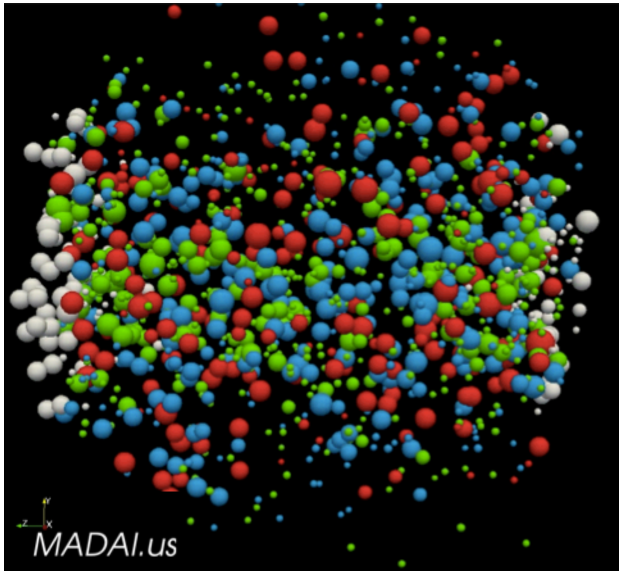
Strong interaction: Future projects in heavy-ion collisions



Tetyana Galatyuk
Technische Universität Darmstadt /
GSI Helmholtzzentrum für Schwerionenforschung

Research topic: nuclear and quark-gluon matter

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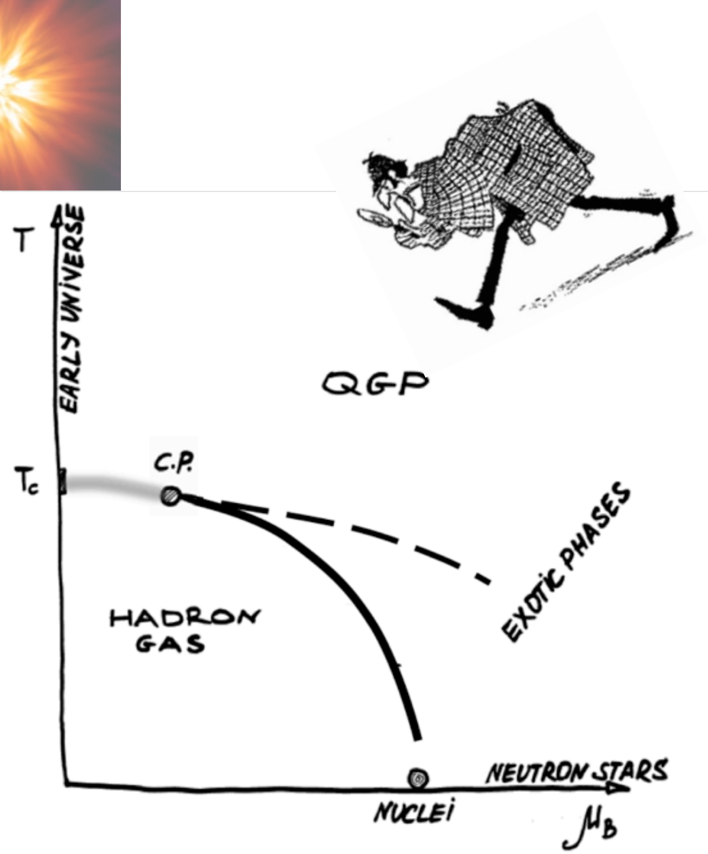
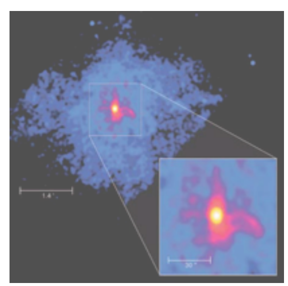
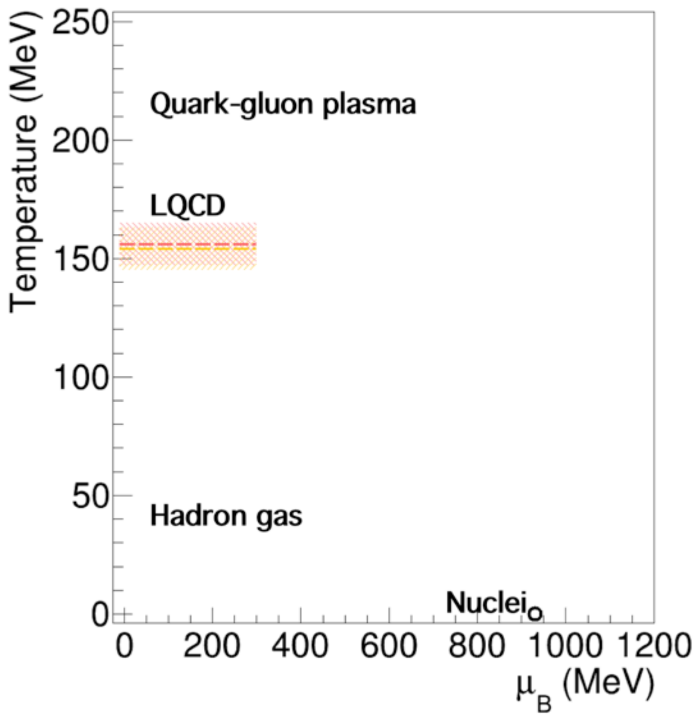


Fundamental questions addressed:

- What are the properties of matter under extreme temperatures and densities?
- Where are the phase boundaries located?
- Is there a critical point?
- Where are the limits of hadronic existence?



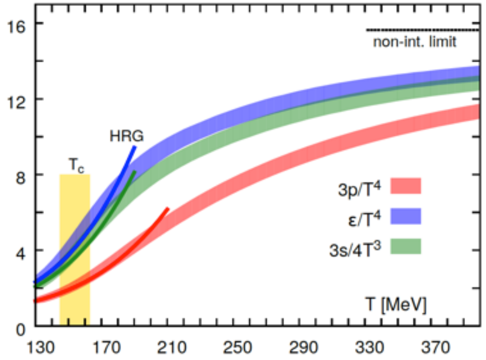
Theoretical guidance



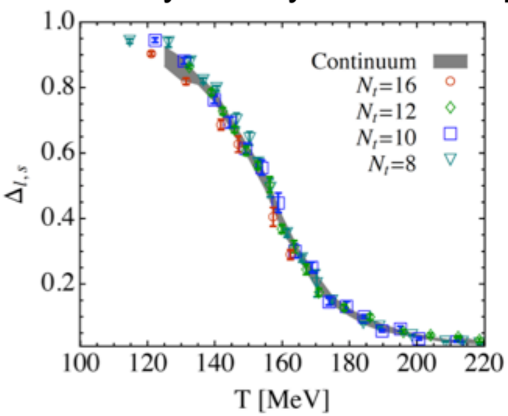
Vanishing μ_B, high T (Lattice QCD)

- Crossover transition
- ε_c~1 GeV/fm^3, T_c~155 MeV

Deconfinement transition [2]

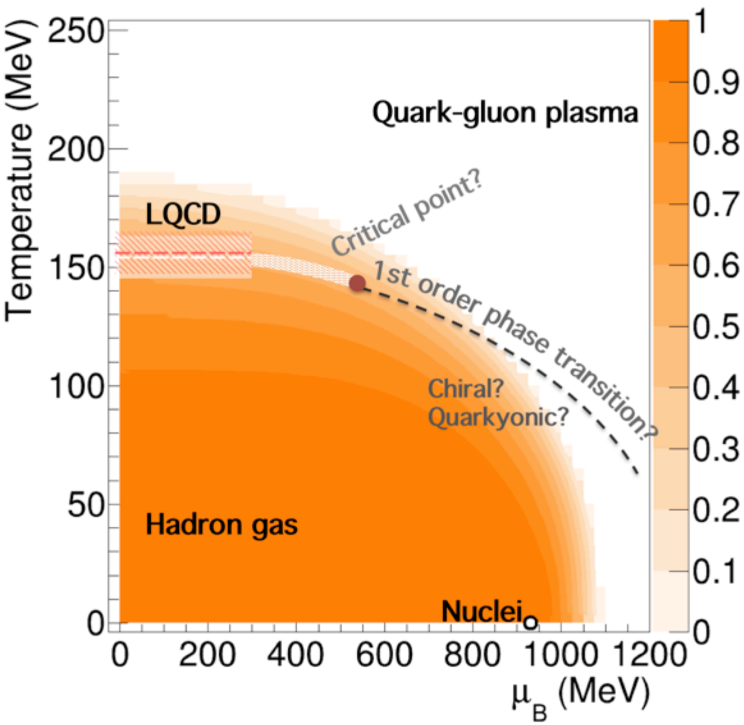


Chiral symmetry restoration [3]



[1] O. Kaczmarek et al., PRD 83 (2011) 014504
[2] S. Borsanyi et al. [Wuppertal-Budapest Coll.], JHEP 1009 (2010) 073
[3] A. Bazavov et al. [Hot QCD Coll.], PRD90 (2014) 094503

Theoretical guidance



$\frac{\langle \bar{q}q \rangle_{T,\mu_B}}{\langle \bar{q}q \rangle_{T=0,\mu_B=0}}$ B.J. Schaefer et al.., PRD 76 (2007) 074023

Vanishing μ_B, high T (Lattice QCD)

- Crossover transition
- ε_c~1 GeV/fm^3, T_c~155 MeV

Large μ_B, moderate T (effective, Lattice QCD inspired models)

- 1st order transition
- QCD critical point
- Melting of the condensate (order parameter $\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{q}_L q_R + \bar{q}_R q_L|0\rangle \neq 0$)

Searching for landmarks of the QCD matter phase diagram

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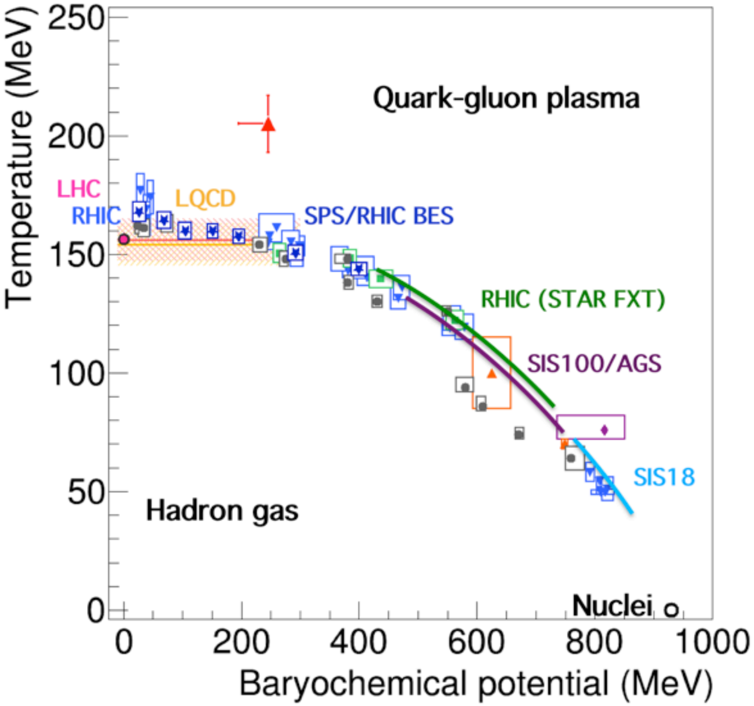


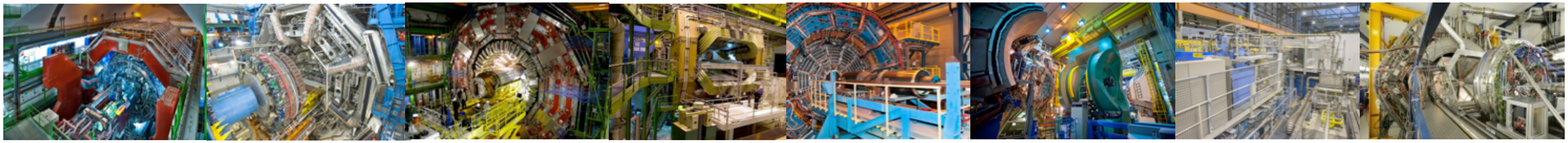
Experimental approach:

- Recreate the conditions of the deconfinement transition in the lab.
- Probe with highest precision different regions of the QCD matter phase diagram

Observables:

- Flavor production (multi-strange, charm)
- Emissivity of matter (dileptons)
- Higher moments of e-b-e multiplicities (B, S, Q)

ALICE CMS ATLAS LHCb STAR PHENIX NA-61 HADES



Flavor production

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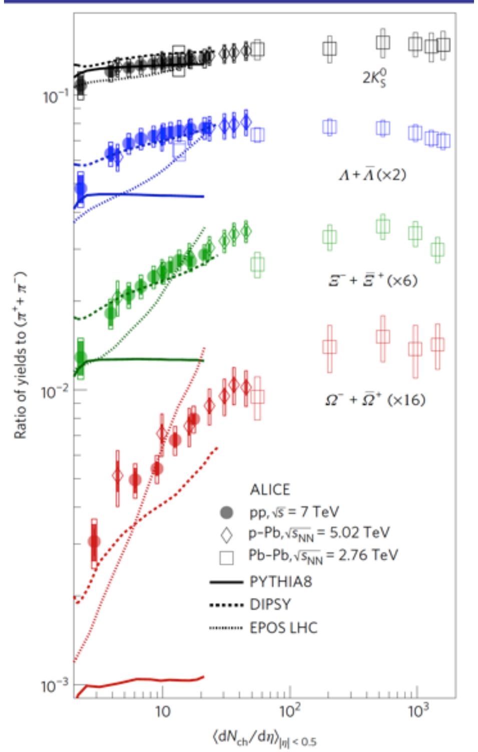
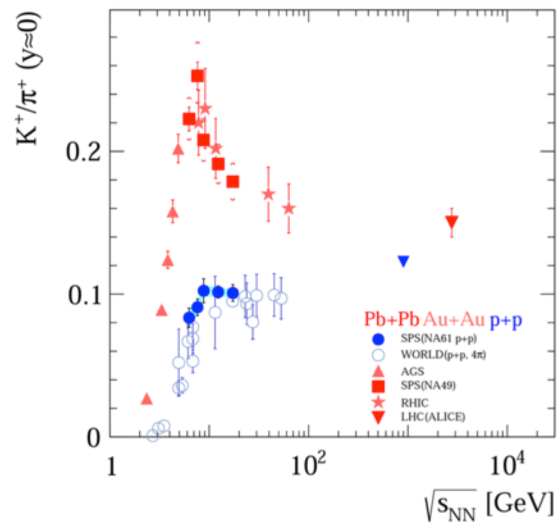
ALICE Collab.,

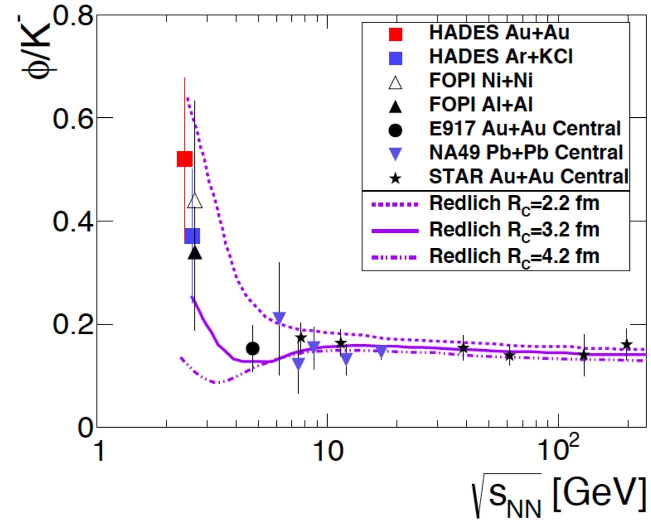
NATURE PHYSICS DOI: 10.1038/NPHYS4111



NA49 Collab., PRC 77 (2008) 024903



HADES Collab., arXiv:1703.08418v1



- An impressive set of data which spans strangeness production from the **sub-threshold** to the **grand-canonical** saturation regime
- **However:** low-energy data are missing for less abundant particles (Ξ, Ω)!

Electromagnetic probes of hot and dense QCD matter

Spontaneously broken in the vacuum

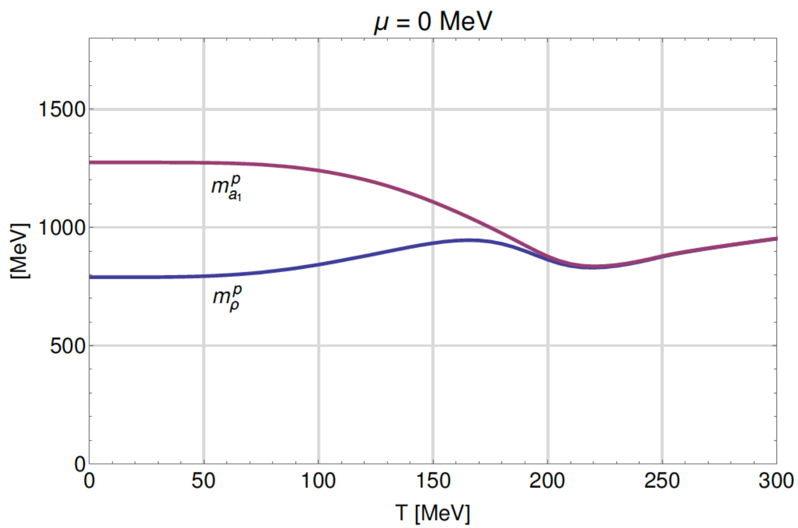
$$\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{q}_L q_R + \bar{q}_R q_L|0\rangle \neq 0$$

Restoration at **finite T** and **μ_B** manifests itself through mixing of vector and axial-vector correlators

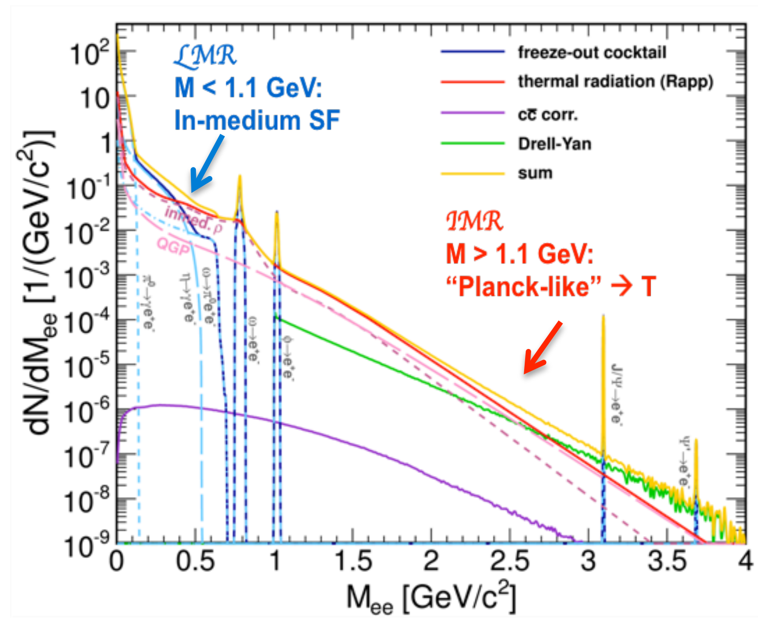
The vector correlator is directly accessible in HIC

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

Degeneracy of hadronic chiral partners

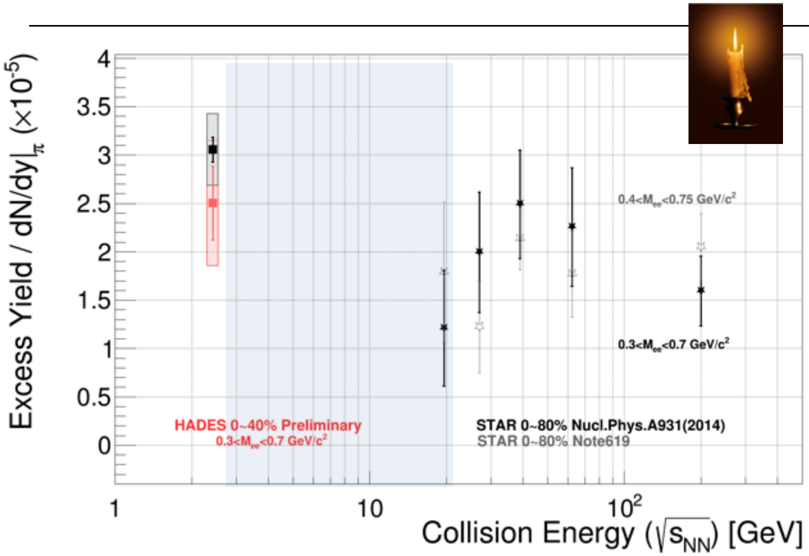


A. Tripolt et al., D89, 034010, 2014



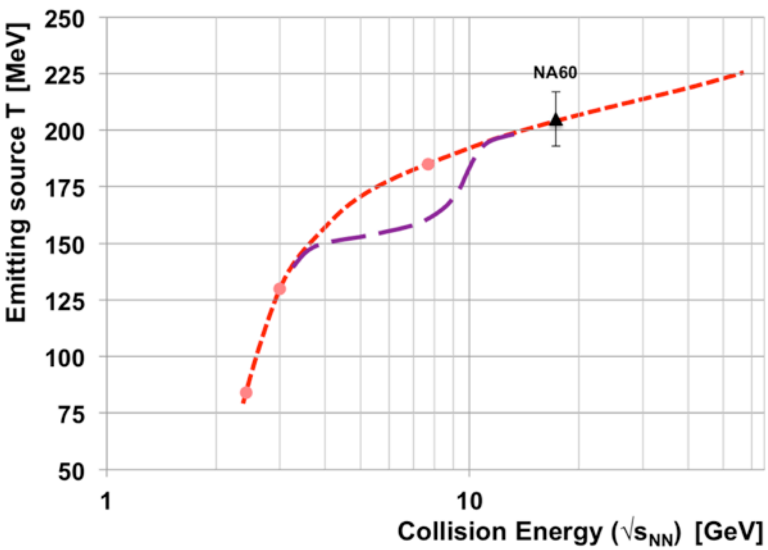
CBM Collab., Eur. Phys. J. A, 53 3 (2017) 60

Mapping QCD phase diagram with dileptons



- Yield in low-mass window tracks fireball lifetime
  - Measure excitation function of ρ spectral function
  - Search for **anomalous fireball lifetime** around phase transition & CP

  → **No measurements $\sqrt{s_{NN}}$= 2 – 17.2 GeV**



- Intermediate mass slope measures the emitting source temperature (true, no blue shift)
  - Measure T_{slope} (note, $T_{slope} < T_{initia}$) **"caloric curve"**
  - Plateau around onset of deconfinement?
    see e.g. M. D'Agostino et al. NPA 749 (2005) 5533

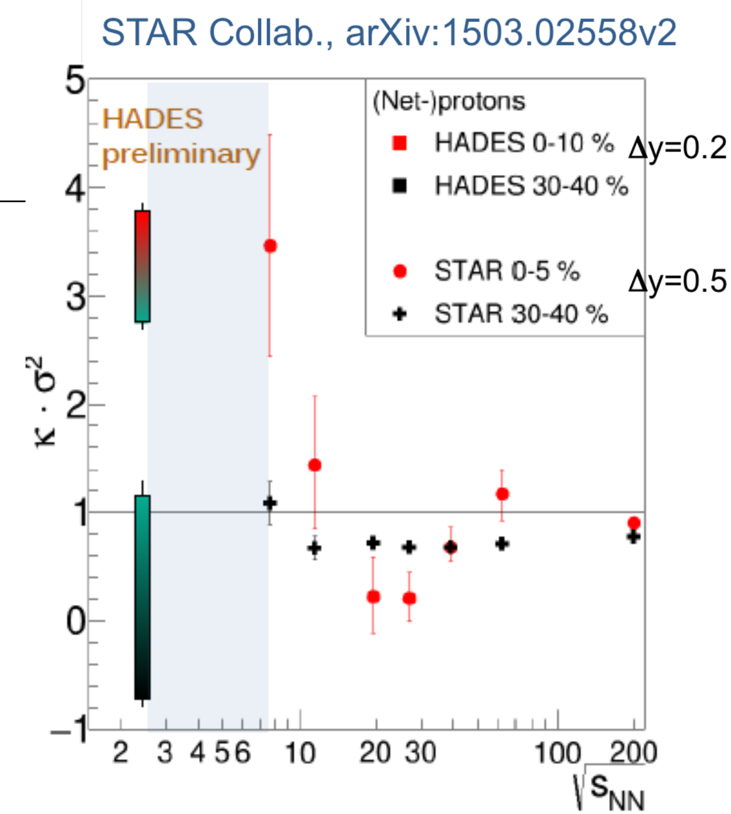
  → **The only NA60 results!**
  NA60 Collab., AIP Conf.Proc. 1322 (2010) 1

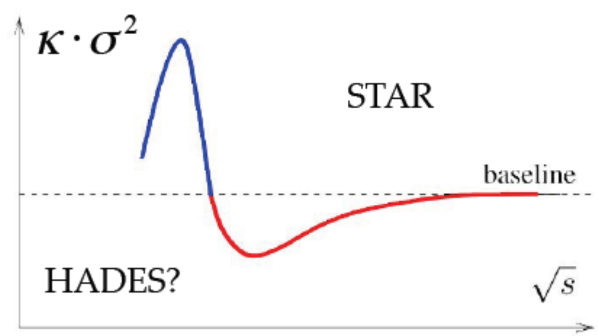
Fluctuations probe features of QCD phase diagram

Crossing features of the QCD phase-diagram (phase boundaries, CEP) is expected to result in:

- Diverging susceptibilities and correlation length
- „Extra“ fluctuations of conserved quantities (e.g. baryon nb, charge, strangeness)
- Observable discontinuities of the higher moments of particle number distributions, visible e.g. in a beam energy scan

STAR Collab., arXiv:1503.02558v2





see e.g. B. Friman et al, EPJC 71 (2011) 1694

M. Stephanov, Phys. Rev. Lett. 107 (2011) 052301

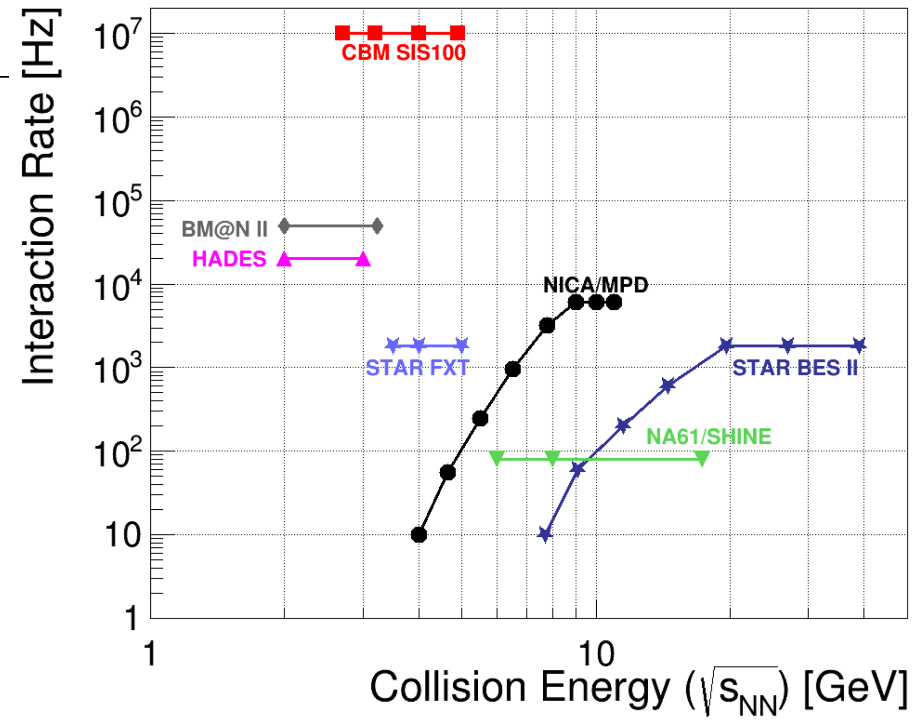
Searching for landmarks of the QCD matter phase diagram

Program needs high precision data!

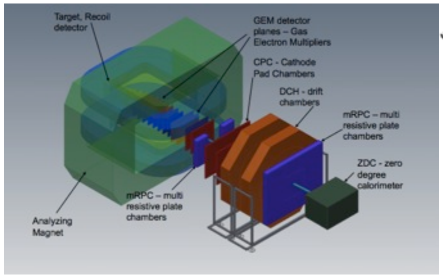
Colliders not competitive to fixed-target experiments in terms of interaction rate
→ Rare probes difficult to access

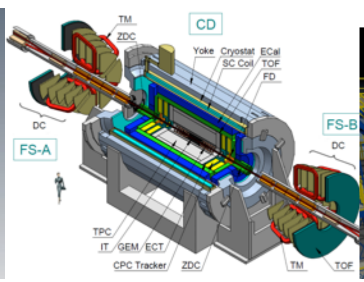
CBM will play play **a unique role** in the exploration of the QCD phase diagram in the region of high net-baryon densities!

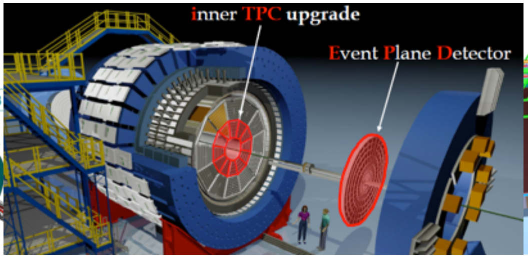
CBM Collab.,
EPJA, 53 3 (2017) 60

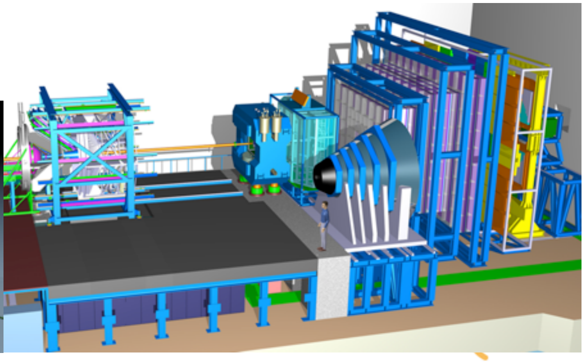


2017 – BM@N **2019 – MPD** **2019 – 2020 STAR BESII + FXT** **2025 – CBM**



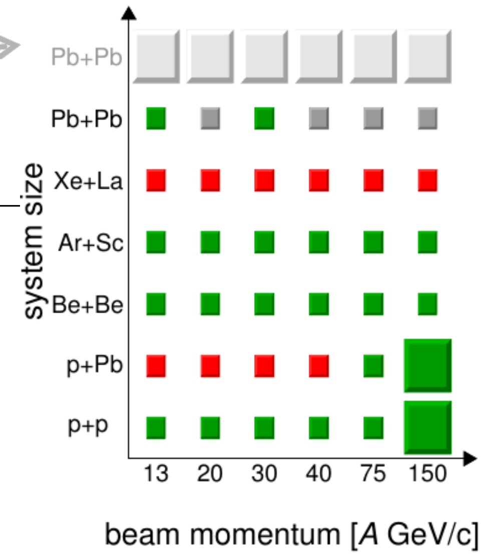






NA61/SHINE 2020+ at SPS

https://cds.cern.ch/record/2222876?ln=en (see Section 7 for details)



Physics program

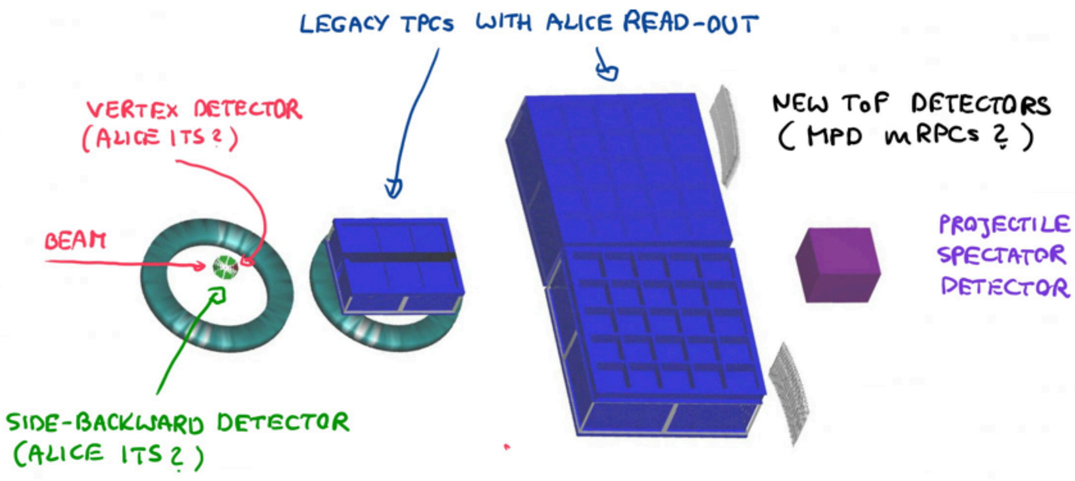
- **Strong Interactions**: onset of deconfinement and search for critical point
- **Neutrinos**: hadron production for T2K and FERMILAB neutrino beams
- **Cosmic-Rays**: hadron and resonances production in π^-+C interactions to understand cosmic ray showers

- **Strong Interactions**:
  - Open charm and multi-strange hadron production → statistical vs dynamical models
  - Event-by-event fluctuations of conserved quantum numbers

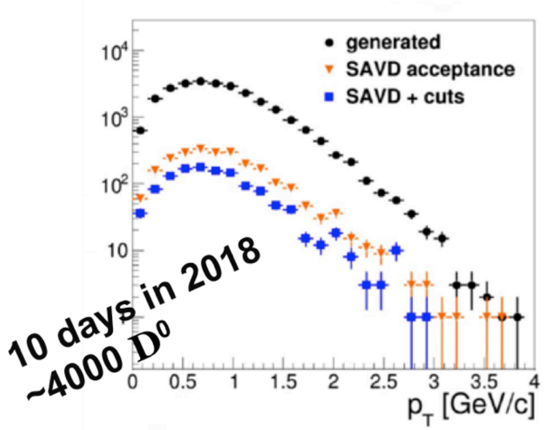
- **Neutrinos**: measurements for DUNE and HyperK experiments with proton beam at 20 – 120 GeV

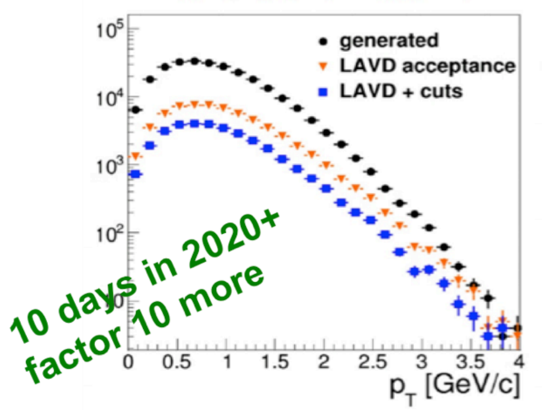
NA61/SHINE 2020+ detector upgrades

The measurements require major detector upgrades



D^0 reconstruction
Pb+Pb 150*A* GeV





- Increase event rate from 100 Hz to 1kHz
- Increase acceptance of vertex detector from total surface of 32 cm^2 to at least 240 cm^2
- Precise tracking along DUNE, HyperK targets

Hope to profit from developments for ALICE, CBM, MPD

NA61/SHINE 2020+

The measurements require major beams upgrades

- Beams:
  - Protons at 20–120 GeV/c
  - Pb ions at 13A–158A GeV/c
- Improved beam quality mostly at low energies secondary beams
  - Beam transverse size < 8 mm
  - Beam slope < 200 μrad
- Beam intensity ≈ 10^6 Pb ions/spill (10 s)
  - Upgrade of the H2/NA61 radiation protection
- Reduced beam intensity oscillation on NA61 target during the spill to < 10%

Hope for the support from CERN

marek.gazdzicki@cern.ch

Plan to submit a first document on NA61/SHINE 2020+ to the CERN SPSC in September 2017

MANY THANKS TO NA61/SHINE 2020 TEAM FROM
BERGEN, FRANKFURT, KATOWICE, KRAKOW, MOSCOW
ST. PETERSBURG, WARSAW ET AL.

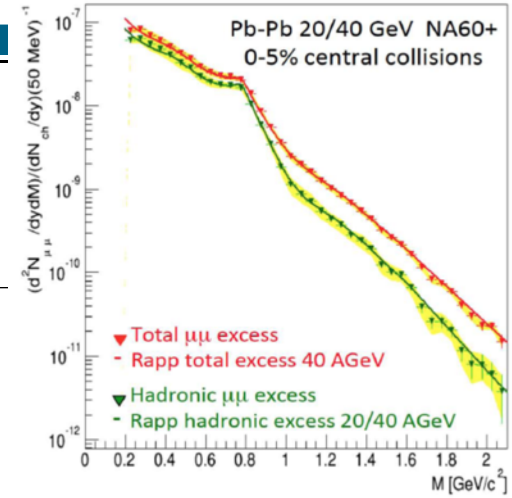
NA60+ at SPS

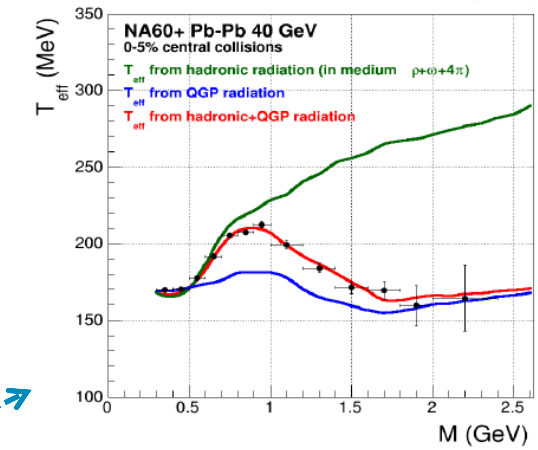
https://arxiv.org/abs/1602.04120 (see Ch.5 for details)

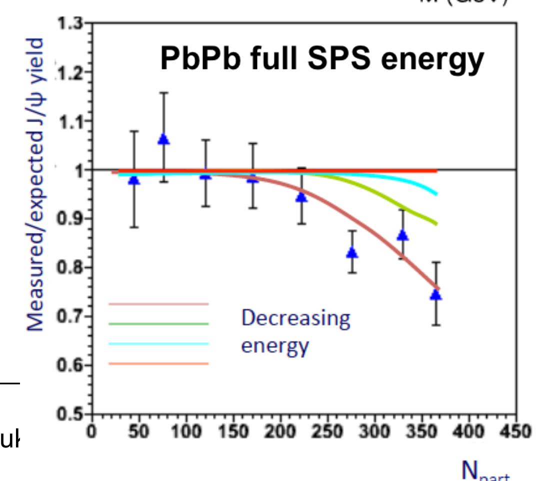
Scientific case: "New precision measurements of dimuon production via a beam energy scan ($\sqrt{s_{NN}}$ ~ 4.5 –17.3 GeV) with a dedicated experimental set-up

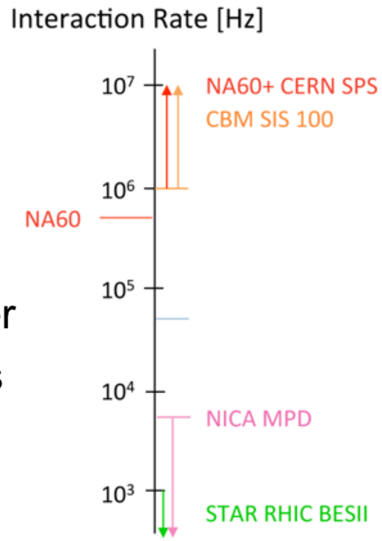
- Chiral symmetry restoration
  - ρ spectral function (rely on theory)
  - ρ-a1 (vector – axialvector mixing) – direct probe
- Onset of deconfinement and order of transition
  - T of thermal dileptons (M > 1.5 GeV/c^2)
  - T_{eff} of thermal dileptons (p_t spectra for M bins)

- Identify thresholds for J/ψ suppression
- Open charm semi-muonic decays D→μ^+X





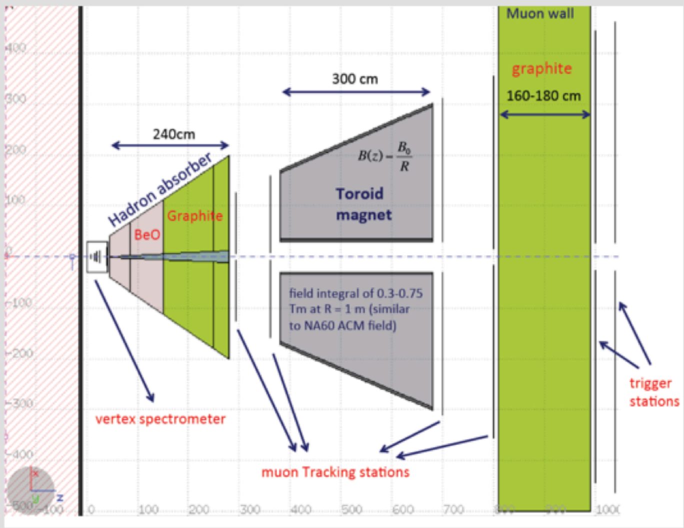




NA60+ at SPS

Described in detail in Ch.5 of the document https://arxiv.org/abs/1602.04120

- **NA60+ layout close to NA60:**
  → muon measurement with tracking in front of and behind hadron absorber
- **CERN SPS:** wide μ_B coverage of phase diagram and high interaction rates
- 2 weeks running (per energy) at 10^7 Pb/s (5 s burst)
  → increase in statistics over NA60 by a factor ≈50-100



Possible detector strategy

- Vertex spectrometer: Monolithic active pixel sensors
  - Low material budget
  - Read-out speed might be limited (~1MHz needed)
  - Fluences~ 10^{14}neq/cm^2
- Hadron absorber (BeO-graphite sections)
- Muon spectrometer
  - GEM with ~200 μm space resolution
  - Toroid magnet (BL=0.75 Tm at r = 1m)
- Trigger

NA60+ at SPS: Timeline

Goal → installation of the experiment during LHC run-3

Requirements:

- Location for a possible installation
- Beam intensities of ~10^7 ions/s are mandatory (assuming ~5 s bursts)
- Few week periods with ion beams from ~20 GeV to top SPS
- Corresponding reference measurements with proton beam (~5×10^8 p/s)

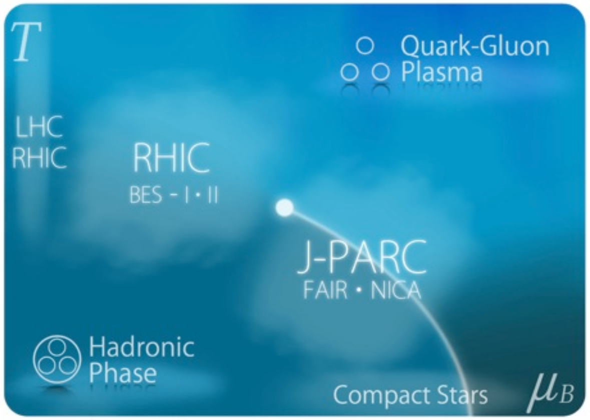
Timeline still being discussed

- No explicit involvement of funding agencies up to now
- Finalization of realistic detailed layout is a (top) priority! (MAPS, toroid magnet, …)
- Layout for all energies of beam energy scan (absorber size, position of the vertex detector in z)
- Formation of an **international Collaboration!**

→ Participation of groups from Germany would have a significant impact on the proposal

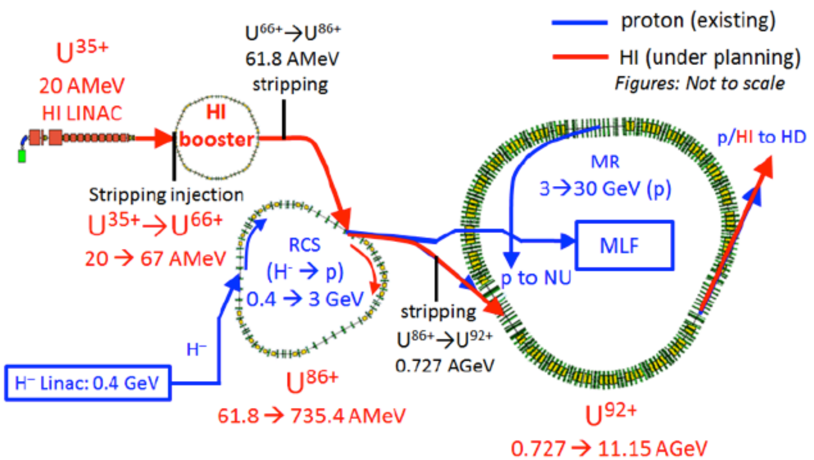
J-PARC-HI

https://j-parc.jp/researcher/Hadron/en/pac_1607/pdf/LoI_2016-16.pdf



Scientific case: "Studies of QCD phase structures in high density regime (5-10ρ_0) with world's highest intensity HI beams"

- $\sqrt{s_{NN}}$ = 2 – 6.2 GeV (U^{92+})
- 4×10^{11} ions/spill (~ 4.5 sec)



Possible heavy-ion acceleration scheme to adapt in the existing J-PARC facilities

- Existing 3 GeV and 50 GeV synchrotrons

→ HI injector and injection section in RCS are necessary

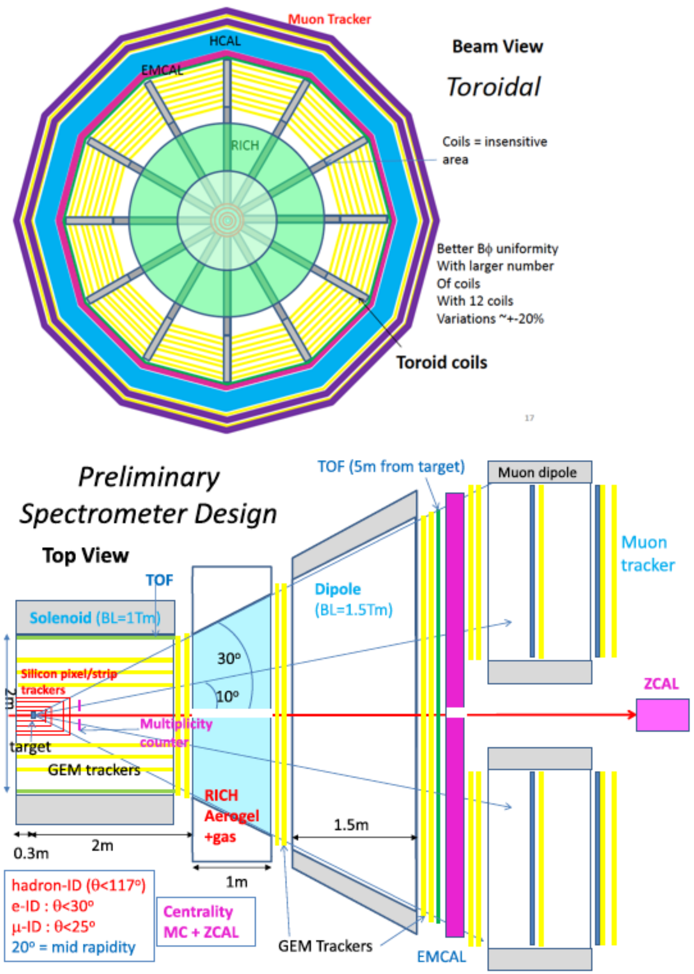
- Proven performance for high-intensity proton beam for RCS and MR
  - Slowly extracted proton beams 2.5×10^{13}/cycle → 1.3×10^{14} /cycle (2017)

→ Parallel RCS operations for MR(HI) and MLF(proton) are a must

- Limited freedom in RCS for operation parameters (magnets, RF cavity…)

→ The injection booster is being designed to fit to RCS operations

J-PARC-HI Conceptual design



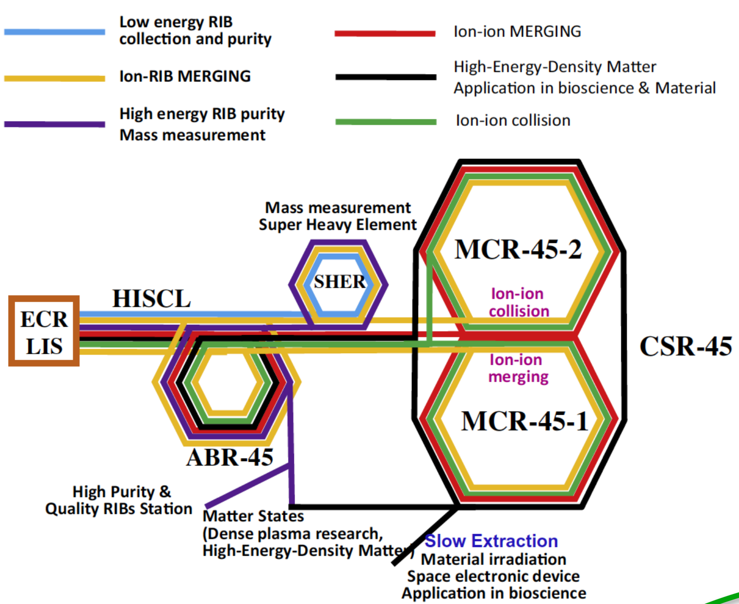
Near-4π HI spectrometer with Toroidal magnet setup to measure dileptons, hadrons and photons

- High rate capability
  - Fast detectors (silicon trackers, GEM trackers, …)
  - Fast DAQ (triggerless DAQ >= 100kHz)
- High granularity
  - (at 1m from the target, θ<2°, 10% occupancy)
- Large acceptance
- Field free region for RICH close to the target

Project leader: Hiroyuki Sako
sako@post.j-parc.jp

High-Intensity Heavy Ion Accelerator Facility

NIMP Research B 317 (2013) 263–265



Machine	Ion	Energy	Intensity
MCR-45-1(2)	U^{34+}	1.2 GeV/u	$1.0–5.0 \times 10^{11}$ ppp
	U^{76+}	3.4 GeV/u	$0.2–1.0 \times 10^{11}$ ppp
	U^{92+}	4.4 GeV/u	$0.2–1.0 \times 10^{11}$ ppp

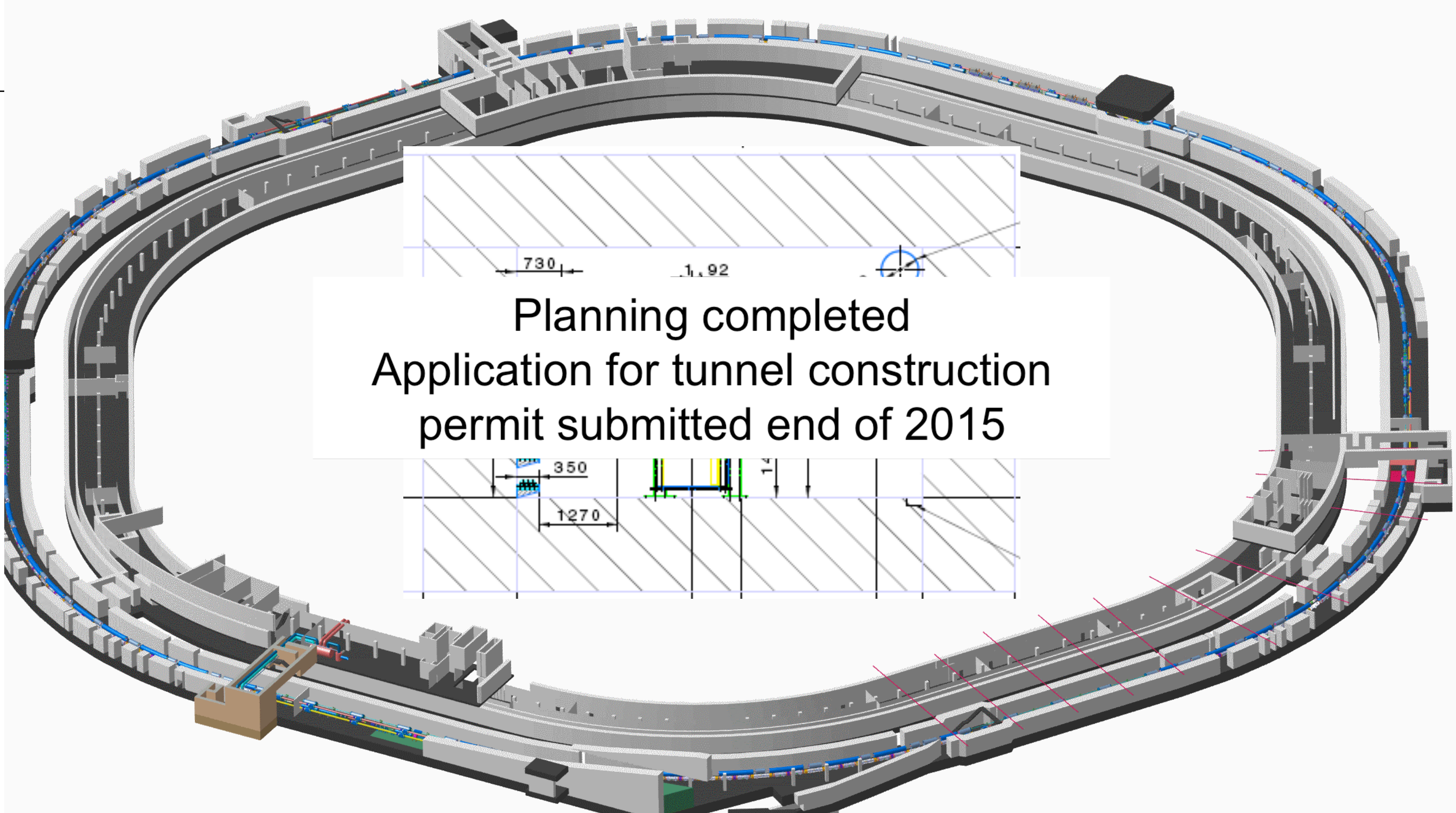
One of 16 large-scale research facilities proposed in China in order to boost basic science, now under design optimization and technical R&D

- Scientific drivers:
  - Nuclear Physics
  - Nuclear Astrophysics
  - **Heavy-ion Applications**

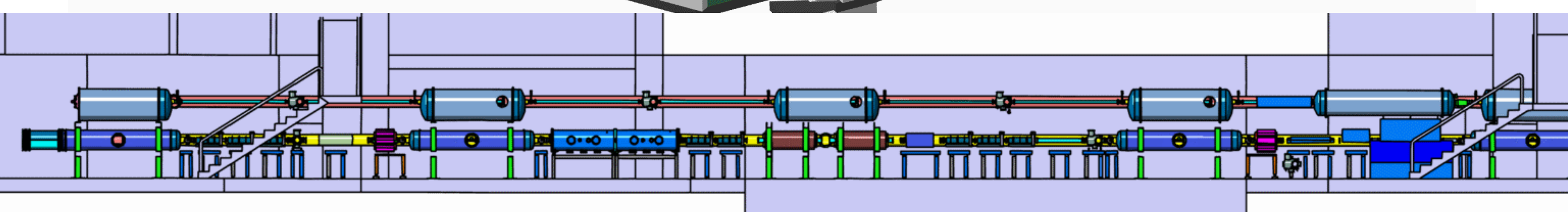
- Proposed to IMP in 2009
- Approved by China Government Dec. 2015
- Construction starts – end of 2017

Tunnel for SIS100/300+

SCHE
SITÄT
TADT



Planning completed
Application for tunnel construction permit submitted end of 2015



Summary

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Encouraging prospects for studying QCD matter at high T and/or μ_B

- Explore unknown territory of the QCD matter phase diagram
  - Aim: establish a complete excitation function of dilepton and (multi-)strangeness production from SIS18 up to LHC
- Much more emphasis are put on running at energies optimal for the study of the QCD phase transitions and high baryon densities
  - CBM has largest discovery potential
  - Support of FAIR Phase-0 experiments (HADES, STAR BESII & FXT, BM@N) is a must
  - In future, installation of SIS300+ on top of SIS100 in the same tunnel → benefit from parallel operation
- Future experiments allows for overlap and independent confirmation of results

Thank you for your attention!

A Fixed Target ExpeRiment for hadron, heavy-ion and spin physics (AFTER) at LHC

Without interfering with other experiments!

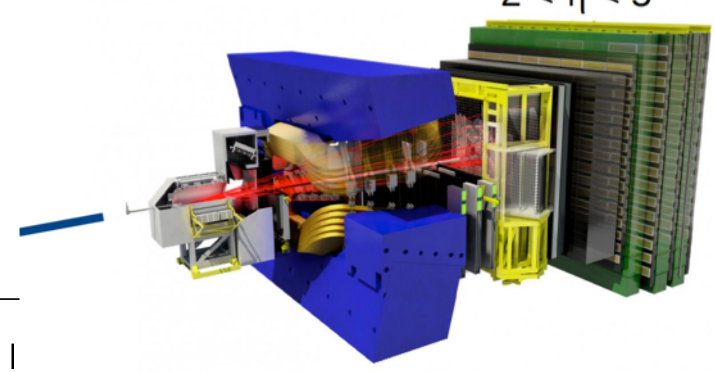
Physics motivations:

- The high x frontier: new probes of the confinement and connections with astroparticles
- The nucleon spin and the transverse dynamics of the partons
- **The approach to the deconfinement phase transition**

- Two ways towards fixed target collisions with the LHC beams:
  - An internal **gas target** inspired from e.g. SMOG@LHCb…
  - A slow extraction with a **bent crystal**

- An expression of interest: http://after.in2p3.fr

$2 < \eta < 5$



Main kinematic features:

→ LHCb and ALICE muon arm become backward detectors in fixed target mode

→ Acceptance for an LHCb-like detector : $2 < \eta < 5$

Heavy-ion collisions toward larger rapidities

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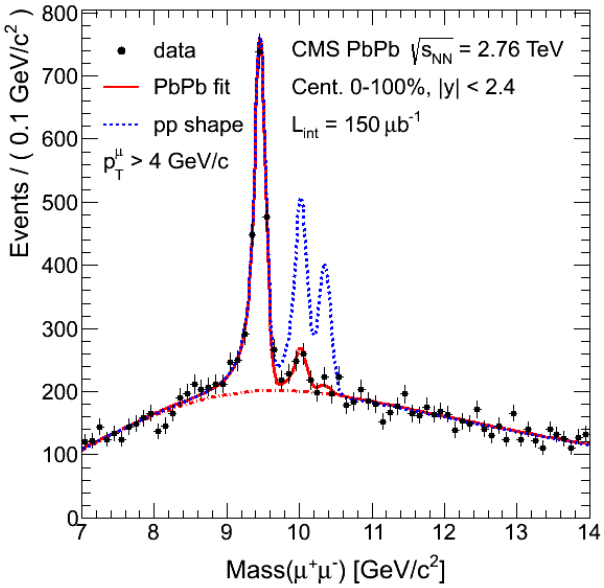
- A complete set of heavy-flavour studies between SPS and RHIC energies → at AFTER@LHC energy, ϒ(3S) and ϒ(2S) are expected to melt
- Explore the longitudinal expansion of QGP formation (particle yields, azimuthal correlations)
- Test the factorization of Cold Nuclear Matter effects (use Drell-Yan as a probe)



CBM Collab., PRL 109 (2012) 222301

7 TeV proton beam on a fixed target

c.m.s. energy:	$\sqrt{s} = \sqrt{2m_N E_p} \approx 115\,\mathrm{GeV}$	**Rapidity shift:** $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.8$
Boost:	$\gamma = \sqrt{s}/(2m_N) \approx 60$	

2.76 TeV Pb beam on a fixed target

c.m.s. energy:	$\sqrt{s_{NN}} = \sqrt{2m_N E_{Pb}} \approx 72\,\mathrm{GeV}$	**Rapidity shift:** $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.3$
Boost:	$\gamma \approx 40$	