# J-PARC における
# 重イオン衝突の物理

## ~ 新たなアプローチによる*QCD*相図解明に向けて ~

中條 達也（筑波大学）

Heavy Ion Pub

２０１５年７月２４日

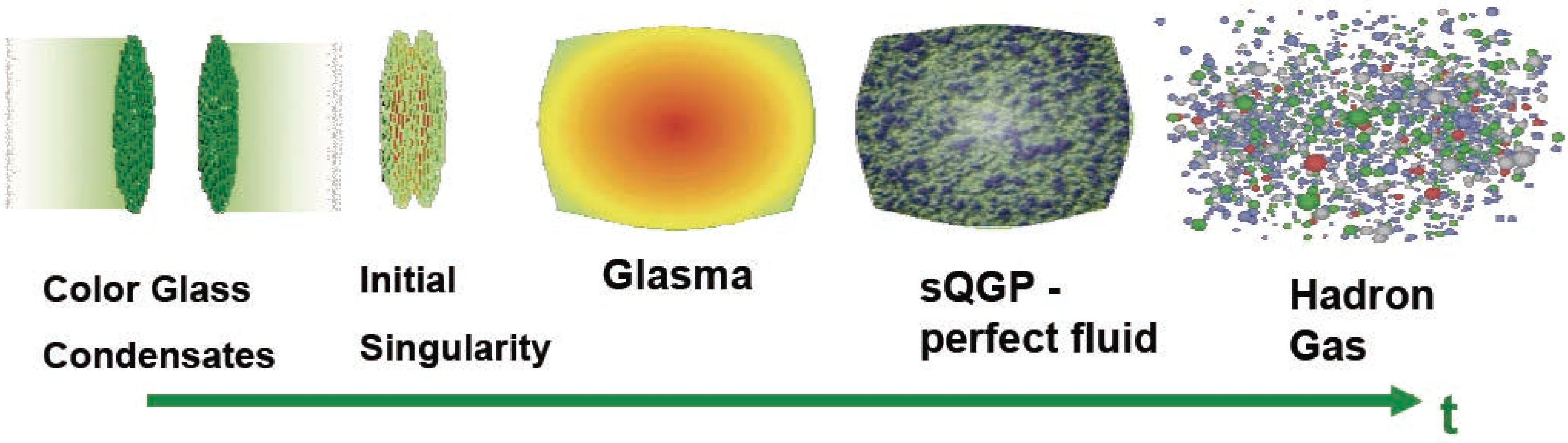
筑波大学
University of Tsukuba

# 目次

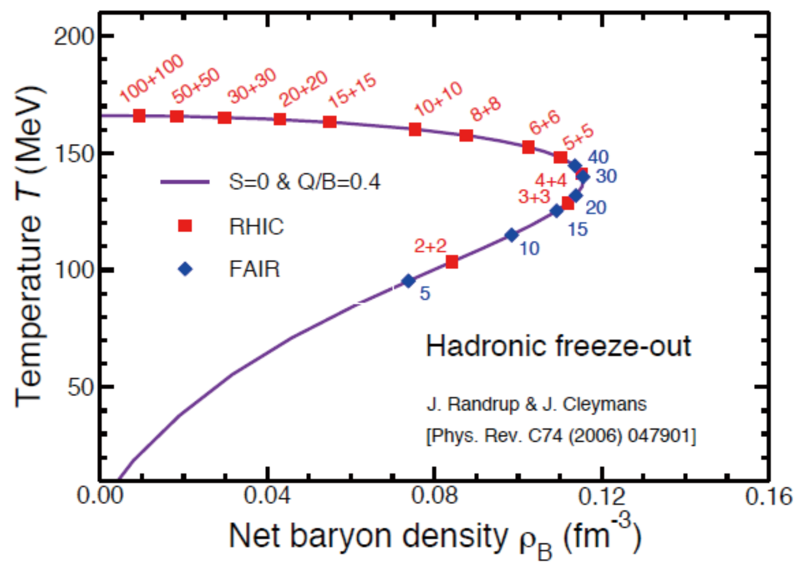
1. 高エネルギー重イオン実験の（簡単な）歴史
2. 分かったこと、まだ分からないこと
3. なぜ今、 J-PARC による重イオン実験か？
   – 目指す物理
4. J-PARC 重イオン実験計画
   – 重イオン加速計画、実験計画
5. まとめ

# I. 高エネルギー重イオン 実験の簡単な歴史

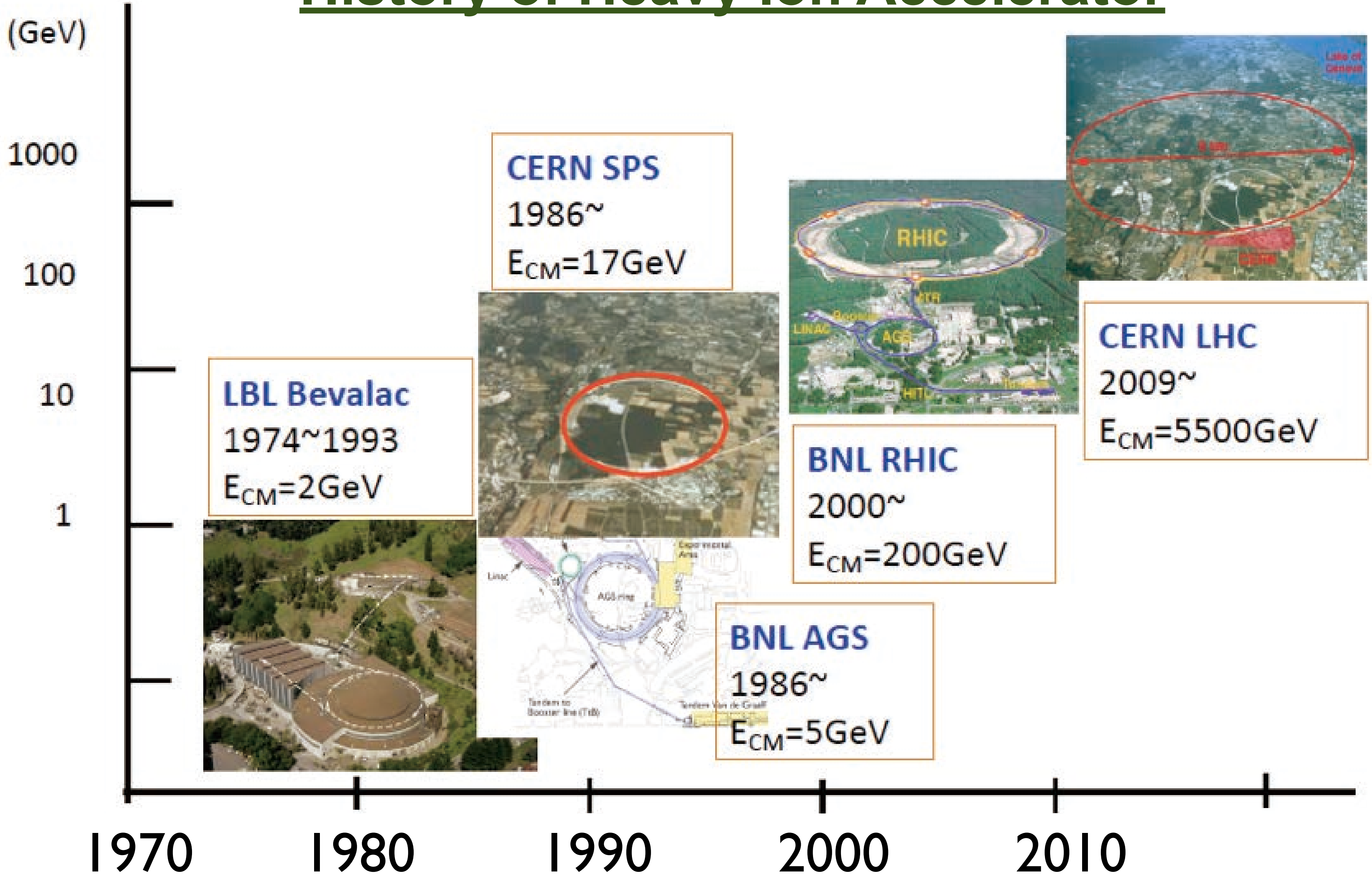
# 高エネルギー重イオン反応



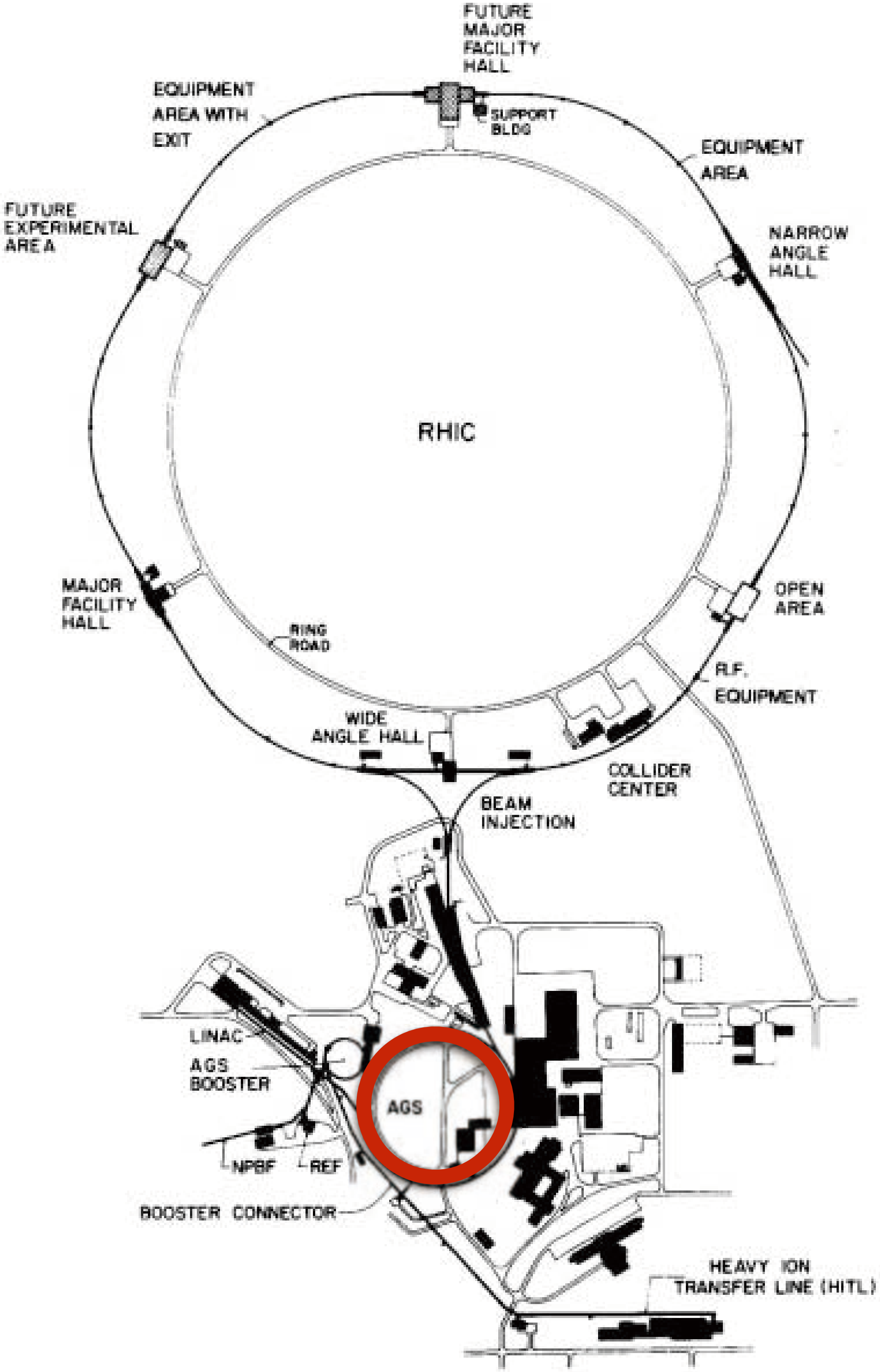

- 重イオン衝突＝非常に dynamical. 時空発展による物理現象の理解が不可能
- 衝突エネルギーの変化→ dynamics と QCD 相図上の軌跡が変化



# History of Heavy Ion Accelerator

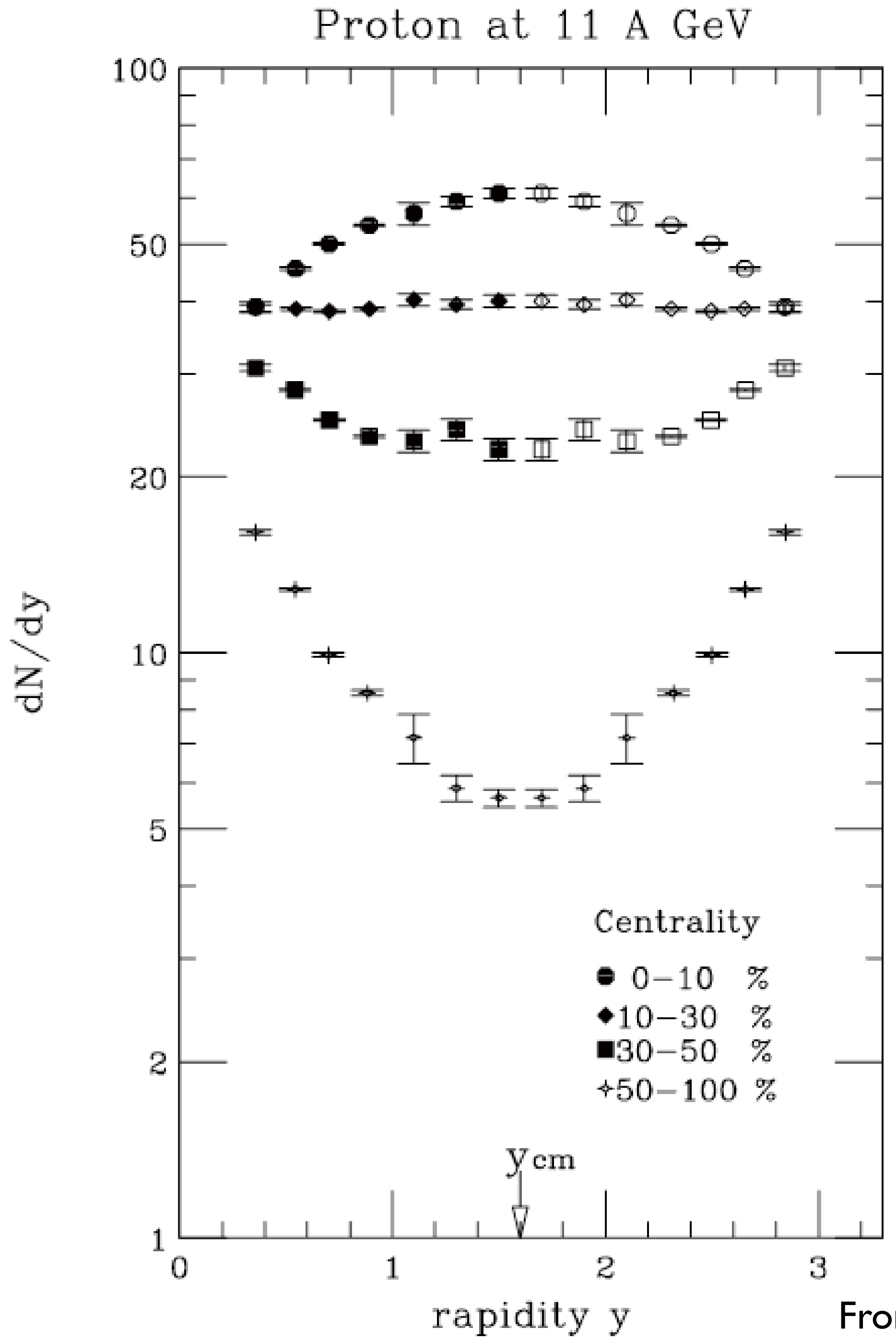



Slide from H. Hamagaki



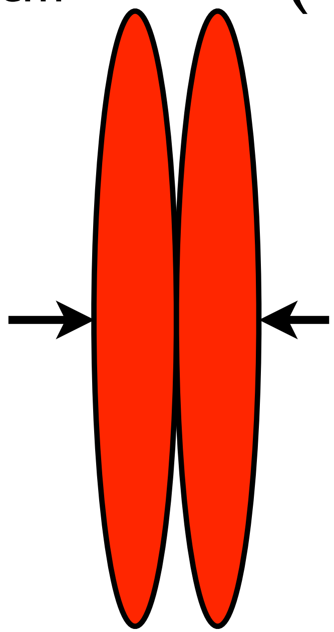

# BNL-AGS; Alternating Gradient Synchrotron (1986-, $\sqrt{s_{NN}} = 5$ GeV)

# Baryon stopping




**Proton rapidity distributions**

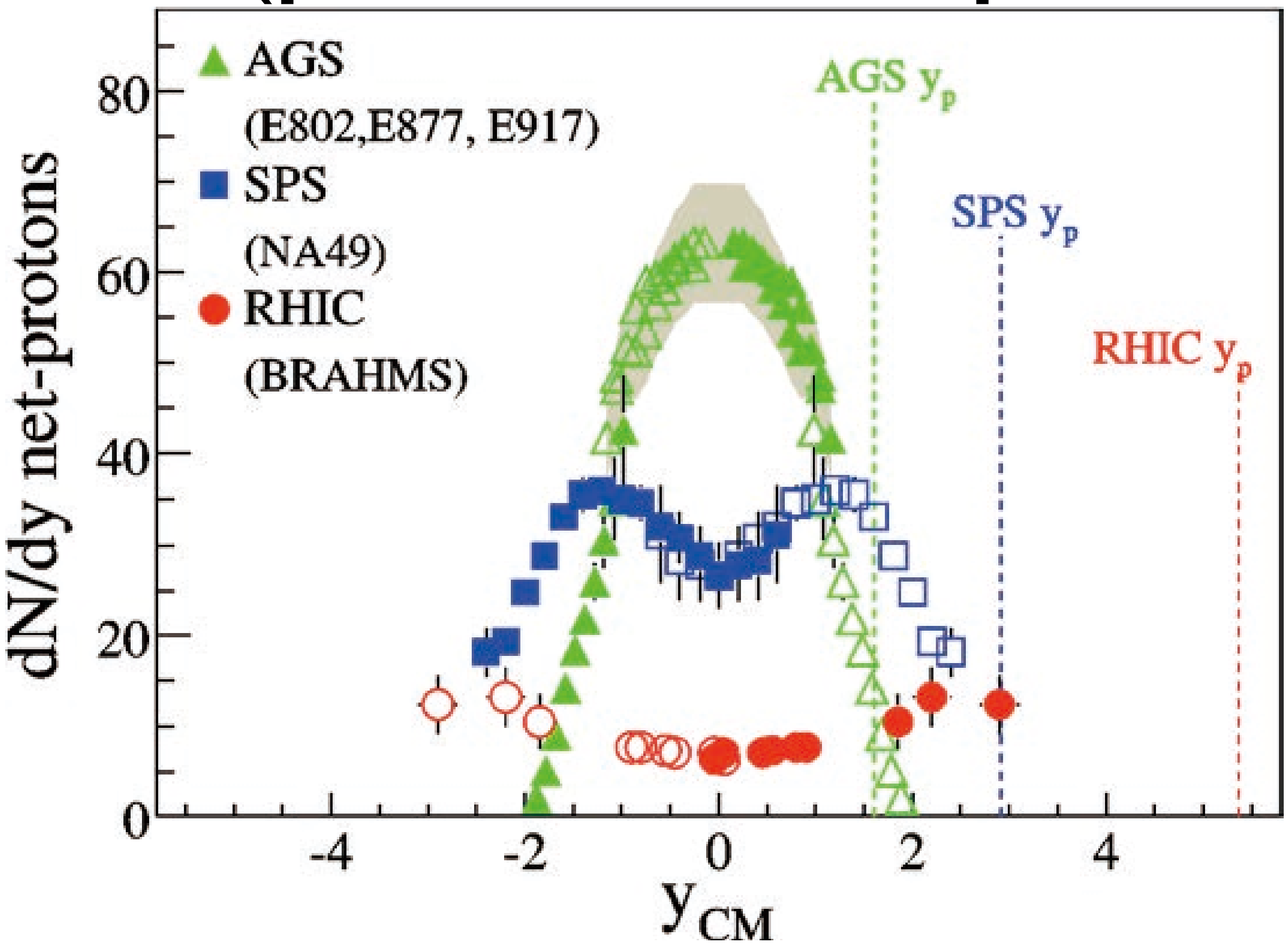
$y_{cm}$ = 1.6 (AGS)



maximum proton density at mid-rapidity = maximum baryon stopping at AGS

From TC, PhD thesis (2000)

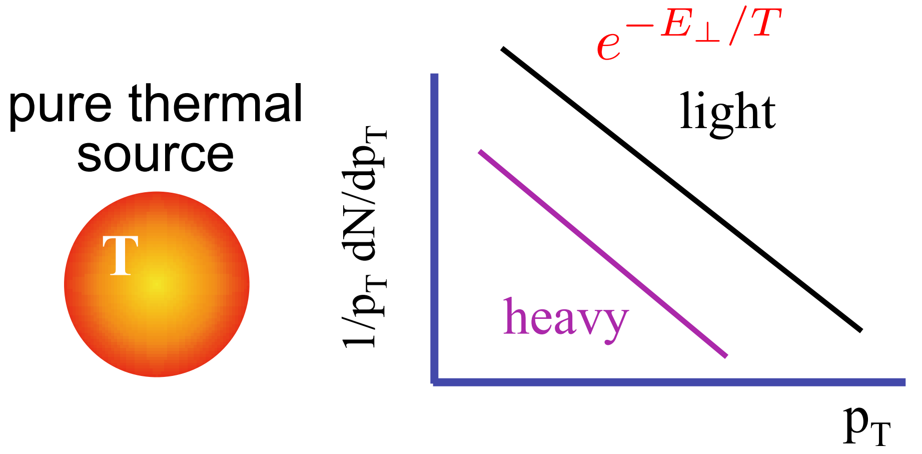
# Net proton dN/dy (proton - antiproton)




BRAHMS collaboration, Nucl. Phys. A 757 (2005) 1-27

Fig. 1. Rapidity density of net protons (i.e., number of protons minus number of antiprotons) measured at AGS, SPS, and RHIC (BRAHMS) for central collisions [19]. At RHIC, where the beam rapidity is $y = 5.4$, the full distribution cannot be measured with current experiments, but BRAHMS will be able to extend its unique results to $y = 3.5$ from the most recent high statistics Au + Au run, corresponding to measurements extending to 2.3 degrees with respect to the beam direction.

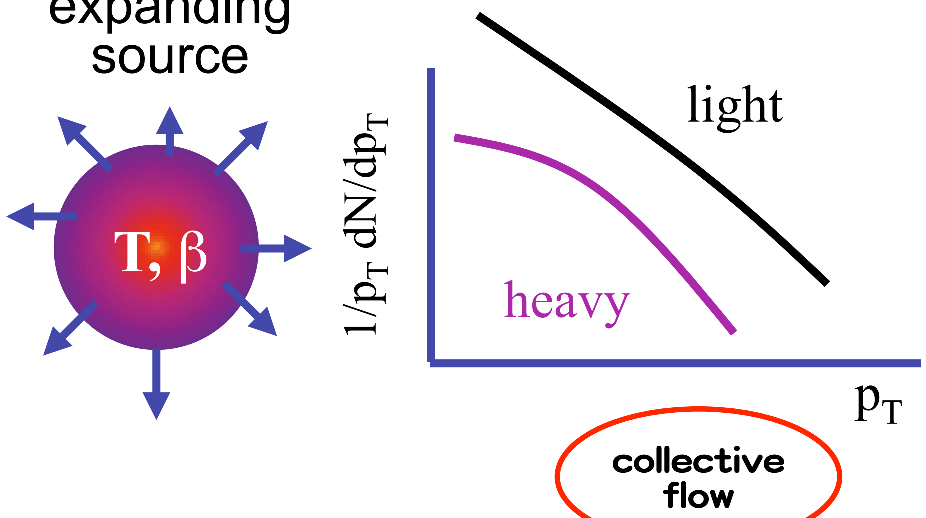
# Radial flow (expansion) and blue shift




**w/o expansion:**

Energy ($p_T$) distribution determined by temperature T:

**Boltzmann distribution (thermal distribution)**




$$T \approx T_0 + \frac{1}{2} m v_r^2$$

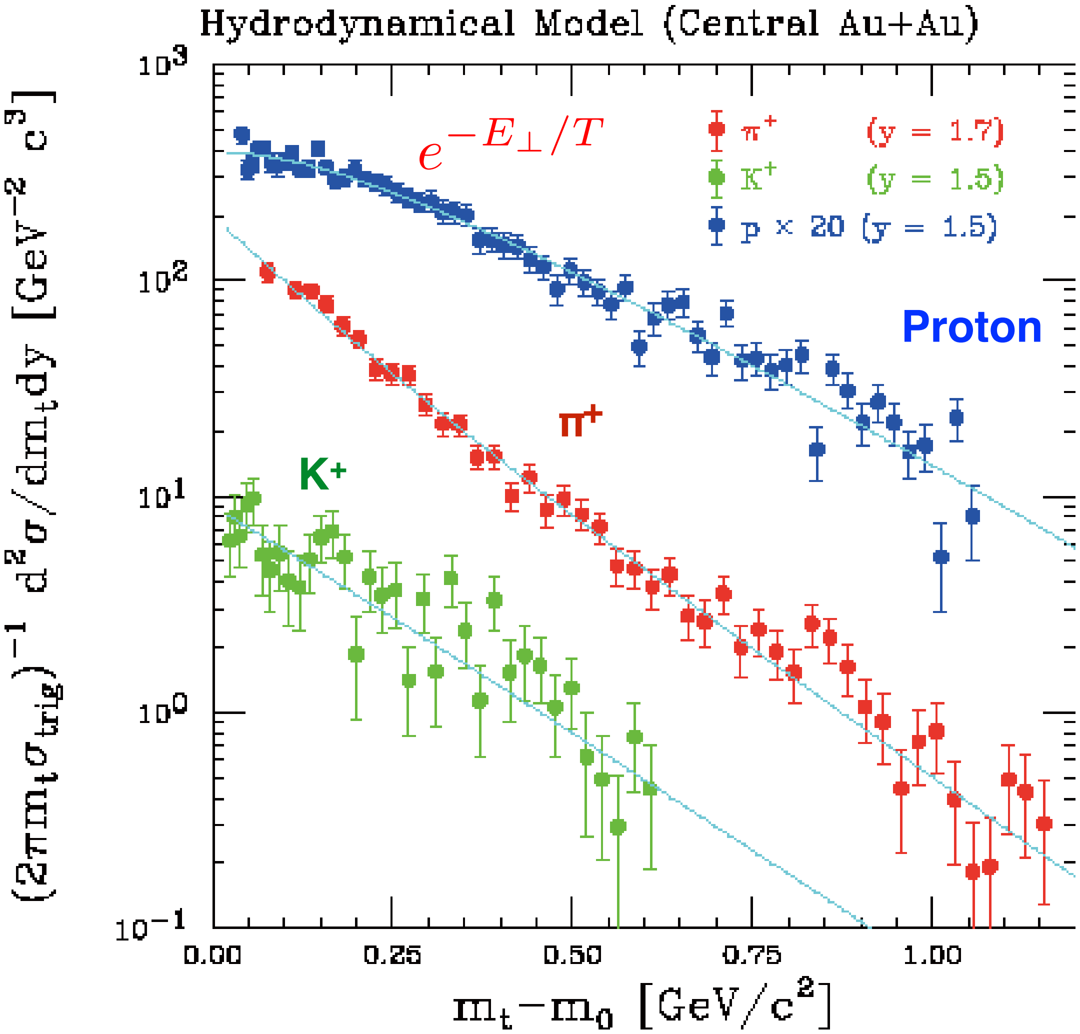
**w/ expansion:**

Particles are pushed by common velocity (flow). The larger energy for the heavier particle (kinetic energy ~ $mv^2$).

Particles come towards an observer (blue shift)

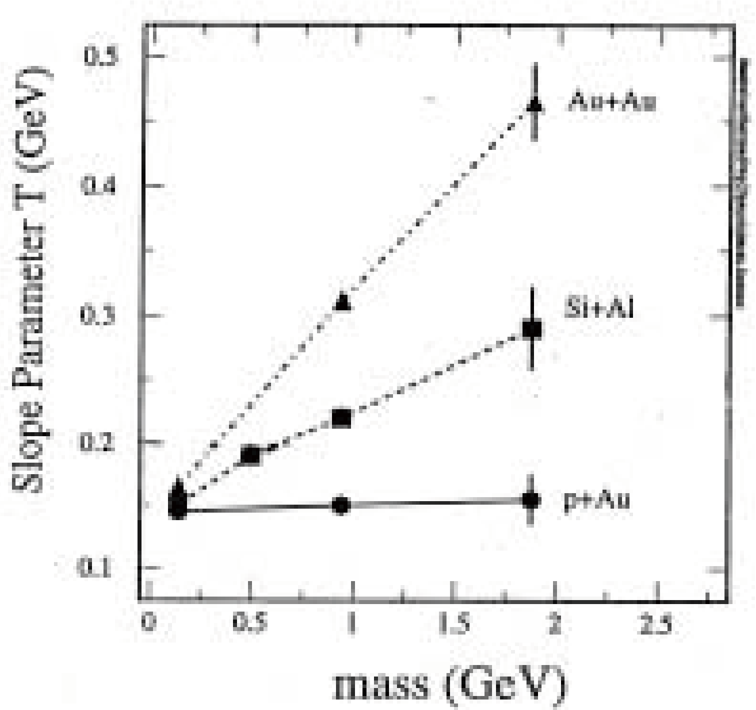
**Boltzmann + radial flow effect**

# Collective flow



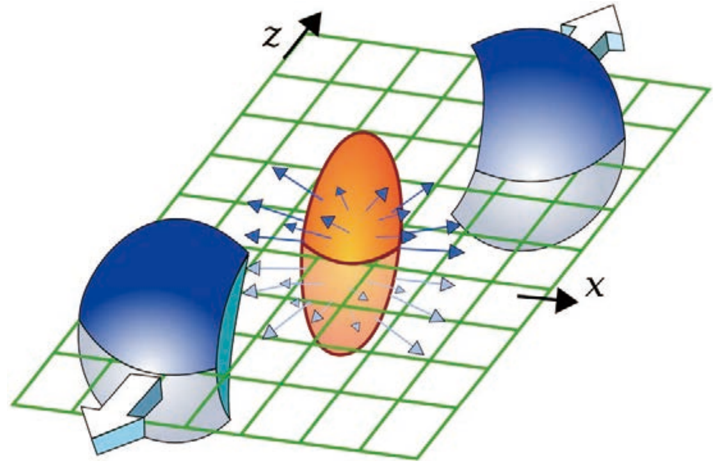

$$T \approx T_0 + \frac{1}{2} m v_r^2$$

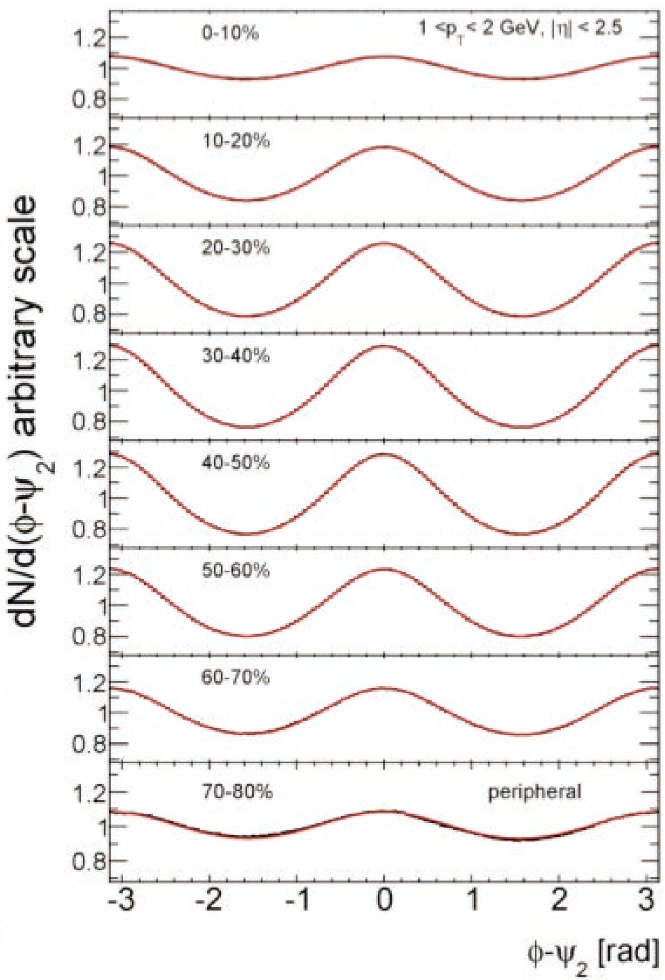
collective flow

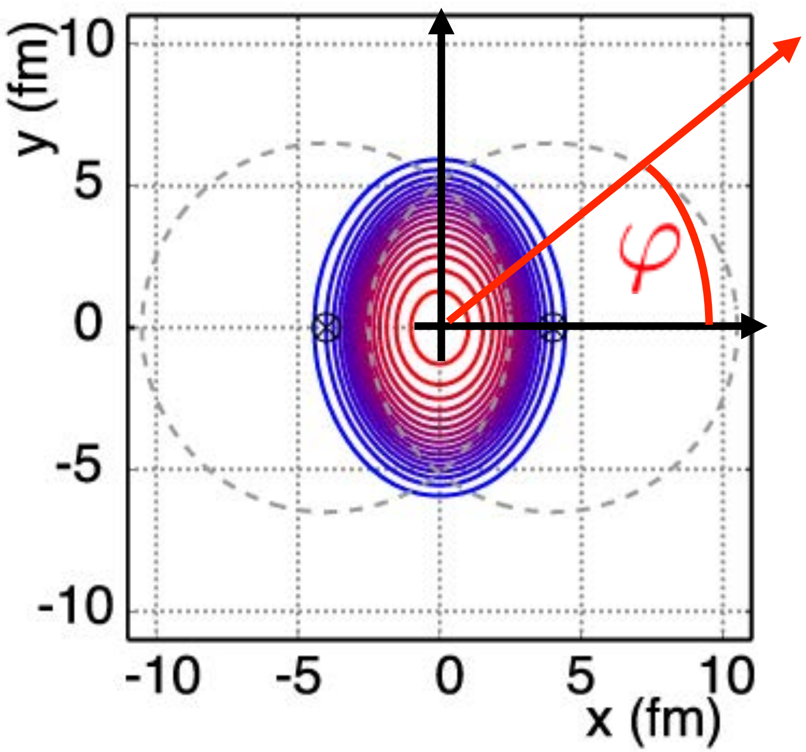



- ✓ Flatter $m_t$ distr for heavier particle mass
  - Mass Ordering of slope parameter T.
- ✓ Collective flow boosts pt distr. according to its mass

# Elliptic flow



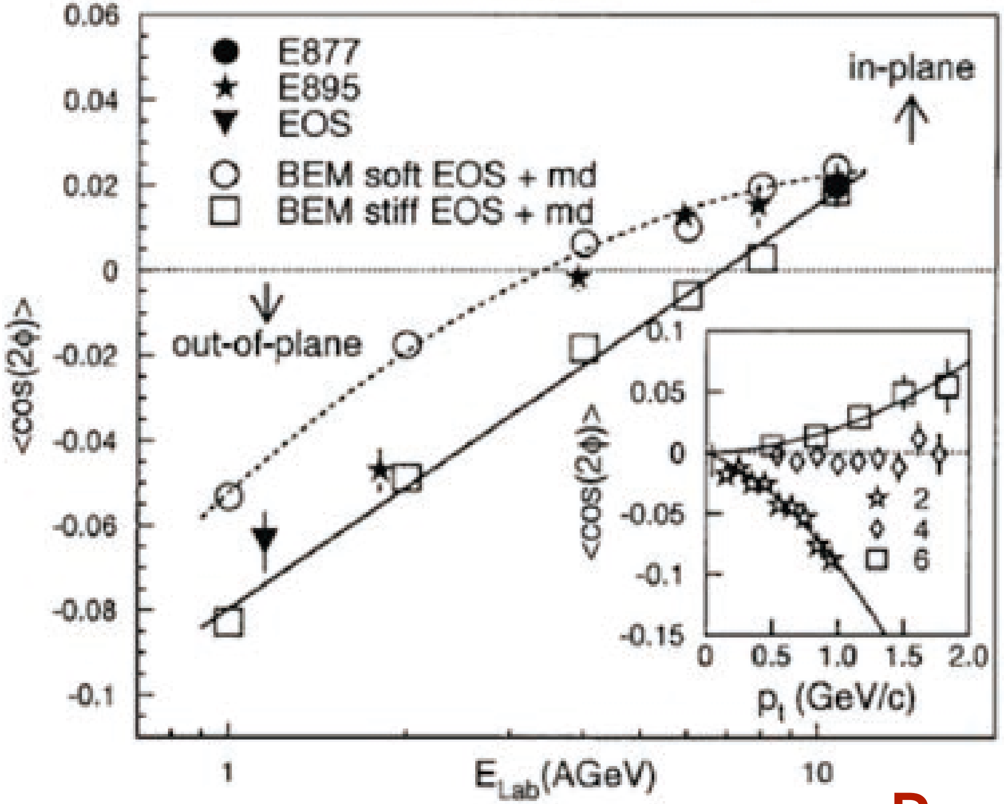



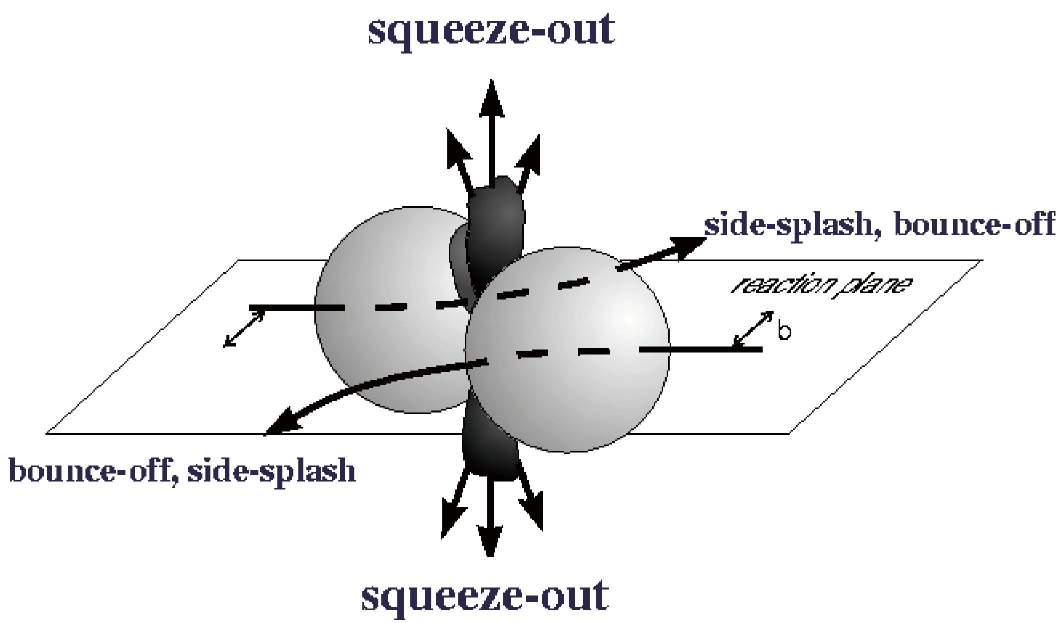

$$\frac{dN}{p_T dp_T dy d\varphi}(p_T, \varphi; b) = \frac{dN}{2\pi p_T dp_T dy}\left(1 + 2v_2(p_T; b)\cos(2\varphi) + \ldots\right)$$

# Elliptic flow crossover at AGS energy

$v_2$



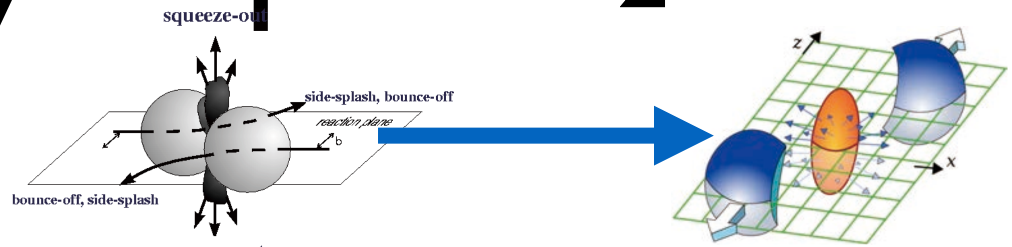

C. Pinkenburg et al. (E895 Collaboration), PRL 83 (1999) 1295-1298.

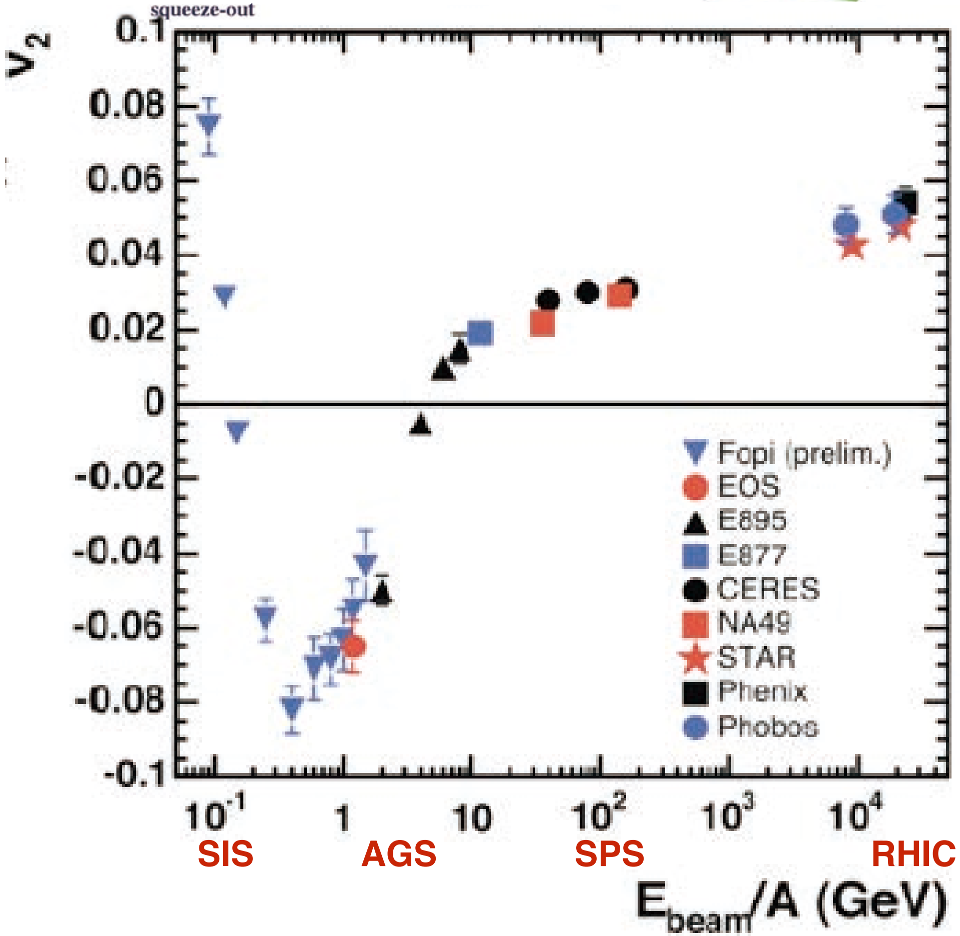



Beam Energy (A GeV)

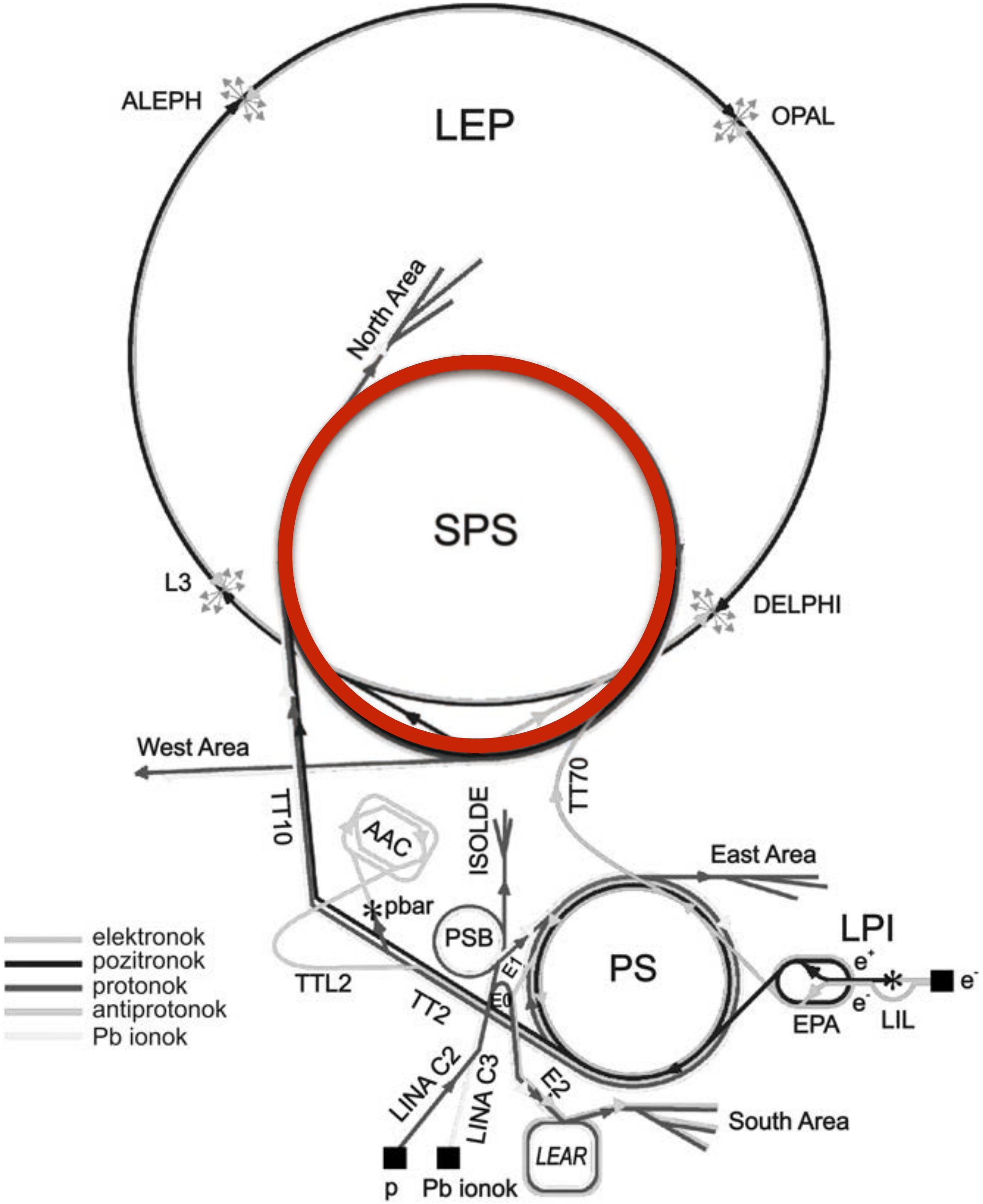
# Beam energy dep. of $v_2$

- **Low energy (~200MeV): positive $v_2$**
  - bouncing off of colliding nuclei
- **Medium energy (200 MeV - 4 GeV): negative $v_2$**
  - blocking effect by spectators
- **High energy (>4 GeV): negative to positive $v_2$**
  - better separation between spectators and participants
  - Nuclear mean field
  - Pressure gradient (EOS)

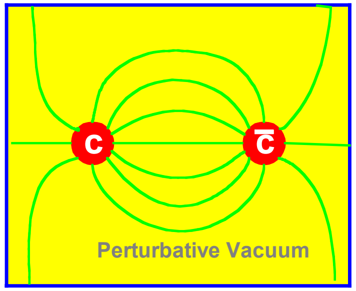


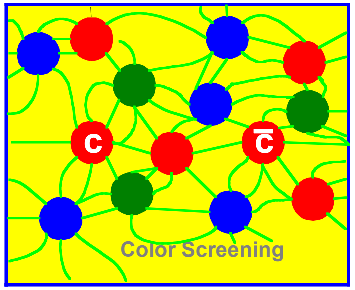



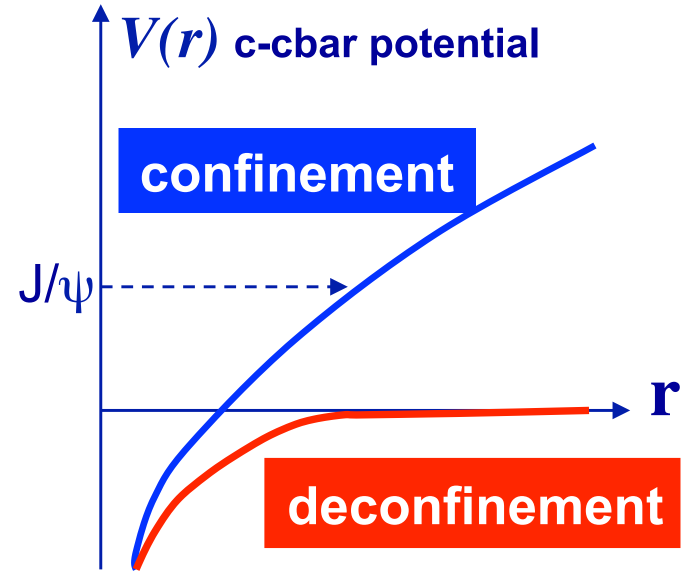

Beam energy




# CERN-SPS; Super Proton Synchrotron (1986-, $\sqrt{s_{NN}} = 17$ GeV)

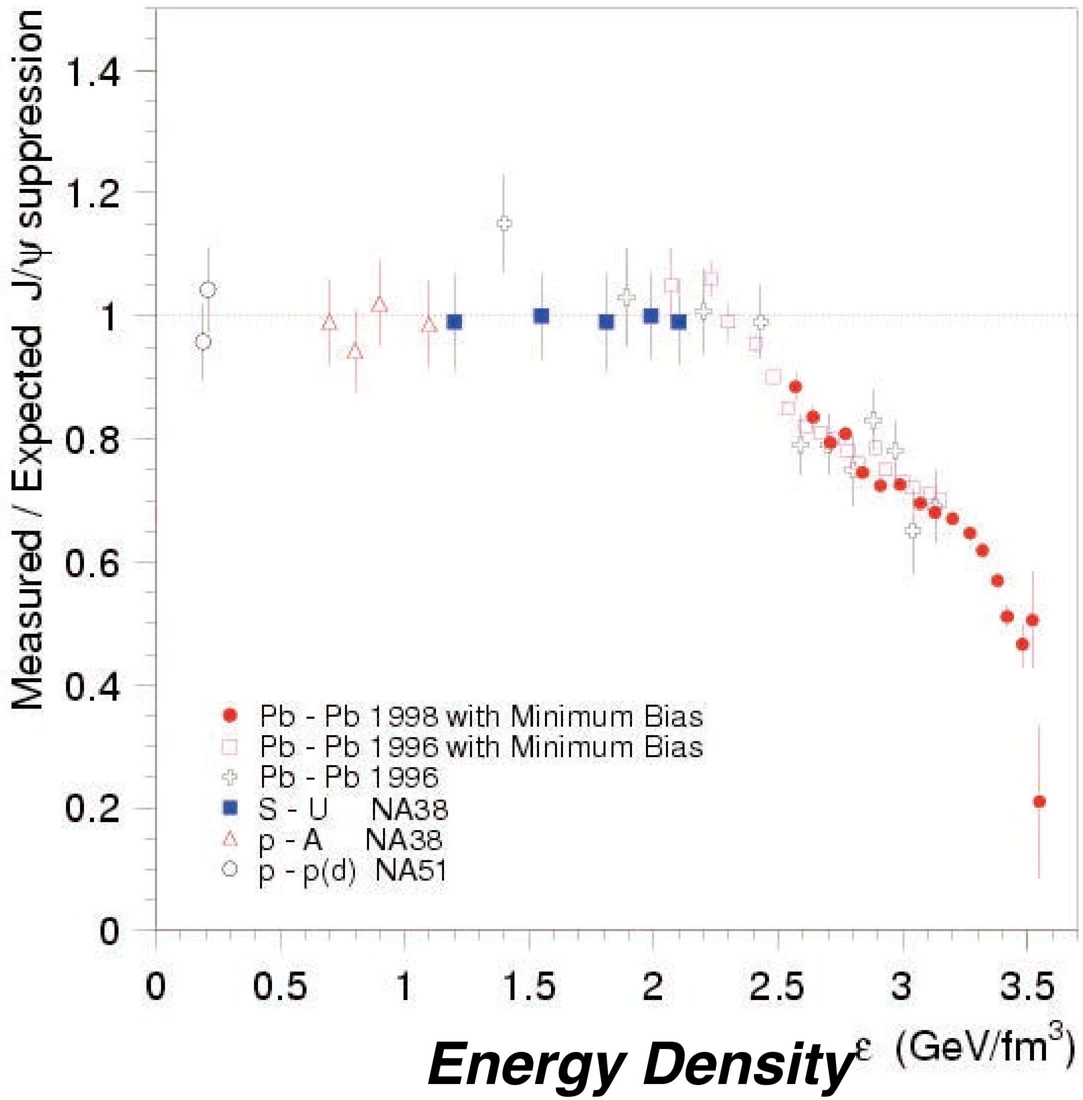



CERN SPS
NA50 Collaboration
http://na50.web.cern.ch/NA50/

## *Survival Probability*

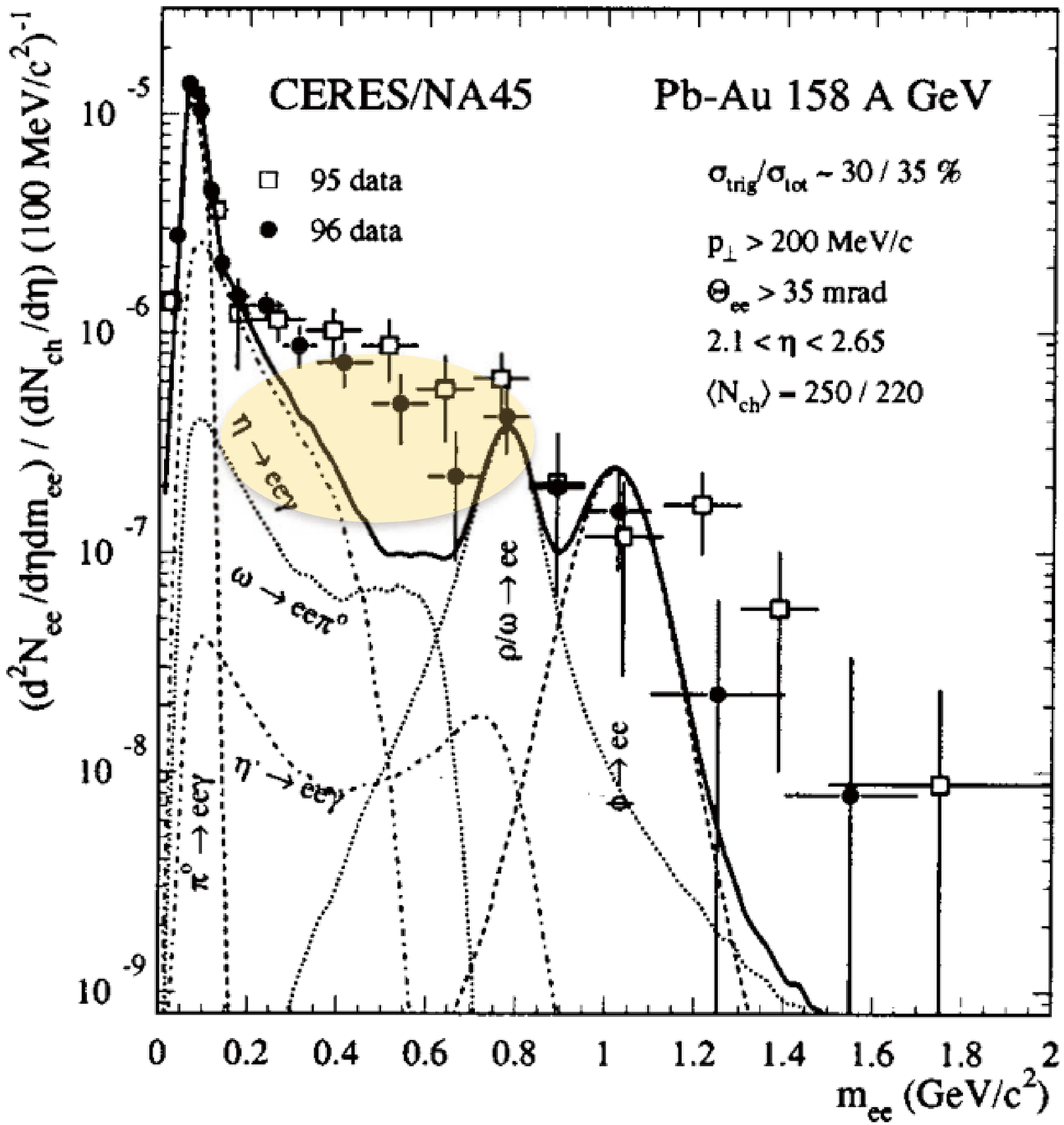



•T. Matsui and H. Satz, Phys. Lett. **B178,** 416 (1986).

Anomalous J/ψ suppression is observed.

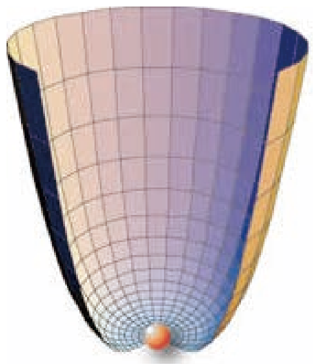
$$\epsilon_0(y) = \langle m_\perp \rangle \frac{1}{\tau_0 A_\perp} \frac{dN}{dy} \quad ,$$

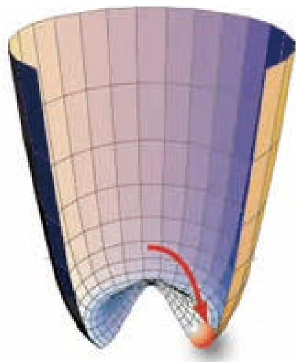
# CERES/NA45

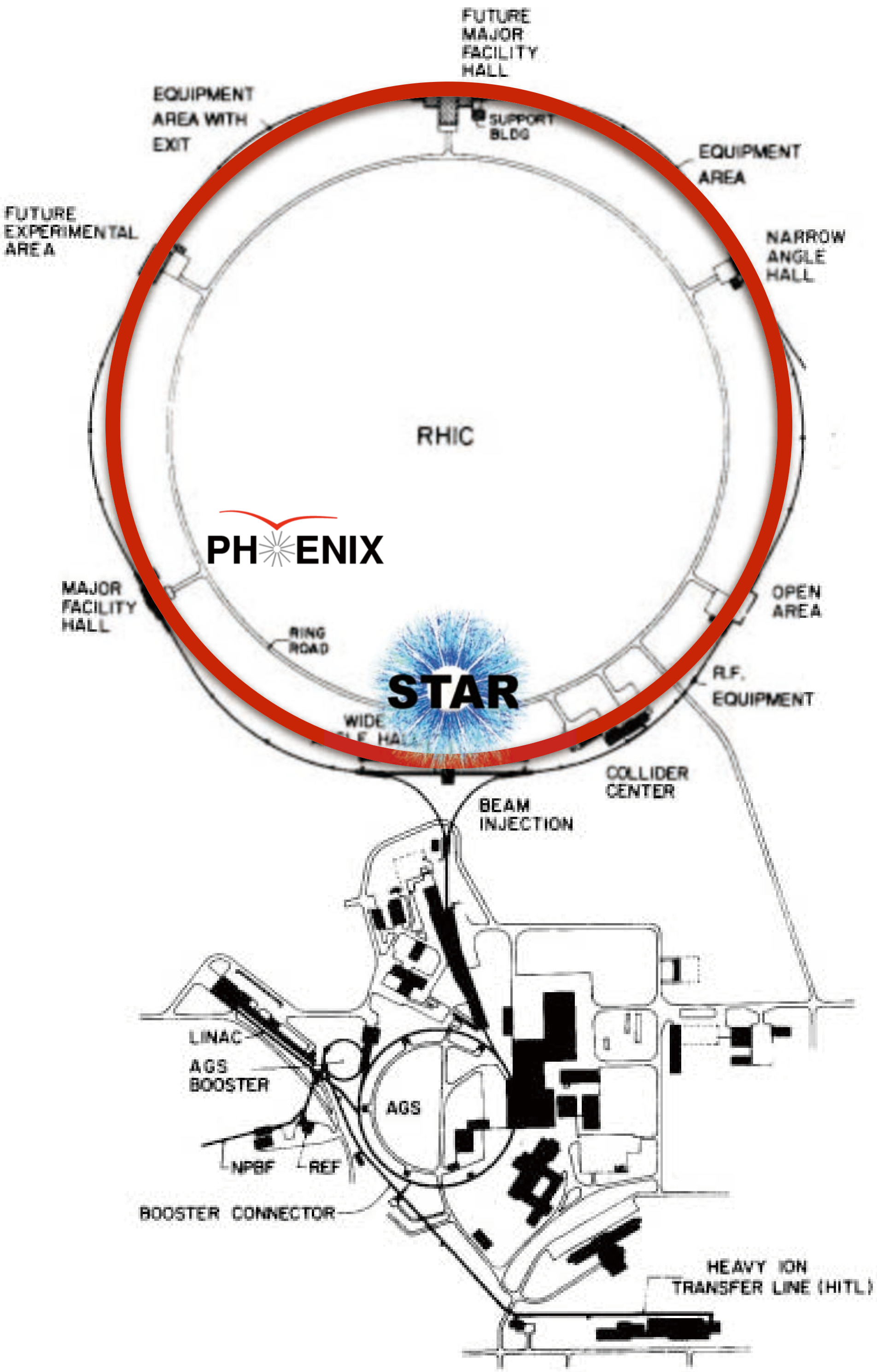



Anomalous enhancement of dilepton pairs are observed.

A hint of chiral symmetry restoration
(but other models can also explain it)



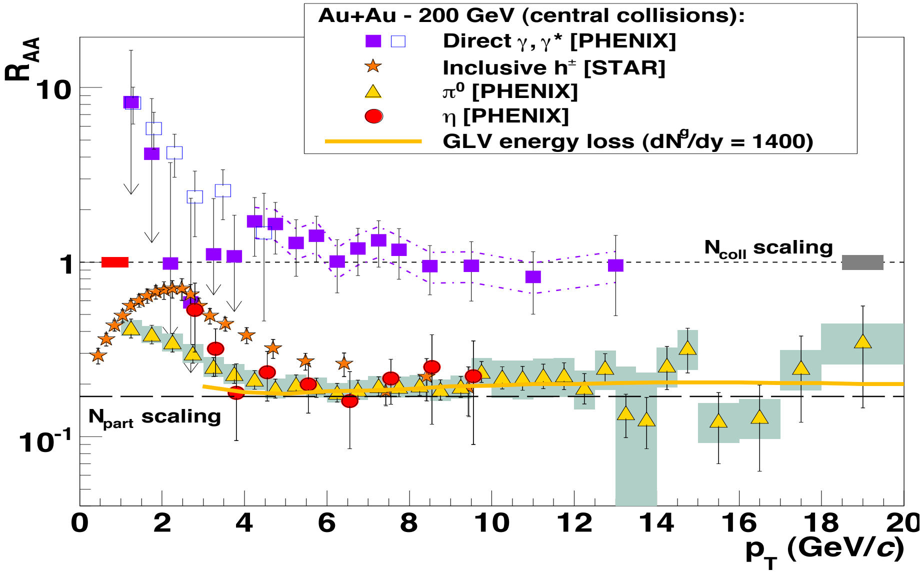





BNL-RHIC;
Relativistic Heavy Ion Collider
(2000-, $\sqrt{s_{NN}}$ = 200 GeV)

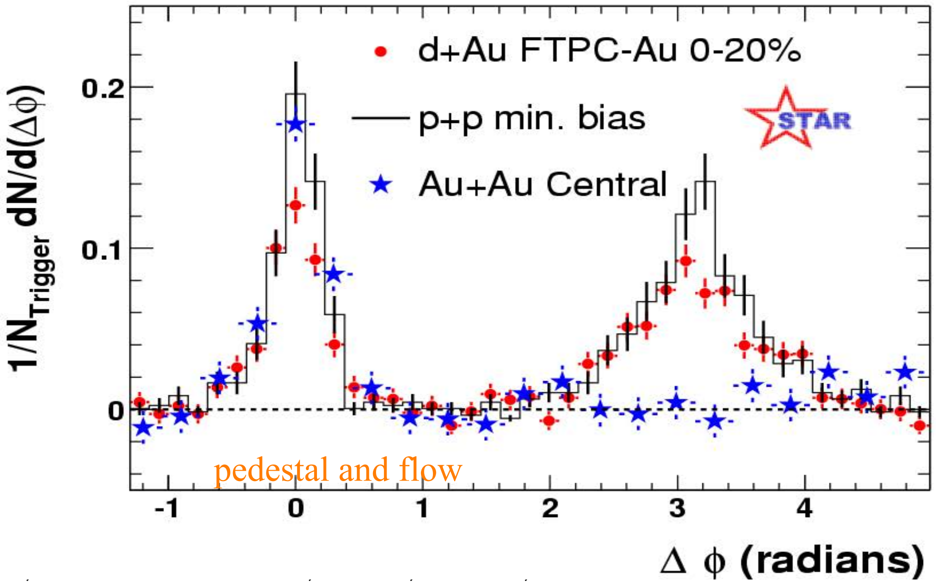
# Jet quenching @ RHIC (= energy loss of parton in QGP)

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




✓ 1) Decrease of high momentum particle yields

- No observation at lower colliding beam energy (e.g. SPS)
- To reproduce data by "Jet quenching" parton energy loss model:
  - Gluon density: dNg/dy ~ 1100
  - Energy density: $\varepsilon > 100\ \varepsilon_0$ (!)
  - (= $\varepsilon$ > 15 GeV / fm3)




✓ 2) Disappearance of back-to-back jets

Energy loss ~ few GeV/fm

- Cannot explained by hadron gas.
- → One of the evidences of QGP formation

# Strongly interacting QGP, perfect fluid (2005)

BROOKHAVEN
NATIONAL LABORATORY

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

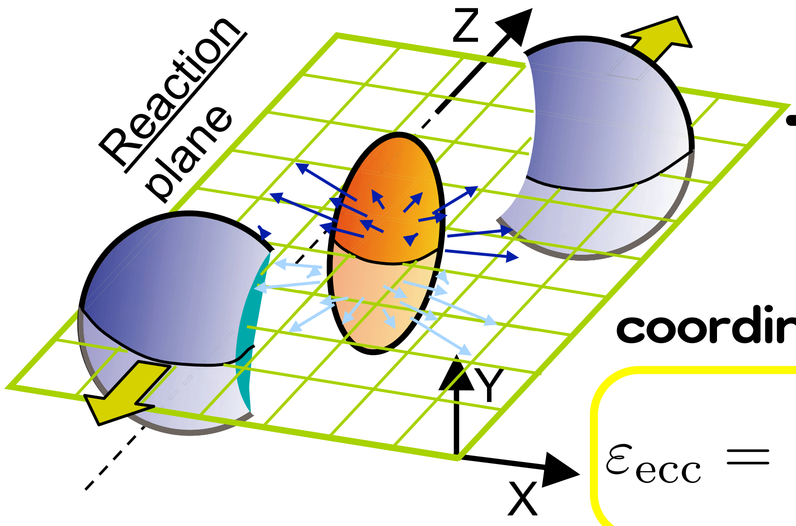
**RHIC Scientists Serve Up "Perfect" Liquid**

**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.

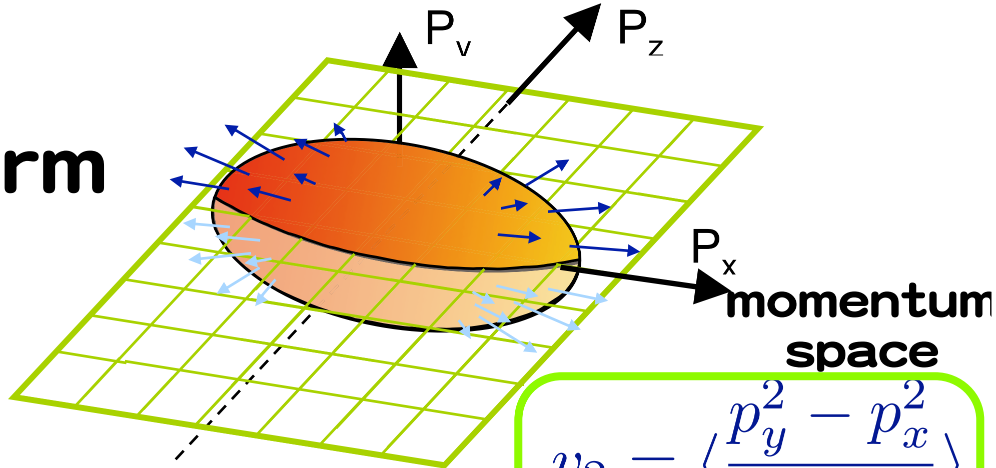
# Azimuthal Anisotropy




**Transform**

coordinate space

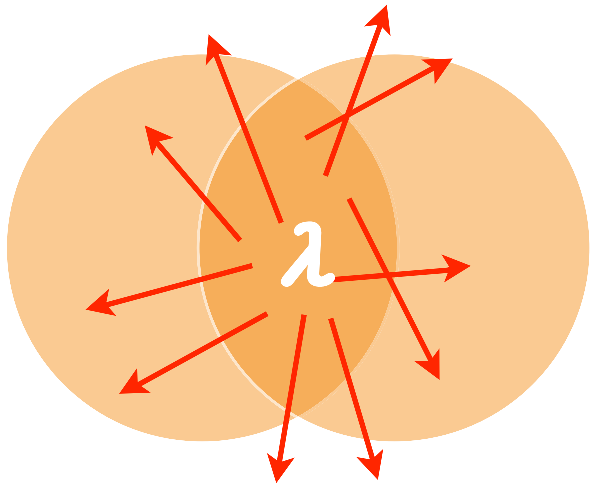
$$\varepsilon_{\rm ecc} = \langle \frac{y^2 - x^2}{y^2 + x^2} \rangle$$




momentum space

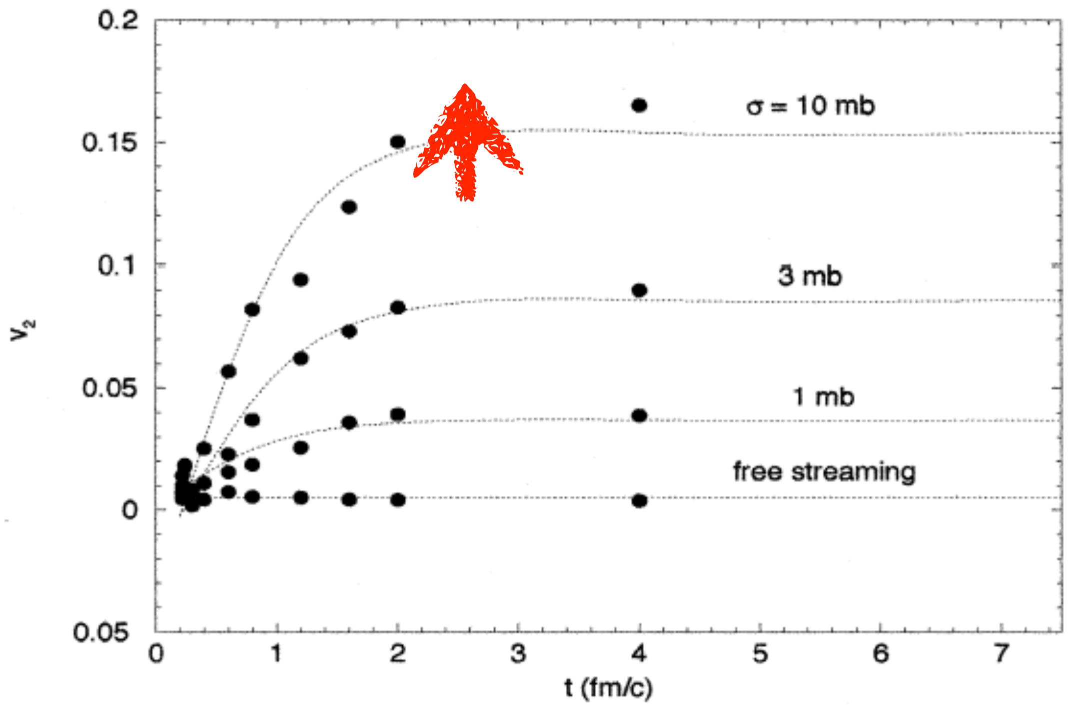
$$v_2 = \langle \frac{p_y^2 - p_x^2}{p_y^2 + p_x^2} \rangle$$

**hydrodynamics !** $\lambda/R \to 0$

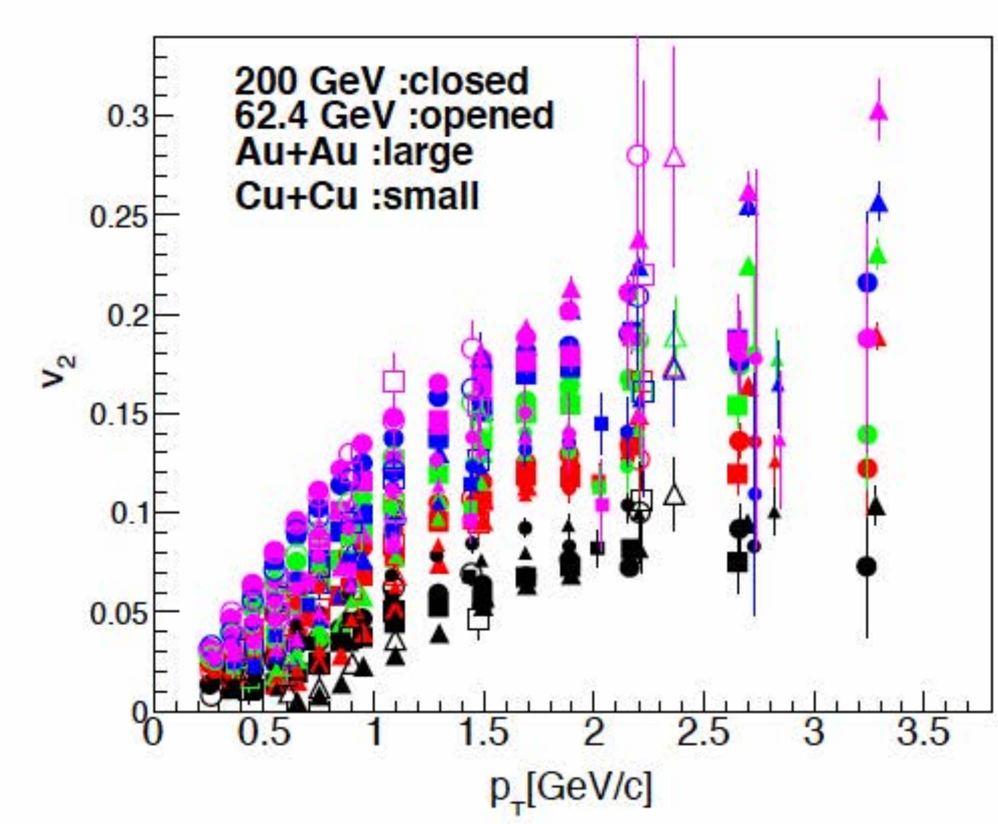


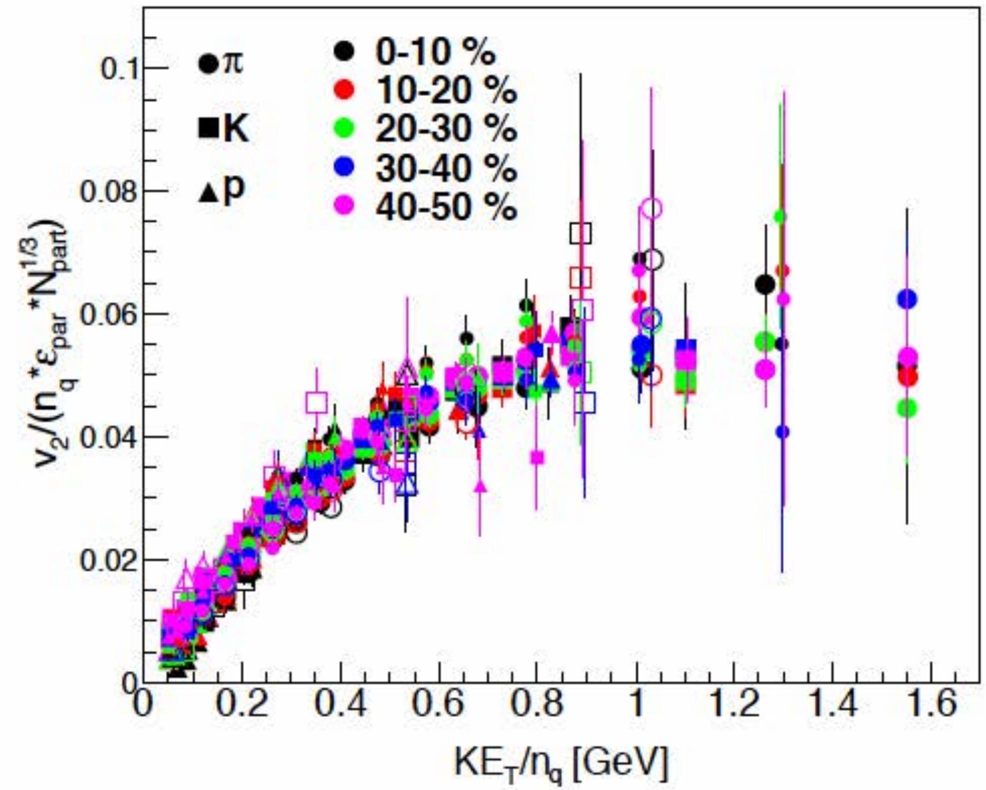

$\lambda/R \to 0$

**Higher efficiency of transformation (space → momentum), approching hydrodynamics**



# $v_2$: quark number scaling

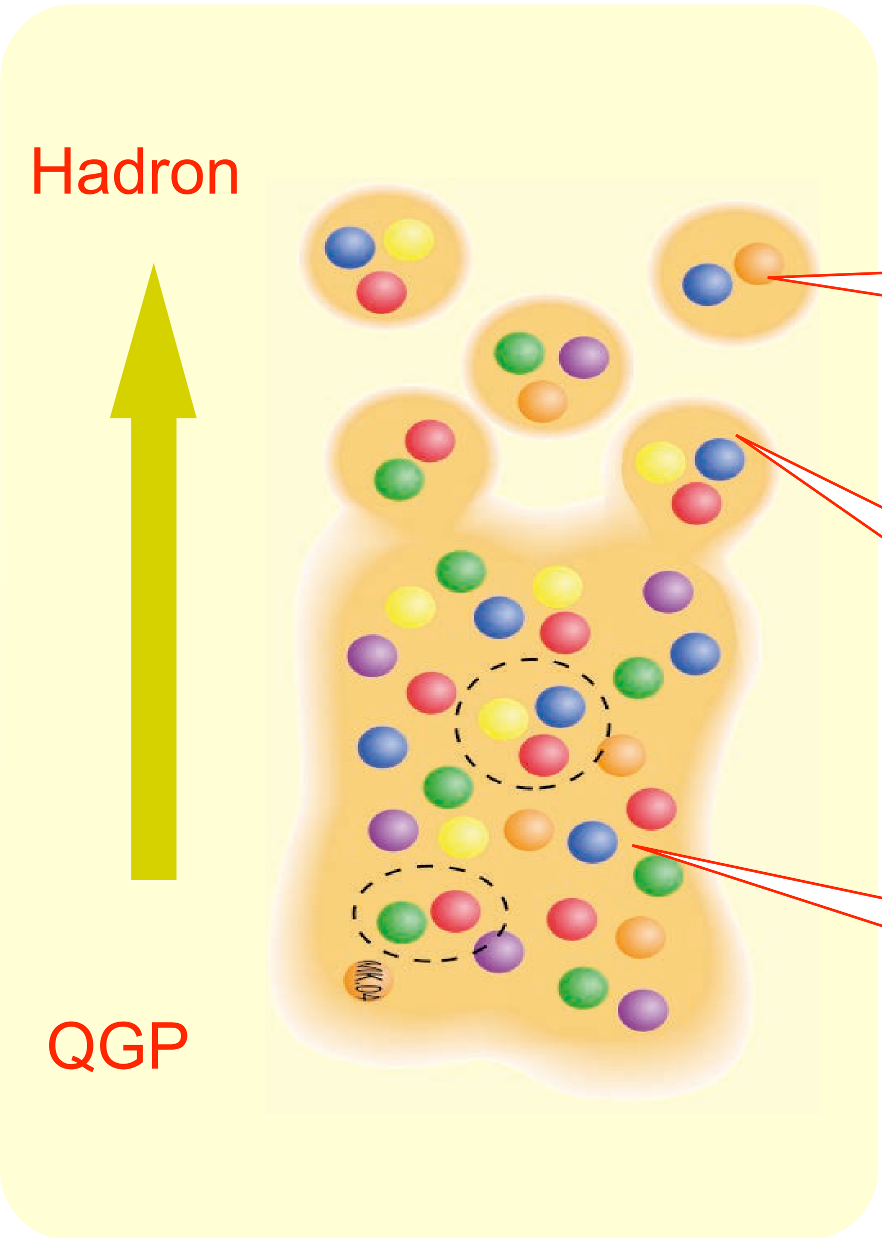



arXiv:1412.1043v1 (PHENX)

✓ Quark number ($n_q$) scaling
→ **Indication that anisotropy developed at parton level, not hadronic level.**

# 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 $v_2$ !!**

# Strong coupling and shear viscosity

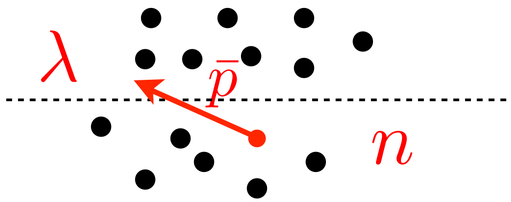
slide from Y. Miake

**internal resistance to flow**

Low $\eta$

High $\eta$

**From view point of Kinetic theory,**

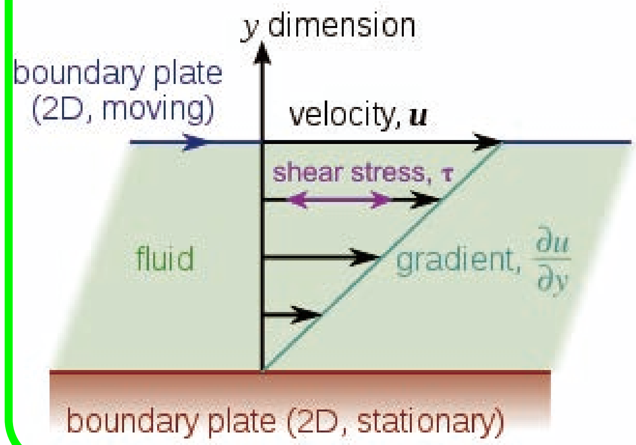



$$\begin{cases} \eta \approx \frac{1}{3} n \bar{p} \lambda \\ s \approx n \end{cases}$$

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

(uncertainty principle)

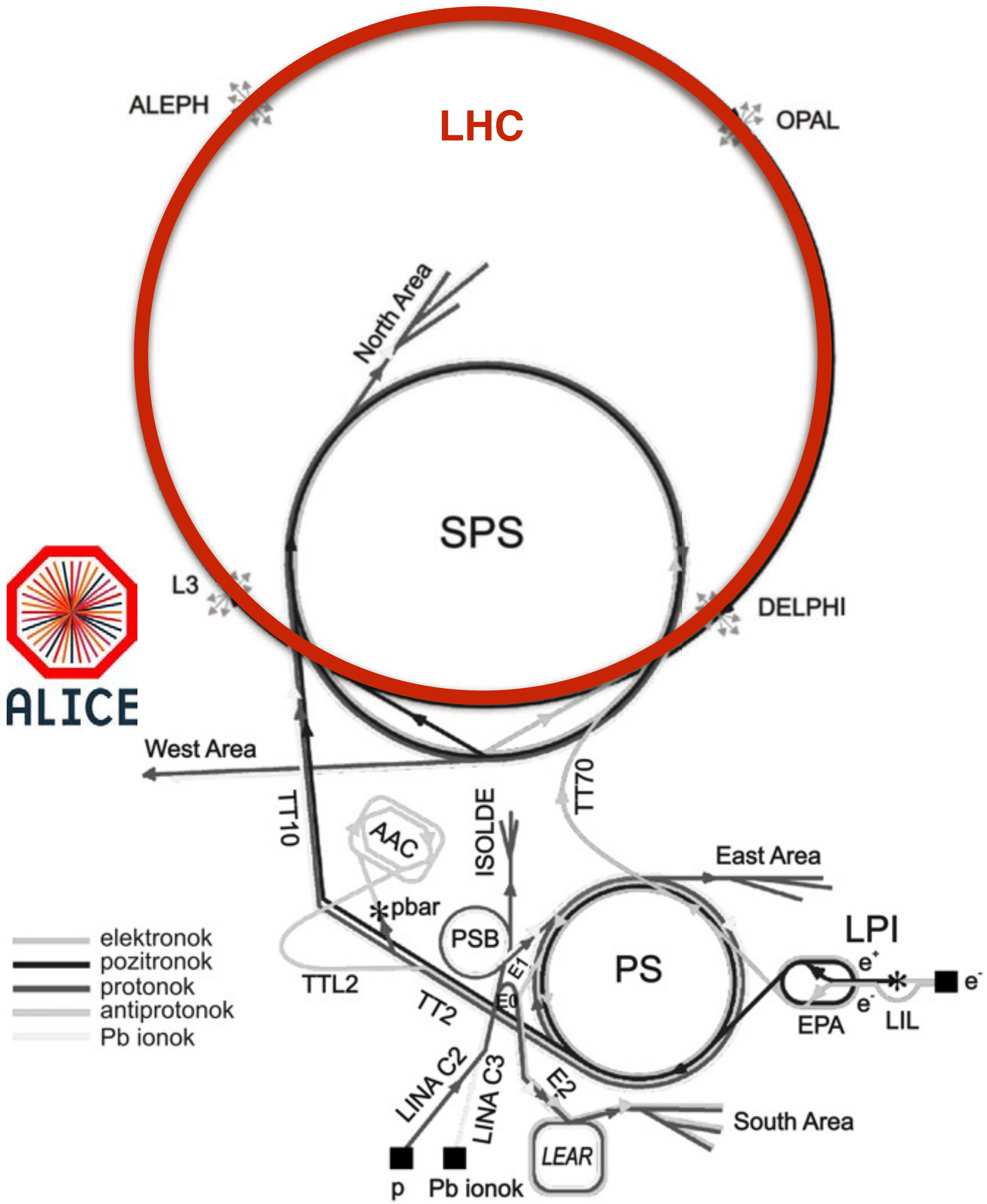
**dimension less in natural unit**




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

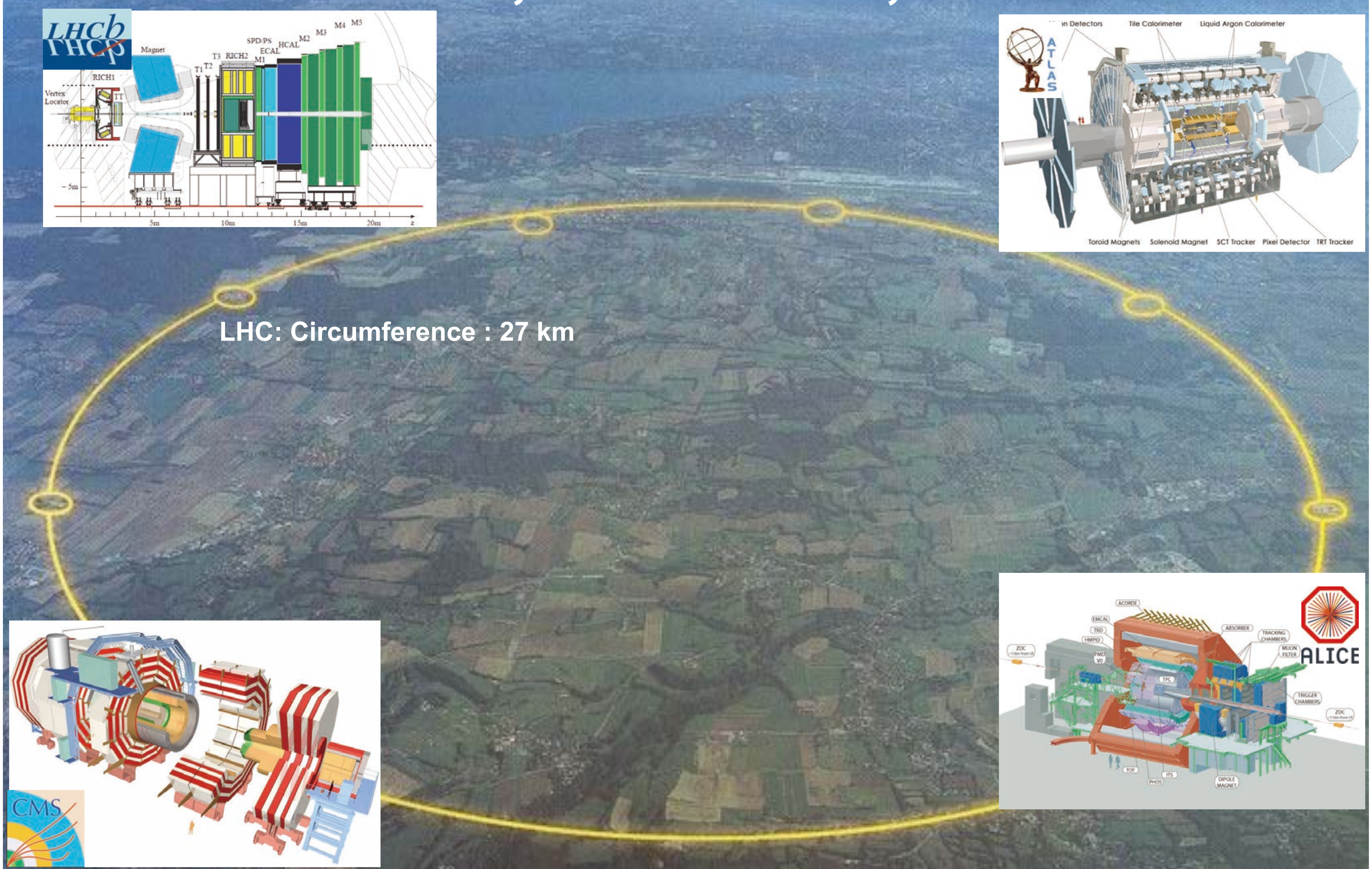
Wikipedia

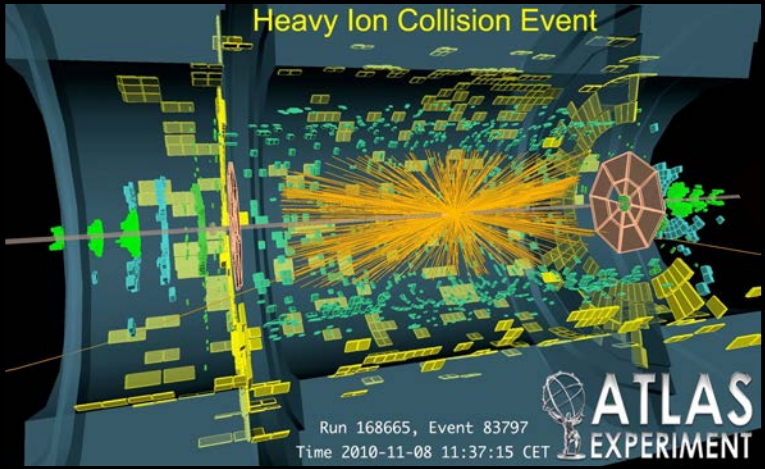
**✓ Strong coupling**

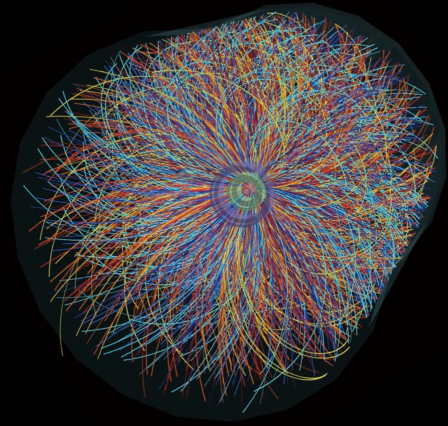


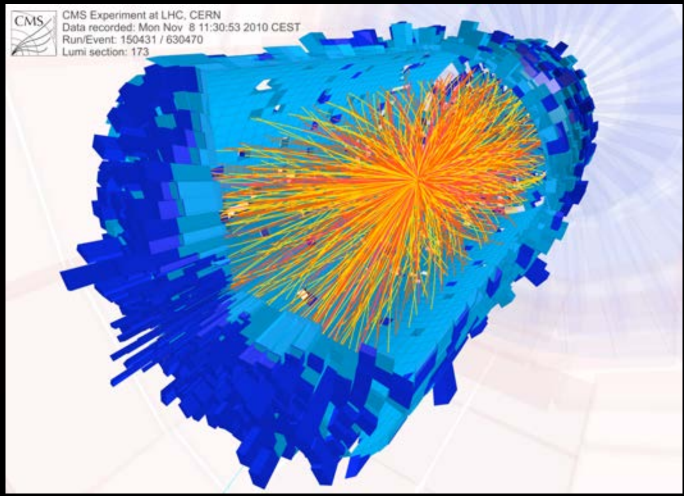

LHC
(2009-,
$\sqrt{s_{NN}}$ = 2.76, 5.1
TeV)

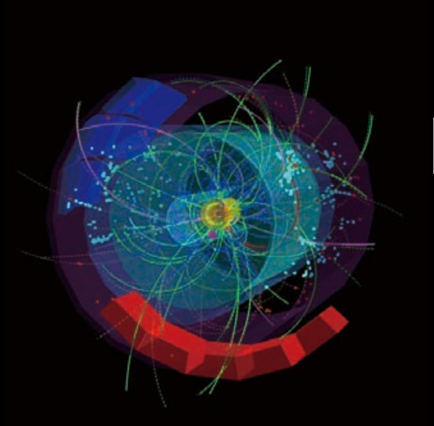
# LHC (Large Hadron Collider) 2009-, $\sqrt{s_{NN}}$ = 2.76, 5.1 TeV





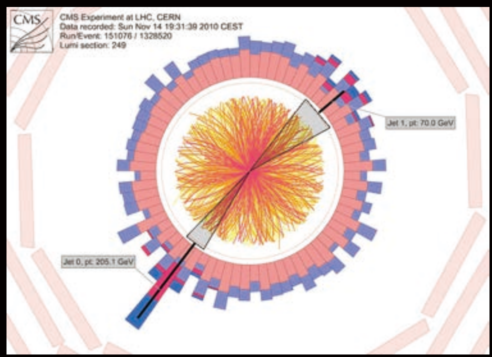



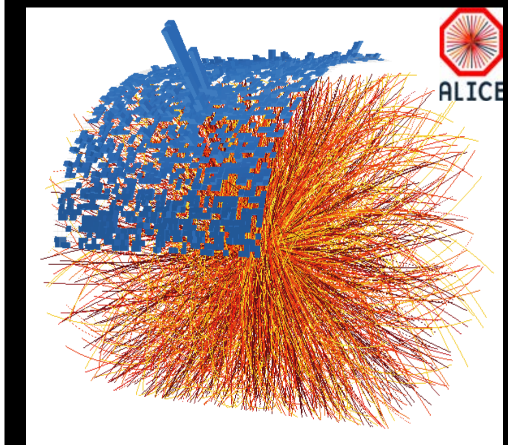


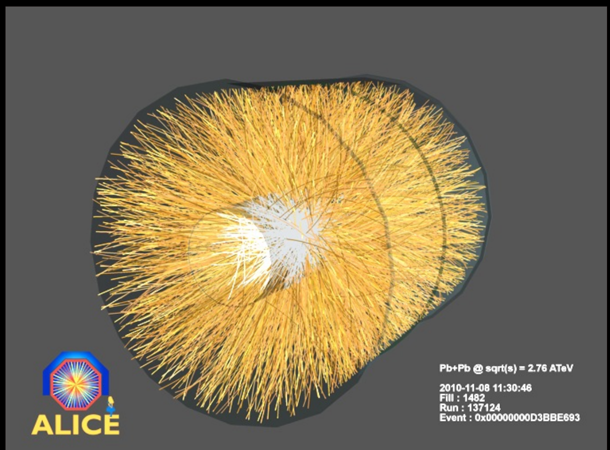



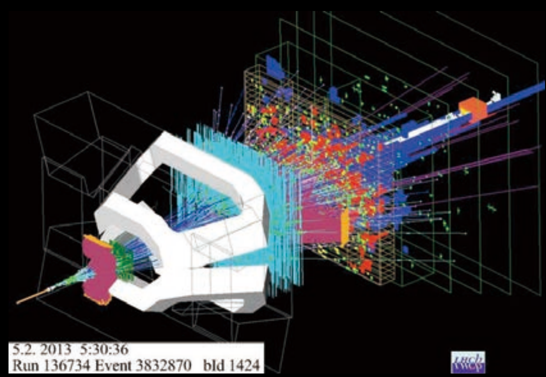
# Nov. 8, 2010

First Pb-Pb collisions at LHC, the opening new era of heavy ion program at LHC



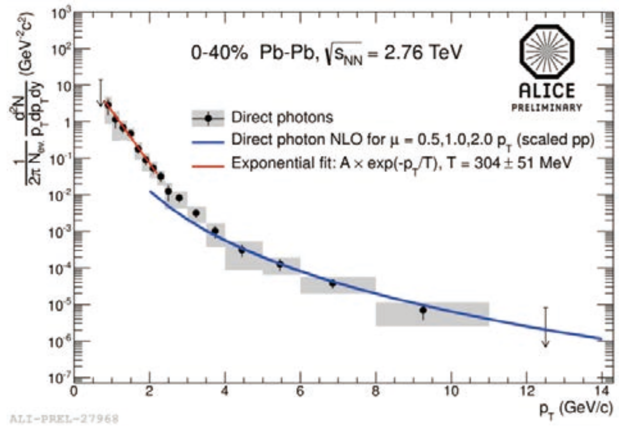



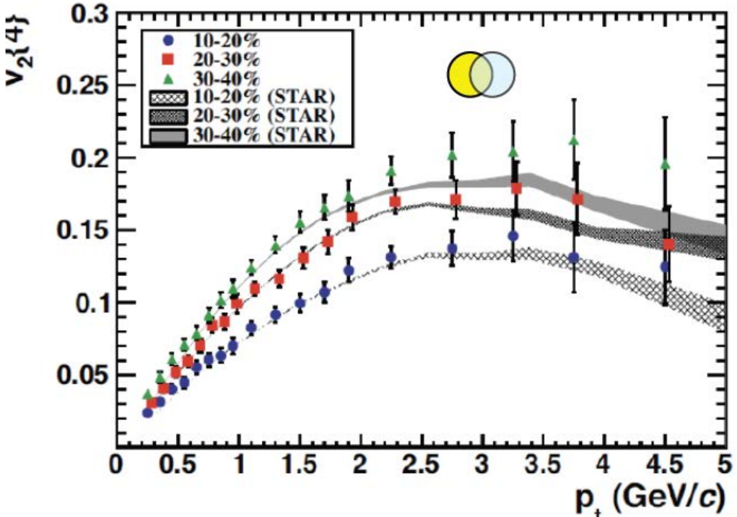



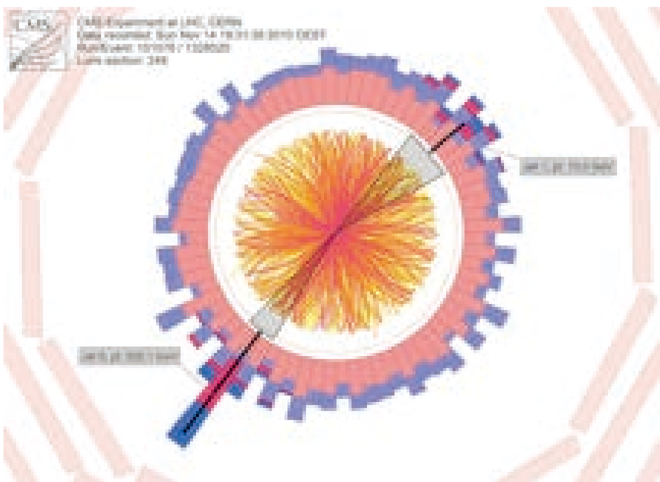
# 第１期　LHC重イオン衝突実験結果のハイライト

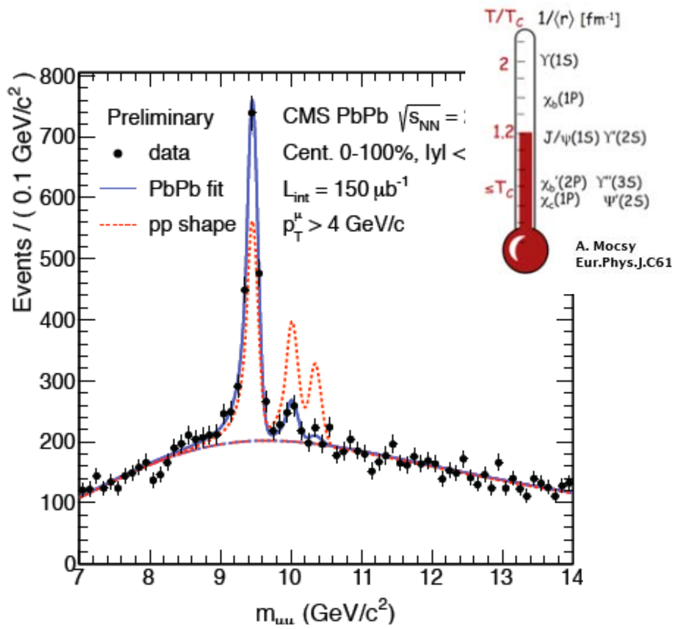
# (Run-I : 2009-2013)

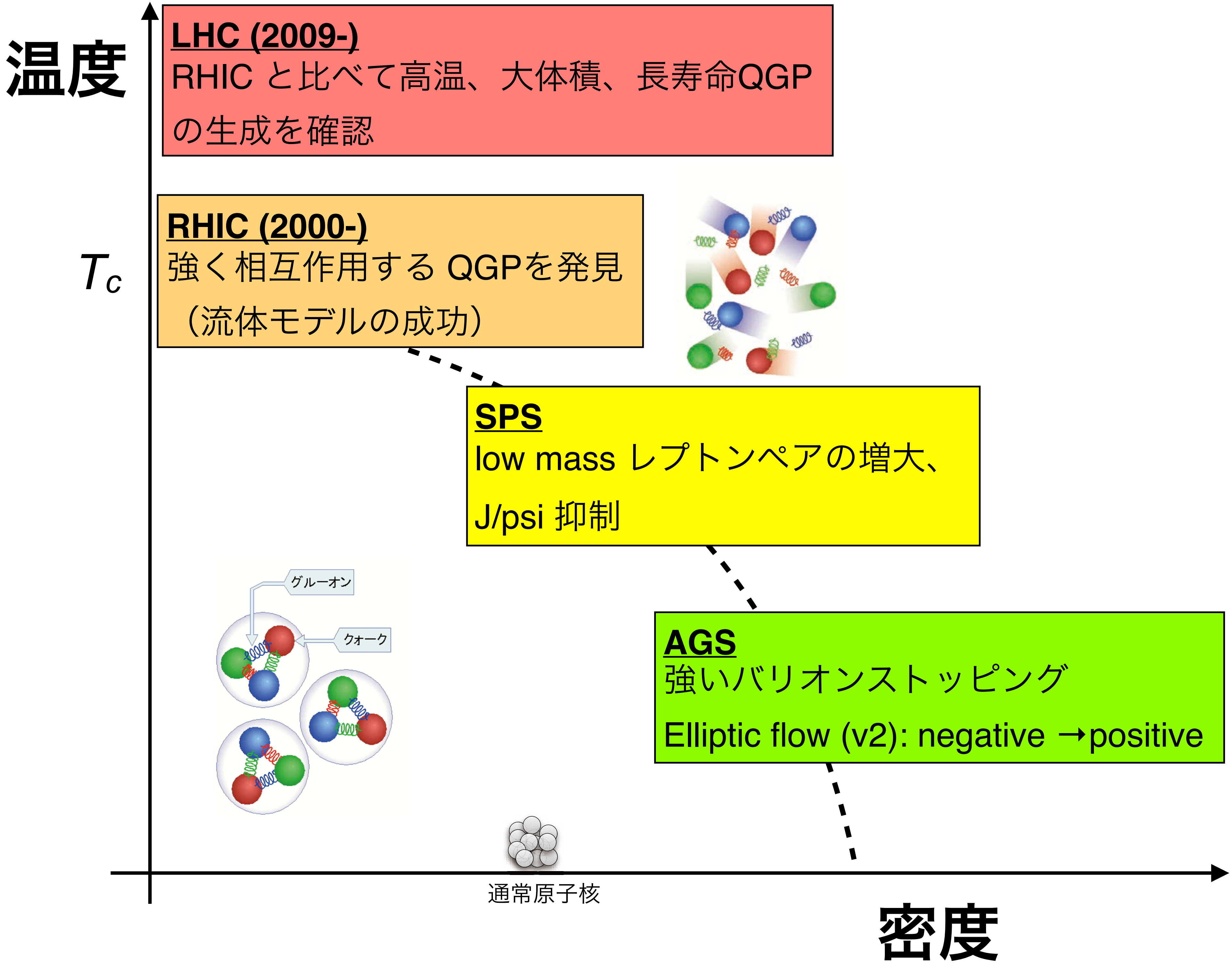
- 初期到達温度: $T_{int}$ ~ 304 ± 51 MeV (RHIC の 1.4 倍).
- 大きな集団膨張 (等方, 楕円) (ALICE, ATLAS, CMS)
- 大きなジェット抑制効果 (ALICE, ATLAS, CMS)
- ϒ 励起状態の消滅 ＝高温物質生成の証拠 (CMS)



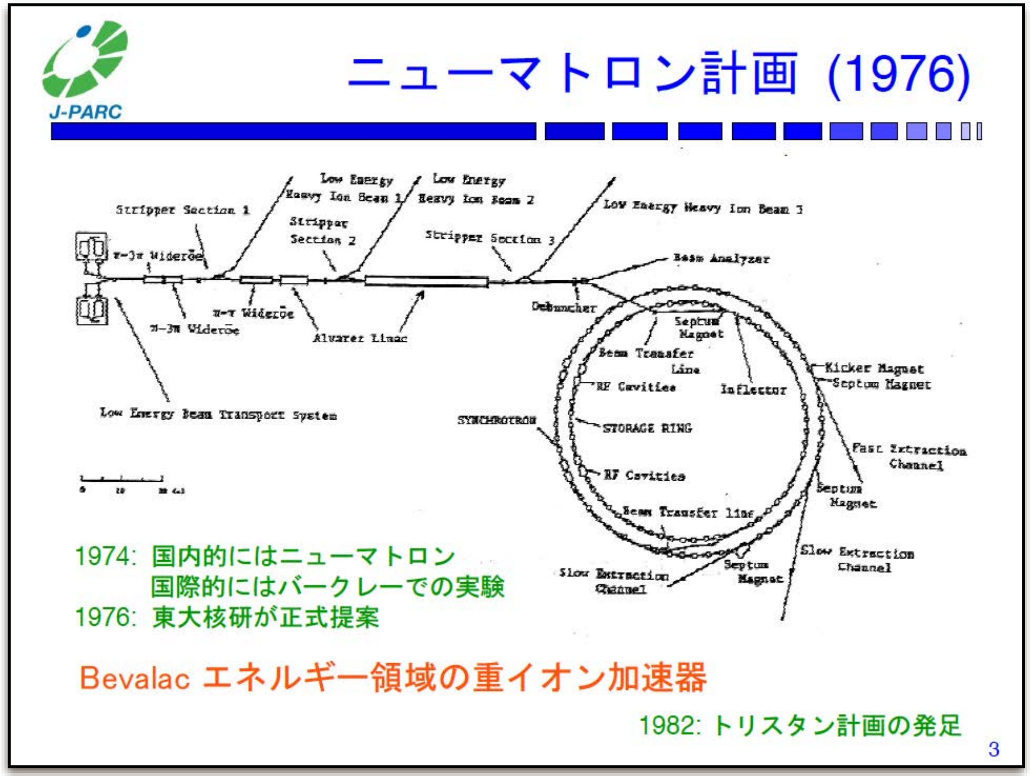


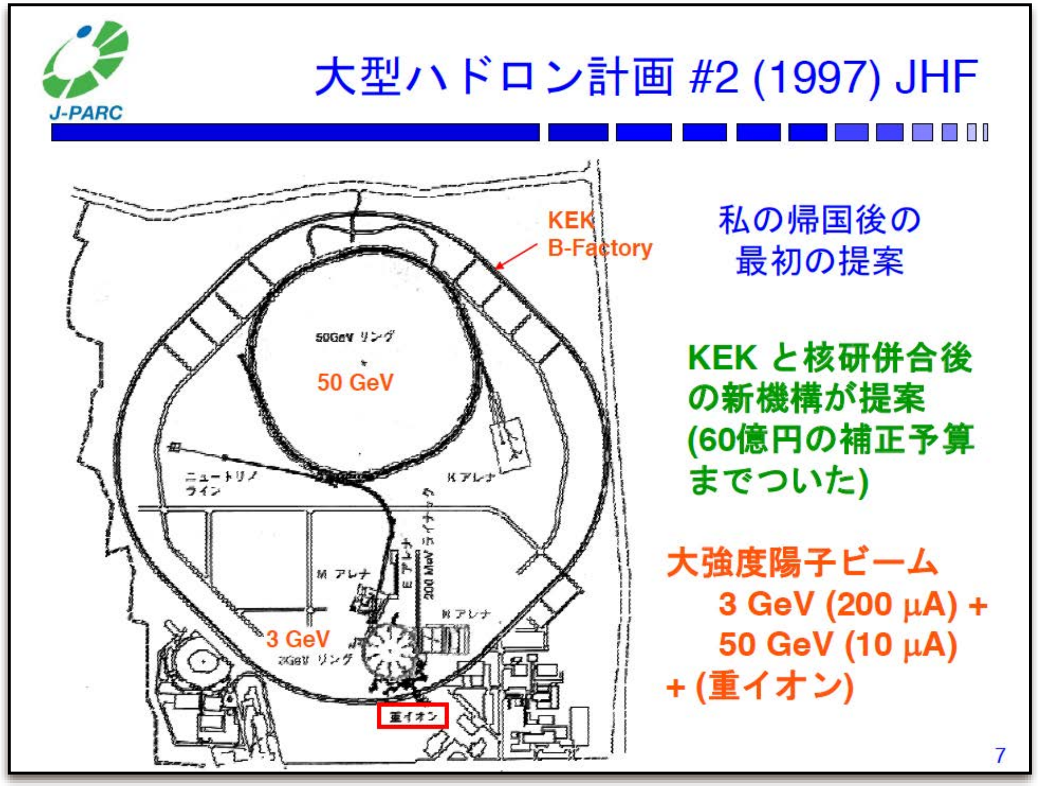


温度
$T_c$
LHC (2009-)
RHIC と比べて高温、大体積、長寿命QGPの生成を確認
RHIC (2000-)
強く相互作用する QGPを発見
（流体モデルの成功）
SPS
low mass レプトンペアの増大、
J/psi 抑制
AGS
強いバリオンストッピング
Elliptic flow (v2): negative →positive
グルーオン
クォーク
通常原子核
密度

# 一方、日本では

Slides from S. Nagamiya (J-PARC HI workshop @ KEK, Nov. 2014)



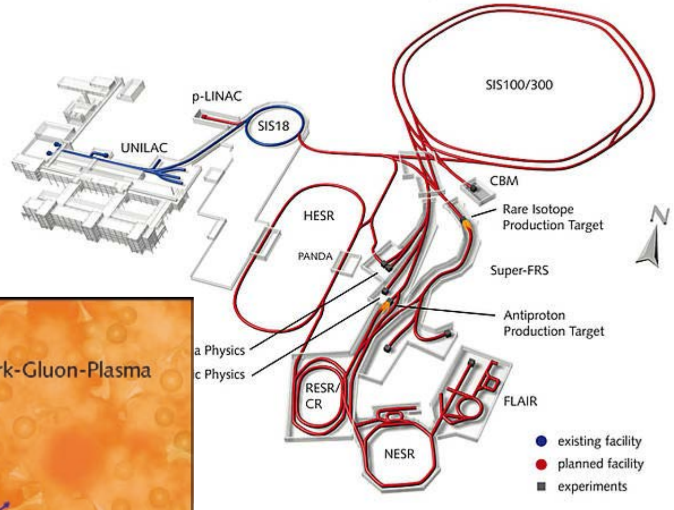

➟ Bevalac で重イオン加速

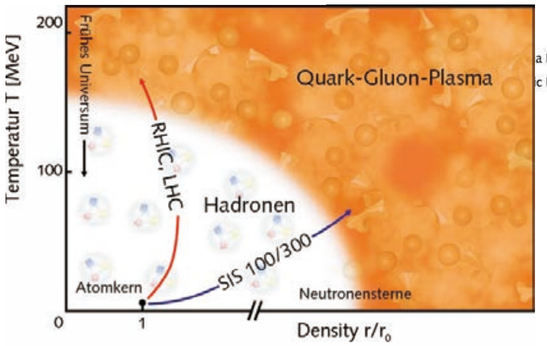
➟ J-PARC 計画へ統合

KEK トリスタン計画発足 (1982)

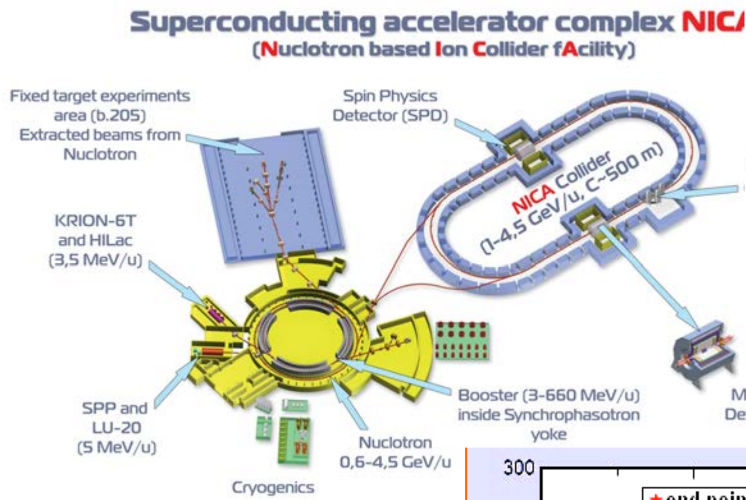
＊　日本人重イオン研究者は、海外で実験を行うことになる（AGS, SPS, RHIC, LHC）

# 世界の動向

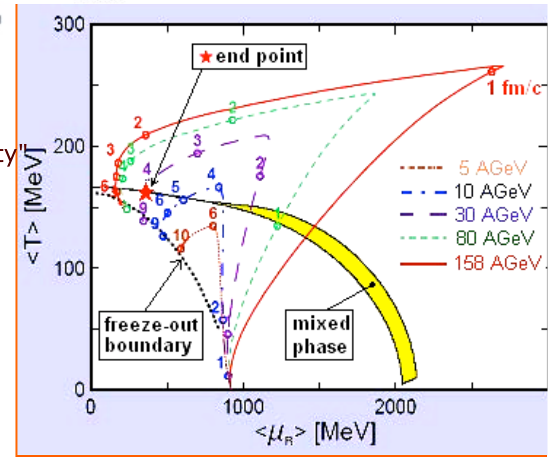


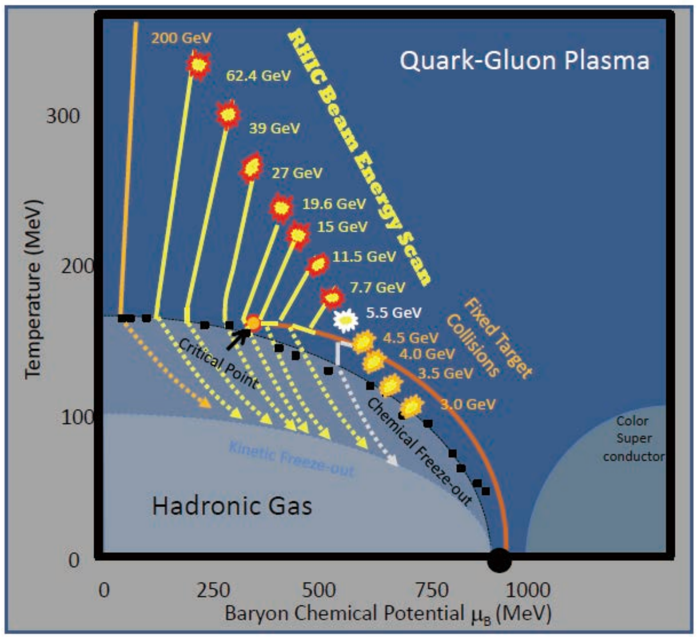




https://www.gsi.de/en/research/fair.htm?nr=8




Booklet "Search for the Mixed Phase of Strongly Interacting Matter at Nuclotron-based Ion Collider Facility"





- アメリカ・BNL RHIC Beam Energy Scan II (2018-2019)
- ドイツ・GSI FAIR SIS-100 (2021-)
- ロシア・JINR NICA (2020-)

# 国内の動向

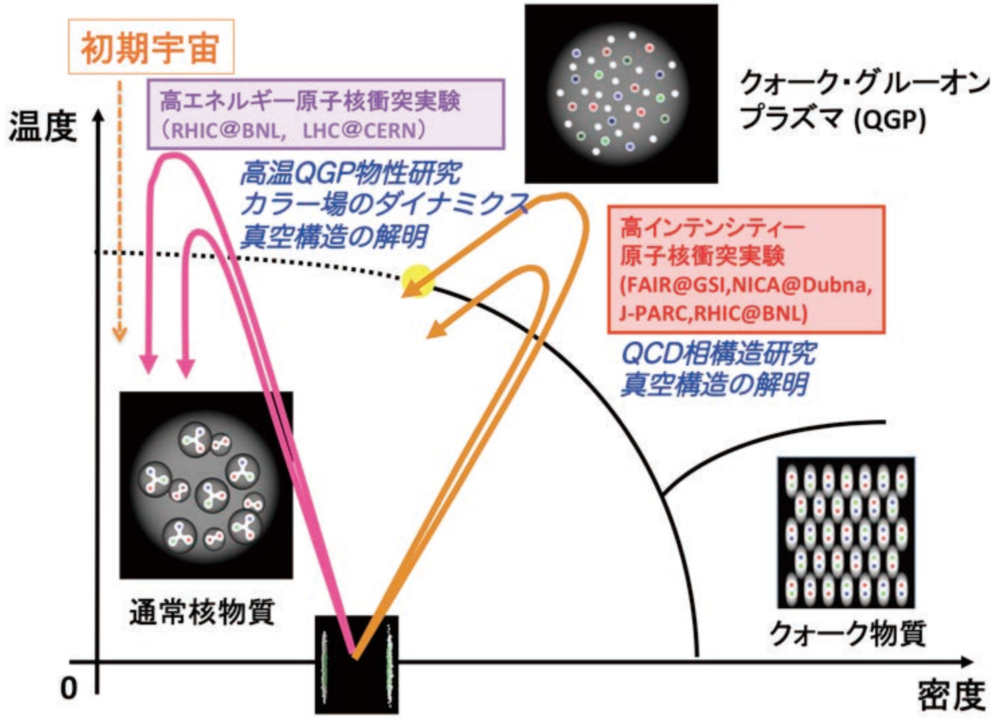
- しかしながら（米・RHIC BES-II を除き）計画が遅れ気味。
- 将来計画として、日本の J-PARC で重イオンを加速し、このエネルギー領域で、これまでなかった別の観点から新しい物理を目指してはどうか
- 「日本の核物理の将来レポート」作成開始 (2010-)
- 2013 年頃より、本格的に議論を開始
- エネルギーフロンティア志向 → 高統計・精密測定で迫る高バリオン密度物質、QCD相構造の解明
- 日本における重イオン衝突実験
  - ある意味、日本人重イオン研究者、あるいは原子核物理研究者の悲願とも言える

# 日本の核物理の将来レポート
# 「高エネルギー重イオン」

原子核研究 Vol. 57, Suppl. 2 (2013)

**３つの研究の柱：**

- QGP物性の精密研究、熱平衡化機構（ゲージ場のダイナミクス）の研究
- **有限密度QCD相構造の研究**
- **カイラル対称性の回復現象の研究**




「日本の核物理の将来レポート」より抜粋

# 2. 何がわかったのか、
# 何がまだわかっていないのか

## (特にQCD相図について)

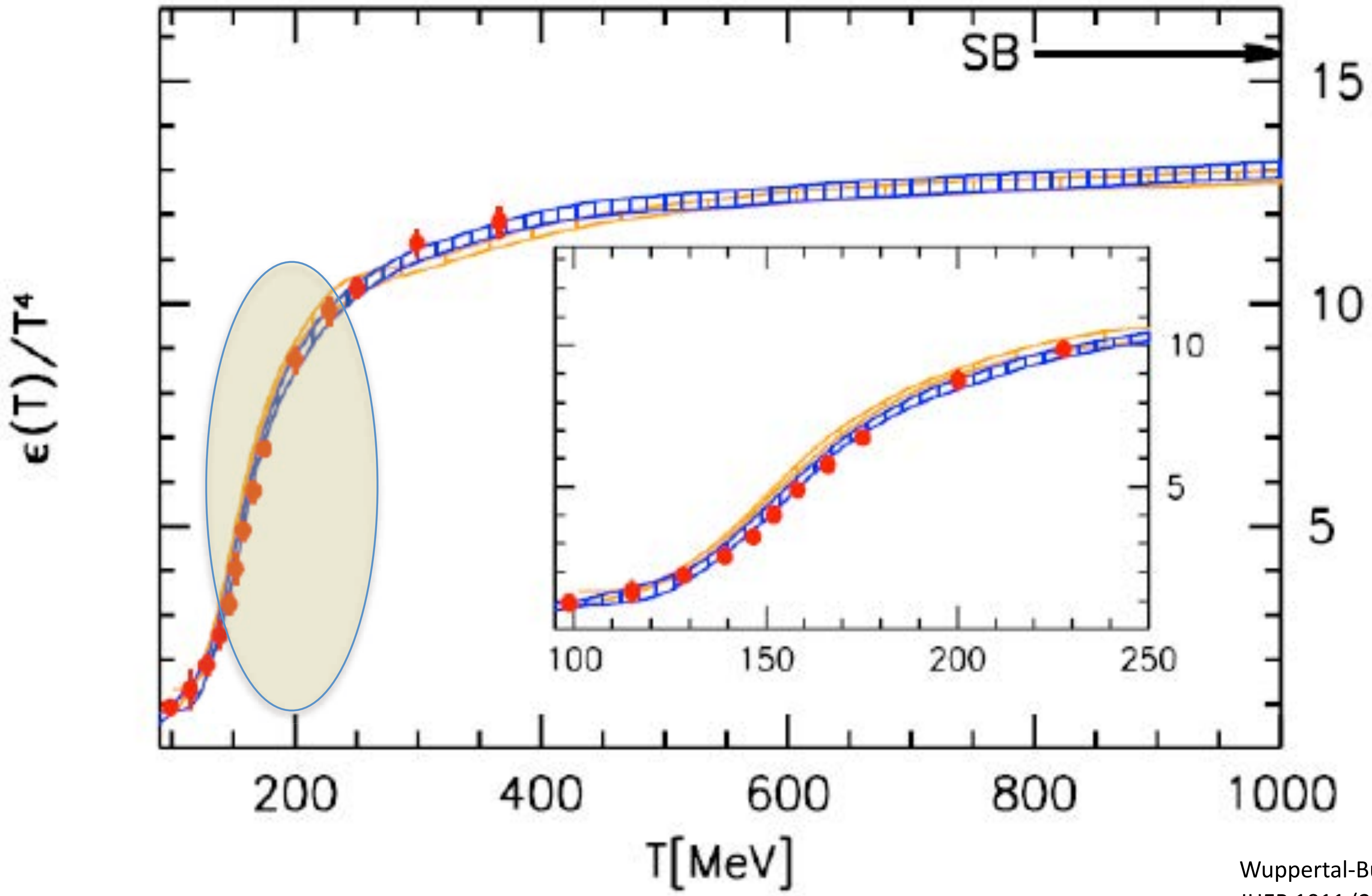
# 分かったこと
# その１

低バリオン密度・高温領域では、QGPからハドロン相へ、クロスオーバー相転移する

## Recent Lattice QCD calculations:

$T_c$ = 150-200 MeV,

cross over phase transition from hadronic phase to partonic phase (QGP).

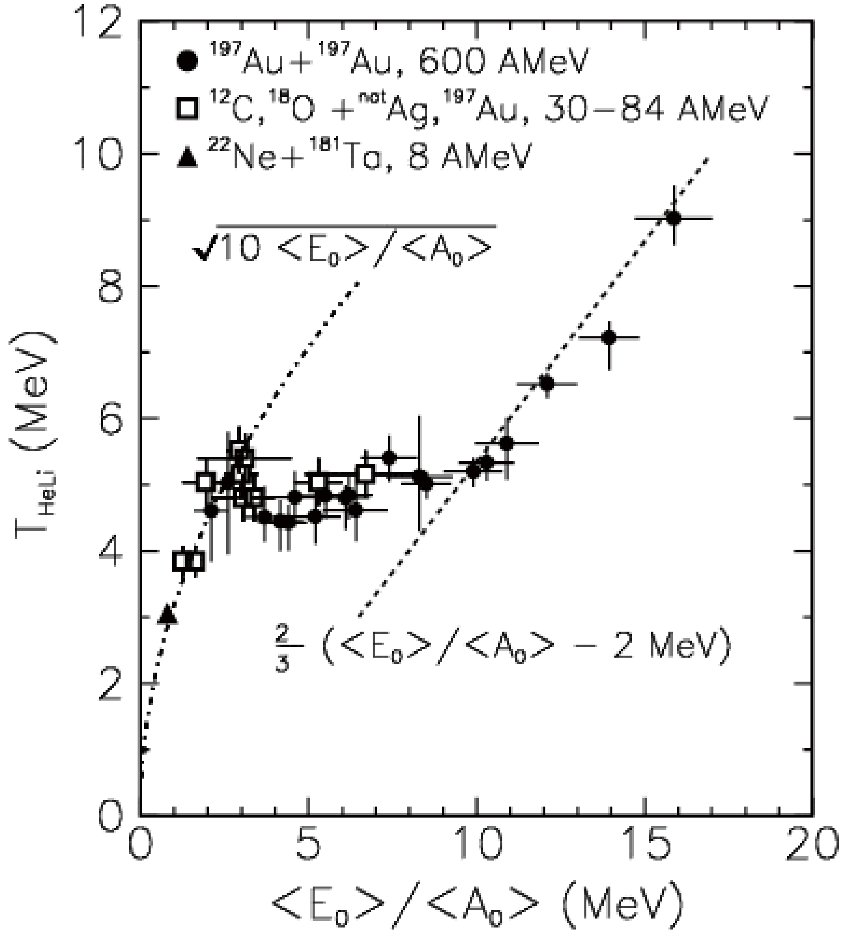


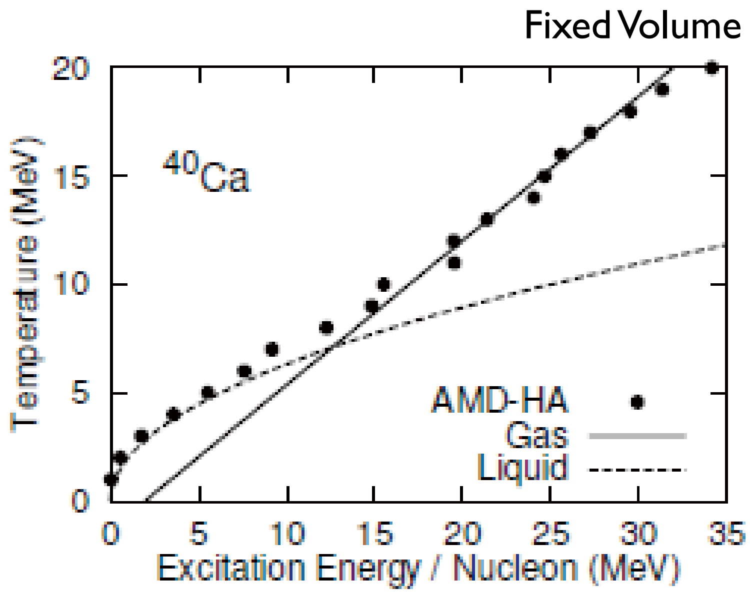

Wuppertal-Budapest's LQCD EOS
JHEP 1011 (2010)77

# 分かったこと
# その２

原子核液体気体相転移
が存在する

# Nuclear Liquid-Gas Phase Transition




Ohnishi, Randrup ('98)

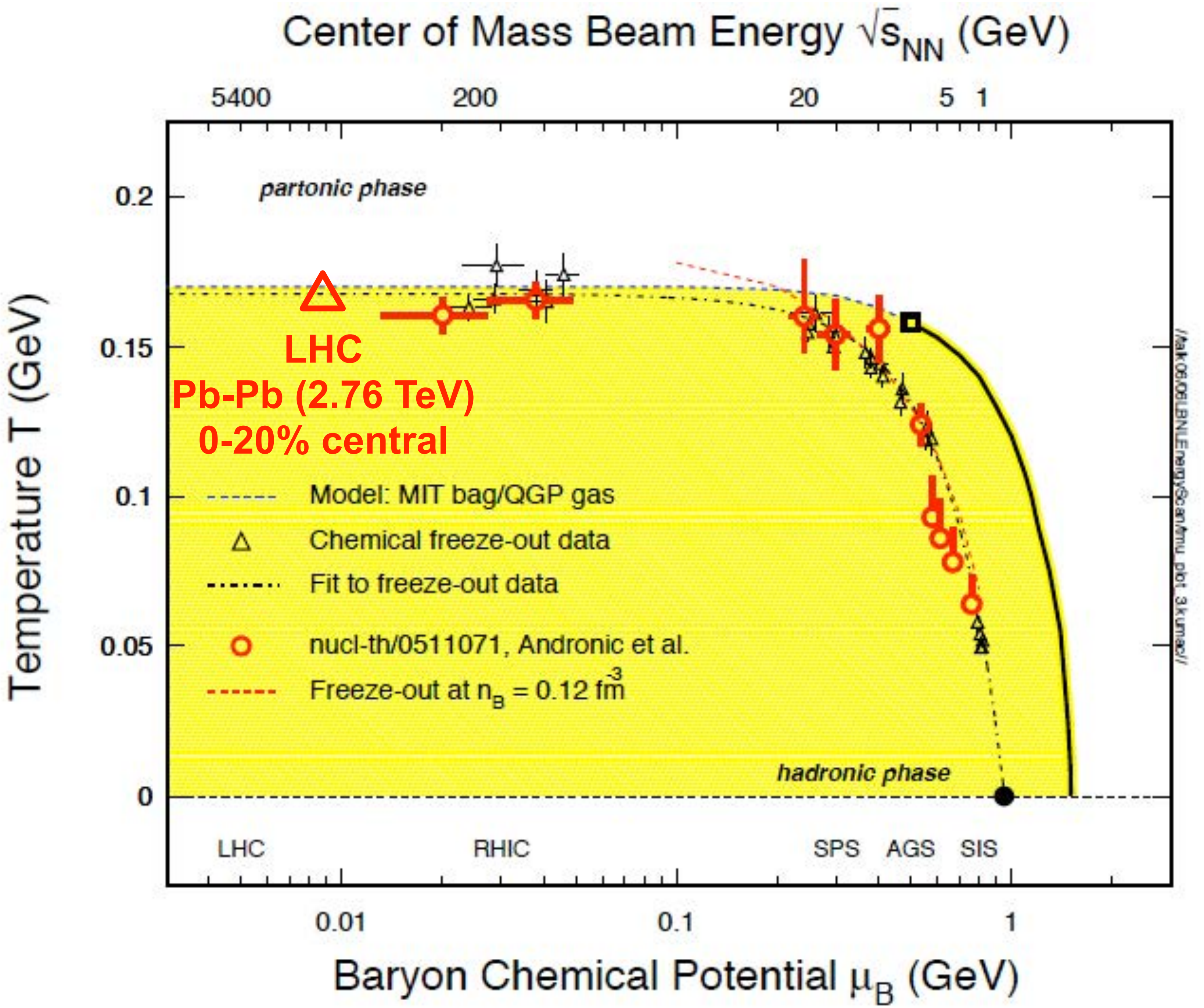
J. Pochadzalla et al. (GSI-ALLADIN collab.),PRL 75 (1995) 1040.

FIG. 2. Caloric curve of nuclei determined by the dependence of the isotope temperature $T_{\mathrm{HeLi}}$ on the excitation energy per nucleon. The lines are explained in the text.

* A temperature scale was derived from observed yield ratios of He and Li isotopes.

# 分かったこと
# その３

どのエネルギー領域の粒子比も、熱的統計モデルを使ってよく記述できる。また、そこで決定される化学的凍結温度とバリオン密度はQCD 相図上にあるラインを形成する。



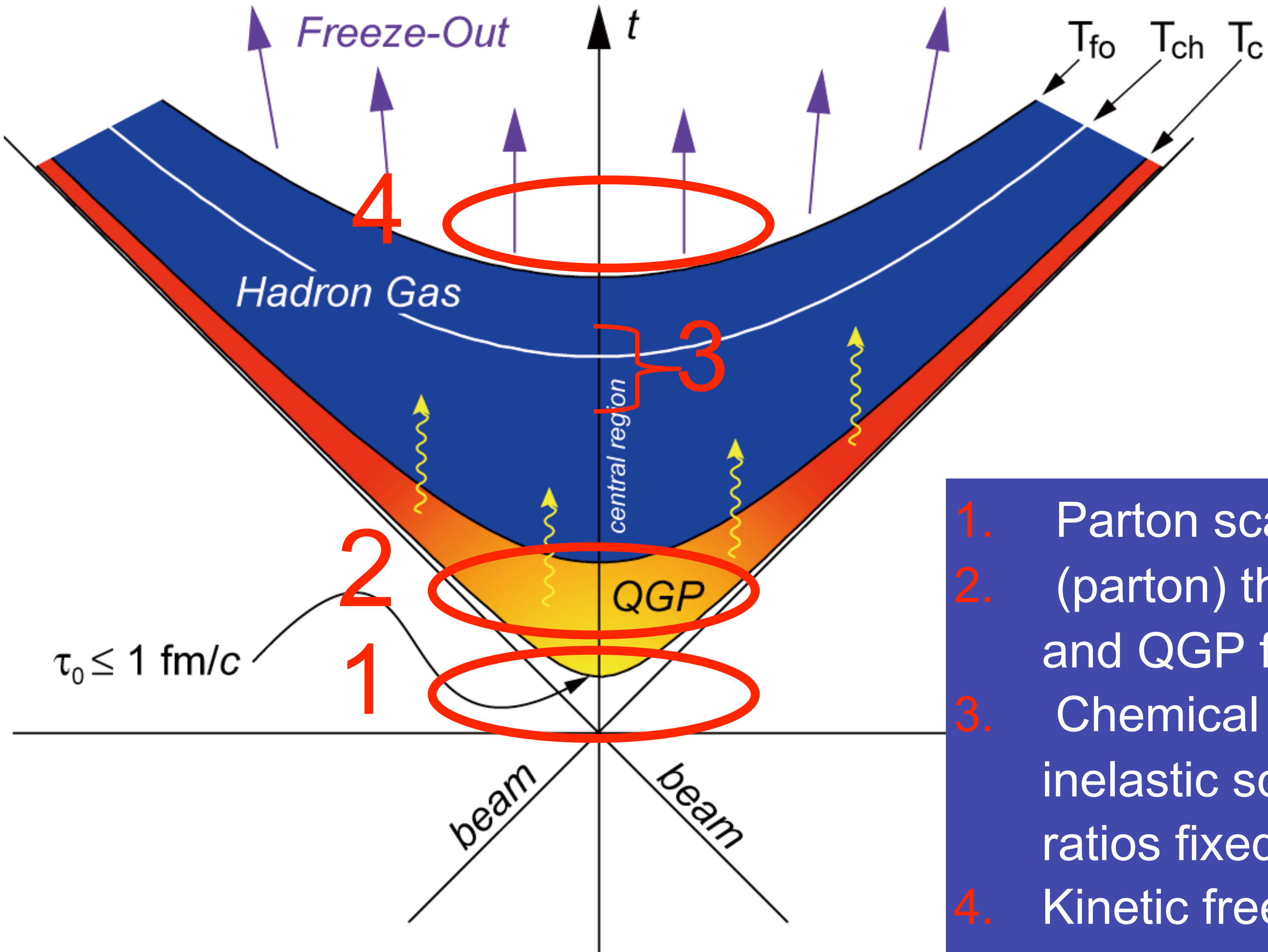


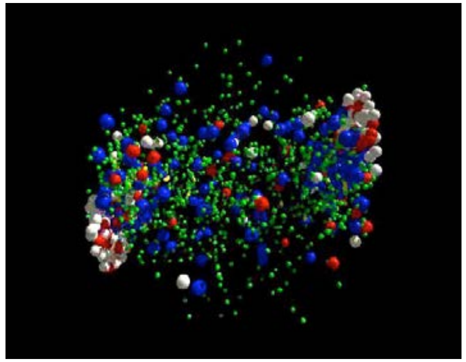
Braz. J. Phys. vol.37 no.2c São Paulo June 2007

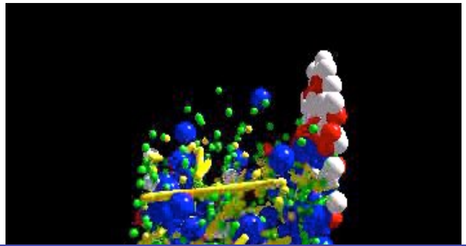
**http://dx.doi.org/10.1590/S0103-97332007000500024**


N. Xu

# 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)

# Hadron production in the local thermal equilibrium (1)

- Assume (1) **local thermal equilibrium (T = const.)** and (2) **chemical equilibrium ($n_i$: particle multiplicity = const.)**
- Particle multiplicity ($n_i$) can be determined by Temperature T, chemical potential μ,
- From Grand Canonical Ensemble for fermions and bosons:

$$n_i = \frac{g}{2\pi^2}\int_0^{\infty}\frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$

**Simplest form:** $dn \sim e^{-(E-\mu)/T} d^3 p$

# Hadron production in the local thermal equilibrium (2)

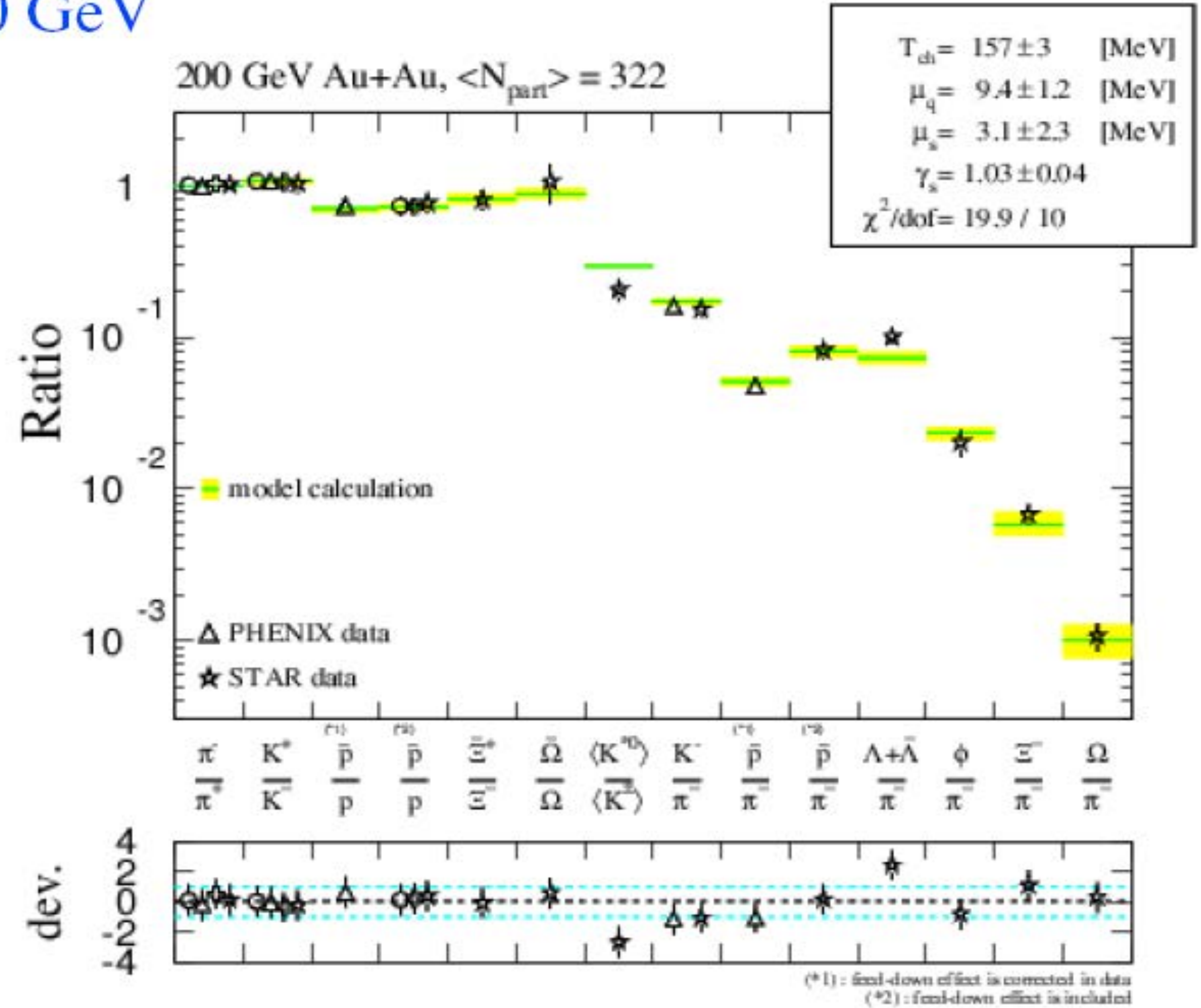
- A particle ratio (e.g. pbar-p ratio)
  - Ratio of μ/T is determined.
- Another particle ratio (e.g. K/π ratio)
  - T → μ
- By repeating these procedure (fit), one can determine the all particle ratios and abundances by from **T and μ only**.
- This model is called **"statistical thermal model"**
- Need the measurements of particle ratios and parameter fitting for T and μ ($\mu_B$).

$$\frac{\bar{p}}{p} = \frac{e^{-(E+\mu)/T}}{e^{-(E-\mu)/T}} = e^{-2\mu/T}$$

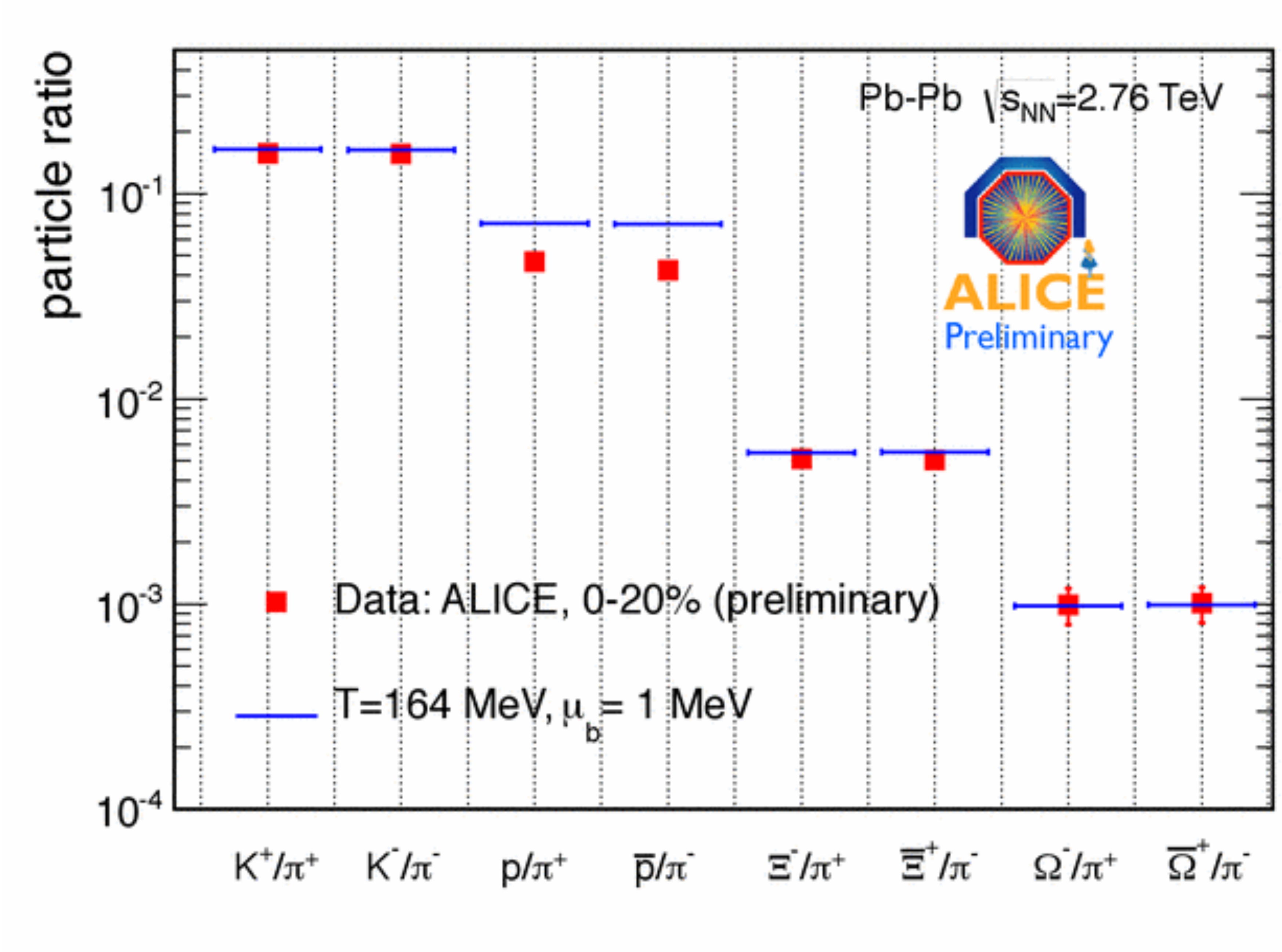
$$\frac{K}{\pi} = \frac{e^{-(E_K)/T}}{e^{-(E_\pi)/T}} = e^{-(E_K-E_\pi)/T} \approx e^{-\Delta m/T}$$

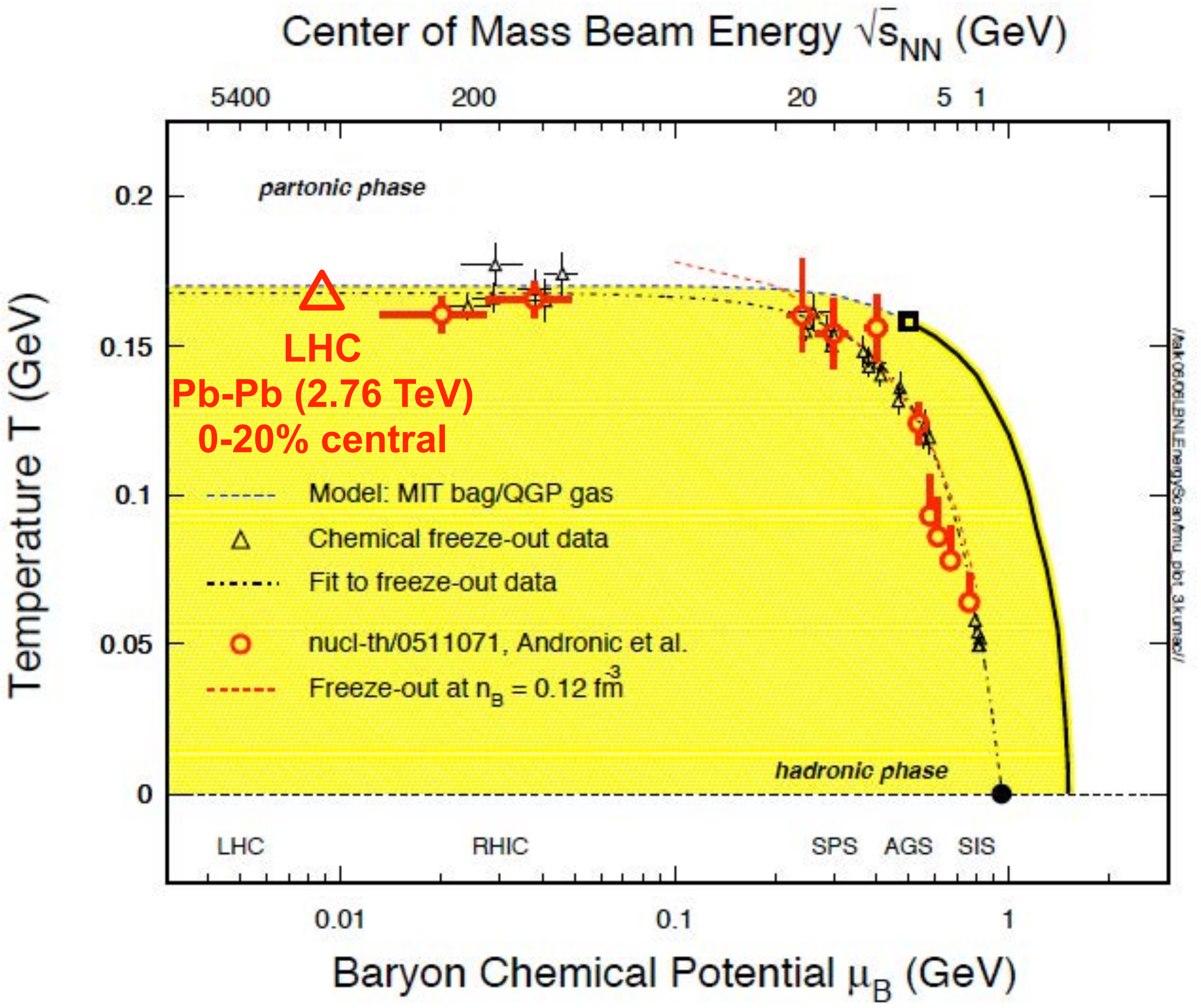
# RHIC data: Au+Au 200 GeV

200 GeV



# LHC data: 2.76 TeV Pb+Pb



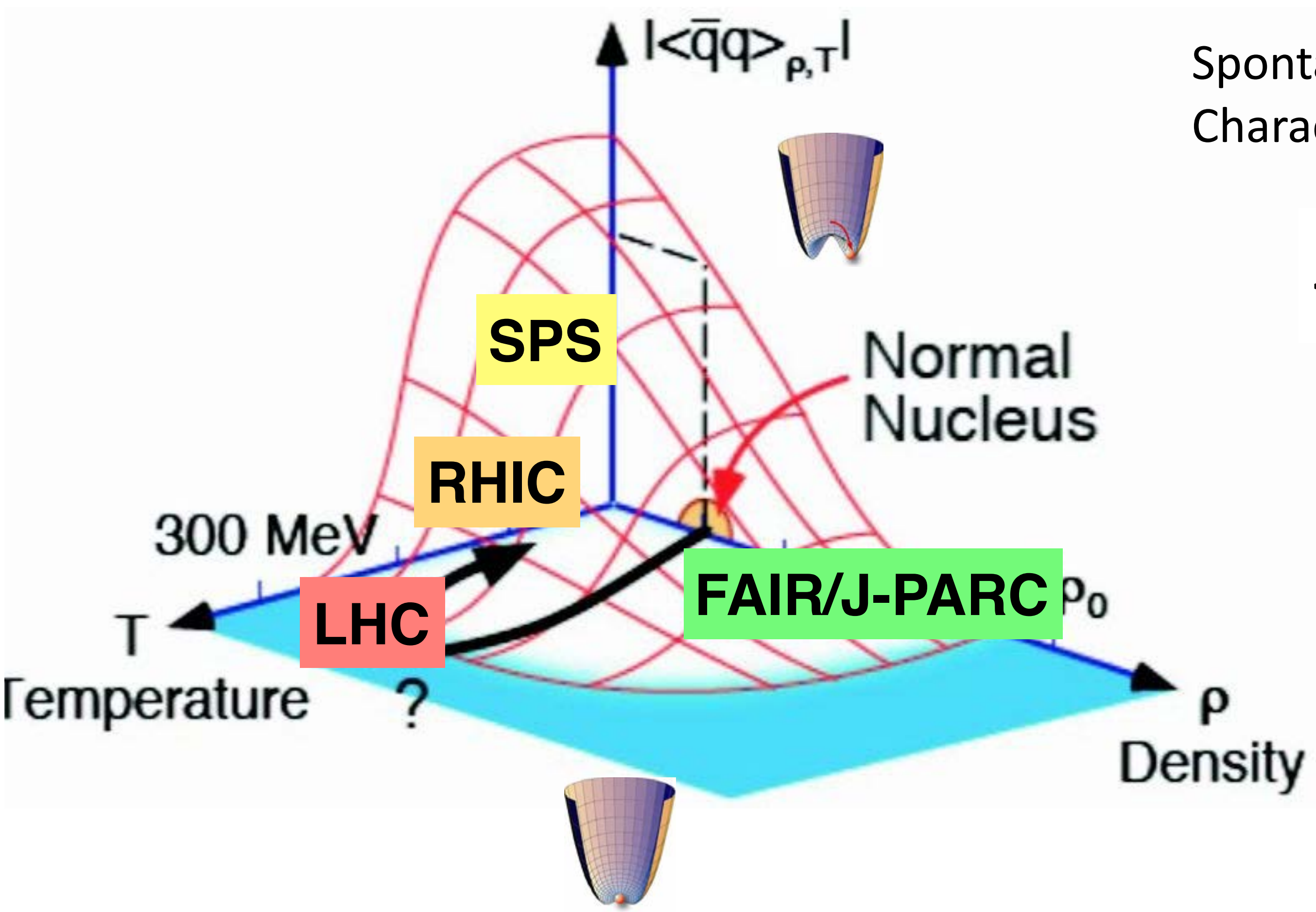



Braz. J. Phys. vol.37 no.2c São Paulo June 2007
**http://dx.doi.org/10.1590/S0103-97332007000500024**
N. Xu

# 分かったこと
# その４

SPS 以上のエネルギーではレプトン対生成に
既知のハドロンからの寄与以上の余剰成分が
ある (LHC は未発表)

# Spontaneous Chiral Symmetry Braking




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

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

$$< \bar{q}q > \approx 0$$

**High T**
**High ρ**

# Dileptons from fireball

**Dalitz:**
- $\pi^0 \rightarrow \gamma e^+e^-$
- $\eta \rightarrow \gamma e^+e^-$
- $\omega \rightarrow \pi^0 e^+e^-$
- $\phi \rightarrow \eta e^+e^-$

**Heavy flavor:**
- $c\bar{c} \rightarrow e^+e^- + X$
- $b\bar{b} \rightarrow e^+e^- + X$

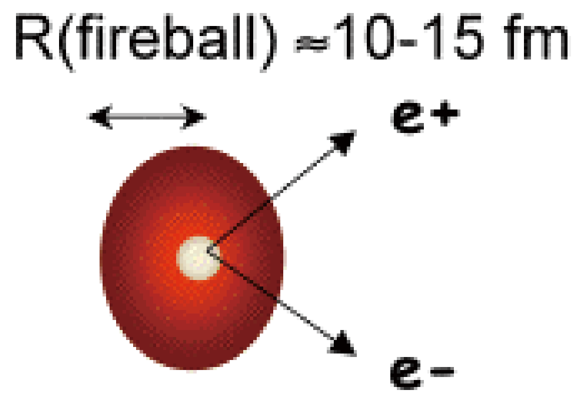
**Drell-Yan:**
- $q\bar{q} \rightarrow e^+e^-$

**Direct:**
- $\rho \rightarrow e^+e^-$
- $\omega \rightarrow e^+e^-$
- $\phi \rightarrow e^+e^-$
- $J/\psi \rightarrow e^+e^-$
- $\psi' \rightarrow e^+e^-$

**= Known Source = "Cocktail"**

**vs.**

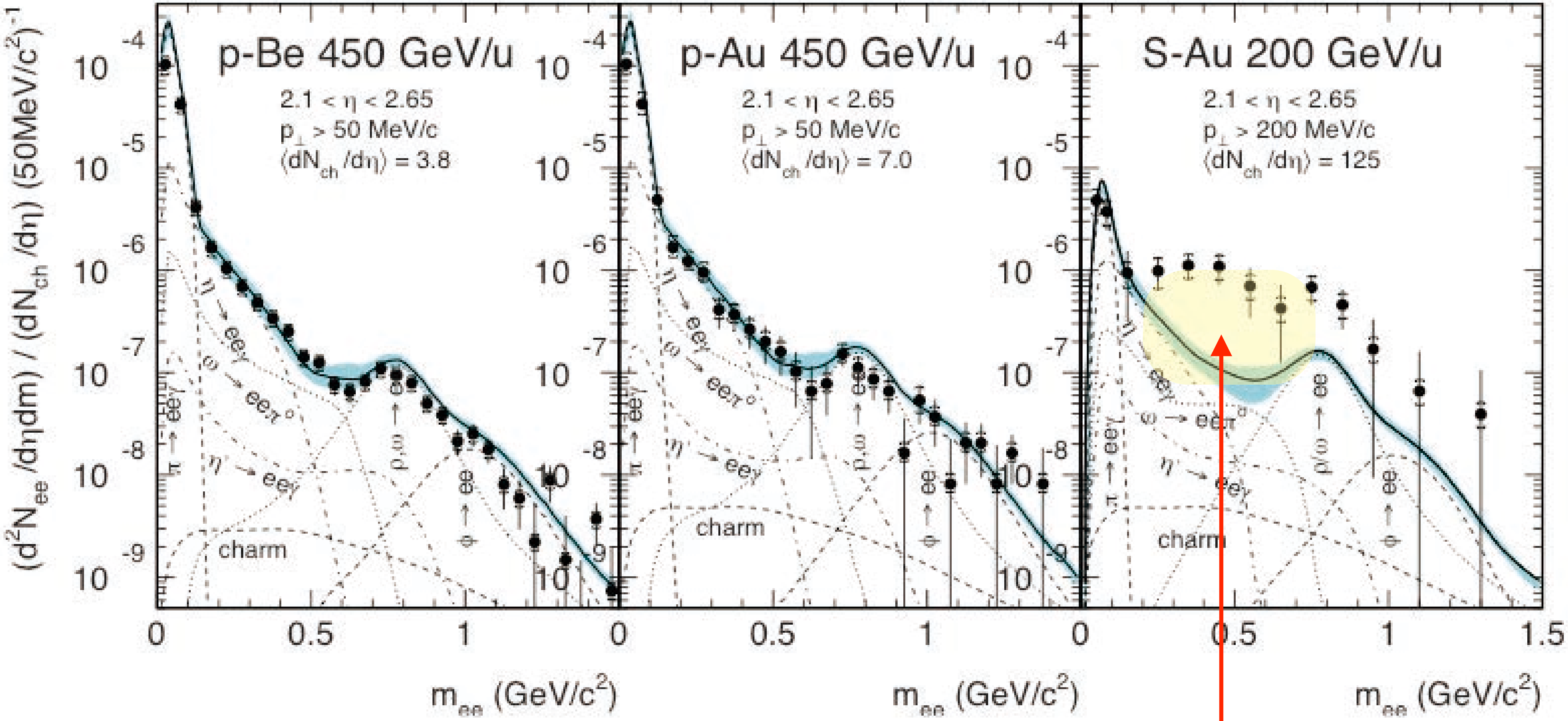
**Experimental data**




$$m_{e+e-} = \sqrt{p_{e+}p_{e-}} \sin\frac{\vartheta_{e+e-}}{2}$$

- **Dileptons**
  - probe the entire space-time evolution of the fireball (continuously emitted during the evolution)
  - Not subject to strong interactions, not significantly affected by the medium at later stages of the collision

# Excess on di-electron mass spectrum (data)

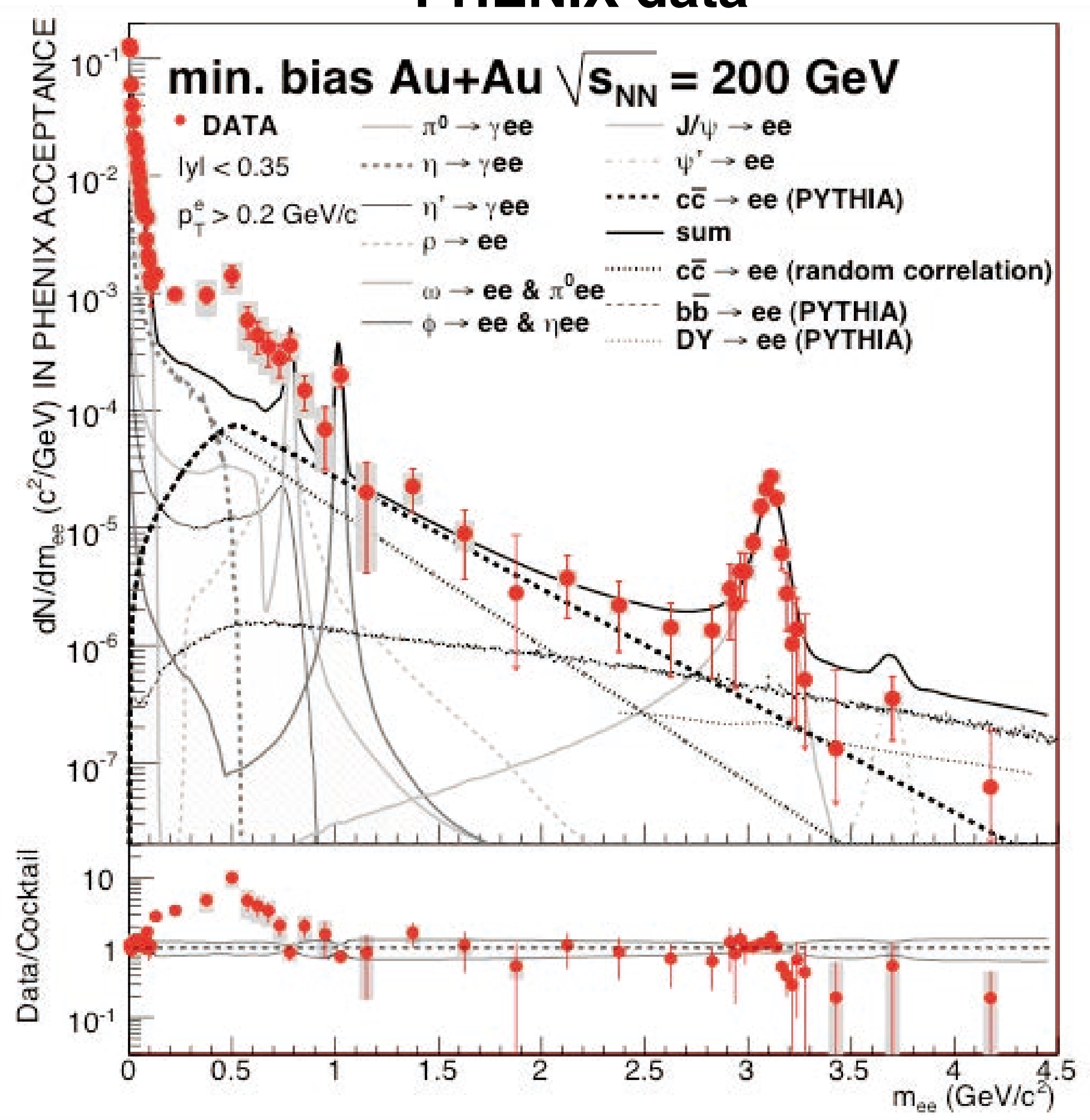



CERES (SPS)

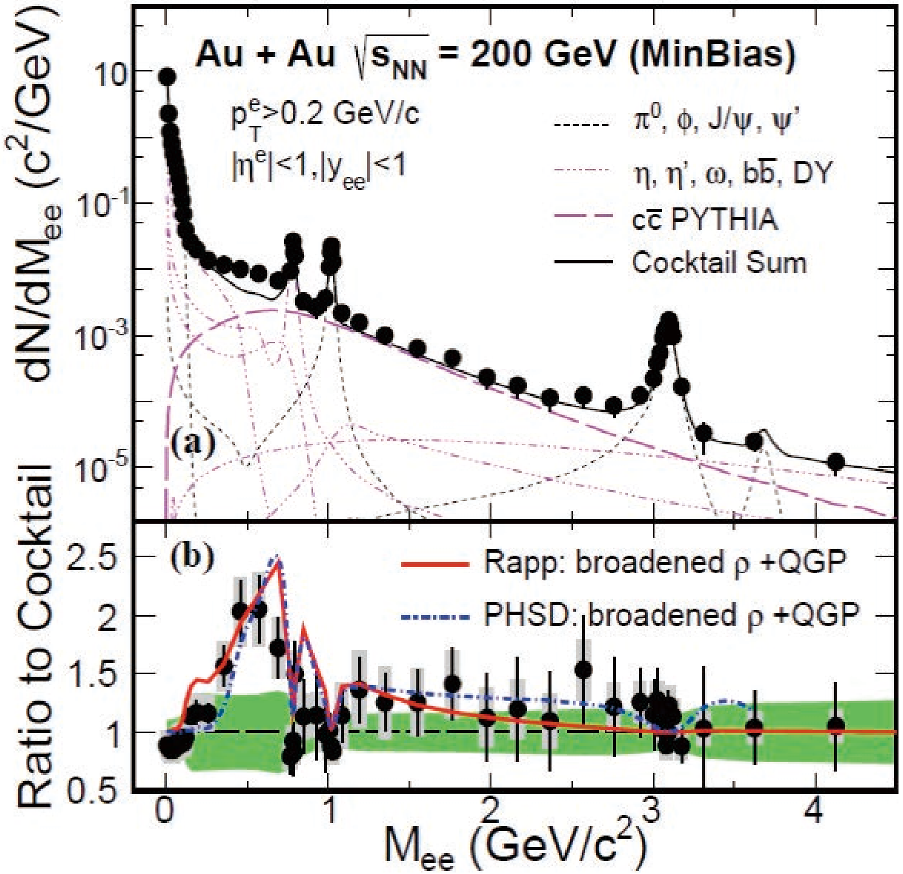
**Enhancement**

# Excess on di-electron mass spectrum (data)

**PHENIX data**

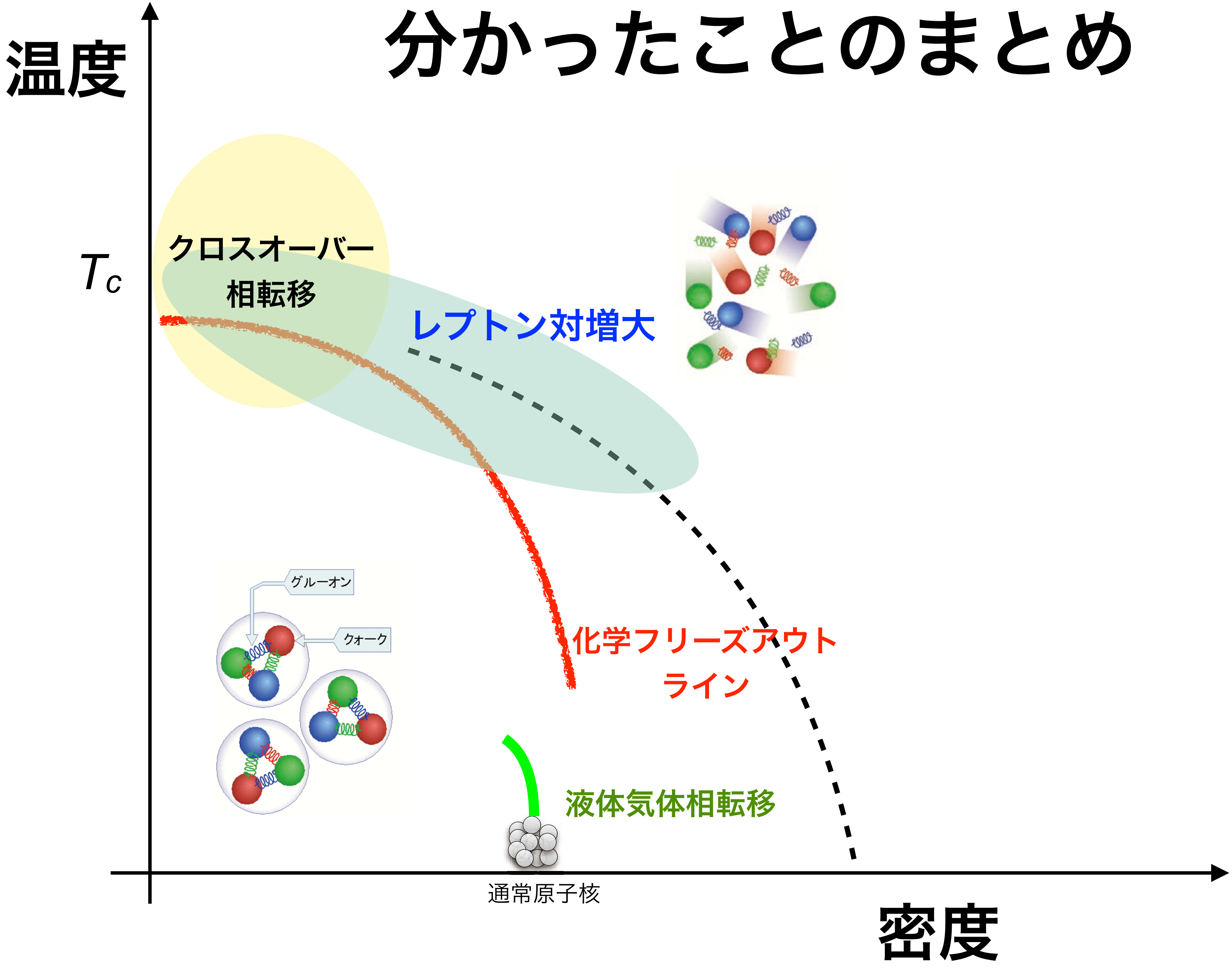



**STAR data**



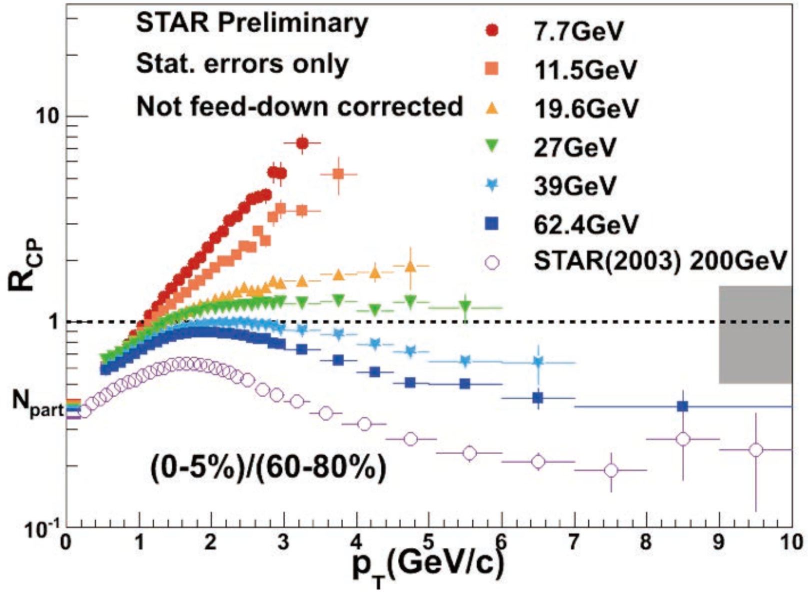

A. Agakichiev et al., Phys. Rev. Lett. 75, 1272 (1995). A. Agakichiev et al., Eur. Phys. J. C4, 231 (1998).

# 分かったことのまとめ

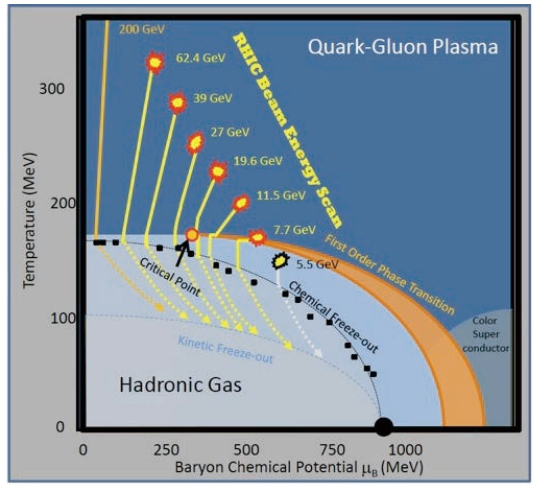

温度
$T_c$
クロスオーバー
相転移
レプトン対増大
化学フリーズアウト
ライン
液体気体相転移
グルーオン
クォーク
通常原子核
密度

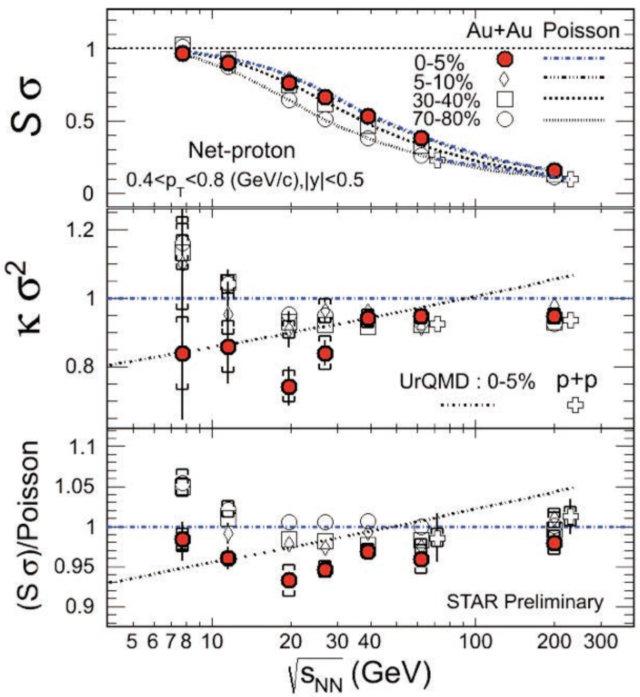
# まだ分かっていないこと

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




# I.　１次相転移か、クロスオーバーか？臨界点はあるのか？



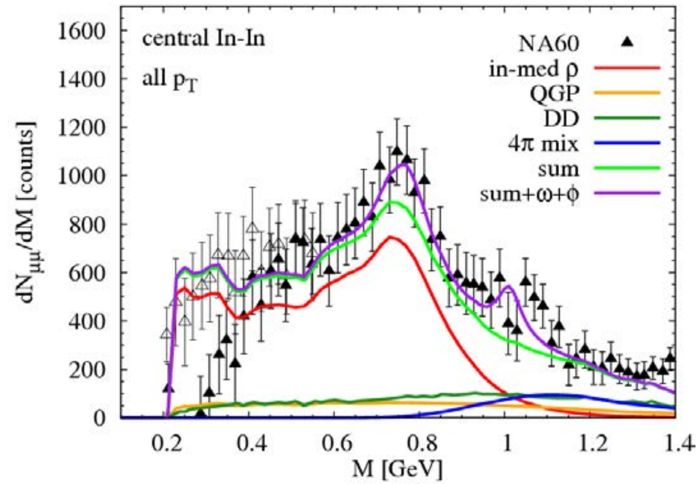




$$\sigma^2 = \langle (N - \langle N \rangle)^2 \rangle$$
$$S = \langle (N - \langle N \rangle)^3 \rangle / \sigma^3$$
$$\kappa = \langle (N - \langle N \rangle)^4 \rangle / \sigma^4 - 3$$

- 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)

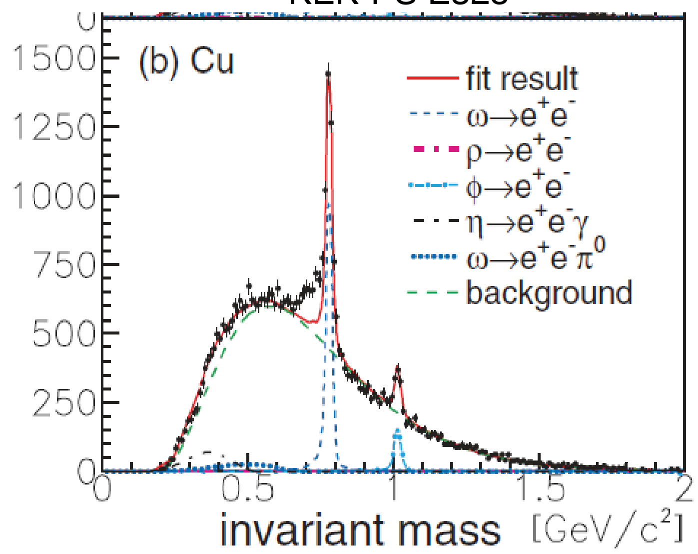
# 2. レプトン対測定の解釈の難しさ:
# カイラル対称性の破れは見えたのか、見えないのか？

[van Hees+R. Rapp '06]




- 高エネルギー重イオン
  - SPS-NA60 (PRL 96 (2006) 162302)
    - **Modification of ρ meson due to hadronic effects**
  - RHIC-PHENIX (PRC81(2010) 034911)
    - **Origin of the enhancement is under discussion**
  - RHIC-STAR
    - **Enhancement is seen, but much smaller than PHENIX**
- 原子核標的 (p-A)
  - HADES (G. Agakishiev et al. Eur.Phys.J. A 48 64 (2012).)
    - Enhancement in low mass region
  - CBELSA/TAPS (Phys.Rev. C82 (2010) 035209)
    - Modification of ω is not observed
  - J-LAB CLAS G7 (PRL 99 (2007) 262302)
    - Mass broadening of ρ due to hadronic effects
  - KEK-PS E325 (PRL 96 (2006) 092301)
    - Peak shift and width broadening of ρ/ω

KEK-PS E325




Slides from K. Ozawa (RIKEN HI tutorial, Mar. 2014), modified

# 3. 今なぜ J-PARC で
# 重イオン実験なのか？

# J-PARC 重イオン衝突の物理

## ($\sqrt{s_{NN}}$ =1.9 - 6.2 GeV )

●軽イオンから U 重イオンまで加速

**●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し、世界最高のバリオン密度物質を研究する**

– レプトン対(電子, ミューオン)

➡ **カイラル対称性回復の研究**

• 直接光子

➡ **高バリオン物質からの熱光子放出？**

- 揺らぎの測定（バリオン数・電荷等の保存量)

➡ **QCD 臨界点探査**

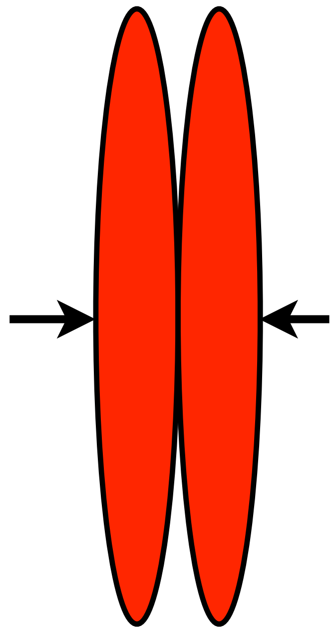
– エキゾティックハドロン/原子核、チャームの物理

• multiple-strangeness (ストレンジレット探査)

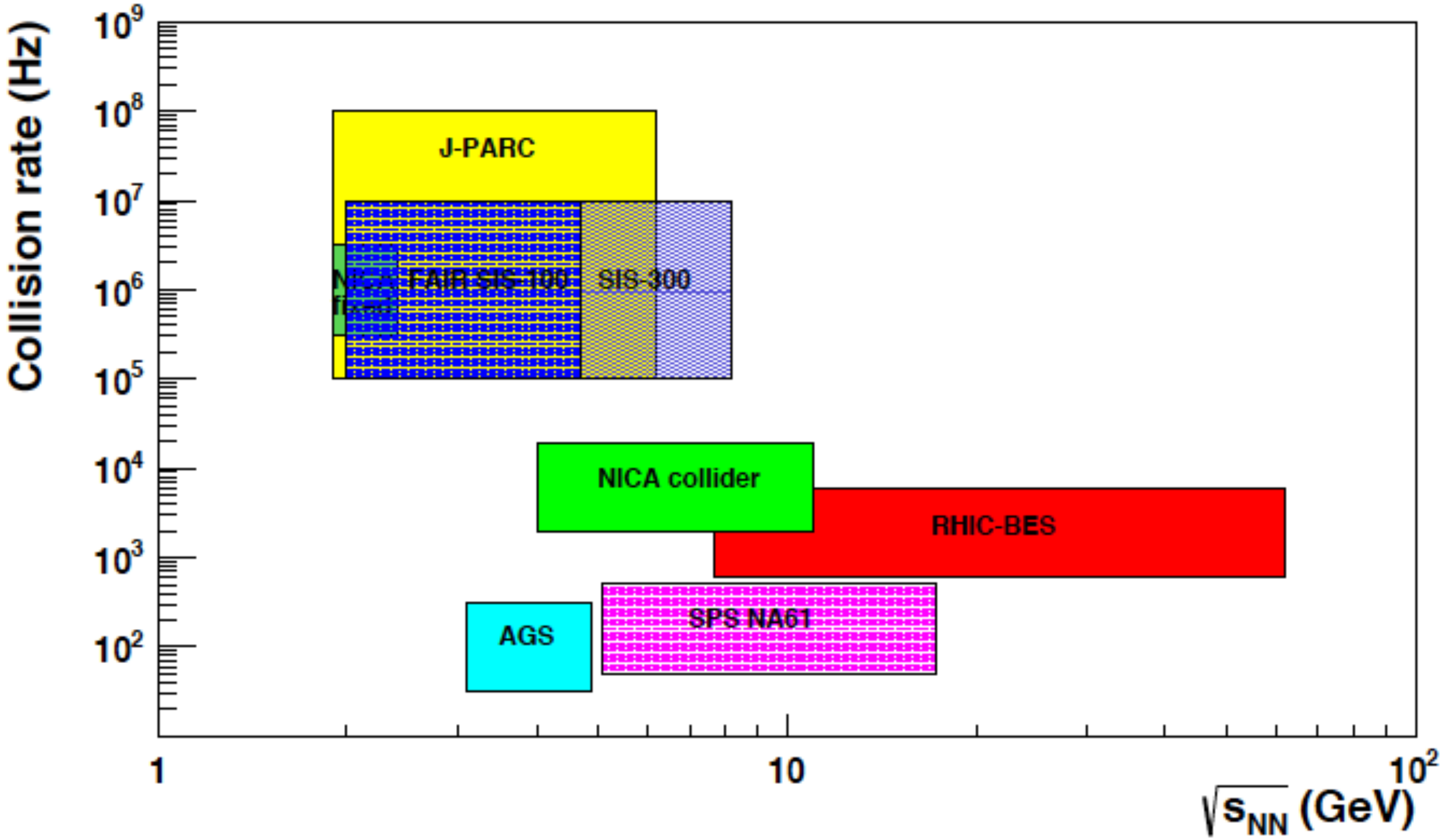
• ２重、３重 ハイパー核

• 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**



# Beam energy vs. collision rate



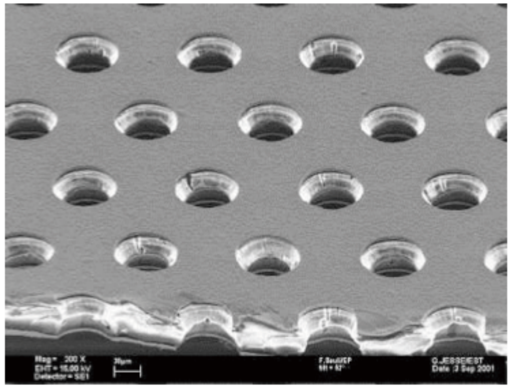

J-PARCでの重イオン衝突実験では、世界最高のビーム強度で、

1.9 - 6.2 GeV での重イオン固定標的実験が可能に

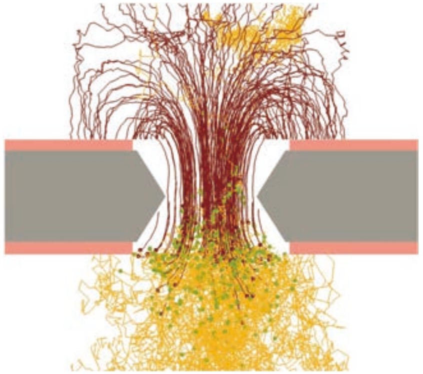
この計算（固定標的）では、各加速器でのビームレートと1% 反応率を仮定.

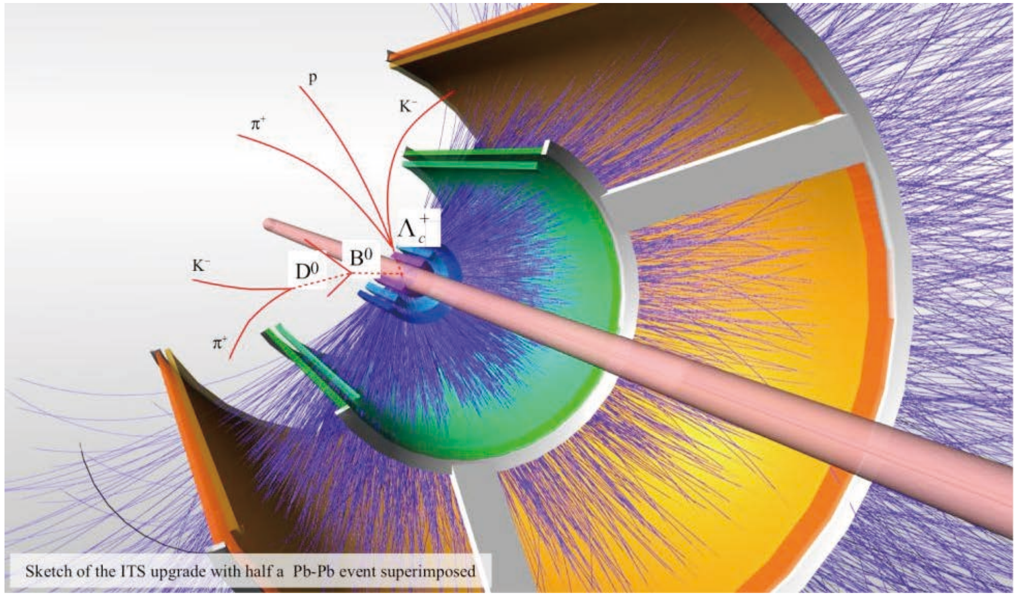
AGS, SPS (NA61) については、データ取集レートを計算に採用

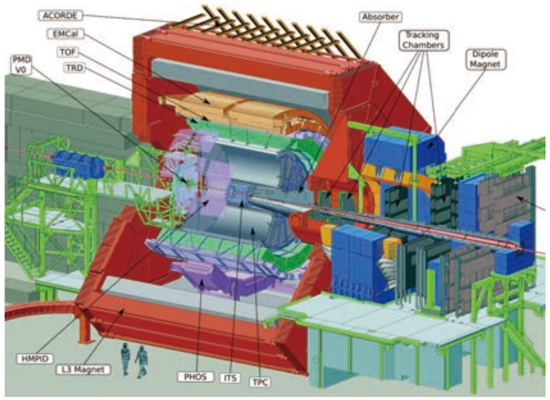
# 実験技術の向上

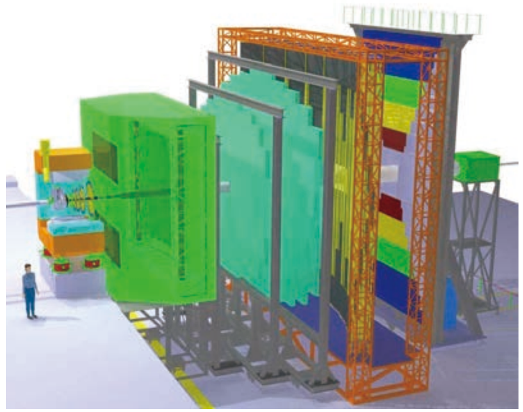


Standard GEM
Pitch=140µm
Hole ϕ=70µm



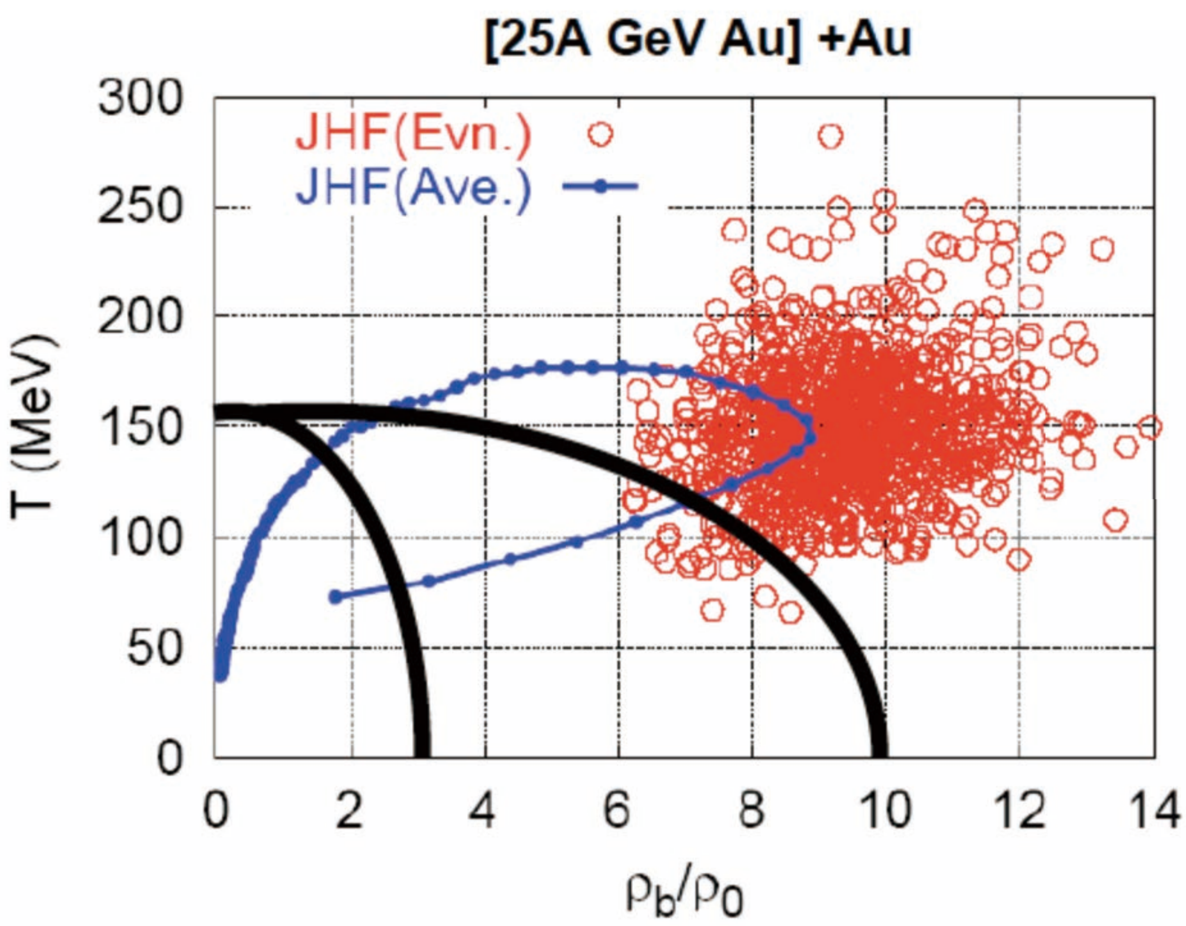


- 高レートに耐えうる検出器・データ収集系が利用可能になってきた (例：ALICE, CBM (FAIR))

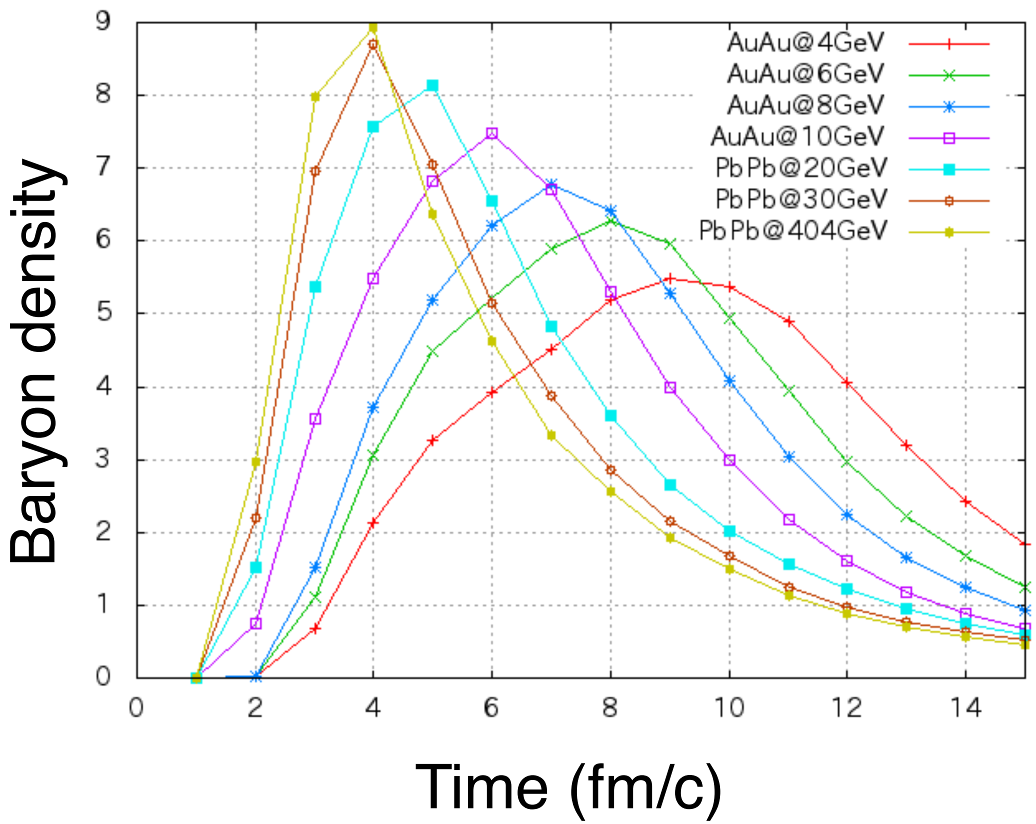
# J-PARC 重イオン衝突で達成可能なバリオン密度

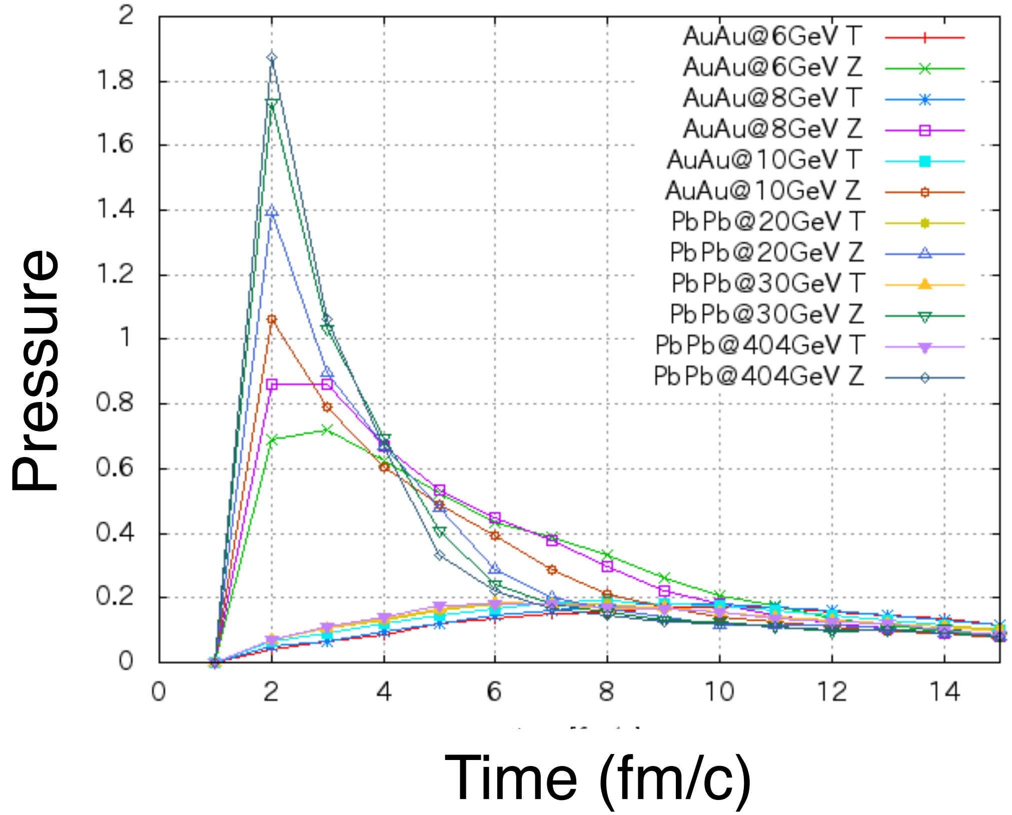



JAM
(Hadronic cascade model)
Y. Nara et al, PRC61 (2000)

$\rho_B > 6\ \rho_0$
for about 3 fm/c

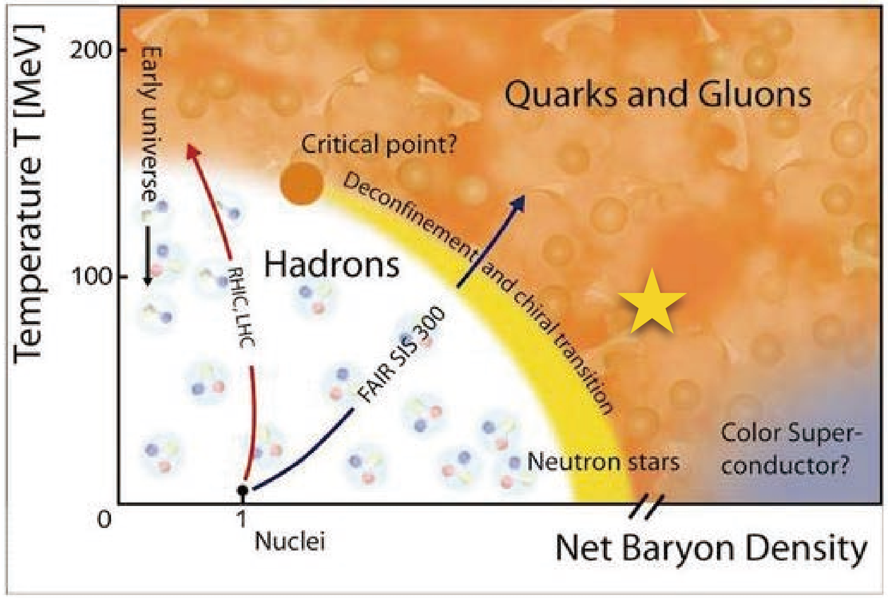
# Baryon density (simulation, JAM Cal. by H. Sako, 2014)




- JAM: hadronic cascade model
- http://phits.jaea.go.jp/OvPhysicalModelsJAM.html
  Y.Nara et.al. Phys. Rev. **C61** (2000) 024901

# 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

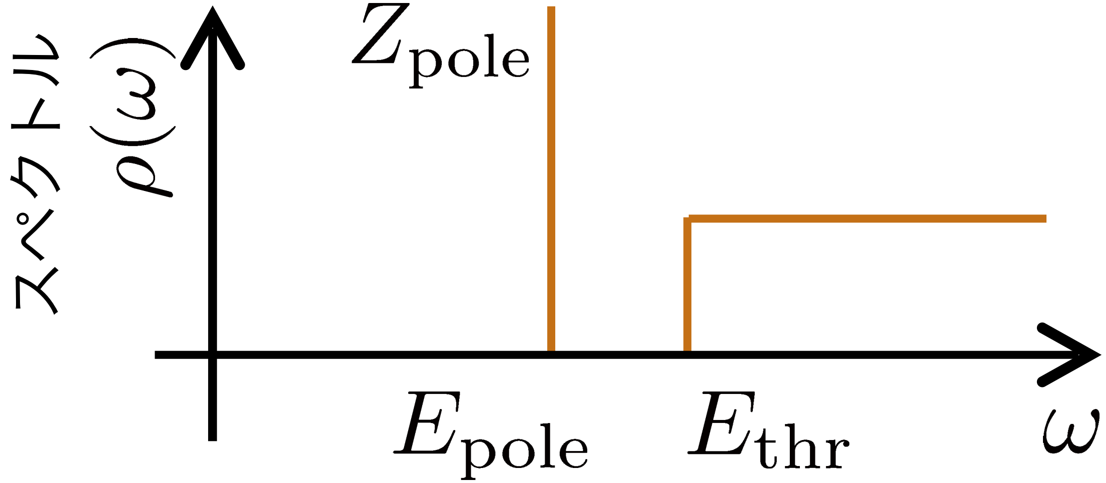
**NS-NS merger can touch unreachable region in phase diagram**
**"high density and (relatively) high temperature"**
**cf T ~ 100MeV, $\mu_B$~ 1000MeV (Shapiro 1998, Chen,Labun 2013)**

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

# QCD和則とスペクトル関数

Slides from M. Kitazawa (RIKEN HI tutorial, Mar. 2014), modified

①スペクトルに構造を仮定 → ②パラメータを、QCD和則から推定



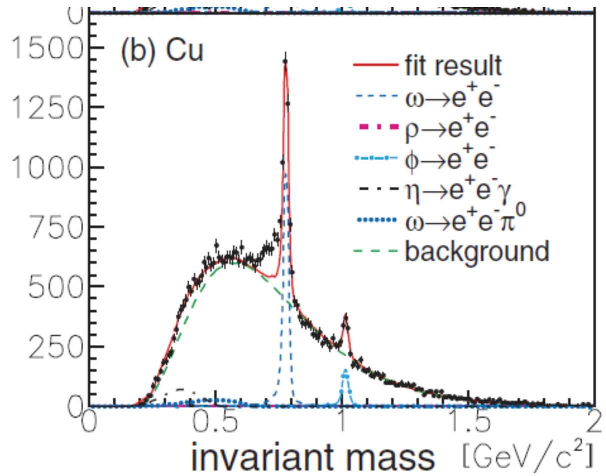

媒質中のQCD和則

Hatsuda-Lee, 1992

$$\frac{m_\rho}{m_\rho^{\mathrm{vac}}} = 1 - c\frac{\rho}{\rho_{\mathrm{vac}}}$$

→ 核物質中の媒質変化？

E325@KEK




T. Chujo (U. Tsukuba)

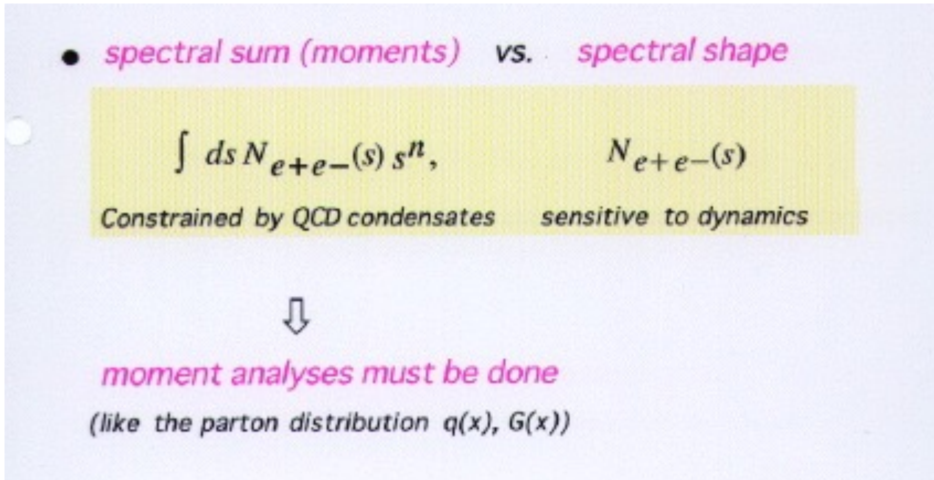
# QCD和則とスペクトル関数

Slides from M. Kitazawa (RIKEN HI tutorial, Mar. 2014), modified

## comment by 初田さん

International Conference on Soft Dilepton Production
LBNL, 1997
http://macdls.lbl.gov/DLS_WWW_Files/DLSWorkshop/proceedings.html

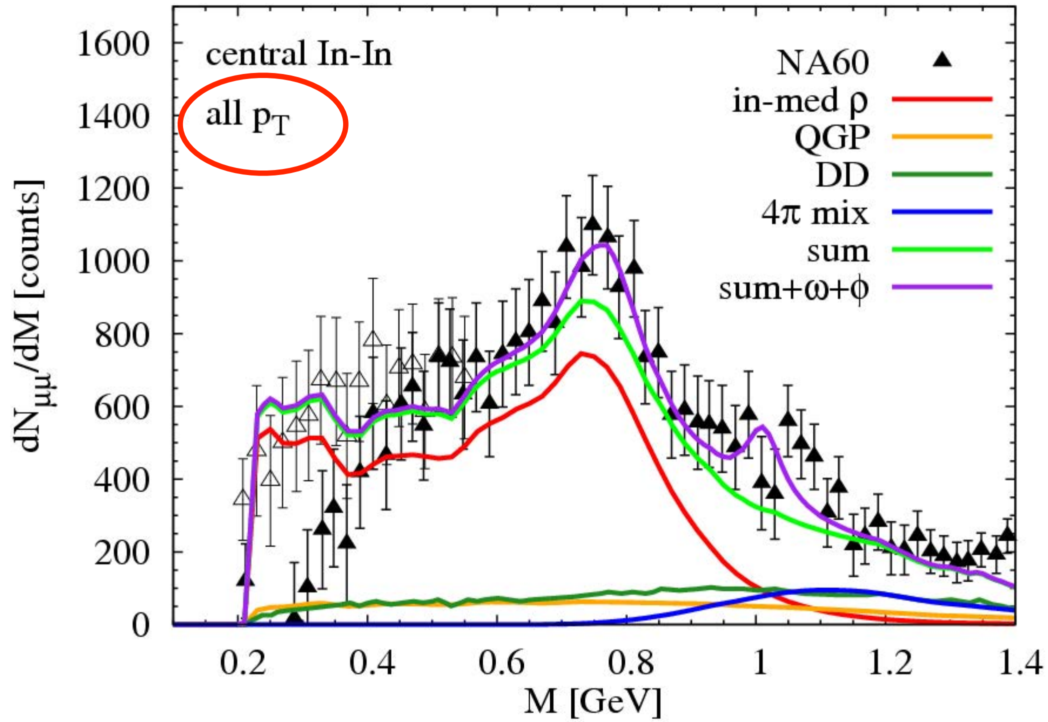
スペクトル自身よりも、積分値の方がより直接的に実験とQCD凝縮を比較できる



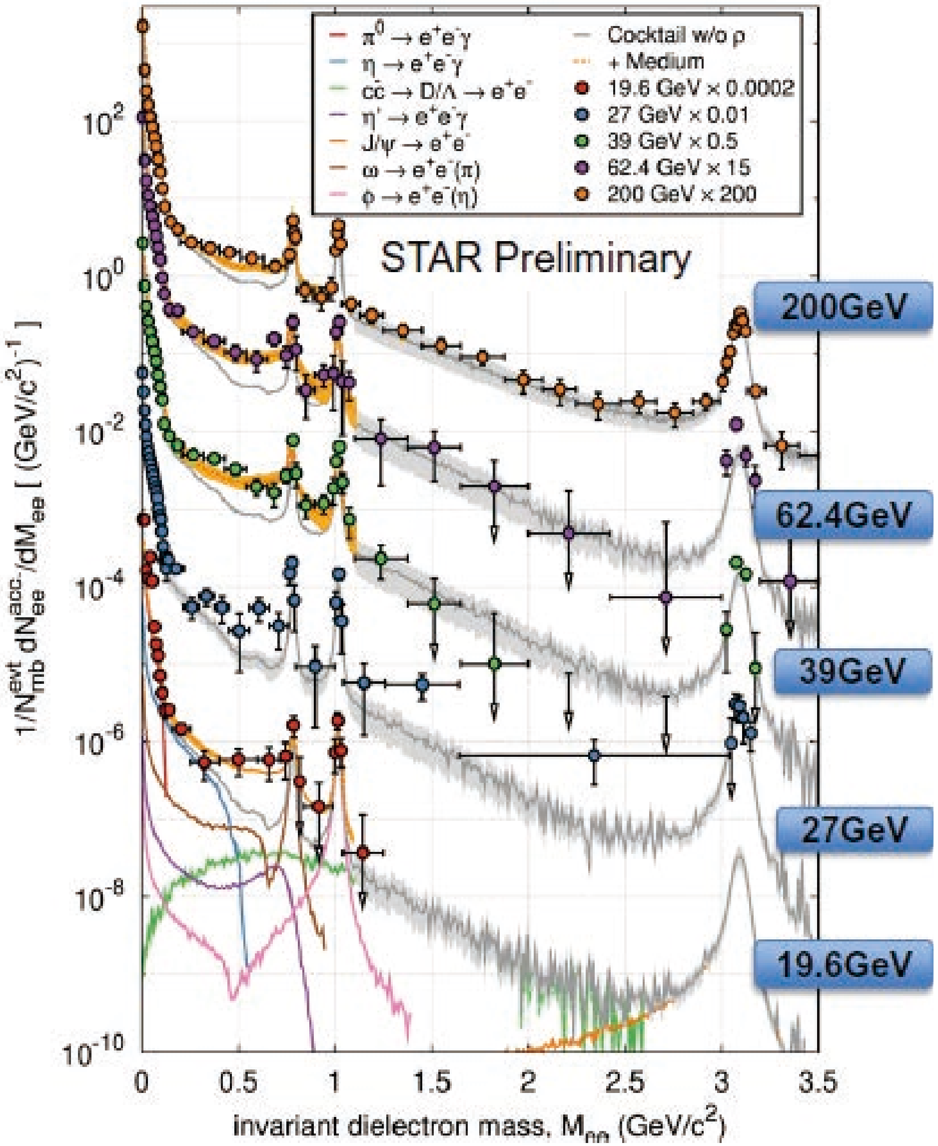

See also, Hatsuda, Hayano, RMP**82**, 2949

# 測定精度の時代へ

SPS-NA60




RHIC-STAR




**J-PARC では…**

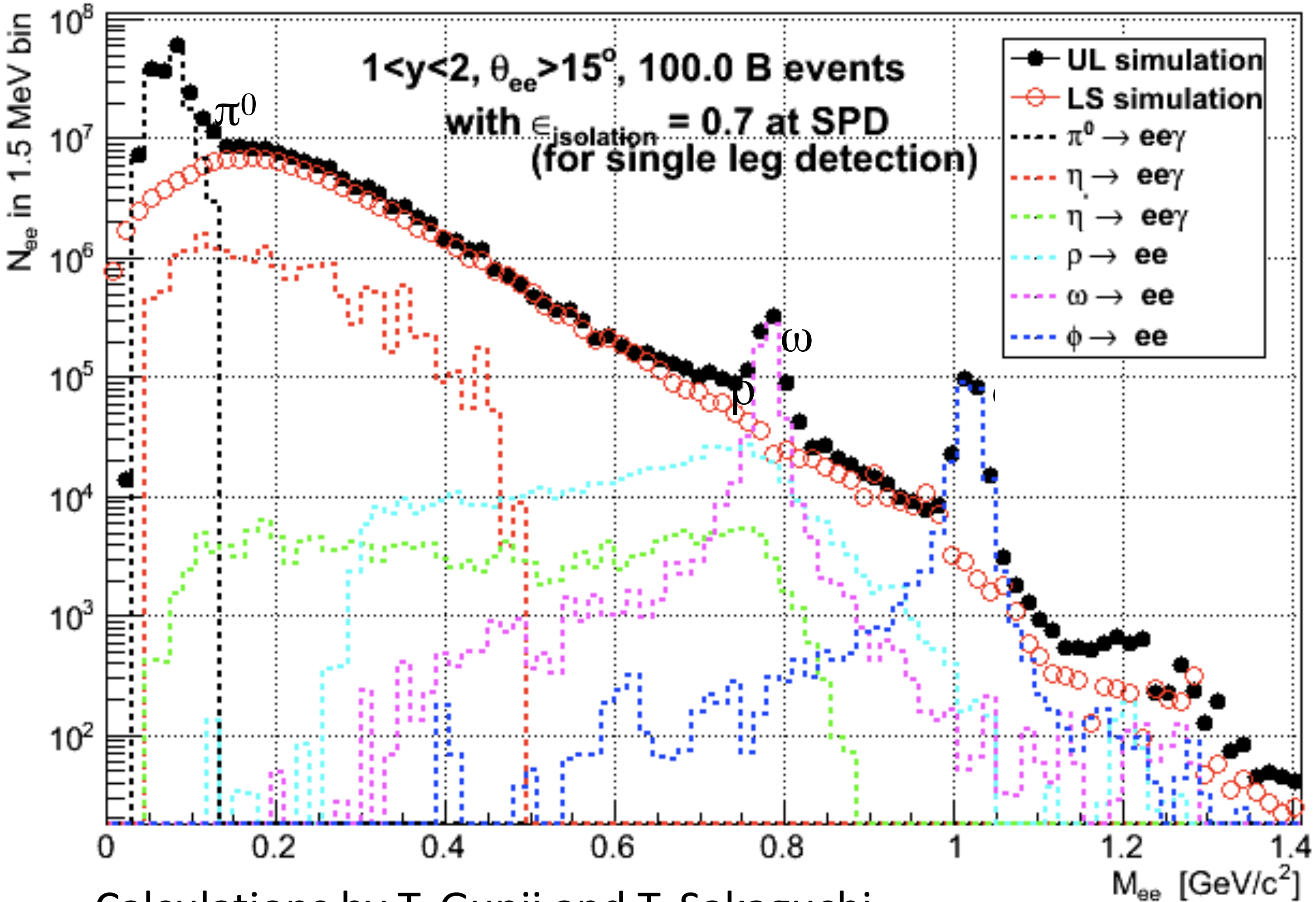
$p_T$ ビン毎、質量分布の精密測定

→ QCD sum rule との直接比較

(moment 解析)

T. Chujo (U. Tsukuba)

# Simulated di-electron spectrum (preliminary)




Calculations by T. Gunji and T. Sakaguchi

Based on $\pi^0$ 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

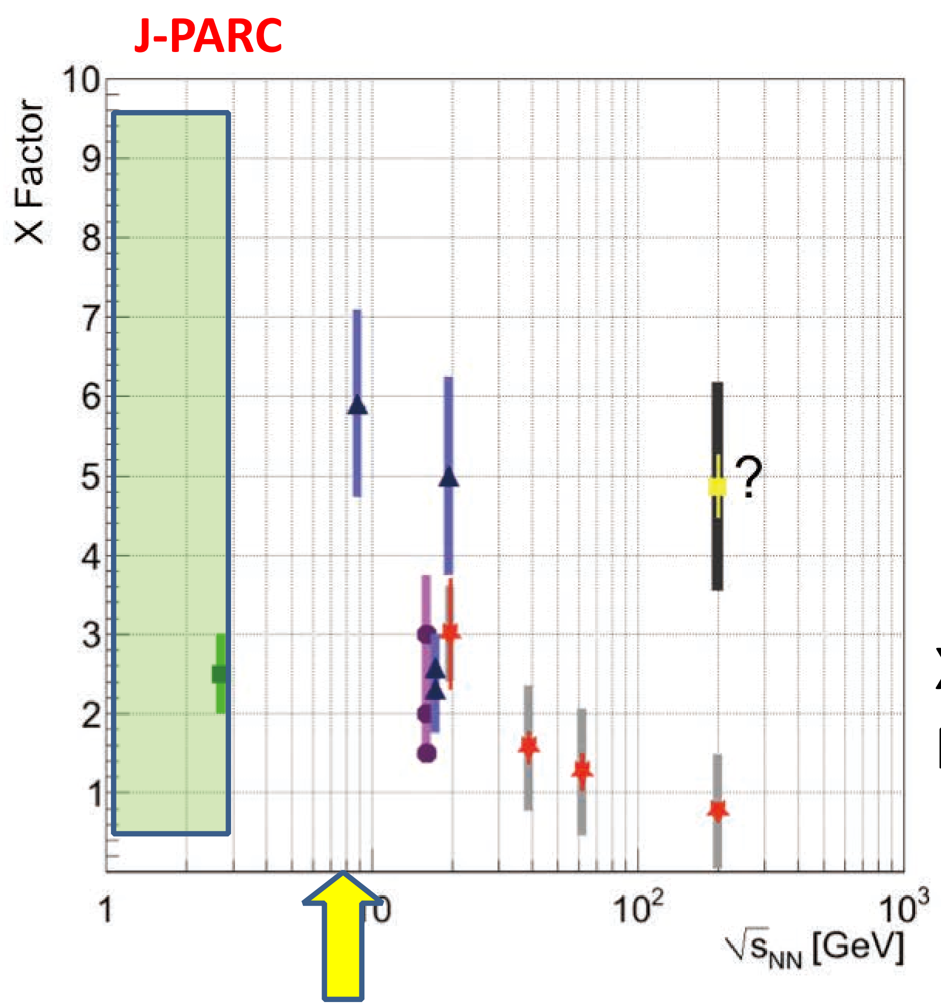
x 1 month running

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

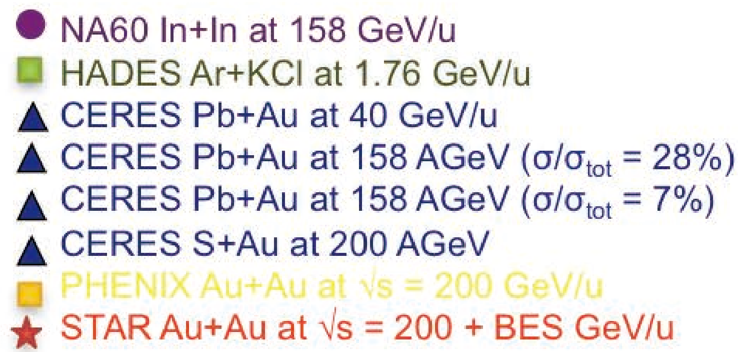
NA45 (CERES) データより**３桁高い統計量を１ヶ月で取得**！

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

# Low-mass dielectrons, maximum at J-PARC ?




Maximum baryon density~8GeV




X: Low-mass dilepton enhancement factor

Measured / cocktail in m=0.2-0.8 GeV/$c^2$

- **Maximum low mass enhancement at $\sqrt{s_{NN}}$ = 3-8GeV?**
- **Highest baryon density ~ 8GeV (Randrup, PRC74(2006)047901)**

T. Galatyuk, EM probes of Strongly Interacting Matter, ECT*, Trento 2007

# Event-by-event fluctuations

STAR PRL112 (2014) 032302

- **Search for the critical point and phase boundary**

Direct comparison to lattice-QCD may be possible

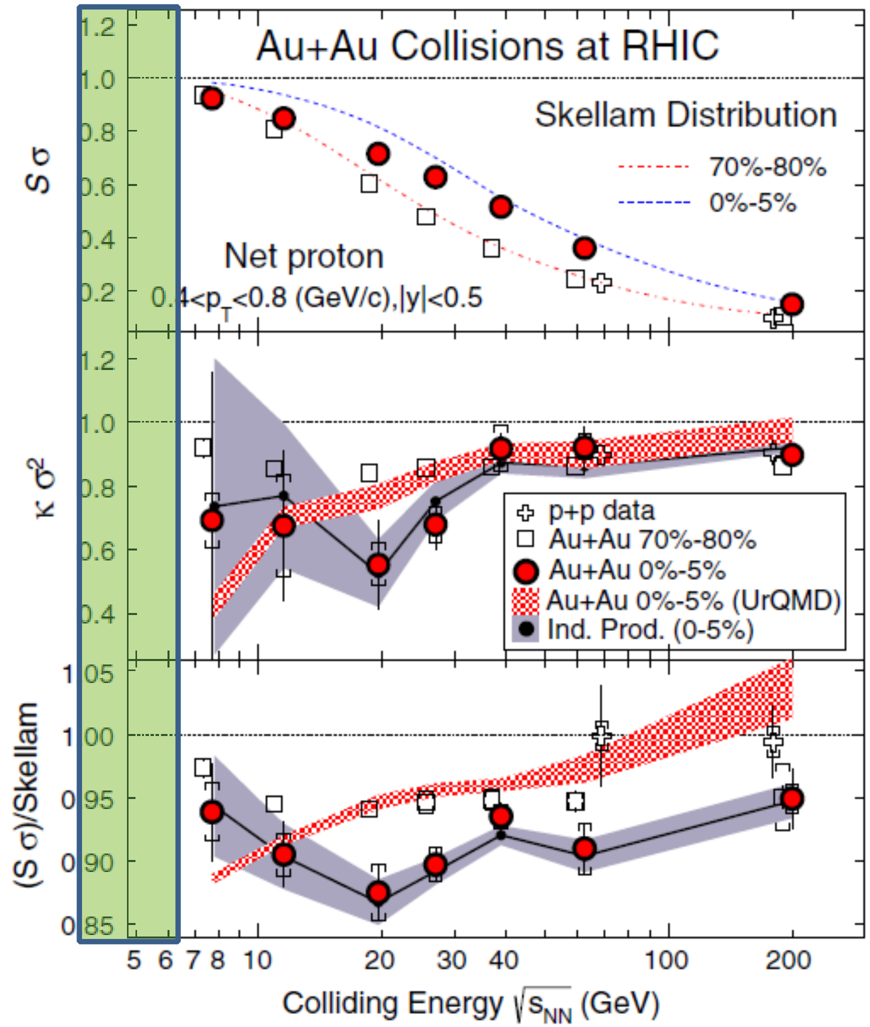
- Net-charge
- Net-proton
- Strangeness
- Higher-order fluctuations

$$S\sigma \cong \frac{\chi_B^3}{\chi_B^2}$$

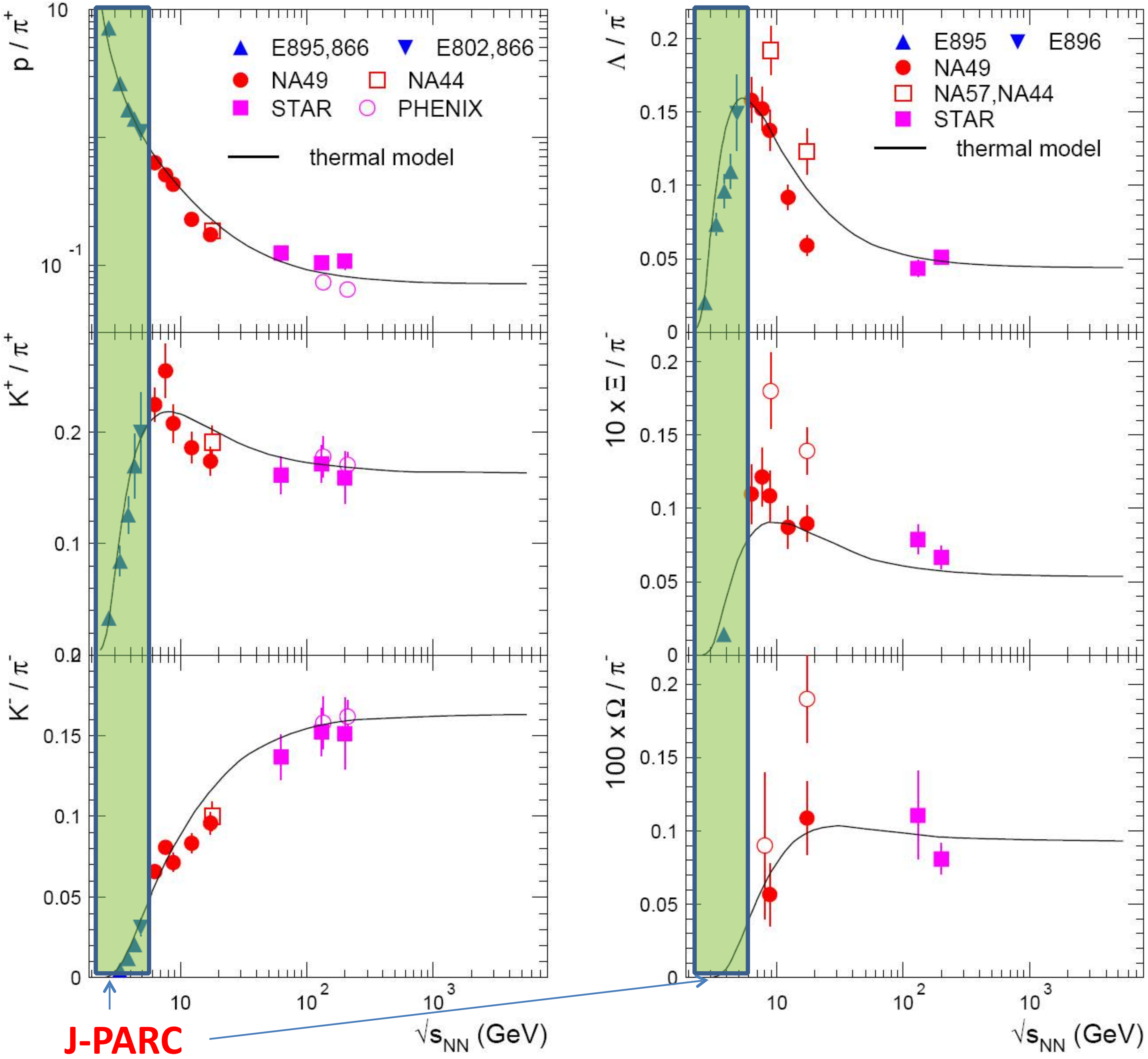
$$\kappa\sigma^2 \cong \frac{\chi_B^4}{\chi_B^2}$$

High event statistics

Wide y, $p_T$ acceptance



# Strange meson/baryons

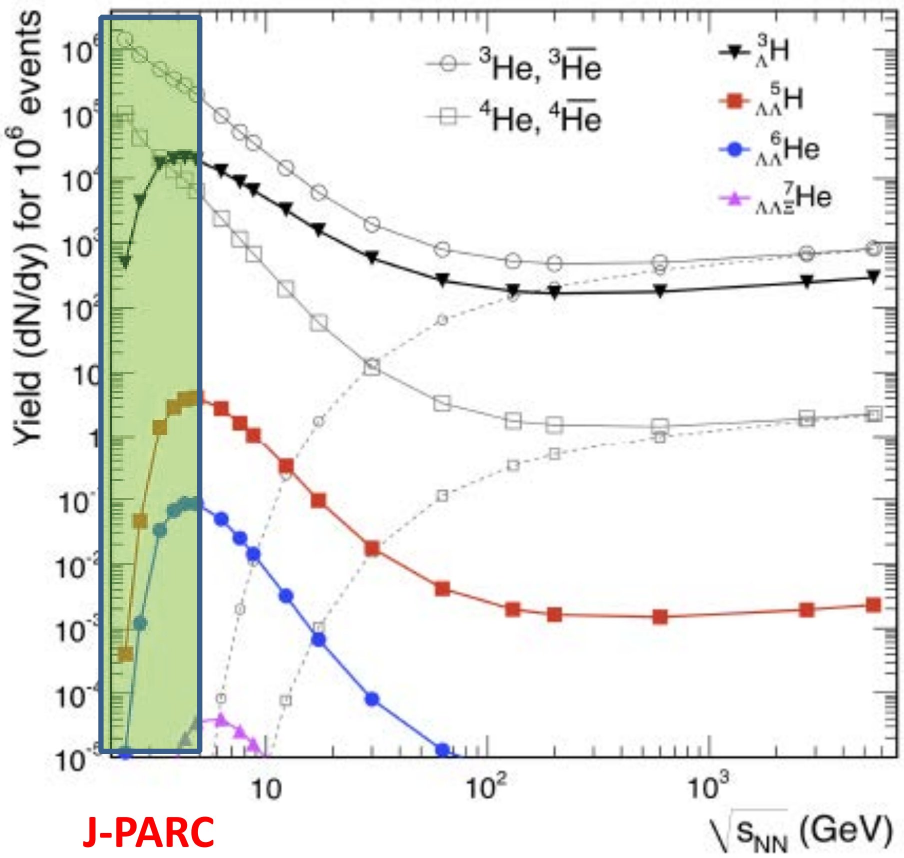



A. Andronic et al, Nucl. Phys. A 837 (2010) 65

Systematic energy scan below the "horn" at ~8 GeV

Almost no Ξ, Ω measurements

# Hypernuclei




A. Andronic, PLB697 (2011) 203

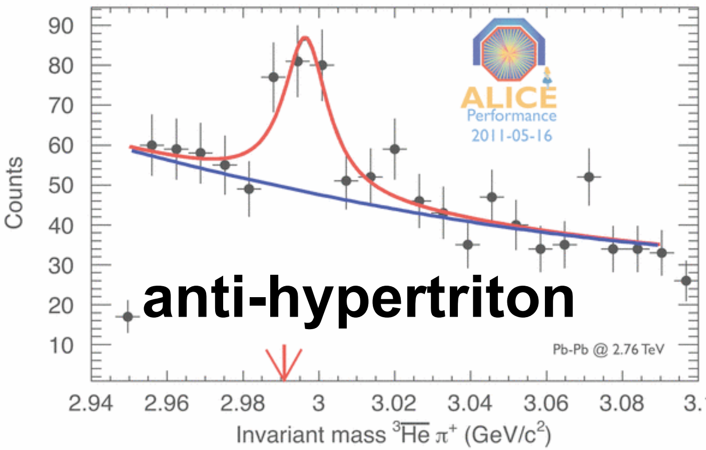
## Maximum yield at J-PARC

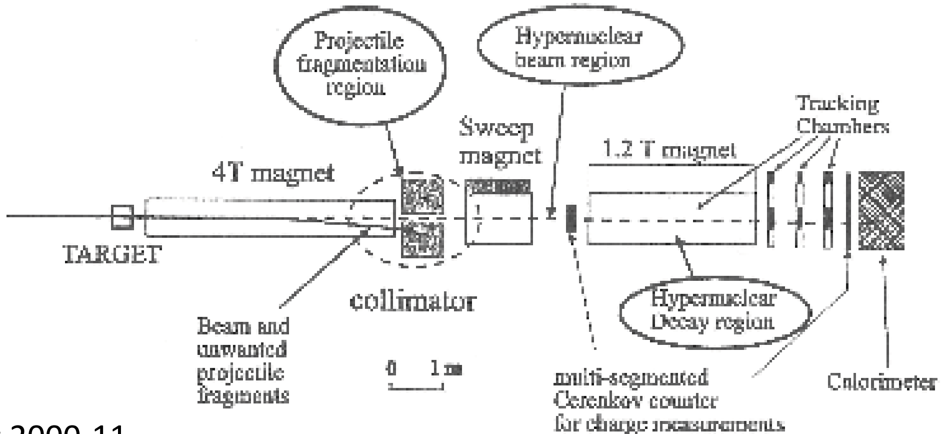
- Coalescence of high-density baryons

S=-3 Hypernuclei

only possible in HI collisions

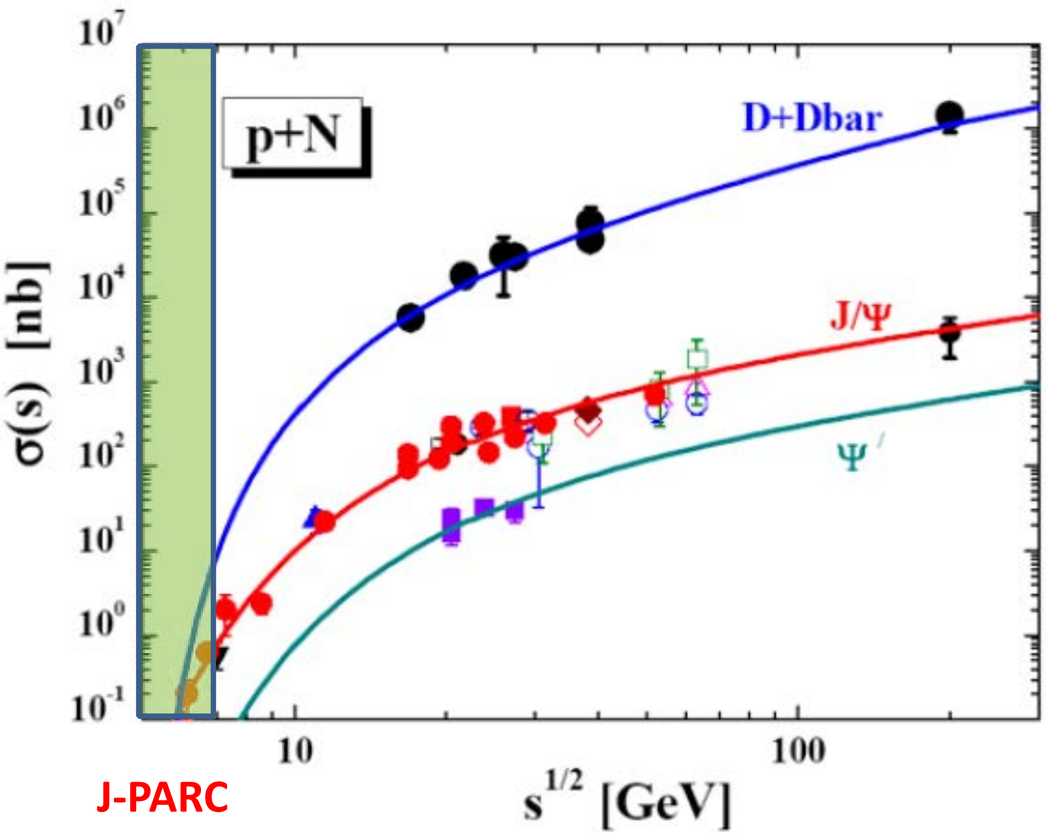
- Precise secondary vertex reconstruction (mid rapidity)
- Closed geometry (projectile rapidity) with full beam intensity




KEK Report 2000-11
Expression of Interest for Nuclear/Hadron Physics Experiments at the 50-GeV Proton Synchrotron

# Charmed particles




CBM Physics Book,
W. Cassing, E. L. Bratkovskaya and
A. Sibirtsev, Nucl. Phys. A 691 (2001) 753

- c-$\bar{c}$ produced in the early stage of collisions
  - D,J/ψ may be modified
  - Probe of high density state

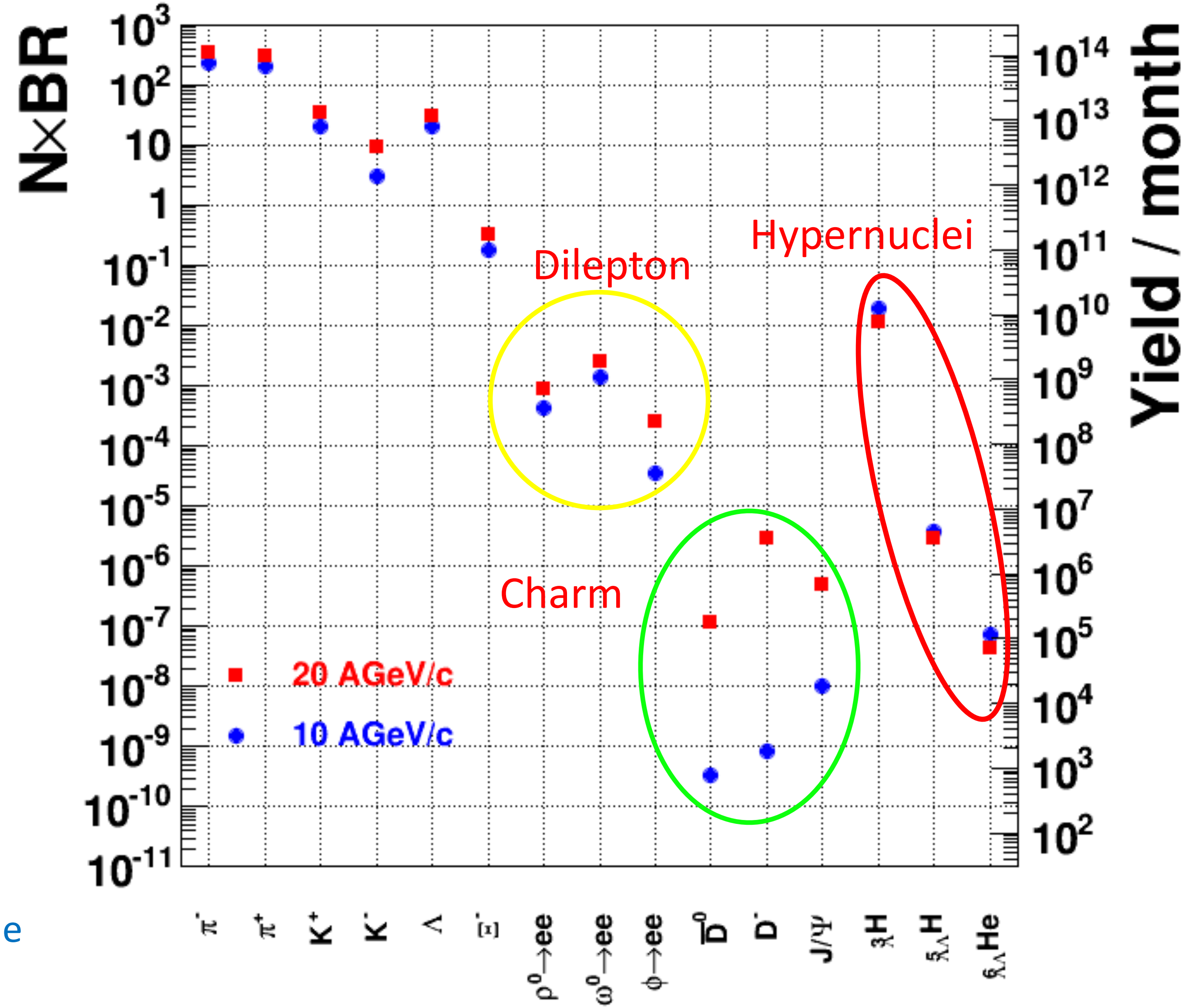
  J-PARC energies close to the production thresholds
  - D (5.07 AGeV),J/ψ (4.77 AGeV)

  May be possible increase of beam energy from 12 →19 AGeV/c
  - √s= 4.9→6.2GeV (U)
  - Enhancement due to multi-step processes in A+A?
  - Search for charmed baryon in dense matter.

# 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:
ρ,ω,φ→ee $10^7$-$10^9$
D,J/Ψ $10^5$-$10^6$ (20AGeV)
($10^3$ -$10^4$(10AGeV))
Hypernuclei $10^5$ -$10^{10}$




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

# 4. J-PARC における
# 重イオン実験の提案

# *J-PARC HI Collaboration*

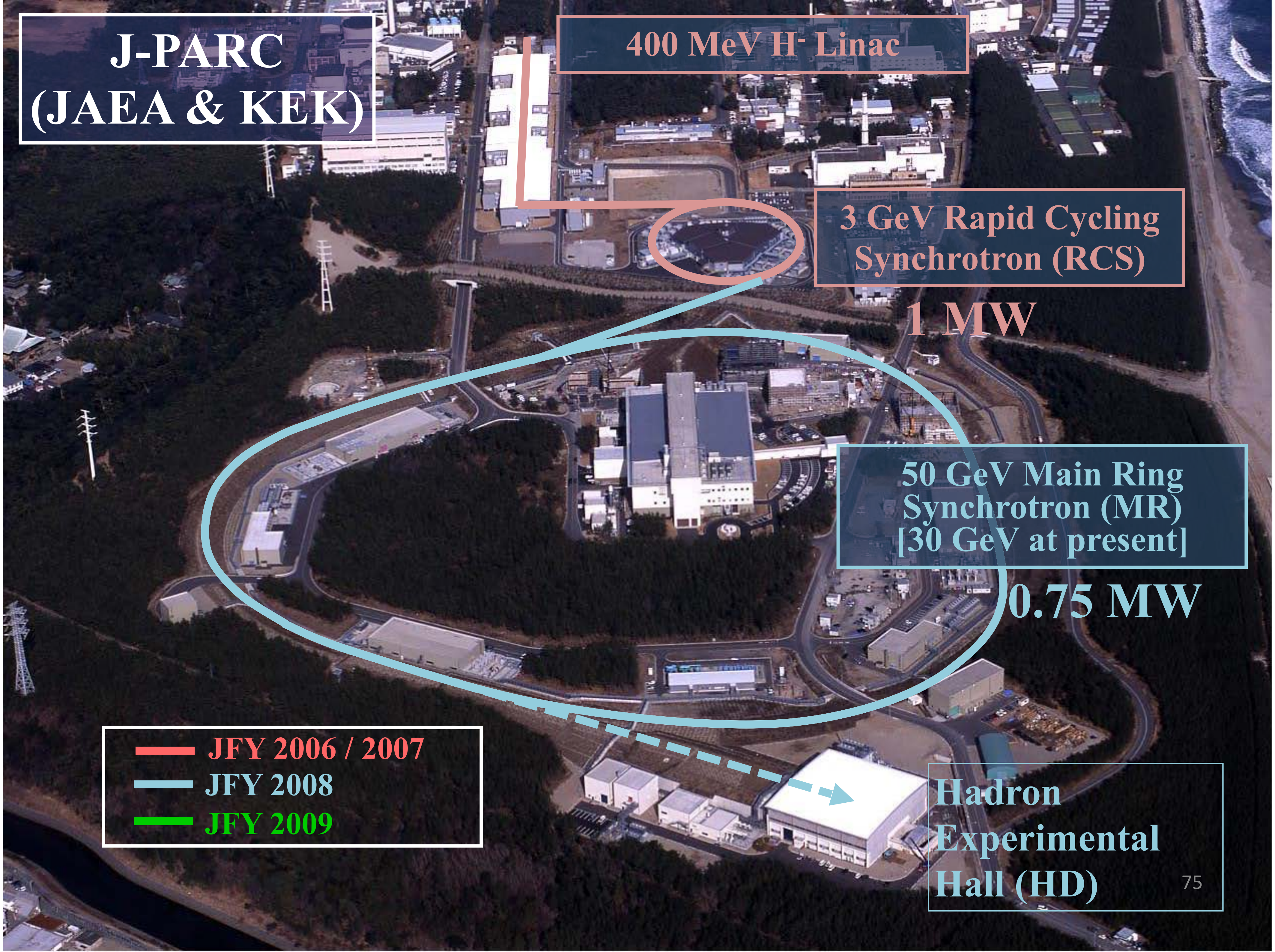
Nuclear Experimentalists and Accelerator Physicists

S. Nagamiya (JAEA/KEK/RIKEN)
H. Sako, K. Imai, K. Nishio, S. Sato, S. H. Hwang (ASRC/JAEA)
H. Harada, P. K. Saha, M. Kinsho, J. Tamura (J-PARC/JAEA)
K. Ozawa, Y. Liu (J-PARC/KEK)
T. Sakaguchi (BNL)
K. Shigaki (Hiroshima Univ.)
T. Chujo, B. C. Kim (Univ. of Tsukuba)
T. Gunji (CNS, Univ. of Tokyo)
M. Kaneta (Tohoku Univ.)
K. Oyama (Nagasaki Institute of Applied Science)

# Heavy-ion programs in the world

| Accelerator | Type | Beam energy | C.M. energy | 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) ($\sigma_{total}$=6b)* | *2004-2010 2018-2019 (e-cooling)* |
| *NICA (JINR)* | *Collider*<br>*Fixed target* | *0.6-4.5* | *4-11*<br>*1.9-2.4* | *$10^{27}$ $cm^{-2}s^{-1}$ (√s=9AGeV Au+Au)* | *~6000 ($\sigma_{total}$=6b)* | *2019-*<br>*2017-* |
| *SIS-100 (FAIR)* | *Fixed target* | *2-11(Au)* | *2-4.7* | *1.5x$10^{10}$ $cycle^{-1}$ (10s cycle,$U^{92+}$)* | *$10^5$-$10^7$ (detector)* | *2021-2024* |
| *SIS-300* | *Fixed target* | *35(Au)* | *8.2* | *1.0x$10^9$ $cycle^{-1}$* | | *?* |
| *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


J-PARC
(JAEA & KEK)
400 MeV H- Linac
3 GeV Rapid Cycling Synchrotron (RCS)
1 MW
50 GeV Main Ring Synchrotron (MR)
[30 GeV at present]
0.75 MW
Hadron Experimental Hall (HD)
JFY 2006 / 2007
JFY 2008
JFY 2009

# Advantages of RCS/MR for HI beam

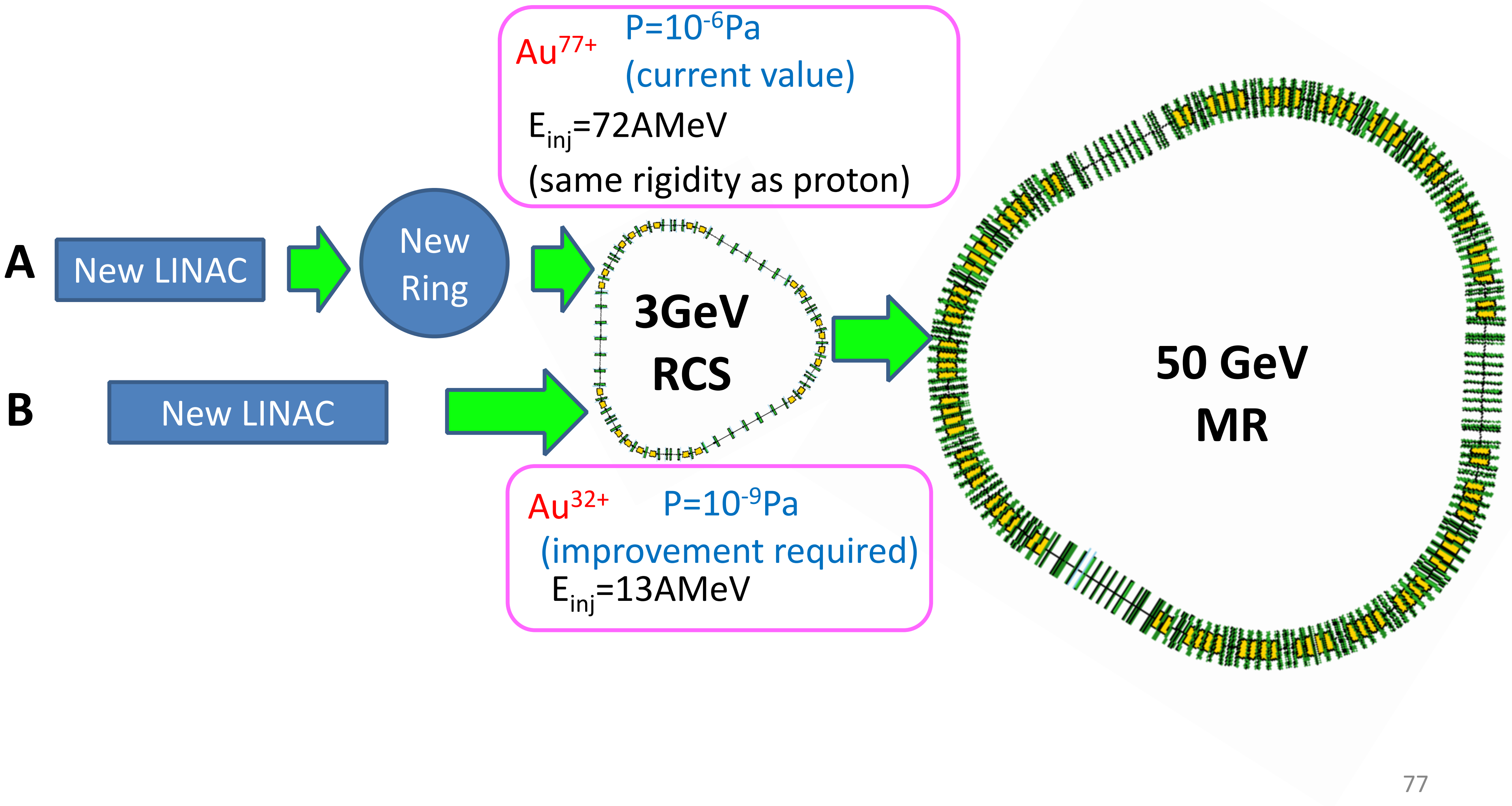
1. Existing 3 GeV and 50 GeV synchrotrons
   HI injector and injection section in RCS are necessary

2. Large acceptance
   (transverse $\varepsilon$>486$\pi$mmxmrad, longitudinal $\Delta p/p$>1%)
   ⇒ Multi-turn injection of high-intensity HI beam

3. Proven performance for high-intensity proton beam
   Current status of MR
   - Slowly extracted proton beam at 30 GeV
     $2.5 \times 10^{13}$/cycle (6s)→$1.3 \times 10^{14}$ (2017)

   Well understood accelerator performance
   Optics, lattice imperfections, acceleration, beam loss

# Possible accelerator schemes at J-PARC



# Physics goals

- **Dileptons (dielectron and dimuon)**

  ⟺ J-PARC E16 p+A

- Systematic and high statistics hadron measurements
  - Strange meson and baryons
  - **Event-by-event fluctuations (higher-order cumulants)**
  - HBT (YN, YY correlations in high baryon density)
  - flow (EOS)
- Rare particles
  - Hypernuclei
  - Exotic hadrons
    - $\Lambda(1405)$
    - Dibaryon (H-dibaryon, $\Omega$N, $\Delta\Delta$,…)
    - Kaonic nucleus ($K^-$pp,…)

  ⟺ J-PARC $\pi$/K beams

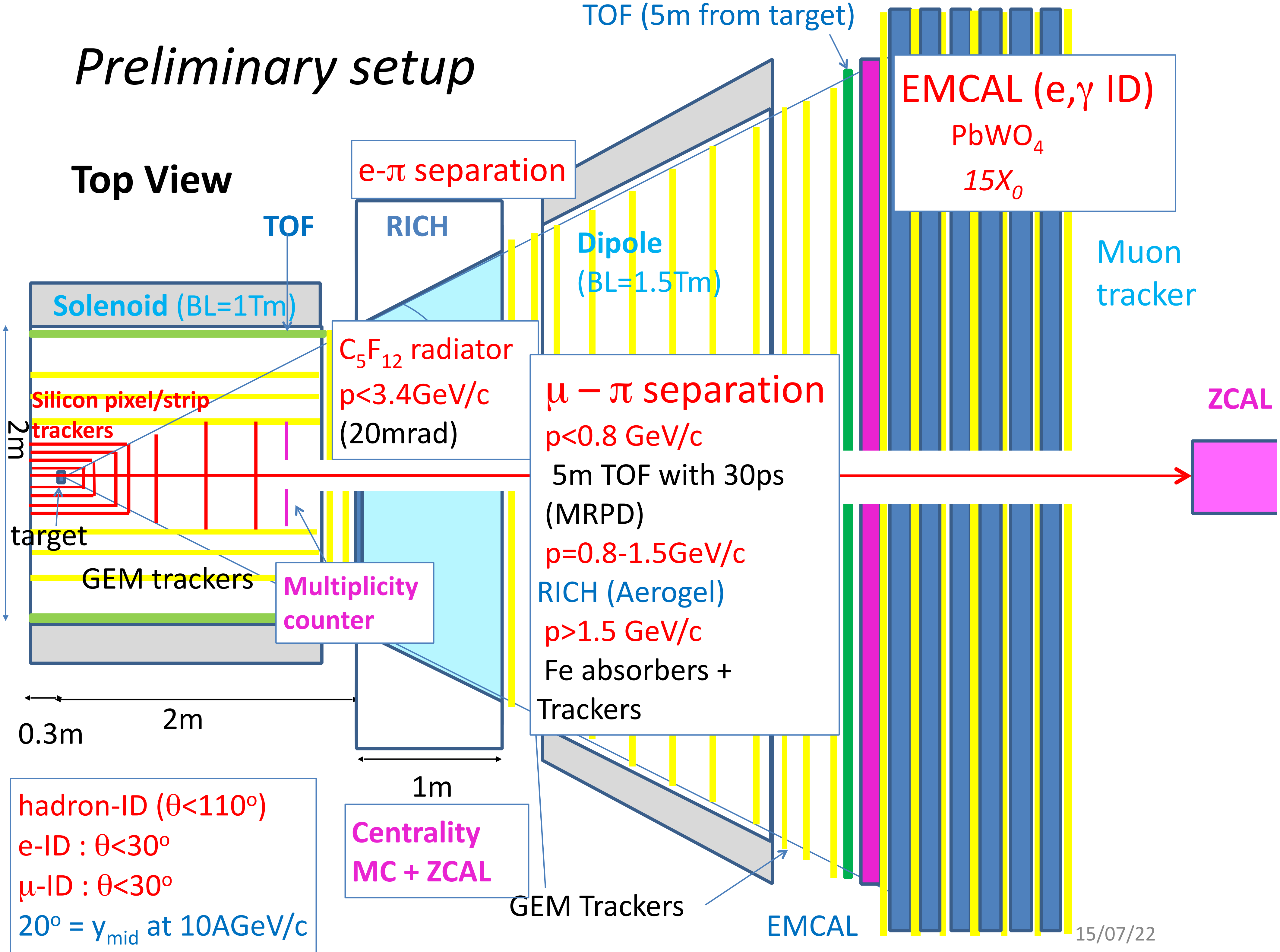
  - Charm
    - J/$\psi$, D, charmed baryons
- Photons
  - Thermal photons from QGP

# Experimental requirements

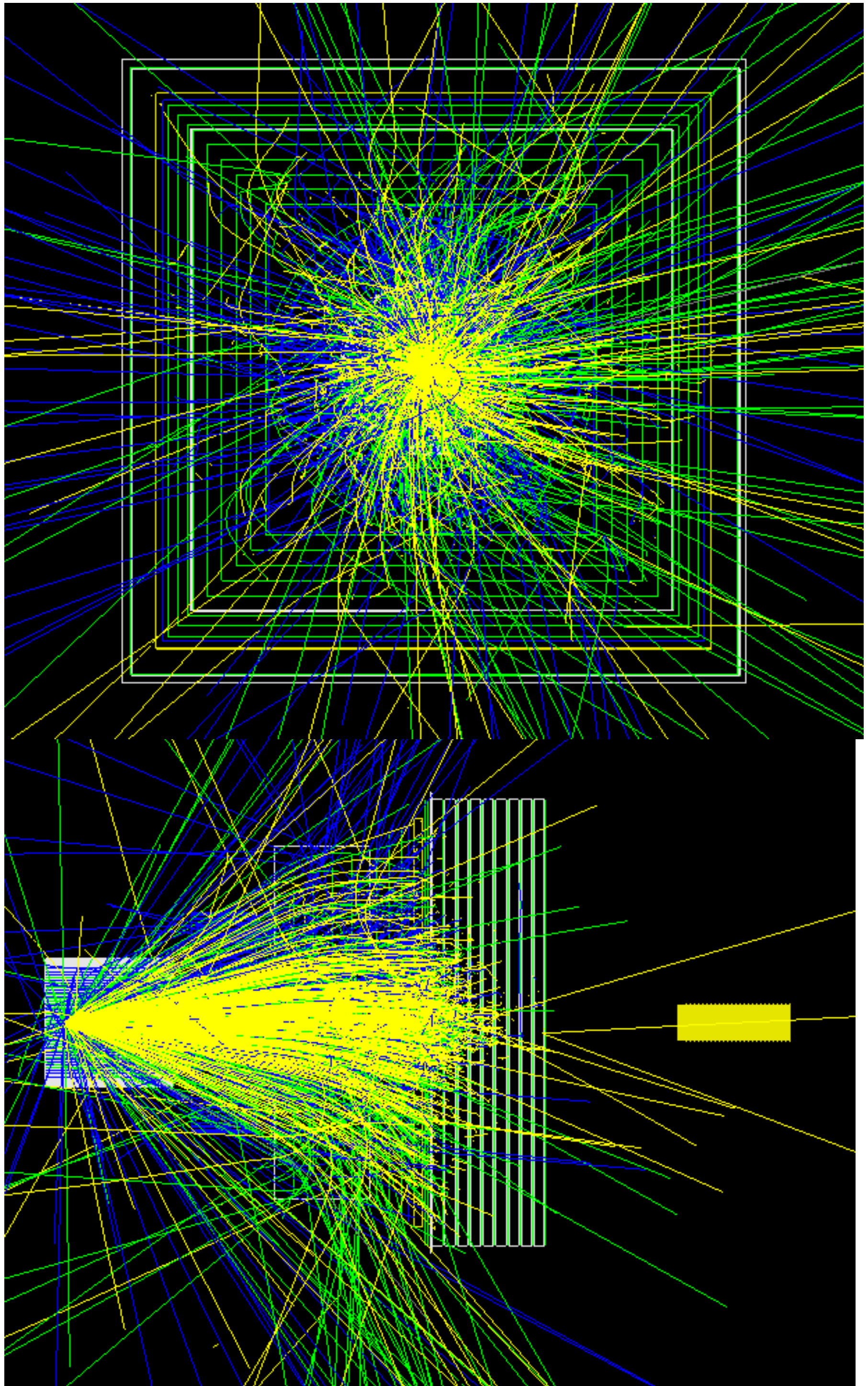
- High rate capability
  - Fast detectors
    - Silicon trackers, GEM trackers, …
  - Extremely fast DAQ
    - >= 100kHz
- High granularity
  - Pixel size < $3x3mm^2$

  (at 1m from the target, $\theta$<2deg, 10% occupancy)
- Large acceptance (~4$\pi$)
  - Coverage for low beam energies (CBM<30$^o$ , beam energy>=8AGeV/c)
  - Maximum multiplicity for e-b-e fluctuations
  - Backward physics (target fragment region)

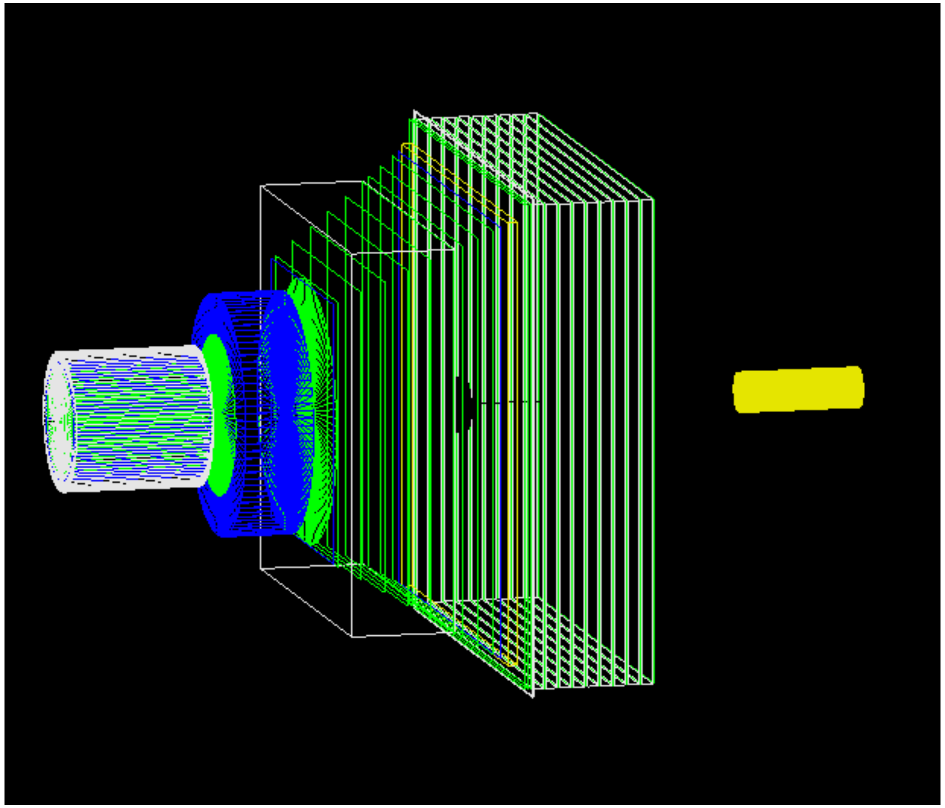
# *Preliminary setup*



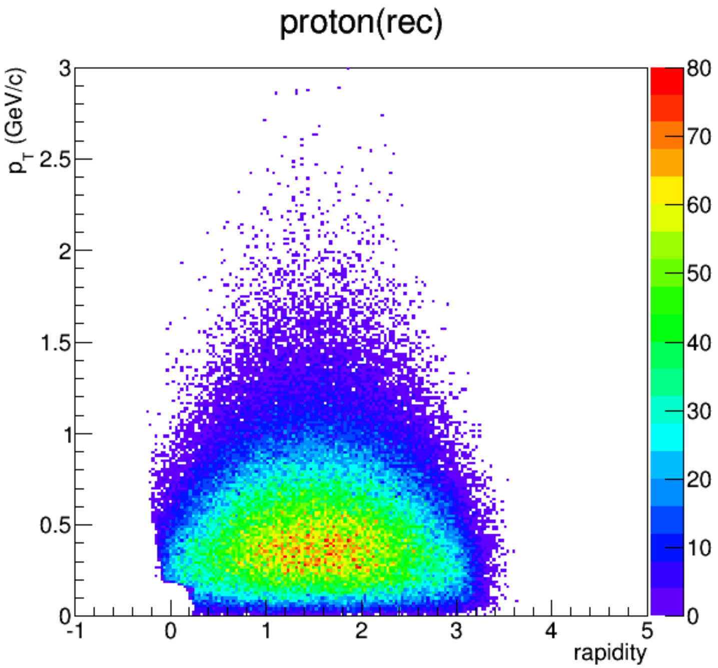
# GEANT4 simulation

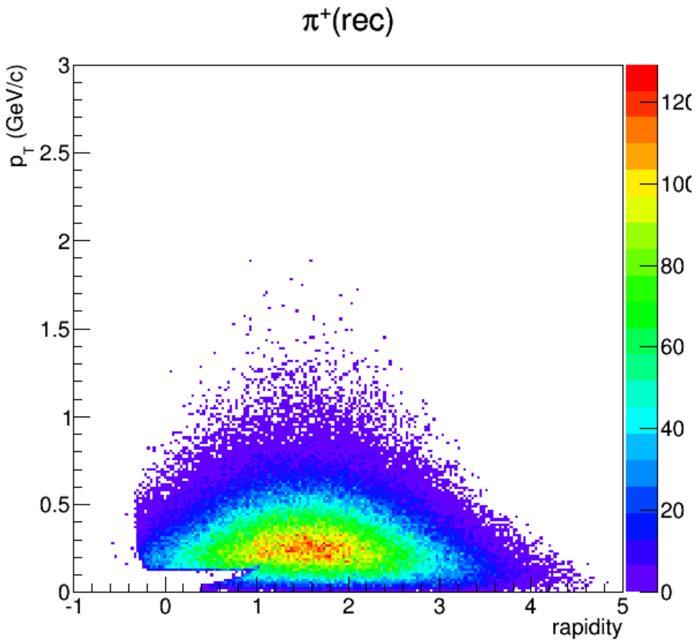


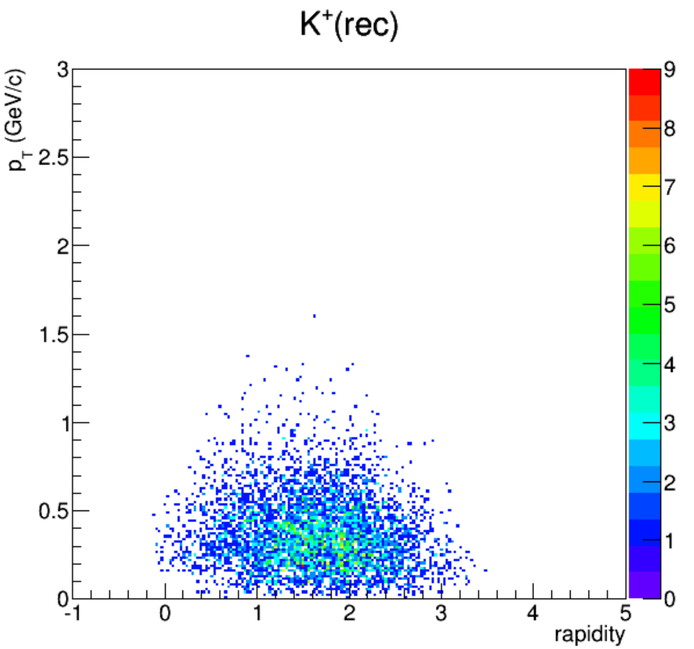
- JAM model
  U+U collisions
  (10AGeV)



# U+U at 10 AGeV (Preliminary)



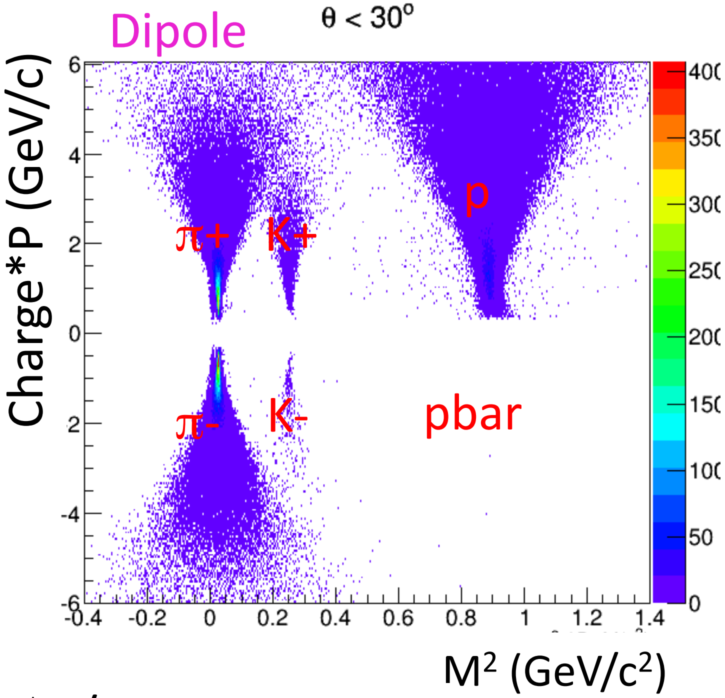

Acceptance

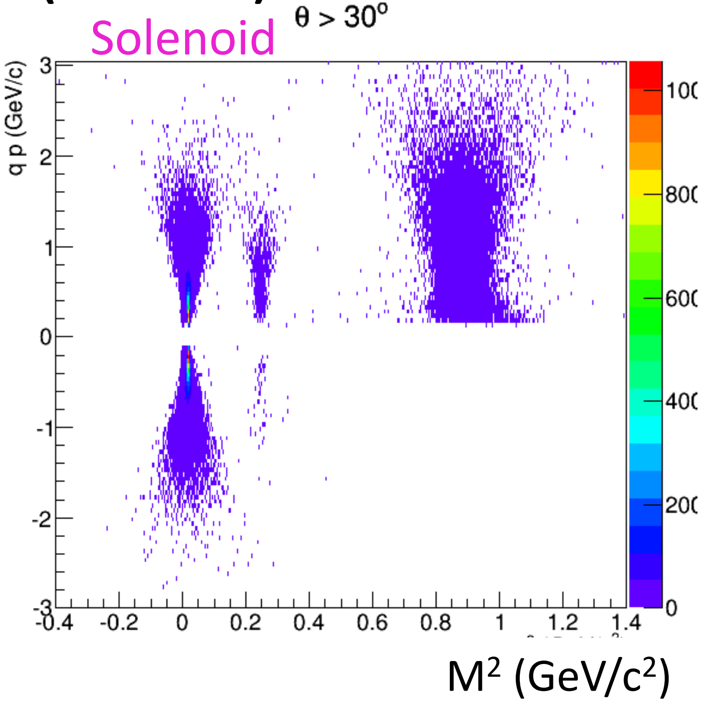
(including decay loss)

| | |
|---|---|
| p | 97.5% |
| ***K*** | ***72.3%*** |
| π | ***87.1%*** |

# PID and momentum (Preliminary)

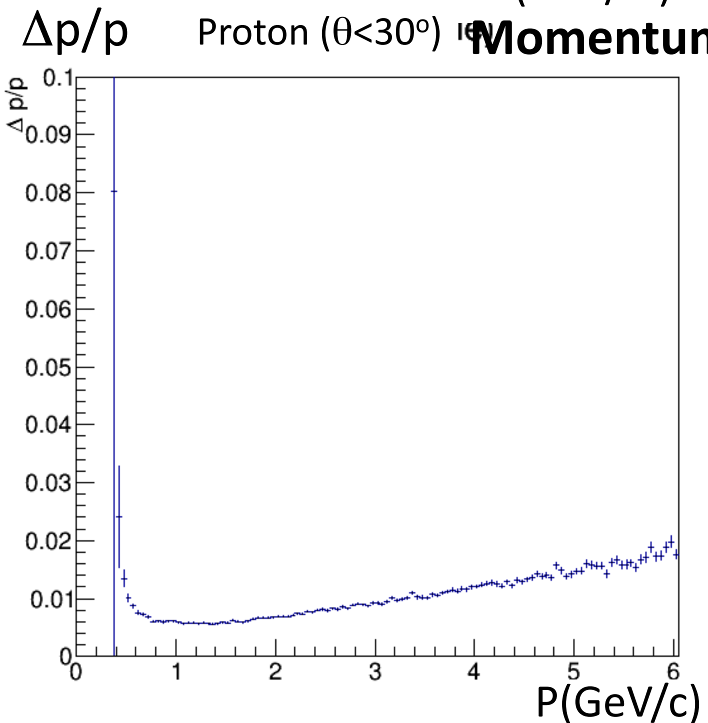
## Momentum vs m² (with TOF)

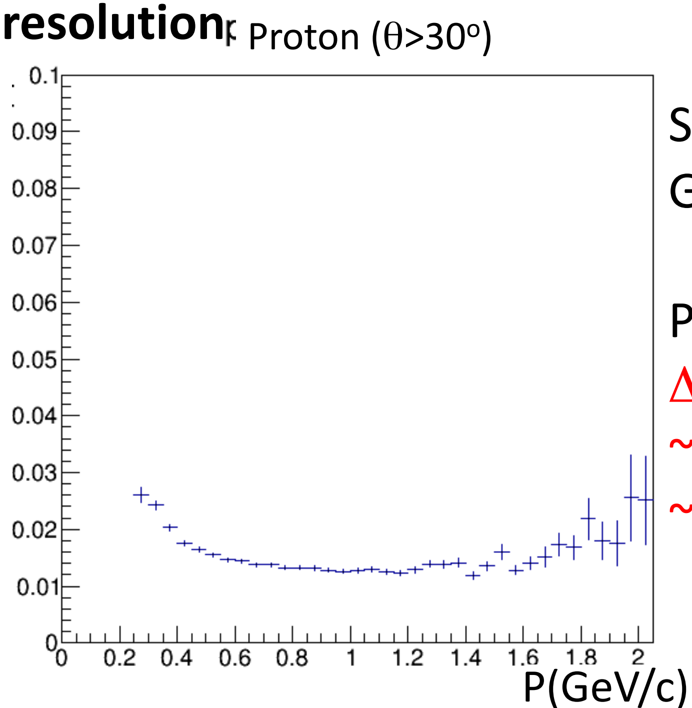



TOF resolution 50 ps
2σ π-K separation
p<2.8 GeV/c
(dipole)

## Momentum resolution

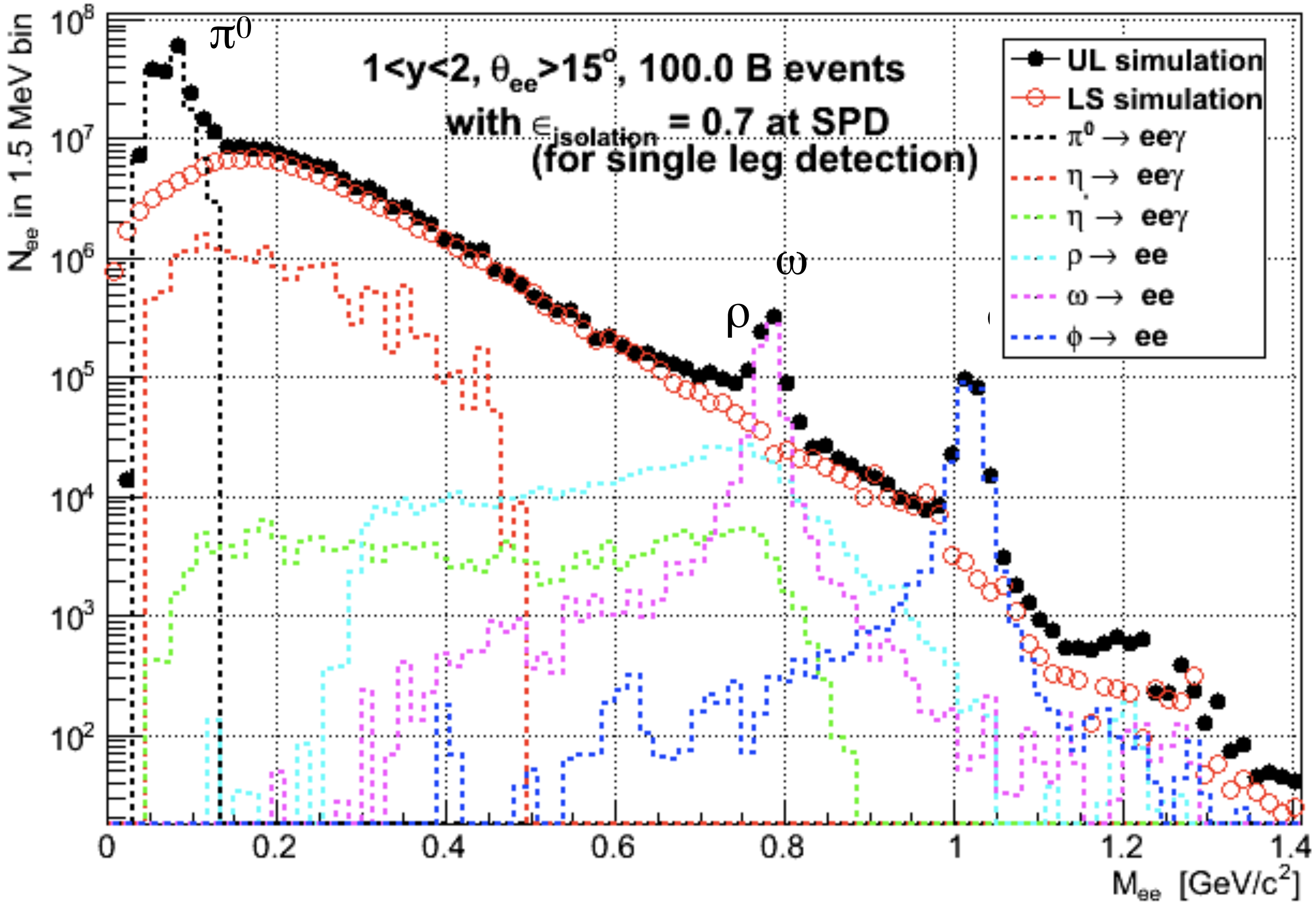



Silicon trackers : 14-23 μm
GEM trackers: 0.2-0.4 mm

Position resolution
Δp/p
~ 0.4% x p (GeV/c) (dipole)
~ 1.5% (solenoid)

# Simulated di-electron spectrum (preliminary)




Calculations by T. Gunji and T. Sakaguchi

Based on $\pi^0$ spectra of JAM

Other hadrons $m_T$-scaled

b<1fm (0.25% centrality)

Momentum resolution 2%

Electron efficiency 50%

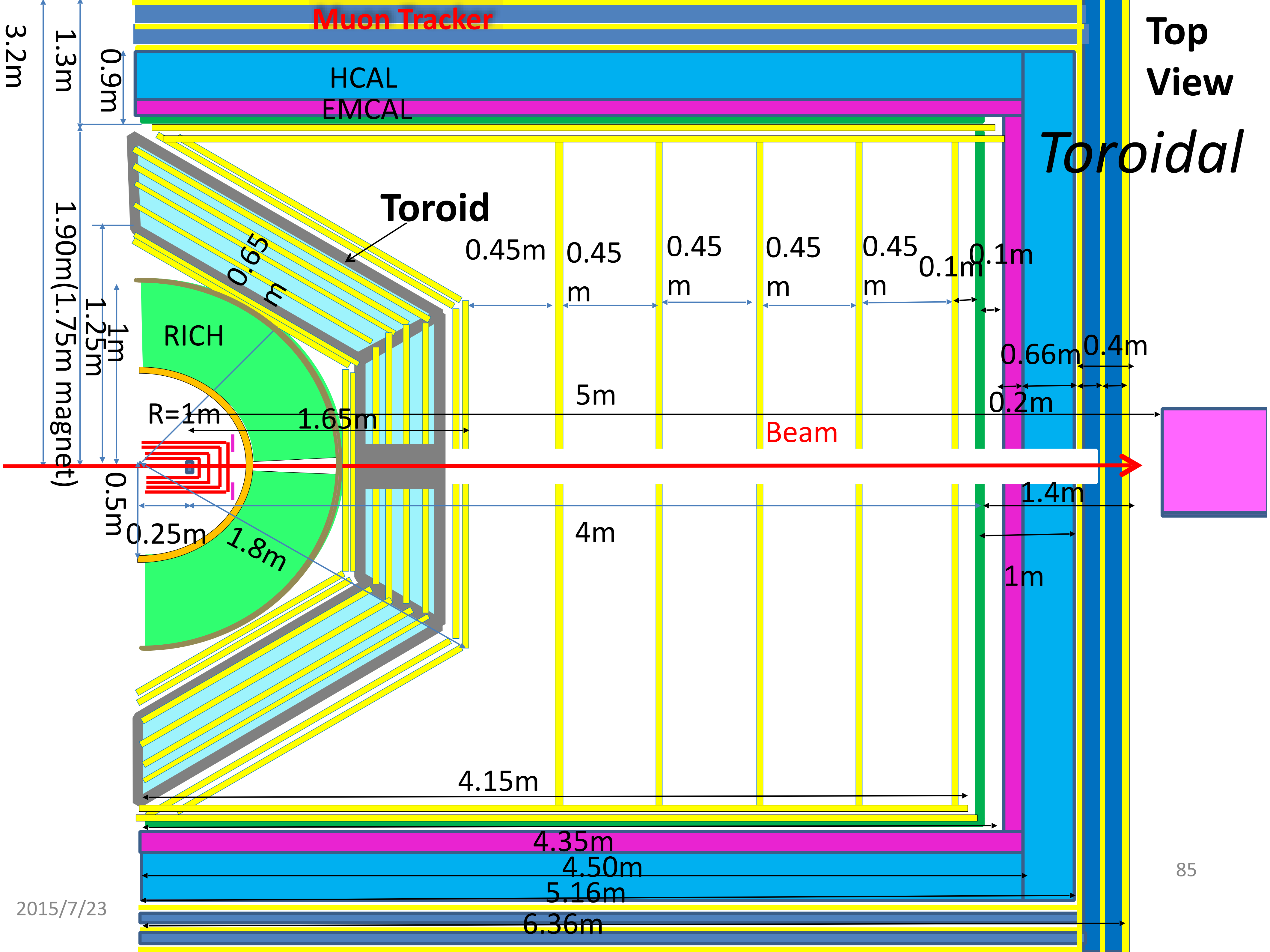
No detector response

$10^{11}$ events

⇔100k events/s

x 1 month running

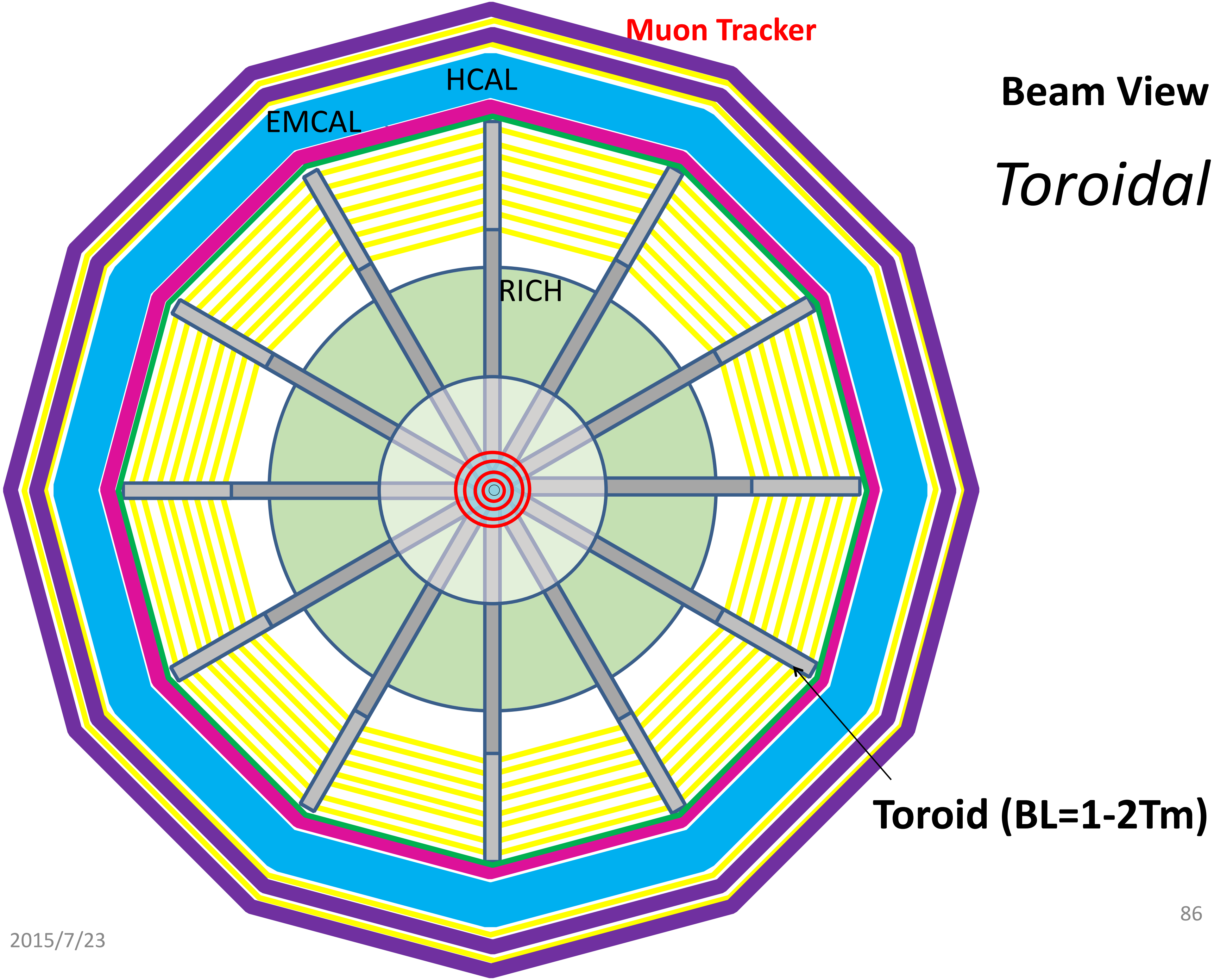
$\varepsilon_{isolation}$ = rejection efficiency of close opening angle Dalitz pair



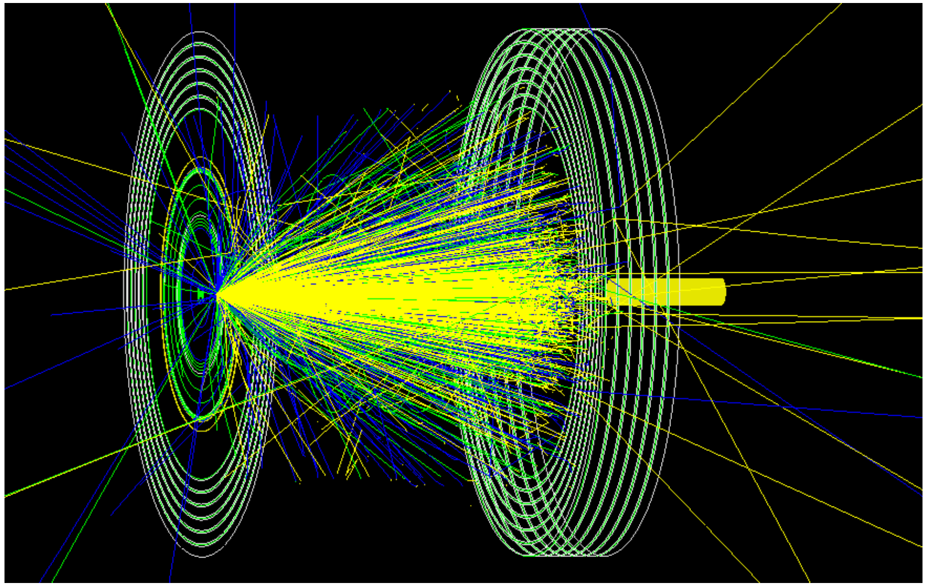
Muon Tracker
HCAL
EMCAL
Top View
Toroidal
Toroid
RICH
Beam
R=1m
1.65m
0.65 m
1.8m
0.25m
0.5m
1m
1.25m
1.90m(1.75m magnet)
1.3m
0.9m
3.2m
0.45m
0.45 m
0.45 m
0.45 m
0.45 m
0.1m
0.1m
0.66m
0.4m
0.2m
5m
4m
1.4m
1m
4.15m
4.35m
4.50m
5.16m
6.36m

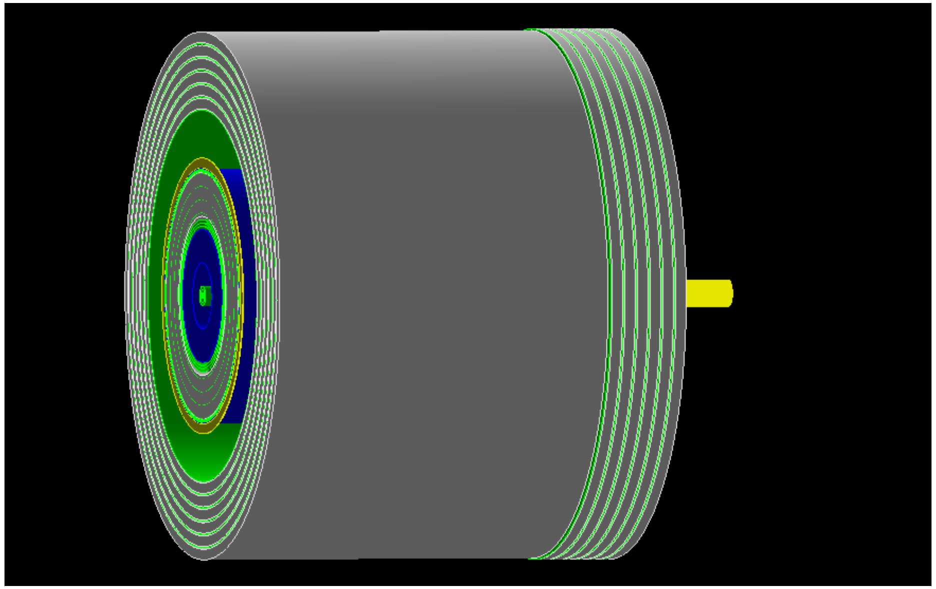
**Beam View**

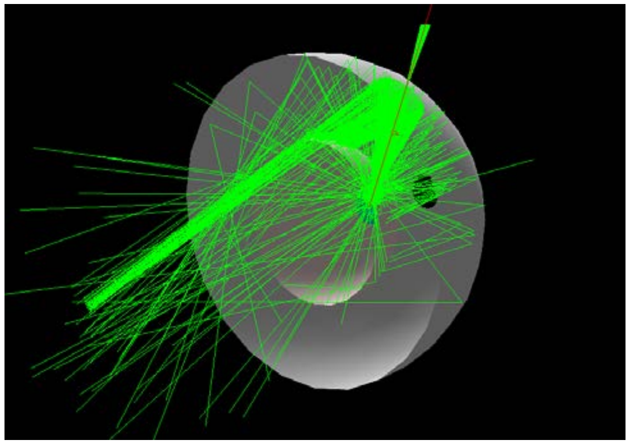
*Toroidal*

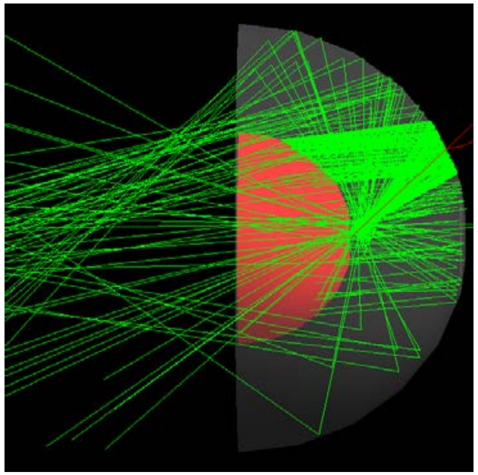


# GEANT4 (Toroidal) setup







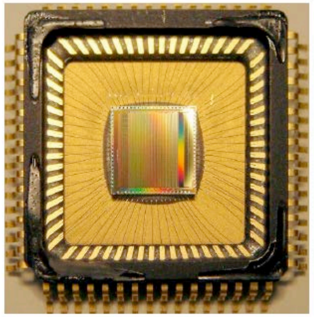


全体：佐甲氏 (JAEA)

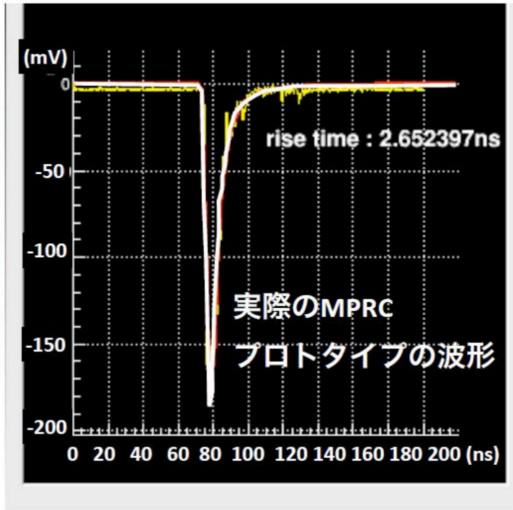
RICH 担当：B. Kim (筑波大, M1)

# 検出器 R&D: MRPC-TOF

- 時間分解能 ３０ ps は達成可能な見込み
- 中條（筑波大）、稲葉（筑波技術大）、野中 (D1, 筑波大)
- JAEA, KEK との共同研究開始 (2015-)
- J-PARC E-16 でのハドロン測定、J-PARC 重イオン実験へ

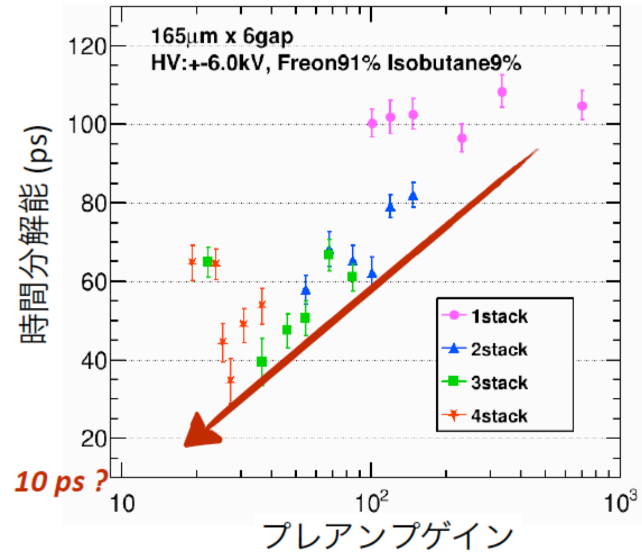


DRS-4 ASIC




switched コンデンサアレイを搭載した
5GSa/s 高速波形読み出しボード DRS-4 (PSI 社製)

図４　DRS-4 波形読み出しと実際の波形

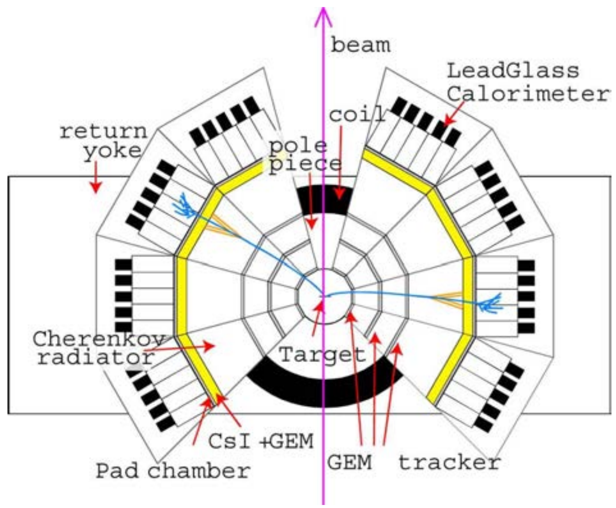



筑波大学
University of Tsukuba

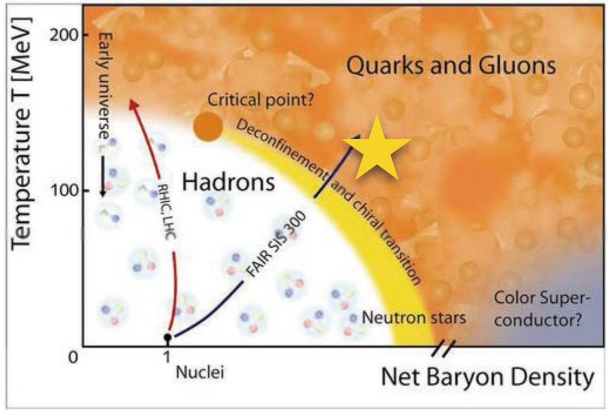
# Status of J-PARC HI Program

- Design of accelerators and experiments
  - A conceptual design report (white paper).
  - Collaboration with CBM
  - Acceleration schemes with RCS and MR are being studied
  - Simulation studies of the experiment are going on

- Detector R & D
  - J-PARC E16 (electron/hadron in p+A)
    - J-PARC proton beams ($10^{10}$ Hz)
    - Starting in 2016
      - Baseline data for A+A data



# まとめ




- J-PARC における重イオン衝突実験
- 最大バリオン密度領域でのQCD相構造の研究
  - 新たなアプローチ（高統計・高精度・系統測定）で拓ける新物理
    - レプトン対測定：QCD sum rule との直接比較により、高密度領域でのカイラル対称性
    - 揺らぎ測定：臨界点探査およびQCD相構造の解明
- 実現に向けて、様々な活動が進行中（e.g. White Paper 作成、J-PARC E-16 実験とのコラボ、検出器 R&D、simulation）
- 皆様のご支援、ご協力、ご参加を！

# 謝辞


- この講演スライドを作成するにあたり、以下の方々から多くの有用なスライドを拝借いたしました。ここに感謝申し上げます。
- 佐甲博之さん (JAEA)
- 北沢正清さん (大阪大)
- 小沢恭一郎さん (KEK)


✓ 参考


- 原子核研究 (2015) 新しい潮流「J-PARCでの重イオン衝突によるQCD相構造研究への道筋」佐甲博之、北沢正清 共著
- 研究会「J-PARCにおける重イオン衝突実験が拓く新しい物理」（KEK, Nov. 2014）の講演スライド