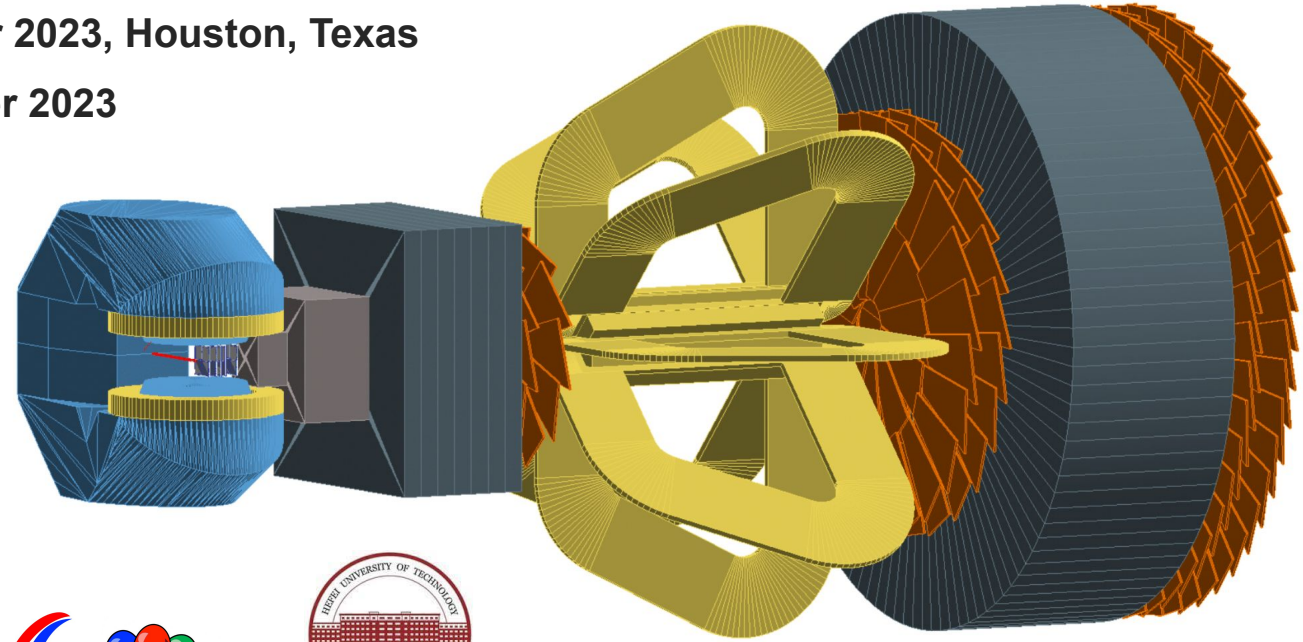
Overview of the NA60+ experiment at the CERN SPS

Giacomo Alocco (**University & INFN Cagliari**) on behalf of the NA60+ collaboration

Quark Matter 2023, Houston, Texas

6th September 2023



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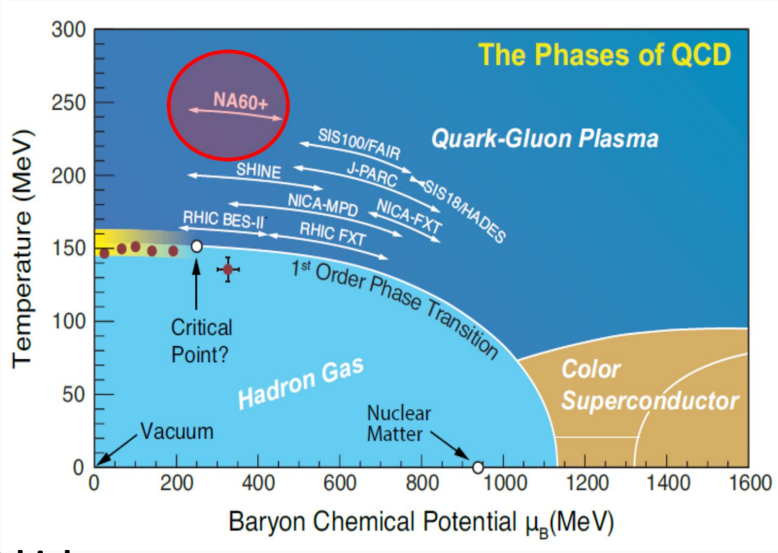
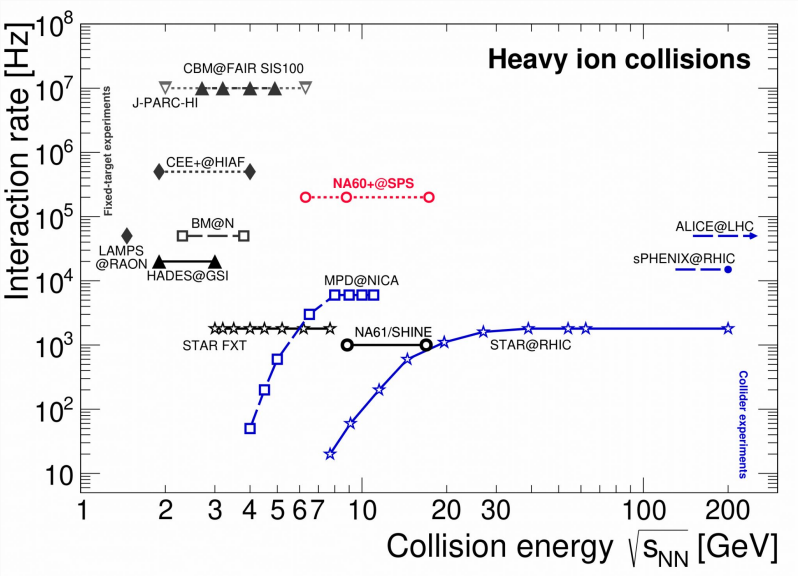
NA60+

- New experiment at the CERN SPS to explore the QCD phase diagram at high baryon chemical potential (μ_B)
- NA60+ will precisely study **hard and electromagnetic processes**
- Beam **energy scan in the range $\sqrt{s_{NN}}$ ~ 6-17 GeV** with **high interaction rates** (~100 kHz)



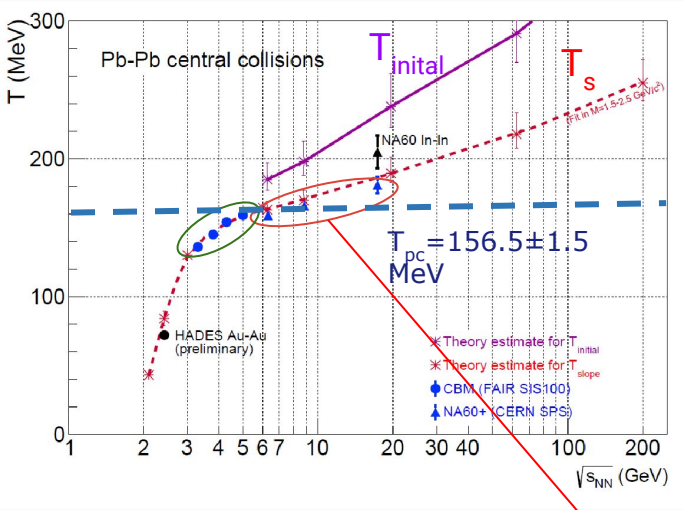


- **Open points at high μ_B:**
  - Presence of a critical point
  - First order phase transition at large μ_B
  - Restoration of the chiral symmetry
  - Properties of the QGP at large μ_B
  - Onset of deconfinement

- Ongoing studies at RHIC and NA61/SHINE, but the results are mostly on soft processes

Physics motivation: em probes

- Measure:
  - **Thermal dimuons from QGP/hadronic phase: caloric curve for first order transition**
  - **ρ-a_1 chiral mixing: chiral symmetry restoration**



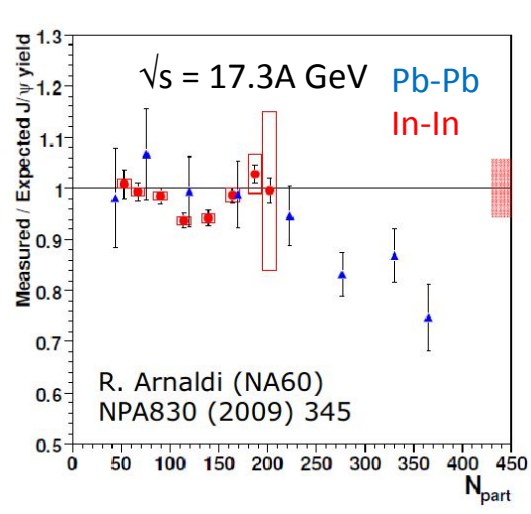
Compilation T. Galatyuk, QM2018
Hades,Nature Phys, 15(2019) 1040
√s>6 GeV, R. Rapp, PLB 753 (2016) 586
√s<6 GeV, T. Galatyuk, EPJA 52 (2016) 131

$\sqrt{s_{NN}}$ range covered by NA60+
→ complementarity with **CBM**

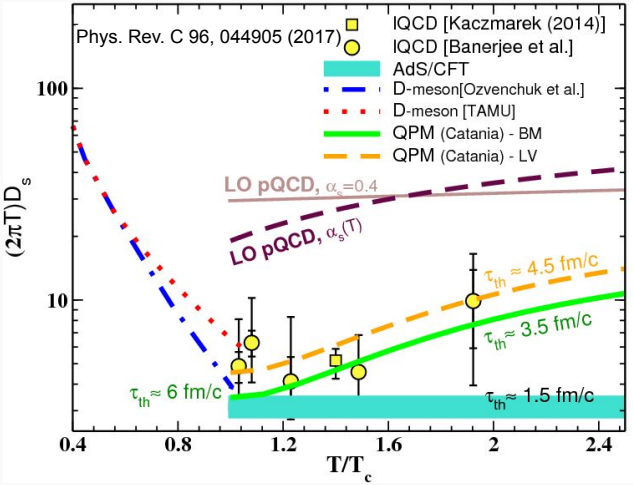
- **Extract temperature via fit** of the thermal dimuon spectrum in $1.5 < M < 2.5$ GeV/c^2:
  - $dN/dM \propto M^{3/2}\exp(-M/T_s)$
  - Possible flattening in $\sqrt{s}$-dependence of T_s
- **ρ-a_1 chiral mixing** observation from the extra yield of dilepton in thermal dimuon mass region $0.8 < M < 1.5$ GeV/c^2
- **First measurement** of dimuon elliptic flow at SPS energies

Physics motivation: hard probes

- Measure:
  - **Quarkonium suppression: signal of deconfinement**
  - **Hadronic decays of charmed hadrons: QGP transport coefficients**

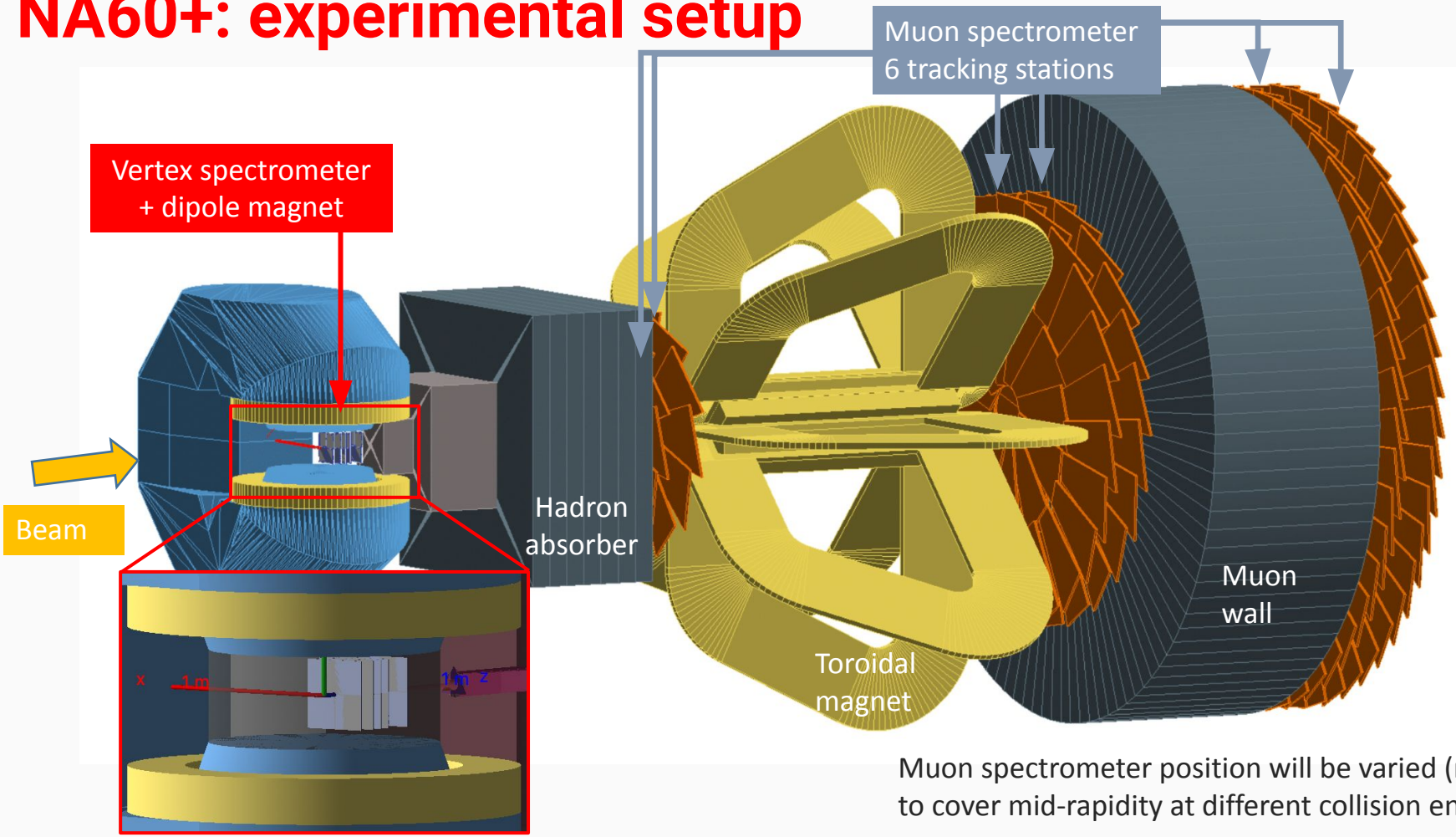


- NA50/NA60 experiments detected an **anomalous J/ψ suppression** → not explainable by cold nuclear matter effects
  - NA60+ can explore the centrality dependence of **J/ψ suppression vs √s**
- Measure 2 and 3 prong decays of charmed mesons and baryons:
  - R_{AA},v_2 : **transport coefficients**
  - Λ_c,D, D_s : study **hadronization mechanisms**



Also study strangeness and hypernuclei production via their hadronic decays

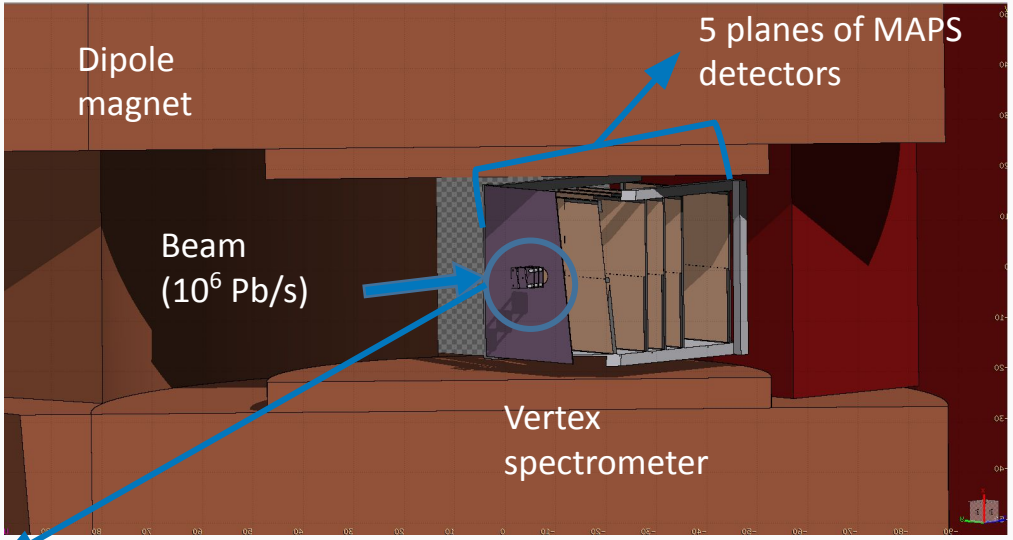
NA60+: experimental setup

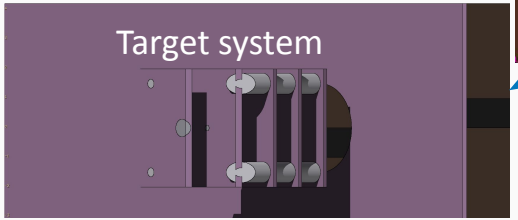


Muon spectrometer position will be varied (rails), to cover mid-rapidity at different collision energies

NA60+: vertex region

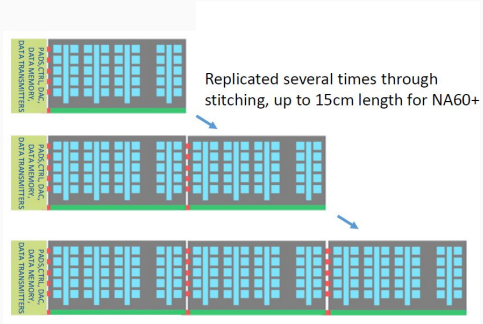
- Target system: 5 Pb sub-targets of 1.5 mm thick
- Vertex spectrometer: 5 layers of large area pixel sensors placed at 7 < z < 38 cm starting from the closest target
- Vertex spectrometer embedded in a 1.5 T dipole magnetic field → MEP48 is already available at CERN

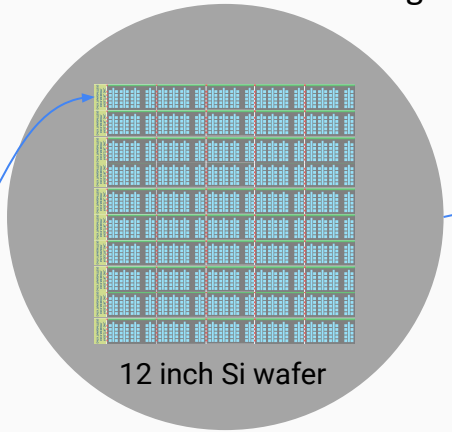


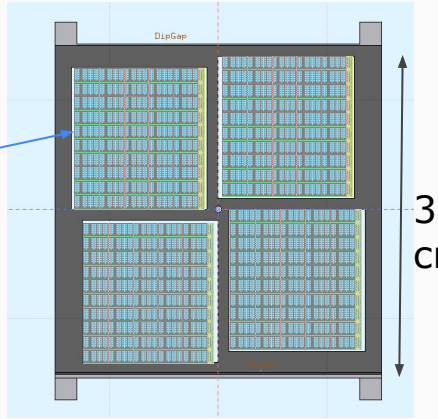


NA60+: vertex spectrometer

- High charged particle multiplicity in Pb-Pb collisions (up to $dN_{ch}/dy = 450$) requires:
  - High granularity, fast and radiation hard detectors in the vertex region
- Use of **state-of-the-art Monolithic Active Pixel Sensors**
- Synergy with **ALICE ITS3** → first large area stitched sensor (MOSS) is currently being tested
- Sensor based on 25 mm long units, replicated several times through stitching up to **15 cm length** for NA60+





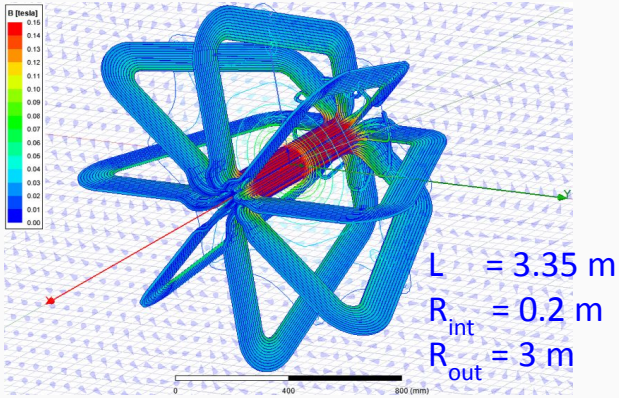


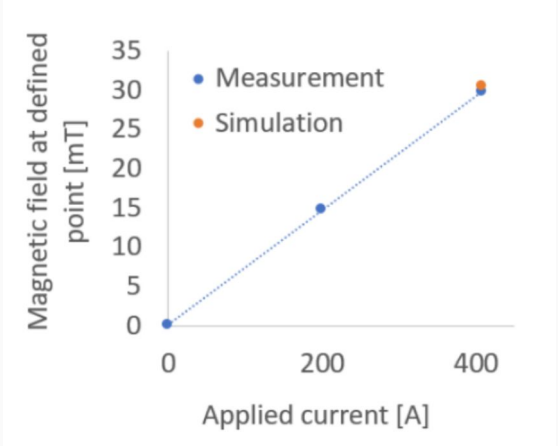
4 sensors per station

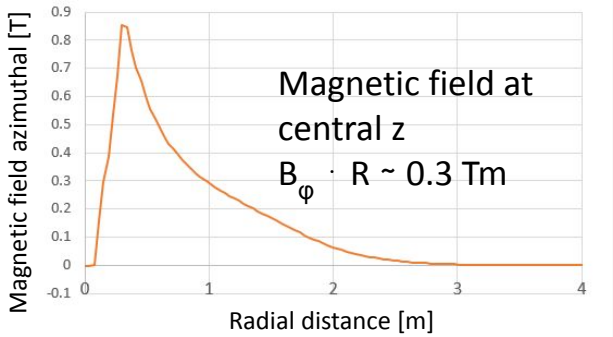
- Few tens of microns of silicon → material budget **< 0.1% X_0**
- Spatial resolution **≤ 5 µm**
- Cooling with airflow and water

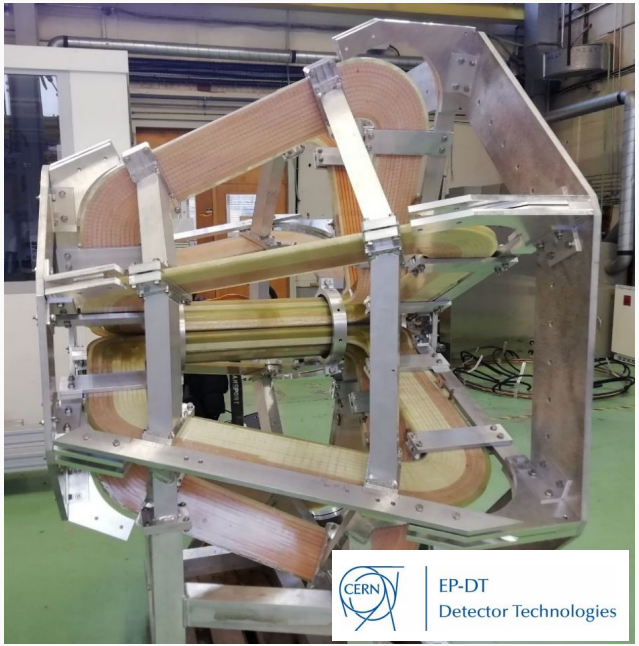
R&D: toroidal magnet

- Eight sectors with 12 turns per coil
- Light design → **low material budget** in the acceptance area





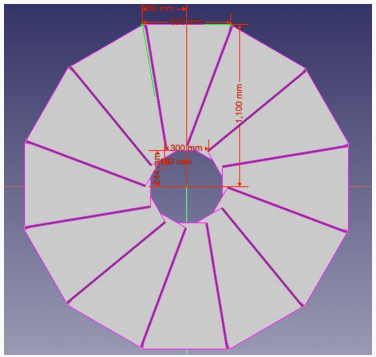


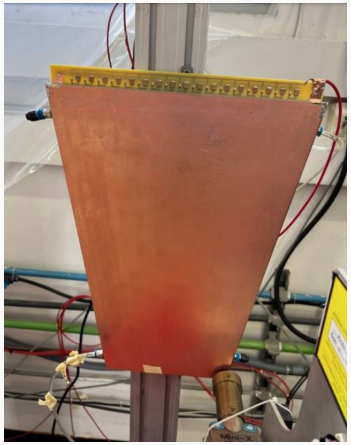


- **Prototype (1:5 scale)** built and tested in 2020-2021 to check calculations and investigate mechanical solutions → **works as expected**

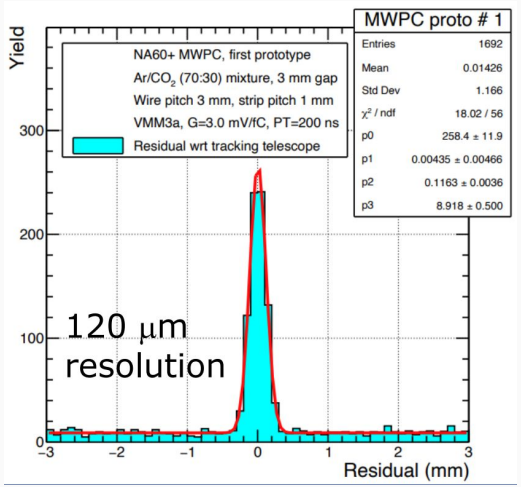
R&D: muon tracker

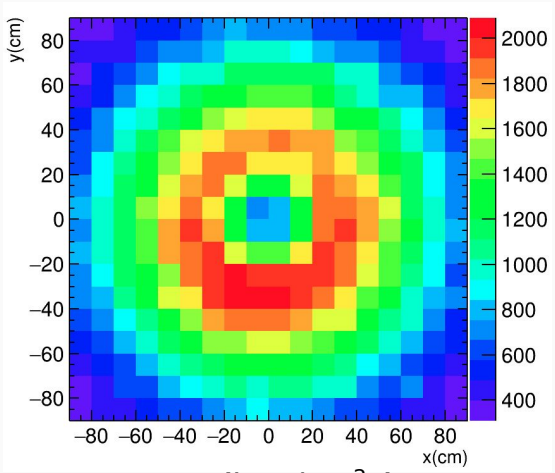
- Thick hadron absorber (235 cm of BeO + C) ⟶ rates in the upstream stations are modest (simulated with FLUKA)
- With a 10^6 ions/s beam ⟶ charged particle rate ~2kHz/cm^2
- The rate can be matched by **MWPC** or **GEM**
- First prototype of a MWPC module built and tested at Weizmann institute





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





Rate (hits/cm^{2}s) in the first station

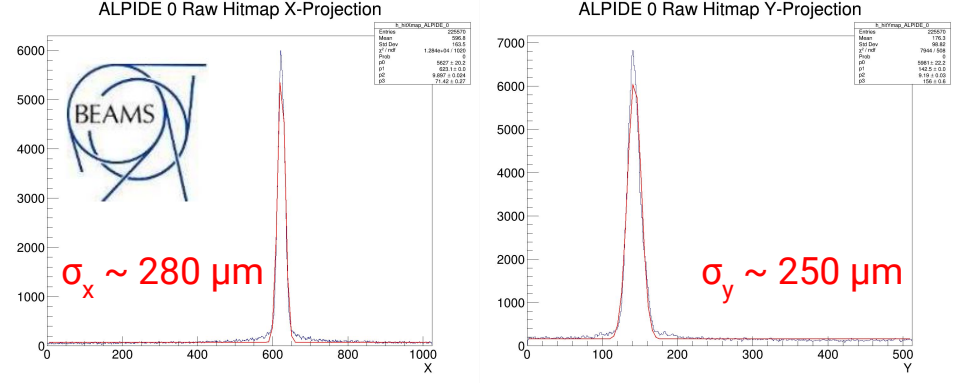
- Test beam at CERN in October 2023 of MWPC and GEM prototypes

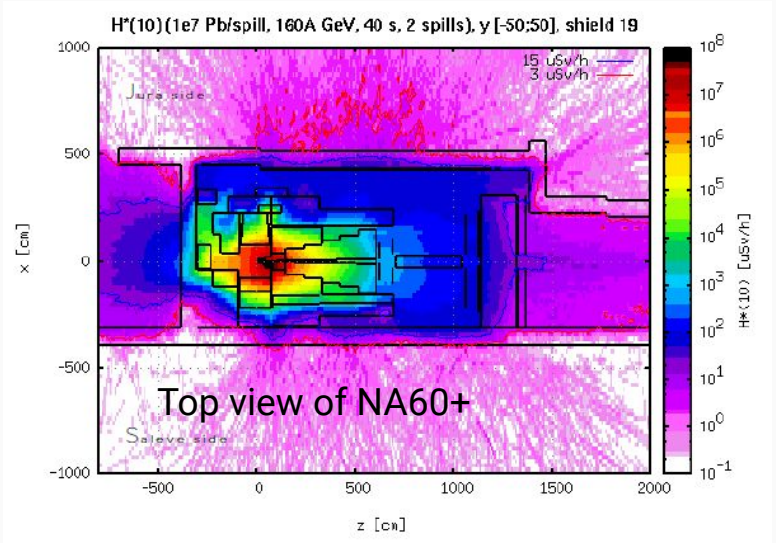
Beam and Radioprotection studies

HSE
Occupational Health & Safety and Environmental Protection unit

- NA60+ will be installed in the CERN EHN1 - PPE138 area along the H8 beam line
- **High-intensity** (10^6 ions/s)
- **Collimated** beam → a fully re-designed optics
  - First test at SPS in November 2022: promising results (σ ~ 250 μm)
  - New test beam in October 2023

Pb beam profile from November 2022 TB results at E = 150 GeV/c

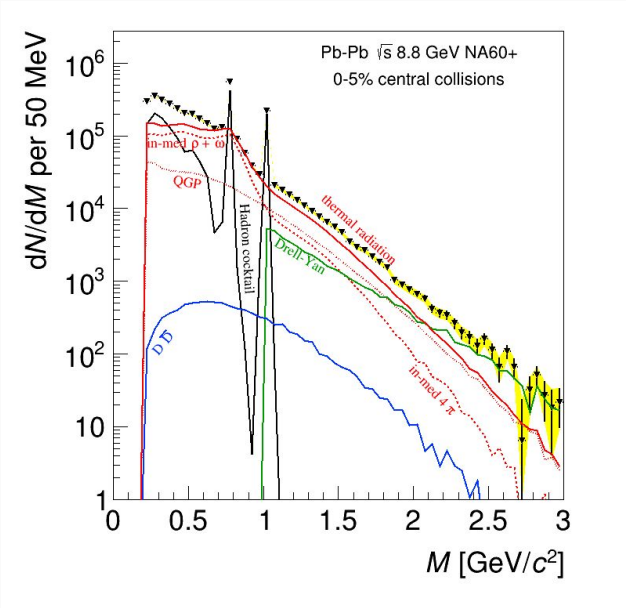


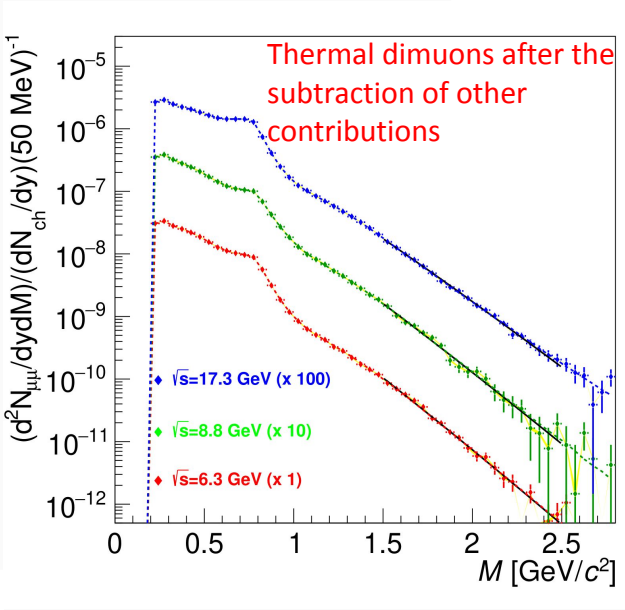


- **Heavy shielding** of iron and concrete:
  - Dose below 3 μSv/h externally to the experiment
- Integration studies for detector and infrastructure were also performed

Thermal dimuons: mass spectra

- ~$4 \cdot 10^6$ reconstructed dimuons in central Pb-Pb in ~1 month data taking ➞ 20 times with respect to NA60
- Thermal radiation yield accessible up to M = 2.5-3 GeV/c^2
- T_s extracted by fitting the region 1.5 < M < 2.5 GeV/c^2

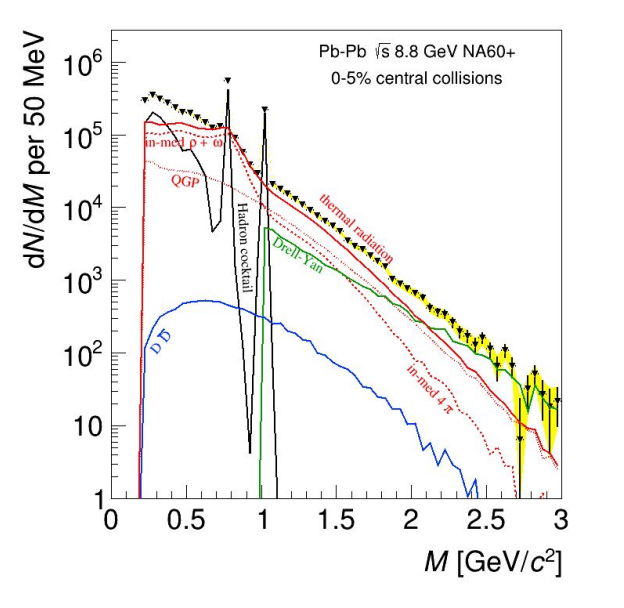


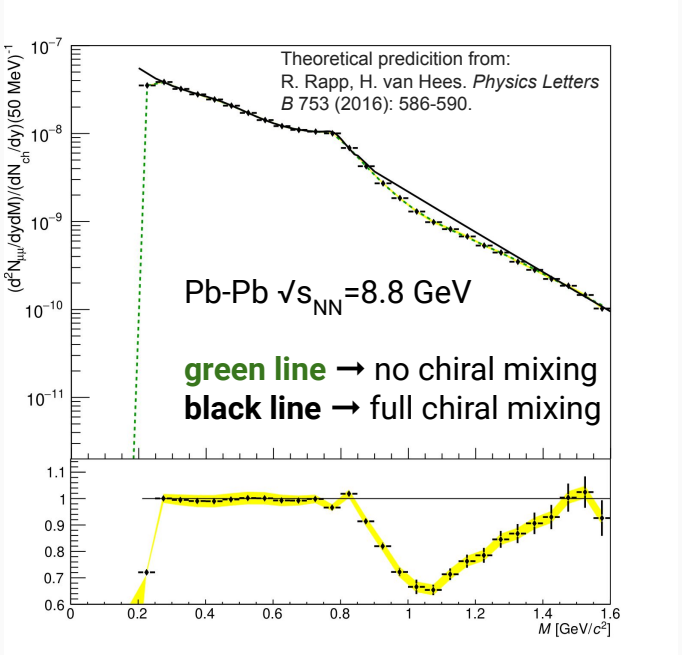


- ~2% uncertainty on the T_s measurement:
  - Allows an **accurate mapping of the √s-dependence of T_s** around T_c

Dimuon mass distribution: ρ-a_1 mixing

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



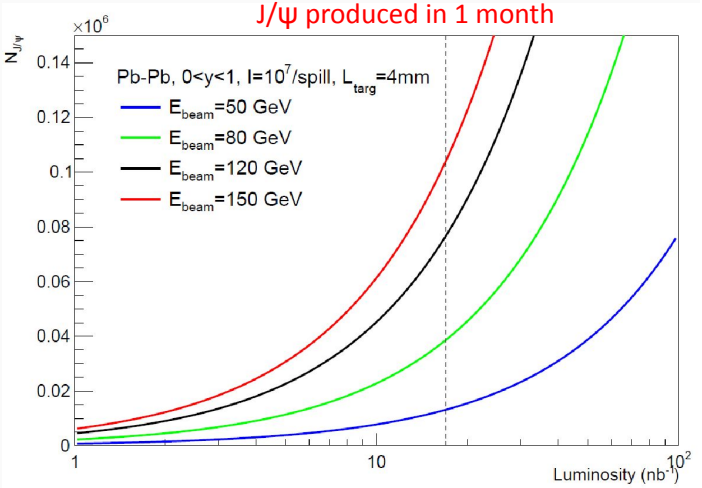


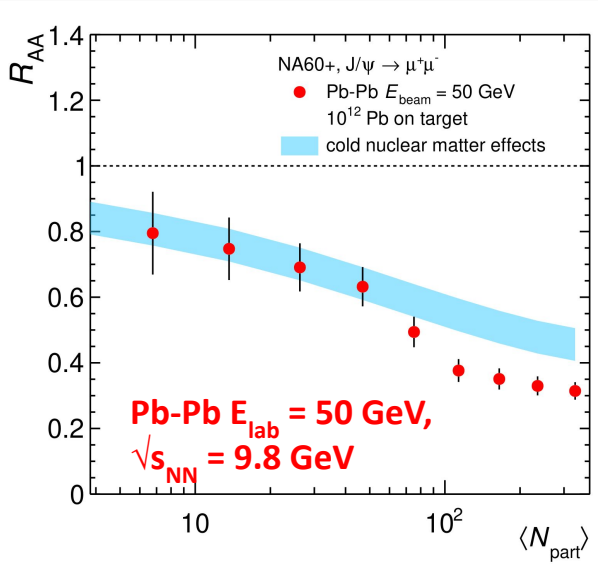
- NA60+ could clearly detect a signal of chiral symmetry restoration

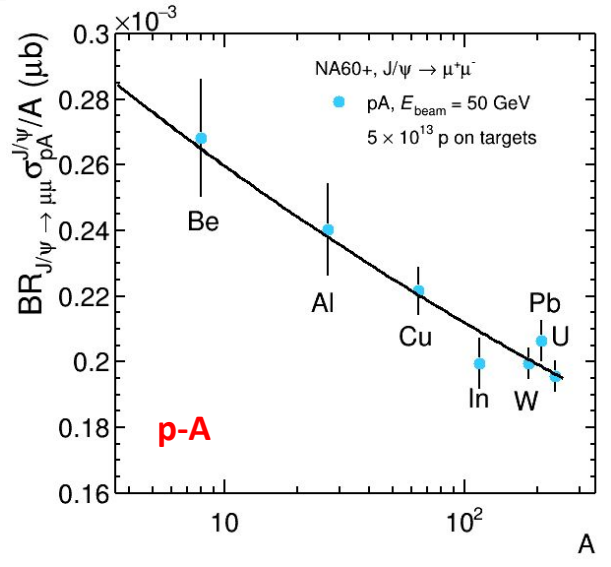
Quarkonium suppression

[More in the poster by Roberta Arnaldi]

- **Quarkonium measurements** in the dimuon channel







- NA60+ aims at:
  - **~O(10^4) J/ψ at √s = 9.8 GeV**
  - **~O(10^5) J/ψ at √s = 17.3 GeV**
- ψ(2S) within reach down to √s ~ 15 GeV

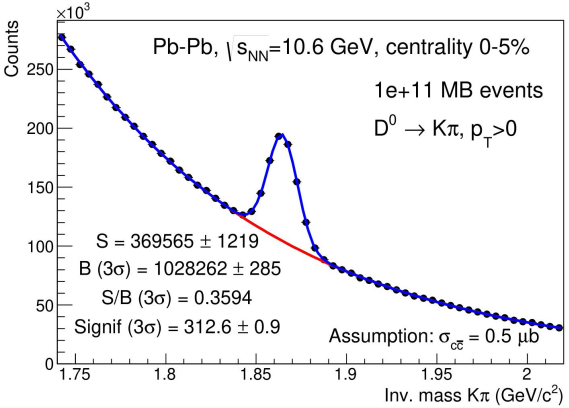
- Allows detection of onset of anomalous suppression effects down to low SPS energy
- Need to calibrate Cold Nuclear Matter effects → p-A data taking (few weeks/year)

Open charm

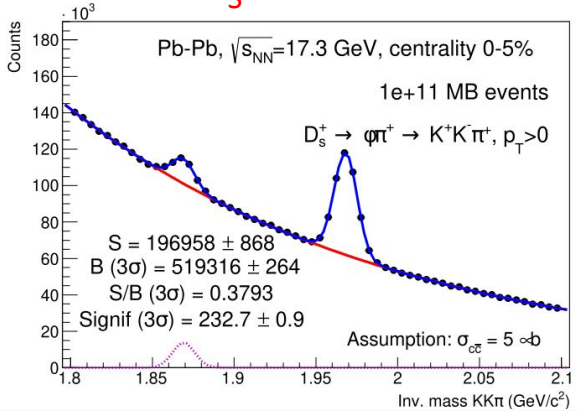
More in the poster by Roberta Arnaldi

- Decay products reconstructed in the vertex spectrometer
- Geometrical selections on the displaced decay-vertex topology (cτ~60-300 μm) to enhance the S/B
- All simulations based on 10^{11} minimum bias events in Pb-Pb collisions (~1 month data taking)

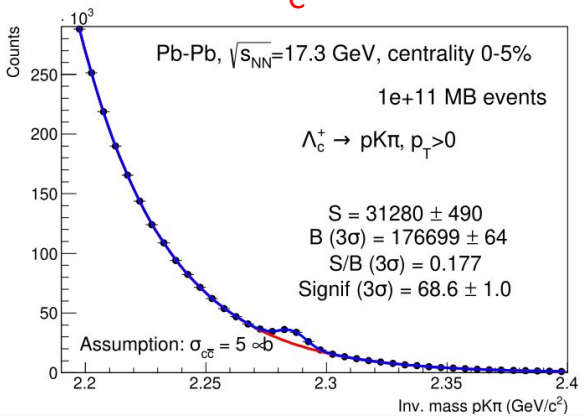
$D^0 \rightarrow K\pi$



$D^+_s \rightarrow \phi\pi \rightarrow KK\pi$



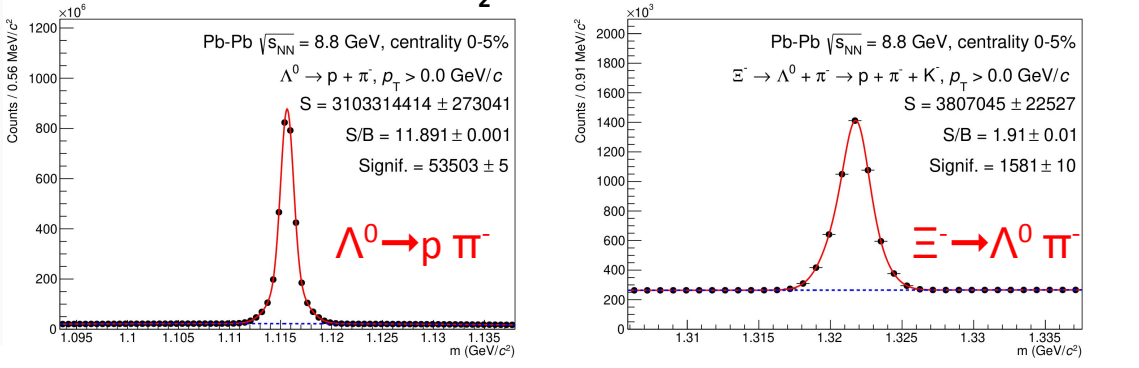
$\Lambda_c^+ \rightarrow pK\pi$

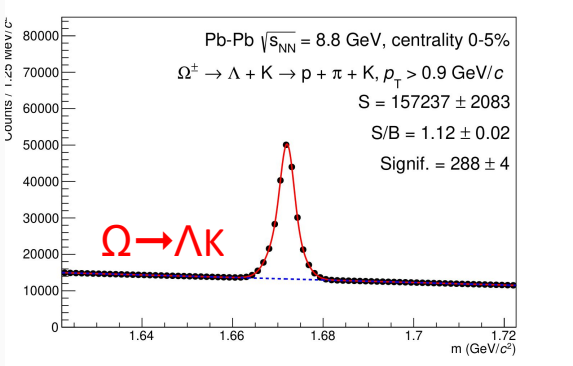


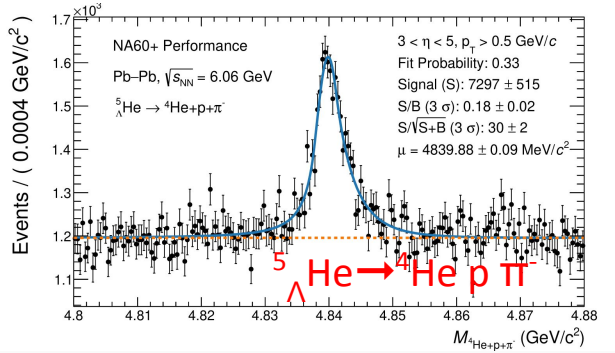
- Allows for **differential studies** of yield and v_2 vs p_T, y and centrality
- NA60+ will be **able to measure D^0 , D^+ , D_s^+ , Λ_c^+ , and possibly $\Xi_c^{0,+}$**

Strangeness and hypernuclei

- Decay products reconstructed in the vertex spectrometer as for the open charm
- Strange baryons and hypernuclei are abundantly produced at SPS energies
- Performance studies for K^0_S, Λ^0, ϕ, Ξ and Ω hyperons:
  - **Strong improvement in their measurement w.r.t. the NA49 and NA57 measurements**
    → possibility of v_2 measurements







- **High precision** of for the measurement of the properties of Λ hypernuclei
- **Possible discovery** of light **Ξ** and **Σ hypernuclei**

Timeline

- NA60+ is part of the **CERN Physics Beyond Colliders** initiative since 2016
  ➞ substantial support on several technical aspects

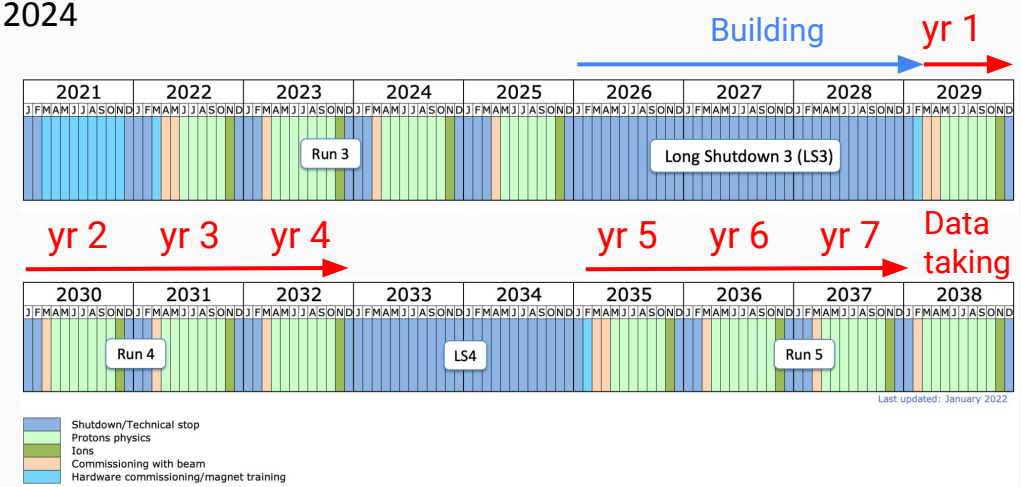
- The **Letter of Intent** (http://cds.cern.ch/record/2845376) was submitted in 2022 ➞ discussed with CERN SPSC in February 2023 with favorable feedback:

> 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**

- The technical proposal will be submitted ~ end 2024

- Start construction in 2026 to start taking data after the Long Shutdown 3 in 2029

- Foresee **at least 7 yrs** of data taking (one energy point per year with p-A and Pb-Pb)



Conclusion

- Precision studies of **electromagnetic and hard probes** in the region $6 < \sqrt{s_{NN}} < 17.3$ GeV are currently lacking

- **NA60+: a new dimuon experiment** with a similar concept but based on state-of-the-art technology choices that may collect unprecedented large statistics at the SPS energies

- We plan to submit to SPSC a proposal by 2024-25 ⟶ Our goal is to take data starting in 2029

- Present stage: consolidation of collaboration and completion of R&D (pixel and muon detectors, magnet)

- **We welcome additional teams to join the effort!** There is still room for impactful contributions in various areas: gas detectors, MAPS, magnet, trigger systems, and data acquisition (DAQ)

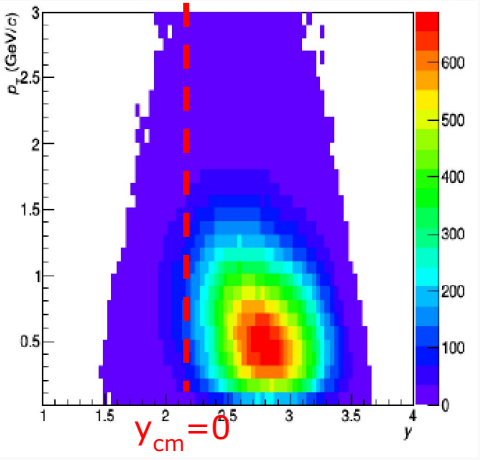
https://na60plus.ca.infn.it/

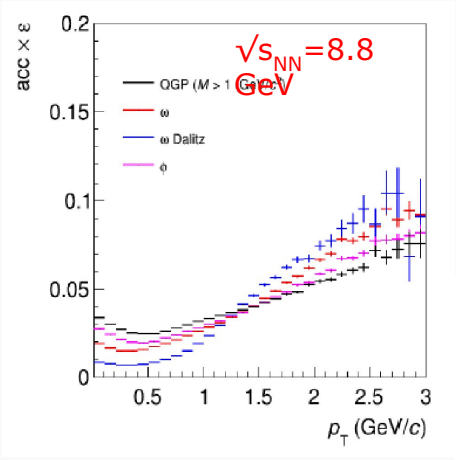
Backup

(Di)muon detection performance

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

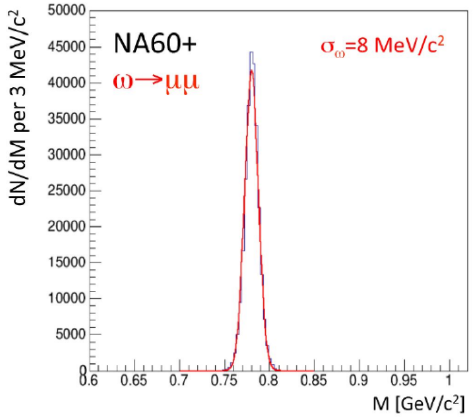
QGP (m>1 GeV/c^2)

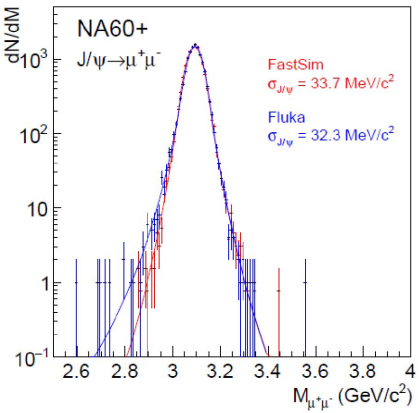




- Full phase-space acceptance at dimuon low and intermediate masses → >1%
- Good coverage down to midrapidity AND zero p_T, realized at all energies by displacing the muon spectrometer

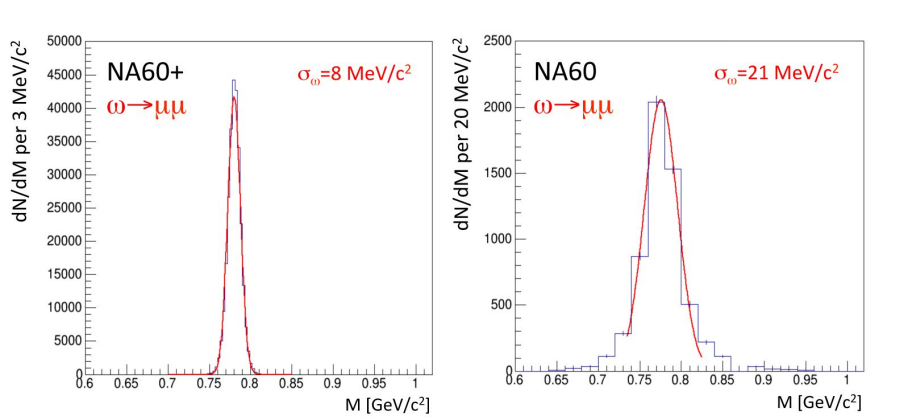
- The mass resolution for resonances varies from < 10 MeV (ω) to ~30 MeV (J/ψ):
  - Factor >2 improvement with respect to NA60





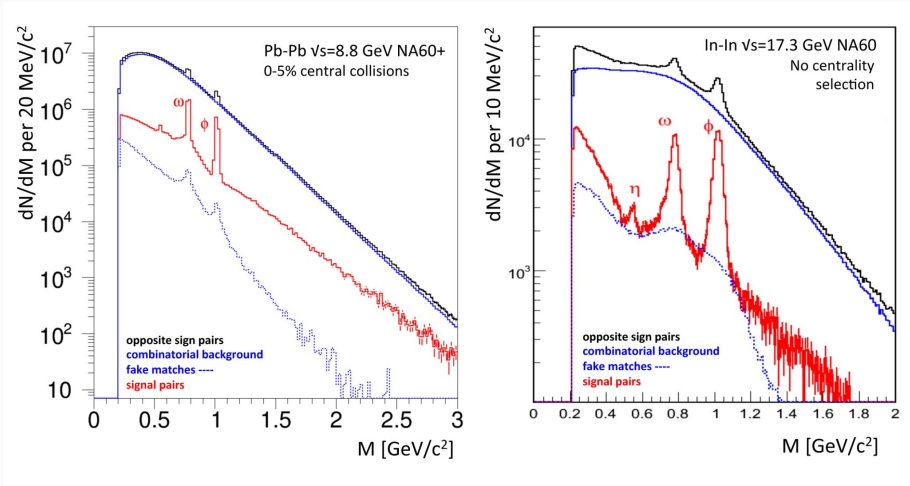
Dimuon detection performance: NA60 vs NA60+

- Detector performance studies:
  - Simulation framework tested simulating NA60 → results in according to what was obtained by NA60



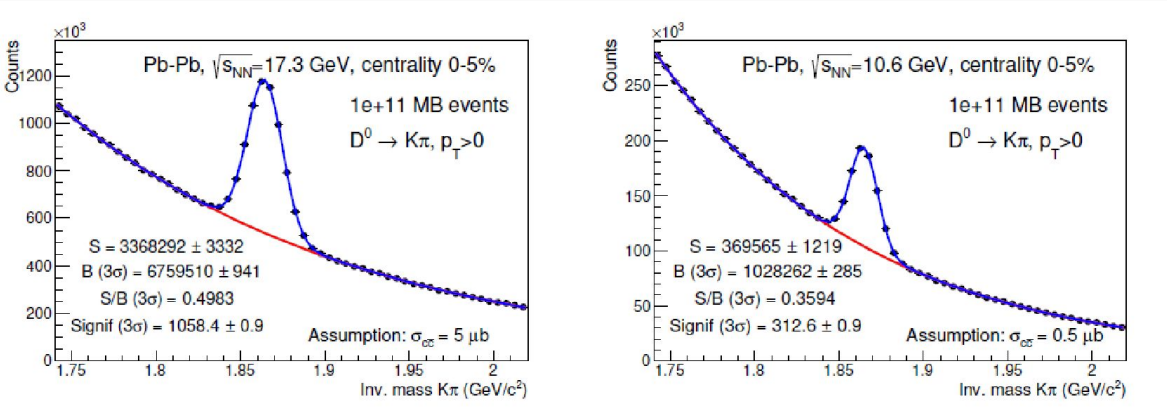
- Dimuon spectrum comparison → similar signal-to-background ratio but:
  - Higher statistics
  - Better resolution
  - Centrality selection (0-5%)

- The mass resolution for resonances varies from < 10 MeV/c^2 (ω) to ~30 MeV/c^2 (J/ψ):
  - Factor >2 improvement with respect to NA60 (21 MeV/c^2)



Open charm simulations

- Hadronic decays of charmed particles can be reconstructed in the vertex spectrometer (no PID)



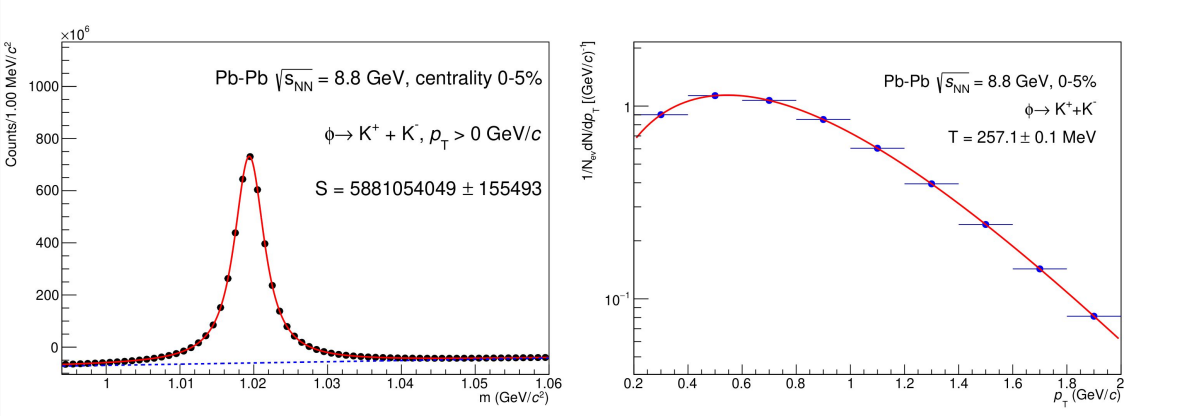
- $D^0 \rightarrow K^+\pi^-$ (POWHEG-BOX+PYTHIA6):
  - Background from NA49 light hadron production data
- 0-5% Pb-Pb, $\sqrt{s_{NN}}$=17.3 GeV :
  - 1200 p,K,π per event
  - 8×10^3 candidates in $m_D \pm 60$ MeV
  - S/B~10^{-7}, enhanced with kinematic and geometric selections

(equivalent to 30 days data taking at 150 kHz)

- Measurement for $\Lambda_c \rightarrow pK\pi$ more challenging 3-particle decay, S/B~ 10^{-10}
- Alternatively, $\Lambda_c \rightarrow pK^0_S\, K^0_S \rightarrow \pi\pi$ (lower BR, lower background)
- Measurement of $D^+_S \rightarrow KK\pi$

Strangeness simulations

- Hadronic decays of strange particles can be reconstructed in the vertex spectrometer (no PID)

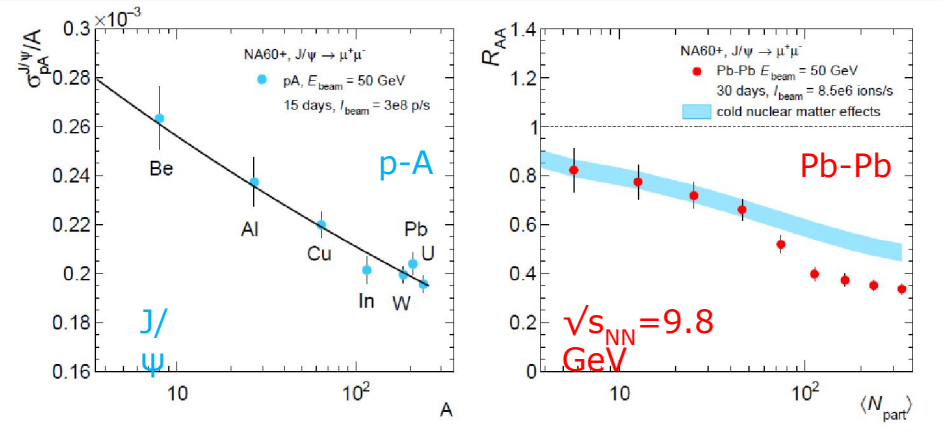


- 0-5% Pb-Pb, $\sqrt{s_{NN}}$ = 8.8 GeV :
  - Background and signal from NA49 light hadron production data
  - Analysis performed using Boosted Decision Trees (except for the ϕ)
  - ϕ signal extracted subtracting the background with the event mixing

(equivalent to 30 days data taking at 75 kHz)

- K^0_S, Λ^0, ϕ, Ξ^-: very low statistical uncertainties for p_T and rapidity spectra measurements ➞ dominated by the systematic uncertainties
- Ξ^+,Ω : very good prospects
- Improvements respect to the NA49 measurements

Charmonium suppression

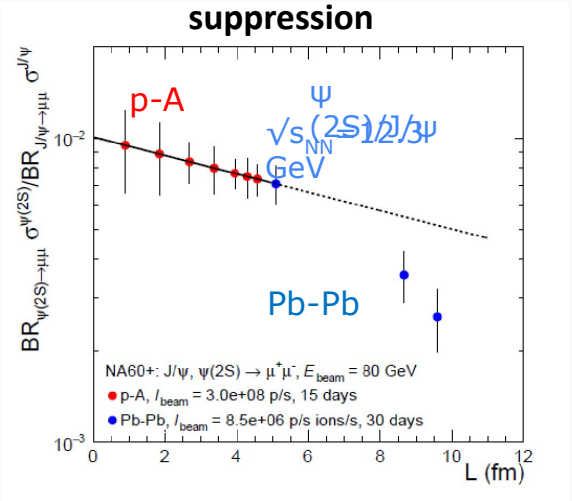


- p-A measurement calibrate CNM effects (assume same effect as measured by NA60 at $\sqrt{s_{NN}}$=17.3 GeV)
- Extrapolate CNM effect to Pb-Pb and compare with a scenario where anomalous suppression sets in at N_{part} ~50 and reaches 20% (was ~30% at $\sqrt{s_{NN}}$=17.3 GeV)
- Assume 30 days of Pb beam and ~10^7 Pb/s

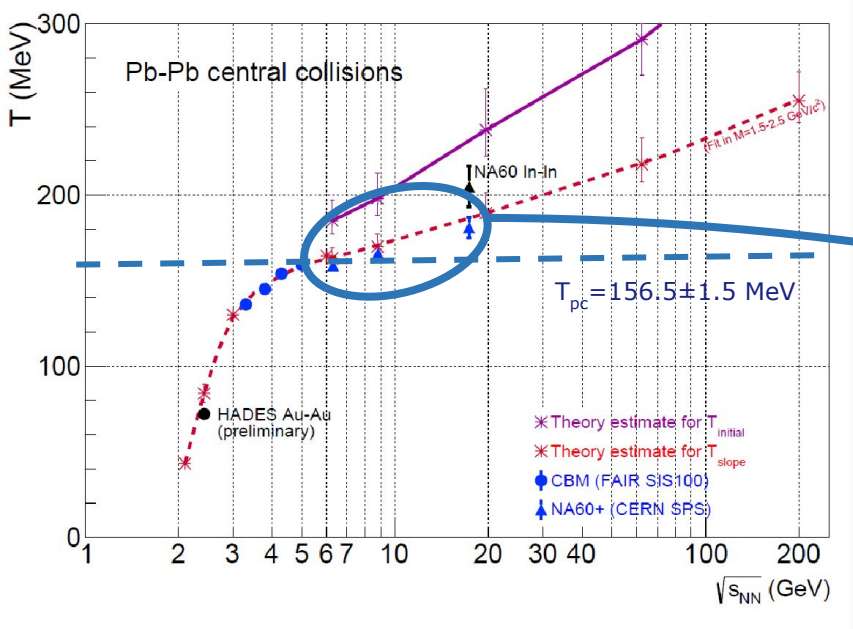
Good sensitivity to J/ψ suppression onset

- ψ(2S):
  - pA → assume stronger suppression for ψ(2S) relative to J/ψ (as measured by NA50 at $\sqrt{s_{NN}}$=29 GeV)
  - Pb-Pb → simulation assuming factor 2 stronger suppression for ψ(2S)

Look for the onset of ψ(2S) suppression



Tslope measurement



T_{slope} values from thermal yields in 1.5<M<2.5 GeV/c^2

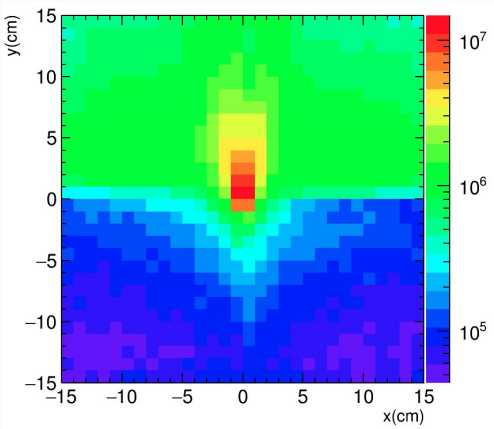
Theory $\sqrt{s}$>6 GeV, R. Rapp, PLB 753 (2016) 586
$\sqrt{s}$<6 GeV, T. Galatyuk, EPJA 52 (2016) 131

A few MeV accuracy can be reached (1.4 to 5 MeV for $\sqrt{s_{NN}}$ to 6.3 to 17.3 MeV) on T_{slope}

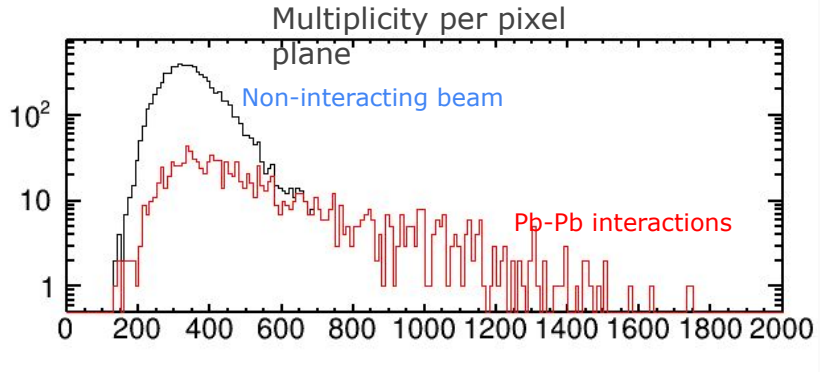
- Accurate mapping of the region where the pseudocritical temperature is reached
- Sensitive to potential effects expected in case of 1st order phase transition

Operation conditions for vertex spectrometer

- Based on **FLUKA simulations** implementing a detailed experiment geometry
- 40 A GeV Pb beam on 5 Pb targets, 10^6 Pb/s

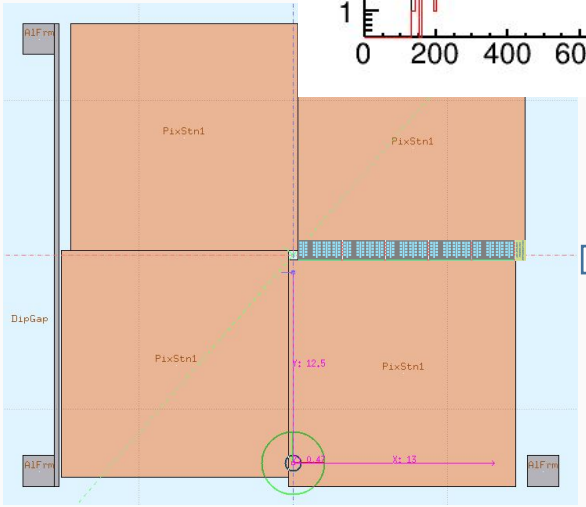


Upstream MAPS plane
(7.1 cm from last target)



Fluences up to 10^7/s close to the beam axis

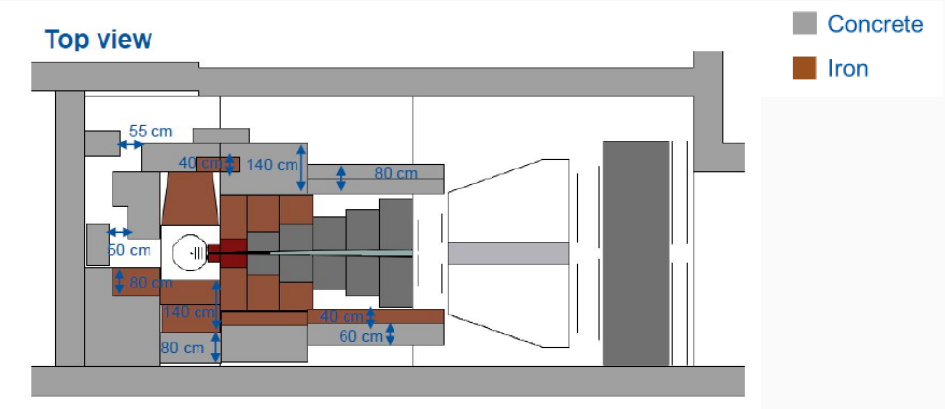
Significant contribution from δ-ray production (upward bent by dipole magnet)

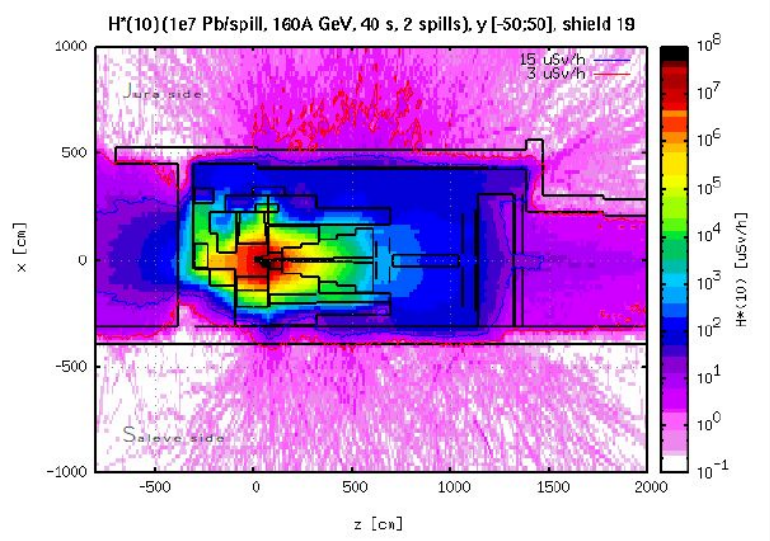


Most “exposed” sensors get a 10-15 MHz rate: 20-30 MB/s data throughput

Integration, beam and radioprotection studies

- Studies based on FLUKA geometry of the NA60+ set-up



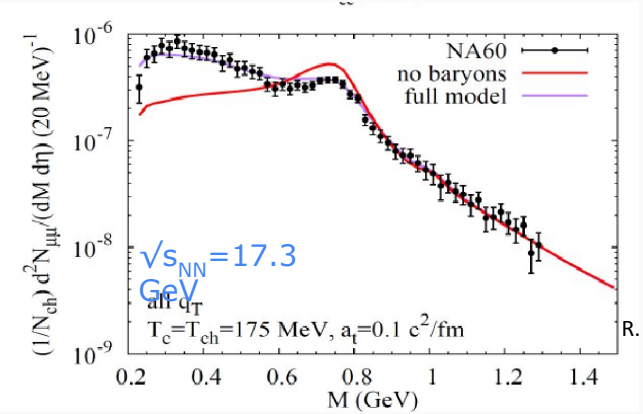


- Installation on a surface zone implies strict requirements on radiation safety
- Dose has to be:
  - <3 µSv/h in permanent workplaces external to the experimental hall
  - <15 µSv/h in low occupancy region → A thick shielding is necessary!

5. Conclusions: Feasibility Evaluation and Cost Estimation

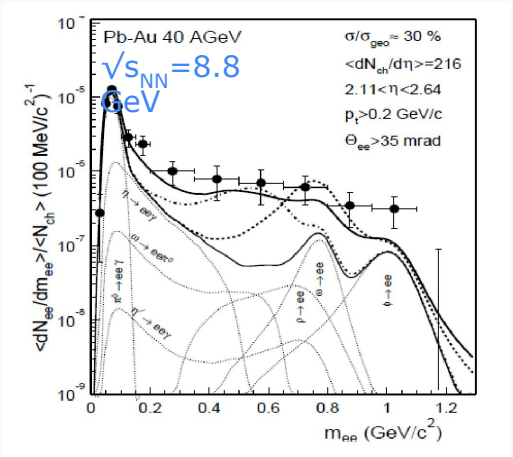
The potential integration of the NA60+ experiment in user zone PPE138 of EHN1 has been examined concerning beam physics requirements (Chapter 2), the infrastructure integration (Chapter 3) and radiation protection (Chapter 4). **The experiment is deemed to be feasible** with regard to these aspects. The aspects of general infrastructure, detector design, data acquisition and analysis as well as the physics reach have not been evaluated.

Dilepton studies at CERN SPS energy



R. Arnaldi et al. (NA60), EPJC 61(2009) 711

- NA60 : low and intermediate-mass dileptons at top SPS energy
- First precision measurement of:
  - in-medium ρ modifications
  - Temperature via thermal dimuons in $1.5<m_{\mu\mu}<2.5$ GeV/c^2



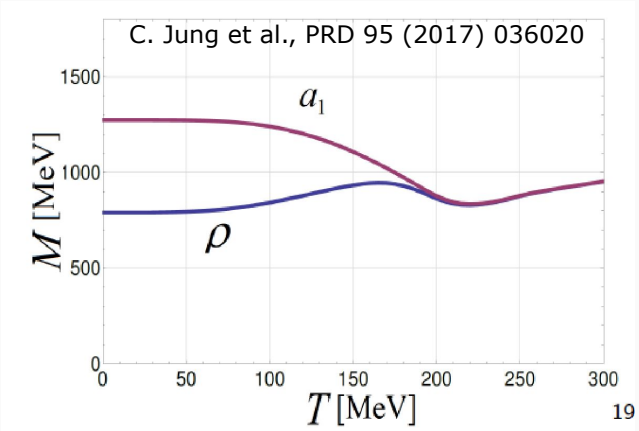
Region below top SPS energy almost unexplored

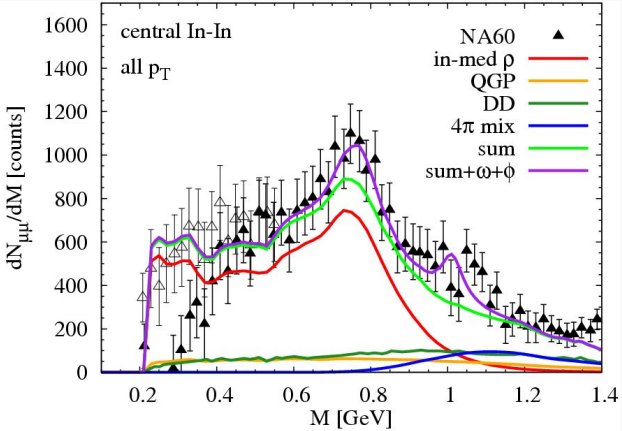
- Only a CERES measurement (low-mass dileptons at $\sqrt{s_{NN}}$=8.8 GeV):
  - **Dielectron excess** (central Pb-Au)
  - Indication (1.8 σ) for excess due to in-medium modifications of ρ spectral function

D. Adamova et al. (CERES), PRL91 (2003)042301

Dilepton spectrum and chiral symmetry restoration

- NA60 observed a broadening of ρ-meson spectral function → qualitatively consistent with chiral symmetry restoration need to investigate the chiral partner a_1



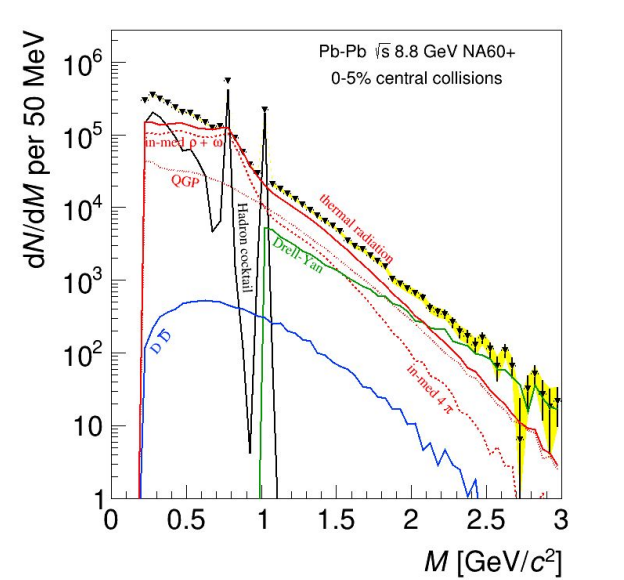


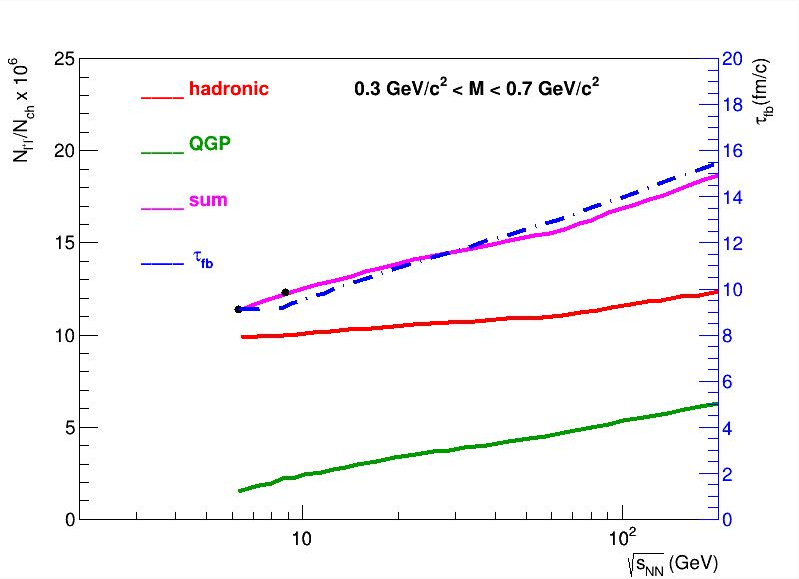
R. Rapp et al., arXiv:0901.3289

- No direct coupling of axial states to the dilepton channel → in vacuum the (e^+e^-→ hadrons) cross section has a dip in the a_1 mass range
- Chiral symmetry restoration → mixing of vector and axial-vector (A) correlators enhancement of the dilepton rate for $m_{\mu\mu}$ ~1-1.4 GeV/c^2
- Low-energy measurement expected to be more sensitive to chiral restoration effects:
  - The thermal dimuon yield from QGP becomes smaller
  - Contribution from open charm becomes relatively negligible

Dimuon mass distribution: fireball lifetime

- The multiplicity of dimuon in the region $0.3 < M < 0.7$ GeV/c^2 is related to the fireball lifetime
- The only measurement up to now is from NA60 at $\sqrt{s}$= 17.3 GeV $\tau_{fb} = 7 \pm 1$ fm/c

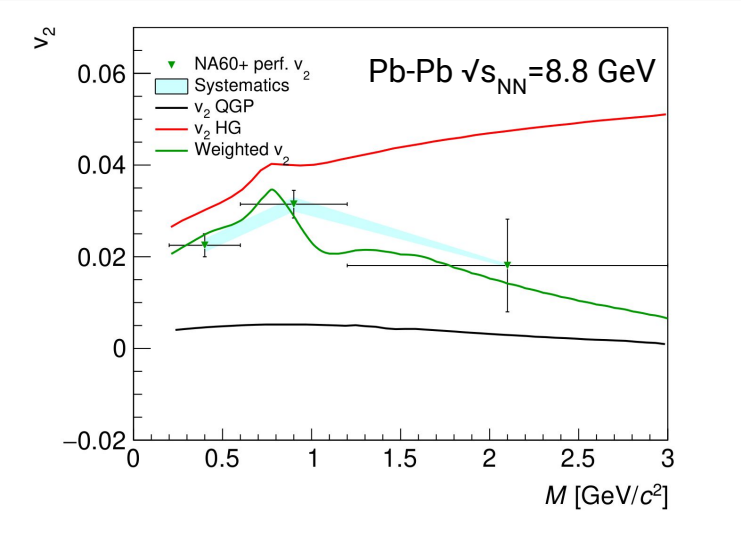


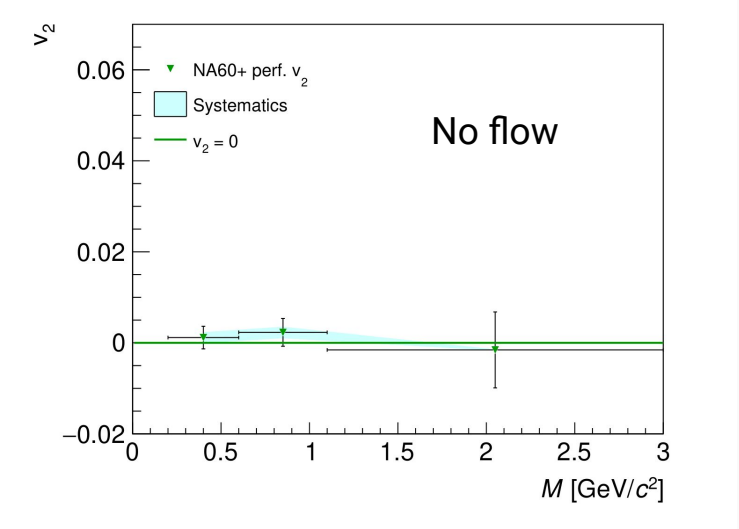


- Excellent accuracy for NA60+ (errors smaller than the black markers)
- Soft mixed phase in a first-order transition:
  - Pressure gradients in the system are small and thus stall the fireball expansion
  - Increased lifetime in the collision-energy regime where the mixed phase forms

Dimuon elliptic flow

- No measurements of the dimuon elliptic flow are available below RHIC energies
- Also theoretical prediction are missing
- At $\sqrt{s_{NN}}$ = 200 GeV ⟶ increase of v_2 versus mass (Hagedorn Gan) and a drop in the intermediate mass region (QGP)





- Performance studies using v_2 prediction for $\sqrt{s_{NN}}$ = 200 GeV and v_2 = 0
- Measurement with uncertainty between 0.003 and 0.008