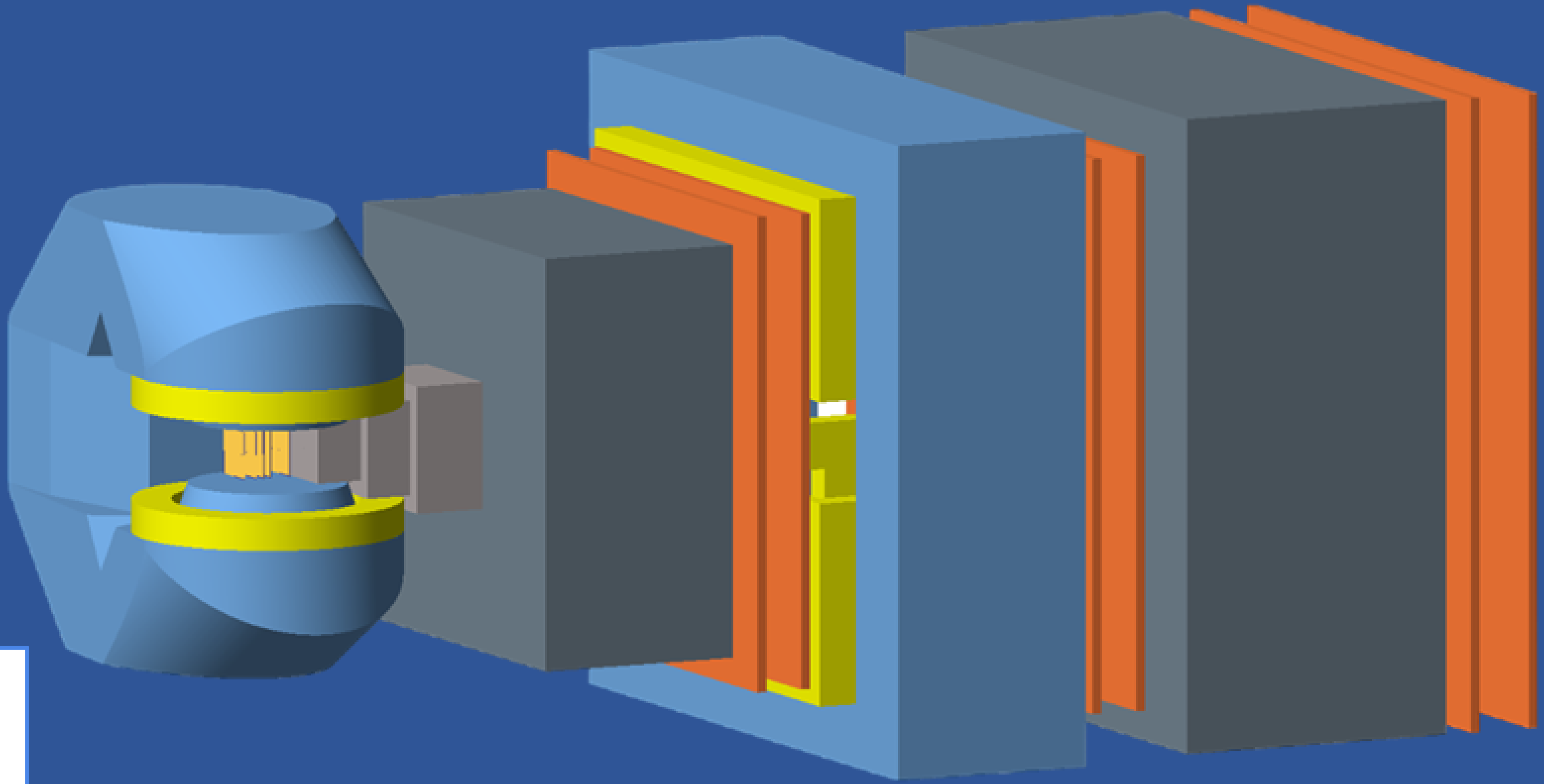
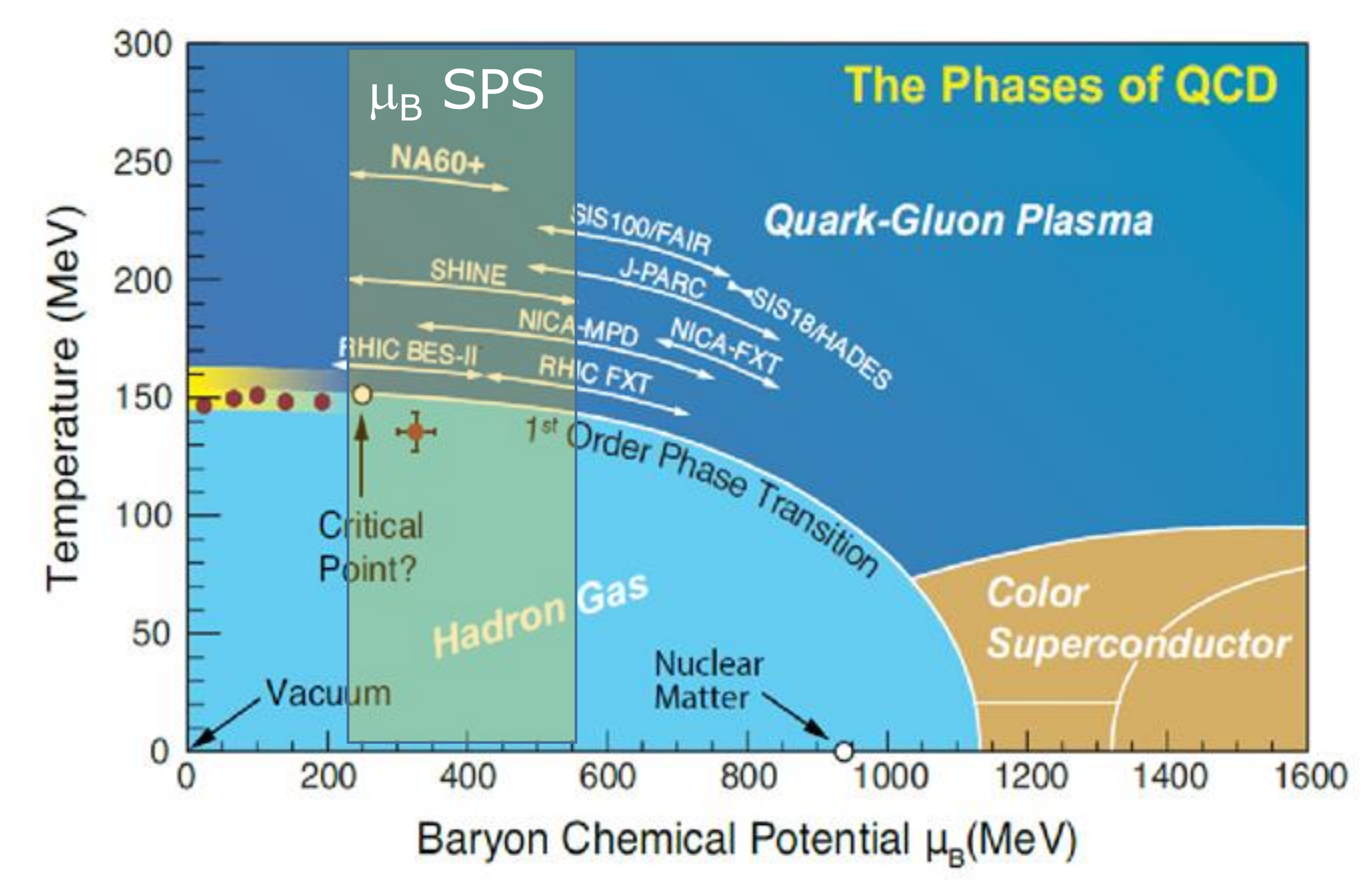
Precision measurements of hard and electromagnetic probes of the high-μ_B QGP: the NA60+/DiCE experiment at the CERN SPS

G. Usai - University of Cagliari and INFN(Italy)



PHD 2025 - GSI

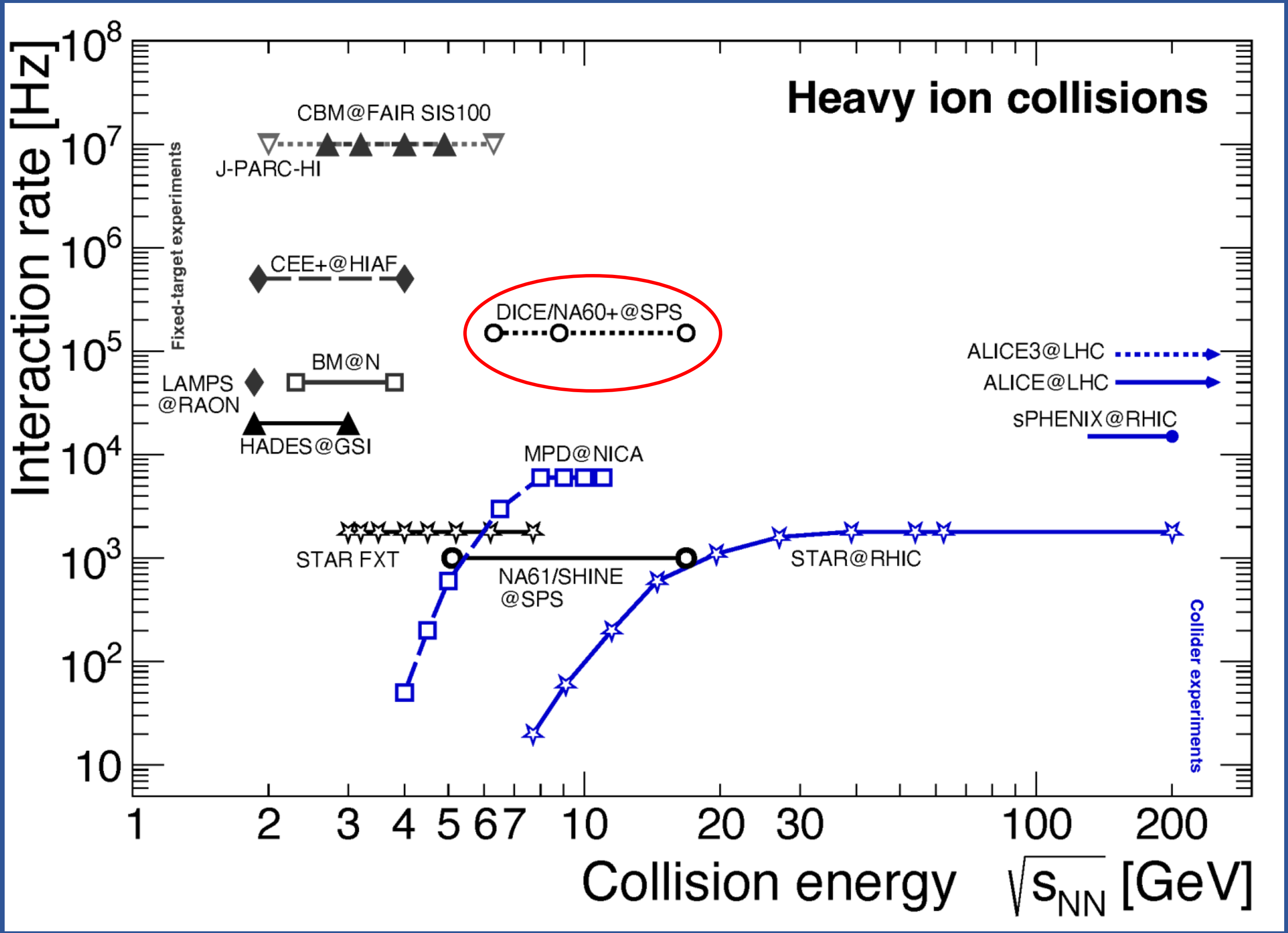
The NA60+/DiCE experiment at the CERN SPS



- Crucial observables currently not explored in the finite-μ_B region:
  - **Heavy-quark** production (open charm, charmonium)
  - **Dilepton** production(low-mass resonances, thermal dileptons)

NA60+/DiCE: beam energy scan with Pb and p beams in 6< $\sqrt{s_{NN}}$<17 GeV

NA60+/DiCE in the international landscape



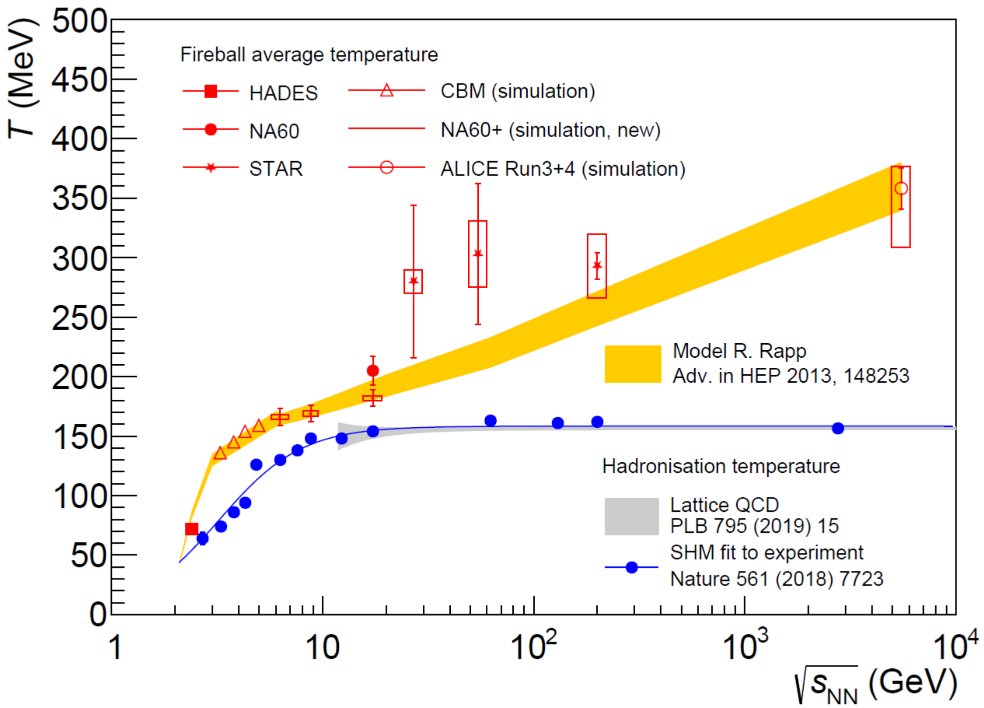
NA60+/DiCE

Unique combination of
→ **√s-coverage**
→ **Interaction rate**

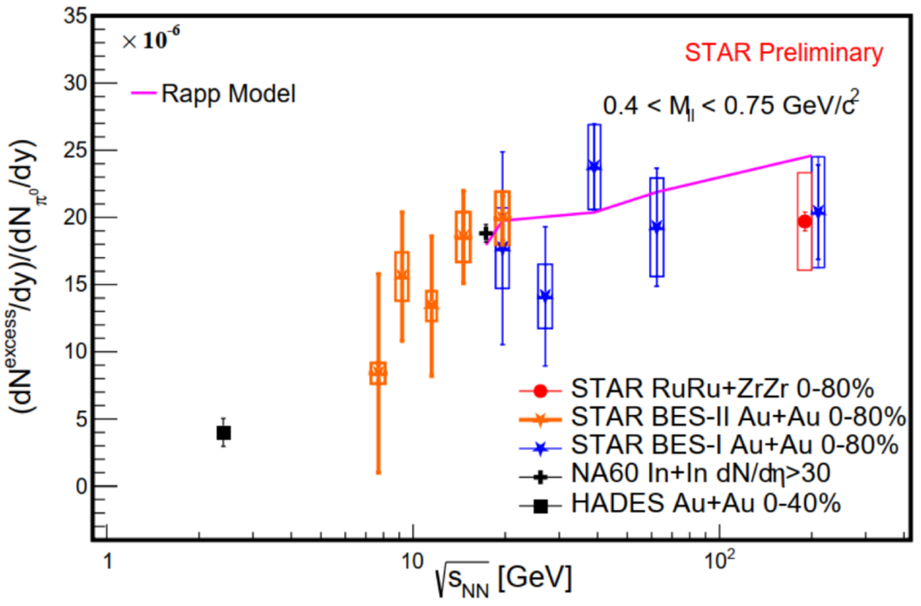
Complementary to CBM
→ Same observables
→ Different √s

Thermal dileptons and phase transition

- Dilepton T_{slope} measurements → (average) **temperature of the early stage of the system**
- Precise measurement of thermal yield in 0.3<M<0.7 GeV **sensitive to the fireball lifetime**
- Thermal dilepton elliptic flow
- Beam energy scan at CERN SPS might provide signals of a **1st order transition**

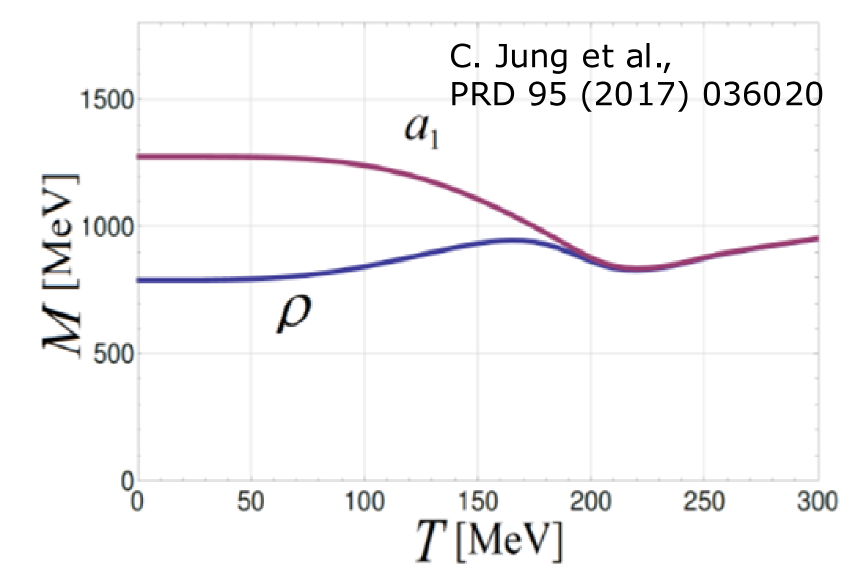


Normalized excess yield



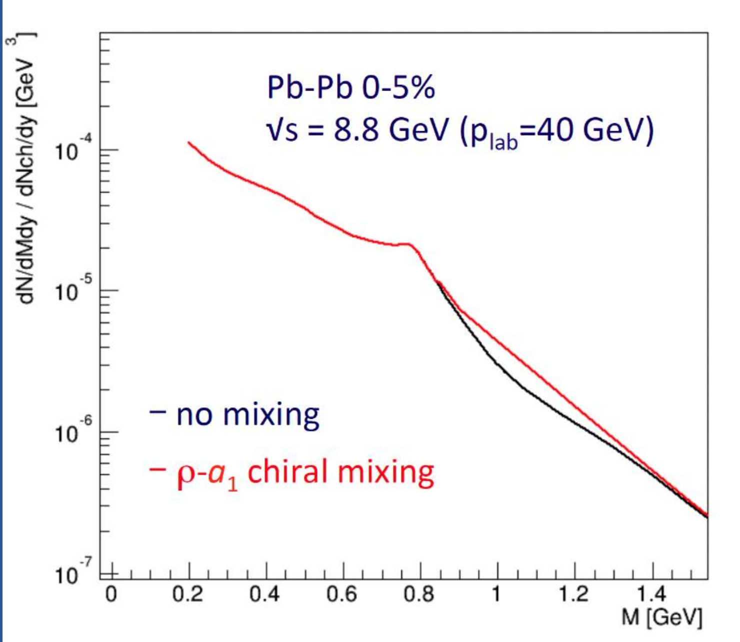
Chiral symmetry restoration

- Chiral restoration at the phase boundary: melting of ρ and a_1



- ρ meson strong broadening consistent with chiral restoration
- a_1 not measurable exclusively

- Mixing of vector (V) and axial-vector (A) correlators → **dilepton enhancement** for $M_{\mu\mu}$ ~ 1-1.4 GeV/c²



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

- Measurements at low energy:
  → (Exponential) thermal dimuon yield from QGP becomes small
  → Contribution from open charm becomes relatively negligible

Open charm

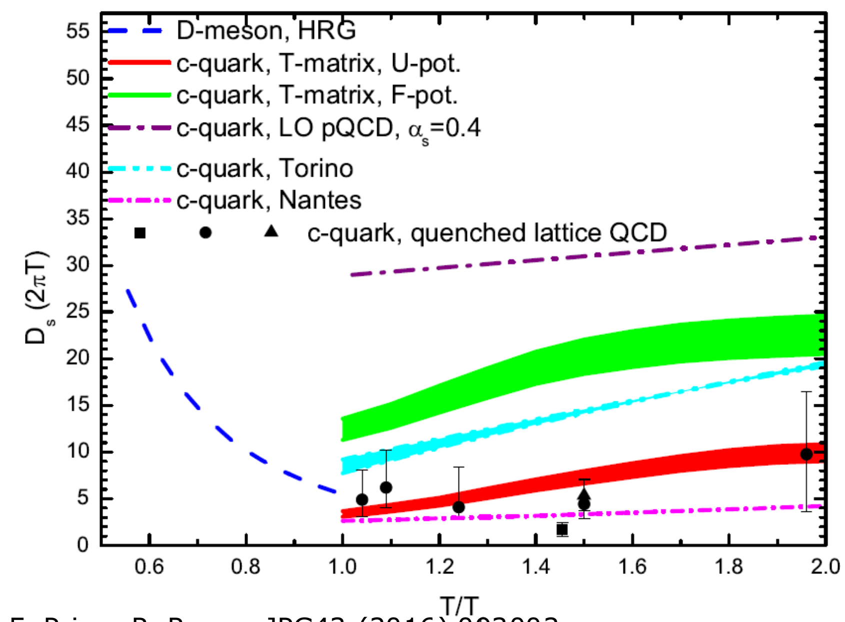
- ❑ No measurements below top SPS energy

- ❑ Moving toward lower collision energies
  - ❑ Explore temperature closer to T_C
  - ❑ Shorter-lived medium and **stronger impact of hadronic phase**
  - ❑ Expect increase of charm diffusion coefficient

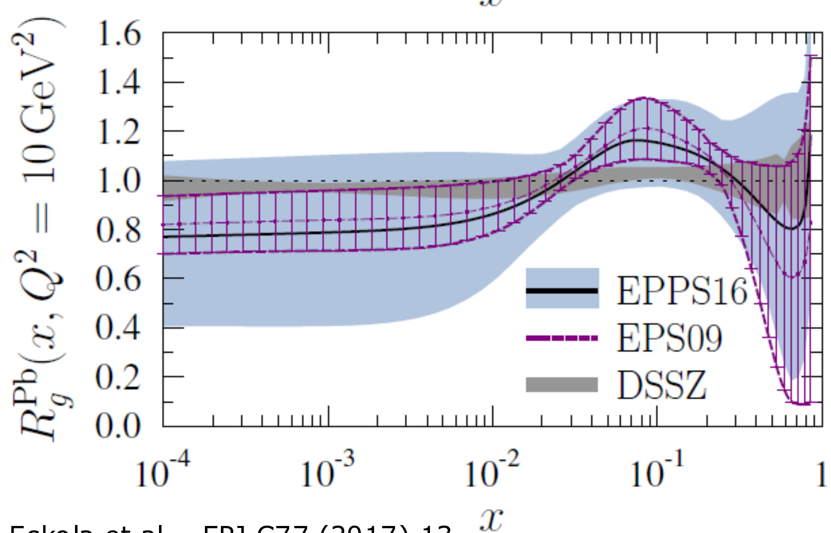
- ❑ Impact on **hadronization mechanism** of a baryon-rich QGP
  - ❑ Baryon/meson ratios (Λ_c/D)
  - ❑ Influence of strangeness (D_s/D)

- ❑ **Open charm cross section** close(r) to threshold
  - ❑ Explore nPDF at large x_{Bj}
    → anti-shadowing and EMC region
  - ❑ Reference for charmonium studies

- ❑ Intrinsic charm
  (R. Vogt, Phys.Rev.C 106 (2022) 2, 025201)



F. Prino, R. Rapp, JPG43 (2016) 093002

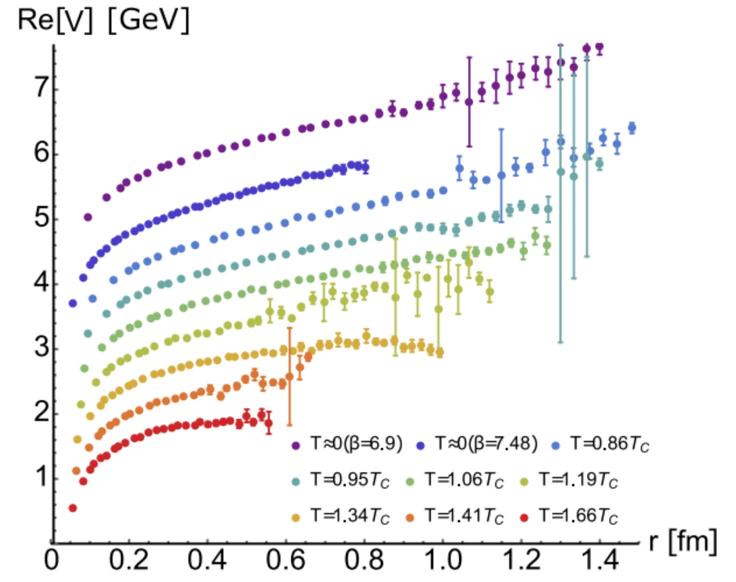


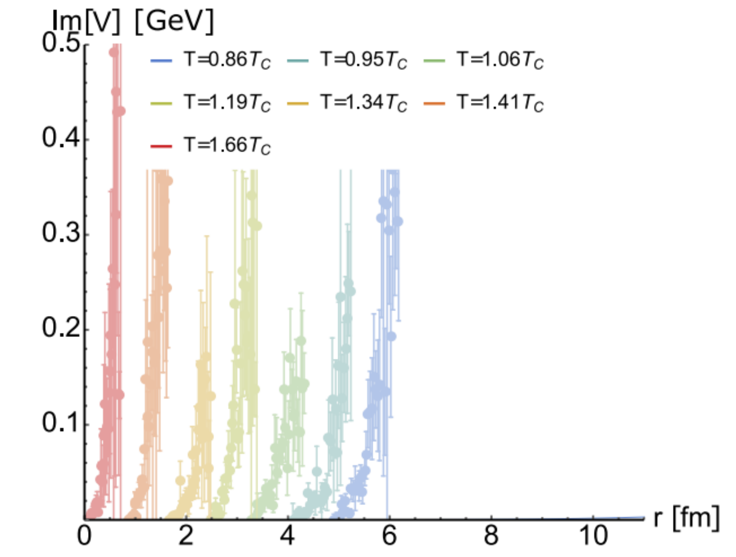
Eskola et al. , EPJ C77 (2017) 13

Quarkonium

- No measurements below top SPS energy
- Moving toward lower collision energies
  - Explore temperature closer to T_C
  - Investigate role of feed-down from $\psi(2S)$ and χ_c
  - **Anomalous suppression effects** should (gradually?) disappear
- Can a **correlation of suppression effects with the temperature** of the fireball be established?
- Are **CNM effects** increasing when lowering collision energy?
- When approaching the **production threshold**, is the ratio $(J/\psi)/D$ increasing? Sensitivity to variation of the spectral functions?

Burnier et al., JHEP12 (2015) 101



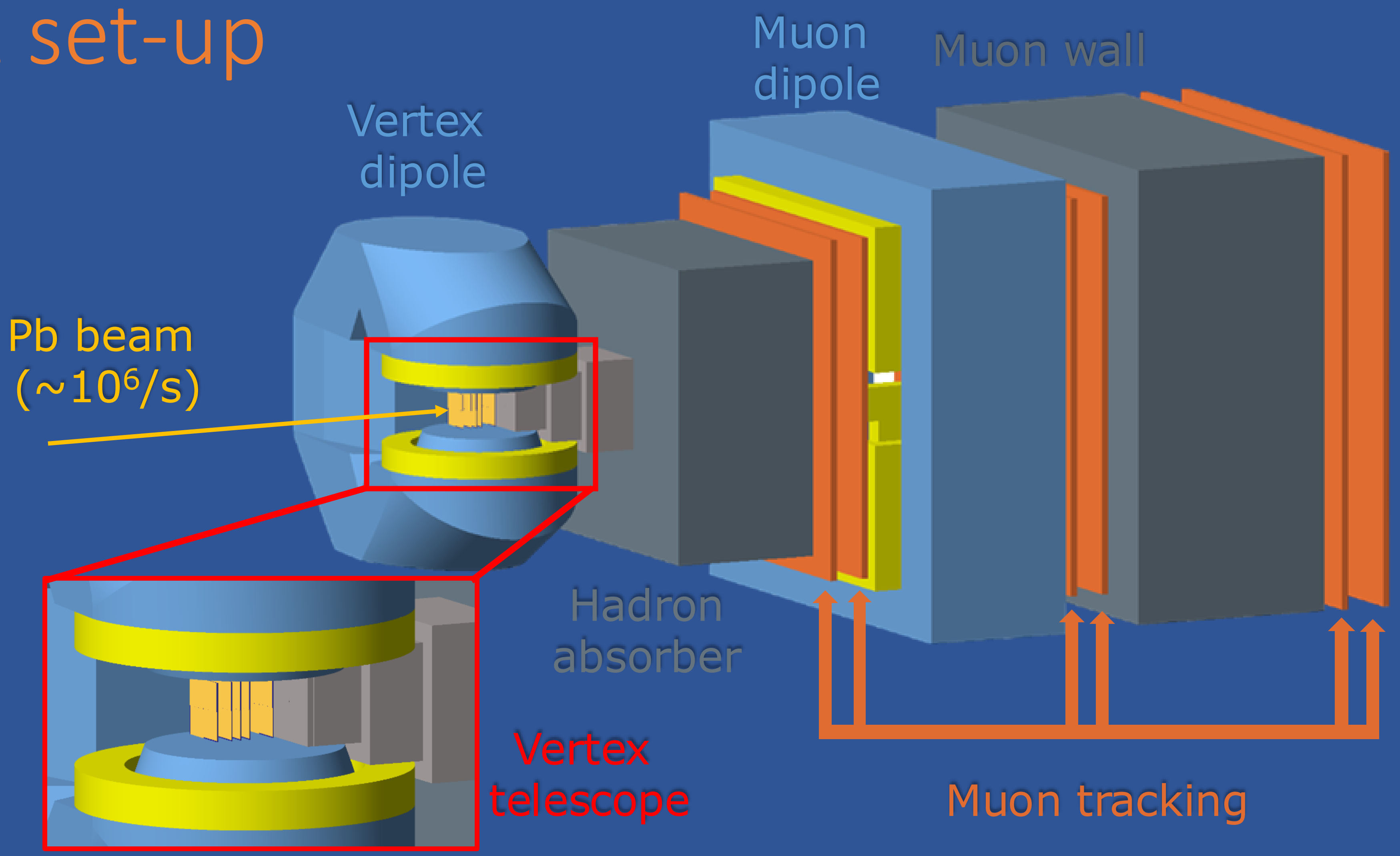


NA60+/DiCE set-up

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



Significant **evolution of the original design** from its inception (EoI, 2019) and from the finalization of the LoI (2023)

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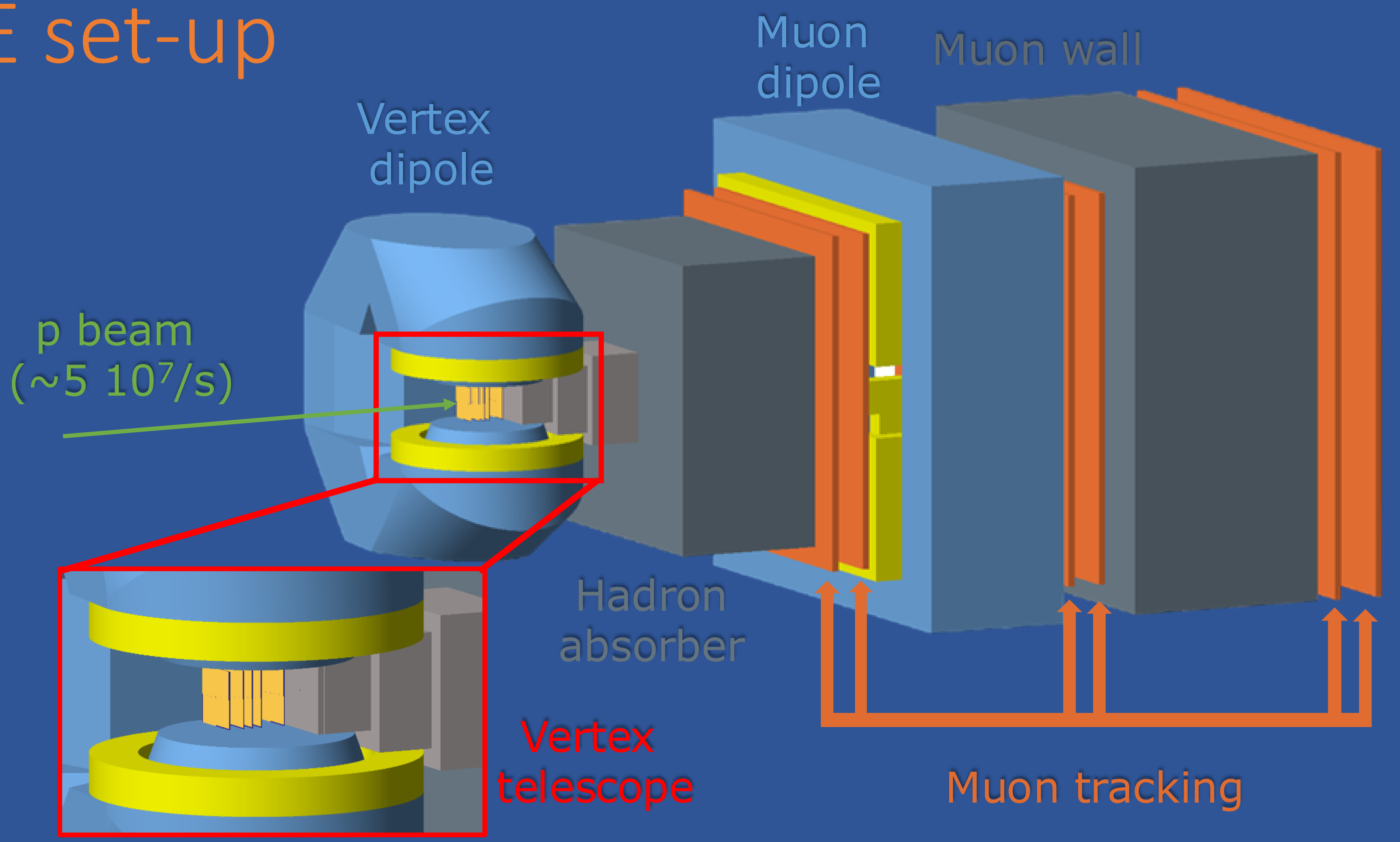
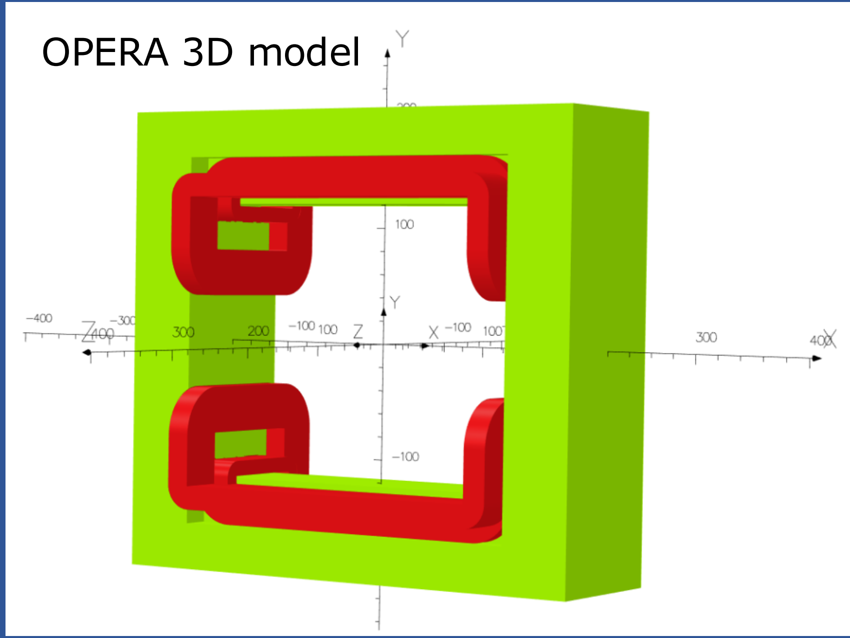


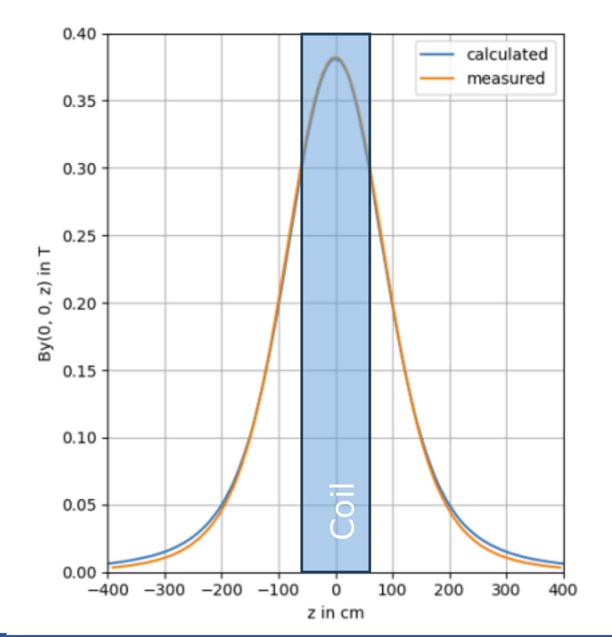
Significant **evolution of the original design** from its inception (EoI, 2019) and from the finalization of the LoI (2023)

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 in front of the last two stations, to improve muon identification

BL = 0.83 Tm
Significant fringe field

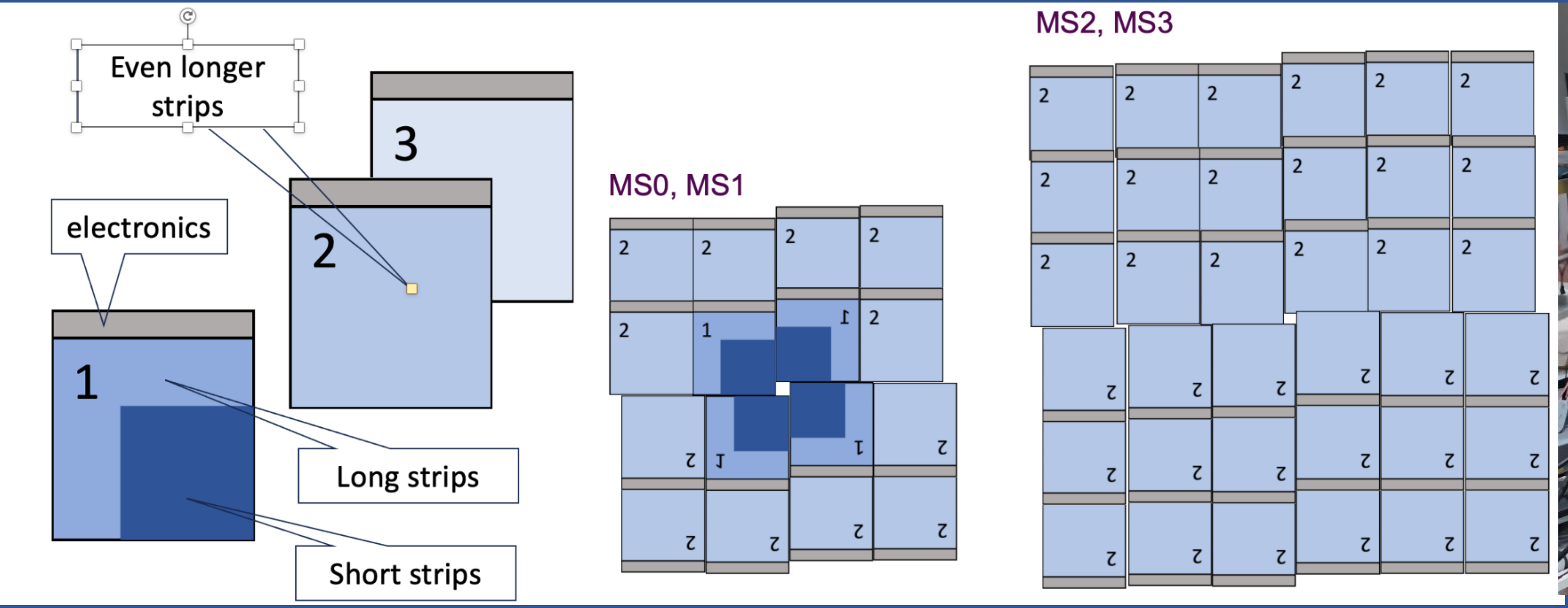


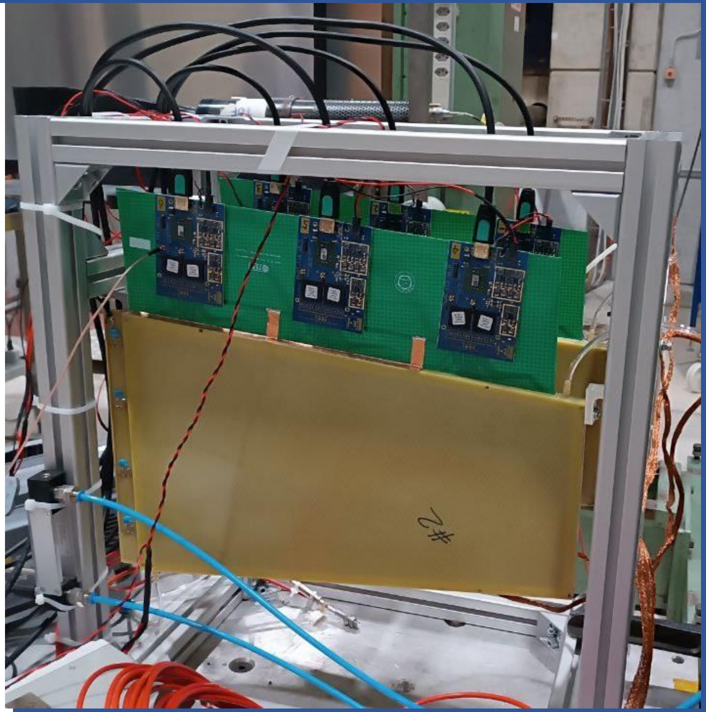


- ❑ **Used by NA62** experiment (rare K decays) till the end of run3, discussion ongoing with EP-DT group and CERN Magnet WG, to assess integration aspects in the NA60+ set-up (powering, cooling)
- ❑ Previous versions of the set-up were considering a toroidal magnet, to be built→ strong cost reduction (4 MEuro)

Muon spectrometer

- Tracking stations realized with **modular structure** and varying strip pitch
  - 100 μm spatial resolution in bending plane (0.5-1 mm in non bending)
  - Readout based on VMM3 chip

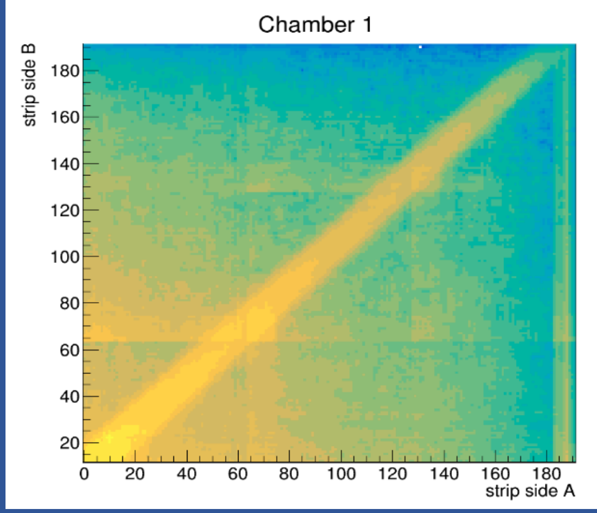




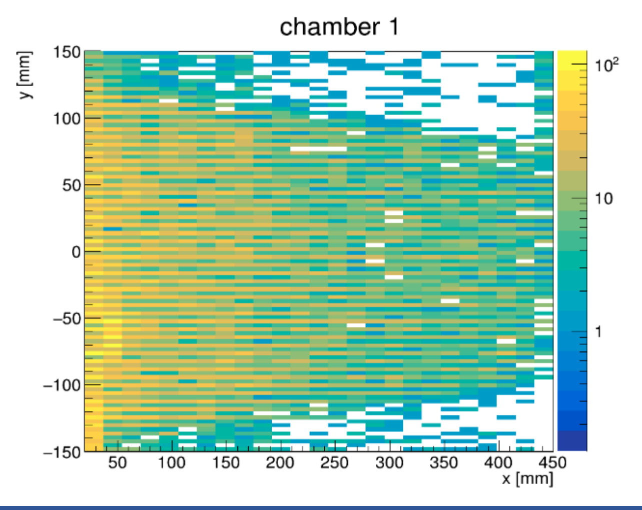
Muon spectrometer

❑ **Prototypes tested** with secondaries from Pb-Pb collisions in 2023 and 2024

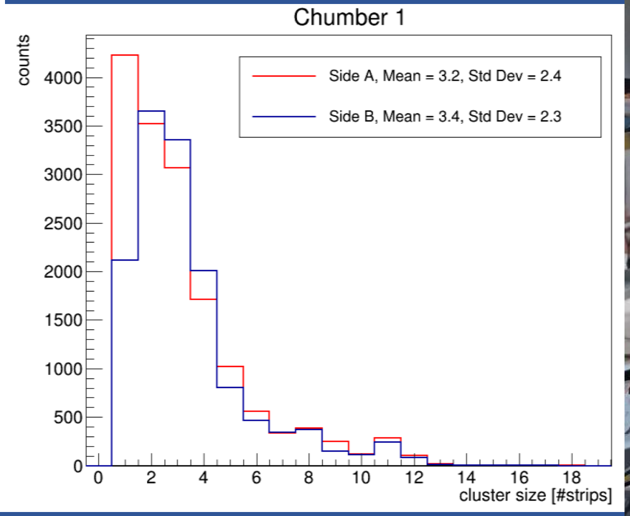
Strip correlation

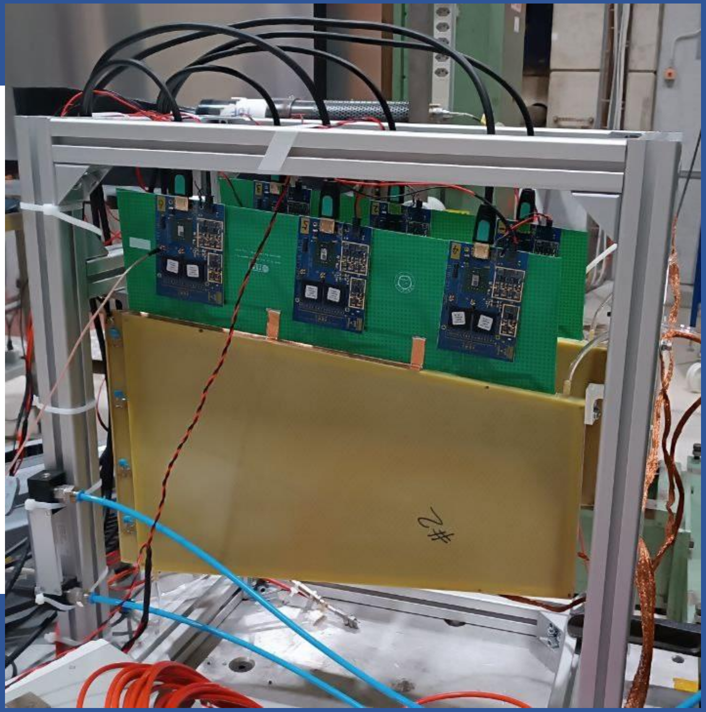


Hitmap Pb-Pb 150 A GeV



Cluster size

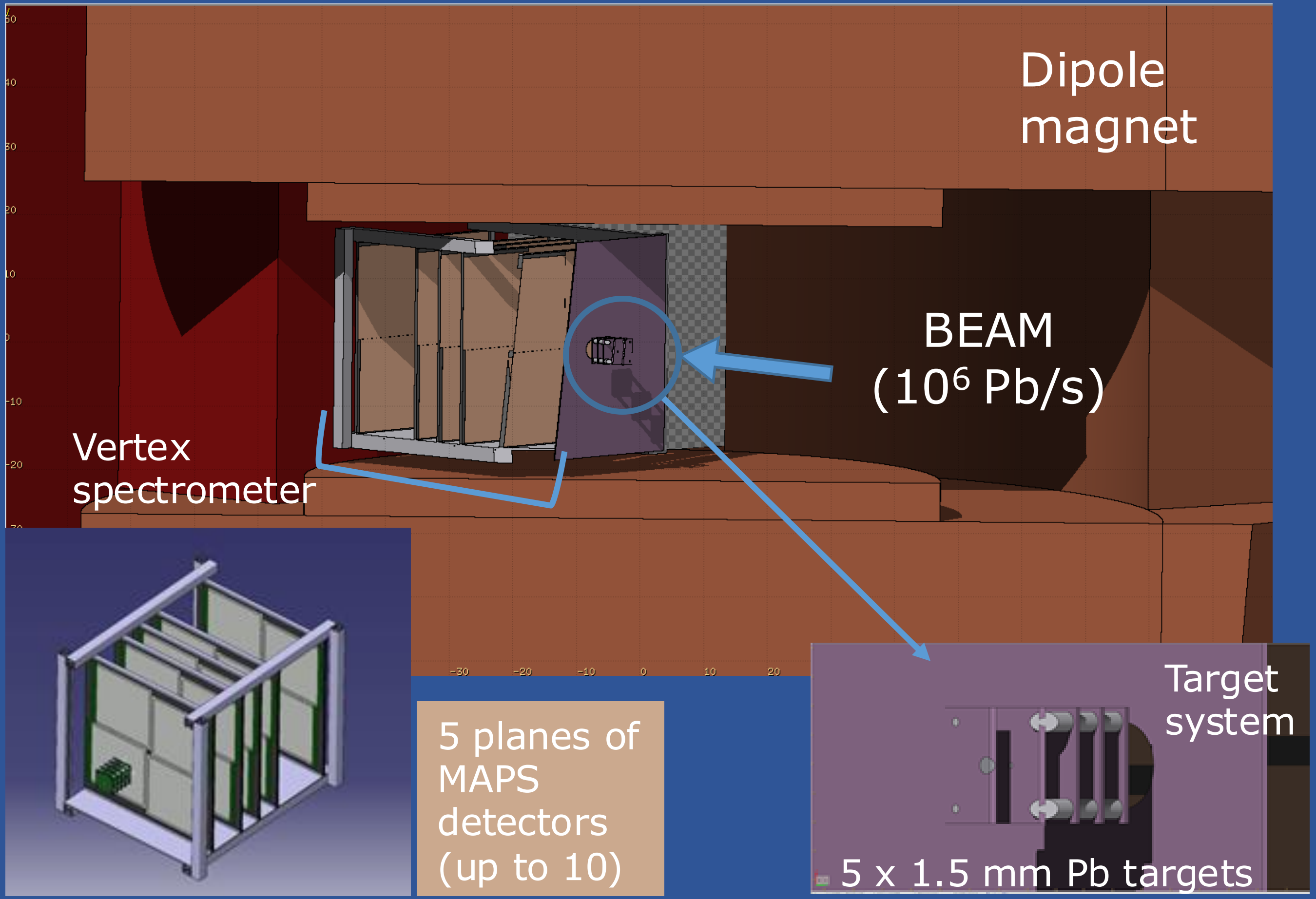




Space resolution ~100 μm (strips)

Vertex spectrometer

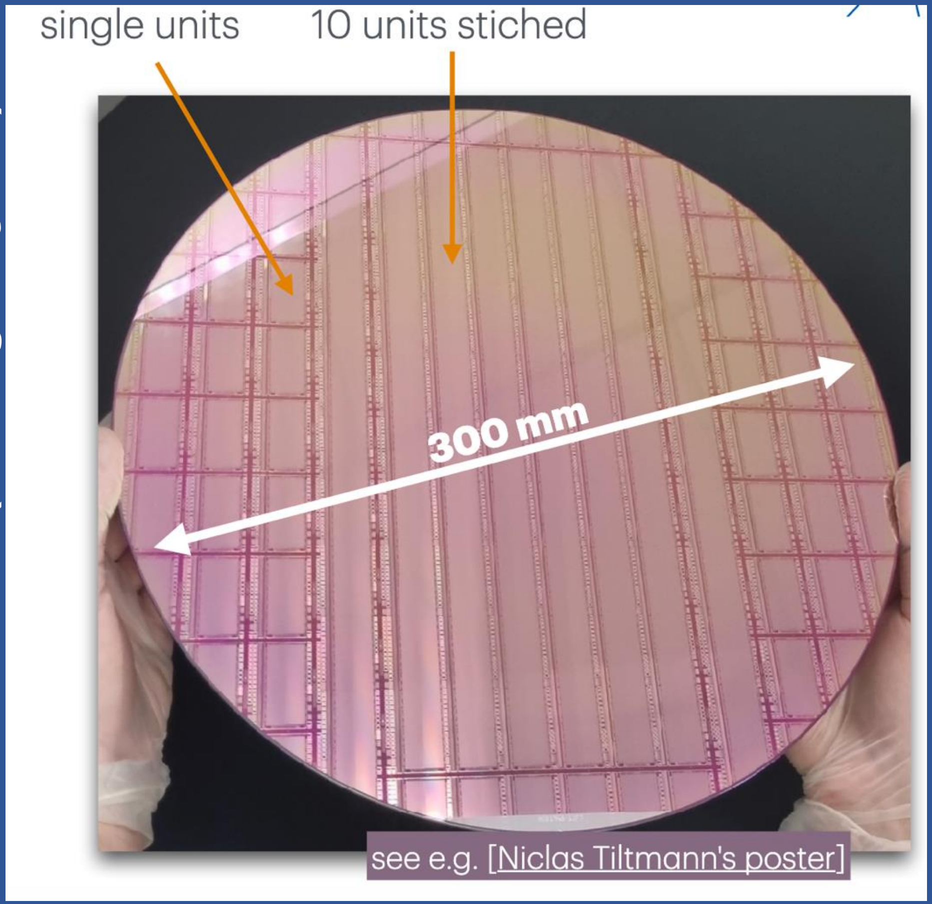
- Positioned inside the gap of the **MEP48 dipole** magnet (1.5 T over 400 mm)
    - **Five tracking stations** → large area MAPS produced with stitching technique
    - Extremely low material budget ($<0.1\%\ X_0$) and excellent spatial resolution ($<5\ \mu m$)



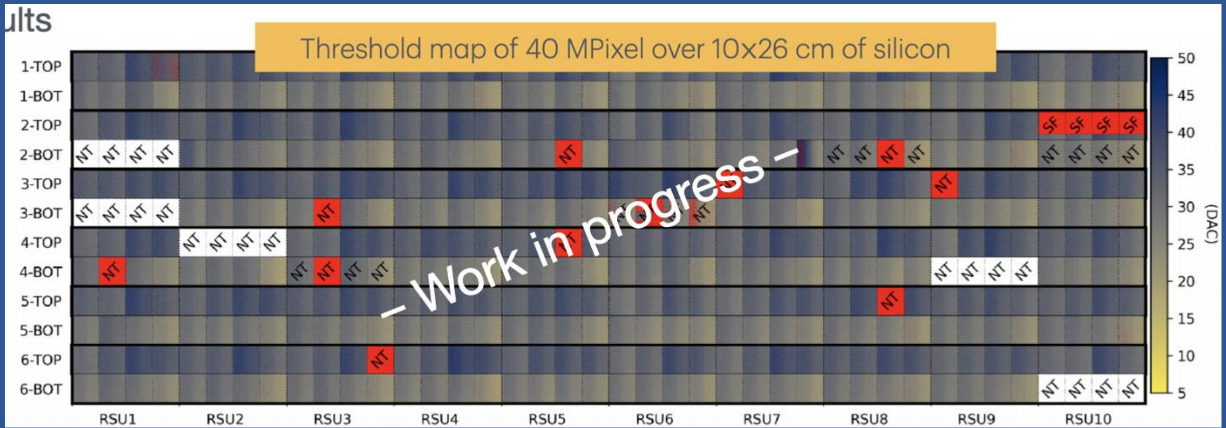
Large area silicon sensors

- Production of large area monolithic sensors:
  - Strong **synergy with ALICE ITS3** project (same timeline as NA60+/DiCE)
  - MOSS (Monolithic Stitched Sensor): first large area sensor prototype produced in 2023

ALICE ITS3 (M. Mager QM25)

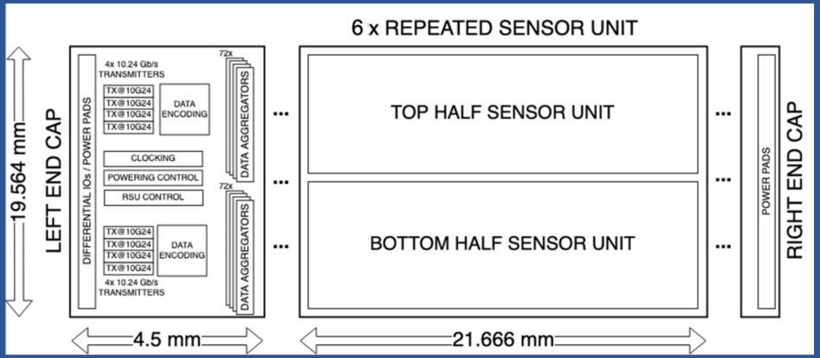


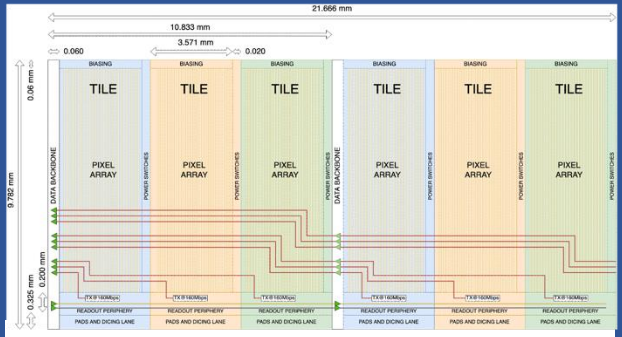
- Prototypes of stitched sensors have been successfully produced:
  - tested for **yield** and detection efficiency
- The sensors are fully integrated detector modules
- This technology forms **the ideal construction elements for ultra-light detectors**



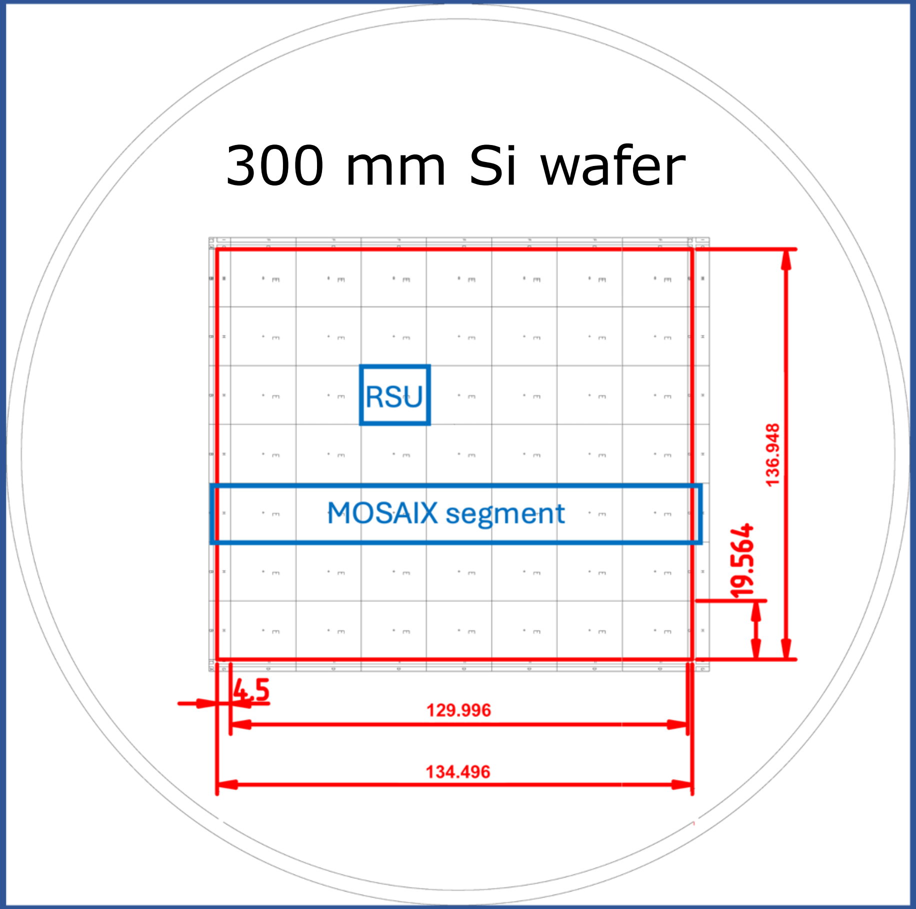
NA60+/DiCE sensor (the magics of stitching)

- **Based on MOSAIX**: (almost)-final sensor prototype, submission expected in June 2025





Top half-unit (bottom is mirrored)

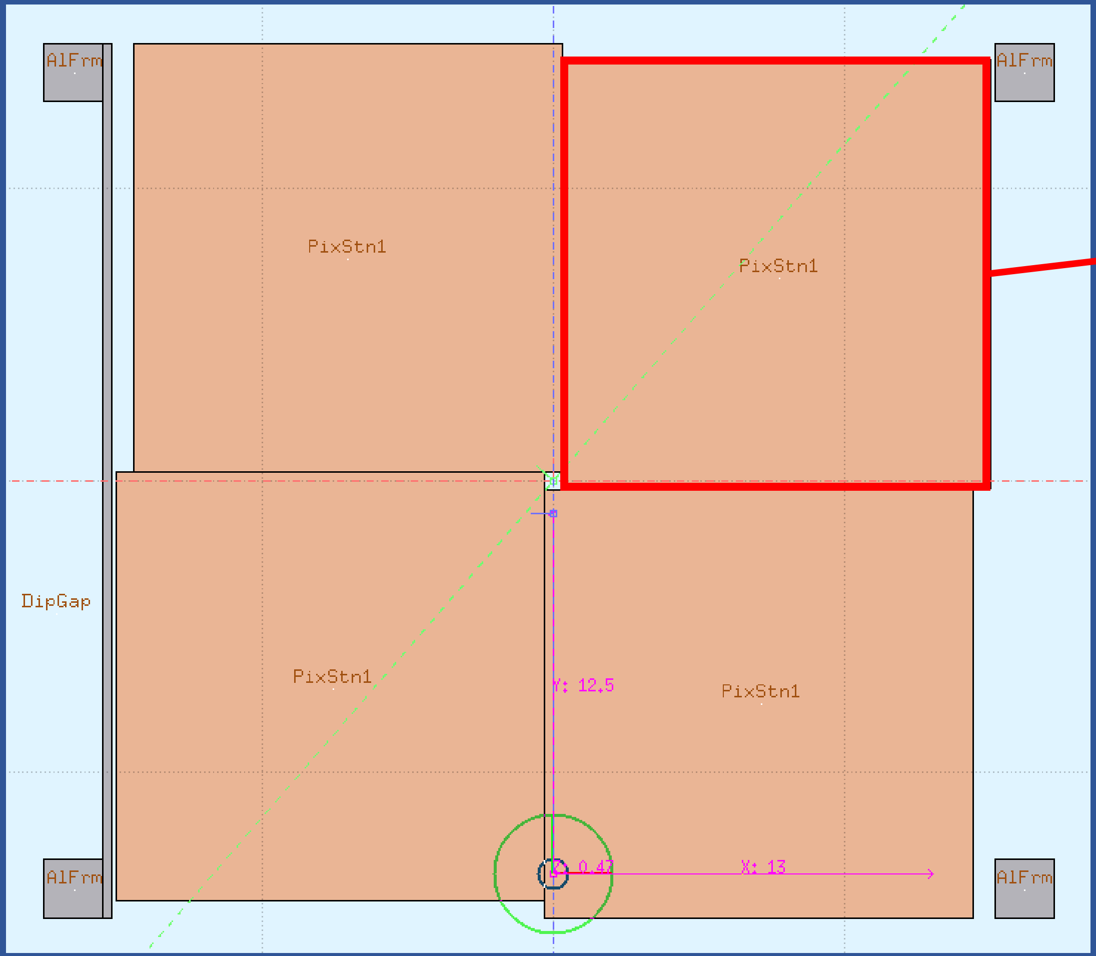


- Stitching plan:
  - 1 MOSAIX segment with 6 RSUs
  - Replicated 7 times vertically

13.6x13.6 cm² sensor

Silicon pixel stations

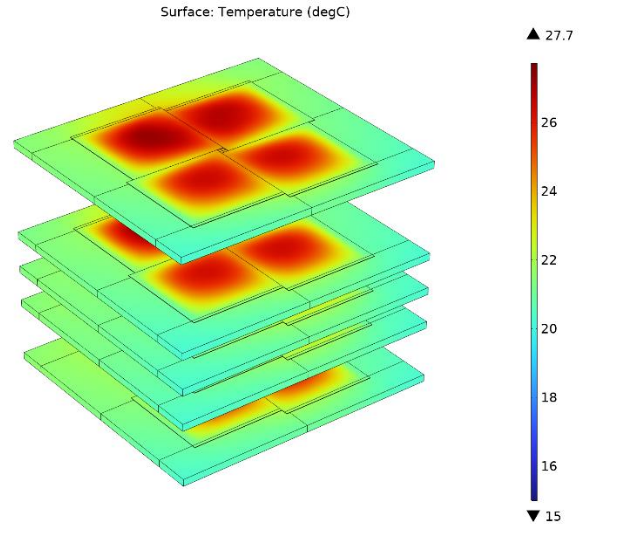
- ❑ Pixel station with 4 large sensors



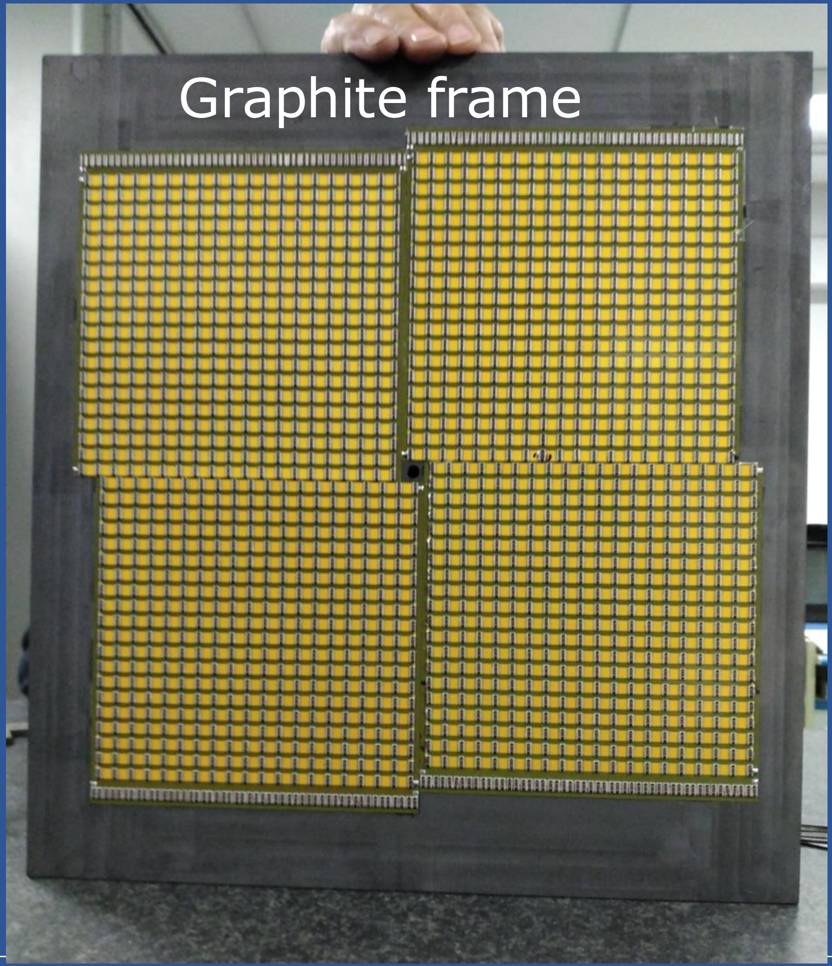
- ❑ Powering and data transmission from right side:
  - 10.24 Gb serial links (optical to DAQ)
- ❑ Maximum rate: 6 MHz/cm^2:
  - ok for 1-1.5x10^6 Pb/s

Mechanics and cooling for silicon stations

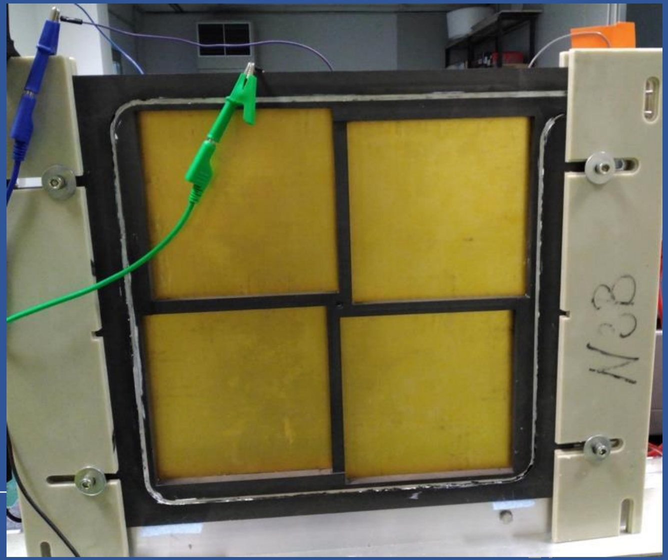
- Large area sensors → mechanics + cooling issues:
  - 50 mm thick, 180 cm^2 flexible sensors
  - 40 mW/cm^2 power dissipation in pixel matrix (+ 800 mW/cm^2 in periphery)



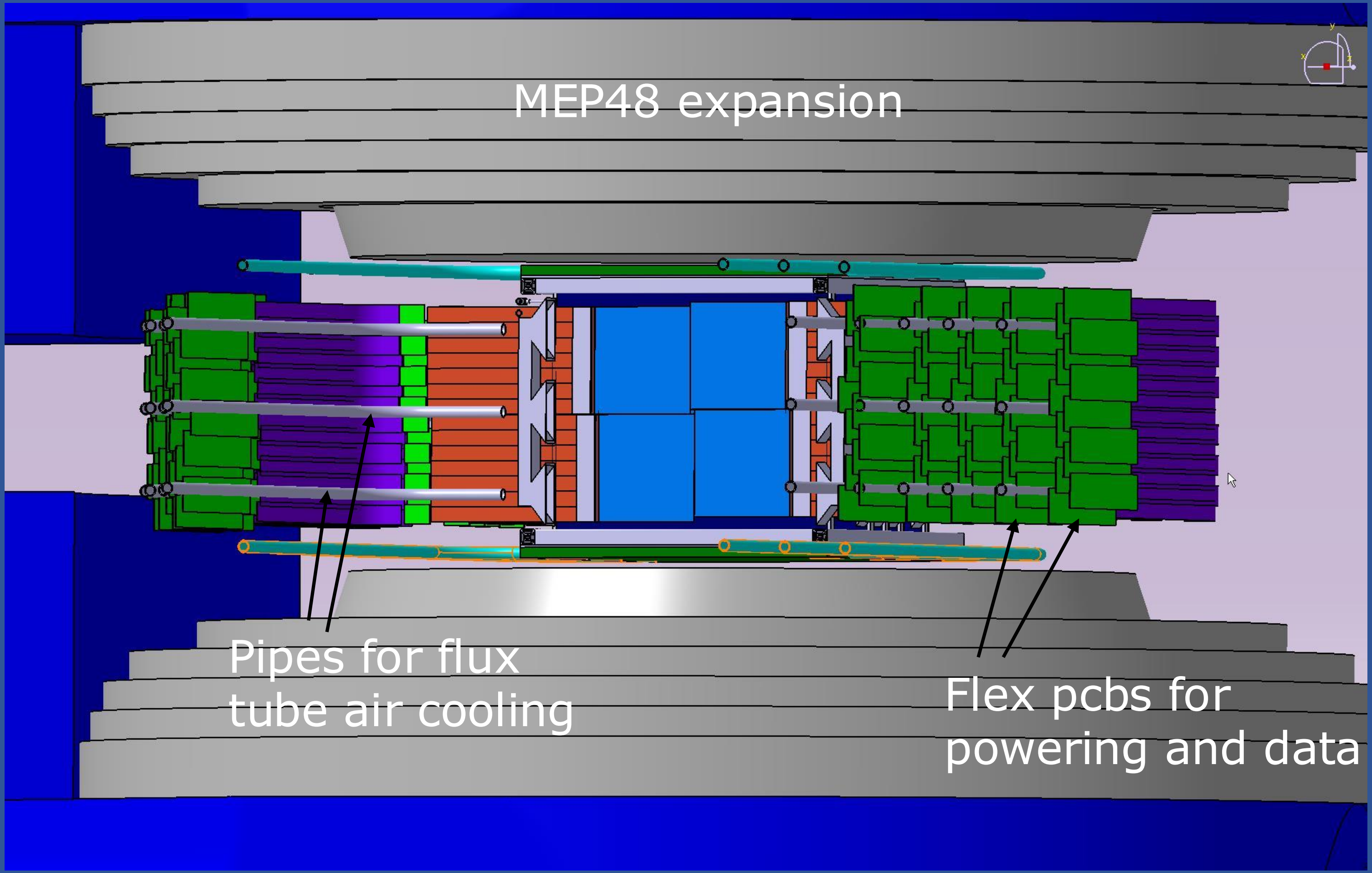
COMSOL/ANSYS simulations
Mixed water + air cooling
0.4 mm carbon fiber substrate to improve heat dissipation



- Simulations calibrated on a test set-up:
  - pcbs with resistor arrays mounted on graphite frame to mimick power dissipation

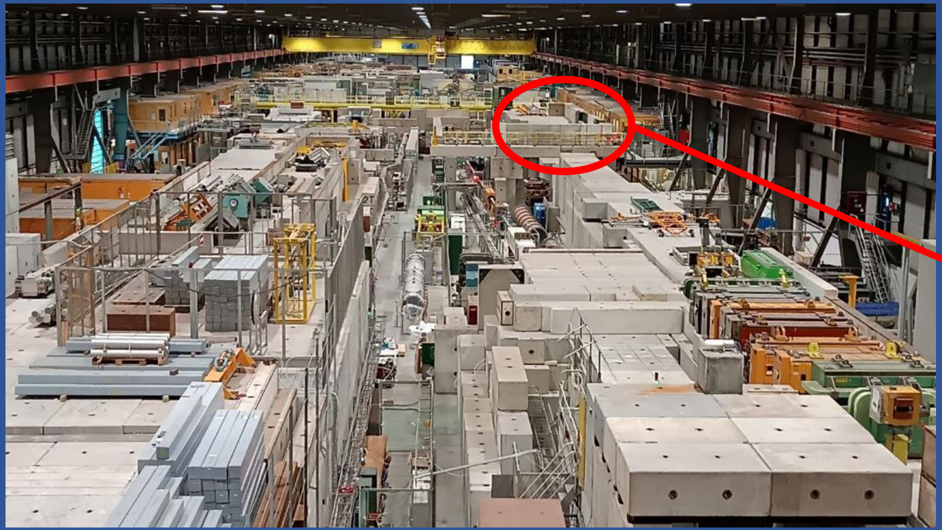


Integration of the silicon tracker inside MEP48



Location of the experiment

- The location chosen for the experiment is the **EHN1-PPE138 experimental hall**, on the **H8 beam** extracted from the SPS (the former location of the NA45/CERES experiment)



- Modifications to the hall and integration aspects currently worked-out within a **dedicated PBC study group** including a **CERN BE-EA team**

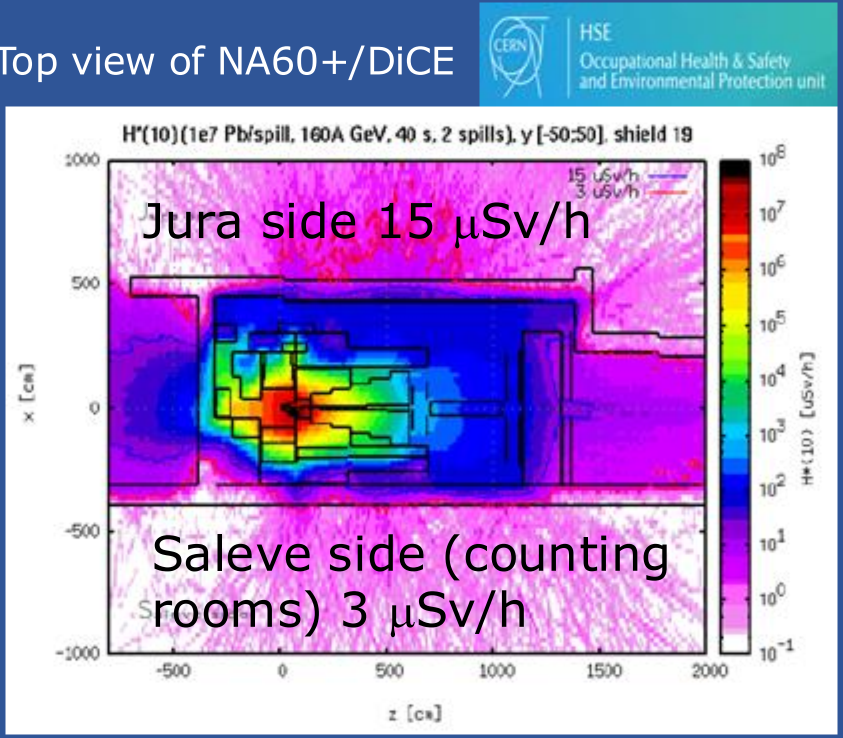
- A crucial aspect for the feasibility of the experiment is the possibility of delivering a **high-intensity Pb and p beam** to this hall, at various energies
- The beam should be very **well focused**, due to the only 6x6 mm^2 hole defining the acceptance of the vertex spectrometer

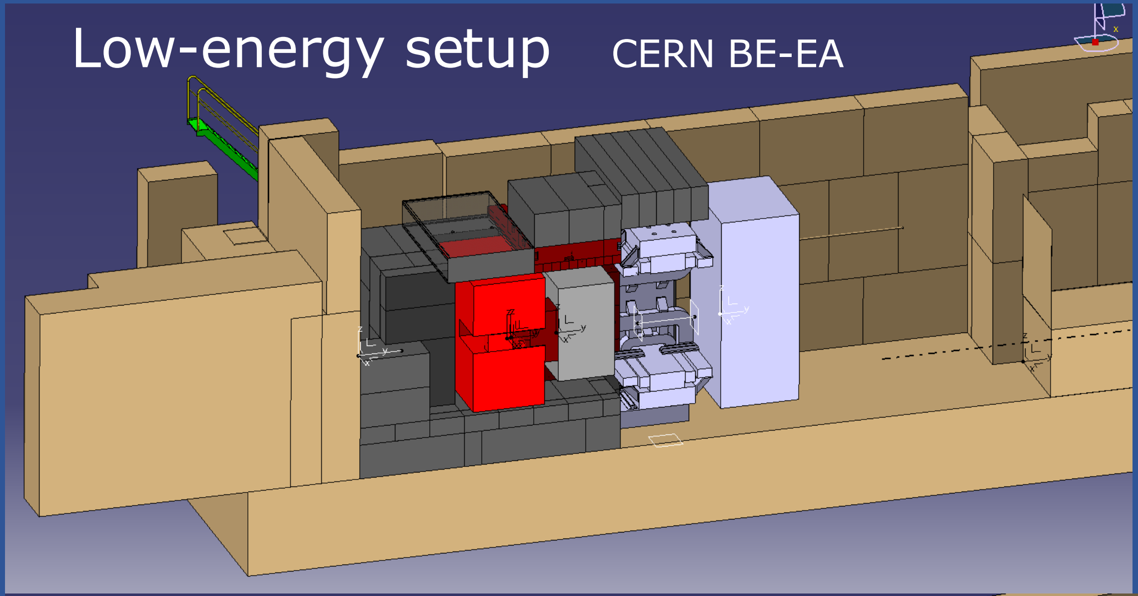
⇓

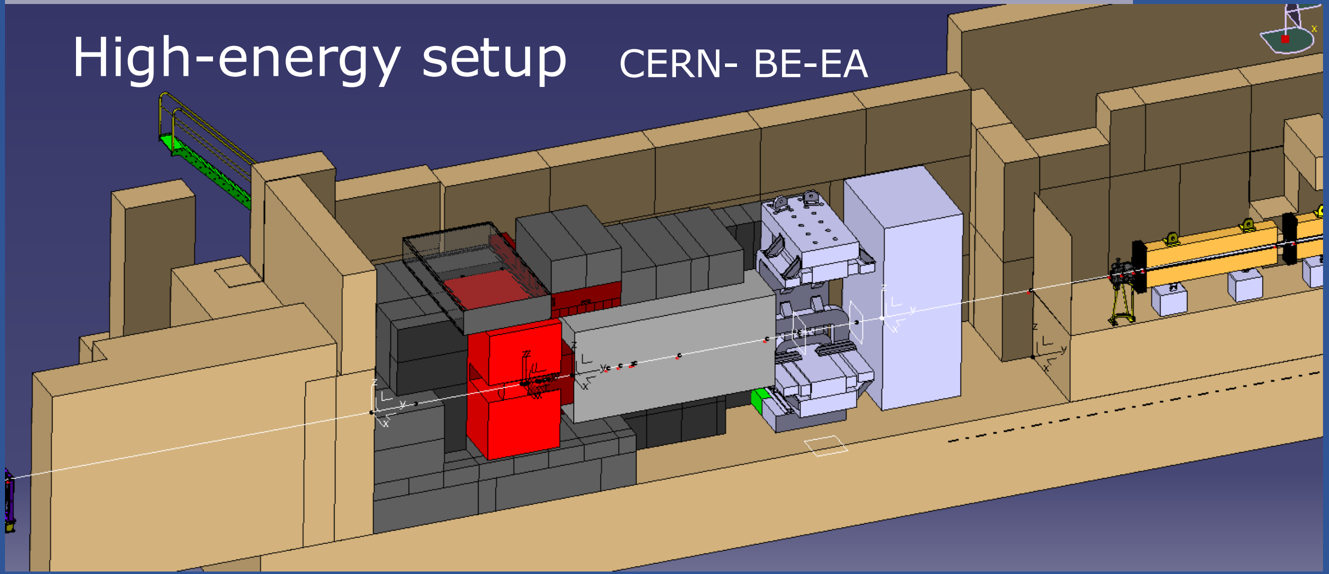
Non-trivial accelerator and radioprotection issues

Integration in experimental area PPE138

Top view of NA60+/DiCE



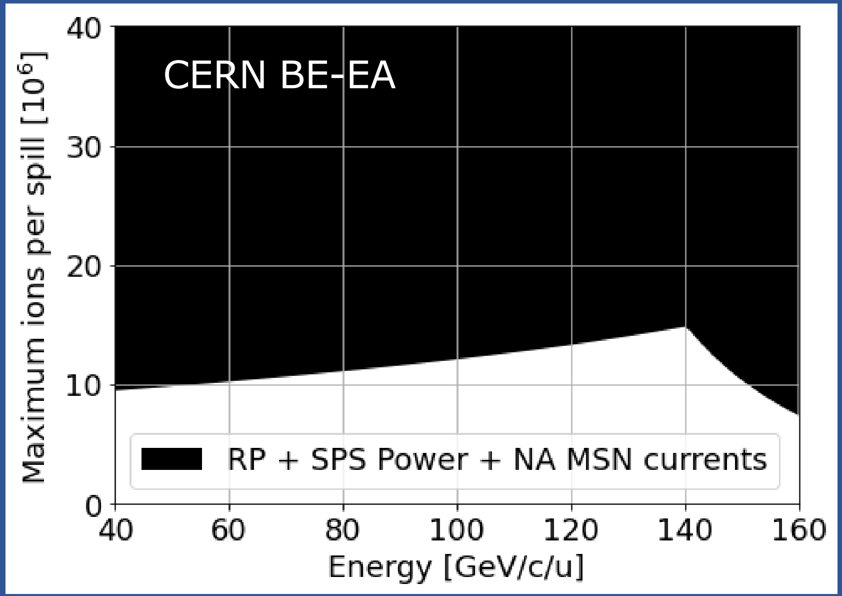




- Heavy shielding of iron and concrete:
  - dose below 3 μSv/h externally to the experiment
- Integration studies for detector and infrastructure also performed

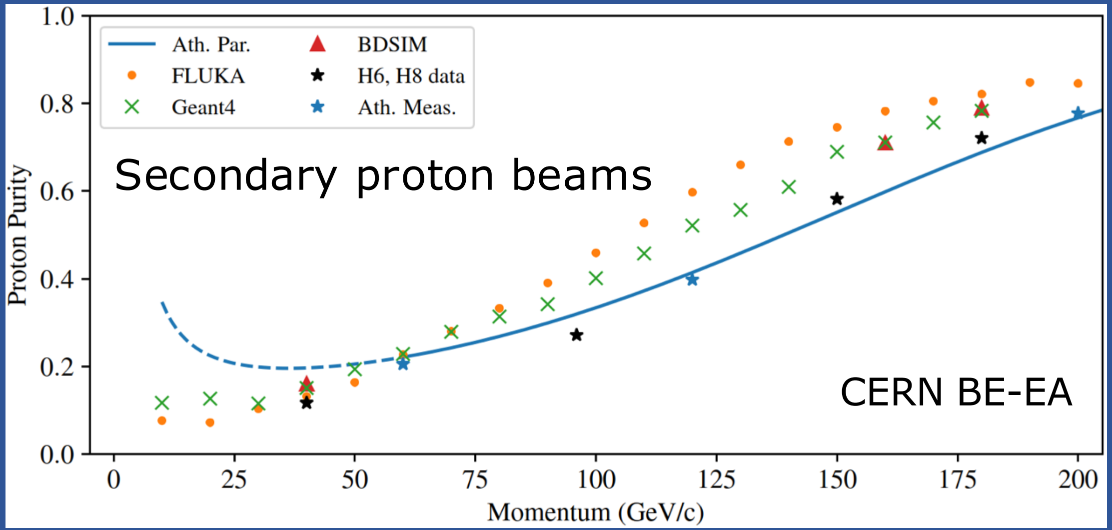
High-intensity Pb and proton beams

Pb



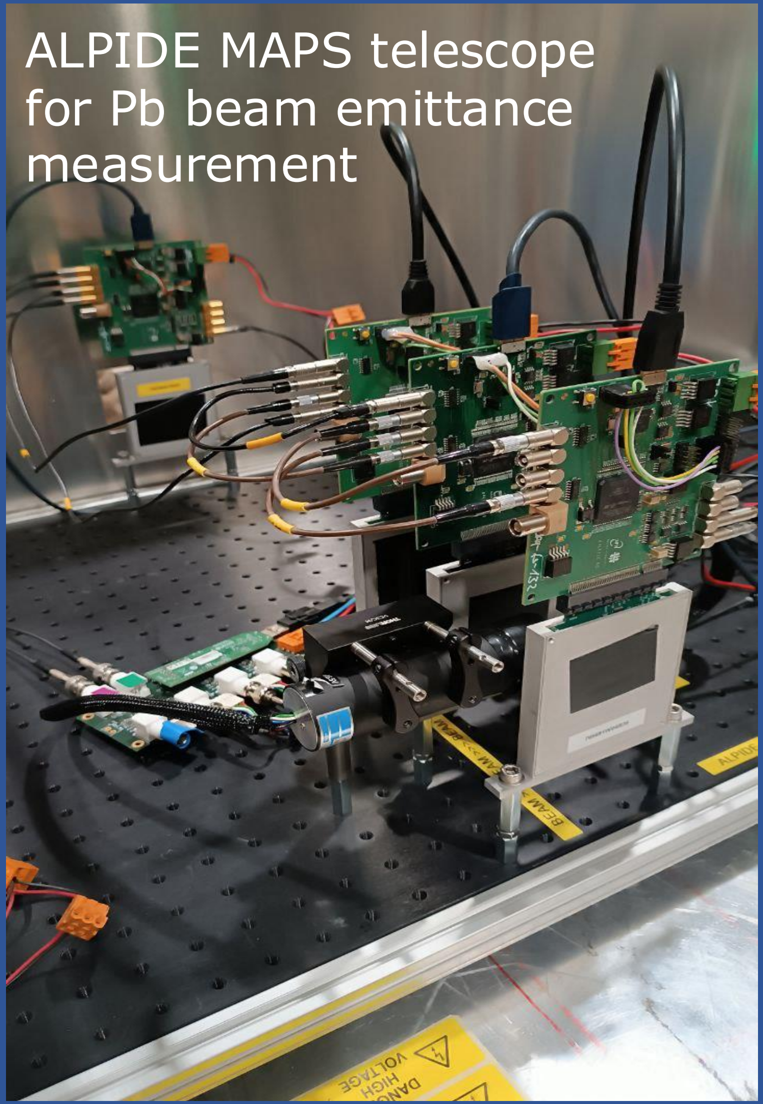
- Maximum possible **Pb ions/spill ~ 10^7**
- Estimate of **0.6×10^{12} Pb on target** assuming ~4 weeks running time and realistic machine efficiency (dominated by RP considerations)
- Interaction probability is 15%, leading to 150 kHz interaction rate → L_{int} ~ 14.7 nb^{-1}

p

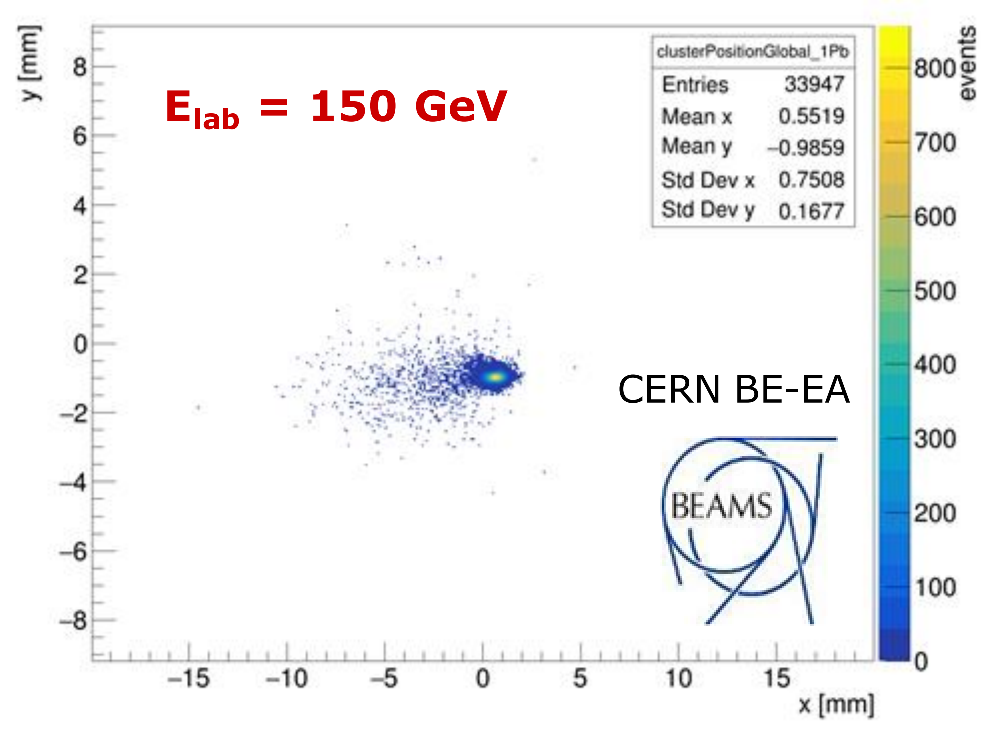


- Need a similar number of nucleons on targets(s)
- **Secondary beams** from fragmentation of 400 GeV primary proton beam → insufficient purity and luminosity
- Use **primary proton beam** from SPS:
  - **Possible during ion run periods**
  - technical issues under investigation by CERN BE-EA

Focusing high-intensity Pb beams

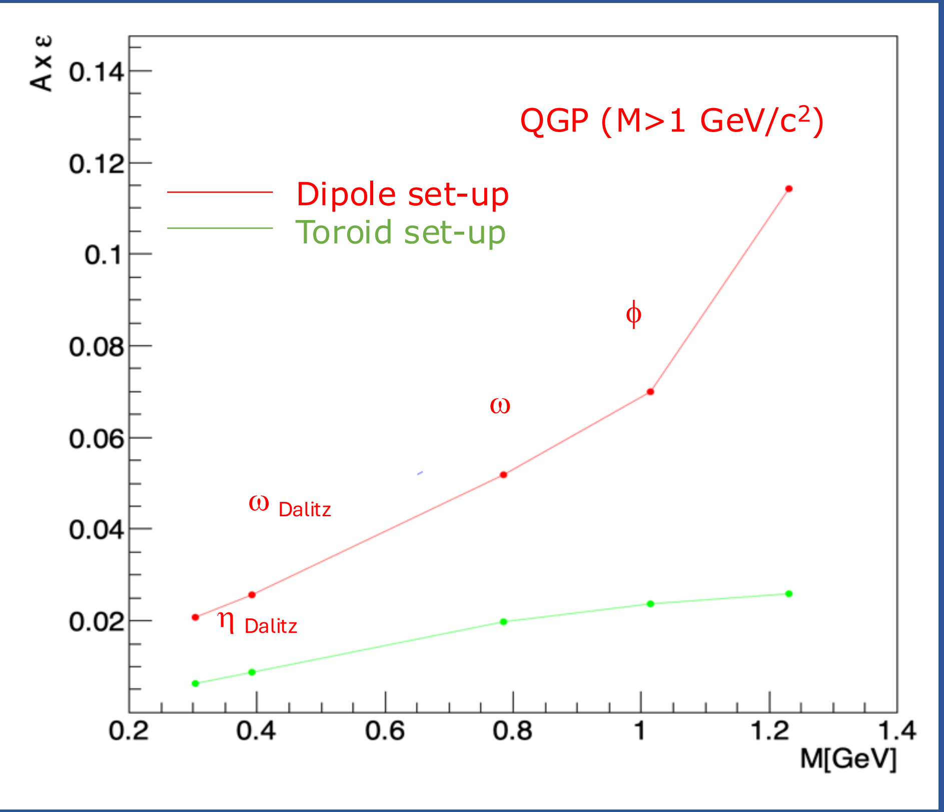


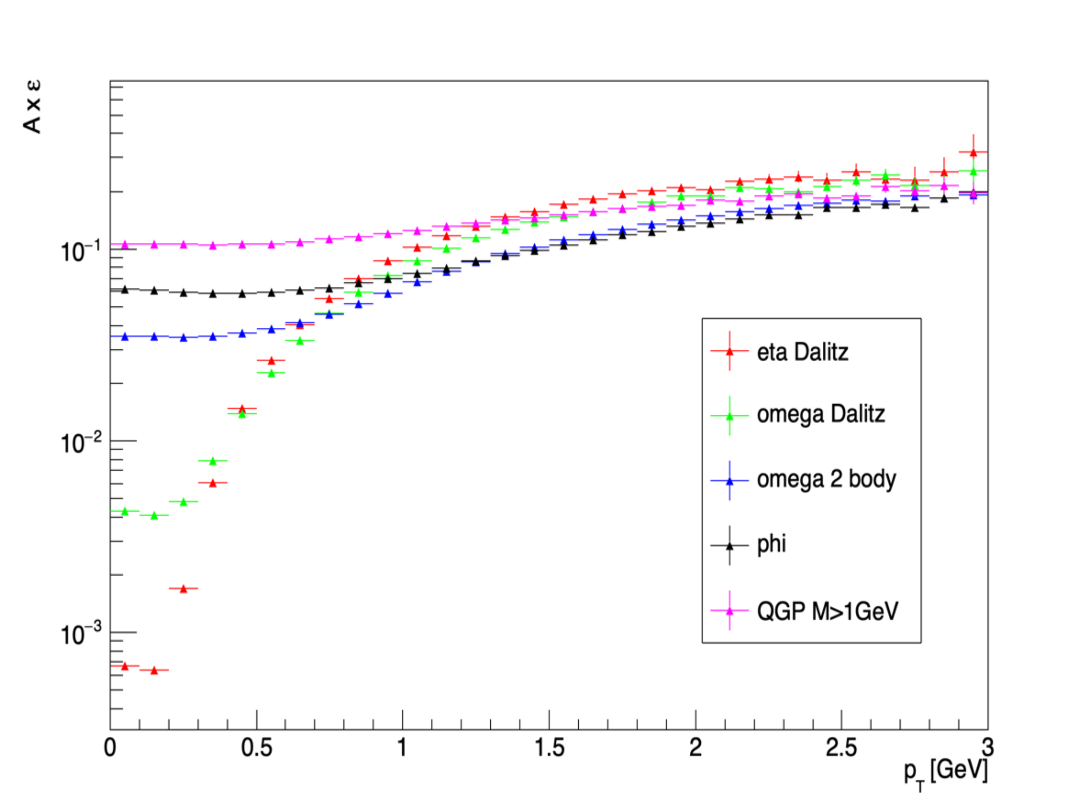
- New beam optics **validated in test beams**
- Reached the target intensity:
  - **1.2 x 10^6 Pb/s** at 150 GeV with a **very narrow beam spot**
  - Reasonable results even at 13.5 GeV:
    - 5 x 10^5 Pb/s and a 1200 x 750 μm² beam spot
    - Room for further optimization by CERN BE-EA team



Physics performance – e.m. probes

- Detection efficiency extends down to **low-mass/low p_T**
- Moving from toroidal to dipole magnet
→ further improvement, no central dead zone

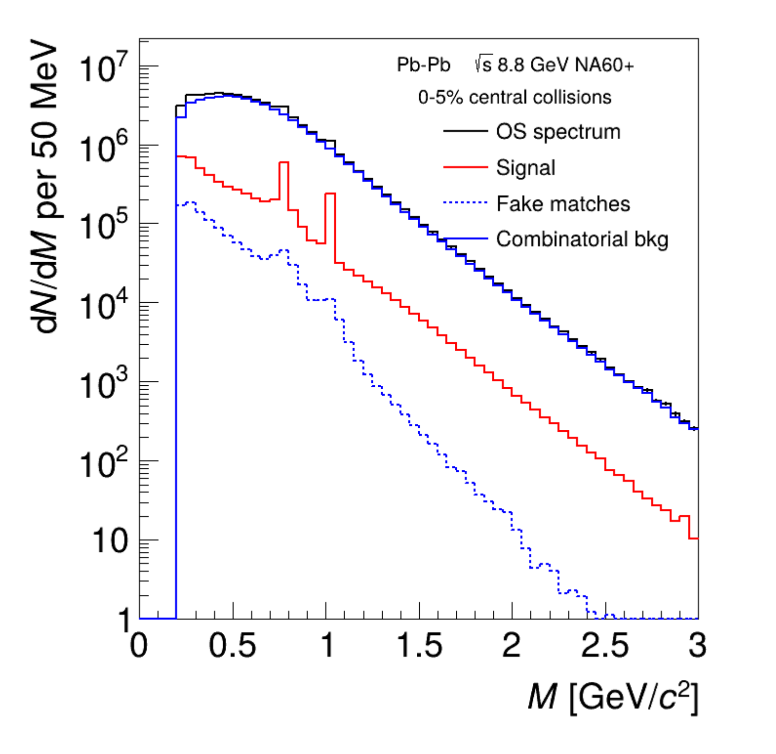




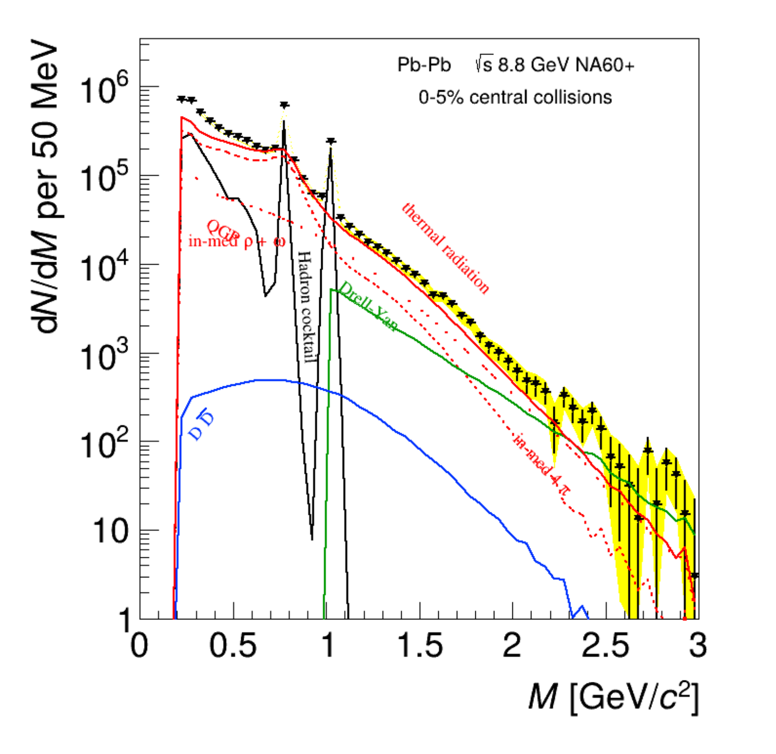
- Efficiencies are about a **factor 10 larger** than in the old NA60 experiment

Thermal dimuons

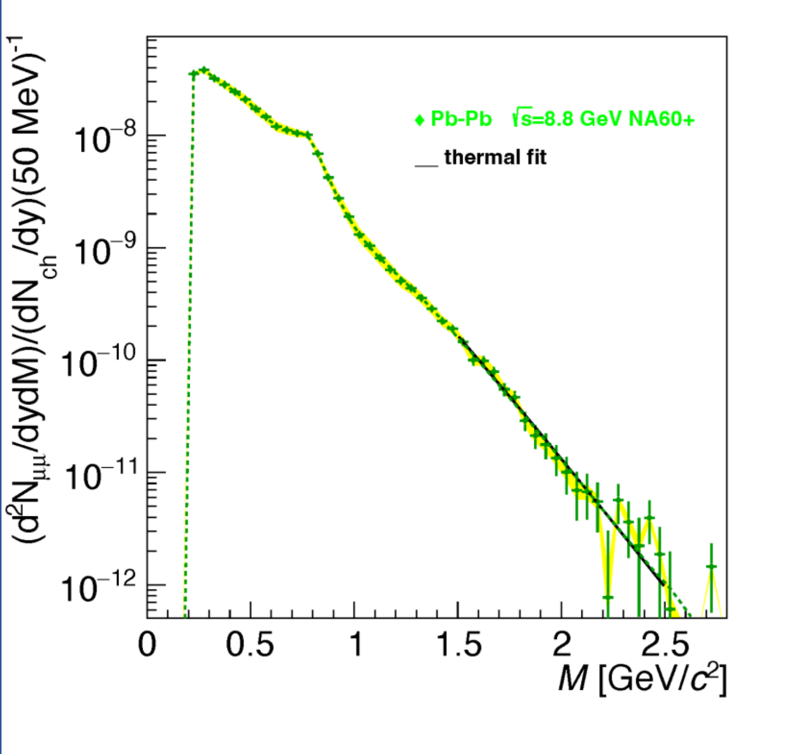
Pb-Pb 40 A GeV



0.6x10^{12} Pb on target (1month)



Thermal radiation yield accessible up to M = 2.5-3 GeV/c^2



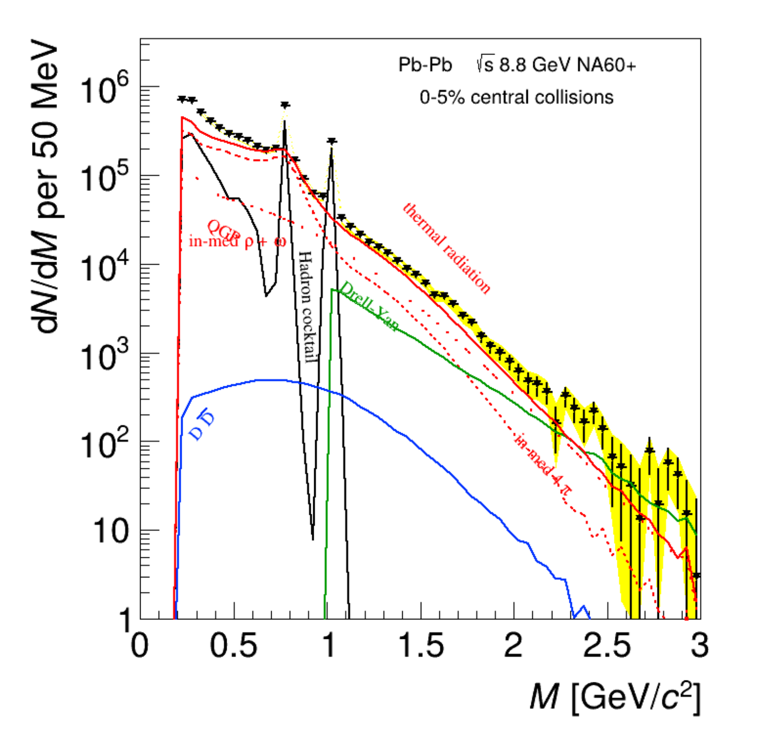
- B/S (M=0.6 GeV/c^2) ~ 20
- Fake matches contribution: 25% at η Dalitz, 10% at ϕ
- Mass resolution 7 MeV at ω

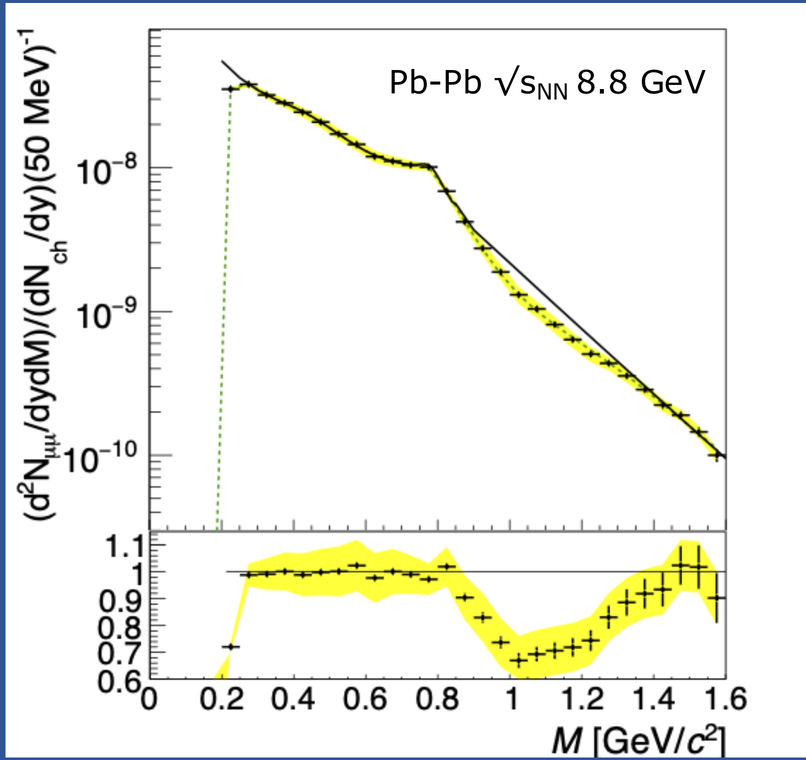
- Hadronic cocktail + Drell-Yan + charm (PYTHIA) + thermal radiation

- Temperature from **fit of thermal radiation continuum** in 1.5<M<2.5 GeV /c^2: 4% uncertainty

ρ-a_1 mixing

- Chiral symmetry restoration investigated with the measurement of the ρ- a_1 mixing
- Full ρ-a_1 chiral mixing → 20-30% enhancement is expected in the region 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

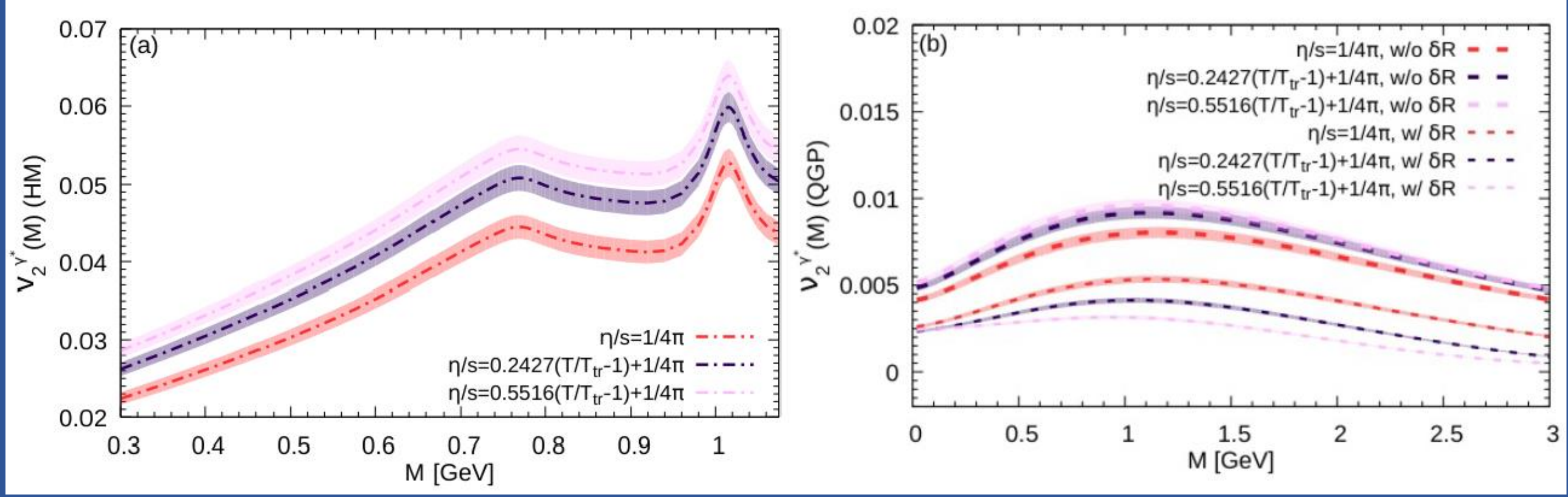
green line → no chiral mixing
black line → full chiral mixing

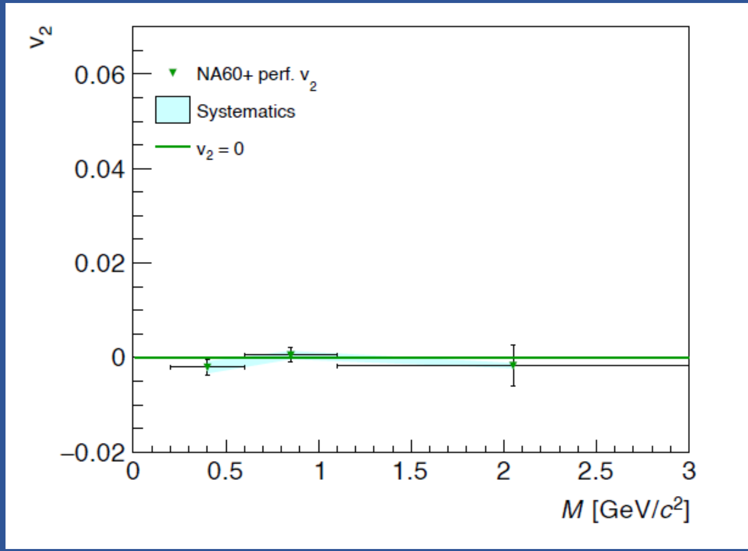
NA60+/DiCE could clearly detect a signal of chiral symmetry restoration

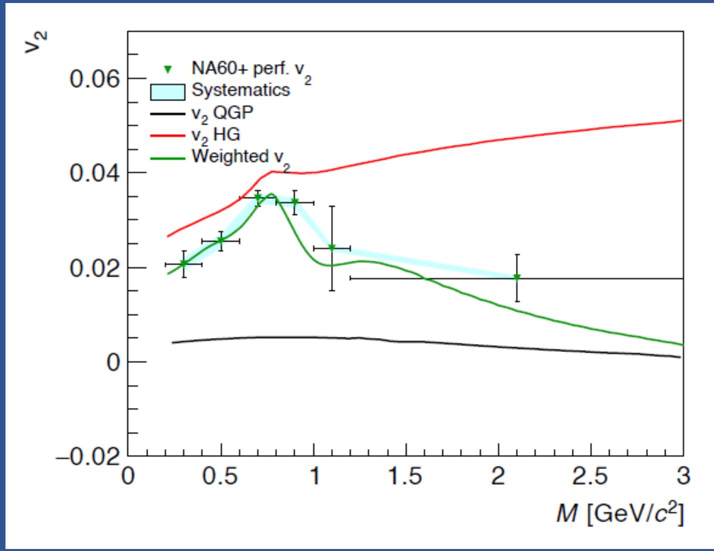
Elliptic flow of thermal dileptons

- **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)







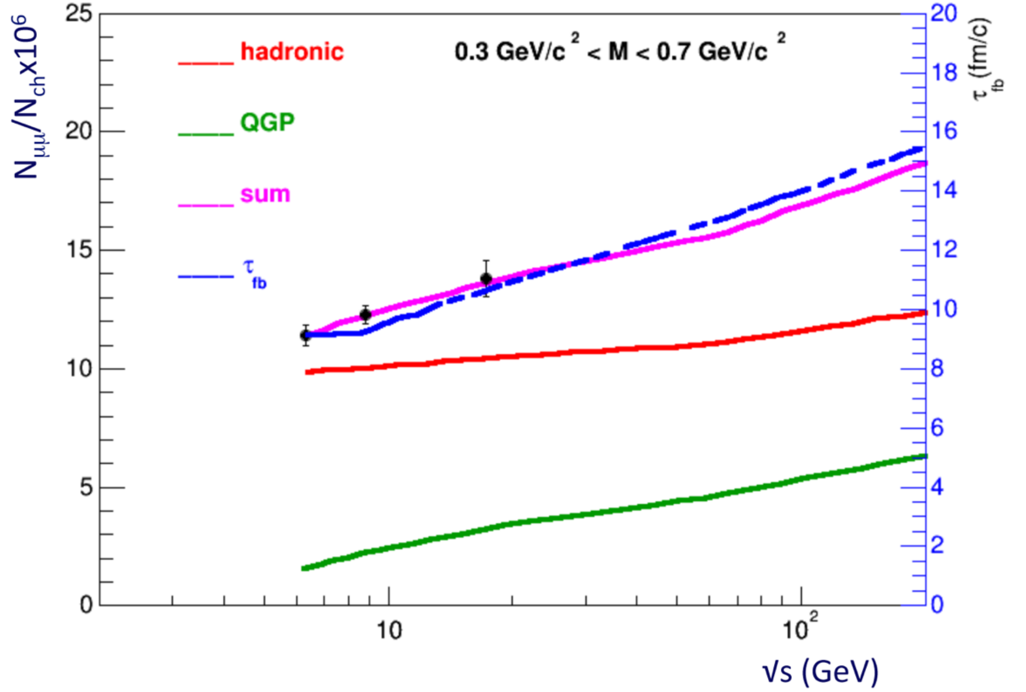
- No prediction at SPS energies
- Two possible scenarios: $v_2=0$
  - **Measurement with uncertainty between 0.003 and 0.008**
- $v_2=v_2^{RHIC}$
  → increase of v_2 versus mass (HG) and a drop in the IMR (QGP)

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**

Hees, Rapp, Phys. Lett. B 753 (2016) 586



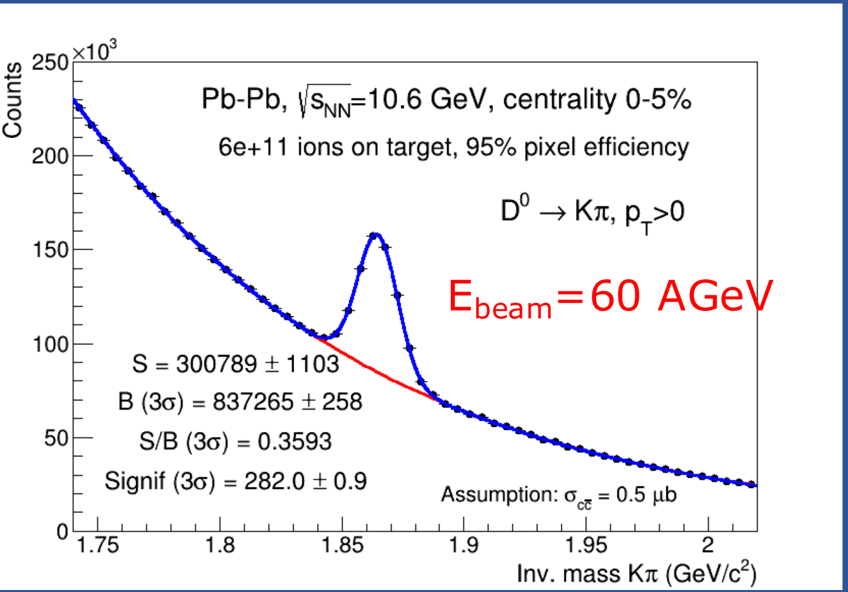
- Soft mixed phase in a **first-order transition:**
  - pressure gradients in the system are small and thus stall the fireball expansion
  - increased lifetime in the collision-energy regime where the mixed phase forms

- Black points → NA60+ projections (N.B. EOI plot, expect some increase of errors with new setup, but still very good accuracy)

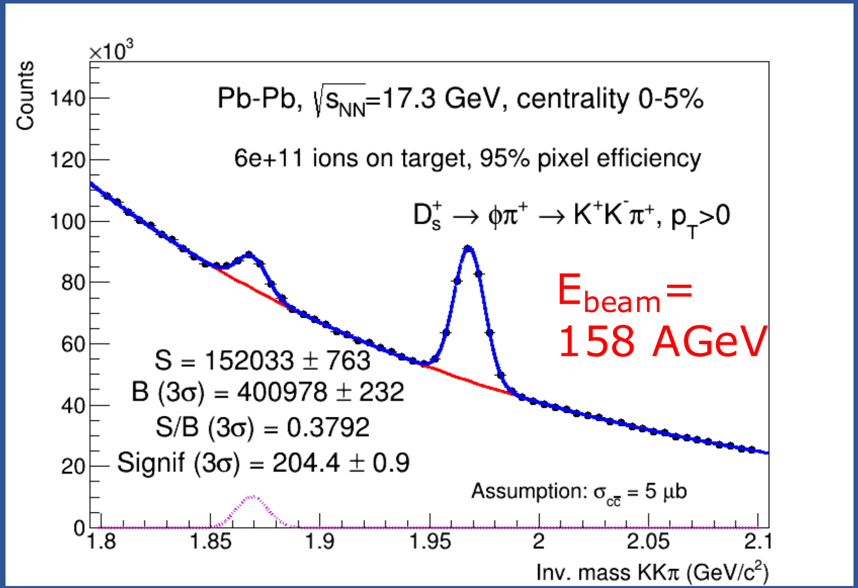
Physics performance – open charm

- Decay products reconstructed in the vertex spectrometer
- Geometrical selections on the displaced decay-vertex topology ($c\tau$~60-300 μm) to enhance
- All simulations based on 0.6 x 10^{12} Pb ions on target (1 month of data taking)

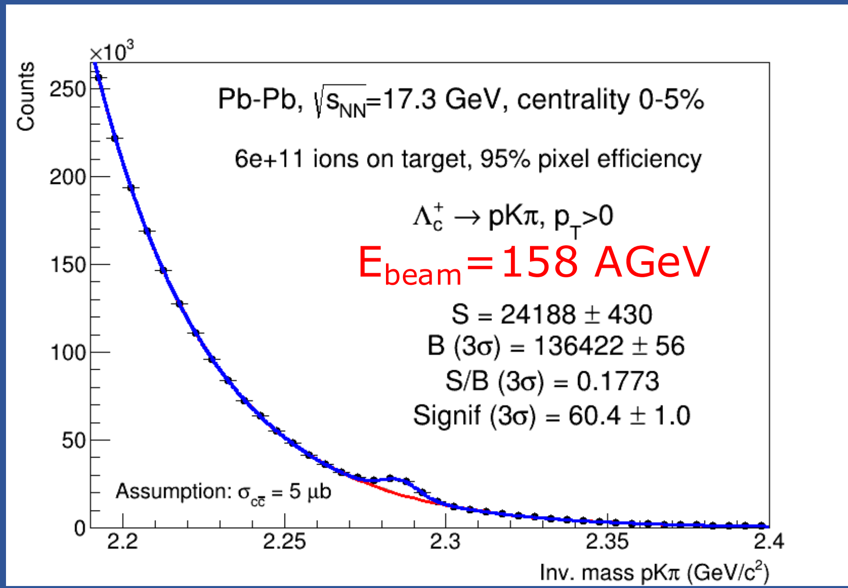
$D^0 \rightarrow K\pi$



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

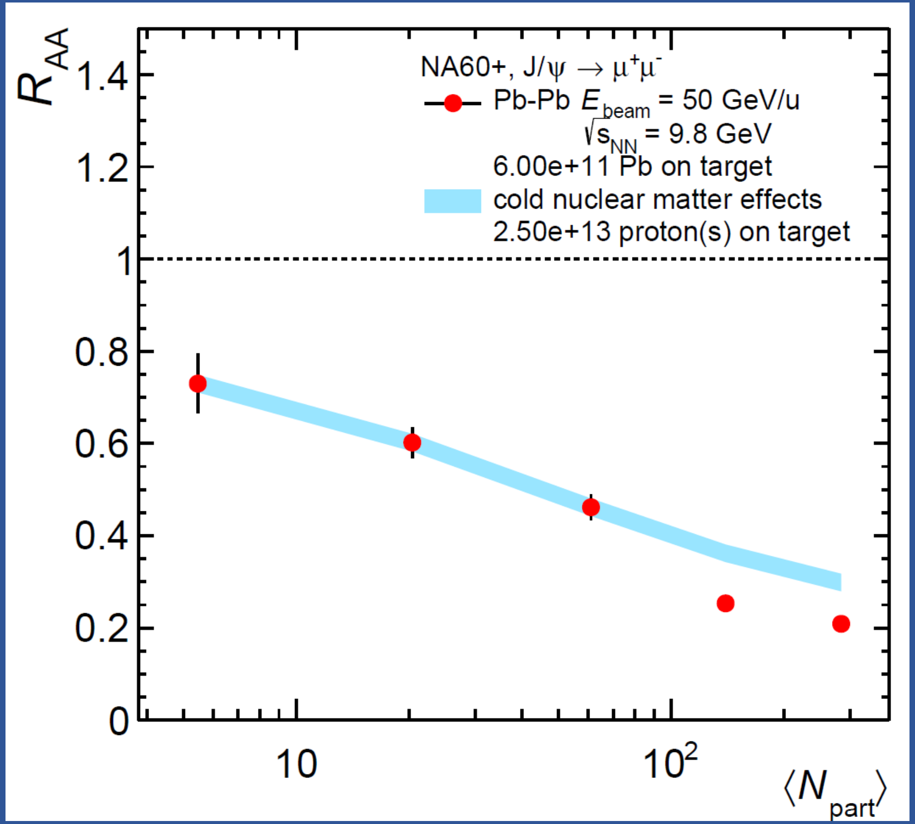


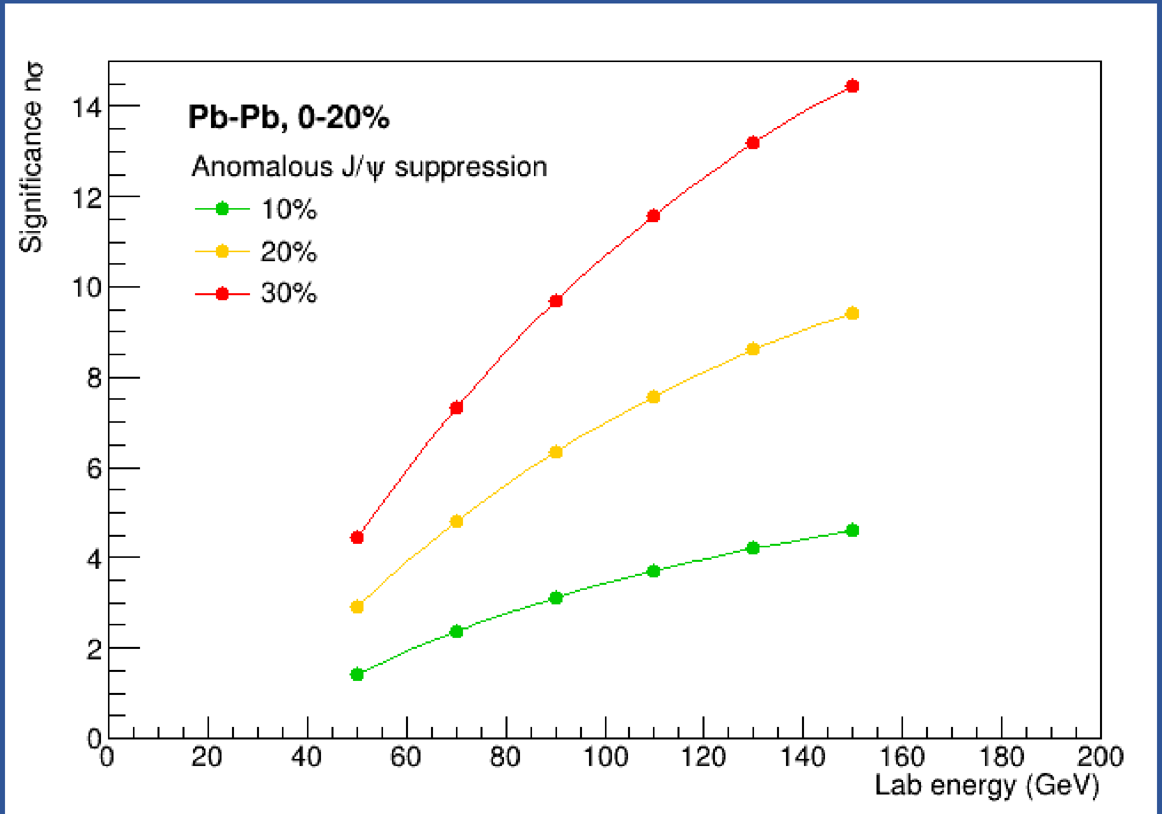
$\Lambda_c^+ \rightarrow pK\pi$



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

Physics performance – quarkonium





- ❑ Data taking with p-Be, p-Cu, p-Pb to calibrate for CNM effects
- ❑ Extrapolate A-dependence to pp, then used in R_{AA} calculations (here assume 30% suppression in 0-20% and 20-40%)

- ❑ Expected **significance** for the observation of an anomalous suppression signal
  → Study the √s-dependence of this effect

Timeline of NA60+/DiCE

2022 LOI	2025 Technical proposal	2026-2028/29 Construction	2029/30-2036/37 Data taking

- Project is part of CERN Physics Beyond Collider Initiative
- LOI released at the end of 2022 (arXiv:2212.14452) and discussed with SPSC
- **Technical proposal will be submitted in May 2025**
- Aim is taking data in 2029/30 after LHC LS3
  - 7-years running with Pb beam (one beam energy per year)
  - proton beams for reference and dedicated p-A studies

Conclusions

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

Measurements from $\sqrt{s_{NN}} \sim 6 - 17$ GeV/c extremely relevant to investigate

- ❑ Caloric curve measurement at high μ_B
- ❑ Chiral symmetry restoration
- ❑ Onset of charmonium anomalous suppression, correlation with temperature
- ❑ QGP transport properties at high μ_B
- ❑ Charm thermalization, hadronization and intrinsic charm
- ❑ Strangeness and hypernuclei production

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

ESPP: arXiv:2503.23872

Backup

Aspects relevant to ESPP

- **Fixed-target experiments** represent a key asset for the future of our field
  - Complementary to collider experiments
  - With CERN playing a complementary role with respect to lower energy facilities (FAIR)

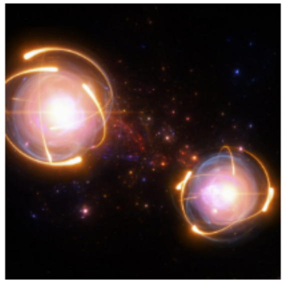
- They represent a typical example of **“scientific diversity”** which CERN management affirms to encourage and promote

- The realization of a fixed-target ion program at CERN requires the **continuing availability of heavy-ion beams in the SPS**
  - It implies an adequate level of investment for upgrade of beam lines and experimental areas (NA-CONS,…)

- **NA60+ is the first new HI experiment proposal in >15 years**
  - Technical support from CERN, already quite substantial in the design phase thanks to the PBC initiative, is a key ingredient for the success of the experiment

ECT*

About Us External Funding Activities Research



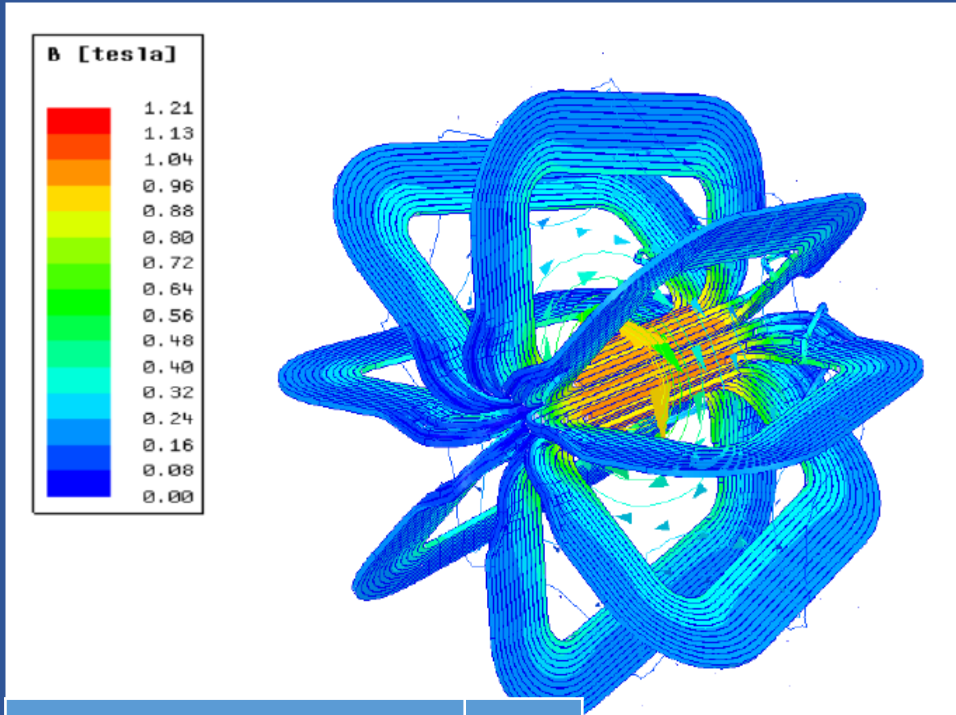
21 July 2025 — 25 July 2025

PENETRATING PROBES OF HOT HIGH-MU_B MATTER: THEORY MEETS EXPERIMENT

The study of the QCD phase diagram in the high-muB region is a key avenue toward understanding strongly interacting matter under extreme conditions. First accurate data in the collision energy region around 10 GeV, corresponding to baryo-chemical potentials of several hundred MeV, became available recently, with the completion of the Beam Energy Scan at RHIC. Hadronic and electromagnetic observables were the main addressed topics. The next breakthrough is expected with the CBM/HADES experiments at FAIR/GSI and the proposed NA60+ experiment at SPS/CERN that will take data at interaction rates larger by at least two orders of magnitude, allowing a much more accurate study of electromagnetic probes and first results on heavy-quark production. Following an exploratory workshop held at ECT* in 2021, we now aim at substantial progress in reviewing currently available results, analyzing the physics potential of the forthcoming experiments, and discussing first actual predictions for the future measurements. We will also review the progress on new detectors for high-luminosity experiments, identifying possible developments and synergies between the various projects.

More info

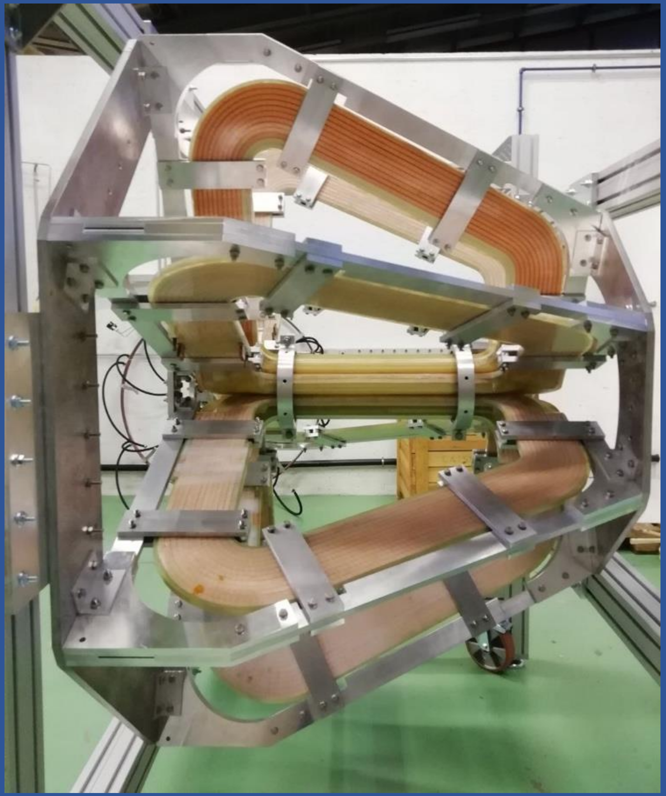
The NA60+ toroid



Warm magnet

Eight sectors,
12 turns per coil

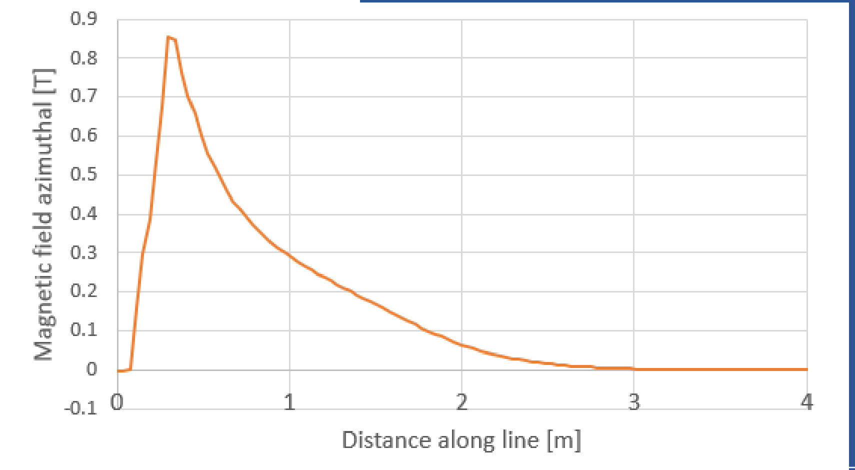
Conductor has a square copper section with a circular cooling channel in the centre



Prototype (1:5 scale)

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

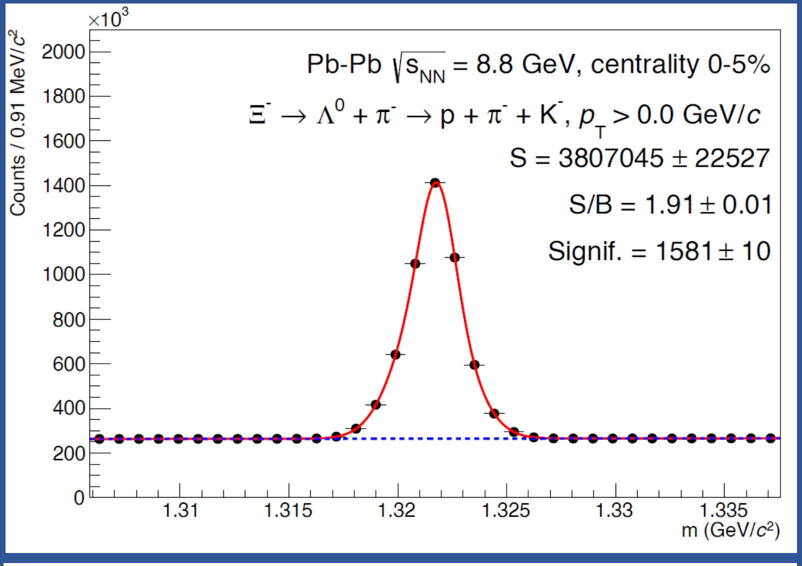
Operating Current [kA]	16.6
Amp-turns [kA]	199
Combined inductance [mH]	9.5
Resistivity Al 1100 @RT [μΩ.cm]	2.67
Length Conductor [m]	800
Total resistance [mΩ]	10.4
Dissipated power [MW]	2.8

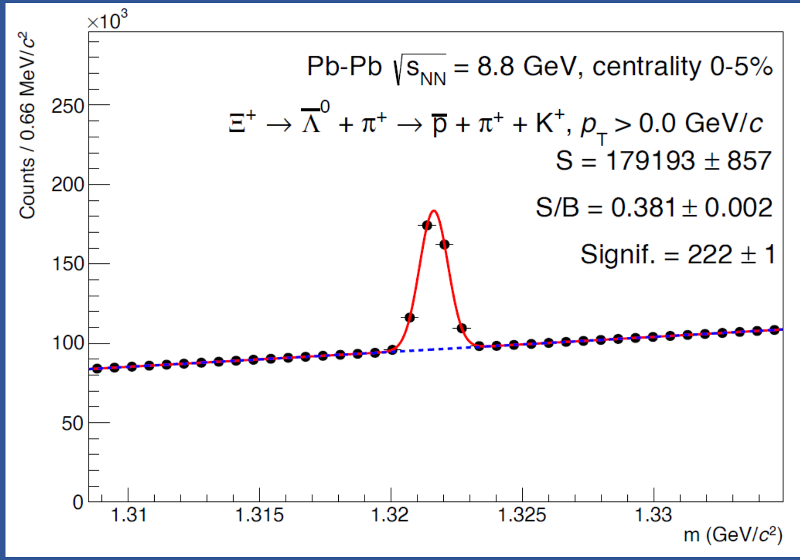


- ❑ Measurements of resistance, inductance, cooling performance and magnetic field were carried out
- ❑ B measurement
  → agreement with simulations by 3%

Design of the final toroid to be started

Strangeness measurements: hyperons





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

- Channels studied

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

and charge conjugated

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

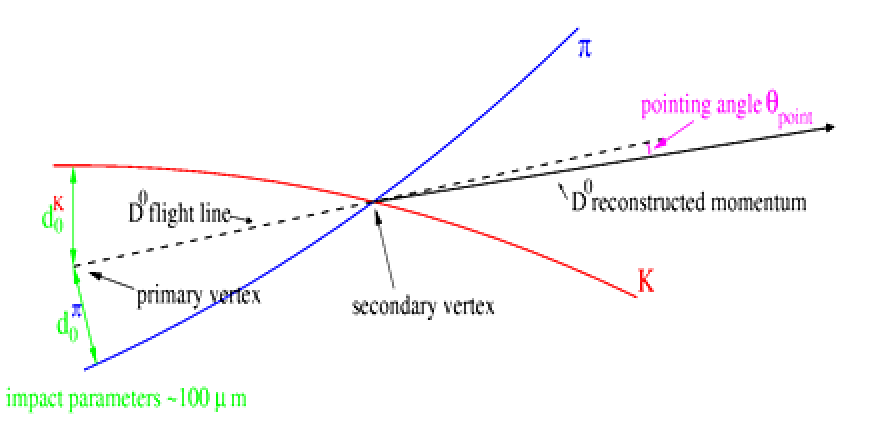
- Also ϕ → KK and K_s → $\pi\pi$ were studied

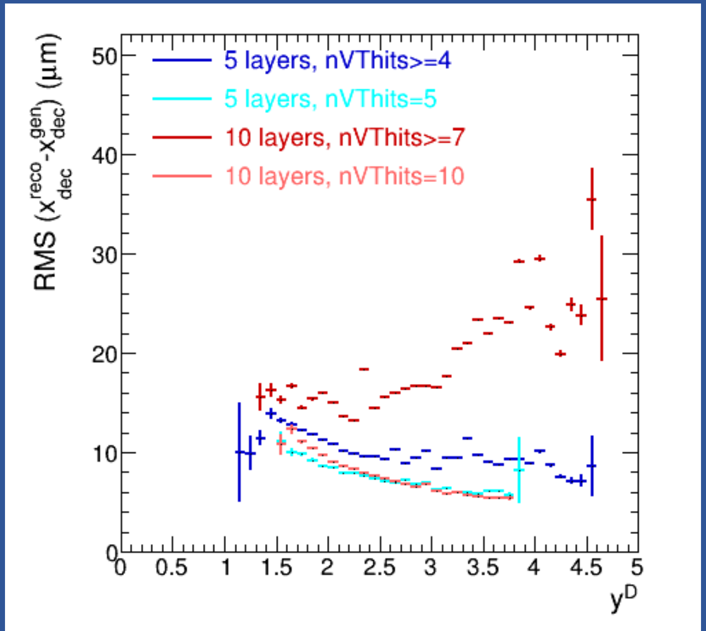
D-meson performance studies

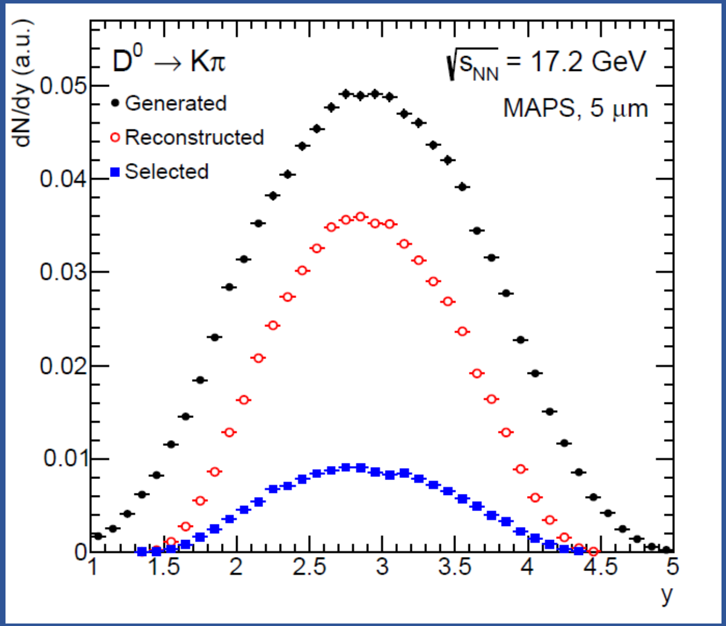
- **Fast simulation** for central Pb-Pb collisions:
  - D-meson signal simulation: p_T and y distributions from POWHEG-BOX+PYTHIA
  - Combinatorial background: dN/dp_T and dN/dy of p, K and p from NA49

  - Parametrized simulation of VT detector resolution + track reconstruction with Kalman filter

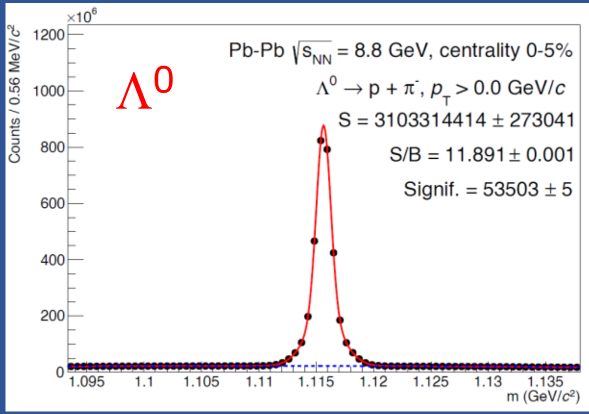
  - Reconstruct D-meson decay vertex from decay tracks
  - Geometrical selections based on displaced decay vertex topology
    - For D^0 in central Pb-Pb:
      - initial S/B ~10^{-7}
      - → after selections S/B ~0.5

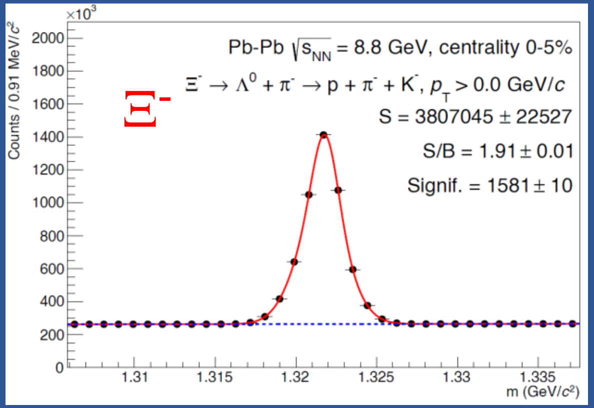


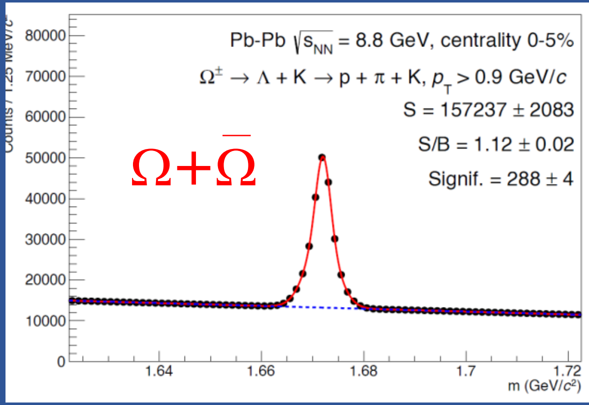




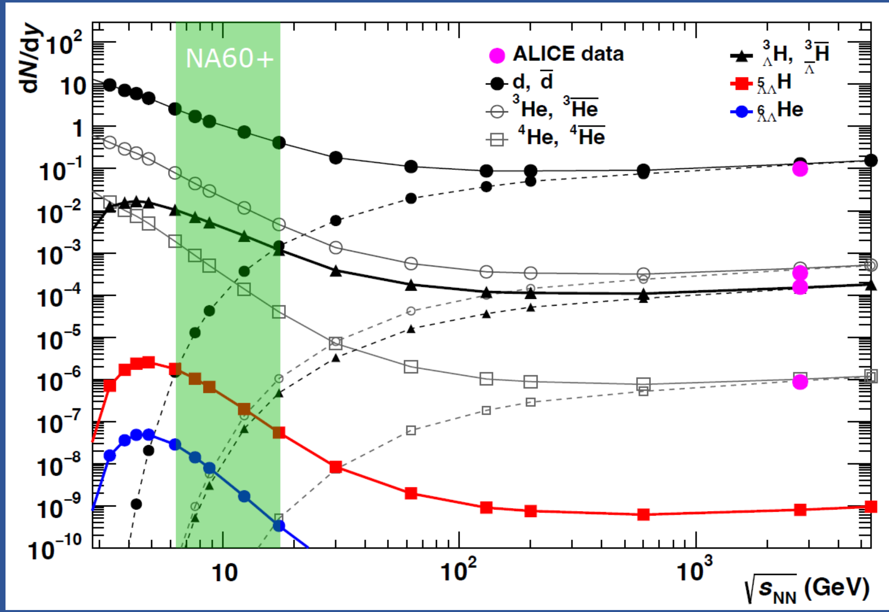
Physics performance: strangeness and hypernuclei



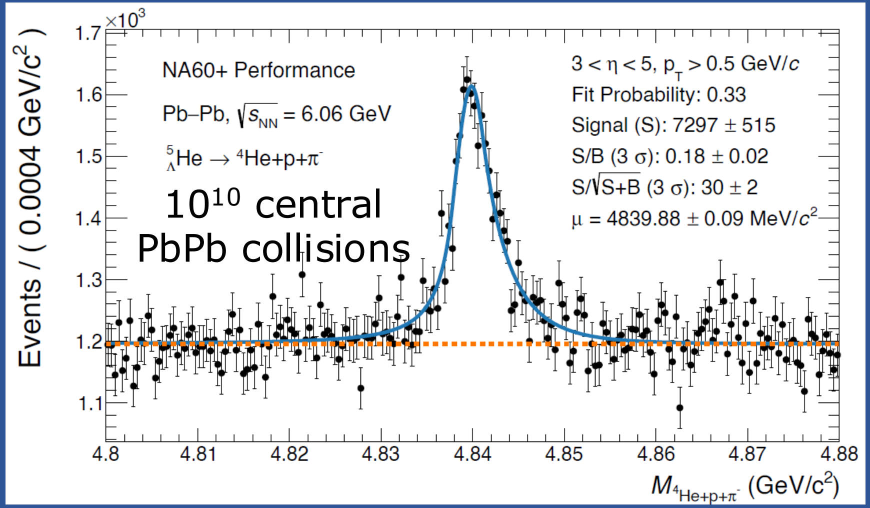




- **Topological selections with BDT** employed to **enhance the significance** of the signal
- Among the variables:
  - Product of the impact parameter of decay tracks
  - Distance of closest approach between the decay tracks
  - Decay length and the cosine of the pointing angle
- Also $\phi \rightarrow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



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

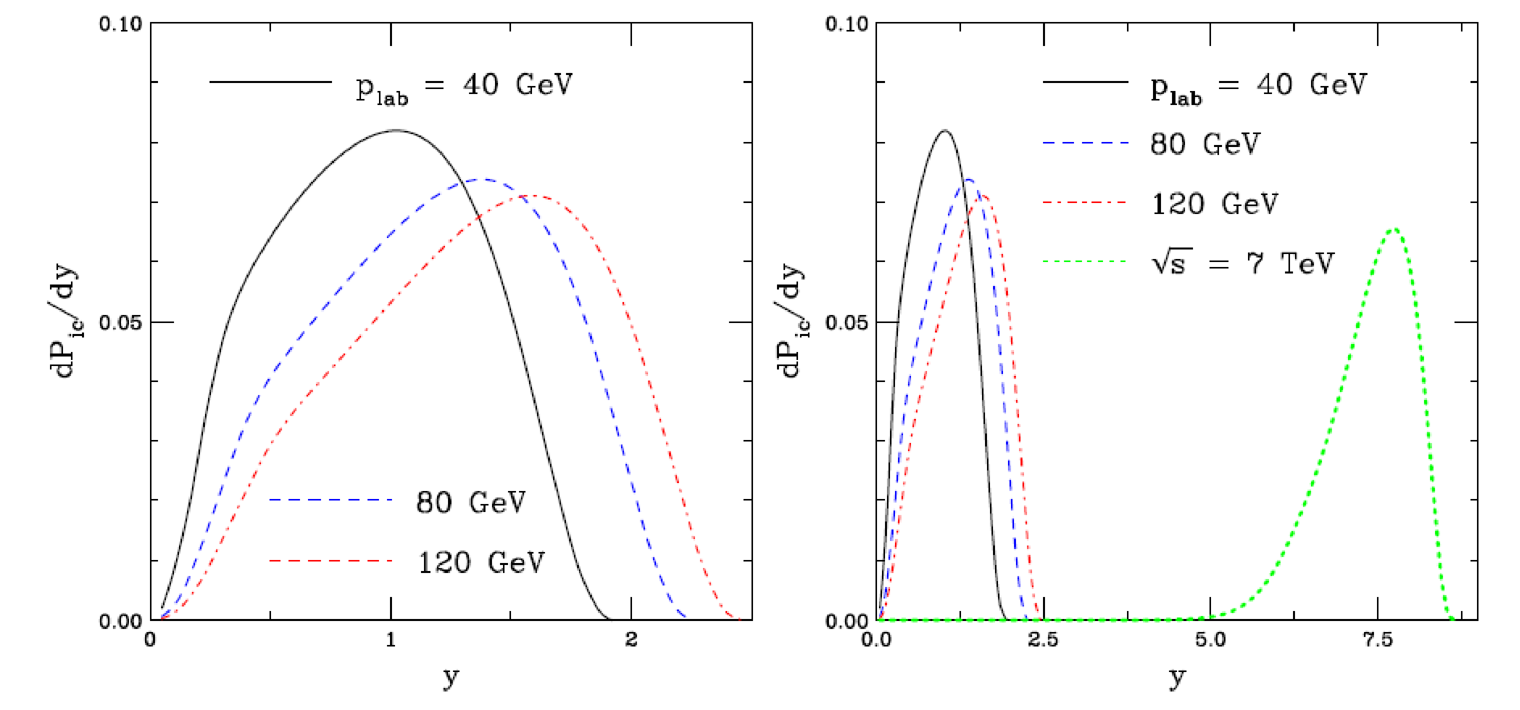


Separation of heavily ionising particles from ordinary hadrons → **size of the clusters** associated with the track

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%

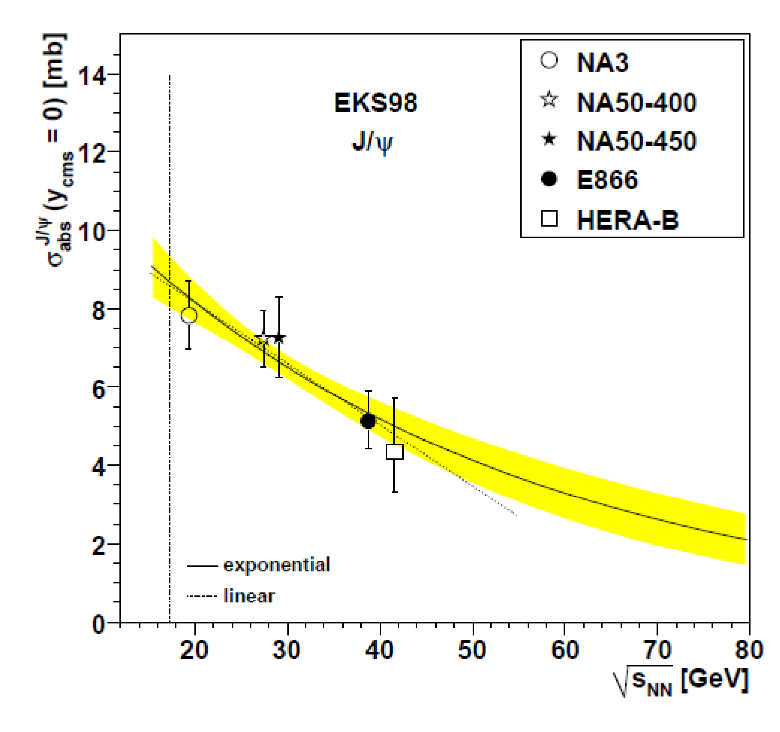
R. Vogt, PRC 103, 035204 (2021)
R. Vogt, arXiv:2207.04347

CNM effects

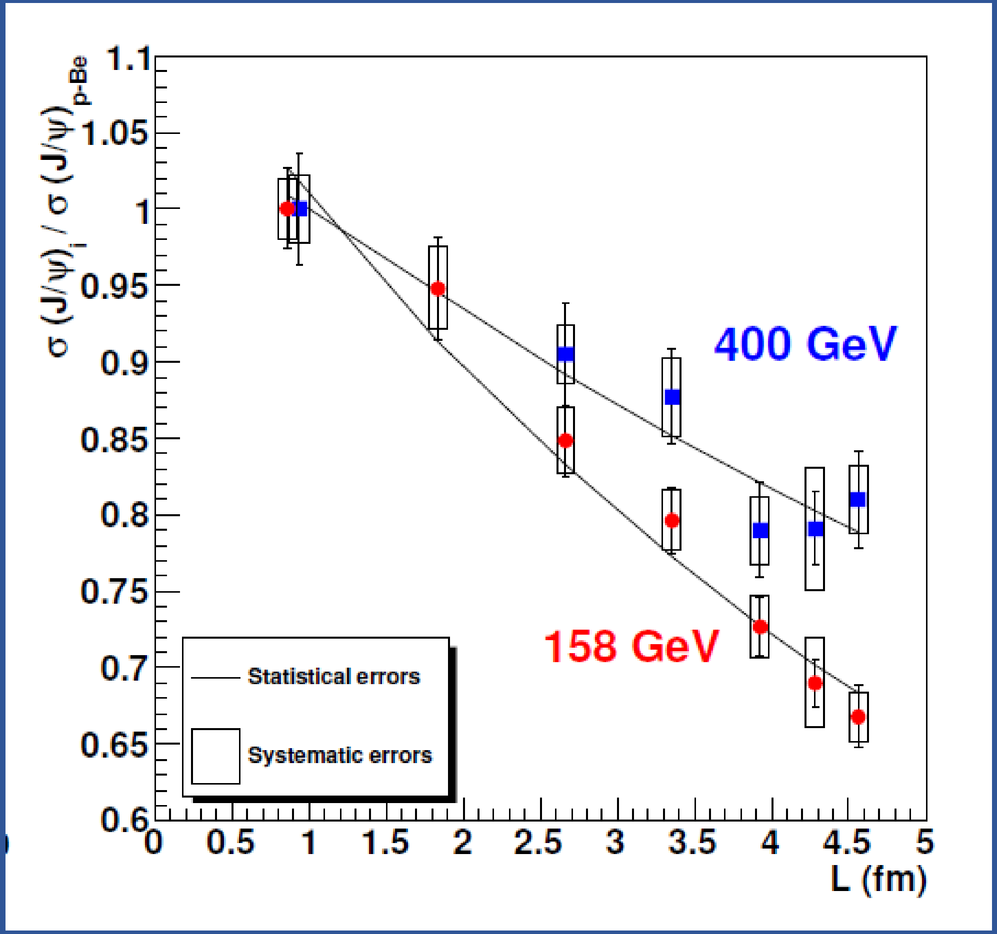
- Shadowing effects are moderate
- Dominated by nuclear absorption
  → ~30% effect in p-Pb at $\sqrt{s_{NN}}$ = 17 GeV

- **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)

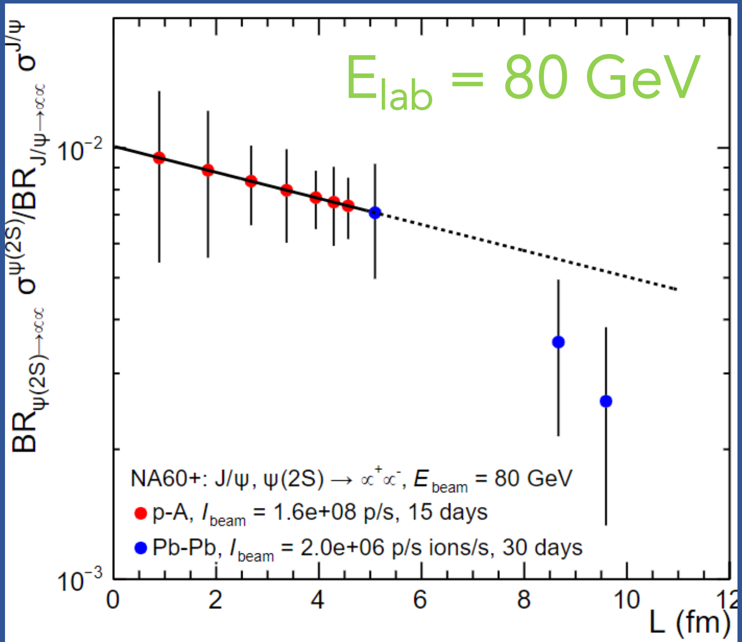
Prospects for ψ(2S) measurements at low √s

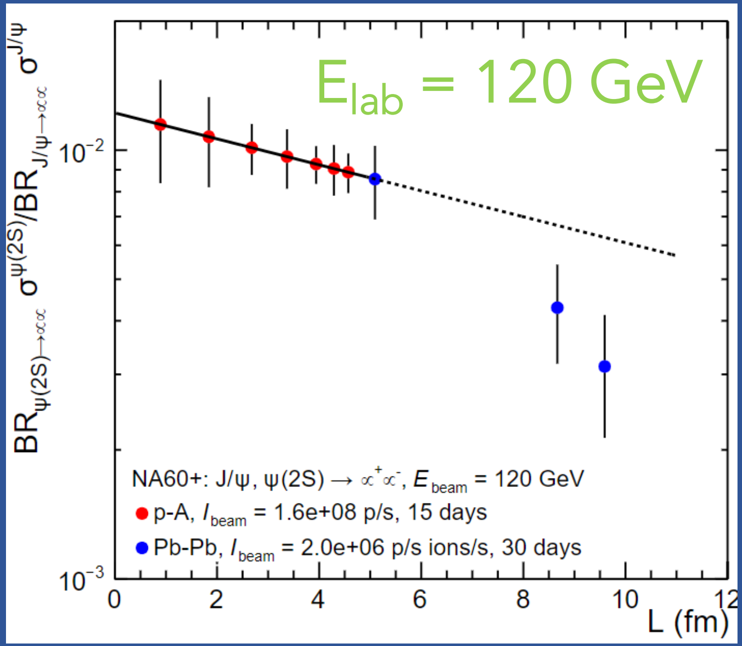
Good charmonium resolution (~30 MeV for the J/ψ) will help ψ(2S) measurements

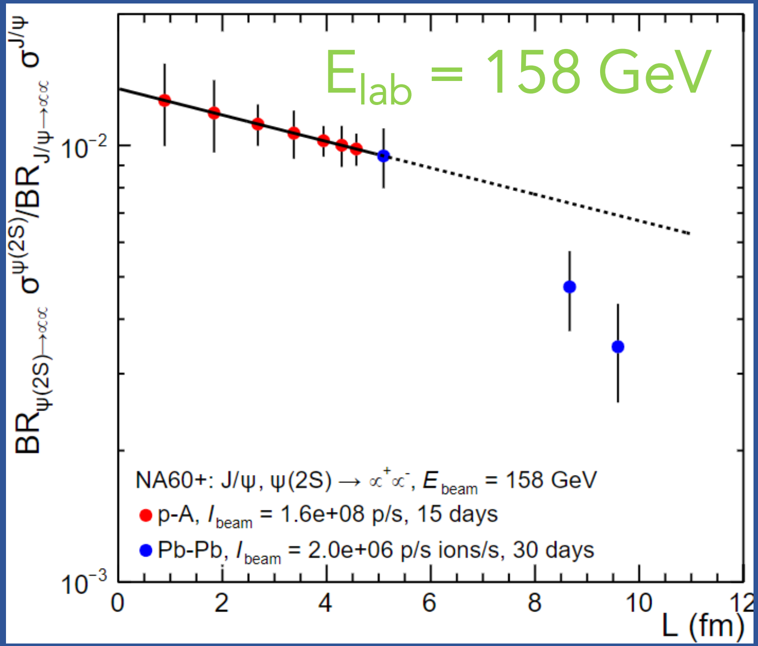
Expectations based on

- 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