Future Prospects of Quark Cluster Physics using ultra-relativistic heavy-ions

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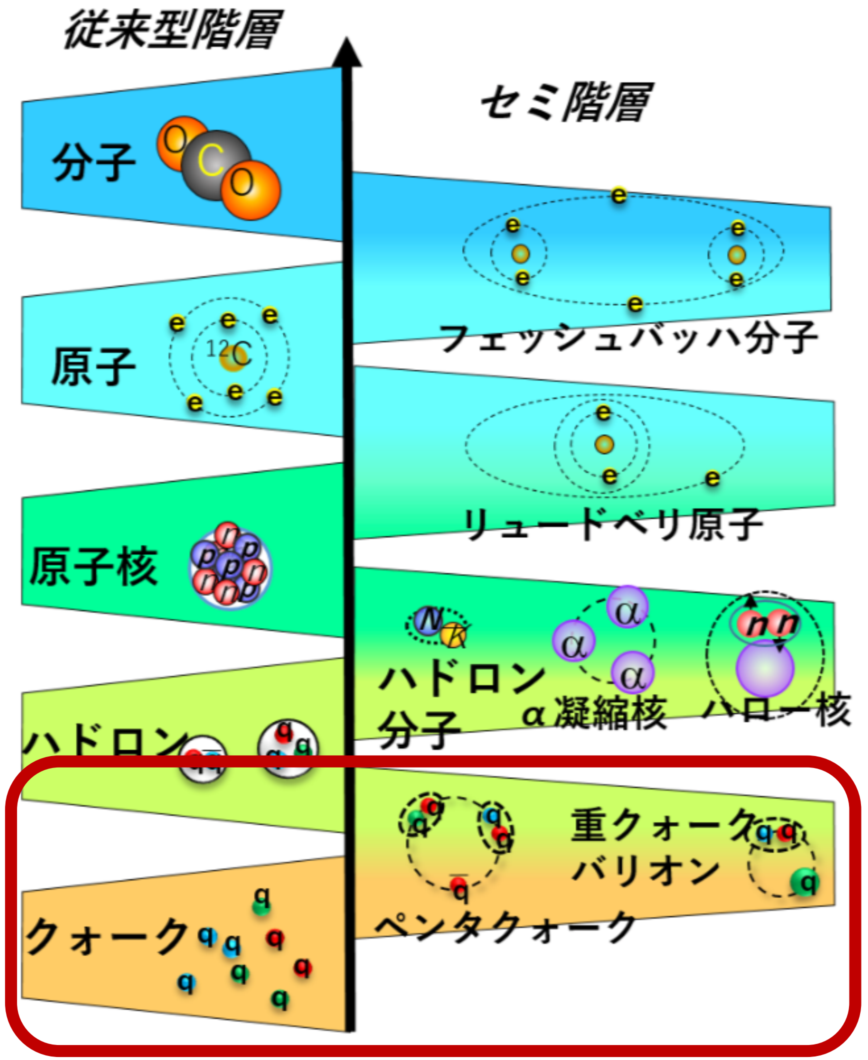
Outline

- Quark cluster physics
- Future Propsects
  - **ALICE3 : High-temperature frontier**
  - **FAIR-CBM and J-PARC-HI : High-density frontier**
  - **EIC : High-energy frontier**
- Summary and Outlook

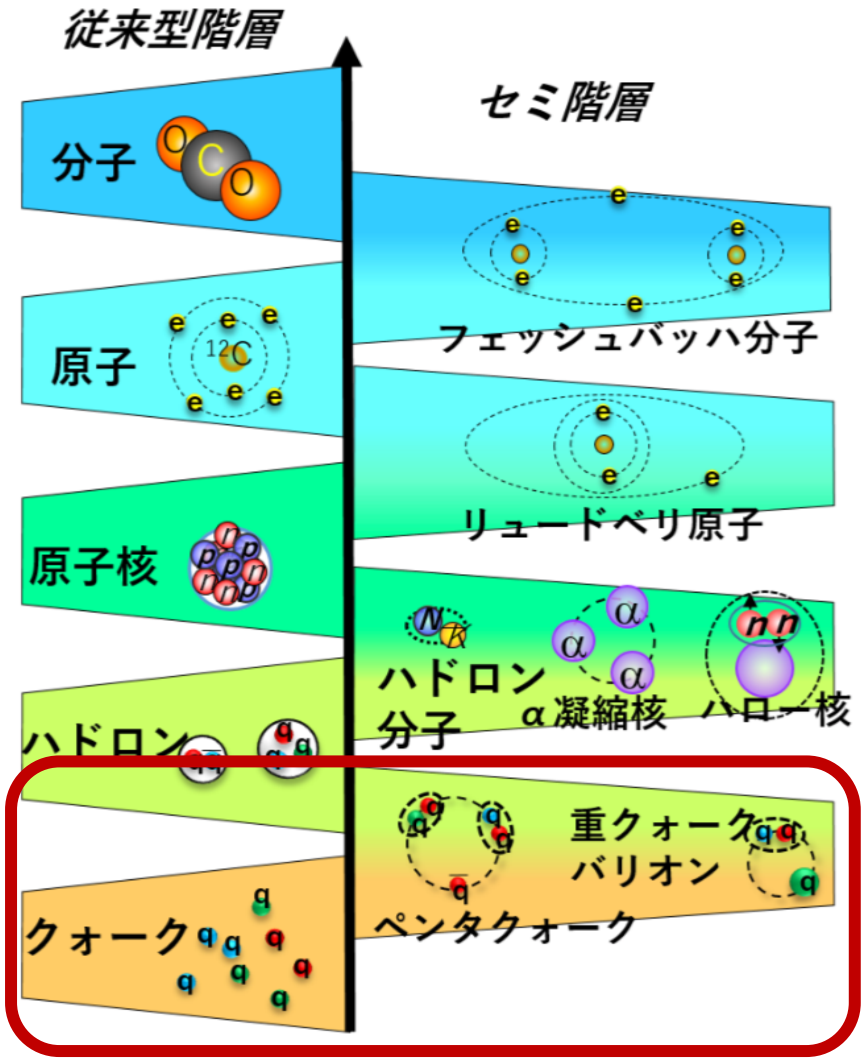
Quark Cluster Physics



- Bridging Quark and Hadron Hierarchies
  - Dynamics of quarks and gluons
  - Emergent properties of quark-gluon matter
    - Bulk properties (EoS, transport coefficients)
    - QCD phase diagram
  - Emergence of hadrons from quarks
    - Color Confinement
    - Chiral Symmetry Restoration

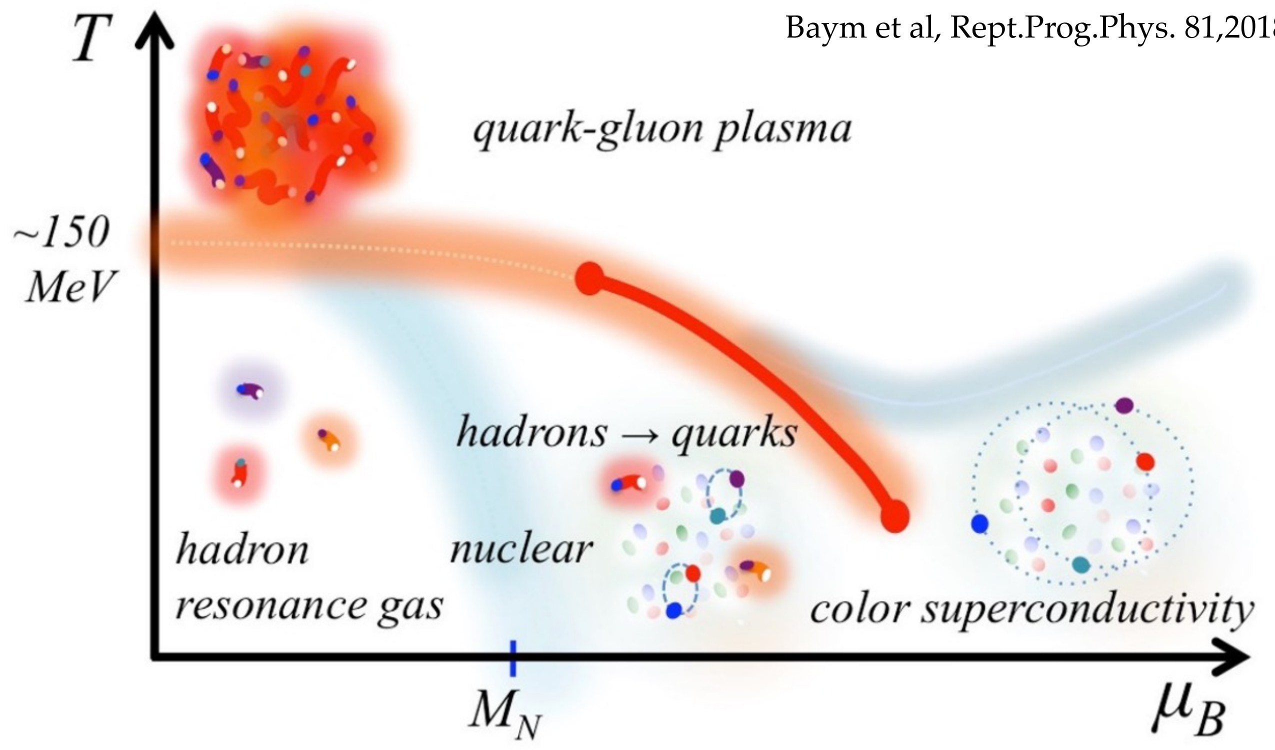
- Ultra-relativistic heavy-ion collisions at RHIC and LHC
  - *See S. Yano's presentation*

Quark Cluster Physics



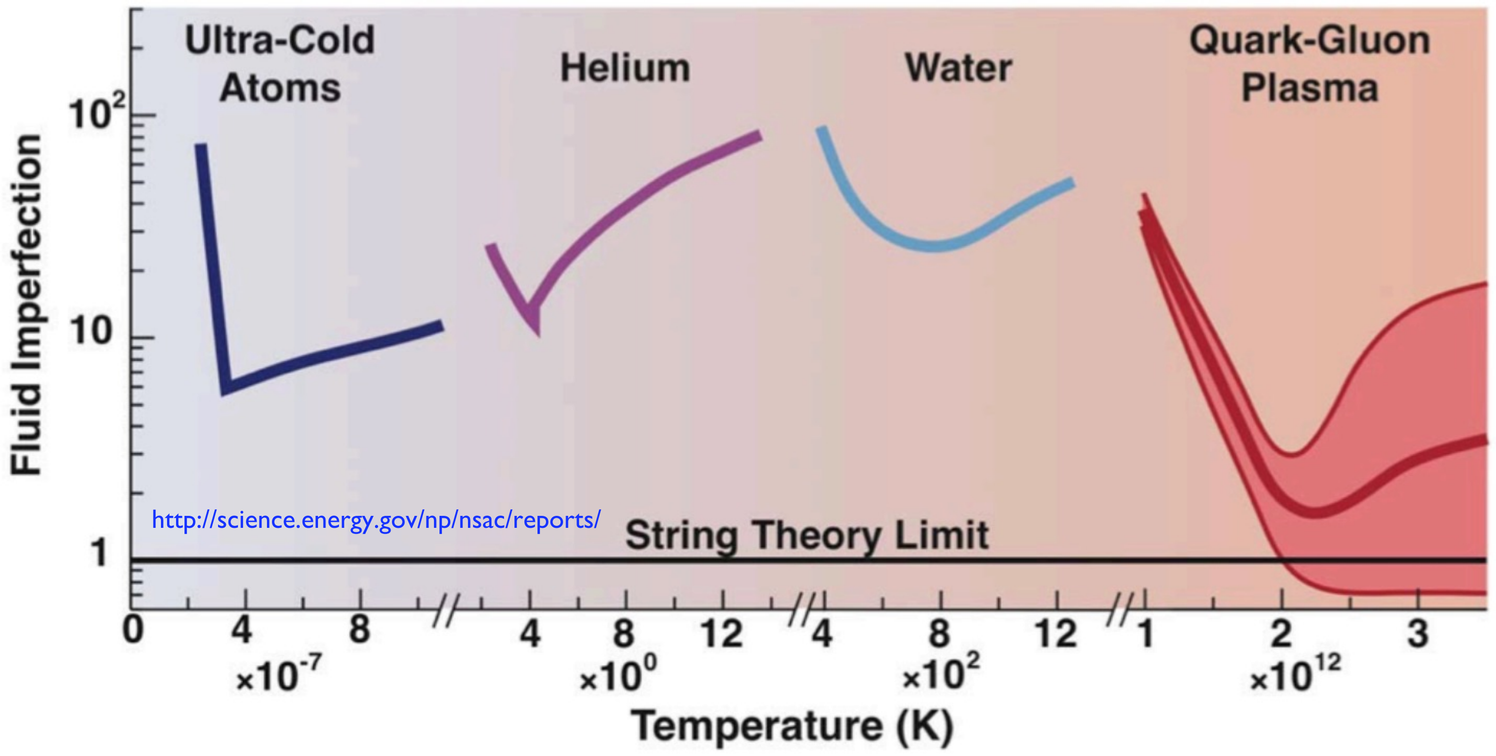
- **QCD Phase diagram**
  - Quark-Gluon Plasma, Color superconductivity
  - Phase boundary and transition between hadrons and quarks

Baym et al, Rept.Prog.Phys. 81,2018

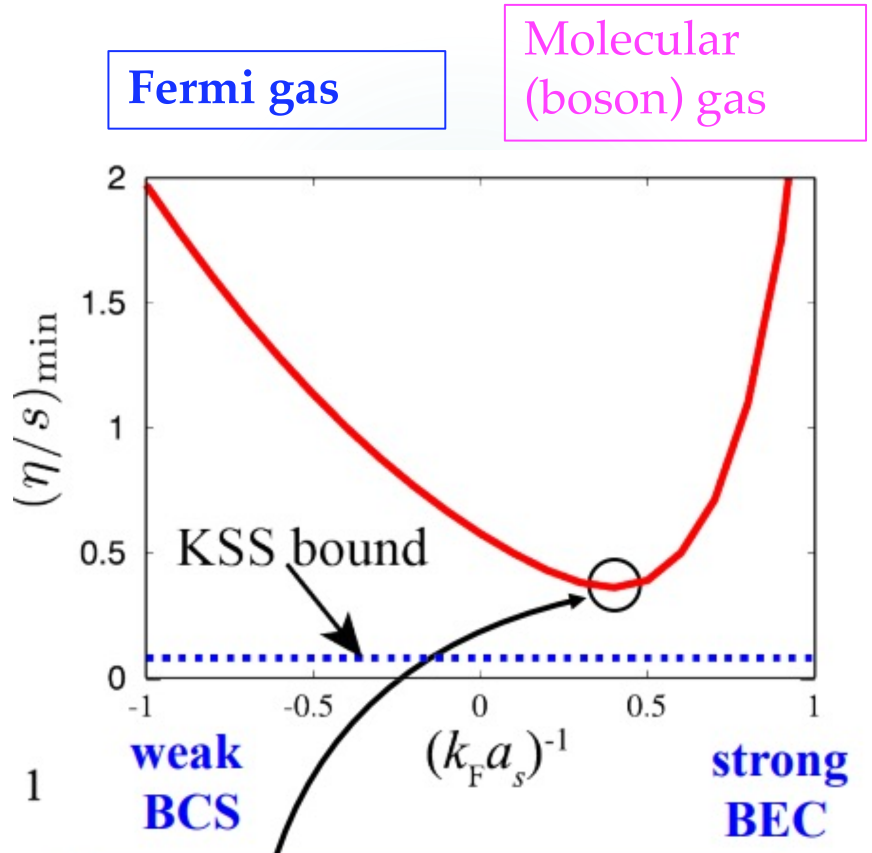


Strongly interacting QGP

- **Realization of Strongly interacting system from 10^{-7} to 10^{12} K**



Y. Ohashi, JPS meeting, symposium March 15 (2021)



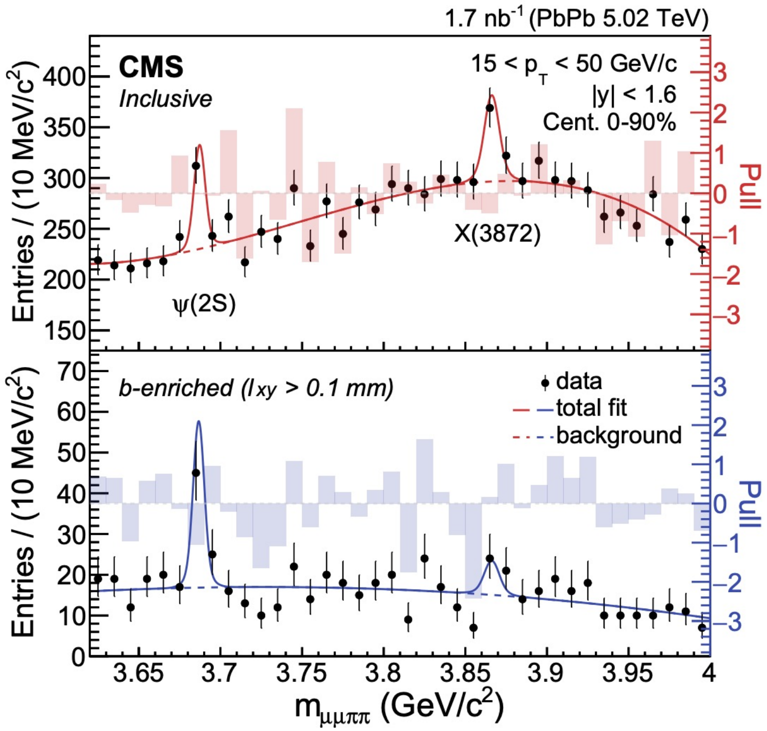
$$\left(\frac{\eta}{s}\right)_{\rm min} \simeq 4.5 \times \frac{\hbar}{4\pi k_B}$$

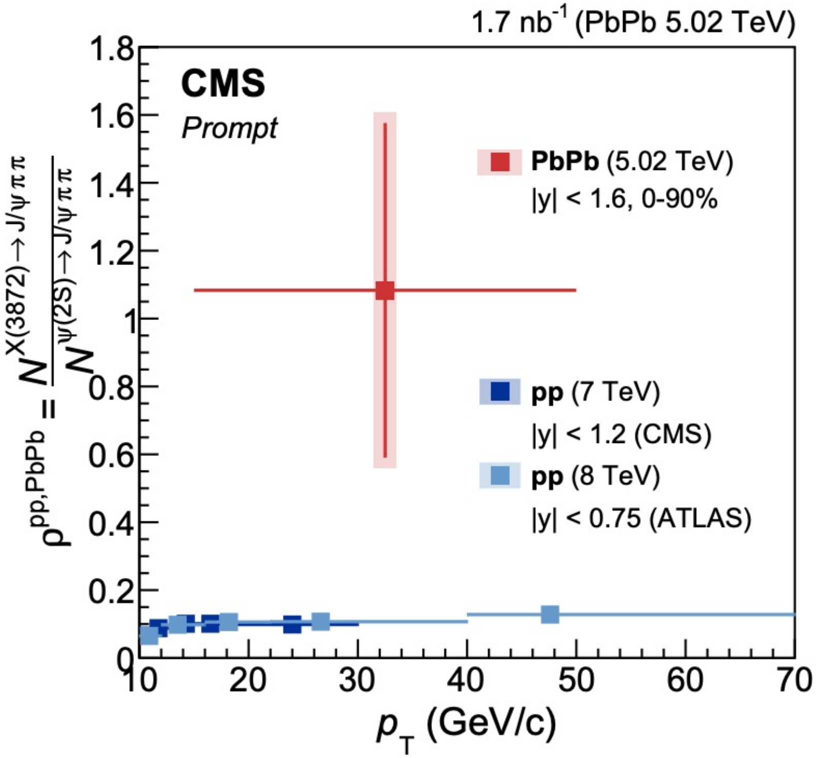
Increase of shear viscosity/entropy ratio due to formation of fermion pairs (clusters)
→ Shear viscosity/entropy ratio increases when the system changes from quarks to hadrons (quark-clusters)

Exotic Hadrons

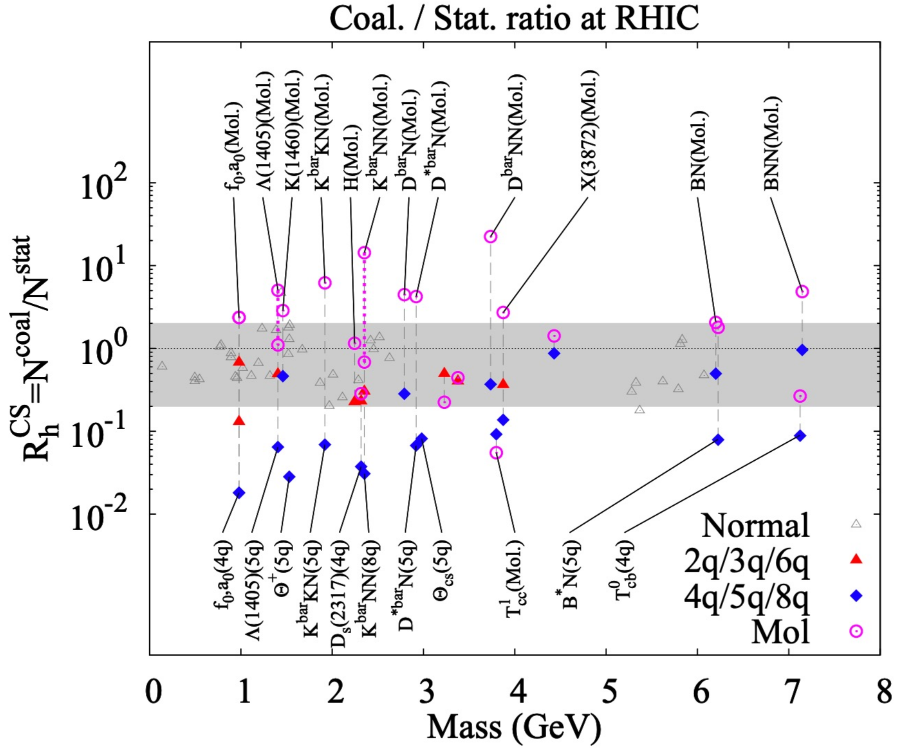
- **Loosely bound hadronic molecules are favored in HIC, with coalescence**
- **X(3872) not suppressed or even enhanced in HIC**

R_{AA} (Psi) = 0.1 – 0.15 → $\mathbf{R_{AA}(X) = 1 – 1.5}$





CMS, Phys. Rev. Lett. 128 (2022) 032001



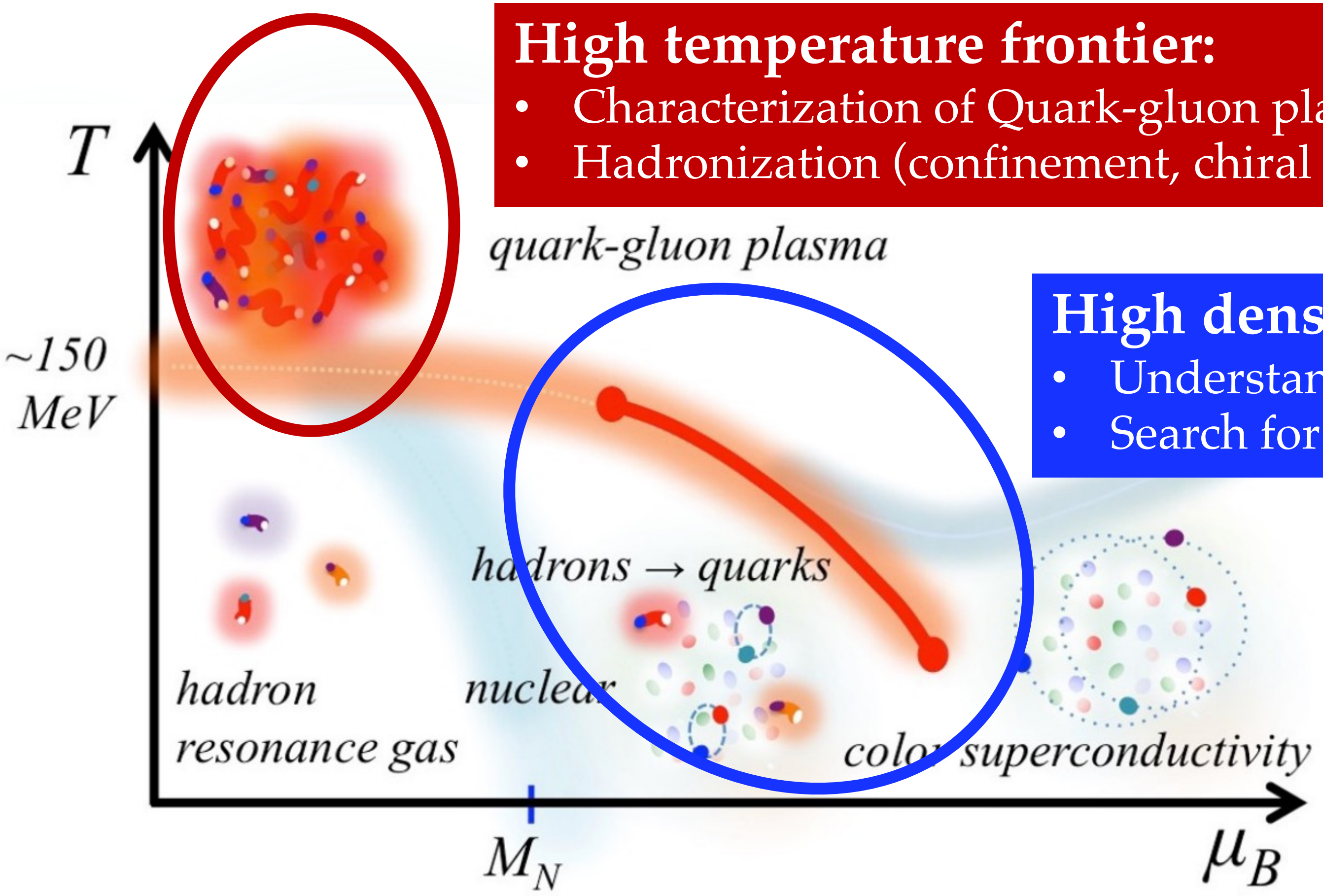
ExHIC, Phys.Rev. C84 (2011) 064910

Future Quark Cluster Physics

- **Understanding of quark-gluon dynamics and QCD emergent properties at high temperatures, high densities, and high energies**

High temperature frontier:
- Characterization of Quark-gluon plasma
- Hadronization (confinement, chiral symmetry restoration)

High density frontier:
- Understanding of phase diagram (phase transition)
- Search for color superconductivity, quarkonic matter

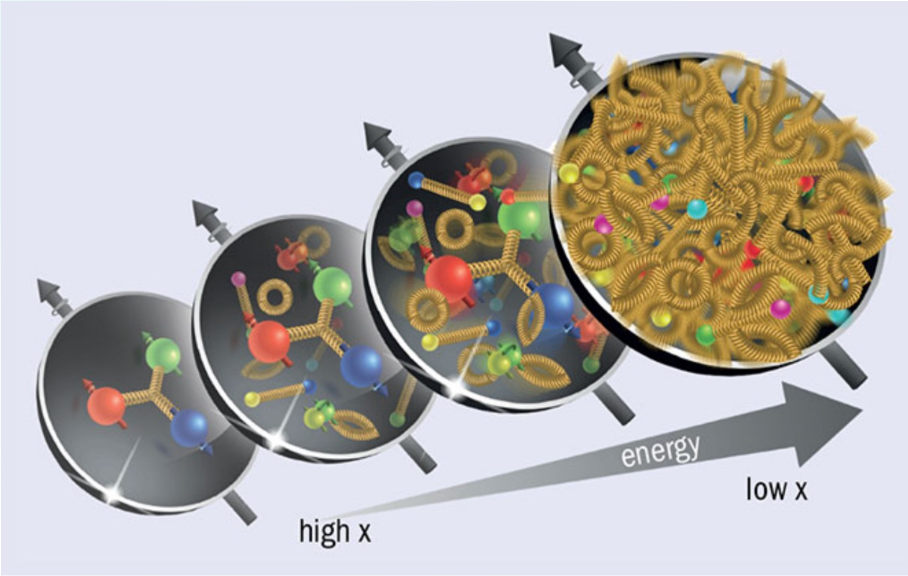


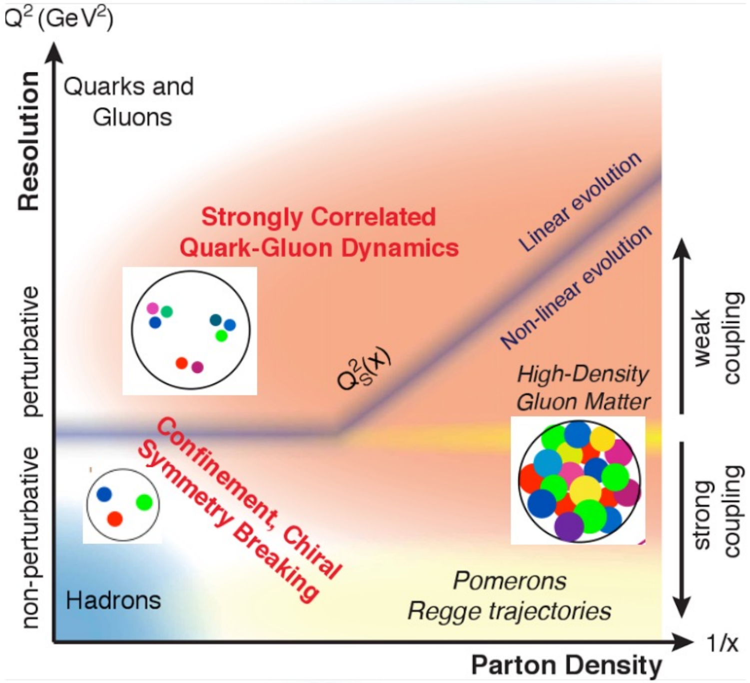
Future Quark Cluster Physics

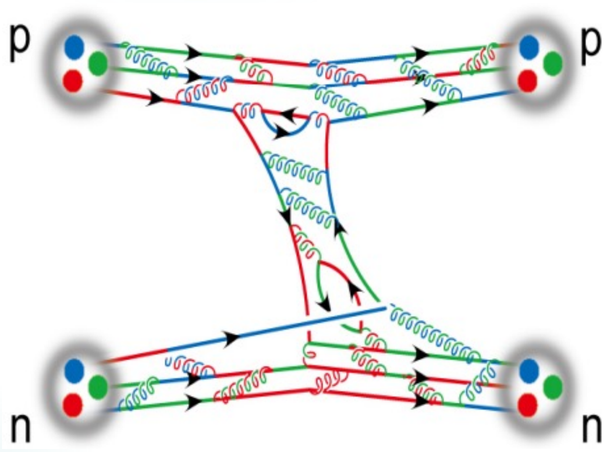
- Understanding of quark-gluon dynamics and QCD emergent properties at high temperatures, high densities, and high energies

High energy frontier:

- From constituent quark description to high dense quark and gluonic matter
- Strongly correlated quark-gluon dynamics inside nucleon and nuclei
- N-N interactions from QCD



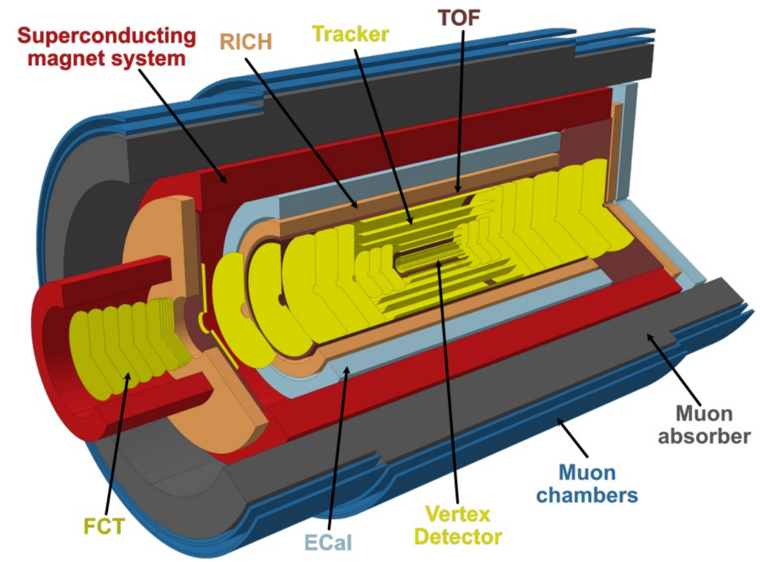




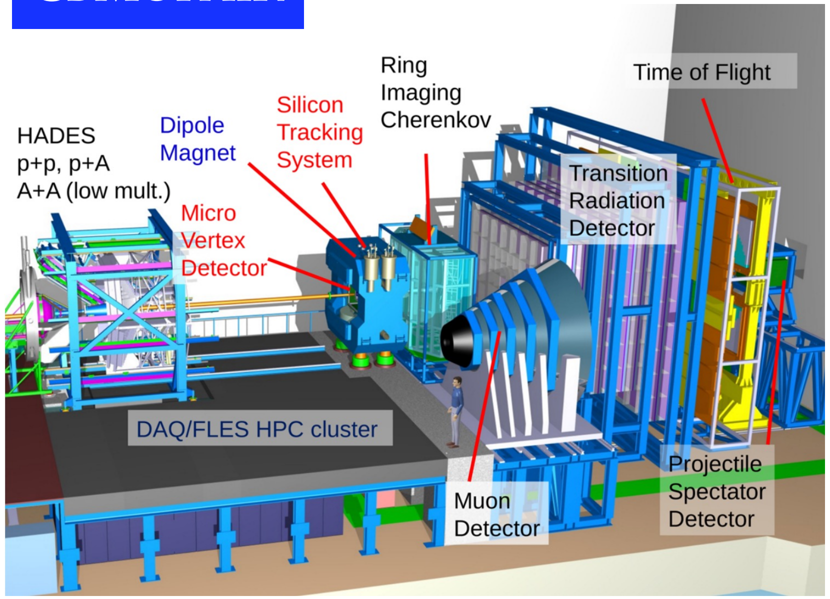
Future Quark Cluster Experiments

- Future Experimental Programs
  - ALICE3 @ LHC (2035-) : High temperature frontier
  - CBM (2030-) and J-PARC-HI (203X? -) : high density Frontier
  - ePIC @ EIC (2032-): high energy Frontier

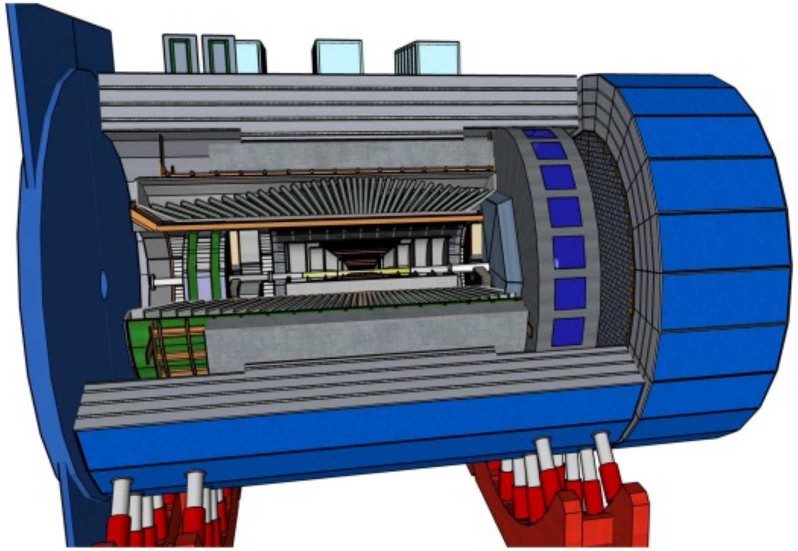
ALICE3@LHC



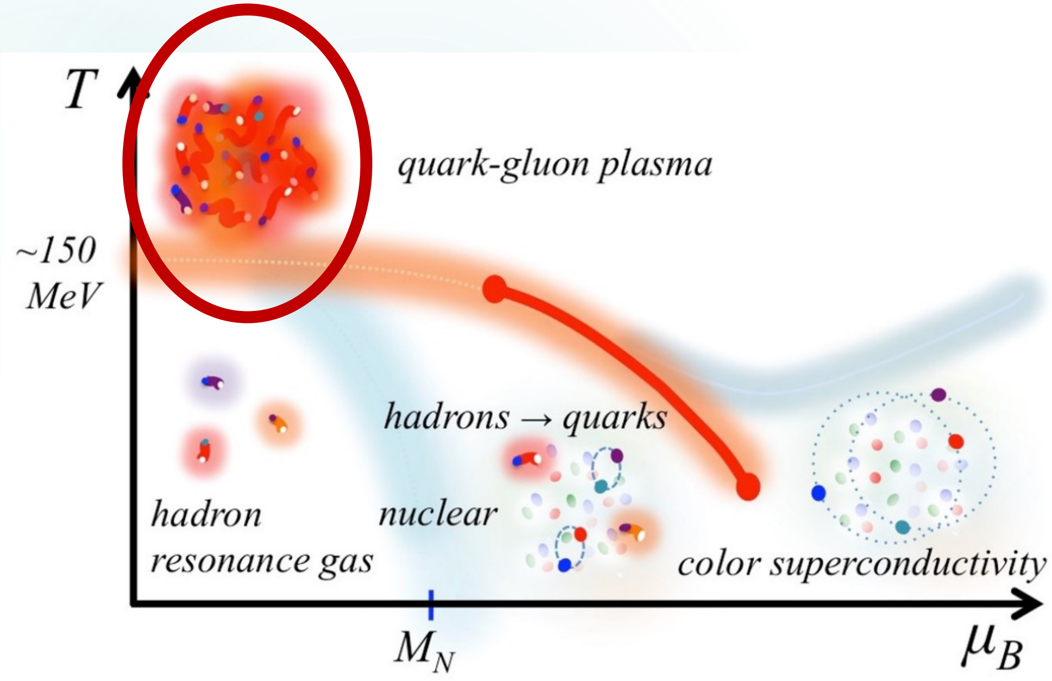
CBM@FAIR

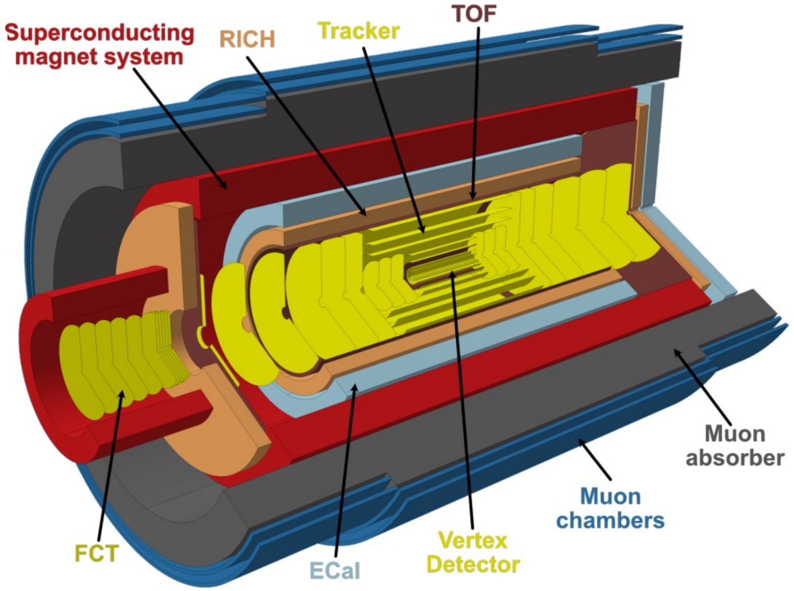


ePIC@EIC (electron-Ion collider)

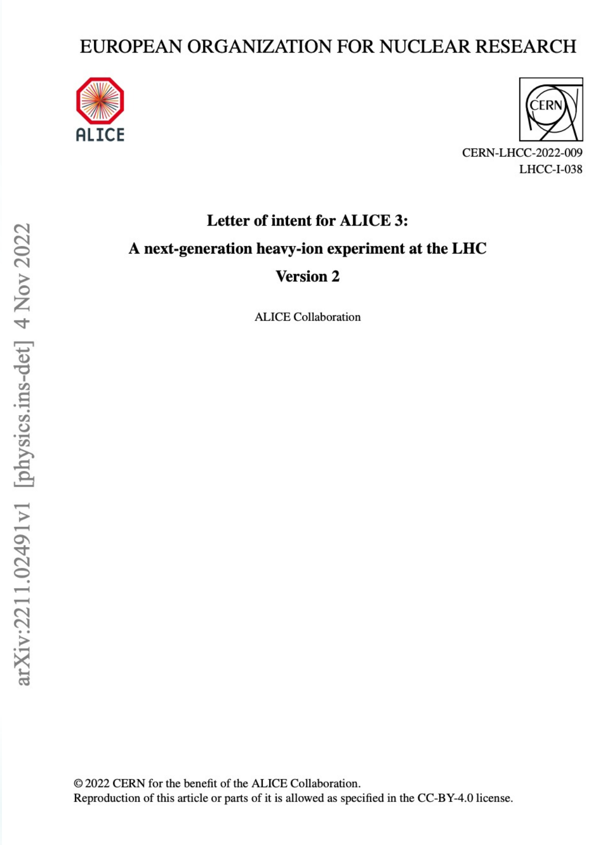


ALICE3 @ LHC (2035-)





arXiv:2211.02491


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE

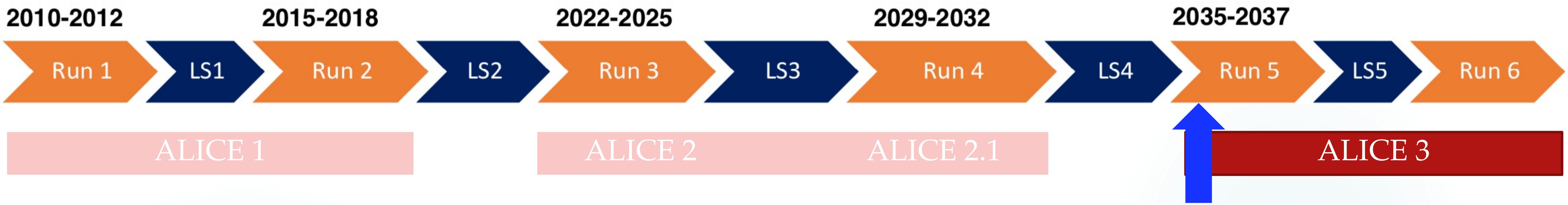
CERN-LHCC-2022-009
LHCC-I-038

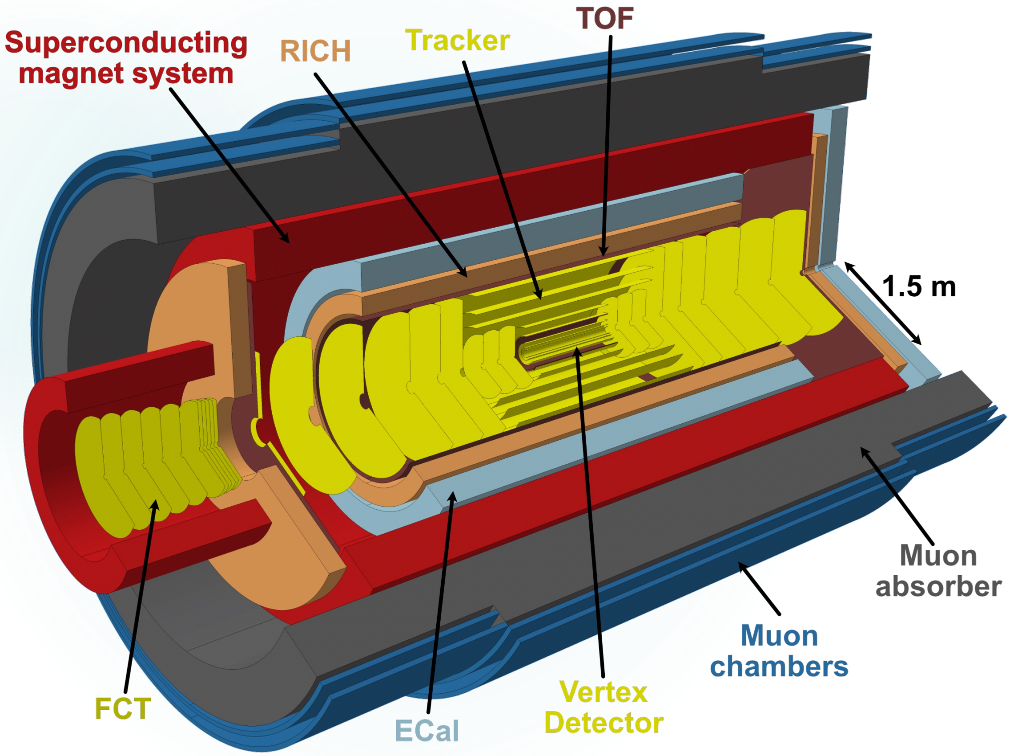
arXiv:2211.02491v1 [physics.ins-det] 4 Nov 2022

Letter of intent for ALICE 3:
A next-generation heavy-ion experiment at the LHC
Version 2

ALICE Collaboration

ALICE3 program (2035-)





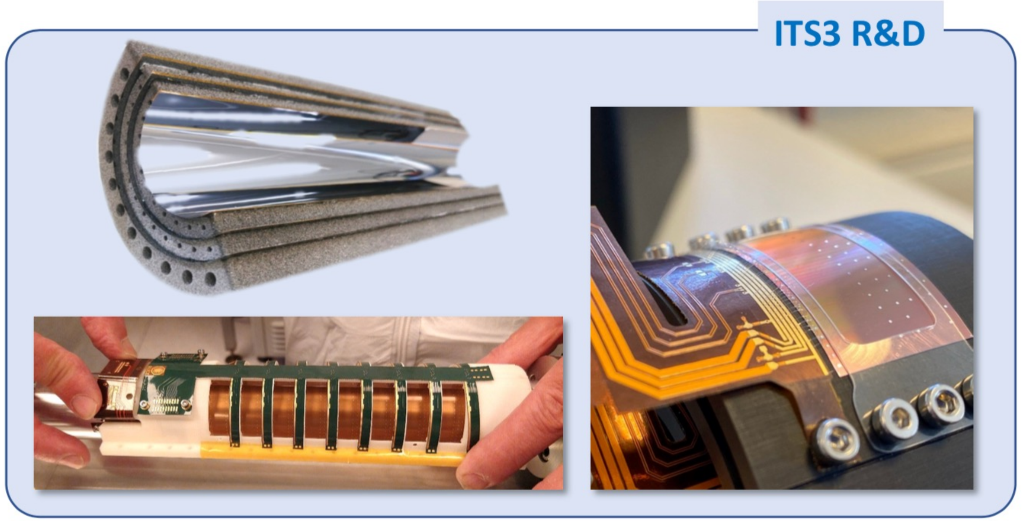
- Proposal for heavy-ion program beyond 2035 with a next generation experiment
  - arXiv:2211.02491
- Compact, ultra-lightweight all-silicon trackers
- Large acceptance ($|\eta|<4$)
- Unprecedented pointing resolution
  - $\sigma_{DCA} \approx 10\mu m$ (p_T = 200 MeV)
- Excellent electron, hadron, and muon identification

ALICE3 technologies

Wafer-size, ultra-thin, curved, CMOS MAPS sensor

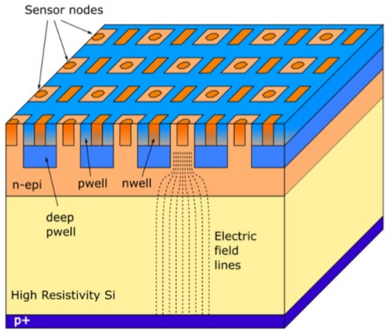
Vertex Tracker

- 5mm radial distance from interaction point (inside beampipe, retractable configuration)
- unprecedented spatial resolution: $\sigma_{pos} \approx 2.5\ \mu m$
- … and material budget $\approx 0.1\%\ X_0$ / layer



TOF

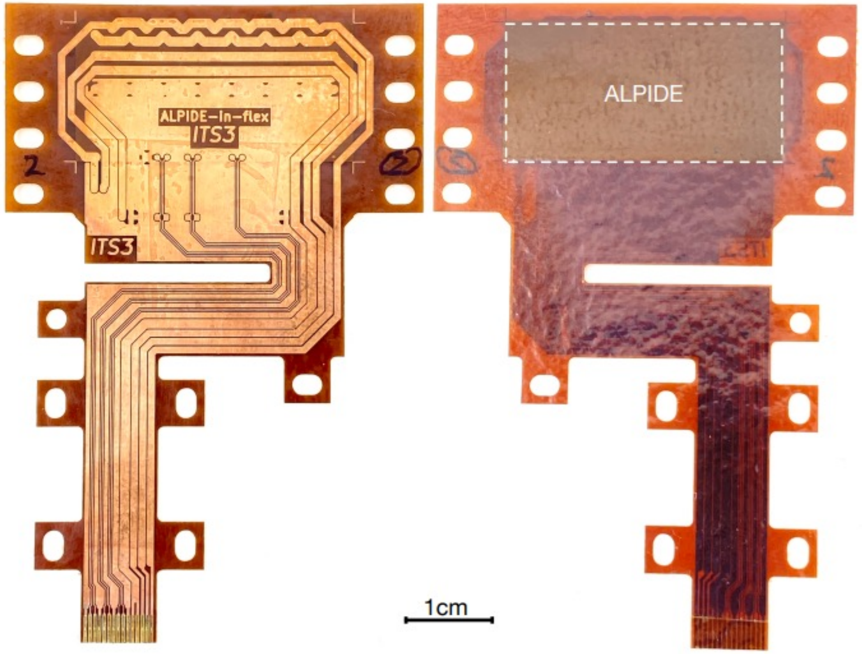
CMOS MAPS with gain layer for $\sigma_{TOF} < 20$ ps

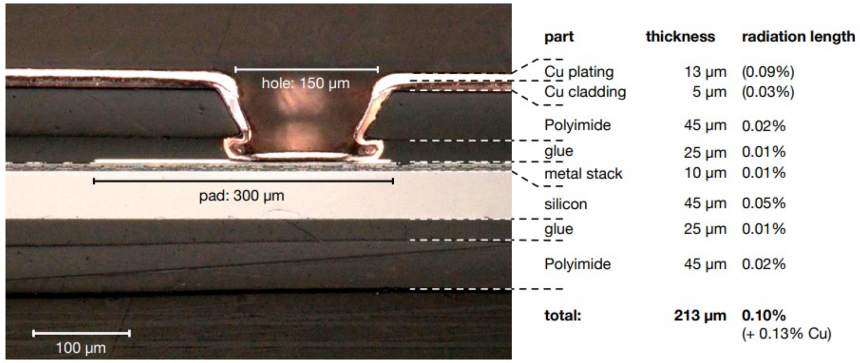


Vertex

MAPS foil https://arxiv.org/pdf/2205.12669.pdf

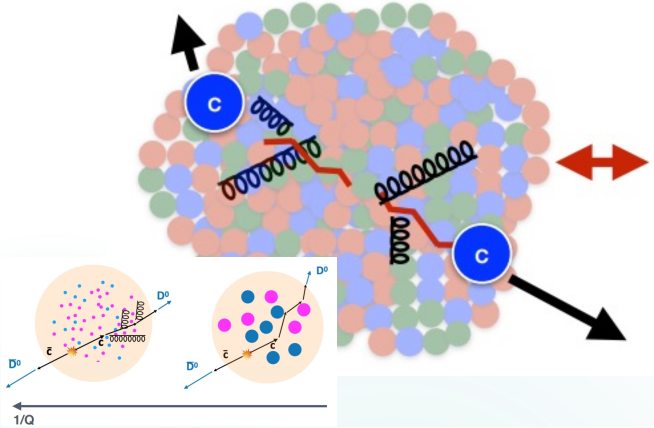
embedding a MAPS into a FPC board



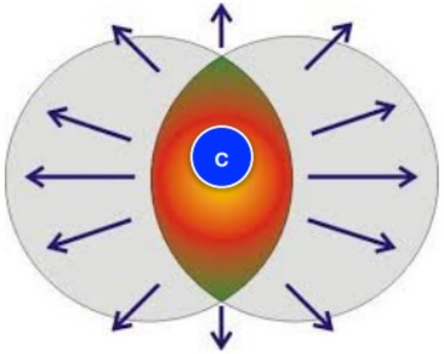


(some) ALICE3 Physics Goals

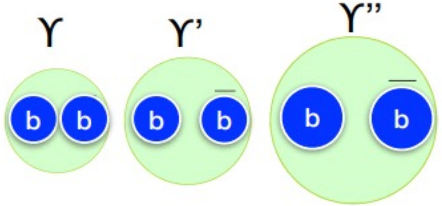
Heavy quarks interact and lose energy



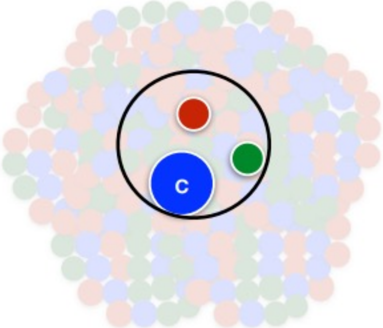
Heavy quarks "flow" within the medium

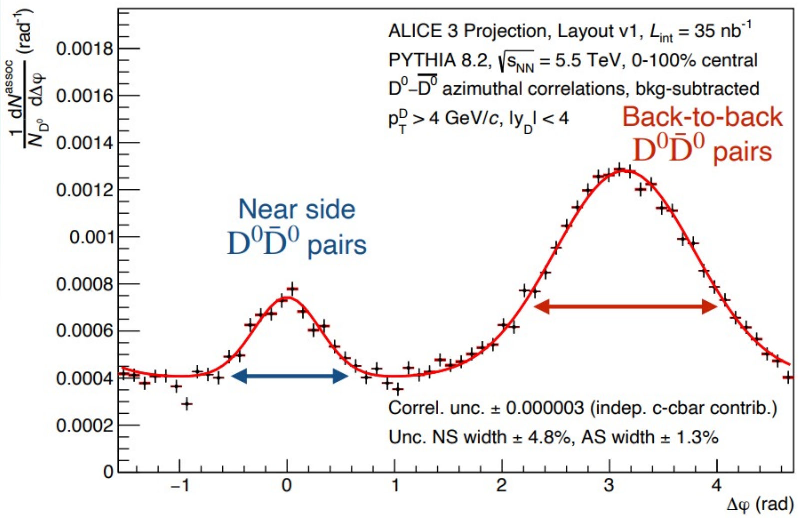


Bound states are affected by deconfined medium



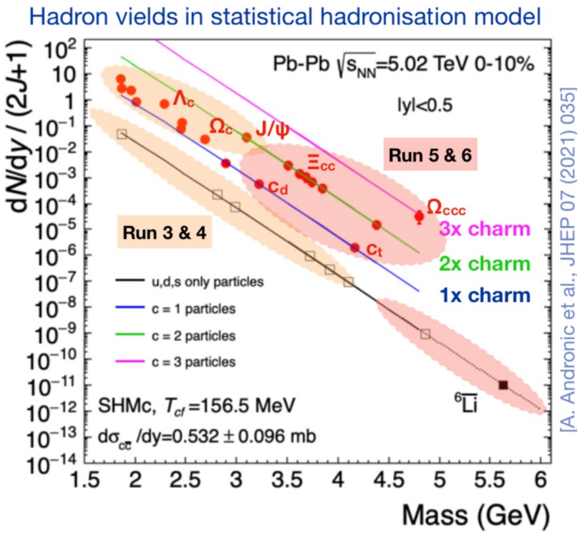
HF-hadron production modified at high densities





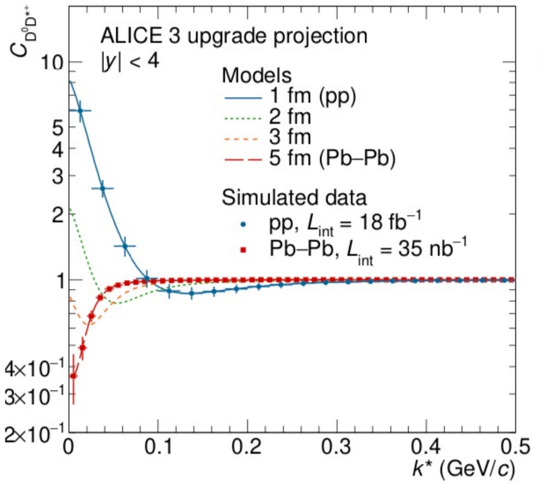
arXiv:2211.02491

Multi-charm states



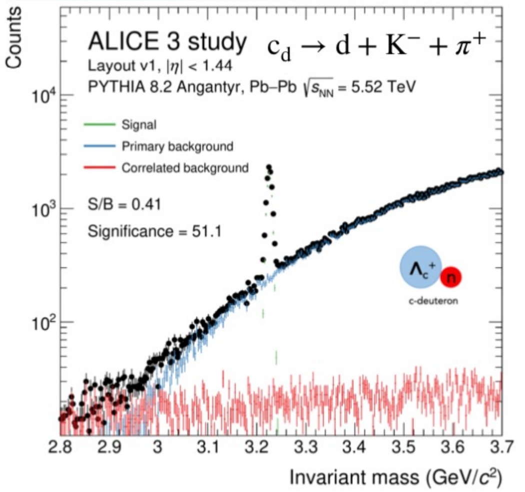
To test thermalization microscopically and hadronization (flavor, size, binding energy)

DD* momentum correlation



Characteristic sign-change between pp and Pb-Pb in case of bound T_{cc} state

High mass charm-nuclei

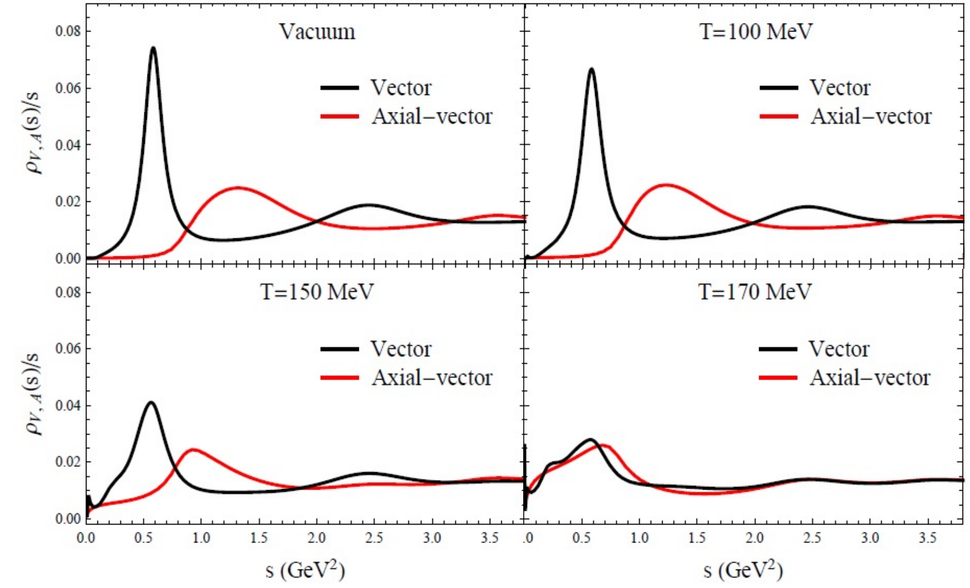


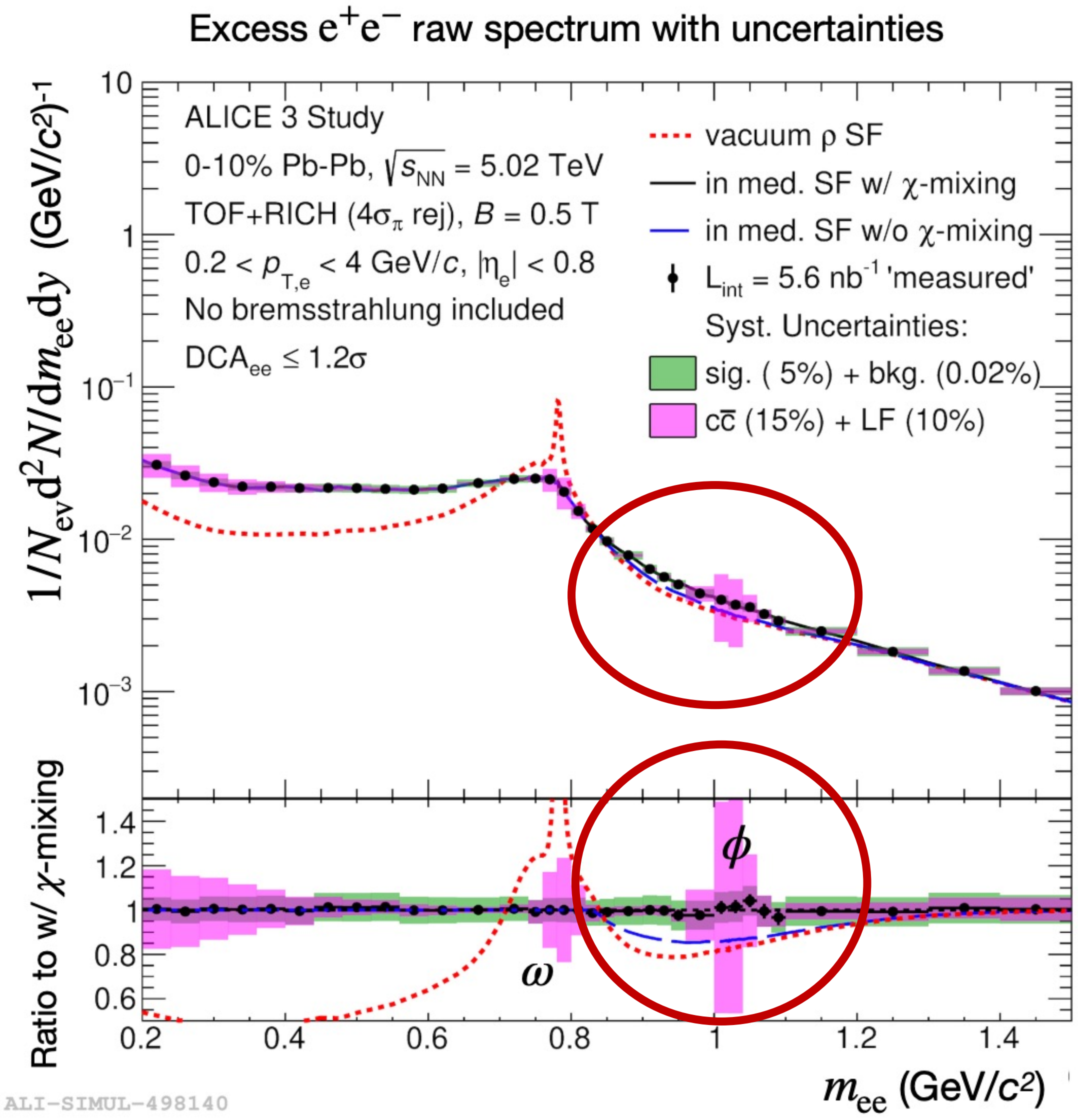
Unique sensitivity to undiscovered charm-nuclei: c-deuteron, c-triton

(some) ALICE3 Physics Goals

Chiral Symmetry restoration → vector-axial-vector degeneracy

R. Rapp, Nucl.Phys. A870 (2013)
P. Hohler, R. Rapp PLB 731 (2014) 103





Chiral mixing has direct consequences on the thermal dilepton rate:

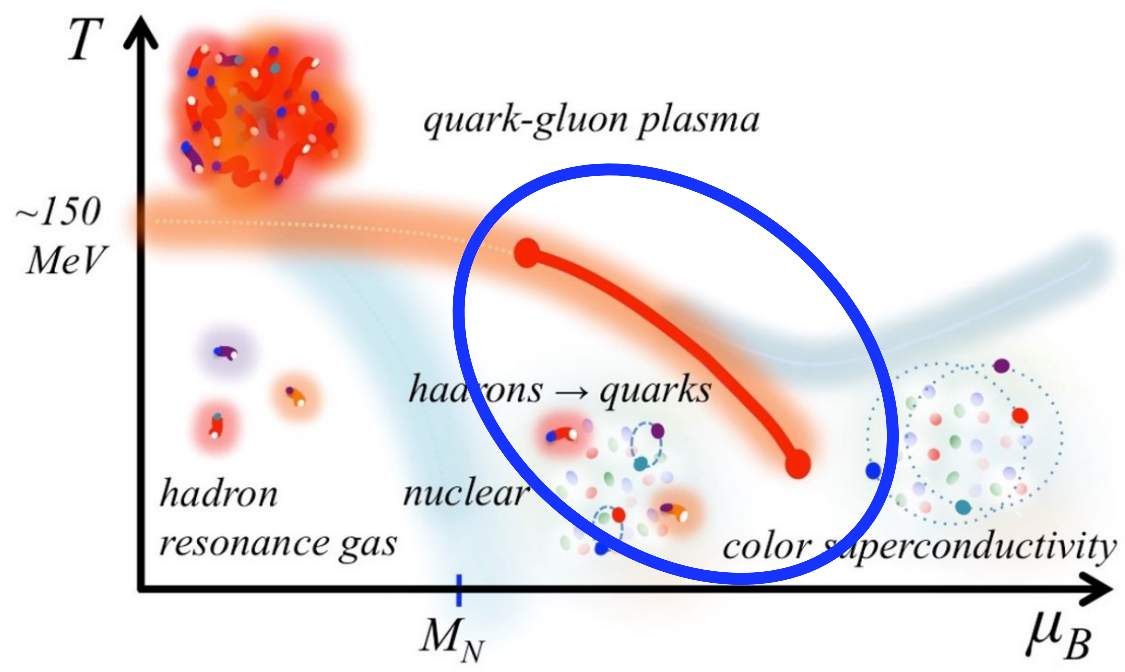
$$\Pi_V(q) = (1-\varepsilon)\,\Pi_V^0(q) + \varepsilon\,\Pi_A^0(q)$$

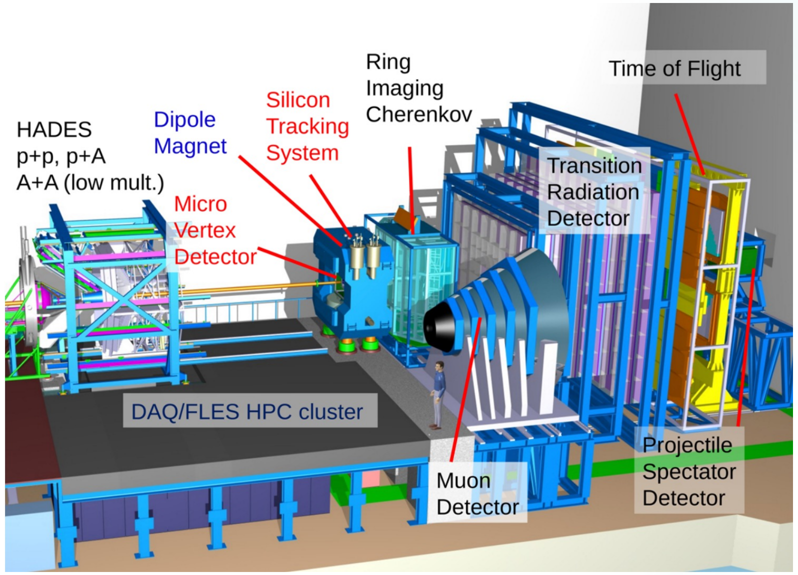
$$\frac{dN_{ll}}{d^4x d^4q} = \frac{4\alpha_{\mathrm{EM}}^2 f^B}{(2\pi)^2}\left\{\rho_{\mathrm{EM}} - (\varepsilon - \frac{\varepsilon^2}{2})(\rho_V - \rho_A)\right\}$$

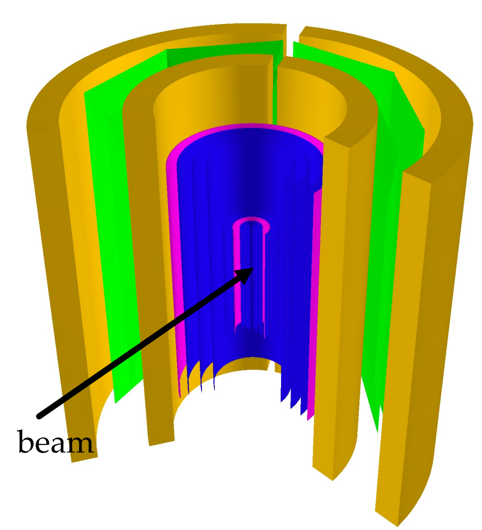
[M. Dey et al., Phys. Lett. B 252 (1990), 620-624] [Z. Huang, Phys. Lett. B 361 (1995) 131-136]

arXiv:2211.02491

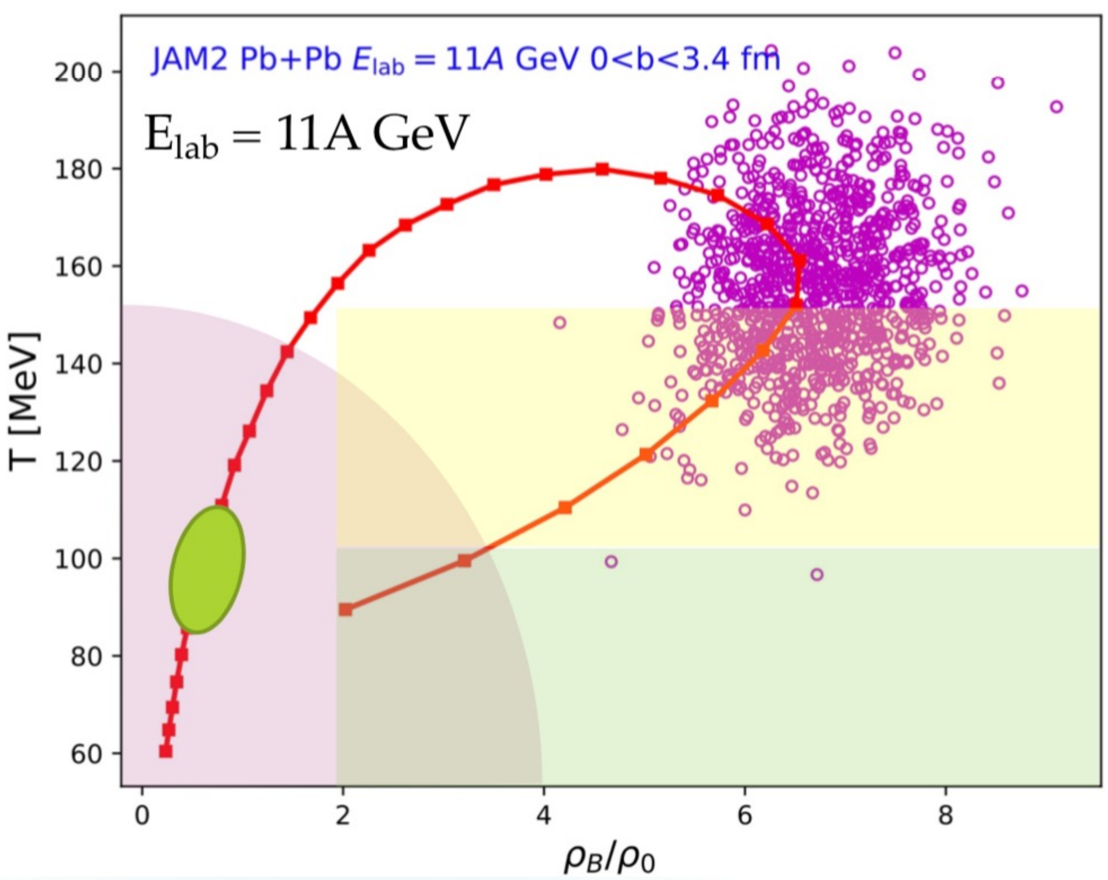
CBM and J-PARC-HI

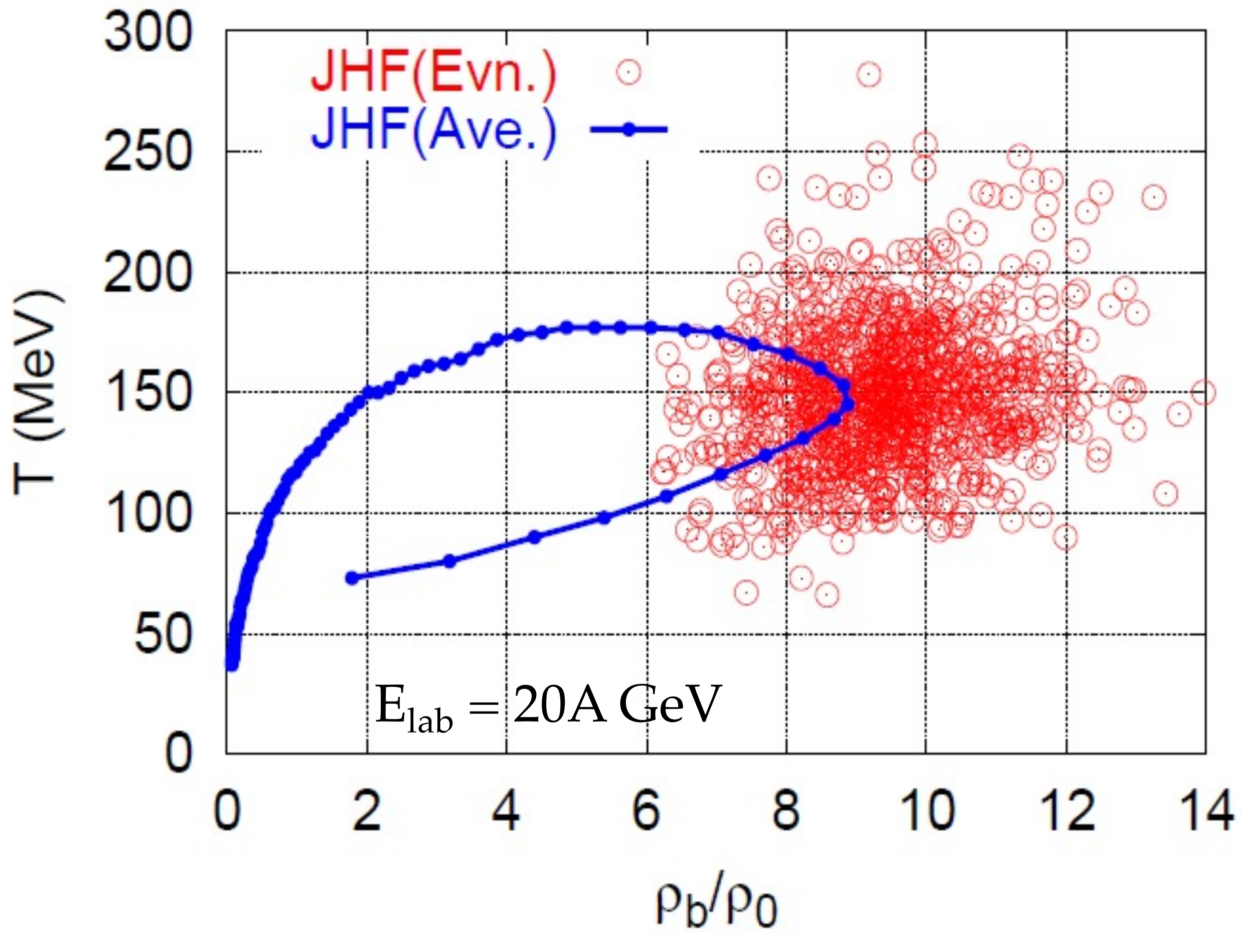






Maximum baryon density at CBM/J-PARC energy

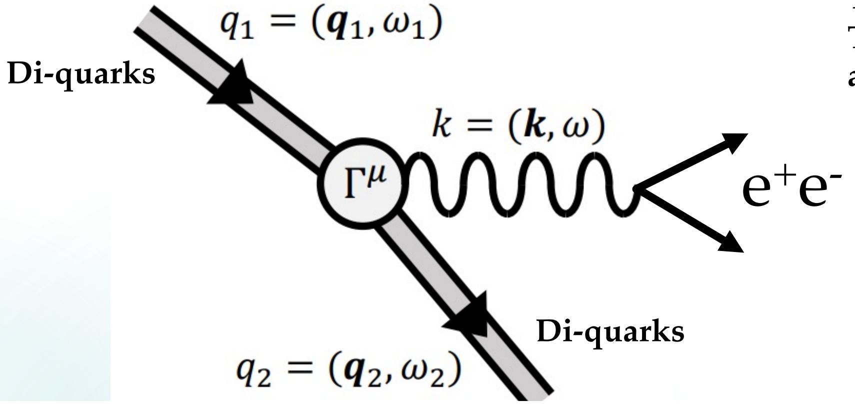


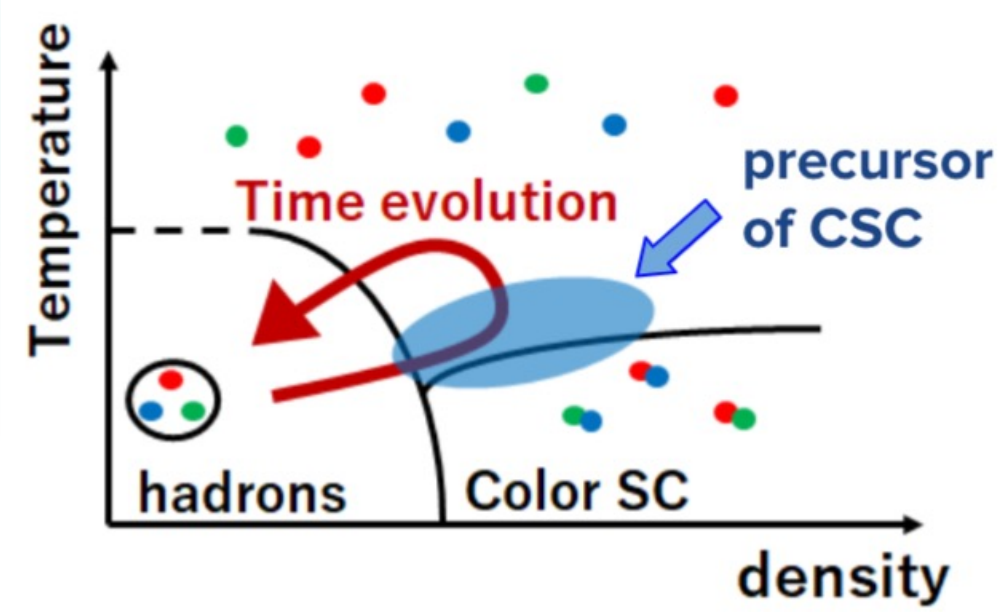


CBM and J-PARC-HI energy is unique in reaching the maximum baryon density 5-10 ρ_0 (> 4 ρ_0 for NS at 2 $M_{\odot}$)

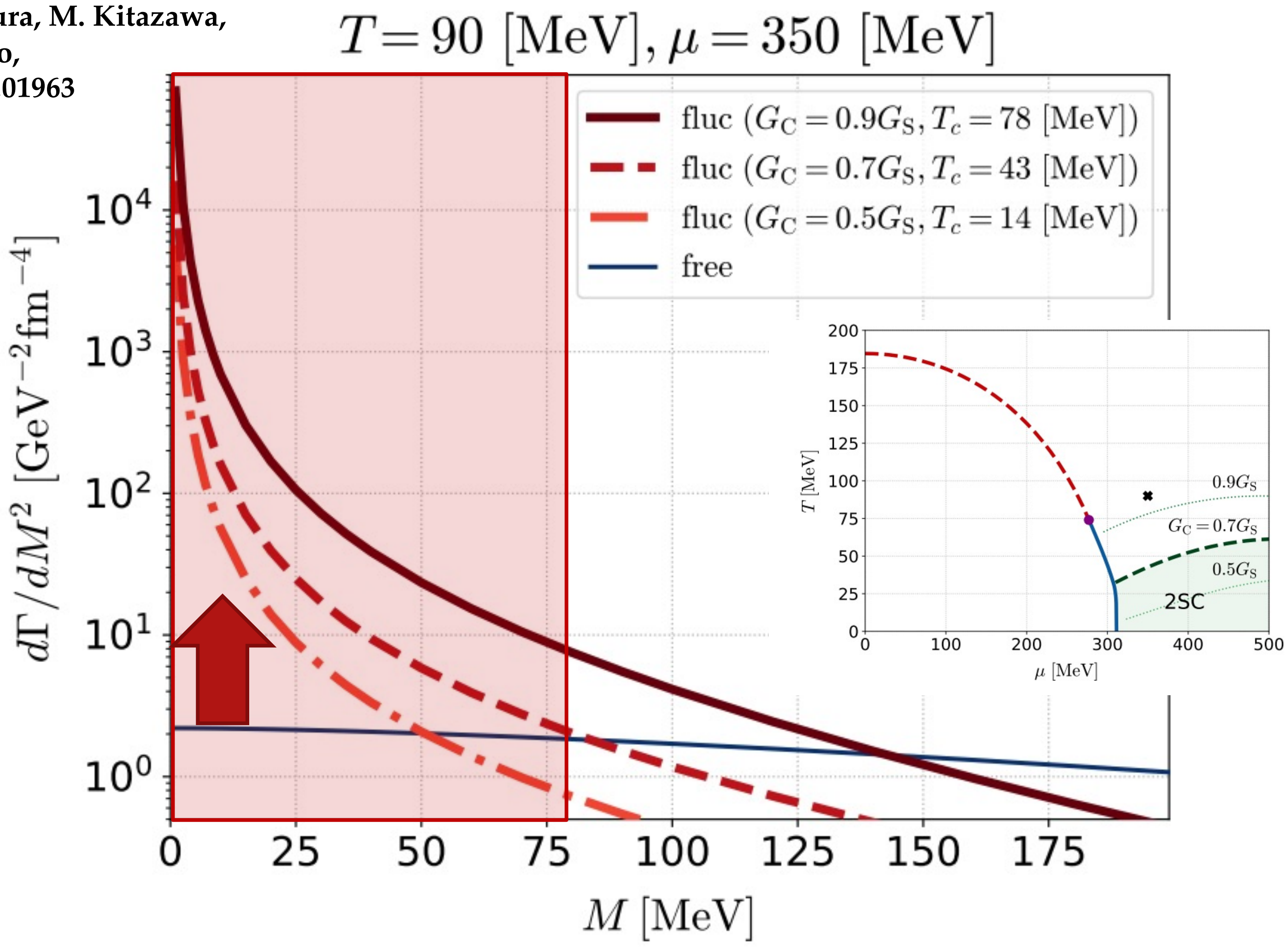
Probing color superconductor

Enhanced production of dielectrons in pseudo-gap (precursor) of color superconductor

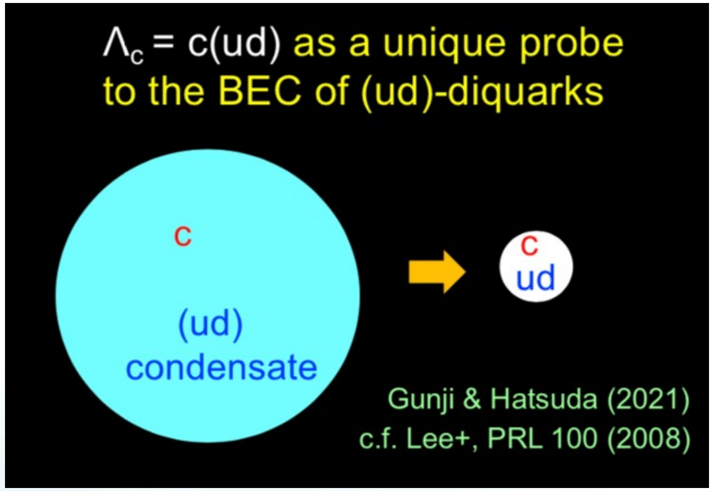




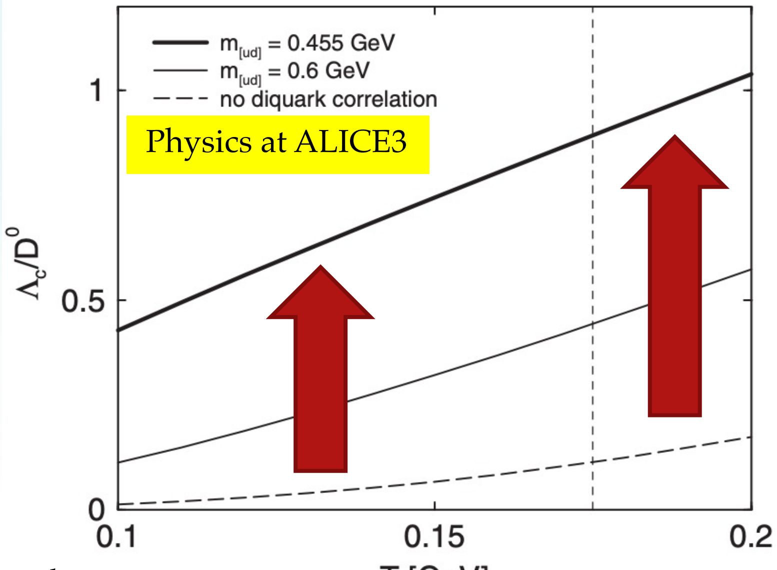
T. Nishimura, M. Kitazawa, T. Kunihiro, arXiv:2201.01963



Probing color superconductor



Enhancement of Λ_c/D at high T



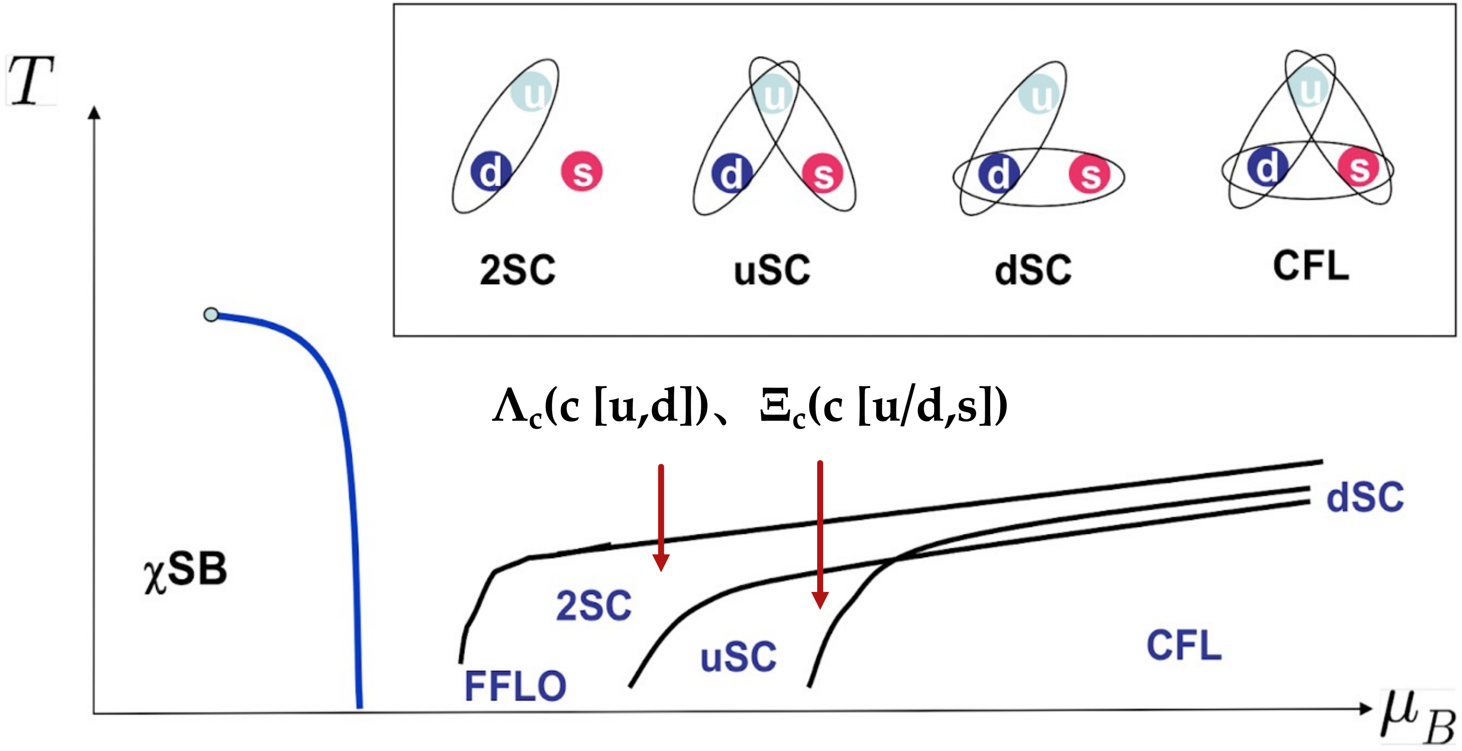
Phys. Rev. Lett.100.222301 T [GeV]

Enhanced production of charmed baryons in color superconductor

2SC: Λ_c(c [u,d])>Ξ_c^+(c [u,s])

uSC: Λ_c(c [u,d])~Ξ_c^+(c [u,s]) > Ξ_c^0 (c [d,s])

dSC: Λ_c ~Ξ_c^0 > Ξ_c^+

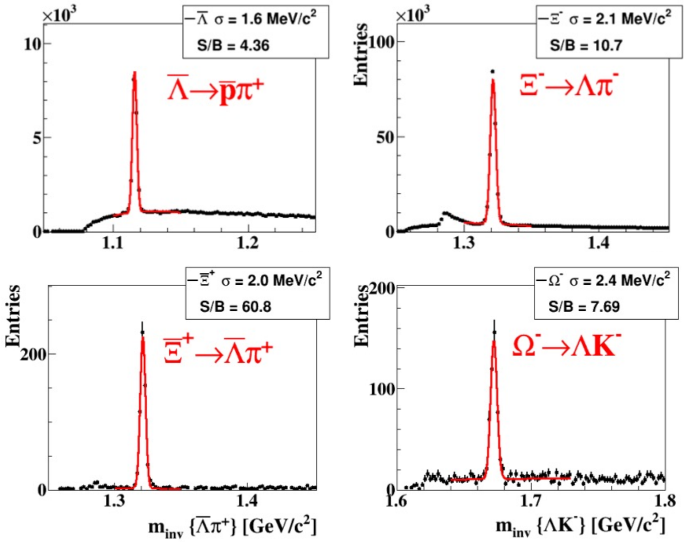


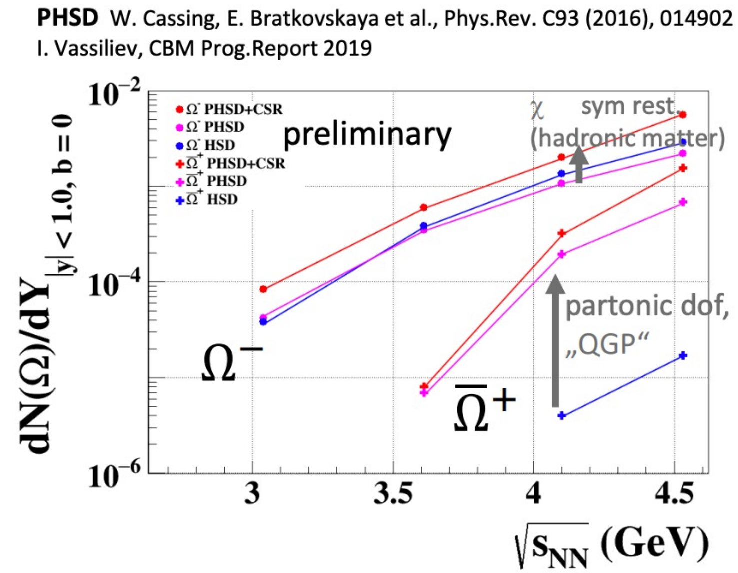
CBM@FAIR

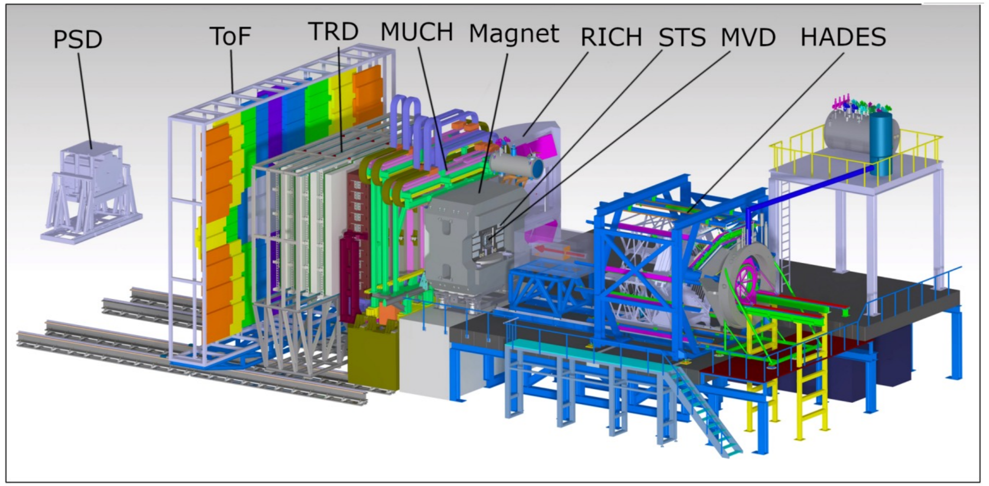
2022: Buildings / shell construction complete
2023-2025: General services, detector installation, commissioning
2026: Start of operations with beam

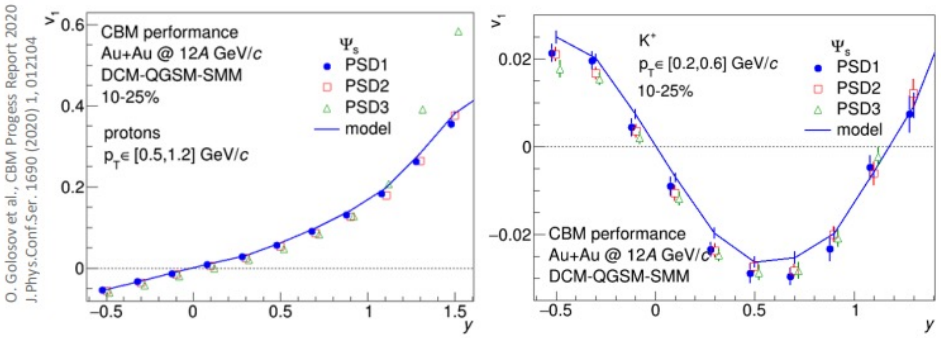
- CBM Day-1 (2026-2027) : 100 kHz Au+Au
  - **di-lepton, multi-strange baryons, light hypernuclei, flow**
- MVD (>2027): Measurements with rates of up to 10 MHz
  - **double Λ hypernuclei, J/ψ, charmed particles, exotics**

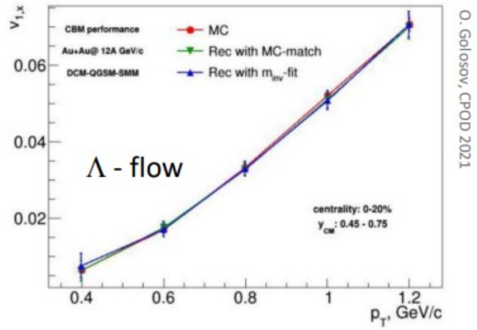
+2 years delay





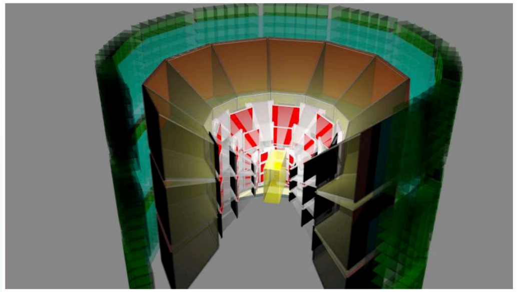


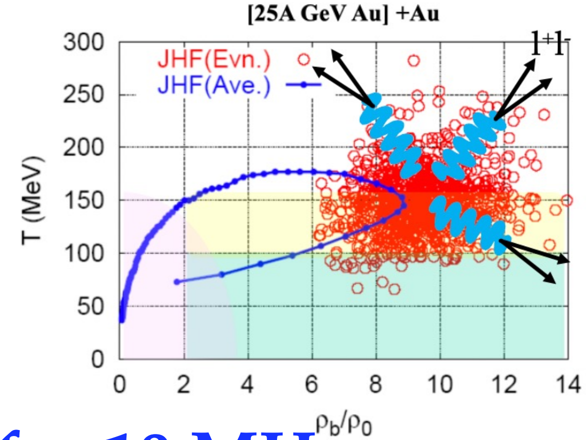


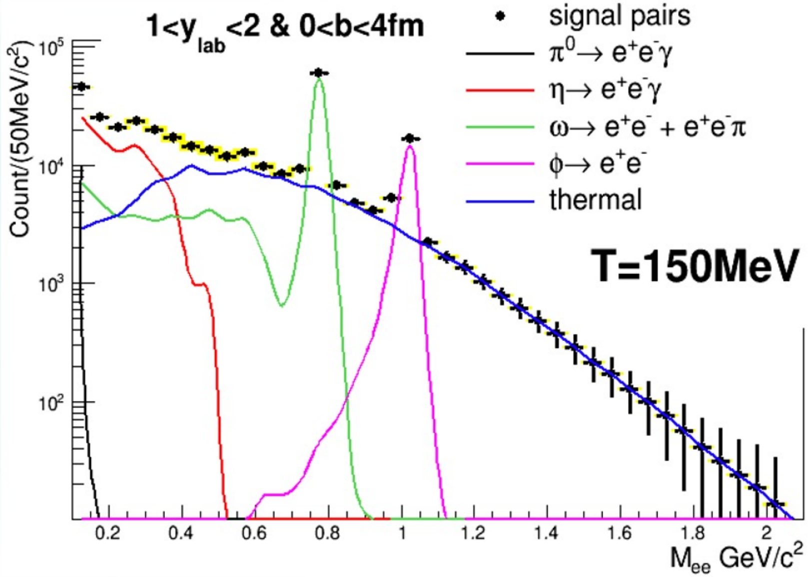


J-PARC-HI

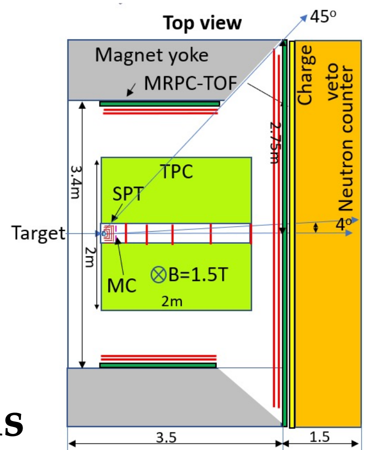
- **Phase-I: E16 upgrade (pA and low rate AA)**
  - Search for thermal dielectrons from quark phases

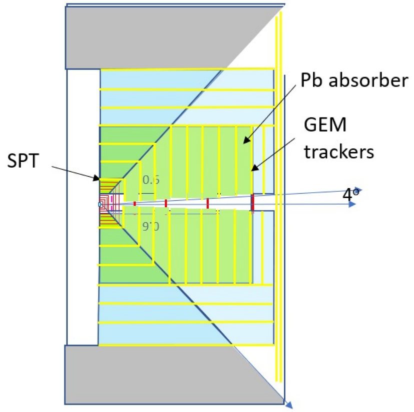


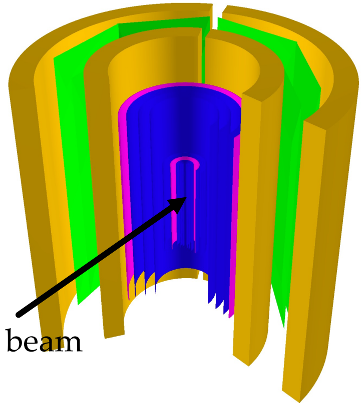




- **Phase-II: New spectrometer for 10 MHz high rate**
  - Search for color superconductors
    - Dielectrons, charmed baryons, etc
  - Strangeness physics



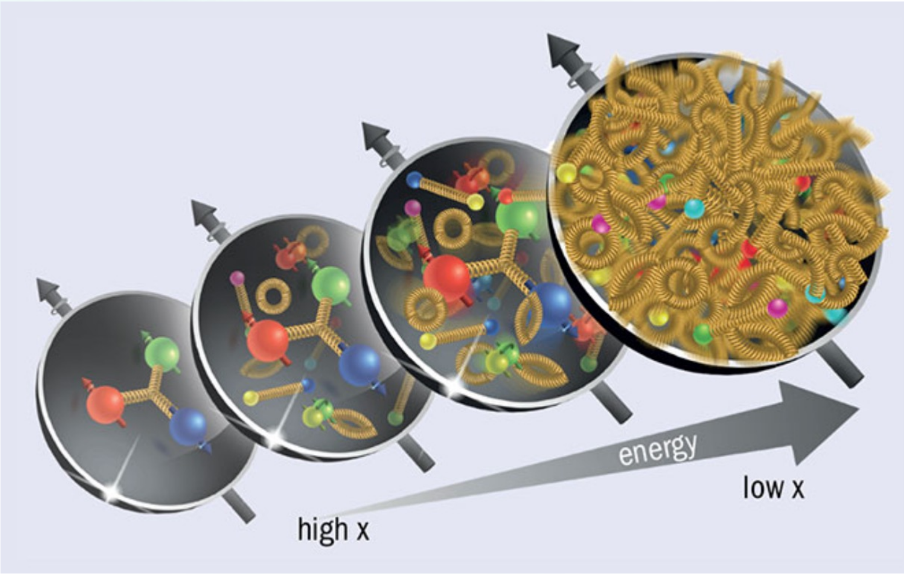


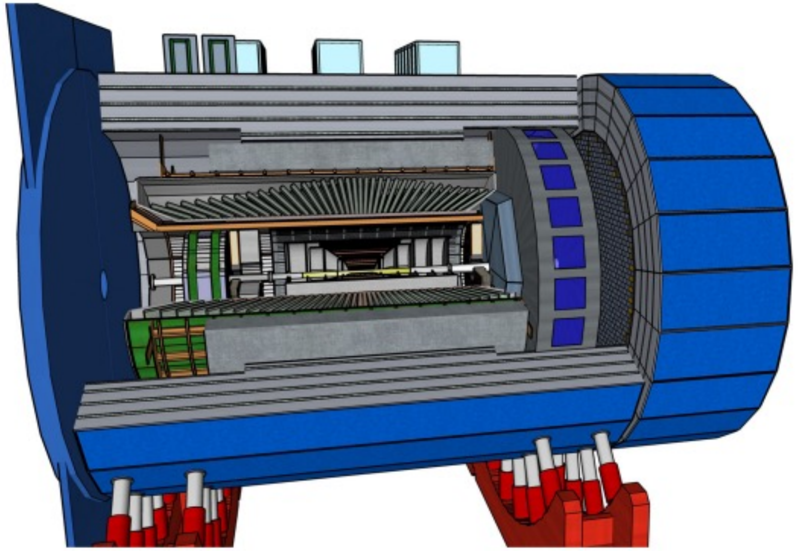


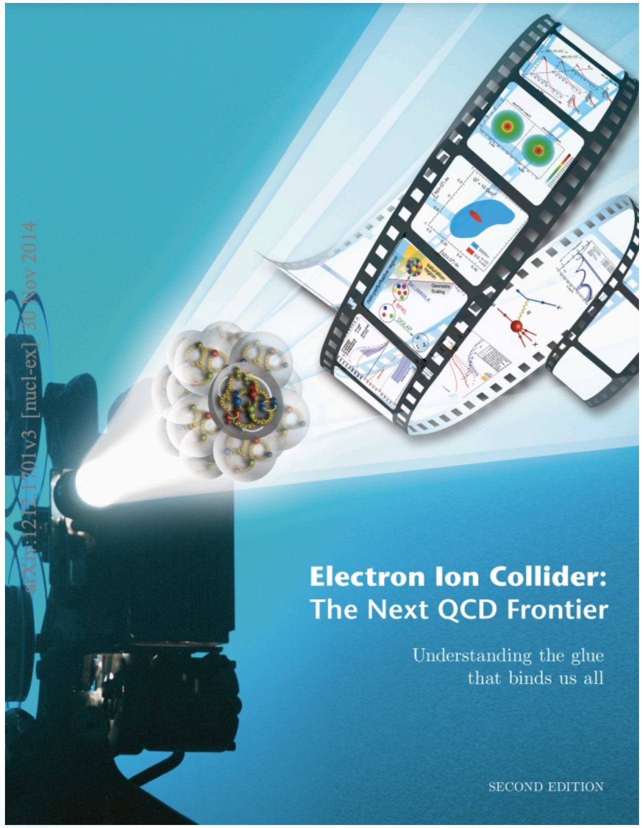
Simulation studies ongoing to fix detector designs

ePIC @EIC (2032-)

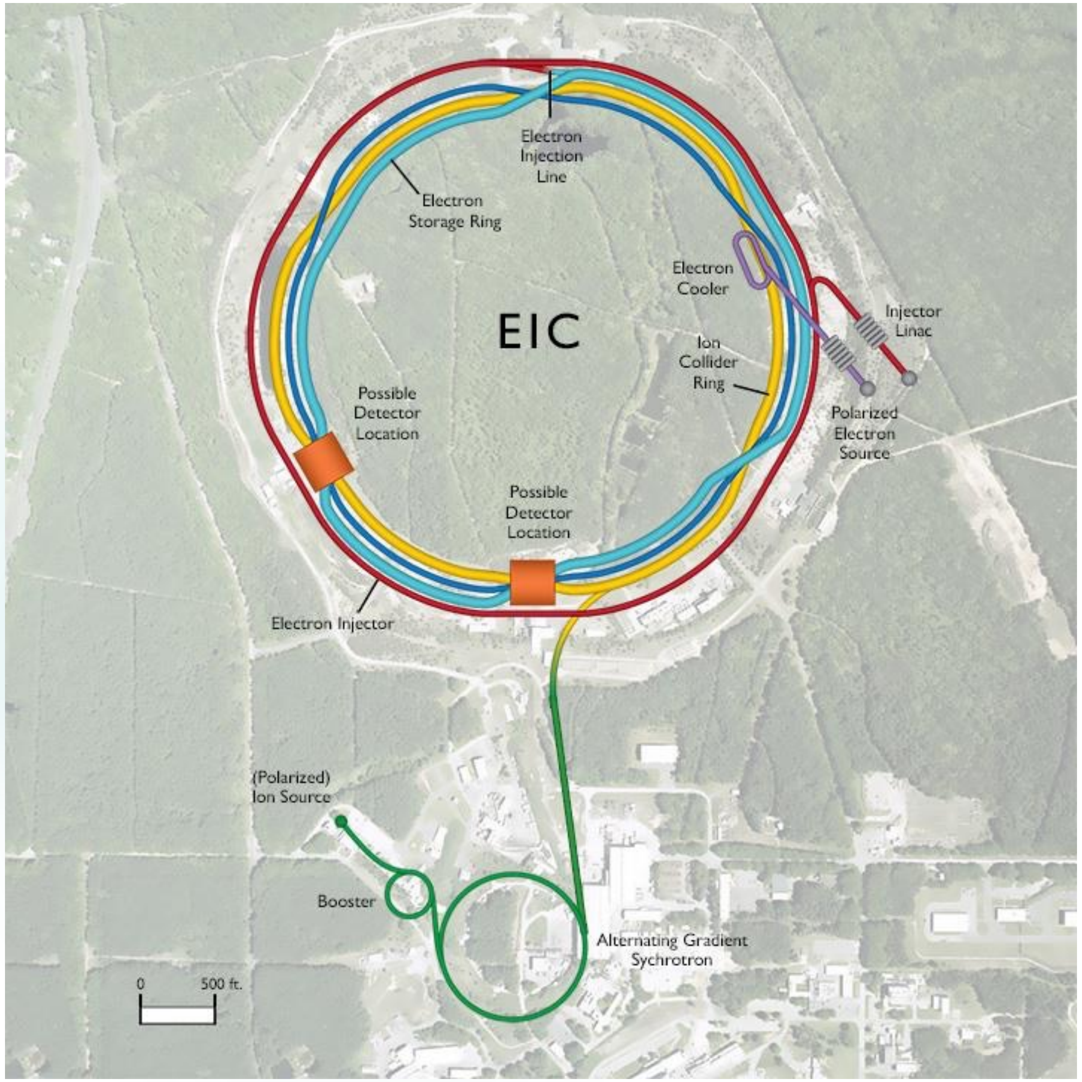
arXiv:1212.1701

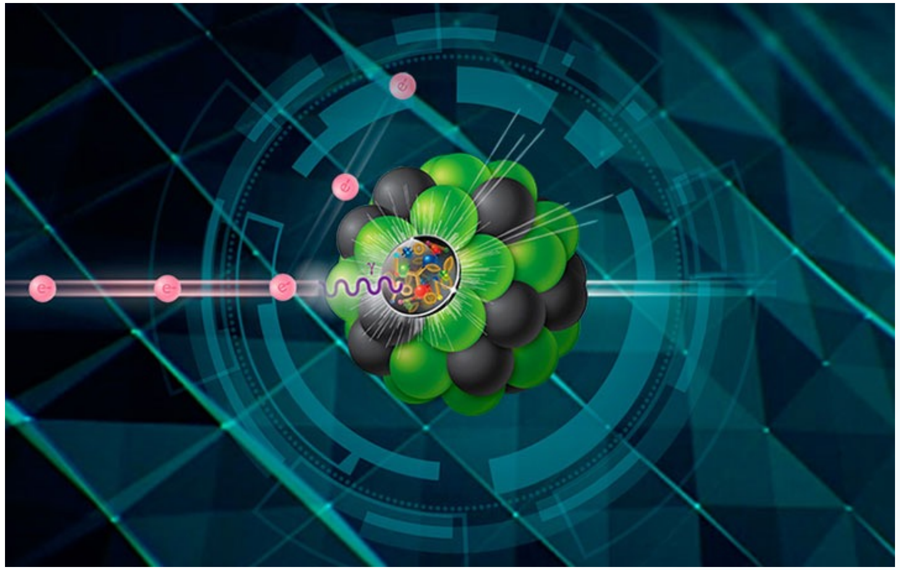






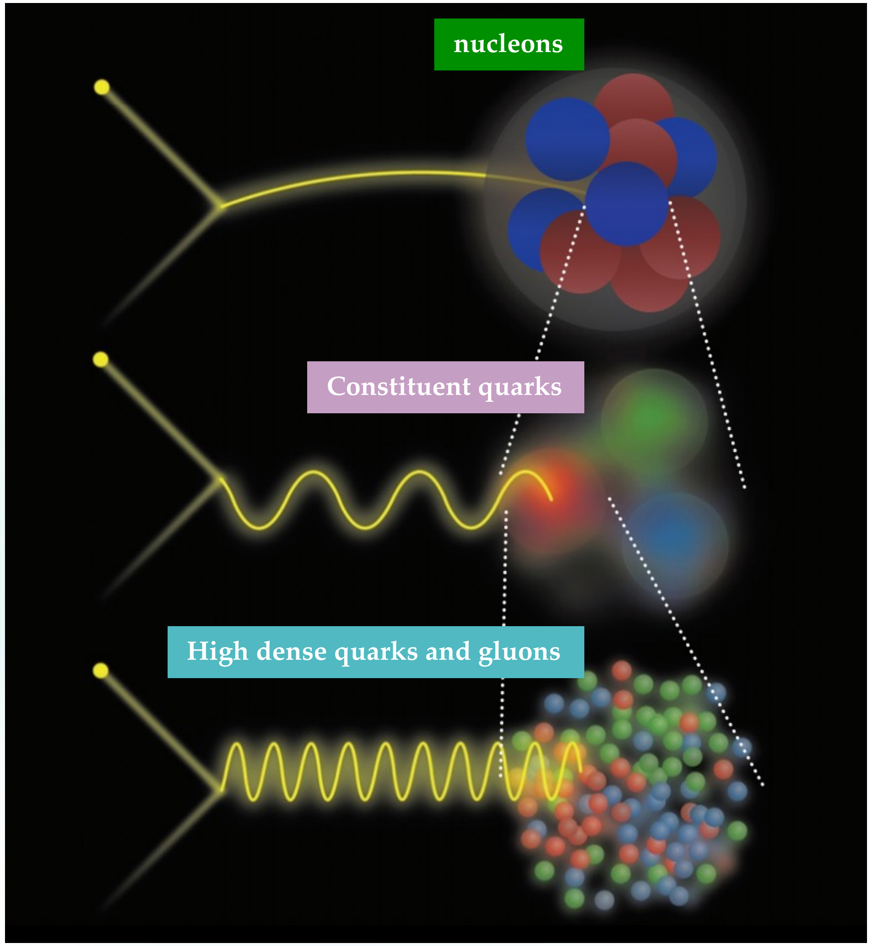
Electron Ion Collider

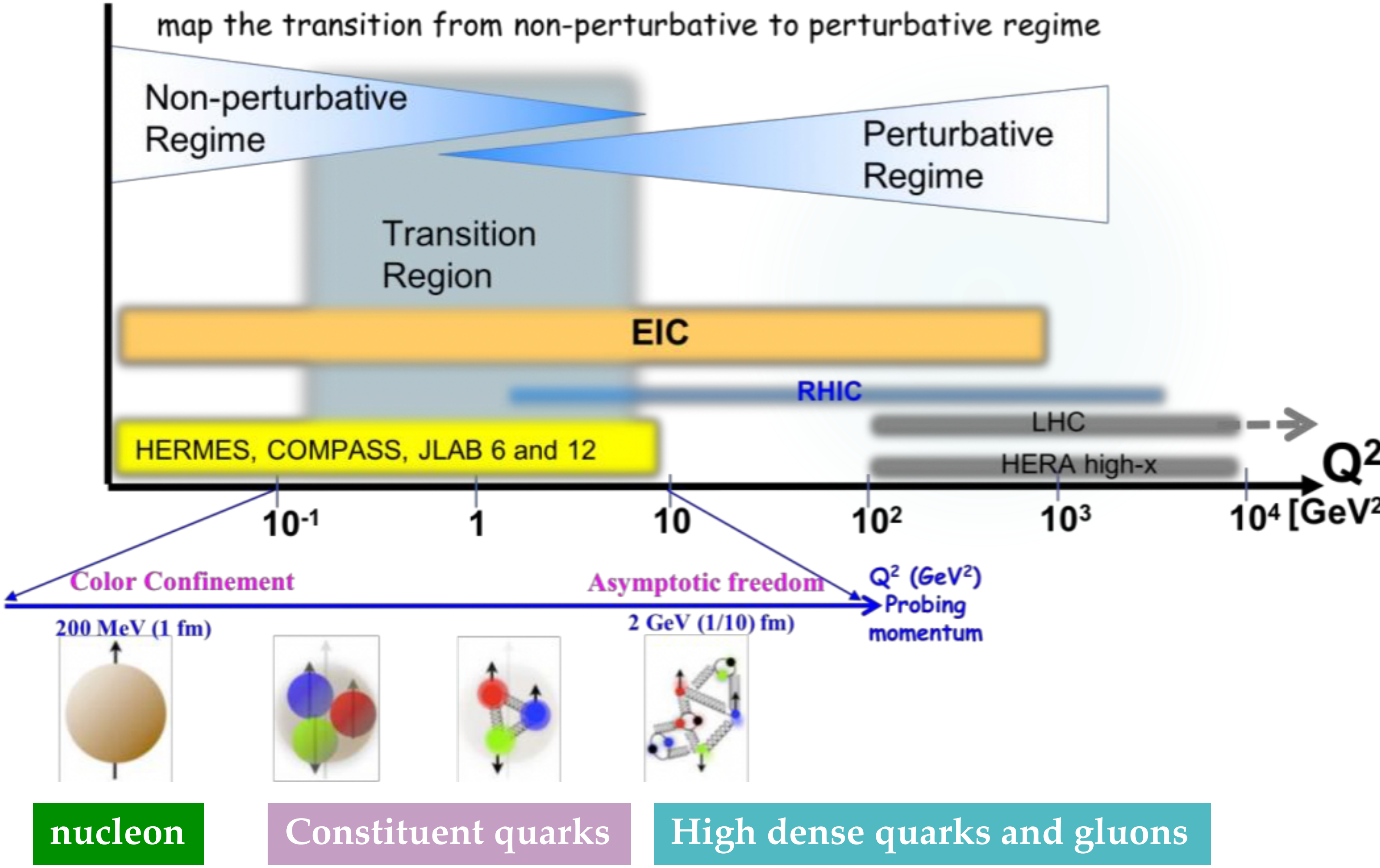




- EIC hosted at Brookhaven National Laboratory
- 80% polarized electrons from 5-18 GeV
- 70% polarized protons from 40-275 GeV
- Ions from 40-110 GeV/u
- Polarized light ions 40 -184 GeV (He^3)
- 100-1000 x HERA luminosities:10^{33}-10^{34} $cm^{-2}s^{-1}$
- CMS energies: $\sqrt{s}$ = 29–140 GeV
- CD1 obtained in July 2021

Electron Ion Collider

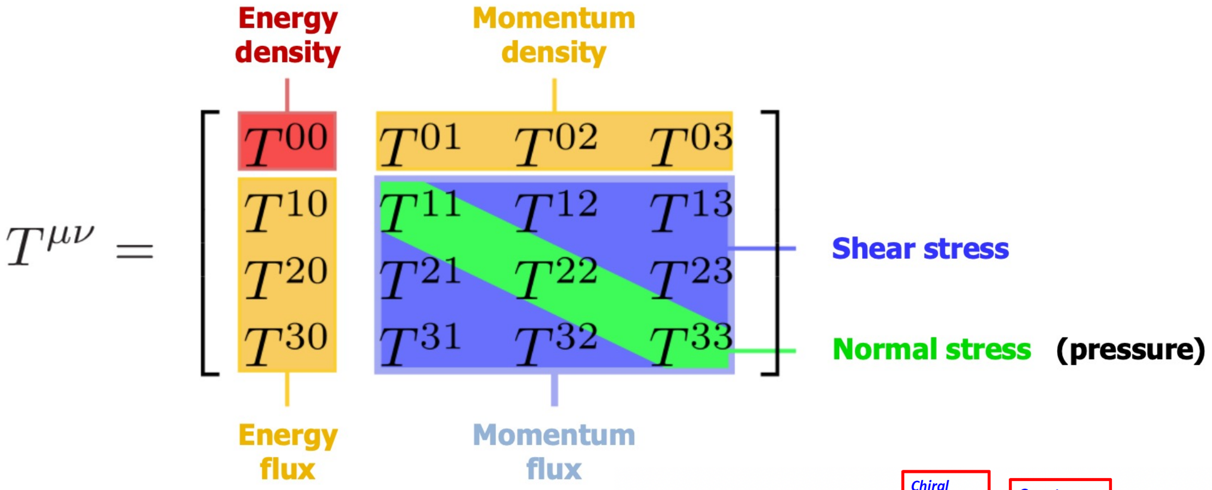


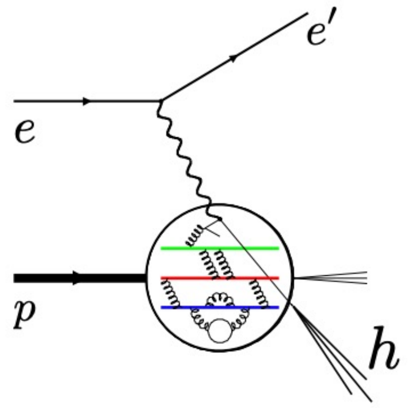


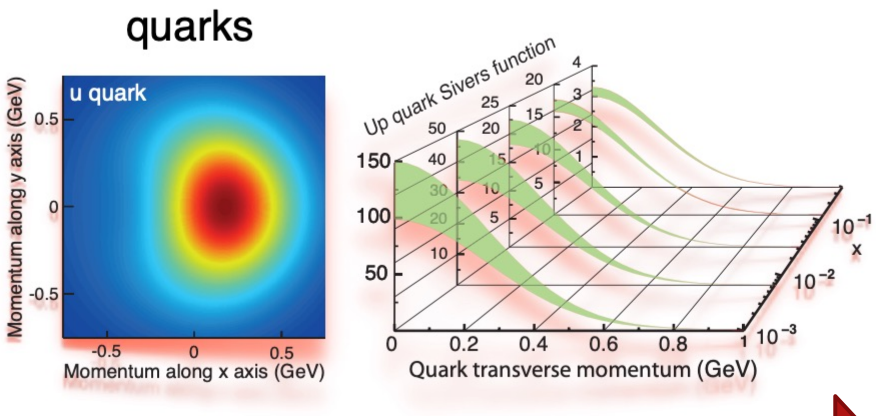
Covering wide Q^2 range → probing various degree of freedom

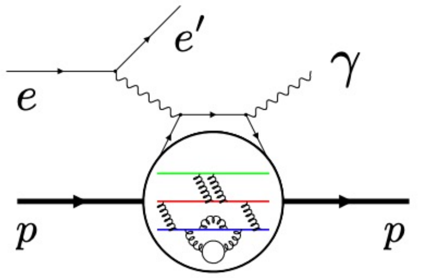
(some) Main Physics Goals at EIC

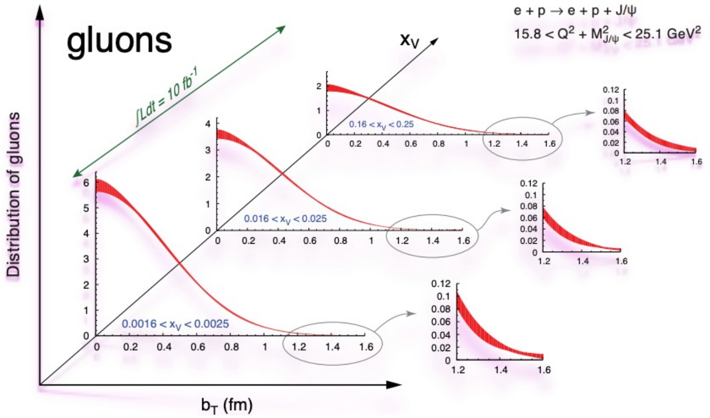
- 3D nucleon structure (Tomography)
  - Spatial distributions, transverse motion
  - Origin of mass and spin, confinement



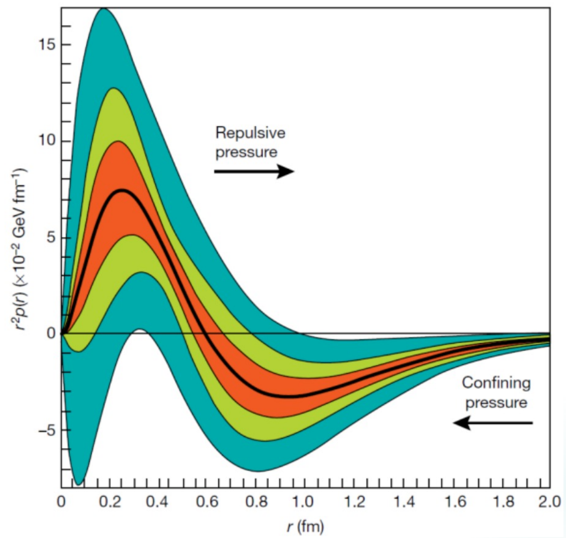


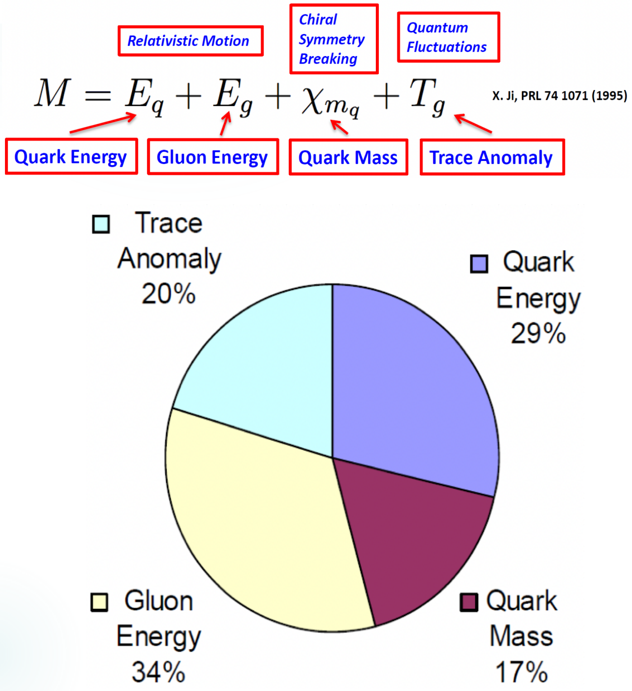






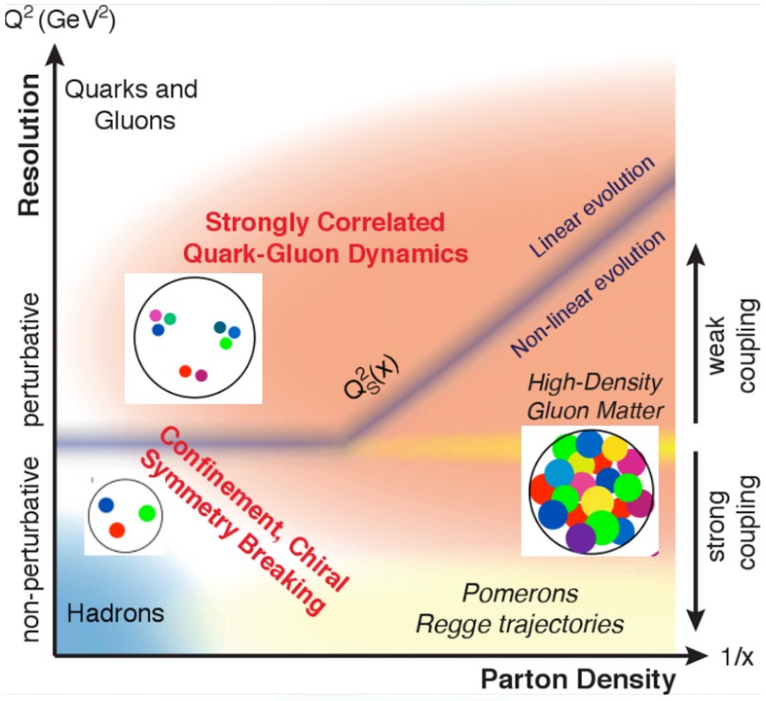
Burkert+, Nature 557, 396 (2018)

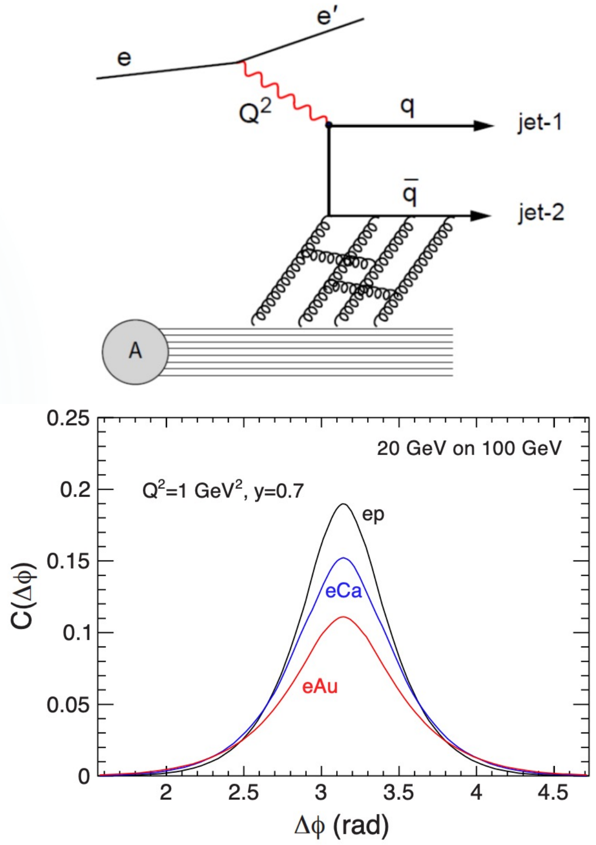


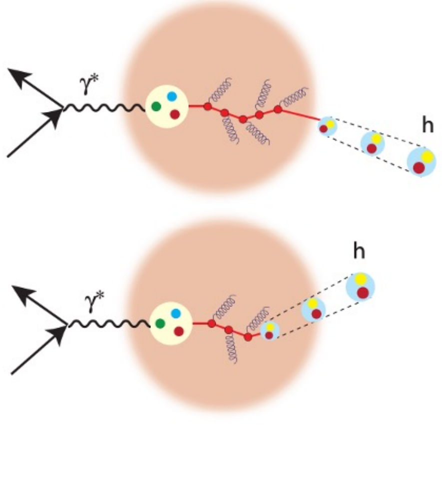


(some) Main Physics Goals at EIC

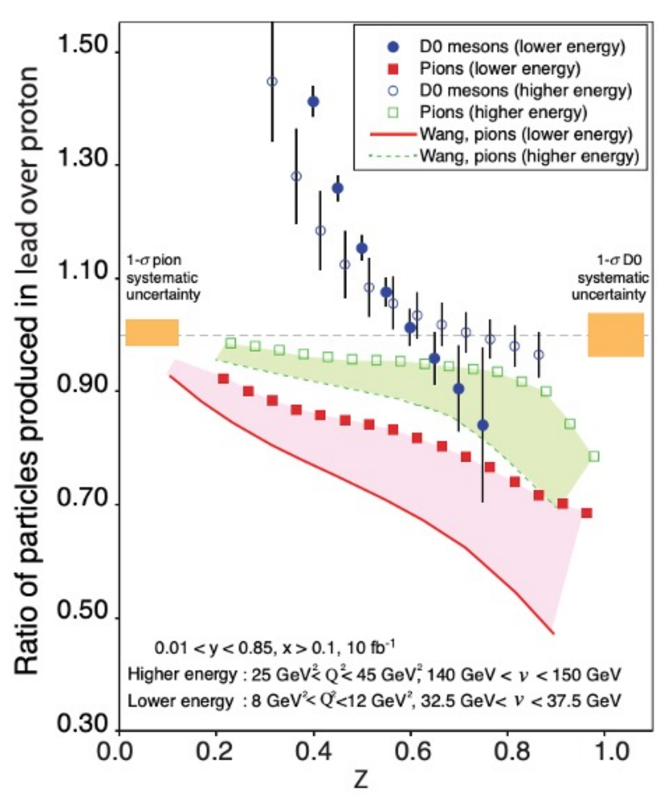
- QCD in nuclei
  - Gluon saturation at small-x
  - Color transparency, color propagation, medium effects, and hadronization





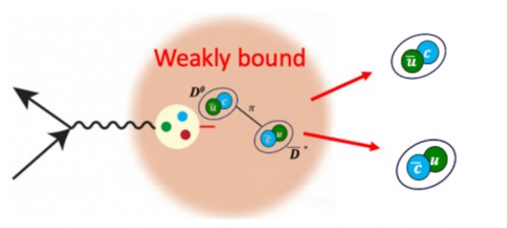


arXiv:1212.1701

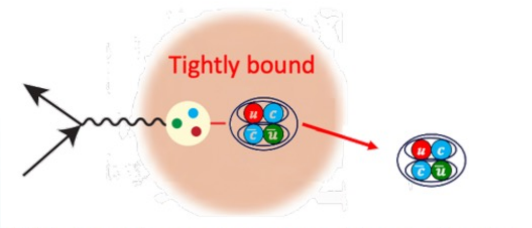


(some) Main Physics Goals at EIC

- **Exotic hadron spectroscopy**



Weakly bound hadronic molecule has large radius, samples large volume of nucleus



Tightly bound compact tetraquark has small radius, could more easily escape nucleus unscathed

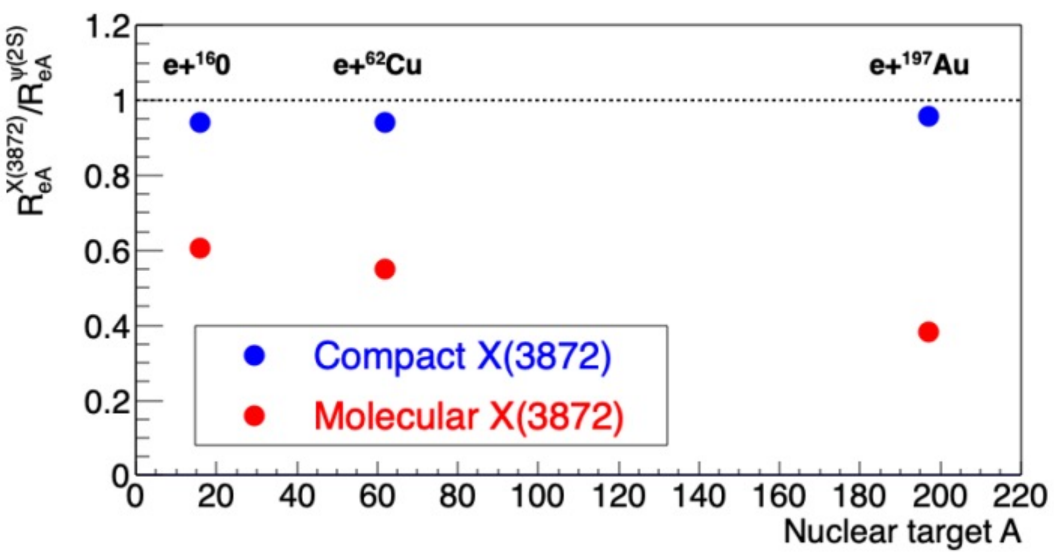


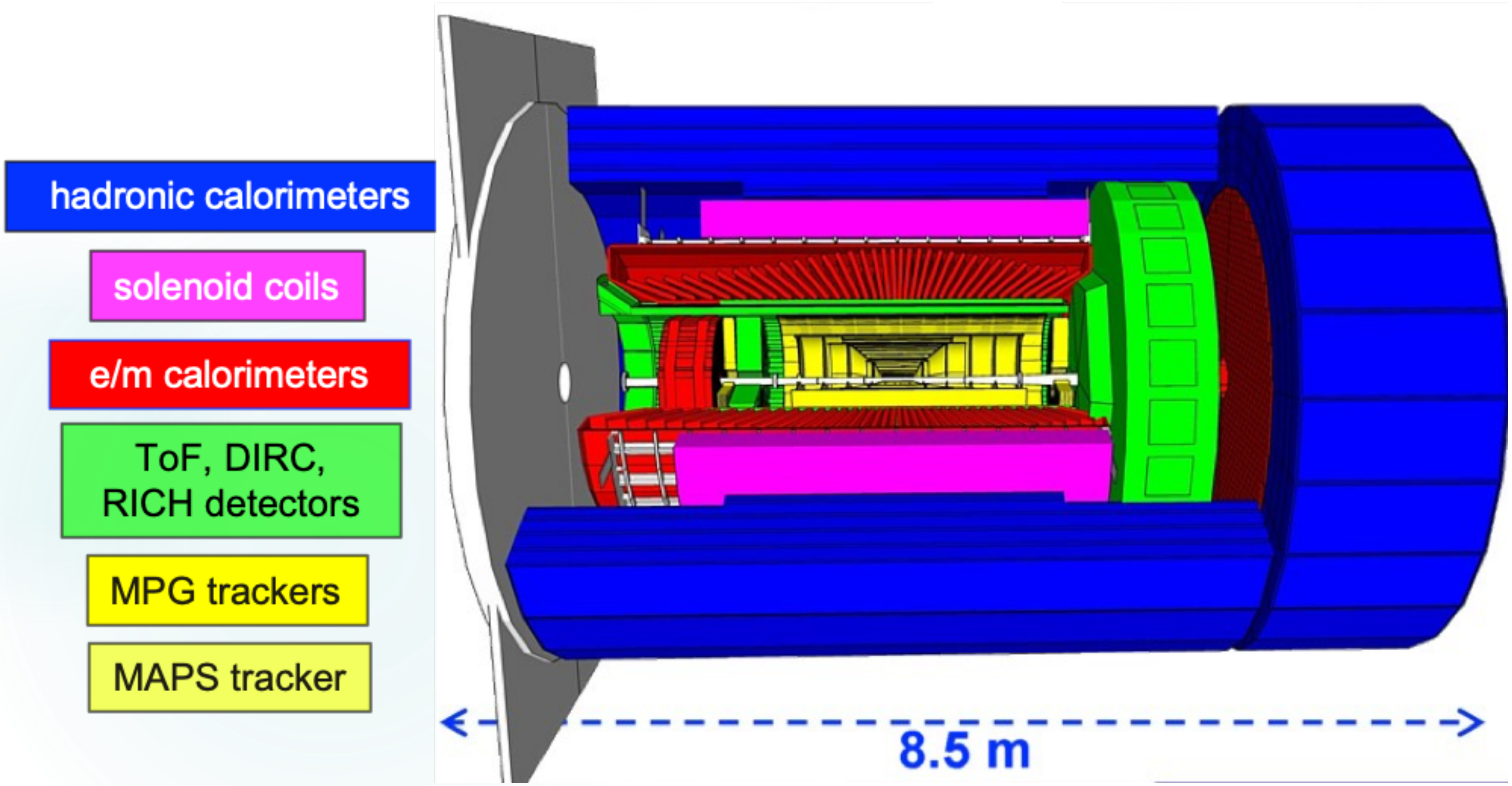
TABLE II: Integrated cross sections (in units of pb) for $l + p \to$ HM+all, where HM = $X(3872)$, $Z_c(3900)^{0/+}$, $Z_c(4020)$, and seven P_c states. The listed quantum numbers for these

	Constituents	$J^{P(C)}$	COMPASS	EicC	US-EIC
$X(3872)$	$D\bar{D}^*$	1^{++}	19(78)	21(89)	216(904)
$Z_c(3900)^0$	$D\bar{D}^*$	1^{+-}	$0.3\times10^3(1.2\times10^3)$	$0.4\times10^3(1.3\times10^3)$	$3.8\times10^3(14\times10^3)$
$Z_c(3900)^+$	$D^{*+}\bar{D}^0$	1^+	$0.2\times10^3(0.9\times10^3)$	$0.3\times10^3(1.0\times10^3)$	$2.7\times10^3(9.9\times10^3)$
$Z_c(4020)^0$	$D^*\bar{D}^*$	1^{+-}	$0.1\times10^3(0.5\times10^3)$	$0.2\times10^3(0.6\times10^3)$	$1.7\times10^3(6.3\times10^3)$
Z_{cs}^-	$D^{*0}D_s^-$	1^+	8.3(29)	19(69)	253(901)
Z_{cs}^{*-}	$D^{*0}D_s^{*-}$	1^+	6.2(22)	14(51)	192(679)
$P_c(4312)$	$\Sigma_c\bar{D}$	$\frac{1}{2}^-$	0.8(4.1)	0.8(4.1)	15(73)
$P_c(4440)$	$\Sigma_c\bar{D}^*$	$\frac{3}{2}^-$	0.6(4.3)	0.7(4.7)	11(79)
$P_c(4457)$	$\Sigma_c\bar{D}^*$	$\frac{1}{2}^-$	0.5(2.0)	0.6(2.2)	9.9(36)
$P_c(4380)$	$\Sigma_c^*\bar{D}$	$\frac{3}{2}^-$	1.6(8.0)	1.6(8.4)	30(155)
$P_c(4524)$	$\Sigma_c^*\bar{D}^*$	$\frac{1}{2}^-$	0.8(3.6)	0.8(3.9)	14(67)
$P_c(4518)$	$\Sigma_c^*\bar{D}^*$	$\frac{3}{2}^-$	1.2(6.6)	1.2(6.9)	22(123)
$P_c(4498)$	$\Sigma_c^*\bar{D}^*$	$\frac{5}{2}^-$	1.1(9.3)	1.2(9.8)	21(173)

There will be around X(3872) 4×10^5 events produced per day at US-EIC.
The branching fractions $B(X(3872)\to J/\psi\pi\pi) = (3.8 \pm 1.2)\%$, $B(J/\psi \to l^+l^-) = 12\%$ and assuming the detection efficiency to be 50%, then the reconstructed event numbers will be about 1000 per day for US-EIC.

arXiv:2107.12247

ePIC Detector Design (Current)



Tracking:

- New 1.7T solenoid
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

PID:

- hpDIRC
- mRICH/pfRICH
- dRICH
- AC-LGAD (~30ps TOF)

Calorimetry:

- SciGlass/Imaging Barrel EMCal
- PbWO4 EMCal in backward direction
- Finely segmented EMCal +HCal in forward direction
- Outer HCal (sPHENIX re-use)

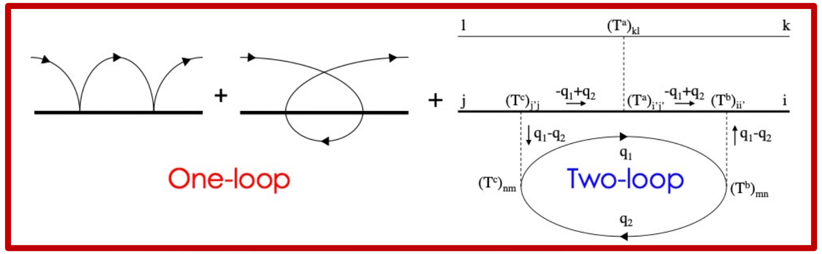
Summary

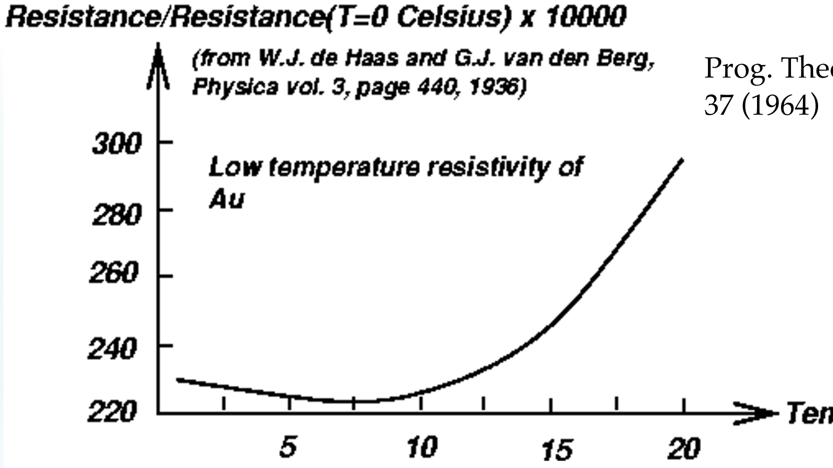
- Quark-cluster physics has been advanced by heavy-ion collisions at RHIC and LHC.
- Much deeper understandings of the QCD will be achieved during 2030s.
  - ALICE3@LHC(2035-): Quark-clusters at high-temperatures
    - New technologies
    - Chiral symmetry restoration
    - Heavy quark physics (transport properties, hadronizations, di-quark states)
  - CBM@FAIR (2030-) and J-PARC-HI : Quark-clusters at high density
    - phase transitions, chiral symmetry restoration by di-leptons
    - Color superconductors
  - ePID@EIC (2032-): Quark-gluon dynamics at high-energy
    - Evolution of quark-gluon dynamics in nucleons and nuclei in (x, Q^2)
      - Emergence of new degree of freedom (nucleon -> constituent quarks -> high dense quark and gluon matter)
      - Energy-momentum tensor → Color confinement (pressure) and origin of proton mass and spin
      - Properties of high dense gluon matter
    - Exotic hadrons
- Good to keep a close collaboration with different hierarchies

backup

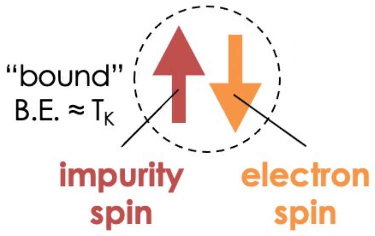
QCD Kondo effect

Stronger interaction between light and heavy quarks (impurity)
→ Measure of bulk properties of quark matter at high density

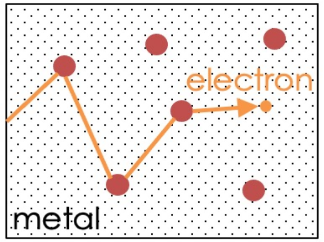




Prog. Theor. Phys. 32, 37 (1964)



Impurity atom with spin ½ with $T^a \cdot T^a$ interaction



S.Y., S. Ozaki, arXiv:1710.03434 [hep-ph]

Phys. Rev. D 96, 114027 (2017)