Investigating the QCD phase transitions with dileptons: new opportunities at the CERN SPS

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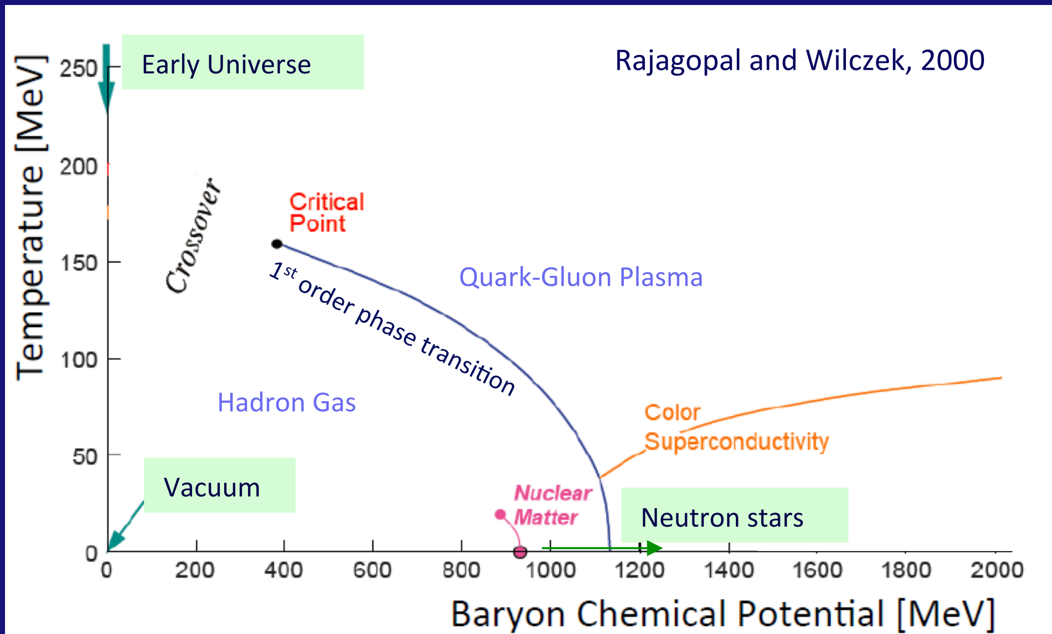
Physics beyond colliders kickoff workshop
CERN 07/09/2016

Theoretical guidance for the QCD phase diagram



Small μ_B (Lattice QCD)

crossover transition
ε_c~1 GeV/fm^3, T_c~160 MeV

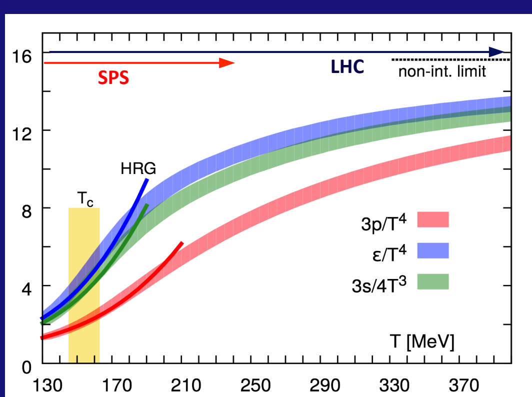
Large μ_B, moderate T (field th.)

QCD critical point,
1st order transition

μ_B related to density of (baryons - anti-baryons)

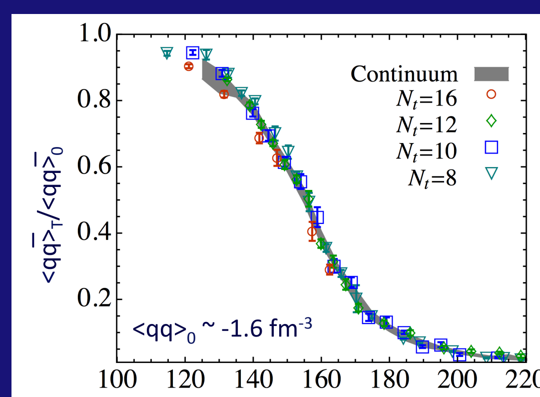
QCD mass (u,d) dominant in
the visible part of the Universe

Hot QCD coll., arXiv:1407.6387 (2014)



deconfinement transition

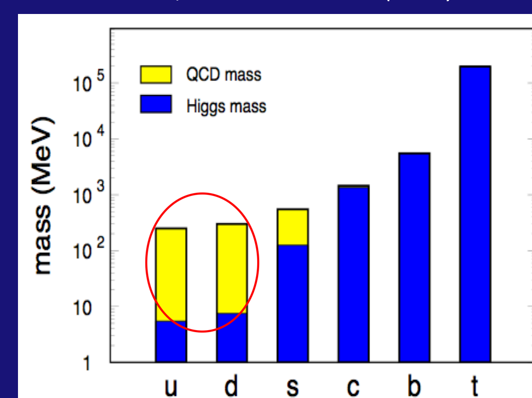
Borsanyi et al., arXiv:1011.4030.v1 (2010)



chiral symmetry restoration

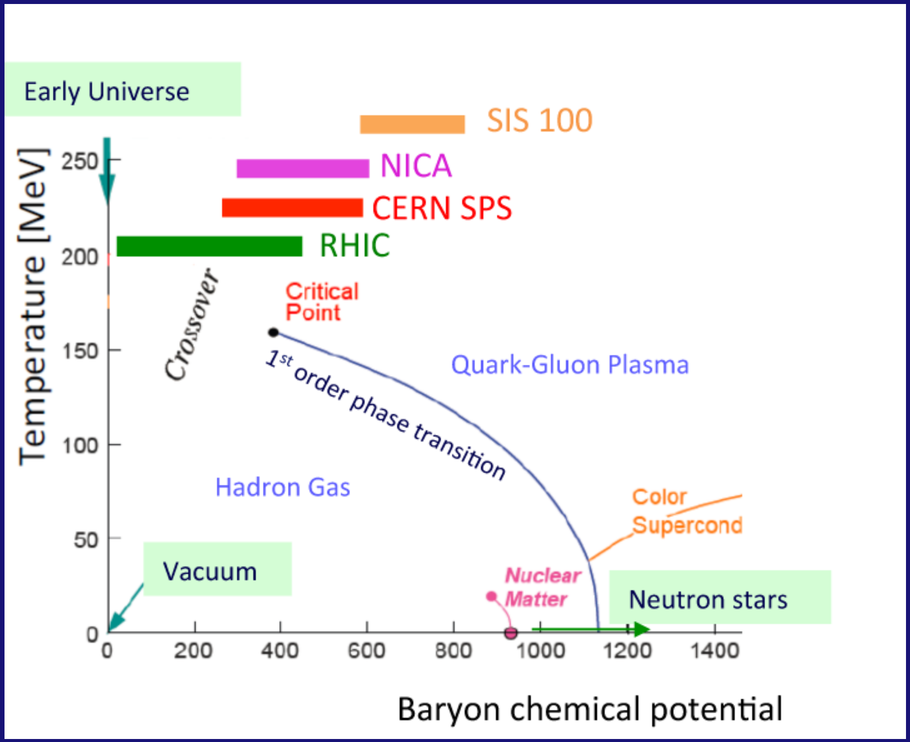
Lattice QCD, μ_B=0

B. Mueller, arXiv:0404015.v2 (2004)



chiral symmetry breaking: masses
of the 6 quark flavours

Precision studies of the QCD phase diagram



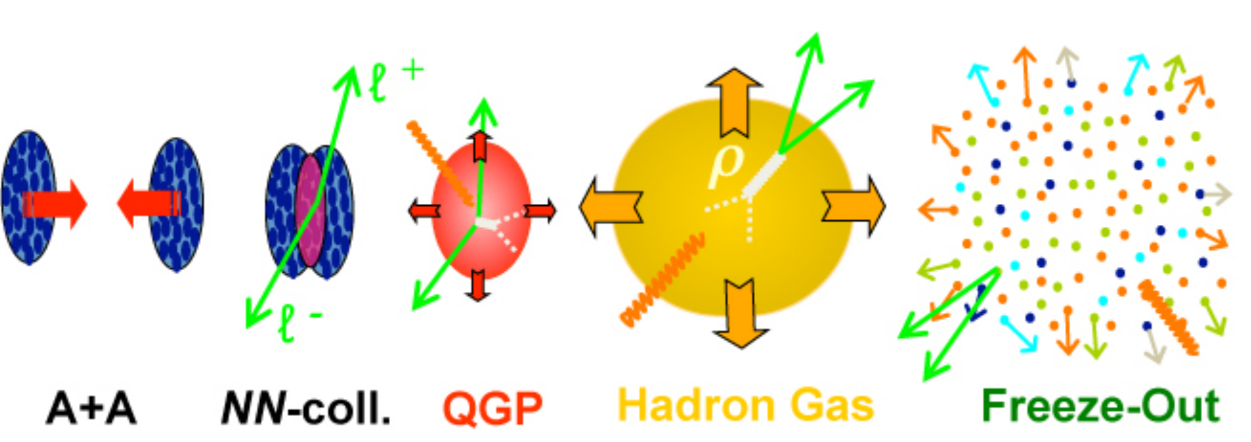
- Basic aspects of QCD phase diagram not yet confirmed experimentally:
  - Existence of critical point and first order phase transition
  - How chiral restoration affects the hadron spectrum

- Low energy experiments:
  - RHIC energy scan, SPS, FAIR

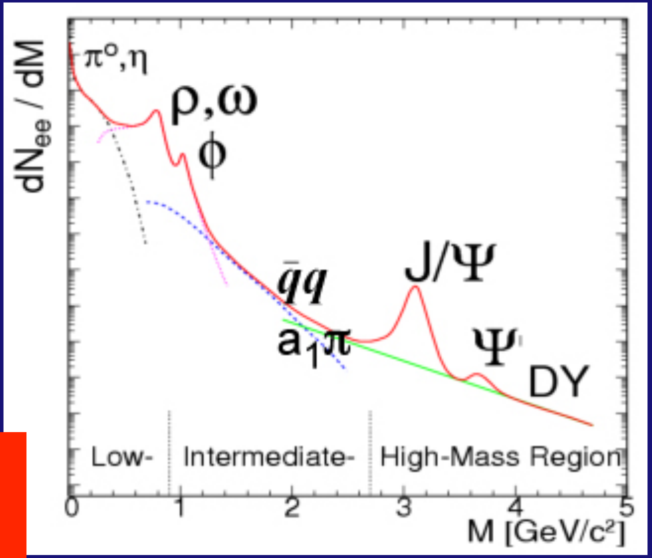
- Exploration of new measurements with high scientific impact impact:
  - Discussed by heavy ion italian community within INFN What Next workshops
  - White paper: arxiv.org/abs/1602.04120

NA60+: New precision measurements of dimuon production via a beam energy scan ($\sqrt{s}$ ~ 4.5 – 17.3 GeV) with a dedicated experimental set-up at the CERN SPS

Lepton pairs: observables and physics goals



lepton pairs emitted at all stages;
no final state interactions



NN-collisions: (Drell-Yan), J/ψ, $D\bar{D}$ pairs

QGP: thermal $q\bar{q}$ annihilation

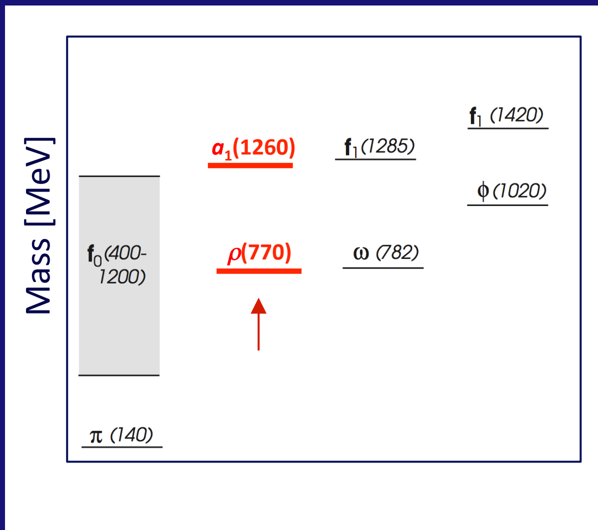
Hot+Dense Hadron Gas: ρ, $a_1\pi \rightarrow \ell^+\ell^-$

} *Thermal dileptons*

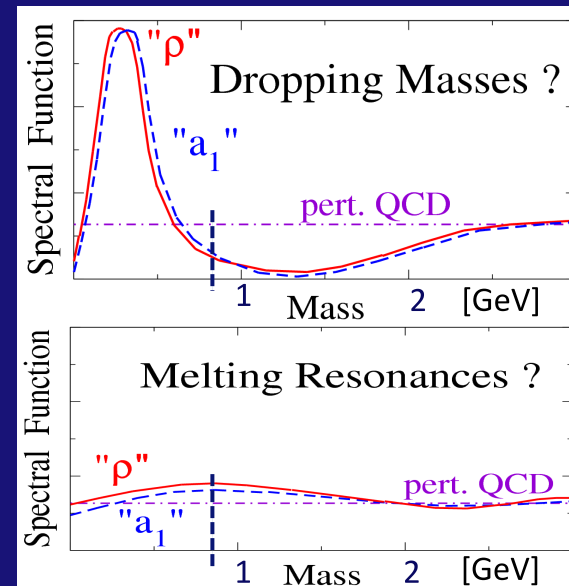
- Signals of onset of deconfinement and order of transition
  - T of thermal $\ell^+\ell^-$ (high M) ➡ $T>T_c$ partonic, $T<T_c$ hadronic sources
  - T_{eff} of thermal $\ell^+\ell^-$ ➡ T_{eff} - inverse slope of p_T/m_T spectra → radial flow partonic *vs.* hadronic sources
  - J/ψ anomalous suppression ➡ QGP temperature
- Signals of chiral symmetry restoration
  - ρ spectral function ➡ ρ width diverges (indirect probe)
  - ρ-a_1 (V-A) mixing ➡ a_1 visible in $\ell^+\ell^-$ channel (direct probe)
  - change of $D\bar{D}$ threshold ➡ sudden drop $J/\psi/(D+\bar{D})$ ratio

Dileptons and the spectral functions of the chiral doublet ρ/a_1

P-S, V-A splitting in the physical vacuum due to spontaneous breaking of chiral symmetry



at T_c: Chiral Restoration



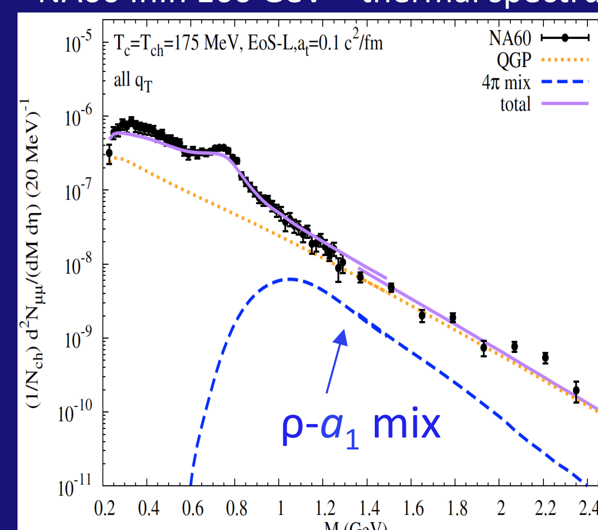
ρ (1^{--}): main mediator of thermal dileptons with M<1 GeV through $\pi^+\pi^- \rightarrow \rho \rightarrow \mu\mu$

$a_1(1^{+-})$: accessible in thermal dileptons with 1<M<1.5 GeV through ρ-a_1 chiral mixing: $\pi\, a_1 \longrightarrow \mu\mu$

Full SPS energy: ρ-a_1 masked by QGP

➔ Precision measurement of ρ-a_1 mixing requires collision energy with initial state close to the phase boundary: negligible QGP yield (also smaller Drell-Yan)

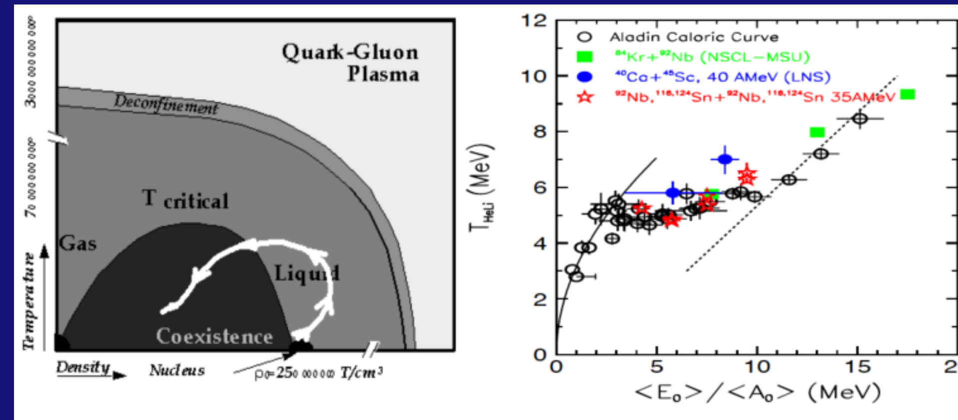
NA60 InIn 160 GeV – thermal spectrum



First order phase transition: measurement of the caloric curve

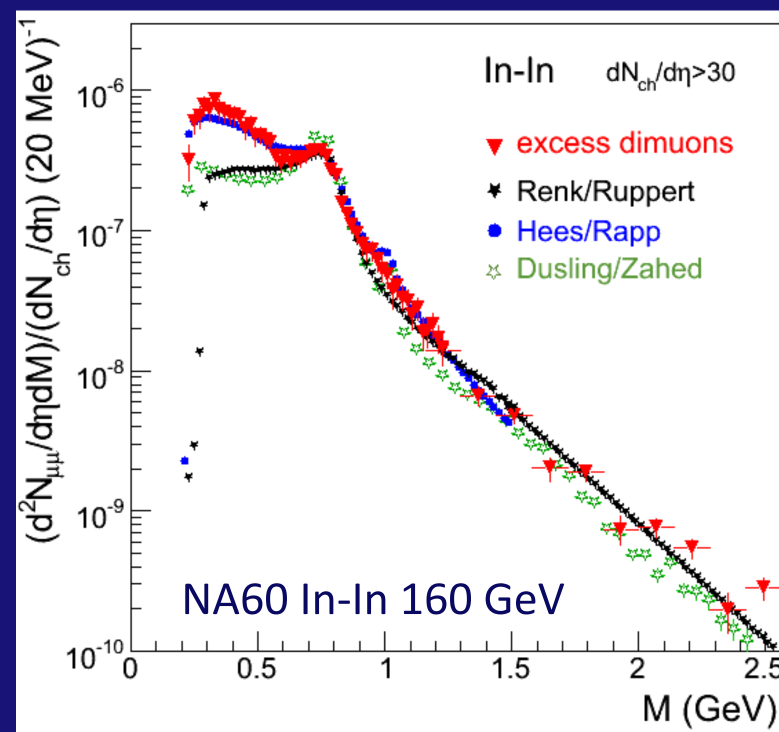
- Example: caloric curve for liquid-hadron gas phase transition in nuclear matter

M. D'Agostino et al., Nucl. Phys. A749 (2005) 55–64



- First order hadron gas-QGP phase transitions: caloric curve with dilepton thermometer
    - *T* vs energy density with beam energy scan: search for a possible flattening of *T*
- Dilepton thermometer
    - *T* measured from dilepton thermal mass spectrum for M>1.5 GeV: $dN/dM \sim M^{3/2} \exp(-M/T)$
    - First pioneered by NA60 at 160 GeV (T~200 MeV, above T_c)

[Eur. Phys. J. C 59 (2009) 607] → CERN Courier 11/ 2009, 31
Chiral 2010, AIP Conf.Proc. 1322 (2010) 1



Onset of deconfinement: study of dilepton yield from QGP

Theoretical expectation for T_{eff} in central Pb-Pb at 40 GeV (R. Rapp)

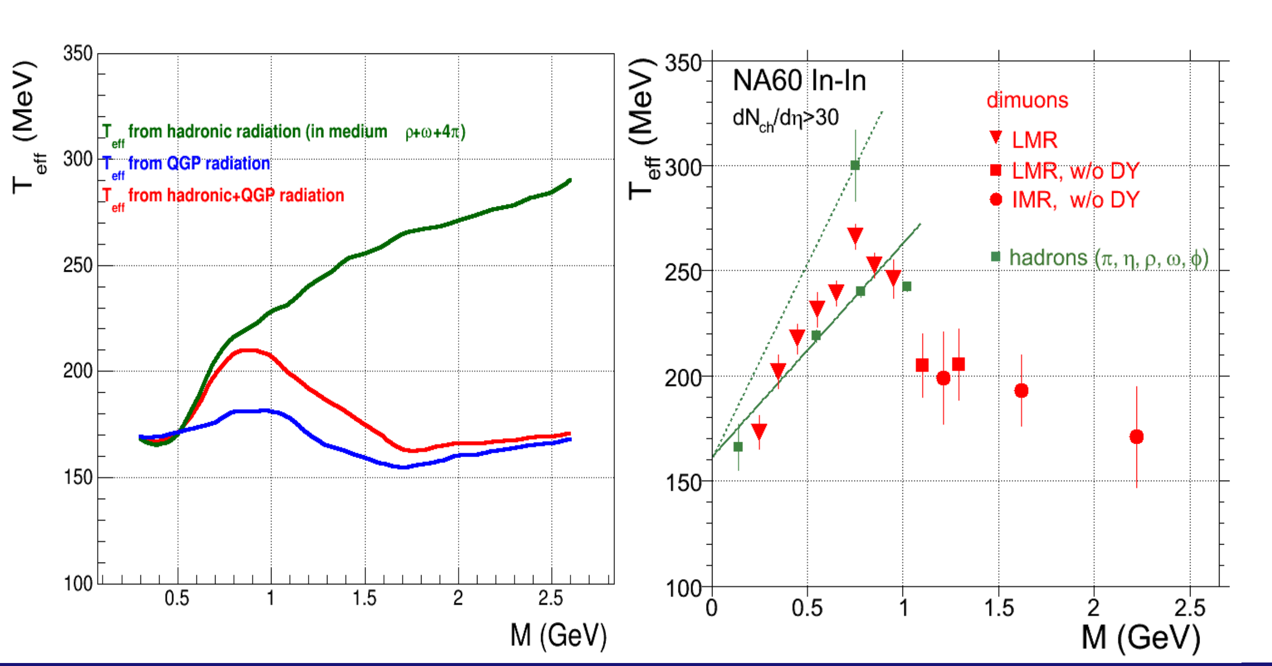
NA60 In-In at 160 GeV
Phys. Rev. Lett. 100, 022302 (2008)

transverse mass:
$m_T = (p_T^2 + M^2)^{1/2}$

m_T spectra exponential:
$1/m_T\, dN/m_T \sim \exp(-m_T/T_{eff})$

two components in m_T spectra: thermal and radial collective ('Hubble') expansion

$T_{eff} \sim T_f + M \langle v_T \rangle^2$

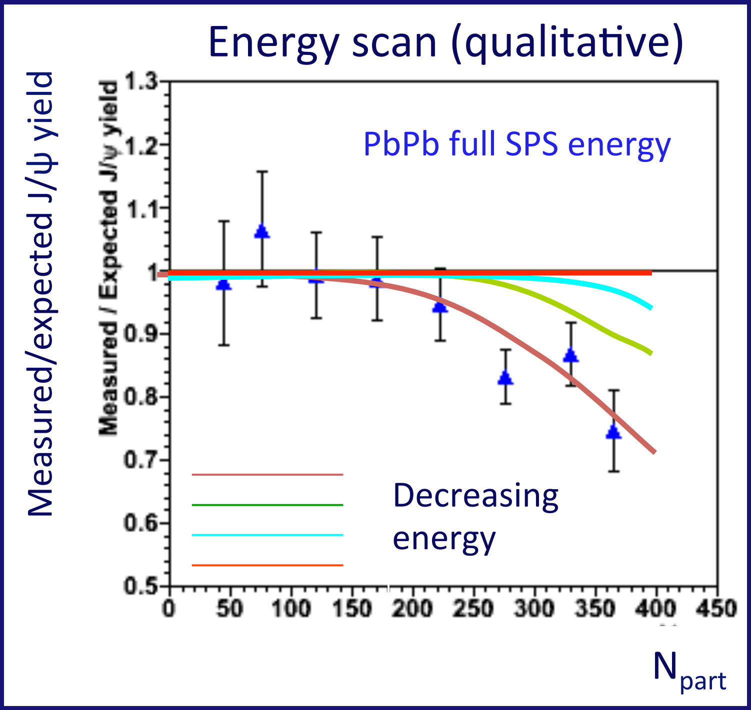


- Below onset of deconfinement: T_{eff} expected to steadily increase vs M (large v_T for hadronic matter)
- At onset of deconfinement: emergence of a drop at M≈1 GeV (very small v_T for QGP which starts to dominate for M>1 GeV)

  ➔ drop experimentally observed at full SPS energy: evidence for large QGP yield

➔ Low energy scan: T_{eff} quantitative tool to tag onset of deconfinement

Charmonium and open charm

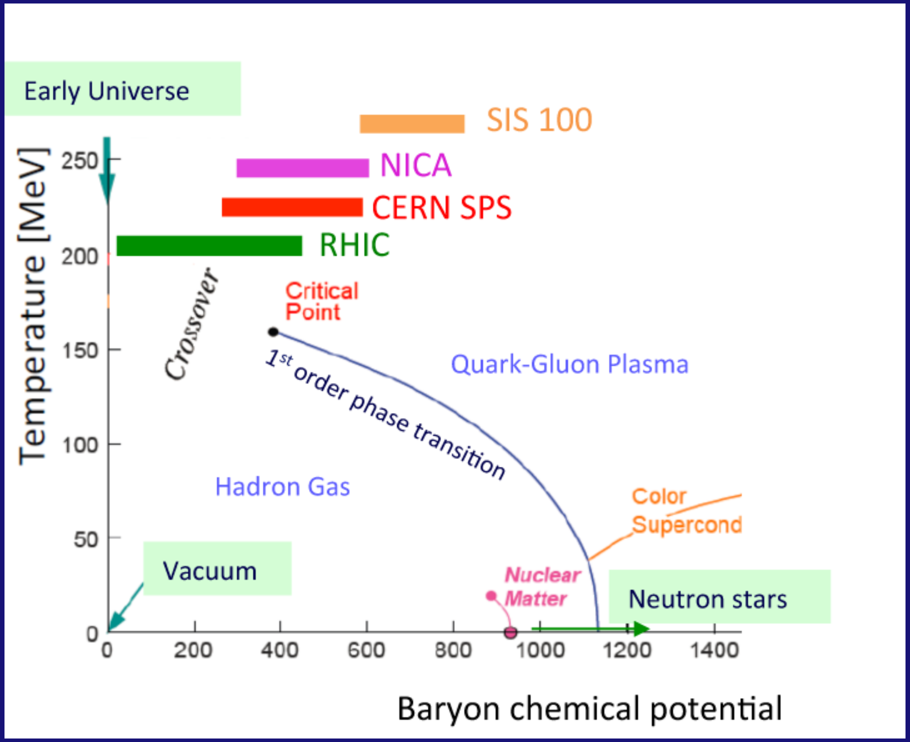


- Full SPS energy (160 GeV): J/ψ anomalous suppression relevant for PbPb collisions
- Energy scan: possibility of investigating the onset of the suppression and to relate it with the onset of deconfinement
- No existing measurements for energies below top SPS energy
- Other possible measurements: ψ(2S), χ_c

- At chiral restoration:
  - production threshold of $D\bar{D}$ pair may be reduced
    → enhancement of production by a large factor
- At onset of deconfinement:
  - J/ψ melting in the QGP and enhancement of $D\bar{D}$ in the chirally-symmetric medium
    → possible drop of ratio (J/ψ) / ($D+\bar{D}$)

Why the CERN SPS?

- Various facilities can in principle investigate the high μ_B region of the QCD phase diagram



High interaction rates (>1 MHz) can be reached at the CERN SPS ($\sqrt{s}$ = 4.5 – 17.3 GeV)

Forthcoming FAIR facility at GSI: complementary region $\sqrt{s}$ = 2-4.5 GeV (possibly too limited for onset of deconfinement)

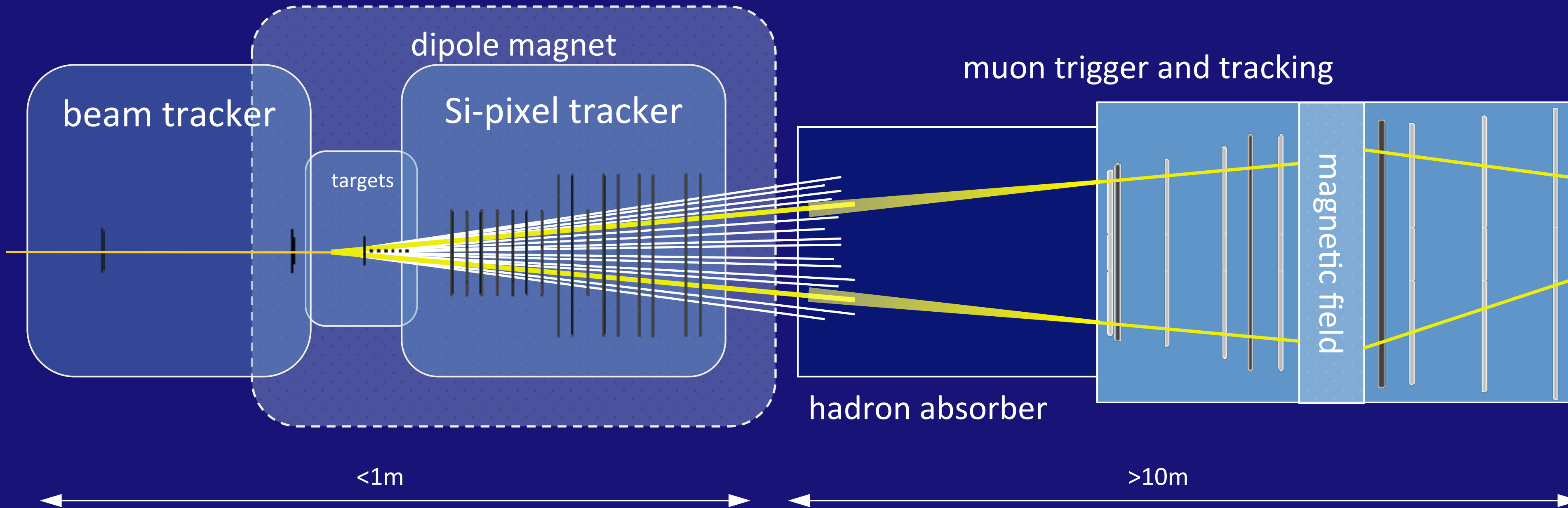
Collider facilities (NICA, RHIC): interaction rates lower by 2-3 orders of magnitude

- CERN SPS:
  - Optimal combination of wide μ_B coverage of phase diagram and large interaction rates

→ Best machine in the world to cover the low energy range

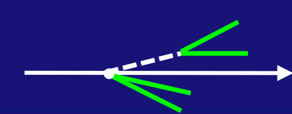
Precision measurement of dimuons in heavy ion collisions

(pioneered by NA60; basic idea P. Sonderegger, exp. approved 2000, spokespersons C. Lourenço, G. Usai)



Track matching in coordinate and momentum space

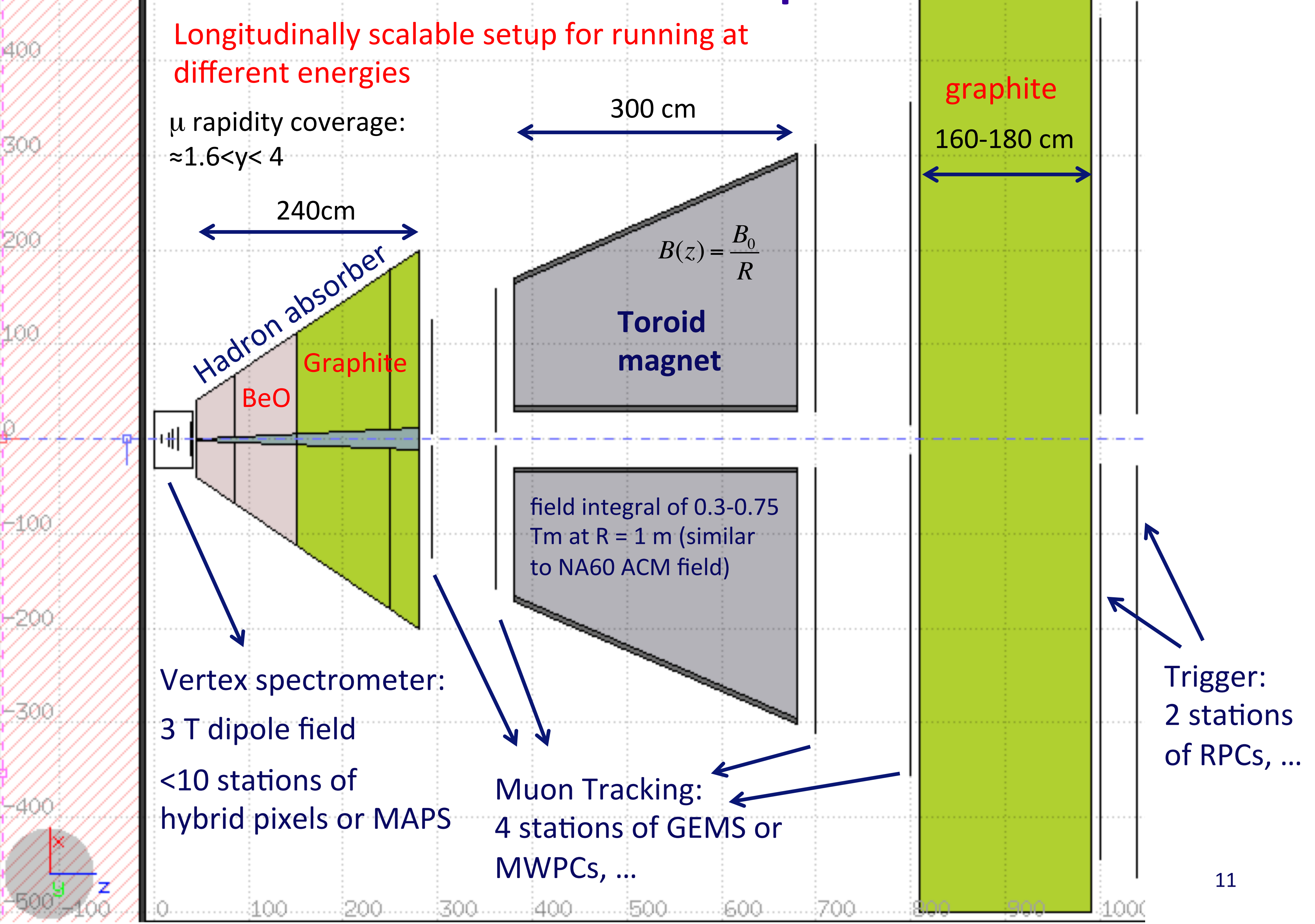
- Improved dimuon mass resolution
- Distinguish prompt from decay dimuons



Radiation-hard silicon pixel detectors

- High luminosity of dimuon experiments maintained

NA60+ detector concept



Experimental objectives for BES at the CERN SPS

- Energy scan in Pb-Pb collisions at several energies in the lab energy range ~20-160 GeV/nucleon (example 20-30-40-80-120-160 GeV/nucleon)

- Objectives for reconstructed dilepton pairs at each energy:
  - isolation of dilepton spectrum from hadronic phase up to M~2 GeV
  - measurements of T and T_{eff} vs M with an accuracy at the MeV level

  ➔ $> 5 \cdot 10^7$ reconstructed pairs from thermal radiation per energy point (statistics increase by a factor ≈100 over NA60 at each energy)
  - $2\text{-}3 \cdot 10^4$ reconstructed J/ψ mesons per energy point

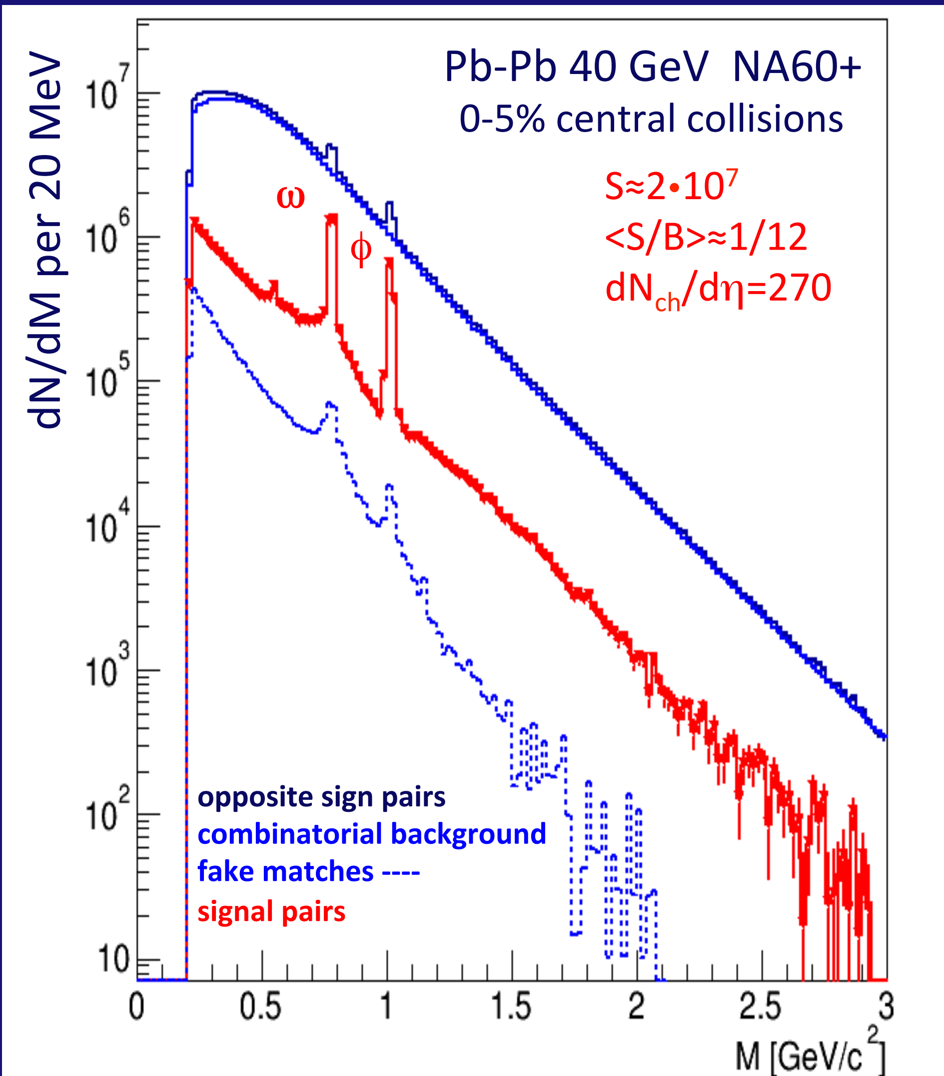
- Data taking goal: run at each energy in a ~15 days beam-time period
  - Interaction rate ~ 0.5-1 MHz

  ➔ beam-intensity: $\sim 2\text{-}3 \cdot 10^7$/s (assuming 5 s burst, 3 burst/minute)

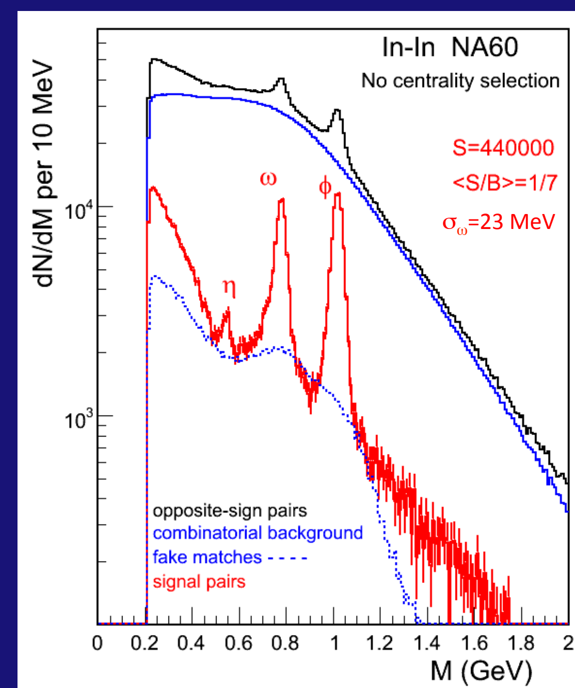
- pA data at some energy point also needed

Basic physics program accomplished in ≈5 years of data-taking

Performance study for thermal radiation Pb+Pb central collisions at 40 GeV/nucleon: data sample

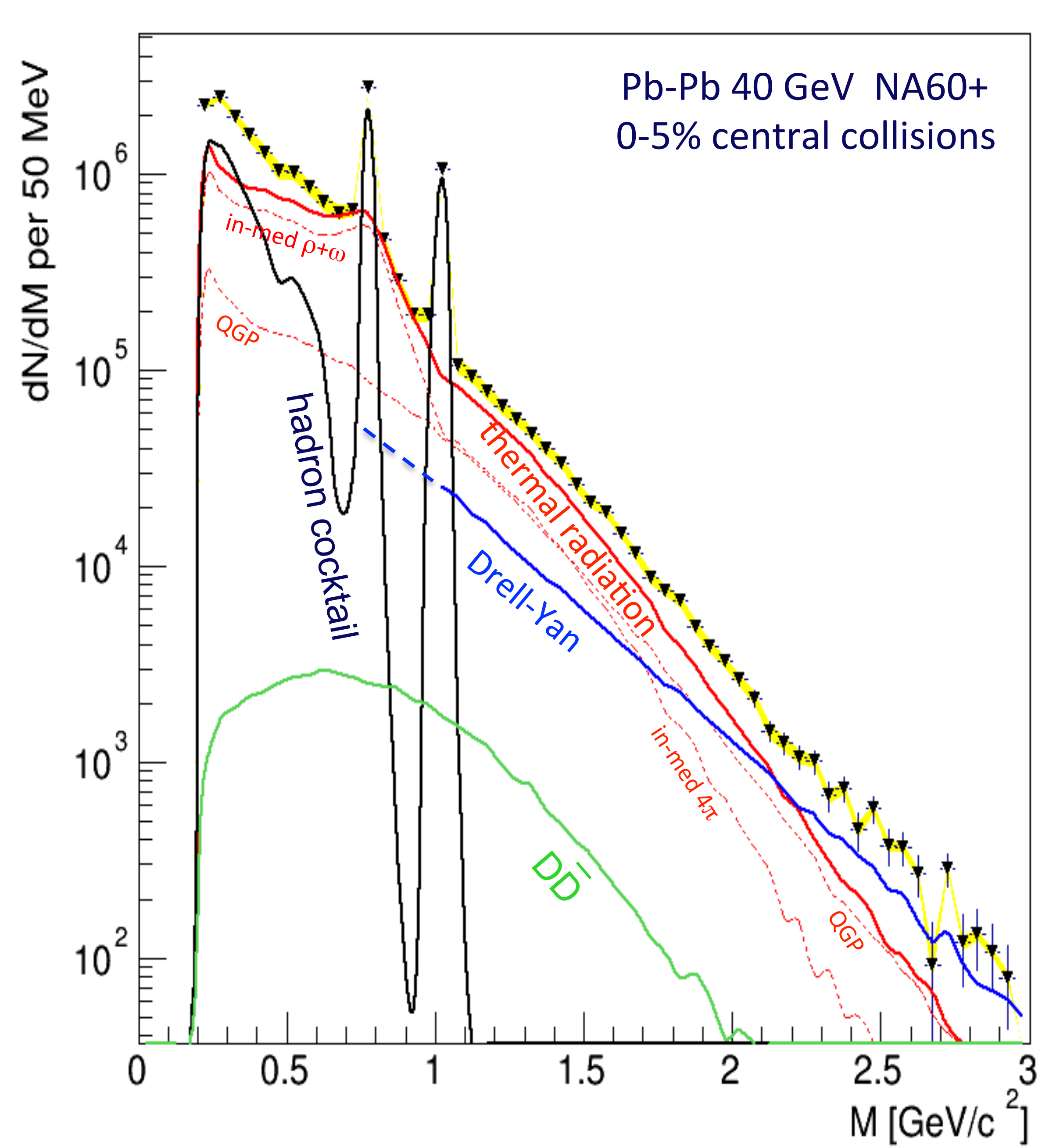


- $2 \cdot 10^7$ reconstructed signal pairs
- Mass resolution: 10-15 MeV at the ω position
- Subtraction of:
  - combinatorial background (0.5% precision)
  - fake matches



➔ progress in statistics over NA60 by a factor ≈ 100

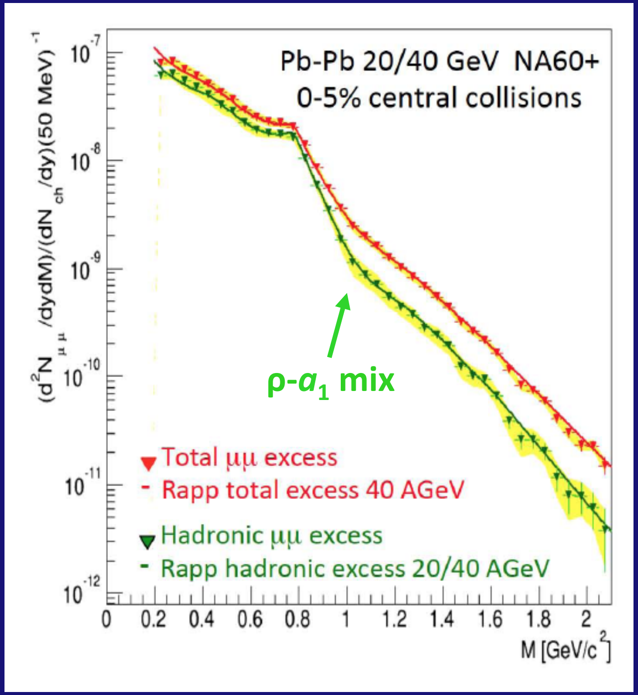
Thermal mass spectrum after background subtraction

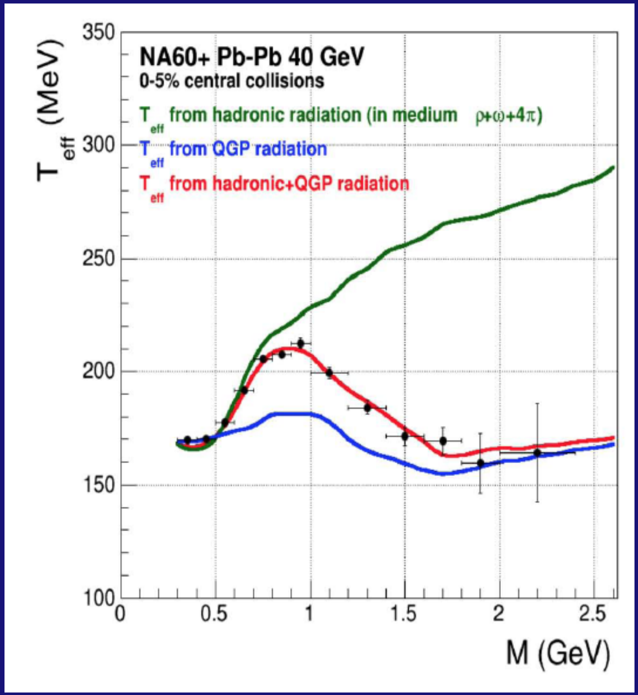


- Thermal radiation yield up to 2.5-3 GeV
- QGP yield still significant at 40 GeV
- Isolation of thermal radiation subtracting:
  - Drell-Yan (stronger than QGP only above ~2.3 GeV)
  - Open charm (yield negligible)
  - Freeze-out processes (η, ω, ϕ)

Performance on temperature and T_{eff} from m_T spectra

Acceptance corrected mass spectra





- Inclusive thermal dilepton spectrum measurable up to 2.5-3 GeV
  - fit of mass spectrum (red points) ➔ T_{slope}=163±4±1 MeV

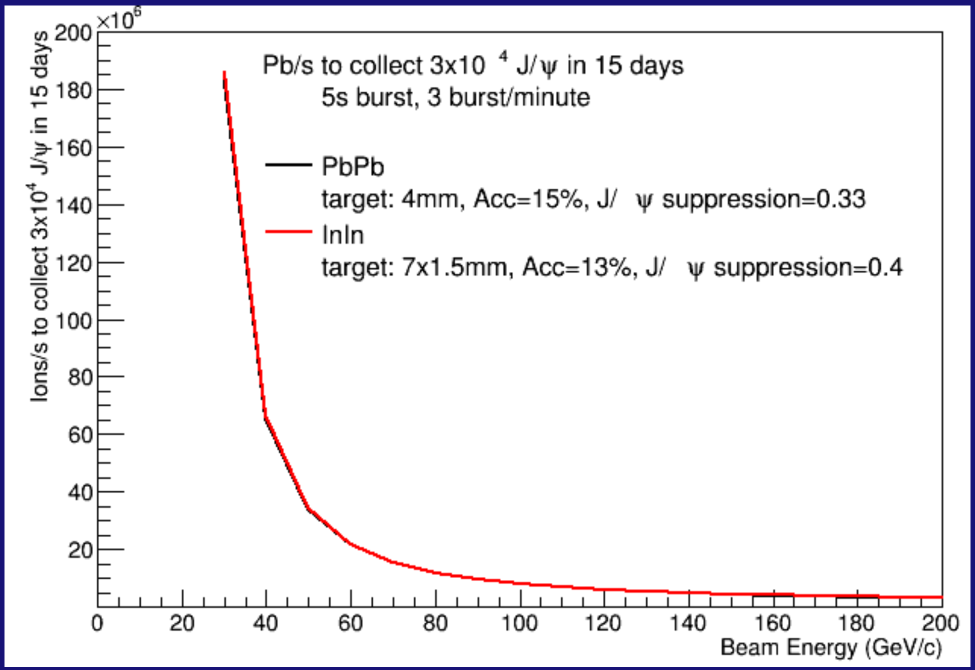
  ➔perfect recovery of theoretical input (160 MeV) of generator

- Thermal spectrum from hadronic phase (ρ+a_1) measurable up to M ~ 2 GeV:
  ➔best sensitivity to ρ-a_1 chiral mixing

- m_T spectra: T_{eff} extracted up to M ~ 2.5 GeV:

  ➔strong sensitivity to distinguish even a small contribution of QGP down to the onset of deconfinement

Performance studies for J/ψ and open charm reconstruction



J/ψ production feasible from top SPS energy down to ~40-60 GeV, depending on the available beam time

Sample of ~2-3 · 10^4 J/ψ can be collected with beam intensities similar to those already available in the NA50/NA60 experiments, running the experiment for 2 weeks at each energy

- Reconstruction of open-charm:
  - Semi-leptonic decay D➔μ+X (BR~10%)
    ➔tag of displaced muon tracks wrt primary interaction point
  - Hadronic decays D➔Kπ (BR~4%) and D➔Kππ (BR~9%)
    ➔standalone track reconstruction in the silicon vertex tracker

Summary and outlook

- NA60+ at the CERN SPS → unique opportunity for dilepton measurements of utmost precision over the widest possible energy range:
  - Systematic measurement of EM radiation over the energy range from ≈ 20 to 160 GeV/nucleon (thermal, charmonia and open charm)

  → New horizon for quantitative understanding of chiral symmetry restoration, onset of deconfinement, order of transition

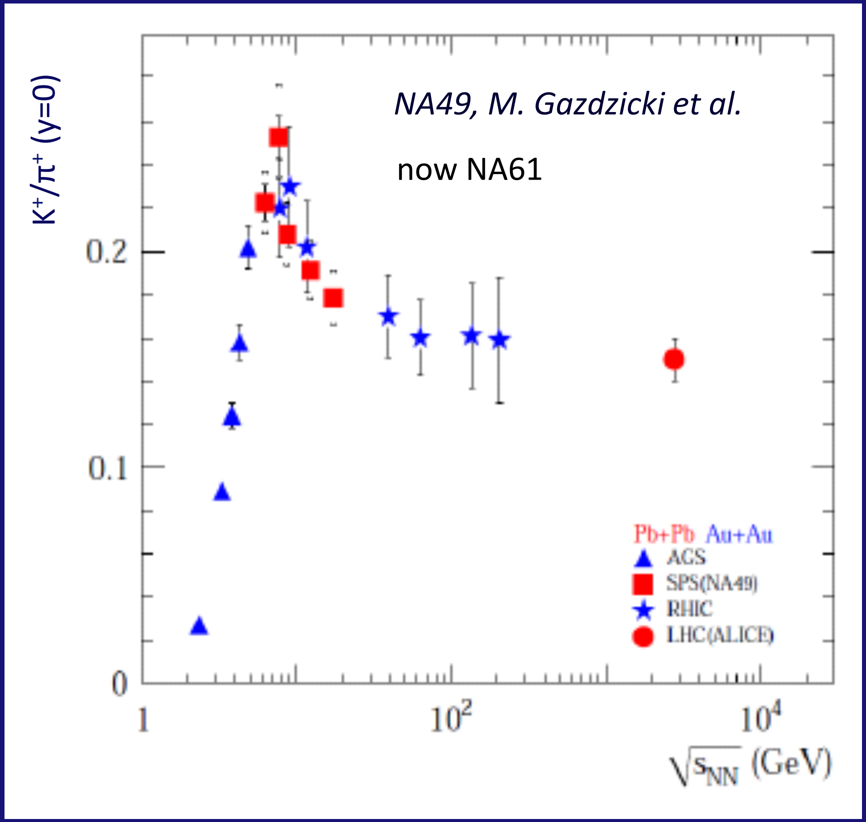
- Steps towards formation of an international collaboration and preparation of a Letter of Intent to be submitted to the SPS Committee within 2018 (timely in view of the update of the European Strategy for Particle Physics)

- Construction and running of the experiment envisaged for the following decade:
  - 2–3 years devoted to R&D for detectors and toroid magnet design
  - 2 years for construction
  - 5 years of data-taking

backup

Hints for onset of deconfinement

- Present experimental strategy:
  - Evolution of observables as hadronic particle ratios as a function of collision energy → beam energy scan (BES)
  - Search for anomalous structures



- CERN SPS NA49 BES: peak of K^+/π^+ at $\sqrt{s_{NN}}$=8 GeV (E_{lab}=30 GeV/nucleon)
- only structure known in BES
- Highest baryon density at freeze-out at the same energy

→ Onset of deconfinement?