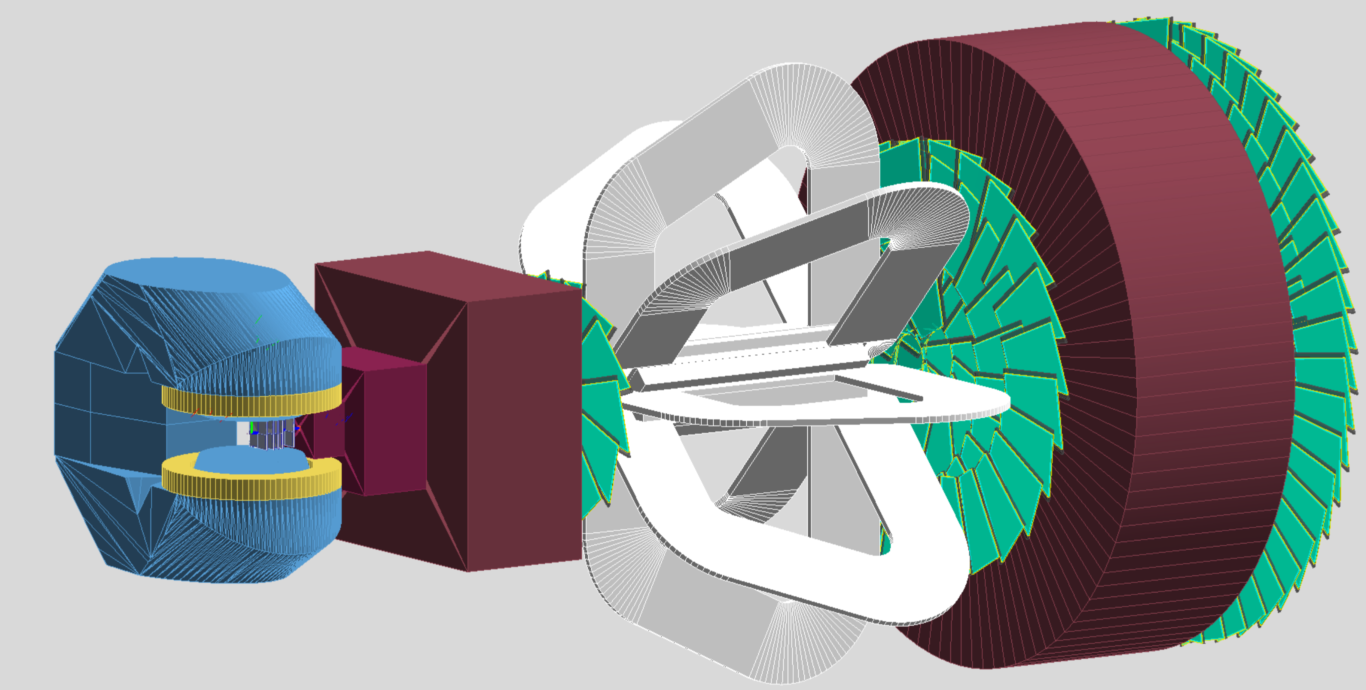
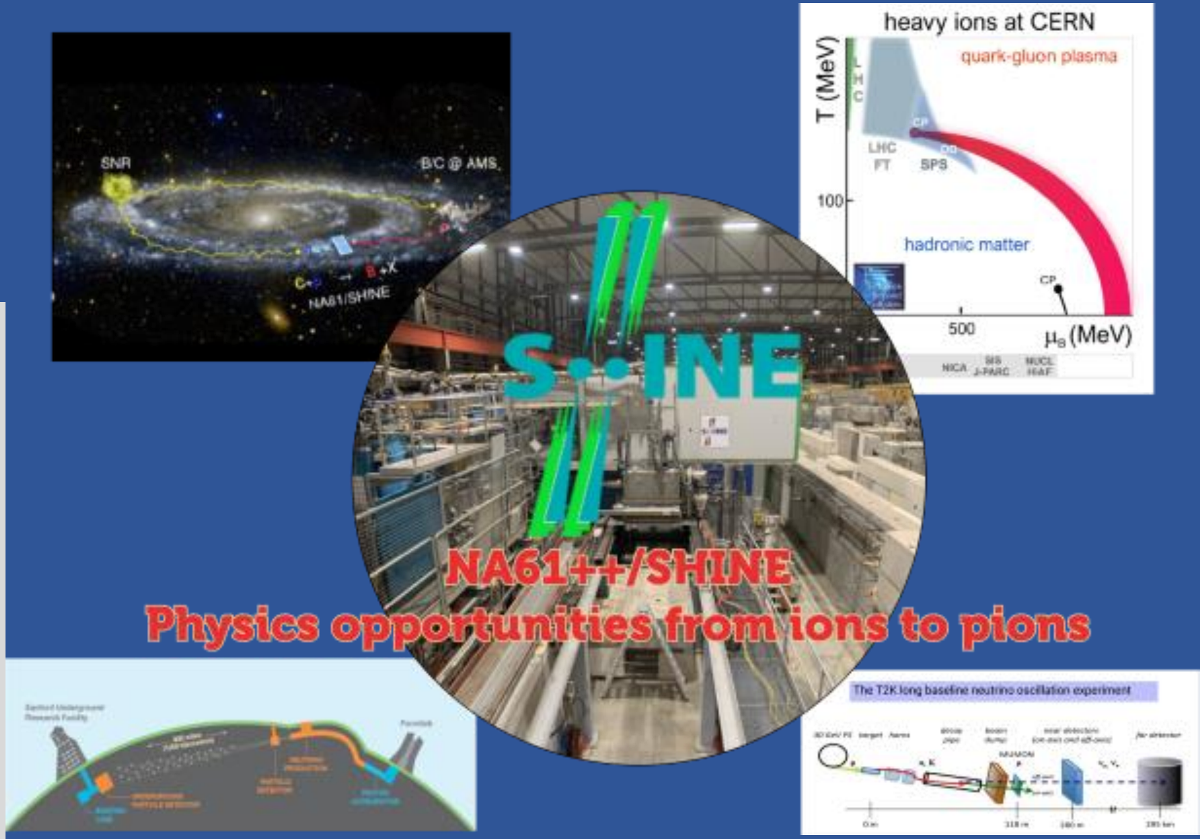
An(other) heavy-ion collision experiment at the CERN SPS: NA60+

E. Scomparin – INFN Torino (Italy)

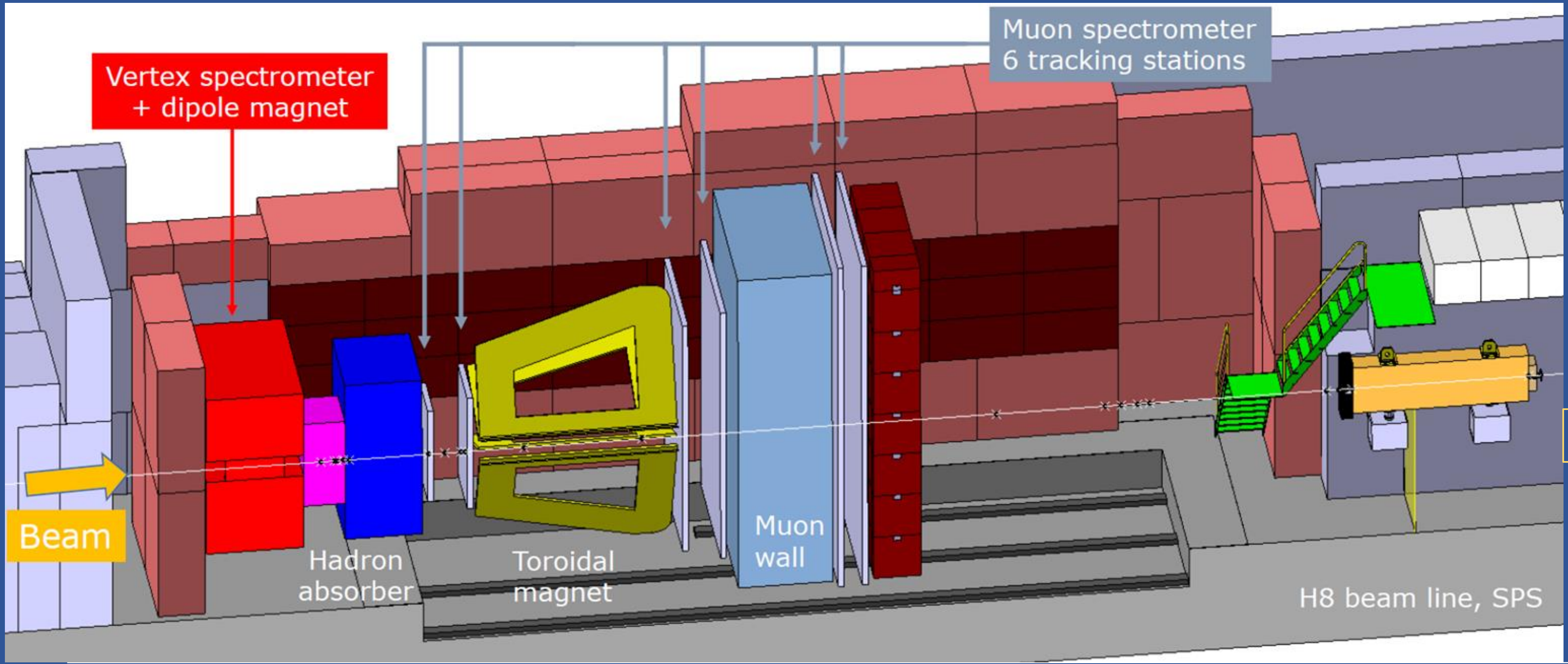




CERN– December 15-17, 2022

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



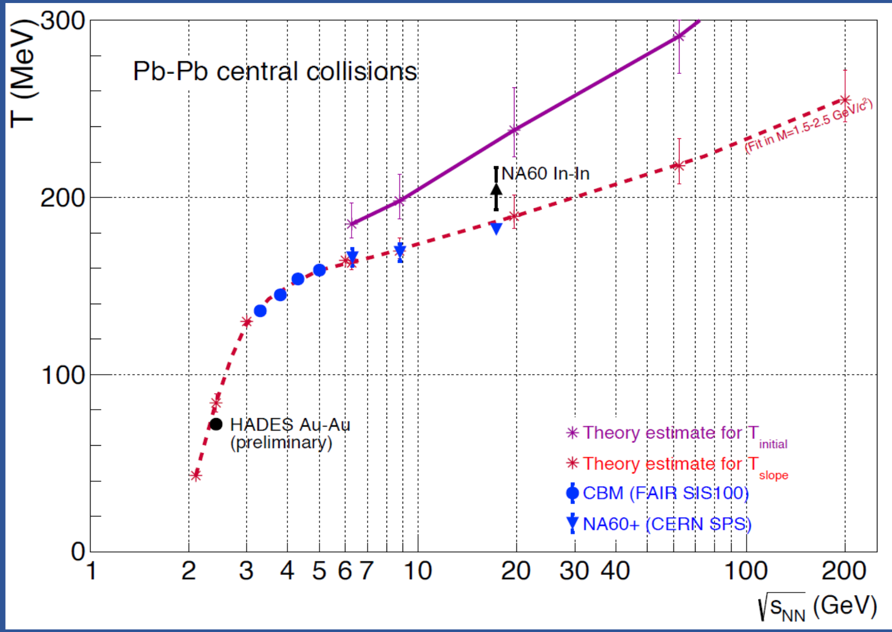
NA60+

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

The "pillars" of the NA60+ physics case

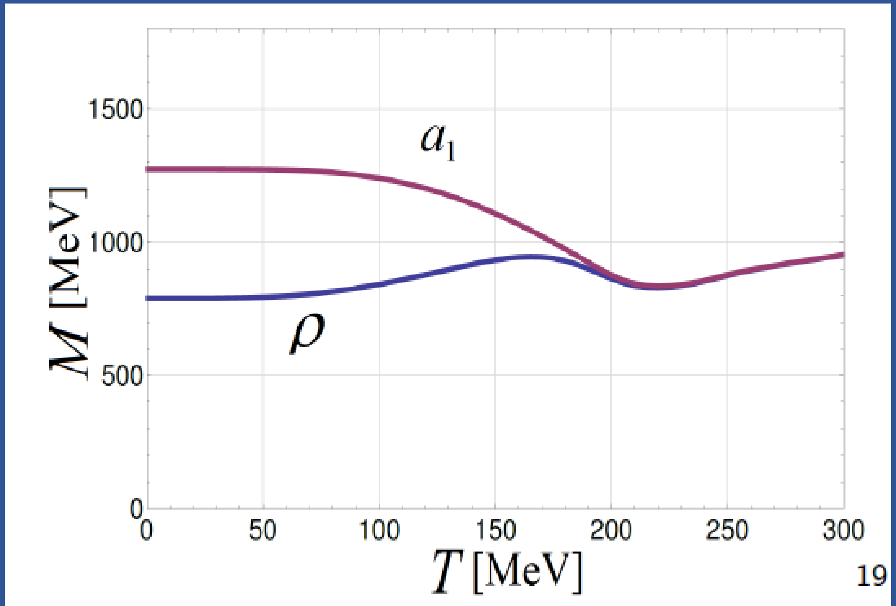
Measure:

- **Thermal dimuons from QGP/hadronic phase: caloric curve for first order transition**
- **ρ-a_1 modifications: chiral symmetry restoration**
- Quarkonium suppression: signal of deconfinement
- Hadronic decays of charmed mesons/baryons: QGP transport coefficients



Extract temperature via fit $dN/dM \propto M^{3/2}\exp(-M/T_s)$
→ Possible flattening in √s-dependence of T_s

Full chiral ρ-a_1 mixing
→ dimuon enhancement in the region $1<M<1.4$ GeV/c^2



HADES, Nature Phys. 15(2019) 1040
NA60, EPJC 61(2009) 711

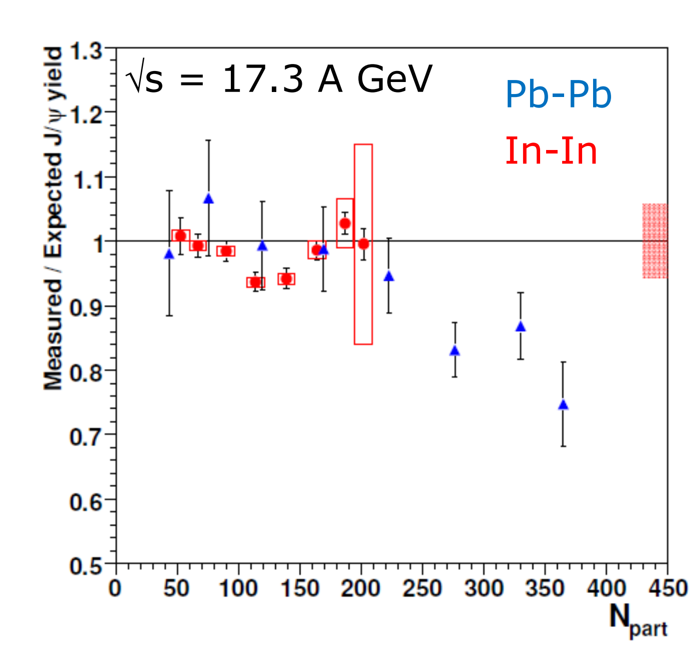
C. Jung et al., PRD 95 (2017) 036020

The "pillars" of the NA60+ physics case

Measure:

- Thermal dimuons from QGP/hadronic phase: caloric curve for first order transition
- ρ-a_1 modifications: chiral symmetry restoration
- **Quarkonium suppression: signal of deconfinement**
- **Hadronic decays of charmed mesons/baryons: QGP transport coefficients**

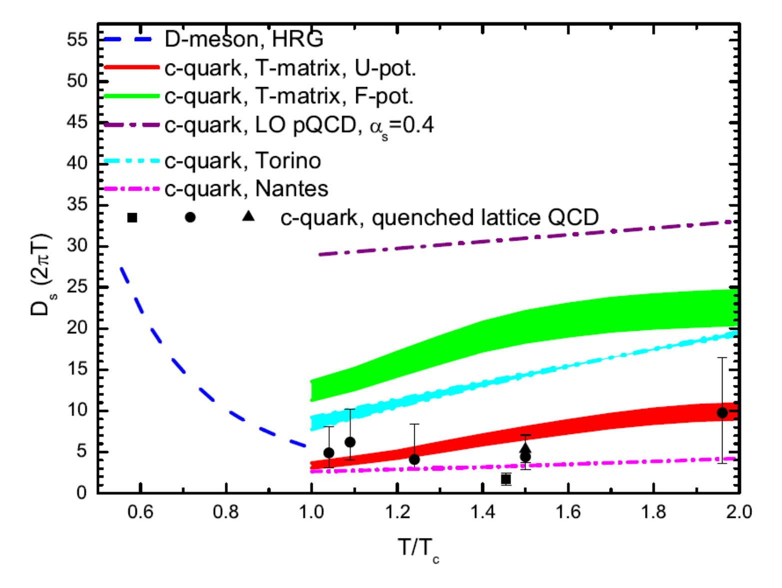
F. Prino and R. Rapp, J.Phys.G 43 (2016) 9, 093002



R. Arnaldi et al. (NA60), NPA830 (2009) 345

Explore the centrality dependence of J/ψ suppression vs √s
→ Detect deconfinement threshold and correlate with T

Measure 2 and 3 prong decays of charmed mesons and baryons
→ R_{AA},v_2 : transport coefficients
→ Λ_c ,D, D_s : study hadronization mechanisms

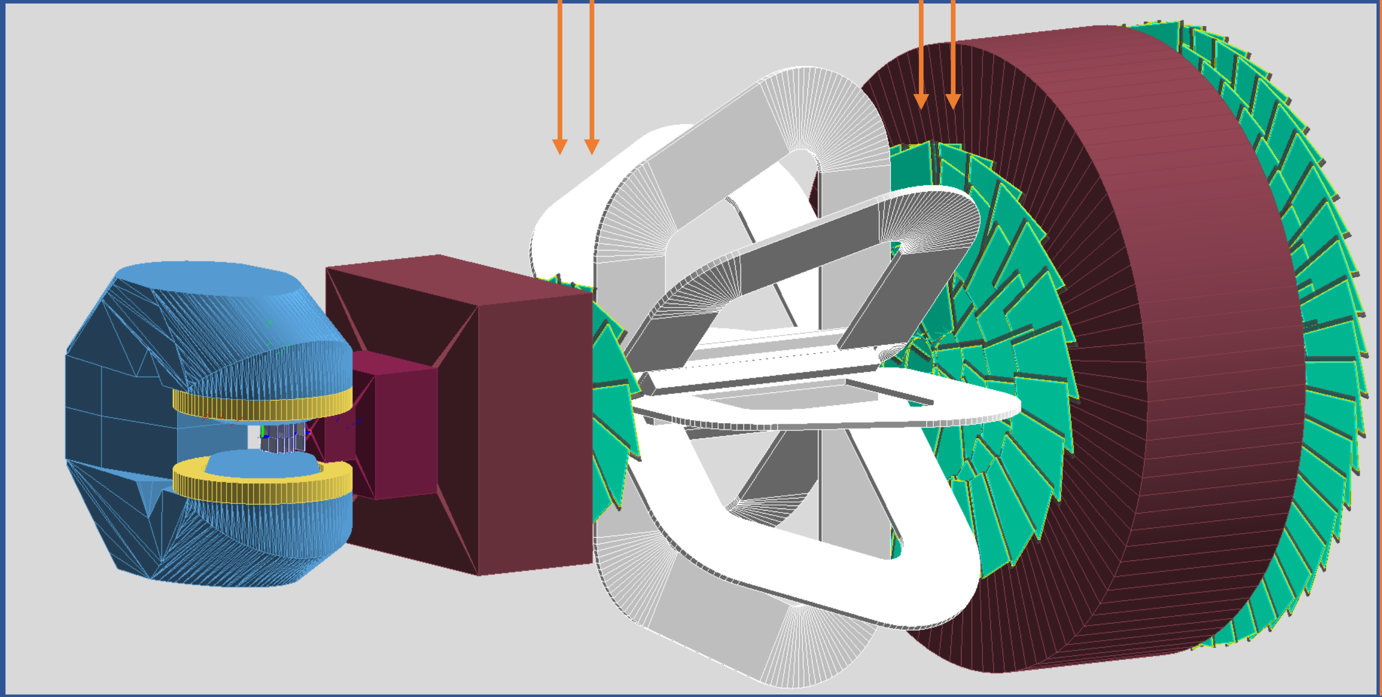


F. Scardina et al., PRC96 (2017) 044905

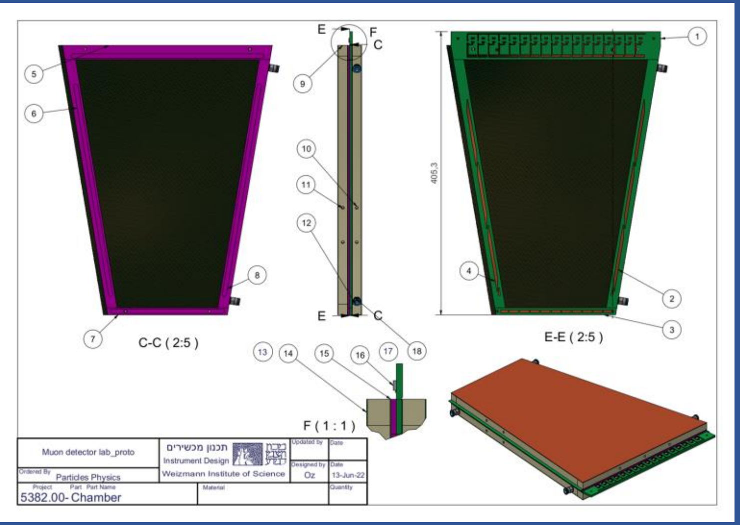
Also study strangeness production → hadronic decays of K_S^0, ϕ and hyperons

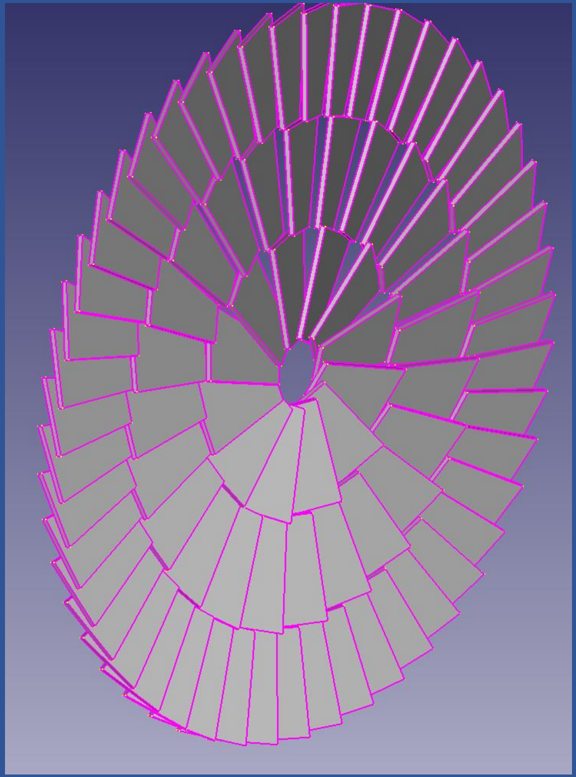
Detector studies

Muon tracker



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



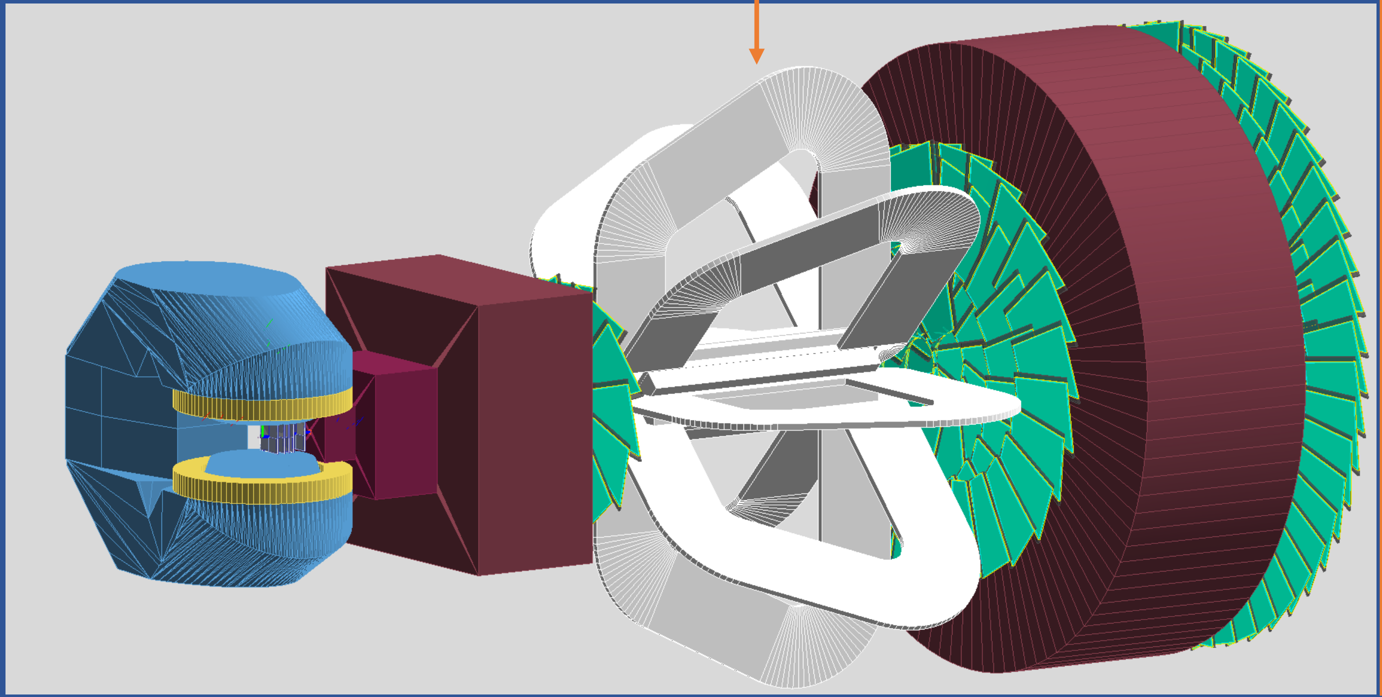


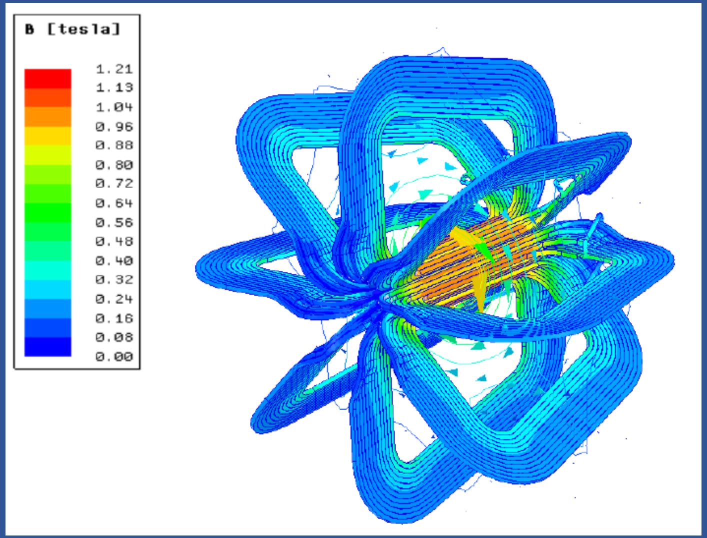
- Relatively low incident flux: <2kHz/cm^2
- Considering MWPC and/or GEM options
- First MWPC prototype on SPS test beam at the beginning of 2023

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

Detector studies

Toroidal magnet





Warm pulsed magnet → 0.5 T over 120 m^3

Eight sectors, 12 turns each

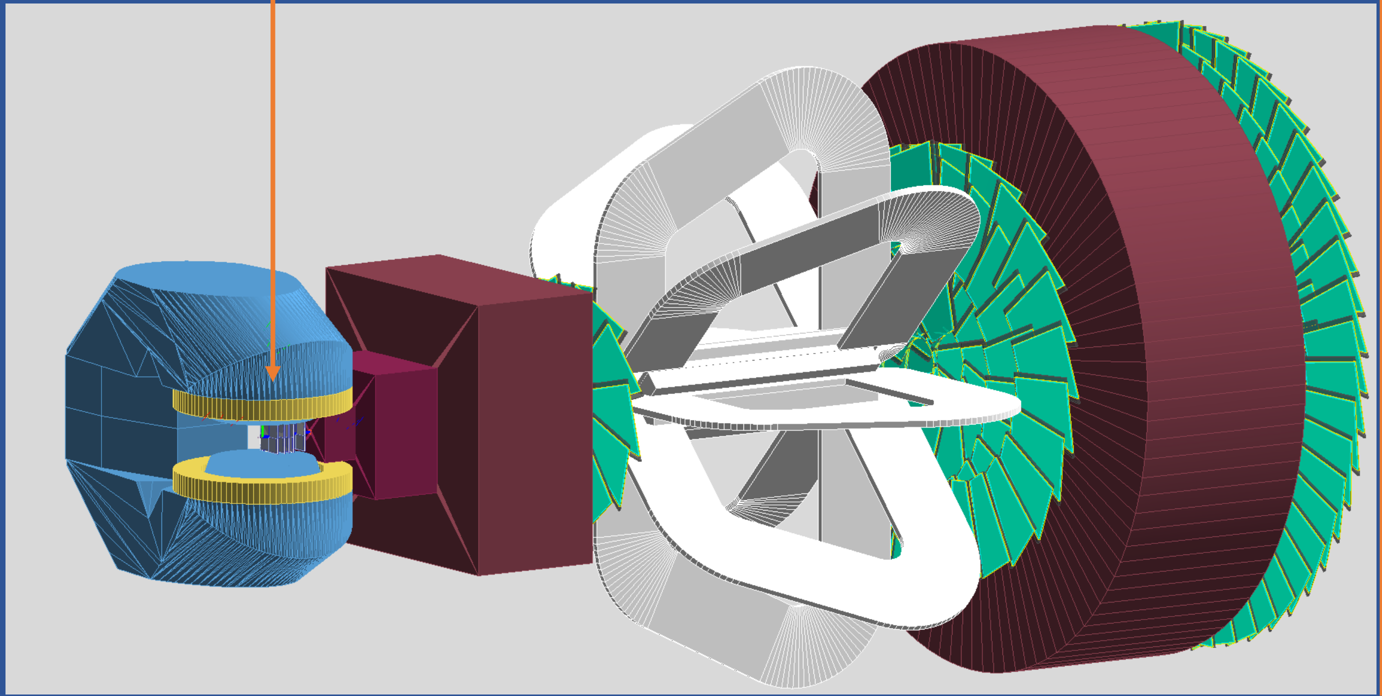
Current → 190 kA, total power 3 MW

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

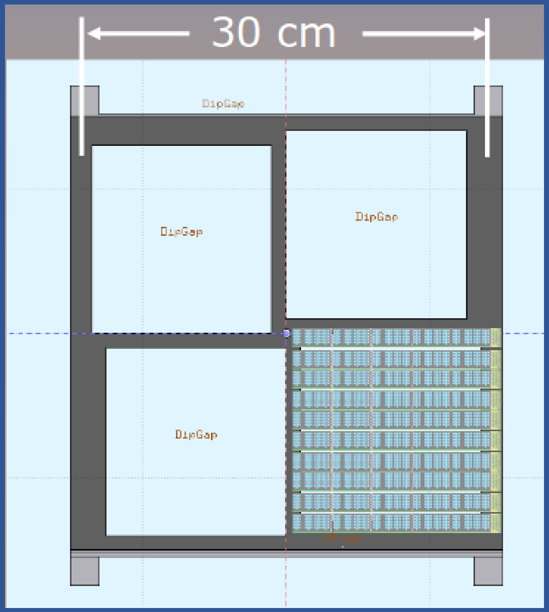
Measurements of the magnetic field in the prototype in agreement with simulations within 3%

Detector studies

Vertex spectrometer

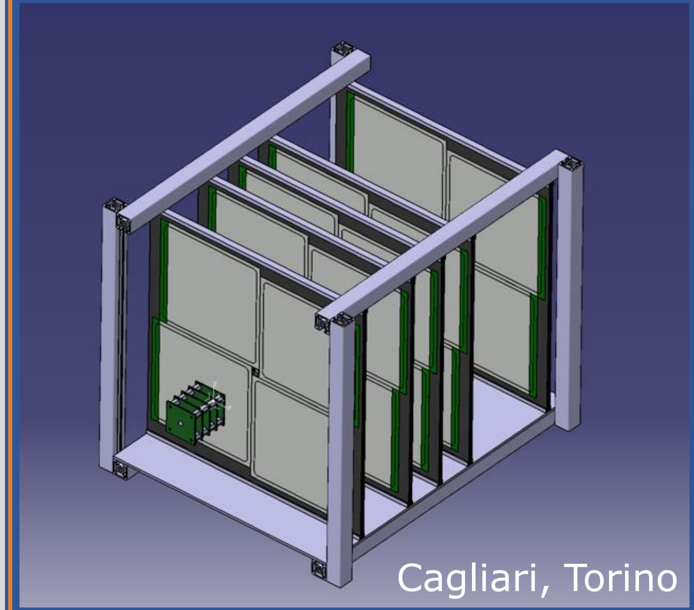


Common development ALICE → NA60+, state-of-the-art imaging technology TowerJazz 65 nm



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

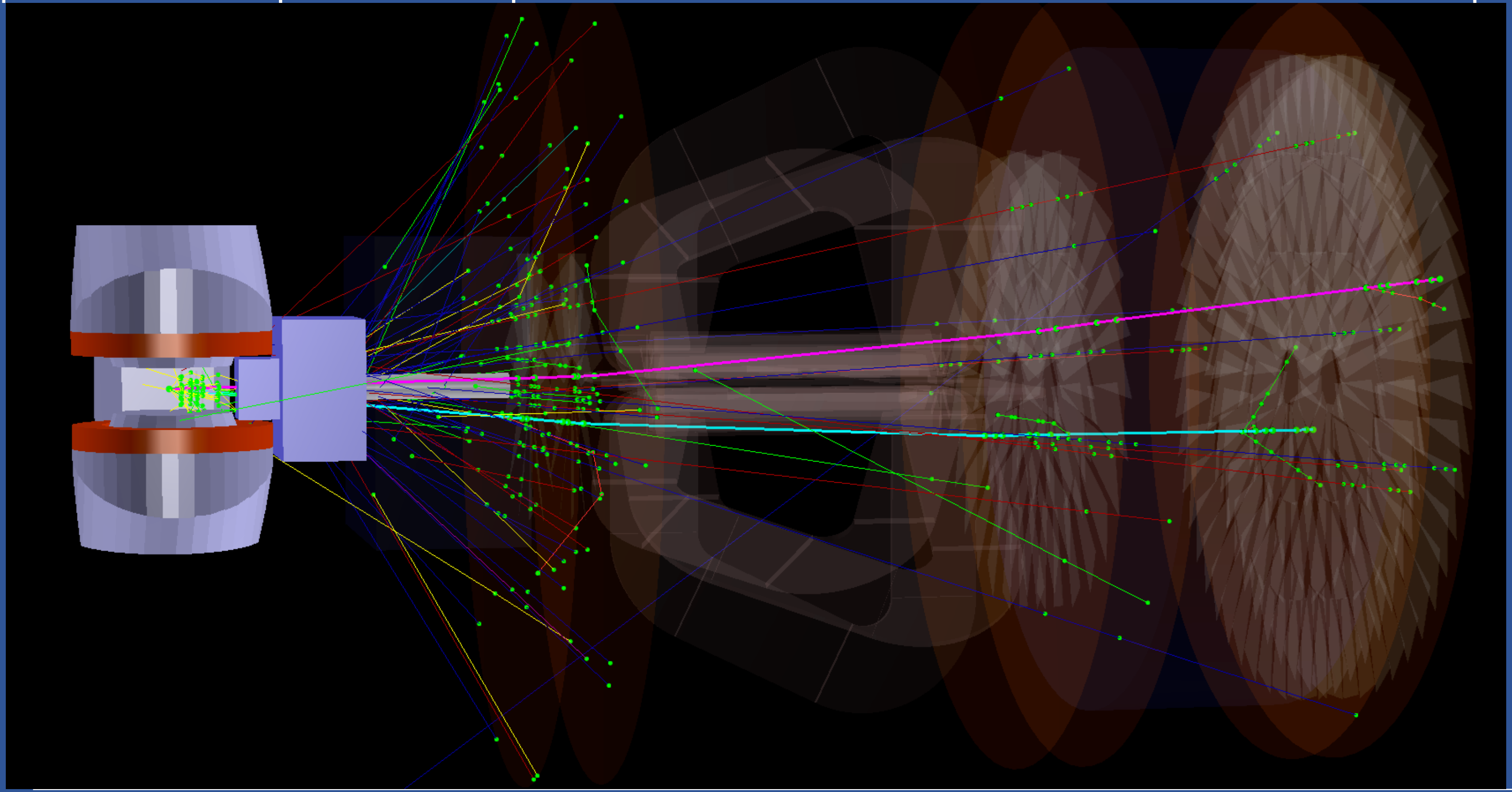
Dimuon measurement

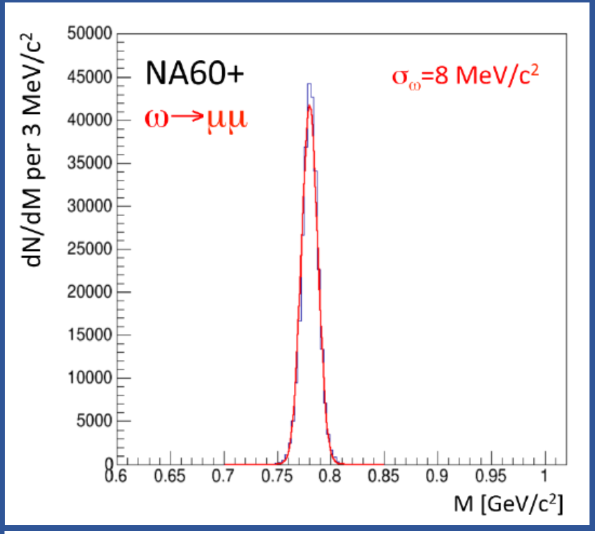
Track matching: measure muon kinematics before multiple scattering and energy loss

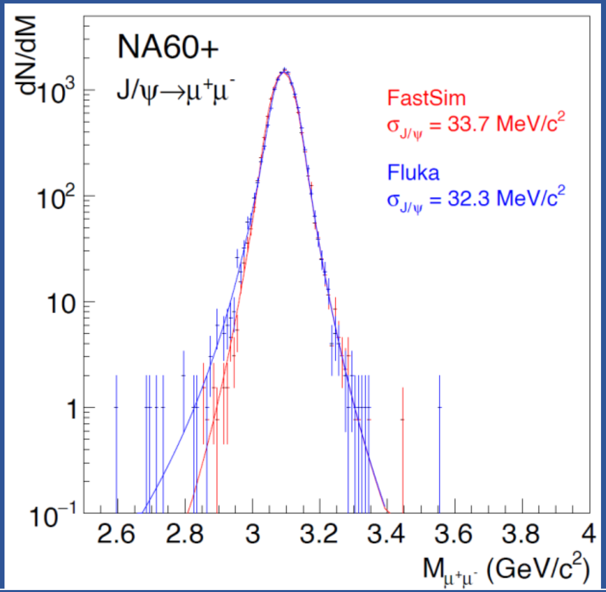
Track matching

Vertex tracking (dipole field)

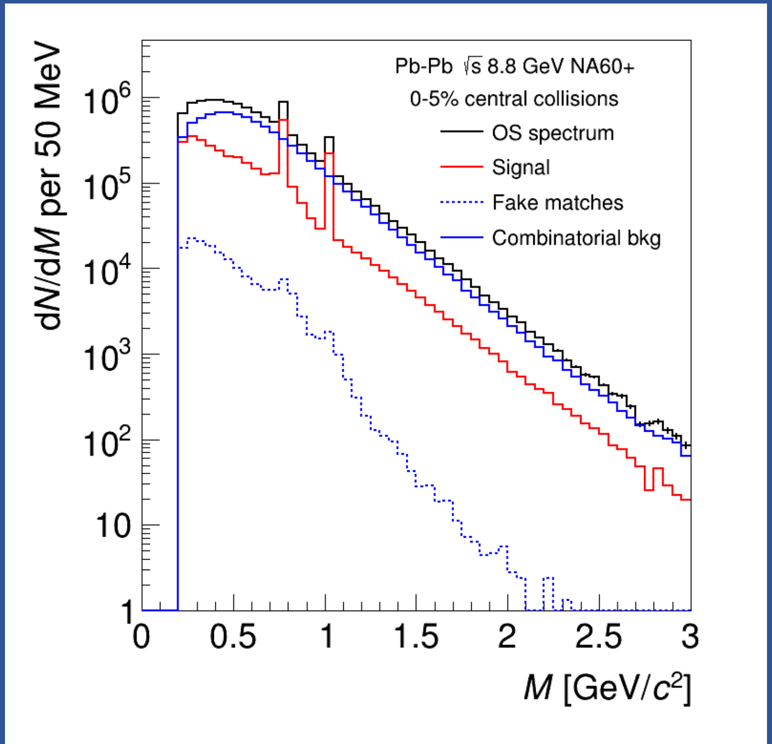
Muon identification in a spectrometer (toroidal field)

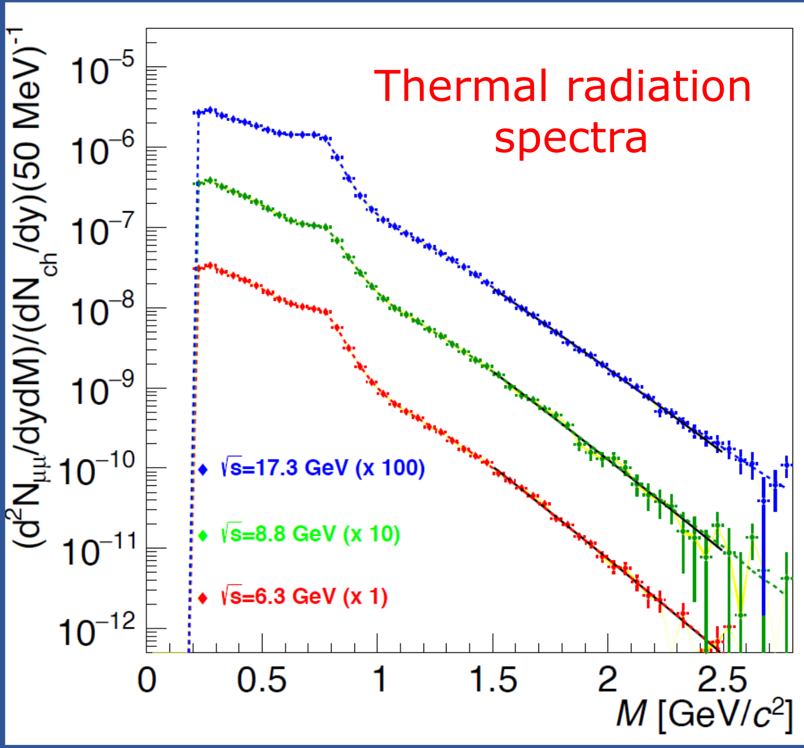






Dilepton spectrum





- ❑ Thermal radiation yield
  - ❑ Dominated by ρ contribution at low mass
  - ❑ Accessible up to M=2.5-3 GeV/c^2
- ❑ Drell-Yan contribution
  → to be also estimated via p-A measurements
- ❑ Open charm
  Negligible dimuon source

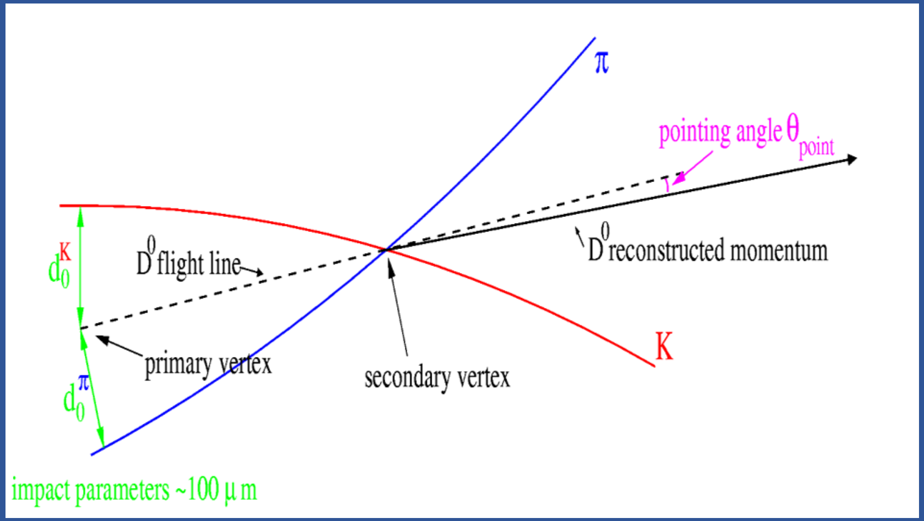
~1-3% uncertainty on the evaluation of T_{slope}

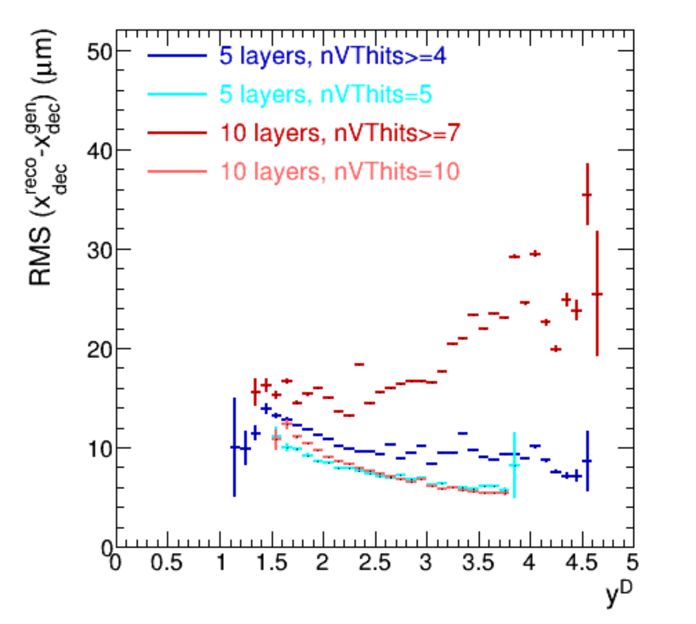
	Energy (GeV)	Thermal pairs	T_{slope}
2 months →	6.3	$3.52 \cdot 10^6$	$166 \pm 4.7 \pm 1$
1 month →	8.8	$3.56 \cdot 10^6$	$169 \pm 4.4 \pm 1$
1 month →	17.3	$9.70 \cdot 10^6$	$182 \pm 1.8 \pm 1$

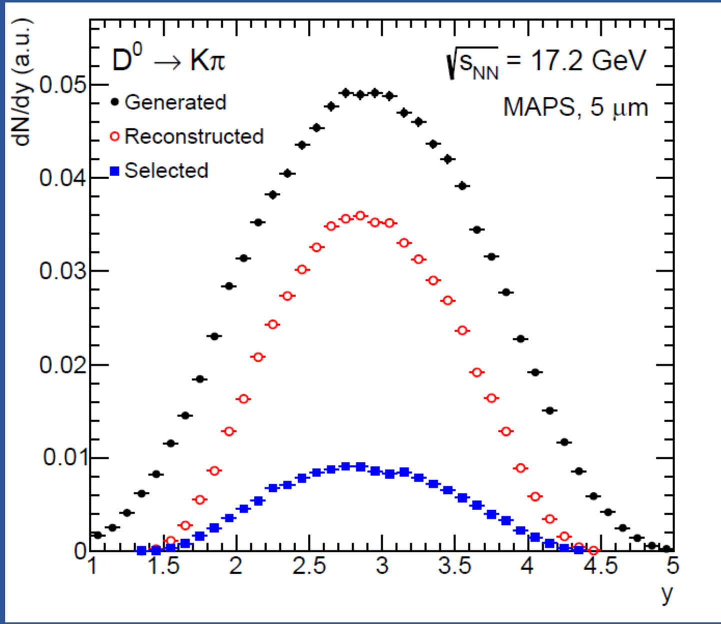
Accurate mapping of the region where T_{pc} is reached
→ Strong **sensitivity** to possible flattening due to 1st order transition

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}
      - $\rightarrow$ after selections S/B ~0.5

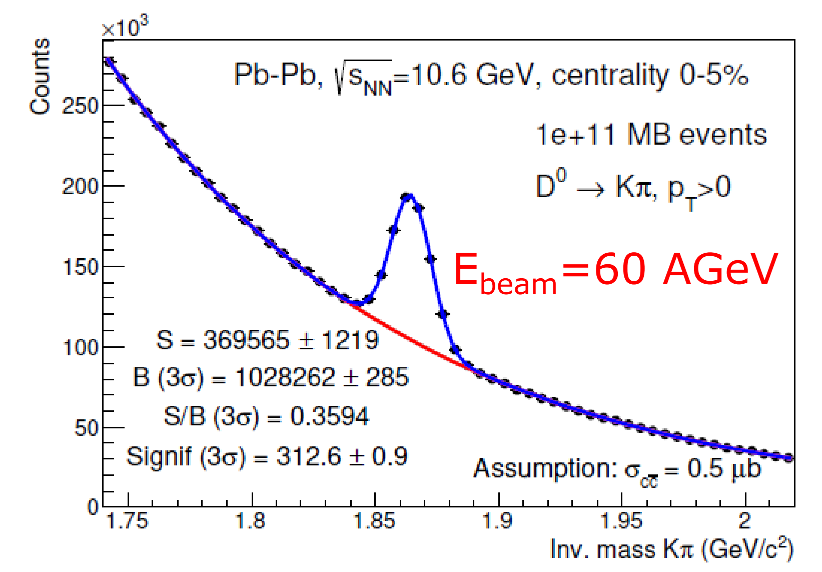




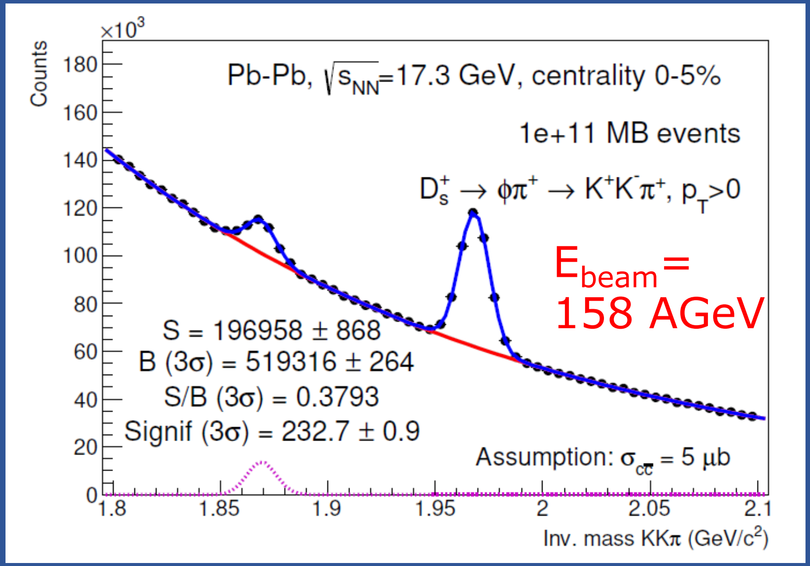


Charm hadrons: performance plots

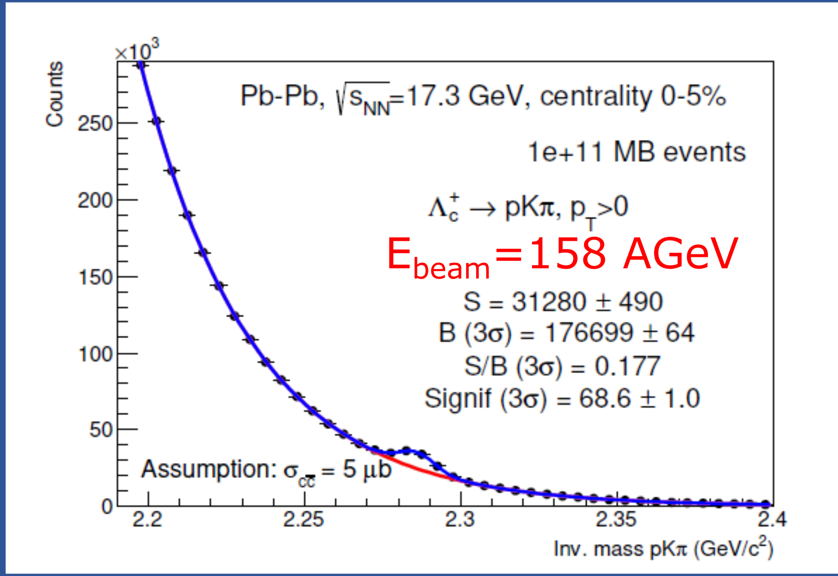
- With 10^{11} minimum bias Pb-Pb collisions (1 month of data taking)
  - More than $3 \cdot 10^6$ reconstructed D^0 in central Pb-Pb collisions at $\sqrt{s_{NN}}$=17.3 GeV
    - Allows for differential studies of yield and v_2 vs. p_T, y and centrality
  - **D^0** accessible also at lower collision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



$D^0 \rightarrow K\pi$

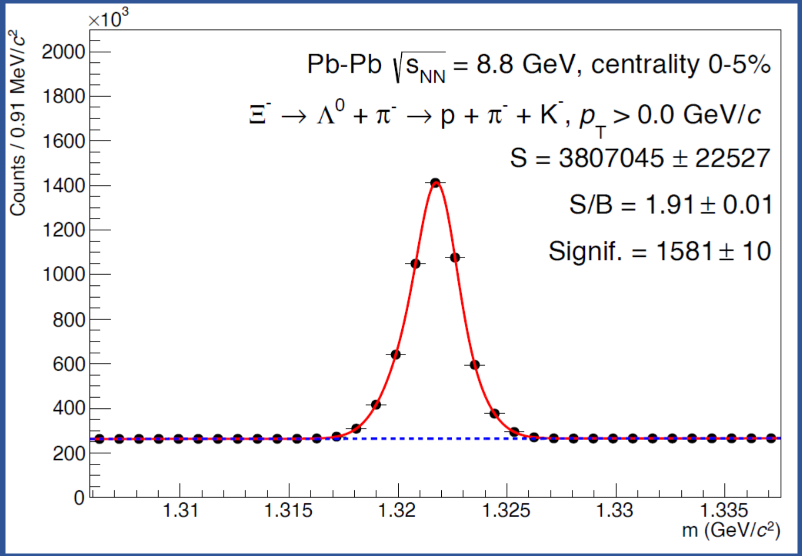


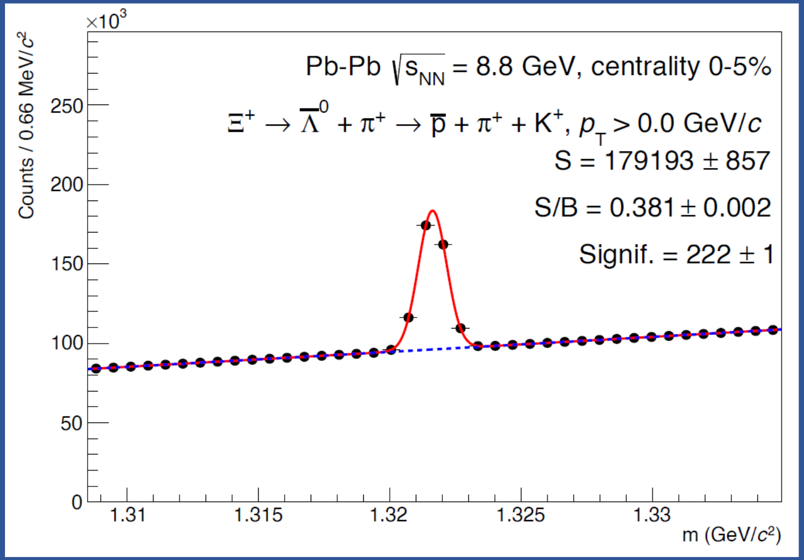
$D_s^+ \rightarrow \Phi\pi \rightarrow KK\pi$



$\Lambda_c^+ \rightarrow pK\pi$

Strangeness measurements: hyperons





- Hyperon decays simulated with EvtGen, decay products propagated in the VT using the fast simulation of NA60+
- Background from hadron production → **NA49 results**

- Channels studied

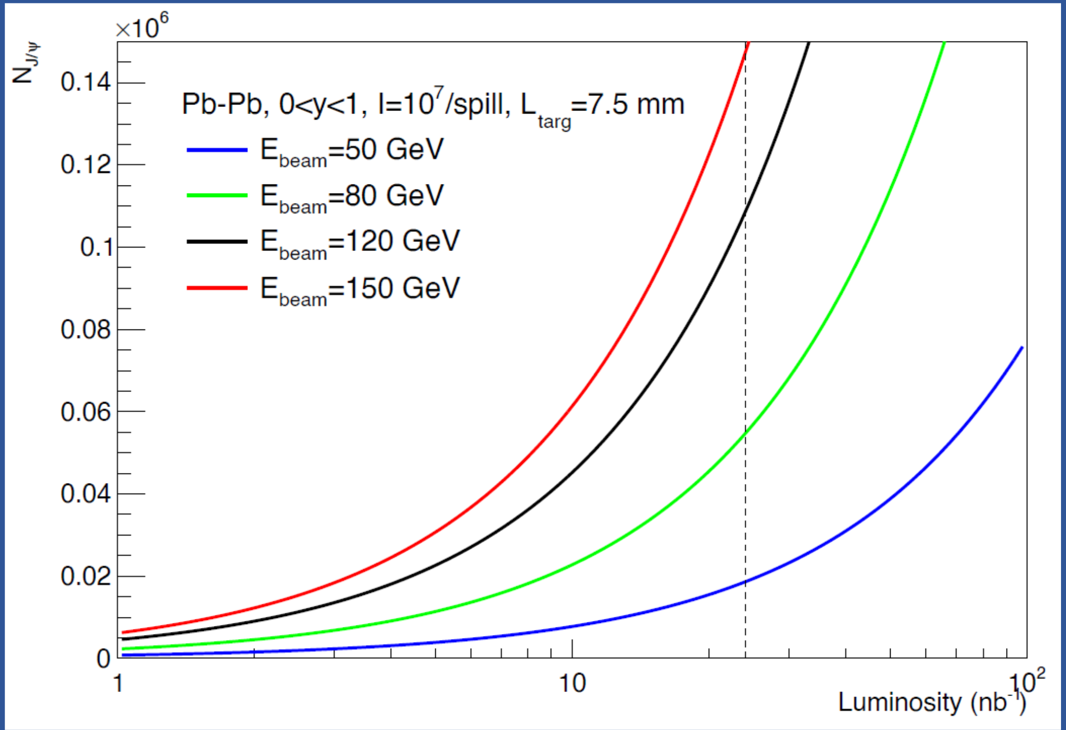
$\Lambda^0 \to p + \pi^-$ $\quad$ $\Xi^- \to \Lambda^0 + \pi^-$ $\quad$ $\Omega^- \to \Lambda^0 + K^-$

and charge conjugated

- **Topological selections** applied
- **BDT employed to enhance the significance of the signal**
- Among the variables:
  - Product of the impact parameter of decay tracks,
  - Distance of closest approac between the decay tracks
  - Decay length and the cosine of the pointing angle

- Also ϕ → KK and K_s → $\pi\pi$ were studied

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



- With ~10^{12} incident Pb on a7.5mm Pb target (1month 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

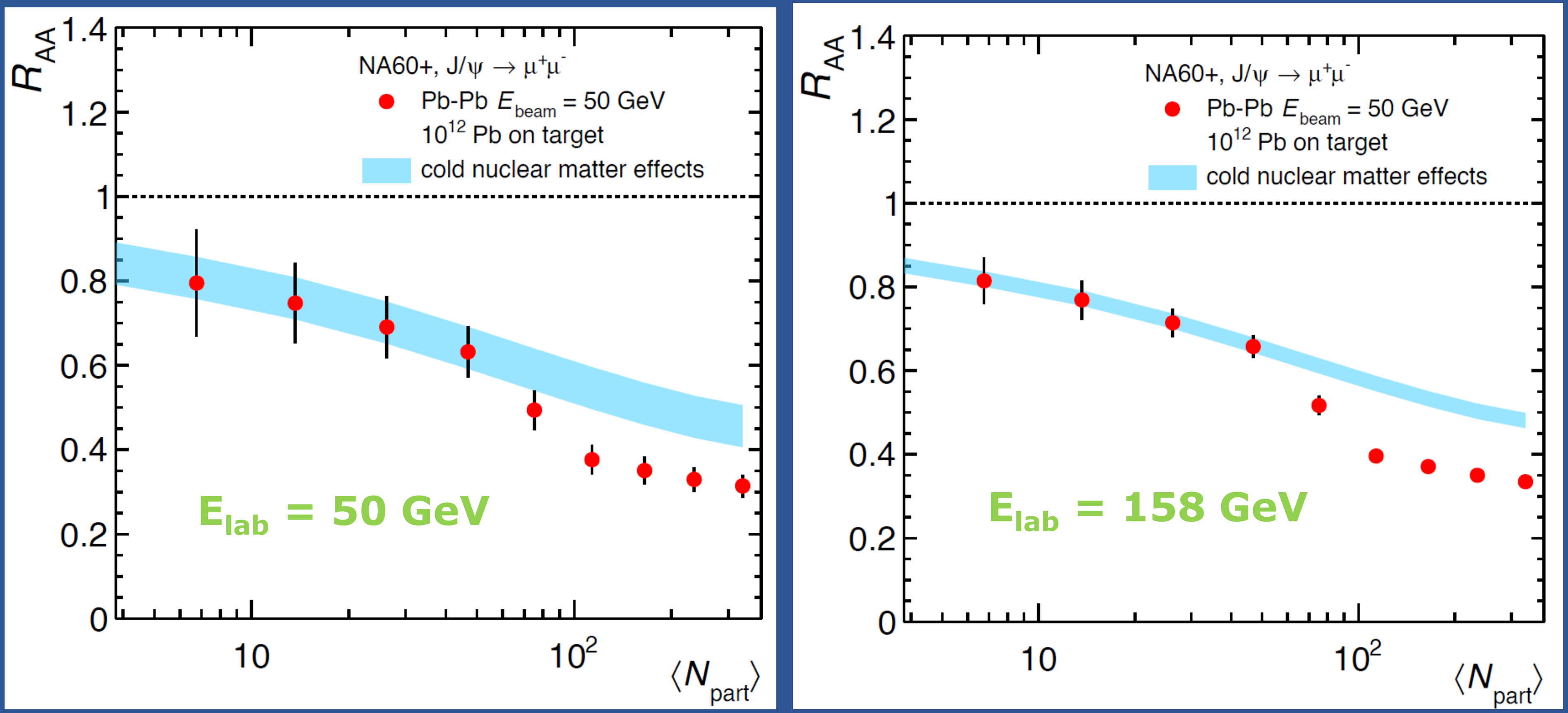
Quarkonium production not studied below top SPS energies!

⇩

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

NA60+, R_{AA} estimate



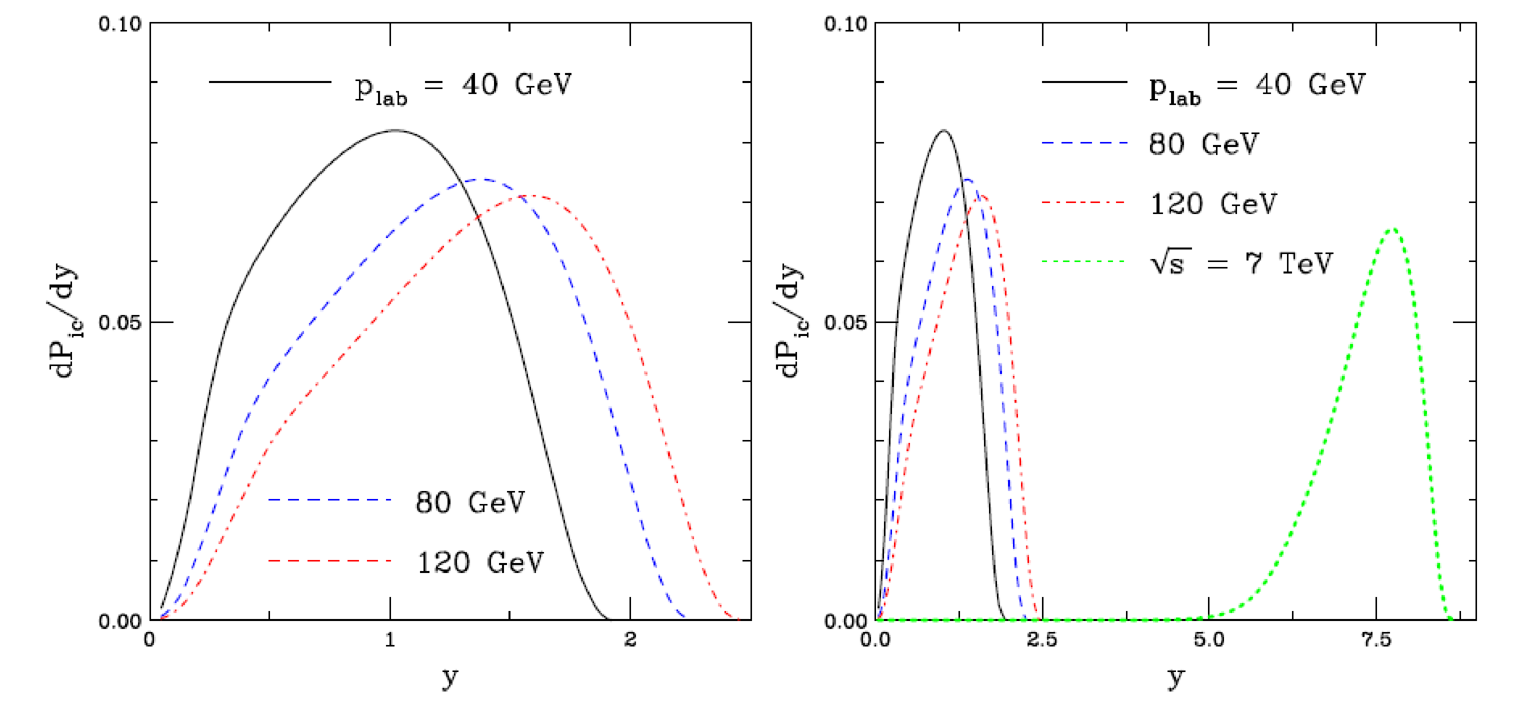
- Based on
  - 10^{12} incident Pb
  - pA reference: 5 10^{13} incident p
- Assume only CNM effects for $N_{part}<50$ and 20% extra suppression in Pb-Pb for $N_{part}>50$

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

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

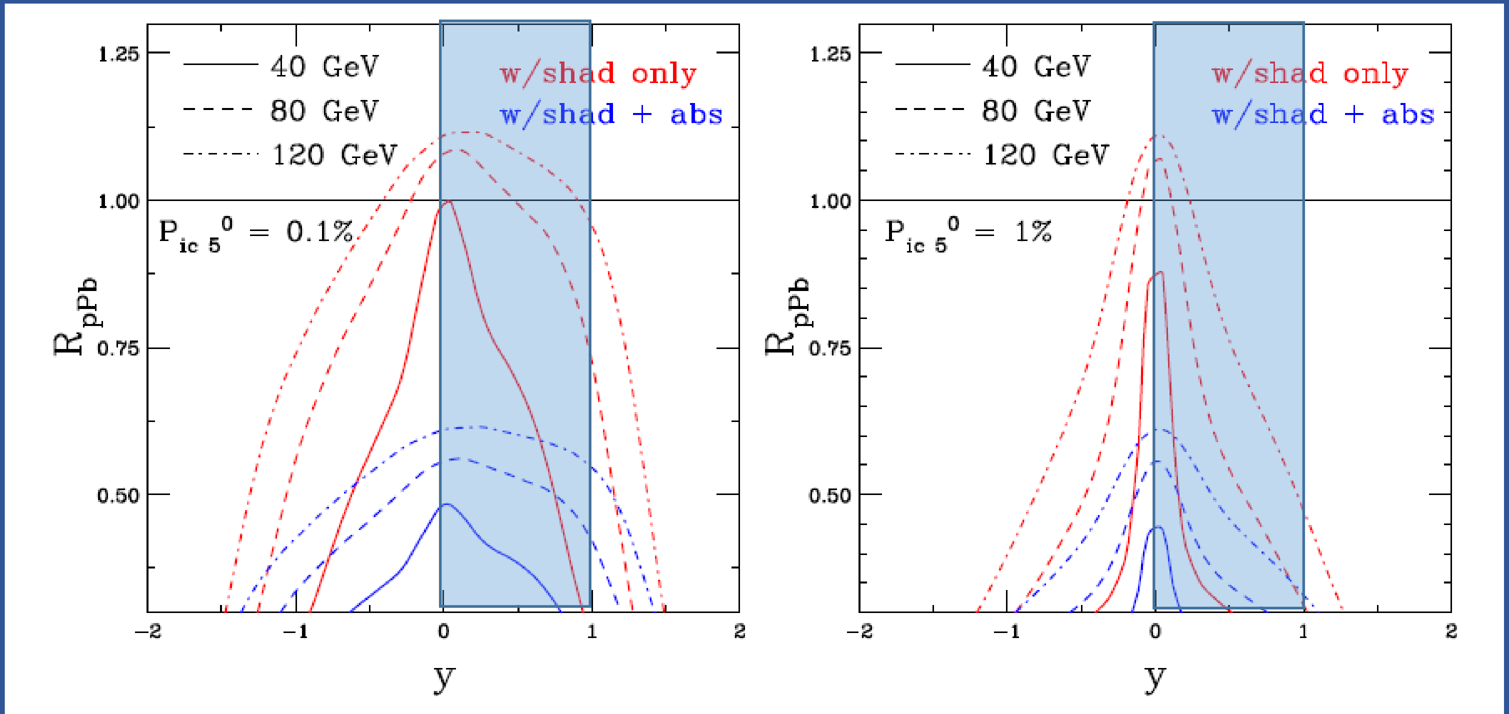


Assumed intrinsic charm content varied between 0.1% and 1%

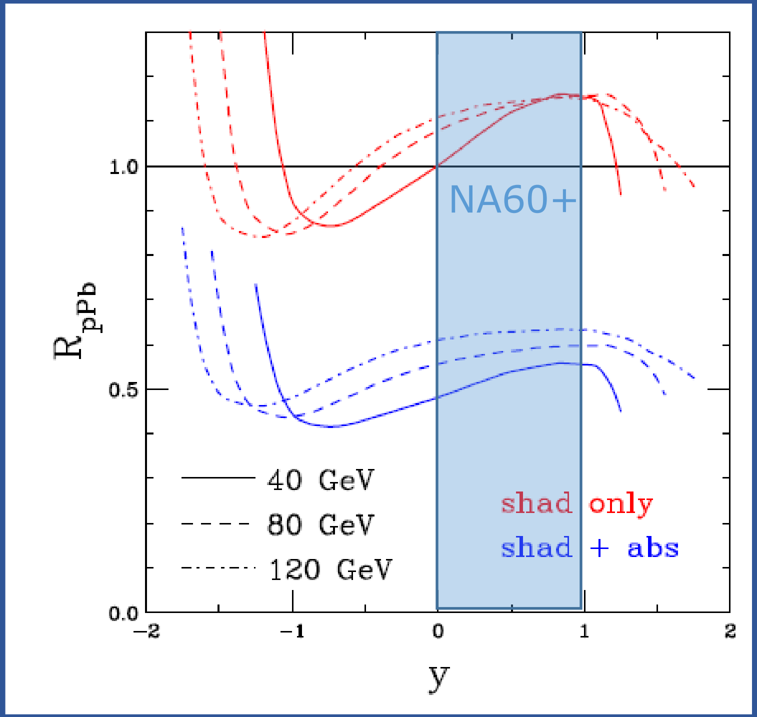
R. Vogt, PRC 103, 035204 (2021)
R. Vogt, arXiv:2207.04347

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%



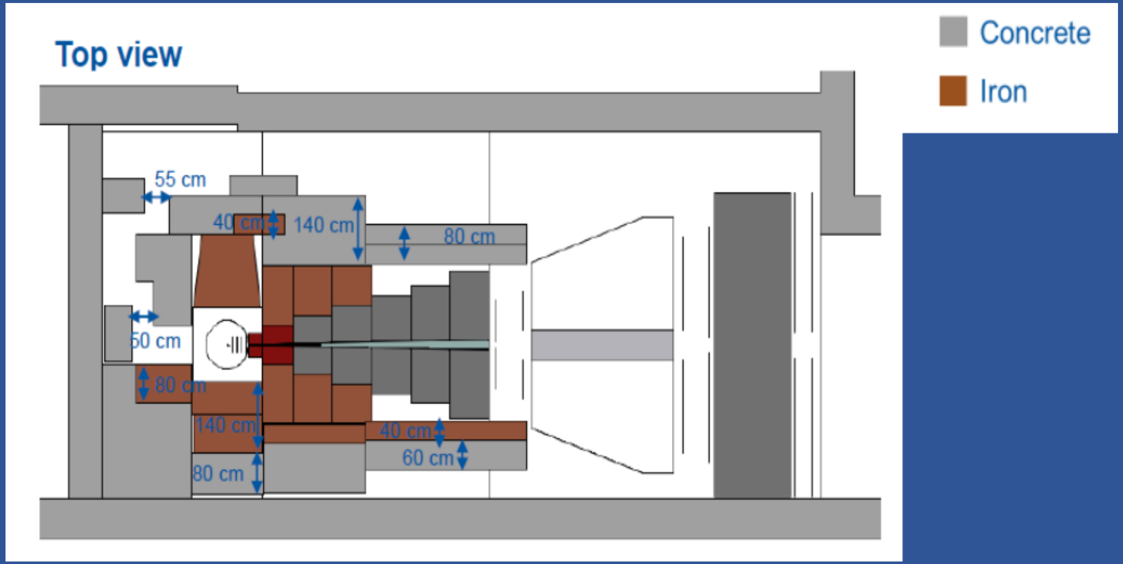
(w/o intrinsic charm)



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

Installation, beam, planning

- The experiment will be installed in the PPE138 experimental area in the SPS Nort Hall (H8 beam)
- Integration studies, including radioprotection aspects (shieldings), already quite advanced



- Sub-mm beam optics was designed (σ_x~ σ_y~ 0.2-0.4 mm down to low SPS energy)
  → tested in November at CERN

- Project recognized by CERN in the frame of the "Physics Beyond Collider" initiative
  → important technical support from CERN groups
- Expression of Interest: May 2019
- **Letter of Intent**: ready for submission, by 2022

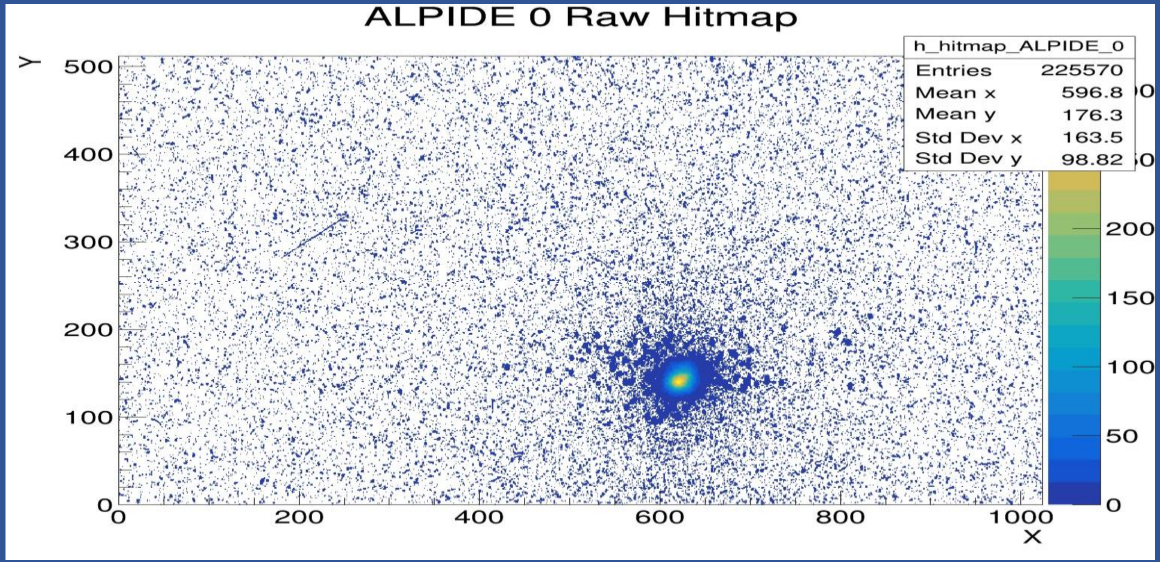
- Aim at taking **first data in 2029** (after LHC long shutdown 3)
- 5-6 years data taking with a 1 month period with a primary Pb ion beam, one energy point per year
- Corresponding data taking with proton beams, for reference and QCD studies

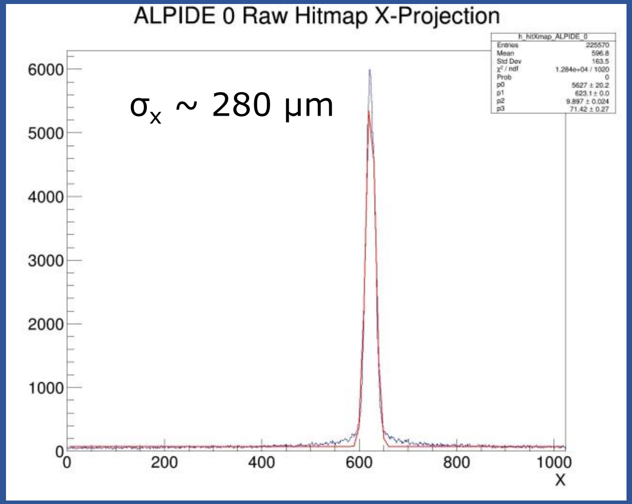
First test beam in the H8 experiment location

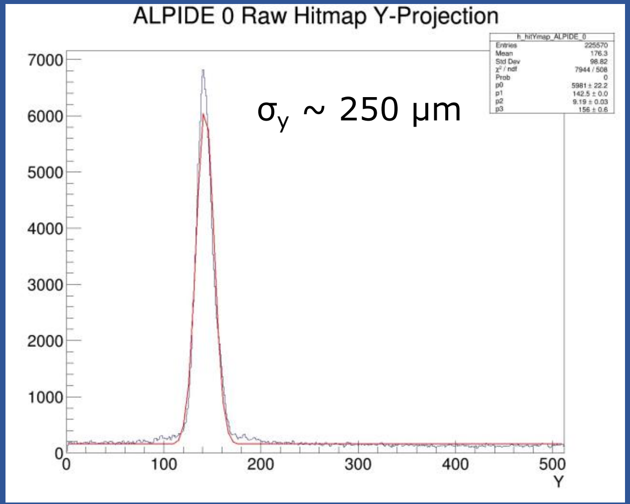
Max beam intensity
~ 2 10^5 /spill

150 AGeV

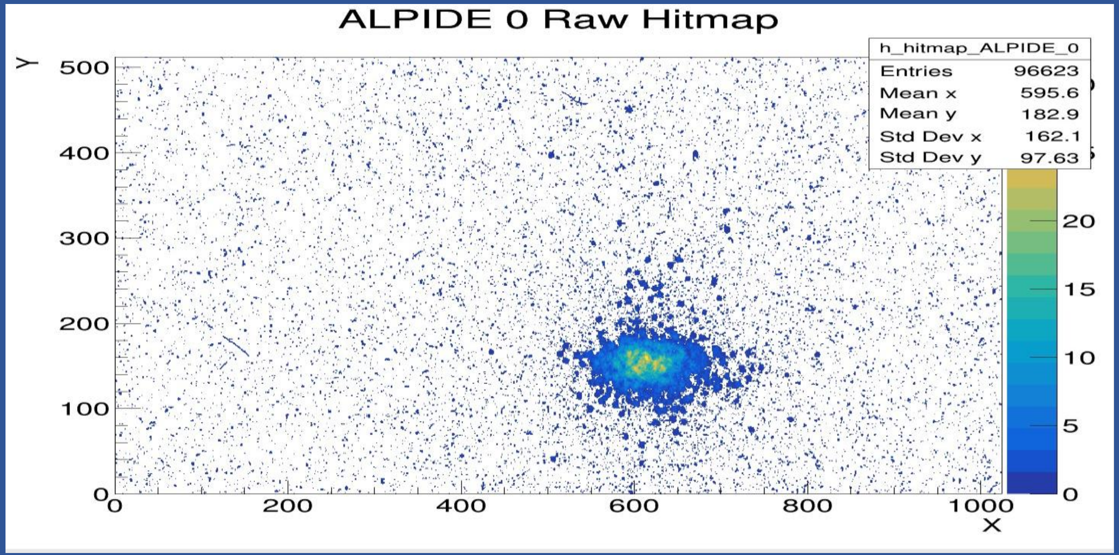
Focused optics

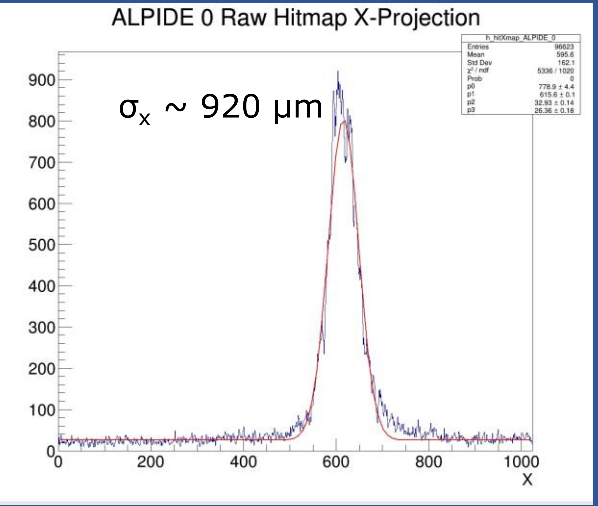


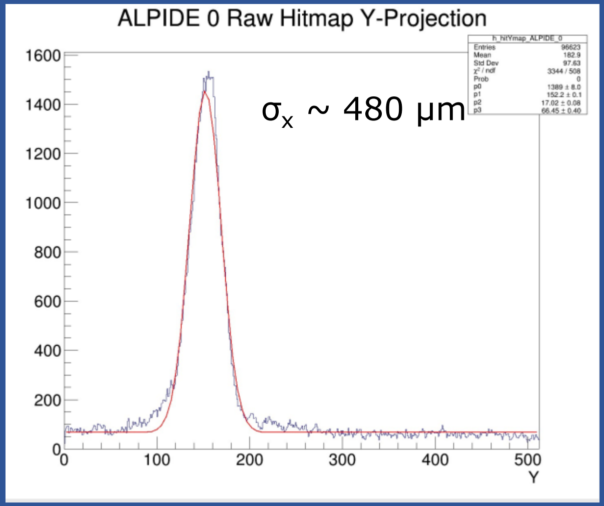




Microcollimator







Conclusions

- In addition to the future NA61++ program being planned in this workshop, the NA60+ project is aiming at a study of physics topics that can be addressed with an energy scan at the CERN SPS → **emphasis on rare probes**

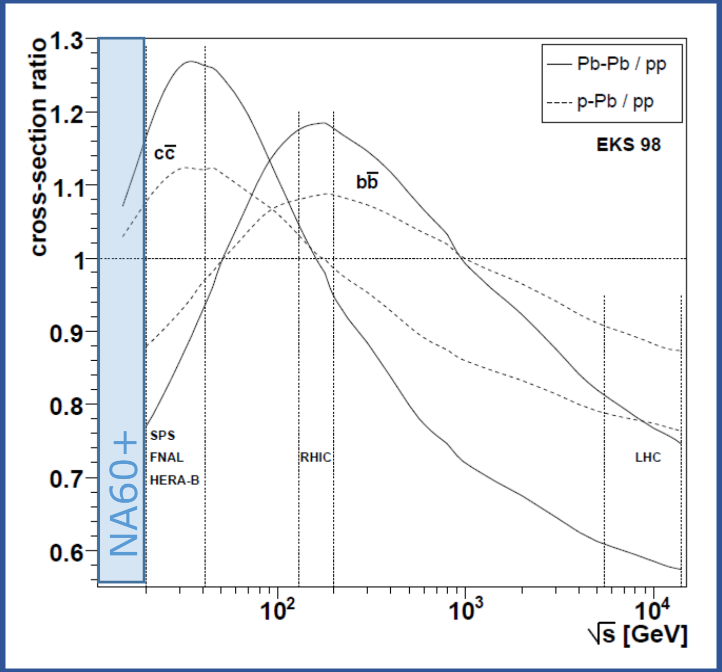
- **A LoI will be submitted next week, the goal is to take data after LS3**

- Further discussions on possible **synergies with the program of NA61++** will be a very important aspect, with the goal of building a solid ensemble of measurements for the next decade

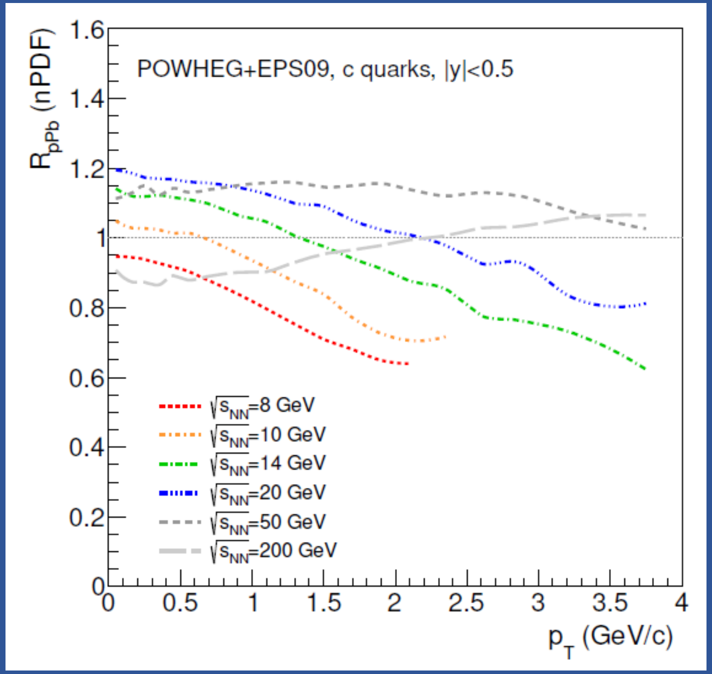
Backup

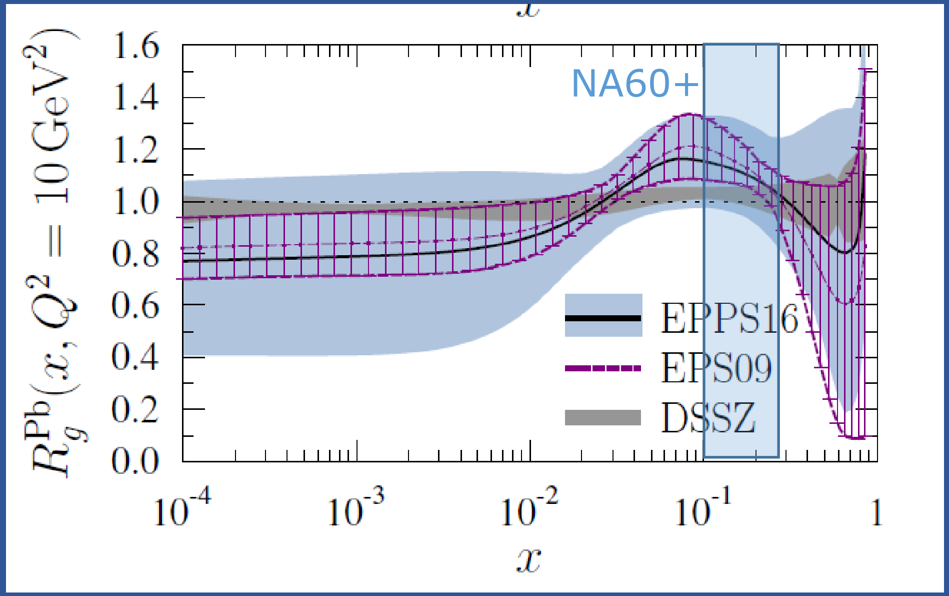
Open charm at low √s in pA: nuclear PDFs

- 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 $Q^2\sim 10\text{-}40$ GeV^2



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



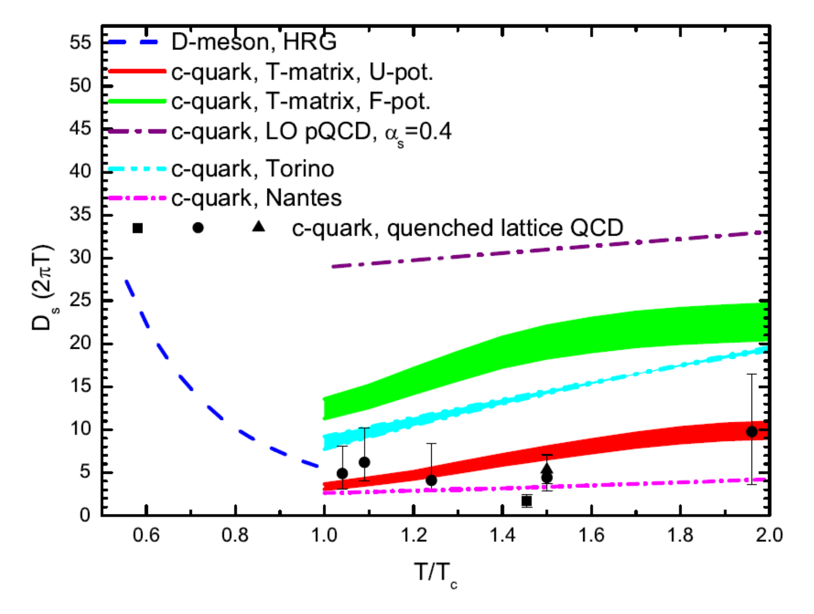


Eskola et al. , EPJ C77 (2017) 13

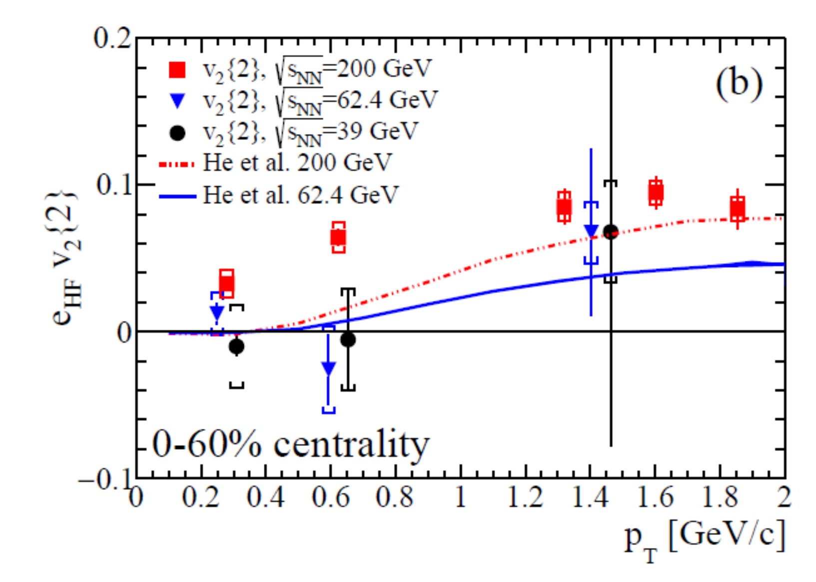
Open charm in Pb-Pb: R_{AA} and v_2

- 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



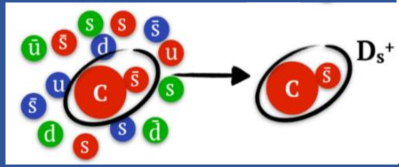
Prino, Rapp, JPG43 (2016) 093002

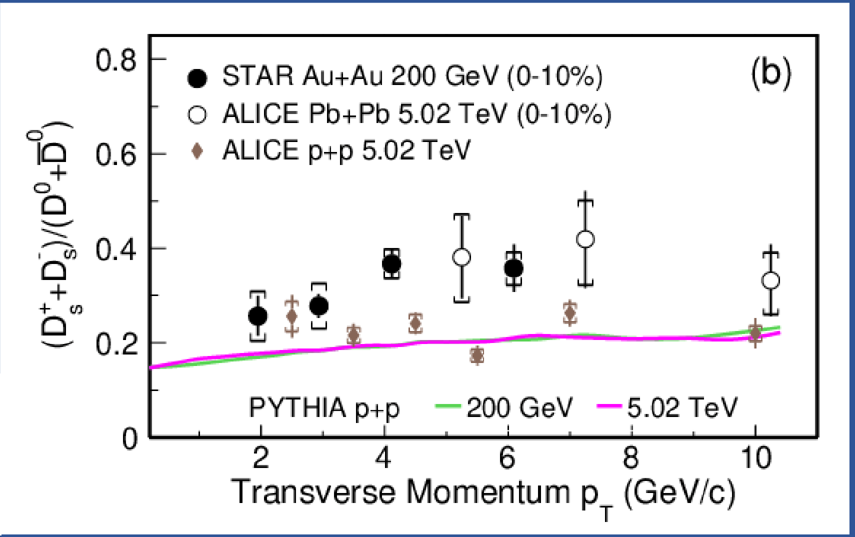


STAR, PRC 95 (2017) 034907

Open charm hadrochemistry

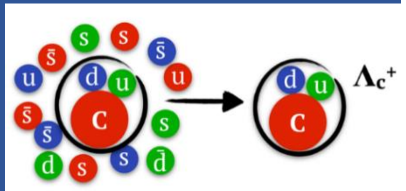
- Reconstruct different charm hadron species to get insight into **hadronization mechanism**
- **Strange/non-strange** meson ratio (D_s/D):
  - D_s/D enhancement expected in A-A collisions due to hadronisation via **recombination** in the strangeness rich QGP



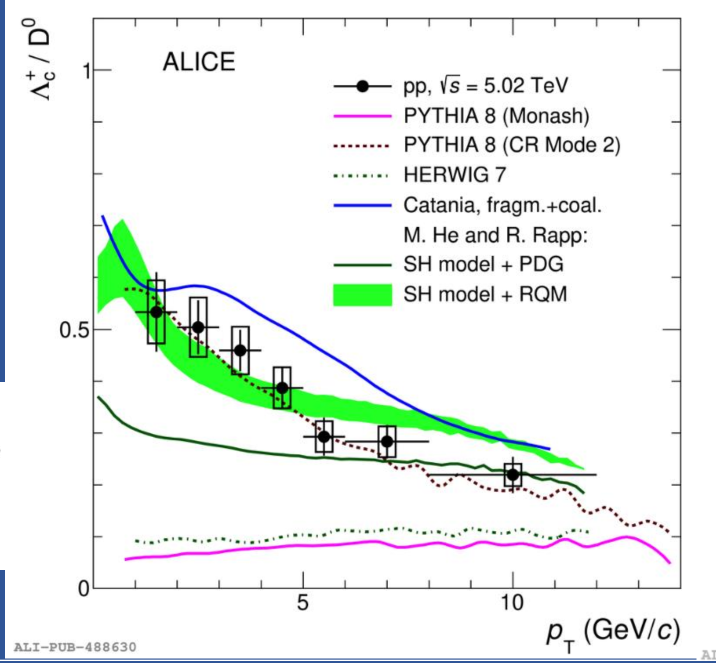


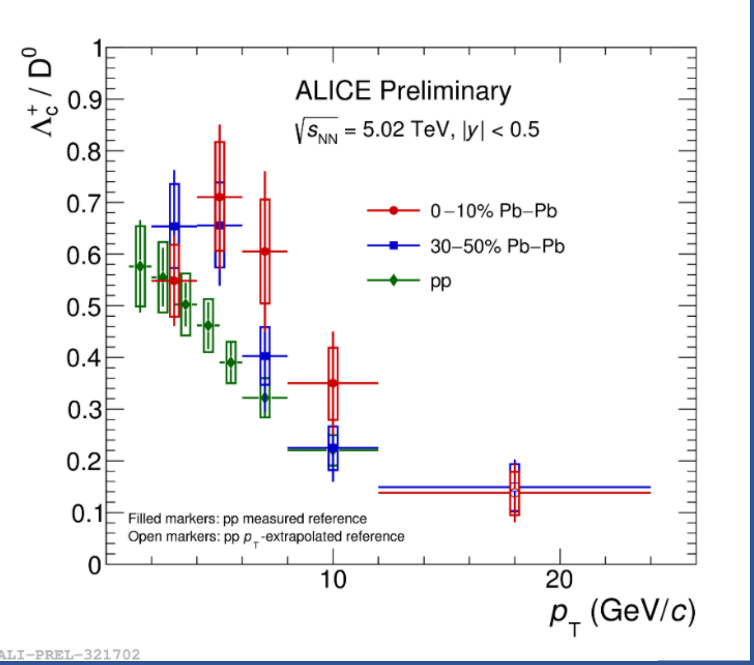
STAR, PRL 127 (2021) 092301
ALICE, PLB827 (2022) 136986

- **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^-



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
    NA60, EPJ C59 (2009) 607
  - Upper limit from NA49 measurements of D^0 mesons
    NA49, PRC73 (2006) 034910

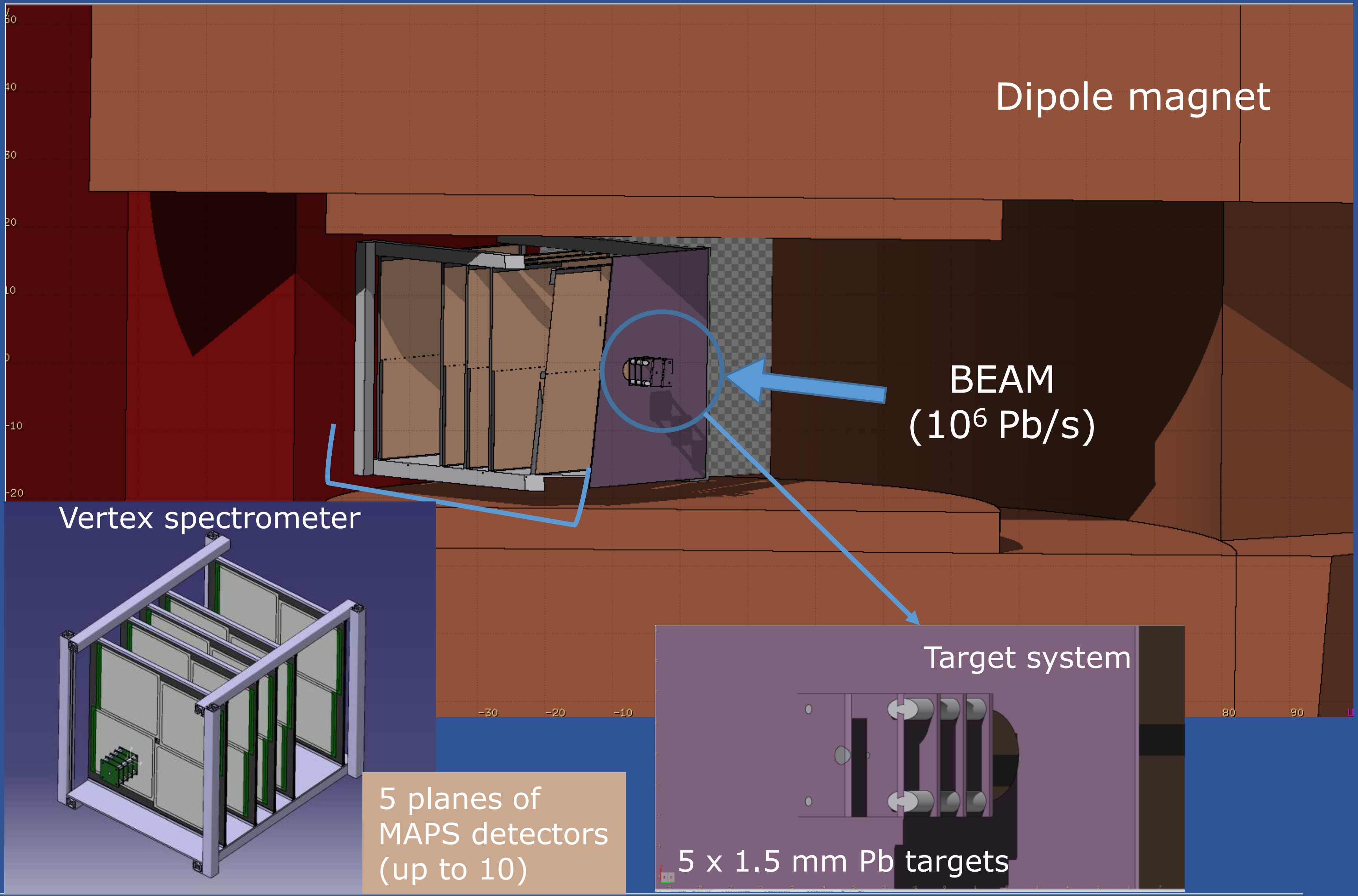
- Precise measurement requires to reconstruct all meson and baryon ground states (D^0, D^+, D_s^+ and Λ_c^+ and their antiparticles)

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

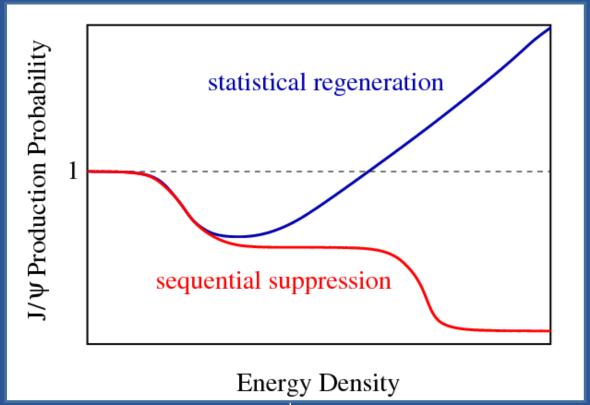
Towards a precise measurement of open charm at SPS energy

A measurement of **hadronic decays** is required

	Mass MeV)	$c\tau$ (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%



Charmonia: high vs low √s

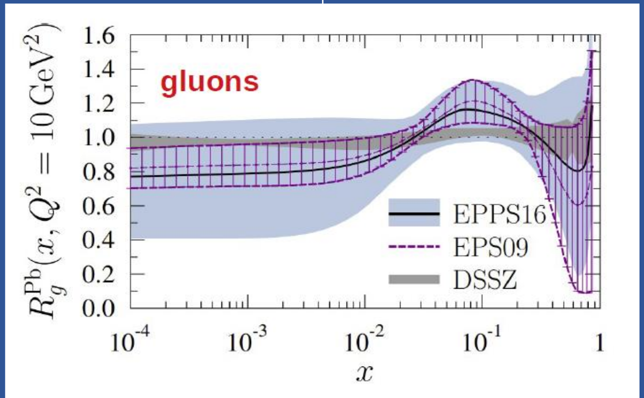


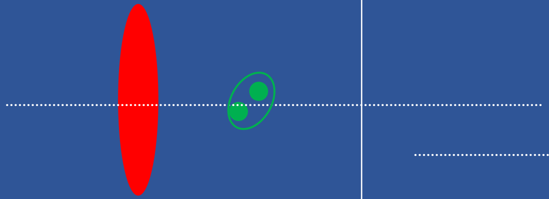
Collider (LHC)

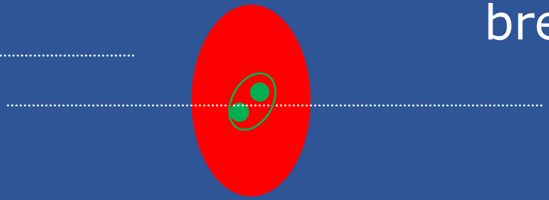
Hot matter effects: regeneration counterbalances (overcomes) suppression

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 ($y \sim -3$)







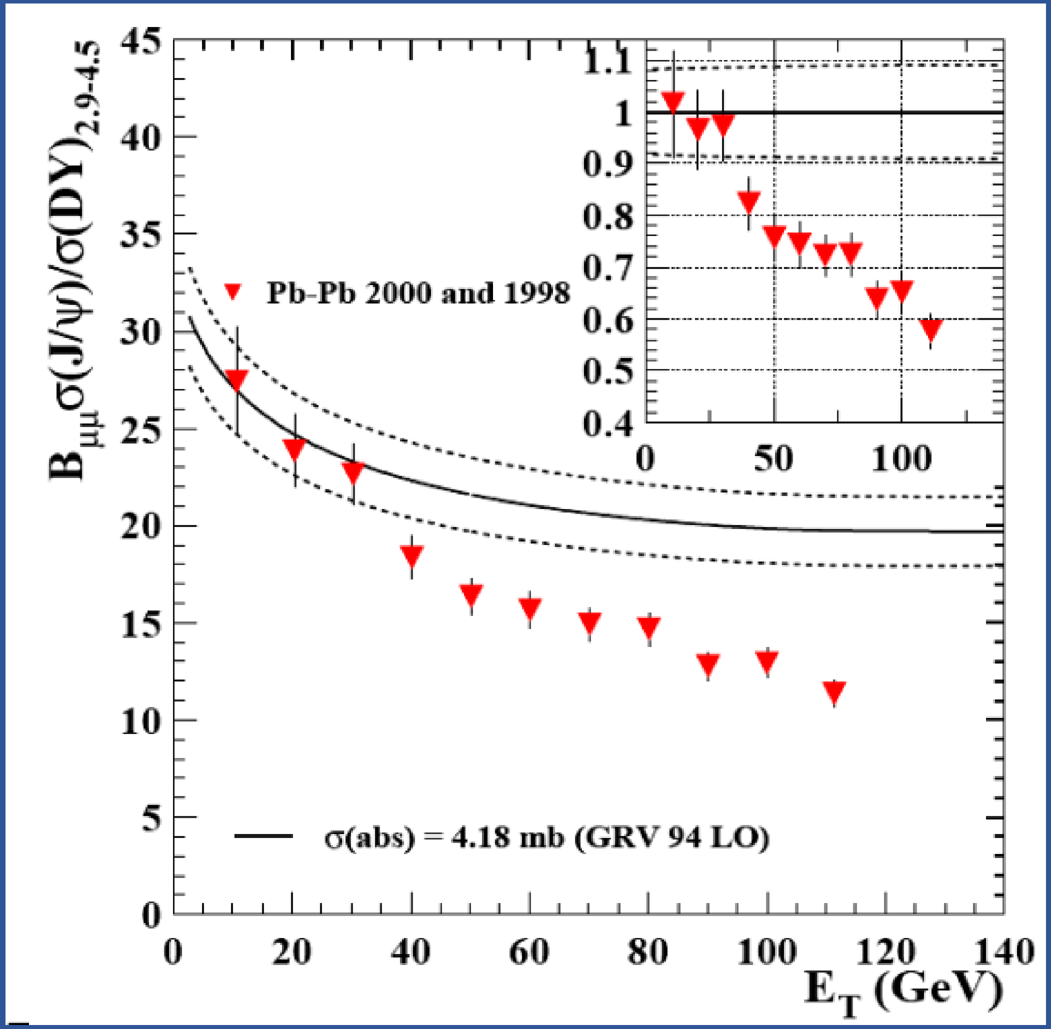
Fixed target (SPS)

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

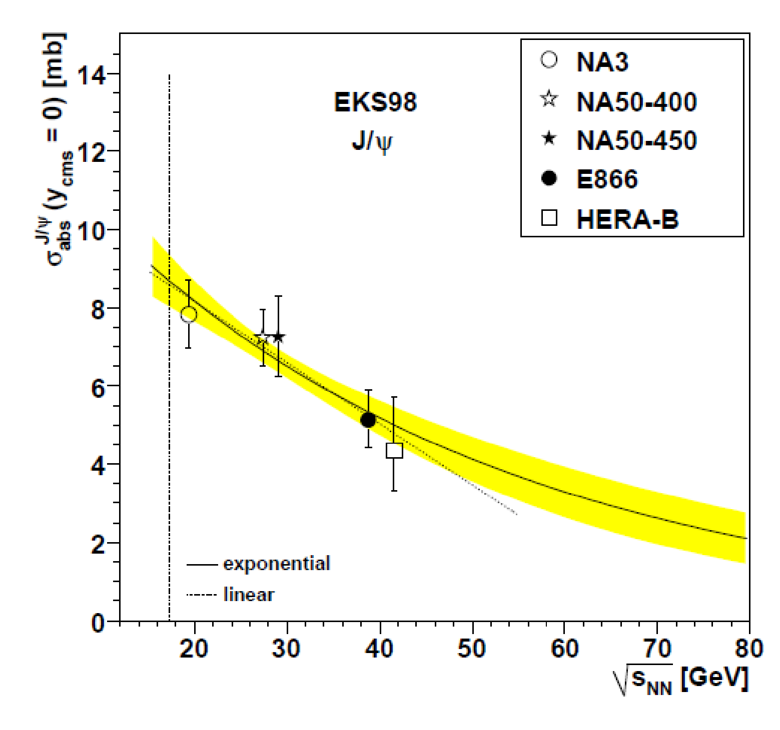


- Contrary to open charm, accurate studies were performed at $\sqrt{s}$=17.3 GeV (NA50, NA60)
- J/ψ yields normalized to Drell-Yan reference
- QGP-induced suppression evaluated with respect to a CNM reference obtained with systematic p-A studies
- **~30-40% anomalous suppression effect** possibly due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

CNM effects are (very) large

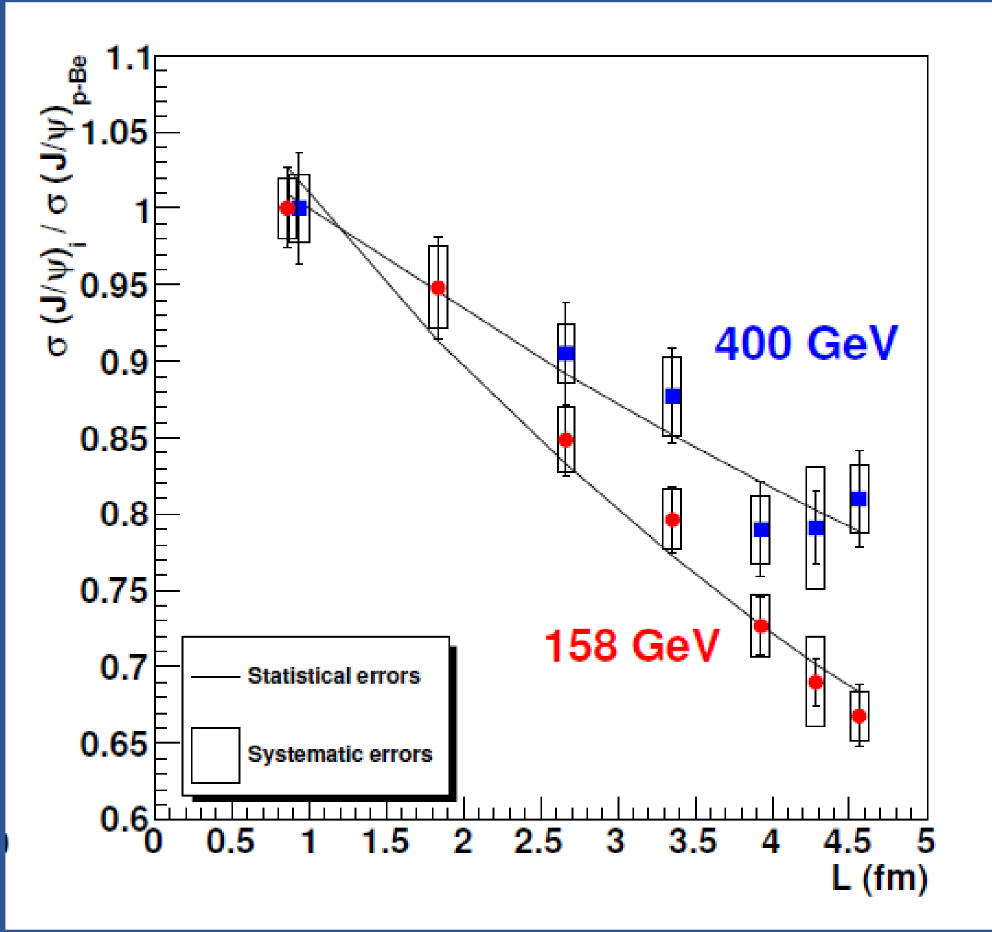
- ❑ Shadowing effects are moderate
- ❑ Dominated by nuclear absorption
  → ~30% effect in p-Pb at $\sqrt{s_{NN}}$ = 17 GeV

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



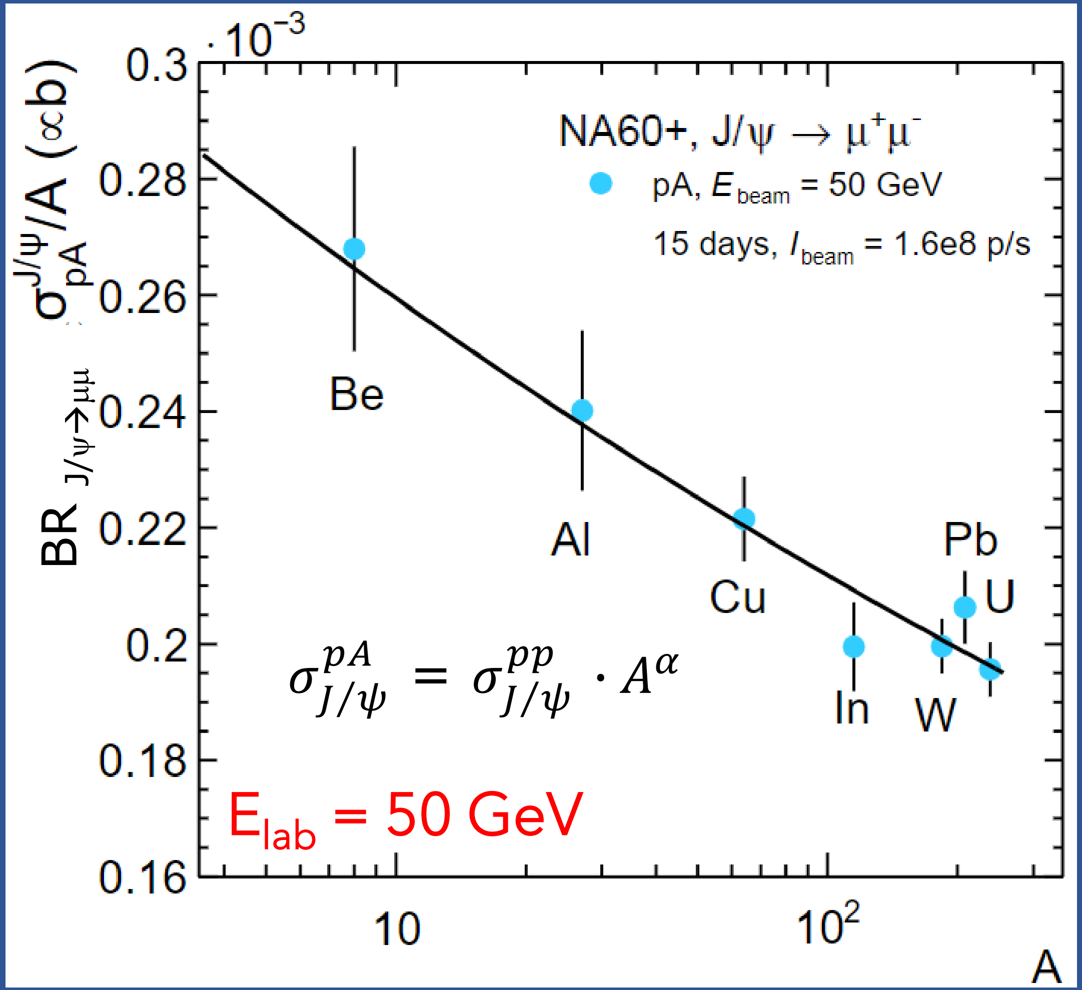
Lourenco, Vogt, Woehri, JHEP 0902:014,2009

NA60, PLB 706 (2012) 263



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

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**

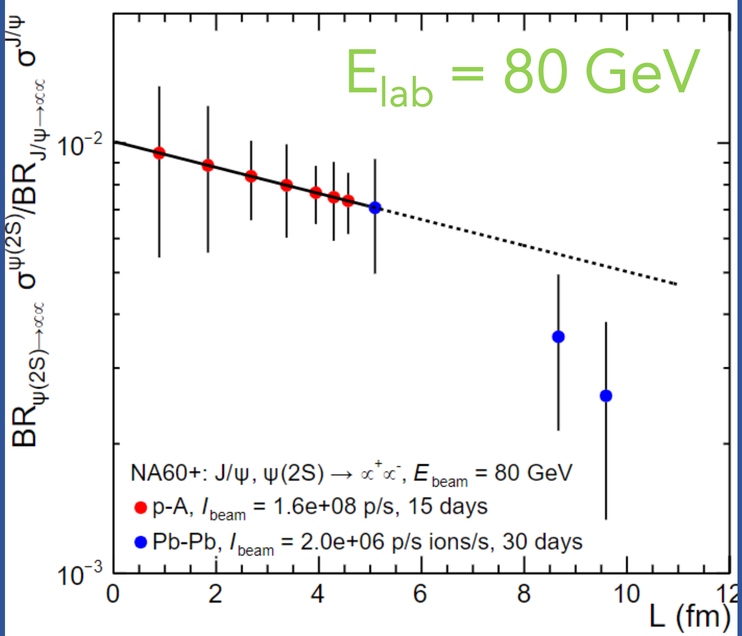
- pp collisions unpractical
  → Use a system of several targets simultaneously exposed to the p beam

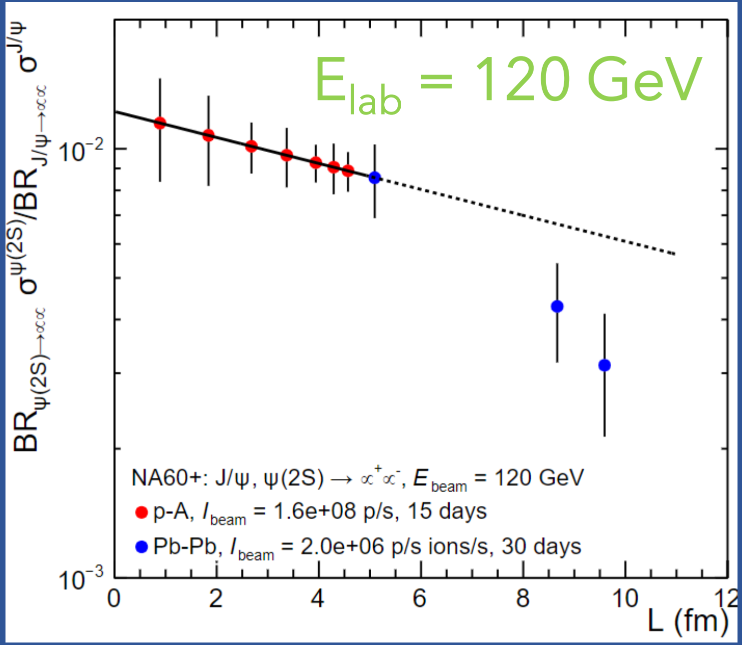
Prospects for ψ(2S) measurements at low √s

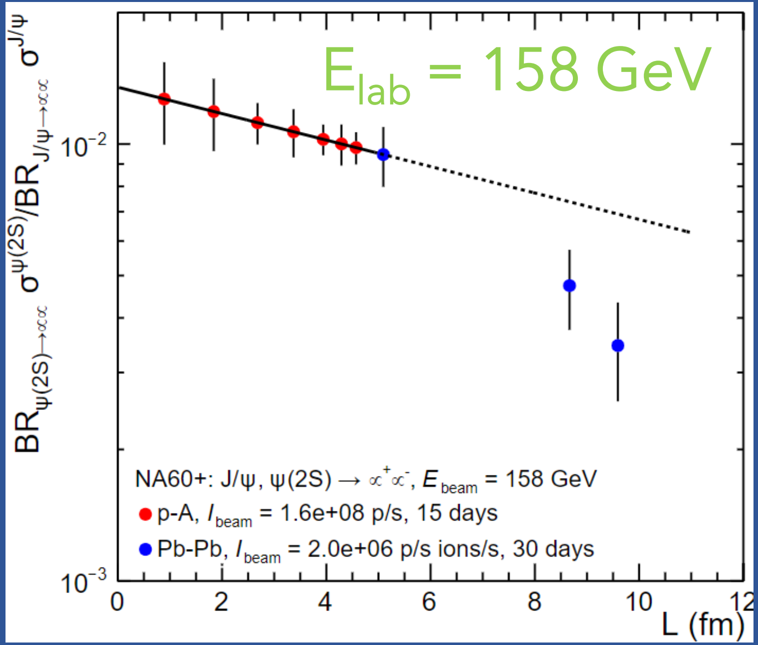
Good charmonium resolution (~30 MeV for the J/ψ) will help ψ(2S) measurements

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

Conclusions

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

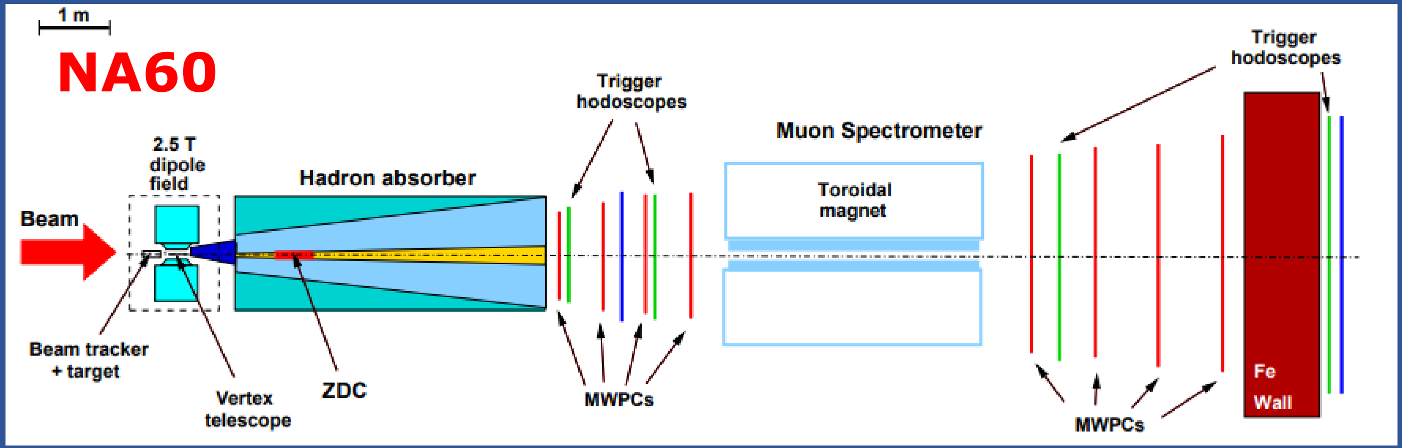
- Measurements from $\sqrt{s_{NN}} \sim 6$ to 17 GeV have a **strong physics interest**
  - QGP transport properties at high μ_B
  - Charm thermalization and hadronization
  - Intrinsic charm
  - Onset of charmonium anomalous suppression (and correlation with temperature)

- 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

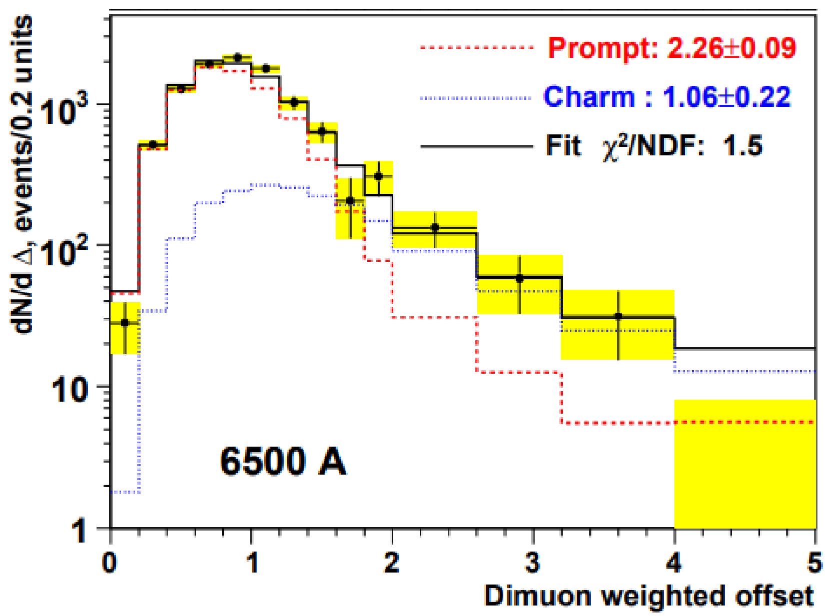
- Project is part of the CERN Physics Beyond Collider Initiative
- Letter of Intent ready for submission to SPSC
- Aim is **taking data after LHC Long Shutdown 3** → 2029 onwards!

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

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)



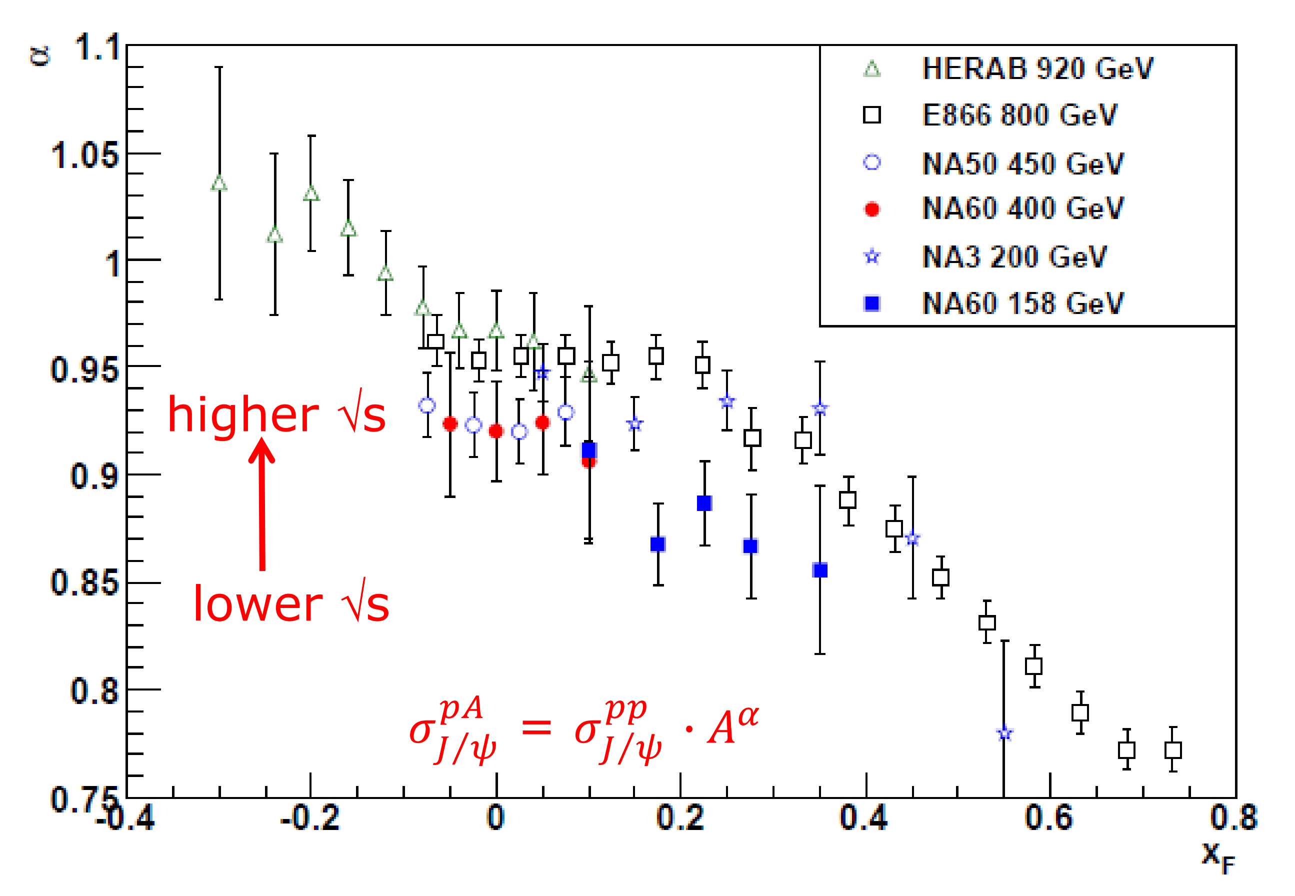
NA60, EPJ C59 (2009) 607

- ❑ 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

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

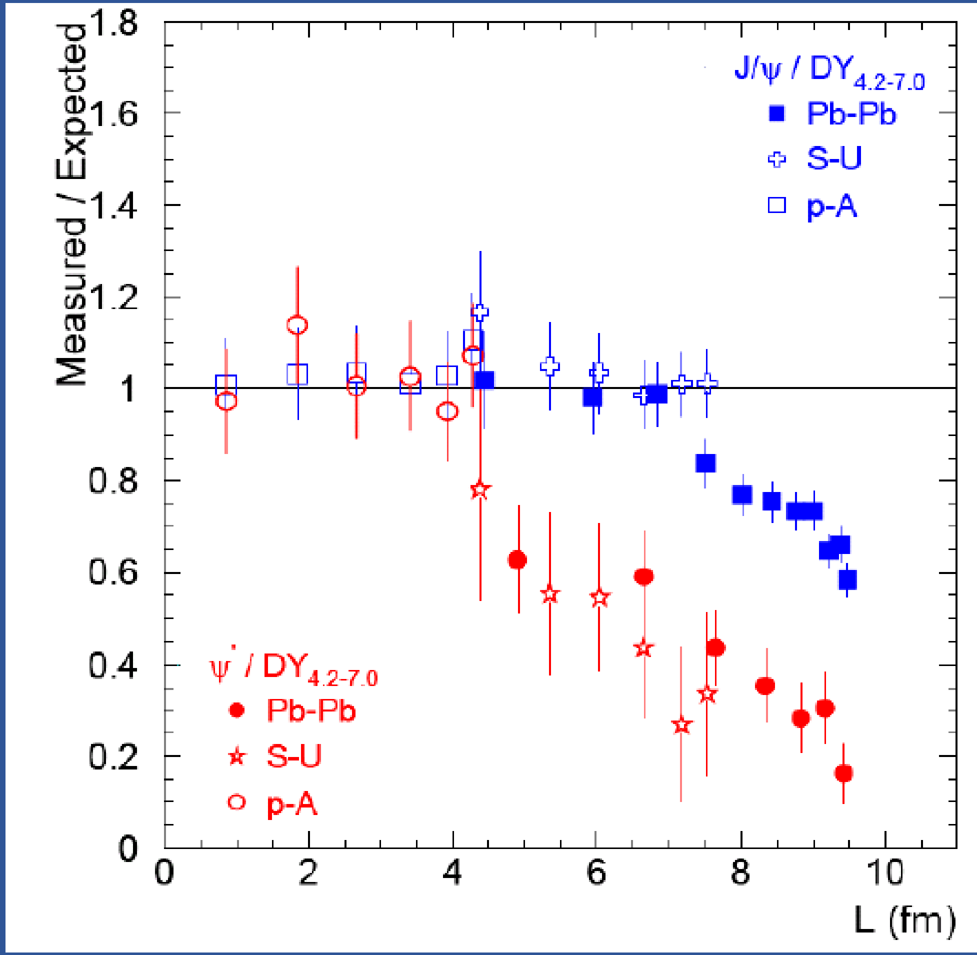
⇩

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

No consistent theory description over the whole x_F range

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!

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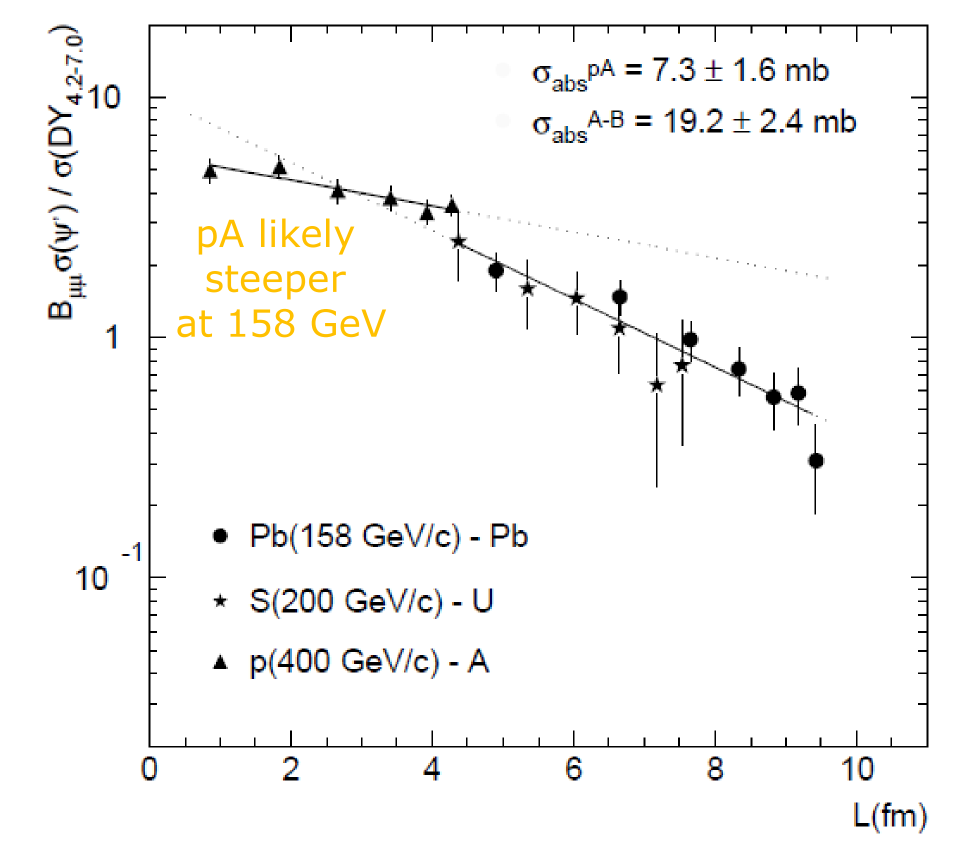

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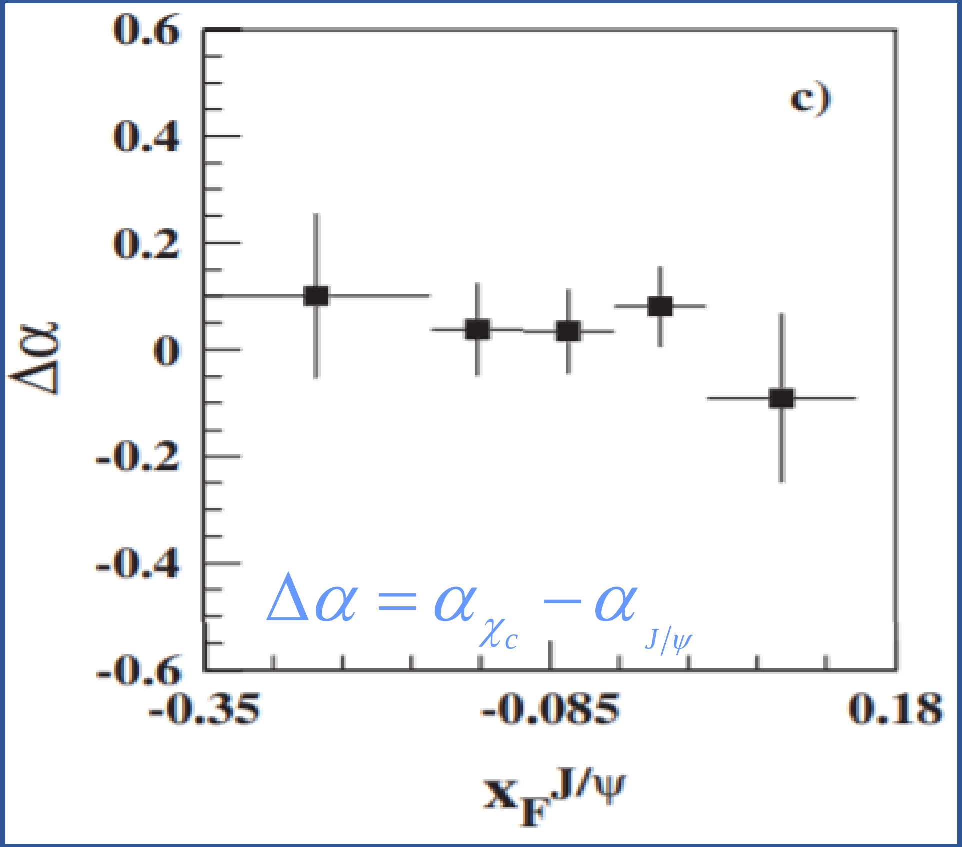
χ_c measurements

- ~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