed-down** from ψ(2S) (measured) and χ_c (not measured)
- **In-In** result shows **small or no suppression**, with the origin of "wiggle" at intermediate centrality unclear (coupling to X(3872) via DD^* proposed in Blaschke et al., NPA927(2014) 1)

Extrapolation of CNM effects

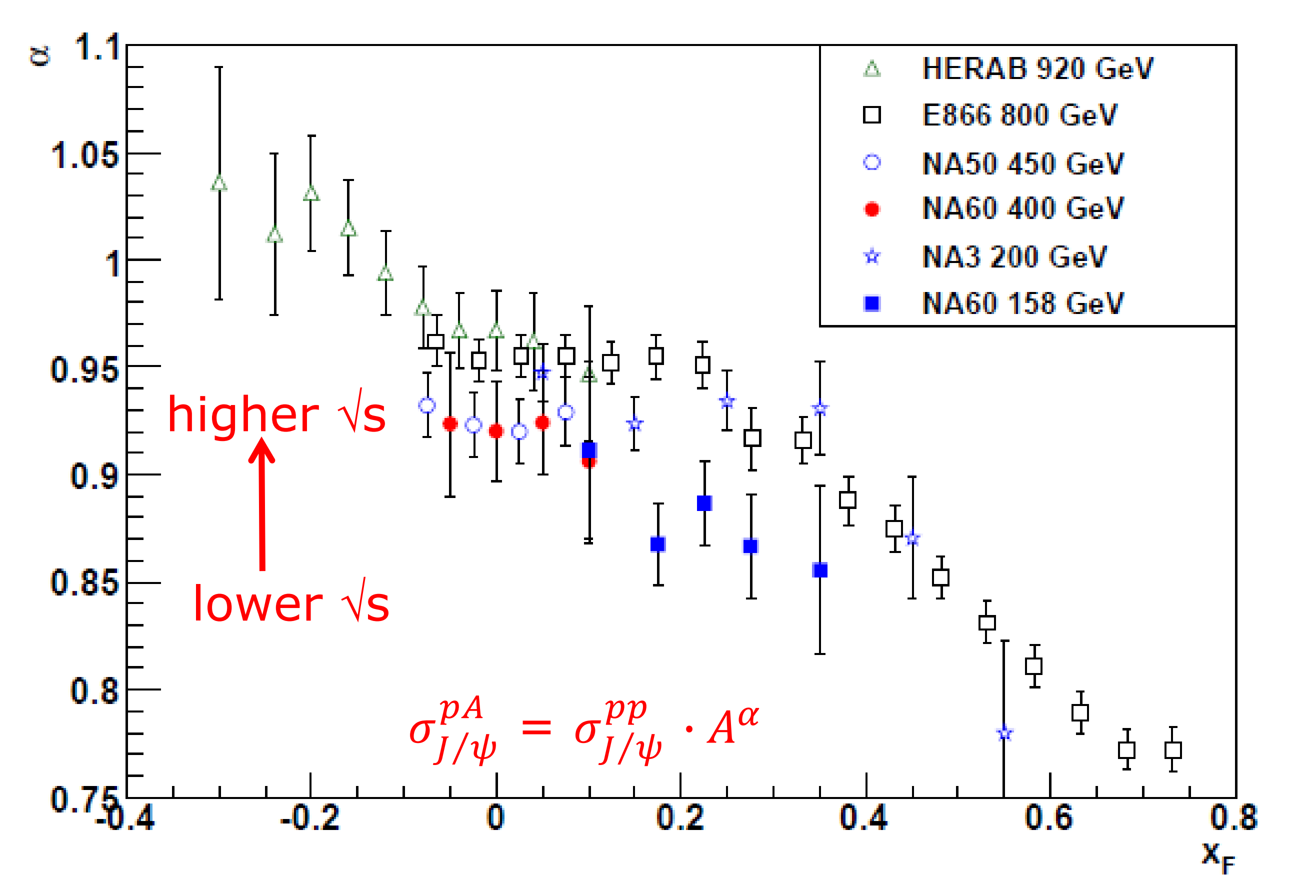


NA38 Coll., PLB449 (1999)128
NA50 Coll., EPJC39 (2005)335

- **Use L as scaling variable**
  → average thickness of nuclear matter crossed by the cc pair
- **Exponential behaviour in pA**
  → break-up effects dominate
- **Light AA collisions (S-U)**
  → compatible with pA behaviour
- **Pb-Pb collisions**
  → breaking of L-scaling: anomalous suppression

- **Caveats**
  - Assume √s-independence of nuclear effects
  - Extrapolation of shadowing effects is more complex
    → to be taken into account

p-A results at fixed target: a complex environment



NA60 Coll., Phys. Lett. B 706 (2012) 263-367

J/ψ yield in pA is modified with respect to pp, with a significant kinematic dependence

- **α strongly decreases with x_F**
- **for a fixed x_F, stronger CNM at lower √s**

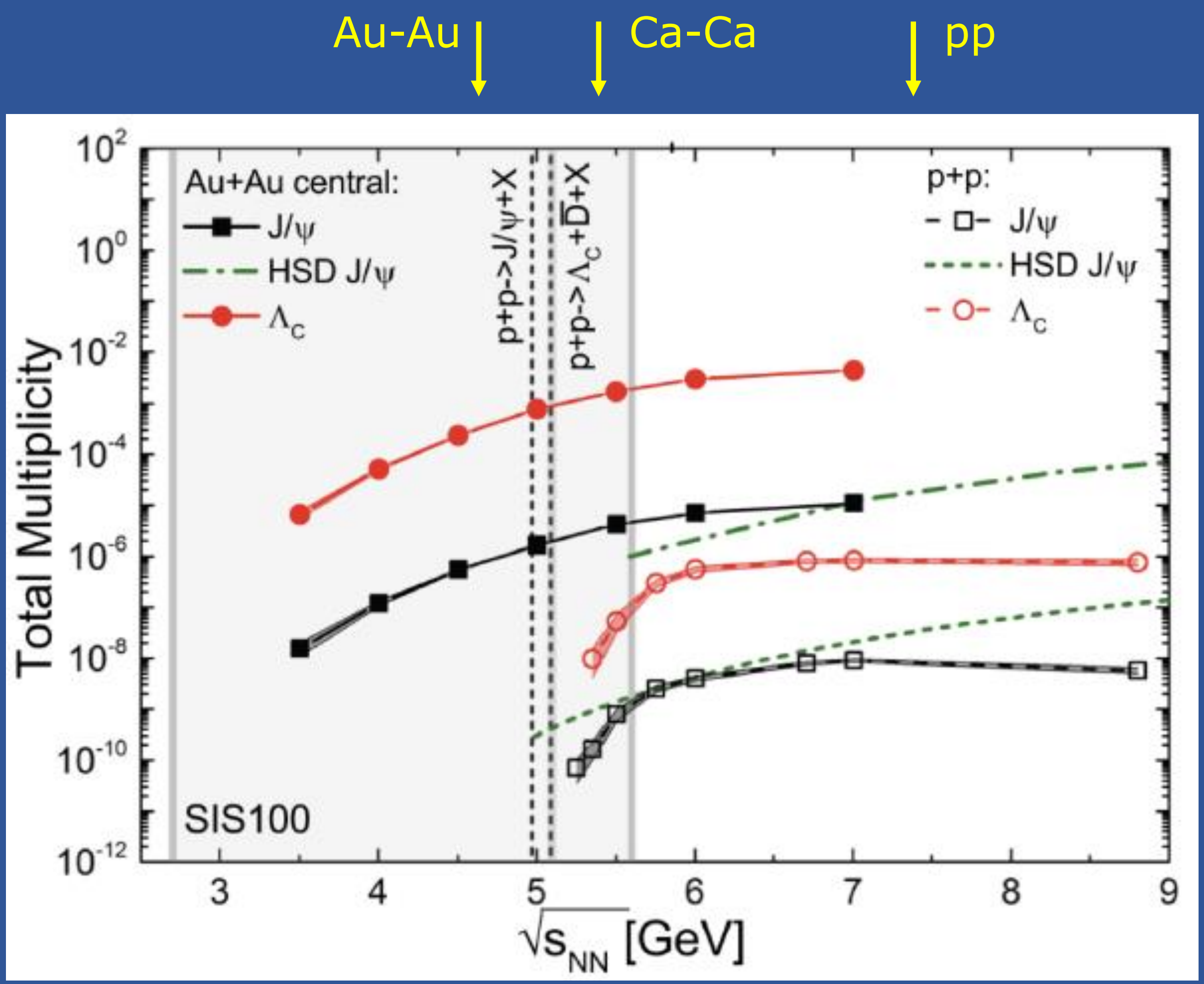
Superposition of several effects

Shadowing
Nuclear break-up
Energy loss (at large x_F)

No consistent theory description over the whole x_F range

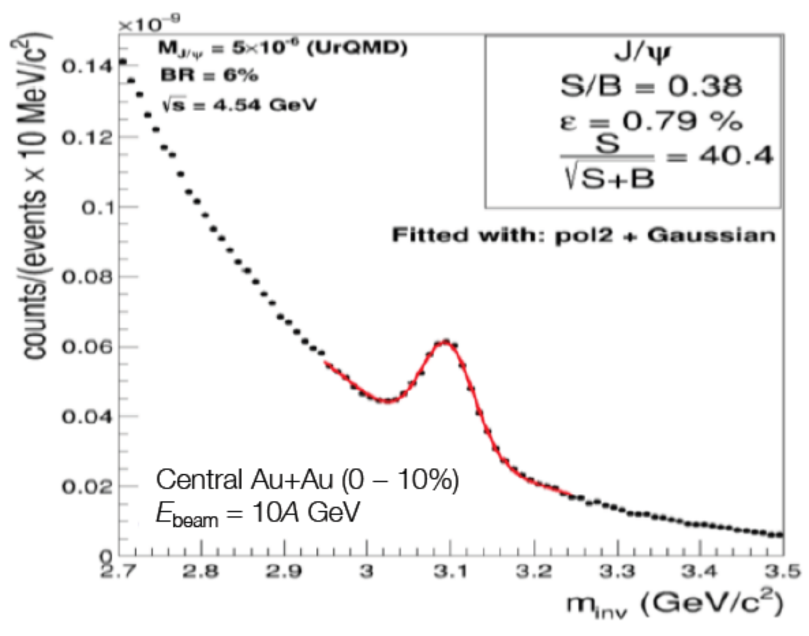
Quarkonium at CBM: threshold production

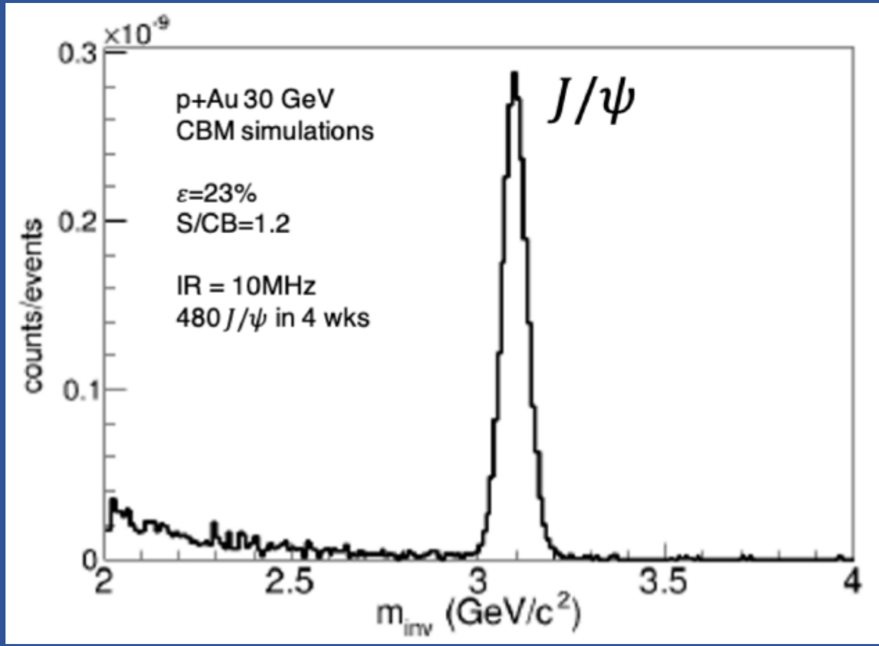
- **Sub-threshold production** (rare but feasible) via multiple collision processes
- Production threshold might be exceeded with SIS100 beam of N=Z nuclei
- Both $\mu^+\mu^-$ and e^+e^- decay channels accessible
- Needs **very large interaction rates** → 10 MHz (50 times NA60+)
- Beam intensities → 10^9/s A, 10^{11}/s p

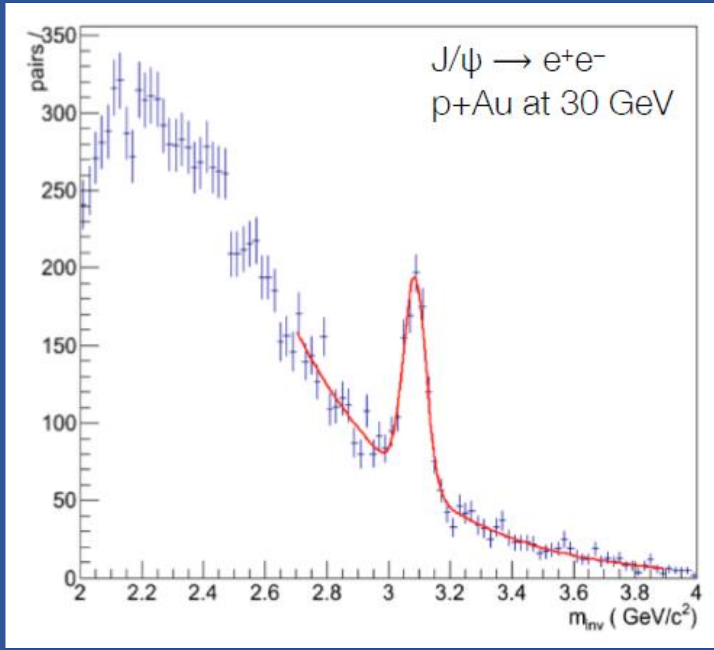


J. Steinheimer et al, Phys. Rev, C95 (2017) 014911

Quarkonium at CBM: physics performance







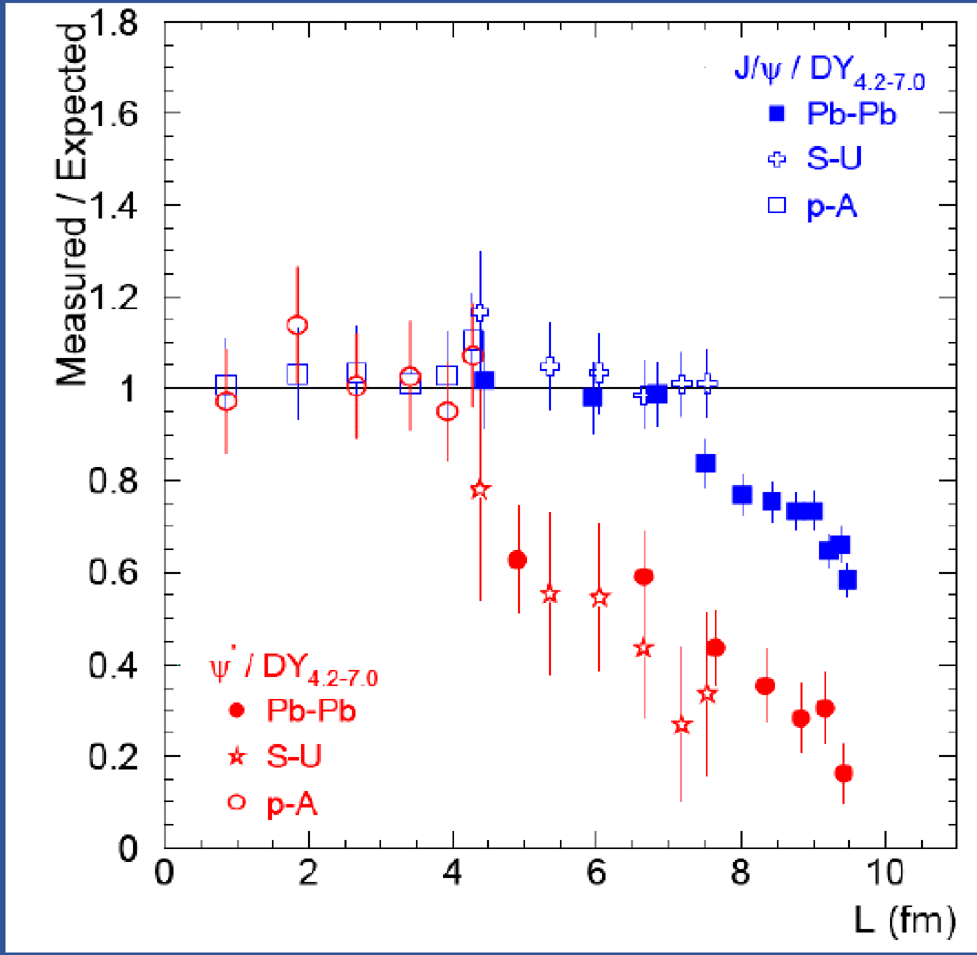
J/ψ→μμ
AuAu ~30k J/ψ in 4 weeks at 10 MHz interaction rate
pAu ~500 J/ψ in 4 weeks at 10 MHz interaction rate

J/ψ→ee
pAu ~450 J/ψ in 4 weeks at 10 MHz int. rate

pA → lower statistics, but very clean signal

Excited charmonium states: $\psi(2S)$, χ_c

NA50, EPJC39 (2005) 335, EPJC49 (2007) 559

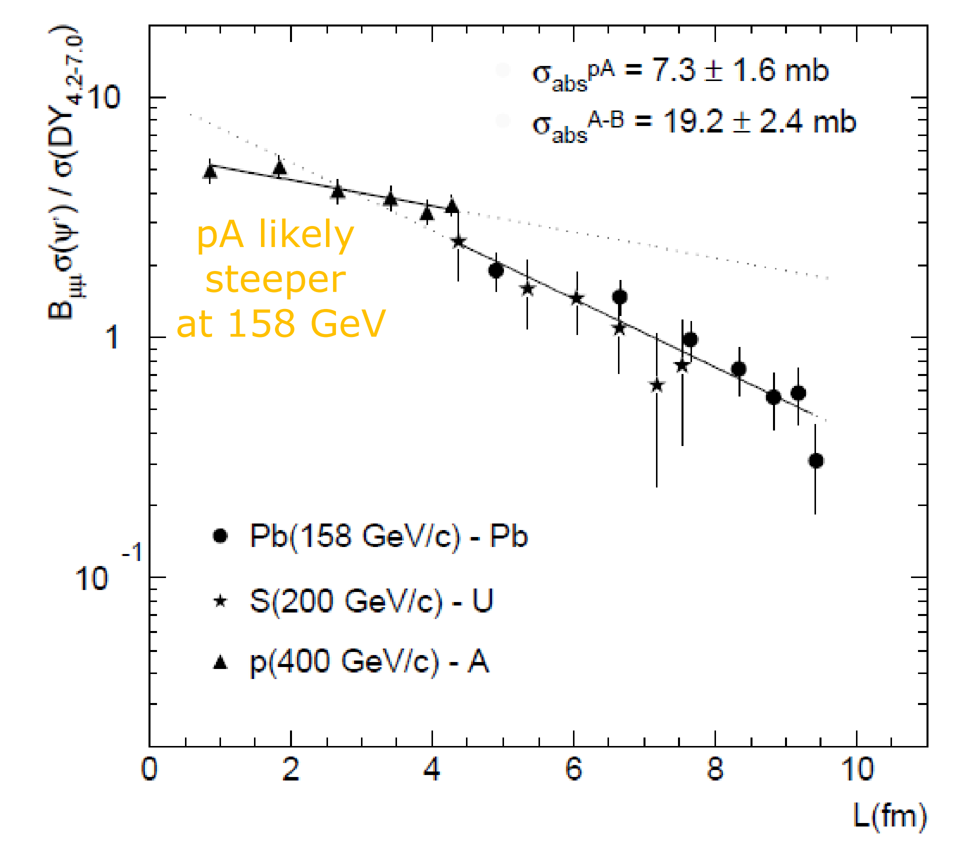


- ❑ Clear **ordering in the suppression** when moving from J/ψ to $\psi(2S)$
- ❑ The first **discovery of sequential suppression!**
  → Later confirmed by CMS in the Υ sector
- ❑ Typical yields in the dilepton channel
  → Lower by a factor ~100

No measurement of CNM on $\psi(2S)$ available at E_{lab}=158 GeV → not enough stat for NA60

N.B. here (weaker) CNM effects tuned at 450 GeV were used → bias!

Excited charmonium states: $\psi(2S)$, χ_c



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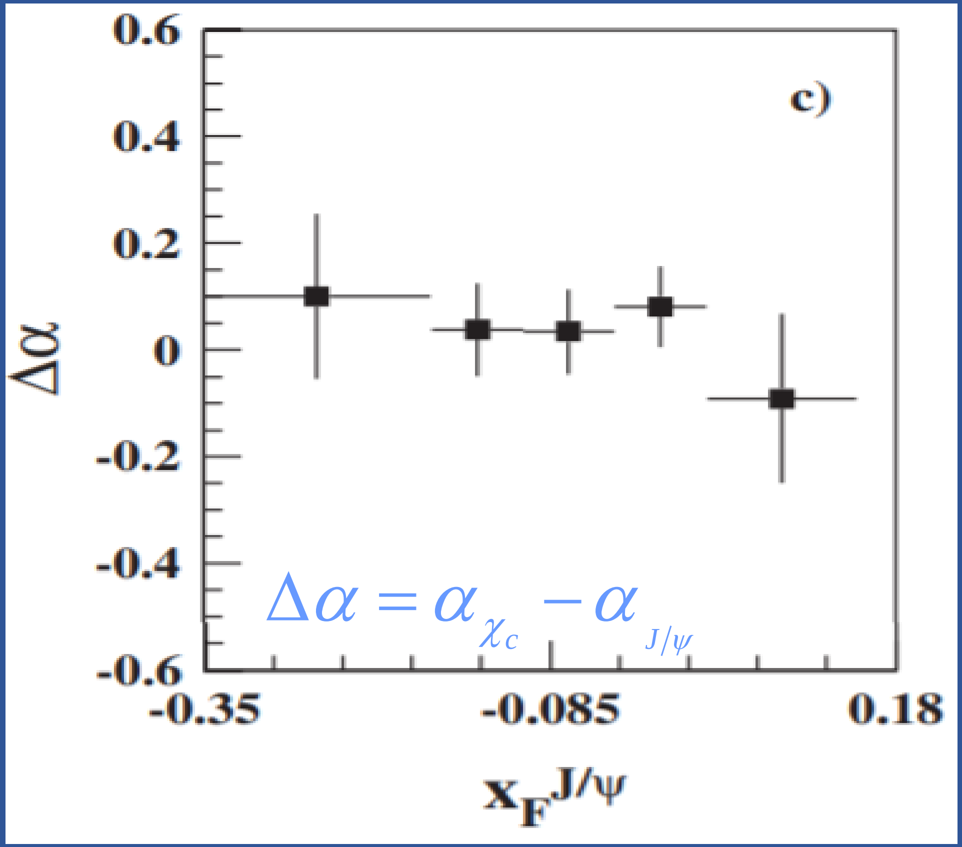
χ_c measurements

- ~25% of the J/ψ comes from the χ_c decay
  → $\alpha(\chi_c)$ important to understand the J/ψ suppression



HERA-B, Phys.Rev.D79:012001,2009

- χ_c not measured at SPS (no AA data)
- Available results at HERA-B, pA@ 920 GeV (large χ_c sample: ~15000 χ_c $-0.35<x_F^{J/\psi}<0.15$)
- HERA-B observed no significant difference between $\alpha(\chi_c)$ and $\alpha(J/\psi)$

→ similar "global" CNM effects on both resonances in the covered kinematical range (average value $\Delta\alpha=0.05\pm0.04$), but more accurate results are needed

- Non-trivial measurement, needs detection of low-momentum photon (<1 GeV)
  → conversion or calorimetry