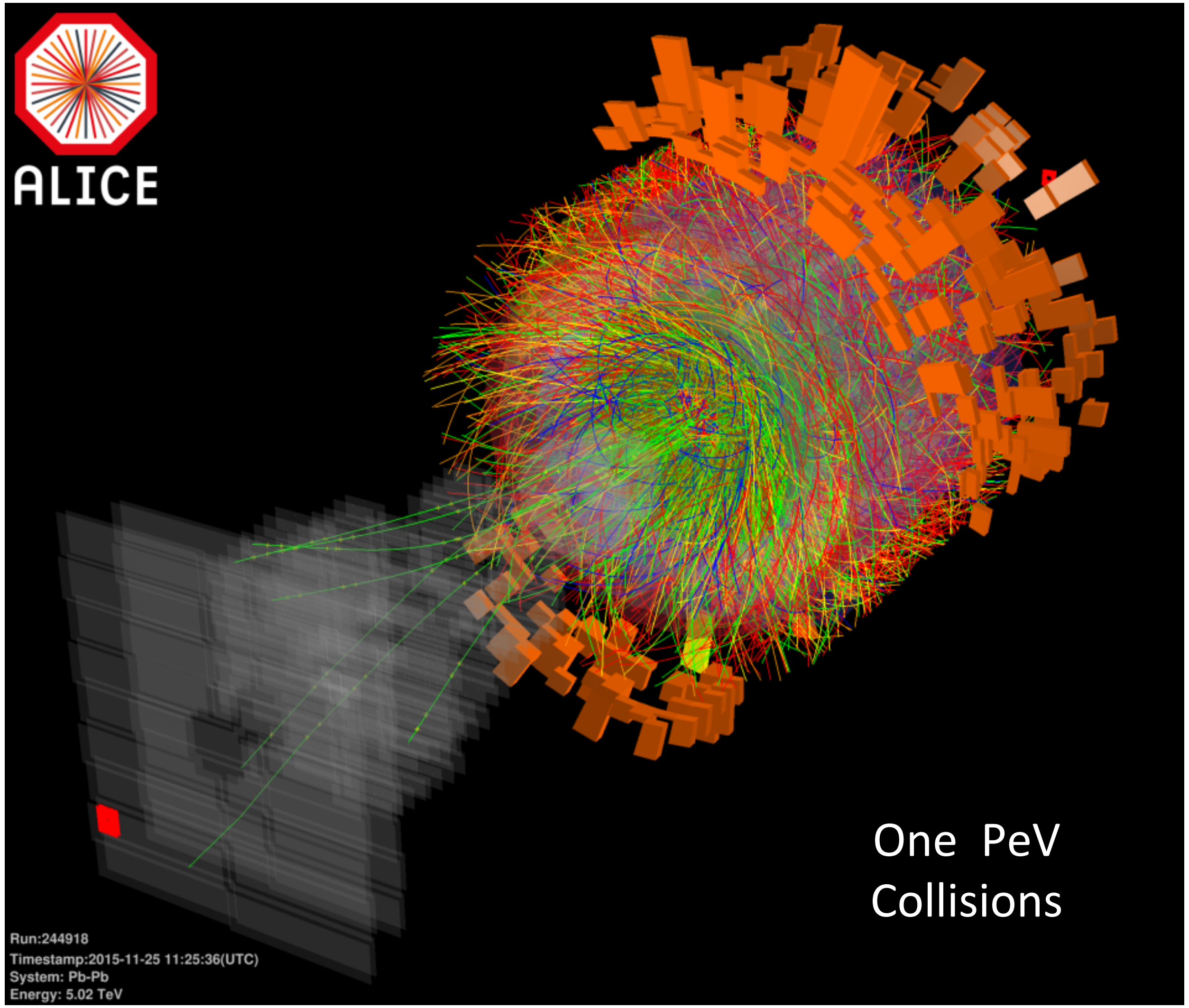


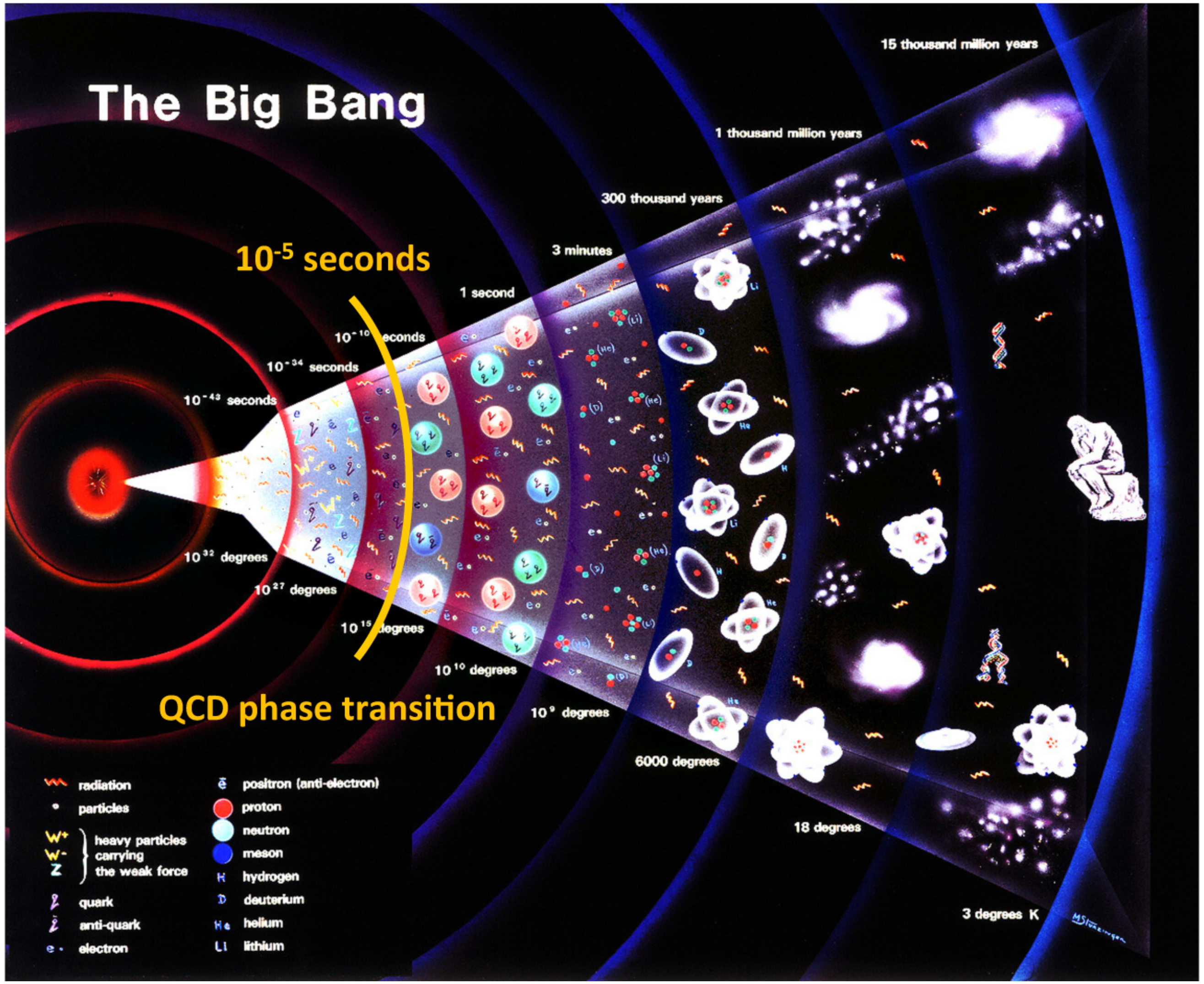
Highlights from physics of strongly coupled systems: ALICE and NA60+

Gianluca Usai *– Unversità di Cagliari*
On behalf of the Cagliari group of high energy nuclear physics

C. Cicalò, A. De Falco, A. Masoni, S. Siddhanta, G. Usai
Post doc P. Biswarup, E. Casula, P. Bhattacharya
Phd S. Boi, A. Chauvin, A. Mulliri

The QCD phase transition in the early Universe

Early universe up to 10^{-5} s: plasma of quarks and gluons (QGP) plus leptons and photons



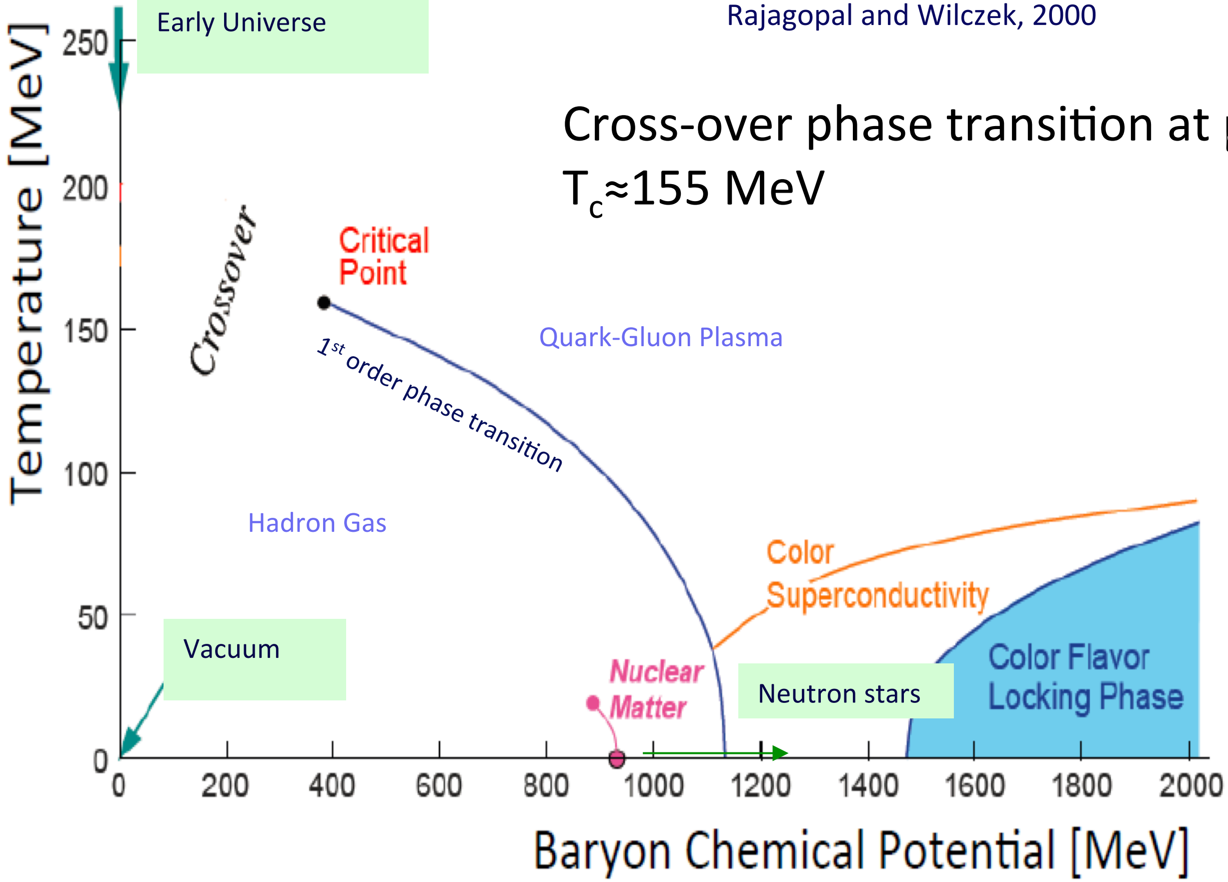
The QCD phase transition is the only one involving fundamental degrees of freedom of the standard model accessible to laboratory experiments

The QCD phase diagram

LHC: probes the early Universe phase transition ($\mu_B \approx 0$)

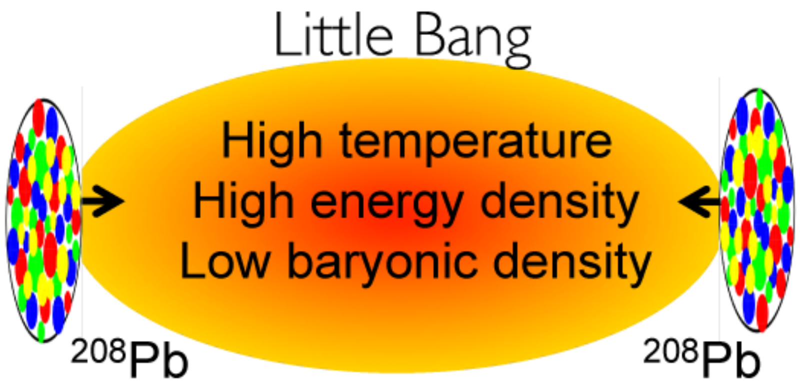
Rajagopal and Wilczek, 2000

Cross-over phase transition at $\mu_B \approx 0$
$T_c \approx 155$ MeV



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

High-energy heavy ion collisions:



Energy energy density up to

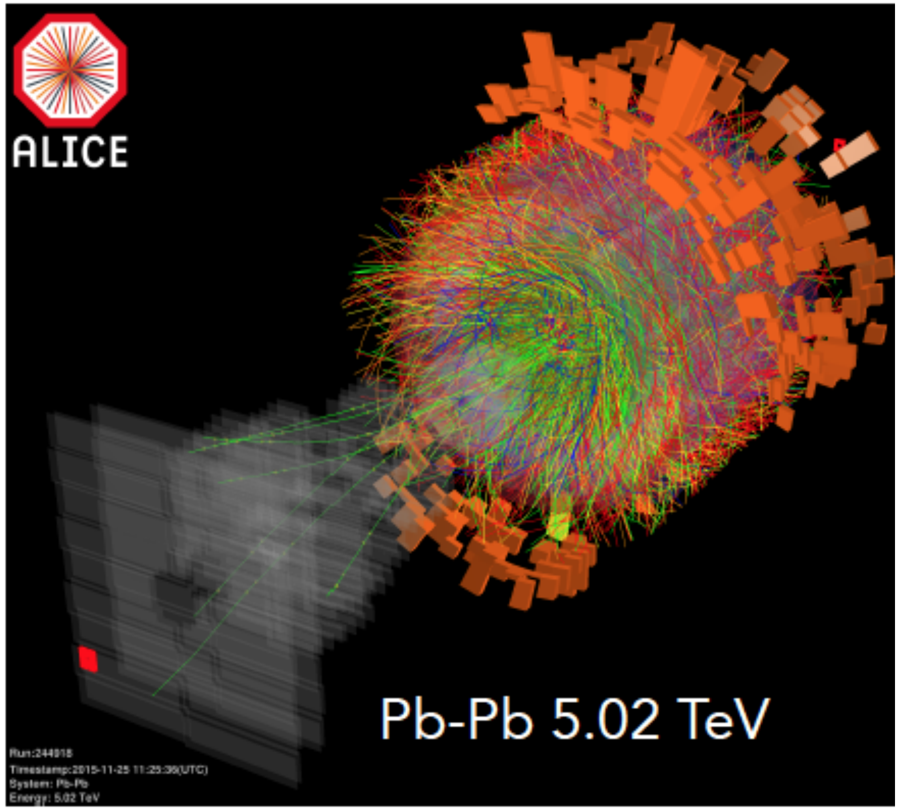
~15 GeV/fm^3 at LHC

over a large volume

~ 5000 fm^3 at LHC

Data taking since 2010

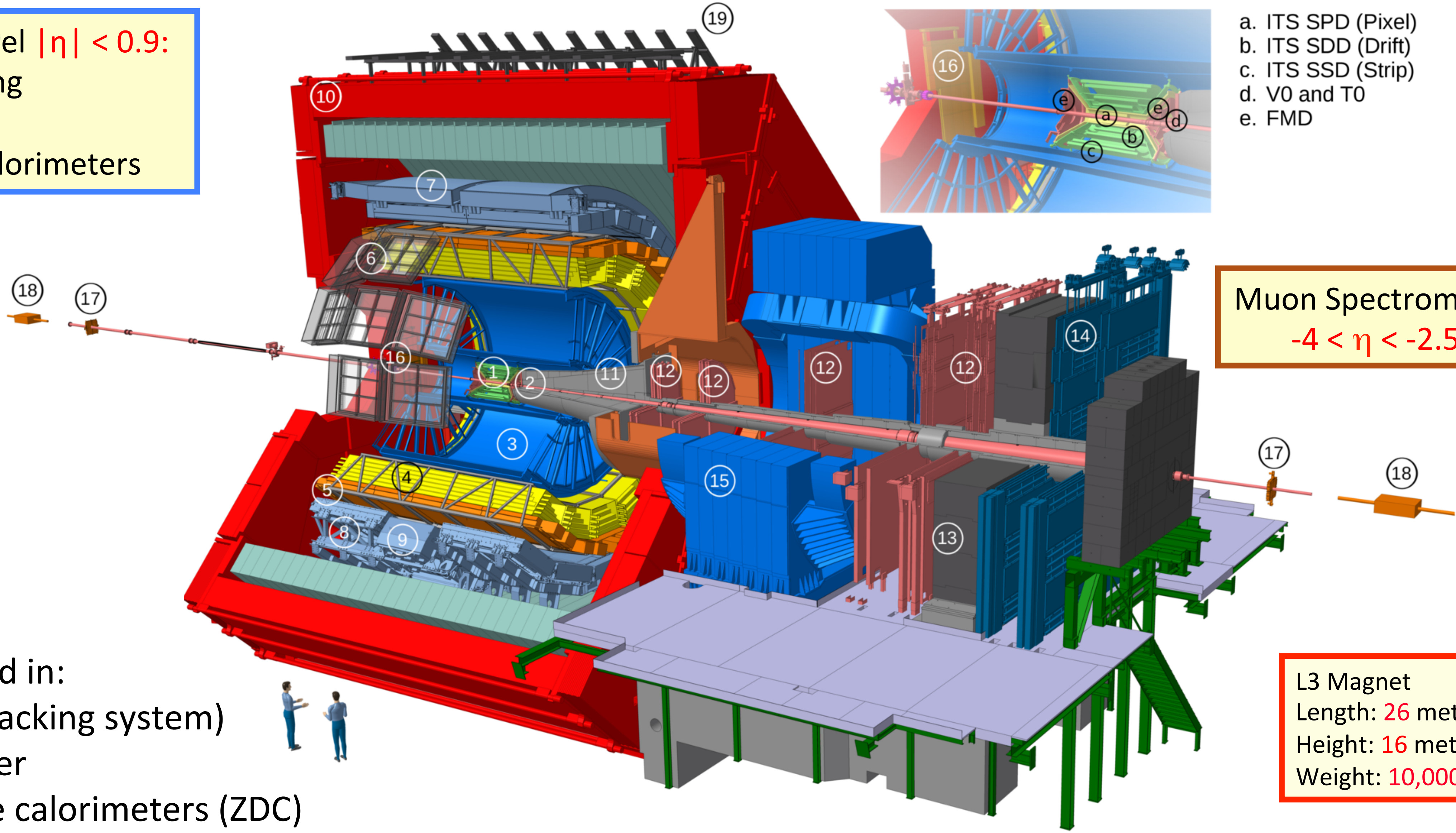
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010-2011	2.76	~75 μb^{-1}
	2015	5.02	~250 μb^{-1}
	by end of 2018	5.02	1 nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013	5.02	~15 nb^{-1}
	2016	5.02, 8.16	~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013	0.9, 2.76, 7, 8	~200 μb^{-1}, ~100 nb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1}
	2015,2017	5.02	~1.3 pb^{-1}
	2015-2017	13	~25 pb^{-1}



- LHC Run 2 data analysis is in full swing.
- Significant increase in integrated luminosity in pp, p-Pb, and Pb-Pb collisions allows more and more precise investigation of statistics hungry probes.

The ALICE Experiment

Central Barrel $|\eta| < 0.9$:
- Tracking
- PID
- EM-Calorimeters

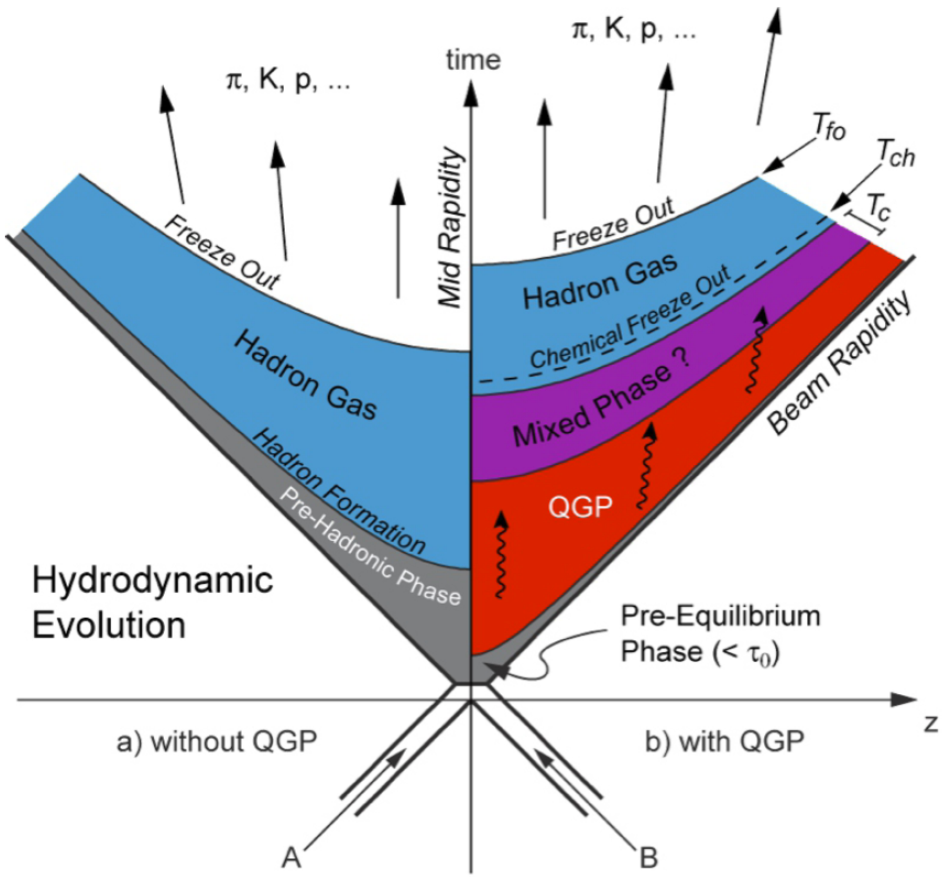


Muon Spectrometer
$-4 < \eta < -2.5$

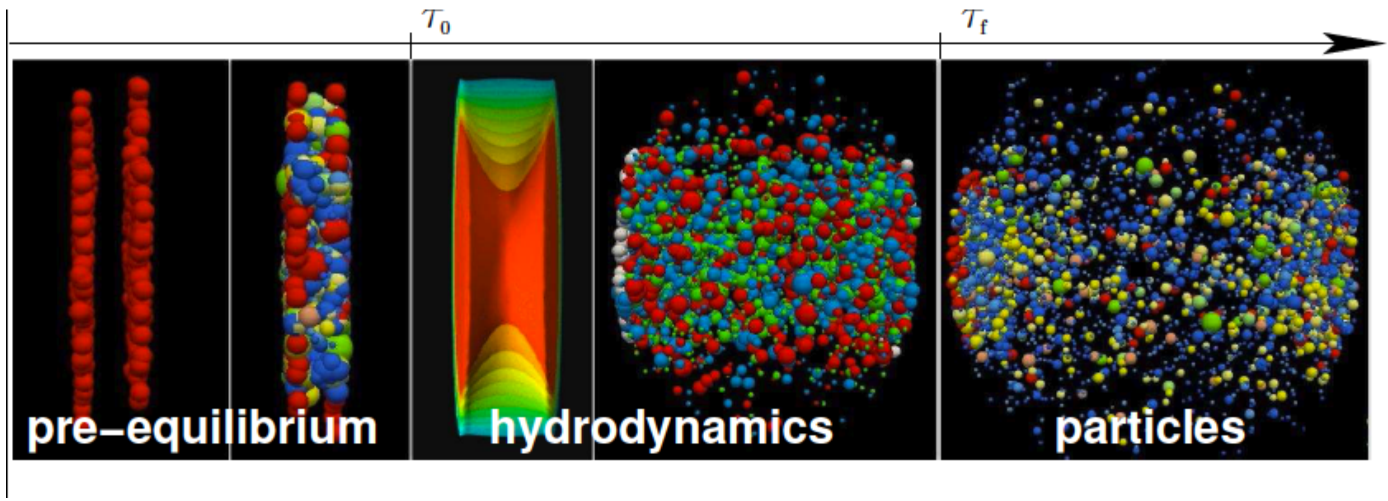
L3 Magnet
Length: 26 meters
Height: 16 meters
Weight: 10,000 tons

Cagliari involved in:
- ITS (inner tracking system)
- Muon tracker
- Zero Degree calorimeters (ZDC)

The standard model of high-energy heavy ion collisions

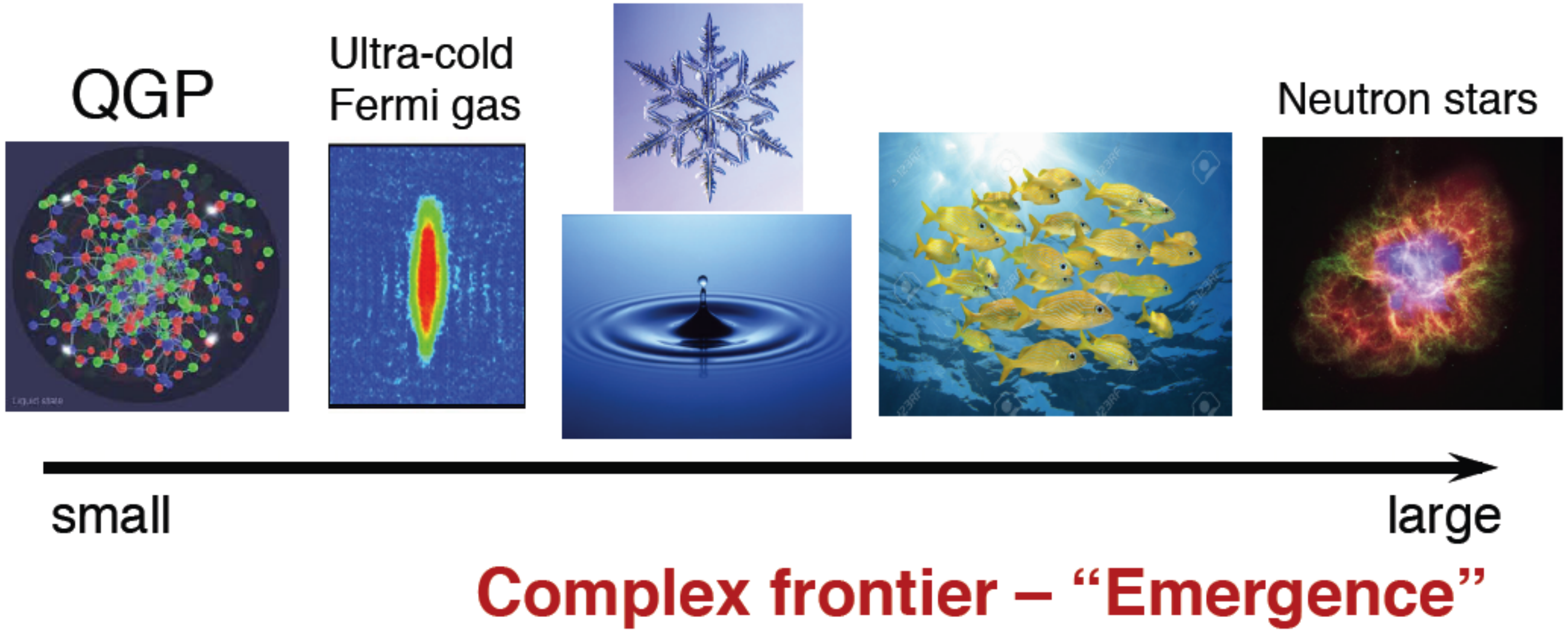


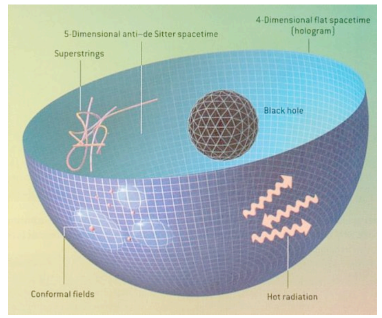
- Particle detection (t ~ 10^{15} fm/c)
- Kinetic freeze-out (t ~ 10-15 fm/c, T ~ 100 MeV)
- Chemical freeze-out (T ~ 150 MeV)
- Hydrodynamic evolution (t ~ 0.5 fm.c)
- Pre-equilibrium
- Collision (t= 0 fm/c)



Collective phenomena

A central them in the study of strongly correlated, interacting many body systems





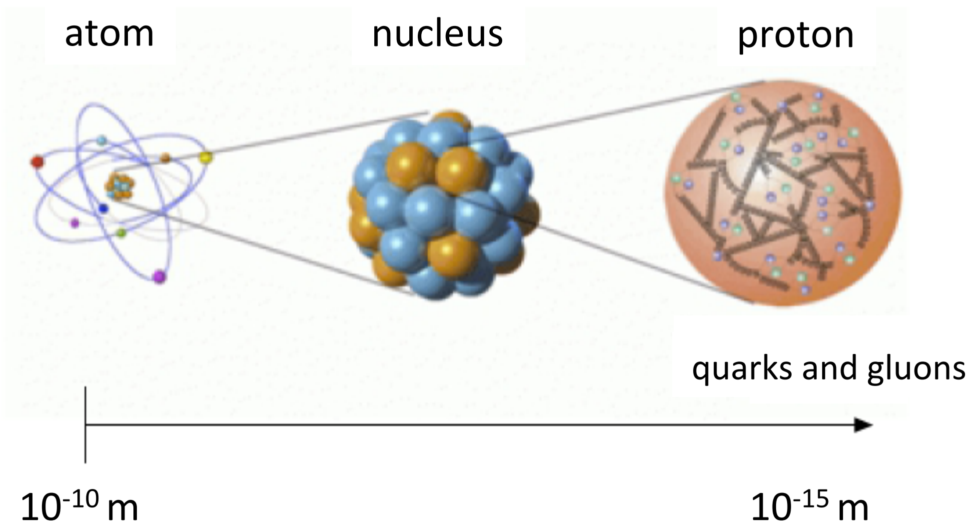
Black-hole in 5D ADS spacetime

Key questions:

- What is the underlying mechanism to drive?
- Can they be understood form fundamental forces?

QCD matter and the ultimate frontier in fluid dynamics

"Macro" scales → nuclear/particle physics



FLUID??

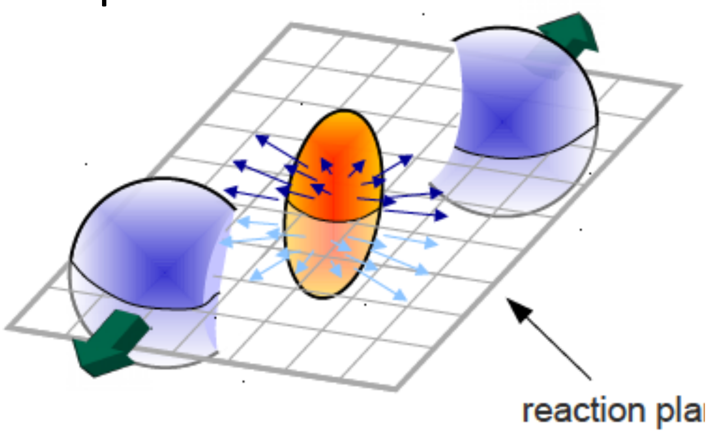
At its mos fundamental level: **collectivity in heavy ion collisions**

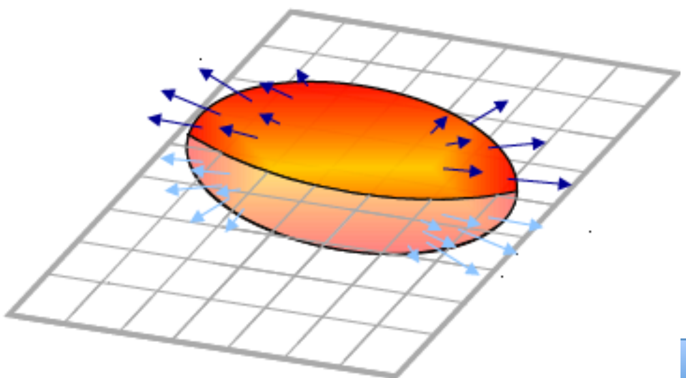
Strong interactions ➔ strong correlations:
- quasiparticles loosing their identity when mean free path for these excitations ≈ interparticle spacing
- Failing of Kinetic theories (in particular Boltzmann equation)

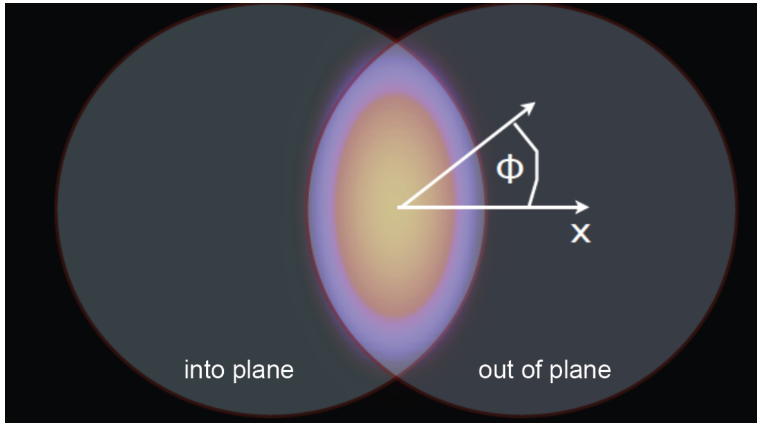
Nearly ideal (low viscosity) hydrodynamics is a very good description of these systems

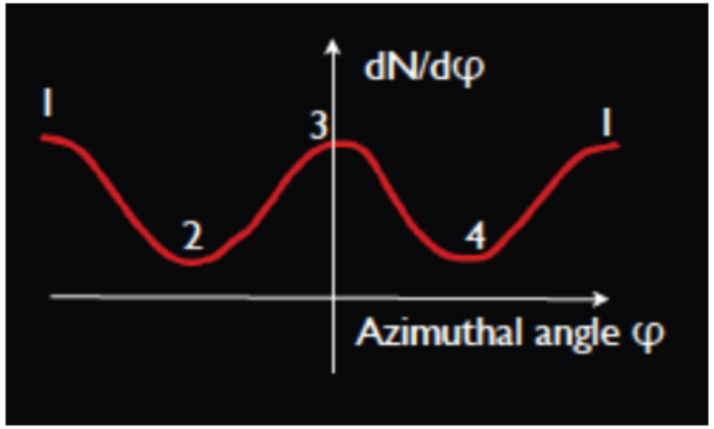
Collective expansion and elliptic flow

Peripheral collisions are azimuthally asymmetric
Pressure in the hot drop of strongly interacting fluid affects the momentum of emitted particles





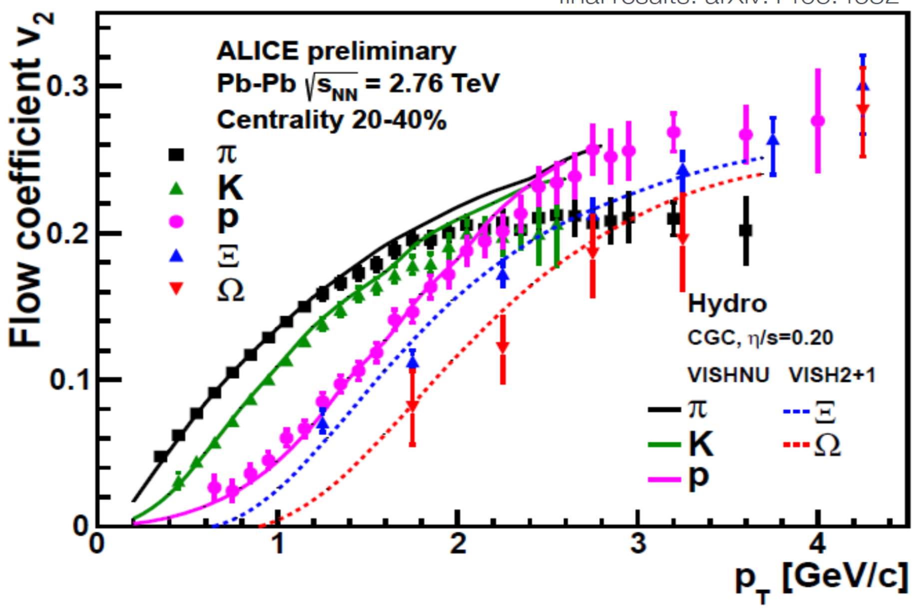




Study particle production as a function of the emission angle w.r.t. the reaction plane

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi)]\right)$$

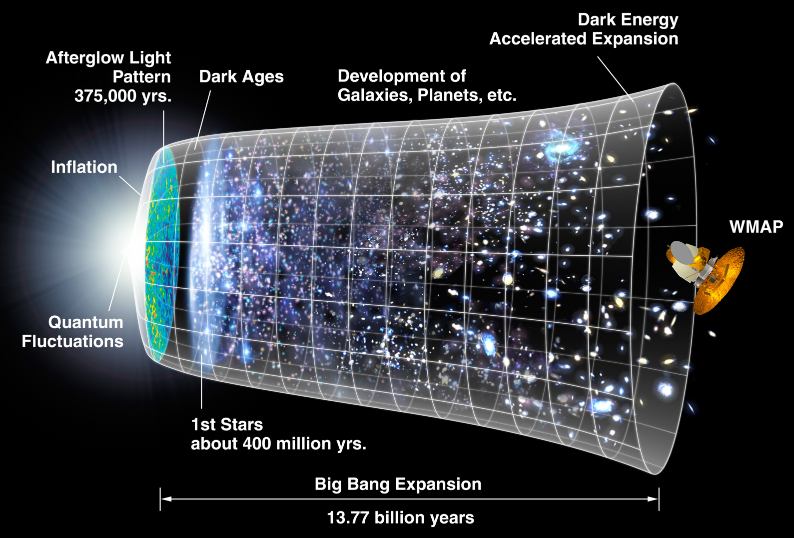
final results: arXiv:1405.4632



Fourier expansion, usually dominated by v_2, the so-called **elliptic flow**

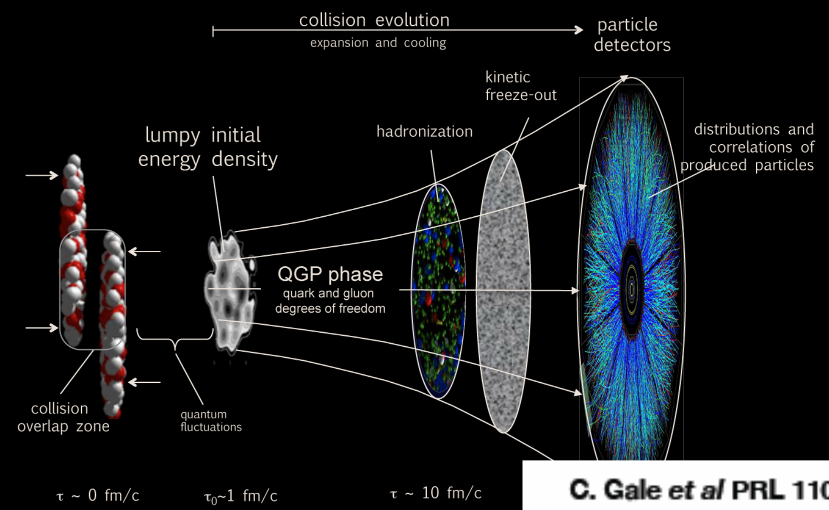
Survival of initial state fluctuations: Universe and HI collisions

The Universe



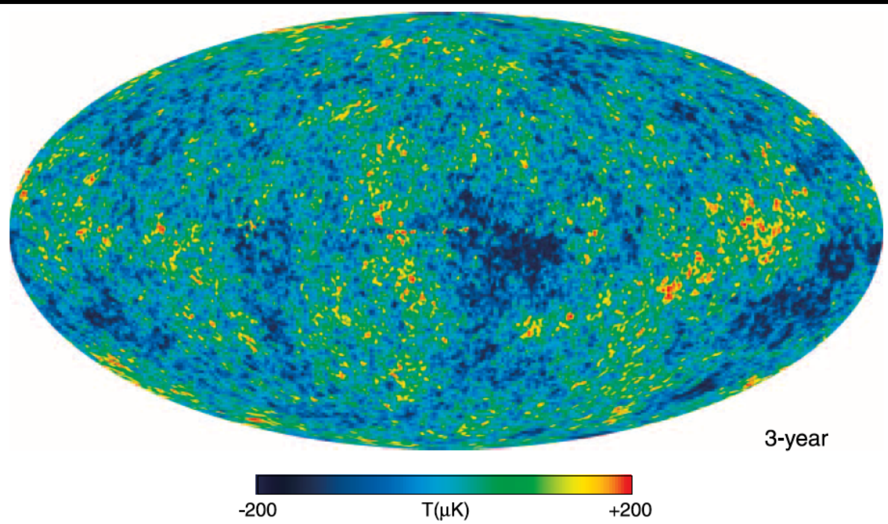
Credit: NASA

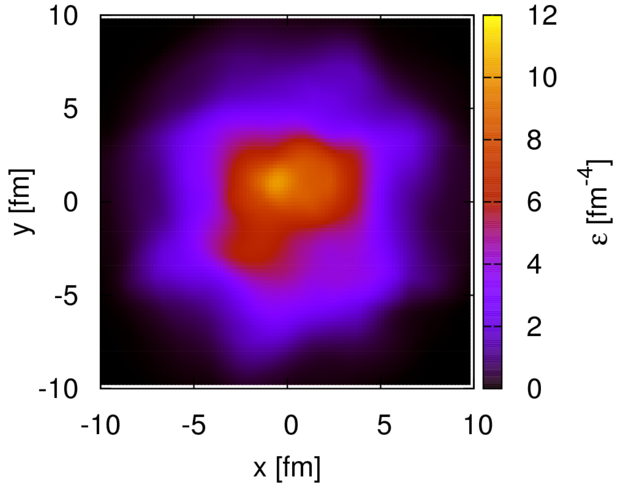
Heavy ion collision



Credit: P. Sorensen

NASA/WMAP Science Team



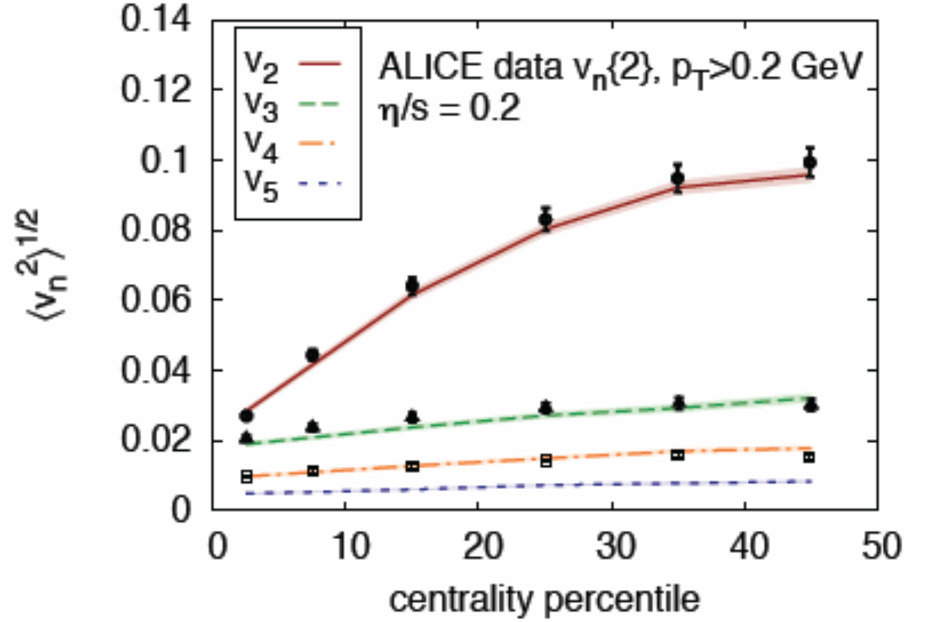


Medium transport coefficients:

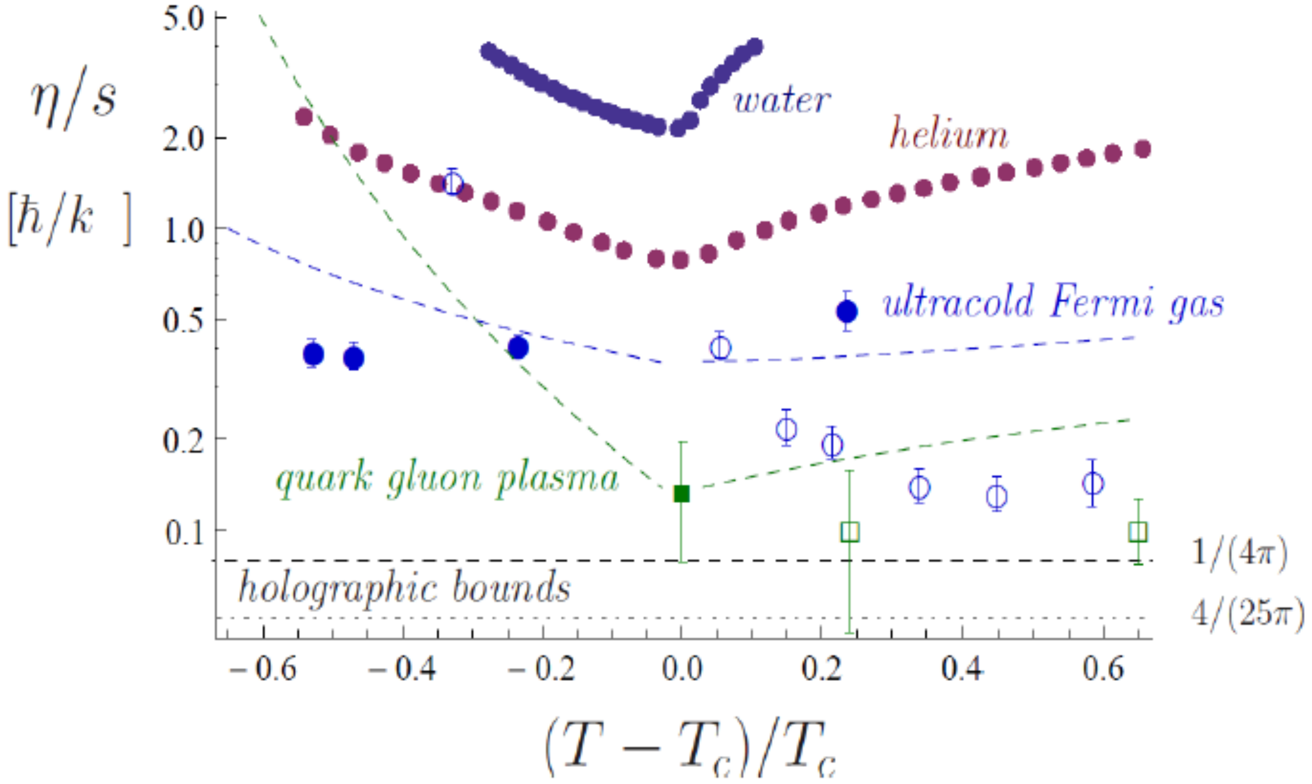
- Shear viscosity η?
- Bulk viscosity?

➔fluctuations of initial state: power spectrum of vn coefficients

C. Gale *et al* PRL 110, 012302 (2013) ALICE, PRL 107, 032301 (2011)



The competition for the most ideal fluid



A. Adams, L.D. Carr, T. Schaefer, P. Steinberg. J.E. Thomas, arXiv:1205.5180

Estimating the viscosity of QGP:

$$\eta = \frac{\hbar}{4\pi} s = \frac{10^{-27}\, erg \cdot s}{\left(10^{-13}\, cm\right)^3} = 10^{14}\, cp$$

Very high absolute value in normal unit.

Almost glass!

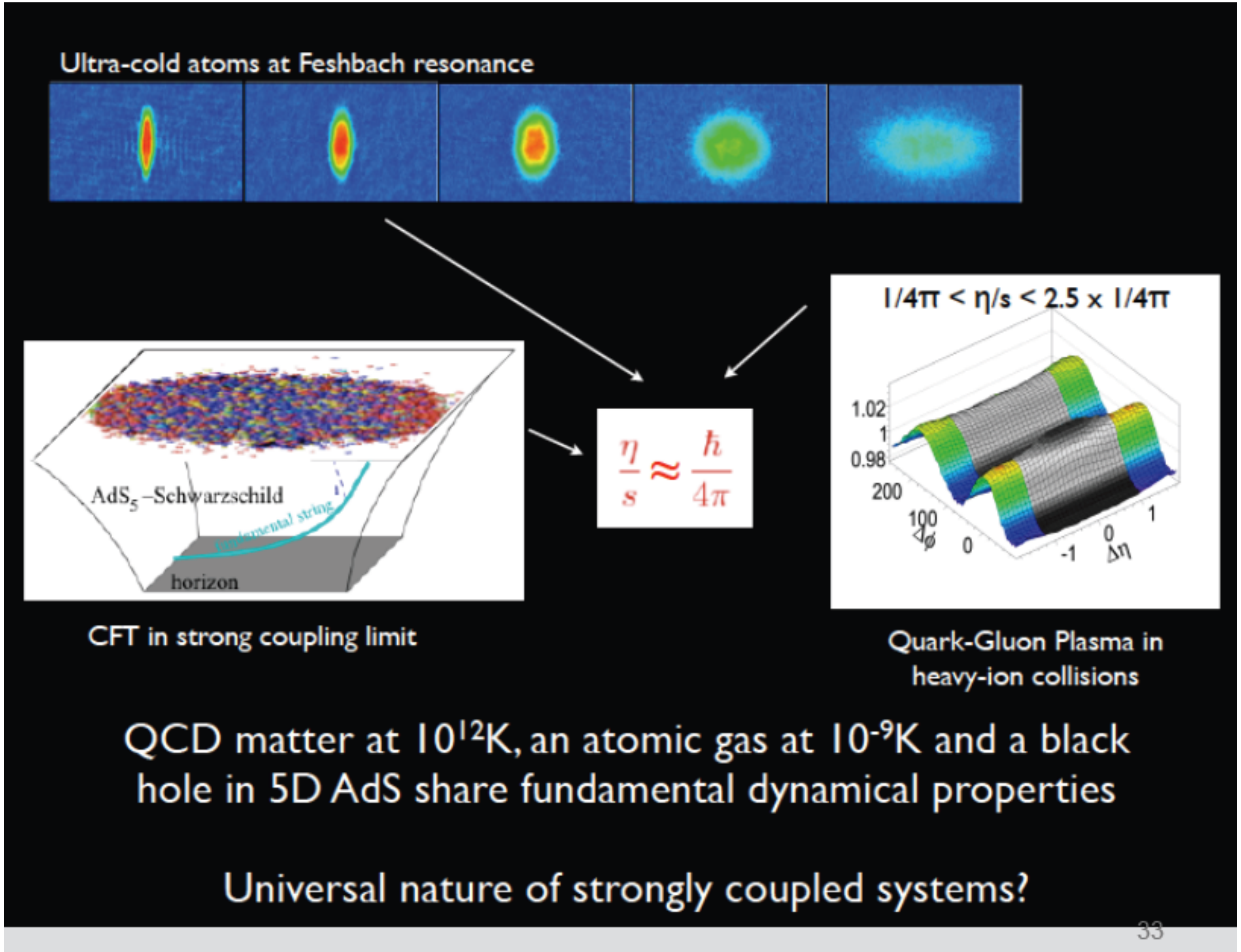
Low viscosity in the sense of η/s

Table 8.4.1. *Viscosities η for some common materials in centipoise (10^{-2} erg s/cm^3).*

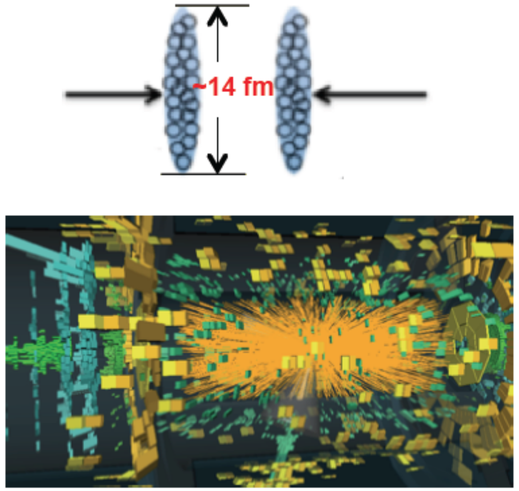
Substance	Temperature	Viscosity (cp)
Air	18°C	0.018
Water	0°C	1.8
Water	20°C	1
Water	100°C	0.28
Glycerin	20°C	1500
Mercury	20°C	1.6
n-Pentane	20°C	0.23
Argon	85K	0.28
He^4	4.2K	0.033
Superfluid He^4	< 2.1K	0
Glass		> 10^{15}

Note that, by popular convention, the designation "glass" is applied to any disordered material once its viscosity exceeds 10^{15} cp.

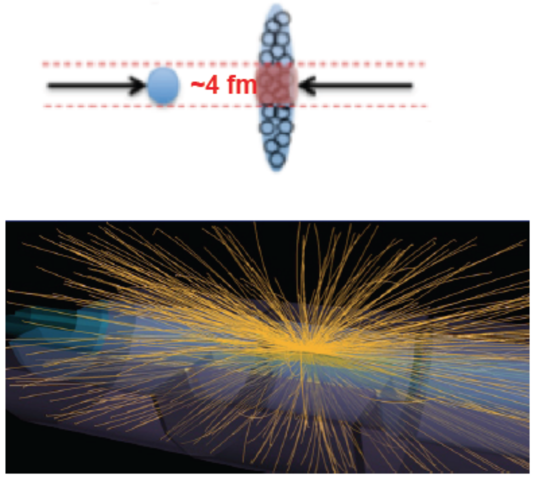
The dynamics of strongly coupled systems



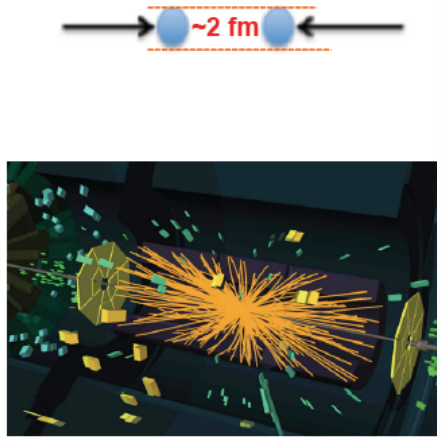
The ultimate open question: what's the nature of the medium created in different collision systems?



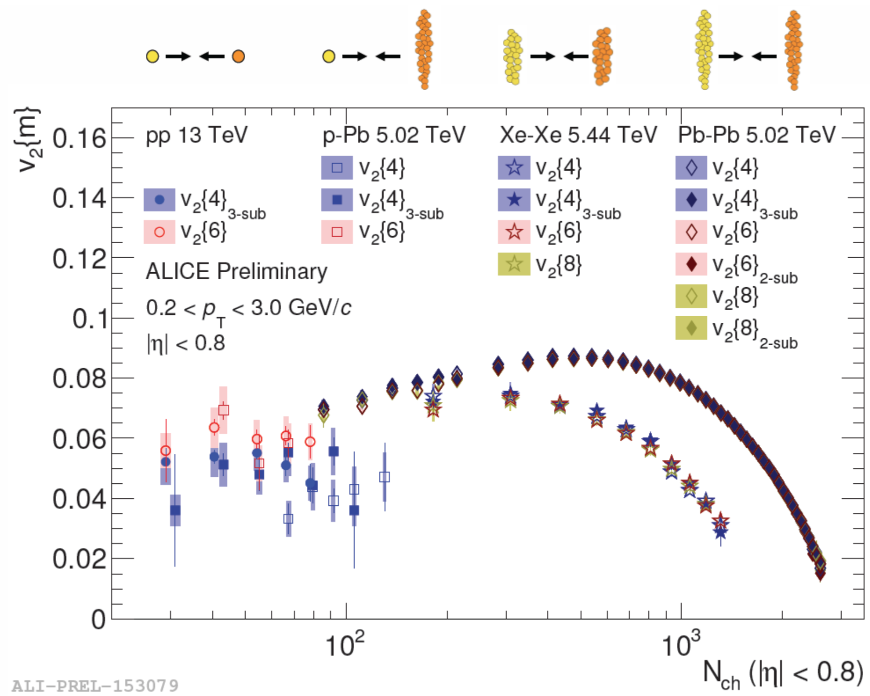
~30000 particles*



~2000 particles*



~ 600 particles*



What is the smallest droplet of QGP created in these collisions?

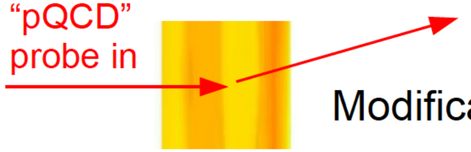
→ Change matter size, life-time and space-time dynamics @ RHIC and LHC

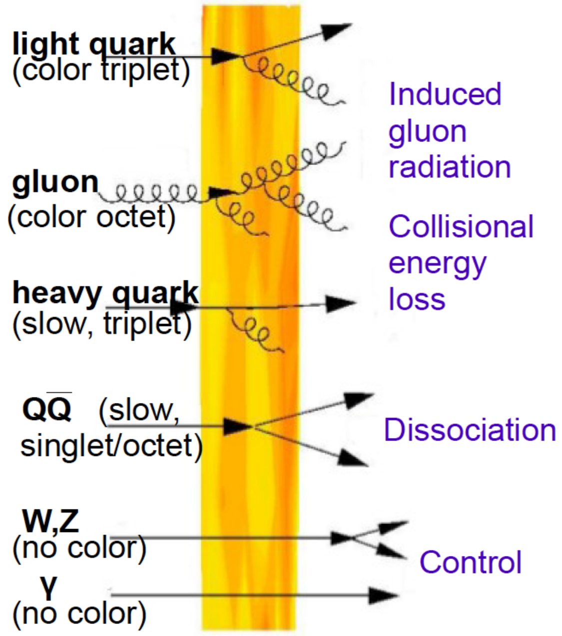
One fluid to rule them all?

* rough number of particles emitted in very high central collisions at LHC energies

Short wave-length degrees of freedom: tomography of QCD matter

- Hard (large Q^2) probes of QCD matter: jets, heavy-quark, $Q\bar{Q}$, γ, W, Z
    - Measurable in pp/pA and/or calculable in pQCD
- "Self-generated" in the collision at proper time $\tau \approx 1/Q^2 << 0.1$ fm/c
- "Tomographic" probes of hottest and densest phase of medium

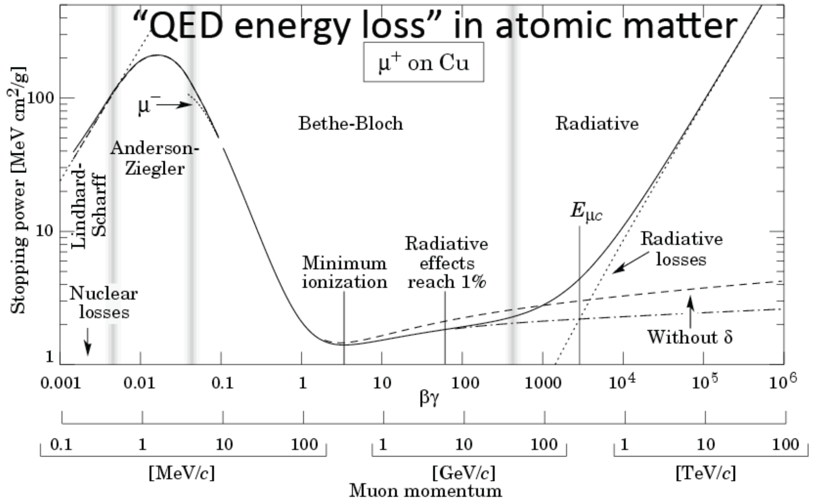




~ Study QCD "Bethe-Block" curve for partons in the QGP

Connection of "local" interactions with global medium properties

"QED energy loss" in atomic matter

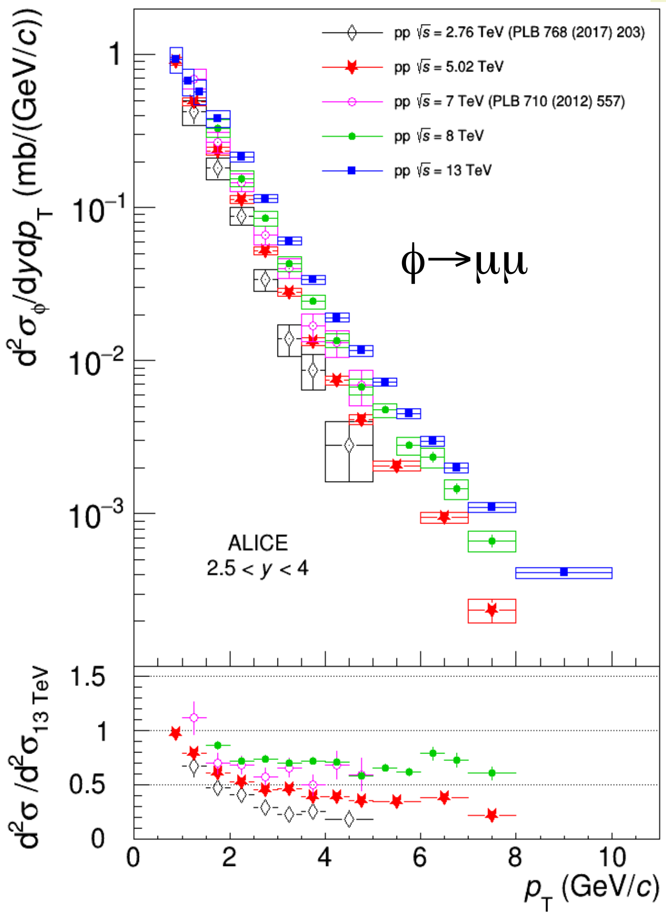


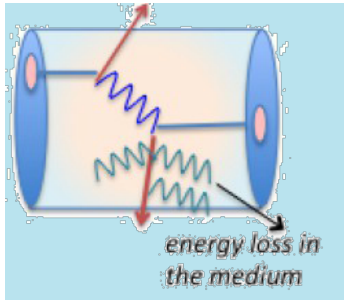
The measurement of energy loss: nuclear Modification Factor

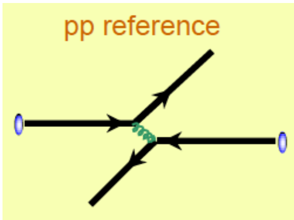
$$R_{AA} = \frac{AA}{\text{scaled pp}} = \frac{d^2N_{AA}/dp_T dy}{\langle N_{coll}\rangle d^2N_{pp}/dp_T dy}$$

No nuclear effects: scaling with n. of binary collisions N_{coll} → $\mathbf{R_{AA} = 1}$

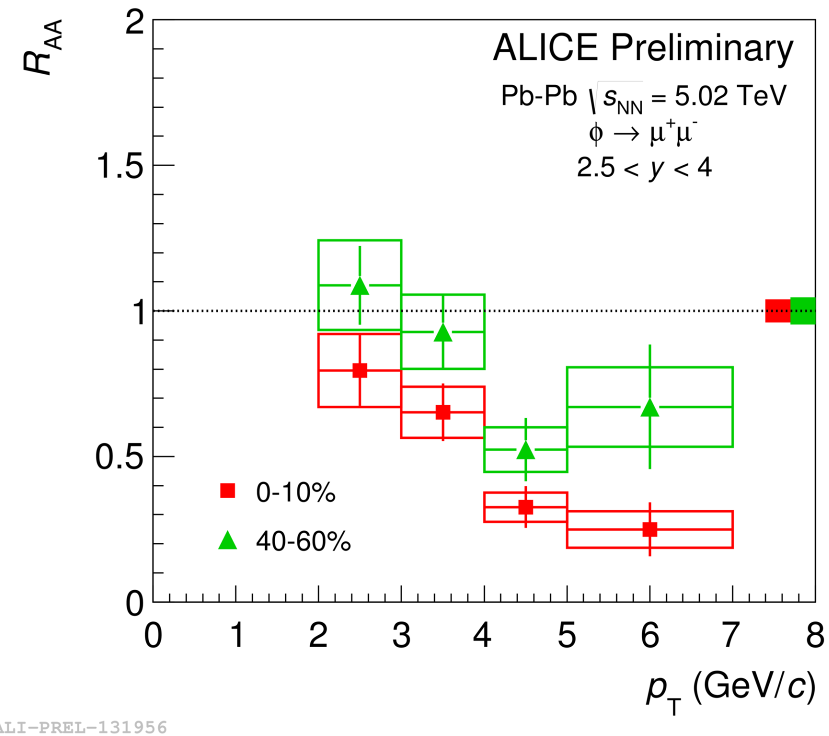
Final state effects → breakup of binary scaling and $\mathbf{R_{AA} \neq 1}$







non medium effects
$R_{AA} = 1$
hot matter effects
$R_{AA} \neq 1$

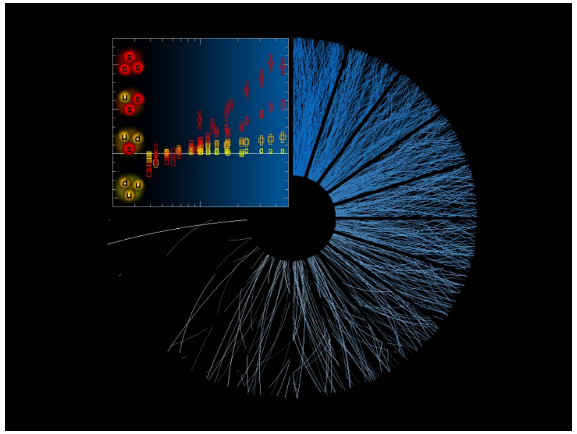


Pb-Pb: suppression vs p_T in central collisions → Interplay between hydrodynamic expansion of the fireball (low-p_T) and suppression due to energy loss mechanisms like **gluon bremstrahlung** (dominant high p_T)

A. De Falco, E. Casula, A. Chauvin

Strangeness Enhancement

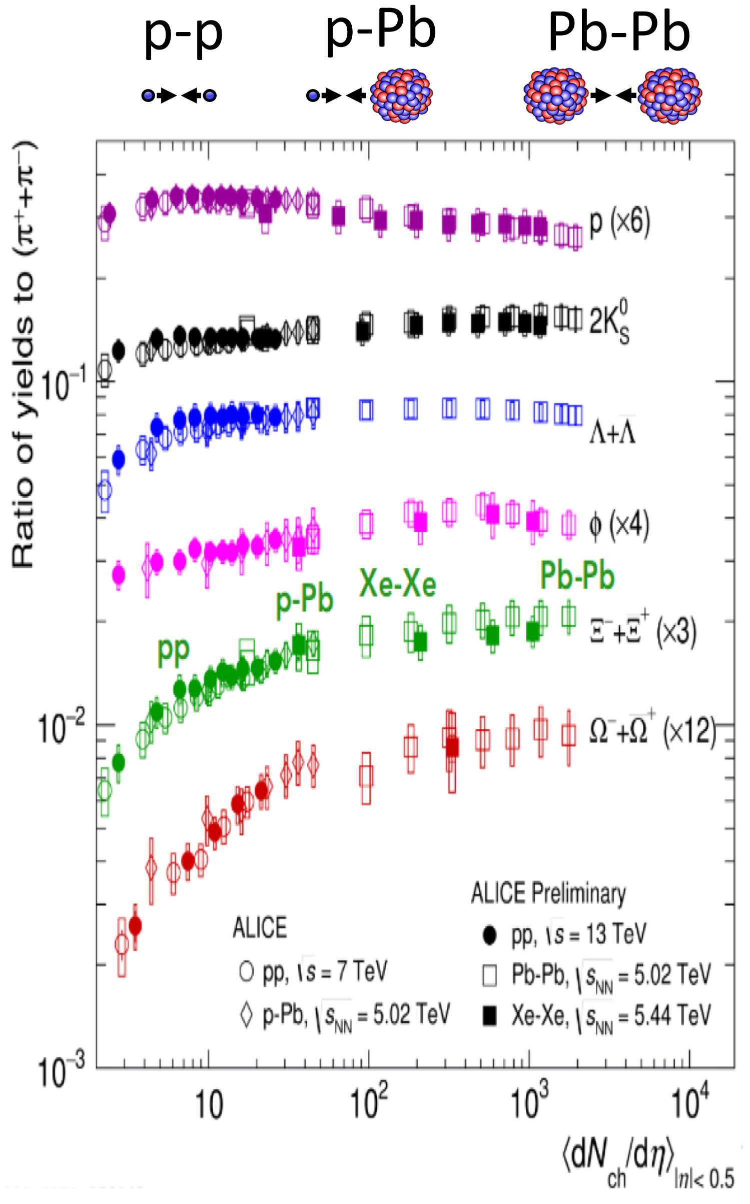
Strangeness enhancement as a signature of QGP



Nature Physics (2017) doi:10.1038/nphys4111

Additional insight on ϕ vs multiplicity at forward rapidity

A. De Falco, E. Casula, A. Chauvin



Significant enhancement of strangeness with multiplicity in high mult pp events and pPb, scaling with net strangeness content |S|

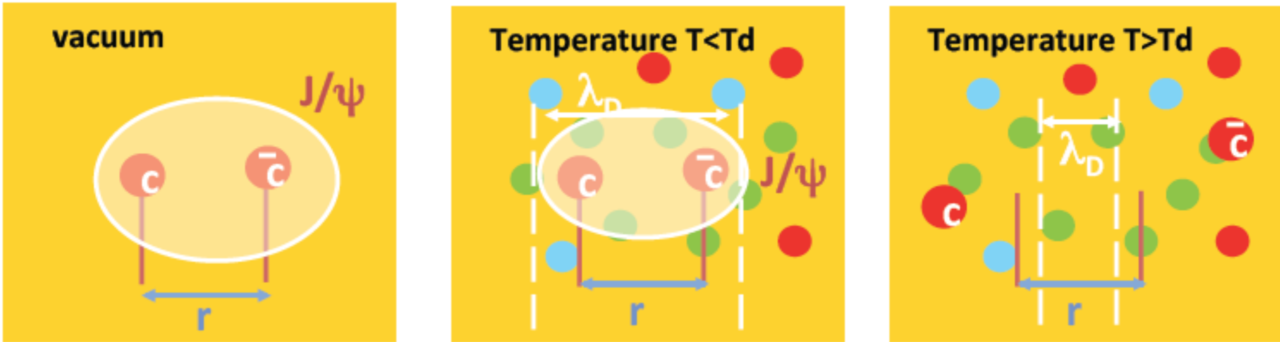
pp behavior resembles p-Pb: both in term of value of the ratio and shape

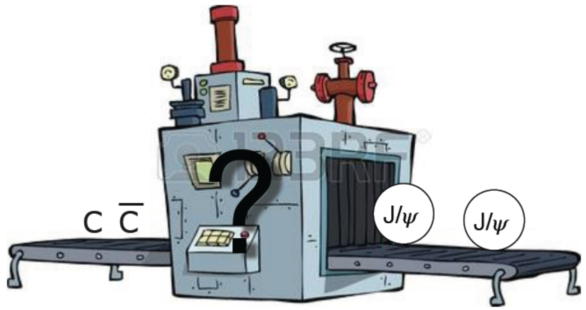
No evident dependence on cms energy: strangeness production apparently driven by final state rather than collision system or energy

At high multiplicity pp ratio reaches values similar to the one in Pb-Pb (when ratio saturates)

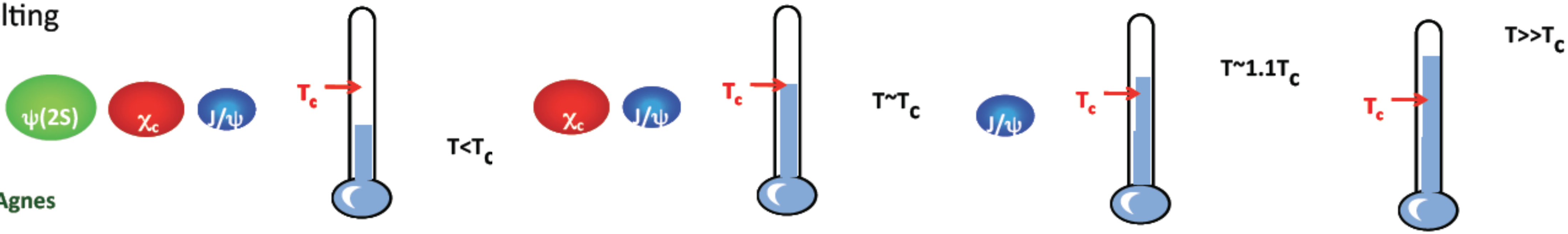
Quarkonium: sequential melting in the QGP

Debye screening of QQbar potential in the medium





Sequential melting



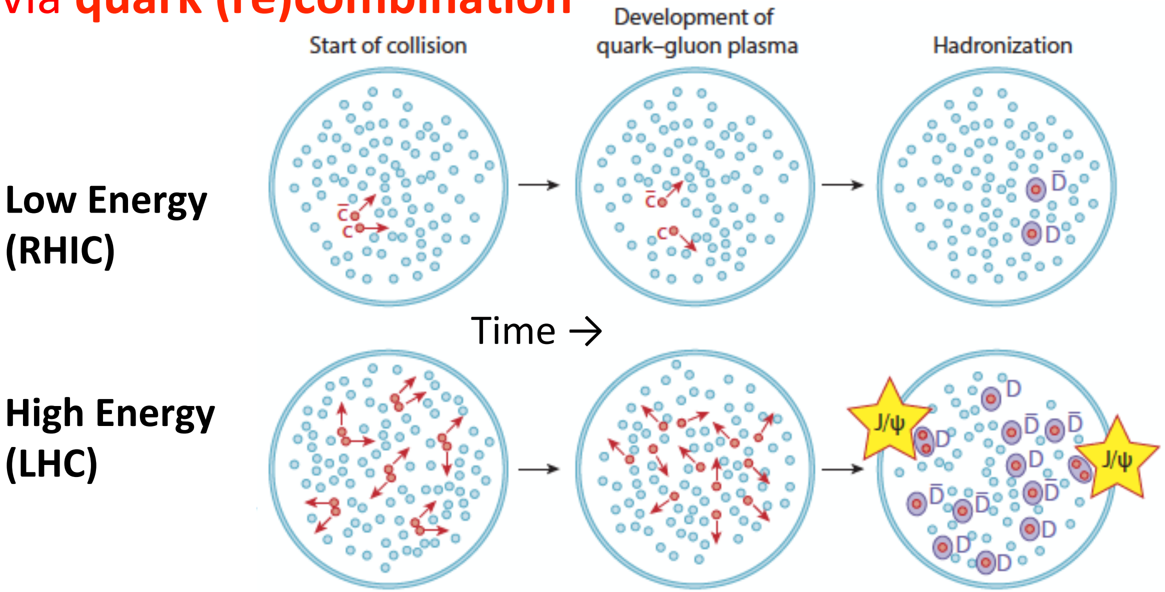
Nice picture by Agnes Moscy

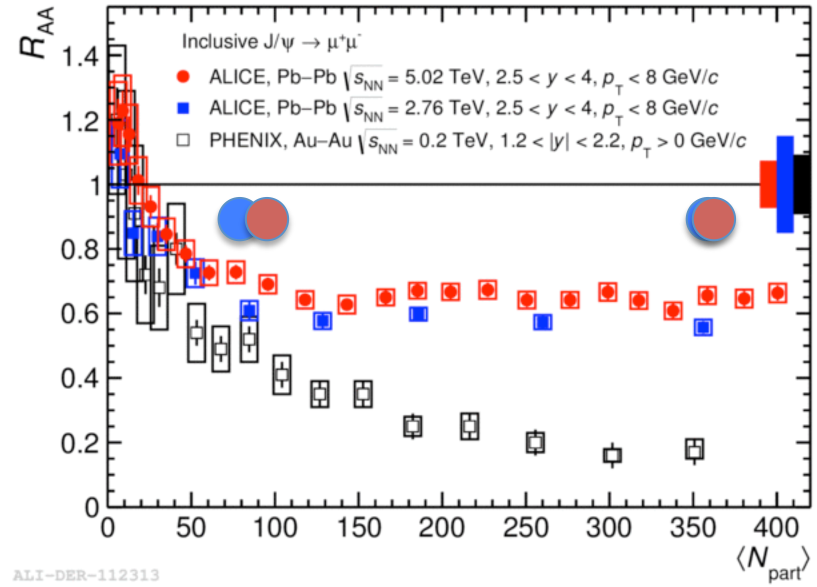
A new twist: J/ψ "regeneration" at LHC energies

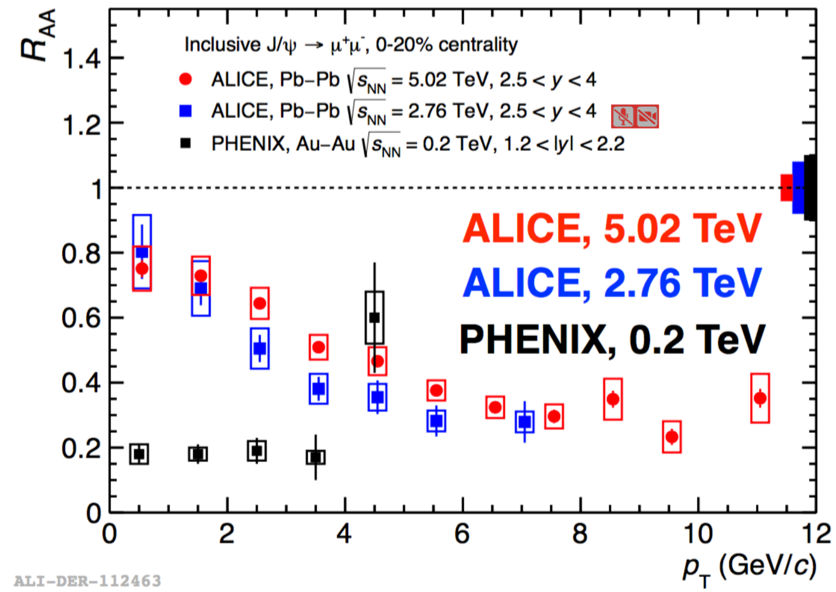
High energy: $c\bar{c}$ pair multiplicity becomes large

In most central A-A collisions	SPS 20 GeV	RHIC 200 Gev	LHC 2.76 TeV
N_{ccbar}/event	~0.2	~10	~60

➔J/ψ can form via **quark (re)combination**







2.76 and 5.02 TeV: significant (similar) suppression wrt pp but much less than RHIC at 0.2 TeV

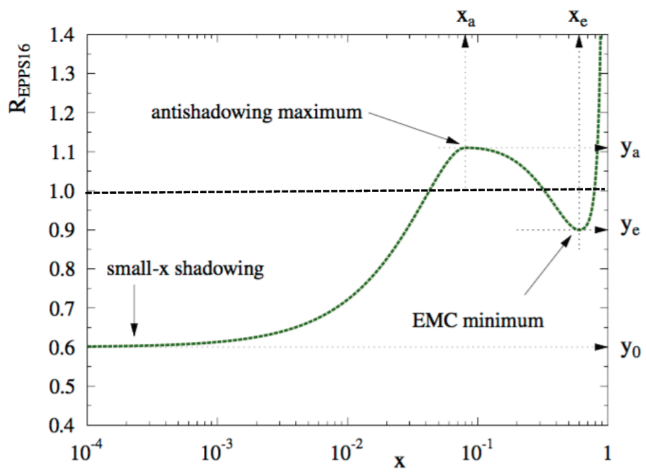
Suppression stronger at high p_T and central collisions

Consistent with **strong recombination** effect at LHC

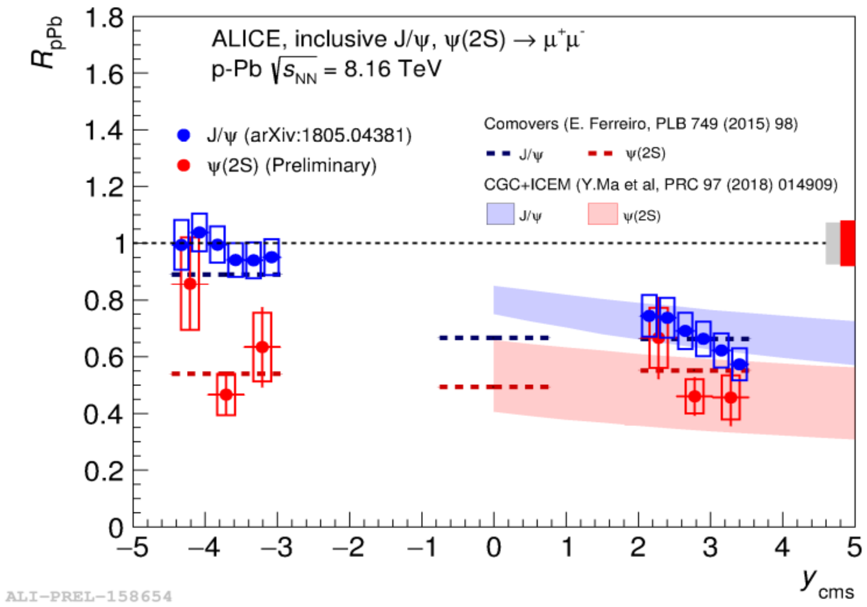
R_{pPb} quarkonia in p-Pb collisions and initial state effects

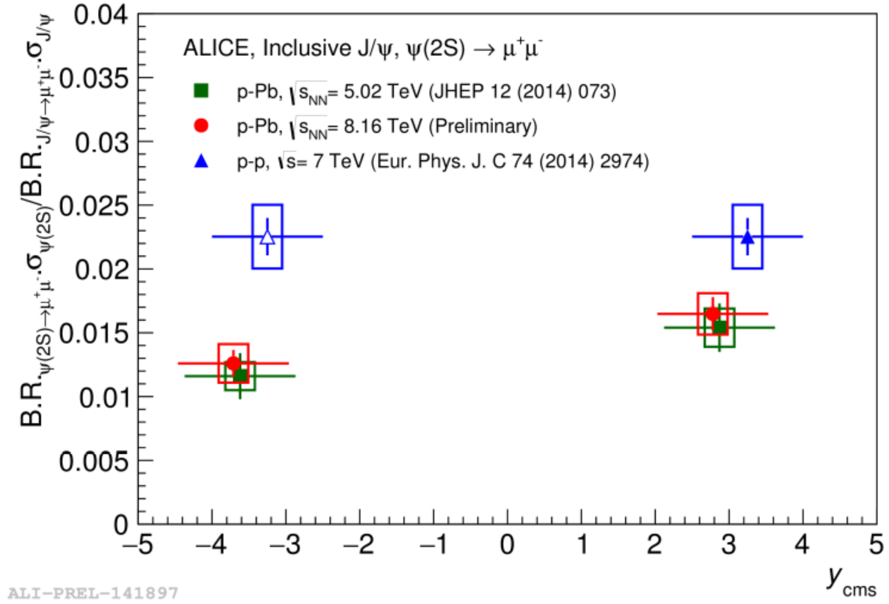
Binary scaling can be broken due to initial state effects:

- PDF modifications in nuclei:shadowing, anti-shadowing, saturation at low x (color glass condensate)
- k_T boradening: multiple elastic collisions before hard scattering can cause R_{pA}>1 at p_T=2-3 GeV



➔these effects can be addressed in p-Pb interactions





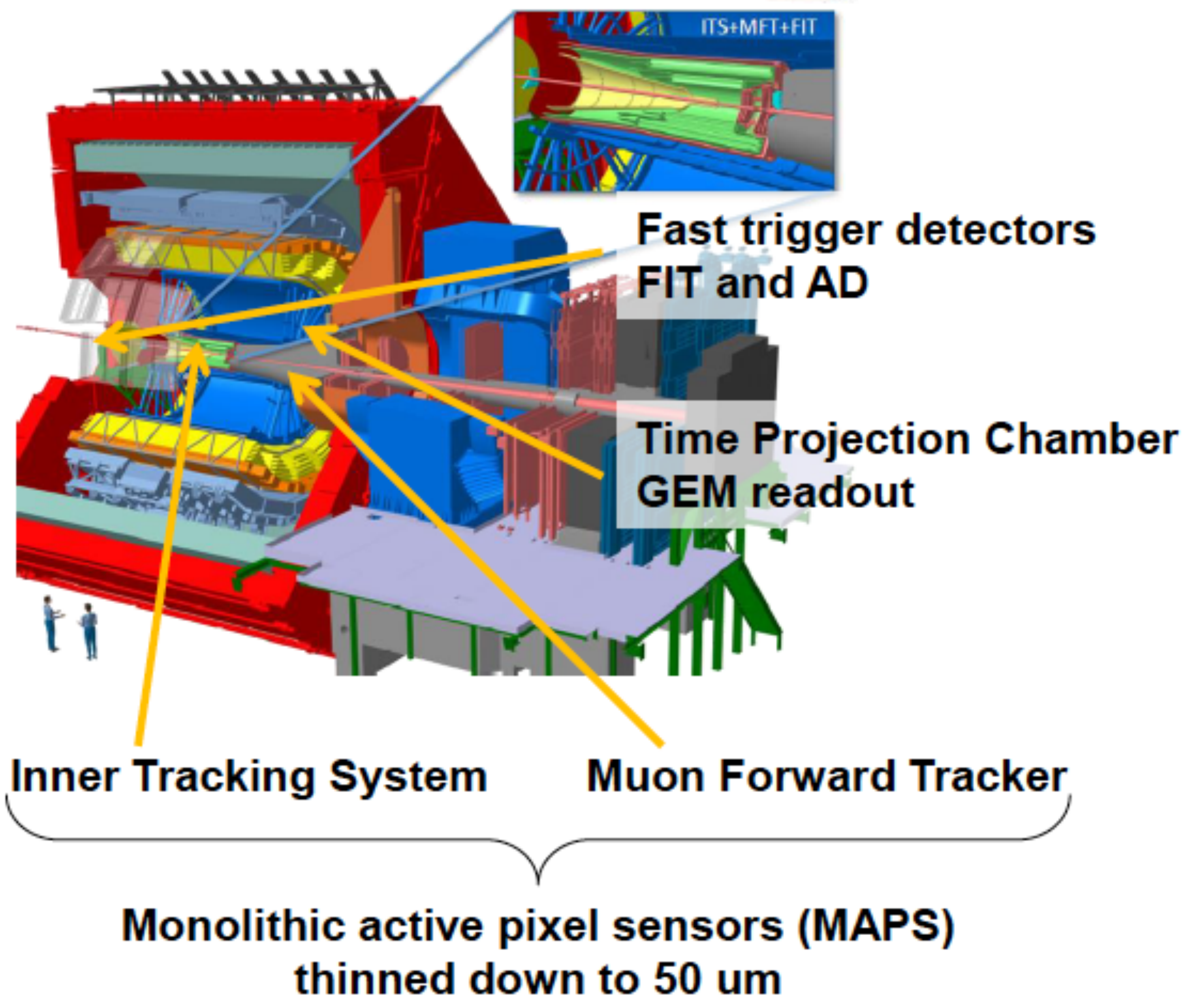
P. Biswarup, A. De. Falco

- J/ψ shows a stronger suppression at forward-*y* than at backward-*y*, where R_{pPb} is compatible with unity
- ψ(2S) shows a stronger suppression than J/ψ, final-state effects needed to explain the ψ(2S) behaviour

ALICE future: run 3

(data taking from 2021)

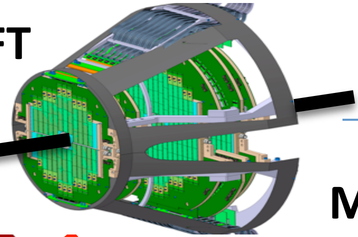
- Significant upgrade, including
  - increasing data rate by factor 100
  - impact parameter resolution by factor 3
- Collision spacing < TPC drift time
  - No notion of event during data taking
- Continuous data-taking
  - 50 kHz Pb-Pb
  - Offline reconstruction determines which track belongs where
  - Online reduction 3.4 TB/s → 0.1 GB/s
  - 10 nb^{-1} = 10^{11} Pb-Pb events in 2021-29
- Focus on "untriggerable" signals with tiny signal over background



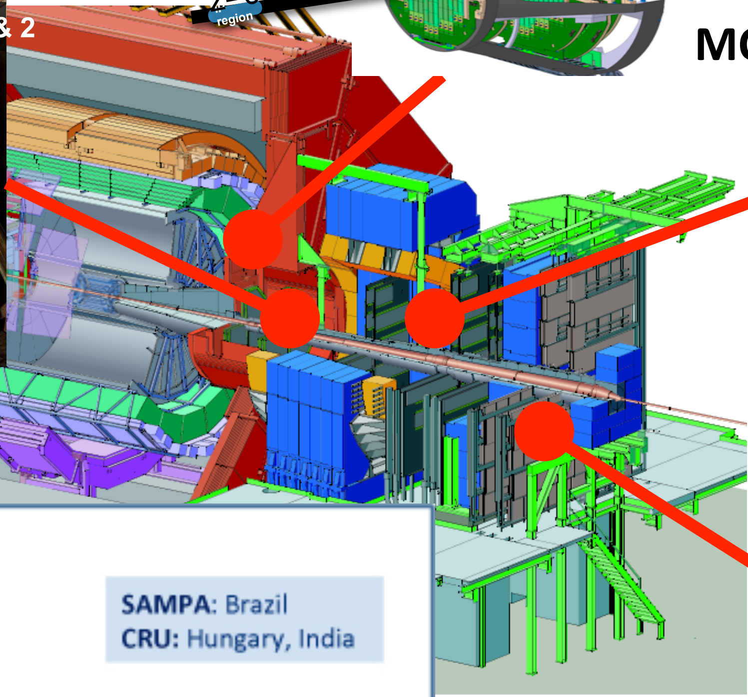
Cagliari involved in new ITS and upgrade of muon tracker readout electronics

The muon tracking

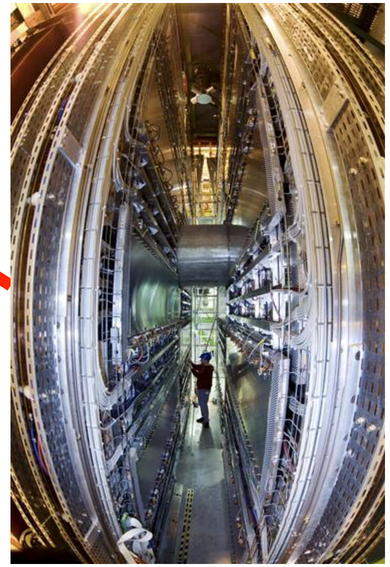
MFT



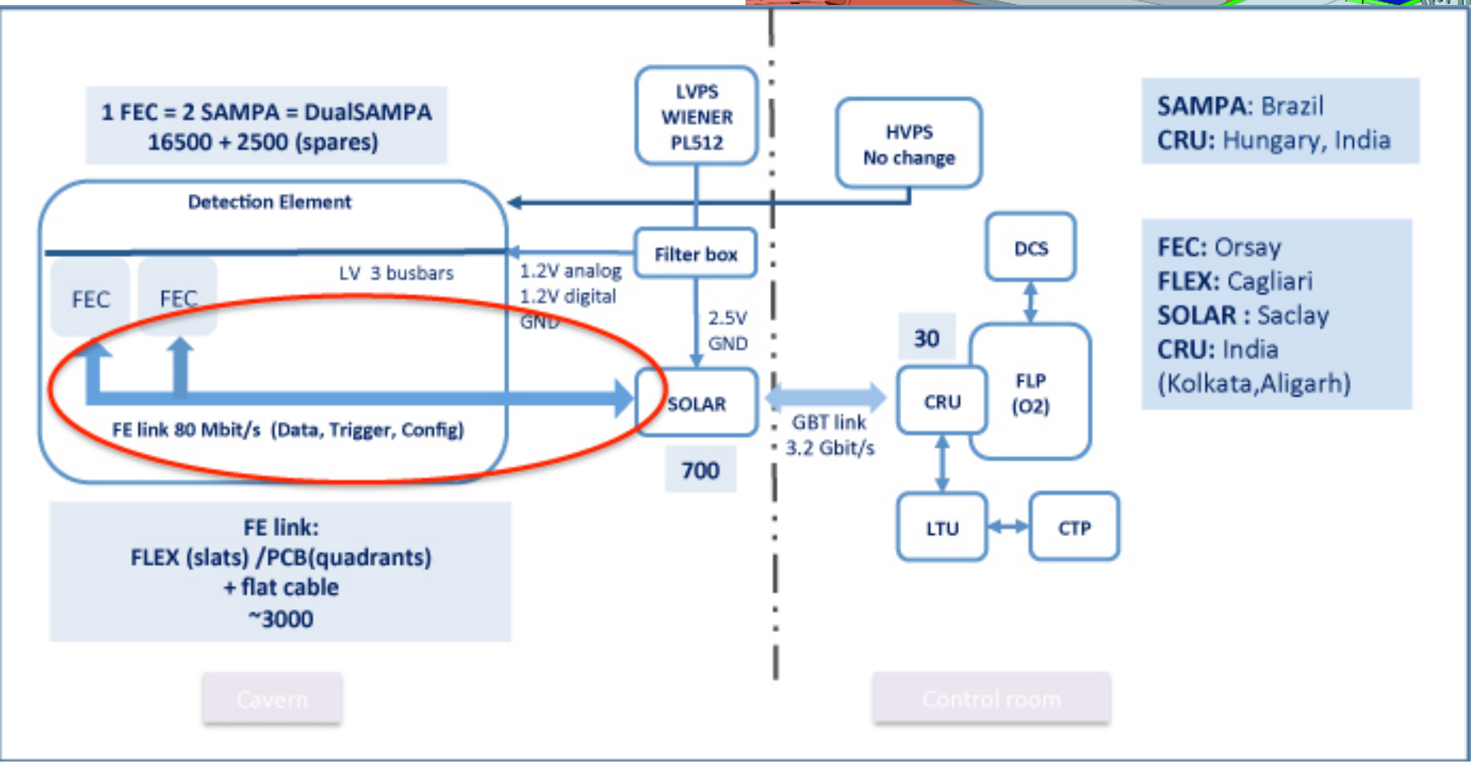
MCH



MCH

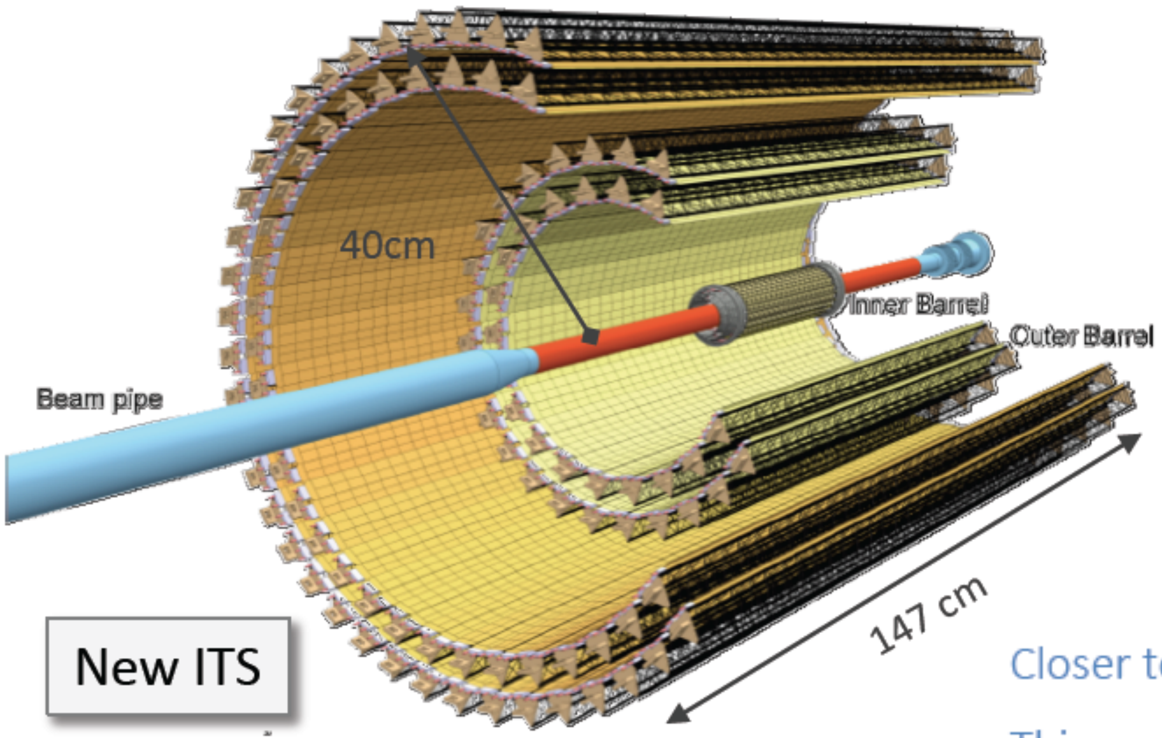


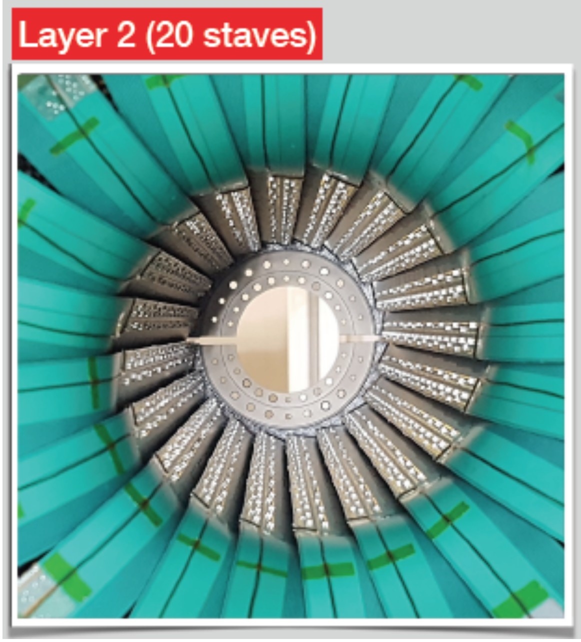
MTR



C. Cicalò, S. Siddhanta, D. Marras, M. Arba, M. Tuveri, S. Boi

The new ALICE ITS



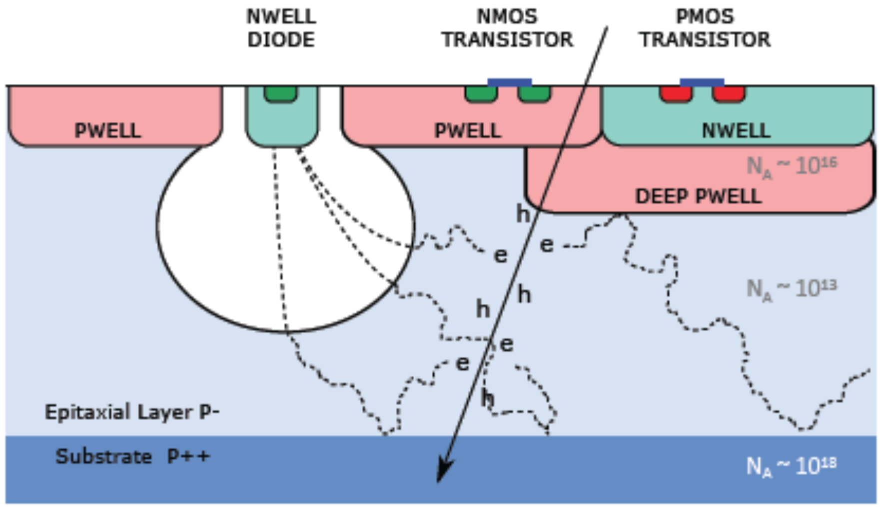


Closer to IP:	39mm ➡ 22mm
Thinner:	~1.14% ➡ ~ 0.3% (for inner layers)
Smaller pixels:	50µm x 425µm ➡ 27µm x 29µm
Increase granularity:	20 chan/cm^3 ➡ 2k pixel/cm^3
Faster readout:	x 10^2 Pb-Pb, x 10^3 pp
10 m^2 active silicon:	12.5 G-pixels, $\sigma \approx 5\mu m$

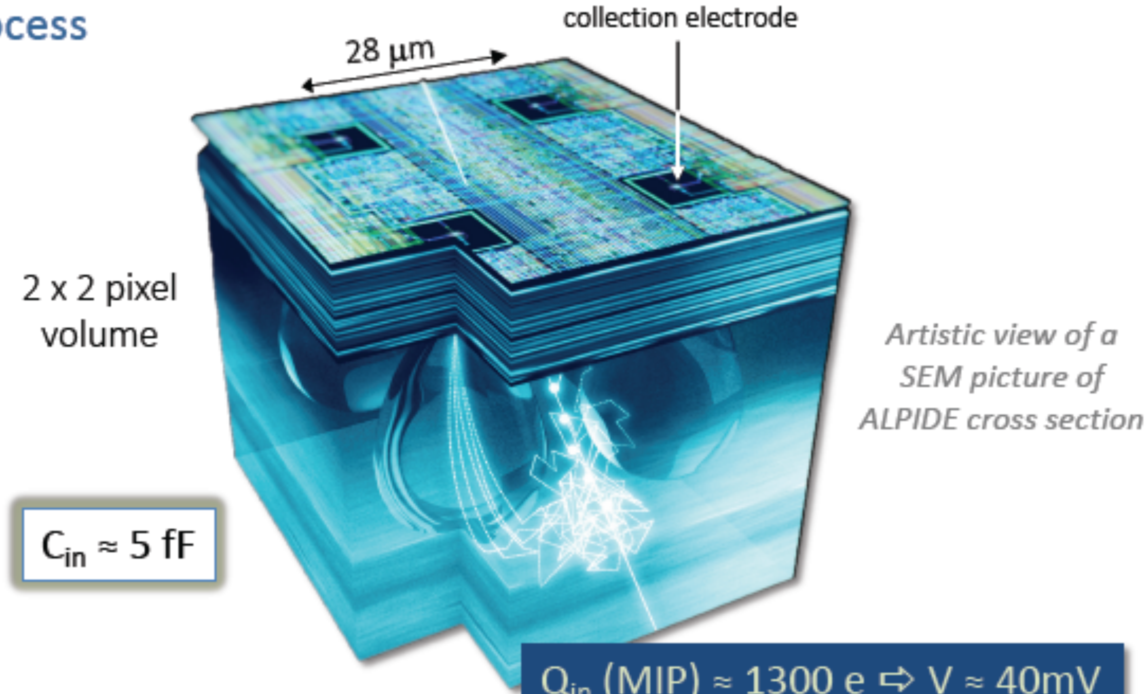
G. Usai, S. Siddhanta, D. Marras

The ALPIDE sensor (CCNU, INFN (TO, CA), IPHC, IRFU, NIKHEF, Yonsei

CMOS Pixel Sensor using TJ 0.18μm CMOS Imaging Process



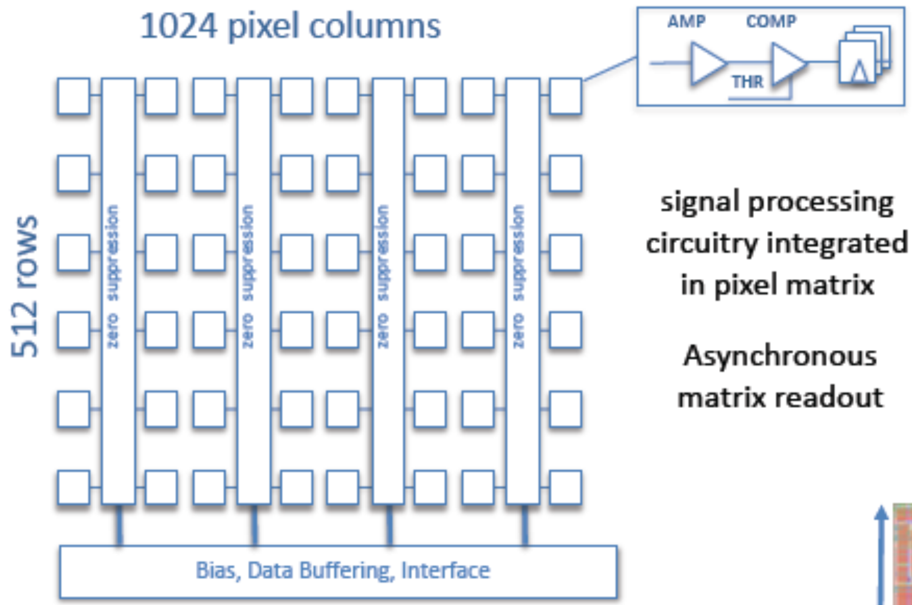
pixel capacitance ≈5 fF (@ V_{bb} = -3 V)



- High-resistivity (> 1kΩ 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

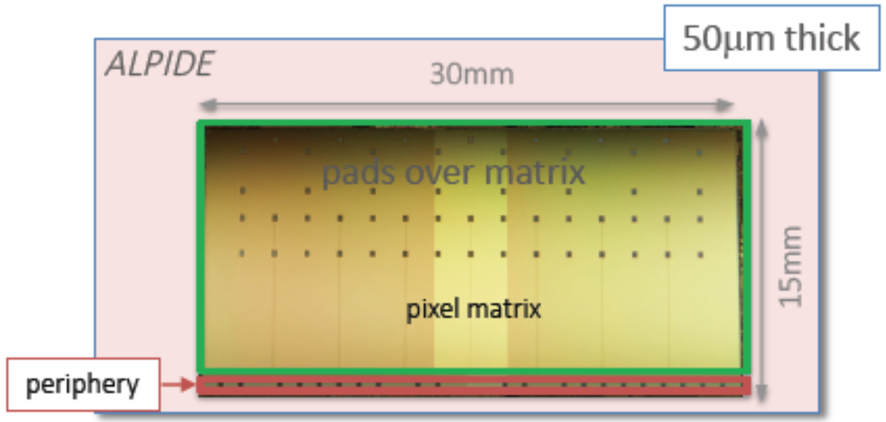
→ full CMOS circuitry within active area

The ALPIDE sensor (CCNU, INFN (TO, CA), IPHC, IRFU, NIKHEF, Yonsei



signal processing circuitry integrated in pixel matrix

Asynchronous matrix readout



130,000 pixels / cm^2 27x29x25 μm^3

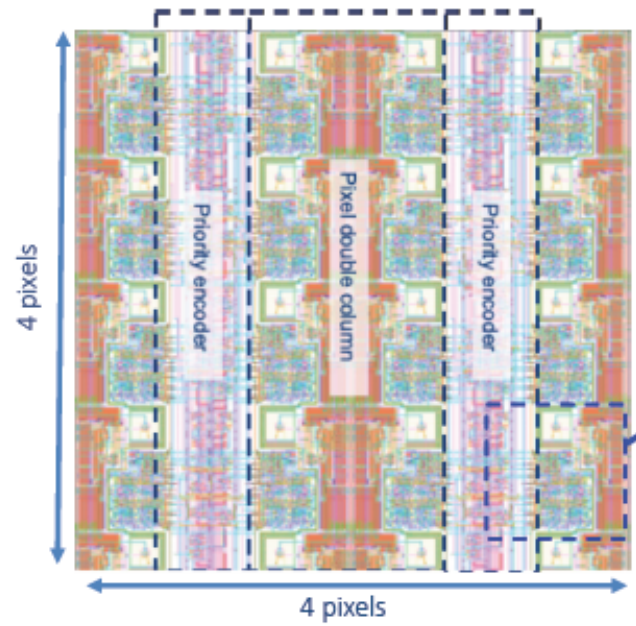
charge collection time <30ns (V_{bb} = -3V)

Max particle rate: 100 MHz/cm^2

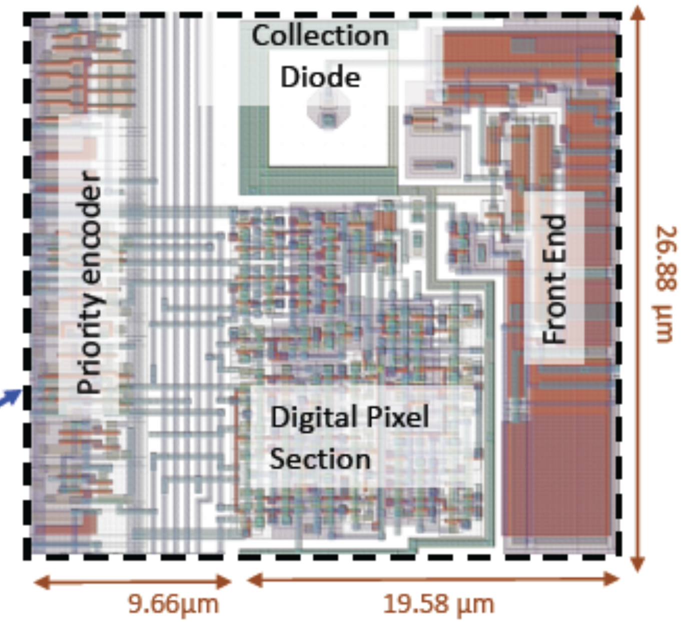
fake-hit rate: < 1 Hz/ cm^2

power : ≈300 nW /pixel (<40mW/cm^2)

Matrix Layout



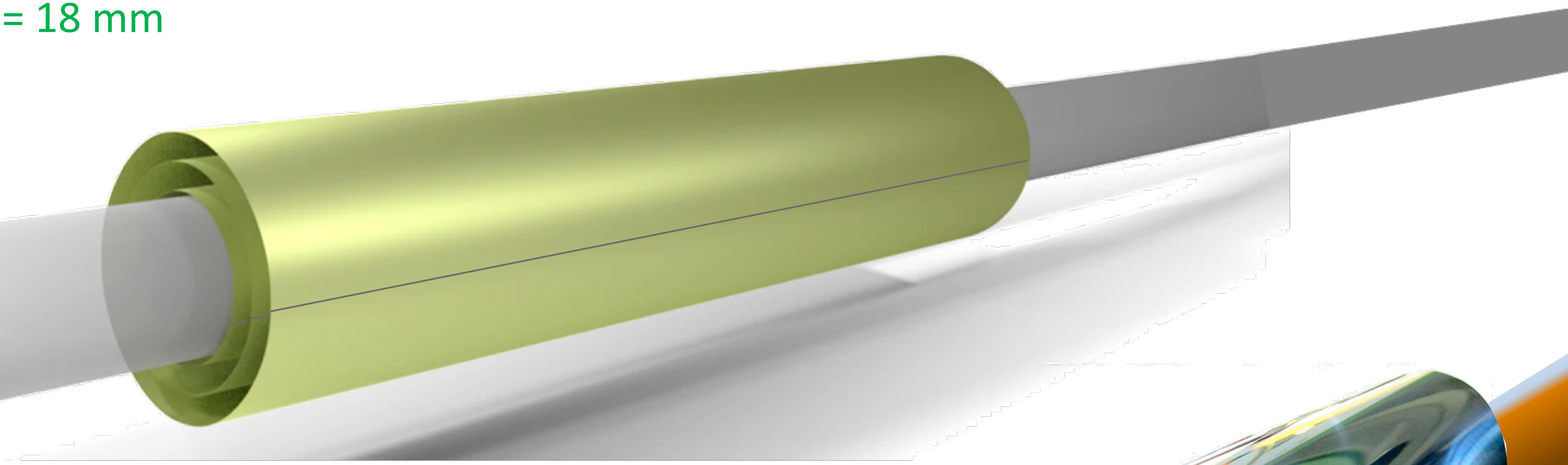
Pixel Layout



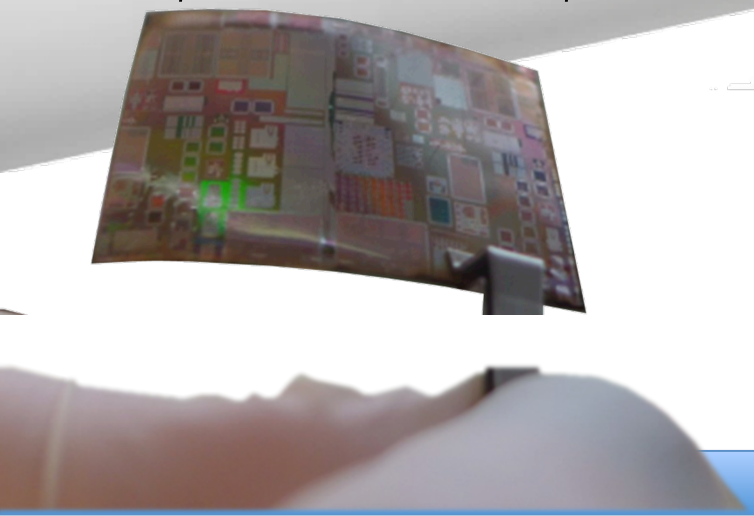
ALICE ITS3 proposal

ALICE proposal for a new vertex detector:

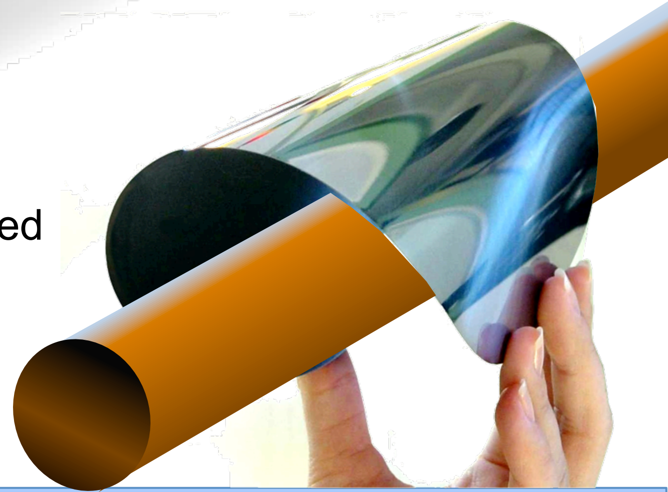
- new beam pipe with IR = 16 mm, ΔR = 0.5 mm
- three truly cylindrical Si-pixel layers based on ultra-thin, curved sensors
- material budget: X/X0 ≈ 0.05%
- inner-most layer: at R = 18 mm



Chipworks: RF-SOI CMOS, 30µm-thick



→ Bending Si wafers + circuits is possible!
→ Radii much smaller than ALICE needs are obtained
→ Circuit-specific R&D is needed
→ Investigating options to start with existing ALPIDE chips + wafers

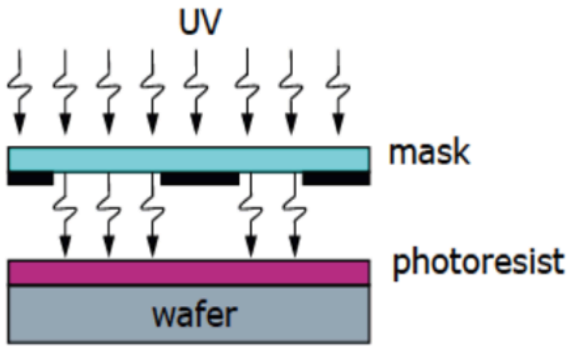


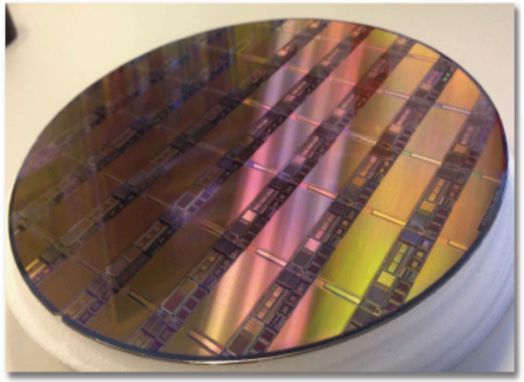
Wafer-scale MAPS: stitching

CMOS photolithographic process defines wafer reticles size

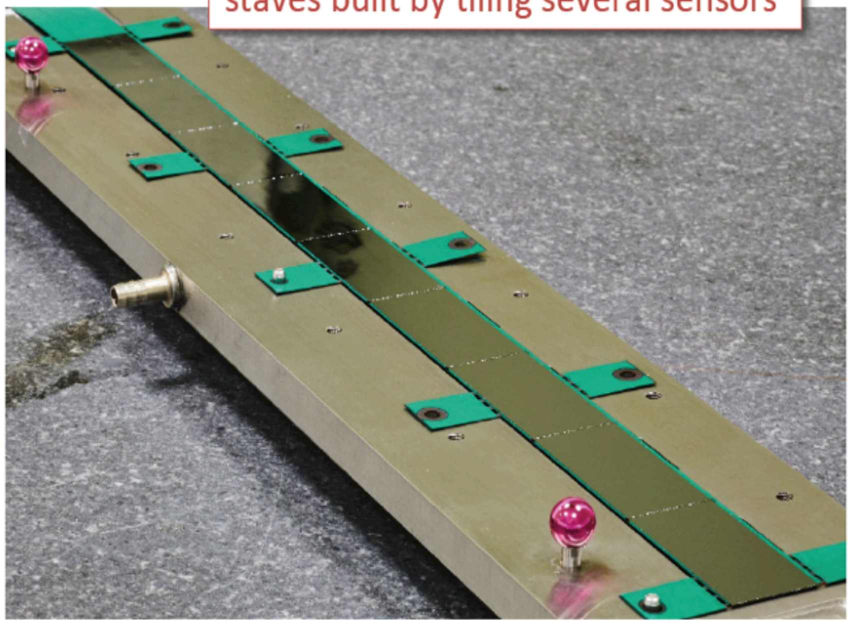
➪ Typical field of view O(2 x 2 cm²)

Reticle is stepped across the wafers to create multiple identical images of the circuit(s)

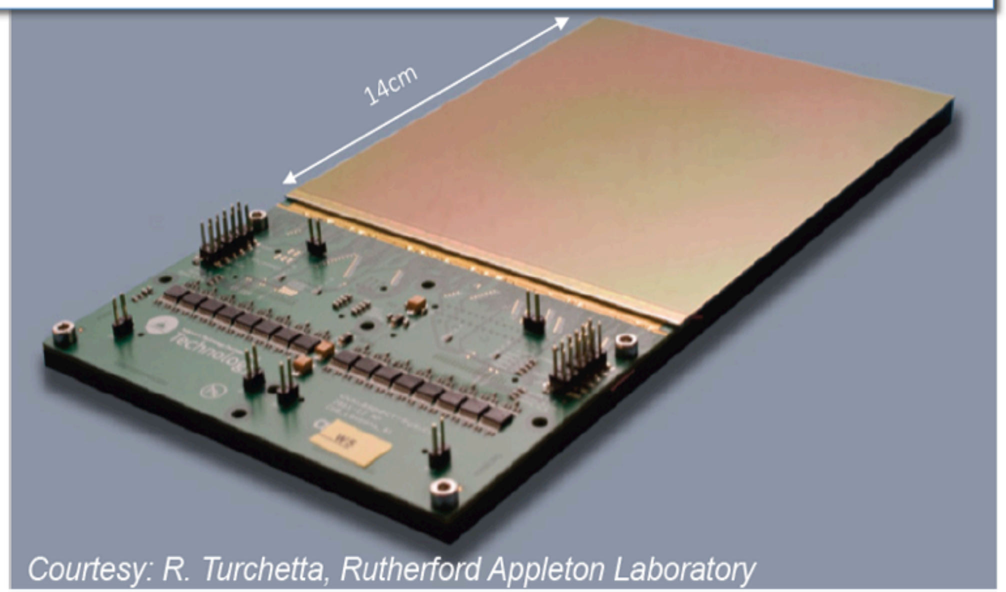




staves built by tiling several sensors



Stitching allows fabrication of sensors larger than the reticle size



Courtesy: R. Turchetta, Rutherford Appleton Laboratory

Stitched-MAPS: new R&D for a wafer-scale MAPS

A novel large area, fast, radiation-tolerant monolithic active pixel sensor for tracking devices of unprecedented precision

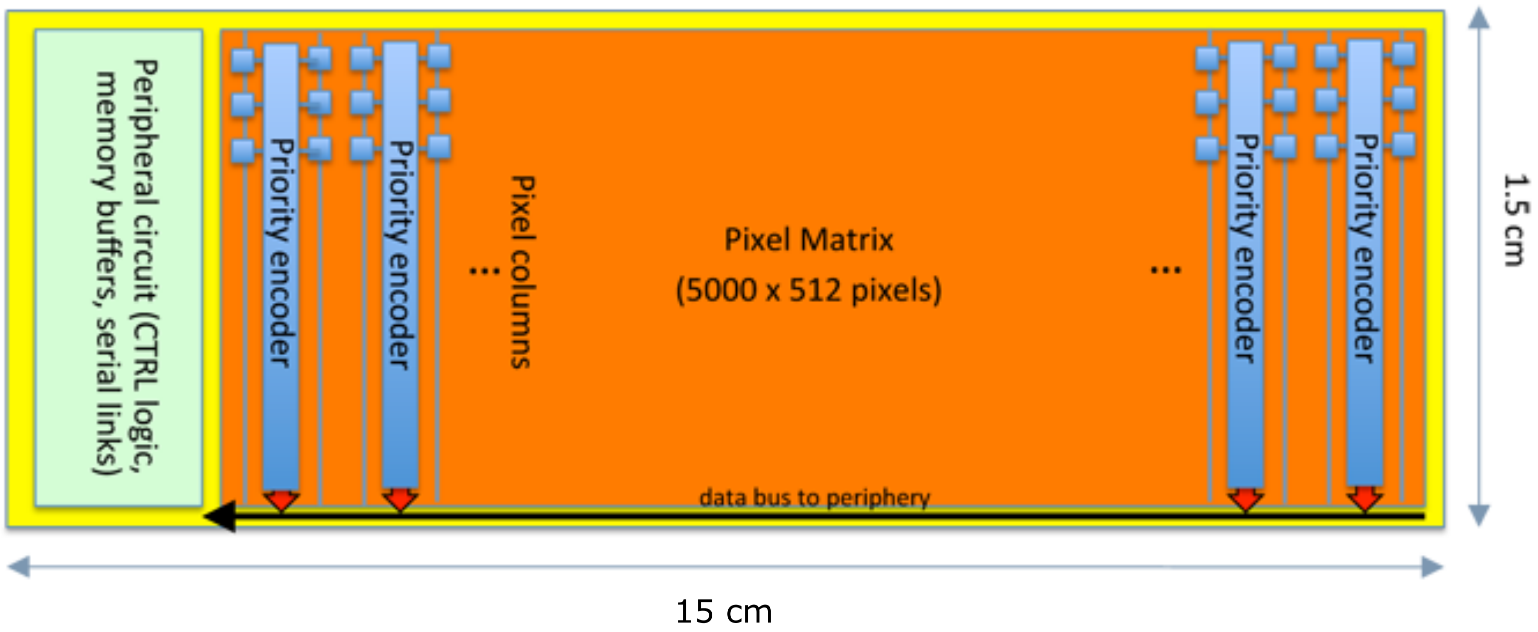
Funded project with 1 MEuro (starting September 2019)

Cagliari University, Bari University and Politecnico, INFN (G. Usai PI)

Common R&D effort together with CERN and other labs

New sensor suitable for different applications:

- NA60+
- ALICE LS3 upgrade
- CLIC vertex detector
- Proton computer tomography scan for hadron therapy



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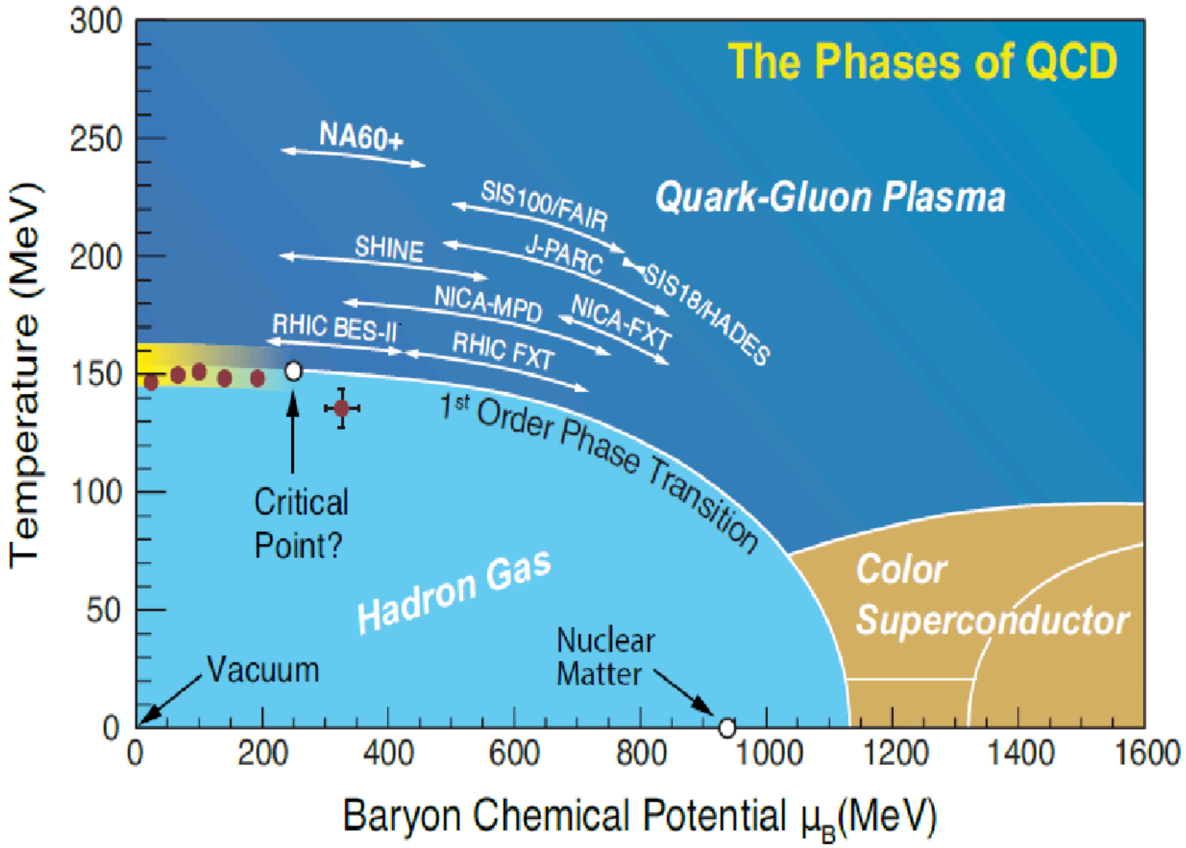
Migration of the design to Tower 65 nm
→ 10-20 μm pixel pitch

The phase diagram of QCD at high baryonic density



Many effective models suggest **1st order phase transition ending with a critical point (CP)**

High μ_B accessible at lower collision energy ($\sqrt{s_{NN}}$<~20 GeV)

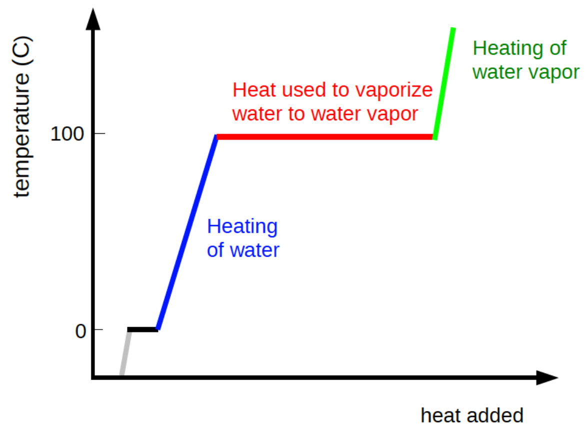
CP main motivation of RHIC low energy program:

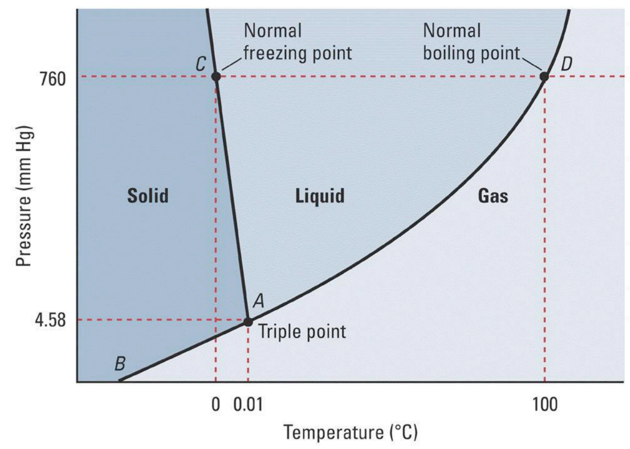
- some intriguing results from phase 1, but statistically limited

NA60+: new experiment proposal to measure the first order phase transition
(Nuova sigla INFN Commissione 3; responsabili nazionali E. Scomparin, G. Usai)

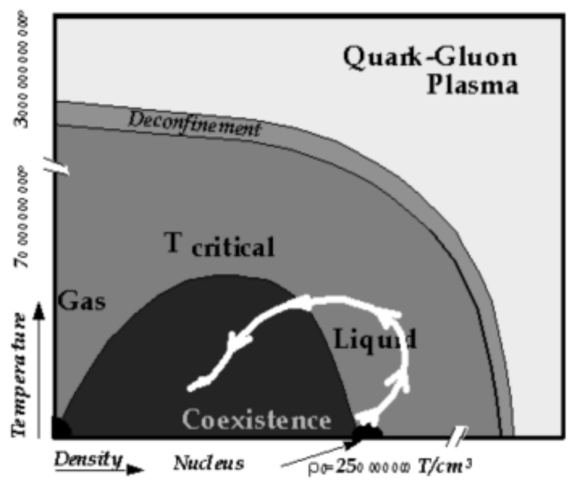
Phase transitions and caloric curves

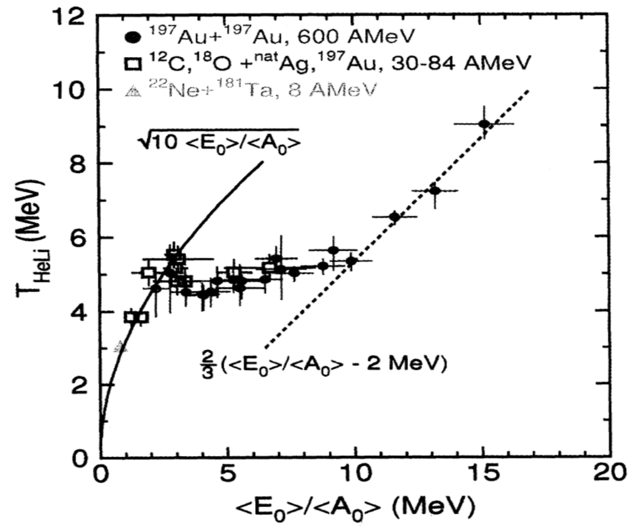
- Caloric curve and phase diagram of water





- Caloric curve for liquid-hadron gas phase transition in nuclear matter (Pochodzalla et al., Phys. Rev. Lett. 75 (1995), D'Agostonio et al., Nucl. Phys. A749 (2005) 55–64)





Measuring the QCD phase transition

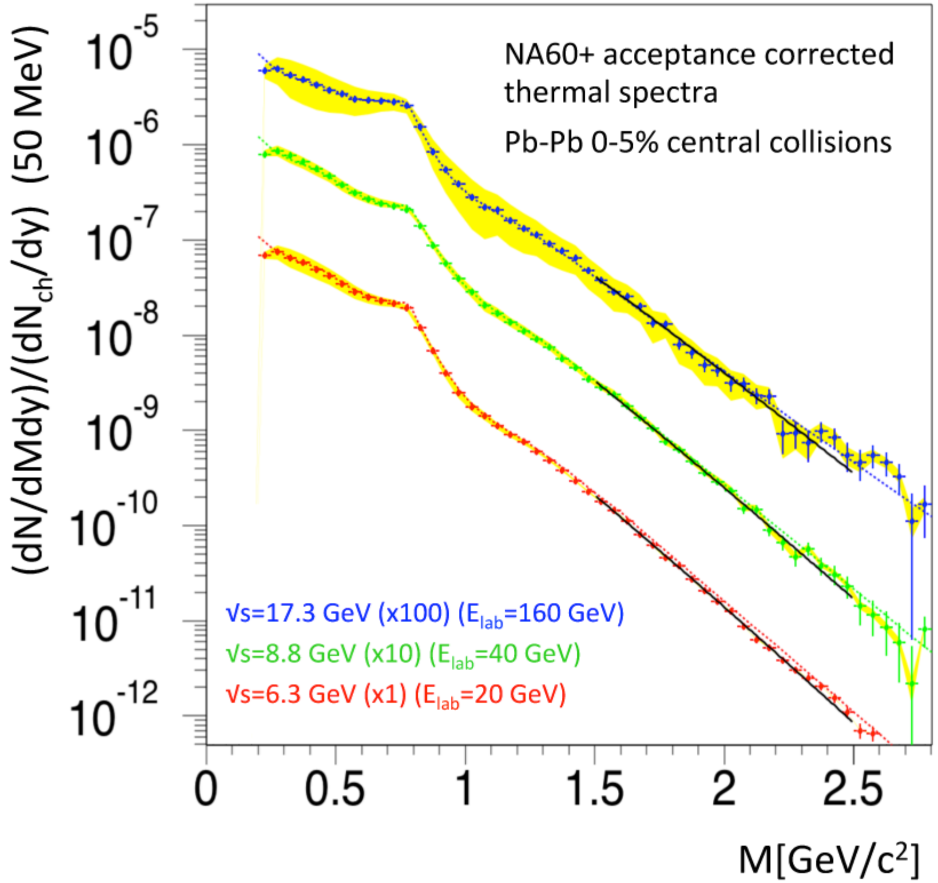
- Caloric curve: T vs energy density
- Shape of mass spectrum of lepton pairs emitted from thermalized medium for M>1.5 GeV is uniquely dependent on medium temperature T:

$$dN/dM \propto M^{3/2} \exp(-M/T_s)$$

- Energy density can be varied changing the vary collision energy → beam energy scan

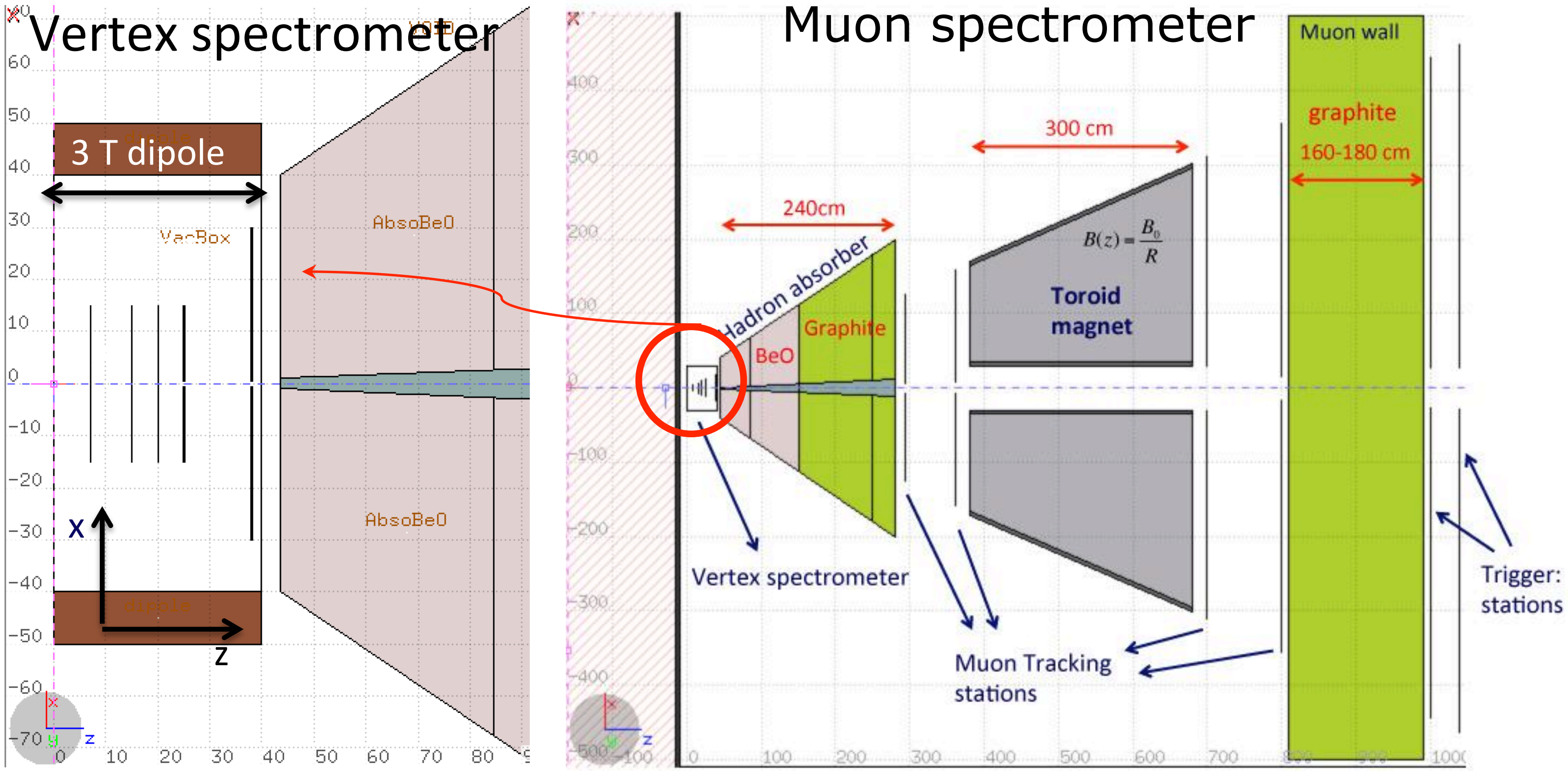
NA60+: measurement of $\mu^+\mu^-$ at √s=6-17 GeV at the CERN SPS

Proposal for data taking from run4



Thermal spectrum (QGP+hadronic) after subraction of η, ω, ϕ, $D\bar{D}$ and Drell-Yan (measured in pA collisions)

NA60+: detector concept



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Expression of Interest

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

Open questions

The quest for the QGP has turned into a precision excercise

The questions remain puzzling:

- What is the underlying dynamics:
  - Model describing long wavelength (ideal fluid) and short wave-length (“quenching” behaviour)
- What are the relevant degrees of freedom/microscopic structure?
  - How to derive behaviour from QCD?
- QGP onset in light of discoveries in small systems:
  - How far down in system size does the “SM of heavy ions” remain valid?
- Is there a first order phase transition and a critical end-point?