CBM overview
Facts and Fictions

Frédéric Julian Linz for the CBM Collaboration
Budapest, Hungary - 04.12.2023

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Facts and Fictions

Visions/Plans:

- Physics motivation/CBM goals
  - QCD phase diagram
  - Experimental access
  - Extreme conditions in the laboratory
  - Key observables, CBM performance goals
- Project timescale

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Facts and Fictions

Achievements:

- Towards CBM
  - Detector prototypes and pre-seris production
  - Simulations/Performance
- mCBM demonstrator and precursor
  - Recent results
  - Upcoming data taking

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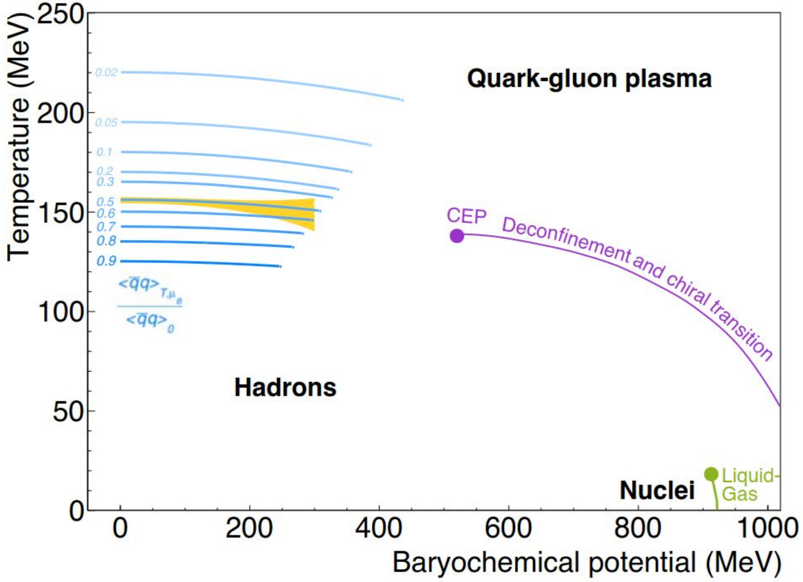
Part I

Physics motivation and performance studies of CBM

QCD phase diagram

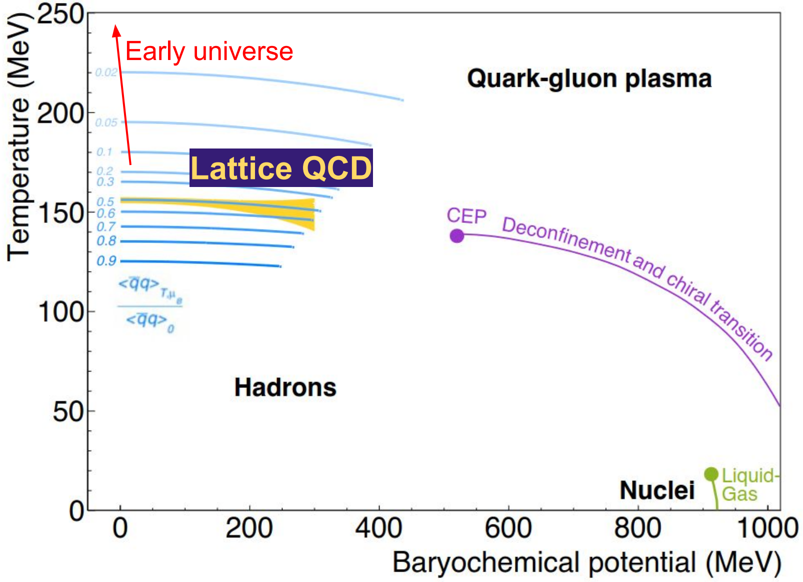


Borsanyi et al. [Wuppertal-Budapest Collab.], JHEP 1009 (2010) 073
Isserstedt, Buballa, Fischer, Gunkel, PRD 100 (2019) 074011
Gao, Pawlowski, PLB 820 (2021) 136584
Cuteri, Philipsen, Sciarra, JHEP 11 (2021) 141

QCD matter: many body system of quarks and gluons:

- Properties are very different depending on:
  - Temperature T (kinetic energy of the constituents)
  - Baryo-chemical potential μ_B (difference between number of baryons and anti-baryons)

QCD phase diagram



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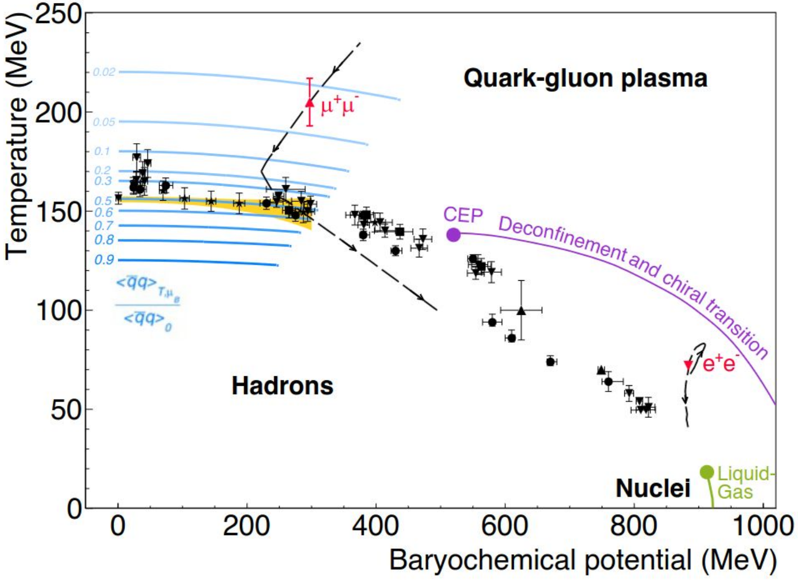
Phase transition from hadronic to deconfined QCD matter:

- At vanishing μ_B and high T:
  - Smooth crossover (lattice QCD)
  - Close to perfect liquid
  - No indication for critical endpoint for $\mu_B/T < 3$

Bazavov et al. [HotQCD], PLB 795 (2019) 15-21
Ding et al., [HotQCD], PRL 123 (2019) 6, 062002
Dini et al., Phys.Rev.D 105 (2022) 3, 034510

- At large μ_B and moderate T:
  - First order phase transition?
  - Critical endpoint?
  - Equation-of-state for baryon-rich matter?

QCD phase diagram



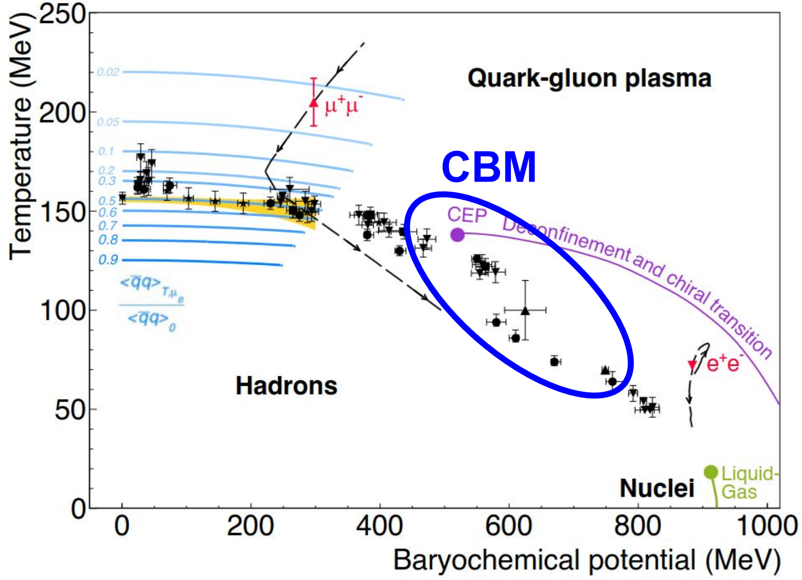
[HADES], Nature Phys. 15 (2019) 10, 1040-1045
Andronic et al., Nature 561 (2018) no.7723

Experimental scan with relativistic nucleus-nucleus collisions in the laboratory. Experimentally can vary:

- Nucleus charge and mass:
  - Initial baryon number relative to the total number of produced constituents
    → related to baryo-chemical potential μ_B
  - System size
- Beam energy:
  - Initial energy available to the system
    → related to temperature T (also influences μ_B)

➔ Both together define accessible area in the phase diagram

QCD phase diagram



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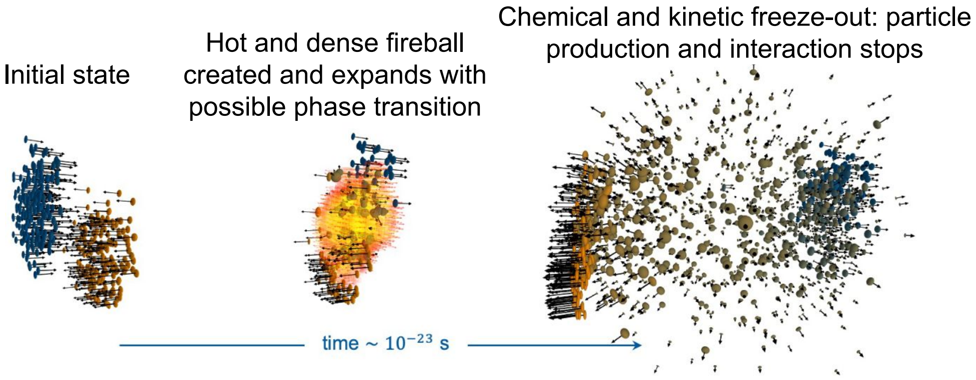
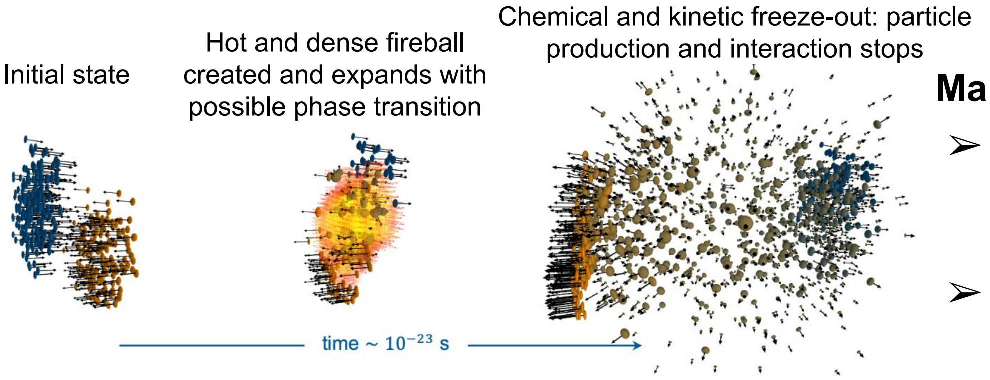
CBM:

- ➢ High baryo-chemical potential: $500 < \mu_B$ [MeV] < 850
- ➢ Moderate temperatures T ~ 100 MeV

Evolution of a nucleus-nucleus collisions



Nucleus-nucleus collisions in the laboratory



Main measures at CBM:

- Strangeness production (from bulk):
  - Equilibration of the system and density of the created matter
- Event-by-event fluctuations:
  - First order phase transition, critical end point, susceptibilities to restrict equation-of-state (EoS)
- Collective behavior and correlations:
  - Vorticity via (global) spin polarization, YN & YNN potentials
- Dileptons:
  - Emissivity of dense baryonic matter: lifetime, temperature, density, in-medium properties
- Hypernuclei

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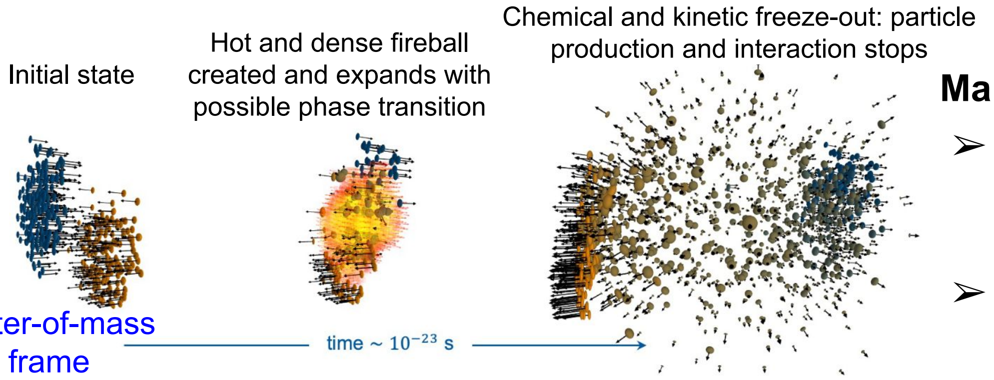
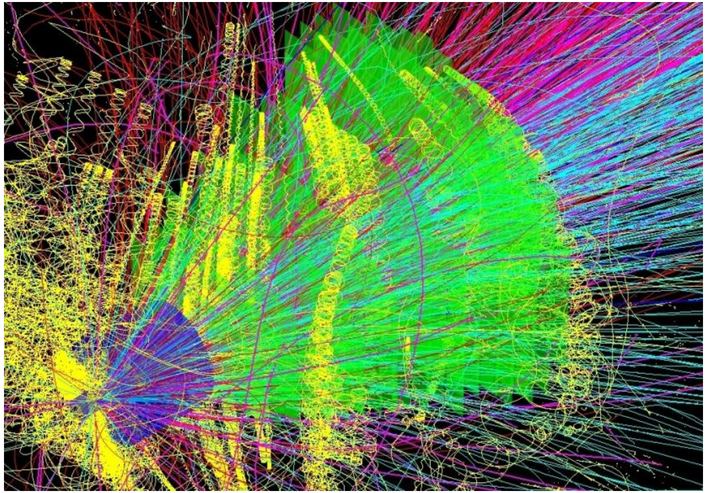


center-of-mass frame

fixed target experiment



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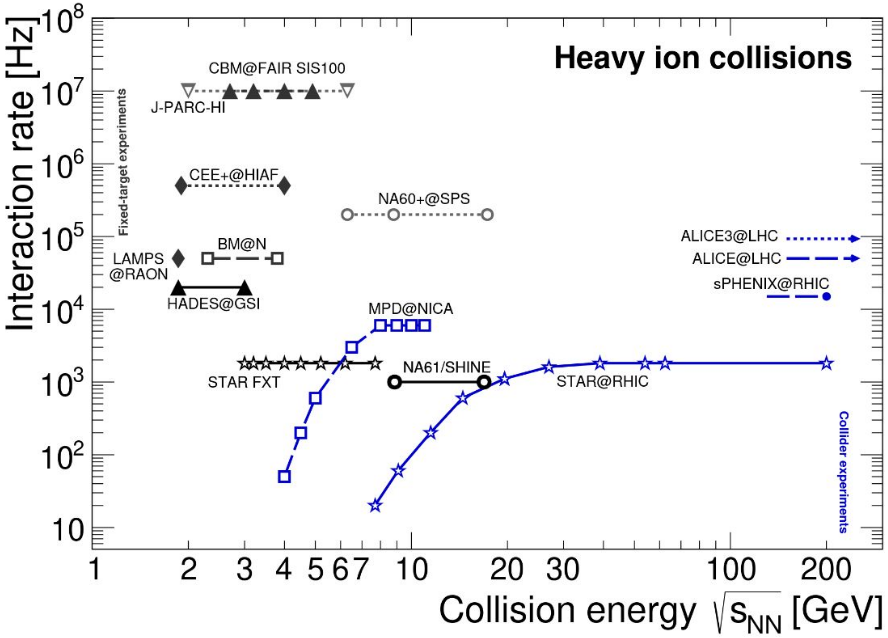
Experimental challenges for CBM



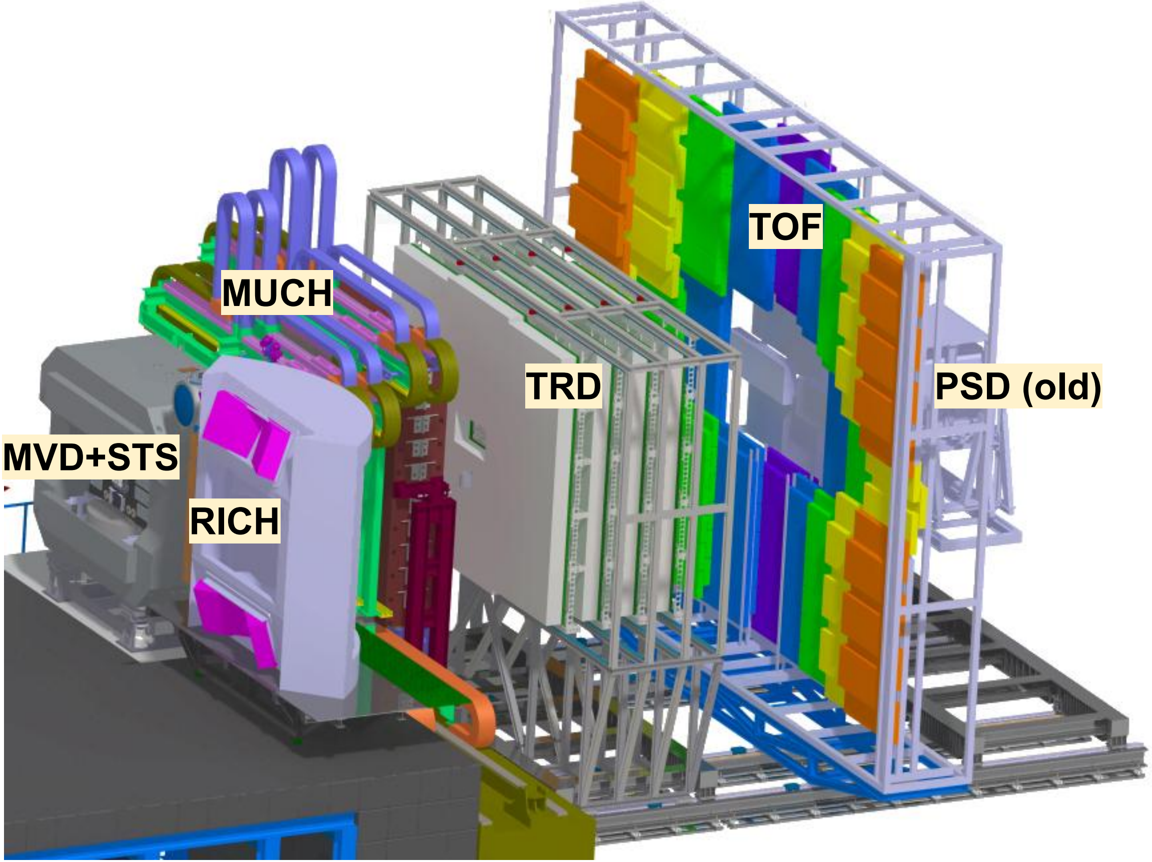
T. Galatyuk, NPA 982 (2019), update 2023
https://github.com/tgalatyuk/interaction_rate_facilities
CBM, EPJA 53 3 (2017) 60

Investigation of rare probes requires high statistics to reach high sensitivity

- ➢ High intensity beams
- ➢ Capable detectors
  - ○ High primary and secondary vertex resolution
  - ○ Large detector acceptance and high efficiency
  - ○ Free streaming read-out electronics
  - ○ Light material budget (control beam backgrounds, …)
  - ○ High radiation tolerance
- ➢ High performance computing
  - ○ Online event selection instead of hardware triggers

The Compressed Baryonic Matter experiment

MVD
Micro Vertex Detector*
STS
Silicon Tracking System*
* inside magnetic field
MUCH or RICH
Muon Chamber System /
Ring Imaging Cherenkov Detector
TRD
Transition Radiation Detector
TOF
Time-of-Flight Detector
PSD
Projectile Spectator Detector



The Compressed Baryonic Matter experiment

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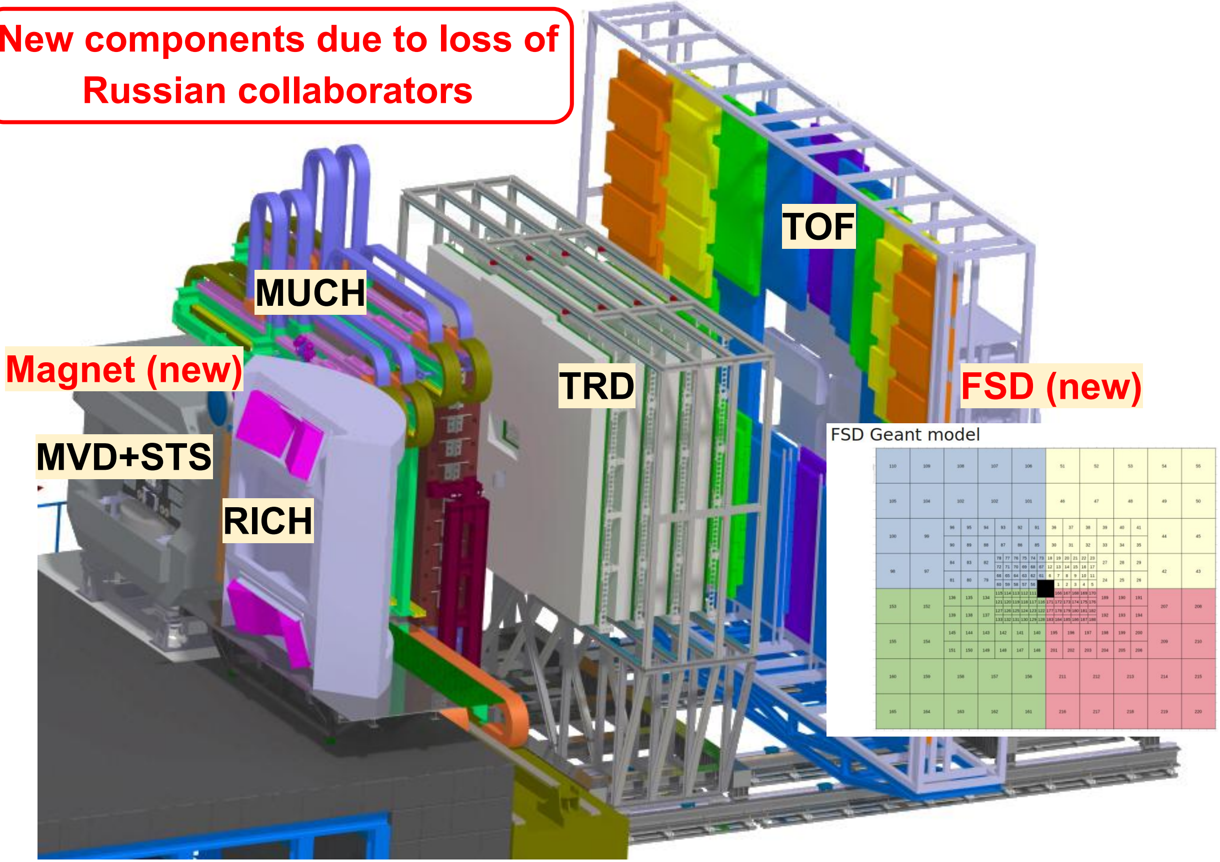
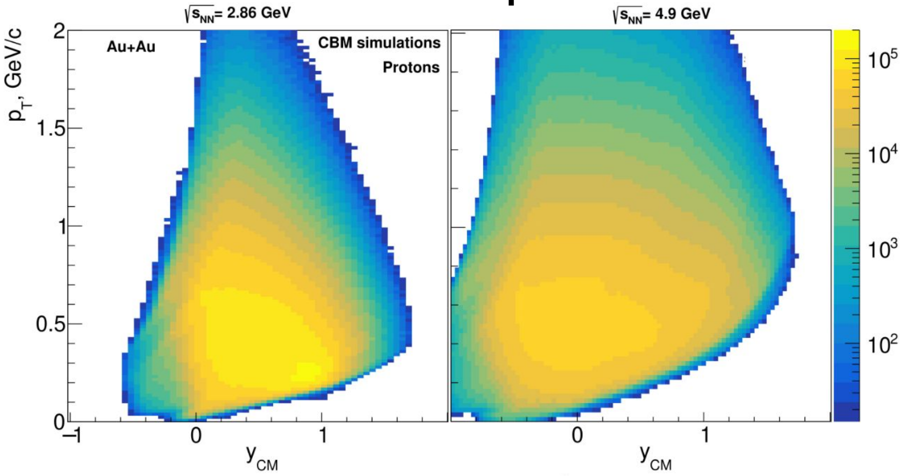
TRD
Transition Radiation Detector
TOF
Time-of-Flight Detector
FSD
Forward Spectator Detector
(similar to HADES Forward Wall)

New components due to loss of Russian collaborators

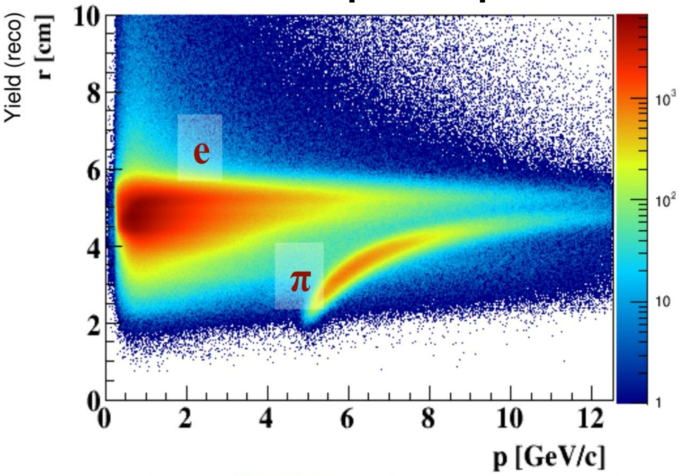


The Compressed Baryonic Matter experiment

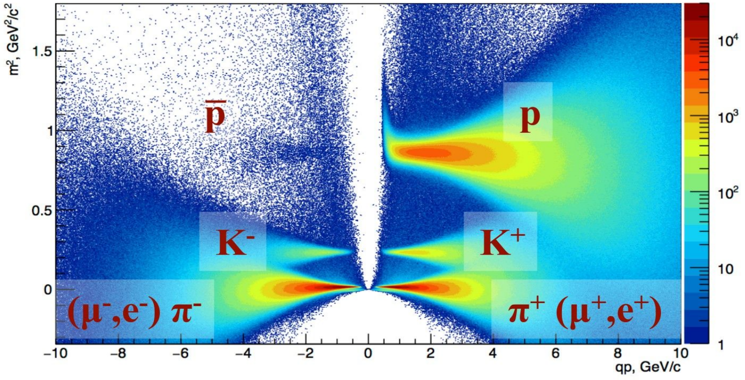
Detector acceptance

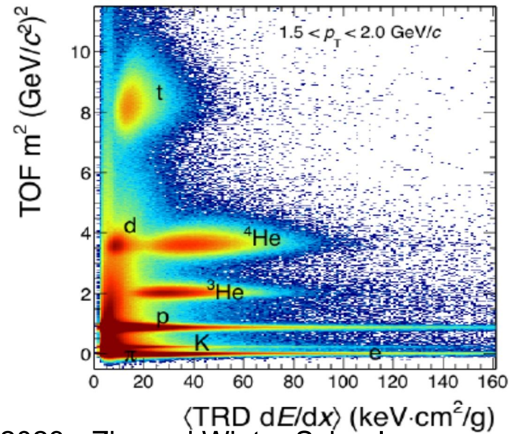


RICH electron-pion separation



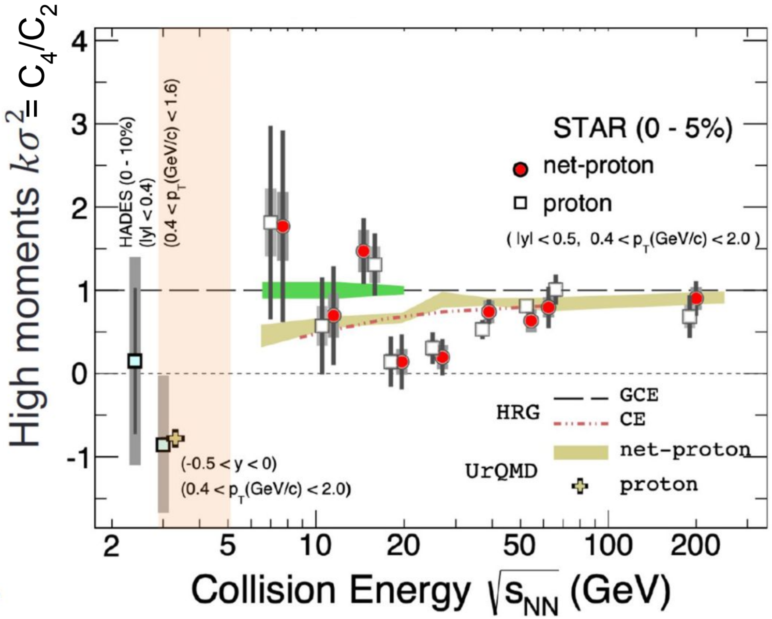
Hadron ID with TOF





TRD+TOF PID via energy loss

CBM physics goals: critical fluctuations



STAR, PRL 128 (2022) 20, 202303
HADES, PRC 102 (2020) 2, 024914

- Thermal susceptibilities for baryon number:

$$\chi_n \equiv \frac{\partial^n (p/T^4)}{\partial(\mu_B/T)^n} = \frac{C_n}{T^3}$$

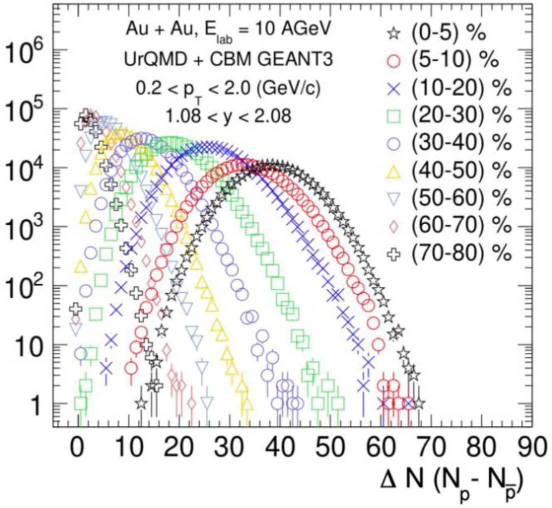
n-th order cumulant

- 6th order derivative particularly sensitive to phases in the QCD diagram
- Requires measurement of higher order moments of net-proton number distribution:

$$\begin{aligned}
\text{mean}: \mathrm{M} = \langle N \rangle &= C_1, \\
\text{variance}: \sigma^2 = \langle (\delta N)^2 \rangle &= C_2, \\
\text{skewness}: \mathrm{S} = \langle (\delta N)^3 \rangle / \sigma^3 &= C_3/C_2^{3/2}, \\
\text{kurtosis}: \kappa = \langle (\delta N)^4 \rangle / \sigma^4 - 3 &= C_4/C_2^2.
\end{aligned}$$

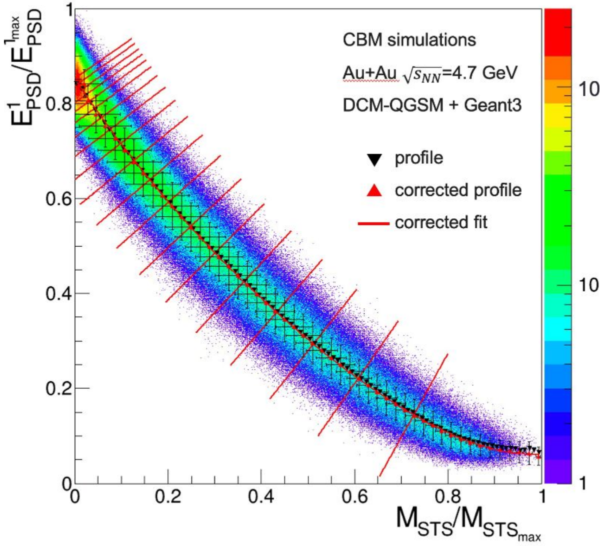
1st order phase transition:
Discontinuity of the density ⇒ non-monotonous behavior of higher order moments of particle number distributions

CBM performance: critical fluctuations



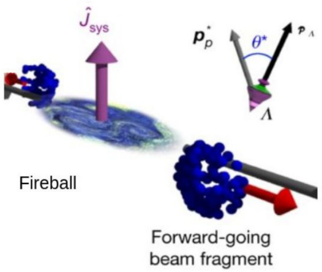
Experimental challenge for CBM:

- ➢ Higher order moments probe the tails of the distributions:
  - ○ Large statistics required for most central collisions (0-5%)
- ➢ Important to have precise (independent) centrality determination!
  - ○ Control of volume fluctuations

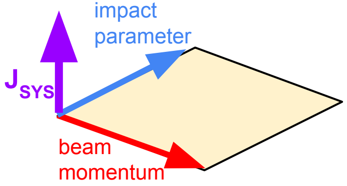


- ➢ Measure excitation function for $k\sigma^2 = C_4 / C_2 = \chi_4 / \chi_2$ (improve STAR stat. errors by factor 10)
- ➢ Precise results for $C_6(N_{proton}-N_{anti\text{-}proton})$
- ➢ Extension into strangeness sector (e.g. net-Λ number fluc.)

CBM physics goals: spin polarization



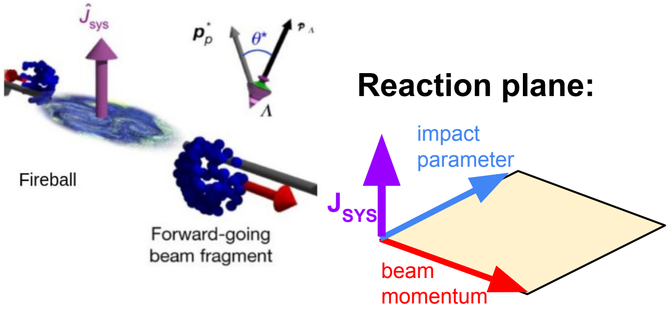
Reaction plane:



Vortical structure of the QCD matter?

- Non-central heavy-ion collisions:
  - Large orbital angular momenta **$\sim 10^3$-$10^7\hbar$**
- Vorticity couples to the spin degrees of freedom of the matter

CBM physics goals: spin polarization



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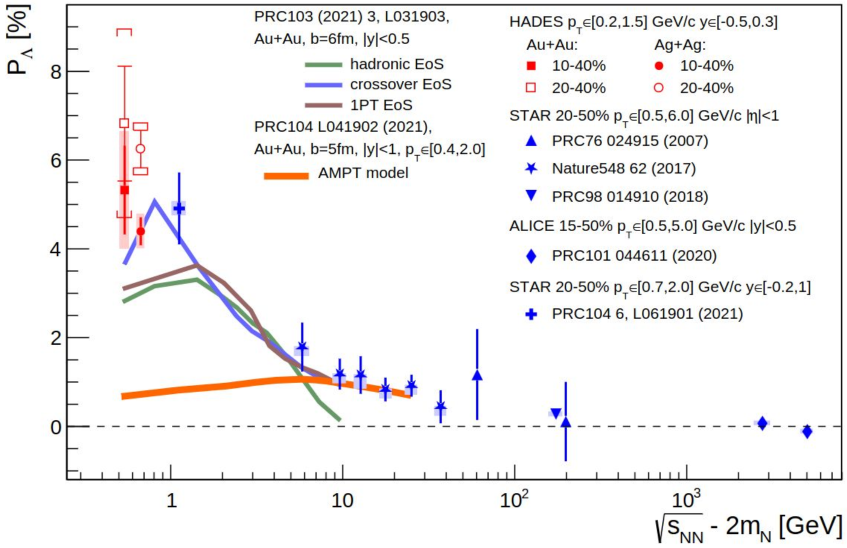
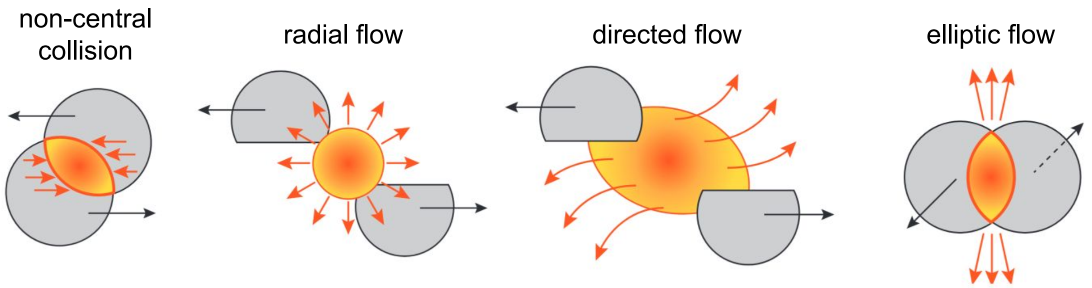
- Non-central heavy-ion collisions:
  - Large orbital angular momenta **~10^3-$10^7\hbar$**
- Vorticity couples to the spin degrees of freedom of the matter

- Experimentally accessible via parity violating weak decays, e.g.:
  - **$\Lambda \rightarrow p + \pi^-$** (proton predominantly emitted in the direction of the lambda spin)
- Strong rise of the Λ polarization function towards lower energies
- Sensitivity to EoS?



HADES, Phys .Lett. B 835 (2022) 137506

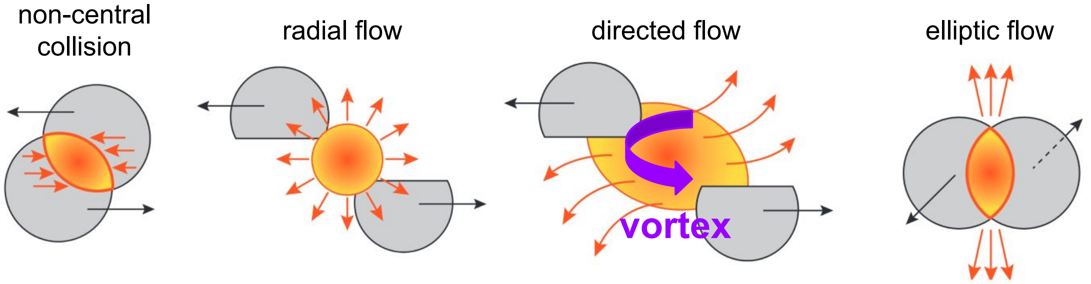
CBM physics goals: collective flow



Flow coefficients describe emission anisotropy in momentum space:

- ➢ Radial flow (v_0=1) sensitive to expansion velocity and temperature
- ➢ Higher order harmonics sensitive to EoS, nuclear mean field, …

CBM performance: spin polarization & directed flow



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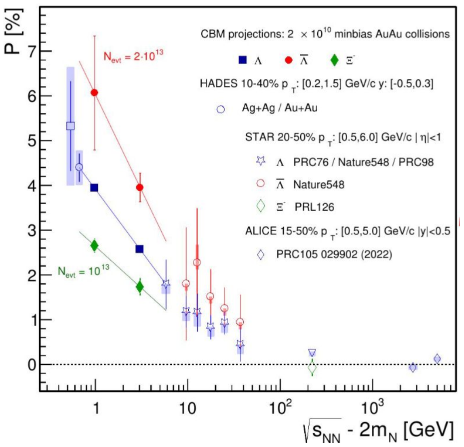
- ➢ Radial flow (v_0=1) sensitive to expansion velocity and temperature
- ➢ Higher order harmonics sensitive to EoS, nuclear mean field, …

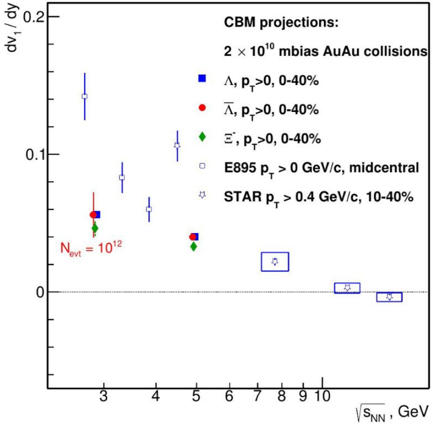
Relation between polarization and directed flow v_1:

- ➢ Both sensitive to the initial velocity field
- ➢ Directed flow measure momentum distribution

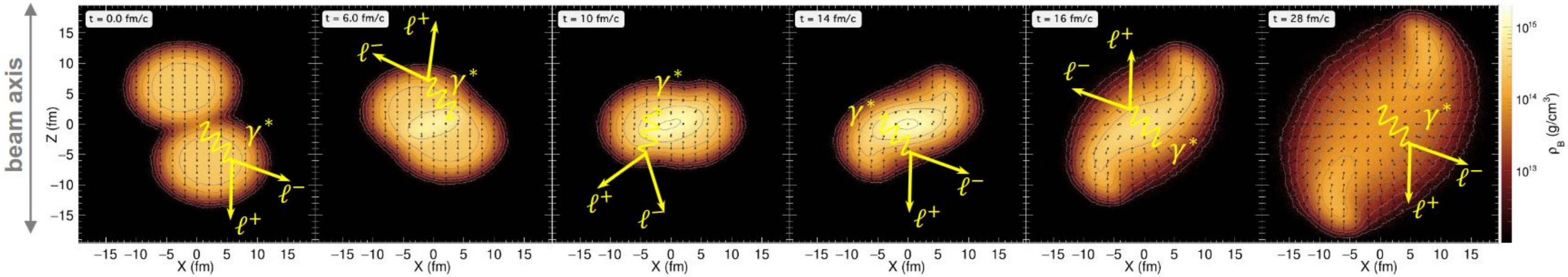
Different behavior in peripheral events:

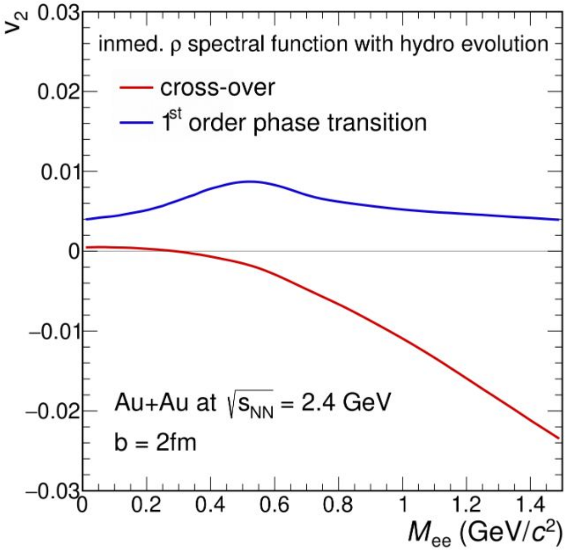
- ➢ Polarization mechanism?
- ➢ Simultaneous description of v_1 and P_H?
- ➢ Differences between p and Λs?





CBM physics goals: dileptons





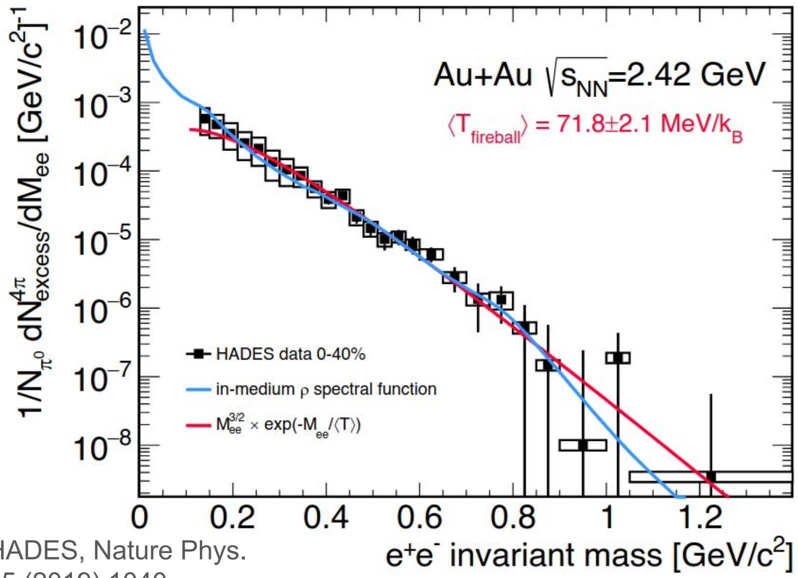
(Virtual-)Photons:

- ➢ No strong interaction involved ⇒ sensitive to all stages of the evolution:
  - ○ Lifetime of the fireball, temperature, restoration of chiral symmetry, polarization, emissivity, …

Elliptic flow:

- ➢ Initial positive v_2(proton) →positive v_2(dilepton) ?
  - ○ Sign of elliptic flow sensitive to phase transition ?

CBM physics goals: dileptons



HADES, Nature Phys. 15 (2019) 1040

Thermal excess radiation:

- ➢ ϱ-meson spectral function:
  - Strong in-medium broadening

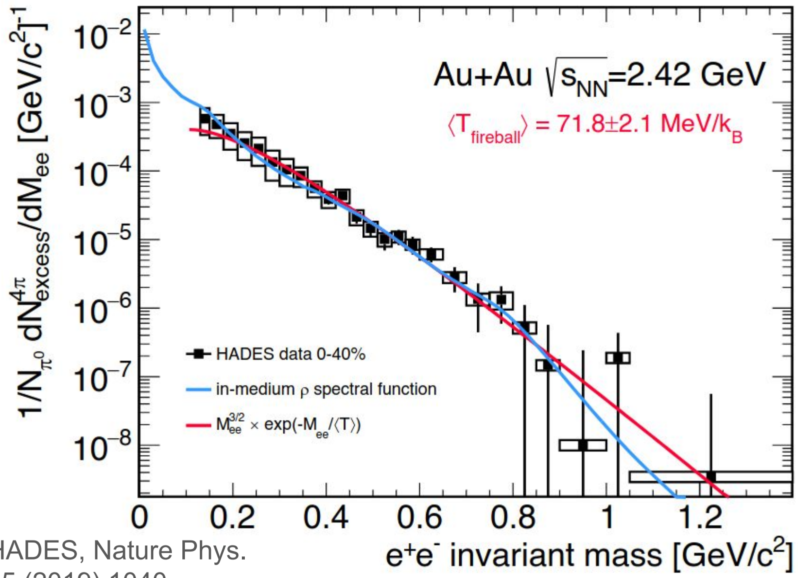
$$\frac{dN_{l+l-}}{d^4 d^4 x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^B(q_0, T) \overbrace{Im\, \Pi_{em}(M, q, T, \mu_B)}^{\text{In-medium spectral function}}$$

McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545

- ➢ Consistent description of in-medium spectral function from many body theory from SIS18 to RHIC, LHC energies
  - Baryonic effects crucial

Rapp and Wambach, Adv.Nucl.Phys. (2000) 25

CBM physics goals: dileptons



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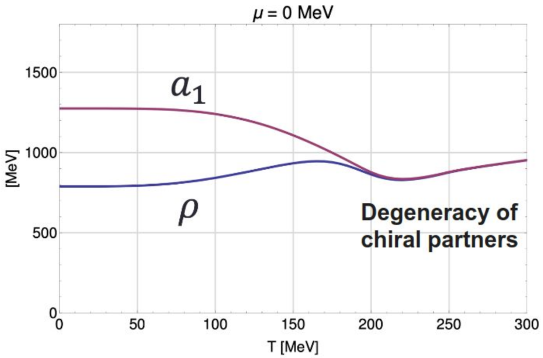
Chiral symmetry:

- ➢ Spontaneously broken in vacuum
- ➢ Restoration at finite T and high μ_B:
  - ○ Mixing of vector and axial-vector mesons

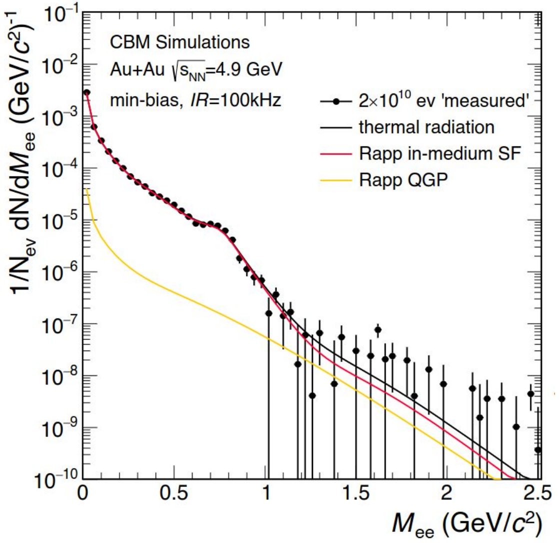


Jung et al., PRD 95, 036020 (2017)

Hohler and Rapp, PLB 731 (2014)

CBM performance: dileptons

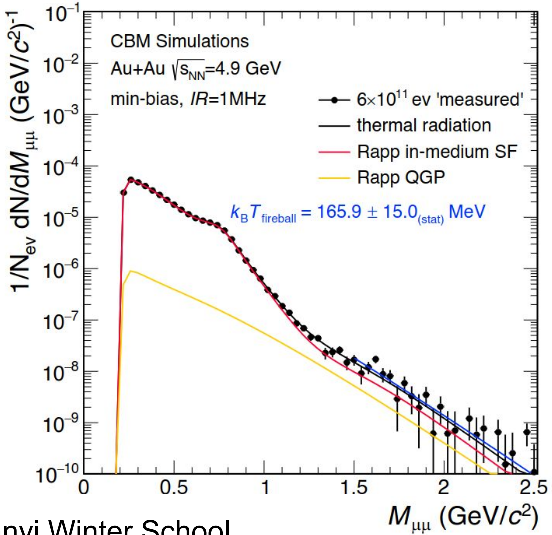
dielectrons



Dielectrons:

- ϱ-meson contribution dominates at low masses < 1 GeV/c^2
  - Measurement of fireball lifetime < 10% errors on $T_{fireball}$
  - Transport properties - electrical conductivity
- Excess yield in LMR
  - High precision to observe 1st order phase transition?

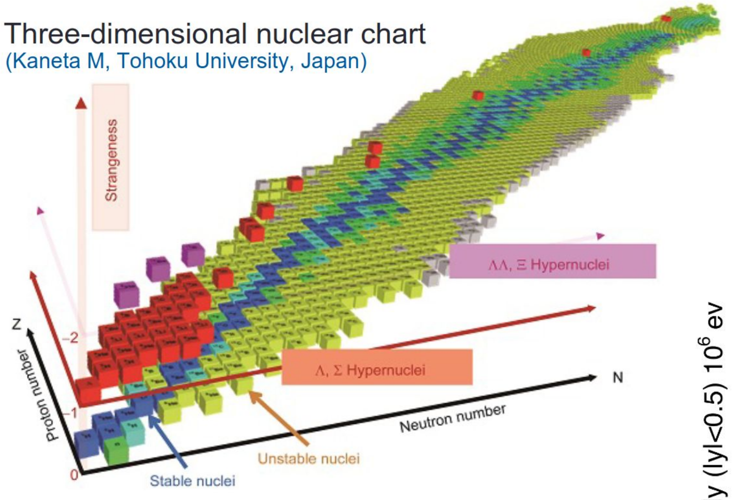
dimuons



Dielectrons/-muons:

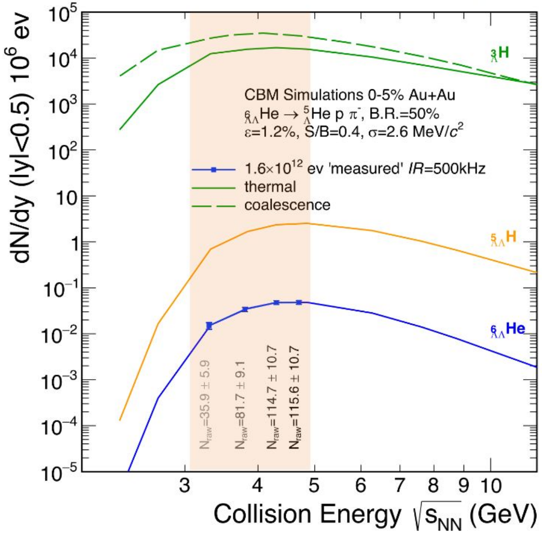
- Slope of invariant mass spectra
  - Flattening of the caloric curve (T vs. beam energy)
    - Evidence for phase transition

CBM performance: hypernuclei

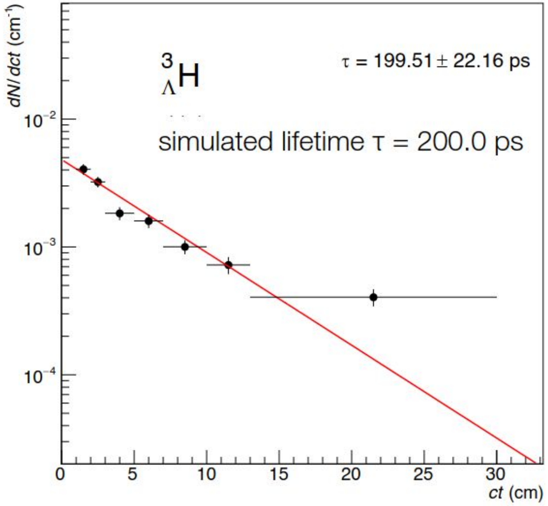


Extending nuclear chart in strangeness direction:

- ➢ Increasing baryon density: hypernuclei production
  - ○ Search for multi-strange hypernuclei
- ➢ Flow pattern
- ➢ Lifetime measurements



Lifetime measurement



Relation to neutron star physics:

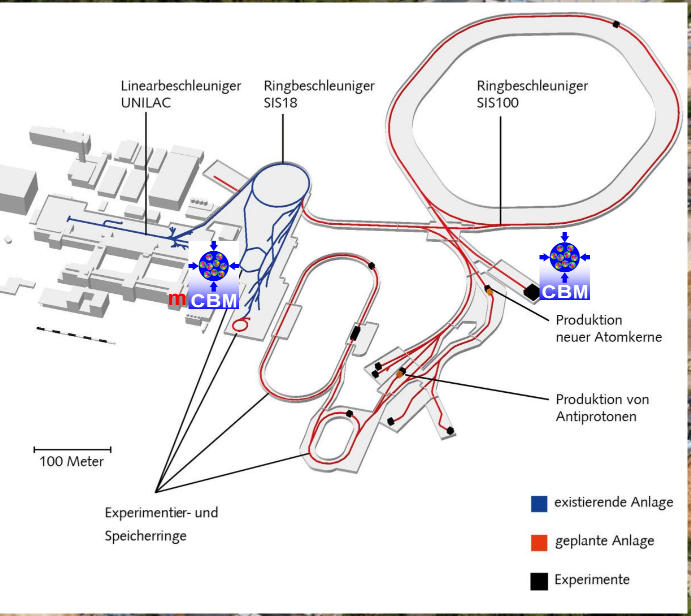
- ➢ Lifetime of hypernuclei sensitive to YN- and YY-interaction
  - ○ EoS of high density matter
- ➢ Explain mass vs. radius relation of neutron stars

D. Lonardoni et al. PRL114 (2015) 092301

Part II

Construction and preparation status of CBM

Darmstadt, Germany




Darmstadt, Germany
GSI
FAIR
Facility for Antiproton and Ion Research in Europe GmbH
Start of operation in 2028

CBM construction

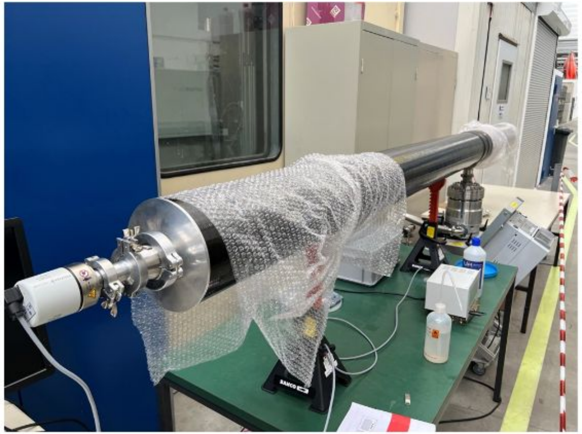
Recent achievements:

➢ CBM building (cave, control room, …) has been constructed, upstream platform installed

CBM construction

Recent achievements:

- ➢ CBM building (cave, control room, …) has been constructed, upstream platform installed
- ➢ First prototypes of the beam pipe are tested

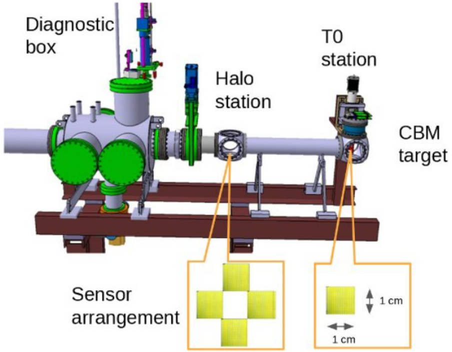


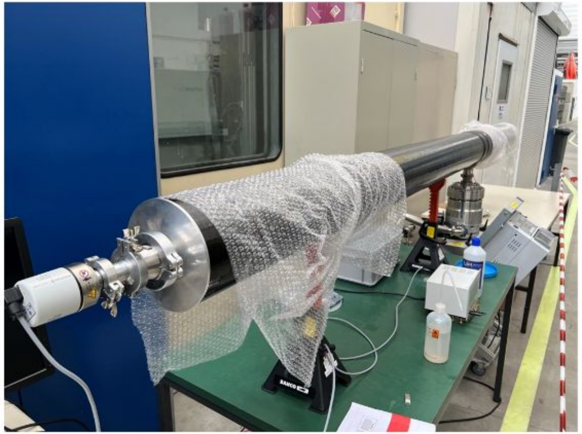
CBM construction

Recent achievements:

- ➢ CBM building (cave, control room, …) has been constructed, upstream platform installed
- ➢ First prototypes of the beam pipe are tested
- ➢ Technical design finalized for beam monitoring system

BMON

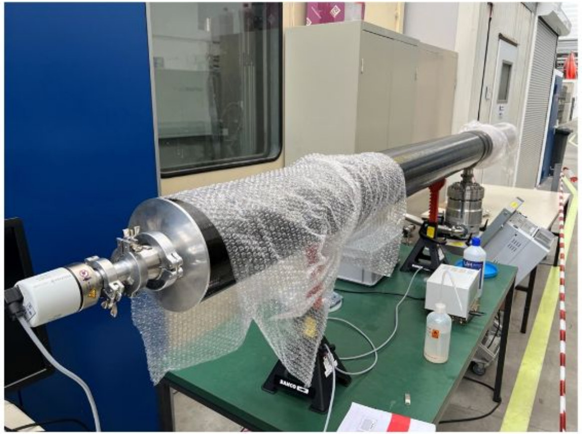


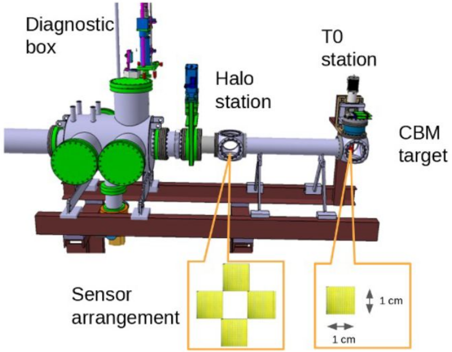


CBM construction

Recent achievements:

- ➢ CBM building (cave, control room, …) has been constructed, upstream platform installed
- ➢ First prototypes of the beam pipe are tested
- ➢ Technical design finalized for beam monitoring system
- ➢ Alternative solution to missing Russian components:
  - ○ Dipole-magnet (key element for tracking/PID)
    - ■ Offers by companies solicited
    - ■ Ongoing process of signing the contract





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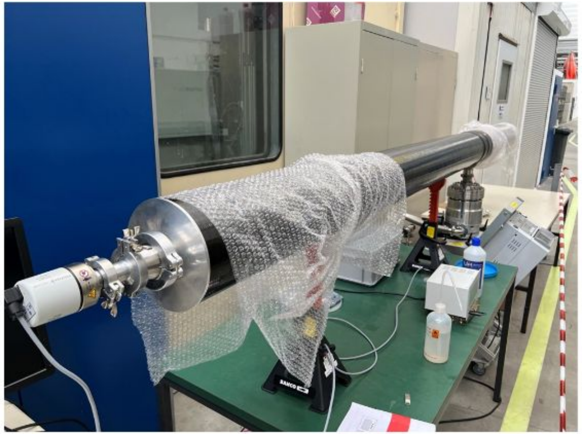
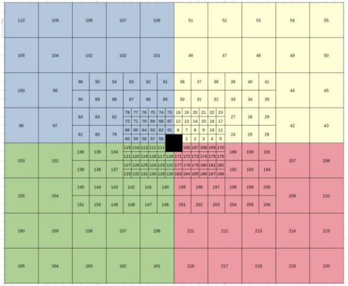
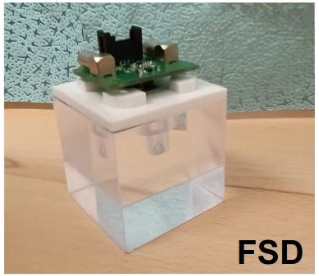
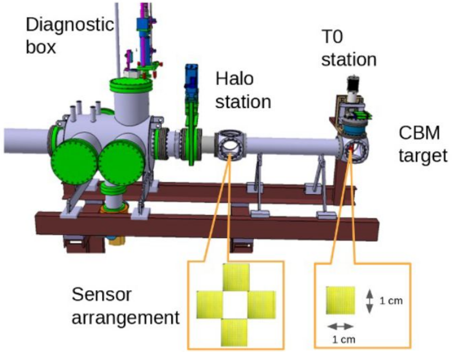
    - Ongoing process of signing the contract
  - New forward wall (FSD) based on HADES concept in preparation (first prototypes, software development)



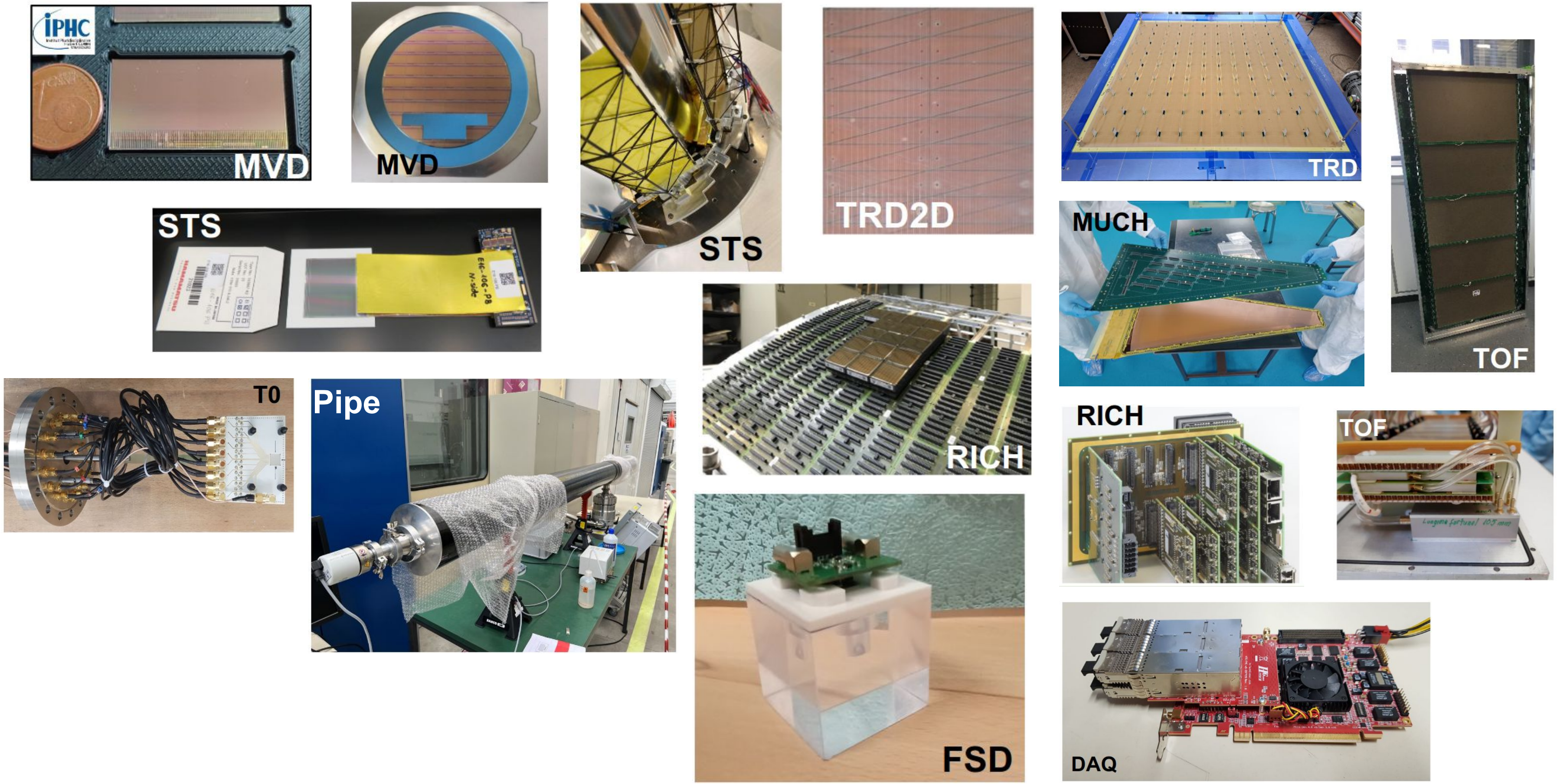
FSD Geant model



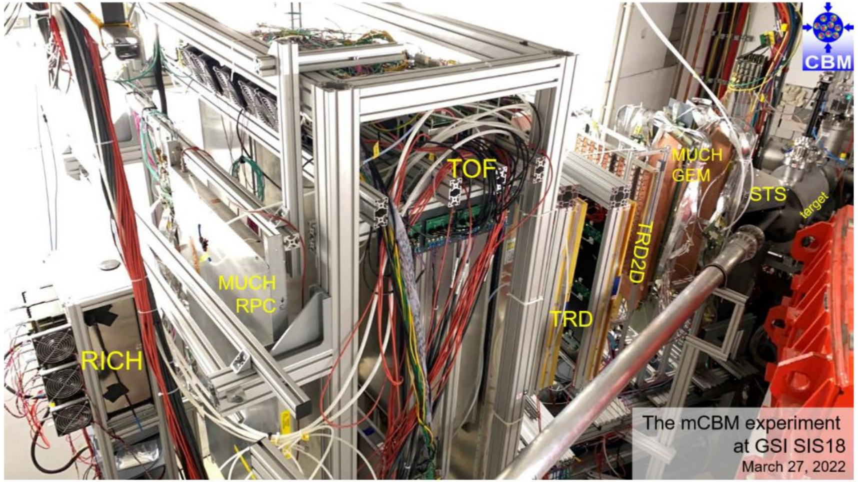


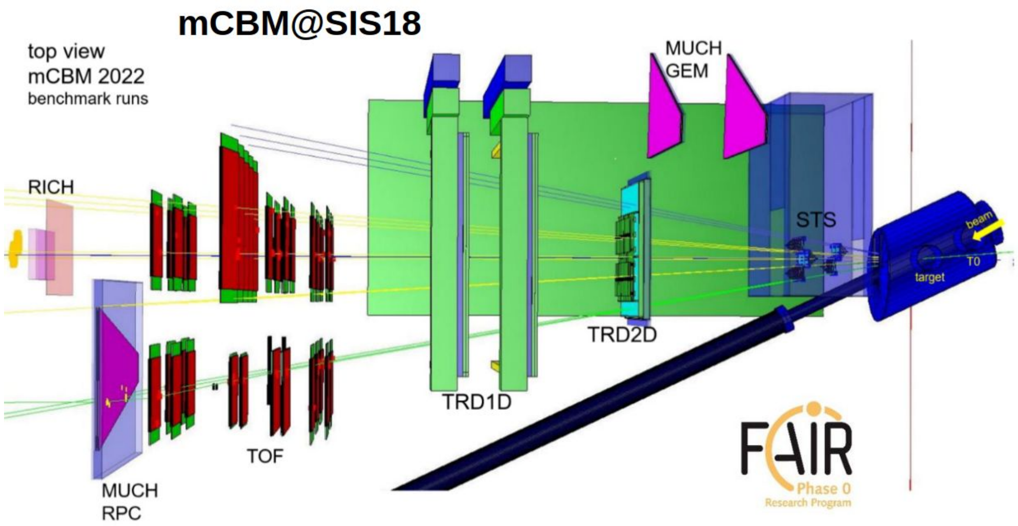


CBM construction - pre-series production started



The mCBM experiment at GSI / SIS18



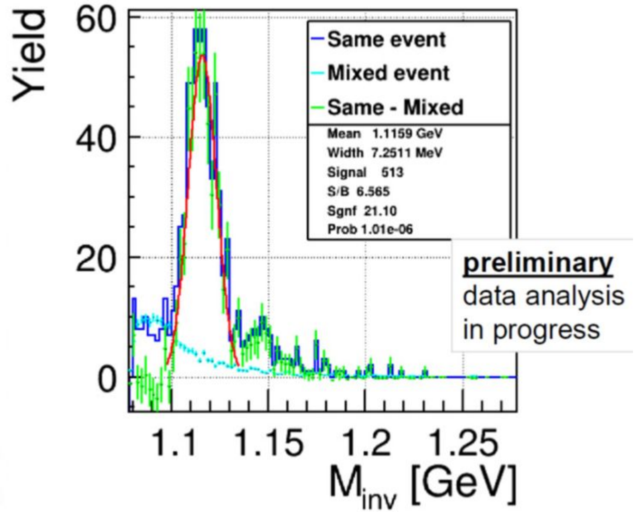


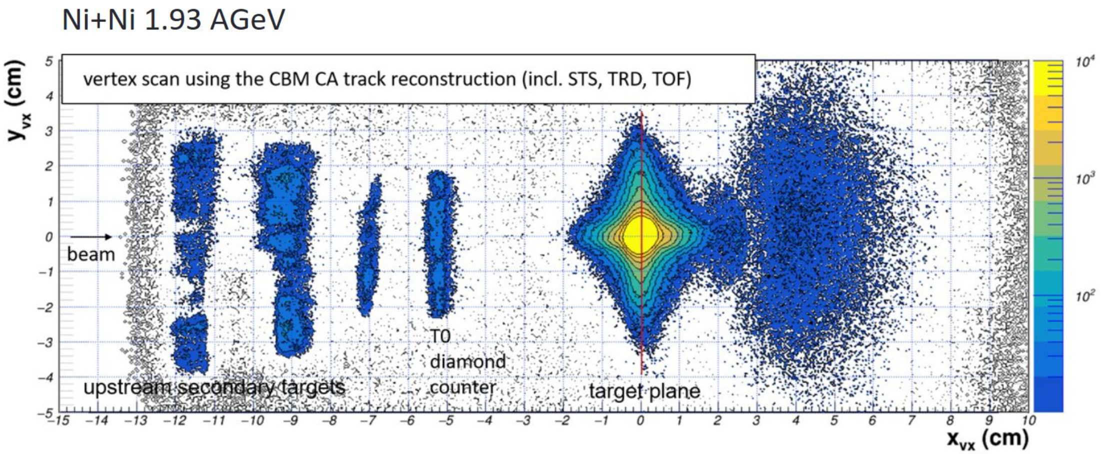
- ➢ Testing of the detector components:
  - ○ High rate tests ≲ 10 MHz collision rates
- ➢ Testing of the triggerless streaming read-out
- ➢ Verification of data acquisition
  - ○ Benchmark with Λ reconstruction
- ➢ Use mCBM data to validate online reconstruction and selection algorithms

The mCBM experiment at GSI / SIS18

Milestones reached with mCBM campaign in 2022:

- ➢ Stable operation over long periods
- ➢ Verification of the CBM read-out concept
- ➢ High rate validation of detector components
- ➢ Λ reconstruction in Ni+Ni@1.93AGeV (400-500kHz average collision rate, offline analysis)
- ➢ Demonstration of vertex reconstruction using CA tracker





mCBM in 2024-2025:

- ➢ Approved by GSI-PAC
- ➢ Preparations for upcoming beam times
- ➢ Λ excitation function in Au+Au & Ni+Ni
- ➢ Installation of new prototypes (e.g. FSD)
- ➢ Online reconstruction/selection

Summary: CBM facts

- **Rich physics program:**
  - Strangeness, EbE fluctuations, collective behavior, dileptons, hypernuclei, etc.
  - Extending of physics program with proton induced reactions
- **CBM preparations are progressing towards the SIS100 beams**
  - Finalization of detector design
  - CBM cave ready, platform installed
  - Pre-series production started
- Evaluation of ultimate supporting structures for detectors and beam pipe (additional background)
- **Performance studies from upcoming mCBM beamtimes using new prototypes**
- Final review →Start of series production (end of 2024/2025)
- CBM pre-commissioning: 2026-2028
- **Ready for data taking in 2028**

CBM overview

Facts ~~and Fictions~~

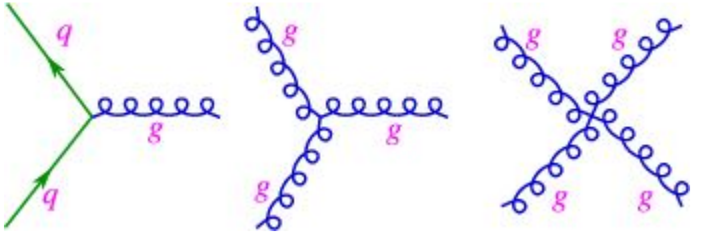
THANK YOU FOR YOUR ATTENTION!

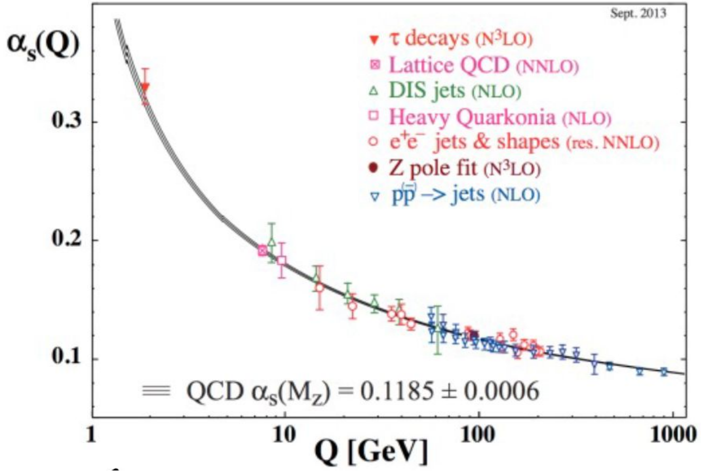
Extra luggage (back up slides)

Frédéric Julian Linz for the CBM Collaboration
Budapest, Hungary - 04.12.2023

Properties of Quantum Chromo Dynamics

main difference compared to QED





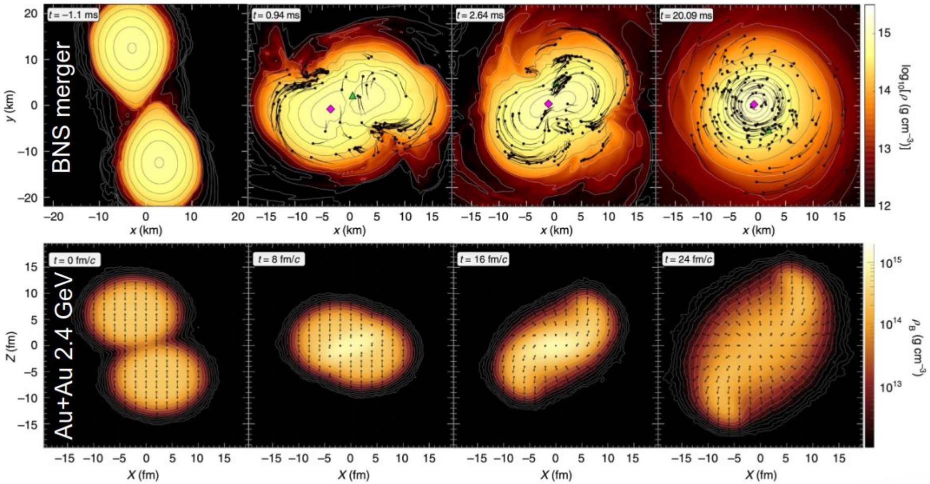
Microscopic consideration:

- ➢ Interaction of quarks and gluons which both carry color charge!
  - ○ self-interaction among gluons
- ➢ leads to a "running" coupling constant α_S: dependence on momentum transfer Q (or distance R)
- ➢ two distinct extremes:
  - (1) confinement of quarks and gluons in hadrons (large R, small Q)
  - (2) asymptotic freedom (small R, large Q) = hot and dense matter
- ➢ QCD Lagrangian:

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \sum_{\mathrm{u,d,s}} \bar{q}_a (i\gamma^\mu(\partial_\mu - igA_\mu) - m)_{ab} q_b$$

Can only be solved using perturbation theory for (2); in case of (1), effective Lagrangians, hadronic models, discretization via space-time lattice, …

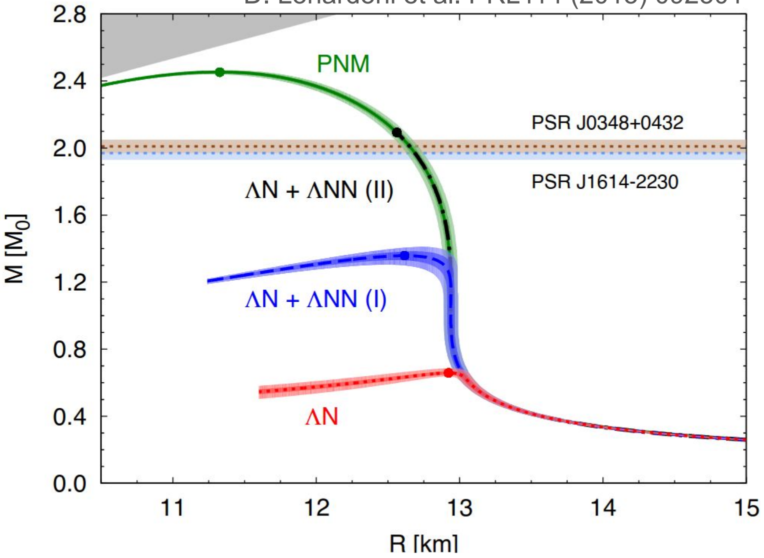
QCD phase diagram II



Neutron stars/neutron star mergers:

- ➢ Similar densities and temperatures in HIC and NSM
  - ○ Densities: $\rho/\rho_0 \approx 3$
  - ○ Temperature: T < 70 MeV (~10^{12}K)
- ➢ Observation of neutron stars, for instance mass-radius relation

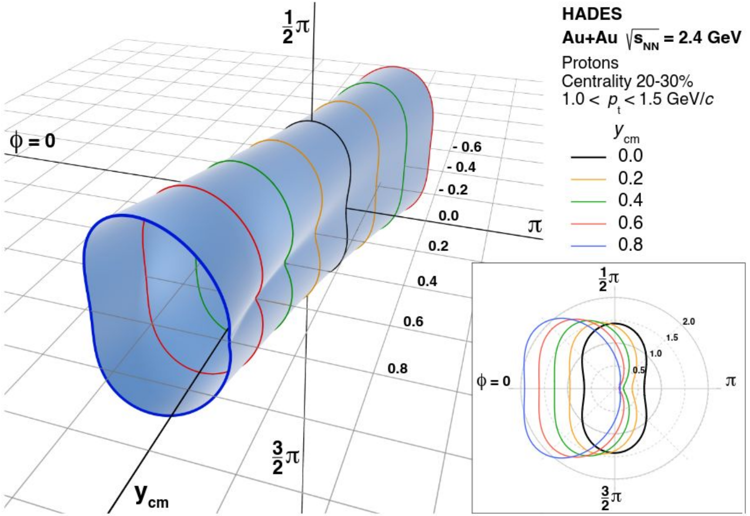
D. Lonardoni et al. PRL114 (2015) 092301



- ➢ Hyperons naturally appear at high densities
  - ○ Softening of the EoS →lower maximum mass predicted
- ➢ Hyperon-nucleon interaction play a fundamental role:
  - ○ 2-body and 3-body (YN and YNN) interactions are important to understand the inner structure of neutron stars
- ➢ Stronger constraints on the hyperon-nucleon force needed
  - ○ CBM can contribute here!

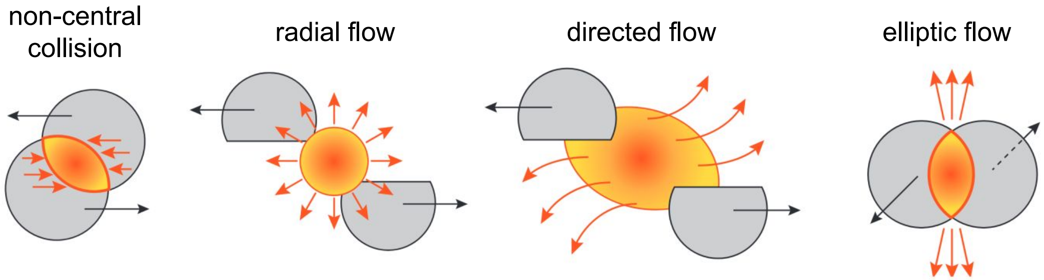
Collective flow coefficients

HADES, *Phys.Rev.Lett.* 125 (2020) 262301



➢ Measure harmonics of azimuthal angular distribution w.r.t. reaction plane: $\Delta\phi = \phi - \Psi_{RP}$

$$\frac{1}{N_{\text{all}}}\frac{dN}{d\Delta\phi} = \frac{1}{2\pi}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n\Delta\phi)\right)$$



➢ v_3: sensitivity to the EoS of the hadronic medium

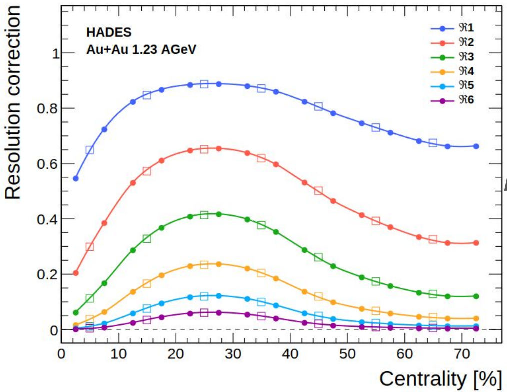
P. Hillmann, J. Steinheimer, and M. Bleicher, J. Phys. G45, 085101 (2018)
P. Hillmann et al., J. Phys. G47, 055101 (2020).

➢ v_4: constraints to nuclear mean field at high bayron densities

P. Danielewicz, Nucl. Phys. A673, 375 (2000)

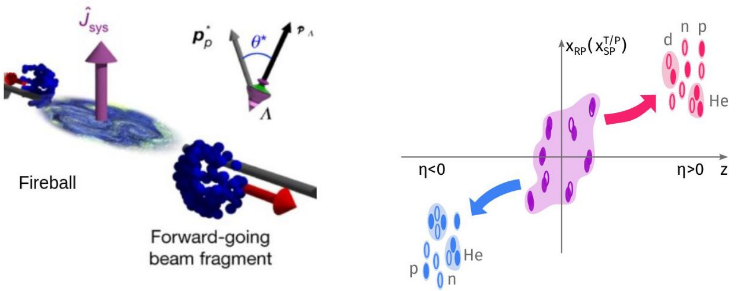
➢ Constraints to theoretical descriptions:
$v_4(p_t)/v_2^2(p_t)$ = ½ (ideal fluid)

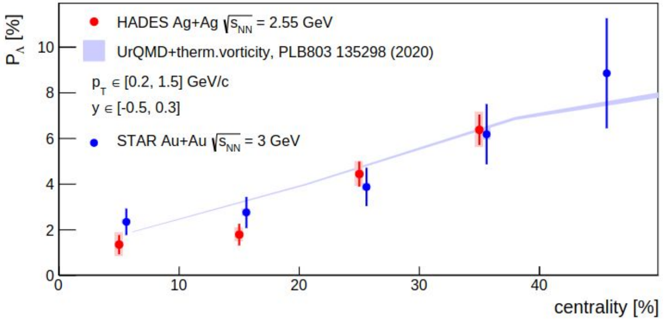
N. Borghini and J.-Y. Ollitrault, Phys. Lett. B642, 227 (2006)



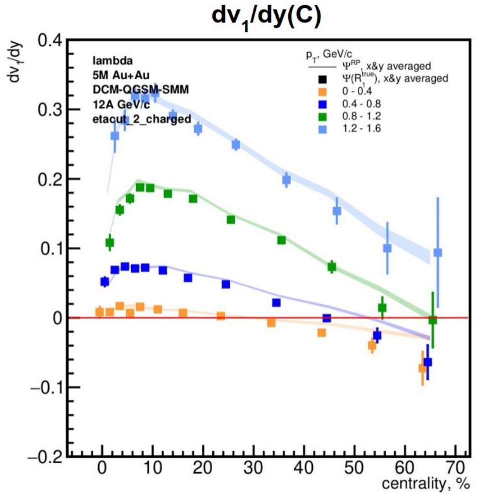
HADES, *Phys.Rev.Lett.* 125 (2020) 262301

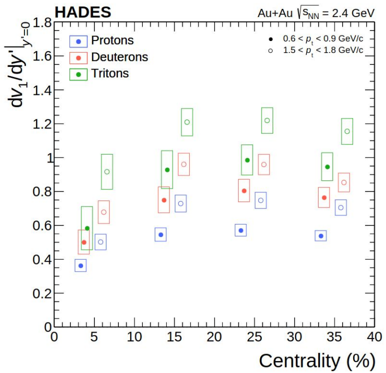
Connection between spin polarization & directed flow





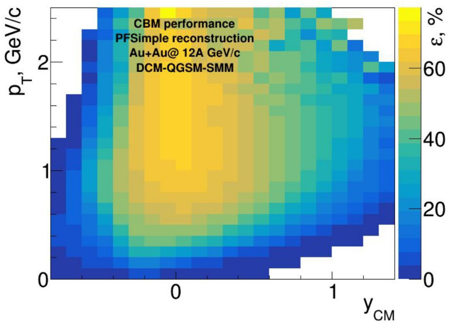
Different centrality dependence!





HADES, *Eur.Phys.J.A* 59 (2023) 4, 80

High Λ reconstruction efficiency



Large statistics ⇒ precise measurements multi-differential!