Hard and electromagnetic probes: plans for future measurements at the CERN SPS

E. Scomparin – INFN Torino (Italy)

Hard Probes 2023
Aschaffenburg (Germany)
March 26-31, 2023

CERN SPS: an ideal facility for "low" energy / "high" luminosity measurements

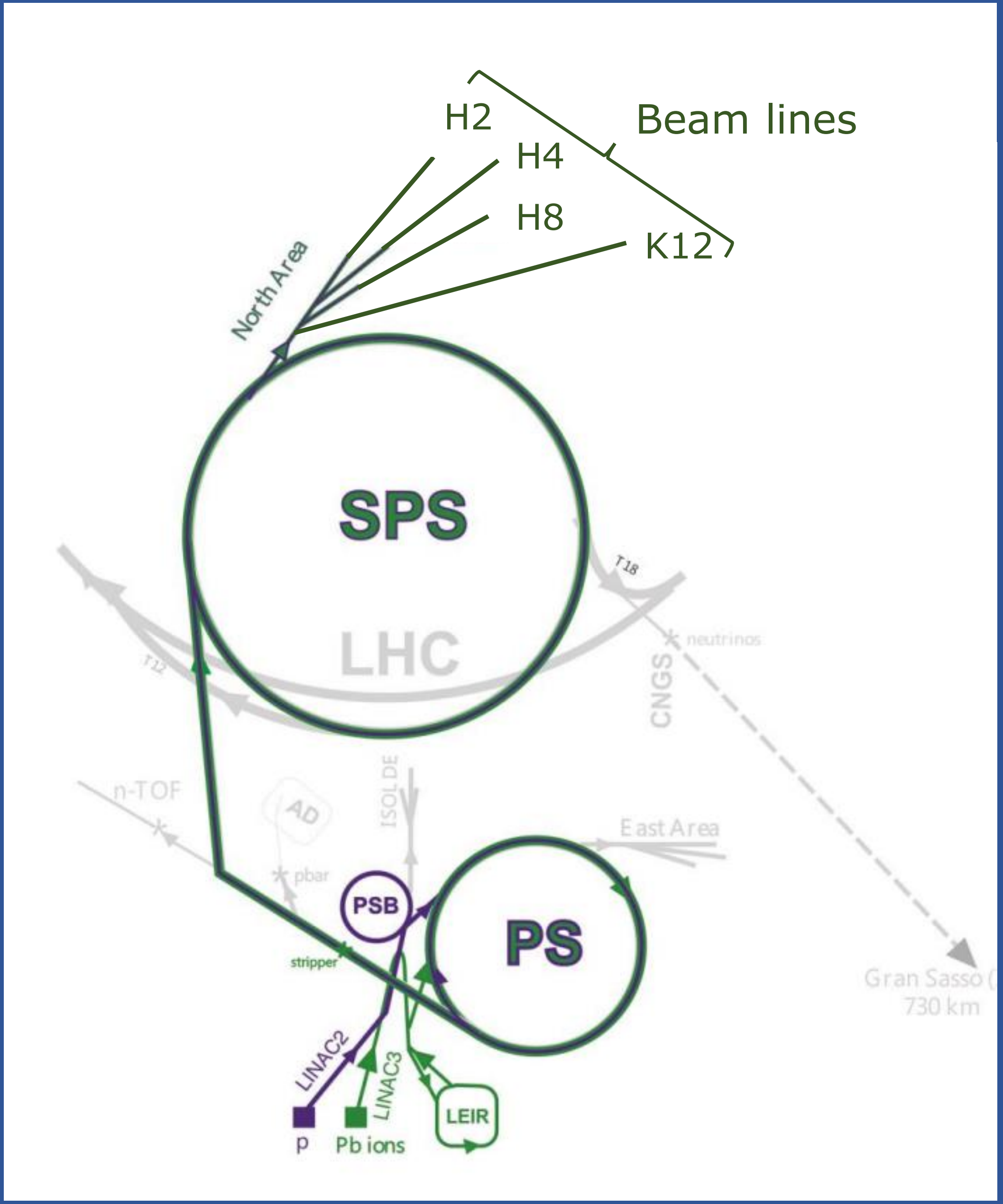
- Wide energy range for fixed-target experiments: **$6 < \sqrt{s_{NN}} < 17$ GeV**, with presently little competition

- Can deliver high luminosity ion beams, up to **$10^6 - 10^7$ s^{-1}**

- One month/year devoted to ion data taking

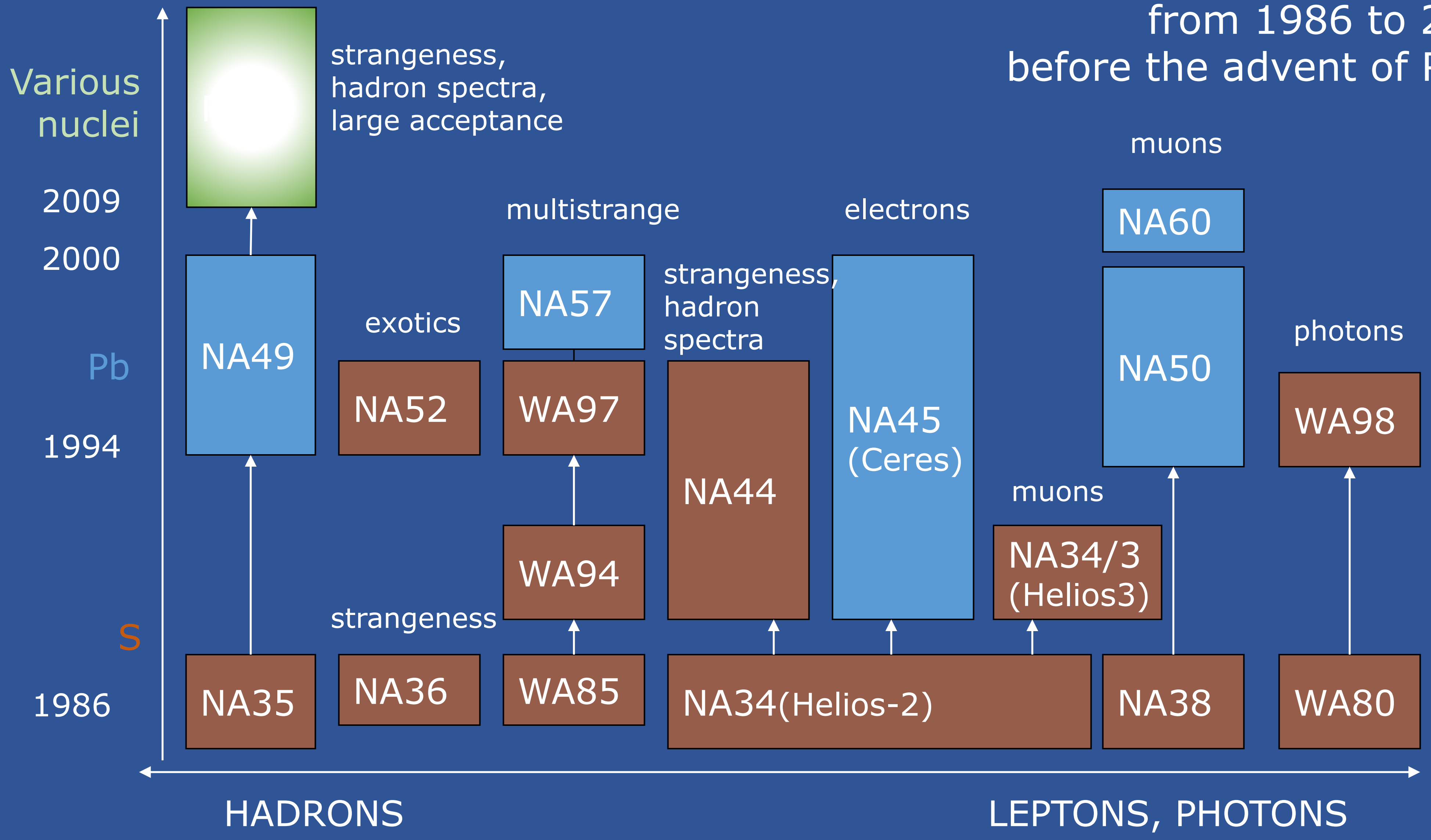
- Numerous beam lines and experimental areas

- Existing and reliable facility

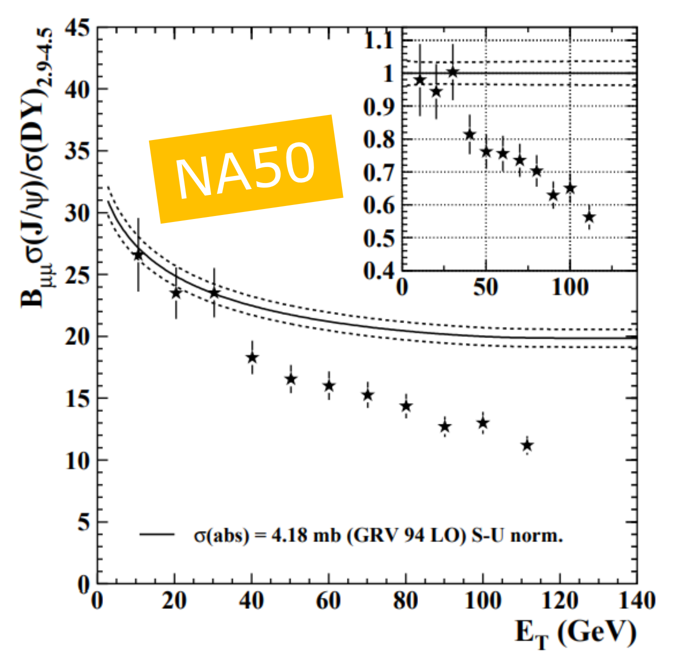


A glorious past…

Higher-energy heavy-ion facility from 1986 to 2000, before the advent of RHIC collider



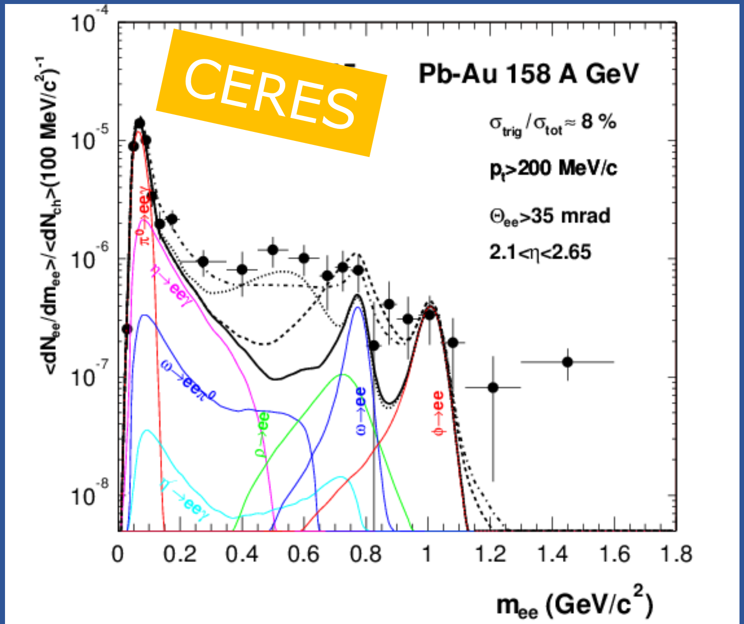
…with historic first results on hard / e.m. probes



NA50, EPJC39(2005) 335

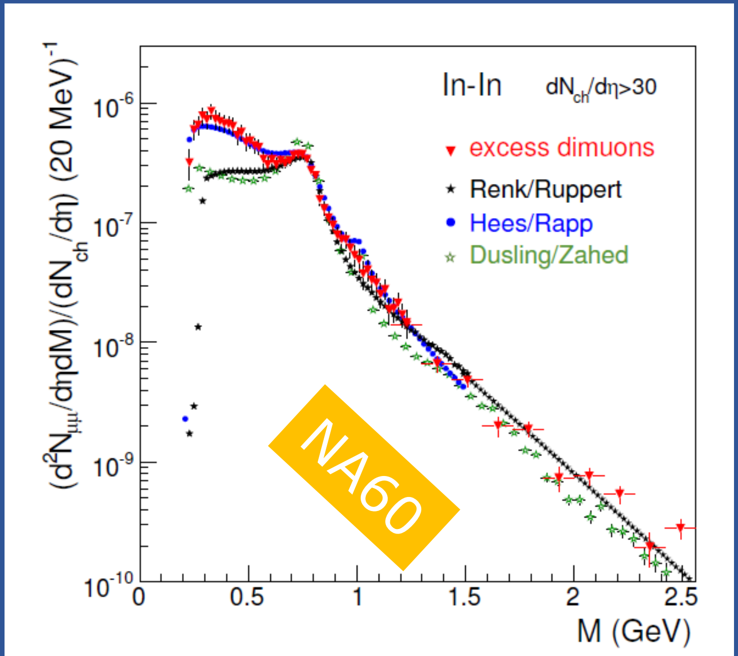
Discovery of **"anomalous" J/ψ suppression** (beyond CNM effects)

Evidence for **modification of ρ spectral function**



CERES, EPJC41(2005)475

First direct measurement of a temperature exceeding T_c, with **thermal dimuons**



NA60, EPJC59(2009)607

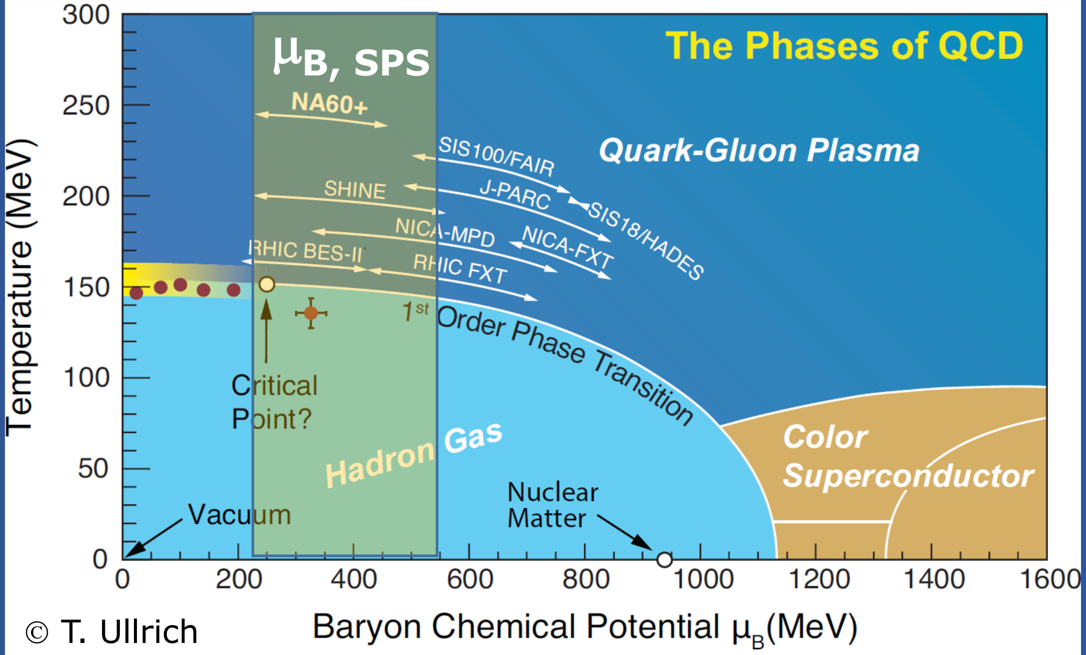
Accuracy of SPS measurements **unsurpassed** until today, for various observables

… and still an exciting future ?

- Most (all) accurate measurements of hard/e.m. probes were carried out at **top SPS energy**

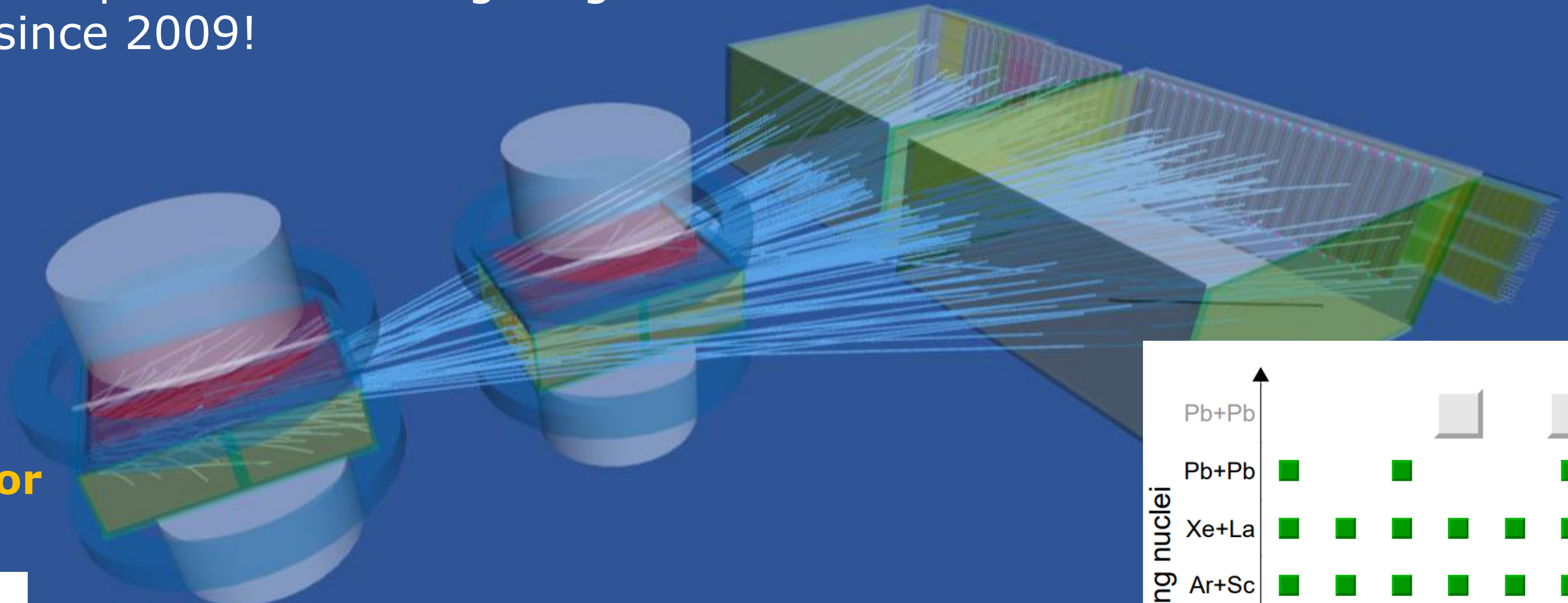
- Among the reasons
  - QGP "discovery" program aimed at reaching **highest energy densities**
  - Limited emphasis on finite μ_B physics at that time
  - Cross sections quickly **vanishing towards low energy**

- A **systematic study of hard/e.m. probes below top SPS energy** would access an unexplored domain for these observables, in the (approx) region 220<μ_B<550 MeV

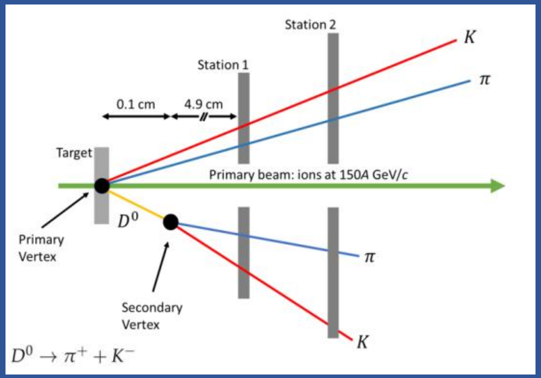


First step: charm measurement with **NA61/SHINE**

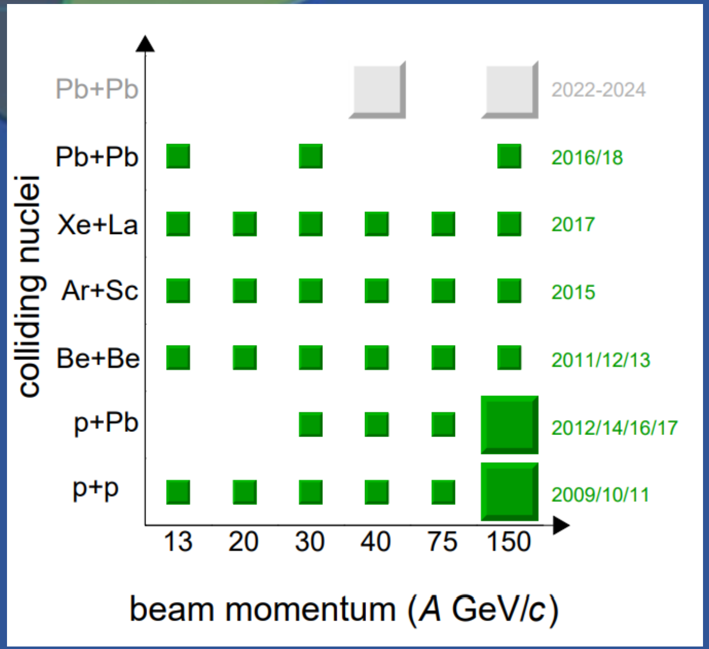
- **Multi-purpose experiment investigating hadron production** since 2009!



New **vertex detector** (ALPIDE sensors)



- Systematic studies with various ion species and different energies, to investigate signals of the **onset of deconfinement**



First step: charm measurement with **NA61/SHINE**

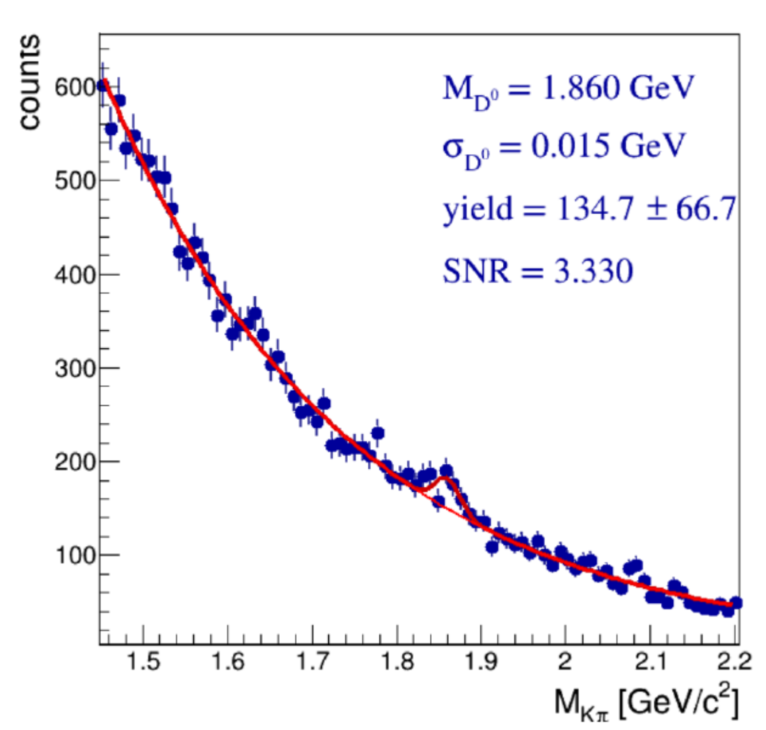
- Measurement of **open charm cross section** among the main physics goals for 2022-2025 (upgrade of vertex detector to stand 1 kHz interaction rate)

Estimate for 5 10^8 MB events at **150 A GeV**

	0–10%	10–20%	20–30%	30–60%	60–90%
$\#(D^0 + \overline{D^0})$	31k	20k	11k	13k	1.3k
$\#(D^+ + D^-)$	19k	12k	7k	8k	0.8k
$\langle W \rangle$	327	226	156	70	11

Evaluation of
D cross sections
feasible!

exploratory measurement,
top SPS energy

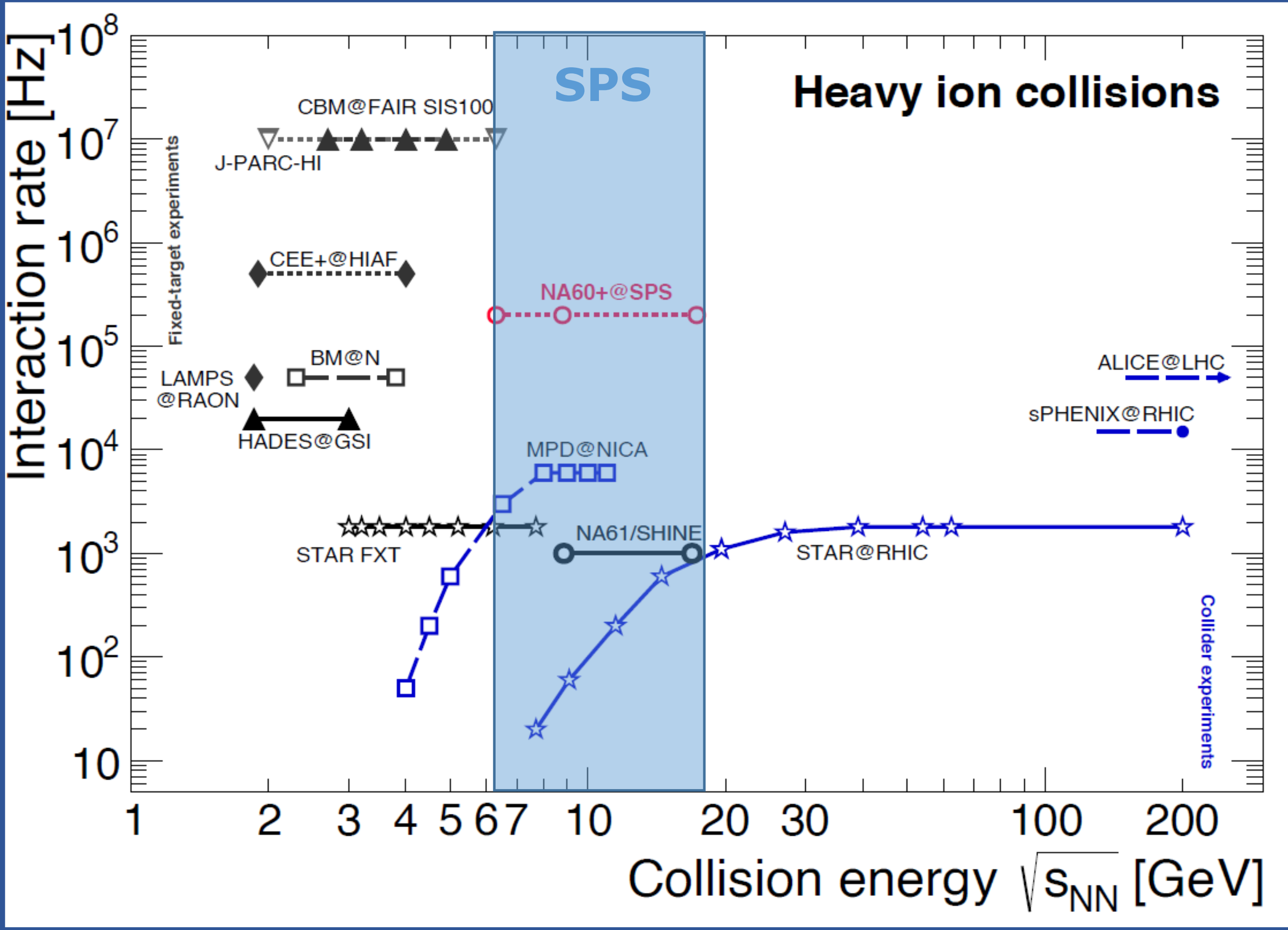


- Measurement at **40 AGeV** also planned, smaller statistics expected

- Study of **$c\bar{c}$ correlations** could be attempted, might be statistics limited

A further increase of sustainable interaction rates necessary for a high-statistics study

High luminosity measurements: the **NA60+** project



from T. Galatyuk, NPA982(2019) update 2022

- A **new experiment** at the CERN SPS for the measurement of **rare probes of QGP**
- Interaction rates > **10^5 Hz**
- **Energy scan,** $6<\sqrt{s_{NN}}<17$ GeV ($20<E_{lab}<160$ AGeV)
- Access **muon pair** production from threshold up to $m_{\mu\mu}$ ~ 4 GeV/c^2 (**dilepton continuum + quarkonia**)
- Perform measurements of hadronic decays of **strange and charm** hadrons

Unique in the heavy-ion landscape (energy coverage AND interaction rate) and **complementary** to other experiments/facilities (CBM/FAIR,…)

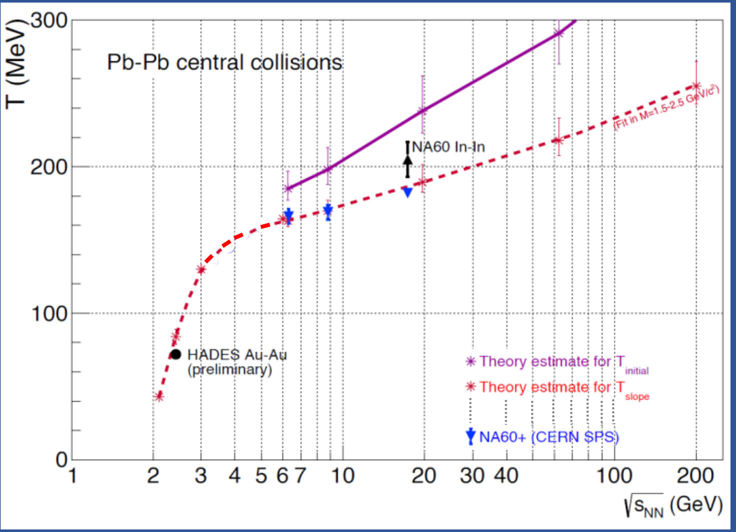
The NA60+ physics program

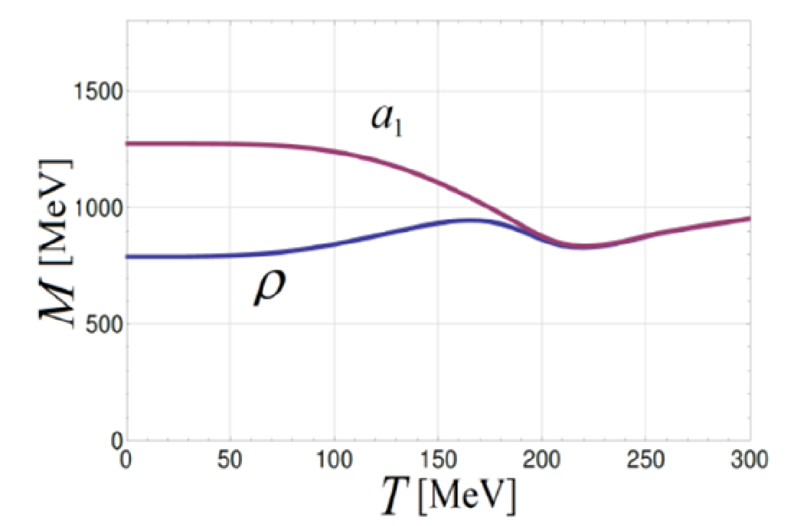
Several **new and unique measurements**

Caloric curve of QGP

Measurement of temperature of thermal dimuons vs $\sqrt{s_{NN}}$

Rapp and v.Hees, PLB753(2016) 586
T. Galatyuk et al., EPJA52(2016) 131





Chiral symmetry restoration

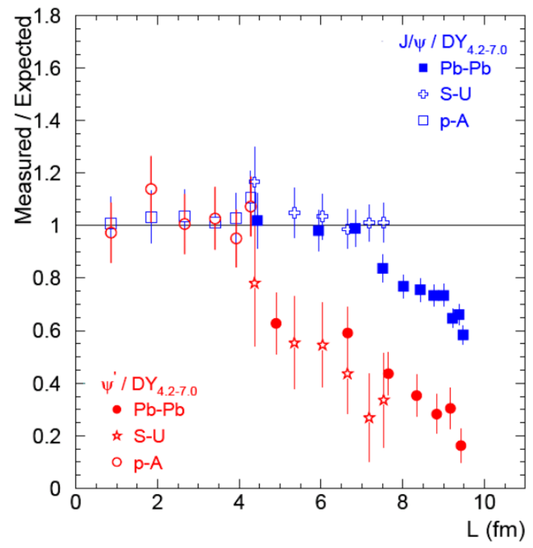
ρ-a_1 mixing in the dimuon channel

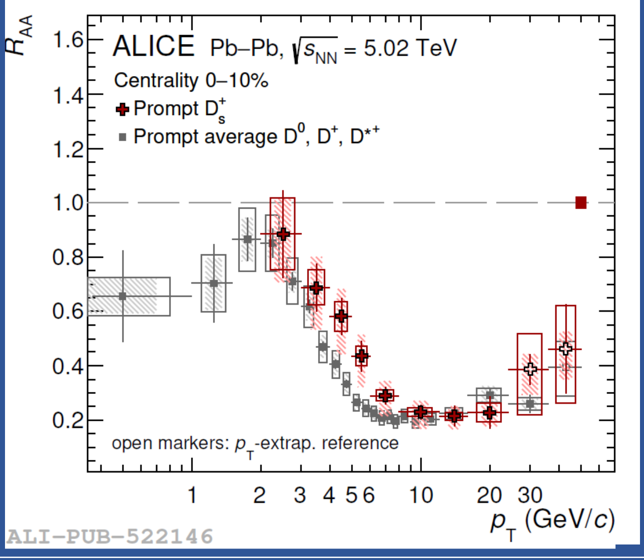
C. Jung et al., PRD 95 (2017) 036020

Charmonium melting in the QGP

Charmonium suppression vs $\sqrt{s_{NN}}$ (dimuon decay channel)

NA50, PLB 477 (2000) 28
NA50, EPJC49 (2007) 559



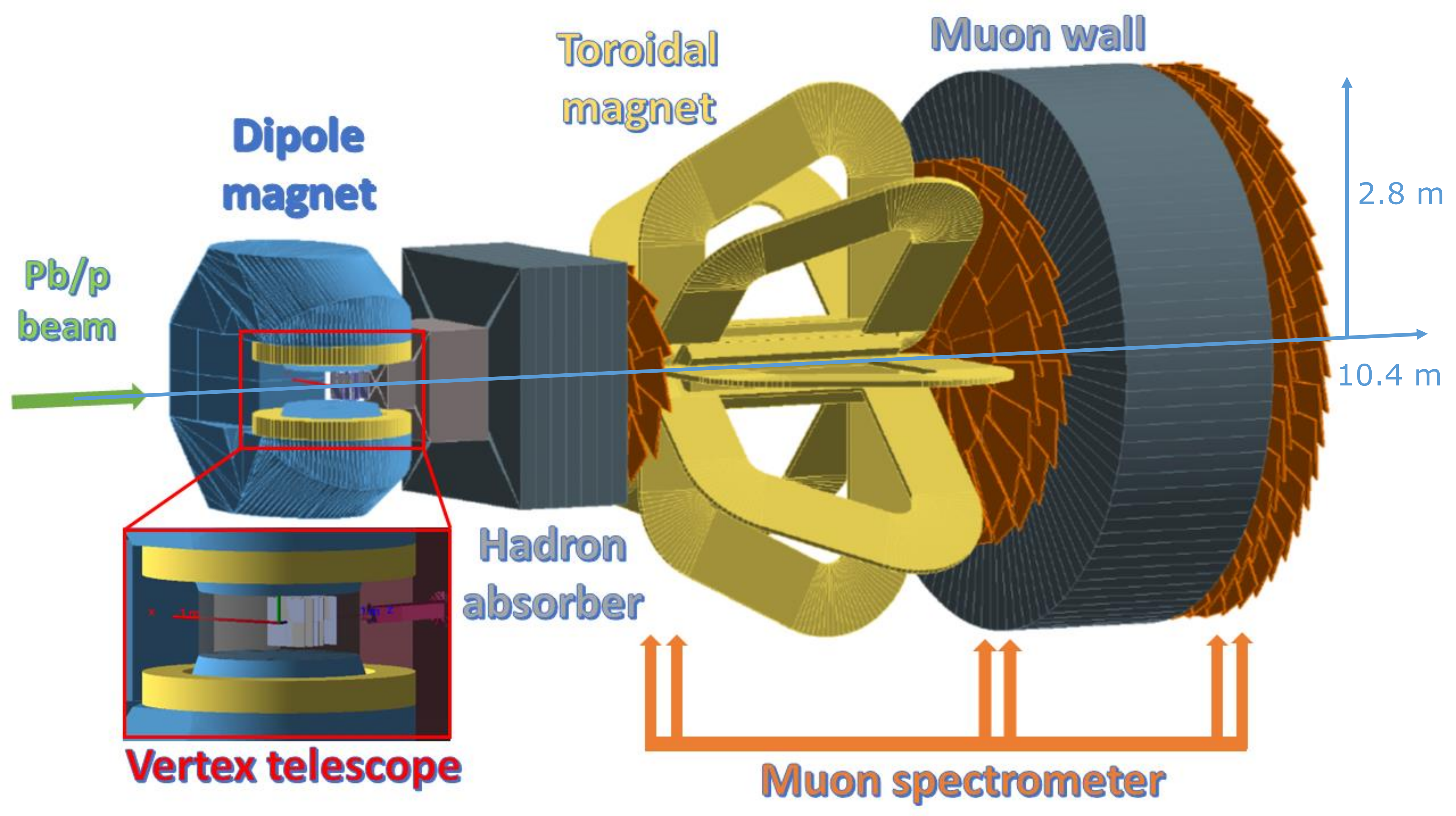


QGP transport coefficients and charm hadronization

Hadronic decays of open HF mesons/baryons

ALICE, PLB 827 (2022) 136986

The NA60+ detector



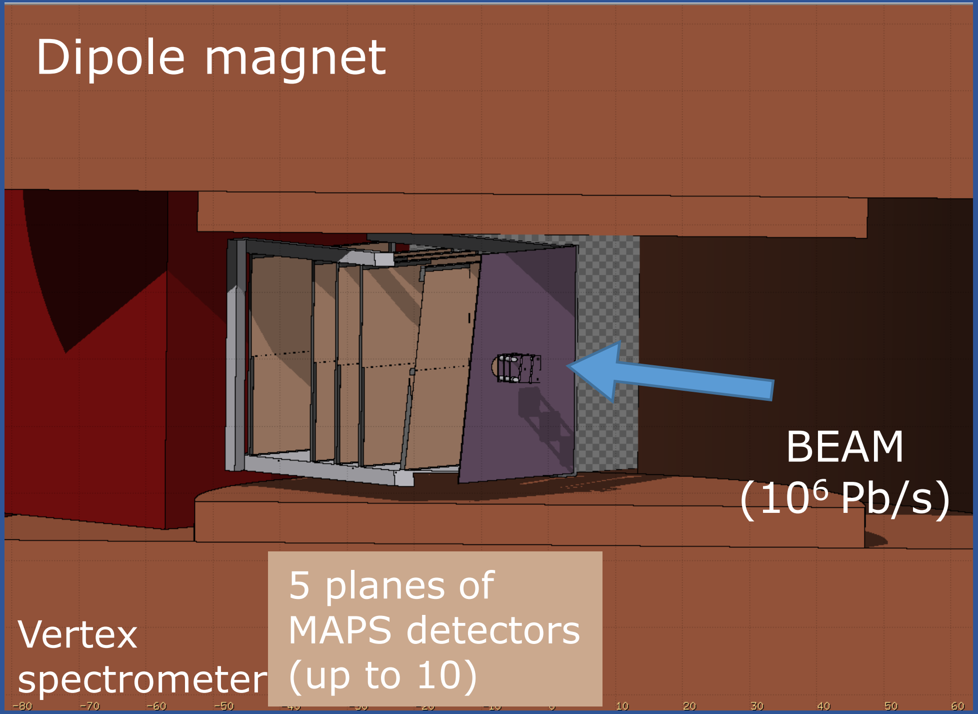
Inspired by the **former NA60** detector (2002-2004)

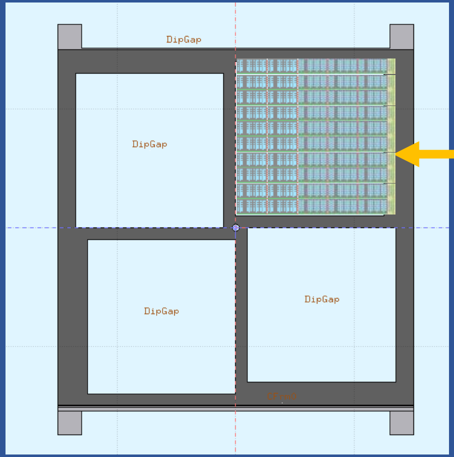
Measurement of **(di)muon** production and hadronic decays of **strange** and **charm** hadrons

SPS **energy scan**: vary z-position of the muon spectrometer and thickness of hadron absorber

The NA60+ vertex region

MEP48 dipole magnet
Field 1.5 T over a 400mm gap



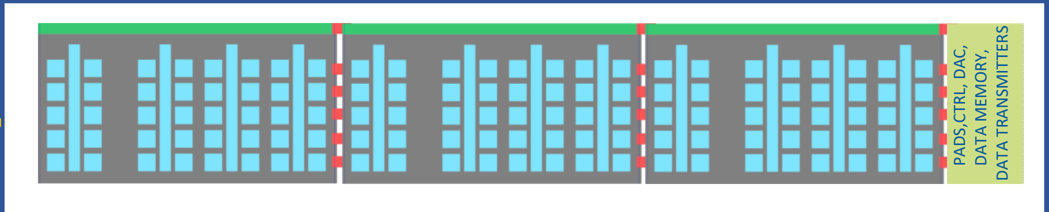


R&D in progress
Common development
ALICE ←→ NA60+
(same timeline!)

State-of-the-art imaging technology
TowerJazz 65 nm

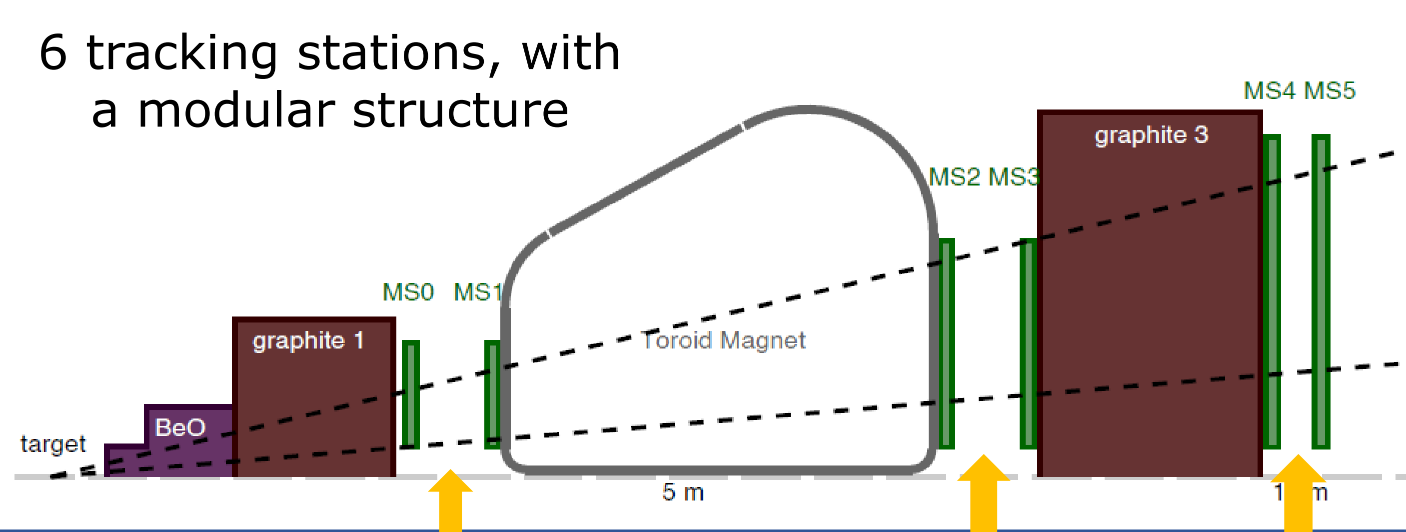
Sensor thickness:
few tens of microns of silicon
→ material budget **$<0.1\%\ X_0$**

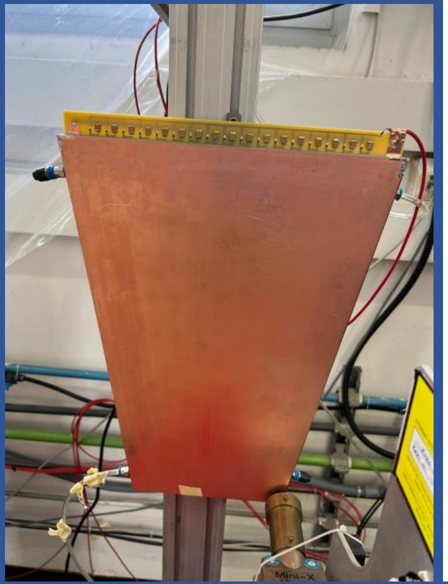
Spatial resolution **$\leq 5\ \mu m$**

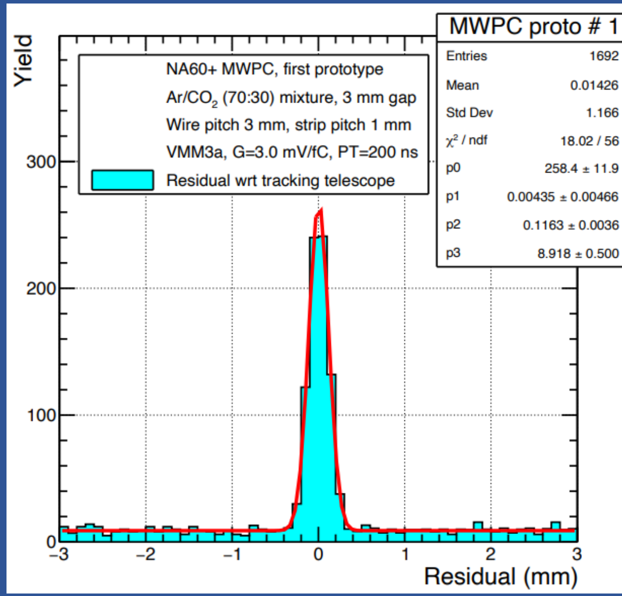


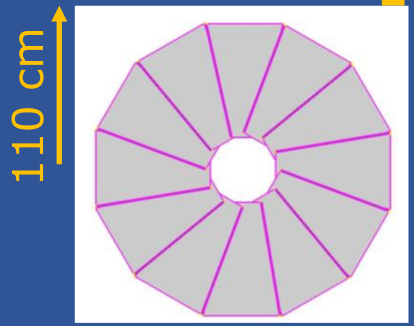
Sensor based on 25 mm long units,
replicated several times through
stitching → up to 15cm length

The NA60+ muon spectrometer

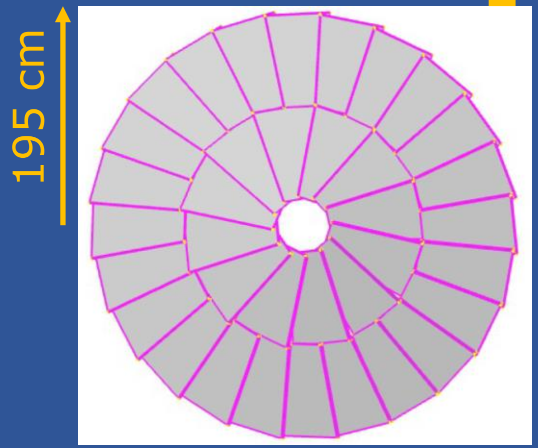




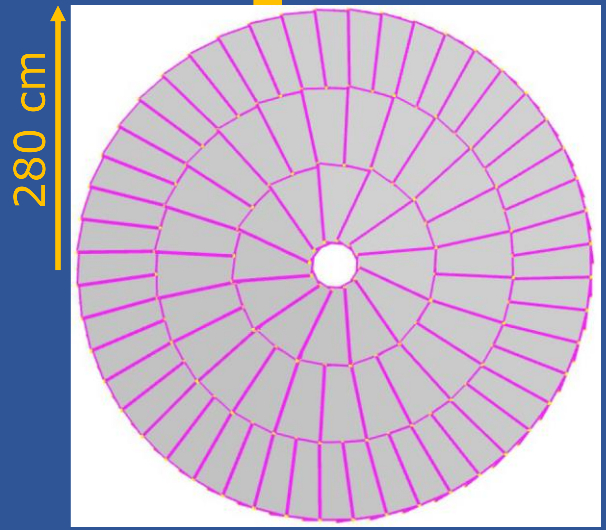




12x2 modules



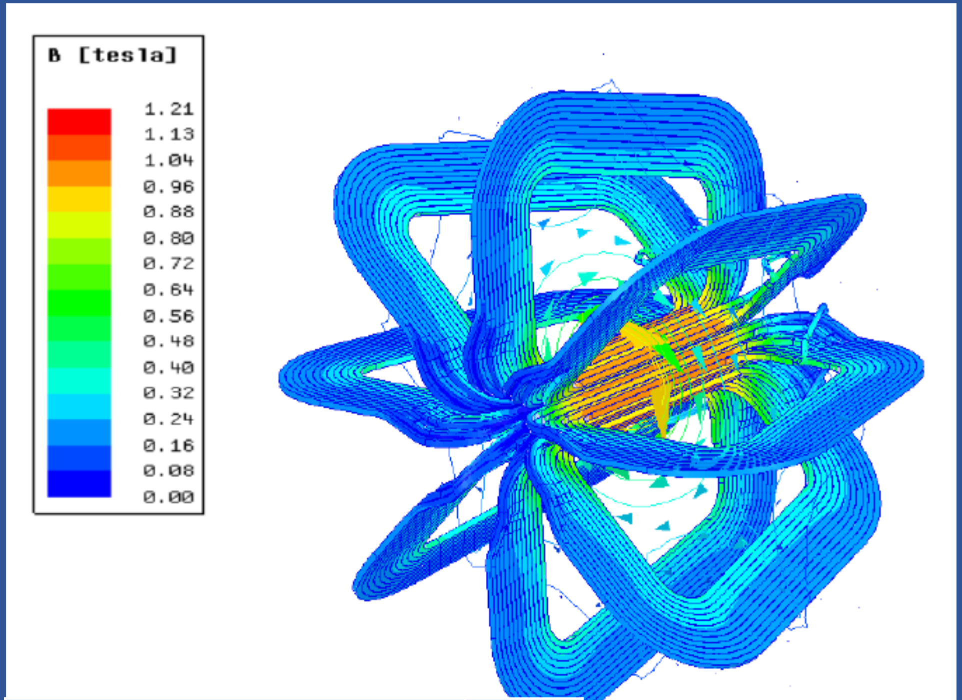
36x2 modules



84x2 modules

- For a 150 kHz interaction rate (10^6 s^{-1} beam), charged rate ~2kHz/cm^2
- Can be matched by **GEM or MWPC** detectors
- First prototype of a **MWPC module built and tested**

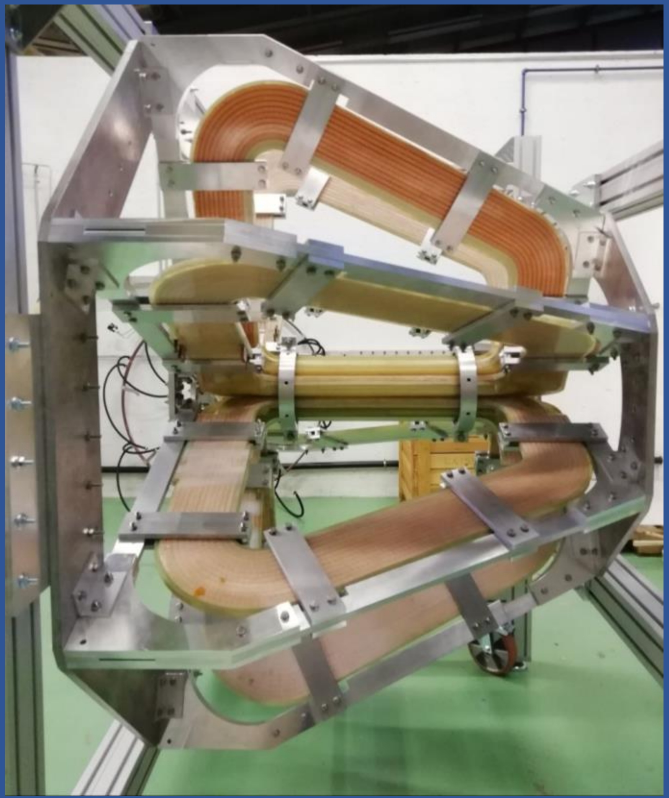
The NA60+ toroid



Warm magnet

Eight sectors,
12 turns per coil

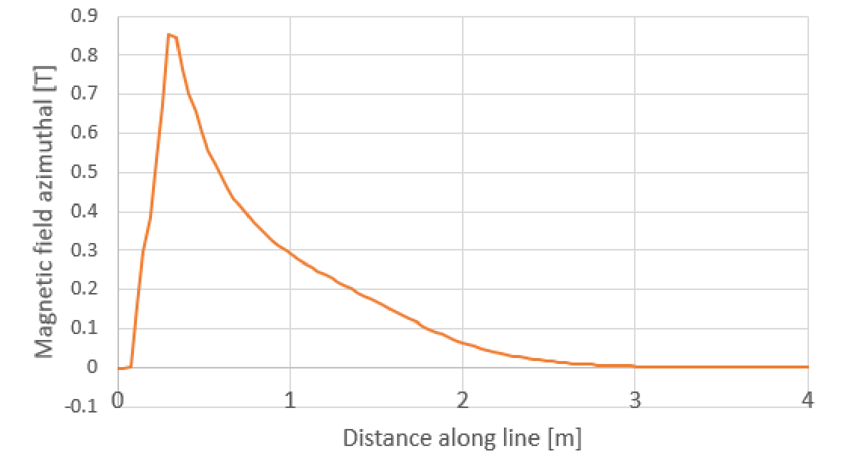
Conductor has a square copper section with a circular cooling channel in the centre



https://edms.cern.ch/document/2694487/1

Prototype (1:5 scale)

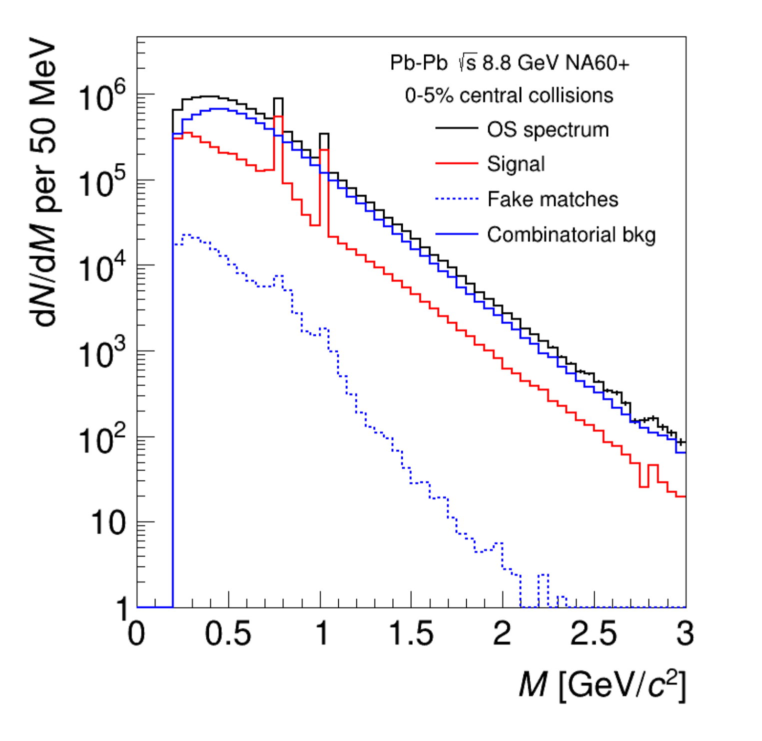
Operating Current [kA]	16.6
Amp-turns [kA]	199
Combined inductance [mH]	9.5
Resistivity Al 1100 @RT [μΩ.cm]	2.67
Length Conductor [m]	800
Total resistance [mΩ]	10.4
Dissipated power [MW]	2.8

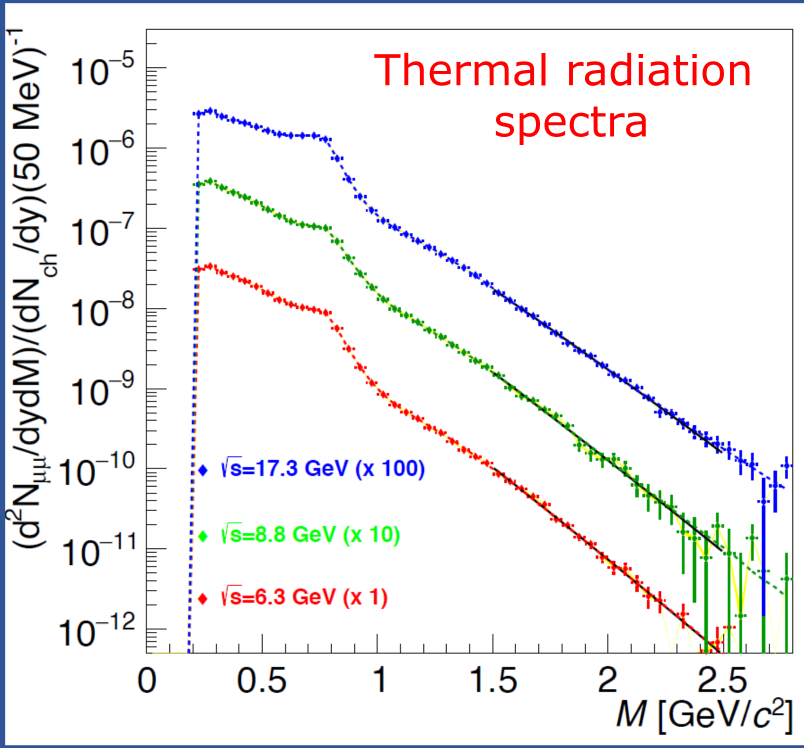


- ❑ Measurements of resistance, inductance, cooling performance and magnetic field were carried out
- ❑ B measurement
  → agreement with simulations by 3%

Design of the final toroid to be started

Physics performance: thermal radiation





- ❑ 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}

2 years → 6.3

1 year → 8.8, 17.3

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

(0-5% central Pb-Pb collisions)

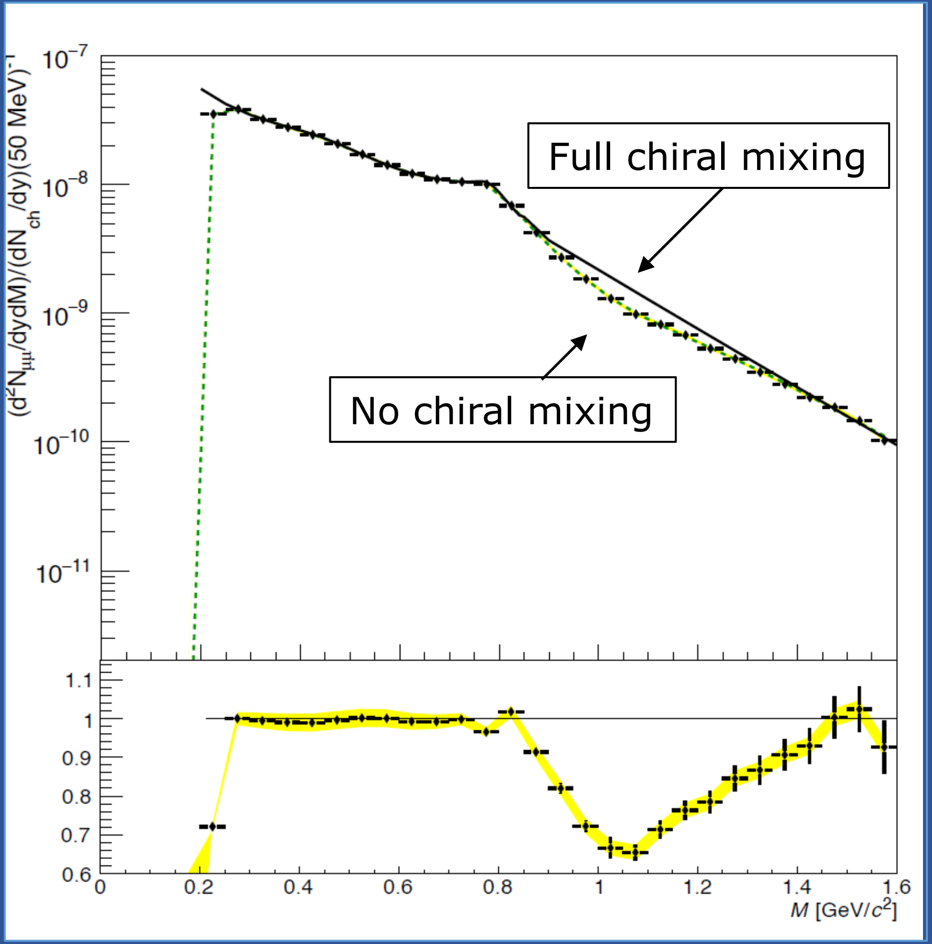
- ❑ Accurate mapping of the region where T_{pc} is reached
  - → Strong **sensitivity** to possible flattening due to 1st order transition

- ❑ **Elliptic flow** measurement also feasible

Physics performance: chiral symmetry

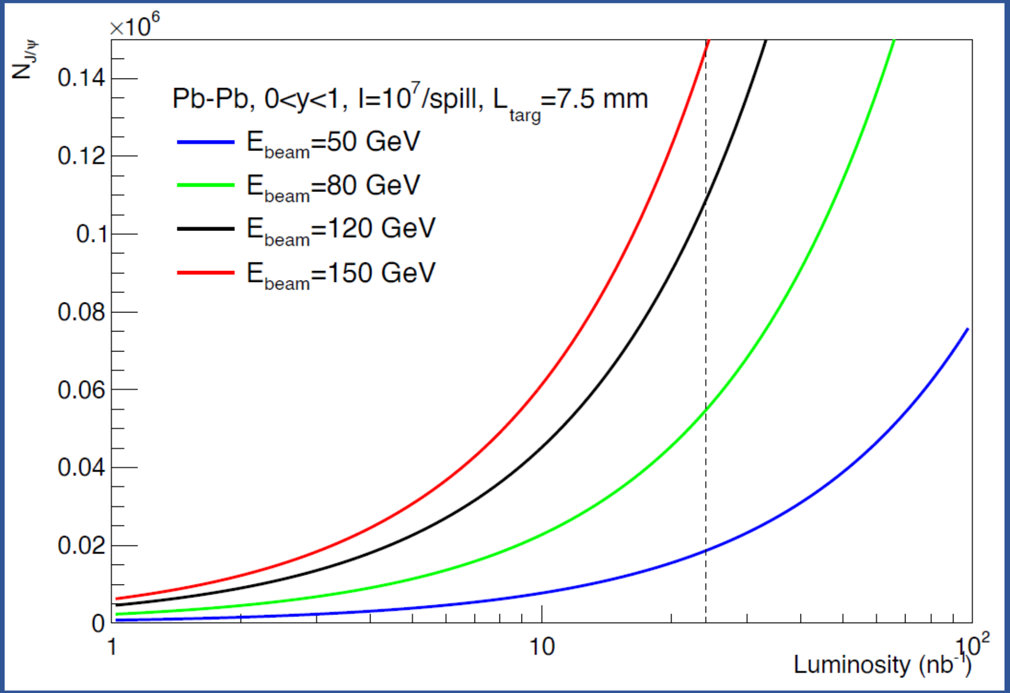
- Detect **modification of continuum** in $1<m_{\mu\mu}<1.4$ GeV, related to chiral symmetry restoration

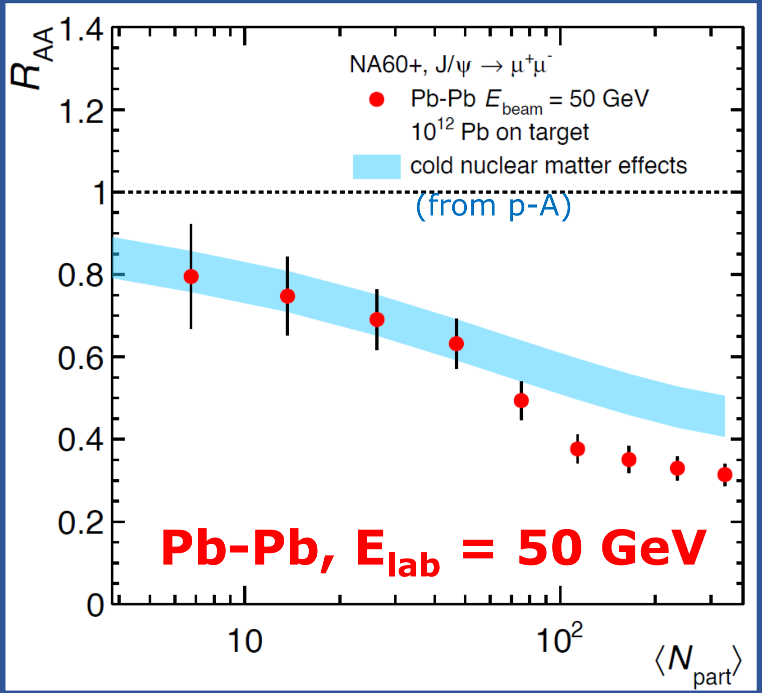
R. Rapp and H. van Hees,PLB753 (2016) 586



- Comparison of spectra ($\sqrt{s_{NN}}$ = 8.8 GeV), based on the assumption of no chiral mixing, with expectation of full chiral mixing
- Statistical and systematic uncertainty provide a very good sensitivity to an **increase of the yield due to chiral mixing of ~20–30%**

Physics performance: charmonium





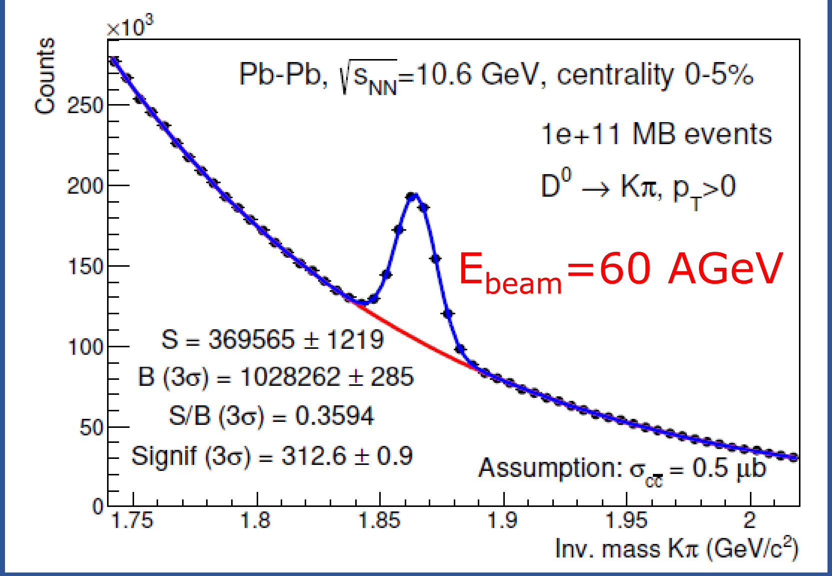
- 7.5mm Pb target and 1 month data taking
  → L_{int} = 24 nb^{-1}
  Can aim at
  - **~O(10^4) J/ψ at 50 GeV**
  - **~O(10^5) J/ψ at 158 GeV**

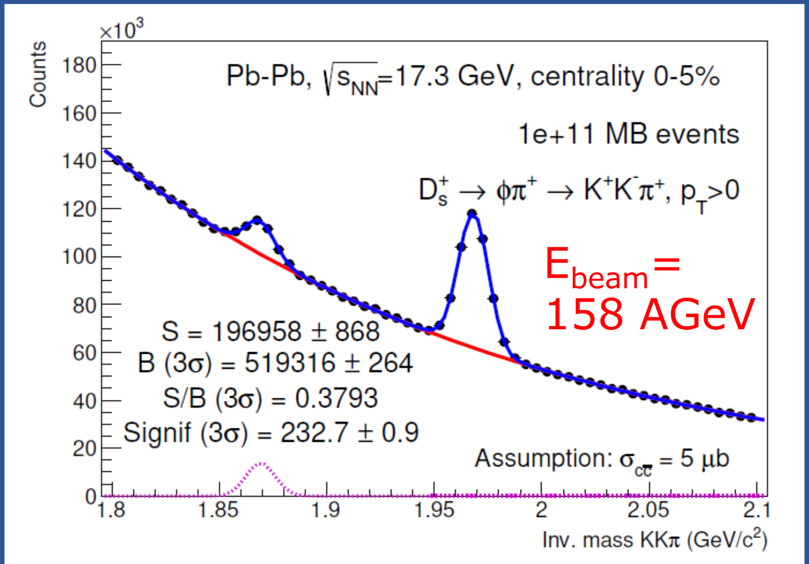
- Detection of **onset of anomalous suppression** effects down to low SPS energy
- **p-A data taking mandatory** to calibrate CNM effects
- **ψ(2S)** also within reach, down to E=100-120 A GeV

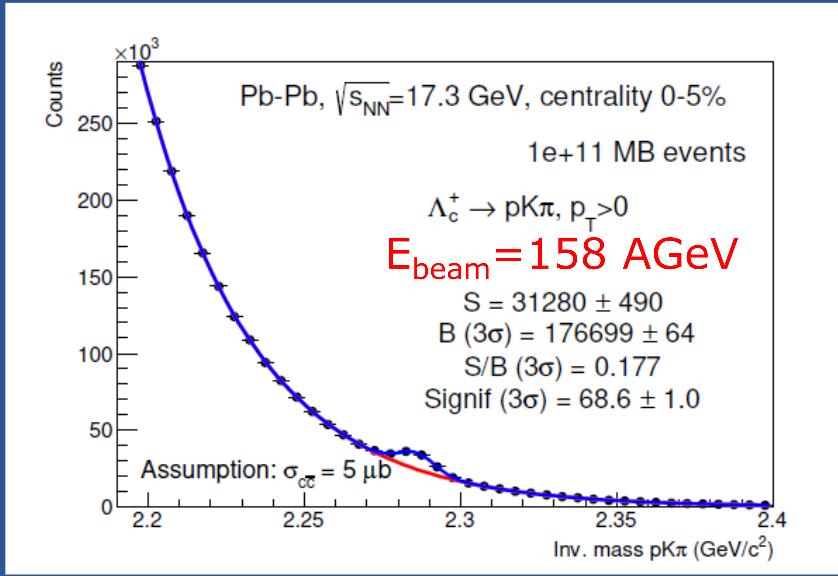
- NA60+ is also ideally placed to look for signals of **intrinsic charm** in p-A collisions, which are pushed much closer to midrapidity wrt collider energies

Physics performance: open charm

- Combine tracks in the vertex spectrometer only, apply topological cuts
- 10^{11} minimum bias Pb-Pb collisions: >$3\cdot10^6$ reconstructed D^0 in central Pb-Pb at $\sqrt{s_{NN}}$=17.3 GeV
  - **D^0** accessible also at lower collision energies with statistical precision at the percent level
    → R_{AA}, v_2, constrain the **charm diffusion coefficient**, thermalization of charm in short-lived QGP
  - Measurement of **D_s and Λ_c yield feasible** with statistical precision of few percent
    → strange/nonstrange and baryon/meson ratio, insight on **hadronization mechanism**



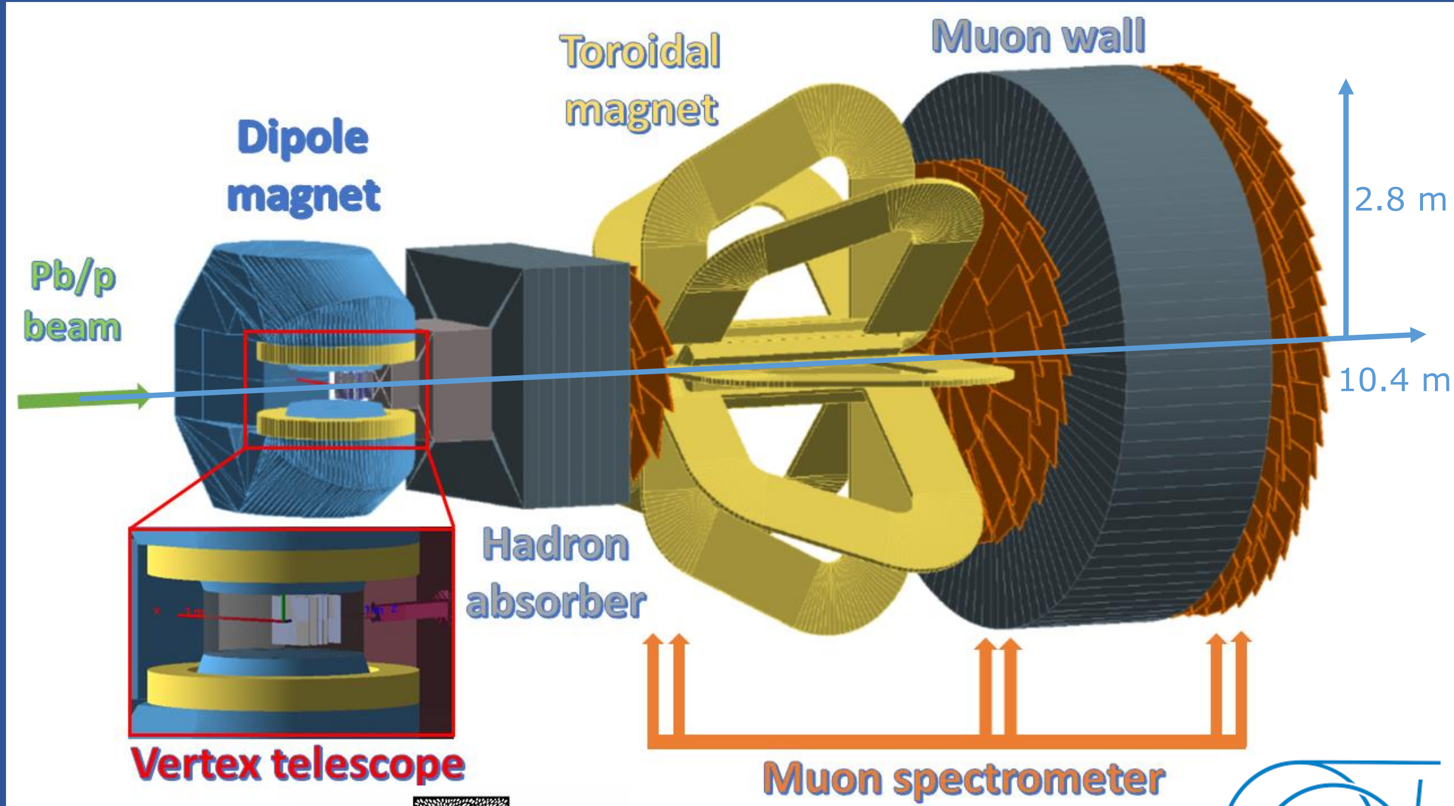




$D^0 \to K\pi$ **$D_s^+ \to \Phi\pi \to KK\pi$** **$\Lambda_c^+ \to pK\pi$**

Similar technique allows measurements of **hyperons and hypernuclei**

Formal steps (until now)

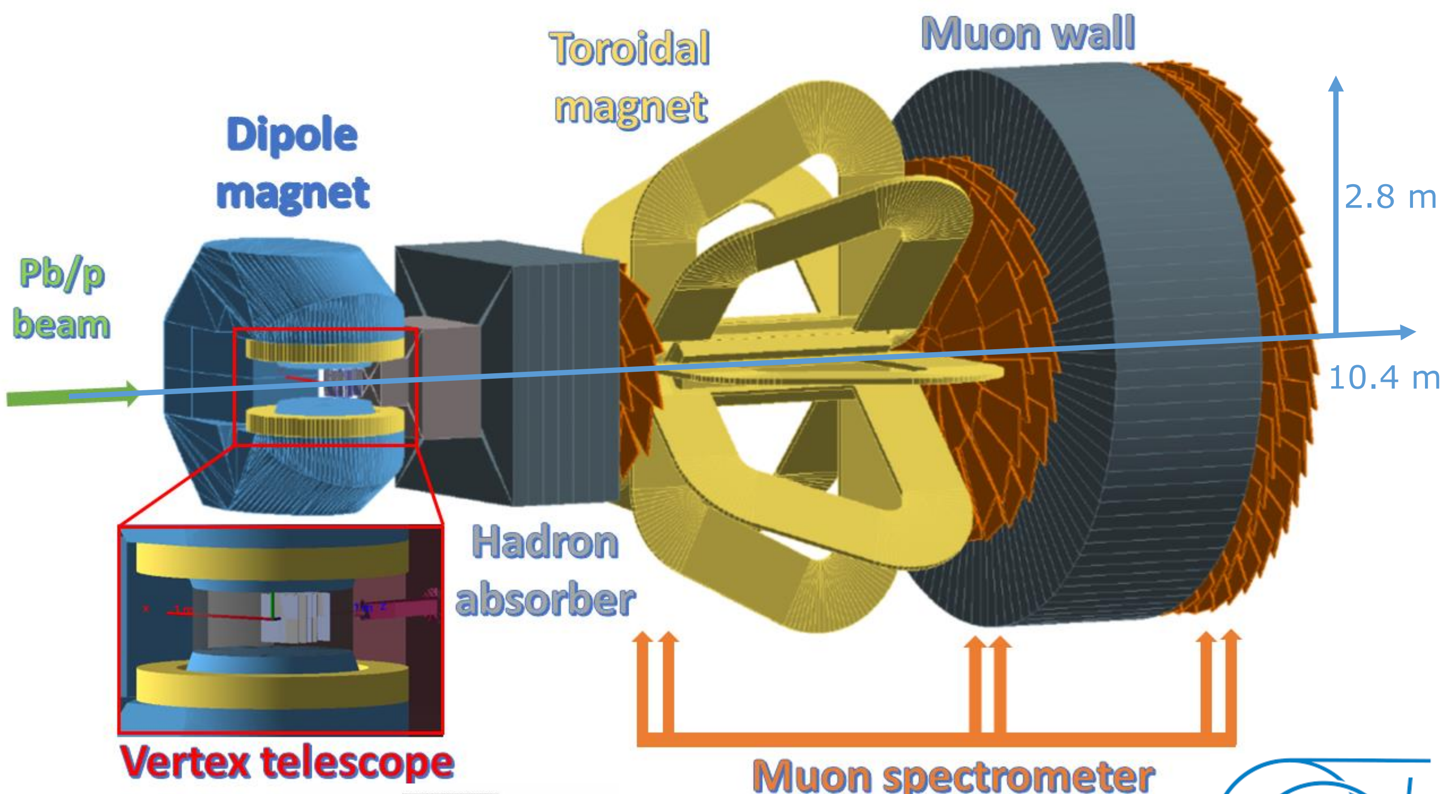


- Project developed in the frame of the CERN **"Physics beyond colliders"** Initiative, from 2016
- **Expression of Interest** prepared in 2019
https://cds.cern.ch/record/2673280
- **Letter of Intent** submitted in 2022
http://arxiv.org/abs/arXiv:2212.14452

LoI presented at the CERN SPSC in February 2023 → Favorable feedback!

> The SPSC **recognizes** the fundamental interest of the measurements proposed by the NA60+ collaboration, which are focused on electromagnetic and hard probes of the quark gluon plasma at high baryochemical potential. In order for the project to proceed with the suggested roadmap (starting construction in 2026 and data taking in 2029), the SPSC **would expect to start examining** a proposal by 2024.

Formal steps (to come)



- ❑ 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)
- ❑ **Proton beams** for reference and dedicated p-A studies

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

Conclusions

- There is ample margin for a **physics program at CERN SPS energy**, devoted to the study of hard and electromagnetic probes

- **NA61/SHINE** is breaking the ground with a first measurement of open charm cross section in Pb-Pb collision (top and possibly low-energy) → 2022-2025

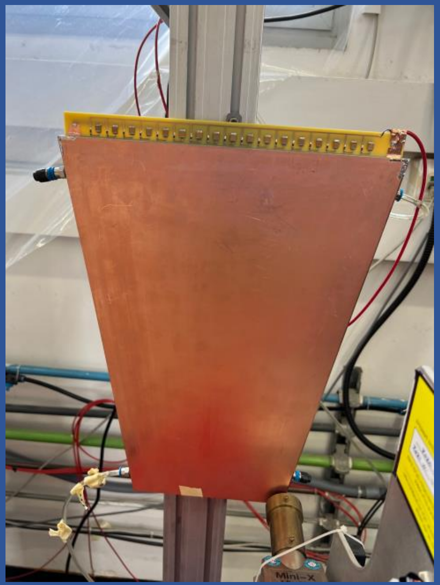
- A new project, **NA60+**, is aiming at a systematic and accurate study of hard/e.m. observables with (di)muons and hadron production, from 20A GeV to 150AGeV → from 2029

- The approval and construction of a new experiment at CERN is not a trivial task!
- Can succeed only if
  - **The heavy-ion community (also theory) actively supports the project**
  - **Further groups join the effort!** Still ample space for decisive contributions on all items: gas tracking detectors, MAPS, magnet, trigger, DAQ,…
- May represent an excellent testbench for detectors to be used at future facilities

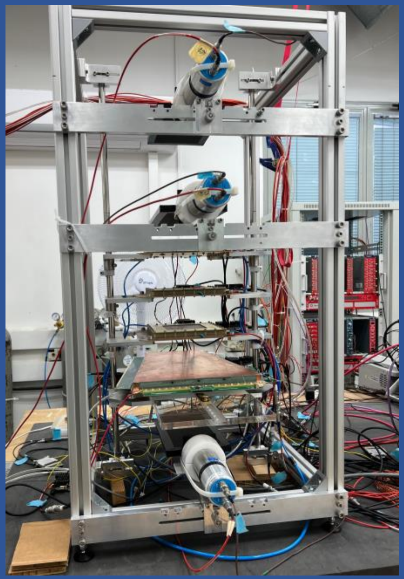
Backup

The NA60+ muon spectrometer R&D

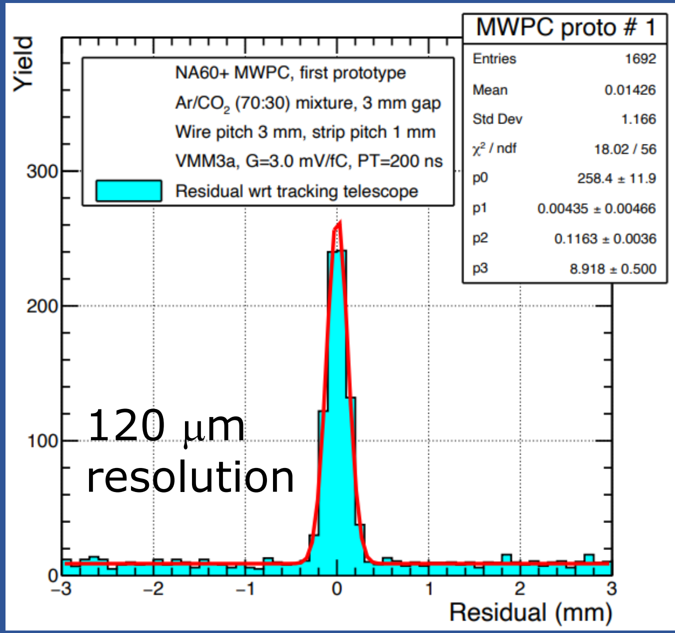
- ❑ First prototype of a **MWPC module built and tested**



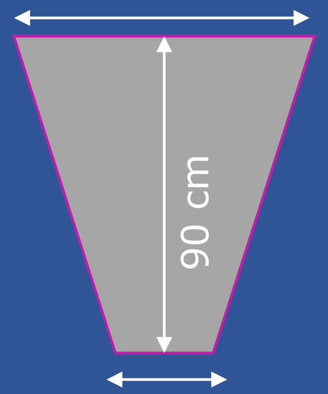
Prototype



Cosmic testbench



Collaborating institutes have availability of large facilities for **the production** of the detector modules for the NA60+ muon spectrometer

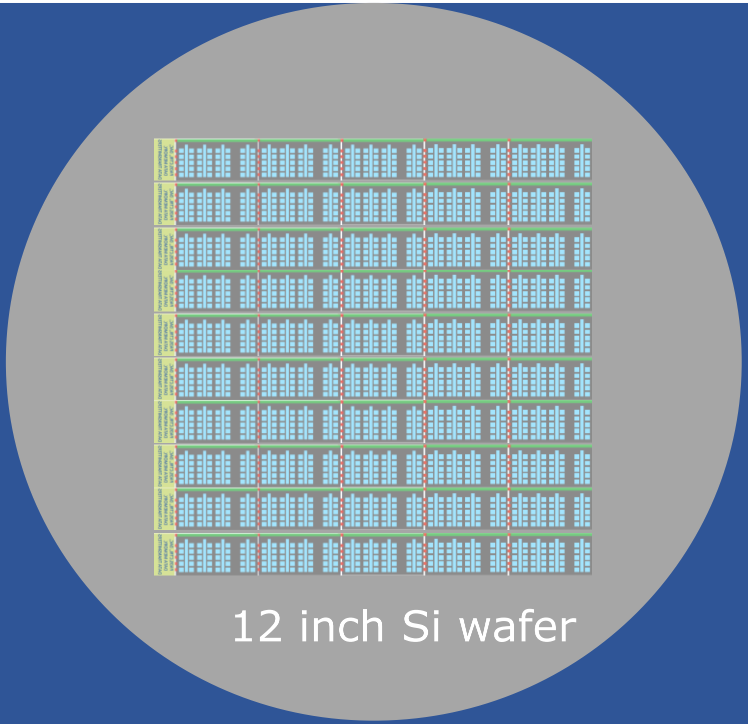


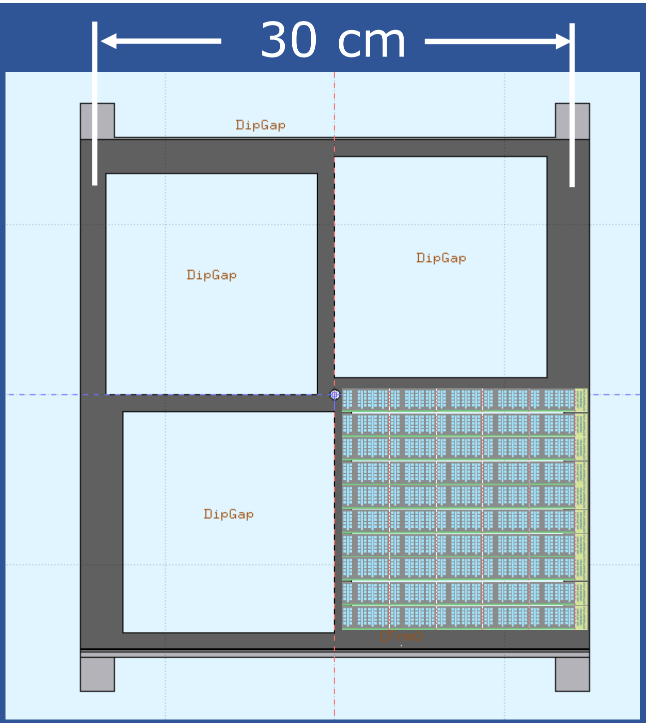
- ❑ Ongoing discussions on the final set-up of the spectrometer, various possible solutions, as
  - ❑ GEM technology for upstream stations (MS0-MS1)
  - ❑ MWPC technology for downstream stations (MS2-MS5)

R/O electronics likely to be based on the **VMM3a ASIC,** interface card to be designed

The NA60+ vertex telescope R&D

- Sensor based on 25 mm long units, replicated several times through stitching → up to 15cm length for NA60+





R&D in progress
Common development
ALICE ←→ NA60+
(same timeline!)

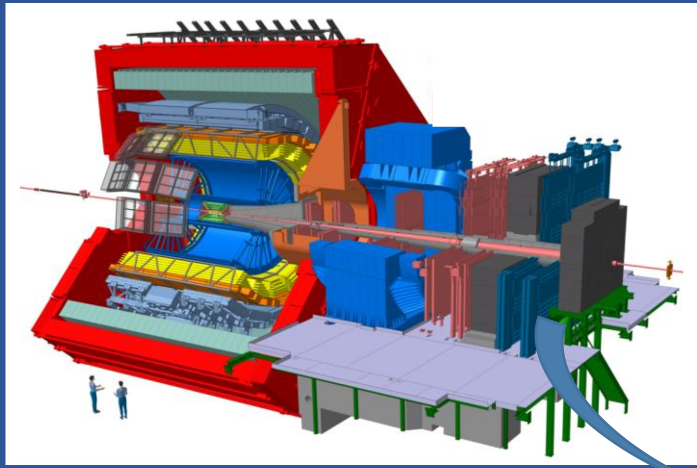
State-of-the-art imaging technology
TowerJazz 65 nm

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

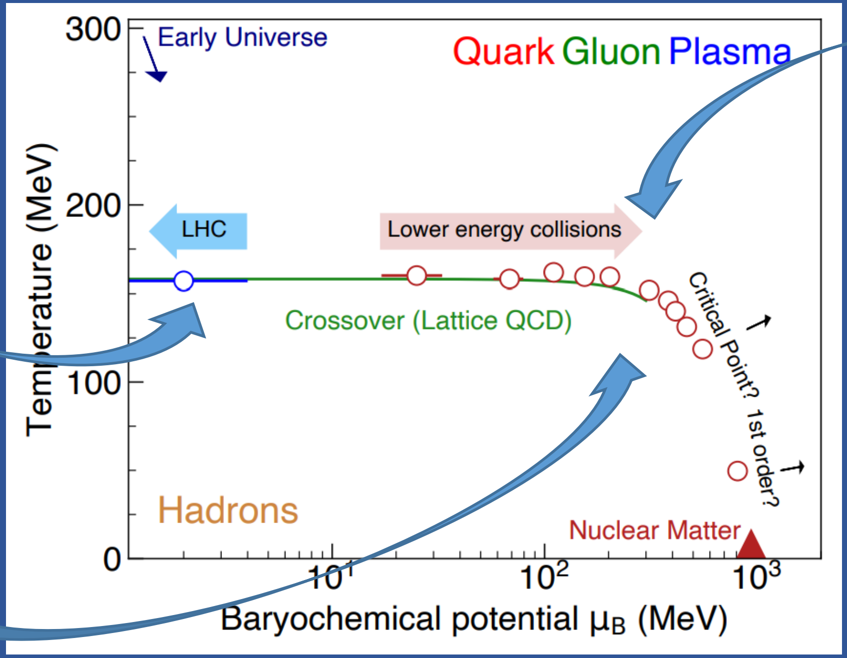
Spatial resolution **≤ 5 μm**

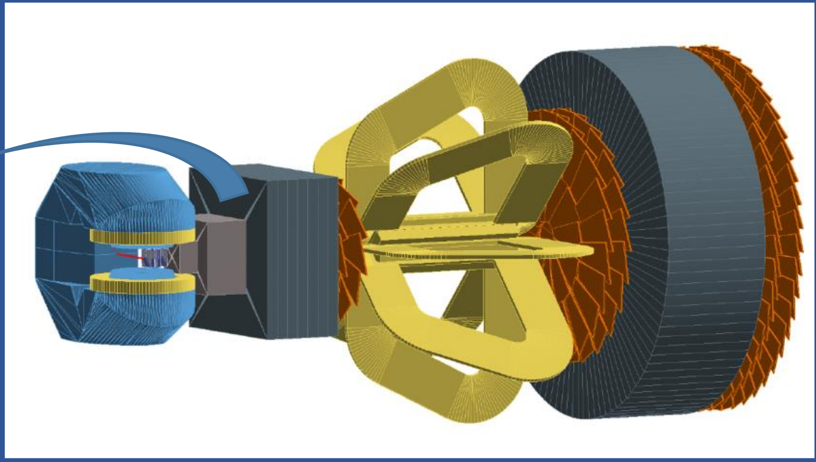
Cooling studies (NA60+ geometry)
→ **airflow+water**

A new heavy-ion experiment at CERN

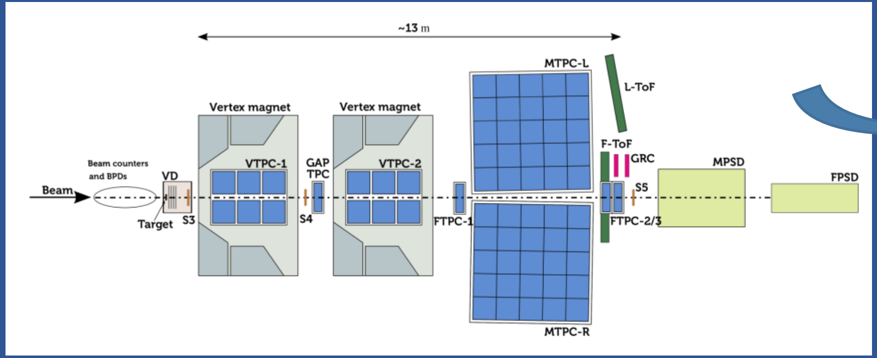


ALICE: general purpose HI detector at LHC: study high T, zero μ_B region (+ **ATLAS**, **CMS**, LHCb)





NA60+: high-μ_B studies of hard and electromagnetic probes of the Quark-Gluon Plasma at SPS energies



NA61/SHINE: (only) hadron detector at SPS: study intermediate T, finite μ_B region

Complete access to QGP-related observables in a wide range of T and μ_B

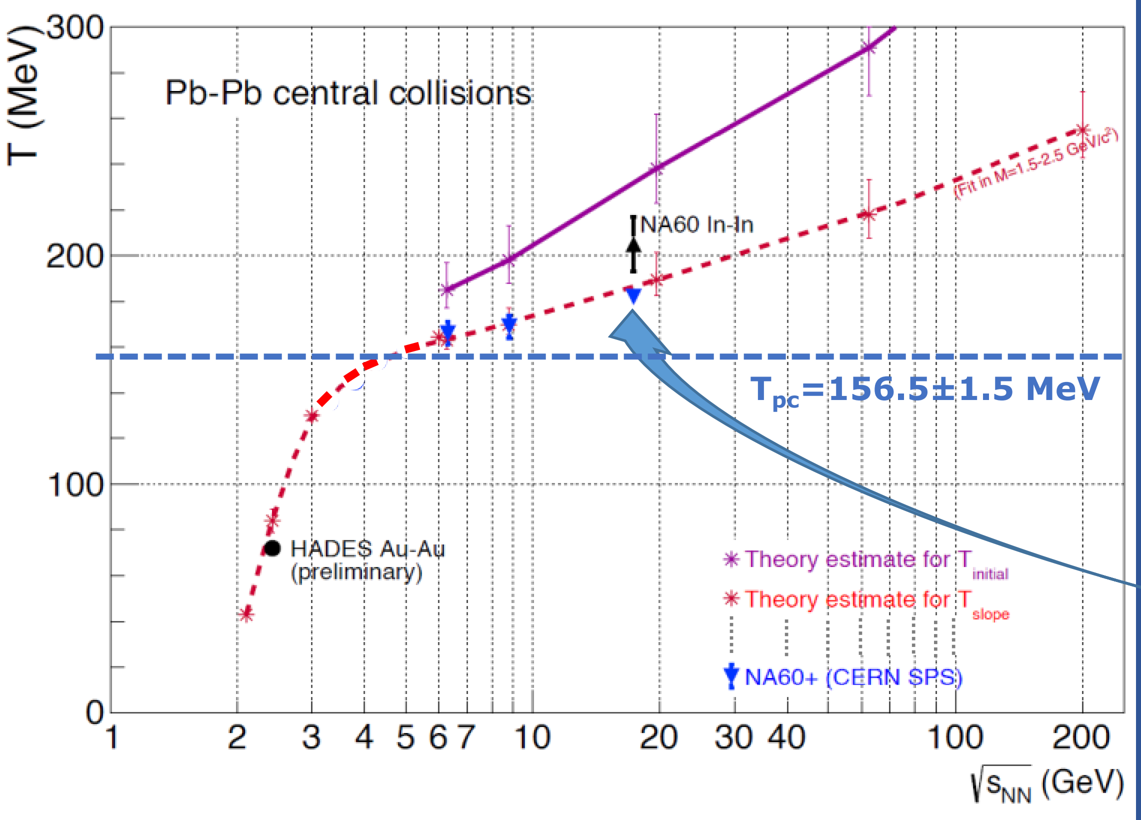
The NA60+ physics program

Several **new and unique measurements** in the region $6<\sqrt{s_{NN}}<17$ GeV ($20<E_{lab}<160$ AGeV)

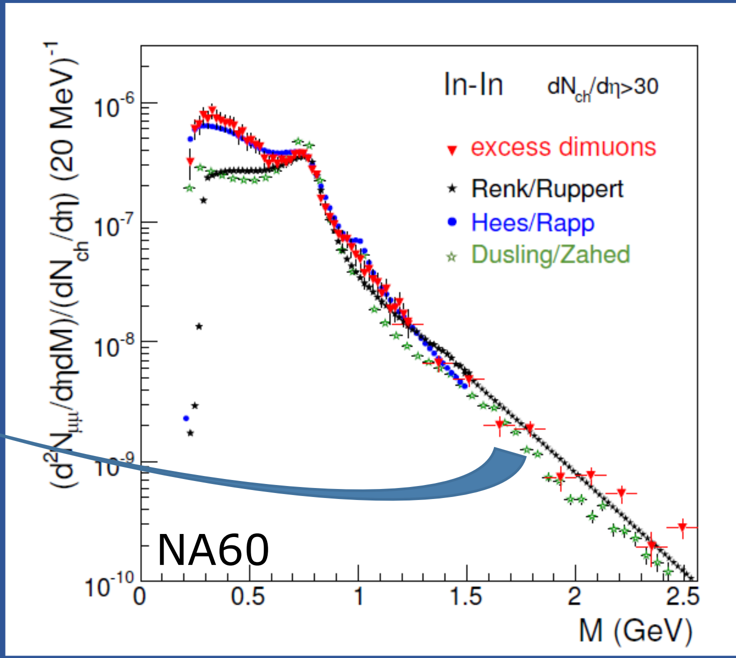
Caloric curve of QGP

1

Measurements only at top SPS energy and at very low energy



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

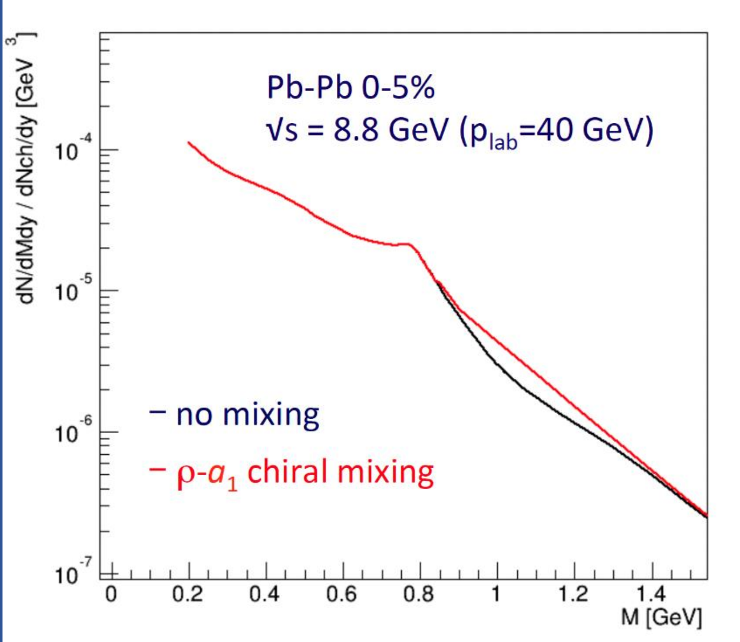


- ❑ Dilepton T_{slope} measurements → (average) **temperature of the early stage of the system**
- ❑ SPS energy → accurate information on the region close to the deconfinement transition temperature
  → possible signal of a **1st order phase transition**

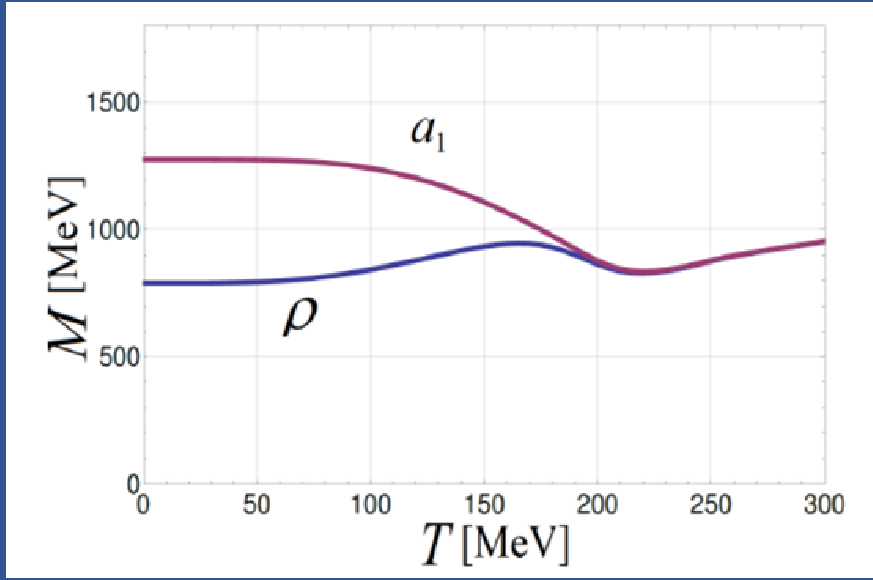
The NA60+ physics program

Several **new and unique measurements** in the region $6<\sqrt{s_{NN}}<17$ GeV ($20<E_{lab}<160$ AGeV)

- Mixing of vector (V) and axial-vector (A) correlators
  → **dilepton enhancement** for $m_{\mu\mu}$ ~ 1-1.4 GeV/c^2



R. Rapp and H. van Hees,PLB753 (2016) 586



Chiral symmetry restoration

2

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

- SPS vs LHC: low-energy measurement expected to be more sensitive to chiral restoration effects
  → (Exponential) thermal dimuon yield from QGP becomes smaller
  → Contribution from open charm becomes relatively negligible

No measurements available

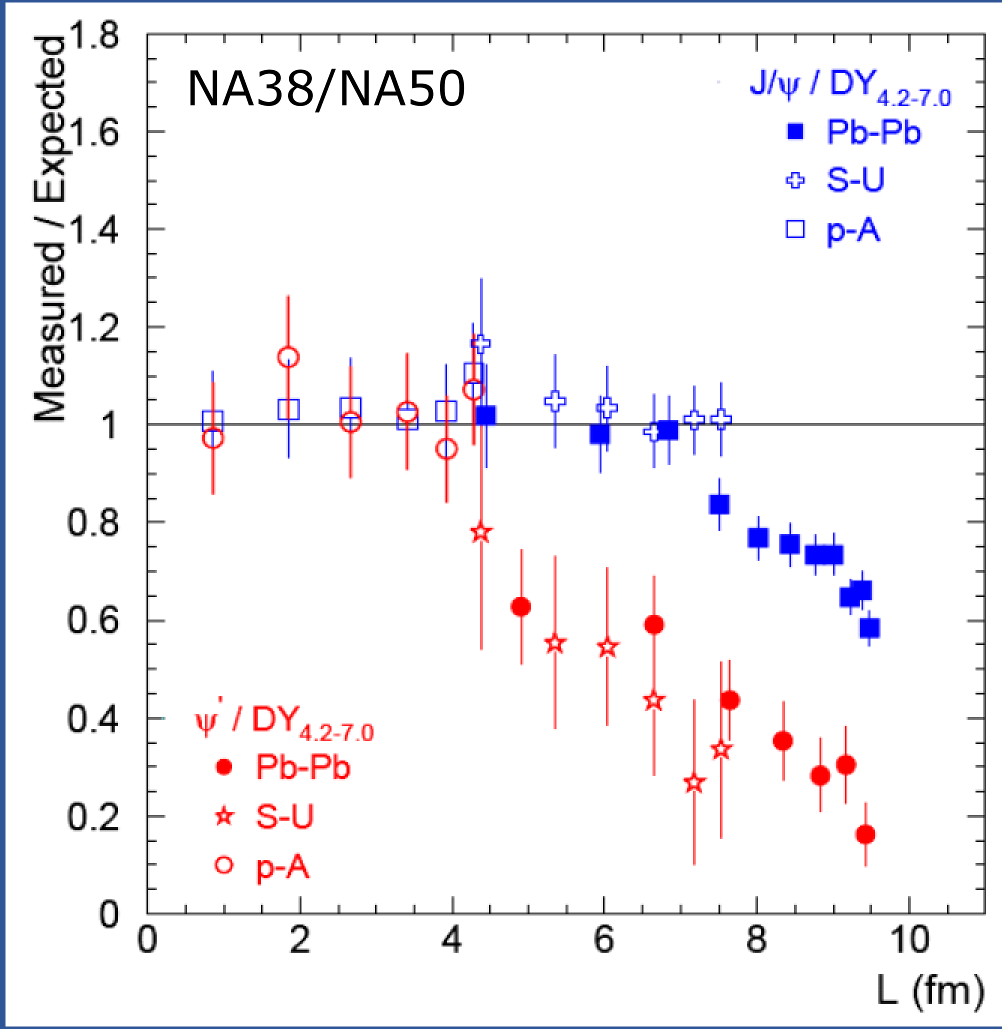
The NA60+ physics program

Several **new and unique measurements** in the region $6<\sqrt{s_{NN}}<17$ GeV ($20<E_{lab}<160$ AGeV)

No measurements below top SPS energy

Charmonium melting in the QGP

3



NA50, PLB 477 (2000) 28
NA50, EPJC49 (2007) 559

J/ψ

- 30% suppression for central Pb-Pb events at top SPS energy
  → Compatible with suppression of more weakly bound χ_c and ψ(2S) states decaying to J/ψ

ψ(2S)

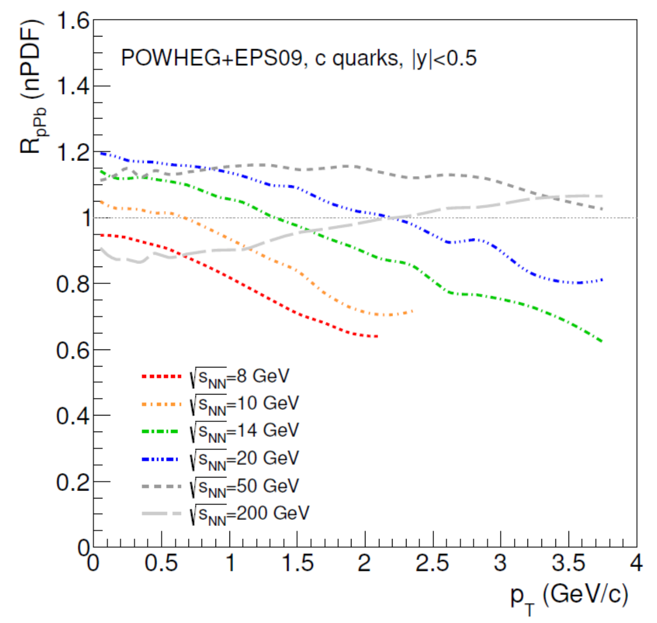
- Strong(er) suppression already in peripheral Pb-Pb collisions

- Energy scan towards low SPS energy
  → Detect **suppression threshold** and correlate with T via thermal dimuons

The NA60+ physics program

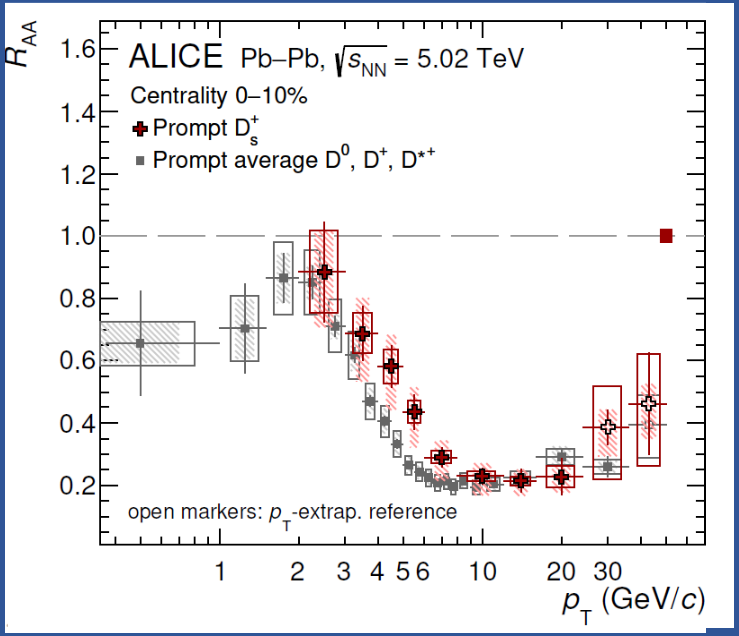
Several **new and unique measurements** in the region $6<\sqrt{s_{NN}}<17$ GeV ($20<E_{lab}<160$ AGeV)

- Charm production in **proton-nucleus**
  - → Sensitive to **nPDFs**
  - → $Q^2 \sim 10–40$ GeV^2 and $0.1<x_{Bj}<0.3$ ($p_T<3$ GeV/c) (from anti-shadowing to EMC region)



No measurements at SPS energy

- D-meson p_T-dep. suppression and azimuthal anisotropy
  - → Time spent in QGP and hadronic phase varies with $\sqrt{s_{NN}}$: constrain the charm diffusion coefficient
  - → **Do charm quarks thermalize** in a short-lived QGP ?
- D_s^+, Λ_c
  - → Hadronization studies (quark recombination)



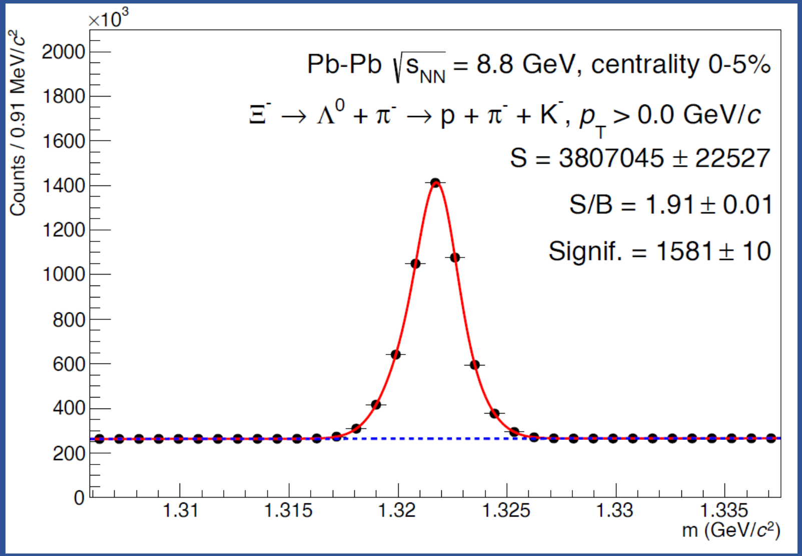
ALICE, PLB 827 (2022) 136986

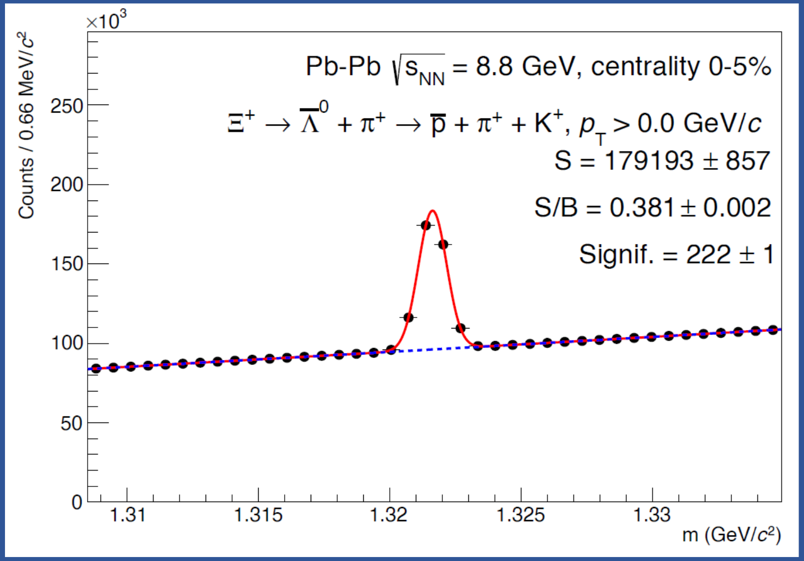
QGP transport coefficients and charm hadronization

4

Strangeness and hypernuclei

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

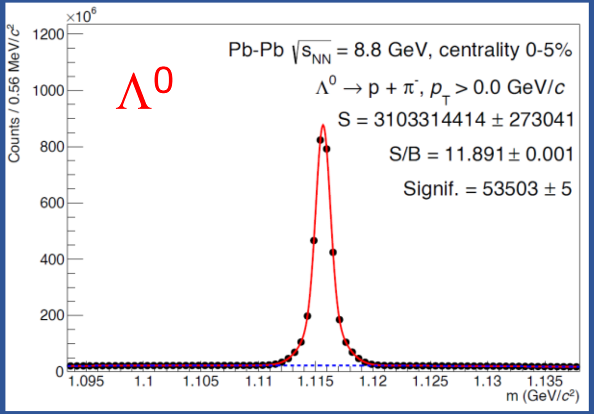
$\Lambda^0 \rightarrow p + \pi^-$ $\quad$ $\Xi^- \rightarrow \Lambda^0 + \pi^-$ $\quad$ $\Omega^- \rightarrow \Lambda^0 + K^-$

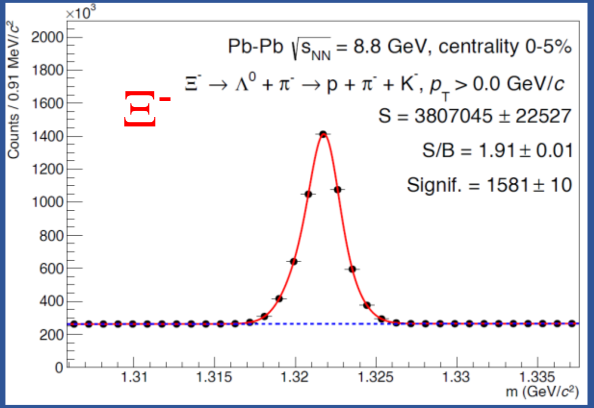
and charge conjugated

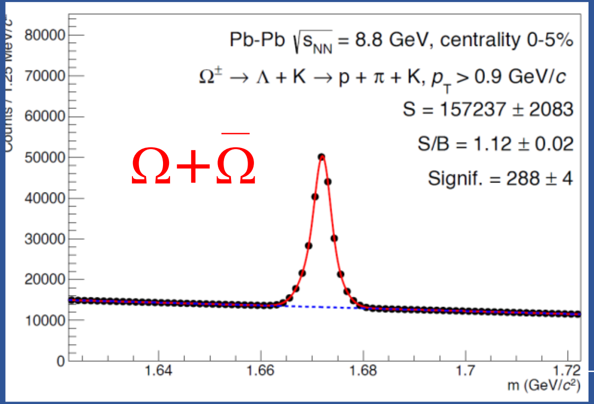
- ❑ **Topological selections** applied
- ❑ **BDT employed to enhance the significance of the signal**
- ❑ Among the variables:
  - ❑ Product of the impact parameter of decay tracks,
  - ❑ Distance of closest approac between the decay tracks
  - ❑ Decay length and the cosine of the pointing angle

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

Physics performance: strangeness and hypernuclei

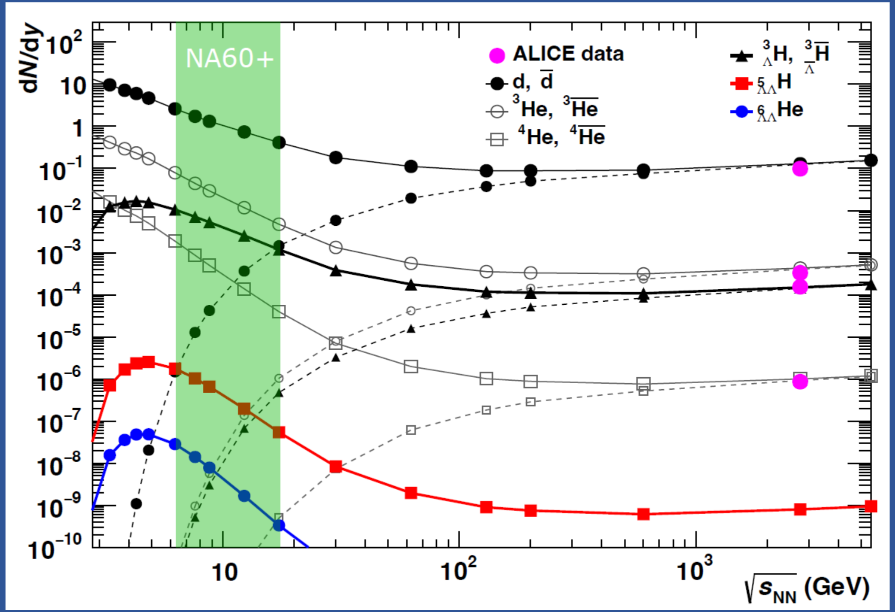




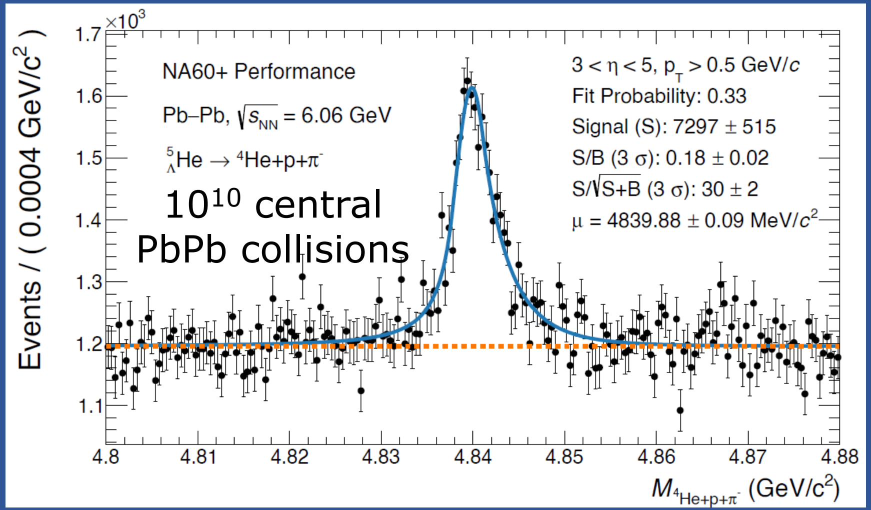


- **Topological selections with BDT** employed to **enhance the significance** of the signal
- Among the variables:
  - Product of the impact parameter of decay tracks
  - Distance of closest approach between the decay tracks
  - Decay length and the cosine of the pointing angle

- Also $\phi \rightarrow KK$ and $K_s \rightarrow \pi\pi$ have been studied



Low energy HI collisions → **high baryon density** favours the production of hypernuclear clusters



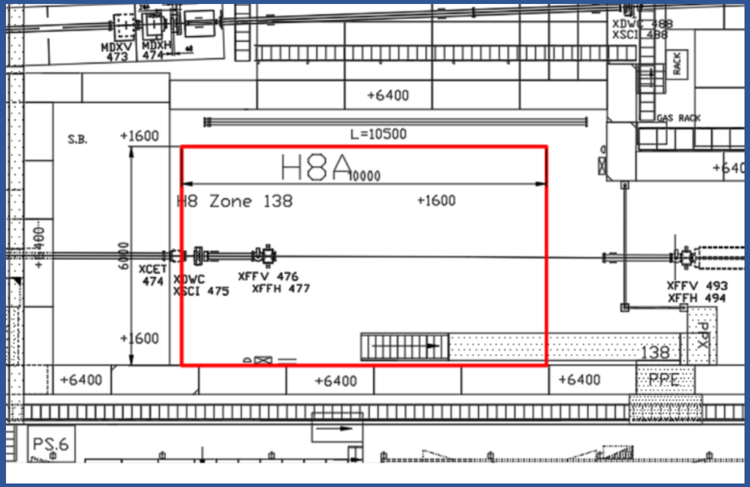
Separation of heavily ionising particles from ordinary hadrons → **size of the clusters** associated with the track

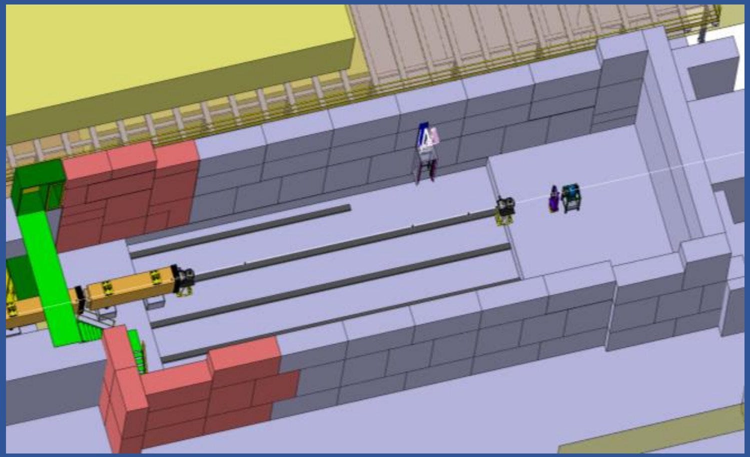
Integration

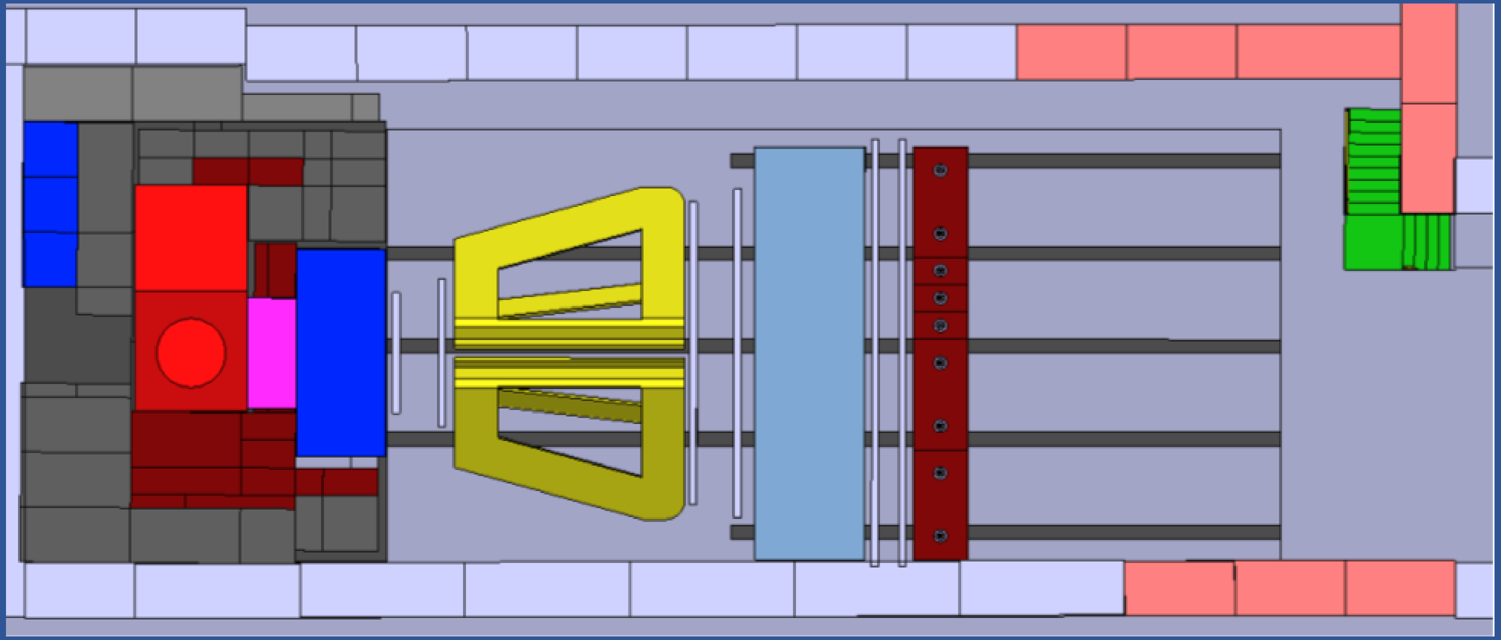
NA60+: where

Physics Beyond Colliders

- Thorough studies carried out in 2020/2021 thanks to **PBC support**, with the decisive help of the **CERN-BE-EA group**
  → integration feasible in the PPE138 area on the H8 beam







Need rail installation (muon spectrometer shifting) and a possible floor excavation due to the current vertical position of the beam line

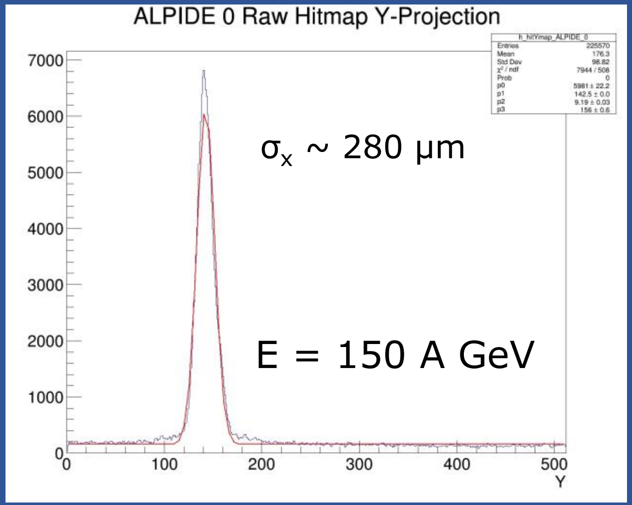
NA60+, NIM A1047 (2023) 167887

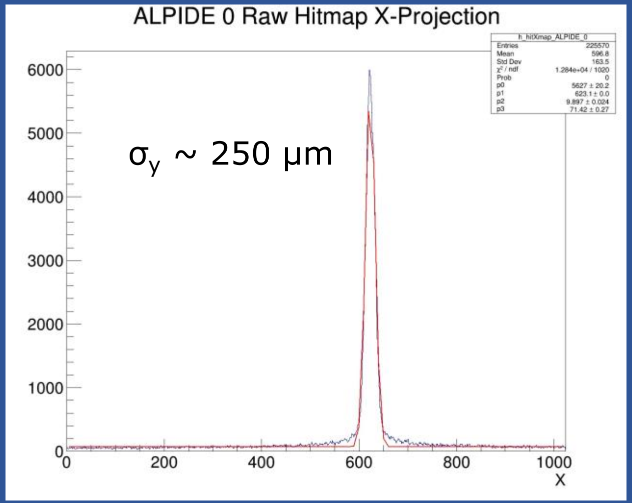
NA60+: beam studies R&D

- A **high-intensity Pb beam** (~10^6/s) is needed, from 20-30 A GeV to 160 A GeV
- Beam optics studies carried out to provide sub-mm beam all over the energy range

Goal

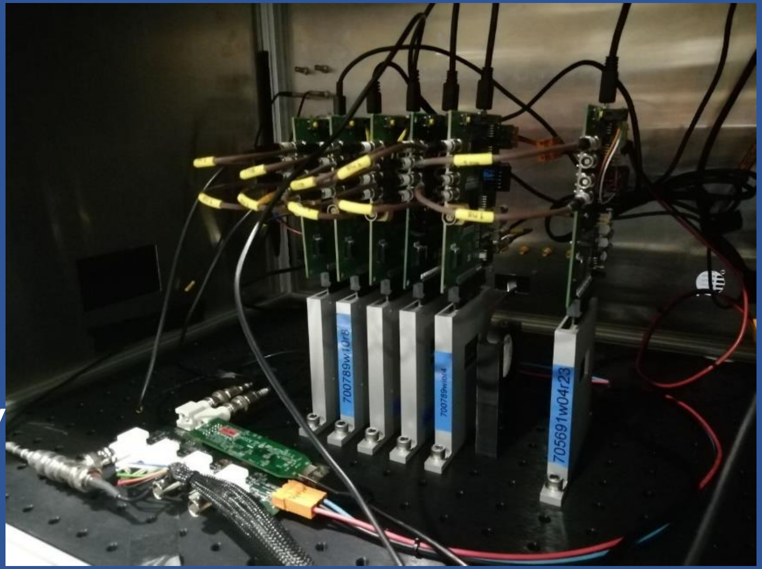
Parameter in zone 138	160 GeV/c	30 GeV/c
σ_x (mm)	0.19	0.33
σ_y (mm)	0.19	0.36
Transmission from T4 (%)	32.43	23.5





N.B.: Vertex spectrometer central hole, ∅ ~ 0.6 cm

A first **test beam in PPE138** was carried out in November 2022, using a telescope of pixel sensors for a precise measurement



Result already promising, further tests needed
→ Lower beam energy
→ Higher beam intensity (now ~10^4 s^{-1})

Pb beam also in fall 2023

NA60+, NIM A1047 (2023) 167887

NA60+: beam requests

- Our plan is to run each **~ 1month/year with Pb ions** at a different energy, using a **~10^6 s^{-1} beam**
  - Start at top energy, to have a calibration point for observables already studied at that energy
  - At 20 A GeV two months of data taking can be necessary to fulfil the physics program
  - The order of the beam energies is tentative and could be adjusted following the results

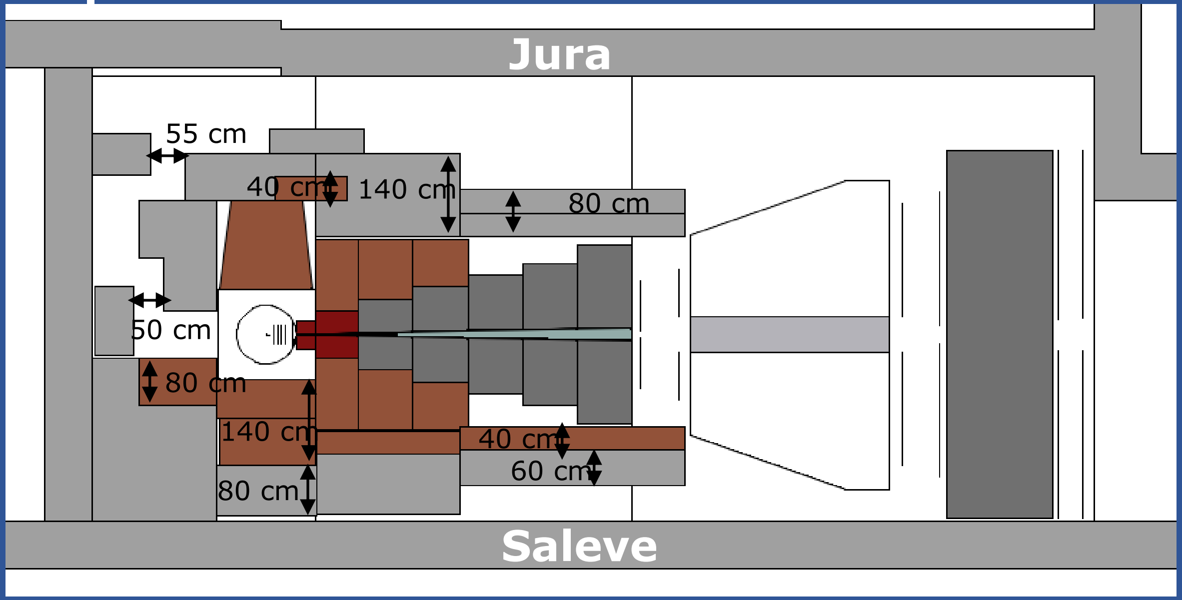
	Year 1	Year 2	Year 3	Year 4-5	Year 6	Year 7
Beam energy (A GeV)	160	40	120	20 (30)	80	60
Momentum per charge (GeV/c/Z)	406	101	304	50.7 (76.1)	203	152
Pb ions on target	$\sim 10^{12}$ per energy ($\sim$ 30 days)					
protons on target	$5-6 \cdot 10^{13}$ per energy ($\sim$ 22 days)					

- Corresponding periods with **proton beams** at the same energy are also needed
  - Reference for Pb-Pb results
  - Specific studies with p-A collisions
- Integrated luminosity per N-N collision similar for p-A and Pb-Pb
- Beam intensity ~8x10^8/spill, 3000 spills/day (preliminary estimate)

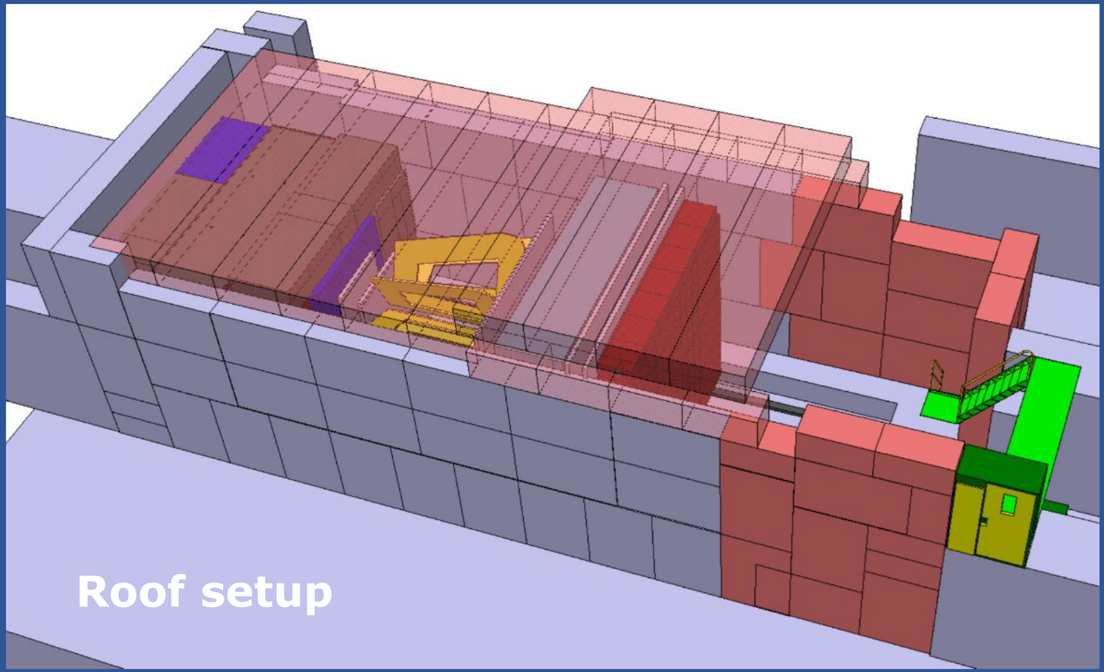
RP studies

Using a high-intensity beam in the EHN1 surface zone poses non-negligible **radioprotection issues**
→ Thorough studies carried out by the **CERN-HSE** group

Top view



Prompt ambient dose, residual ambient dose, air activation and accidental beam loss scenarios were studied



A **massive shielding** around the absorber region, where the beam will be dumped, has been designed

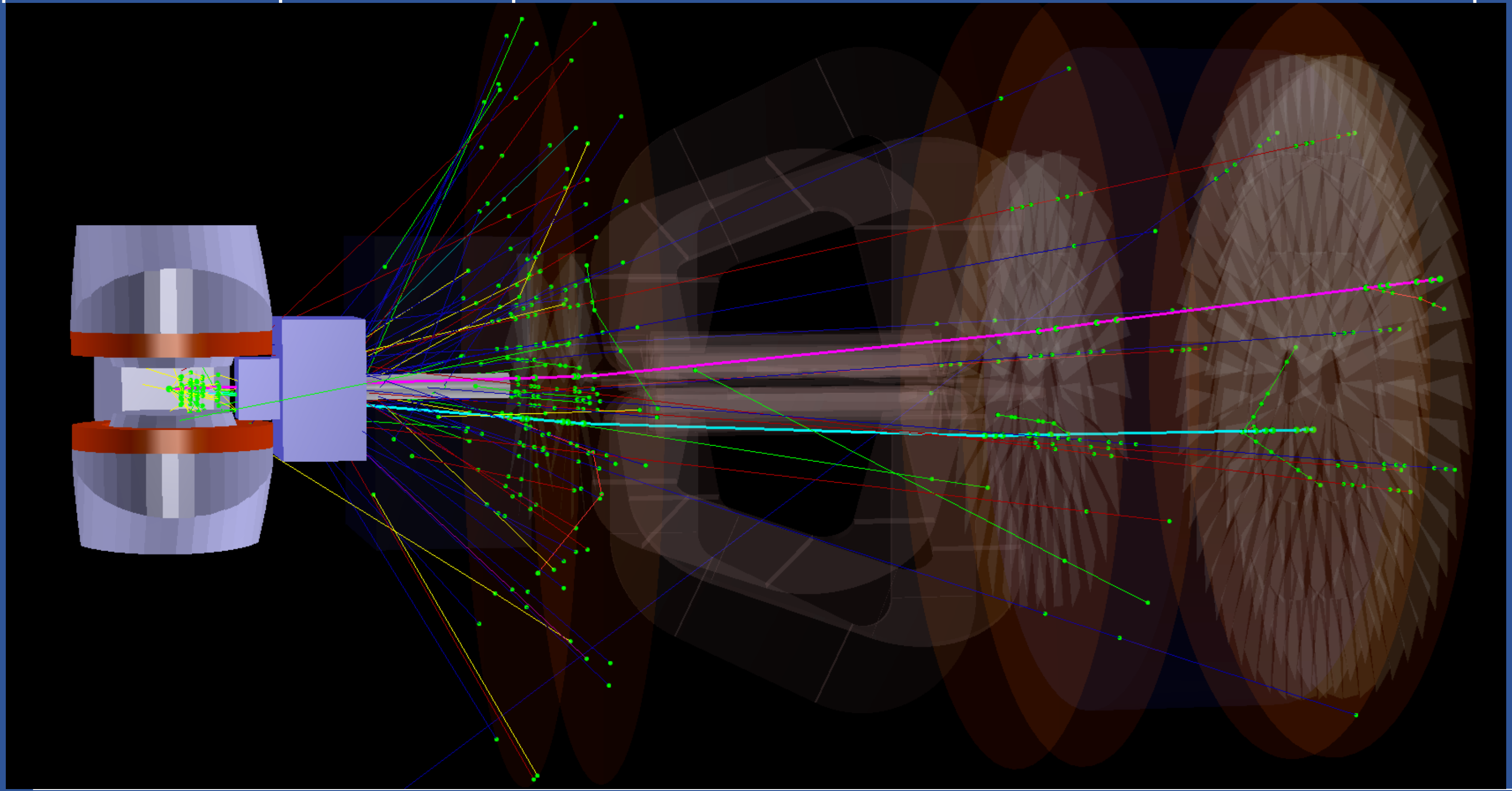
Physics performance: dimuons

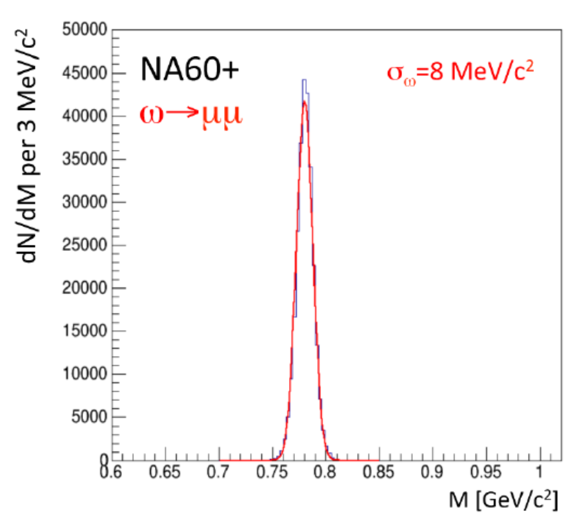
Track matching: measure muon kinematics before multiple scattering and energy loss

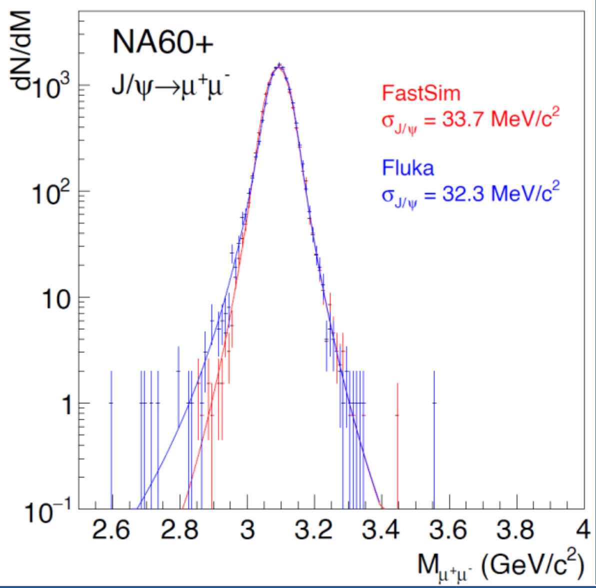
Track matching

Vertex tracking (dipole field)

Muon identification in the spectrometer (toroidal field)







Collaboration institutes

Appendix: NA60+ Collaboration

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

1 .European Organization for Nuclear Research (CERN), Geneva, Switzerland
2 .Dipartimento di Fisica dell'Università di Cagliari, Cagliari, Italy
3 .INFN, Sezione di Cagliari, Cagliari, Italy
4 .INFN, Sezione di Padova, Padova, Italy
5 .INFN, Sezione di Torino, Turin, Italy
6 .Dipartimento di Fisica dell Università di Torino, Turin, Italy
7 .Department of Particle Physics and Astrophysics, Weizmann Insitute of Science, Rehovot, Israel
8 .Kyiv Institute for Nuclear Research (KINR), Natl. Acad. of Sci. of Ukraine (NASU)
9 .Dipartimento DISAT del Politecnico di Torino, Turin, Italy
10 .Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale, Alessandria, Italy
11 .Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, New York, USA
12 .Department of Radiation Oncology, University of Groningen, Groningen, The Netherlands
13 .Department of Physics and Astronomy, Rice University, Houston, Texas, USA
14 .Dipartimento di Fisica e Astronomia dell'Università di Catania, Catania, Italy
15 .INFN, Laboratori Nazionali del Sud, Catania, Italy
16 .INFN, Laboratori Nazionali di Frascati, Frascati, Italy
17 .Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, Texas, USA
18 .Institut de Physique des 2 Infinis de Lyon, Université de Lyon, CNRS/IN2P3, Lyon, France

- The LoI was signed by 62 physicists/engineers/technicians representing institutions in
  - **Italy** (Cagliari, Padova, Torino)
  - **Israel** (Weizmann)
  - **USA** (StonyBrook, Rice)
  - **France** (Lyon)
  - and **CERN**
- Support also from prominent members of the QGP theory community
- **Funding for the R&D phase** since 2020 allowed us to complete the LoI preparation
- Contacts ongoing to **strengthen the Collaboration** on specific items and reach critical manpower level

Cost estimates

- Final definition of the set-up details still in progress
- Estimate of costs related to data acquistion, storage and computin is still in progress
- Current evaluation subject to oscillation in the cost of raw materials, electronic, etc.
- Assume 1 Euro ~ 1 CHF ~ 1 US$

PRELIMINARY

Sub-system	Estimated cost (MCHF)
Vertex spectrometer	2.5 – 3.1
Muon spectrometer	2.7 – 4.0
Toroidal magnet	3.8
RP monitors, Shielding	1.5
Total	10.5 – 12.4

Table 17: Estimated costs of the various NA60+ subsystems.

Toroid

Estimated cost (MCHF)	
Copper Conductor	0.6
Manufacturing of coils	1.7
Power converter (confirmation ~1/8)	0.8
Mechanical structure	0.4
Cooling system	0.3
TOTAL	**3.8**

MAPS

	kCHF
Engineering runs	600-1200
Wafer post-processing	300
FPC and wire bonding	200
Mechanical support	200
Cables, patch panels	300
Readout and power distribution	900
TOTAL	2500-3100

Muons

All MWPCs

	kCHF
Detectors	500
FEE	1000
HV system	150
Mechanical support	750
Gas system	300
TOTAL	2700

MS0/1 GEMs

	GEM: kCHF
Detectors	530
Readout electronics	790
HV system	20
Mechanical support	50
Gas system	50
TOTAL	1,440

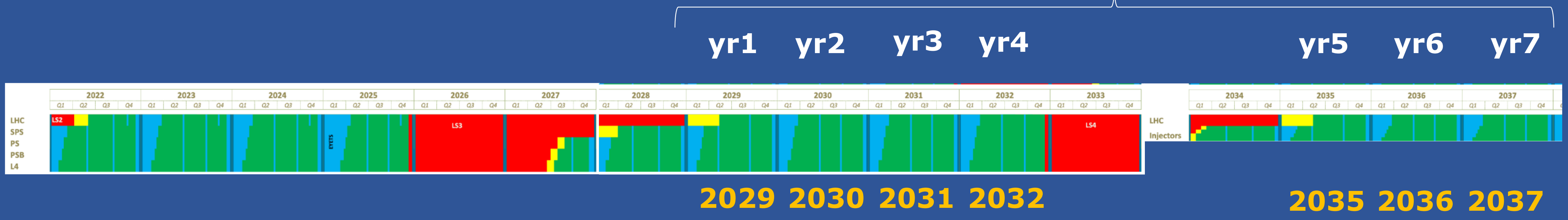
Timeline

- Project followed by PBC since 2016
- EoI in 2019
- LoI in 2022

Our current plan is to have the experiment on the floor by the end of LS3 → **2029**

- Possible roadmap
  - Technical proposal: **2024-2025**
  - Construction and installation: **2026-2028**

NA60+ data taking



To do list towards technical proposal

Muon spectrometer
- ❑ Beam tests on prototypes
- ❑ Finalize set-up and resolution (strip size) for MWPC and GEM detectors
- ❑ Define/design read-out electronics

Toroidal magnet
- ❑ Design of the full-scale magnet, based on expertise gained with prototype

Vertex spectrometer
- ❑ Continue R&D on MAPS development. N.B.: **same timeline as ALICE** for the final detector!
- ❑ Test first prototype of stitched MAPS detector
- ❑ Finalize test set-up with NA60+ geometry (dummy sensors), perform mechanics and cooling tests

Simulation, reconstruction, DAQ
- ❑ From fast simulation/reconstruction to final framework
- ❑ Define DAQ framework for the estimated trigger rate

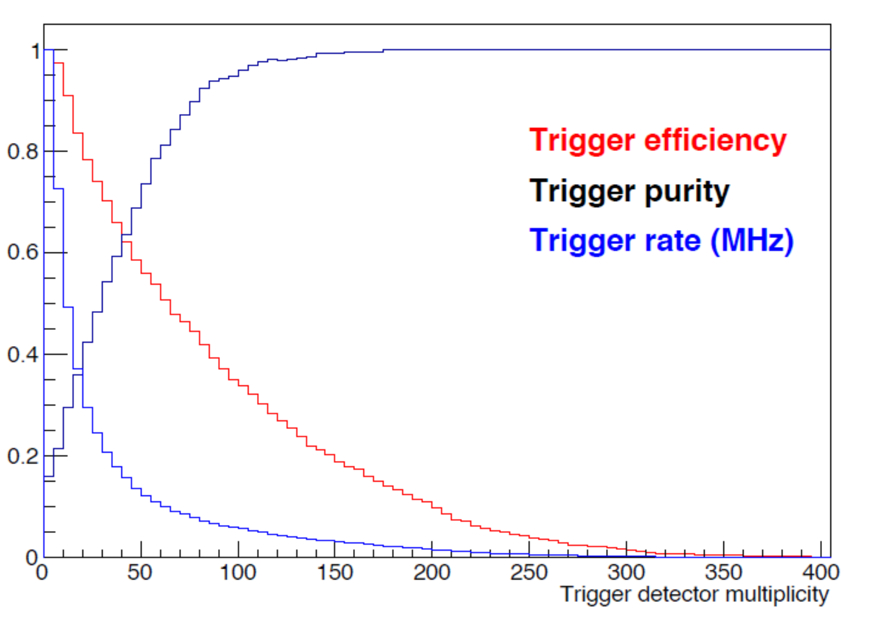
Based on this to do list, we estimate a 1.5-2.5 yrs timeline for the submission of TP

Trigger and DAQ

Data acquisition, processing, computing (1)

- **Data rate** dominated by the vertex telescope, for the assumed 10^6 ions/s Pb beam intensity,
  - → ~ **3.3 GB/s** data rate
  - → ~ 3.3 PB of data collected per year
- **δ-ray** production from non-interacting Pb ions (85% of the incident beam) significantly contribute to the data rate

- Consider to acquire data **triggered** by a fast scintillator close to the interaction region
  → increase purity at the price of discarding peripheral Pb-Pb events



selection,%	trigger rate, kHz	purity, %	hits readout per incoming ion	hits readout per trigger	readout rate, GB/s
50	100	80	300	2960	0.94
80	365	35	675	1541	2.1
100	1000	16	1030	1030	3.3

↑ Centrality selected

Data acquisition, processing, computing (2)

- **Offline data reconstruction**
  - → Use a modified version of the Cellular Automaton track finder developed for the ALICE ITS

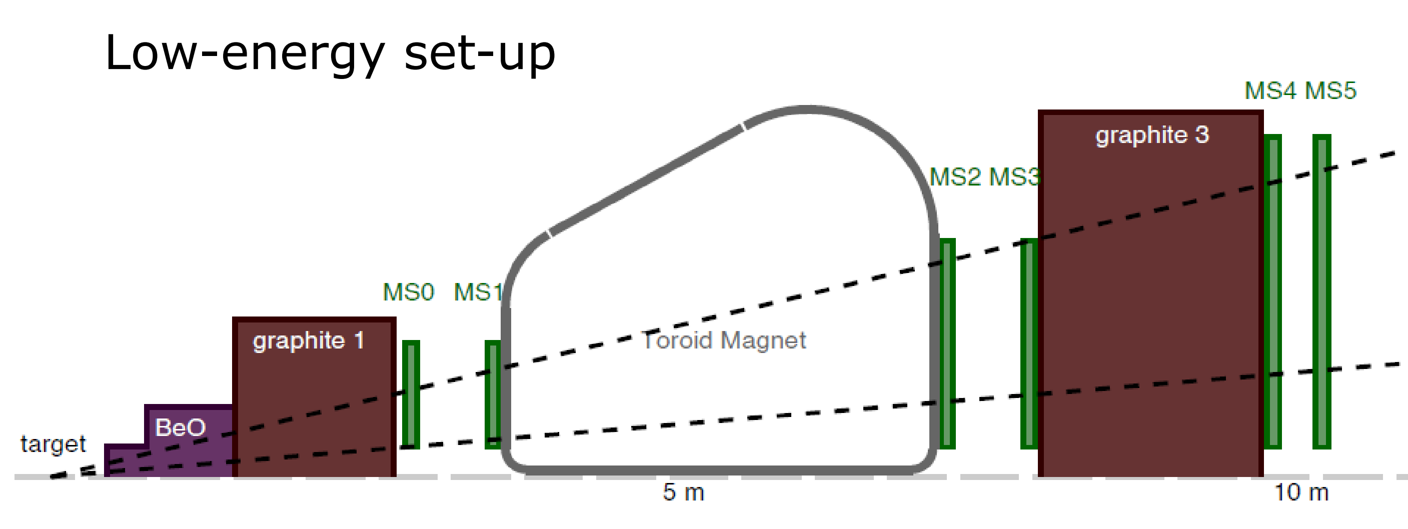
- **Data decoding and cluster-finding** require ~240 (~450) CPU seconds for 50% (80%) efficiency triggering scenarios, for 10^6 incoming ions ← preliminary!

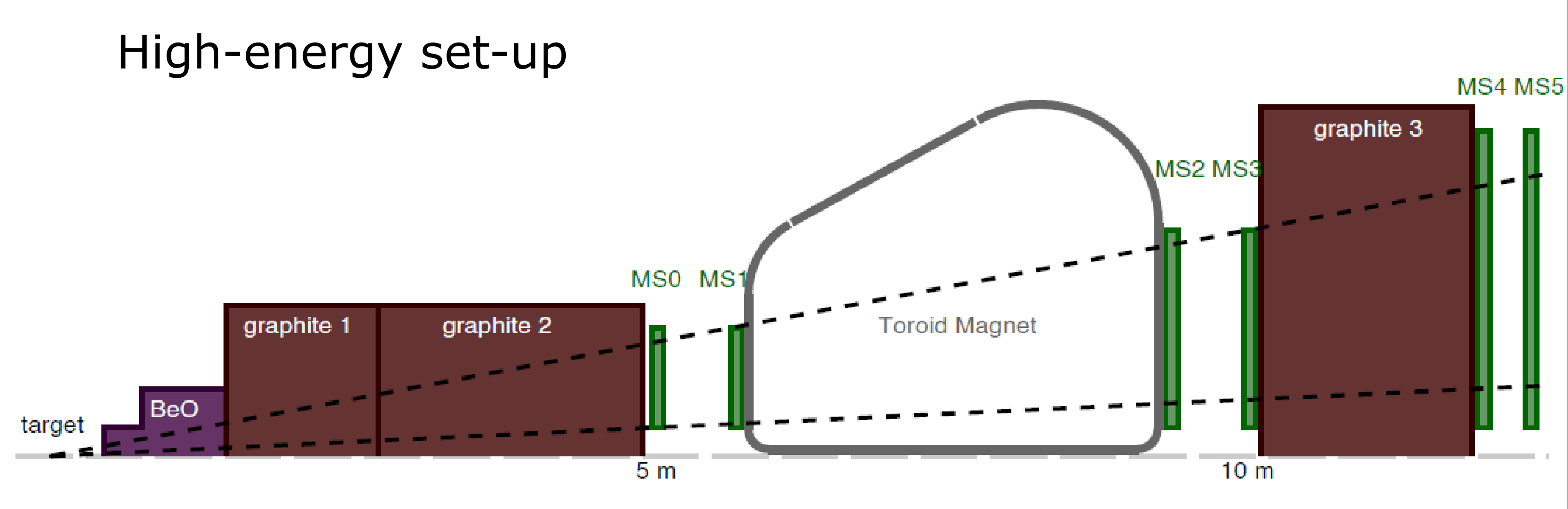
- Corresponding **track finding time** ~ 4200 CPU seconds (assume Intel i7-8700K @ 3.7 GHz processor)

- Data collected per heavy-ion run can be **fully processed in 2–3 months** by a farm of ~ 100 modern multicore processors or equivalent GRID jobs

Muon spectrometer

The NA60+ muon spectrometer

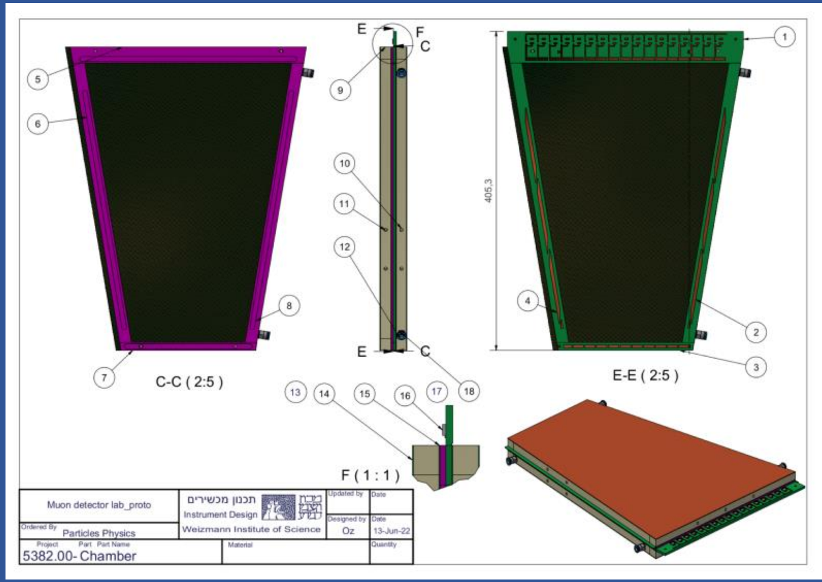




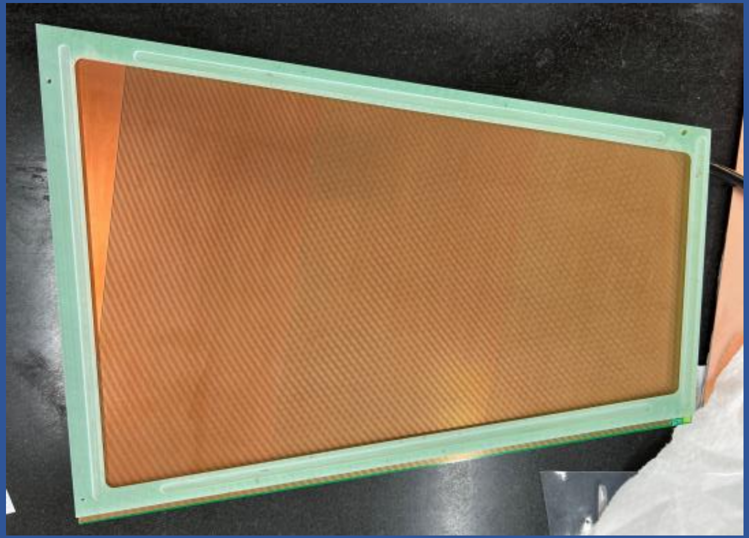
- ❑ (At least) two configurations of the muon spectrometer are foreseen
- ❑ **Low-energy set-up**
  →Thinner absorber
  →Smaller distance from target
- ❑ **High-energy set-up**
  →Thicker absorber
  →Larger distance from target

Keep maximum acceptance around $y \sim y_{CM}$

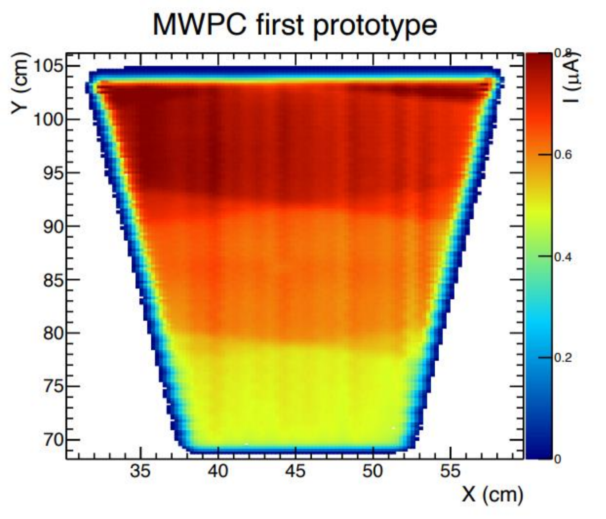
MWPC prototype tests

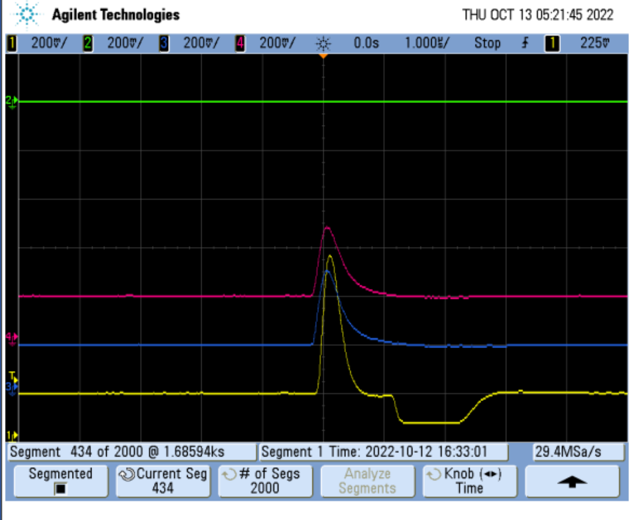


- Wire pitch: 3 mm
- Distance wire to cathode: 3 mm
- 1 mm strip pitch
- 2 cathodes with strips running in two different directions
  → Small angle stereo readout
- Readout electronics cards with VMM3a ASIC (128 ch each)

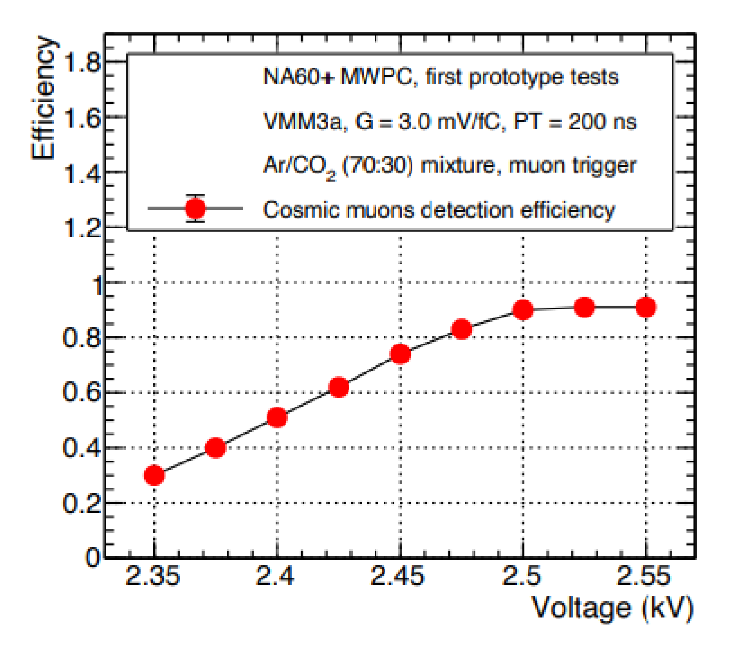


Detector tomography





Trigger and MWPC signals



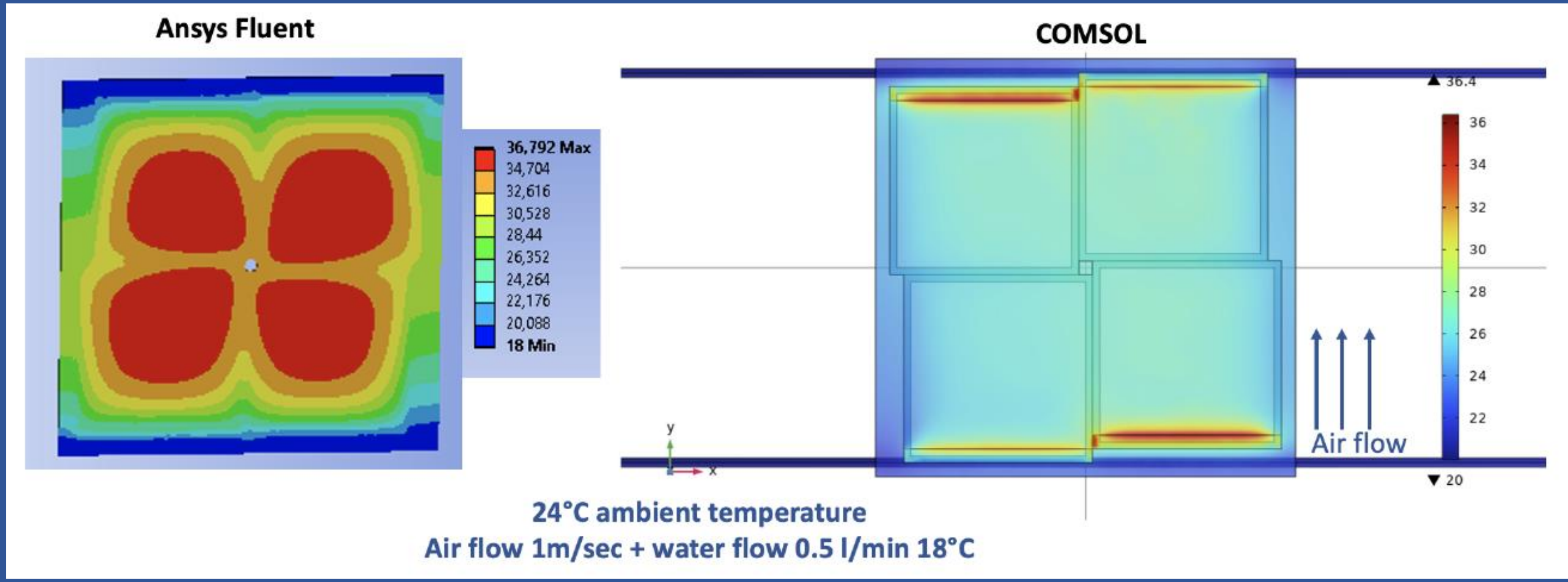
Vertex spectrometer

Ongoing R&D on vertex spectrometer

- Detector
  - Characterization of small-scale structures
  - Submission of first large area MAPS with the stitching technique (MOSS)
  - Development of test system for large area MAPS

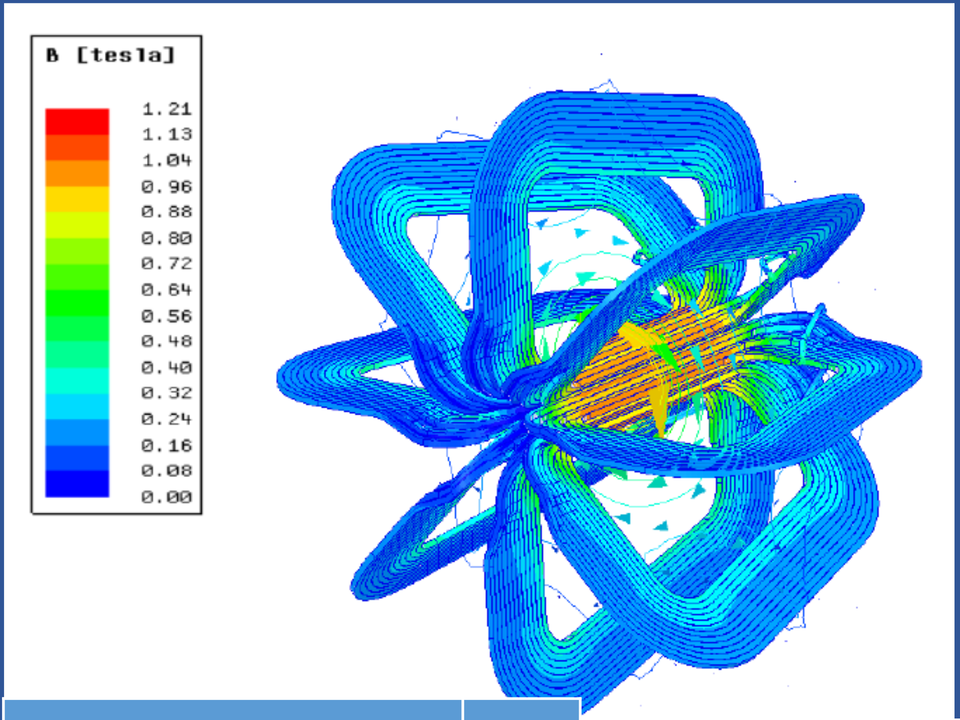
- Mechanics
  - Positioning and gluing tests of (dummy) sensors on carbon foam/fiber supports with optical bench

- Cooling calculations
  → Mix air flow + water flow



Toroid

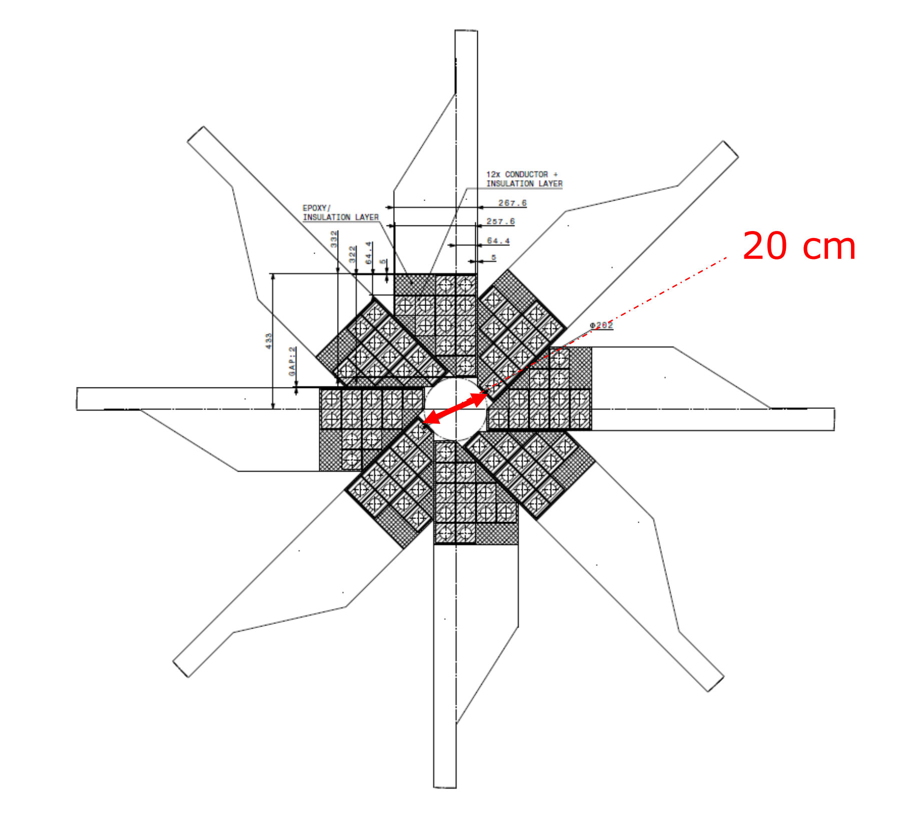
The NA60+ toroid



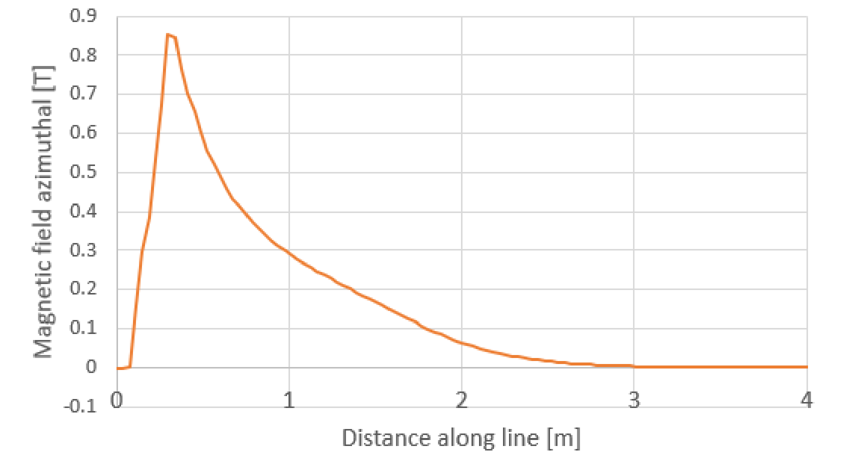
Warm magnet

Eight sectors,
12 turns per coil

Conductor has a square copper section with a circular cooling channel in the centre



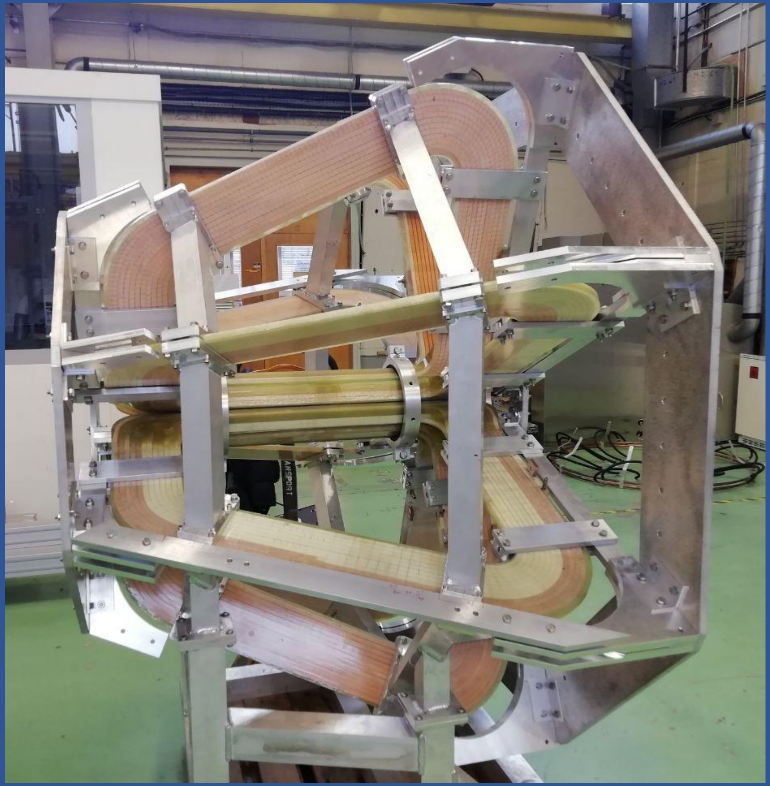
Operating Current [kA]	16.6
Amp-turns [kA]	199
Combined inductance [mH]	9.5
Resistivity Al 1100 @RT [μΩ.cm]	2.67
Length Conductor [m]	800
Total resistance [mΩ]	10.4
Dissipated power [MW]	2.8



Complex arrangement of the coils close to the beam axis to reduce the ‘dead zone’ at forward y

Ongoing discussions on strategy for **reducing the dissipated power** (<2 month/yr, pulsed operation,…)

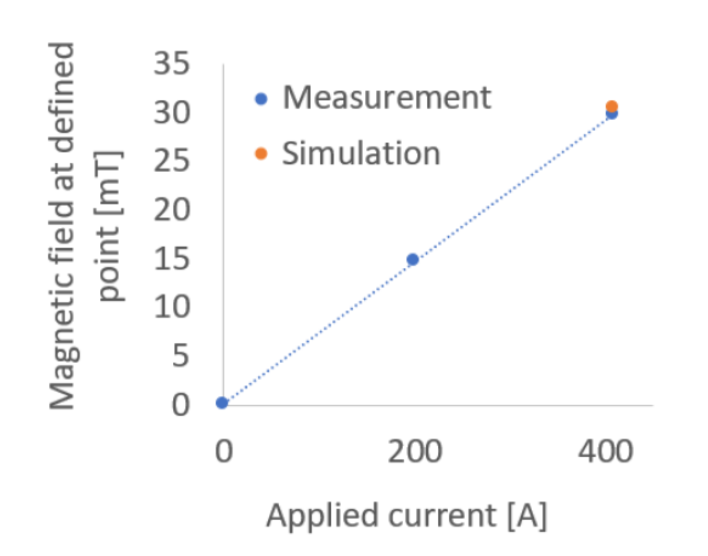
The NA60+ toroid R&D



- A **prototype (1:5 scale)** was built and tested in 2020-2021 by the **CERN-EP-DT group**, to check calculations and investigate mechanical solutions, in view of the final object

→ **works correctly and as expected**

- Measurements of resistance, inductance, cooling performance and magnetic field were carried out

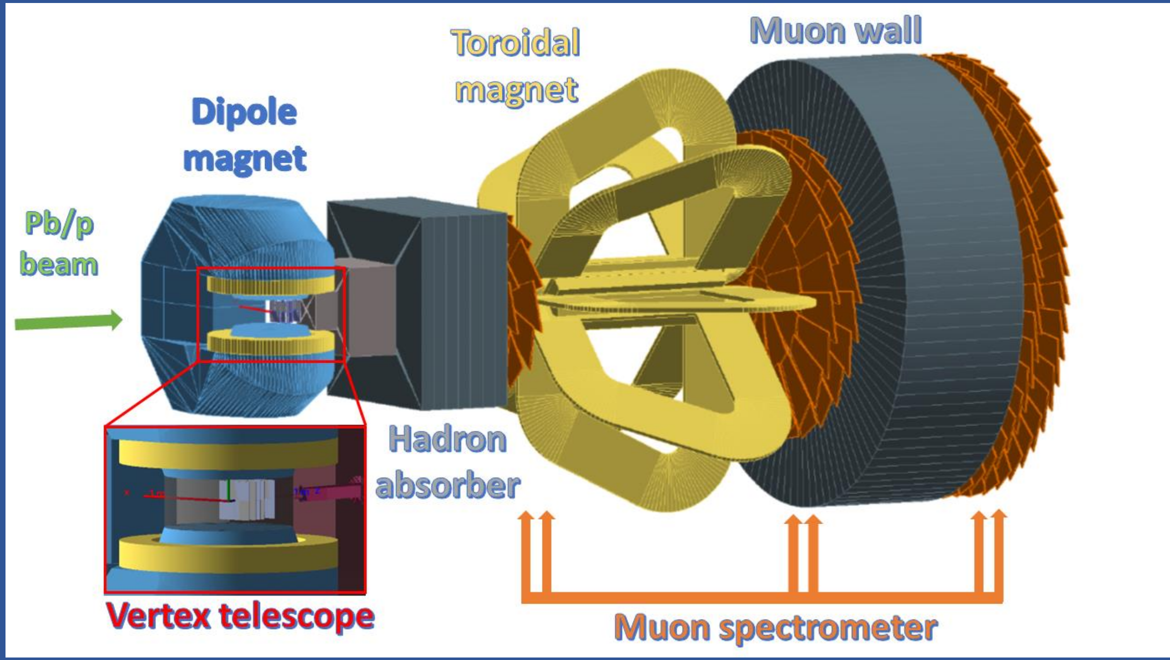


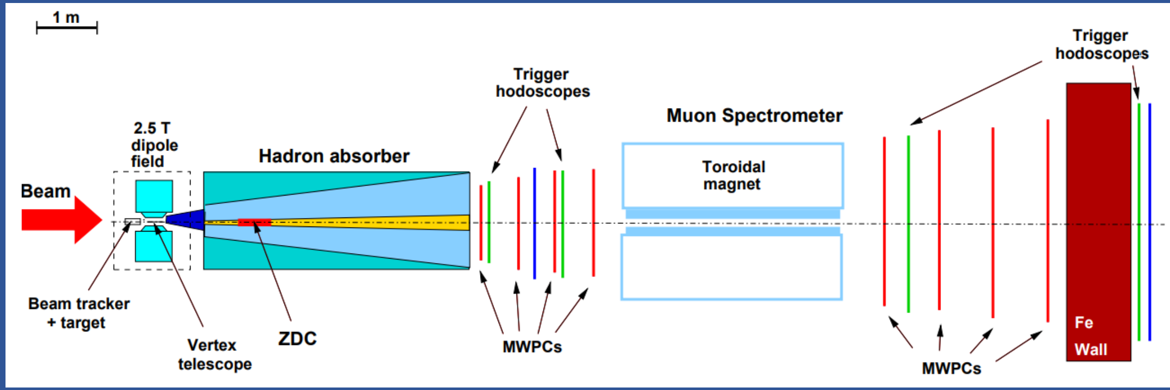
- B measurement
  → agreement with simulations by 3%

Support and participation of CERN in the design of the final toroid is very important

NA60+ vs others

NA60+ vs NA60





Some important improvements:

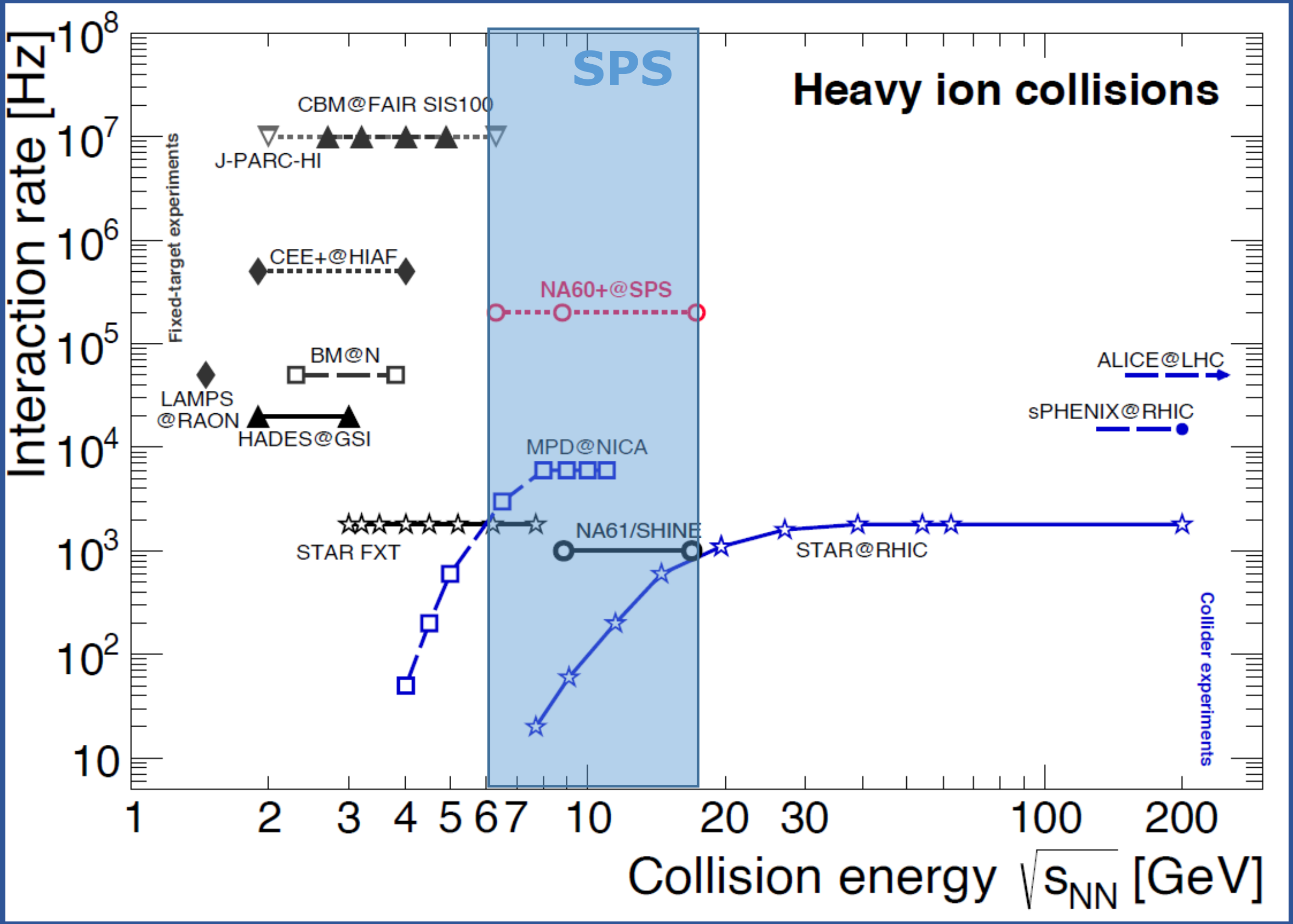
Physics program extended to lower energy
→ Fundamental to explore rare probes in the high-μ_B region

Larger angular acceptance
→ cope with lab rapidity shift when varying energy down to low SPS energy

Access new observables (open charm etc.)
NA60: (di)muon trigger ~ 5 kHz
NA60+: MB trigger (>100 kHz)

State-of-the art detectors
Pixel size: from 50x425 μm^2 (NA60) to 30x30 μm^2 (NA60+), thinner sensors (from 2% to 0.1% X_0)
→ Improved resolution and signal over background
from 21 to 8 MeV at the ω mass
from 70 to 30 MeV at the J/ψ mass

Uniqueness of NA60+ program



NA60+ vs NA61

NA61

Measurement of hadron production properties for
- Neutrino beams
- Cosmic ray experiments
- Strong interaction

NA60+

Measurement of rare probes in HI collisions
- Dileptons
- Quarkonium
- Open heavy flavour(*)
- Strangeness and hypernuclei

(*) Also part of the NA61 program, but with 2-3 orders of magnitude smaller statistics

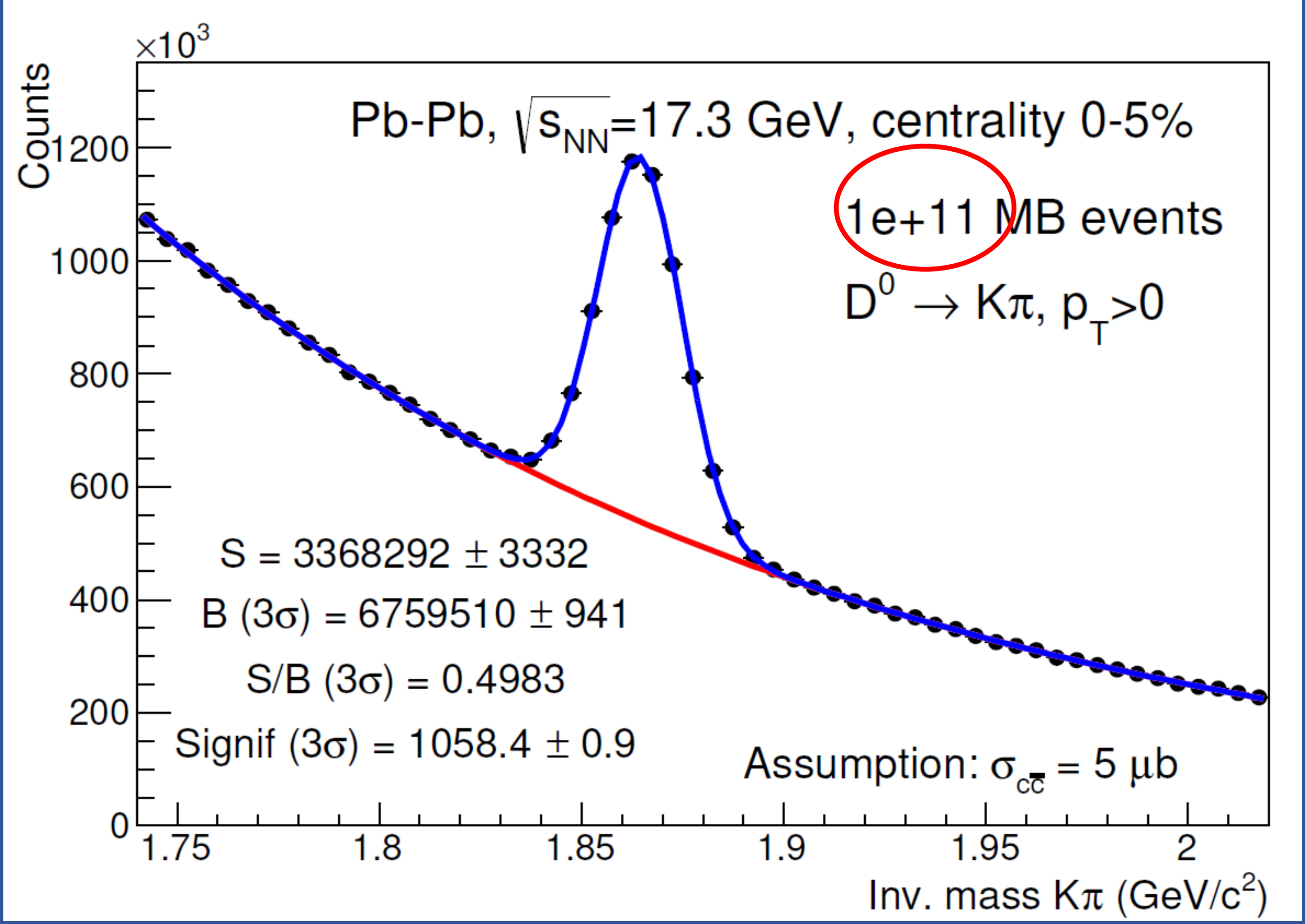
- **Complementarity** with experiments accessing
  - different (hadronic) observables in the same energy range (STAR BES, NICA, NA61)
  - similar observables in a lower energy range (CBM at FAIR)

Open charm NA60+ vs NA61

NA61

Year	Beam	#days	#events	$\#(D^0 + \overline{D^0})$	$\#(D^+ + D^-)$
2022	Pb at 150*A* GeV/*c*	42	250M	38k	23k
2023	Pb at 150*A* GeV/*c*	42	250M	38k	23k
2024	Pb at 40*A* GeV/*c*	42	250M	3.6k	2.1k

NA60+



N.B.: different assumptions for open charm cross section

Collaboration institute-wise

Collaboration members

CERN: C. Ahdida[HSE-RP], A. Baratto Roldan[BE-EA-LE], J. Bernhard[BE-EA-LE], H. Danielsson[EP-DT-EF], A. Gerbershagen*, M. Mentink[TE-MPE-PE], L. Musa[EP-AIO], M. Puccio[EP-AIP-PAP], B. Schmidt[EP-DT,], R. Shahoyan[EP-AIP-SDS], H. Vincke[HSE-RP], I. Vorobyev[EP-AIP-PAP] (*)now at Groningen

Cagliari Univ. and INFN: G. Alocco, M. Arba, M. Aresti, E. Casula, C. Cicalo, A. De Falco, F. Fionda, D. Marras, A. Masoni, L. Mirasola, A. Mulliri, B. Paul, C. Puggioni, V. Sarritzu, S. Siddhanta, M. Tuveri, G. Usai

Padova INFN: F. Antinori, A. Dainese, A. Rossi

Torino Univ. and INFN: R. Arnaldi, S. Beole, L. Bianchi, S. Bufalino, S. Coli, P. Cortese, A. Ferretti, M. Gagliardi, M. Masera, L. Micheletti, F. Mazzaschi, P. Mereu, C. Oppedisano, M. Pennisi, F. Prino, E. Scomparin

Weizmann Inst.: M. Borysova, S. Bressler, A. Milov, I. Ravinovich

Stony Brook Univ.: A. Drees, K. Dehmelt

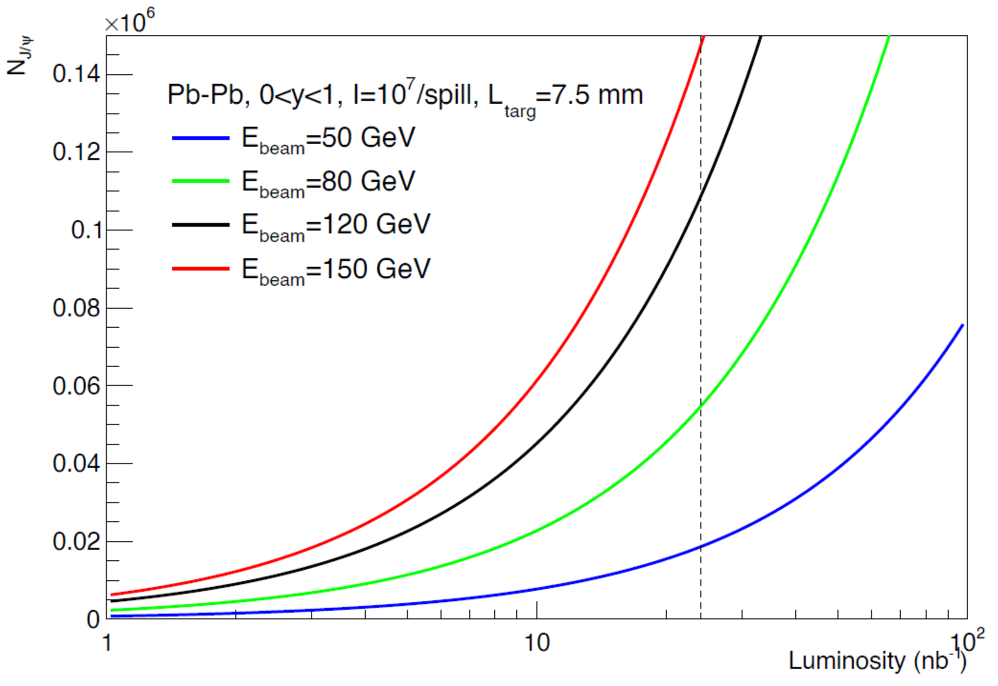
Rice Univ.: F. Geurts, W. Li

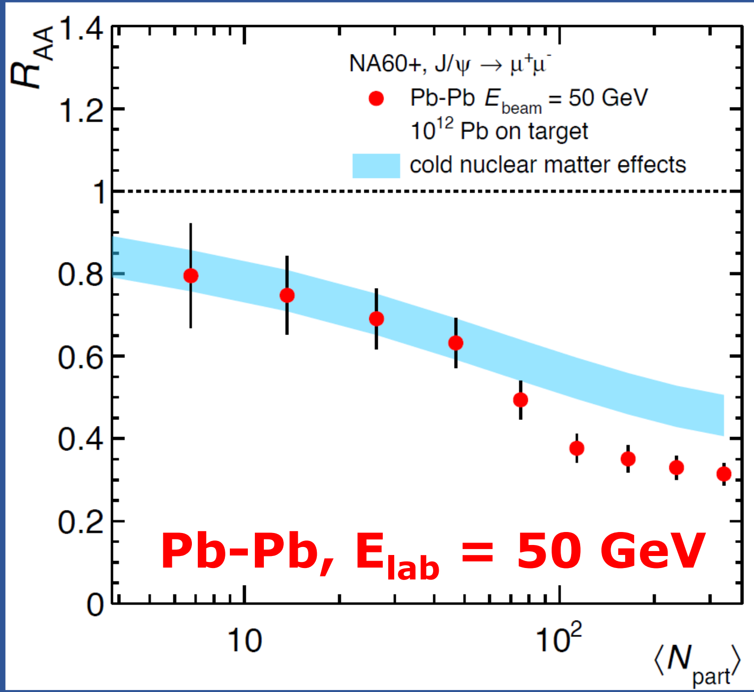
IN2P3 Lyon: A. Uras

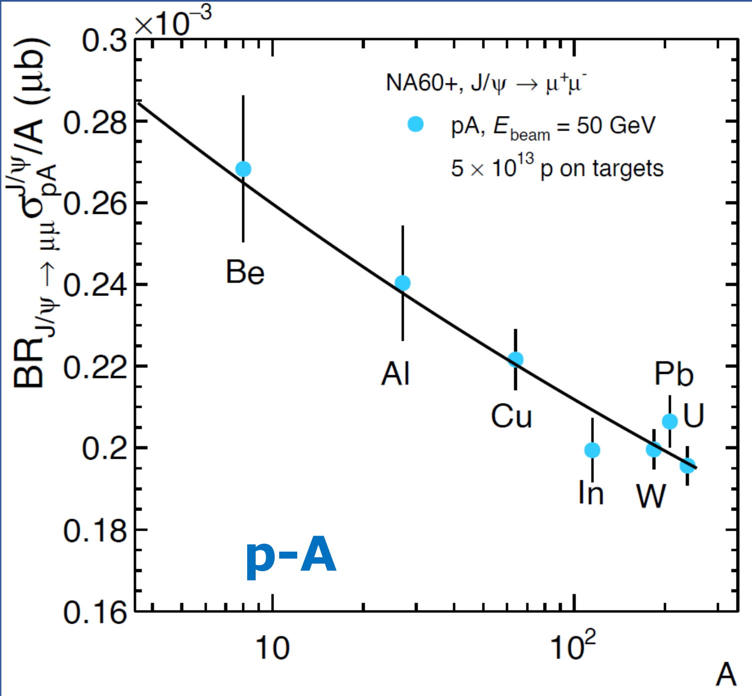
Theorists: A. Beraudo (Torino), V. Greco (Catania), M.P. Lombardo (Firenze), S. Plumari (Catania), R. Rapp (Texas A&M)

Charmonia

Physics performance: charmonium





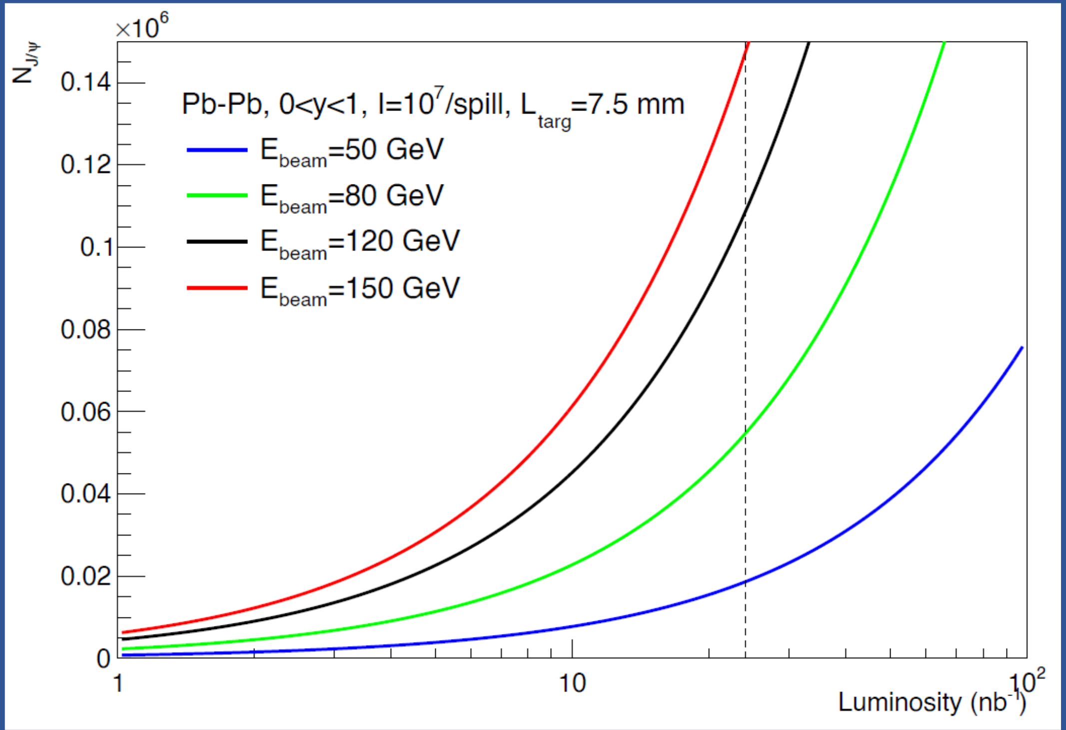


- ❑ 7.5mm Pb target and 1 month data taking → L_{int} = 24 nb^{-1}

  Can aim at
  - ❑ **~O(10^4) J/ψ at 50 GeV**
  - ❑ **~O(10^5) J/ψ at 158 GeV**
- ❑ Allows detection of **onset of anomalous suppression** effects down to low SPS energy
- ❑ **p-A data taking mandatory** (few weeks/year), to calibrate CNM effects
- ❑ **ψ(2S)** also within reach, down to E=100-120 A GeV

- ❑ NA60+ is also ideally placed to look for signals of **intrinsic charm** in p-A collisions, which are pushed much closer to midrapidity wrt collider energies

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

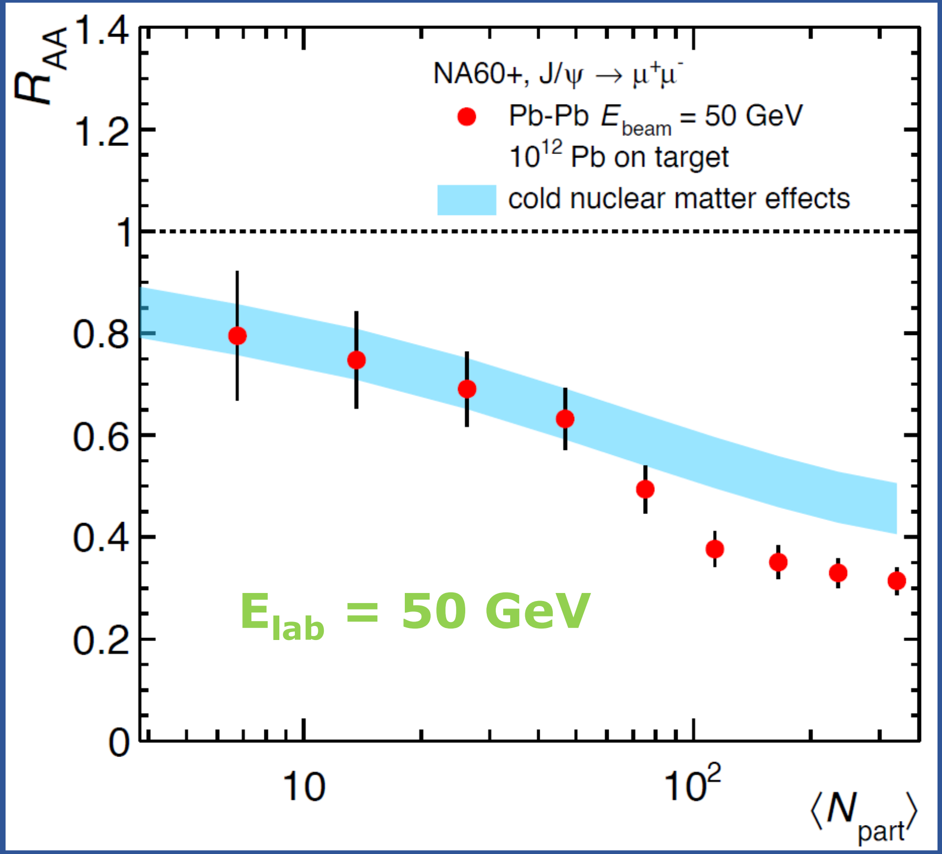
Quarkonium production not studied below top SPS energies!

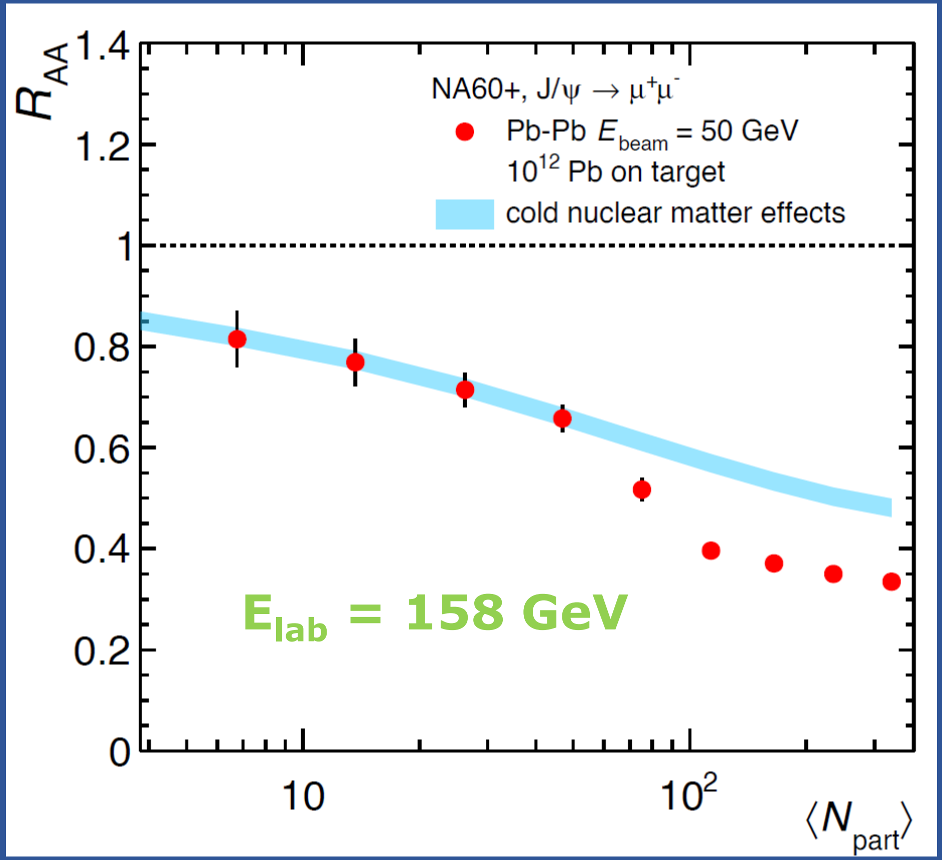
⇓

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

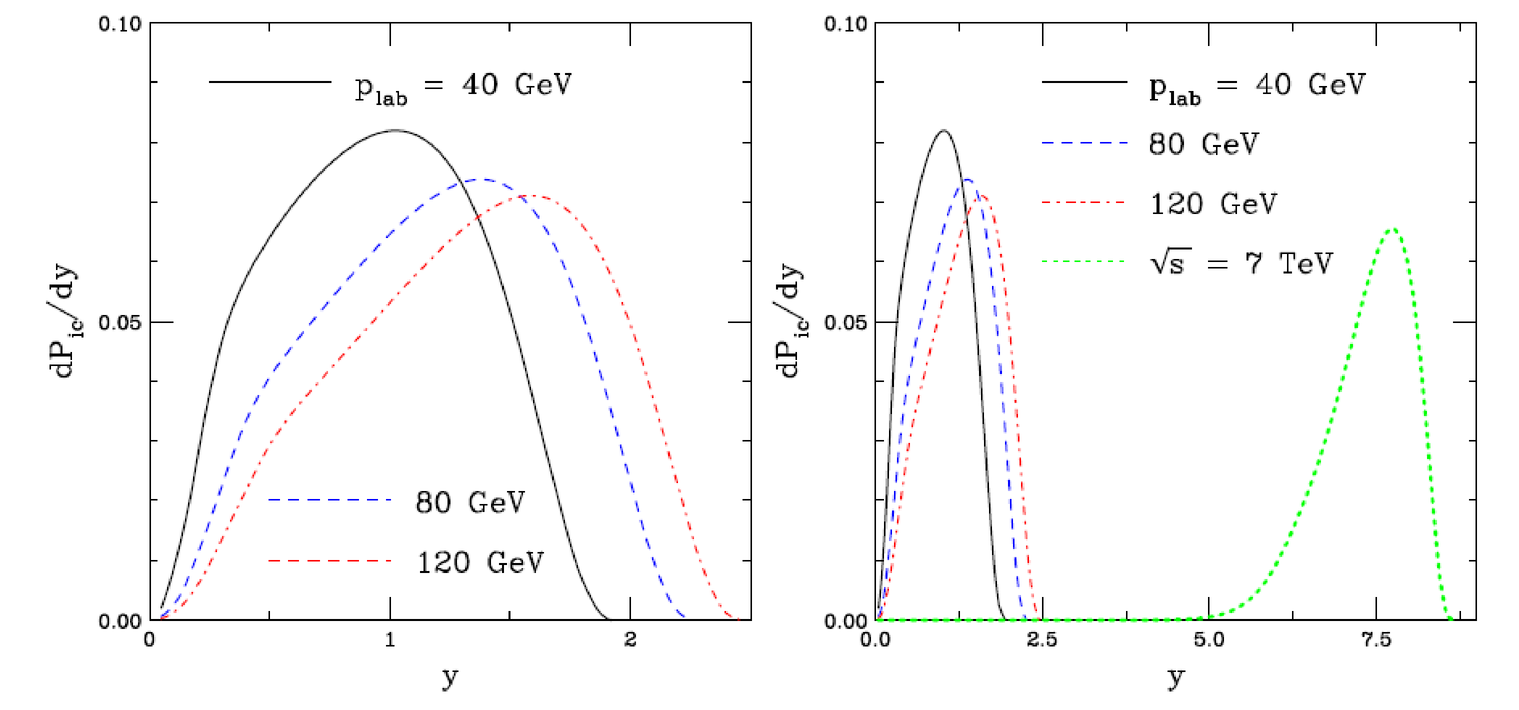
- Assume only CNM effects for N_{part}<50 and 20% extra suppression in Pb-Pb for N_{part}>50

→ **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

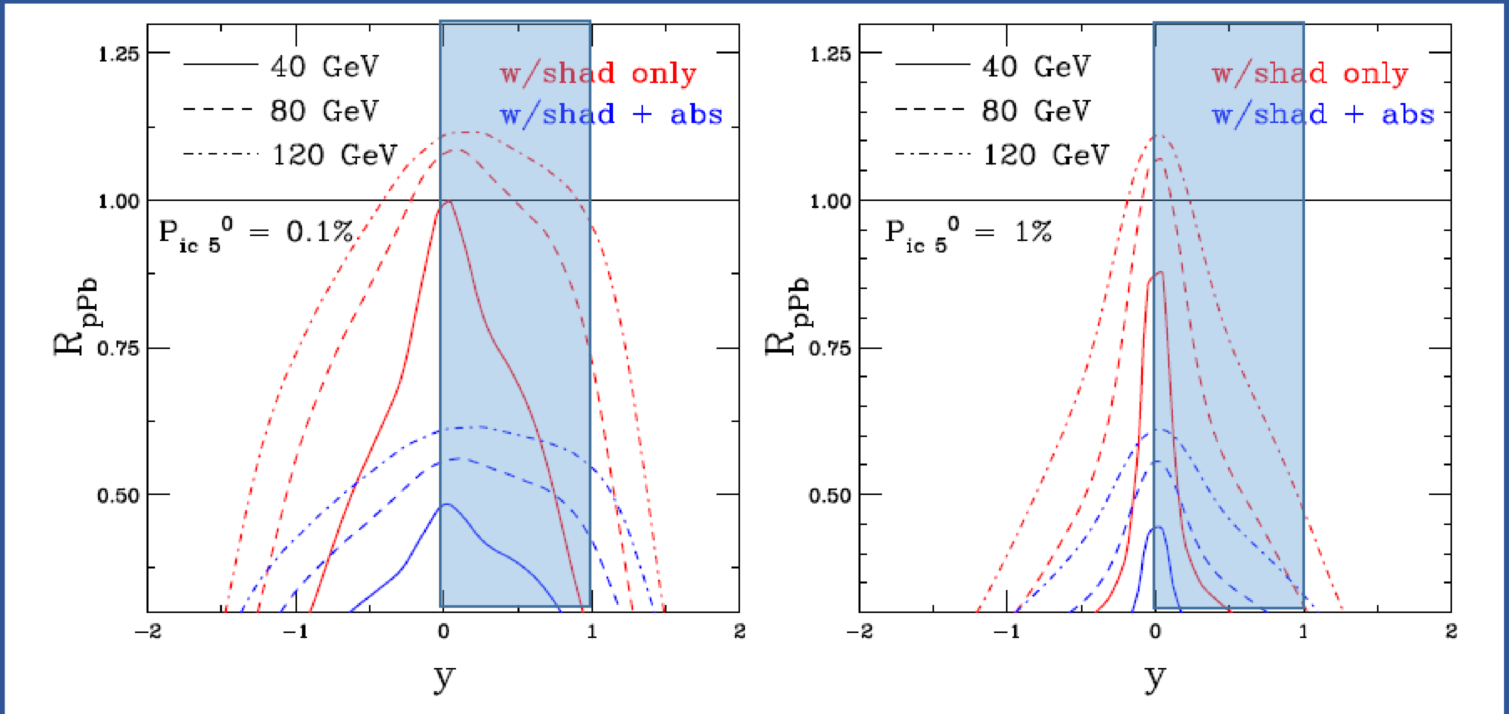


Assumed intrinsic charm content varied between 0.1% and 1%

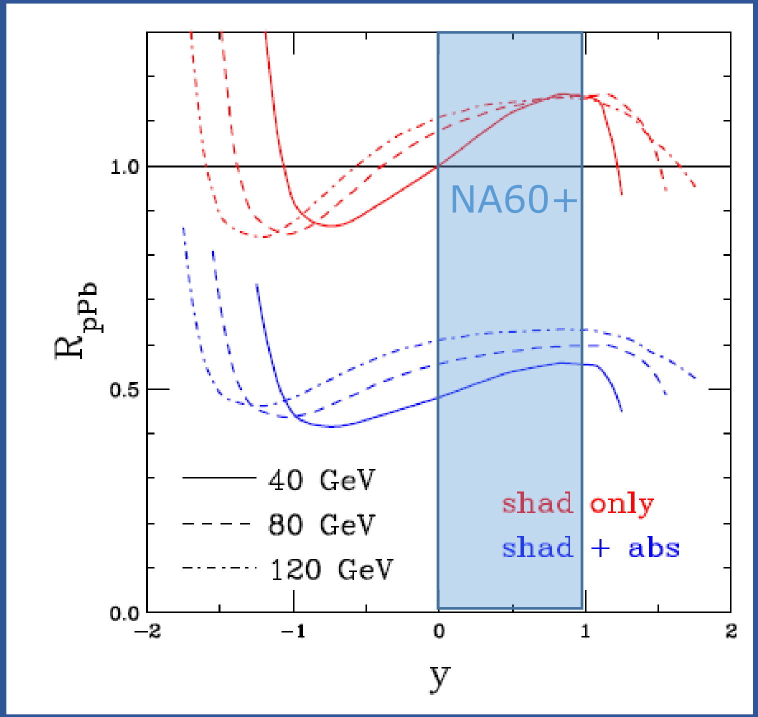
R. Vogt, PRC 103, 035204 (2021)
R. Vogt, arXiv:2207.04347

Low-√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%

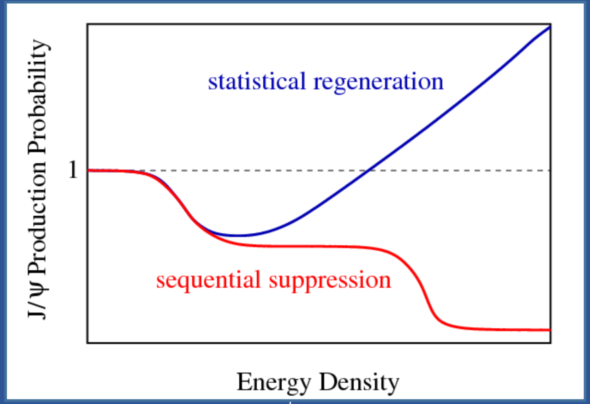
Charmonia: high vs low √s

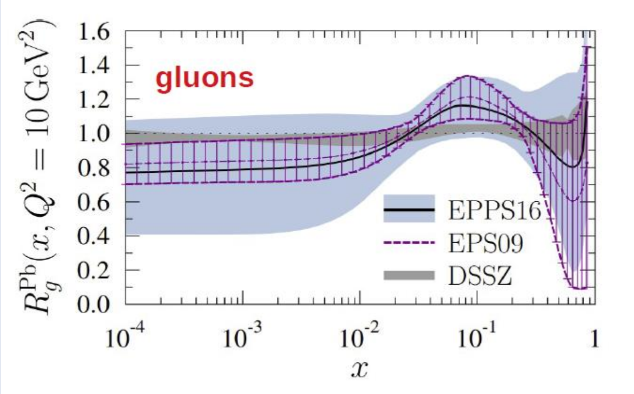
Collider (LHC)

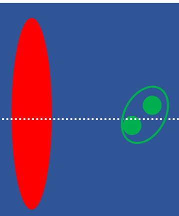
Hot matter effects: regeneration counterbalances (overcomes) suppression

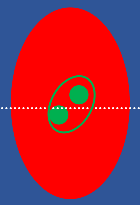
Initial state effects:
shadowing
$x \sim 10^{-5}$ ($y \sim 3$),
$x \sim 10^{-3}$ ($y = 0$),
$x \sim 10^{-2}$ ($y \sim -3$)

(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 ($y \sim -3$)









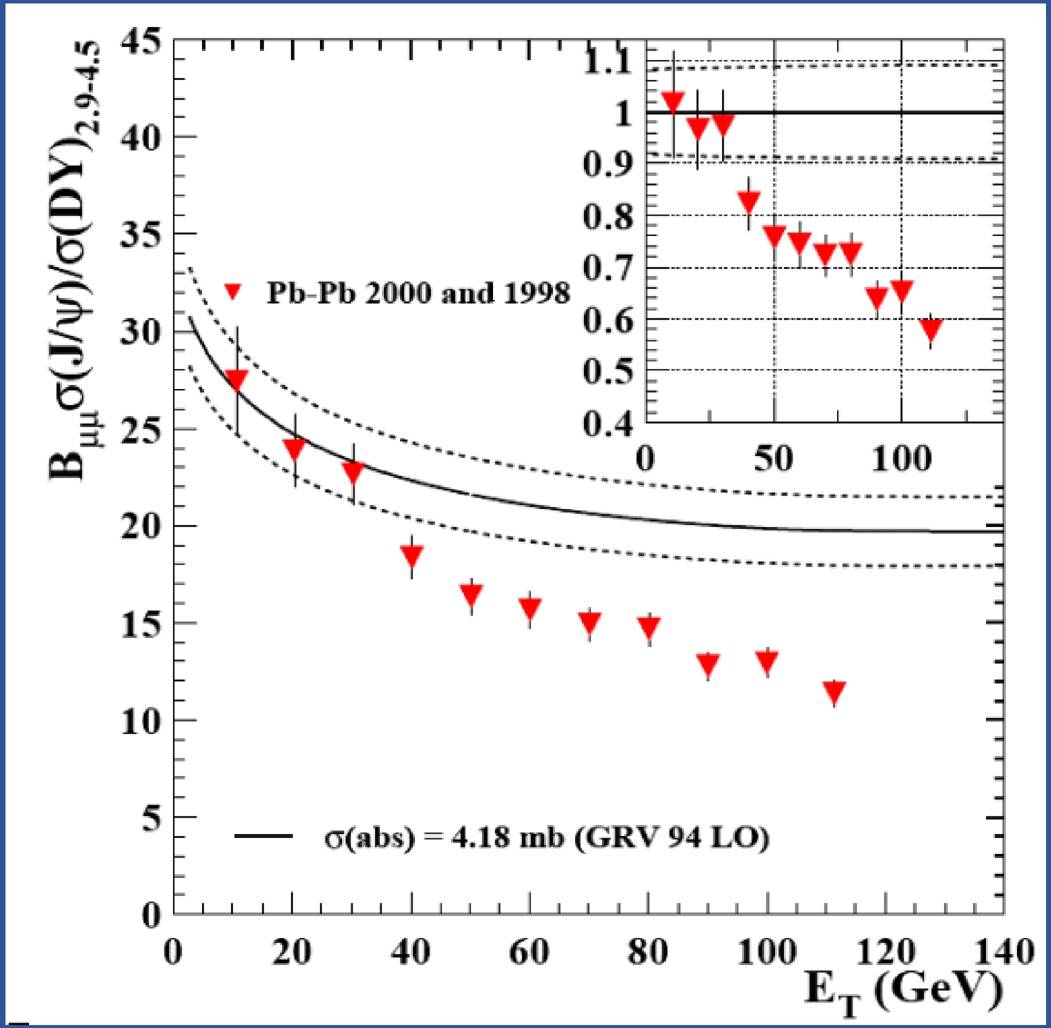
Fixed target (SPS)

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



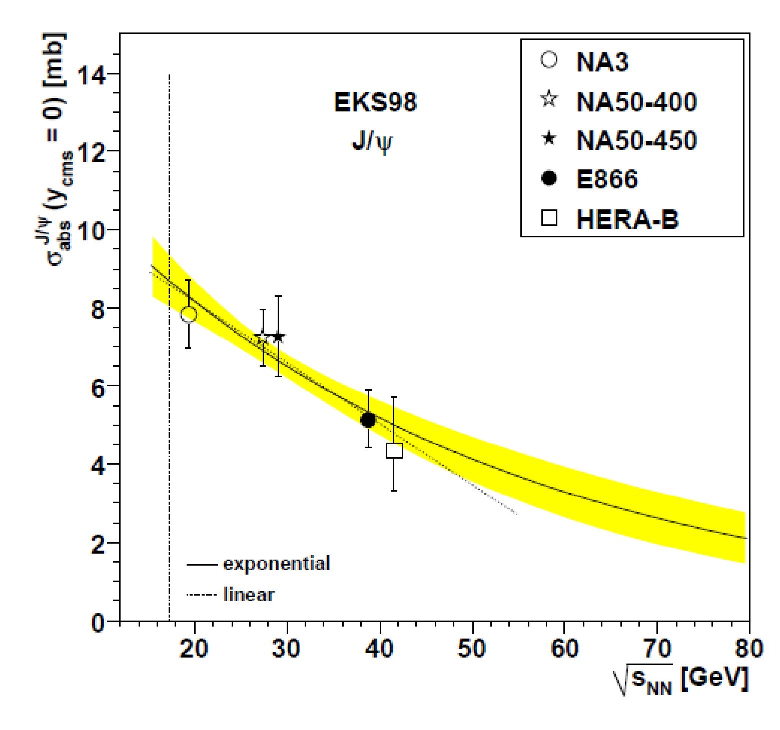
- Contrary to open charm, accurate studies were performed at $\sqrt{s}$=17.3 GeV (NA50, NA60)
- J/ψ yields normalized to Drell-Yan reference
- QGP-induced suppression evaluated with respect to a CNM reference obtained with systematic p-A studies
- **~30-40% anomalous suppression effect** possibly due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

CNM effects are (very) large

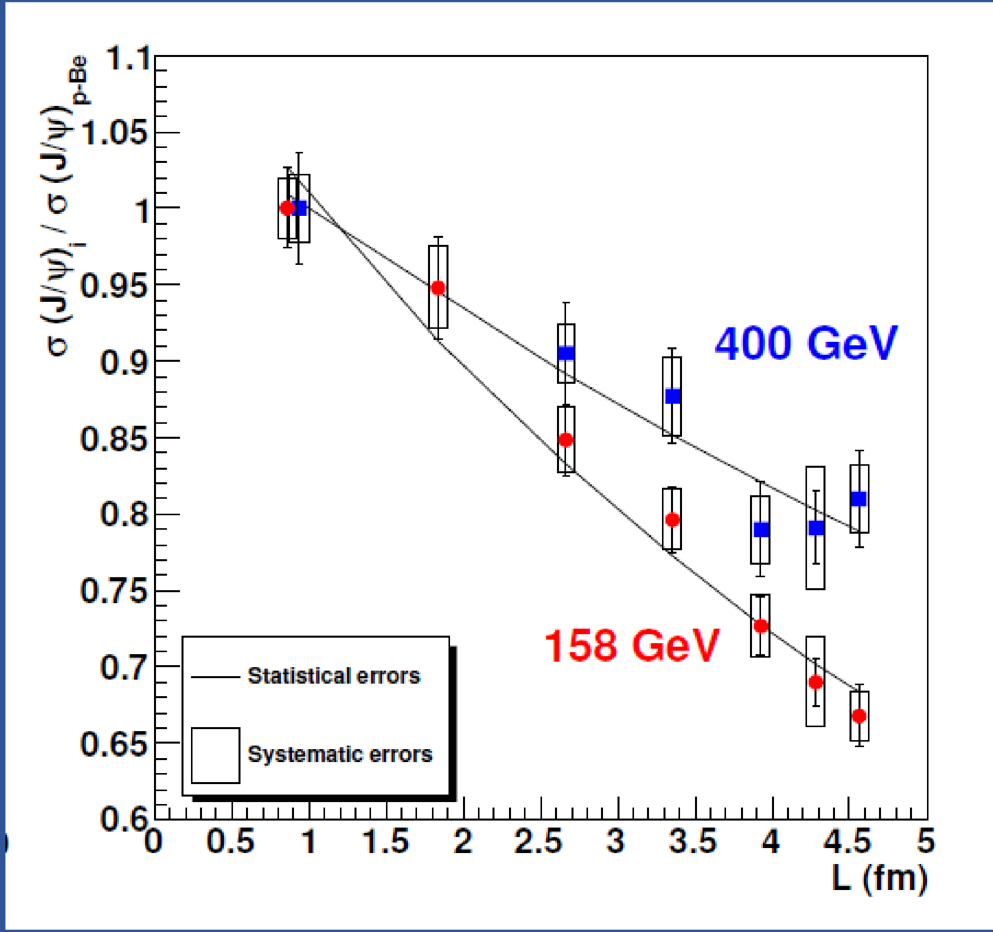
- ❑ Shadowing effects are moderate
- ❑ Dominated by nuclear absorption
  → ~30% effect in p-Pb at $\sqrt{s_{NN}}$ = 17 GeV

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

NA60, PLB 706 (2012) 263



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



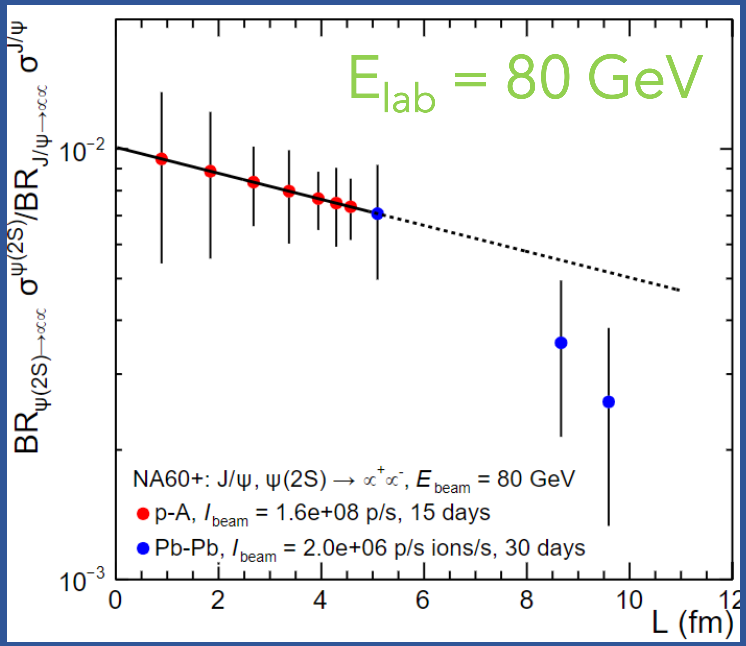
L: thickness of nuclear matter crossed by the cc pair (evaluated with Glauber model)

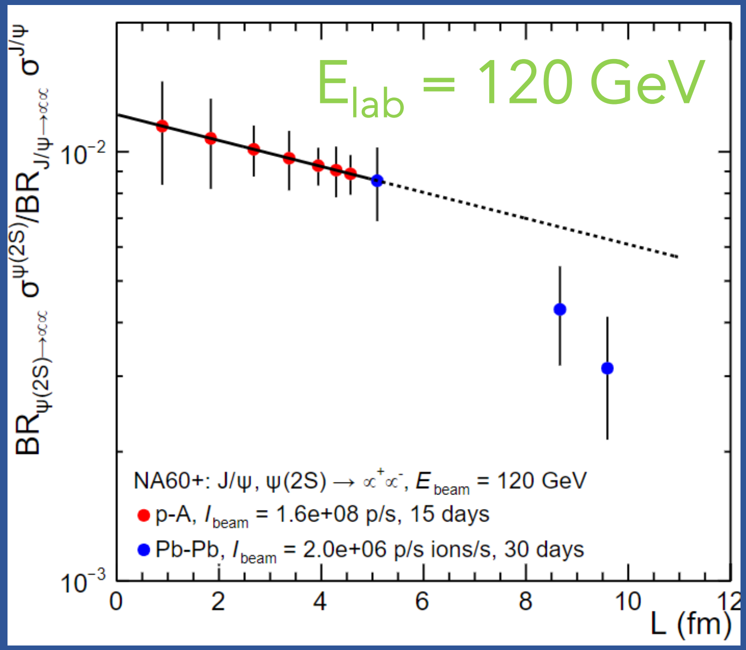
Prospects for ψ(2S) measurements at low √s

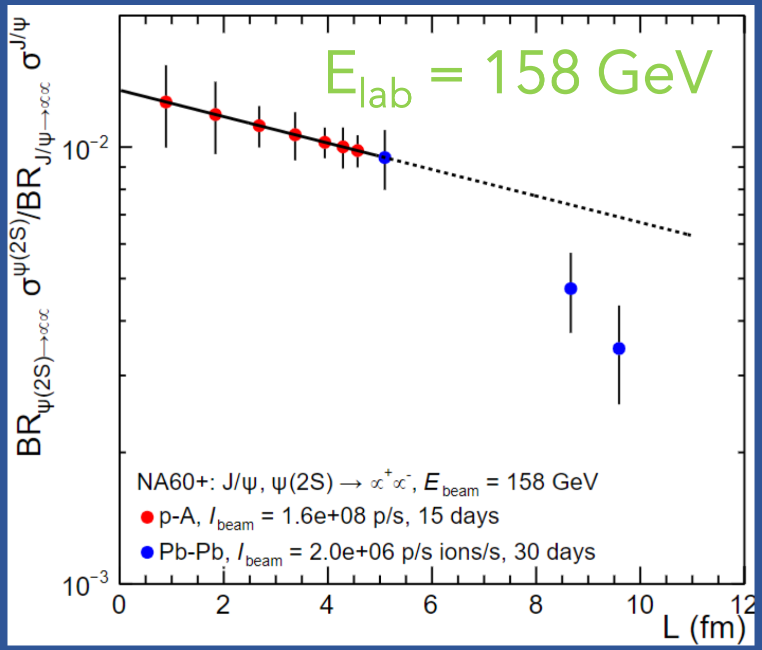
Good charmonium resolution (~30 MeV for the J/ψ) will help ψ(2S) measurements

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)

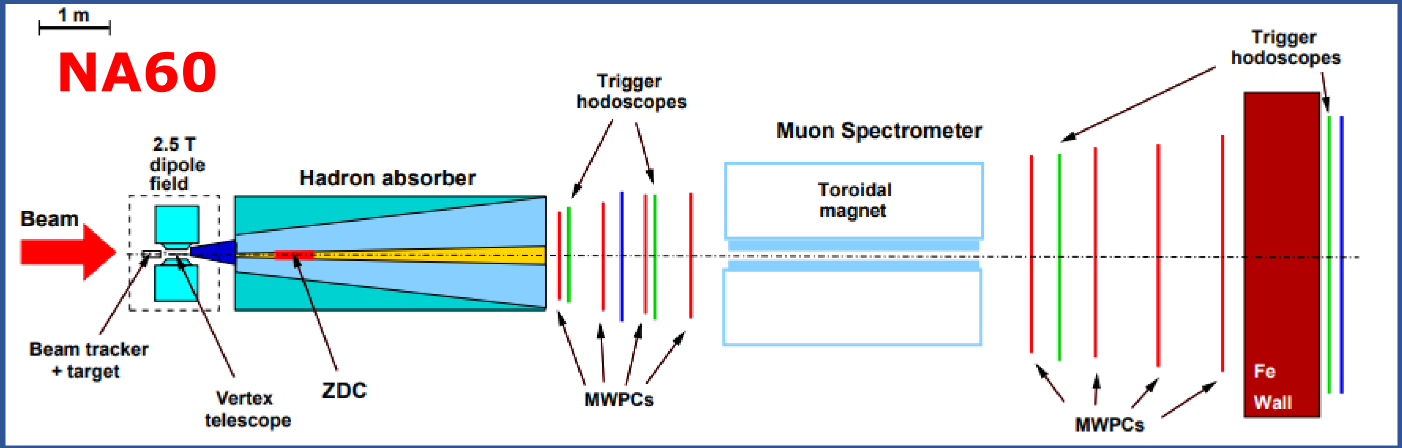




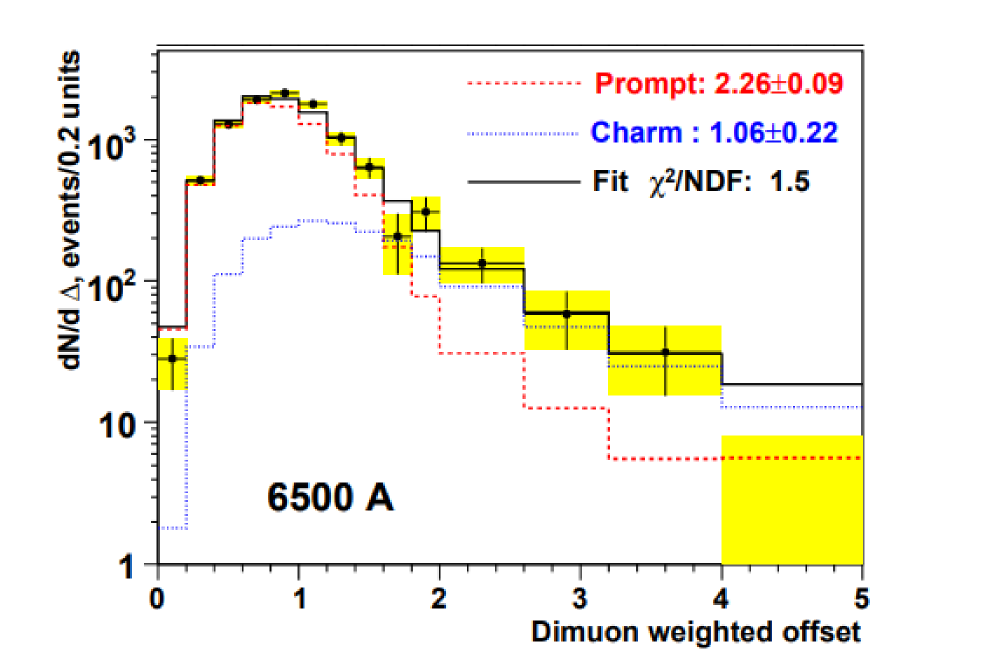


- ❑ **ψ(2S)/ψ measurement looks feasible down to E_{lab} = 120 GeV**
- ❑ Lower E_{lab} would require larger beam intensites/longer running times

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

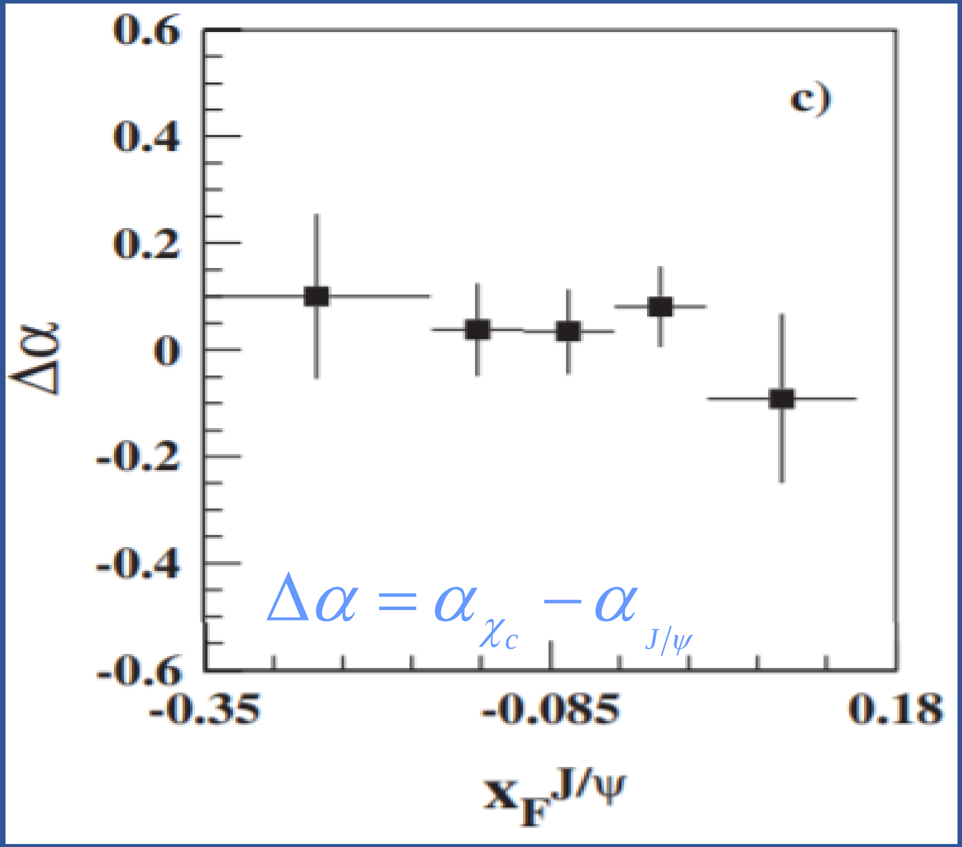
- ❑ Analysis of open charm contribution (semileptonic decays of charm hadron pairs) leads, for In-In collisions at $\sqrt{s_{NN}}$=17.3 GeV, to σ_{cc}= 9.5±1.3(stat.)±1.4(syst.) μb assuming kinematic distribution as in PYTHIA6

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

No other results available below top SPS energy

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

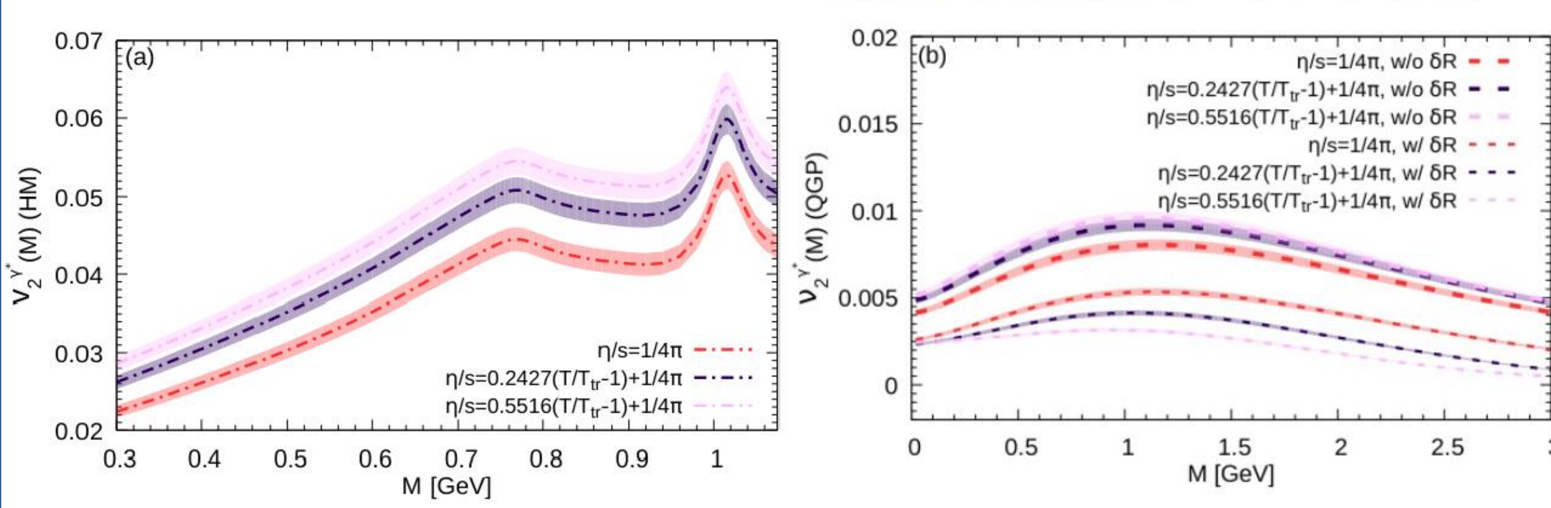
- Non-trivial measurement, needs detection of
  low-momentum photon (<1 GeV)
  → conversion or calorimetry

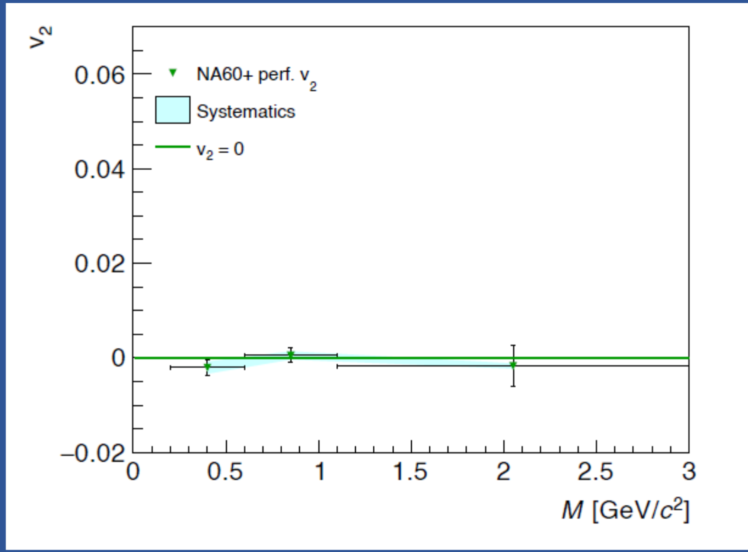
Thermal dileptons and chiral symmetry

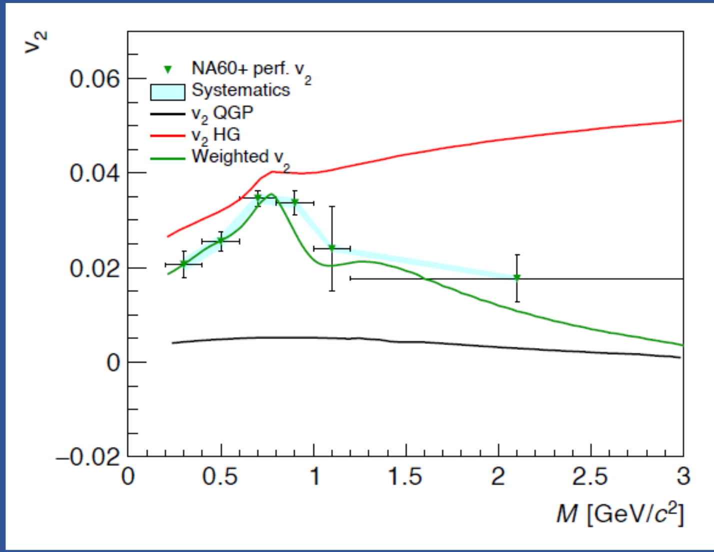
Elliptic flow of thermal dileptons

- ❑ **No measurements at present**
- ❑ Predictions at RHIC energies
  - ❑ LMR dominated by hadron gas: almost linear increase of v_2 vs mass
  - ❑ IMR dominated by QGP: small v_2

Vujanovic et al, Phys. Rev. C 98, 014902 (2018)





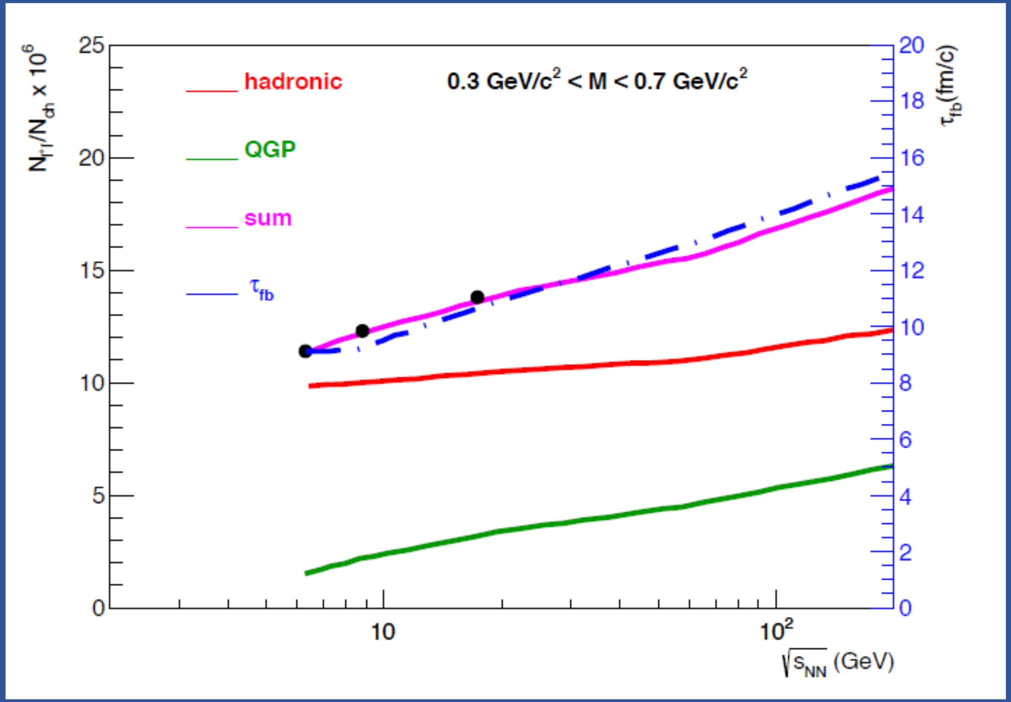


- ❑ No prediction at SPS energies
- ❑ Two possible scenarios: v_2=0
  - ❑ **Measurement with uncertainty between 0.003 and 0.008**
- ❑ v_2=v_2^{RHIC}
  → increase of v_2 versus mass (HG) and a drop in the IMR (QGP)

Fireball lifetime

- Thermal "excess" radiation in the mass region $0.3 < M < 0.7$ GeV/c^2
  → sensitive to all emission stages
  → tracks the **total fireball lifetime** within an accuracy of ~10%

  → NA60 measurement, In-In at $\sqrt{s_{NN}}$=17.3 GeV : **τ_{FB} = 8 ± 1 fm/c**



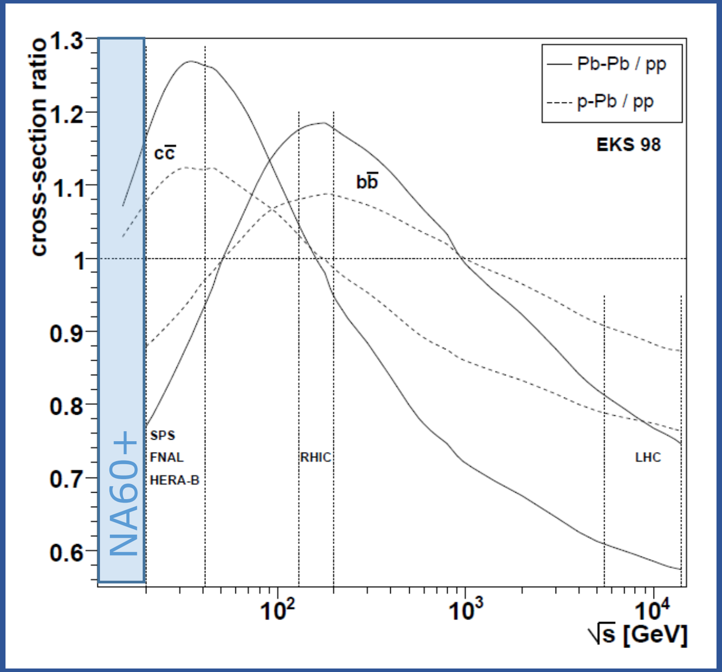
Black points → NA60+ projections
Excellent accuracy

Soft mixed phase in a **first-order transition**
→ pressure gradients in the system are small and thus stall the fireball expansion
→ increased lifetime in the collision-energy regime where the mixed phase forms

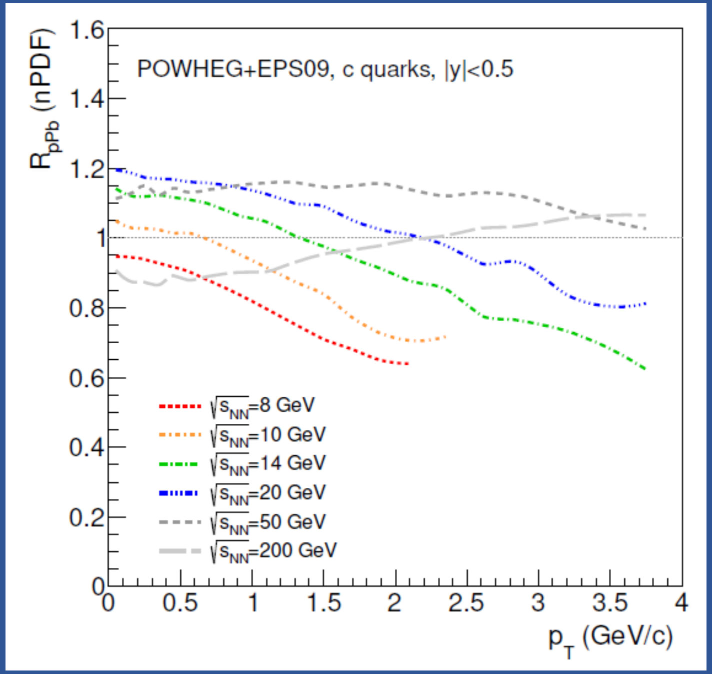
Open charm

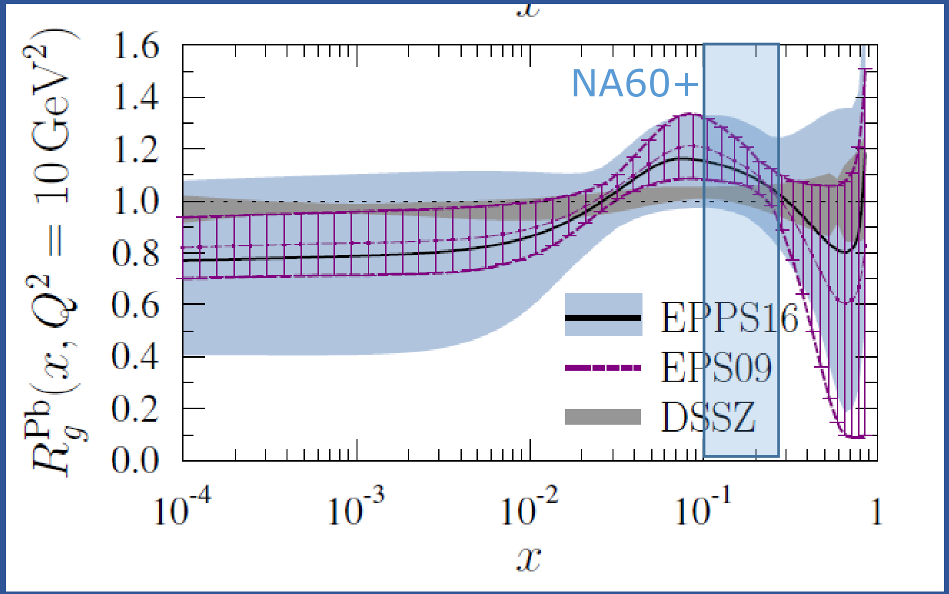
Open charm at low √s in pA: nuclear PDFs

- 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 $Q^2\sim10\text{-}40$ GeV^2



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

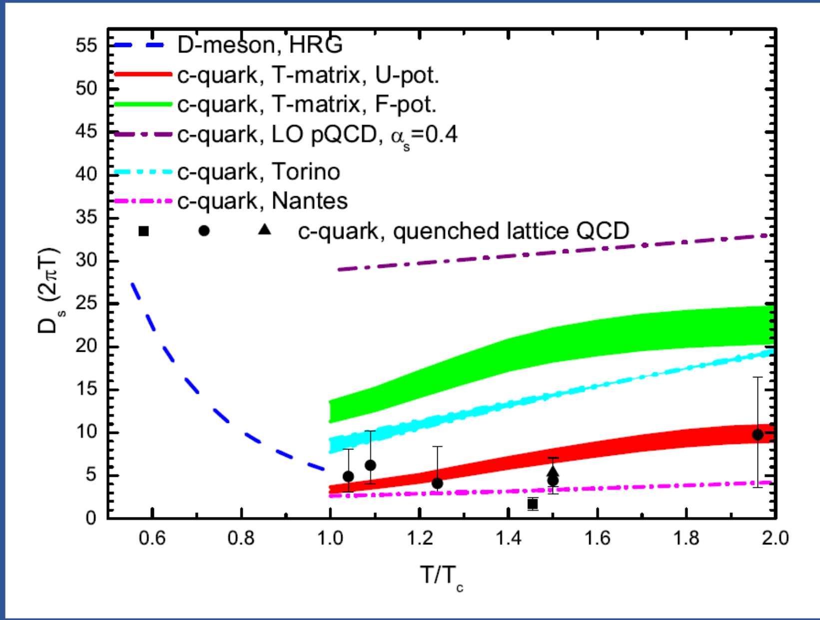




Eskola et al. , EPJ C77 (2017) 13

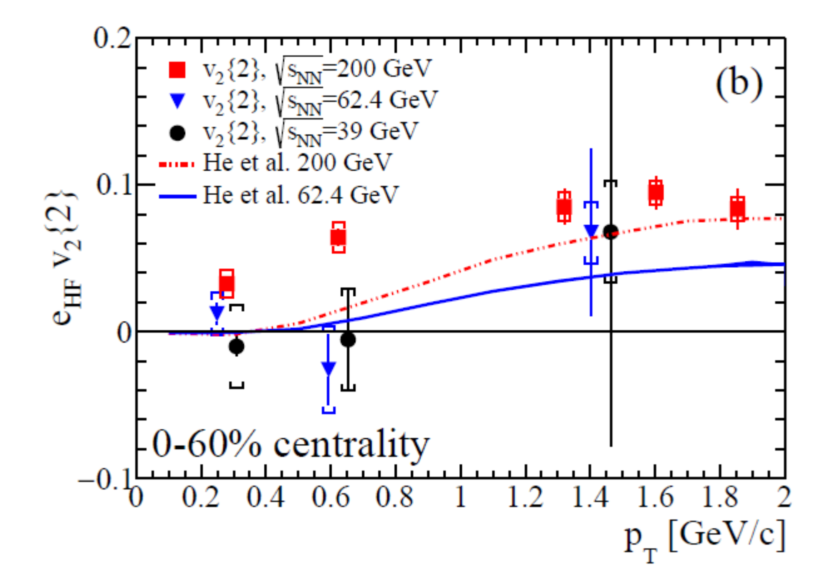
Open charm in Pb-Pb: R_{AA} and v_2

- 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



Prino, Rapp, JPG43 (2016) 093002

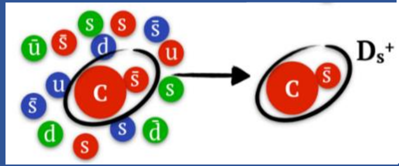
- Study **charm thermalization at low √s**
  - Current measurements of HF-decay electron v_2 at $\sqrt{s_{NN}}$=39 and 62 GeV/c from RHIC
    - → Smaller v_2 than at √s=200 GeV
    - → Not conclusive on v_2>0

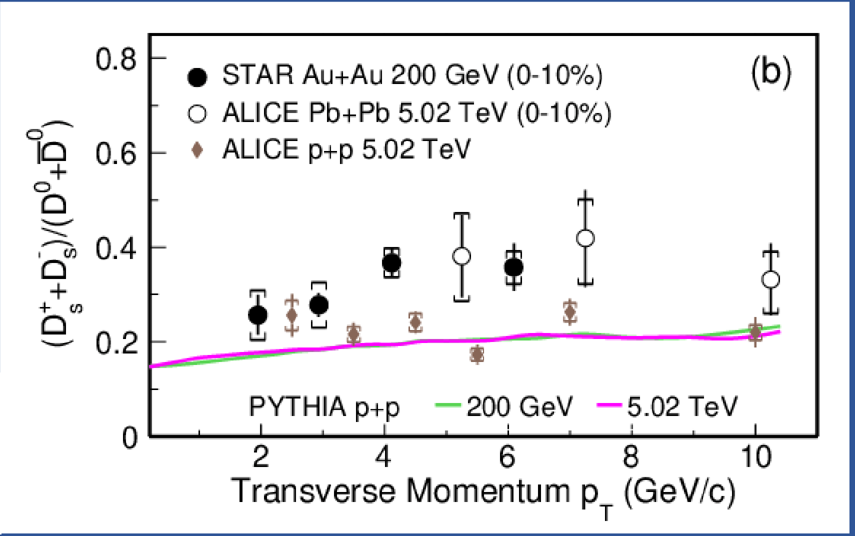


STAR, PRC 95 (2017) 034907

Open charm hadrochemistry

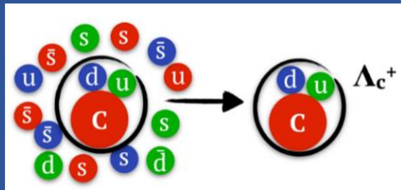
- Reconstruct different charm hadron species to get insight into **hadronization mechanism**
- **Strange/non-strange** meson ratio (D_s/D):
  - D_s/D enhancement expected in A-A collisions due to hadronisation via **recombination** in the strangeness rich QGP



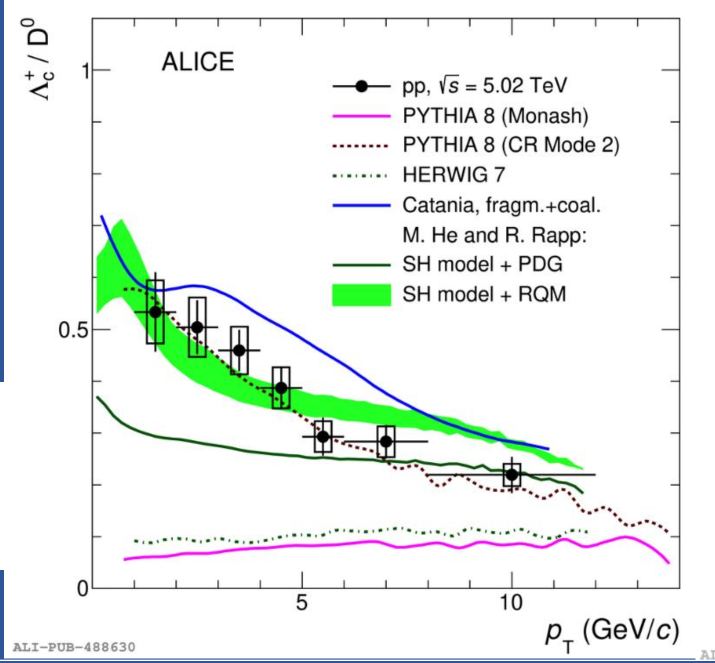


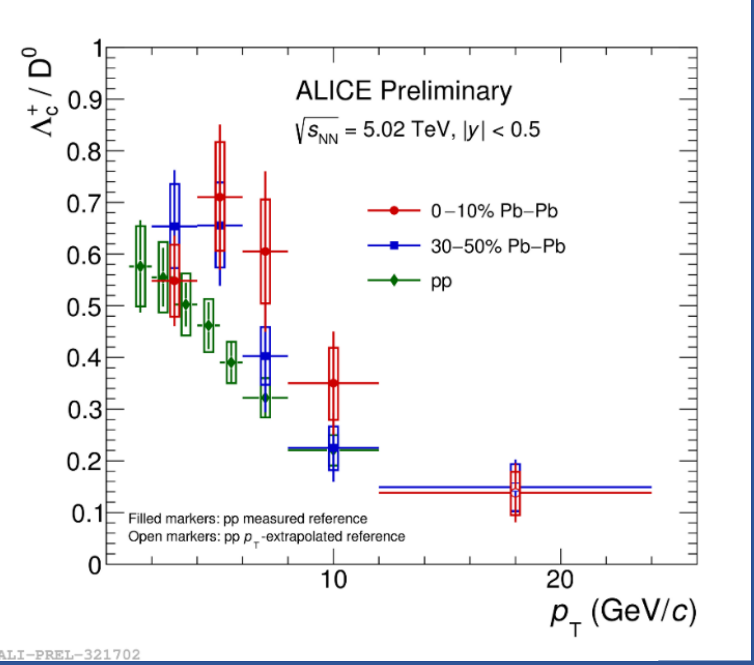
STAR, PRL 127 (2021) 092301
ALICE, PLB827 (2022) 136986

- **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
  - Upper limit from NA49 measurements of D^0 mesons

NA60, EPJ C59 (2009) 607

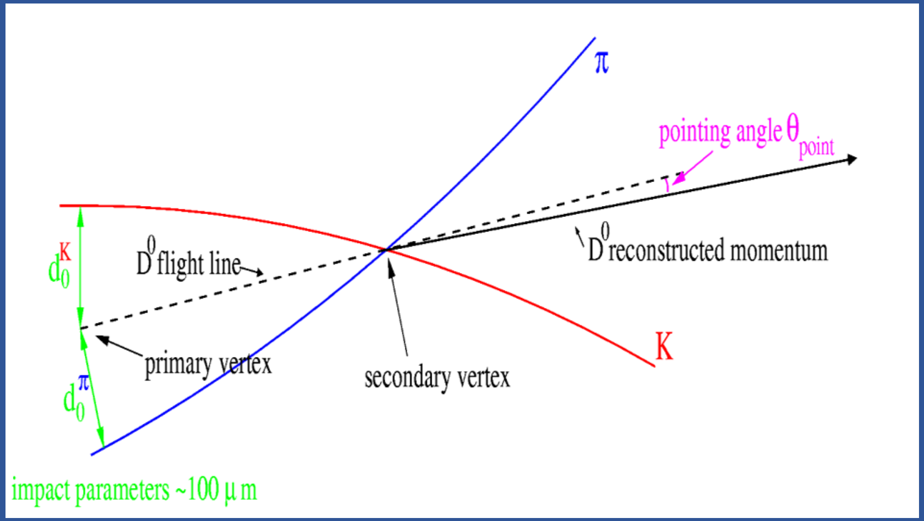
NA49, PRC73 (2006) 034910

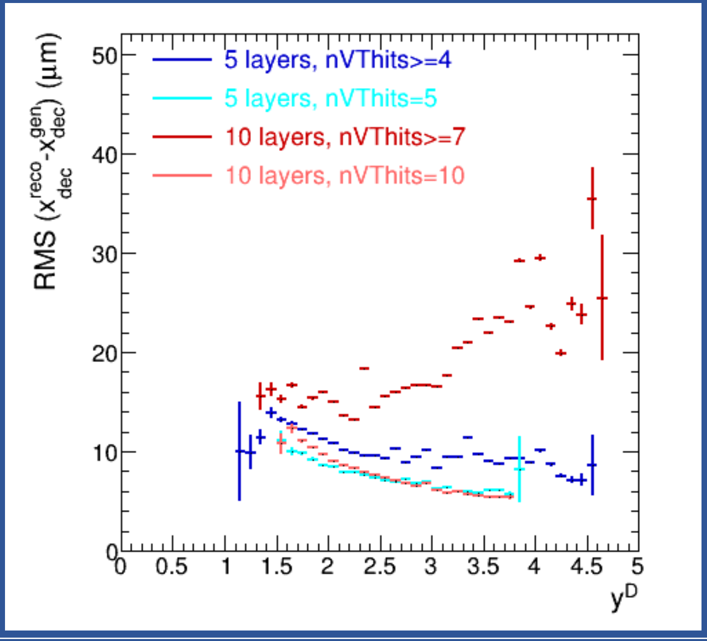
- Precise measurement requires to reconstruct all meson and baryon ground states (D^0, D^+, D_s^+ and Λ_c^+ and their antiparticles)

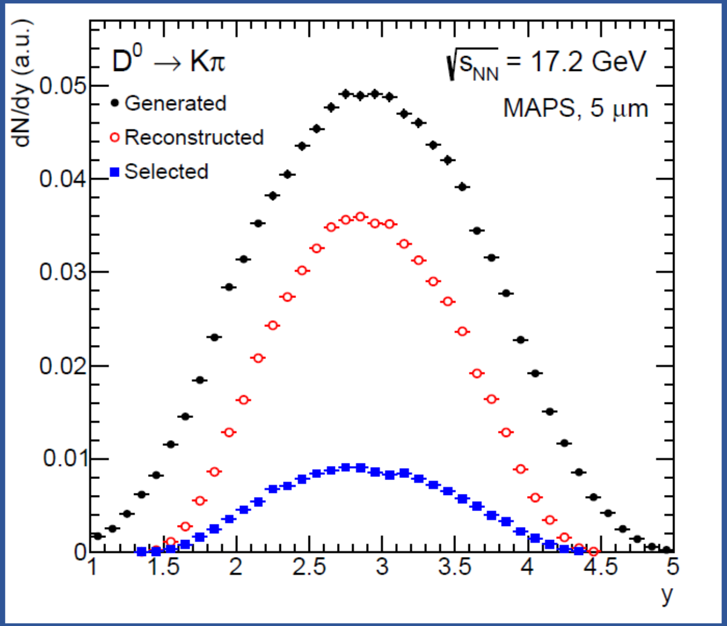
- Charm cross section **ideal reference for charmonia**

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







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%