QGP物理実験の現状と将来

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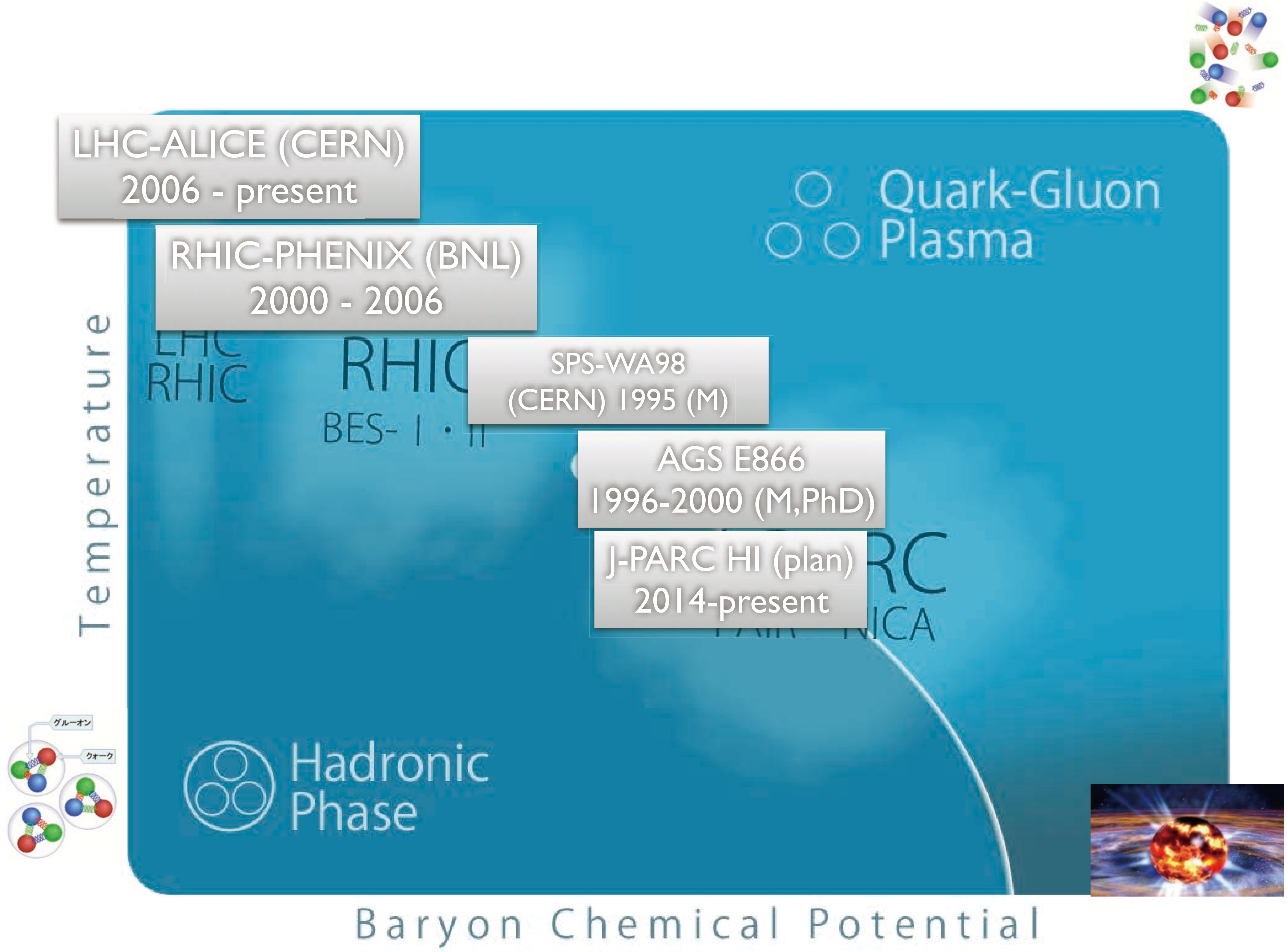
インフォーマル研究会（QGPの新展開２）
名古屋大学
２０１６年2月6日

筑波大学
University of Tsukuba

はじめに

- このトークの方向性：
  - QGP物理、高エネルギー重イオン衝突実験の魅力を、特に分野外の方と共有
  - 日本グループが現在考えてる将来計画とは
  - 他分野との連携

✳ 準備時間の都合上、英語と日本語のスライドが混じりますが、ご容赦ください。



LHC-ALICE (CERN)
2006 - present
RHIC-PHENIX (BNL)
2000 - 2006
SPS-WA98
(CERN) 1995 (M)
AGS E866
1996-2000 (M,PhD)
J-PARC HI (plan)
2014-present
Quark-Gluon
Plasma
RHIC
BES- I・II
NICA
Hadronic
Phase
グルーオン
クォーク
Temperature
Baryon Chemical Potential

私の専門分野

1. ALICE 実験 (2006- present)

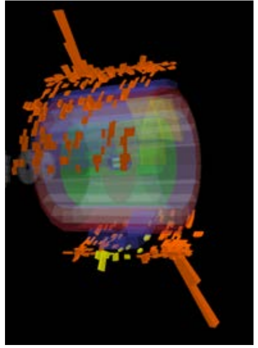
- ジェット・光子の物理
- EMCal/DCal 電磁カロリメータ准責任者
- 超前方光子検出器 R&D、前方の物理
- Grid computing (Tsukuba T2 建設)

2. PHENIX 実験 (2000-2006)

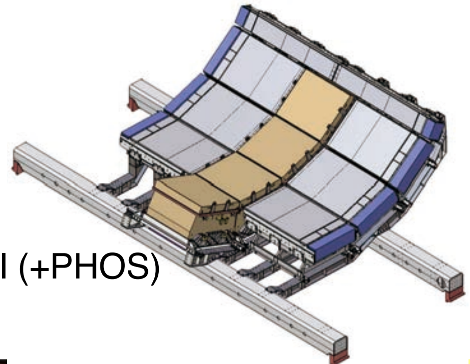
- ハドロン物理 (PID hadron spectra)
- TOF 運用責任者、Run2 データ再構成責任者

3. J-PARC 重イオン計画 (2014- present)

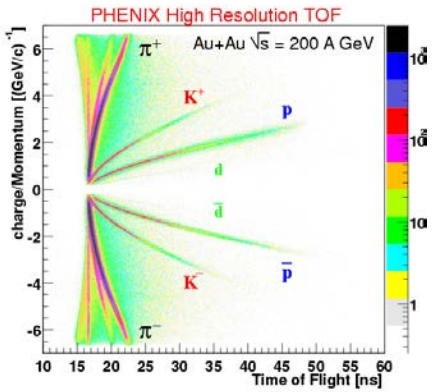
- MRPC-TOF 検出器開発など



ALICE EMCal-DCal
で測定されてdi-jet イベント



ALICE DCal (+PHOS)
検出器

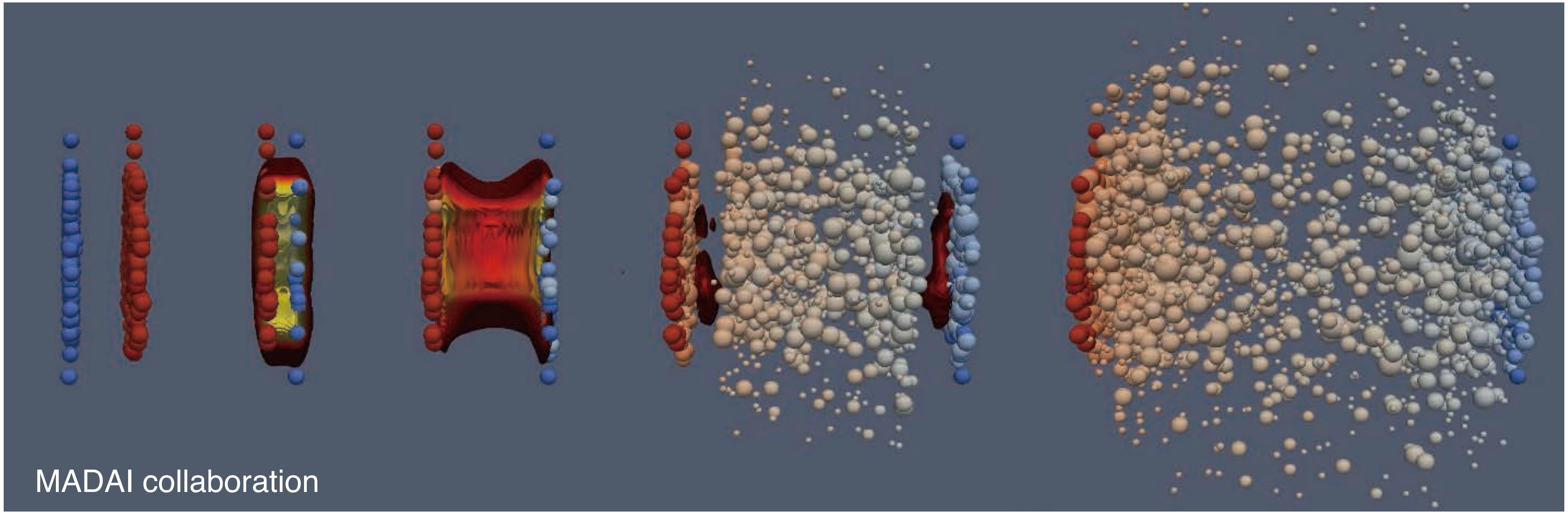


PHENIX TOF
と粒子識別

Outline

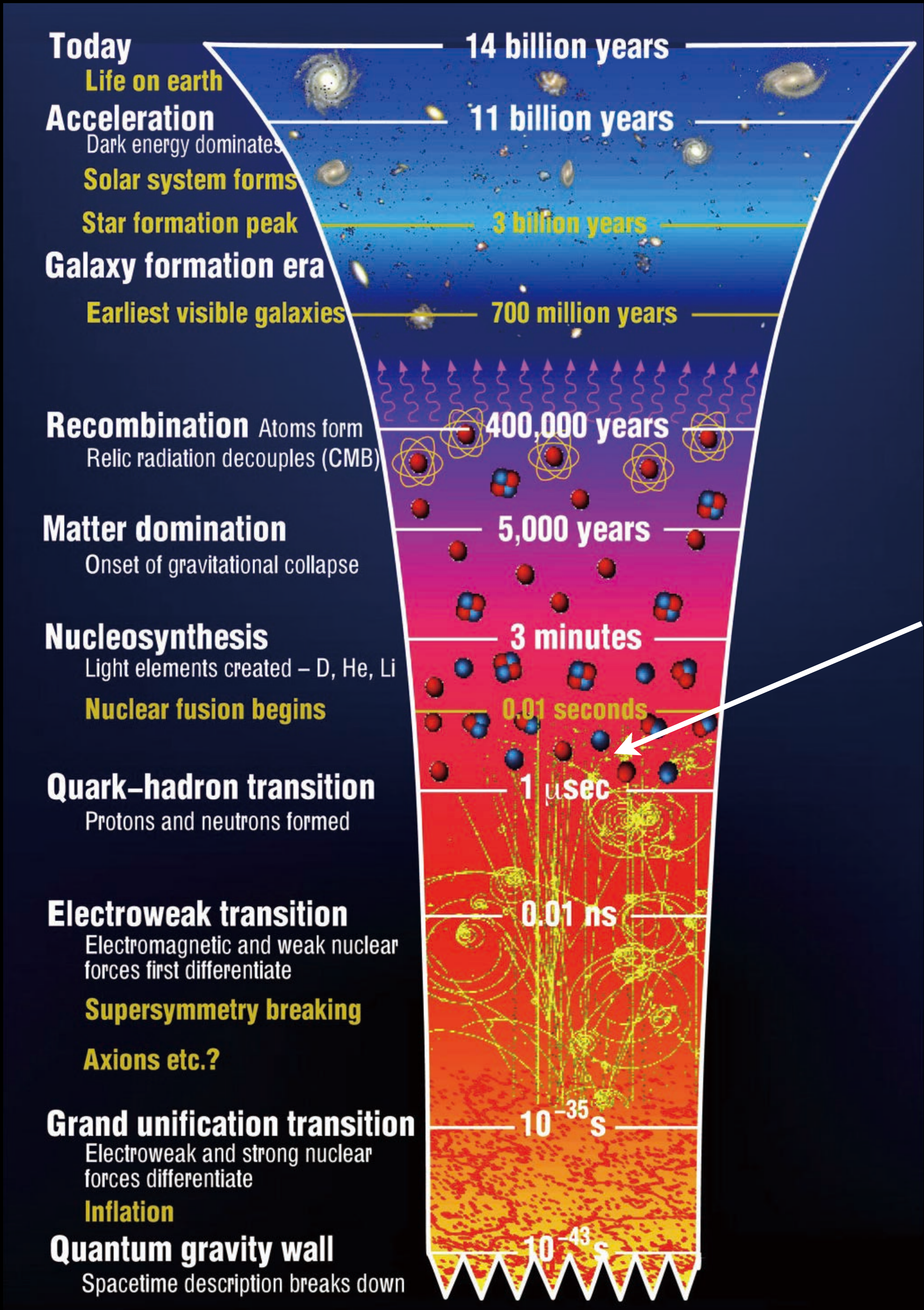
1. Introduction (High energy heavy ion collisions and QGP)
2. What we have learned from RHIC and LHC data (2000- present)
3. What is missing?
4. Connections to other fields
5. Summary

1. High energy heavy ion collisions and QGP



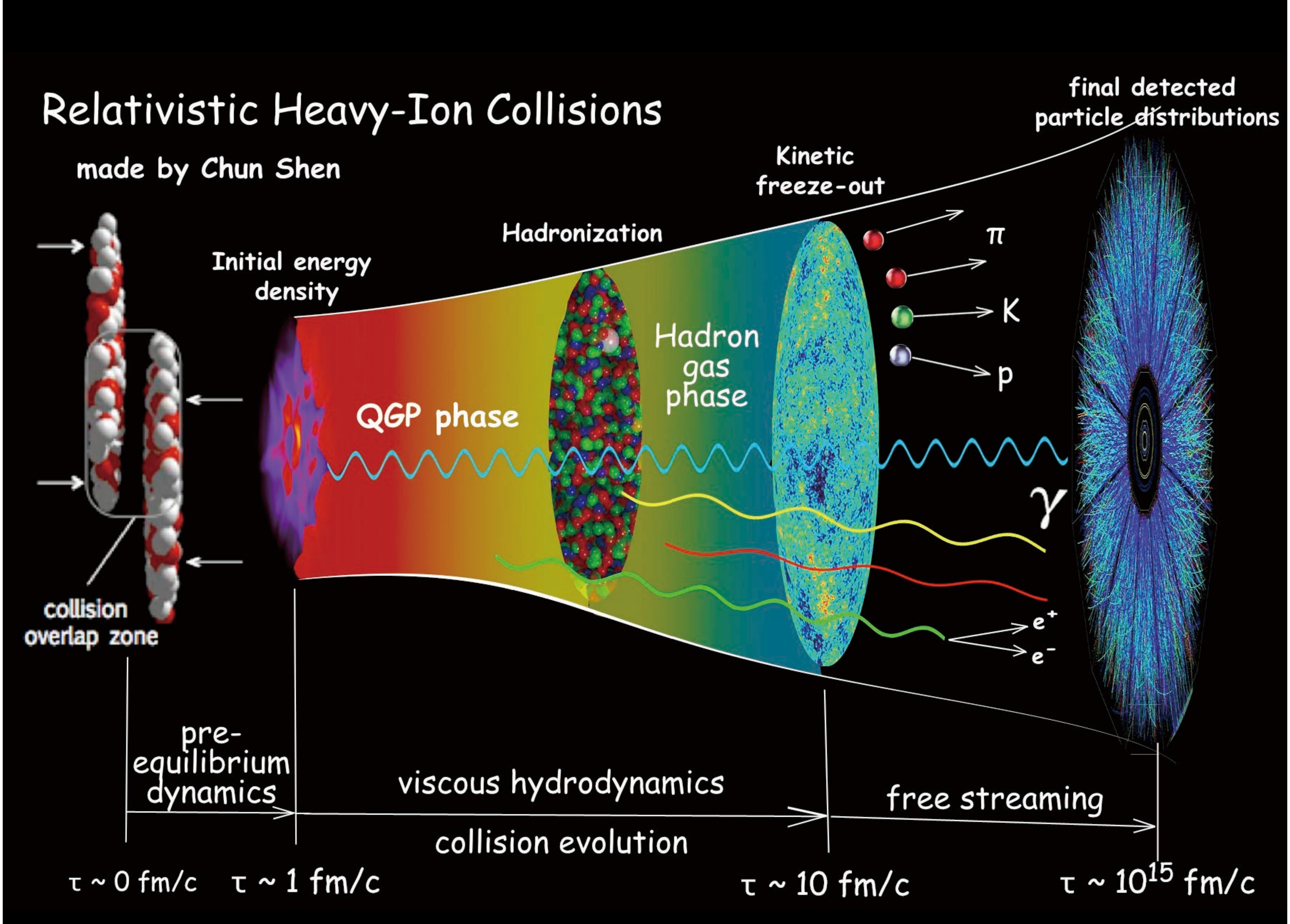
Time

History of our Universe



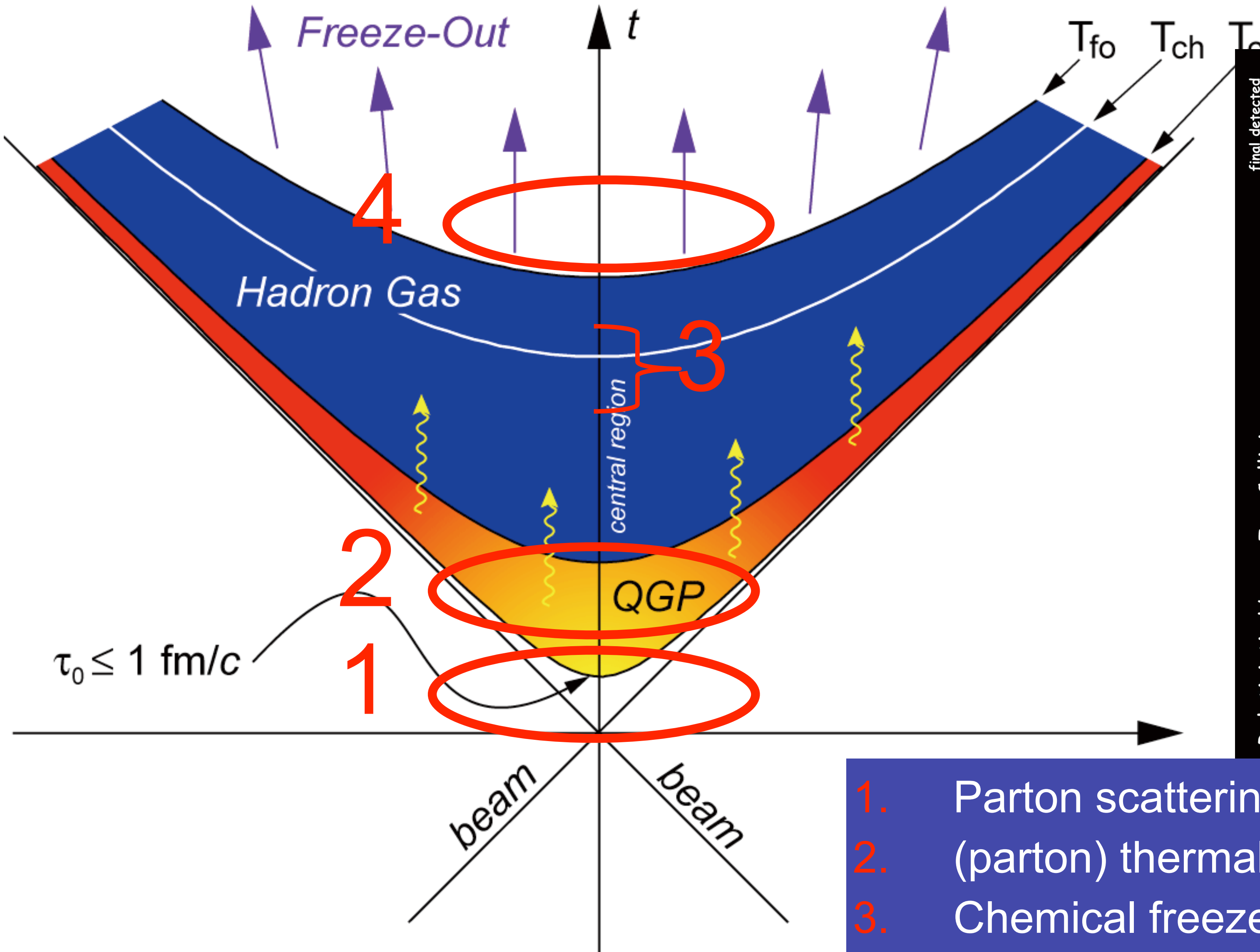
QCD phase transition
Quark Gluon Plasma (after 10^{-6} sec)

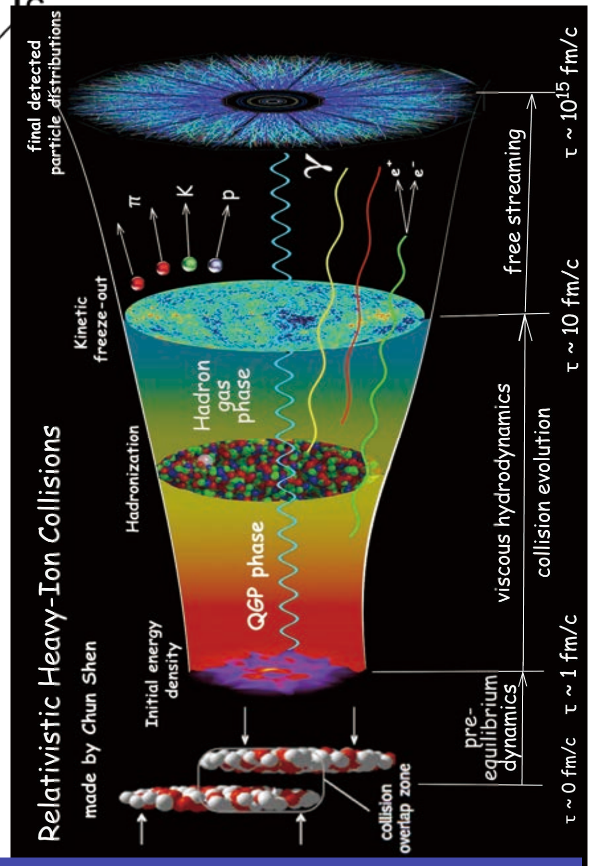
Our research field



Courtesy of Paul Sorensen and Chun Shen

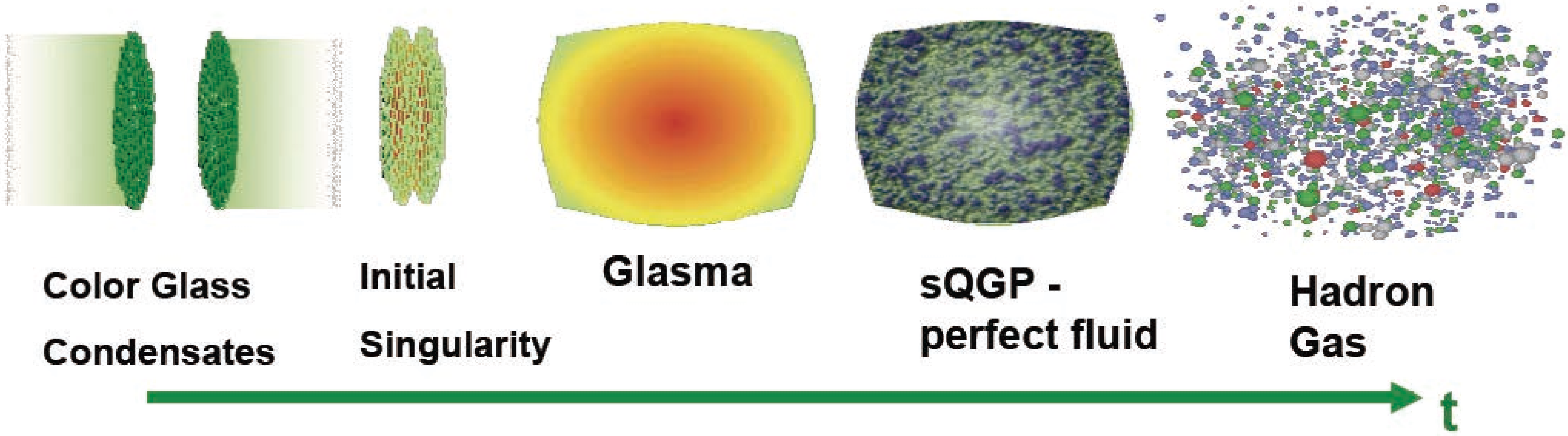
Space-time evolution of Heavy Ion Collisions



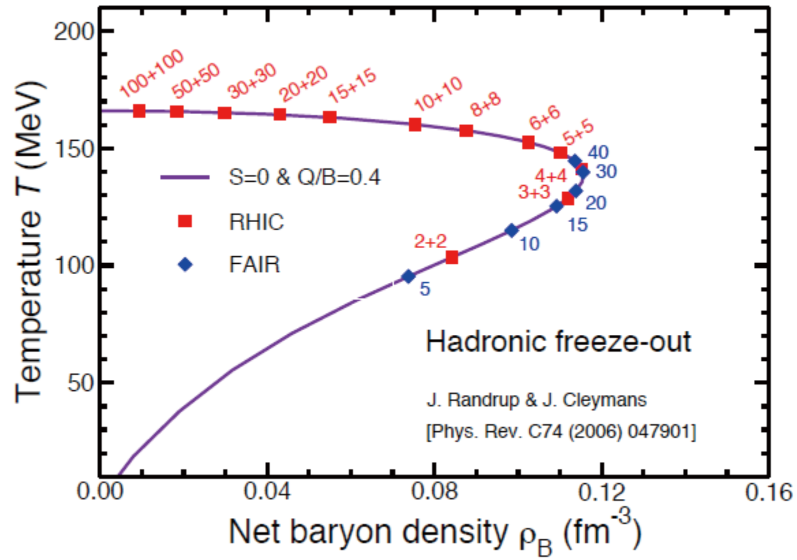


1. Parton scattering
2. (parton) thermal equilibrium and QGP
3. Chemical freeze-out (ceases inelastic scattering, particle ratios fixed)
4. Kinetic freeze-out (ceases elastic scatting, particle momentum fixed)

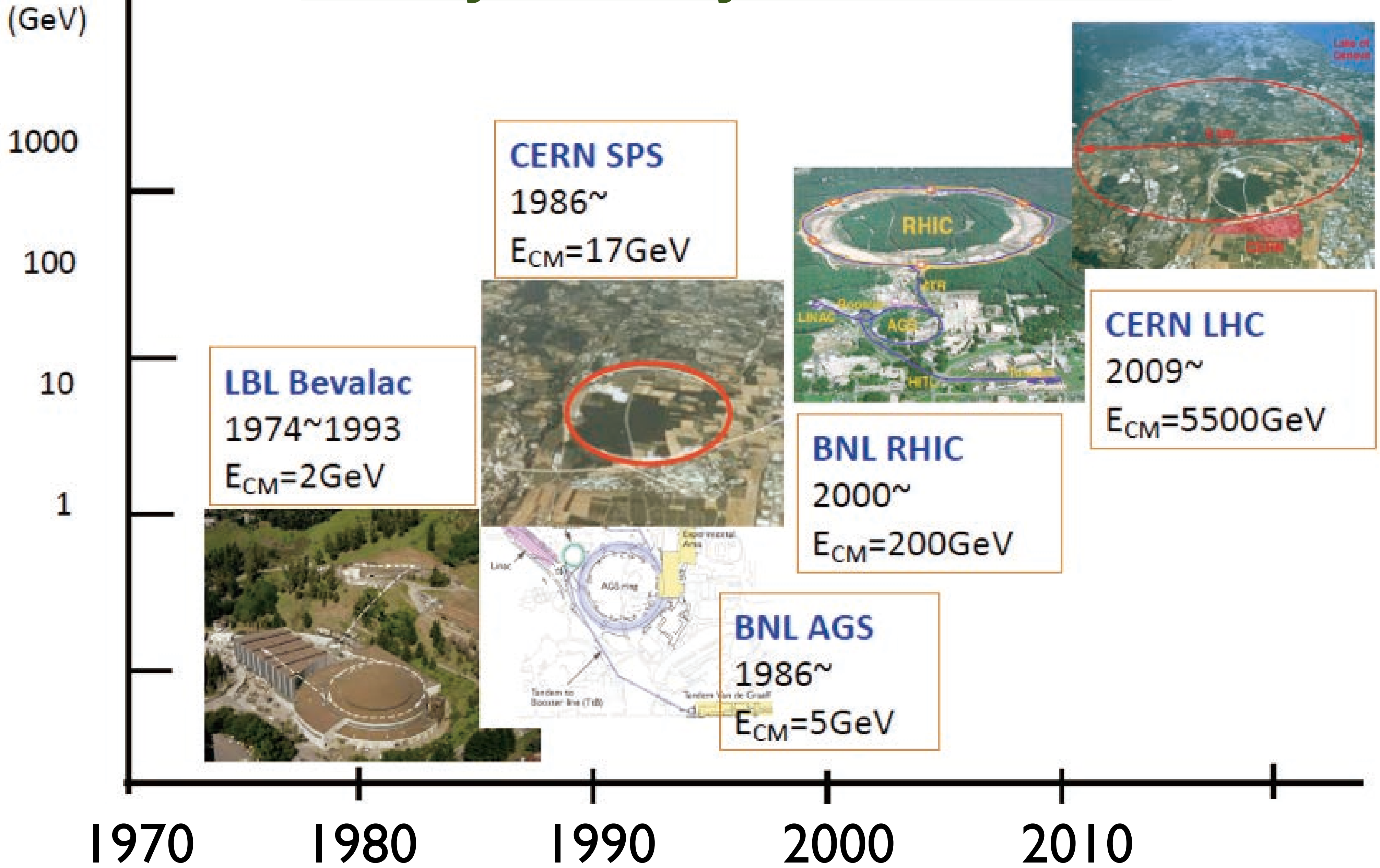
高エネルギー重イオン反応



- 重イオン衝突＝非常に dynamical. 時空発展による物理現象の理解が不可欠
- 衝突エネルギーの変化→ dynamics と QCD 相図上の軌跡が変化



History of Heavy Ion Accelerator



Slide from H. Hamagaki

RHIC （相対論的重イオン衝突型加速器）
2000-

ブルックヘブン国立研究所 BNL（米・ニューヨーク）

RHIC = Relativistic Heavy Ion Collider

周長：3.8 km

1740 個の超伝導マグネット

最高エネルギー：200 GeV 金＋金

500 GeV 偏極陽子＋陽子

様々な衝突系、エネルギーで実験

RHIC run history

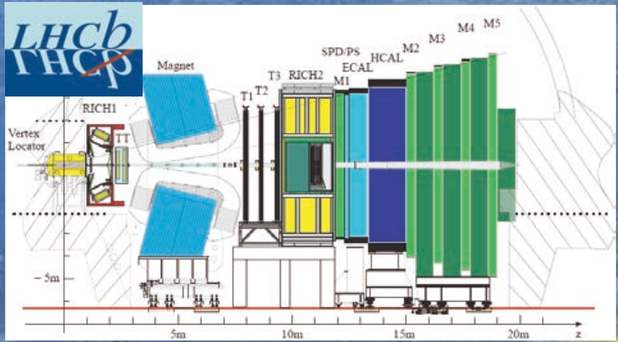
energy GeV	Collision System U+U	Au+Au	Cu+Au	Cu+Cu	3He+Au	d+Au	p+Au	p+Al	p+p
500									x
200	x	x	x	x	x	x	x	x	x
130		x							
62.4		x		x		o			x
39		x				o			
27		x							
~20		x		x		o			
14.5		x							
7.7		x							

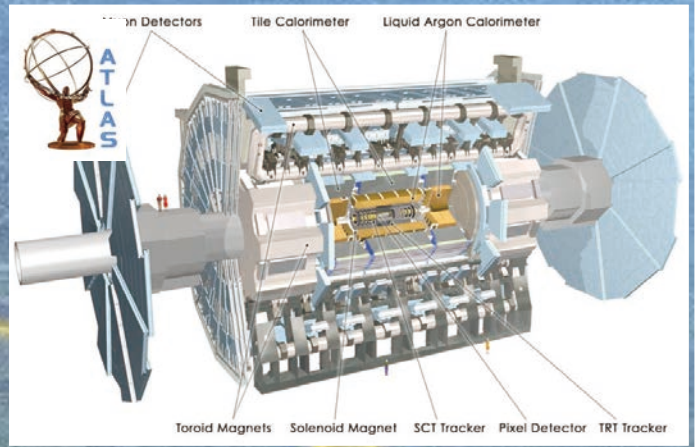
2014

2015

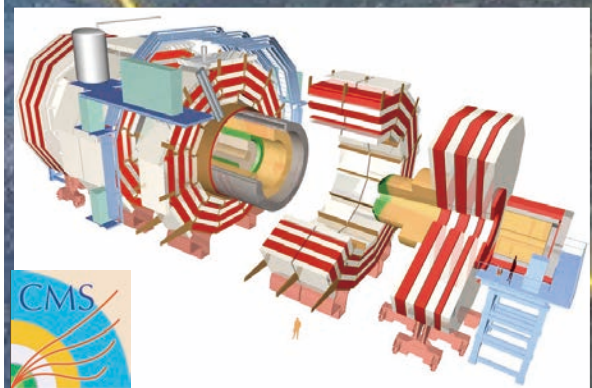
2016

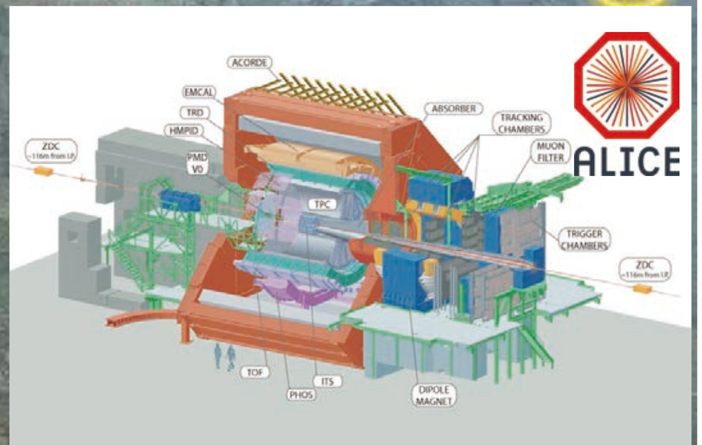
LHC (Large Hadron Collider)
2009-, $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV



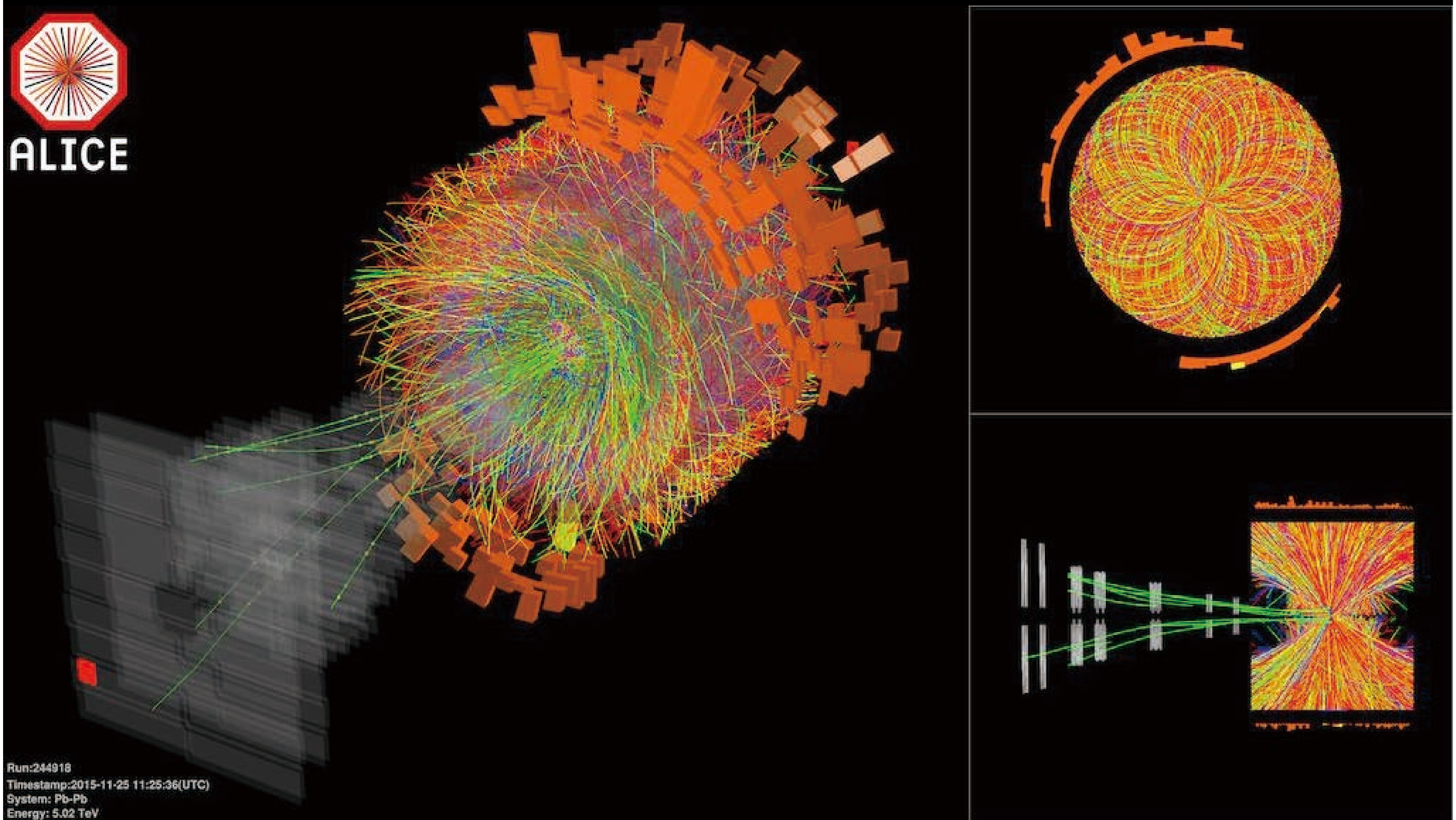


LHC: Circumference : 27 km



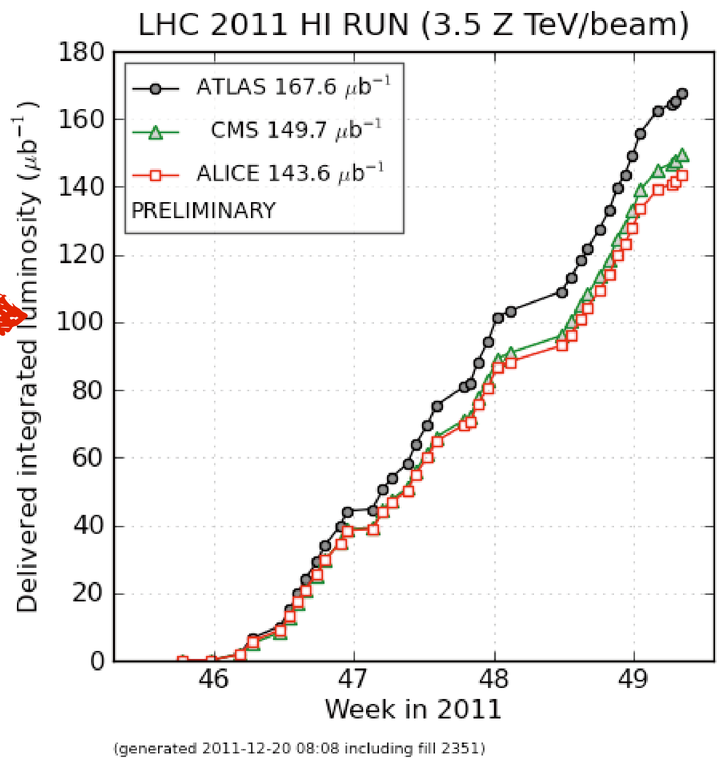


Pb-Pb 5.02 TeV (One PeV collisions , Nov. 2015) !!



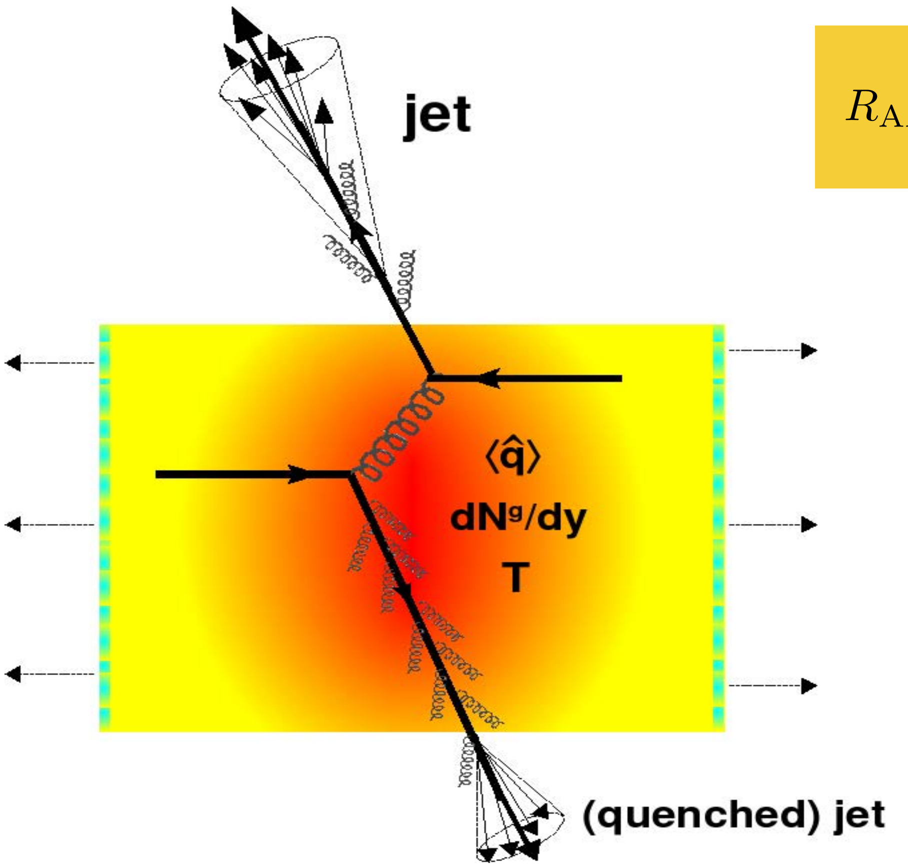
LHC run history

- **2009**: Commissioning and first data p-p (900 GeV)
- **2010**: First p-p run (7 TeV) and **first Pb-Pb run (2.76 TeV)**
- **2011**: Long p-p (7 TeV) and **one month Pb-Pb (2.76 TeV)** = x10 luminosity than that in 2010. first p-p (2.76 TeV).
- **2012**: Long p-p (8 TeV), one day p-Pb (5.02 TeV) pilot run
- **2013**: 1.5 month **p-Pb (5.02 TeV)**, (32 nb^{-1} in ALICE)
- **2013.02 - 2014 winter**: LHC Long Shutdown 1 (LS1)
- **2015: pp (13 TeV), pp (5.02 TeV, few days), Pb-Pb (5.02 TeV, 1 month)**

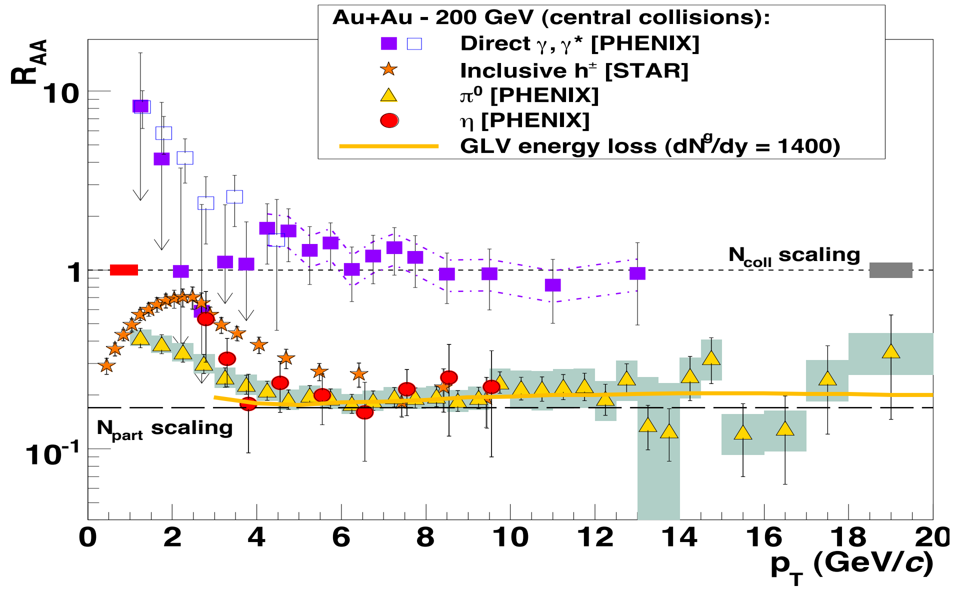


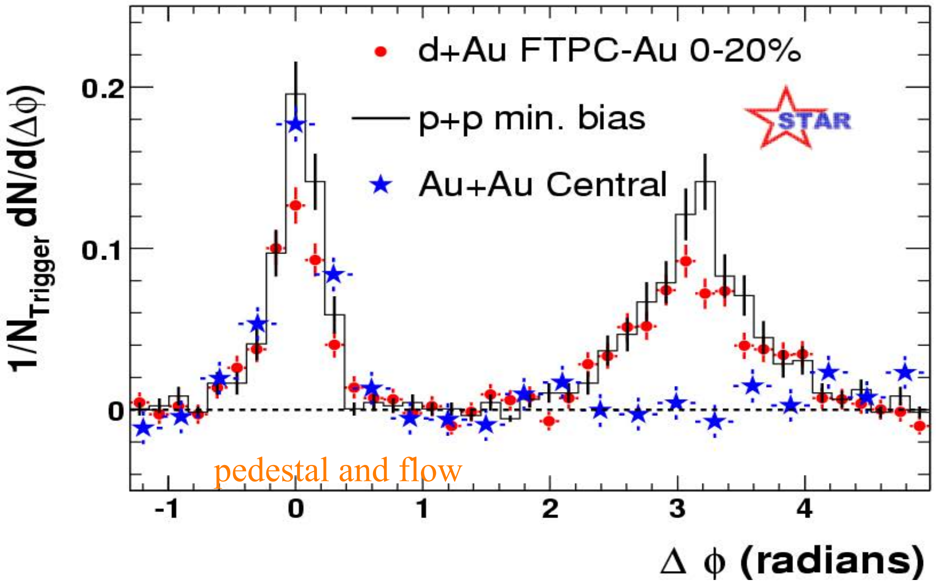
2. What we have learned from RHIC and LHC HI

（1）ジェットクエンチング　(パートンのQGP中でのエネルギー損失)



$$R_{AA} = \frac{\text{"hot/dense QCDmedium"}}{\text{"QCD vacuum"}} = \frac{dn_{AA}/dp_T dy}{\langle N_{binary}\rangle \cdot dn_{pp}/dp_T dy}$$

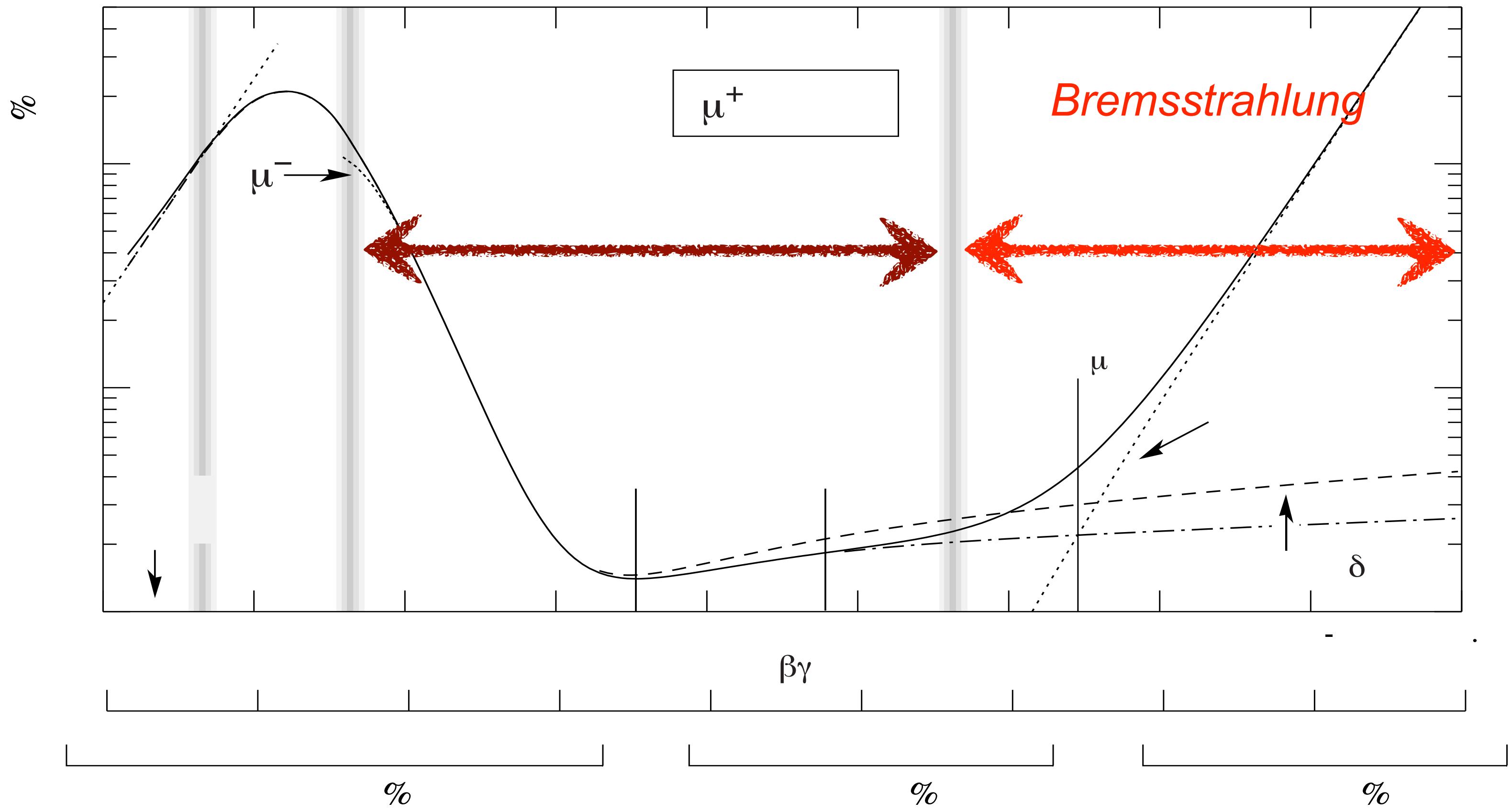




- ✓ 1）高運動量粒子の減少
  - 低エネルギー衝突では見られない
- ✓ 2）相反ジェットの消失
- ✓ エネルギー損失～数GeV/fm
  - ハドロンガスではかんがえられない
  - →QGP生成の証拠のひとつ

QED の場合、

Energy loss of charged particle in a matter



Collisional

√Bethe-Bloch

Radiative

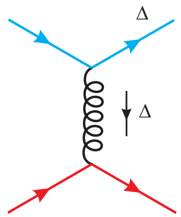
√Bethe-Heitler (thin; L<<λ)

√Landau-Pomeranchuk-Migdal (thick; L>>λ)

√ dE/dx 測定→物性を決定

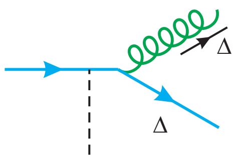
- QEDプラズマ中でのエネルギー損失 → T & m_D を与える

QGPに特徴的なエネルギー損失



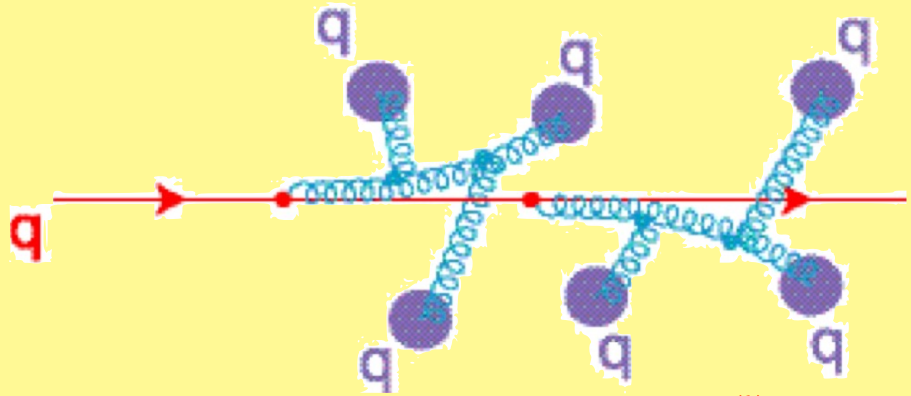
Collisional

$$\Delta E \propto \ell^1$$



Radiative

$$\Delta E \propto \ell^2$$



$$\Delta E \propto \alpha_S C_{\mathrm{R}} \langle \hat{q} \rangle L^2$$

pQCD

- グルーオン放射によるエネルギー損失が支配的

✓ **dE/dx 測定→物性やJet Tomography**

- **QGPの物性研究にジェット（高エネルギーパートン）は大変有効なプローブ**

◉ Transport coefficient:

$$\hat{q} \equiv m_D^2/\lambda = m_D^2 \rho\sigma \approx \frac{< k_T^2 >}{L}$$

• <u>Scattering power</u> of the medium through the average transverse momentum squared (k_T^2) , transferred to the traversing particle per unit path length.

• Combined both thermodynamical (m_D, ρ) and dynamical (σ) properties of medium.

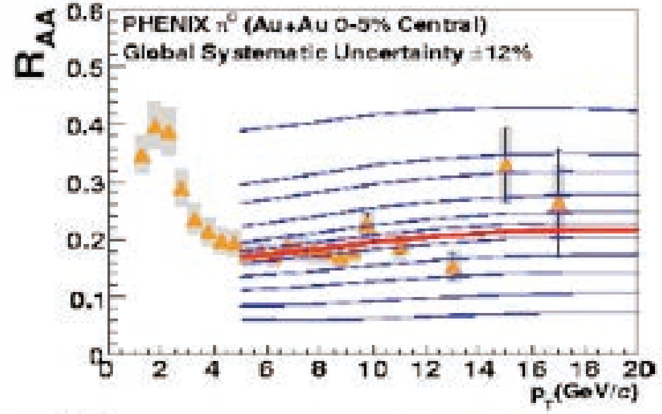
High p_T suppression ⇒ QCD medium properties

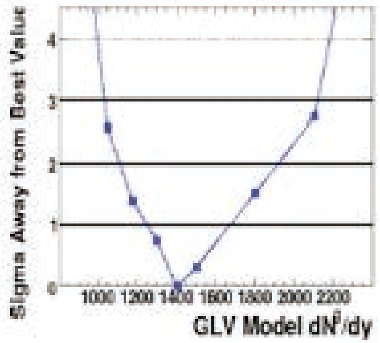
- Medium properties via data vs. jet quenching models:

Initial gluon densities (GLV):

$dN^g/dy = 1400^{+270}_{-150}$

[Vitev & Gyulassy]

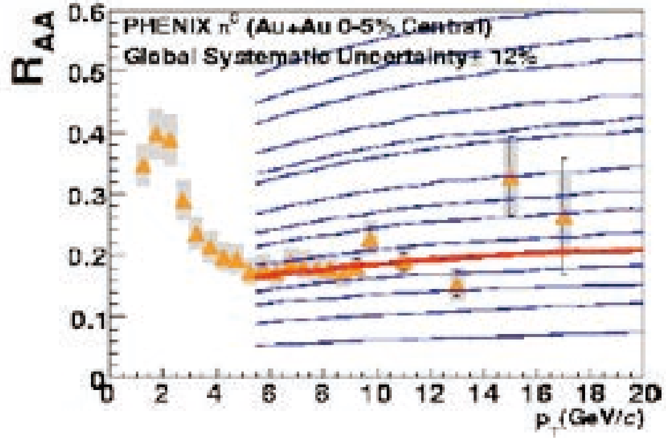


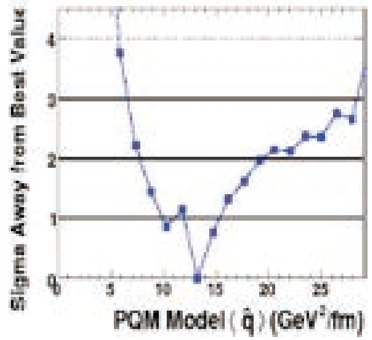


Transport coefficients

$\langle q_0 \rangle \sim 13.2^{+2.1}_{-3.2}$ GeV²/fm

[BDMPS/PQM]





PHENIX, arxiv:0801.1655

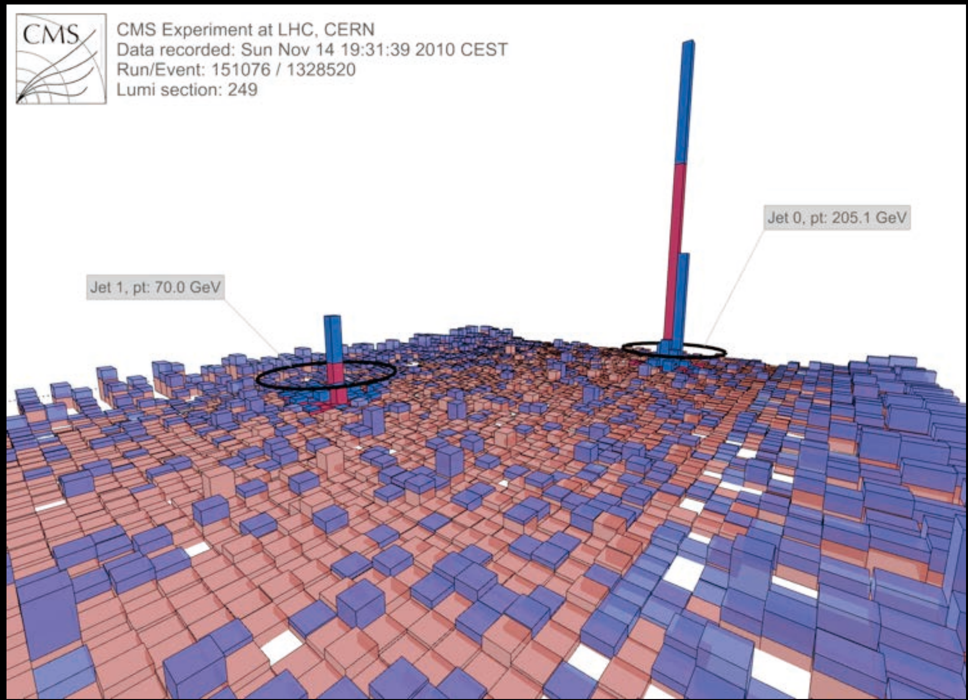
- Other models:

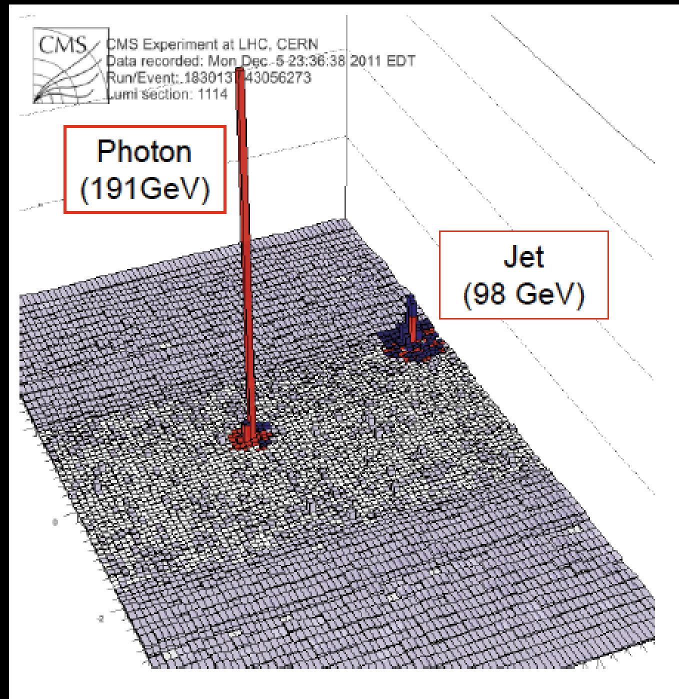
Temperatures [AMY]: T ~ 0.4 GeV [G. Moore], Opacities: $\langle n \rangle = L/\lambda \approx 3$ 4 [Levai et al.]

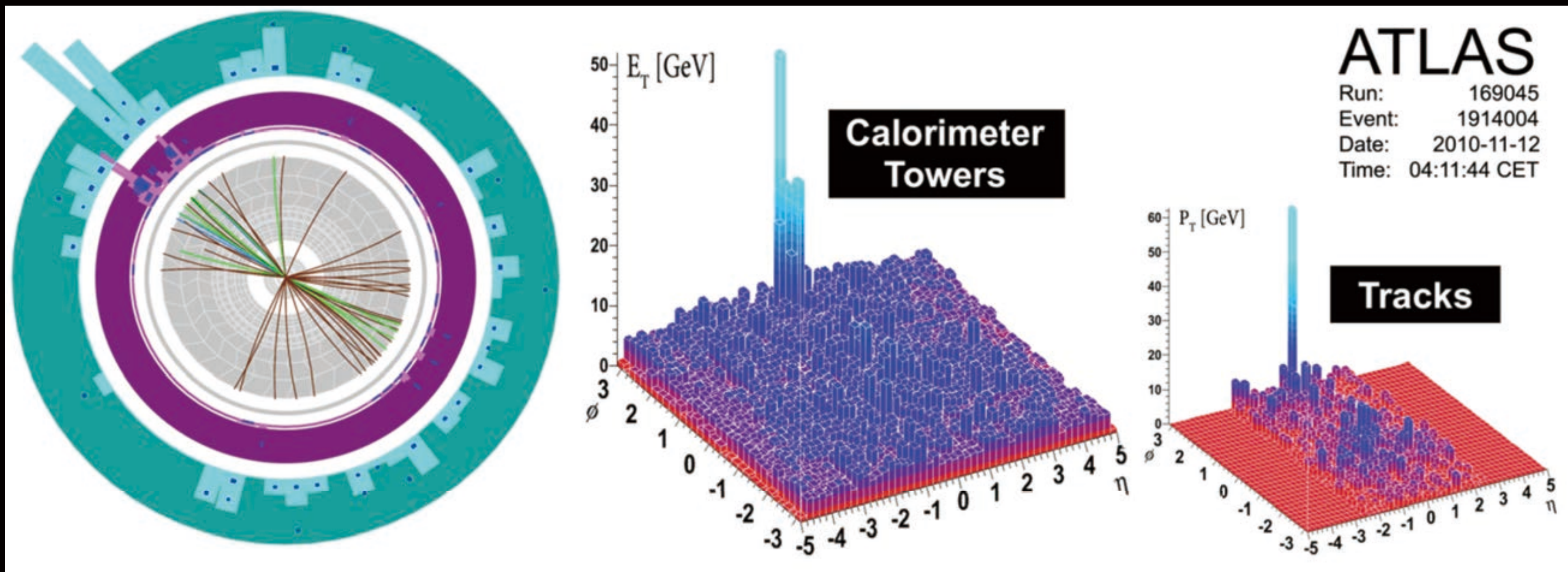
Energy losses: $dE/dx \approx 0.25$ GeV/fm (expanding), $dE/dx|_{eff} \approx 14$ GeV/fm (static) [X.N.Wang]

from D. d'Enterria (slide at QGPWS, 2008)

Jets in LHC heavy ion collisions

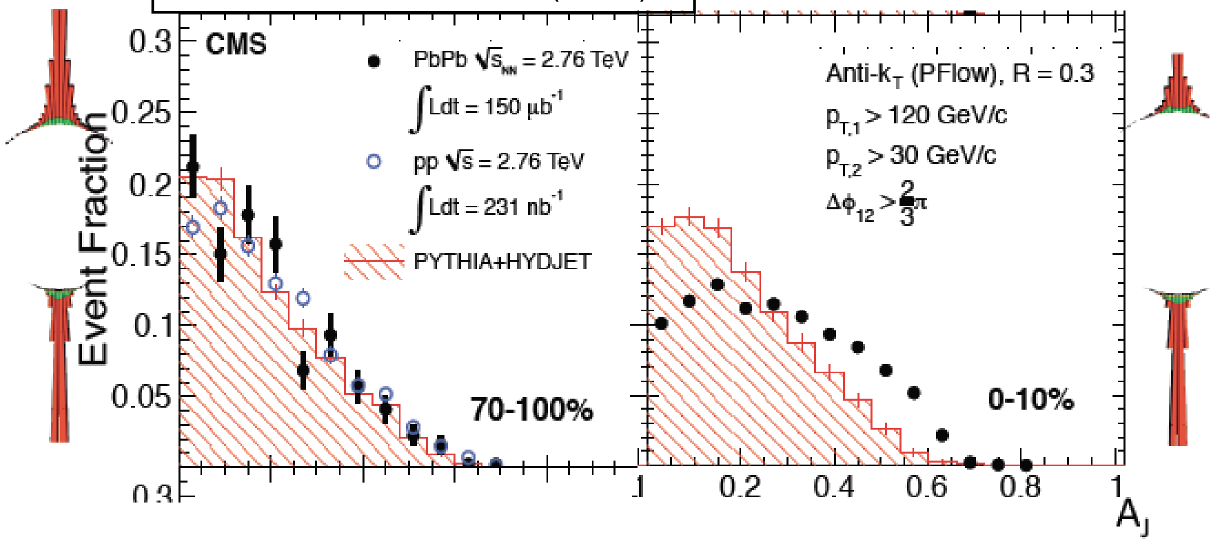




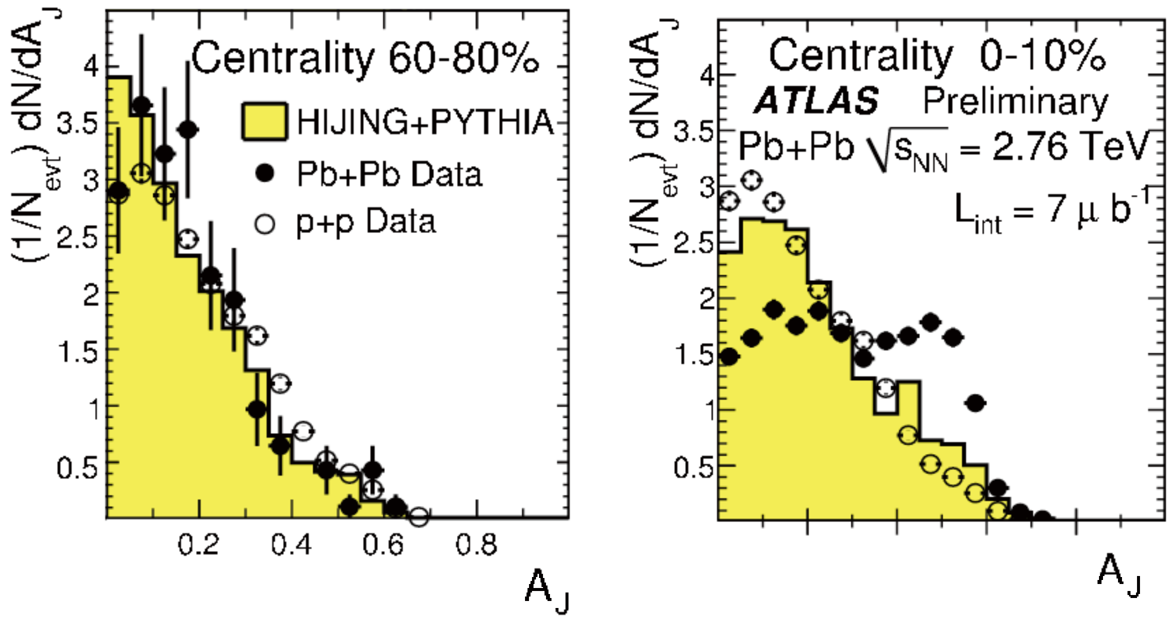


Di-jet energy imbalance

CMS, PRC 84, 024906 (2011)



ATLAS, PRL, 105 (2010) 252303



1) Large energy imbalance is observed in central Pb-Pb.

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

$p_{T,1}$: leading jet
$p_{T,2}$: sub-leading jet

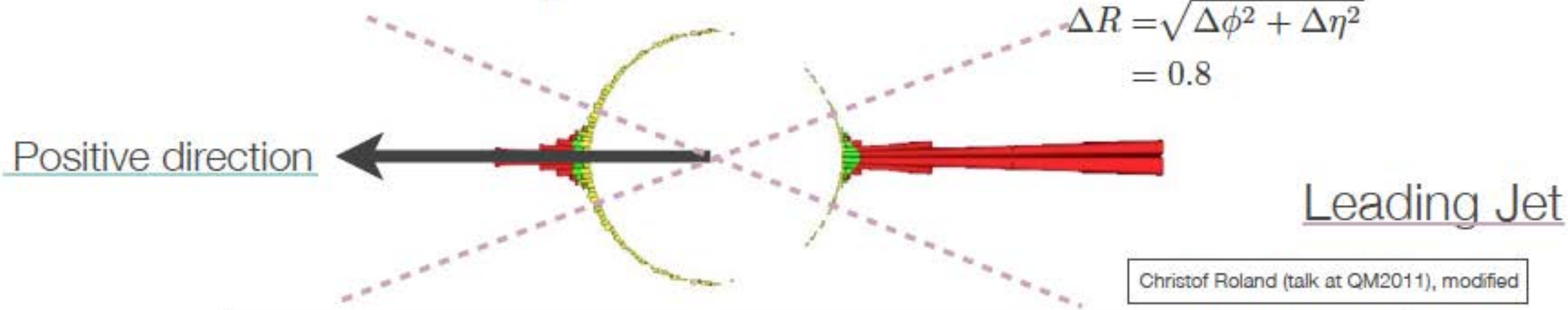
2) Large A_J : low momentum particle (< 4 GeV/c) emitted at large angle on away side.

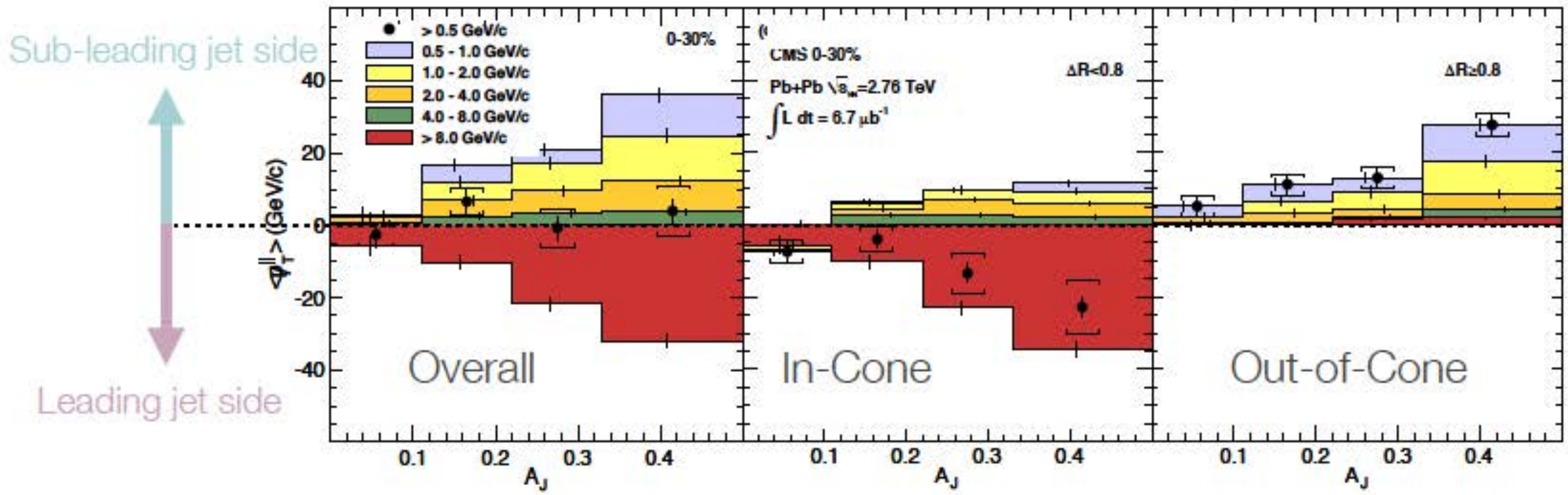
Energy balance by low p_T particle at large angle

Net-p_T along the sub-leading jet

CMS (2011)

$$\not{p}_T^{||} = \sum_i -p_T^i \cos(\phi_i - \phi_{\text{Leading Jet}})$$





S. Chatrchyan et al. [CMS Collaboration], Phys. Rev. C 84, 024906, modified

Slide from Y. Tachibana (ATHIC 2014)

(2) Strongly interacting QGP, perfect fluid

BROOKHAVEN
NATIONAL LABORATORY

Contact: Karen McNulty Walsh, (631) 344-8350 or Mona S. Rowe, (631) 344-5056

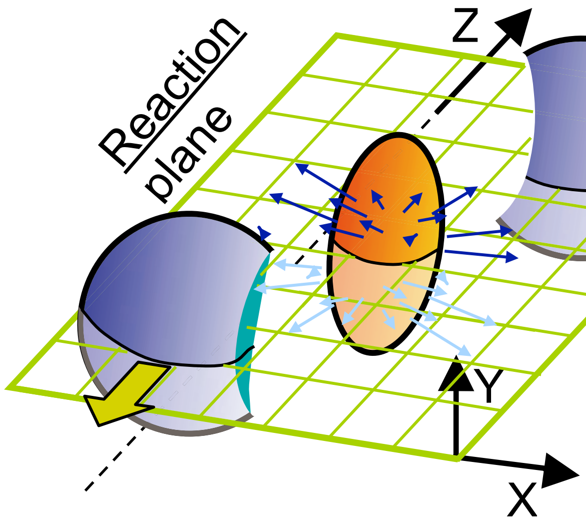
RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a liquid.

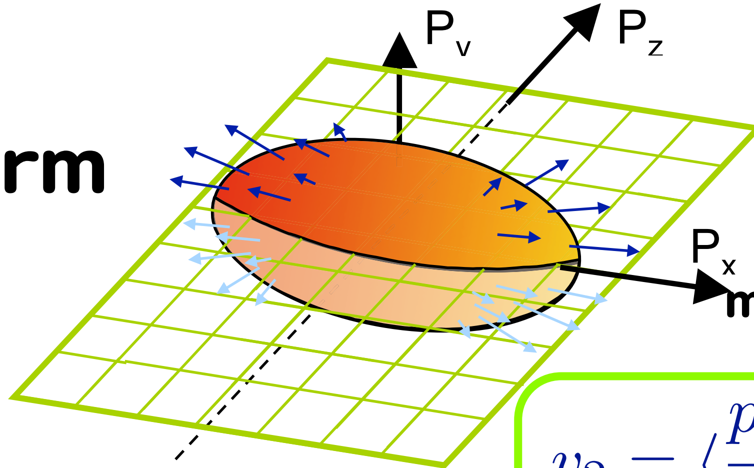
Azimuthal Anisotropy



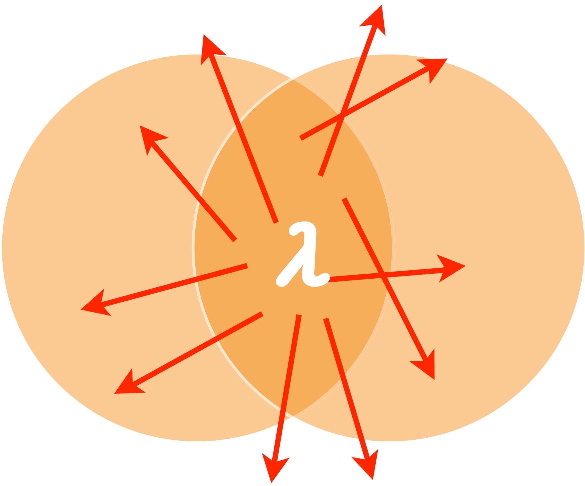
Transform

coordinate space

$$\varepsilon_{\rm ecc} = \langle \frac{y^2 - x^2}{y^2 + x^2} \rangle$$

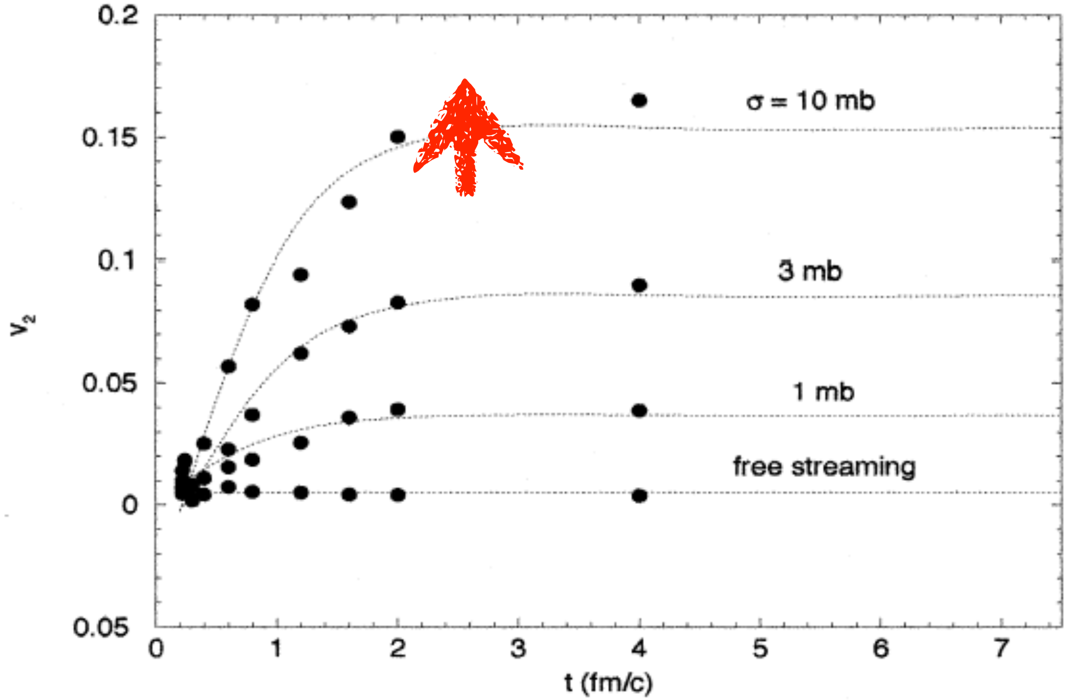


$$v_2 = \langle \frac{p_y^2 - p_x^2}{p_y^2 + p_x^2} \rangle$$

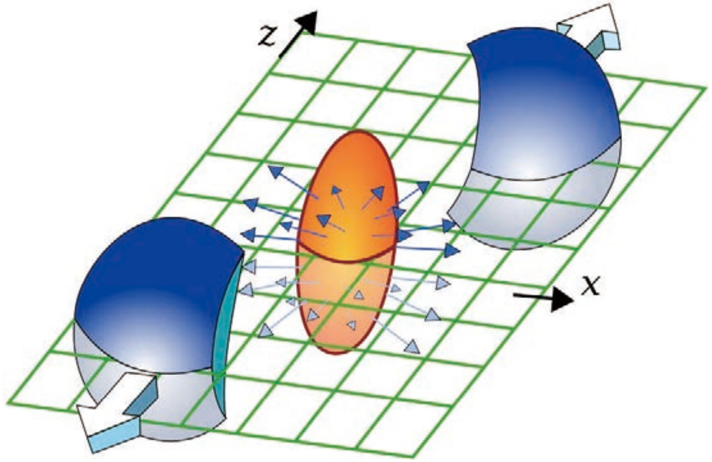


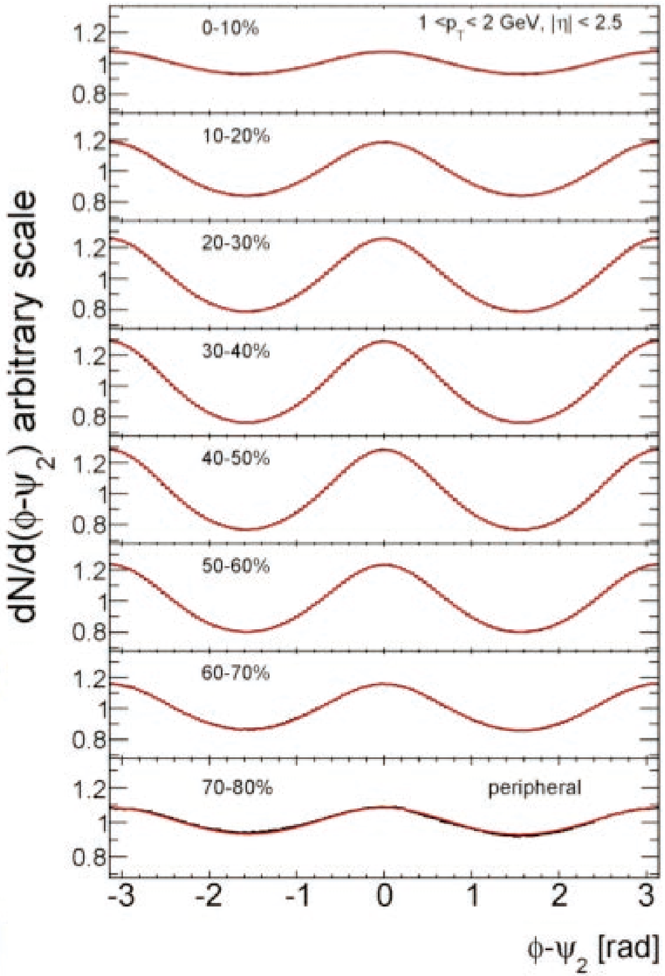
$\lambda/R \rightarrow 0$ **Higher efficiency of transformation (space → momentum), approching hydrodynamics**

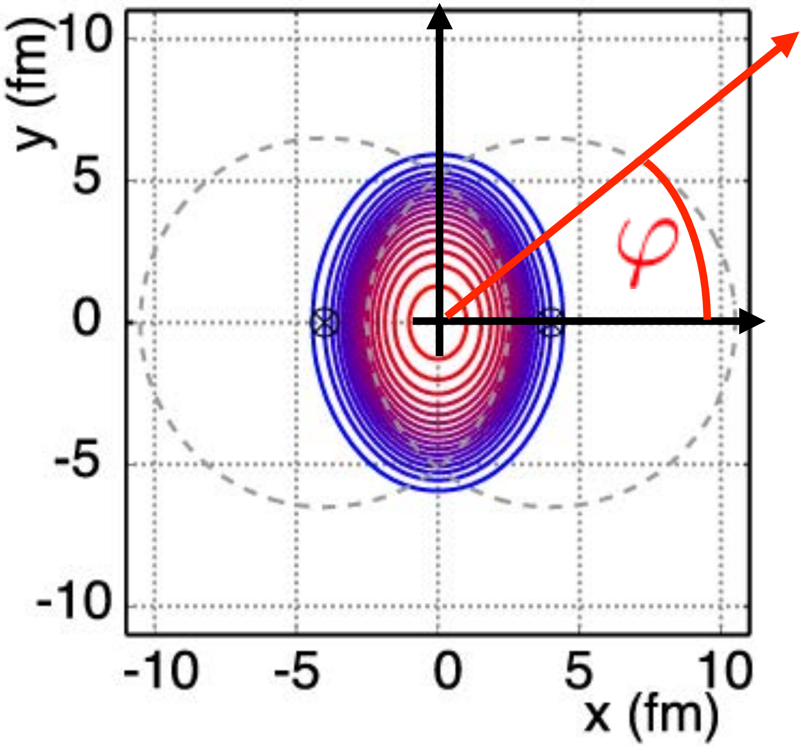
hydrodynamics ! $\lambda/R \rightarrow 0$



Elliptic flow

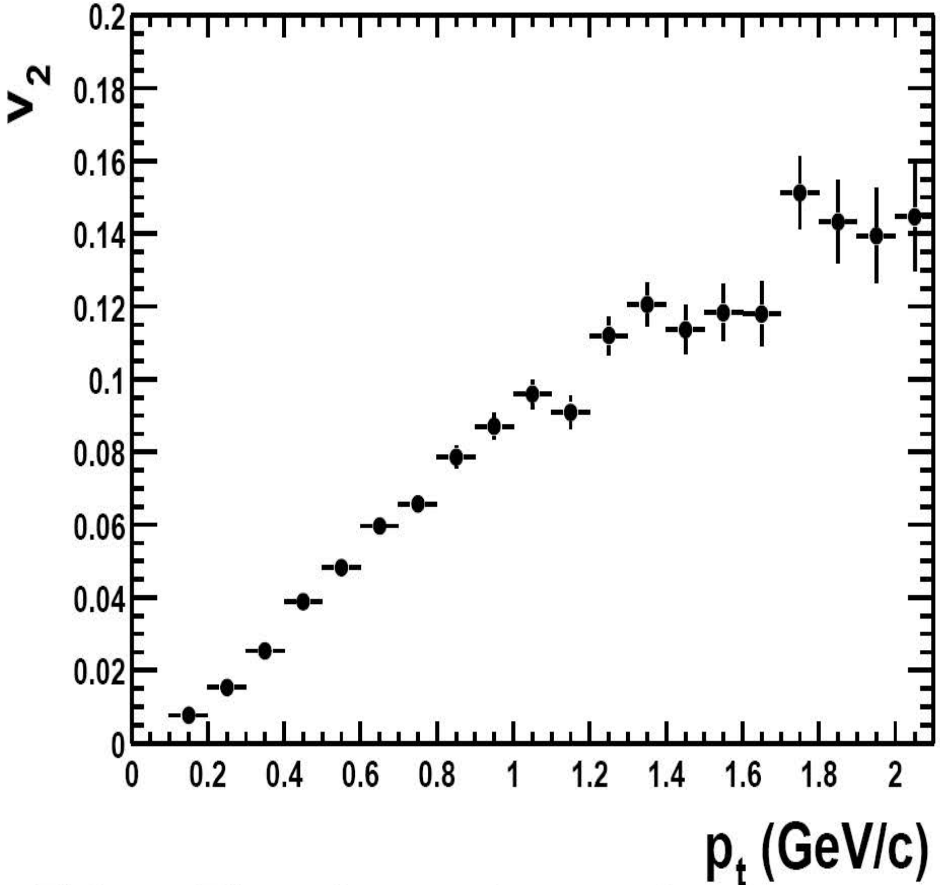






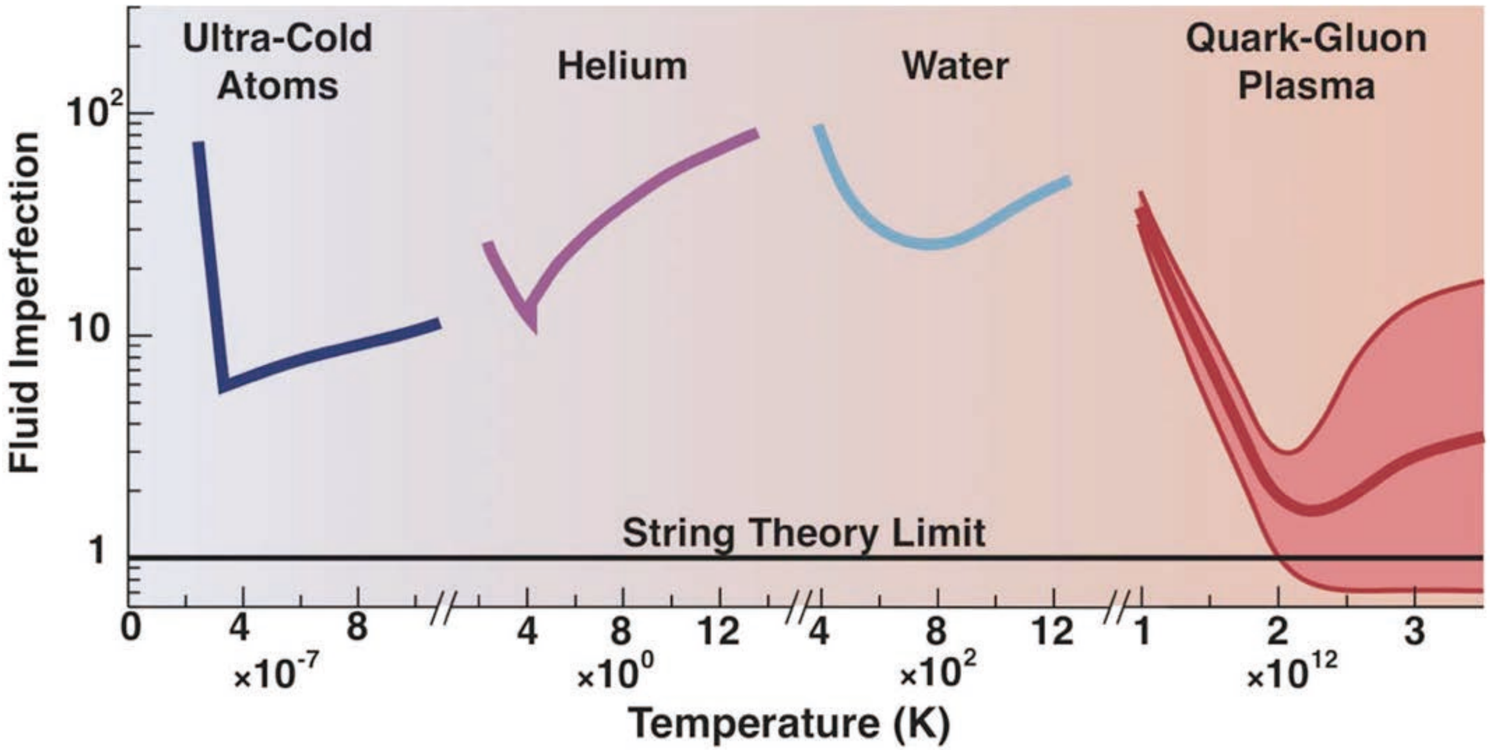
$$\frac{dN}{p_T dp_T dy d\varphi}(p_T, \varphi; b) = \frac{dN}{2\pi p_T dp_T dy}\left(1 + 2\underline{v_2}(p_T; b)\cos(2\varphi) + \ldots\right)$$

STAR PRL86,402 (2001)

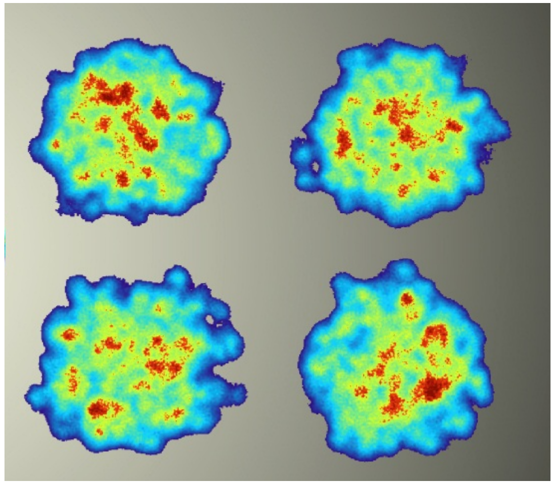


- **大きな楕円的方位角異方性 (v_2) の観測**
  - 極めて早い thermalization〜 0.6 fm/c
  - 完全流体! →**強結合 QGP の発見**

高次の方位角異方性



Higher Harmonics



重イオン衝突の揺らぎ

- RHICにおける方位角異方性→比ずれ粘性 (η/s) ~ 0.1　＝　**世界最小の η/s**

→ストリング理論における量子リミット (1/4π) に近い

- **高次異方性**の測定により重イオン衝突の初期条件に制限がかけられるようになってきた（e.g.カラーグラス凝縮 (CGC) など）.

Strong coupling and shear viscosity

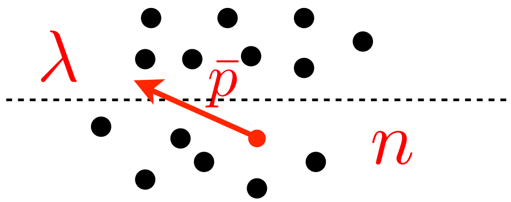
slide from Y. Miake

internal resistance to flow

Low η

High η

From view point of Kinetic theory,

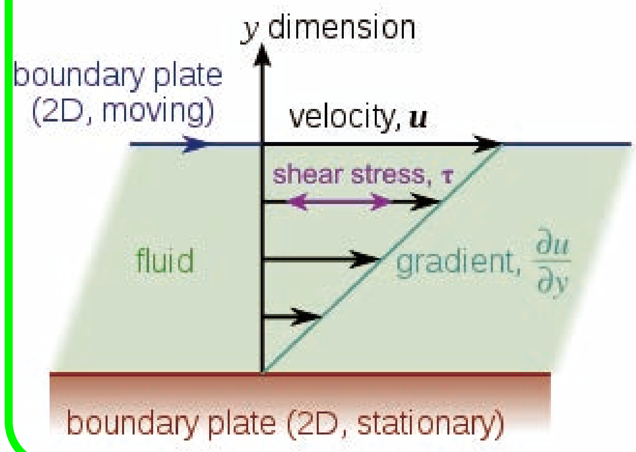


$$\begin{cases} \eta \approx \frac{1}{3} n \bar{p} \lambda \\ s \approx n \end{cases}$$

$$\therefore (\eta/s) \sim \bar{p}\lambda \overset{(\lambda \to 0)}{\searrow} 0$$

(uncertainty principle)

dimension less in natural unit

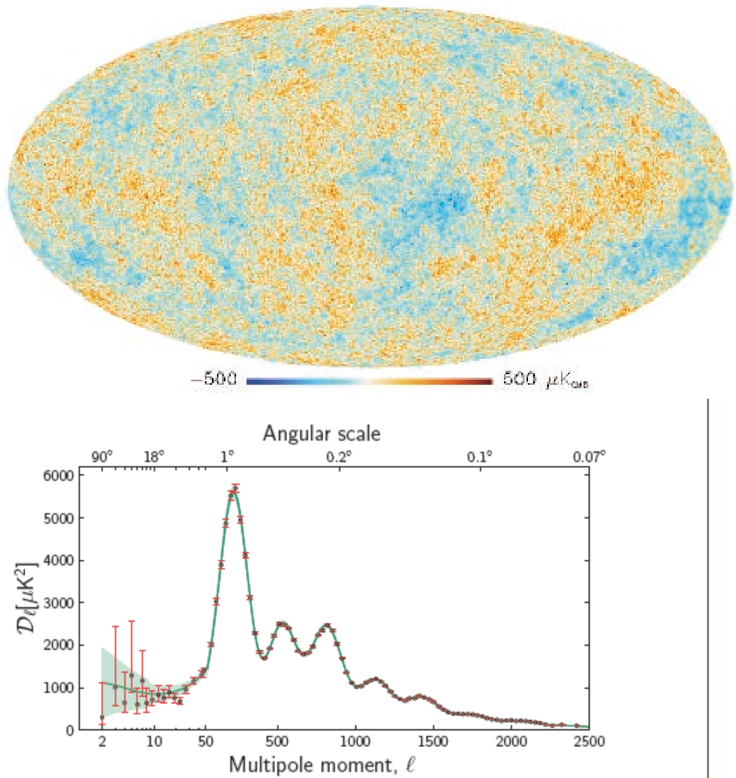


$$\tau \left(= \frac{F}{S}\right) \equiv \eta \frac{\partial u}{\partial y}$$

✓ Strong coupling

高次異方性 (higher harmonics)で分かるQGP物性

Fluctuations of the Universe



Plank (2013)
宇宙論パラメータの決定

Fluctuations of Little bang

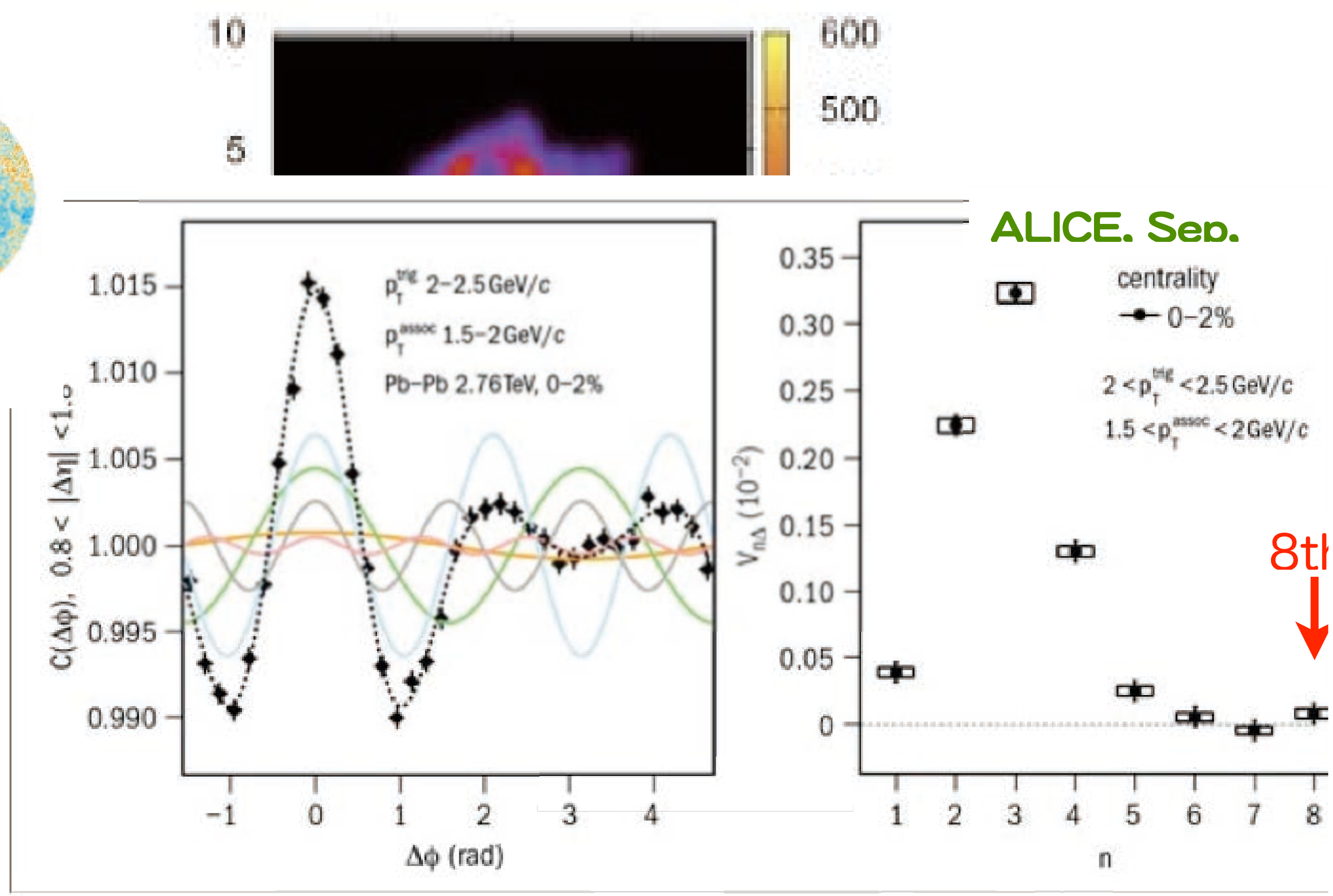
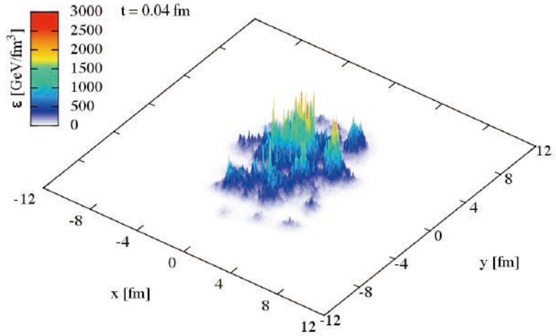


Fig. 1. Left: correlation function for charged hadron pairs from head-on Pb–Pb collisions. Right: corresponding spectrum of Fourier harmonic amplitudes vs n.

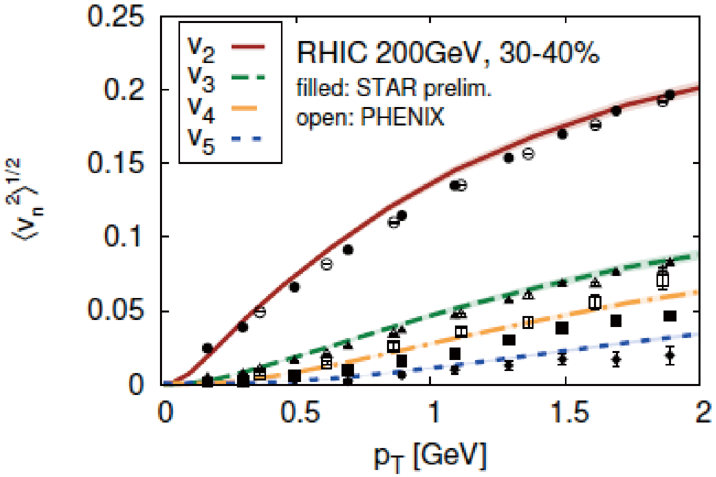
レアプローブ（種々のハドロン、フォトン、lepton, light quark, heavy quark）の
高次異方性測定により、熱化メカニズム、 衝突初期条件、 QGP物性（粘性等）がわかる

→　**測定装置の高速化と High-p_T 化が鍵**

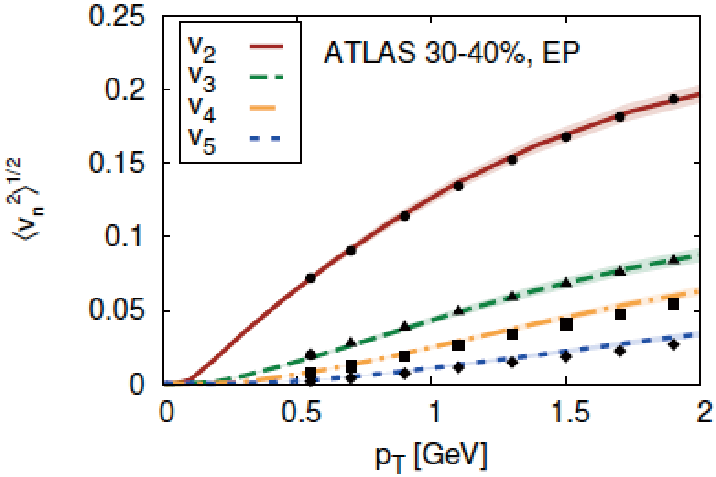


η/s 温度依存性？

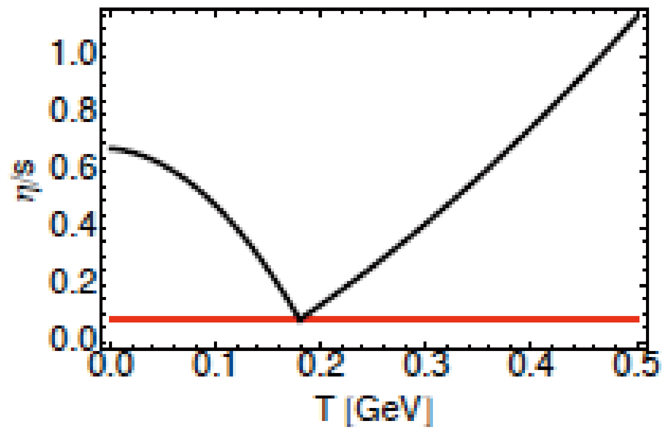
RHIC $\eta/s = 0.12$



LHC $\eta/s = 0.2$



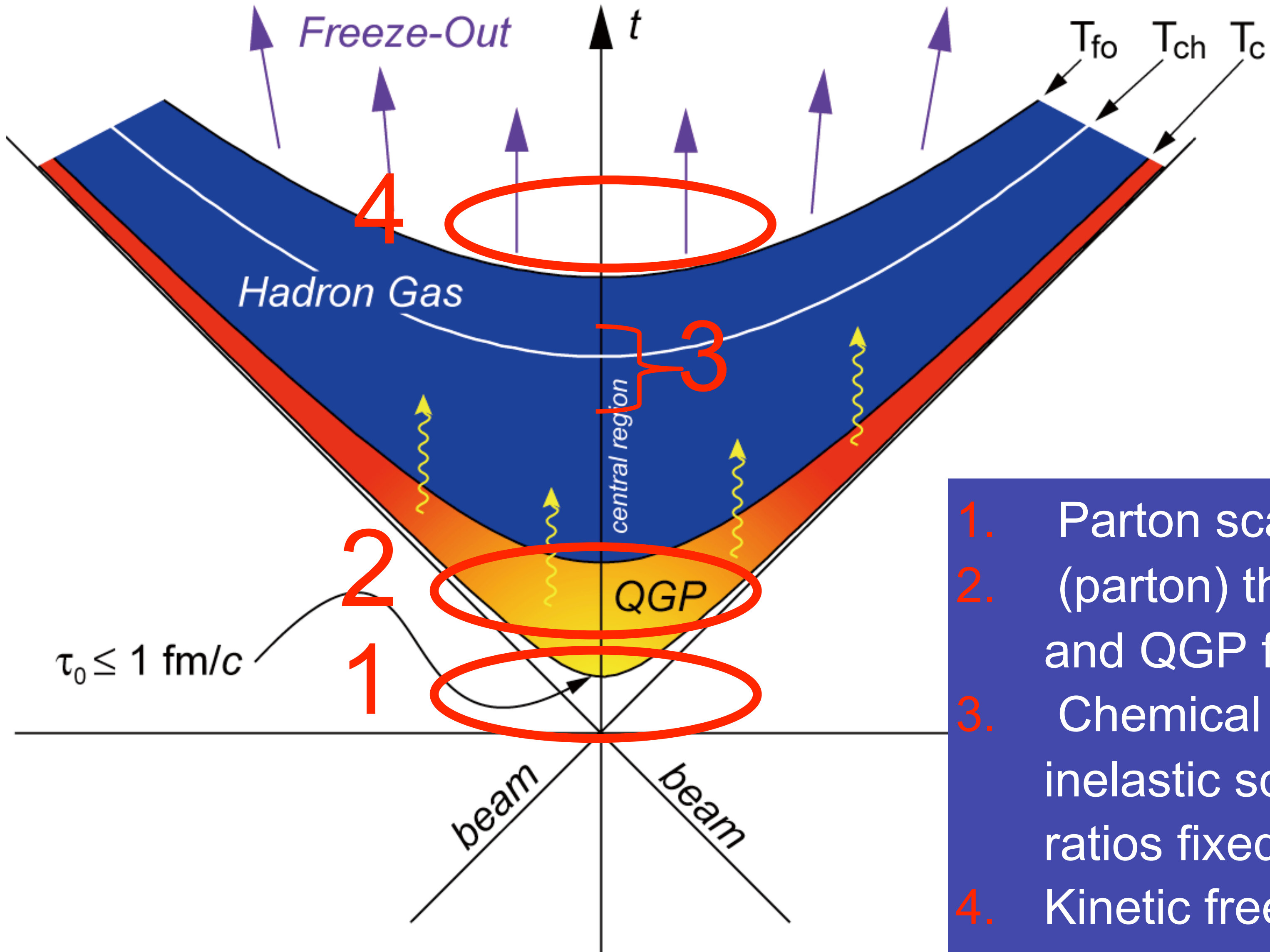
- IP-Glasma モデル (color charge fluctuation)
- 高次異方性の測定と比較、η/s がRHIC と LHC で異なる可能性
- RHIC で最小の η/s ？
- 温度度依存性はあるのか？

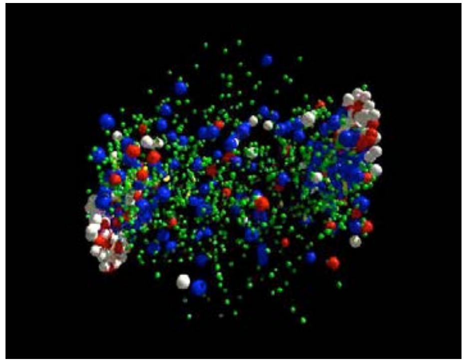


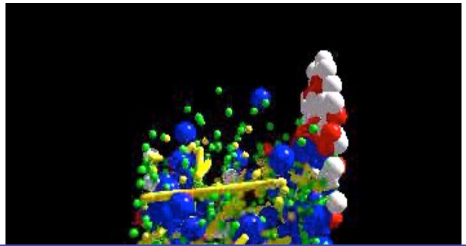
Björn Schenke (BNL) RHIC AGS Users' Meeting 2013, BNL
C. Gale, S. Jeon, B.Schenke,
P.Tribedy, R.Venugopalan, PRL110, 012302 (2013)

(3) Thermalization

Space-time evolution of Heavy Ion Collisions







1. Parton scattering
2. (parton) thermal equilibrium and QGP formation
3. Chemical freeze-out (ceases inelastic scattering, particle ratios fixed)
4. Kinetic freeze-out (ceases elastic scatting, particle momentum fixed)

Thermal yields

- The formula for the number density of all species:

$$n_i^0 = \frac{g_i}{2\pi^2} \int \frac{p^2 dp}{e^{\left(E - \mu_B B_i - \mu_s S_i - \mu_3 I^3\right)/T} \pm 1}$$

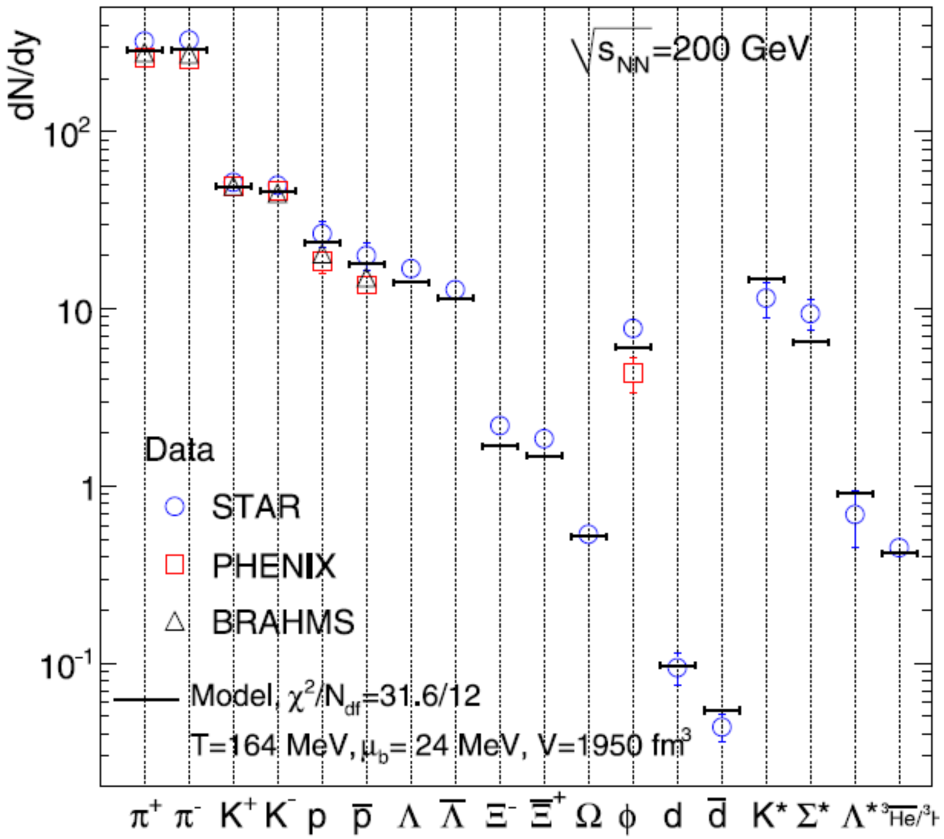
- g_i is the degeneracy
  $E^2=p^2+m^2$
  μ_B, μ_S, μ_3 are baryon, strangeness, and isospin chemical potentials respectively.

- Given the temperature and all m, one can determines the equilibrium number densities of all various species.

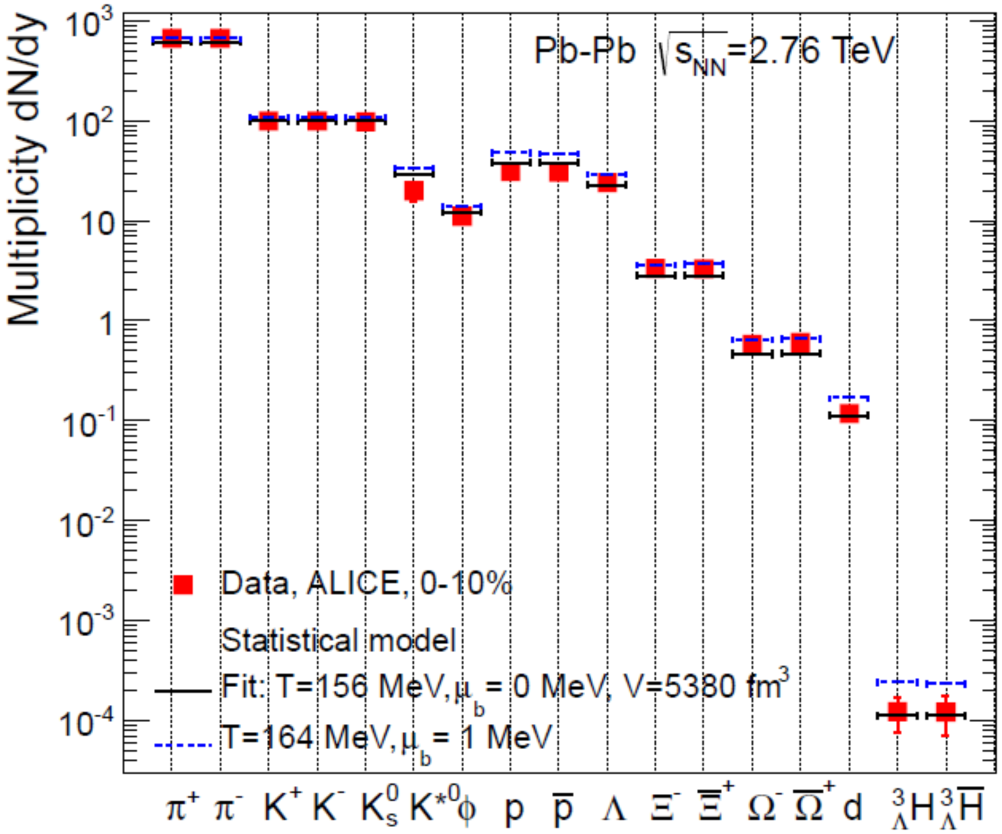
- The ratios of produced particle yields between various species can be fitted to determine T, μ.

Hadronization Temperature

RHIC



LHC



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

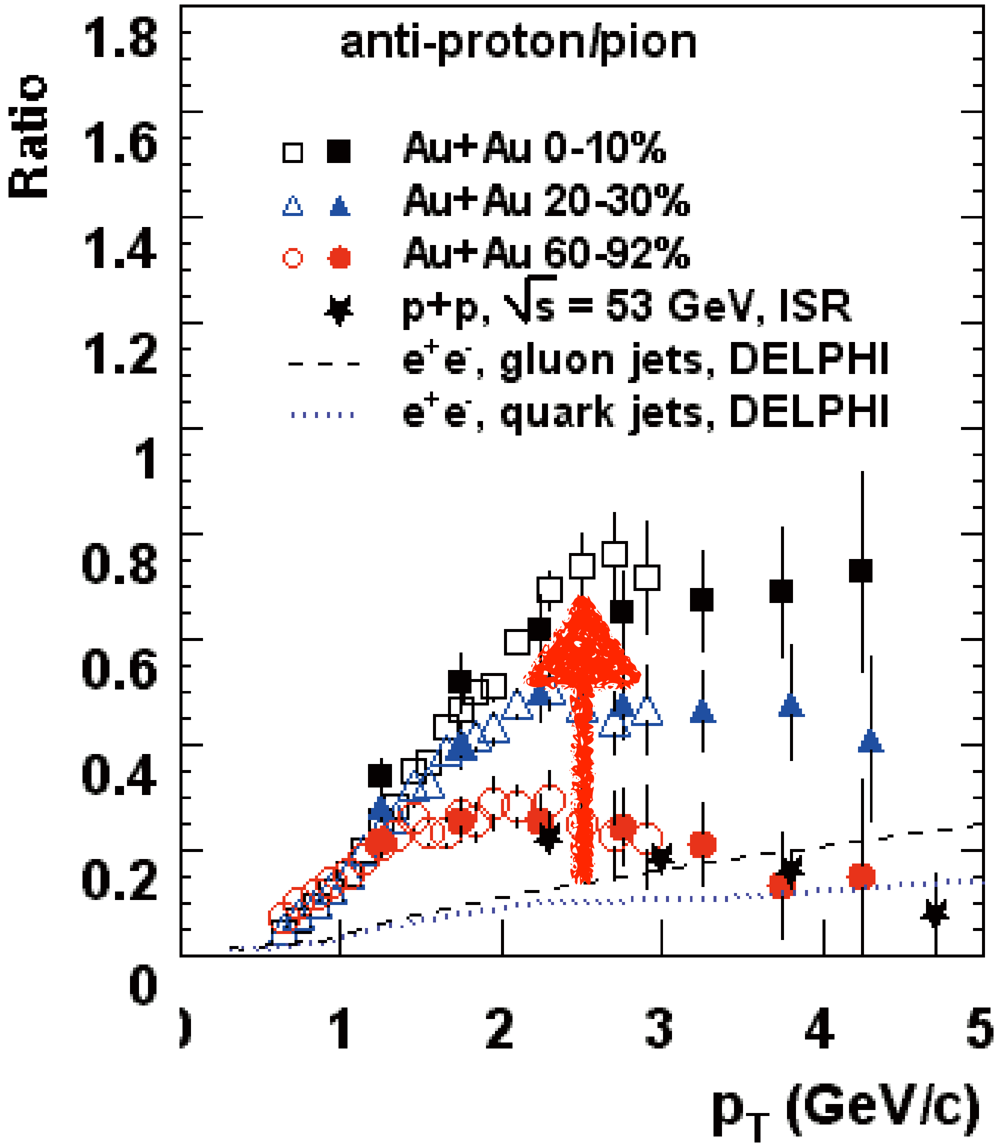
J. Stachel, A. Andronic, P. Braun-Munzinger, K. Redlich, J. Phys. Conf. Ser. 509 (2014) 012019

Hadronization Temperature ~ 160 MeV

(4) Quark recombination & regeneration

Baryon Anomaly (p/π ratio)

Phenix; P.R.L. 91(2003)172301

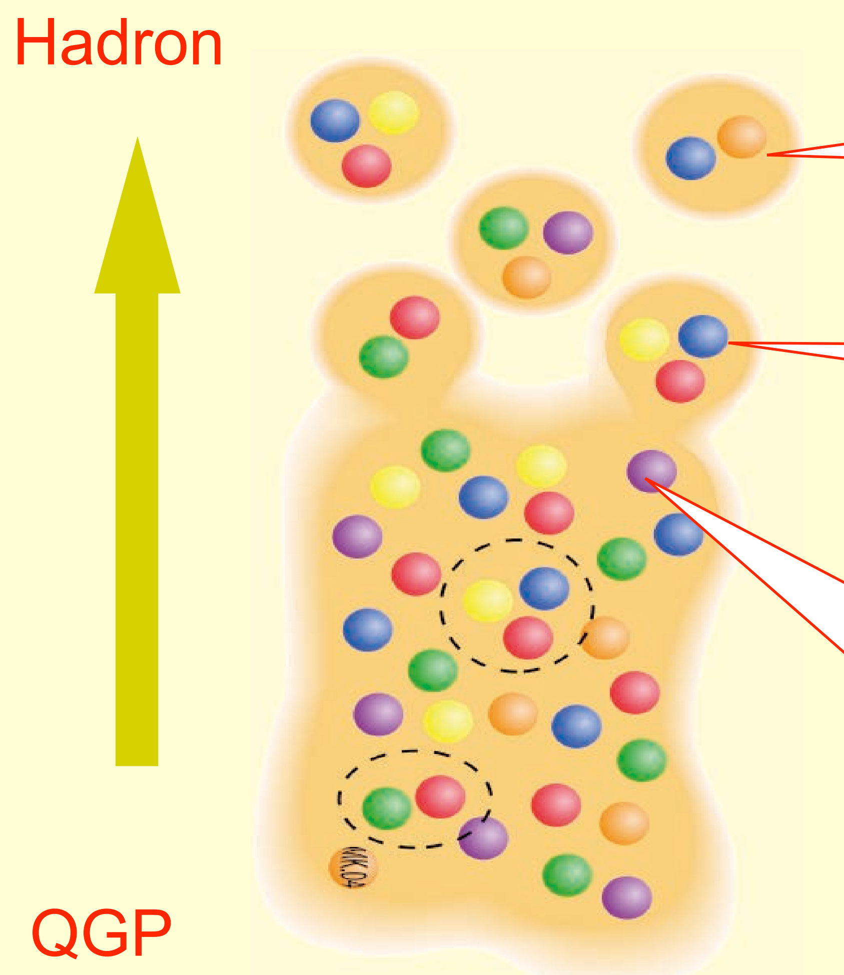


- ✓ In peripheral, p/π ratio at high pt similar to those in ee/pp suggesting fragmentaton process
- ✓ In central col., p/π ratio is very large, while.
  - Fragmentation process should show $n_p < n_\pi$ as seen in ee/pp.
- ✓ Suggesting other production mechanism.

↓

Quark Recombination Model
(Quark Coalescence Model)

Quark Coalescence explains Baryon Anomaly



Because of the steep distr. of *w(pt), RECO* wins at high pt even w. small *Cx*.

- ✓ **Quarks, anti-quarks combine to form mesons and baryons from universal quark distribution, w(pt).**

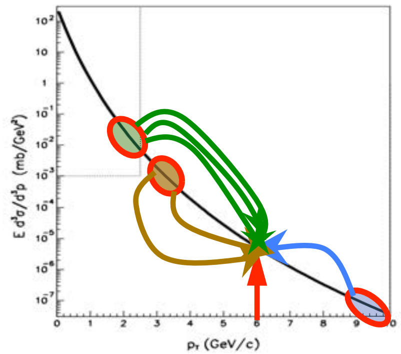
Mom. distr. of meson (2q);

$$W_{M}(p_t) \approx C_{M} \cdot w^2(p_t/2)$$

Mom. distr. of baryon (3q);

$$W_{B}(p_t) \approx C_{B} \cdot w^3(p_t/3)$$

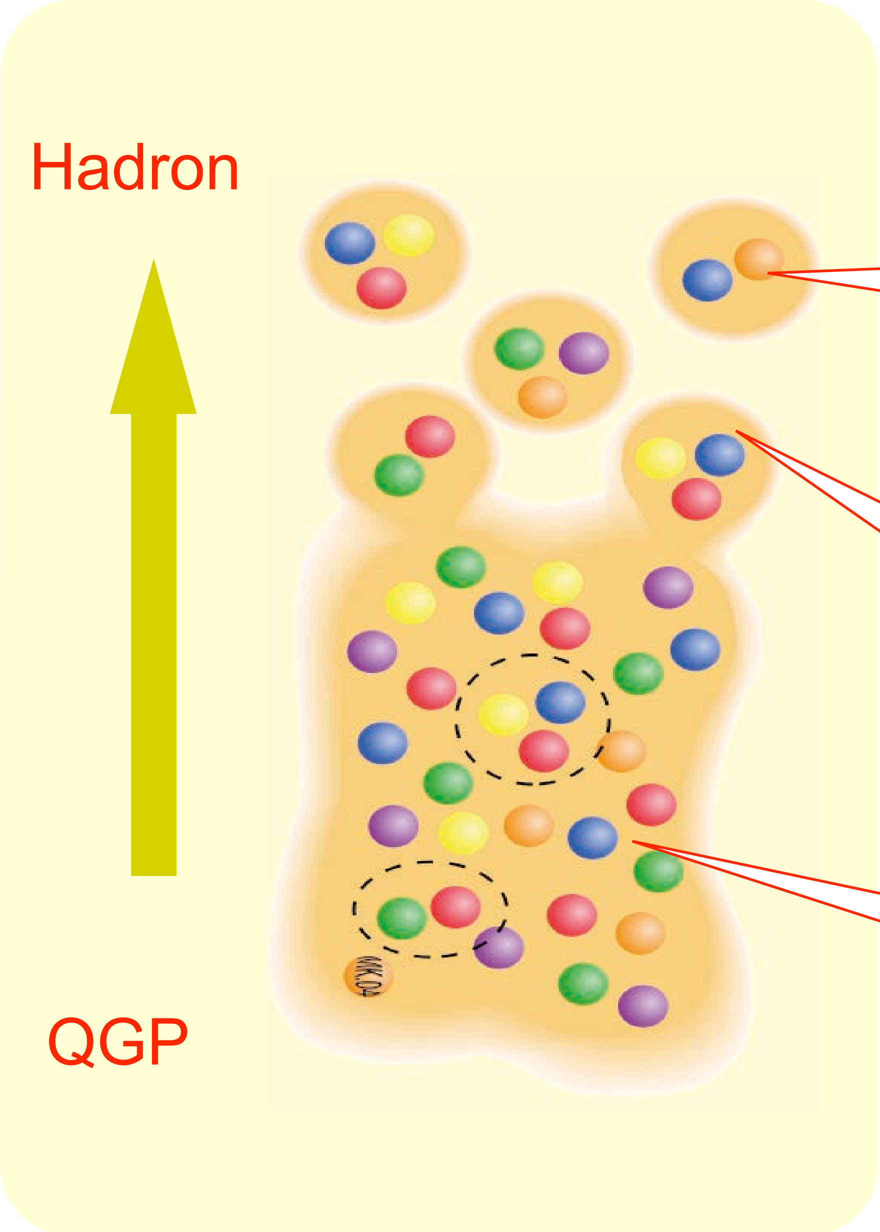
w(pt);
Universal mom. distr. of quarks
{*steep in pt*}



Characteristic scaling features expected.

➔Quark Number Scaling (QNS)

Quark Coalescence also explains v_2 behavior



✓ **Universal azimuthal distribution of quarks**

Azimutal distr. of meson (2q);

$$\frac{dN_M}{d\phi} \propto w^2 = (1+2v_{2,q}\cos 2\phi)^2$$

$$\approx (1+4v_{2,q}\cos 2\phi)$$

Azimuthal distr. of baryon (3q);

$$\frac{dN_B}{d\phi} \propto w^3 = (1+2v_{2,q}\cos 2\phi)^3$$

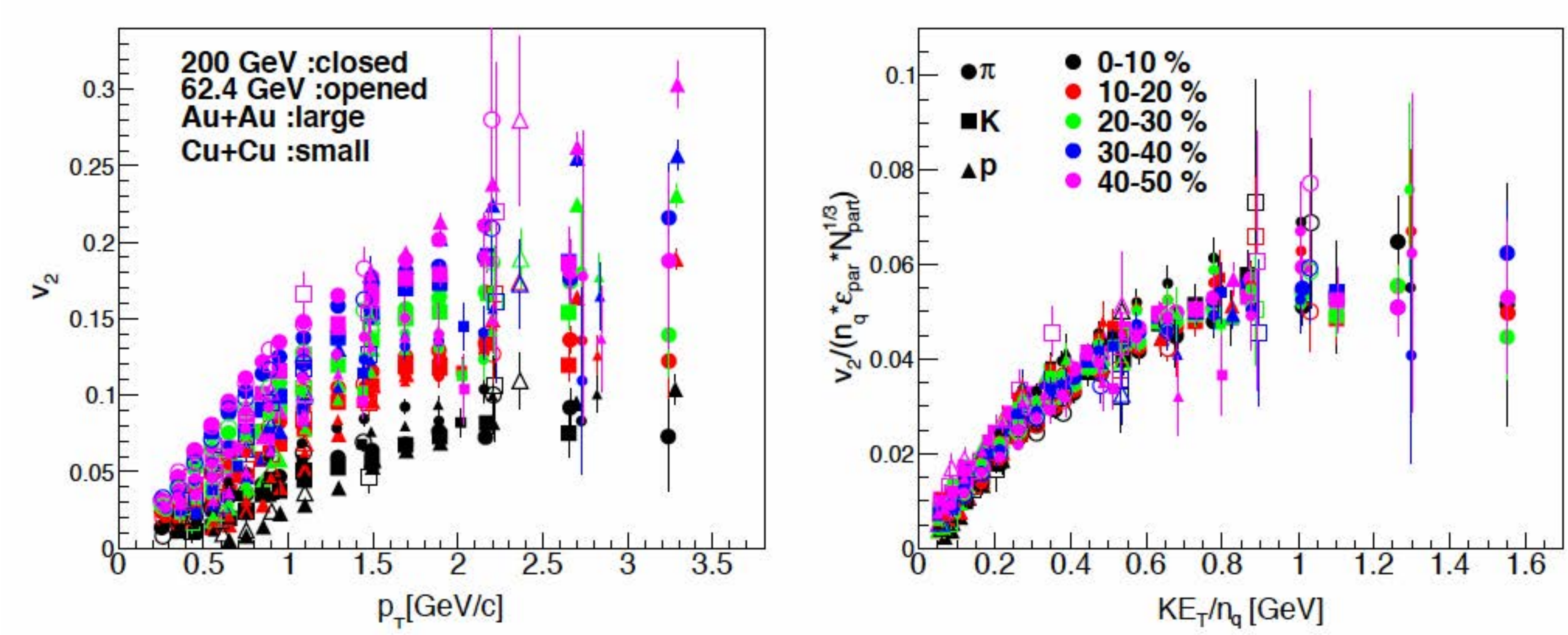
$$\approx (1+6v_{2,q}\cos 2\phi)$$

Azimuthal distr of quark: w

$$w \propto (1+2v_{2,q}\cos 2\phi)$$

→ Quark Number Scaling in v_2 !!

v_2: quark number scaling



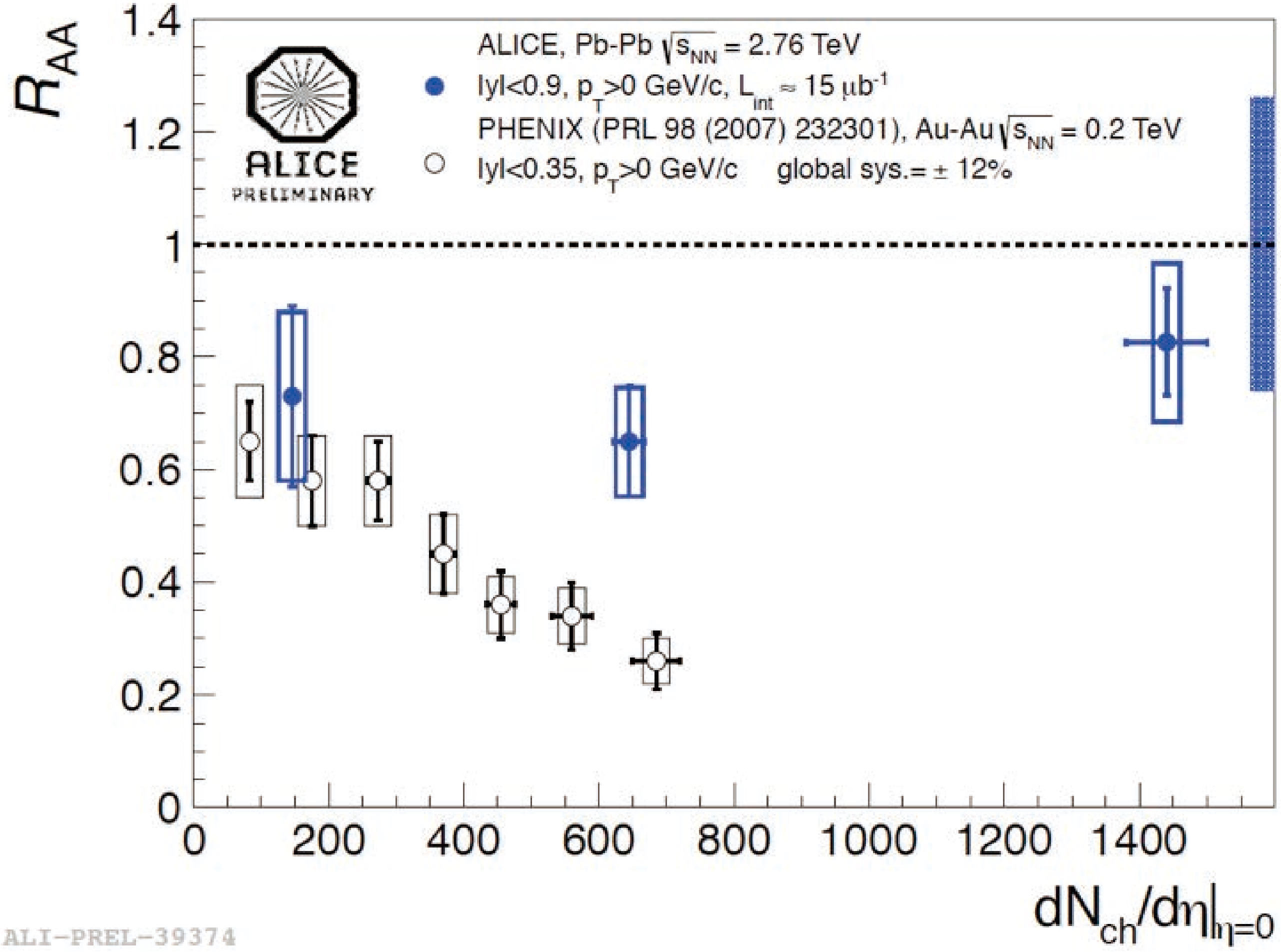
arXiv:1412.1043v1 (PHENX)

✓ Quark number (n_q) scaling

→ **Indication that anisotropy developed at parton level, not hadronic level.**

J/ψ (color screening vs. regeneration)

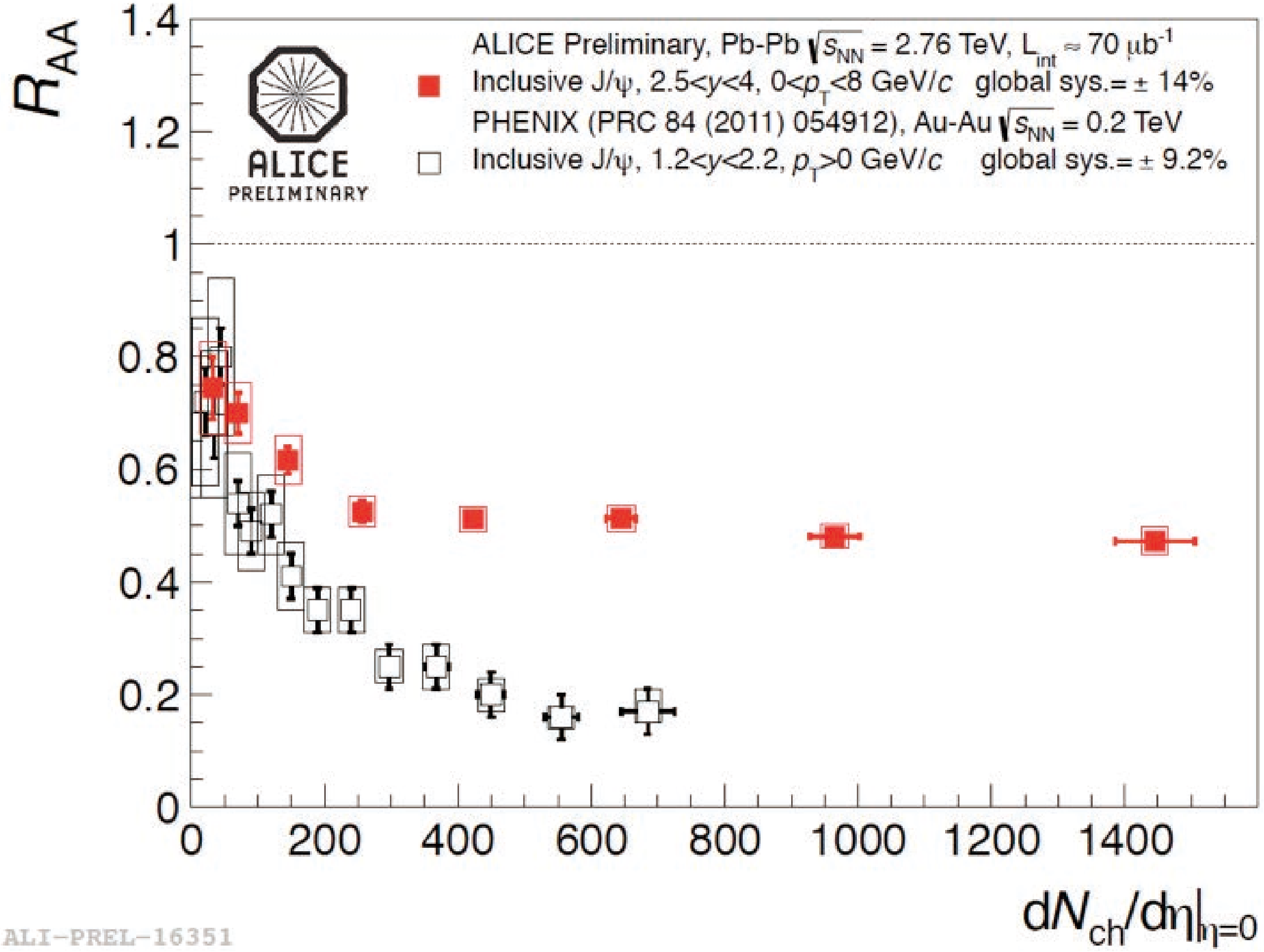
mid-rapidity R_{AA} for J/ψ



- J/ψ measured at mid-rapidity |y|< 0.9, by e^+e^- at LHC.
- Compared to RHIC mid-rapidity data.
- Significant larger R_{AA} than those at RHIC.

J/ψ (color screening vs. regeneration)

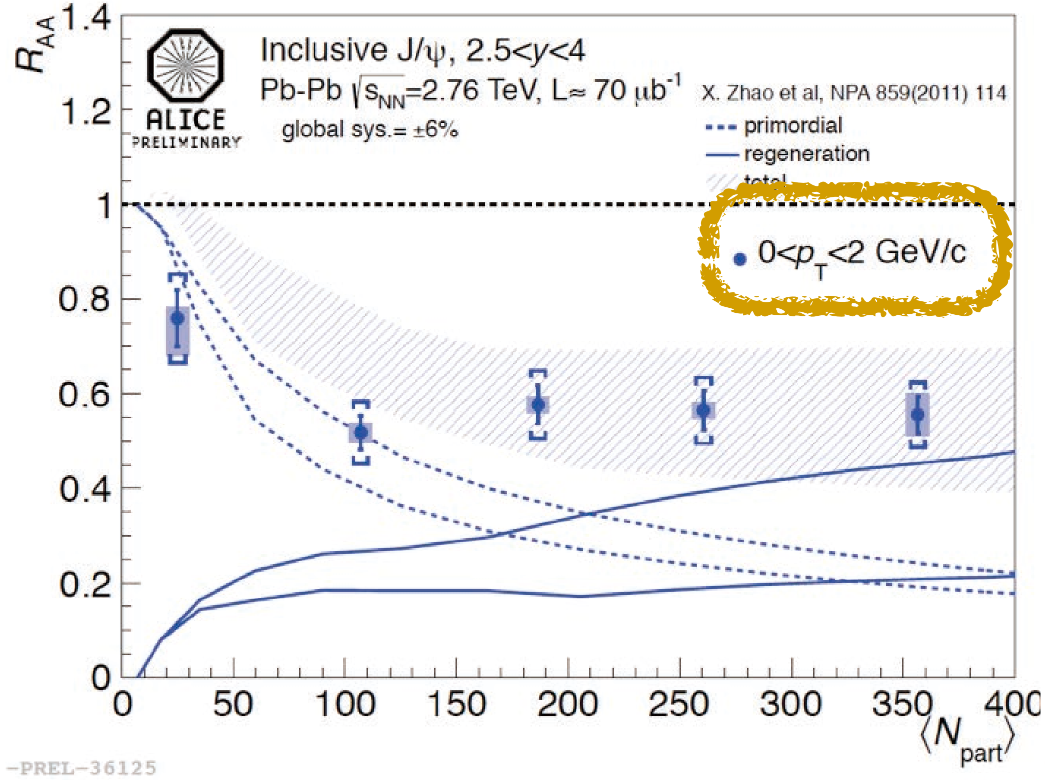
forward-rapidity R_{AA} for J/ψ



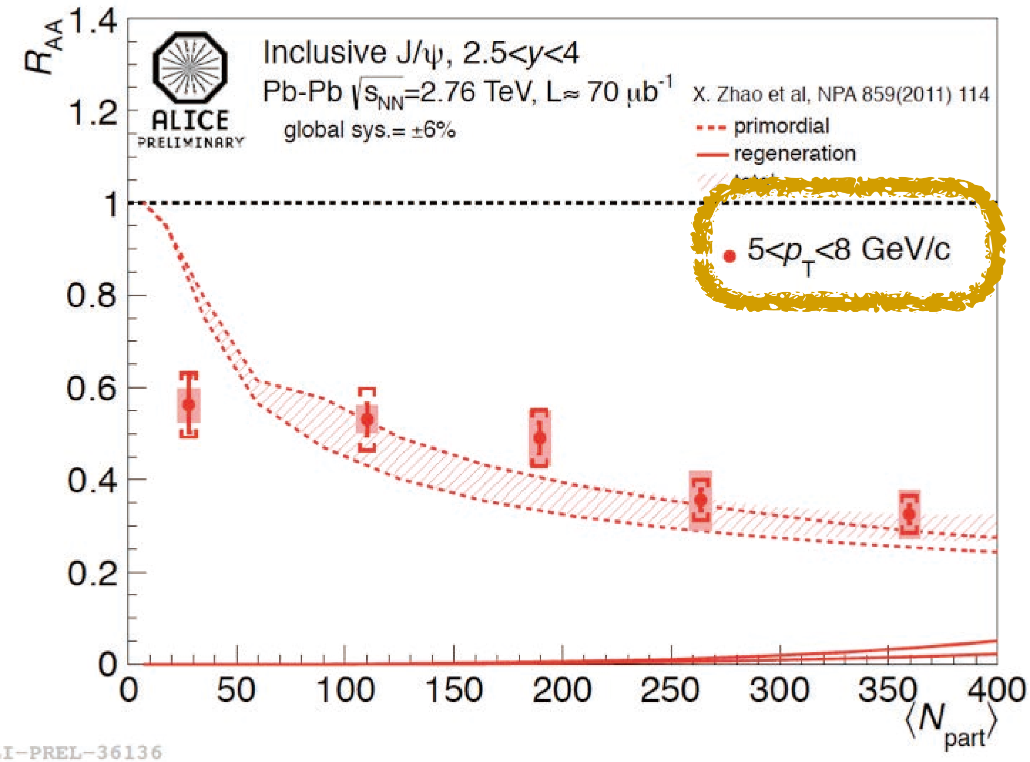
- J/ψ measured at forward-rapidity 2.5 < y < 4, by $\mu^+\mu^-$ at LHC.
- Compared to RHIC forward data.
- Significant larger R_{AA} than those at RHIC.
- Suppression is stronger than that at mid-rap.

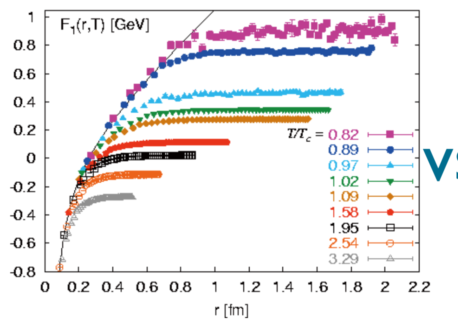
J/ψ (color screening vs. regeneration)

Low p_T: R_{AA} at forward y, $J/\psi \rightarrow \mu^+\mu^-$

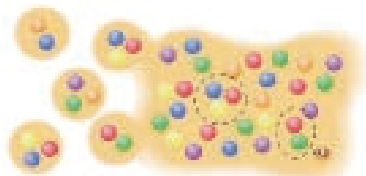


High p_T: R_{AA} at forward y, $J/\psi \rightarrow \mu^+\mu^-$





vs.



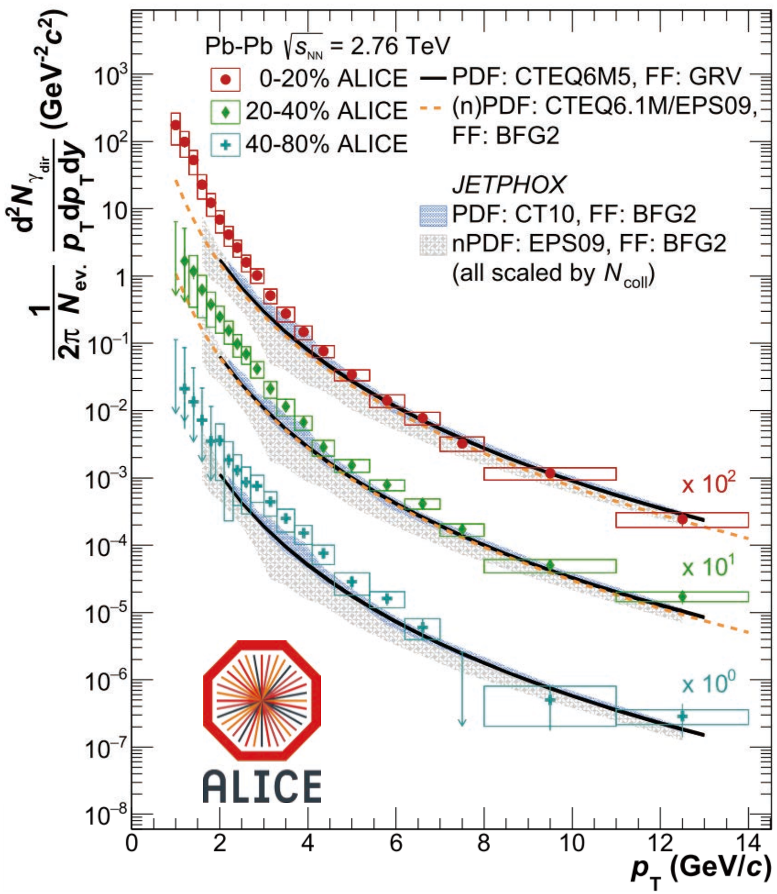
- J/ψ R_{AA} is enhanced at low p_T.
- Compatible with models including regeneration.

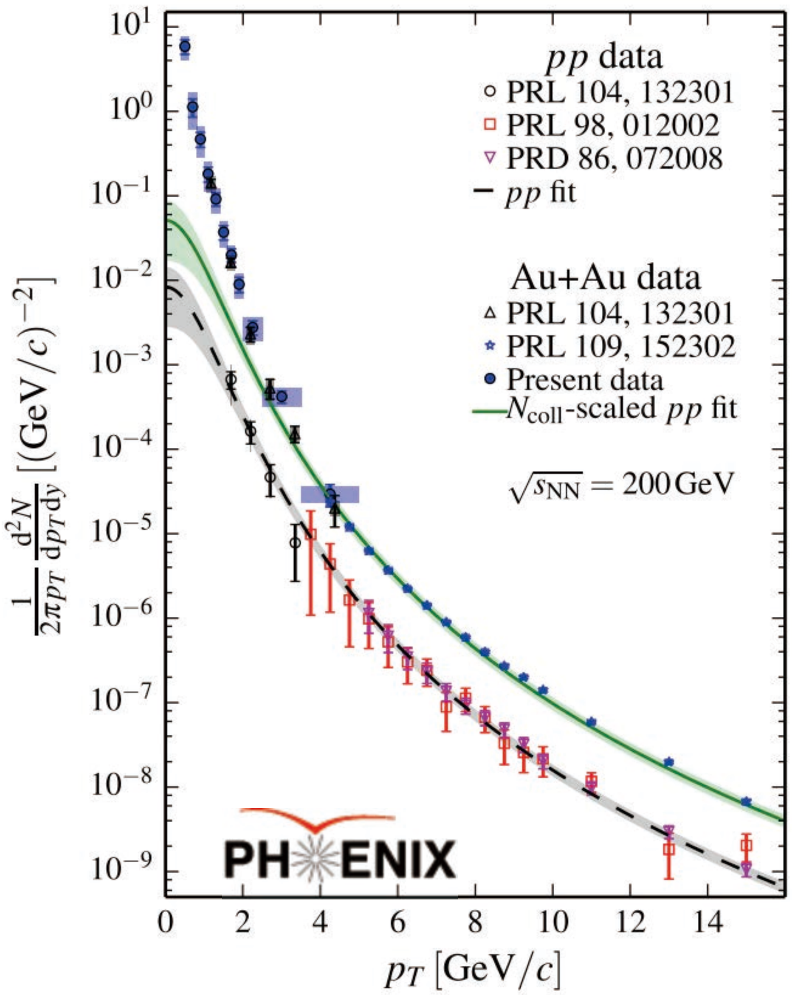
(4) High temperature matter

Thermal photons

arxiv:1509.07324

PHENIX: Phys. Rev. C 91 064904 (2015)





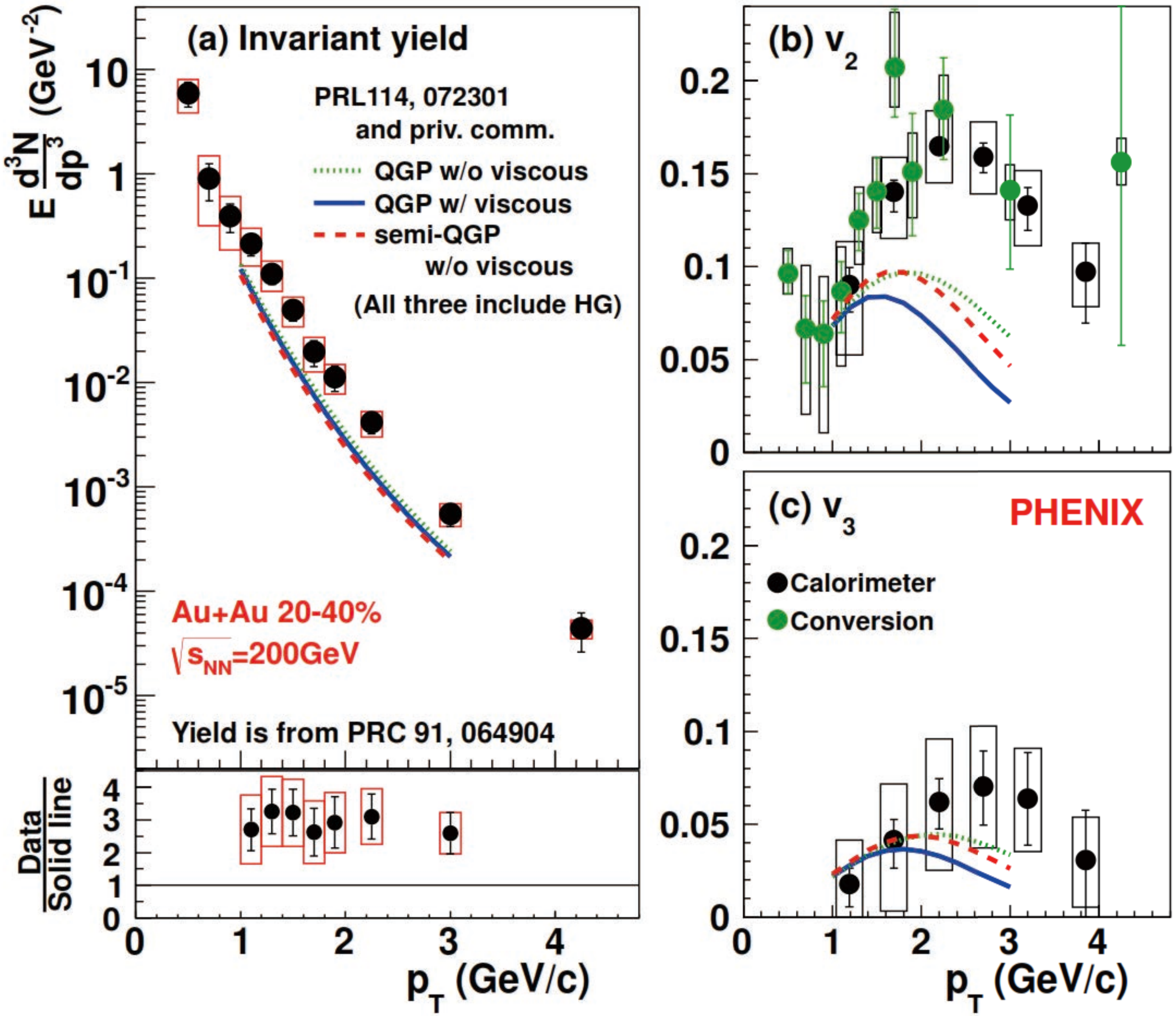
Excess from pQCD component is visible

- –PHENIX: Tslope~ 240±~20MeV independent of centrality
- –ALICE: Tslope~ 304±11$stat$±40$syst$MeV(0–20%)
- –PHENIX: dN/dy $\propto Npart^{\alpha}$ (α= 1.38 ±0.03stat±0.07syst)
- –Similar to dielectron excess (α=1.44±0.1, STAR)
- ・~30% higher than RHIC

Direct photon puzzle

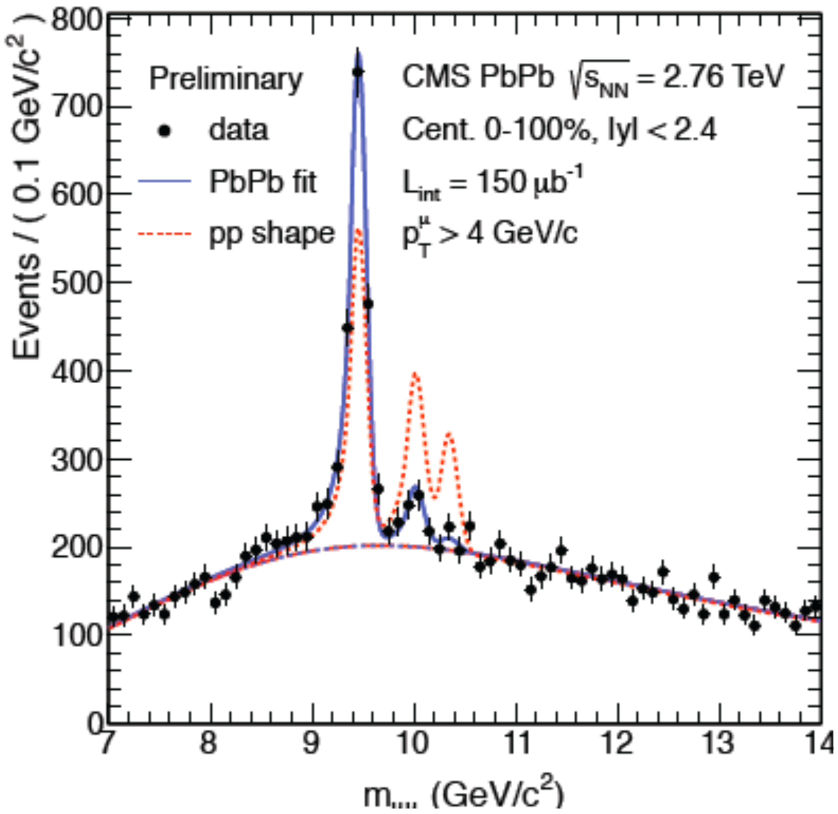
- **Large yield and vn challenge understanding of sources, emission rates and space-time evolution**

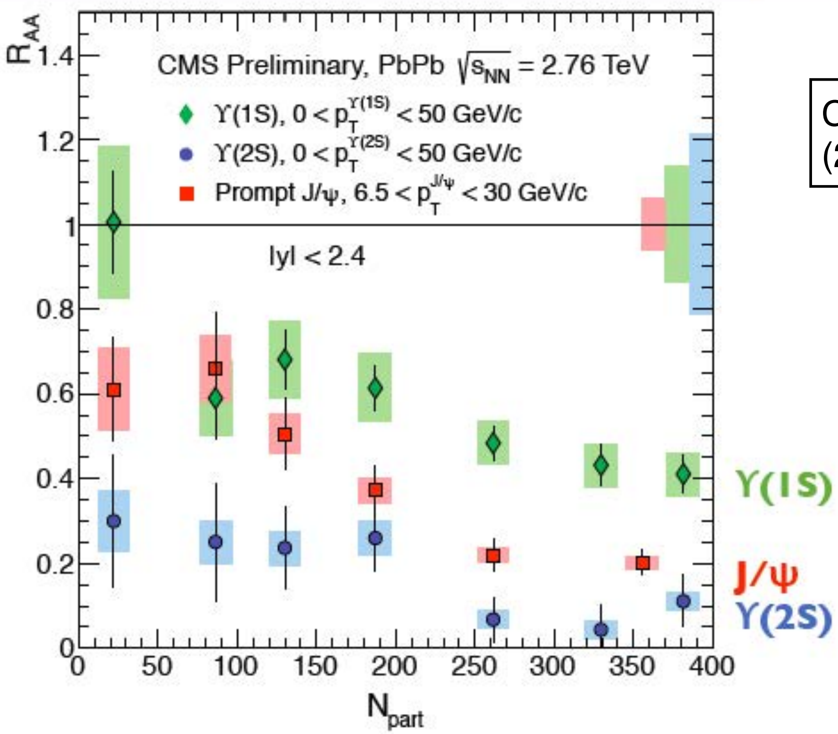
- **Late time emission (HG)?**



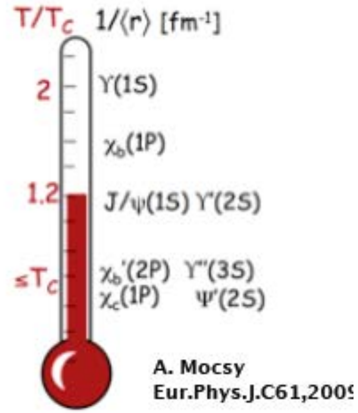
PHENIX: Phys. Rev. C 91 064904 (2015)

Dissociation temperature





CMS, PRL 109 (2012) 222301



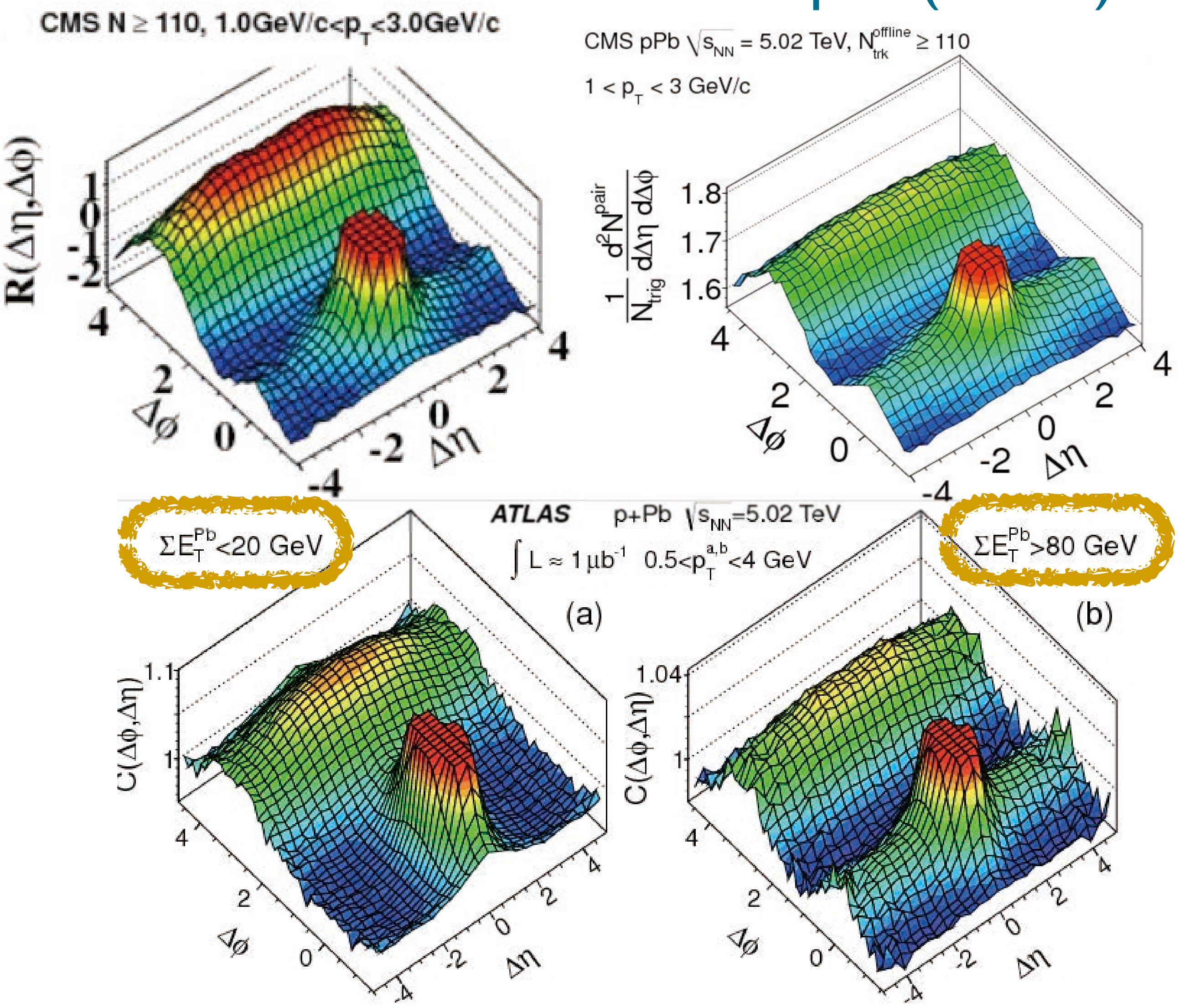
Melting excited ϒ states

- Suppression of ground state Y(1s), and excited states Y(2S) and Y(3S).
- Consistent with **the sequential melting scenario**, Y(3S) > Y (2S) > Y (1S).

(5) Collective behavior in small system (high multiplicity event)

Di-Hadron Correlations in p-p & p-Pb

p-p (N ≧110) | p-Pb (N ≧110)



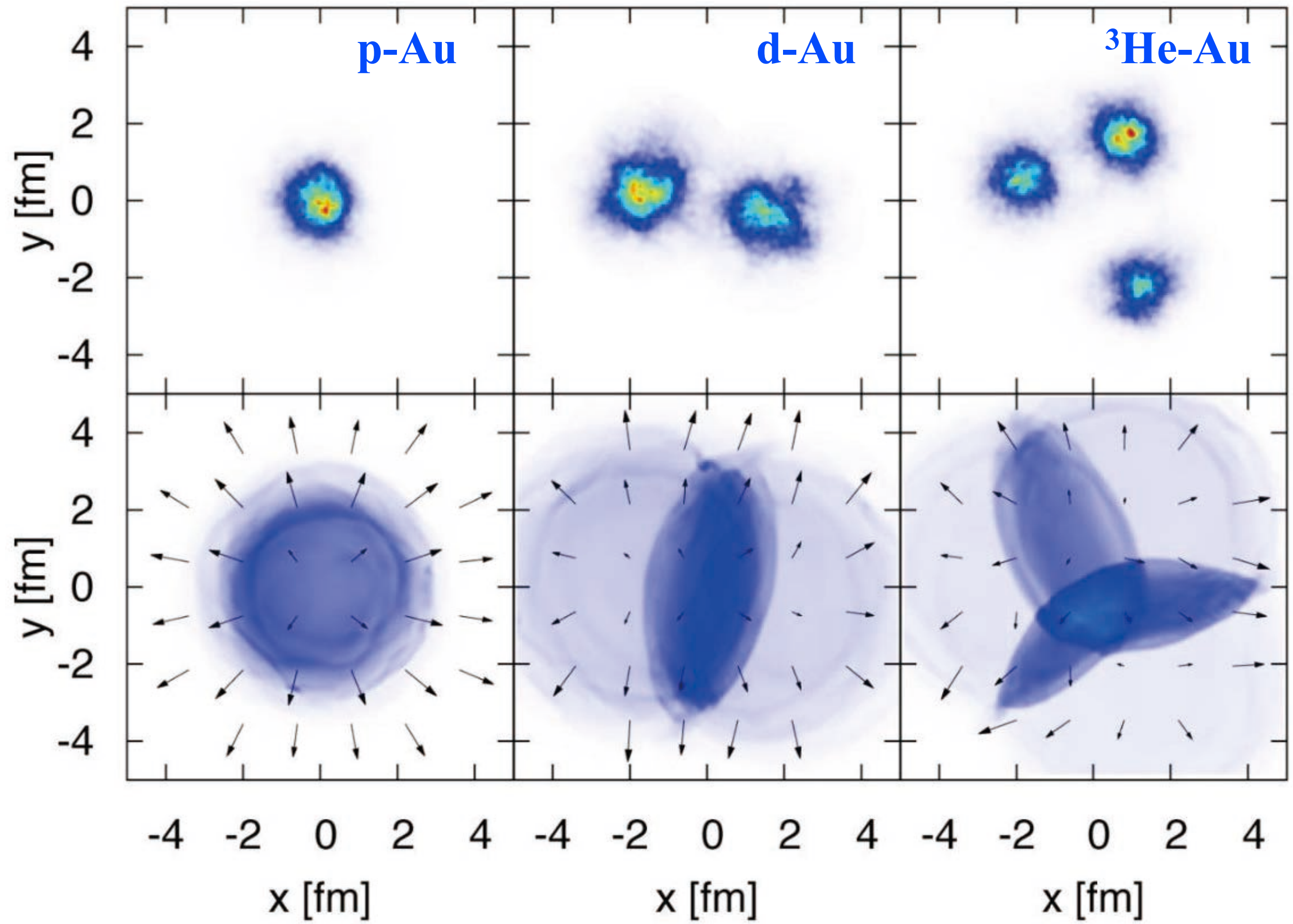
p-Pb ($\Sigma E_T{}^{Pb}$) < 20 GeV | p-Pb ($\Sigma E_T{}^{Pb}$) > 80 GeV

- First observation of **ridge structure in high multiplicity p-p** (CMS).
- Also confirmed in **p-Pb high multiplicity events.**
- Alway side ridge structure is observed in high multiplicity p-Pb.

CMS, JHEP 1009 (2010) 91
CMS, PLB 718 (2012) 795
ATLAS, PRL 110, 182302 (2013)

small system @ RHIC

Phys. Rev. Lett. 113, 112301 (2014), figure courtesy of B. Schenke



Initial State Hot Spots
Glauber with nucleons

Hydrodynamics

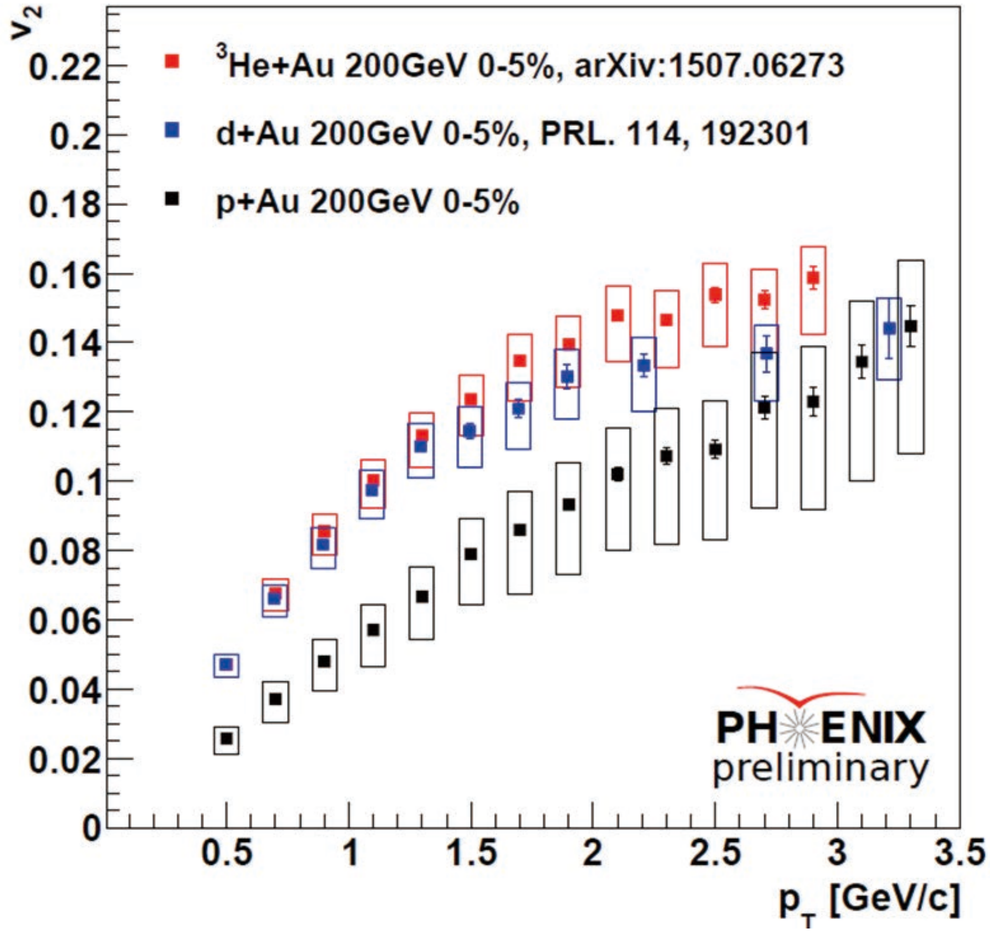
Collectivity in
Final State

Sensitivity to initial conditions
and early time evolution

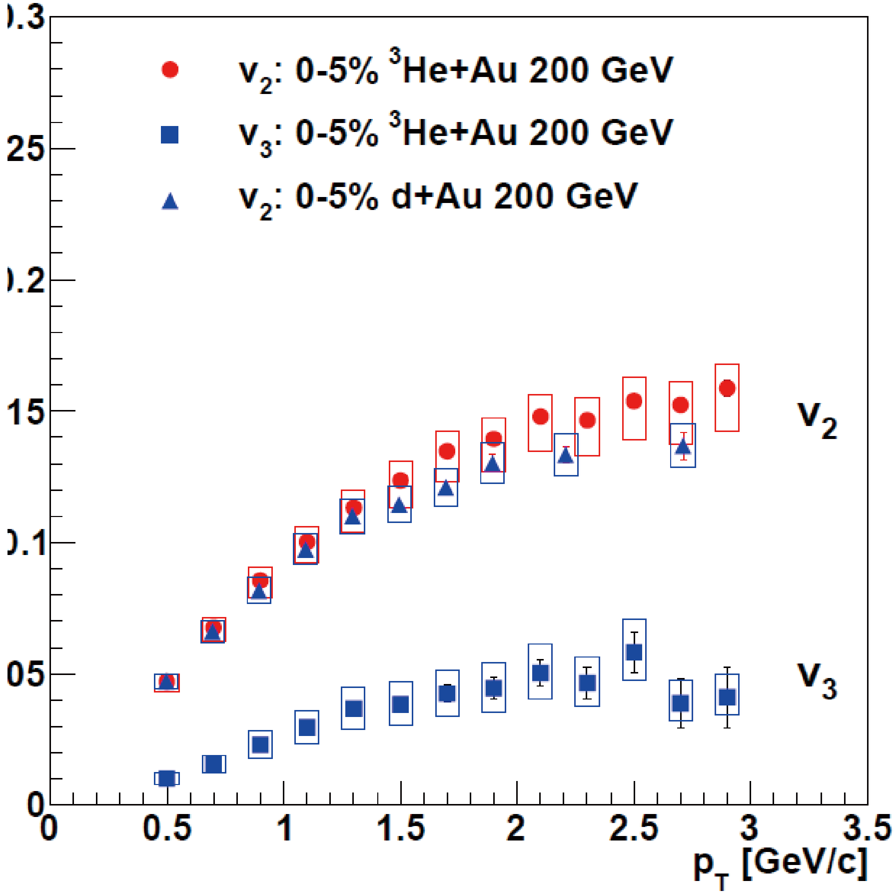
Flow in Small Systems at √sNN= 200 GeV

Top 5% in centrality

$v_2\ (^3HeAu) \geq v_2\ (dAu) > v_2\ (pAu)$

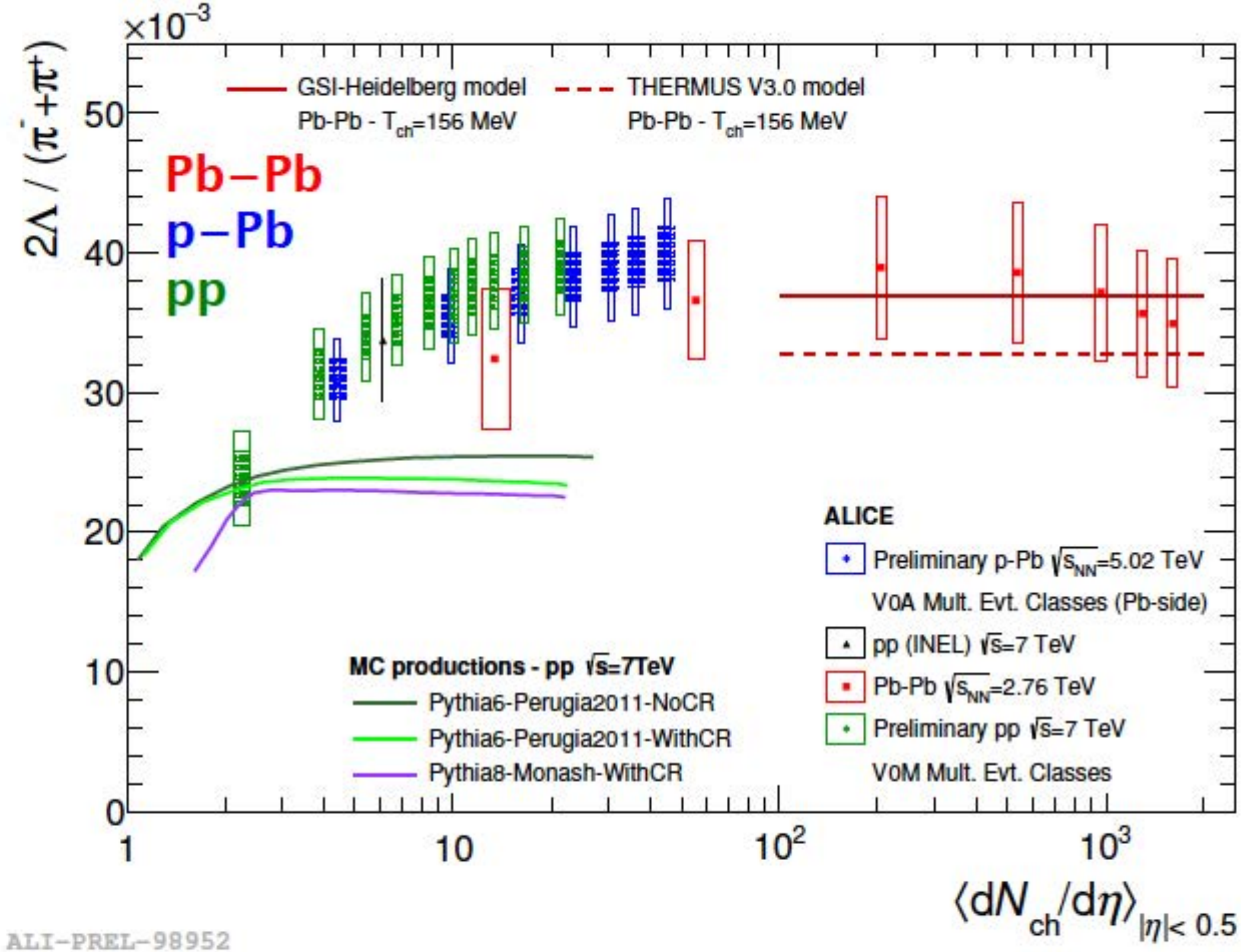


PHENIX ³HeAu: Phys. Rev. Lett. 115, 142301 (2015)
PHENIX dAu: Phys. Rev. Lett. 114, 0192301 (2015)



Collective motion: Large anisotropy v_2 in p+Au, d+Au & v_2, v_3 in ^{3}He+Au

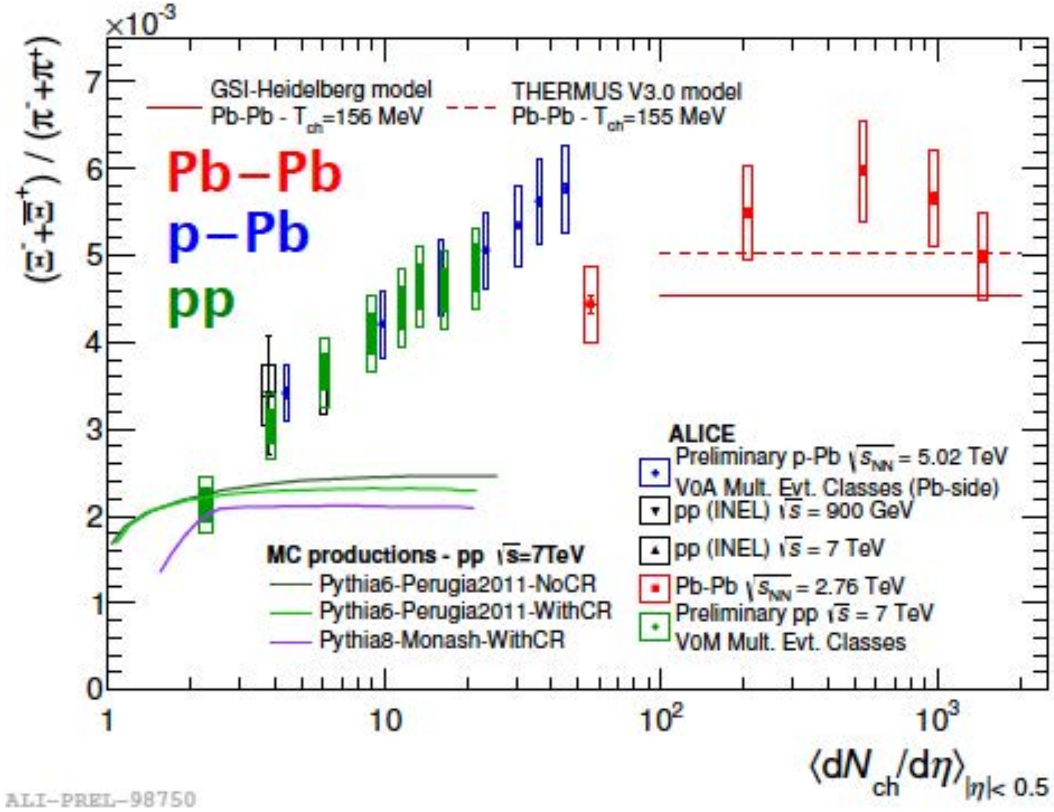
Λ/π vs. $dN_{ch}/d\eta$

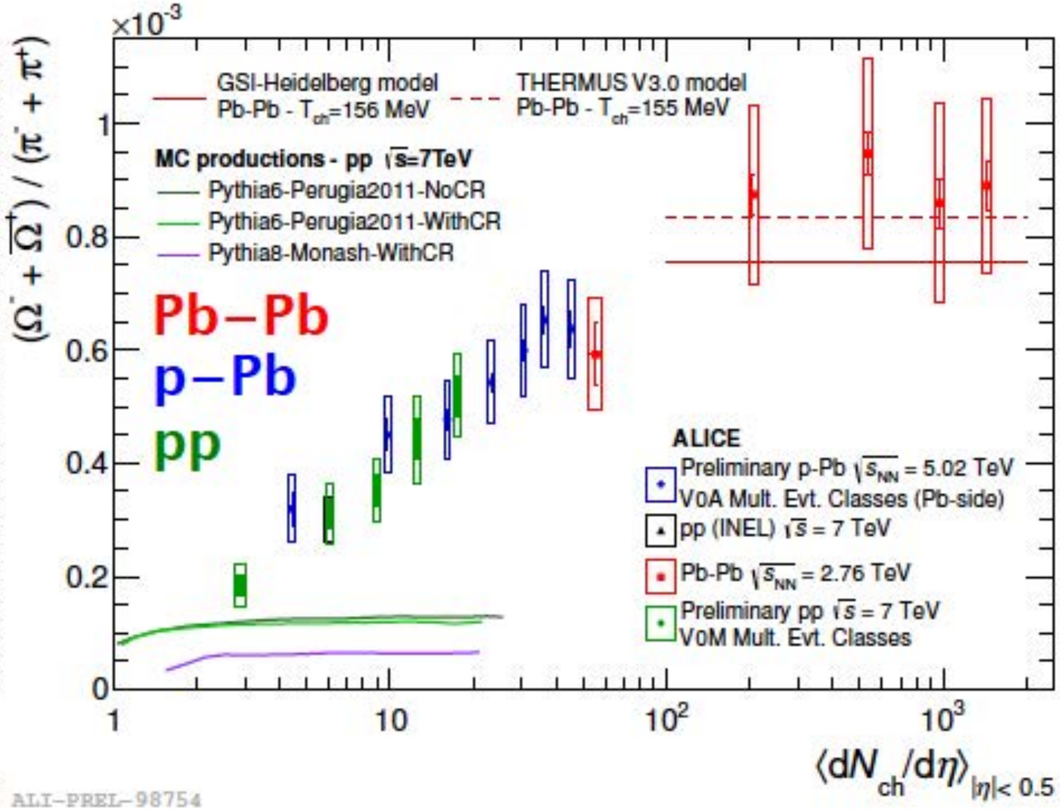


- Λ/π ratio reaches Grand Canonical limit in Pb-Pb
- Similar multiplicity dependence in pp and p-Pb
- Neither PYTHIA6 nor 8 reproduce data in any of the tunes tested

Ξ/π , Ω/π vs. $dN_{ch}/d\eta$

ALICE

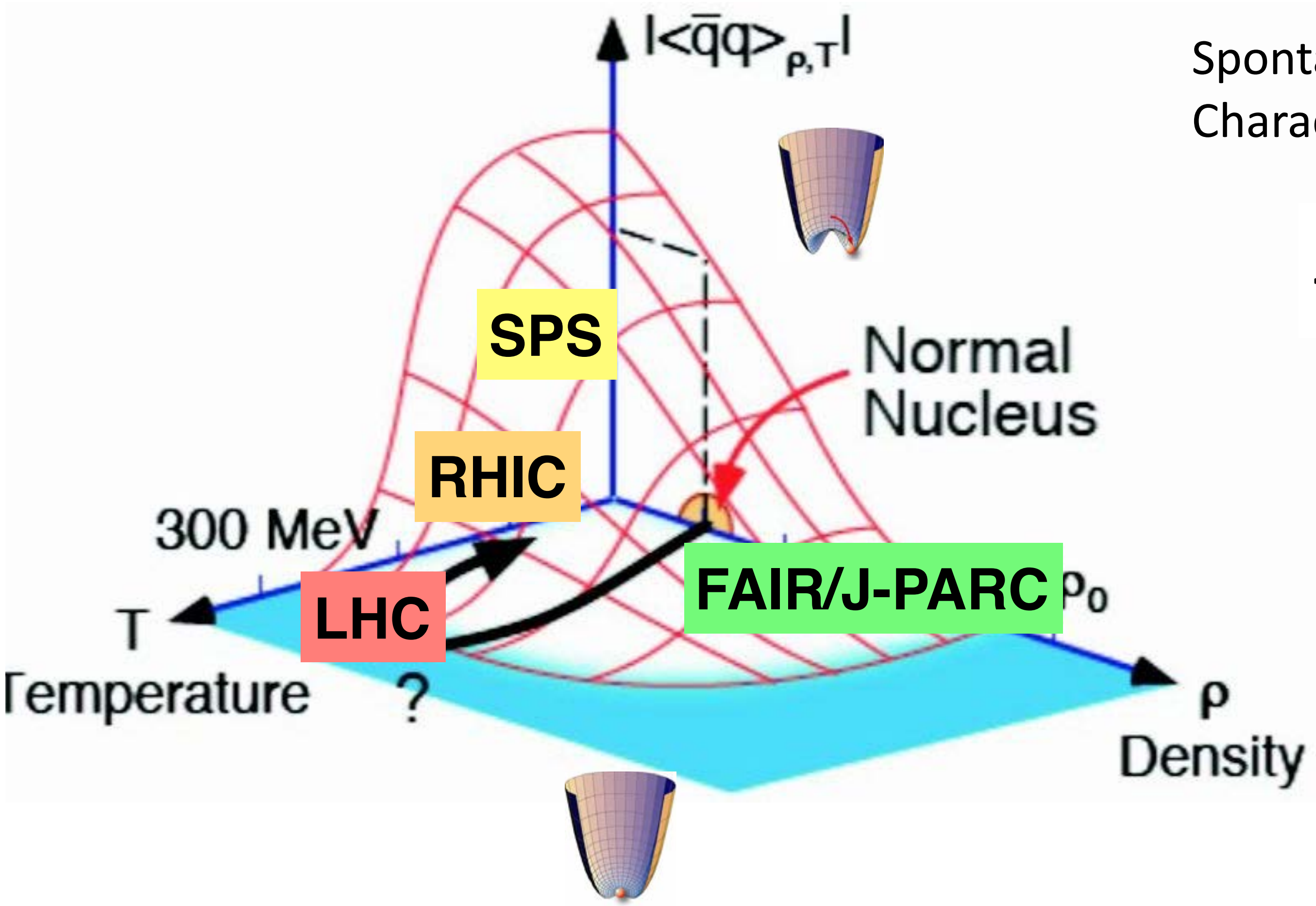




- Same for Ξ/π and Ω/π

(6) Search for restoration of chiral symmetry breaking

Spontaneous Chiral Symmetry Braking



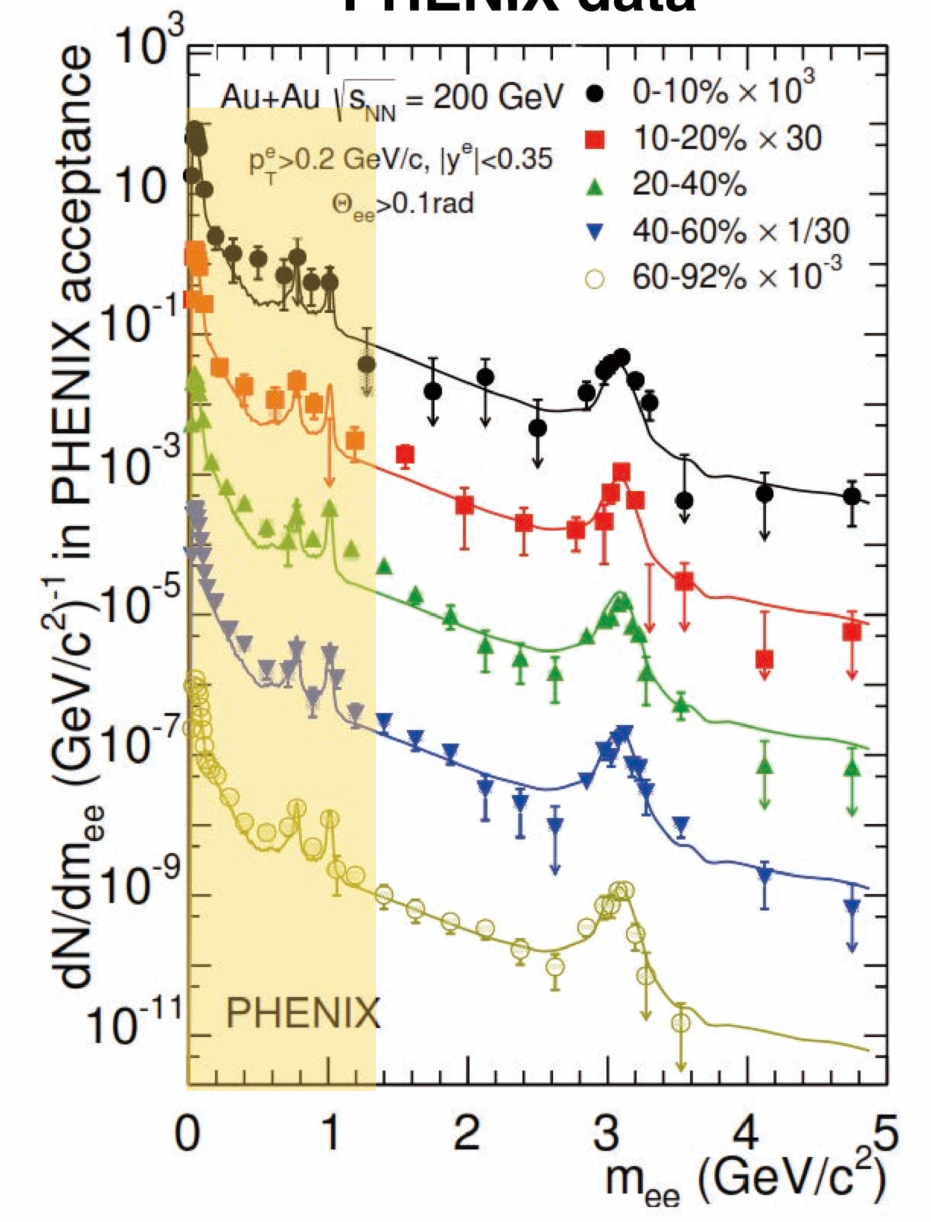
Spontaneous Chiral Symmetry Breaking:
Characterized by Order Parameter $\langle\bar{q}q\rangle$

$$<\bar{q}q> \approx 250MeV^3$$

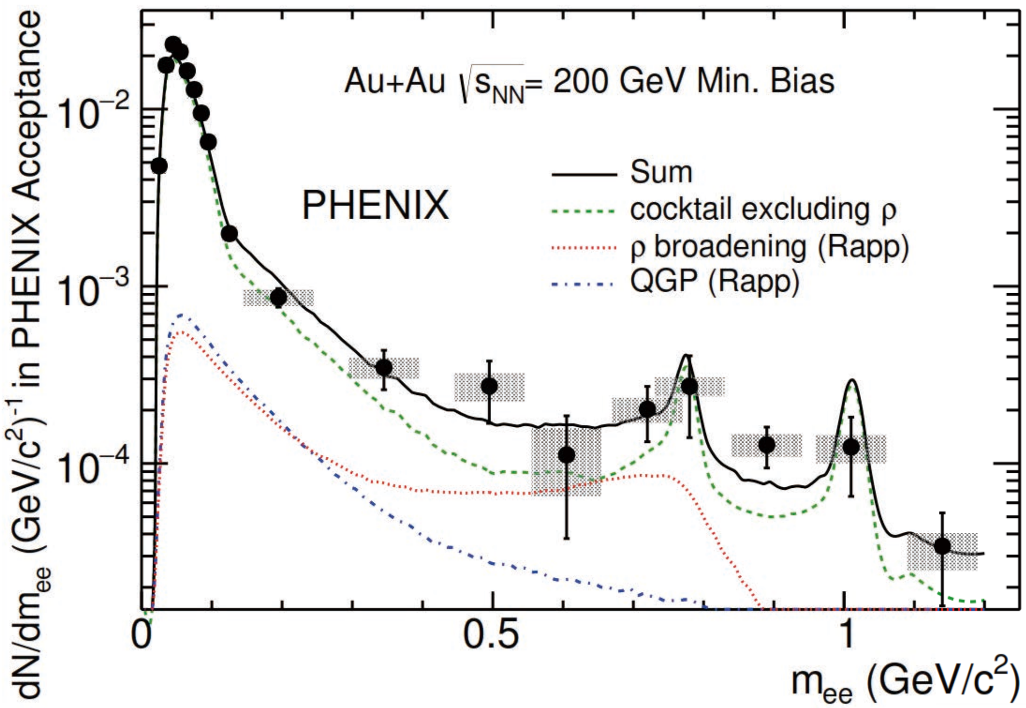
$$<\bar{q}q> \approx 0$$ **High T** **High ρ**

Excess on di-electron mass spectrum

PHENIX data



PHENIX: arXiv01509.04667 (2015)

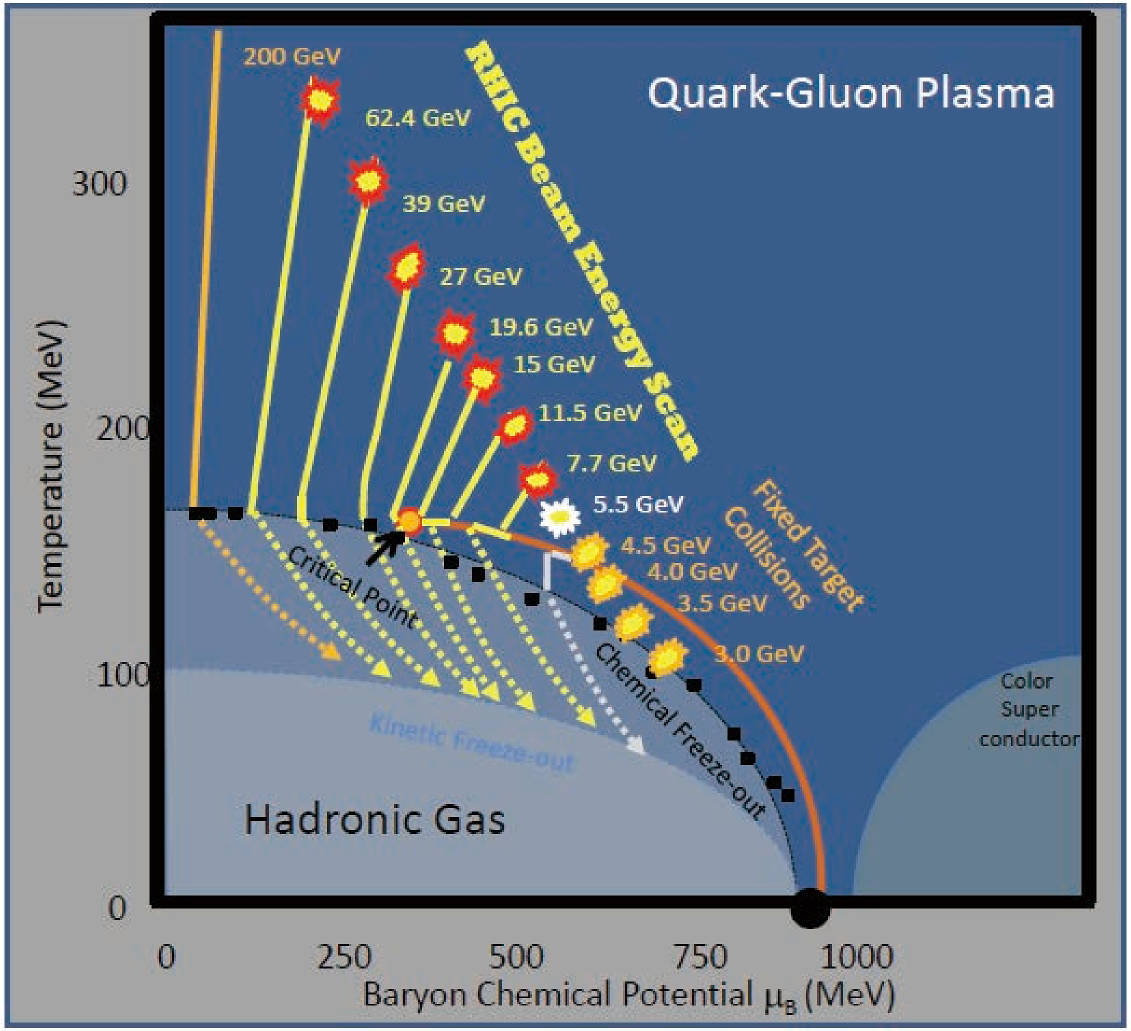


Moderate enhancement

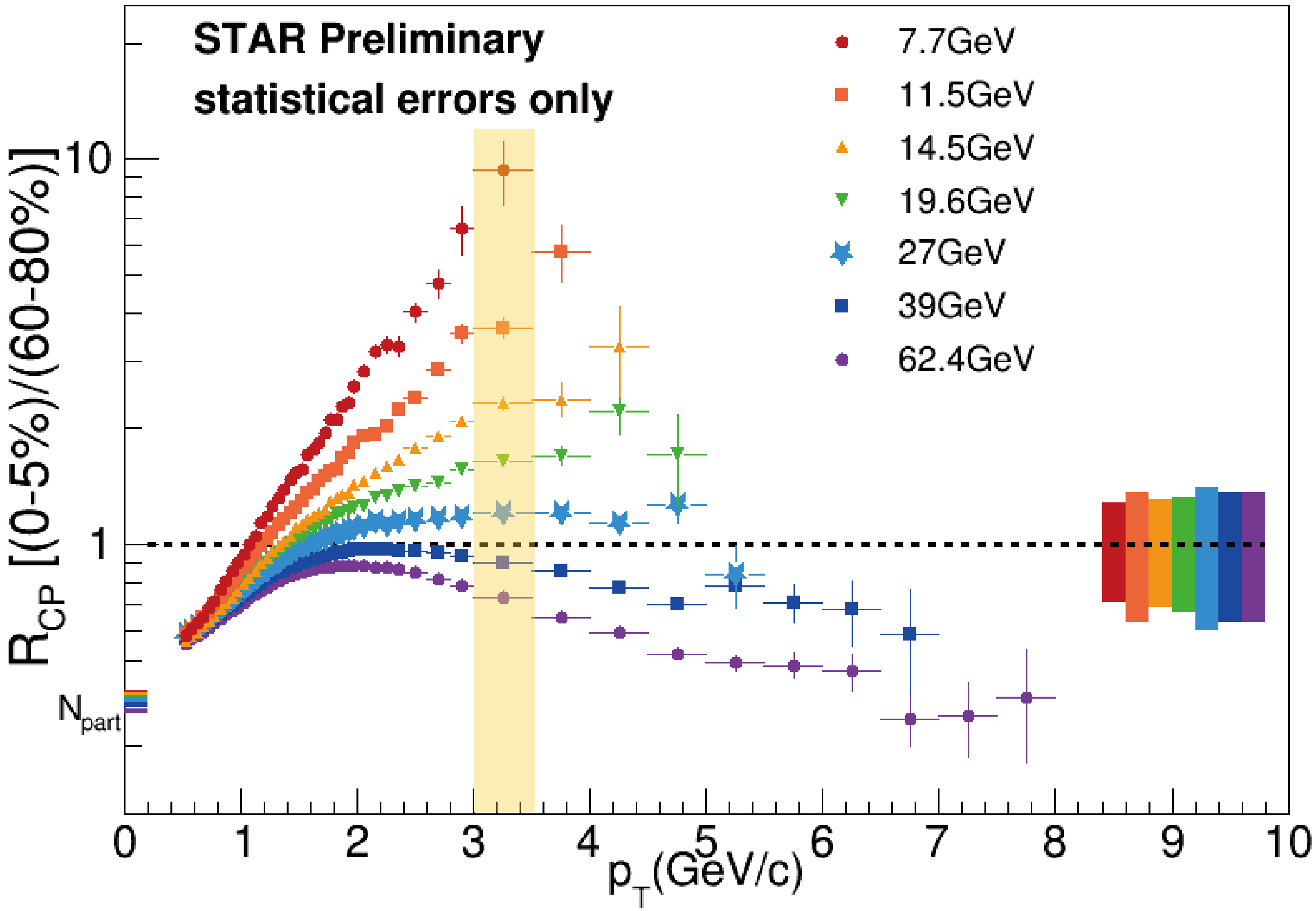
for 300 < m < 750 MeV factor
MB: 2.3 ± 0.4 ± 0.4 ± 0.2
central: 3.2 ± 1.0 ± 0.7 ± 0.2

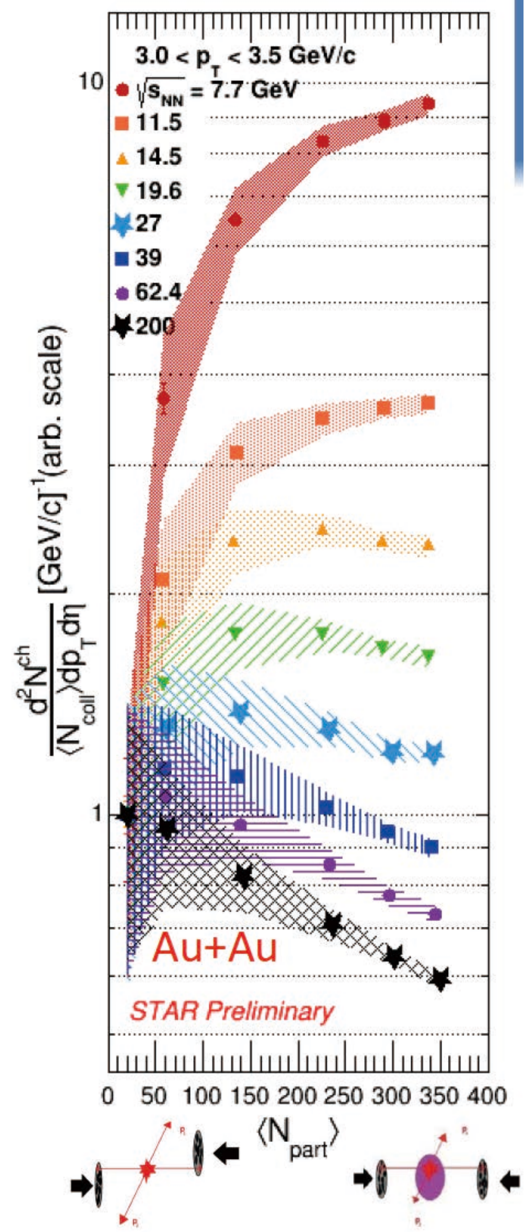
Consistent with STAR data.
Consistent with ρ broadening

(7) QCD phase structure



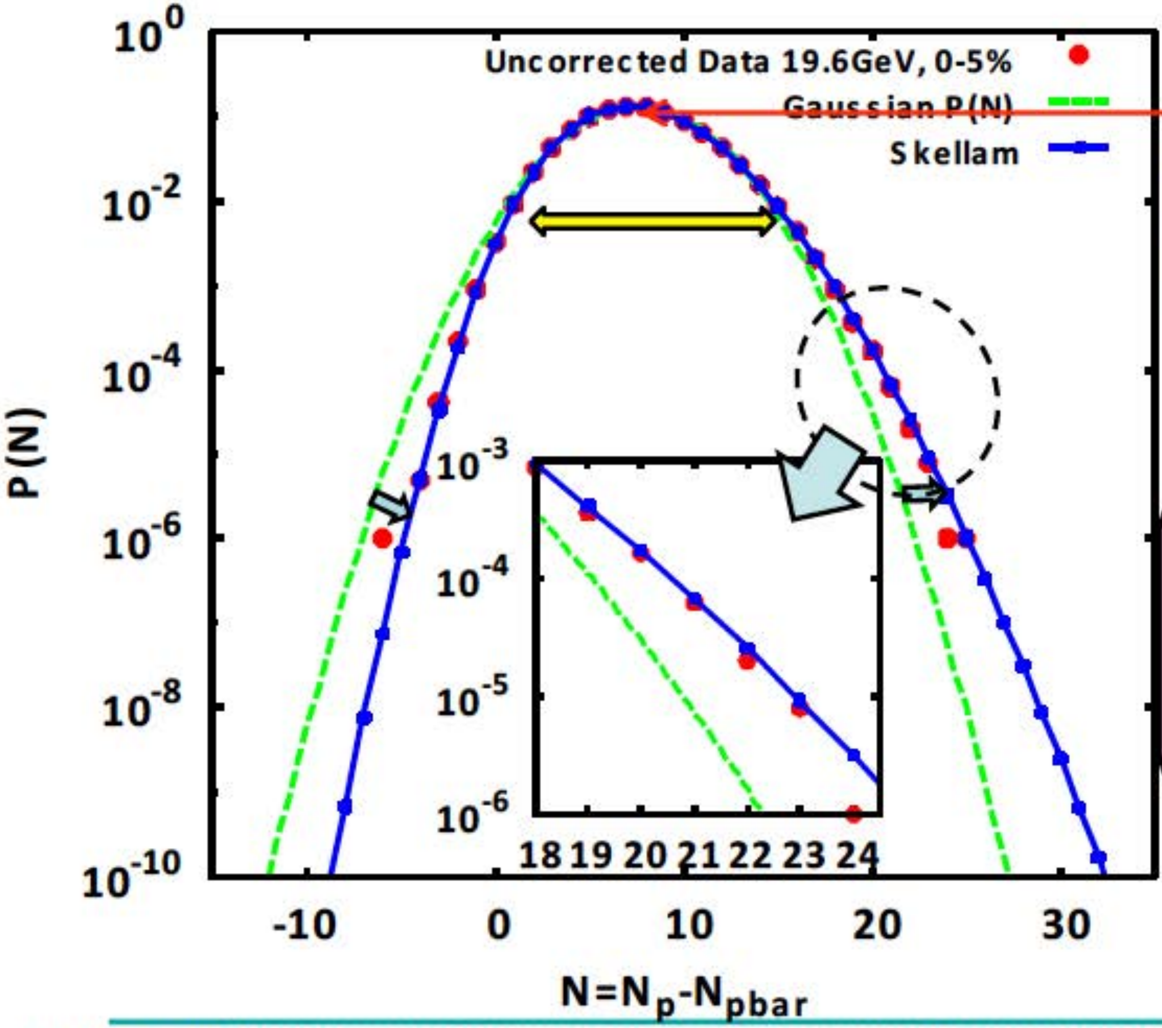
Search for the Onset of QGP Formation: Charged Hadrons R_{cp}





- **Smooth transition from a strong suppression at high energies to enhancement at lower beam energies.**
- Cronin effects play a bigger role at lower energies.
- Yields per binary collision show indicates a balance of enhancement and suppression effects at $\sqrt{s_{NN}} = 14.5$ GeV.

Characterizing Fluctuations



Cumulants

$M = \langle N \rangle$ (=7.61)

$\sigma^2 = \langle (\delta N)^2 \rangle$ (=9.16)

$S\sigma^3 = \langle (\delta N)^3 \rangle$ (=7.23)

$\kappa\sigma^4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$ (=7.36)

$\kappa\sigma^2 = 1$ Skellam

$= 0.8$ (Data)

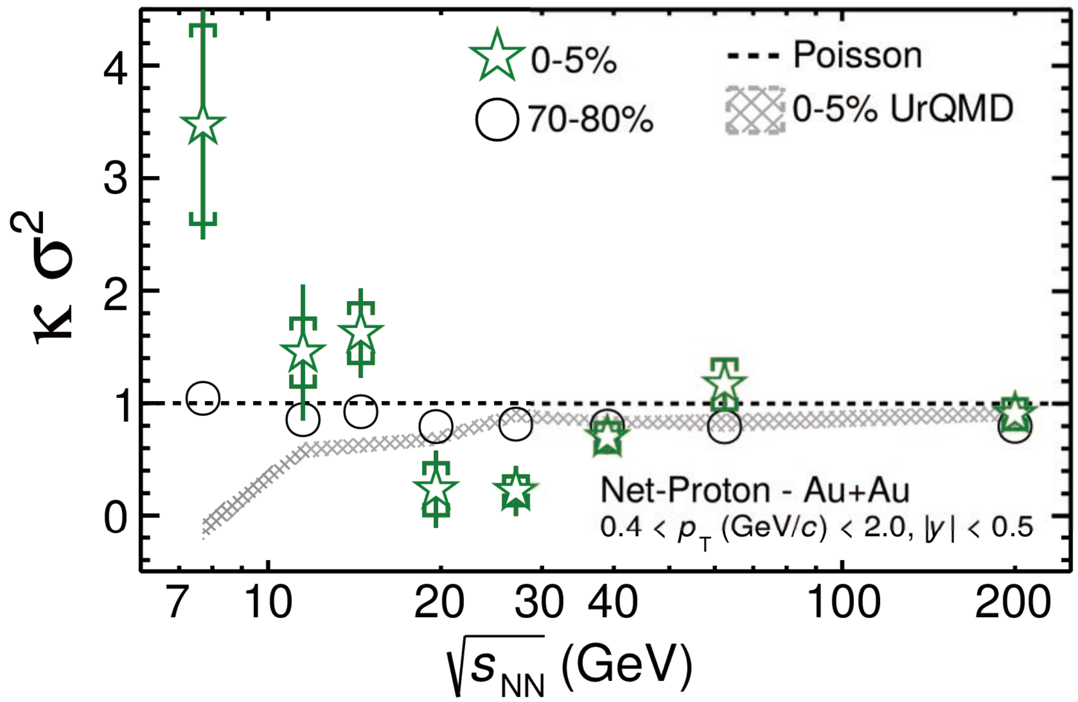
$= 0$ Gauss

Ratios characterize the shape of P(N)

Search for the Critical Point: Higher Moments Fluctuations (Net-Protons)

- Higher moments of conserved quantum numbers (Q, S, B) are expected to be sensitive to the proximity to a critical point

- Higher order moments → higher sensitivity to criticality



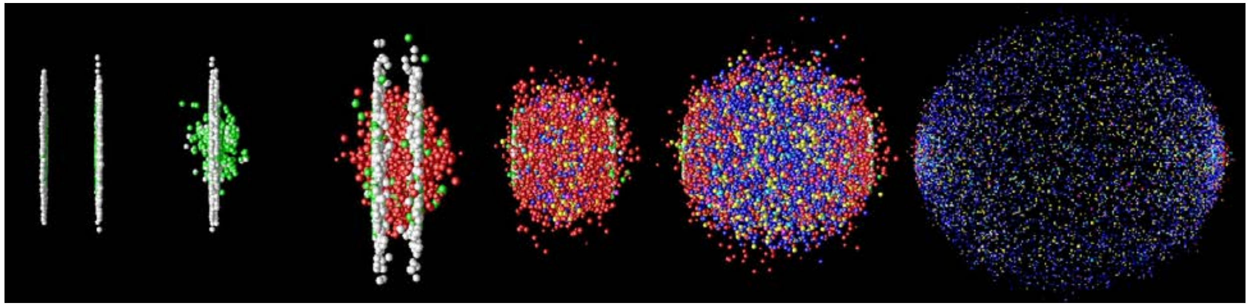
Non-monotonic change of $\kappa\sigma^2$ for in central Au+Au collisions

Summary of observations

- Jet quenching
- Strongly coupled QGP
- Thermalization
- Quark recombination (regeneration)
- High temperature matter
- Collectivity in small system
- Search for Chiral symmetry restoration
- QCD phase structure

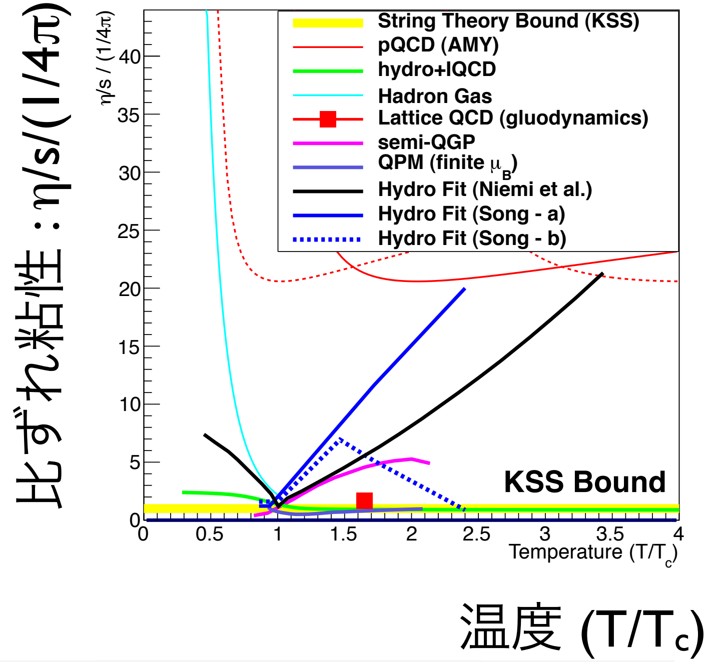
3. What is missing?
Next 20 years plan

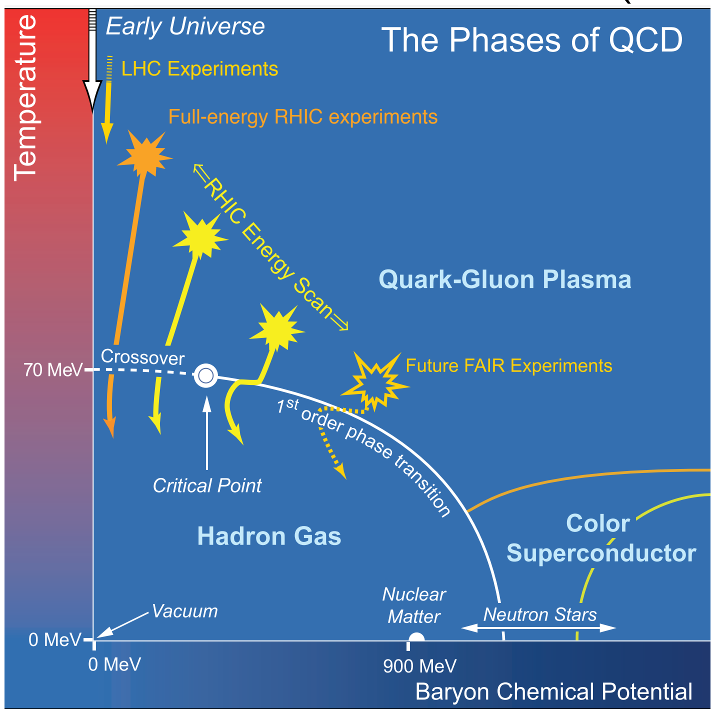
まだ分かっていないこと



初期条件→前平衡→パートン散乱→熱化(QGP)→ハドロン生成→膨張

- 衝突初期条件の解明（カラーグラス凝縮？）
- <u>Thermalizationのメカニズム</u>
- QGP物性量(比粘性、輸送係数等)の温度依存性
- 相図の構造
  - QCD critical point の探査 (RHIC)





<u>鍵となる測定量：</u>

(1) ジェット (high p_T)

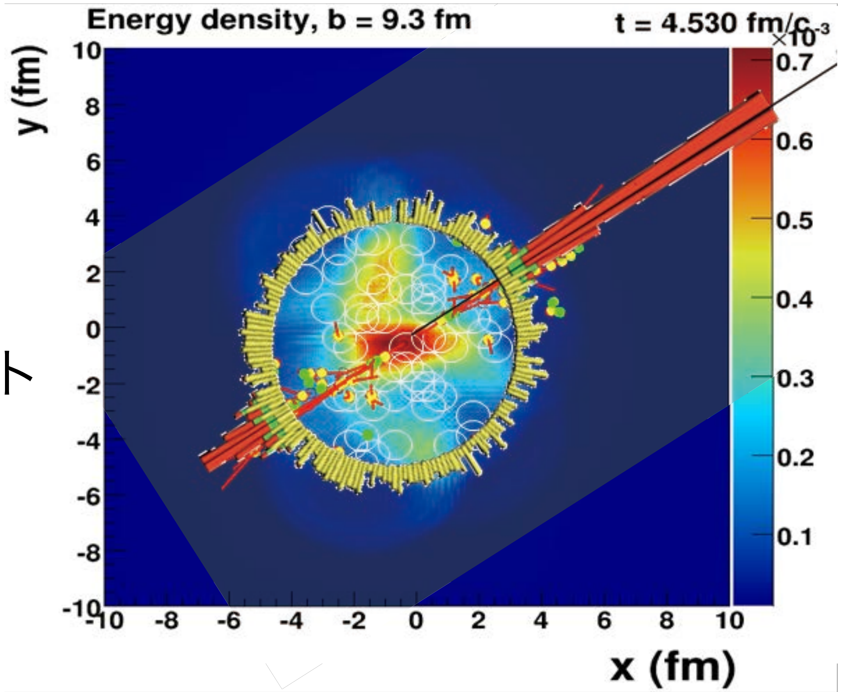
(2) より高次の異方性（種々のハドロン、フォトン、light quark, heavy quark）

ジェット測定で分かるQGP物性

LHC エネルギー：

- RHIC に比べてハードプロセスが支配的
- ジェットを基軸とした新たな観測量：
  - ジェット通過によるQGP媒質応答
  - 重クォークジェット、ジェット対、光子-ジェット
  - 失ったエネルギーの再分配、EOS、音速
  - 重いクォークの強結合系QGPとの相互作用（熱化、相互作用の強さ）

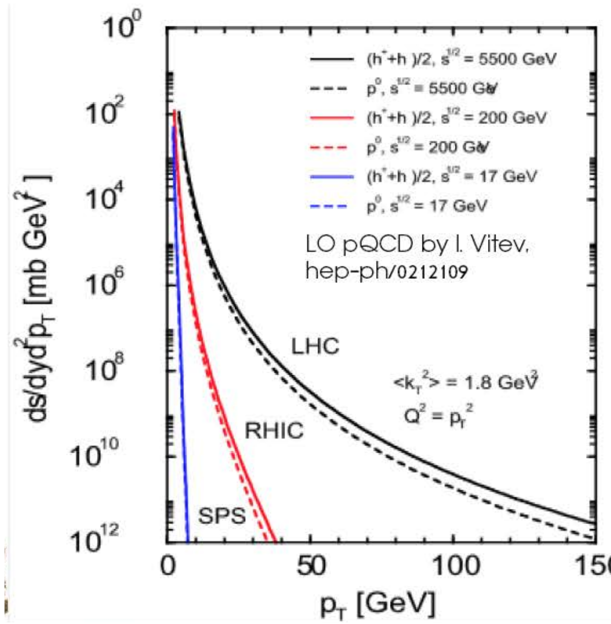
→　**データ読み出し高速化が必要**



RHIC エネルギー：

- 既存の装置はジェット測定に特化されてなく、収量や精度の点で、ジェットの直接測定が困難
- 2 πカロリメータを設置. **High p_T 化**を図り、RHIC エネルギーでのジェット測定が可能に

→　ジェットエネルギー損失の温度依存性



ジェット・フォトンで探るQGP物性 (LHC-Run-2)

1.jet-jet (di-jet), γ-jet, h-jet 測定

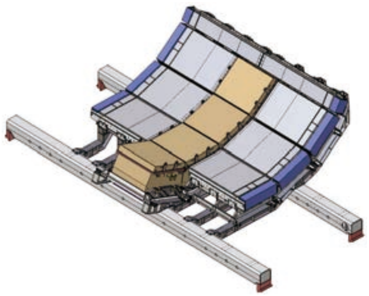
- パートン衝突位置の決定、エネルギー損失の通過距離依存性
- パートンエネルギー損失機構の解明

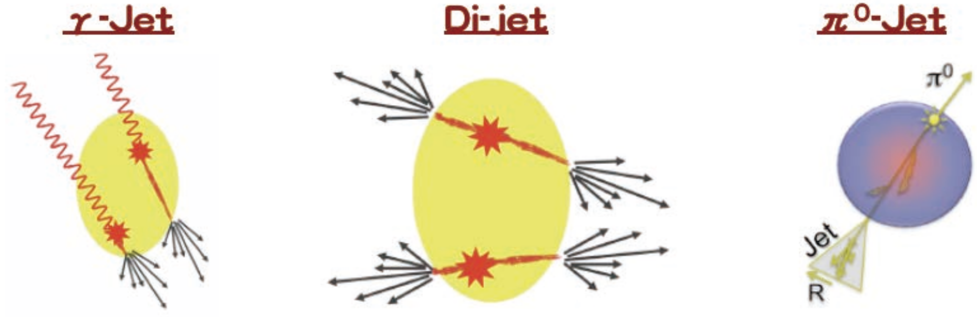
2.jet エネルギ損失とソフトハドロン生成

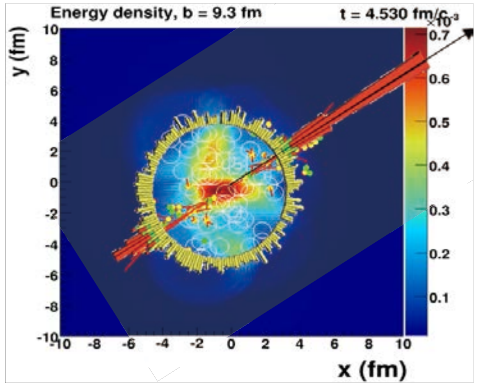
- QGPの媒質応答
- グルーオン衝撃波→EOS 決定の可能性

ALICE Run-2:

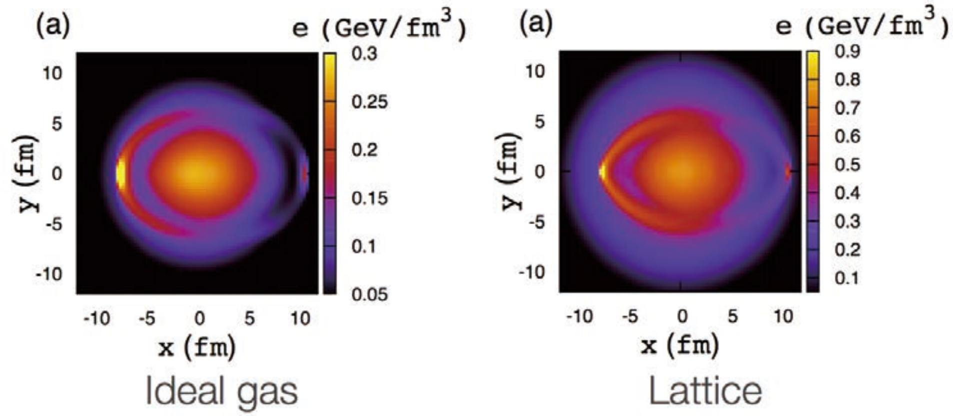
- 高統計（ダイ）ジェットサンプルが不可欠に
- DCal(Run-2 に新規導入) + PHOS:ジェット Level-1 トリガー導入（筑波大）





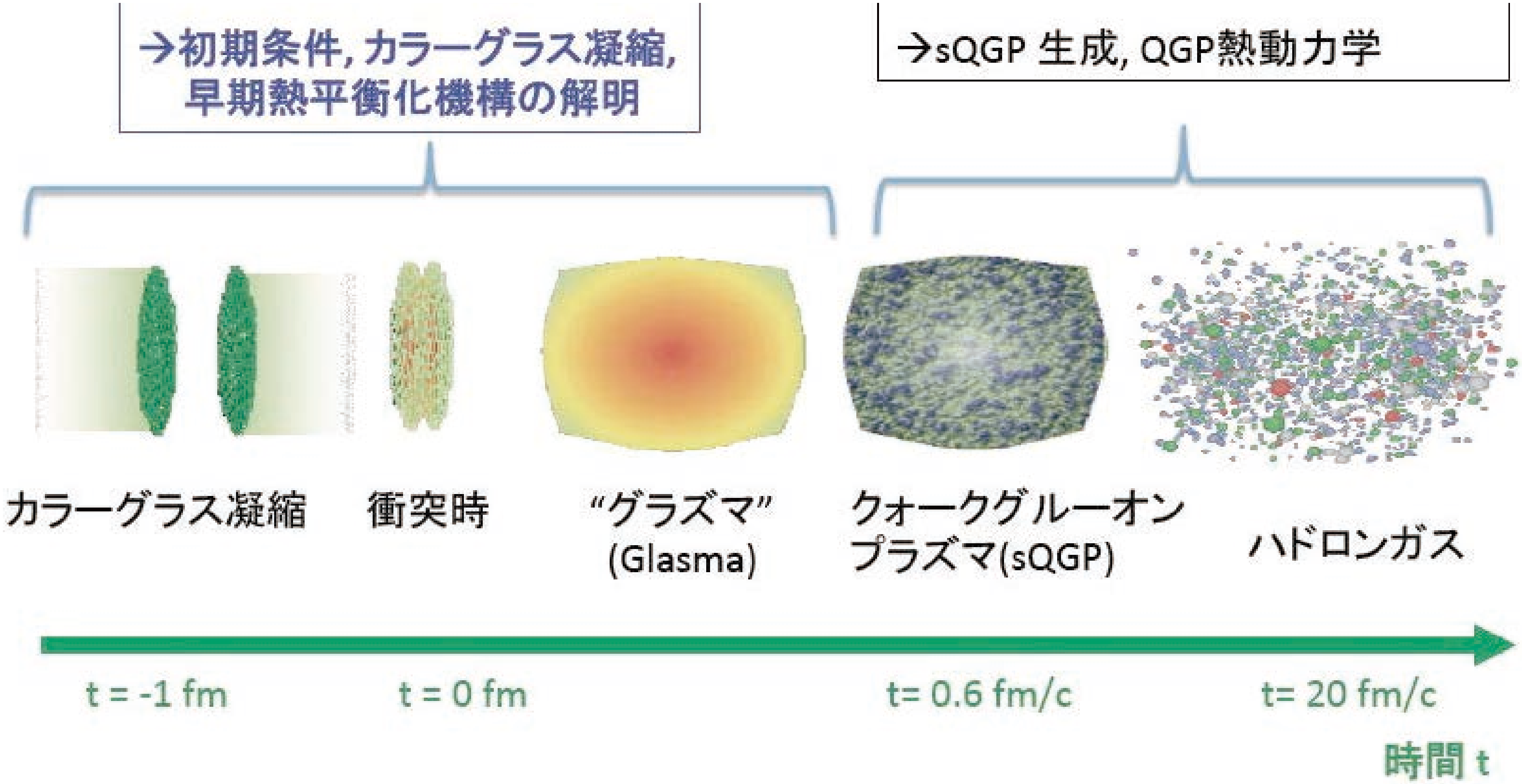


ジェットのエネルギー損失
とソフトハドロン生成の様子



ジェットが落としたエネルギーによるソフトハドロン生成.
状態方程式により、放出角度が変化. Y. Tachibana, T. Hirano (2014)

衝突初期条件の決定、早期熱化の謎



- d-Au (RHIC), p-Pb (LHC) の結果には カラーグラス凝縮（CGC） を示唆するものの、未だ決定的ではない (final state interaction を含むハドロン測定が主)。
- 実験的課題：よりクリーンなプローブによる前方の測定が不可欠（例：直接光子）
- CGC vs. Glauber 初期条件 → **QGPにおける早期熱化機構の解明へ**

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

p+A collisions

A+A collisions

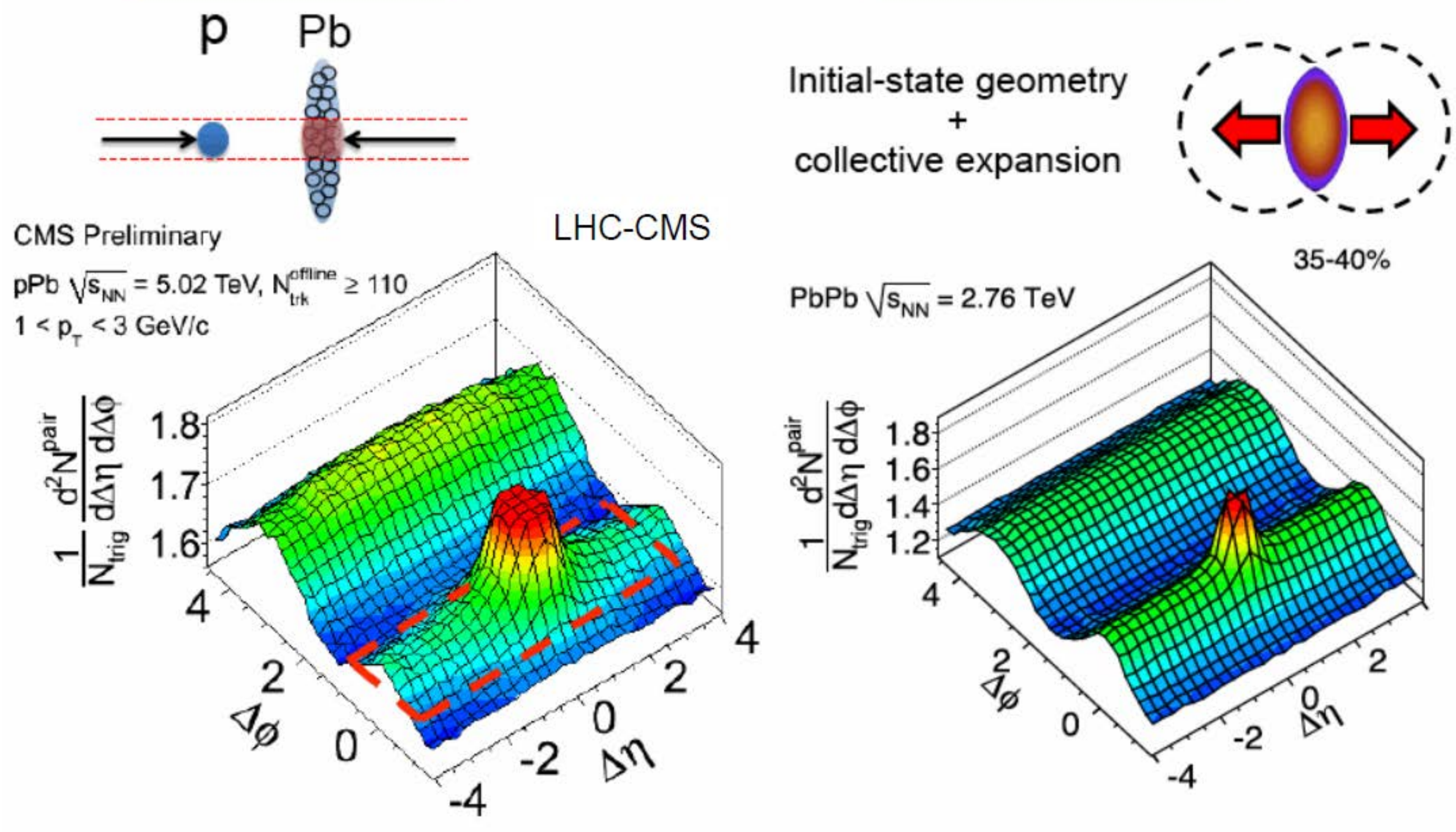
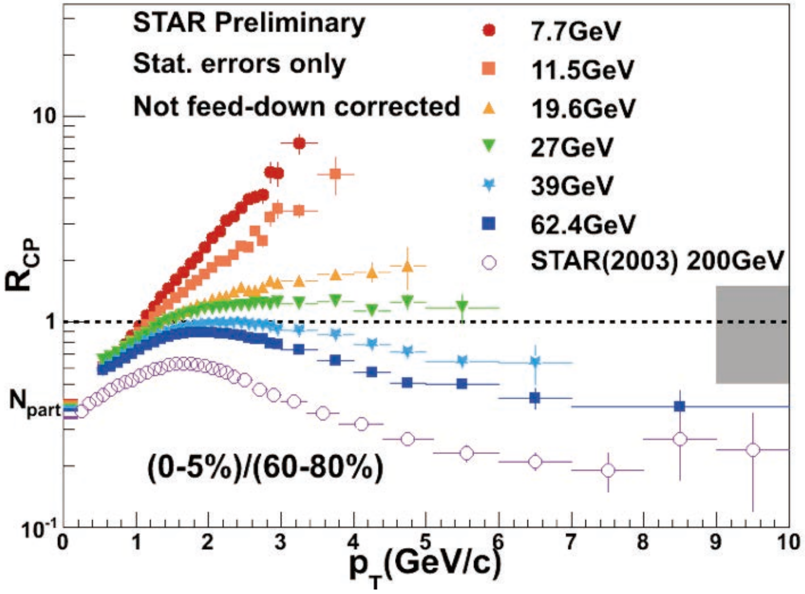


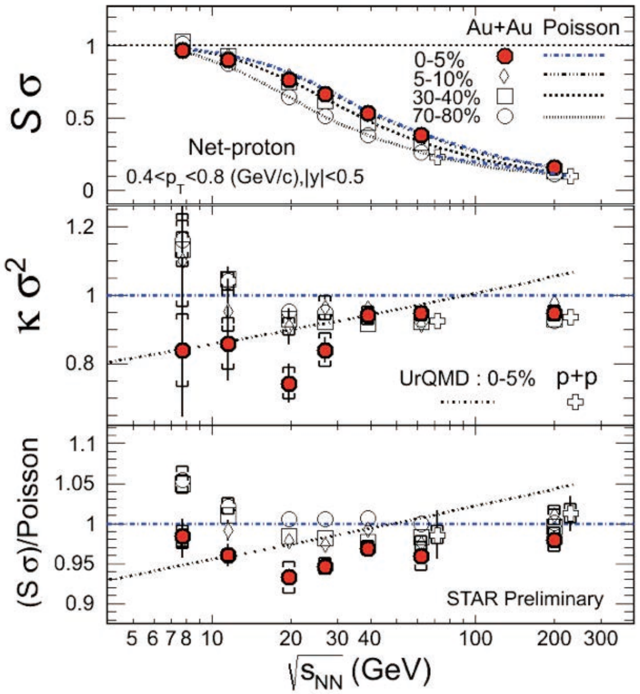
Figure taken from CMS

Need to be solved !

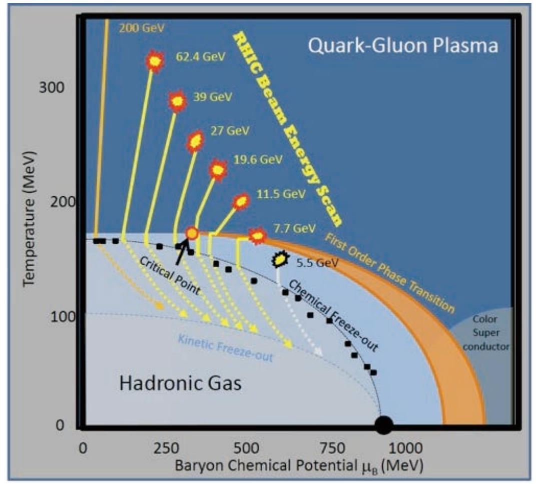
R_{CP} = (yields in central x $N_{coll(cent)}$)/(yields in peripheral x $N_{coll(peri)}$)



１次相転移か、クロスオーバーか？臨界点はあるのか？

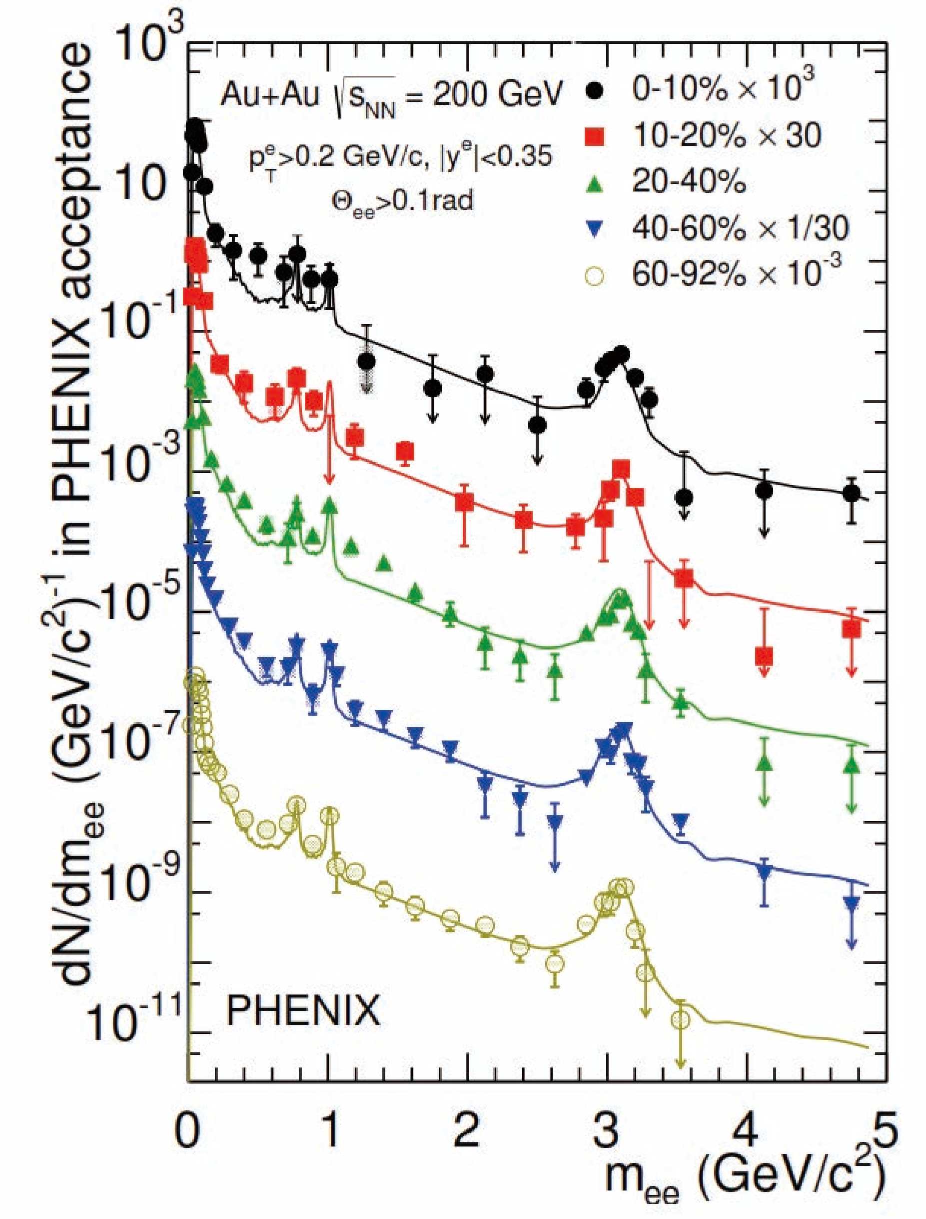


$$\sigma^2 = \langle (N - \langle N \rangle)^2 \rangle$$
$$S = \langle (N - \langle N \rangle)^3 \rangle / \sigma^3$$
$$\kappa = \langle (N - \langle N \rangle)^4 \rangle / \sigma^4 - 3$$

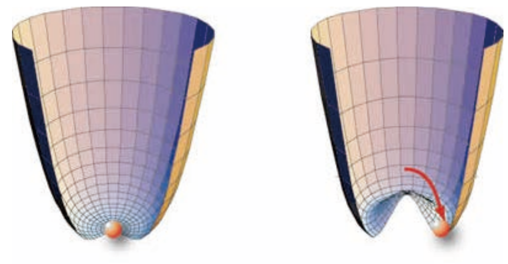


- RHIC ビームエネルギースキャン (BES-I; **B**eam **E**nergy **S**can), 7.7 - 62.4 GeV による臨界点探査
  - R_{AA}, v_2 のクォーク数スケーリング、揺らぎ測定など
  - 未だ明確な兆候なし
- より詳細なスキャン (BES-II) @ RHIC (2018-2019)

カイラル対称性の回復現象



PHENIX: arXiv01509.04667 (2015)



- レプトン対質量分布の余剰成分：
  - 媒質効果によるρ 中間子の broadening の効果と無矛盾
- 高温領域 (LHC) ではどうか？
- 高密度領域（例えば FAIR, J-PARC) では測定されていない

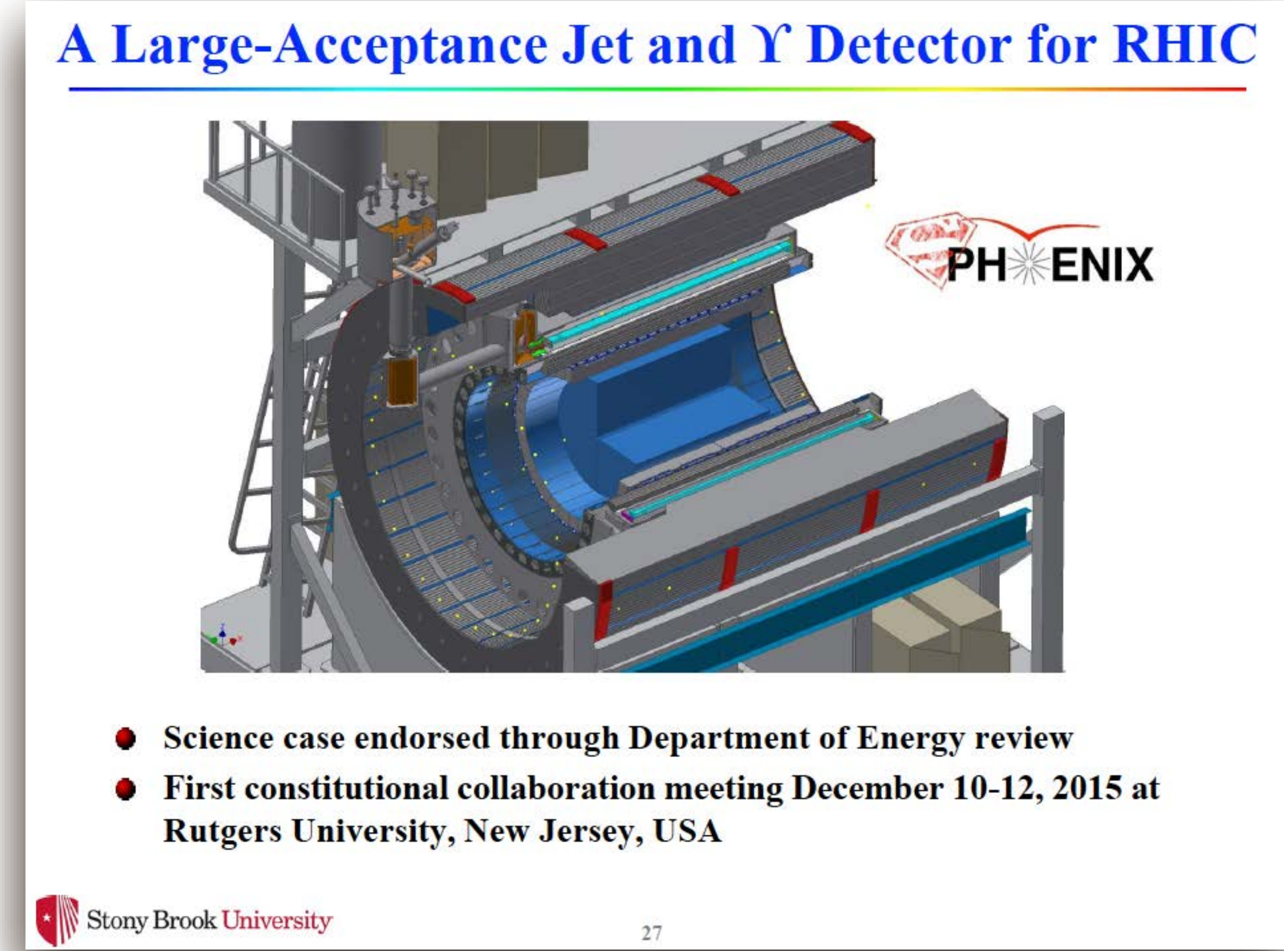
高温側、高密度側の両方のアプローチが不可欠

＋

理論の進展

RHIC-PHENIX実験 High-p_T 化

High-p_T 化
ジェット測定強化
重クォーク測定強化



QM2015, A. Dress

- 測定器の新規建設

  PHENIX → sPHENIX

- 日本が建設を主導する検出器：

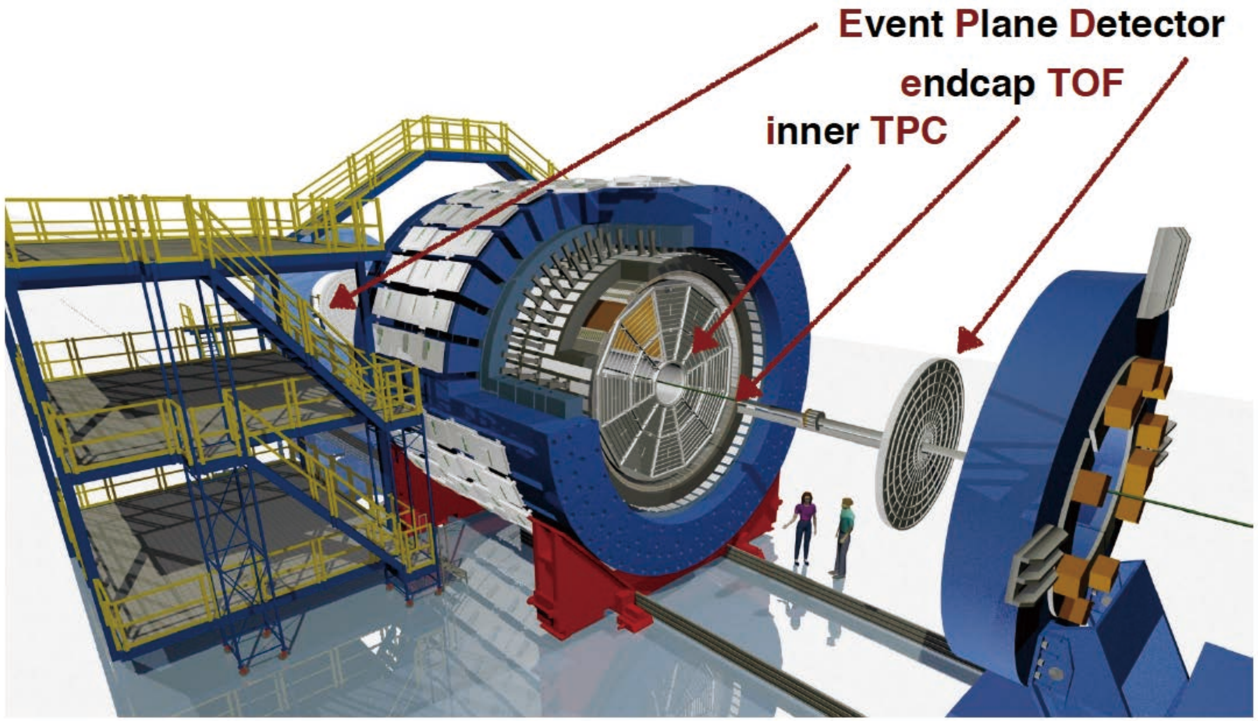
  ✓ シリコン飛跡検出器

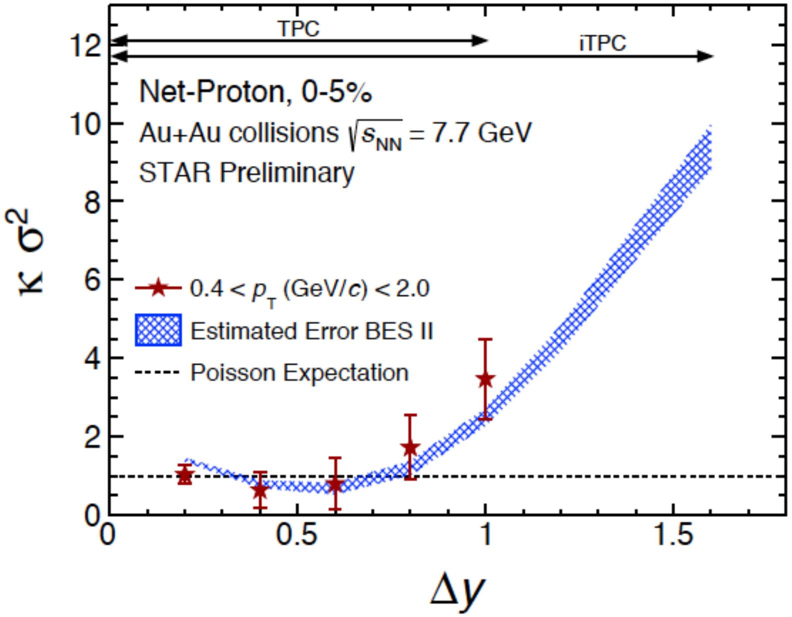
ジェット、重クォーク測定から、RHICエネルギーでのQGP中でのエネルギー損失 (輸送係数)の温度依存性を決定

sPHENIX実験: 総額$20M-30M
arXiv:1207.6378

STAR BES-II

STAR Upgrades and BES Phase-II (2019-2020)





iTPC proposal: http://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
BES-II whitepaper: http://drupal.star.bnl.gov/STAR/starnotes/public/sn0598
Larger rapidity acceptance crucial for further critical point search with net-protons

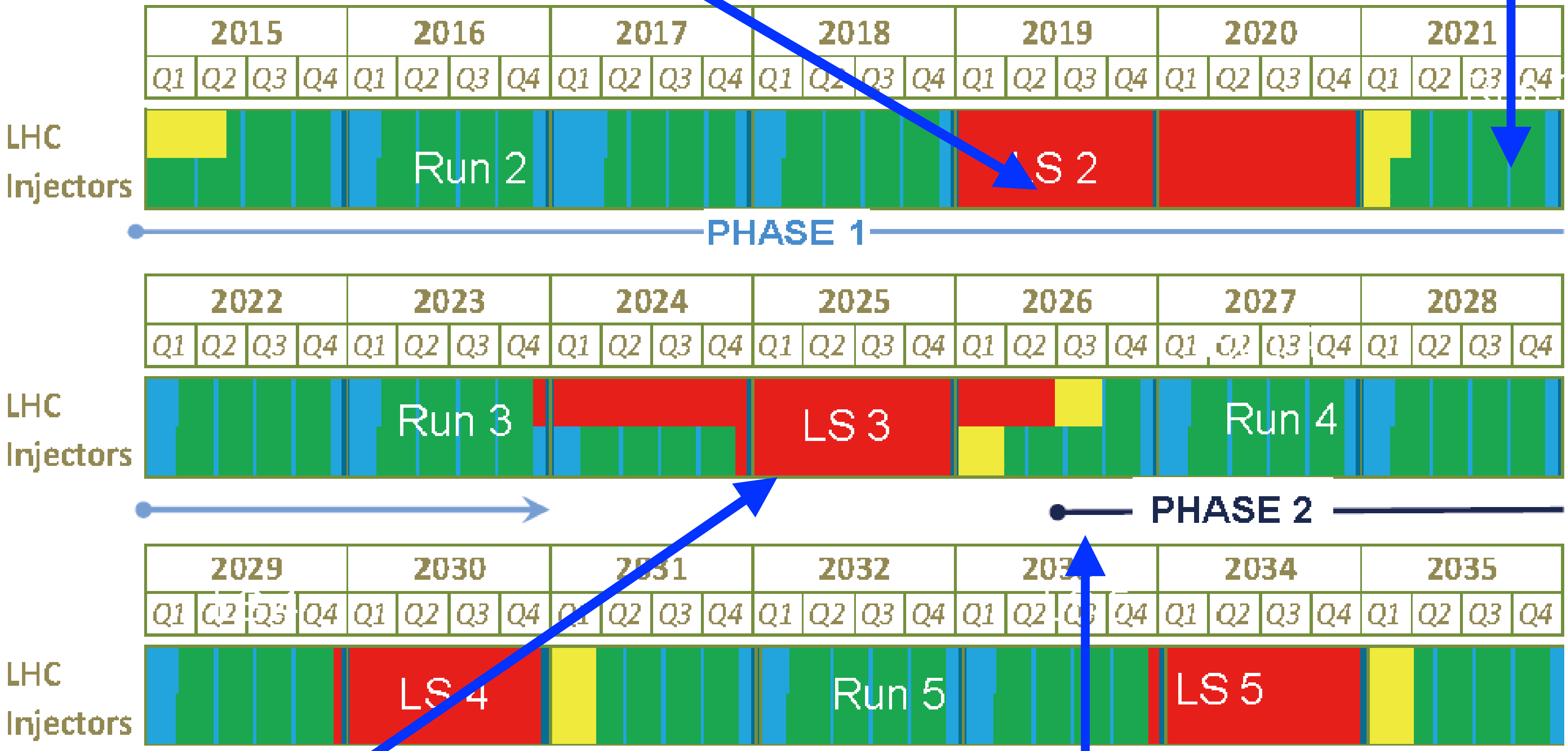
- Electron cooling upgrade will provide increased luminosity ~ 3-10 times.
- Inner TPC(iTPC) upgrade : $|\eta| < 1$ to $|\eta| < 1.5$. Better dE/dx resolution.
- Forward Event Plane Detector (EPD): Centrality and Event Plane Determination.

$1.8 < |\eta| < 4.5$

LHC schedule

PHASE I Upgrade
ALICE, LHCb major upgrade
ATLAS, CMS ,minor upgrade

Heavy Ion Luminosity
from 10^{27} to 7×10^{27}



PHASE II Upgrade
ATLAS, CMS major upgrade

HL-LHC, pp luminosity
from 10^{34}(peak) to 5×10^{34}(levelled)

LHC-ALICE実験 高速化

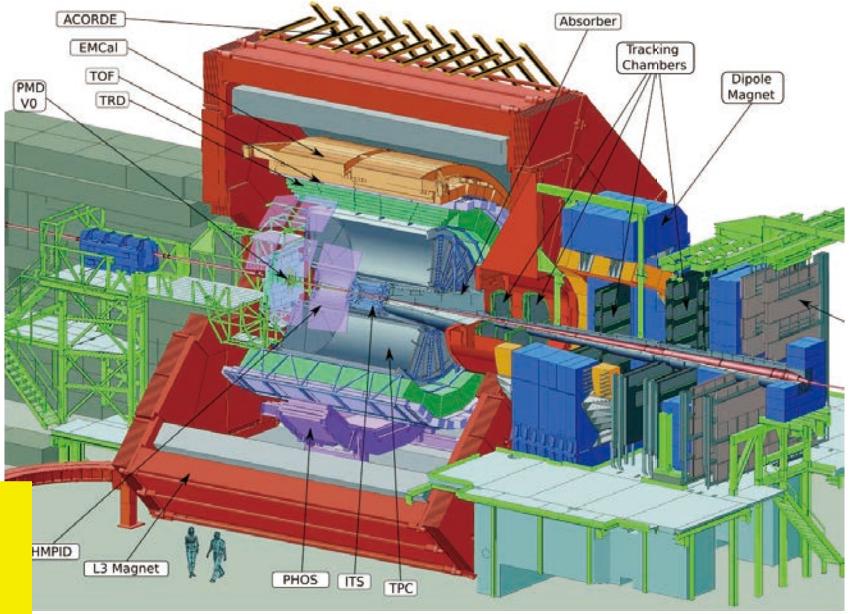
ALICE 実験測定器の高速化

日本グループが担当する検出器：

GEM-TPC連続読出高速化

カロリメータ高速化

グリッド計算機 (Tier2) の強化



LHCの高輝度化、Pb-Pb衝突(50kHz)に対応

全衝突事象を記録し、これまでの100倍のデータ取得

（ATLAS, CMS 実験では不可能）

→　**高精度測定、レア事象へのアクセスが可能に**

ALICE実験高度化: 総額€40M

LHCCによるendorsement (2012年9月)

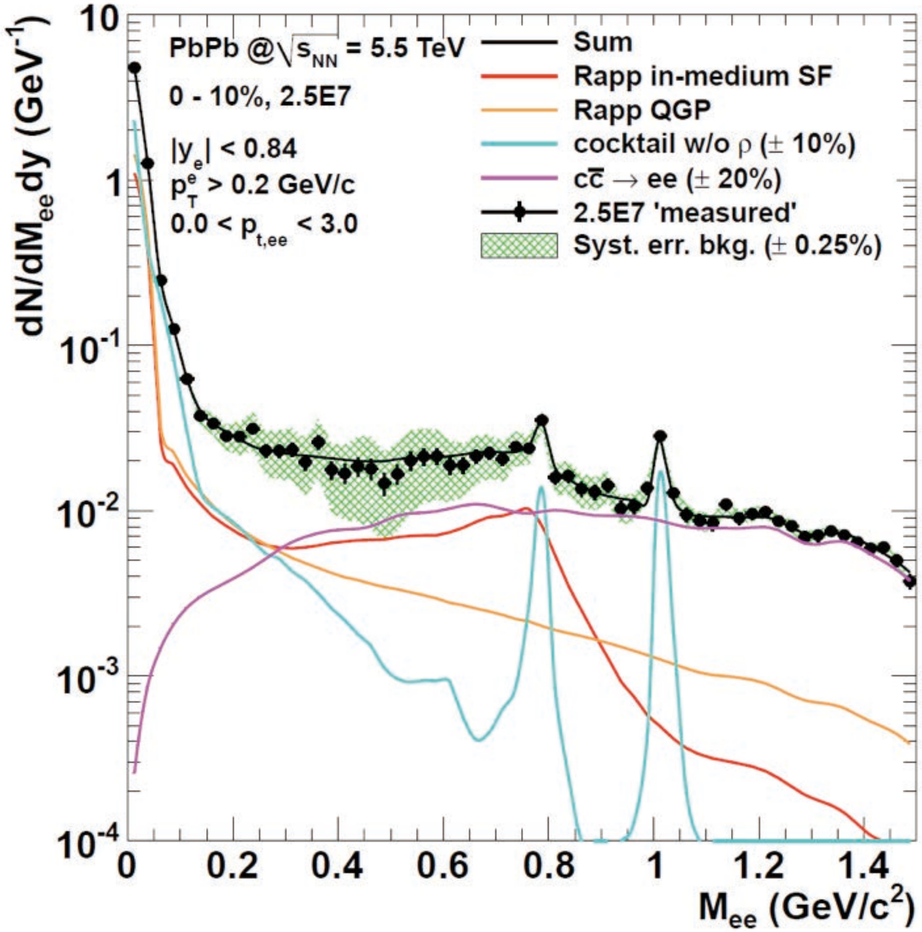
物理の目標：

ジェットともに低運動粒子 (PID含)、重クォークや光子やレプトン対の方位角異方性を同時測定

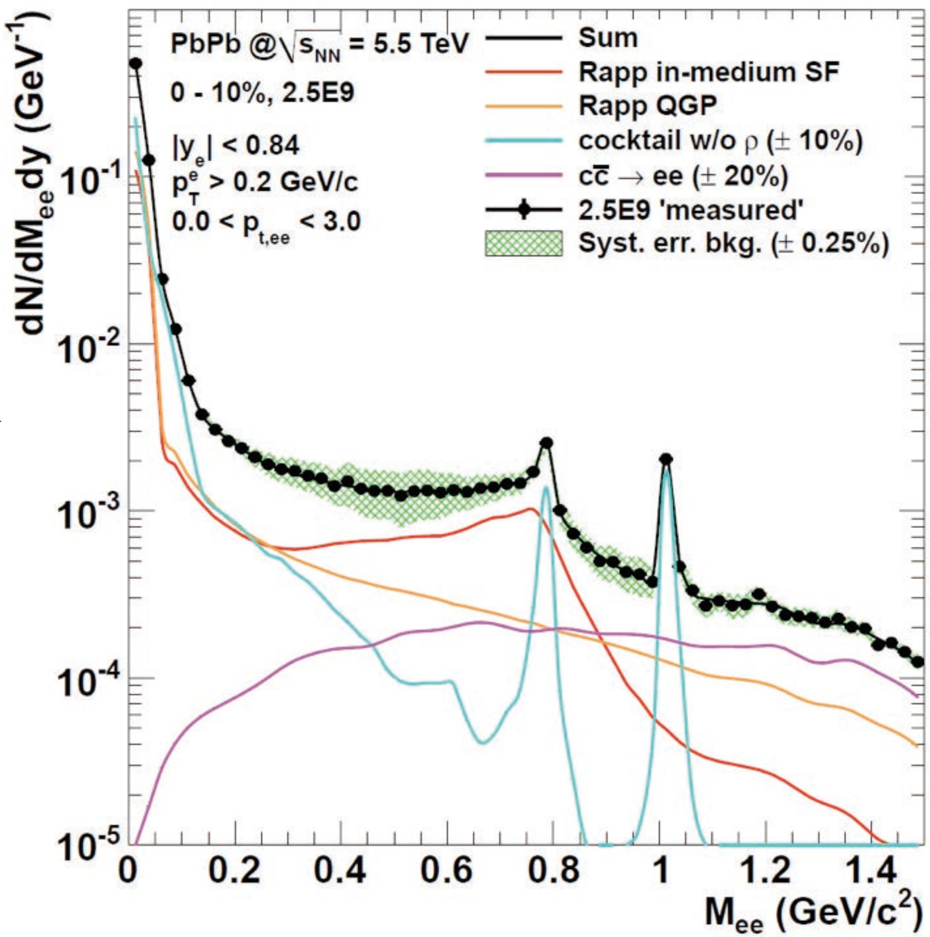
→QGP媒質応答、重クォークと強結合系の相互作用（熱化、相互作用の強さ）を決定

Expected performance (low-mass di-electron pair), w/ hadronic BG

Before

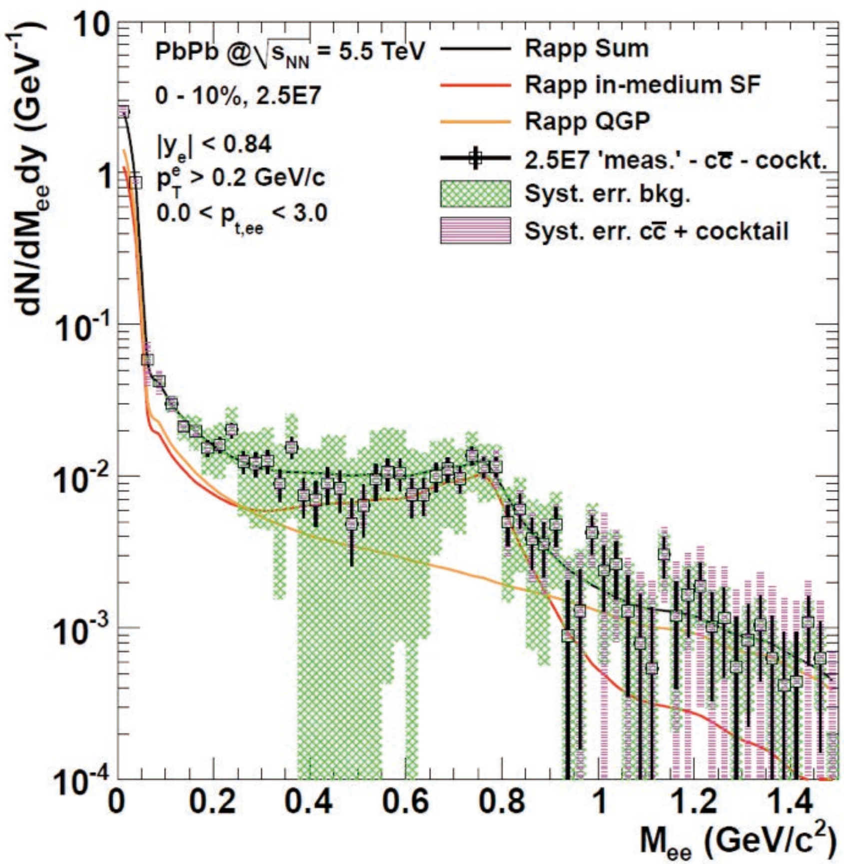


After

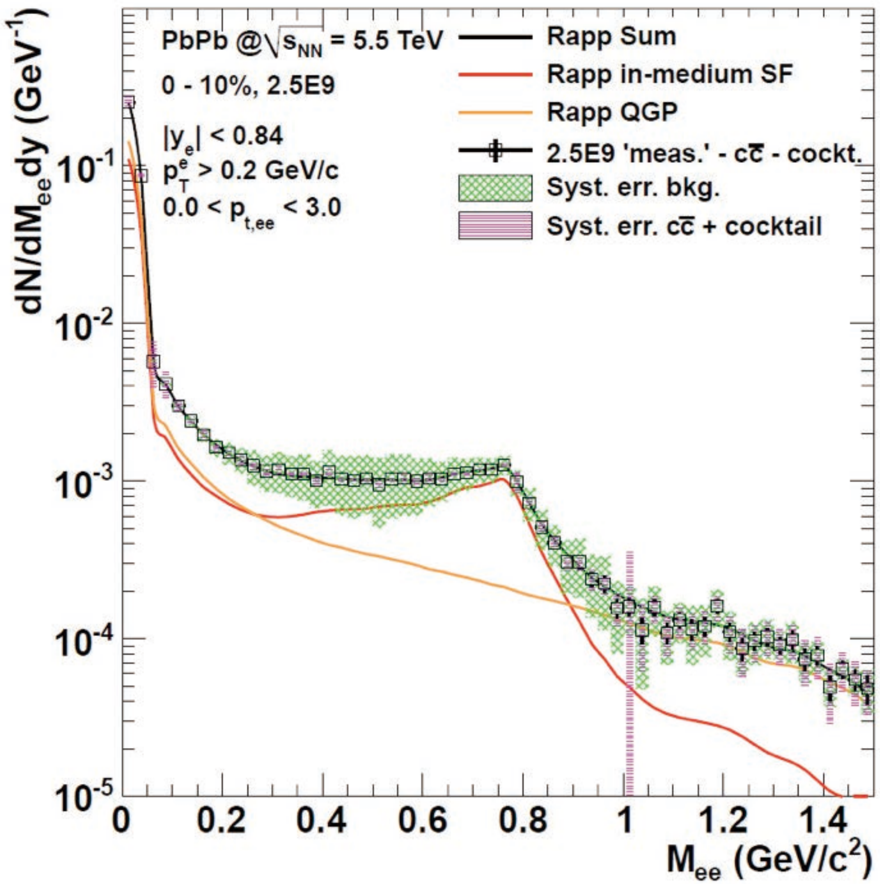


Expected performance (low-mass di-electron pair), w/o hadronic BG

Before



After

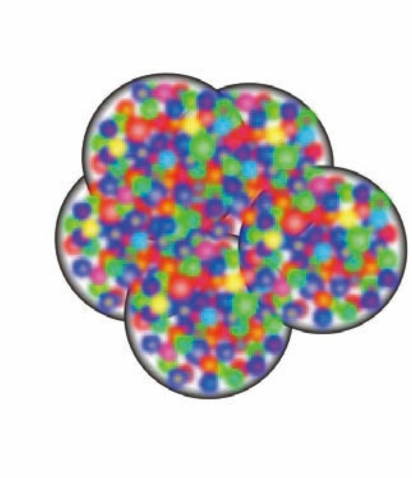


アップグレード前後の余剰成分（シグナル）

→カイラル対称性の回復現象の精密測定へ！

前方物理、CGC、衝突初期条件の決定

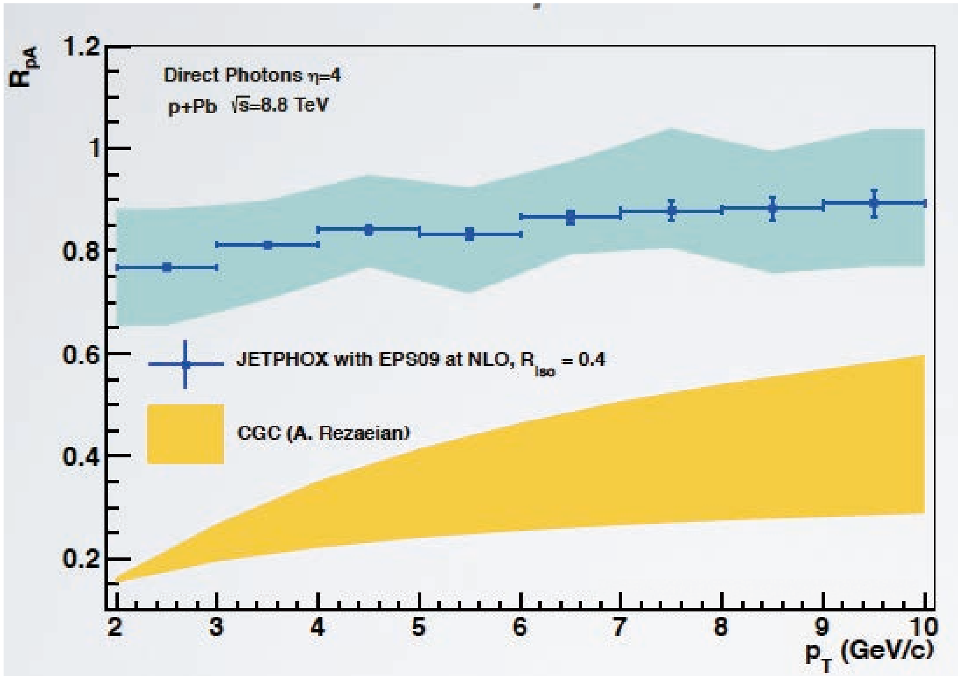
単光子の収量比： (p+Pb)/ (p+p)

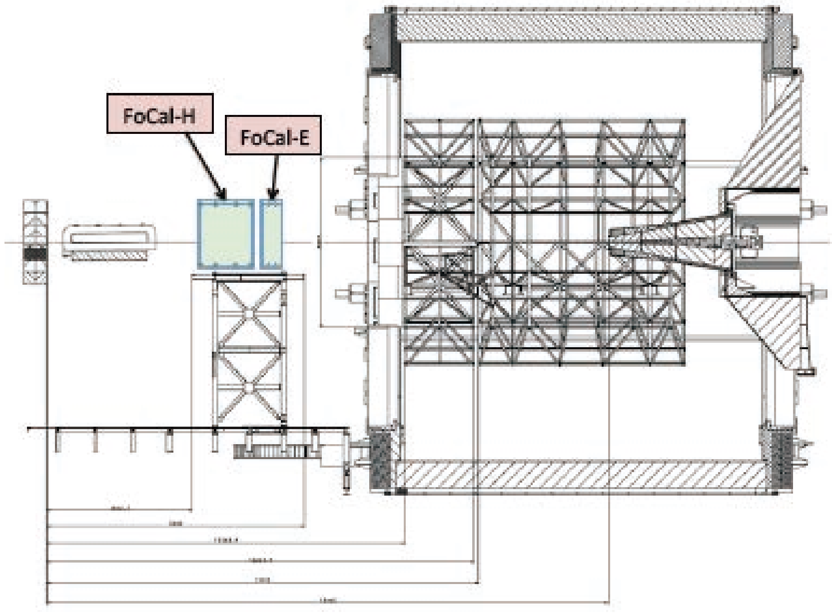


CGC なし
(通常の原子核効果)

CGC あり

A. Rezaeian, PLB 718, 1058

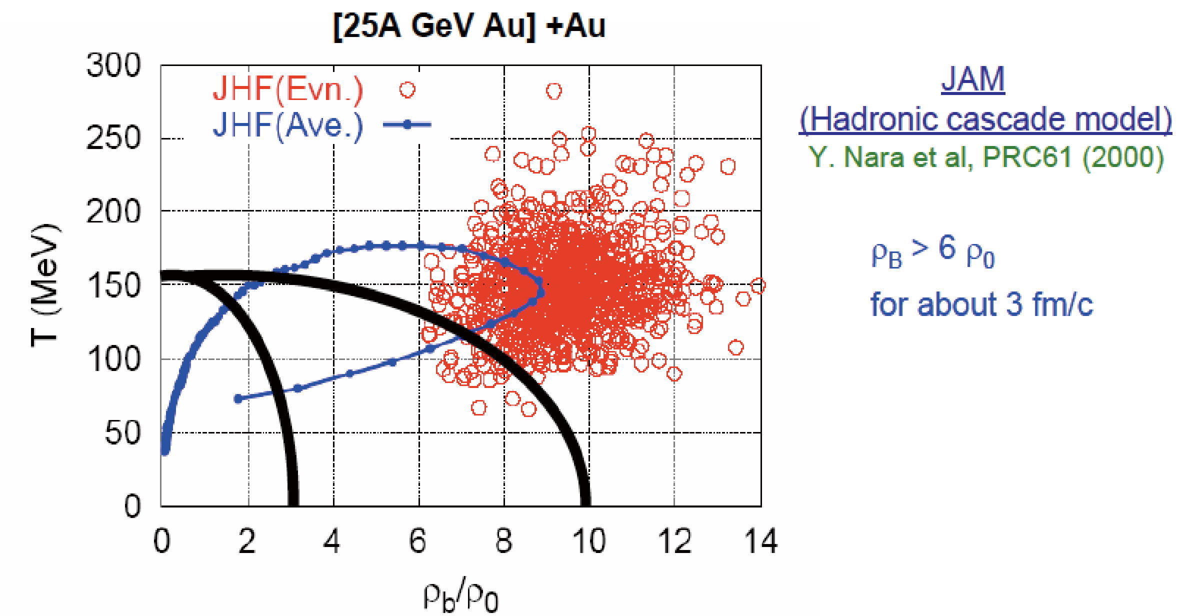




- η = 3-5 をカバーする前方光子検出器（筑波大）
- 電磁カロリメータとハドロンカロリメータ
- ALICE 実験内で導入を検討中
- 前方での**直接光子測定**により、CGC を検証、衝突初期条件の決定とQGP熱化機構に迫る。

J-PARC における重イオン実験の検討

- **J-PARC:**
  - 高ルミノシティー原子核衝突実験目
  - **高バリオン密度におけるＱＣＤ相構造解明、ＱＣＤ臨界点の探索**
  - 重イオン衝突では 、5-10 ρ_0 程度まで達成可能



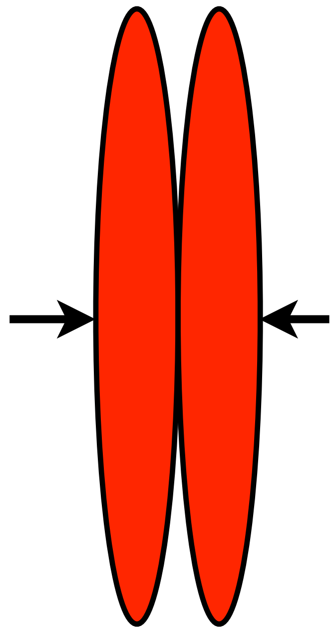
J-PARC 重イオン衝突の物理@10-15GeV/A

($\sqrt{s_{NN}}$ =4.5-5.4 GeV)

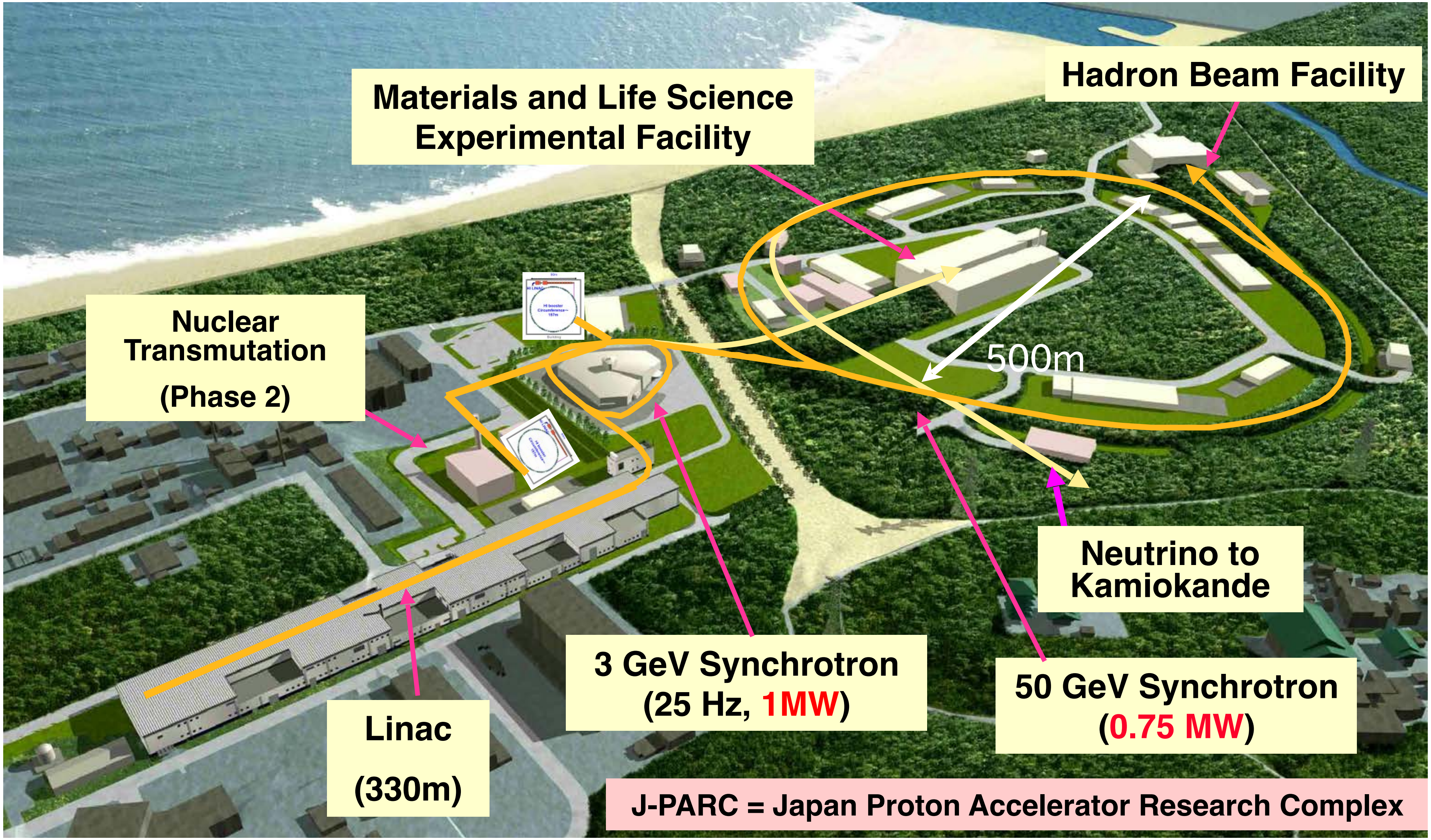
●軽イオンからU重イオンまで加速（新イオン源; ECR, laser, EBIS）

●AGSでは測定しなかった（出来なかった）物理量を初めて測定

– 物理量のゆらぎ（粒子数、運動量、v_n 等)
  ➡ **QCD臨界点探査、QCD相図の mapping**
– レプトン対(電子, muon)、光子、σメソン（？）
  ➡ **カイラル対称性回復の研究、熱光子測定**
– エキゾティックハドロン/原子核、チャームの物理
  • multiple-strangeness (ストレンジレット探査)
  • ２重、３重 ハイパー核
  • チャームハドロン(J/Ψ,D)
– ハドロンガスの物性量測定、**高密度核物質の物性**



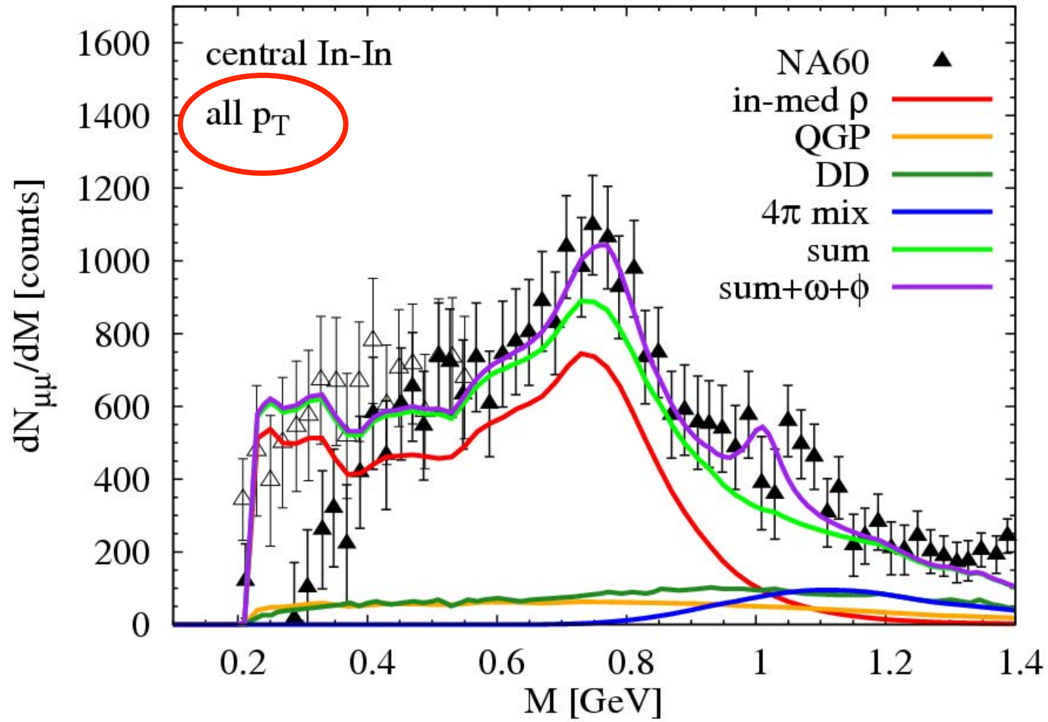
J-PARC Facility



Joint Project between KEK and JAEA

測定精度の時代へ

SPS-NA60



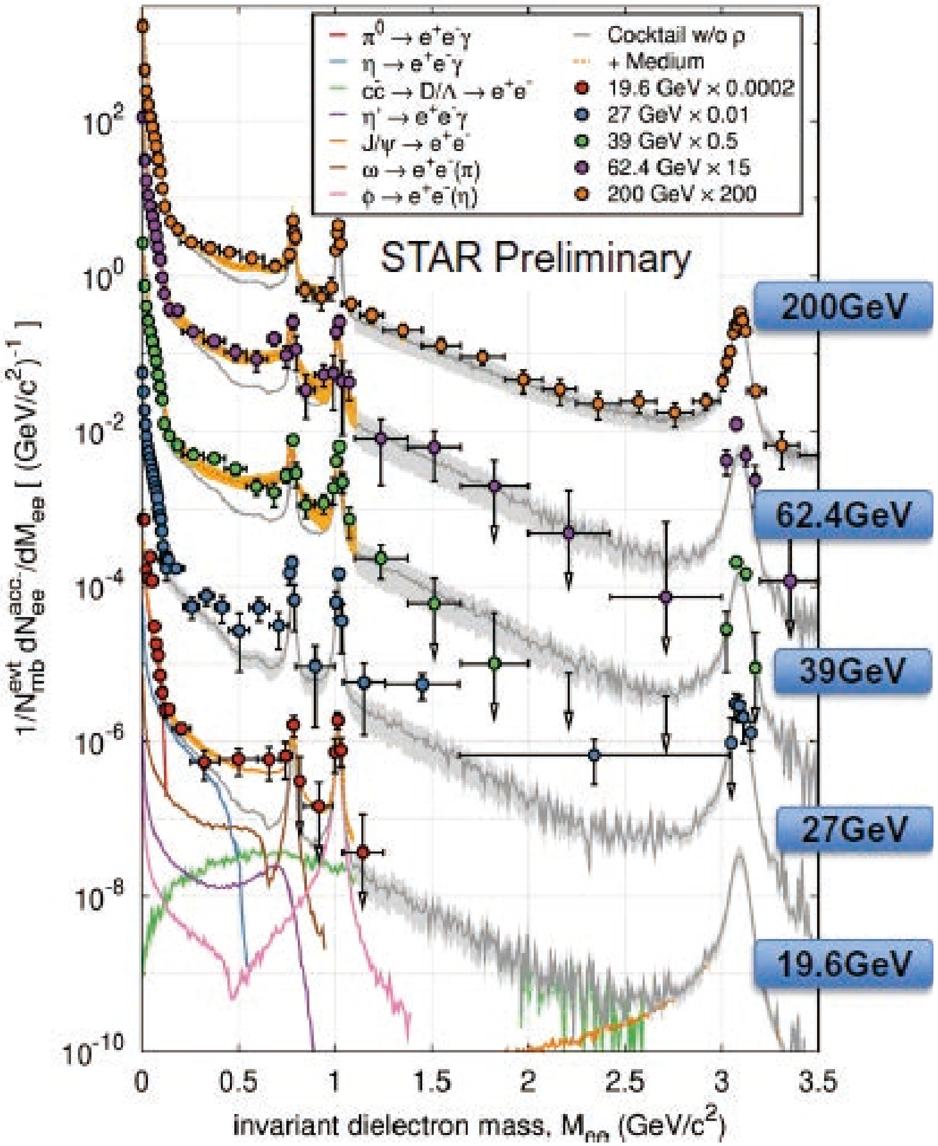
J-PARC では…

p_T ビン毎、質量分布の精密測定

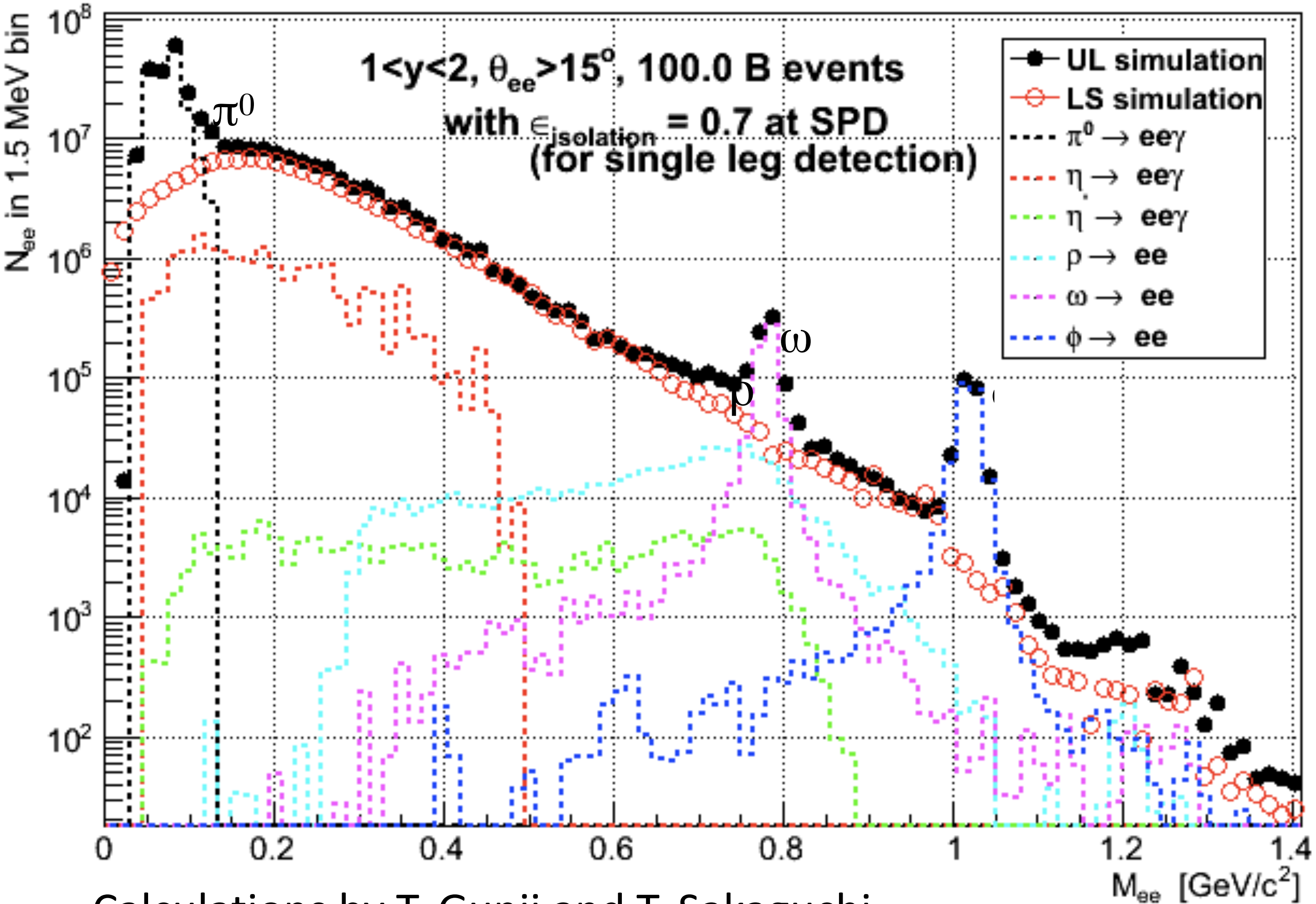
→ QCD sum rule との直接比較

(moment 解析)

RHIC-STAR



Simulated di-electron spectrum (preliminary)



Calculations by T. Gunji and T. Sakaguchi

Based on π^0 spectra of JAM

Other hadrons m_T-scaled

b<1fm (0.25% centrality)

Momentum resolution 2%

Electron efficiency 50%

No detector response

10^{11} = 100 G events

⇔100k events/s

x 1 month running

$\varepsilon_{isolation}$ = rejection efficiency of close opening angle Dalitz pair

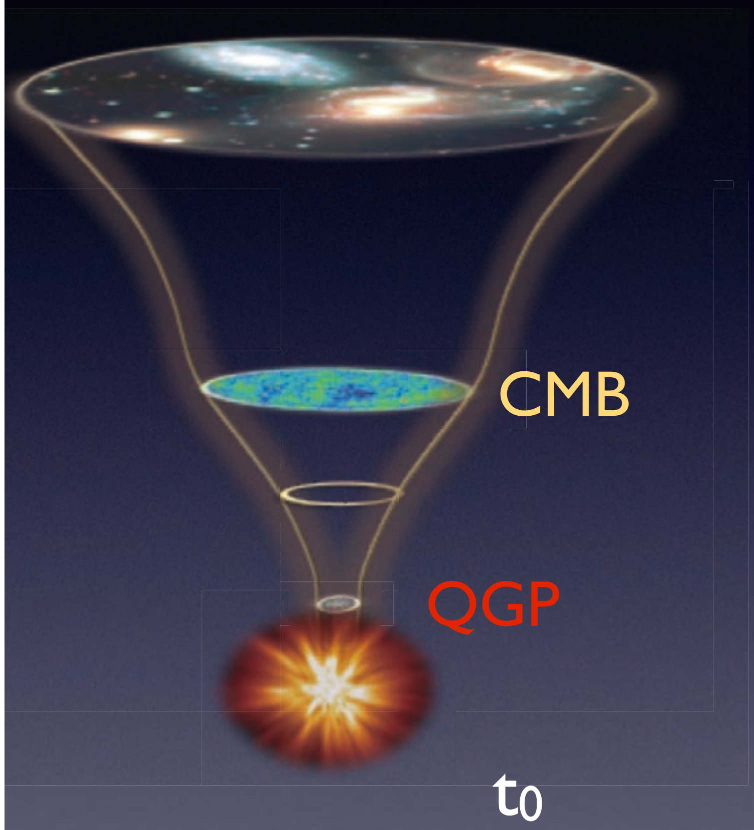
NA45 (CERES) データより**３桁高い統計量を１ヶ月で取得**！

cf.) STAR (BES-II) fixed target program: 5 M events @ $\sqrt{s_{NN}}$ = 5 GeV

4. Connections to other fields

ビッグバン

t_0+138 億年（現在）



リトルバン

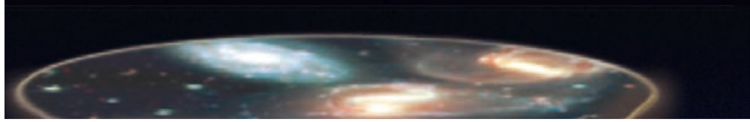
$t_0+3\times10^{-23}$ 秒間持続

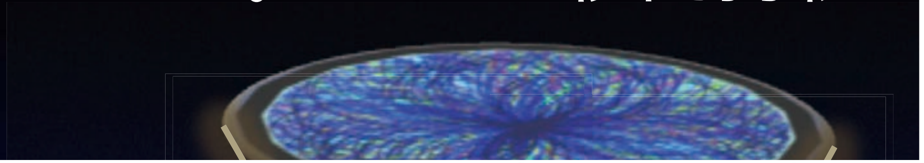
ビッグバン

リトルバン

t_0+138 億年（現在）

$t_0+3\times10^{-23}$ 秒間持続





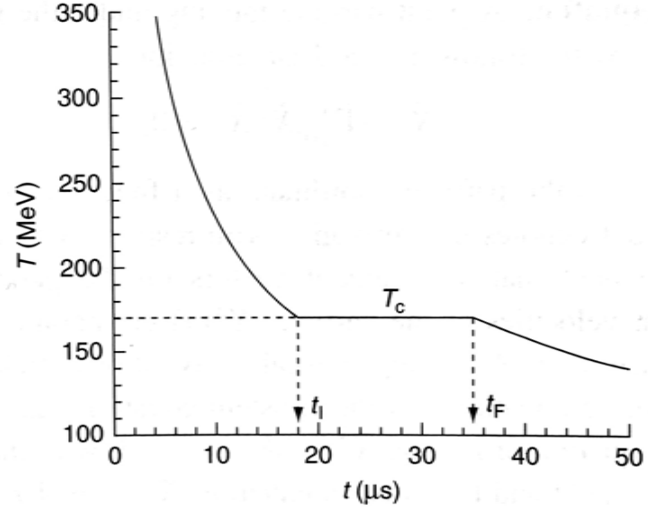


Fig. 8.11. Temperature, T, of the Universe as a function of the age, t, around the epoch of the QCD phase transition. Typical scales used are $T_c = 170$ MeV and $\lambda = 78$ µs. Compare this figure with that in the relativistic heavy ion collisions, Fig. 13.7.

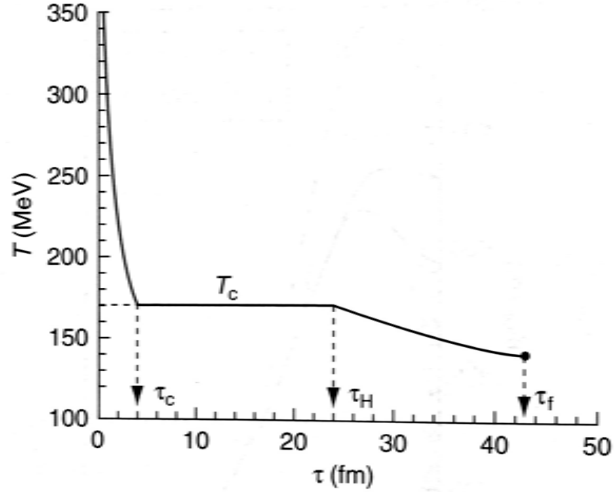
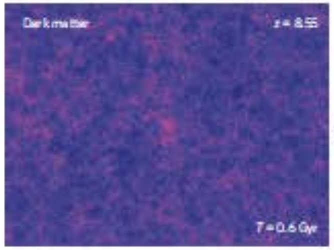
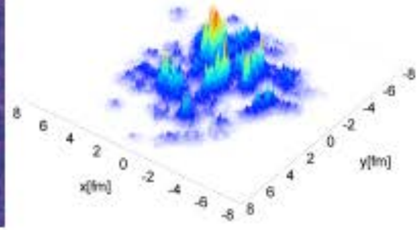


Fig. 13.7. Time evolution of the temperature of hot matter with a first-order QCD phase transition (solid line) at $T_c = 170$ MeV created in the central region of an ultra-relativistic heavy nucleus–nucleus collision. The initial temperature is taken to be $T_0 = 2T_c$ at $\tau_0 = 0.5$ fm, and the freeze-out time is given by $\tau_H/\tau_c = 5.9$, as shown in Eq. (13.19). Compare this figure with that in the early Universe, Fig. 8.11.

Figures from, "Quark-Gluon Plasma", K. Yagi, T. Hatsuda, Y. Miake, Cambridge Univ. press (2005)

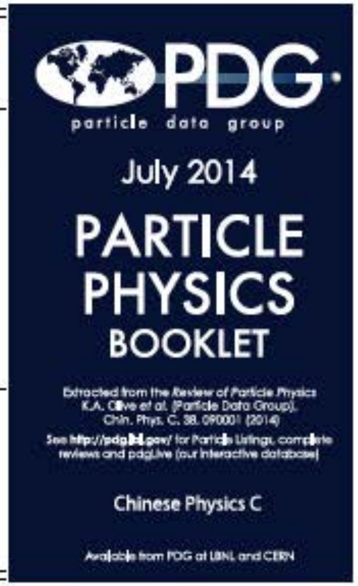
The problem of initial conditions





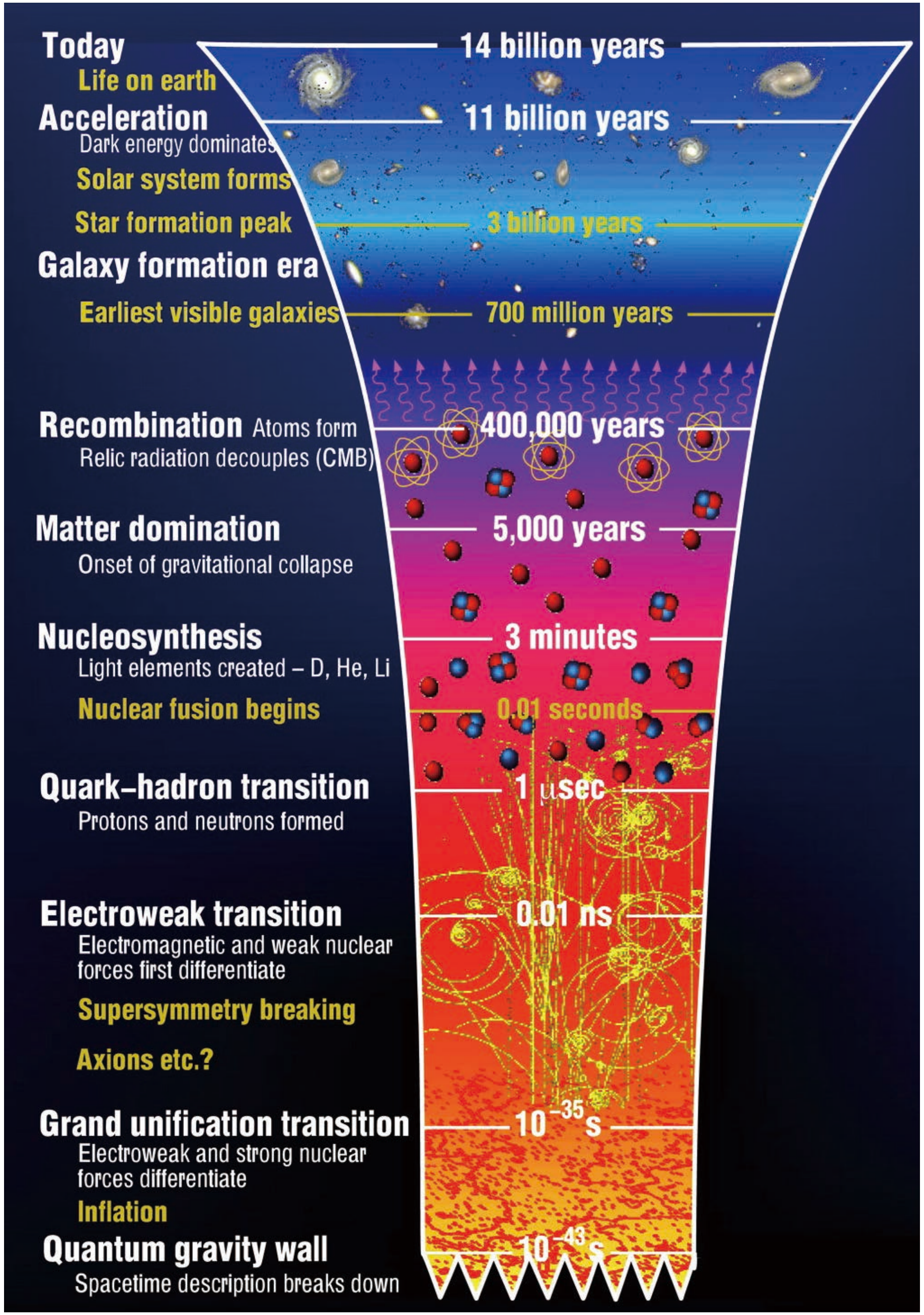
- Problem for cosmology and heavy ion physics: precise initial conditions for fluid dynamic description not known

	Planck+WP +highL	*Planck*+WP +highL+BAO	*WMAP9*+eCMB +BAO
$\Omega_b h^2$	0.02207 ± 0.00027	0.02214 ± 0.00024	0.02211 ± 0.00034
$\Omega_c h^2$	0.1198 ± 0.0026	0.1187 ± 0.0017	0.1162 ± 0.0020
$100\,\theta_{MC}$	1.0413 ± 0.0006	1.0415 ± 0.0006	–
n_s	0.958 ± 0.007	0.961 ± 0.005	0.958 ± 0.008
τ	$0.091^{+0.013}_{-0.014}$	0.092 ± 0.013	$0.079^{+0.011}_{-0.012}$
$\ln(10^{10}\Delta^2_{\mathcal{R}})$	3.090 ± 0.025	3.091 ± 0.025	3.212 ± 0.029
h	0.673 ± 0.012	0.678 ± 0.008	0.688 ± 0.008
σ_8	0.828 ± 0.012	0.826 ± 0.012	$0.822^{+0.013}_{-0.014}$
Ω_m	$0.315^{+0.016}_{-0.017}$	0.308 ± 0.010	0.293 ± 0.010
Ω_Λ	$0.685^{+0.017}_{-0.016}$	0.692 ± 0.010	0.707 ± 0.010



- Nevertheless, cosmology is now a precision science!
- How is that possible?

S. Florchinger (QM2015)



For heavy ions and the cosmos, **fluctuation analysis** can provide detailed **information about material properties and expansion history** without full control over initial conditions.

Common challenges require commonalities in analysis techniques.

Interplay between both fields likely to become more important in the next decade

S. Florchinger (QM2015)

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

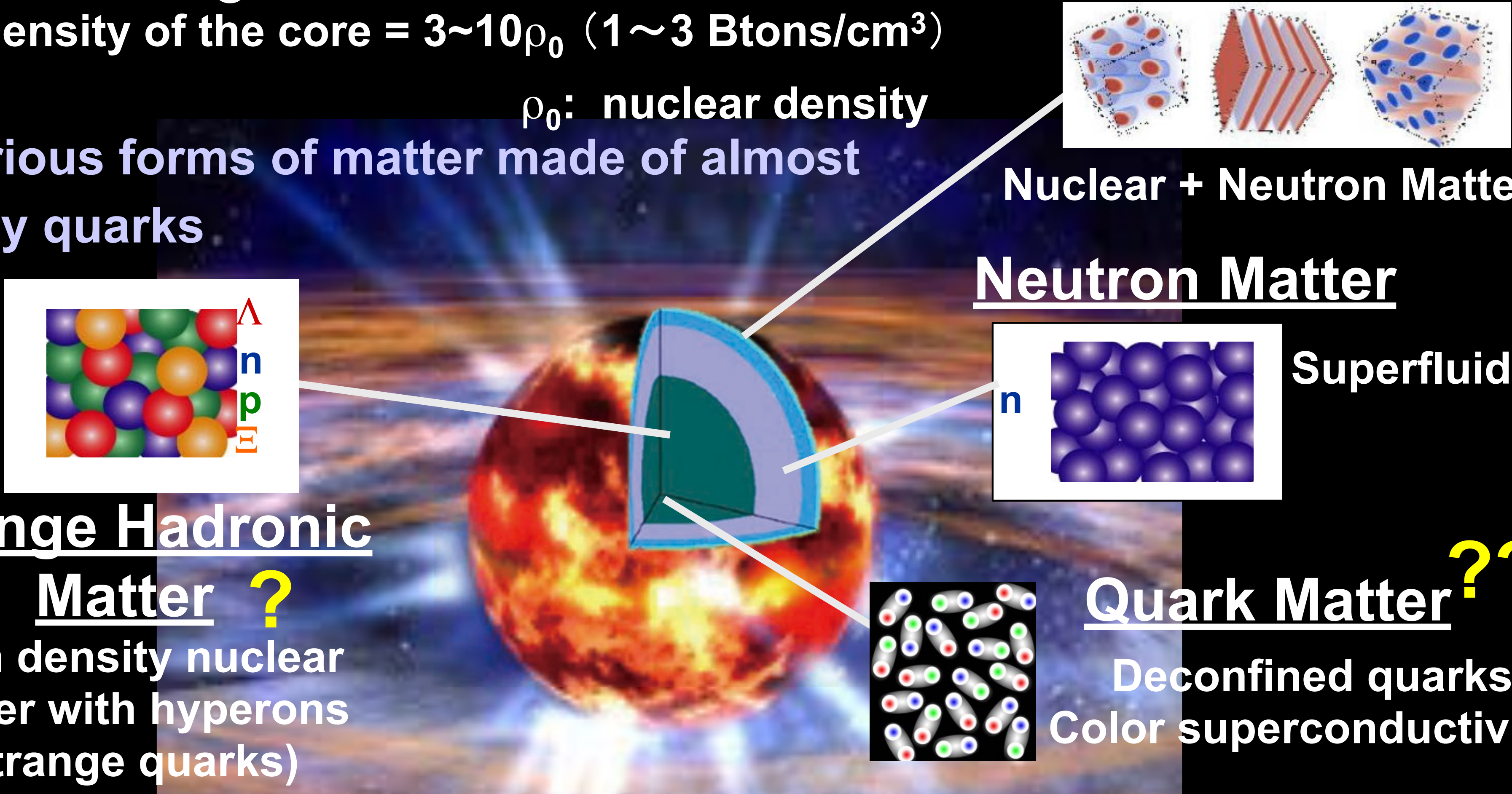
- Highest density matter in the universe

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

  => Density of the core = $3\sim10\rho_0$ (1～3 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 ?

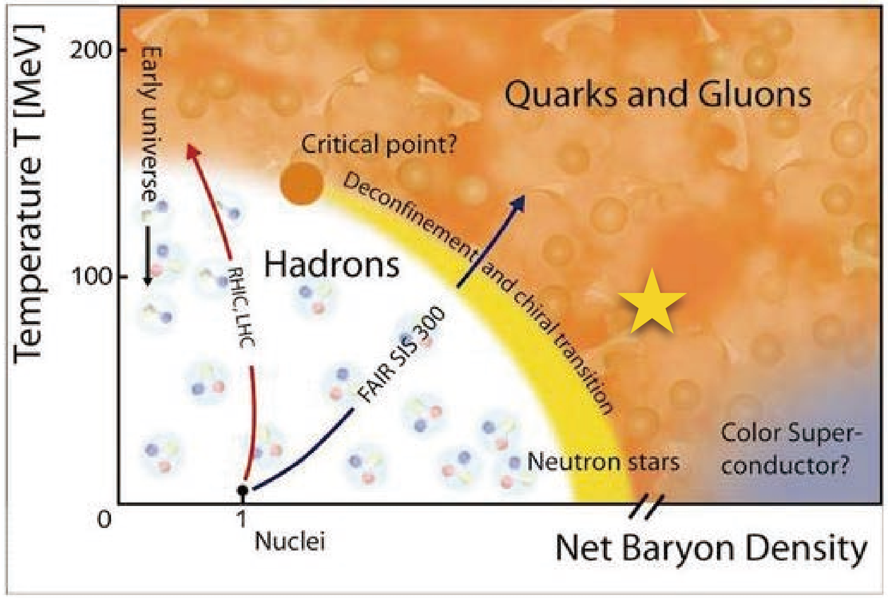
High density nuclear matter with hyperons (strange quarks)

Quark Matter ??

Deconfined quarks
Color superconductivity

High density formation may help multi-strangeness production

Neutron Star - Neutron Star (NS-NS) merger vs. HI collisions at J-PARC

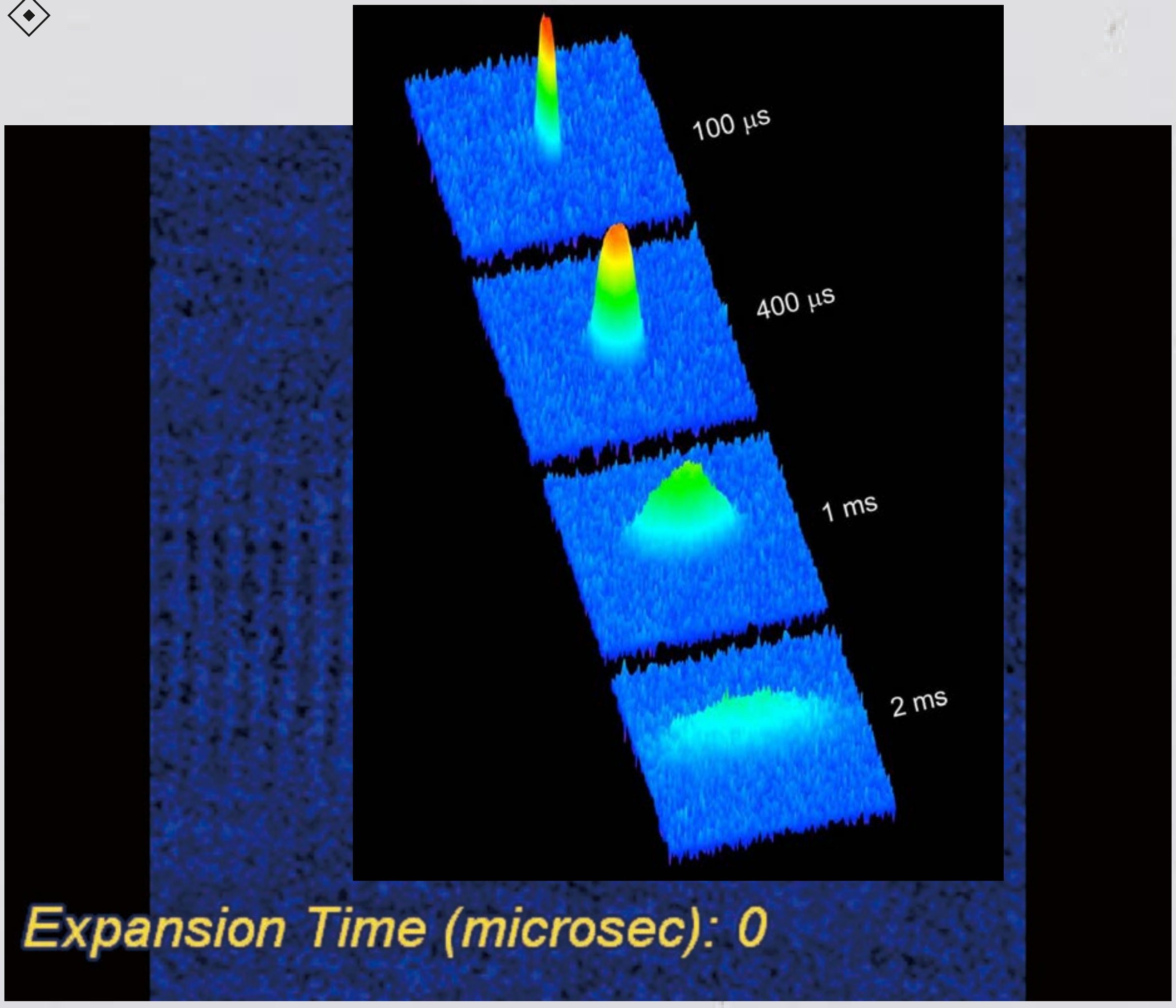


CNN ニュース:
http://www.cnn.co.jp/fringe/35035080.html
プレスリリース
http://www.cfa.harvard.edu/dvlwrap/open_night/PressConference_2013-07-17_640x360_low.mp4

NS-NS merger can touch unreachable region in phase diagram
"high density and (relatively) high temperature"
cf T ~ 100MeV, μ_B~ 1000MeV (Shapiro 1998, Chen,Labun 2013)

Slides from K. Itakura (J-PARC HI workshop @ KEK, Nov. 2014)

strongly coupled system at 10^{-6} K



<u>World at 10^{-6} K</u>

^{6}Li (optical laser cooling)

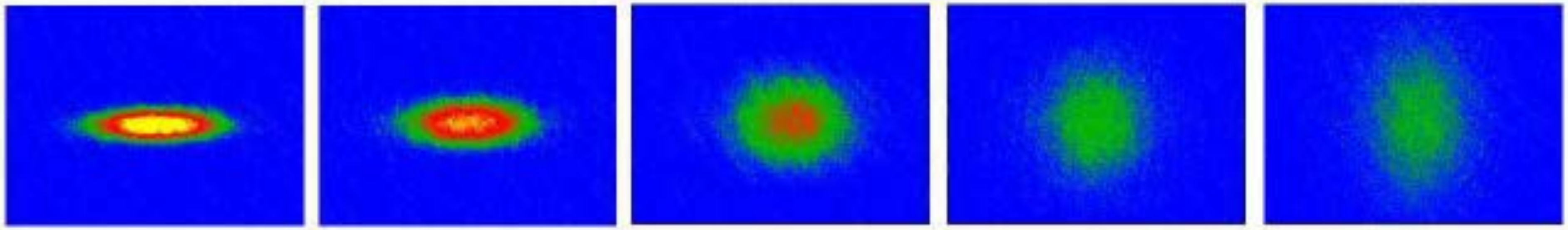
Fermi gas system

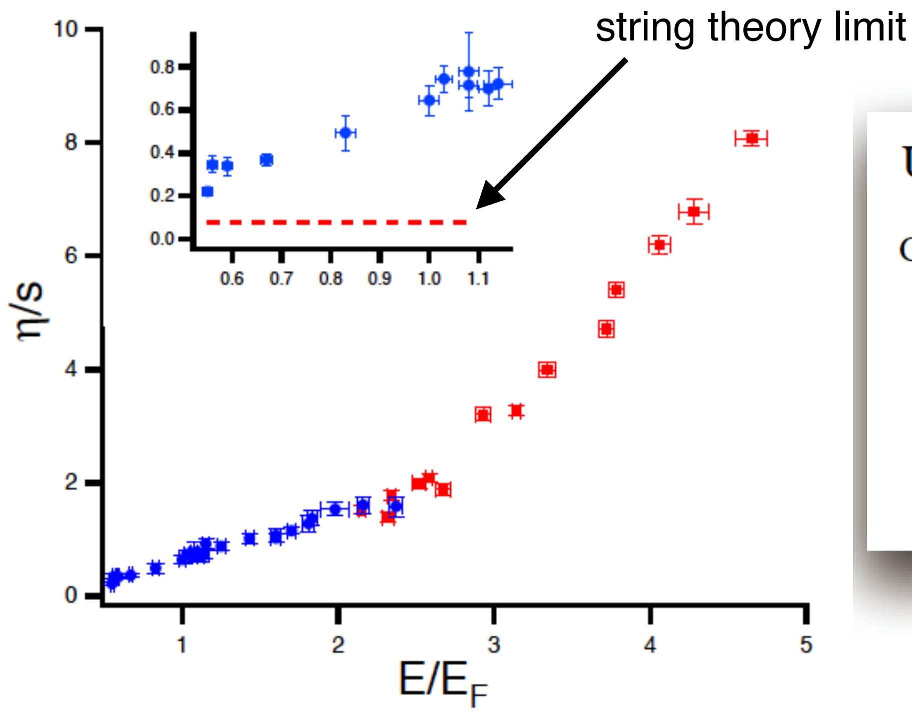
= strongly coupled system

Very similar at 10^{12} K

= strongly coupled QGP (sQGP)

Viscosity/entropy in ultra-cold ^{6}Li gas





Initial energy per atom

Universal Quantum Viscosity in a Unitary Fermi Gas

C. Cao, E. Elliott, J. Joseph, H. Wu, J. Petricka[1], T. Schäfer[2], and J. E. Thomas*

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[1]Physics Department, Gustavus Adolphus College, Saint Peter, Minnesota 56082
[2]Physics Department, North Carolina State University, Raleigh, North Carolina 27695

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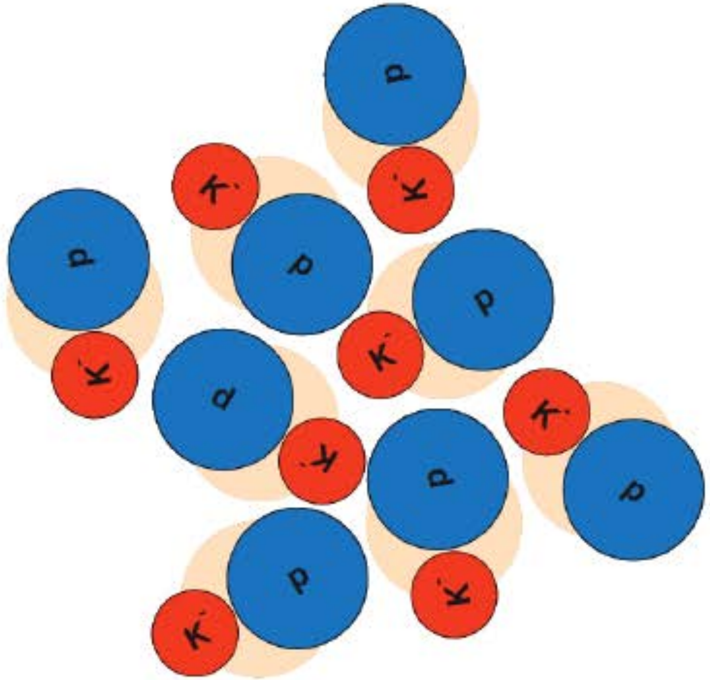
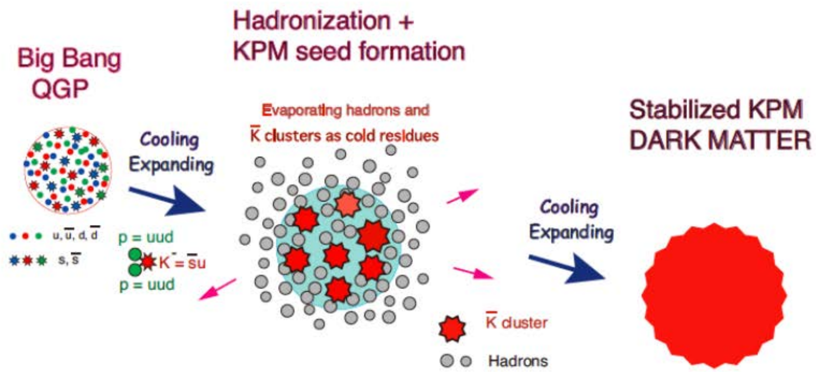
Science 58, 311 (2011)
arXiv:1007.2625v2

KPM

- Strong binding Λ^* = K^- - p (I=0); B=27 MeV
- Stronger inding Λ^*-p; B ~ 100 MeV
- Stronger binding Λ^*-Λ^*; B ~ 200 MeV
- Heitler-London type molecular bonding
- Multi-bonded: Λ^* strangelet -> stable matter?
- Chiral symmetry restoration:
  enhanced binding: furthermore
- Stable, large, heavy, dense, inert, neutral:
  fulfil required properties for DARK MATTER
- How KPM created: Big Bang universe
  right after Big Bang, before hadronization:
  anti-particles are proceeding to annihilation

K^-p (Λ^*) condensed matter

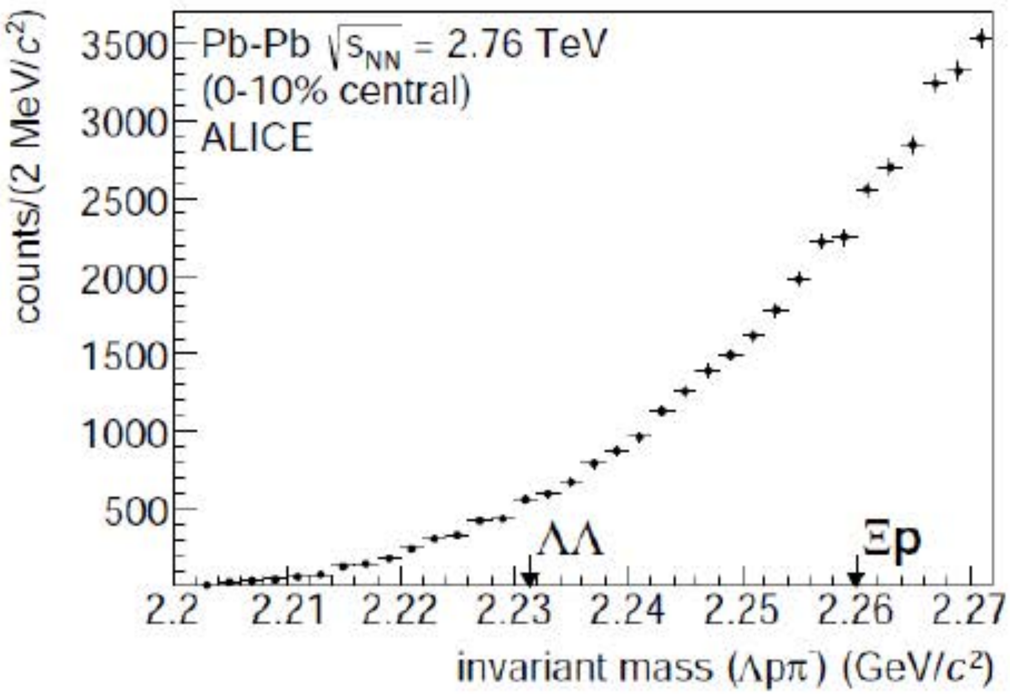


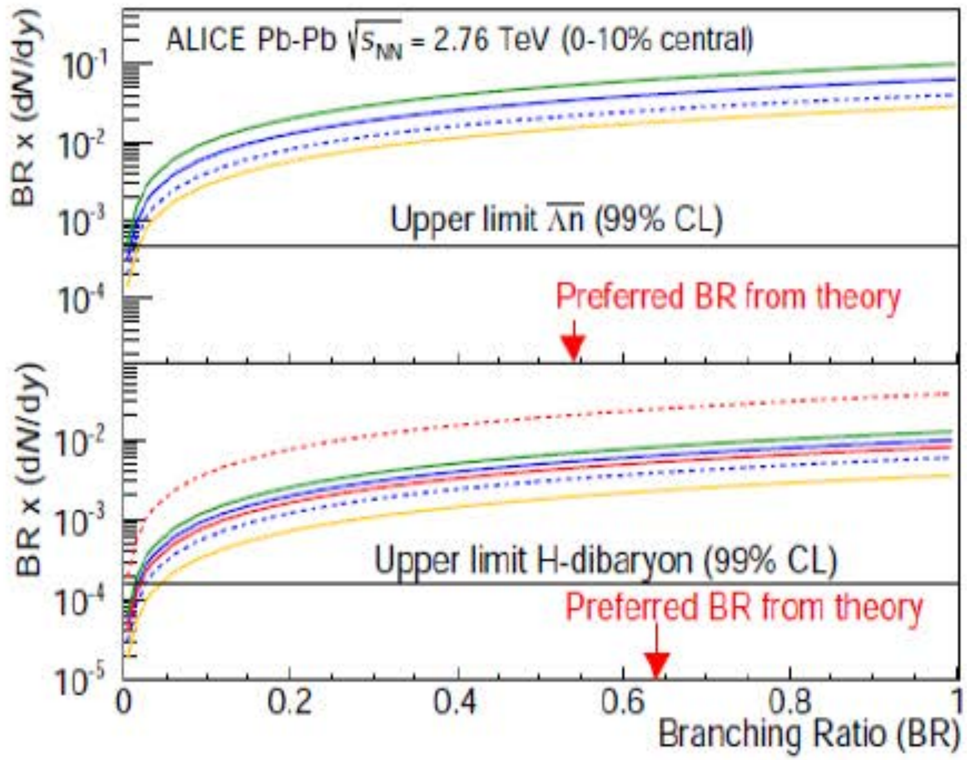


T. Yamazaki
(Reimei WS, 2016)

searches for exotic bound states

Nicole Martin and Benjamin Doenigus, ALICE



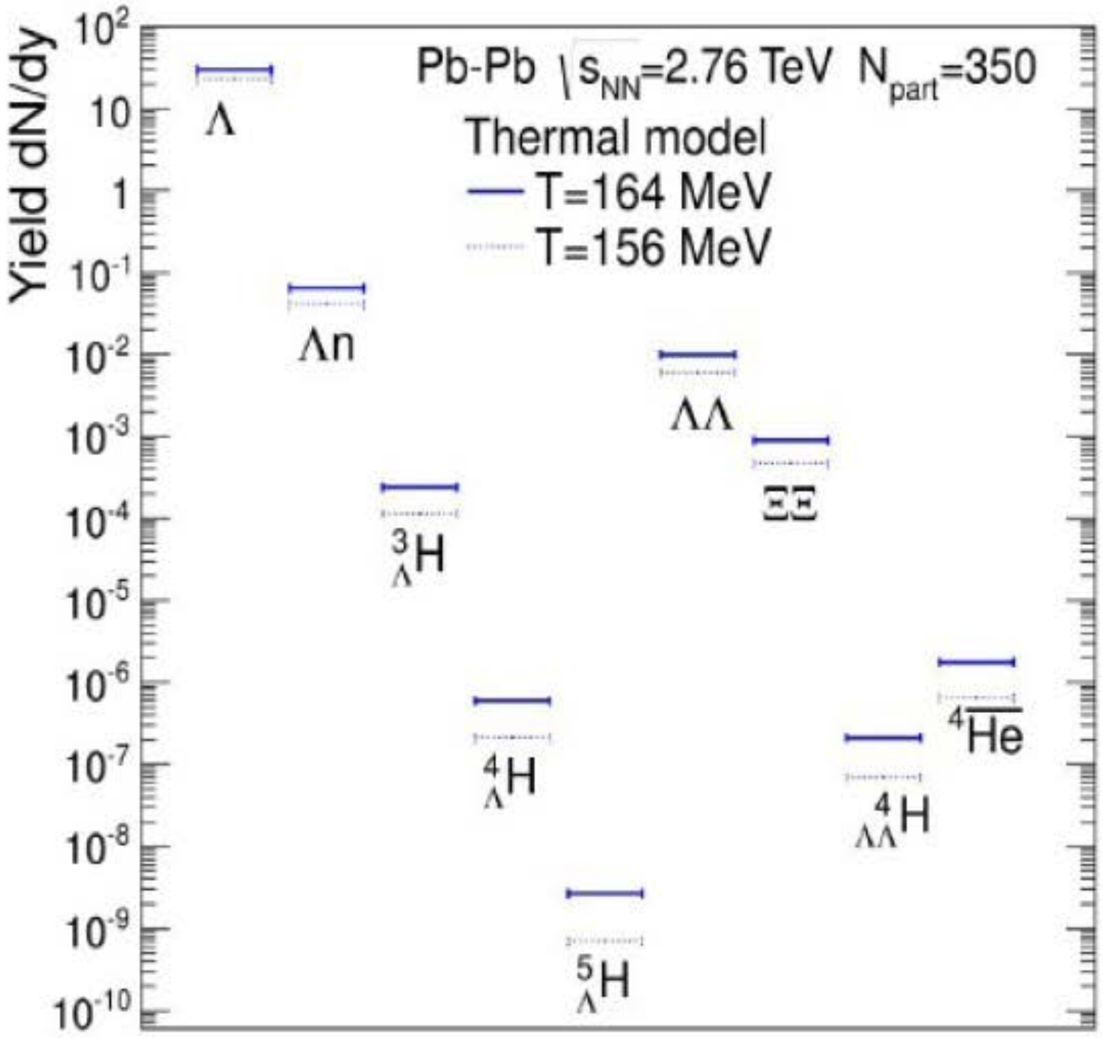


no H, Lambda-n bound states

arXiv:1506.07499

P. Braun-Munzinger (HYP2015)

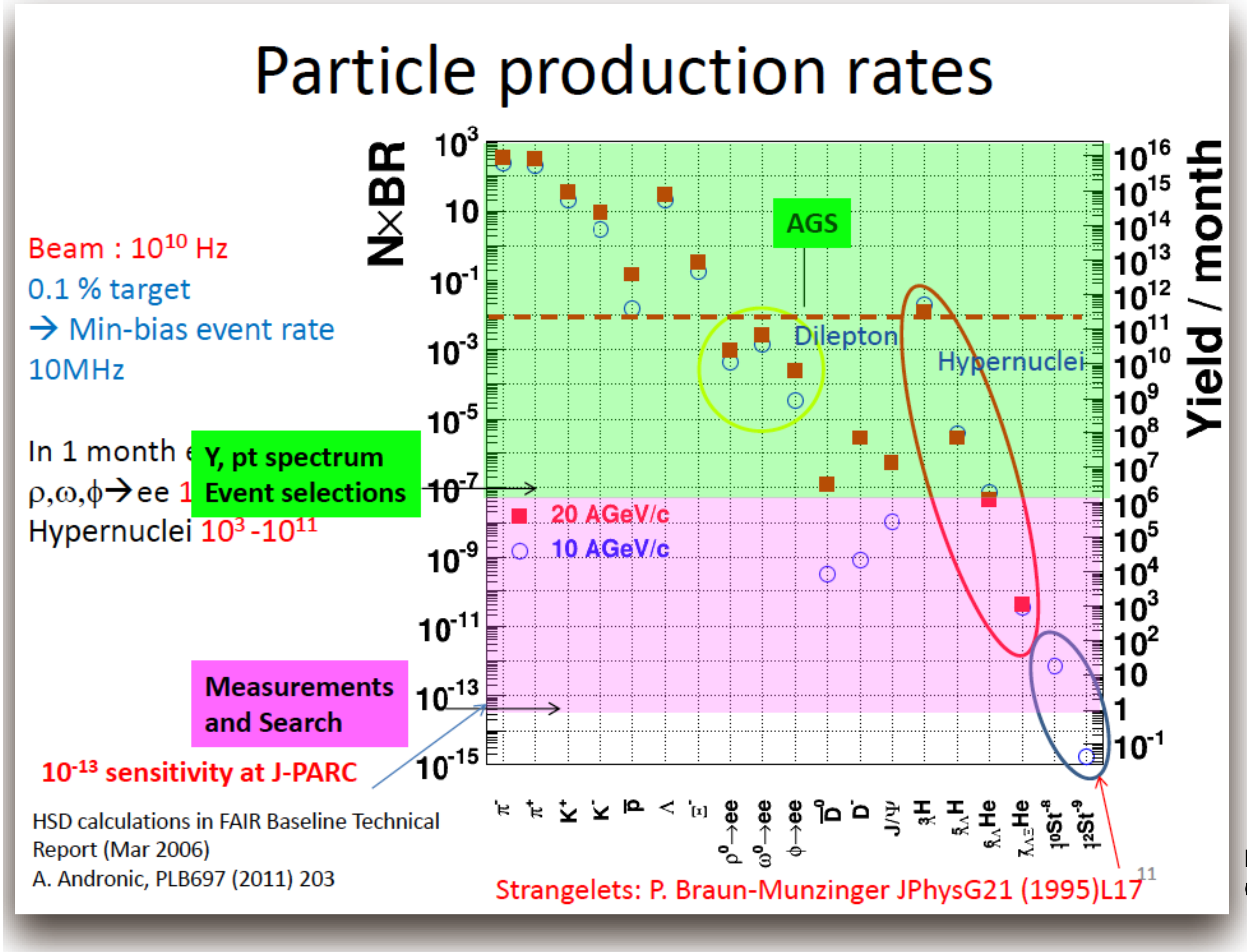
Outlook: what is in reach?



Exciting possibilities for LHC Run2 and in particular Run3

P. Braun-Munzinger (HYP2015)

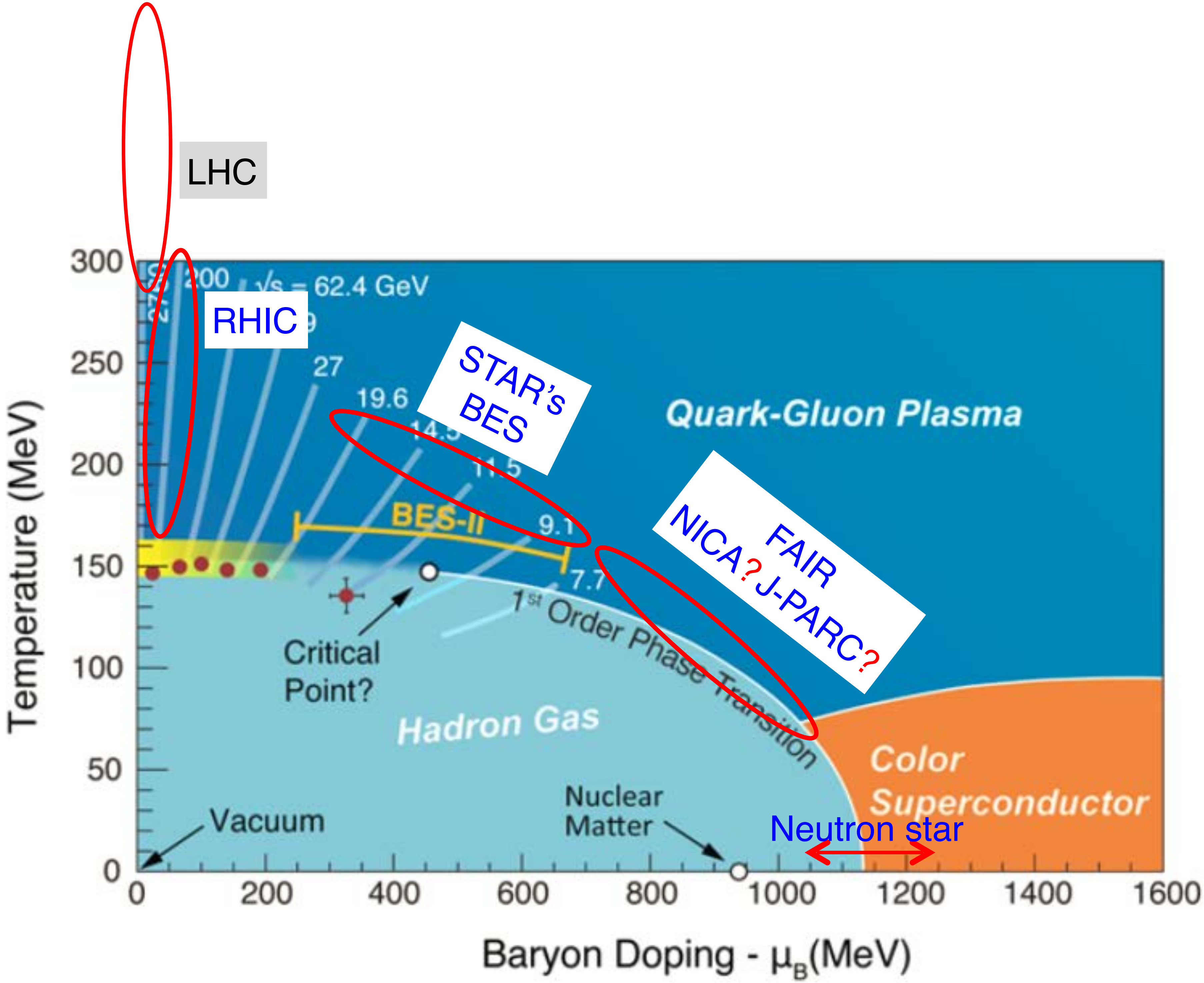
@ J-PARC

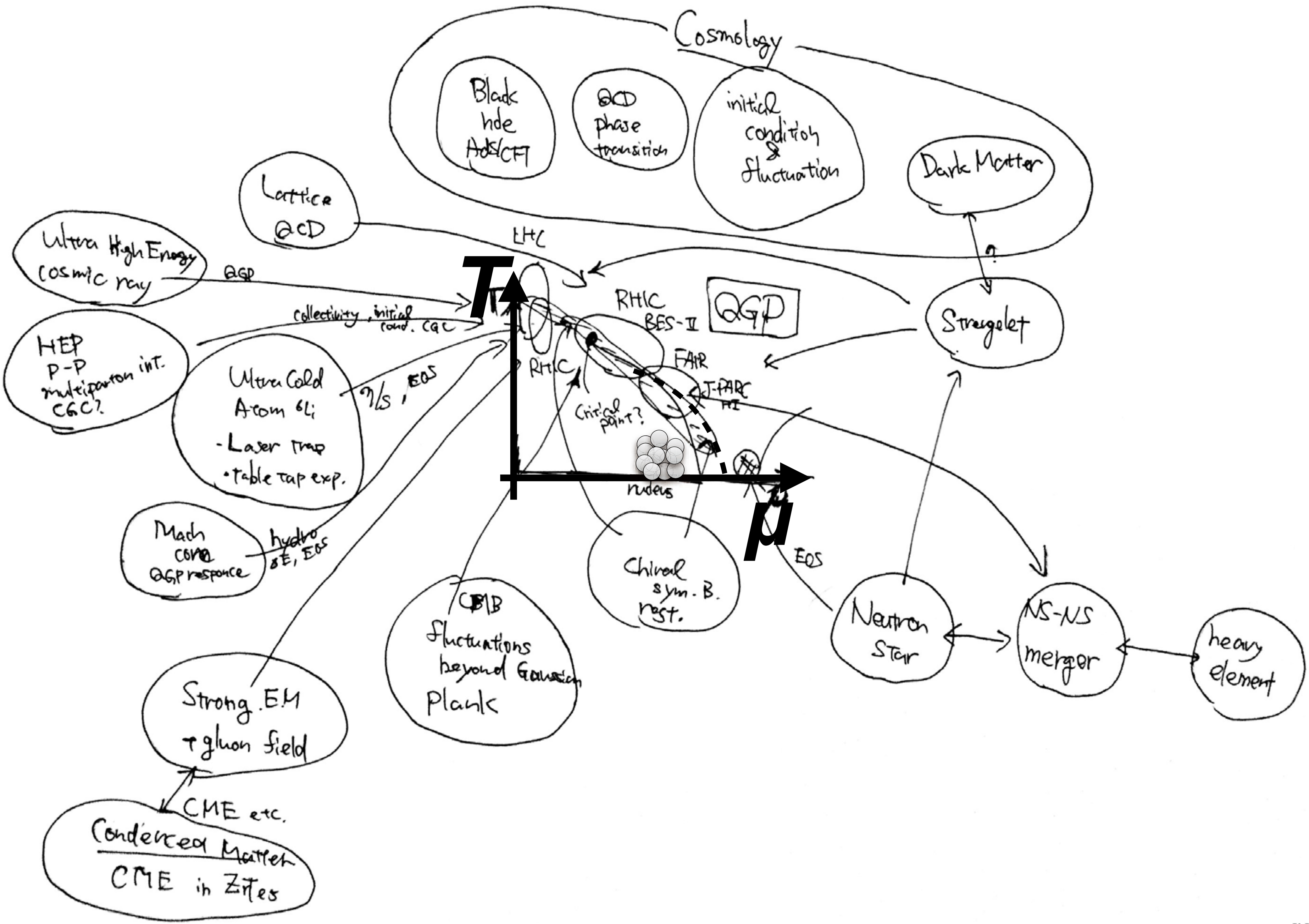


H. Sako
(Reimei WS, 2016)

Many others…

- High energy physics ⇔ small system ⇔ multi-parton scattering or CGC.
- Fluctuation ⇔ non Gaussian fluc.
- Charmed meson, baryon (LHCb (penta quark,exotic))
- High energy cosmic ray & QGP (LHCf)
- Crossover phase transition
- He anti-He (CTP invariance)
- Strong and intense field (E, B), color field.
- CME (chiral magnetic field effect) in condense matter physics (observed; $ZrTe_5$ etc.).
- String theory, black hole and AdS/CFT


LHC
RHIC
STAR's BES
FAIR
NICA? J-PARC?
$\sqrt{s}$ = 62.4 GeV
200
27
19.6
14.5
11.5
9.1
7.7
BES-II
Quark-Gluon Plasma
Critical Point?
1st Order Phase Transition
Hadron Gas
Color Superconductor
Neutron star
Vacuum
Nuclear Matter
Temperature (MeV)
Baryon Doping - μ_B(MeV)
0
50
100
150
200
250
300
0
200
400
600
800
1000
1200
1400
1600


Cosmology
Black hole AdS/CFT
QCD phase transition
initial condition & fluctuation
Dark Matter
Lattice QCD
Ultra High Energy cosmic ray
QGP
LHC
T
collectivity, initial cond. CGC
HEP p-p multiparton int. CGC?
Ultra Cold Atom 6Li
-Laser trap
·table tap exp.
η/s, EOS
RHIC
RHIC BES-II
QGP
FAIR
J-PARC HI
Critical point?
Strangelet
nucleus
μ
EOS
Mach cone QGP responce
hydro δE, EOS
Chiral sym. B. rest.
Neutron Star
NS-NS merger
heavy element
fluctuations beyond Gaussian
Planck
Strong E.M + gluon field
CME etc.
Condensed Matter
CME in Zrtes

Summary

- In this 16 years, a rich physics program using heavy ion beams at RHIC and LHC.
  - Many discoveries (e.g. sQGP) and progress on understanding of nature of QGP.
  - New paradigm (small system), and unresolved issues.
- Presented our scope in 20 years & connections to other fields.
- In my view, interplay with other fields, in particular cosmology, cold atom physics, and condense matter physics will become importance in the next decade(s), to reveal a nature of QGP and history of universe.