Quarkonia and heavy flavours in NA60+

G. Usai (University of Cagliari and INFN, Italy) for the NA60+ Collaboration

STVDIORVM UNIVERSITAS CARALITANA

INFN Istituto Nazionale di Fisica Nucleare

CERN

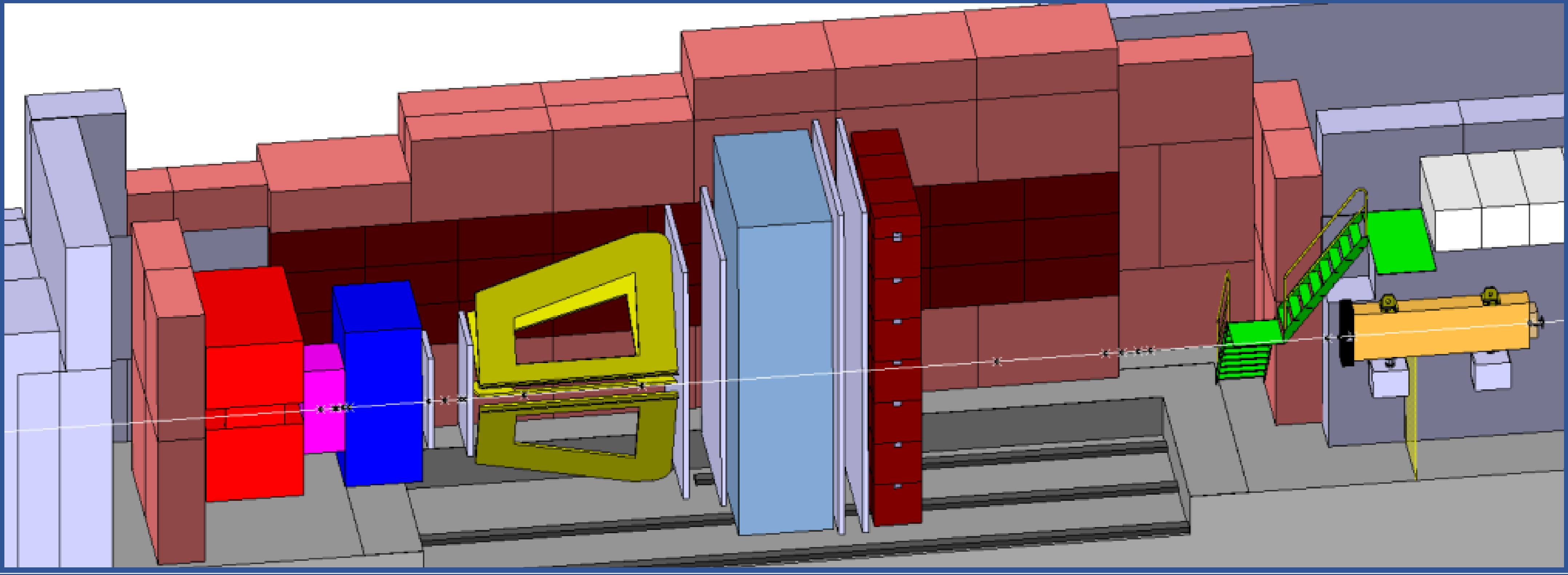
Physics Beyond Colliders

HFwINC 2020

Overview

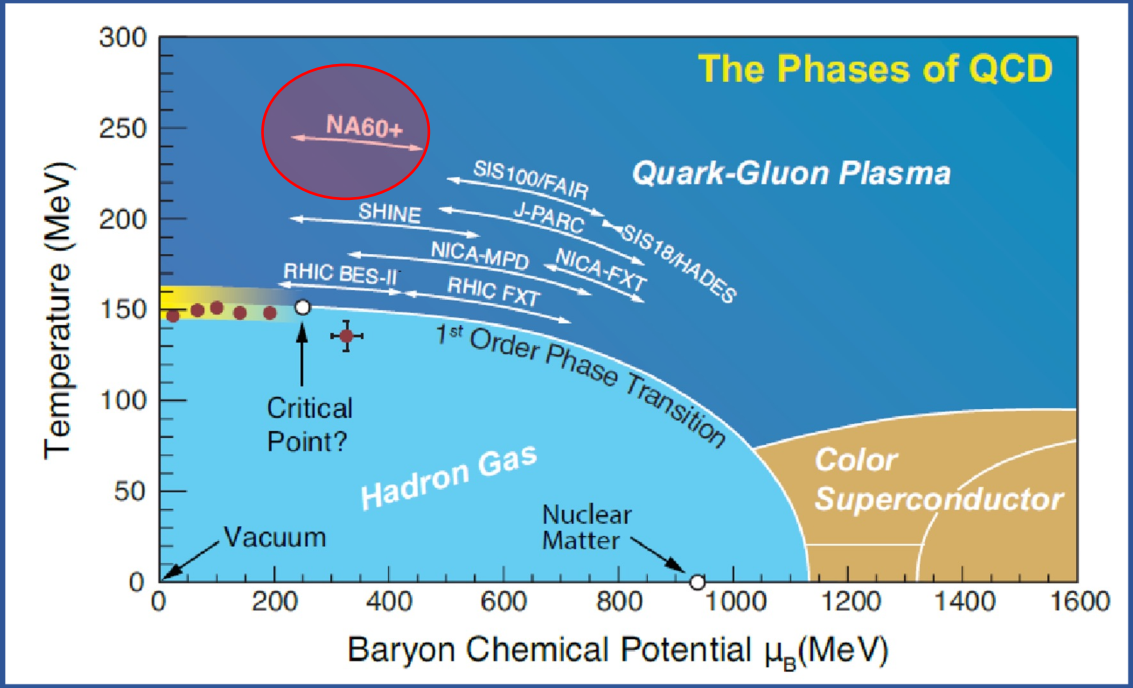
- The **physics case**: dimuon, heavy quark and strangeness production in Pb-Pb collisions at the SPS
- Designing a fixed-target experiment for a beam energy scan from 20 A GeV to 160 A GeV
    - Integration and ongoing **R&D studies**
- **Physics performance** studies for quarkonia and open charm
- Timescale and conclusions

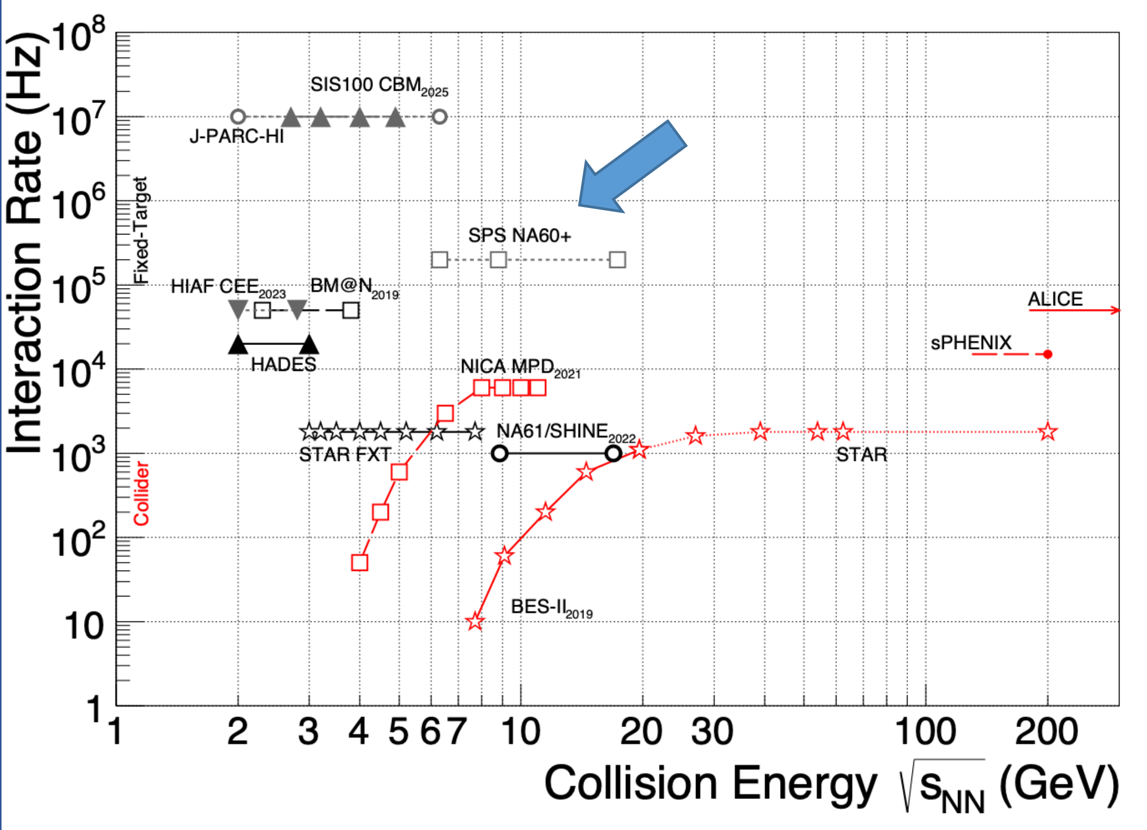
https://na60plus.ca.infn.it/



NA60+

- Study of hard and electromagnetic processes at the CERN-SPS: an investigation of the high-μ_B region of the QCD phase diagram via an **energy scan** ($\sqrt{s_{NN}}$=6 to 17 GeV)





(from T. Galatyuk)

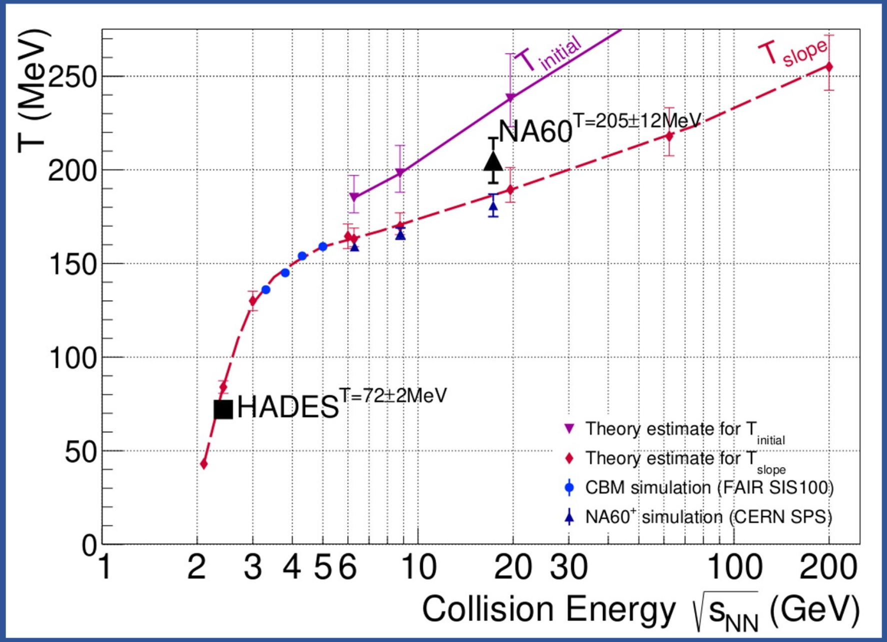
- Main features
  - Coverage of a **wide μ_B region**
  - Precision physics: possibility of reaching **high interaction rates** (hundreds kHz)
  - Complete physics reach for **dimuons and charm**
  - Energy range complementary to FAIR/GSI (and J-PARC)

Aim at significant improvement (and extension) of the physics reach wrt the former NA60 experiment

The “pillars” of the NA60+ physics case

Measure:

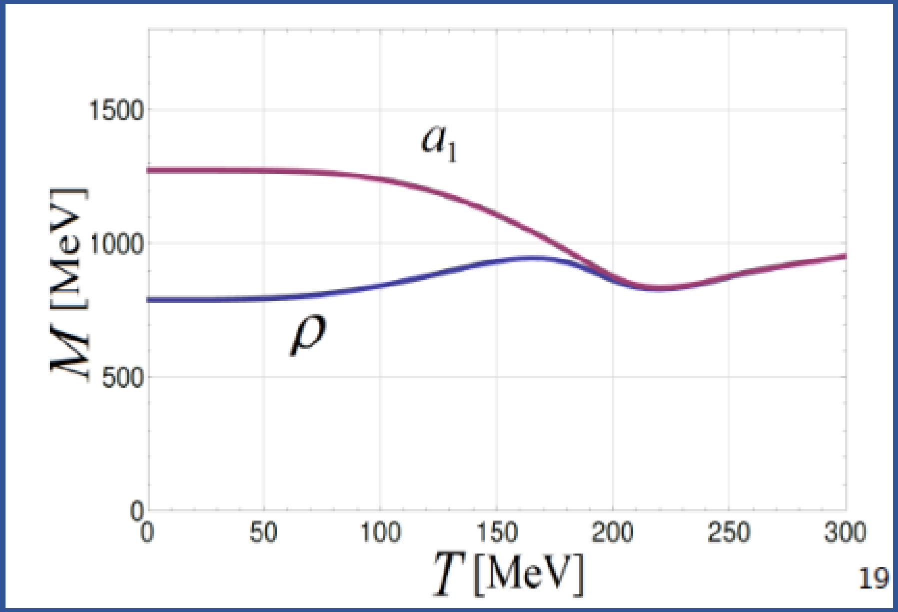
- **Thermal dimuons from QGP/hadronic phase: caloric curve for first order transition**
- **ρ-a_1 modifications: chiral symmetry restoration**
- Quarkonium suppression: signal of deconfinement
- Hadronic decays of charmed mesons/baryons: QGP transport coefficients



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

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

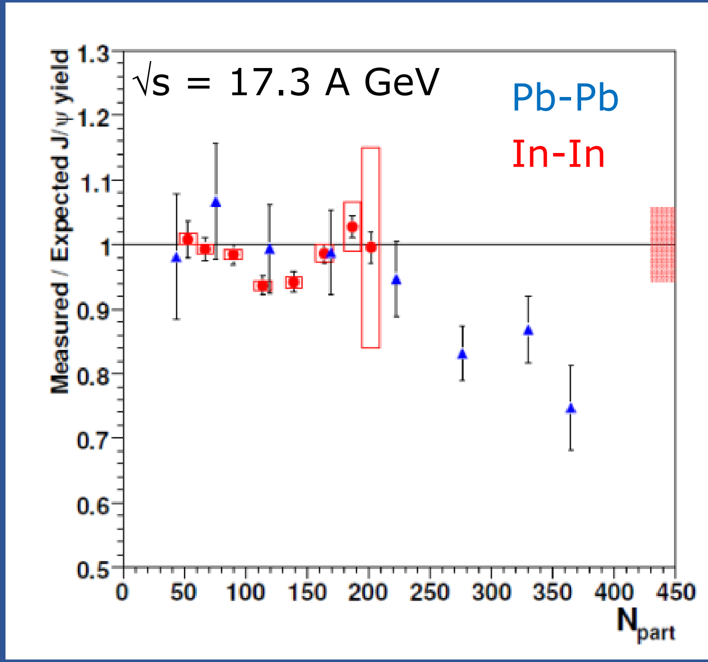
Full chiral ρ-a_1 mixing
→ dimuon enhancement in the region $1<M<1.4$ GeV/c^2



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

The “pillars” of the NA60+ physics case

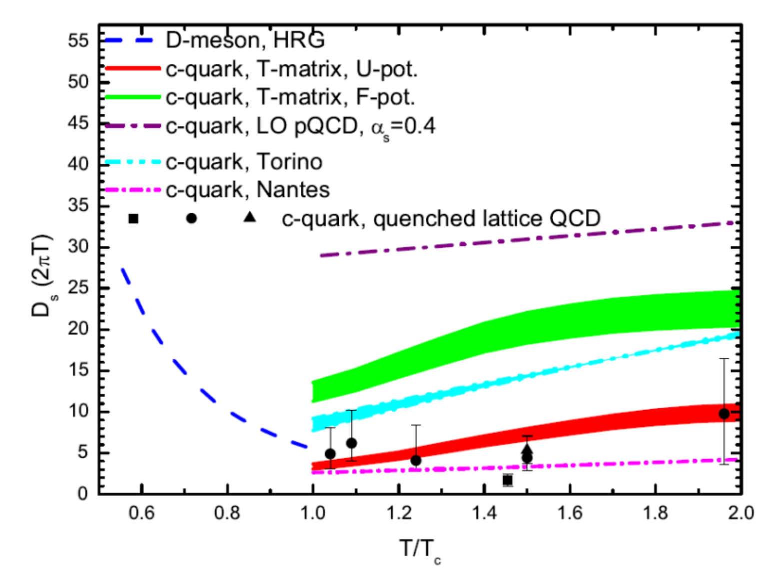
Measure:
- Thermal dimuons from QGP/hadronic phase: caloric curve for first order transition
- ρ-a_1 modifications: chiral symmetry restoration
- **Quarkonium suppression: signal of deconfinement**
- **Hadronic decays of charmed mesons/baryons: QGP transport coefficients**



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

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

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



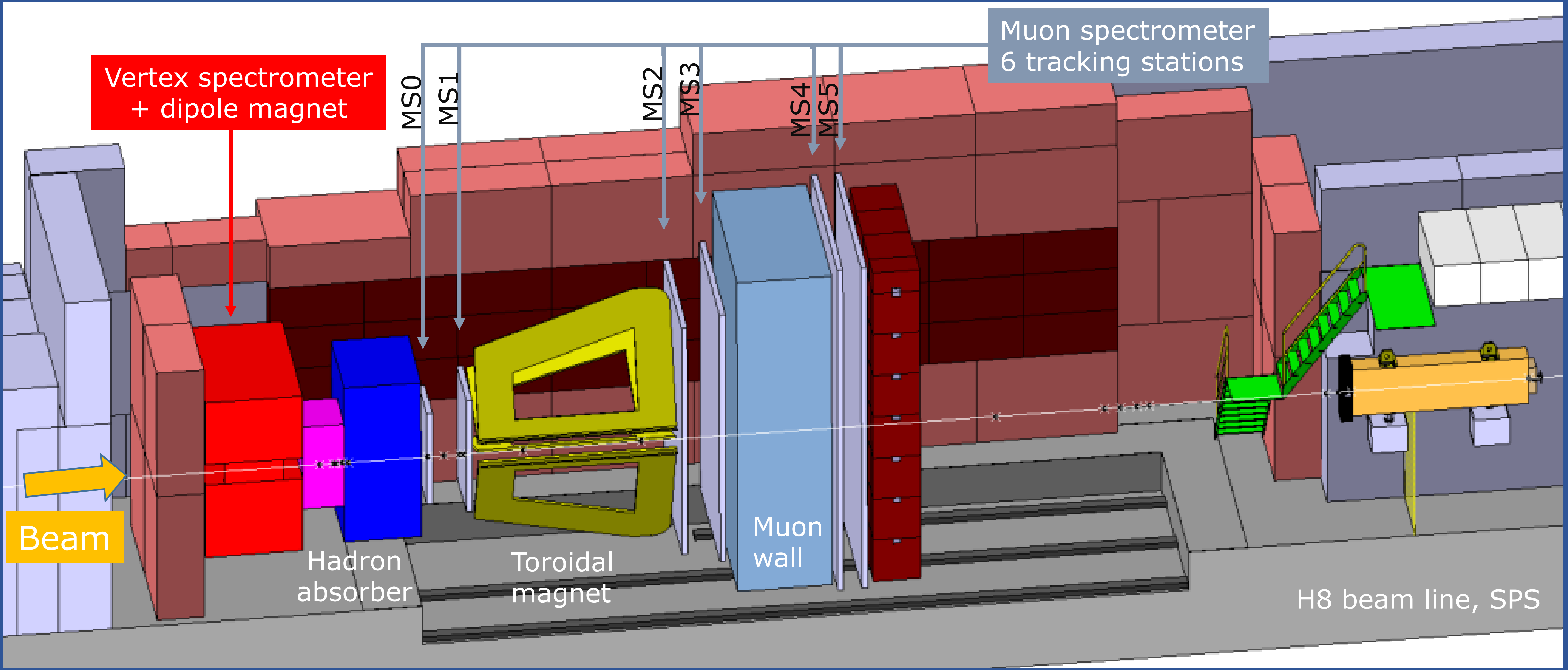
F. Scardina et al., PRC96 (2017) 044905

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

NA60+ set-up in EHN1-H8

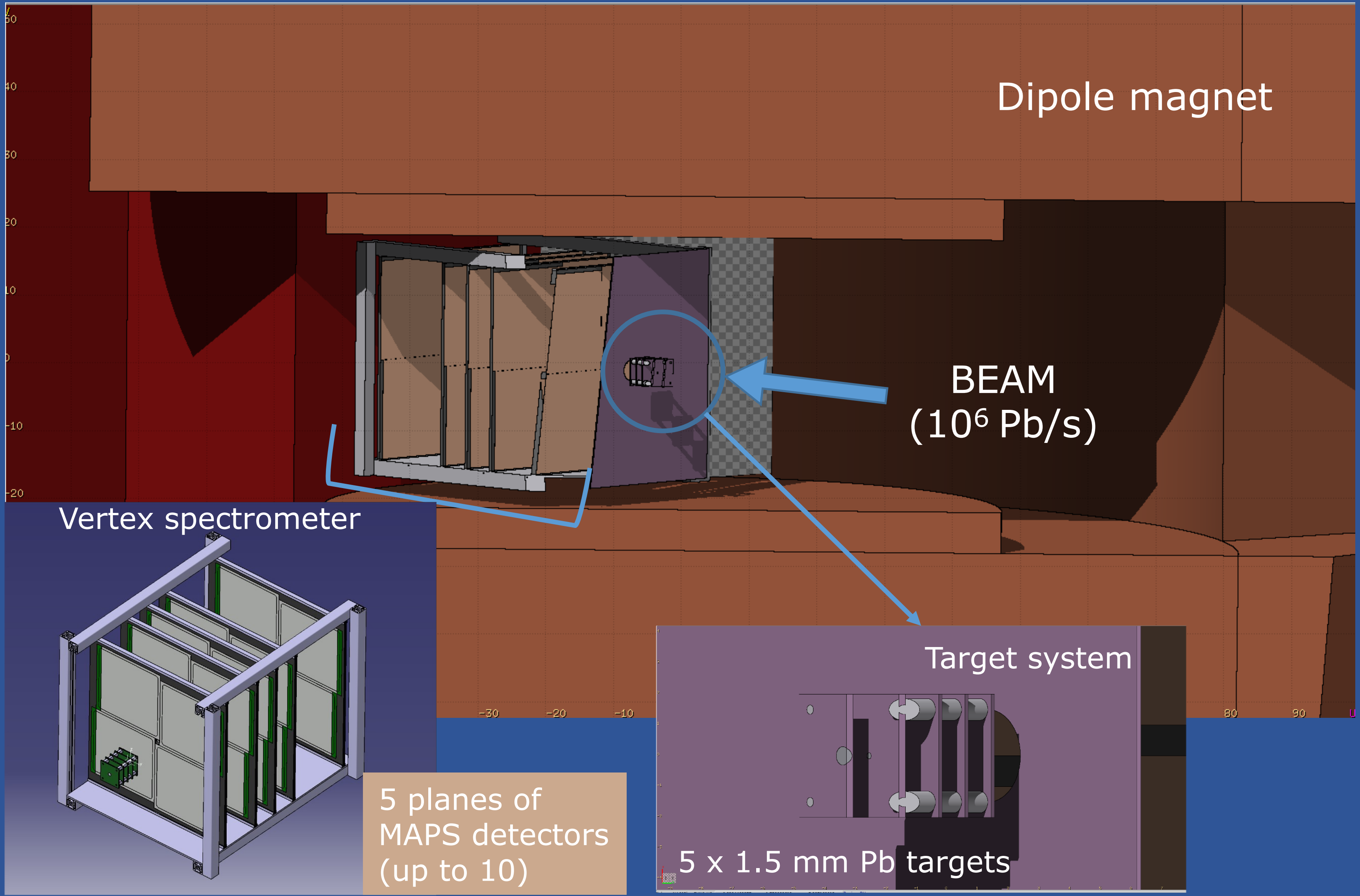
CERN support to the project through Physics Beyond Colliders

Muon spectrometer position will be varied (rails), to cover mid-rapidity at different collision energies



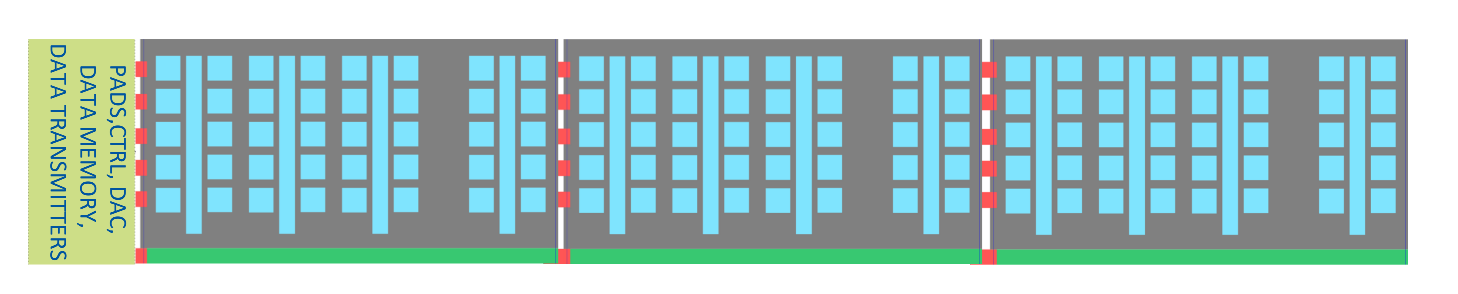
NA60+ set-up: vertex region

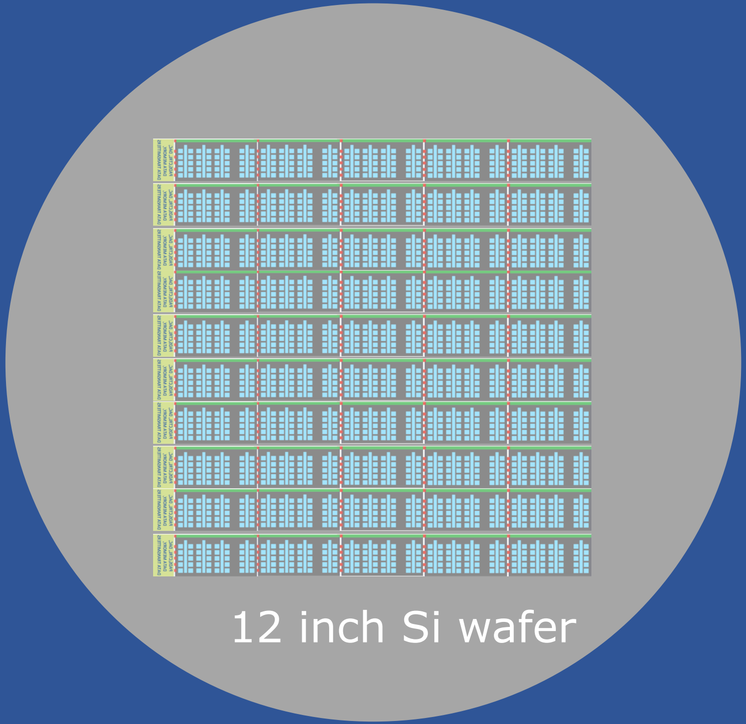
MEP48 dipole magnet
Field: 1.5 T over a 400mm gap



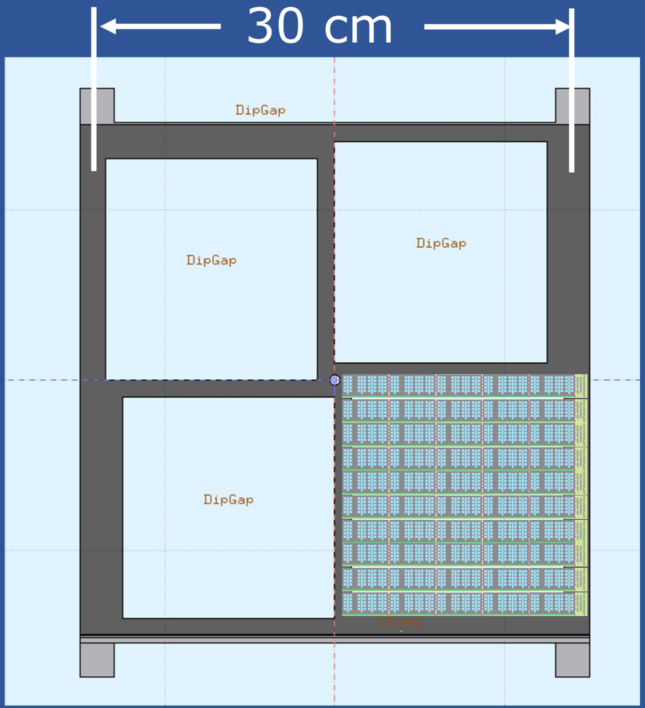
R&D: vertex spectrometer

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





12 inch Si wafer



Complete NA60+ station → 4 sensors

R&D in progress - Common development **ALICE ←→ NA60+**

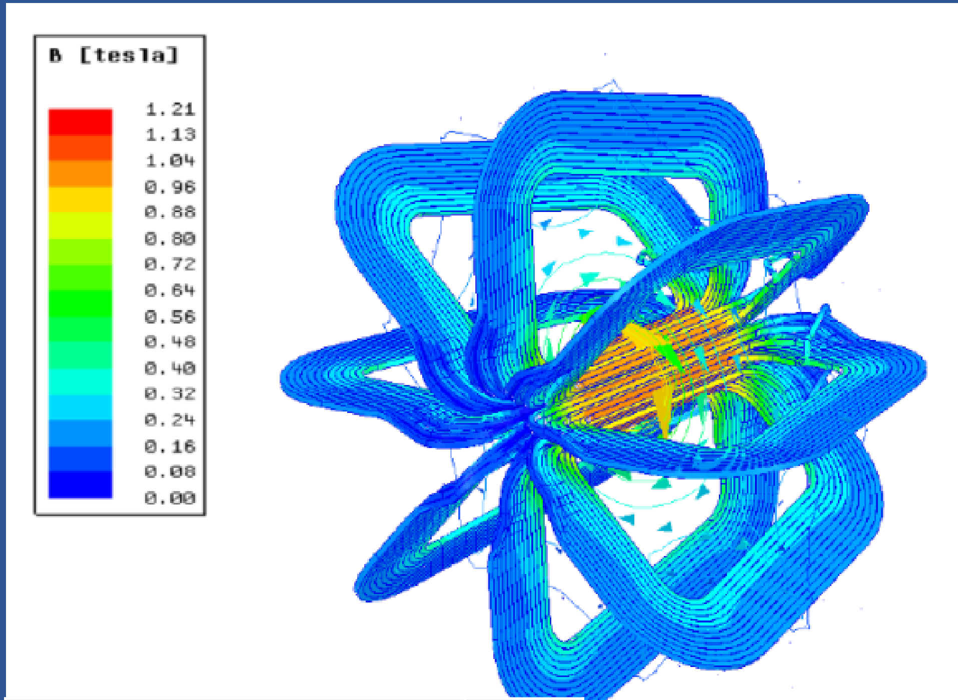
State-of-the-art imaging technology TowerJazz 65 nm

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

Spatial resolution ≤ **5 μm**

Cooling studies (NA60+ geometry) in progress

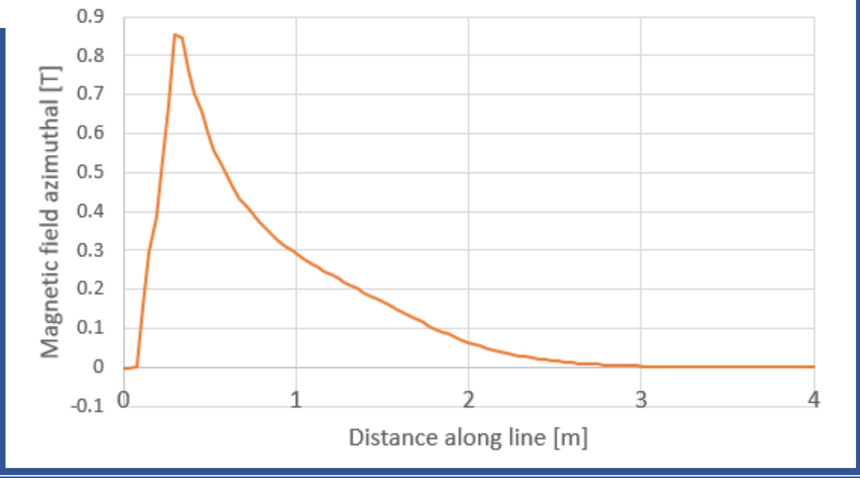
R&D: toroidal magnet

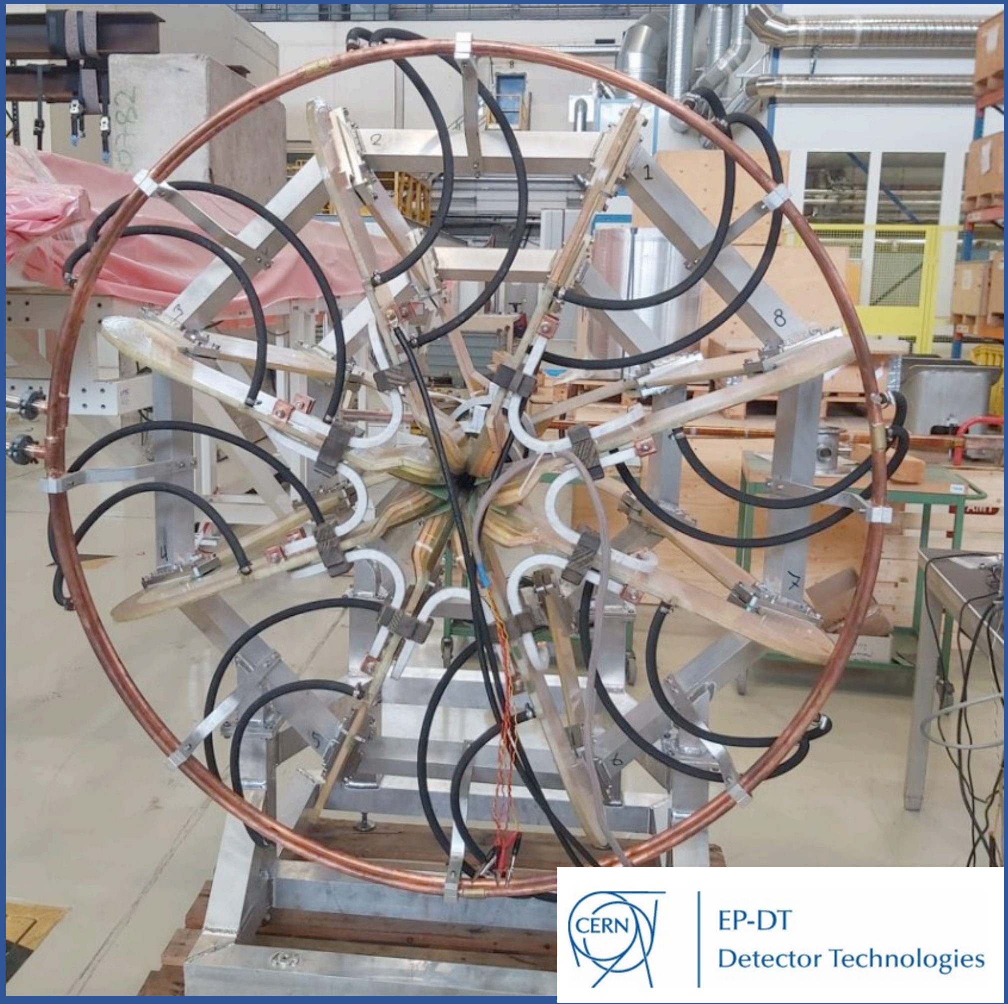


Eight sectors, 12 turns per coil

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

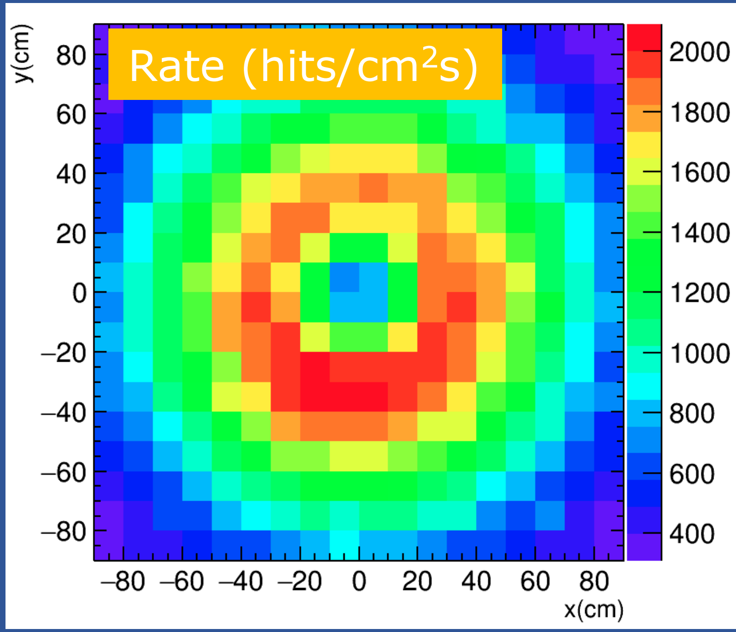




- **Prototype (1:5 scale)** was built and tested in 2020-2021, to check calculations and investigate mechanical solutions, in view of the final object

→ **works correctly and as expected**

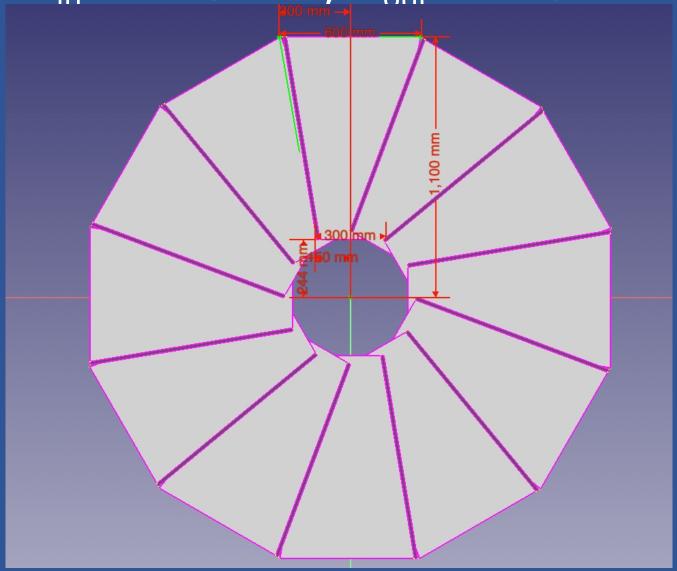
R&D: muon tracker



Rates (FLUKA) in the upstream stations are modest, thanks to the thick absorber (235 cm BeO +C)
For a 10^6 s^{-1} beam → charged particle rate ~2kHz/cm^2

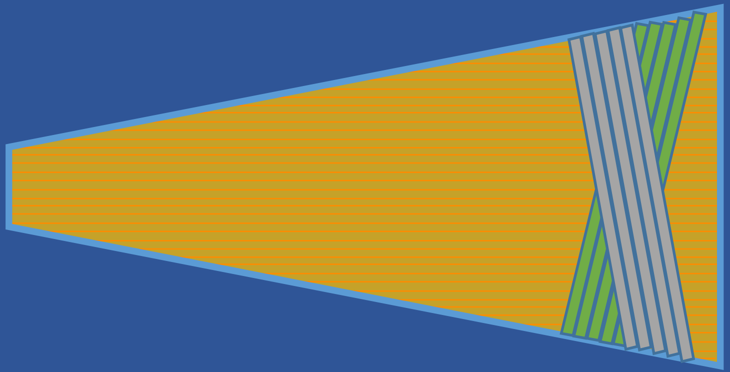
Can be matched by GEM or MWPC detectors
Discussion on technology choice in progress

Upstream stations
R_{in} =24.5 cm , R_{out} = 110 cm



Triple **GEM chambers** with 2D strip readout

MWPC with 3 mm wire pitch and 3 mm gap from anode wire to cathode
Analog strip R/O (strip pitch to be defined during R&D this year)

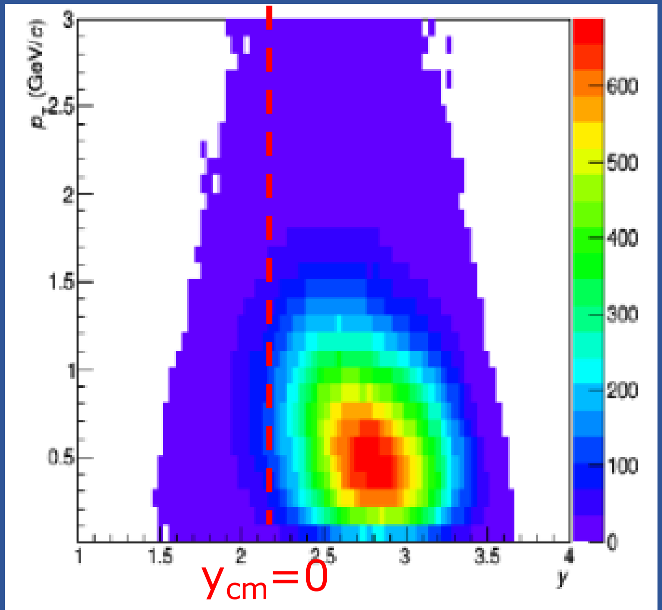


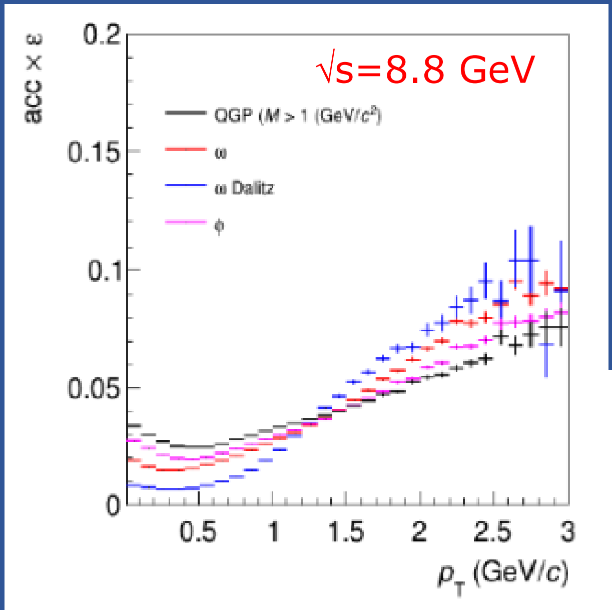
SPS beam test of first prototype(s) in October/November

Dimuon detection efficiency

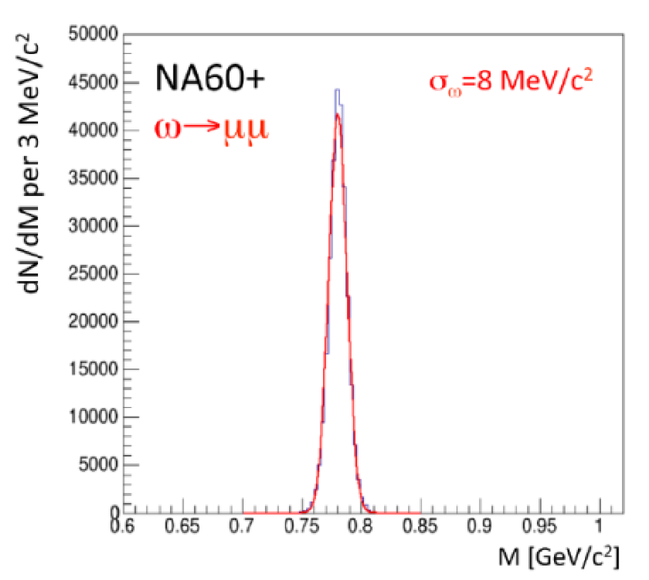
Detector performance studies → based on a **simulation framework** with a semi-analytical tracking algorithm (Kalman filter)
FLUKA for background studies

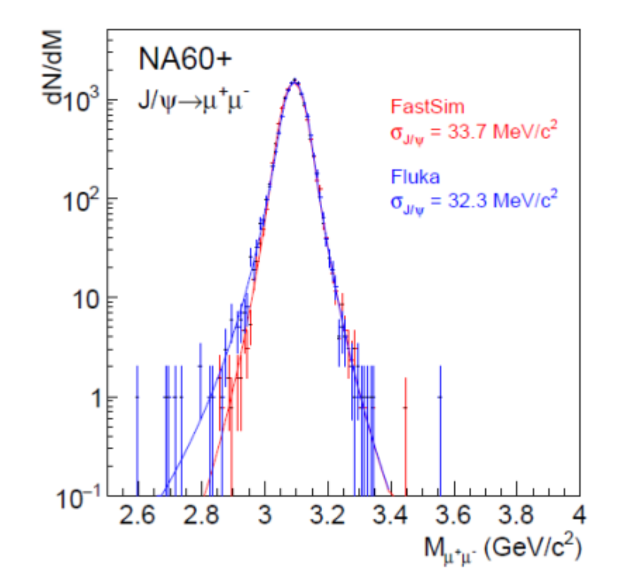
QGP (M>1 GeV/c^2)





- ❑ Full phase-space acceptance at dimuon low and intermediate masses → >1%
- ❑ Good coverage down to midrapidity AND zero p_T, realized at all energies by displacing the muon spectrometer

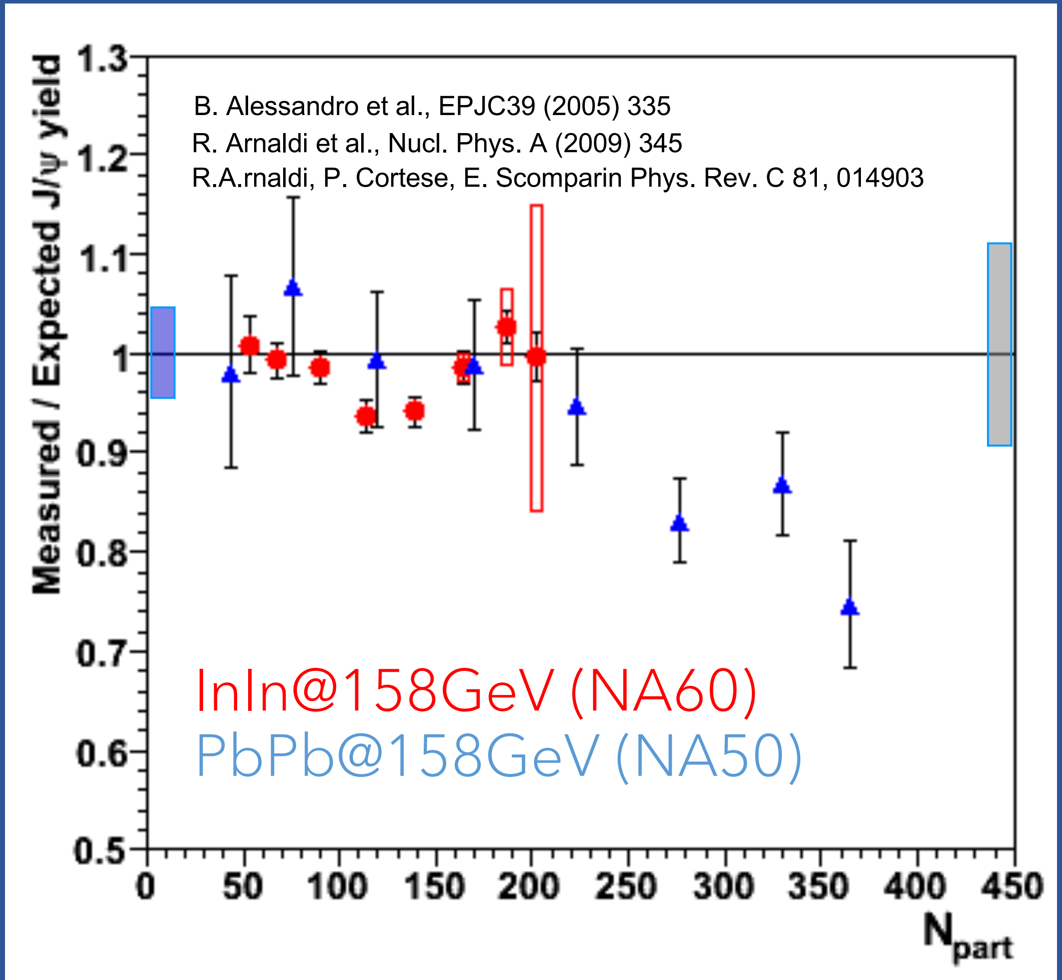




The mass resolution for resonances varies from <10 MeV (ω) to ~30 MeV (J/ψ)

(factor >2 improvement with respect to NA60)

J/ψ in NA60+



SPS results based on the pA reference curve at 158 GeV (same energy as AA)

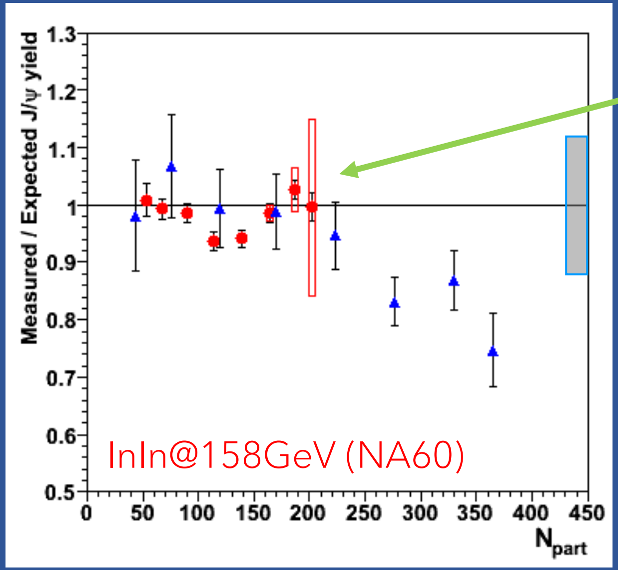
Full SPS energy: size of J/ψ suppression quantitatively consistent with melting of ψ(2S) and χ_c

Decreasing in √s:

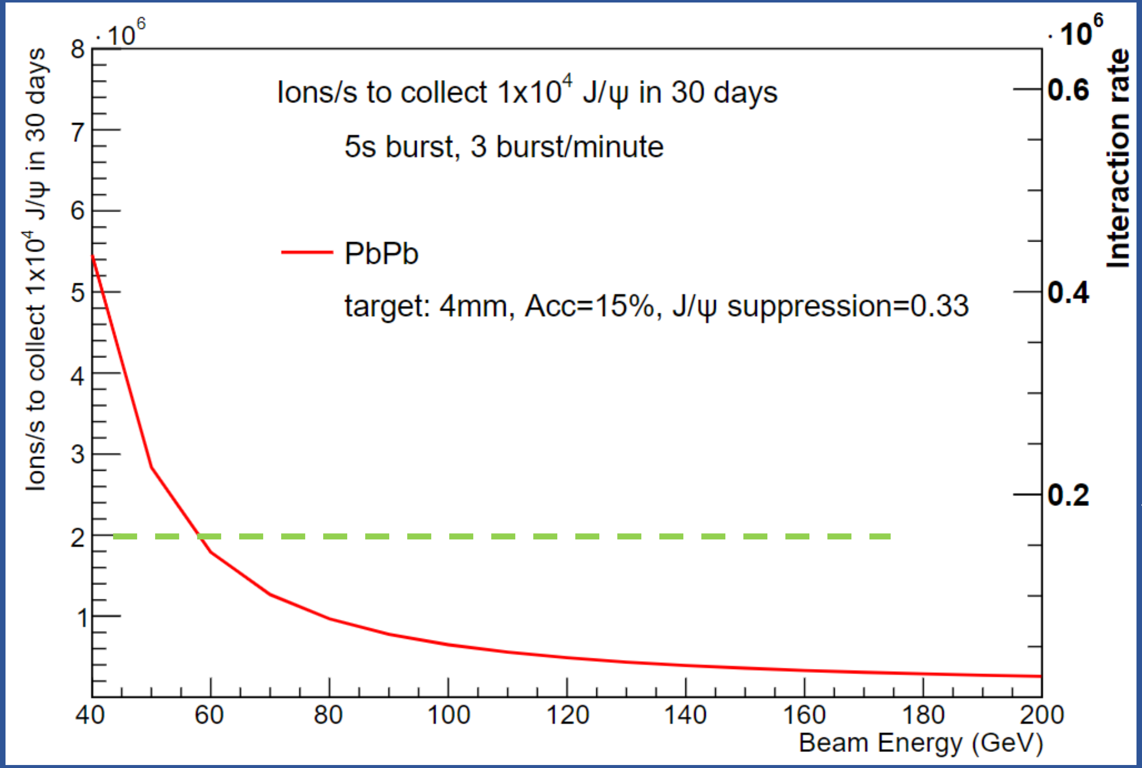
- high μ_B QGP effects on quarkonium
  → still need theory guidance
- onset of χ_c and ψ(2S) deconfinement
  → can be correlated to T measurement via thermal dimuons
- stronger CNM effects
  → to be accounted for with pA data taking at the same √s

J/ψ in NA60+, AA collisions

High luminosity is needed to cope with the low production cross sections at low √s



AA: precise NA60 data (InIn at 158 GeV) correspond to 3 x 10^4 J/ψ



NA60+ CERN-SPSC-2019-017 ; SPSC-EOI-019

With I_{beam}~2x10^6 Pb/s and 1 month of data taking NA60+ can aim to

- ~10^4 J/ψ at 50 GeV
- ~5 10^4 J/ψ at 158 GeV

J/ψ in NA60+, pA collisions

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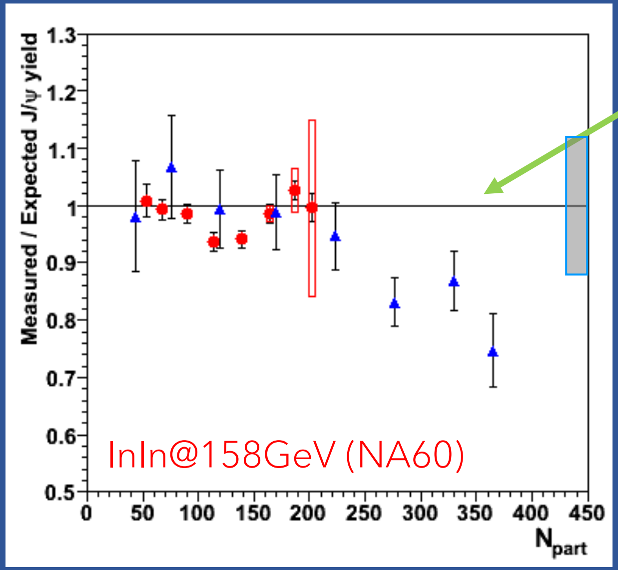
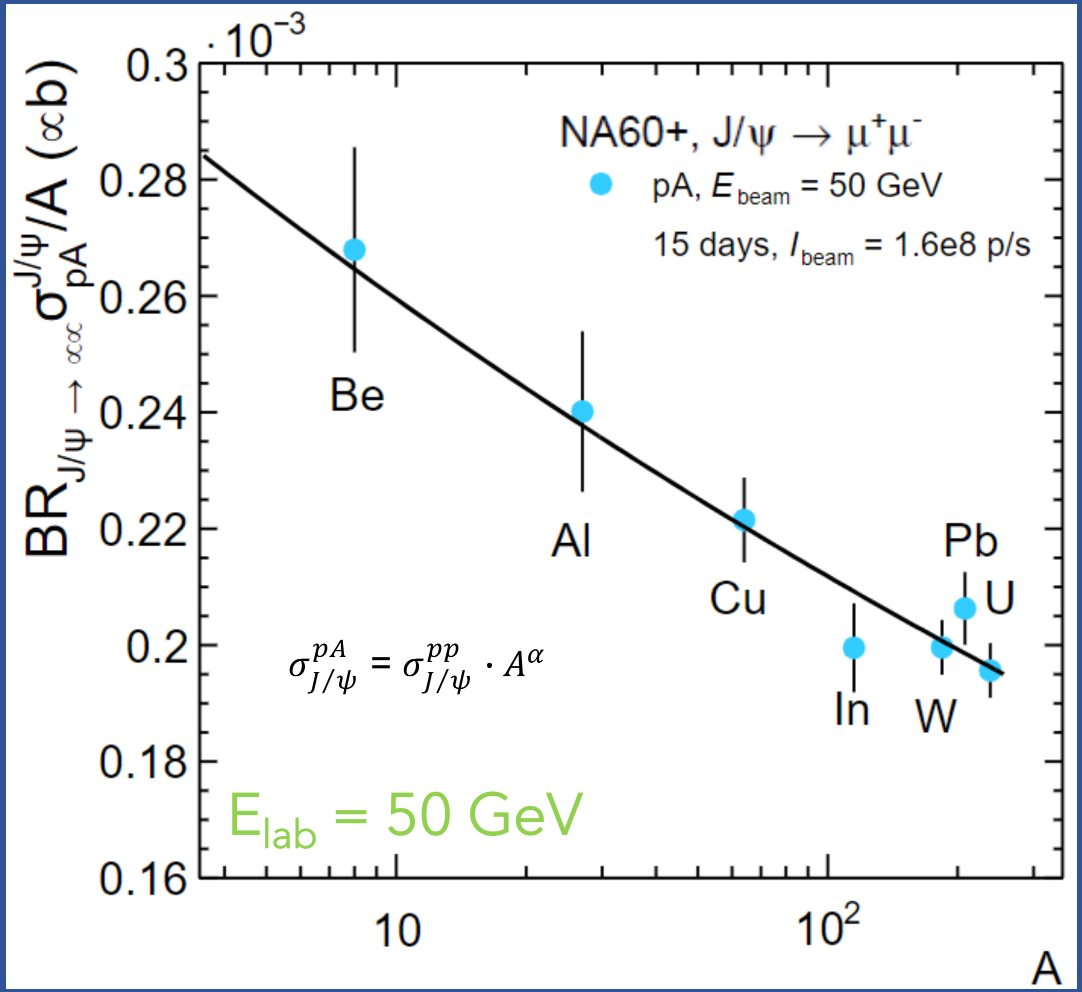
NA60+ CERN-SPSC-2019-017 ; SPSC-EOI-019



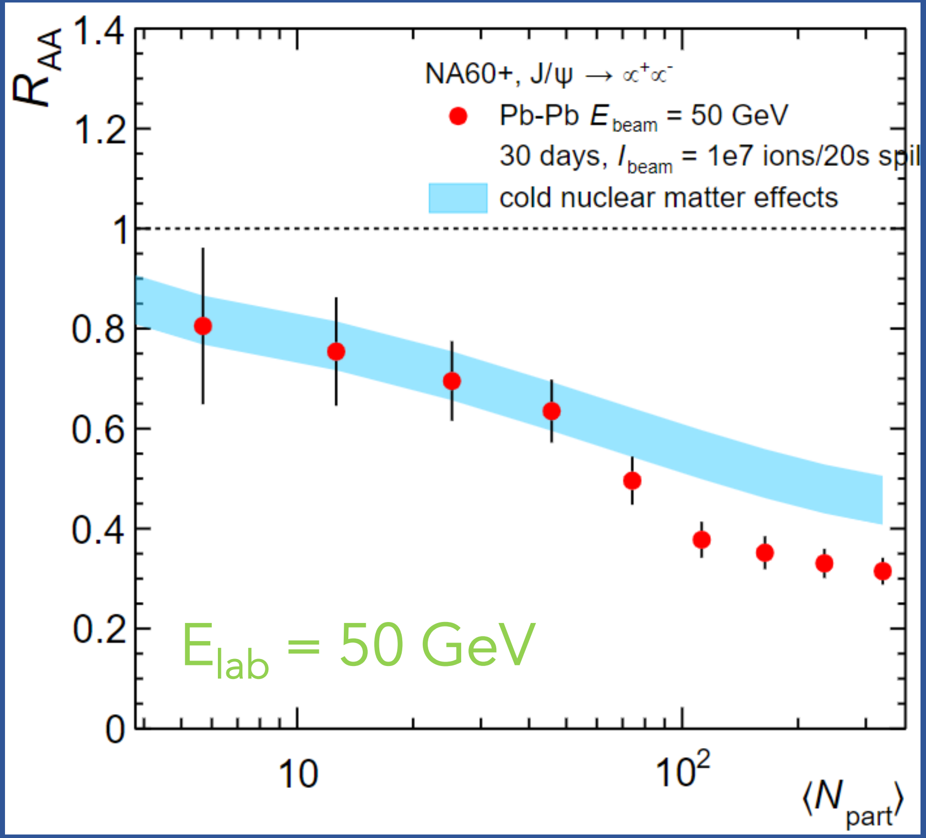
pA: NA60 data taking at 158 GeV was ~1.5 x 10^4 J/ψ

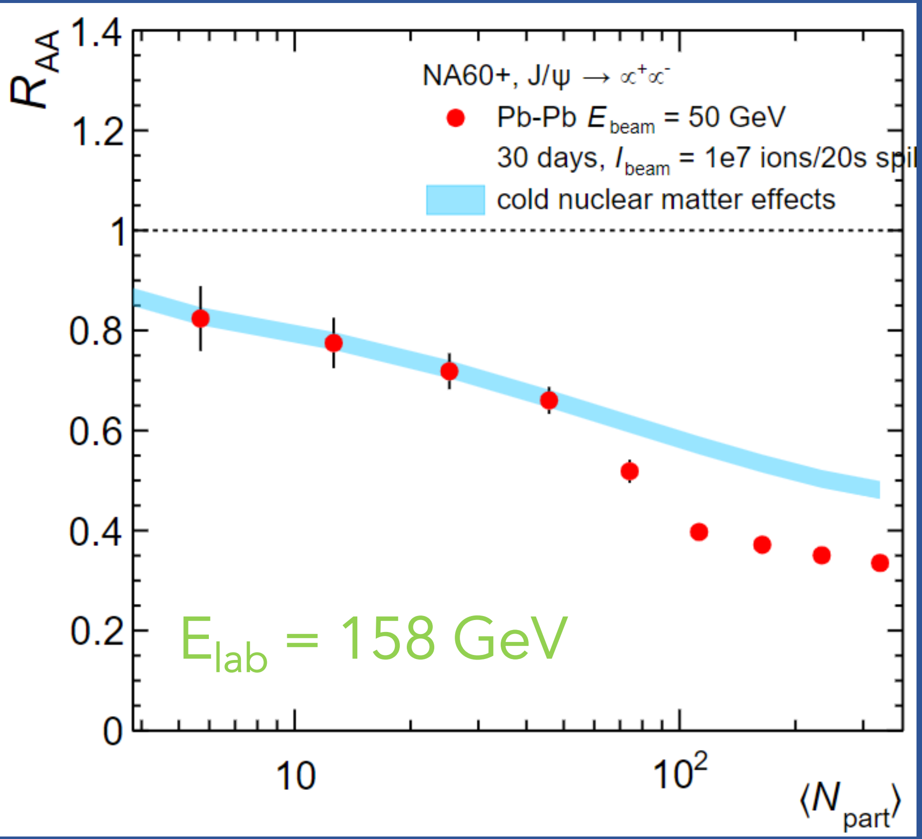


In 15 days of data taking at 1.6 x 10^8 p/s NA60+ should collect

- E_{lab} = 50GeV ~6000 J/ψ
- E_{lab} = 158GeV ~50000 J/ψ

J/ψ in NA60+, pA and AA collisions





Based on

- 30 days PbPb
  I_{beam} = 2x10^6 Pb/s
- 15 days pA
  I_{beam} = 1.6x10^8 p/s

assuming only CNM effects for N_{part}<50 and 20% suppression for N_{part}>50

→ Precise evaluation of anomalous suppression within reach even at low E_{lab}

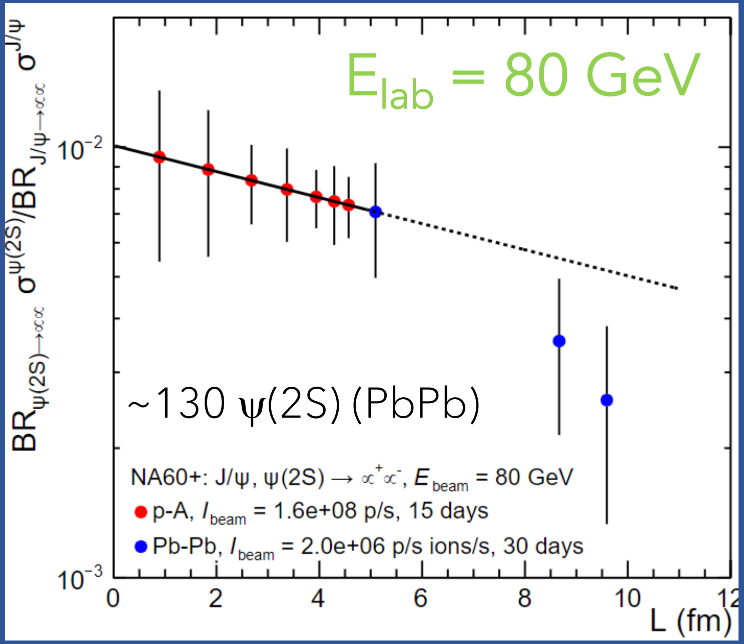
NA60+ CERN-SPSC-2019-017 ; SPSC-EOI-019

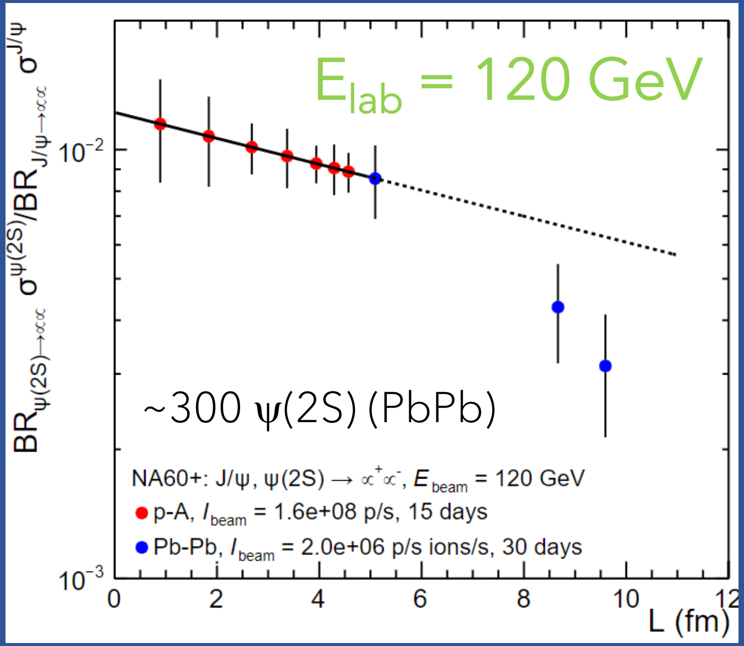
ψ(2S) in NA60+, pA and AA collisions

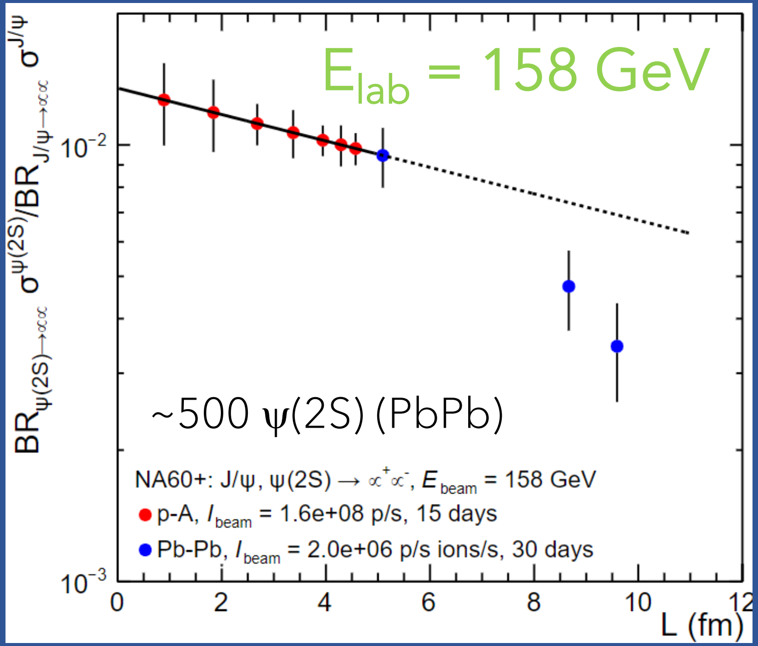
Good charmonium resolution (~30 MeV for the J/ψ) will help ψ(2S) measurements

Expectations based on

- 30 days PbPb, $I_{beam} = 2\times10^6$ ions/s (assuming larger suppression for ψ(2S) than J/ψ)
- 15 days pA, $I_{beam} = 1.6\times10^8$ p/s







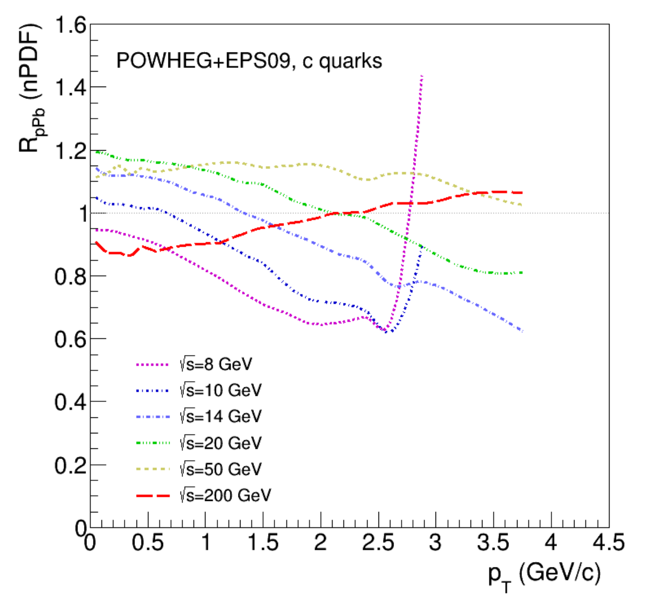
ψ(2S)/ψ measurement down to E_{lab} = 120 GeV

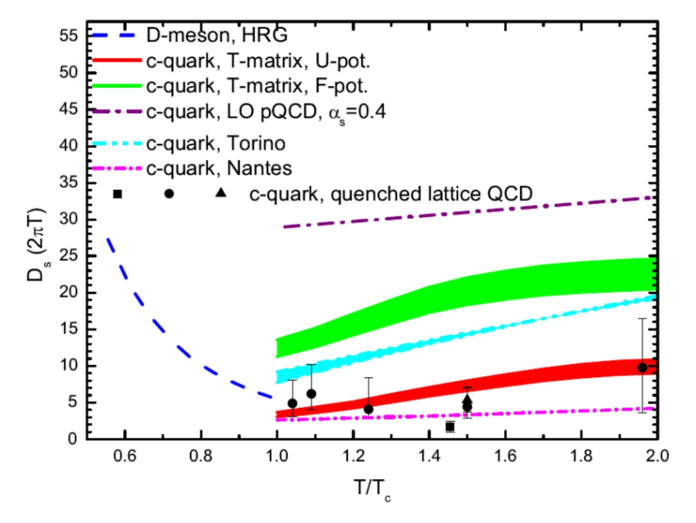
Lower E_{lab} would require larger beam intensites/longer running times

Open charm at SPS: what can we learn

- Almost unexplored energy domain
  - → No results available below top SPS energy
- Charm production in p-A collisions
  - → Sensitive to nuclear PDFs
    - ✓ Q^2~10–40 GeV^2 and $0.1<x_{Bj}<0.3$ (anti-shadowing and EMC)
  - → Possible sensitivity to intrinsic charm
- Charm hadron yield and v_2 in A-A collisions
  - → Constrain estimates of the charm diffusion coefficient
  - → Charm quark thermalization in a short-lived QGP
  - → Insight into hadronization mechanism
    - ✓ Enhanced D_s/D and Λ_c/D ratios in case of quark recombination
  - → Charm cross section sensitive to chiral symmetry restoration:
    - ✓ Enhancement of charm production at chiral restoration where the threshold for production of a $D\bar{D}$ pair may be reduced

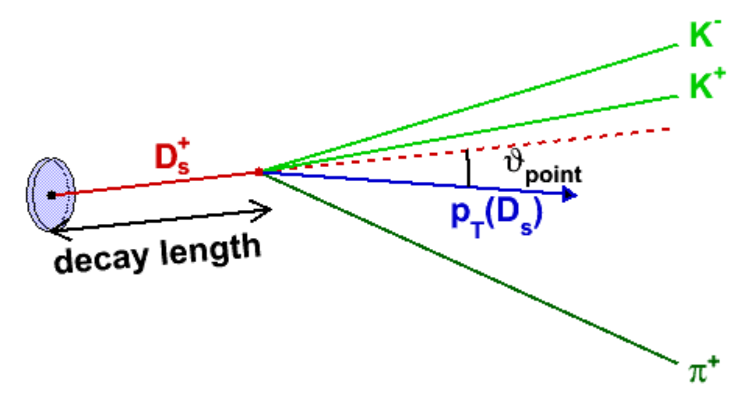
📖 Friman et al., Lect. Notes Phys. 814 (2011), 1





Charm hadron reconstruction

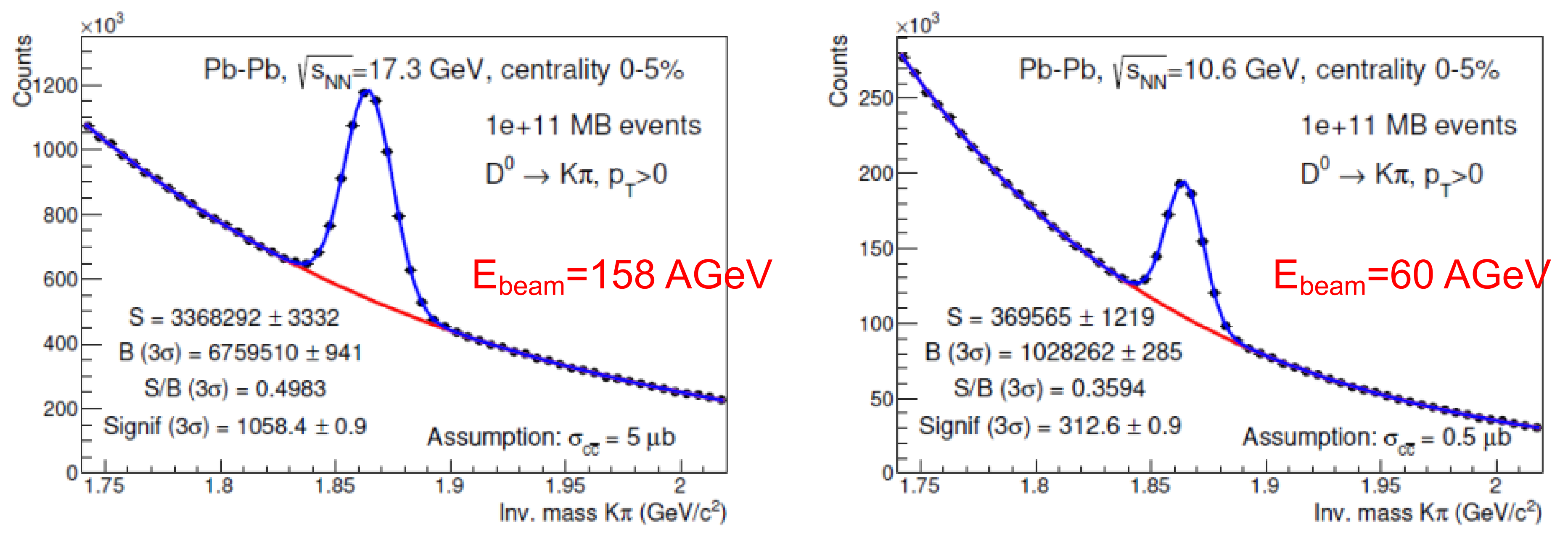
- Charmed mesons and baryons reconstructed from their decays into 2 or 3 charged hadrons
- Small production cross sections + small(ish) BRs
  → large samples of minimum-bias collisions
- Mean proper decay lengths $c\tau$ ~60-300 μm
  → High precision on tracking and vertexing required to discriminate the charm-hadron decay vertex from the interaction point



Hadron	Mass (MeV/c²)	$c\tau$ (μm)	Decay	BR
D^0	1865	123	$\to K^-\pi^+$	3.95%
D^+	1869	312	$\to K^-\pi^+\pi^+$	9.38%
D_s^+	1968	147	$\to \phi\pi^+ \to K^-K^+\pi^+$	2.24%
Λ_c^+	2285	60	$\to pK^-\pi^+$ $\to pK^0_s$ $\to \Lambda\pi^+$	6.28% 1.59% 1.30%

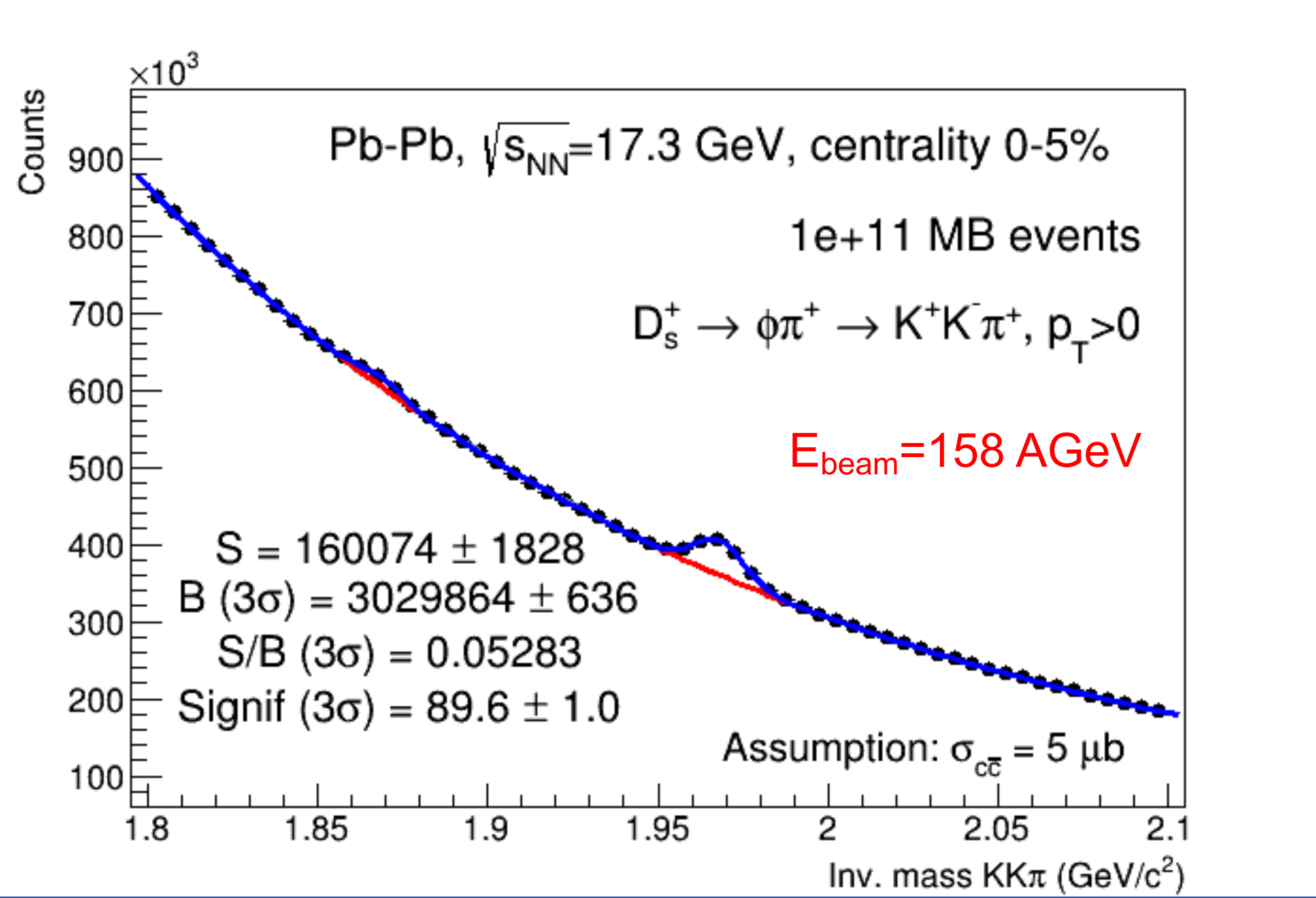
NA60+ physics performance: D^0 mesons

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

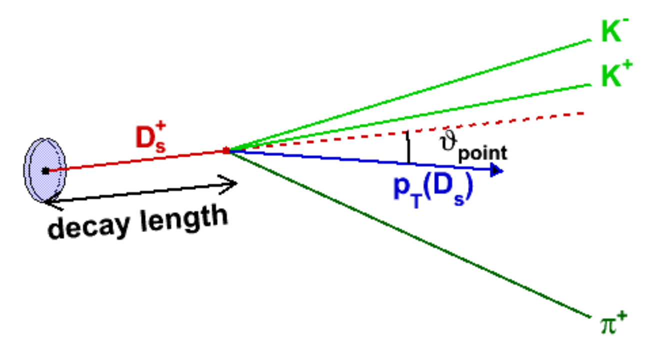


NA60+ physics performance: D_s mesons

- With 10^{11} minimum bias Pb-Pb collisions (1 month of data taking)
  → Measurement of D_s yield feasible with statistical precision of few percent
  Still room to improve the selections in the simulations

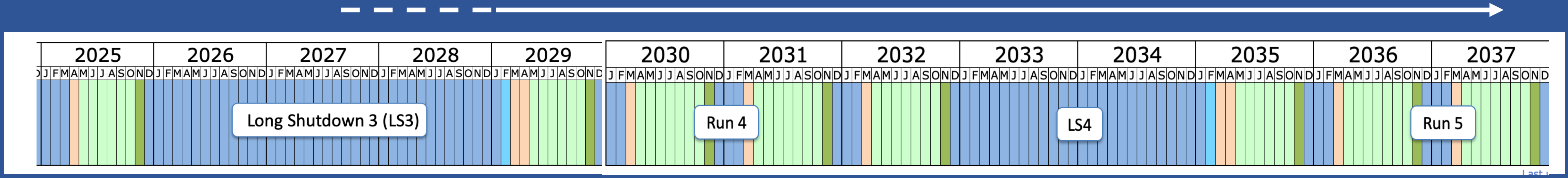


$D_s^+ \longrightarrow \phi\pi \longrightarrow KK\pi$



Timeline

- ❑ 2022 → Letter of Intent
- ❑ 2024-25 → Proposal
- ❑ 2025-2028 → Construction
- ❑ From 2029 → Data taking



- ❑ Foresee **at least 6 yrs** of data taking (one energy point per year with p-A and Pb-Pb)

Number of days for Pb assumes a 25.2 s SPS supercycle
Would increase to 52 (58) days for a 45 (50) s SPS supercycle

PBC Report - Post-LS3 North Area Experiments ion beam requirements

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Momentum for p (GeV/c)	160	40	120	20 (or 30)	80	100
Momentum for Pb (GeV/c/Z)	400	101	304	50.7 (76.1)	203	254
Pb ions on target	$\sim 10^{12}$ per energy ($\sim$ 29 days)					
protons on target	$5-6 \cdot 10^{13}$ per energy ($\sim$ 22 days)					

Conclusions

- Precision studies of **electromagnetic and hard probes** in the region $6<\sqrt{s_{NN}}< 17$ GeV are currently lacking

- The CERN NA60 experiment had obtained measurements with unsurpassed precision in the study of dilepton production at top SPS energy ($\sqrt{s_{NN}}$ =17.3 GeV)

- **NA60+: a new dimuon experiment** with a similar concept but based on state-of-the-art technology choices may collect a factor ~20 larger statistics for several collision energies at the SPS

- Expected physics performance → possible **breakthrough** on several hot topics

- From **design to realization**: R&D studies ongoing, CERN test beam periods from 2022

A Collaboration is being built and still needs to be strengthened in order to bring the project to approval → you are welcome to contact us for discussions!

Letter of intent

- Editing in advanced stage
- Editorial team:
  - INFN CA, TO
  - Weizmann
  - Stony Brook
  - CERN EP-DT, BE-EA, HSE
- To be finalized in the next few months

LoI: NA60+ — NA60+ Collaboration

Contents

i

LoI: NA60+ — NA60+ Collaboration

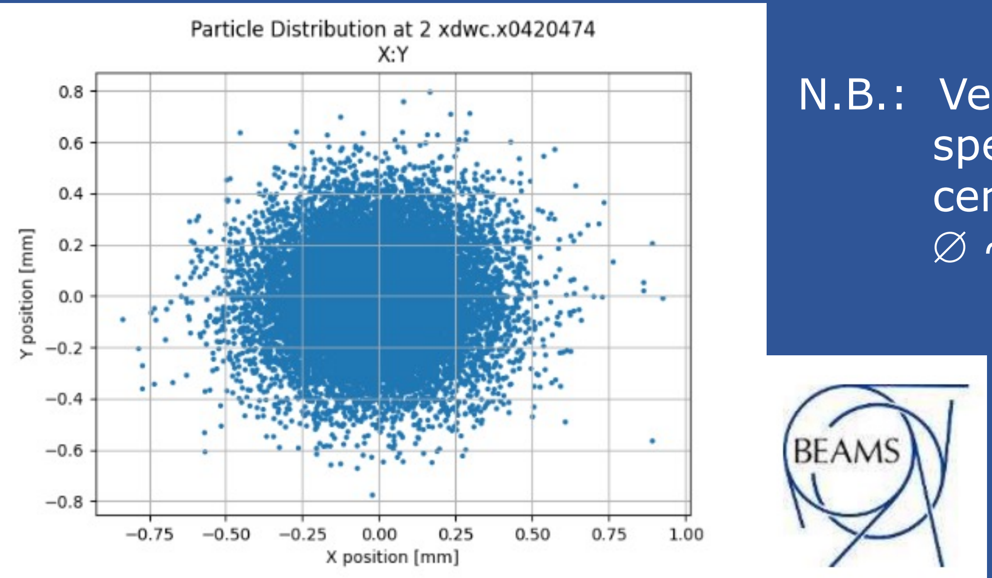
ii

Beam and RP studies

- Need **high-intensity** (10^7/spill), **collimated** (σ < 1mm) beam at all foreseen energies

→ Fully re-designed optics (final CERN PBC note submitted), to be **tested at SPS** in November 2022

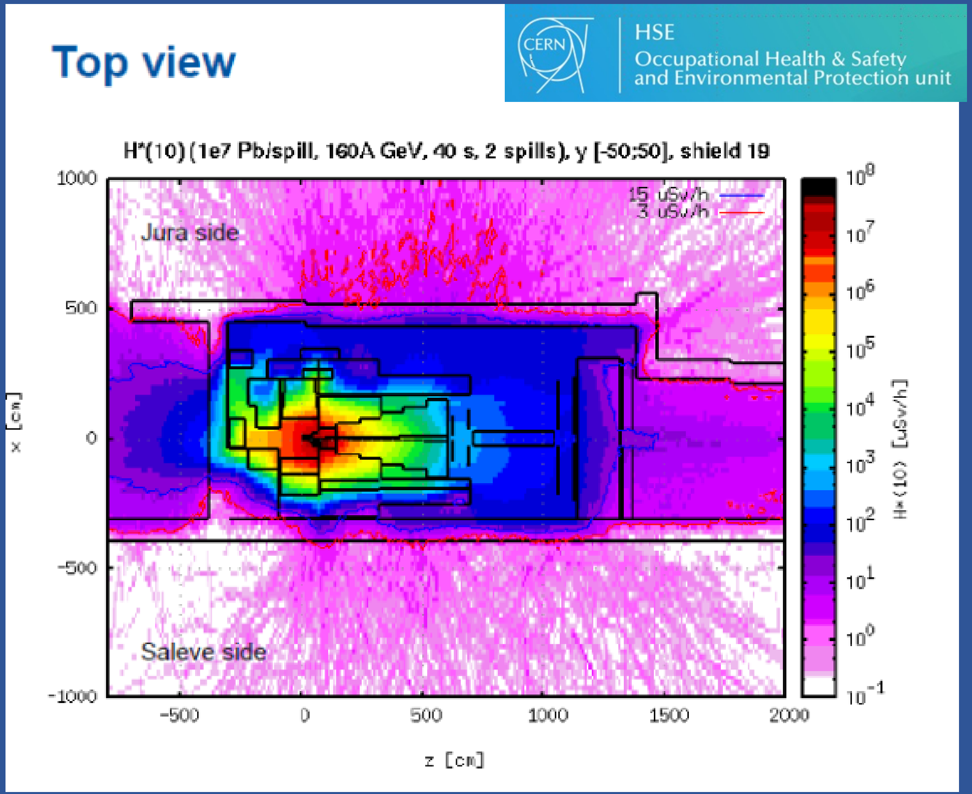
Parameter in zone 138	160 GeV/c	30 GeV/c
σ_x (mm)	0.19	0.33
σ_y (mm)	0.19	0.36
Transmission from T4 (%)	32.43	23.5



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

- Radioprotection studies represent a major technical issues

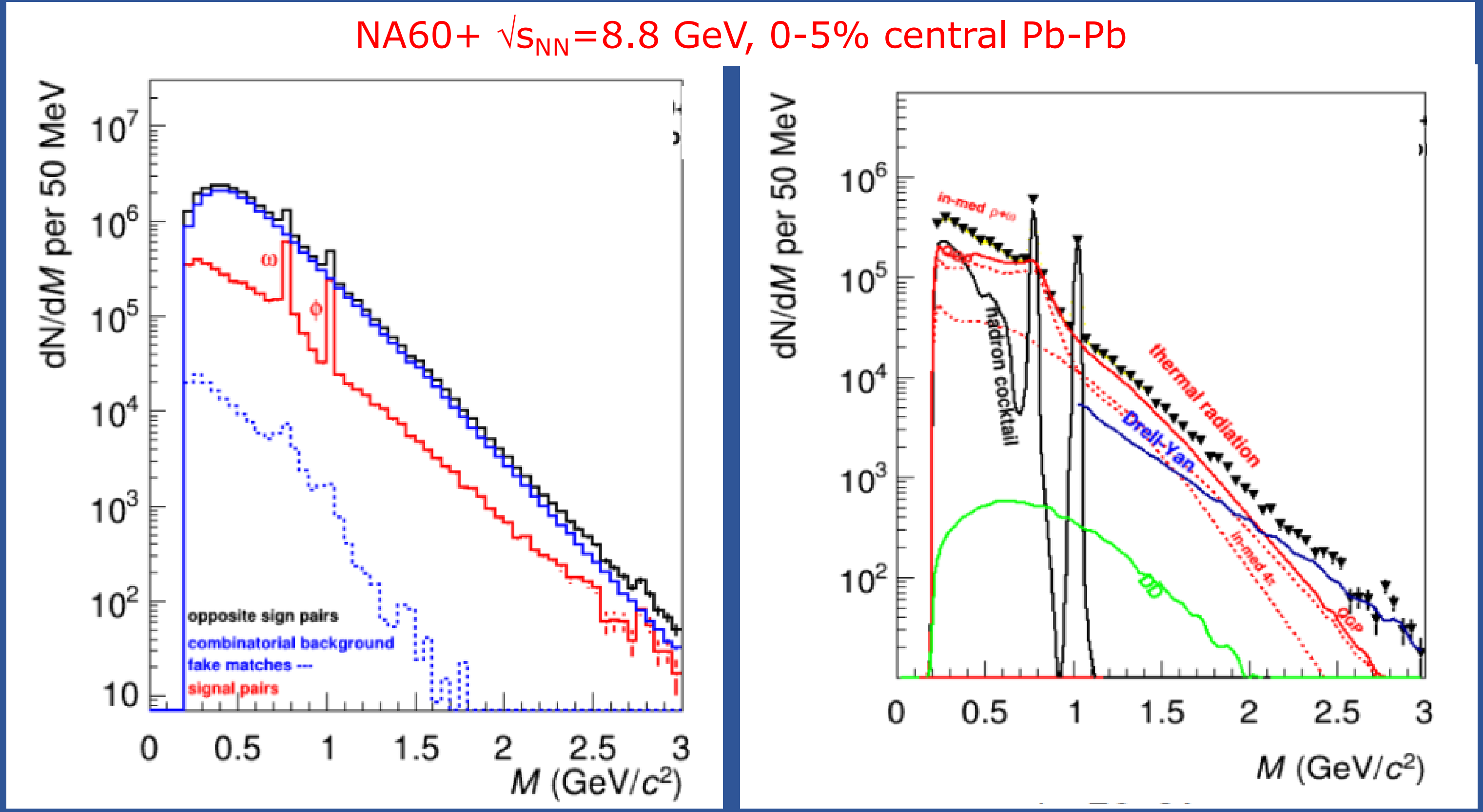
→ **Heavy shielding** (iron/concrete) was designed



Dose below 3 μSv/h externally to the experimental hall

Integration studies for detector and infrastructure also performed → proposal finalized

Dilepton spectrum and measurement of T



Temperature extracted from Thermal dimuon invariant mass fit (M> 1.5 GeV) with ~2% uncertainty

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

- ❑ 4×10^6 reconstructed central Pb-Pb for 1 month data taking at interaction rate ~200 kHz
  → Factor ~20 improvement with respect to NA60 (min. bias)!