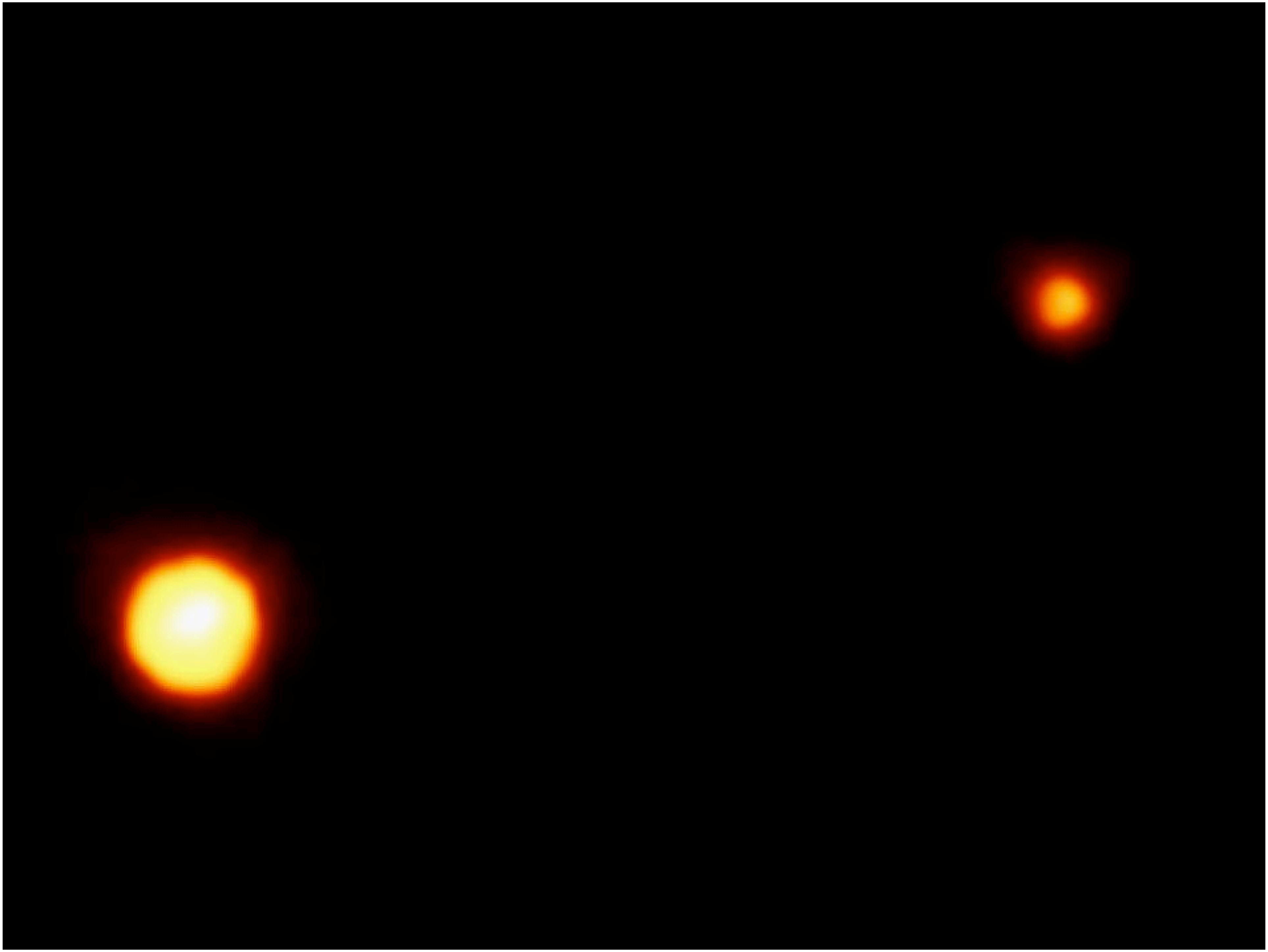
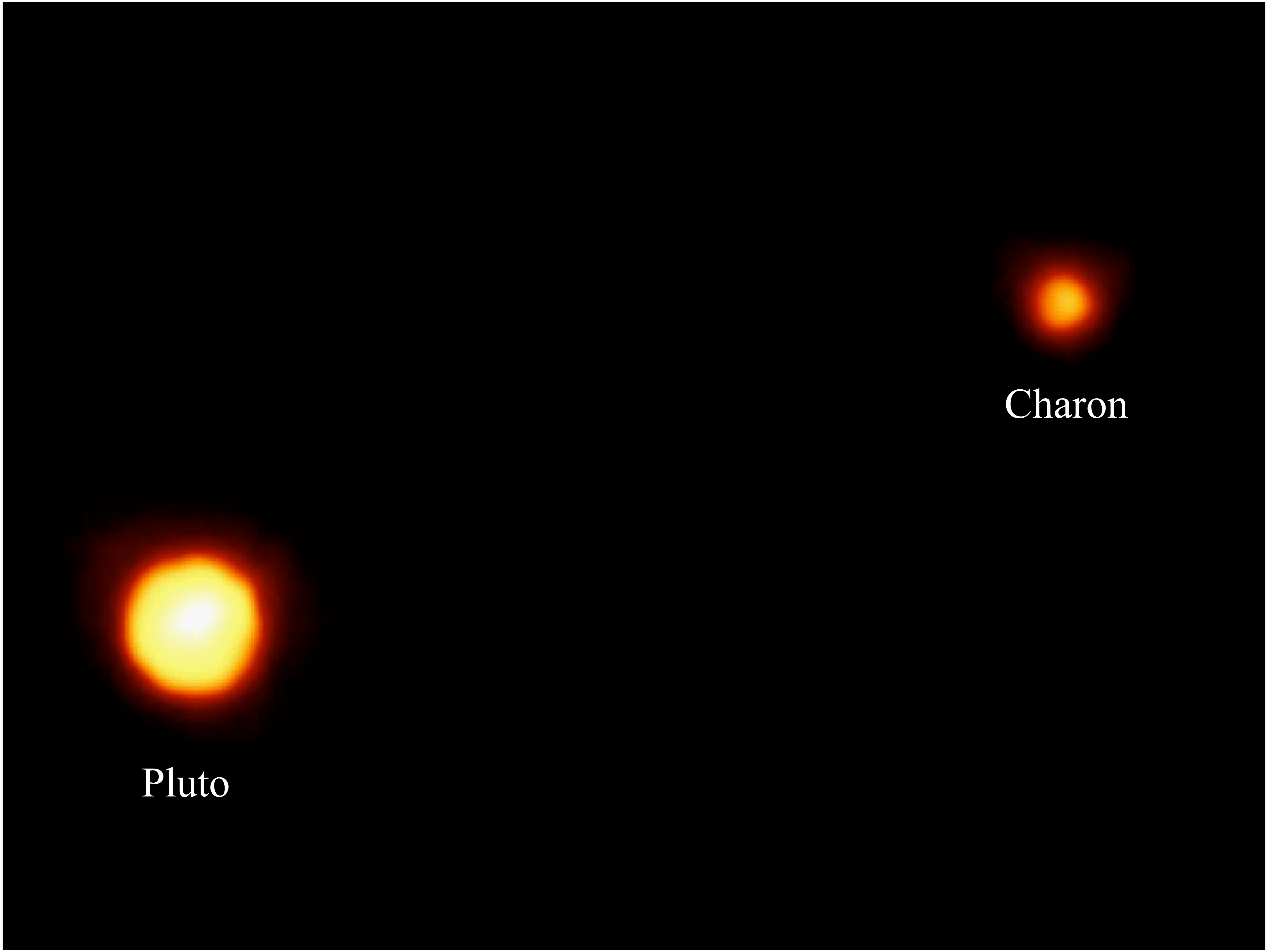
Experimental Probes of QGP (Part I)

Student Lecture, QM 2004, Oakland, CA

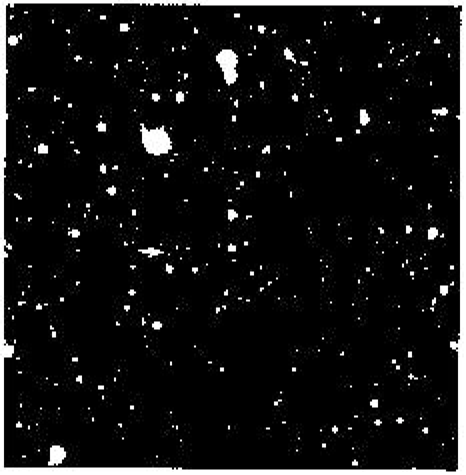
January 11, 2004

Thomas Ullrich, BNL



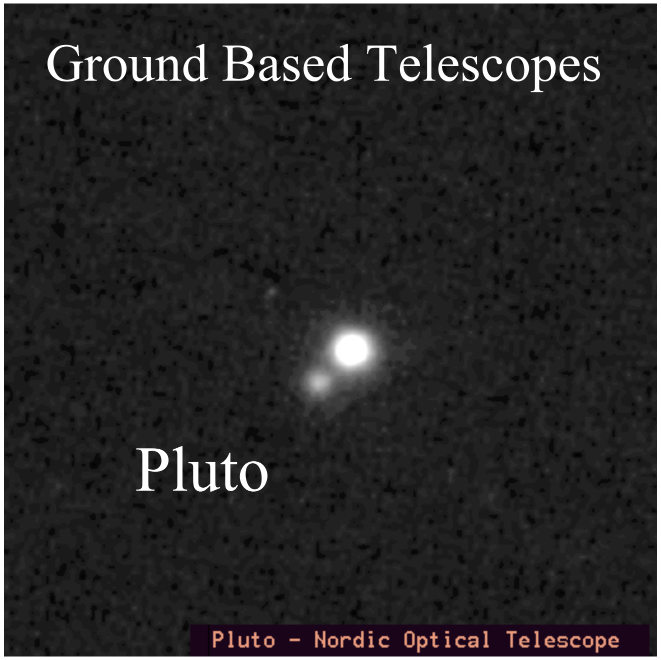

Charon
Pluto

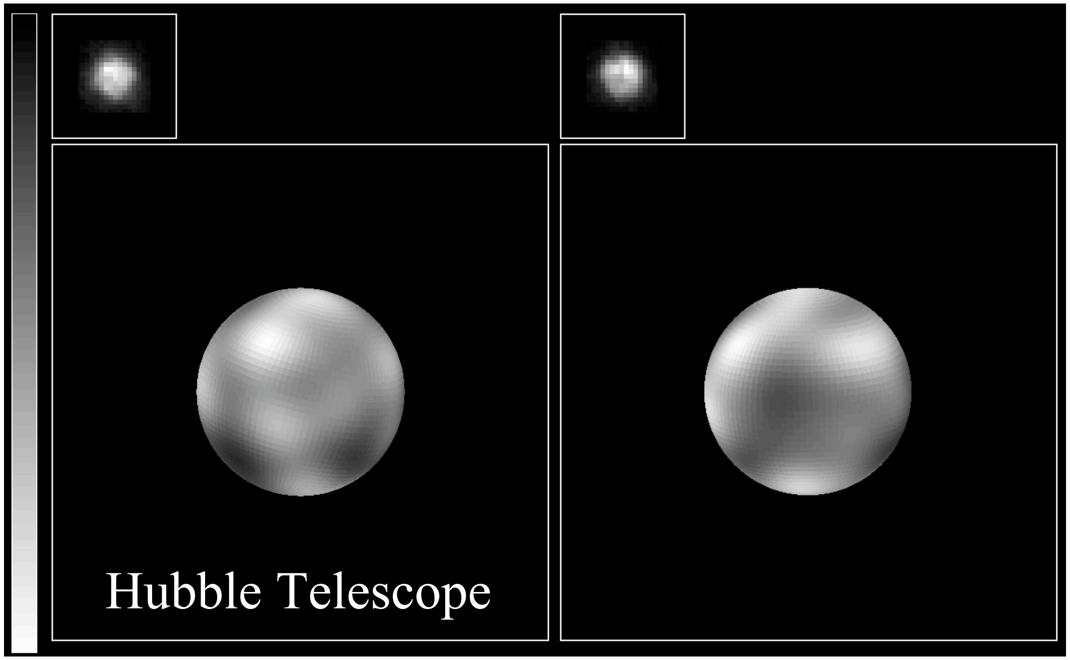
A Discovery



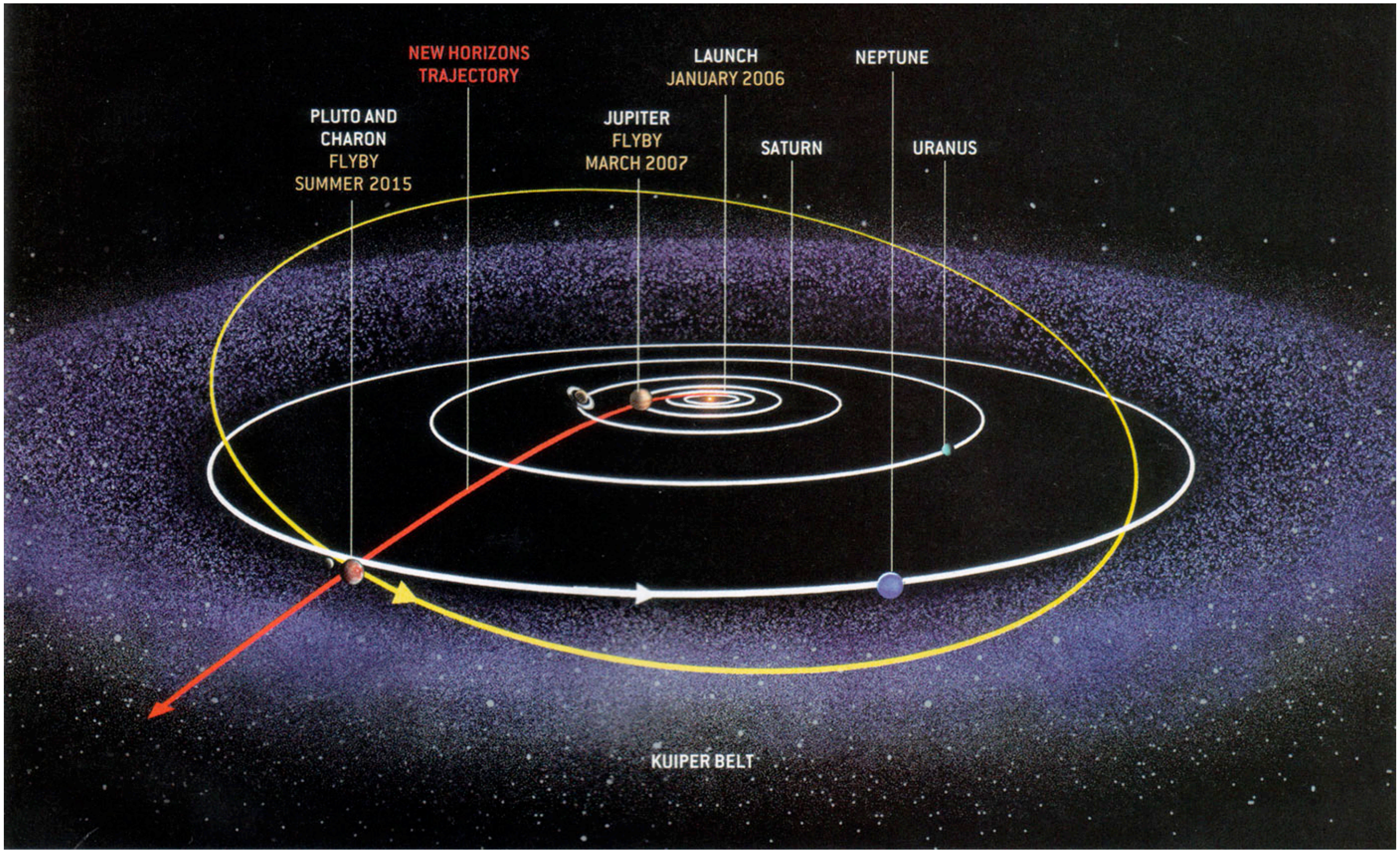
Clyde Tombaugh(1906-1997) took a photographic plate on January 23, 1930 that contained a tiny image of Pluto.

Pluto was officially labeled the ninth planet by the International Astronomical Union in 1930 and named for the Roman god of the underworld.





Is it a Planet ?



Kuiper Belt

- suggested 1951
- confirmed 1992

~ 30,000 objects larger than 100 km

1. Historically Pluto has been classified as a planet
2. Some think Pluto better classified as a large asteroid or comet
3. Some consider it to be the largest of the Kuiper Belt objects

A Matter of Definition …

POSITION STATEMENT ON THE DEFINITION OF A "PLANET"

WORKING GROUP ON EXTRASOLAR PLANETS (WGESP) OF THE INTERNATIONAL ASTRONOMICAL UNION

Created: February 28, 2001

Last Modified: February 28, 2003

Rather than try to construct a detailed definition of a planet which is designed to cover all future possibilities, the WGESP has agreed to restrict itself to developing a working definition applicable to the cases where there already are claimed detections, e.g., the radial velocity surveys of companions to (mostly) solar-type stars, and the imaging surveys for free-floating objects in young star clusters. As new claims are made in the future, the WGESP will weigh their individual merits and circumstances, and will try to fit the new objects into the WGESP definition of a "planet", revising this definition as necessary. This is a gradualist approach with an evolving definition, guided by the observations that will decide all in the end.

Emphasizing again that this is only a working definition, subject to change as we learn more about the census of low-mass companions, the WGESP has agreed to the following statements ...

So what is the Definition of "Quark Gluon Plasma"?

No working group on the definition of a *Quark Gluon Plasma* (yet)

*"The word **plasma** has a Greek root which means to be formed or molded.*
The term plasma is generally reserved for a system of charged particles large enough to behave collectively.
The typical characteristics of a plasma are:

- *Debye screening lengths that are short compared to the physical size of the plasma.*
- *Large number of particles within a sphere with a radius of the Debye length.*
- *Mean time between collisions usually are long when compared to the period of plasma oscillations"*

wordIQ.com

So what is the Definition of "Quark Gluon Plasma"?

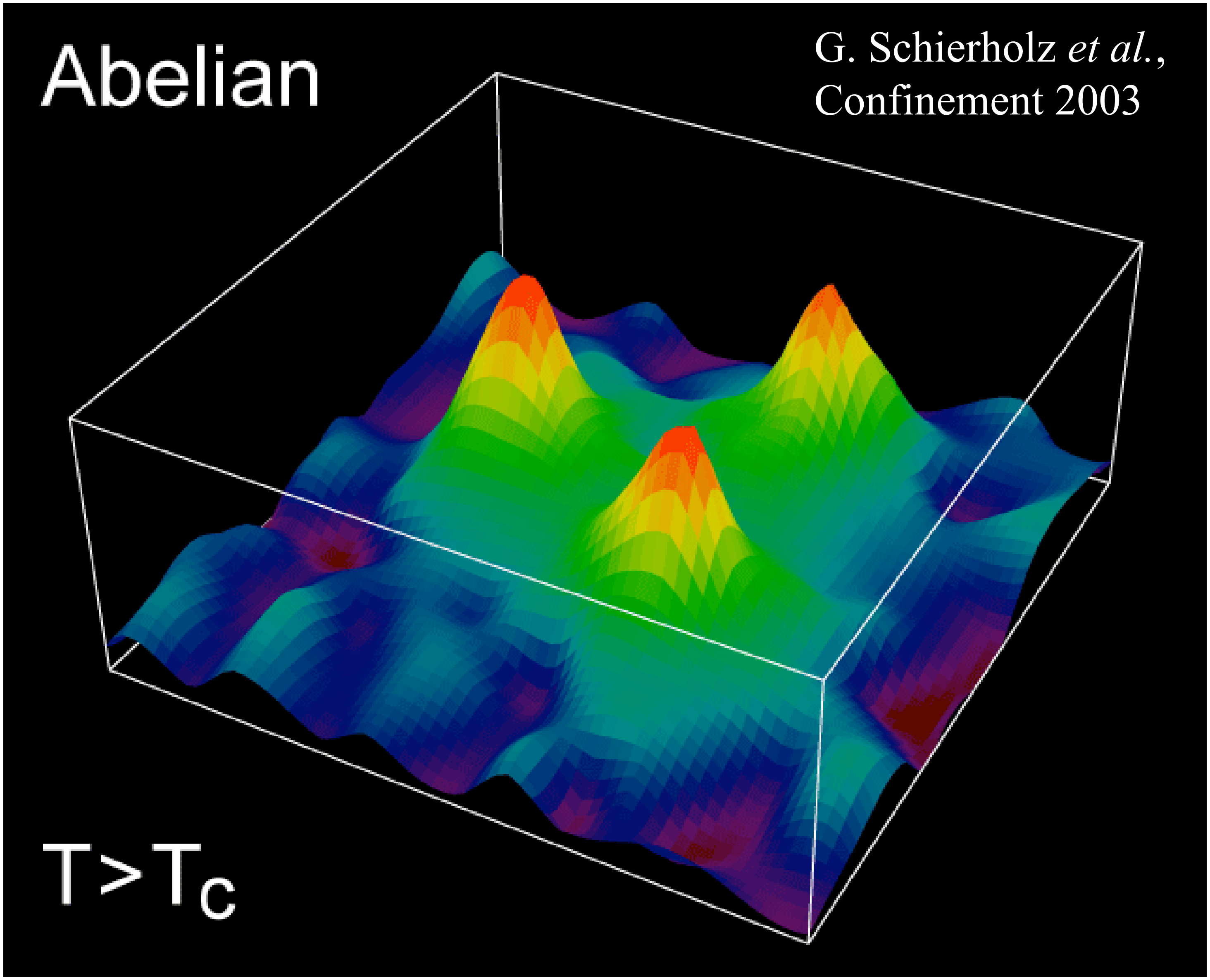
No working group on the definition of a *Quark Gluon Plasma* (yet)

Quark Gluon Plasma

"A deconfined system of strongly interaction matter (quarks and gluons) in thermal equilibrium at high temperatures and/or densities."

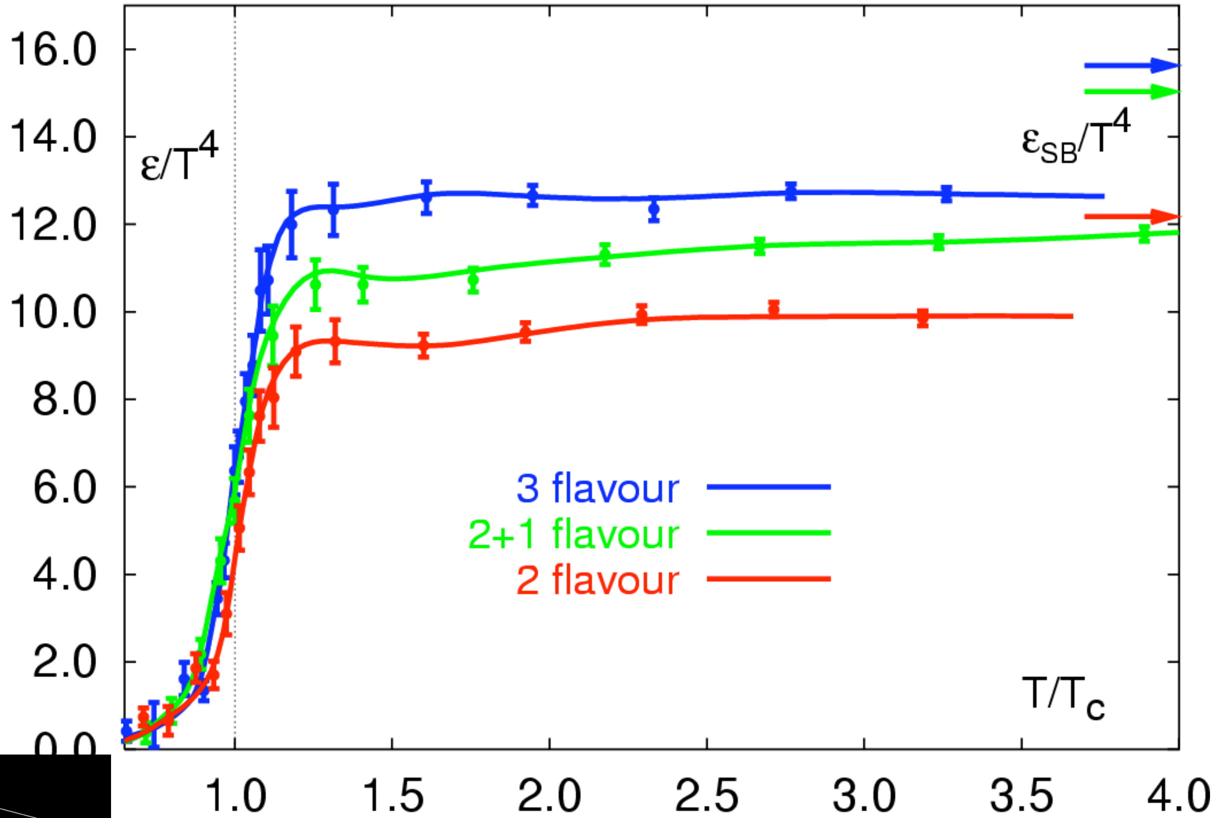
based on common wisdom

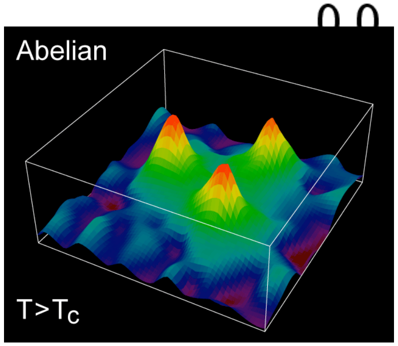
Lattice QCD at Finite Temperature



Lattice QCD at Finite Temperature

- Coincident transitions: deconfinement and chiral symmetry restoration
- Recently extended to $\mu_B > 0$, order still unclear (1st, 2nd, crossover ?)

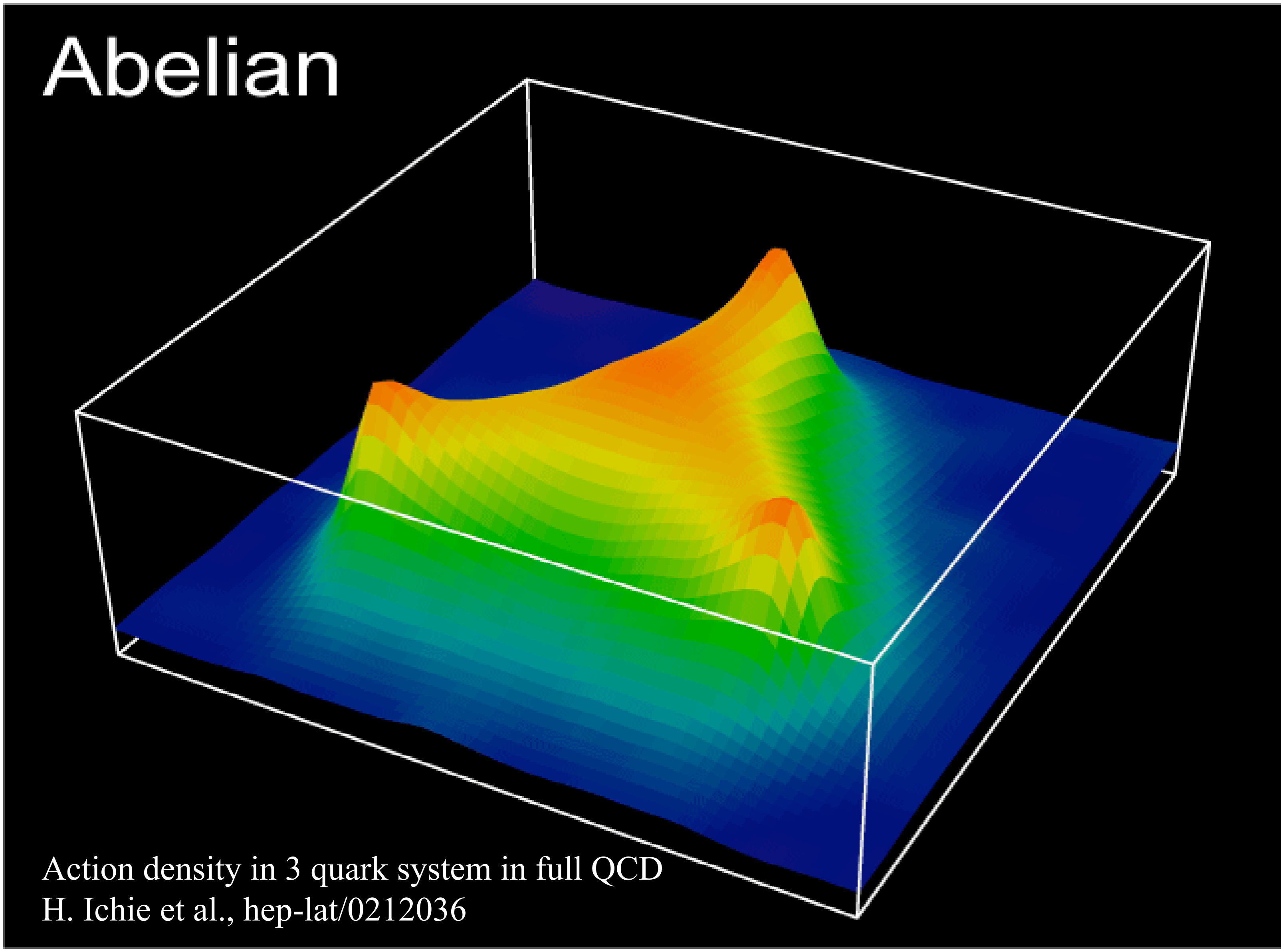




$T_C \approx 170$ MeV

F. Karsch, hep-ph/0103314

Lattice QCD at Finite Temperature



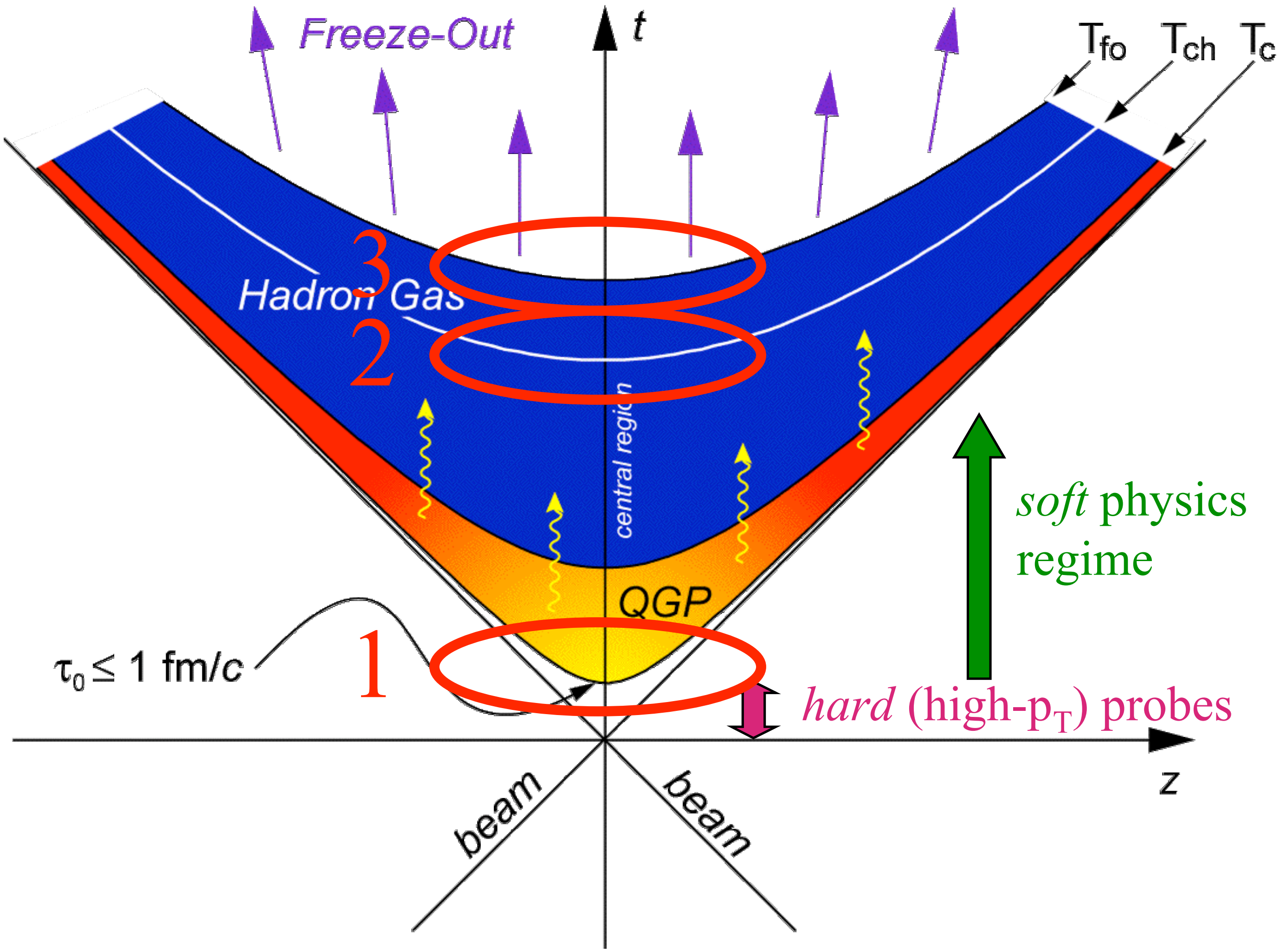
Action density in 3 quark system in full QCD
H. Ichie et al., hep-lat/0212036

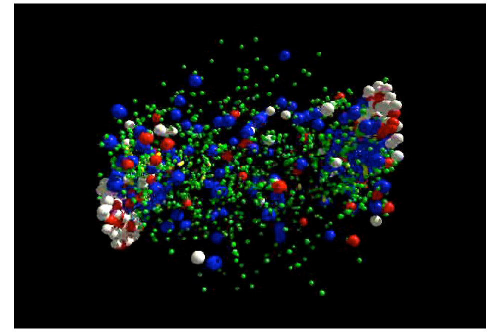
Probes of the QGP – A Laundry List

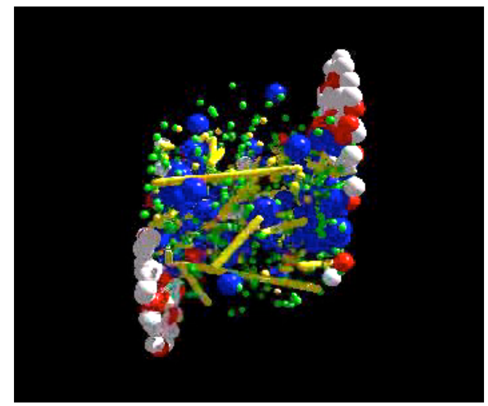
- **Kinematic Probes**
  - ϵ, p, s(T,μ_B)
  - Spectra → $\langle p_T \rangle$, dN/dy, dE_T/dy
  - Particle Ratios
  - Radial and Elliptic Flow
  - Correlations:
    - Identical and Non-Identical Particle Interferometry (HBT)
    - Balance Function
  - Fluctuations:
    - $\langle p_T \rangle$, N_{ch}
- **Electromagnetic Probes**
  - Direct Photons
  - Thermal Dileptons / Leptonpairs
- **Probes of Deconfinement**
  - Quarkonium Suppression
  - Strangeness Enhancement
- **Probes of Chiral Symmetry Restoration**
  - Medium Effects on Hadron Properties
  - Disoriented Chiral Condensates
- **Hard QCD Probes**
  - Jet Quenching
- **Models/Theory**
  - QGP Models
  - Non-QGP Models

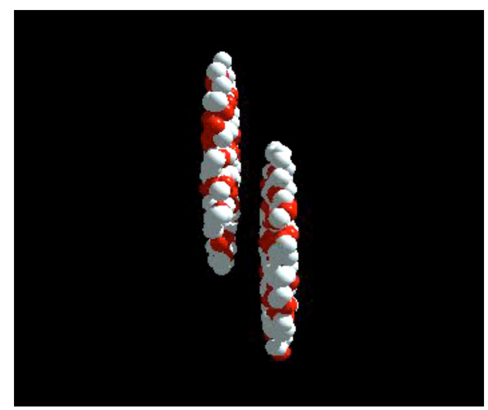
For more see for example: C.P. Singh, Physics Reports 236 (1993) 147-224, J. Harris and B. Müller, Annu, Rev. Nucl. Part. Sci. 1996 46:71-107 (http://arjournals.annualreviews.org/doi/pdf/10.1146/annurev.nucl.46.1.71) and QM Proceedings

Outline





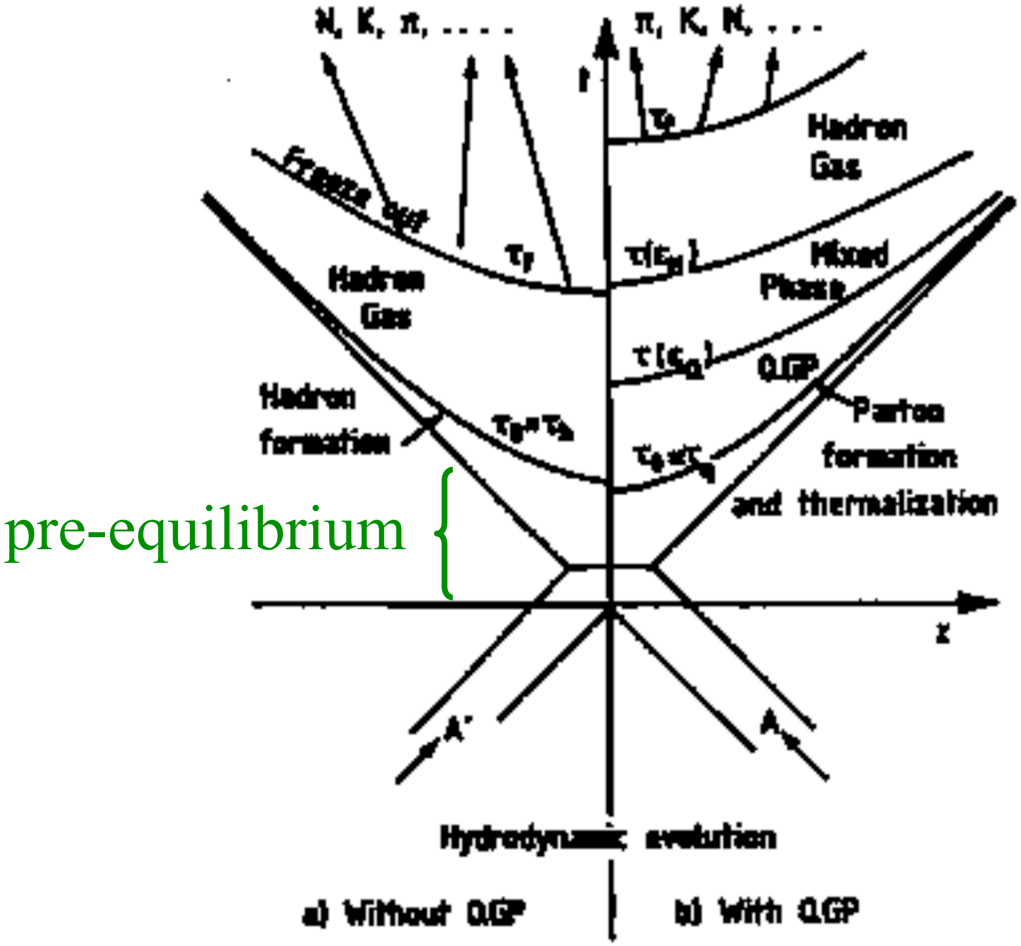




Chemical freezeout (T_{ch} □ T_c): inelastic scattering ceases

Kinetic freeze-out (T_{fo} □ T_{ch}): elastic scattering ceases

Are the conditions at SPS/RHIC met to form a QGP?



QCD on Lattice (2-flavor):

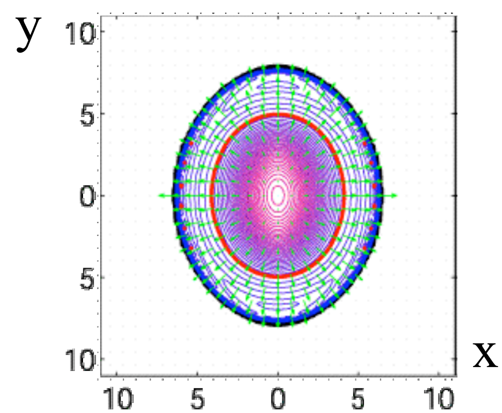
Phase transition at

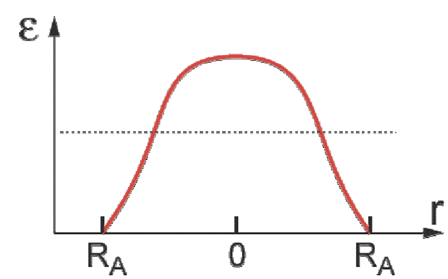
$T_C \approx 173 \pm 8$ MeV, $\varepsilon_C \approx (6\pm2)\, T^4$

hence $\varepsilon_C \approx 0.70 \pm 0.27$ GeV/fm^3

Remember: cold nuclear matter

$\varepsilon_{cold} \approx$ u / $^4/_3\pi r_0^{\,3} \approx 0.13$ GeV/fm^3





At a minimum we need to create ε_C in order to create a QGP.

Note: this is a necessary but **not** sufficient condition

Tevatron (Fermilab) ε($\sqrt{s}$ = 1.8 TeV pp) >> ε(Au+Au RHIC)

Thermal Equilibrium → many constitutents → Size matters !!!

Assessing the Initial Energy Density: Calorimetry

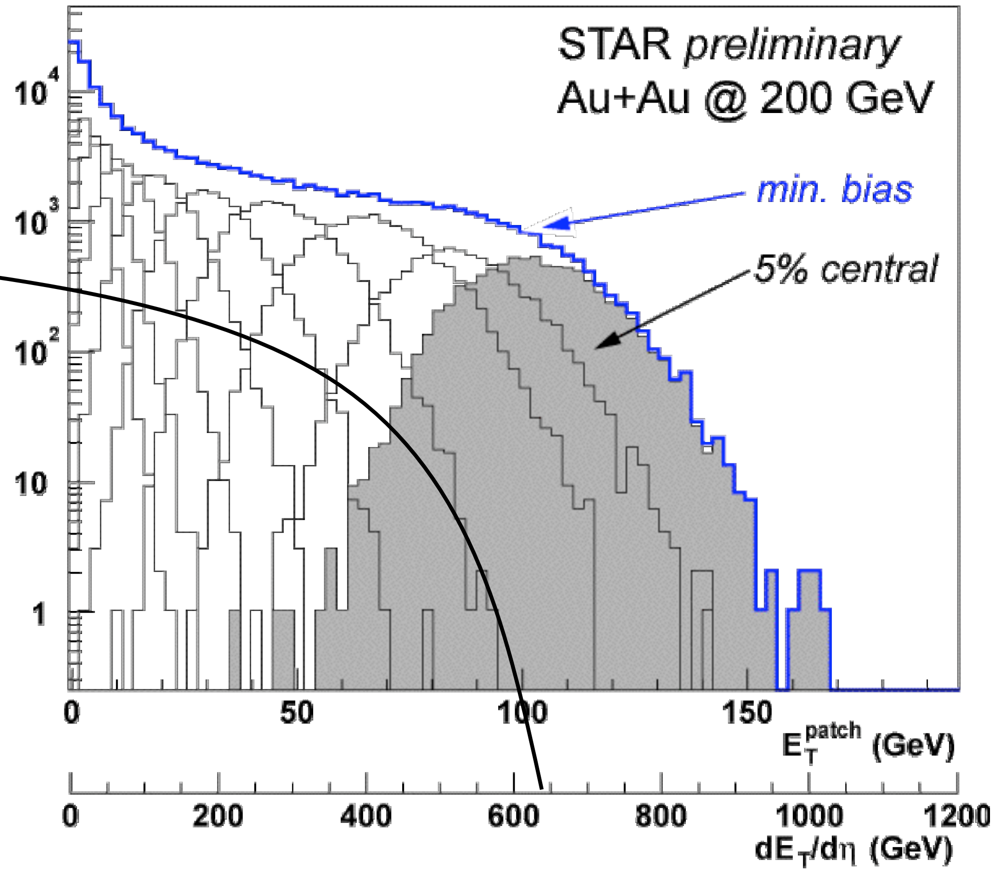
Bjorken-Formula for Energy Density:

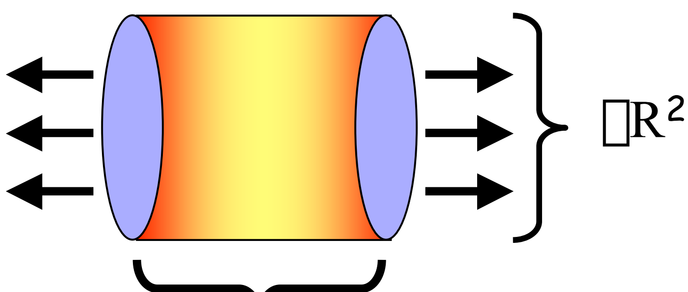
PRD 27, 140 (1983) – watch out for typo (factor 2)

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\,\frac{1}{\tau_0}\,\frac{dE_T}{dy}$$

~6.5 fm

Time it takes to thermalize system (τ_0 ~ 1 fm/c)





$$dz = \tau_0 dy$$

Note: τ_0 (RHIC) < τ_0 (SPS)
commonly use 1 fm/c in both cases

Central Au+Au (Pb+Pb) Collisions:
17 GeV: $\varepsilon_{BJ} \approx$ 3.2 GeV/fm^3
130 GeV: $\varepsilon_{BJ} \approx$ 4.6 GeV/fm^3
200 GeV: $\varepsilon_{BJ} \approx$ 5.0 GeV/fm^3

Assessing the Initial Energy Density: Tracking

Bjorken-Formula for Energy Density:

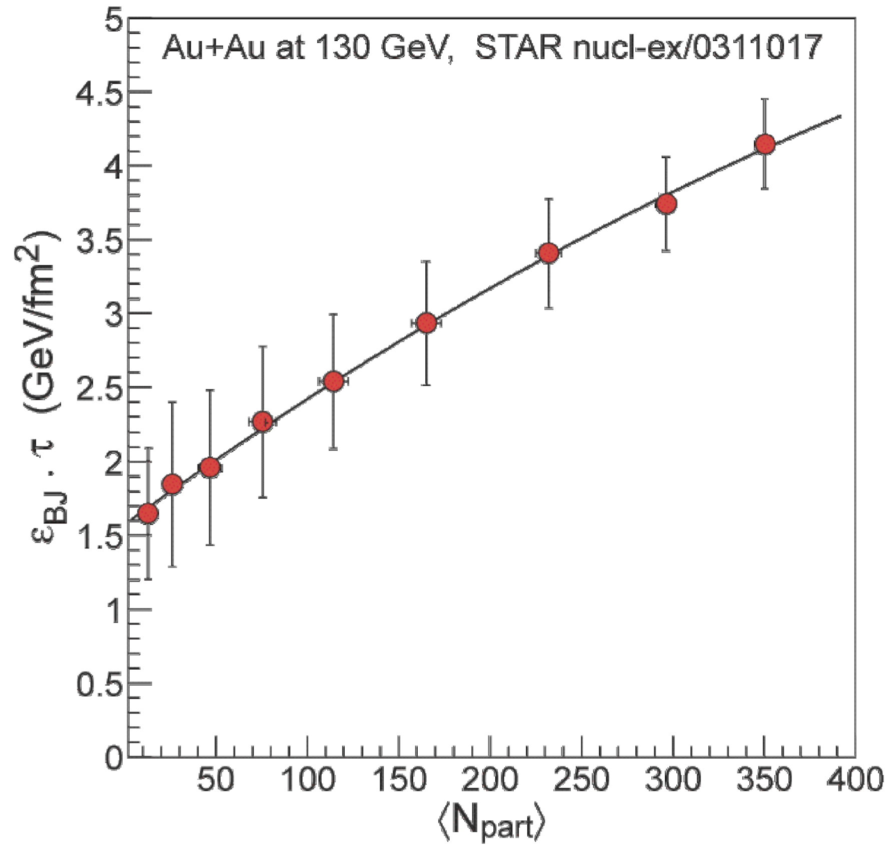
$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

$$\frac{dE_T}{dy} = \langle m_T \rangle \frac{3}{2} \frac{dN_{ch}}{dy} \qquad \text{at } y=0$$

$$\frac{dN_{ch}}{dy} = \left(1 - \frac{m^2}{\langle m_T \rangle^2}\right)^{-1/2} \frac{dN_{ch}}{d\eta}$$

and hence

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \langle m_T \rangle \frac{3}{2} \left(1 - \frac{m^2}{\langle m_T \rangle^2}\right)^{-1/2} \frac{dN_{ch}}{d\eta}$$



Gives interestingly always slightly smaller values than with calorimetry (~15% in NA49 and STAR).

The Problem with ϵ_{BJ}

- ϵ_{BJ} is not necessarily a "thermalized" energy density
  - no direct relation to lattice value

- τ_0 is not well defined and model dependent
  - usually 1fm/c taken for SPS
  - 0.2 – 0.6 fm/c at RHIC ?

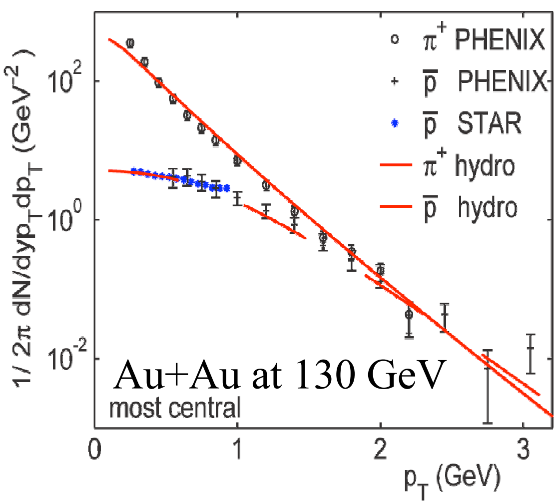
- system performs work p·dV $\Rightarrow$ $\epsilon_{real} > \epsilon_{BJ}$
  - from simple thermodynamic assumptions
    $\Rightarrow$ roughly factor 2

Other Means of Assessing Energy Density

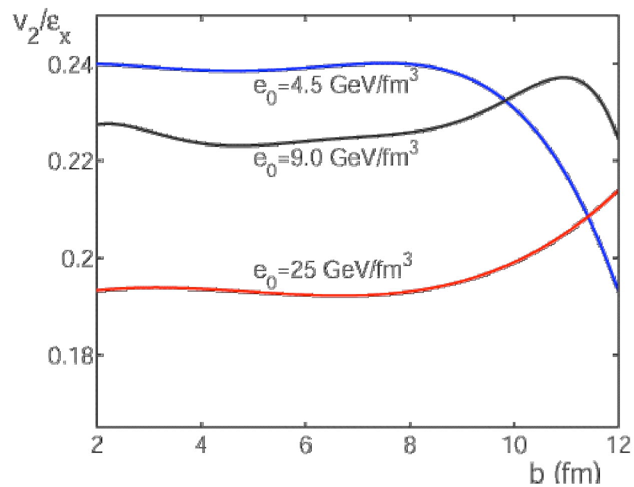
Hydrodynamic Models (*more later*):

- need to fix initial conditions to describe spectra & flow
- at RHIC: $\epsilon_0 \approx 25$ GeV/fm^3 at $\tau_0 = 0.6$ fm/c in fireball center
- Careful
  - depends on EOS
  - thermalization is fundamental ingredient of model

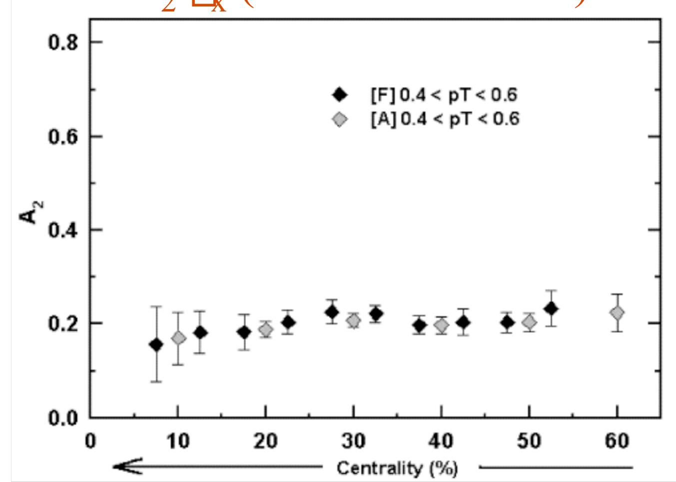
spectra: data&hydro



v_2/ϵ_x hydro-model



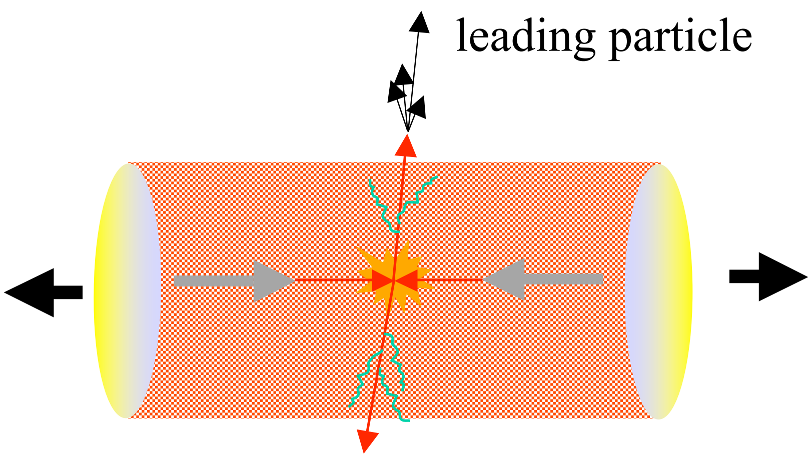
v_2/ϵ_x (Phenix 130 GeV)

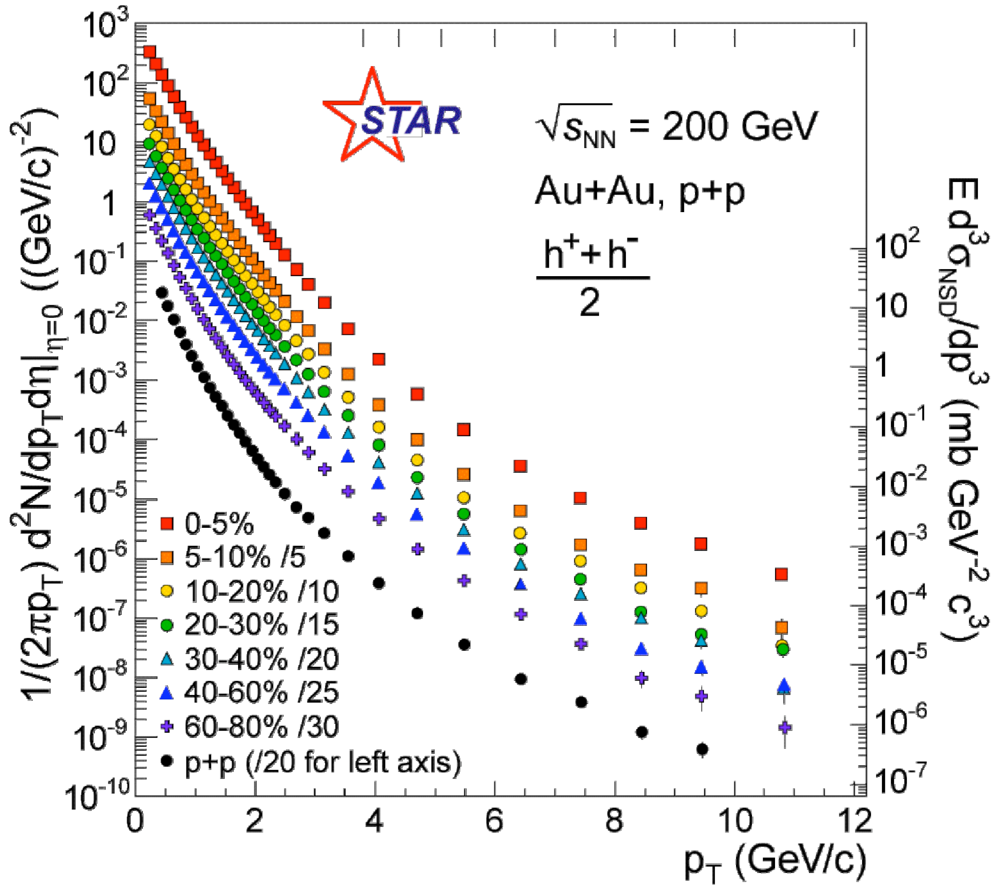


Kolb,Heinz, nucl-th/0305084

Yet another Means of Assessing Energy Density

"Jet Quenching"





Energy loss via induced gluon bremsstrahlung

$\Delta E \propto \rho_{glue} \propto dN_{glue}/dy \Rightarrow$ estimate of ε

Yet another Means of Assessing Energy Density

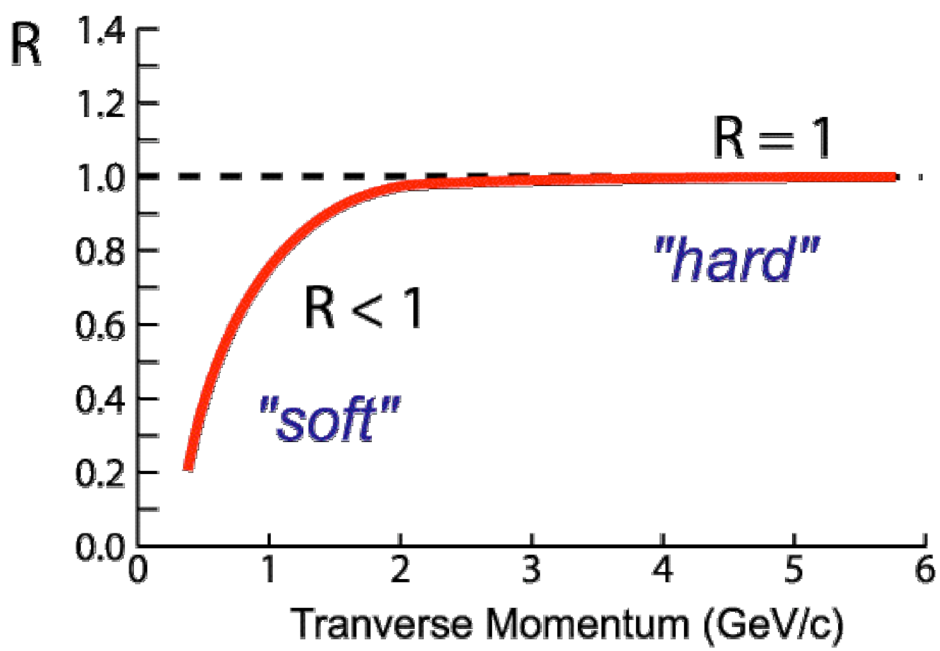
Compare Au+Au with p+p Collisions ⇒ R_{AA}

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA}\, d^2\sigma^{NN}/dp_T d\eta}$$

N-N cross section

$\langle N_{binary}\rangle/\sigma_{inel}^{p+p}$

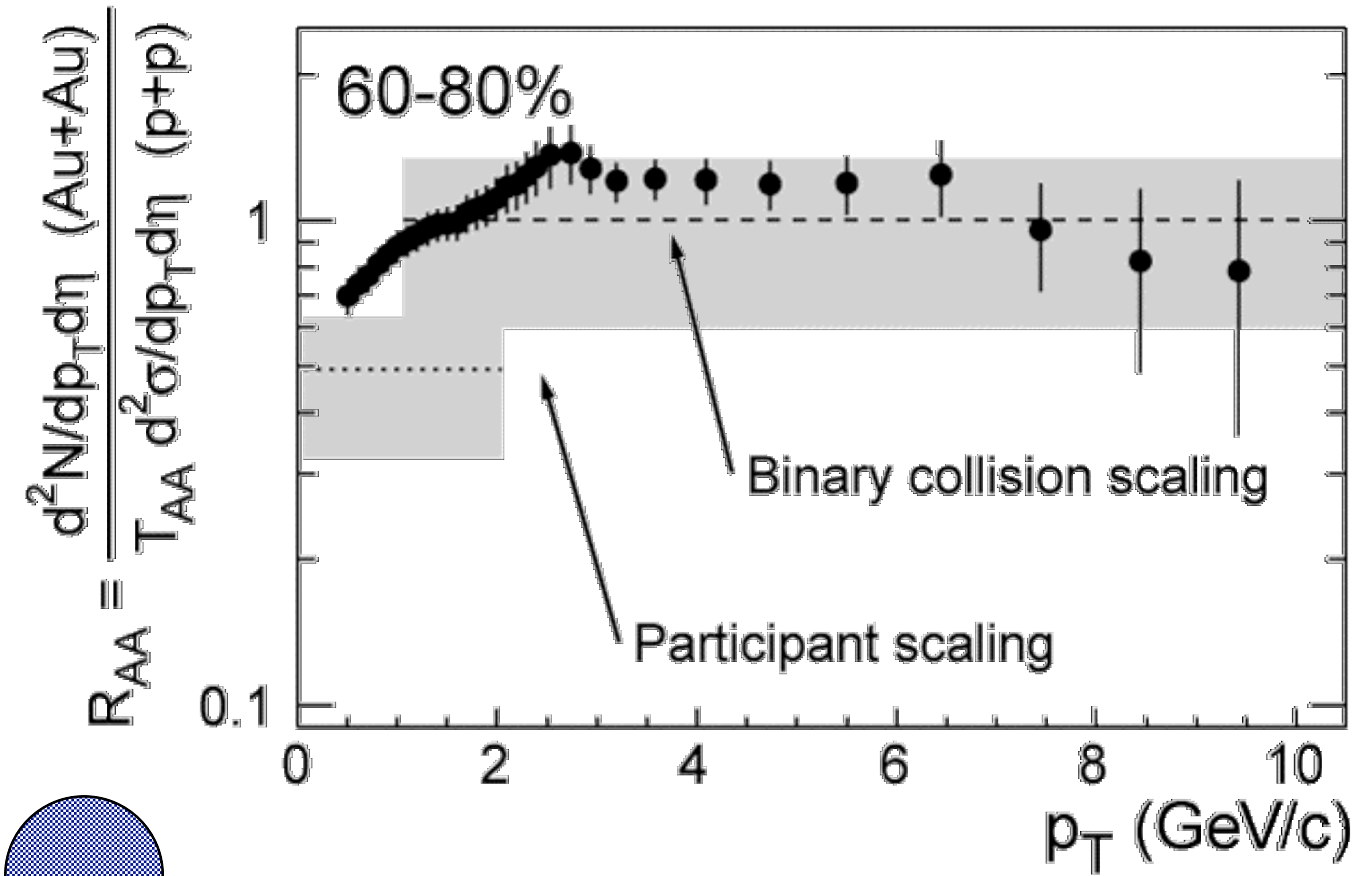


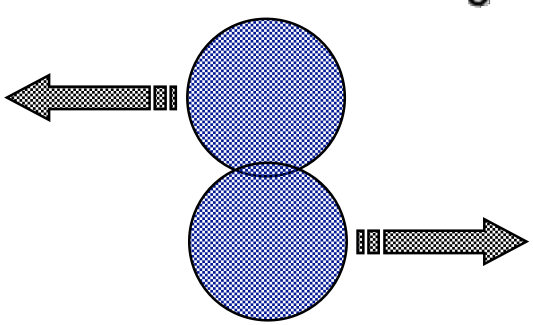
No "Effect":
- $R < 1$ at small momenta
- $R = 1$ at higher momenta where hard processes dominate

Suppression: $R < 1$

Yet another Means of Assessing Energy Density

STAR, nucl-ex/0305015





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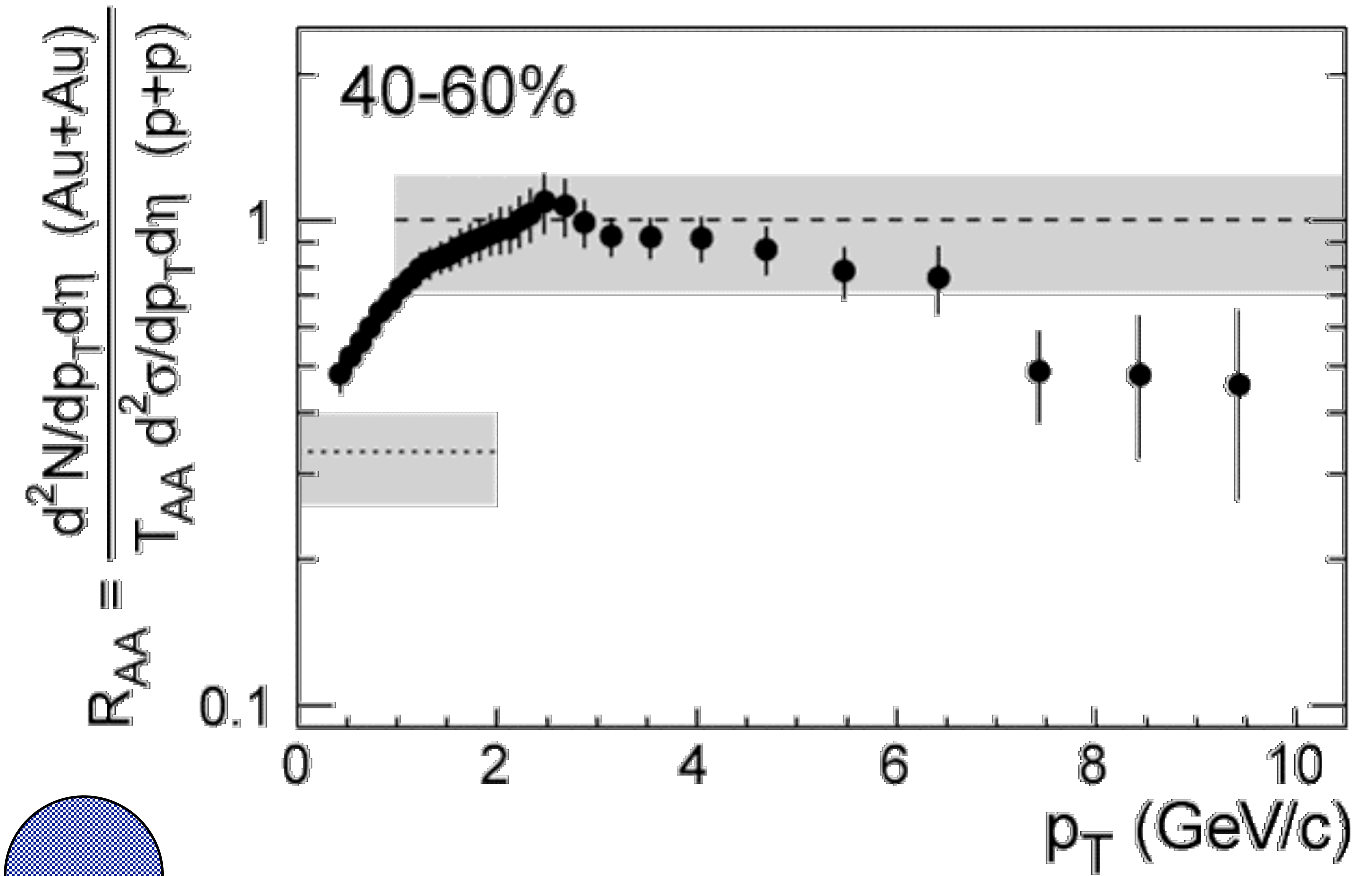

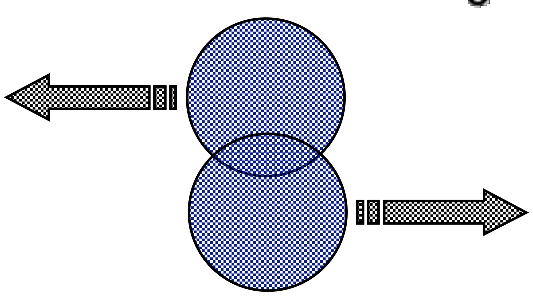

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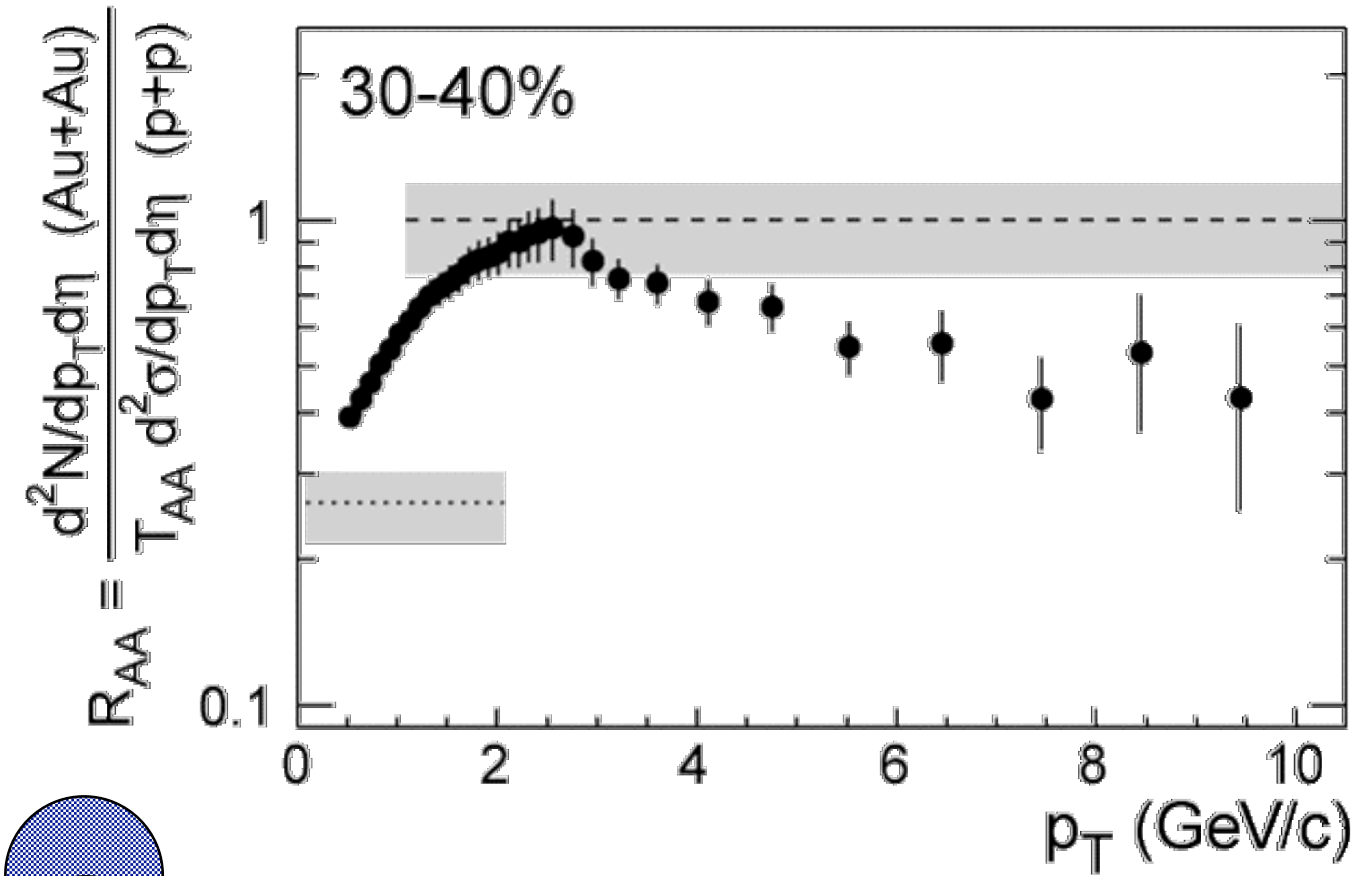

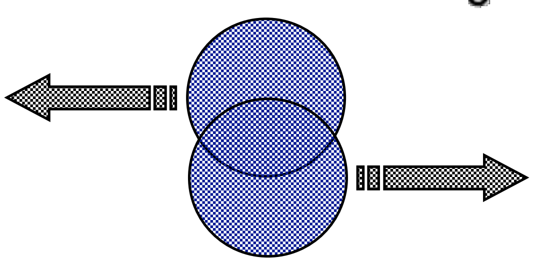

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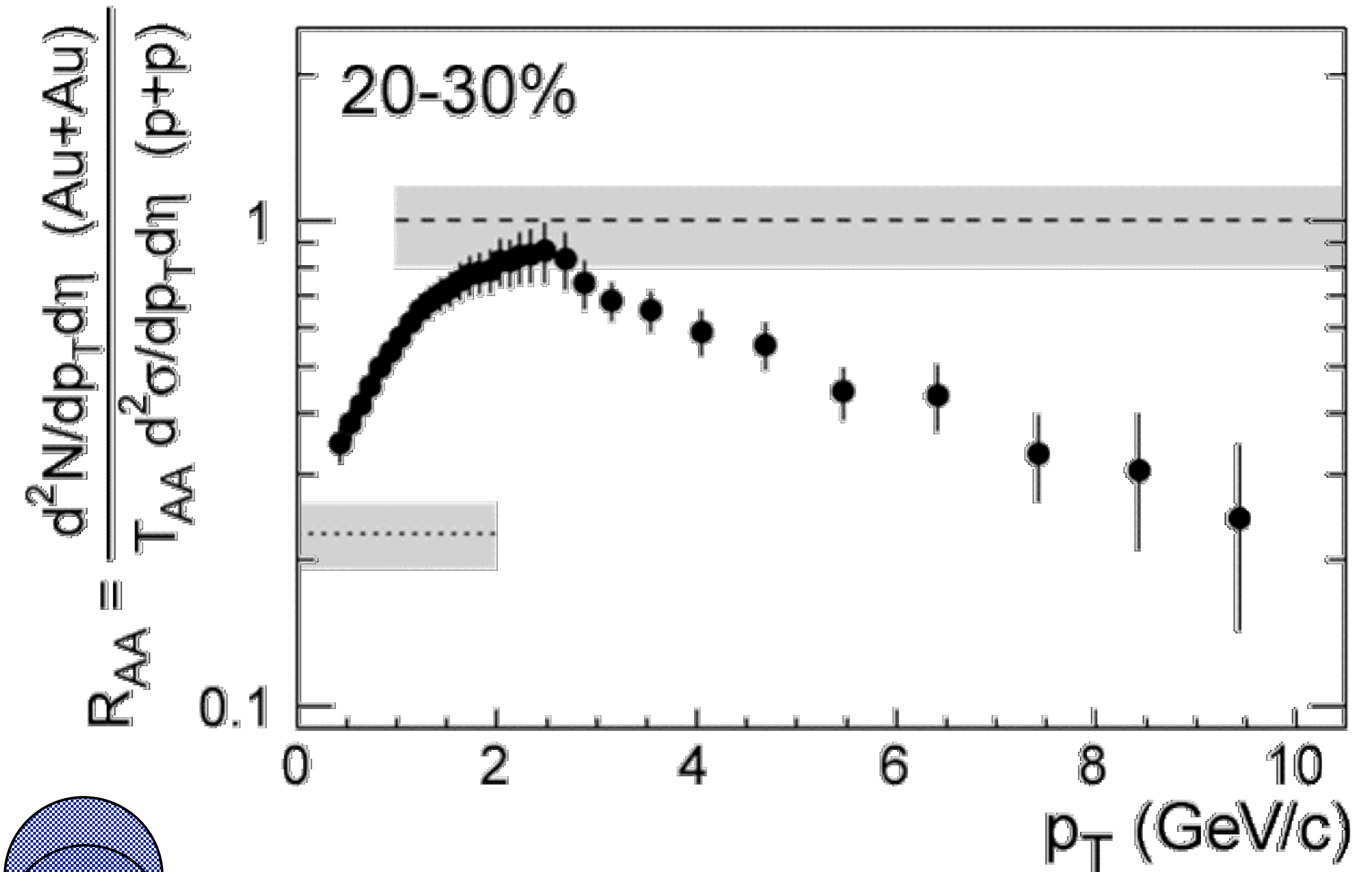

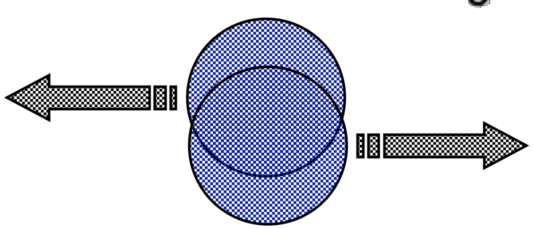

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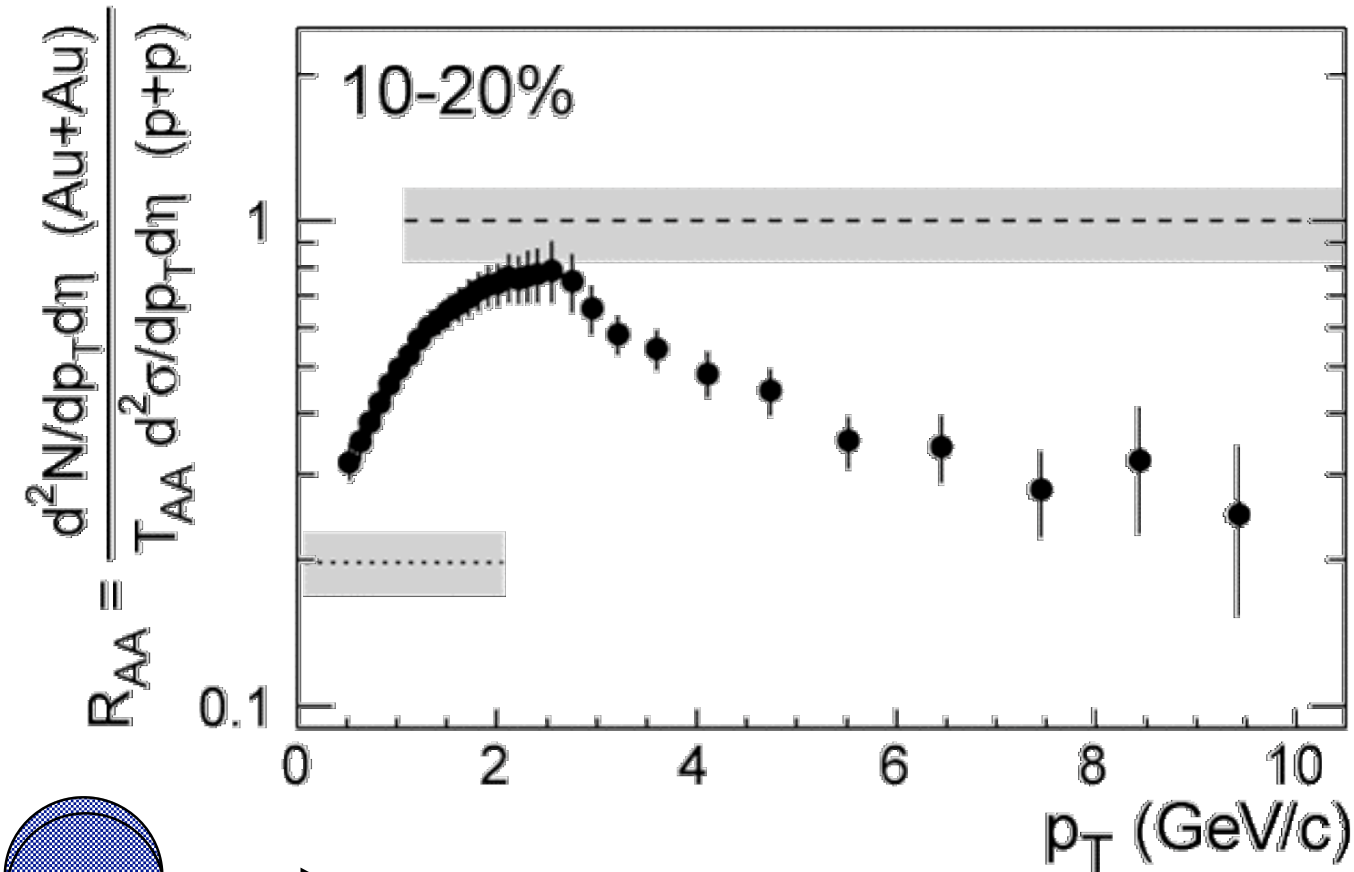

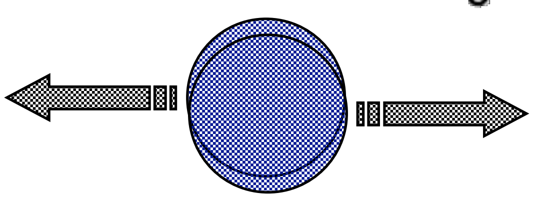

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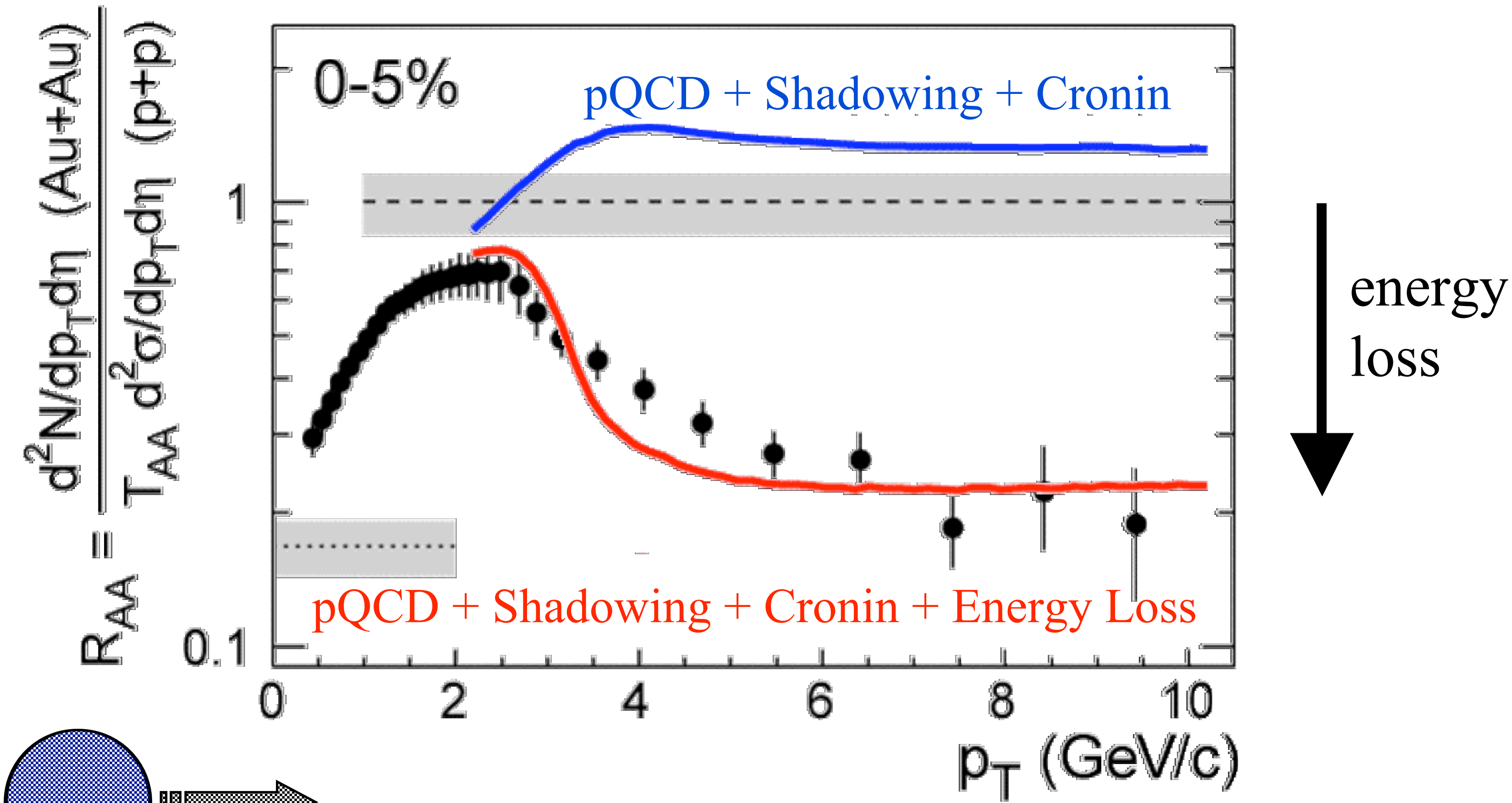

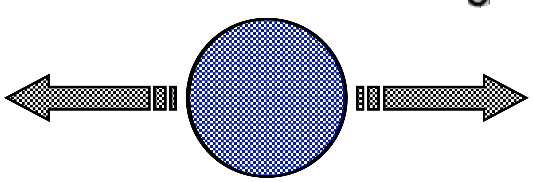

Yet another Means of Assessing Energy Density

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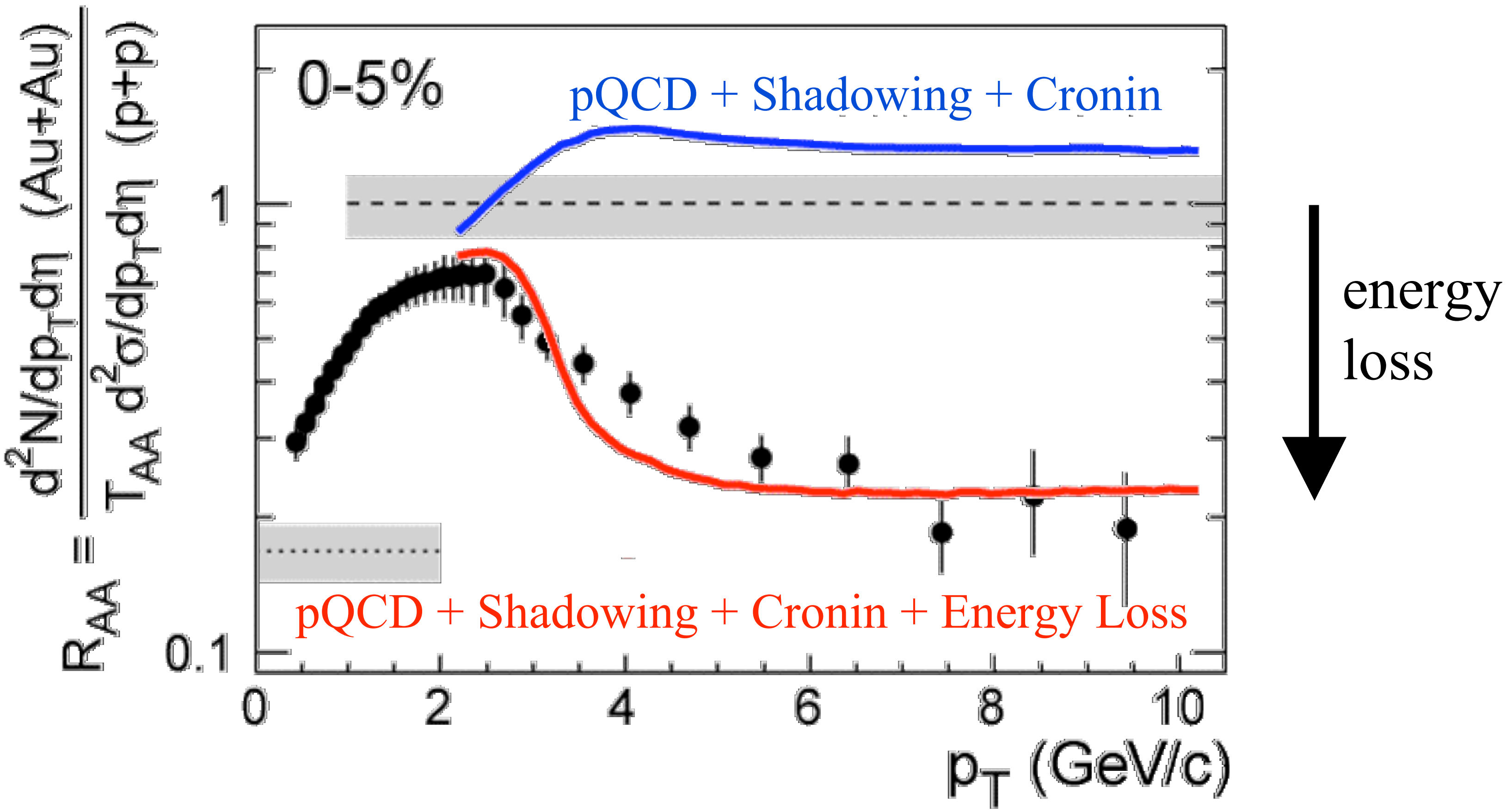


Deduced initial gluon density at □$_0$ = 0.2 fm/c $dN_{glue}/dy \approx$ 800-1200

□ □$\approx$ 15 GeV/fm^3

(e.g. X.N. Wang nucl-th/0307036)

So what is ε now ?

At RHIC energies, central Au+Au collisions:

1. From Bjorken estimates via E_T and N_{ch} $\varepsilon >$ 5 GeV/fm^3
2. Calculations of energy loss of high-p_T particles $\varepsilon \approx$ 15 GeV/fm^3

Both do not tell us anything about thermalization or deconfinement
(the proof can only come indirectly through models)

3. Hydro models assuming thermalization give $\varepsilon_{center} \approx$ 25 GeV/fm^3

All are rough estimates and model dependent (EOS, τ_0, ... ?)
Methods not completely comparable

But are without doubt good enough to support that $\varepsilon >> \varepsilon_C \approx$ 1 GeV/fm^3

Thermalization and Freeze-Out

What can final-state particle yields and momenta tell us about thermal conditions at **freeze-out**?

Chemical freeze-out

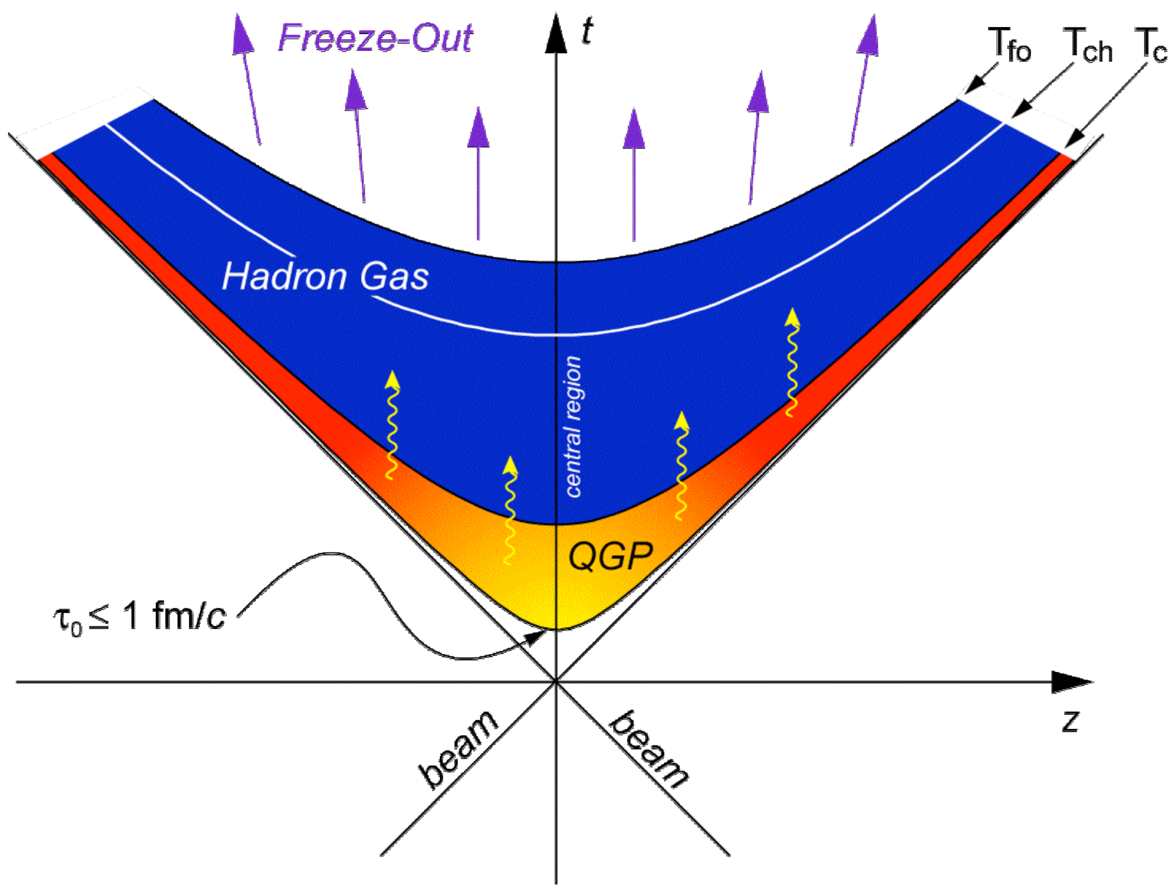
(yields & ratios)

- inelastic interactions cease
- particle abundances fixed (except maybe resonances)

Thermal freeze-out

(*shapes* of p_T,m_T spectra):

- elastic interactions cease
- particle dynamics fixed

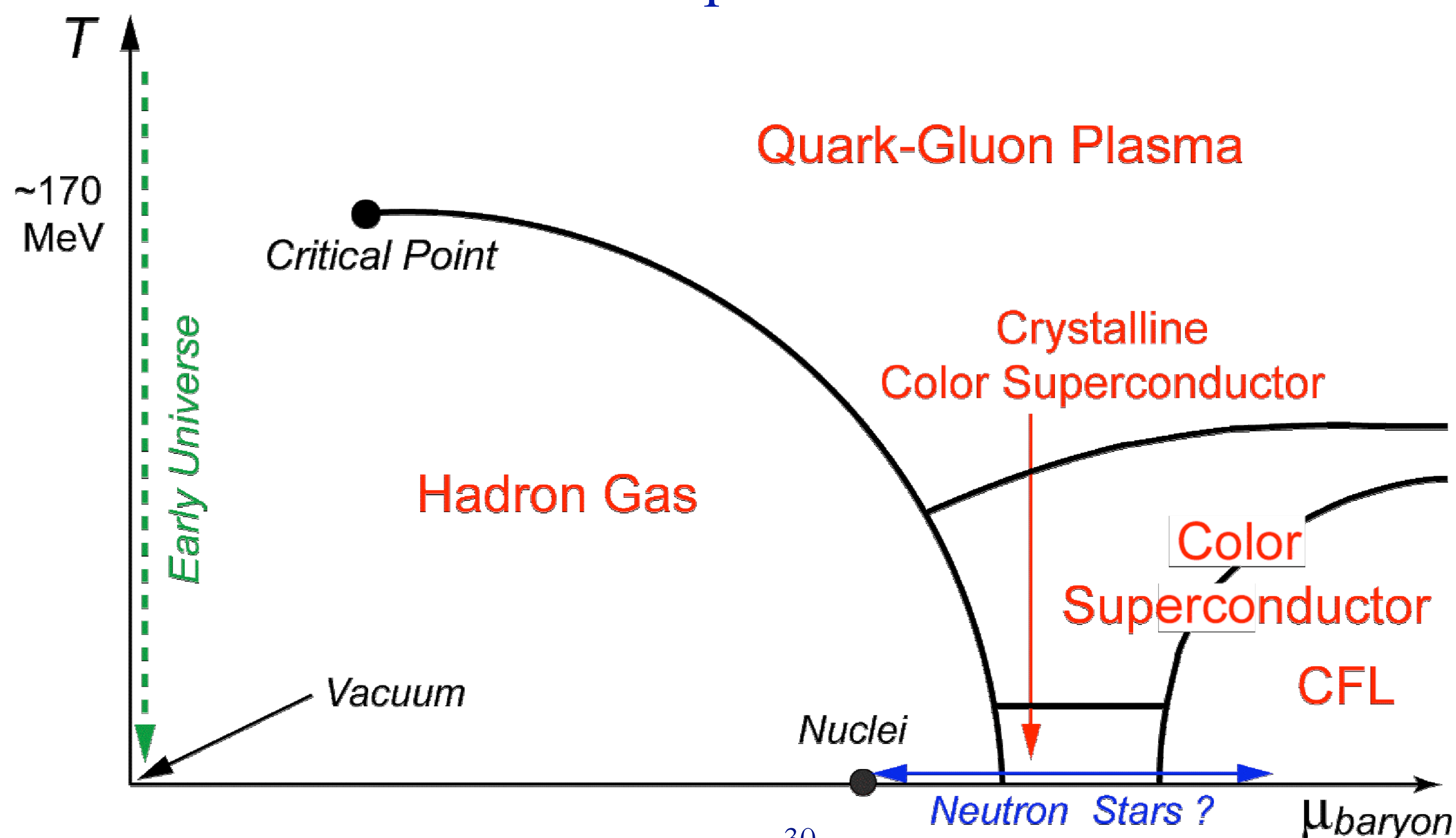


Statistical Models in RHI Collisions

Where in the phase diagram is the system at chemical freeze-out?

What values have T_{ch}, μ_B ?

 Statistical Thermal Models: a means to extract (T_{ch}, μ_B) from particle ratios



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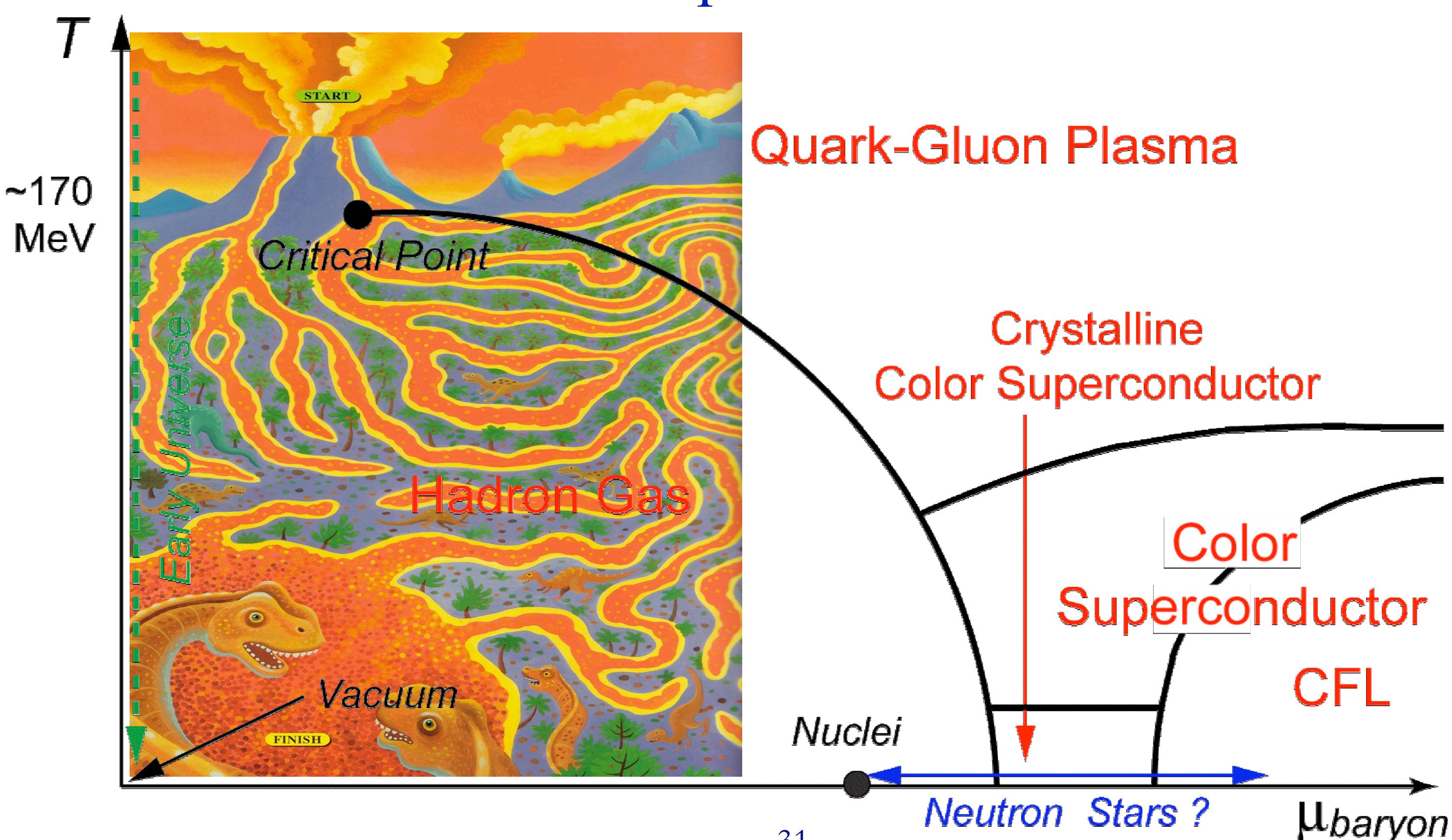


The Basic Idea behind Statistical Hadronic Models

- Assume thermally (constant T_{ch}) and chemically (constant n_i) equilibrated system at chemical freeze-out
- System composed of non-interacting hadrons and resonances
- Given T_{ch} and μ's (+ system size), n_i's can be calculated in a grand canonical ensemble

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

- Obey conservation laws: Baryon Number, Strangeness, Isospin
- Short-lived particles and resonances need to be taken into account

T_{ch}, μ_B

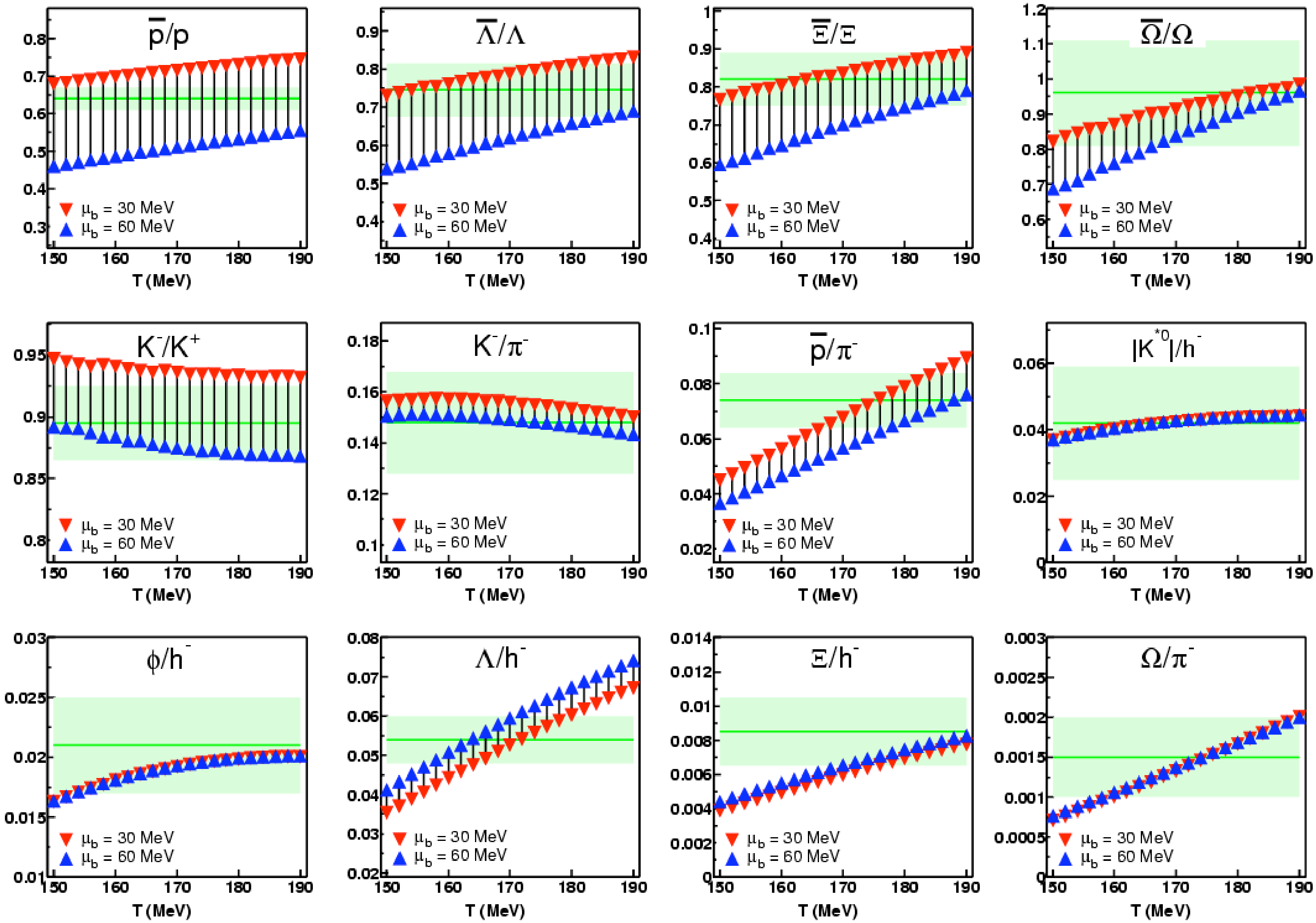
Iterate

Compare particle ratios to experimental data

Statistical Hadronic Models : Misconceptions

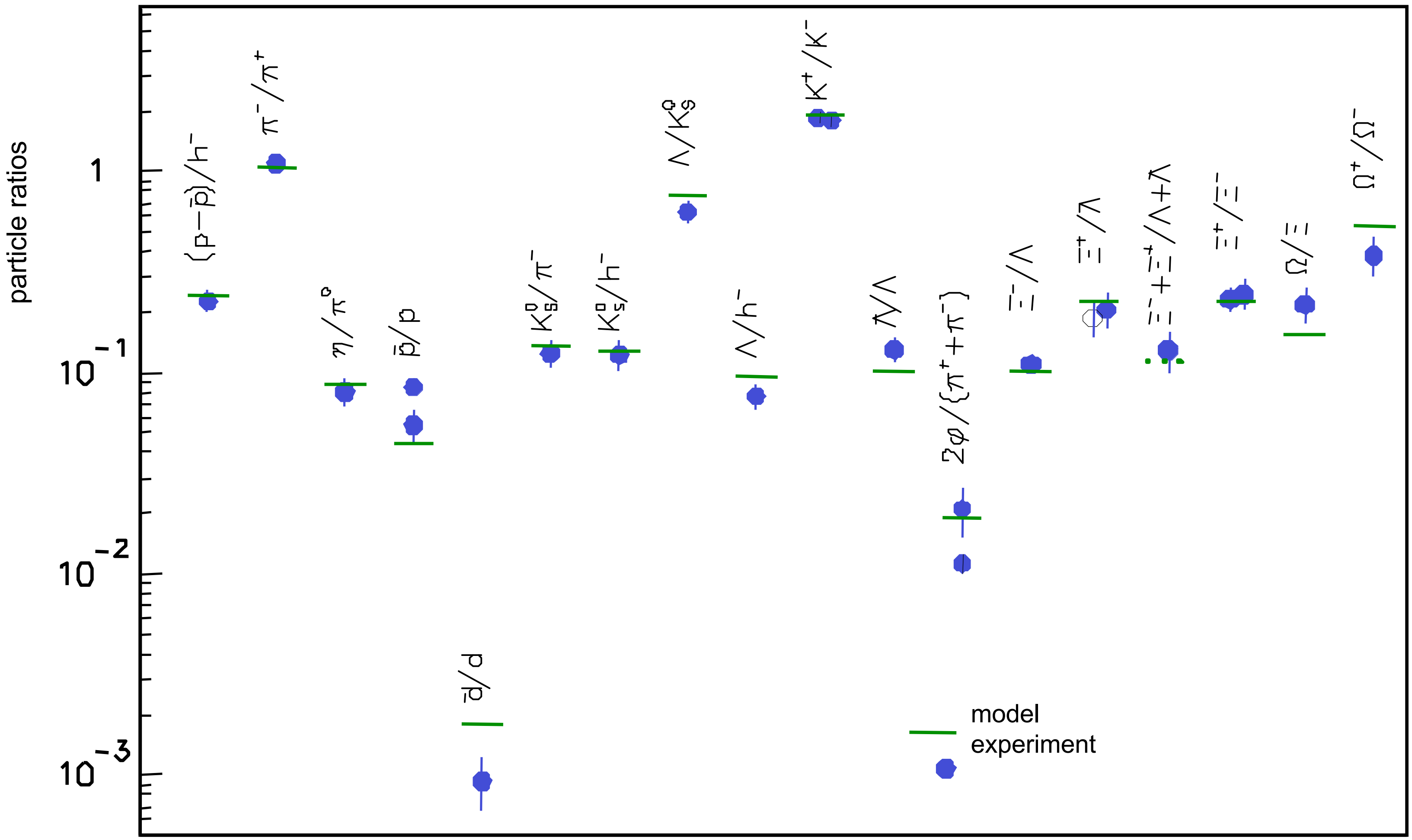
- Model says nothing about how system reaches chemical equilibrium
- Model says nothing about when system reaches chemical equilibrium
- Model makes no predictions of dynamical quantities
- Some models use a strangeness suppression factor, others not
- Model does not make assumptions about a partonic phase; However the model findings can complement other studies of the phase diagram (e.g. Lattice-QCD)

Ratios which constrain model parameters



D. Magestro, J. Phys G28 (2002) 1745; updated July 21

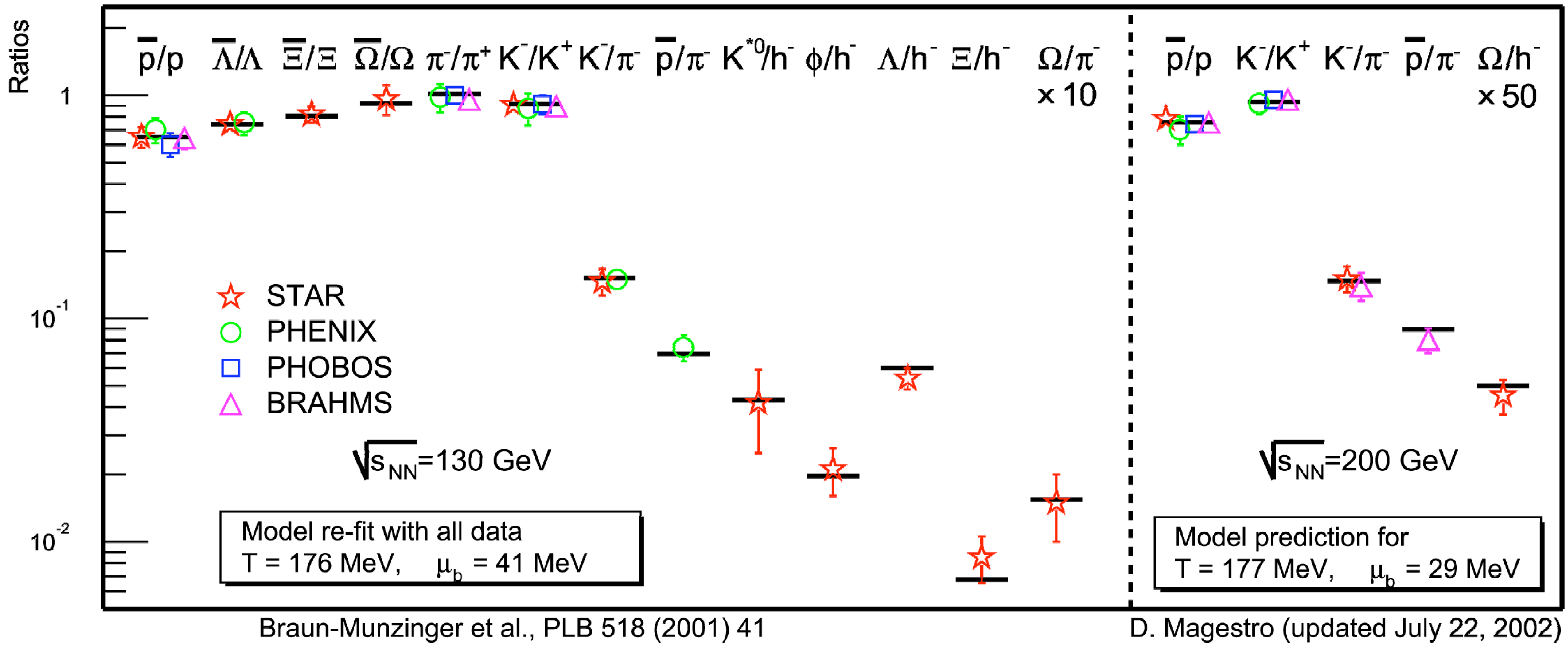
Statistical Thermal Models work well at SPS



- T = 168 ± 2.4 MeV
  μ_B = 266 ± 5 MeV

Braun-Munzinger, Heppe, & Stachel, PLB 465 (1999) 15

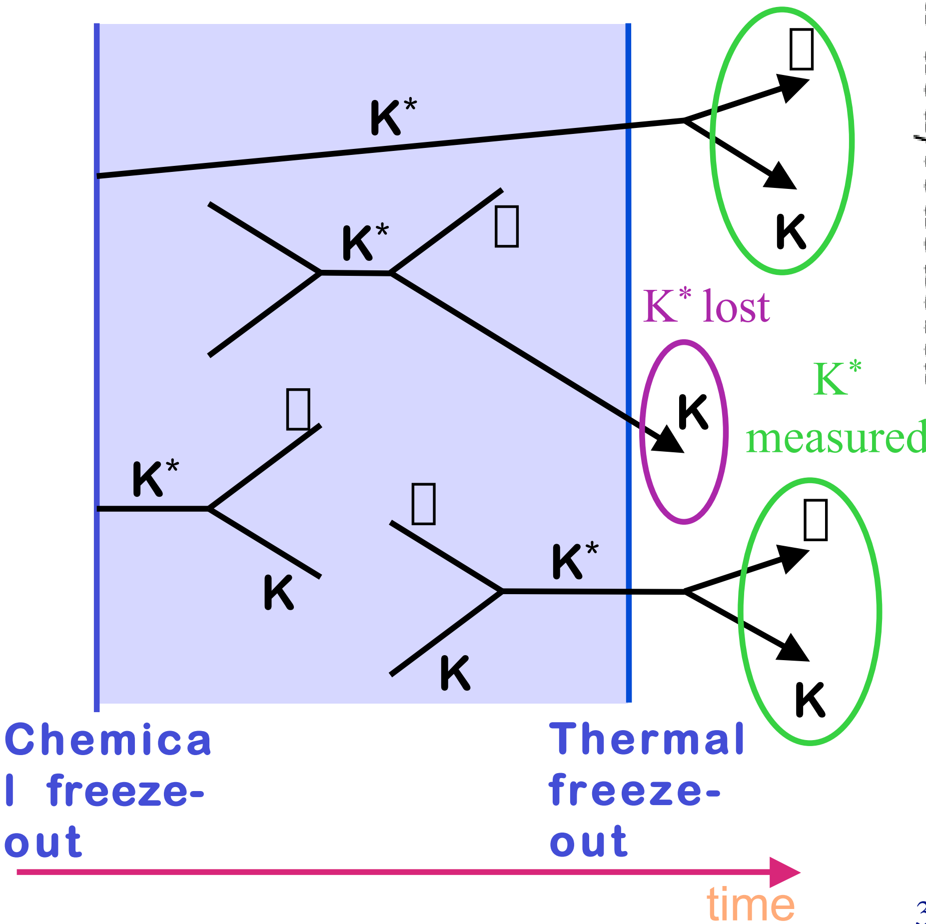
Statistical Thermal Models work well at RHIC

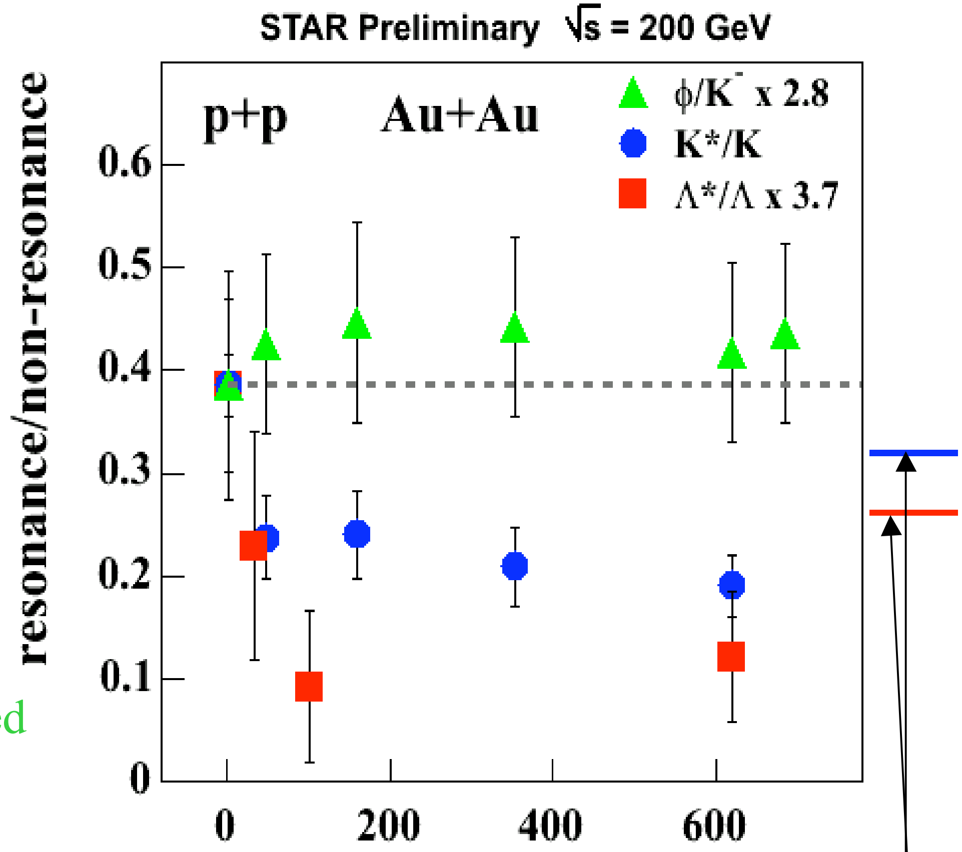


Except …

Produced short lived resonances (K*, □)

- rescattering of daughters
- regeneration effect





Life time:
□(1020) = 40 fm/c
□(1520) = 13 fm/c
K(892) = 4 fm/c

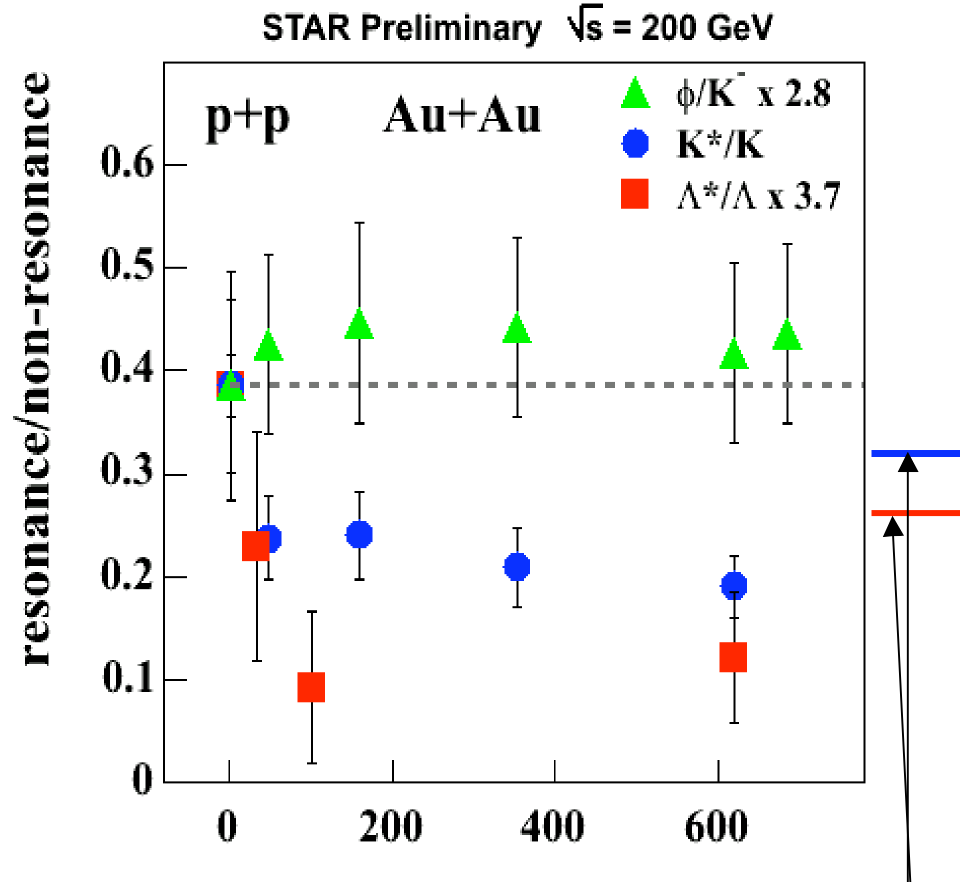
Thermal model [1]:
T = 177 MeV
$□_B$ = 29 MeV

Except …

Produced short lived resonances (K*, □)

- rescattering of daughters
- regeneration effect

Ratios short-lived/long-lived are smaller in Au+Au than in p+p collisions.
Thermal model predictions are higher than data.



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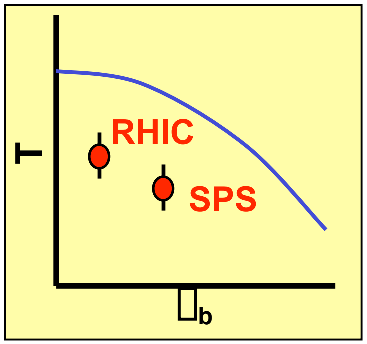
Thermal model [1]:
T = 177 MeV
$□_B$ = 29 MeV

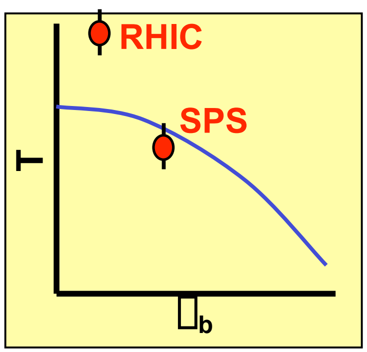
Lattice QCD vs. Statistical Model

Lattice-QCD   Stat.Thermal Model



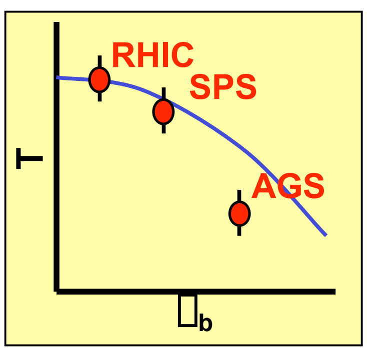
Case 1: (T,μ_b) far below Lattice QCD phase boundary

- Long-lived hadronic phase?
- Maybe system never reaches phase boundary?
- Maybe it doesn't make sense to compare?



Case 2: (T,μ_b) far above Lattice QCD phase boundary

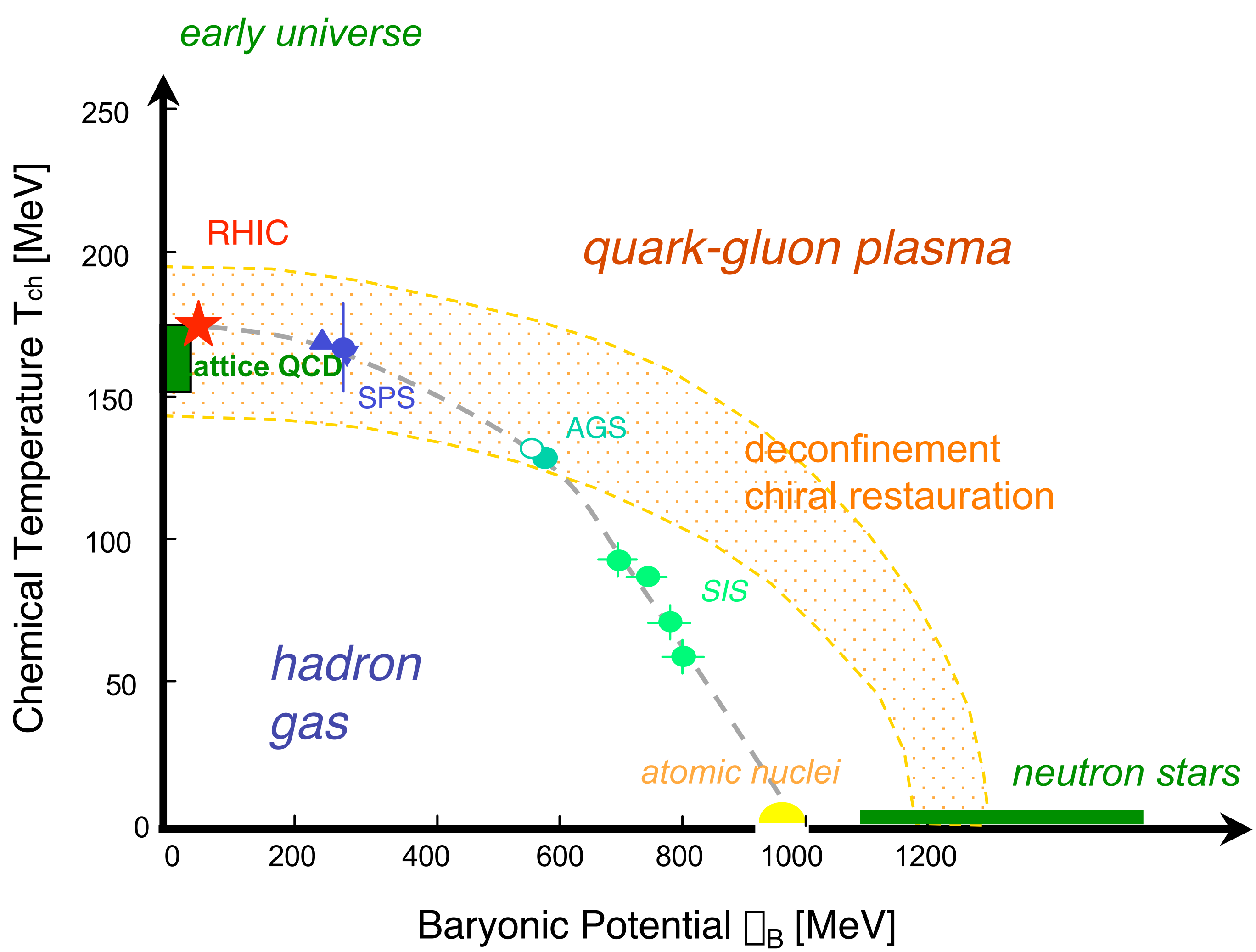
- Something wrong with statistical model formalism?
- Something wrong with Lattice-QCD formalism?
- Maybe it doesn't make sense to compare?



Case 3: (T,μ_b) very close to Lattice QCD phase boundary

- Sudden hadronization?
- Hadrons are "born" into equilibrium?
- Maybe it doesn't make sense to compare? Well...

Lattice QCD vs. Statistical Model



Thermalization in Elementary Collisions ?

Thermal Model:

$e^+e^- \rightarrow q\bar{q}$ hadronic jets ~ hadron gas = fireball (jets = fireballs)

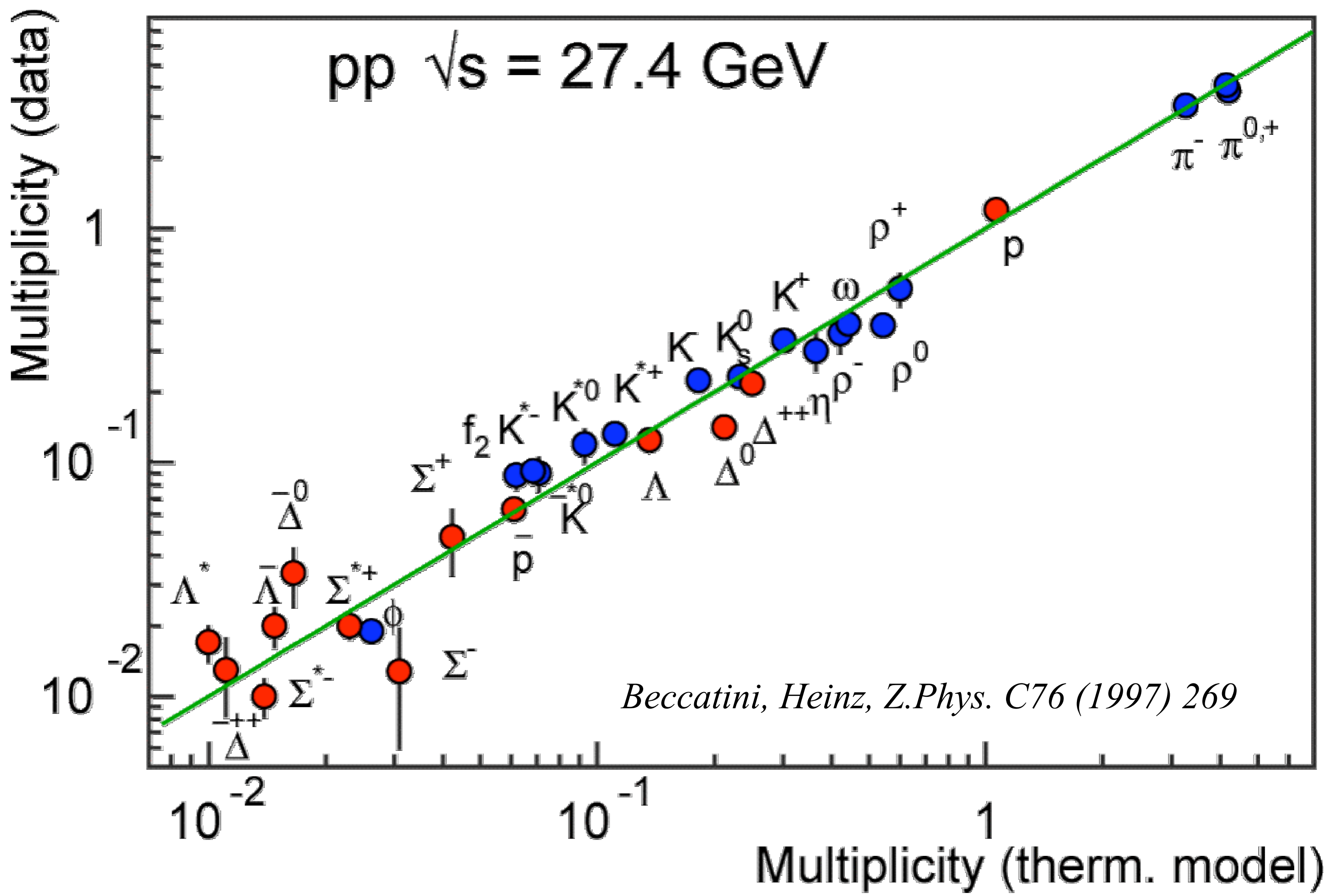
Correlated jets: small systems + quantum numbers conservation ⇒ canonical form

Recipe:

- Assume thermal and chemical equilibrium
- canonical ensemble to describe partition function
- input: measured particle yields
- output: T, V, γ_s ⇒ determined by fit
  (γ_s to account for incomplete saturation of strangeness)

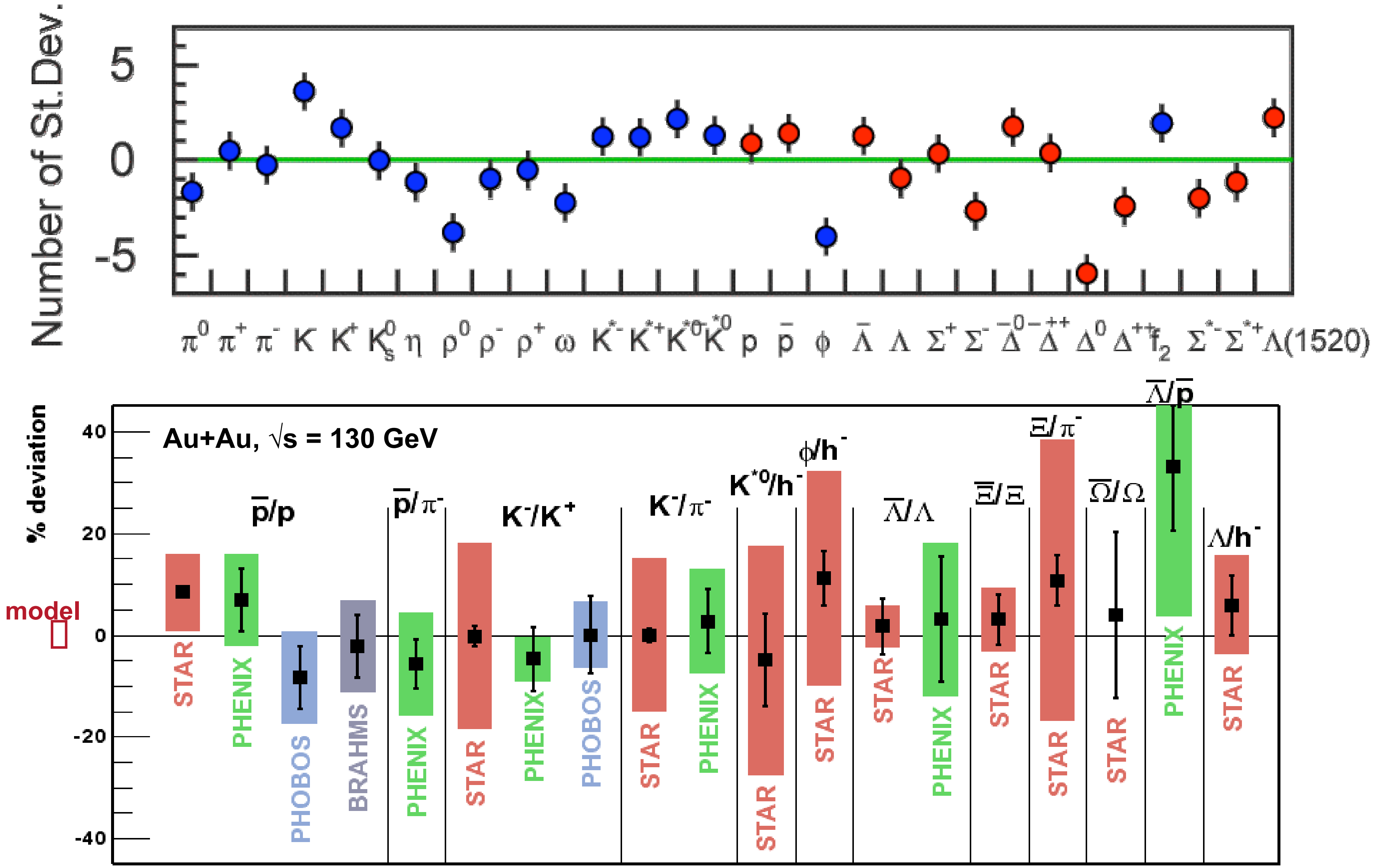
Studies performed at several $\sqrt{s}$ and various systems: $\bar{p}p$, pp, e^+e^-

Thermalization in Elementary Collisions ?



Seems to work rather well ?!

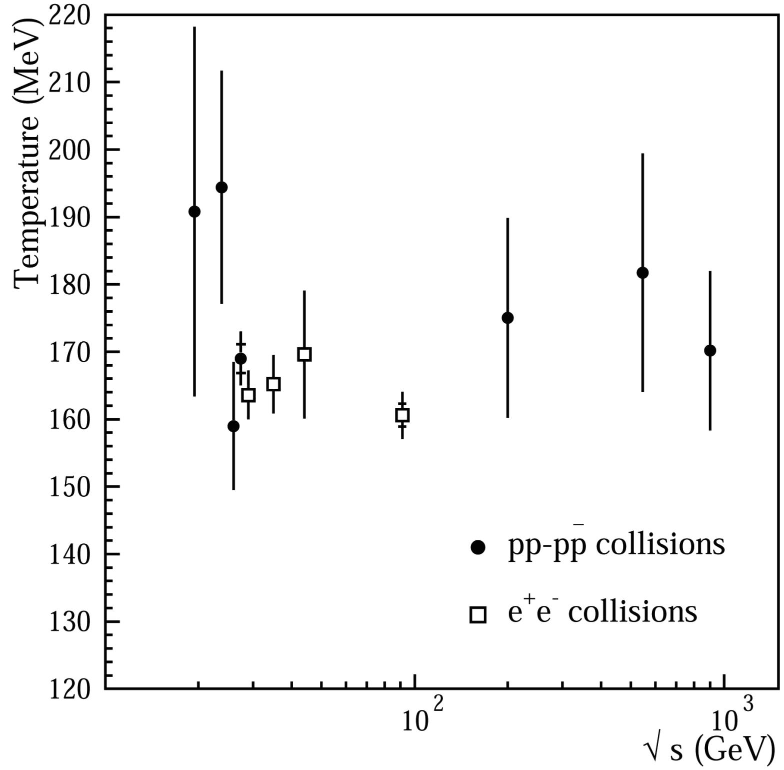
Thermalization in Elementary Collisions ?



Model: Braun-Munzinger *et al*, PLB 518 (2001) 41

D. Magestro, CIPANP, May 2003

Thermalization in Elementary Collisions ?



Beccatini, Heinz,
Z.Phys. C76 (1997) 269

- T 170 MeV (good old Hagedorn temperature)
- T_{ch} does not (or only weakly) depends on s
- Universal hadronization mechanism at critical values ?

Thermalization in Elementary Collisions ?

Is a process which leads to multiparticle production thermal?

- *Any* mechanism for producing hadrons which evenly populates the free particle phase space will mimic a microcanonical ensemble.
- Relative probability to find a given number of particles is given by the ratio of the phase-space volumes $P_n/P_{n'} = \square_n(E)/\square_{n'}(E)$

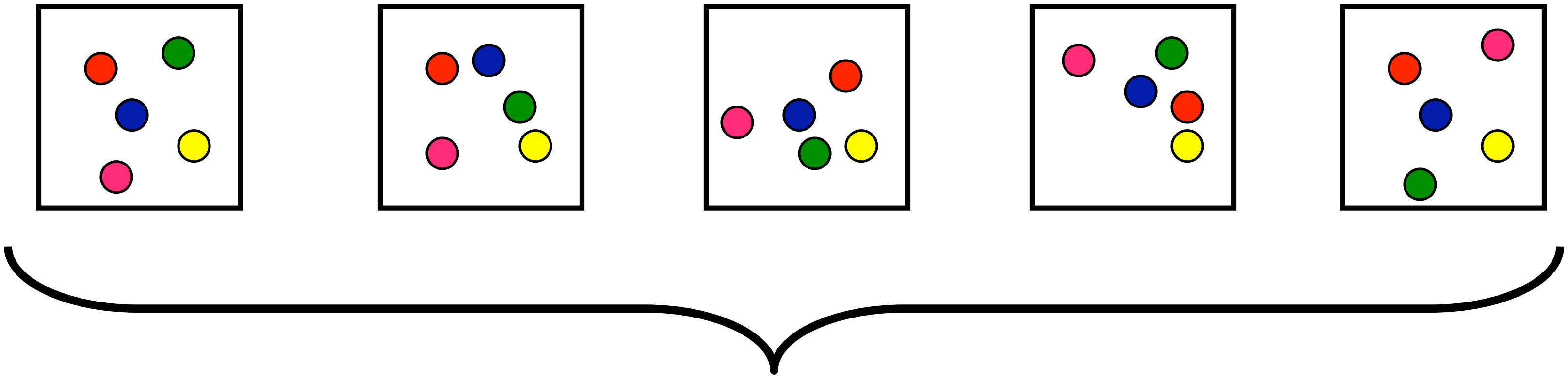
  □ given by statistics only.
- Difference between MCE and CE vanishes as the size of the system N increases.

This type of "thermal" behavior requires no rescattering and no interactions. The collisions simply serve as a mechanism to populate phase space without ever reaching thermal or chemical equilibrium

In RHI we are looking for large **collective** effects.

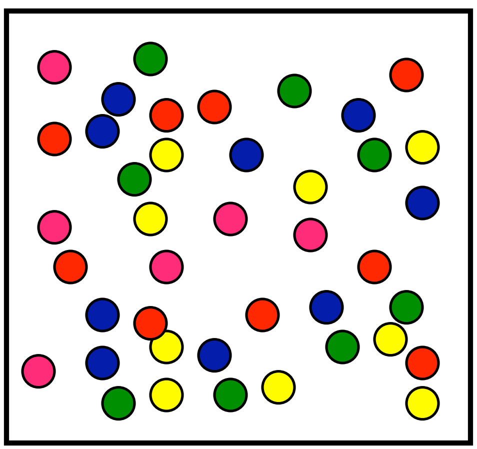
Statistics ≠ Thermodynamics

p+p



Ensemble of events constitutes a statistical ensemble
T and μ are simply Lagrange multipliers
"Phase Space Dominance"

A+A



One (1) system is already statistical !

- We can talk about pressure
- T and μ are more than Lagrange multipliers

When canonical becomes more grand canonical - like

Strangeness enhancement:

1. Lower energy threshold

   Key concept is that $T_{QGP} > T_C \sim m_s = 150$ MeV

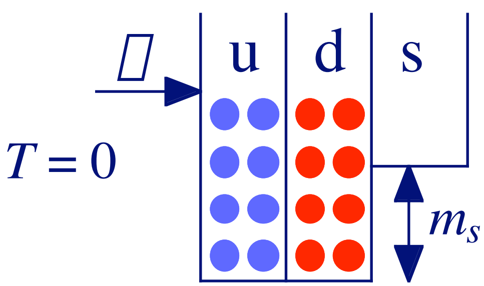
$q + \bar{q} \Box\ s + \bar{s}$	$E_{thres} = 2m_s \Box 300$ MeV
$g + g \Box\ s + \bar{s}$	
$\Box + N \Box\ \Box + K$	$E_{thres} \Box 530$ MeV
$K + \Box \Box\ \Box + N$	$E_{thres} \Box 1420$ MeV

Note that strangeness is conserved in the strong interaction

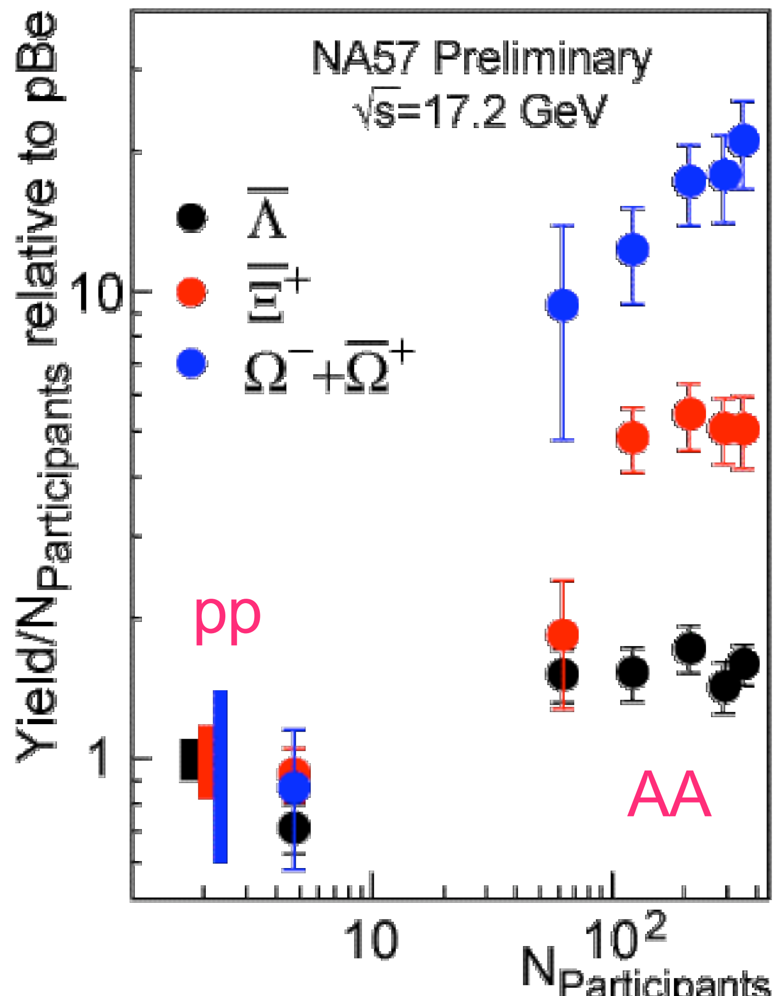
2. Larger production cross-section

$$\Box_{QGP}(s\bar{s}) > \Box_{HG}(s\bar{s})$$

3. Pauli blocking (finite chemical potential)

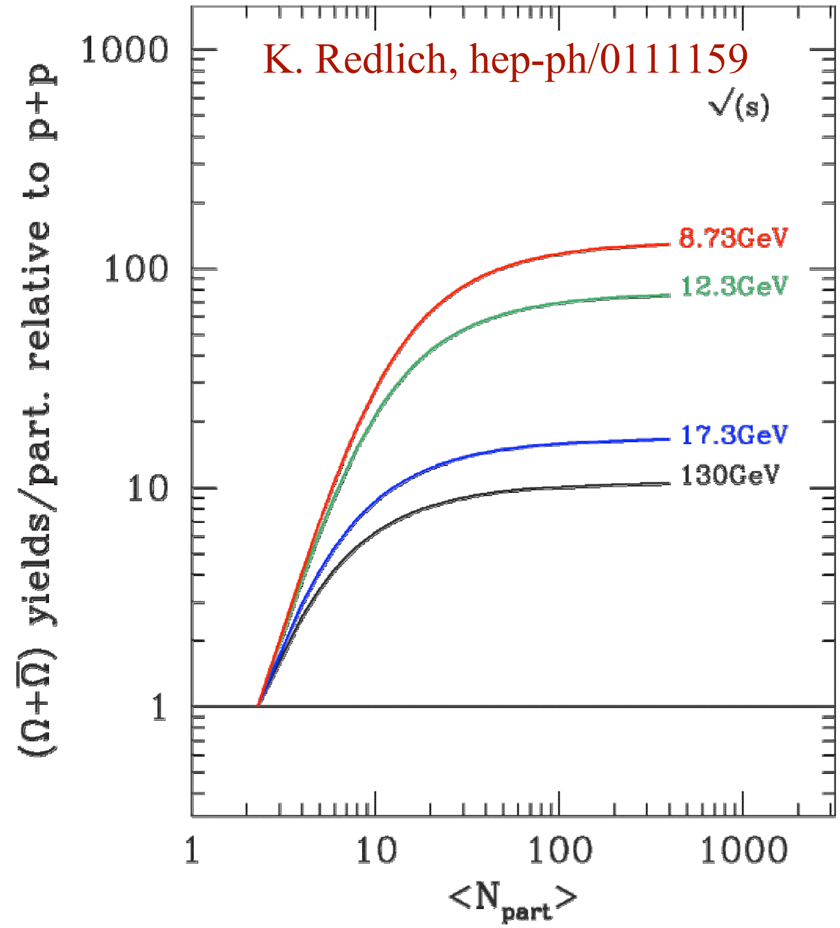


Enhancement is expected to be more pronounced for the multi-strange baryons and their anti-particles



When canonical becomes more "grand" canonical

Enhancement $E = \text{yield}|_{AA} \,/\, N_{part} \cdot \text{yield}|_{pA(pp)}$



Small systems:

conservation laws □ canonical formulation

conservation of quantum numbers reduces phase space available for particle production

"*canonical suppression*" □ E ↗

"thermal" density $n_{□}^{C}$ μ $V_0 = V_N \cdot N_{part}$

V_0: correlation volume

Large(r) Systems:

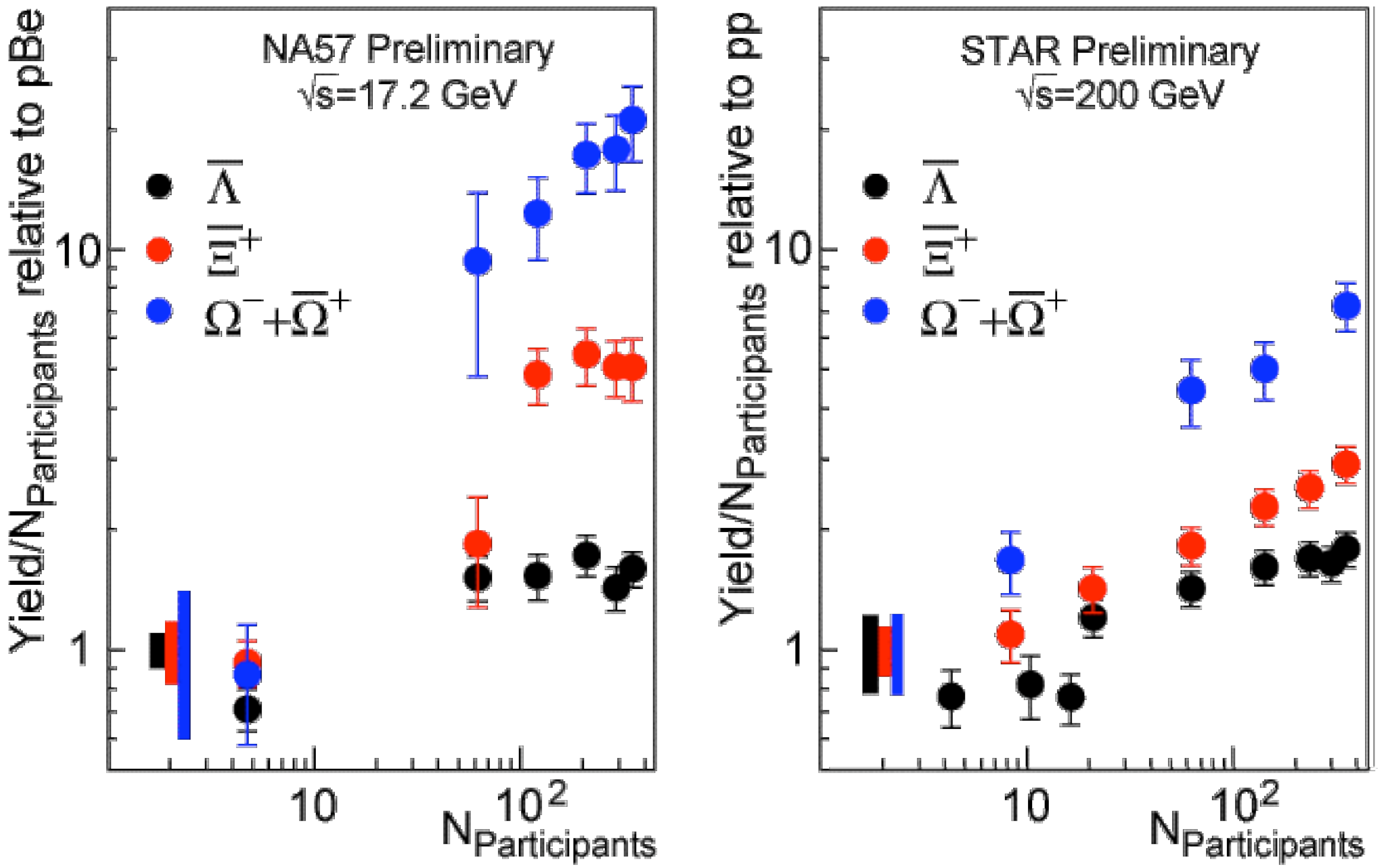
$n_{□}$ □ $n_{□}^{GC}$ (independent of V at some point)

V_0 increases from p+p to A+A possibly due to:

- equilibration in quark or hadronic matter
- initial state multi-particle collisions
- initial state correlations in A+A

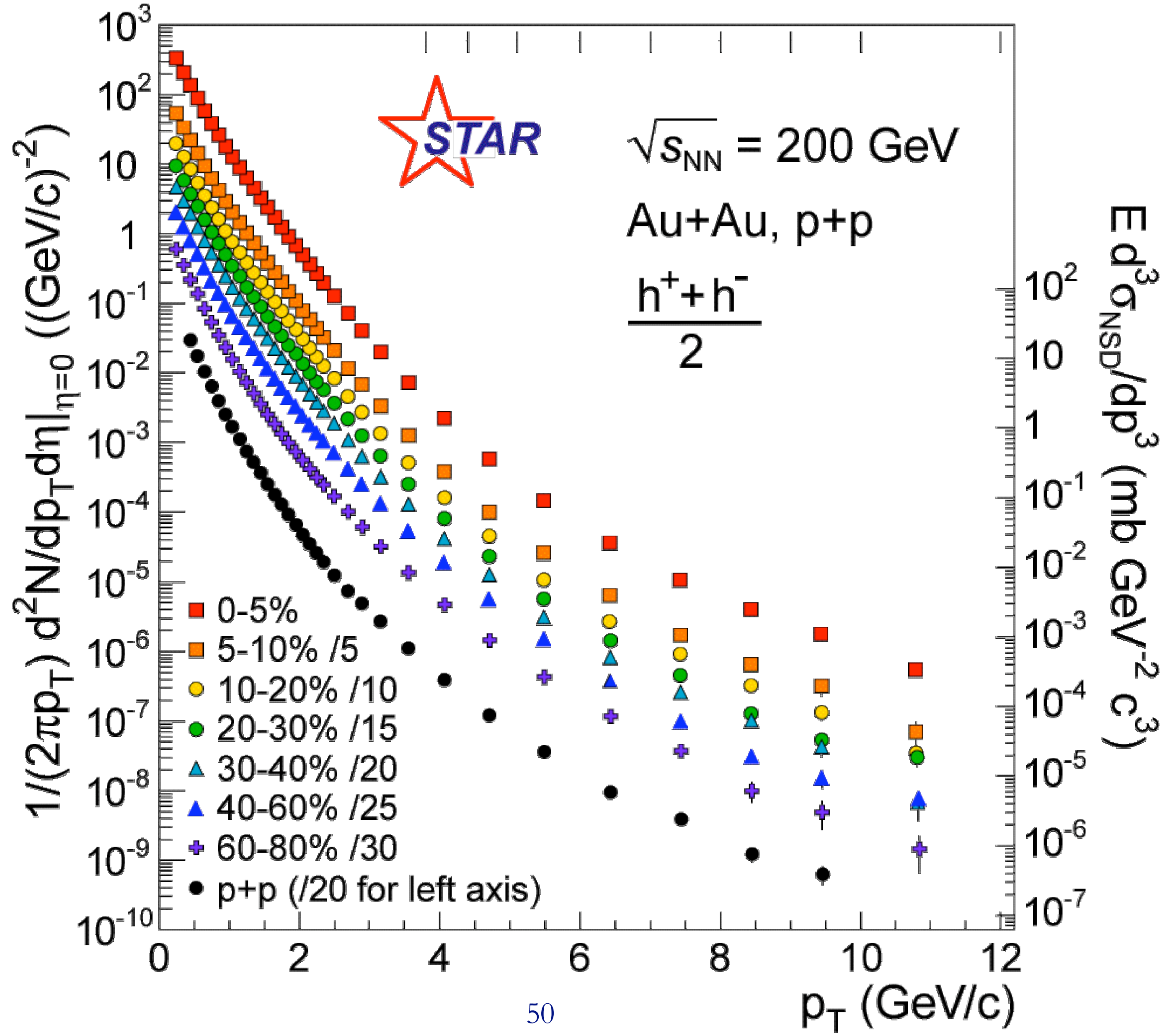
s ↗ □ Enhancement ↘
because denominator (pp/dA) becomes more "grand canonical"

When canonical becomes more "grand" canonical



s ↗ □ Enhancement ↘
because denominator (pp/dA)
becomes more "grand canonical"

Describing and Interpreting Particle Spectra (T_{th}, $□_T$)

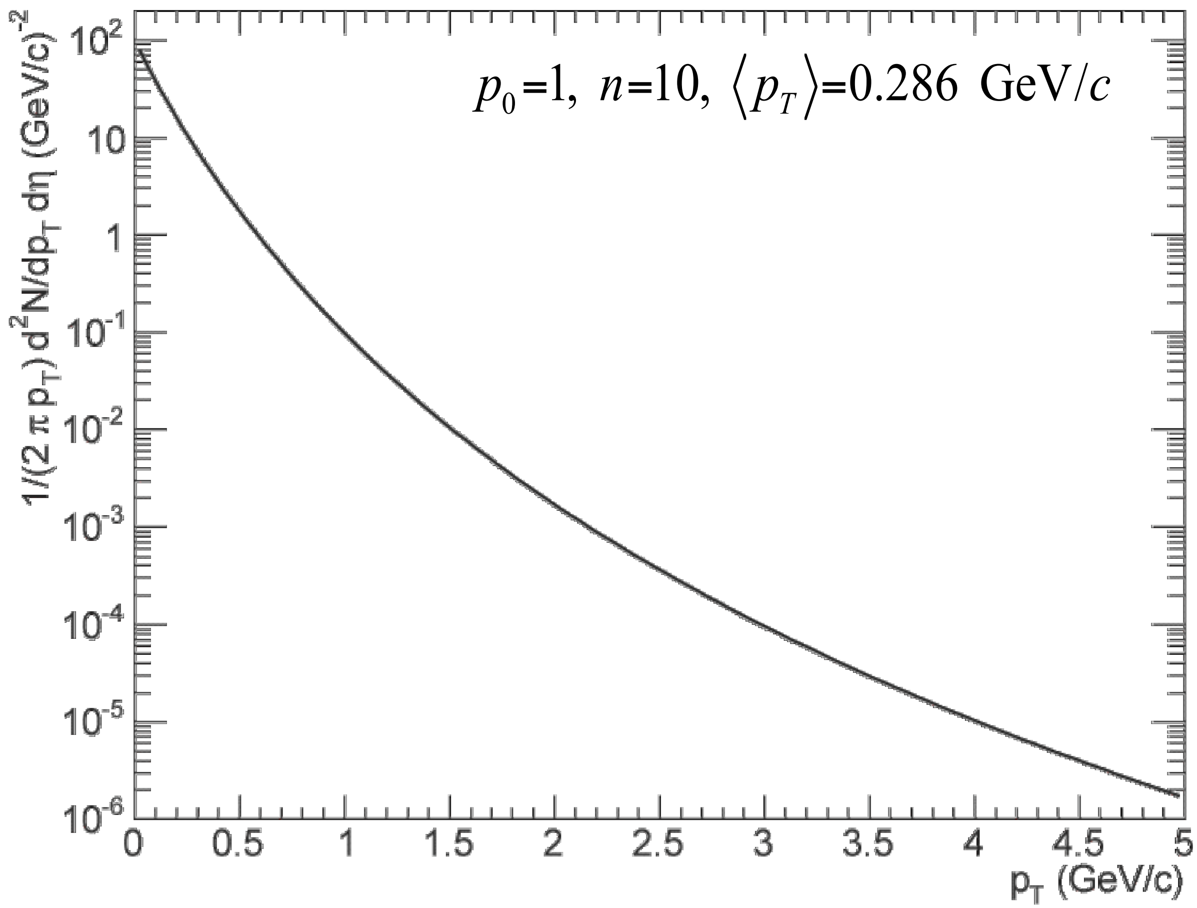


The Powerlaw Function

pQCD approach for $Ed^3\sigma/dp^3$

- Point-like scattering process $a+b \rightarrow c+d$ (via vector gluon exchange) (Berman, Bjorken, Kogut 1971)
  - $d\sigma/dt \sim 1/s^2$
  - $Ed^3\sigma/dp^3 \sim p_T^{-4}\ f(x_T,\theta)$
- "*Black Box model*" (Feynman, Field, Fox)
  - assume arbitrarily $d\sigma/dt \sim 1/(s\,t^3)$
  - $Ed^3\sigma/dp^3 \sim p_T^{-8}$
- *Constituent Interchange Model* and quark-fusion model
  - add other subprocesses (quark-meson,quark-diquark scattering)
  - $n = 8$ for pions
  - $n = 12$ for baryons
- Data (pp,$\bar{p}p$) appears to scale *approximately* like n=8 pions and kaons and n=10-12 for protons but only in *certain regions*

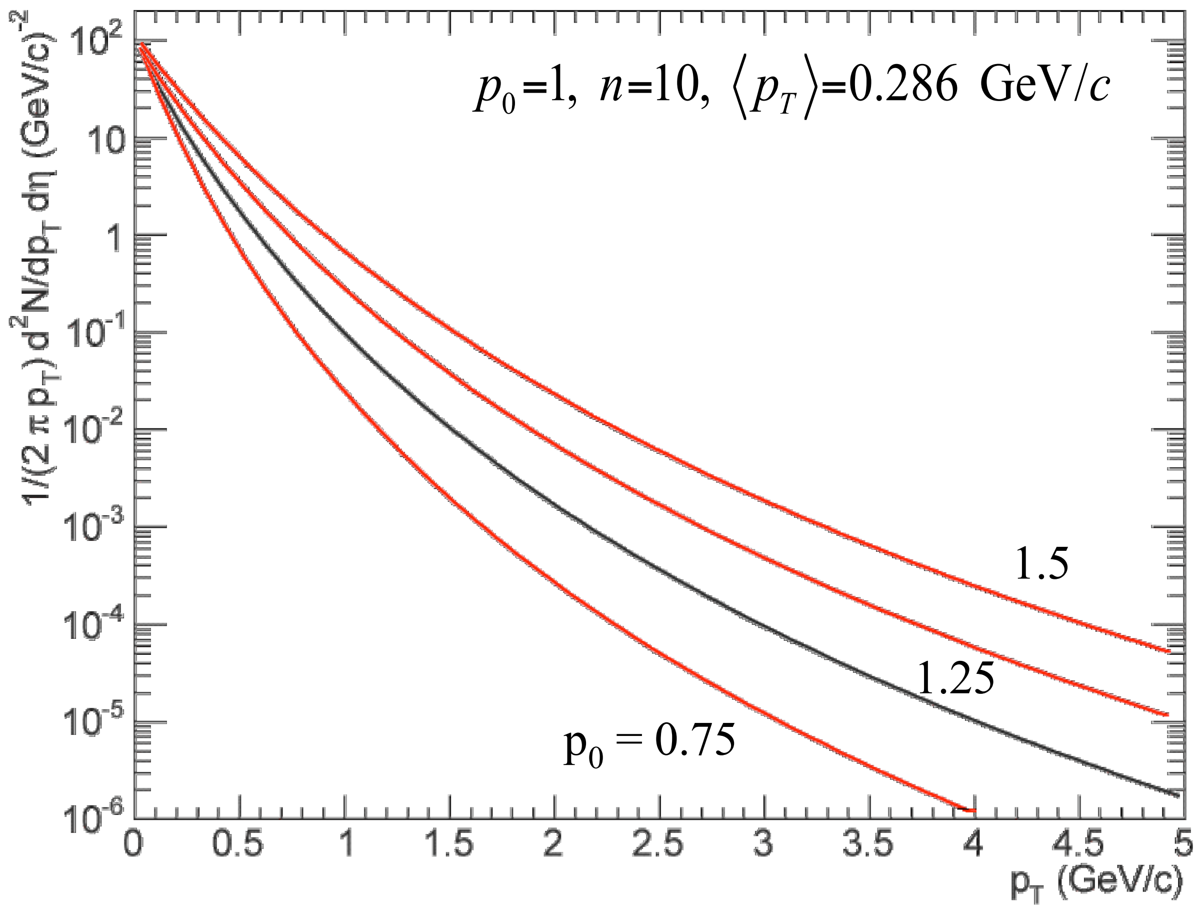
The Powerlaw Function



$$\frac{d\sigma}{p_T dp_T d\eta} = A \cdot \left(1+\frac{p_T}{p_0}\right)^{-n} \quad \text{and} \quad \langle p_T \rangle = \frac{2p_0}{n-3}$$

A pQCD inspired phenomenological approach

The Powerlaw Function



- p_0 ↑ ⇒ flattens spectra
- $p_0 \sim \langle p_T \rangle$

$$\frac{d\sigma}{p_T dp_T d\eta} = A \cdot \left(1 + \frac{p_T}{p_0}\right)^{-n} \quad \text{and} \quad \langle p_T \rangle = \frac{2p_0}{n-3}$$

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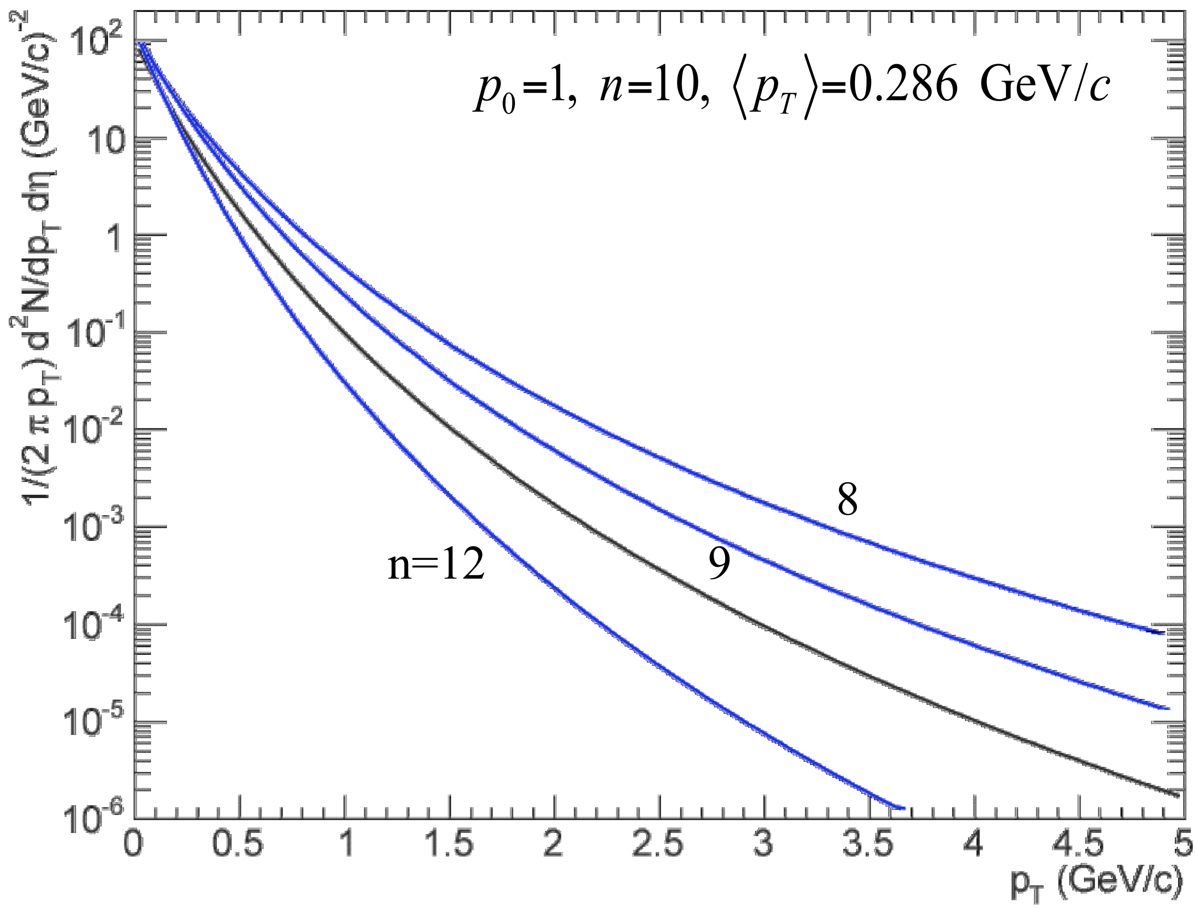
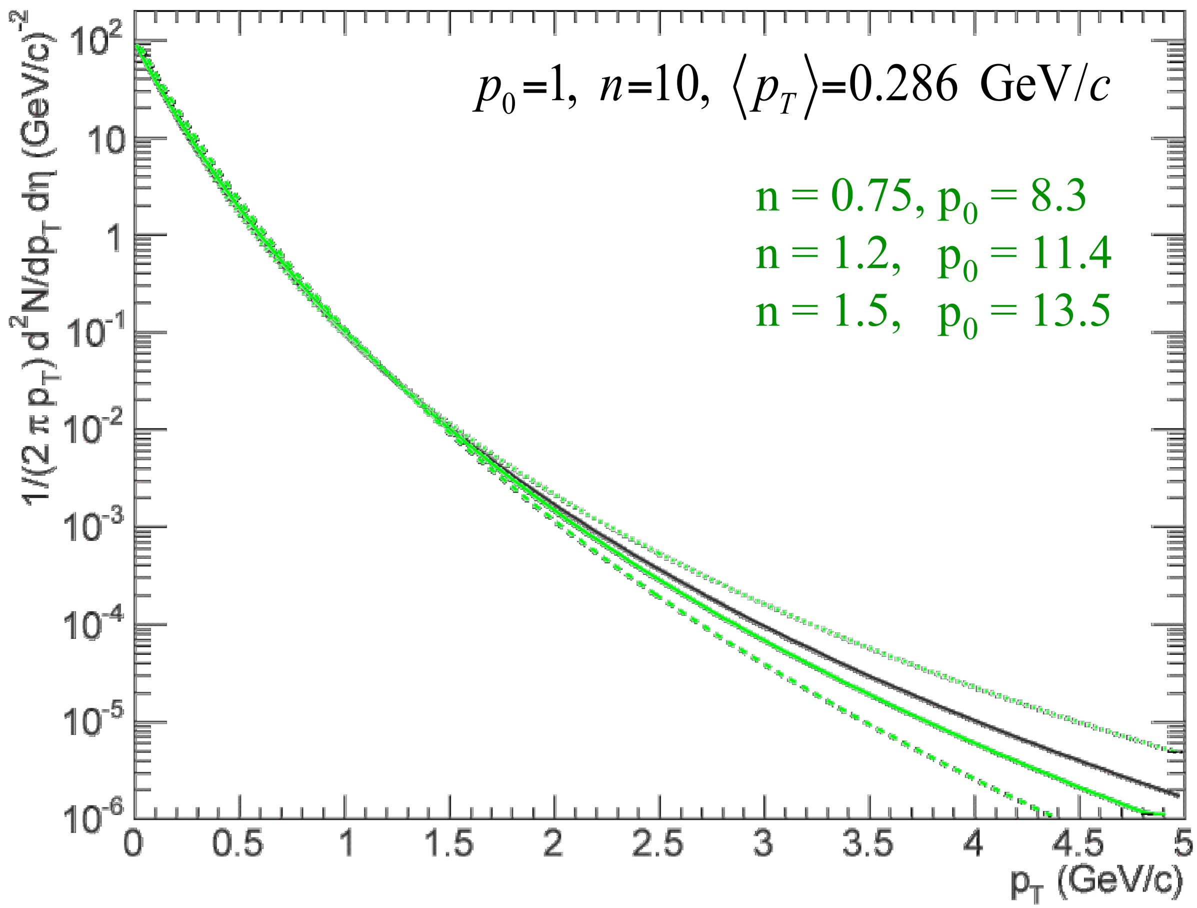


- p_0 _ □ flattens spectra
- $p_0 \sim \langle p_T \rangle$
- n _ □ lifts tail
- n ~ $1/\langle p_T \rangle$

$$\frac{d\sigma}{p_T dp_T d\eta} = A \cdot \left(1 + \frac{p_T}{p_0}\right)^{-n} \quad \text{and} \quad \langle p_T \rangle = \frac{2 p_0}{n\text{-}3}$$

A pQCD inspired phenomenological approach

The Powerlaw Function



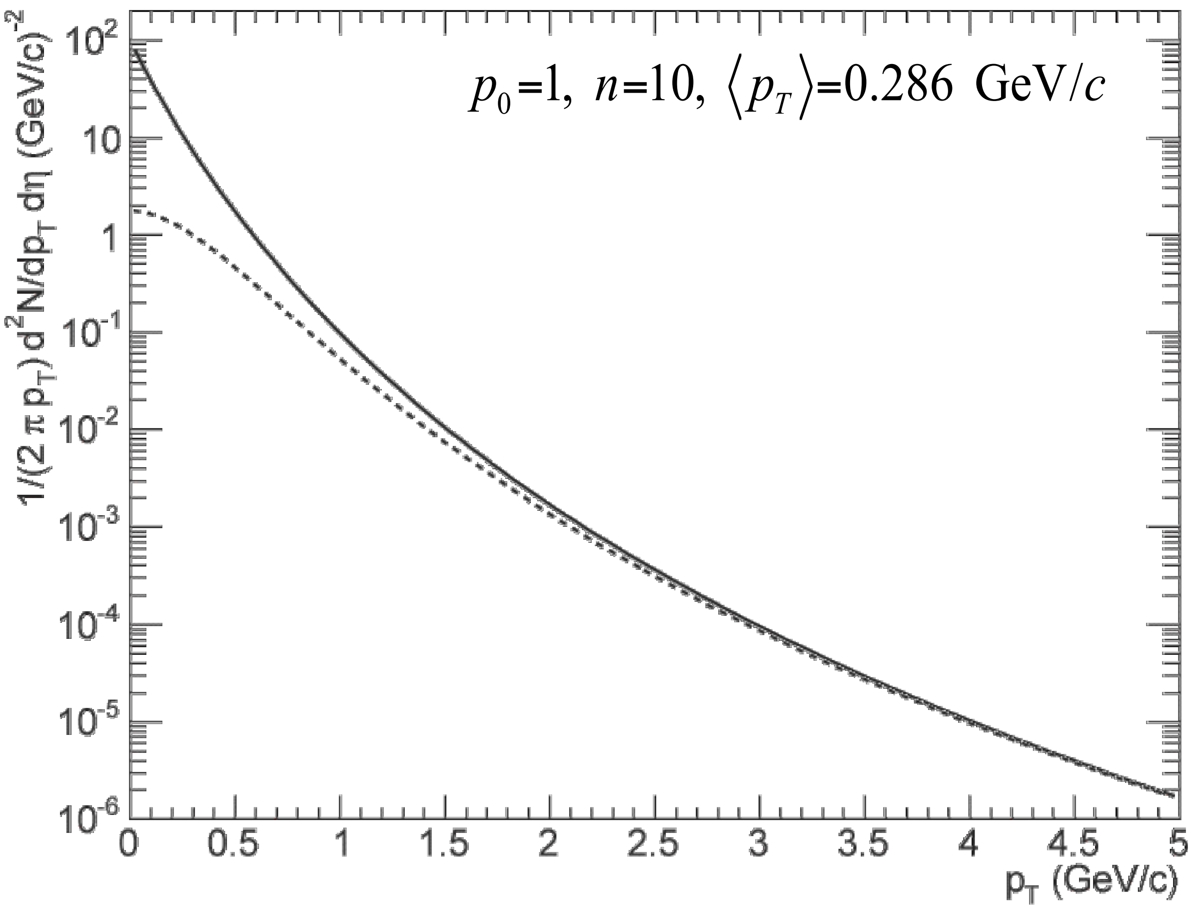
- p_0 _ □ flattens spectra
- p_0 ~ □p_T□
- n _ □ lifts tail
- n ~ 1/□p_T□
- n, p_0 strongly correlated

often:
use □p_T□directly in fit
Beware of extrapolations!

$$\frac{d\sigma}{p_T\, dp_T\, d\eta} = A \cdot \left(1 + \frac{p_T}{p_0}\right)^{-n} \quad \text{and} \quad \langle p_T \rangle = \frac{2 p_0}{n-3}$$

A pQCD inspired phenomenological approach

The Powerlaw Function



- p_0 _ □ flattens spectra
- $p_0 \sim \langle p_T \rangle$
- n _ □ lifts tail
- $n \sim 1/\langle p_T \rangle$
- n, p_0 strongly correlated

often:
use $\langle p_T \rangle$ directly in fit
Beware of extrapolations!

Powerlaw using m_T describes low p_T region usually better

$$\frac{d\sigma}{p_T dp_T d\eta} = A \cdot \left(1 + \frac{p_T}{p_0}\right)^{-n} \quad \text{and} \quad \langle p_T \rangle = \frac{2p_0}{n-3}$$

A pQCD inspired phenomenological approach

“Thermal” Spectra

Invariant spectrum of particles radiated by a thermal source:

$$E\frac{d^3N}{dp^3} = \frac{dN}{dy\, m_T\, dm_T\, d\phi} \propto E e^{-(E-\mu)/T}$$

where: $m_T = (m^2+p_T^2)^{1/2}$ transverse mass (Note: requires knowledge of mass)

$\mu = b\,\mu_b + s\,\mu_s$ grand canonical chem. potential

T temperature of source

Neglect quantum statistics (small effect) and integrating over rapidity gives:

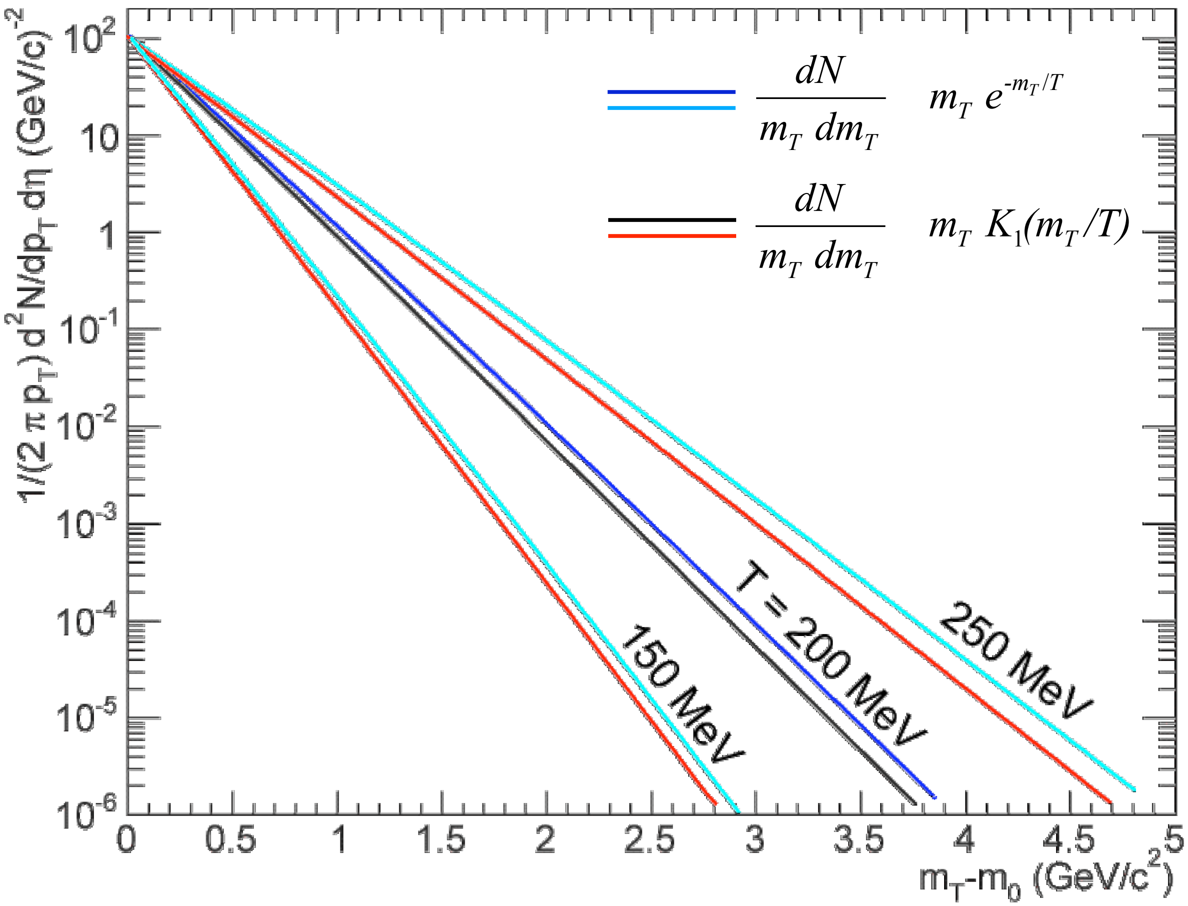
$$\frac{dN}{m_T\, dm_T} \propto m_T\, K_1(m_T/T) \xrightarrow{m_T >> T} \sqrt{m_T}\, e^{-m_T/T}$$

R. Hagedorn, Supplemento al Nuovo Cimento Vol. III, No.2 (1965)

At mid-rapidity $E = m_T \cosh y = m_T$ and hence: $$\frac{dN}{m_T\, dm_T} \propto m_T\, e^{-m_T/T}$$

“Boltzmann”

"Thermal" Spectra (flow aside)



Describes many spectra well over several orders of magnitude with almost uniform slope 1/T

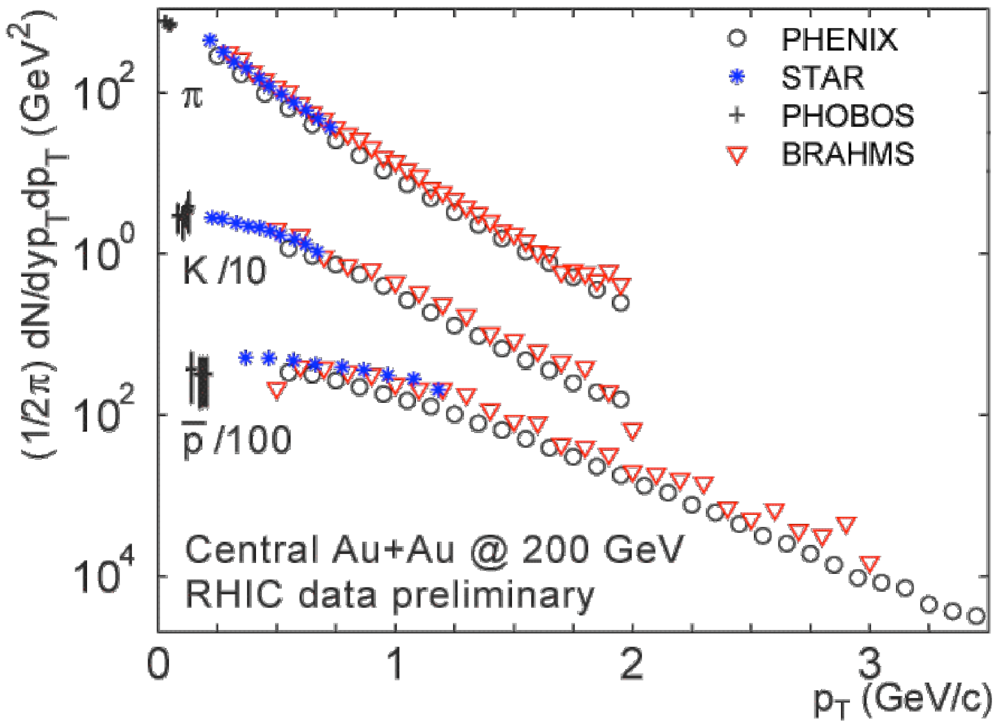
- usually fails at low-p_T (flow)
- most certainly will fail at high-p_T (power-law)

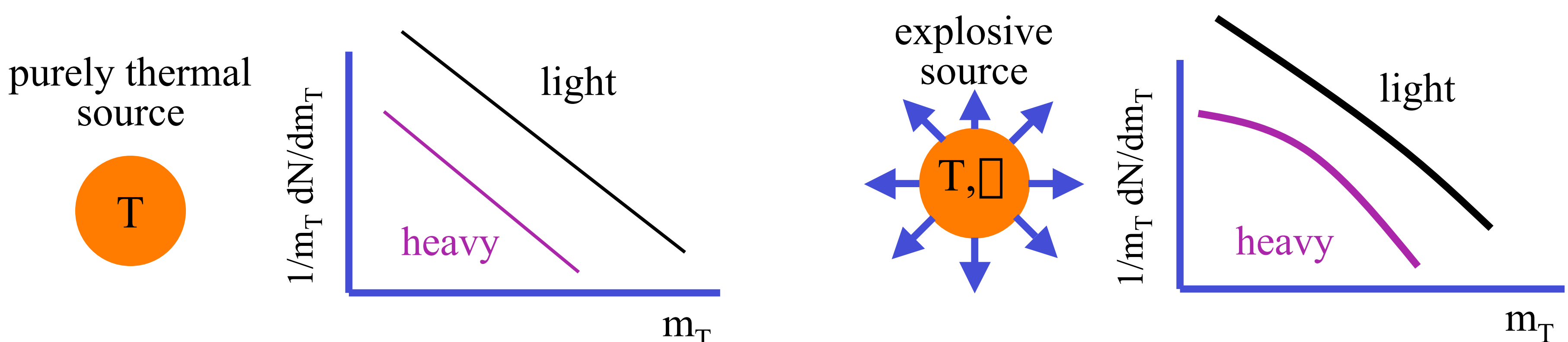
N.B. Constituent quark and parton recombination models yield exponential spectra with partons following a pQCD power-law distribution. (Biro, Müller, hep-ph/0309052)
 T is not related to actual "temperature" but reflects pQCD parameter p_0 and n.

"Thermal" Spectra and Flow

- Different spectral shapes for particles of differing mass
  $\Rightarrow$ strong collective radial flow

- Spectral shape is determined by more than a simple T
- at a minimum T, β_T



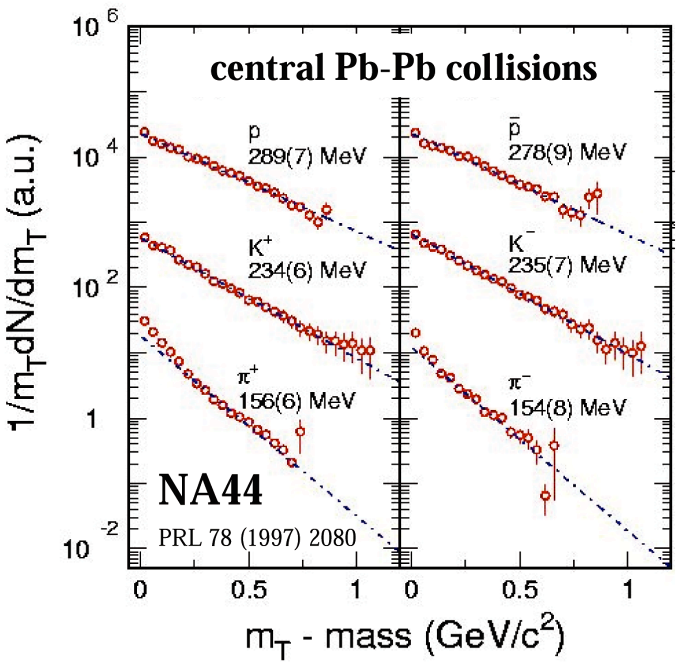


Thermal + Flow: "Traditional" Approach

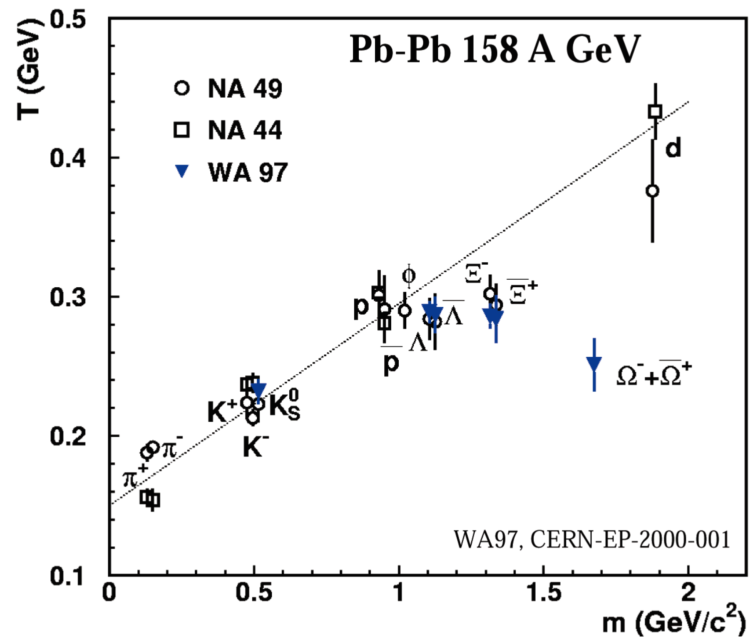
$$T_{measured} = \begin{cases} T_{th} + m\langle \beta_T \rangle^2 & \text{for} \quad p_T \ll m \\ T_{th}\sqrt{\dfrac{1+\langle \beta_T \rangle}{1-\langle \beta_T \rangle}} & \text{for} \quad p_T >> m \quad \text{(blue shift)} \end{cases}$$

Assume ***common*** flow pattern and ***common*** temperature T_{th}

1. Fit Data → T



2. Plot $T(m)$ → T_{th}, $\langle \beta_T \rangle$



Problem: spectra are not exponential in the first place (fit range dependence)

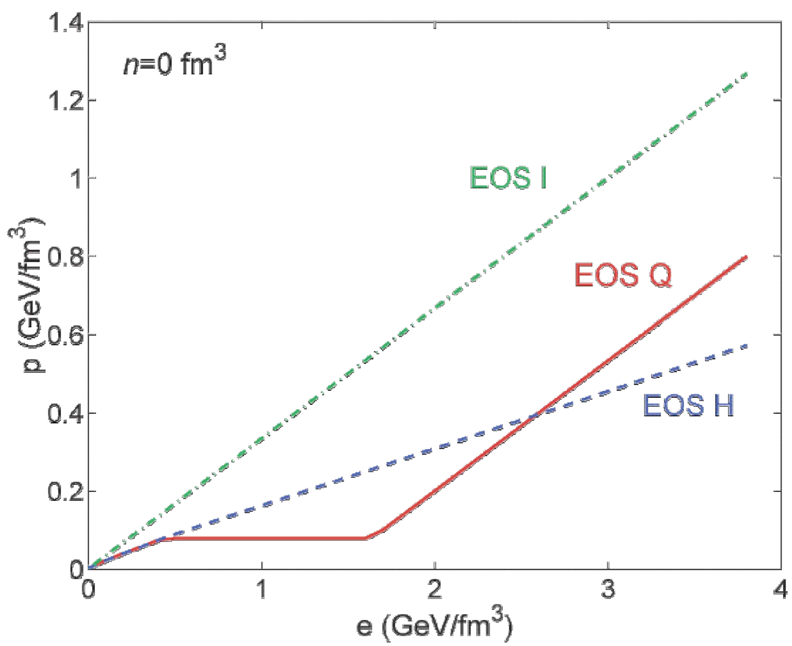
Hydrodynamics: Modeling High-Density Scenarios

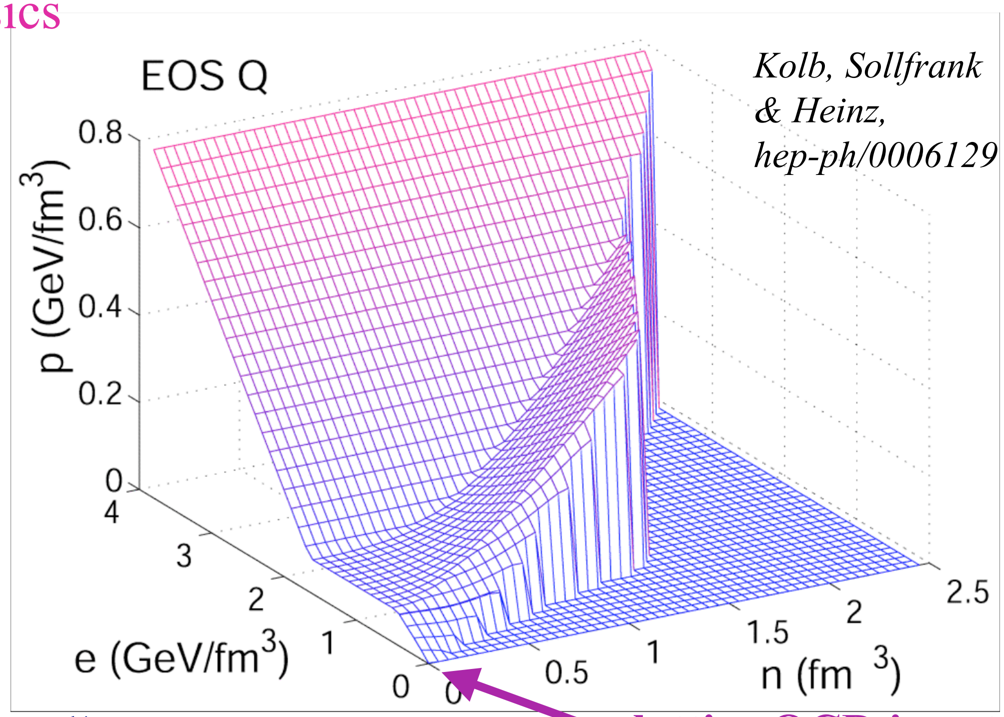
Assumes local thermal equilibrium (zero mean-free-path limit) and solves equations of motion for fluid elements (not particles)

Equations given by continuity, conservation laws, and Equation of State (EOS)

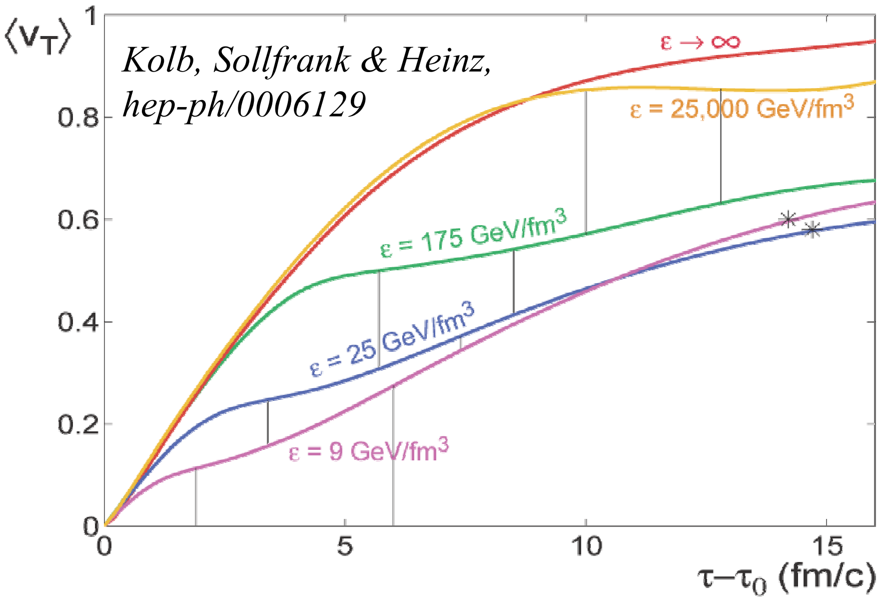
EOS relates quantities like pressure, temperature, chemical potential, volume

- direct access to underlying physics





Use of Hydro Models to describe m_T (p_T) Spectra



EOS & initial conditions

⇓

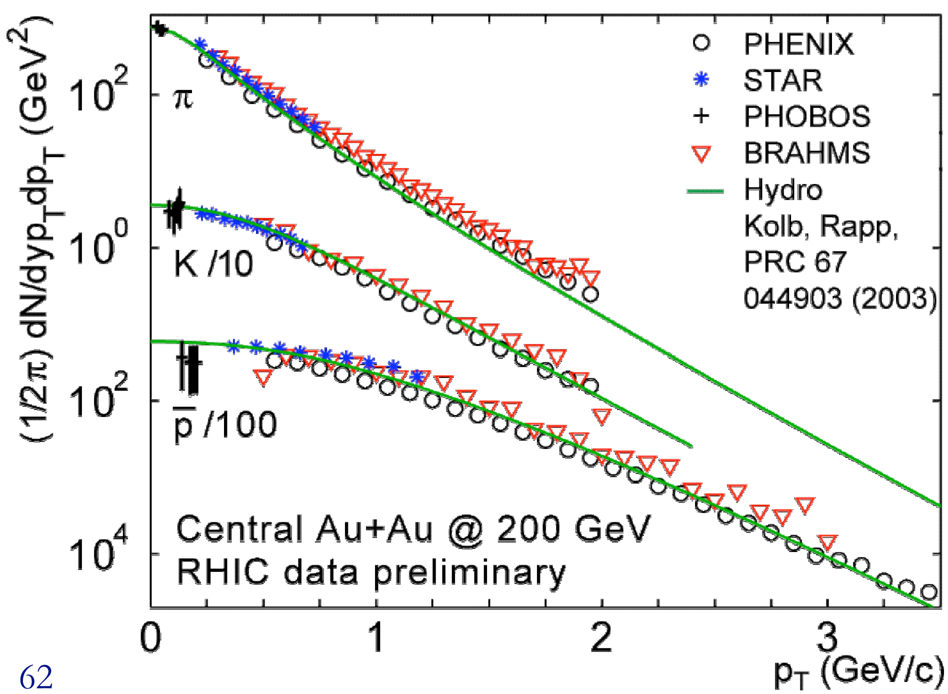
particle m_T-spectra

Most implementations in 2D only

- Good agreement with hydrodynamic prediction at RHIC (and SPS)
- RHIC:

  T_{th}~ 100 MeV

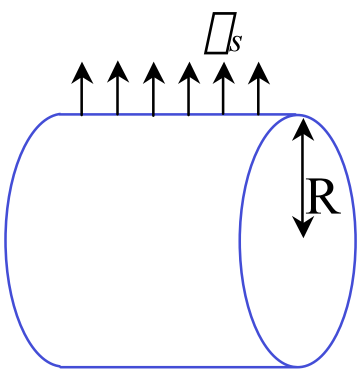
  $\langle \beta_T \rangle$~ 0.55 c



Disadvantage of Hydro:
not very "handy" for experimentalists

Blastwave: a hydrodynamic inspired description of spectra

Spectrum of longitudinal and transverse boosted thermal source:



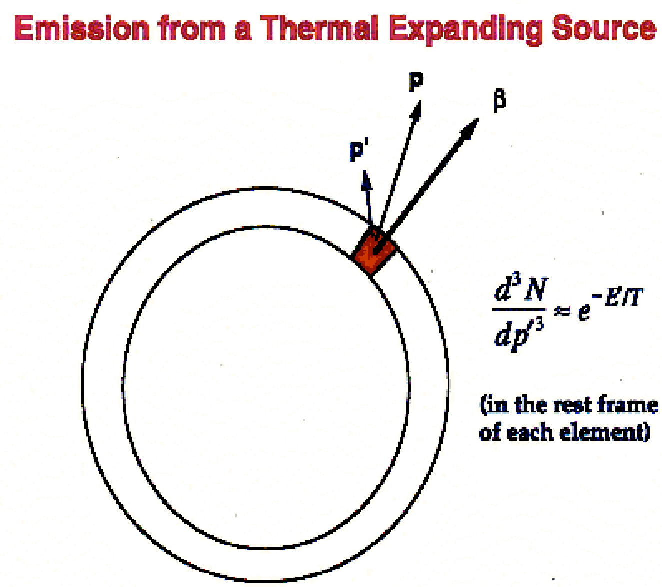
Ref. : Schnedermann, Sollfrank & Heinz, PRC48 (1993) 2462

$$\frac{dN}{m_T dm_T} \propto \int_0^R r\,dr\, m_T\, I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right)$$

with

transverse velocity distribution $\beta_r(r) = \beta_s \left(\frac{r}{R}\right)^n$

and boost angle (boost rapidity) $\rho = \tanh^{-1} \beta_r$

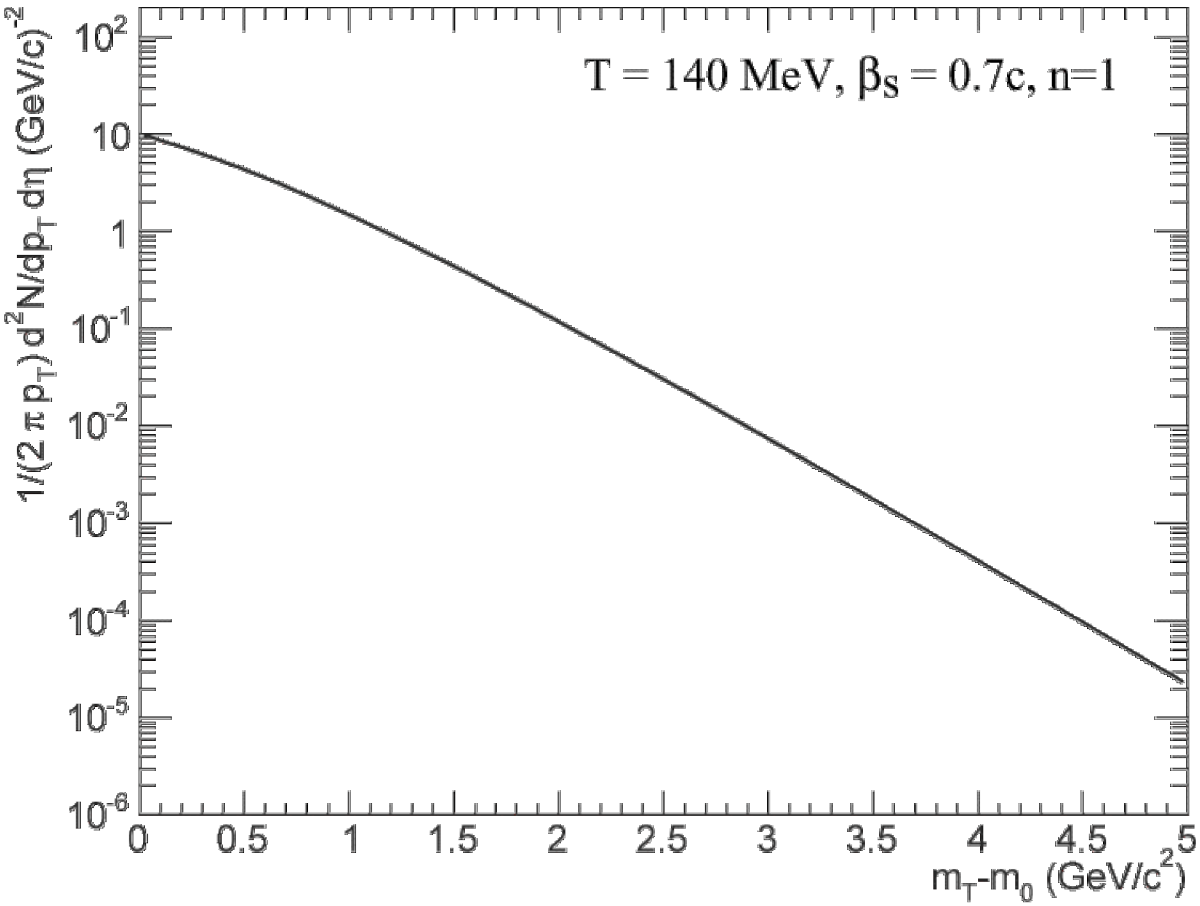


Handy formula that can be fit to m_T (p_T) spectra

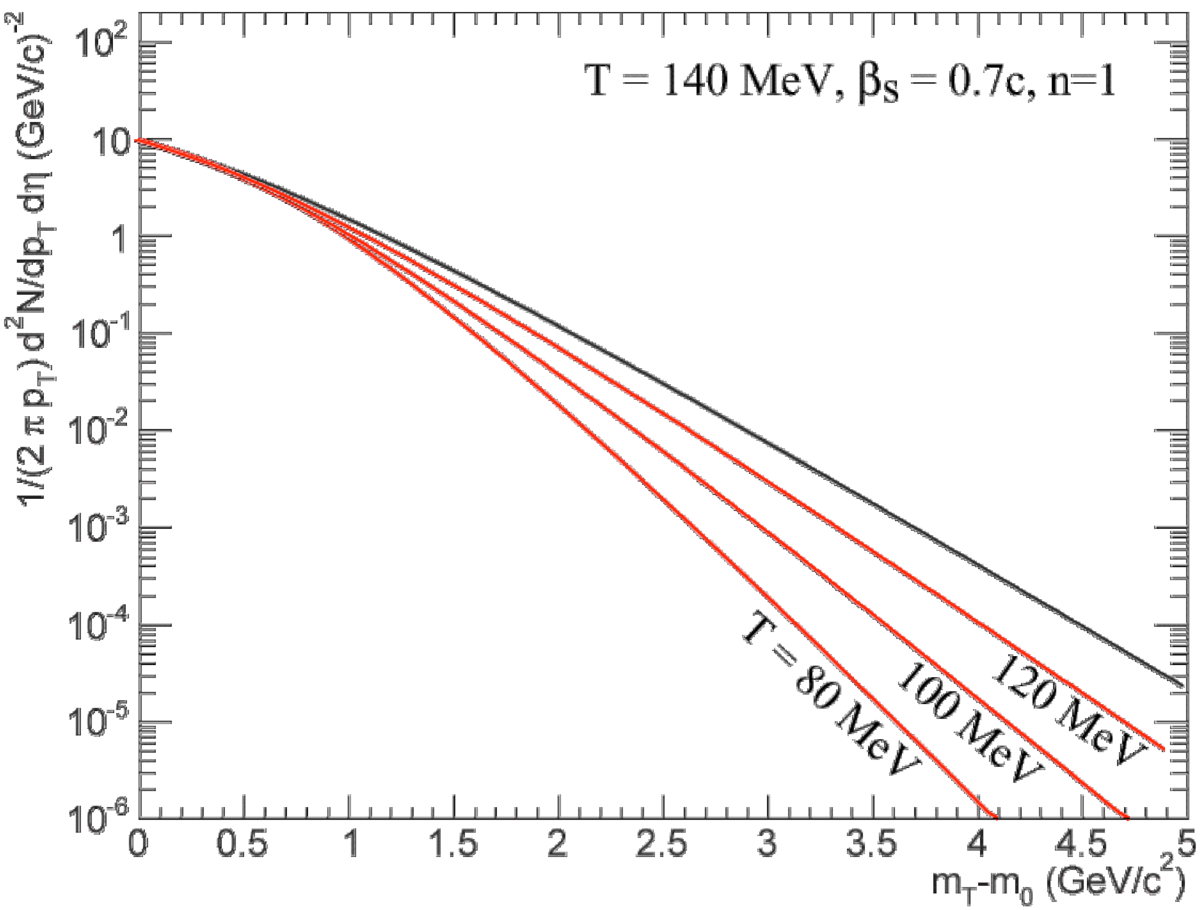
2-parameters: T_{th}, β_s

Note: velocity at surface (β_s) is the "true" parameter but often $\langle\beta_T\rangle$ is quoted

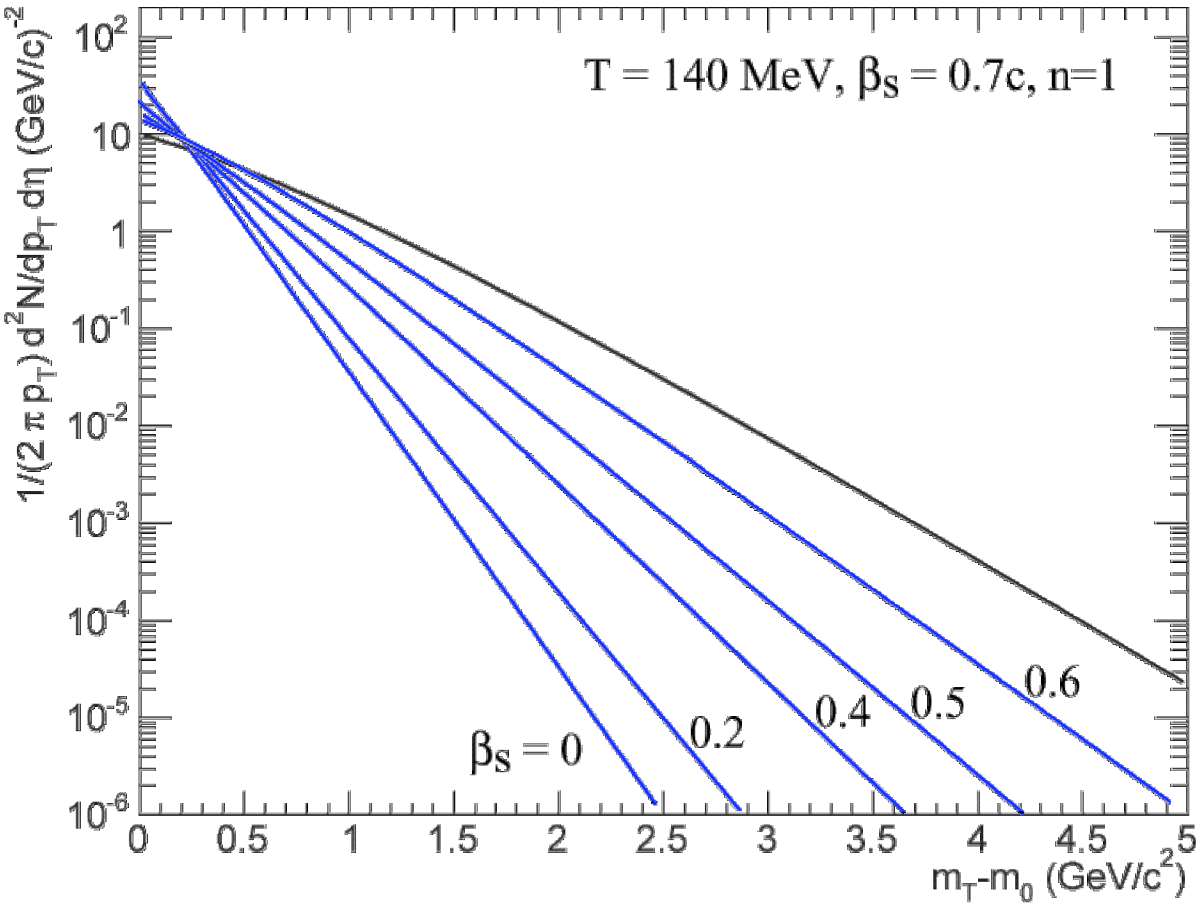
The Blastwave Function



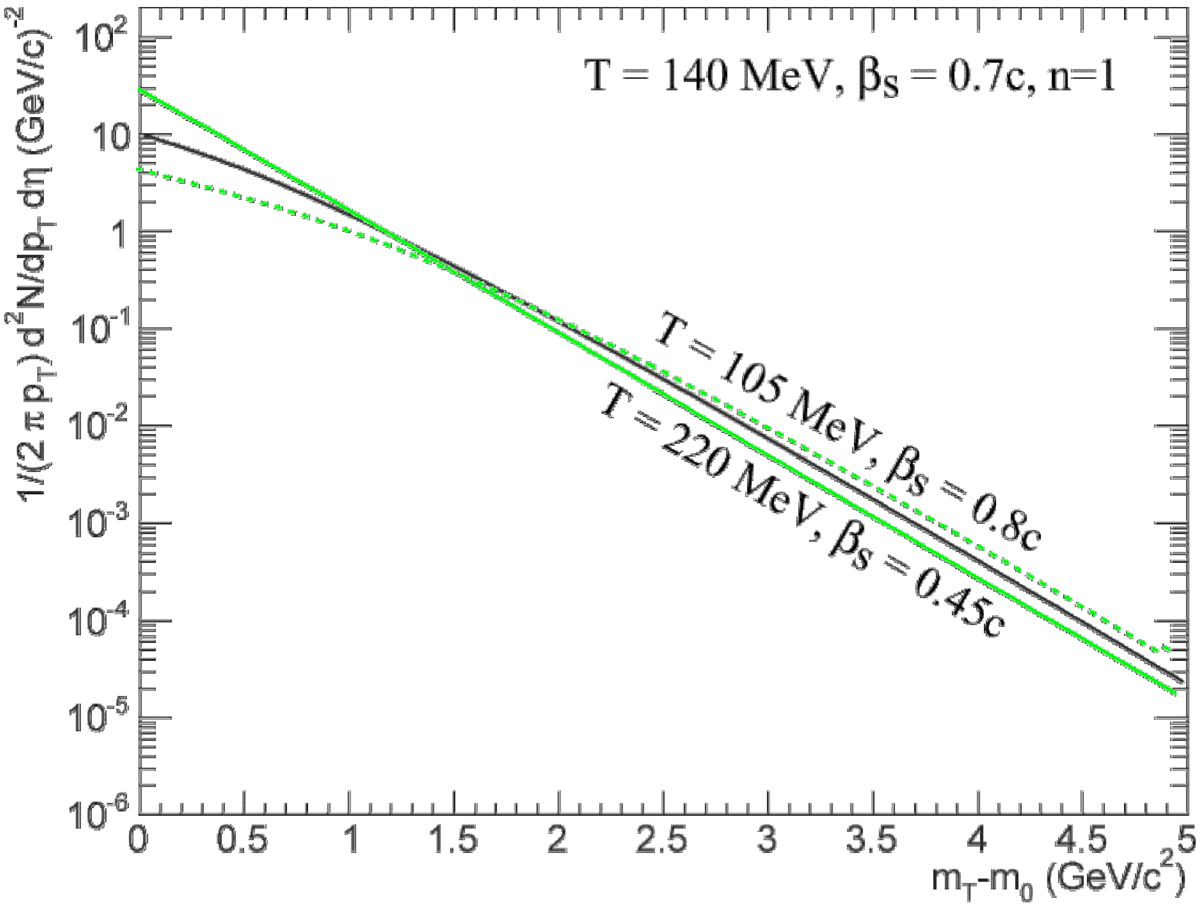
The Blastwave Function

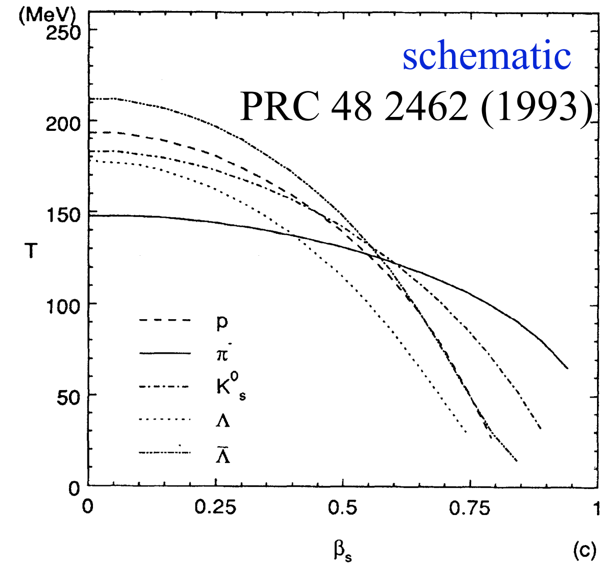


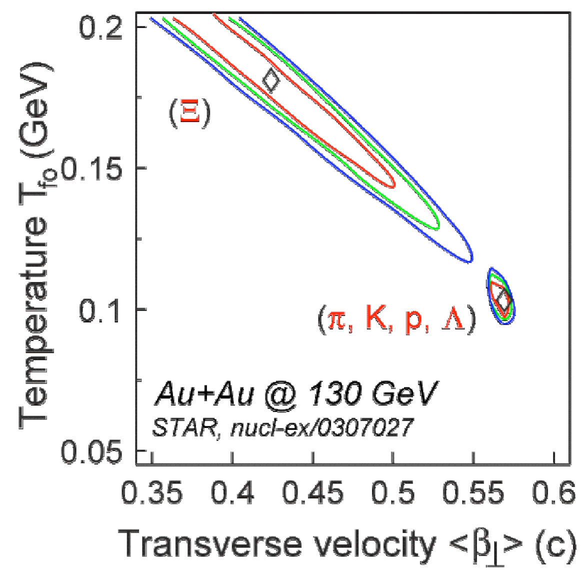
The Blastwave Function



The Blastwave Function

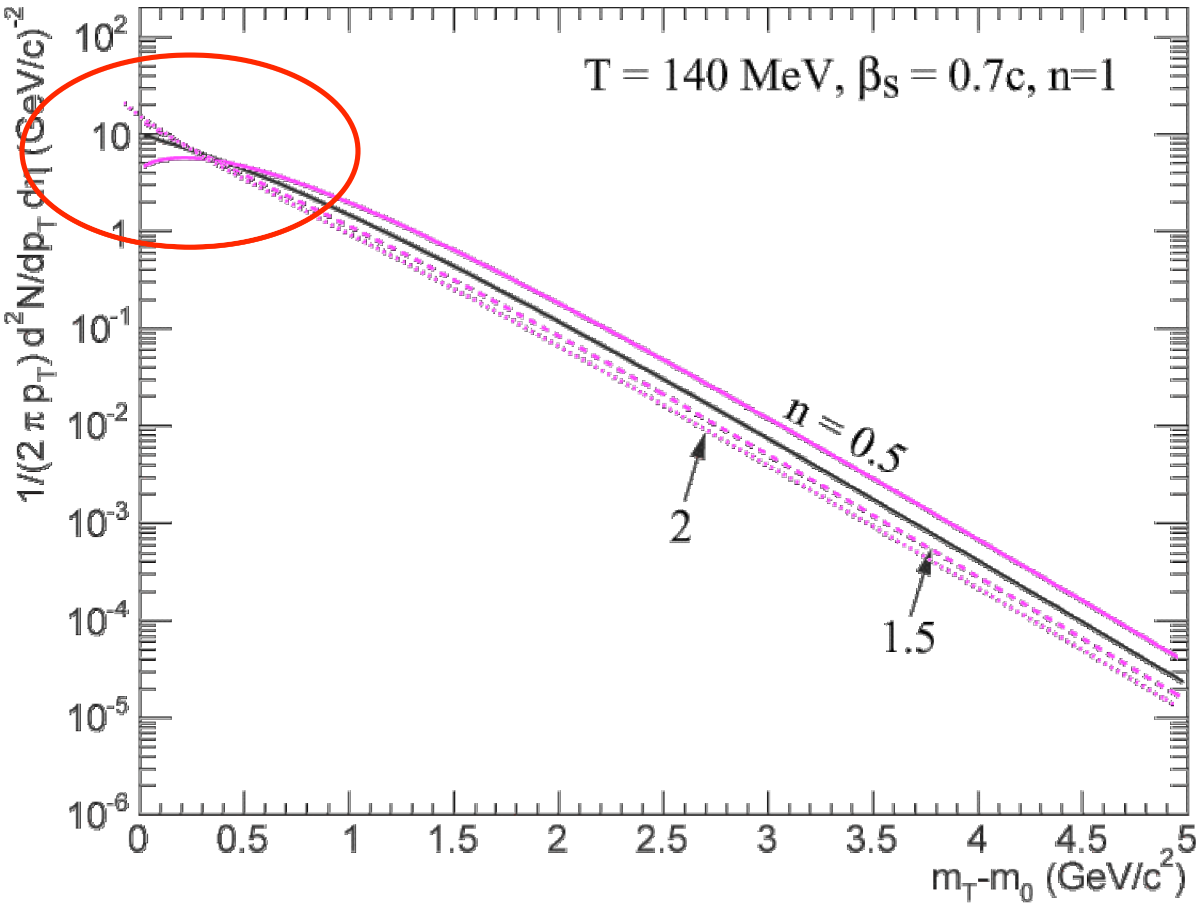


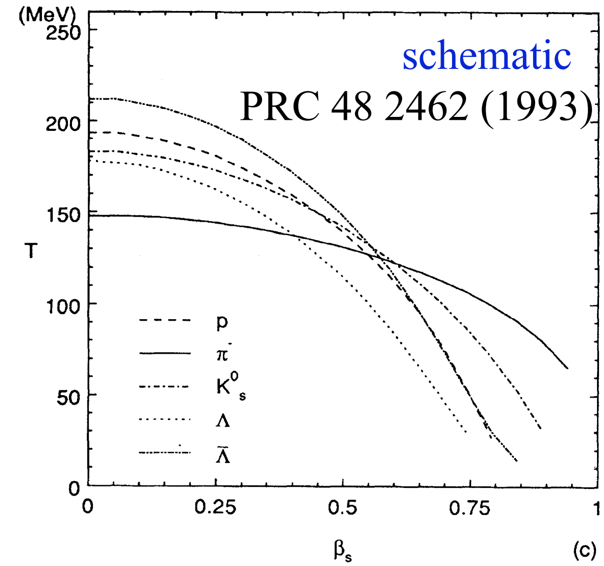


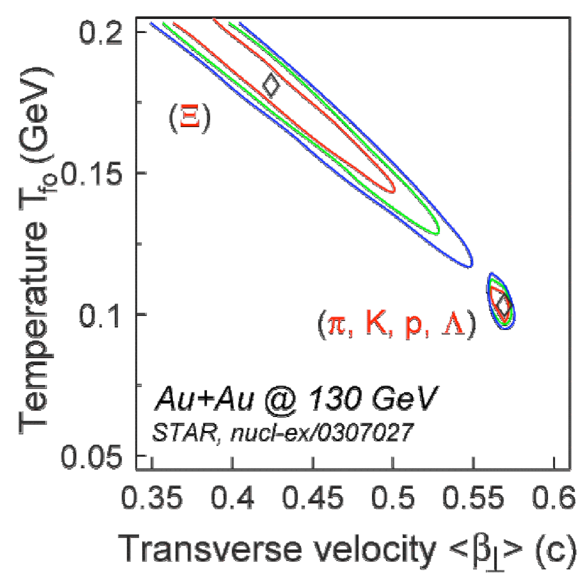


- Increasing T has similar effect on a spectrum as increasing β_s

The Blastwave Function

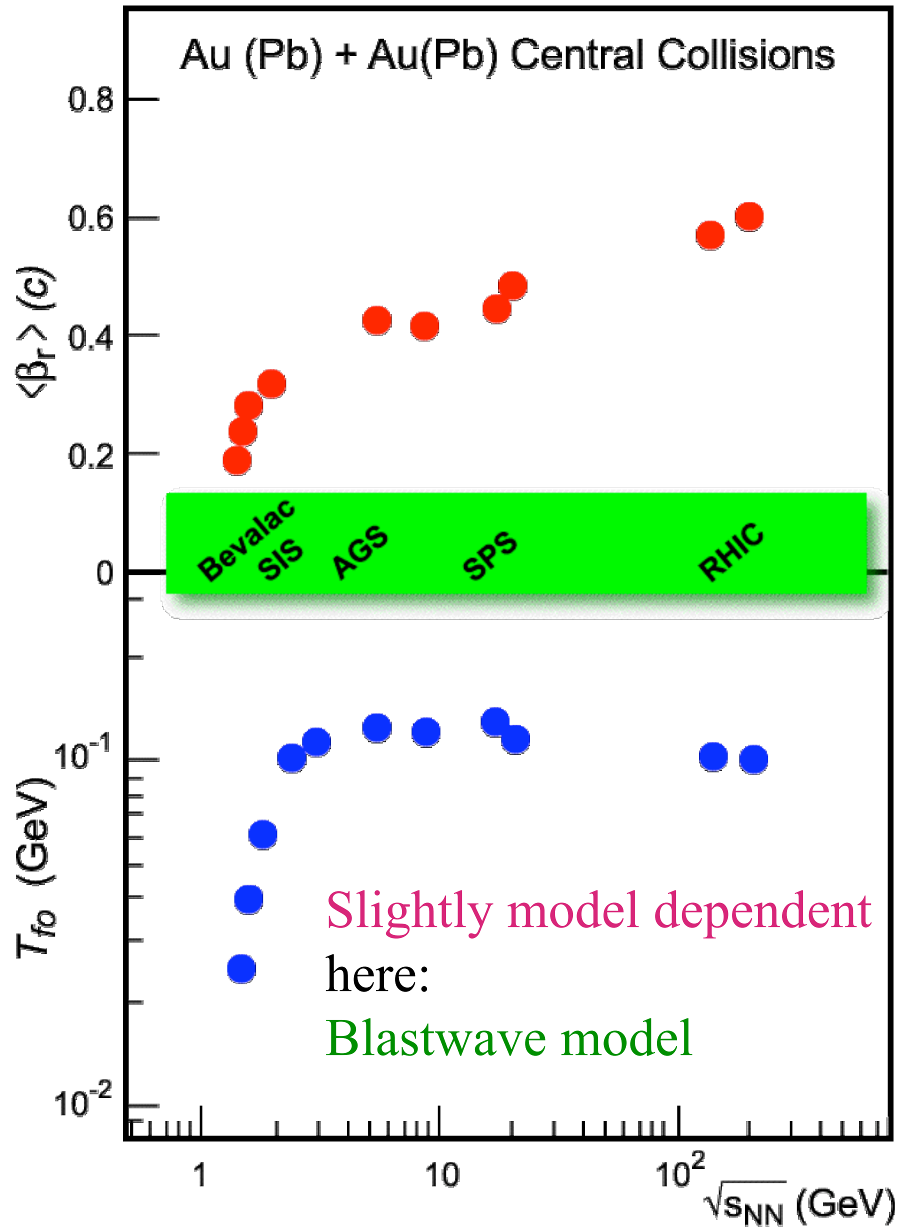






- Increasing T has similar effect on a spectrum as increasing β_s
- Flow profile (n) matters at lower m_T!
- Need high quality data down to low-m_T

Collective Radial Expansion



From fits to , K, p spectra:

< $_r$ >

- increases continuously

T_{th}

- saturates around AGS energy

Strong collective radial expansion at RHIC

- high pressure
- high rescattering rate
- Thermalization *likely*

Functions, Functions, …

$$\frac{dN}{p_T dp_T} \propto \left(1+\frac{p_0}{p_T}\right)^{-n}$$ power law (high-p_T)

$$\frac{dN}{m_T dm_T} \propto m_T \; K_1\left(\frac{m_T}{T}\right) \xrightarrow{m_T >> T} \propto \sqrt{m_T}\, e^{-m_T/T}$$ thermal emission (4π)

$$\frac{dN}{m_T dm_T} \propto m_T e^{-m_T/T}$$ thermal emission ($y=0$)

$$\frac{dN}{m_T dm_T} \propto \int_0^R r\, dr\, m_T \; I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right)$$ thermal + flow

$$\frac{dN}{m_T dm_T} \propto e^{-m_T/T}$$ simple

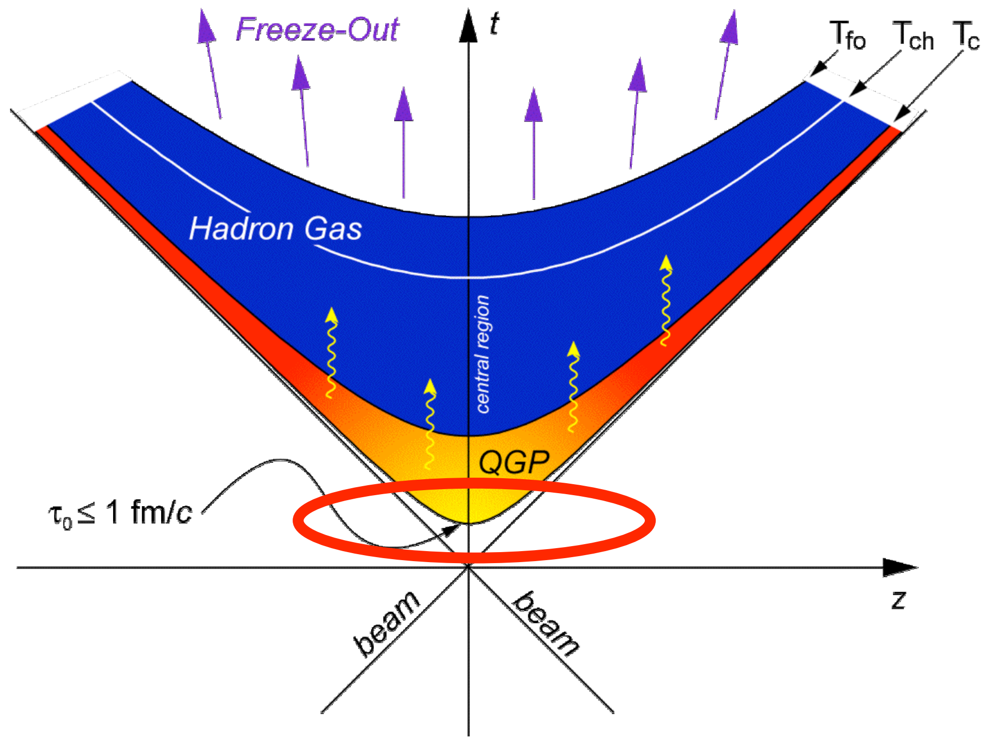
$$\frac{dN}{m_T dm_T} \propto \frac{e^{-m_T/T}}{\mathrm{m_T}^{\lambda}}$$ Empirical parametrization from pp ($\mathrm{m_T}$-scaling)

but also from theoretical model (flux-tube + Schwinger)
(Gatoff, Wong, PRD 46, 997 (1992)

Note: "T" depends on function used
in papers often more than one fit function quoted …

Summary

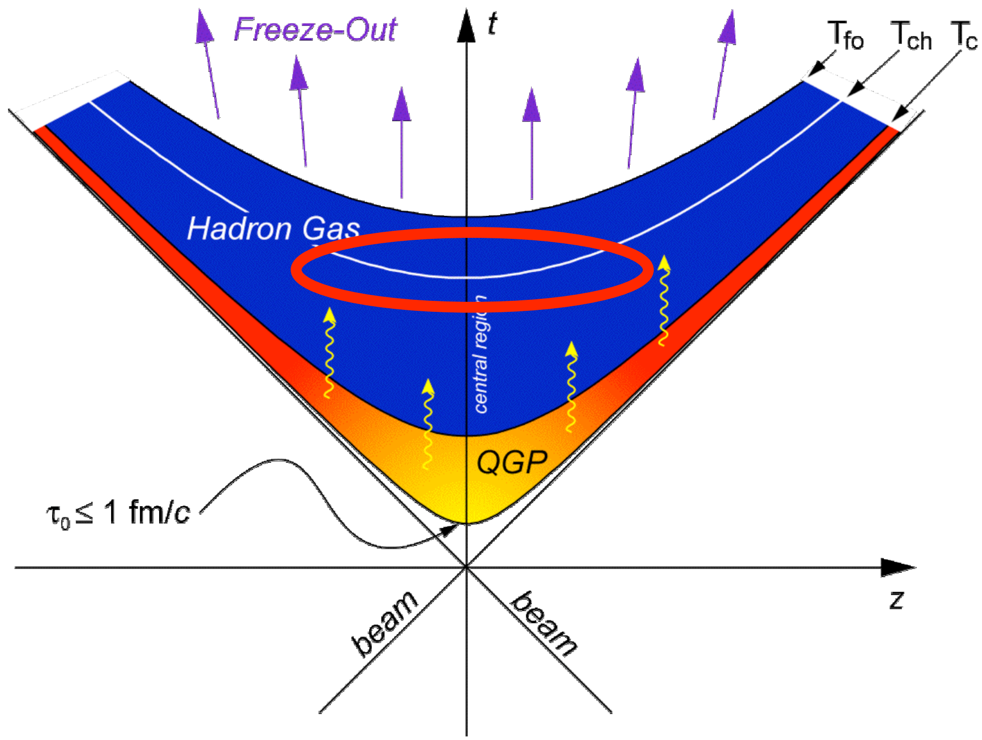
- Initial energy density high enough to produce a QGP
  - $\varepsilon \geq 10$ GeV/fm^3 (model dependent)
  - High gluon density
    dN/dy ~ 800–1200
  - Proof for *high density matter*
    but not for QGP formation
  - density ↗ ⇒ rescattering rate ↗
    ⇒ prerequisite for *thermalization*



Summary

◆ Statistical thermal models appear to work well at SPS and RHIC

- Chemical freeze-out is close to T_C
- Hadrons appear to be born into equilibrium at RHIC (SPS)
- Shows that what we observe is consistent with *thermalization* but again no direct proof



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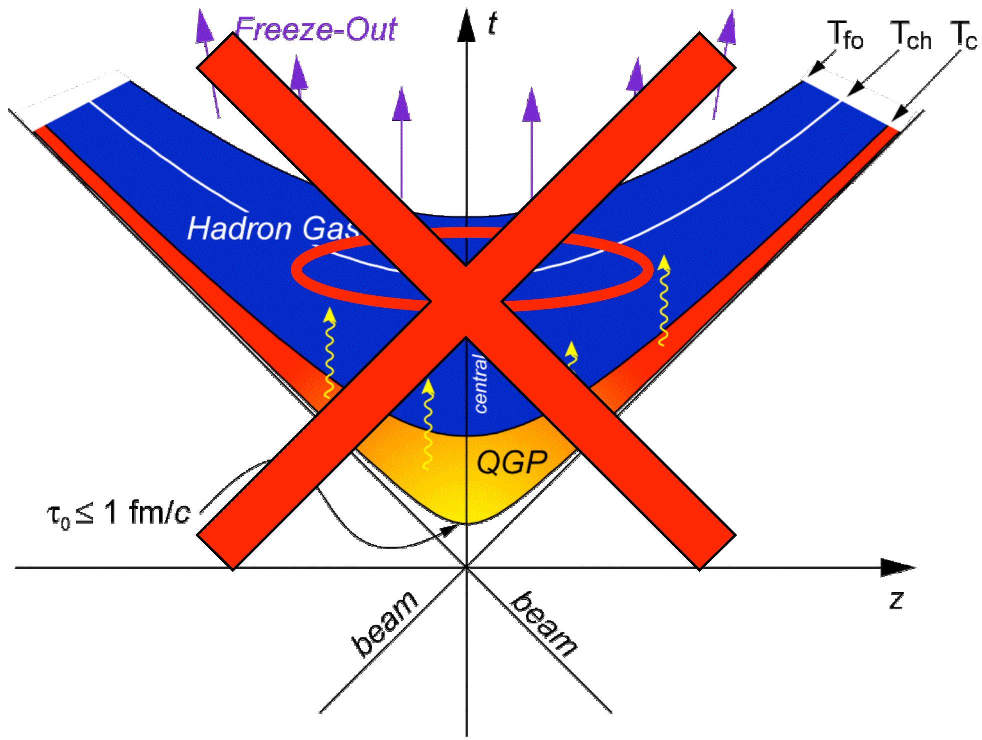


Summary

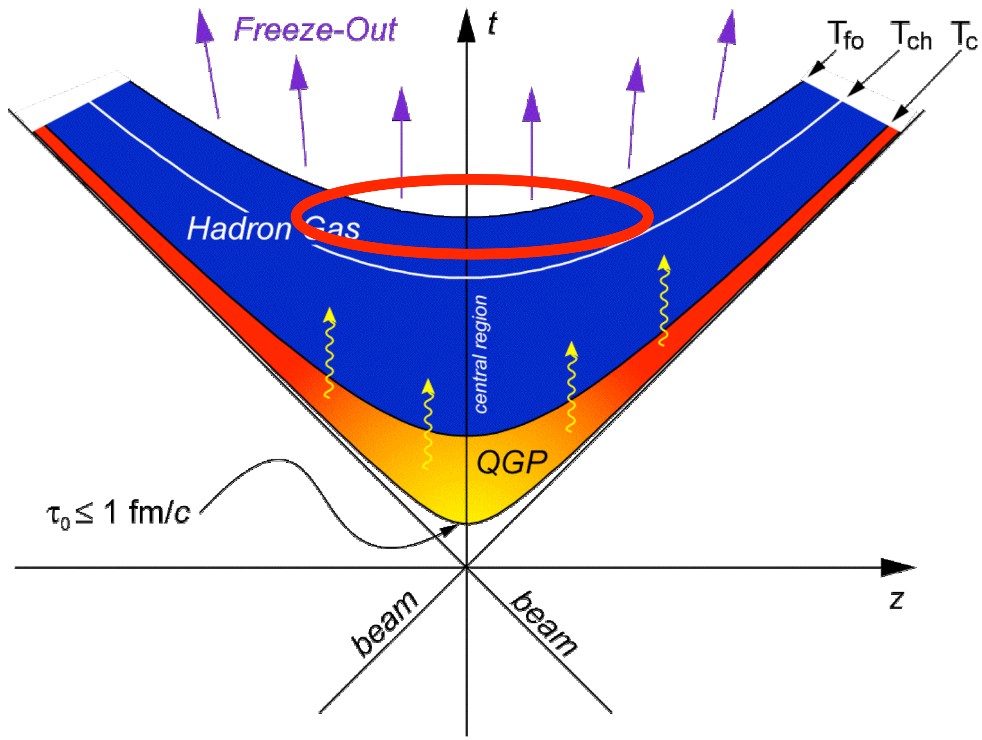
- Kinematic Freeze-Out and Transverse Flow

  - RHIC and SPS spectra cannot be consistently described without flow

  - Many different functions fit
     - different emphasis
     - watch out: different “T”

  - T and β_T are correlated

  - Fact that you derive T,β_T is no direct proof for *thermalization*



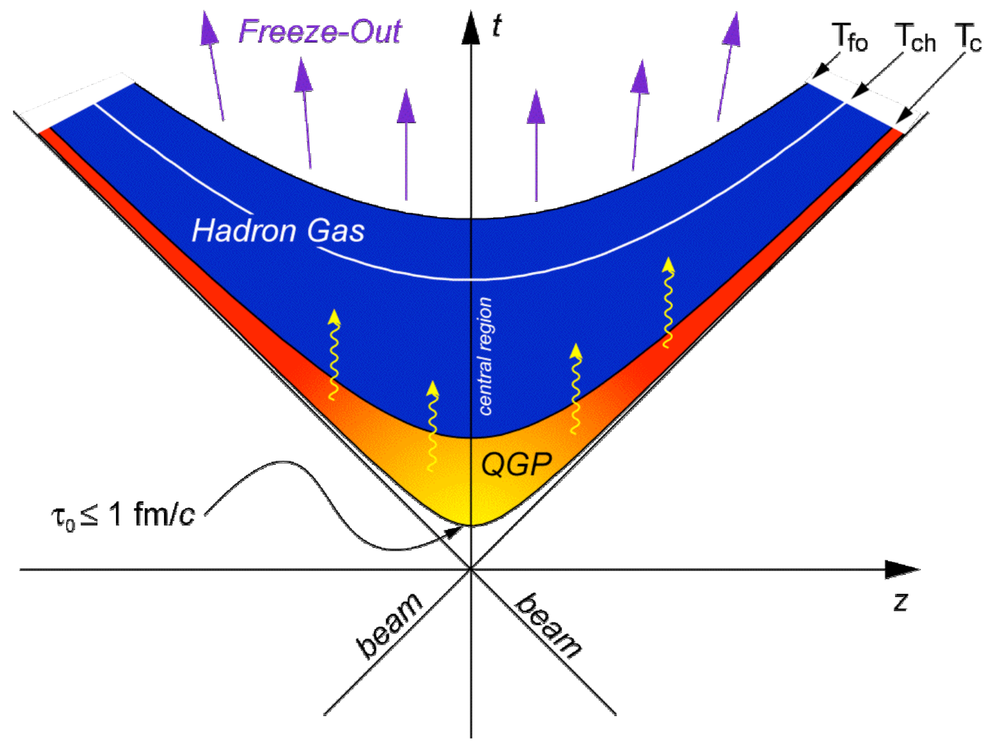
Conclusion

- There is no "  "

However:

- All this provides pieces of a larger evolving picture
- So far all pieces *point* indeed to QGP formation
- Need final proof from theory

  Show that:
  - QGP scenario describes data
  - any other scenarios do not



N.B.: Even if the new state does not fit into the definition of QGP (planet) it's certainly "new" and expands our knowledge (like Pluto)

Next …

For all the remaining signatures see Jamie Nagle's talk …