Future fixed-target program at the CERN SPS

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Strangeness in Quark Matter
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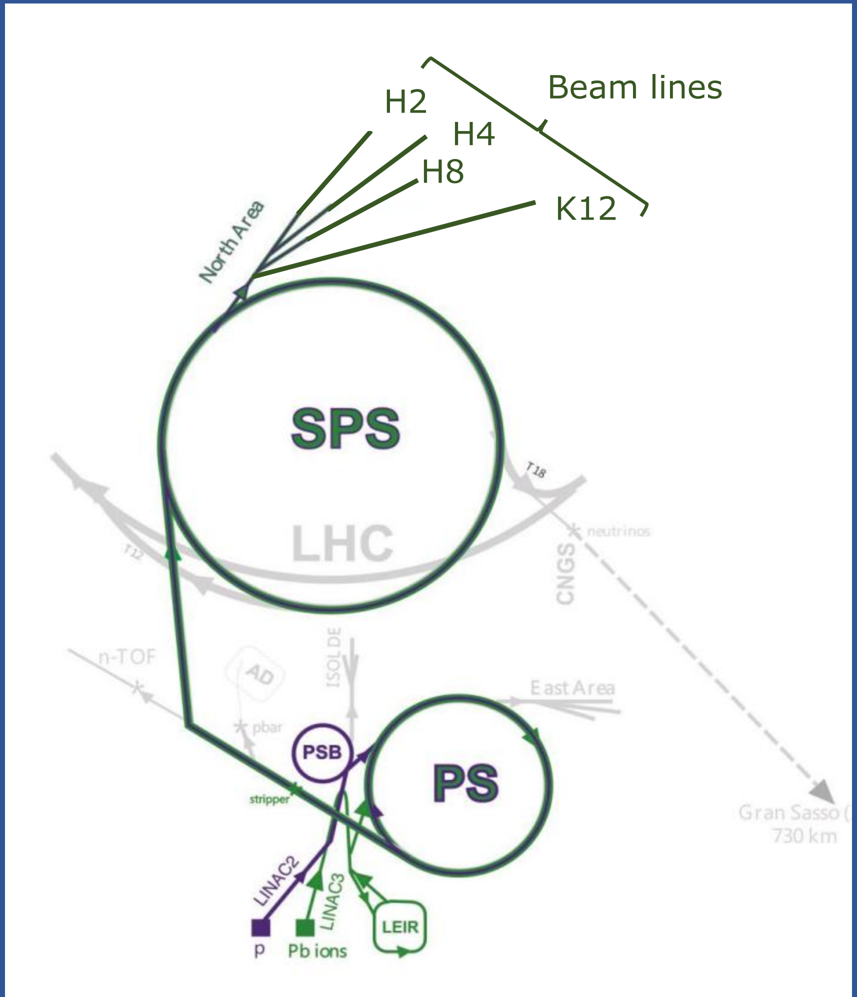
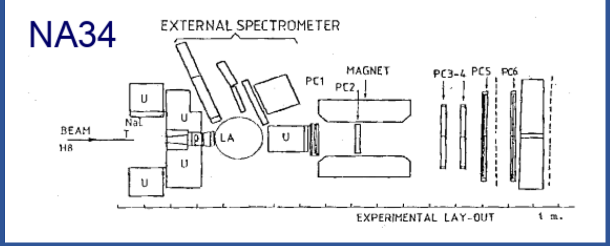
SQM 2026

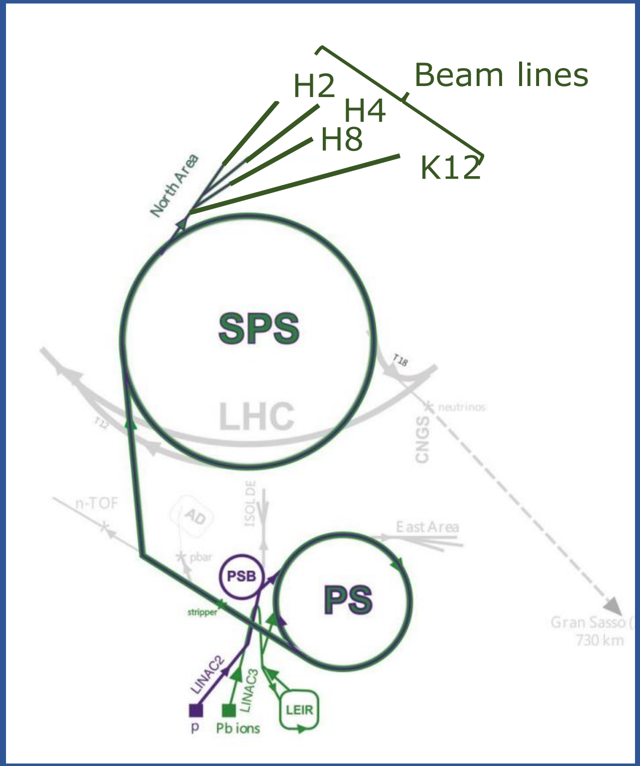
SPS: an existing and reliable machine

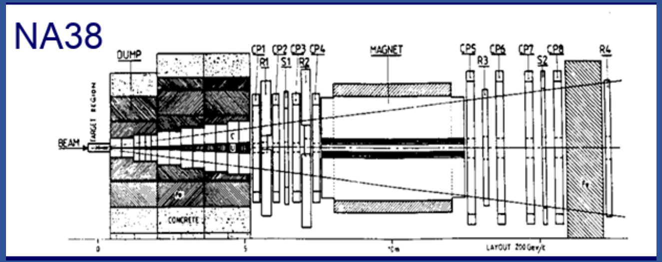
- Wide energy range for fixed-target experiments: **$5 < \sqrt{s_{NN}} < 17$ GeV**, with presently little competition
- Can deliver high luminosity ion beams, up to **$10^6 - 10^7\ s^{-1}$**
- One month/year devoted to ion data taking
- Numerous beam lines and experimental areas
- Different ion species (since 2000, In, Ar, Xe, Pb)
- Existing and reliable facility

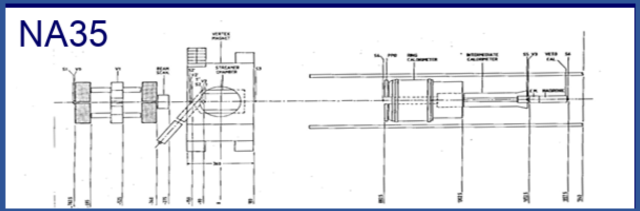


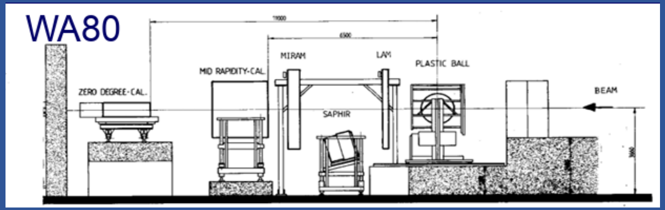
SPS is where the history began…

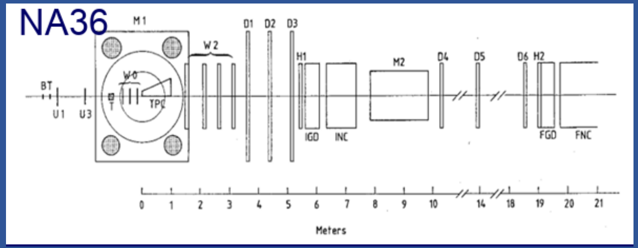


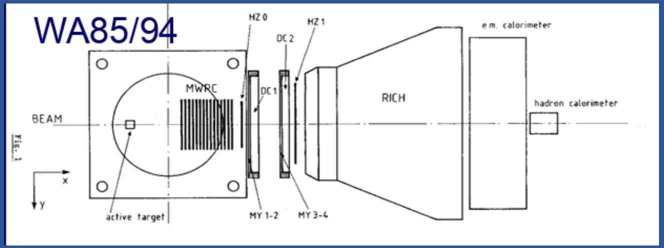






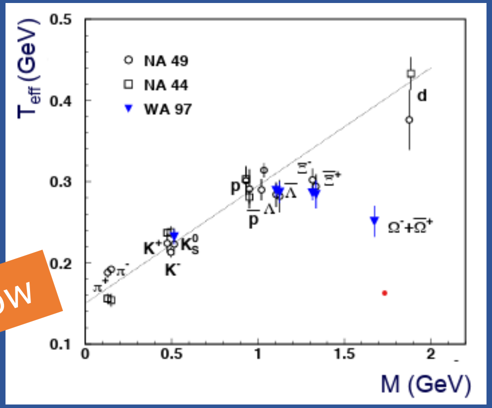




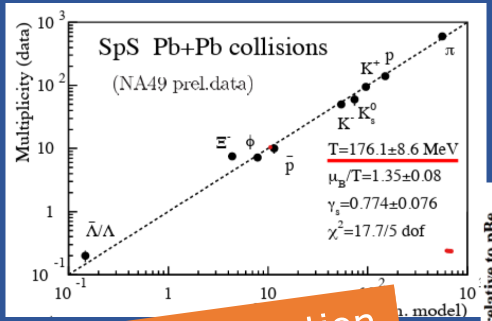


1986: first oxygen beams → **1994:** Pb beams → **2003:** end first phase → **2011:** resume HI with NA61/SHINE

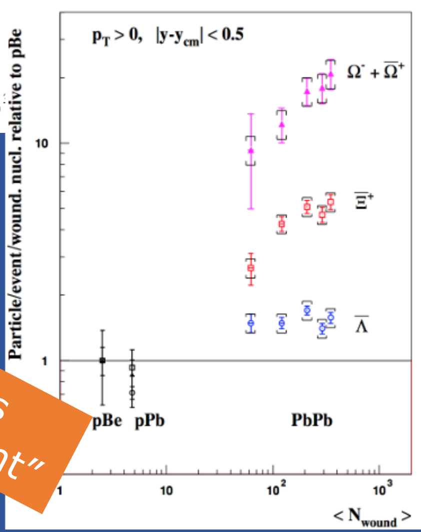
SPS is where the history began…



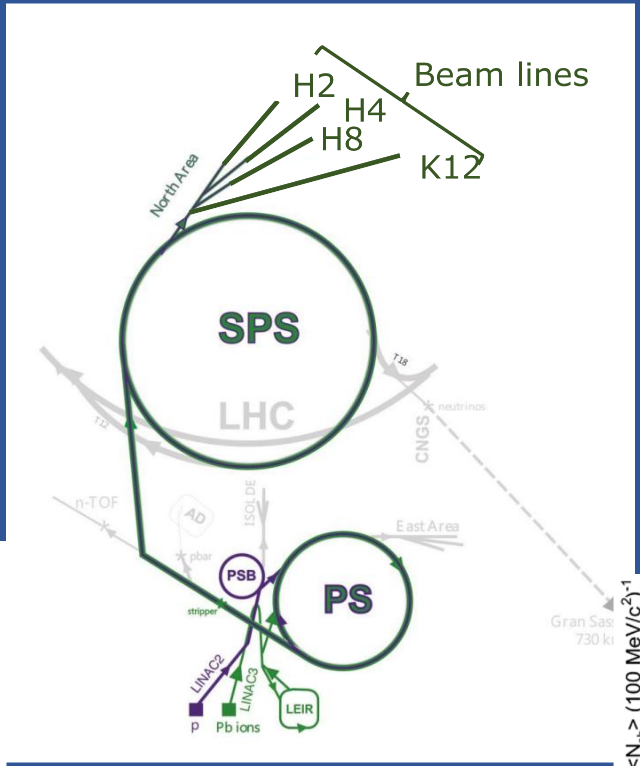
Radial flow

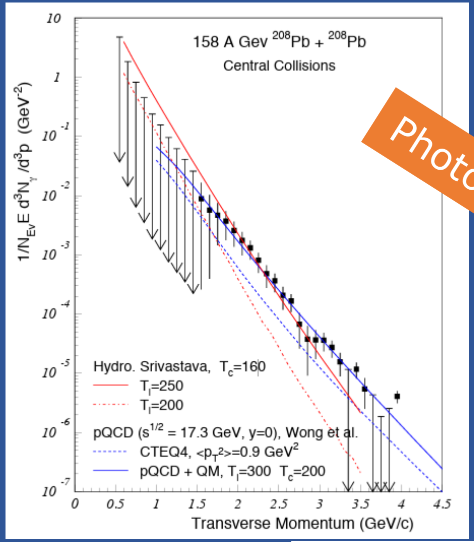


Thermal production

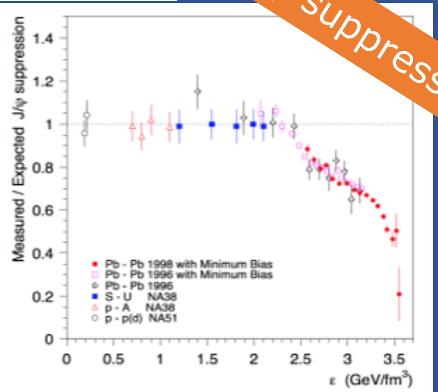


Strangeness "enhancement"

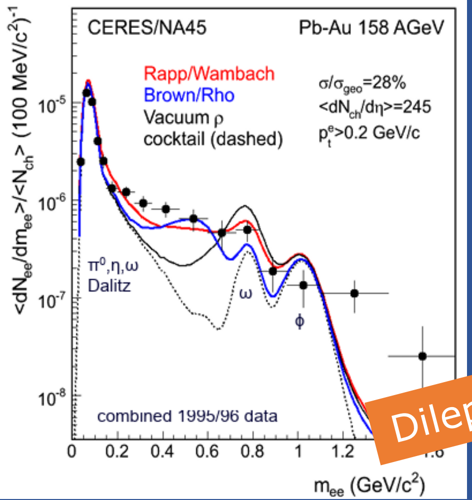




Photon excess

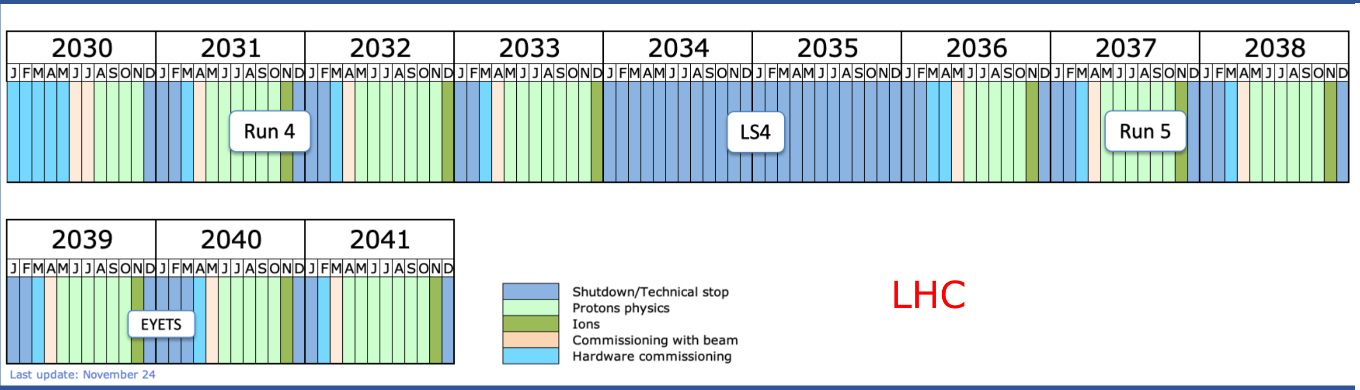


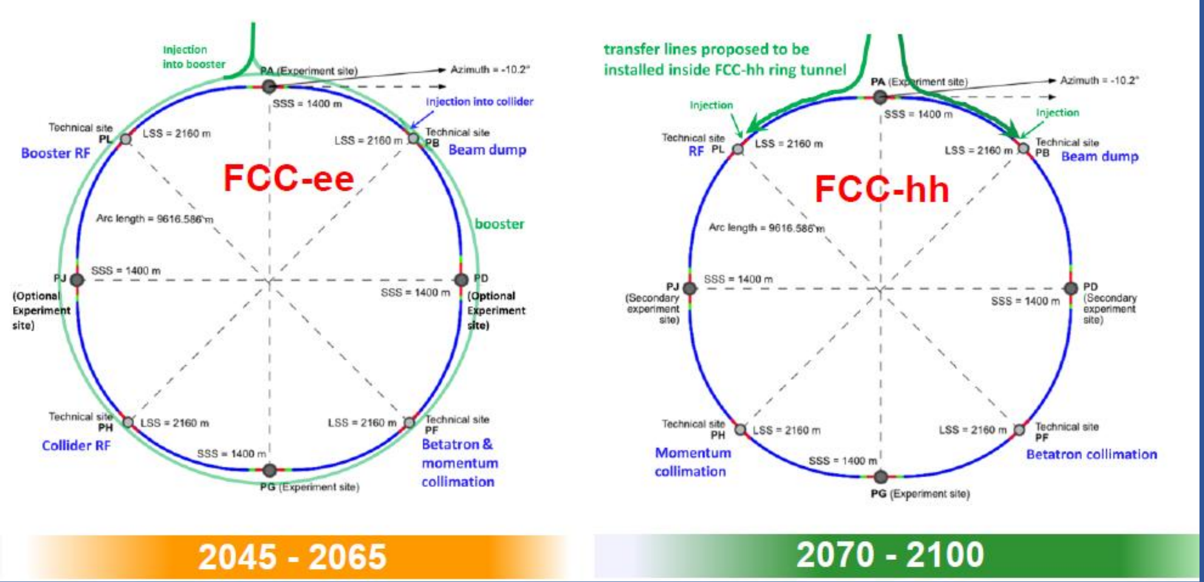
J/ψ suppression



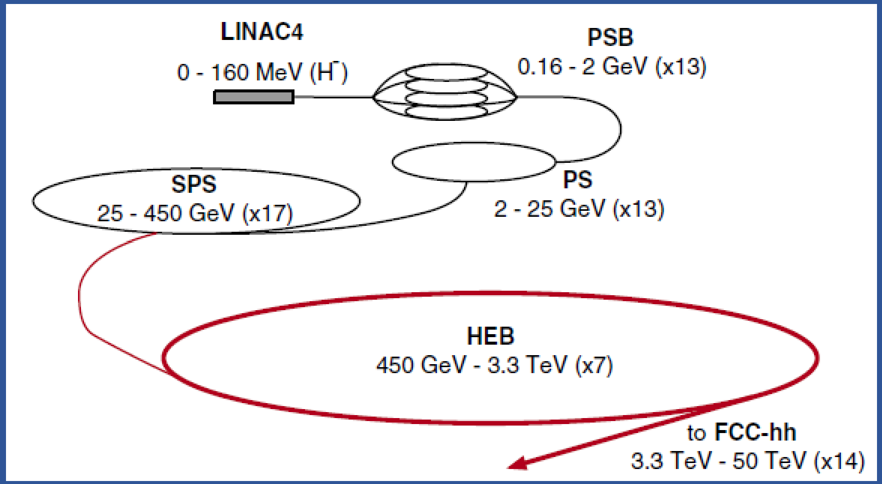
Dilepton excess

… and may still operate for a long time





- SPS could remain **available after LHC shutdown** in 2041 all along the FCC-ee era
- Later on, it may be used as an element of **the injector chain for FCC-hh**



FCC-hh CDR, EPJ ST 228, 4 (2019) 755-1107

Does an improved SPS program make sense ?

- Indeed, the mere existence of a facility does not mean it is of use for our field, so we should ask ourselves some questions

- Is this energy range **still attractive** for our field ?

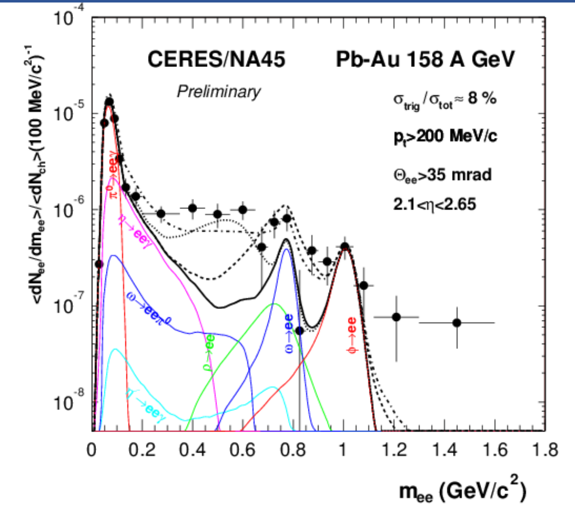
YES, continue/complete the exploration of QGP degrees of freedom and transport properties at finite-μ_B

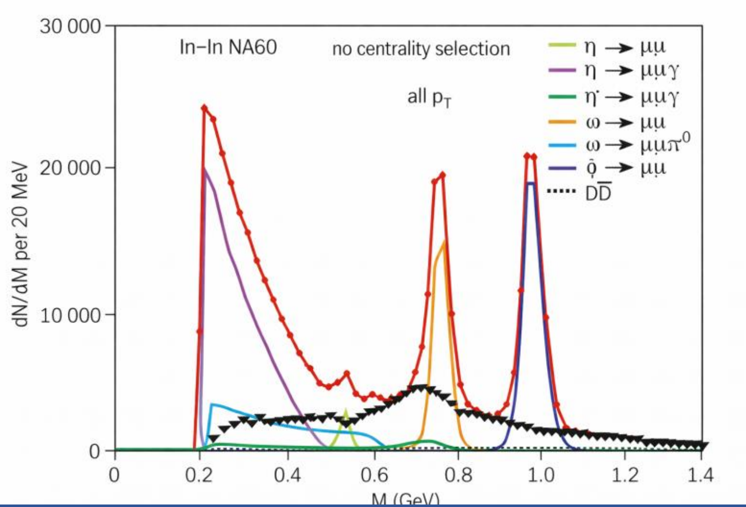
- Was the SPS energy domain ($5.2 < \sqrt{s_{NN}} < 17$ GeV) **sufficiently explored** in the '90s ?

NO, most measurements were carried out only at top SPS energy

- Will >20 years of technical **improvement** place us in a better position ?

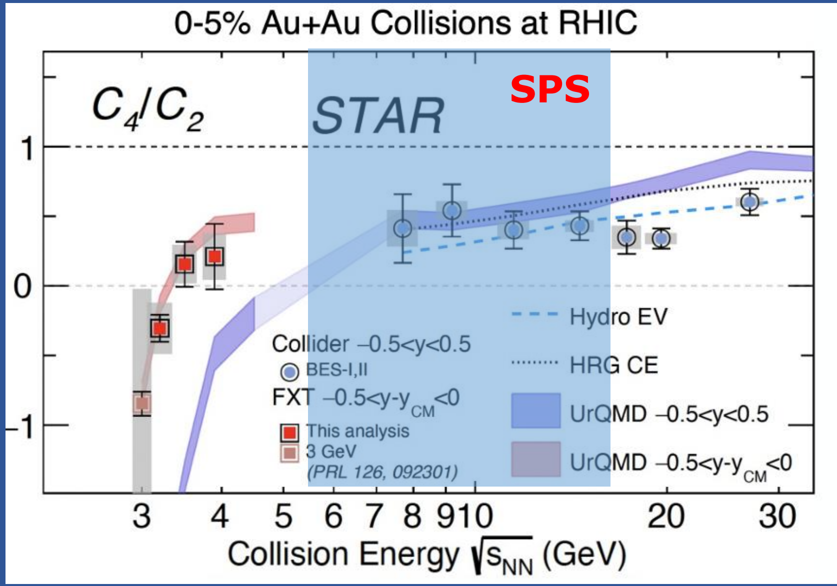
YES, see lessons from the past: studies by NA60 in the e.m. domain (2003-2004) led to strong improvements with respect to previous decade experiments (thanks to the use of LHC-like Si detectors)

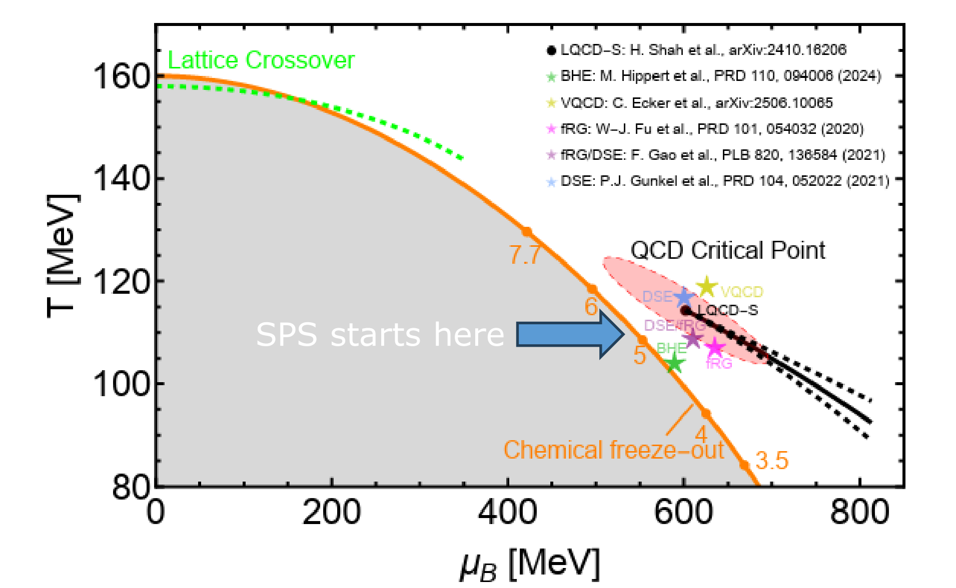


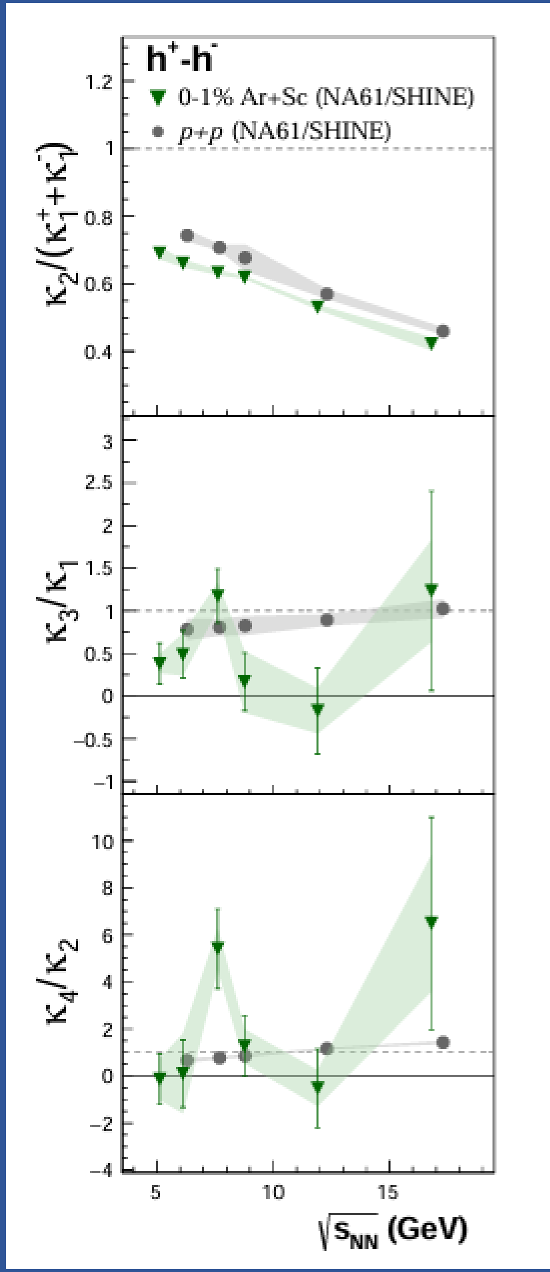


Hints for critical behaviour

H. Shah et al., Phys. Rev. C 113, L012201 (2026)







- **Net proton cumulant ratio → 5σ deviation** from reference calculations without CP at $\sqrt{s_{NN}}$ = 19.6 GeV
- Ratios of cumulants ratios of net charge distribution from NA61/SHINE → possible **hint of non-monotonic behaviour** ?

- **SPS energy range** encompasses a significant part of this domain

→ **Further investigations** with more observables needed!

NA61,arXiv:2503.22484

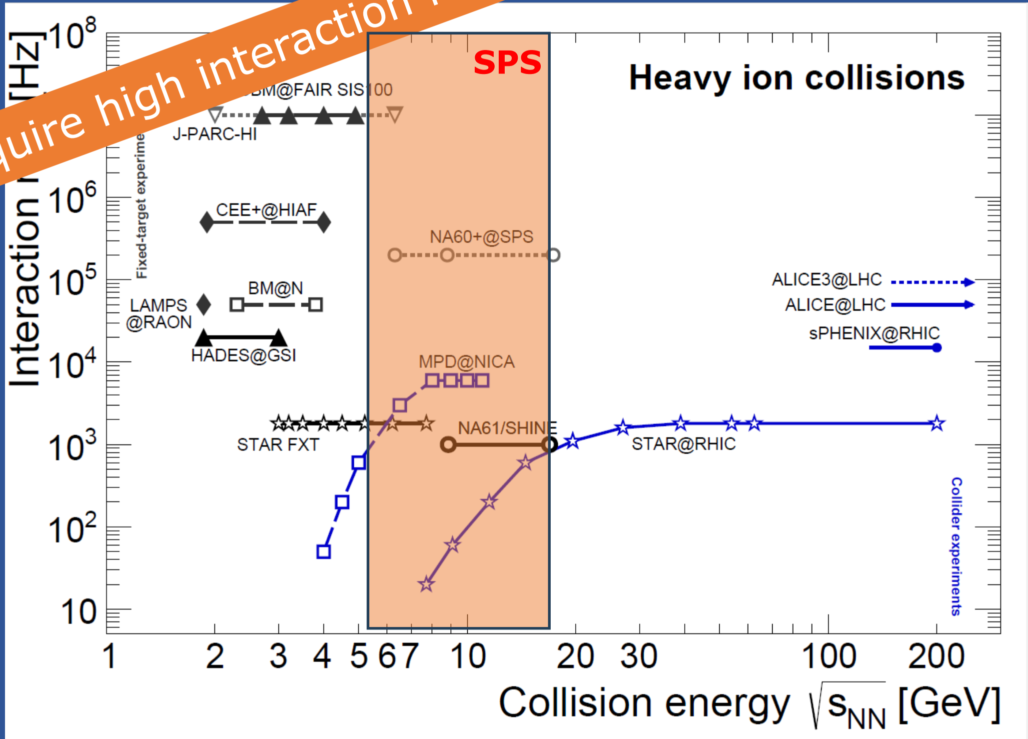
Future SPS program: crucial observables

- ❑ Several observables could not be studied effectively in the first round of experiments (1986-2000), mainly due to **small production cross sections** (rare probes) and/or **insufficient resolution**
- ❑ Top **priorities** for the next future (my own view!)
  - ❑ **Electromagnetic observables**
    - ❑ Access early temperature of the system
    - ❑ Potentially sensitive to the nature of the phase transition and chiral symmetry restoration
  - ❑ **Heavy-quark production**
    - ❑ Characterization of QGP in the vicinity of T_c
      - ❑ Transport properties
      - ❑ Thermalization
      - ❑ Hadronization
      - ❑ Modification of QCD potential
- ❑ **Hadronic observables**
  - ❑ Fluctuations
  - ❑ Collectivity
  - ❑ Strangeness

More data exist (RHIC+SPS)

Require high interaction rates

Courtesy of T. Galatyuk



Investigate **connections with CEP and first order transition**
→ Comprehensive study via **SPS + FAIR** energy range

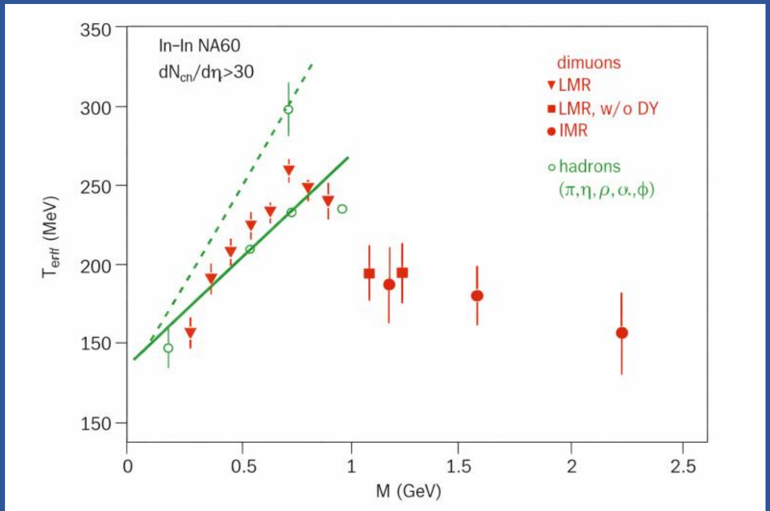
Electromagnetic probes

- Dileptons (and real photons)

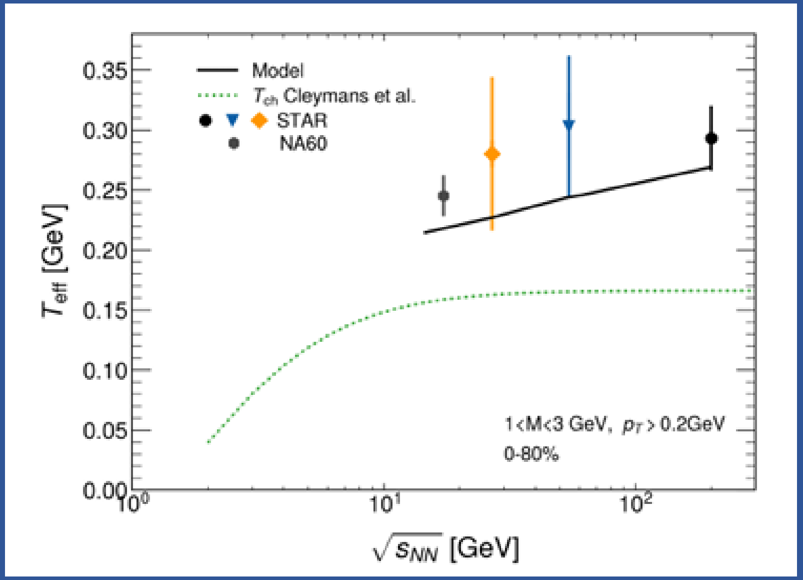
- In the **SPS** energy range
  - Breakthrough measurements from **NA60**
  - Modification of **ρ spectral function** → broadening w/o mass shift
  - Temperature from IMR **> T_{pc}**
  - **Recent LMR results** from STAR (BES-II)

- Prospects for future measurements
  - T vs √s in the IMR → **caloric curve**
  - **Polarization observables** → sensitive to microscopic processes (pre-equilibrium, QGP, hadronic) that drive dilepton production
  - Flow of thermal dileptons
  - Modification of dilepton spectrum due to **ρ-a_1 mixing**
  - Low-mass electron measurements → **conductivity**

NA60, EPJC (2009) 59: 607–623

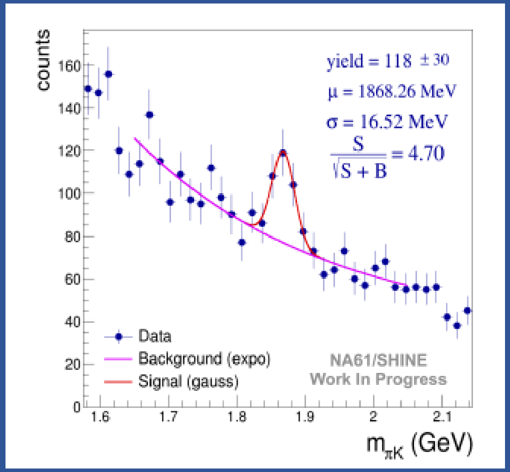


X.Y. Wu et al., arXiv:2511.08773



Open charm

- Practically **no available physics results** in this energy range

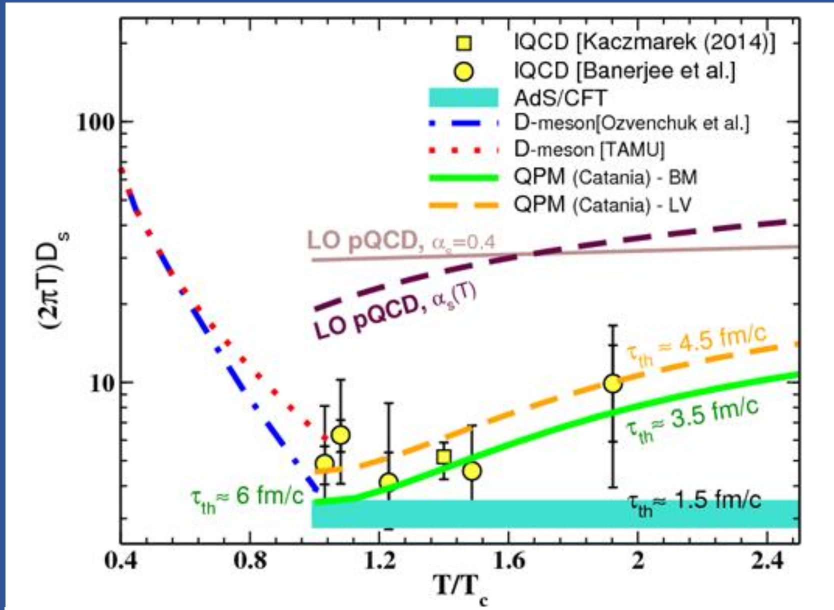


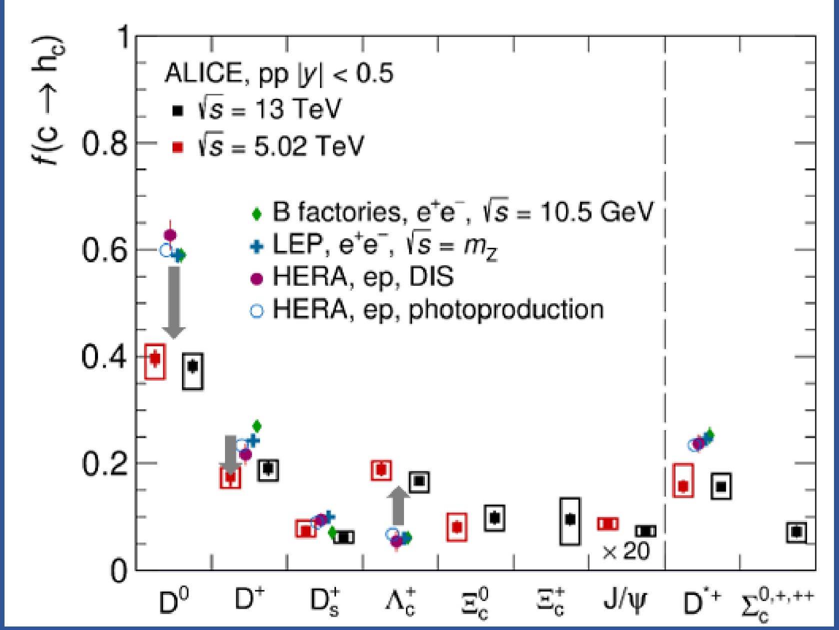
NA61, CERN-SPSC-2025-032
Pb-Pb 150 A GeV

- Possible exciting measurements (among many!)
  - Low energy: diffusion in momentum space prevails over energy loss → **R_{AA} increases with p_T**
  - High(er) energy, **DDbar angular correlations** (only 1 pair per event) → charm interactions in QGP

  - **Λ_c /D^0**, intermediate between collider A-A/pp and e^+e^- ?
  - **D_S/D^0**, role of recombination vs strangeness enhancement
  - **$v_2(\Lambda_c)/v_2(D^0)$** potentially sensitive to hydro behaviour and hadronization the relevance of the partonic phase

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

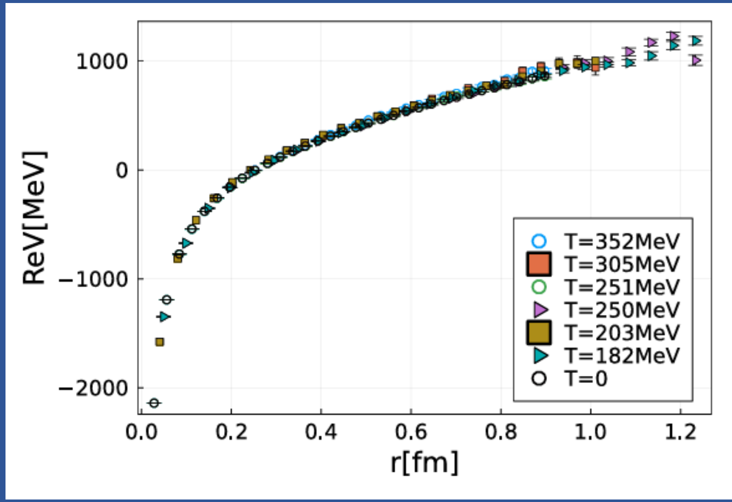




ALICE, JHEP 12 (2023) 086

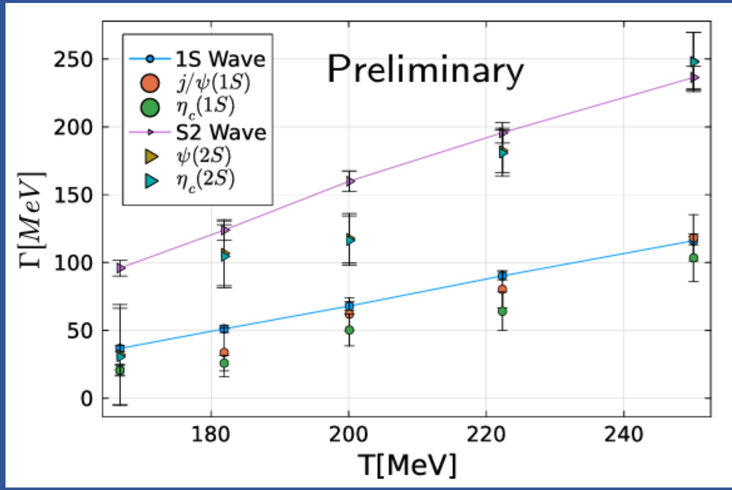
Charmonium

- How is the **fundamental QCD potential** binding heavy quark-antiquark affected by the high-μ_B environment ?
- Are there effects on quarkonium states related to the **chiral symmetry** ? Enhancement of $\psi(2S) \leftrightarrow J/\psi\ 2\pi$ due to pions in scalar channel σ becoming massless
  (H. Sorge et al., Phys.Rev.Lett. 79 (1997) 2775-2778)



A. Bazavov et al., PRD 109, 074504 (2024)

- Extensive studies carried out at top SPS energy (NA38/50/60)
- What happens below that energy → **terra incognita**



- Measure **centrality dependence of J/ψ R_{AA}** at various collision energies → role of deconfined and hadronic medium
- Precise **p-A measurements** needed to calibrate CNM break-up
- Access **ψ(2S)** and possibly χ_c in spite of lower cross sections and/or more complicate detection technique
- Connections between T via **thermal dileptons and quarkonium** phenomenology

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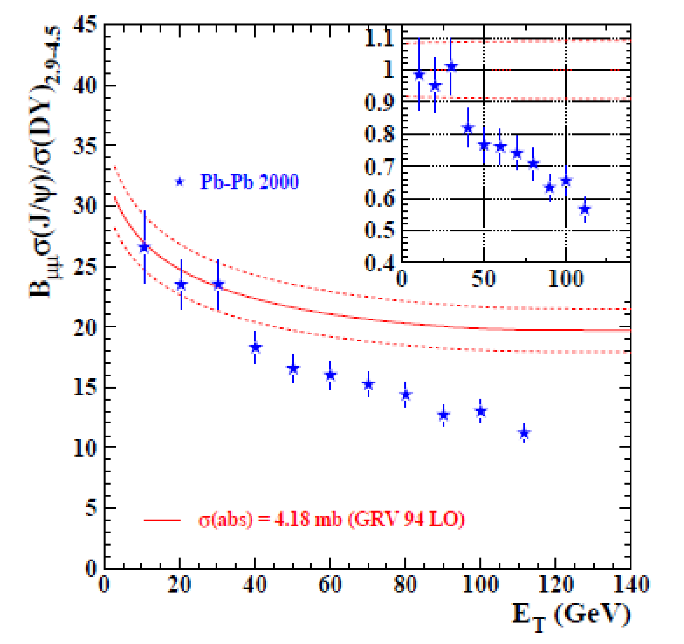
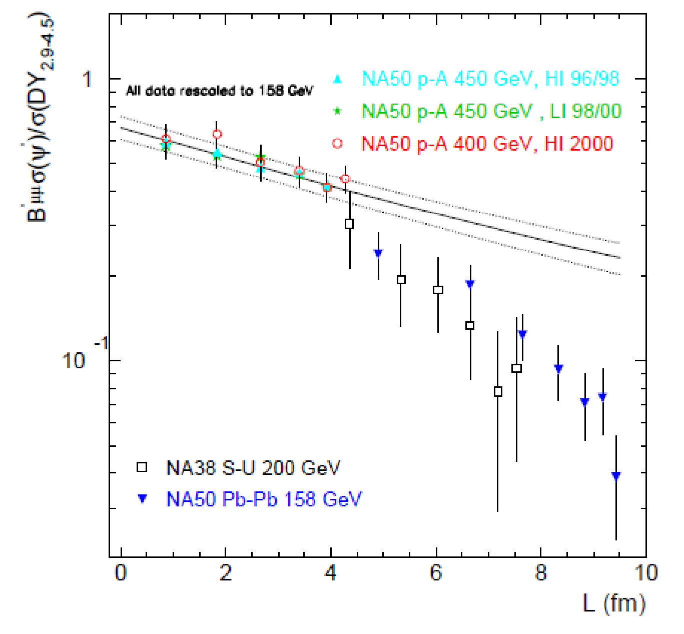

NA50, EPJC 39:335-345,2005

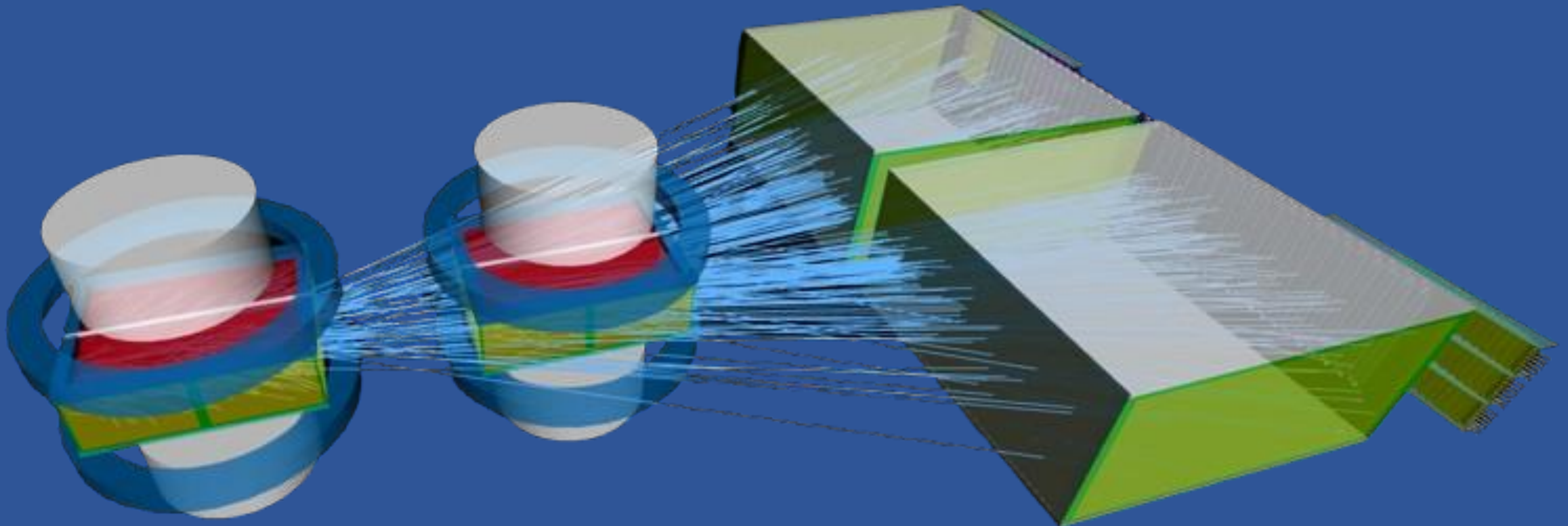

NA50, EPJC49:559-567,2007

Hadronic observables: NA61/SHINE

Multi-purpose experiment exploring (mainly) hadron production since 2009

- Study the properties of the **onset of deconfinement** and fireball
- Search for **critical point**
- Measurement of open **charm**
- **(Neutrino and cosmic ray** physics)

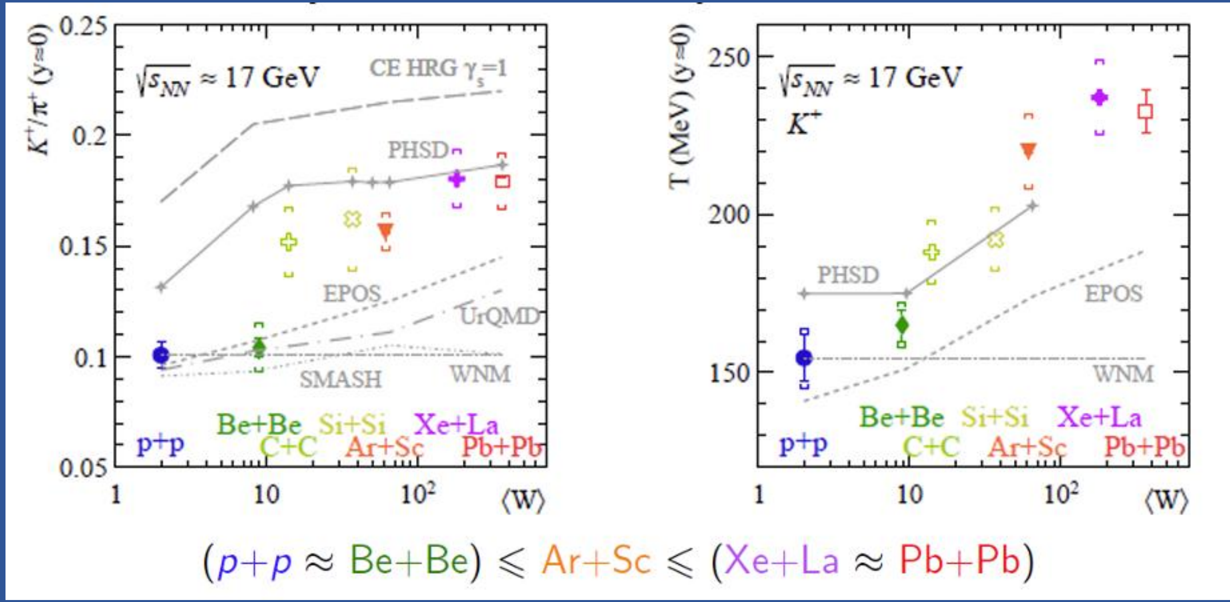
- In recent years:
  - Energy scan with **light ions** for phase diagram studies
  - **Pb-Pb collisions** mainly for charm studies



N Abgrall et al., 2014 JINST **9** P06005

NA61/SHINE: future measurements

- ❑ Current status reviewed by the Collaboration on the first day
- ❑ Two **main directions** for Run4



NA61,EPJC84(2024) 416

- ❑ **Rapid change in hadron production** between:
  - ❑ Be+Be (string-dominated)
  - ❑ Ar+Sc (collective/QGP-like)
- ❑ **Possible transition** between dominant production mechanisms ?
  - ❑ Resonance/string dominated regime
  - ❑ Collective QGP fireball formation
- ❑ This feature appears at top SPS energies and intermediate nuclear mass

- ❑ **Measure hadron production in O+O, Mg+Mg, B+B**
- ❑ Probe three dynamical regimes:
  - 13*A* GeV/*c* → resonance-dominated domain
  - 30*A* GeV/*c* → mixed/transition region
  - 150*A* GeV/*c* → strings → QGP changeover region

These data will be relevant also to further investigate the **isospin violation results ($\langle K^+ + K^- \rangle / 2K^0_s > 1$)** recently reported by NA61/SHINE (Nat Commun **16**, 2849 (2025))

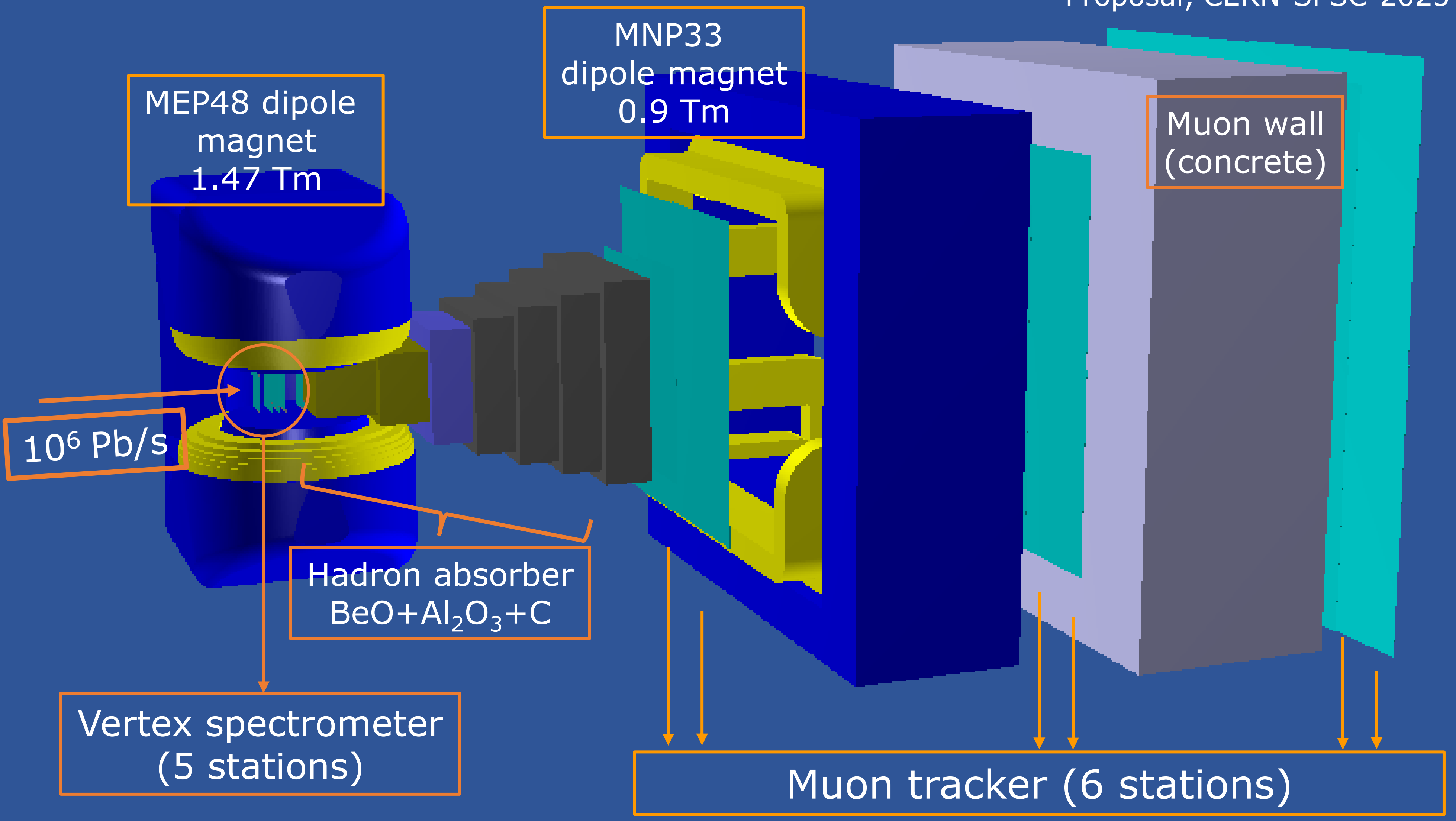
Hard and e.m. probes: NA60+/DiCE

Proposal, CERN-SPSC-2025-023

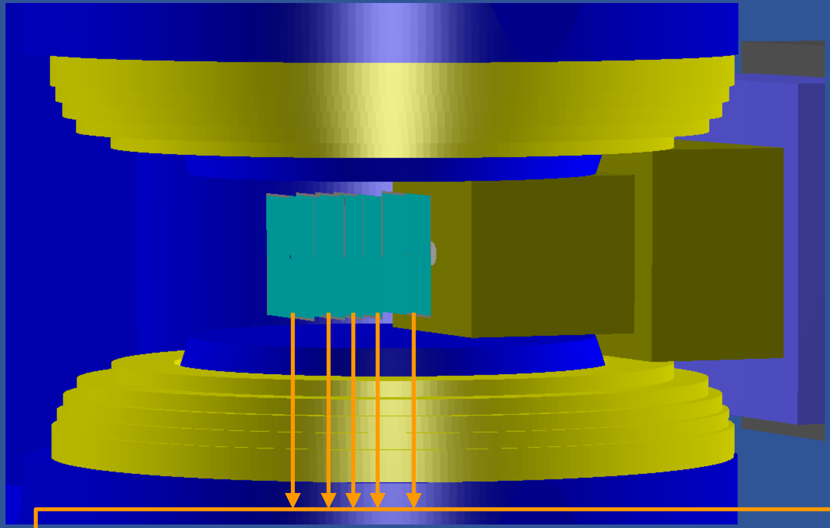
Inspired by the **former NA60** detector (2002-2004)

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

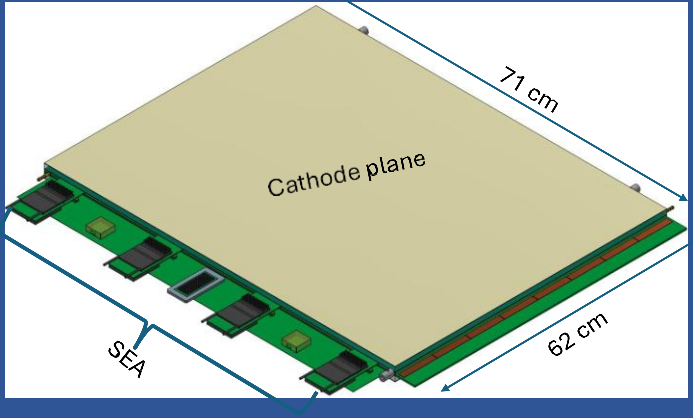
SPS **energy scan**: vary z-position of the muon spectrometer and thickness of hadron absorber

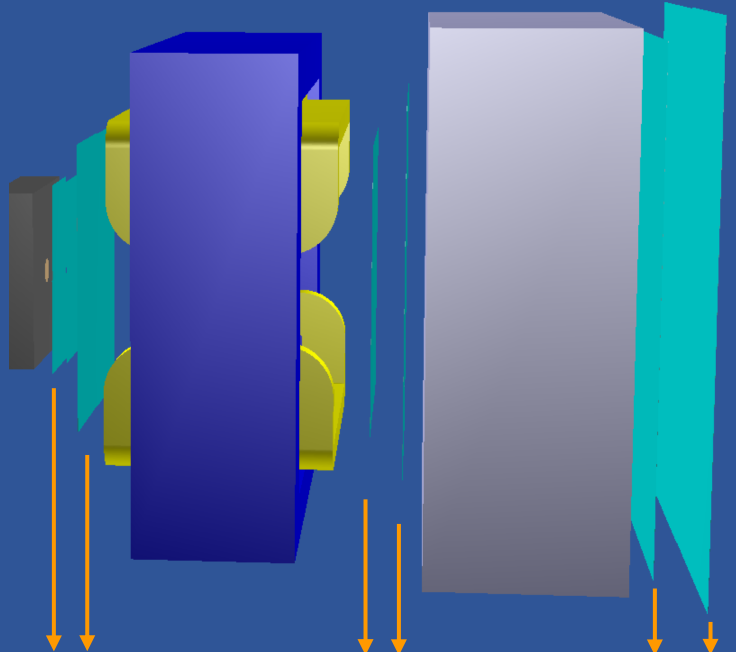


NA60+/DiCE: detectors



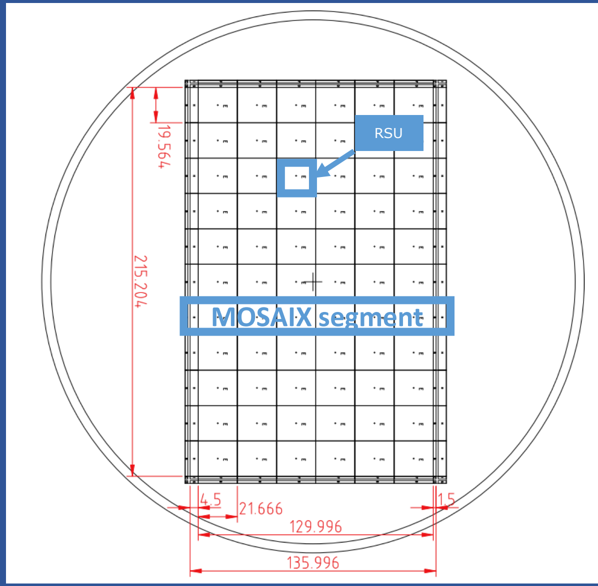
Vetex tracker (5 stations)





Muon tracker (6 stations)

- ❑ Expected rate → max 5 MHz/cm^2
- ❑ **Synergy with ALICE ITS3**
  - ❑ **MAPS detectors**
  - ❑ Pixel pitch 20.5 μm
  - ❑ 0.1%X_0 material budget
  - ❑ Stitching procedure to realize needed geometry
  - ❑ First production submitted



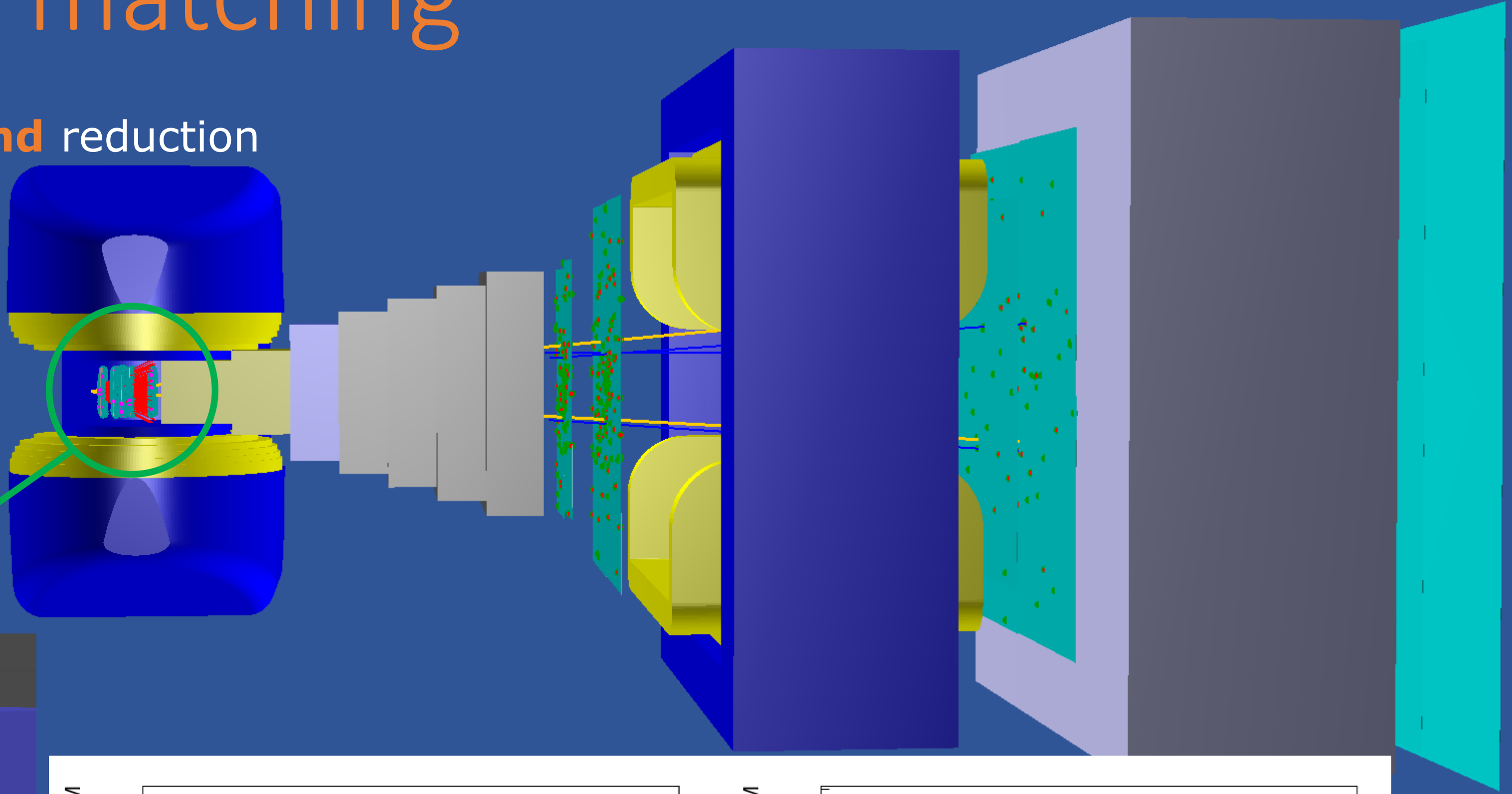
- ❑ Expected rate ~ 2kHz/cm^2 (max)
- ❑ Current choice
  - → **MWPCs** for most stations
  - → **GEM** or **μRWELL** for first station under discussion
- ❑ 100 μm spatial resolution in bending plane
- ❑ <3-4 % X_0 material budget
- ❑ Two prototypes already tested at the CERN SPS, third was built

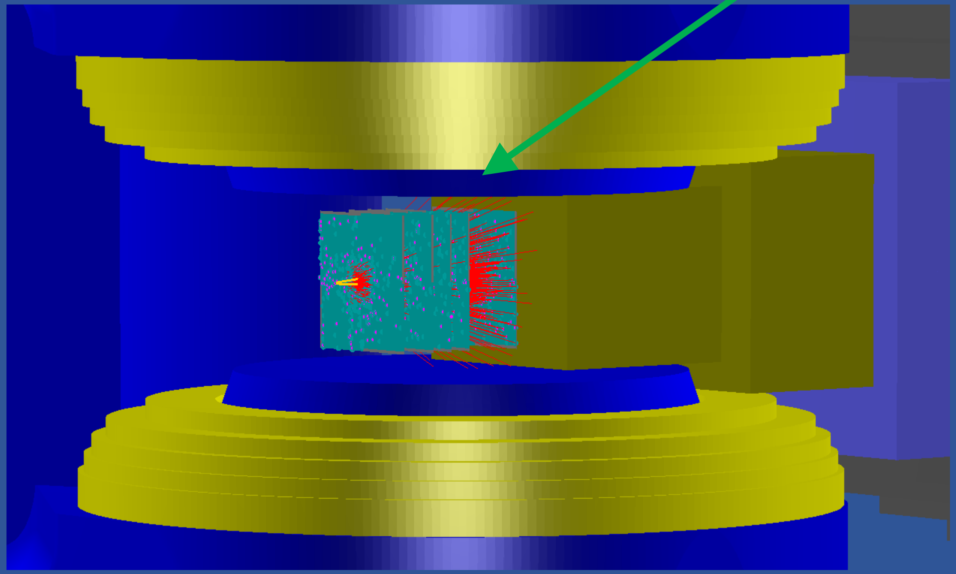
NA60+/DiCE: track matching

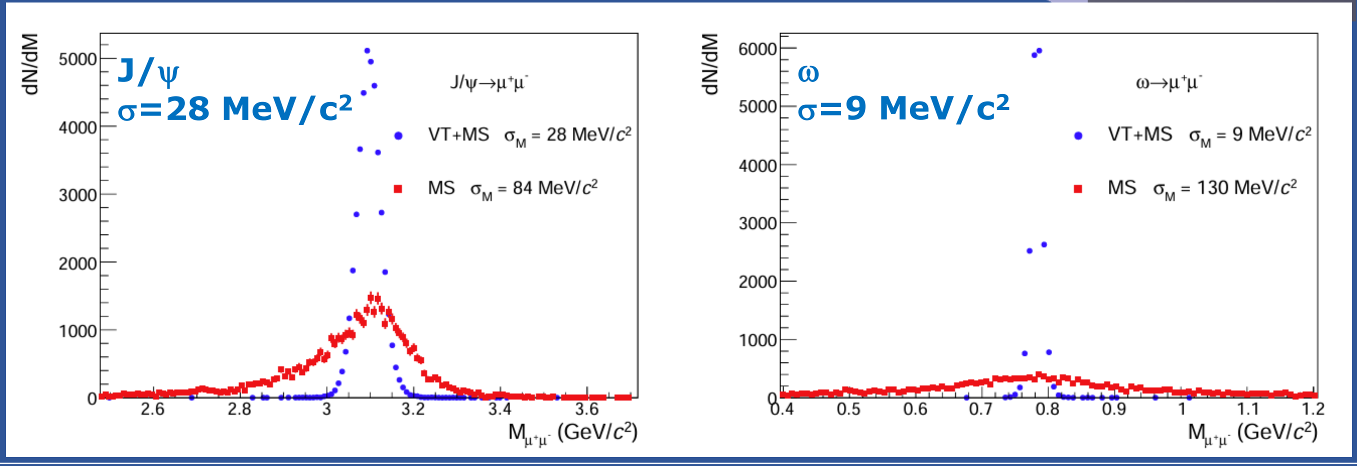
Essential for **resolution** and **background** reduction

- Vertex tracks (red)
- "Muon" tracks (blue)
- Matched tracks (yellow)

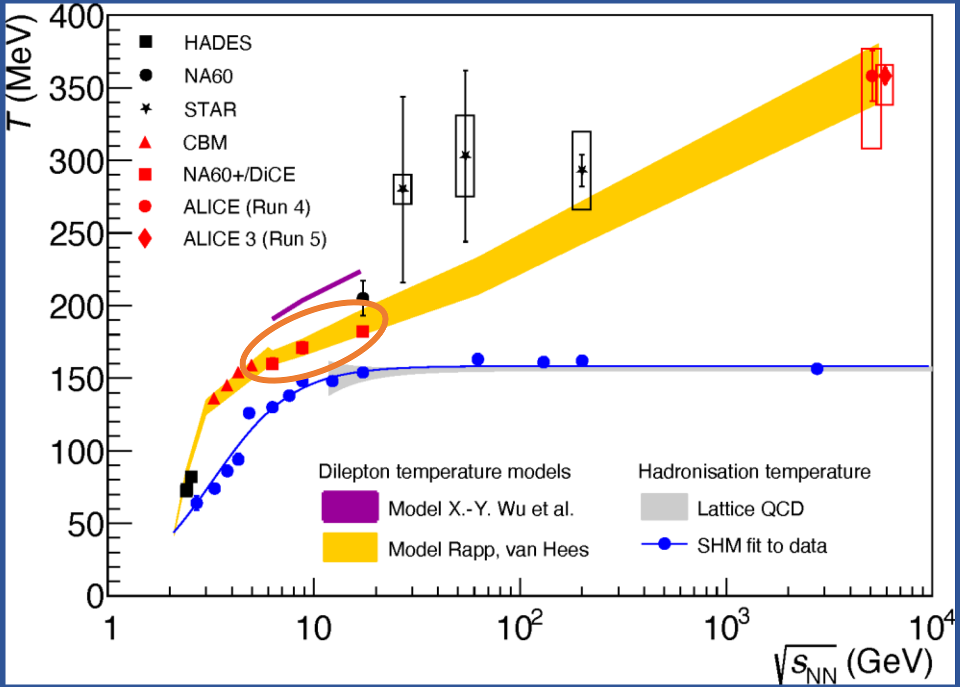
χ^2 matching
(coordinates+momentum)







NA60+/DiCE: dileptons

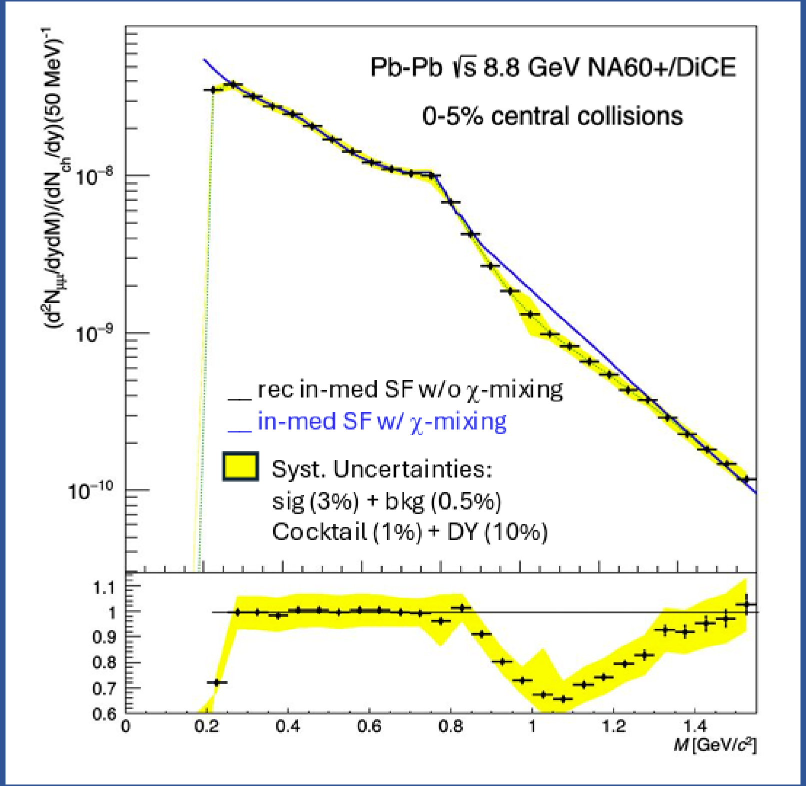


R.Rapp and H.v.Hees, PLB753(2016) 586
T. Galatyuk et al., EPJA52(2016) 131
X.Y. Wu et al., arXiv:2511.08773

- Probing temporal evolution of medium via multi-differential measurements vs M, p_T and v_2

multi-dimensional tomography of the QCD medium

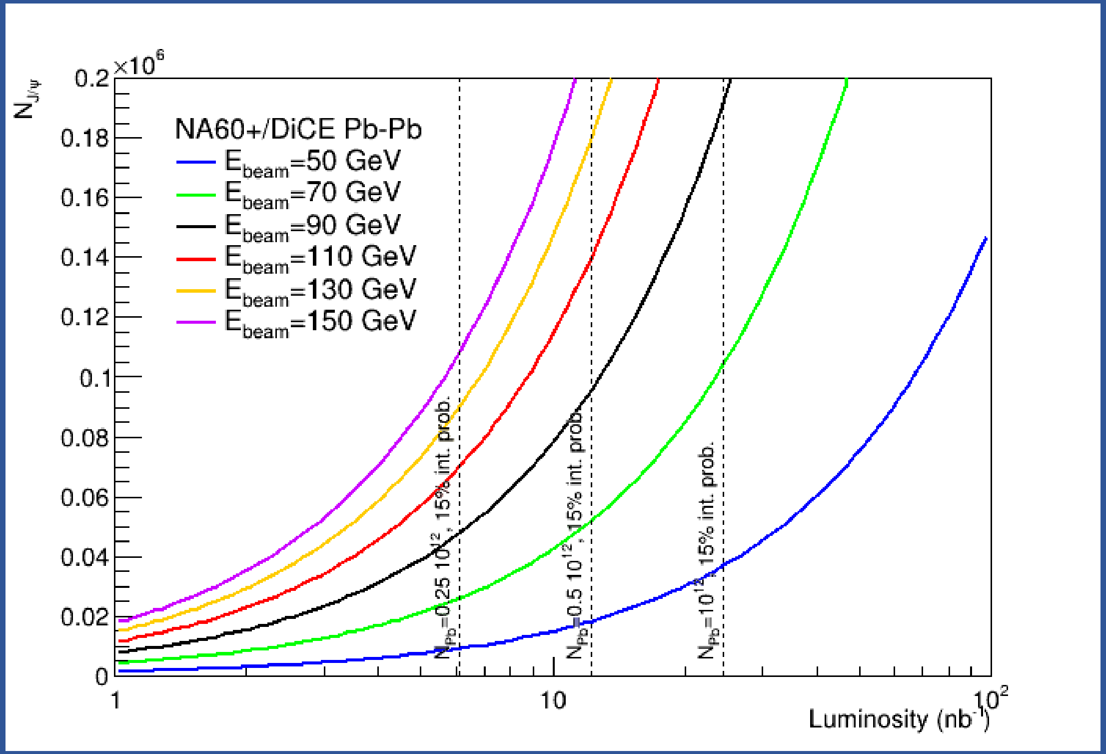
- Chiral symmetry restoration: full ρ-a_1 chiral mixing should give **20-30% enhancement** expected in $0.8 < M < 1.5$ GeV/c^2 w.r.t. no mixing

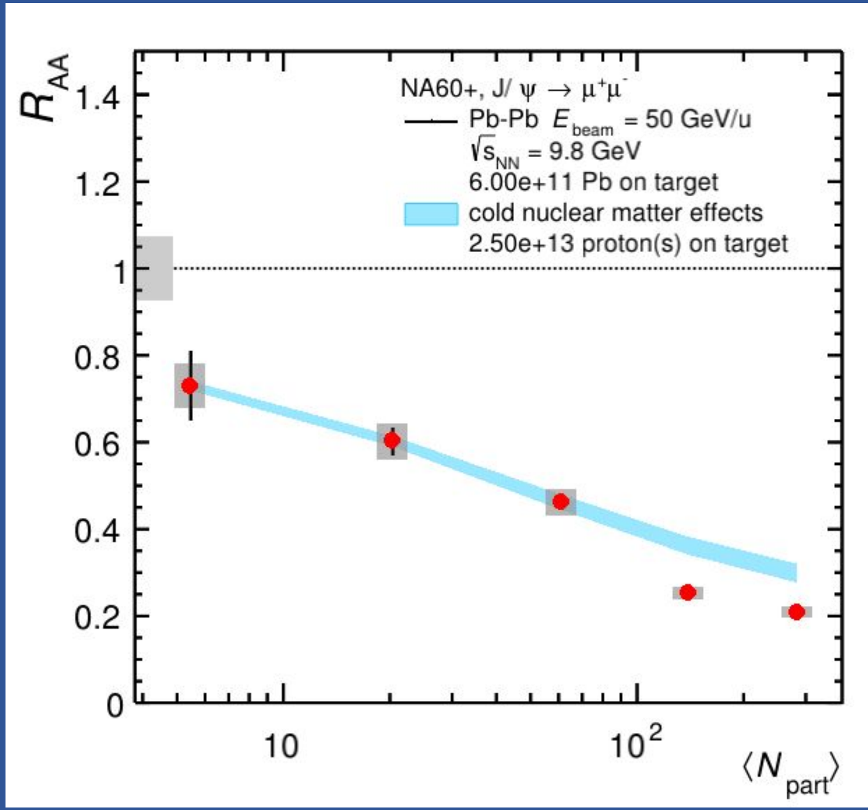


R. Rapp and H. van Hees,PLB753 (2016) 586

- Precise mapping of T over the range $6 < \sqrt{s} < 17$ GeV
- → 2-3% uncertainty expected
- Flattening of caloric curve may give evidence of **first order phase transition**

NA60+/DiCE: quarkonium



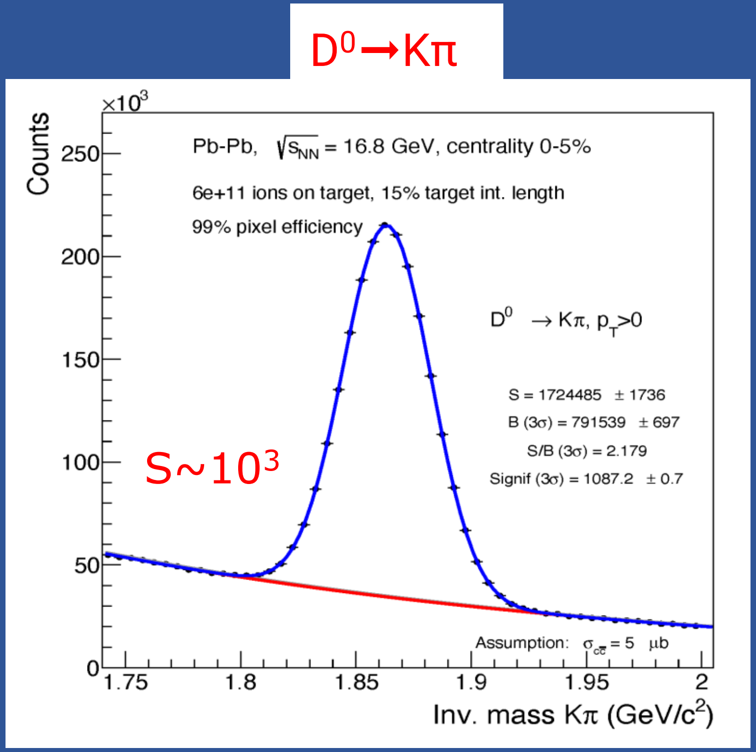


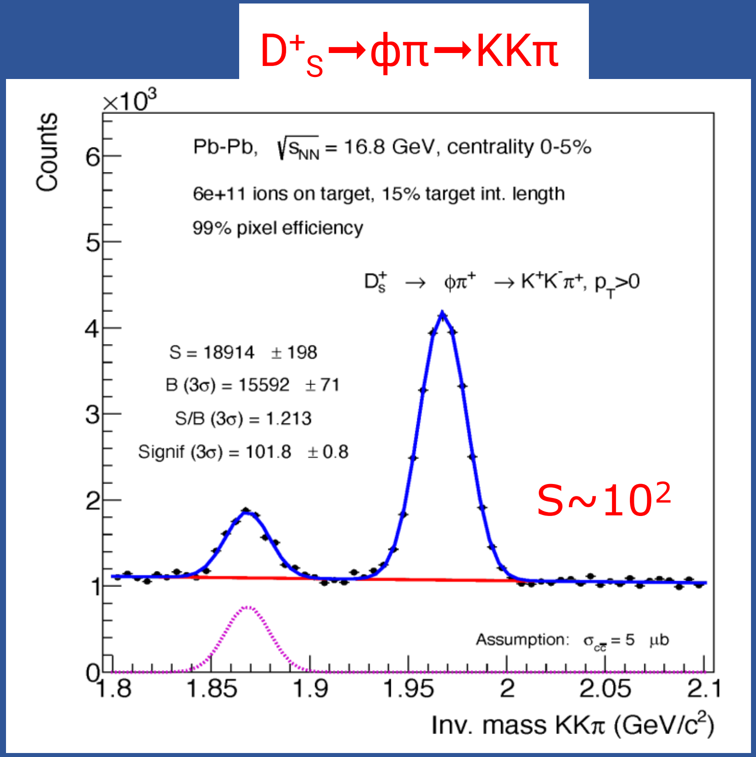
- **Luminosity:** ~0.5 10^{12} Pb ions on 15% interaction probability Pb target(s)
- **Expected statistics:** 10^4 – 10^5 J/ψ from low to high energy
- **ψ(2S)** → factor ~10^2 smaller

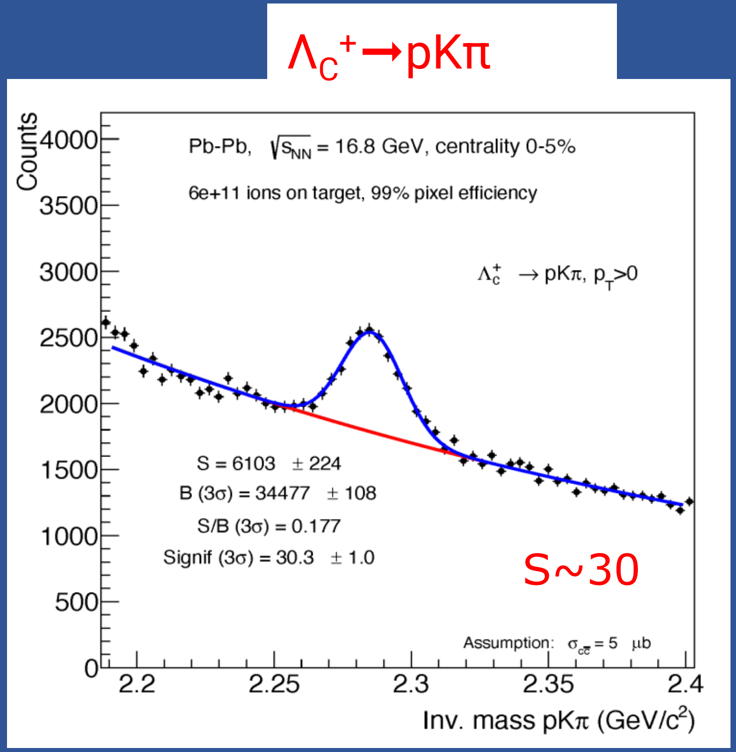
- **Performance** for J/ψ R_{AA} at E_{lab} = 50 GeV
  - Assume 30% suppression in 0-20% and 20-40% centralities
  - Cold nuclear matter effects from p-Be, p-Cu, p-Pb data

NA60+/DiCE: open charm

- Decay products reconstructed in the vertex spectrometer
- Geometrical selections on the displaced decay-vertex topology (cτ~60-300 μm) to enhance the S/B
  - Boosted Decision Tree for Λ_c : decisive to enhance significance

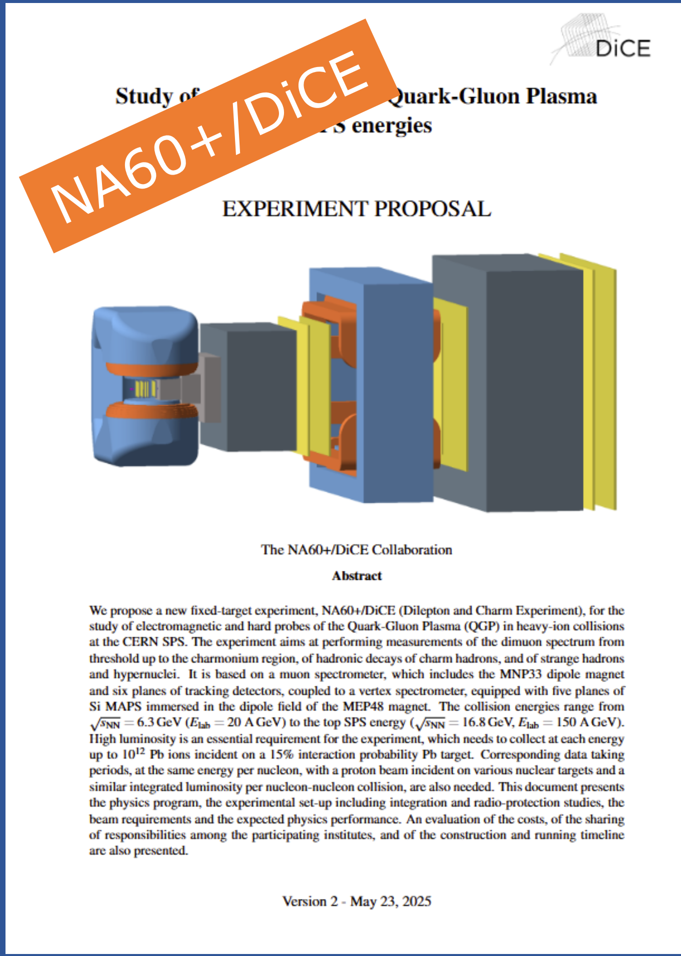






- **Complete measurement of charm states**
- D^0 , D^+ , D_s^+ , Λ_c^+ , and possibly $\Xi_c^{0,+}$ → Charm cross section measurement
- Multi-differential studies vs v_2, p_T, y and centrality

Current planning



EXPERIMENT PROPOSAL

The NA60+/DiCE Collaboration

Abstract

We propose a new fixed-target experiment, NA60+/DiCE (Dilepton and Charm Experiment), for the study of electromagnetic and hard probes of the Quark-Gluon Plasma (QGP) in heavy-ion collisions at the CERN SPS. The experiment aims at performing measurements of the dimuon spectrum from threshold up to the charmonium region, of hadronic decays of charm hadrons, and of strange hadrons and hypernuclei. It is based on a muon spectrometer, which includes the MNP33 dipole magnet and six planes of tracking detectors, coupled to a vertex spectrometer, equipped with five planes of Si MAPS immersed in the dipole field of the MEP48 magnet. The collision energies range from $\sqrt{s_{NN}} = 6.3$ GeV ($E_{lab} = 20$ A GeV) to the top SPS energy ($\sqrt{s_{NN}} = 16.8$ GeV, $E_{lab} = 150$ A GeV). High luminosity is an essential requirement for the experiment, which needs to collect at each energy up to 10^{12} Pb ions incident on a 15% interaction probability Pb target. Corresponding data taking periods, at the same energy per nucleon, with a proton beam incident on various nuclear targets and a similar integrated luminosity per nucleon-nucleon collision, are also needed. This document presents the physics program, the experimental set-up including integration and radio-protection studies, the beam requirements and the expected physics performance. An evaluation of the costs, of the sharing of responsibilities among the participating institutes, and of the construction and running timeline are also presented.

Version 2 - May 23, 2025

Submission of **experiment proposal** in May 2025 **https://cds.cern.ch/record/2932302**

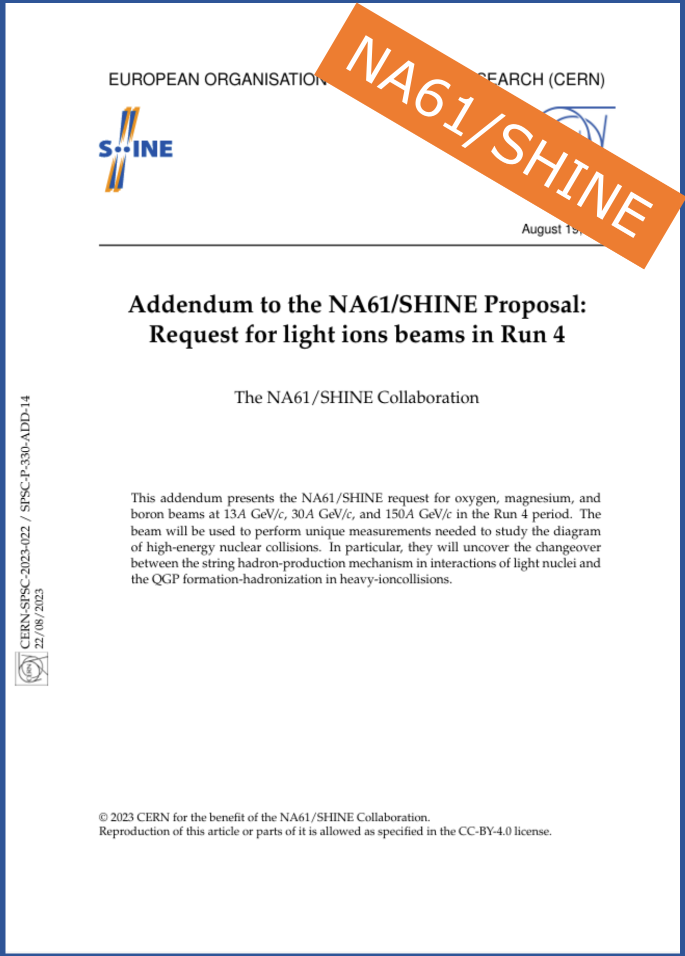
Recommended for approval by SPSC in September 2025

Now under discussion at the **Research Board:** discuss resources for infrastructure and beam
→ **Expected approval** later this year

Request for **oxygen, magnesium, and boron** beams at **13A, 30A and 150A GeV/c** during the Run4 period

7 days per species per energy
(9 weeks total)

Further upgrade during Run4
→ new magnetic spectrometer (Si tracking+ large-area MPGDs), increase DAQ rate to ~10 kHz



Addendum to the NA61/SHINE Proposal: Request for light ions beams in Run 4

The NA61/SHINE Collaboration

This addendum presents the NA61/SHINE request for oxygen, magnesium, and boron beams at 13A GeV/c, 30A GeV/c, and 150A GeV/c in the Run 4 period. The beam will be used to perform unique measurements needed to study the diagram of high-energy nuclear collisions. In particular, they will uncover the changeover between the string hadron-production mechanism in interactions of light nuclei and the QGP formation-hadronization in heavy-ioncollisions.

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Start **physics data taking** likely in 2031
→ 7 years physics program with Pb-Pb and p-A at various energies

Envisage data taking from the beginning of **run4**

Conclusions

The **CERN SPS** is a **powerful and versatile facility** in the energy range $5<\sqrt{s_{NN}}<17$ GeV, that offers significant possibilities for QGP studies at finite μ_B

In particular, little is known **on hard and e.m. probes** in this energy range, and their penetrating nature makes them ideal for the characterization of a system that spends significant time in the **region around deconfinement and chiral transition**

A brand-new experiment, **NA60+/DiCE**, was recently recommended for approval by CERN, with a physics program spanning the '30s, after Long Shutdown 3

Also, **NA61/SHINE** is proposing a continuation of its systematic measurements of hadronic observables

The support of this community, in terms of **theoretical** ideas and developments, as well as contribution to the **experimental** effort, will greatly improve the physics outcome!

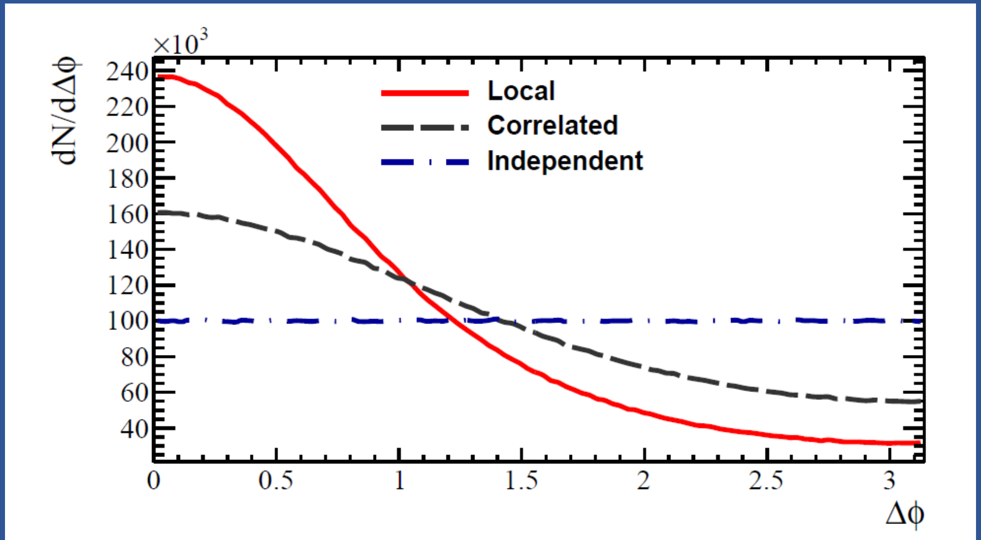
Notes

NA61/SHINE: future measurements

- Current status reviewed by the Collaboration on the first day
- Two **main directions** for Run4

- **Charm correlation measurements**
  - SPS regime is unique because
    - Only ~1 char pair per event
    - Minimal combinatorial background
  - Clean two-body system

- **Investigate various potential scenarios**
  - Local Production & Coherent Transport
  - Independent Emission
  - Correlated Production Without Medium Effects



(from M. Gazdzicki et al., arXiv:2507.08602)

- Measurement inNA61/SHINE requires better rate capability than now
- Upgrade with **new magnetic spectrometer (Si ALPIDE +MPGDs)** proposed for the second part of Run 4
- NA60+/DiCE may be better placed for such a measurement

(Hidden) charm

Indications for small screening effects + large reaction rates (dissociation + regeneration)
Does this situation persist at finite μ_B ?
How is the fundamental QCD potential affected ?
In medium spectral functions ?

Influence of hadronic medium at finite μ_B
Strong collisional broadening for low-mass hadrons (ρ)
Possibly a small effect for tightly bound J/psi
Psi(2S) may be affected →already strong indications from p-Pb/d-Au results at LHC/RHIC
Need

Possible connection with chiral symmetry restoration
Enhancement of ψ(2S)←→J/ψ 2π due to pions in scalar channel σ becoming massless at CEP
Equilibration of ratio ψ(2S)/J/ψ, strongly T-dependent

Single-out energy threshold for suppression effects ?
Understanding of CNM effects
Connection of charmonium related observables with T measurements (thermal dileptons)

(Open) charm

Add what is experimentally known from the past

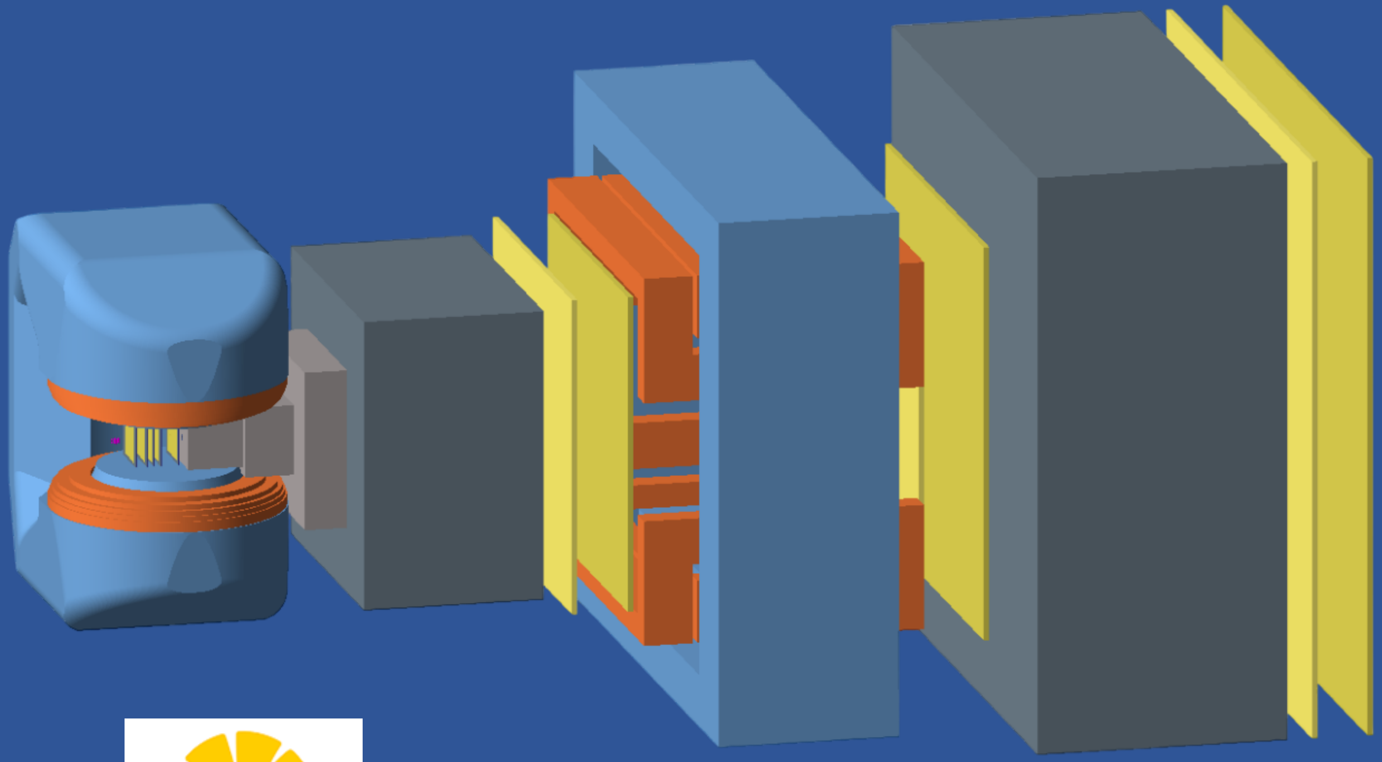
Sensitivity to CEP ?

- Initial production
  - Nuclei crossing time ~ QGP lifetime
  - Λ_c / antiΛ_c production in a finite-μ_B matter
  - Fermi motion (low-$\sqrt{s}$ range)
- Diffusion in the "QCD liquid" around T_c and in hadronic phase
  - Matter spends (more) time around T_c and in hadronic phase (complementary to LHC)
  - Discontinuity of $D_s(T)$ around the phase transition (or too broad ?) ? Influence of finite μ_B ?
  - (Incomplete) charm thermalization ?
  - Low-$\sqrt{s}$ range: diffusion in momentum space prevails over energy loss, R_{AA} increases with p_T ? → spatial diffusion cioefficient
  - High-$\sqrt{s}$ range: DDbar angular correlations in a no background environment → charm interactions in QGP (needs clean pp-pA reference)
- Hadronization mechanism
  - Λ_c /D^0 ratio, intermediate between collider A-A/pp and e^+e^- ?
  - D_S/D^0, role of recombination vs strangeness enhancement
  - $v_2(\Lambda_c)/v_2(D^0)$ potentially sensitive to hydro behaviour and hadronization the relevance of the partonic phase
- Directed flow
  - Sensitivity to initial state (lower magnetic field wrt RHIC/LHC, electric field dominant → split D^0/D^0bar)
- Supernuclei production ?

Backup

The NA60+/DiCE collaboration

Proposal signed by institutes from China, France, Israel, Italy, Japan, USA and by CERN



Berkeley Lab

RICE

Stony Brook University

筑波大学 University of Tsukuba

UTokyo

University of Science and Technology of China

Weizmann Institute of Science

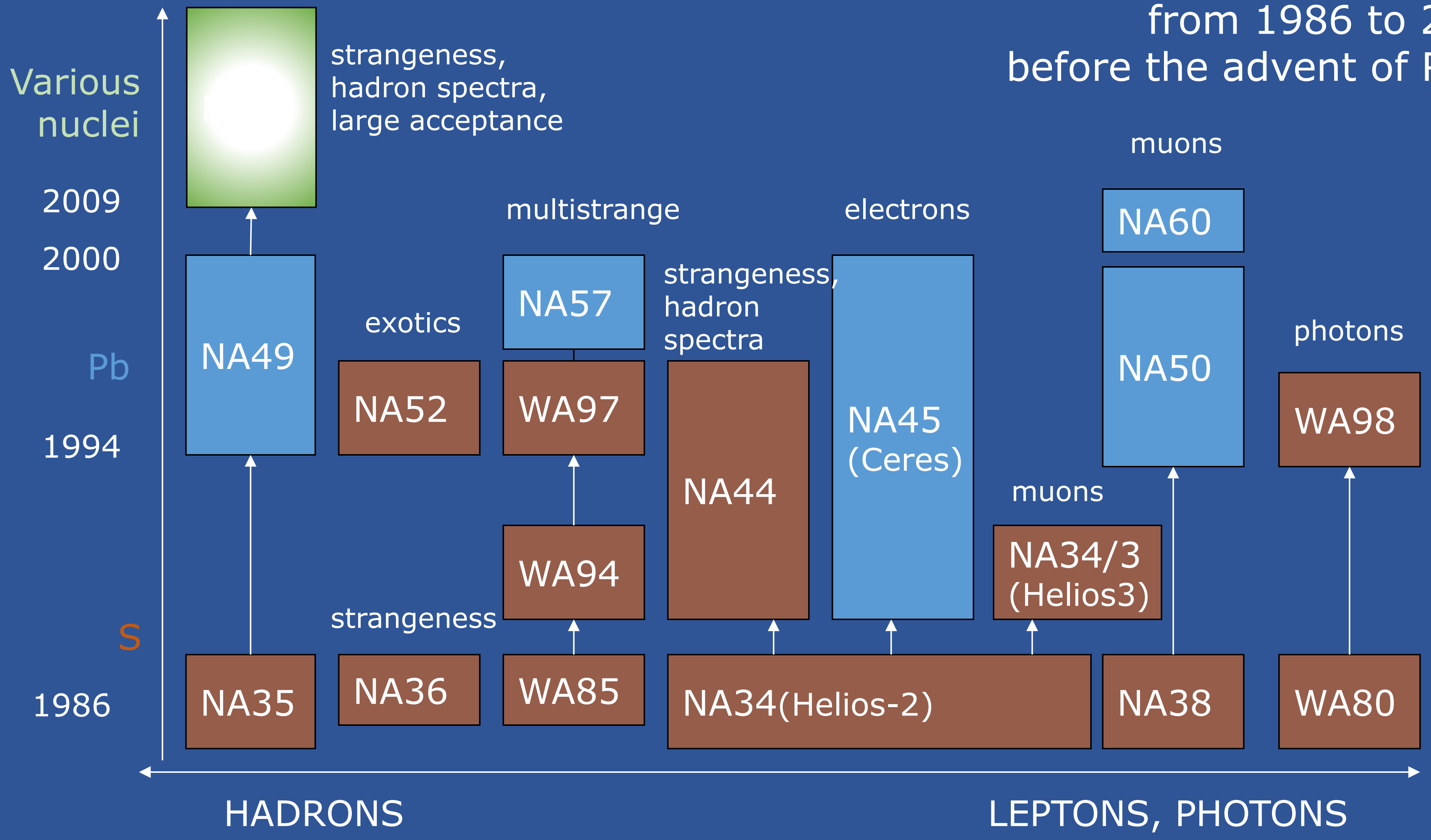
CERN

iP2i Les 2 Infinis Lyon

INFN Istituto Nazionale di Fisica Nucleare

A glorious past…

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

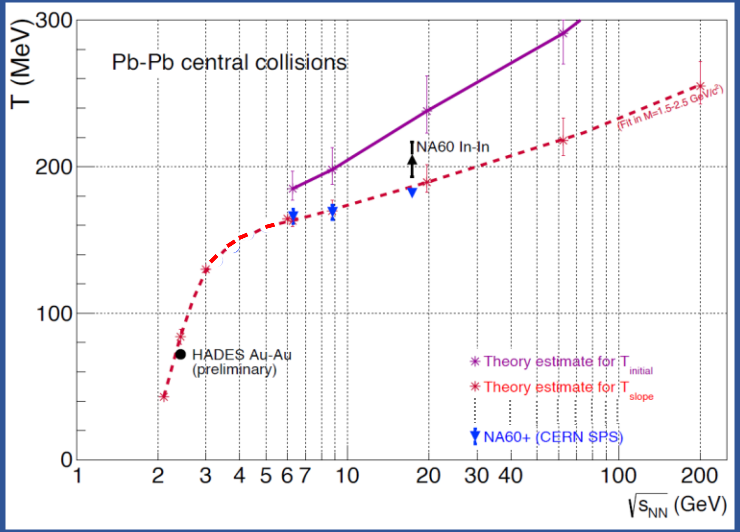


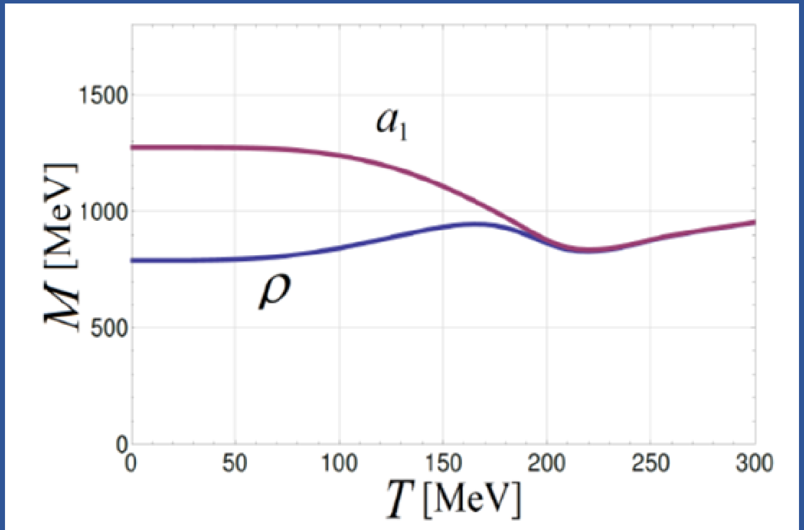
The NA60+ physics program

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

1 **Caloric curve of QGP**

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



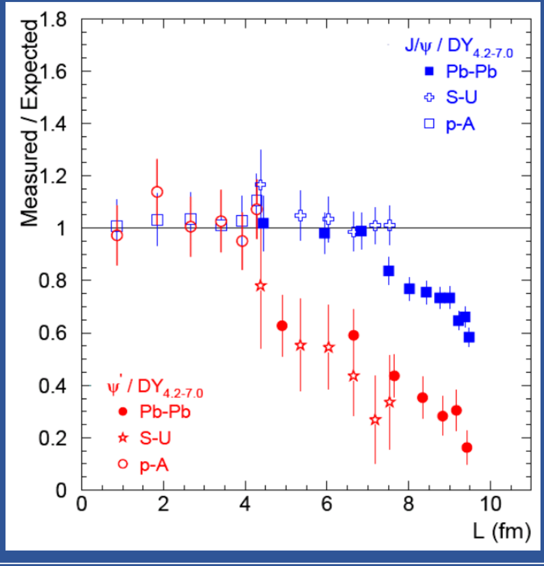


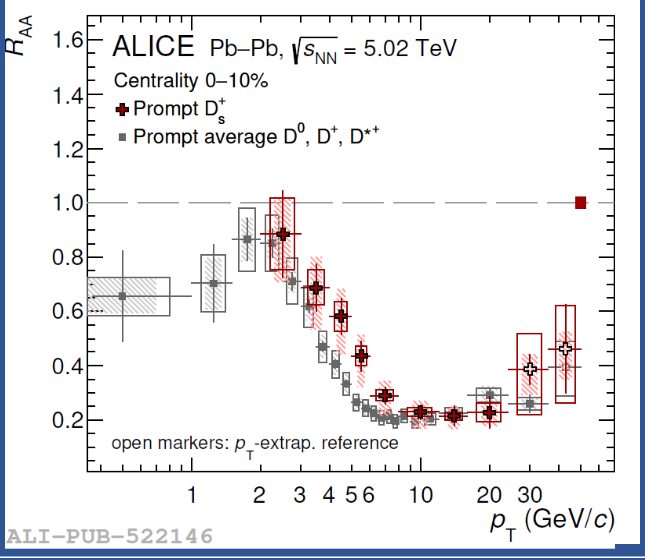
2 **Chiral symmetry restoration**

ρ-a_1 mixing in the dimuon channel

3 **Charmonium melting in the QGP**

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





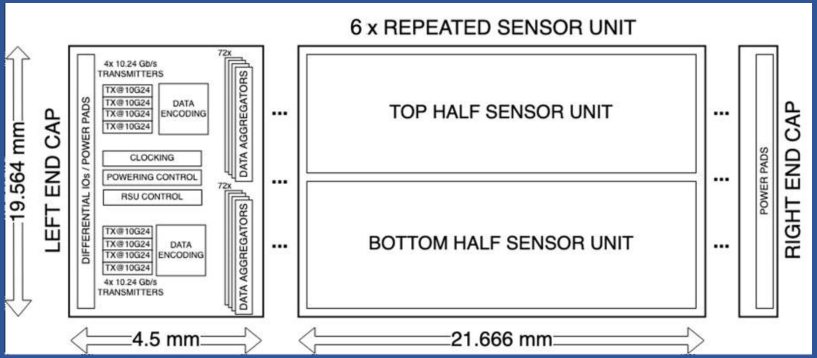
4 **QGP transport coefficients and charm hadronization**

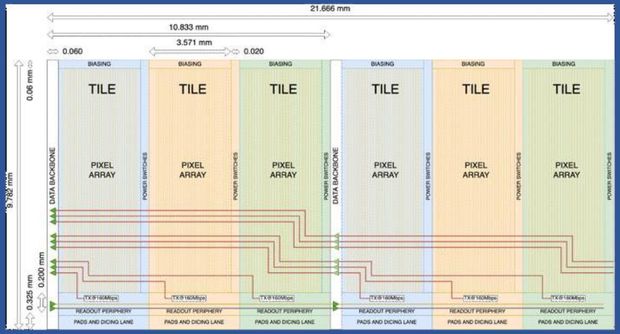
Hadronic decays of open HF mesons/baryons

Vertex detector

Si pixel technology – breaking area boundaries

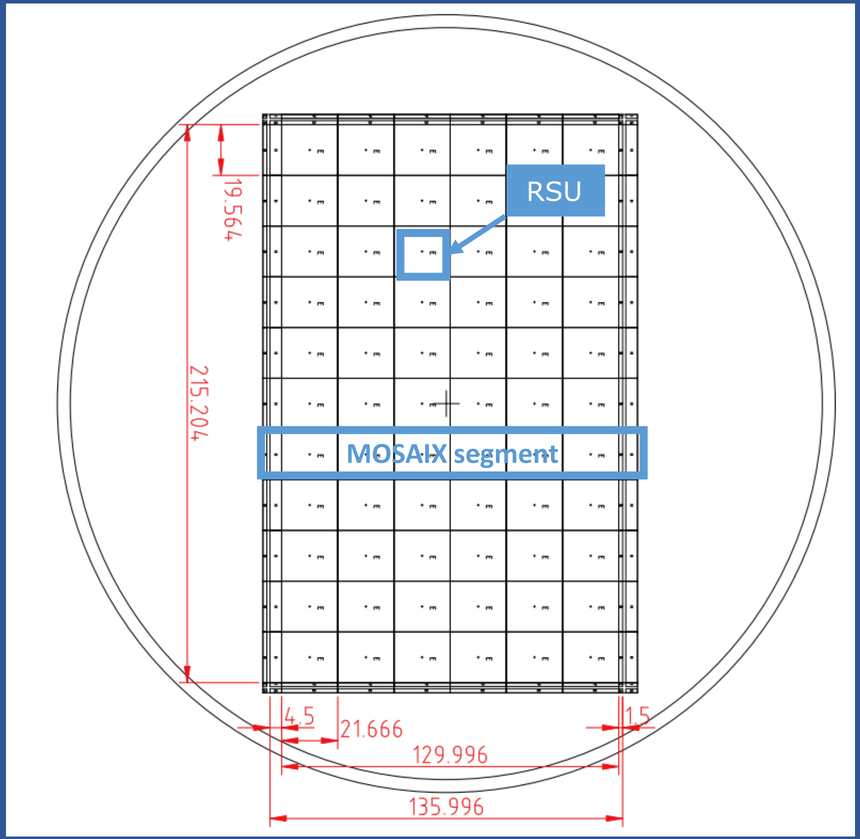
- **Synergy with ALICE ITS3** project
- Basic units designed in reticle:
  - RSU: 21.67x19.56 mm² pixel matrix
    - Pixel pitch 20.5 μm
  - Digital periphery with 8 10.24 Gb/s serializers



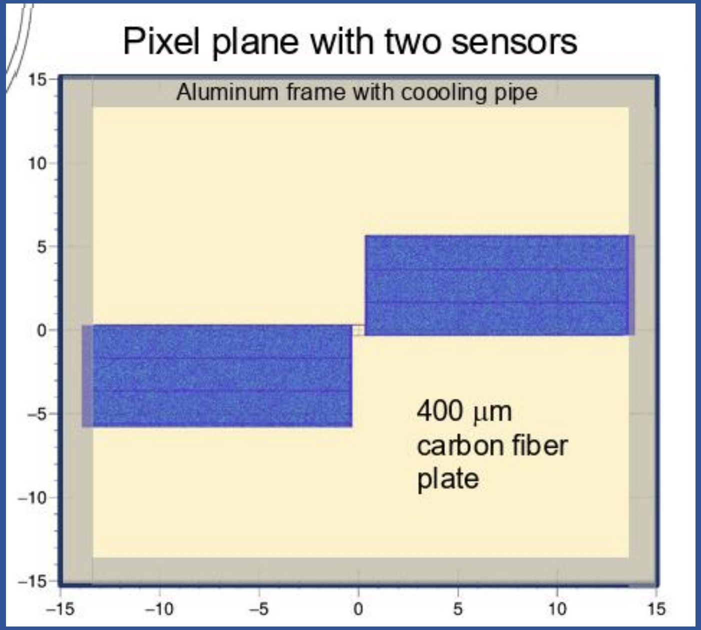


Top half-unit (bottom is mirrored)

- **NA60+/DiCE wafer** :
  - MOSAIX segment with 6 RSU
  - 11 MOSAIX segments replicated vertically



- **Silicon station** inside MEP48: 2 planes with 2 sensors each (reduce dead zones at periphery)



- Sensors with variable number of segments (from 6 to 3):
  - Advantage: increase sensor yield/wafer

Magnets

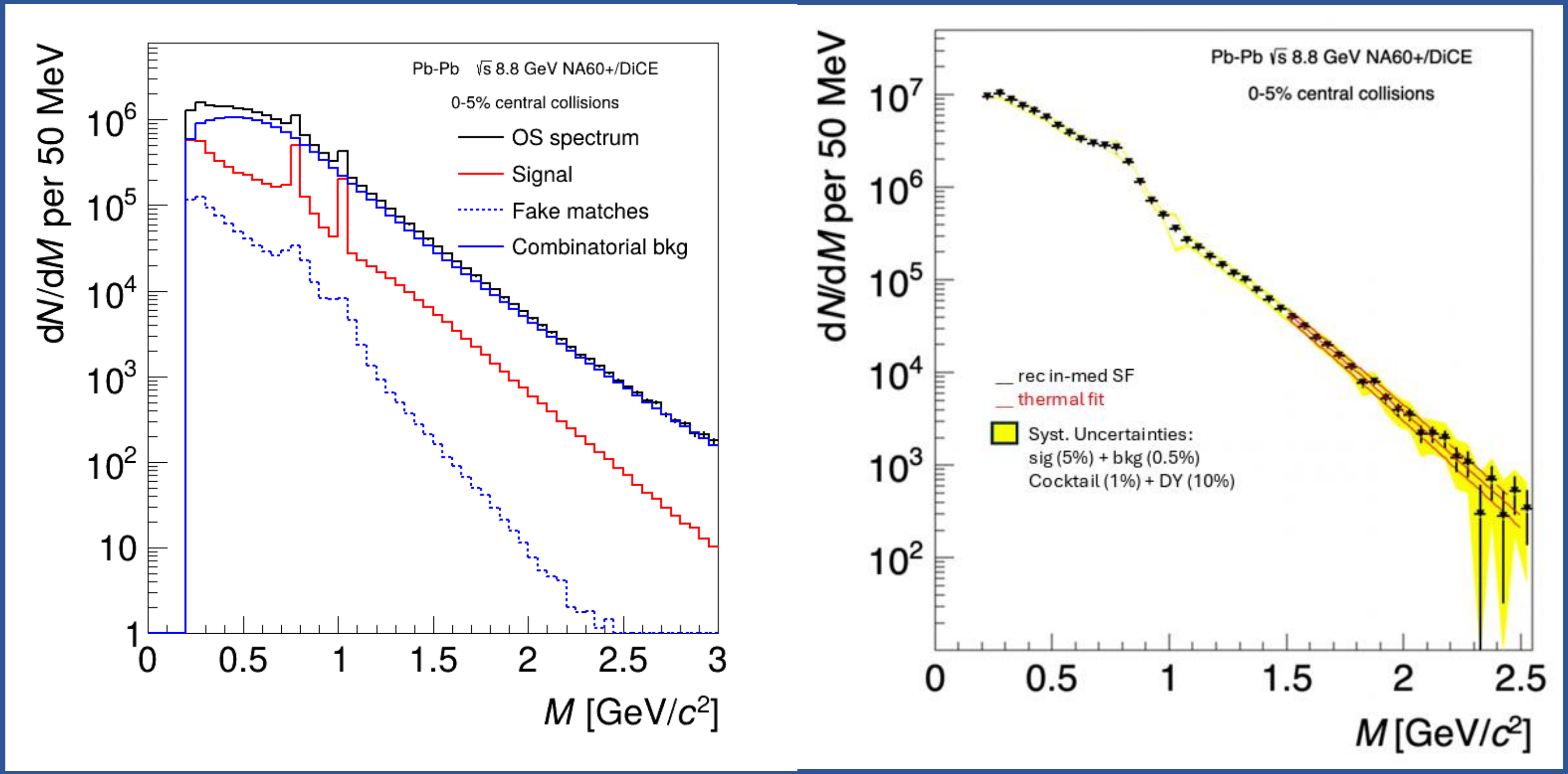
Dipole magnets for NA60+/DiCE

Vertex: MEP48, stored at CERN
400 mm vertical gap
Max. field: 1.47 T

Muon spectrometer: MNP33, in use by NA62 until 2026
2400 mm gap, 2450 mm aperture width
2 coils: 0.9 Tm

Thermal radiation and chiral symmetry

Thermal radiation: the thermometer of QGP



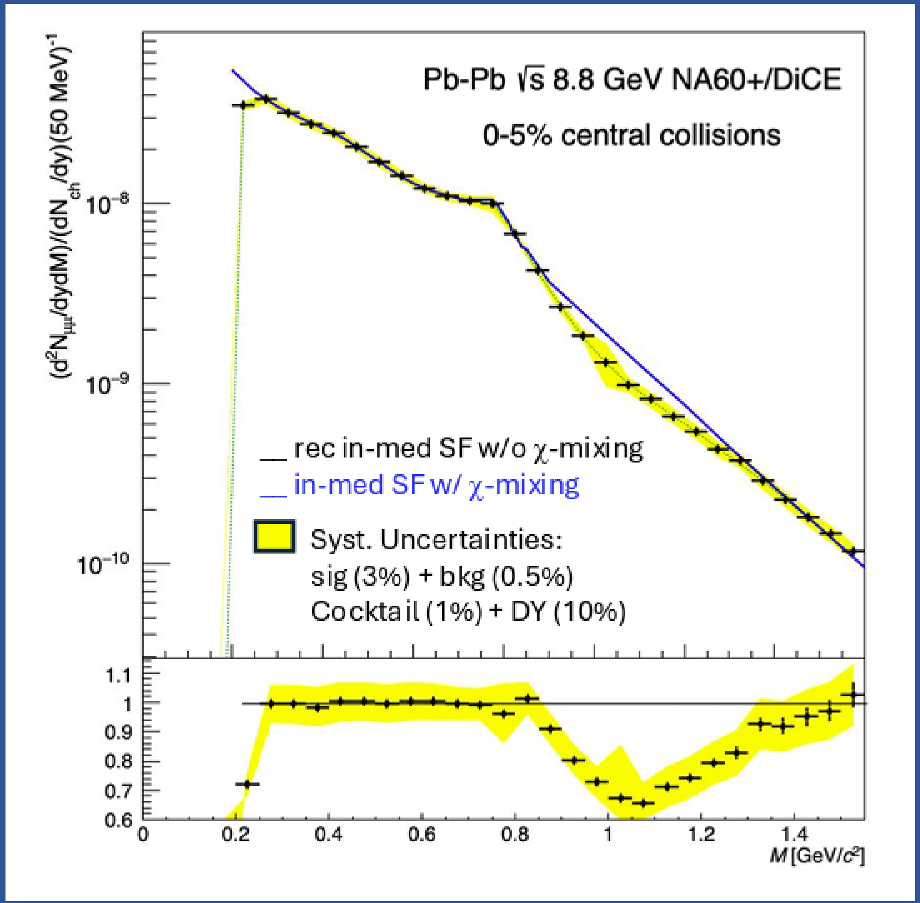
- **Thermal radiation** yield
  - Dominated by ρ contribution at low mass
  - Accessible up to M=2.5-3 GeV/c^2
- **Drell-Yan** contribution
  - To be measured in p-A
- **Open charm**
  - Small or negligible dimuon source

T_{slope} ($\sqrt{s}$=8.8 GeV) = 171 ± 4(stat.) ± 5(syst.) MeV
(similar uncertainties at the other energies)

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

QCD chiral symmetry restoration

- **Chiral symmetry restoration** investigated with the measurement of the ρ- a_1 mixing
- Full ρ-a_1 chiral mixing → **20-30% enhancement** expected in 0.8 < M < 1.5 GeV/c^2 w.r.t. no mixing



Theoretical prediction from:
R. Rapp, H. van Hees. Physics Letters
B 753 (2016): 586-590

- **green line** → no chiral mixing
- **black line** → full chiral mixing

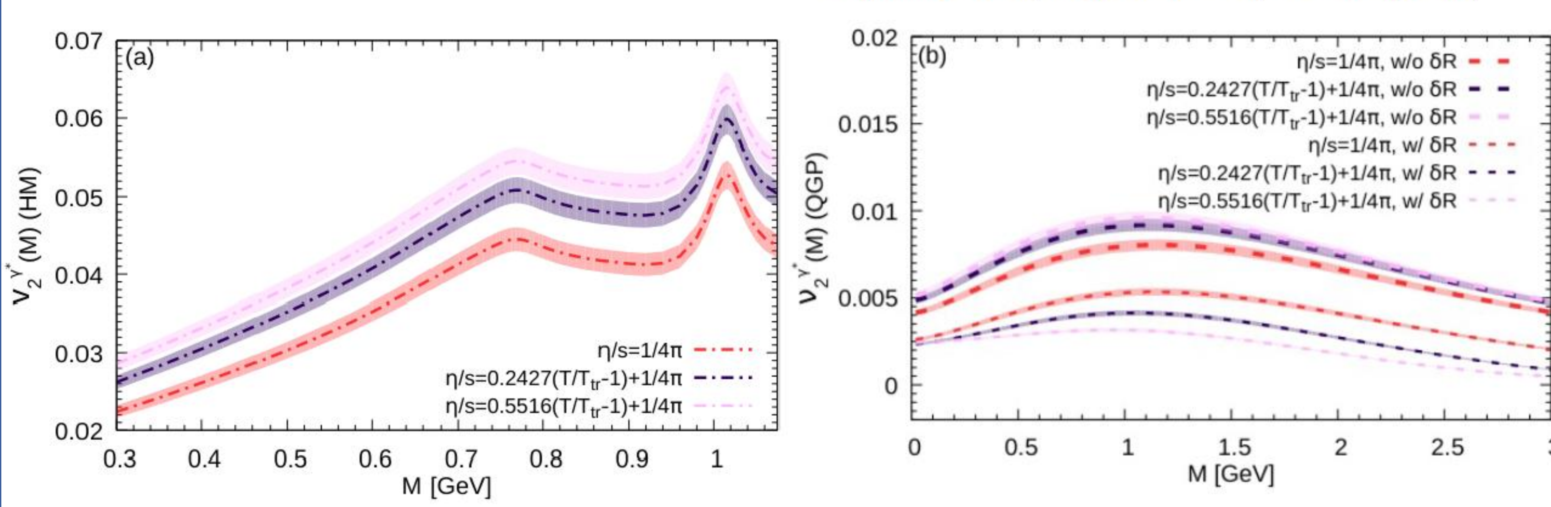
Same approach followed by CBM and ALICE3

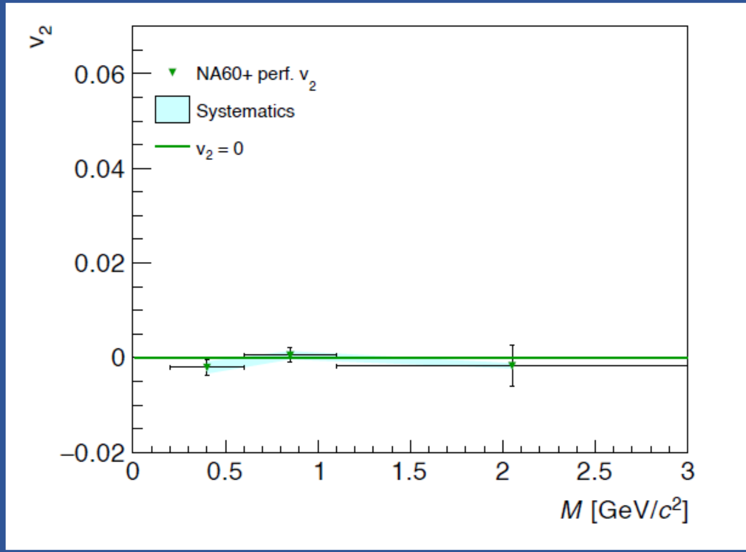
- NA60+/DiCE **can clearly detect a signal** of QCD chiral symmetry restoration

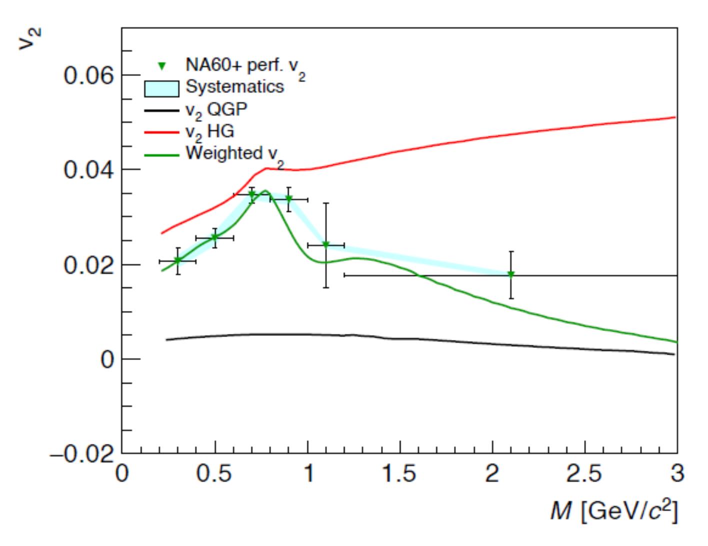
Elliptic flow of thermal dileptons

- **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)





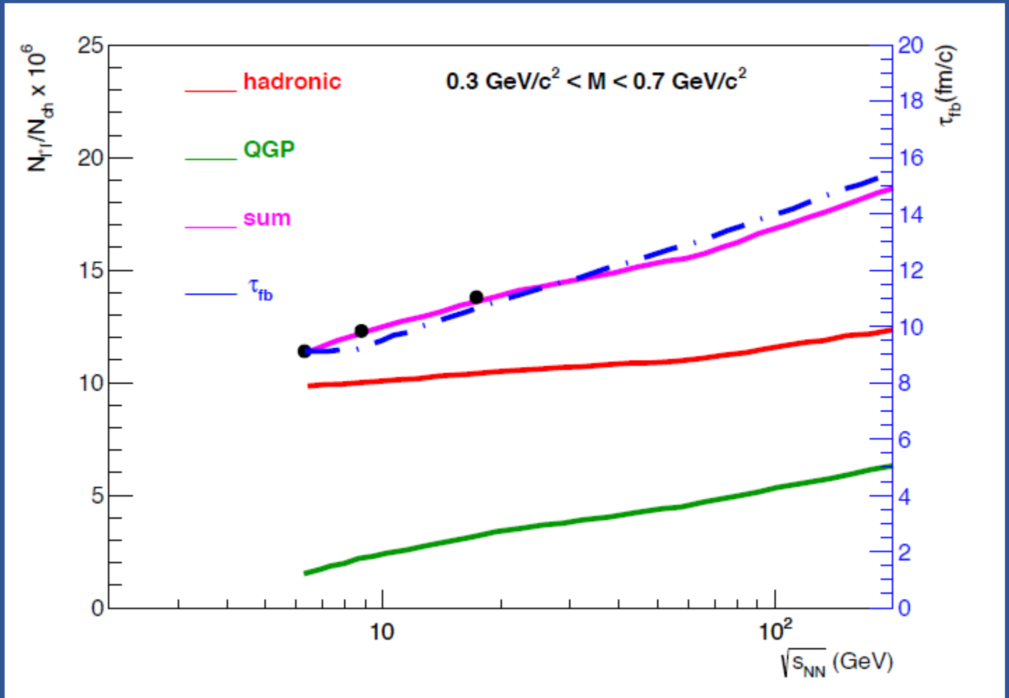


- No prediction at SPS energies
- Two possible scenarios: $v_2=0$
  - **Measurement with uncertainty between 0.003 and 0.008**
- $v_2=v_2^{RHIC}$
  → increase of v_2 versus mass (HG) and a drop in the IMR (QGP)

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**

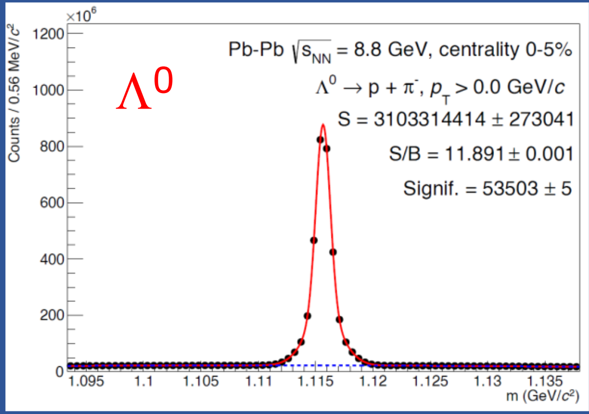


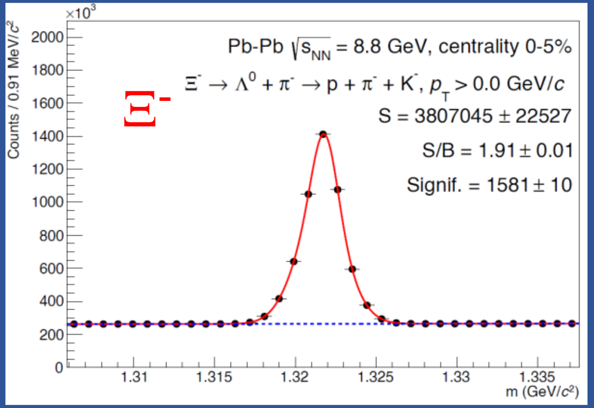
Black points → NA60+ projections
Excellent accuracy

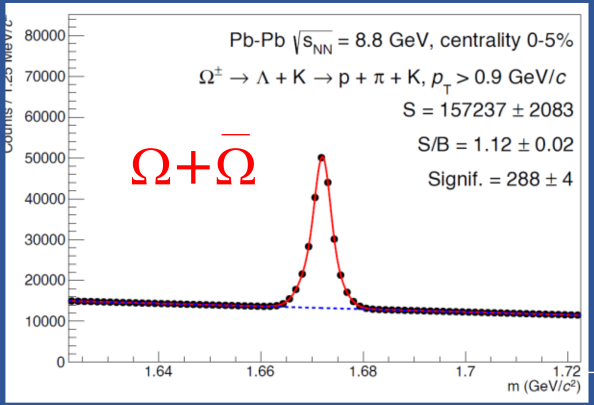
Soft mixed phase in a **first-order transition**
→ pressure gradients in the system are small and thus stall the fireball expansion
→ increased lifetime in the collision-energy regime where the mixed phase forms

Strangeness and hypernuclei

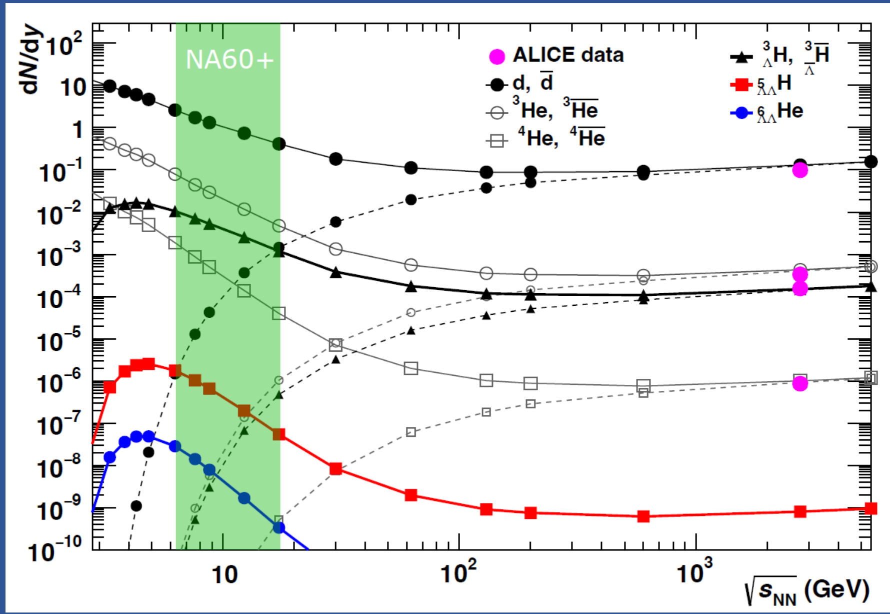
Physics performance: strangeness and hypernuclei



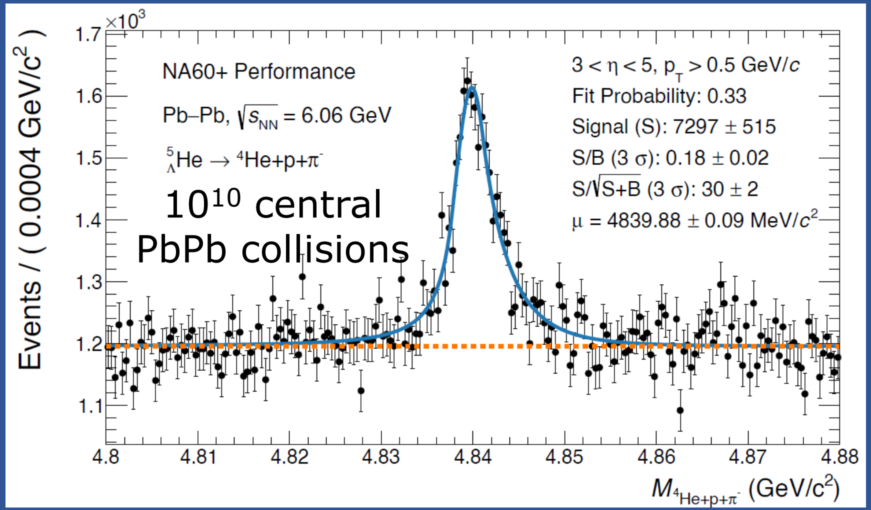




- **Topological selections with BDT** employed to **enhance the significance** of the signal
- Among the variables:
  - Product of the impact parameter of decay tracks
  - Distance of closest approach between the decay tracks
  - Decay length and the cosine of the pointing angle
- Also $\phi \rightarrow$ KK and $K_s \rightarrow \pi\pi$ have been studied



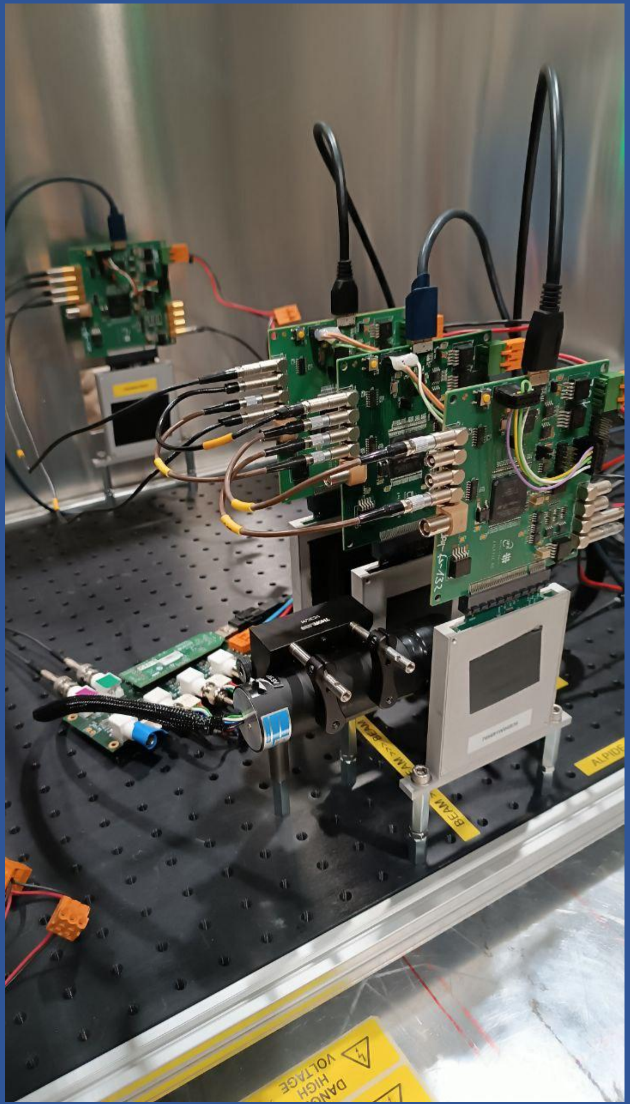
Low energy HI collisions → **high baryon density** favours the production of hypernuclear clusters

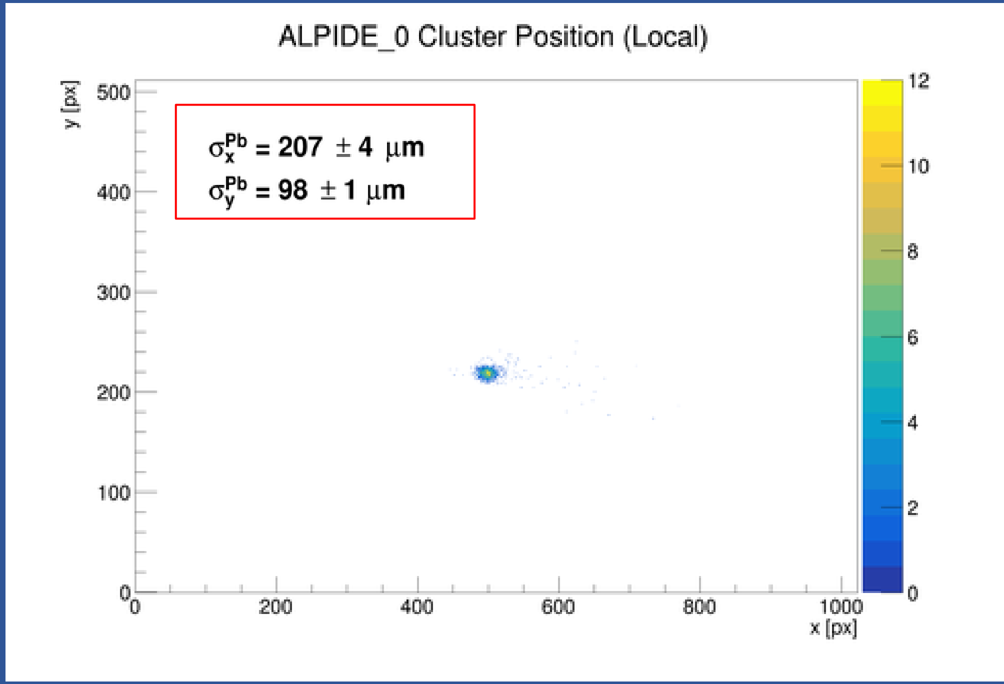


Separation of heavily ionising particles from ordinary hadrons → **size of the clusters** associated with the track

Beam

Focusing a high-intensity Pb beam





November 2024: accurate measurement of **150 A GeV Pb beam** at nominal NA60+ intensity (10^6 Pb s^{-1})

- Well **within requirements** of the experiment ($6x6$ mm^2 square hole)
- Moving to lower energy the beam transmission and focusing become **more challenging**
- First test at 13.5 A GeV carried out → 1 x 0.8 mm^2 measured
- Optimization under study with EA group

Planning of data taking – energies and luminosity

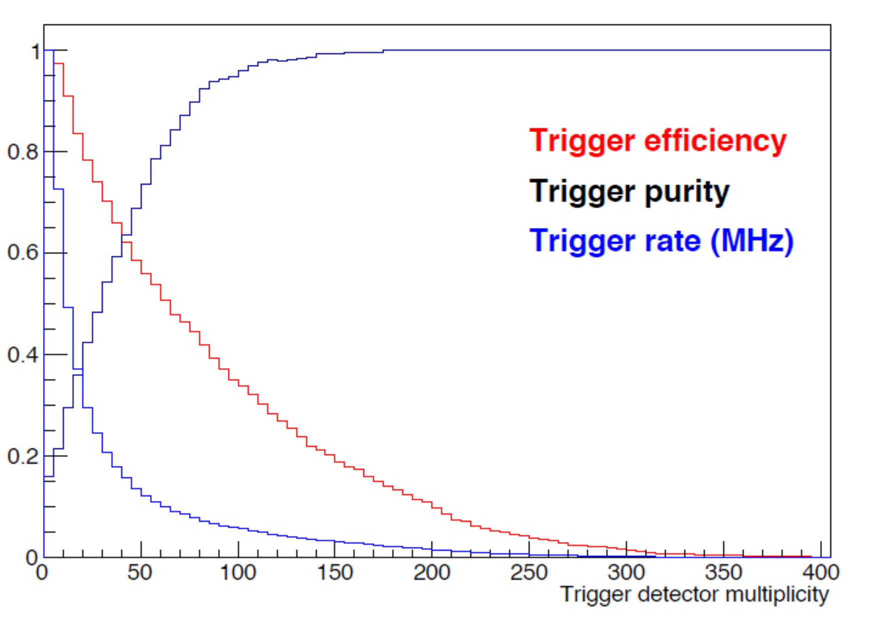
	Low-energy set-up						High-energy set-up
$^{208}Pb_{82+}$ Momentum [QGeV/c]	50.7 (76.1)	50.7 (76.1)	101	152	216	292	380
$^{208}Pb_{82+}$ Momentum [GeV/c/u]	20 (30)	20 (30)	40	60	85	115	150
$\sqrt{s_{NN}}$	6.3 (7.6)	6.3 (7.6)	8.8	10.7	12.7	14.7	16.8
Pb [10^{12} IoT]	0.6	0.3	0.6	0.45	0.45	0.45	0.45
Number of days	28	14	28	21	21	21	21
Proton momentum [GeV/c]	–	40	–	85	85	150	150
$\sqrt{s}$	–	8.8	–	12.7	12.7	16.8	16.8
Protons on target [10^{13} PoT]	–	6	–	3	3	3	3
Number of days	–	14	–	7	7	7	7

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)

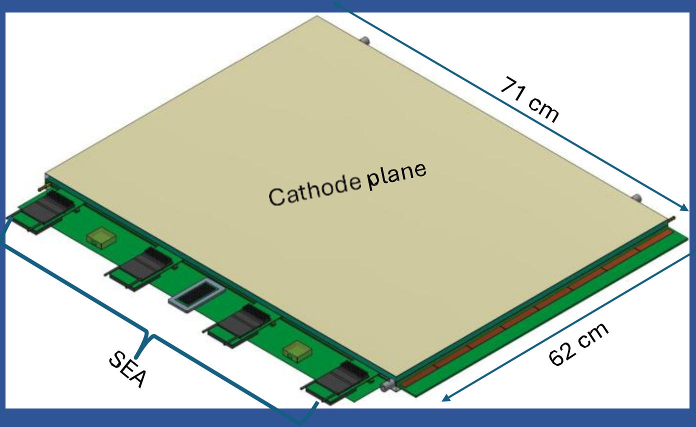
- Data collected per heavy-ion run can be **fully processed in 2–3 months** by a farm of ~ 100 modern multicore processors or equivalent GRID jobs

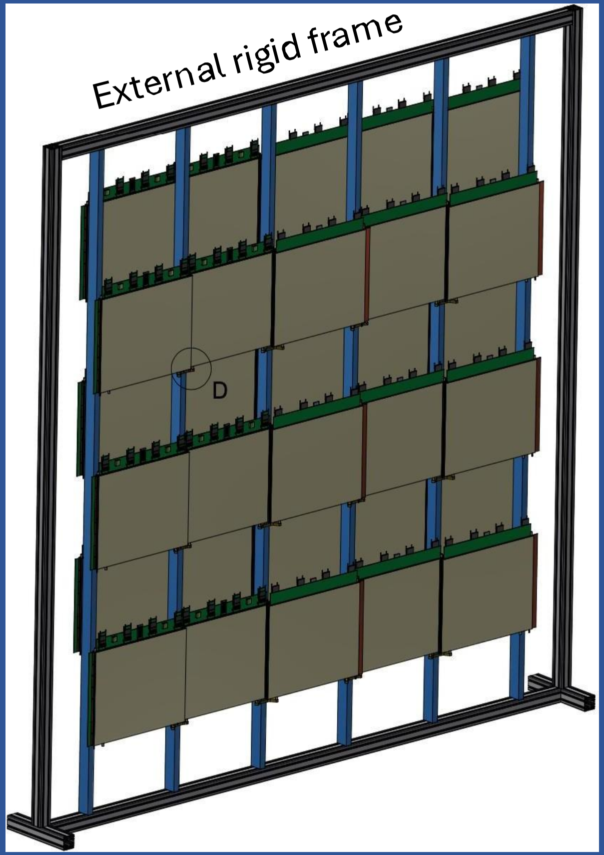
Muon spectrometer

MWPCs – precision through modular design

- Detector modularity adopted with rectangular units
  - Ar/CO_2 (70/30) gas volume 6 mm thick
  - Two-directional strips etched on a multi-layer FR PCB
  - Solid FR cathod panel on other side
  - **30 μm wires, 2-3 mm pitch**
  - **100 μm spatial resolution in bending plane**
  - **<3-4 % X_0 material budget**

- Strip Extension Area (SEA):
  - Strip PCB extends for hosting frontend electronics
  - **Readout with 8 VMM chips** (into 4 mezzanines):
    - Continous readout (240 ns dead time)
  - Readout controller (ROC) with FPGA module





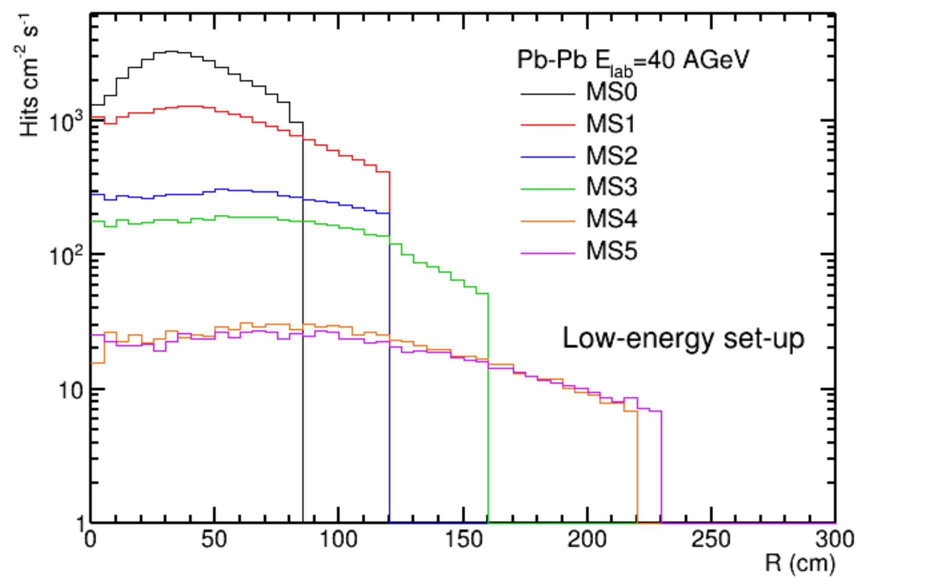
- Preliminary layout of the MS station:
  - Rigid frame outside acceptance
  - Chambers aligned on rows mounted on vertical bars

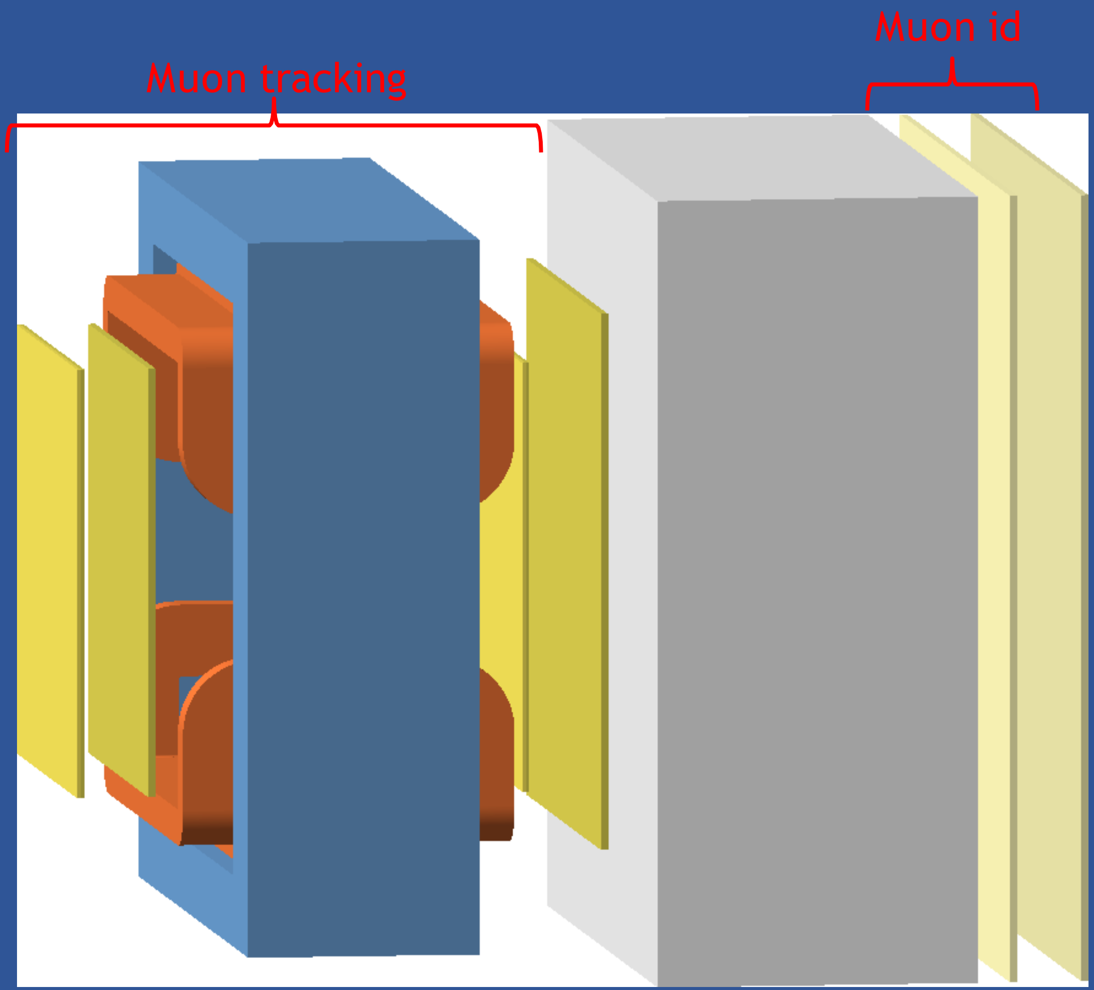
- Gas distribution and HV:
  - 100 l/h all stations (standard bottle/2 days)
  - Standard HV multichannel CAEN housed in mainframe

Muon spectrometer

- Primary purpose of the Muon Spectrometer (MS):
  - Measuring kinematic parameters of muons
  - **Matching** muon tracks to the vertex spectrometer

FLUKA simulation





- Particle densities at different stations:
  - Conventional MWPC for all MS but MS0
  - MS0: rate at the limit, GEM-like more suited

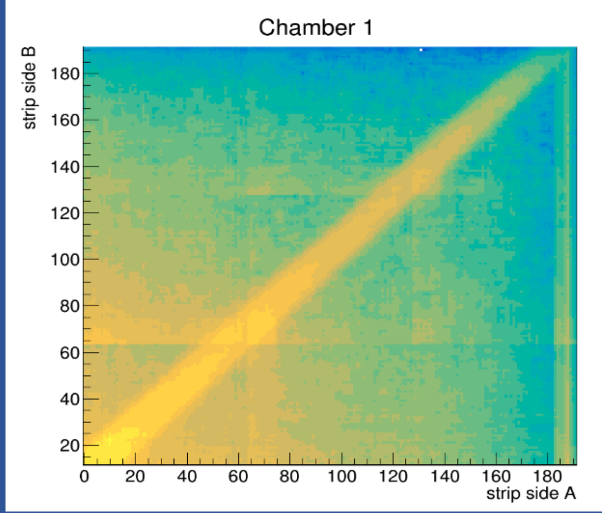
station	z cm	$\Delta x, \Delta y$ cm	σ_x mm	σ_y mm	peak fluence $cm^{-2}s^{-1}$	$n_{hits}^{central}$	$\Delta r^{central}$ cm
MS0	300	162	0.1-0.2	0.5-1	3.5k	250	10
MS1	340	240	0.1-0.2	0.5-1	1.5k	200	17
MS2	550	240	0.1-0.2	0.5-1	0.5k	120	22
MS3	590	318	0.1-0.2	0.5-1	0.3k	80	35
MS4	810	437	5–50	5–50	0.06k	40	70
MS5	850	458	5–50	5–50	0.05k	30	85

positions for low-energy setup

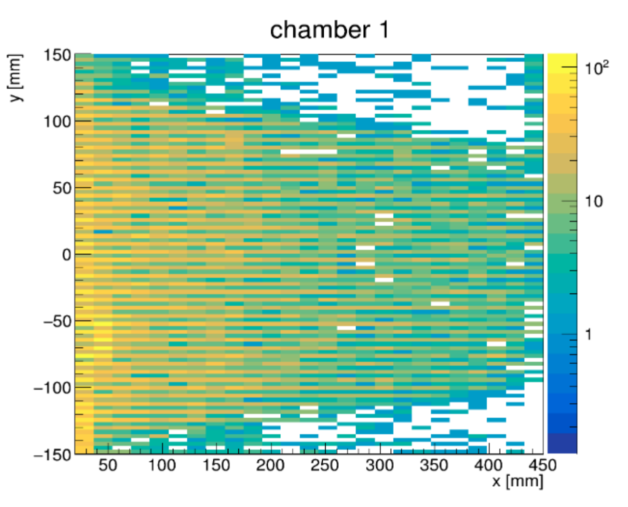
Muon spectrometer

- Positioned downstream of a thick hadron absorber (BeO + C)
  - **MNP33 dipole** magnet
  - **Six tracking stations** → MWPC detectors (max. rate ~2 kHz/cm^2)
  - C wall precedes the last two stations, to improve muon identification

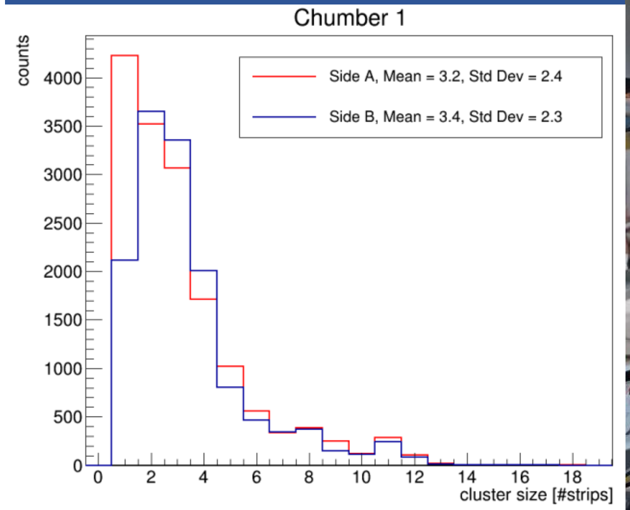
Strip correlation

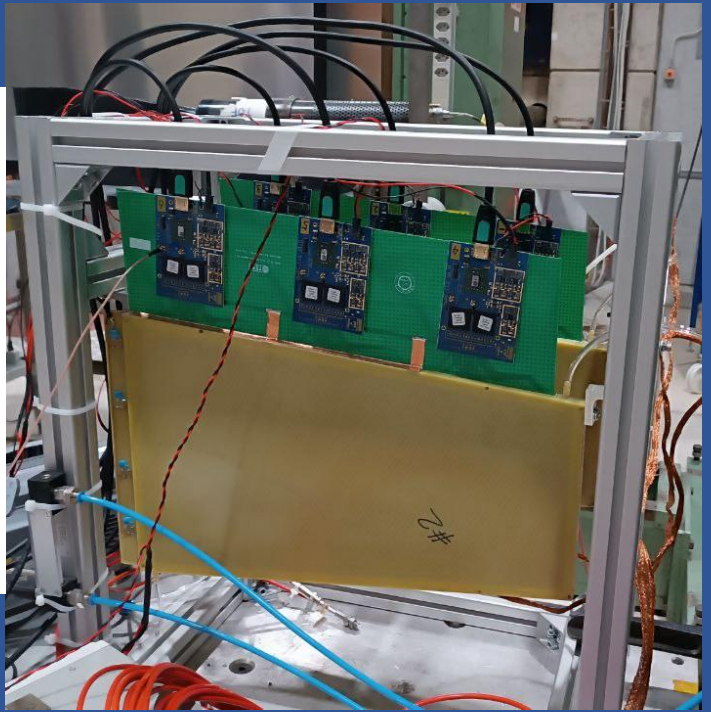


Hitmap Pb-Pb 150 A GeV



Cluster size



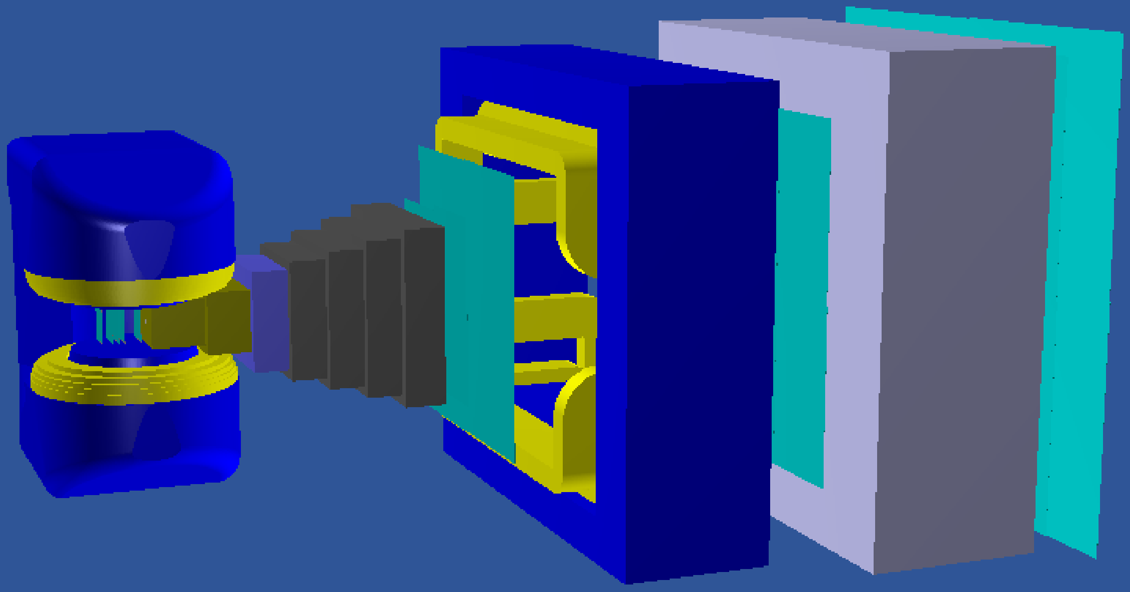


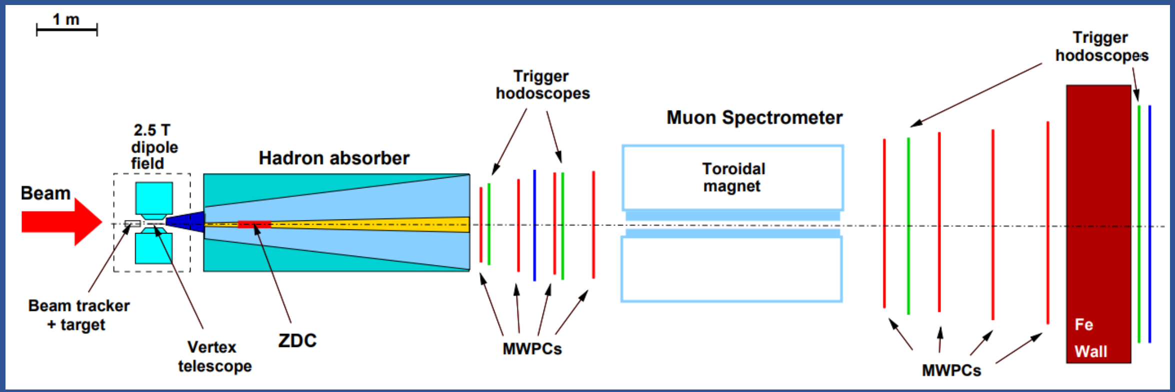
Space resolution ~0.1 mm (strips)

- Tracking stations realized with **modular structure** and varying strip pitch
- **Second prototype tested** with secondaries from Pb-Pb collisions in 2024

NA60+ vs others

NA60+ vs NA60





Some important improvements:

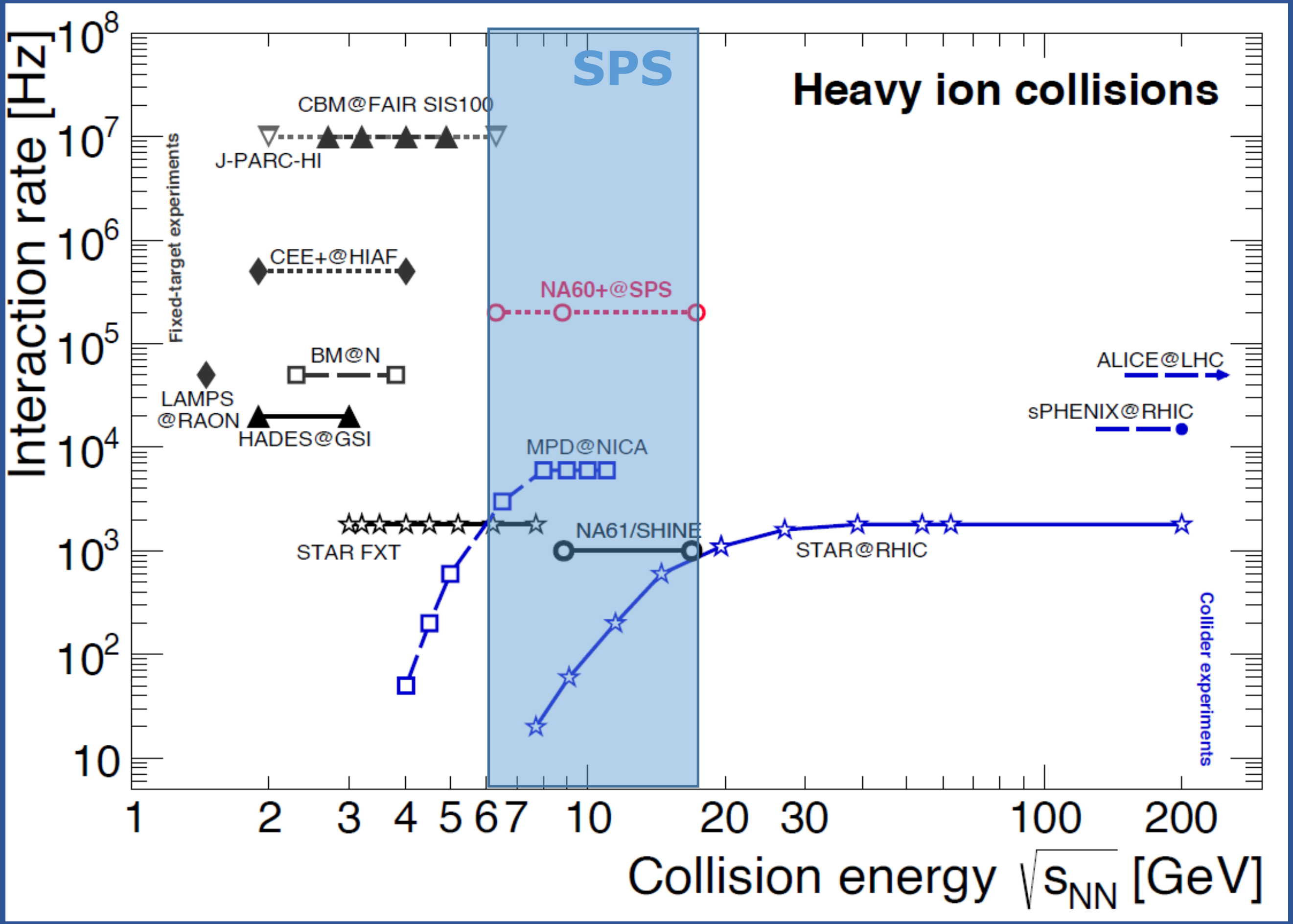
Physics program extended to lower energy
→ Fundamental to explore rare probes in the high-μ_B region

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

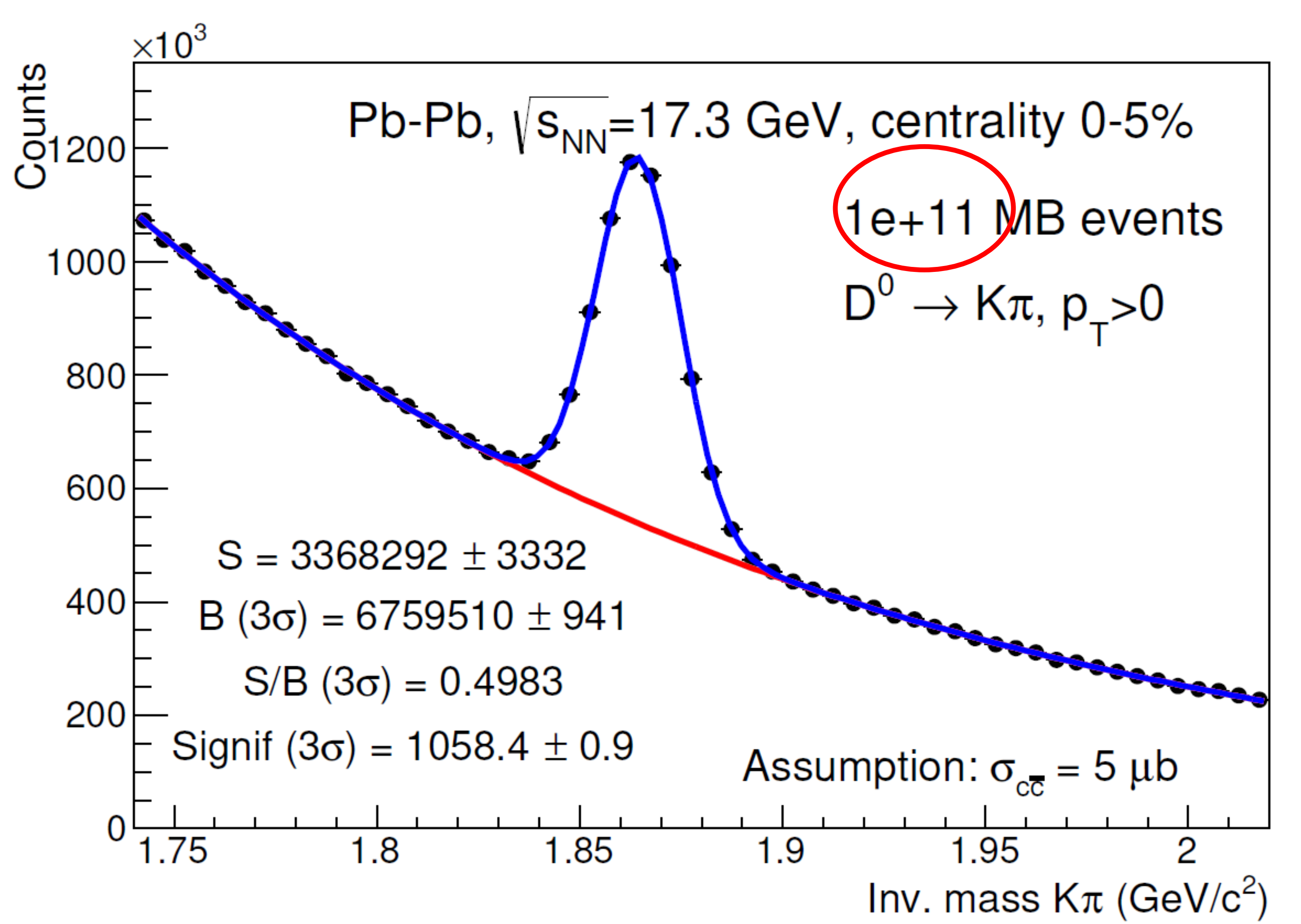
- **Complementarity** with experiments accessing
  - different (hadronic) observables in the same energy range (STAR BES, NICA, NA61)
  - similar observables in a lower energy range (CBM at FAIR)

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+



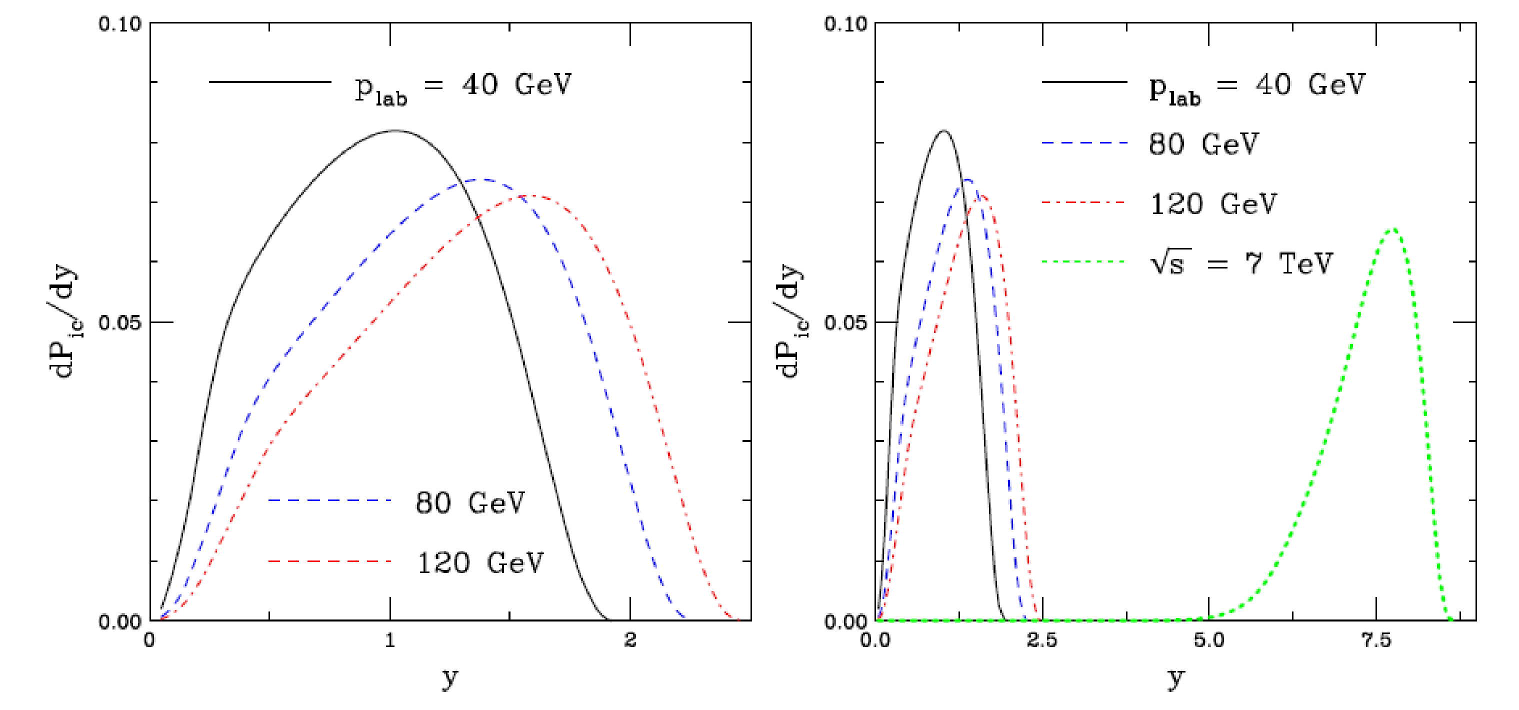
N.B.: different assumptions for open charm cross section

Intrinsic charm

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

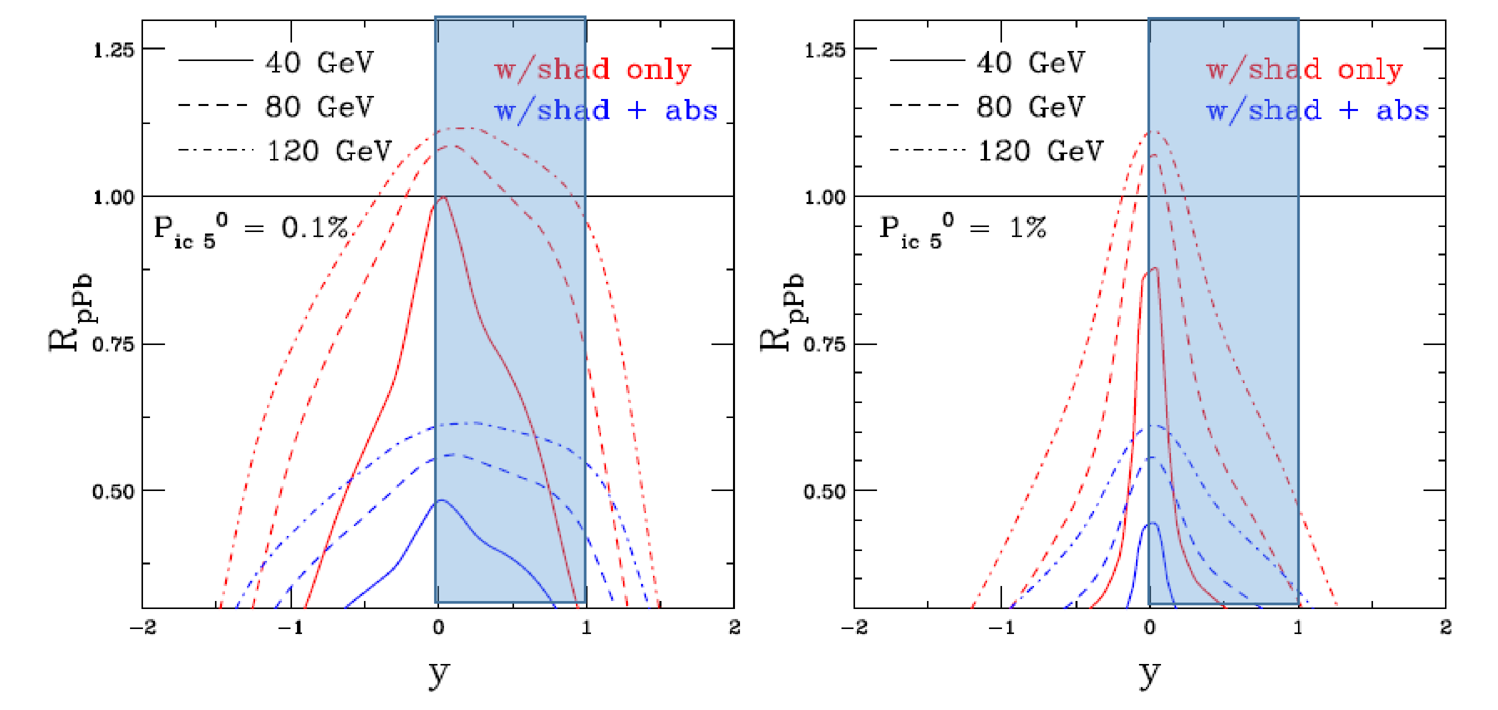


Assumed intrinsic charm content varied between 0.1% and 1%

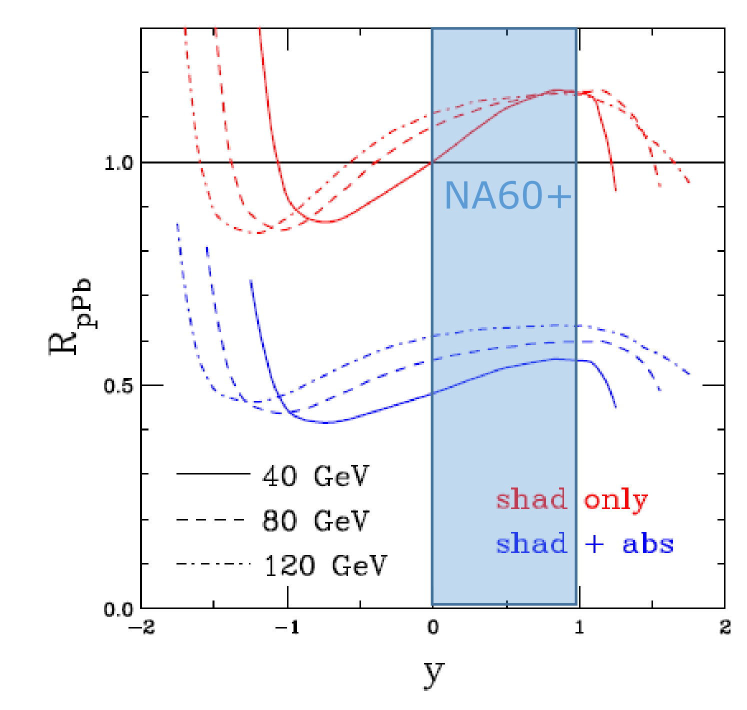
R. Vogt, PRC 103, 035204 (2021)
R. Vogt, arXiv:2207.04347

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%



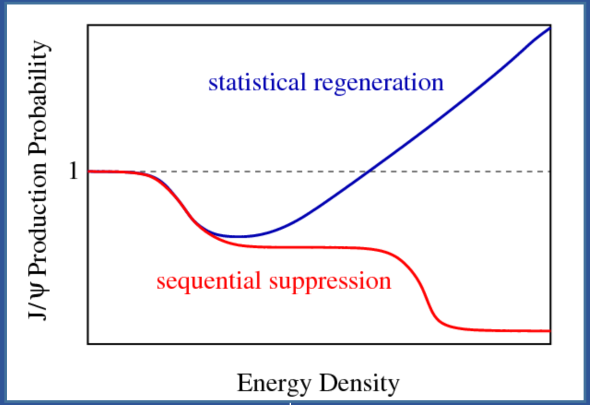
(w/o intrinsic charm)

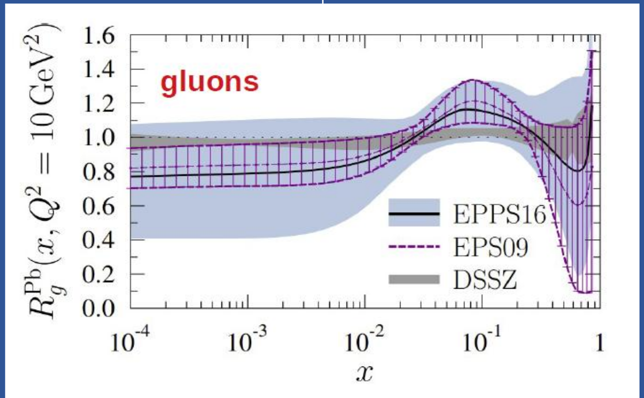


- **R_{pPb} shape is dominated by intrinsic charm**, already with P_{ic}=0.1%

Charmonia

Charmonia: high vs low √s



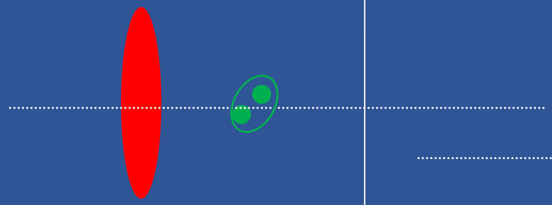


Collider (LHC)

Hot matter effects: regeneration counterbalances (overcomes) suppression

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

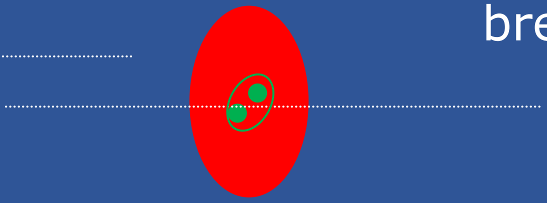
(Final state) CNM effects:
negligible, extremely short crossing time
$\tau = L/(\beta_z\gamma) \sim 7\ 10^{-5}$ fm/c ($y \sim 3$)
$\tau = L/(\beta_z\gamma) \sim 4\ 10^{-2}$ fm/c ($y \sim -3$)



Fixed target (SPS)

Hot matter effects:
suppression effects (if existing) dominate

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



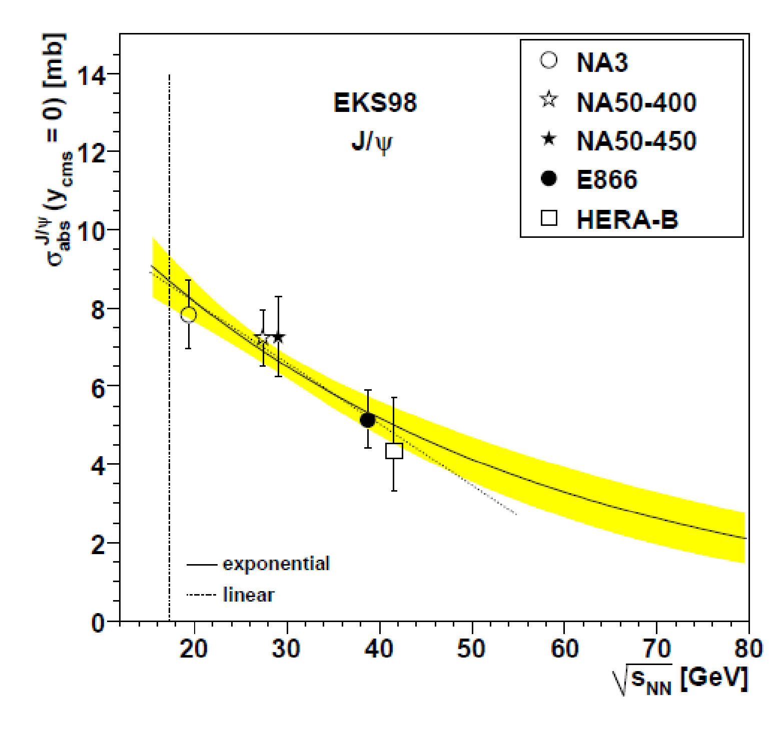
(Final state) CNM effects:
break-up in nuclear matter can be sizeable
$\tau = L/(\beta_z\gamma) \sim 0.5$ fm/c ($y=0$)

CNM effects are (very) large

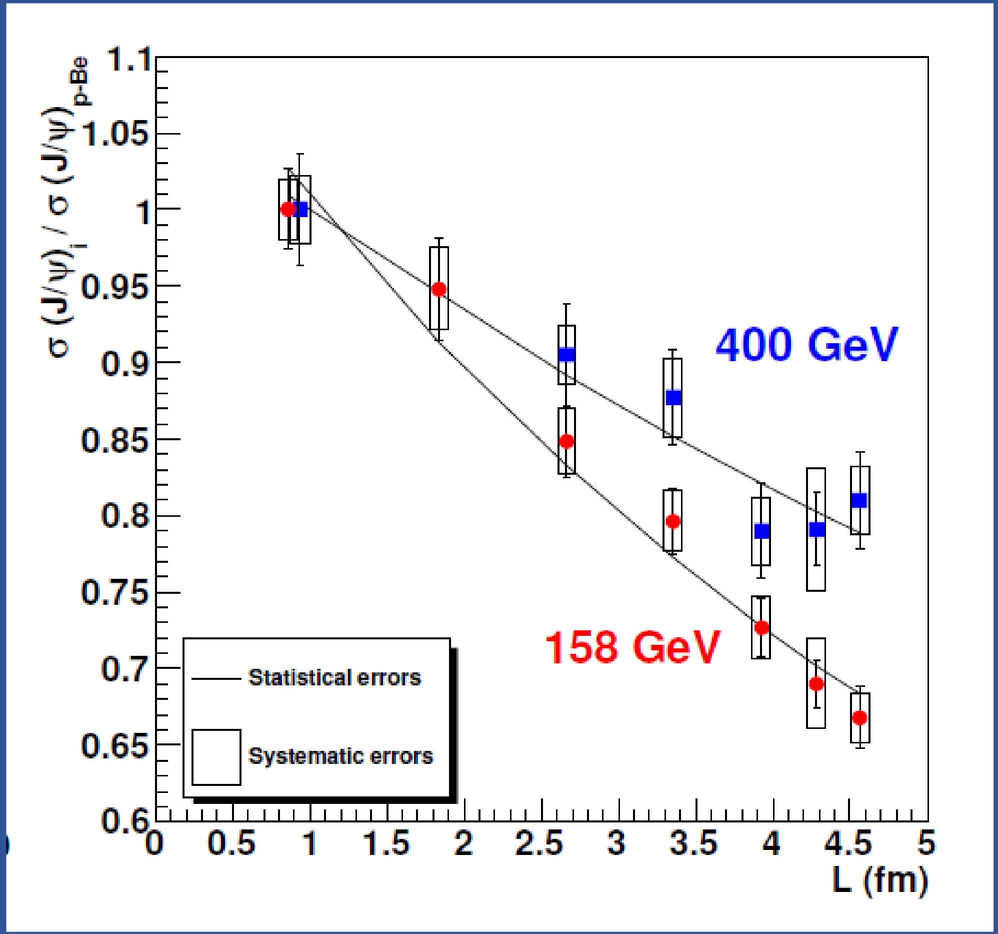
- Shadowing effects are moderate
- Dominated by nuclear absorption
  → ~30% effect in p-Pb at $\sqrt{s_{NN}}$ = 17 GeV

- **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)

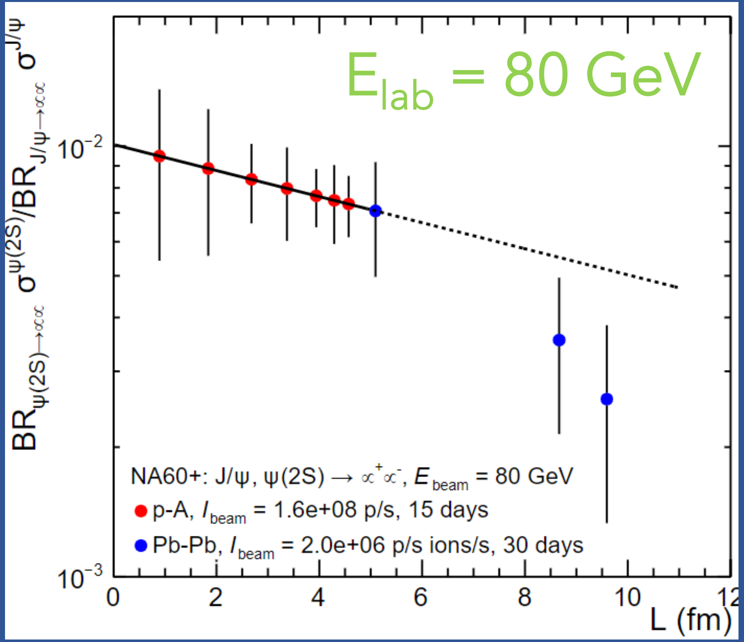
Prospects for ψ(2S) measurements at low √s

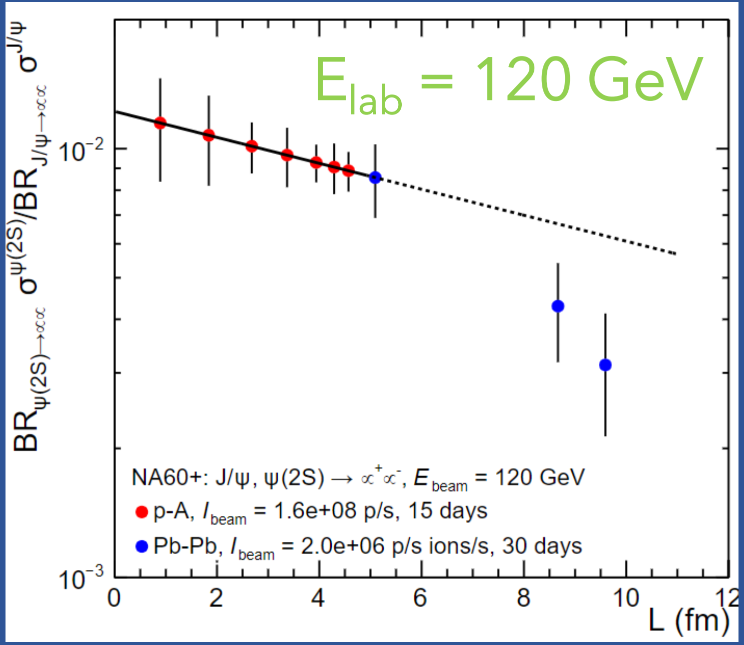
Good charmonium resolution (~30 MeV for the J/ψ) will help ψ(2S) measurements

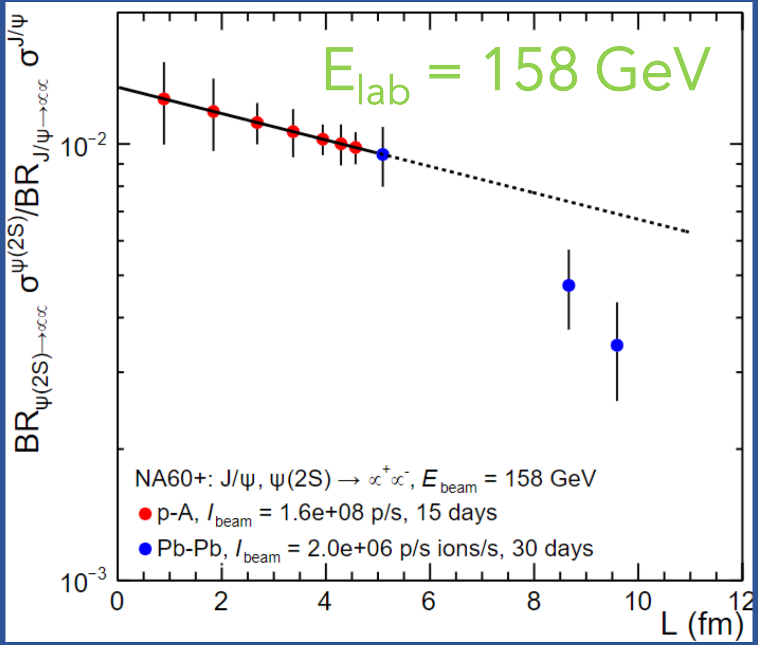
Expectations based on

- 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)



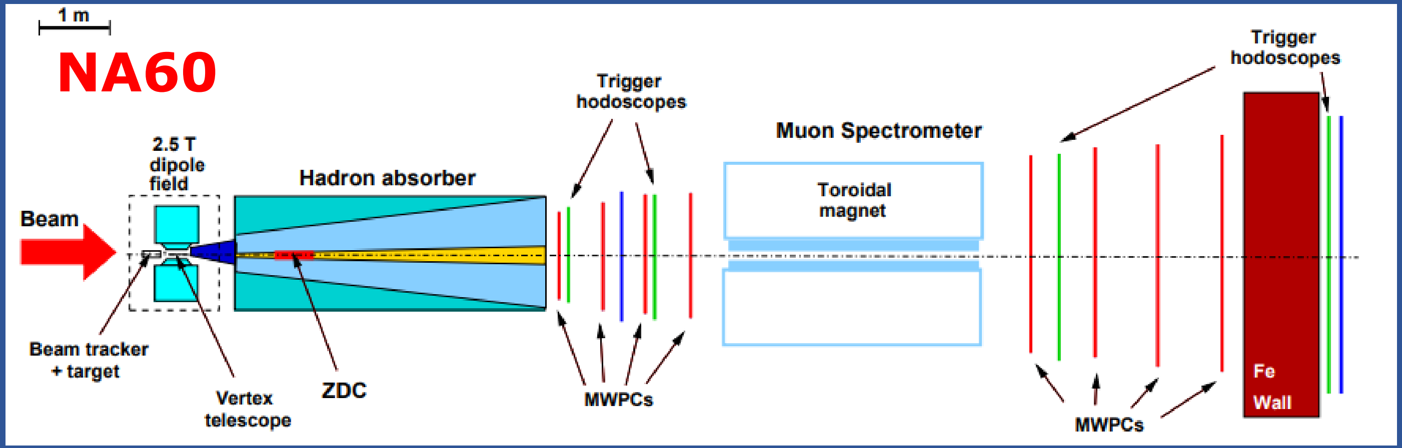




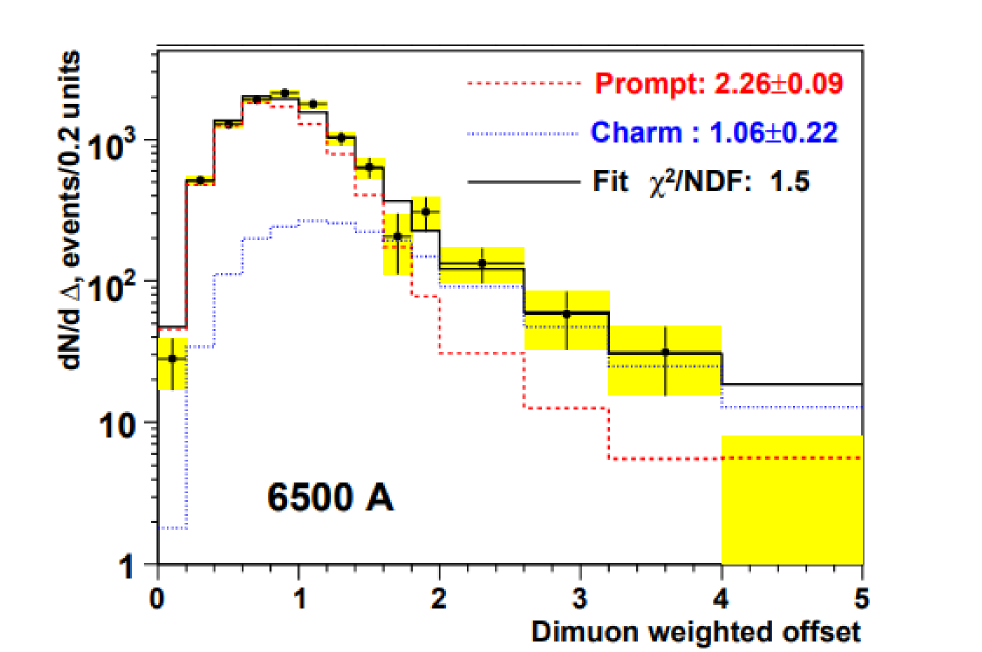
- ❑ **ψ(2S)/ψ measurement looks feasible down to E_{lab} = 120 GeV**
- ❑ Lower E_{lab} would require larger beam intensites/longer running times

Open charm

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

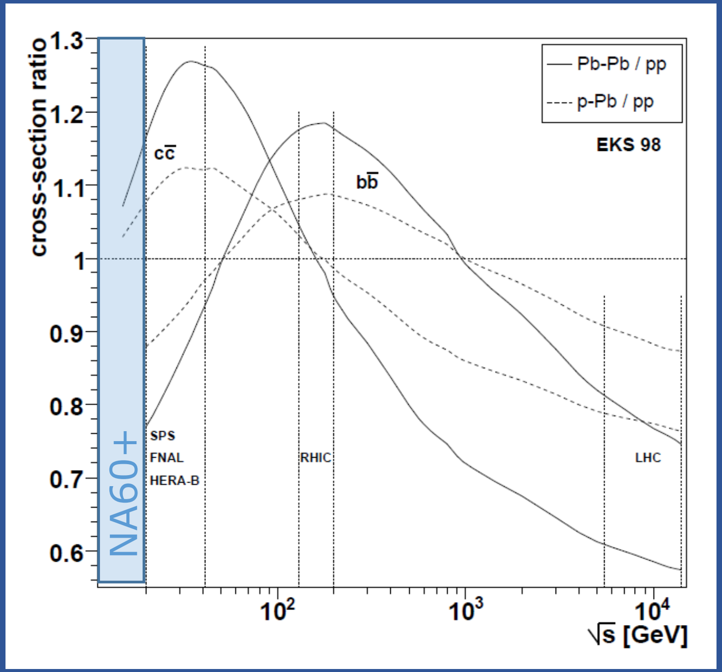
❑ Analysis of open charm contribution (semileptonic decays of charm hadron pairs) leads, for In-In collisions at $\sqrt{s_{NN}}$=17.3 GeV, to σ_{cc}= 9.5±1.3(stat.)±1.4(syst.) μb assuming kinematic distribution as in PYTHIA6

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

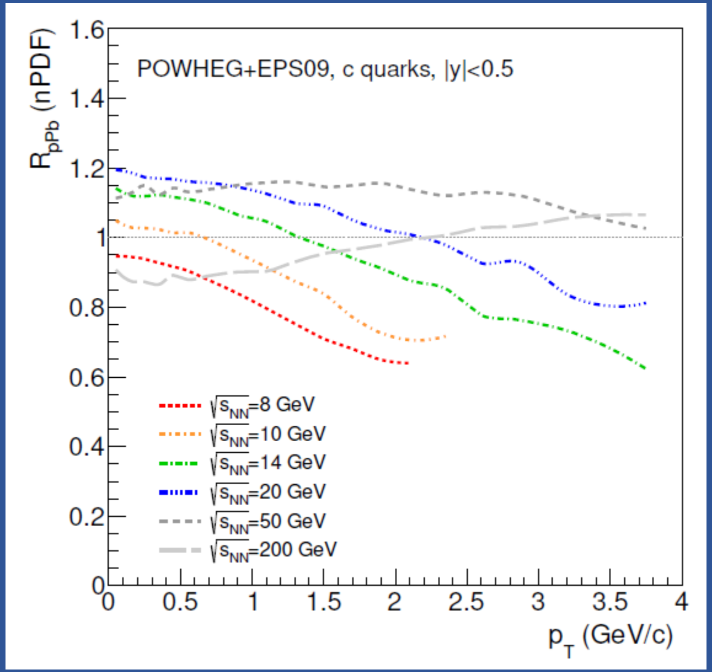
No other results available below top SPS energy

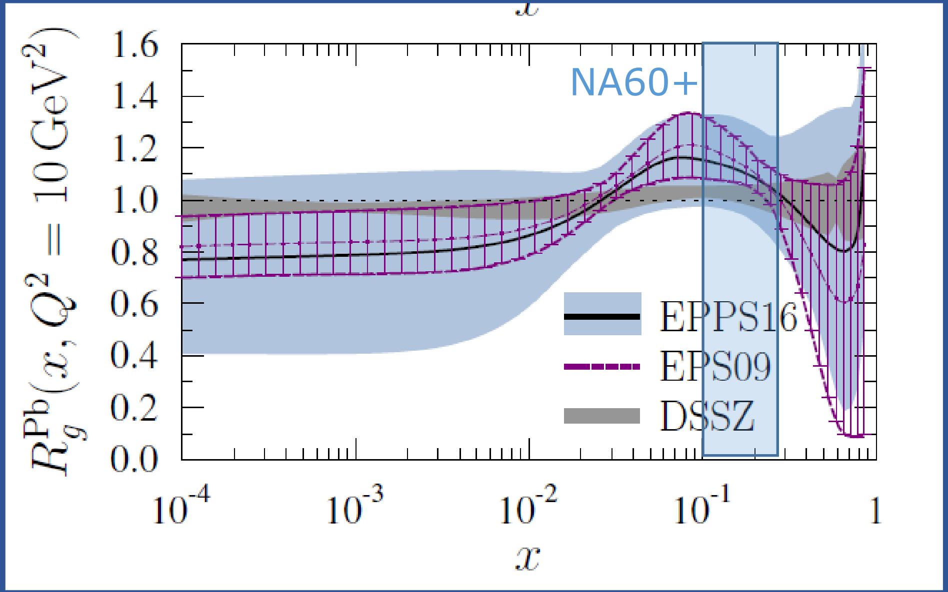
Open charm at low √s in pA: nuclear PDFs

- Sensitivity to **nuclear PDFs in p-A** collisions
  - Probe EMC and anti-shadowing for $\sqrt{s_{NN}}$ ~ 10-20 GeV
  - Perform measurements with various nuclear targets to access the A-dependence of nPDF
- NA60+ offers a unique opportunity to investigate the **large x_{Bj} region** (study ratio to pA/pBe)
  - $0.1<x_{Bj}<0.3$ at Q^2~10-40 GeV^2



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

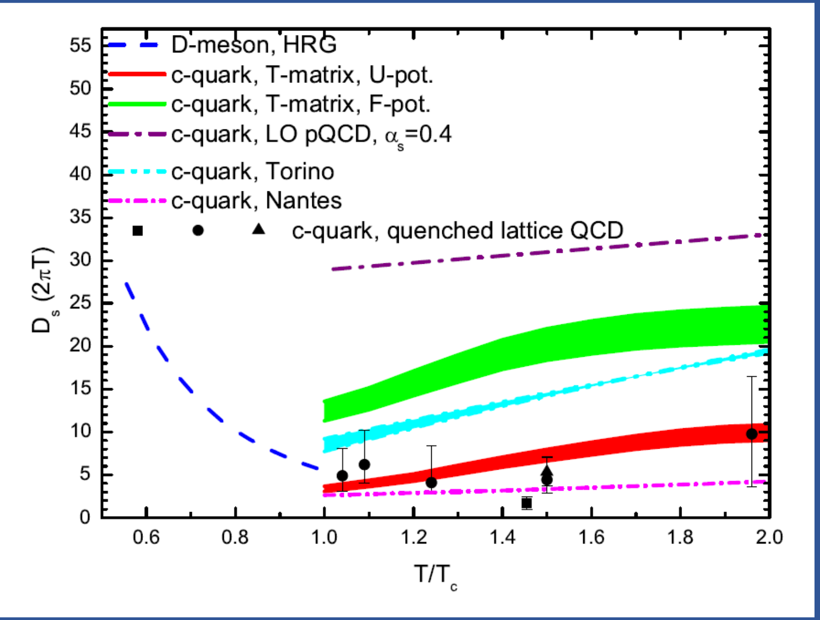




Eskola et al. , EPJ C77 (2017) 13

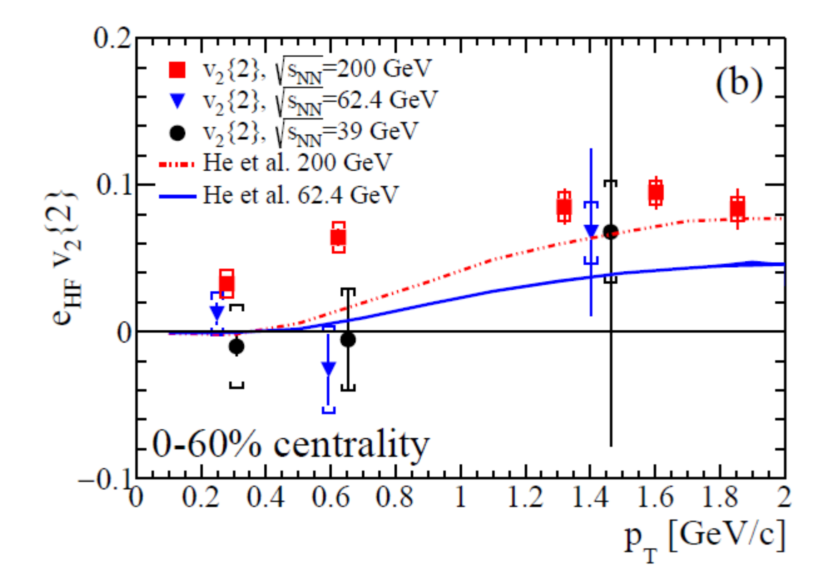
Open charm in Pb-Pb: R_{AA} and v_2

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



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

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}
      - → after selections S/B ~0.5