RHICで生成された
高温・高密度QCD物質

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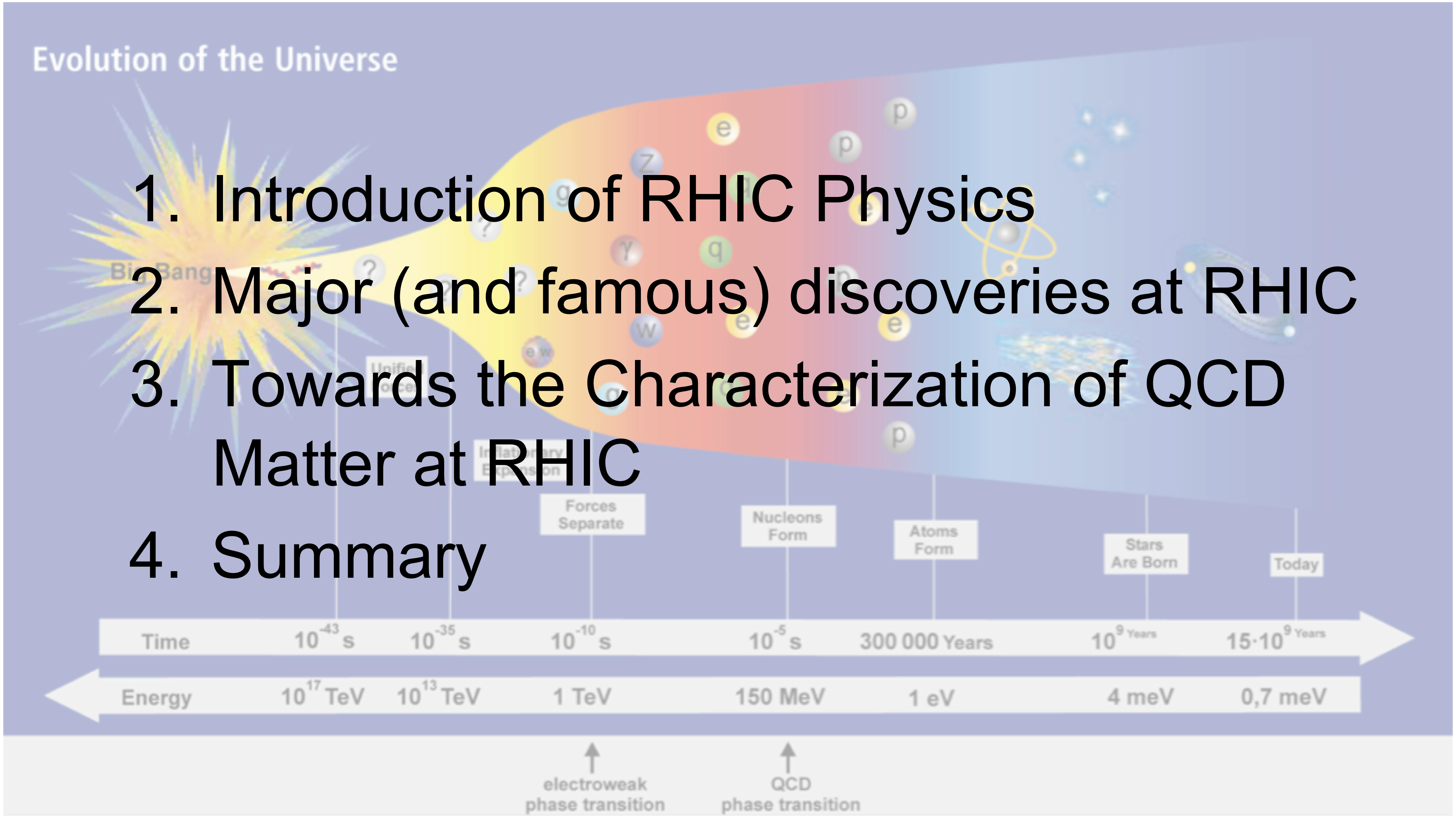
日本物理学会 2008年秋季大会　山形大学　2008年9月22日
シンポジウム 「RHICで切り拓くQCD物性の世界」

Outline



1. Introduction of RHIC Physics
2. Major (and famous) discoveries at RHIC
3. Towards the Characterization of QCD Matter at RHIC
4. Summary

1. INTRODUCTION

2008年9月10日

asahi.com　現在位置：asahi.com　ニュース　サイエンス　記事

質量の謎に迫る　超大型加速器、１０日始

2008年9月9日13時59分

YOMIURI ONLINE | 読売新聞

世界最大「円形加速器」が欧州で
発見に期待

欧州合同原子核研究機関（ＣＥＲＮ）がフラン
した世界最大の円形加速器「ＬＨＣ」（１周約２
構成する陽子のビームを入射して周回させる試験

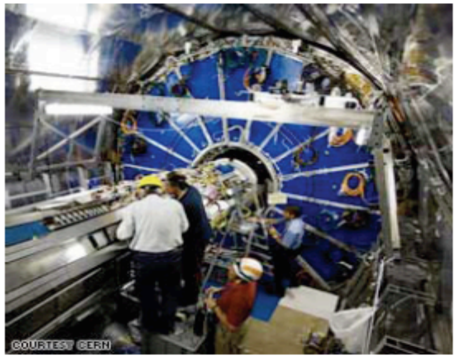
CNN.co.jp

2008.09.10 Web posted at: 17:38 JST Updated - CNN/AP

サイエンス

世界最大の粒子加速器「ＬＨＣ」が始動、宇宙の謎を解明へ

「ＬＨＣ」の始動を喜ぶ科学者たち



建設中の超大型粒子加速器「ＬＨＣ」

ジュネーブ――スイス・ジュネーブ郊外、フランスと国境の地下に建設された欧州合同原子核研究機関（ＣＥＲＮ）の超大型粒子加速器「ＬＨＣ」が１０日、始動した。建設費用は９０億ドル（約９７２０億円）で、米国や日本も協力。ここでの実験結果が、宇宙の謎を解明する大きな手がかりになるとして、世界中から注目を集めている。

「ＬＨＣ」は「大型ハドロン衝突型加速器（Large Hadron Collider）」の頭文字を取った呼称。地下約１００メートルに１周２７キロのトンネルを掘り、超伝導電磁石１７００台を設置し、陽子を光速の９９．９９％まで加速して衝突させる。

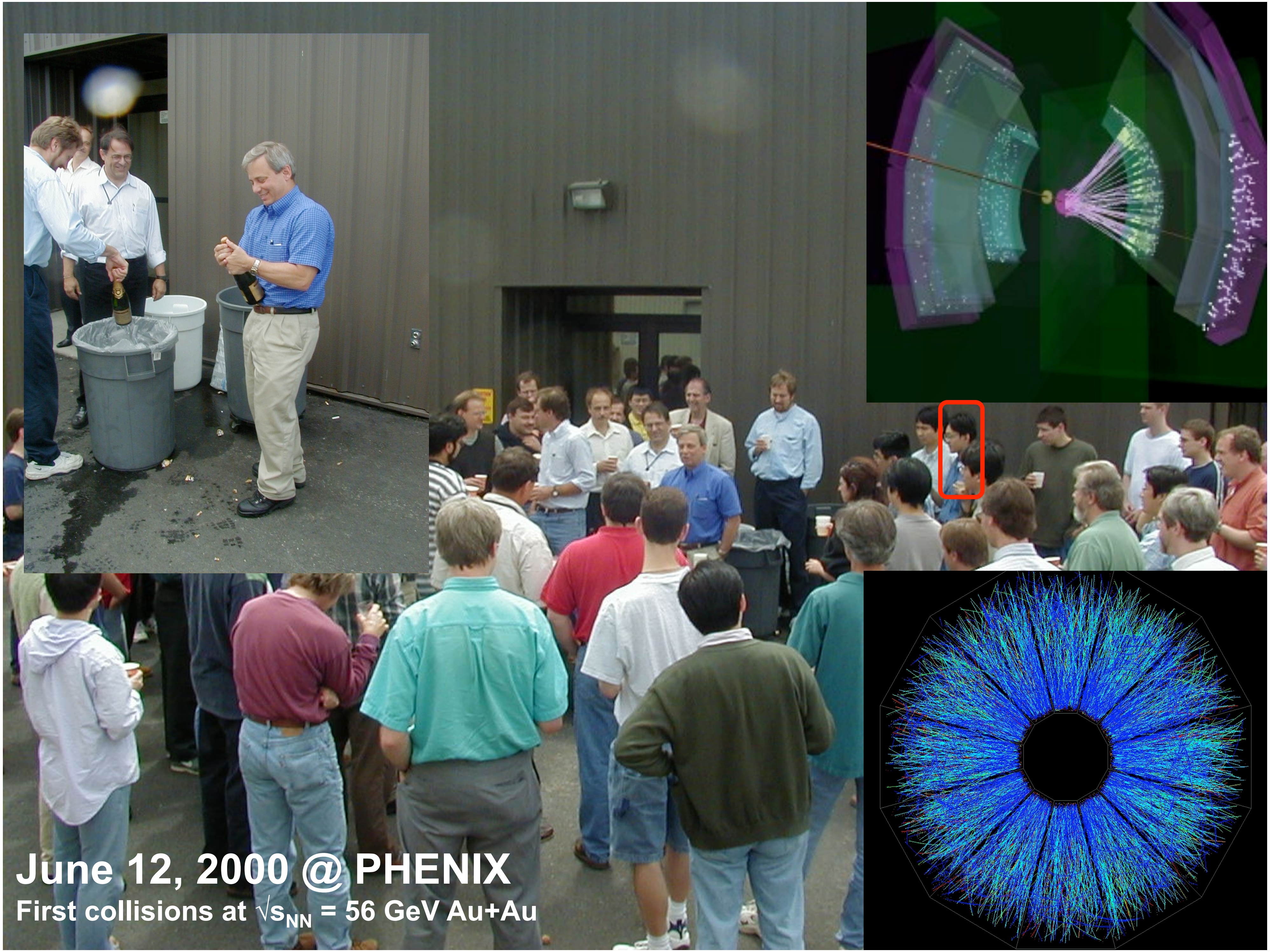
高エネルギーで陽子を衝突させ、宇宙誕生とされる大爆発「ビッグバン」直後の超高温・超高圧状態を人工的に再現。質量のもととされるヒッグス粒子の存在や、宇宙空間を占める謎の暗黒物質（ダークマター）候補とされる、「ニュートラリーノ」といった超対称性粒子が発見される可能性がある。

毎日jp

サイエンス

大型粒子加速器：ジュネーブ郊外で始動へ

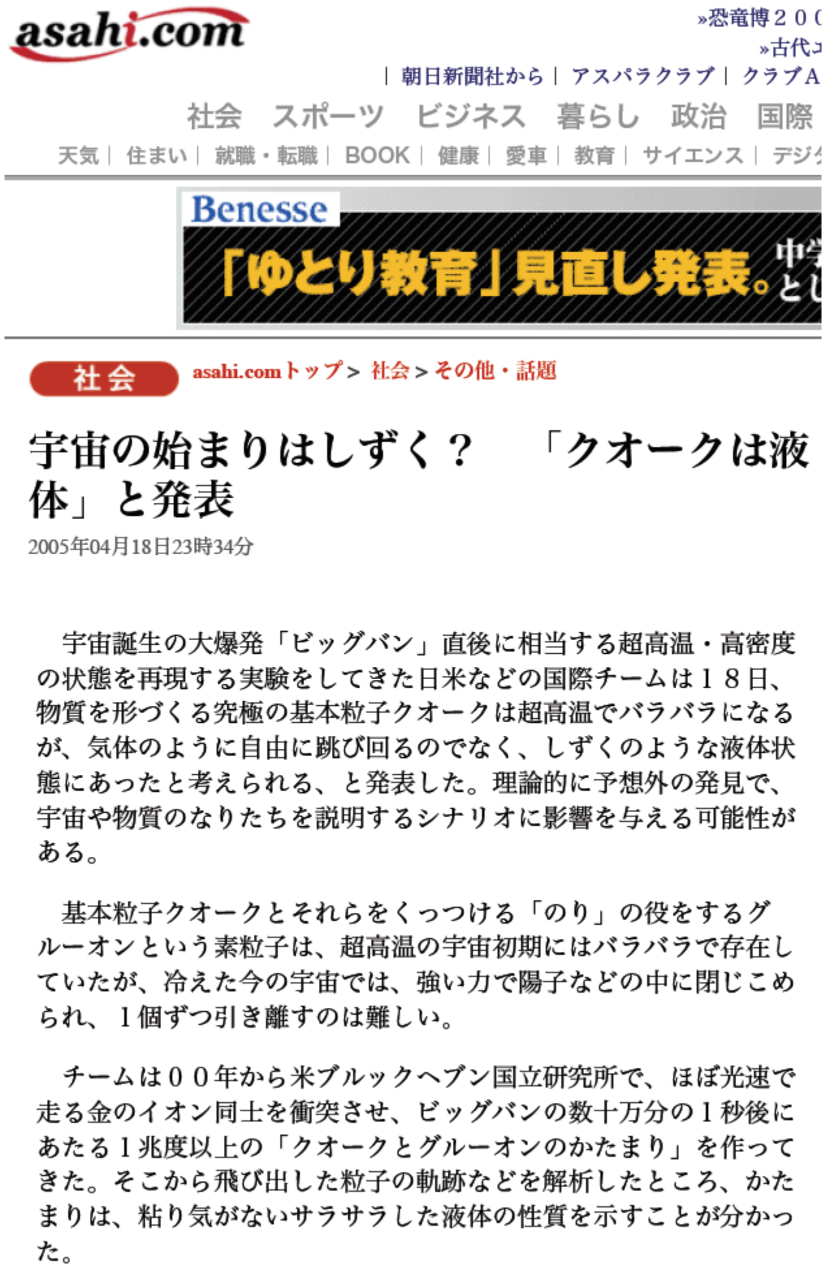
質量の起源と考えられる「ヒッグス粒子」の発見などを目指して造られた大型粒子加速器「ＬＨＣ」が１０日、スイスのジュネーブ郊外で運転を始める。



June 12, 2000 @ PHENIX

First collisions at $\sqrt{s_{NN}}$ = 56 GeV Au+Au

First Collision 後…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»恐竜博２０(
»古代ｴ

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Benesse
「ゆとり教育」見直し発表。中学
とし

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宇宙の始まりはしずく？　「クオークは液体」と発表

2005年04月18日23時34分

宇宙誕生の大爆発「ビッグバン」直後に相当する超高温・高密度の状態を再現する実験をしてきた日米などの国際チームは１８日、物質を形づくる究極の基本粒子クオークは超高温でバラバラになるが、気体のように自由に跳び回るのでなく、しずくのような液体状態にあったと考えられる、と発表した。理論的に予想外の発見で、宇宙や物質のなりたちを説明するシナリオに影響を与える可能性がある。

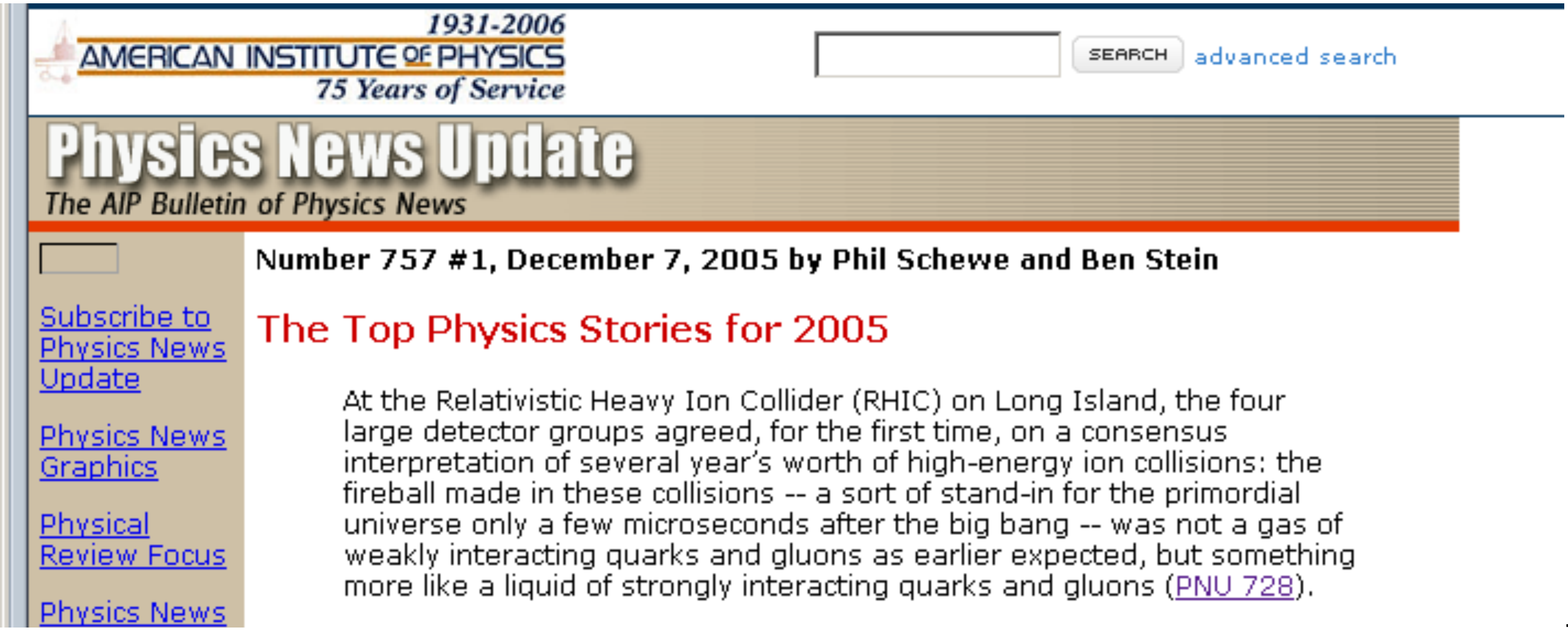
基本粒子クオークとそれらをくっつける「のり」の役をするグルーオンという素粒子は、超高温の宇宙初期にはバラバラで存在していたが、冷えた今の宇宙では、強い力で陽子などの中に閉じこめられ、１個ずつ引き離すのは難しい。

チームは００年から米ブルックヘブン国立研究所で、ほぼ光速で走る金のイオン同士を衝突させ、ビッグバンの数十万分の１秒後にあたる１兆度以上の「クオークとグルーオンのかたまり」を作ってきた。そこから飛び出した粒子の軌跡などを解析したところ、かたまりは、粘り気がないサラサラした液体の性質を示すことが分かった。

RHIC 物理のインパクト

- **~200 の物理論文** (102 PRLを含む)
  - トータルで 15,000 以上の引用回数.
  - これまで全ての原子核物理学実験分野での高い引用論文の 58% を占める。

- “The 2005 AIP physics story of the year”.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Physics News

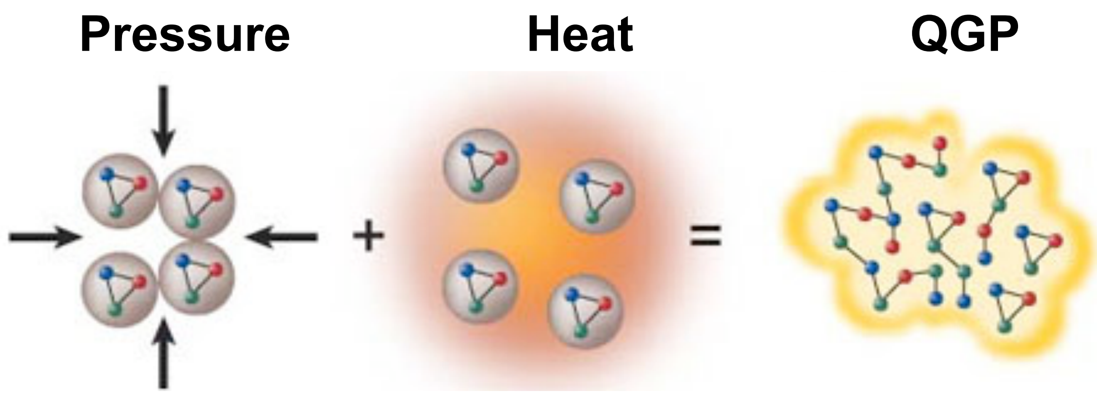
Number 757 #1, December 7, 2005 by Phil Schewe and Ben Stein

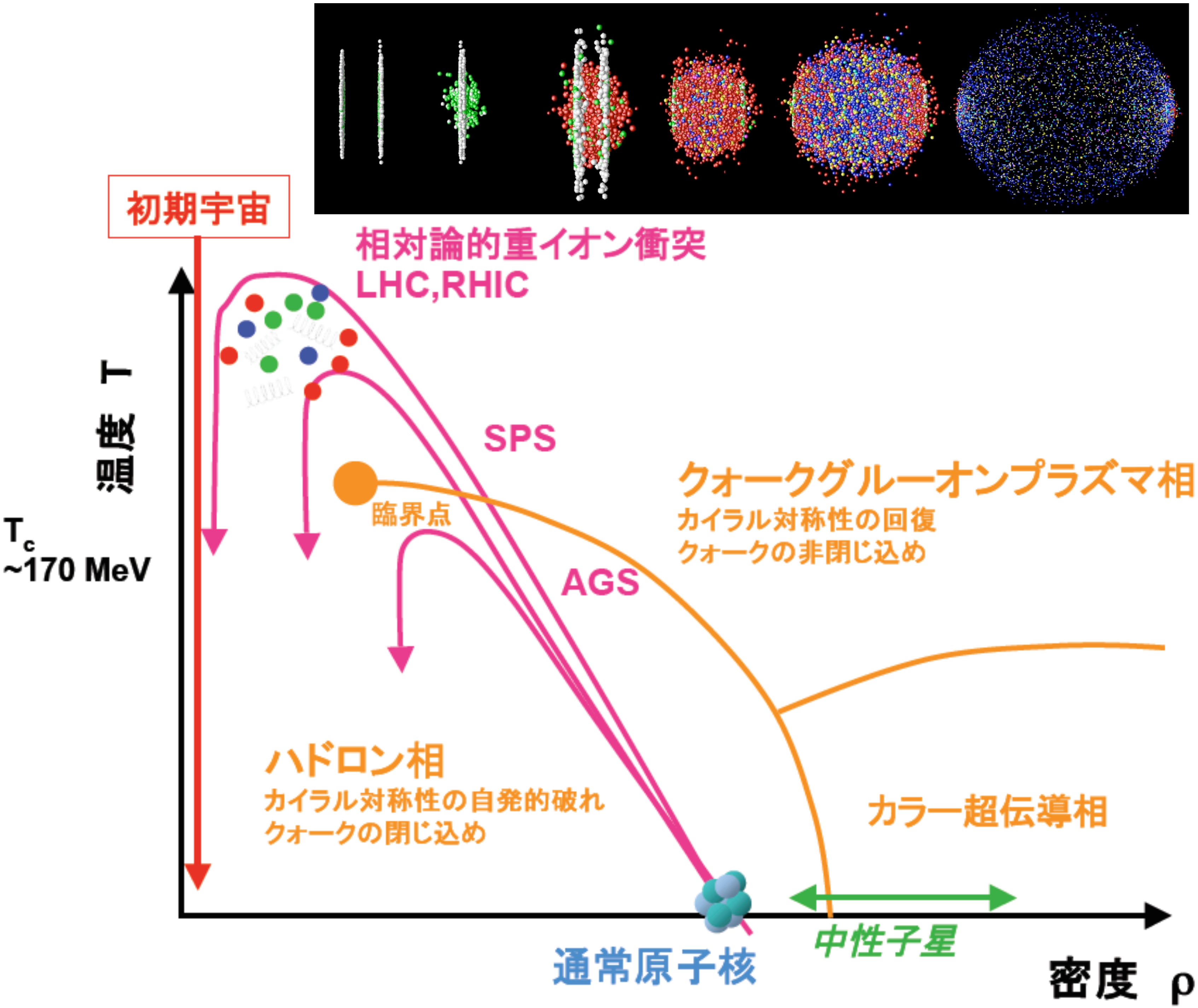
The Top Physics Stories for 2005

At the Relativistic Heavy Ion Collider (RHIC) on Long Island, the four large detector groups agreed, for the first time, on a consensus interpretation of several year's worth of high-energy ion collisions: the fireball made in these collisions -- a sort of stand-in for the primordial universe only a few microseconds after the big bang -- was not a gas of weakly interacting quarks and gluons as earlier expected, but something more like a liquid of strongly interacting quarks and gluons (PNU 728).

RHIC における重イオン物理

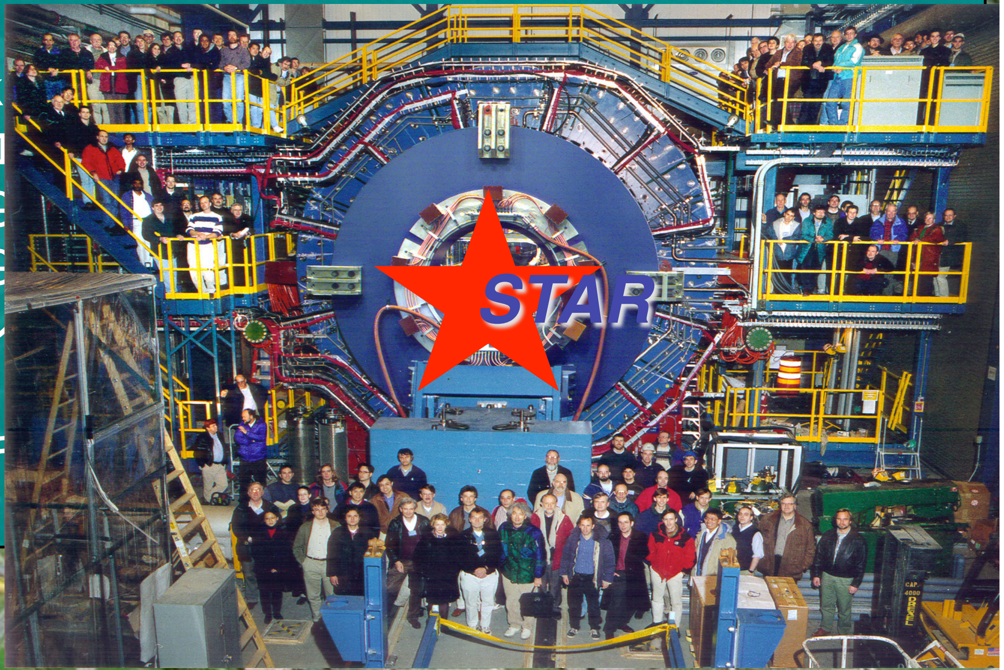
- 高エネルギー重イオン衝突による、高温高密度QCD物質の研究
  - クォークグルーオンプラズマ (QGP)の性質の解明
  - 核物質相図の探索
  - クォークの閉じ込め機構
  - カイラル対称性の回復





初期宇宙
相対論的重イオン衝突
LHC,RHIC
SPS
AGS
温度 T
T_c
~170 MeV
臨界点
クォークグルーオンプラズマ相
カイラル対称性の回復
クォークの非閉じ込め
ハドロン相
カイラル対称性の自発的破れ
クォークの閉じ込め
カラー超伝導相
中性子星
通常原子核
密度 ρ

RHIC = Relativistic Heavy Ion Collider



2. MAJOR (AND FAMOUS) DISCOVERIES AT RHIC

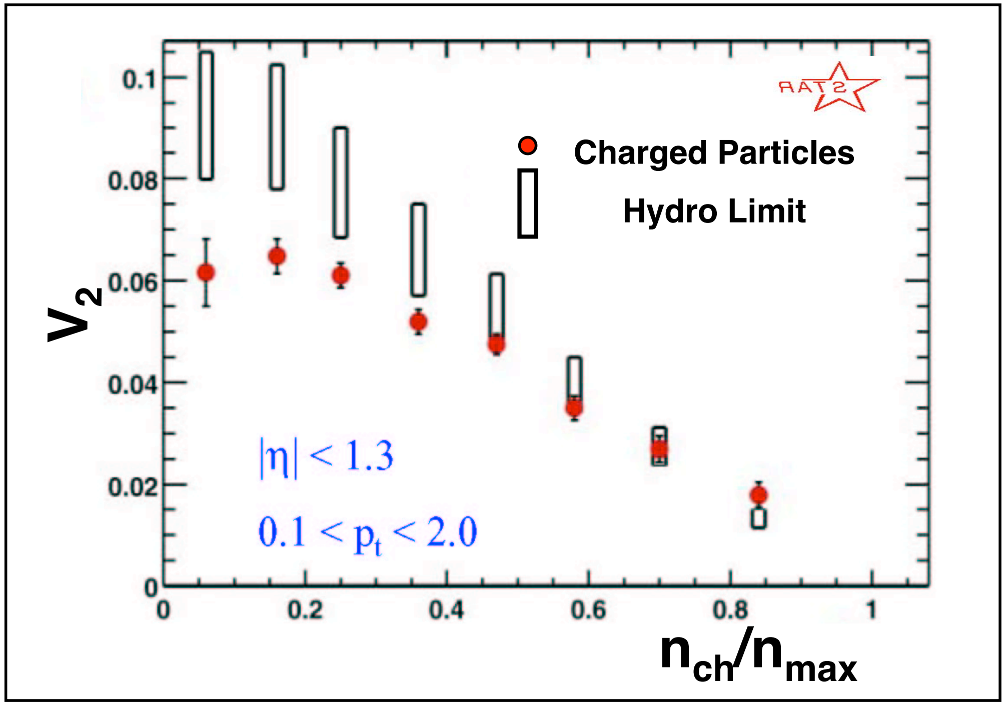
RHIC Discoveries from Run-1 (2000)

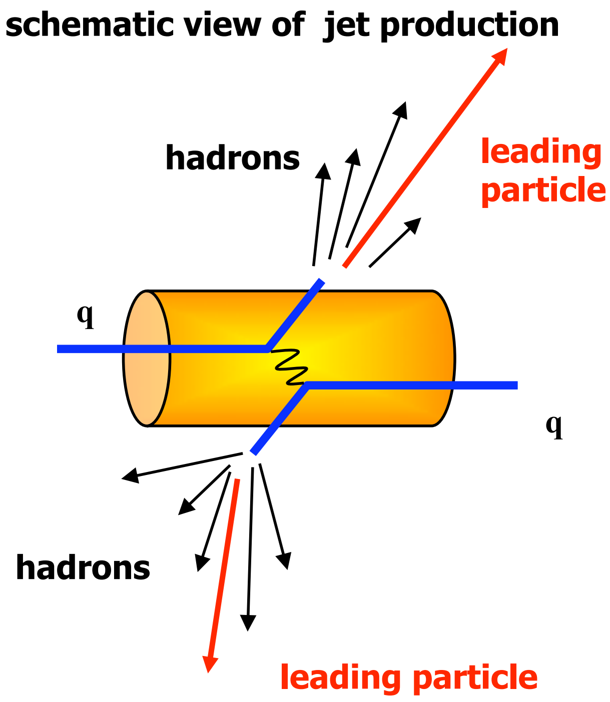
Jet Quenching

Au+Au 130 GeV
PHENIX: PRL 88,(2002) 022301
SPIRES citations: 446
Most cited PRL in RHIC papers !

Large Elliptic Flow

Au+Au 130 GeV
STAR: PRL 86, (2001) 402
SPIRES citations: 358



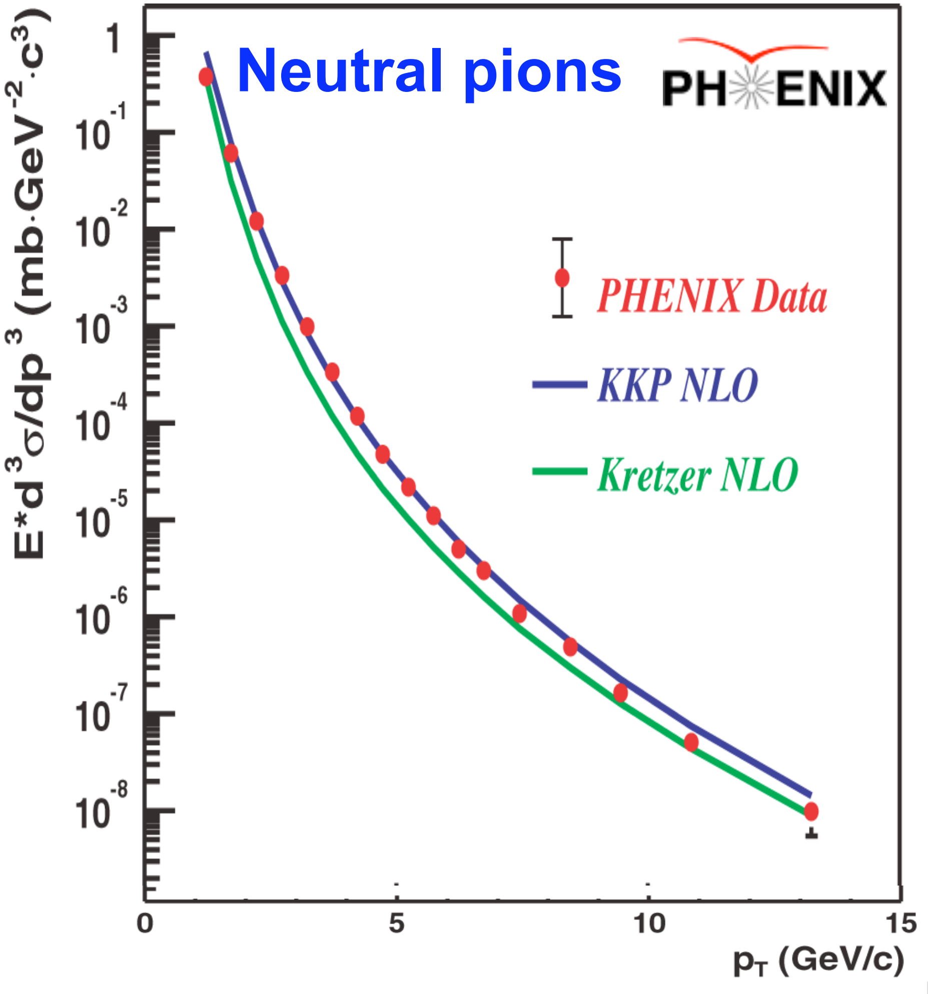


HIGH PT HADRONS;

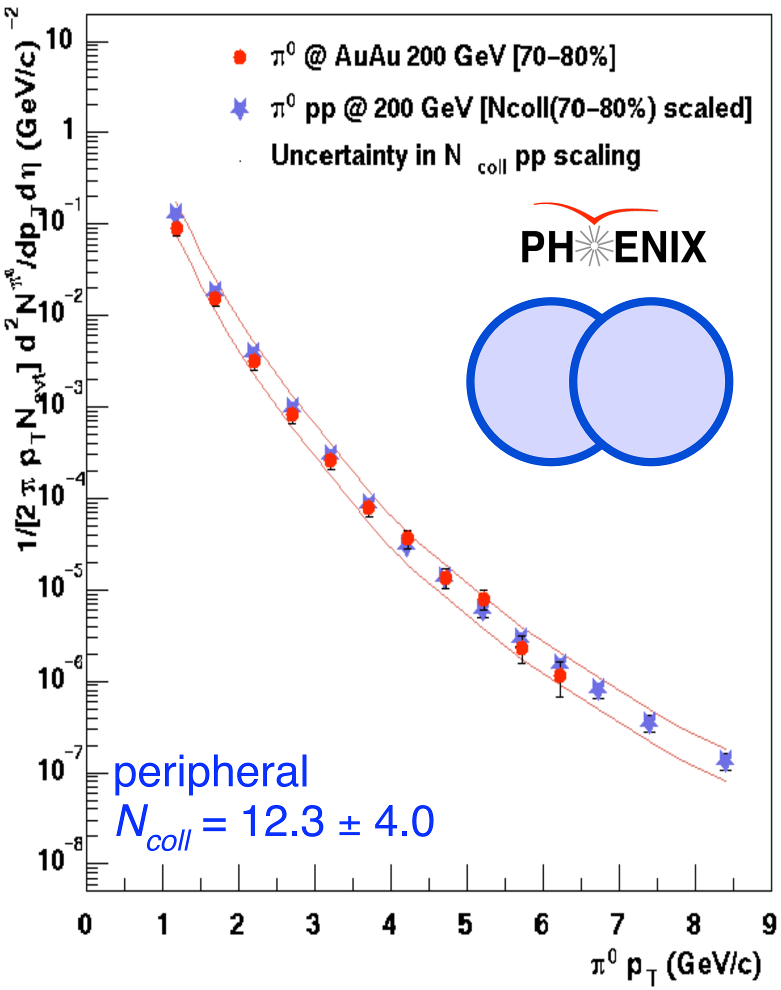
PROBING THE DENSITY OF MATTER BY THE CALIBRATED PROBE.

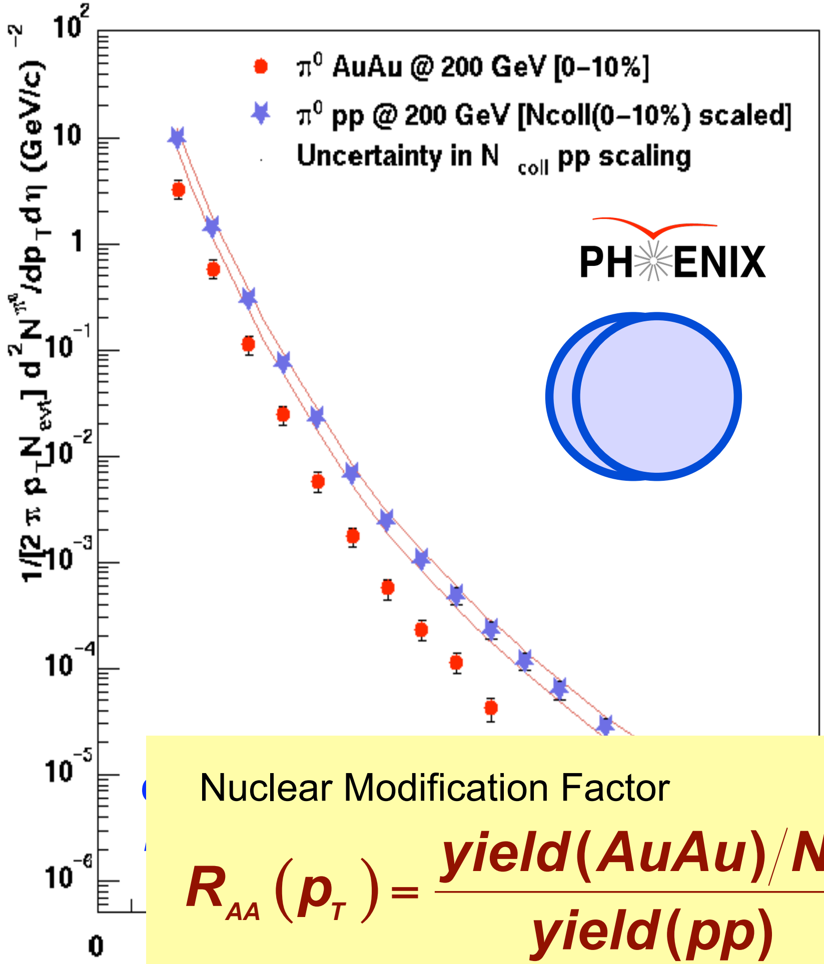
pQCD Calibrated Probes (p+p)

- Baseline measurements in p+p collisions at RHIC
  - Calibrated probes
  - Supported by well-established theory (perturbative QCD = pQCD)



Discovery of Strong Suppression (Au+Au)





Nuclear Modification Factor

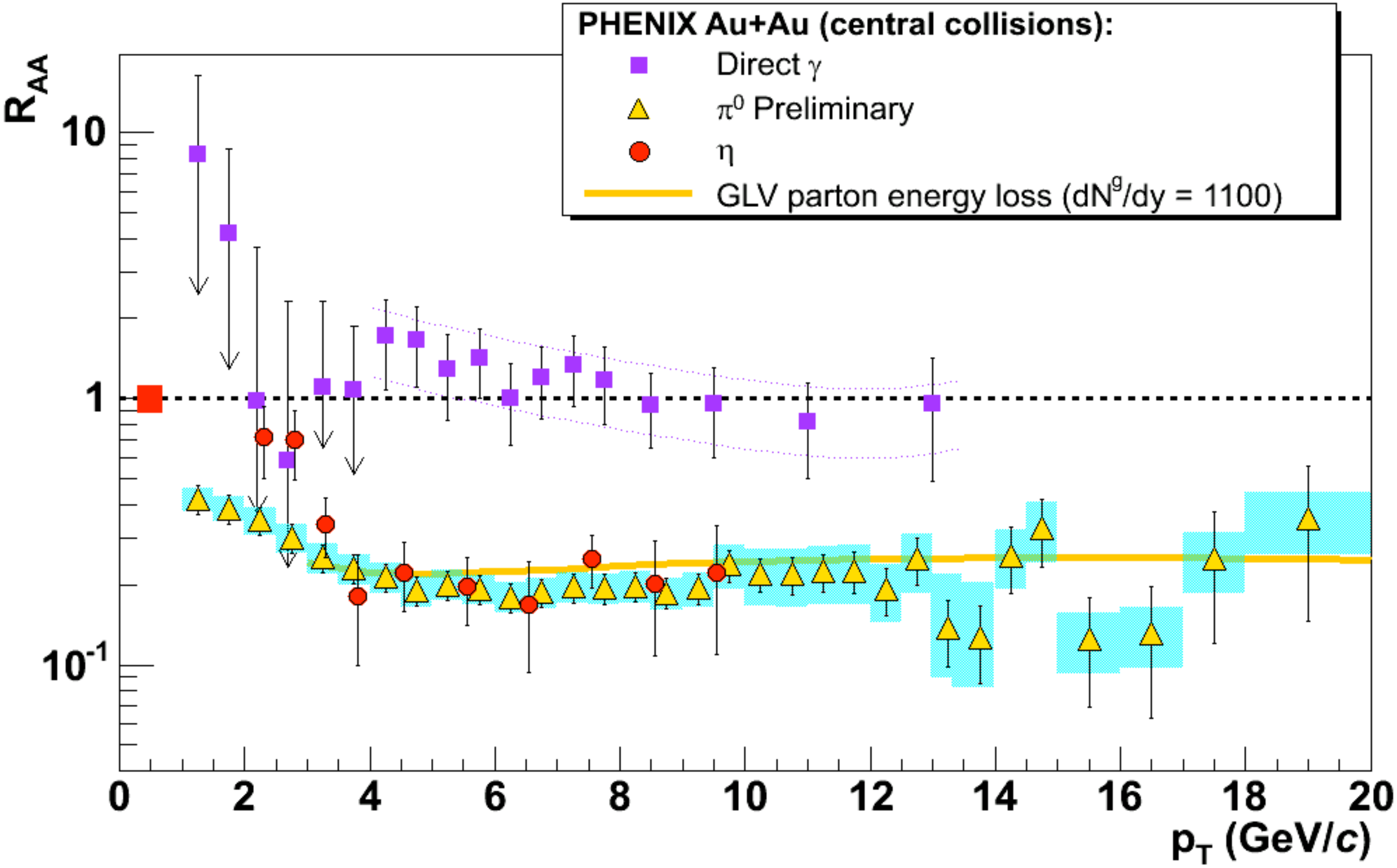
$$R_{AA}(p_T) = \frac{yield(AuAu)/N_{coll}}{yield(pp)}$$

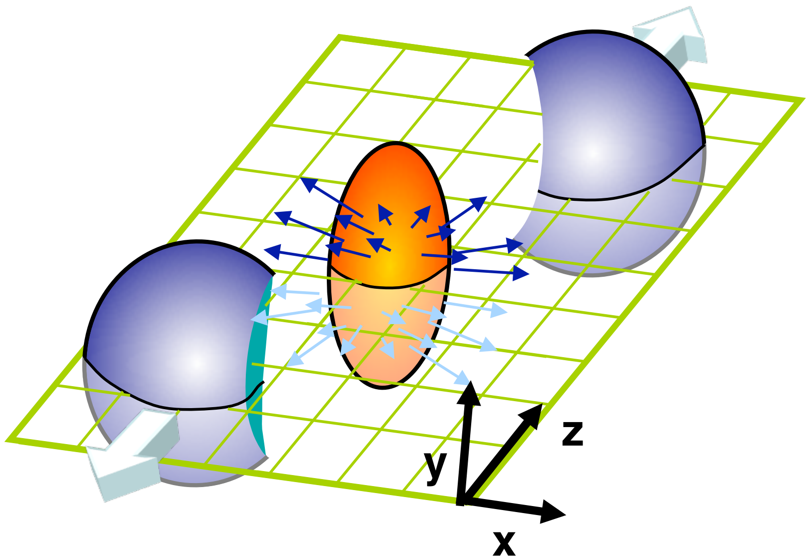
~ Survival Probability in medium

Scaling of calibrated probe **works in per**
strong suppression **in central Au+Au**

Observation of Jet Quenching

直接光子は抑制されず。ハドロンは強い抑制（~ factor 5 ）。

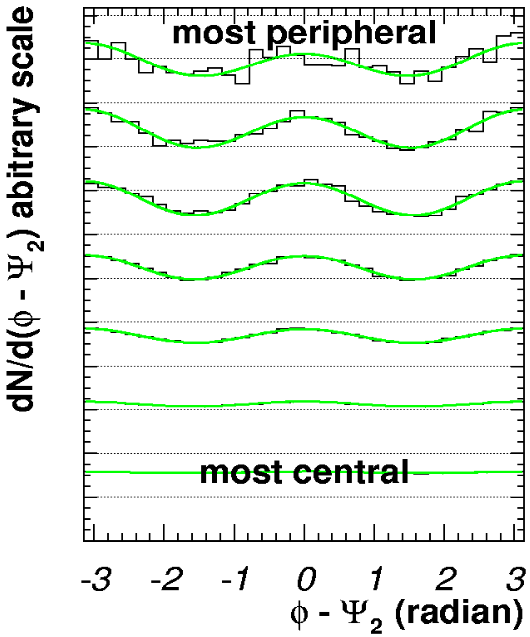


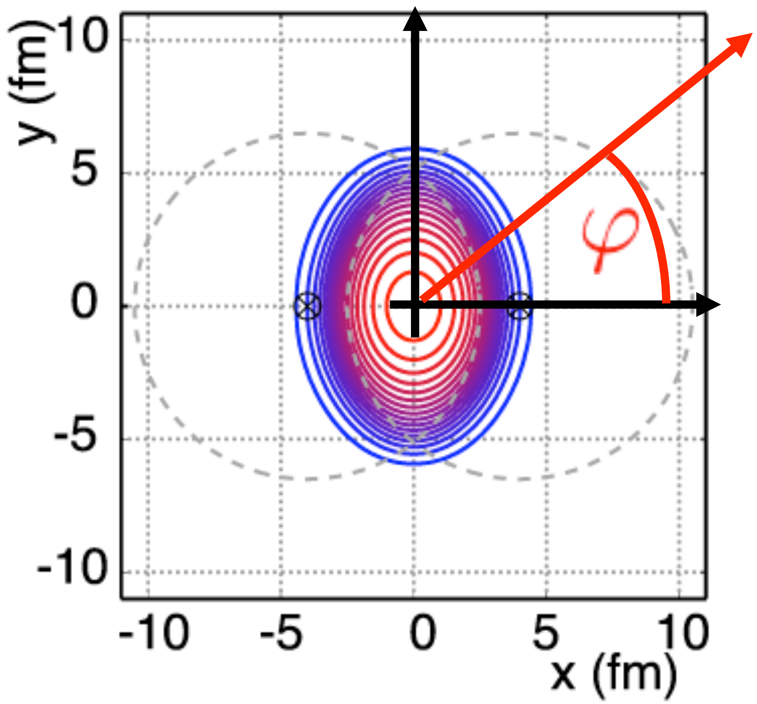


Access to the early time of the collisions,
Pressure, Equation of State (EoS).

ELLIPTIC FLOW

Elliptic Flow とは?



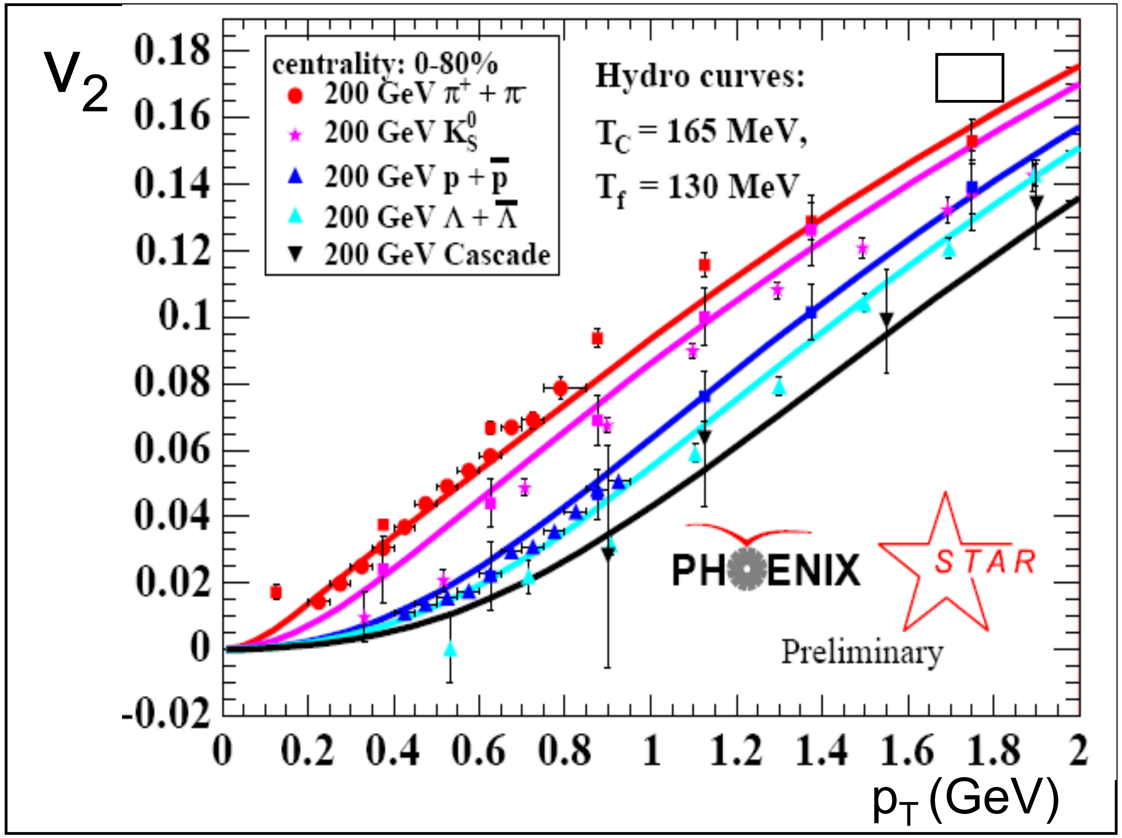


$$\frac{dN}{p_T dp_T dy d\varphi}(p_T, \varphi; b) = \frac{dN}{2\pi p_T dp_T dy}\left(1 + 2\underline{v_2}(p_T; b)\cos(2\varphi) + \ldots\right)$$

- Very high degree of collectivity is seen at RHIC.

Like a Perfect Fluid?

- First time hydrodynamics without any viscosity describes heavy ion reactions.

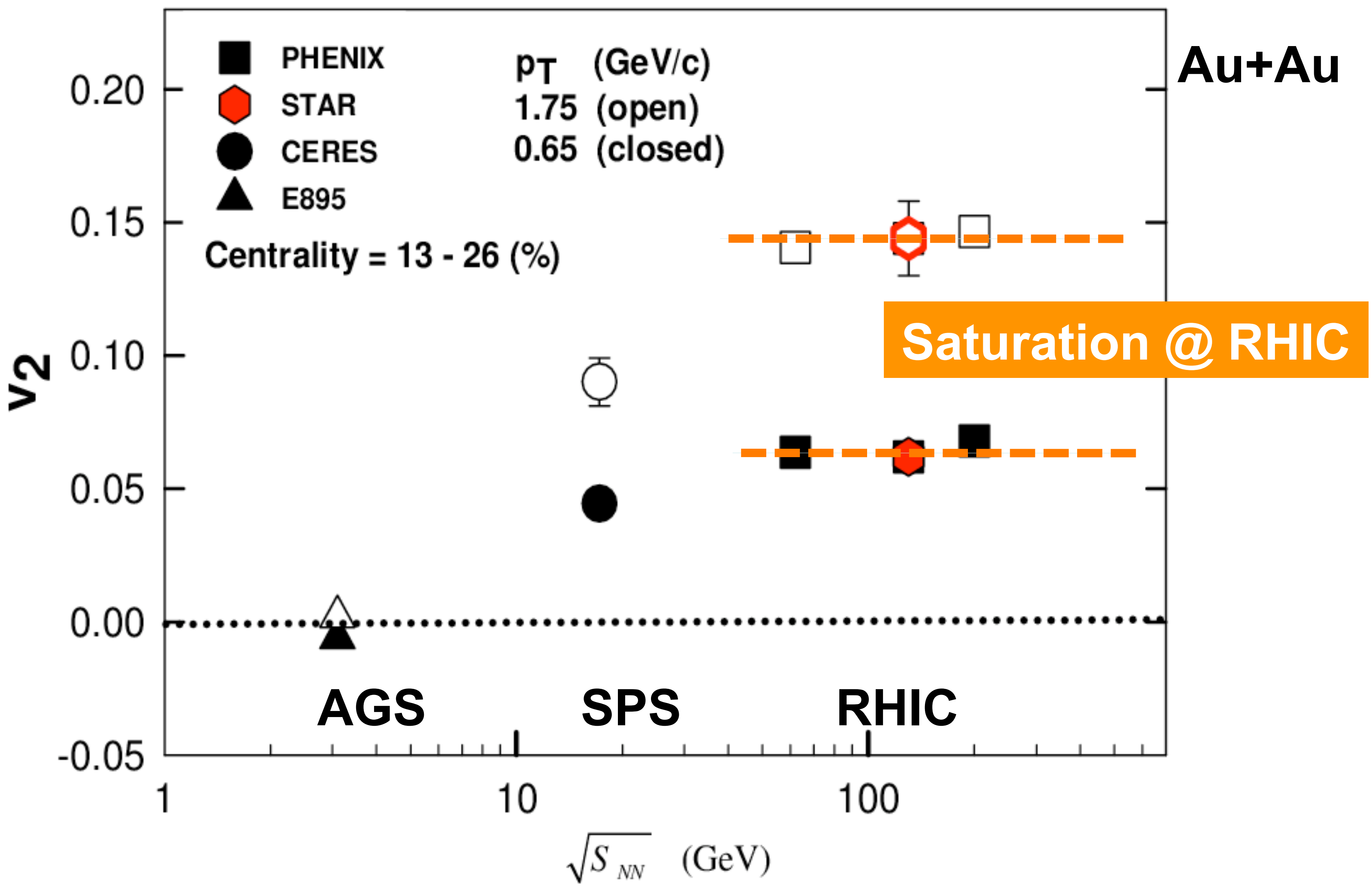


Lines:
Hydrodynamics calc.
with QGP type EoS.

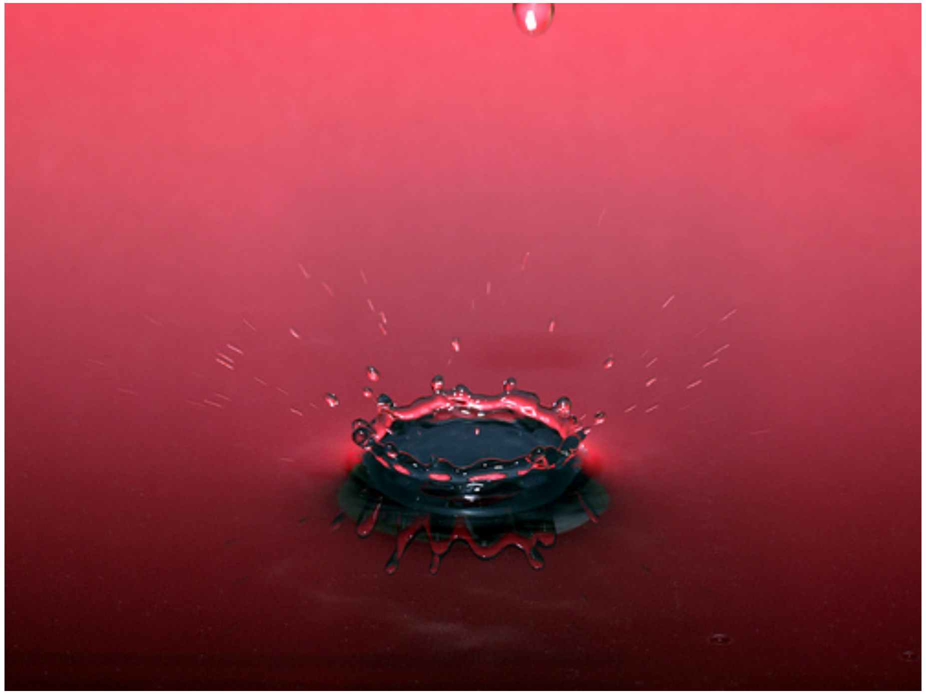
*viscosity = resistance of liquid to shear forces (and hence to flow)

Thermalization time <u>t=0.6 fm/c</u> and <u>ε=20 GeV/fm^3</u>
Required QGP Type EoS in Hydro model

Saturation of v_2 at RHIC energies (charged hadrons)



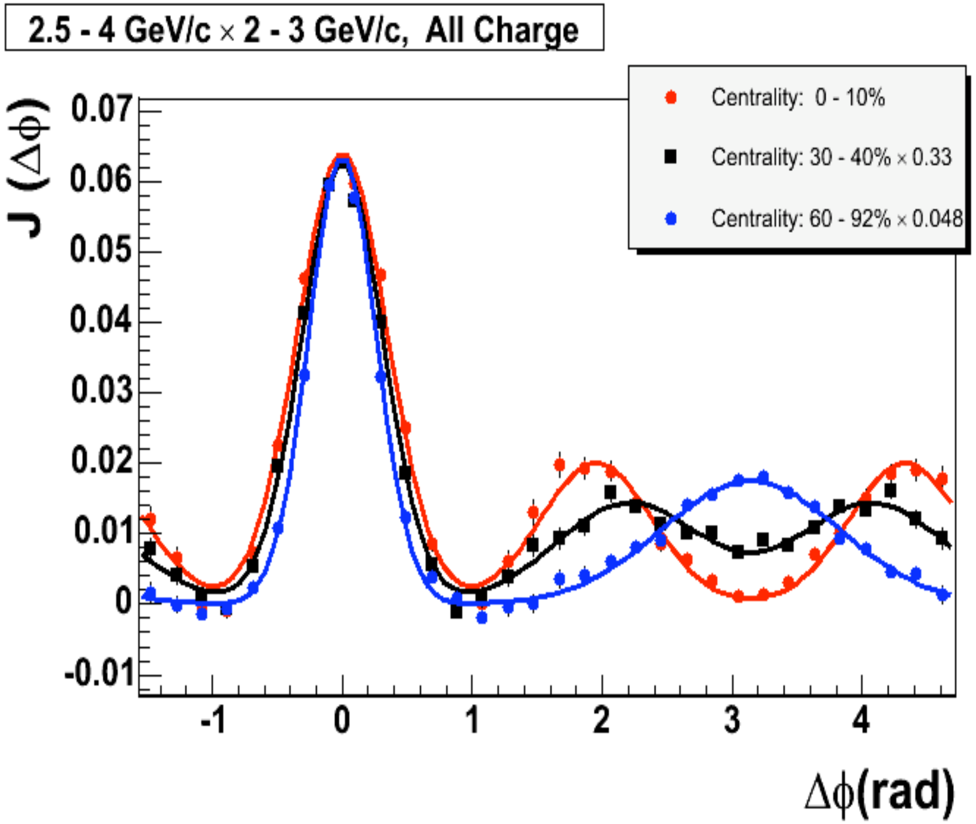
3. 発見から性質の解明へ・・・



MEDIUM RESPONSE OF JET PROPAGATIONS

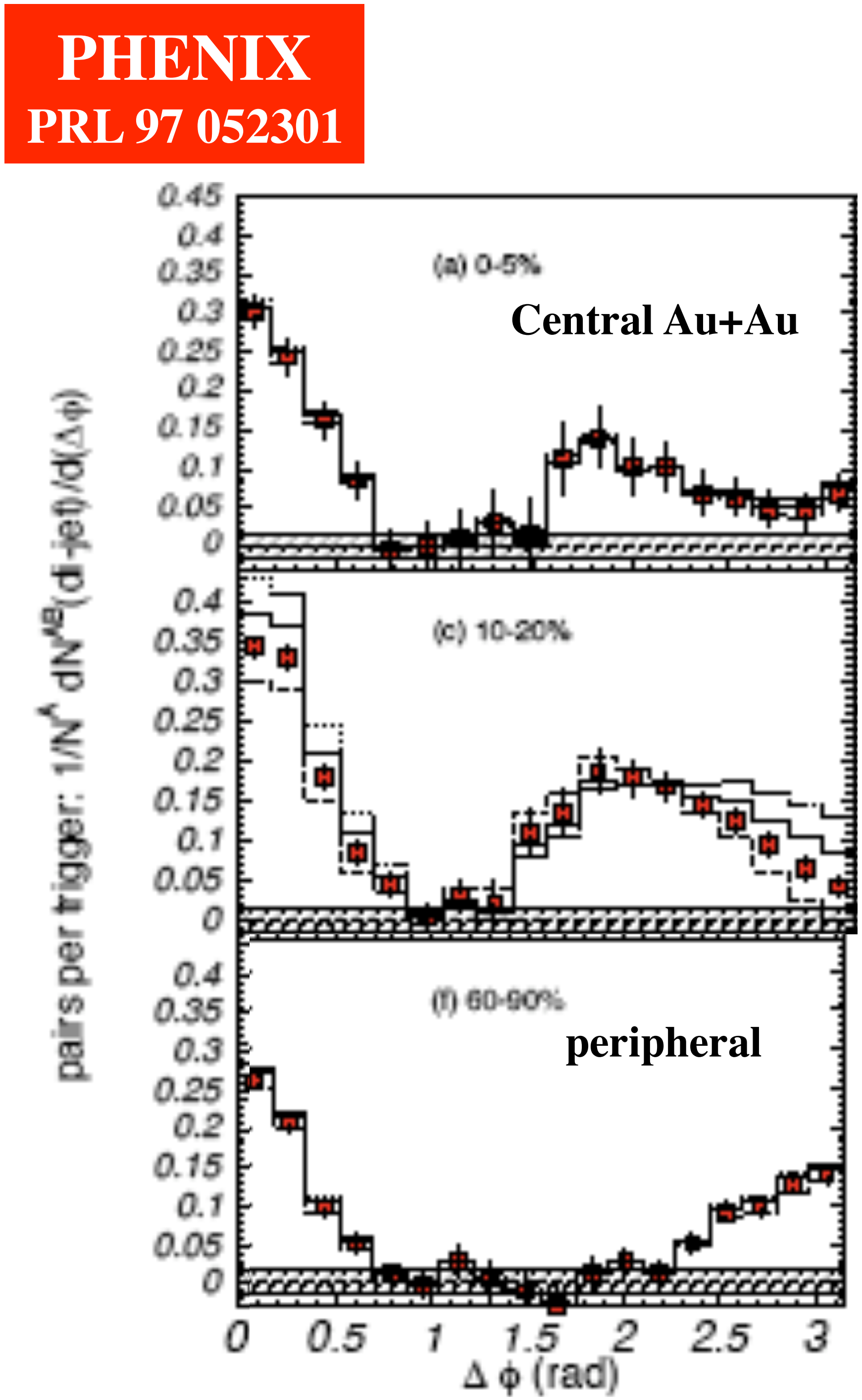
高エネルギーパートンが物質中
を通過した際に失われた
エネルギーはどこに?

どのように物質中を
伝播するのか?



Away side に2つのピーク?

Sonic shock wave?

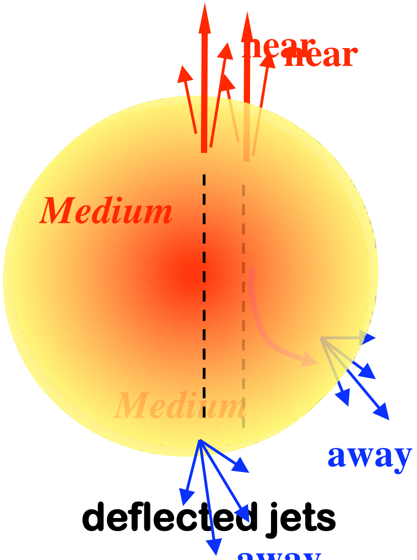


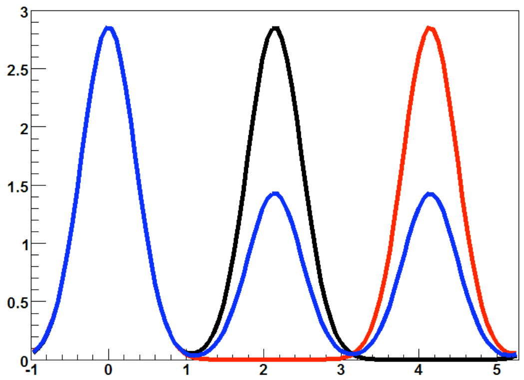
なぜ Jet modification が生じたか?

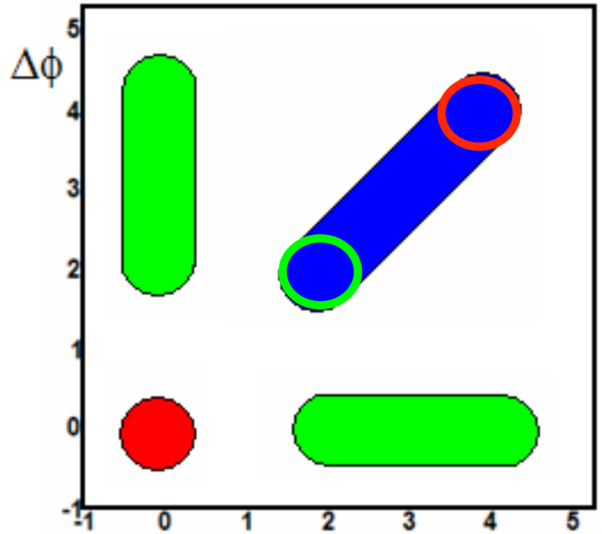
1. Deflected jets due to collective radial flow?
2. Conical emission due to Cherenkov gluon radiation?
3. Mach-cone shock wave generated by large energy deposition in the hydrodynamic medium?

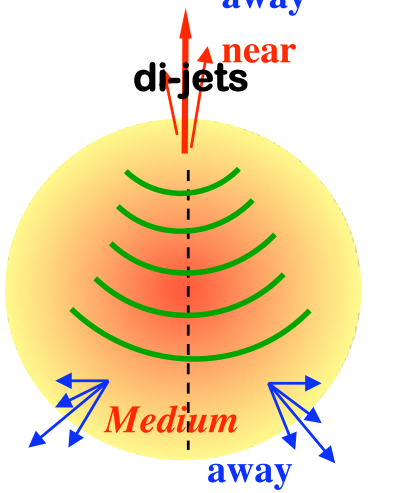
- **3-particle correlation:**
  - Powerful tool to identify the underlying physics process.
- If it is Mach-cone shock wave:
  - Speed of sound (c_s).
  - EOS.

Azimuthal 3-Particle Correlations

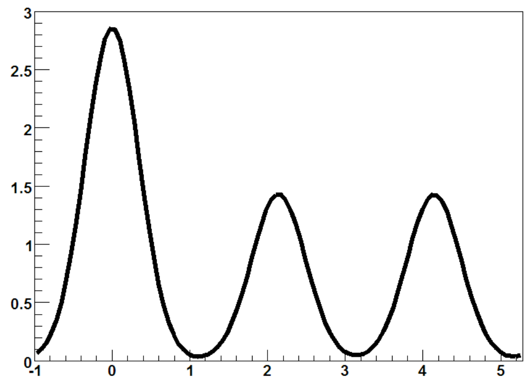


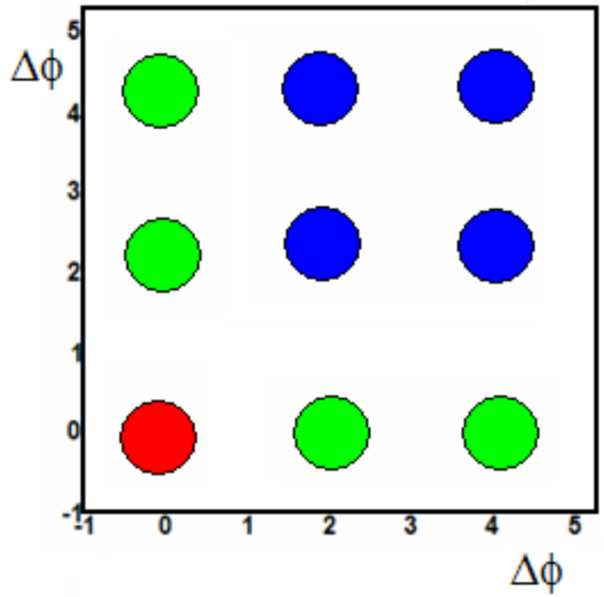






Conical Emission

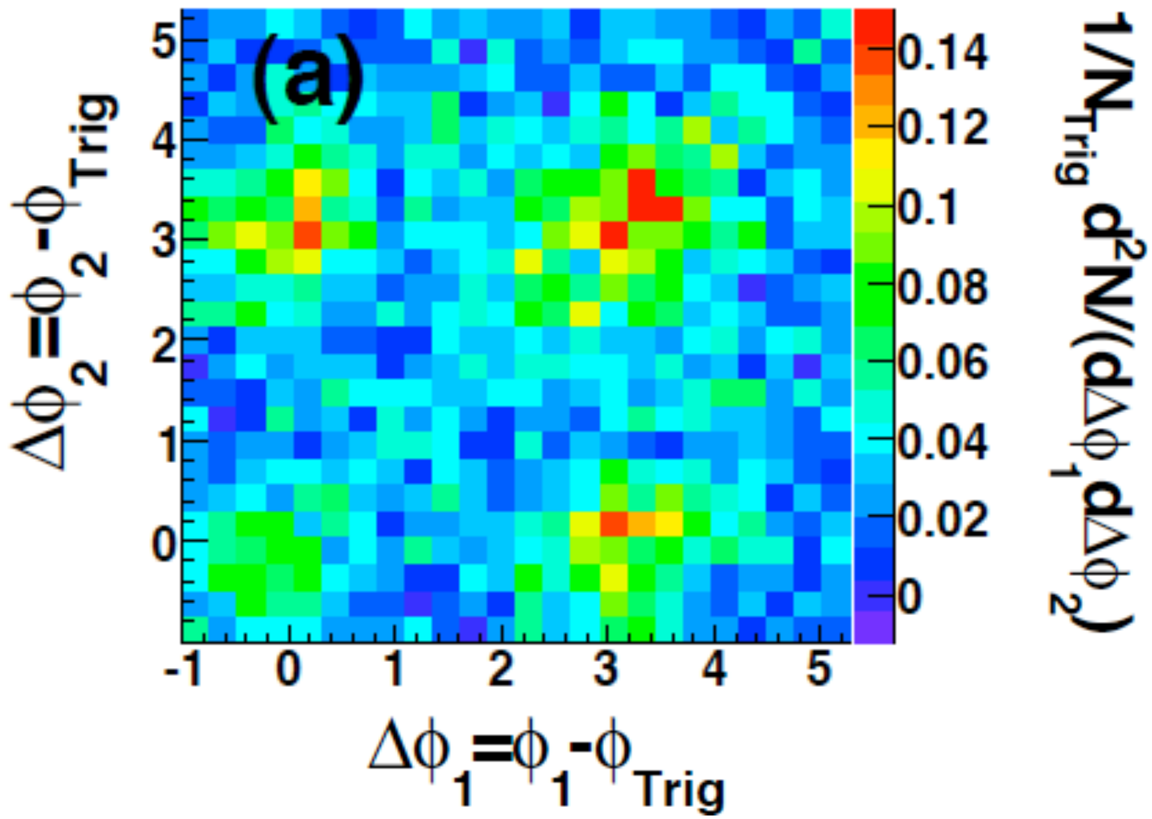




From : Jason Glyndwr Ulery (QM 2008)

(a) p+p

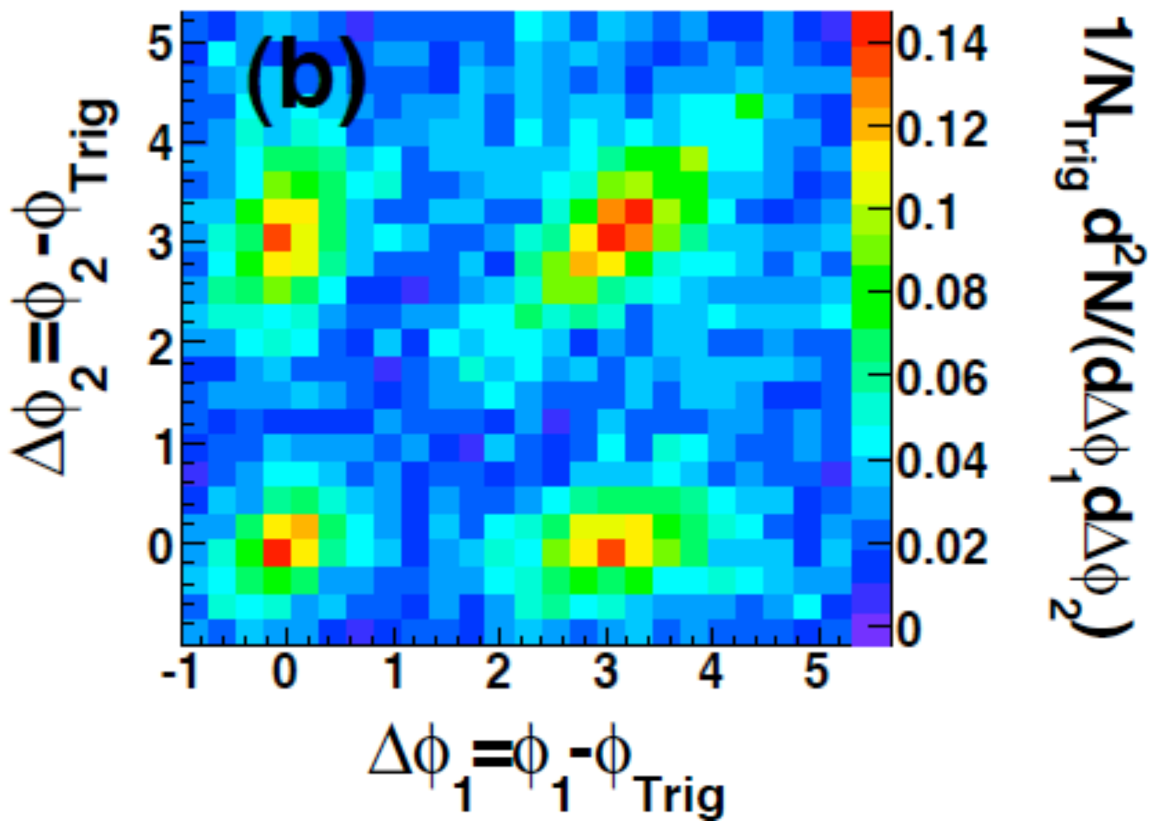
B.I. Abelve et al. (STAR),
arXiv:0805.0622v1



Trigger particle ($3 < p_T < 4$ GeV/c),
Associated particle ($1 < p_T < 2$ GeV/c) .

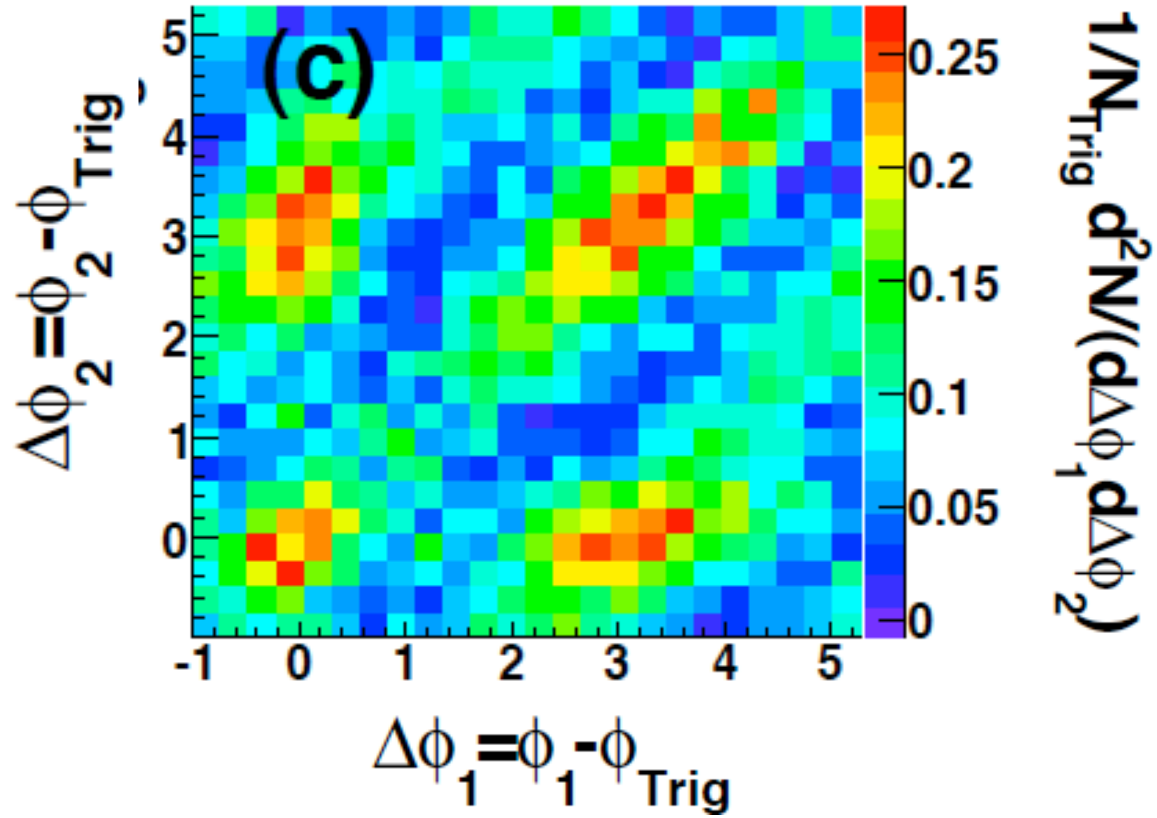
(b) d+Au

B.I. Abelve et al. (STAR),
arXiv:0805.0622v1



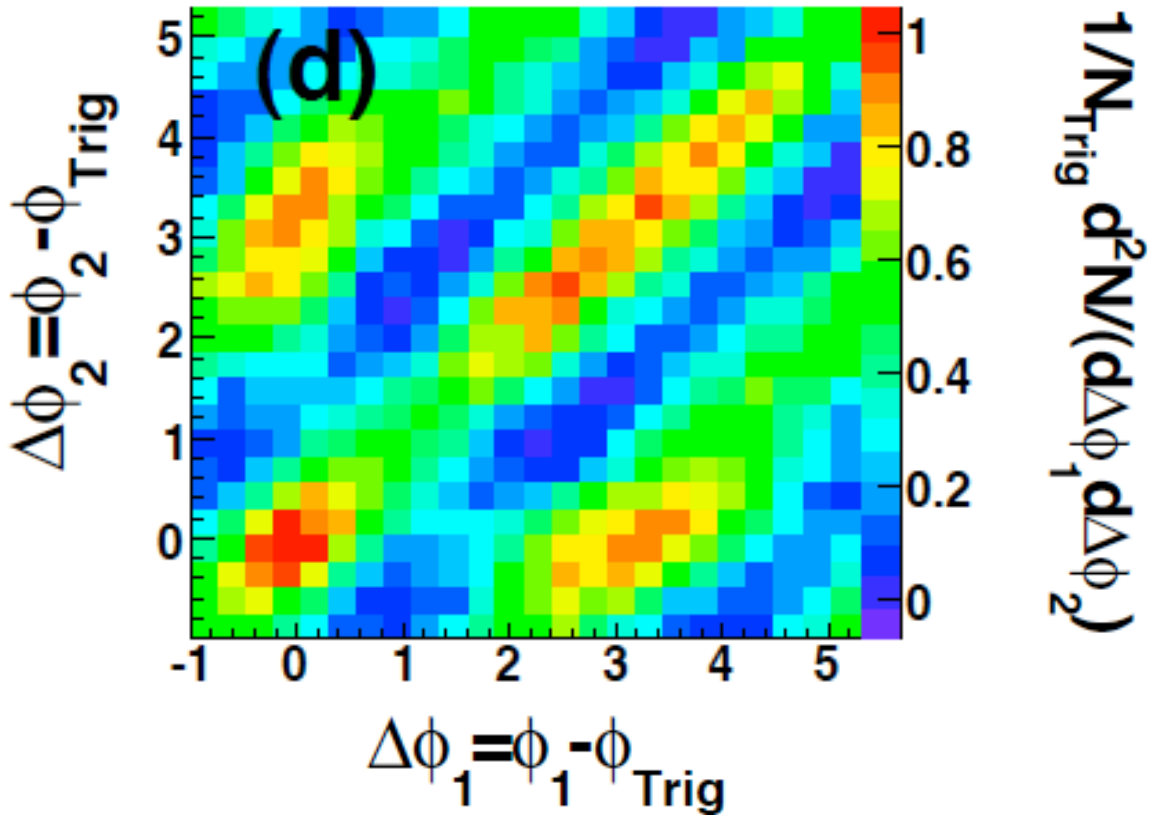
(c) Au+Au 50-80%

B.I. Abelve et al. (STAR),
arXiv:0805.0622v1



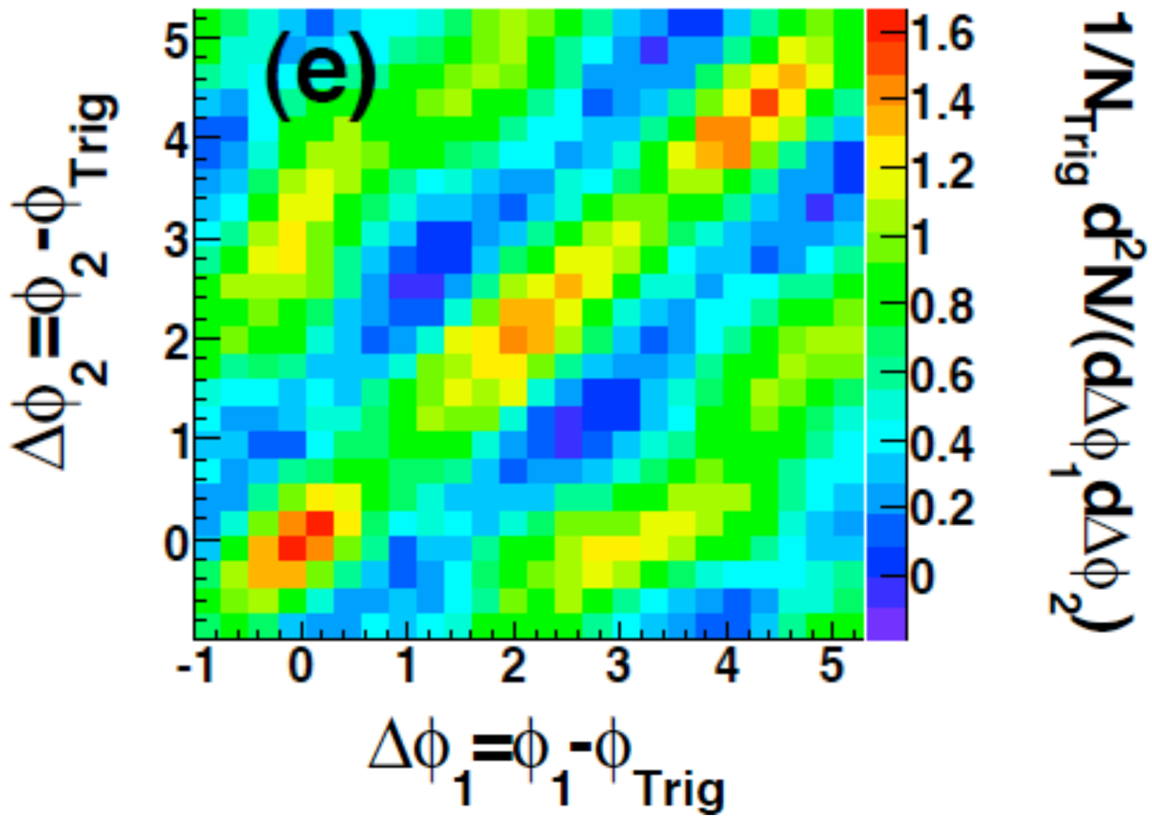
(d) Au+Au 30-50%

B.I. Abelve et al. (STAR),
arXiv:0805.0622v1



(e) Au+Au 10-30%

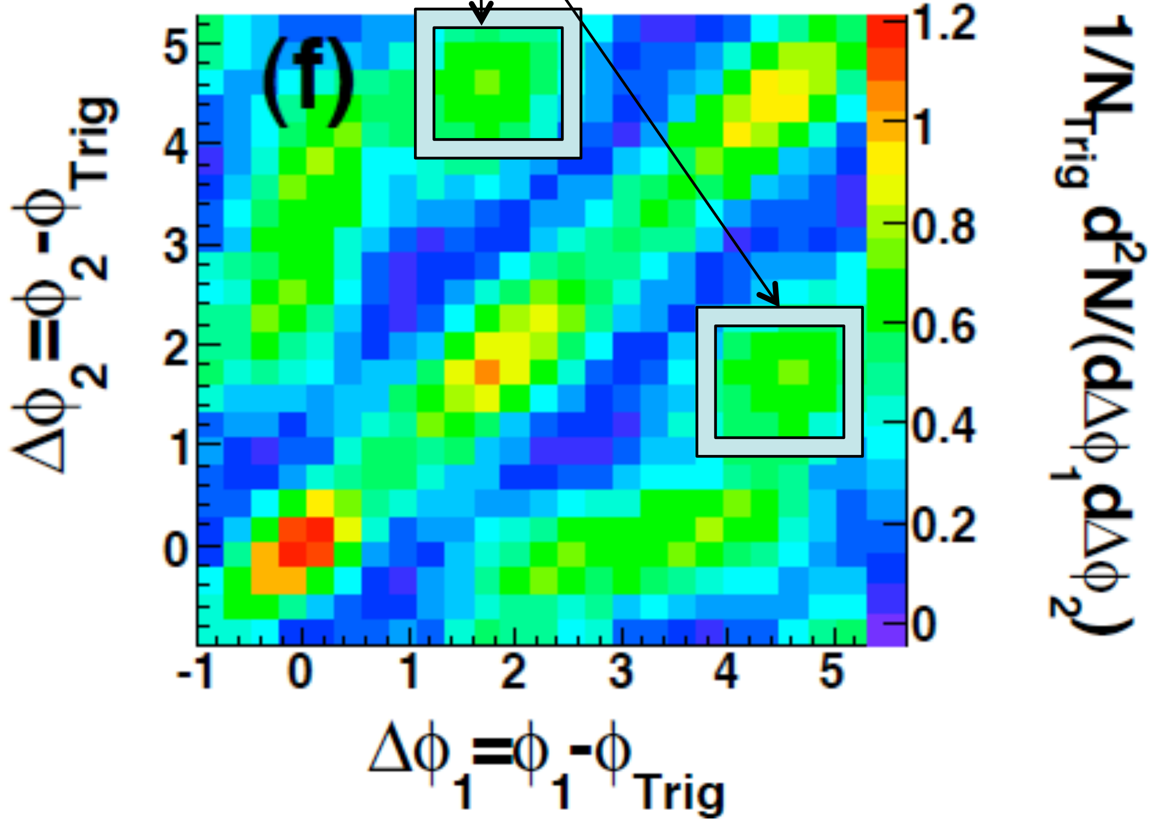
B.I. Abelve et al. (STAR),
arXiv:0805.0622v1



(f) Au+Au 0-12%

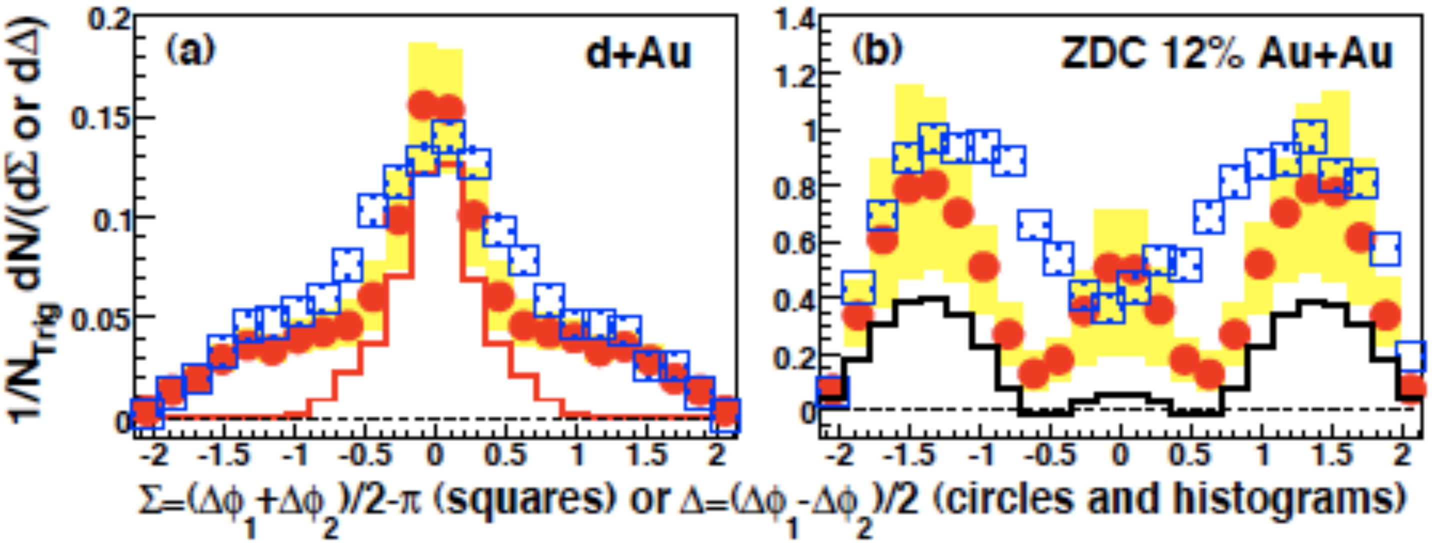
Off-diagonal成分の出現

B.I. Abelve et al. (STAR), arXiv:0805.0622v1



Observation of off-diagonal peak

B.I. Abelve et al. (STAR), arXiv:0805.0622v1

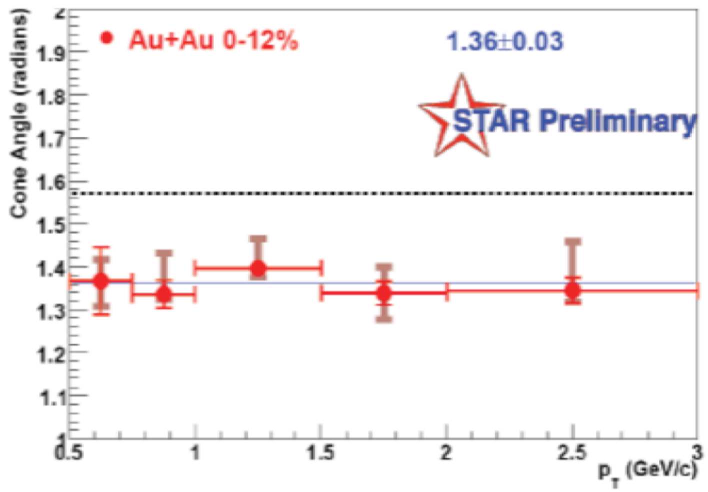


Histogram (a) :
Near side off-diagonal projection
Histogram (b):
Away side off-diagonal projection

- **Totally different shape between d+Au and Au+Au central!**
- Distinct peak at θ = 1.38 ± 0.02 (stat.) ± 0.06 (syst.) from π.
- Evidence of **conical emission** of hadrons correlated with high p_T particles.

p_T dependence of θ

- No significant p_T dependence of observed emission angle.
  - Consistent with Mach-cone
  - Inconsistent with simple Čerenkov radiation



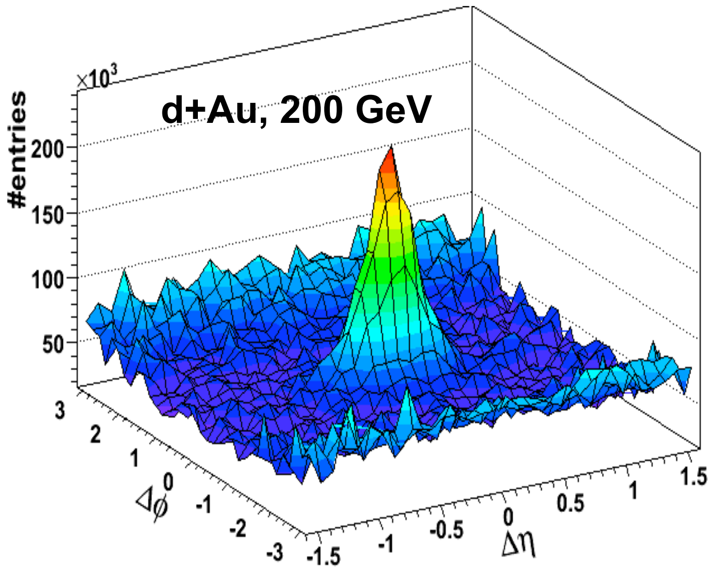
Ulery QM05, QM06 (poster)

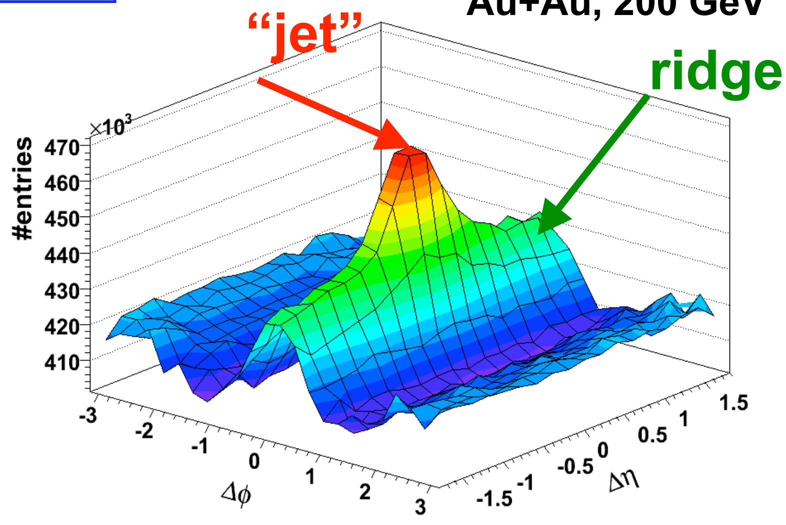
Poster: P36 Ma

$\Delta\eta$-independent near-side correlation: ``The Ridge"

p_T^{trig}=3-6 GeV/c, 2 GeV/c <p_T^{assoc}< p_T^{trig}

STAR preliminary





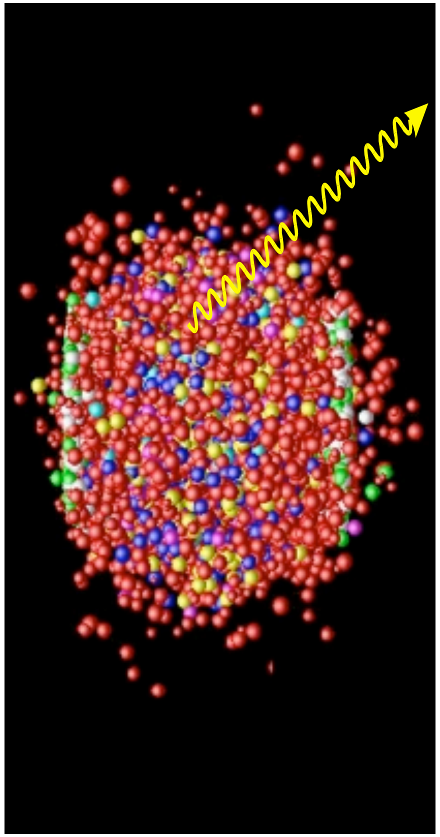
Jana Bielciekova XLIII
Rencontres de Moriond

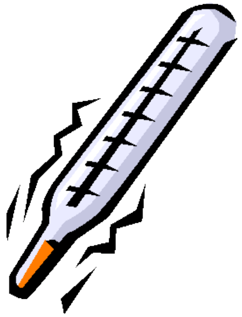
What is the ridge?

Still unclear the relationship with away side jet modification,
but it is observed at the similar momentum range.

5) Longitudinal broadening of quenched

6) Momentum kick imparted on partons in medium

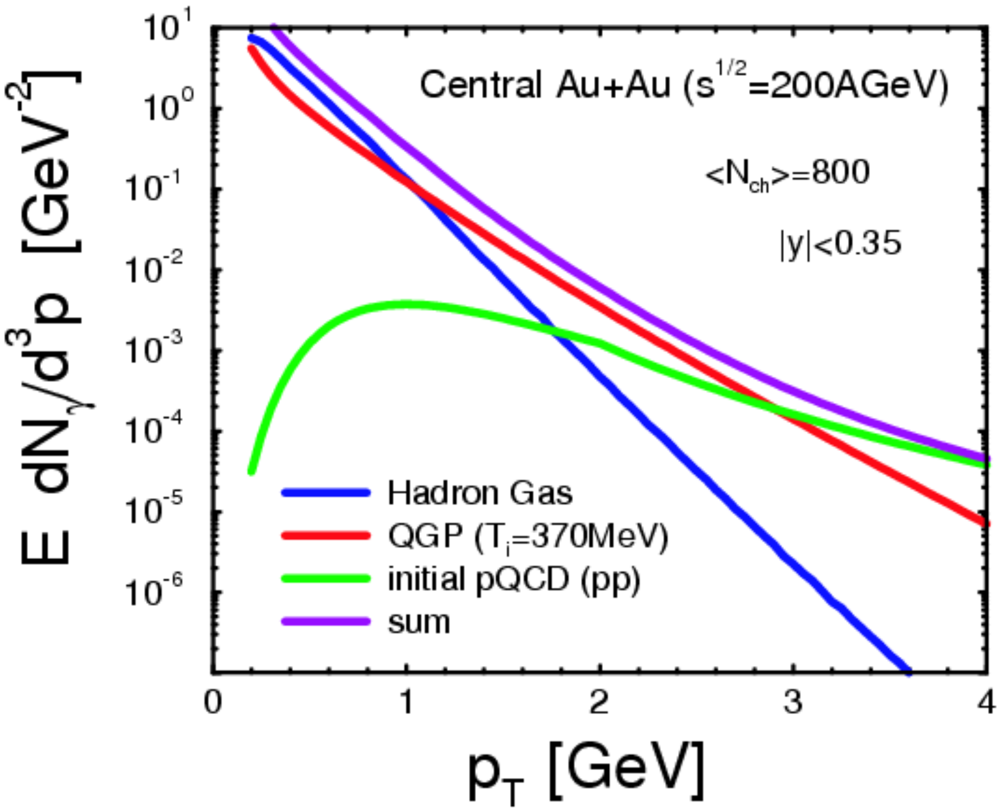




MEASUREMENT OF INITIAL TEMPERATURE

Need to access to low p_T region!

Turbide, Rapp, Gale, Phys. Rev. C 69 (014903), 2004



- Huge back ground to measure thermal photons (only 10% of hadron BG).
- Window for thermal photons from QGP in this calculation: ***p_T = 1 - 3 GeV/c***
- ***Limitation of the hadronic BG subtraction method.***

A new Idea of thermal photon measurement

Use lepton pairs to measure

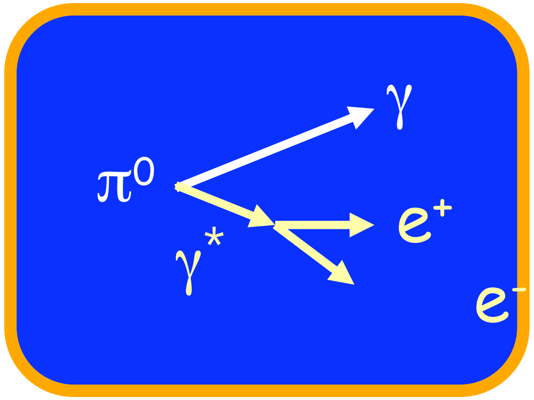
virtual γ

<u>**Two sources of virtual γ with very low (invariant) mass:**</u>

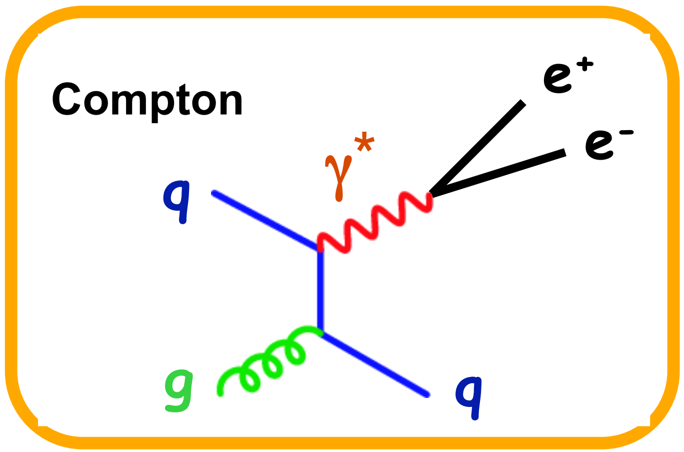
1. **Background from Dalitz decay**
   - **Kroll-Wada formula**
2. **Hard photon (signal) = thermal photon candidate**

$$\frac{\gamma^*_{direct}}{\gamma^*_{incl.}} = \frac{\gamma_{direct}}{\gamma_{incl.}}$$

excess over known hadronic source



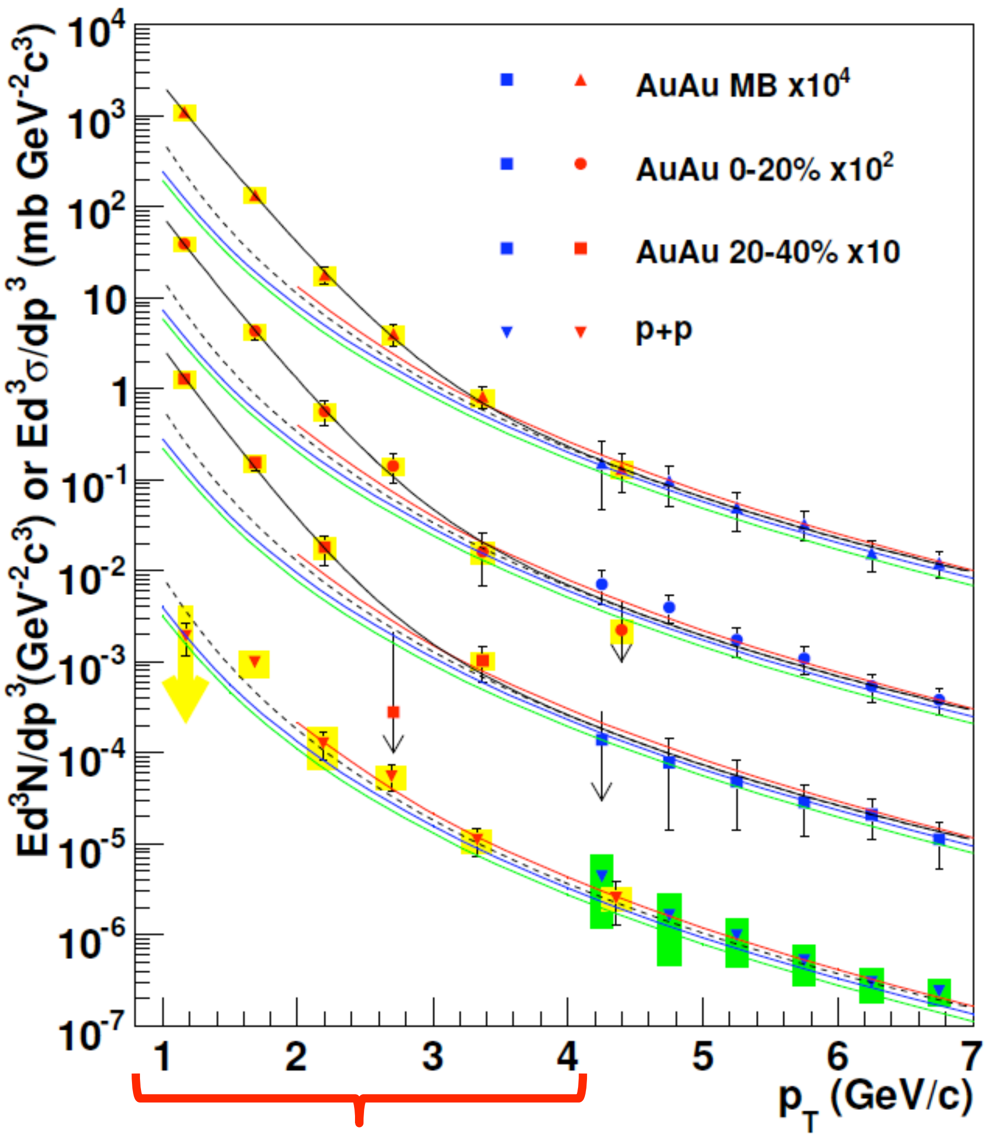
Daliz decay



e^+e^- internal conversion pair from hard scattering

PHENIX, arXiv: 0804.4168

Direct photon yields



New measurement (int. conversion)

Previous measurement (subtraction)

$$\gamma_{direct} = \gamma_{incl.}(\gamma^*_{direct}/\gamma^*_{incl.})$$

Measured inclusive spectrum

measured Ratio

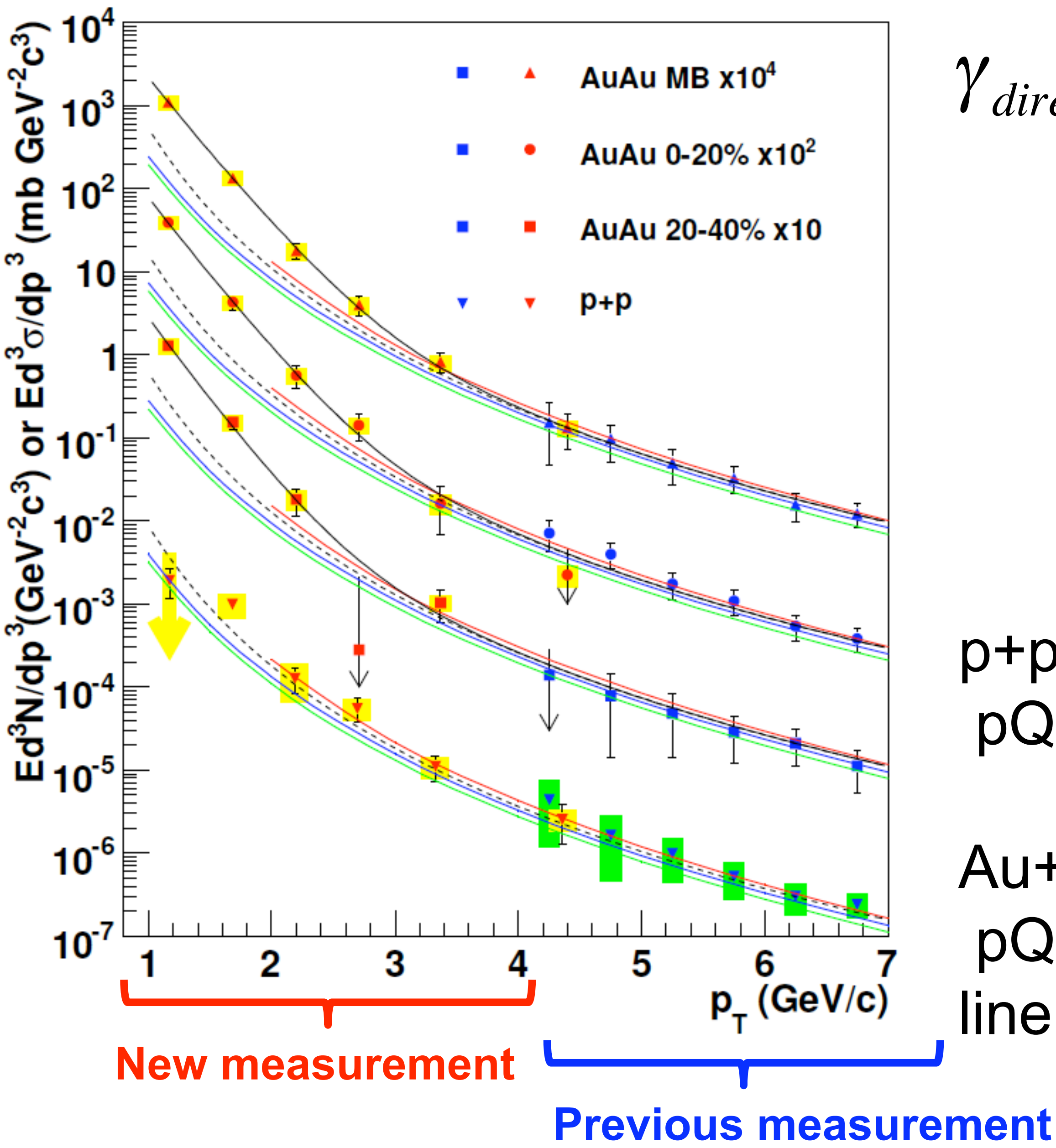
NLO pQCD direct photon cal.

Power law fit to p+p data (Au+Au; TAA scaled)

Exp. + power law fit

PHENIX, arXiv: 0804.4168

Direct photon yields



$$\gamma_{direct} = \gamma_{incl.}(\gamma^{*}_{direct} / \gamma^{*}_{incl.})$$

measured Ratio

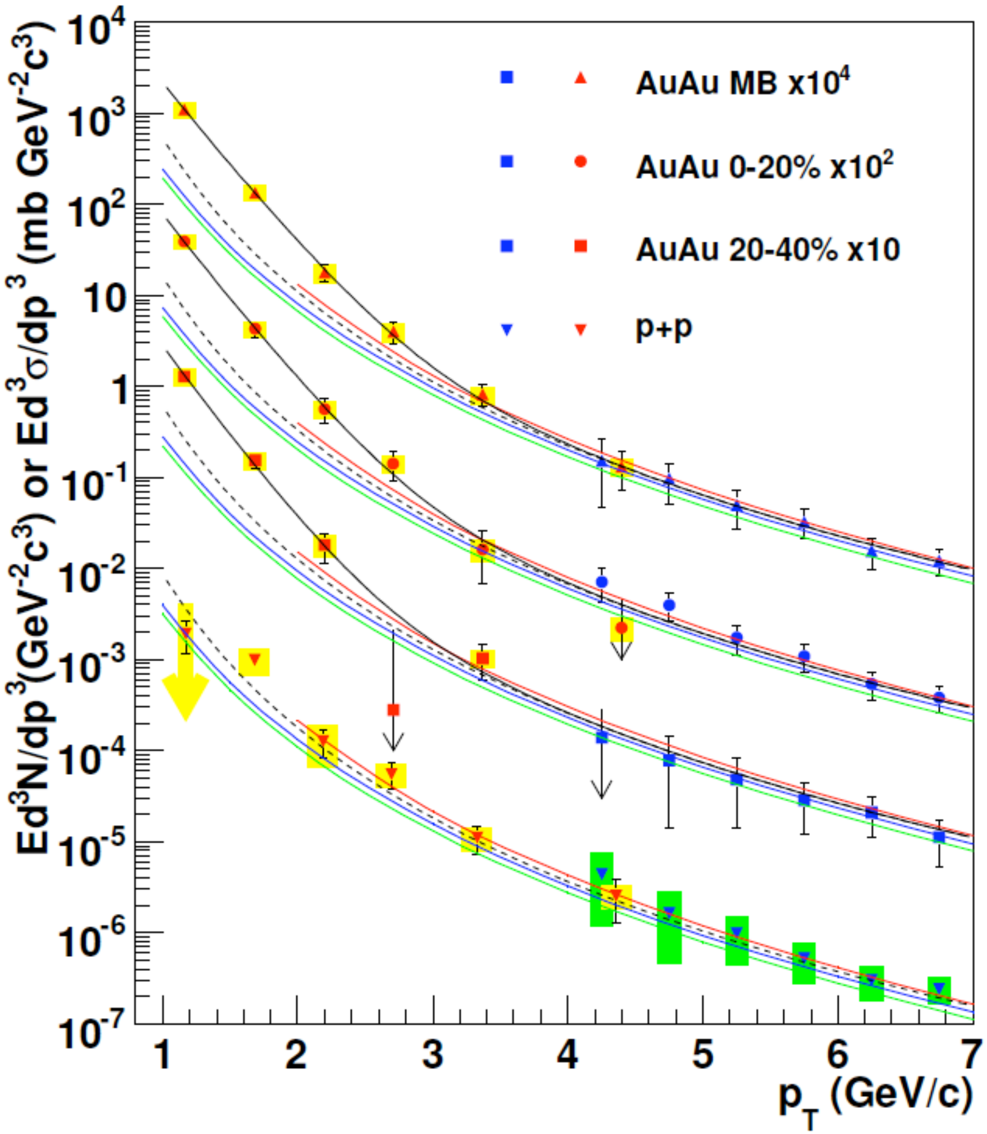
Measured inclusive spectrum

p+p: consistent with NLO pQCD, even at low pT.

Au+Au: larger than the NLO pQCD T_{AA} scaled line for $1 < p_T < 2.5$ GeV/c.

Extract "T" (temperature)

PHENIX, arXiv: 0804.4168



Black line (two component fit):

$$Ae^{-p_T/T} + Bp_T^n$$

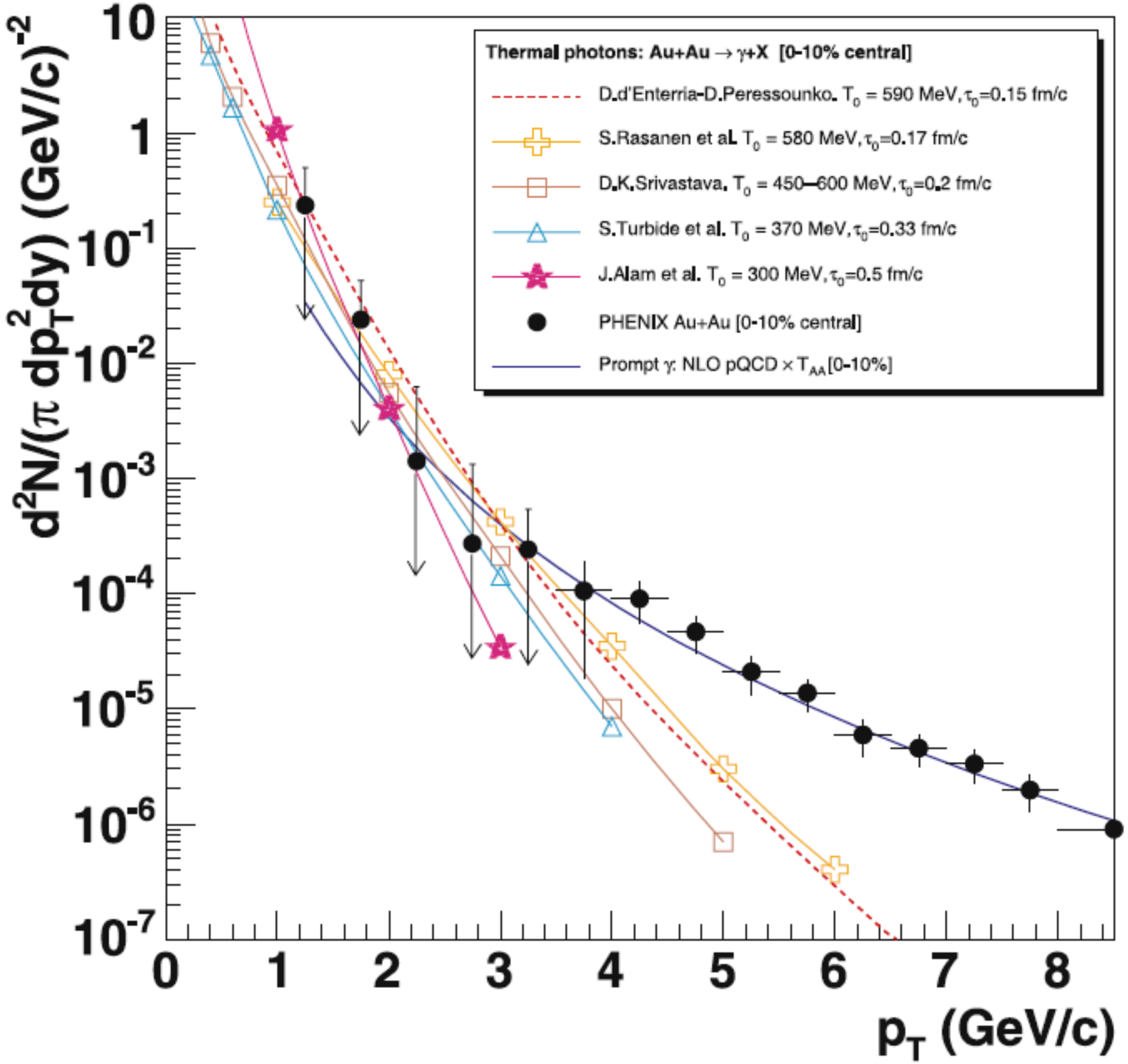
Fixed by TAA scaled
Power low fit to p+p data

A, T : free parameters.

Inverse slope for Au+Au
200 GeV for central 0-20% is;
T = 238 ± 2 ± 10 MeV

Centrality	A ($GeV^{-2}c^3$)	T (MeV)
0-20 %	41.8 ± 24.0	238 ± 2
20-40%	19.2 ± 11.2	226 ± 2
MB	9.5 ± 3.8	247 ± 2

Data vs. Theory



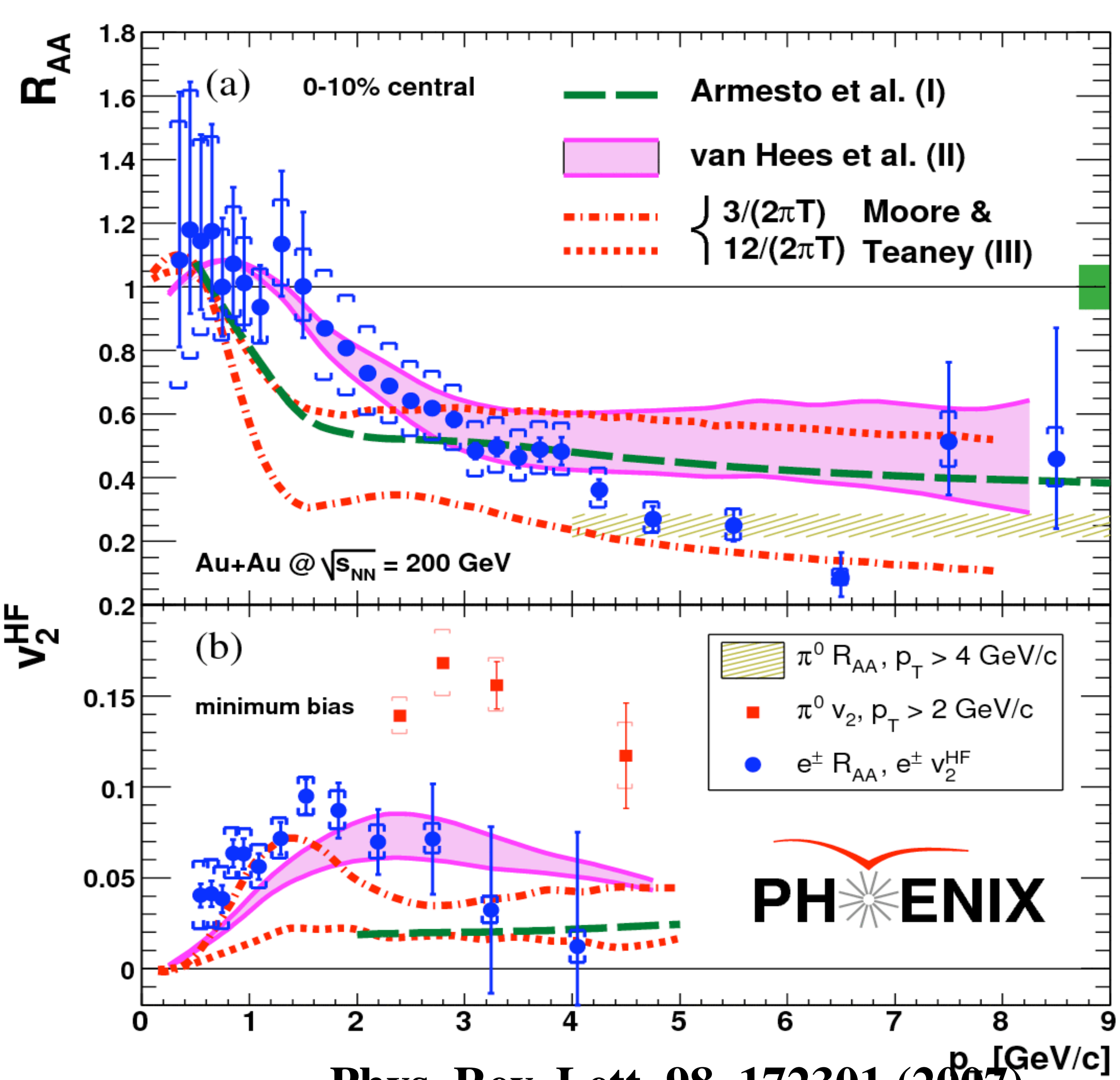
D. d'Enterria and D. Peressounko, EPJ C46, 451 (2006).

- The initial temperature is 1.5 to 3 times of the slope of the photon spectrum.
- A thermal photon spectrum in central Au+Au collisions at RHIC with an T_{ini} = 370 MeV in agrees with the data.
- **T_0^{max} ~ 500-600 MeV**
  T_0^{ave} ~ 300-400 MeV

OPACITY IS HUGE;

CHARM STOPS AND FLOWS?

Heavy quarks lose energy & flow

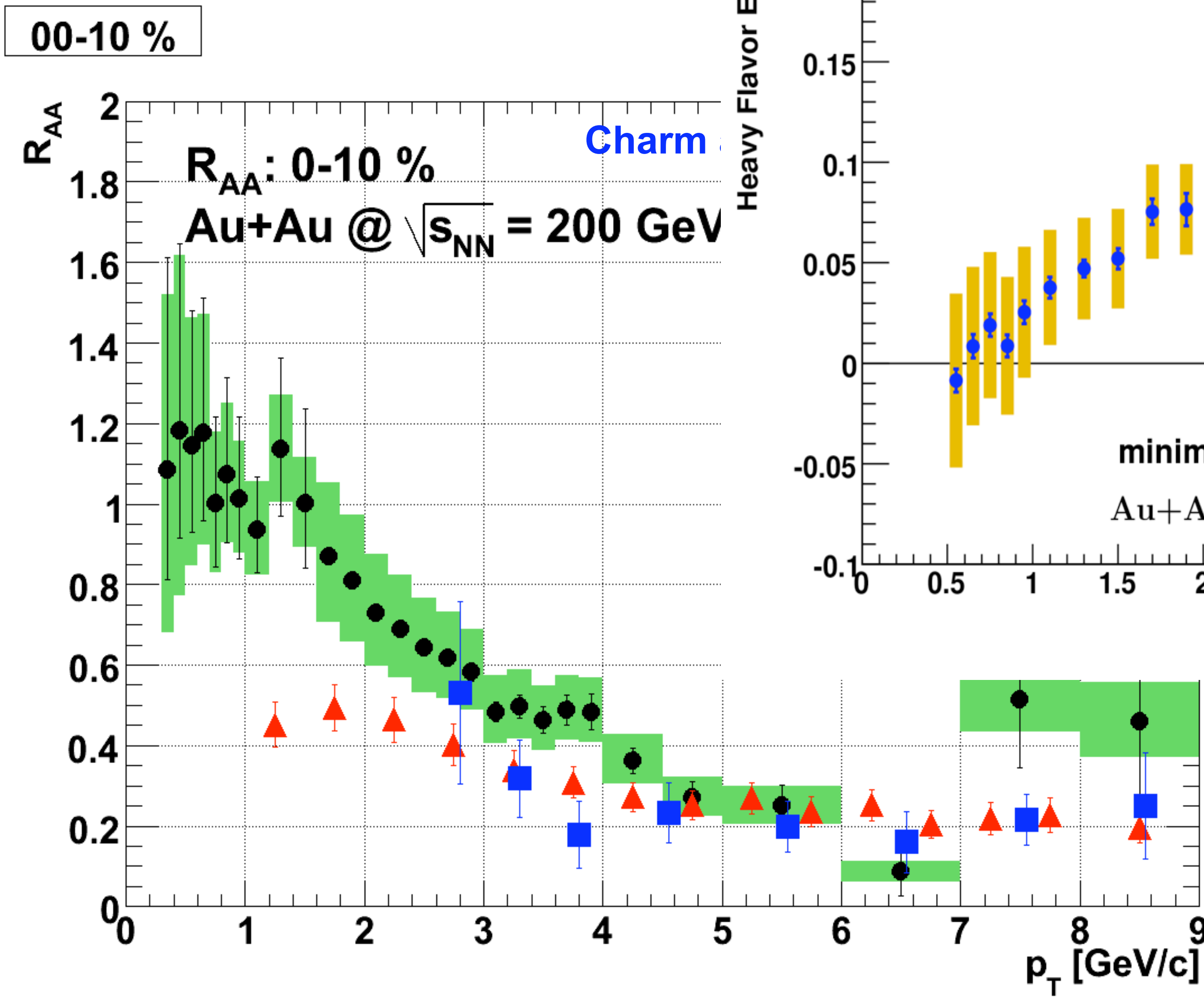


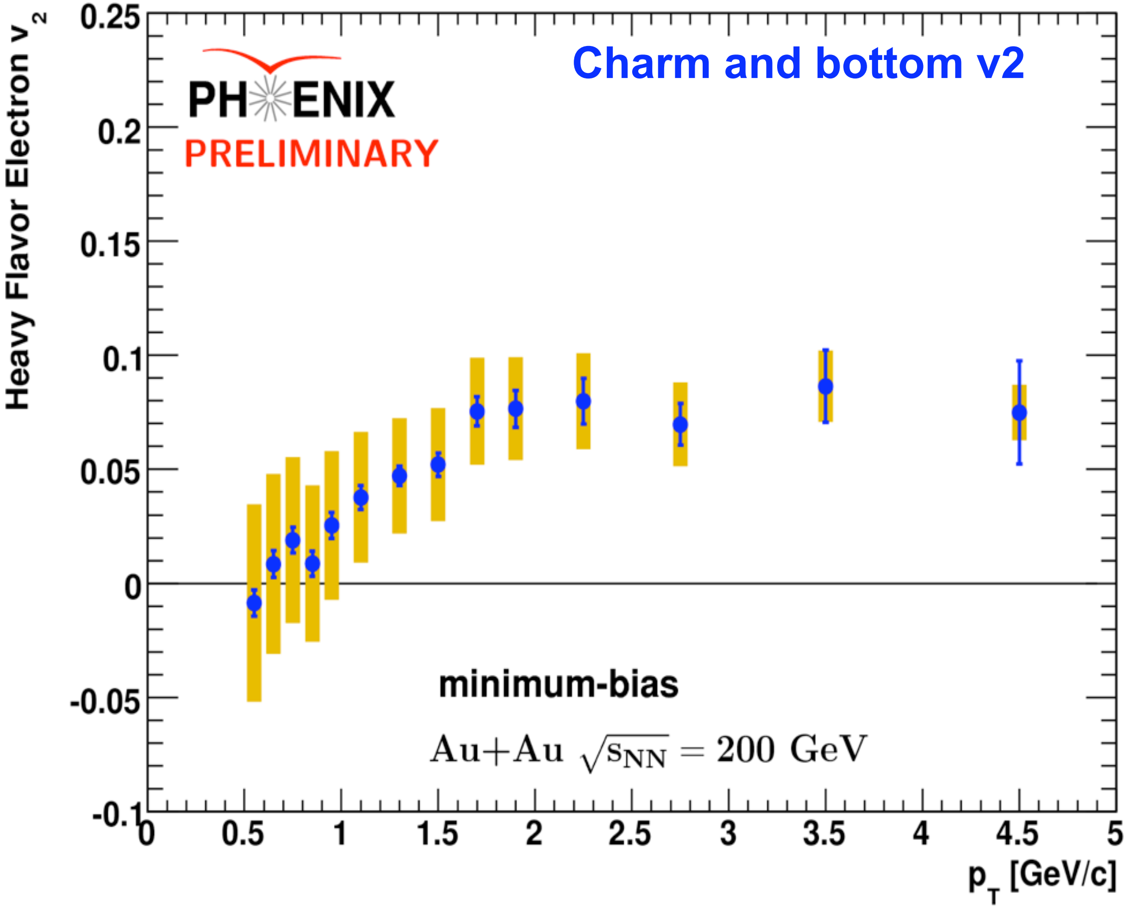
Phys. Rev. Lett. 98, 172301 (2007)

Electrons from heavy quark decay have nearly same R_{AA} as pions!

Electrons from heavy quark decay flow ("stopped in medium")?

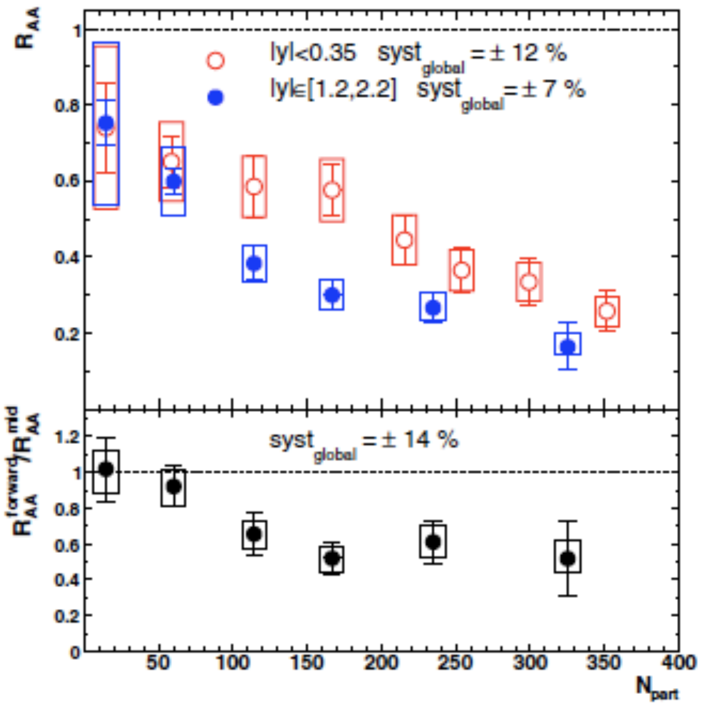
Update of c,b R_{AA} and v2

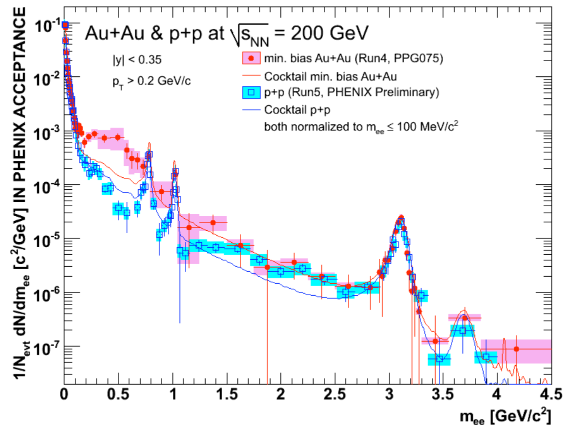


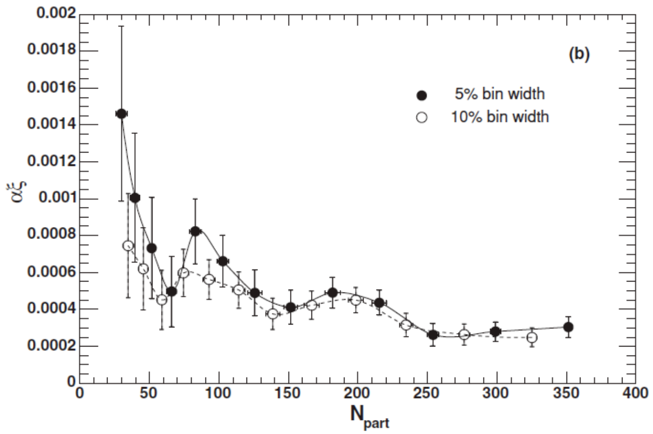


Other interesting topics (experimental)

- J/psi (S. Oda)
- Low-mass di-electron (Y. Tsuchimoto)
- Fluctuations (K. Homma)





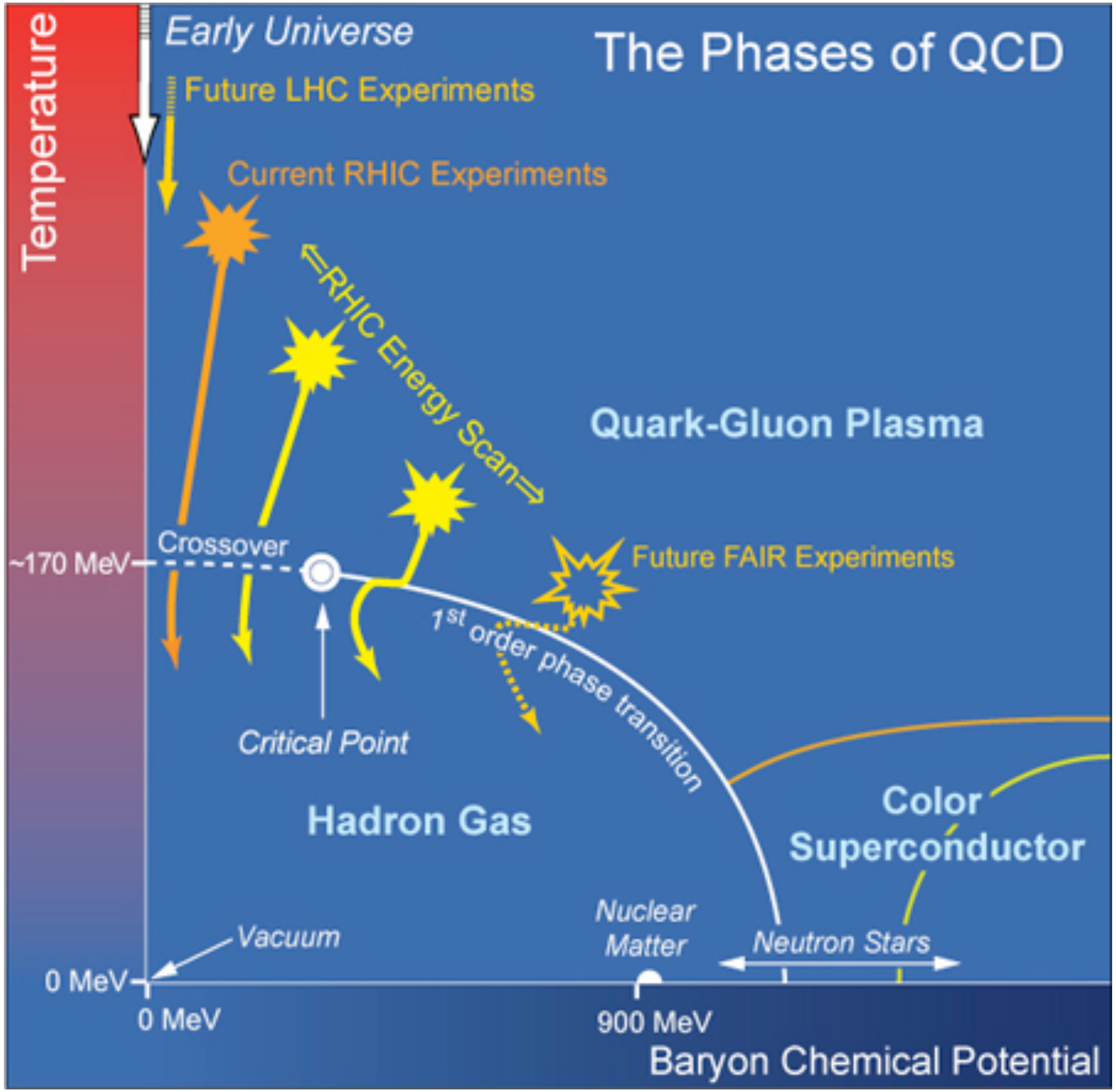


4. Summary

RHIC = QGP & QCD machine !

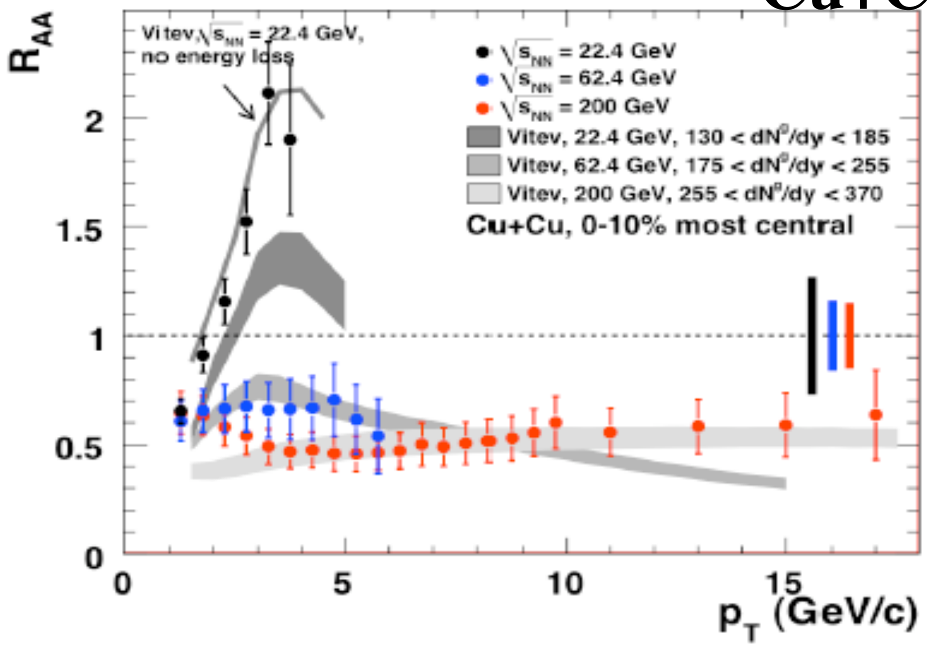
- **Many (unexpected) discoveries.**
- **Energy density.**
  - **$\varepsilon \sim 15$ GeV / fm^3 , i.e. ~100 normal nuclear density.**
- **Behaving as zero viscosity "perfect" liquid, coupling is strong.**
- **First measurement of the initial temperature via thermal photon.**
  - T_0^{ave} = 300-400 MeV
- **Away side Jet modification at intermediate p_T suggests the generation of shock wave.**
  - Access to the sound velocity, EOS?
- **Huge Opacity & large flow for heavy quarks.**

Next Big Question:
Where is the Critical Point?



Onset of RHIC's perfect liquid?

Cu+Cu

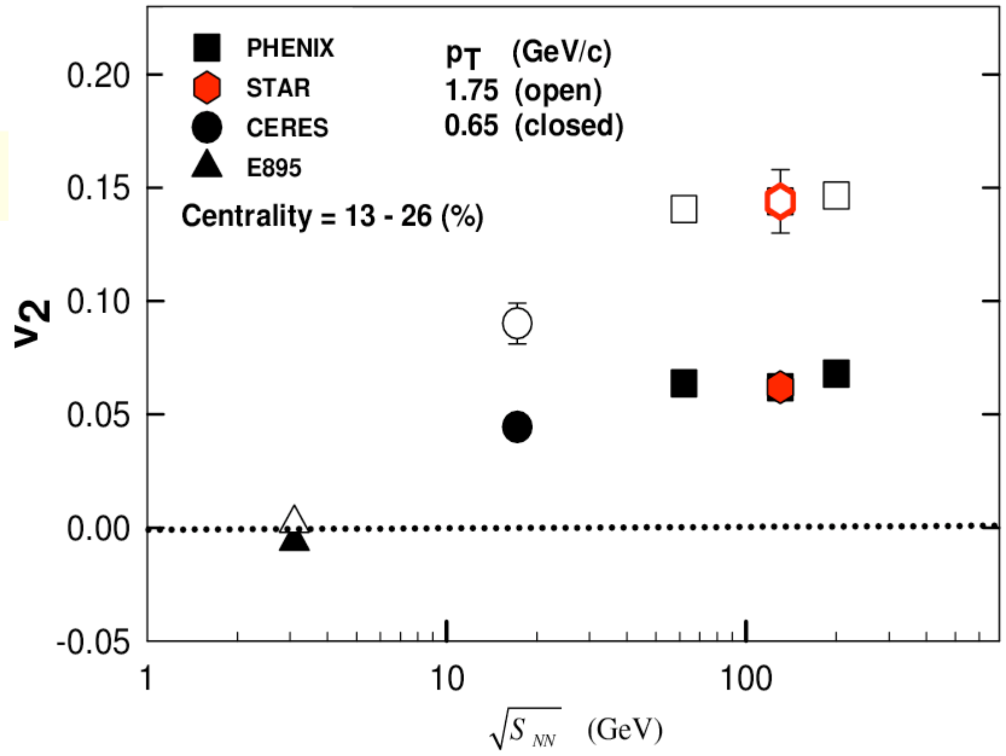


PHENIX, arXiv:0801.4555 [nucl-ex]

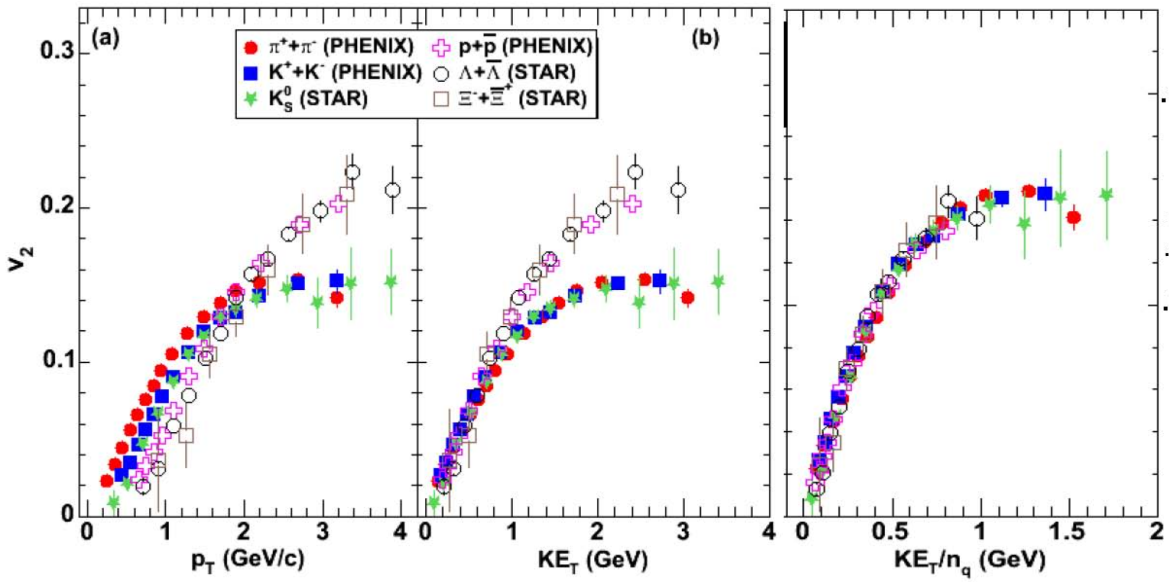
Emergence of opacity

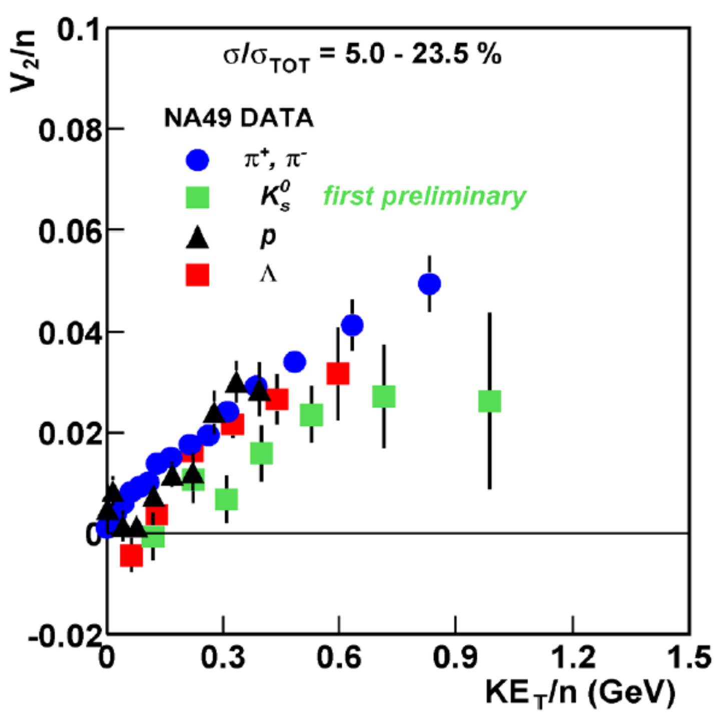
Approach to constant v_2 and hydrodynamic limit?

Au+Au



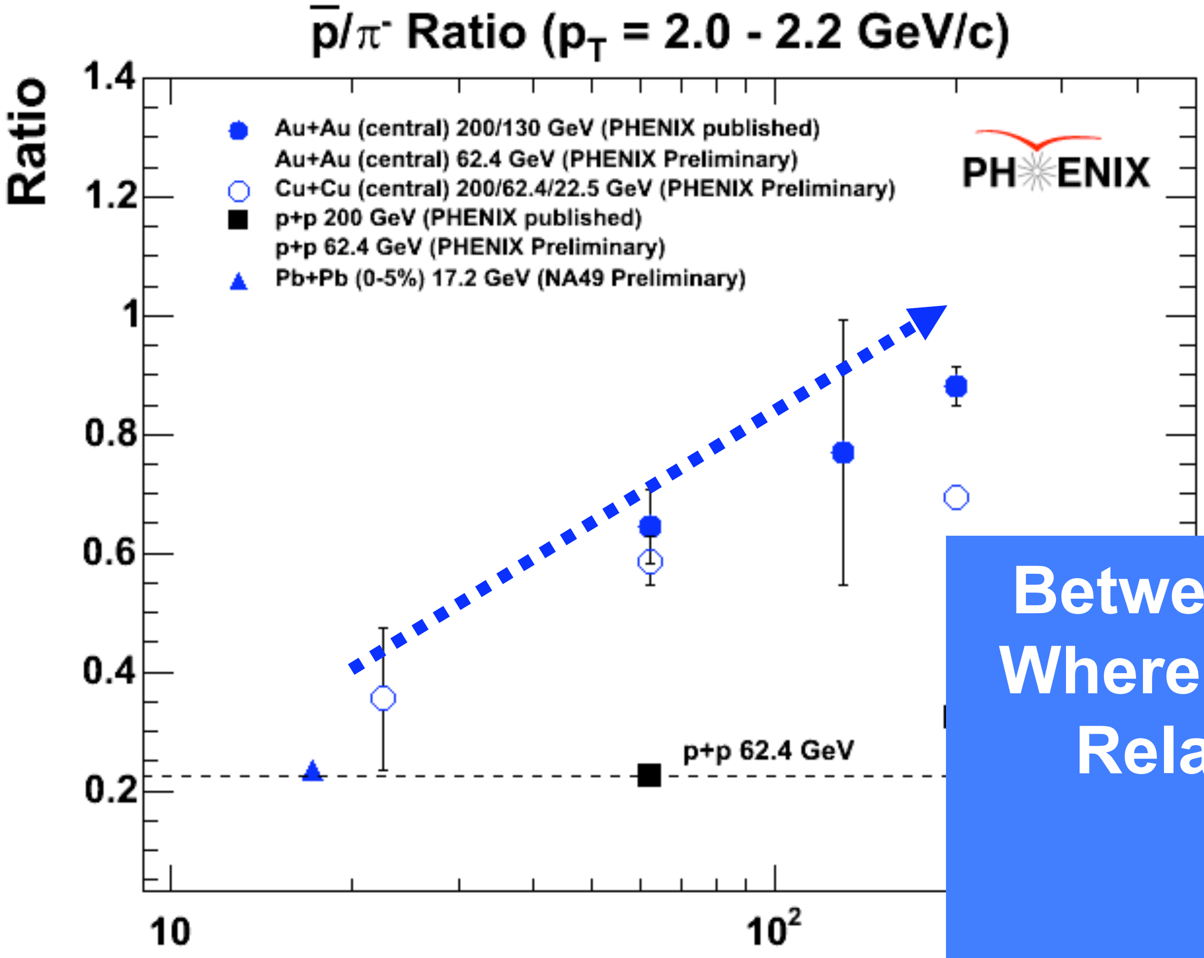
Onset of Quark Number Scaling?





Where is the onset of quark number scaling?
Relationship to quark DOF ?

p-bar/π^- ratio vs. $\sqrt{s_{NN}}$



* No weak decay feed-down correction applied.

- Increasing as a function of $\sqrt{s}$.
- Indicates the onset of baryon enhancement is in **between 22 GeV and 62 GeV**.

Between 22.4 and 62.4 GeV.
Where? Properties? (T_o, etc)
Relation to QCD critical point?

Detail energy scan at RHIC should provide a critical information about CEP & Tc.

THANK YOU
FOR YOUR ATTENTION!

Many thanks to:

- Ed O'Brien, 434^{th} BNL Lecture (2008.3.19)
- B. Jacak, DOE review (2008 July)

- The 2nd Asian Triangle Heavy Ion Conference (ATHIC2008)
- Oct 13-15, 2008
- Univ. of Tsukuba
- http://www.utkhii.px.tsukuba.ac.jp/athic2008/

BACKUP SLIDES

Future HI Milestones

Year	#	Milestone
2009	DM4	Perform realistic three-dimensional numerical simulations to describe the medium and the conditions required by the collective flow measured at RHIC.
2010	DM5	Measure the energy and system size dependence of J/Ψ production over the range of ions and energies available at RHIC.
2010	DM6	Measure e^+e^- production in the mass range $500 \leq m_{e+e-} \leq 1000$ MeV/c2 in $\sqrt{s_{NN}} = 200$ GeV collisions.
2010	DM7	Complete realistic calculations of jet production in a high density medium for comparison with experiment.
2012	DM8	Determine gluon densities at low x in cold nuclei via p + Au or d + Au collisions.
2015	DM9 (new)	Measure bulk properties, particle spectra, correlations and fluctuations in Au + Au collisions at $\sqrt{s_{NN}}$ from 5 to 40 GeV to search for evidence of a critical point in the QCD matter phase diagram.
2014	DM10 (new)	Perform calculations including viscous hydrodynamics to quantify, or place an upper limit on, the viscosity of the nearly perfect fluid discovered at RHIC.
2014	DM11 (new)	Measure jet and photon production and their correlations in A≈200 ion+ion collisions at energies from $\sqrt{s_{NN}} = 30$ GeV up to 5.5 TeV.
2016	DM12 (new)	Measure production rates, high pT spectra, and correlations in heavy-ion collisions at $\sqrt{s_{NN}} = 200$ GeV for identified hadrons with heavy flavor valence quarks to constrain the mechanism for parton energy loss in the quark-gluon plasma.
2018	DM13 (new)	Measure real and virtual thermal photon production in p + p, d + Au and Au + Au collisions at energies up to $\sqrt{s_{NN}} = 200$ GeV.

RHIC Run Plan

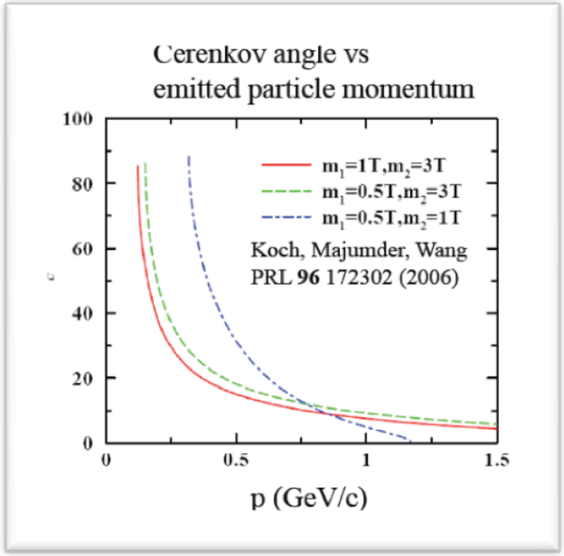
Fiscal Year	Colliding Beam Species/Energy	Comments
2009	500 GeV p+p	Assuming ~April 1 start, about 5-6 physics weeks to commission collisions, work on polarization & luminosity and obtain first W production signal to meet RIKEN milestone
2010	200 GeV p+p	~12 physics weeks to complete 200 GeV A_{LL} measurements – could be swapped with 500 GeV Run 9 if Run 9 can start by March 1, 2009; STAR DAQ1000 fully operational
	200 GeV Au+Au	9-10 physics weeks with PHENIX HBD, STAR DAQ1000 & TOF permits low-mass dilepton response map and 1st collision test of transverse stochastic cooling (one ring)
2011	Au+Au at assorted low E	1st energy scan for critical point search, using top-off mode for luminosity improvement – energies and focus signals to be decided; commission PHENIX VTX (at least prototype)
	200 GeV U+U	1st U+U run with EBIS, to increase energy density coverage
2012	500 GeV p+p	1st long 500 GeV p+p run, with PHENIX muon trigger and STAR FGT upgrades, to reach ~100 pb^{-1} for substantial statistics on W production and ΔG measurements
	200 GeV Au+Au	Long run with full stochastic cooling, PHENIX VTX and prototype STAR HFT installed; focus on RHIC-II goals: heavy flavor, γ-jet, quarkonium, multi-particle correlations
2013	500 GeV p+p	Reach ~300 pb^{-1} to address 2013 DOE performance milestone on W production
	200 GeV Au+Au or 2nd low-E scan	To be determined from 1st low-E scan and 1st upgraded luminosity runs, progress on low-E e-cooling, and on installation of PHENIX FVTX and NCC and full STAR HFT
2014	200 GeV Au+Au or 2nd low-E scan	Run option not chosen for 2013 run – low-E scan addresses 2015 DOE milestone on critical point, full-E run addresses 2014 (γ-jet) and 2016 (identified heavy flavor) milestones. Proof of principle test of coherent electron cooling.
	200 GeV p+p	Address 2015 DOE performance milestone on transverse SSA for γ-jet; reference data with new detector subsystems; test e-lenses for p+p beam-beam tune spread reduction

PHENIX run history

Run	Year	Species	$\sqrt{s_{NN}}$ (GeV)	$\int L\,dt$	N_{Tot}	p+p Equivalent	Data Size
01	2000	Au+Au	130	1 μb^{-1}	10M	0.04 pb^{-1}	3 TB
02	2001/2002	Au+Au	200	24 μb^{-1}	170M	1.0 pb^{-1}	10 TB
		p+p	200	0.15 pb^{-1}	3.7G	0.15 pb^{-1}	20 TB
03	2002/2003	d+Au	200	2.74 nb^{-1}	5.5G	1.1 pb^{-1}	46 TB
		p+p	200	0.35 pb^{-1}	6.6G	0.35 pb^{-1}	35 TB
04	2004/2004	Au+Au	200	241 μb^{-1}	1.5G	10.0 pb^{-1}	270 TB
		Au+Au	62.4	9 μb^{-1}	58M	0.36 pb^{-1}	10 TB
05	2004/2005	Cu+Cu	200	3 nb^{-1}	8.6G	11.9 pb^{-1}	173 TB
		Cu+Cu	62.4	0.19 nb^{-1}	0.4G	0.8 pb^{-1}	48 TB
		Cu+Cu	22.5	2.7 μb^{-1}	9M	0.01 pb^{-1}	1 TB
		p+p	200	3.8 pb^{-1}	85G	3.8 pb^{-1}	262 TB
06	2006	p+p	200	10.7 pb^{-1}	230G	10.7 pb^{-1}	310 TB
		p+p	62.4	0.1 pb^{-1}	28G	0.1 pb^{-1}	25 TB
07	2007	Au+Au	200	0.813 nb^{-1}	5.1G	33.7 pb^{-1}	650 TB
08	2008	d+Au	200	80 nb^{-1}	160G	32.1 pb^{-1}	437 TB
		p+p	200	5.2 pb^{-1}	115G	5.2 pb^{-1}	118 TB

Conical Emission

- Mach-cone shock wave
  - Shock waves excited by a supersonic parton.
  - Can be produced in different theories (Hydrodynamics, Colored plasma, AdS/CFT)
  - Cone angle: no dependence on a velocity of particle.
- Cherenkov gluon radiation
  - Radiation of gluon by superluminal parton.
  - Angle is dependent on the emitted momentum.

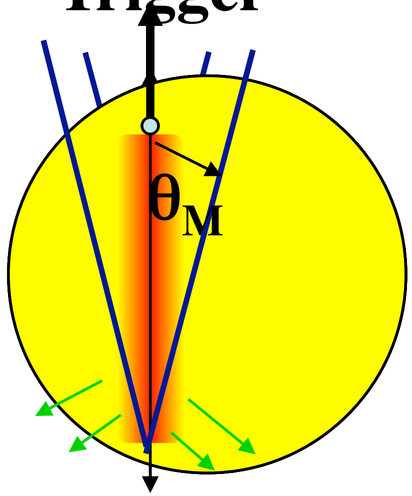


Mach-Cone Scenario

$$\frac{c_s}{v_{parton}} = \cos(\theta_M)$$

$$c_s^{\ 2} = \frac{\partial p}{\partial \varepsilon};\ v_{parton} \approx c$$

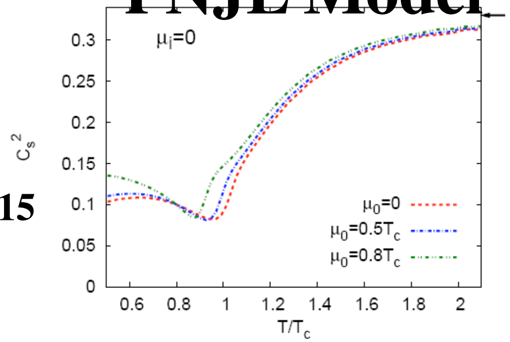
Trigger



Away-side

- **Mach angle depends on speed of sound in medium**
    - **Temp. dependent**
- **Angle independent of associated p_T.**

PNJL Model



Mikherjee, Mustafa, Ray

Phys. Rev. D75 (2007) 094015