Recent Results from the RHIC Heavy Ion Program

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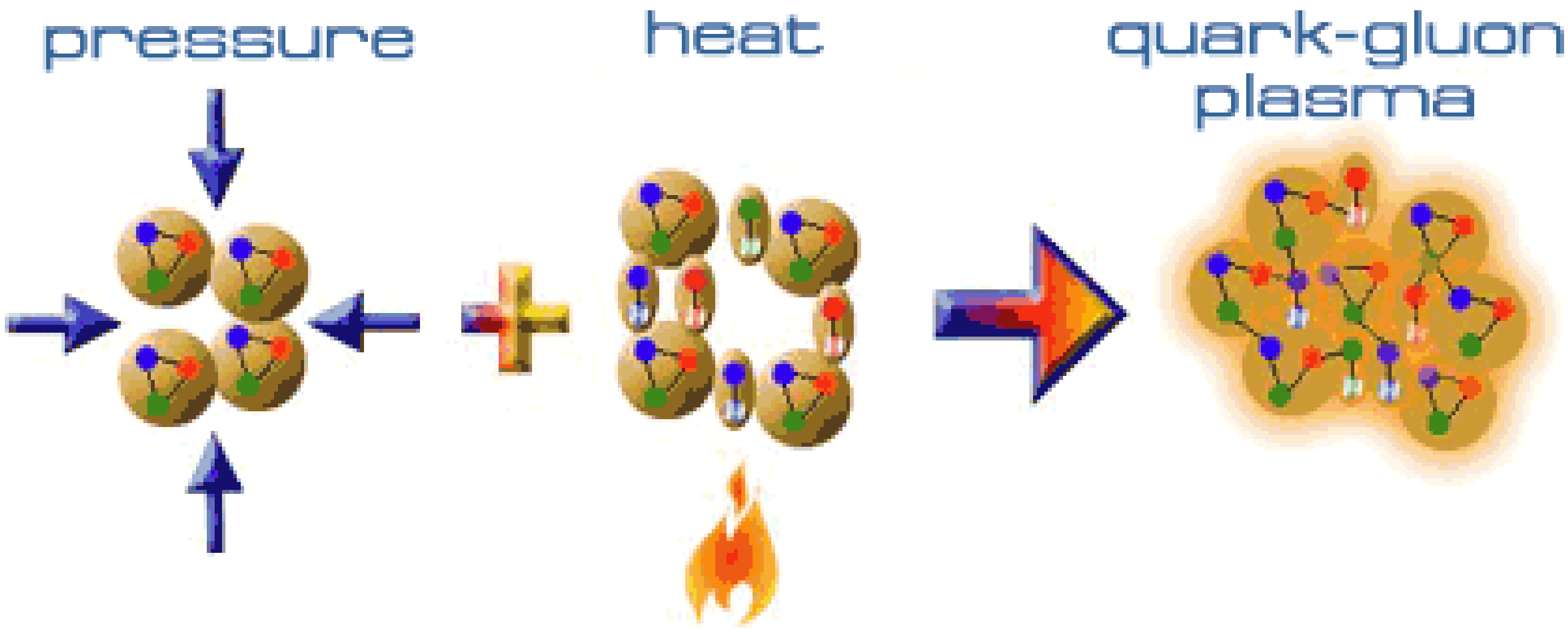
Outline

- Motivation and RHIC History
- Highlights of the Recent RHIC Results: Temperature Measurement of the Hot QCD Medium
- Outlook

Motivations

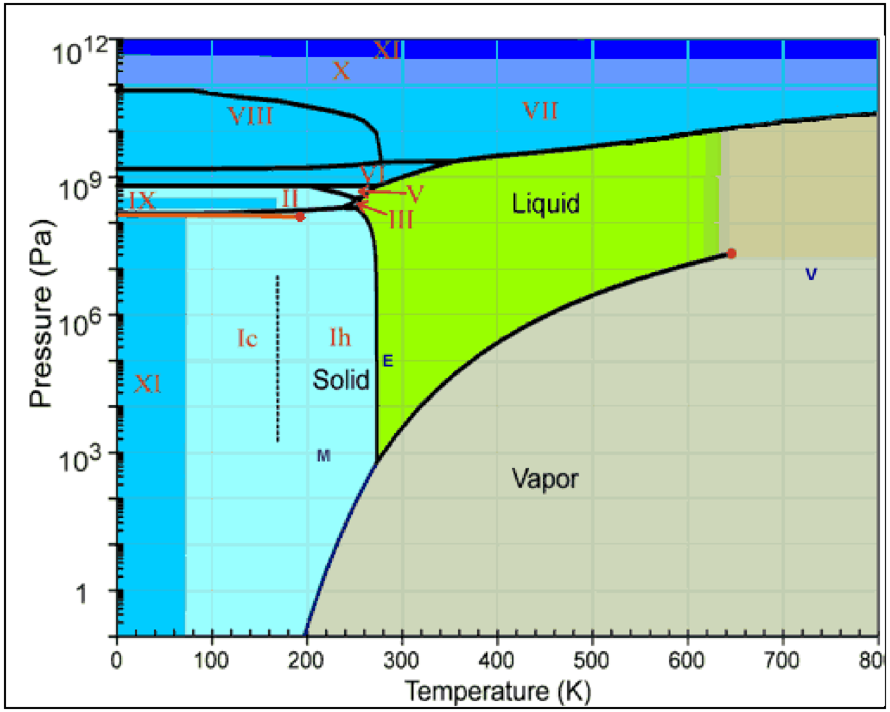


- **It is probably the only venue to study the properties of the high temperature and density QCD matter experimentally in a controlled laboratory – explore the QCD matter phase space.**
- **It also provides a laboratory-based test of the standard model of cosmology.**

Phase Diagram (H_2O) – We Have Done This!

A fundamental understanding requires the knowledge of

i) The location of the Critical End Point (CEP)
ii) The location of phase coexistence lines
iii) The properties of each phase

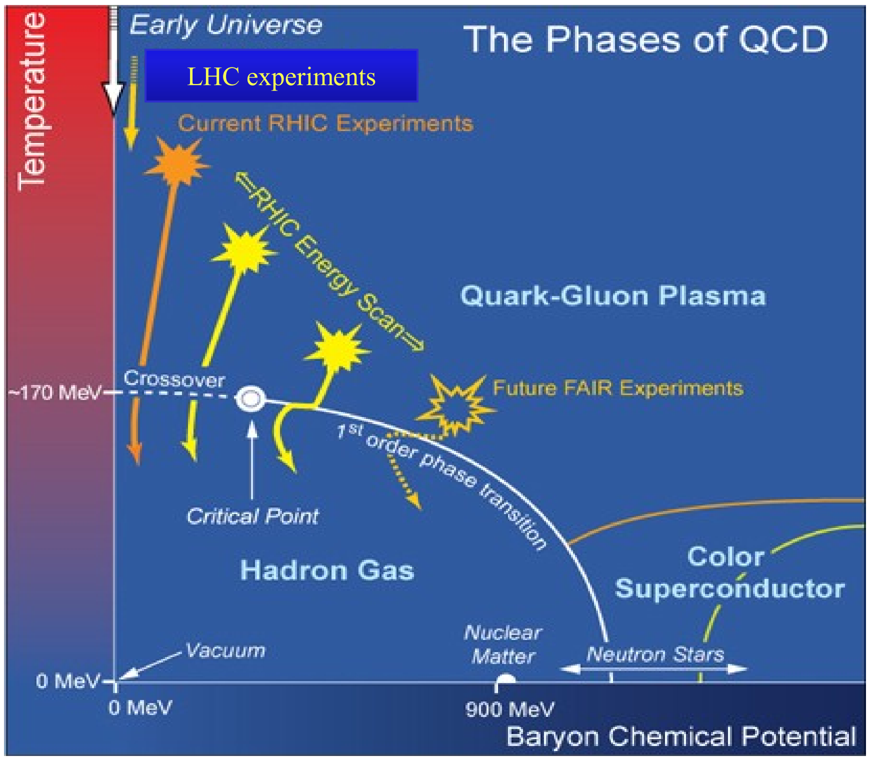


http://www.btinternet.com/~martin.chaplin/phase.html

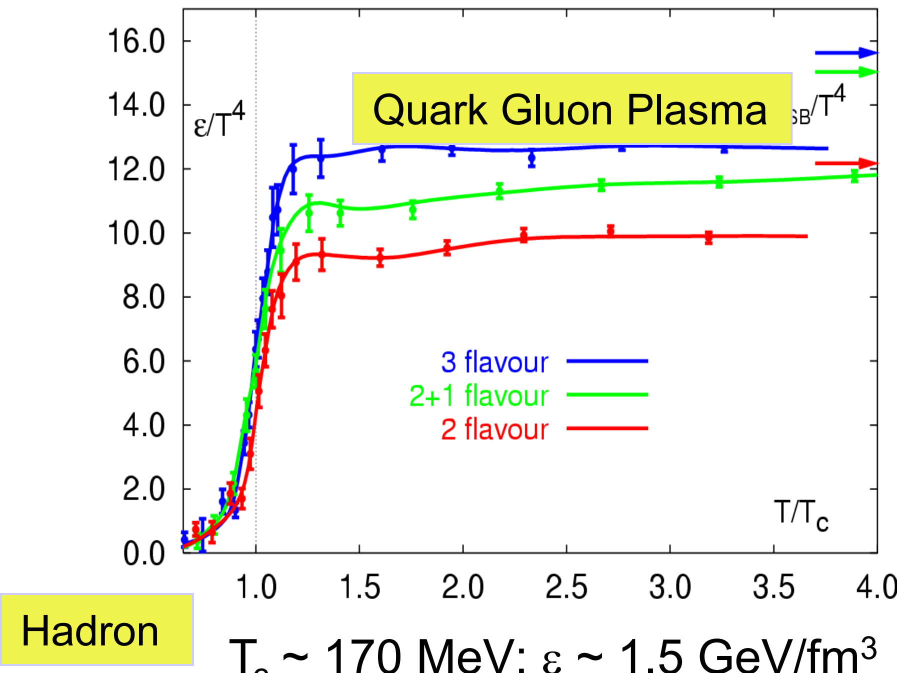
This knowledge is fundamental to the phase diagram of any substance !

Explore QCD Phase Space

- **The colliding nuclei at RHIC energies would melt from protons and neutrons into a collection of quarks and gluons**



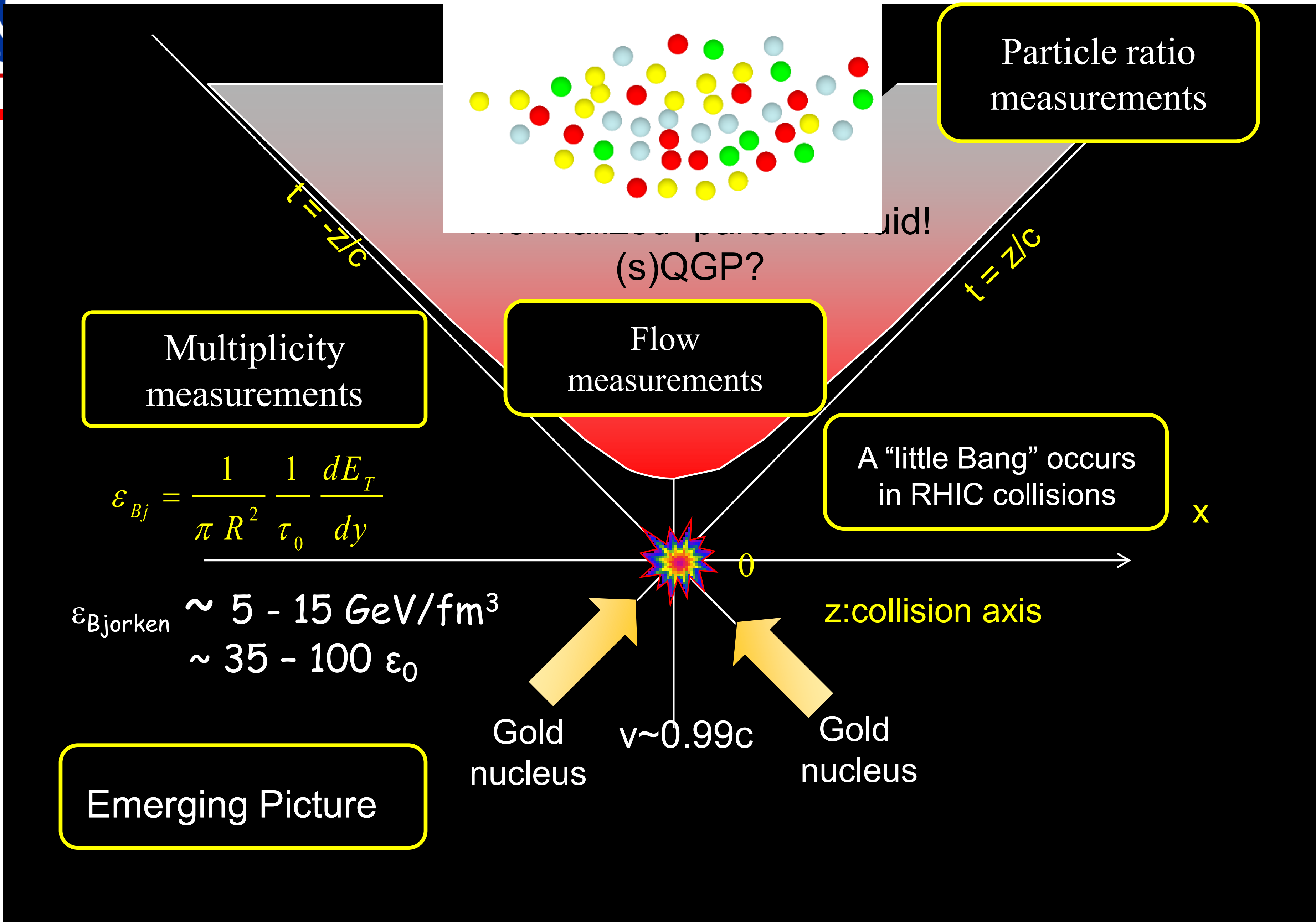
$$\varepsilon_{SB}(T) = \frac{\pi^2}{30}(N_{bosons} + 7/8\, N_{fermions})T^4$$



$T_c \sim 170$ MeV; $\varepsilon \sim 1.5$ GeV/fm^3

Measure the initial temperature of matter formed at RHIC

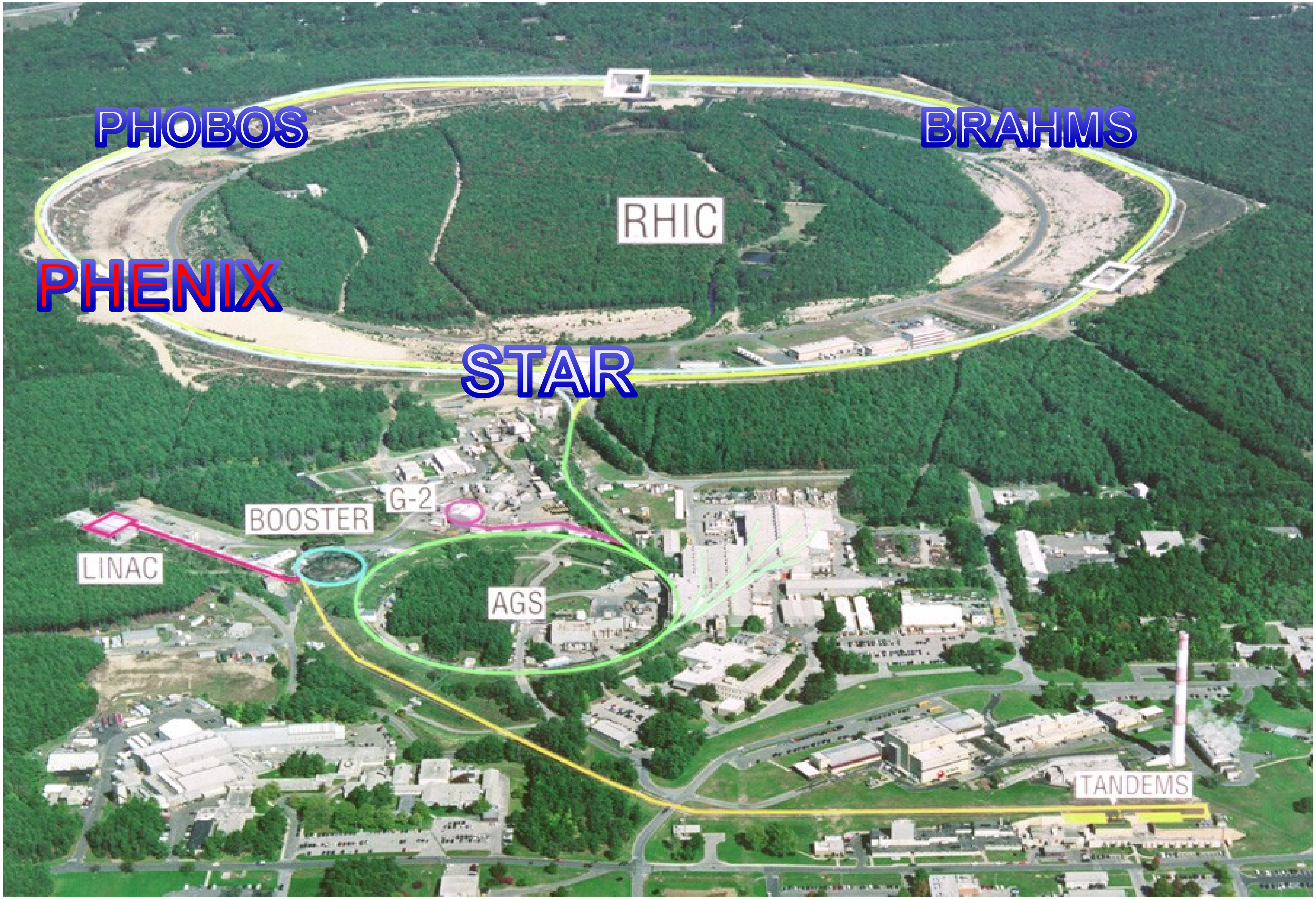
Is T_{init} higher than $T_c \sim 170$ MeV?

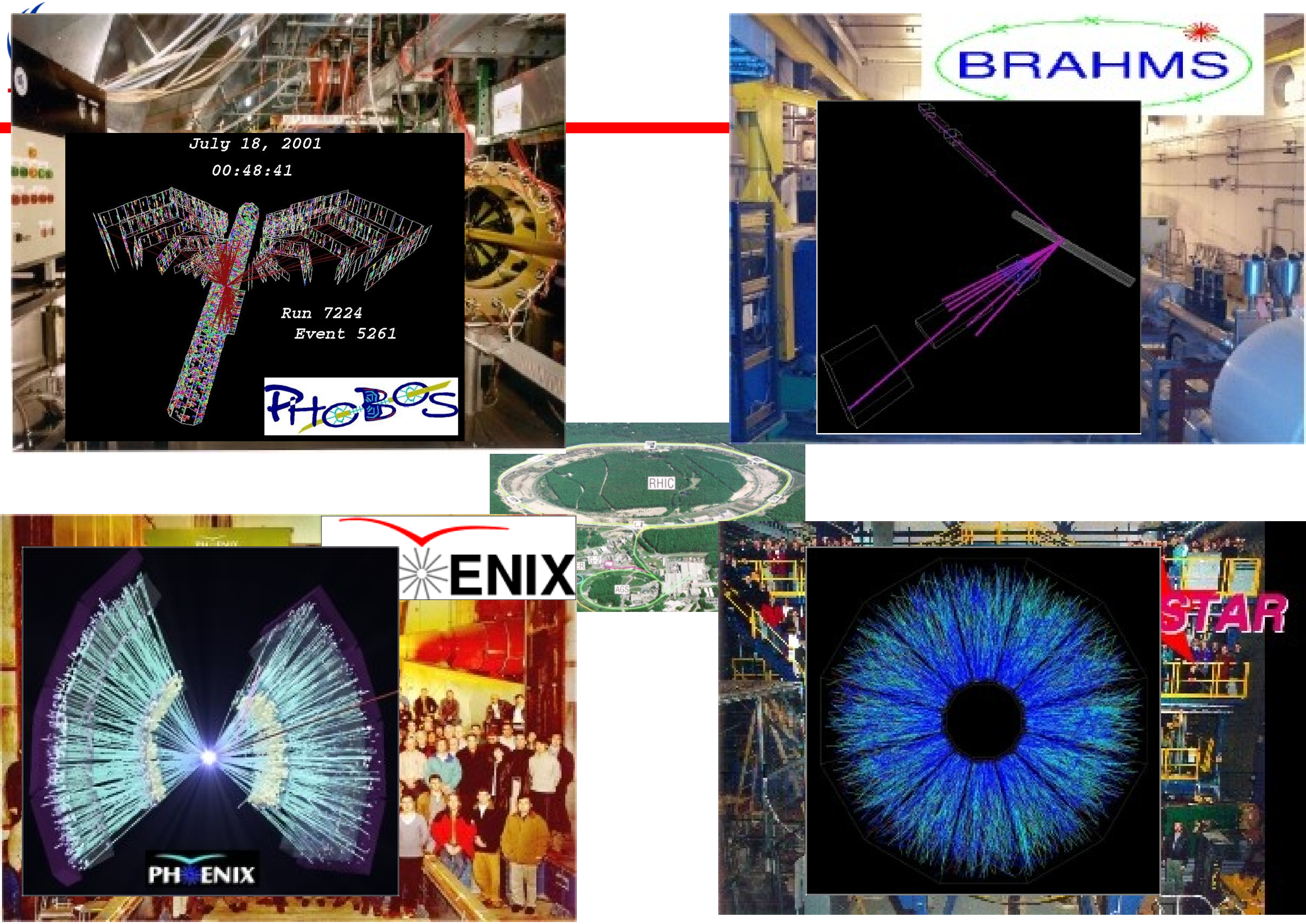

Particle ratio measurements
t = -z/c
t = z/c
(s)QGP?
Multiplicity measurements
Flow measurements
A “little Bang” occurs in RHIC collisions
x
$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$
0
$\varepsilon_{Bjorken}$ ~ 5 - 15 GeV/fm^3
~ 35 – 100 ε_0
z:collision axis
Gold nucleus
v~0.99c
Gold nucleus
Emerging Picture

Recreate the Matter State of the Early Universe

- Our expanding universe must have started out much hotter and denser than it is today because the expansion caused matter and energy to cool down and spread out with time.
- As the universe cooled down, it may have undergone a brief period of very rapid expansion known as inflation that could account for several key properties of today's universe.
- Temperatures shortly after the Big Bang were so hot that photons could change into elementary particles and vice versa. The early universe was therefore filled with photons and all kinds of elementary particles.
- After an age of 0.001 second, the universe became too cool to produce protons and antiprotons from pure energy. These particles then annihilated, leaving only a small fraction of the original protons left over.
- Up until 5 minutes after the Big Bang, the universe was still hot enough to fuse hydrogen into helium. The observed amount of helium in the universe agrees with predictions of the Big Bang theory.

RHIC Birdview




July 18, 2001
00:48:41
Run 7224
Event 5261
PHOBOS
BRAHMS
RHIC
AGS
ENIX
PHENIX
STAR

RHIC Run Summary

RHIC operating modes and total integrated luminosity delivered to 5 experiments

Run	species	total particle energy [GeV/nucleon]	calendar time in physics	total delivered luminosity	average store polarization
Run-1 CY2000 FY2000	Au^{79+}-Au^{79+}	27.9	3 shifts	< 0.001μb^{-1}	—
	Au^{79+}-Au^{79+}	65.2	5.3 weeks	20 μb^{-1}	—
Run-2 CY2001/02 FY2001/02	Au^{79+}-Au^{79+}	100.0	15.9 weeks	258 μb^{-1}	—
	Au^{79+}-Au^{79+}	9.8	2 shifts	0.4 μb^{-1}	—
	polarized p-p	100.0	8.3 weeks total, no continous physics operation	1.4 pb^{-1}	14%
Run-3 CY2002/03 FY2003	d-Au^{79+}	100.0	10.2 weeks	73 nb^{-1}	—
	polarized p-p	100.0	9.0 weeks total, no continous physics operation	5.5 pb^{-1}	34%
Run-4 CY2003/04 FY2004	Au^{79+}-Au^{79+}	100.0	12.0 weeks	3.53 nb^{-1}	—
	Au^{79+}-Au^{79+}	31.2	9 days	67 μb^{-1}	—
	polarized p-p	100.0	6.1 weeks total, no continous physics operation	7.1 pb^{-1}	46%
Run-5 CY2004/05 FY2005	Cu^{29+}-Cu^{29+}	100.0	7.8 weeks	42.1 nb^{-1}	—
	Cu^{29+}-Cu^{29+}	31.2	12 days	1.5 nb^{-1}	—
	Cu^{29+}-Cu^{29+}	11.2	5 shifts	0.02 nb^{-1}	—
	polarized p-p	100.0	9.4 weeks	29.5 pb^{-1}	47%
	polarized p-p	204.9	2 stores	0.1 pb^{-1}	30%
Run-6 CY2006 FY2006	polarized p-p	100.0	13.1 weeks	88.6 pb^{-1}	55%
	polarized p-p	31.2	12 days	1.05 pb^{-1}	50%
Run-7 CY2006/07 FY2006	Au^{79+}-Au^{79+}	100.0	12.8 weeks	7.25 nb^{-1}	—
	Au^{79+}-Au^{79+}	4.6	3 shifts total, no continous physics operation	test only	—
Run-8 CY2007/08 FY2008	d-Au^{79+}	100.0	9.0 weeks	437 nb^{-1}	—
	polarized p-p	100.0	3.4 weeks	38.4 pb^{-1}	44%
	Au^{79+}-Au^{79+}	4.6	3 shifts	—	—
Run-9 CY2008/09 FY2009	pol. p-p	250.0	4.1 weeks	110.4 pb^{-1}	34%
	polarized p-p	100.0	9.9 weeks	114.0 pb^{-1}	56%
	polarized pp2pp	100.0	3.5 days	0.6 nb^{-1}	63%
Run-10 CY2009/10 FY2010	Au^{79+}-Au^{79+}	100.0	10.9 weeks	10.0 nb^{-1}	—
	Au^{79+}-Au^{79+}	31.2	2.9 weeks	0.56 nb^{-1}	—
	Au^{79+}-Au^{79+}	19.5			—
	Au^{79+}-Au^{79+}	3.85			—
	Au^{79+}-Au^{79+}	5.75			—

BRIEF HIGHLIGHTS

RHIC White Papers

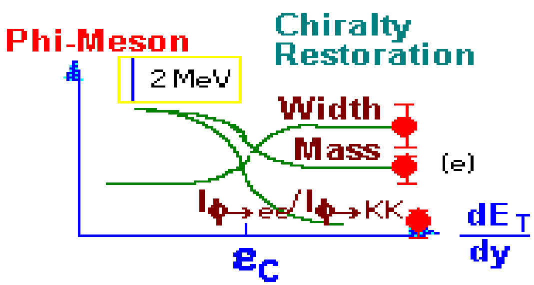
RHIC Experimental Evaluations			
Hunting the Quark Gluon Plasma Assessments by the experimental collaborations Results from the first 3 years at RHIC April 18, 2005 From the BNL "High Energy & Nuclear Physics Directorate" site as one PDF file .			
Published versions			
BRAHMS	PHENIX	PHOBOS	STAR
Nuclear Physics A Volume 757, Issues 1-2 , 8 August 2005, Pages 1-27	Nuclear Physics A Volume 757, Issues 1-2 , 8 August 2005, Pages 184-283	Nuclear Physics A Volume 757, Issues 1-2 , 8 August 2005, Pages 28-101	Nuclear Physics A Volume 757, Issues 1-2 , 8 August 2005, Pages 102-183

SPIRES Citation Report as of Nov. 30, 2010:

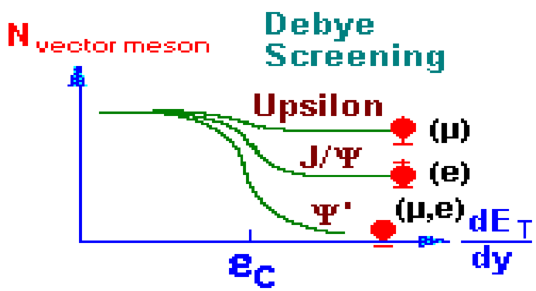
739	971	758	979

What We Set Out to Measure?

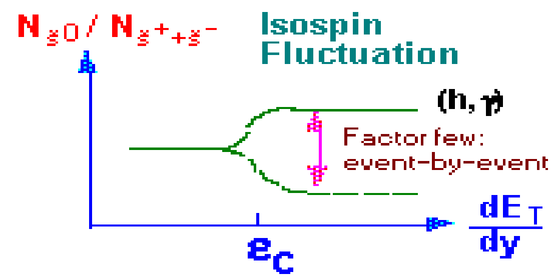
Theorists predicted a number of signals that might abruptly manifest themselves as soon as we crossed the critical Temp. & density for the phase transition



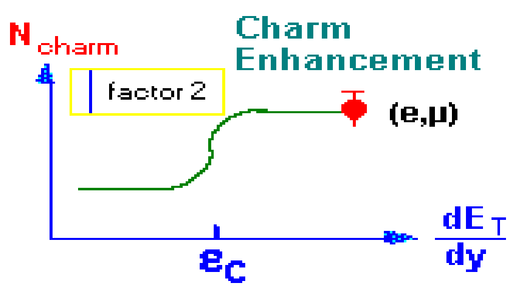
Change in mass, width of ϕ meson



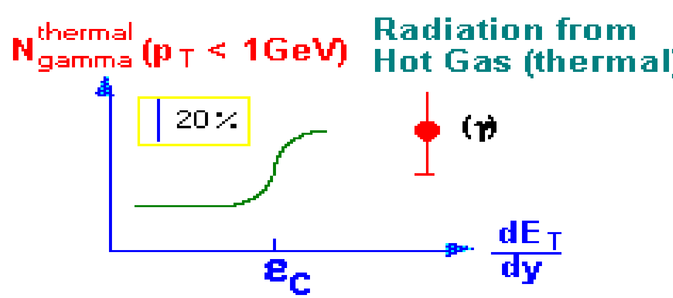
Disappearance of J/ψ



Change in pion charged/neutral



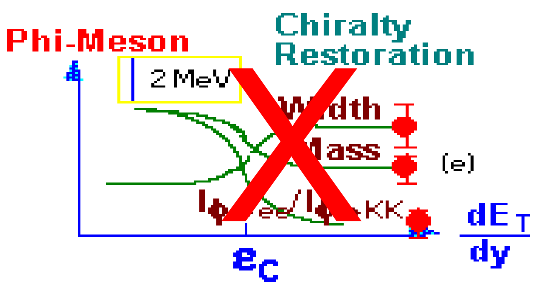
More particles containing the heavy charm quark



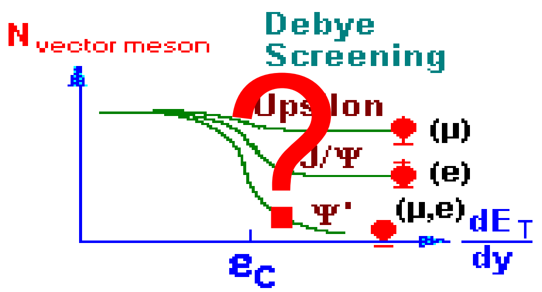
Increase in # of photons @ low momentum

How Did We Do on the Predictions?

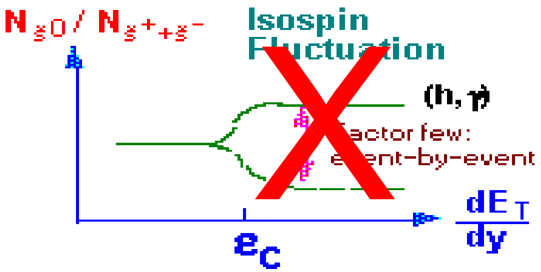
Theorists predicted a number of signals that might abruptly manifest themselves as soon as we crossed the critical Temp. & density for the phase transition



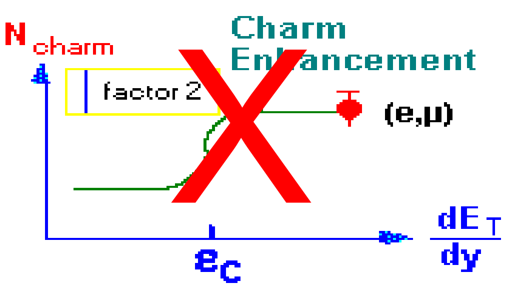
Change in mass, width of ϕ meson



Disappearance of J/ψ



Change in pion charged/neutral



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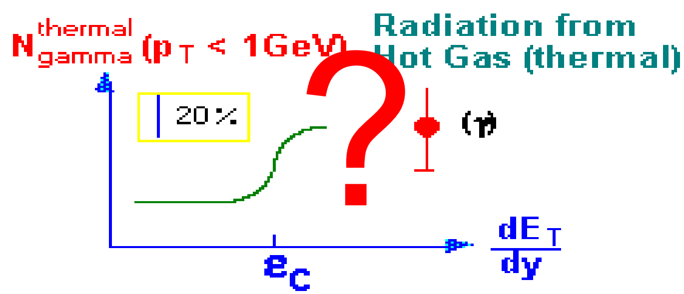
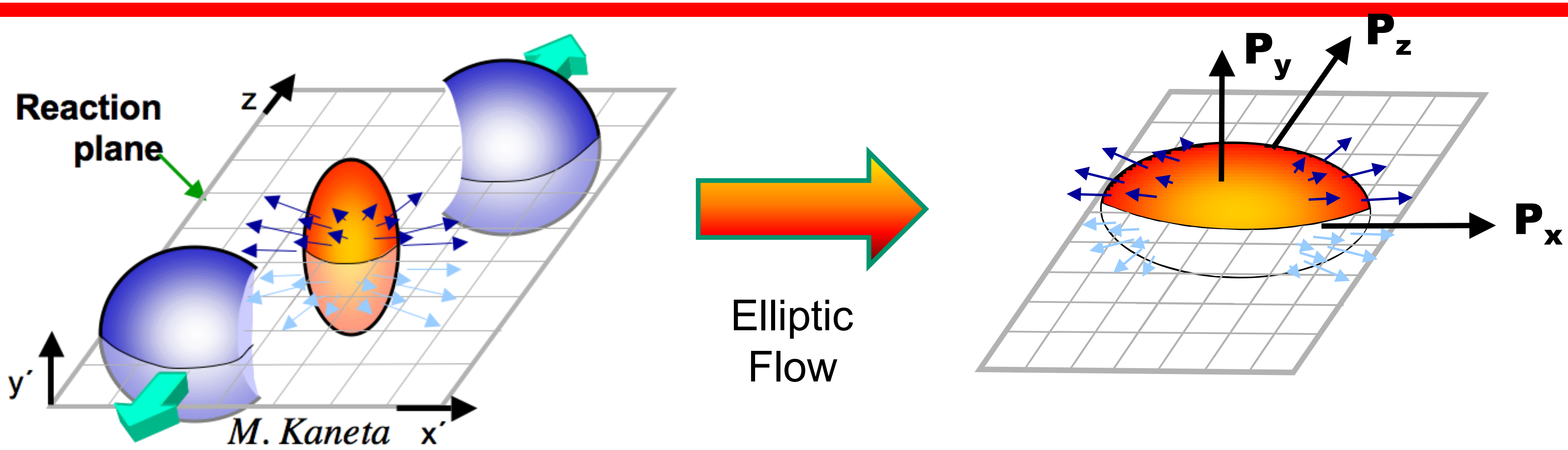


Increase in # of photons @ low momentum

Reaction Plane and Elliptic Flow



Spatial anisotropy

Momentum anisotropy

Fourier expansion of the distribution of produced particle angle wrt reaction plane ($\Delta\phi$):

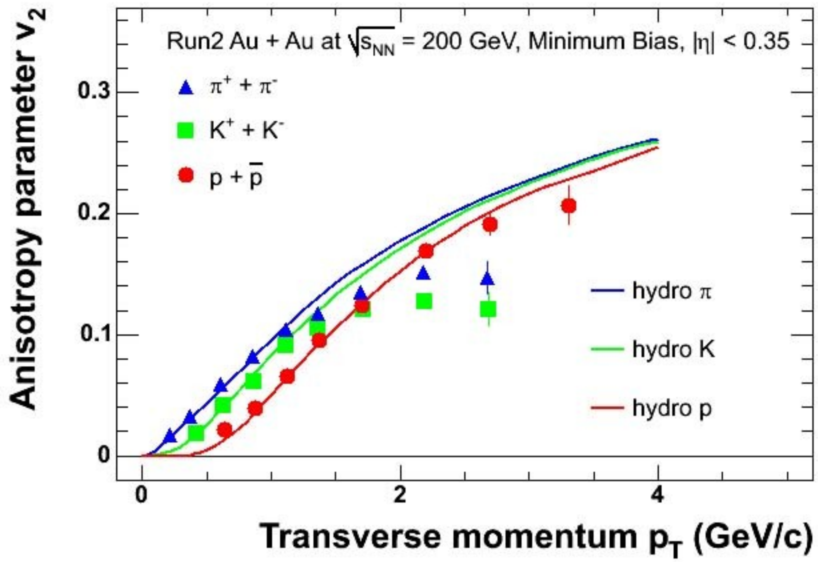
$$\frac{dN}{d\Delta\varphi} = N_0\left[1 + 2v_1 \cos\ 2\Delta\varphi + 2v_2 \cos\ 2\Delta\varphi + \cdots\right]$$

- Momentum anisotropy reflects the characteristics of the hot, dense medium
  - Small mean free path, thermalization, pressure gradients
- v_2 long considered a powerful probe for QGP studies

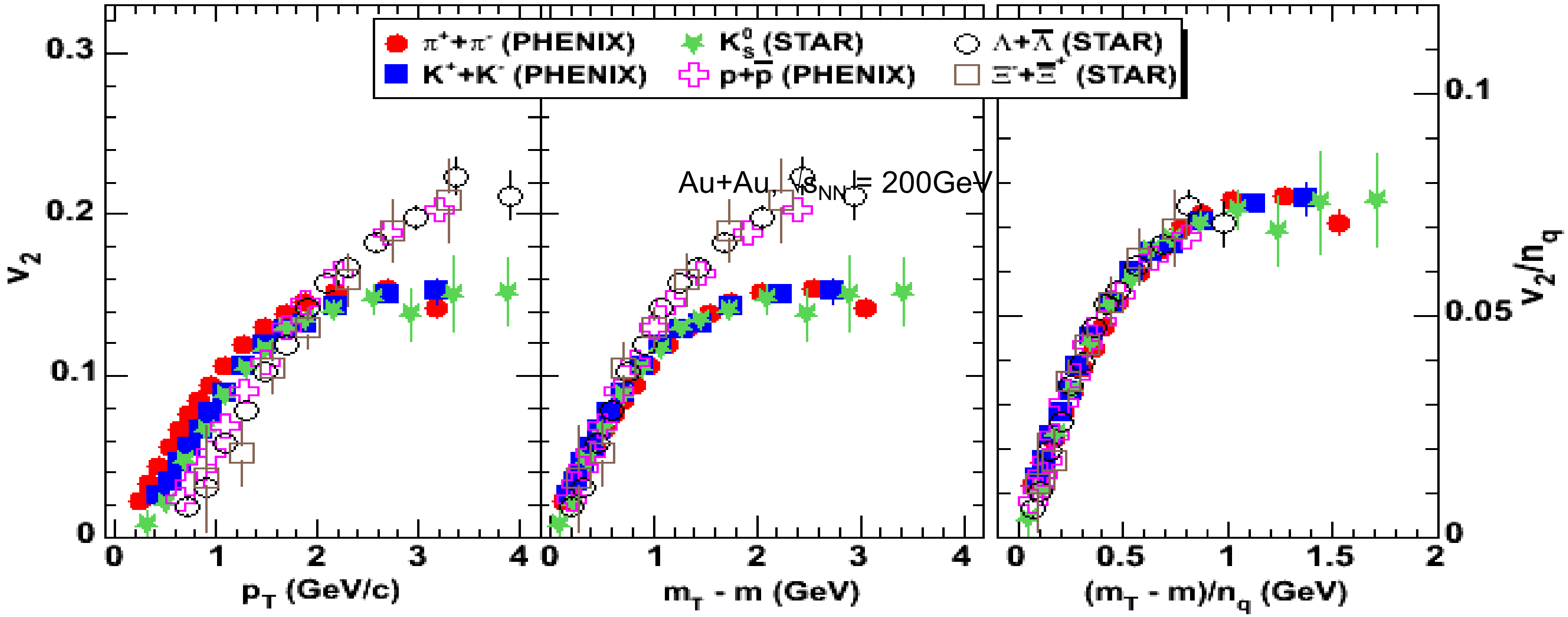
A Classic Result: v_2

- Large v_2 has been observed at RHIC
- v_2 at low p_T (~1.5 GeV/c) predicted by hydrodynamical models
- Results suggest early thermalization (~0.6 fm/c) and quark flow

PHENIX PRL 91, 182301 (2003)

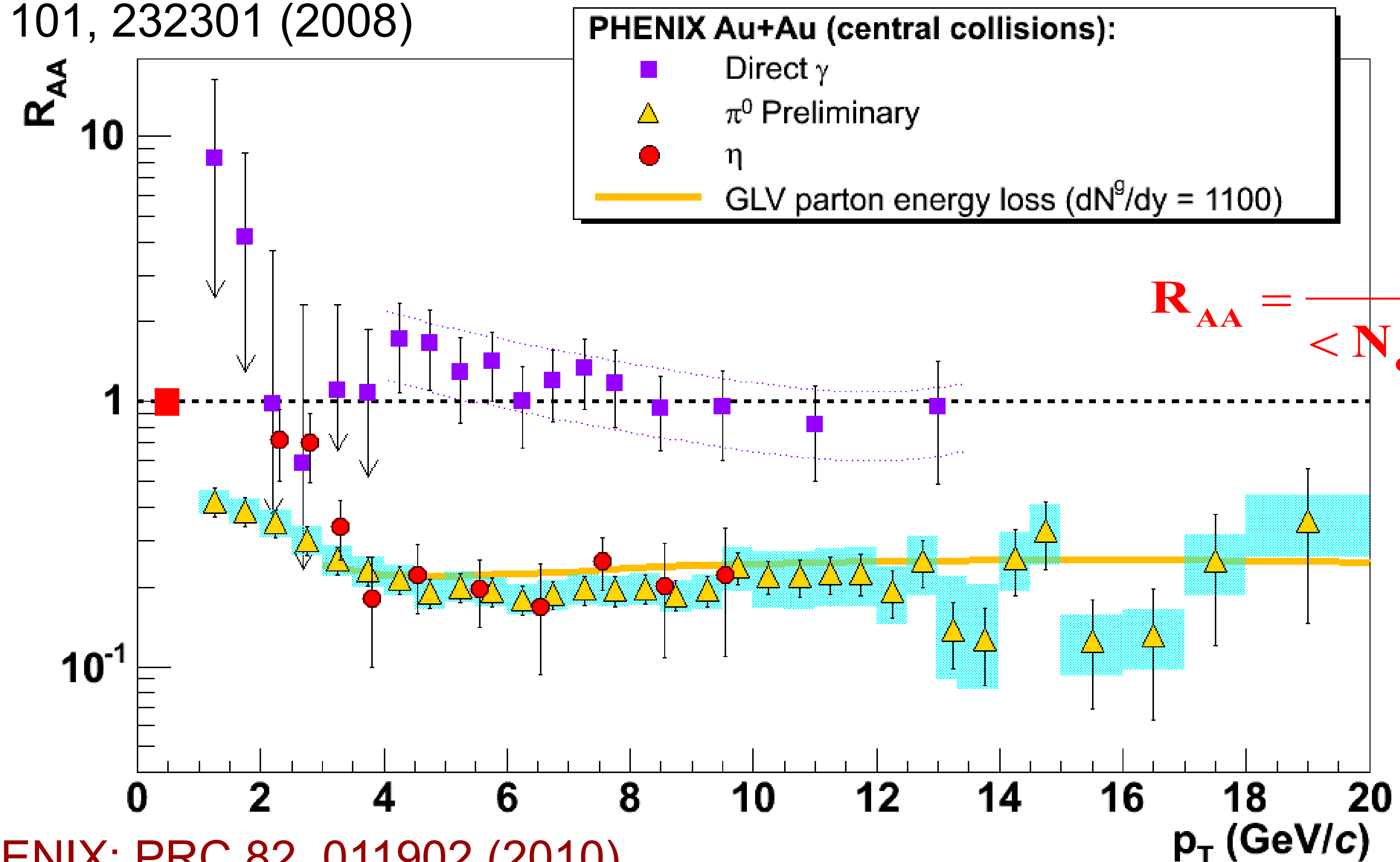


PHENIX PRL. 98, 162301 (2007)



The matter is so opaque that even a 20 GeV π^0 is stopped.

PRL 101, 232301 (2008)



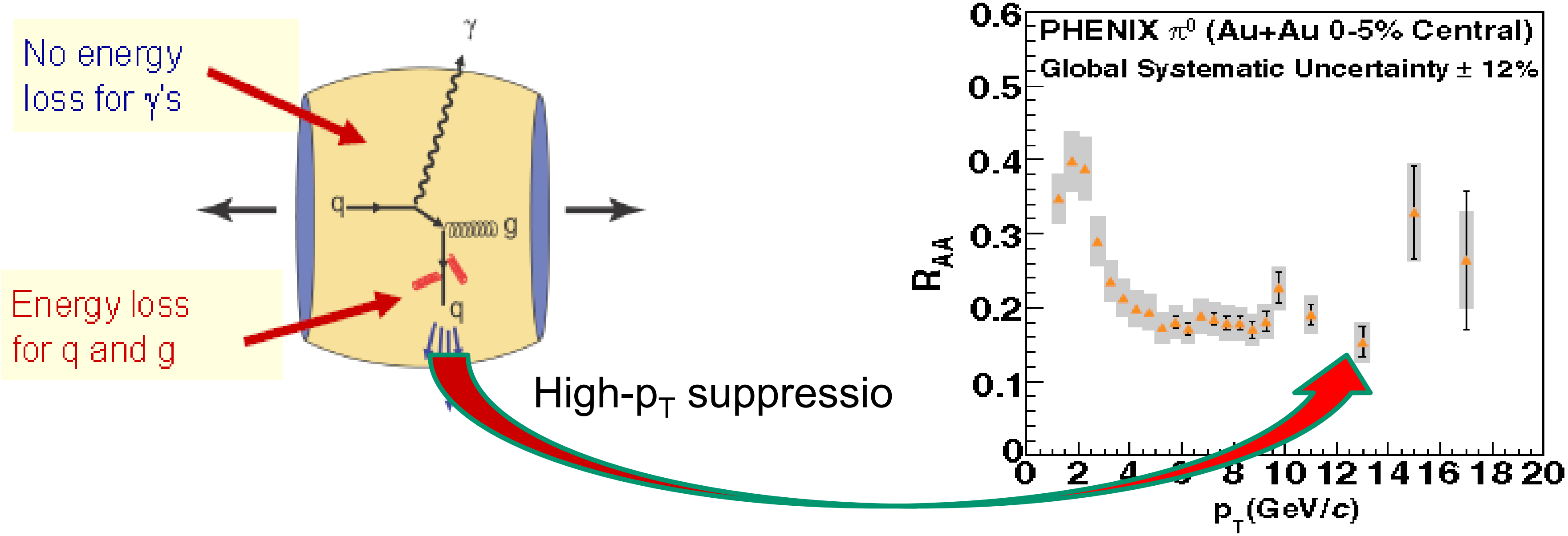
$$R_{AA} = \frac{dN_{AA}}{< N_{coll} > \times dN_{pp}}$$

PHENIX: PRC 82, 011902 (2010)

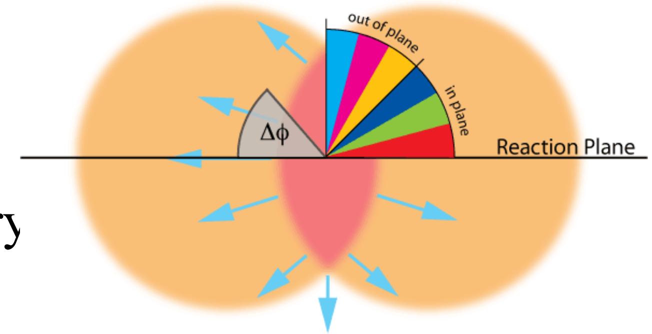
- Suppression is very strong (R_{AA}=0.2!) and flat up to 20 GeV/c
- Common suppression for π^0 and η; it is at partonic level
- $\varepsilon > 15$ GeV/fm^3; $dN_g/dy > 1100$

High-p_T: Domain of hard-scattering

Phys. Rev. C 77, 064907 (2008)

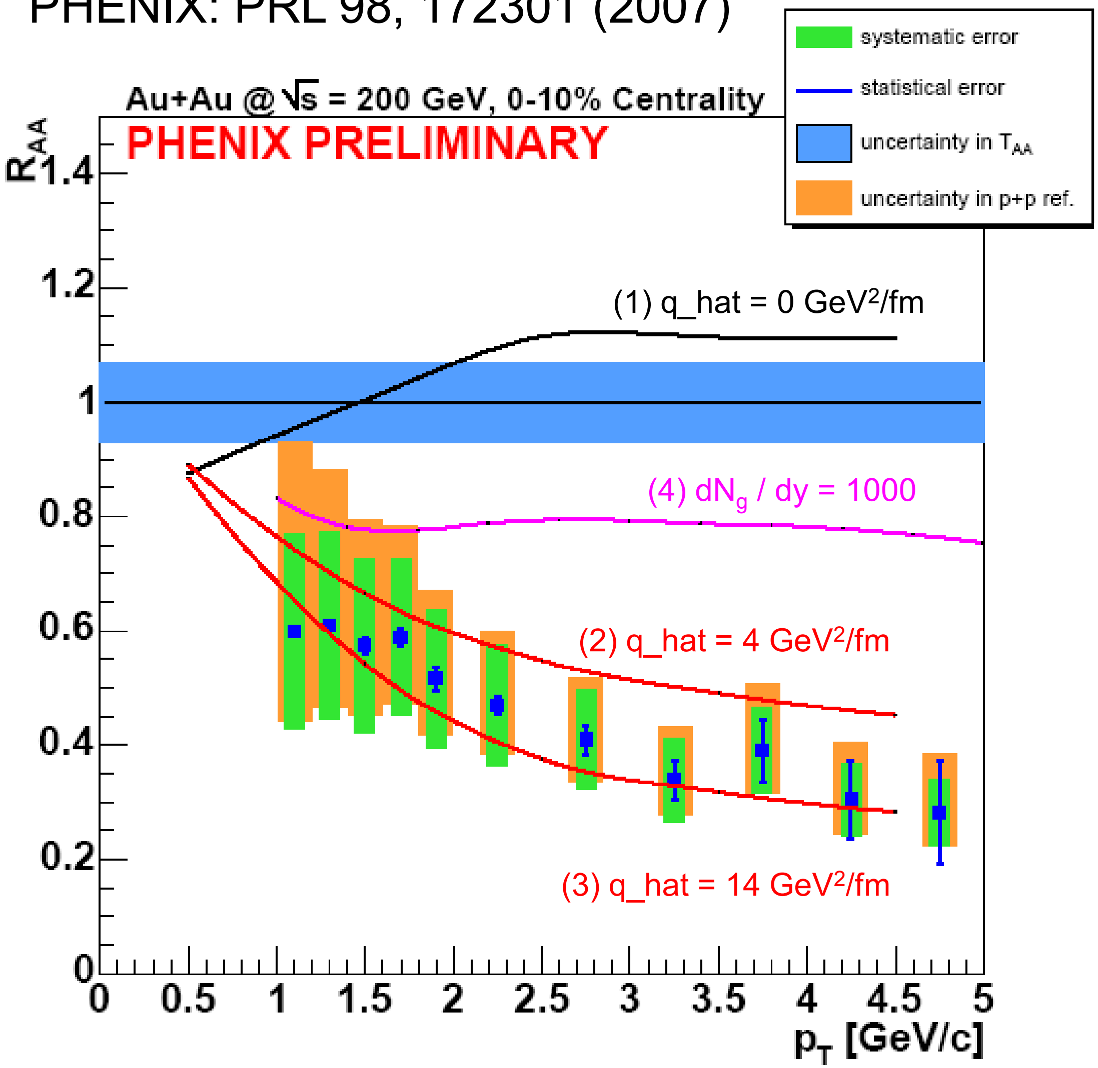


- Jets are quenched
  - But what are the details of the quenching?
- RP to the "rescue"
  - Centrality studies help to constrain the geometry
  - Angle with respect to RP: fix the path length!



The matter is so dense that even heavy quarks are stopped

PHENIX: PRL 98, 172301 (2007)



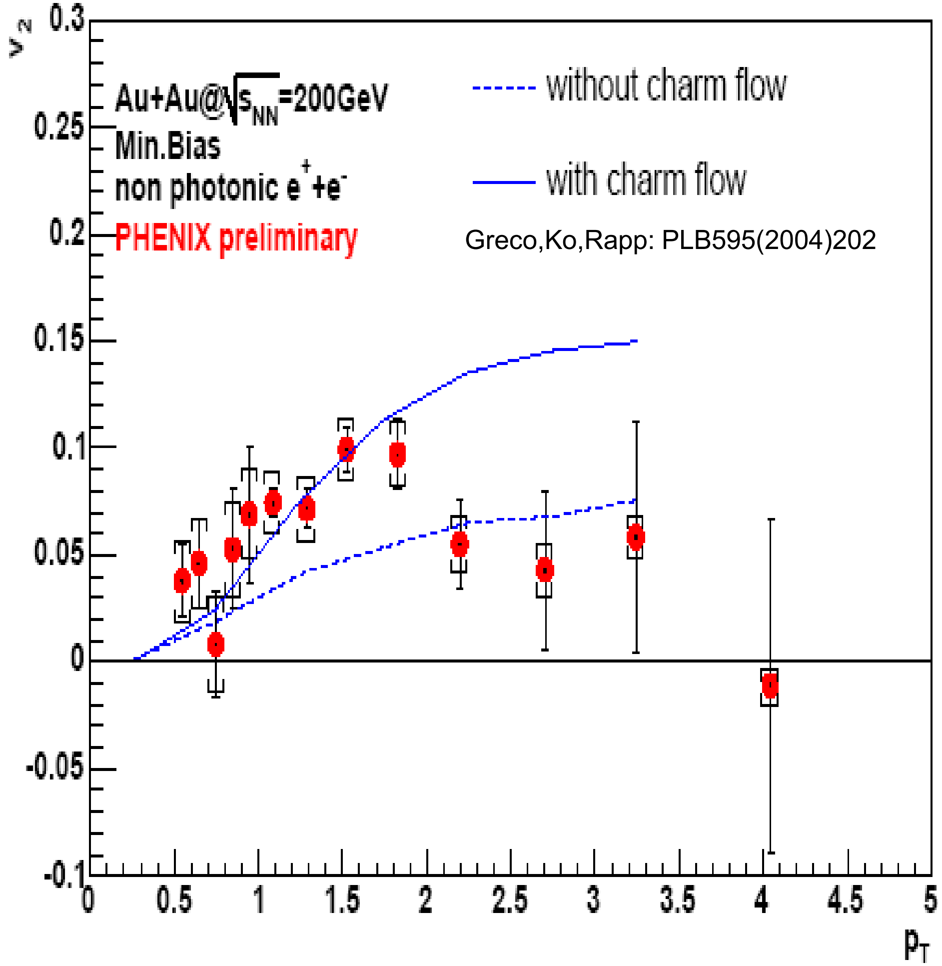
Even heavy quark (charm) suffers substantial energy loss in the matter

The data provide a strong constraint on the energy loss models.

The data suggest large c-quark-medium cross section; evidence for strongly coupled QGP.

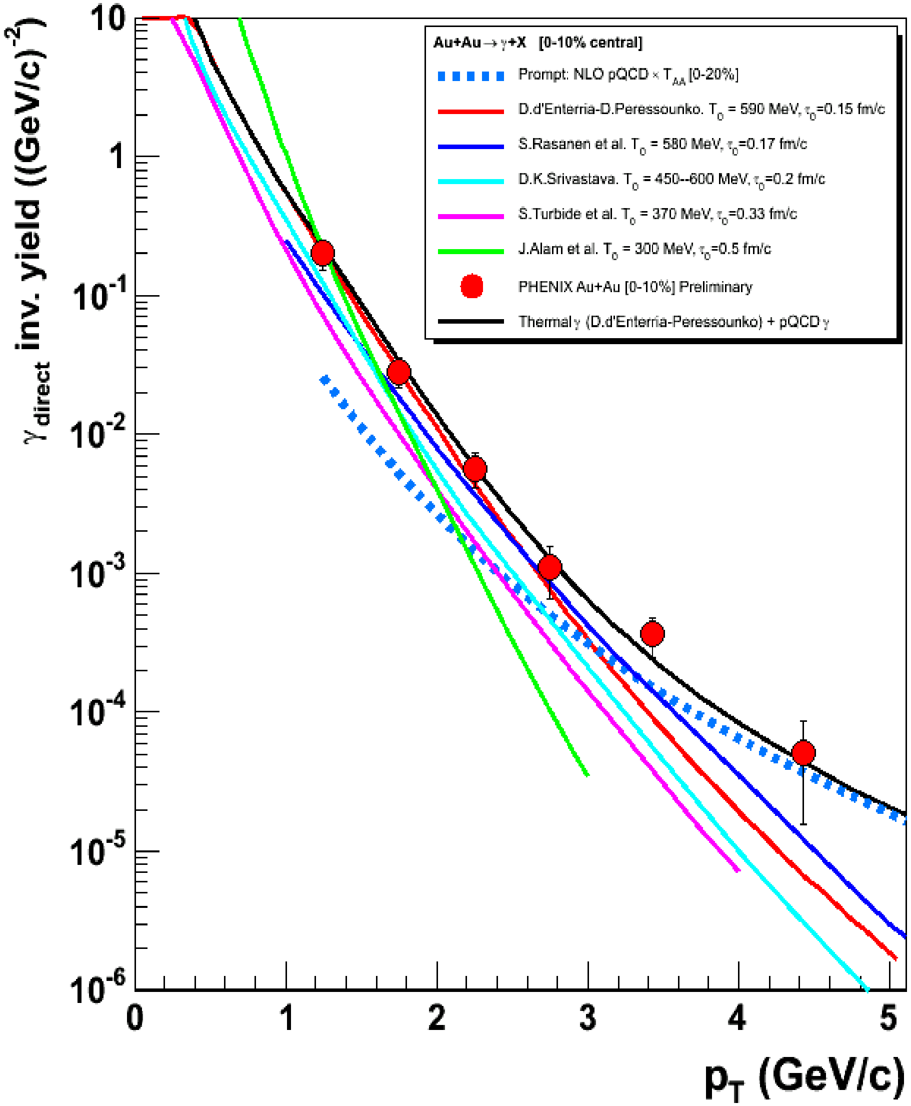
The matter is so strongly coupled that even heavy quarks flow

PHENIX: PRL 98, 172301 (2007)



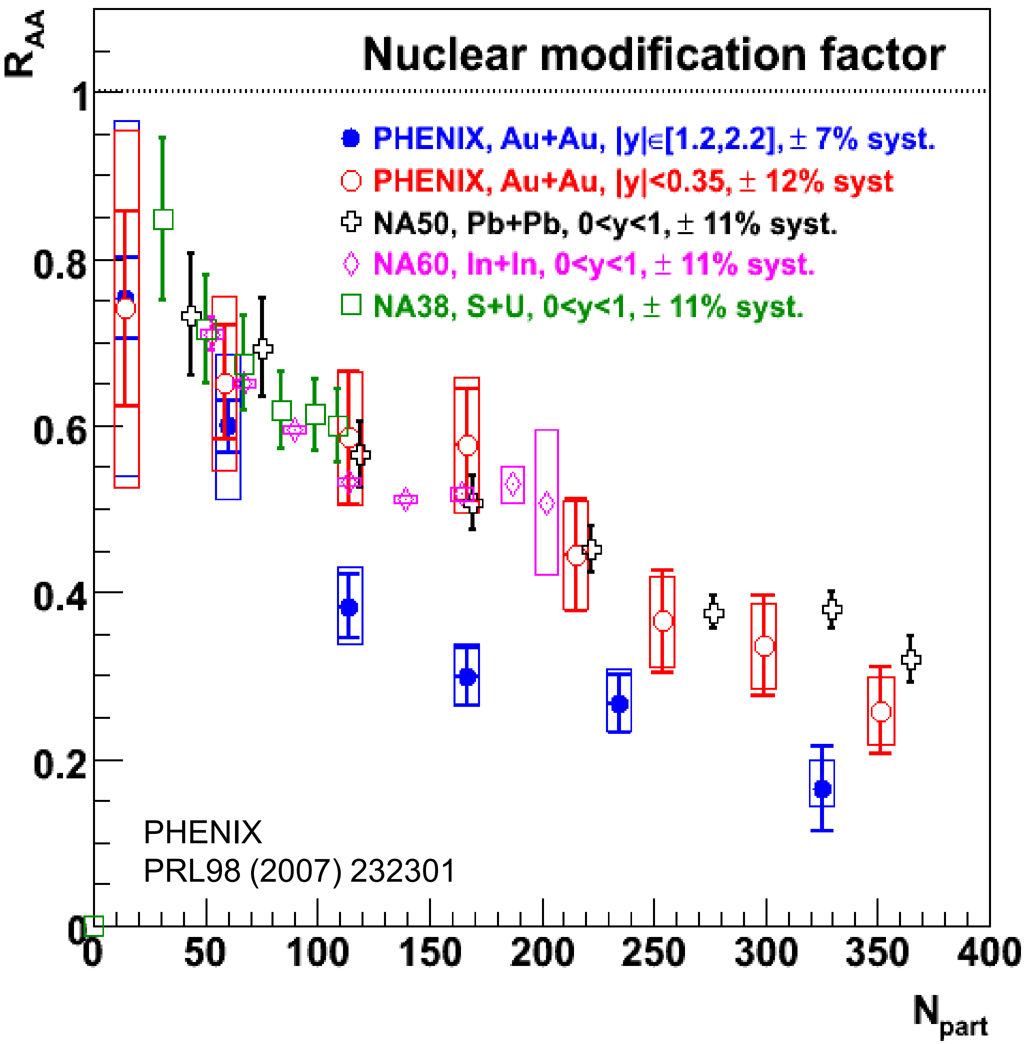
- Charm flows, but not as strong as light mesons.
- Drop of the flow strength at high p_T. Is this due to b-quark contribution?
- The data favors the model that charm quark itself flows at low p_T.
- Charm flow supports high parton density and strong coupling in the matter. It is not a weakly coupled gas.

The matter is so hot that it emits (thermal?) photon copiously



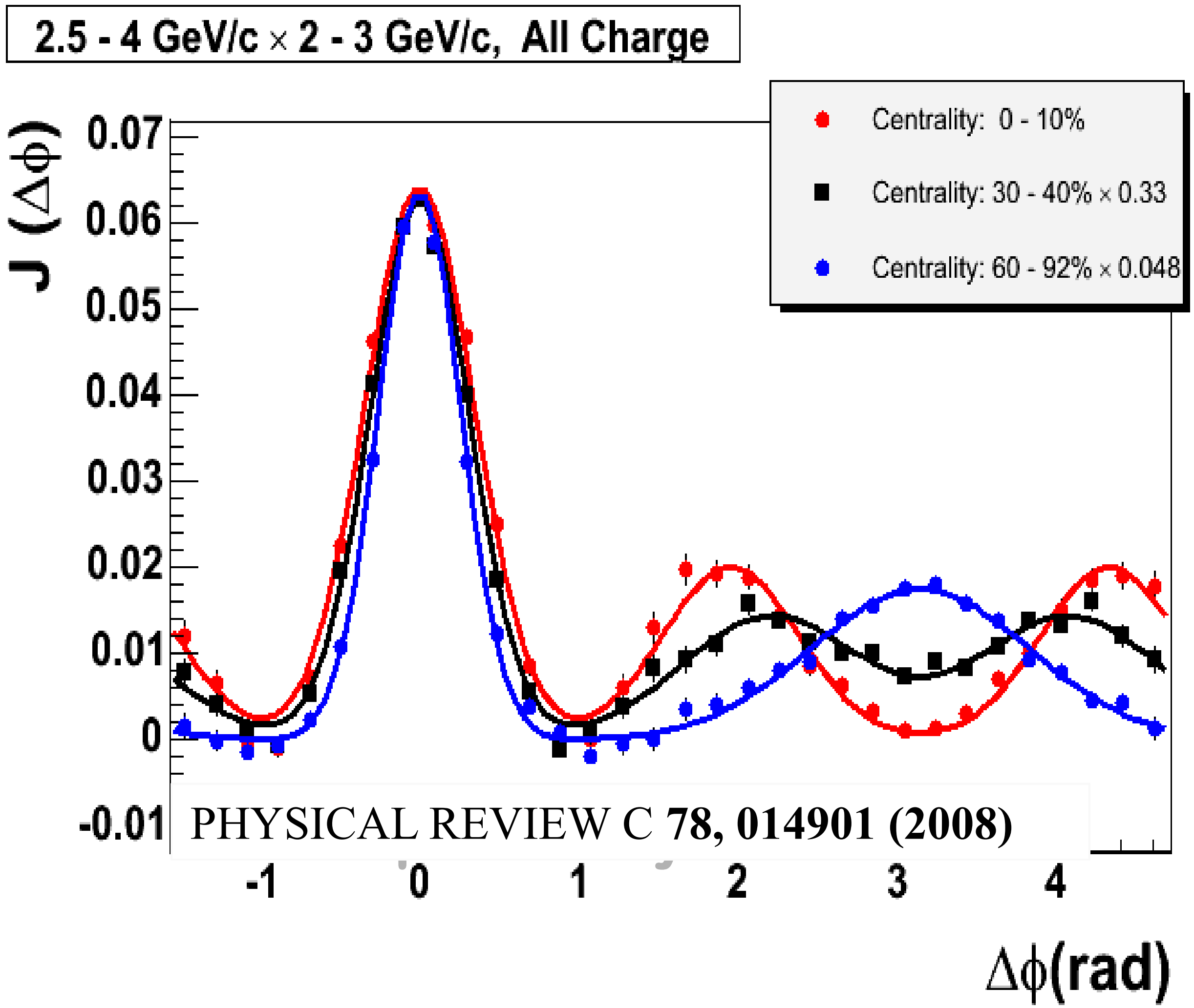
- The first promising result of direct photon measurement at low p_T from low-mass electron pair analysis.
- Are these thermal photons? The rate is above pQCD calculation. The method can be used in *p+p* collisions.
- If it is due to thermal radiation, the data can provide the first direct measurement of the initial temperature of the matter.
- What is the temperature?

The matter is so dense that it melts(?) J/ψ (and regenerates it ?)



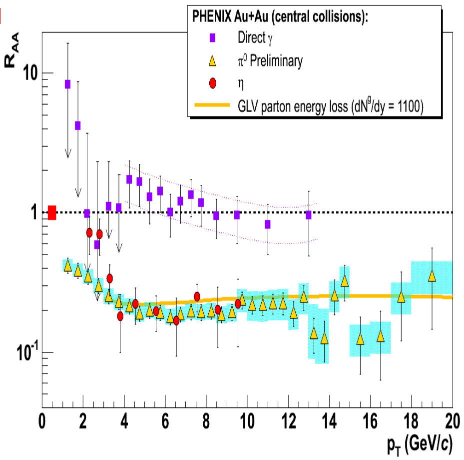
- Suppression is substantially stronger at y=1.7 than at y=0.
- Not expected if suppression increases with energy density.
- There have been attempts to explain this as being due to coalescence of charm pairs in the medium, or at hadronization.
- But SPS (17.3 GeV!) Pb+Pb J/ψ data show comparable suppression at y~0.5 to PHENIX at y~ 0.

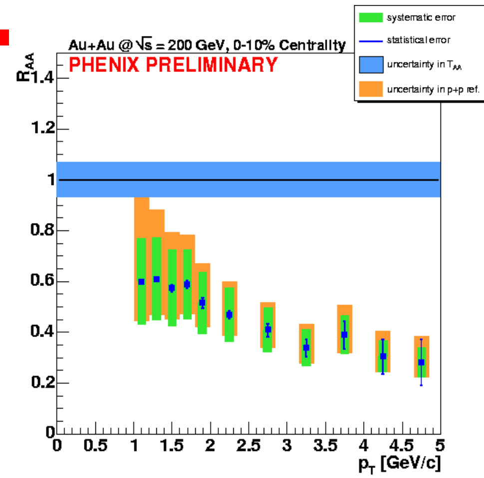
The matter is so dense that it modifies the shape of jets

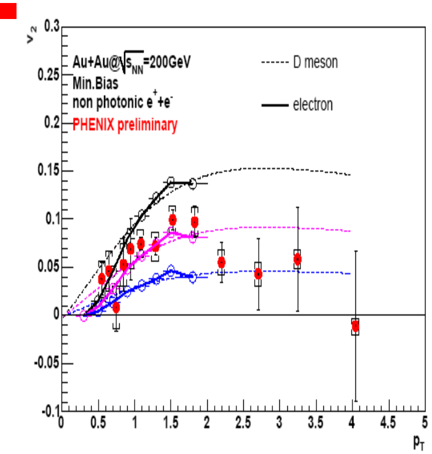


- The shapes of jets are modified by the matter.
  - Mach cone?
  - Cerenkov?
- Can the properties of the matter be measured from the shape?
  - Sound velocity
  - Di-electric constant
- Di-jet tomography is a powerful tool to probe the matter

Put the Results Together

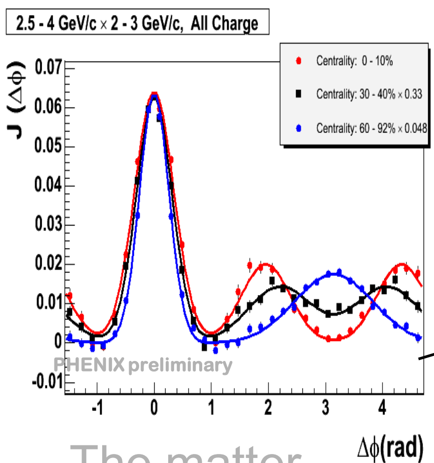






The matter is dense

The matter is strongly coupled



$\varepsilon > 15\ \text{GeV/fm}^3$

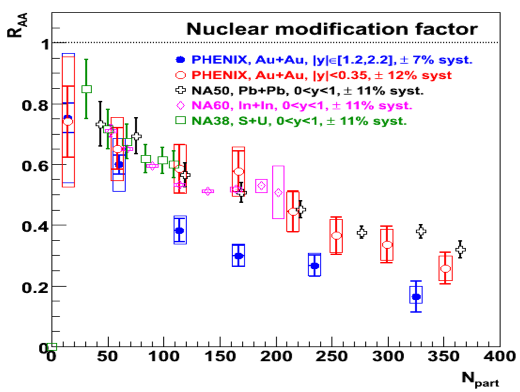
$dN_g/dy > 1100$

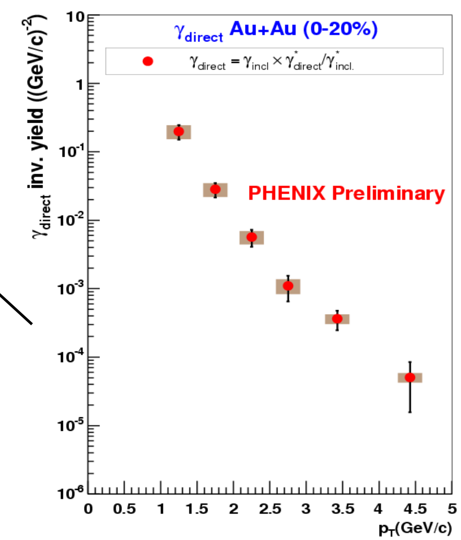
Temperature?

T_{ave} = 300 - 400 MeV (?)

Vs = ?

The matter modifies jets





The matter may melt but regenerate J/ψ's

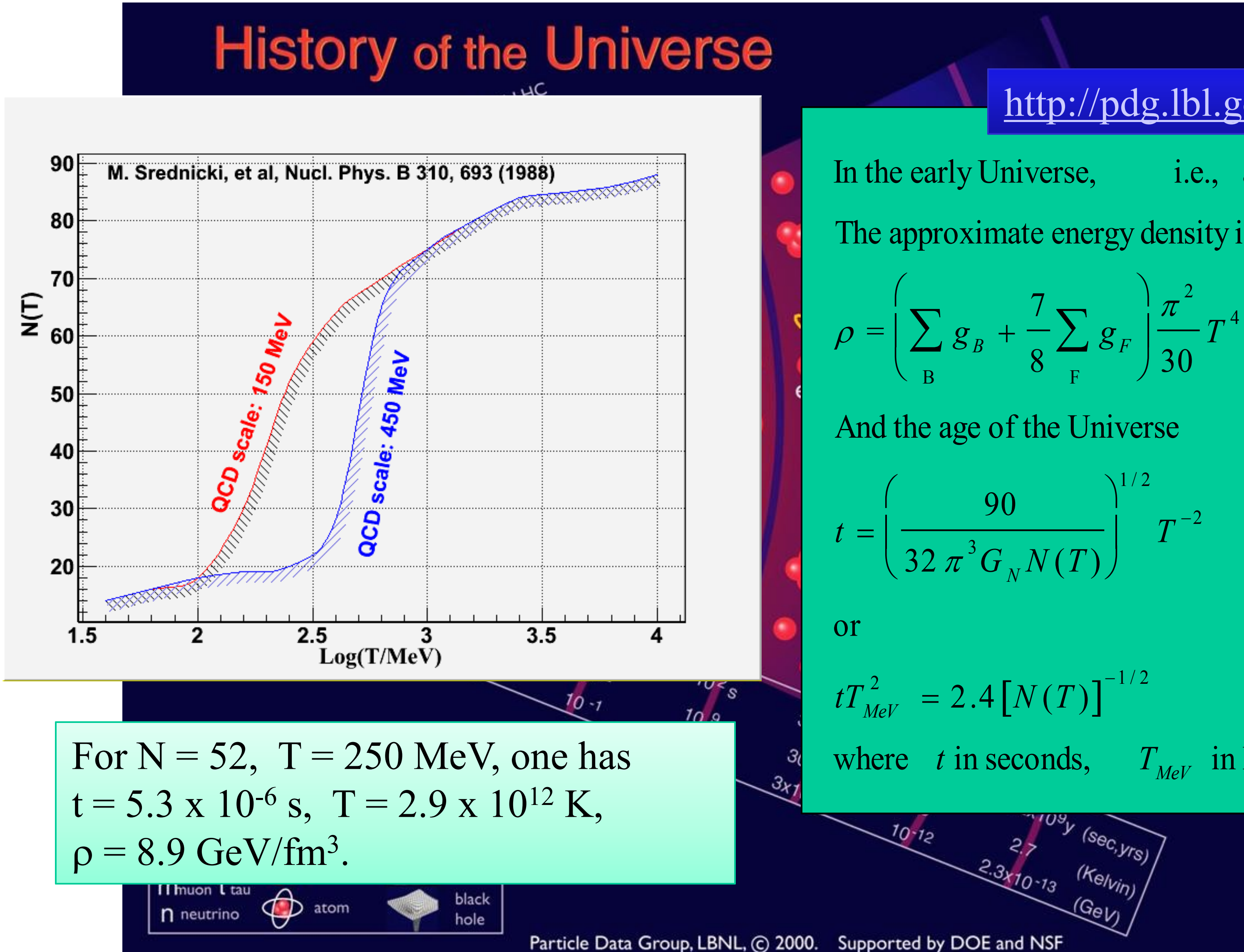
The matter is hot

Phys. Rev. Lett. 104, 132301 (2010)

"Enhanced production of direct photons in Au+Au collisions at sqrt(s_NN)=200 GeV and implications for the initial temperature"

TEMPERATURE MEASUREMENT

Temperature is an Important Physical Variable in the Standard Model in Cosmology



http://pdg.lbl.gov

In the early Universe, i.e., at very high T :

The approximate energy density is given as

$$\rho = \left(\sum_B g_B + \frac{7}{8} \sum_F g_F \right) \frac{\pi^2}{30} T^4 \equiv \frac{\pi^2}{30} N(T) T^4$$

And the age of the Universe

$$t = \left(\frac{90}{32 \pi^3 G_N N(T)} \right)^{1/2} T^{-2}$$

or

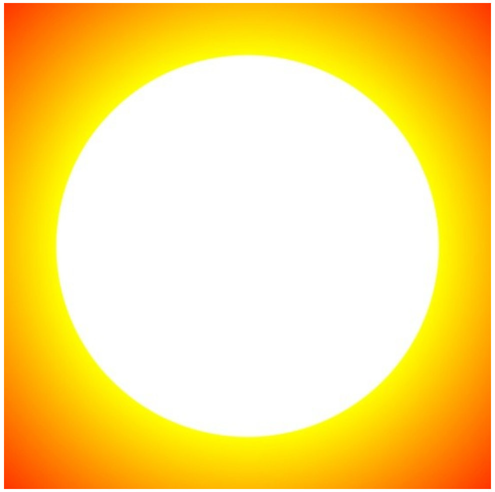
$$t T_{MeV}^2 = 2.4 [N(T)]^{-1/2}$$

where t in seconds, T_{MeV} in MeV.

For N = 52, T = 250 MeV, one has
$t = 5.3 \times 10^{-6}$ s, $T = 2.9 \times 10^{12}$ K,
$\rho = 8.9$ GeV/fm^3.

Remote Temperature Sensing

Red Hot



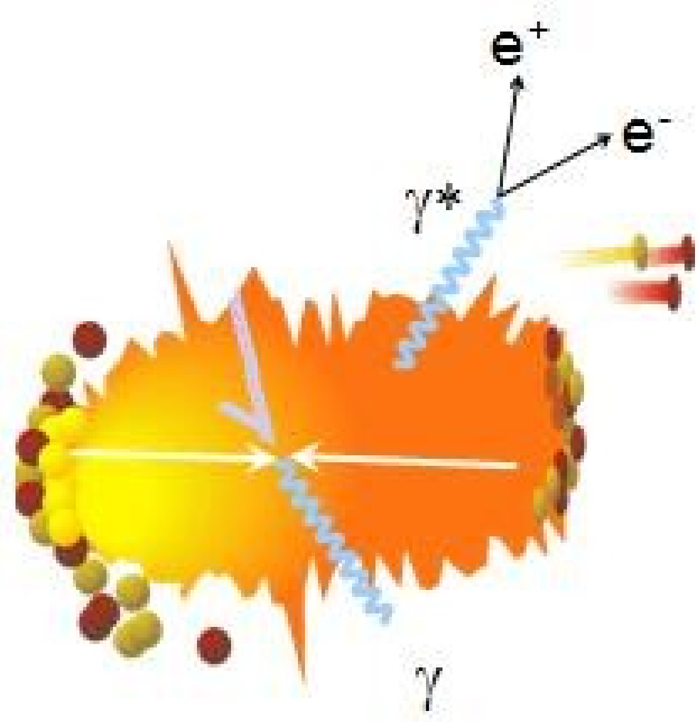
White Hot

- Hot Objects produce thermal spectrum of EM radiation.
- Red clothes are NOT red hot, reflected light is not thermal.

Photon measurements must distinguish thermal radiation from other sources: HADRONS!!!

Not Red Hot!

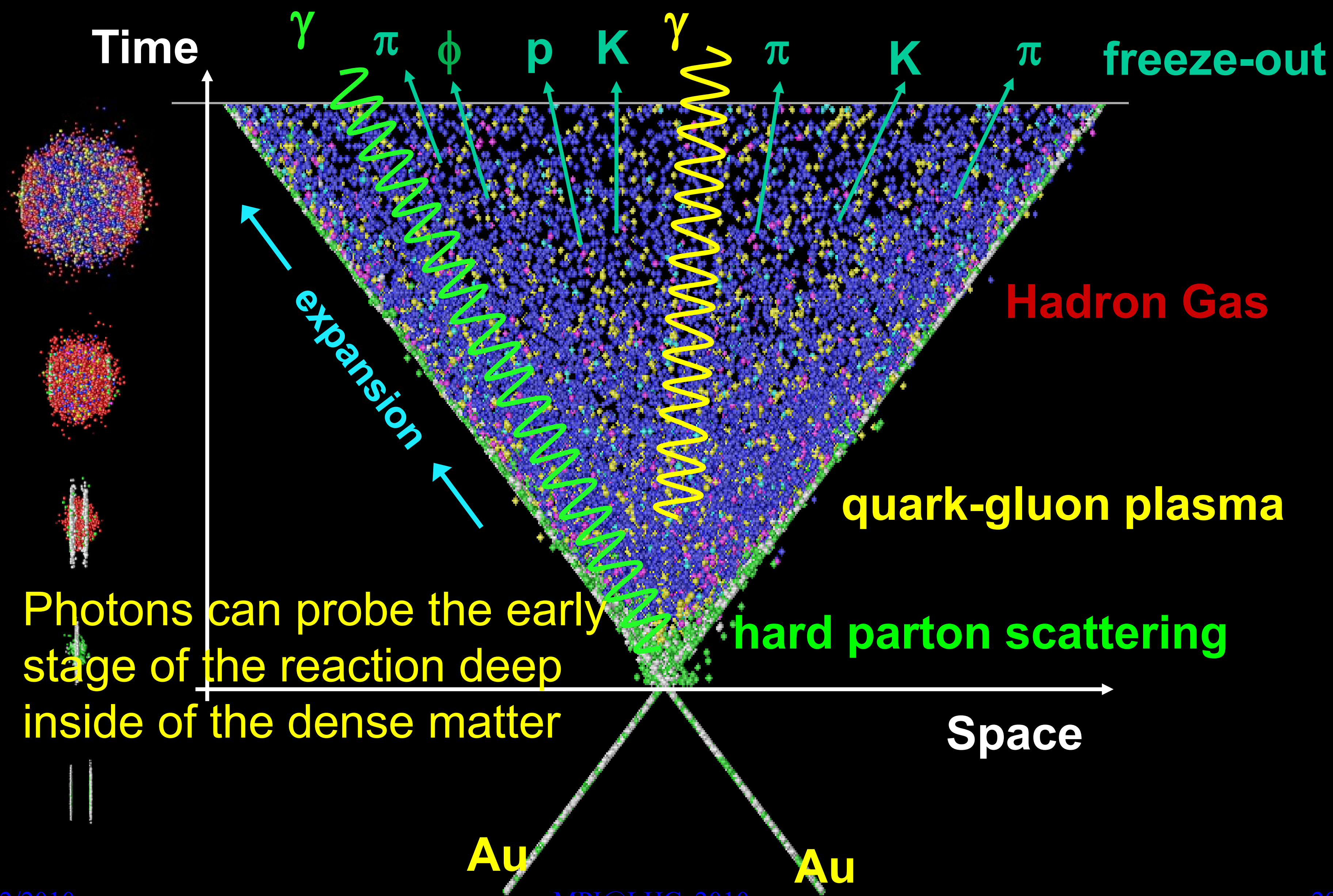
Thermal photon from hot matter



Hot matter emits thermal radiation

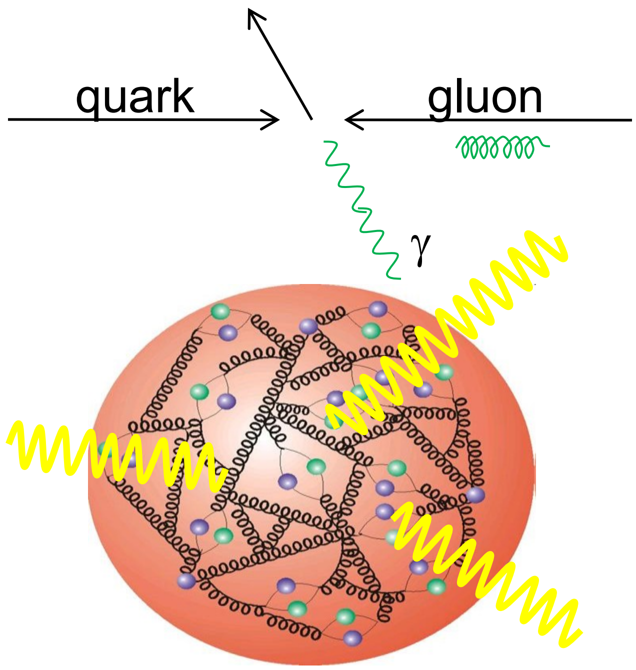
Temperature can be measured from the *emission spectrum*

Photon Probe of Nuclear Collisions



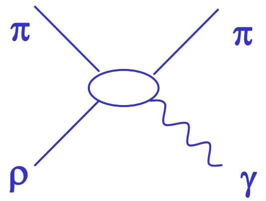
Photons can probe the early stage of the reaction deep inside of the dense matter

Many sources of photons



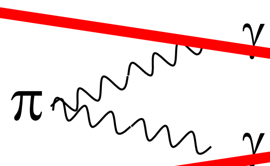
pQCD direct photons from initial *hard scattering* of quarks and gluons

Thermal photons from hot *quark gluon plasma*



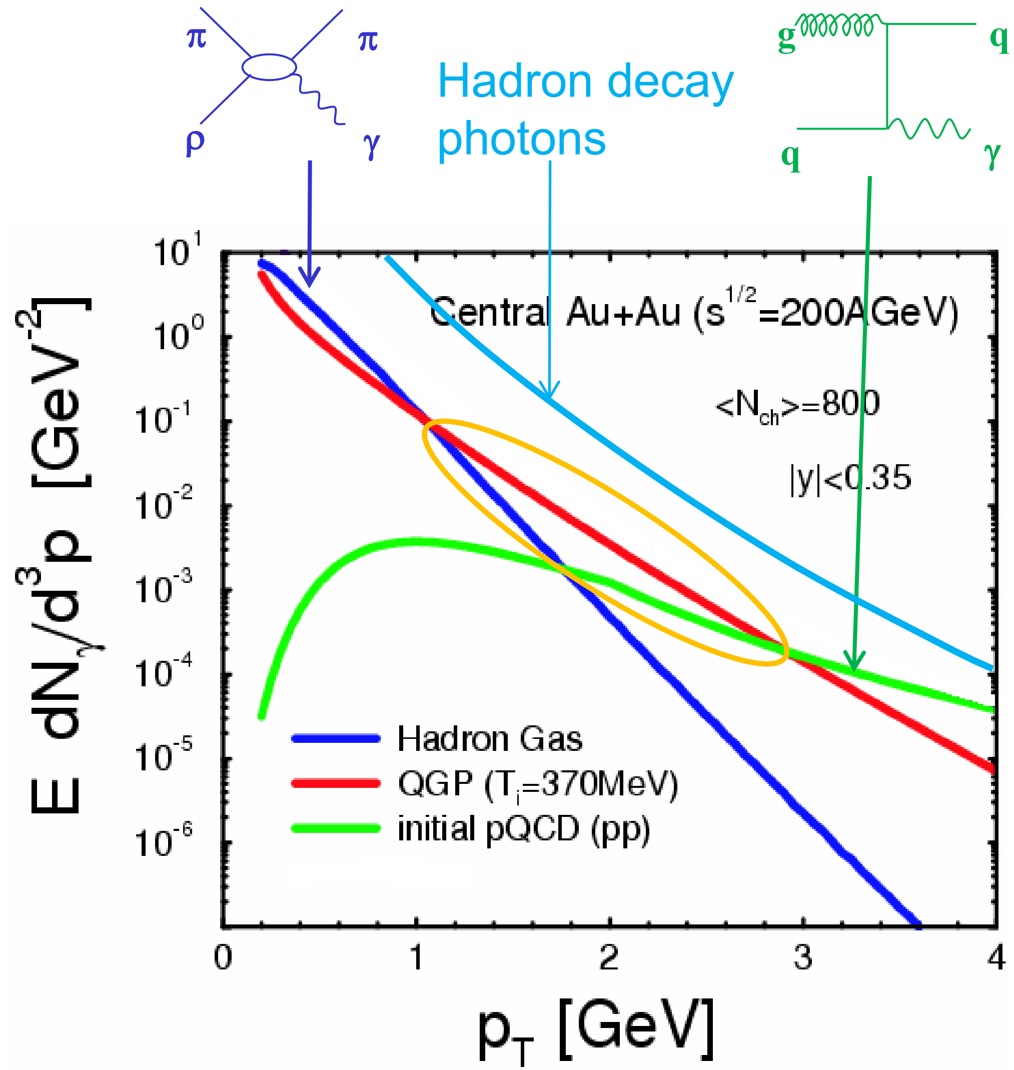
Thermal photons from *hadron gas* after hadronization

background



~~*Decay Photons* from hadrons (π^0, η, etc)~~

Thermal photons (theory prediction)

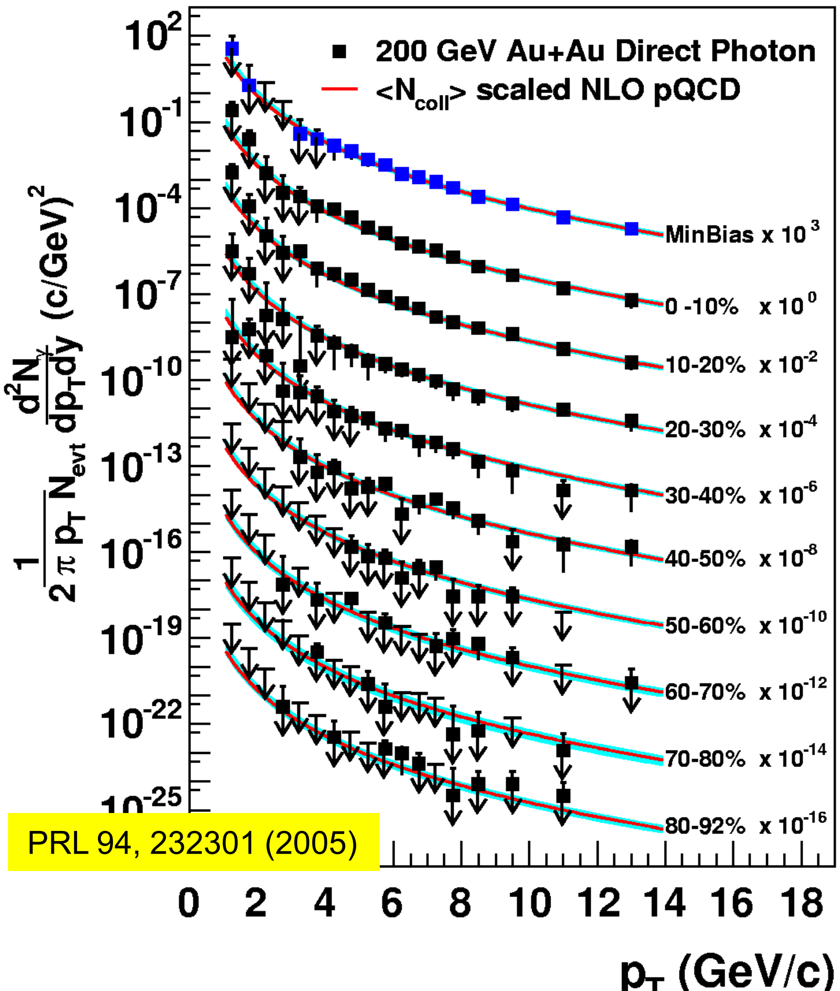


S.Turbide *et al* PRC 69 014903

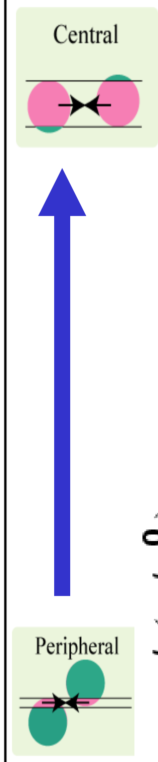
- High p_T (p_T>3 GeV/c) pQCD photon
- Low p_T (p_T<1 GeV/c) photons from hadronic Gas
- Themal photons from QGP is the dominant source of direct photons for 1<p_T<3 GeV/c
- Recently, other sources, such as jet-medium interaction are discussed
- Measurement is difficult since the expected signal is only 1/10 of photons from hadron decays

Direct Photons in Au+Au

Blue line: N_{coll} scaled p+p cross-section

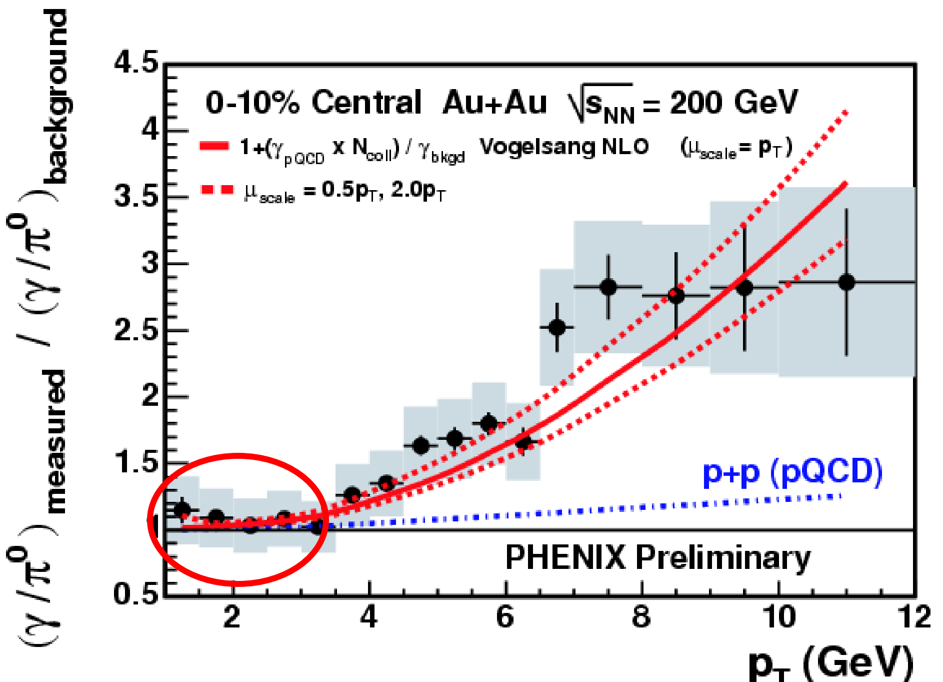


PRL 94, 232301 (2005)



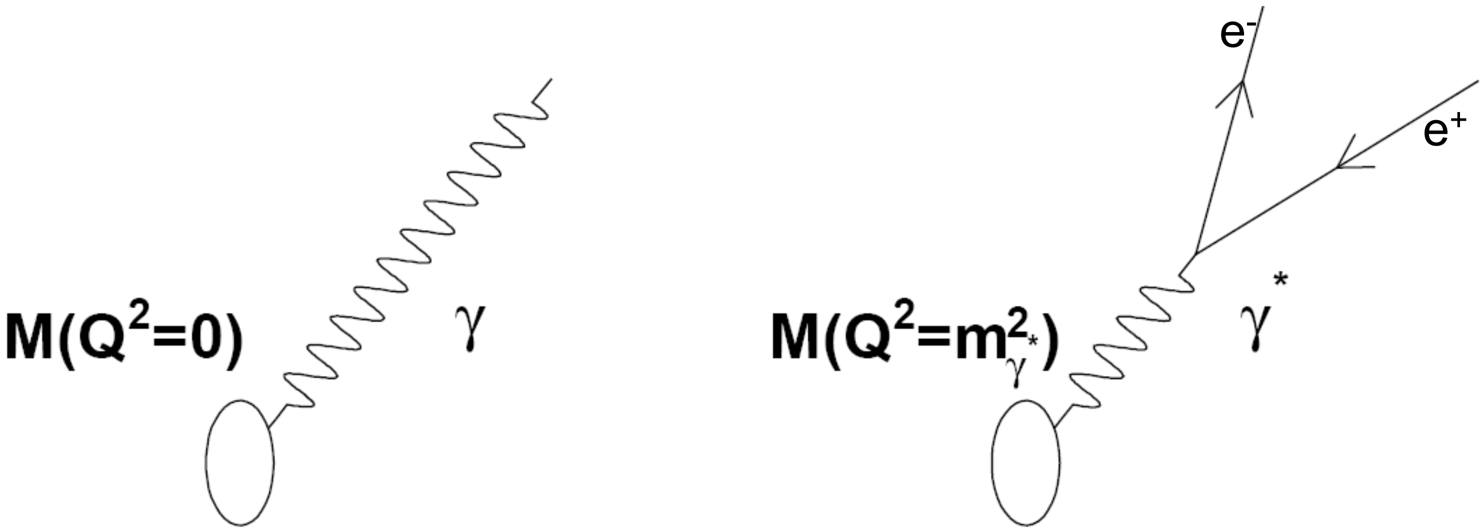
Direct photon is measured as "excess" above hadron decay photons

Measurement below p_T<3 GeV/c is difficult since the yield of thermal photons is only 1/10 of that of hadron decay photons



Au+Au data consistent with pQCD calculation scaled by N_{coll}

Alternative method - measure virtual photons



- Source of real photon should also be able to emit virtual photon
- At m→0, the yield of virtual photons is the same as real photon

→ Real photon yield can be measured from virtual photon yield, which is observed as low mass e^+e^- pairs

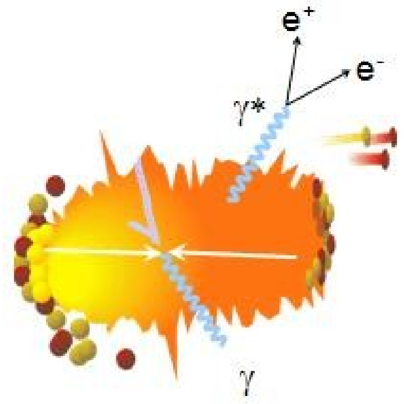
- Advantage: hadron decay background can be substantially reduced. For $m>m_\pi$, π^0 decay photons (~80% of background) are removed

→ S/B is improved by a factor of five

- Other advantages: photon ID, energy resolution, etc
- Cost: the yield is reduced by a large factor (~ $\alpha/3\pi$ ~ 1/1000)

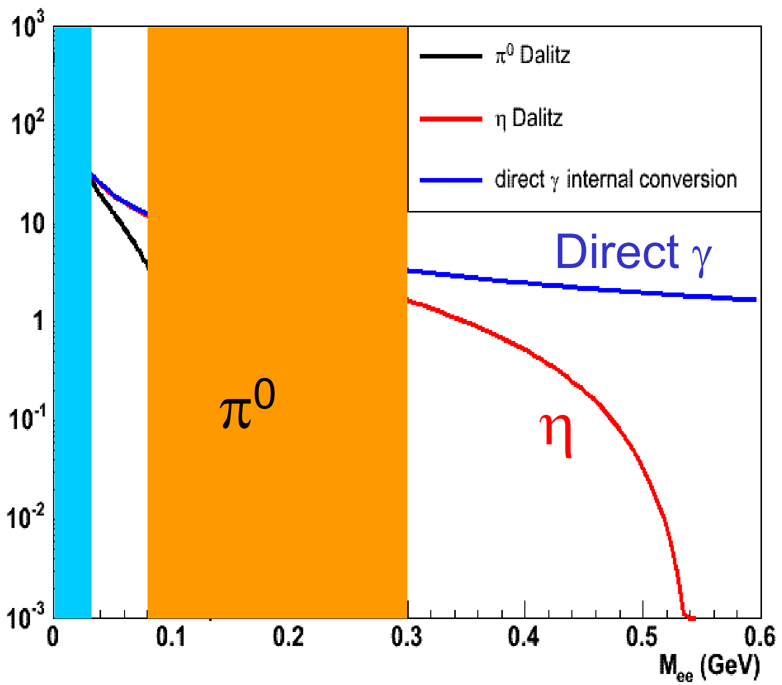
Virtual Photon Measurement

Any source of real γ can emit γ^* with very low mass.
Relation between the γ^* yield and real photon yield is known.



$$\frac{d^2N}{dM_{ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{M_{ee}^2}}\left(1+\frac{2m_e^2}{M_{ee}^2}\right)\frac{1}{M_{ee}}S(M_{ee},p_t)dN_\gamma$$

Process dependent factor $S(M_{ee},p_t) \equiv \frac{dN_{\gamma^*}}{dN_\gamma}$



- Case of hadrons (π^0, η) (Kroll-Wada)

  $$S = \left|F(M_{ee}^2)\right|^2\left(1-\frac{M_{ee}^2}{M_{hadron}^2}\right)^3$$

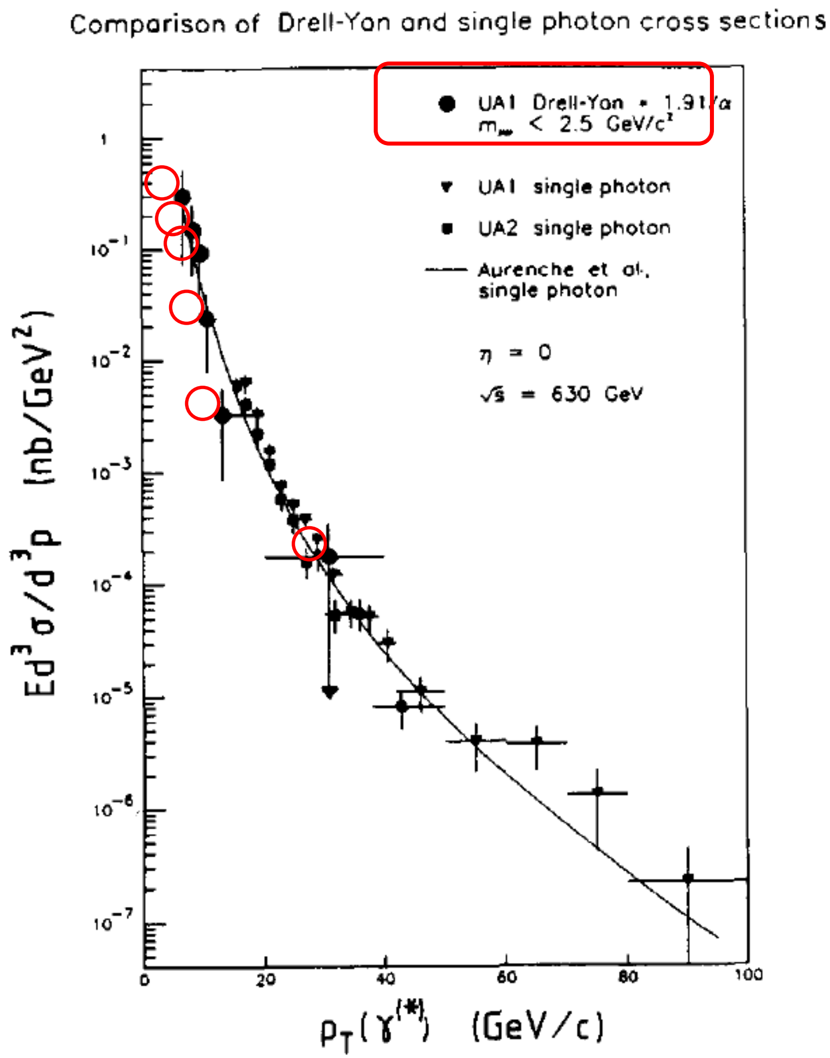
  $S = 0$ at $M_{ee} > M_{hadron}$
- Case of direct γ^*

  If $p_T^2 >> M_{ee}^2$ $S = 1$
- For $m > m_\pi$, π^0 background (~80% of background) is removed

→ S/B is improved by a factor of five

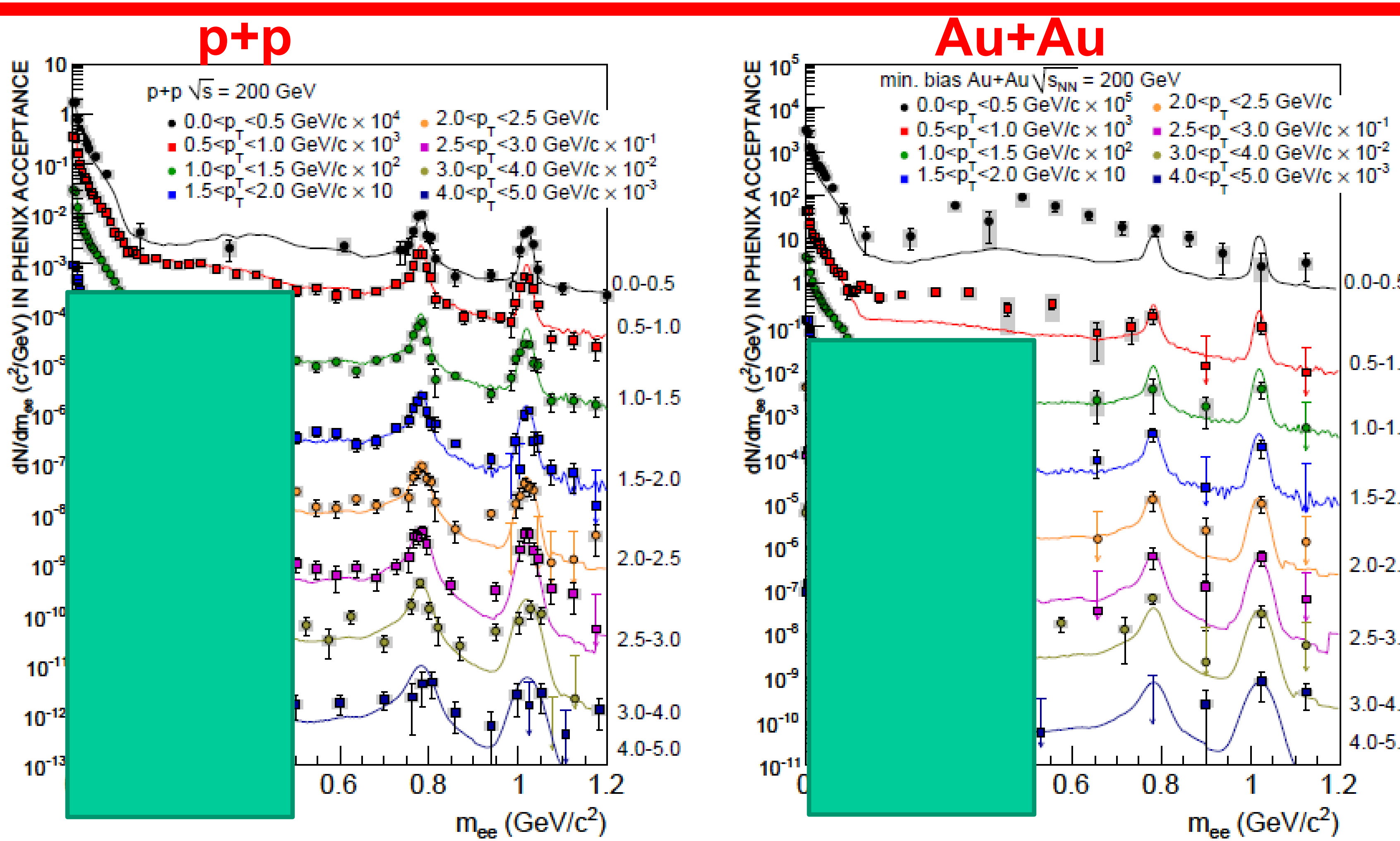
Not a new idea

J.H.Cobb, et al, PL 78B, 519 (1978)
G. Albajar, et al, PL B209, 397 (1988)



- The idea of measuring direct photon via low mass lepton pair is not new one. It is as old as the concept of direct photon.
- This method is first tried at CERN ISR in search for direct photon in p+p at $s^{1/2}$=55GeV. They measured e^+e^- pairs for 200<m<500 MeV, and set one of the most stringent limit on direct photon production at low p_T
- Later, UA1 measured low mass muon pairs and deduced the direct photon cross section.

e^+e^- mass spectra in p_T slices



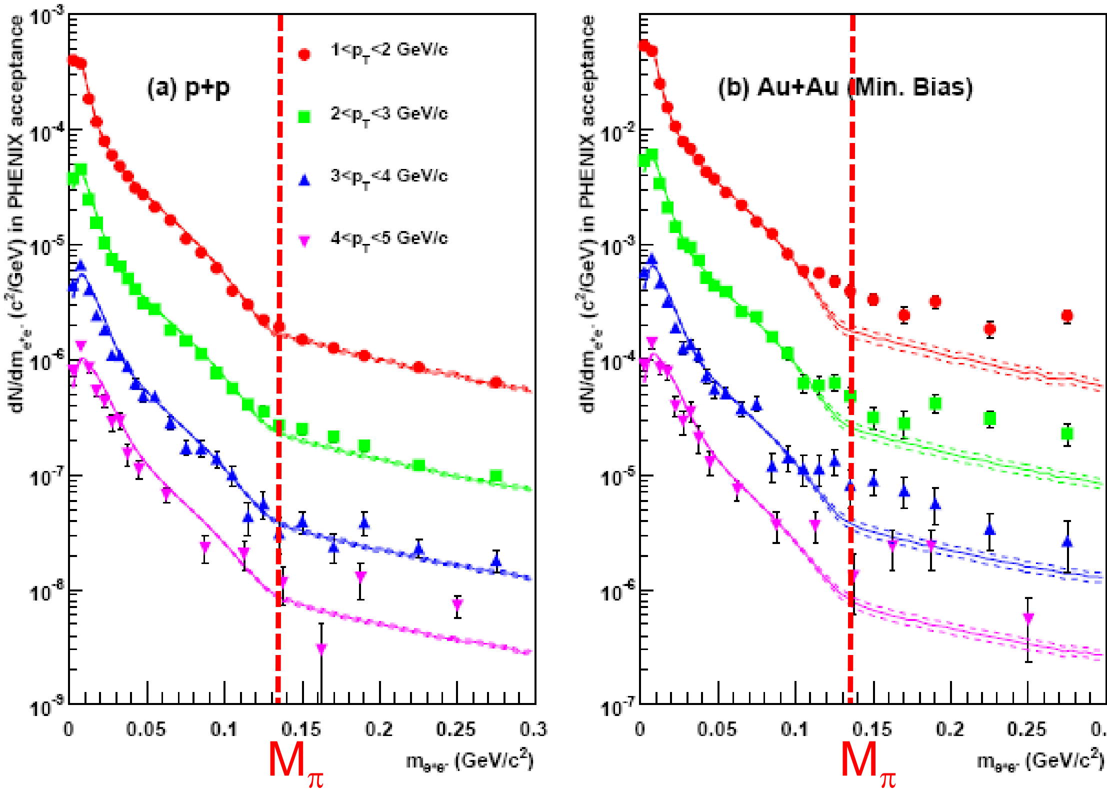
A.Adare et al. Phys. Rev. C81, 034911 (2010)

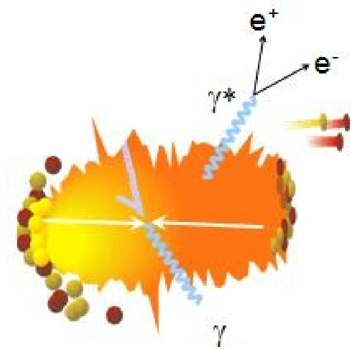
- p+p in agreement with cocktail
- Au+Au low mass enhancement concentrated at low p_T

Enhancement of almost real photon

A. Adare et al., PRL 104, 132301 (2010)

pp   Au+Au (MB)





1 < p_T < 2 GeV
2 < p_T < 3 GeV
3 < p_T < 4 GeV
4 < p_T < 5 GeV

Low mass e^+e^- pairs (m<300 MeV) for 1<p_T<5 GeV/c

p+p:

- Good agreement with hadronic decay cocktail
- Small excess above m_π due to pQCD direct γ at high p_T

Au+Au:

- Clear enhancement visible above m_π =135 MeV for all p_T

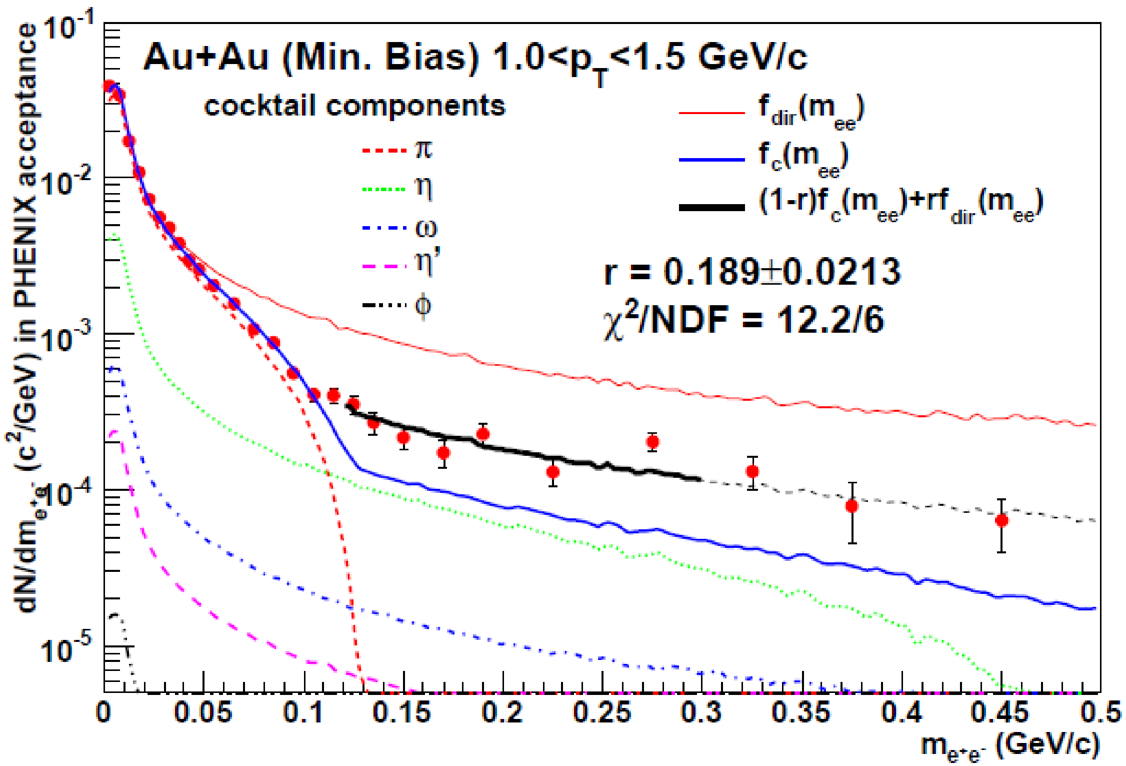
Determination of γ^* fraction, *r*

Direct γ^*/inclusive γ^* is determined by fitting the following function

$$f_{data}(M_{ee}) = (1-r)\cdot f_{cocktail}(M_{ee}) + r \cdot f_{direct}(M_{ee})$$

f_{direct} : direct photon shape with $S = 1$.

r = direct γ^*/inclusive γ^*



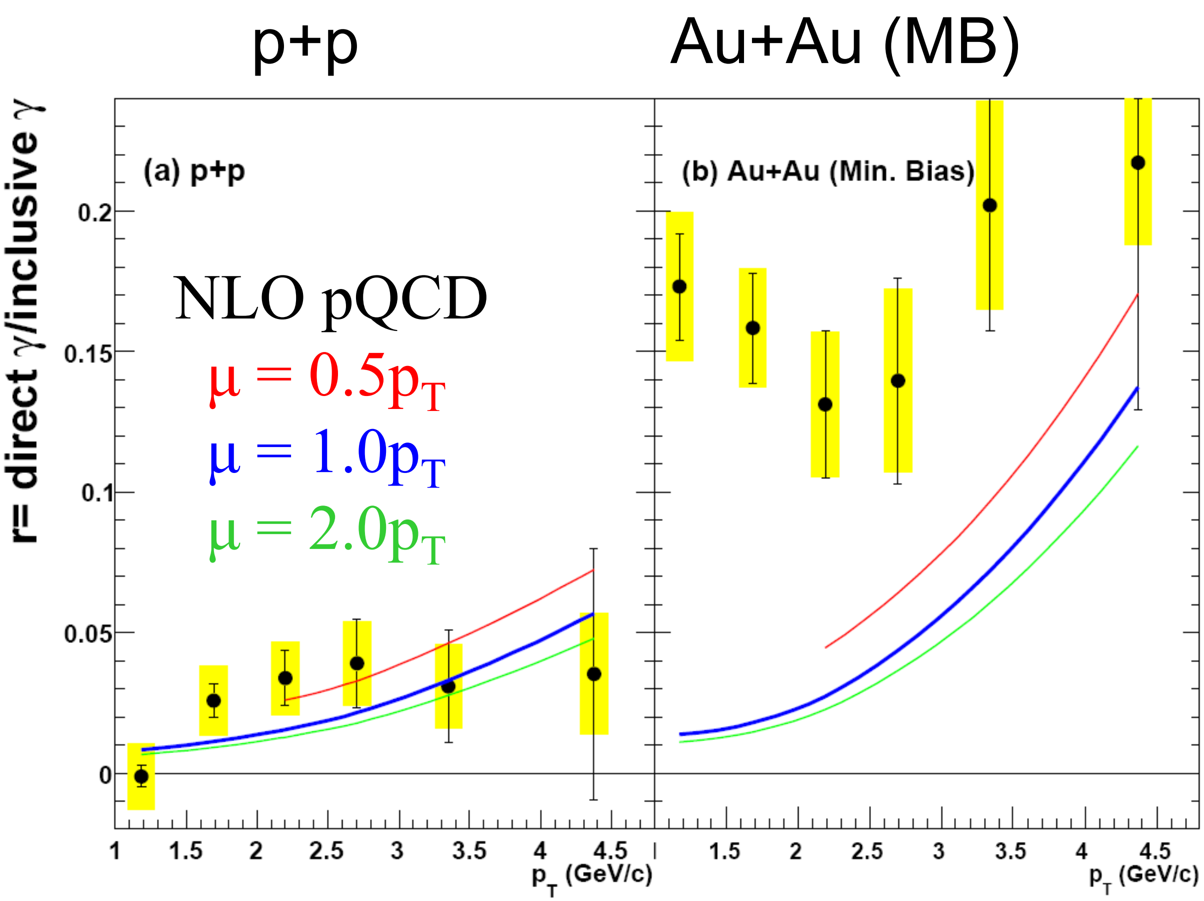
- Fit in 120-300MeV/c^2 (insensitive to π^0 yield)
- The mass spectrum follows the expectation for m > 300 MeV

→ S(m) ~ 1

A. Adare et al., PRL 104, 132301 (2010)

Fraction of direct photons

A. Adare et al., PRL 104, 132301 (2010)



NLO pQCD calculation by Werner Vogelsang

- Fraction of direct photons
- Compared to direct photons from pQCD

p+p

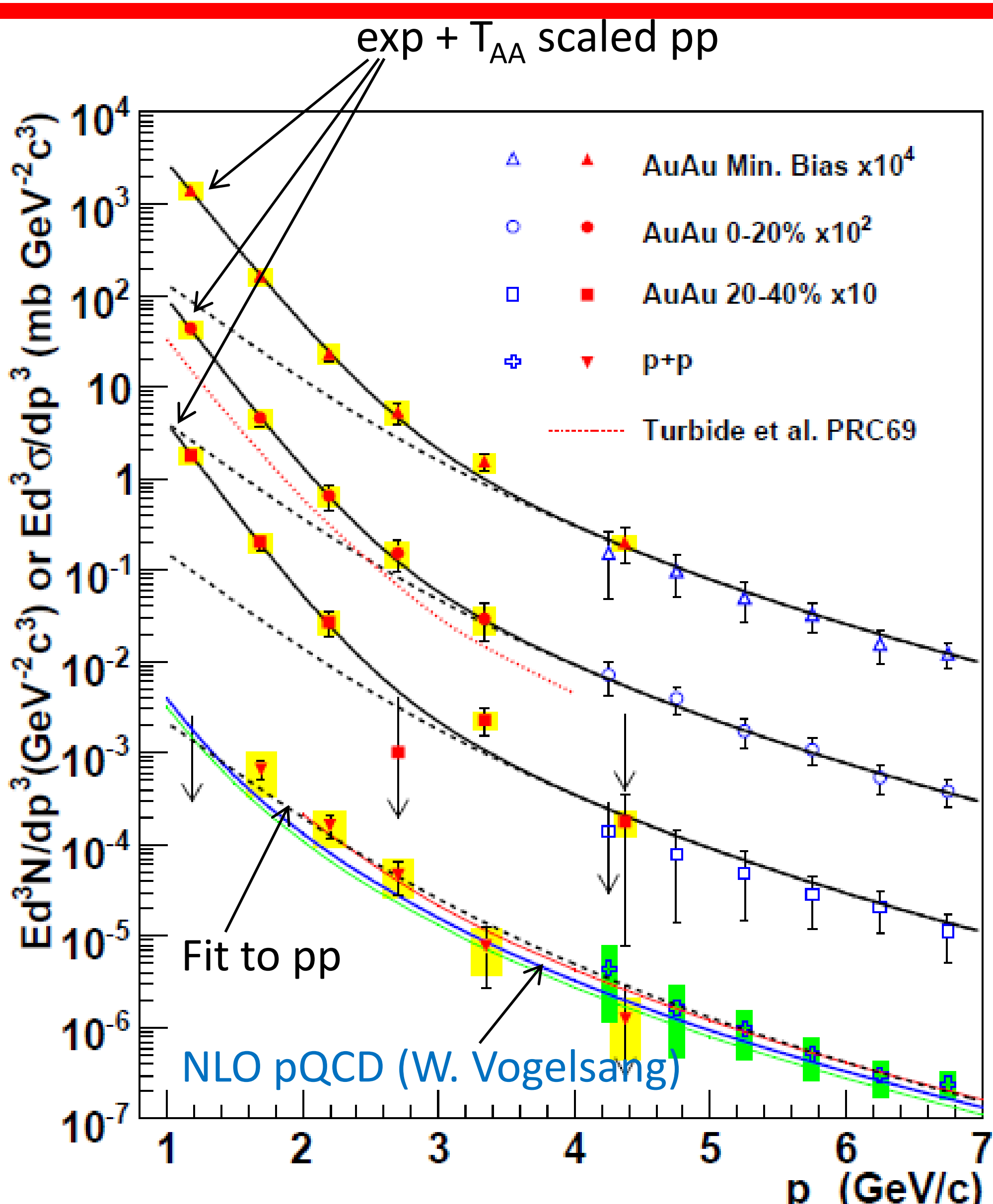
- Consistent with NLO pQCD

Au+Au

- Clear excess above pQCD

Direct photon spectra

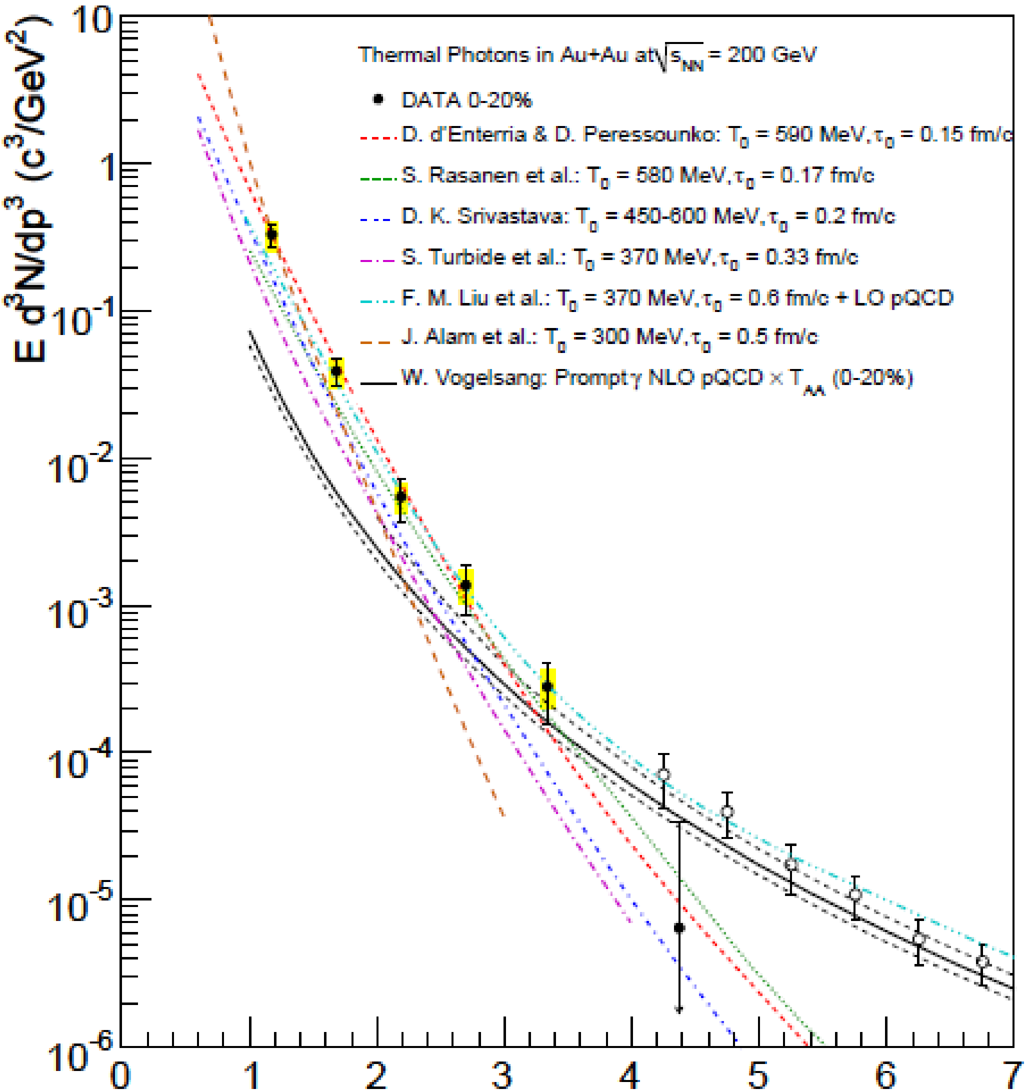
A. Adare et al., PRL 104, 132301 (2010)



- Direct photon measurements
  - real (p_T>4GeV)
  - virtual (1<p_T<5GeV)
- pQCD consistent with p+p down to p_T=1GeV/c
- Au+Au data are above N_{coll} scaled p+p for p_T < 2.5 GeV/c
- Au+Au = scaled p+p + exp: $T_{AuAu} = 221 \pm 19^{stat} \pm 19^{syst}$ MeV

- Theoretical prediction of thermal photon by Turbide et al. agrees with the data within about a factor of two.

Theory Comparison



A.Adare et al. Phys. Rev. C81, 034911 (2010)

Hydrodynamical models are compared with the data

D.d'Enterria &D.Peressounko
T=590MeV, τ_0=0.15fm/c

S. Rasanen et al.
T=580MeV, τ_0=0.17fm/c

D. K. Srivastava
T=450-600MeV, τ_0=0.2fm/c

S. Turbide et al.
T=370MeV, τ_0=0.33fm/c

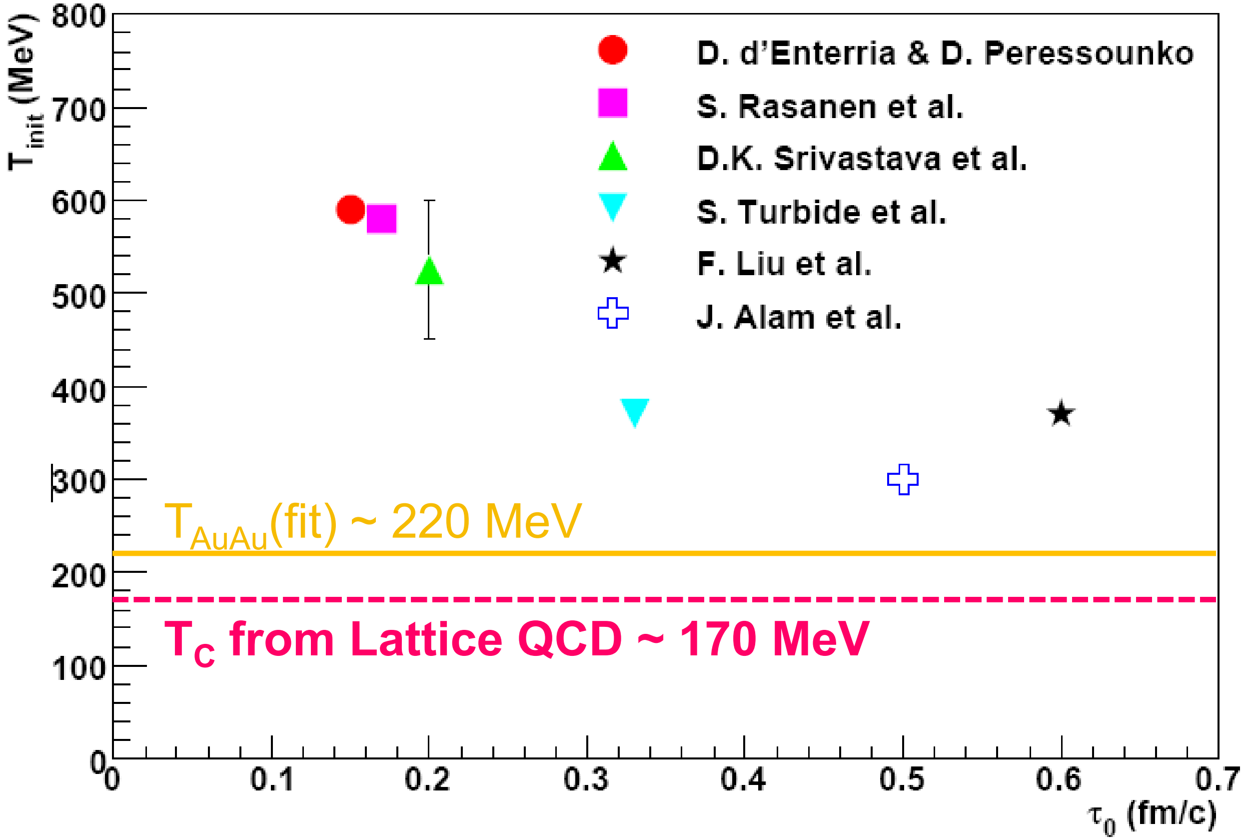
J. Alam et al.
T=300MeV, τ_0=0.5fm/c

F.M. Liu et al.
T=370MeV, τ_0=0.6 fm/c

Hydrodynamical models agree with the data within a factor of ~2

Initial temperature

A.Adare et al.
arXiv:0912.0244

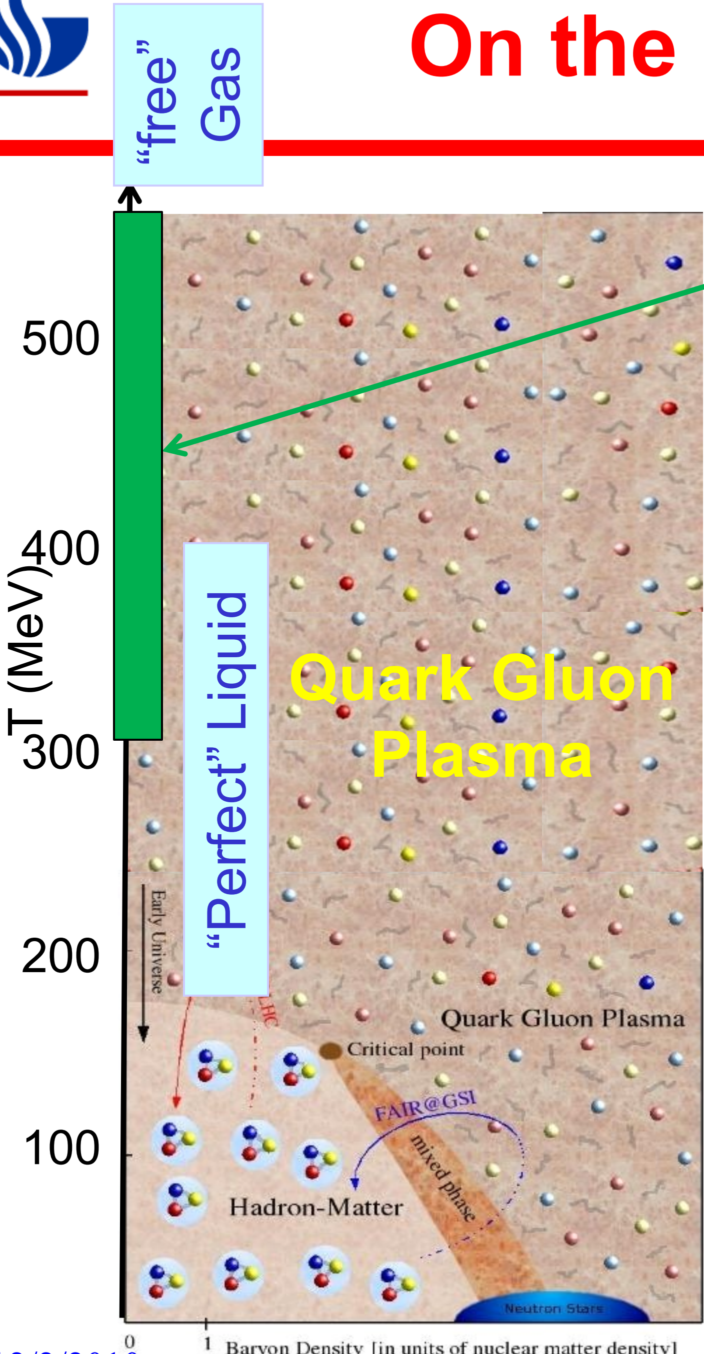


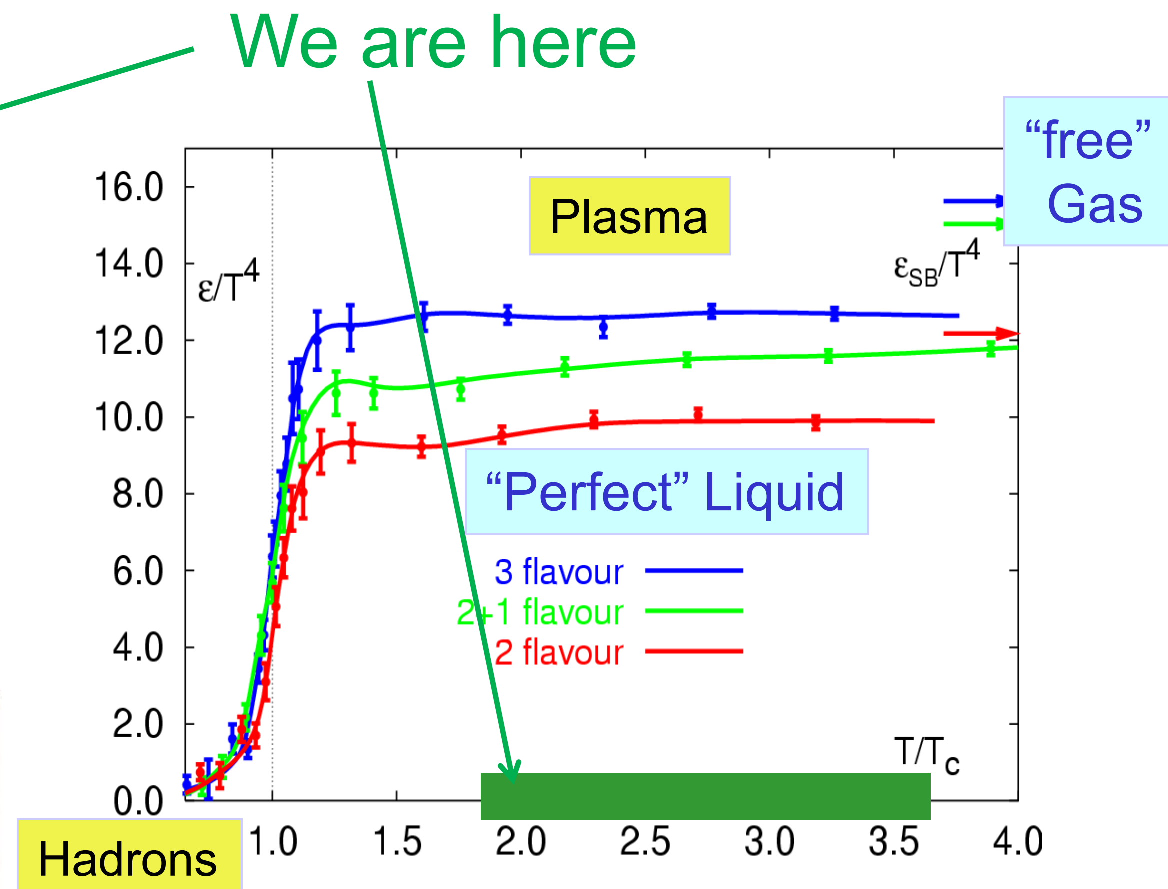
From data: $T_{ini} > T_{AuAu} \sim 220$ MeV

From models: $T_{ini} = 300$ to 600 MeV for $\tau_0 = 0.15$ to 0.6 fm/c

Lattice QCD predicts a phase transition to quark gluon plasma at $T_c \sim 170$ MeV

On the Map of the Phase Space





T_c ~ 170 MeV; ε ~ 1 GeV/fm^3

At these temperature, QGP is *"perfect" liquid.*

At higher temperature, it can become *"gas"*

Summary

- The matter created in Au+Au collisions at per nucleon-nucleon cms energy of 200 GeV is **dense**. Quarks (both the light and the heavy) and gluons experience large energy loss while traversing this medium.
- The system is rapidly **thermalized** from the measurement of elliptic flow of light and charmed hadrons. The quark number scaling of the flow (v_2) indicates the partonic nature of the thermalized medium.
- Such a hot and dense medium emits **thermal radiation**. The observation of thermal photons allows the determination of the initial temperature of the matter!

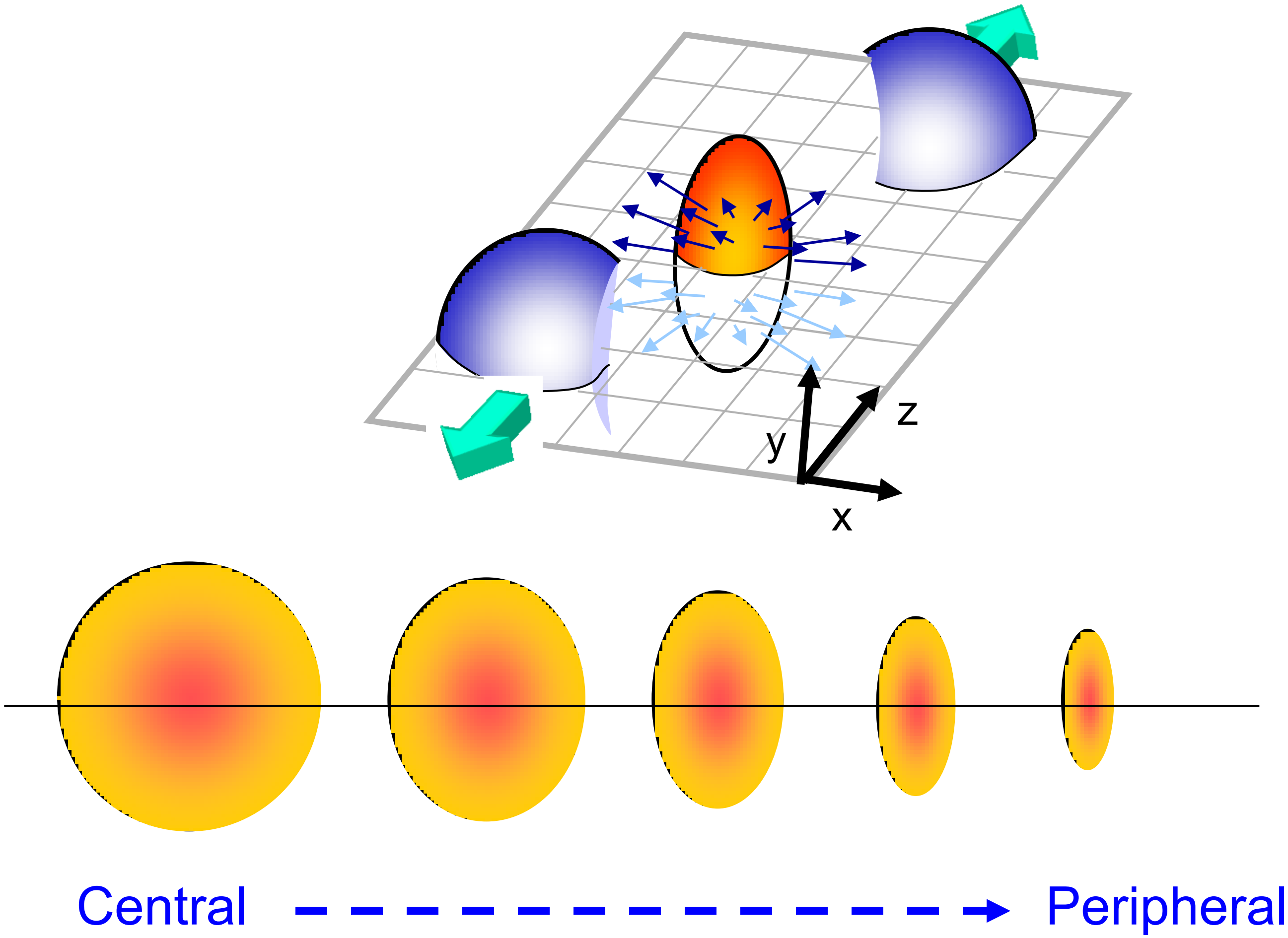
Outlook

- Both experiments (PHENIX and STAR) at RHIC are developing a concrete decadal plan for further characterizing the high temperature QCD matter created from colliding heavy ions.
- LHC heavy ion program just had a great start by colliding Pb+Pb at 2.76 TeV which is a factor of 14 higher in energy over RHIC. We are expecting that results from the new measurements will soon flood the field.
- We are entering an exciting new era of high energy heavy ion physics program which, we hope, allows us to have a better understanding the QCD matter at extreme conditions.

The end

THANKS

Basics of Heavy Ion Collisions at RHIC



The PHENIX Experiment

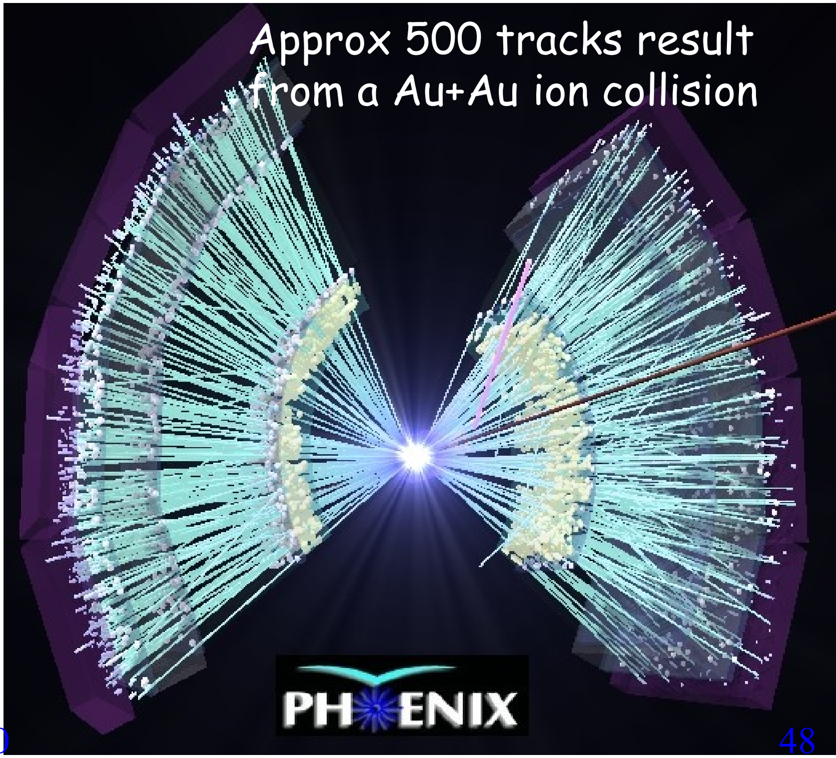
Tale of the Tape:

- Begun Operation June 2000
- 550 Scientists, 14 Countries, 69 Inst.
- 18 Detector subsystems
- 4 Spectrometer arms
  - Large electromagnets
- Total weigh = 3500 Tons
- >300,000 readout channels now
- >3,000,000 channels w/Upgrades
- >125 Varieties of custom printed circuit boards
- We can take 16 Terabytes of data/day
  - Fills One 100 GB computer hard disk every 3 ½ minutes
- Operate 7-8 months/year (24/7)
  - Maintain/repair 4-5 months/yr
- Major components built everywhere
  - US, Russia, Japan, Brazil, Israel, France, Sweden, Germany, Korea
- It takes ~110 people/wk to operate PHENIX while taking data

PHENIX is designed to probe fundamental features of the strong nuclear force, Quantum Chromo Dynamics (QCD)

•PHENIX took approx. 10 years and $120M to design, build & commission

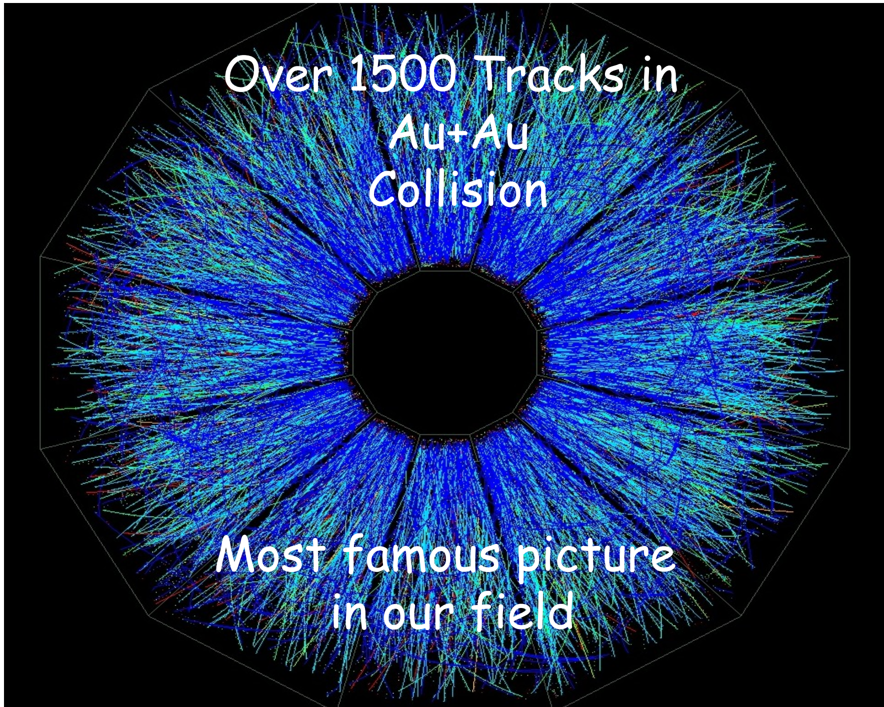
•We are finishing our 9th year of operation

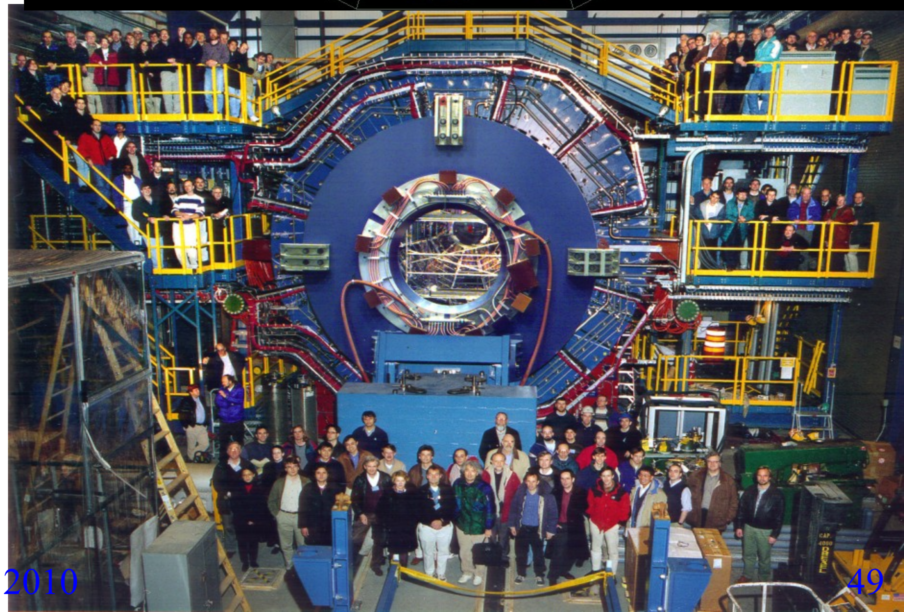


The STAR Experiment

STAR Statistics:

- Begun Operations in June 2000
- 500 scientists, 50 institutions in 14 countries
- 1000 tons total weight
- Contains largest Time Projection Chamber (TPC) currently operating in the world
    - Huge electronic camera
    - Takes “pictures” ~ 100/sec
    - Upgraded to 1000 pictures/sec
- Large area coverage for both tracking and calorimetery
- >10 detector subsystems
- Run 7-8 months/year (24/7)
- Major components built everywhere
    - US, China, Russia, France, Germany, India…
- Over 250 scientist at BNL each year to Operate STAR





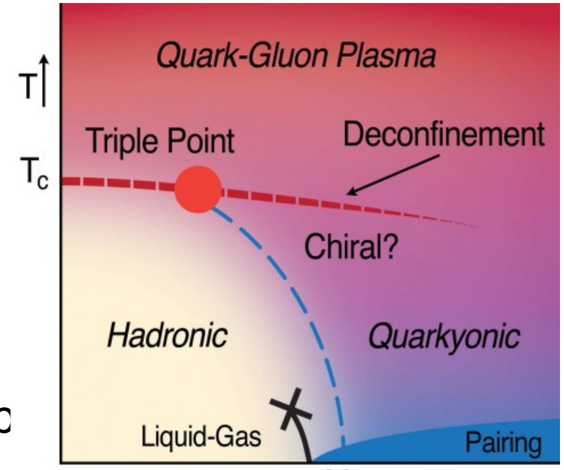
Melting - Quarkonia in A+A

state	J/ψ	χ_c	Υ_{1S}	Υ_{2S}	Υ_{3S}
mass [GeV]	3.10	3.53	9.46	10.02	10.36
ΔE [GeV]	0.64	0.20	1.10	0.54	0.20
radius [fm]	0.25	0.36	0.14	0.28	0.39

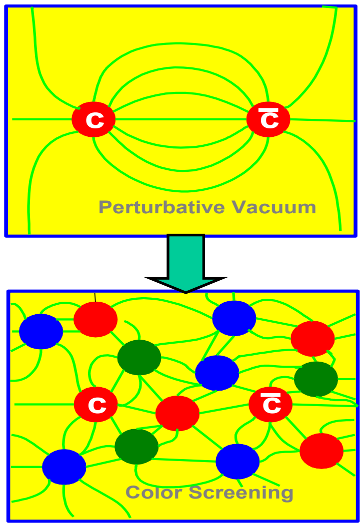
hep-ph/0609197v1 H. Satz

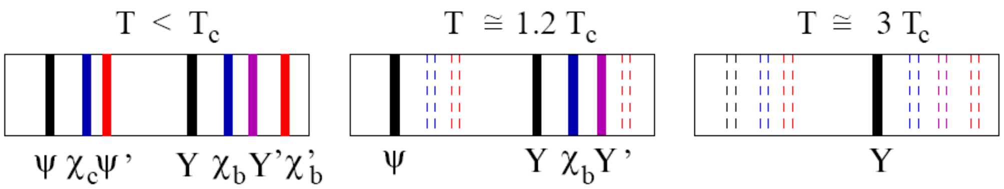
- Each quarkonium has different binding radius.

- Binding of a $Q\bar{Q}$ pair is subject to color screening in QGP.
- Melting temperatures depend on their binding radius.
- Temperature of QGP can be estimated another models like regeneration can b tested.



arXiv:0911.4806





Relation between dilepton and virtual photon

e.g. Rapp, Wambach Adv.Nucl.Phys 25 (2000)

Emission rate of (virtual) photon

$$q_0 \frac{dR_{\gamma^*}}{d^3q} = -\frac{\alpha}{2\pi^2} \mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T) f^B(q_0,T),$$

$$f^B(q_0,T) = 1/(e^{q_0/T}-1)$$

EM correlator
Matter property

Boltzmann factor
temperature

Emission rate of dilepton

$$\frac{dR_{ll}}{d^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M)}{M^2} \mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T) f^B(q_0,T)$$

$$L(M) = \sqrt{1-\frac{4m_l^2}{M^2}}(1+\frac{2m_l^2}{M^2})$$

Relation between them

Prob. $\gamma^* \rightarrow l^+l^-$

$$q_0 \frac{dR_{ll}}{dM^2 d^3q} = \frac{1}{2}\frac{dR}{d^4q} = \frac{\alpha}{3\pi}\frac{L(M)}{M^2} q_0 \frac{dR_{\gamma^*}}{d^3q}$$

Dilepton

virtual photon

This relation holds for the yield after space-time integral

Virtual photon emission rate can be determined from dilepton emission rate

$$q_0 \frac{dn_{\gamma^*}}{d^3q} \simeq \frac{3\pi}{\alpha} M^2 q_0 \frac{dn_{ll}}{d^3q dM^2} = \frac{3\pi}{2\alpha} M q_0 \frac{dn_{ll}}{d^3q dM}.$$

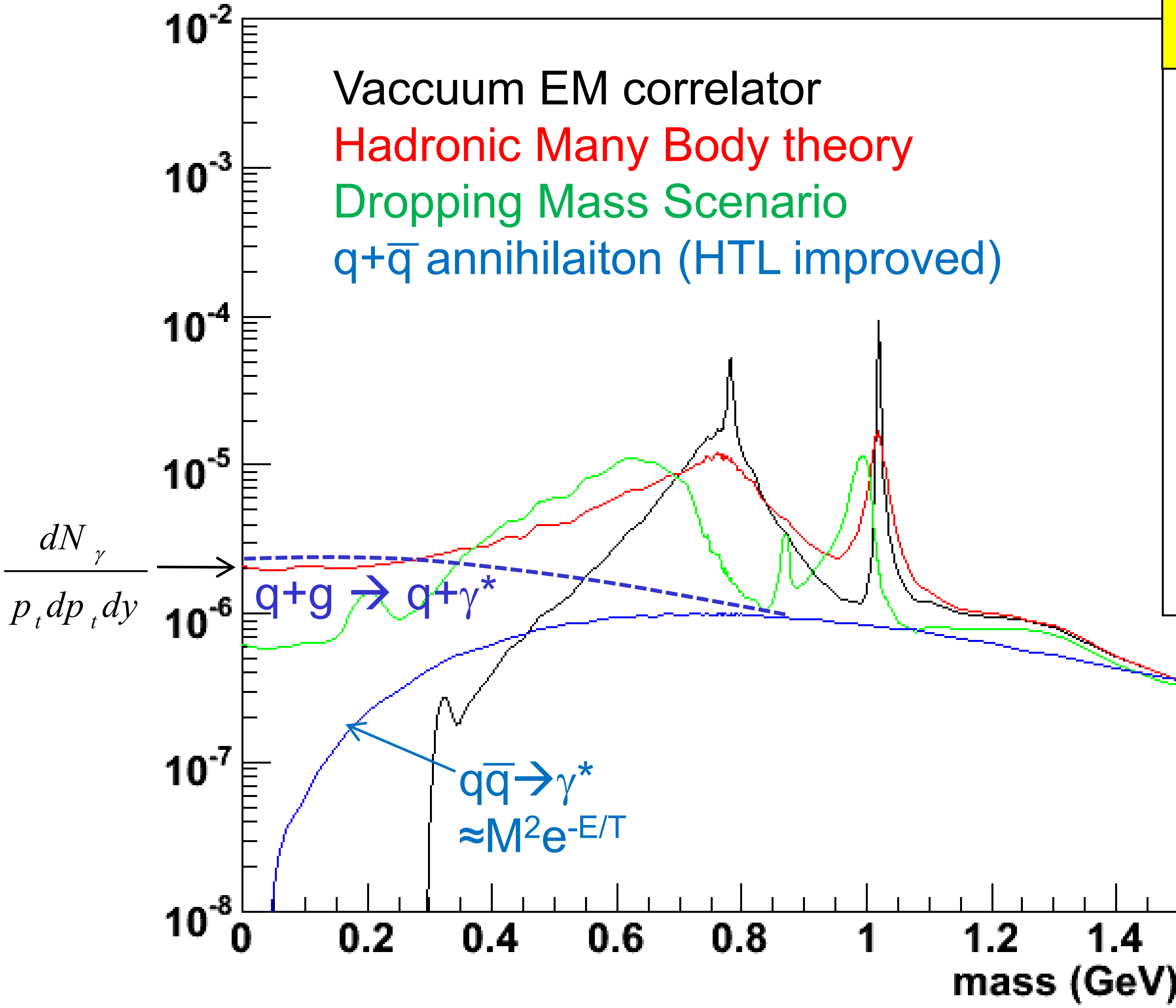
M ×dN_{ee}/dM gives virtual photon yield

For $M \rightarrow 0$, $n_\gamma^* \rightarrow n_\gamma$(real); real photon emission rate can also be determined

Theory prediction of (Virtual) photon emission

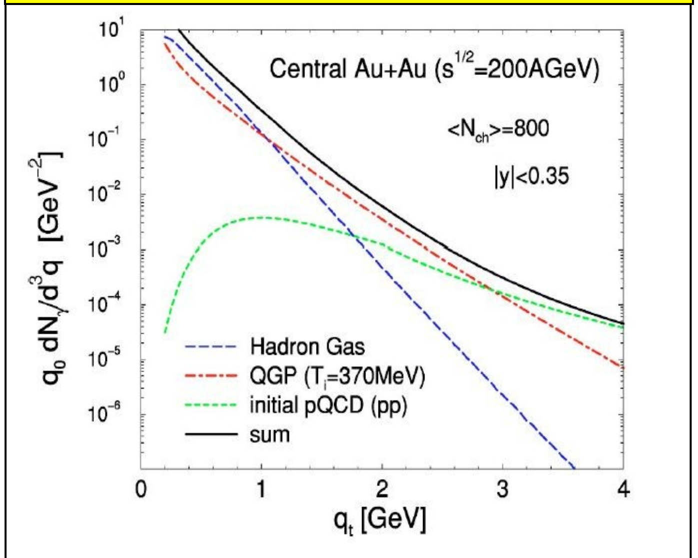
$$M \times \frac{dN_{ee}}{p_t dp_t dM dy} \propto \frac{dN_{\gamma^*}}{p_t dp_t dy}$$ at y=0, pt=1.025 GeV/c

Theory calculation by Ralf Rapp



Real photon yield

Turbide, Rapp, Gale PRC69,014903(2004)



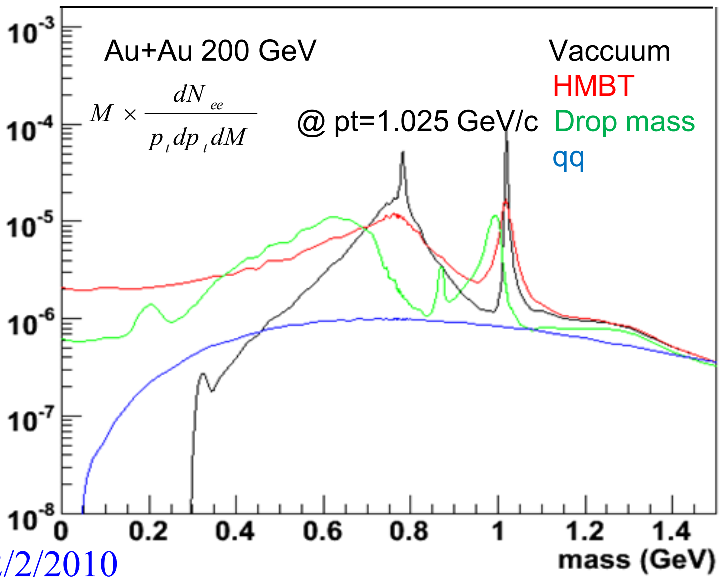
$q+g \rightarrow q+\gamma^*$ is not in the calculation; it should be similar size as HMBT at this p_T

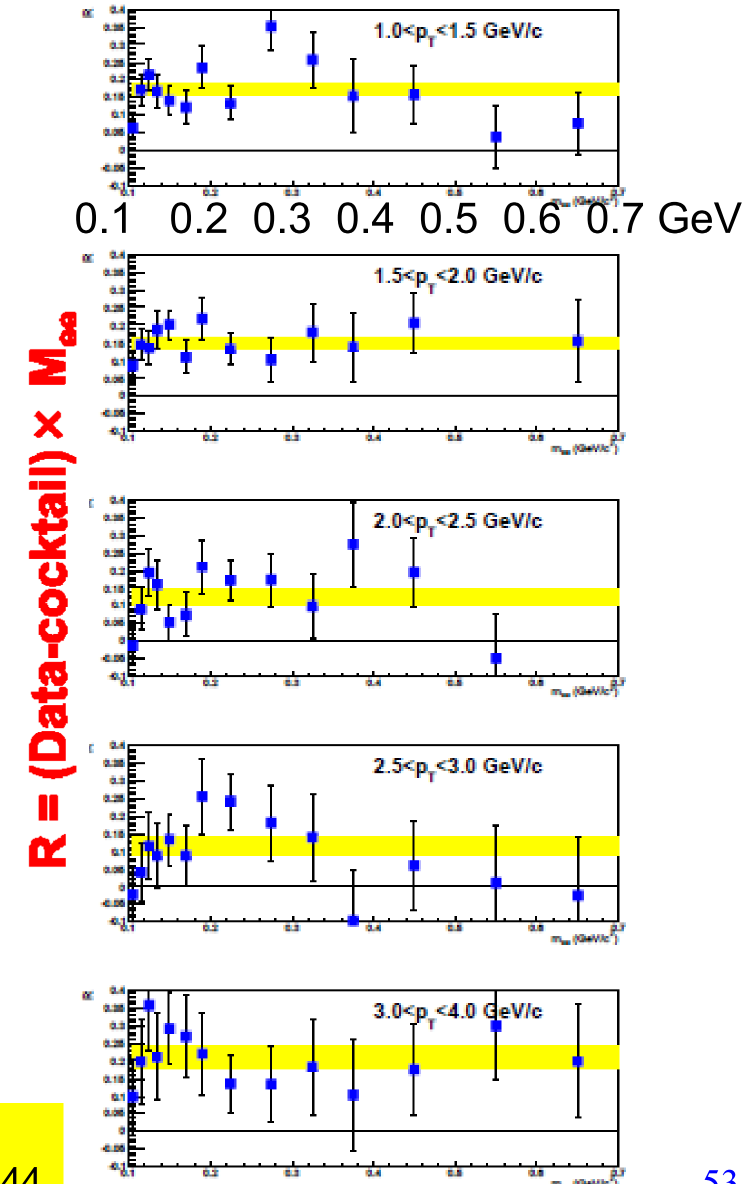
Direct measurement of $S(m_{ee}, p_T)$

$$R(m,p_T) \simeq \frac{dN^{\rm excess}_{\gamma^*}(m,p_T)}{dp_T} \Big/ \frac{dN^{\rm incl}_{\gamma}(p_T)}{dp_T}$$
$$= S(m,p_T)\, dN^{direct}_{\gamma}(p_T) / dN^{\rm incl}_{\gamma}(p_T)$$

No indication of mass dependence of $R(m,p_T)$ in this high p_T region
→ $S(m,p_T)$ is near constant

Extrapolation to M=0 should give the real photon emission rate





A.Adare et al.
arXiv:0912.0244

Summary of the fit

TABLE I: Summary of the fits. The first and second errors are statistical and systematic, respectively.

centrality	$dN/dy(p_T > 1\text{GeV}/c)$	$T(\text{MeV})$	χ^2/DOF
0-20%	$1.50 \pm 0.23 \pm 0.35$	$221 \pm 19 \pm 19$	$4.7/4$
20-40%	$0.65 \pm 0.08 \pm 0.15$	$217 \pm 18 \pm 16$	$5.0/3$
Min. Bias	$0.49 \pm 0.05 \pm 0.11$	$233 \pm 14 \pm 19$	$3.2/4$

- Significant yield of the exponential component (excess over the scaled p+p)
- The inverse slope T_{AuAu} = 221±19±19 MeV (>T_c ~ 170 MeV)
  - p+p fit funciton: $A_{pp}(1+p_t^2/b)^{-n}$
  - If power-law fit is used for the p+p spectrum, T_{AuAu} = 240±21 MeV
- T_{AuAu} is time-averaged "effective" temperature

Threshold Temperature

The threshold is defined as the rest energy divided by Boltzmann const. It is the temperature above which a particle can be freely created out of thermal radiation. (From "The First Three Minutes" by Weinberg, 1977)

Particle	Mass (MeV)	Threshold temp (10^9 K)	Meanlife time (s)
Photon	0	0	stable
Neutrino	0	0	stable
Electron	0.511	5.930	stable
Muon	105.66	1226.2	$2.197\text{x}10^{-6}$
Pions	134.96, 139.57	1566.2, 1619.7	$0.8\text{x}10^{-16}$, $2.60\text{x}10^{-8}$
Proton	938.26	10,888	0
Neutron	939.55	10,903	920