

# ***Experimental study of high density QCD at J-PARC-HI***

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for the J-PARC HI Collaboration

2016 JAEA/ASRC Reimei Workshop : New exotic hadron matter  
at J-PARC

# J-PARC-HI Collaboration (Sep, 2016)

87 collaborators

## Experiment

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## Accelerator

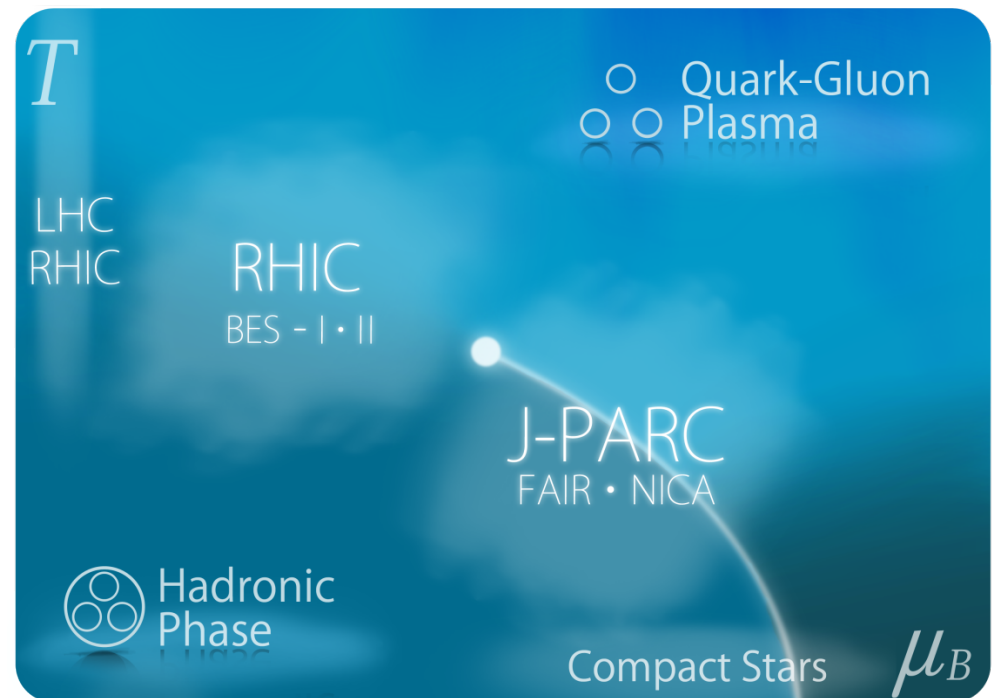
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## Theory

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# Charm of high density QCD

- High density?:  $\sim 3\text{-}4$  times normal nuclear density =  $\sim 0.5\text{GeV}/\text{fm}^3$ 
  - Normal nuclear density:  $0.17\text{ GeV}/\text{fm}^3$
  - Quarks and gluons can be liberated (Quark Gluon Plasma: QGP)
- Connection to astronomy
  - Neutron star core:  $\sim 0.5\text{GeV}/\text{fm}^3$
  - Ground lab for neutron star
- New field in high density
  - Color superconductivity, etc.
- Connection to condensed matter physics
  - Onto BCS-BES cross-over
  - Common properties of multi-body systems: Electro-magnetic and strong interaction



# J-PARC (KEK & JAEA)



**J-PARC  
(KEK & JAEA)**

400 MeV H<sup>-</sup> Linac

Transmutation Experimental  
Facility (TEF)

3 GeV Rapid Cycling  
Synchrotron (RCS)

Neutrino experiment  
(NU)

Materials & Life  
Science Facility  
(MLF)

50 GeV Main Ring  
Synchrotron (MR)  
[30 GeV at present]

Hadron  
Experimental  
Hall (HD)

**J-PARC  
(KEK & JAEA)**

400 MeV H<sup>-</sup> Linac

Transmutation Experimental  
Facility (TEF)

3 GeV Rapid Cycling  
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H<sup>-</sup> booster

H<sup>-</sup> Linac

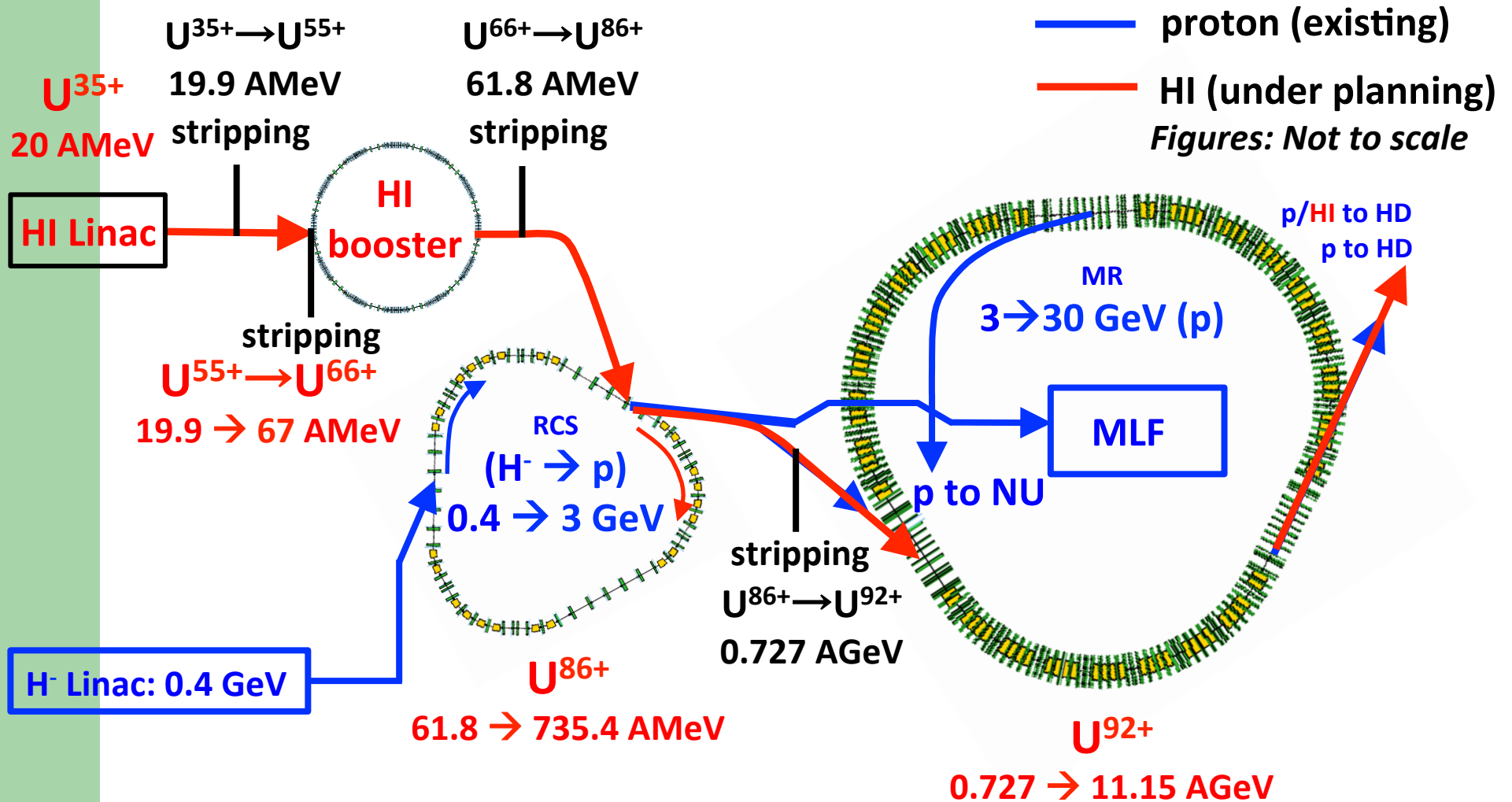
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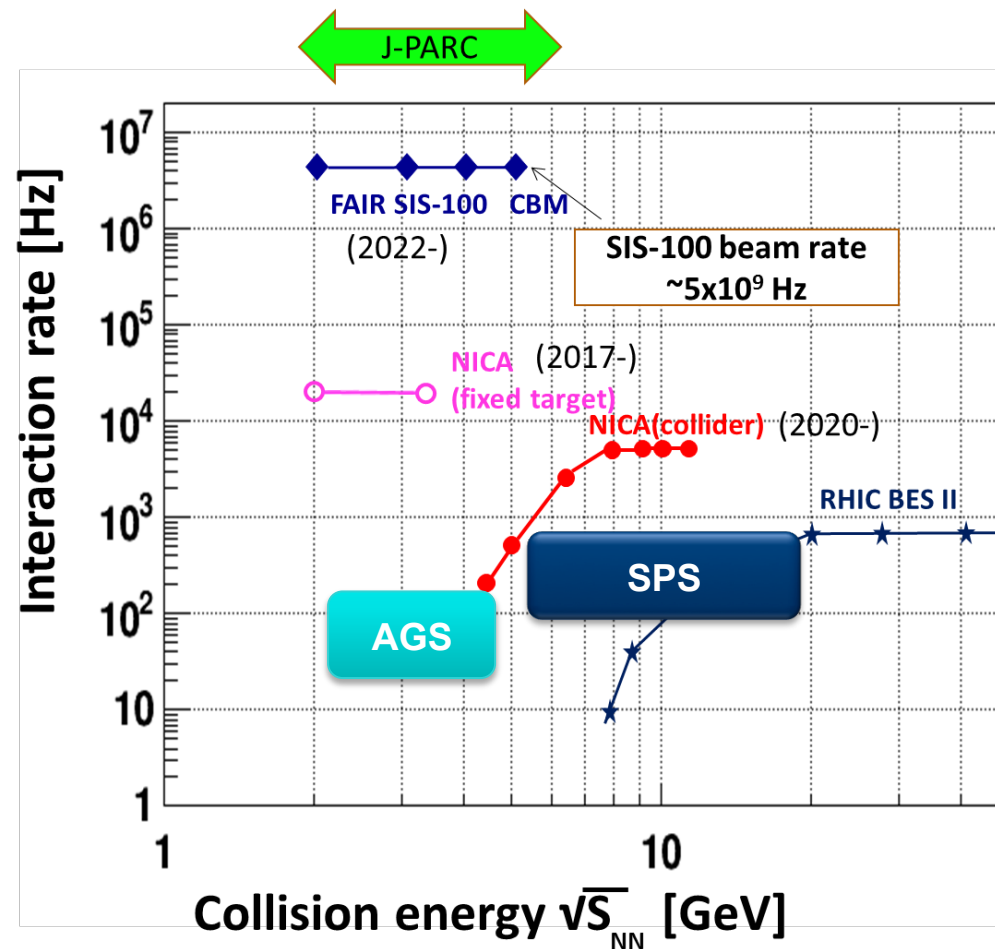
# HI Accelerator scheme in J-PARC



*This HI accelerator scheme has no interference/conflict with proton beam programs*

# Available beam and rate

- *Very high intensity beam is a feature of J-PARC HI accelerator*
  - $E_{\text{lab}}=1\text{-}19\text{GeV}/n$ ,  $\sqrt{s_{\text{NN}}}=1.9\text{-}6.2\text{GeV}$  ( $\sim$  AGS),  $>10^{11}\text{ cycle}^{-1}$  ( $\sim 6\text{s cycle}$ )
- Ion species: p, Si, Ar, Cu, Xe, Au(Pb), U, and also light ions for hypernuclei



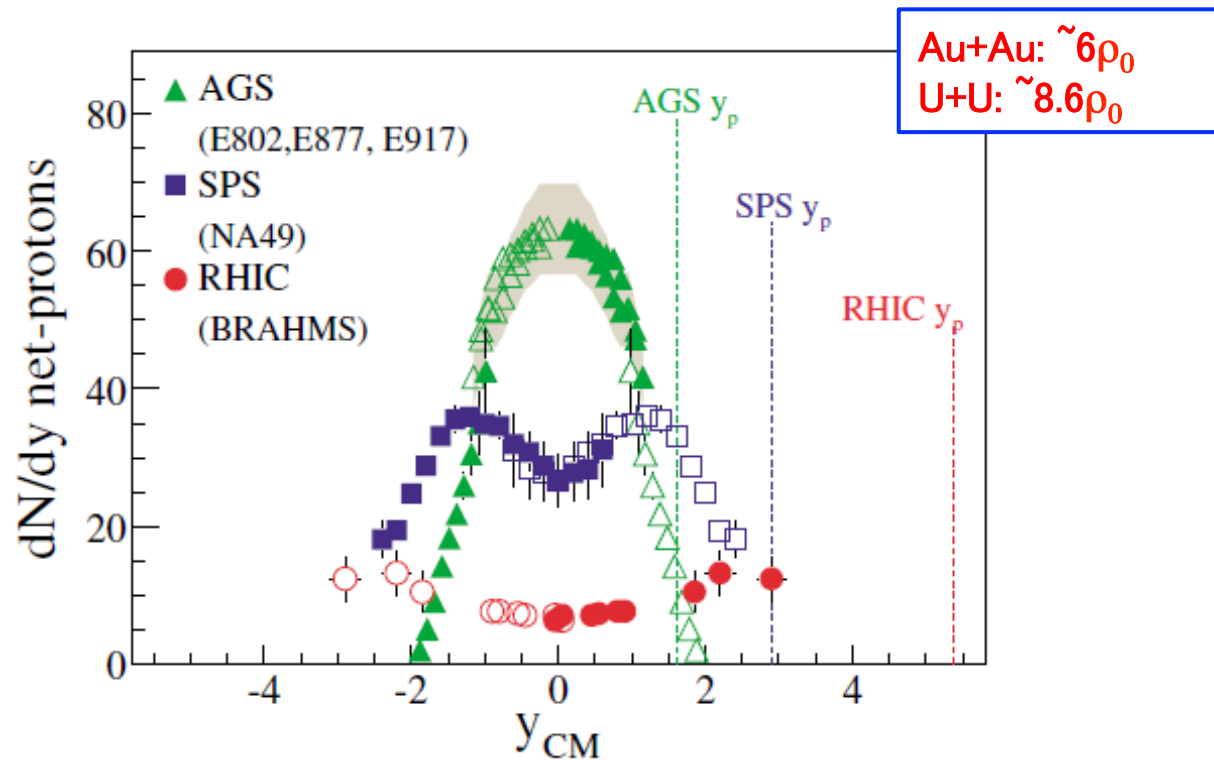
# Review of previous results

- Net proton =  $N(p) - N(\bar{p})$ 
  - A good variable showing the position of incident and target nucleons
- Nucleon centered around mid-rapidity at AGS energy
  - Nucleons stop at mid-rapidity: Baryon stopping → **High density matter**
  - Incident and target nucleons pass through each other at SPS and RHIC

Rapidity

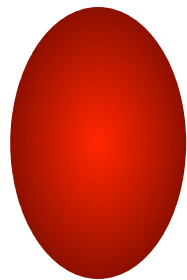
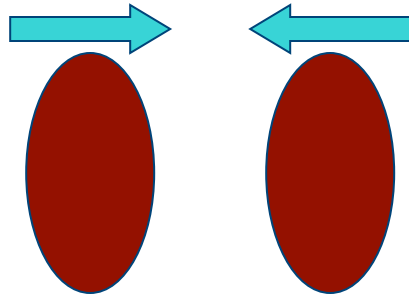
$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

z: Beam direction

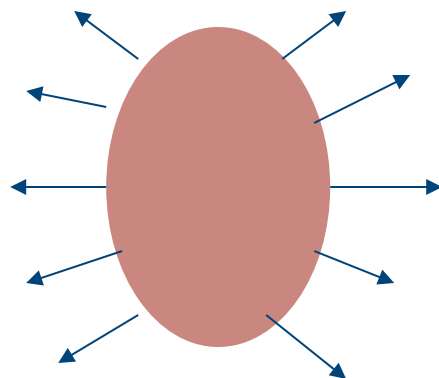


# Collisions at J-PARC energy

Low energy (Landau picture)



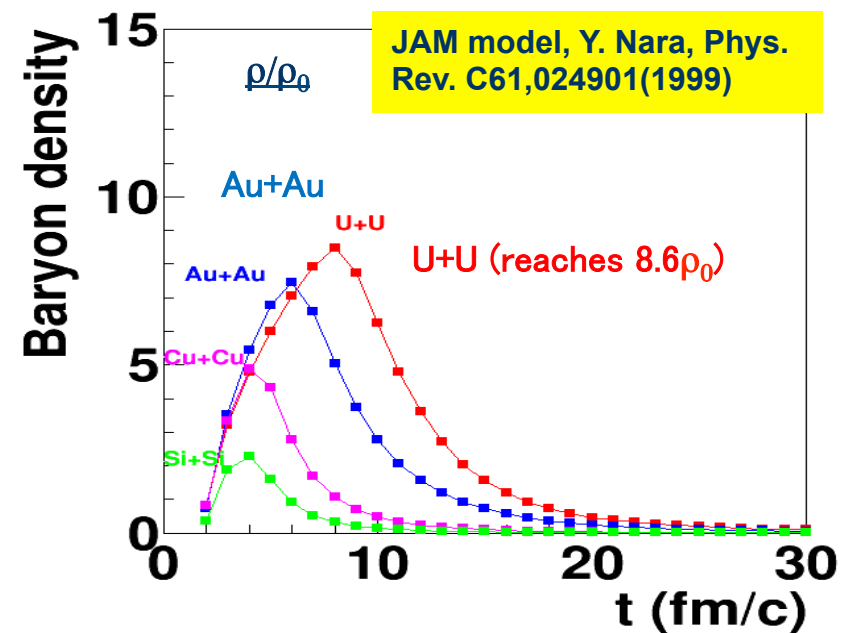
Stopping  
High  $T$ ,  
High  $\mu_b$



Cartoon by the courtesy of K. Itakura

$$\rho = 2A / (V / \gamma_{\text{CM}}) = 2\gamma_{\text{CM}}\rho_0$$

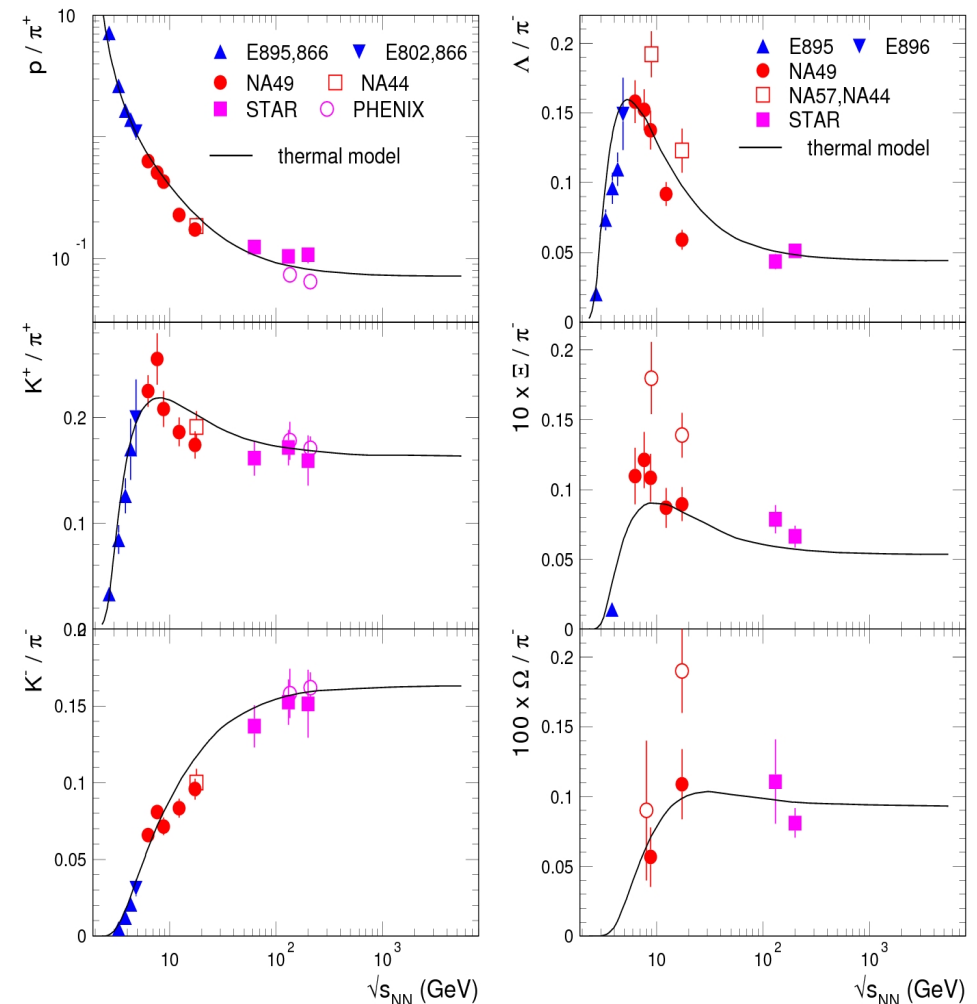
$$\gamma_{\text{CM}} \approx 2.87$$



# Review of previous results

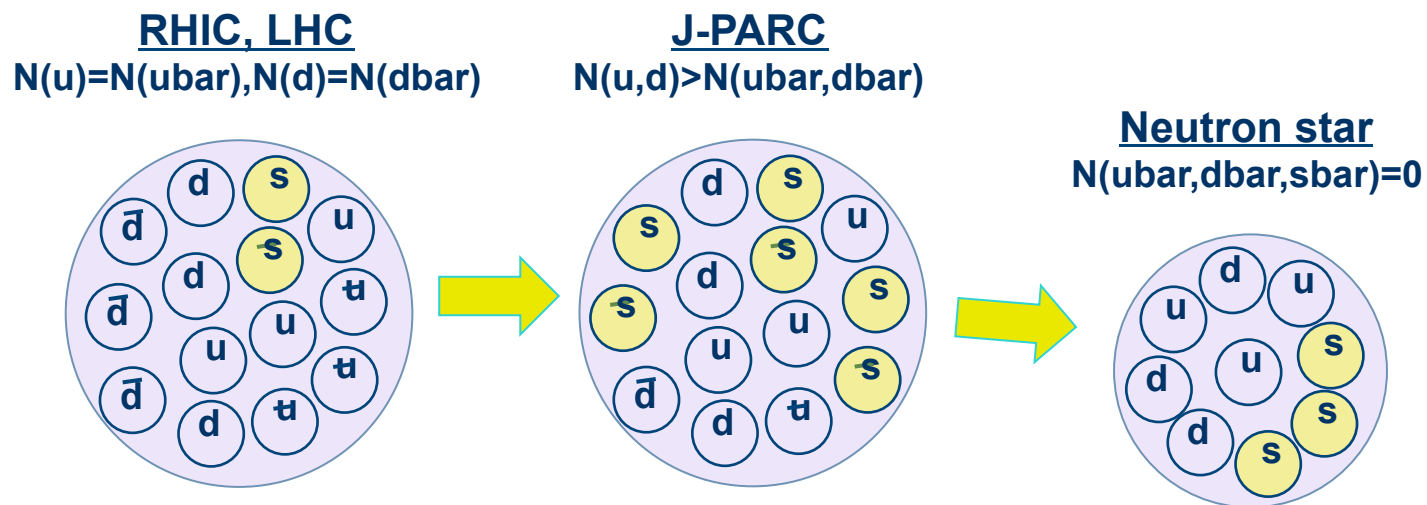
- Compilation of various particle ratios as a function of energy
- Hadrons including strangeness:  $K^+$ ,  $K^-$ ,  $\Lambda$ ,  $\Xi$ ,  $\Omega$
- $\pi$  is a measure of the total number of particles produced in an event
- $K^+$ ,  $K^-$ ,  $\Lambda$ ,  $\Xi$ , have maximum yields around  $\sqrt{s_{NN}}=5\text{GeV}$ 
  - $K^-$  is hard to produce since  $u\bar{b}$  is not copious in the beginning
  - Production cross-section of  $\Omega$  is very small
- **Strangeness is most produced at AGS (J-PARC) energy**

NPA772(2006)167



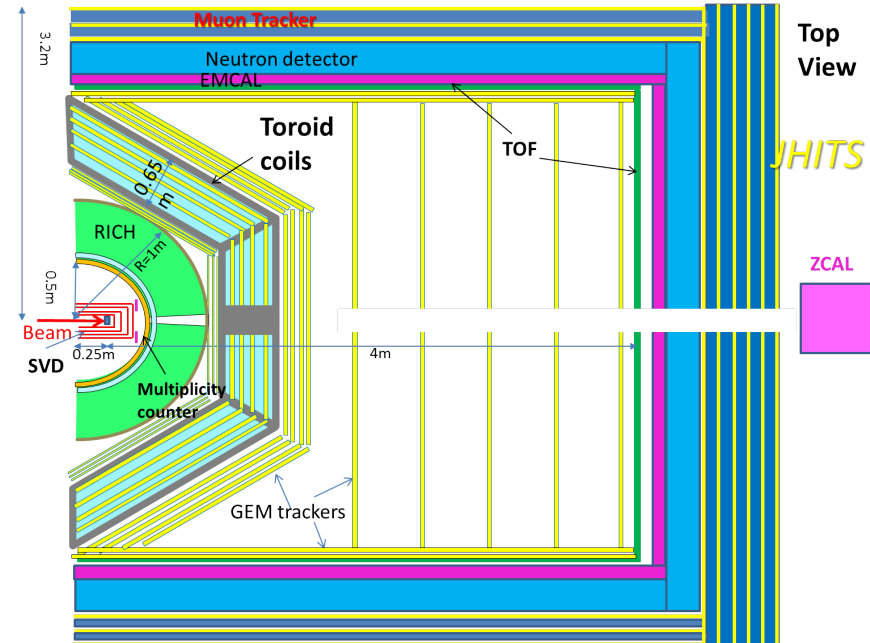
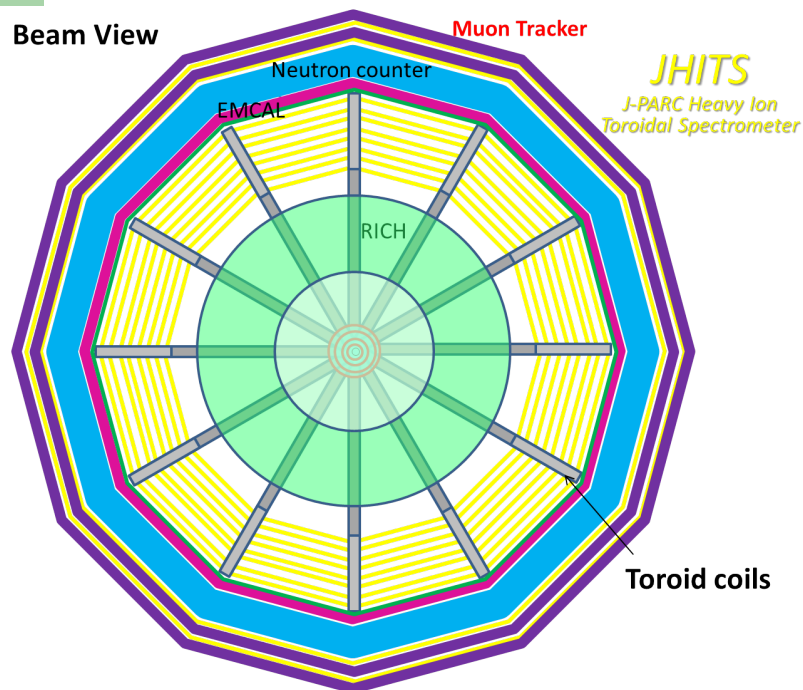
# Strange-rich matter at J-PARC

- High  $T$ , low  $\mu_b$  (RHIC, LHC)  $\rightarrow$  High  $T$ , high  $\mu_b$  (AGS, J-PARC-HI)  $\rightarrow$  Low  $T$ , high  $\mu_b$  (neutron star)
- Approaching to the core of the of neutron stars
  - HI reaction produces Strangeness by **Strong Interaction**
  - Neutron-star core produces Strangeness by **Weak interaction**



# Concept of measurement device

- Detector complex covering wide acceptance
  - High speed tracking, TOF, EM calorimeter, and muon detector
- 0.1%  $\lambda_1$  target:  $\sim 100\text{MHz}$  event rate, 1000 particles/event
- Collect data with minimum bias trigger (Data size: 1TB/s)
  - Continuously take data with no trigger (Import ALICE experience)
  - Select rare events in semi-online, using a high performance computing system



# Particle production rates

Beam :  $10^{10}$  Hz

0.1% target

→ Interaction rate  $10^7$  Hz

Centrality trigger 1%

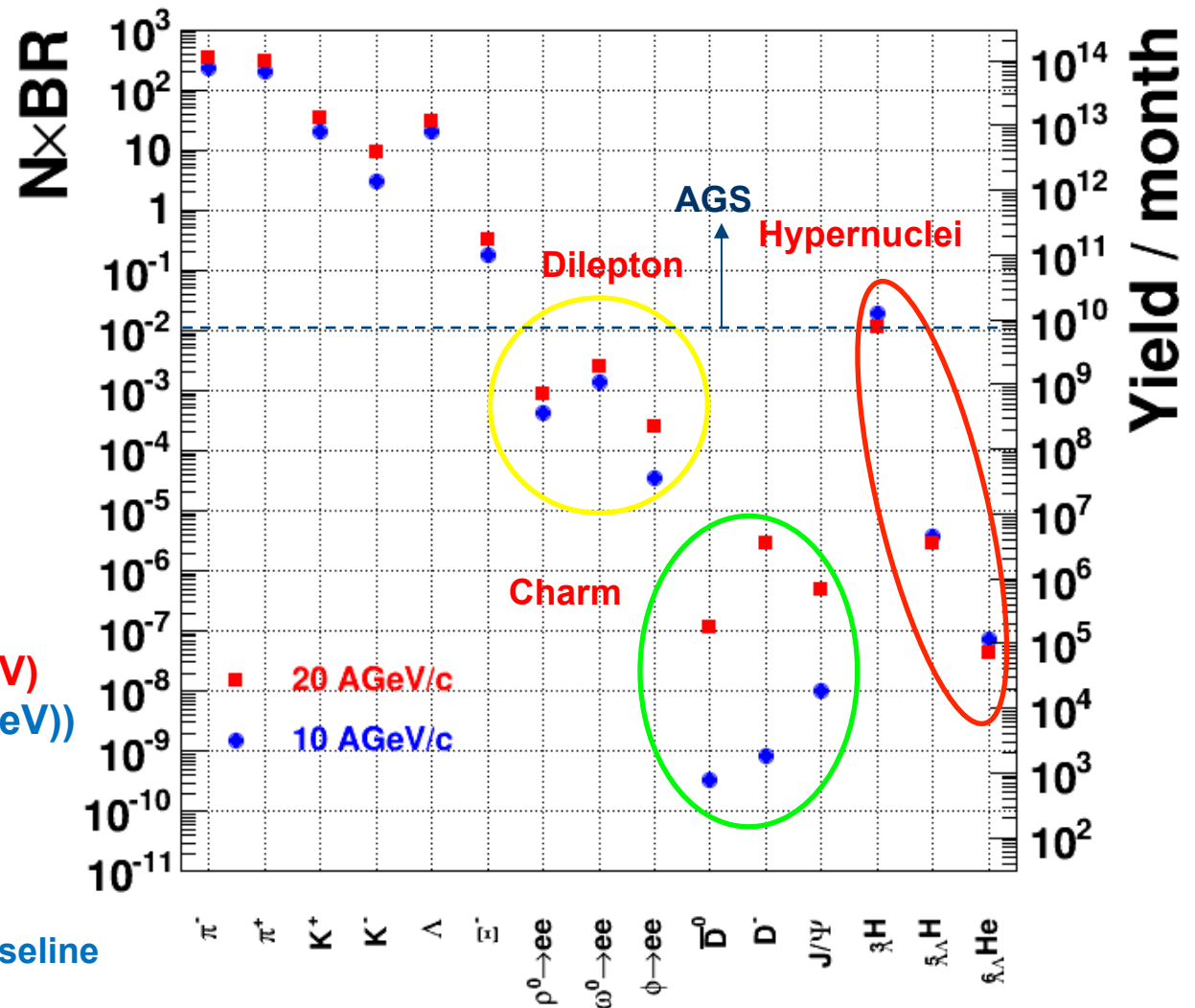
→ DAQ rate = 100kHz

In 1 month experiment:

$\rho, \omega, \phi \rightarrow ee$   $10^7 - 10^9$

$D, J/\psi$   $10^5 - 10^6$  (20 AGeV)  
( $10^3 - 10^4$  (10 AGeV))

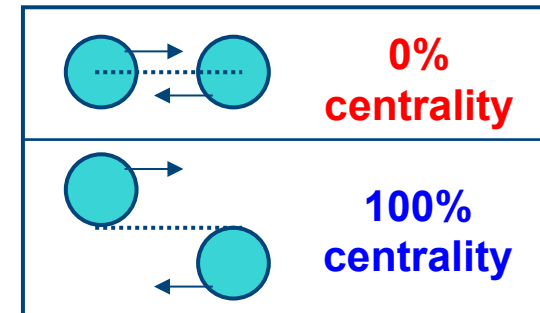
Hypernuclei  $10^5 - 10^{10}$



Ref: HSD calculations in FAIR Baseline  
Technical Report (Mar 2006)  
A. Andronic, PLB697 (2011) 203

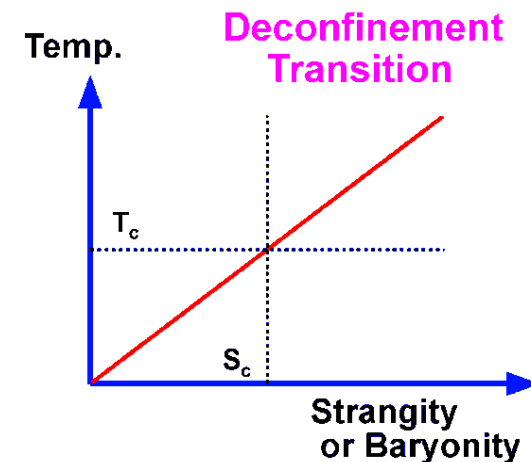
# Event selection consideration

- Centrality: Event class variable proportional to impact parameters
  - 0%:  $b=0$ , **Central collisions**
  - 100%:  $b=b_{\text{max}}$ , **Peripheral collisions**
- Same event selection as we did in the past wouldn't yield new physics
- **We add a new event selection**
  - After pre-selecting most central collisions
- **Strangity, Baryonity**
  - Aggressively select interesting events relevant to the new phenomena found by the AGS experiment
  - **Strangeness enhancement, baryon stopping**
- Statistics-starved “very rare event” selection feasible with high luminosity beam at J-PARC-HI



$$\text{Strangity} \equiv \langle N(K^+) \rangle / \langle N_{ch} \rangle$$

$$\text{Baryonity} \equiv \langle N(p) - N(\bar{p}) \rangle$$



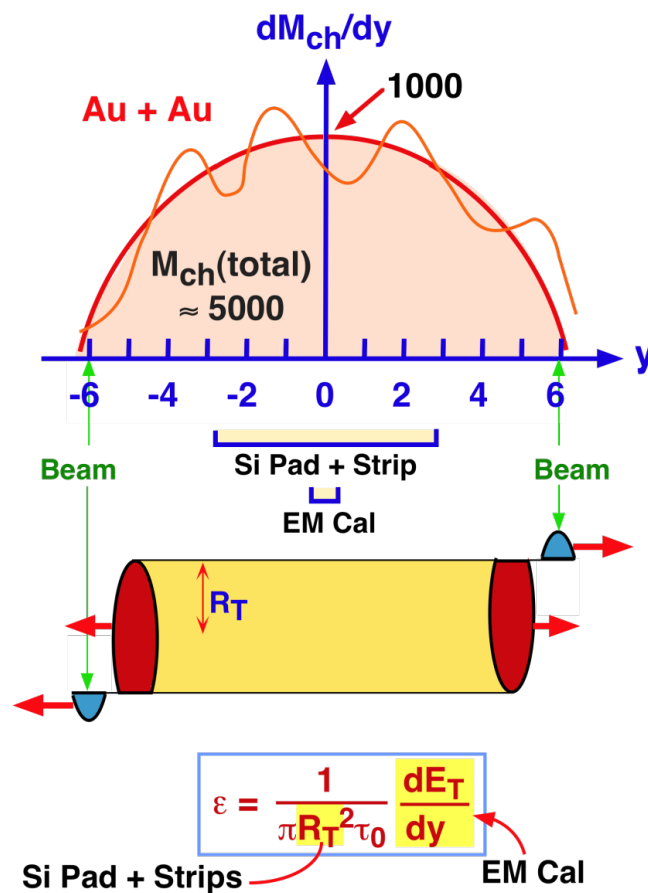
TS, H. Sako and M. Kitazawa, in prep.

# Physics Observable

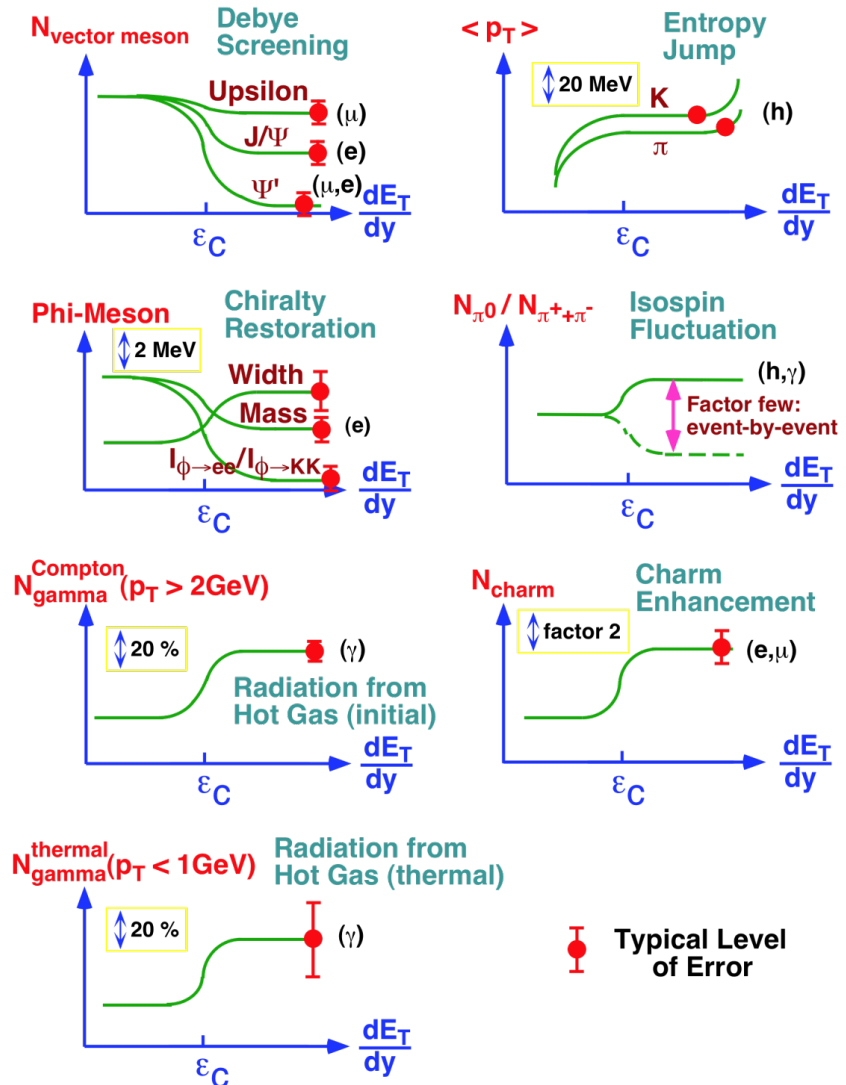
# Physics observables at RHIC

PHENIX

## Global Event Trigger

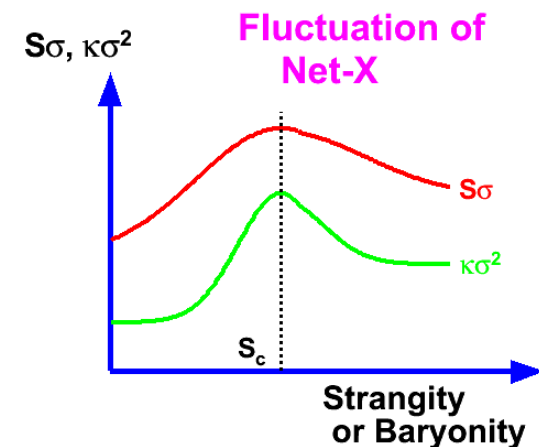
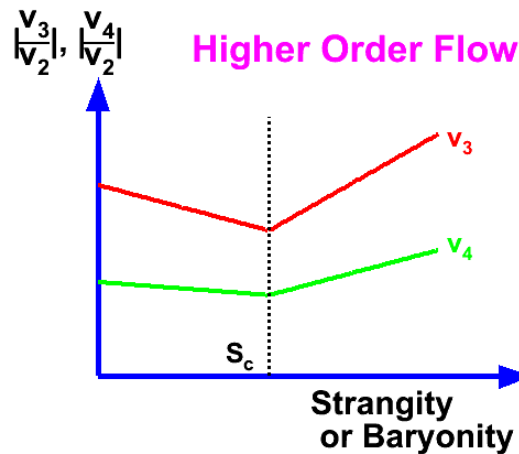
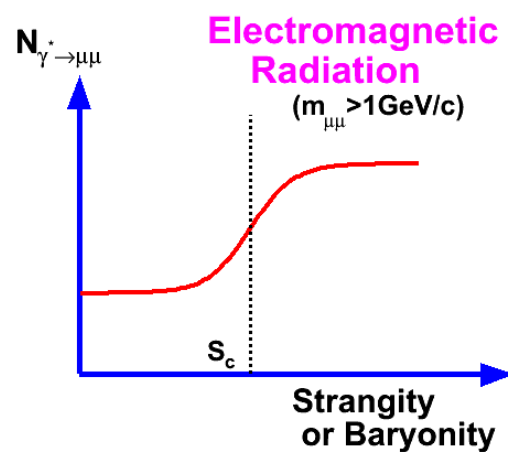


## Signatures of Quark-Gluon Plasma



# Physics observables at J-PARC-HI

- Primarily focus on new observables found at higher energy experiments
  - Based on knowledge gained at RHIC and LHC
- Study characteristics of high density matter
  - Particle emission anisotropy, fluctuation of conserved quantities
  - Lepton pairs, thermal photons



# Thermal photons

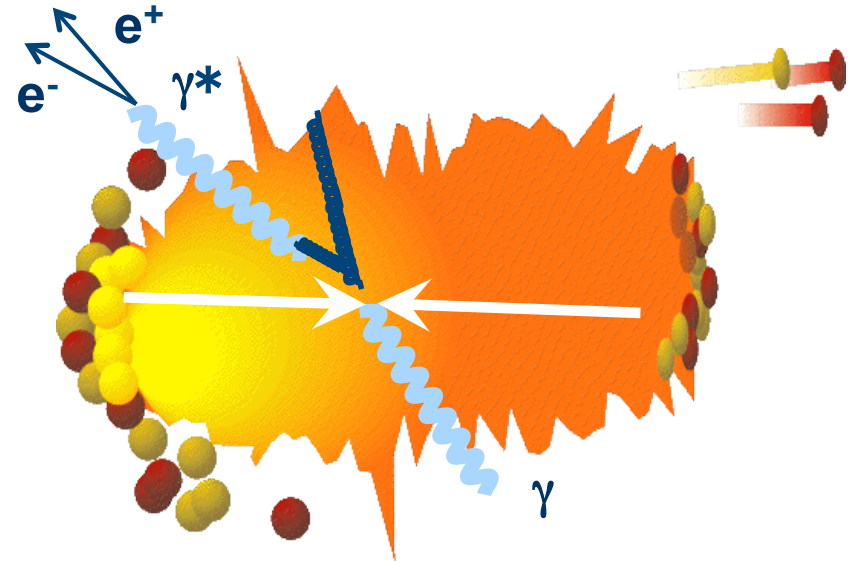
- Emitted from all the stages after collisions
- Penetrate the system unscathed after emission
  - Carry out thermodynamical information such as temperature
- Photons will be produced by Compton scattering or qqbar annihilation at LO

$$E \frac{dR_\gamma}{d^3 p} = -\frac{\alpha_{em}}{\pi^2} \text{Im}\Pi_{em}(\omega, k) \frac{1}{e^{E/T} - 1}$$

$\Pi_{em}$ : photon self energy

$$\text{Im}\Pi_{em}(\omega, k) \approx \ln\left(\frac{\omega T}{(m_{th}(\approx gT))^2}\right)$$

Small Rate: Yield  $\propto \alpha\alpha_s$

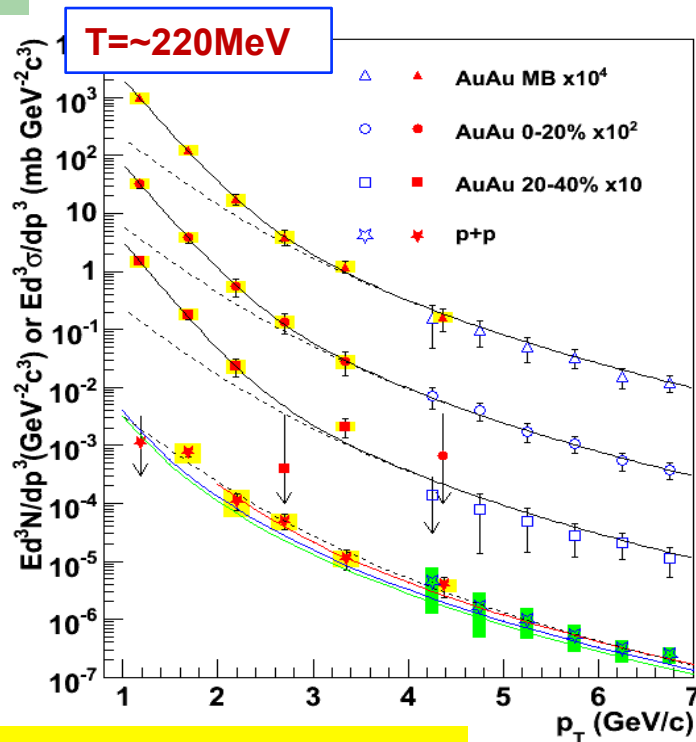
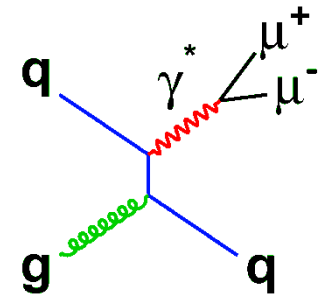


•Product of Bose distribution and transition probability

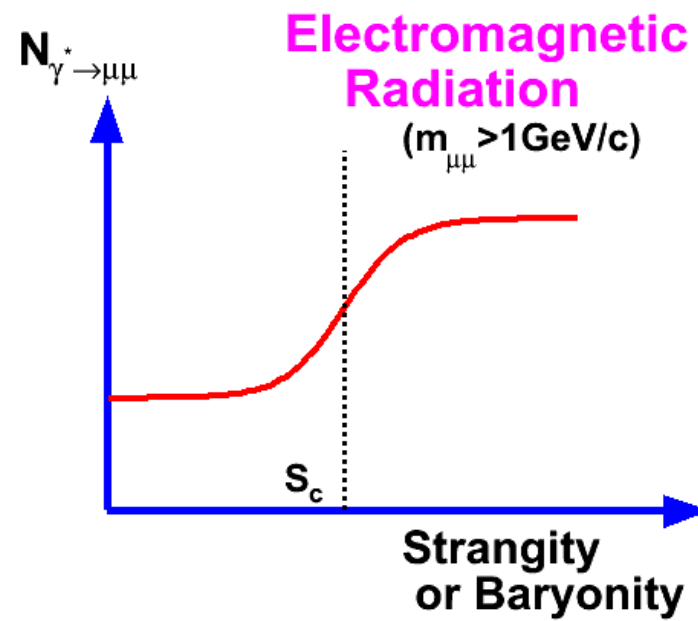
•Slope at  $E \gg T$  tells temperature ( $T \sim 200 \text{ MeV}$ )

# Virtual photon measurement at J-PARC

- Produced in the same process as real photons, but with a virtual mass ( $Q^2$ )
- At RHIC, virtual photons are measured via electron-decay channel
  - PRL 104, 132301(2010)
- At J-PARC, photons will be measured via muon-decay channel
  - $\gamma \rightarrow \mu^+ \mu^-$ : No background muons from  $\pi^0$  or  $\eta$ . S/N is better

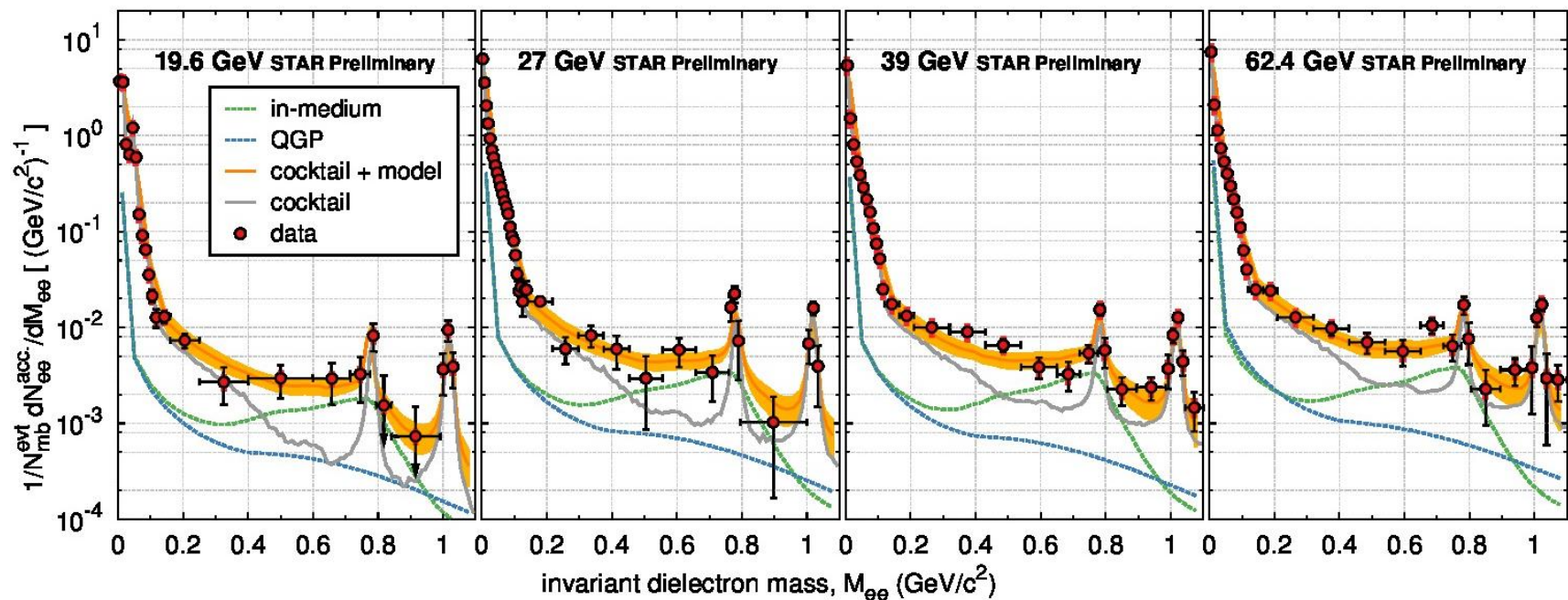


PHENIX, PRL 104, 132301 (2010)



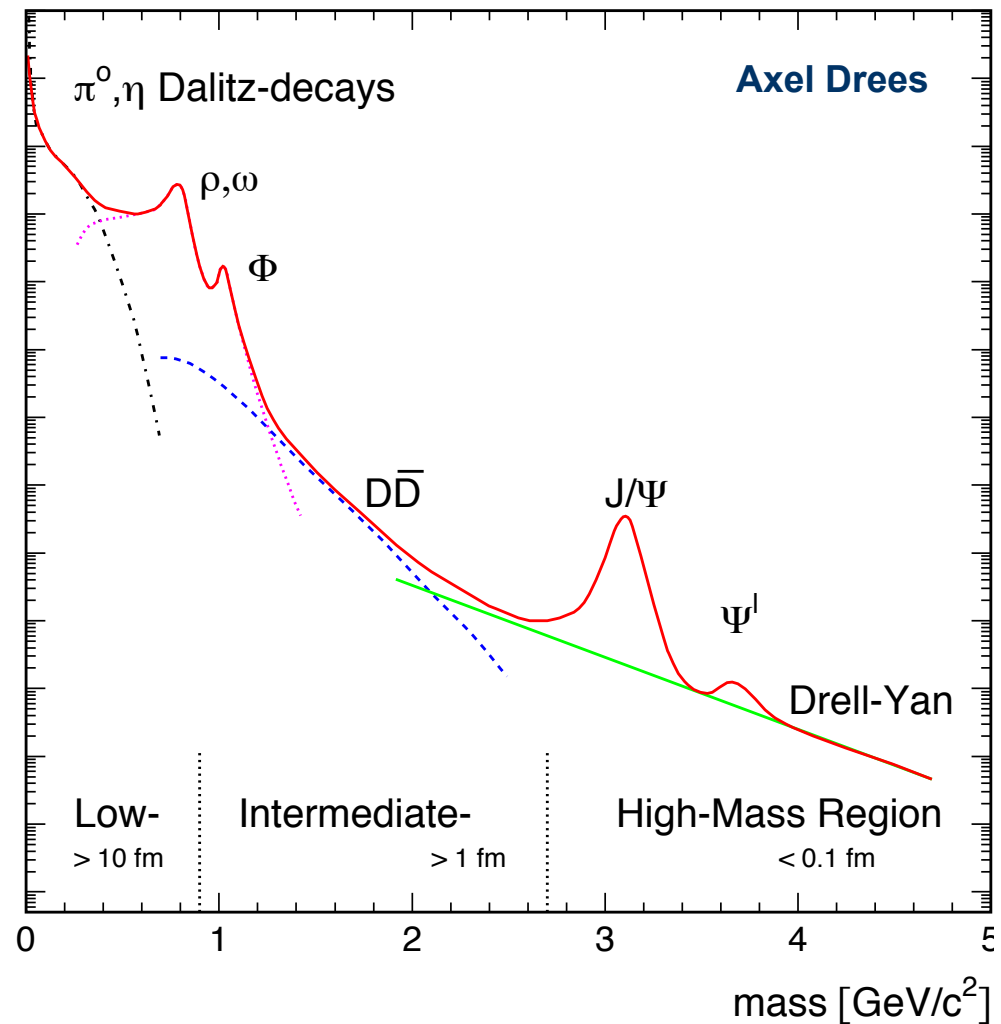
# Low-mass dileptons

- From STAR's BES result
  - Low mass enhancement is well-described by cocktail + in-medium  $\rho$  modification (Rapp model) + thermal radiation
- How does it look like in even lower energy, i.e., in dense matter?
  - At J-PARC, measurement of both di-electrons and di-muons is planned



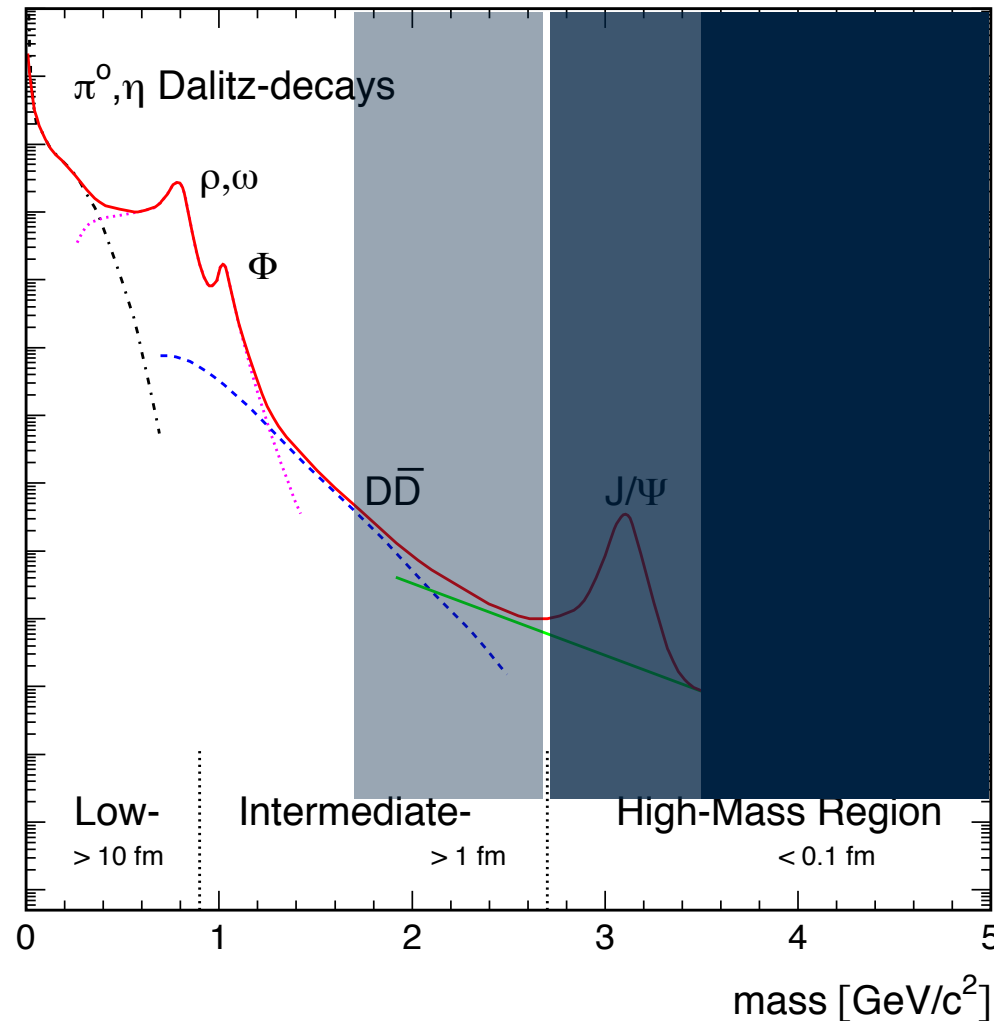
F. Geurts, Thermal photon dilepton workshop, Aug, 2014 and NPA 904–905 (2013) 217c

# Dileptons at RHIC and LHC energy



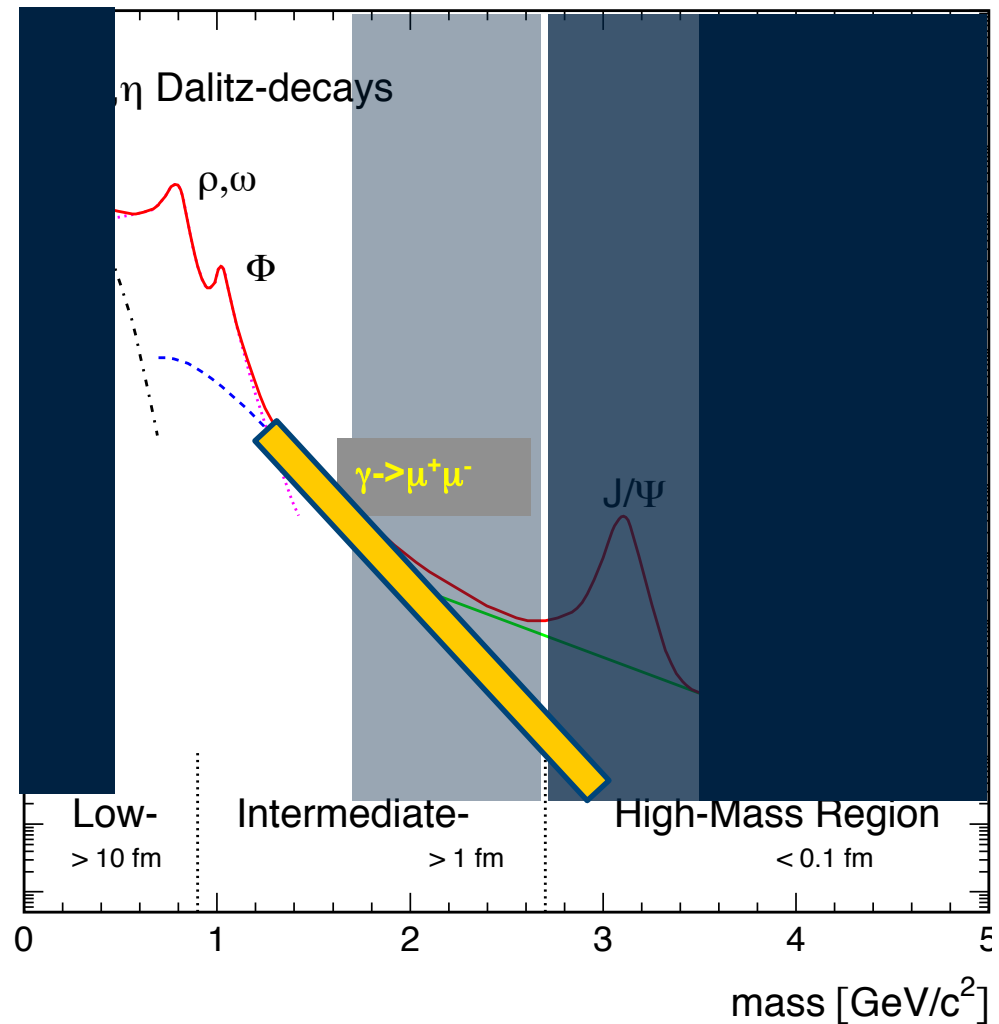
# Dileptons at J-PARC energy

- Landscape for J-PARC ( $\sqrt{s} \sim 5\text{GeV}$ )
- Intermediate Mass Range
  - **DDbar is very hard**
  - Sensitive to QGP thermal radiation?
- Low Mass Range
  - in-medium modification of vector mesons (link to chiral symmetry restoration)
  - Thermal radiation



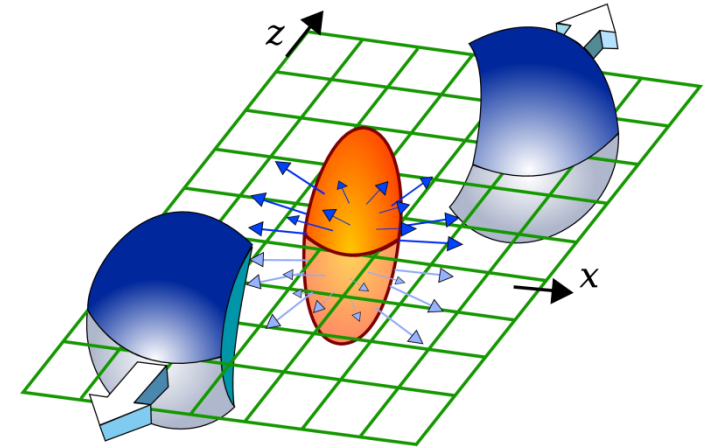
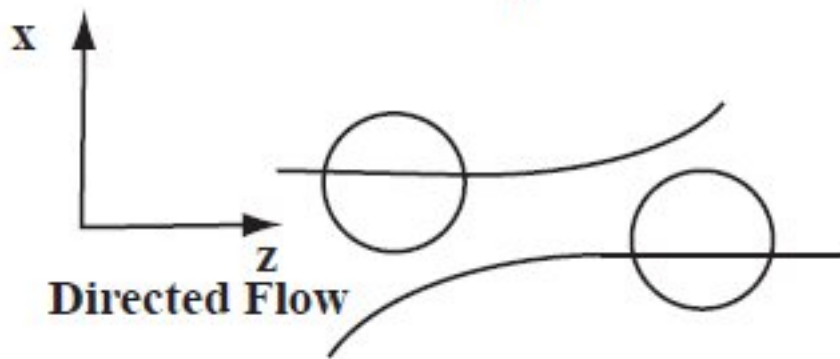
# Dimuons at J-PARC energy

- There is no muon decay for  $\pi^0$  and  $\eta$ 
  - S/B is much better



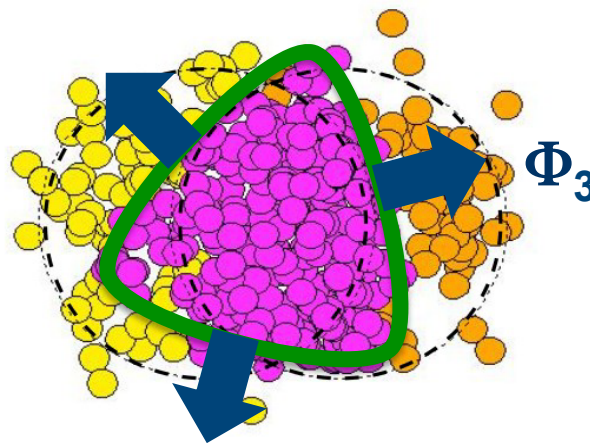
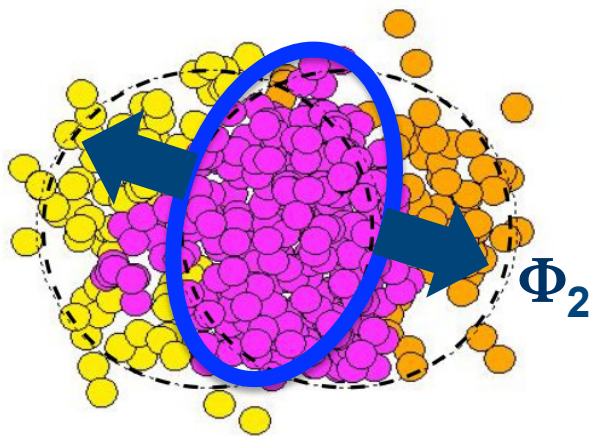
# Particle flow

- In non-central collisions, the collision area is not isotropic
  - Different pressure gradient produces momentum anisotropy of emitted particles



$$\frac{dN}{d(\phi - \Psi_n)} = N_0 \left[ 1 + 2 \sum_{n=1}^{\infty} v_n \cos\{n(\phi - \Phi_n)\} \right]$$

$$v_n = \langle \cos\{n(\phi - \Phi_n)\} \rangle$$



Fluctuation of nucleon position yields higher order anisotropy

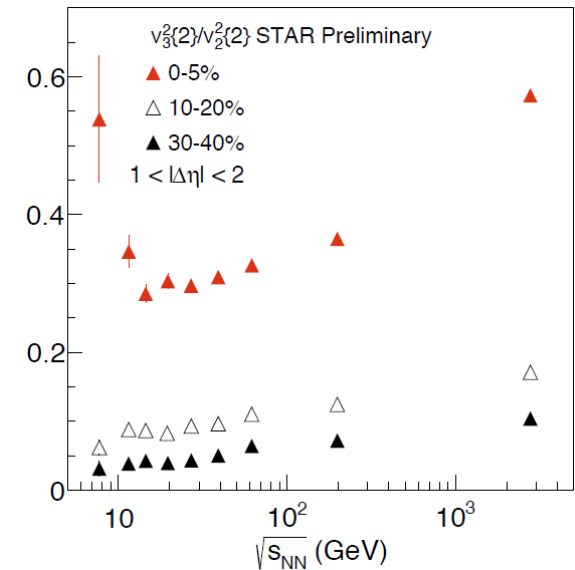
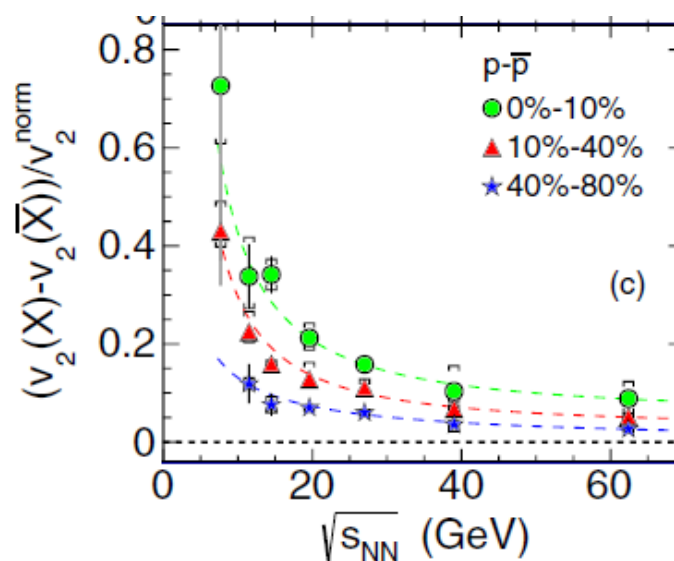
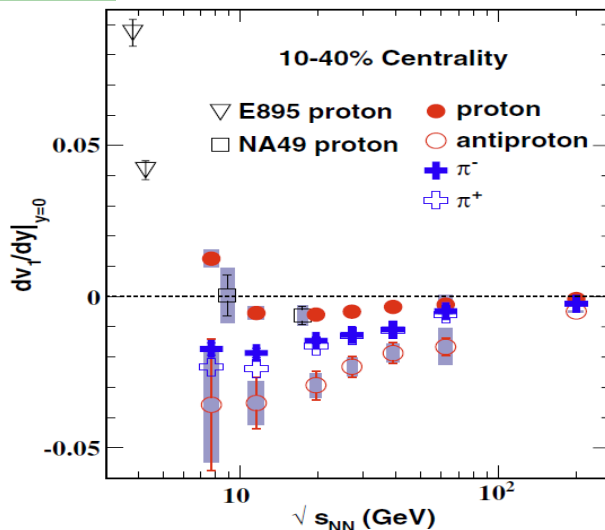
$(v_3, v_4, \dots, v_n)$

Sensitive to EOS, shear viscosity ( $\eta$ ) to Entropy density ( $s$ ) ratio ( $\eta/s$ )

# $V_1, V_2, V_3, V_4, \dots$

- $v_1$ : Slope of directed flow ( $dv_1/dy$ ) for protons will change its sign from positive to negative around mid-rapidity, if a phase transition occurs
- $v_2$ : Flow of protons and anti-protons merges at higher energies.
  - Low  $p_T$ , the pressure from the partonic phase is not well developed
- $v_3, v_4$ : mainly from fluctuations. Will be increased in partonic phase

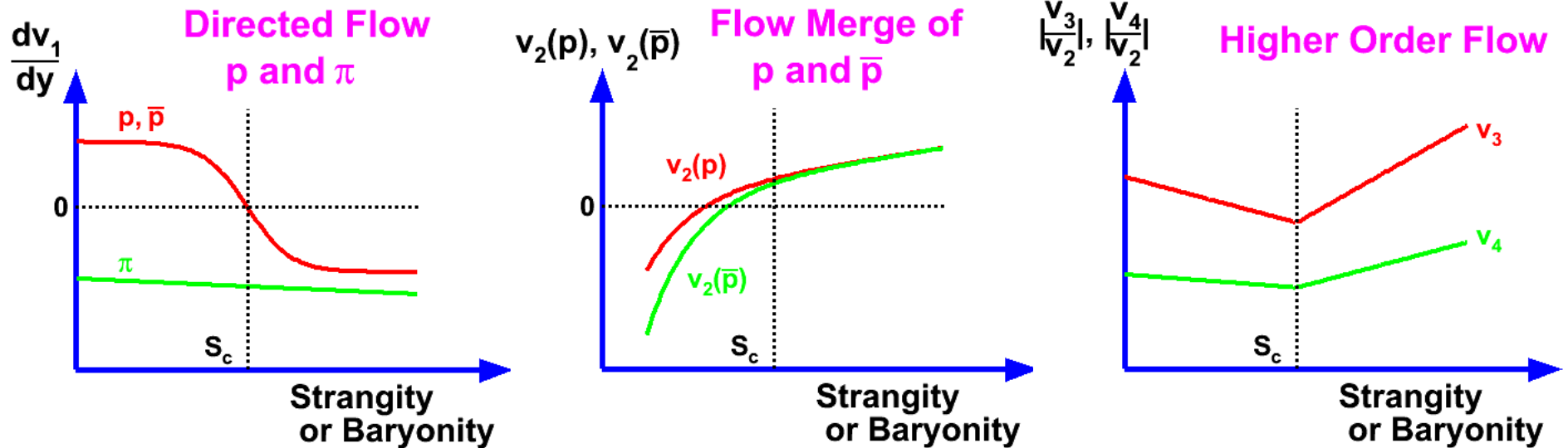
PHYSICAL REVIEW C 93, 014907 (2016)



# $V_1, V_2, V_3, V_4 \dots$

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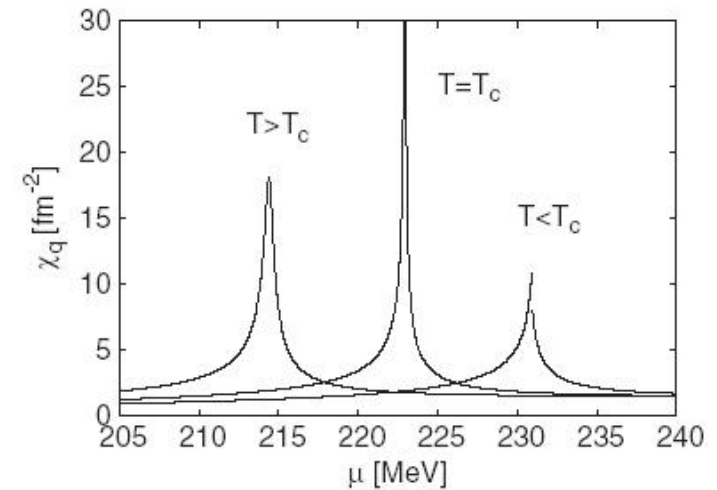


# Fluctuation of quantities

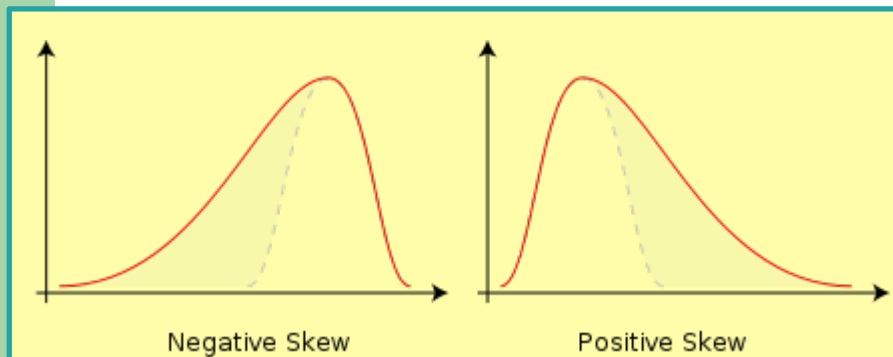
- Energy fluctuation → Specific heat
- Multiplicity fluctuation → Compressibility
- Net-baryon fluctuation → Correlation length (an index for phase transition)

Variance :  $\sigma^2 = \langle (\Delta \mathcal{N})^2 \rangle \sim \xi^2$   $[\chi^{(2)} / \chi^{(1)}]$   
 Skewness:  $S\sigma = \langle (\Delta \mathcal{N})^3 \rangle / \sigma^2 \sim \xi^{5.5}$   $[\chi^{(3)} / \chi^{(2)}]$   
 Kurtosis:  $K\sigma^2 = \langle (\Delta \mathcal{N})^4 \rangle / \sigma^2 - 3\sigma^2 \sim \xi^9$   $[\chi^{(4)} / \chi^{(2)}]$

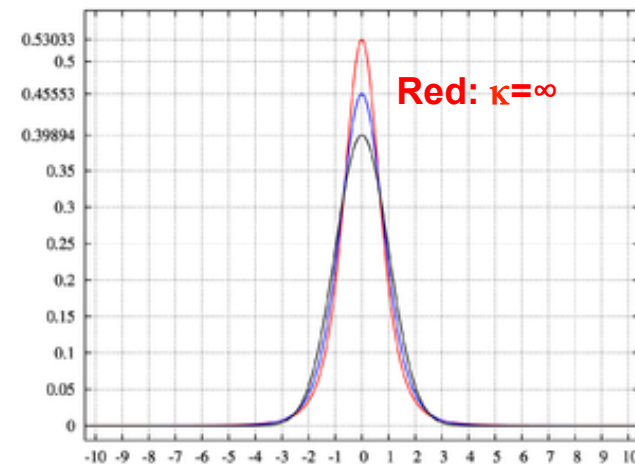
B.-J. SCHAEFER AND J. WAMBACH



## Skewness



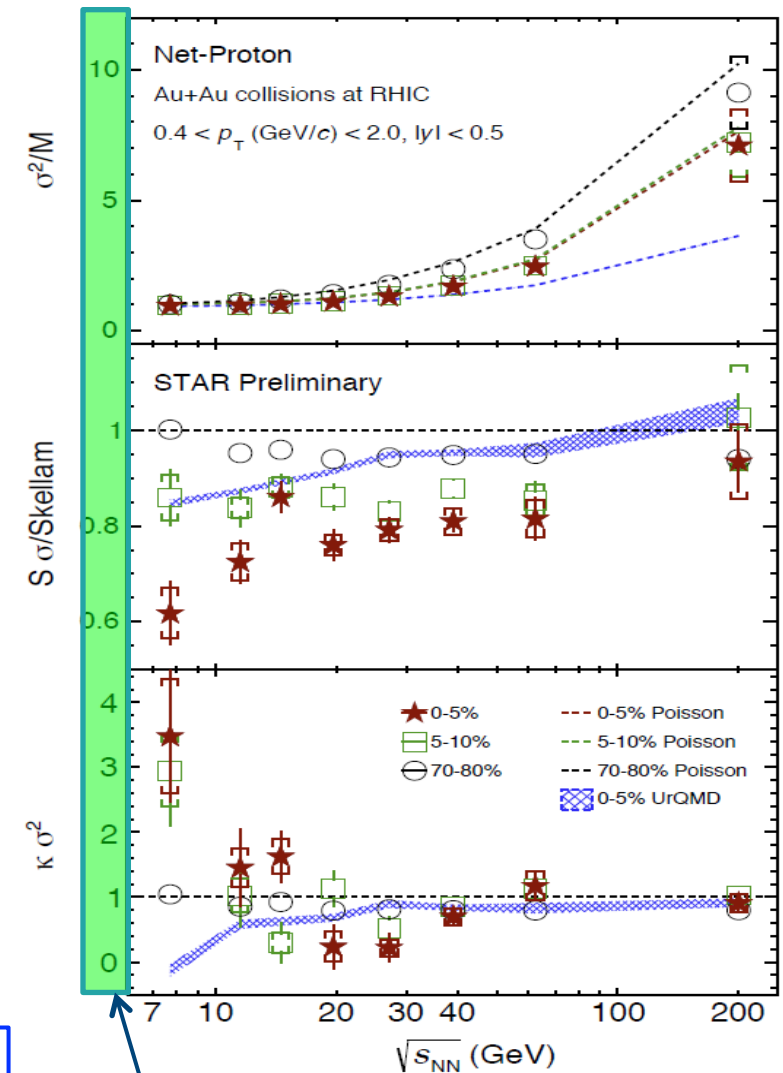
## Kurtosis



# Net-proton fluctuation

- Net-protons scanned over wide cms energy by STAR experiment at RHIC
  - Variance follows Poisson
  - Skewness doesn't
    - But it is expected from UrQMD
  - Kurtosis does follow Poisson, except for 0-10% centrality
    - Out of UrQMD expectation
    - Critical point?
- UrQMD has no Critical Point
- **Need confirmation at J-PARC**
  - **Statistic-starved measurement**
  - **A strong tool to point critical point**

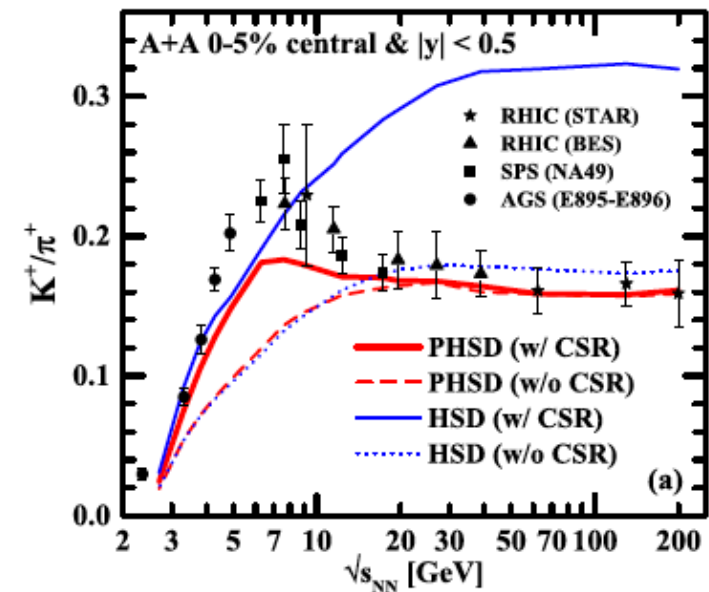
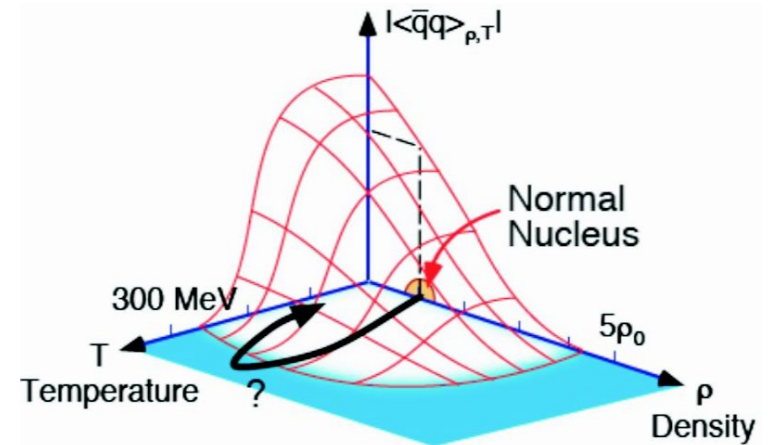
Variance :	$\sigma^2 = \langle (\Delta \mathcal{N})^2 \rangle \sim \xi^2$	$[\chi^{(2)} / \chi^{(1)}]$
Skewness:	$S\sigma = \langle (\Delta \mathcal{N})^3 \rangle / \sigma^2 \sim \xi^{5.5}$	$[\chi^{(3)} / \chi^{(2)}]$
Kurtosis:	$K\sigma^2 = \langle (\Delta \mathcal{N})^4 \rangle / \sigma^2 - 3\sigma^2 \sim \xi^9$	$[\chi^{(4)} / \chi^{(2)}]$



J-PARC region

# One comment on chiral symmetry

- $q$ - $\bar{q}$  condensate changes more rapidly in baryon density axis.
- Studying chiral symmetry restoration is essential in understanding the property of the QCD vacuum.
- Kaon mass is also said to shift
- Recent PHSD calculation with  $\chi$ -sym. restoration reproduces  $\pi$  “horn”
  - Cassing, Palmese, Moreau, Bratkovskaya, PRC93, 014902 (2016)
- This is an interesting topic to be pursued at J-PARC-HI



# Summary

- Density at J-PARC-HI can reach as ~8 times high as normal nuclear density
  - Approach to the core of neutron star
  - Approach to color superconductivity
  - Exploring BEC-BCS crossover, common feature between condensed and nuclear matter
- Focus on “very rare events” using high beam luminosity
  - 10~100MHz event rate
  - Triggerless data acquisition (importing ALICE experience)
  - Select rare events in semi-online using high performance computing system
- Introducing a new aspect on measurement
  - Introducing a new event selection based on the knowledge gained at AGS
  - **Strangity, baryonity**
- Measurement of new observables found by RHIC and LHC experiments
  - Particle emission anisotropy, fluctuation of conserved quantities
  - Lepton pairs, thermal photons