NA60+
Status and plans

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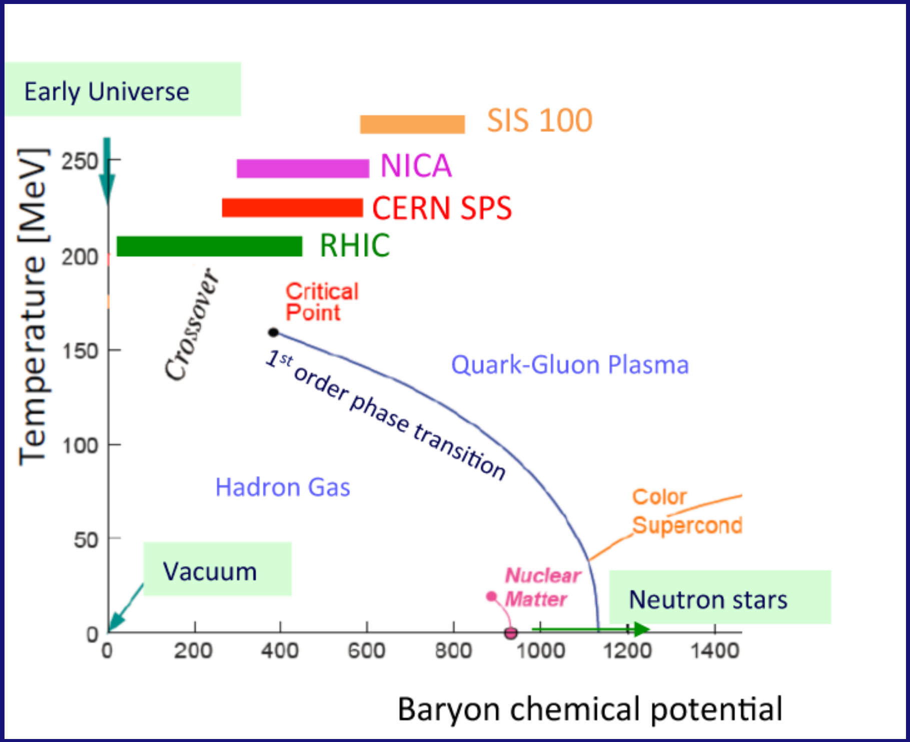
Physics Beyond Colliders workshop
CERN 21/11/2017

Precision studies of the QCD phase diagram



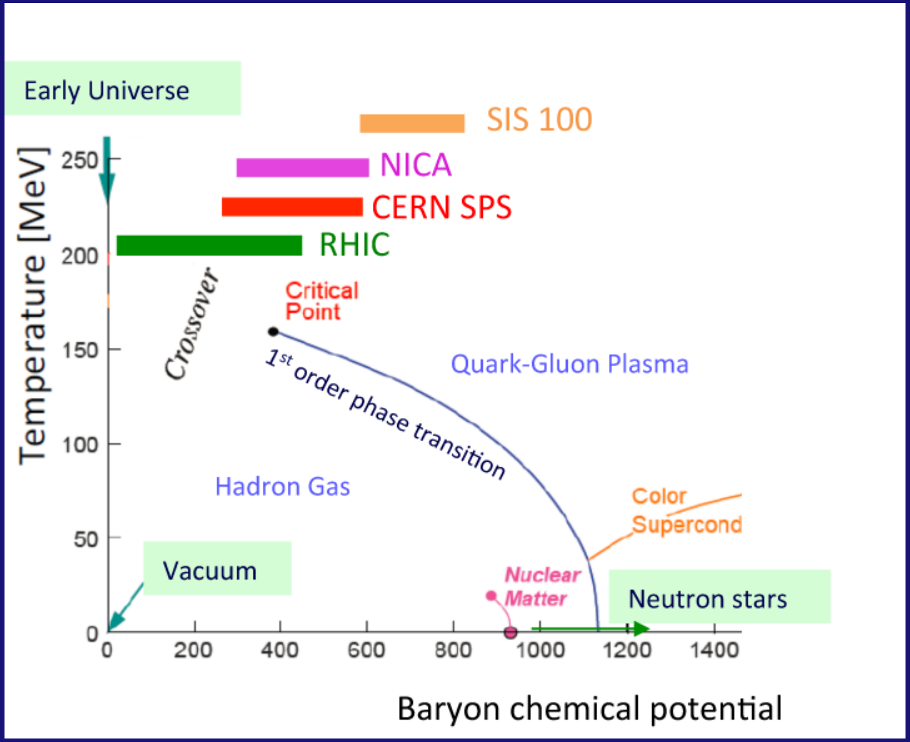
- Basic aspects of QCD phase diagram not yet confirmed experimentally:
  - Existence of critical point and first order phase transition
  - Chiral restoration and the hadron spectrum

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

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

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)

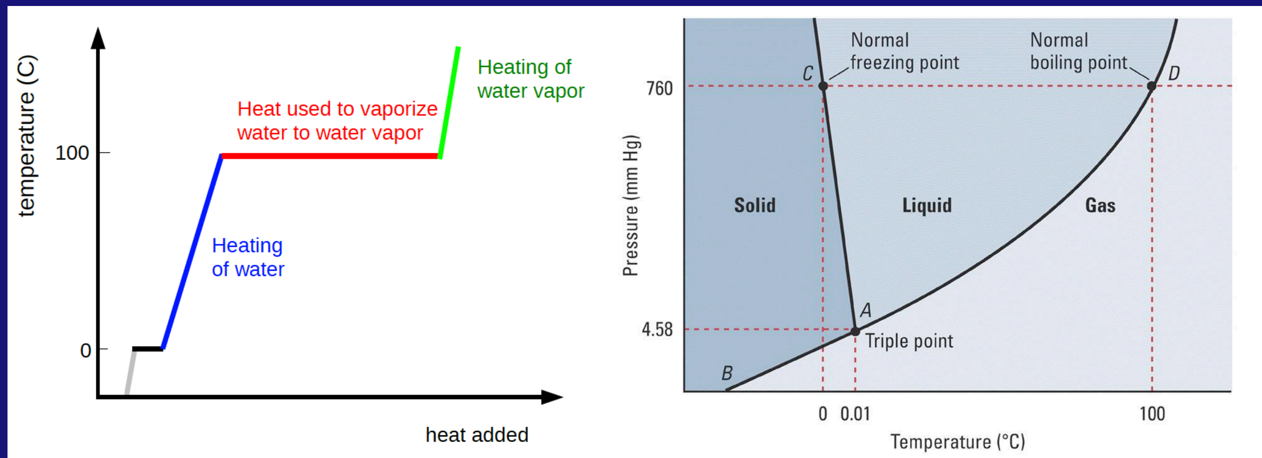
Forthcoming FAIR facility at GSI: complementary region $\sqrt{s}$ = 2-4.5 GeV (possibly too limited for onset of deconfinement)

Collider facilities (NICA, RHIC): interaction rates lower by 2-3 orders of magnitude
Also RHIC fixed target program not competitive for high precision dilepton measurements

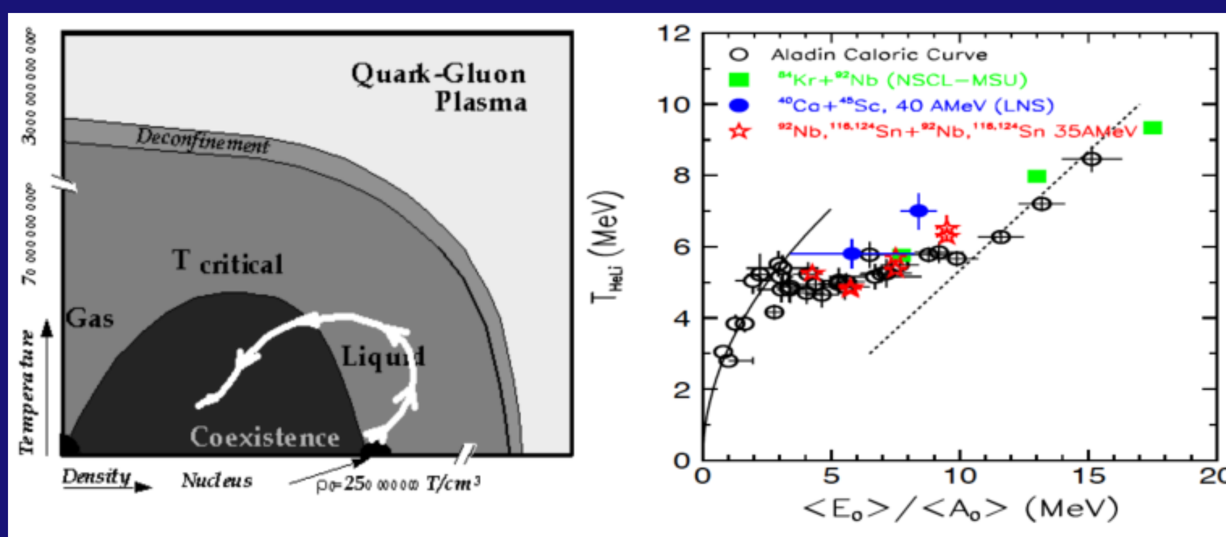
- CERN SPS:
  - Optimal combination of wide μ_B coverage of phase diagram and large interaction rates

Phase transitions and caloric curves

- Caloric curve and phase diagram of water



- Caloric curve for liquid-hadron gas phase transition in nuclear matter (M. D'Agostino et al., Nucl. Phys. A749 (2005) 55–64)



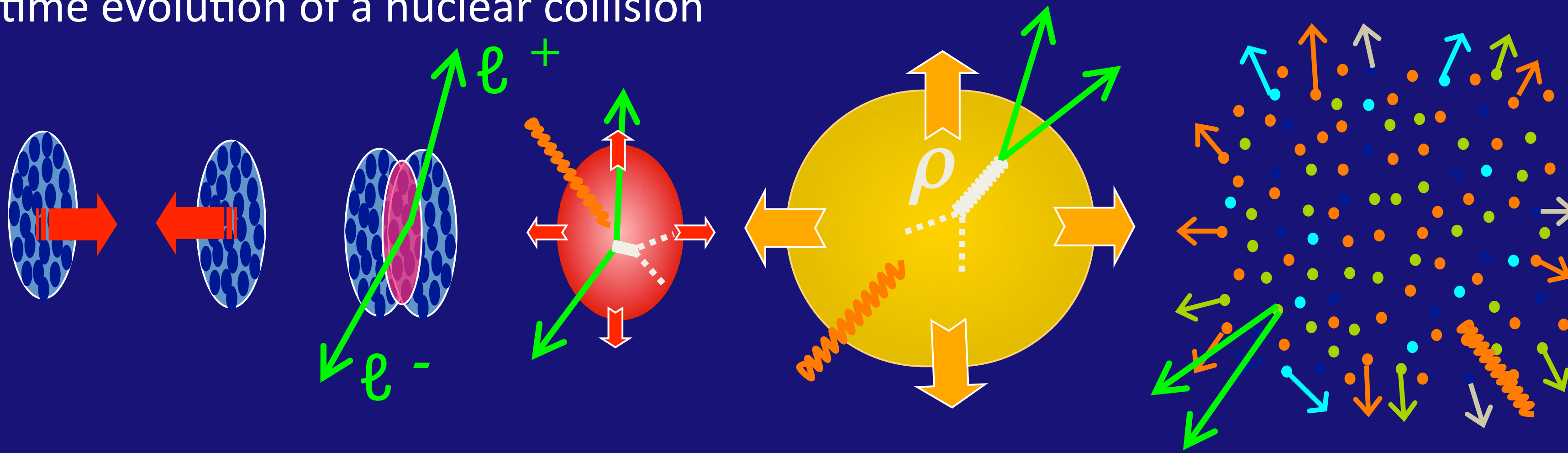
The big question: measuring a caloric curve for the hadron gas-QGP first order phase transition?

Key ideas:

- Temperature from thermal dilepton production
- Beam energy scan

Dilepton production in high-energy nuclear collisions

time evolution of a nuclear collision



A+A ***NN*-coll.** **QGP** **Hadron Gas** **Freeze-Out**

"Hubble" expansion: T= 240→≈160 160→110 ~110 (MeV)

Lepton pairs emitted at all stages; no final state interactions

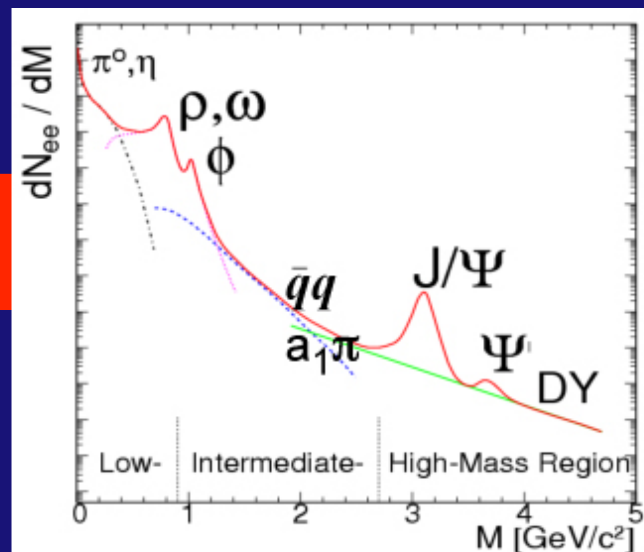
NN-collisions: (Drell-Yan), J/ψ, $D\bar{D}$ pairs

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

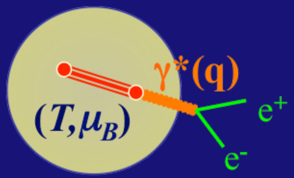
Hot+Dense Hadron Gas: ρ, $a_1\pi \rightarrow \ell^+\ell^-$

} *Thermal dileptons*

Freeze-out: free hadron decays

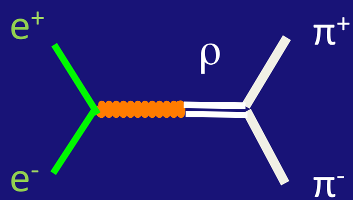


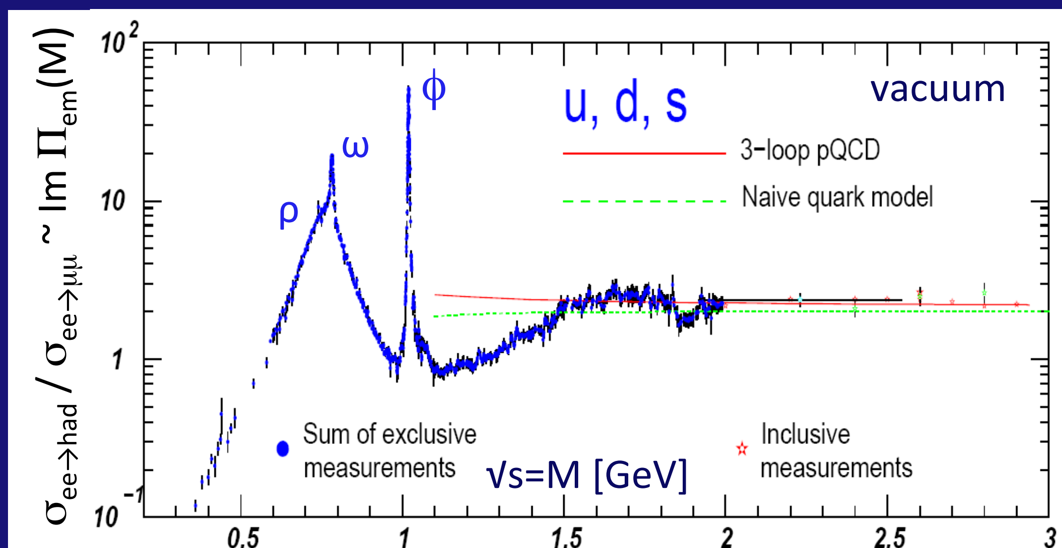
Thermal dilepton rate and the measurement of T

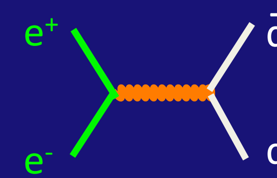


$$\frac{dN_{ee}}{d^4x d^4q} = \frac{-\alpha_{em}^2}{\pi^3 M^2} f^B(q_0,T) \times \mathrm{Im}\,\Pi_{em}(M,q;\mu_B,T)$$

e.m. spectral function







non-perturbative in-medium spectral function(s)

$\mathrm{Im}\Pi_{em} \sim \mathrm{Im}\, D_\rho + \dots$

perturbative hadron-parton duality (flat SF)

$\mathrm{Im}\,\Pi_{em} \sim N_c \sum (e_q)^2$

Flat spectral function for M>1.5 GeV → mass spectrum after integration over momenta and emission 4-volume:

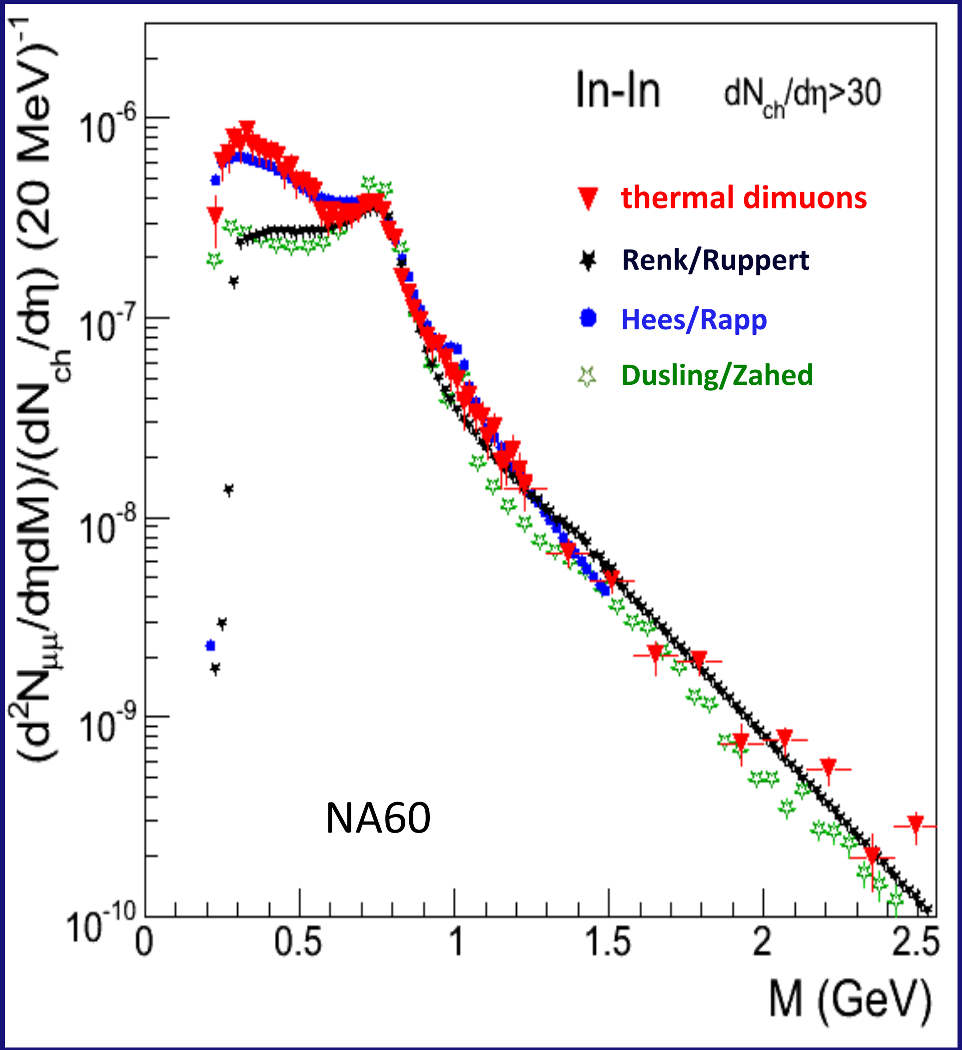
$$dN_{\mu\mu}/dM \propto M^{3/2} \times \langle \exp(-M/T) \rangle$$

T: average temperature which tracks initial temperature (dominant contribution from early stages)
Robust theoretical result

Fit of mass spectrum for M>1.5 GeV → thermometer!

NA60 measurement of T at √s=17.3 GeV: deconfinement

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



All physics background sources subtr. and integrated over p_T

Correction for acceptance and normalization to $dN_{ch}/d\eta$

effective statistics highest of all experiments, past and present (by a factor of nearly 1000)

M<1 GeV

ρ dominates, 'melts' close to T_c

M>1 GeV

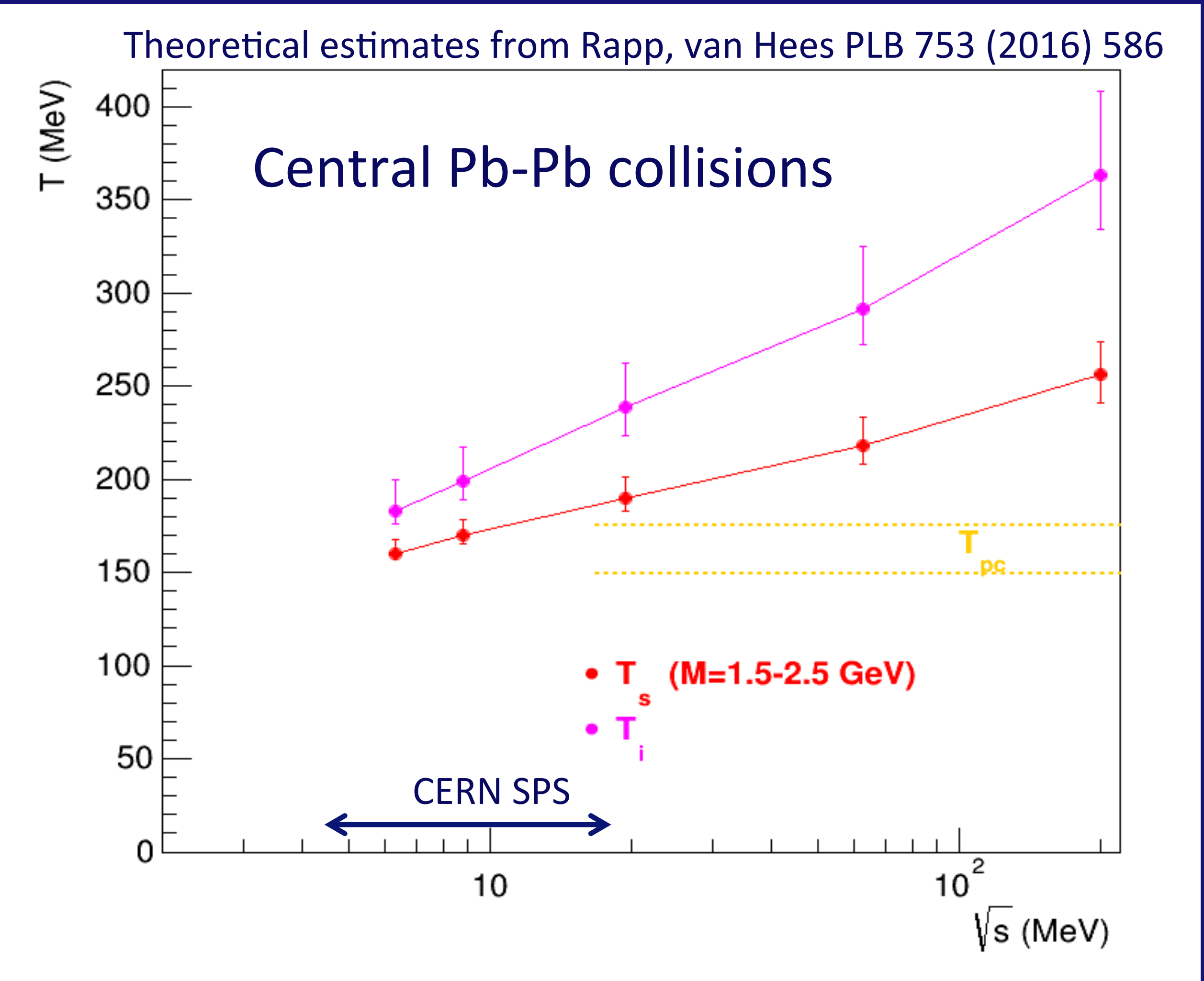
~ exponential fall-off → 'Planck-like'

fit to $dN/dM \propto M^{3/2} \times \exp(-M/T)$

range 1.1-2.0 GeV: T=205±12 MeV
1.1-2.4 GeV: T=230±10 MeV

$T>T_c$=160-170 MeV: partons dominate

Caloric curve: theoretical guideline



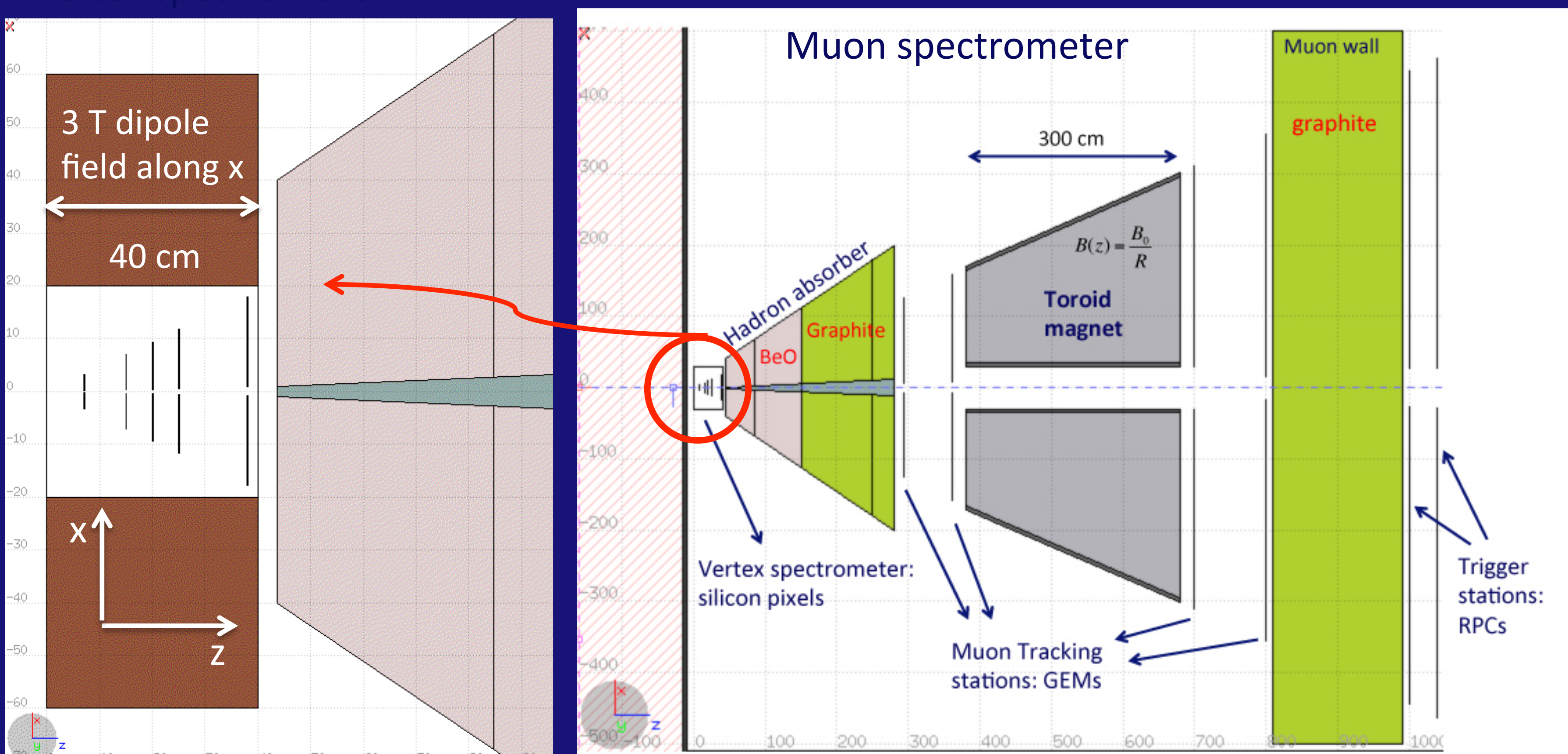
- First order hadron gas-QGP phase transitions: caloric curve with dilepton thermometer
  - *T* vs energy density with beam energy scan: search for a possible flattening of T_{slope}

- Beam Energy scan in Pb-Pb collisions:
  - √s = 4.5 – 17.3 GeV CERN SPS

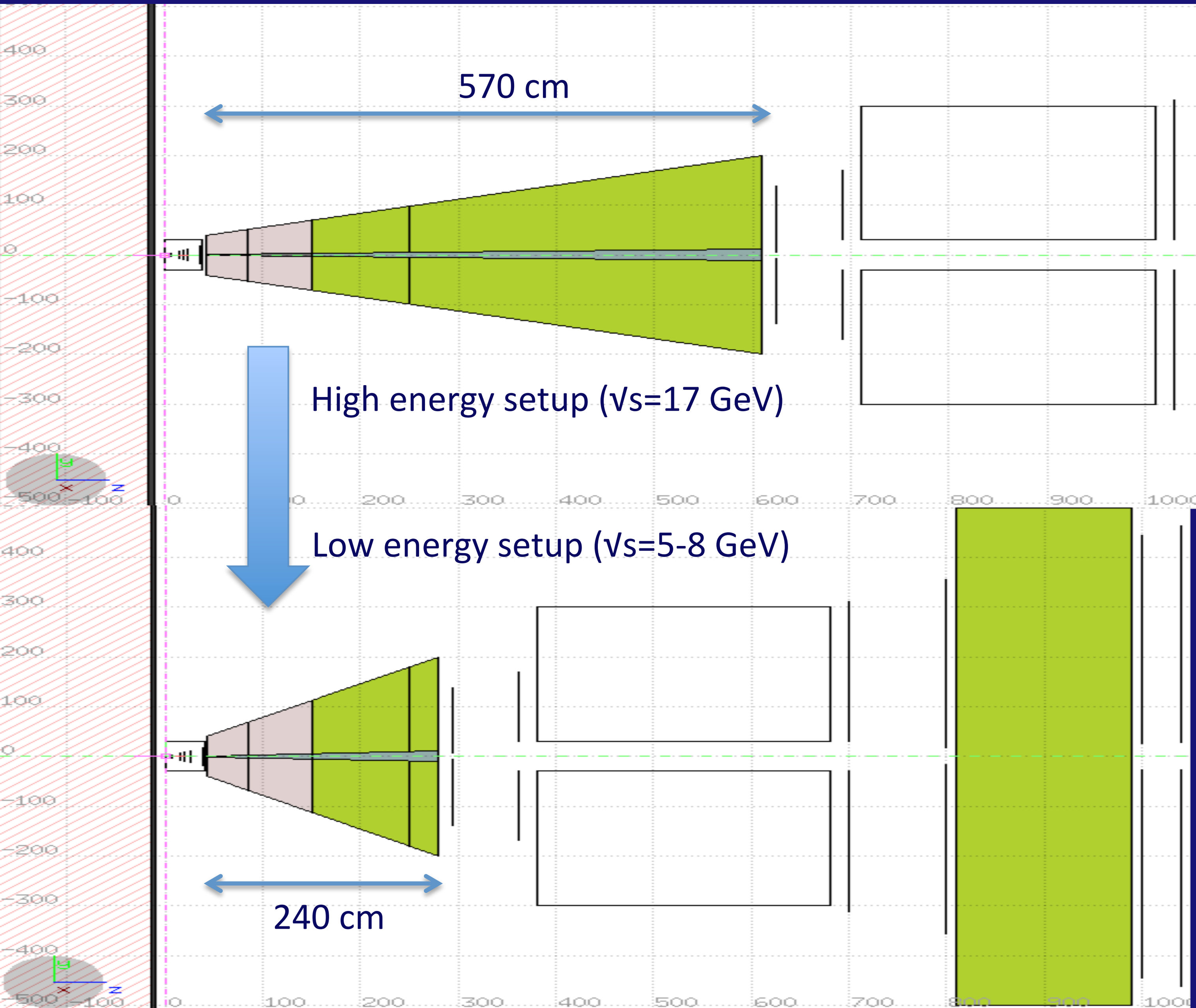
The NA60+ proposal at the CERN SPS

- NA60+ layout close to NA60:
  - precision muon measurement with tracking before and after hadron absorber
  - possibility of adapting the set-up to cover the same kinematic region for various beam energies

- NA60 experiment was housed in the ECN3 underground zone
  - dismantled in 2010 to make space for NA62 installation



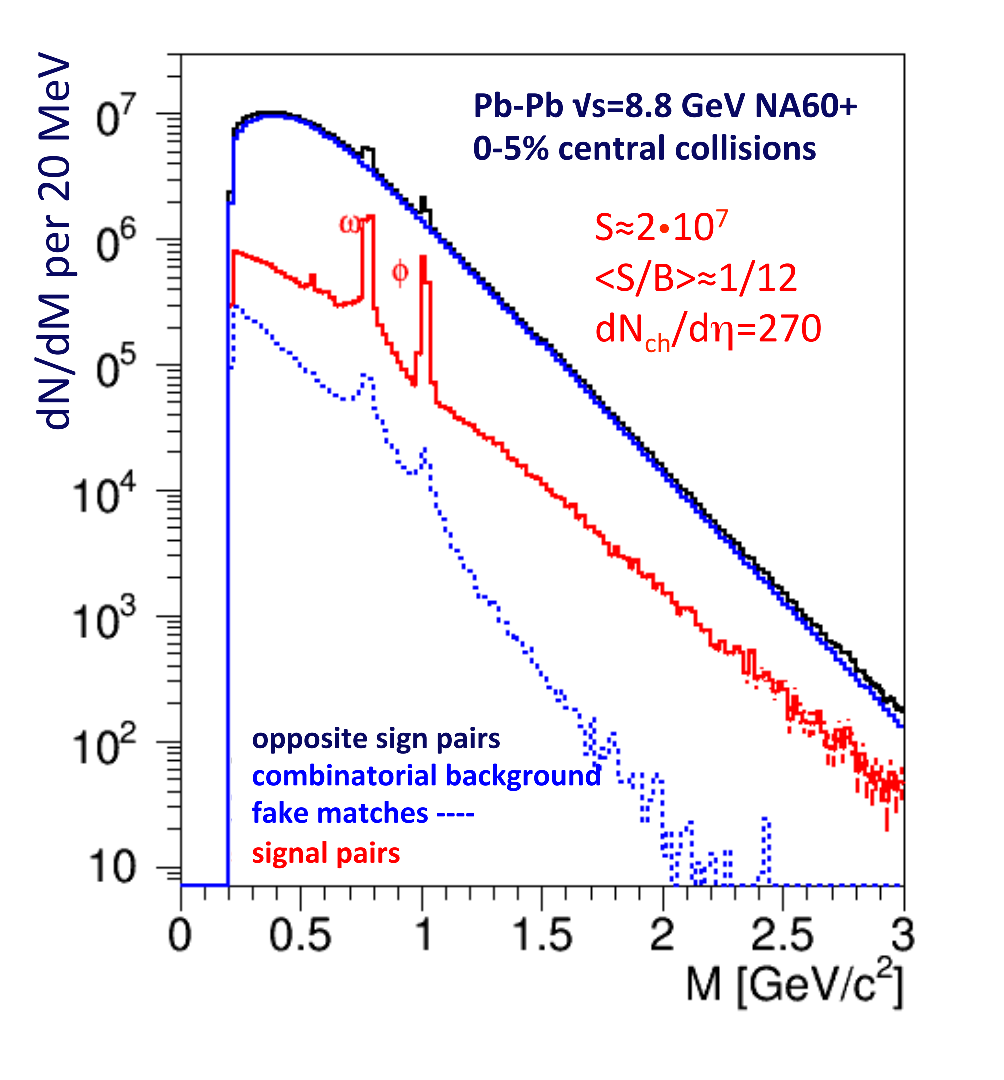
Scalable spectrometer for a beam energy scan √s=4.5-17 GeV



Scaling in terms of:

- absorber thickness
- longitudinal positions of detectors

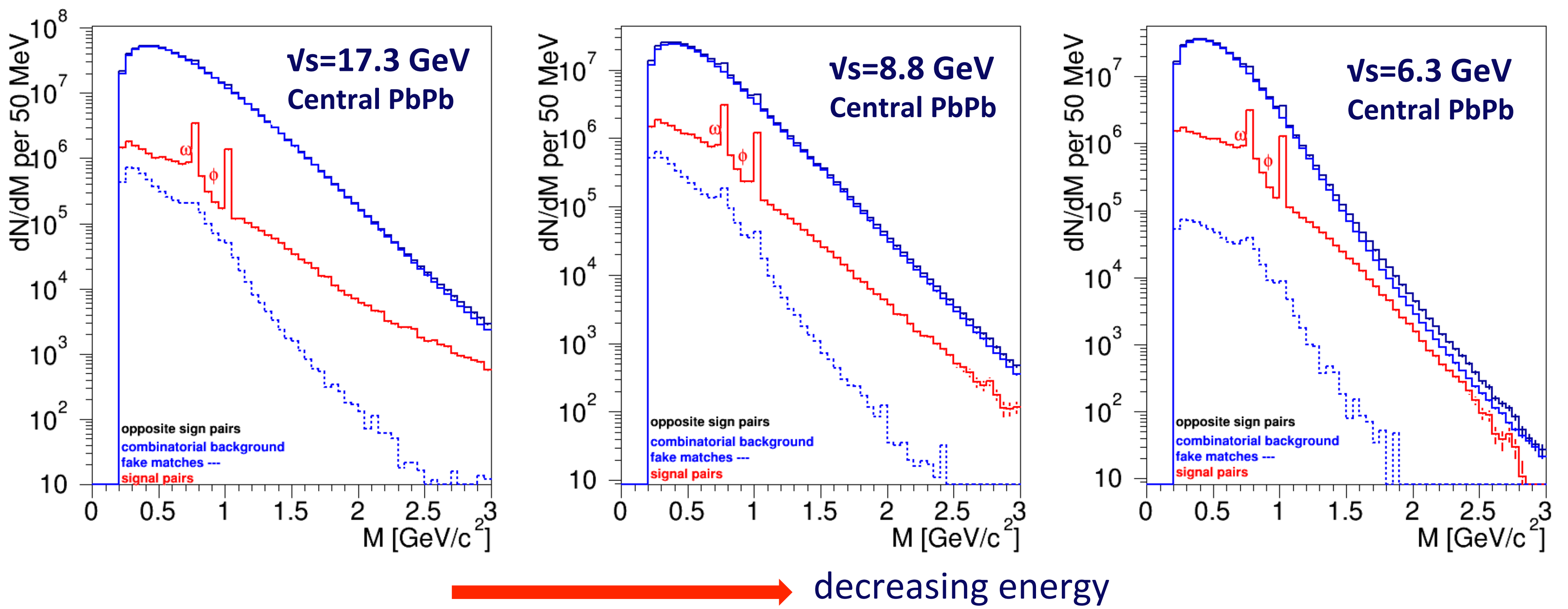
NA60+ performance for thermal radiation in central Pb+Pb : data sample size and quality (example for √s=8.8 GeV)



- $2 \cdot 10^7$ reconstructed signal pairs - factor 100 over NA60
- Combinatorial background: μ from π,K or hadron puch-through - B/S similar as in NA60
- Fake matches: signal μ matched to wrong track in pixel telescope - much better than NA60
- Mass resolution 10-15 MeV - factor ≈2 better than NA60

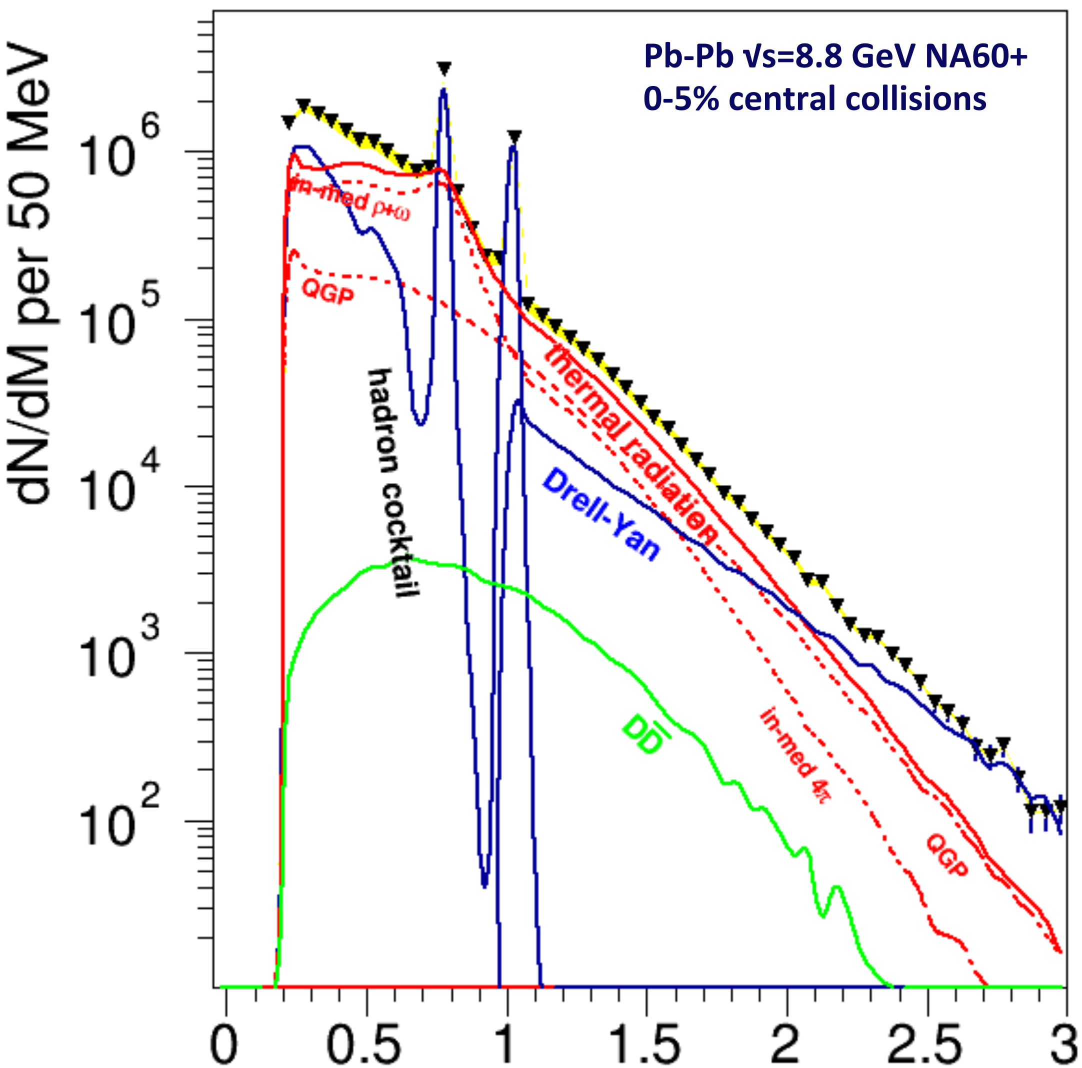
NA60+ performance for central Pb+Pb in beam energy scan: data samples at √s=6.3-8.8-17.3 GeV

$2 \cdot 10^7$ reconstructed signal pairs at each energy



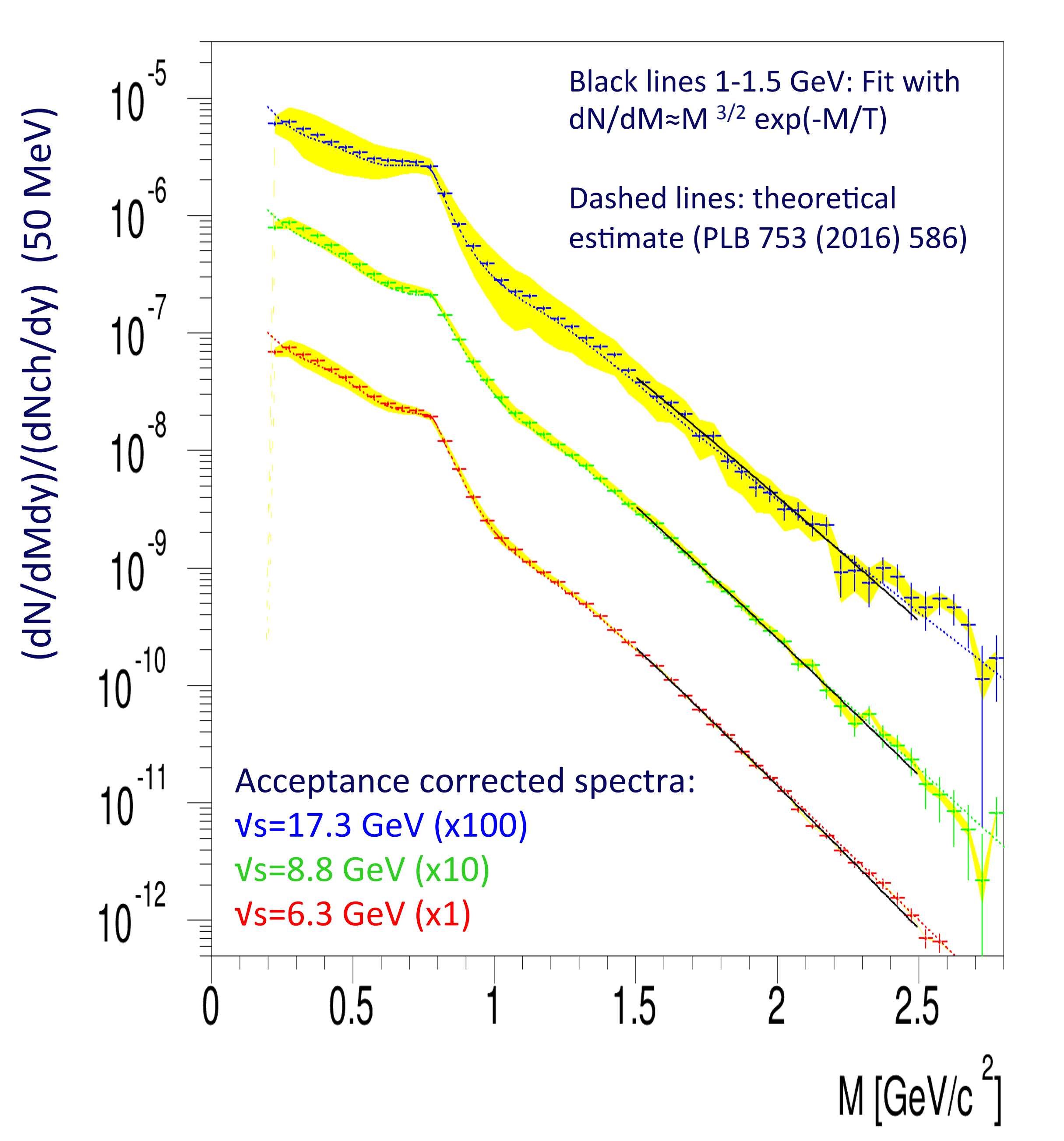
- From full SPS energy towards low energy:
  - Significant reduction of Drell-Yan
  - Open charm becomes negligible
  - Decrease of QGP

Signal mass spectrum: example for central Pb+Pb at √s=8.8 GeV



- Signal spectrum:
  - Subtractions of comb. Bkg (0.5% precision)
  - Subtraction of fake matches
- Dilepton sources M<1 GeV:
  - Thermal radiation ρ+ω
  - Thermal radiation QGP
  - Freeze-out hadron cocktail (η, ω, ϕ) (M<1 GeV)
- Dilepton sources M>1 GeV:
  - Thermal radiation 4π
  - Thermal radiation QGP
  - Drell-Yan
  - Open charm

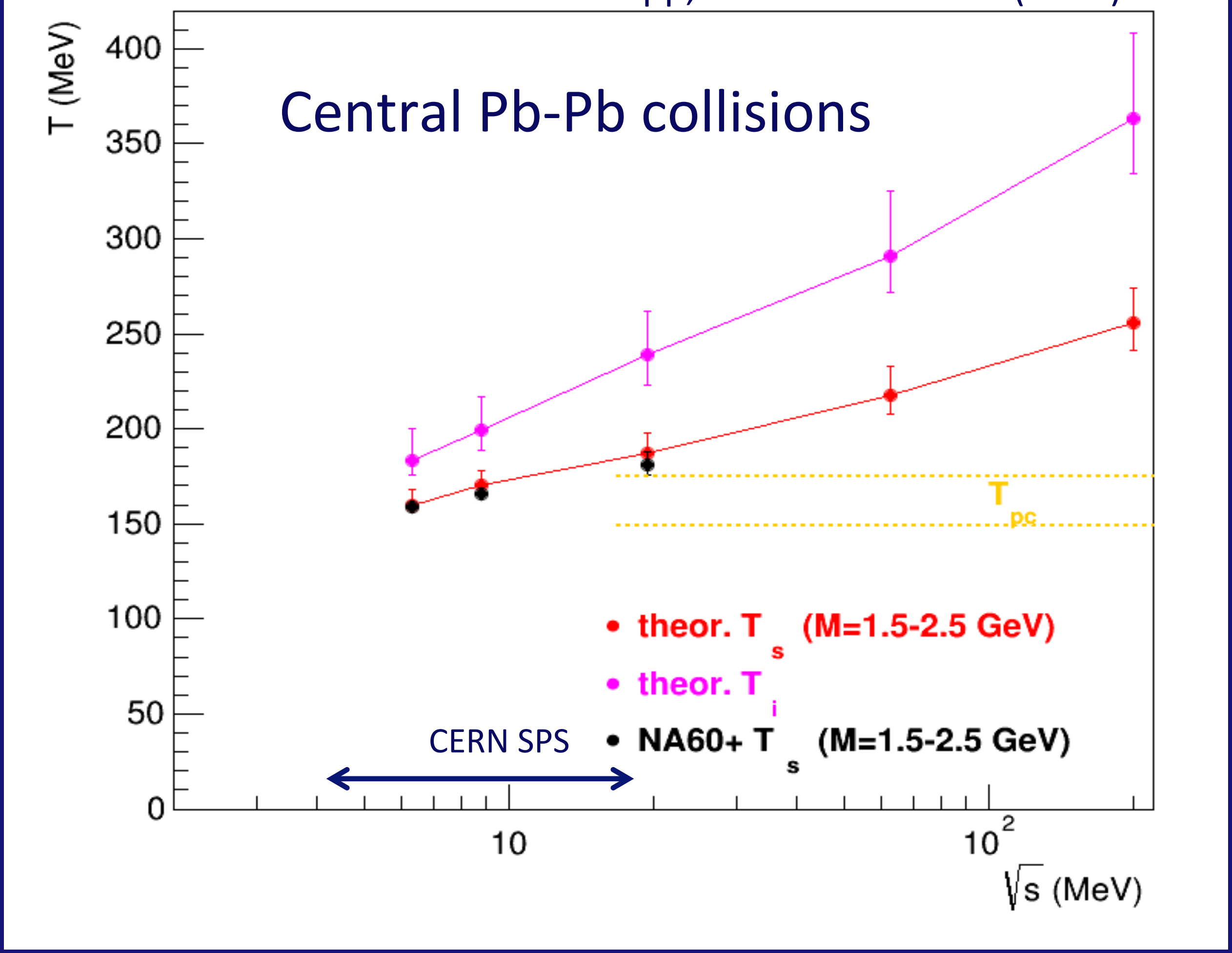
The measurement of temperature from thermal spectra



- Thermal spectra from subraction of:
  - Freeze-out cocktail
  - Open charm
  - Drell-Yan
- Thermal radiation yield meareusable up to 2.5-3 GeV
- Temperature:
  - Acceptance correction
  - 1.5<M<2.5 GeV fit to $dN/dM \approx M^{3/2} \exp(-M/T)$
  - Systematic uncertainty: vary bkg subtraction by 0.5% before fitting

Towards a precise measurement of a caloric curve in high-energy nuclear collisions: NA60+ performance

Theoretical estimates from Rapp, van Hees PLB 753 (2016) 586



NA60+: precision of T measurement at MeV level
Sensitivity to flattening of T!

The second chapter of the story: chiral symmetry restoration

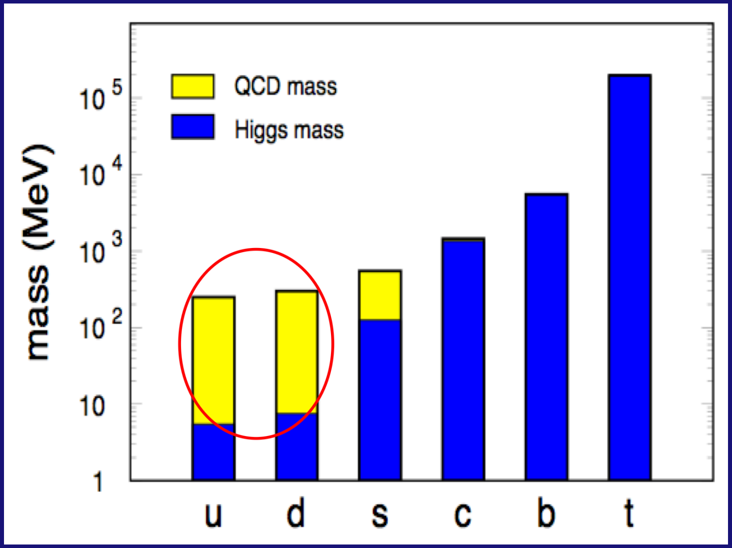
Key ideas:

- ρ-a_1 chiral mixing
- Thermal radiation at onset of deconfinement in 1<M<1.5

Chiral symmetry breaking and the hadron spectrum

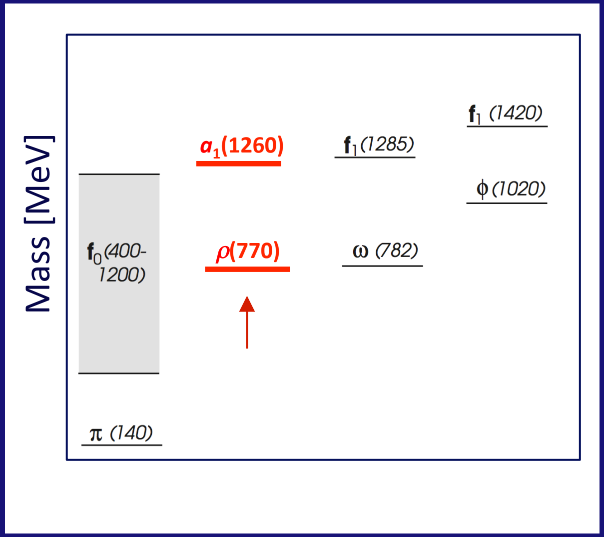
Chiral symmetry breaking: masses of the 6 quark flavours

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



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

Hadron spectrum

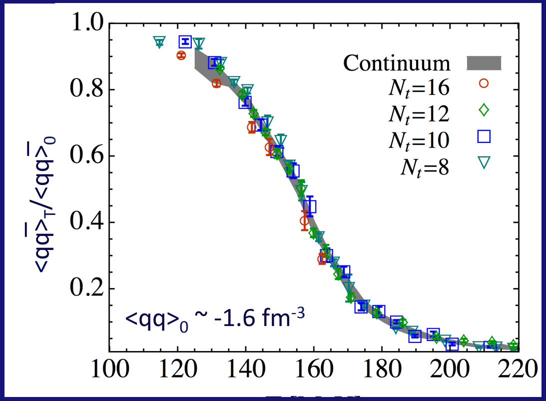


Vector-Axial vector splitting (also pseudoscalar-scalar) in the physical vacuum due to spontaneous breaking of chiral symmetry

Chiral symmetry restoration and the hadron spectrum

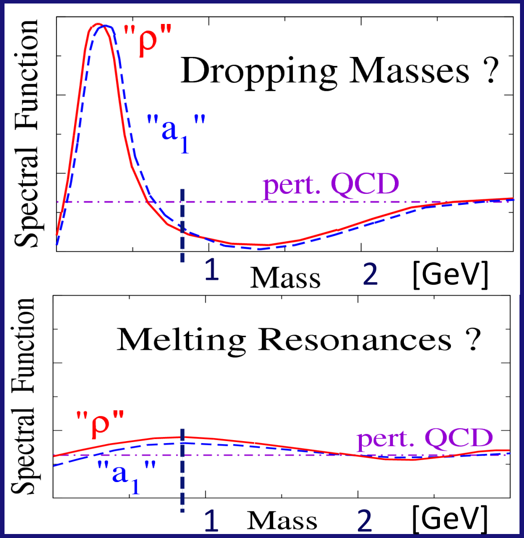
at T_c: Chiral Restoration

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



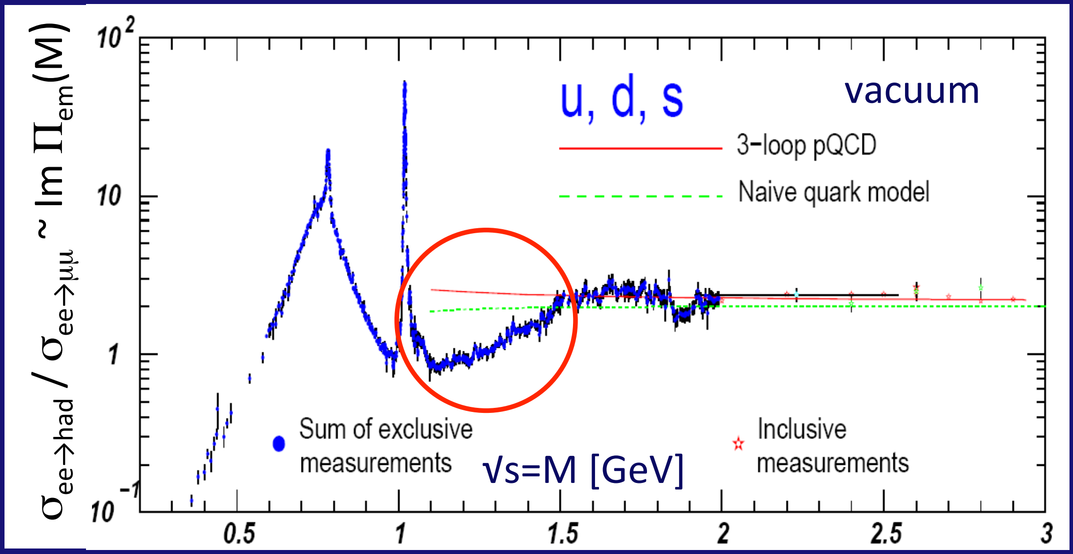
chiral symmetry restoration

Lattice QCD, $\mu_B=0$



Vector and axial vector spectral functions expected to change (left: two possible qualitative scenarios)

Chiral mixing in the vector/axial vector spectral functions (at correlator level)



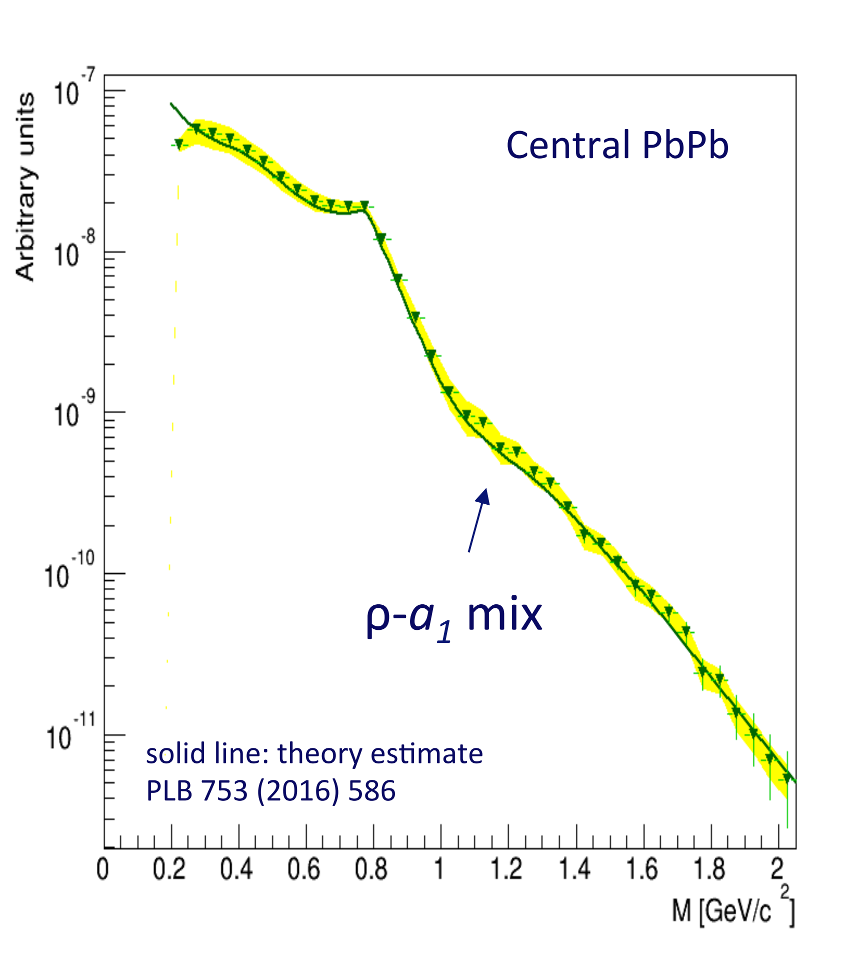
What visible effects on the dilepton spectrum?

In vacuum (left) the region M=1-1.5 GeV is significantly depleted

Chiral mixing: M=1-1.5 GeV is filled by $\pi\, a_1 \rightarrow \mu\mu$ (trace of bumpy structure from a_1?)
➔direct evidence of chiral symmetry restoration

The measurement of ρ-a_1 chiral mixing

- Key idea: measure the thermal dilepton spectrum at the onset of deconfinement best sensitivity because of negligible QGP and increased lifetime in the mixed phase



- Performance for measurement of thermal radiation close to onset of deconfinement based on
  - Total thermal yield = thermal yield from hadronic phase at the level of central Pb-Pb at 20-40 GeV (no QGP)
  - same background level as central Pb-Pb 40 GeV

Study of spectrum up to M ≈ 2 GeV possible

sensitivity to ρ-a_1 chiral mixing

Summary and outlook

- Feasibility studies for caloric curve and ρ-a_1 mixing well advanced

- Further studies under way for:
  - J/ψ , ψ(2S)
  - open charm
  - χ_c

- Further studies for apparatus layout:
  - Detector technologies (e.g. monolithic pixels, gems, magnet)
  - Optimization for possible space constraints

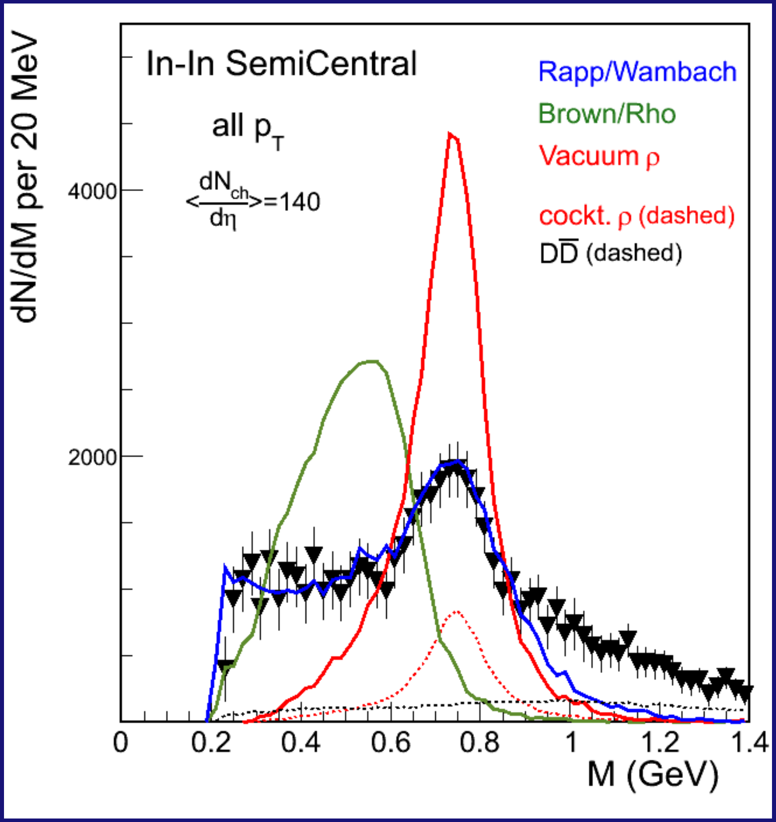
- Timeline: Still being discussed (no explicit involvement of funding agencies up to now)

- Formation of an international collaboration and expression of interest (presently interest from physicists from several institutions: Cagliari (INFN), Padova (INFN), Torino (INFN), Munich (TUM), Stony Brook University, Rice University, Lyon (IPNL))

backup

Towards chiral restoration: ρ mass shift vs. broadening

PRL 96 (2006) 162302; AIP Conf.Proc. 1322 (2010) 1

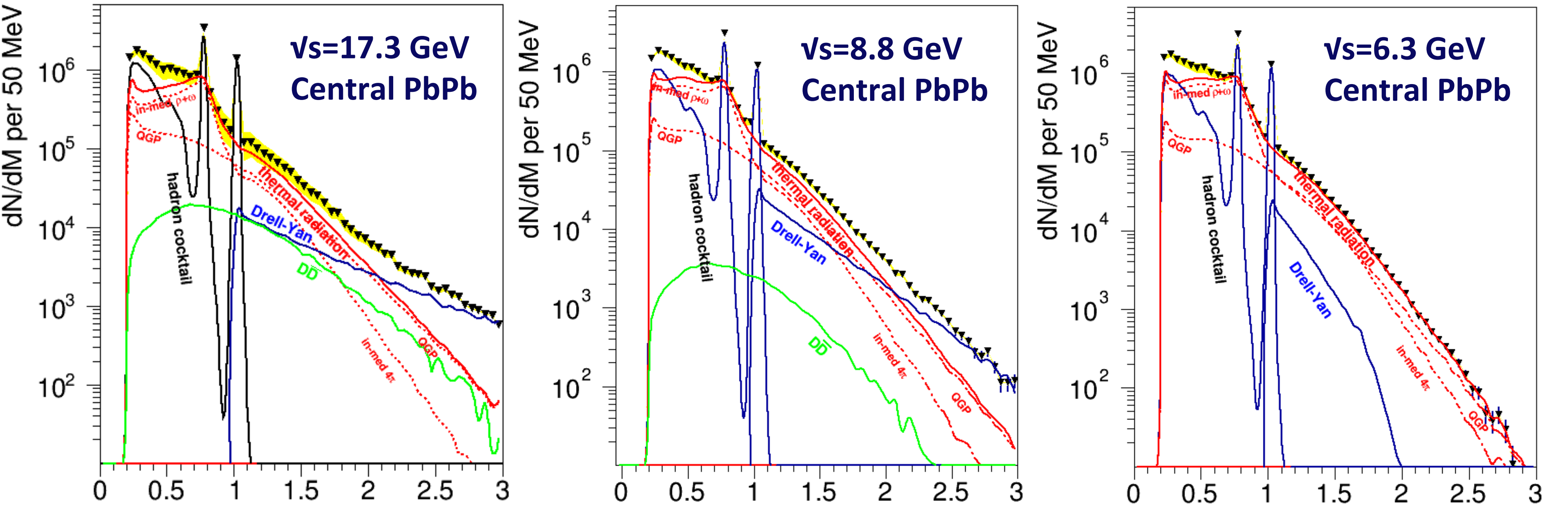


- NA60 In-In 160 AGeV - data before acceptance correction
- Comparison to theoretical models:
  - Brown/Rho - dropping mass scenario
  - Rapp/Wambach – only broadening

Strong broadening of ρ observed (no mass shift) → 'hadrons melt'
(indirect) evidence of chiral symmetry restoration

On chiral restoration and ρ melting: *P.M.Hohler and R. Rapp, PLB 731 (2014) 103*

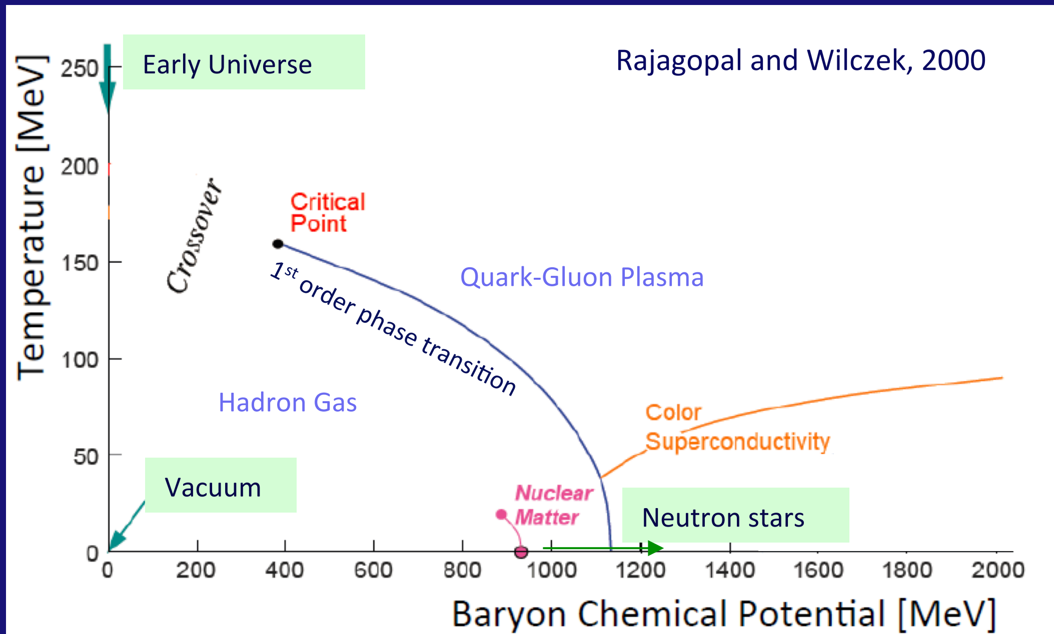
Signal mass spectra vs √s



decreasing energy

- From full SPS energy towards low energy:
  - Significant reduction of Drell-Yan
  - Open charm becomes negligible
  - Decrease of QGP

Theoretical guidance for the QCD phase diagram



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

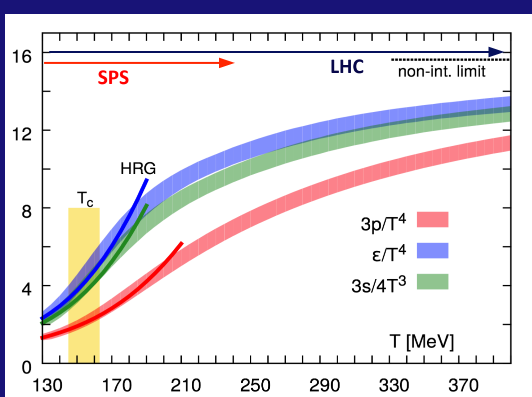
Small μ_B (Lattice QCD)

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

Large μ_B, moderate T (field th.)

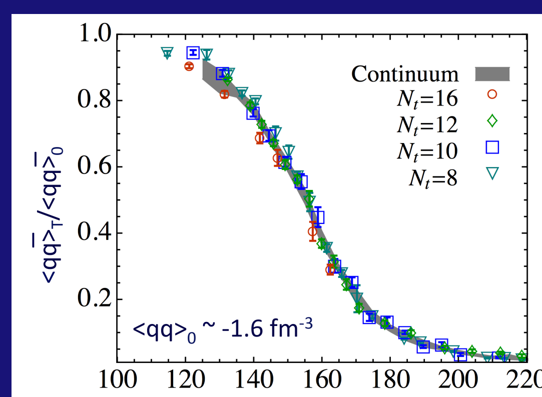
QCD critical point,
1st order transition

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

Requirements (beam, space)

- Size of the experiment
- → further studies needed to fit North Area Halls as ECN3

- To get the necessary integrated luminosity, beam intensities of $\sim 10^7$ ions/s are mandatory (assuming ~5 s bursts)
  - → does this restrict the choice to ECN3?
  - → is it possible to share it with other experiments?

- The physics program of NA60+ includes, in terms of beam:
  - → few week periods with ion beams from ~20 GeV to top SPS, performing a detailed energy scan (example: 20, 30, 40, 80, 120, 160 GeV/nucleon)
  - → corresponding periods of proton beams (reference), scan could be coarser, beam intensities $\sim 5\times10^8$ p/s

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)

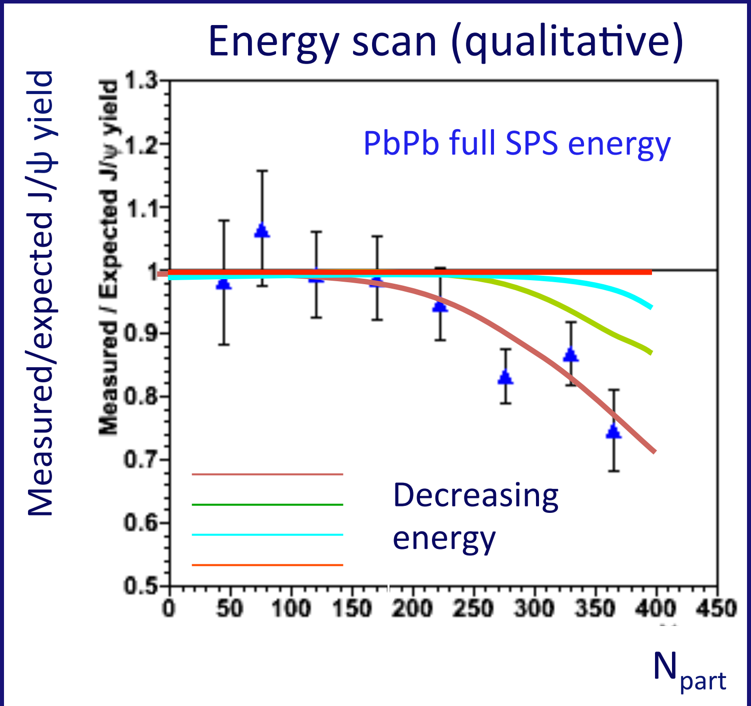
- pA data at some energy point also needed

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

Possible detector strategy

- Vertex spectrometer
  - Monolithic active pixel sensors:
    - → Low material budget (5-10 times better than hybrid pixels)
    - → Possibly lacking in terms of read-out speed (~1MHz needed)
    - → Fluences~ $10^{14} n_{eq}/cm^2$
- Hadron absorber
  - → BeO-graphite sections, variable thickness
- Muon spectrometer
  - → GEM with ~200 μm space resolution for tracking chambers
  - → Toroid magnet (BL=0.75 Tm at r = 1m)
- Trigger
  - → Muon triggering based on two stations positioned after a C wall
  - → Possibility of using (also) vertex spectrometer information

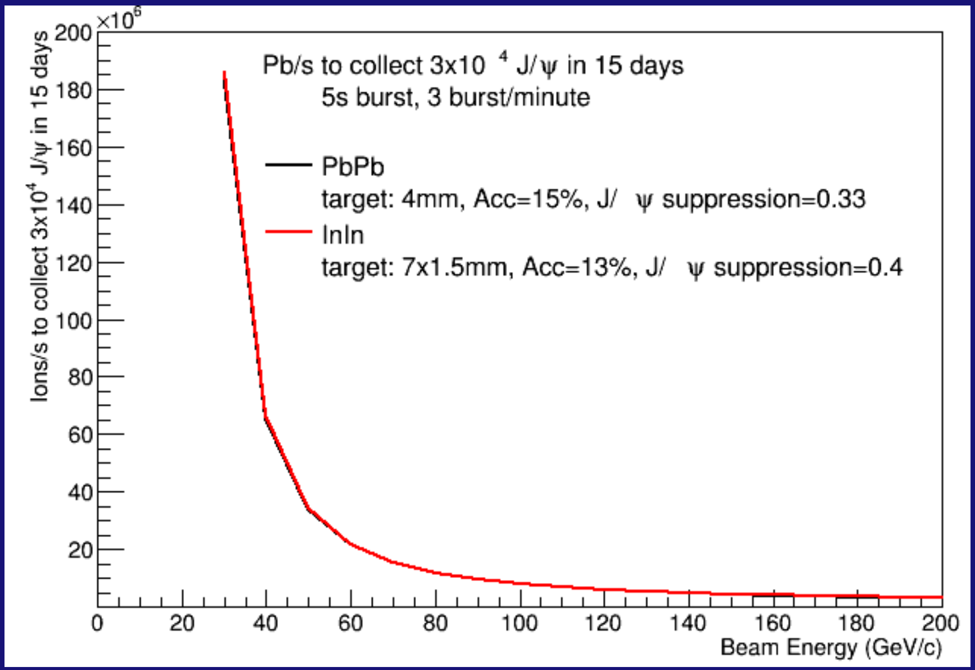
Charmonium and open charm



- 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) / ($D+\bar{D}$)

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