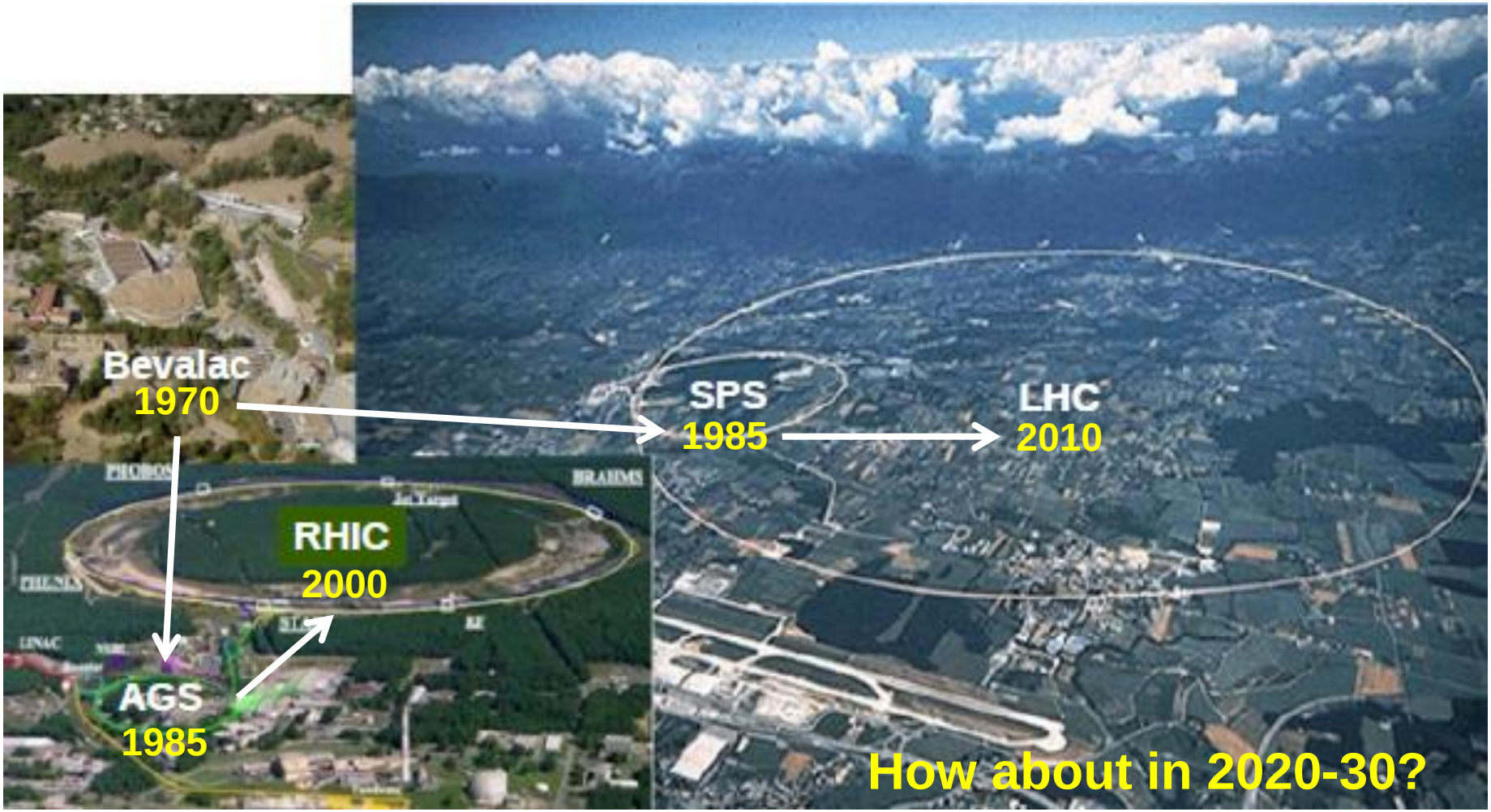
October 3, 2015
QM2015, Kobe

Heavy-Ion Physics in the Future

Shoji Nagamiya

RIKEN / KEK

1) Past Highlights at RHIC and LHC
2) Tentative Summary and Future Issues
3) Lower Energy Scope



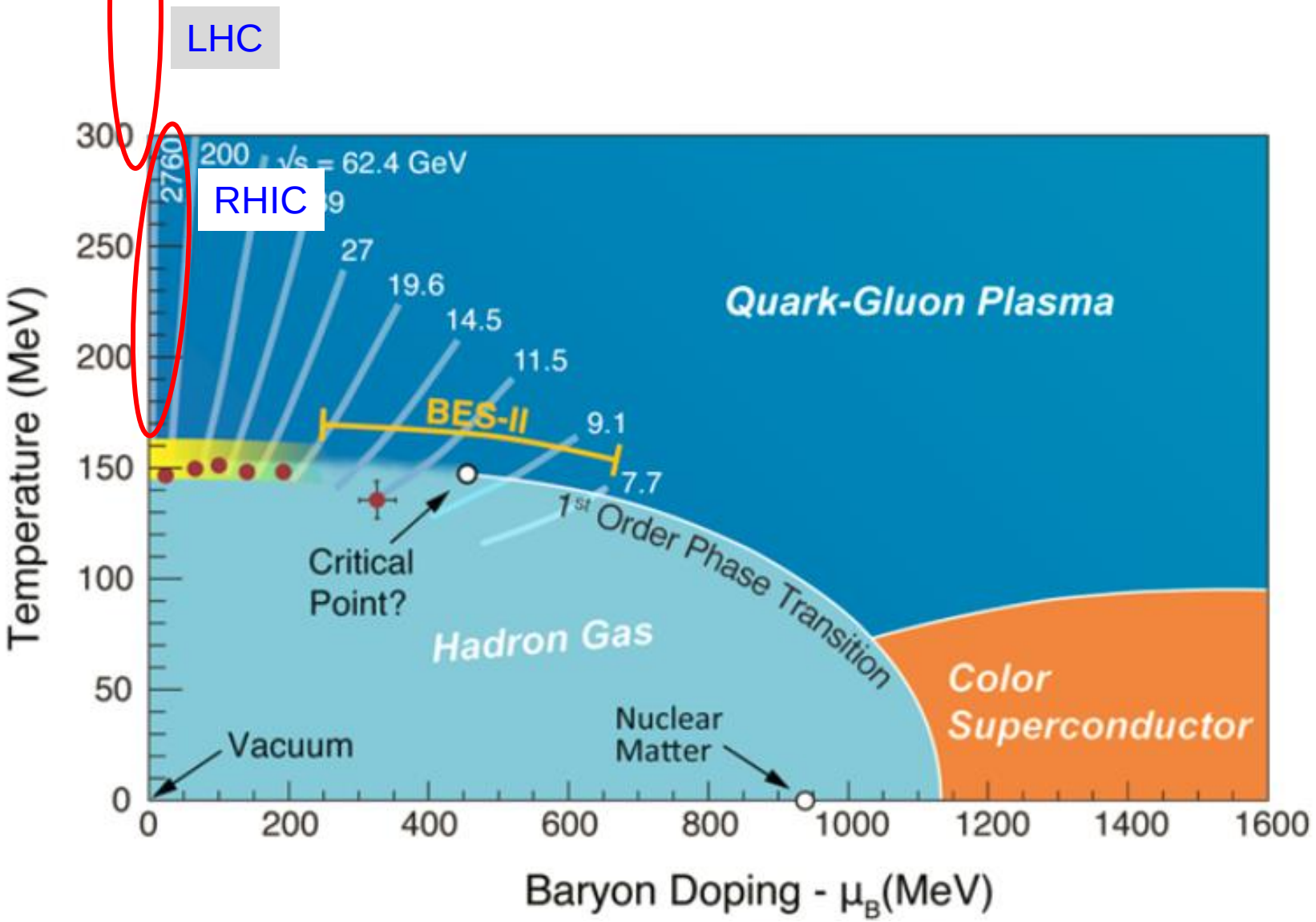
(Figure provided by M. Gyulassy)

1) Significant Progress since 1970's.

2) What will be our future?

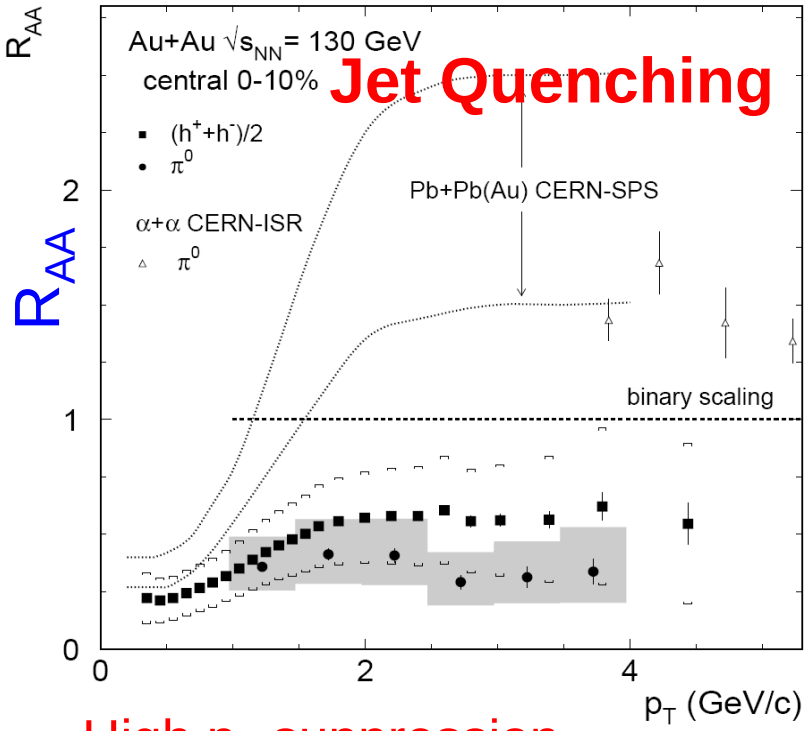
RHIC and LHC

Temperature vs. Baryon Density



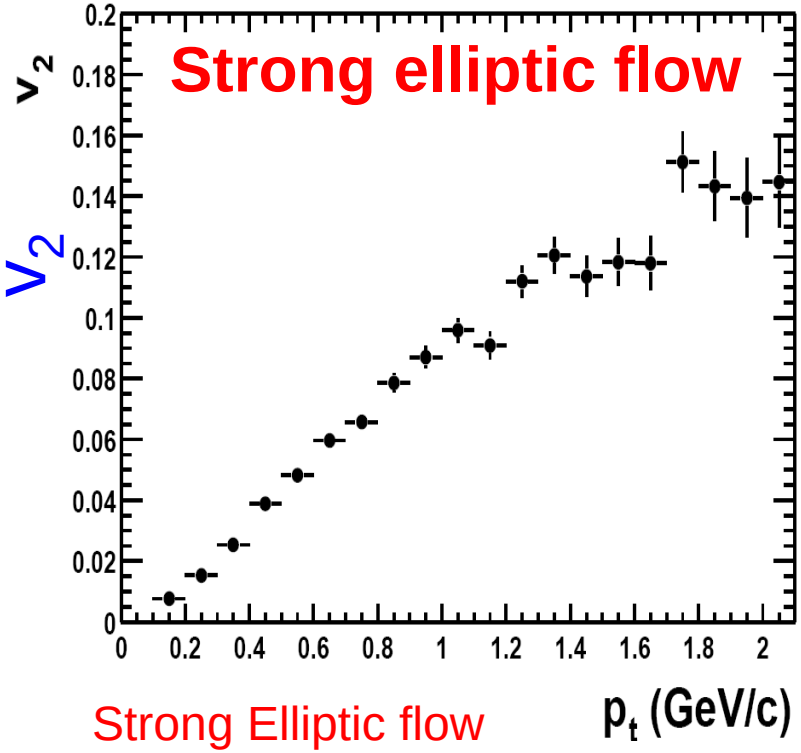
Two Major Discoveries at RHIC

PHENIX PRL88,022301(2002)



High p_T suppression
→ Particle energy was lost through a dense matter like QGP

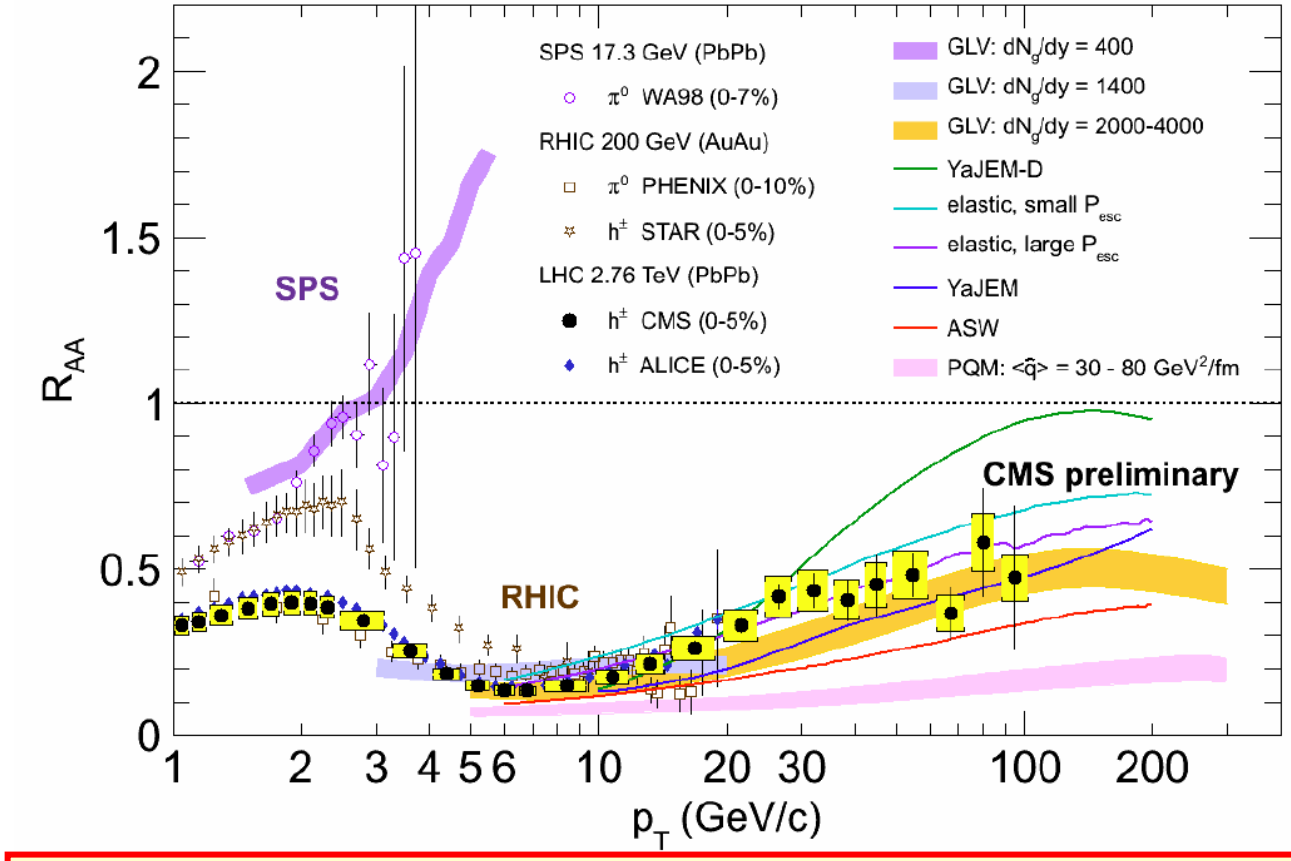
STAR PRL86,402 (2001)



Strong Elliptic flow
→ Agree with the hydrodynamics
→ Low viscosity/entropy (η/s)

Dense and Low-Viscous Fluid is formed in nuclear collisions at RHIC. These results are confirmed at LHC also.

Extended R_{AA} to p_T ~100 GeV/c (LHC)



Parameter related to the energy loss in QGP, $\hat{q}$

$\hat{q}$ = 1.2 ± 0.3 GeV^2/fm at T = 370 MeV (RHIC)

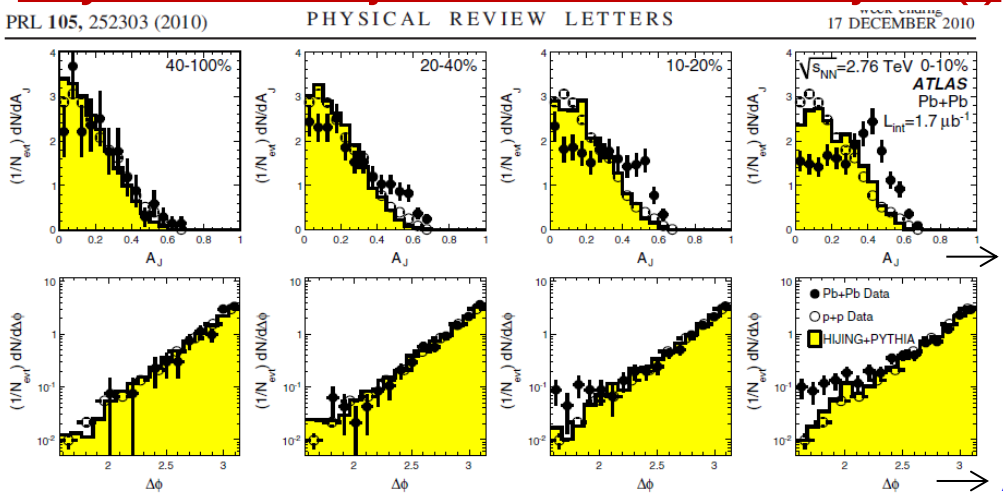
$\hat{q}$ = 1.9 ± 0.7 GeV^2/fm at T = 470 MeV (LHC)

JET Collaboration, Phys. Rev. C90, 014909 (2014)

Jet Modification

Asymmetric di-jets and even mono-jets (!)

ATLAS



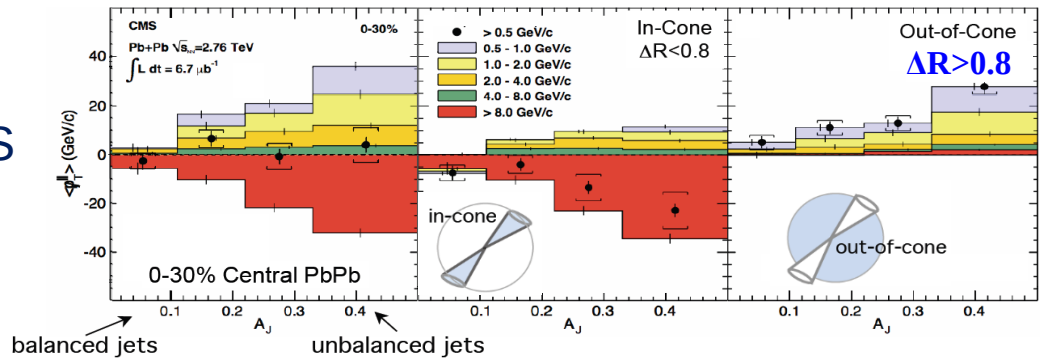
A_j

$$A_j = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

Δφ

Lost jet energy distributed very widely

CMS

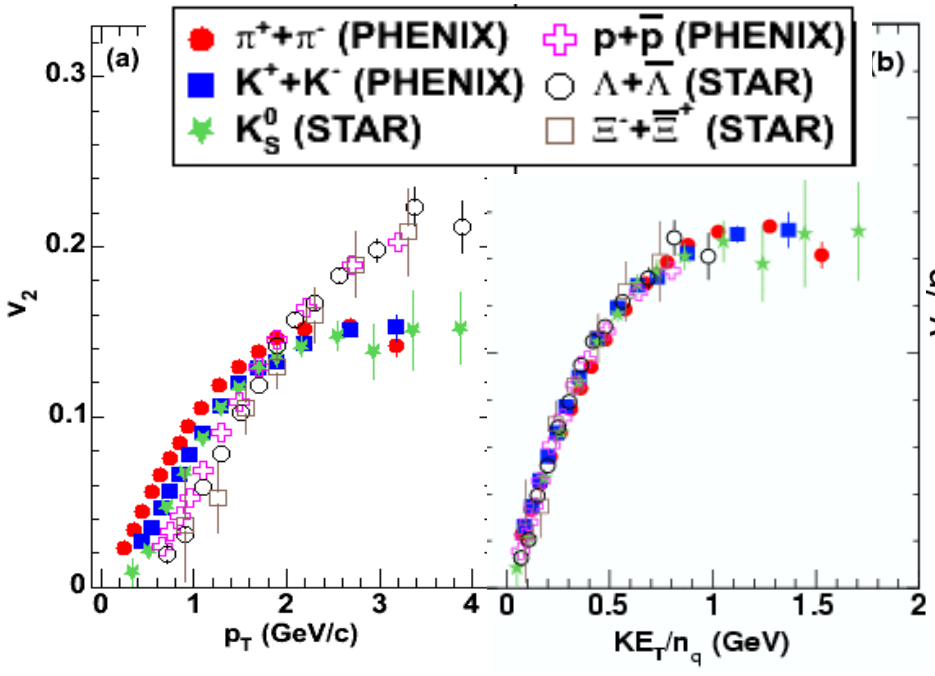


ΔR > 0.8 ~ π/4,
enhancement at low p_T

A large jet E_T asymmetry
→ Perhaps, direct evidence of parton energy loss in QGP?

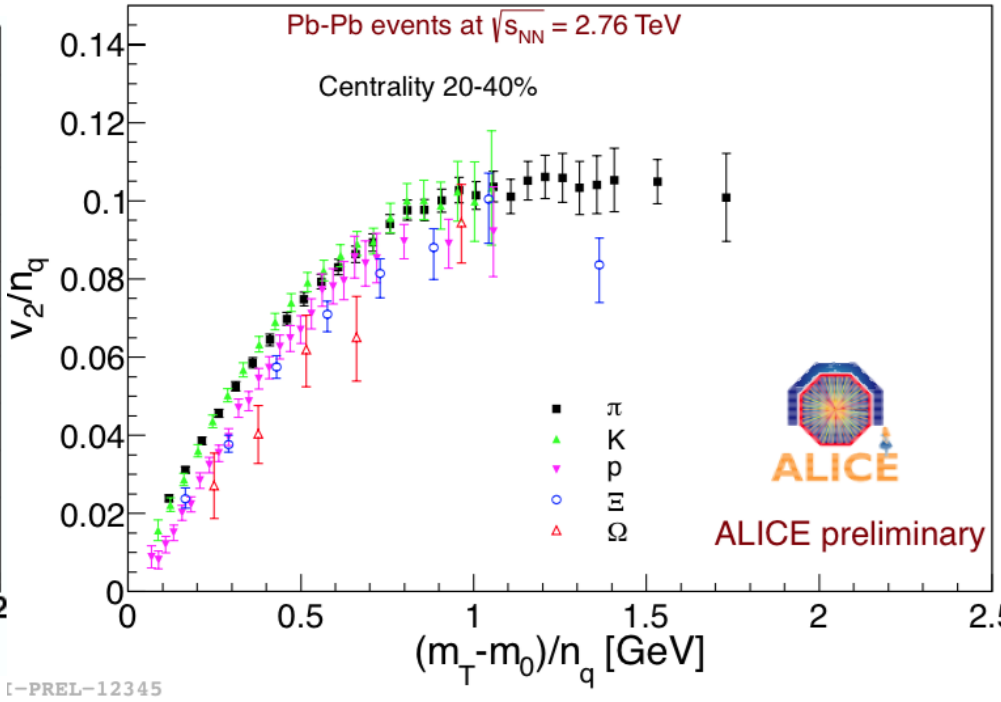
Elliptic Flow and Quark Number Scaling

RHIC



Measured Data

LHC

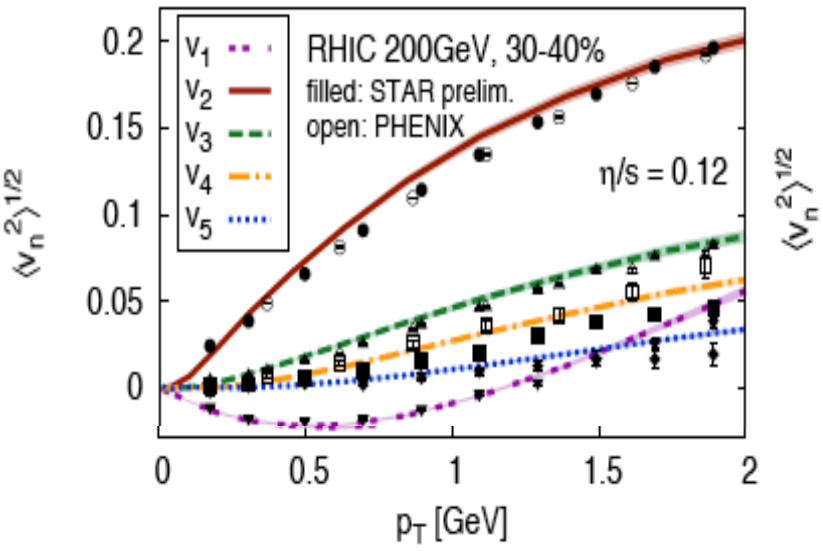


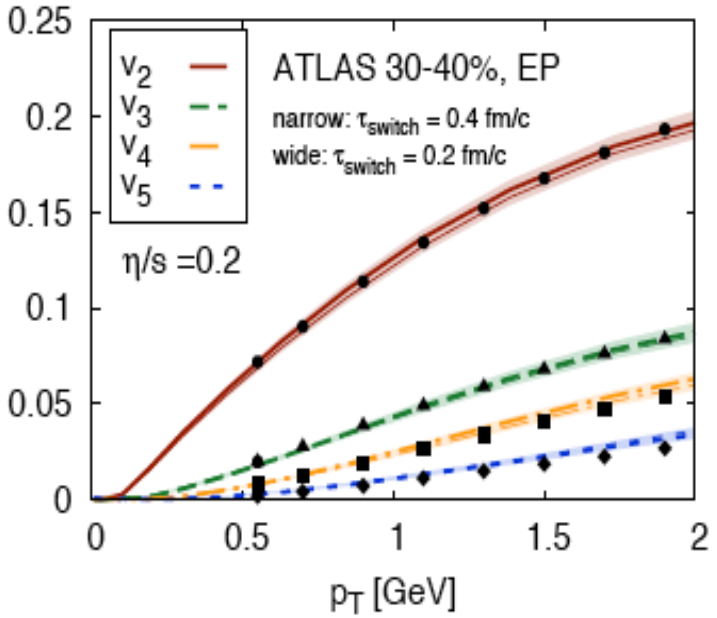
Normalized by # of quarks

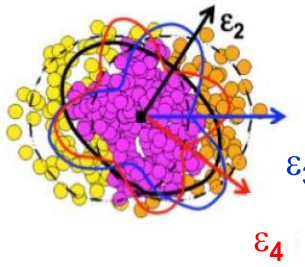
K_{ET}/n_q scaling works well at RHIC but may not work at LHC.

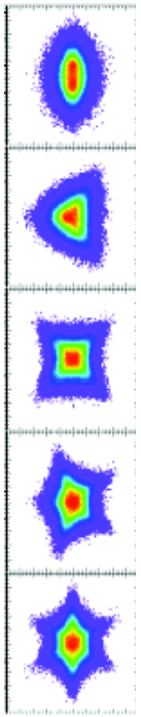
Affected by a strong radial flow??? (for protons)

Current Tentative Understanding for Flows









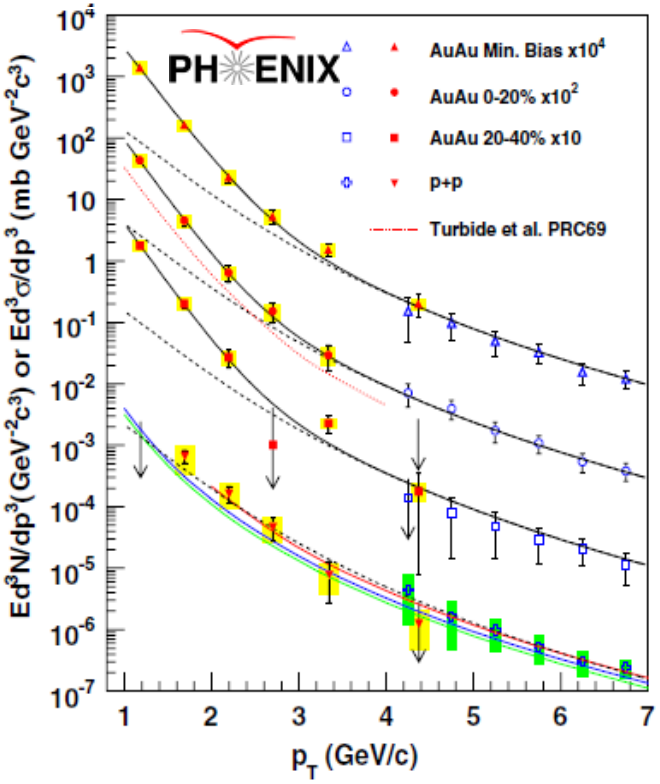
C. Gale, et al. , PRL 110, 012302 (2013)

Current RHIC & LHC flow (v2,v3,v4,v5) data are explained.
η/s (LHC) = 0.2 and η/s (RHIC) = 0.12 > $1/4\pi$ = 0.08
η/s (LHC) ~ 1.6 η/s (RHIC)

Gas is mixed to Liquid at an initial stage? (in a gas, η/s is large)

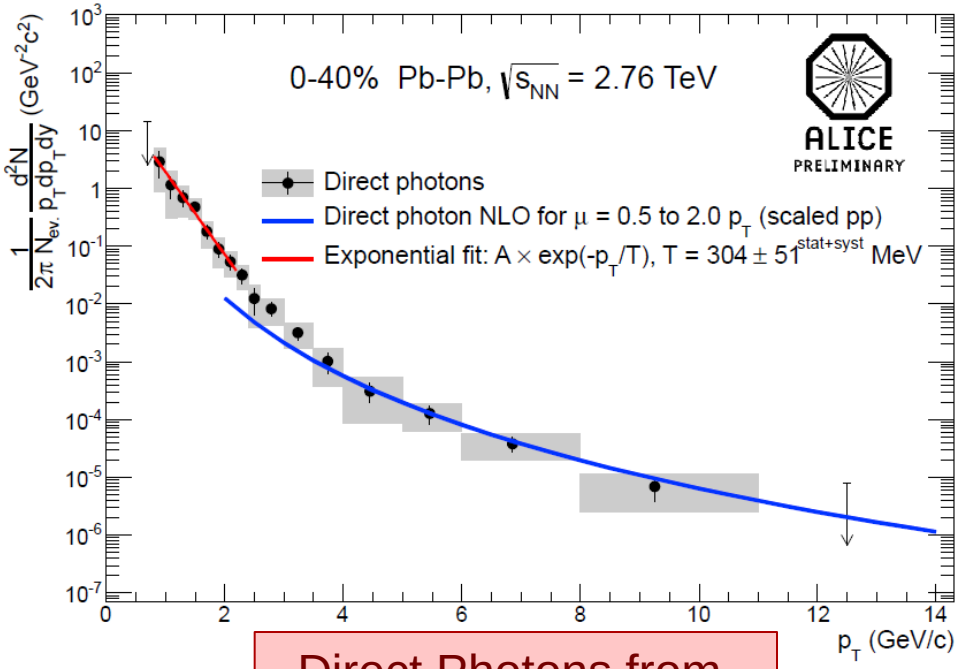
Ealirer Temperature via Direct Photons

PHENIX, PRL104, 132391 (2010)



Slope = 221 ± 19 ± 19 MeV

ALICE, Nucl.Phys. A904-905, 573c (2013)



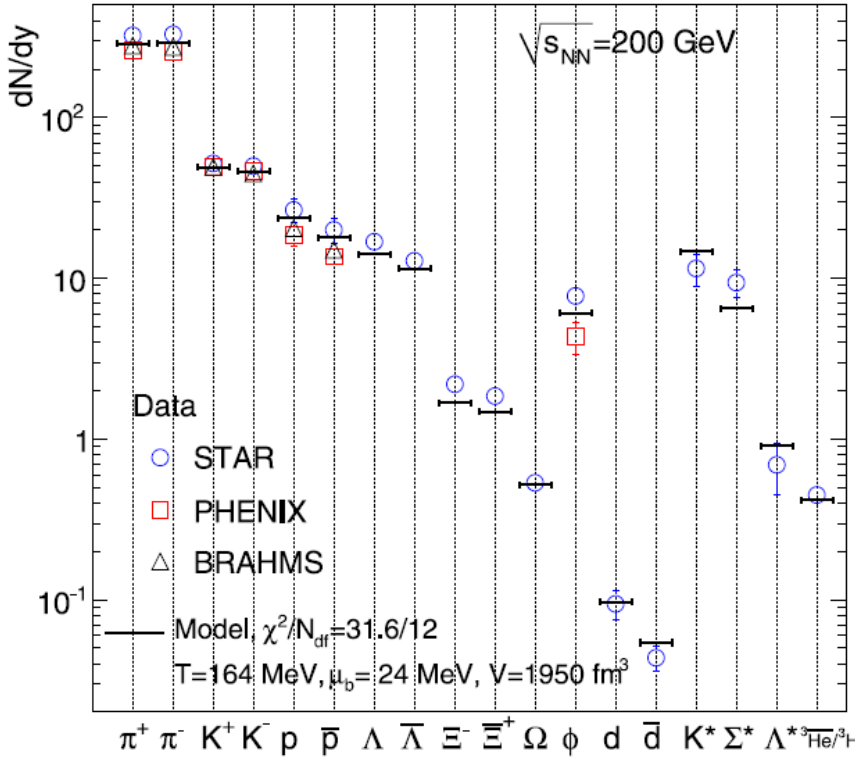
Direct Photons from Mass = 0 for Electrons

Slope ~ 304 ± 51 MeV

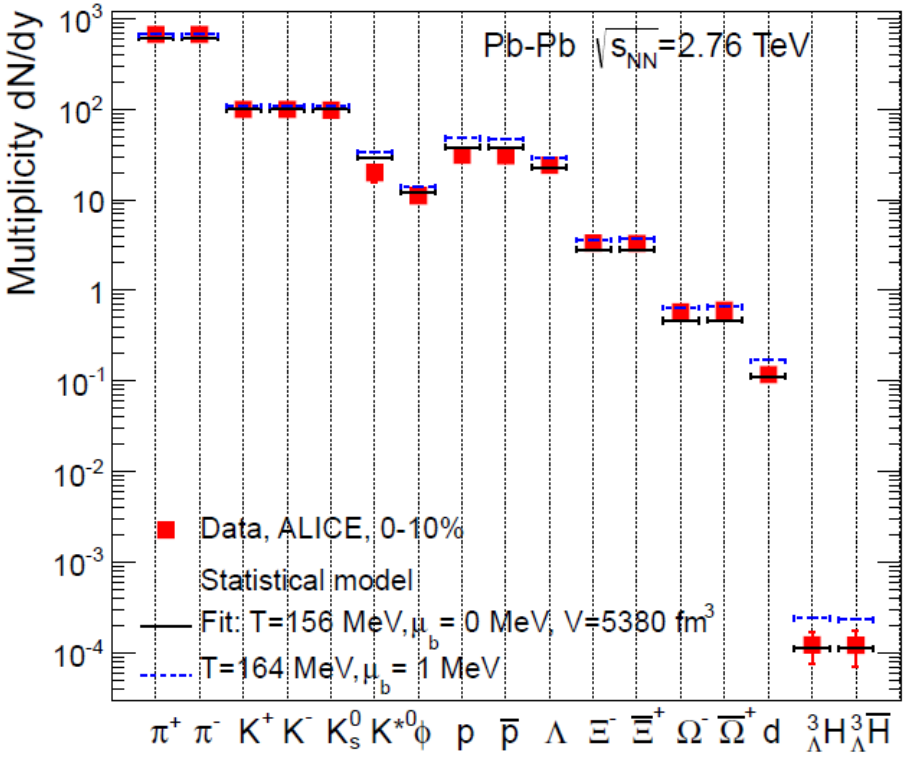
Average temperature at LHC is higher than RHIC, but both are higher than Tc ~ 160 - 170 MeV.
Real initial temperature is 30-40% higher than the above?

Hadronization Temperature

RHIC



LHC



A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stocker, Phys. Lett. B 697 (2011) 203

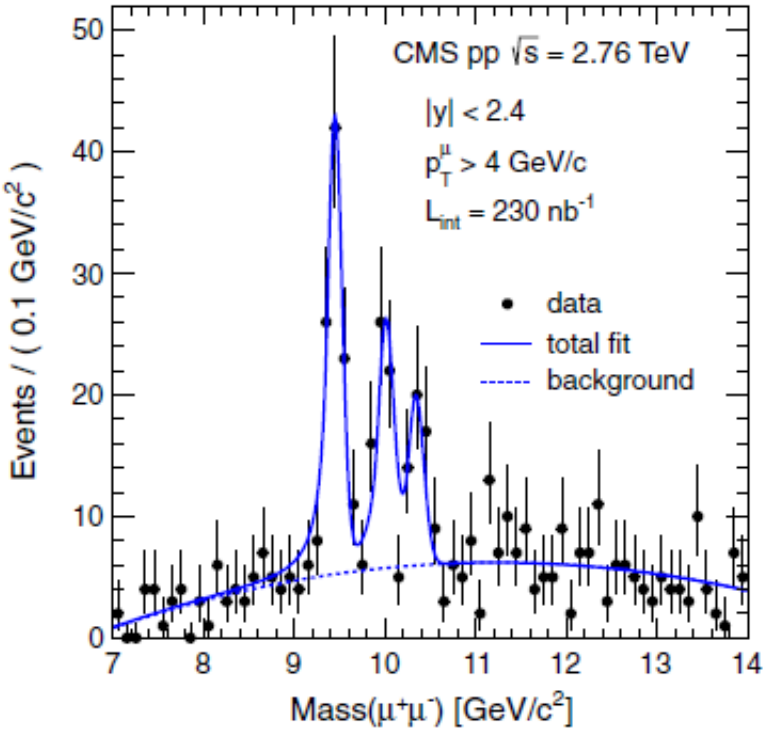
J. Stachel, A. Andronic, P. Braun-Munzinger, K. Redlich, J. Phys. Conf. Ser. 509 (2014) 012019

Hadronization Temperature ~ 160 MeV

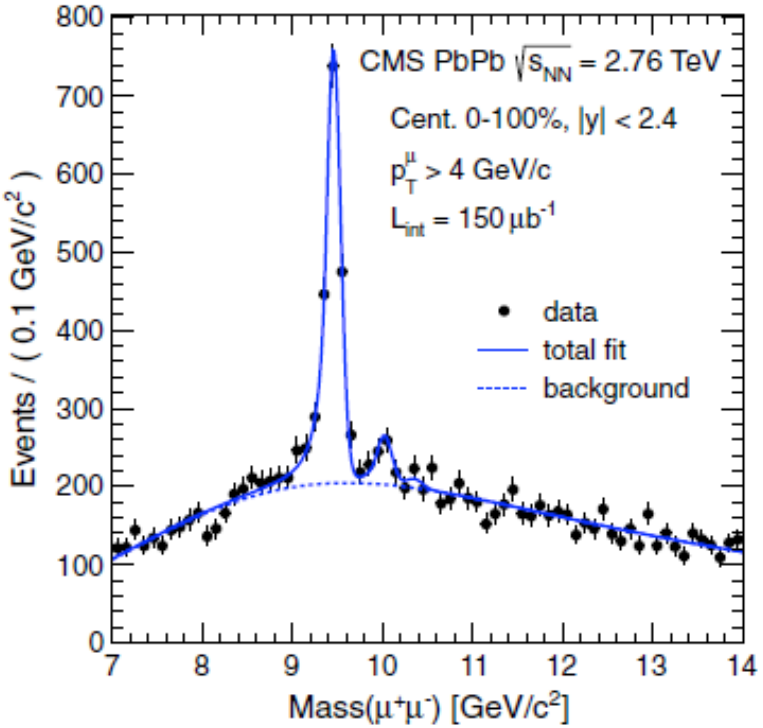
Sequential Melting of Quaokonia

Υ(2S) more suppressed than Υ(1S) in HI

Υ(3S) even more suppressed in HI ? CMS, PRL 109, 222301 (2012)



p + p

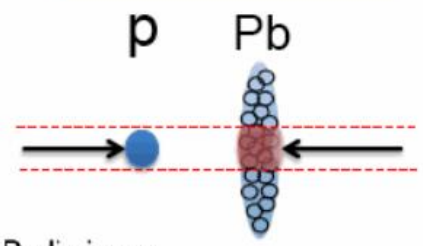


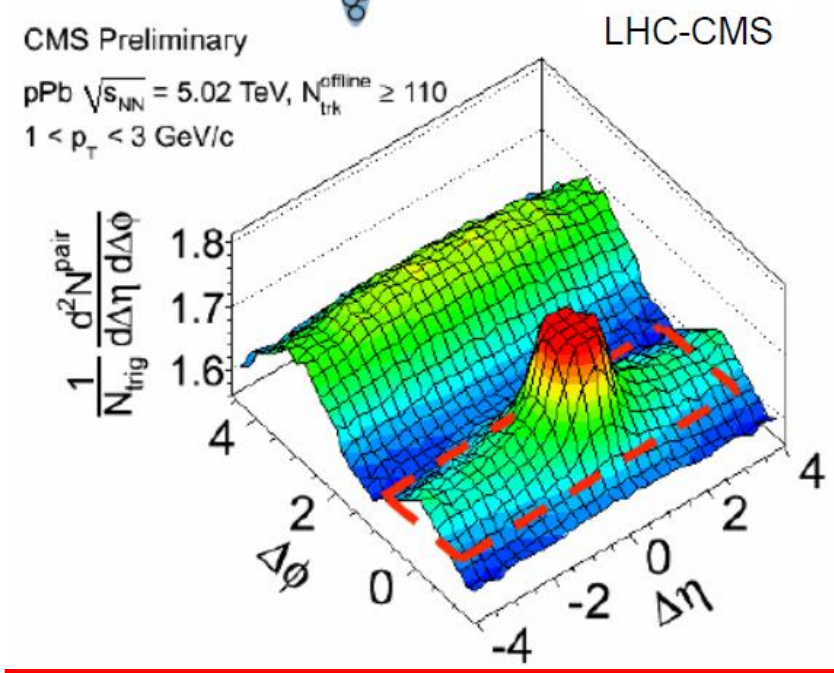
Pb+Pb

Deconfinement observed in HI Collisions?

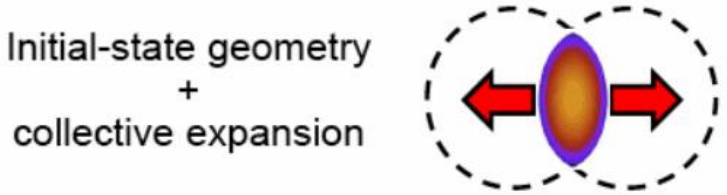
New Puzzle in *p*+*p* and *p*+A

p+A collisions





A+A collisions



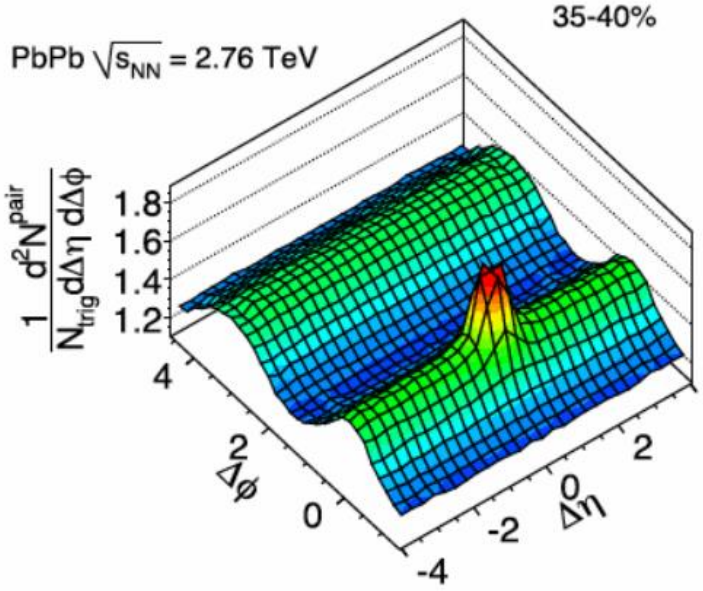


Figure taken from CMS

The above is still a puzzle and there was a special session on this issue at this conference

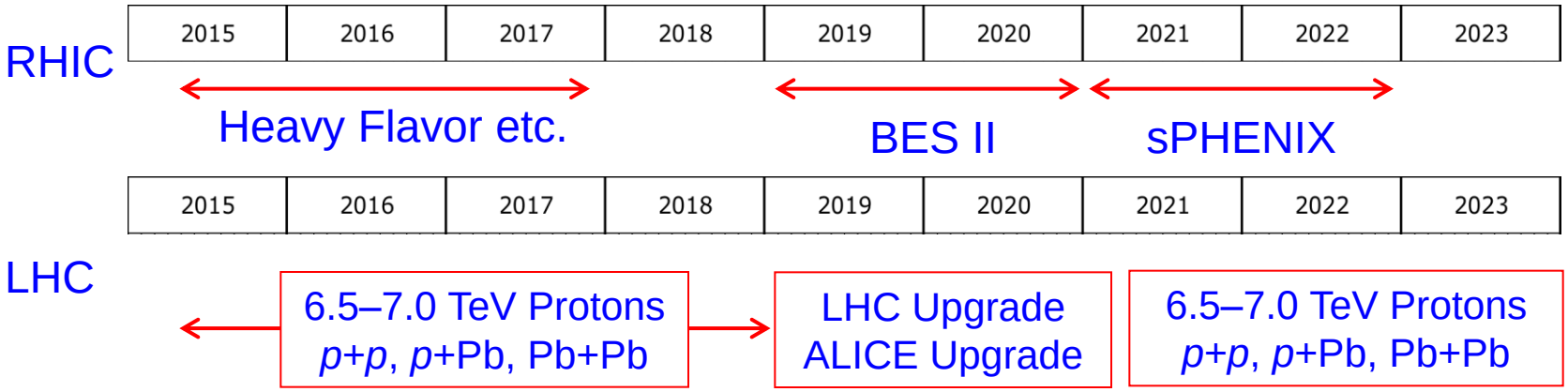
Tentative Summary and Future

What Have We Learned from RHIC and LHC and Their Future?

- Energy loss $\hat{q}$, η/s Initial temperature T_{init}, T_C.

	$\hat{q}$	η/s	T_{init}	T_c
RHIC 200 GeV	1.2 ± 0.3	0.12	> 300 MeV	~160 MeV
LHC 2.67 TeV	1.9 ± 0.7	0.2	> 400 MeV	
	GeV^2/fm	Ratio = 1.6	From Photons T = 220 MeV & >300 MeV	

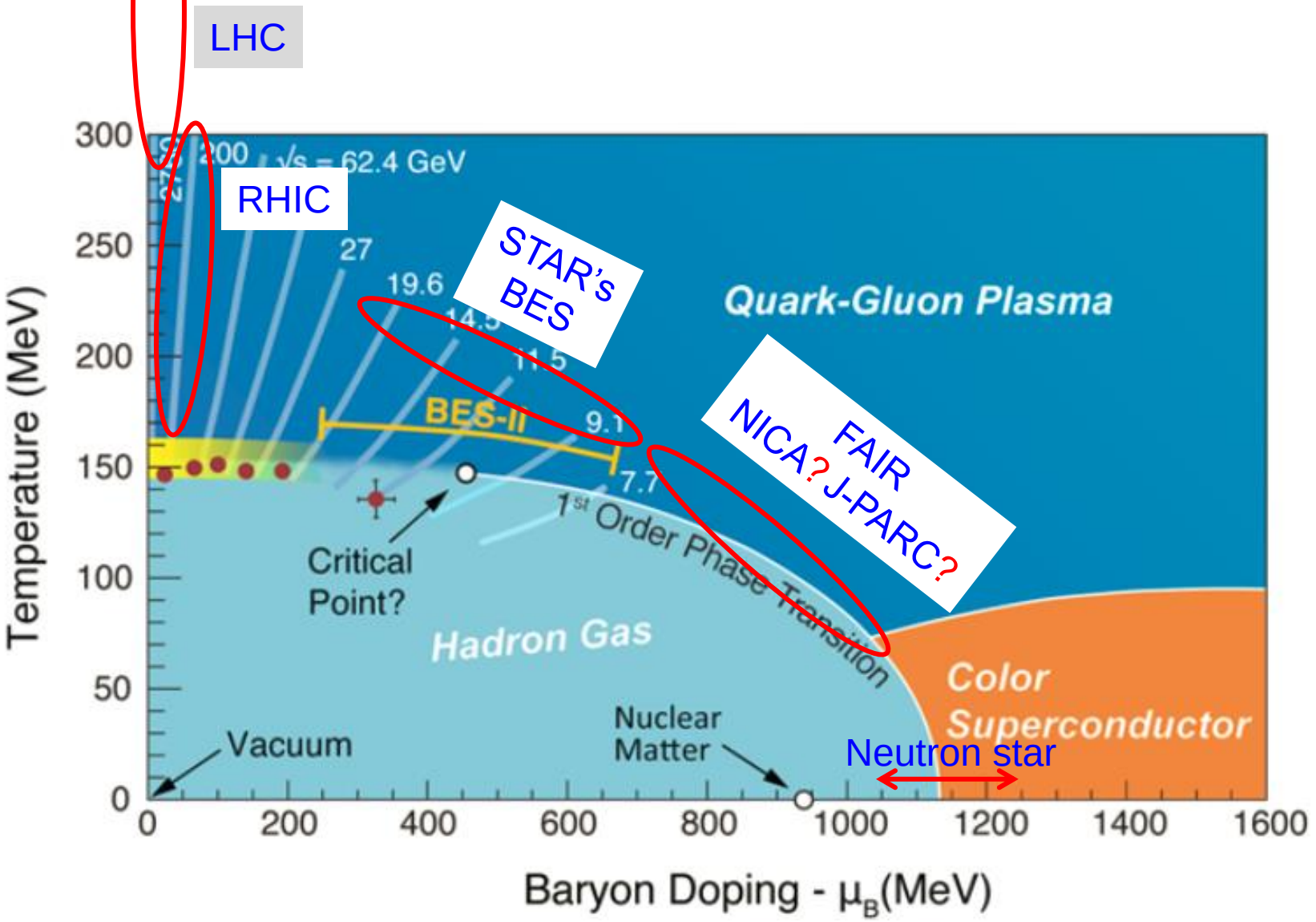
- RHIC and LHC Plans



Future Issues

- LHC has definitely >10 years for the future programs in association with the energy recovery and the HL-LHC.
  - Study of QGP properties at high T ~ 3Tc by three experimental groups with various probes, such as sequential quarkonia melting, v2 to v5 (or even higher order) flows, jets, heavy flavors, J/Ψ melting vs. recombination, chiral magnetic effects, etc.
- RHIC will complete its scientific mission by mid-2020's.
  - Complete the study of QGP blow Tc to ~2Tc.
  - BES-II to complete the search for Critical Point
  - sPHENIX run to study jets at T~2Tc
- Also, *p*A or *pp* puzzle must be solved.
- eRHIC?
- Lower energy HI to probe higher density region?

Temperature vs. Baryon Density



Comparison: Collider vs. Fixed Target

Comparison between collider and fixed target experiments

Collider (Pb+Pb or Au + Au): 10^{27} ~ 10^{28} $cm^{-2}s^{-1}$ for RHIC and LHC

If 10^{28} /(cm^2/s) for Au + Au → 10^{28} x 7 barn = 7x10^4 /s = 70 kHz

… 50 kHz data rate is a future challenge at both RHIC and LHC.

Fixed Target Equivalent : ~ Currently, 10^9 per bunch at AGS for RHIC

If, an interaction rate of 1% target order

→ for Au + Au collisions, 10^9 x 0.01 = 10^7 = ~ 10 MHz/bunch

→ If 1 pulse = 5 bunches and 5 seconds = 1 pulse,
per bunch is almost equal to *per second*.

~$10^{10\text{-}11}$ beams/s on a fixed target, 1% target implies 100MHz to 1GHz collision rate → A new physics may come out with high intensity heavy ion beams on a fixed target, and this direction could be interesting.

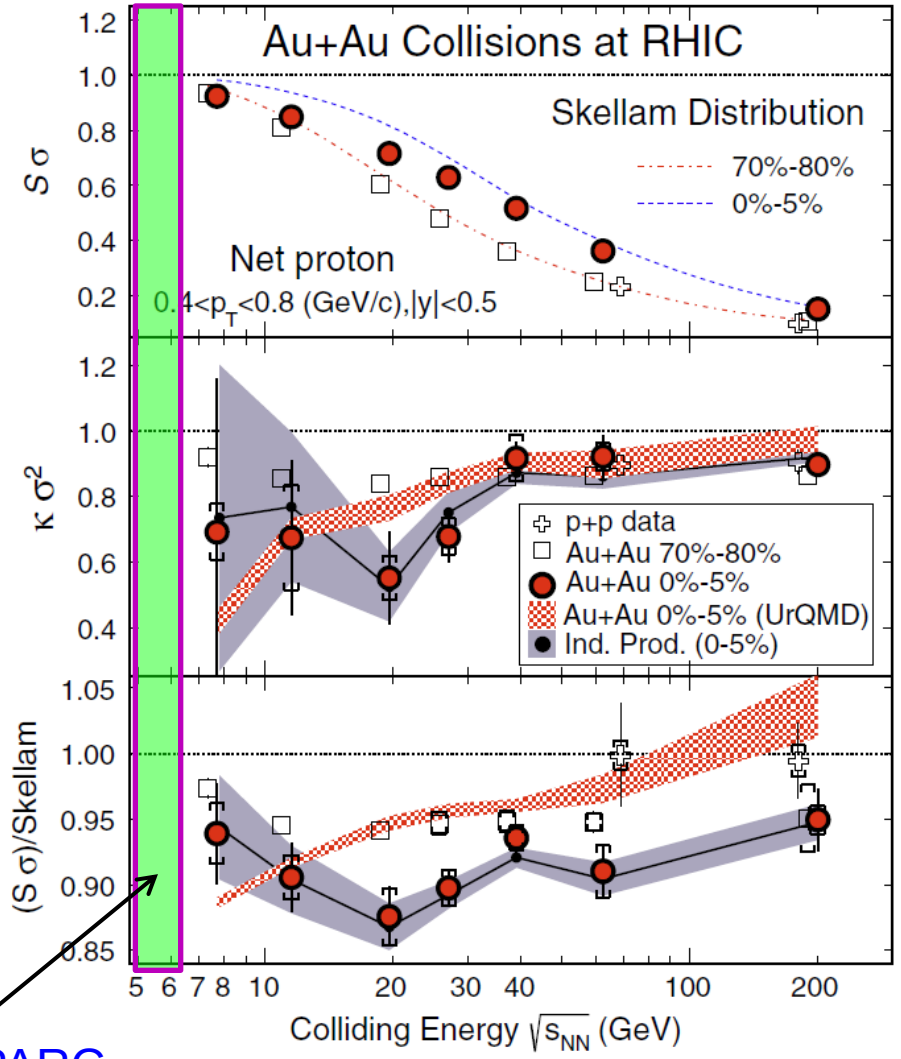
Event-by-Event Fluctuations

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

The 3rd and 4th-order fluctuations are sensitive to critical point and phase boundary.
Detailed studies at lower energies are, thus, challenging & interesting.



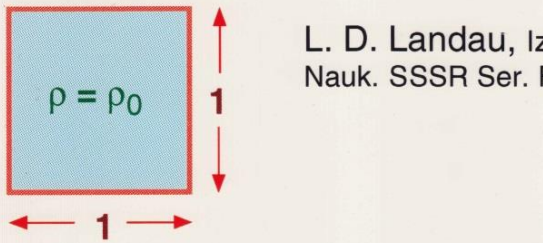
FAIR/J-PARC region

STAR, PRL 112, 032302 (2014)

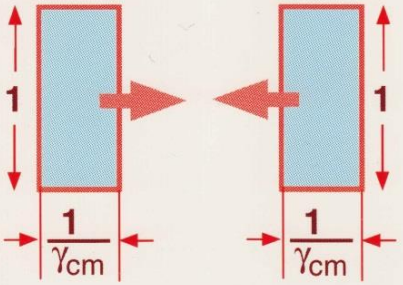
FAIR, NICA? and J-PARC?

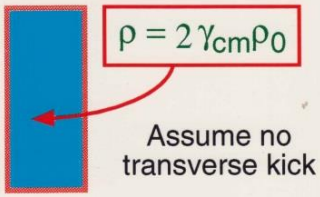
Possibility for High Density Formation

High Density Formation



L. D. Landau, Izv. Acad. Nauk. SSSR Ser. Fiz .17, 51 ('53)

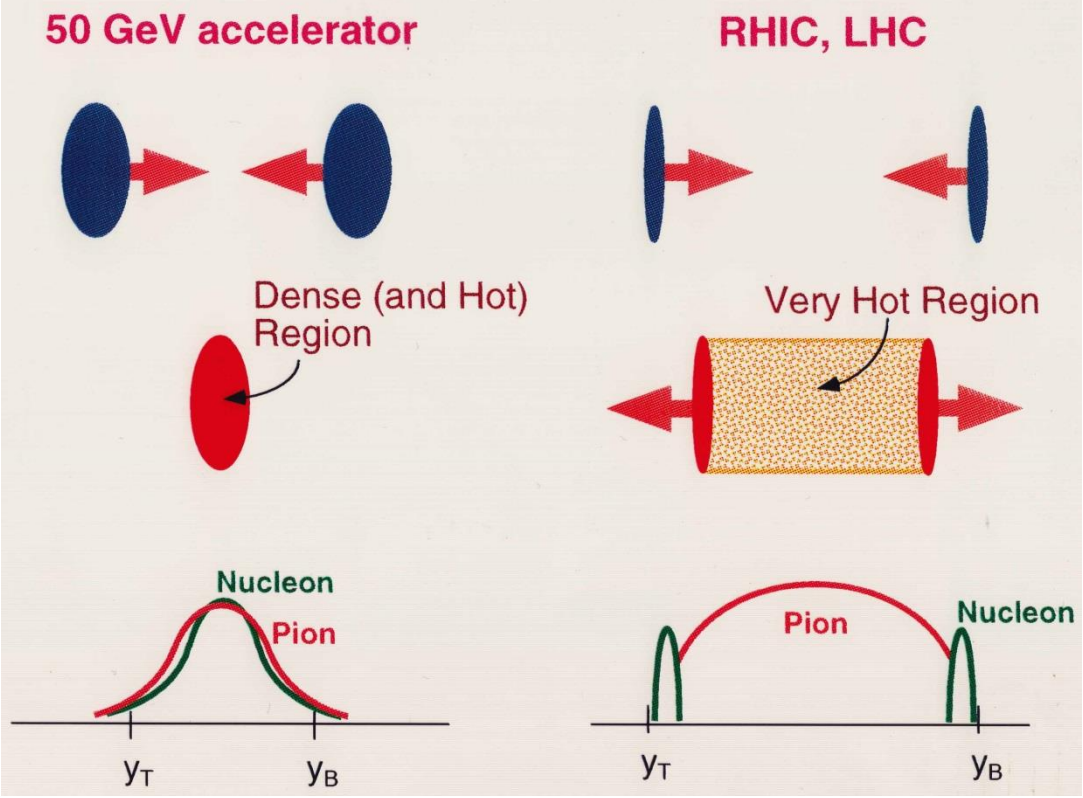




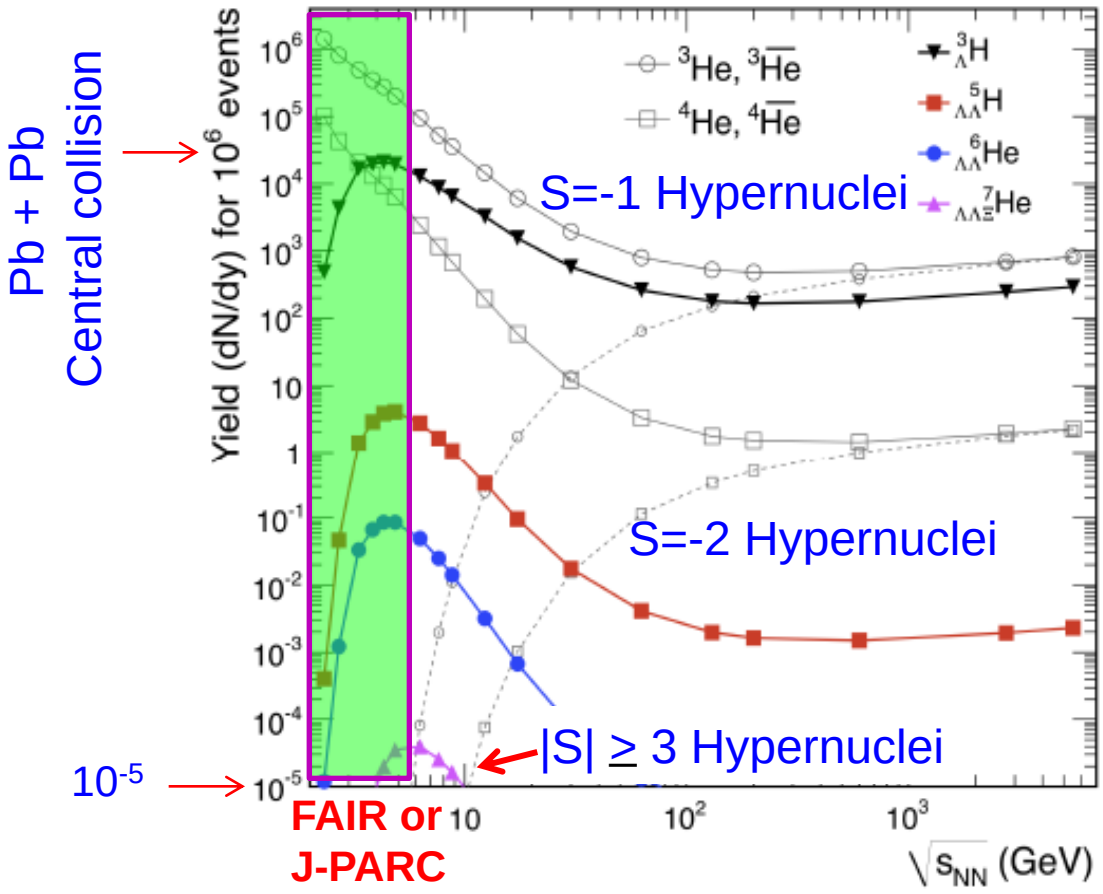
At AGS, $\gamma_{cm} \cong 3$ → $\rho \cong 6\rho_0$!!

$\varepsilon \equiv E/V = 2\gamma_{cm} mc^2 \rho_0 / (1/\gamma_{cm}) = 2\gamma_{cm}^2 mc^2 \rho_0$

High-Energy Heavy-Ion Collisions



Multi-Strangeness Hypernuclei?



A. Andronic, PLB697 (2011) 203

|S| ≥ 3 Hypernuclei

- Full intensity beam of 10^{11}/s is ~10 MHz central collisions
- 10^{-5} for 10^6 events means dN/dy = 10^{--4}
  - → = 0.3 events/hour
  - → Very marginal but not impossible

Mystery of neutron star matter

Slide from H. Tamura

- Final form of matter evolution in the universe

  Produced by supernova explosion, Observed as X-ray pulsars

- Highest density matter in the universe

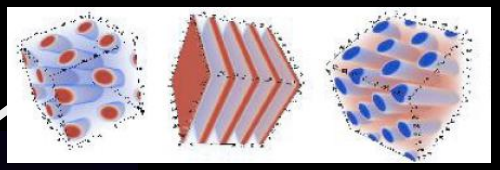
  $M = 1\sim2\ M_\odot$, $R \sim 10\sim20$ km

  => Density of the core = $3\sim10\rho_0$ ($1\sim3$ Btons/cm^3)

  ρ_0: nuclear density

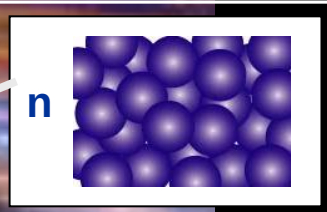
- Various forms of matter made of almost only quarks

Nuclear "Pasta"

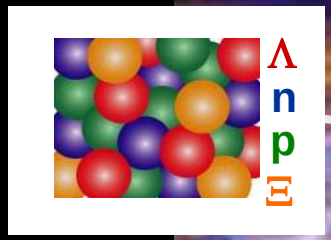


Nuclear + Neutron Matter

Neutron Matter

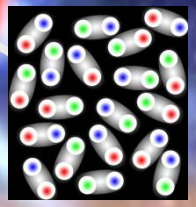


Superfluid



Strange Hadronic Matter ?

High density nuclear matter with hyperons (strange quarks)

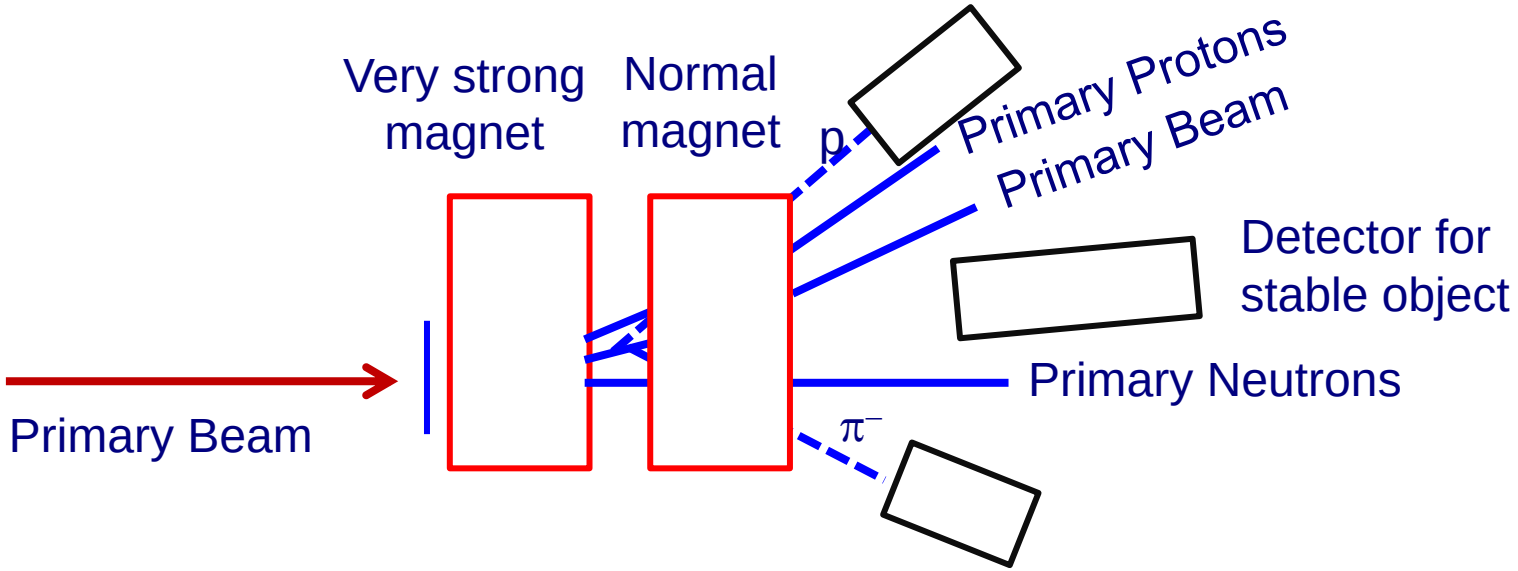


Quark Matter ??

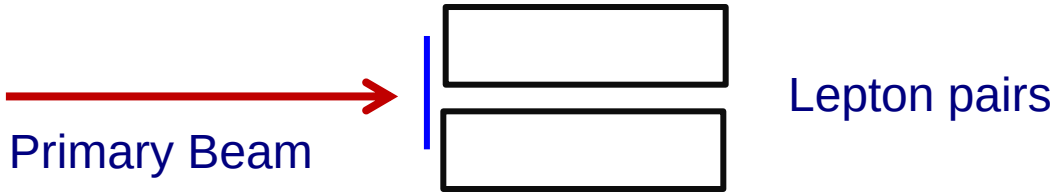
Deconfined quarks
Color superconductivity

High density formation may help multi-strangeness production

Possible Ideas for Fixed Target



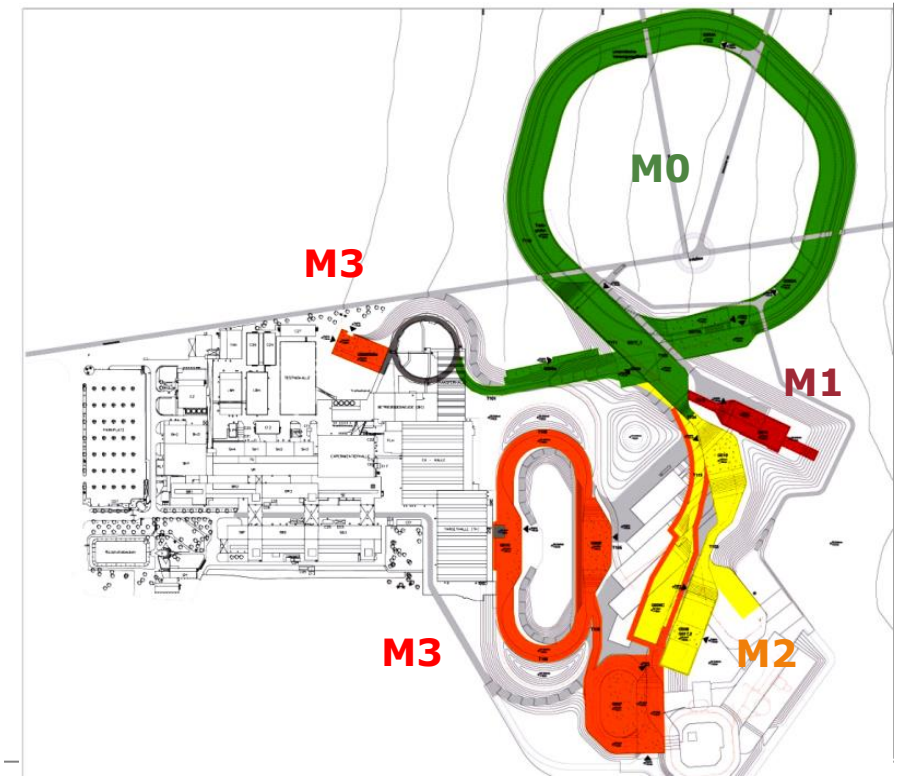
Search of strangeness related objects



Search for lepton pairs

+ many other ideas ….

Current Plan for FAIR



Fully stripped up to ~10 AGeV?

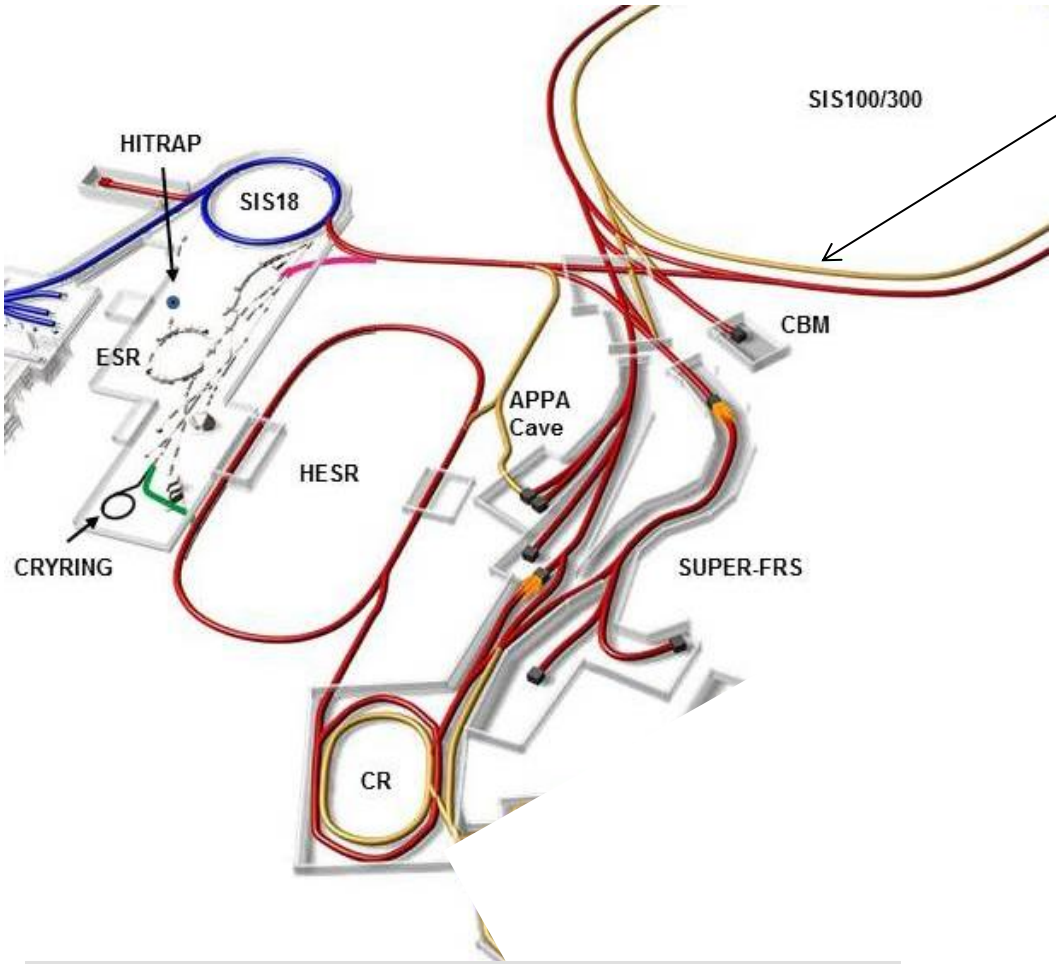
FAIR Exp. Programs:

M1: APPA
M1: CBM/HADES
M2: NUSTAR
M3: PANDA, APPA, NUSTAR

Facility	Particle	Energy	correspond. max.Intensity [s^{-1}]
SIS100	U28+	**2.7 GeV/u**	3.0E11
SIS100	Proton	**29 GeV**	5.0E12

From K. Langanke - September 9 / 10, 2015

Future Plan for FAIR

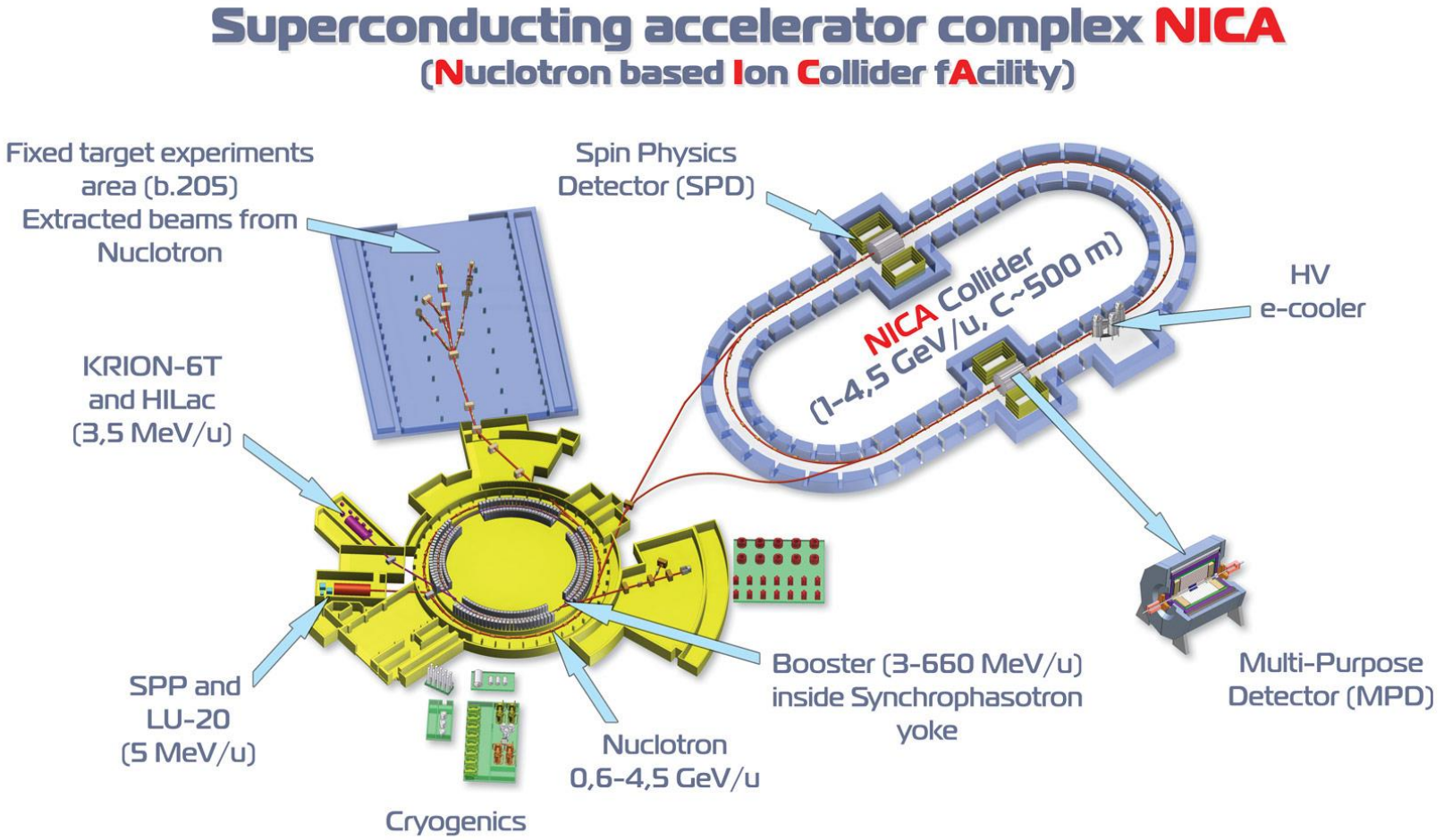


on top of SIS 100:
SIS 300 in the same accelerator tunnel

- serves as stretcher ring for very slow extraction, thereby increasing the event rates of experiments, e.g. NUSTAR
- provides higher energies for exploring the QCD phase diagram (CBM)
- **ultimate advantage: parallel operation of the full FAIR accelerator facility benefiting all scientific pillars**

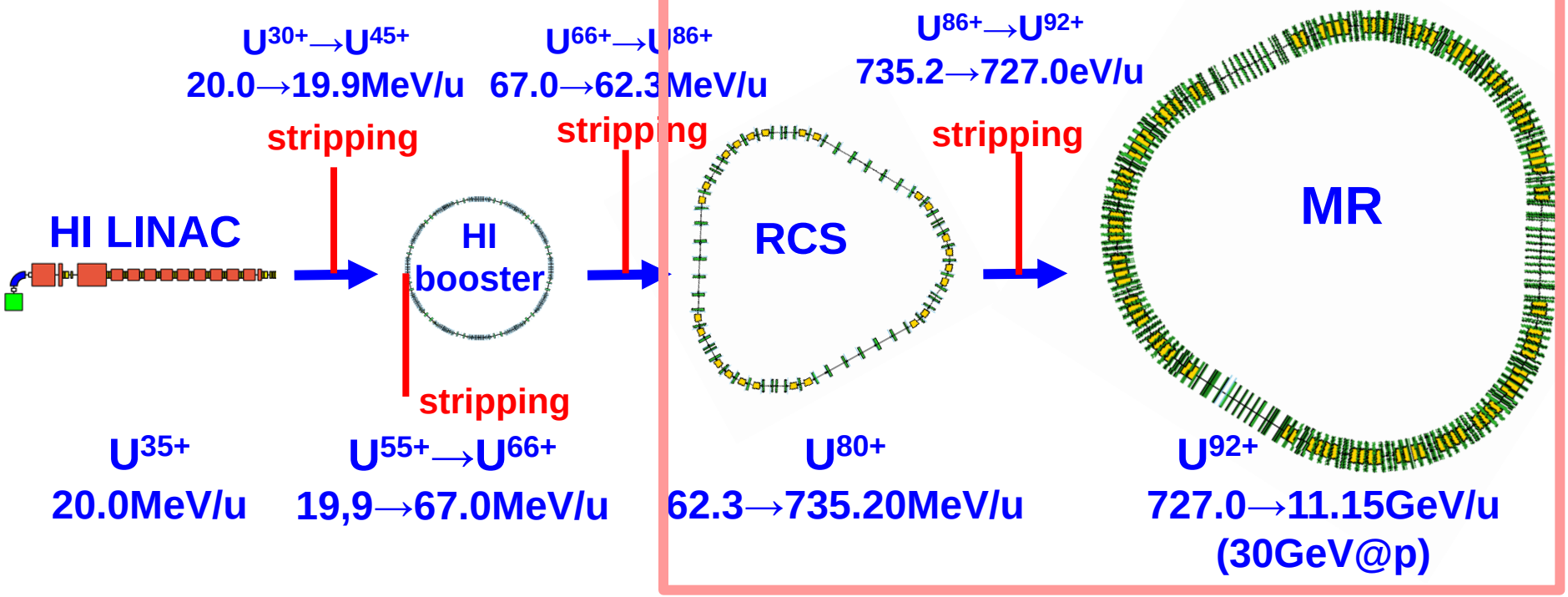
From K. Langanke - September 9 / 10, 2015

NICA Proposal



Strong LoI exists (2015)

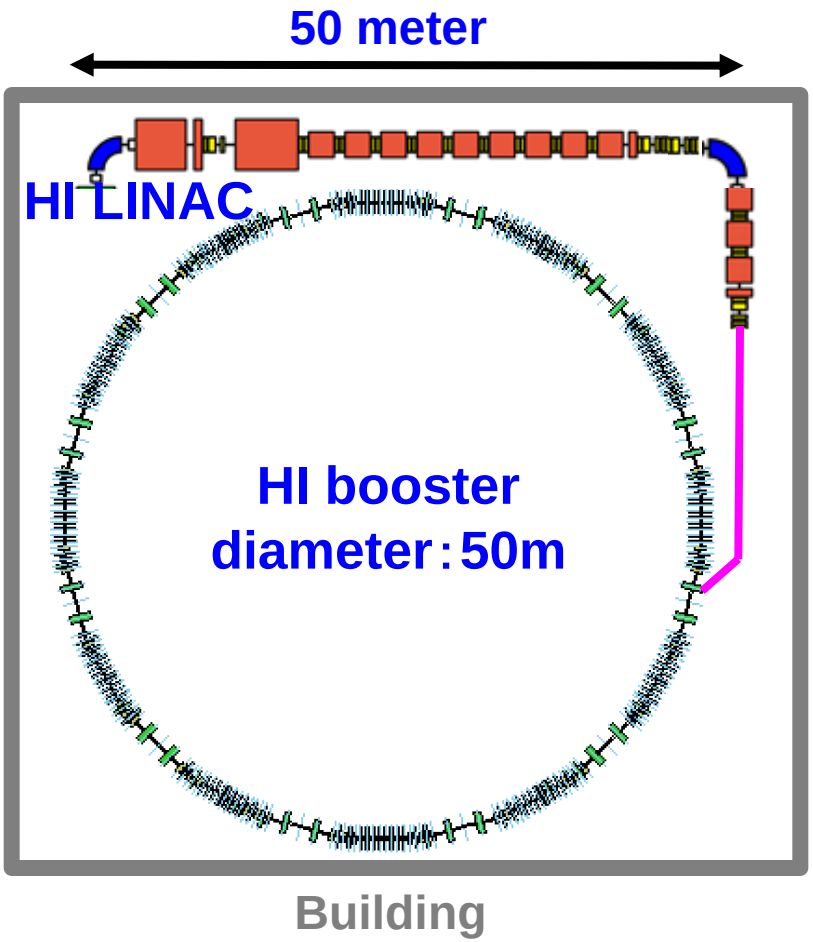
Possibility of HI at J-PARC



Already existing and working

Serious studies for U at 10^{11} beams/s
by the accelerator group

HI Linac and HI Booster



Nuclear Experimentalists and Accelerator Physicists (According to H. Sako)

S. Nagamiya (RIKEN/KEK/JAEA)
H. Sako, K. Imai, K. Nishio, S. Sato, S. Hasegawa, K. Tanida, S. H. Hwang, H. Sugimura, Y. Ichikawa (ASRC/JAEA)
H. Harada, P. K. Saha, M. Kinsho, J. Tamura (J-PARC/JAEA)
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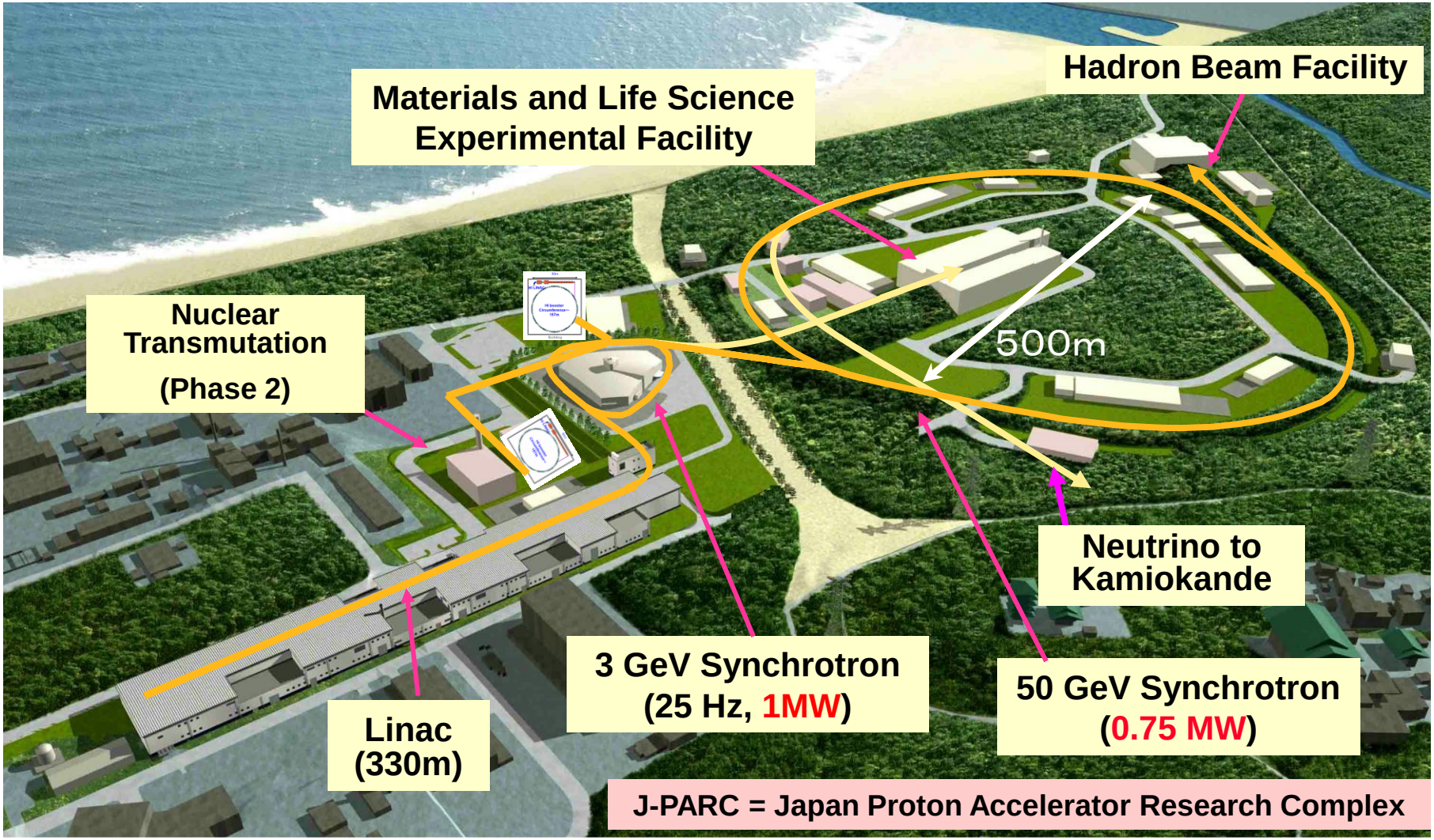
J-PARC Facility



Joint Project between KEK and JAEA

Lower Energy Future Issues

- FAIR is in progress. NICA proposed in 2015. J-PARC LOI is underway (2016) with maximum $10^{10\text{-}11}$ beams/s.

  (1 GHz interactions, but the current detector technology can handle up to 10 MHz)

- High density studies via rare processes (lepton pairs or muon pairs, etc.)
- Search for strangelet, multi-strangeness hypernuclei, etc. if the production probability is > $10^{-(9\text{-}11)}$.

  If hypernuclei are formed in the projectile frame, then the lifetime is elongated to $\beta\gamma\tau$ which is about 30-60 cm

- Study of hyperon mixing in neutron star ?
- Fluctuation studies by the STAR low energy scans.

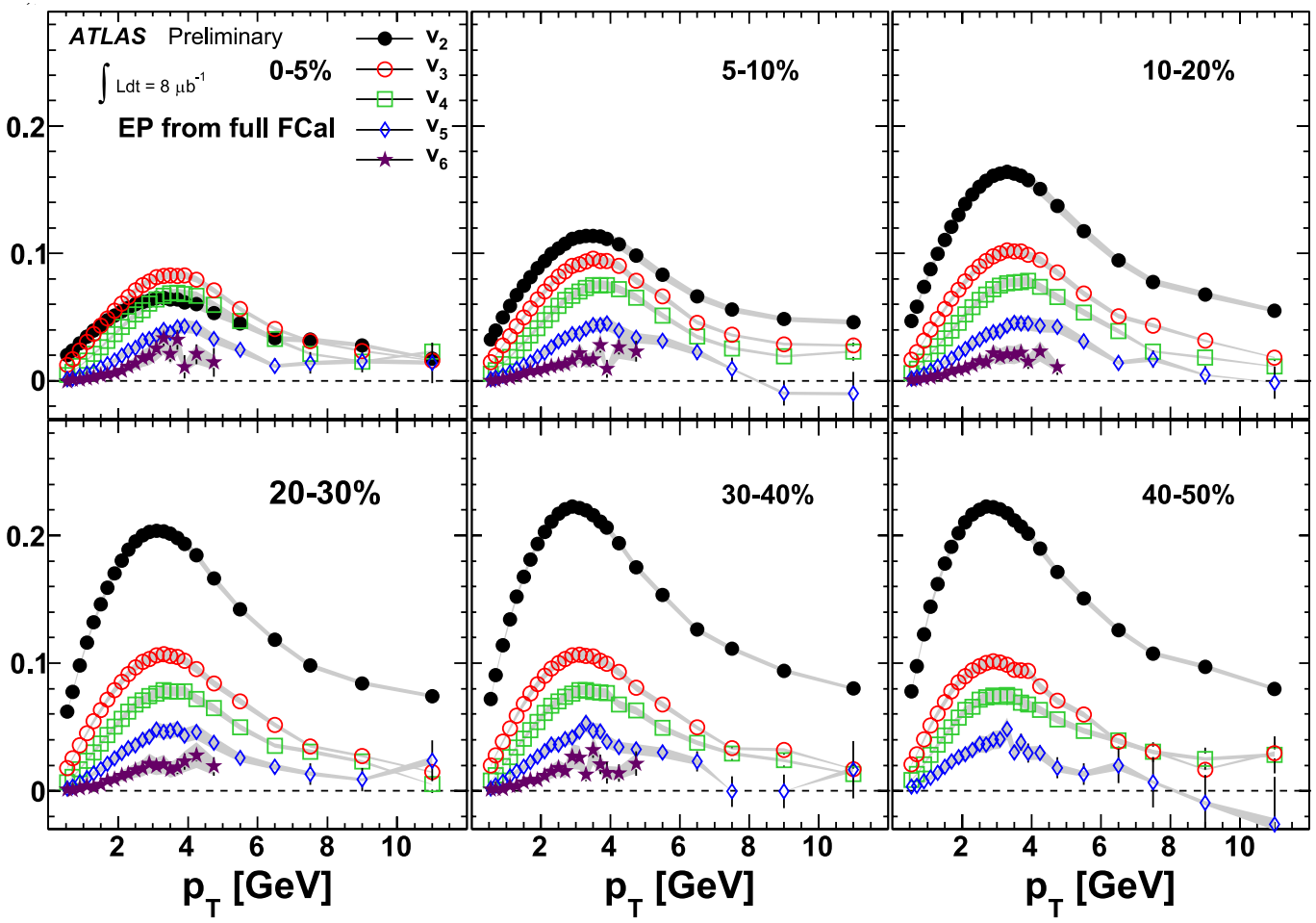
The Entire Summary

- RHIC played an extremely important role for the discovery and properties of QGP. RHIC will complete its scientific mission by mid-2020's.
- LHC has added more surprise and, at least, has > 10 years for future unexpected discoveries.
- Puzzle in *p*+A (or *d*+A) and *pp* collisions.
- Useful to explore high density region with very intense HI beams on the order of $10^{10\text{-}11}$/s at selected facilities.

Thank You

Extra Slides

Higher Order Flows measured by ATLAS



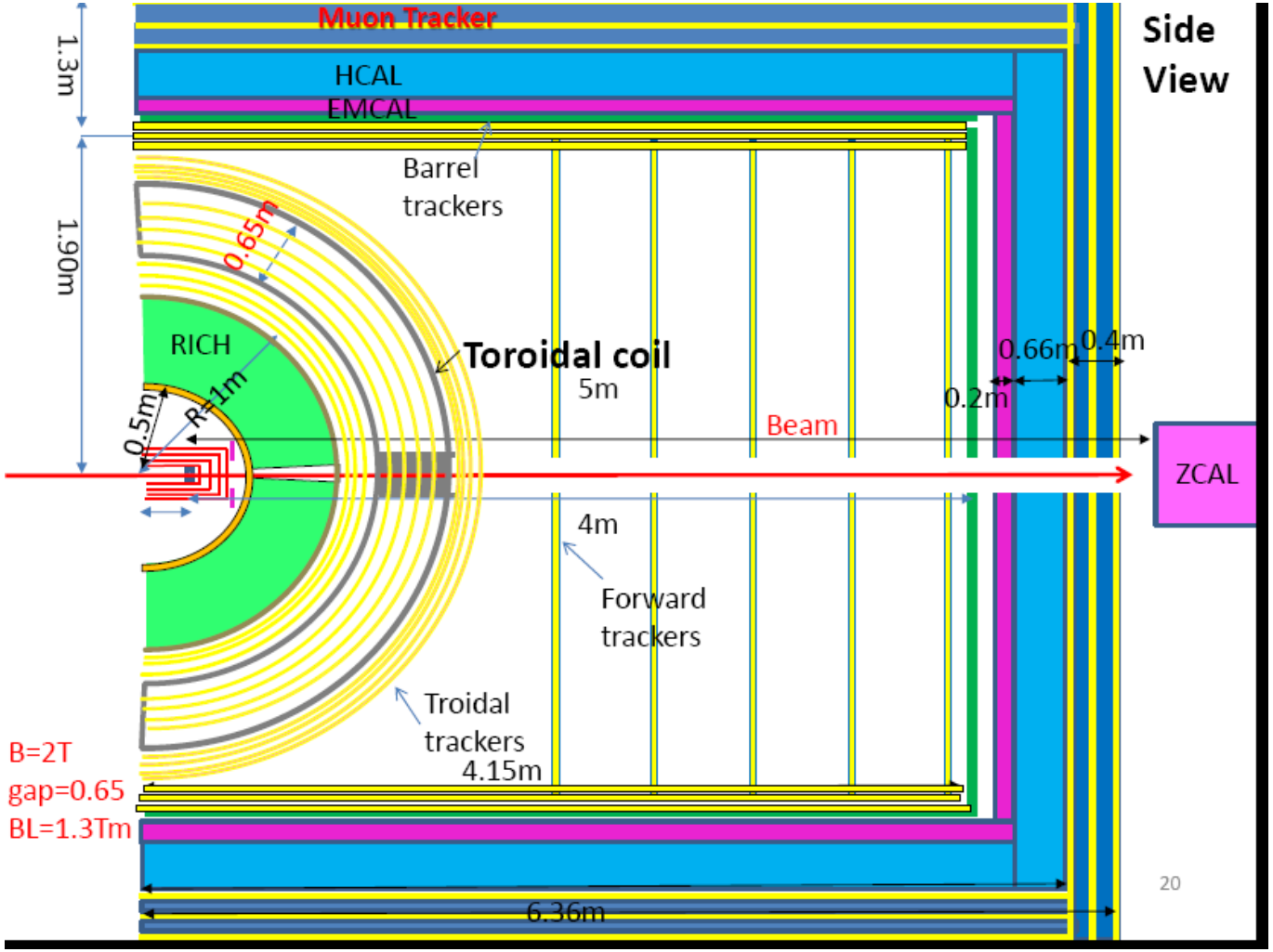
Low-Energy Heavy-Ion Programs

Accelerator	Type	Beam energy (AGeV)	C.M. energy √s(AGeV)	Beam rate / Luminosity	Interaction rate (sec^{-1})	Year of experiment
RHIC Beam Energy Scan (BNL)	Collider		7.7-62	10^{26} -$10^{27}cm^{-2}s^{-1}$ (√s=20AGeV)	600~6000 (√s=20AeV) (σ_{total}=6b)	2004-2010 2018-2019 (e-cooling)
NICA (JINR)	Collider Fixed target	0.6-4.5 1.9-2.4	4-11 1.9-2.4	10^{27} $cm^{-2}s^{-1}$ (√s=9AGeV Au+Au)	~6000 (σ_{total}=6b)	2019- 2017-
FAIR SIS100 (CBM)	Fixed target	2-11(Au)	2-4.7	1.5x10^{10} $cycle^{-1}$ (10s cycle,U^{92+})	10^{5}-10^{7} (detector)	2021-2024
J-PARC	Fixed target	1-19(U)	1.9-6.2	10^{10} -10^{11} $cycle^{-1}$ (~6s cycle)	10^{7}-10^{8} ? (0.1% target)	?

References

RHIC: A. Fedotov, LEReC Review, 2013
FAIR: FAIR Baseline Technical Review, C. Strum, INPC2013, Firenze, Italy; S. Seddiki, FAIRNESS-2013, C. Hoehne, CPOD2014
NICA : A. Kovalenko, Joint US-CERN-Japan-Russia Accelerator School, Shizuoka, Japan, 2013, A. Sorin, CPOD2014

Example of Lepton Pair Studies



Proposed by Dr. Sako, et. al.

FAIR's Charm and Beauty in 2020 ?

Observers

Austria China Finnland France Germany India Italy Poland Slovenia Spain Sweden Romania Russia UK