Experimental Challenge to Origin of Hadronic Mass at RHIC, LHC, and EIC

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Workshop on Recent Developments from QCD to Nuclear Matter

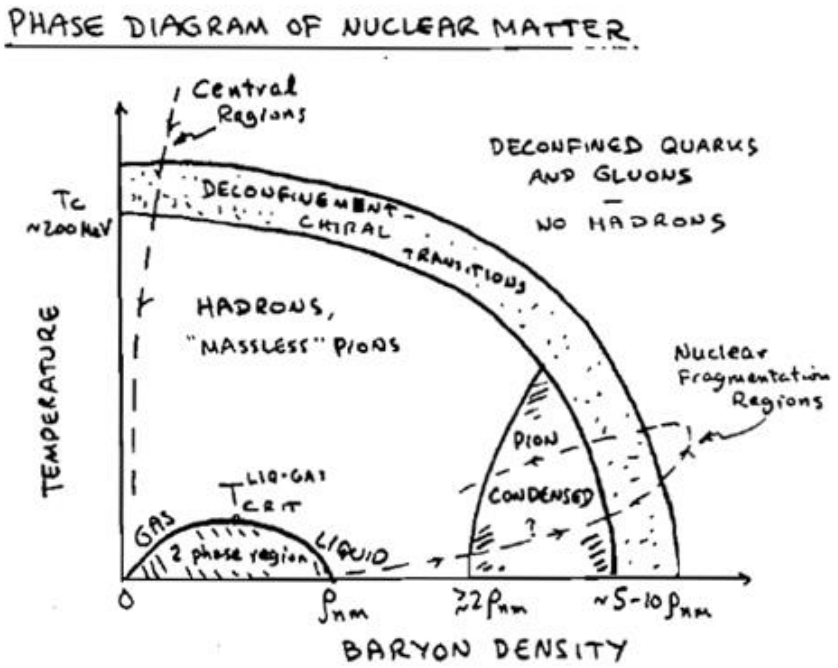
2025/12/17, Academia Sinica, Taiwan

Presentation Outline

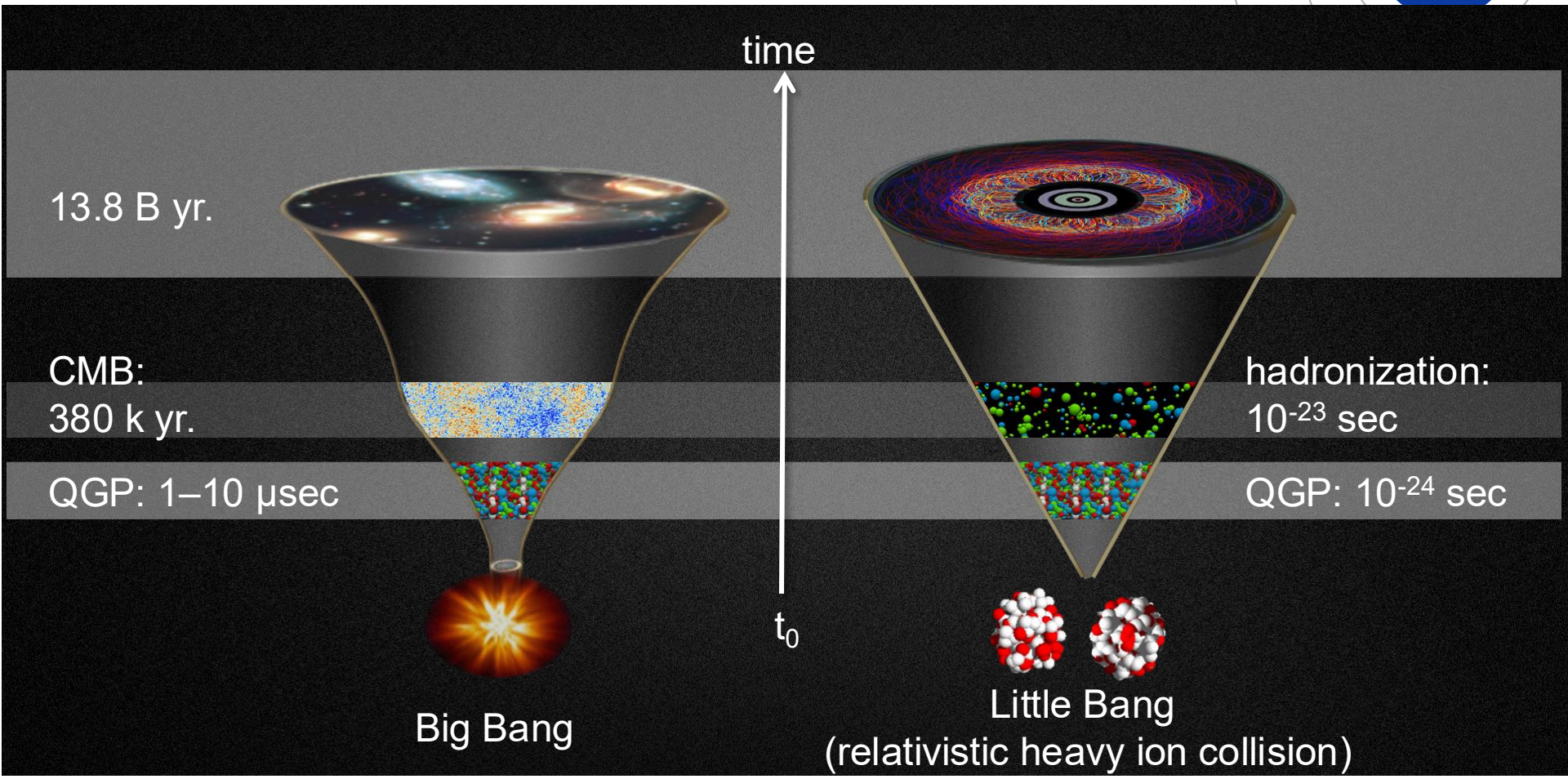
- physics/history of high energy nuclear collisions
  - theo. predictions, fixed target exp., nuclear colliders
- deconfined quark matter surely in our hand
- remaining mystery: hadronic mass
- ongoing/planned approaches
  - muon measurements at very high energy
  - chiral mass degeneracy via chiral (V-A) mixing
  - quark and gluon contributions
- summary and concluding remarks

Birth of High Energy Nuclear Physics

- quark model
  - M. Gell-Mann, G. Zweig (1964)
- Quantum Chromo-Dynamics (QCD)
  - G. 't Hooft, D. Gross, D. Politzer, F. Wilczek (1971–73)
- QCD phase diagram
  - *e.g.* G. Baym (1983)



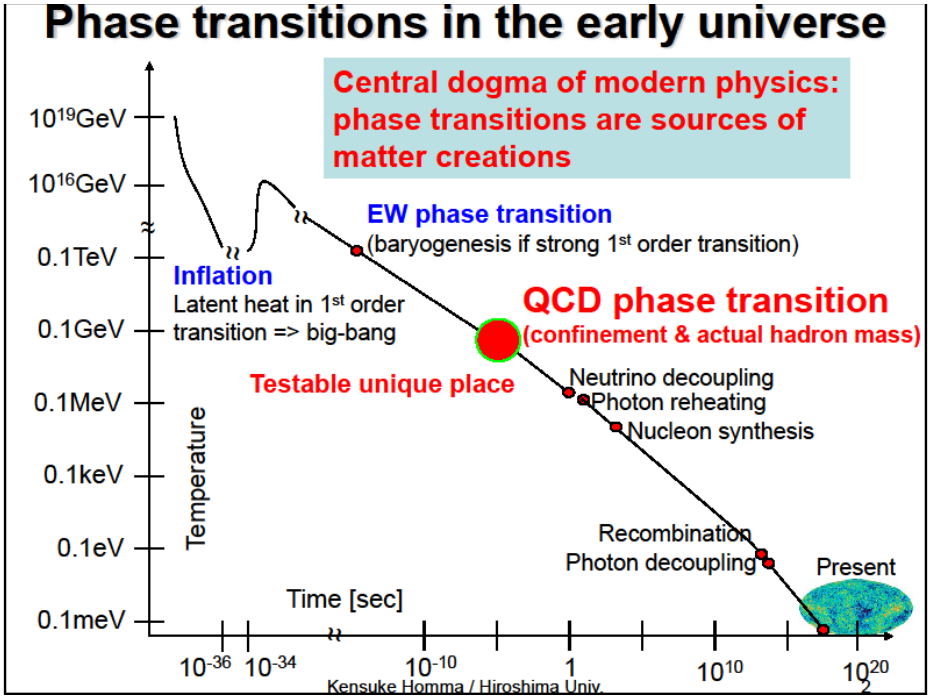
Little Bang (Microscopic Big Bang)



5.36 TeV per nucleon pair × 208 ~ 1 PeV in ~100 fm^3

Uniqueness of QCD Phase Transition

- only possible boundary to experimentally cross
  - to prove (or disprove) paradigm of universe evolution
  - lost phase within experimental reach
    - not just to catch residue



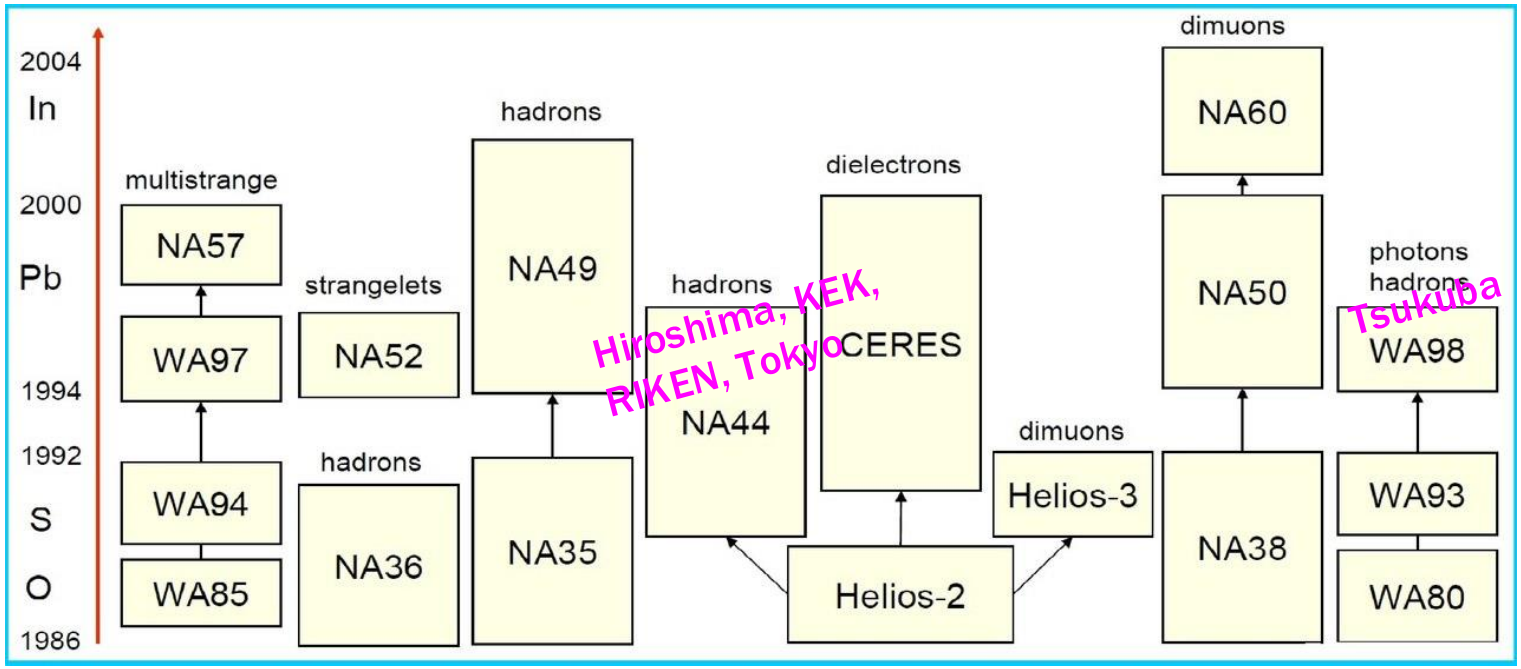
K. Homma, 2008/09

Early Attempts to Find Quark Matter

- 1970's–80's: first trials with "heavy" ions
  - LBL–BEVALAC (2 A GeV ^{40}Ar)
  - BNL–AGS (15 A GeV ^{28}Si)
  - CERN–SPS (200 A GeV ^{32}S)
- 1990's: onsets of discovery with "truly heavy" ions
  - BNL–AGS (11 A GeV ^{197}Au; $\sqrt{s_{NN}}$ ~ 5 GeV)
    - Au beam with new booster in 1992
  - CERN–SPS (158 A GeV ^{208}Pb; $\sqrt{s_{NN}}$ ~ 17 GeV)
    - Pb beam since 1993

Fixed Target Experiments at CERN-SPS

- 158–200 A GeV beam (higher than RHIC ring)
- various probes (hadron, electron, muon, photon)
- onsets (or perhaps creation) of deconfined phase



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Fixed Target Experiments at BNL-AGS

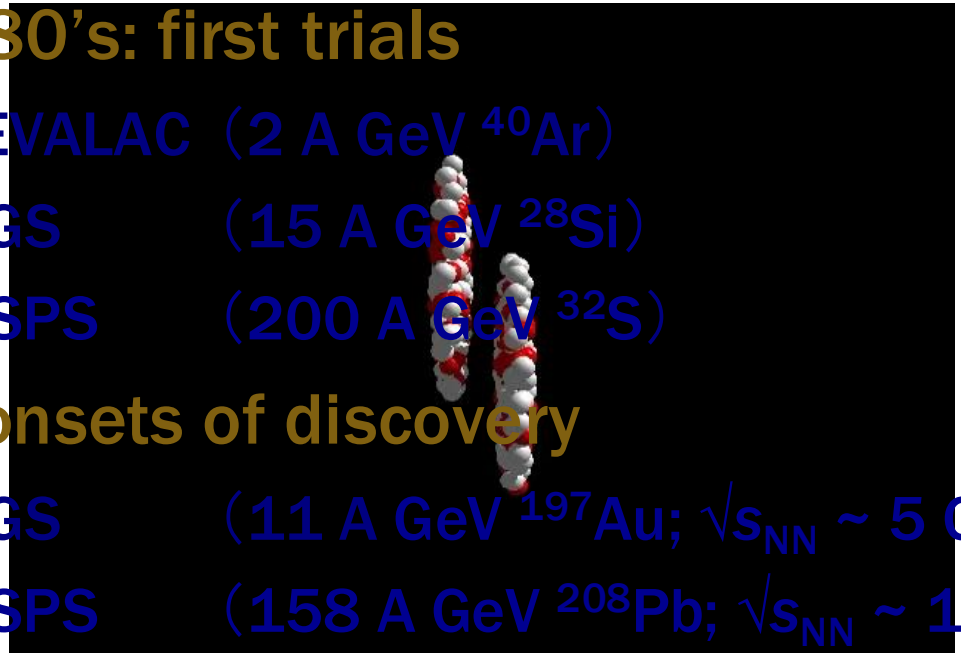
- mostly hadron measurements
  - E802/859/866 (high precision spectrometers)

H. Sako  K. Shigaki

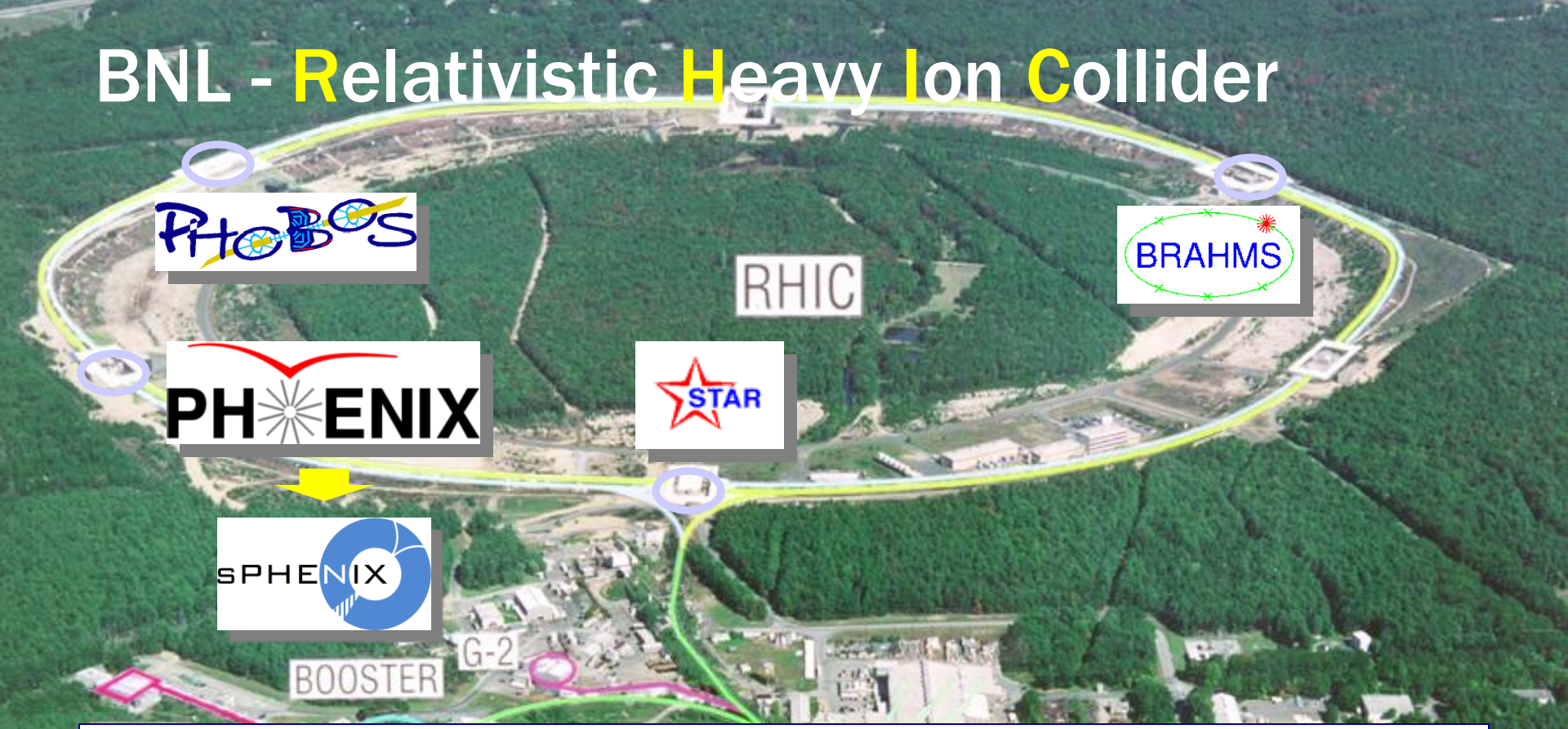
  - E810 (time projection chamber)
  - E814/877 (long spectrometer)
- possible revisit with present knowledge
  - similar energies at FAIR/J-PARC-HI

RHIC, The Game Changer

- 1970's–80's: first trials
  - LBL–BEVALAC (2 A GeV ^{40}Ar)
  - BNL–AGS (15 A GeV ^{28}Si)
  - CERN–SPS (200 A GeV ^{32}S)
- 1990's: onsets of discovery
  - BNL–AGS (11 A GeV ^{197}Au; $\sqrt{s_{NN}}$ ~ 5 GeV)
  - CERN–SPS (158 A GeV ^{208}Pb; $\sqrt{s_{NN}}$ ~ 17 GeV)
- 2000's: discovery of deconfined partonic phase!
  - BNL–RHIC (100 + 100 A GeV ^{197}Au + ^{197}Au)
    - first nuclear collider 2000–2025
  - CERN–LHC (2.8 + 2.8 A TeV ^{208}Pb + ^{208}Pb)



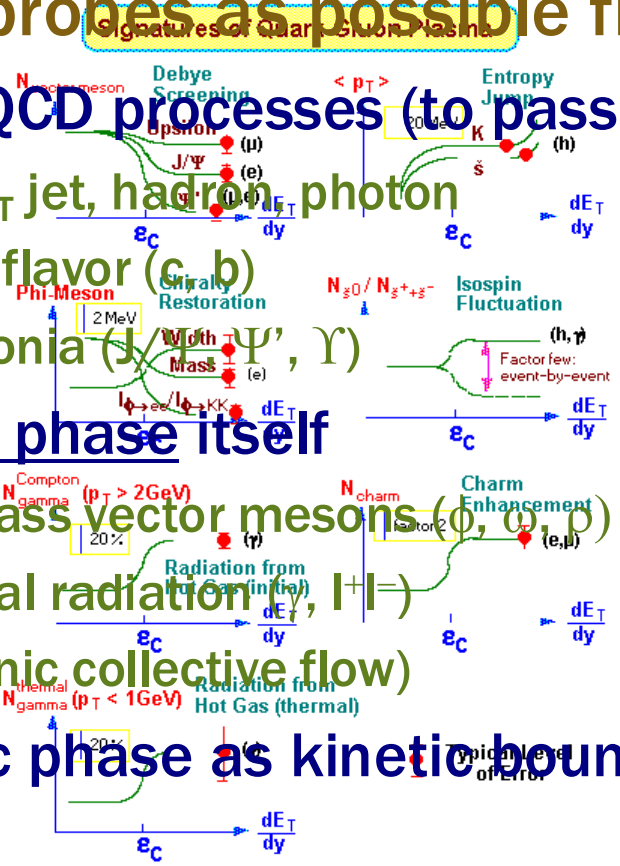
BNL - Relativistic Heavy Ion Collider



- 2 independent super-conducting synchrotrons
- up to 100 A GeV Au and/or 255 GeV (polarized) *p*
  - Au+Au/U+U/Cu+Cu/*p*+*p*/*p*+Au/*d*+Au/^{3}He+Au/Cu+Au…
- 4 → 2 complimentary experiments

Strategy Based on SPS/AGS Lessons

- no single smoking gun → multiple probes
- as many probes as possible from all stages
  - initial pQCD processes (to pass through partonic phase)
    - high p_T jet, hadron, photon
    - heavy flavor (c, b)
    - quarkonia (J/Ψ, Ψ', Υ)
  - partonic phase itself
    - low mass vector mesons (ϕ, ω, ρ)
    - thermal radiation (γ, l^+l^-)
    - (partonic collective flow)
  - hadronic phase as kinetic boundary conditions

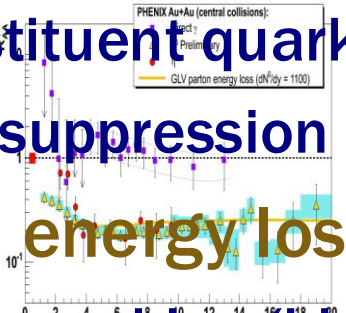


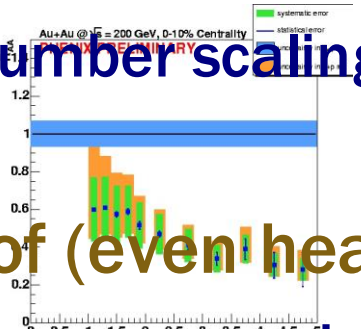
Shoji Nagamiya

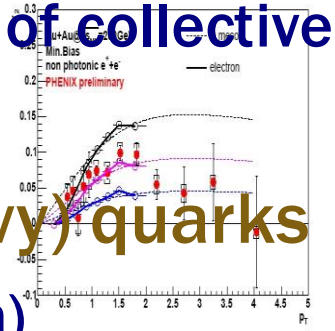
RHIC Outcome: New State of Matter

- partonic: quarks' degrees of freedom, screening
  - constituent quark number scaling of collective motion
  - J/Ψ suppression
- dense: energy loss of (even heavy) quarks
  - jet quenching (high p_T suppression)
  - jet modification
- strongly coupled: perfect fluidity
  - hydro-dynamical collective motion
- hot: thermally radiative
  - thermal (virtual) photons

But the quarks' degrees of freedom for Au+Au at QM05

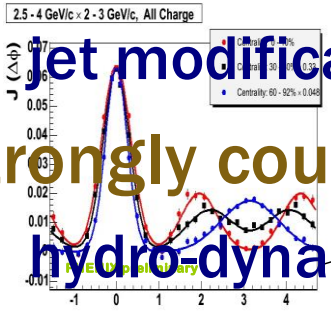






The matter is dense

The matter is strongly coupled



The matter modifies jets

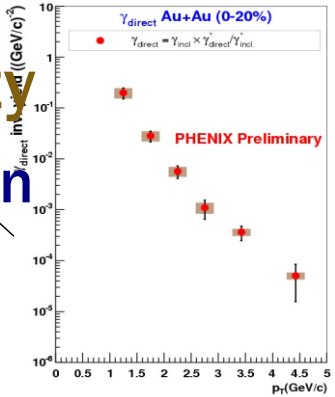
$\varepsilon > 15$ GeV/fm^3

$dN_g/dy > 1100$

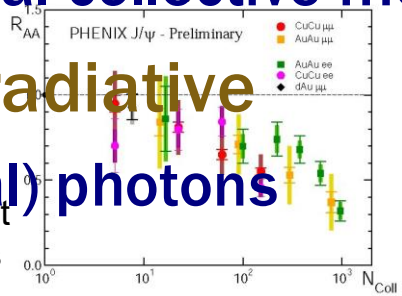
$T_{ave} = 300 - 400$ MeV (?)

Vs = ?

$\eta/s(\text{close to}) = 0$?



The matter is hot



The matter may melt but regenerate J/ψ's

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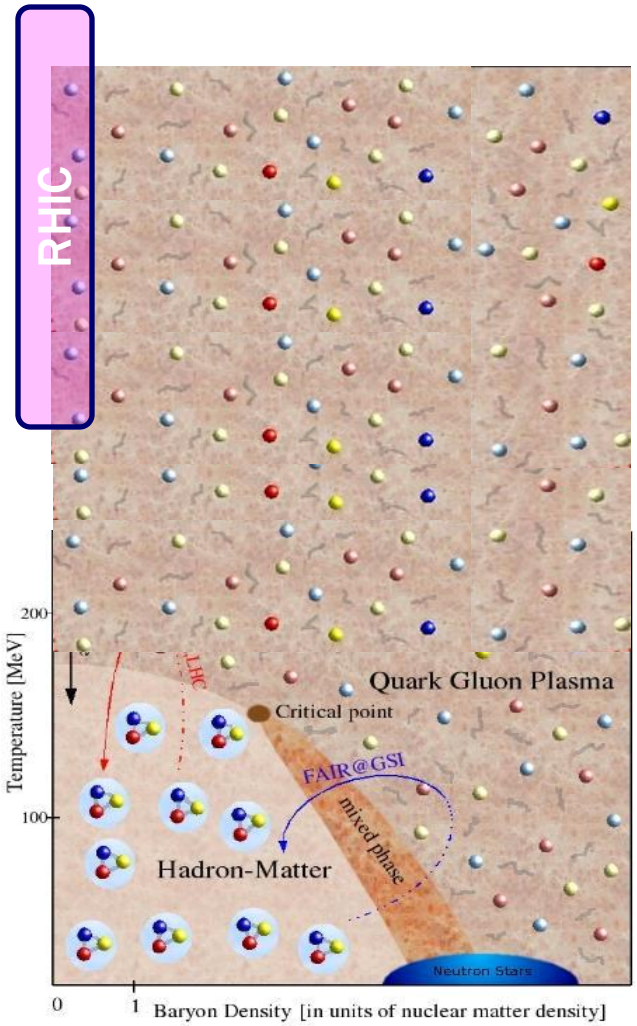
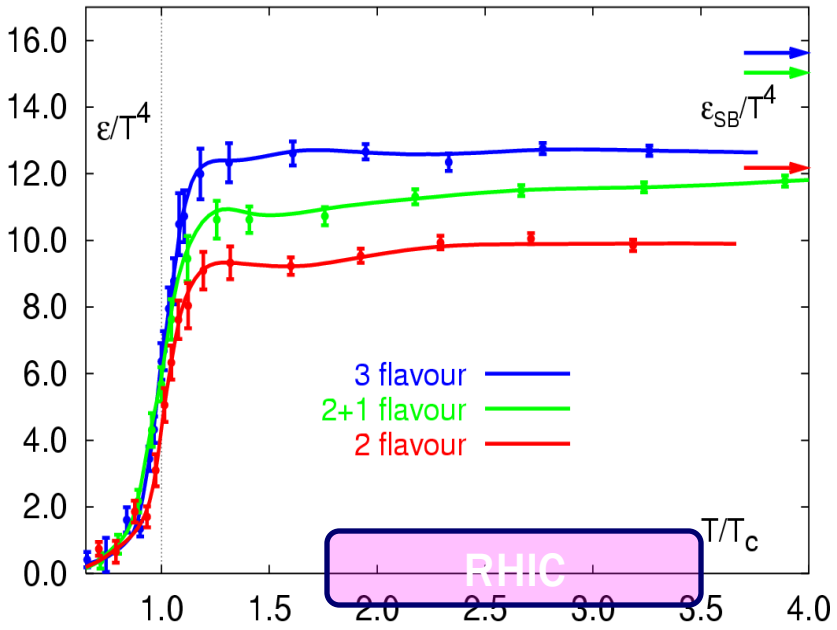
Boundary Certainly Crossed at RHIC



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



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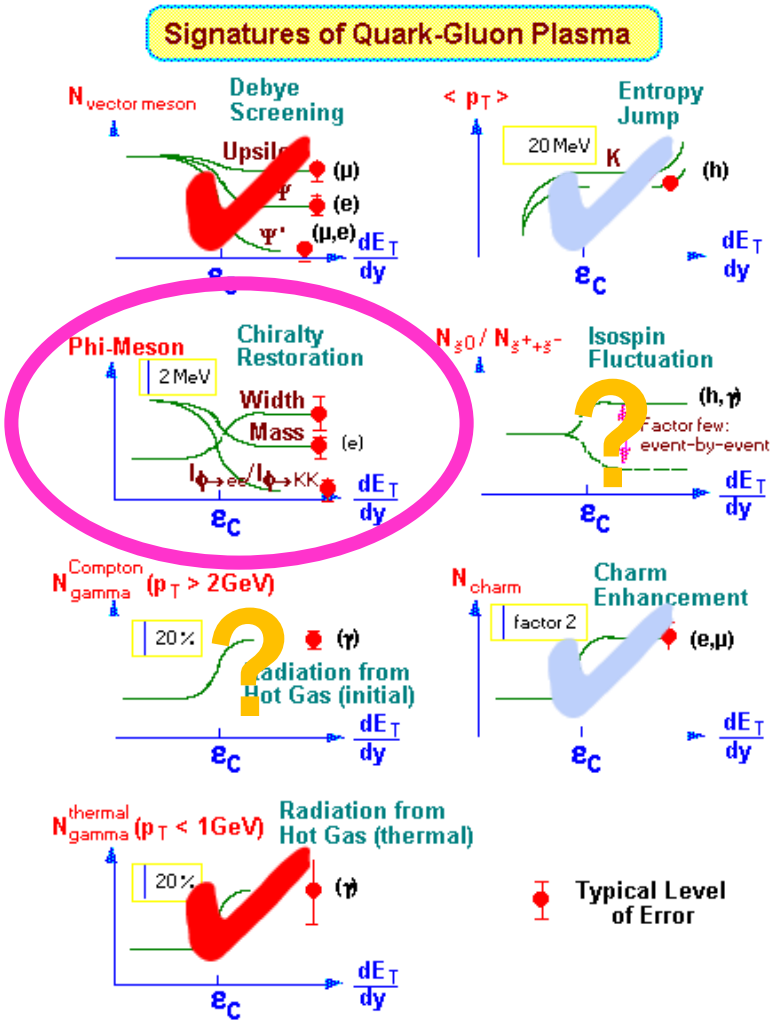
Reflection on (Former) Probes

- chiral symmetry restoration
  - formerly candidate (unfortunately non-working) probe
  - still remaining physics target itself



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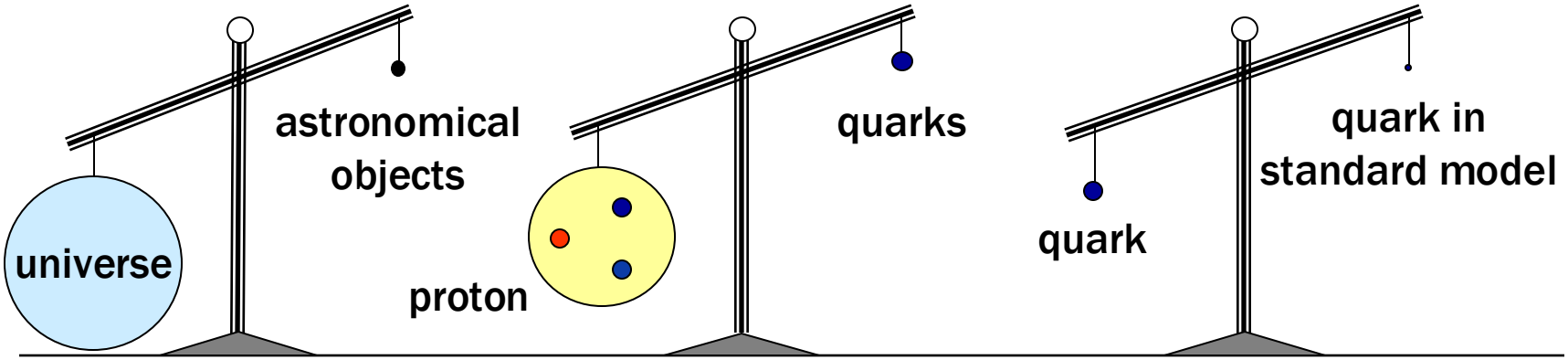
Still Remaining Mystery of Mass

- total mass = sum of components' masses?

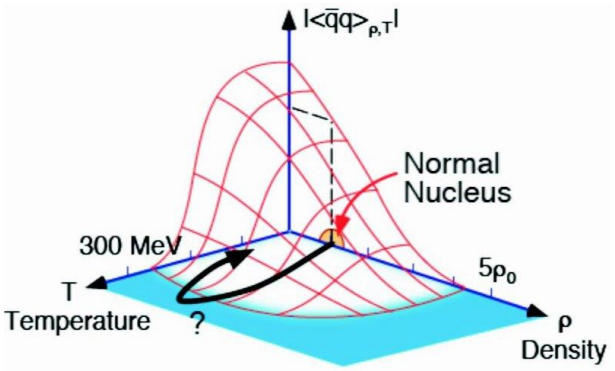
original cartoon from T. Hatsuda

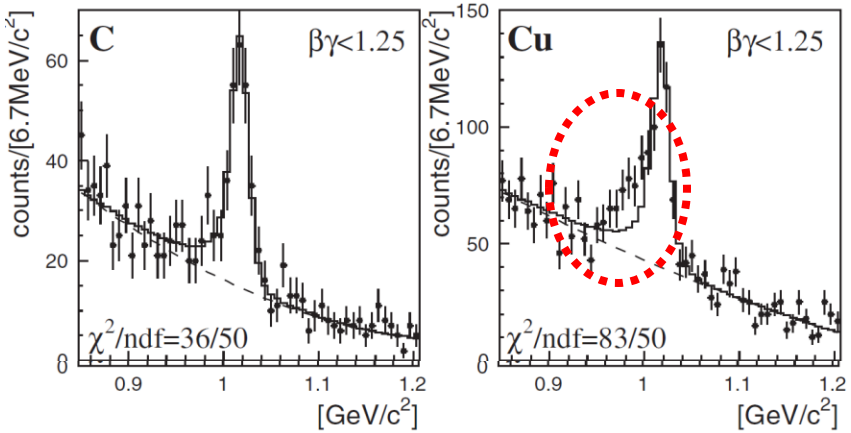


matter	5 %	quark mass	1%	quark mass in standard model = 0
dark matter	27 %	chiral symmetry breaking		BEH mechanism
dark energy	68 %			

Hadronic Mass Modification Search

- golden channel: light vector mesons → dileptons
- "observations" in finite density regime
  - ϕ, ω in nuclei via *p*+A (KEK E325, J-PARC E16)
    - though apparent contradiction to CB-ELSA/TAPS and CLAS-G7
  - π in Sn nuclei via (*d*, ^{3}He)

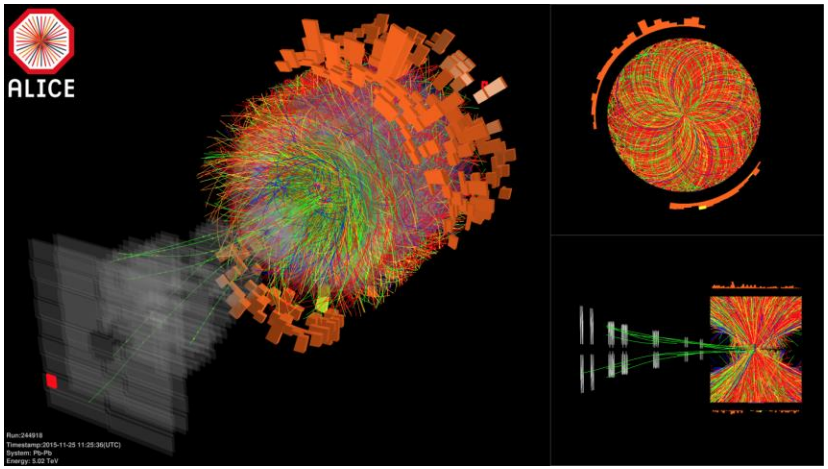




- no evidence in high temperature regime yet
  - lepton measurement technically challenging

Current Main Stage: CERN-LHC

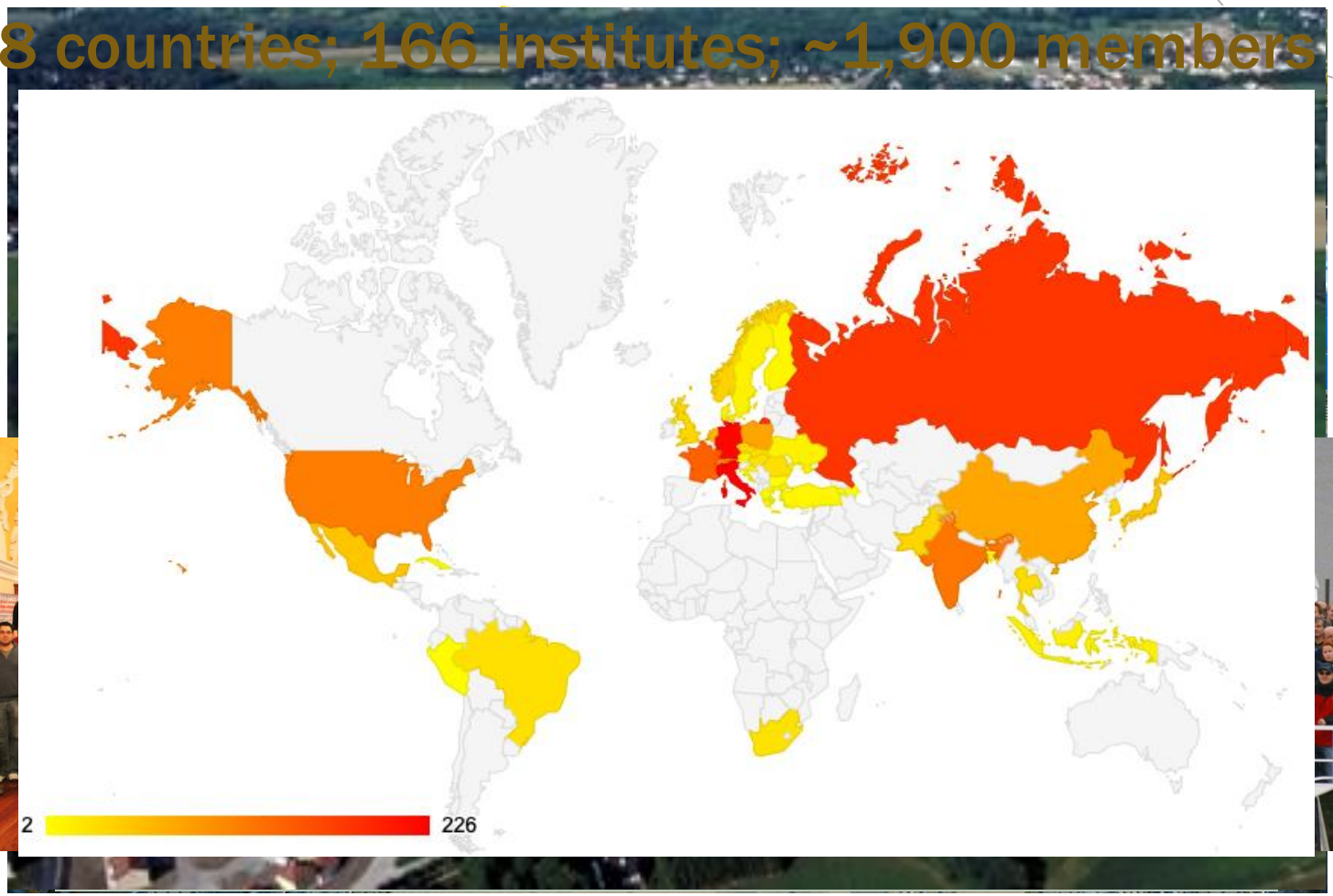
- Pb+Pb at world highest energy of $\sqrt{s_{NN}}$ = 5.36 TeV



- hottest, largest, longest-lived, purest fireball
  - energy density ~ 16 GeV/fm^3 (thermalization time ~ 1 fm/c)
  - volume ~ 300 fm^3
  - lifetime ~ 10 fm/c
  - net quark (baryon) density ~ 0

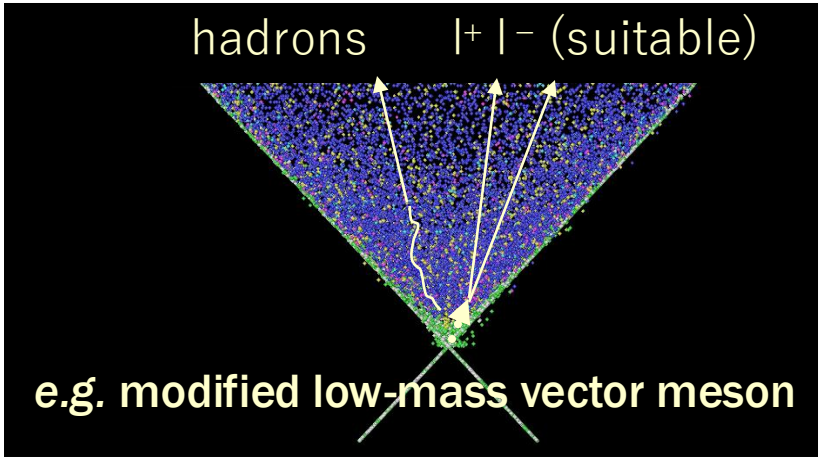
A Large Ion Collider Experiment

- *the* nucleus-nucleus collision experiment at LHC
- 38 countries; 166 institutes; ~1,900 members



Lepton (e, μ) Pairs throughout History

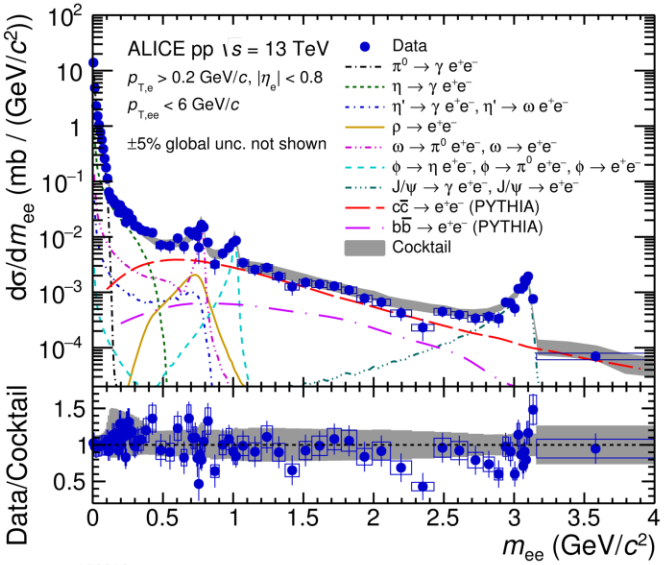
- vital (rare) probes to carry early-stage information
  - no final state disturbance via strong interaction

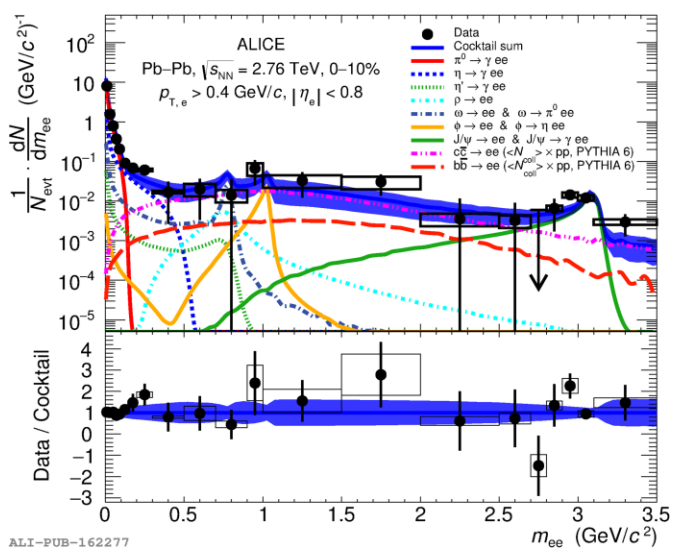


- novel detectors to overcome technical challenge
  - e.g. PHENIX with RICH, hadron blind detector, ...
- my own long-term target channels
  - e^+e^- at PHENIX, e^+e^- at ALICE, $\mu^+\mu^-$ at ALICE

e^+e^- (Japanese Specialty since PHENIX)

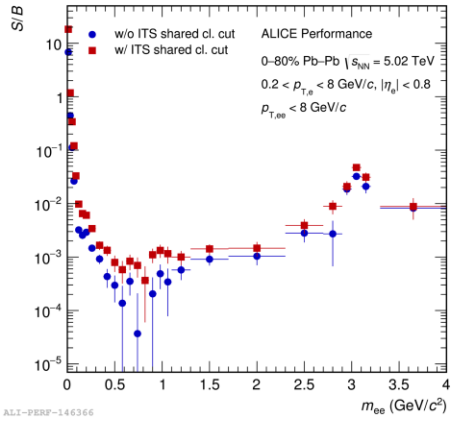
- results from ALICE runs 1, 2 (2009–2018)





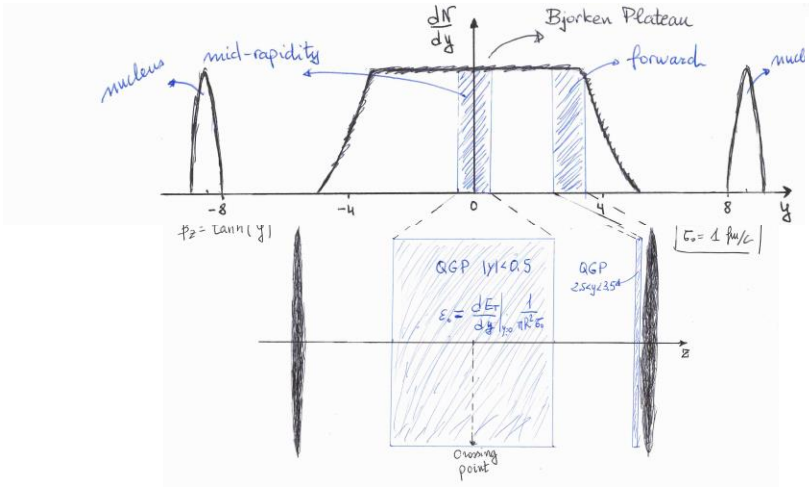
ALICE,
Phys. Lett. B 788, 505 (2019)
Phys. Rev. C 99, 024002 (2019)

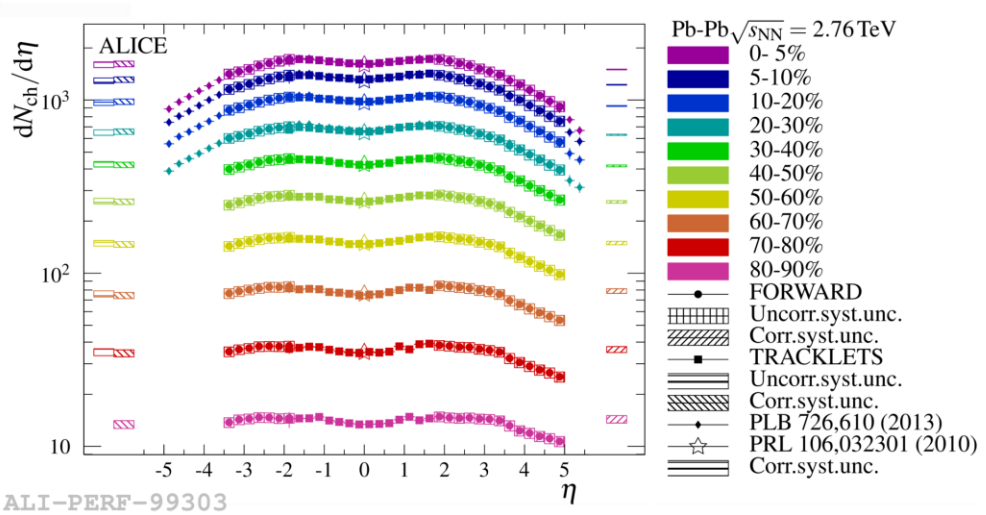
- very challenging S/B ratio in Pb+Pb



Virtue of Very High Collision Energy

- new physics opportunity via muons at LHC/ALICE
  - technically *forward enough* for muon measurement
    - interesting low p_T region accessible with high total momentum
  - *not too forward* for "central" physics ($2.5 < |\eta| < 3.6$)

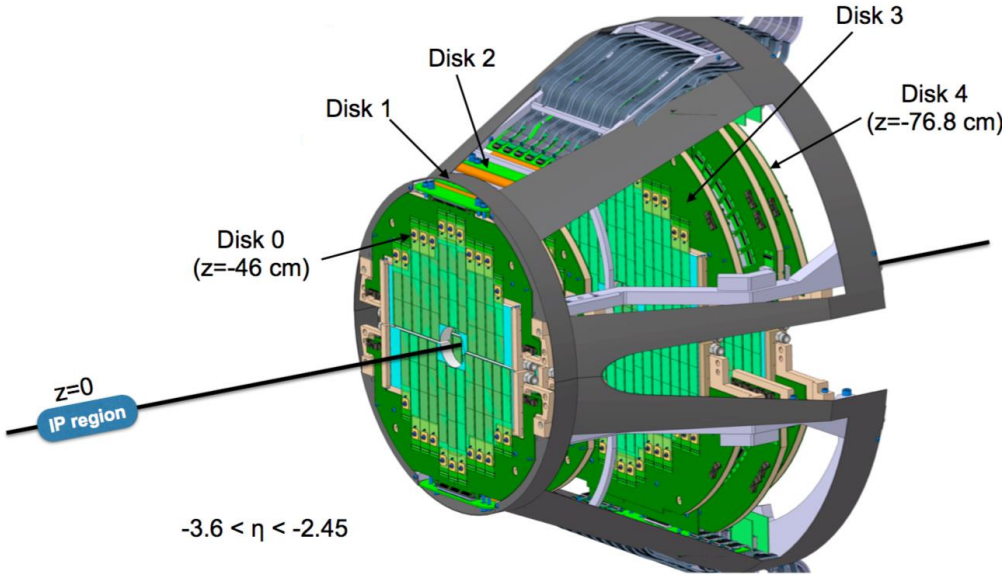




- two interesting regimes of partonic phase
  - exploration on QCD phase diagram

Muon (μ) Forward Tracker (MFT)

- $2.45 < -\eta < 3.6$
  - $-z = 460-768$ mm
- 0.4 m^2 of MAPS silicon pixel sensors
  - 491 M channels
  - 27 μm × 29 μm pixel
  - 0.35% X_0 per layer
- 10 sensitive layers
  - 5 double sided disks

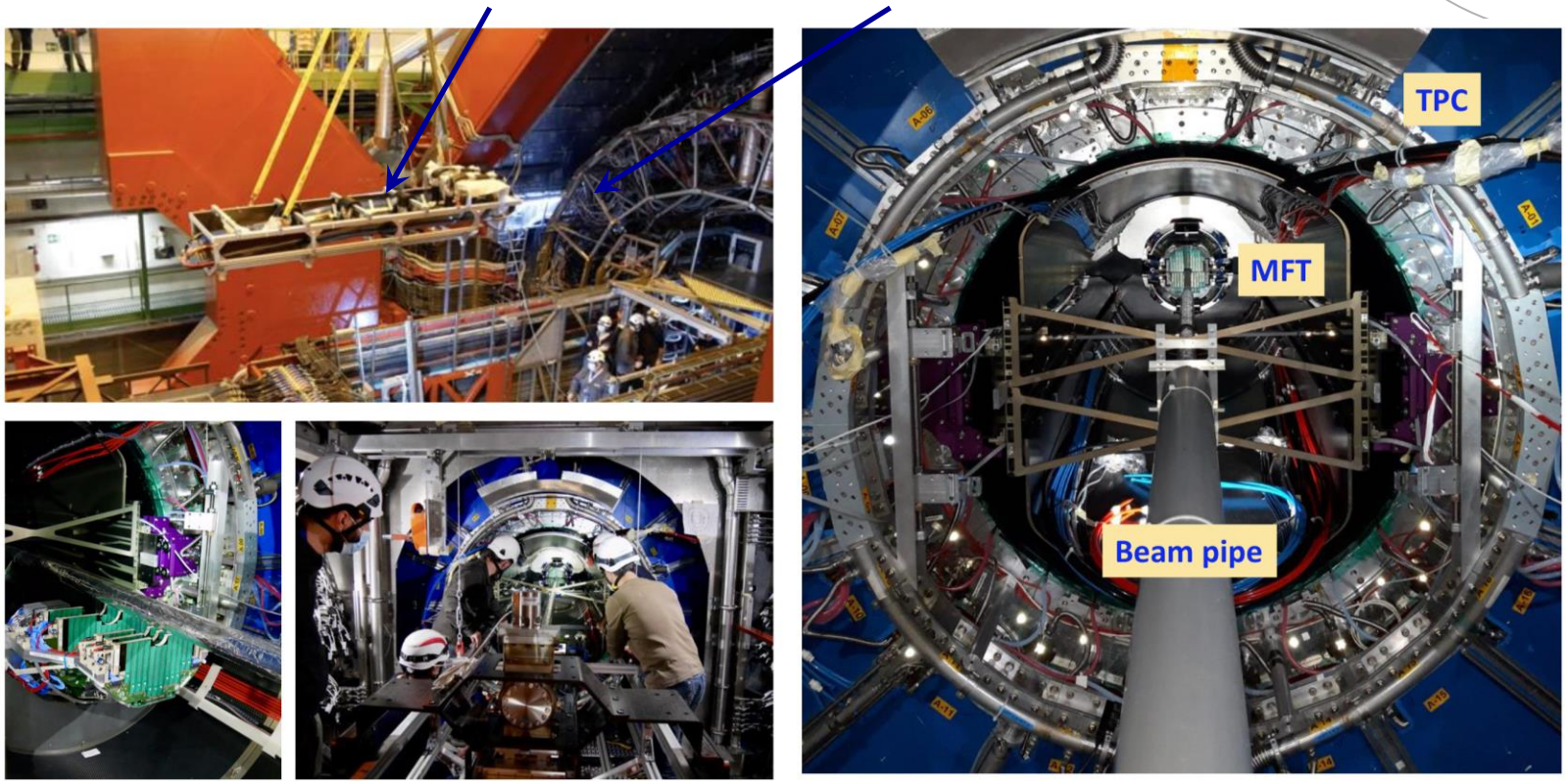


- precise vertexing capability for forward muons
- Pb-Pb ~50 kHz, *p*-*p* ~200 kHz

Development/Construction/Installation

- first half Muon Forward Tracker assembly in 2019

Motomi Oya (HU grad. student) Yorito Yamaguchi (HU)



- installed in 2020 for ALICE Run 3 from 2022

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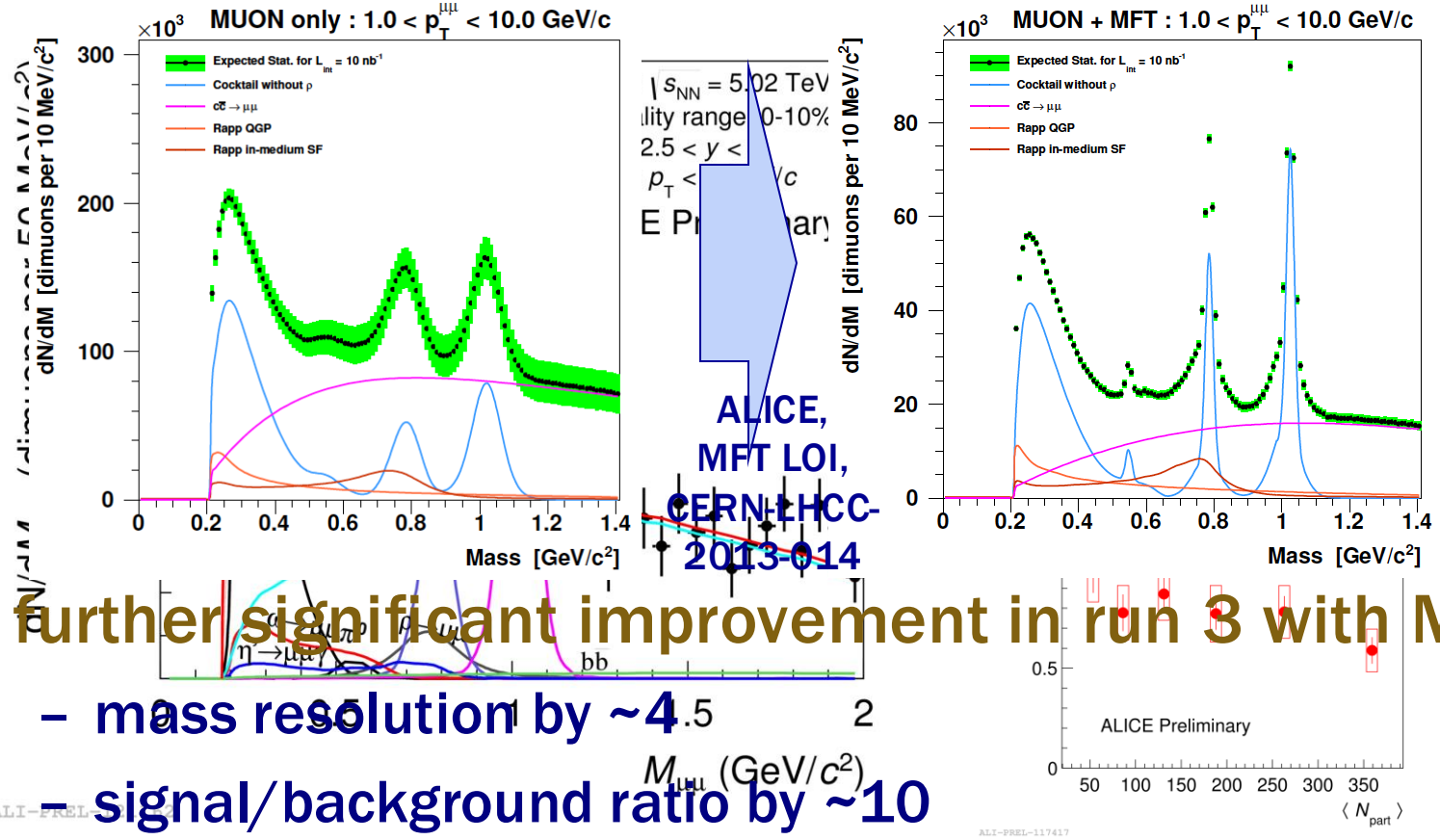
Upgrading μ and $\mu^+\mu^-$ Measurements

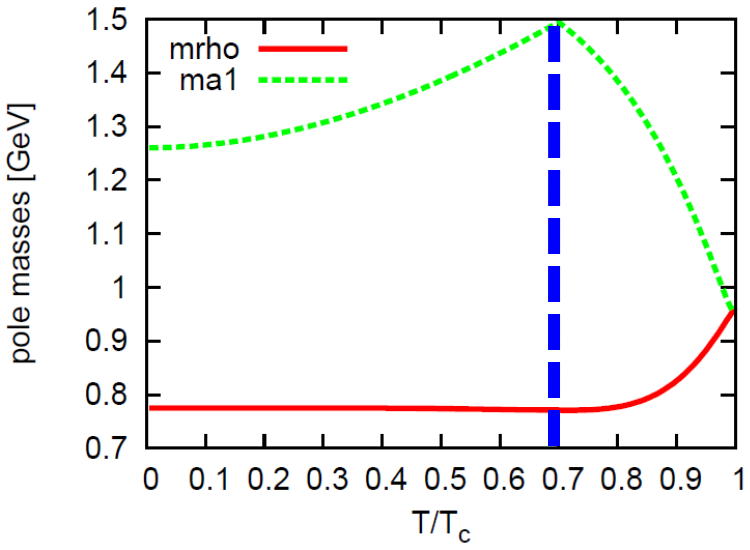
- clean low mass (φ, ω, ρ) $\mu^+\mu^-$ measurement
  - already in runs 1, 2 in reasonable p_T region



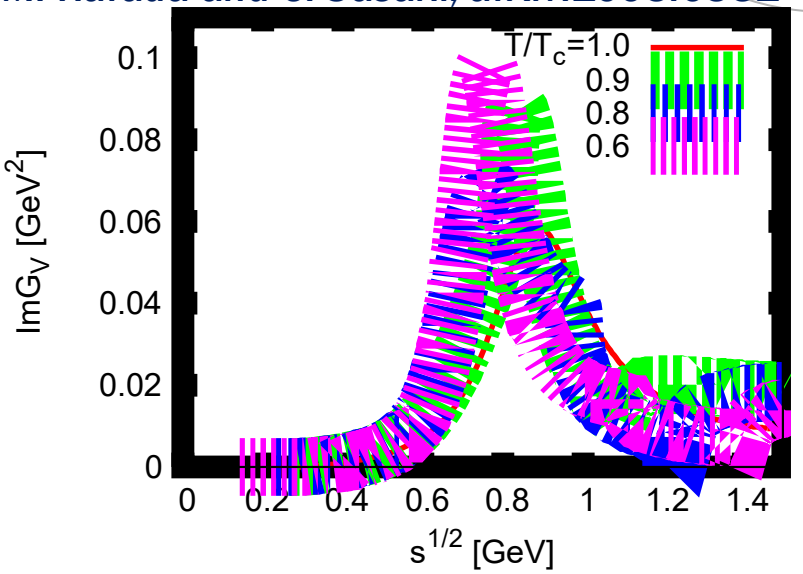
- further significant improvement in run 3 with MFT
  - mass resolution by ~4
  - signal/background ratio by ~10

NEW : Chiral Doublet Mass Degeneracy

- ρ(770) vs a_1(1260), ω(782) vs f_1(1285)



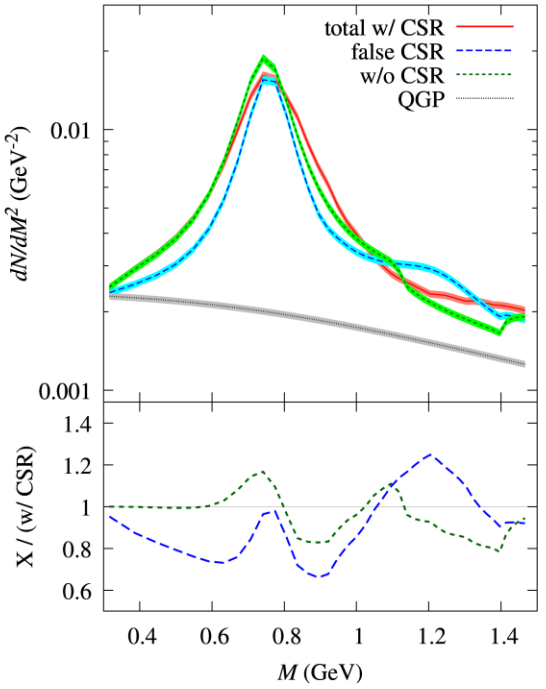
M. Harada and C. Sasaki, arXiv:1003.0331



- long-time favorite of theory people
  - though additional experimental challenges
- had to wait for realistic thoughts

Search via Chiral (V-A) Mixing

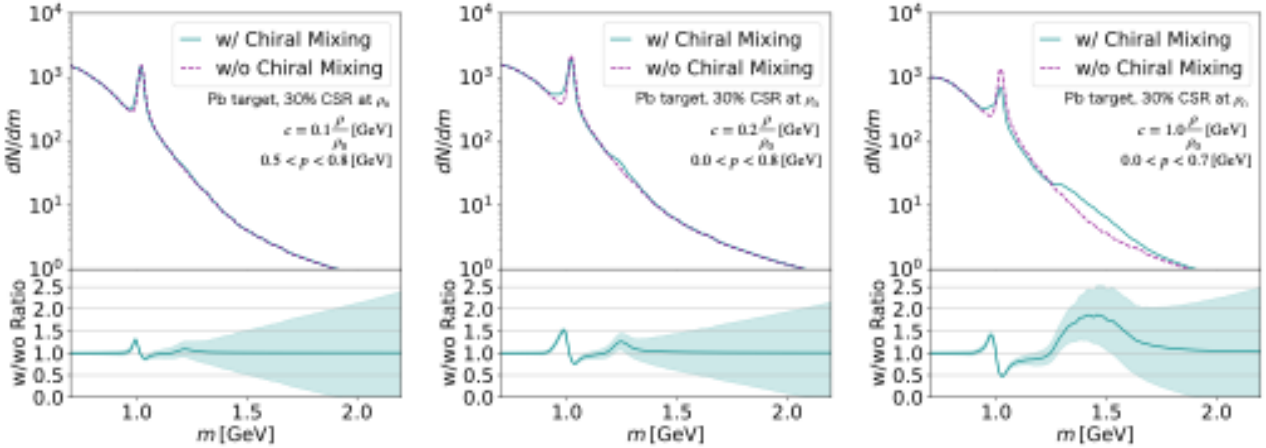
- axial vector meson decaying into dilepton
  - "Probing the QCD phase transition with chiral mixing in dilepton production"
    - A. Sakai, M. Harada, C. Nonaka, C. Sasaki, K. Shigaki, S. Yano
  - arXiv:2308.03305 [nucl-th]



dilepton yields with different CSR scenarios, Pb+Pb at $\sqrt{s_{NN}}$ = 2.76 TeV, centrality 0–5%

Also at Finite Density (Lower Energy)

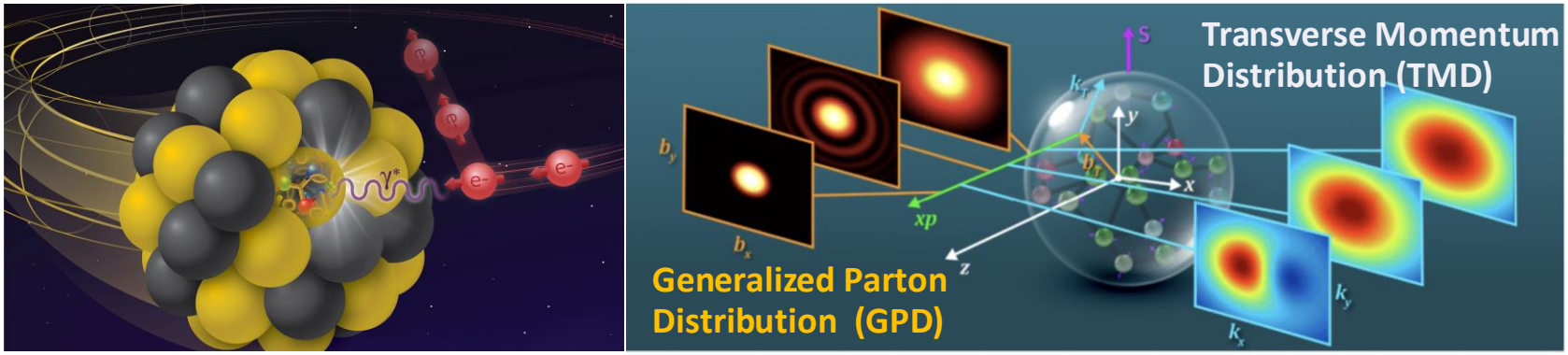
- chiral (V-A) mixing via anomaly in finite density
  - "Toward a direct measurement of partial restoration of chiral symmetry at J-PARC E16 via density-induced chiral mixing"
    - R. Ejima, P. Gubler, C. Sasaki, K. Shigaki
  - Phys. Rev. C 111, 055201 (2025)



expected invariant mass spectrum in optimally selected momentum ranges,
V-A mixing strength 0.1 ρ/ρ_0, 0.2 ρ/ρ_0, 1.0 ρ/ρ_0

“Clear and Present Mass” Approach

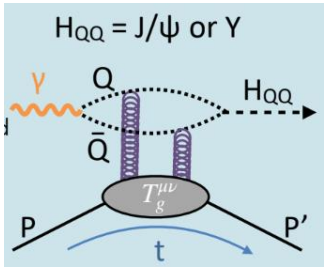
- electron beam as world premiere microscope
- 3-dimensional internal structure and emergence
  - especially hadronic mass and spin

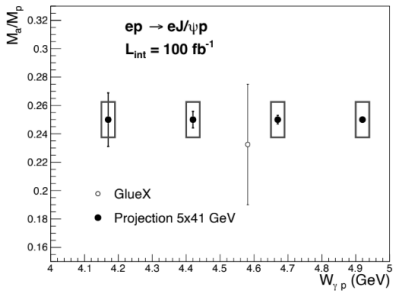


- ePIC experiment at Electron Ion Collider in 2030’s
  - top priority project of US nuclear physics
  - Japan engaged currently with 12 institutes

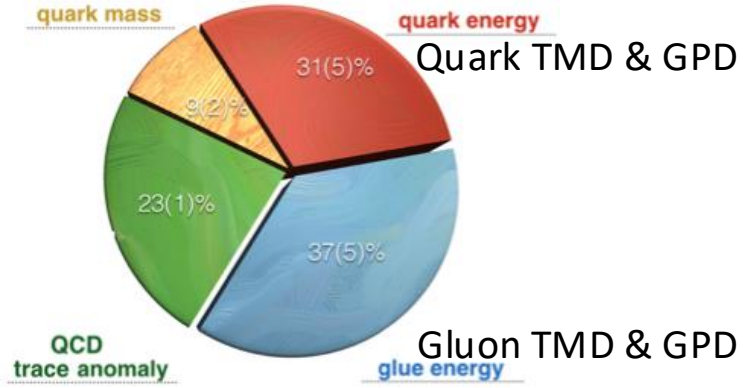
Pincer Attack by HIC and EIC

- chiral sym. breaking ~ quark pair condensation
  - low mass vector meson (ρ, ω, φ) mass spectra
  - chiral mass degeneracy (*e.g.* ρ–a_1(1260), via V-A mixing)
- QCD trace anomaly ~ gluon condensation
  - various hadrons' generalized parton distribution function
  - near-threshold quarkonia production





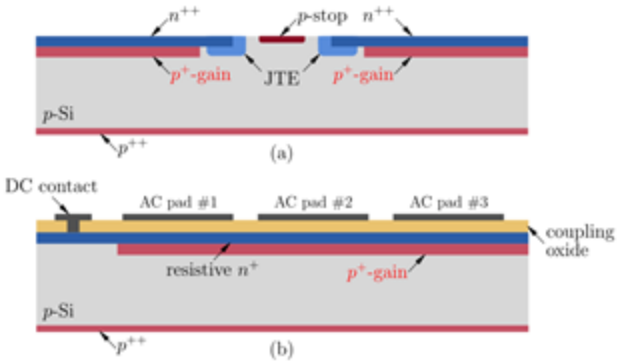
Y.-B. Yang *et al.*,
EPJ Web Conf. 175, 14002 (2018)

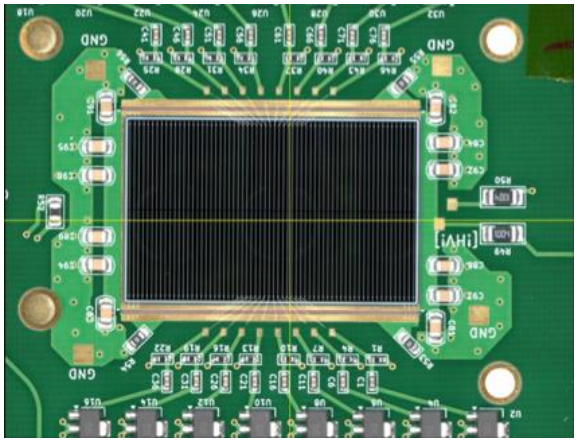


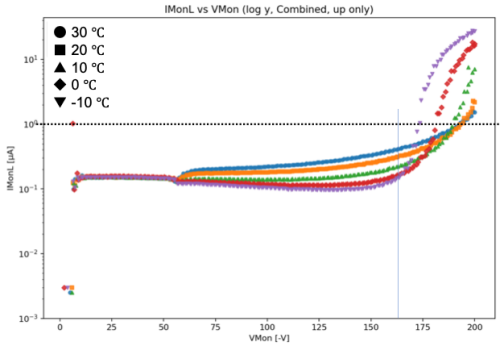
- ultimately toward unified understanding

ePIC AC-LGAD Barrel Time of Flight

- (probably) first strip AC-LGAD detector application
- 4-dimensional resolution ~ 30 ps, ~ 30 μm
- prototyping ⇄ testing with HAMAMATSU PHOTON IS OUR BUSINESS





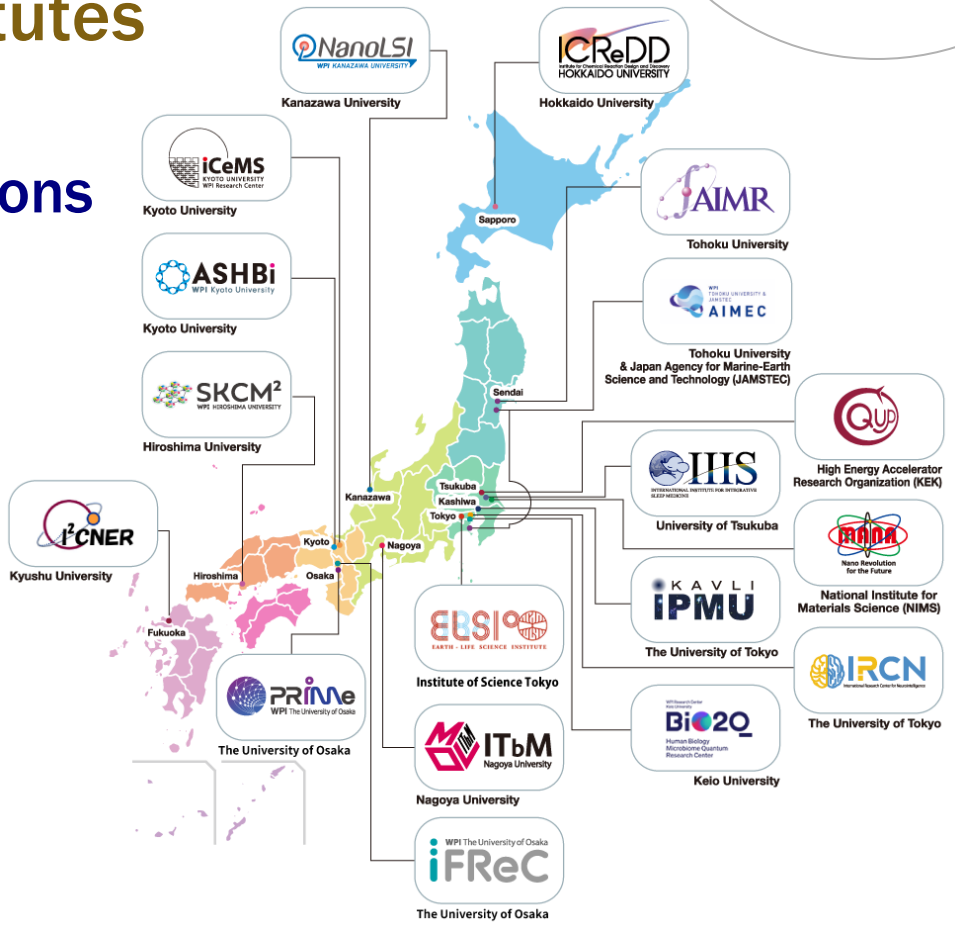


- Japan in collaboration w/ US, Taiwan
  - TOF deputy project lead: S. Yano (Hiroshima U.)

World Premier Int'l Initiative Institute

World Premier Int'l Initiative Program

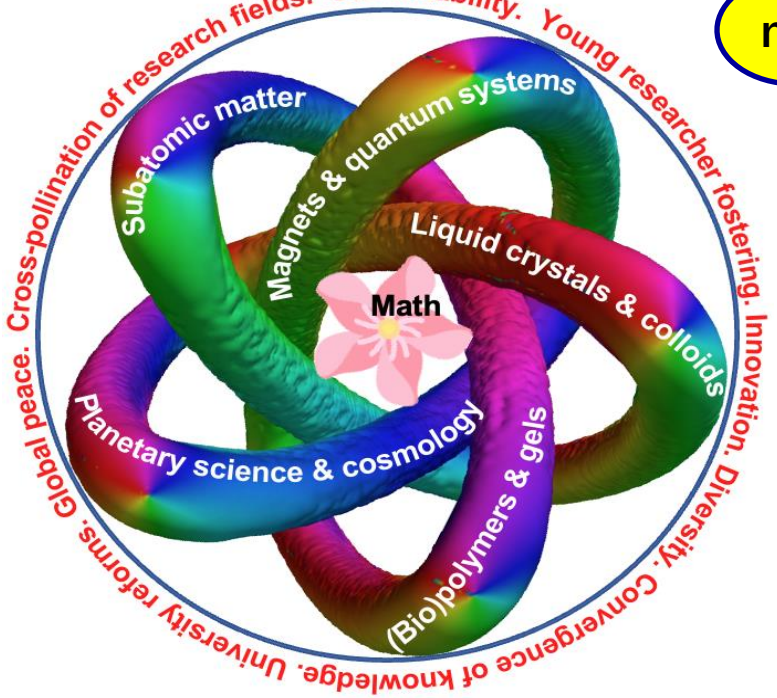
- started in 2007 by Ministry of Education+ (MEXT)
- currently 18 WPI institutes
  - SKCM^2 : only one in Chugoku/Shikoku regions

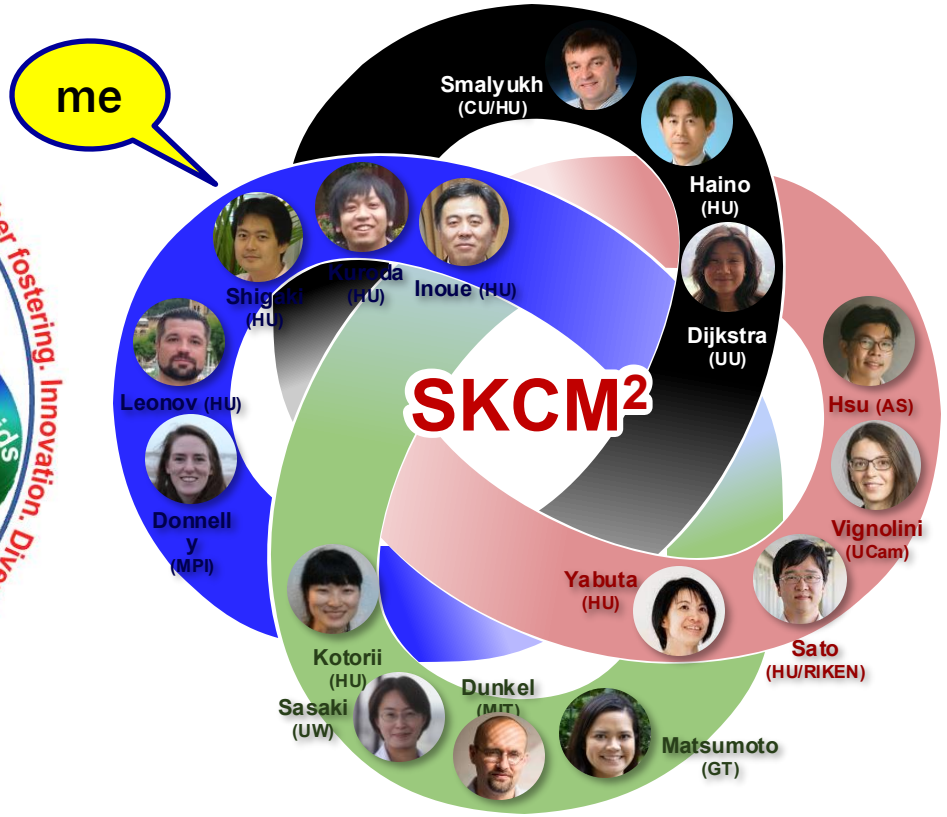


広島大学

Interdisciplinary Fusion Research

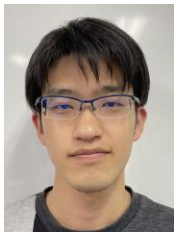
- knotted chiral meta-matter
- math, chemistry, physics, bio, planetary, ...

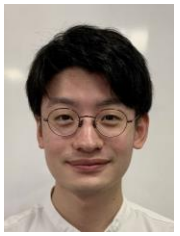


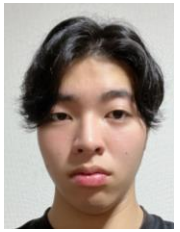


SKCM² High Energy Exp. Physics Group





- 1 professor/PI (KS)
- 1 affiliate assistant prof.
- 1 (or more ?) PD now recruiting
  - application deadline: 2026/01/04
  - contact shigaki@hiroshima-u.ac.jp
- 4 PhD students
- 1 (→ 3) master's students
- … getting even stronger
  - tight connection to theory/other teams
- → quantum particle detector technology team

Summary and Concluding Remarks

- deconfined quarks/gluons in hand in 21st century
  - "little bang" fireball well above *Tc* ~ 170 MeV
  - recreating universe ~ 10 μs after Big Bang
- hadronic mass origin still under exp'l challenge
  - chiral symmetry breaking/restoration
  - QCD trace anomaly
- multiple, exciting, and bright roads ahead of us
  - new opportunity with μ measurement at LHC energy
  - approach to chiral mass degeneracy via V-A mixing
  - toward comprehensive understanding at future EIC
- further experimental/technical endeavors