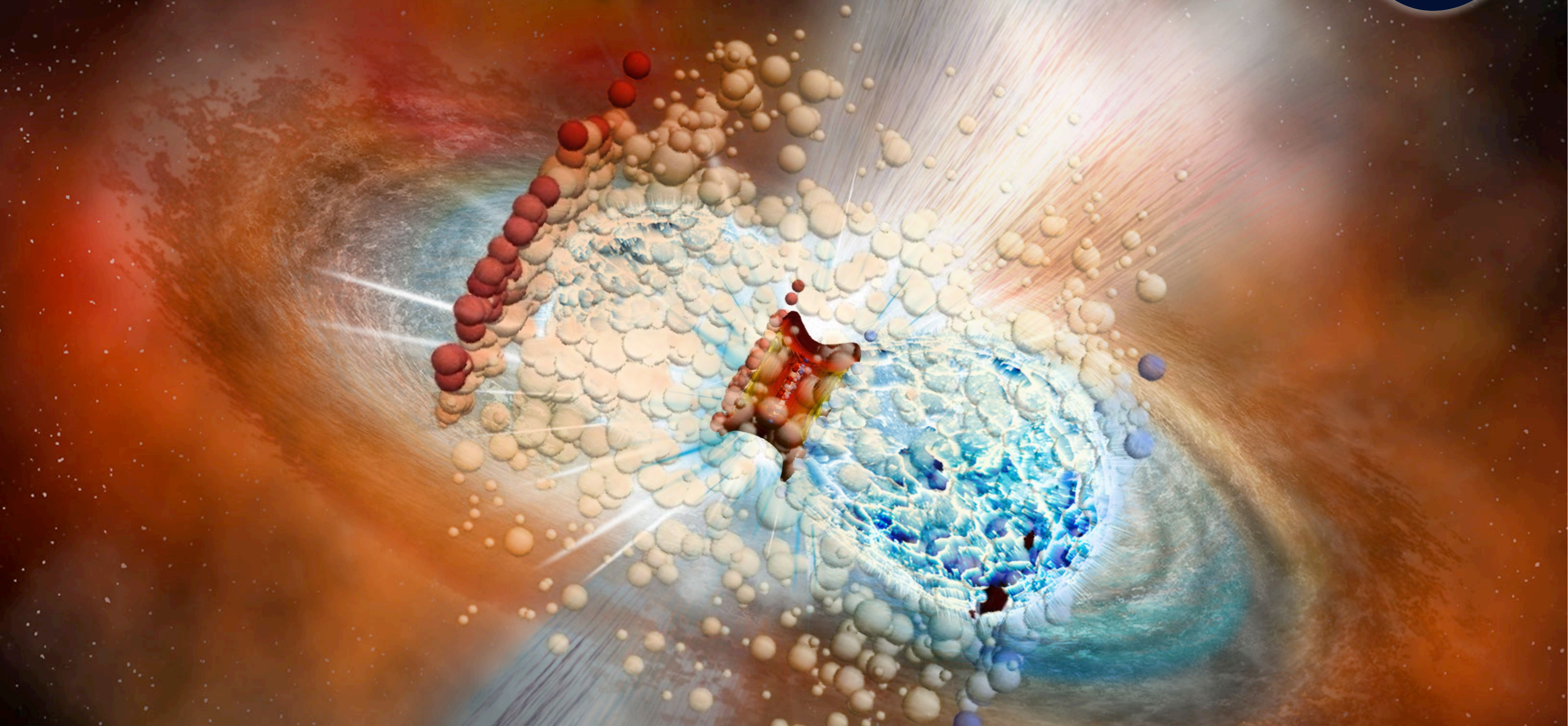
Baryon-Rich Matter: Review of the Experimental Opportunities



Antonio Uras (IP2I)
Rachid Guernane (LPSC)
Béatrice Ramstein (IJCLab)

Séminaire Thématique GT03 “Physique hadronique”
Nantes, March 2-3, 2020

Outline

- Open questions and the experimental context
- Main observables
- HADES at SIS18 (FAIR-Phase0) and HADES/CBM at SIS100 (FAIR-Phase1)
- The NA60+ project at the CERN-SPS
- The J-PARC-HI project

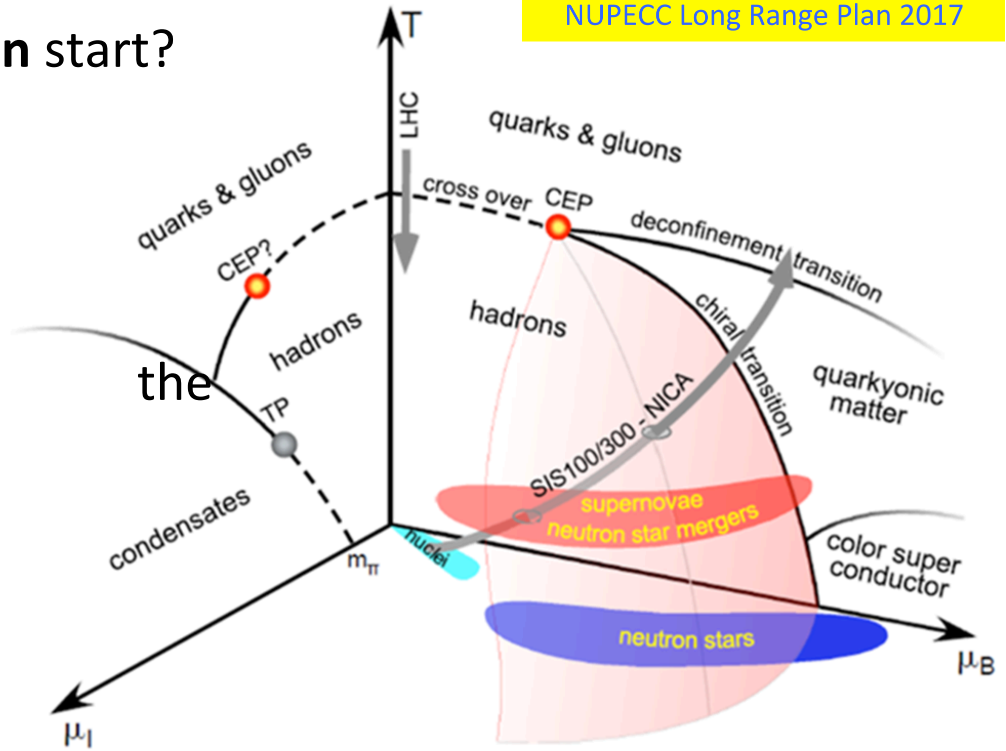
Scientific Case [see talk by M. Nahrgang]

As the baryon density increases, the phase transition is expected to turn from an analytic crossover to a **first-order phase transition, passing through a critical point: crucial inputs to constrain the QCD equation of state**

- **Onset of deconfinement:** where do partonic degrees of freedom start to dominate?
- Where does the **first-order phase transition** start? Is there a **critical end-point?**
- **Chiral symmetry and deconfinement transition:** do they always coincide?
- What are the degrees of freedom in the core of **compact stars**?

Strong complementarity with the studies of the vanishing-μ_B region, both on the theoretical and experimental sides

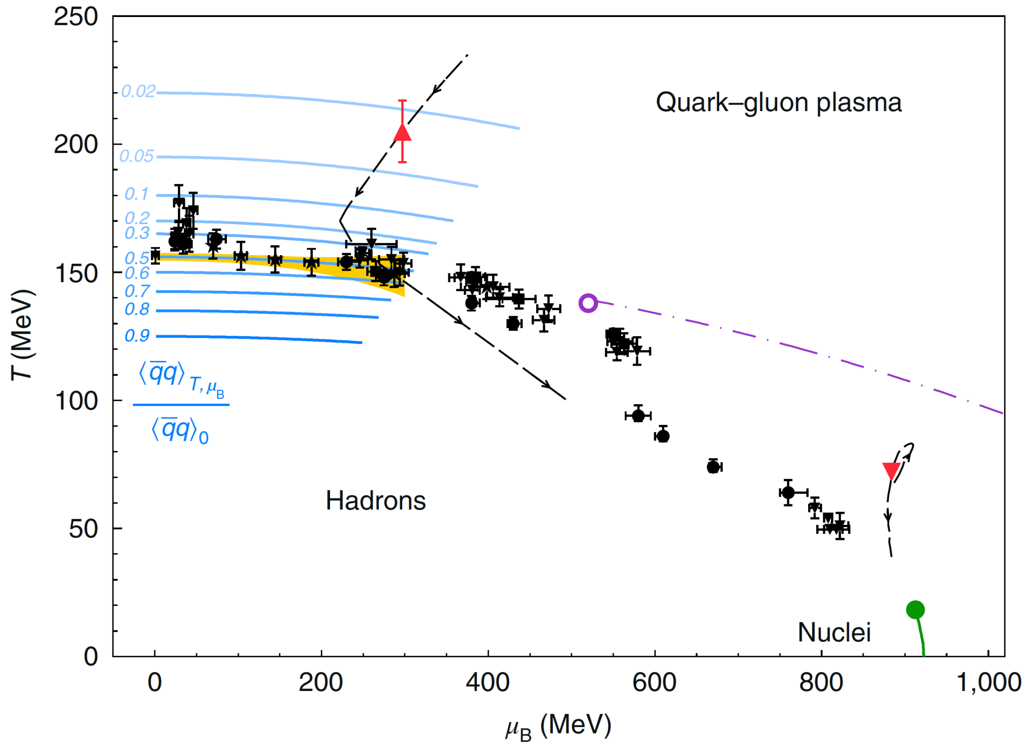
NUPECC Long Range Plan 2017



- **Experimental exploration of the QCD phase diagram:** systematic and precision measurements combining high-intensity and flexible-energy beams, and multi-purpose, high efficiency, dead-time-free detectors

- **Overlaps between the various experimental programs** will be needed for an independent confirmation of results

HADES Coll., Nature Physics, vol. 15, oct. 2019



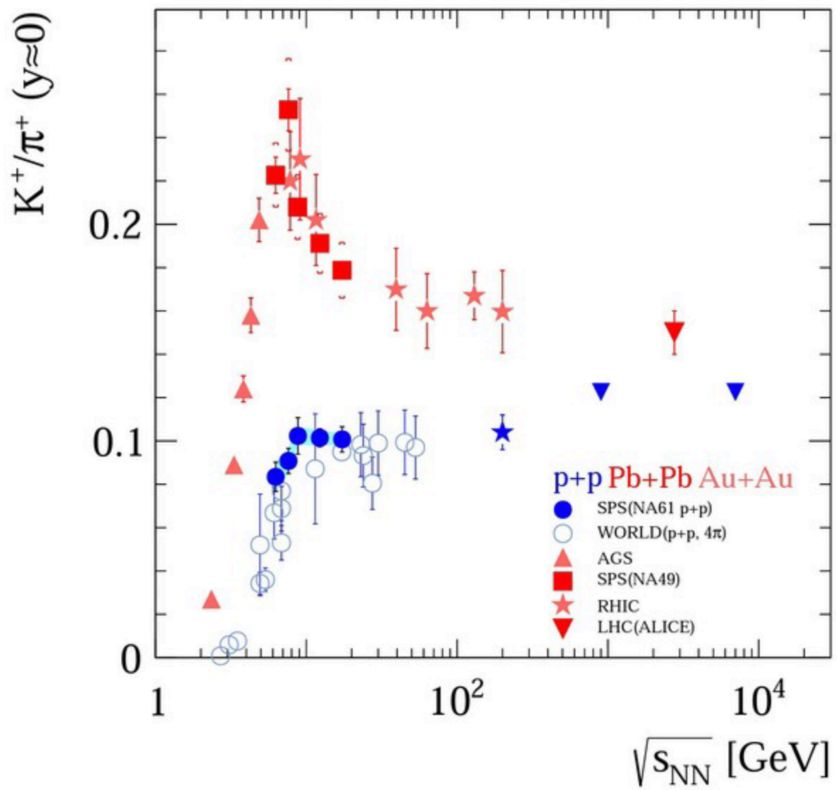
- Charm and strange production
- Dilepton production
- Fluctuation observables
- Collective effects

- **Solid and quantitative theoretical guidance** needed for the thorough interpretation of the expected wealth of high-precision experimental data

Excitation Function of Particle Ratios

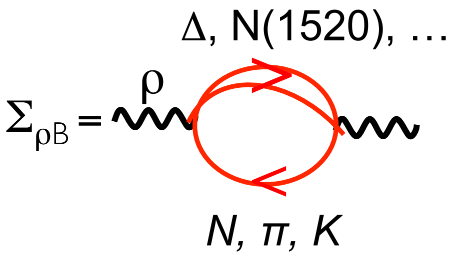
- The properties of the nuclear medium and the hadronic and partonic influences strangeness production to a significant extent

  → **Excitation function of production ratio between strangeness and light flavors** provide precious hints to identify and characterize the phase transition



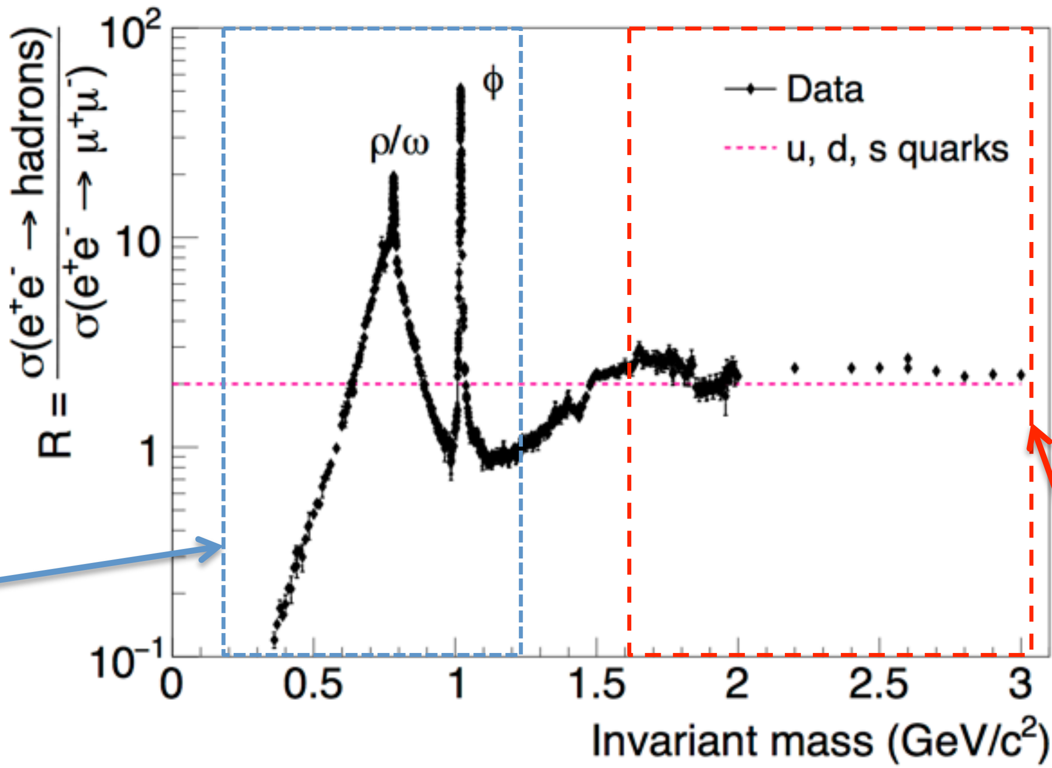
- Charm production also depends on the collision dynamics and environment: the **ratio of charmonium to open charm** could show a sudden drop at deconfinement + chiral transitions (charmonium dissociation + lowering of open charm threshold due to the effect of chiral symmatry restoration on light quarks)

Dileptons: EM Emission Rate and Correlator



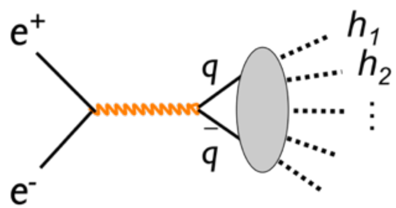
Chanfray, Rapp, Wambach,
Phys. Rev. Lett. 76 (1996) 368-371

Non-perturbative:
Vector Meson Dominance,
in-medium spectral functions

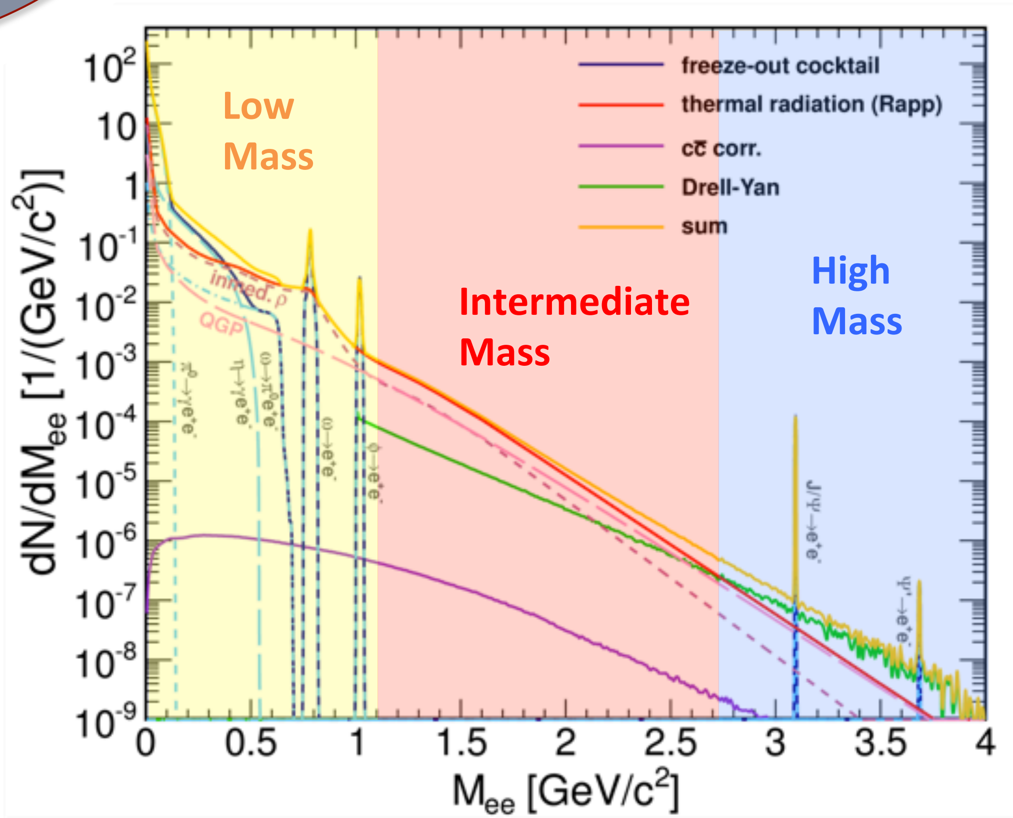


Perturbative: parton-hadron duality. Flat spectral function above 1.5 GeV → mass spectrum after integration over momenta and emission 4-volume:

$$\frac{\mathrm{d}N_{\ell\ell}}{\mathrm{d}M} \propto M^{3/2} \times \langle \exp(-M/T) \rangle$$

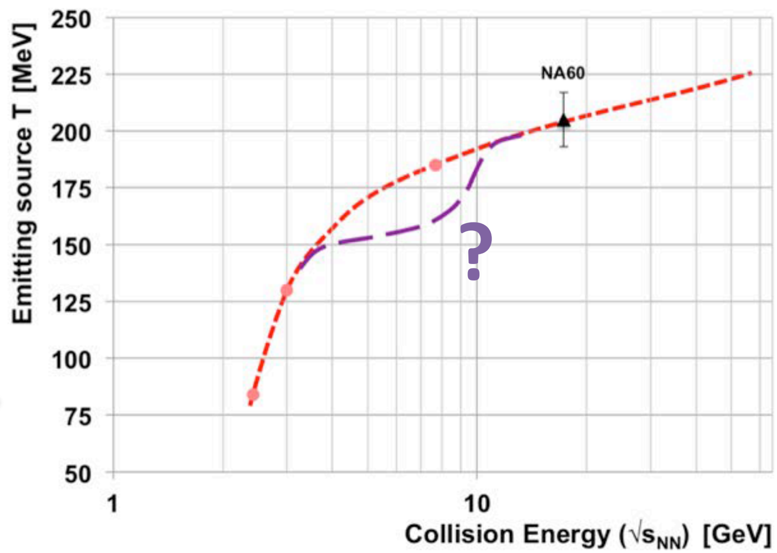


Dileptons: Temperature and Caloric Curve



- **Drell-Yan: power-law ≈ M^n**
- **Heavy-flavor: cc (bb) → $\ell\ell$**
- **Thermal rad. ≈ exp(−M/T)**
  - QGP – highest T, lowest flow
  - $\pi a_1 \rightarrow \ell\ell$
- **In-medium ρ, ω, ϕ – moderate T + flow**

- Intermediate mass region: **measurement of the emitting source temperature** (invariant mass → no blue shift). Measurements vs energy: **caloric curve of QCD matter**



Fluctuations in Bulk Observables

- **The higher moments of thermo-dynamical susceptibilities** are sensitive to the vicinity of the critical point

- These susceptibilities can be related to the **multiplicity distributions of conserved quantities** such as baryon number, strangeness and electrical charge, measured in heavy-ion collisions event-by-event

Cumulants

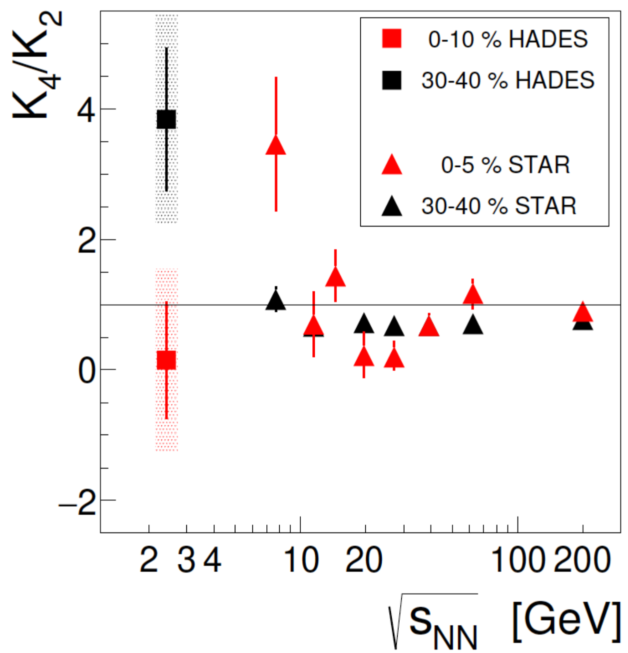
$$C_1 = \langle N_q \rangle, \quad C_2 = \langle (\delta N_q)^2 \rangle, \quad C_3 = \langle (\delta N_q)^3 \rangle,$$
$$C_4 = \langle (\delta N_q)^4 \rangle - 3 \langle (\delta N_q)^2 \rangle^2$$

$N_q = N_{q+} - N_{q-}$ and $\delta N_q = N_q - \langle N_q \rangle$
q can be any conserved quantum number

(net-baryon, net-charge, net-strangeness etc.)

Mean, variance, skewness, kurtosis

$$M = C_1, \quad \sigma^2 = C_2, \quad S = \frac{C_3}{\sigma^3}, \quad \kappa = \frac{C_4}{\sigma^4}$$

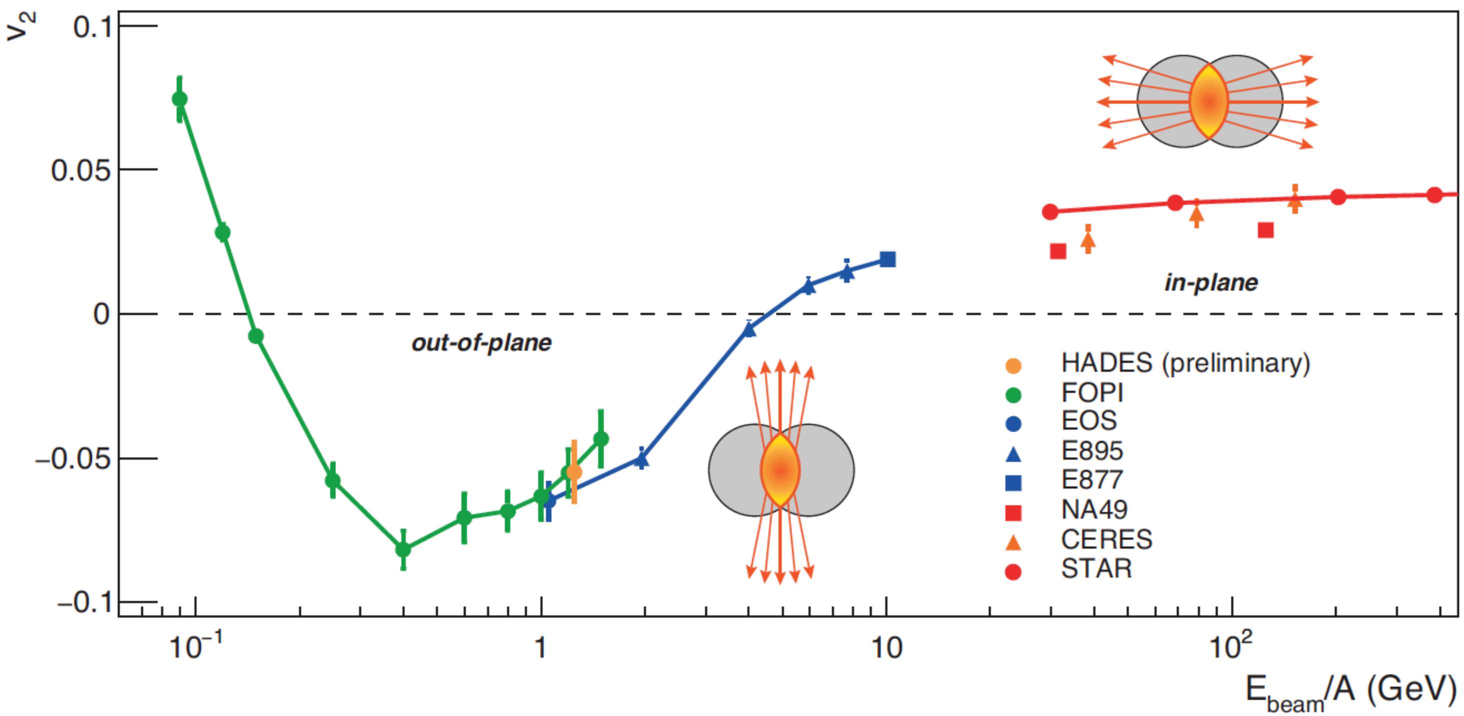


arXiv:2002.08701

Flow Observables

- **Anisotroptic flow:** complex interplay between the initial state geometry, nonequilibrium effects and viscosity, pressure gradients inside the reaction volume → **sensitivity to the equation of state**

- At large μ_B, models must describe the strong **energy dependence of the sign and magnitude of directed (v_1) and elliptic (v_2) flow**



J. Phys.: Conf. Ser. 742 012008

High Baryon Densities in Laboratory

- An important prerequisite: combination of **high-intensity beams**, **multi-purpose detectors** with large acceptance, **high efficiency, dead time free readout schemes**

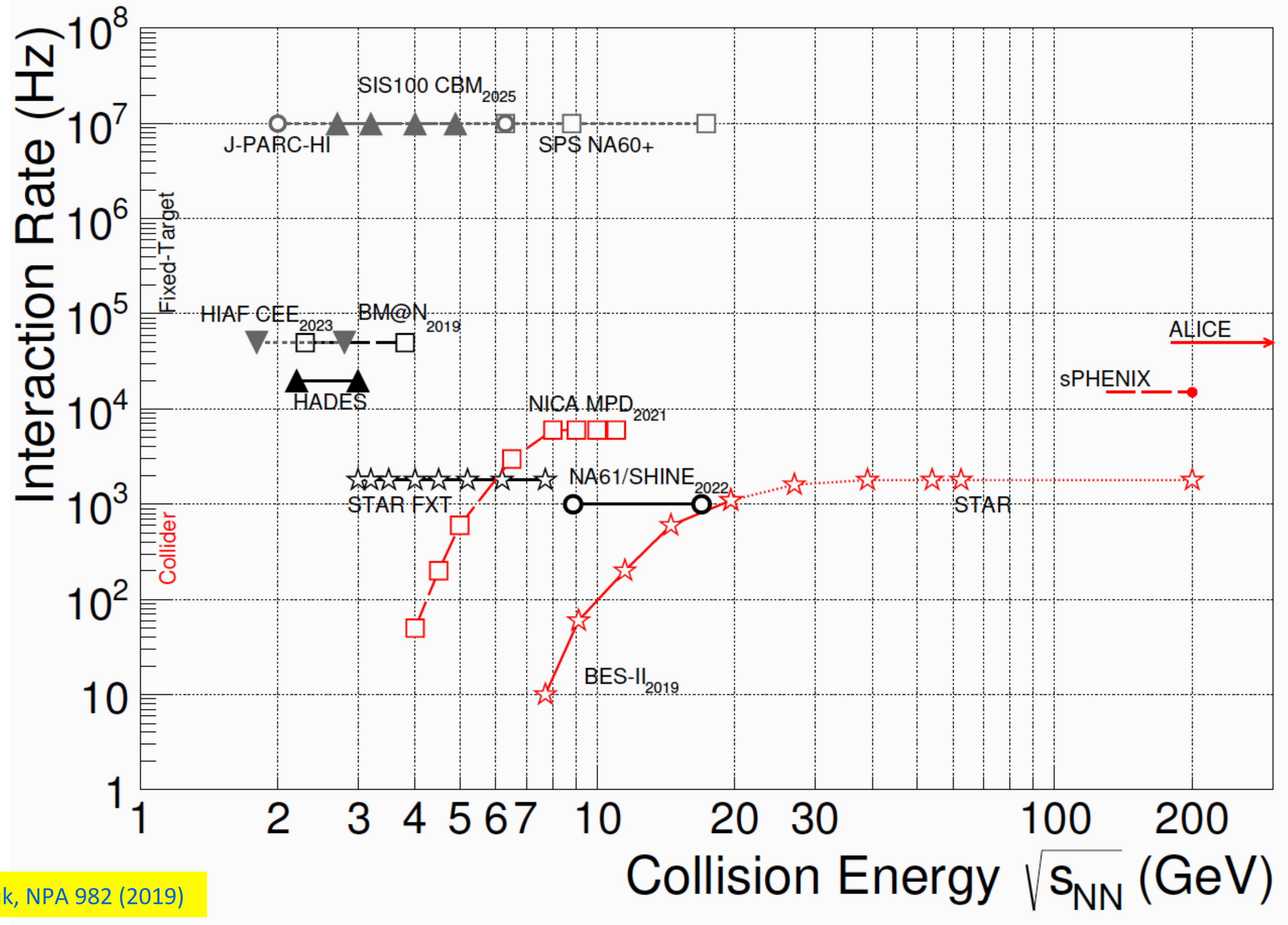
- **Substantial progress in detector technologies and software architectures** has been made (mainly driven by the ALICE upgrade, CBM and sPHENIX)

- **Measurement strategies based on three main pillars:**
  - Identified light-flavor hadrons (collectivity, fluctuations, strangeness)
  - Dileptons (EM radiation, vector meson spectral shapes, ρ/a_1 chiral mixing)
  - Charm (open charm sensitivity on chiral restoration, charmonium suppression)

Facility Experiment	SIS18 HADES / mCBM	HIAF CEE	Nuclotron BM@N	J-PARC-HI DHS, D2S	SIS100 CBM / HADES	NICA MPD	RHIC STAR	SPS NA61	SPS NA60+
Start	2012/2018	2023	2019 (Au)	> 2025	2025	2021	2010, 2019	2009, 2022	> 2025
$\sqrt{s_{NN}}$, GeV	2.4 – 2.6	1.8 – 2.7	2 – 3.5	2 – 6.2	2.7 – 5	2.7 – 11	3 – 19.6	4.9 – 17.3	4.9 – 17.3
μ_B, GeV	880 – 670	880 – 750	850 – 670	850 – 490	780 – 400	750 – 330	720 – 210	560 – 230	560 – 230
Hadrons	+	+	+	+	+	+	+	+	(+)
Dileptons	+		(+)	+	+	+	+		+
Charm				(+)	(+)	+	+	+	+

T. Galatyuk, NPA 982 (2019)

High Baryon Densities in Laboratory



T. Galatyuk, NPA 982 (2019)

NUPECC & ESPP Recommendations

RECOMMENDATIONS

Experimental programme

- Vigorous efforts should be devoted to the continuation of the heavy-ion programme at the LHC with Runs 3 and 4, including man-power support and completing the planned detector upgrades.
- At intermediate energies, we recommend the continuation of the on-going programmes: HADES at SIS-18, NA61 at the SPS.
- In order to investigate nuclear matter at high baryonic density, the timely construction of SIS-100 at FAIR and the realization of the CBM experiment are of utmost importance.
- In parallel, efforts should continue in order to support developments for a future SIS-300 upgrade.
- We recommend the completion of the BM@N experiment at JINR, and the construction of the NICA facility and the realization of the as-sociated MPD experiment.
- Exploratory studies on prospective future heavy ion projects, namely AFTER@LHC, NA60+ at the SPS, and a heavy-ion pro-gramme at the Future Circular Collider, should be continued.

NUPECC Long Range Plan 2017

4.4.3 Future opportunities for fixed-target experiments

The RHIC fixed-target programme, planned to start in 2020, will cover $\sqrt{s_{\rm NN}} = 3.0 - 7.7$ GeV, corresponding to $\mu_B \simeq 400$–700 MeV. The approved FAIR accelerator will deliver high-intensity beams ($\sqrt{s_{\rm NN}}$ up to 5 GeV) starting in 2025; the CBM detector aims at a collision rate of 10 MHz with continuous readout and online tracking and event selection. The NA61/SHINE experiment at SPS, currently being upgraded with vertex capability (using pixel sensors devel-oped for ALICE), will extend in the coming years its suite of observables into the charm sector. An experiment at the SPS (NA60+) dedicated to thermal dimuon, open and hidden charm mea-surements is curently under design and aims at collision rates of 10 MHz [140]. The possibility of a heavy-ion programme with similar characteristics as that at FAIR is currently being consid-ered for the J-PARC facility. The physics motivation [141] is common for all these fixed-target experimental programs and it is shared as well by the BES programme at RHIC and by the NICA programme [142, 143]. It is the investigation of hot and compressed baryon-rich matter, with special focus on the discovery of the critical point and (consequently) of a first order phase transition in the QCD phase diagram. Also prominent is the determination of the Equation of State of compressed baryonic matter, which is of relevance for neutron stars and for neutron star collisions. This will be achieved with correlations and fluctuations observables and with rare probes like dileptons, multi-strange hyperons or hypernuclei, probes that will become for the first time available (with abundant statistics) for this energy regime.

Physics Briefing Book (European Strategy)

SIS18 (FAIR-Phase0) and SIS100 (FAIR-Phase1)

$\sqrt{s_{NN}}$ = 2.4 – 5 GeV

HADES and CBM at GSI/FAIR

SIS18: existing (previously GSI, now FAIR Phase-0)
SIS100: in construction (first beams ≈ 2025)

HADES@SIS18

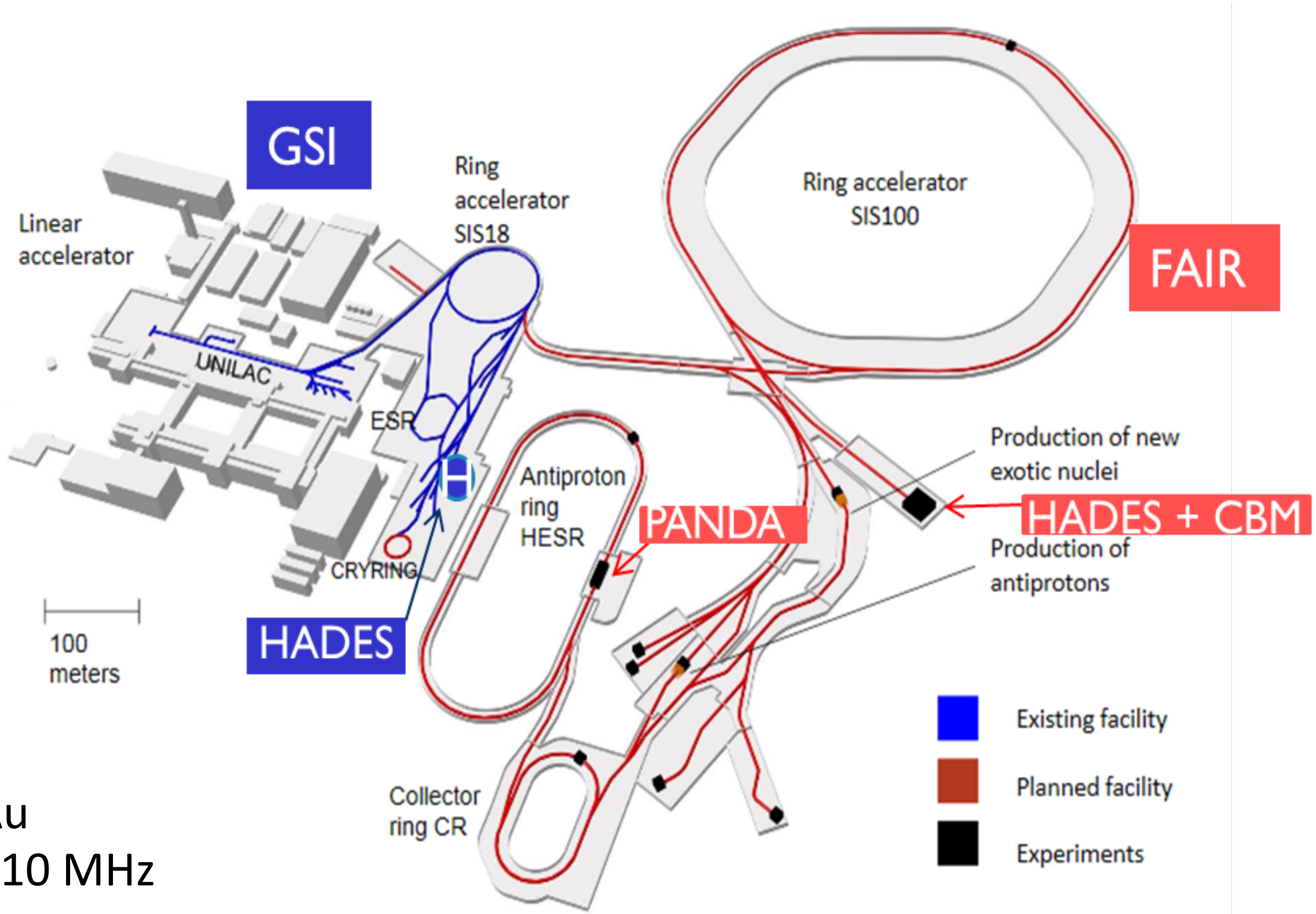
p, d, π, A beams up to Au

HADES@SIS100

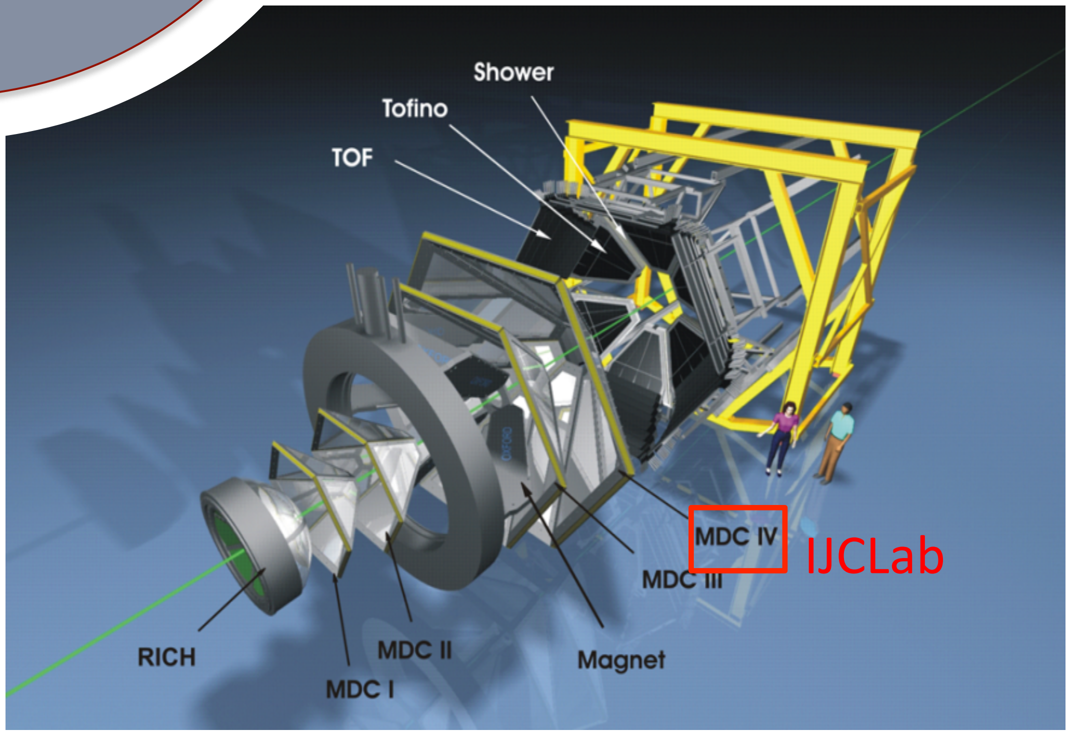
p, d, A beams up to Au
Mainly reference measurements (pp, p-A)

CBM@SIS100

Various ion beams up to Au
Full interaction rate up to 10 MHz



HADES at GSI-SIS18



Expériences réalisées (2004-2019)

❖ **Études de matière hadronique**
C+C 1 et 2 AGeV, Ar+ KCl 1.75 AGeV
Au+Au 1.25 AGeV, Ag+Ag 1.65 AGeV

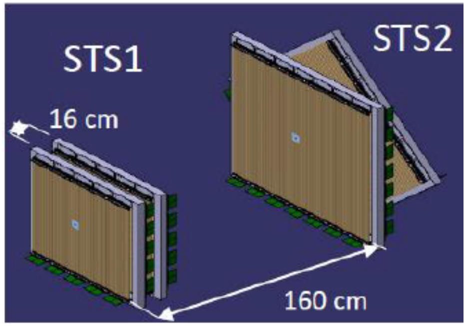
❖ **Matière froide:**
p+Nb 3.5 GeV, π^-+C/W 1.7 GeV/c

❖ **Réactions élémentaires:**
p+ p 1.25, 2.2, 3.5 GeV, d+p 1.25 AGeV
π^-+CH_2/C 0.7 GeV/c

HADES collaboration
about 100 physicists, 20 institutes, Czech Rep., France, Germany, Poland, Portugal, Russia, Sweden,…

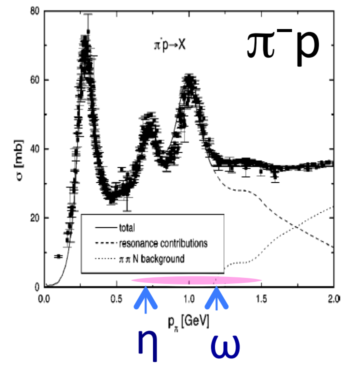
Upgrade 2018-2019:

- New RICH γ detector (HADES-CBM coll.)
- Pb glass ECal
- New forward detector 0.5-6.5° (IJCLab contribution): straw-tube forward tracker + RPC



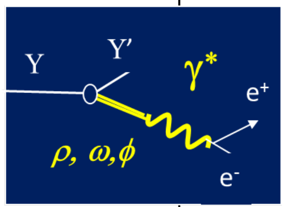
Faisceaux de π^-: 2020-2021

- π^-+p *résonances baryoniques* Δ(1620), N(1720),... + canaux e^+e^- (Dalitz) et hadroniques ππN, ωn, ηn , $K^0\Lambda$, KΣ,....+ γ
- π^-+C *matière nucléaire froide*
- Après 2023 (suivant disponibilité de SIS18) $\sqrt{s}$ > 2 GeV et Λ(1405)



p+p E = 4.5 GeV (2022-....)

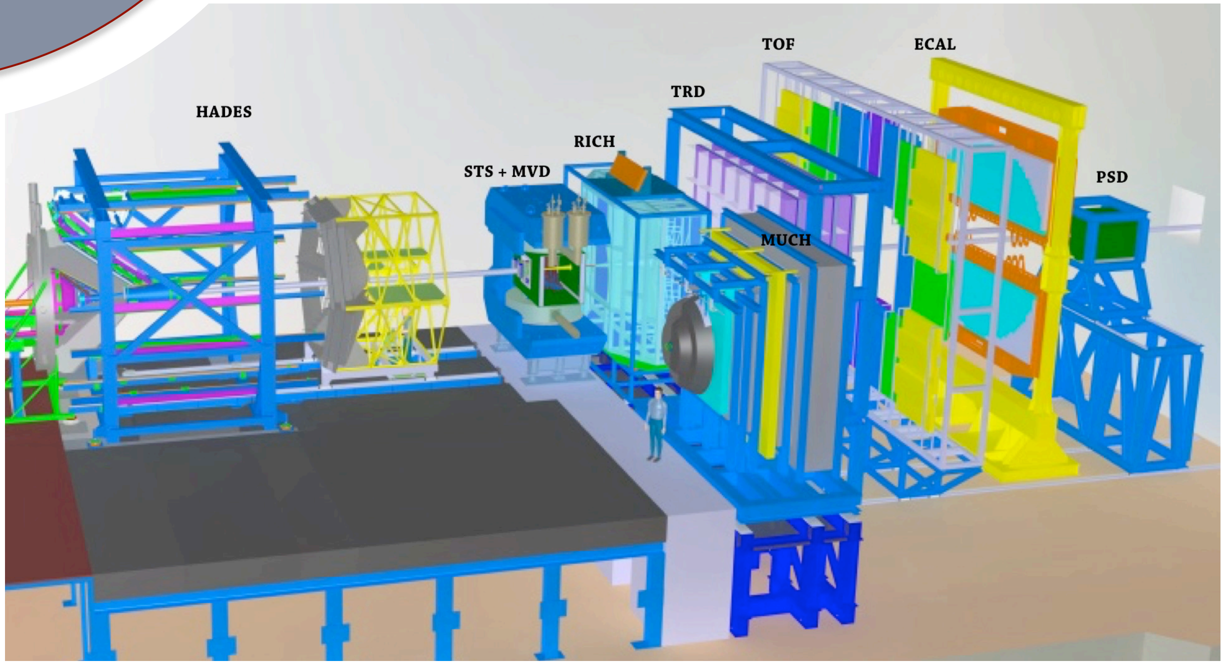
- Décroissances radiatives Y →Λγ et Dalitz Y →Λ e^+e^- (BR ≈ 10^{-3} - 10^{-5}) hypéron = Λ(1520), Σ^0,Σ(1385) : validity of Vector Dominance Model ?
- Production de baryons doublement étranges Ξ^-(1321) (S = −2)
- Production de paires e^+e^- M_{ee} > 1 GeV/c^2 (références pour études de ρ-a_1 mixing)



p+Nb E = 4.5 GeV (2022-...)

- Études de matière nucléaire froide:
  - e^+e^- : ρ,ω,ϕ spectral functions, ρ-a_1 mixing , ω absorption
  - étrangeté : production mechanisms, hyperon-nucleon interaction
- Short Range correlations avec détecteur de neutrons)
- Dark photon search

HADES and CBM at FAIR Phase 1



CBM technological solutions:

- **Free-streaming FEE** → nearly dead-time free data taking
- **Tracking based entirely on Si** → fast and precise track reconstruction
- **On-line event selection** → high-selective data reduction

IJCLab participates to the current HADES program; **IPHC** significantly contributes to the development of the CBM micro-vertex detector

- **After 2025 HADES will be moved to CBM cavern:** alternate data taking at SIS100
- Complementary acceptance: HADES at target rapidities, CBM at forward rapidities
- Interaction rates: CBM up to 10 MHz, HADES limited to 200 kHz

CBM Physics Program

- **QCD matter equation-of-state at large baryon densities, coexistence (quarkyonic) & partonic phases:**
  - Hadron yields, collective flow, correlations, fluctuations
  - (Multi-) strange hyperons (K, Λ, Σ, Ξ, Ω)
  - Production at (sub)threshold energies

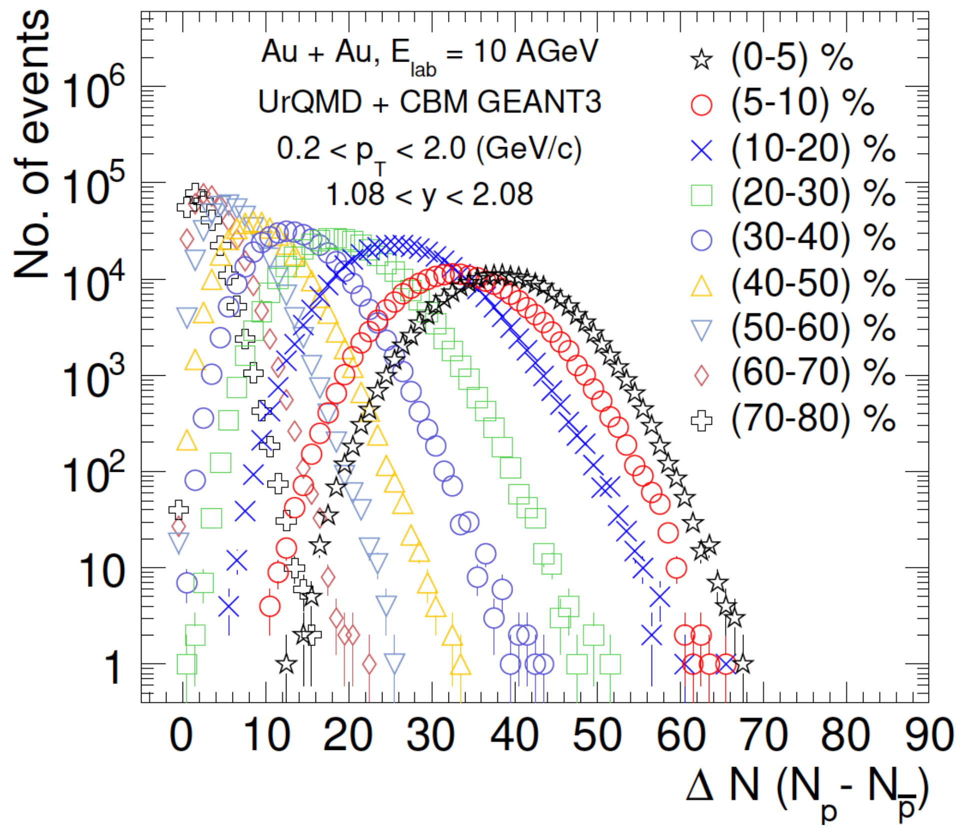
- **Chiral symmetry restoration at large baryon densities**
  - In-medium modifications of light vector mesons
  - ρ, ω, ϕ → ee (μμ) via dilepton measurements

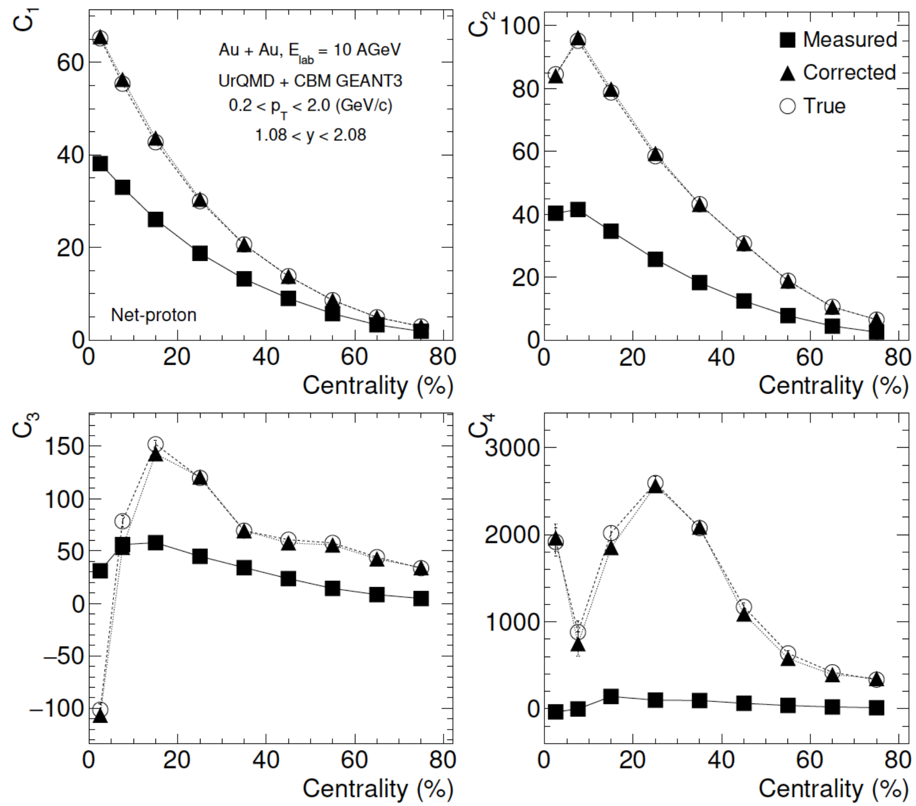
- **Hypernuclei**

- **Charm production and propagation at threshold energies**
  - Excitation function in p+A collisions (J/ψ, D^0 , D^+)
  - Charmonium suppression in cold nuclear matter

From the CBM Physics Program: Cumulants

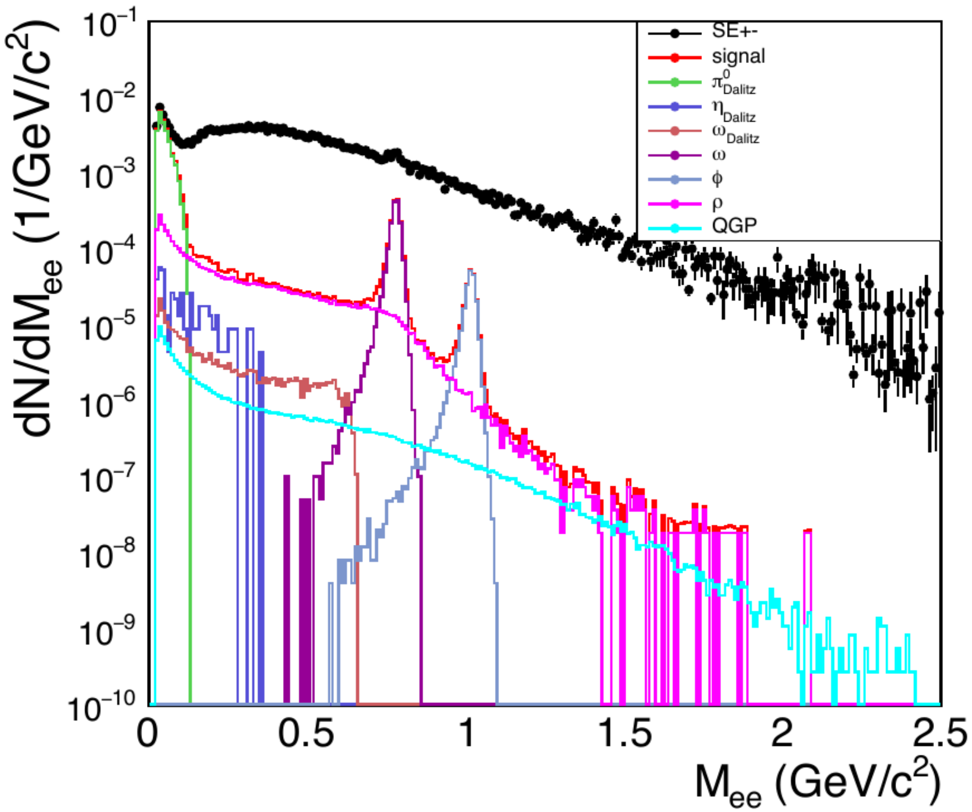
- **Fluctuations of conserved charges** are sensitive to phase transition and critical point
- **Analysis procedure validated by performance studies:** simulated MC net-proton cumulants are properly recovered



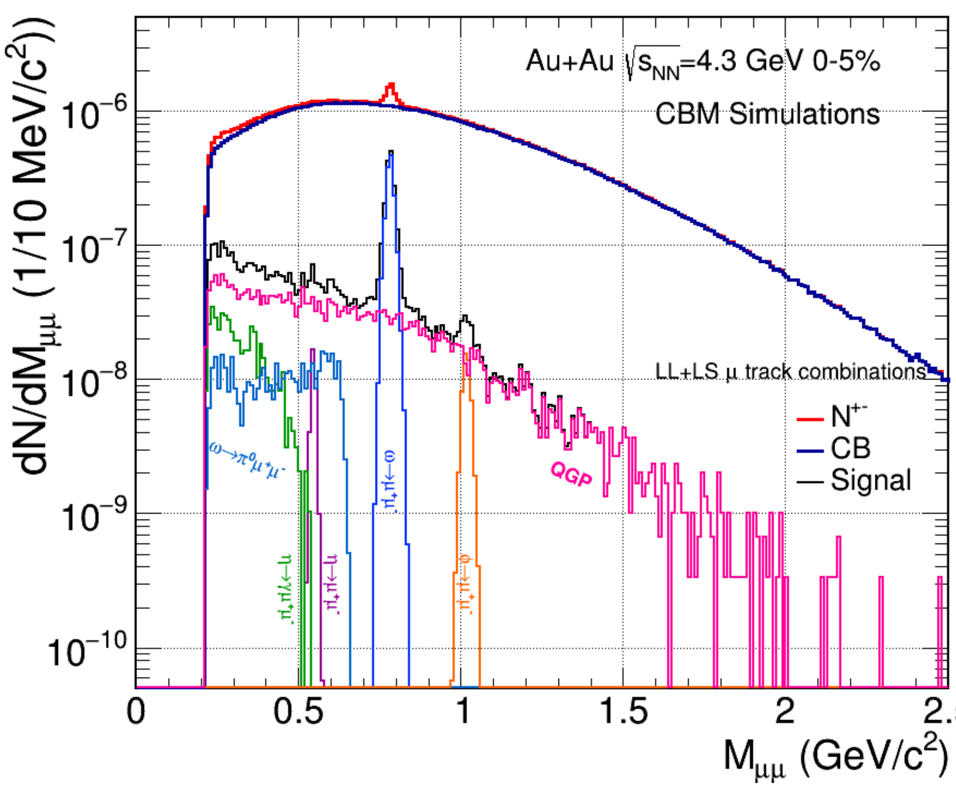


- Peaks of 2-body decays of low-mass vector mesons visible both in the dielectron and dimuon data
- Access to thermal radiation + modified ρ line shape

Di-electrons



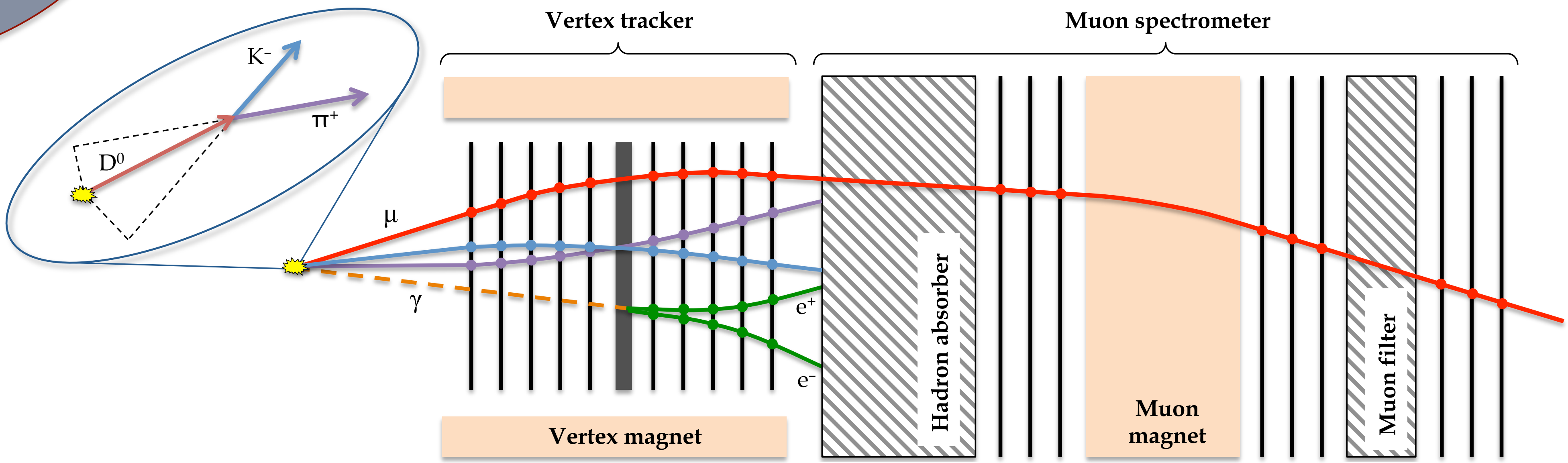
Di-muons



NA60+ at the CERN-SPS

$\sqrt{s_{\mathrm{NN}}}$ = 4.9 – 17.3 GeV

The NA60+ Project at the CERN SPS



- Experimental setup primarily optimized to perform **high-precision measurements of muon pairs** + measurements of **unidentified hadrons** and **real photons** emerging from the interaction region. **Max event rate: 10 MHz**

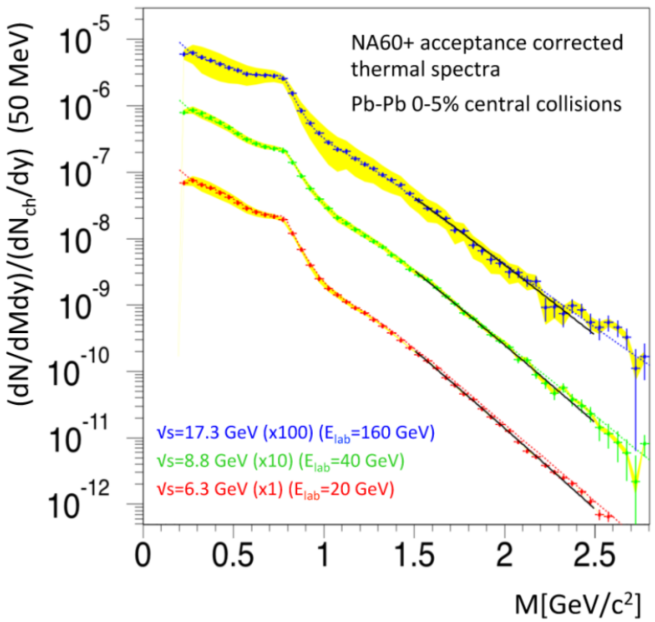
- **Status:** Expression of Interest submitted to SPSC, active R&D on the various sub-systems

CERN SPSC 2019 017

- **Contact in France: Antonio Uras (IP2I Lyon)**

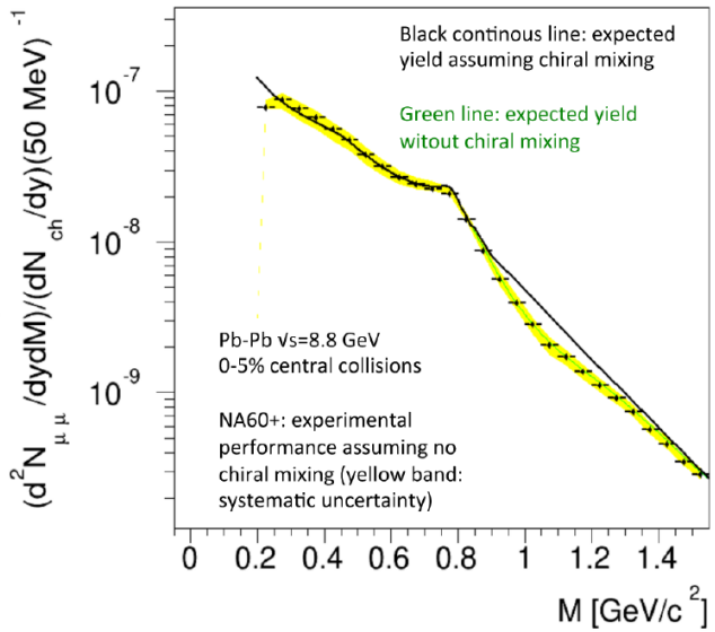
The NA60+ Physics Case

- ρ-a_1 modifications: **chiral symmetry restoration**
- Thermal dimuons from QGP/hadronic phase: **caloric curve for first order transition**
- Quarkonium suppression: **signal of deconfinement**
- Hadronic decays of charmed mesons/baryons: **QGP transport coefficients**



Extract temperature via fit $dN/dM \propto M^{3/2}\exp(-M/T_s)$
Look for a plateau when building T_S vs $\sqrt{s}$

Full chiral ρ-a_1 mixing is expected to provide a 20-30% enhancement in the region $1 < M < 1.4$ GeV/c^2



The NA60+ Physics Case

- ρ-a_1 modifications: **chiral symmetry restoration**
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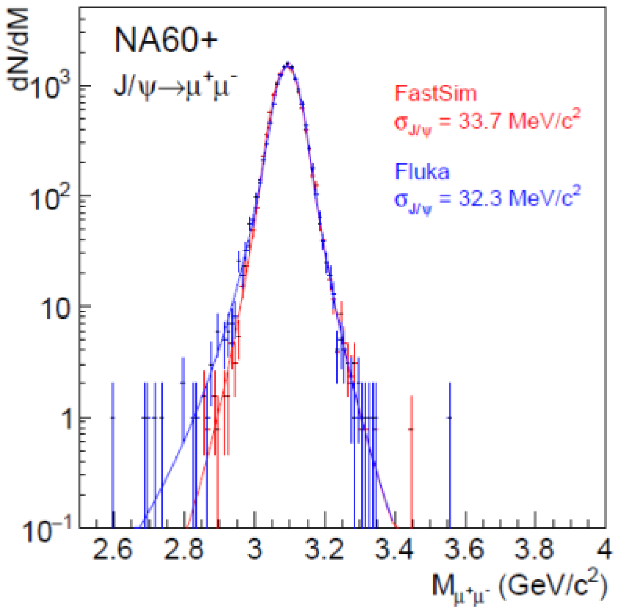


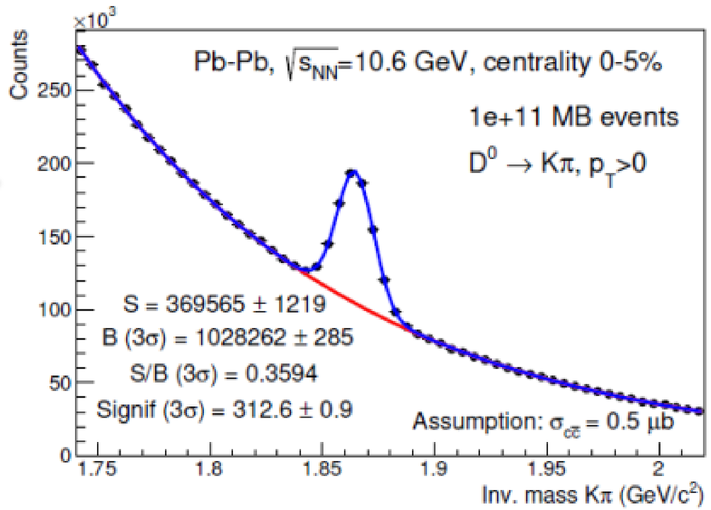
Explore the centrality dependence of J/ψ suppression vs √s

→ Detect deconfinement threshold

Measure 2 and 3 prong decays of charmed hadrons

R_{AA},v_2 : transport coefficients

Λ_c/D : hadronization mechanisms



The NA60+ Project: Preliminary Cost and Timeline

Vertex tracker (see backup)

Item	R&D (kCHF)	Construction kCHF)	Total Cost kCHF)
Pixel CMOS sensors	700	700	1400
Sensor test	100	150	250
Thinning/dicing	200	300	500
Total	**1000**	**1150**	**2050**

Mechanics, cooling, readout electronics: ≈1.5 MCHF

Muon tracker (see backup)

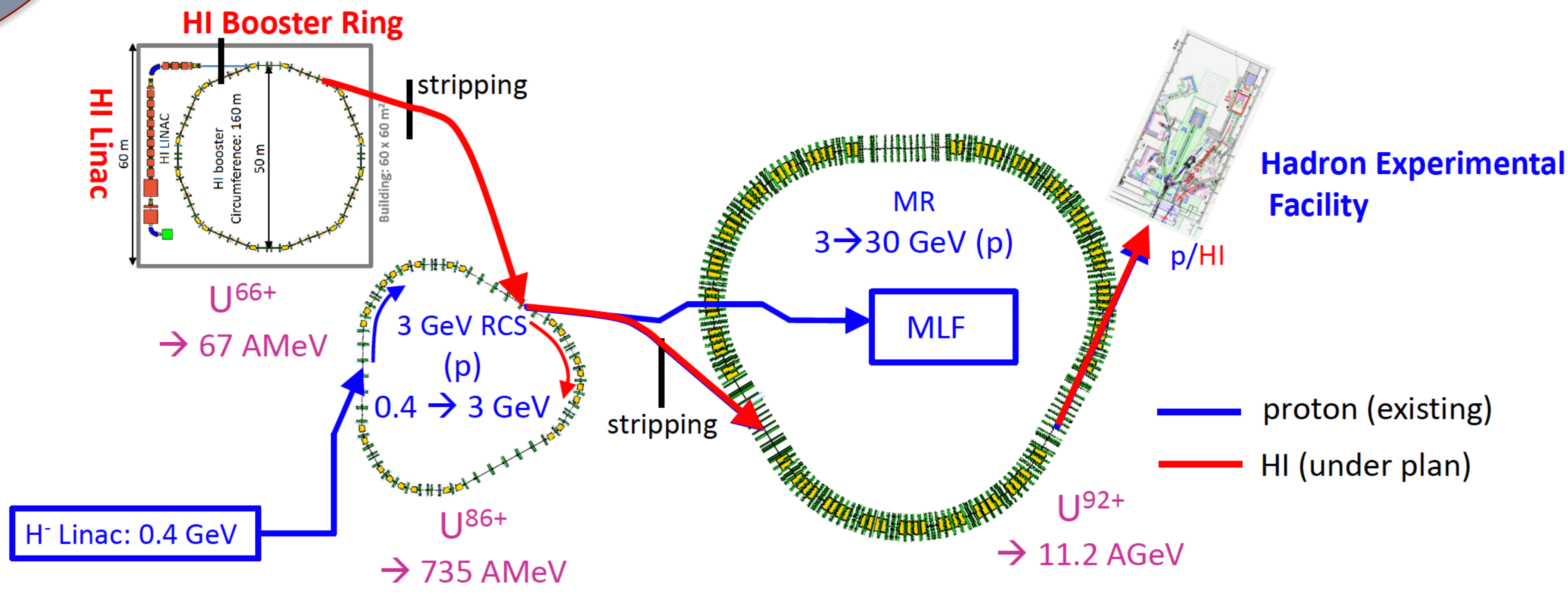
	Baseline 4 stations (kCHF)	Expanded 6 stations (kCHF)
GEM foils	1000	1500
NS2 frames	400	600
Drift + Readout	250	375
FEE	2800	4200
HV system	100	150
Mechanical support	500	750
Gas system	200	300
TOTAL	**5250**	**7875**

- **Total envelope with Muon Trigger and magnets: *o*(20) MCHF**
- **Next steps: consolidation** of a strong international collaboration**, finalization of the LoI**, **availability** of the SPS high-intensity ion beam and the ECN3 experimental hall
- **Tentative timeline**
  - 2020-2022 → project finalization, submission and approval of the proposal
  - 2023-2025 → construction
  - 2026 and beyond → data taking in parallel with the LHC run 4

J-PARC-HI

$$\sqrt{s_{NN}} = 2 - 6.2 \text{ GeV}$$

The Future Heavy-Ion Program at J-PARC-HI

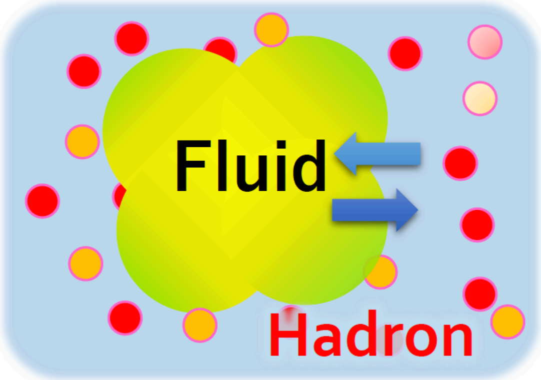


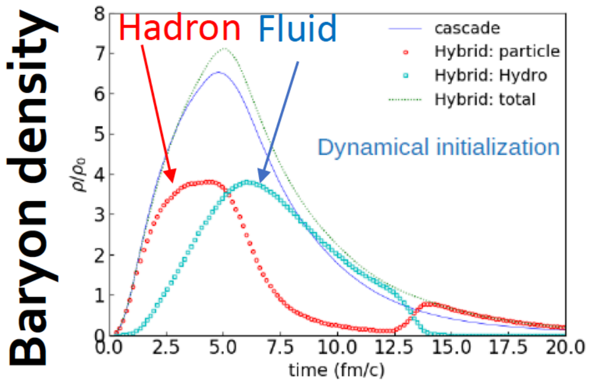
- **Proposal for a Heavy-Ion accelerating facility at J-PARC + dedicated experiment**
- Selected as one of the major research projects in the 2020 Japanese Master Plan for large infrastructure research projects, but not retained as a priority major research project: it can be supported, but the funding still has to be negotiated
- **Contact in France: Rachid Guernane (LPSC Grenoble)**

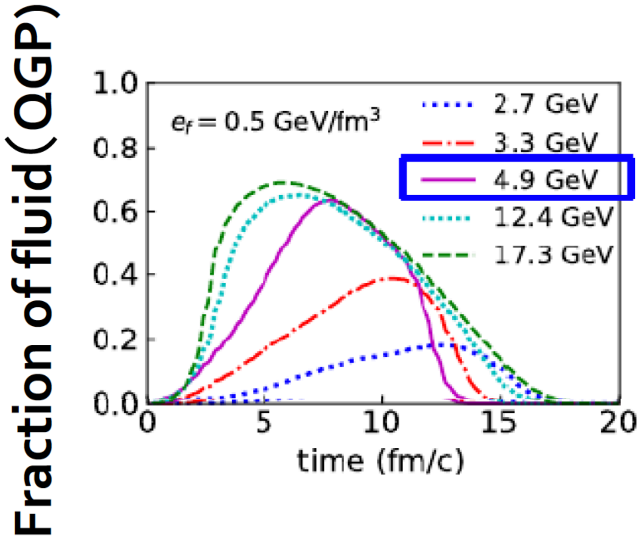
Phase Transition Signals at J-PARC-HI

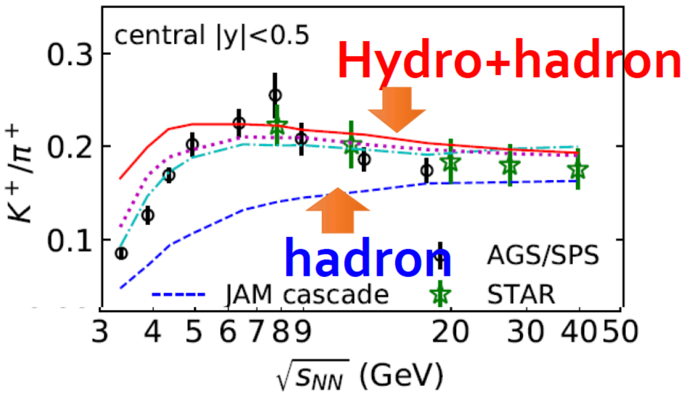
Hydro（QGP）＋Hadron Cascade (JAM)
Dynamically integrated transport model

Akamatsu, Ohnishi, Kitazawa, Nara, et al, PRC98 024909 (2018)







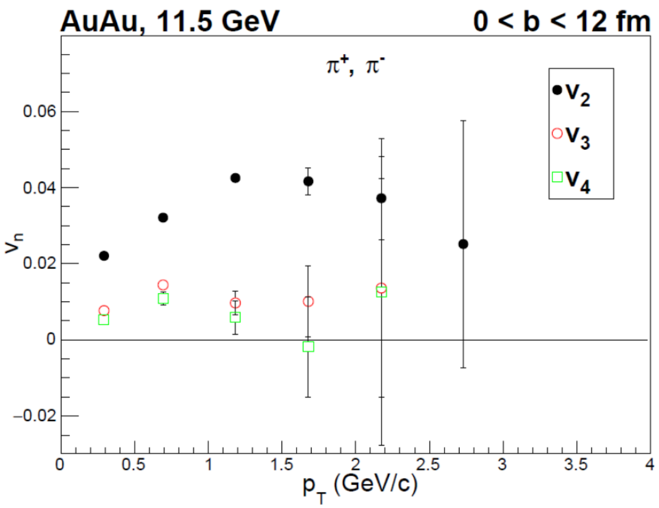


K^+/π^+ was reproduced with the introduction of fluid

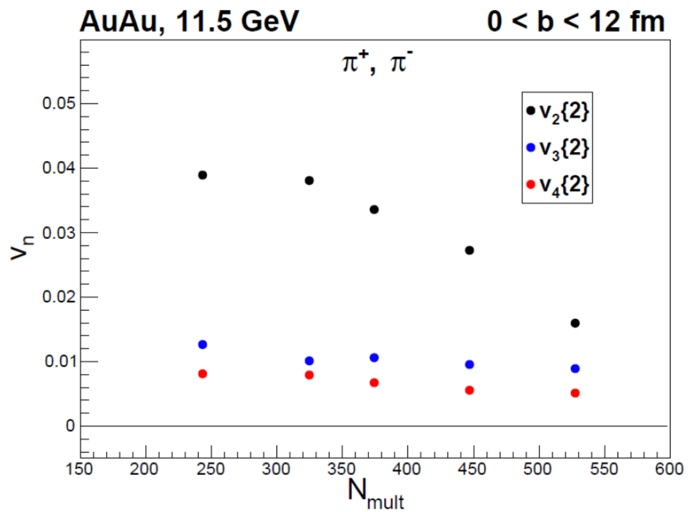
→Suggesting existence of QGP at J-PARC energy

- 54M Au+Au events of hydro + JAM cascade model (JAM-1.9043)
- Higher-order flow: study of "fluid" properties created in the collision
  - Due to low multiplicity, higher statistics is required than RHIC and LHC

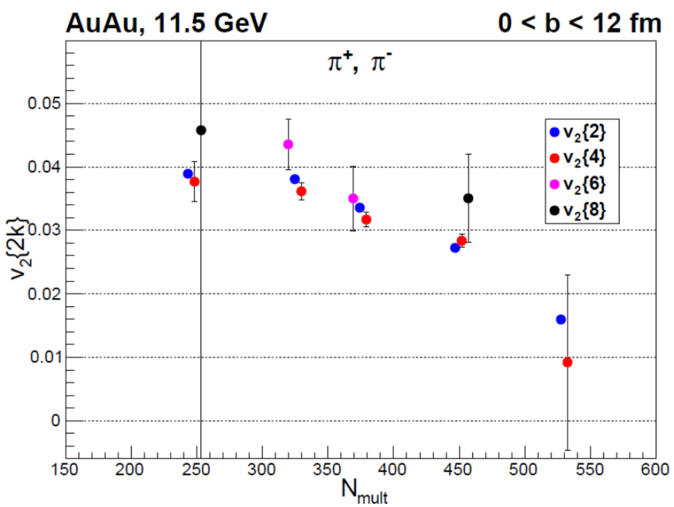
Higher-order harmonics with two-particle correlation (4.5 M events)



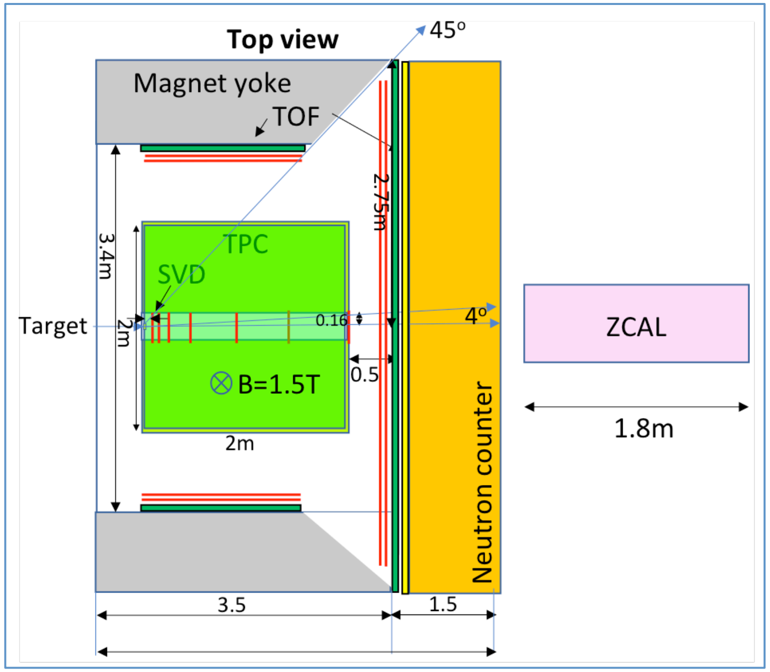
Higher-order harmonics with Cumulants (54M events)

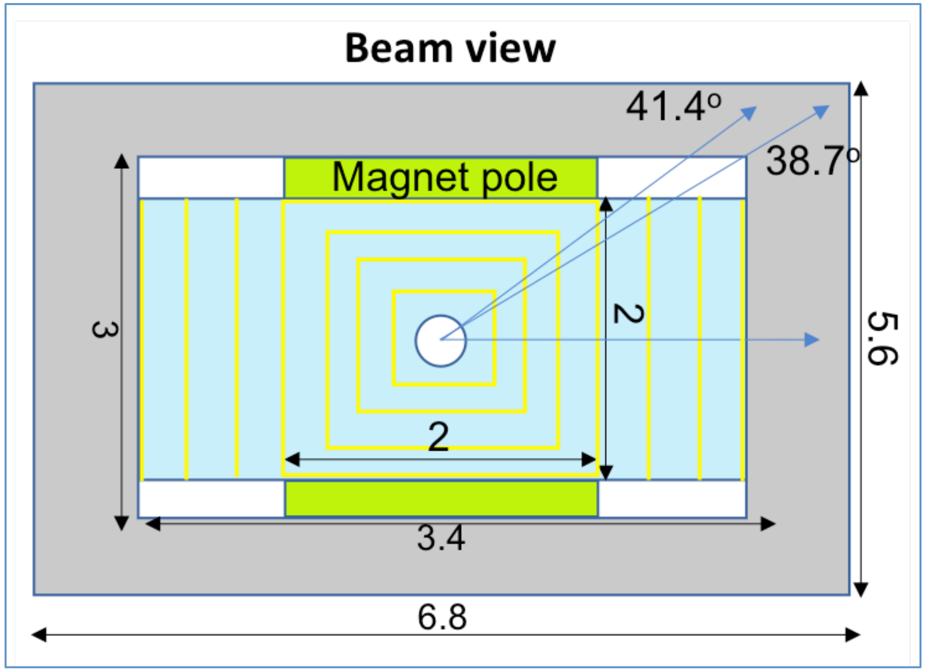


V_2 from n-particle correlations with Cumulants (54M events)



❖ **Experimental setup currently being designed:** Dipole Spectrometer with triggerless continuous read-out scheme

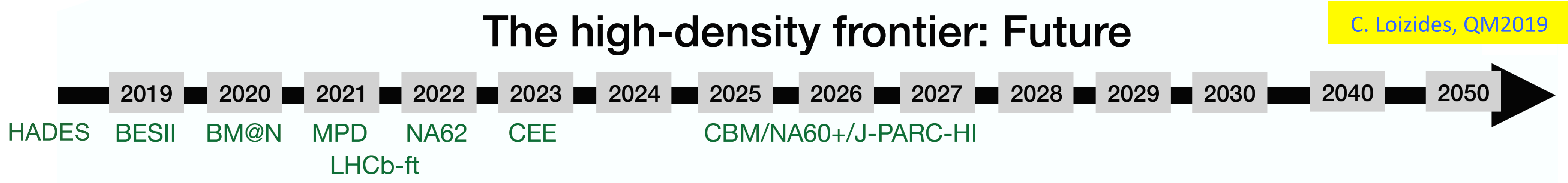




Hadron spectrometer setup
+ neutron counter:
max. event rate ≤ 100 kHz

Dimuon spectrometer setup:
max. event rate ≤ 10 MHz

Experimental Programs: Final Remarks (I)



- A comprehensive approach to the study of QCD phases must **combine observations from vanishing to finite baryon densities** (and the precise characterization of the initial states)

- **Several finite-density experimental projects under development or discussion around the world:** opportunities for the French community:
  - Synergies with the vanishing-density experimental programs (analysis tools, software development, hardware R&D…)
  - Exchanges with the French theory community involved in this domain

Experimental Programs: Final Remarks (II)

- **@FAIR:** existing IJCLab activities on HADES could smoothly converge to CBM at SIS100, complementing on the physics side the activity of IPHC on the detector. Possible extension at higher energies (SIS300) in further future

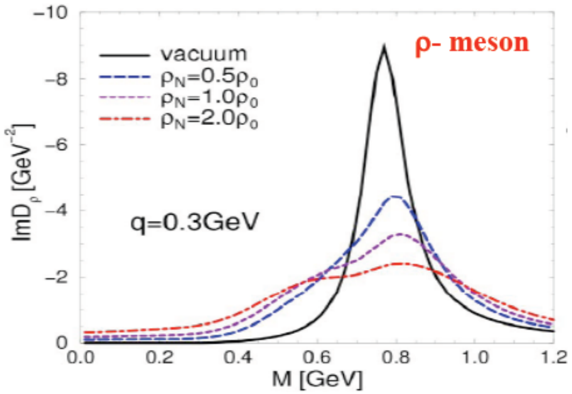
- **@CERN:** large room for contributions to the NA60+ project at the SPS → ongoing R&D of the silicon pixel sensor (currently shared with ALICE ITS3 and ANGHIE) and the R&D + construction of the muon tracking chambers

- **@J-PARC:** full R&D of the hadron and dimuon spectrometer to be installed at the future J-PARC-HI facility (when funded)

→ **Some of the projects need to further evolve and strengthen, before any relevant contribution of the French community could be precisely identified and discussed.** In the meantime, a minimum support should be granted to the exploration activities

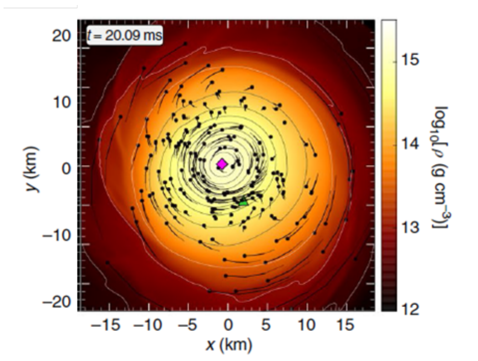
Backup Slides

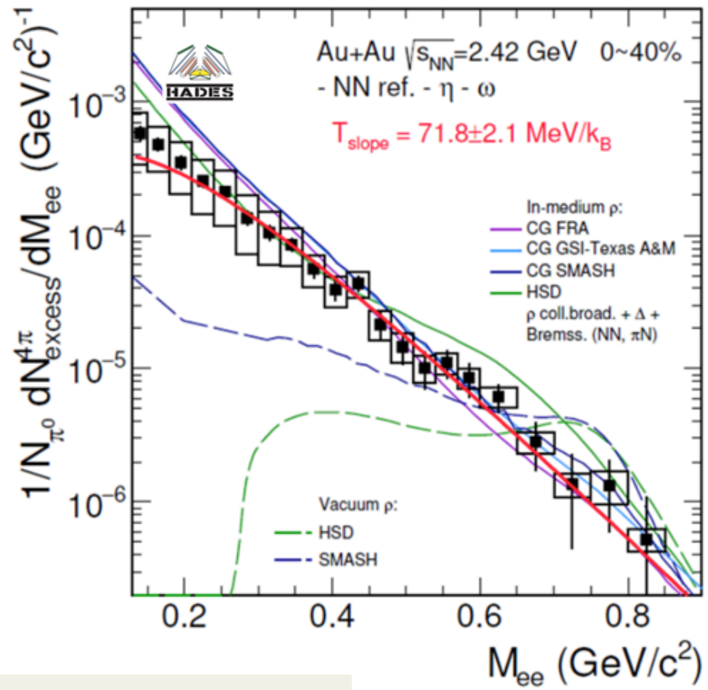
"Probing dense baryon-rich matter with virtual photons", HADES collaboration, *Nature Physics, July 2019*

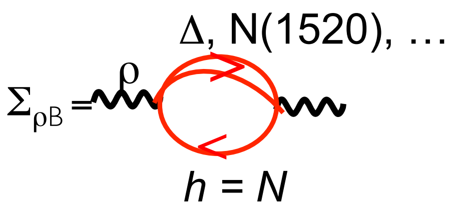


R. Rapp and J. Wambach EPJA 6 (1999) 415

(T,μ_B) similar to
neutron star merger
(gravitational waves)

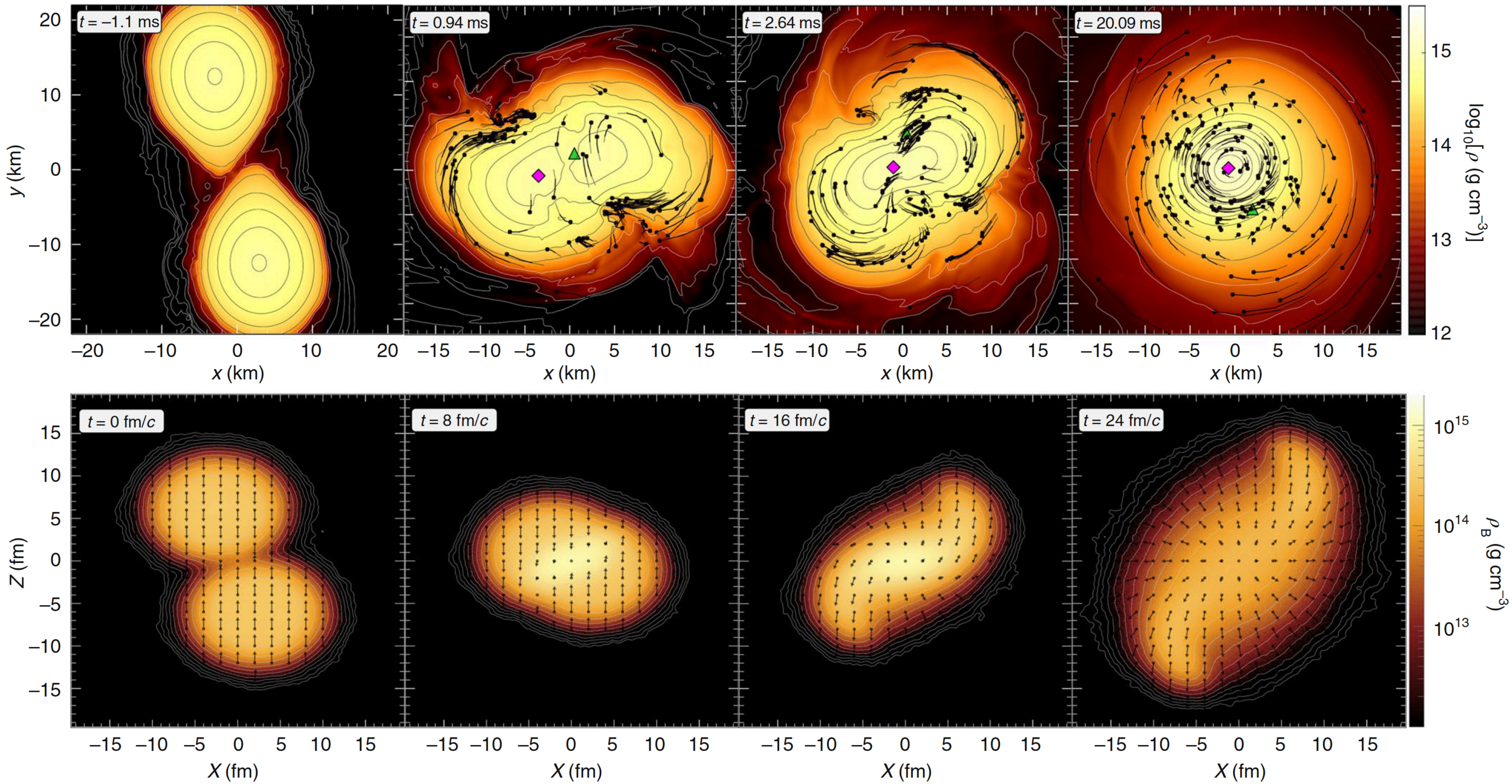






Au+Au $\sqrt{s_{NN}}$=2.42 GeV (E_{lab}=1.25A GeV)
inclusive e^+e^- spectra consistent with

- **thermal emission**
- **strong in-medium ρ meson broadening**
  - mostly due to **coupling to baryons**
  - Related to **chiral symetry restoration**



t = −1.1 ms
t = 0.94 ms
t = 2.64 ms
t = 20.09 ms
y (km)
x (km)
log10[ρ (g cm−3)]
t = 0 fm/c
t = 8 fm/c
t = 16 fm/c
t = 24 fm/c
Z (fm)
X (fm)
ρB (g cm−3)

SIS18 (FAIR-Phase0) and SIS100 (FAIR-Phase1)

FAIR (Facility for Antiproton and Ion Research)

Located at GSI (Darmstadt). Currently SIS100 accelerator under construction: **sqrt(s_{NN}) = 2.7 – 5 GeV**

- **July 2017:** Start of excavation and trench sheeting
- **July 2018:** Start of shell Construction
- **2022:** Buildings completed (including CBM cave)
- **2025:** Completion of full facility and start of operations

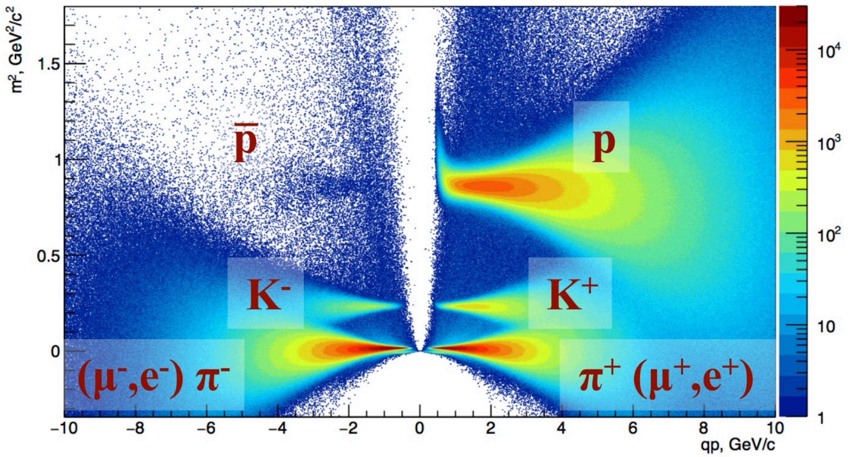
The CBM Detector

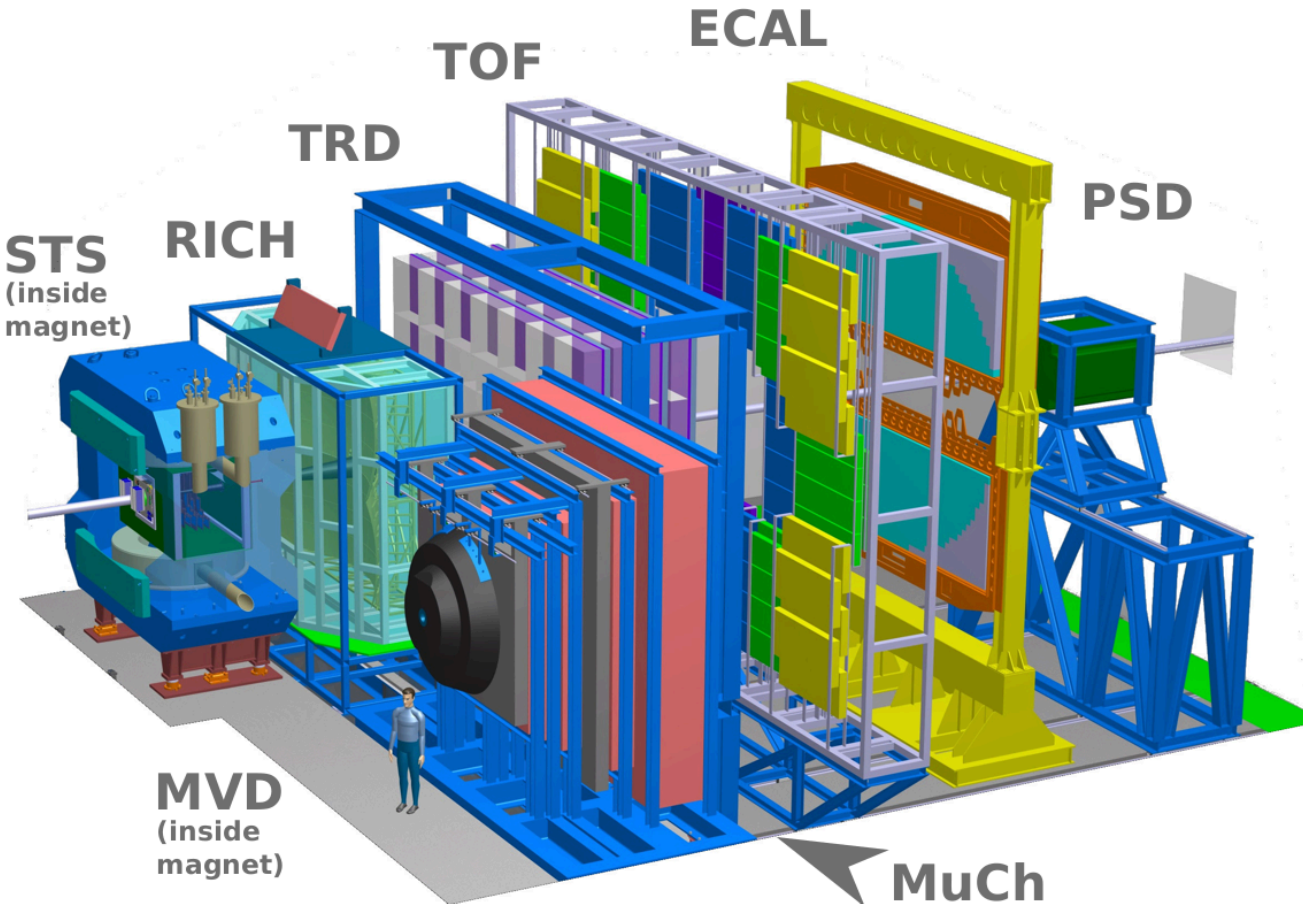
CBM Collaboration:

56 institutions

> 460 members

TOF Particle Identification

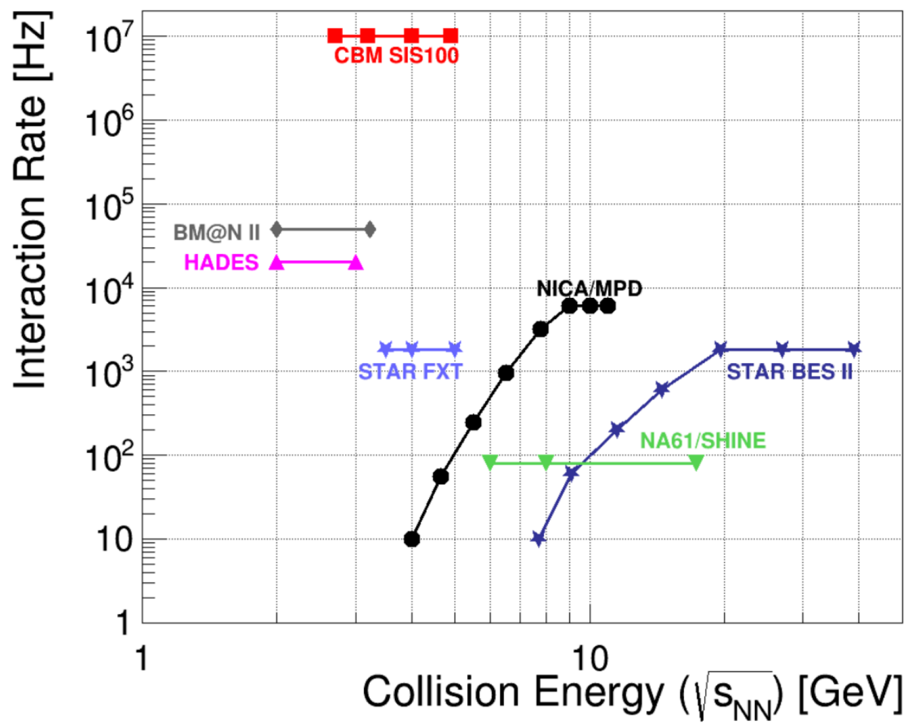




CBM Physics and Observables

- QCD matter equation-of-state at large baryon densities, coexistence (quarkyonic) & partonic phases:
  - Hadron yields, collective flow, correlations, fluctuations
  - (Multi-)strange hyperons (K, Λ, Σ, Ξ, Ω)
  - production at (sub)threshold energies
- Chiral symmetry at large baryon densities
  - In-medium modifications of light vector mesons
  - ρ, ω, φ → $e^+ + e^-$ ($\mu^+ + \mu^-$) via dilepton measurements
- Hypernuclei
- Charm production and propagation at threshold energies
  - Excitation function in p+A collisions (J/ψ, D^0 , D^{+-})
  - Charmonium suppression in cold nuclear matter

Existing and experiments under construction



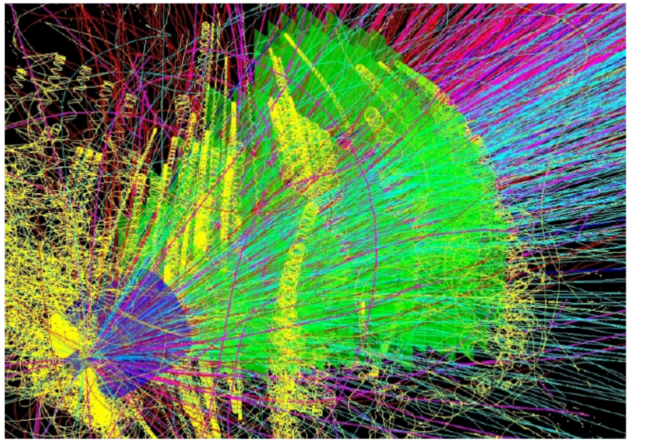
[CBM Collaboration] "Challenges in QCD matter physics"

High statistics needs high reaction rates: 10^5 - 10^7 Au+Au collisions/sec!

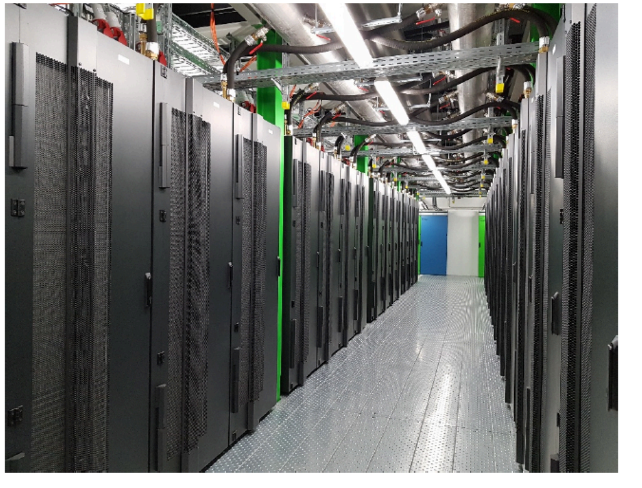
CBM Experimental Requirements

- High event rates: $10^5 - 10^7$ Au+Au collisions/sec
- Fast, radiation hard detectors & front-end electronics
- Free-streaming readout & 4 dimensional (space+time) event reconstruction
- Particle identification: hadrons and leptons, displaced (~50 μm) vertex reconstruction for charm measurements
- High speed data acquisition & performance computing farm for online event selection

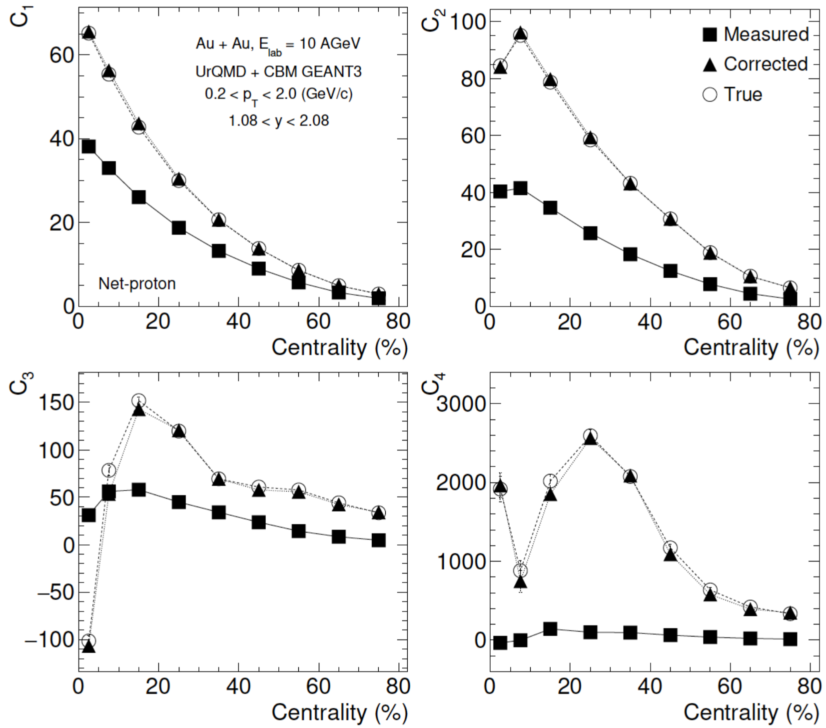
central Au+Au collision @ 10*A* GeV/*c*



GSI IT Center



CBM Physics Program



Cumulants

$$C_1 = \langle N_q \rangle, \quad C_2 = \langle (\delta N_q)^2 \rangle, \quad C_3 = \langle (\delta N_q)^3 \rangle,$$
$$C_4 = \langle (\delta N_q)^4 \rangle - 3 \langle (\delta N_q)^2 \rangle^2$$

$N_q = N_{q^+} - N_{q^-}$ and $\delta N_q = N_q - \langle N_q \rangle$
q can be any conserved quantum number

(net-baryon, net-charge, net-strangeness etc.)

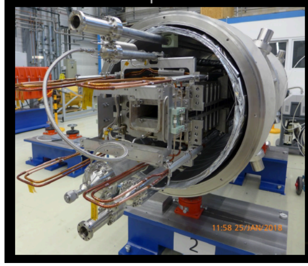
Mean, variance, skewness, kurtosis

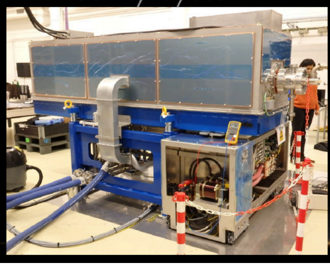
$$M = C_1, \quad \sigma^2 = C_2, \quad S = \frac{C_3}{\sigma^3}, \quad \kappa = \frac{C_4}{\sigma^4}$$

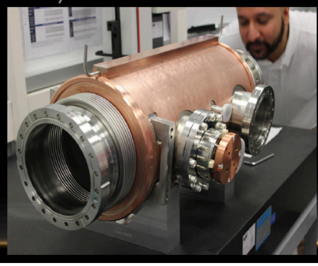
- ⋆ Higher moments of conserved quantities are sensitive to correlation length
  $\langle (\delta N_q)^2 \rangle \sim \zeta^2 \qquad \langle (\delta N_q)^3 \rangle \sim \zeta^{4.5} \qquad \langle (\delta N_q)^4 \rangle \sim \zeta^7$
- ⋆ Non-monotonic variations of $S\sigma = C_3/C_2$, $\kappa\sigma^2 = C_4/C_2$ with beam energy are believed to be good signatures of CP

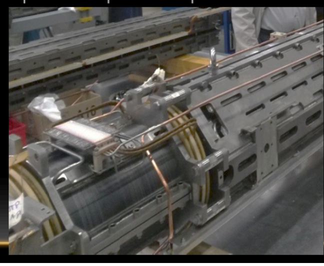
FAIR Status

- FAIR starts 2018
  - FAIR Phase-0 experiments
- SIS18 tunnel upgrade – finished
- Excavation of SIS100 tunnel progresses rapidly
- Serial production of major components for SIS100 (i.e. dipoles) started
- SIS100 commissioning with beam 2024

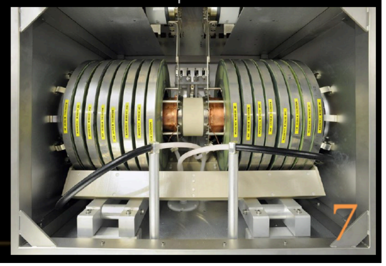

SIS100 Dipole


RF Cavity System


Cryo catcher


Dipole, quadrupole units


Cryo bypas line


Bunch compressor

NA60+ at the CERN-SPS

Stitched-MAPS: new R&D for a waferscale MAPS

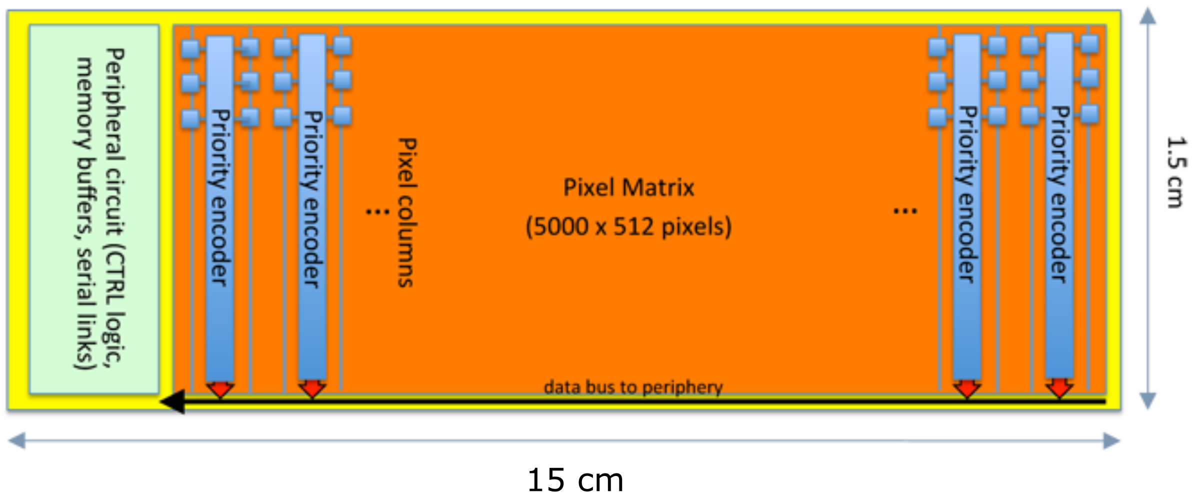
PRIN 2018: *STITCHED MAPS - a novel large area, fast, radiation-tolerant monolithic active pixel sensor for tracking devices of unprecedented precision*

- Funded project by Italy Research Ministry with **1 MEuro (started September 2019)**
- **Cagliari University, Bari University and Politecnico, INFN (G. Usai Principal Investigator)**

Common R&D effort together with CERN and other labs

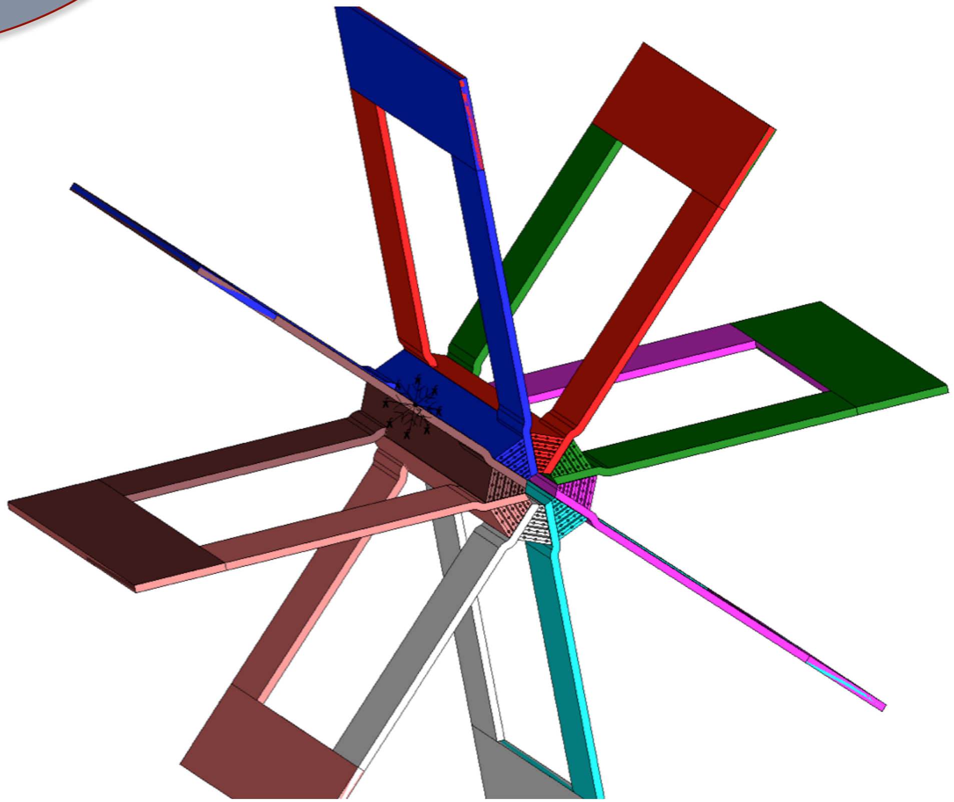
Kick-off meeting at CERN to agree specs of a new sensor suitable for different applications:

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



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

The NA60+ Project: Toroidal Magnet R&D



Open toroid for NA60+ : field circling the beam axis

- L = 3m
- 0.3 < R < 1.65 m at entrance
- 0.3 < R < 2.95 m at exit
- $B \cdot R \approx 0.2\text{-}0.25\ T \cdot m$

Minimal design:

- Concept put forward by F. Bergsma, P.A. Giudici (CERN-EP-DT-EF)
- **Easy to build meccano-like structure**

- **8 sectors (octants)**, tangentially displaced w.r.t. cylinder axis
- Conductors made of **aluminium**
- Segments consist of a single winding, straight conductors joined by screws

The NA60+ Project: Muon Tracking Stations

Two *(three)* 3×3 m^2 and two *(three)* 7×7 m^2 muon tracking stations are installed before and after the muon spectrometer toroid, for a total of 116 *(174)* m^2 of chambers for the foreseen baseline *(expanded)* setup

Technology choice currently under investigation: double 3-GEM modules with 2D strip readout

- Module size: 50 × 110 cm^2
- 300 modules → 1000 GEMs (with spares)
- NS2 system (like CMS) for faster module assembly (no gluing)
- Gas: Ar-CO_2 or Ar-CO_2-CF_4 (non flammable, no ageing effects observed)
- 1 M electronic channels. Readout options: VFAT-3, VMM-3 chips

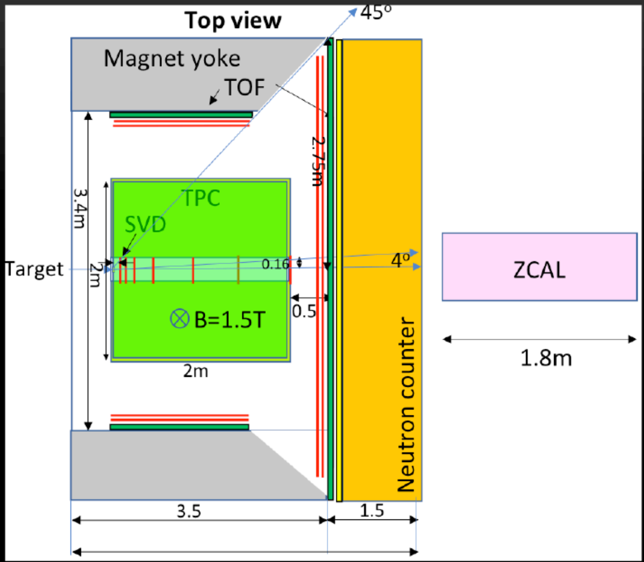
20 × 20 cm^2 prototype for the GEM module **designed** in Munich (TUM)

→ Full production **needs a collaboration of 3-4 Institutes**

J-PARC-HI

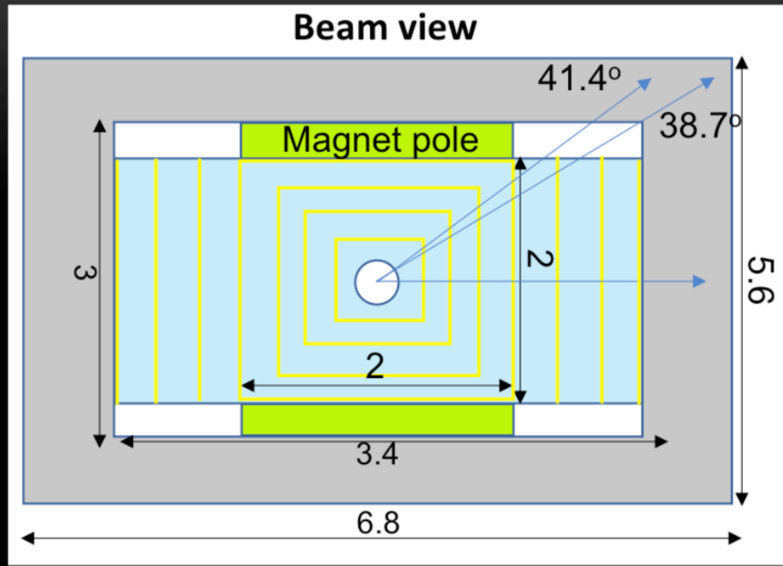
Detector Scenarios at J-PARC-HI

Dipole Hadron Spectrometer



- Fixed-target
- Charged particles and neutron detection
- Dipole field: B=1.5 T
- ~4π acceptance with TPC, TOF, neutron counter
- Trigger-less continuous read-out
- Interaction rate: >100kHz

Dimuon Spectrometer



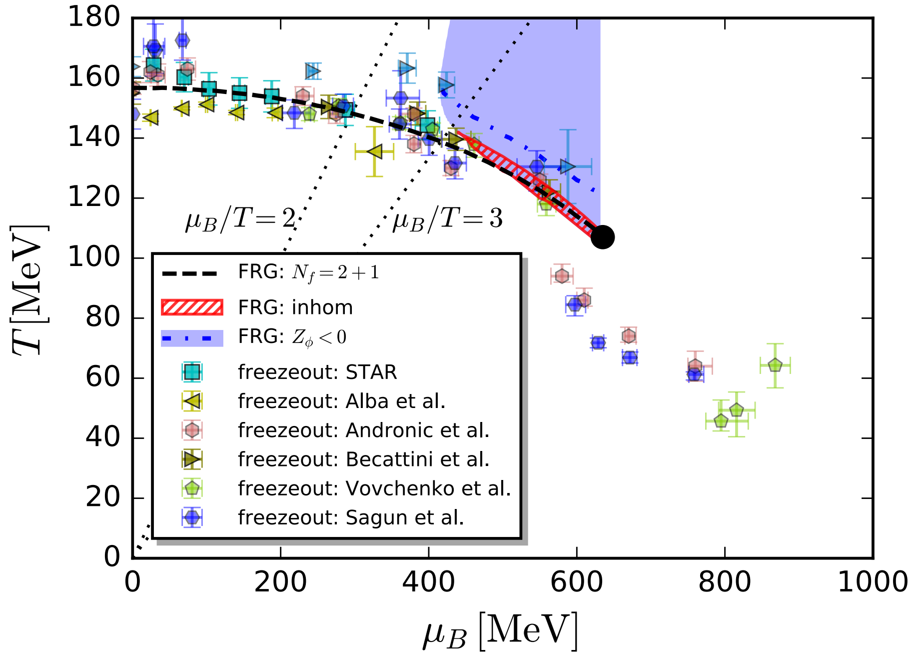
- Replace TPC by Pb absorbers and tracking layers
- 8-layer barrel and forward Silicon pixel detectors (20μm×20μm)
- Dimuon online trigger
- Interaction rate: >10MHz

17

Physics Motivations

Is There a Critical Point, and Where?

Fu et al., arXiv:1909.02991



- **At low densities** various theory approaches and phenomenological freeze-out data agree quite well
- **A critical point and an inhomogeneous regime are observed at finite densities** with the FRG (functional renormalization group) approach. For quantitative statements the current approximations need to be systematically upgraded

At finite baryon density, current lattice QCD methods are not exploitable due to the fermionic sign problem. Possible theoretical avenues:

- Advance approaches aiming to alleviate the sign problem
- Construct effective models, e.g. Polyakov-loop-extended quark-meson models, to be constrained by lattice at small densities and by data from HIC and astrophysical observations at large densities
- Extend truncation schemes, e.g. the FRG approach, to perform calculations at finite density
- Holographic gauge/gravity duality to describe the dense and strongly coupled phase

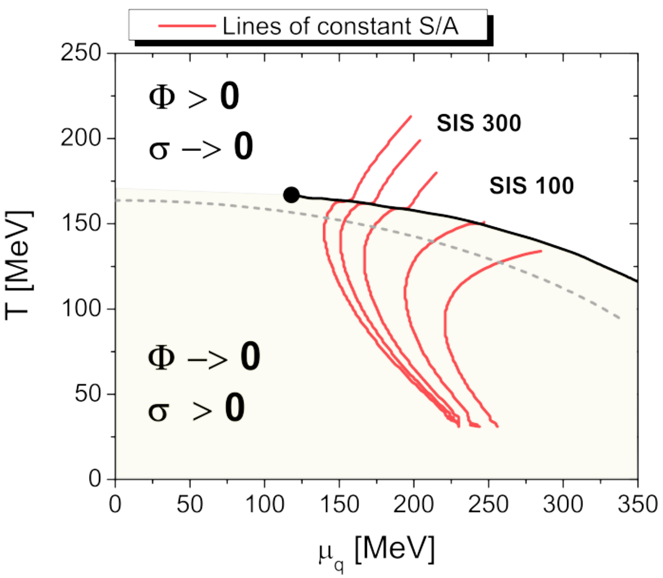
Constraining the Equation of State of QCD

The equation of state (EoS) contains all the thermodynamic information of QCD

At finite densities it should encode the relevant information about:

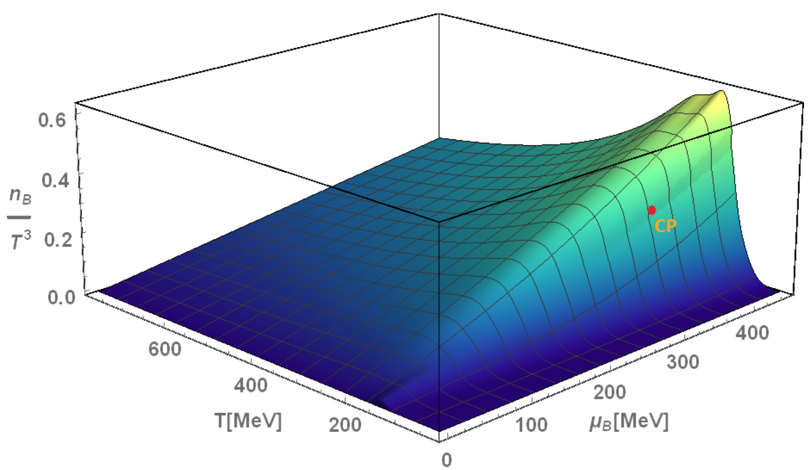
- The existence and location of the critical point
- The coexistence of phases along a first-order phase transition line
- The matter in the interior of compact stars

V. Dexheimer et al., PRC81 (2010)



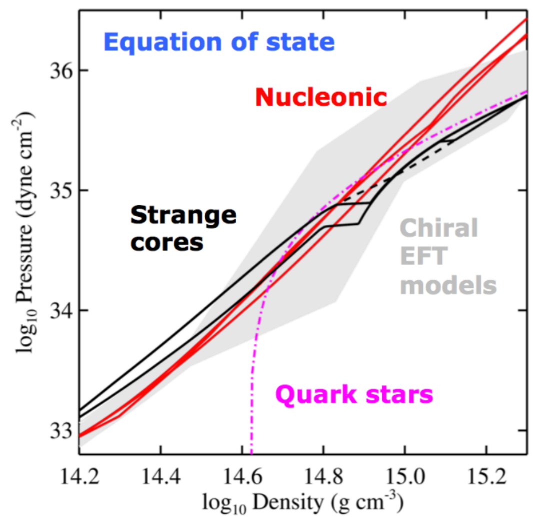
Hadronic SU(3) non-linear sigma model + quarks

P. Parotto, MN et al., arXiv:1805.05249



Lattice QCD + HRG + Ising critical point

A. Watts et al., PoD (AASKA 14) 043

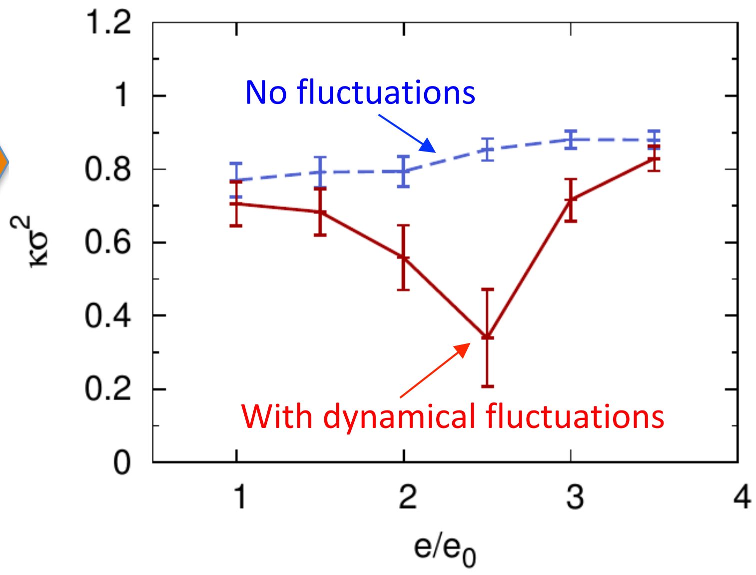


Pressure-density relation for different EoS models

Critical Point: the Role of Fluctuations

- Fluctuation observables, in particular higher-order cumulants of net-baryon number, are sensitive to critical phenomena at the phase transition.

So far predictions are based on grand-canonical thermodynamics, **but a heavy-ion collision is highly dynamical, finite in size and time!** Due to critical slowing down, the system will be out-of-equilibrium near the critical point



C.Herold, MN et al., PRC93 (2016)

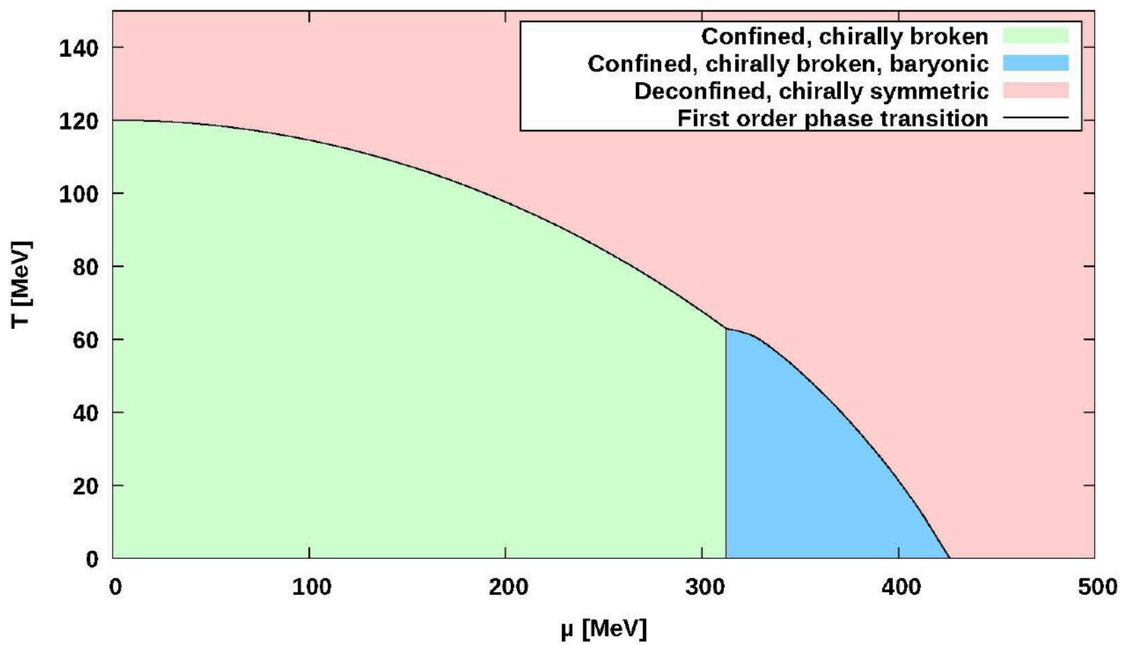
Currently, simulations of heavy-ion collisions do not propagate fluctuations. Theoretical challenges:

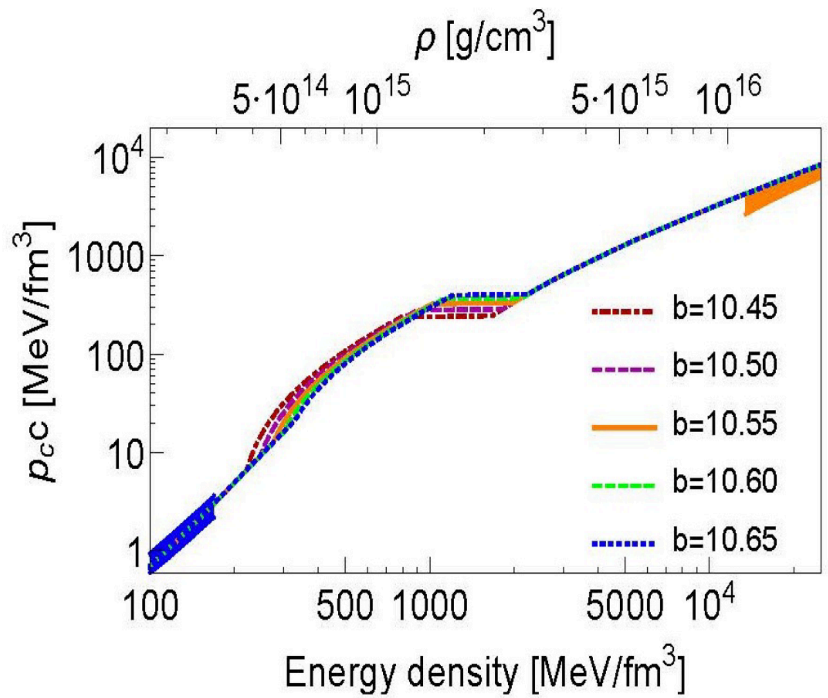
- Propagate fluctuations of the chiral order parameter explicitly, coupled to the evolution of the noncritical part of a heavy-ion collision
- Propagate fluid dynamical fluctuations in 3+1d, highly non-trivial (conceptually and numerically costly) due to renormalization effects on the EoS and transport coefficients (also important for precise determination of the shear viscosity at LHC energies!)
- Couple properly to all noncritical sources of fluctuations, e.g. initial state, final state, …

QCD EoS: Holographic Approach

- **Holography** or the "holographic" correspondence or AdS/CFT is **a duality between strong-coupling gauge theories and string theories.** There is a detailed map between observables in the QFT (correlation functions) and in gravity (S-matrix in asymptotically AdS spaces)

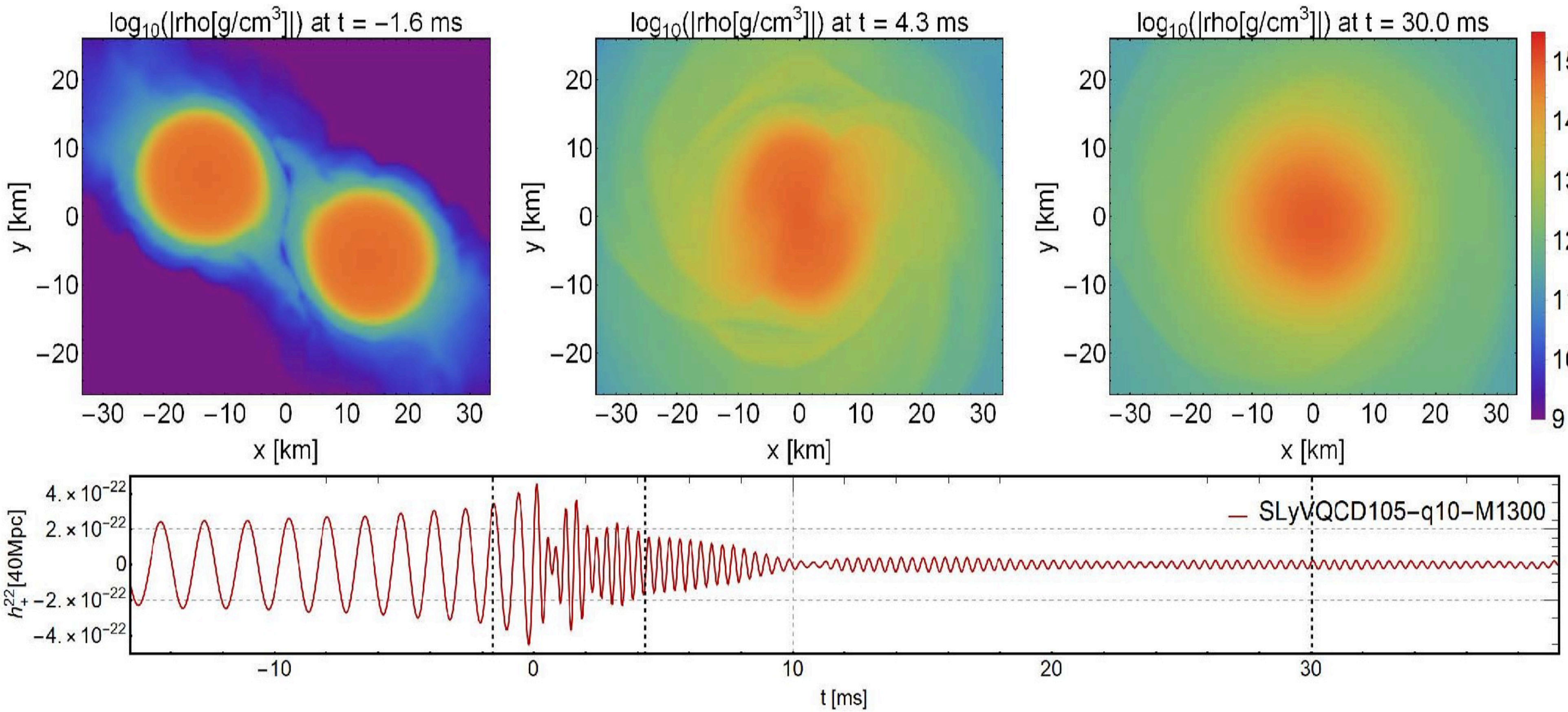
- **One can use the full theory to calculate the phase diagram and the equation of state:**





QCD EoS: Holographic Approach

- By calculating the EoS of QCD matter, the holographic approach can then provide **predictions for extreme astrophysical processes like neutron star mergers** (in the figure, from left to right: late inspiral phase, early post-merge, late post-merger)



Extreme Matter Studies: Global Strategy

Nuclear experiments ⟷ **Theory for dense matter** ⟷ **Global astrophysical modeling** ⟷ **Observational facilities**

Nuclear experiments

CERN (*LHC, SPS*)
GANIL,
GSI (*FAIR*),
DUBNA (*NICA*)…

Theory for dense matter

EoS (*ComPOSE*),
Neutrino diffusion,
Transport coefficients

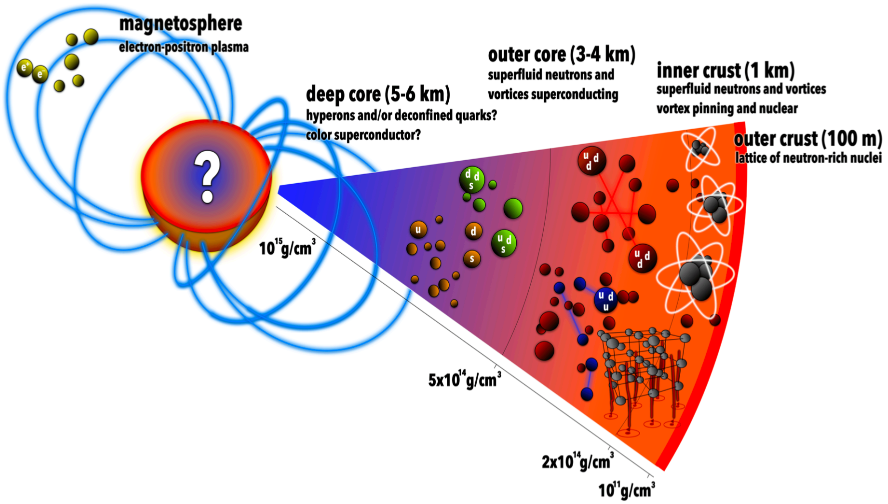
Global astrophysical modeling

Neutron stars
(*Lorene library, meta-model*),
BH & NS mergers
(*Einstein toolkit, WHISKY-THC*),
Kilonova,
Supernova (*COCONUT*),
Galactic chemical evolution

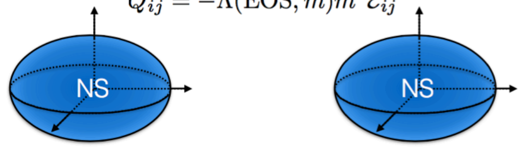
Observational facilities

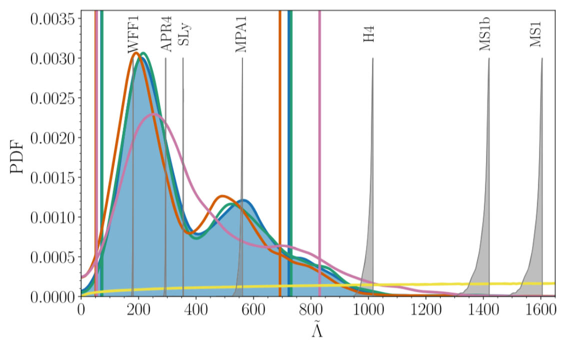
GW (*LIGO-Virgo*),
GRB (*FERMI-LAT, XMM Newton*),
E-M (*GRANDMA, ZTF, …*)

Improved understanding of extreme matter physics ⟷ **Cross-fertilisation** ⟷ **Improved understanding of astrophysical objects**



$$Q_{ij} = -\Lambda(\mathrm{EOS}, m)m^5\mathcal{E}_{ij}$$





A first example with BNS merger:
LVC, Phys. Rev. X 9, 011001 (2019)
Tidal deformalbility measurement

For GW170817
→70 ≤ Λ ≤ 720 (90% CL)
→+E-M 300 ≤ Λ ≤ 800

First constraints from GW put on EoS

Solving QCD in Non-Perturbative Regime

Modeling the equation of state:

- **Agnostic approaches:** no Lagrangian, no matter composition
- Ex.: piece-wise polytropes, sound-speed model, …
- **Semi-agnostic approaches:** no Lagrangian, matter composition
- Ex.: meta-model
- **Phenomenological approaches:** Phenom. Lagrangian, matter composition
- Ex. (nucleon): Skyrme and extensions, Gogny, RMF, RHF, …
- Ex. (quark): PNJL, PQM, …
- **Microscopic approaches:** reproduce NN XS, predict dense matter properties
- Ex. (nucleon): AV16 + 3BF, Nijmegen …
- **QCD based approaches**:
- Ex.: LQCD, chiral EFT (effective field theory), QCD holographic correspondence.

Addressing fundamental questions at the forefront

From the The Gravitational Wave International Committee, third generation ground based observatory (GWIC 3G) science-case meeting (oct. 2018, Postdam), Sanjay Reddy, Neutron Star WG

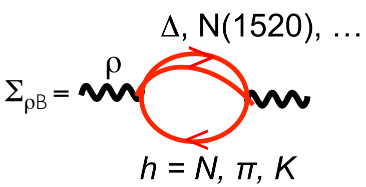
1. Does matter in NS and NS mergers contain **novel QCD phases** not realized inside nuclei and heavy-ion collisions?
2. Can NS observations guide and validate **theories of nuclei and nuclear matter**?

Dileptons: EM Emission Rate and Correlator

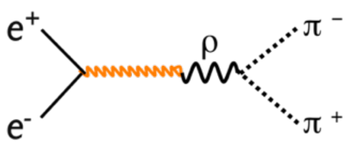
$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha_{EM}^2}{\pi^3 M^2} f^B(q \cdot u; T)\, \mathrm{Im}\Pi_{EM}(M, q; \mu_B, T)$$

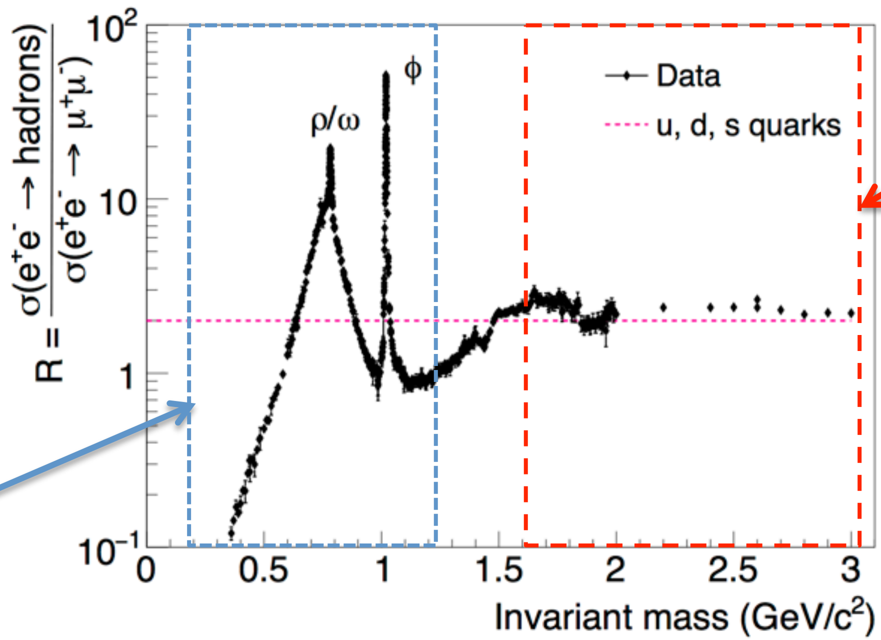
E.M. radiation emission rate

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \propto \frac{\mathrm{Im}\Pi_{EM}^{vac}}{M^2} = \begin{cases} \sum_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 \mathrm{Im}D_v^{vac}(M), & M < M_{dual}^{vac} \simeq 1.5\,\mathrm{GeV/c^2} \\ -\frac{M^2}{12\pi}\left(1 + \frac{\alpha_s(M)}{\pi} + \ldots\right) N_c \sum_{q=u,d,s} (e_q)^2, & M > M_{dual}^{vac} \end{cases}$$

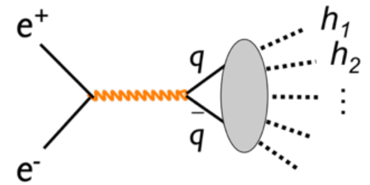


Non-perturbative: VMD, in-medium spectral functions





Perturbative: parton-hadron duality



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

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