NA60+
Status and plans

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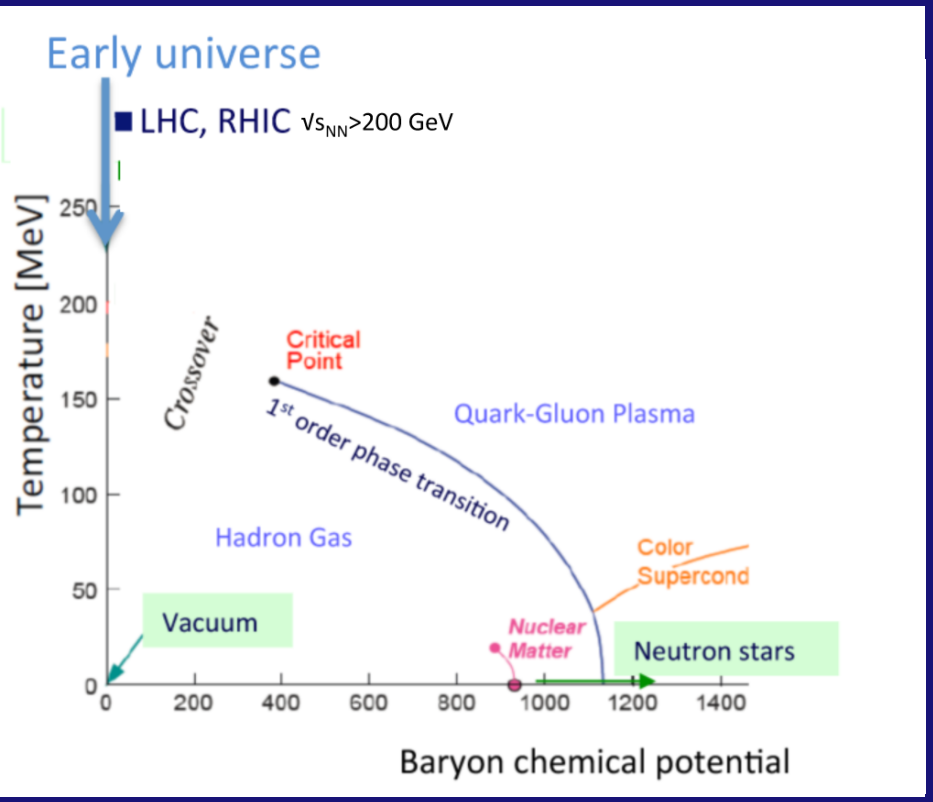
INFN and University of Cagliari

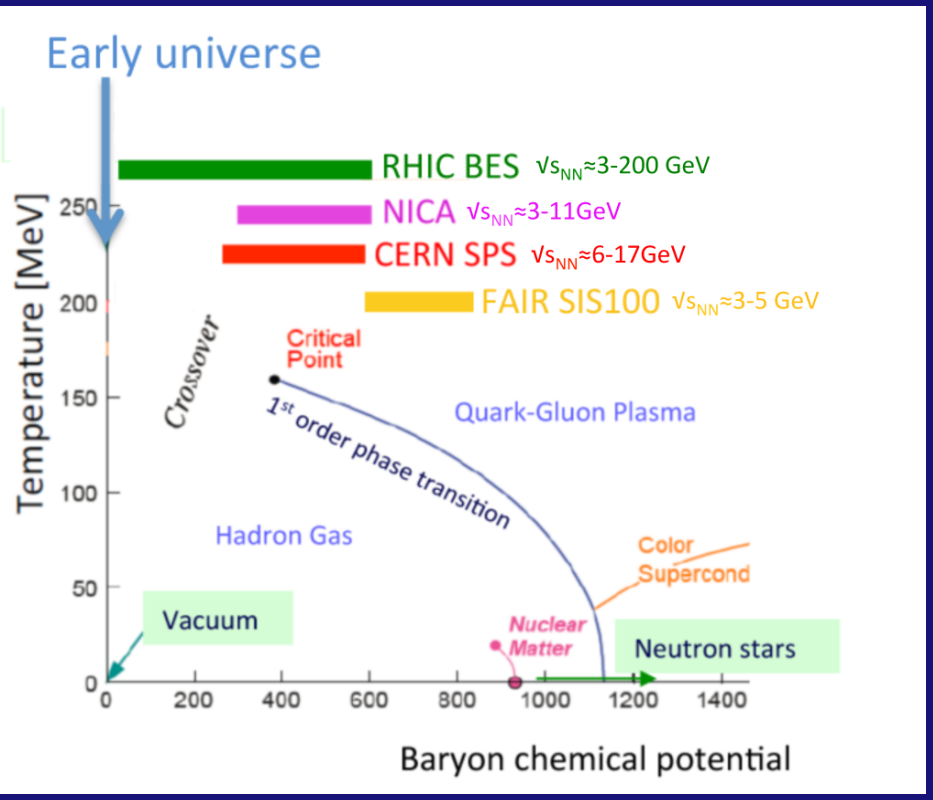
Physics Beyond Colliders - QCD working group meeting
14/06/2018

The high energy frontier: present status



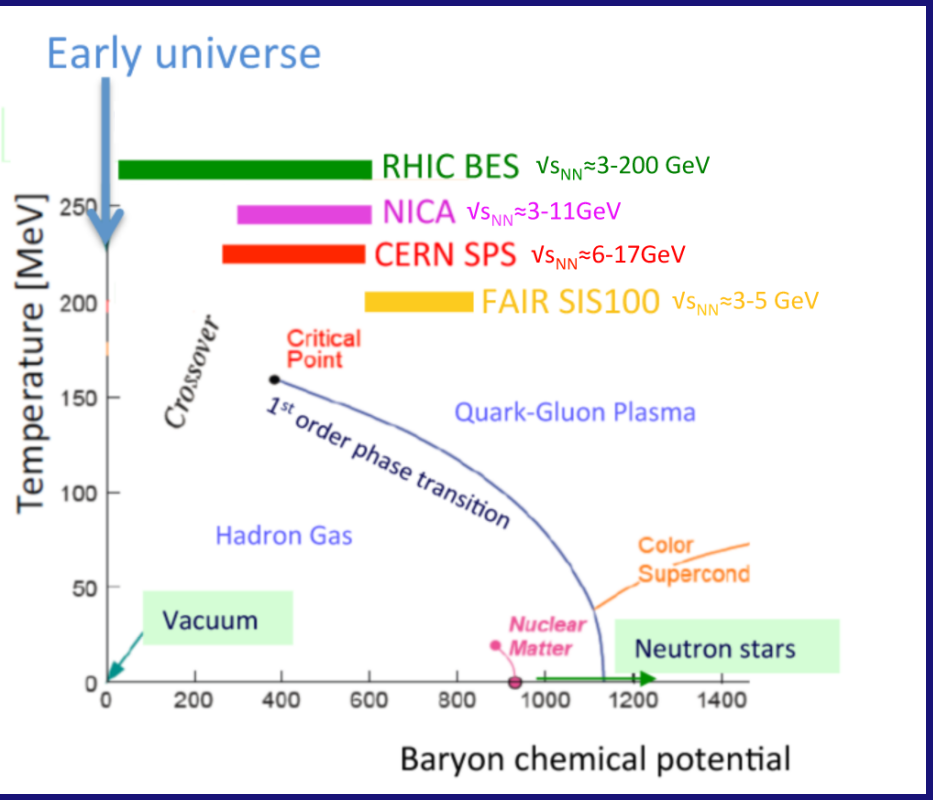
- QCD phase diagram mostly investigated around μ_B=0:
  - Cross-over transition at T_c=155 MeV
  - Produced matter: strongly interacting QGP ➔nearly ideal fluid

The low energy frontier: the QCD phase diagram at high baryon potential μ_B



- Largely unexplored:
  - Existence of critical point and first order phase transition put forward
- First order phase transition:
  - Measurement would provide first direct evidence (in thermodynamic sense) of a phase transition to the QGP
- Additional chiral phase transition:
  - Exploration of changes in the hadron spectrum

The low energy frontier: the QCD phase diagram at high baryon potential μ_B



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Low energy experiments at different facilities:

- RHIC, SPS, NICA, FAIR, (JPARC?)

Investigating the QCD phase diagram at high μ_B: dilepton measurements

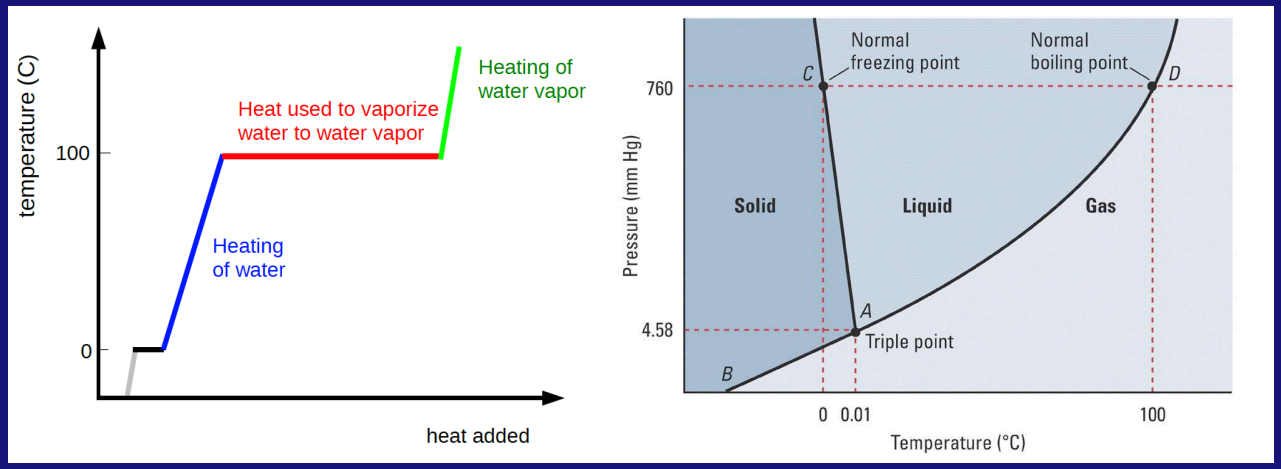
- First order phase transition:
  - Caloric curve T vs energy density
- Chiral symmetry restoration:
  - ρ/a_1 chiral mixing ➔ first measurement of spectral properties of a_1 at chiral restoration
- J/ψ and open charm at low energies

Investigating the QCD phase diagram at high μ_B: dilepton measurements

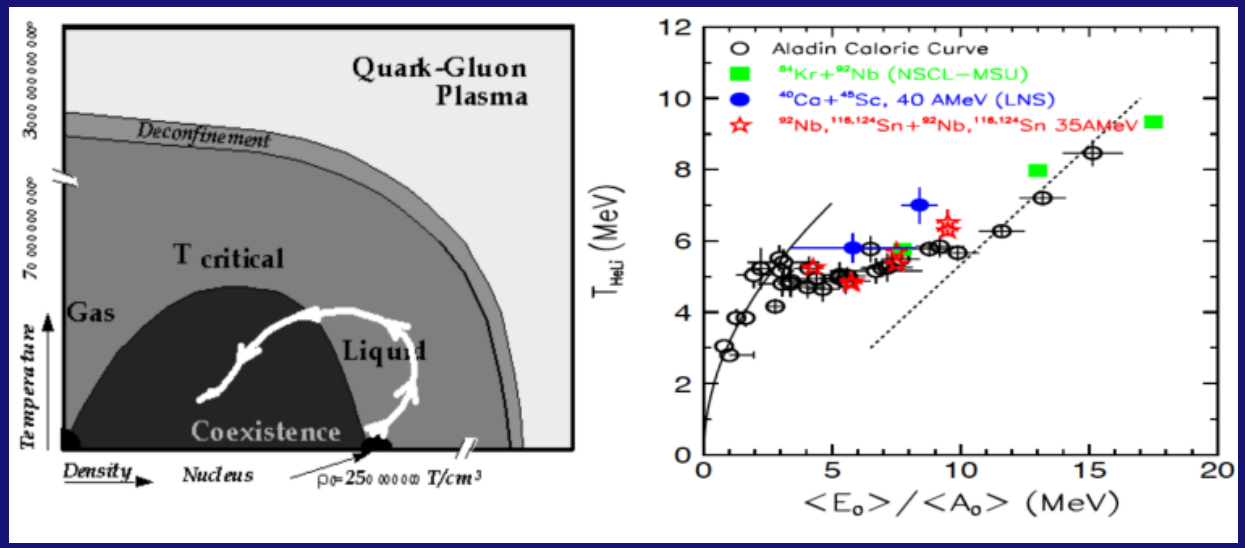
- First order phase transition:
  - Caloric curve T vs energy density (more comprehensive performance plot)
- Chiral symmetry restoration:
  - ρ/a_1 chiral mixing ➔ first measurement of spectral properties of a_1 at chiral restoration
- J/ψ and open charm at low energies (first studies on charm)

First order phase transitions and caloric curves

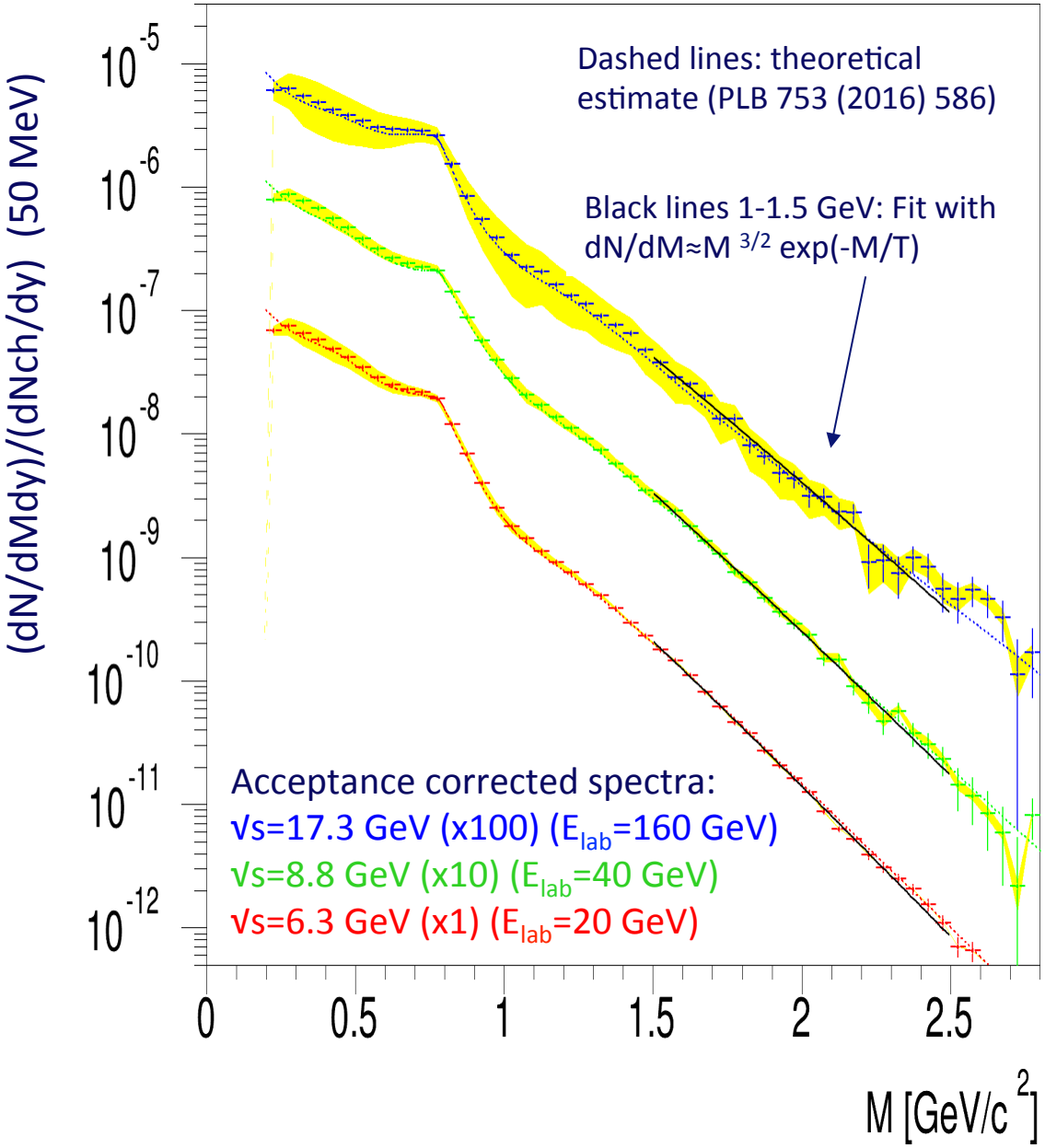
- Caloric curve and phase diagram of water



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



NA60+: principle of the measurement of T vs energy density



- T: fit of dilepton mass spectrum in 1.5<M<2.5 GeV after charm and Drell-Yan subtraction

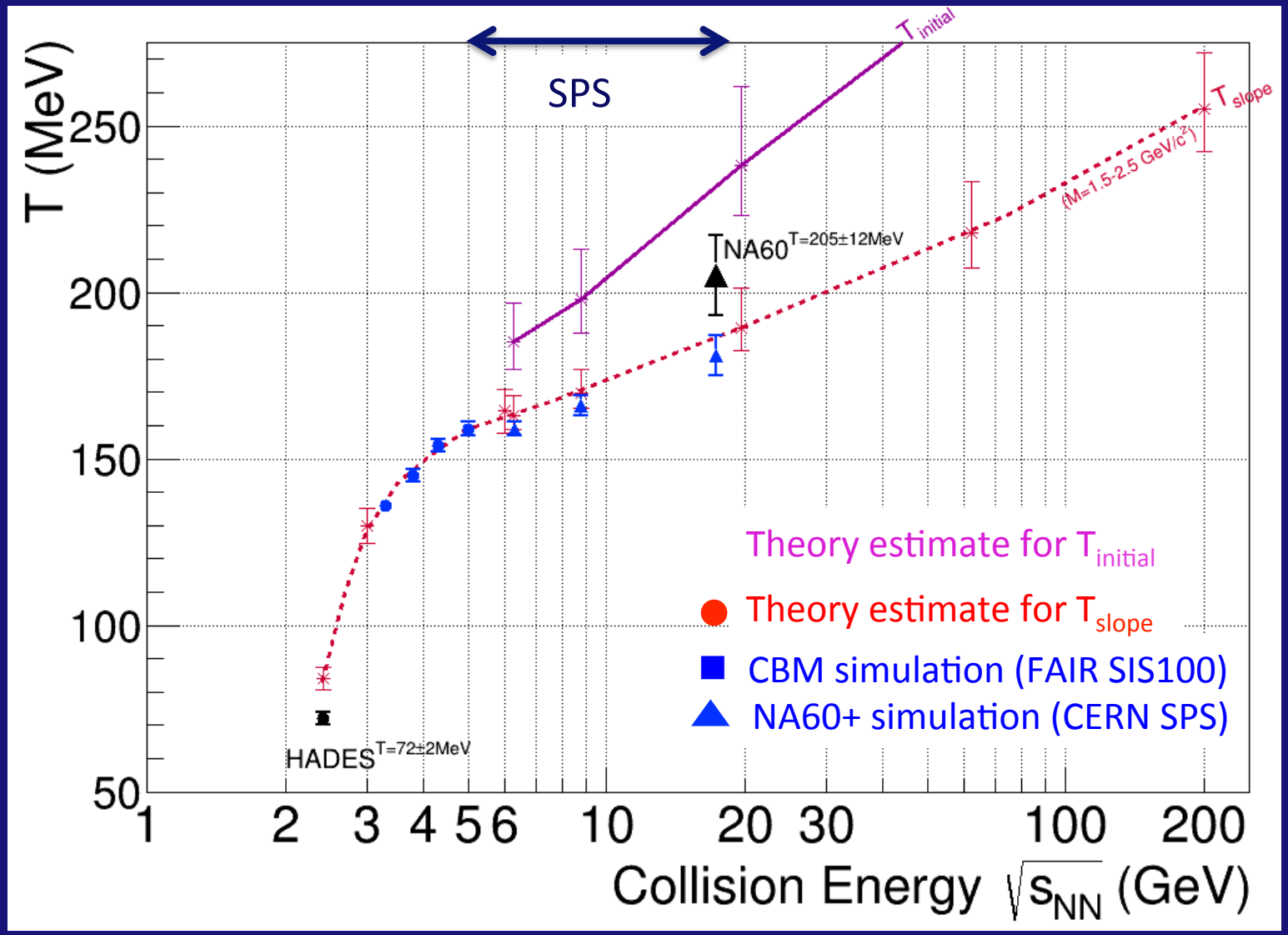
$$dN/dM \approx M^{3/2} \exp(-M/T_{slope})$$

- T_{slope} tracks the initial temperature of the medium

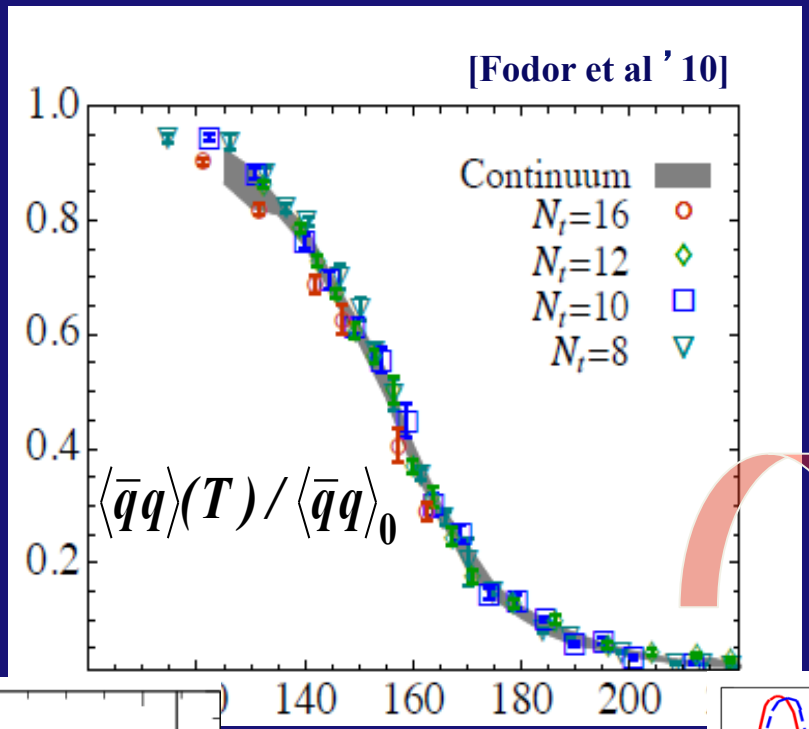
- Measurement perfomed at several collision energies (beam energy scan)

NA60+: expected performance for caloric curve

Indication of flattening around √≈5-10 GeV → unique energy interval covered by SPS

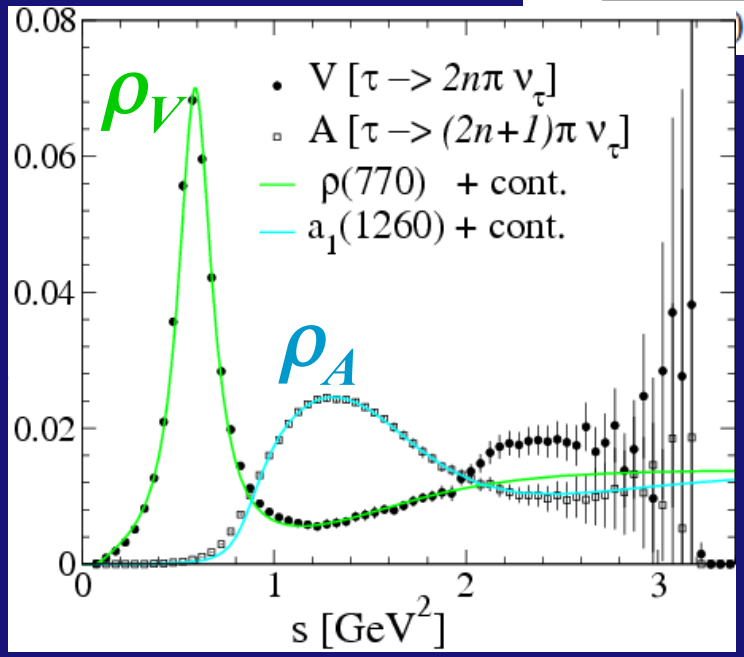


QCD chiral symmetry restoration

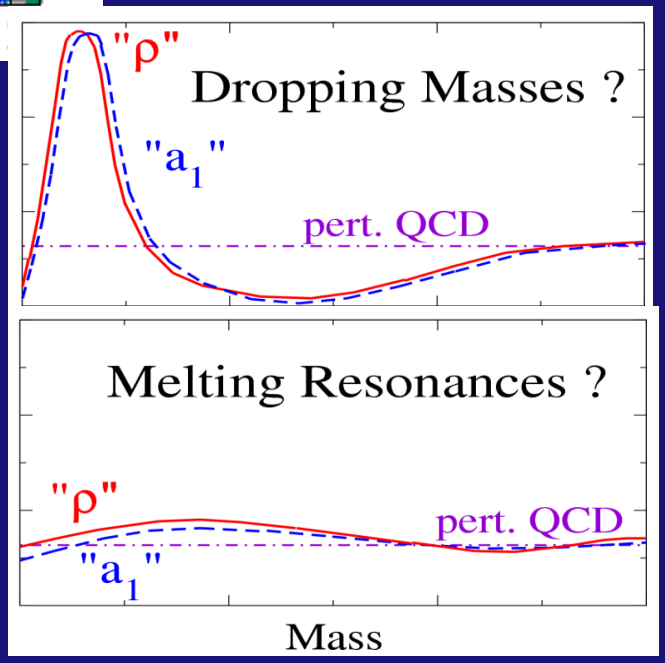


Vacuum

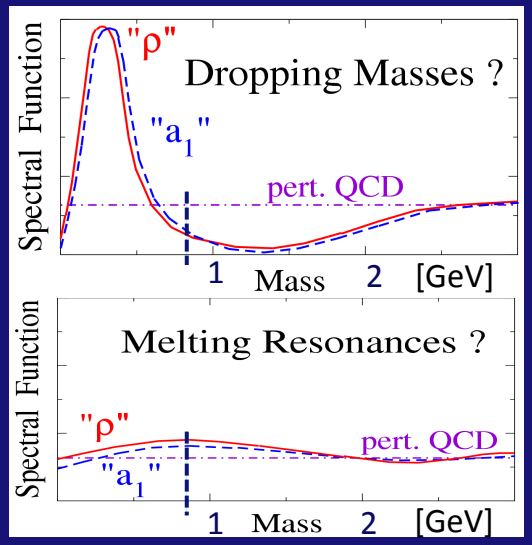
Chiral Restoration



$$\int \frac{ds}{\pi}(\rho_V - \rho_A) = -m_q\langle\bar{q}q\rangle$$



NA60+: axial-vector spectral function at chiral restoration

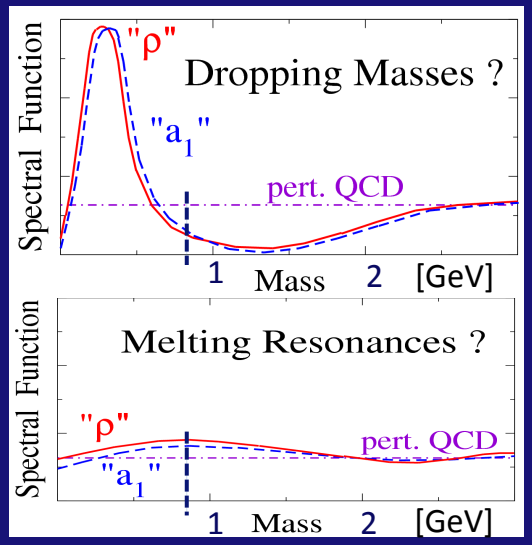


Ultimate test of chiral restoration:

- show that the vector (ρ) and axial-vector (a_1) spectral functions should become (almost) degenerate

a_1 never measured in nuclear colisions. How to measure it?

NA60+: axial-vector spectral function at chiral restoration



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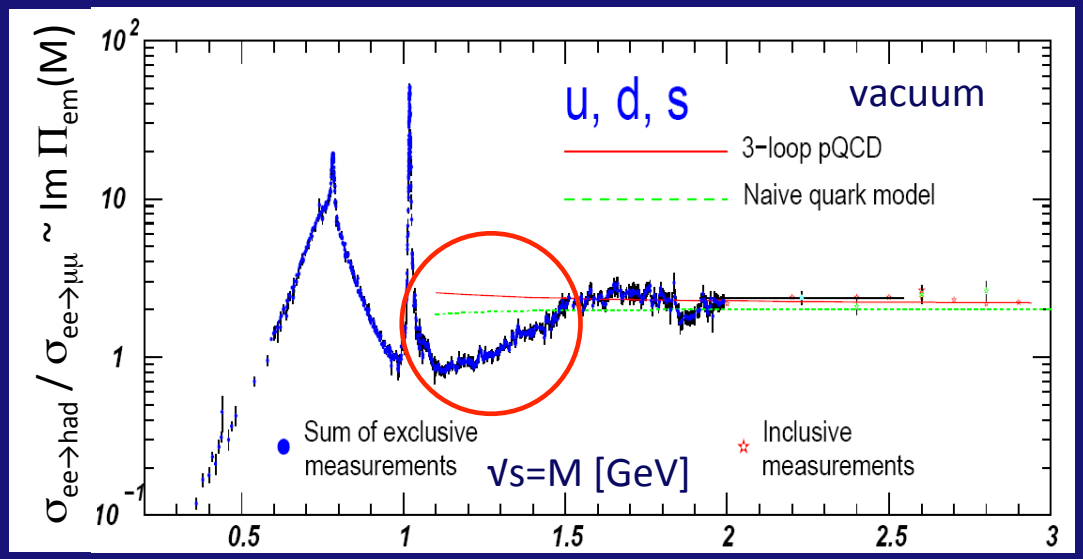
Principle of the measurement

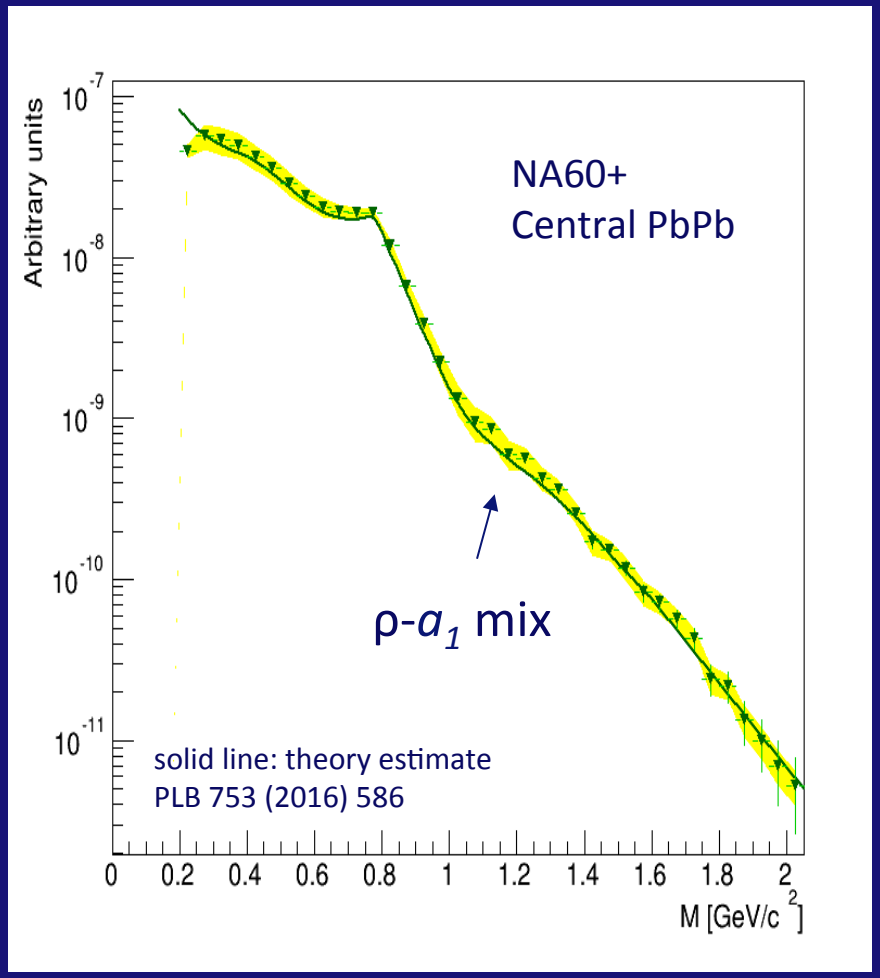


a_1 not coupled to dileptons in vacuum

But in nuclear medium:

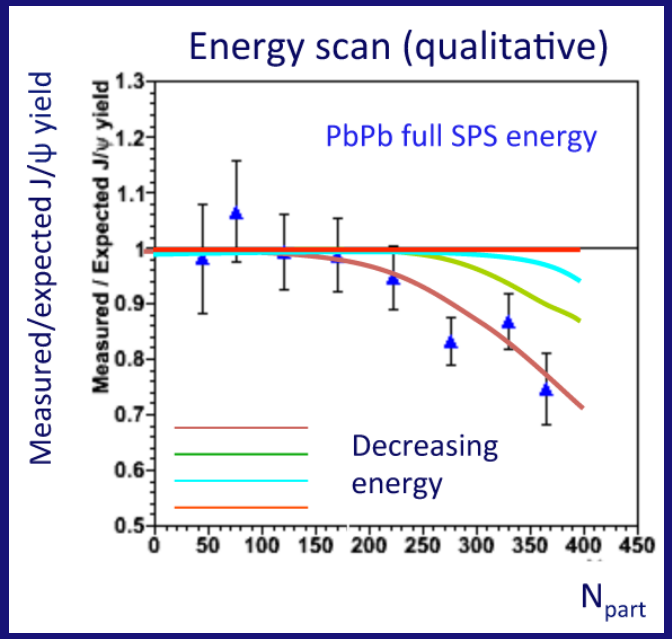
$\pi\, a_1 \rightarrow \mu\mu$ in 1.5 <M <1.5 GeV via chiral mixing
➔direct evidence of chiral symmetry restoration

NA60+: performance for ρ-a_1 chiral mixing



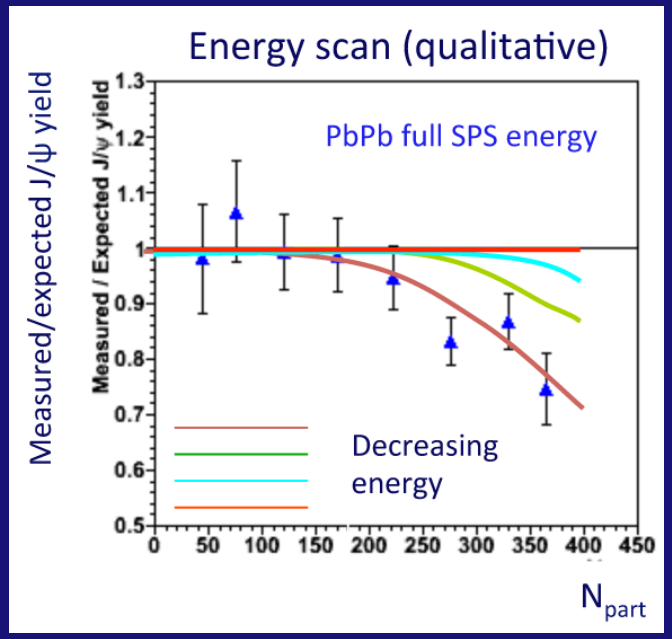
- Sensitivity to mass spectrum region 1 < M < 1.5 GeV close to onset of deconfinement:
  - very small QGP, large $\pi\, a_1$ yield

Charmonium at low energies



- Full SPS energy (160 GeV): J/ψ anomalous suppression relevant for PbPb collisions
- Energy scan: investigation of onset of J/ψ suppression ➔ relation to onset of deconfinement
- Other possible measurements: ψ(2S), χ_c

NA60+: charmonium at low energies



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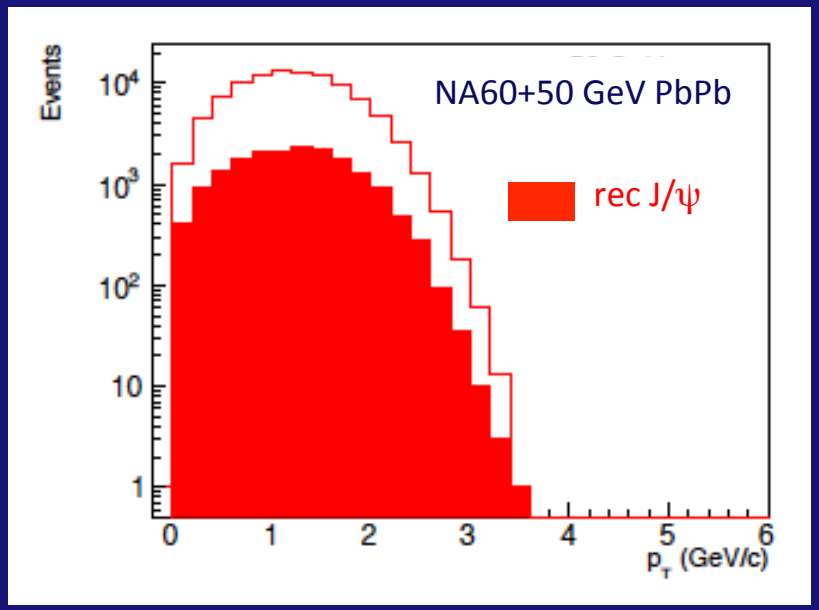
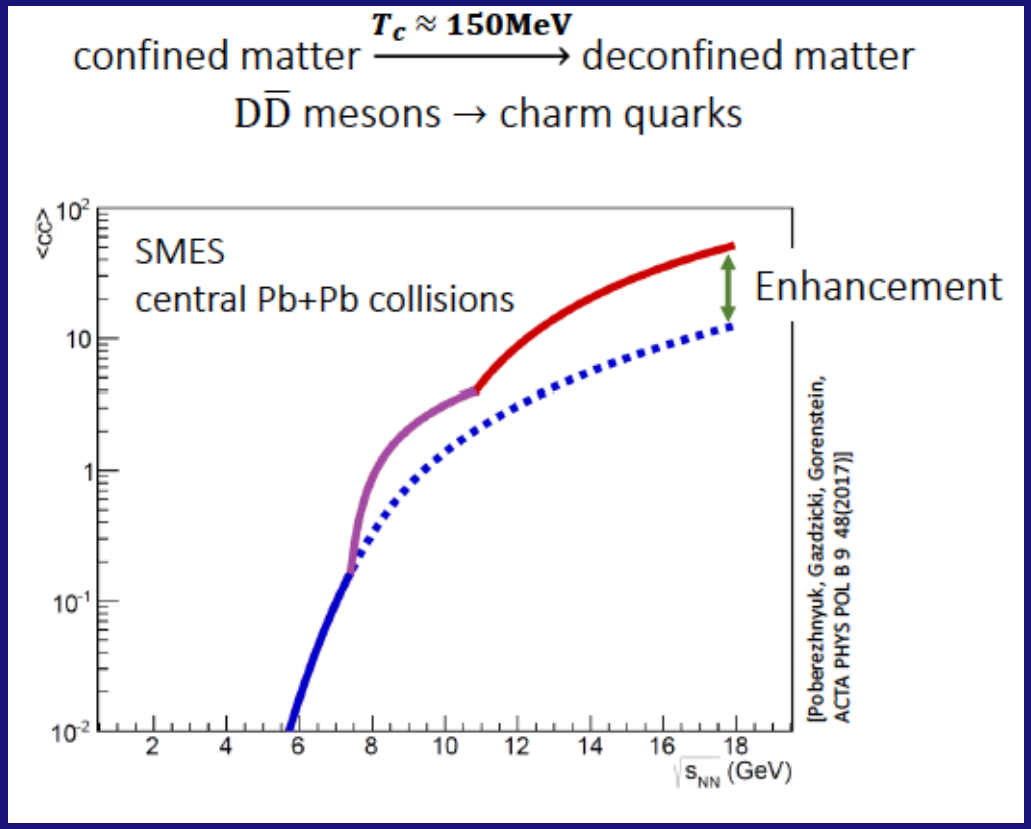


- J/ψ production feasible from top SPS energy down to ~40-50 GeV
  - Large acceptance: ~20%
  - Total sample of ~2-3 · 10^4 J/ψ

NA60+: charmonium and open charm at low energies

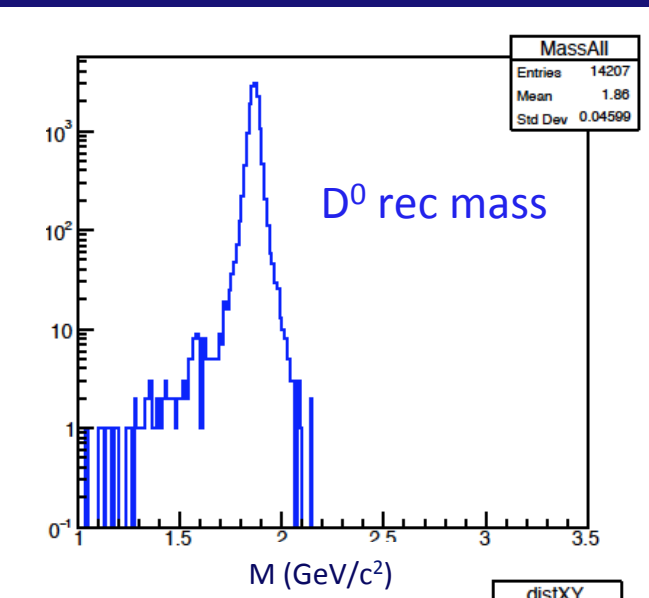


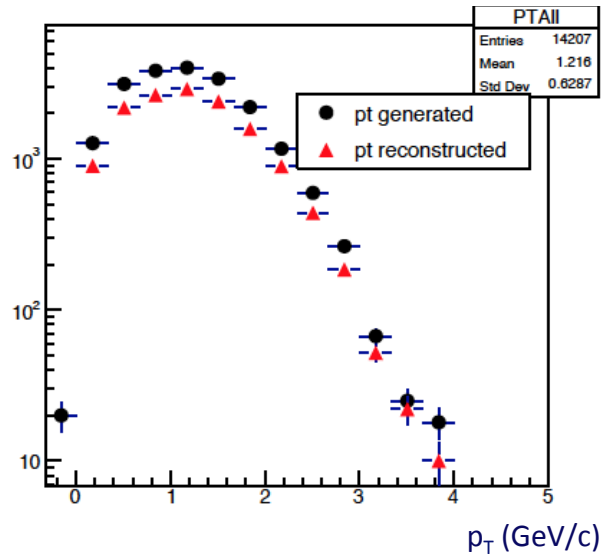
- At onset of deconfinement:
  - Change of $D\bar{D}$ production rate?
  - Onset of J/ψ suppression

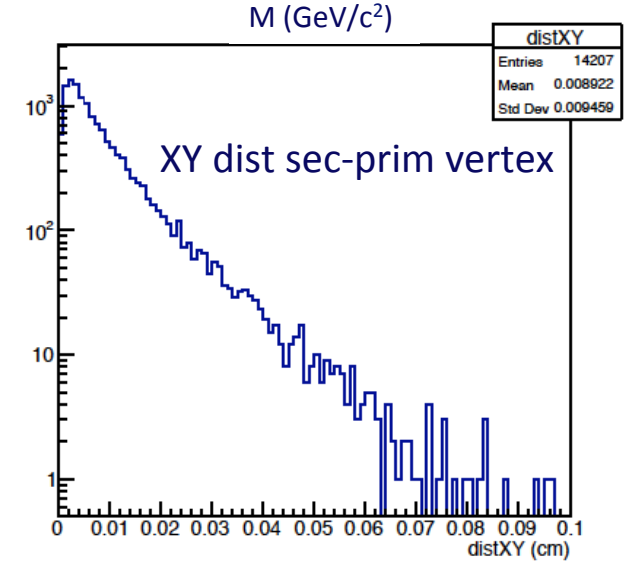
- Unique simultaneous measurement of J/ψ + $D\bar{D}$ vs energy: $\frac{\sigma_{J/\psi}}{\sigma_{c\bar{c}}}$

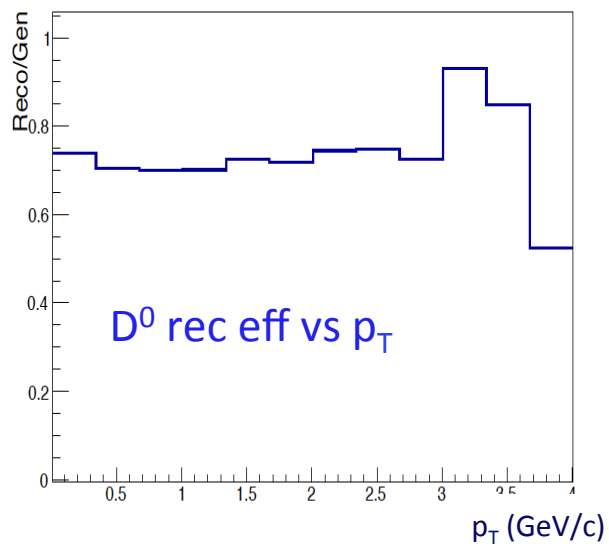
NA60+: first performance studies for open charm

- Measurement of open-charm: Hadronic decays (D➔Kπ and D➔Kππ)
  ➔standalone track reconstruction in the silicon vertex tracker









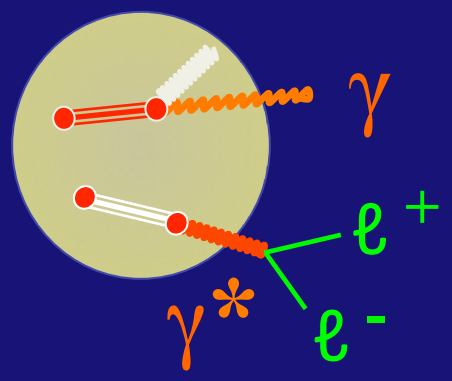
- First studies at 160 GeV:
  - Very high rec eff ≈70-80%
- Next step: simulation of signal embedded in full event

Experimental conditions for dilepton measurements at the CERN SPS

- Beams:
  - Energy scan in the interval $\sqrt{s}\approx$5-17 GeV ($E_{lab}\approx$11-160 GeV) with Pb beams
  - Beam intensity ~10^7/s or more ➔ Interaction rate ~ O(MHz)
  - Dedicated run at each energy in a few weeks beam-time period
  - p-Pb needed at least for some energy for reference measurements (Drell-Yan)

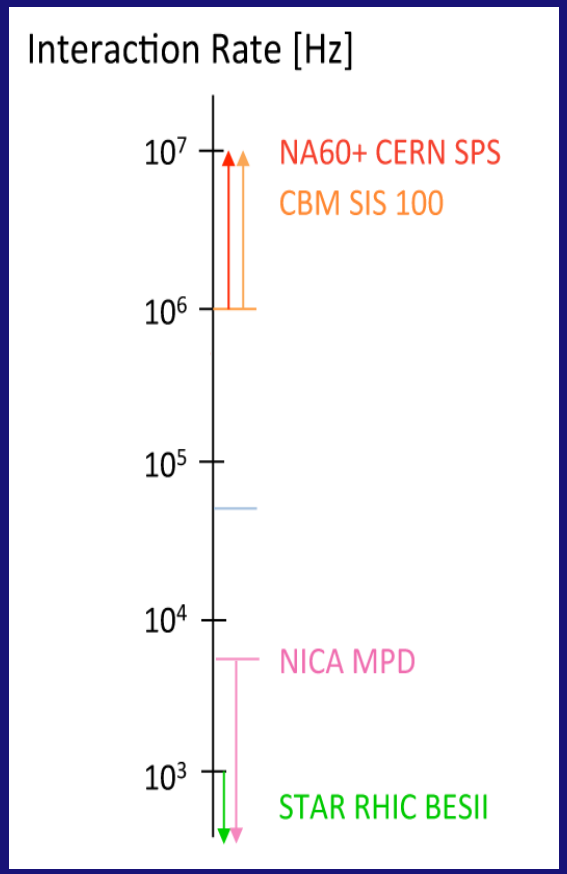
- Statistics goals:
  - $5 \cdot 10^7$ reconstructed pairs from thermal radiation per energy point (statistics increase by a factor ≈100 over NA60 at each energy)
  - 2-3 $\cdot 10^4$ reconstructed J/ψ mesons per energy point (and larger for open charm)

Why large interaction rates to study dileptons



lowest order rate ~ α_{em}^2

Dilepton production: rare processes



<u>Interaction Rates</u> I_R (Luminosity × σ_{int})

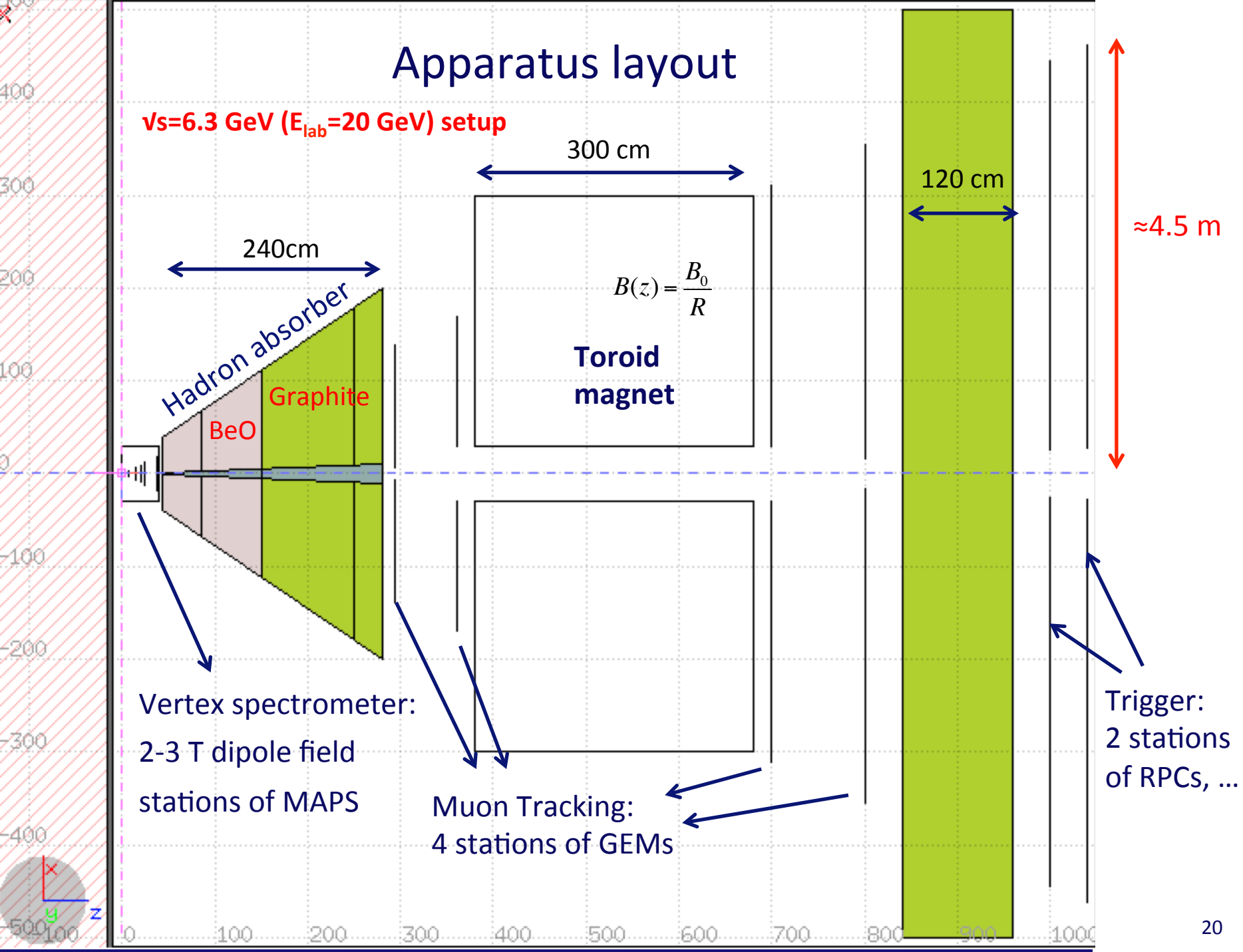
- Fixed target (SPS, SIS100): 10^6-10^7/s
- Colliders (LHC upgrade): 5×10^4/s

<u>Signal/Background ratio</u> S/B (B - combinatorial background)

- range of B/S for different experiments: 20 or more → B/S >>1

Effective signal size: $S_{eff} \sim I_R \times S/B$ reduction by factors of 20-1000 !

Apparatus layout



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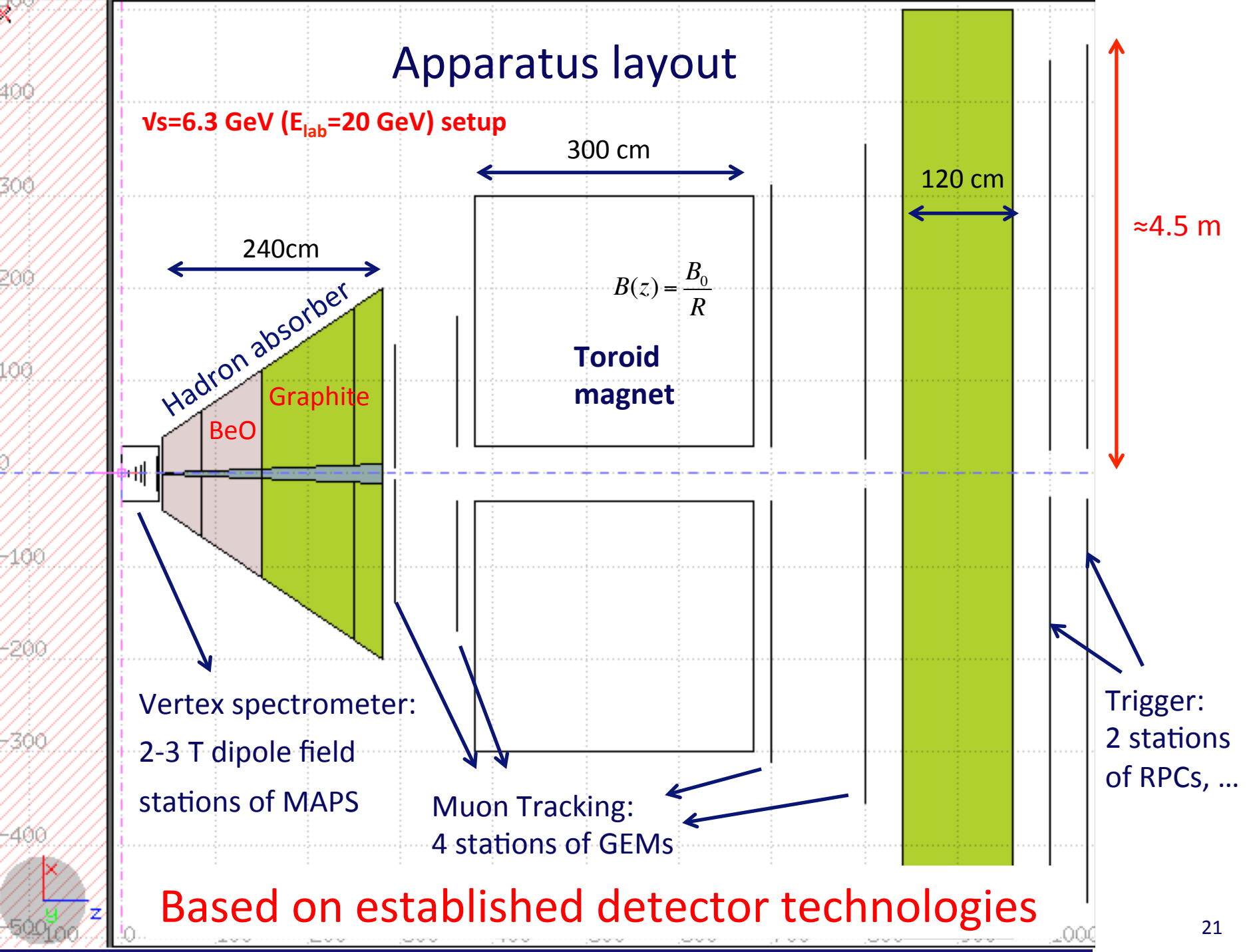


Based on established detector technologies

Installation

The only available installation site is ECN3:

- Coexistence of NA62 (or KLever) with another experiment is excluded
- A second beamline for heavy ions can be implemented without NA62/KLever and NA60+/Dirac+ coexistence is possible

Cost, timeline, collaboration

- The estimated cost is in the range of 15-25 MEuros, depending in particular on the cost of the magnet for the muon tracking
- Data taking: might start from 2025 onward
- Medium-size collaboration of 50-100 researchers
- Informal interest from groups from several institutions:
  - Cagliari (INFN), Padova (INFN), Torino (INFN), Munich (TUM), Stony Brook University, Rice University, Lyon (IPNL), Kolkata (Saha institute)
- Structured document (LOI or similar) to be prepared in next months

backup

Dilepton experiments – present and future

The high energy frontier

- RHIC PHENIX, STAR
- LHC ALICE

The low energy frontier

- RHIC LE STAR
- SPS NA60+
- SIS100 HADES, CBM
- NICA MPD

Relevance

M <1 GeV → chiral restoration
M >1 GeV → chiral restoration, hadrons vs. partons (precise meas. of T)

Dream: energy dependence from

$\sqrt{s}$ = 4 – 5500 AGeV

with data quality equivalent or better than NA60
Principal obstacle to reach this:

colliders not competitive to fixed-target experiments in terms of interaction rate

The STAR BES at RHIC for comparison

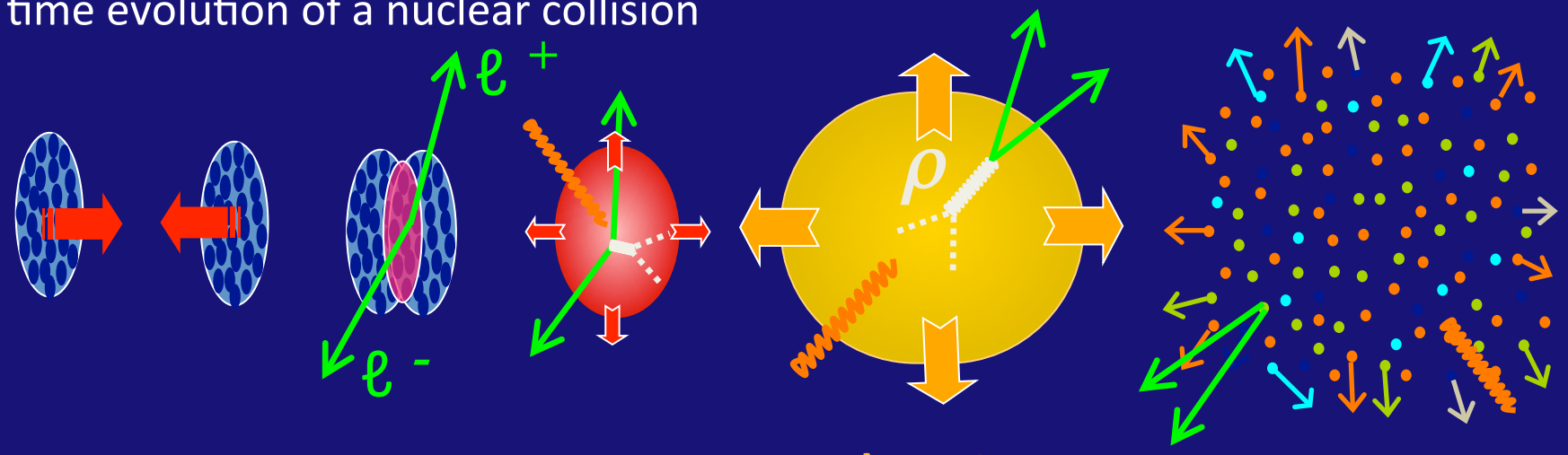
- BES II goal: statistics ranging from $400*10^6$ mbias events ($\sqrt{s}$ = 19.6 GeV) to $100*10^6$ mbias events ($\sqrt{s}$ = 7.7 GeV)
- STAR fixed target : energy range to be extended further down to $\sqrt{s}$ = 3 GeV Statistics goal: 10^8 mbias events/energy (same sensitivity as BES-II)

Collision Energy (GeV)	BES-II Proposed Events Goal (M)	BES-I Events (M)
7.7	100	4
9.1	160	N/A
11.5	230	12
14.5	300	20
19.6	400	36

In 2003 NA60 at $\sqrt{s}$=17.3 GeV collected >$200*10^6$ triggered muon pairs. This means that BESII will not be able to reach even the precision of the former NA60 in dilepton measurements

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

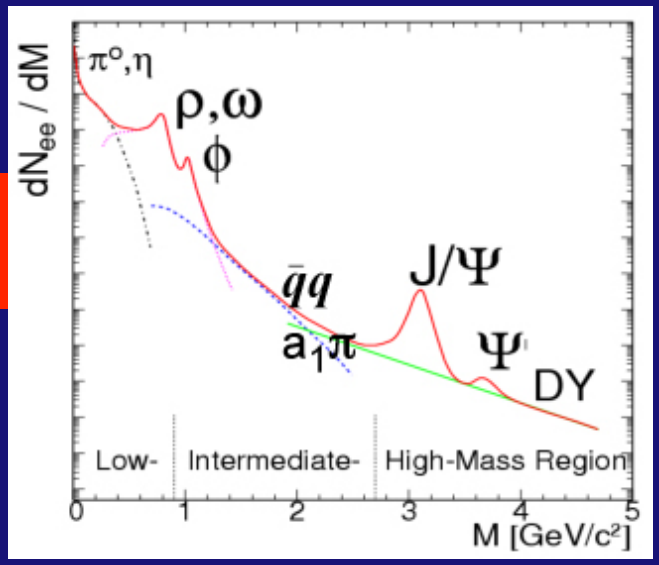
NN-collisions: (Drell-Yan), J/ψ, $D\bar{D}$ pairs

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

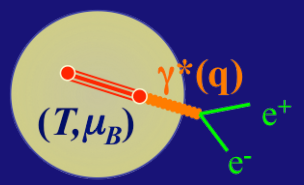
Hot+Dense Hadron Gas: ρ, $a_1\pi \rightarrow \ell^+\ell^-$

} *Thermal dileptons*

Freeze-out: free hadron decays

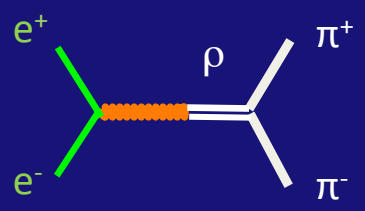


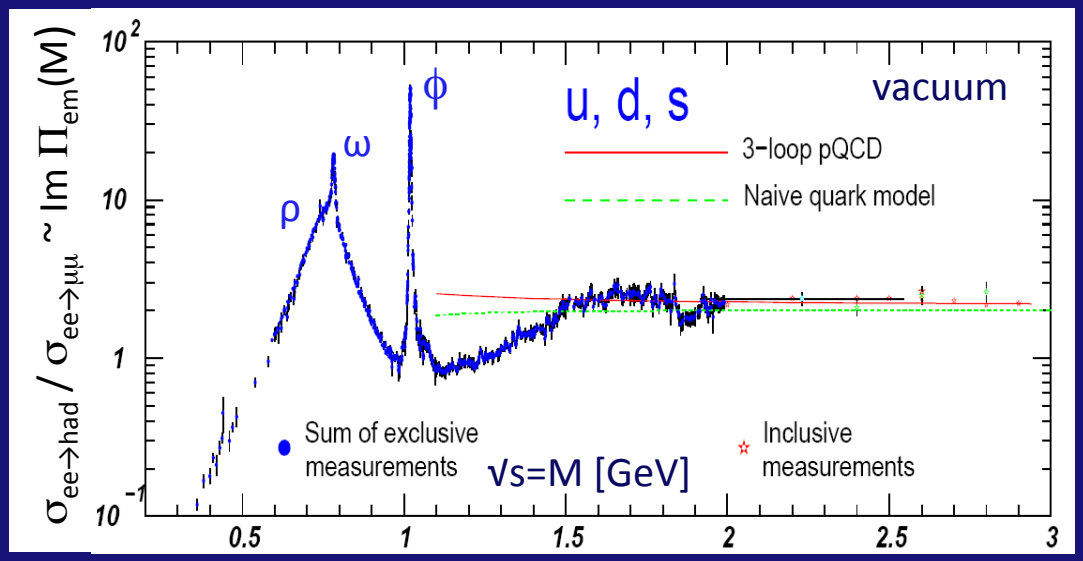
Thermal dilepton rate and the measurement of T

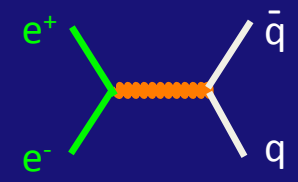


$$\frac{dN_{ee}}{d^4x\,d^4q} = \frac{-\alpha_{em}^2}{\pi^3 M^2} f^B(q_0,T) \times \mathrm{Im}\,\Pi_{em}(M,q;\mu_B,T)$$

e.m. spectral function







non-perturbative in-medium spectral function(s)

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

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

perturbative hadron-parton duality (flat SF)

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

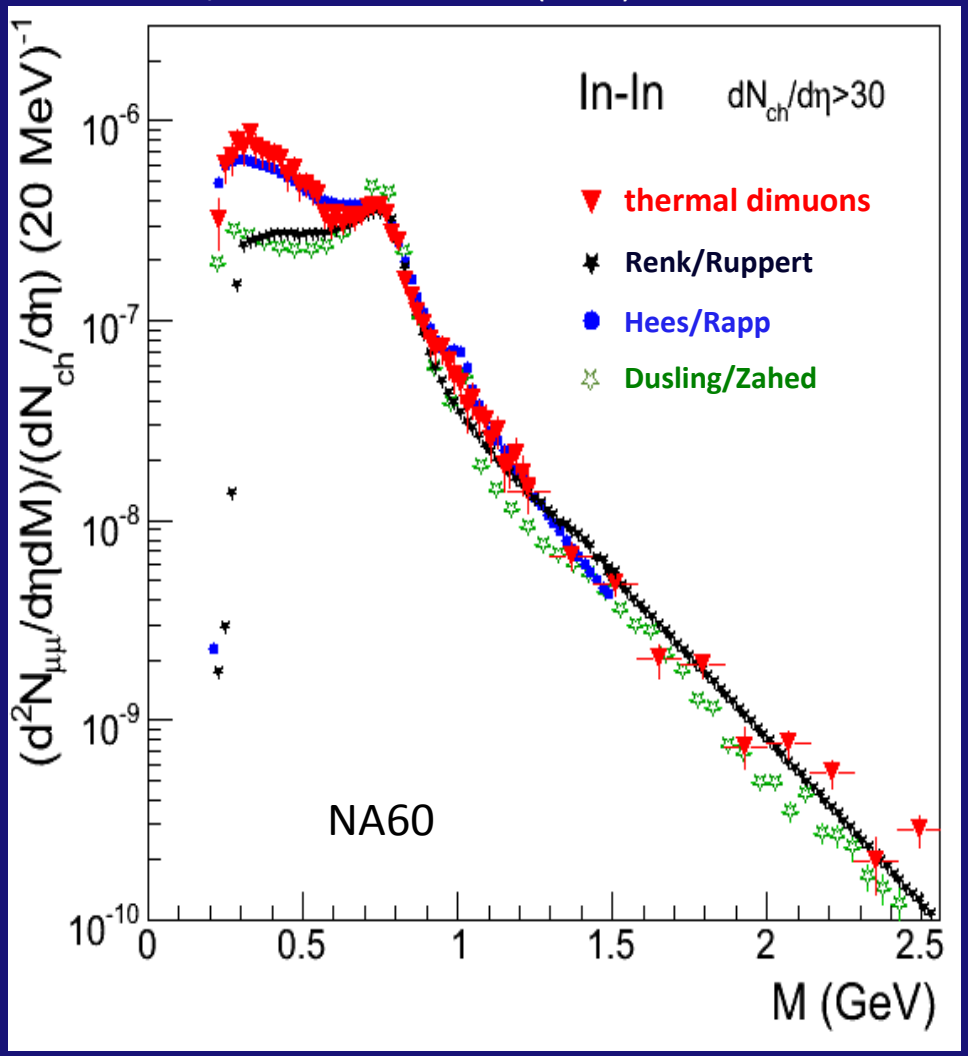
$$dN_{\mu\mu}/dM \propto M^{3/2} \times \langle \exp(-M/T) \rangle$$

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 (E_{lab}=160 GeV): evidence of 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 $dN/dM \propto M^{3/2} \times \exp(-M/T)$

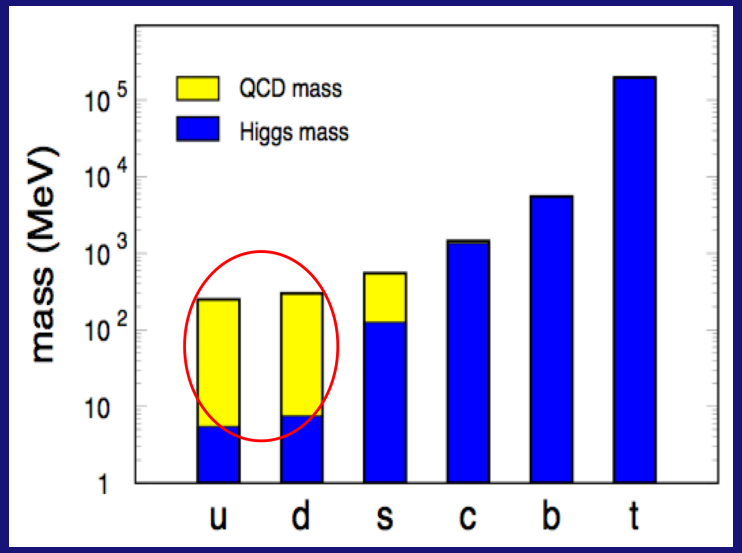
range 1.1-2.0 GeV: T=205±12 MeV
1.1-2.4 GeV: T=230±10 MeV

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

Chiral symmetry breaking and the hadron spectrum

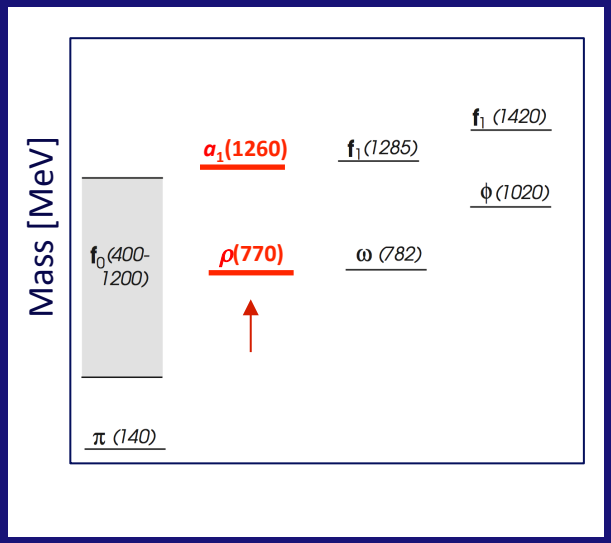
Chiral symmetry breaking: masses of the 6 quark flavours

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



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

Hadron spectrum

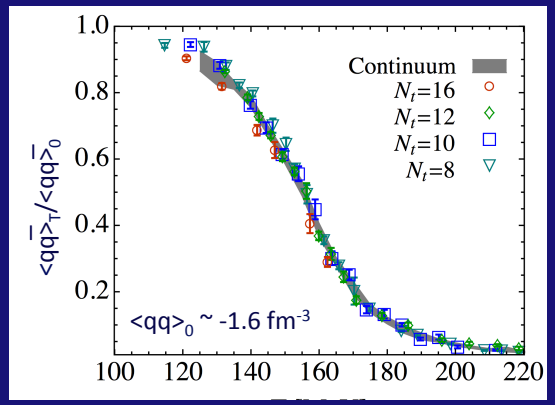


Vector-Axial vector splitting (also pseudoscalar-scalar) in the physical vacuum due to spontaneous breaking of chiral symmetry

Chiral symmetry restoration and the hadron spectrum

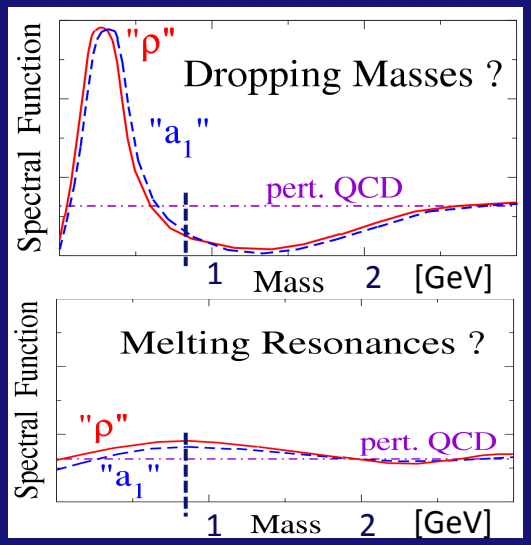
at T_c: Chiral Restoration

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



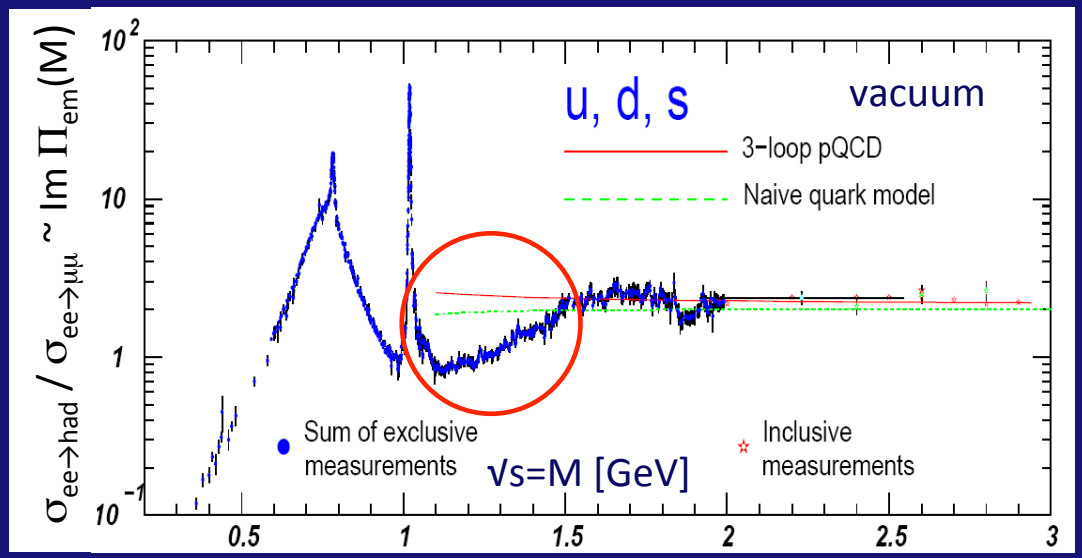
chiral symmetry restoration

Lattice QCD, μ_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?

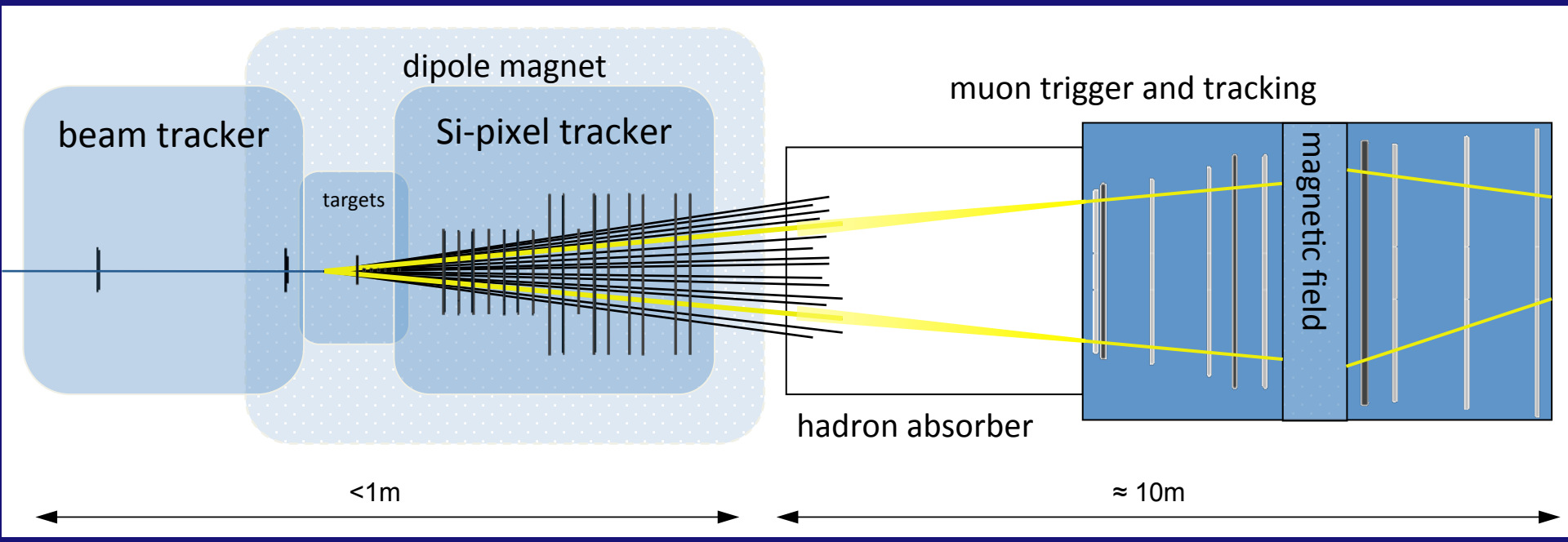
In vacuum (left) the region M=1-1.5 GeV is significantly depleted

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

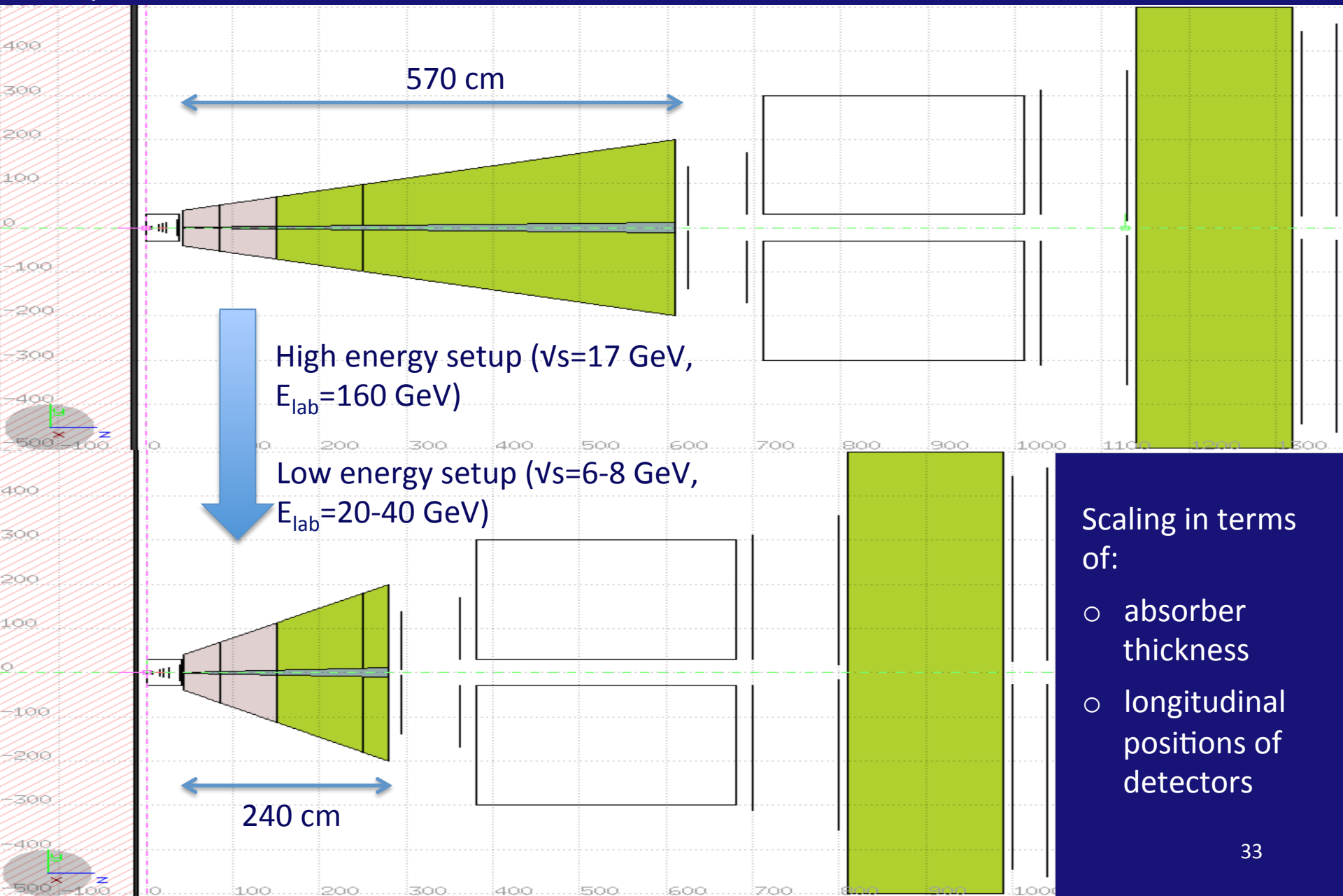
The NA60+ proposal at the CERN SPS

- 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



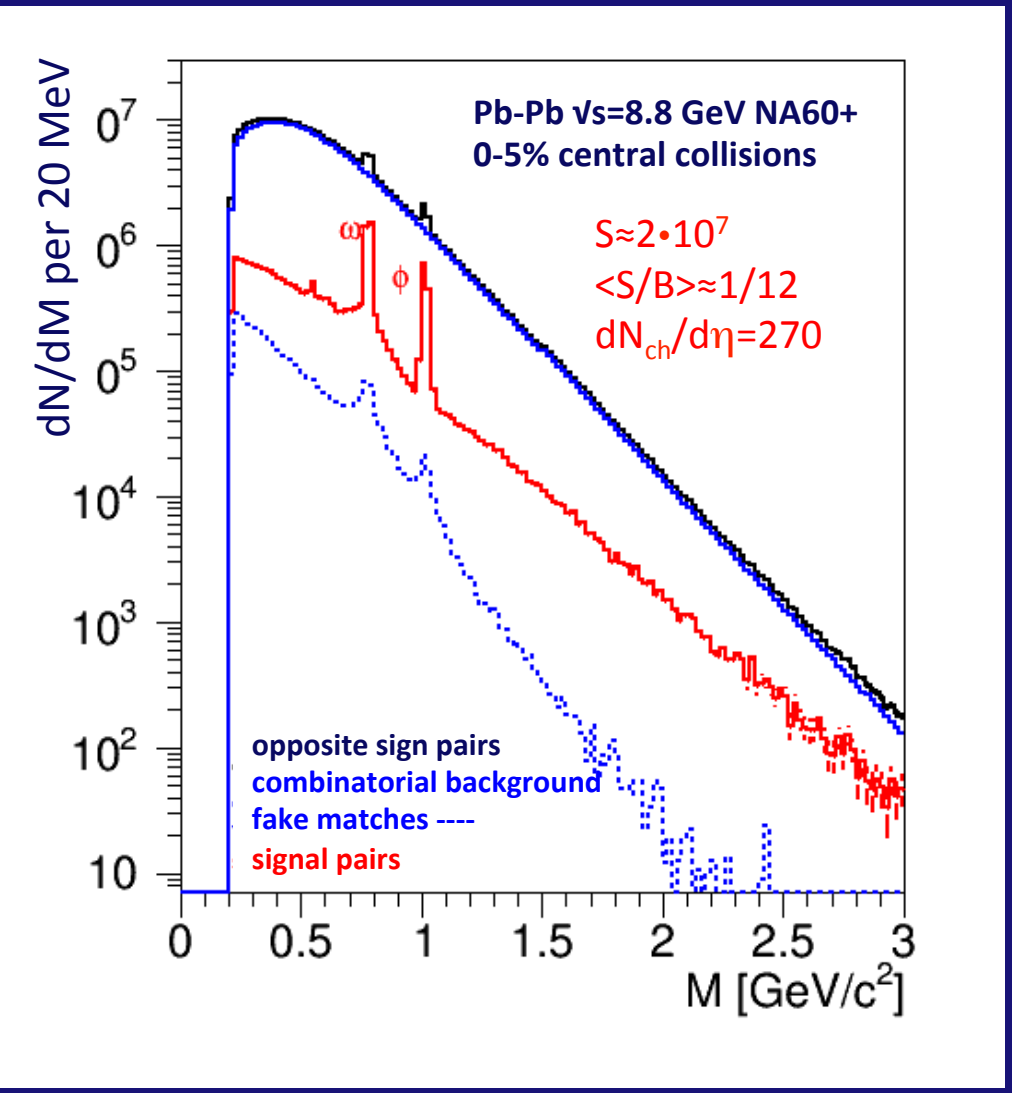
Scalable spectrometer for a beam energy scan √s=6-17 GeV (E_{lab}=20-160 GeV)



Scaling in terms of:

- absorber thickness
- longitudinal positions of detectors

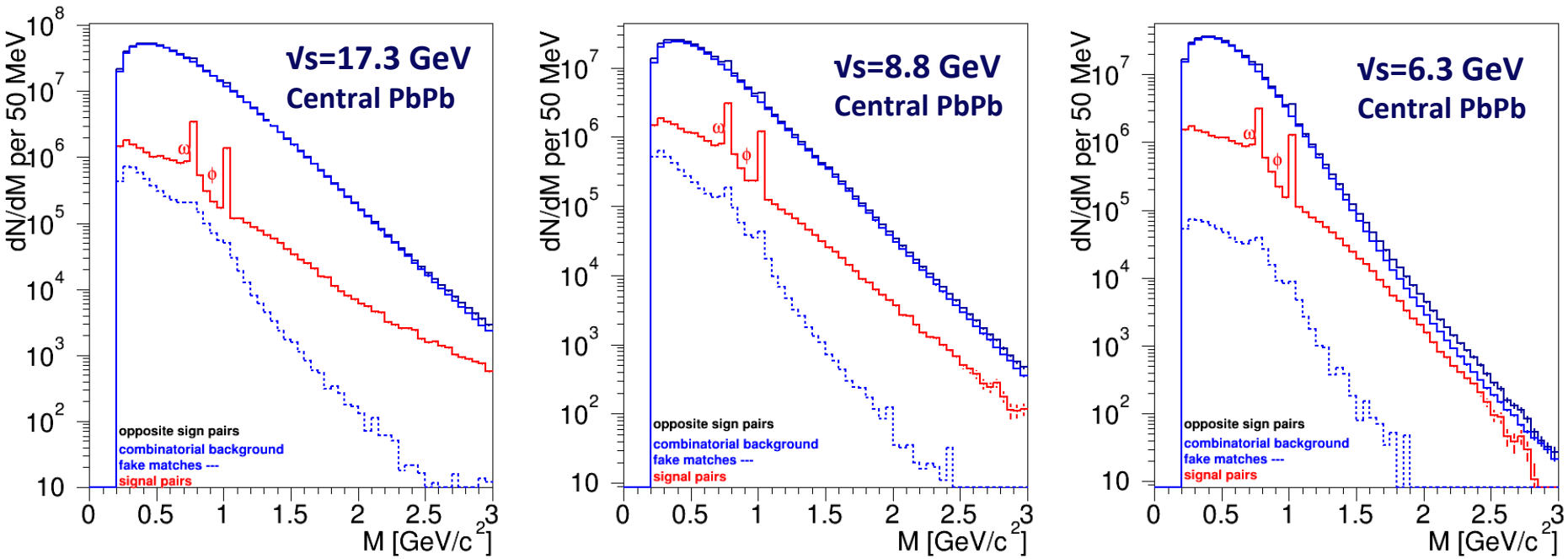
NA60+ performance for thermal radiation in central Pb+Pb : data sample size and quality ($\sqrt{s}$=8.8 GeV; E_{lab}=40 GeV)



- $2 \cdot 10^7$ 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 (E_{lab}=20,40,160 GeV)

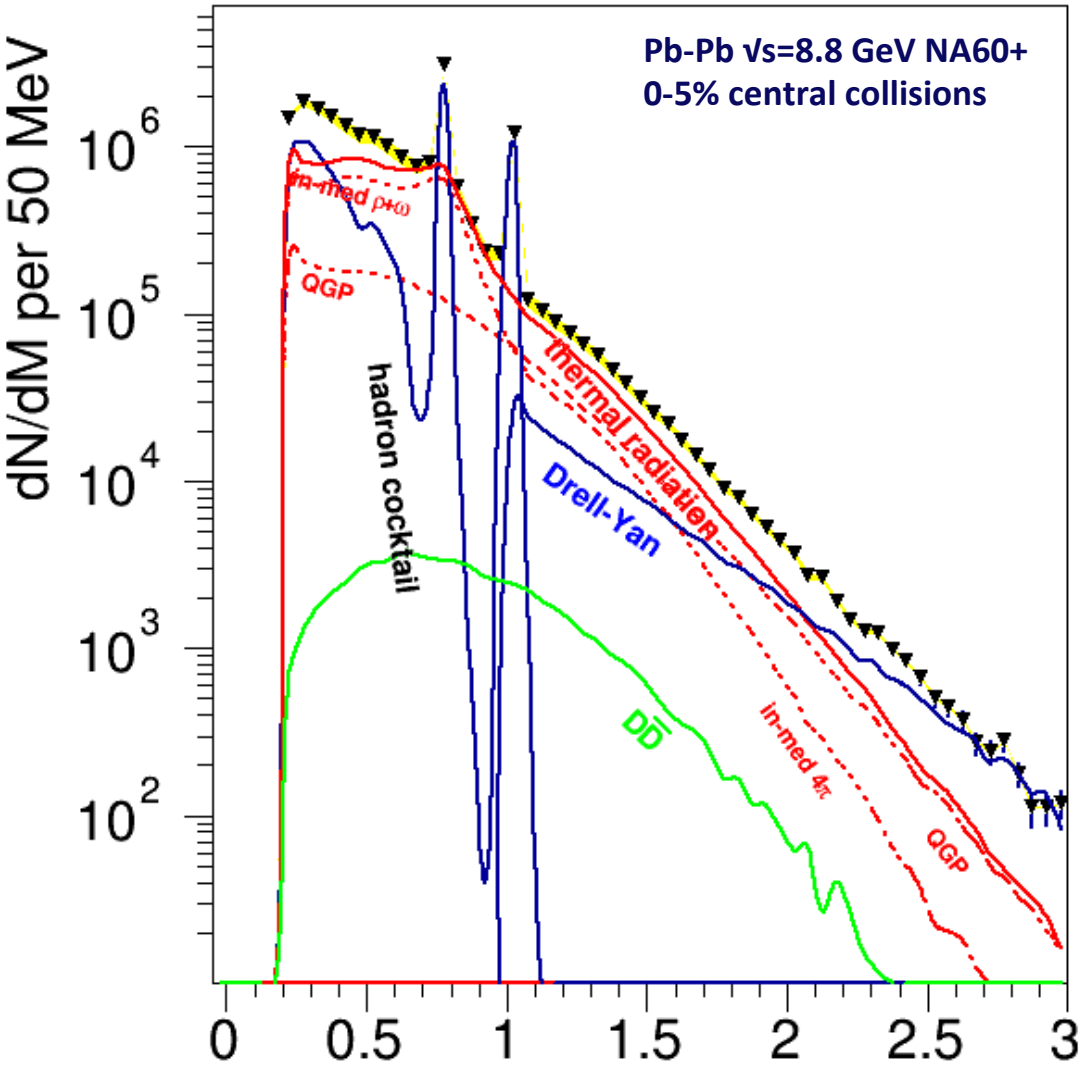
$2 \cdot 10^7$ reconstructed signal pairs at each energy



decreasing energy (Elab=160→20 GeV)

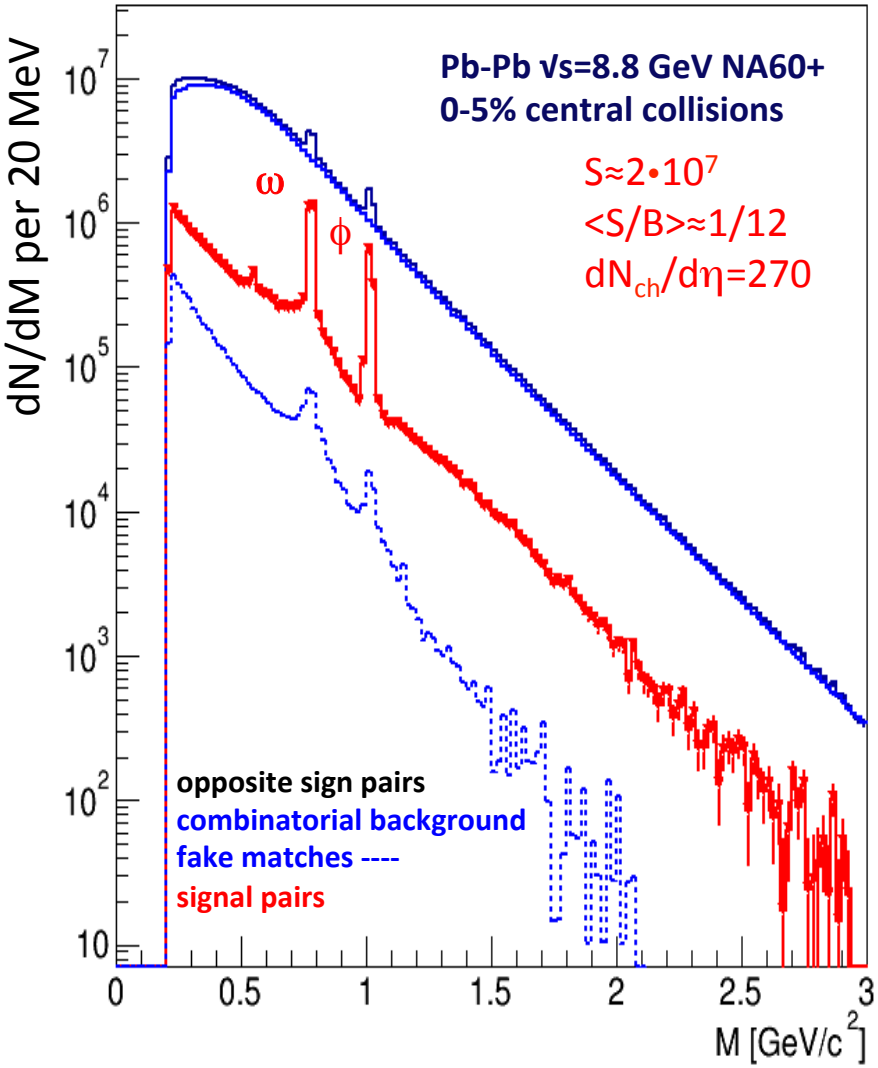
- From full SPS energy towards low energy:
  - Significant reduction of Drell-Yan
  - Open charm becomes negligible
  - Decrease of QGP

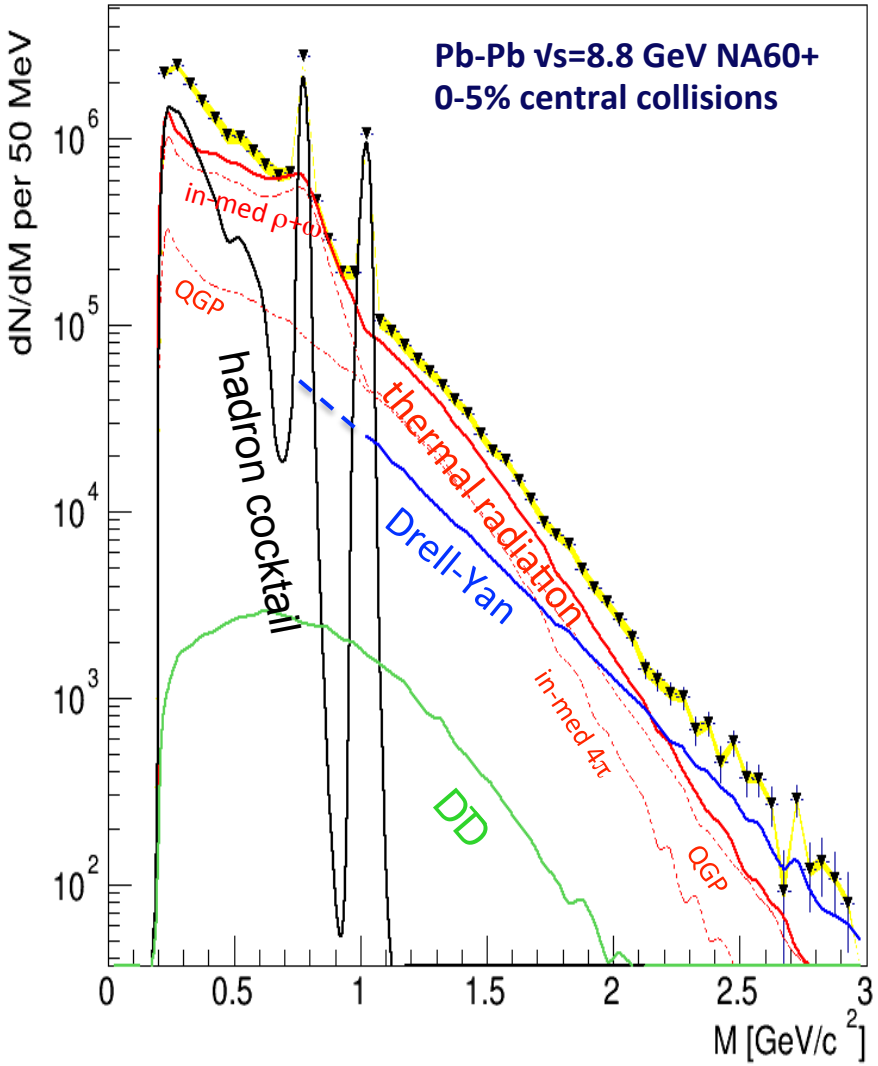
Signal mass spectrum: example for central Pb+Pb at √s=8.8 GeV



- Signal spectrum measurable up to 2.5-3 GeV:
  - 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

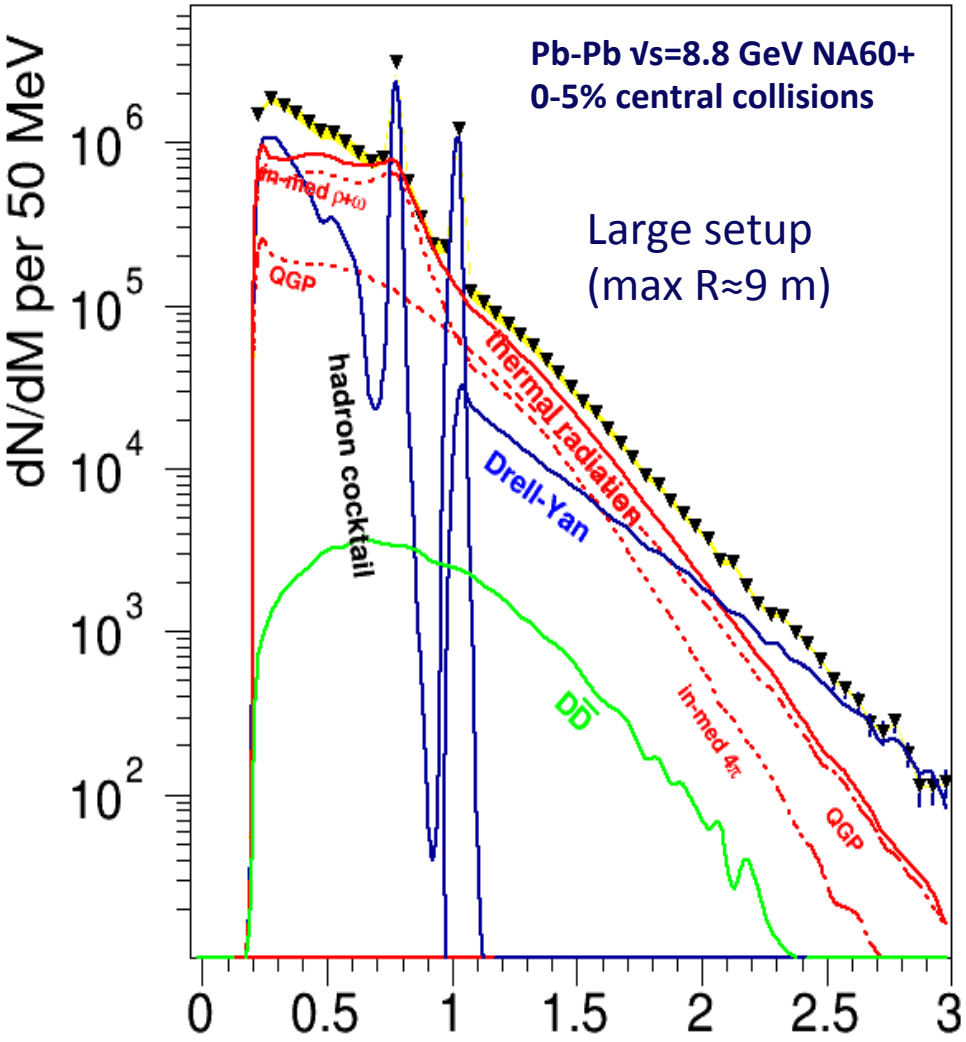
Compact setup: performance for central Pb+Pb at √s=8.8 GeV

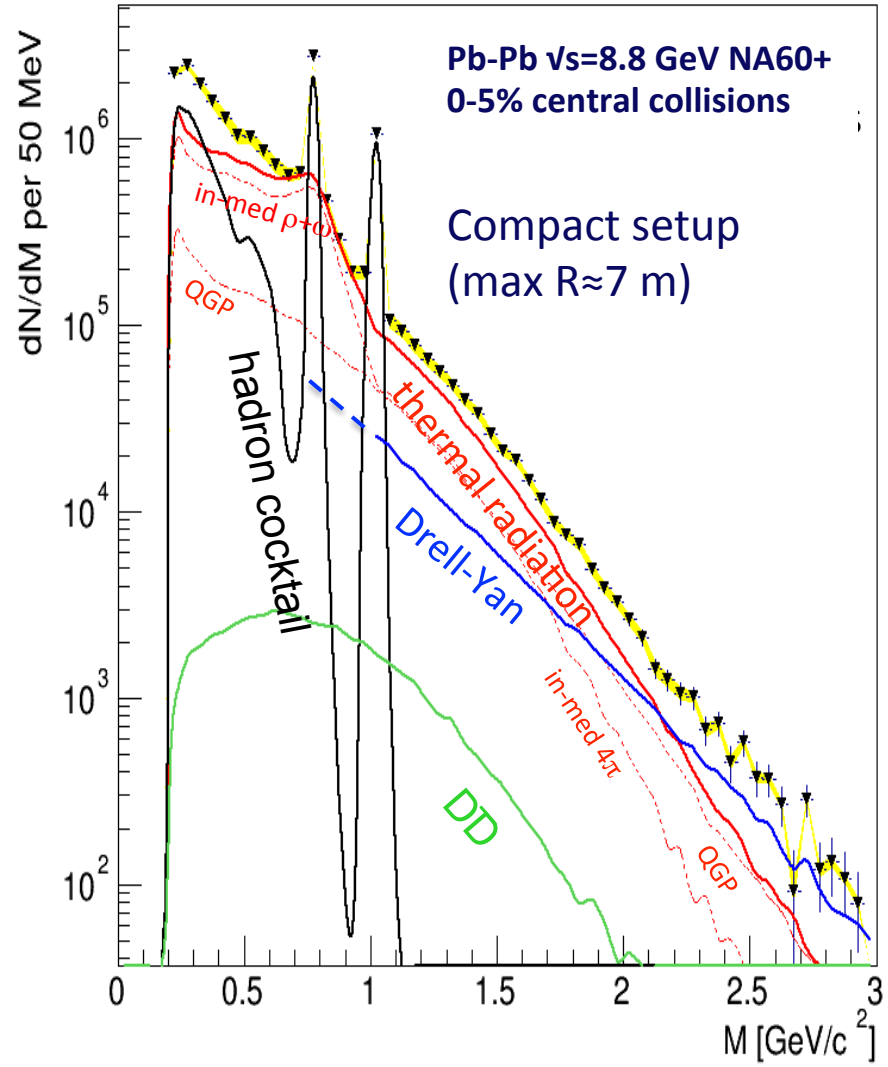




Comparison of performance of different setups at √s=8.8 GeV

Very similar performance – T measurement practically identical

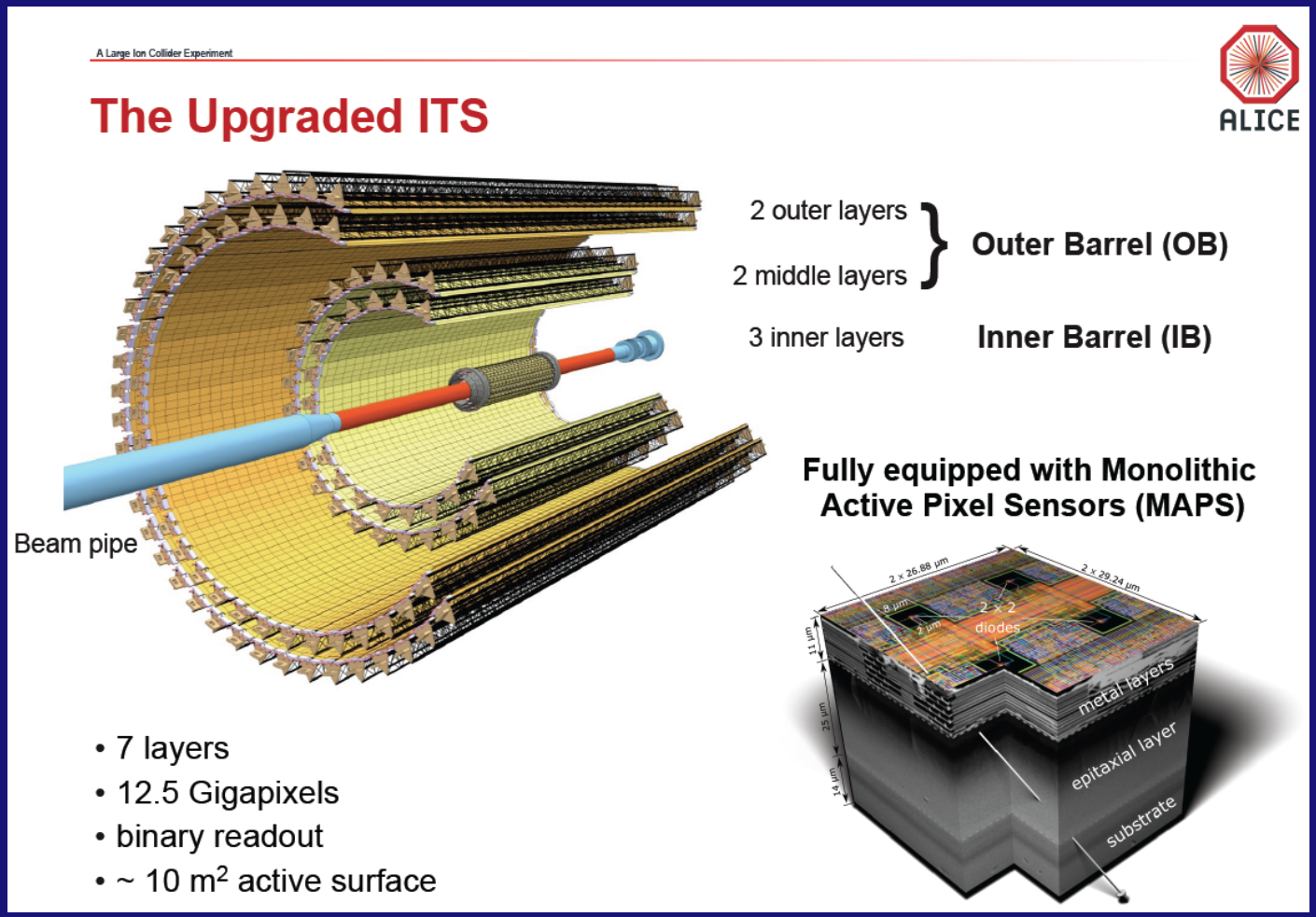




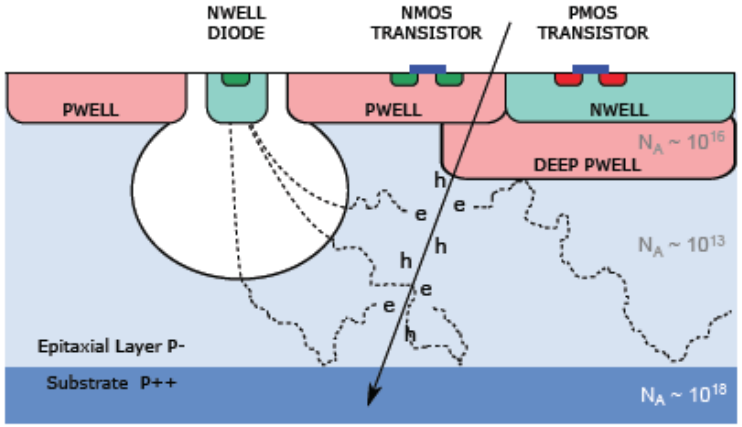
The silicon telescope: a new generation tracker for ultra-precise measurements

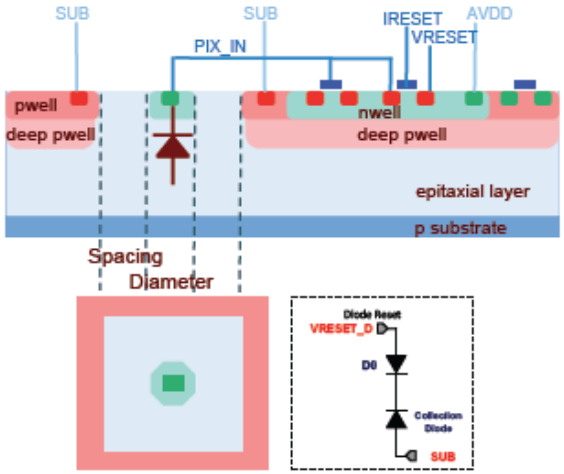
- Main idea: based on monolithic active pixel sensors (MAPS)

Present state of the art: the ALICE ALPIDE sensor for the ITS upgrade



The Alpide pixel sensor





CMOS Pixel Sensor - TowerJazz 0.18μm CMOS Imaging Process

- High-resistivity (> 1kW cm) p-type epitaxial layer (25μm) on p-type substrate
- Small n-well diode (2 μm diameter), ~100 times smaller than pixel => low capacitance (~fF)
- Reverse bias voltage (-6V < V_{BB} < 0V) to substrate (contact from the top) to increase depletion zone around NWELL collection diode
- Deep PWELL shields NWELL of PMOS transistors (full CMOS circuitry within active area)

The Alpide pixel sensor: performance

Pixel chip developed for the ITS Upgrade

Parameter	Inner Barrel	Outer Barrel	ALPIDE
Silicon thickness	50μm	100μm	✔
Spatial resolution	5μm	10μm	~ 5μm
Chip dimension	15mm x 30mm		✔
Power density	< 300mW/cm^2	< 100mW/cm^2	< 40mW/cm^2
Event-time resolution	< 30μs		~ 2μs
Detection efficiency	> 99%		✔
Fake-hit rate *	< 10^{-6}/event/pixel		<<< 10^{-6}/event/pixel
NIEL radiation tolerance **	1.7×10^{13} 1MeV n_{eq}/cm^2	10^{12} 1MeV n_{eq}/cm^2	✔
TID radiation tolerance **	2.7Mrad	100krad	tested at 350krad

* revised numbers w.r.t. TDR
** including a safety factor of 10, revised numbers w.r.t. TDR

Monolithic pixels and fixed target operation

- Advantages:
  - significantly reduced cost
  - exceedingly small material budget (0.1-0.3% X_0)
  - highly granular - excellent spatial resolution (5 μm)
  - improved background rejection for thermal radiation
  - precision measurement of charm

- Improvements for operation with fixed-target experiment:
  - increase of factor ≈5 in readout speed

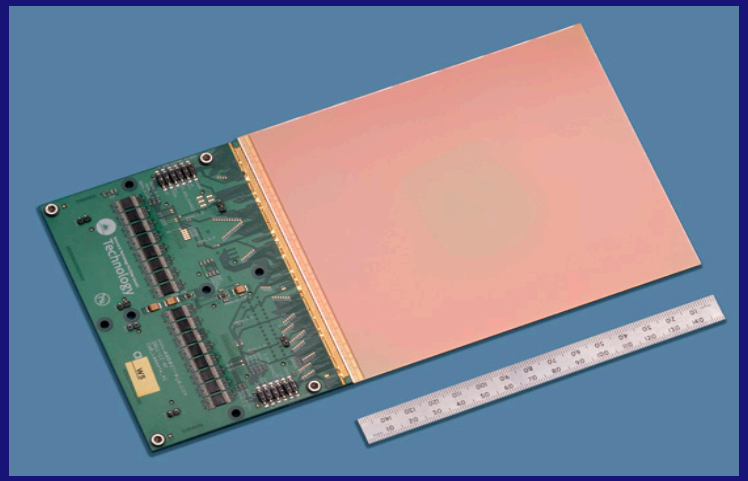
  ➔might be possible from trade-off with power consumption
  - Increase of radiation hardness

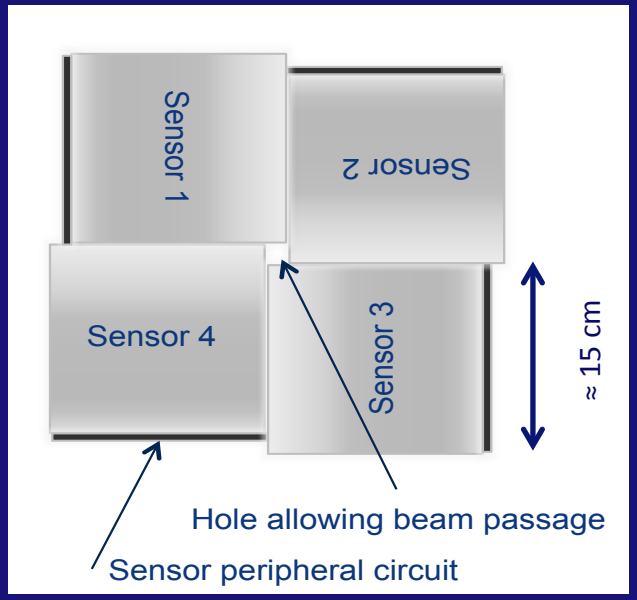
  ➔ feature of the TowerJazz CMOS process would allow the NIEL to be increased up to 10^{15} n_{eq}/cm^2!

≈ 20 cm

Development of new very large area MAPS sensors

Stitching : possibility to fabricate wafer-size chips ➔allows very large sensors to be produced



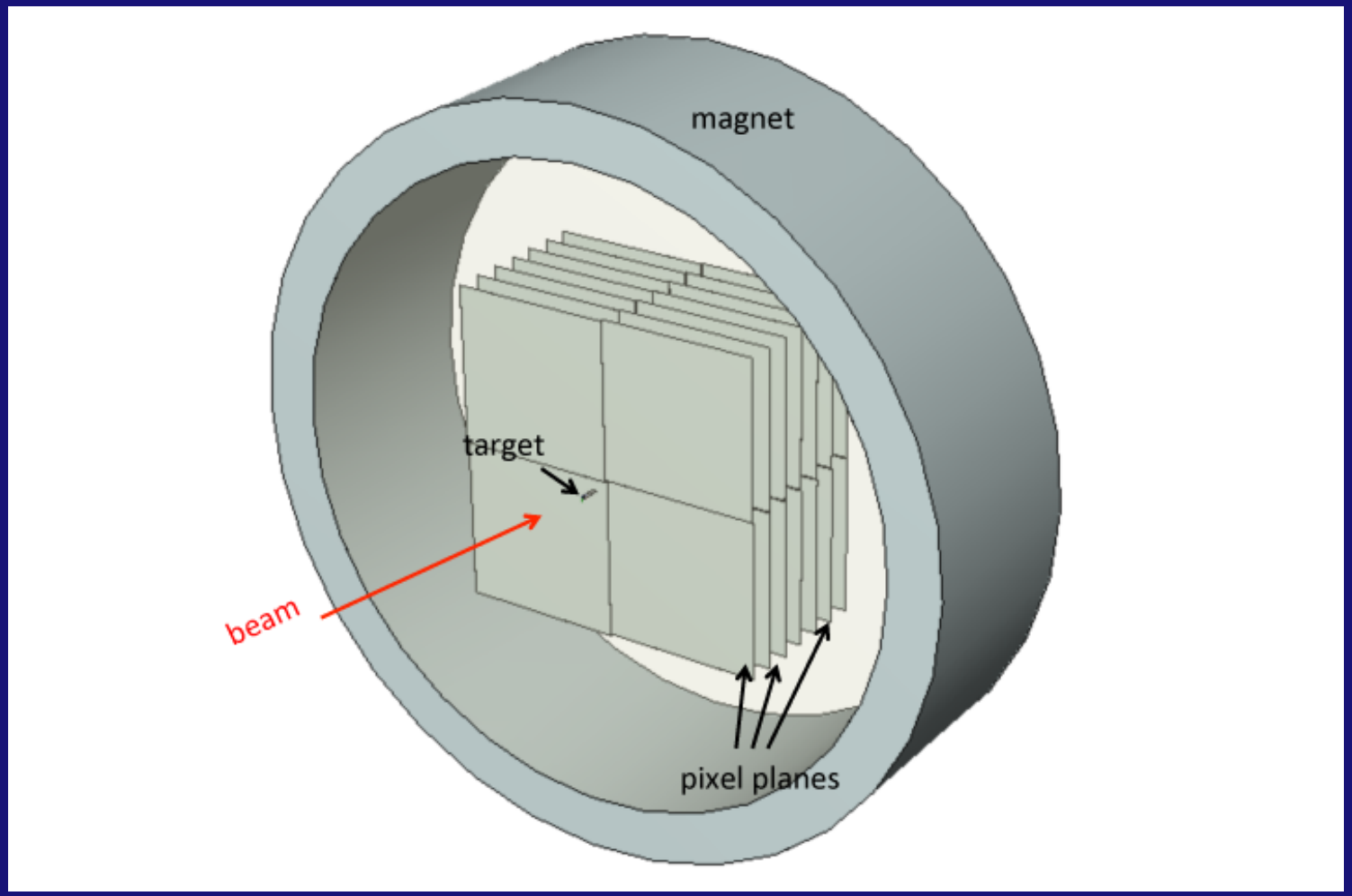


Example of pixel plane with just 4 ≈15x15 cm^2 sensors with total material budget of 0.1% X_0!

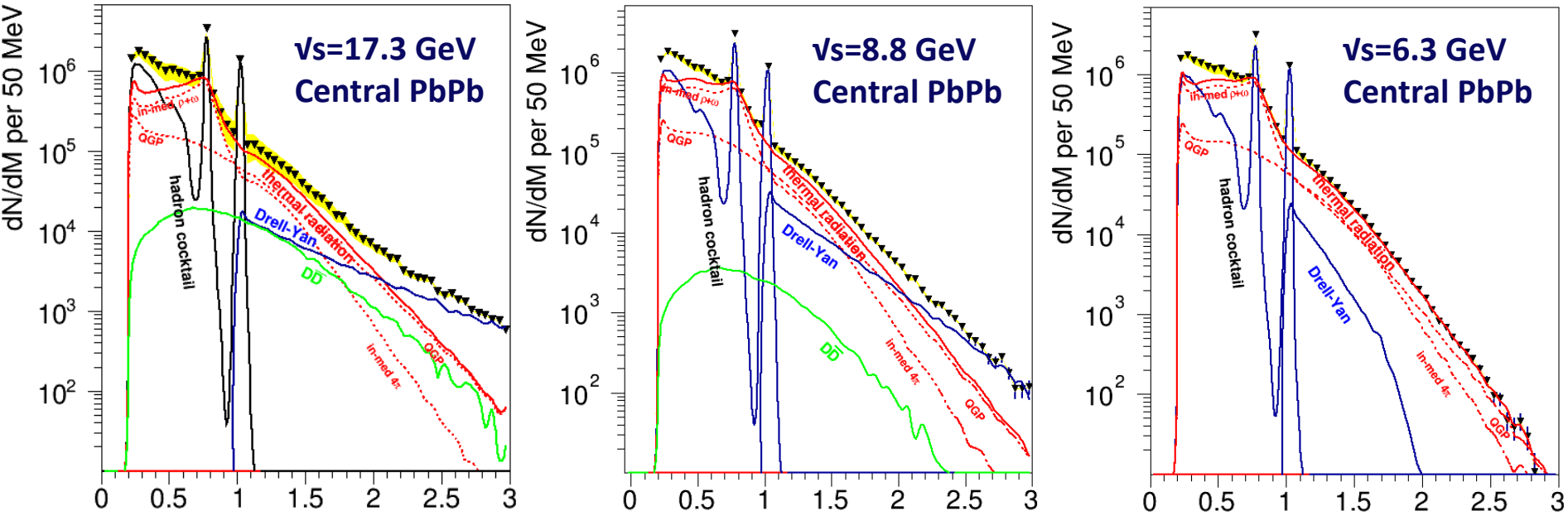
Submission of a request for funds in Italy for the development of a new generation of very large area MAPS

The silicon telescope with very large area MAPS

- Possibility to construct tracking planes from such a sensor excluding all services and mechanical support structures from the acceptance
- Material budget for tracking stations of about 0.1 % X_0 !



Signal mass spectra vs √s



decreasing energy

- From full SPS energy towards low energy:
  - Significant reduction of Drell-Yan
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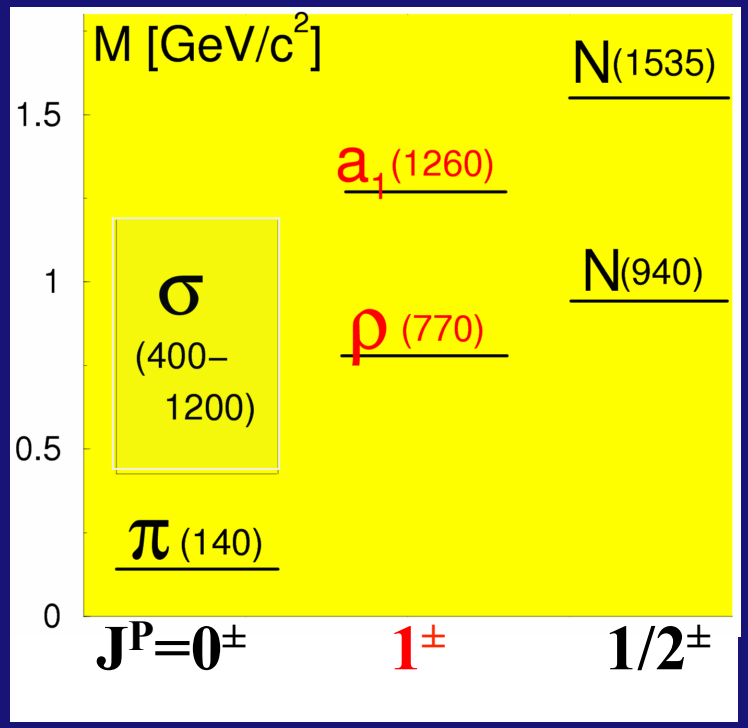
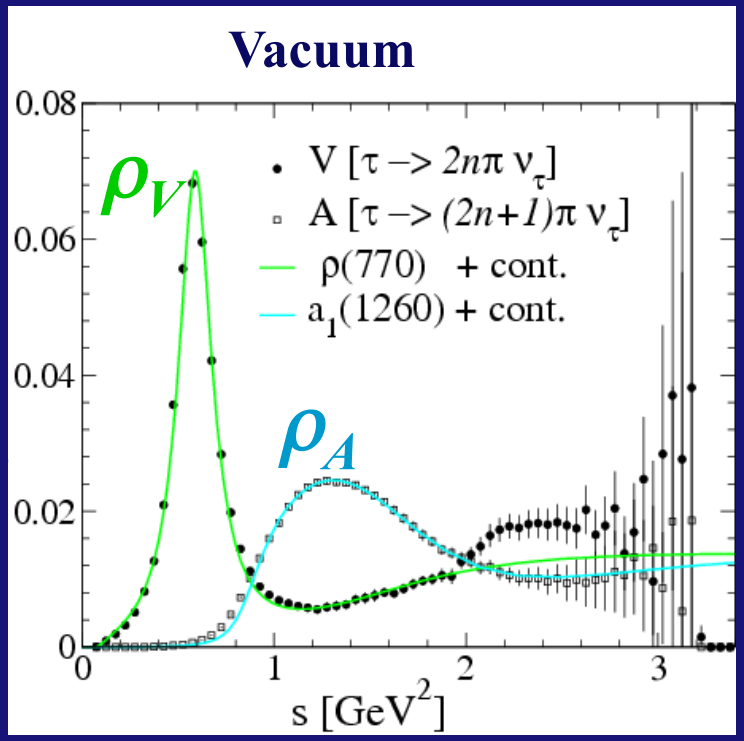
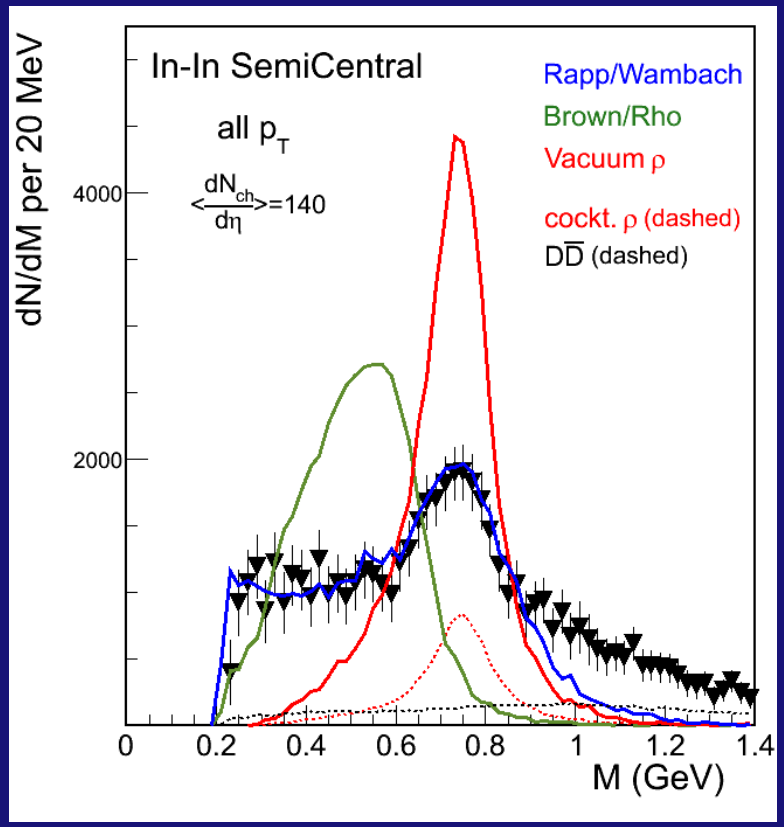
QCD chiral symmetry breaking in vacuum





Chiral symmetry restoration: vector spectral function

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



- High recision measurement by NA60 in In-In collisions at 160 AGeV
- Enormous broadening of ρ: > 400 MeV

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

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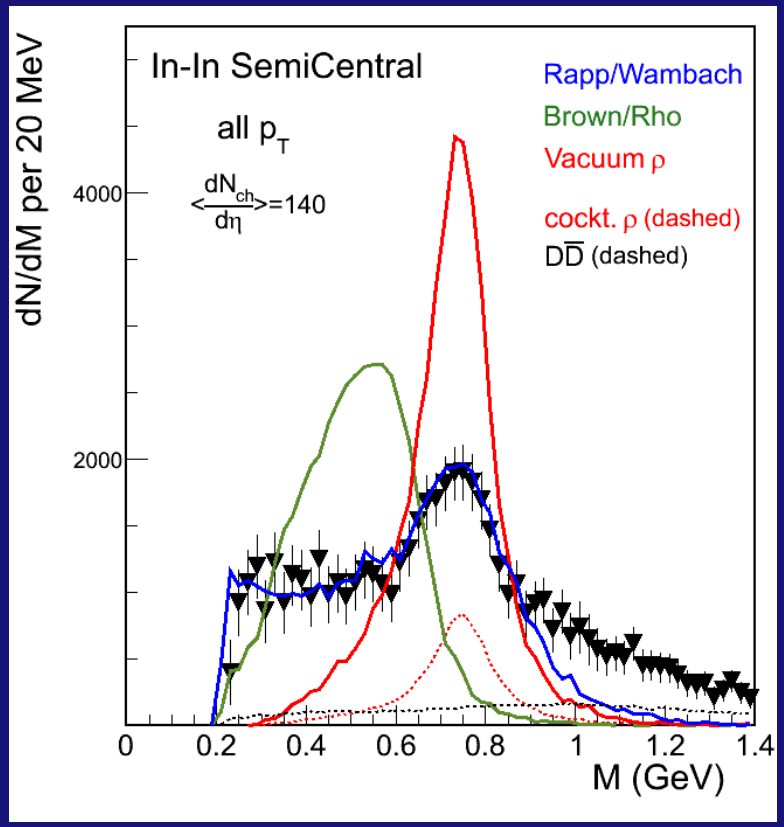

- High recision measurement by NA60 in In-In collisions at 160 AGeV
- Enormous broadening of ρ: > 400 MeV

- Resonance melting ⇒ hadronic rate approaches QGP rate
- Suggestive for deconfinement and chiral restoration
- Robust modeling in heavy-ion collisions

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