From

Bridging Quark and Hadron Hierarchies

to

Even Broader View of QCD World

Kenta Shigaki

（Hiroshima U. 広島大学）

International Symposium on

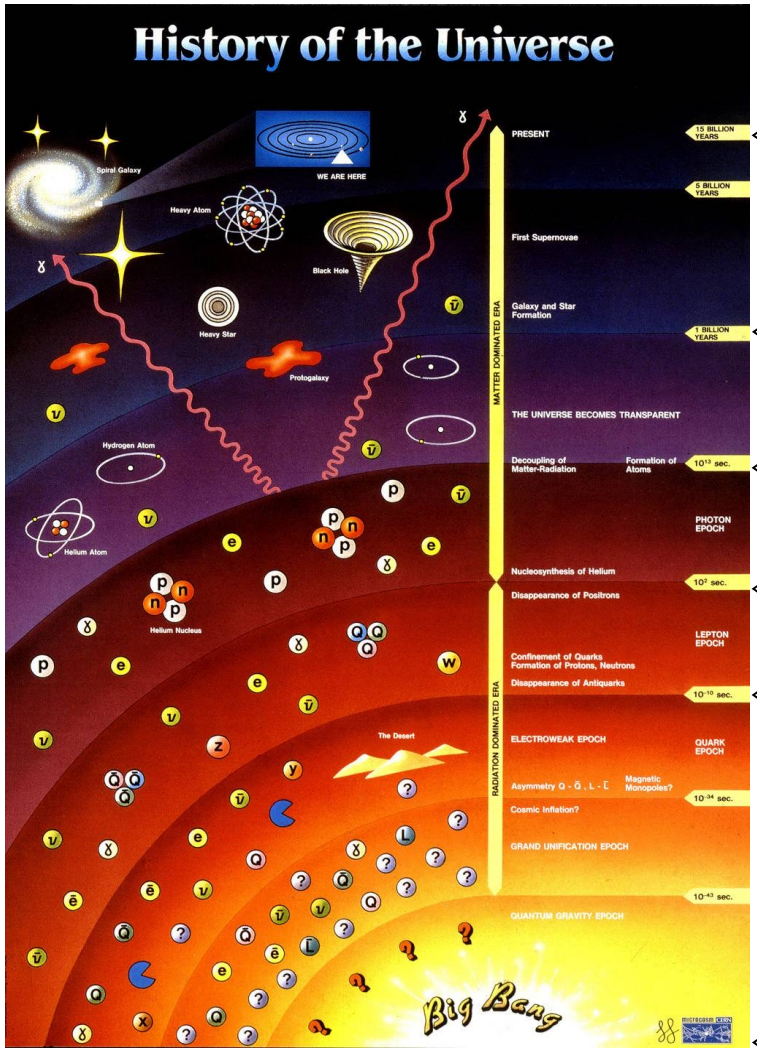
Clustering as a Window on the Hierarchical Structure of Quantum Systems

31 October 2022, Sendai International Center, Miyagi, Japan

Presentation Outline

- appreciation to collaboration/grant
  - "dynamics to bridge quark and hadron hierarchies"
- project goals and outcome
- ALICE "run 3" started in 2022
  - new detectors toward e + μ *Aufheben*
  - physics status and prospects
- multi-visional approach to QCD phenomena
- summary and concluding remarks

History/Hierarchy of Universe/Matter



14 by CLUSHIQ 2022

1 by star/galaxy formation

10^{12} s atom formation

10^{2} s nuclei synthesis

10^{-6} s quark confinement
anti-quark annihilation
quark pair production

0.00 s Big Bang

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Clusters & Hierarchies

Mission in This Collaboration/Grant

- dynamics to bridge quark and hadron hierarchies

Contact Sitemap Japanese

科研費 Grant-In-Aid for Scientific Research on Innovative Areas

Clustering as a window on the hierarchical structure of quantum systems

Clusters & Hierarchies

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- Publication
- Link
- News
- Members Only

Link

理化学研究所 RIKEN NISHINA CENTER

j-PARC

ハドロン実験施設 j-PARC

Research Groups

A01 Dynamics to bridge quark and hadron hierarchies (PI:Kenta Shigaki, Hiroshima University)

A02 Elucidation of hierarchical structure between quark and hadron phases by means of quark clusters (PI: Hiroaki Ohnishi, Tohoku University)

B01 Clusters of strange hadrons for investigating hierarchical structure of matter (PI: Hirokazu Tamura, Tohoku University)

B02 Exotic nuclei for investigating hierarchical structure of matter (PI: Takashi Nakamura, Tokyo Institute of Technology)

C01 Ultracold atom study of exotic phenomena bridging different hierarchies (PI: Yoshiro Takahashi, Kyoto University)

C02 Universal physics of quantum matter at the change of the hierarchy and the state (PI: Munekazu Horikoshi, Osaka City University)

D01 Emergence mechanism of hierarchical structure of matter studied by ab-initio calculations (PI: Emiko Hiyama, Kyusyu University)

A01 Dynamics to bridge quark and hadron hierarchies

PI:
Kenta Shigaki (Hiroshima University)

We aim at elucidating the behavior of deconfined quarks and the dynamics of hadron formation at the ALICE experiment at CERN in Switzerland. Quarks are freed from confinement inside hadrons and turn into the Quark Gluon Plasma phase in high energy nucleus-nucleus collisions. Chiral symmetry restoration phenomena are expected with modified strongly coupled quark pair condensate in the transitions to the high temperature quark phase and back to hadrons. Semi-clusters bridging the quark and hadron hierarchies are looked for, utilizing rare phenomena characteristic and unique to this type of experiments, such as flavor dependent inter-quark interaction up to beauty quarks and production of exotic hadrons via recombination of quarks. The physics goals are only to be reached by measurements in the next stages with unprecedented precision and statistics covering wide kinematic regions. The ALICE detector is hence upgraded with an improved main tracking detector, a new forward tracker, and higher speed data taking, toward its third physics operation from 2021. The A01 plays the key role to unravel the most basic hierarchies of the many in the nature, which this entire Kakenhi project attacks.

Between Quark/Hadron Hierarchies

- What: two main dynamics!
  - quark and gluon confinement into hadron
  - hadron mass generation
- how: relativistic nucleus-nucleus collisions
  - unique and established experimental tool
- Where: CERN LHC ALICE
- When: “run 3” in 2022 (originally 2021)–2024
- Who: A01 research team of this “innovative” grant

Project Scope and Members

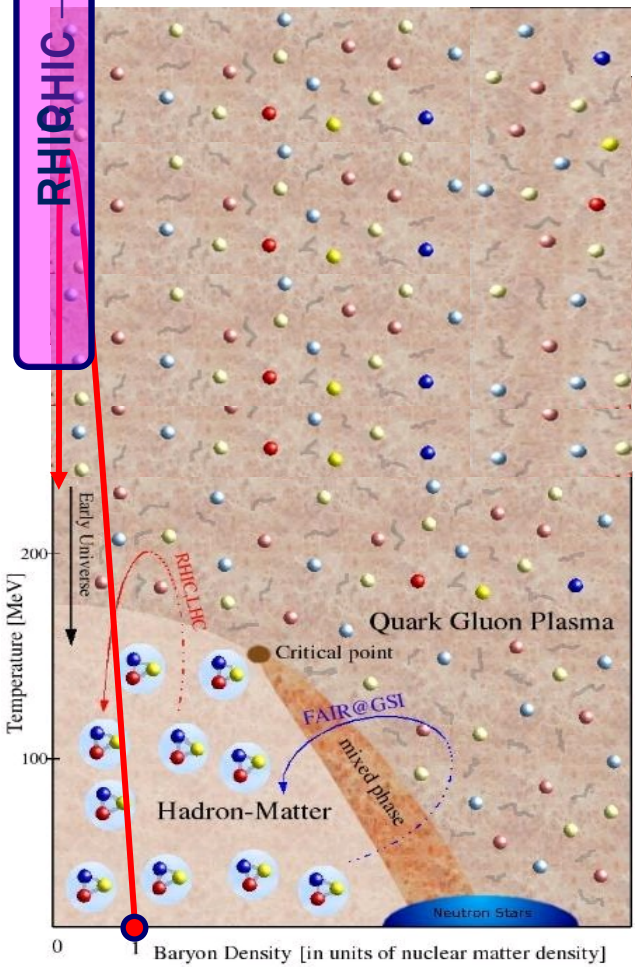
- new forward tracking detector
  - principal investigator **Kenta Shigaki** (Hiroshima)
  - research collaborator **Yorito Yamaguchi** (Hiroshima)
- main tracking detector upgrade
  - co-investigator **Taku Gunji** (Tokyo)
- data handling scheme upgrade
  - co-investigator **Hideki Hamagaki** (Nagasaki IAS)
- computing grid core facilities
  - co-investigator **Tatsuya Chujo** (Tsukuba)
  - project researcher **Masanori Ogino** (Hiroshima)
- conducting experiment, physics analysis
  - everyone listed above
  - research collaborator **Maya Shimomura** (Nara Women's)



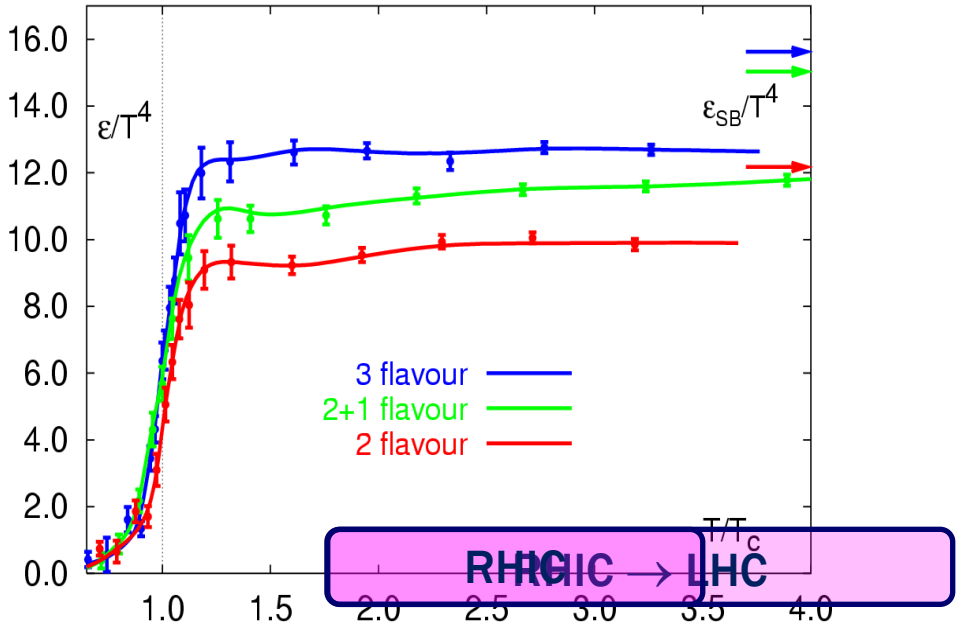




Hadron ⇄ Quark/Gluon Round Trip



F. Karsch,
Lect. Notes Phys. 583, 209 (2002)



Quark/Gluon (De-)Confinement

hadron

deconfinement

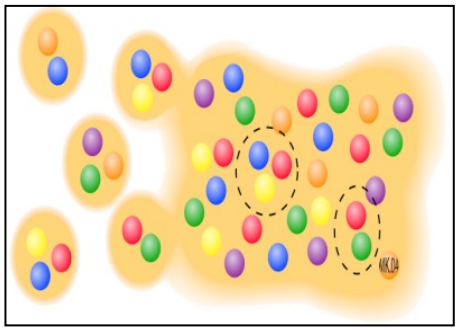
confinement
(hadronization)

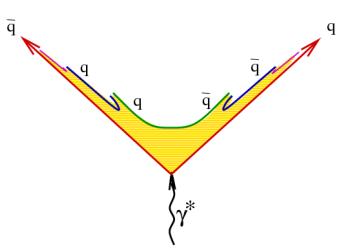
quark/gluon

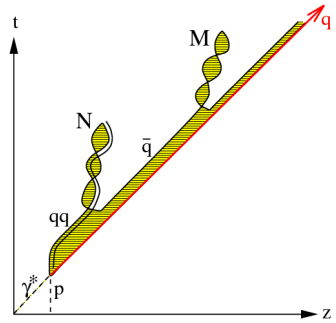
exotic hadron

Unique Mechanism of Q/H Transition

- different mechanisms of hadron production
- quark recombination/coalescence
  - s quark chemical potential ~ 0 at RHIC/LHC
  - late recombination up to c quarks (*e.g.* J/ψ) at LHC







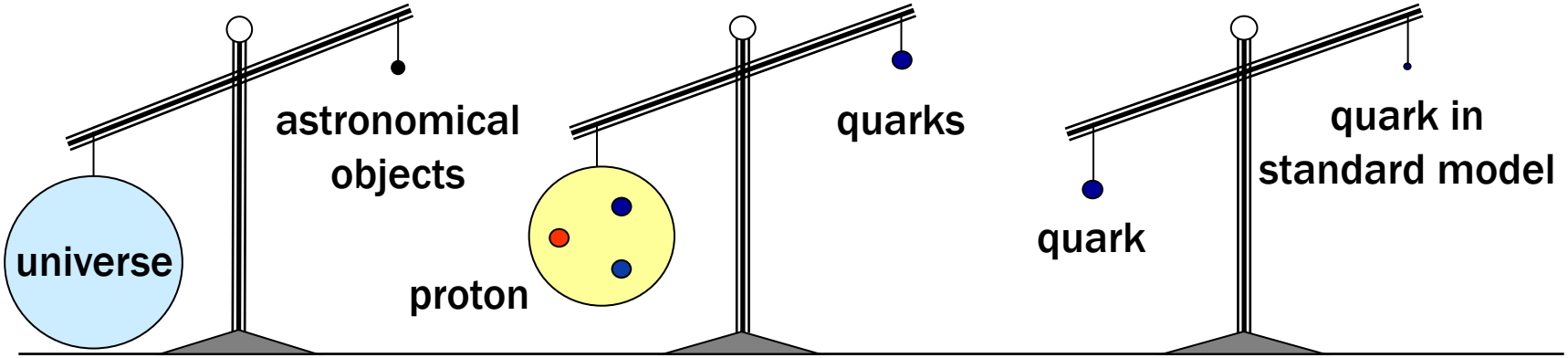
B. Z. Kopeliovich *et al.*,
Int. J. Mod. Phys. E18, 1629 (2009)

- quark pair production (color string fragmentation)
- suitable for exotics, *e.g.* multi-s/c/b systems

(Hadronic) Mass Generation

- total mass = sum of components' masses?

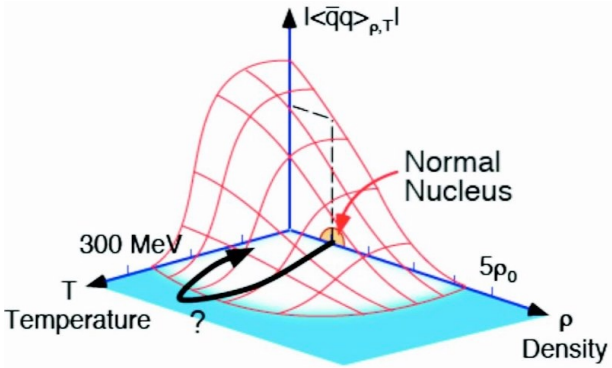
original cartoon from T. Hatsuda

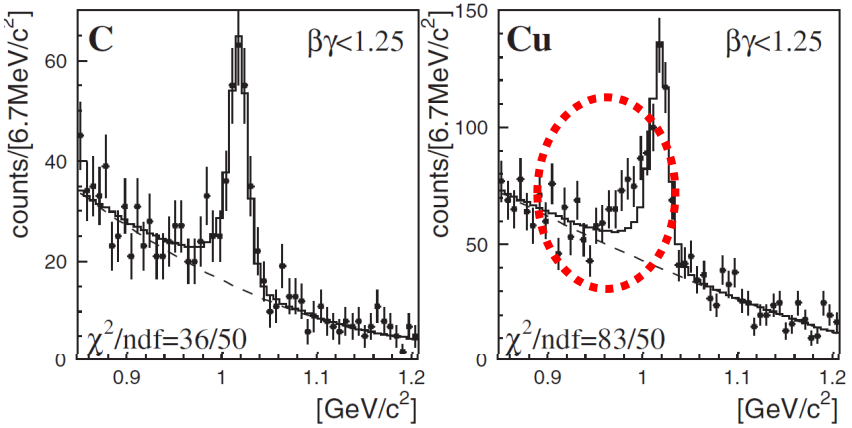


matter	5 %	quark mass	1%	quark mass in standard model = 0
dark matter	27 %	chiral symmetry breaking		BEH mechanism
dark energy	68 %			

Unique Dynamics at Q/H Transition

- chiral symmetry restoration
- "observed" in finite density regime
  - φ, ω in nuclei via *p*A (KEK E325)
    - though apparent contradiction to CB-ELSA/TAPS and CLAS-G7
  - π in nuclei via (*d*, ^{3}He)



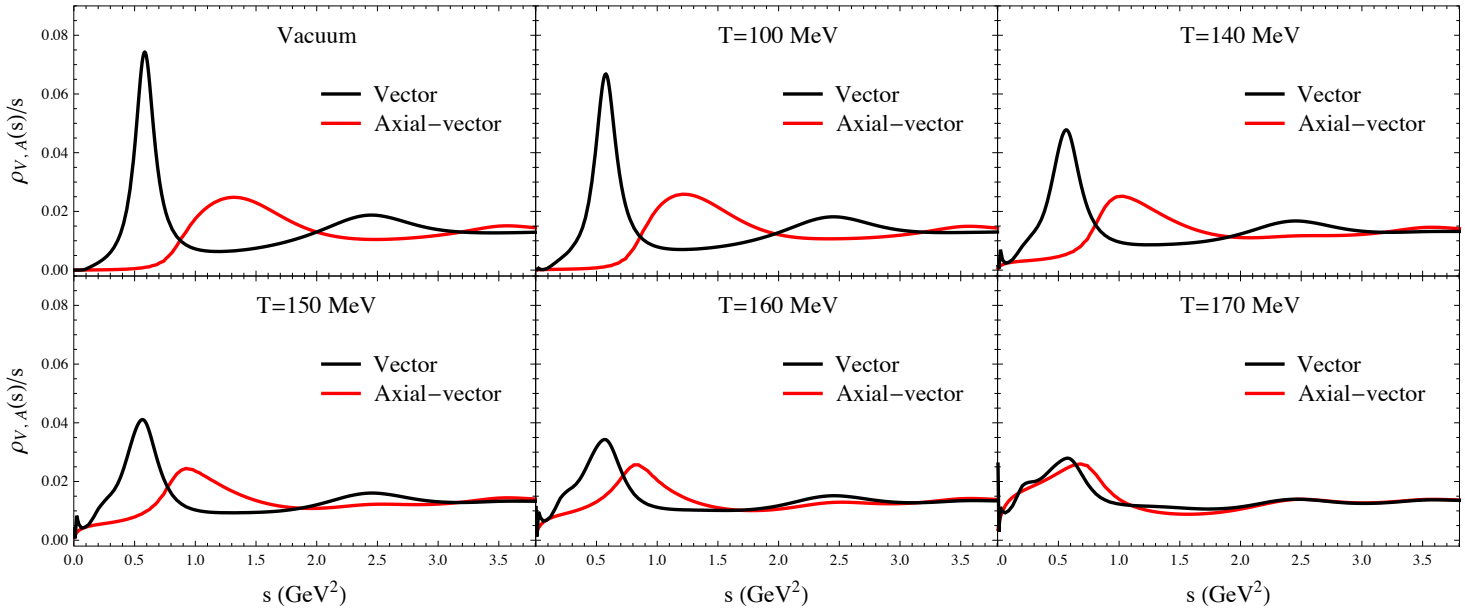


R. Muto *et al.*, Phys. Rev. Lett. 98, 042501

- no evidence in high temperature regime yet
  - challenging di-lepton measurements

Hadron Mass (Spectral) Modification

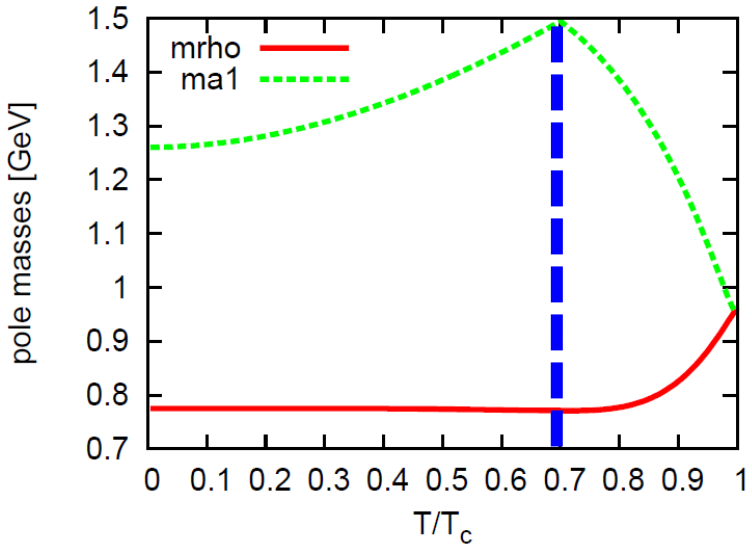
- light vector mesons (ρ, ω, φ): beloved probe
  - good old simple scenarios
  - more complicated spectral modification



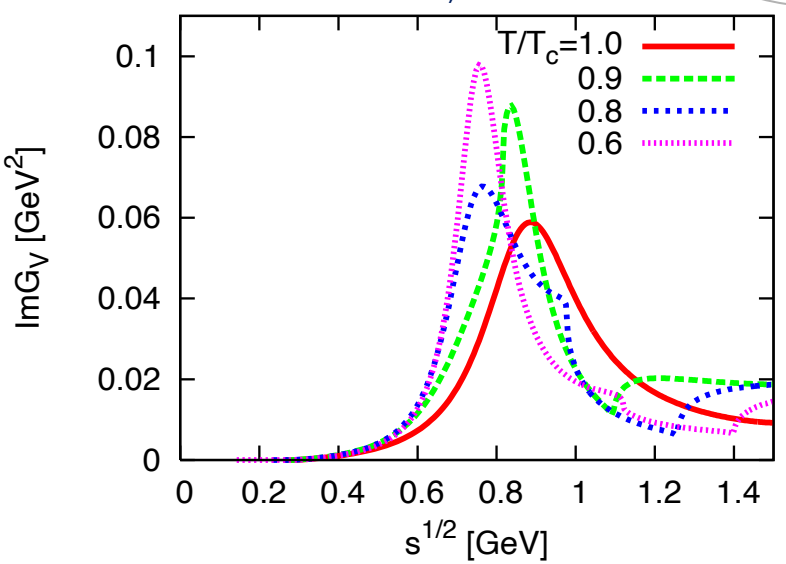
P.M.Hohler *et al.*, J. Phys. Conf. Ser. 535, 012024 (2014)

Chiral Mixing and Degeneracy

- $\rho(770)$ vs $a_1(1260)$, $\omega(782)$ vs $f_1(1285)$



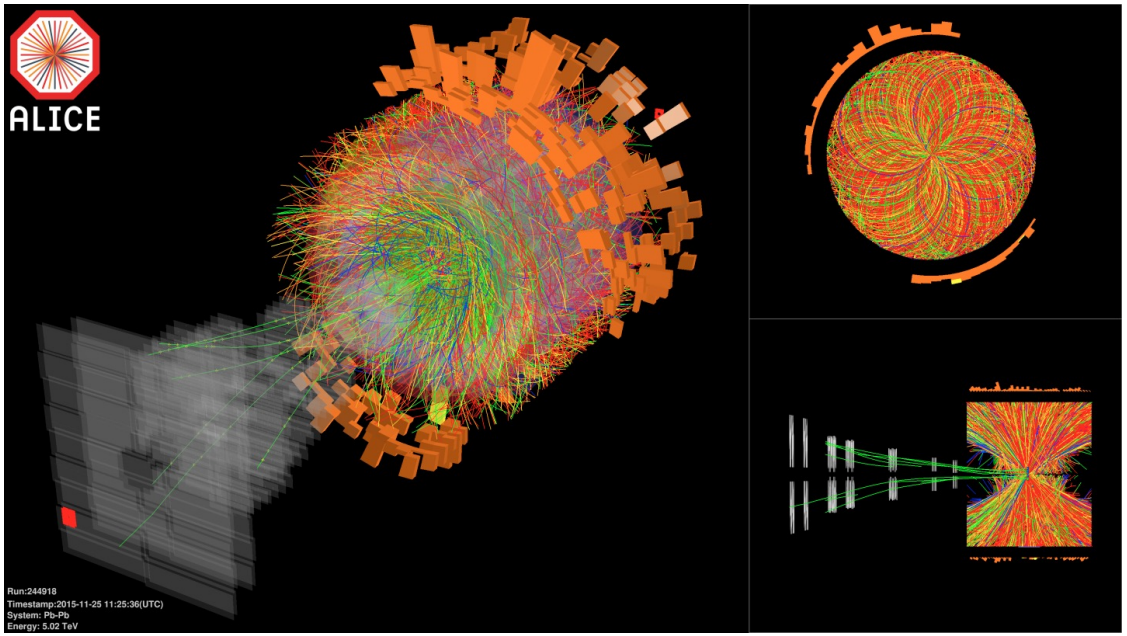
M. Harada and C. Sasaki, arXiv:1003.0331



- long time favorite of theorists
  - though additional experimental challenges
- new focus with improved resolution and statistics

Most Energetic Heavy Ion Collisions

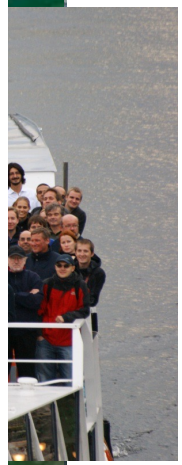
- 5 TeV per nucleon-nucleon pair at CERN LHC
  - latest Pb+Pb in 2018 (run 2 = 2015–2018)
  - 25 times higher than at BNL RHIC



- design energy at 5.5 TeV in near future

A Large Ion Collider Experiment

- *the* nucleus-nucleus collision experiment at LHC
- 40 countries; 172 institutes; ~2,000 members



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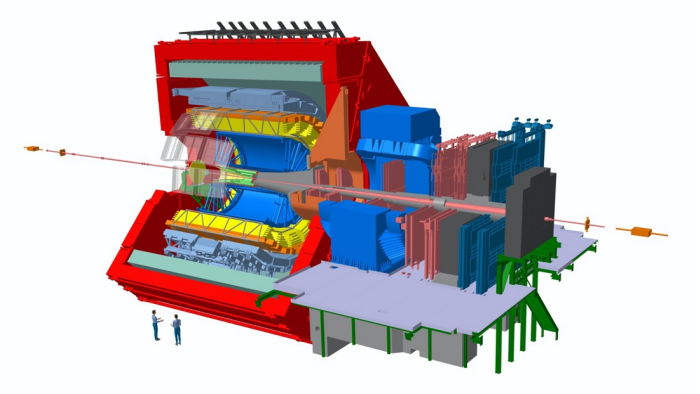
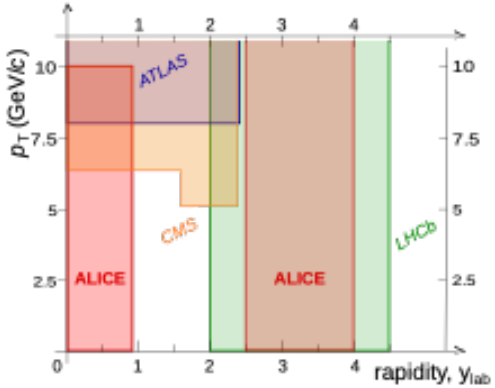
Clusters & Hierarchies

Where We Stand

- LHC: hotter, larger, longer-lived, purer fireball
  - *cf.* RHIC: systematic studies (collision species, energy)
- ALICE: dedicated to nucl.-nucl. physics and probes

  ← based on knowledge at AGS, SPS, RHIC
  - wide kinetic coverage down to low p_T
  - well-identified hadron, lepton, photon measurements





example:
J/ψ acceptance
in Run 1 *p*+Pb

- core player through 2030 (and beyond)

LHC Run Schedule (after Covid-19)

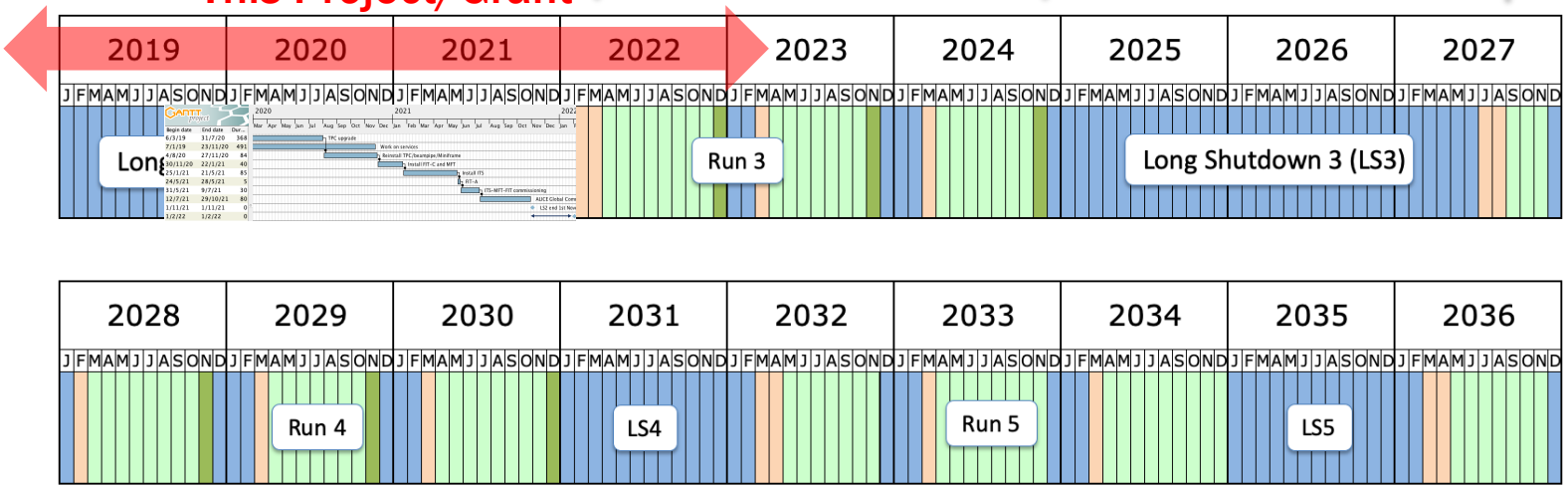
7.0 TeV proton beam *p*+*p*, *p*+Pb, Pb+Pb

LHC luminosity upgrade
ALICE upgrade & speeding up

Run 3

LHC high luminosity upgrade
ALICE upgrade

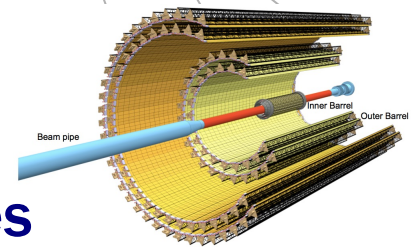
This Project/Grant

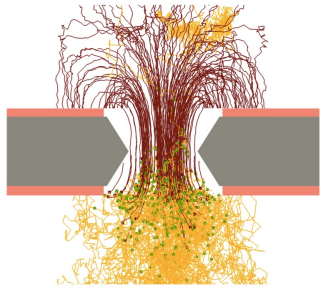


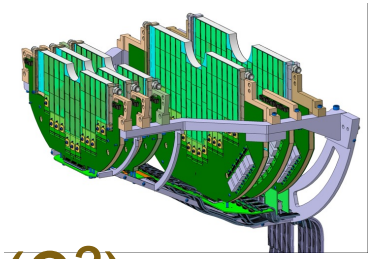
Run 4

7.0 TeV proton beam
p+*p*, *p*+Pb, Pb+Pb

Run 3 (2022–2024) Upgrades



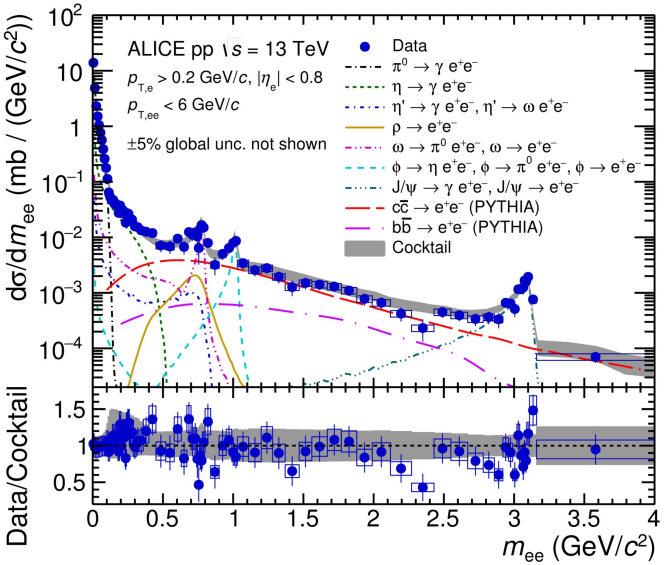


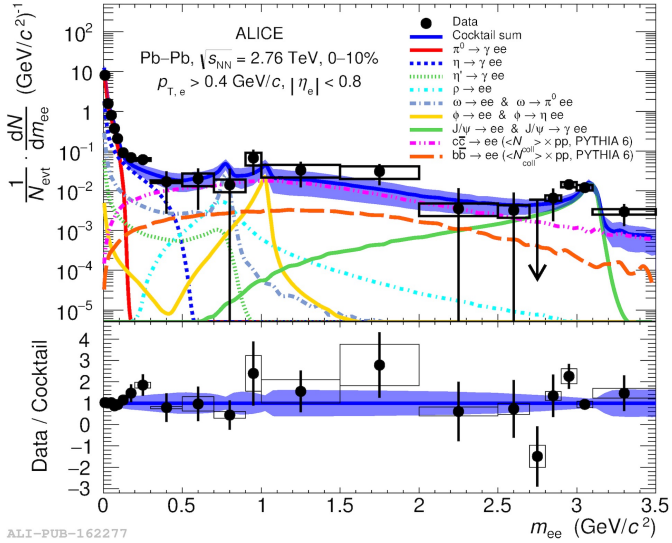


- new inner tracking system
  - 7 layers of MAPS silicon pixel detectors
  - precise measurement of displaced vertices
    - to separate charm/beauty mesons
- new TPC readout chambers
  - GEM technology with no gating grid
  - ~100 times higher data taking rate (50 kHz in Pb+Pb)
    - continuous readout without triggering
- Muon Forward Tracker (MFT)
- integrated online/offline data handling (O^2)

Dielectrons (Japanese Specialty)

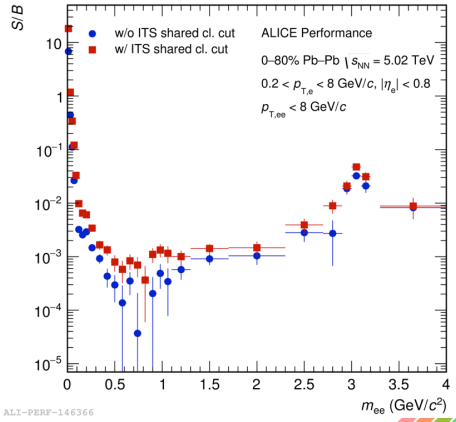
- results from ALICE runs 1, 2 (2009–2018)





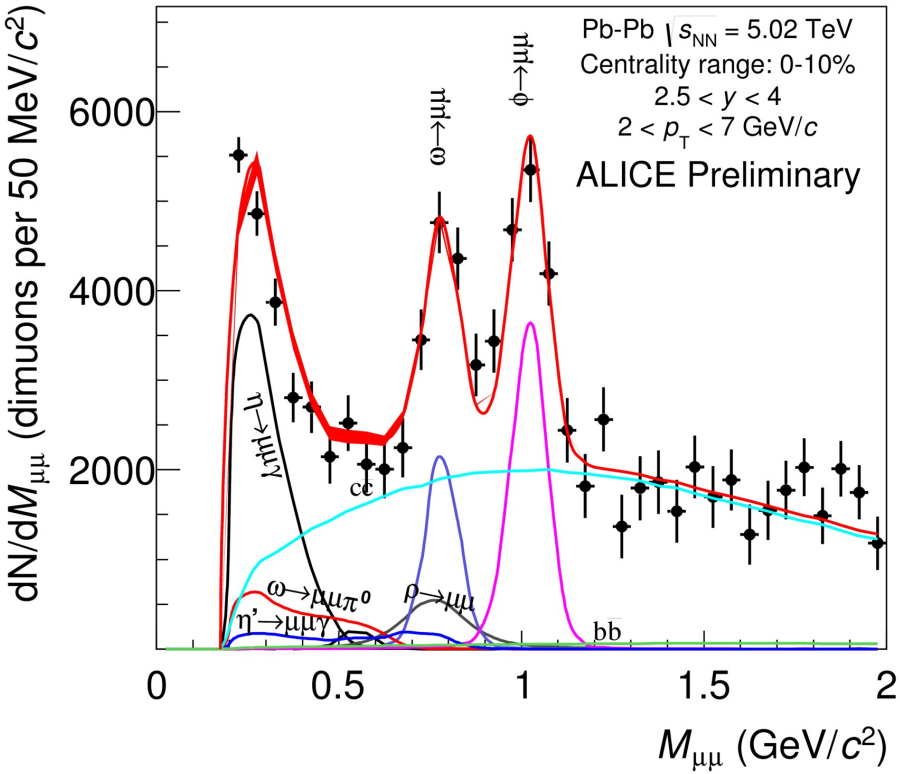
ALICE,
Phys. Lett. B 788, 505 (2019)
Phys. Rev. C 99, 024002 (2019)

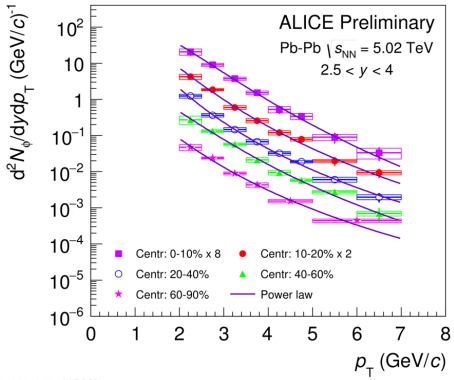
- very challenging S/B ratio in Pb+Pb

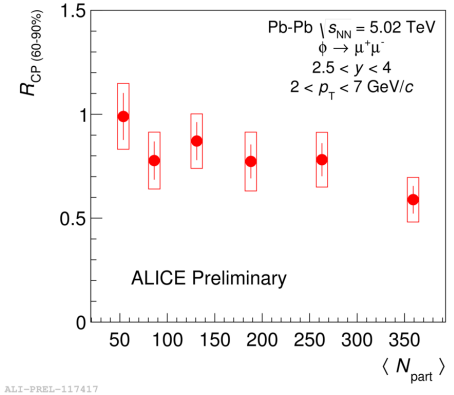


Low Mass (Low p_T) Dimuons at ALICE

- clean low mass (ϕ, ω, ρ) $\mu^+\mu^-$ measurement
  - new challenge toward low p_T with upgraded detector
- to be combined with more traditional e^+e^-

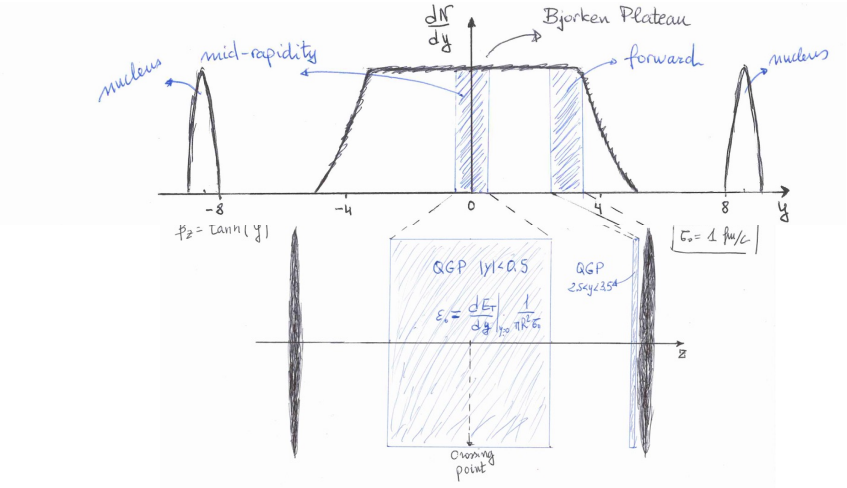


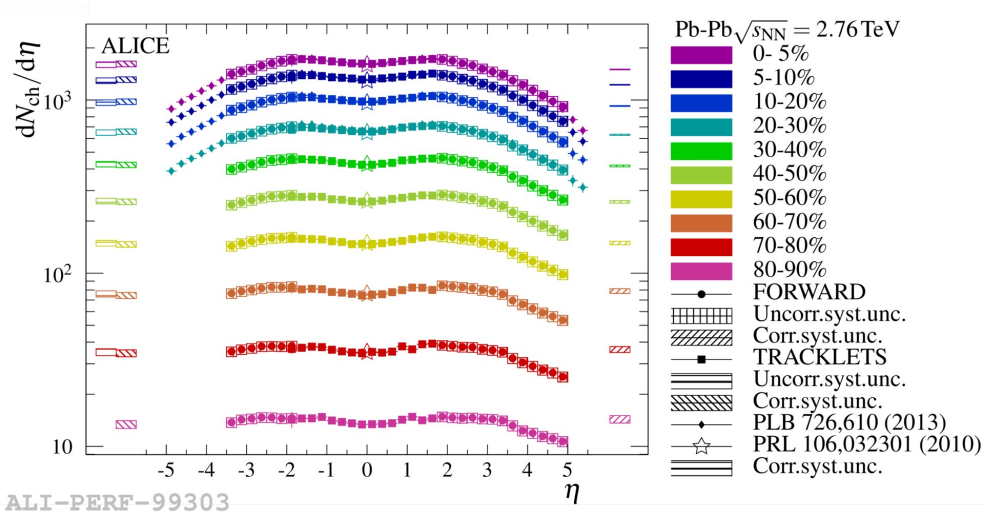




Aufheben of e + μ Measurements

- two interesting regimes of quark-gluon phase
  - exploration on QCD phase diagram

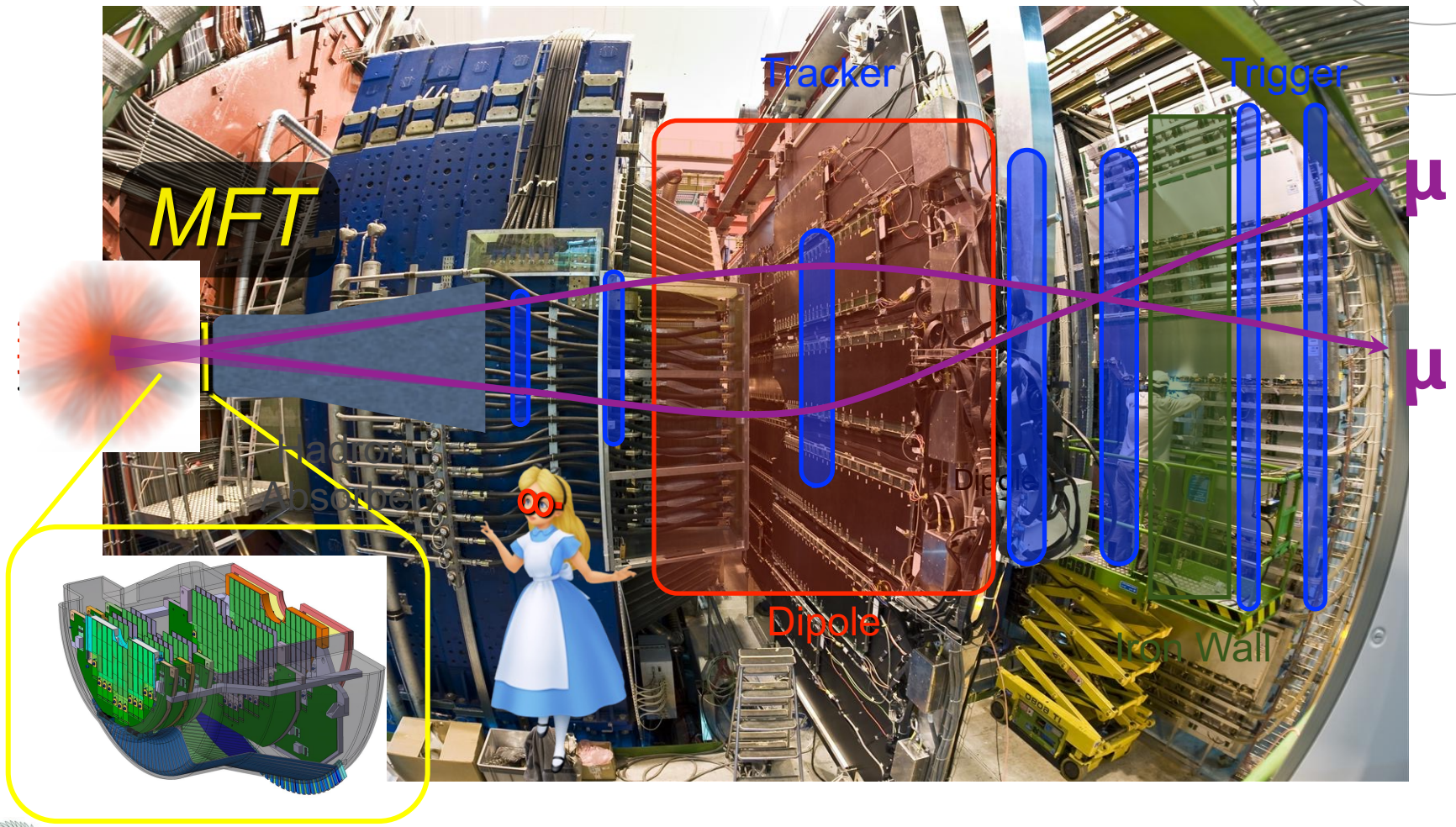




- new opportunity via muons at LHC (and above)
  - *not too forward* for "central" physics
  - technically *forward enough* for muon measurement

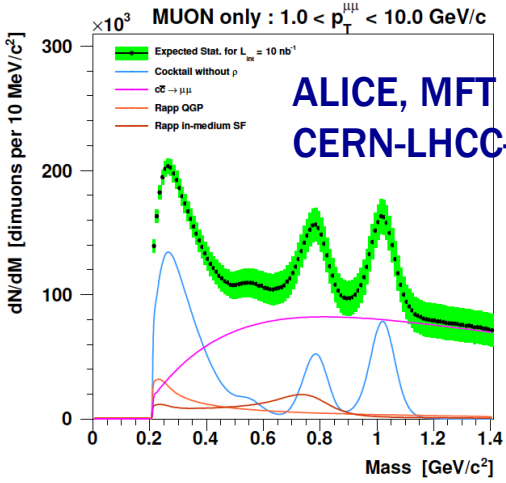
Muon Forward Tracker (2022–)

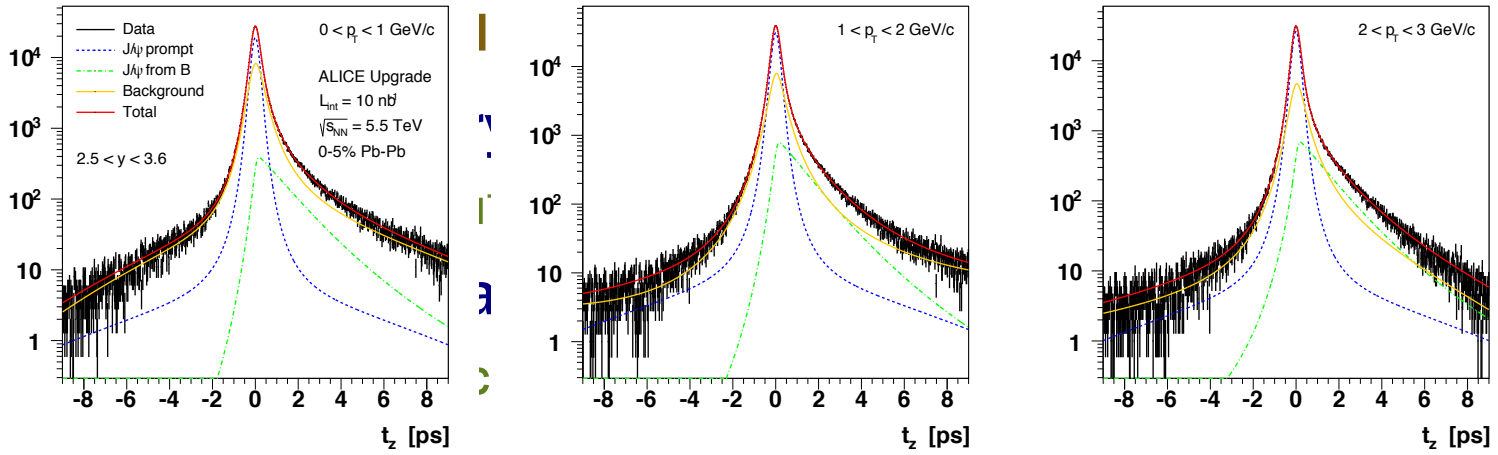
- precise vertex and invariant mass measurements



MFT Physics Goals at a Glance

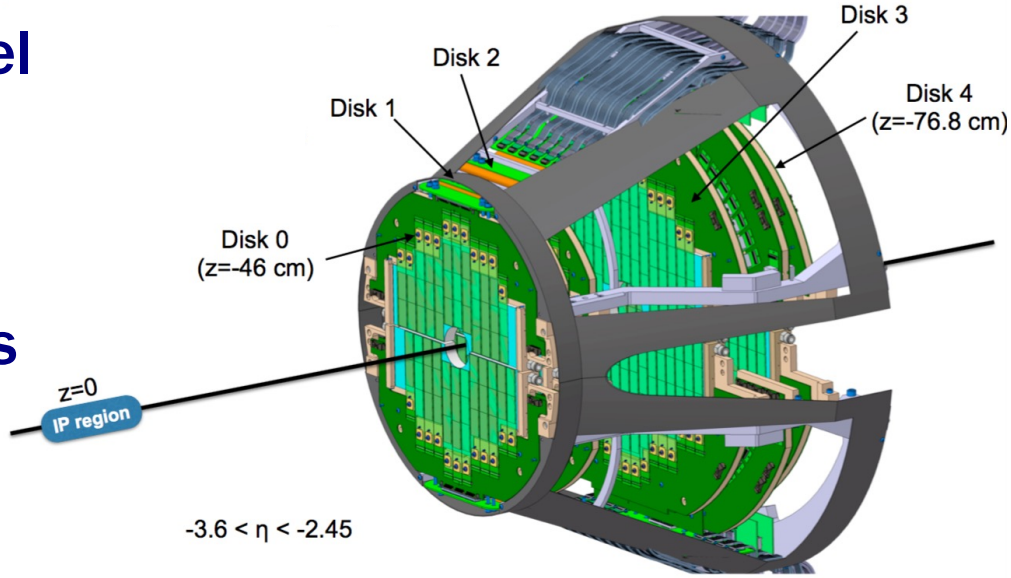
- **separated open heavy flavors**
  - $D \rightarrow \mu$ $p_T > 0$–1 GeV/c
  - $B \rightarrow \mu$ $p_T > 2$ GeV/c
  - J/ψ $p_T > 0$ GeV/c
- **separated quarkonia**
  - prompt/secondary J/ψ, $\psi(2S)$, $\Upsilon(1S/2S/3S)$
-





Muon Forward Tracker Design

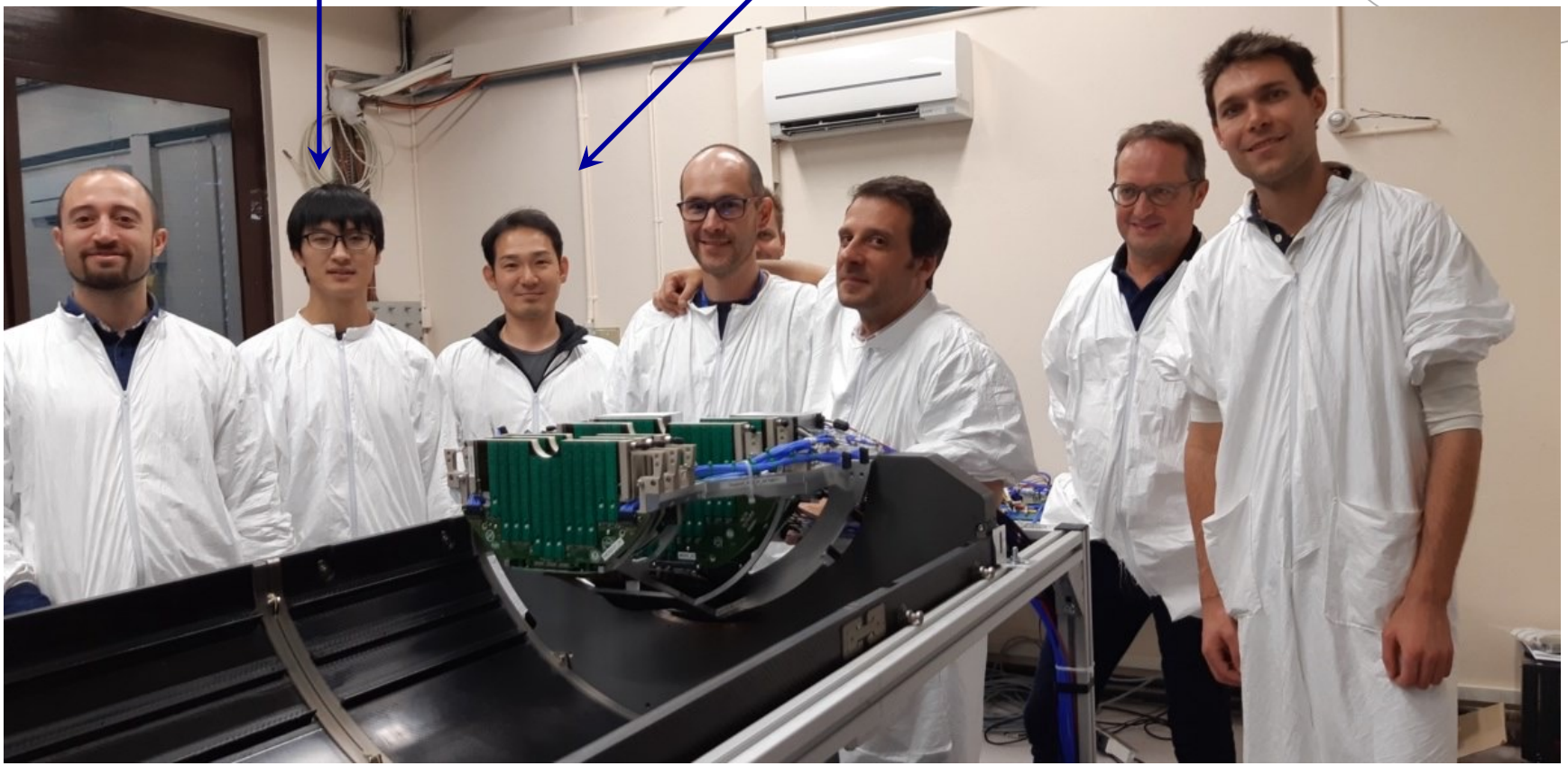
- $2.45 < -\eta < 3.6$
  - $-z = 460-768$ mm
- 0.4 m^2 of MAPS silicon pixel sensors
  - 28 μm × 28 μm pixel
  - 0.35% X_0 per layer
- 10 sensitive layers
  - 5 double sided disks



- precise vertexing capability for forward muons
- Pb+Pb ~50 kHz, *p*+*p* ~200 kHz

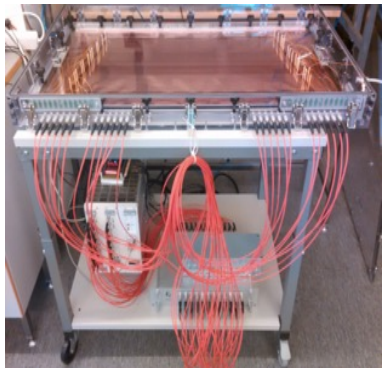
Snapshot at CERN (before Covid-19)

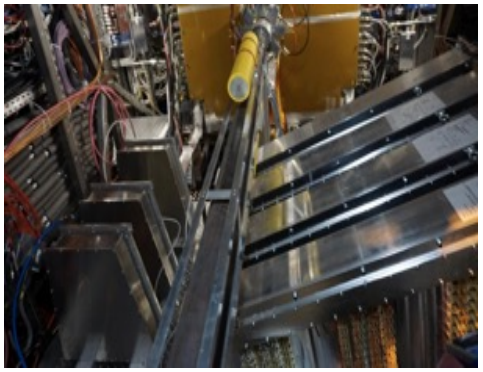
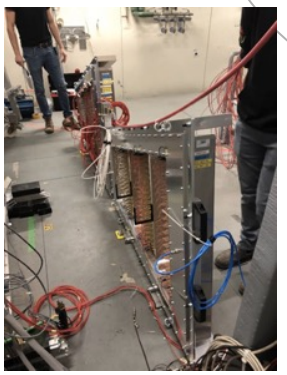
Motomi Oya (HU PhD student) Yorito Yamaguchi (HU Proj. Assist. Prof. → Assoc. Prof.)



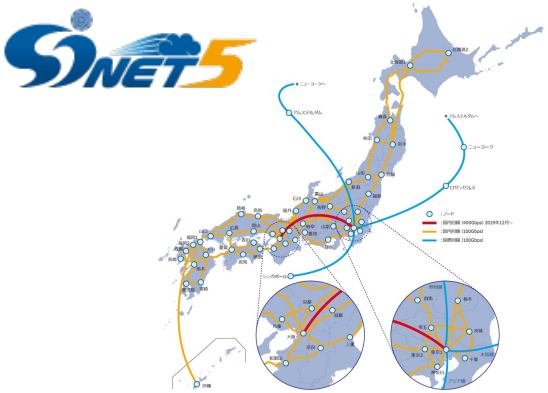
Examples of Other Outcome

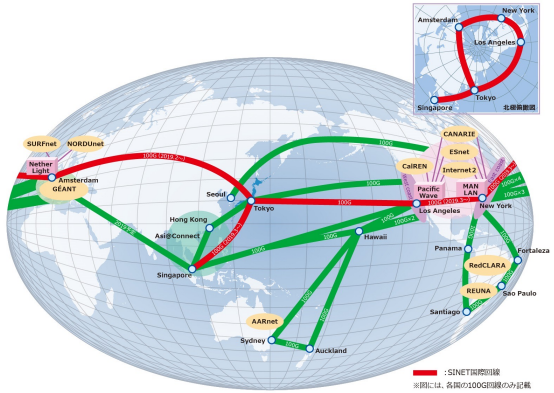
- GEM for time projection chamber (Tokyo)




- computing grid Tier 2 sites (Hiroshima, Tsukuba)
  - enhanced worker nodes, storage, band width





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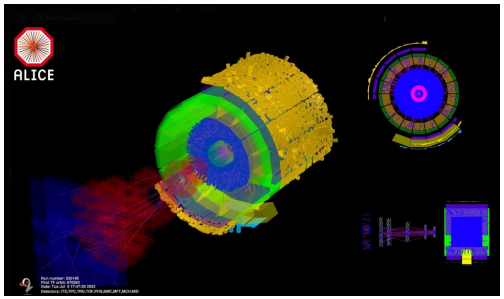
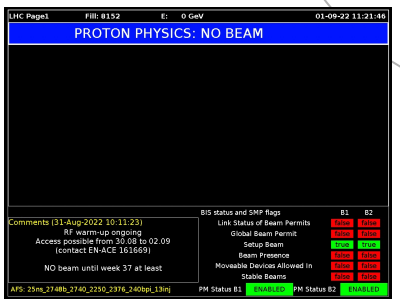
Clusters & Hierarchies

ALICE Run 3 Physics Status/Prospects

- first *p*+*p* collisions at 13.6 TeV on 5 July 2022

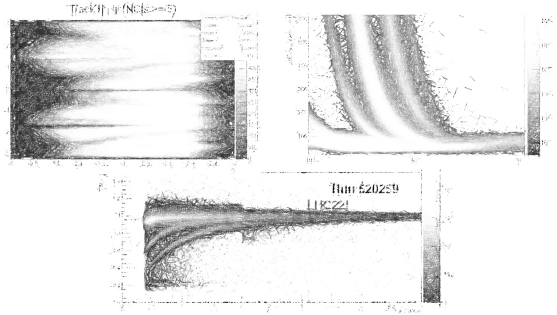


p+*p* at 13.6 TeV

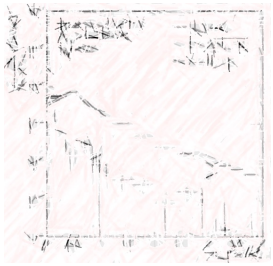


cosmic data taking

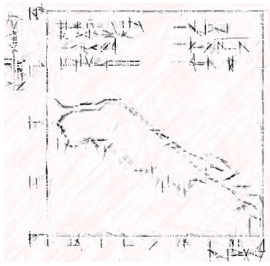
- ~400 hours of data taking so far
- all upgraded detectors working well
  - performance and physics plots yet to publicize (sorry!)



e^+e^- invariant mass



$\mu^+\mu^-$ invariant mass



- ~100 times integrated luminosity 13 nb^{-1} by 2030

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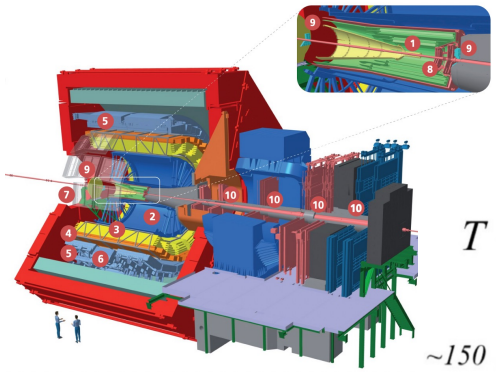
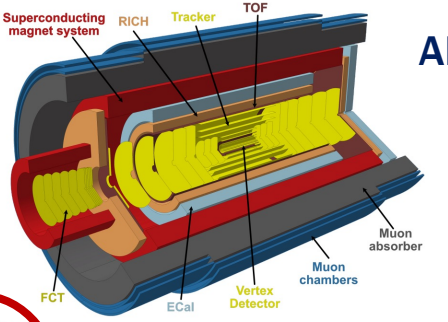
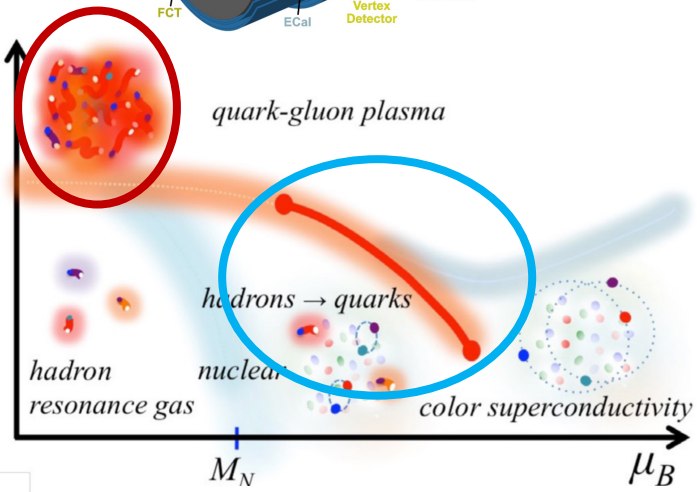
(A Lot of) High Energy QCD Projects

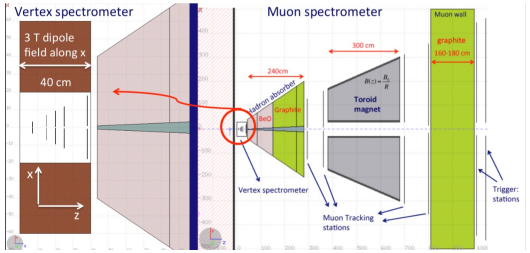


ALICE

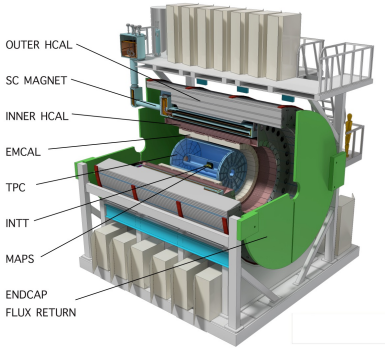


ALICE 3

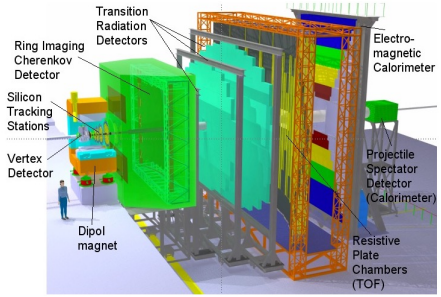




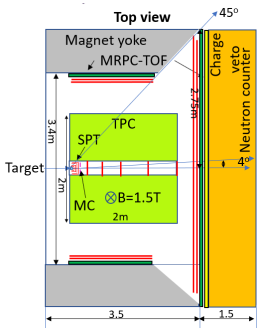
NA60+

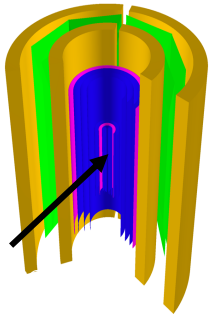


sPHENIX



CBM





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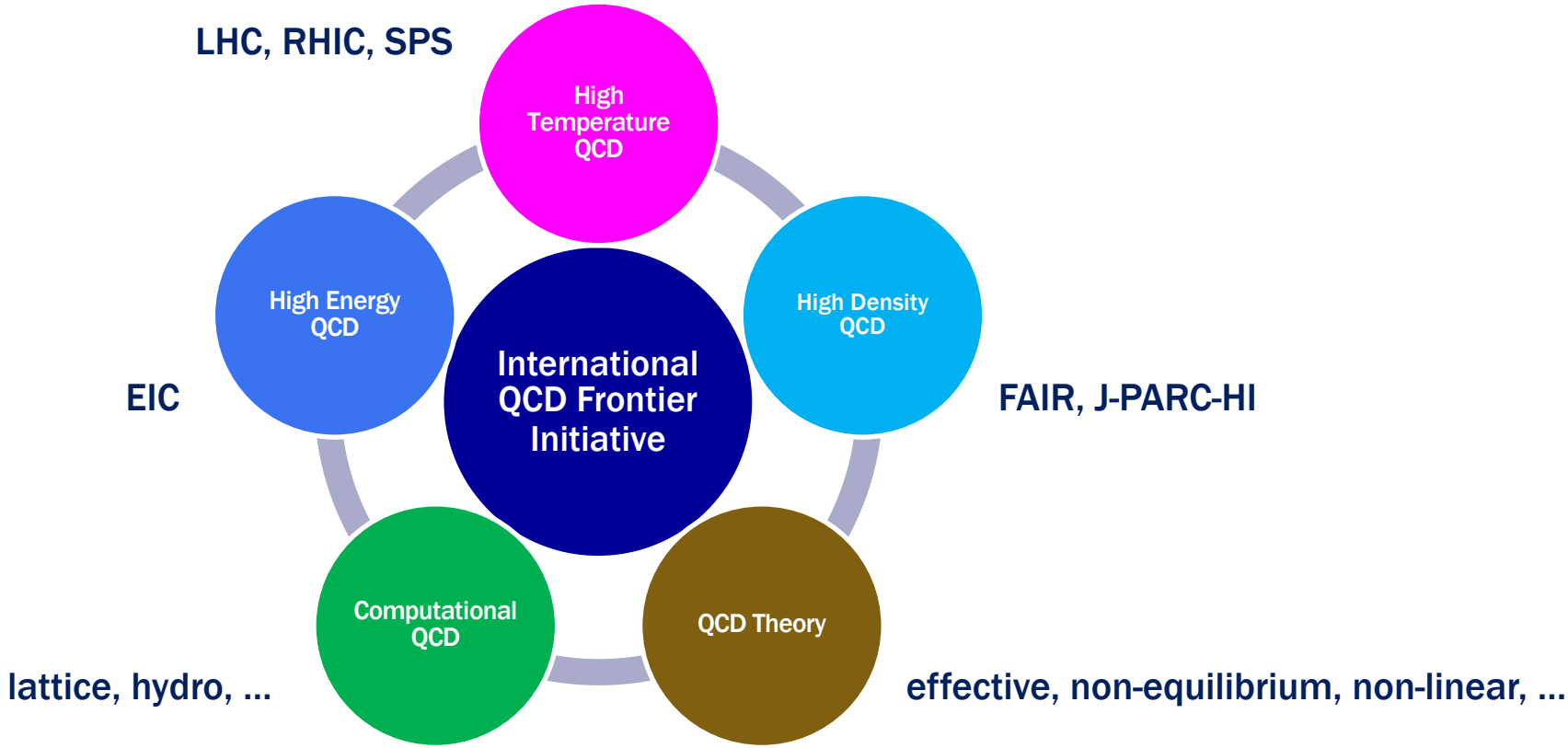
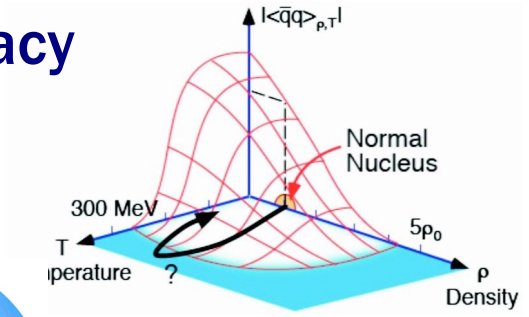
International QCD Frontier Initiative

- being proposed to Science Council of Japan
  - Y. Goto, T. Gunji, T. Saito, K. Shigaki, and many more



e.g. Multi-Visional Approach to Mass

- chiral symmetry breaking ~ quark condensate
  - relativistic nucleus-nucleus collisions
    - ALICE, STAR, sPHENIX, NA60+, CBM, ALICE 3, J-PARC-HI, …
  - ρ, ω, φ, a_1, f_1, … modification + degeneracy
- trace anomaly ~ gluon condensate
  - electron–nucleus collisions
    - EPIC
  - gluon exchange *e.g.* with J/ψ, Y



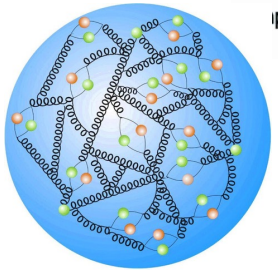


image credit:
DESY/HERA/ZEUS

- must represent single physics at different angles
- toward comprehensive understanding of QCD

Summary and Concluding Remarks

- deconfined quarks: most fundamental hierarchy
  - accessible only via relativistic nucleus-nucleus collisions
- unique dynamics bridging quark-hadron hierarchies
  - quark/gluon confinement into hadron
    → next talk by Y. Yamaguchi
  - hadron mass generation
- ALICE at LHC exploring quark physics frontier
  - upgraded run started in 2022 toward x 100 higher rate
- physics outcome to broom in next decade(s)
- multi-visional approach to QCD phenomena
  - *cf.* int'l high energy QCD frontier initiative plan