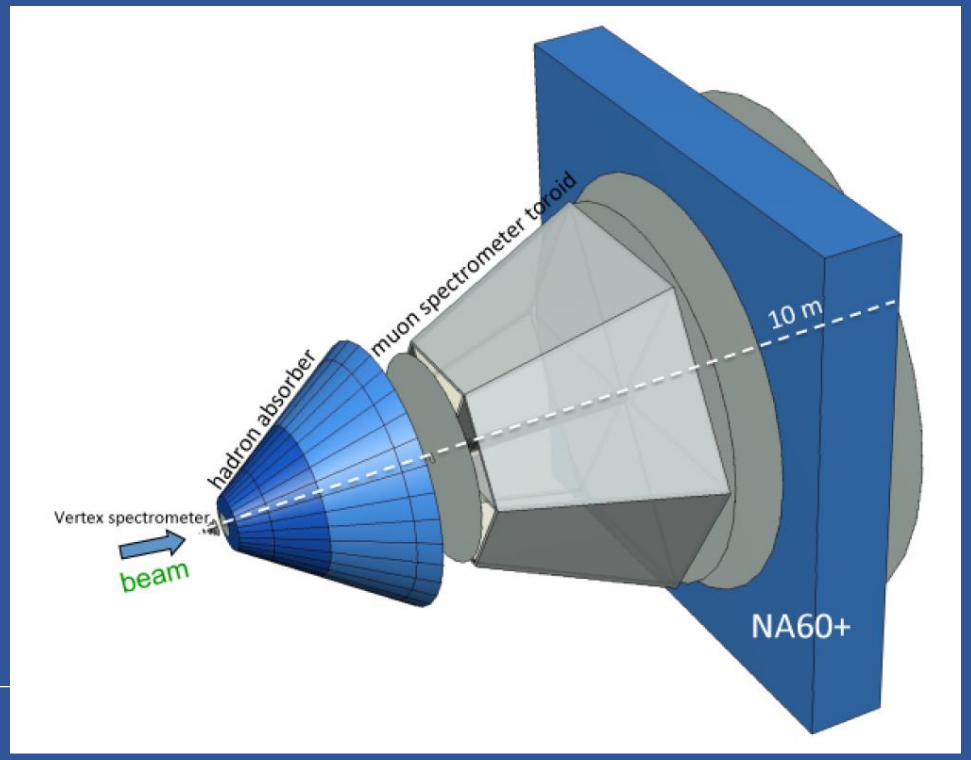
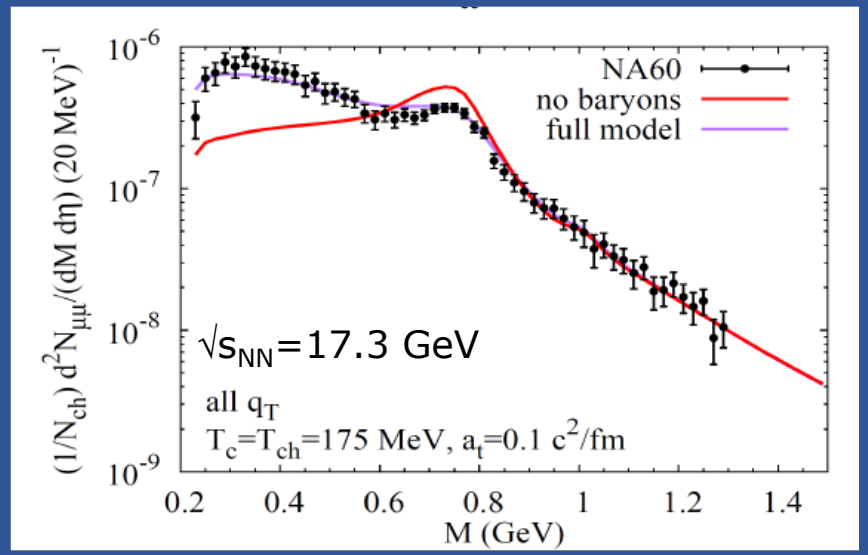
The NA60+ experiment at the CERN SPS: physics goals and prospects

E. Scomparin (INFN Torino) for the NA60+ collaboration

- Introduction: dileptons and hard probes at CERN SPS energy
- NA60+ physics goals
- Status of the experiment and physics performance studies
- Outlook

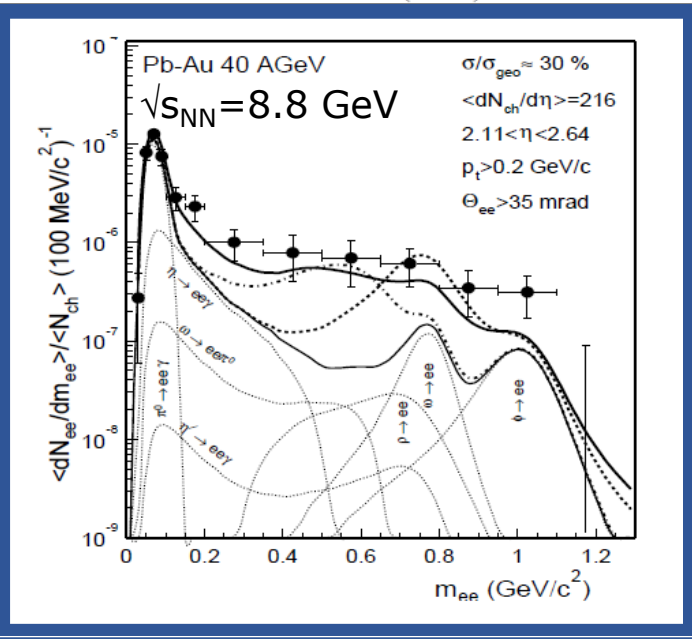


Dilepton studies at CERN SPS energy



- 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

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

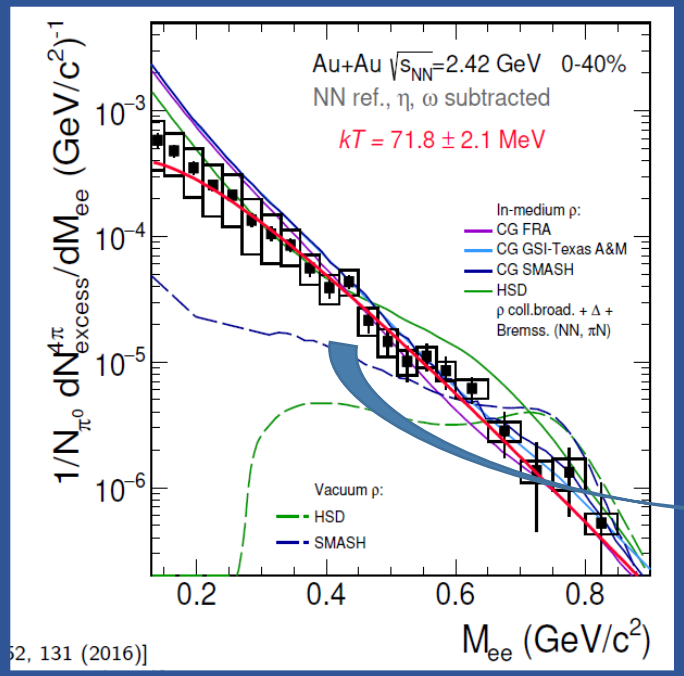


Region below top SPS energy almost unexplored

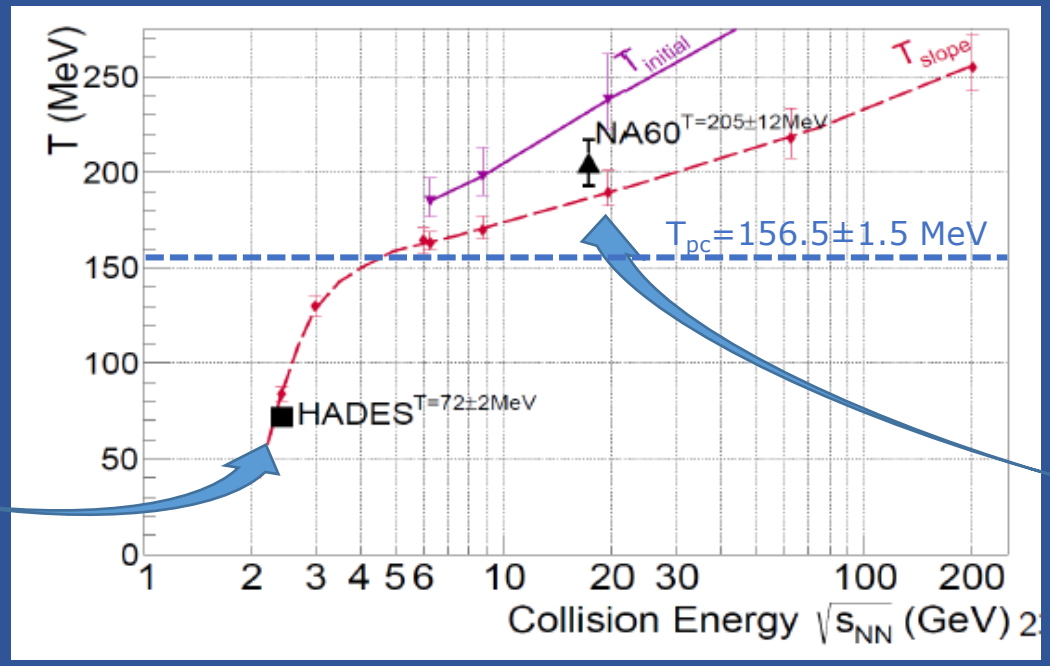
- Only a CERES measurement (low-mass dileptons at $\sqrt{s_{NN}}$=8.8 GeV)
  - Dielectron excess (central Pb-Au)
  - Indication (1.8 σ) for excess due to in-medium modifications of ρ spectral function

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

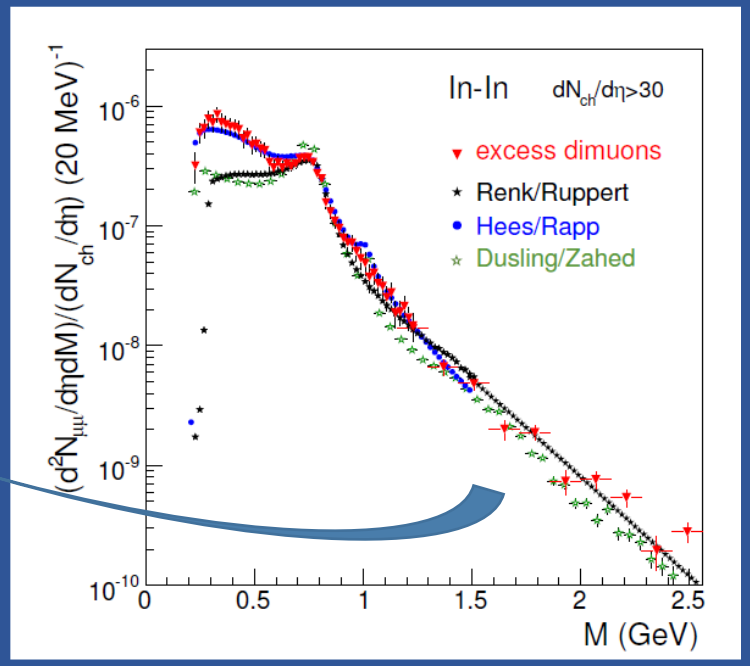
Study of dilepton production at low energy



HADES, Nature Phys. 15(2019) 1040



Adapted from T. Galatyuk



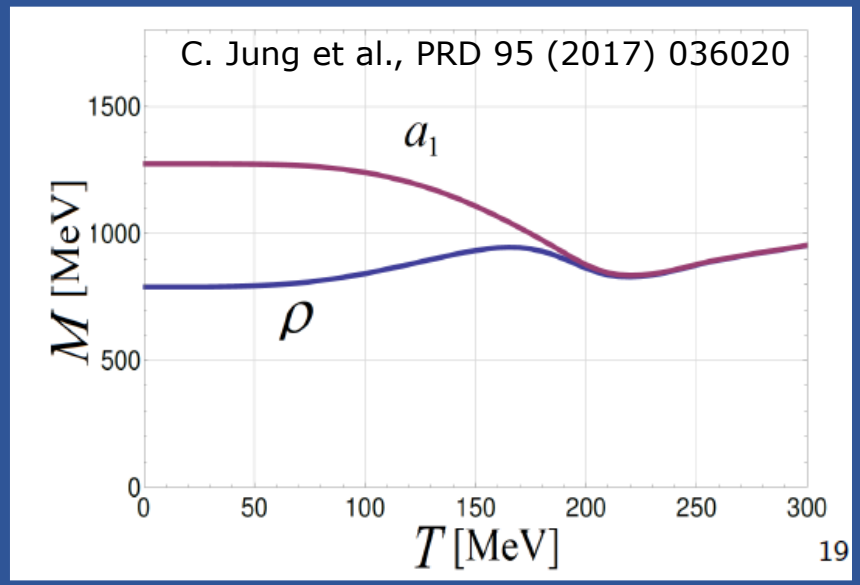
R. Arnaldi et al. (NA60), EPJC 61(2009) 711

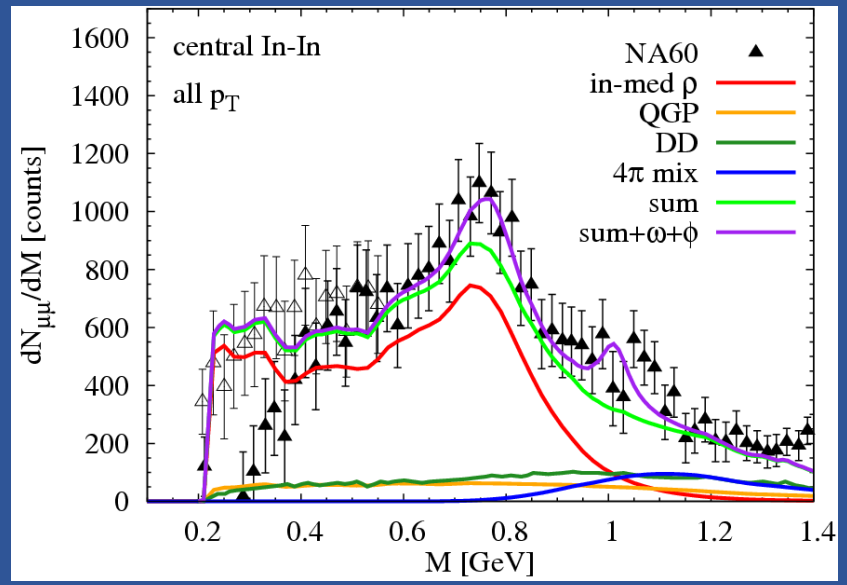
- HADES (SIS) and NA60 (SPS) have provided dilepton T_{slope} measurements
- A study of the T_{slope} evolution in $\sqrt{s_{NN}}$ ~3-20 GeV may provide accurate information on the region of the "transition temperature" associated with the change in the degrees of freedom of the system

→ Strong motivation for a measurement of a caloric curve T_{slope} vs $\sqrt{s_{NN}}$ with a few percent accuracy

Dilepton spectrum and chiral symmetry restoration

- Broadening of ρ-meson spectral function is 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 ($e^+ e^- \rightarrow$ hadrons) cross section has a dip in the a_1 mass range

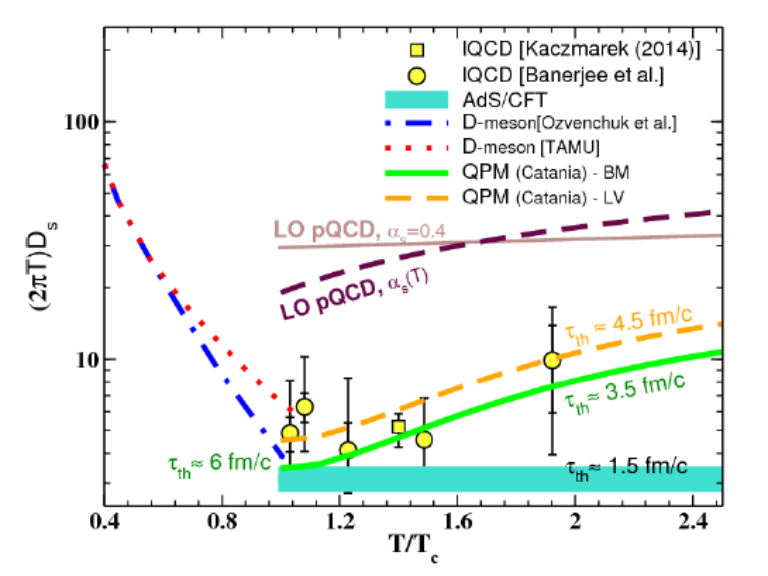
- Chiral symmetry restoration → mixing of vector (V) and axial-vector (A) correlators
  → enhancement of the dilepton rate for $m_{\mu\mu} \sim$ 1-1.4 GeV/c^2
- Low-energy measurement expected to be more sensitive to chiral restoration effects
  → (Exponential) thermal dimuon yield from QGP becomes smaller
  → Contribution from open charm becomes relatively negligible

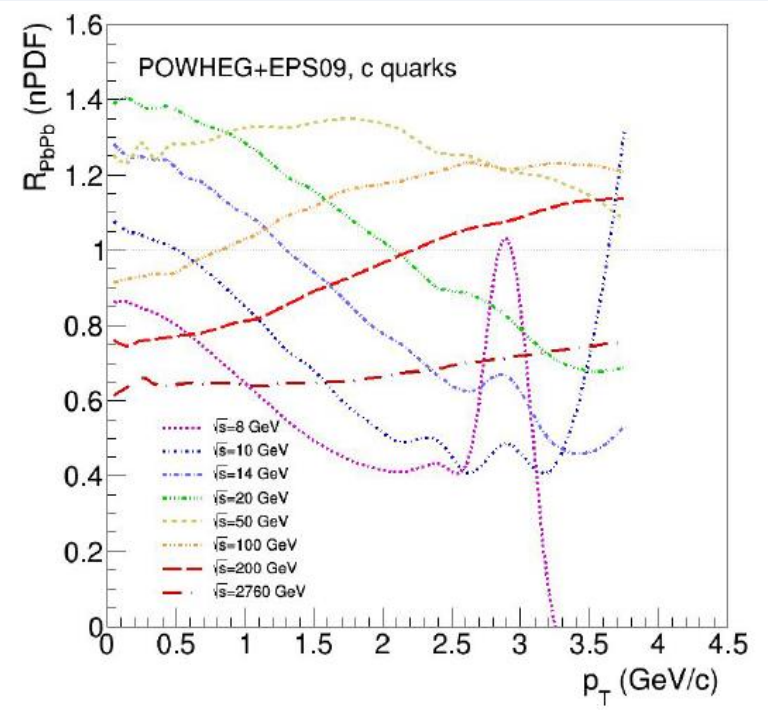
Open charm at SPS energy

- No results available below top SPS energy
- NA60 In-In dimuons $\sqrt{s_{NN}}$ =17.3 GeV
  → σ_{cc} = 9.5 ±1.3±1.4 μb

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

- D-meson p_T distributions and azimuthal anisotropy
  → Time spent in QGP and hadronic phase varies as a function of energy → important constraints for the estimate of the charm diffusion coefficient D_s
  → Charm quark thermalization in a short-lived QGP
- D_s^+,Λ_c
  → Hadronization studies (quark recombination)
- Charm cross section
  → Potentially sensitive to chiral symmetry restoration, due to reduction of DD threshold
- Charm production in pA
  → Sensitive to nPDFs
  → Q^2 ~ 10–40 GeV^2 and $0.1<x_{Bj}<0.3$ (p_T<3 GeV/c) (from anti-shadowing to EMC region)





Charm production at SPS energy is an uncharted territory!

Charmonium at SPS energy

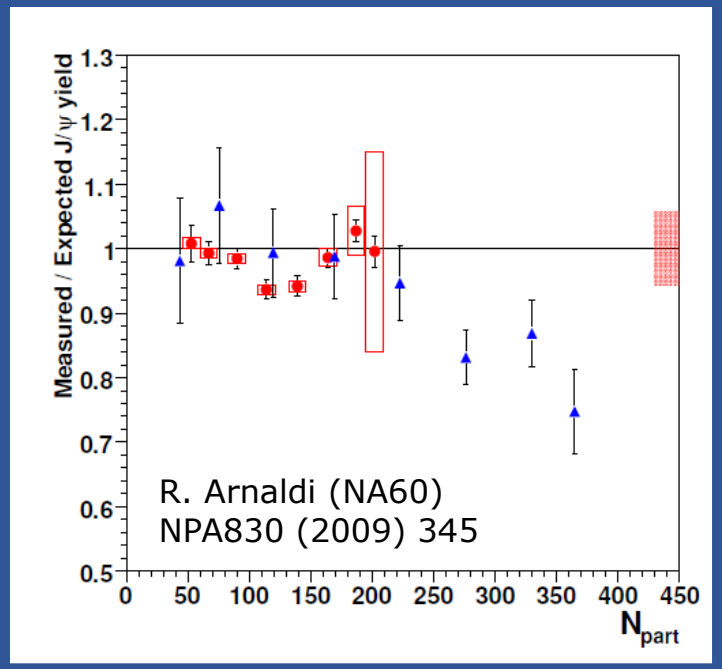
- The only "hard probe" studied at the SPS

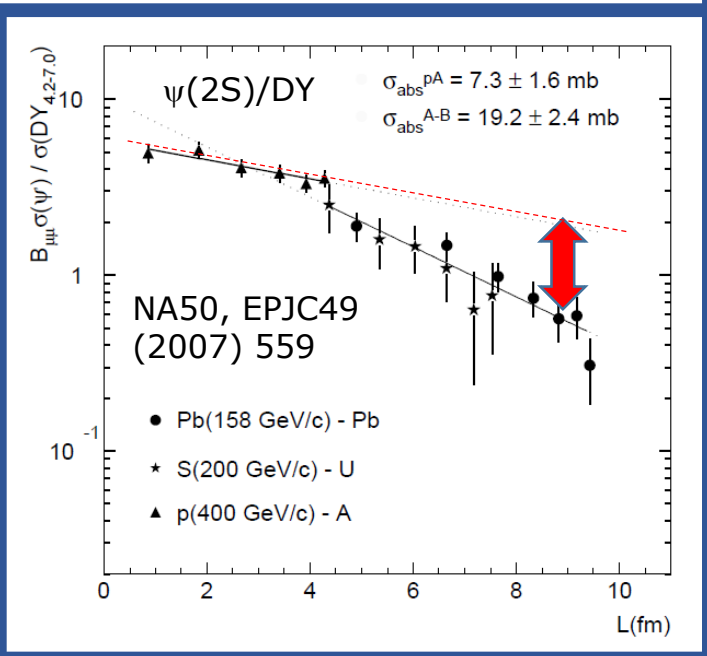
- J/ψ
- 30% suppression for central Pb-Pb events at top SPS energy, after accounting for CNM effects
  → Compatible with suppression of more weakly bound χ_c and $\psi(2S)$ states decaying to J/ψ

- $\psi(2S)$
- Exhibits strong suppression already in peripheral Pb-Pb collisions, up to a factor ~5 for central collisions
  → sensitivity to the hadronic phase

- Energy scan towards low SPS energy
  → Detect suppression threshold and correlate with T via thermal dimuons
  → Strong variations of the ratio $J/\psi/D$ at deconfinement threshold ?

Quarkonium physics not studied below top SPS energy!

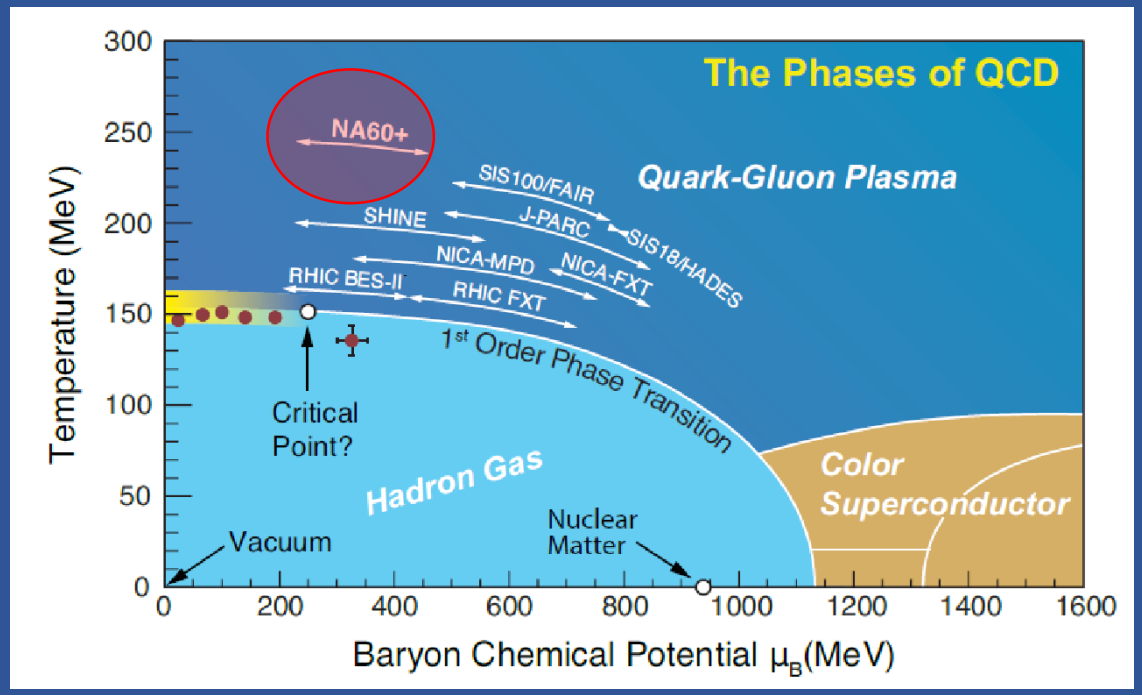




NA60+

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)

Facility/ Experiment	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Interaction rate	Dileptons	Charm
SPS NA60+	~6–17.3	440–220	>MHz	yes	yes
SPS NA61/SHINE	~5–17.3	540–220	5 kHz	no	yes
SIS100 CBM, HADES	2.7–5.5	740–510	>MHz	yes	yes
RHIC STAR	3–19.6	710–200	~1 kHz	yes	yes
NICA MPD	4–11	620–320	~7 kHz	yes	yes
Nuclotron BM@N	2.3–3.5	800–660	20–50 kHz	(yes)	no
J-PARC-HI DHS, D2S	2–6.2	840–480	>MHz	yes	(yes)

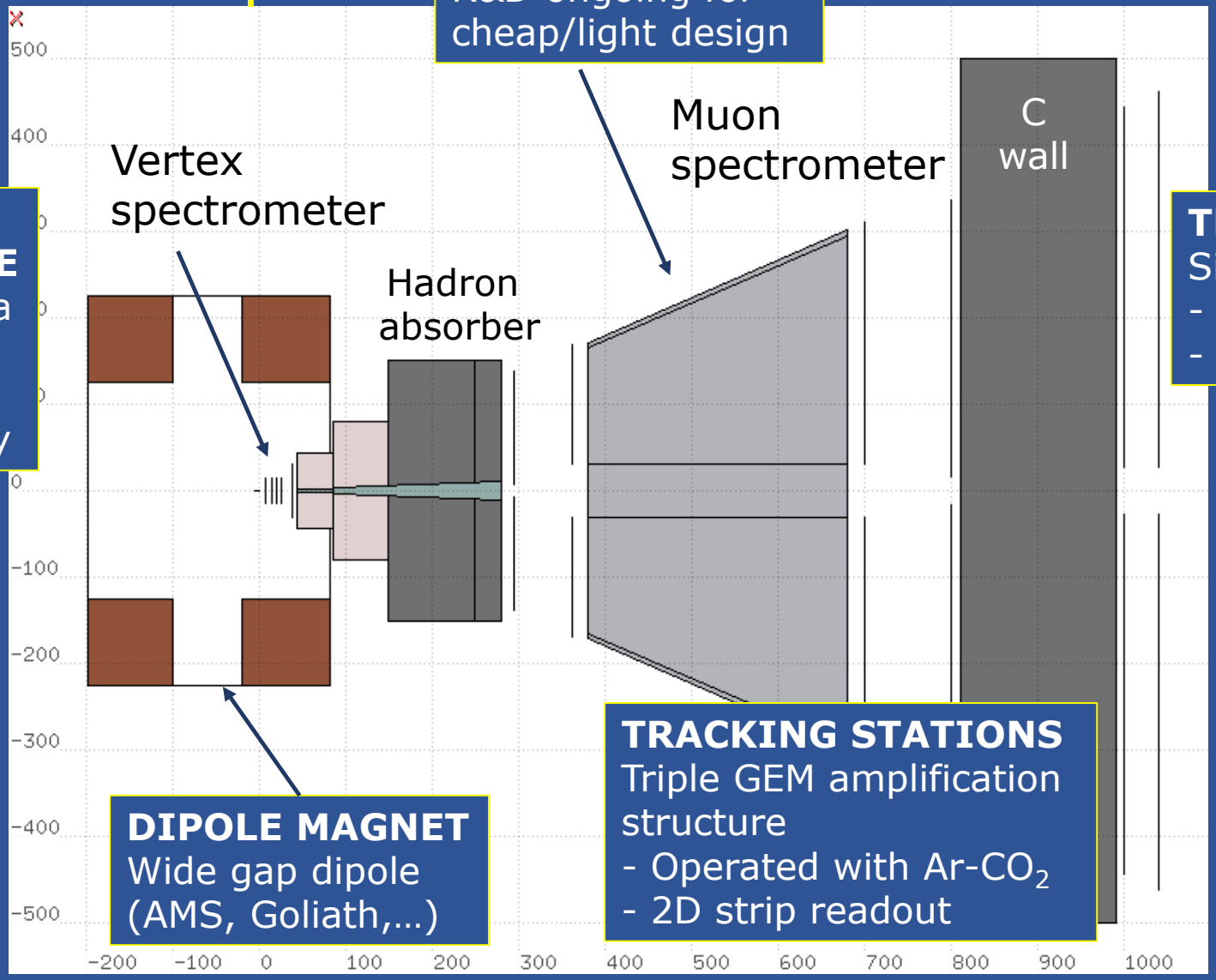


- Main features
  - Coverage of a very wide μ_B region
  - Precision physics: possibility of reaching very high interaction rates (>MHz)
  - Complete physics reach for dileptons and charm
  - Energy range complementary to FAIR/GSI (and J-PARC)

NA60+ set-up

TOROID MAGNET
R&D ongoing for cheap/light design

VERTEX TELESCOPE
- Large area MAPS
- Stitching technology



TRIGGER STATIONS
Single gap RPC
- R/O on both sides
- Orthogonal strips

DIPOLE MAGNET
Wide gap dipole (AMS, Goliath,…)

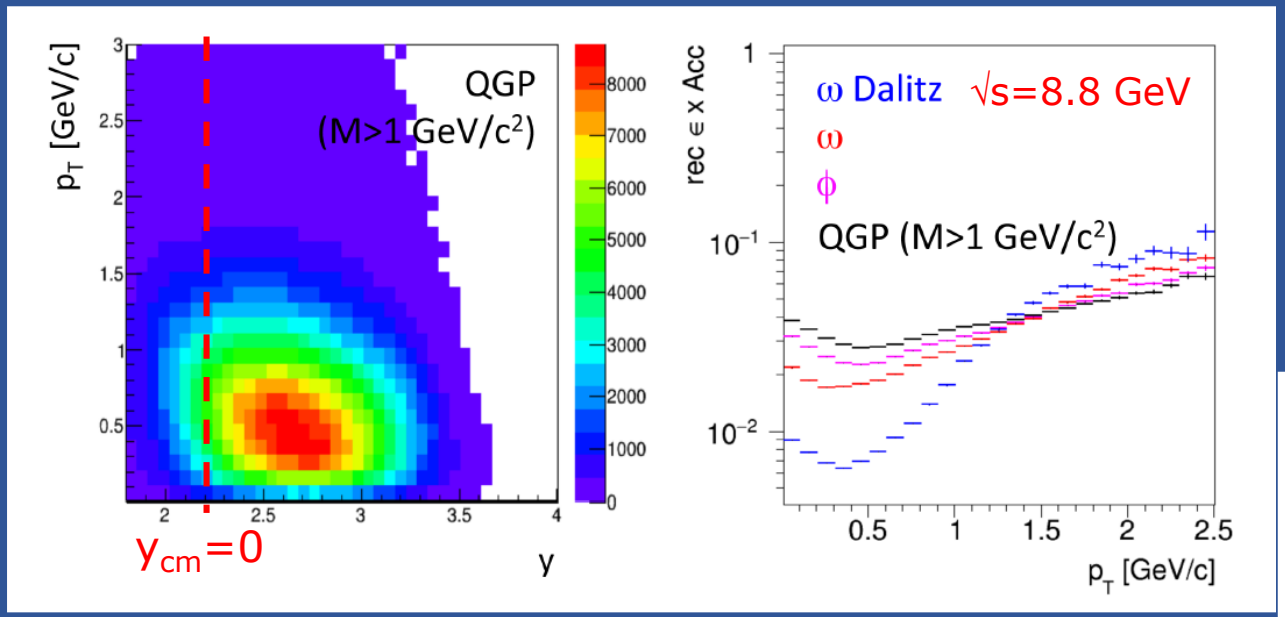
TRACKING STATIONS
Triple GEM amplification structure
- Operated with Ar-CO_2
- 2D strip readout

Muon spectrometer length will be varied, to cover mid-rapidity at different collision energies

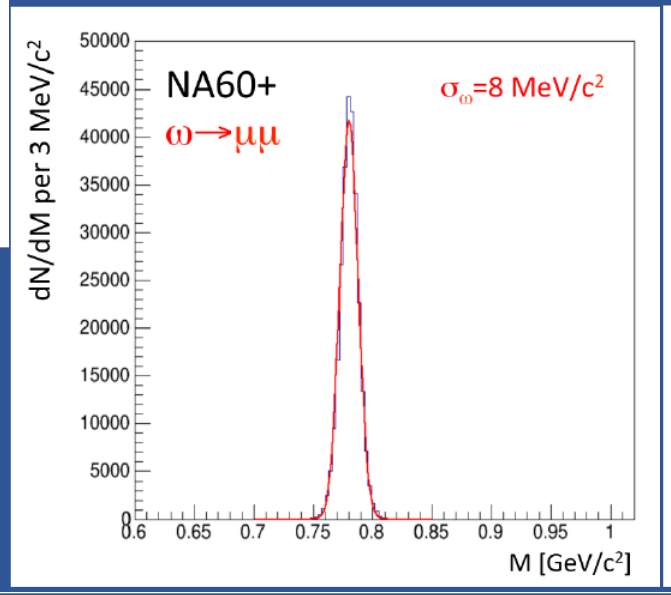
(for details on the set-up see G. Usai, poster presentation #208)

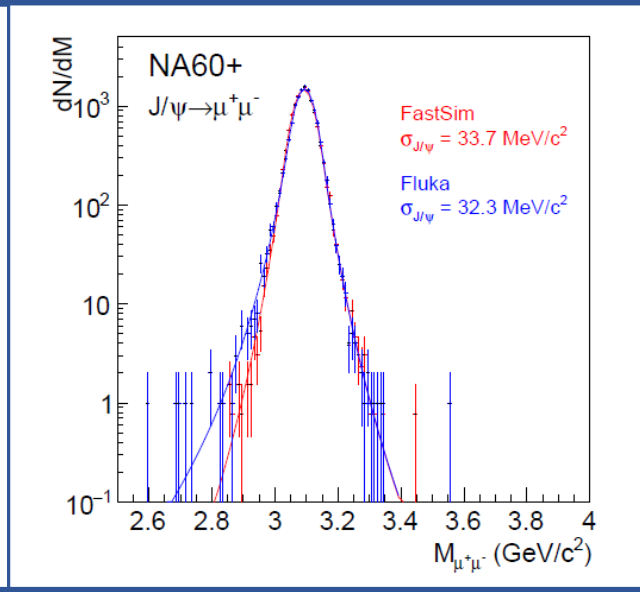
NA60+: muon detection performance

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



- 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

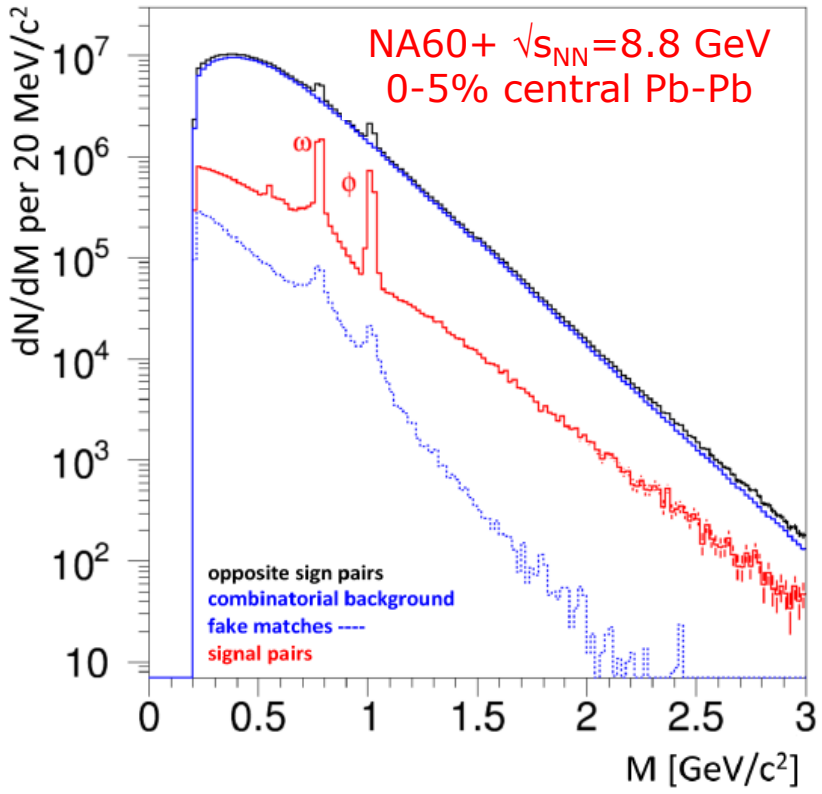


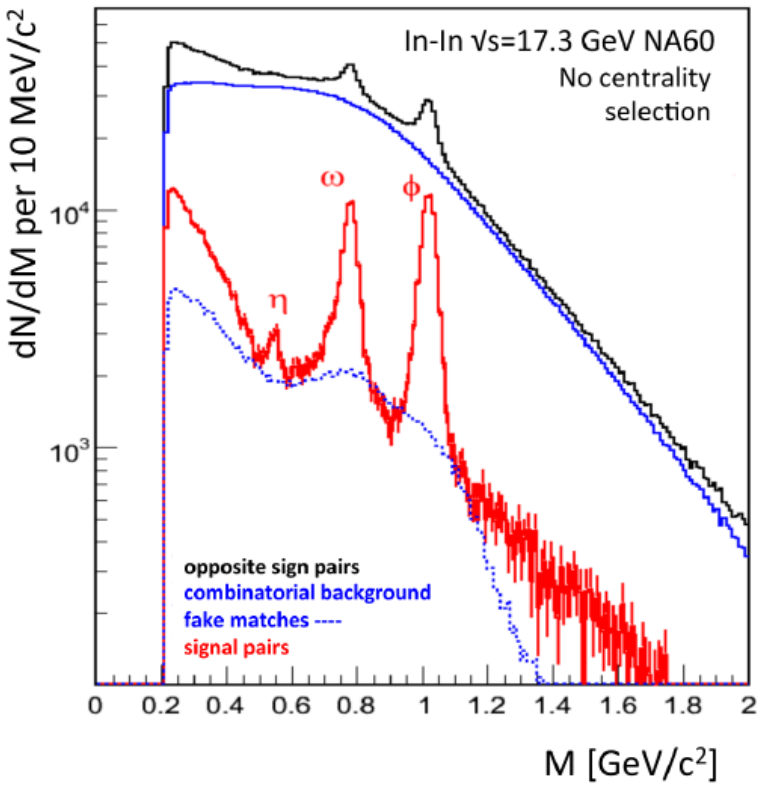


The mass resolution for resonances varies from <10 MeV (ω) to ~30 MeV (J/ψ)

(factor >2 improvement with respect to NA60)

Dilepton spectrum



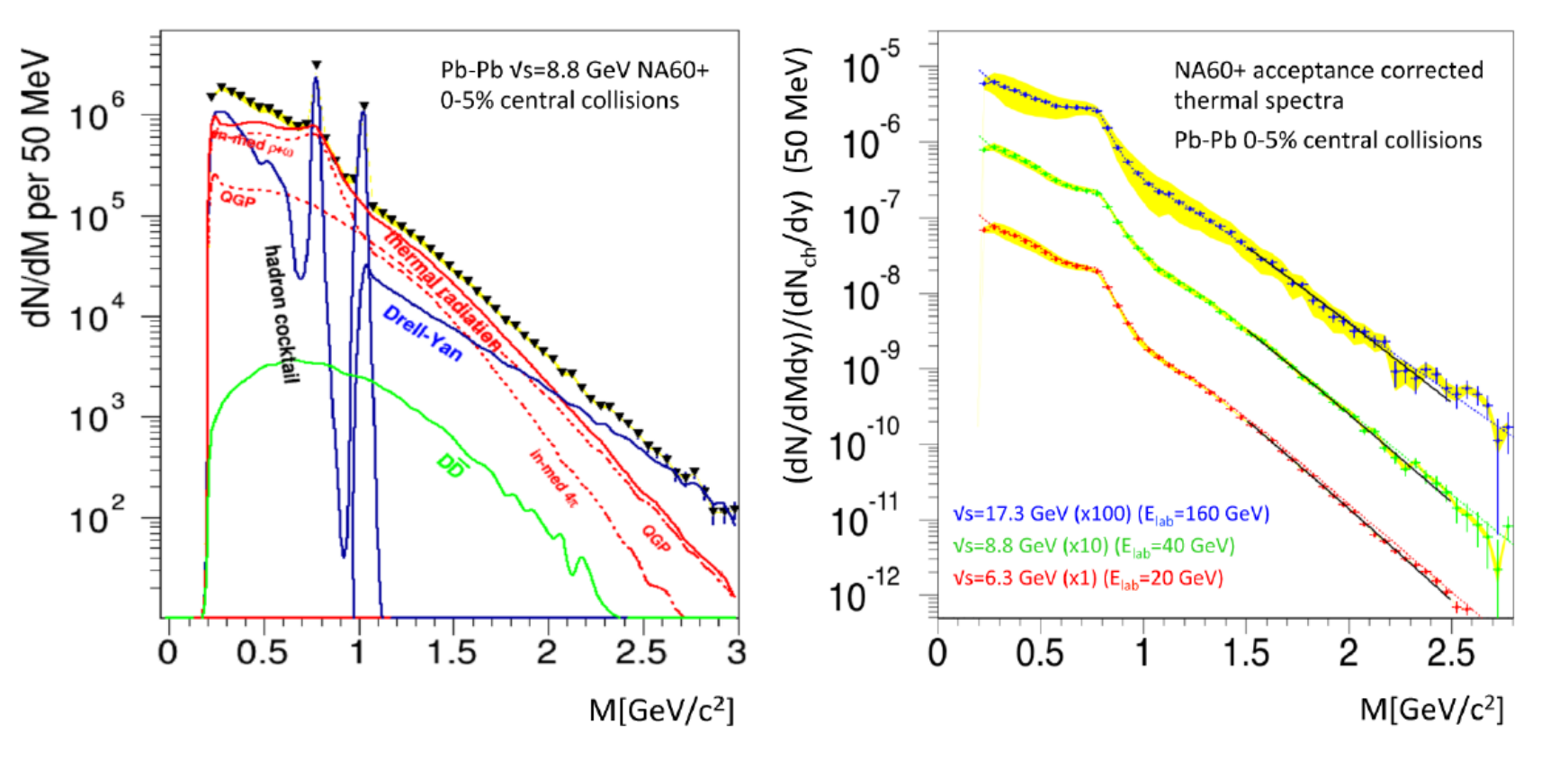


- Thermal dimuon distributions from Rapp et al., PLB753 (2016) 586
- Hadron cocktail from NA60 and statistical model (Becattini et al., PRC73 (2006) 044905)
- Drell-Yan and open charm from PYTHIA
- Combinatorial background: input spectra from NA49 measurements

- 2×10^7 reconstructed central Pb-Pb (1 month data taking at interaction rate ~1 MHz)
- S/B~1/18 at M=0.6 GeV/c^2
- Combinatorial background subtracted with 0.5% uncertainty

Factor ~100 improvement with respect to NA60 (min. bias)!

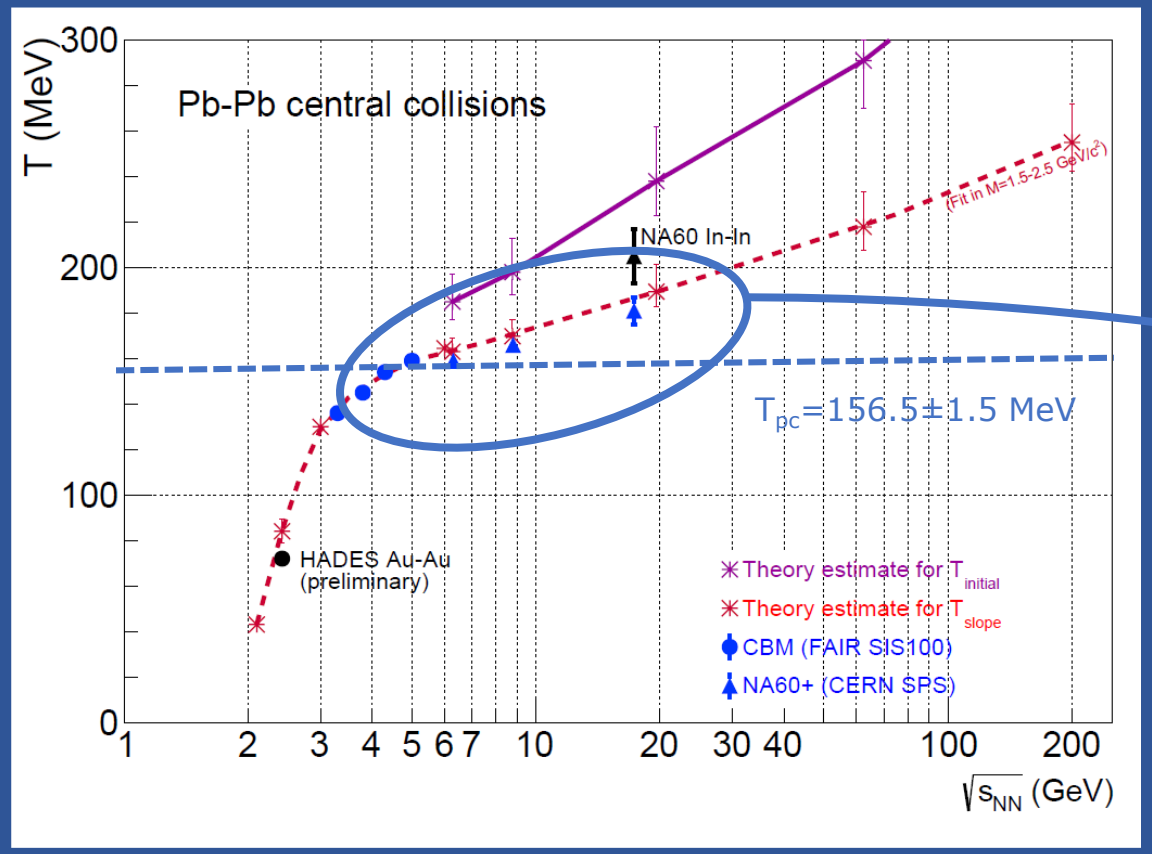
T_{slope} measurement



- Thermal radiation yield
  - Dominated by ρ contribution at low mass
  - Accessible up to M=2.5-3 GeV/c^2
- Drell-Yan contribution
  → to be also estimated via p-A measurements

- Acceptance-corrected signal spectra fitted with $dN/dM=M^{3/2}\exp(-M/T_s)$ in the interval 1.5<M<2.5 GeV/c^2

T_{slope} measurement



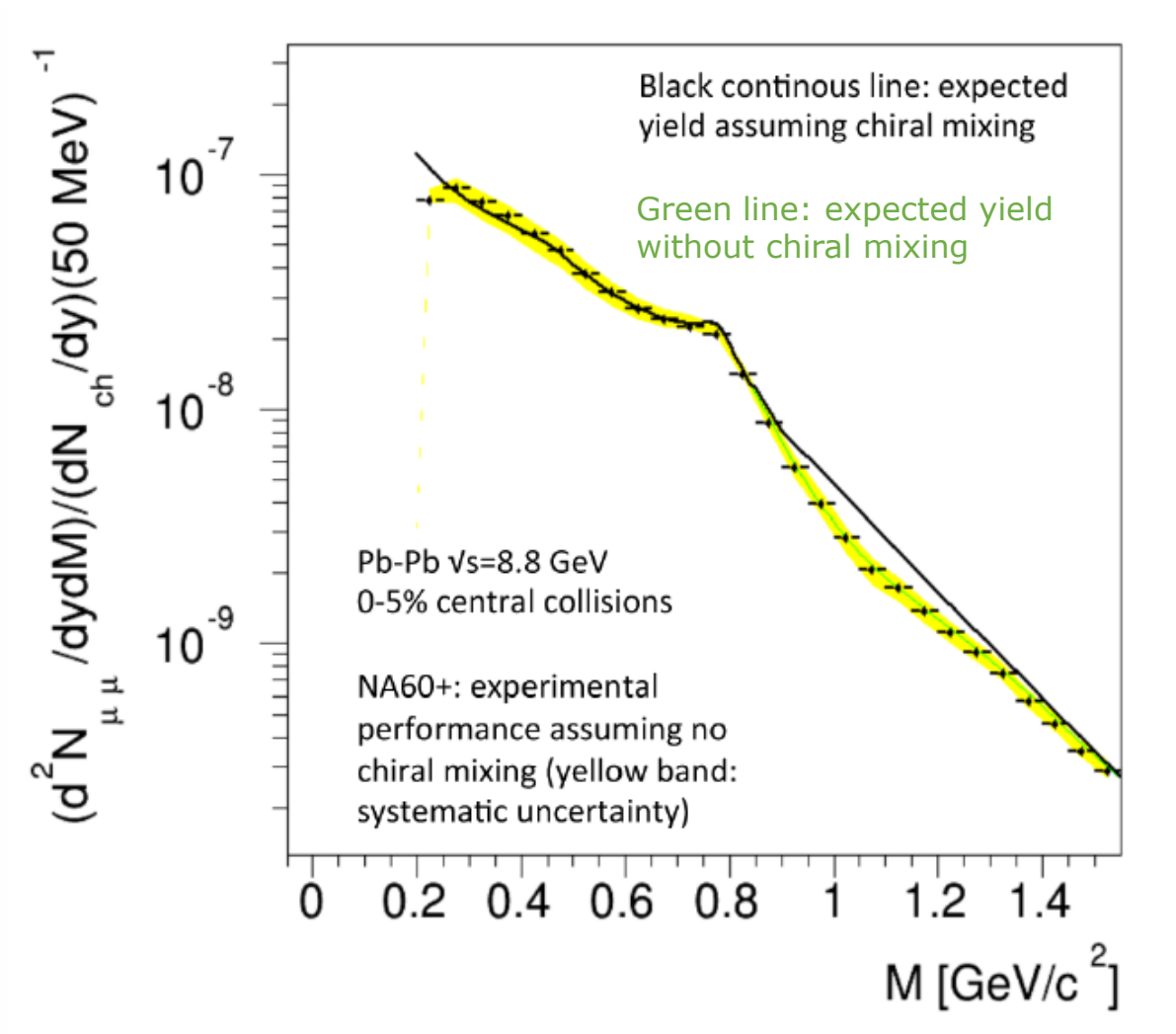
T_{slope} values from thermal yields in $1.5<M<2.5$ GeV/c²

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!

Sensitivity to chiral symmetry restoration



- Simulations carried out by considering
  - No chiral mixing (dip in $1<M<1.4$ GeV/c^2)
  - Full ρ-a_1 chiral mixing

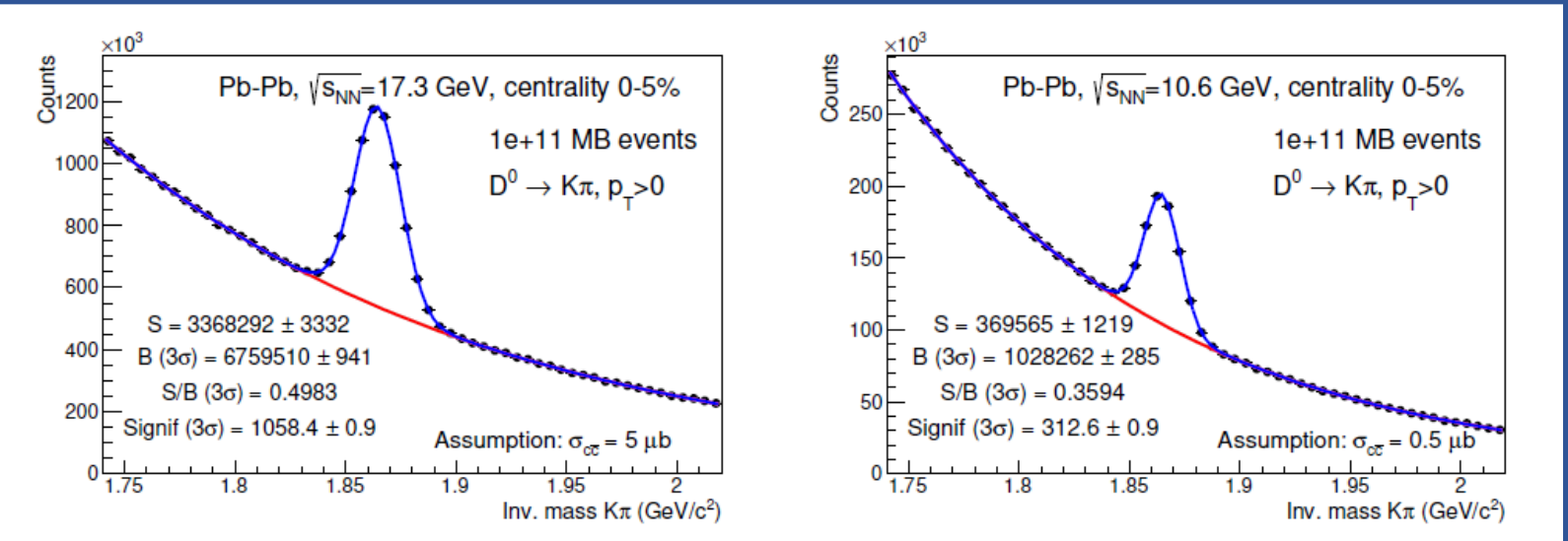
(modeled from Rapp, vanHees, PLB753 (2016) 586)

- A 20-30% enhancement is expected in case of full mixing

With the foreseen accuracy of the measurement the effect can be clearly detected!

Hard probes: open charm

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



- $D^0 \to K^+\pi^-$ (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±60 MeV
  - S/B~10^{-7}, enhanced with kinematic and geometric selections

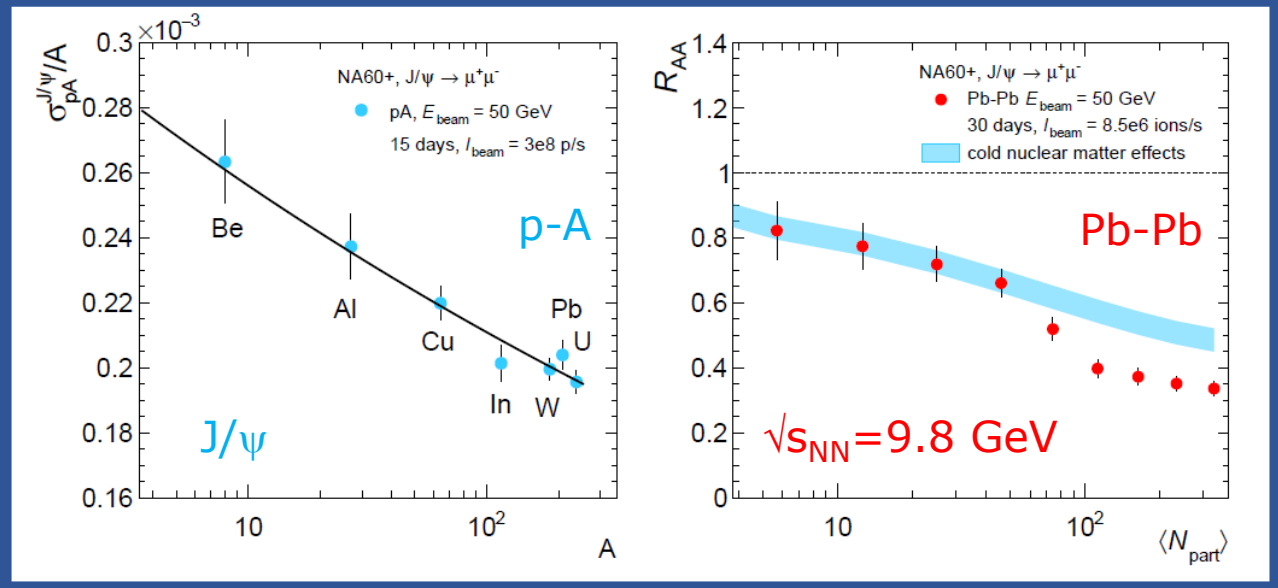
(equivalent to 30 days data taking at 150 kHz)

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

} in progress

Good prospects for a first low-energy measurement of charm in nuclear collisions!

Hard probes: charmonium

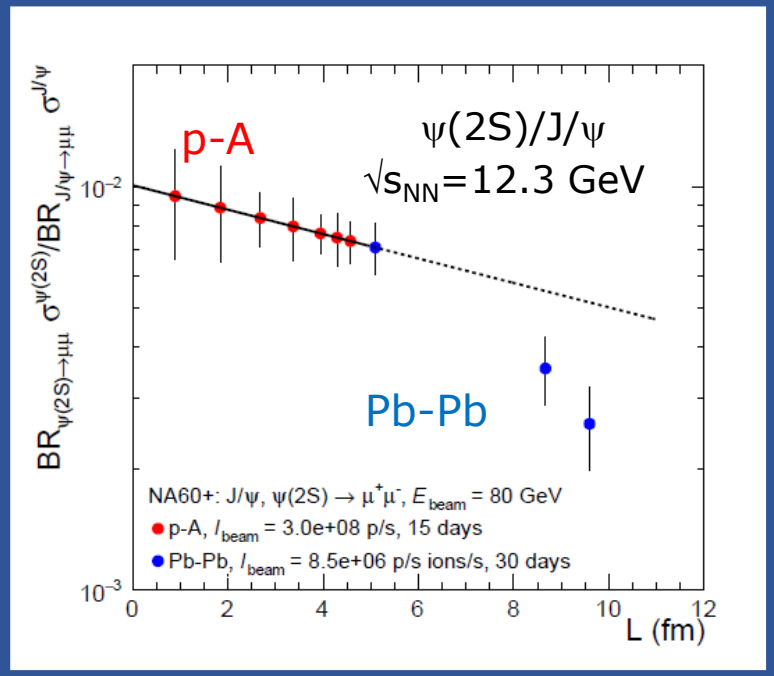


- p-A measurement → calibrate CNM effects (assume same effect as measured by NA60 at $\sqrt{s_{NN}}$=17.3 GeV)
- Extrapolate CNM effect to Pb-Pb and compare with a scenario where anomalous suppression sets in at N_{part} ~50 and reaches 20% (was ~30% at $\sqrt{s_{NN}}$=17.3 GeV)
- Assume 30 days of Pb 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 → assume factor ~2 stronger suppression for ψ(2S)

Look for the onset of ψ(2S) suppression



NA60+: project development

- Project started in 2011-2013 (Italian Research Ministry funding)
- Selected and followed (2017-2020) as one of the CERN future projects in the frame of the "Physics beyond Colliders" initiative → see QCD WG report, arXiv:1901.04482
- Contribution to the European Strategy document → arXiv:1812.07948

The Town Meeting also observed that the CERN SPS would be well-positioned to contribute decisively and at a competitive time scale to central open physics issues at large baryon density with proposals like NA60+. In particular, the CERN SPS will remain also in the future the only machine capable of delivering heavy ion beams with energies exceeding 30 GeV/nucleon, and the potential of investigating charm production and rare penetrating probes at this machine is attractive.

Conclusions of the
CERN Town Meeting 2018: Relativistic Heavy Ion Collisions

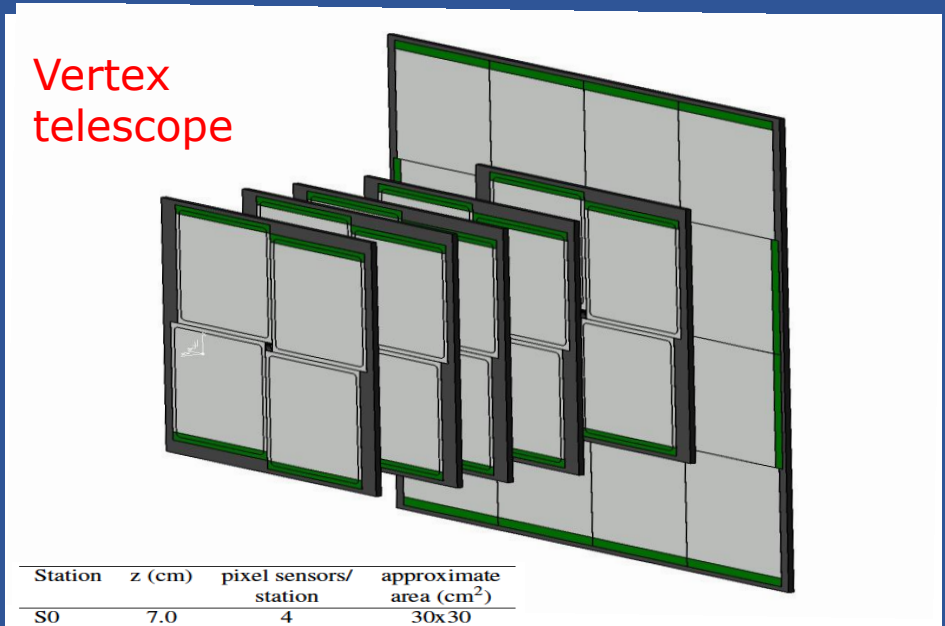
https://indico.cern.ch/event/746182/

A coherent and complementary "hot & dense QCD program" at the SPS brings valuable and unique contributions in the exploration of the QCD phase diagram.

Conclusions of the
EPPSU (European Strategy for Particle Physics) symposium (Granada 2019) for Hot & Dense QCD

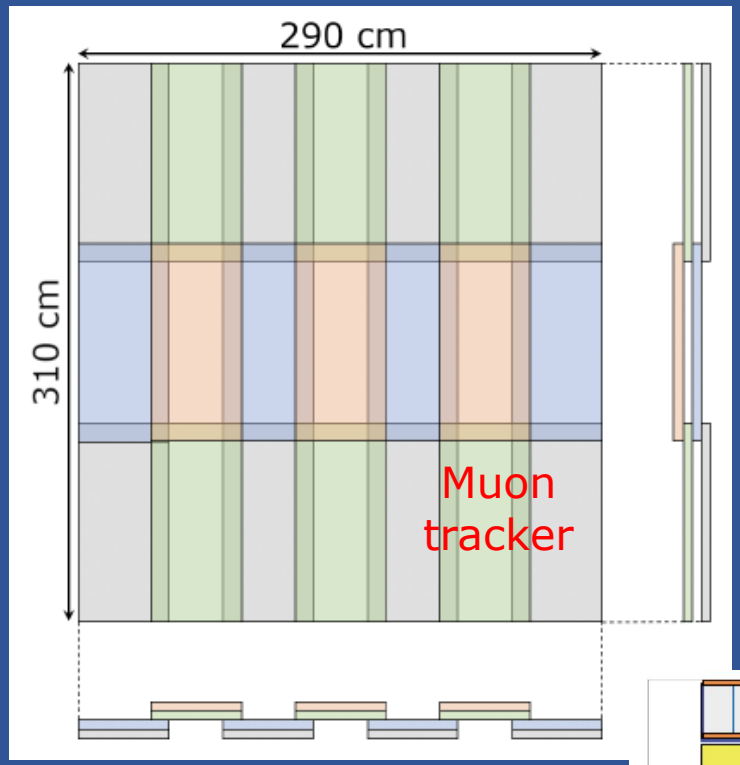
2019: Expression of Interest to the SPSC → http://cds.cern.ch/record/2673280
Next step → Submission of a Letter of Intent for NA60+ to the SPSC

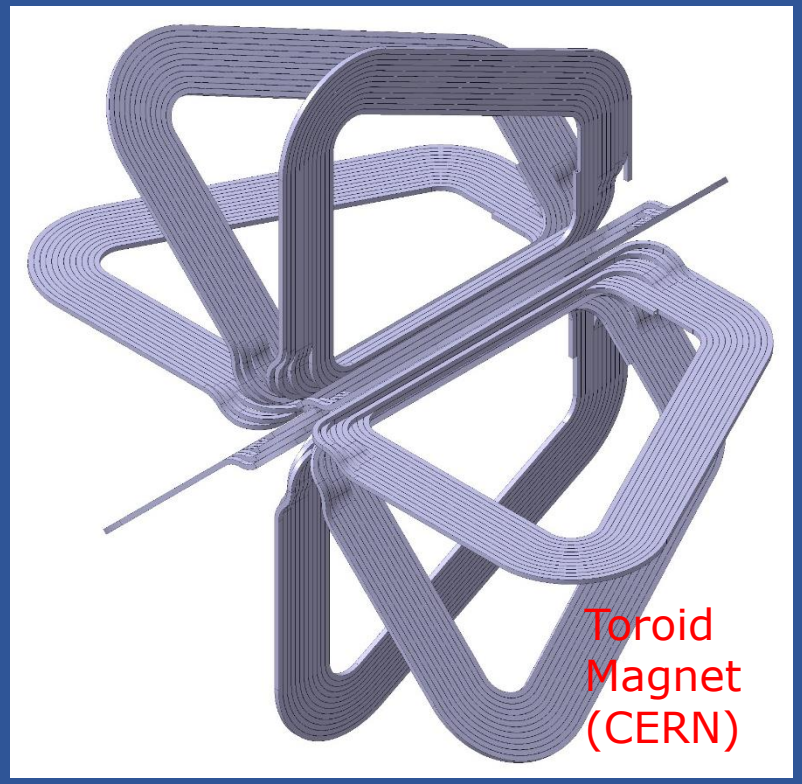
Ongoing detector studies

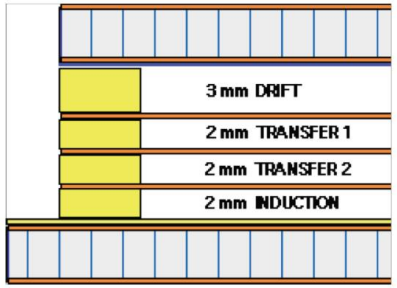


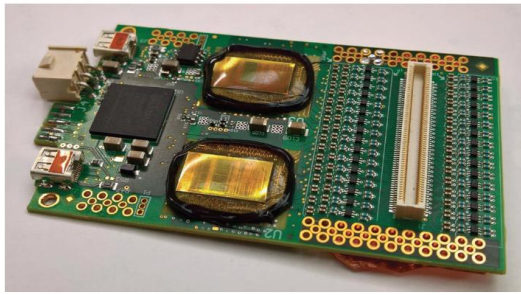
Station	z (cm)	pixel sensors/ station	approximate area (cm^2)
S0	7.0	4	30x30
S1	15.0	4	30x30
S2	20.0	4	30x30
S3	27.0	4	30x30
S4	38.0	16	60x60

Stitched MAPS → novel large area, fast, radiation-tolerant monolithic active pixel sensors for tracking devices of unprecedented precision









Triple GEM amplification structure
- Operated with Ar-CO_2
- 2D strip readout

The contribution of new institutes will be essential for the success of the project!

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 ~100 larger statistics for several collision energies at the SPS

- Physics performance studies show that measurements of
  - Caloric curve from thermal dileptons
  - Continuum modifications due to chiral mixing
  - Open and hidden charm production

  are within reach and would lead to significant advances in the field

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

NA60+ Expression of Interest

http://cds.cern.ch/record/2673280

Signed by 82 physicists from France, Germany, India, Italy, Japan, Switzerland, USA

The NA60+ Collaboration

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- Observables
- Requirements
- Experimental layout
- Detectors
- Physics performances
- Competition with other measurements

CERN-SPSC-2019-017 / SPSC-EOI-019
03/05/2019

Expression of Interest for a new experiment at the CERN SPS: NA60+

NA60+ Collaboration

Abstract

The exploration of the phase diagram of Quantum ChromoDynamics (QCD) is carried out by studying ultrarelativistic heavy-ion collisions. The energy range covered by the CERN SPS ($\sqrt{s_{NN}} \sim$ 5–17 GeV) is ideal for the investigation of the region of the phase diagram corresponding to finite baryochemical potential (μ_B), and has been little explored up to now. In this Expression of Interest, we describe the physics motivations and the exploratory studies for a new experiment, NA60+, that would address several observables which are fundamental for the understanding of the phase transition between hadronic matter and a Quark–Gluon Plasma (QGP) at SPS energies. In particular, we propose to study, as a function of the collision energy, the production of thermal dimuons from the created system, from which one would obtain a caloric curve of the QCD phase diagram that is sensitive to the order of the phase transition. In addition, the measurement of a ρ–a_1 mixing contribution would provide crucial insights into the restoration of the chiral symmetry of QCD. In parallel, studies of heavy quark and quarkonium production would also be carried out, providing sensitivity for transport properties of the QGP and the investigation of the onset of the deconfinement transition. The document defines an experimental set-up which couples a vertex telescope based on monolithic active pixel sensors (MAPS) to a muon spectrometer with tracking (GEM) and triggering (RPC) detectors within a large acceptance toroidal magnet. Results of physics performance studies for most observables accessible to NA60+ are discussed, showing that the results of the experiment would lead to a significant advance of our understanding of (non-perturbative) strong interaction physics. It is also shown that beam intensities of the order of 10^7 lead ions/s are required in order to obtain meaningful results on the various physics topics. Such intensities can presently be reached only in the ECN3 underground hall of the SPS. In addition, the support and engagement of CERN for the development, construction and operation of the toroidal magnet is considered crucial for the success of the project.

May 3, 2019

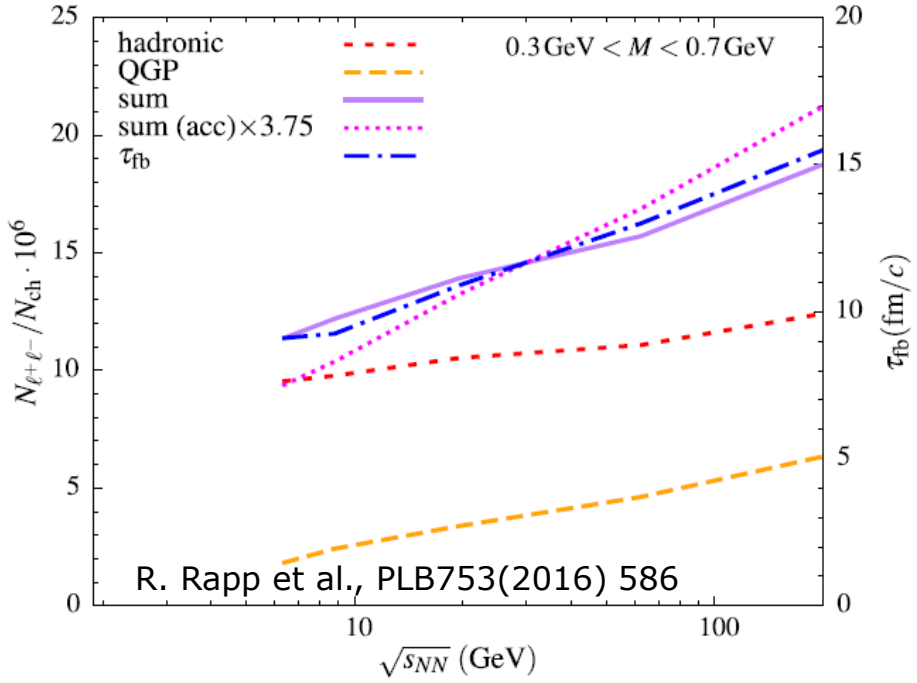
Backup

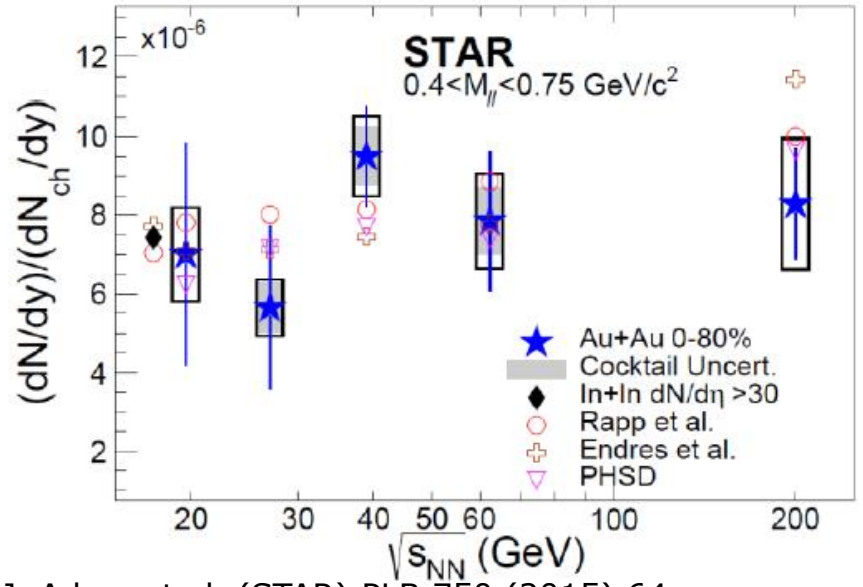
Dilepton excitation function and fireball lifetime

- Fireball lifetime directly related to acceptance corrected low-mass dilepton yield in 0.3>M>0.75 GeV
  → promising tool to detect "anomalous" variations as a function of collision energy

- Such variations could be triggered by the presence of a soft mixed phase during a first order transition
  → fireball lifetime anomalously increased due to the burning of latent heat
  → appearance a plateau in the thermal dilepton yield vs collision energy

Needs a precision measurement at energies below top SPS!





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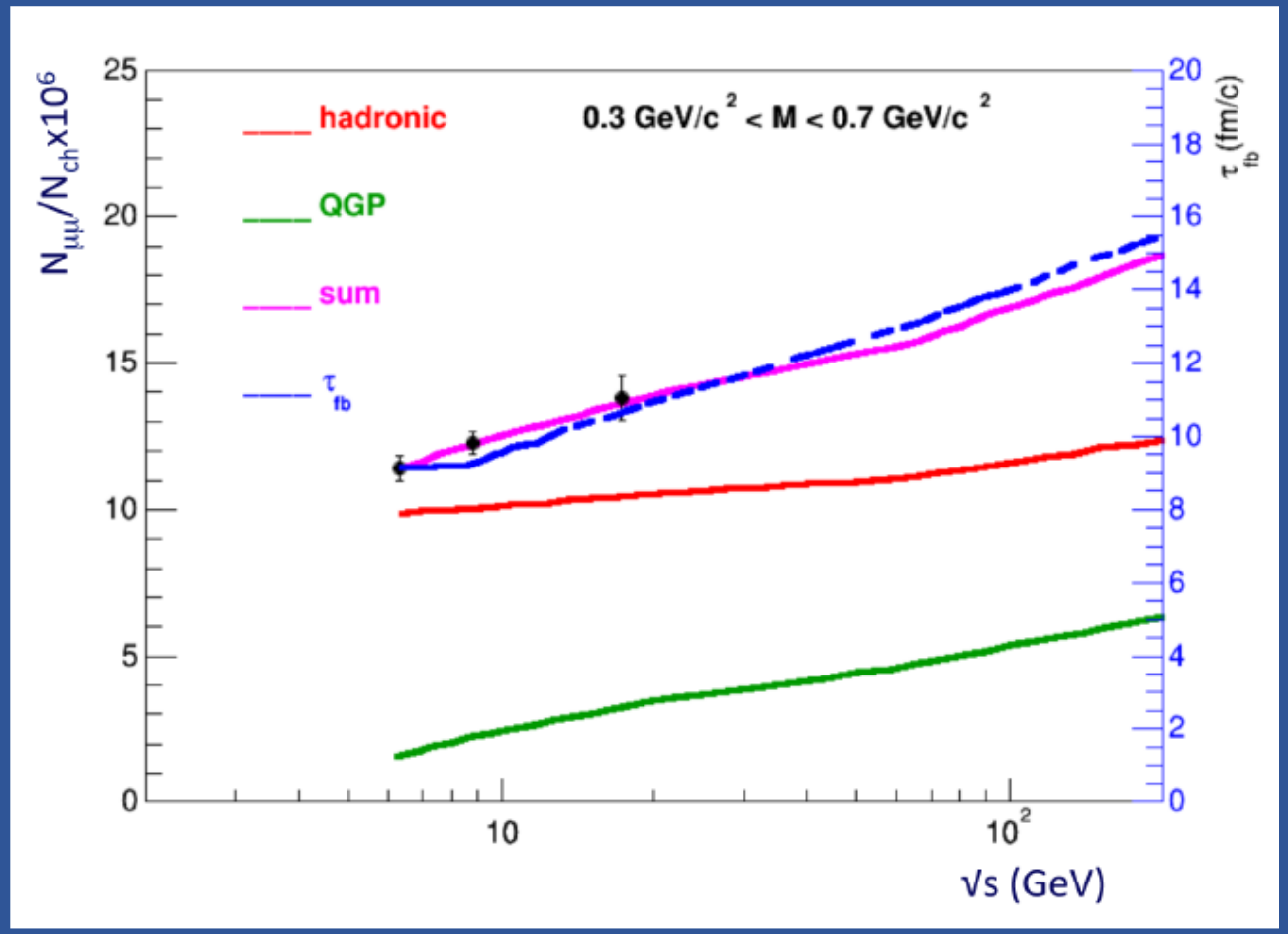
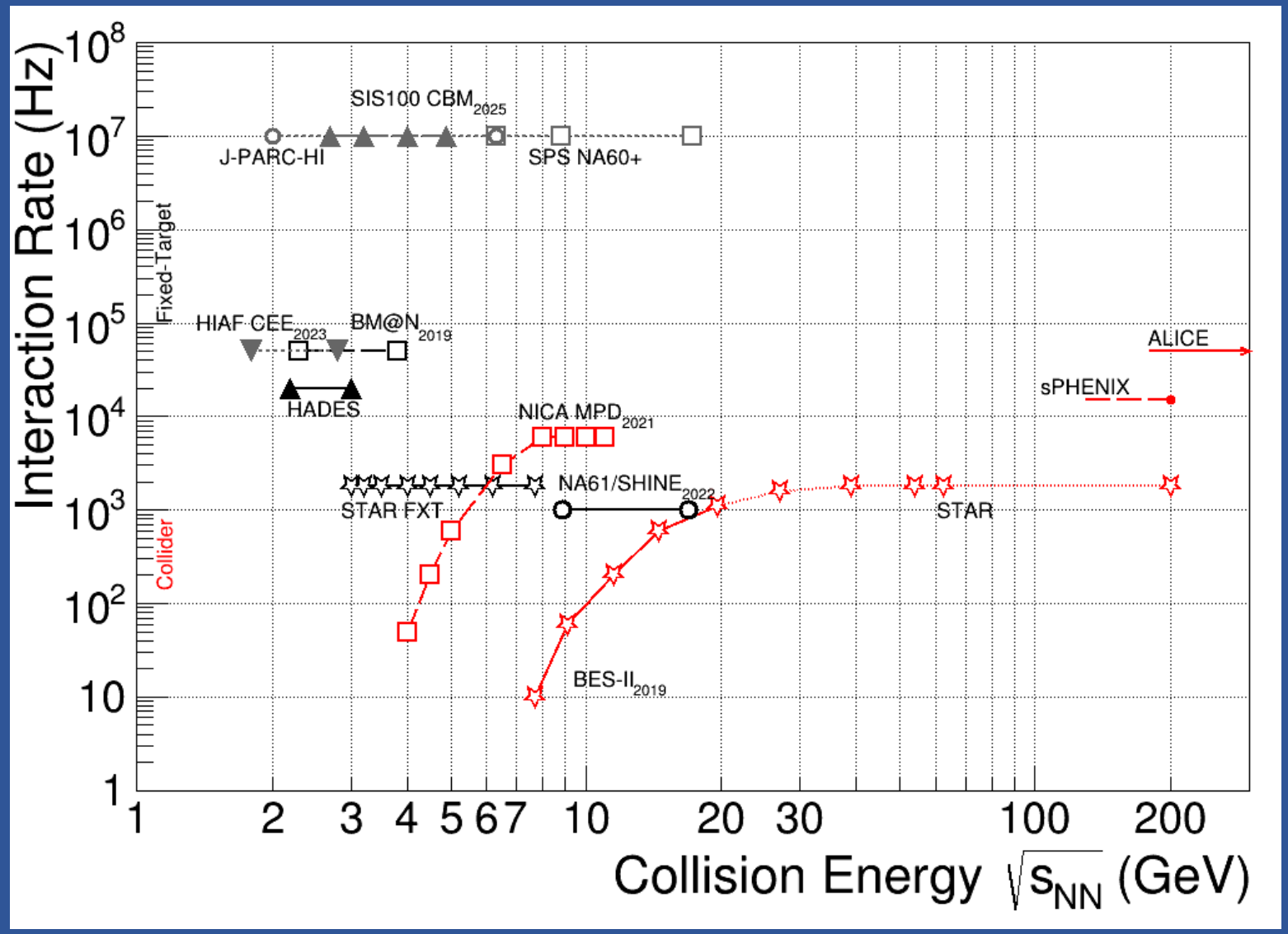
Thermal dimuons as a fireball chronometer



- Measurement of the thermal yield in 0.3<M<0.7 GeV/c^2
- Excellent accuracy → may allow a precise estimate of the fireball lifetime

"Anomalous" variations in the yields as a function of $\sqrt{s_{NN}}$, due to the burning of latent heat, could represent a promising to detect the presence of a first order phase transition



T. Galatyuk, QM2018

NA60+: integration studies

- Integration of the experiment in a CERN experimental hall is under study by CERN accelerator experts
- ECN3 (high intensity hall) → fully exploit SPS luminosity, competition wit non-HI experiments for the use of the beamline
- EHN1 (surface hall) → max. beam intensity limited by radiation safety issues, no competition
  → 2 possible zones singled out (PPE134 most promising)

(see G. Usai, poster presentation #208)