(Prospects) on open and hidden charm production in fixed-target experiments

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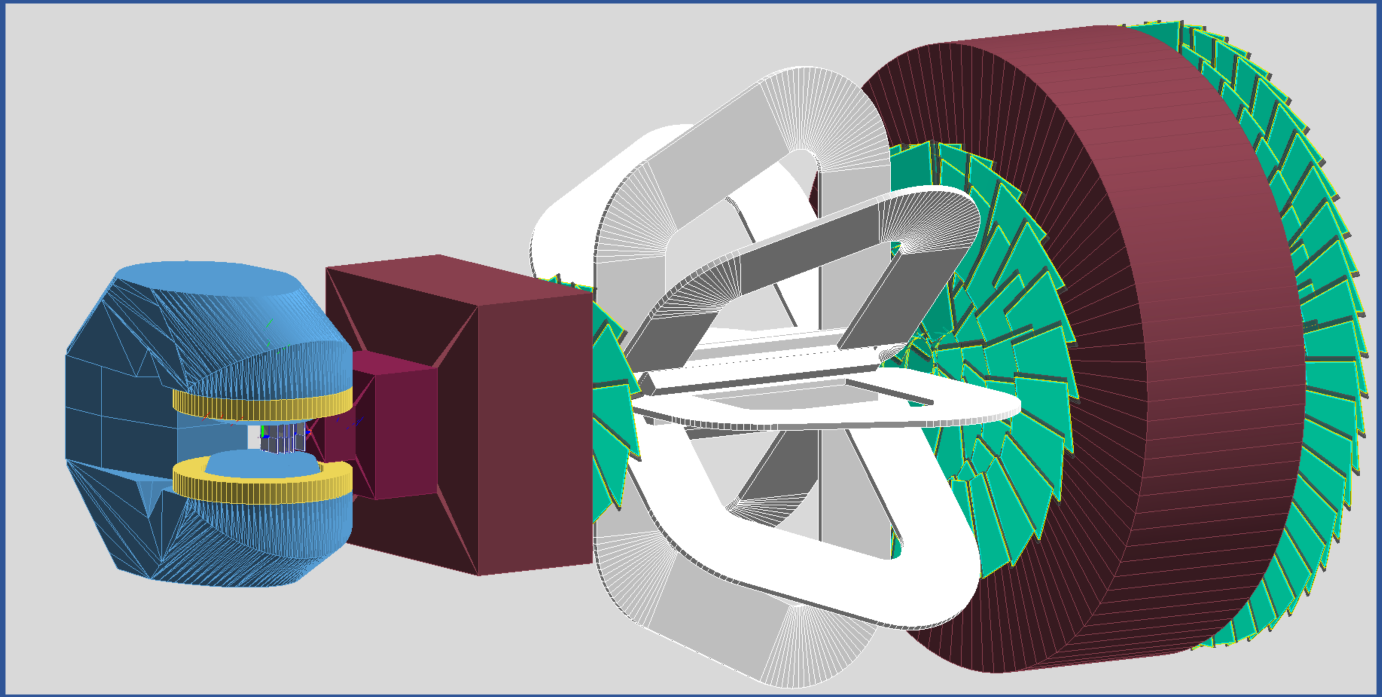


HEAVY FLAVOR PRODUCTION IN HEAVY-ION AND ELEMENTARY COLLISIONS

OCTOBER 21, 2022

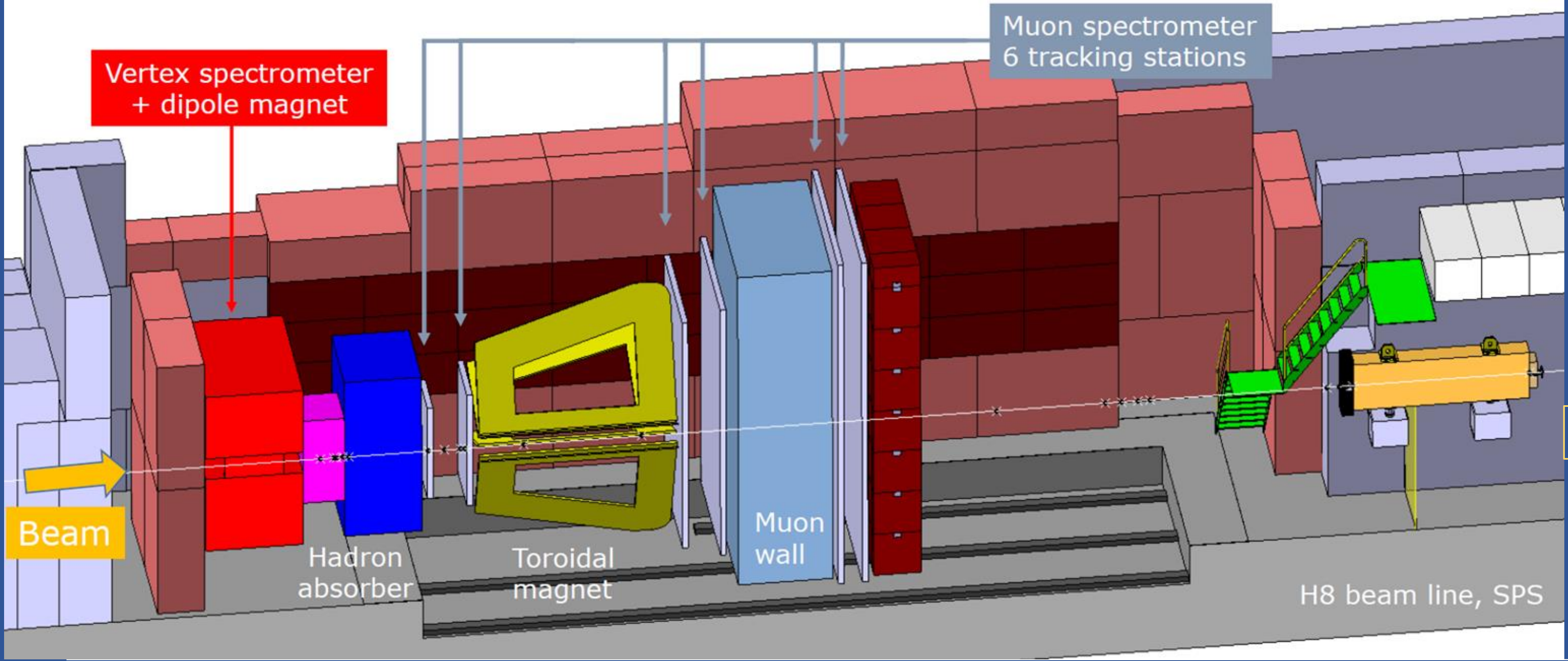
Plan

- **Open charm and charmonia** in nuclear collisions → probe of the QGP
- Extensive information available at collider energy
- Heavy-ion collisions at **fixed target energies**
  - **Few results on open charm** production at top SPS energy → dilepton spectrum
  - **Many results on charmonia** at top SPS energy → J/ψ, $\psi(2S)$
  - 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!

Proposing a new experiment at the CERN SPS

- Aim: perform **accurate measurements of the dimuon spectrum** from threshold up to the charmonium mass region, and of **hadronic decays of charm and strange hadrons**
- **Energy scan** with a Pb beam from top SPS energy ($\sqrt{s_{NN}}$=17 GeV) down to $\sqrt{s_{NN}}$~ 6 GeV (E_{lab}~20 A GeV)
- Based on a muon spectrometer (toroid field) coupled to a vertex spectrometer (dipole field)
- High luminosity, to access rare probes of QGP → ~10^6 s^{-1} Pb ions/s

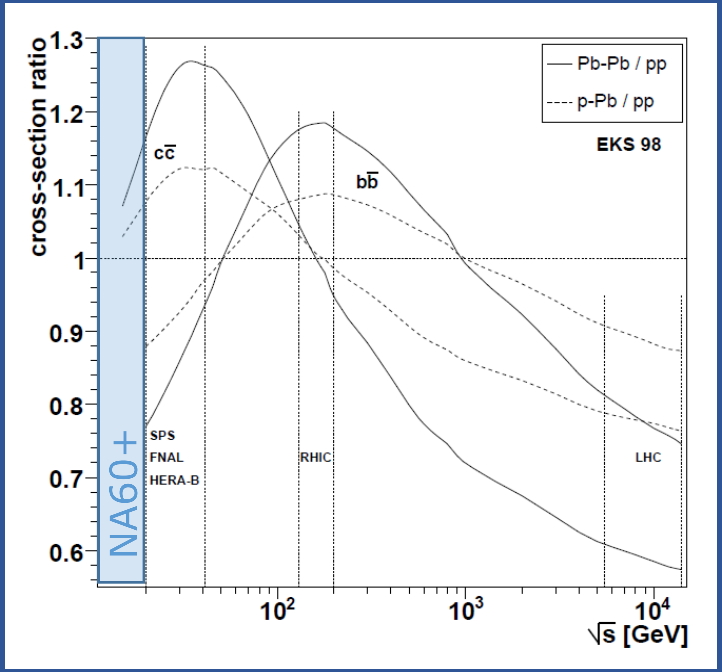


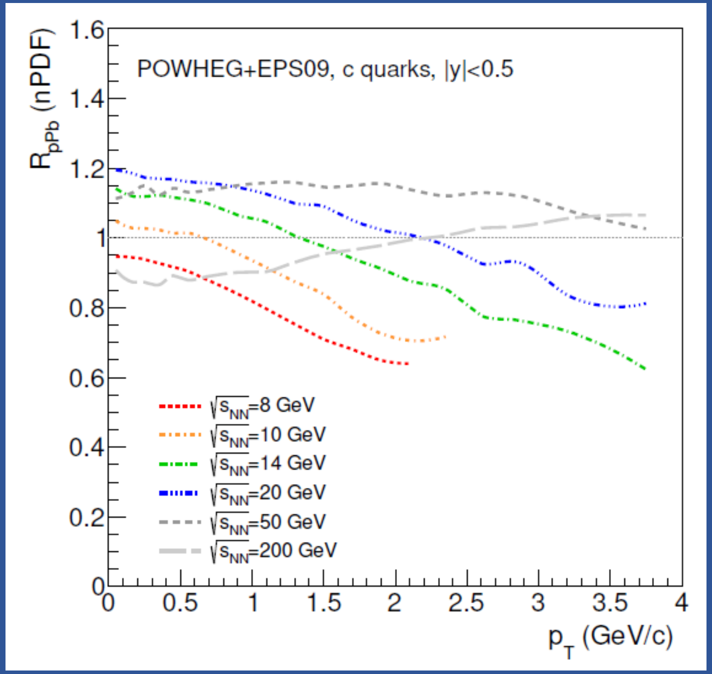
NA60+

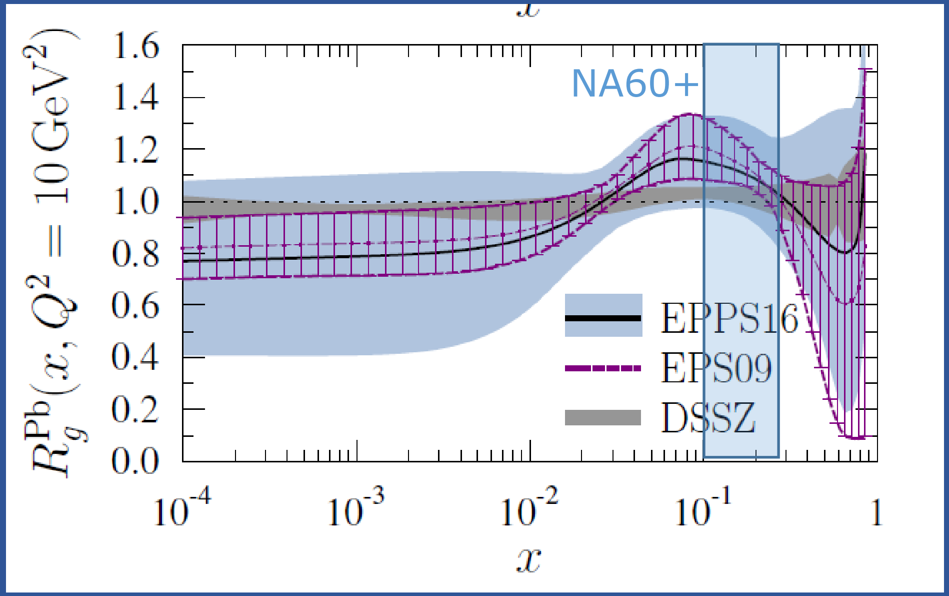
https://na60plus.ca.infn.it/

Open charm at low √s in pA: nuclear PDFs

- Sensitivity to **nuclear PDFs in p-A** collisions
  - Probe EMC and anti-shadowing for $\sqrt{s_{NN}}$ ~ 10-20 GeV
  - 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)
  - $0.1<x_{Bj}<0.3$ at Q^2~10-40 GeV^2







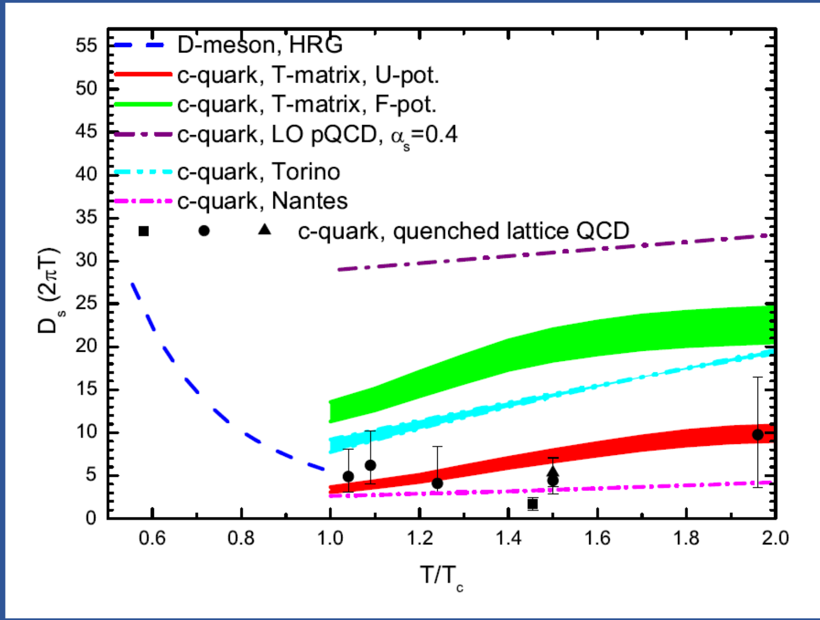
Lourenco, Wohri,
Phys.Rept.433 (2006) 127

Eskola et al. , EPJ C77 (2017) 13

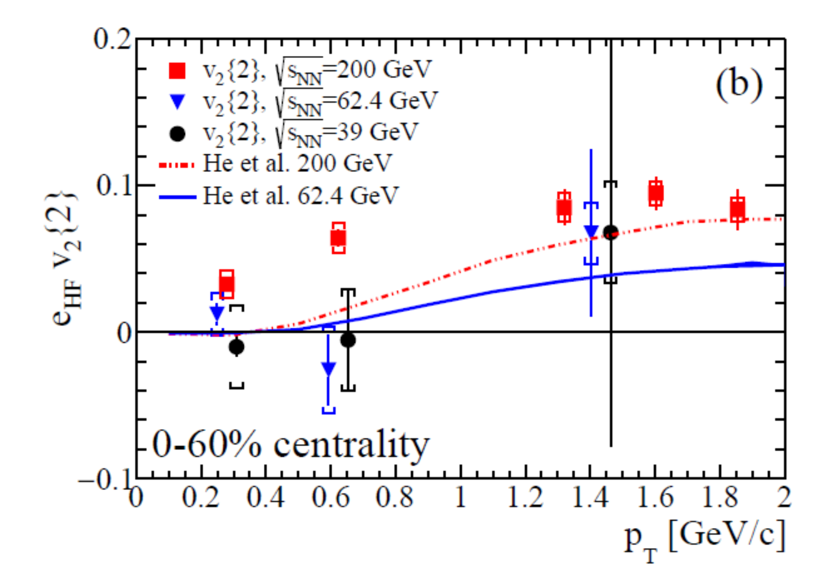
Open charm in Pb-Pb: R_{AA} and v_2

- Insight into **QGP transport properties**
  - Charm diffusion coefficient larger in the hadronic phase than in the QGP around T_c
  - Hadronic phase represents a large part of the collision evolution at SPS energies
    - Sensitivity to hadronic interactions
    - Test models which predict strongest in-medium interactions in the vicinity of the quark-hadron transition
  - Measurement also important for precision estimates of diffusion coefficients at the LHC

- Study **charm thermalization at low √s**
  - Current measurements of HF-decay electron v_2 at $\sqrt{s_{NN}}$=39 and 62 GeV/c from RHIC
    → Smaller v_2 than at √s=200 GeV
    → Not conclusive on v_2>0



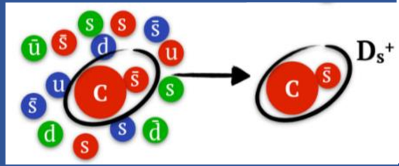
Prino, Rapp, JPG43 (2016) 093002

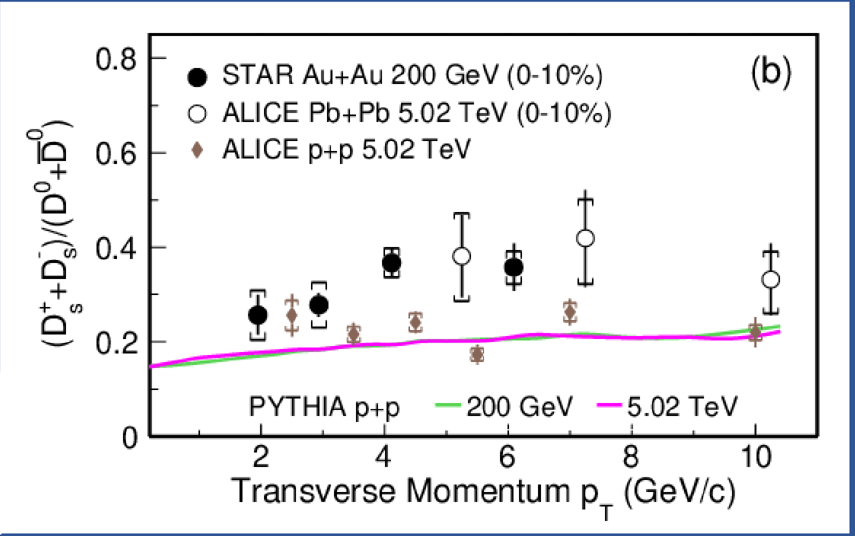


STAR, PRC 95 (2017) 034907

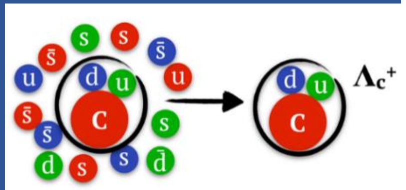
Open charm hadrochemistry

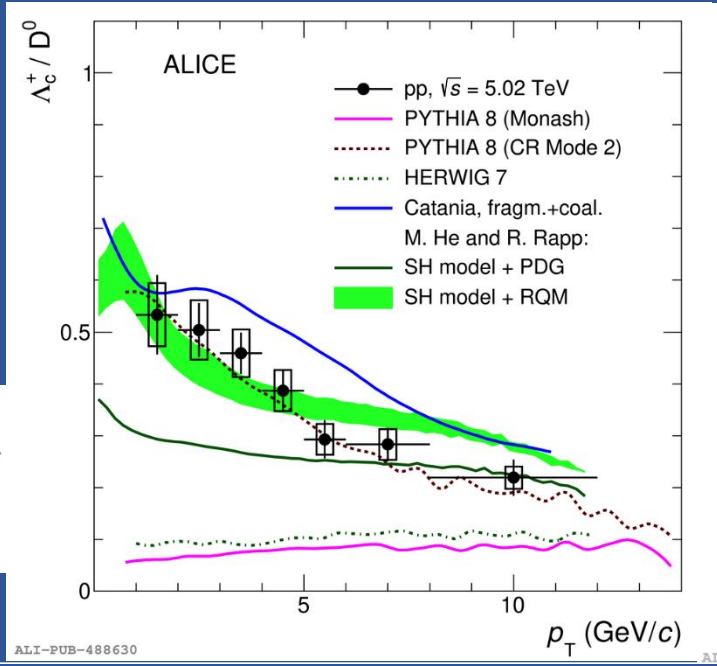
- ❑ Reconstruct different charm hadron species to get insight into **hadronization mechanism**
- ❑ **Strange/non-strange** meson ratio (D_s/D):
  - ❑ D_s/D enhancement expected in A-A collisions due to hadronisation via **recombination** in the strangeness rich QGP
- ❑ **Baryon/meson** ratios (Λ_c/D):
  - ❑ Expected to be enhanced in A-A in case of 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^-

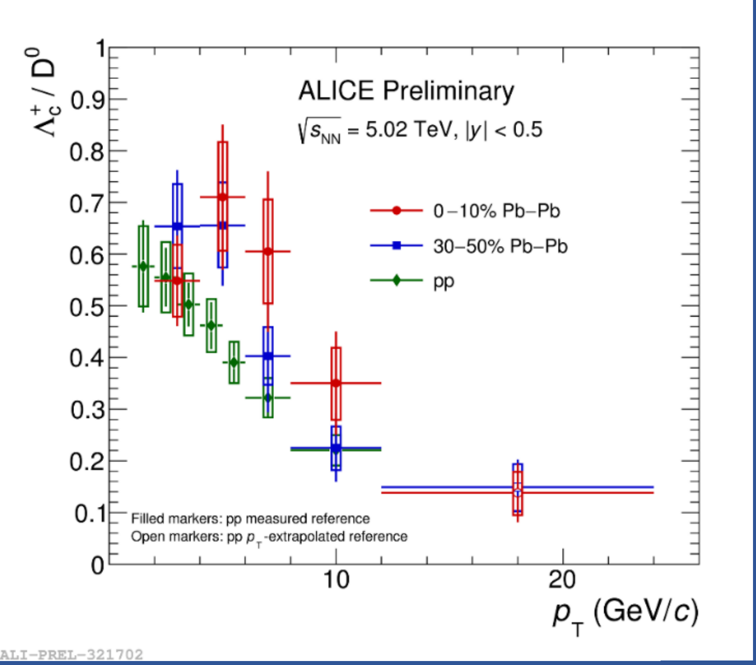




STAR, PRL 127 (2021) 092301
ALICE, PLB827 (2022) 136986







ALICE, PRL127 (2021) 202301

Total charm cross section

- Total charm cross section in A-A collisions
  - Measured so far by NA60 in In-In collisions from intermediate-mass dimuons with 20% precision
  - Upper limit from NA49 measurements of D^0 mesons

NA60, EPJ C59 (2009) 607

NA49, PRC73 (2006) 034910

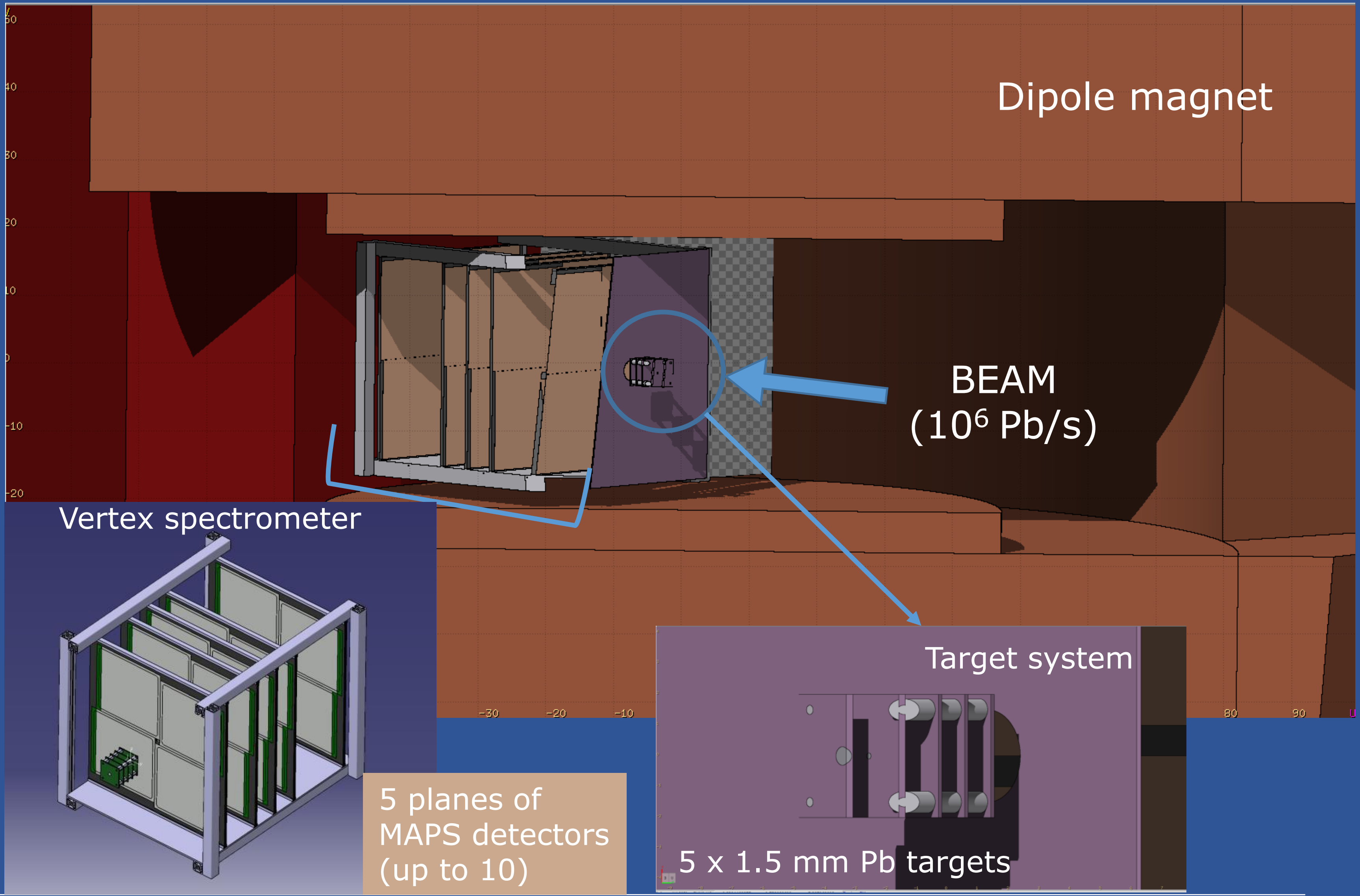
- Precise measurement requires to reconstruct all meson and baryon ground states (D^0, D^+, D_s^+ and Λ_c^+ and their antiparticles)

- Charm cross section **ideal reference for charmonia**

Towards a precise measurement of open charm at SPS energy

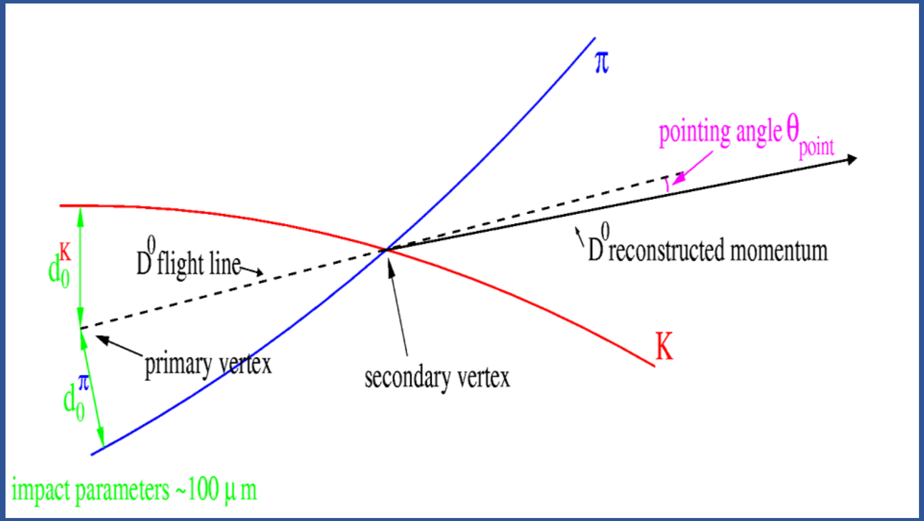
A measurement of **hadronic decays** is required

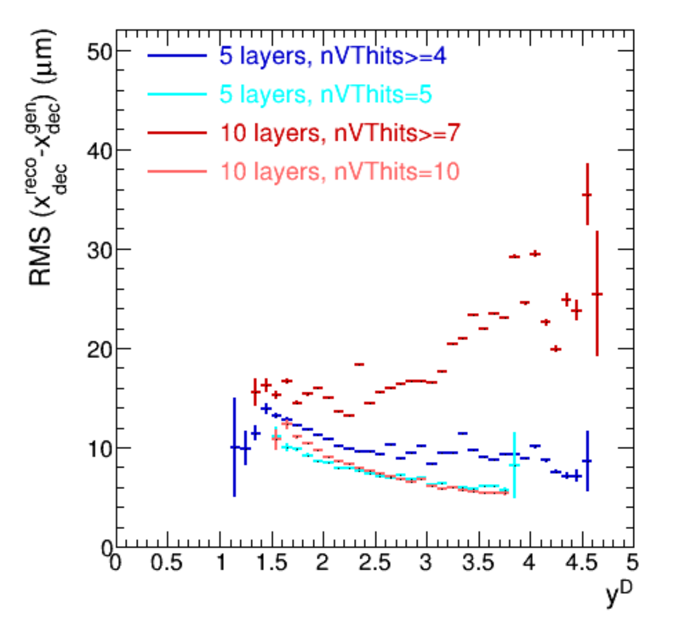
	Mass MeV)	cτ (μm)	Decay	BR
D^0	**1865**	**123**	**$K^-\pi^+$**	**3.95%**
D^+	1869	312	$K^-\pi^+\pi^+$	9.38%
D_s^+	**1968**	**147**	**$\phi\pi^+$**	**2.24%**
Λ_c^+	2285	60	$pK^-\pi^+$ pK^0_s $\Lambda\pi^+$	6.28% 1.59% 1.30%

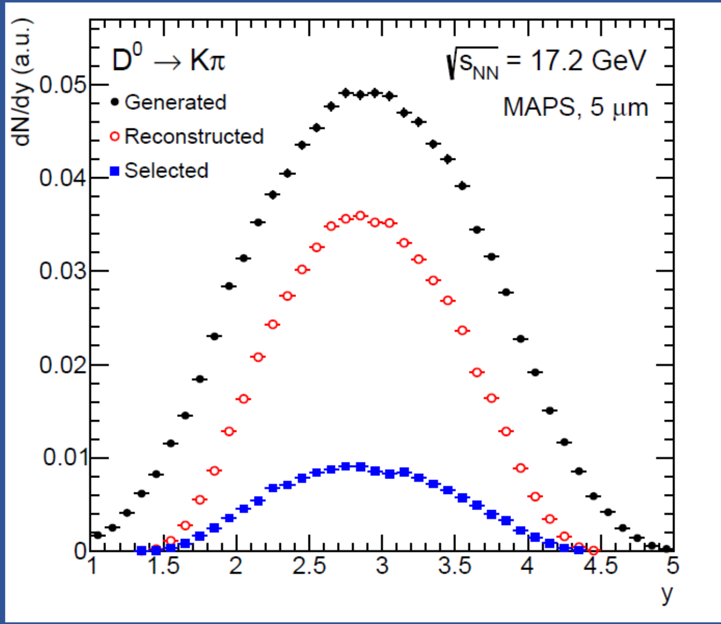


D-meson performance studies

- **Fast simulations** 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

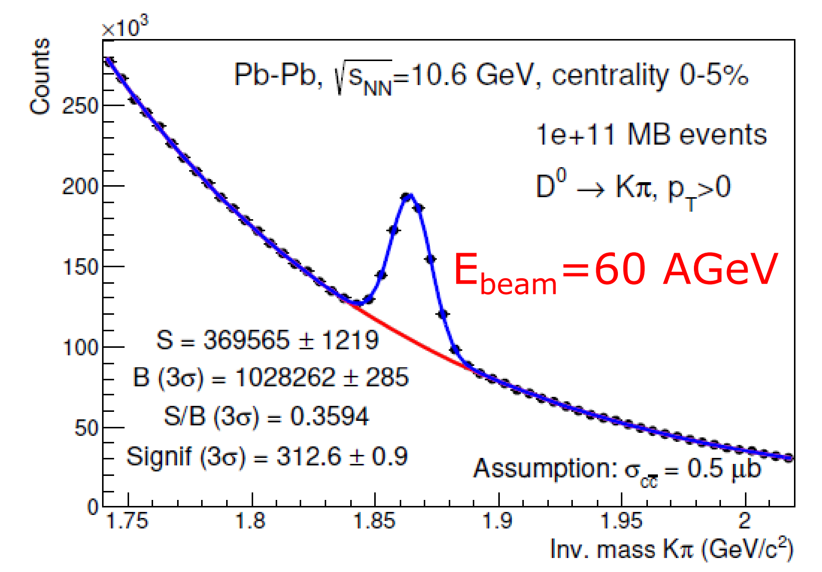




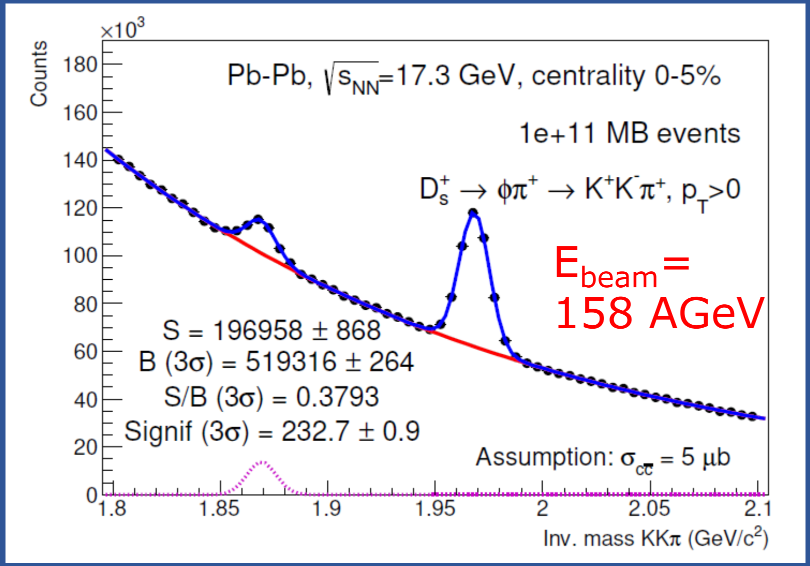


Charm hadrons: performance plots

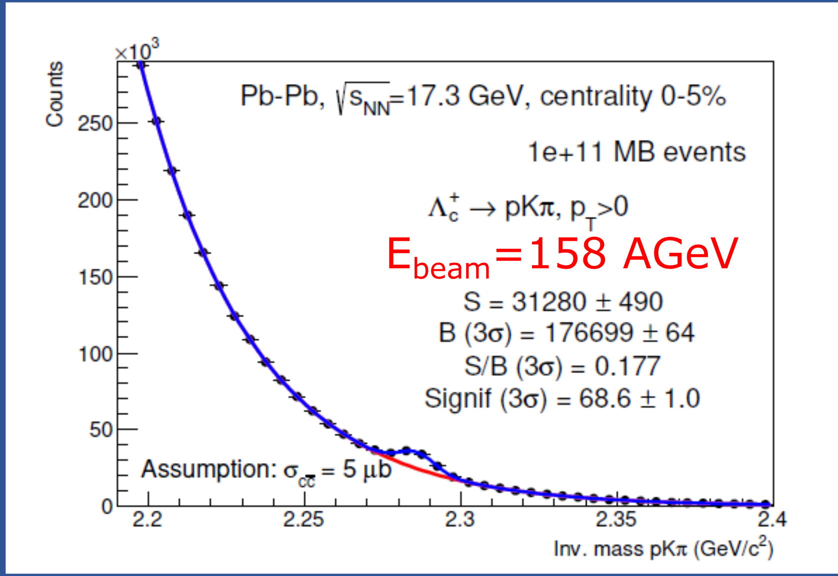
- With 10^{11} minimum bias Pb-Pb collisions (1 month of data taking)
  - More than $3\cdot10^6$ reconstructed D^0 in central Pb-Pb collisions at $\sqrt{s_{NN}}$=17.3 GeV
    - Allows for differential studies of yield and v_2 vs. p_T, y and centrality
  - D^0 accessible also at lower collision energies 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



$D^0 \rightarrow K\pi$



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



$\Lambda_c^+ \rightarrow pK\pi$

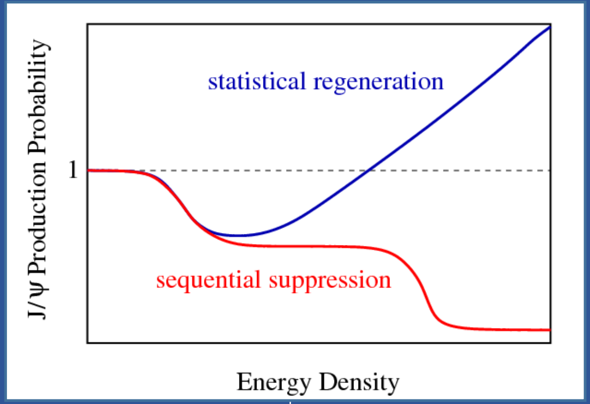
Charmonia: high vs low √s

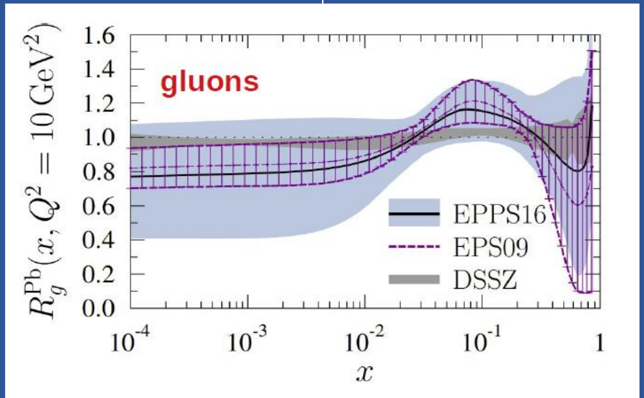
Collider (LHC)

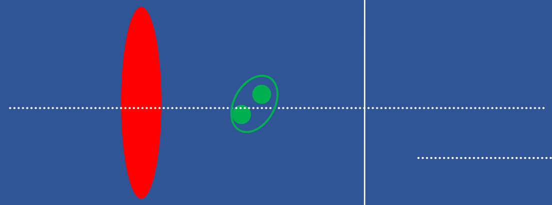
Hot matter effects: regeneration counterbalances (overcomes) suppression

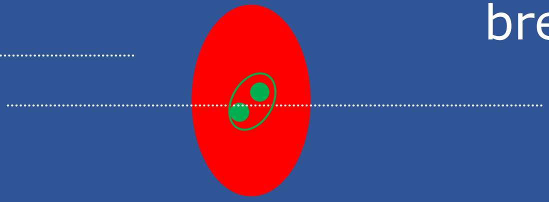
Initial state effects: shadowing
$x \sim 10^{-5}$ ($y \sim 3$),
$x \sim 10^{-3}$ ($y = 0$),
$x \sim 10^{-2}$ ($y \sim -3$)

(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 ($y \sim -3$)









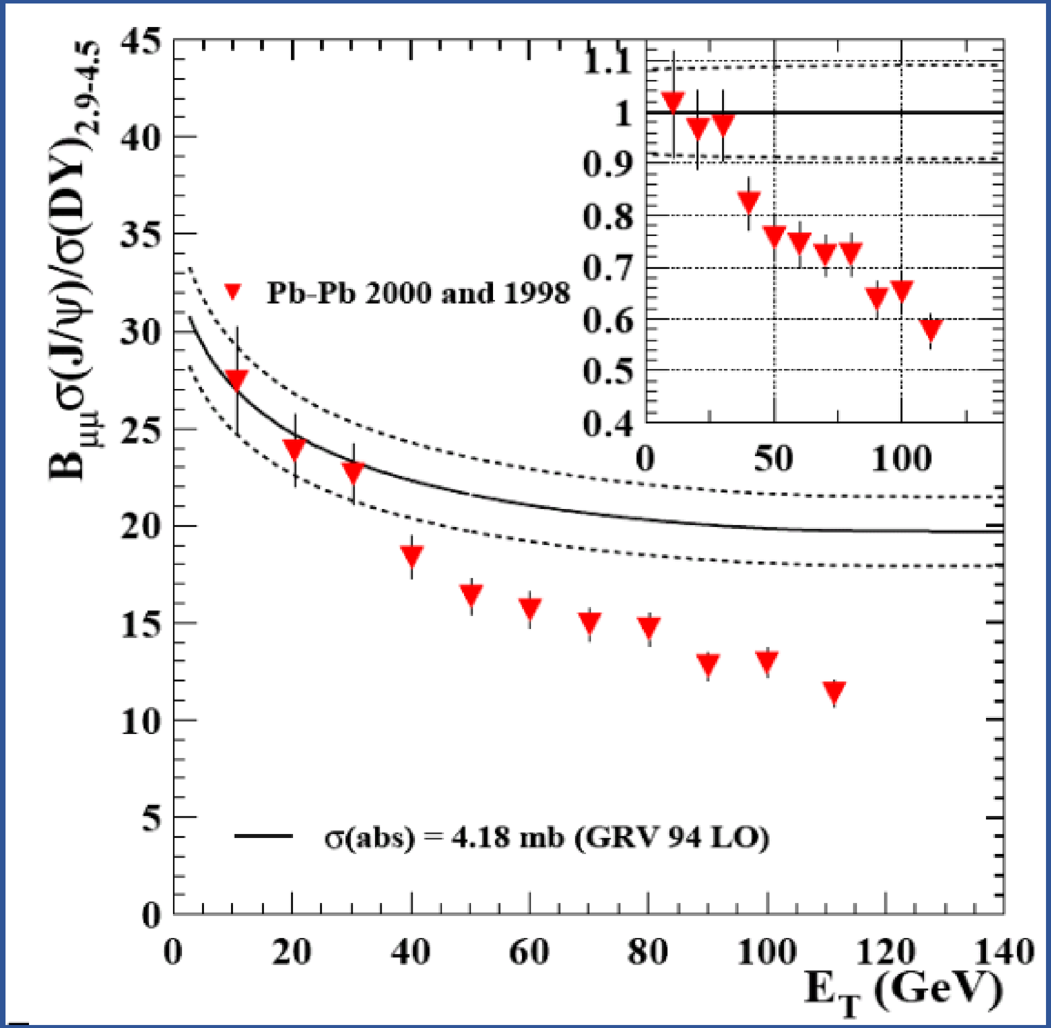
Fixed target (SPS)

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



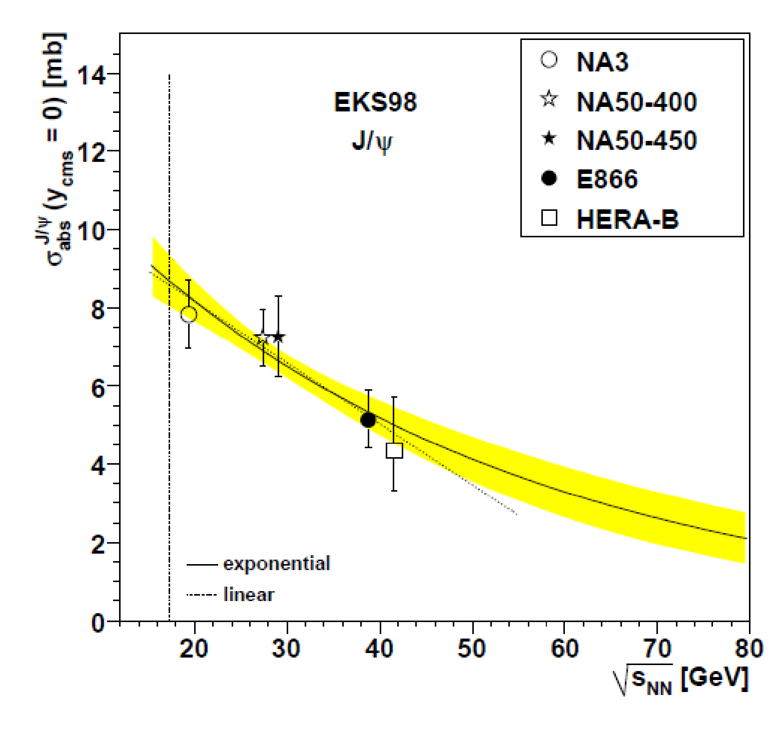
- Contrary to open charm, accurate studies were performed at $\sqrt{s}$=17.3 GeV (NA50, NA60)
- J/ψ yields normalized to Drell-Yan reference
- QGP-induced suppression evaluated with respect to a CNM reference obtained with systematic p-A studies
- **~30-40% anomalous suppression effect** possibly due to disappearance of feed-down from χ_c and ψ(2S)

CNM effects are (very) large

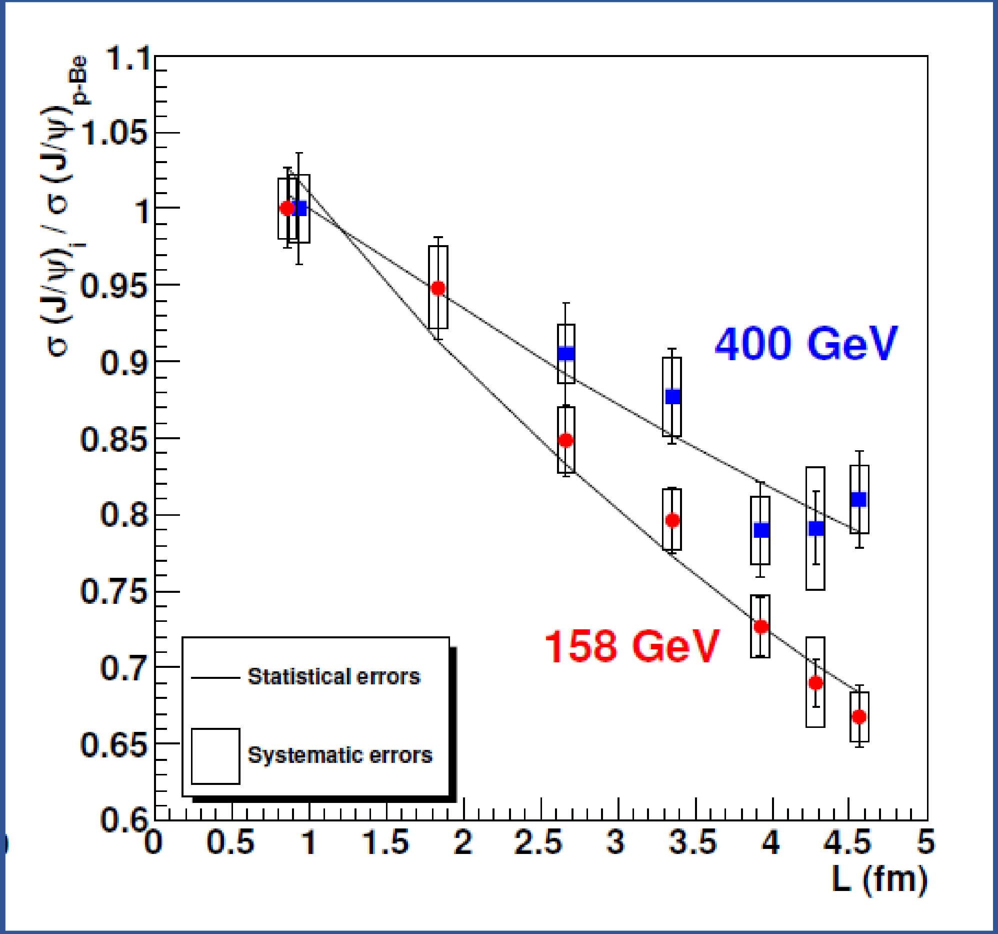
- Shadowing effects are moderate
- Dominated by nuclear absorption
  → ~30% effect in p-Pb at $\sqrt{s_{NN}}$ = 17 GeV

- **Strong √s-dependence**
  → CNM may become the dominant effect at low energy

NA60, PLB 706 (2012) 263



Lourenco, Vogt, Woehri, JHEP 0902:014,2009



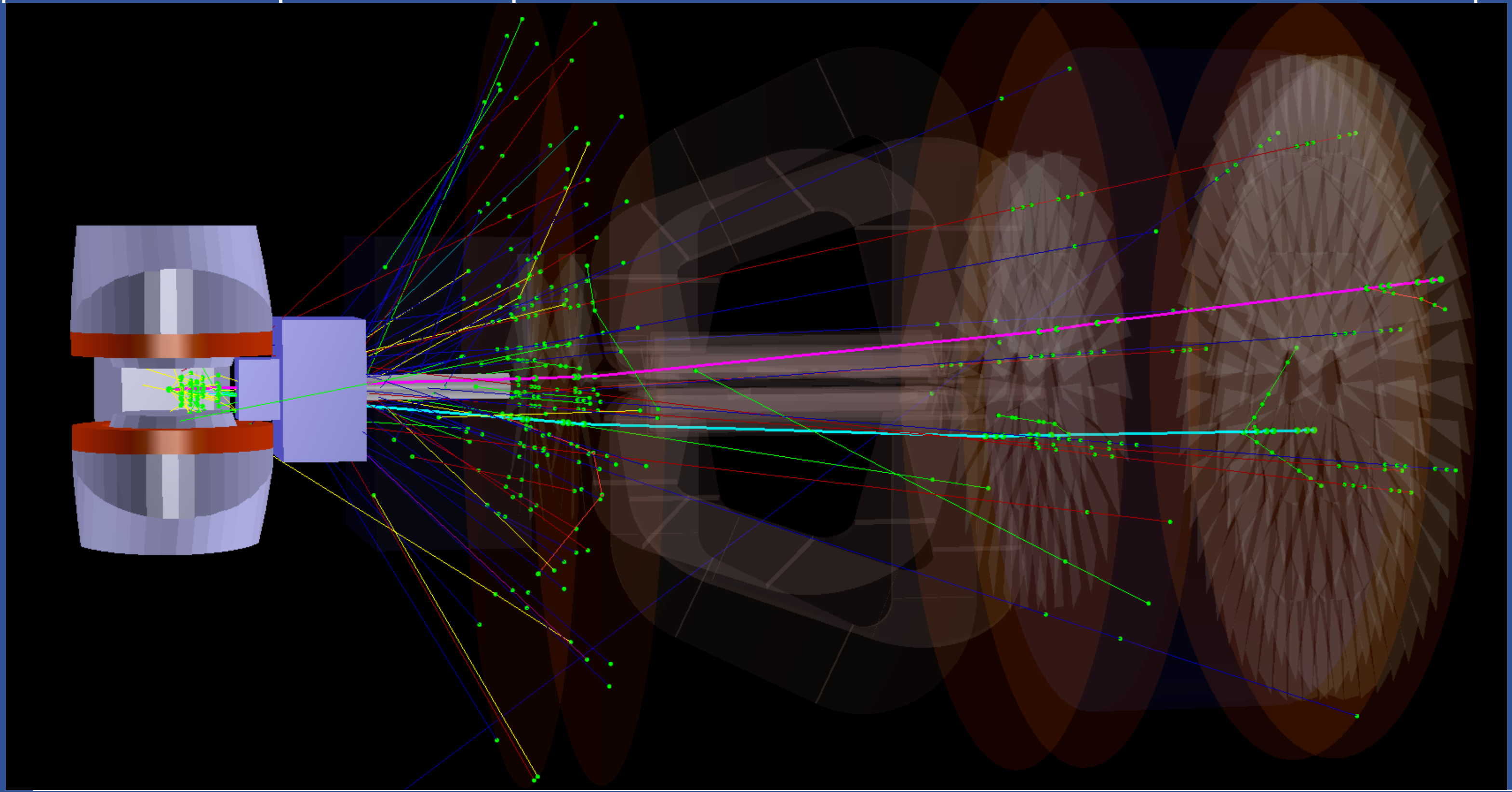
L: thickness of nuclear matter crossed by the cc pair (evaluated with Glauber model)

J/ψ: going below top SPS energy

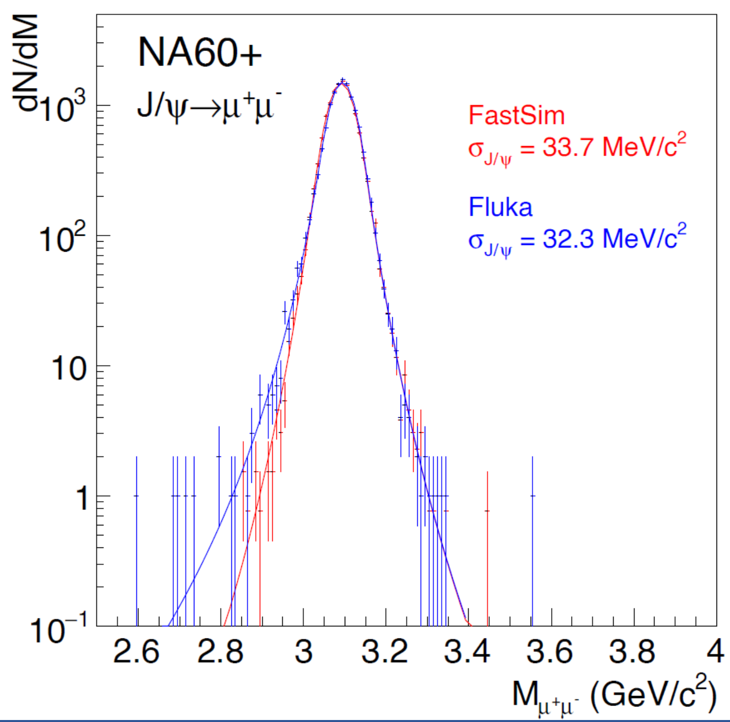
Track matching

Vertex tracking (dipole field)

Muon identification in a spectrometer (toroidal field)



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



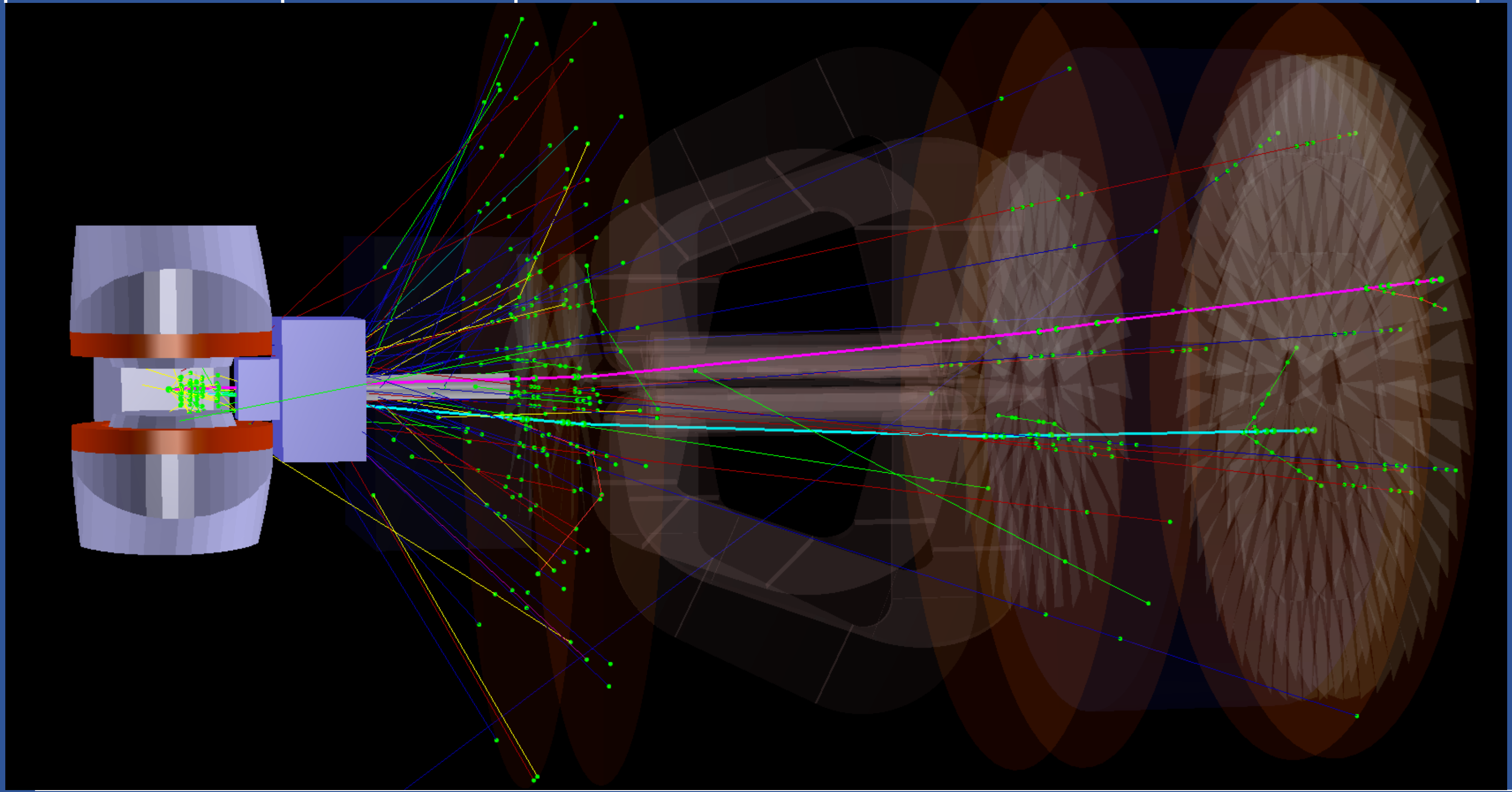
Excellent resolution

J/ψ: going below top SPS energy

Track matching

Vertex tracking (dipole field)

Muon identification in a spectrometer (toroidal field)

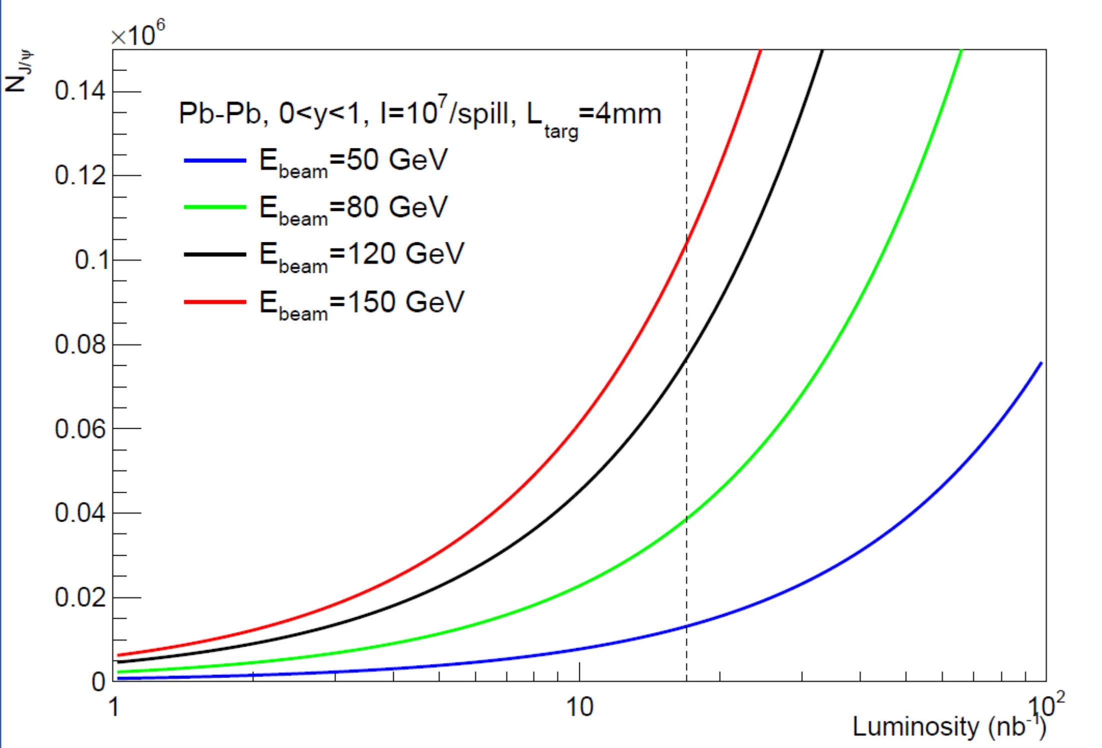


Quarkonium production not studied below top SPS energies!

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

- ❑ Decreasing √s:
  - ❑ **Onset of χ_c and ψ(2S) melting**
    → to be correlated to T measurement via thermal dimuons
  - ❑ **Stronger CNM effects**
    → to be accounted for with pA data taking at the same √s

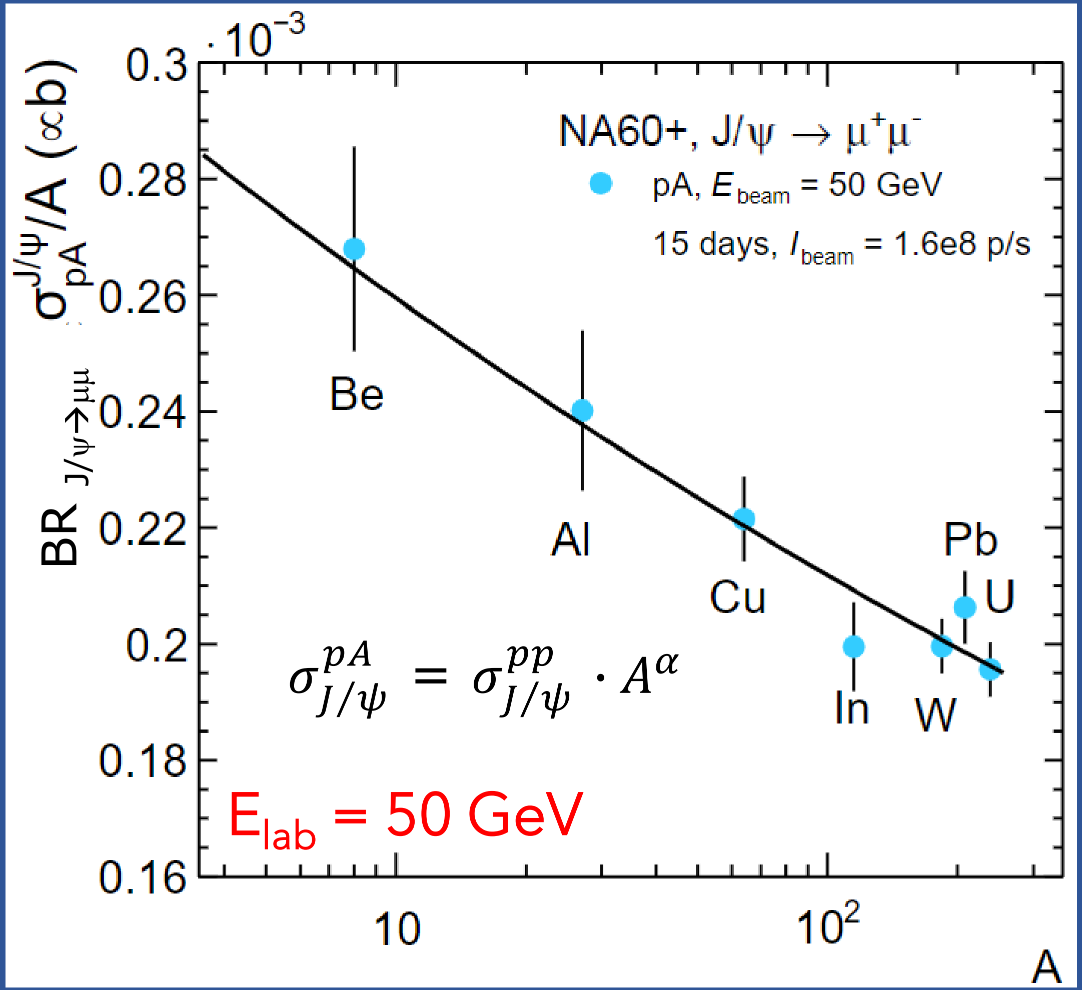
J/ψ in Pb-Pb collisions at (various) SPS energies



- With I_{beam}~10^7 Pb/20s spill, 4mm Pb target and 1 month of data taking → **L_{int} ~17 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

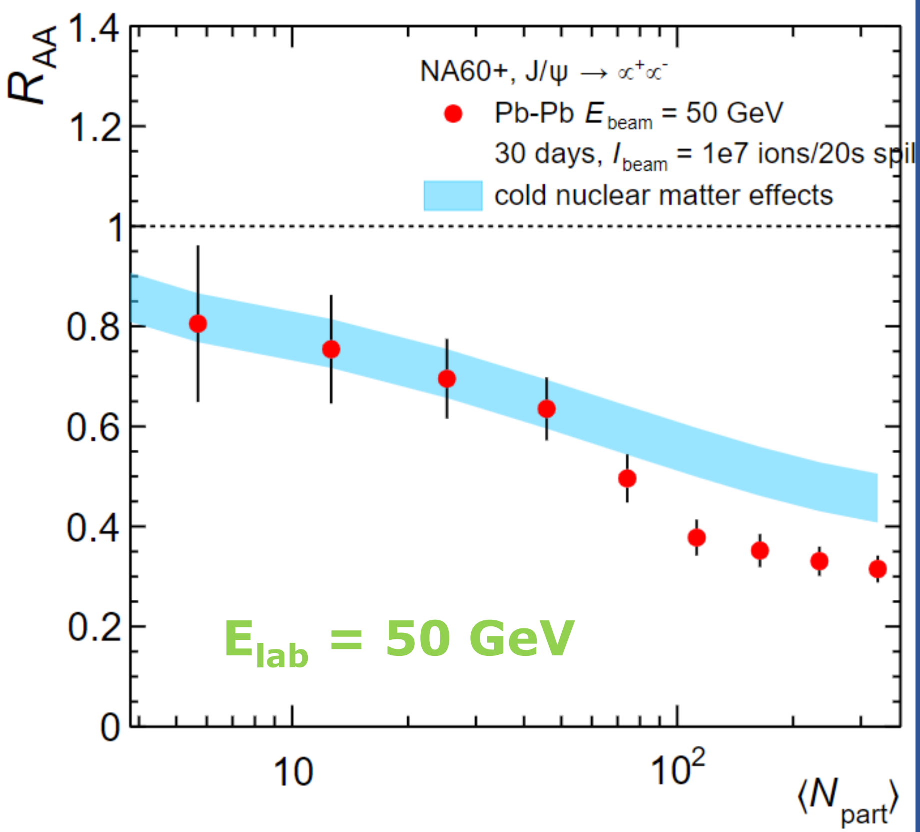
J/ψ in p-A collisions at (various) SPS energies

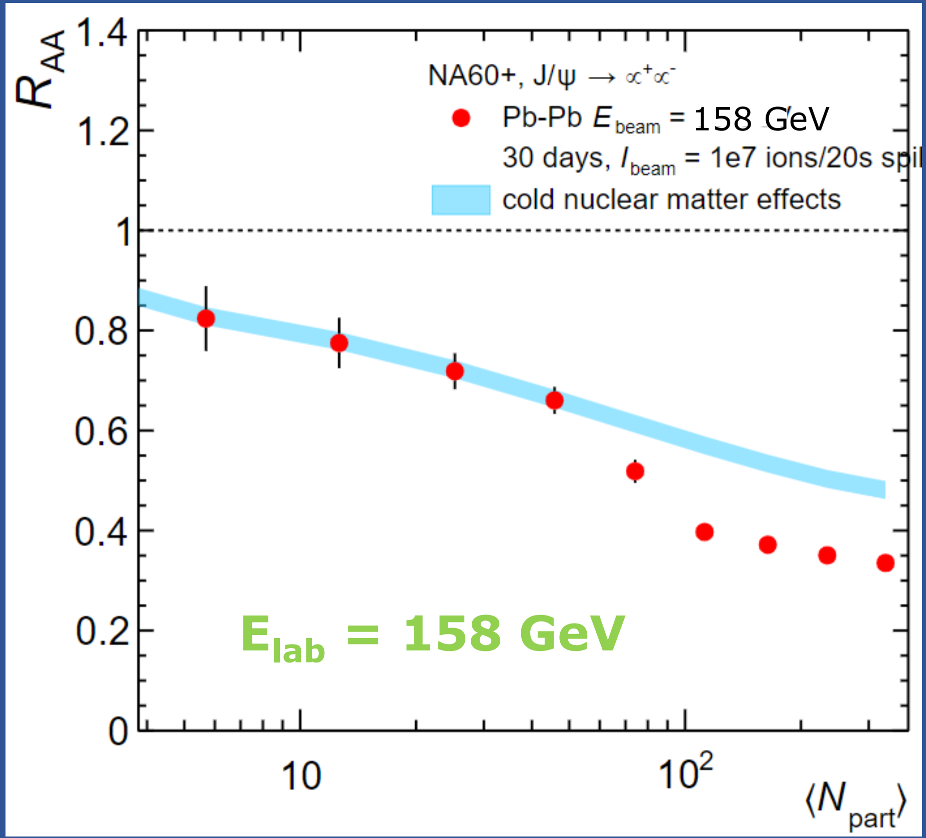


- With I_{beam}~8x10^8 p/20s spill, 7 targets with total interaction length 10% and 0.5 months of data taking NA60+ can aim at
  - **~6000 J/ψ at 50 GeV**
  - **~50000 J/ψ at 158 GeV**

- pp collisions unpractical
  → Use a system of several targets simultaneously exposed to the p beam

NA60+, R_{AA} estimate





- Based on
  - 30 days PbPb
    I_{beam} = 1e7/spill
  - 15 days pA
    I_{beam} = 8e8/spill

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**

In 15 days of data taking at 1.6 x 10^8 p/s the uncertainties on the pA reference are:

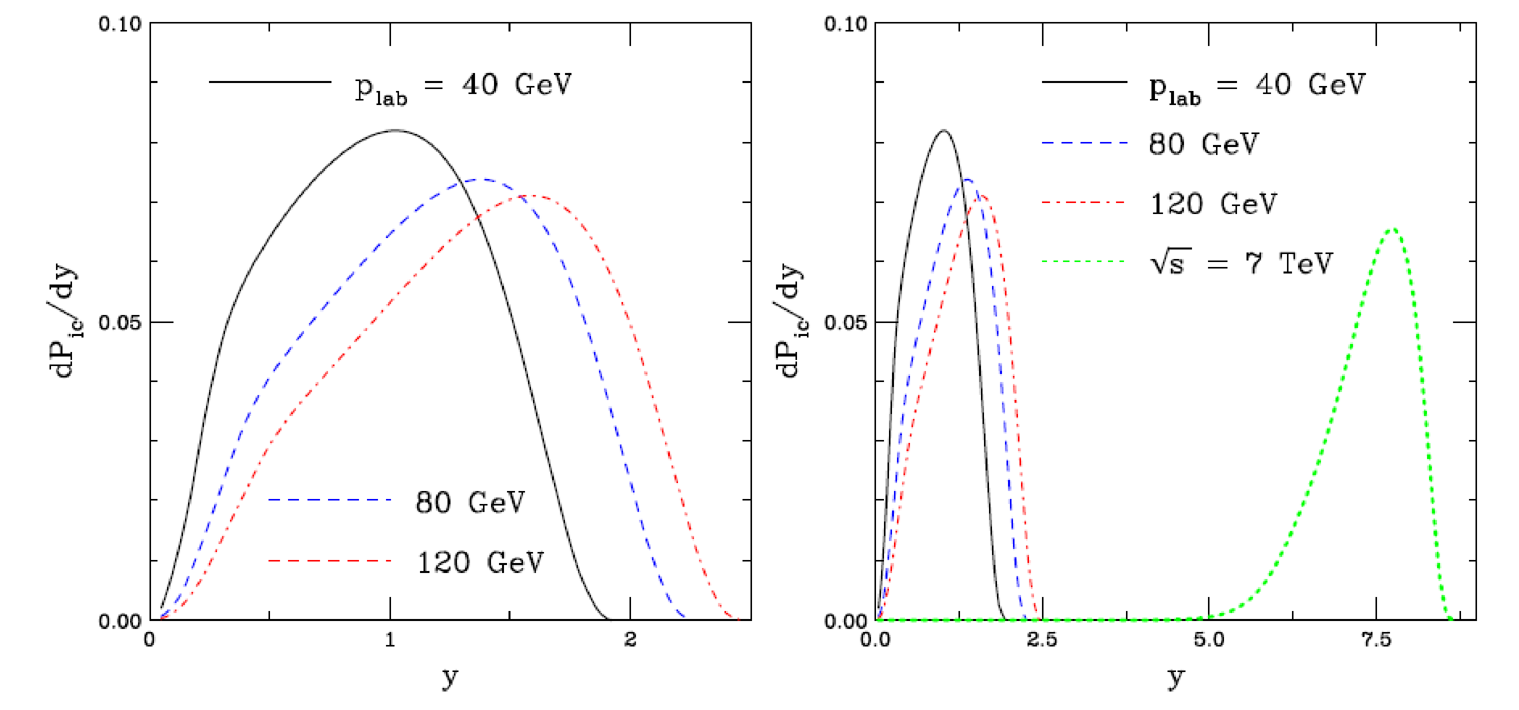
E_{lab} = 50GeV
- ~15% on σ_{abs}
- ~5% on σ_{pp}

E_{lab} = 158GeV
- ~6% on σ_{abs}
- ~2% on σ_{pp}

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, but **no conclusive results**
- At colliders, forward x_F pushed to very high rapidity, difficult to measure
  → fixed-target configurations more appropriate

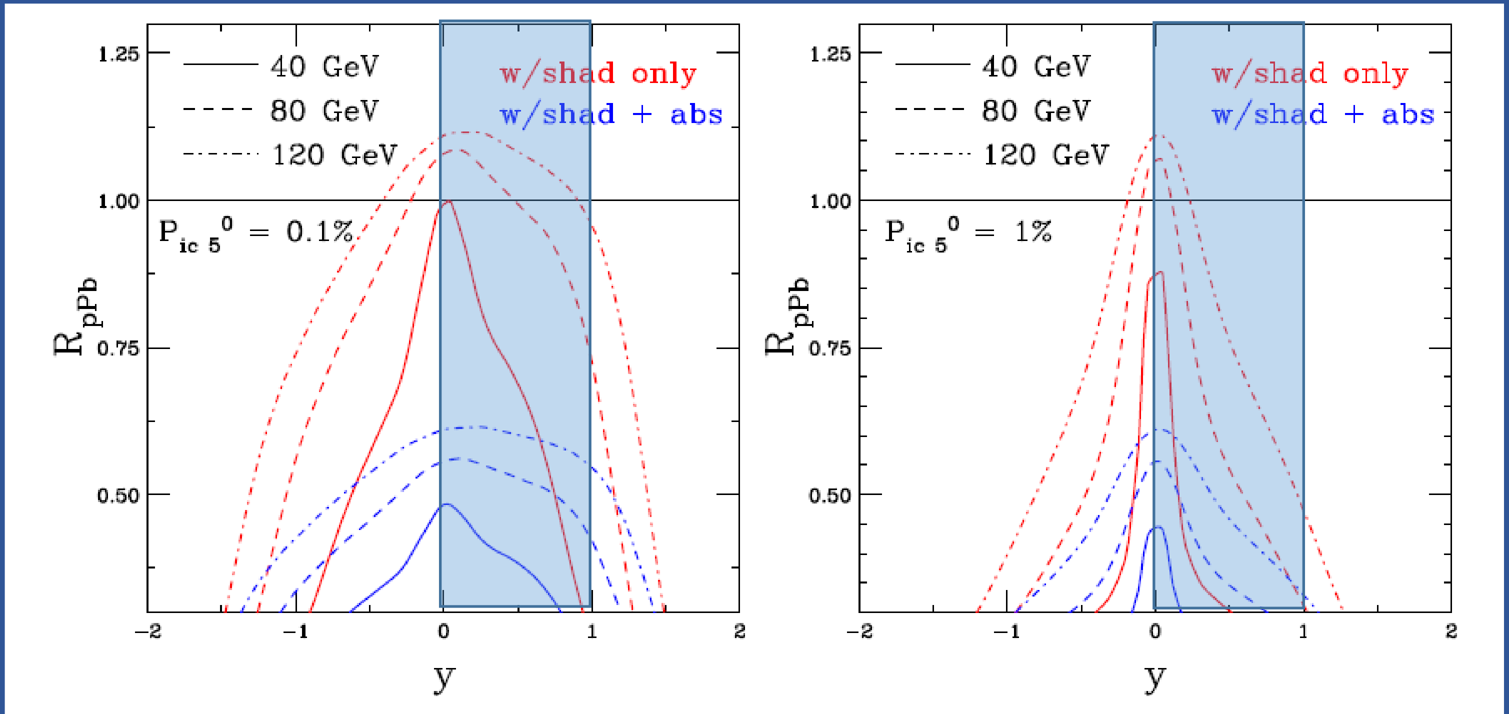


Assumed intrinsic charm content varied between 0.1% and 1%

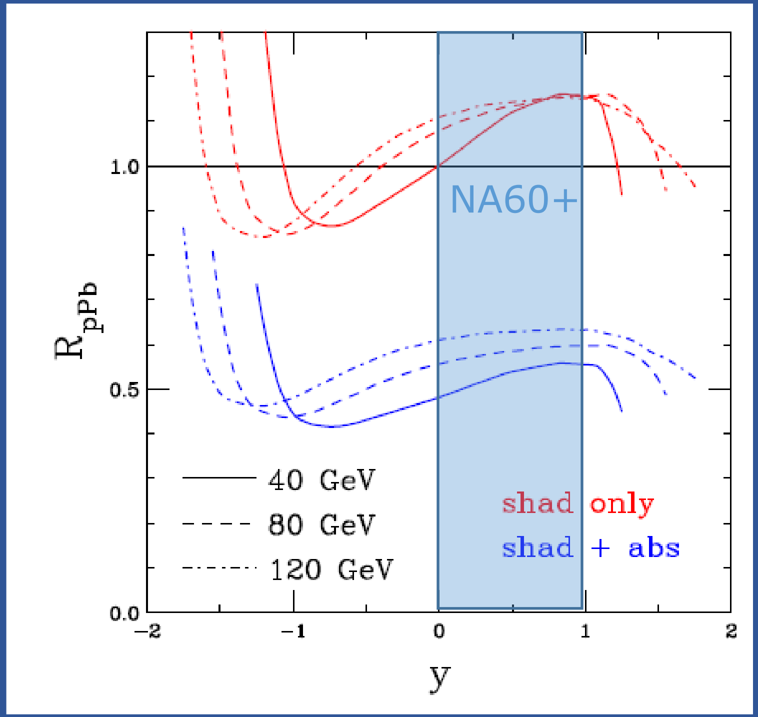
R. Vogt, PRC 103, 035204 (2021)
R. Vogt, arXiv:2207.04347

Low-$\sqrt{s}$ J/ψ: studying intrinsic charm

p-Pb collisions
- EPPS16 shadowing
- σ_{abs} = 9,10,11 mb at E_{lab}=120, 80, 40 GeV
- P_{ic} varied between 0.1 and 1%



(w/o intrinsic charm)



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

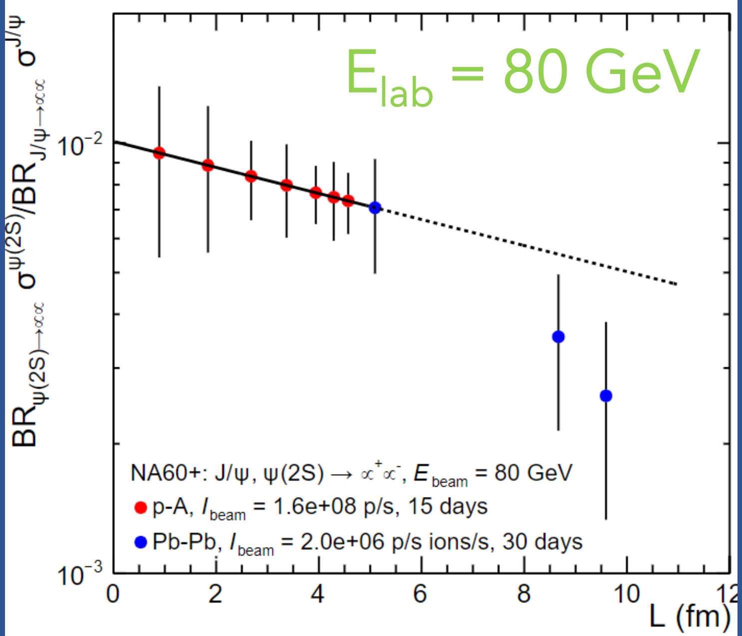
Prospects for ψ(2S) measurements at low √s

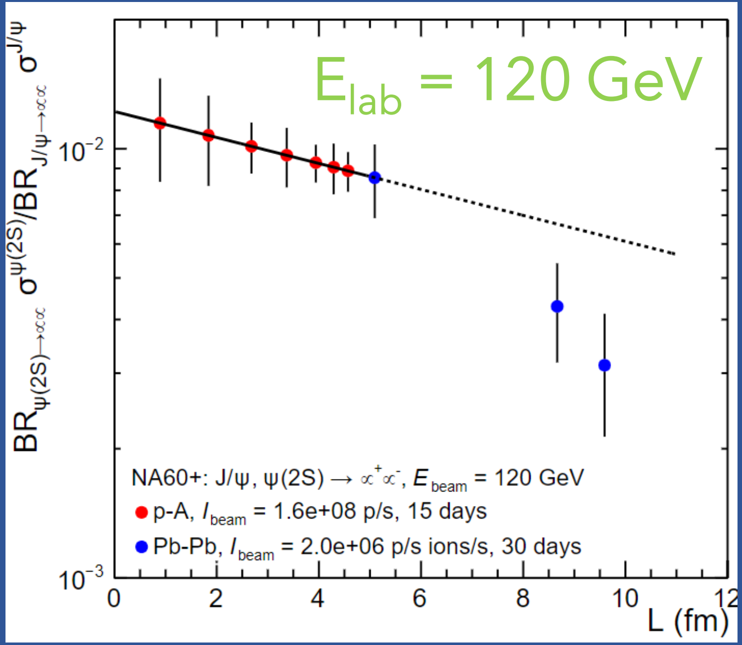
Good charmonium resolution (~30 MeV for the J/ψ) will help ψ(2S) measurements

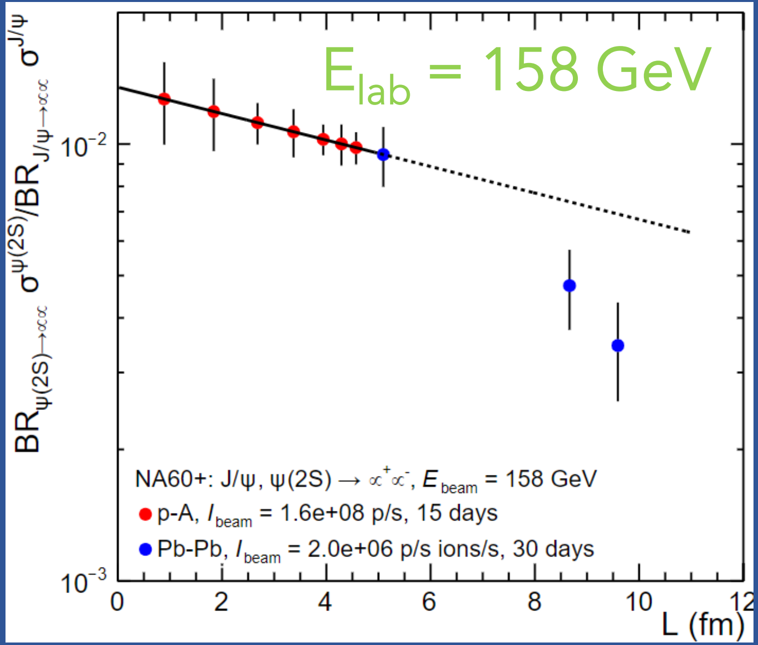
Expectations based on

- 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)



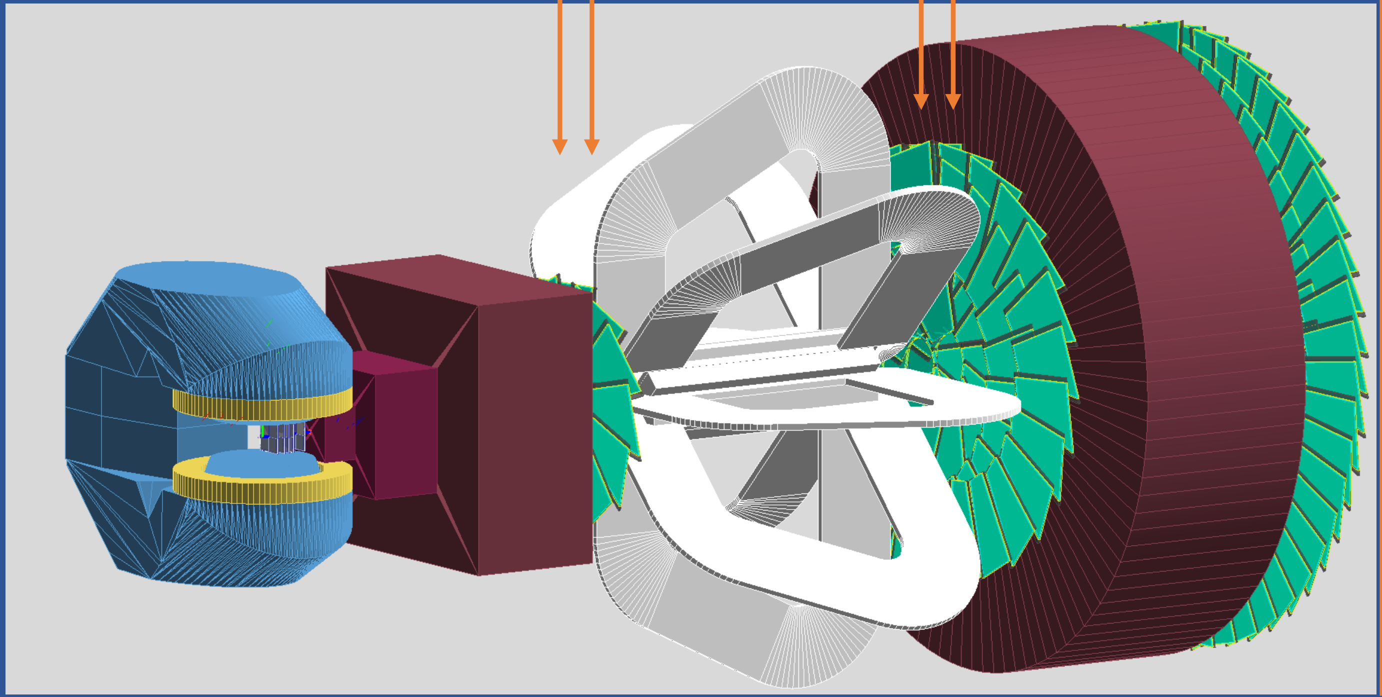




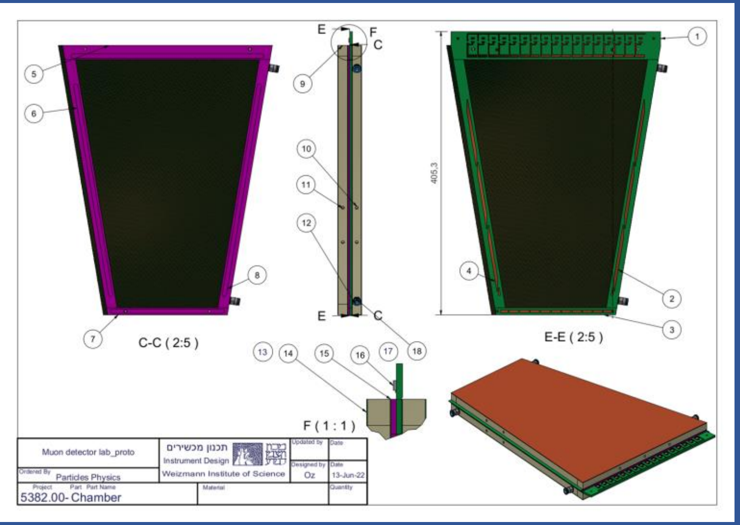
- ❑ **ψ(2S)/ψ measurement looks feasible down to E_{lab} = 120 GeV**
- ❑ Lower E_{lab} would require larger beam intensites/longer running times

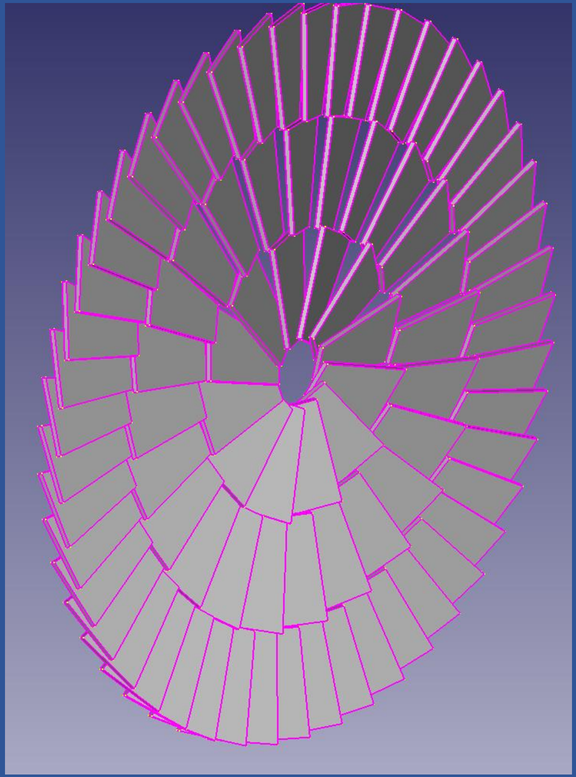
R&D for the NA60+ experiment

Muon tracker



R&D carried out by Israel (Weizmann) and US (StonyBrook) groups



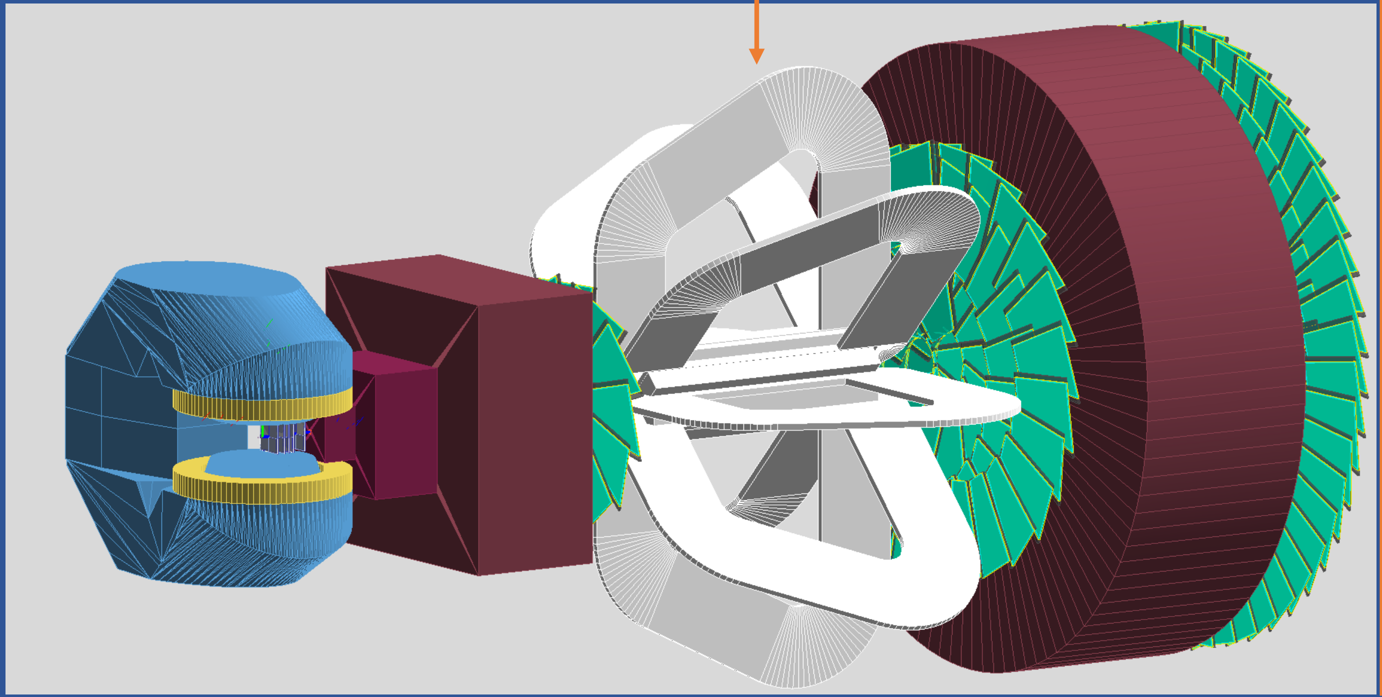


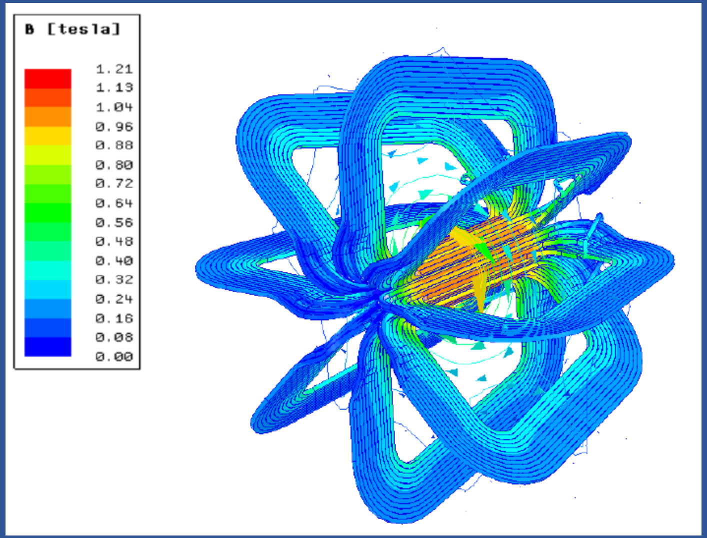
- Relatively low incident flux: <2kHz/cm^2
- Considering MWPC and/or GEM options
- First MWPC prototype on SPS test beam at the beginning of 2023

Complete spectrometer
→264 modules
→~100 m^2 surface

R&D for the NA60+ experiment

Toroidal magnet





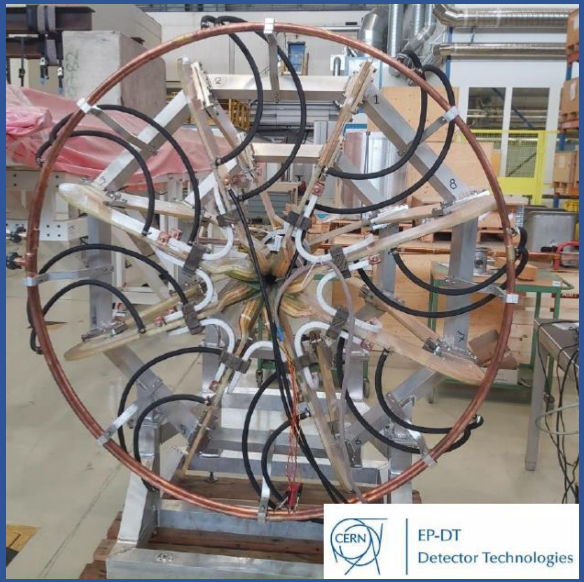
Warm pulsed magnet → 0.5 T over 120 m^3

Eight sectors, 12 turns each

Current → 190 kA, total power 3 MW

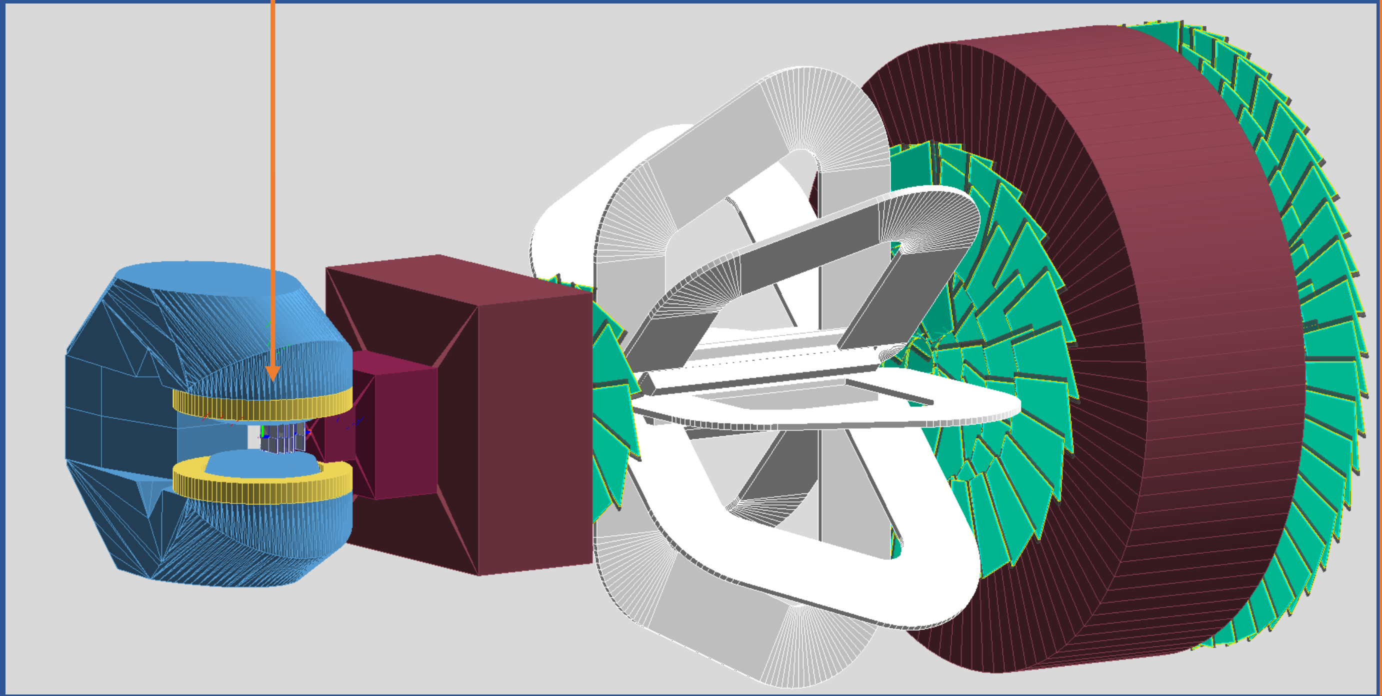
Demonstrator (scale 1:5) constructed and tested (CERN/INFN)
→ cross-check of various aspects of the design

Measurements of the magnetic field in the prototype in agreement with simulations within 3%

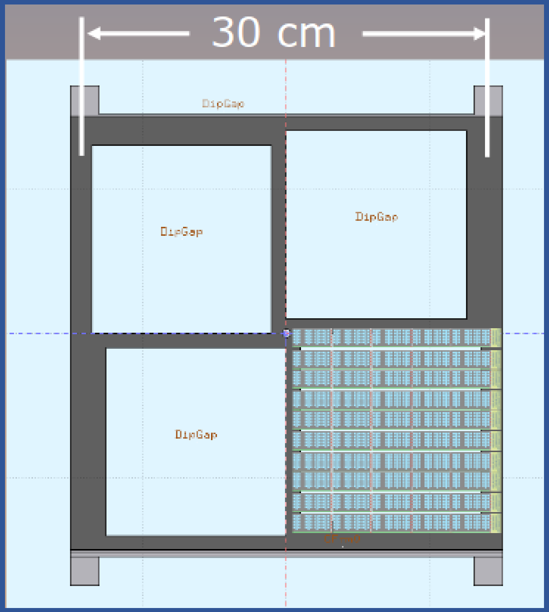


R&D for the NA60+ experiment

Vertex spectrometer

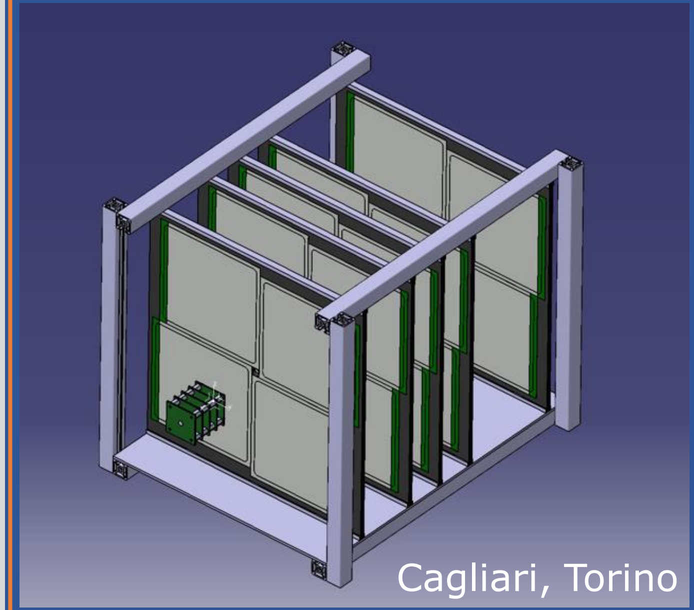


Common development ALICE → NA60+, state-of-the-art imaging technology TowerJazz 65 nm



Sensor thickness:
few tens of μm of silicon → material budget < 0.1% X_0

Spatial resolution 5 μm



Cooling studies for NA60+ geometry → mixed air+fluid

Four sensors per station

Five to ten stations in the spectrometer

MEP48 dipole magnet

Conclusions

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

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

- 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

- Project is part of the CERN Physics Beyond Collider Initiative
- Letter of Intent ready for submission to SPSC
- Aim is **taking data after LHC Long Shutdown 3** → 2029 onwards!

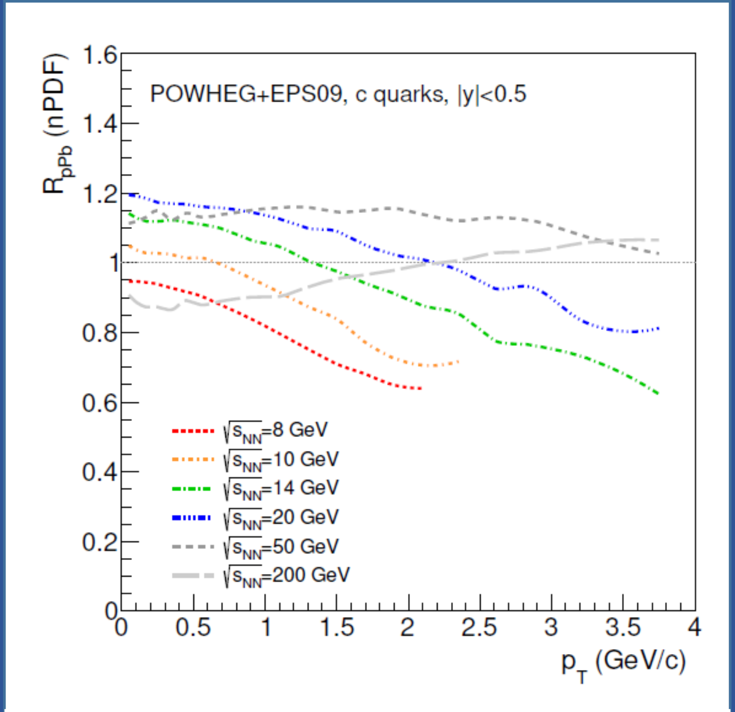
Feedback on physics program and participation in the experimental effort are welcome!

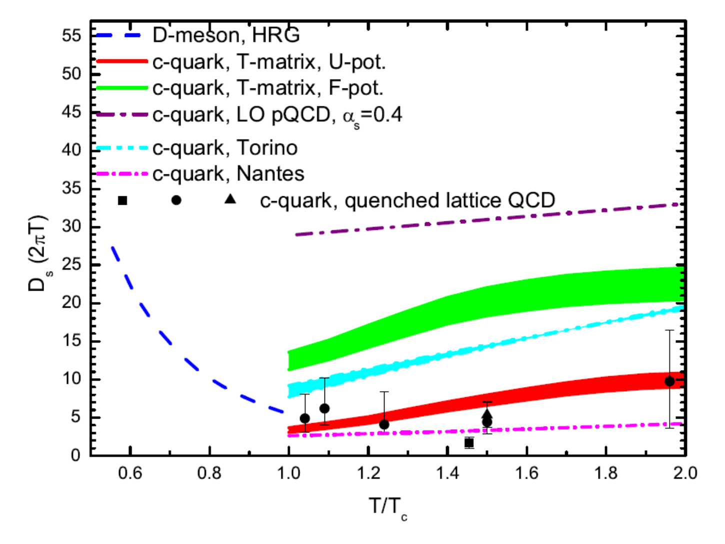
Backup

Open charm at low √s: what can we learn ?

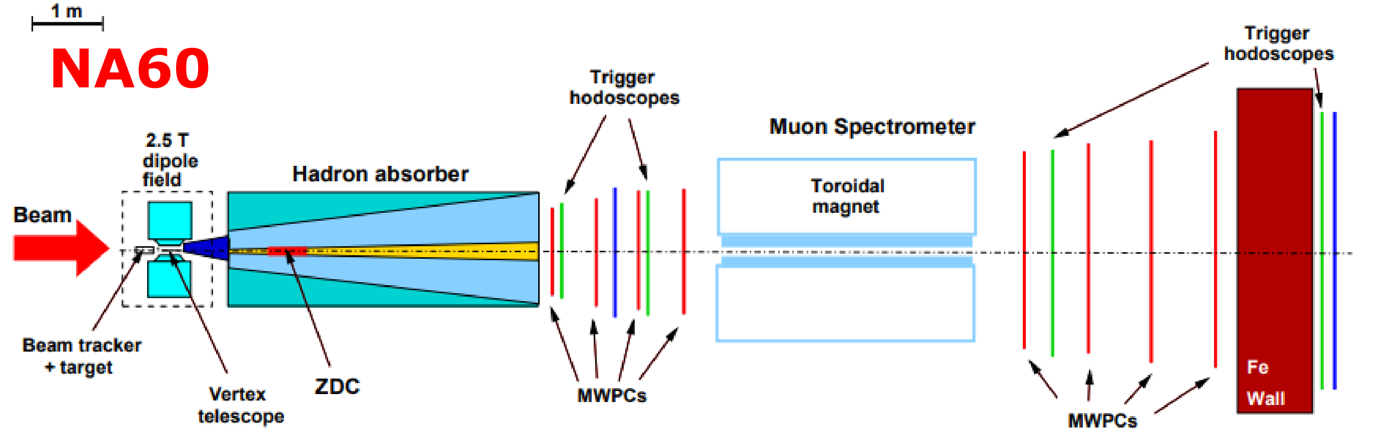
- Charm production in p-A collisions
  - Sensitive to **nuclear PDFs**
    - $Q^2 \sim 10–40$ GeV^2 and $0.1 < x_{Bj} < 0.3$ (anti-shadowing and EMC)
  - Possible sensitivity to **intrinsic charm**

- Charm hadron yield and v_2 in A-A collisions
  - Constrain estimates of the **charm diffusion coefficient**
  - Charm quark **thermalization** in a short-lived QGP
  - Insight into **hadronization mechanism**
    - Enhanced D_s/D and Λ_c/D ratios in case of quark recombination

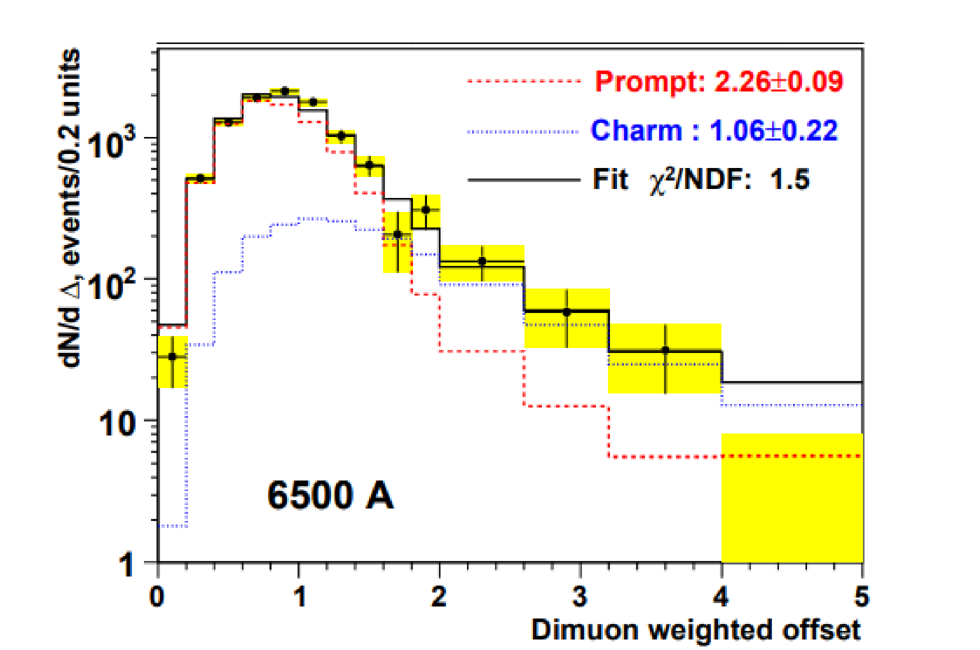




Existing open charm results at SPS energy



- ❑ 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

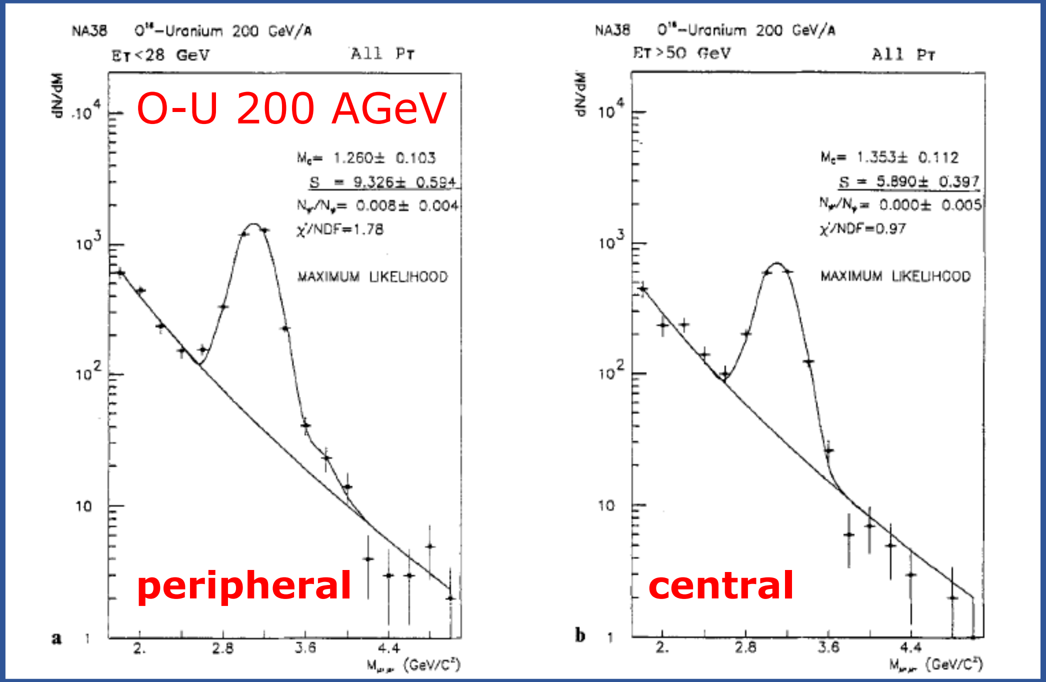
- ❑ Analysis of open charm contribution (semileptonic decays of charm hadron pairs) leads, for In-In collisions at $\sqrt{s_{NN}}$=17.3 GeV, to σ_{cc}= 9.5±1.3(stat.)±1.4(syst.) μb assuming kinematic distribution as in PYTHIA6

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

No other results available below top SPS energy

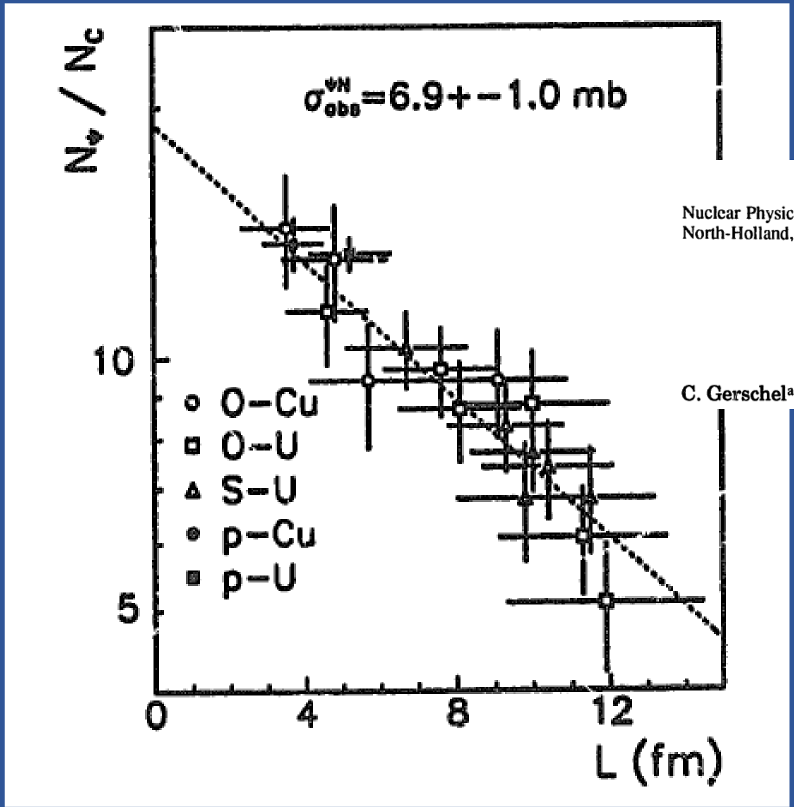
J/ψ at SPS energy: discovery of the suppression

NA38, Z. Phys. 38(1988) 117

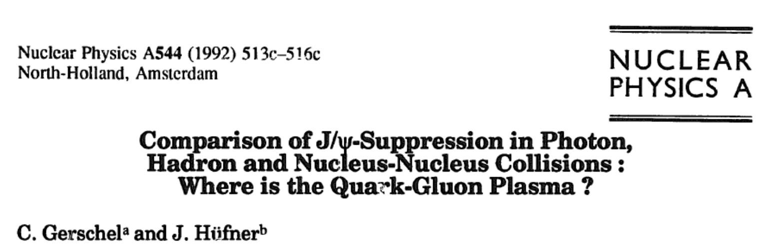


Centrality–dependent ratio J/ψ / continuum → **evidence for suppression**

Reference process?



C. Gerschel et al., PLB207 (1988)253


Nuclear Physics A544 (1992) 513c–516c
North-Holland, Amsterdam

NUCLEAR PHYSICS A

Comparison of J/ψ-Suppression in Photon, Hadron and Nucleus-Nucleus Collisions : Where is the Quark-Gluon Plasma ?

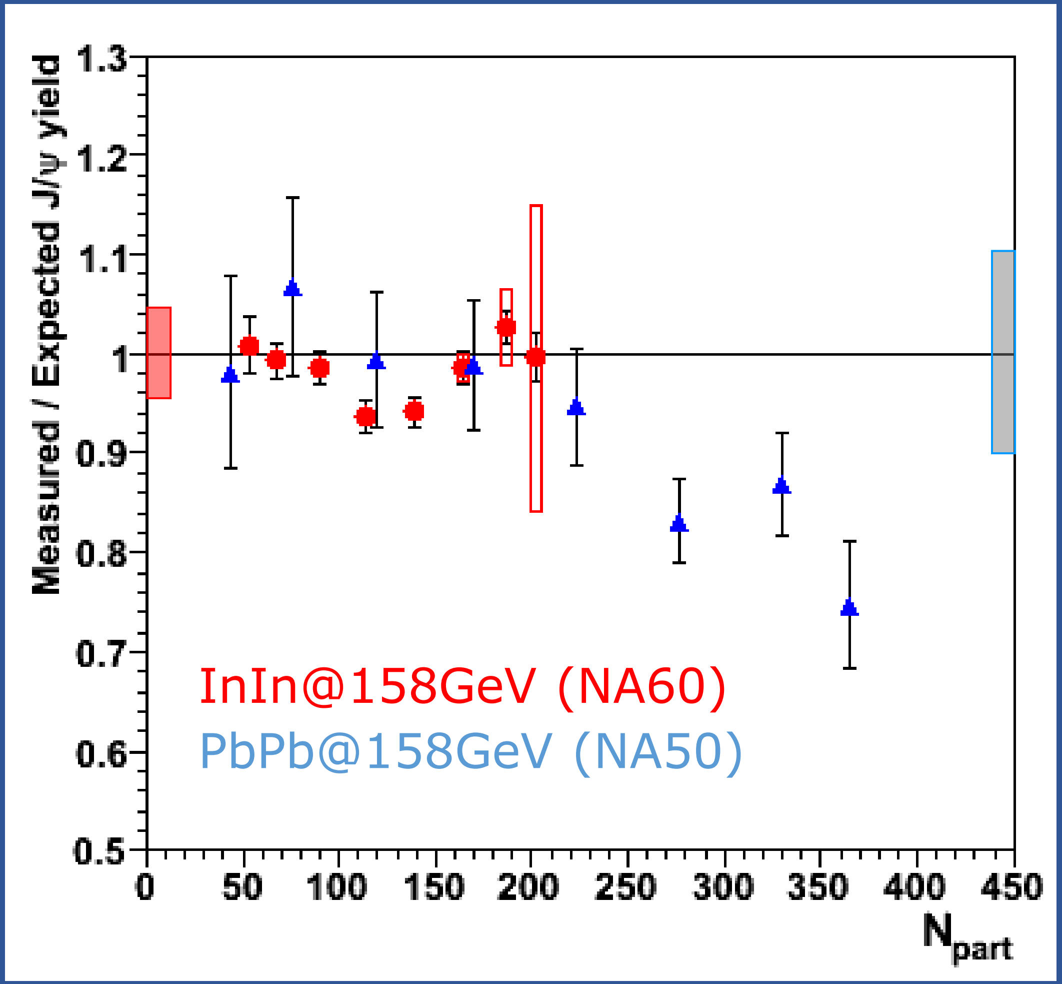
C. Gerschel[a] and J. Hüfner[b]

p-A collision results imply **significant dissociation cross sections in CNM**

→ Crucial ingredient in the interpretation of the data

→ Stimulated an intense experimental program at both CERN and FNAL

"Summary" J/ψ plot



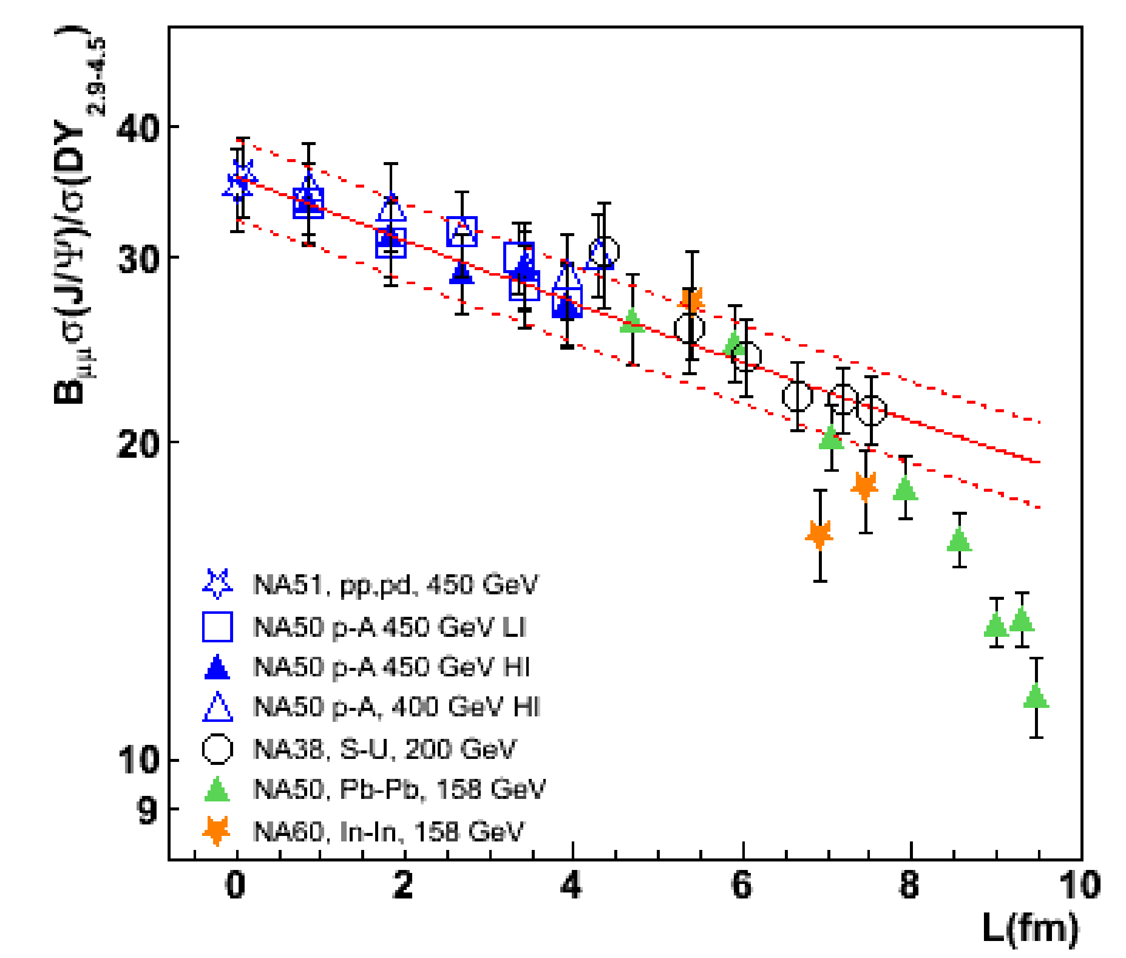
NA50, EPJC39 (2005) 335

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

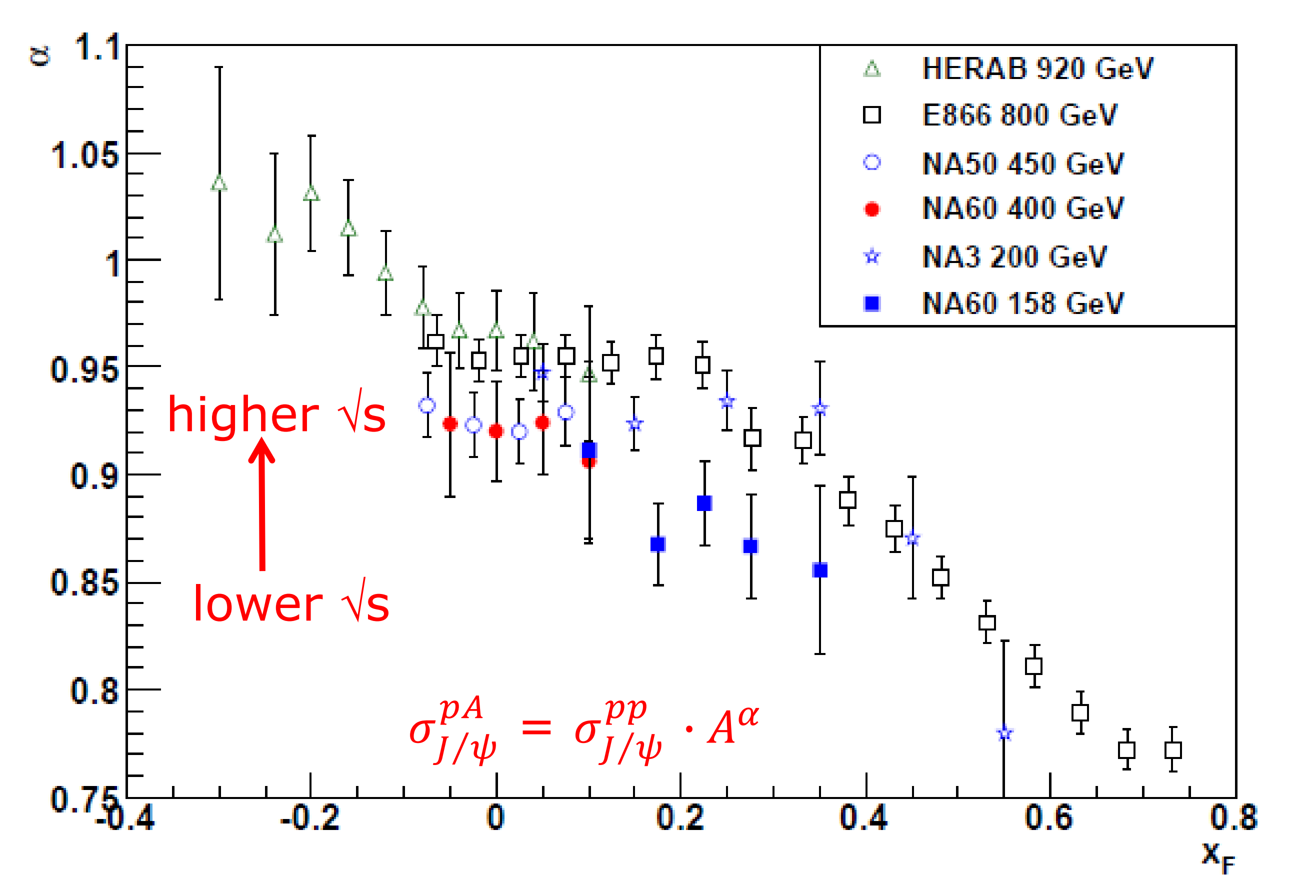


NA38 Coll., PLB449 (1999)128
NA50 Coll., EPJC39 (2005)335

- **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**

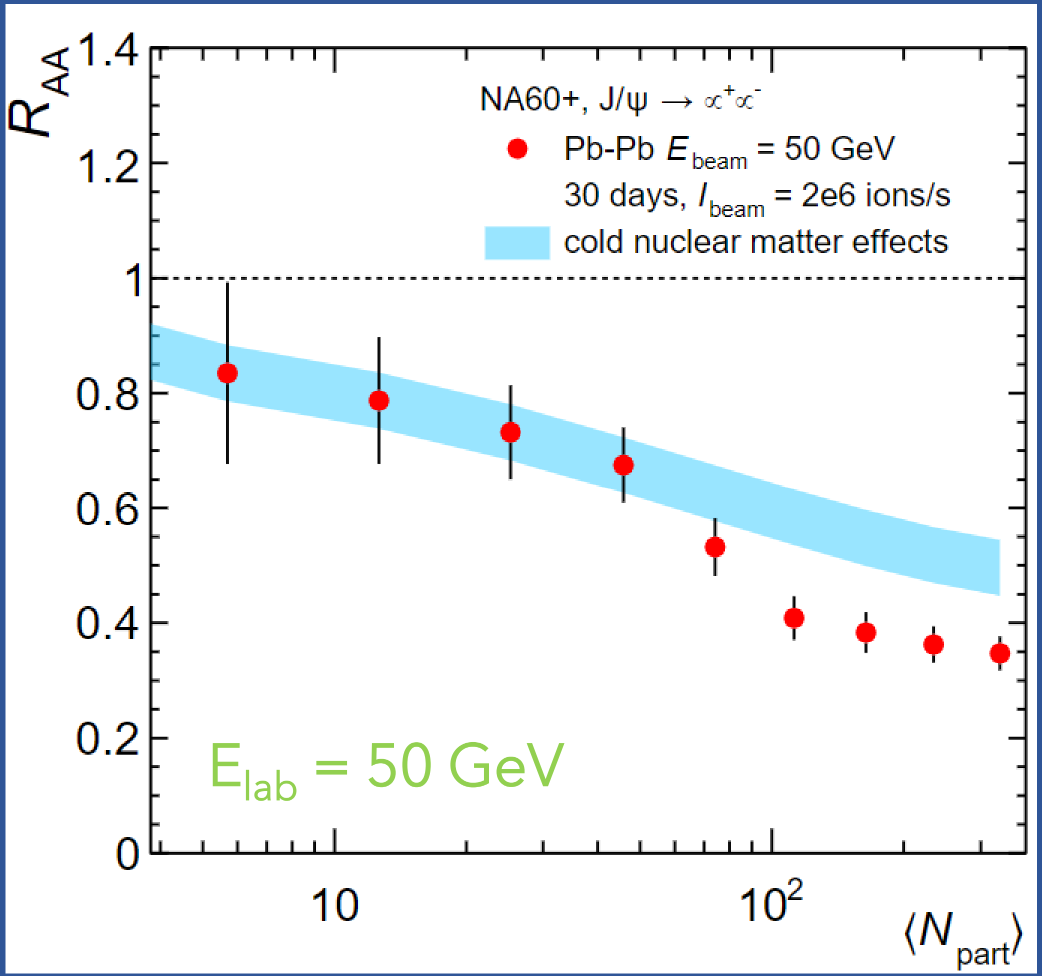
Superposition of several effects

⇓

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

No consistent theory description over the whole x_F range

Quantifying hot matter effects

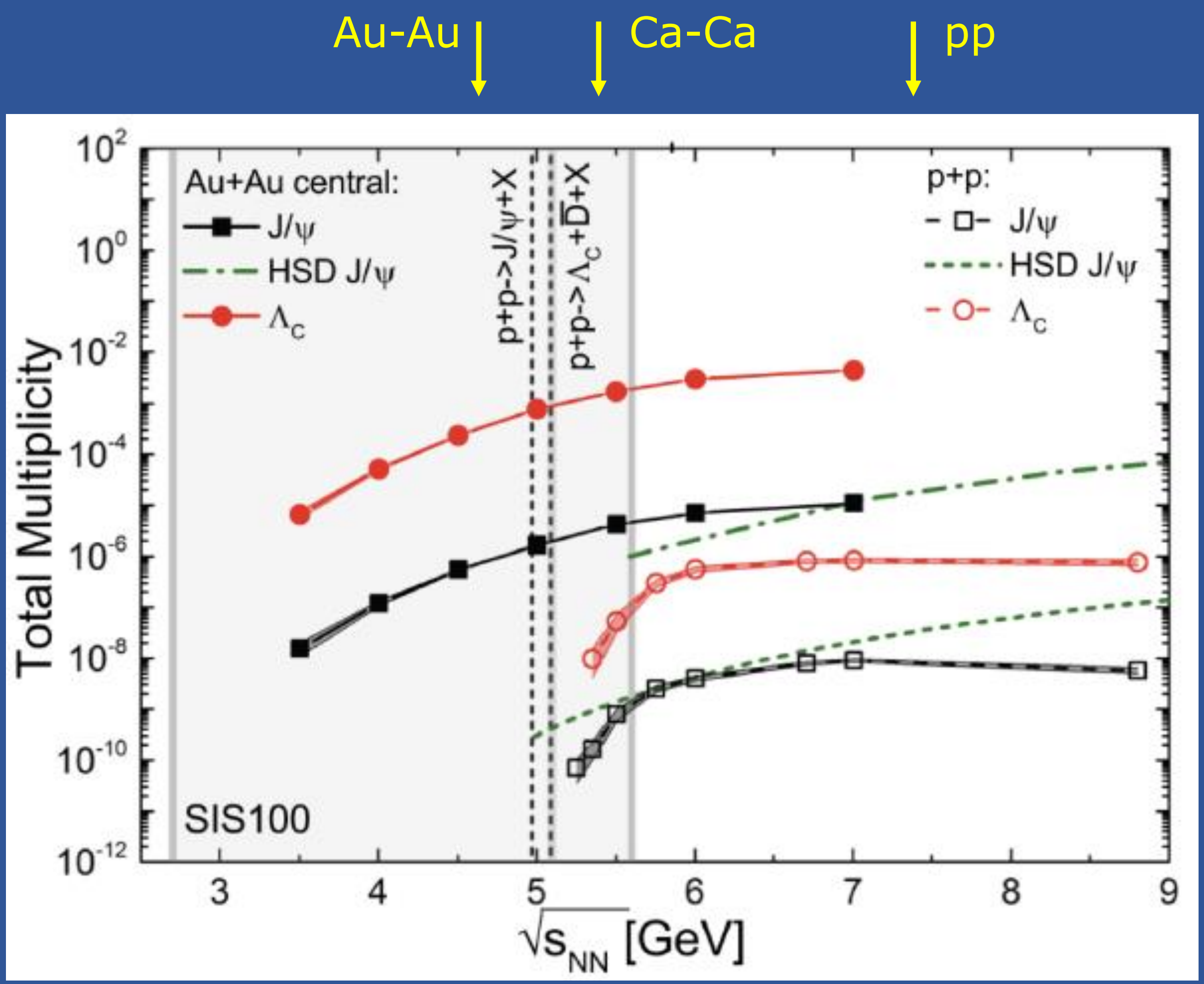


Which observables could be used?

- **R_{AA}** based on pp extrapolated from pA results at the same √s (<5% uncertainty)
- **R_{AA}/R_{pA}** ~ measured/expected à la NA50/60
  → useful to compare results at various √s, since CNM are energy dependent
- **Drell-Yan**
  very much limited by statistics at high mass (x100 less wrt J/ψ for $m>m_{J/\psi}$)
- **J/ψ/(total charm)?**
  potentially accessible via hadronic charm measurements

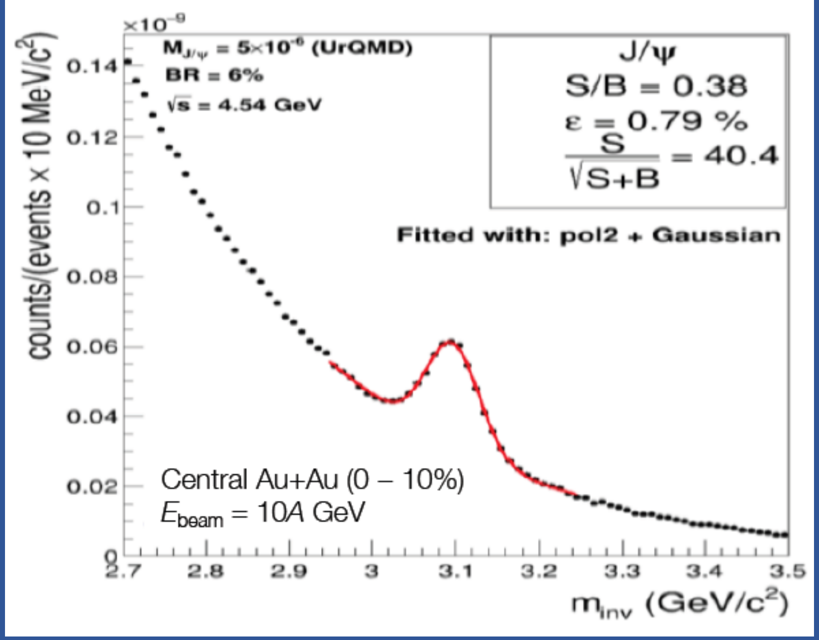
Quarkonium at CBM: threshold production

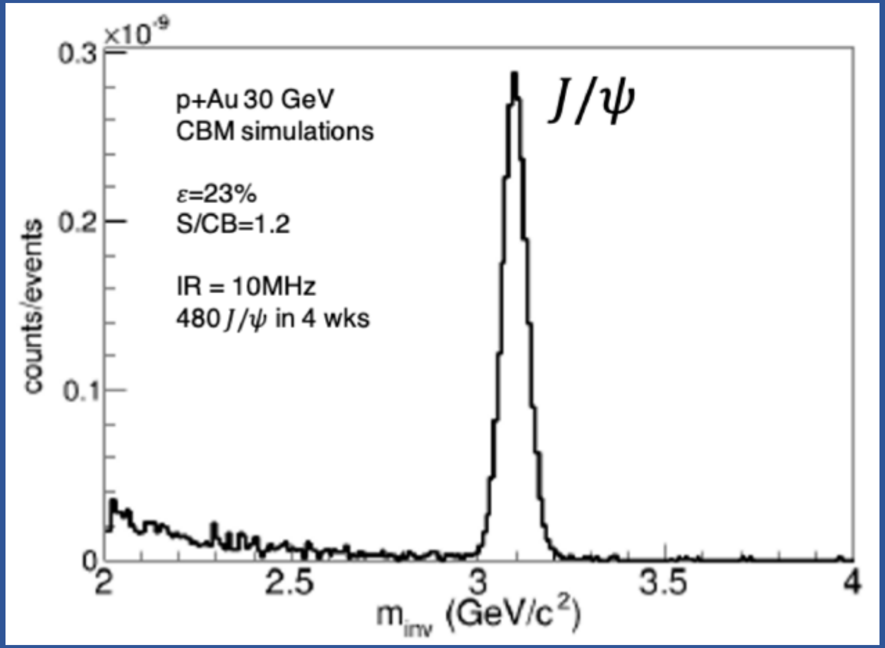
- **Sub-threshold production** (rare but feasible) via multiple collision processes
- Production threshold might be exceeded with SIS100 beam of N=Z nuclei
- Both $\mu^+\mu^-$ and e^+e^- decay channels accessible
- Needs **very large interaction rates** → 10 MHz (50 times NA60+)
- Beam intensities →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

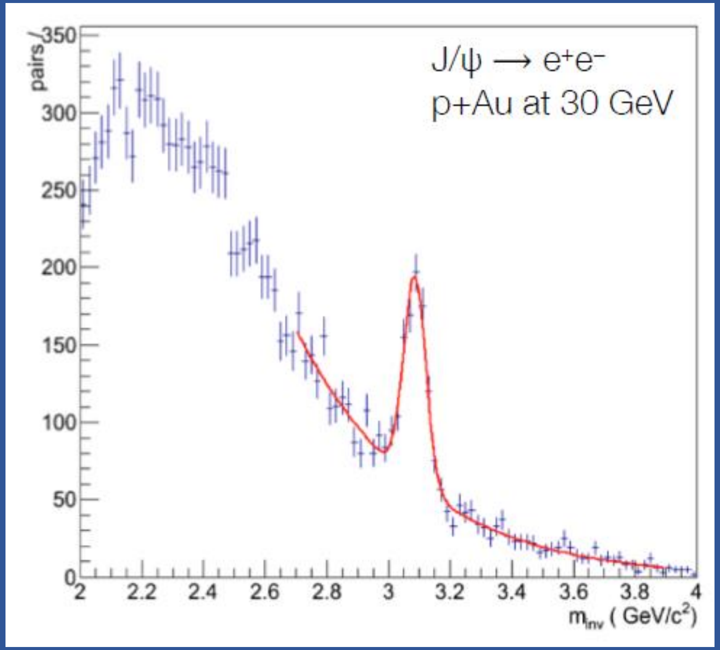


J. Steinheimer et al, Phys. Rev, C95 (2017) 014911

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

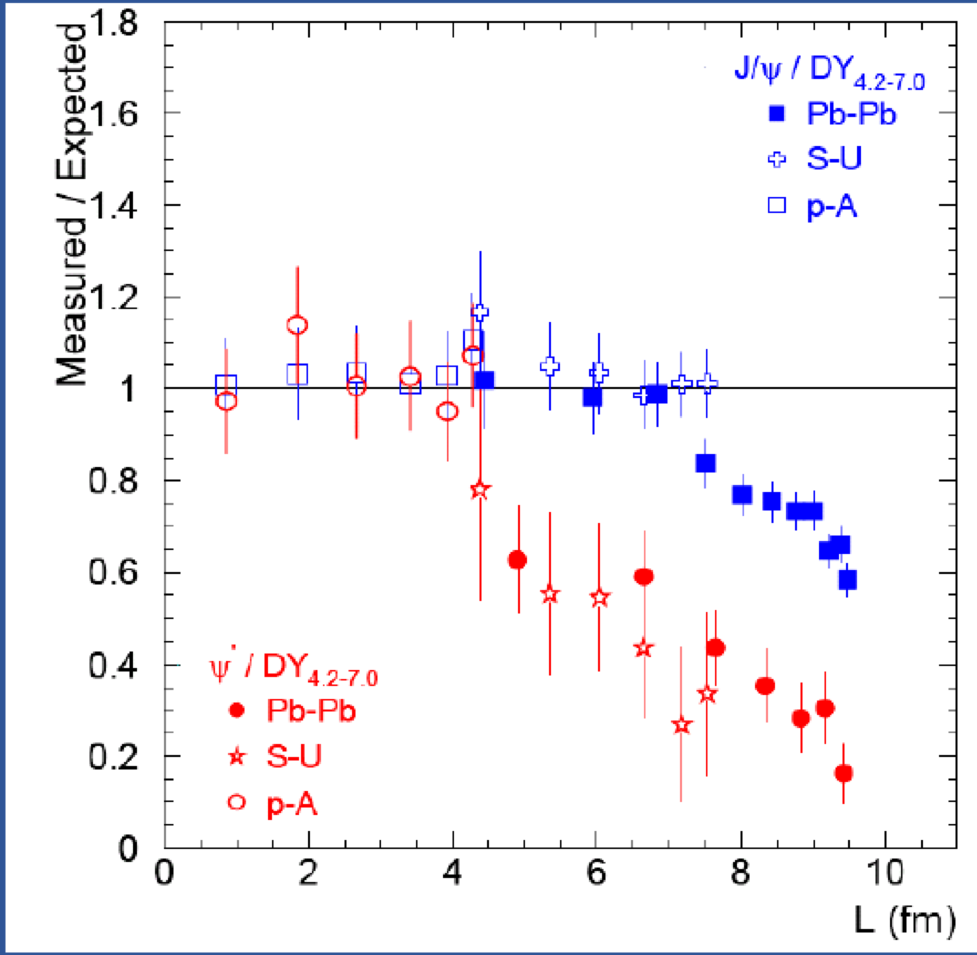
J/ψ→ee

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

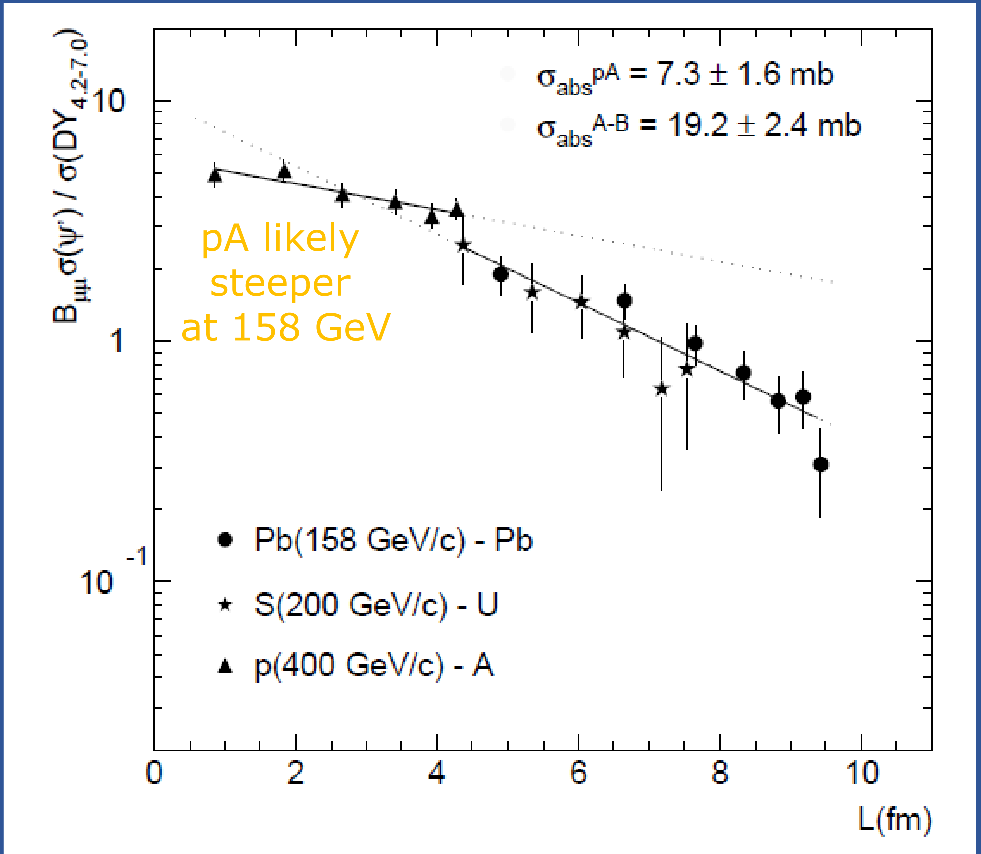


- ❑ Clear **ordering in the suppression** when moving from J/ψ to $\psi(2S)$
- ❑ The first **discovery of sequential suppression!** → Later confirmed by CMS in the Υ sector
- ❑ Typical yields in the dilepton channel → Lower by a factor ~100

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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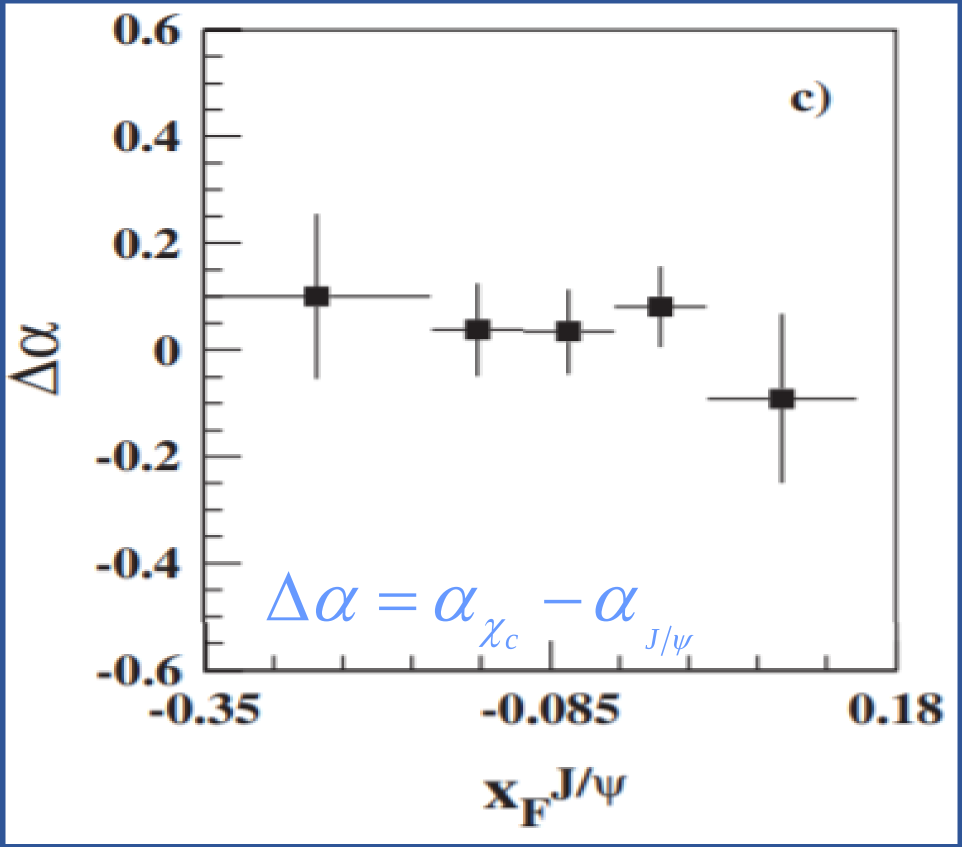
χ_c measurements

- ❑ ~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

Conclusions

- Charmonium measurements in A-A at fixed target energy have provided in the past
  → **Evidence for J/ψ suppression** beyond CNM effects
  → **Ordering of J/ψ and ψ (2S) suppression** according to binding energy

- **p-A studies** have shown a superposition of various effects with **increasing size** at small collision energy

- **No information exists below top SPS energy** ($\sqrt{s_{NN}}$=17 GeV)

- Prospects for measurements
  - Low SPS energy → **NA60+** project
  - Threshold region → **CBM** experiment

- Aims
  - Detecting **threshold for hot matter effects** on charmonia and correlate with **temperature** information obtained with thermal dimuon production
  - Search evidence for new effects → **intrinsic charm**

p-A results at fixed target: a complex environment

- J/ψ production vs A, i.e. varying the amount of nuclear matter crossed by cc pair
- Advantage → do not deal with centrality selection in p-A

⇩

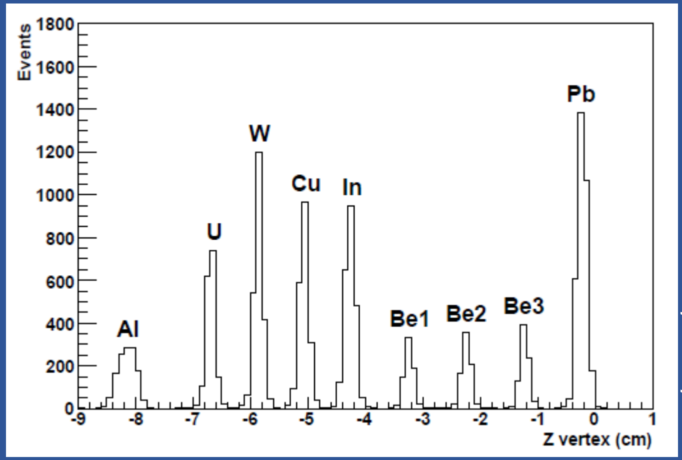
Size of CNM effects defined by **"effective" quantities**

1 $\sigma^{pA}_{J/\psi} = \sigma^{pp}_{J/\psi} \cdot A \cdot e^{-\langle \rho L \rangle \sigma_{abs}}$ ← the larger σ_{abs}, the more important the nuclear effects

2 $\sigma^{pA}_{J/\psi} = \sigma^{pp}_{J/\psi} \cdot A^{\alpha}$ ← $\alpha = 1$ → no nuclear effects; $\alpha \neq 1$ → nuclear effects

3 $R^{pA}_{J/\psi} = \frac{\sigma^{pA}_{J/\psi}}{A \cdot \sigma^{pp}_{J/\psi}}$ ← $R_{pA} = 1$ → no nuclear effects; $R_{pA} \neq 1$ → nuclear effects

not used at fixed target



NA60 Coll. PLB706, 4-5, 263-267

Extrapolation of CNM effects from pA to AA can be delicate → various effects superimposed