Heavy Ion Physics Lecture 1

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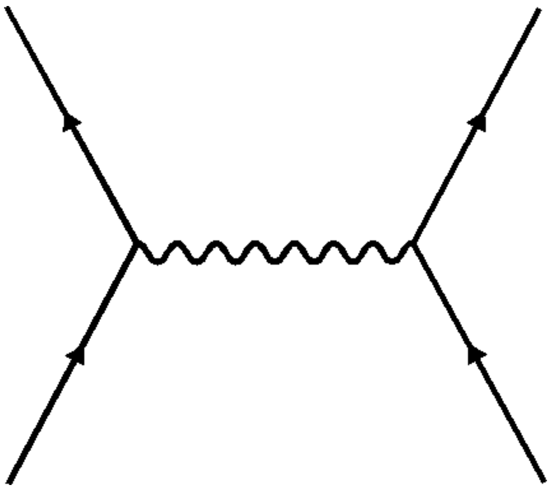
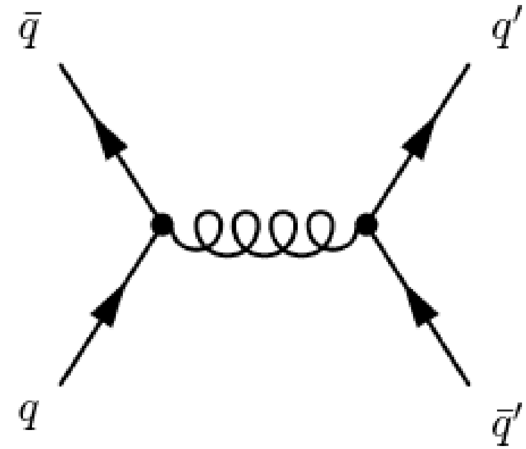
Physics beyond the diagram!





- The water droplets on the window demonstrate a principle.
- Truly beautiful physics is expressed in systems whose underlying physics is QED.

- Does QCD exhibit equally beautiful properties as a bulk medium.
- ANSWER: YES!

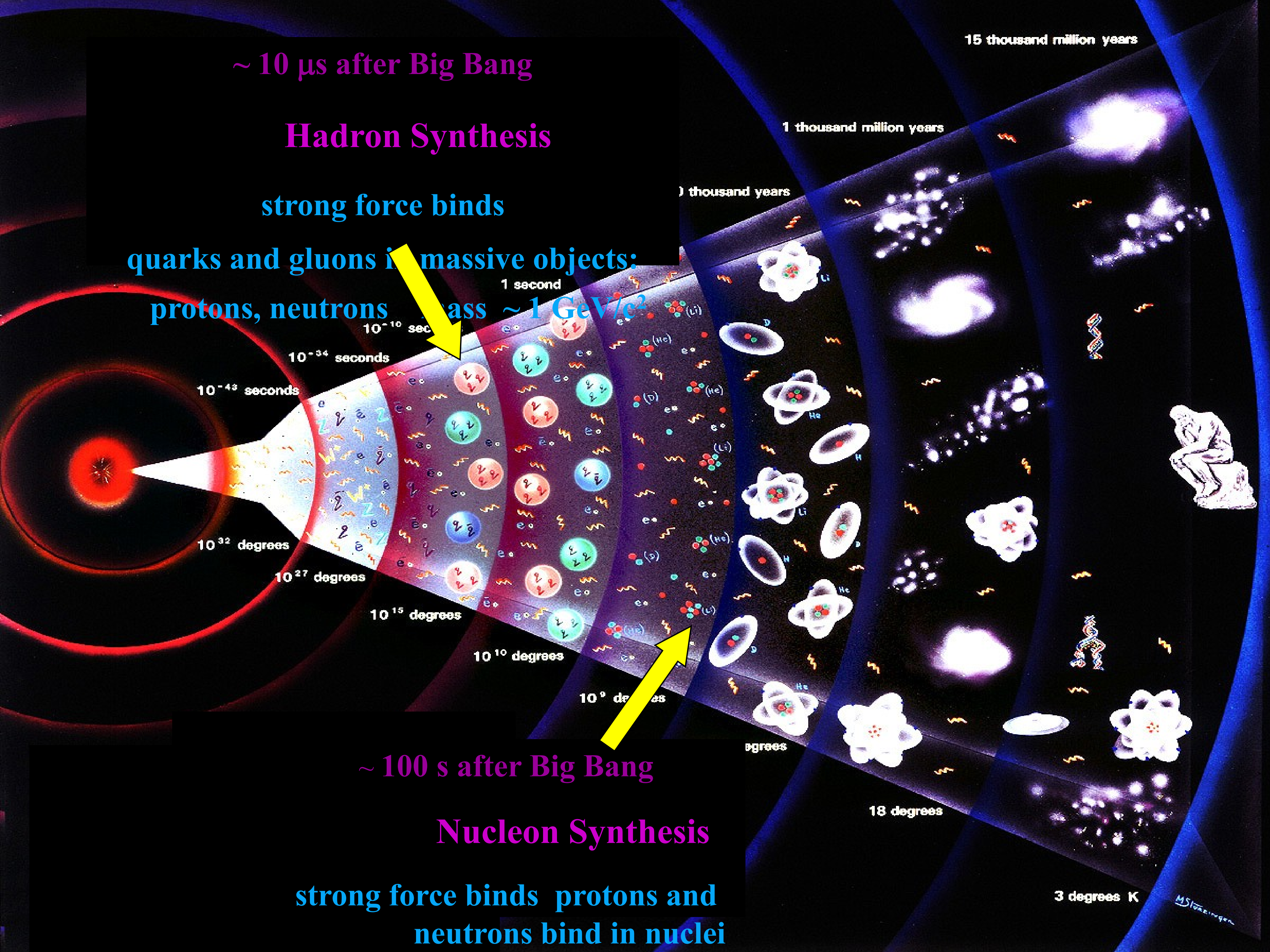
~ 10 µs after Big Bang

Hadron Synthesis

strong force binds

quarks and gluons in massive objects:

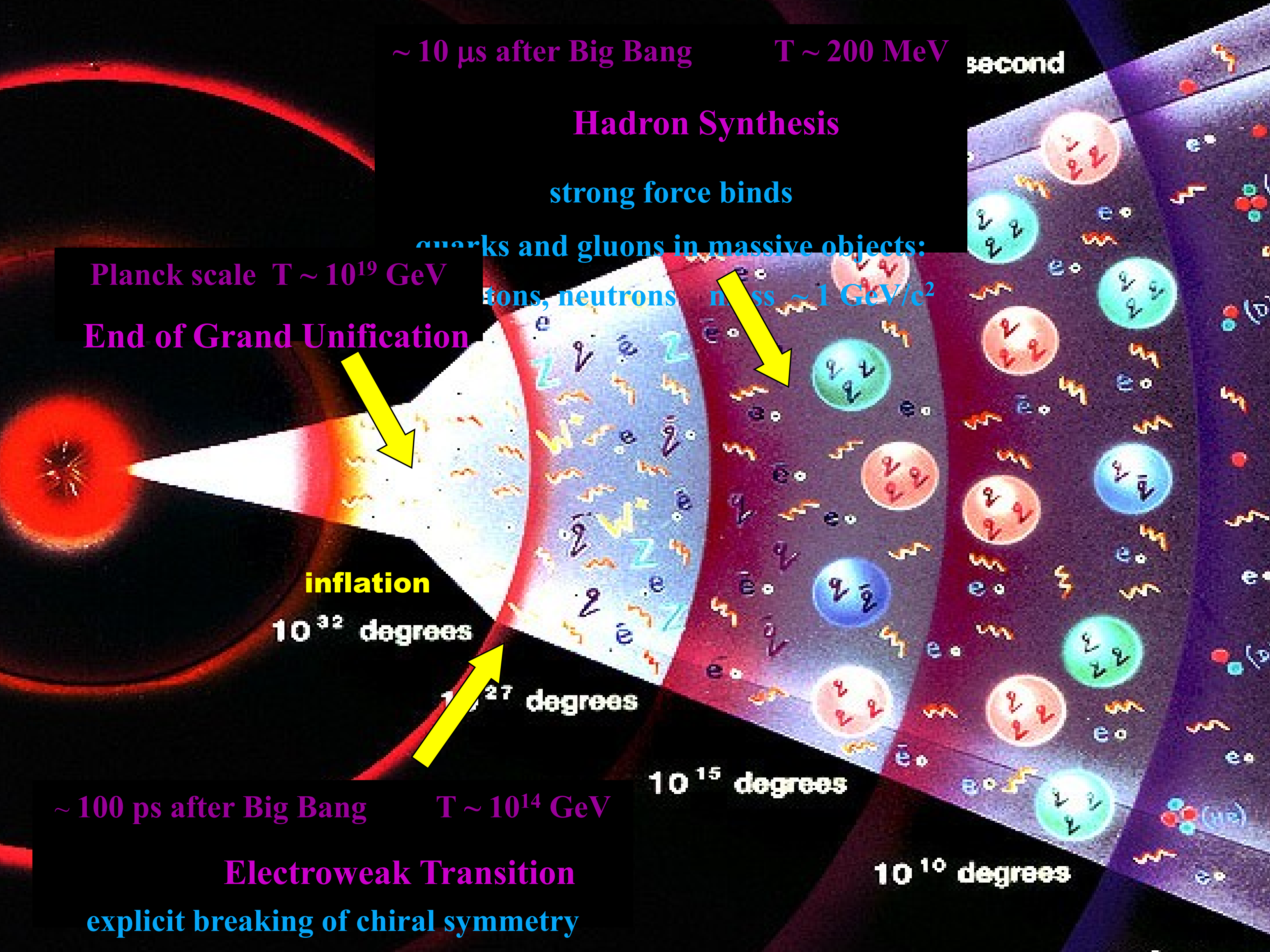
protons, neutrons mass ~ 1 GeV/c^2



~ 100 s after Big Bang

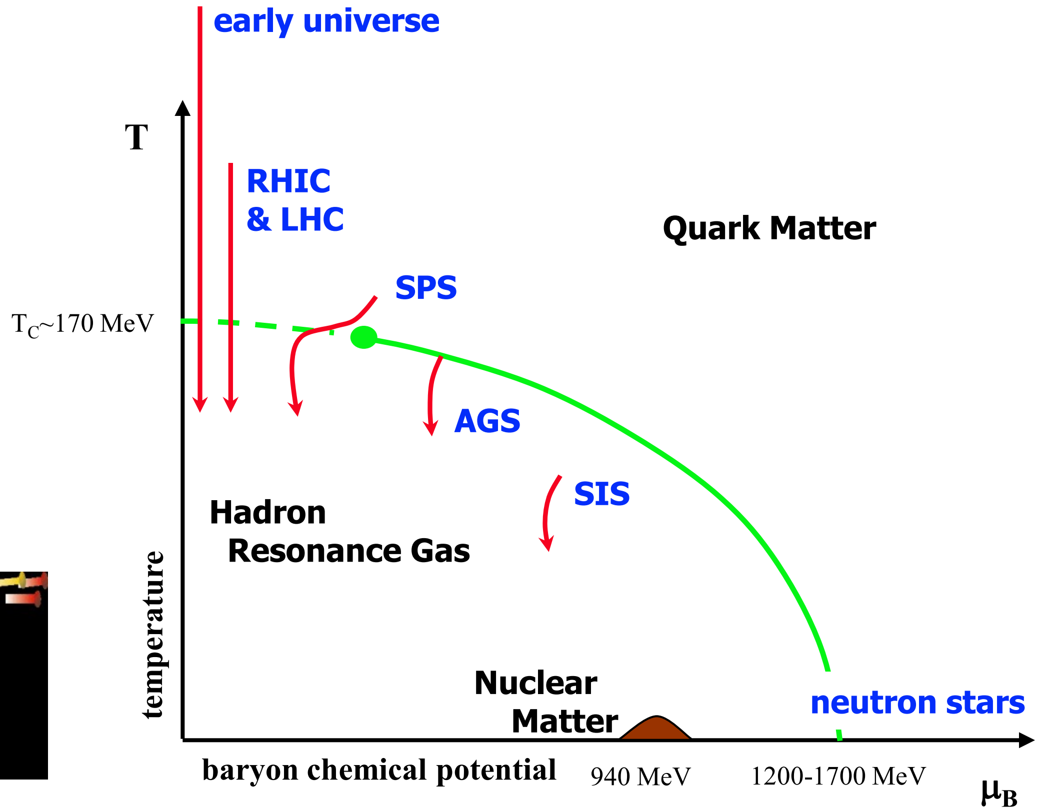
Nucleon Synthesis

strong force binds protons and neutrons bind in nuclei

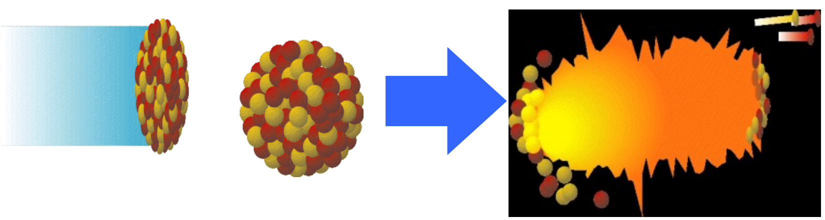

~ 10 μs after Big Bang
T ~ 200 MeV
second
Hadron Synthesis
strong force binds
quarks and gluons in massive objects:
tons, neutrons
ss ~1 GeV/c²
Planck scale T ~ 10¹⁹ GeV
End of Grand Unification
inflation
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
~ 100 ps after Big Bang
T ~ 10¹⁴ GeV
Electroweak Transition
explicit breaking of chiral symmetry

"Travel" Back in Time

- **QGP in Astrophysics**
  - **early universe after ~ 10 μs**
  - **possibly in neutron stars**



- **Quest of heavy ion collisions**

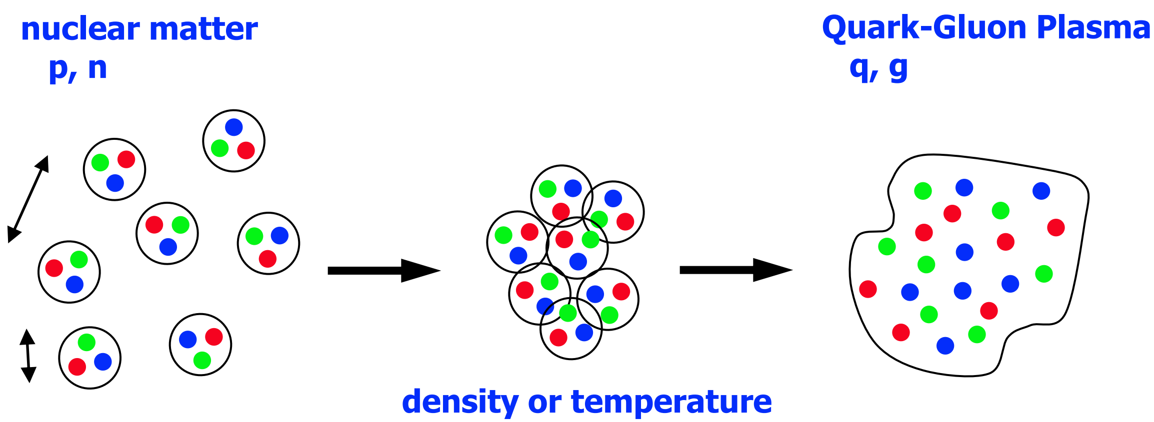


  - **create QGP as transient state in heavy ion collisions**
  - **verify existence of QGP**
  - **Study properties of QGP**
  - **study QCD confinement and how hadrons get their masses**

Estimating the Critical Energy Density

distance of two nucleons:
$2\ r_0 \sim 2.3$ fm

size of nucleon
$r_n \sim 0.8$ fm



- **normal nuclear matter ρ_0**

$$\rho_0 = \frac{A}{\frac{4\pi}{3}R^3} = \frac{3}{4\pi\ r_0^3} \; \square \qquad {}^{-3}$$

$$\varepsilon_0 \; \square \qquad \text{ɘ}V / fm^3$$

- **critical density:**
  naïve estimation
  nucleons overlap $R \sim r_n$

$$\rho_c = \frac{3}{4\pi\ r_n^3} \; \square \qquad {}^3 \approx 3.1\rho_0$$

$$\varepsilon_c \; \square \qquad / \; / fm^3$$

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Critical Temperature and Degrees of Freedom

Noninteracting system of 8 gluons with 2 polarizations and 2 flavor's of quarks (m=0, s=1/2) with 3 colors

- **In thermal equilibrium relation of pressure P and temperature T**

$$\varepsilon_{2-flavor} = \left(2_f \cdot 2_s \cdot 2_q \cdot 3_c \frac{7}{8} + 2_s \cdot 8_c \right) \frac{\pi^2}{30} T^4 = 37 \frac{\pi^2}{30} T^4$$

$$\varepsilon_{3-flavor} = \left(3_f \cdot 2_s \cdot 2_q \cdot 3_c \frac{7}{8} + 2_s \cdot 8_c \right) \frac{\pi^2}{30} T^4 = 47.5 \frac{\pi^2}{30} T^4$$

- **Assume deconfinement at mechanical equilibrium**
  - **Internal pressure equal to vacuum pressure $B = (200\ \text{MeV})^4$**

$$T_c^4 = \frac{B}{4} \qquad \Rightarrow \qquad T_c = \frac{200\,MeV}{\sqrt{2}} \quad V$$

- **Energy density in QGP at critical temperature T_c**

$$\varepsilon_c(T_c) = 0.6\ GeV/fm^3$$

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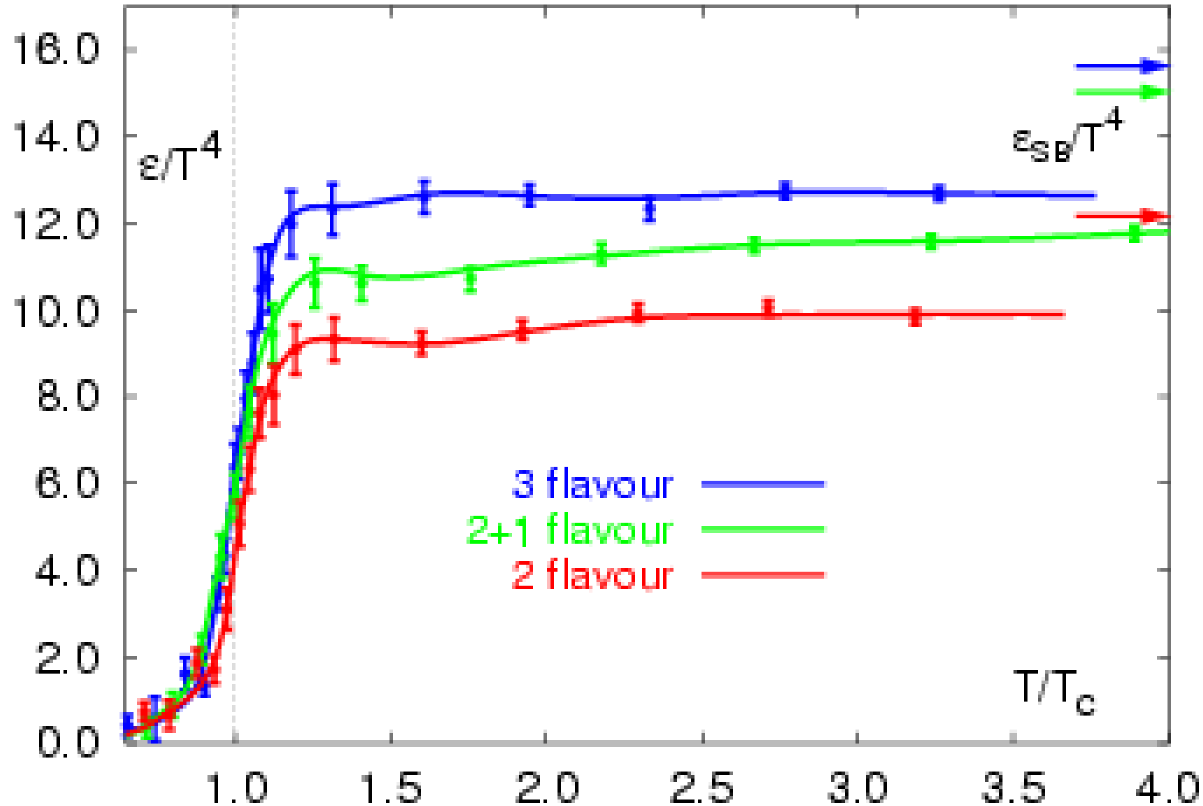
Lattice Calculations

- The onset of QGP is far from the perturbative regime (α_s~1)
- Lattice QCD is the only 1st principles calculation of phase transition and QGP.



- Lattice Calculations indicate:
  - T_C~170 MeV
  - ε_C~1 GeV/fm^4

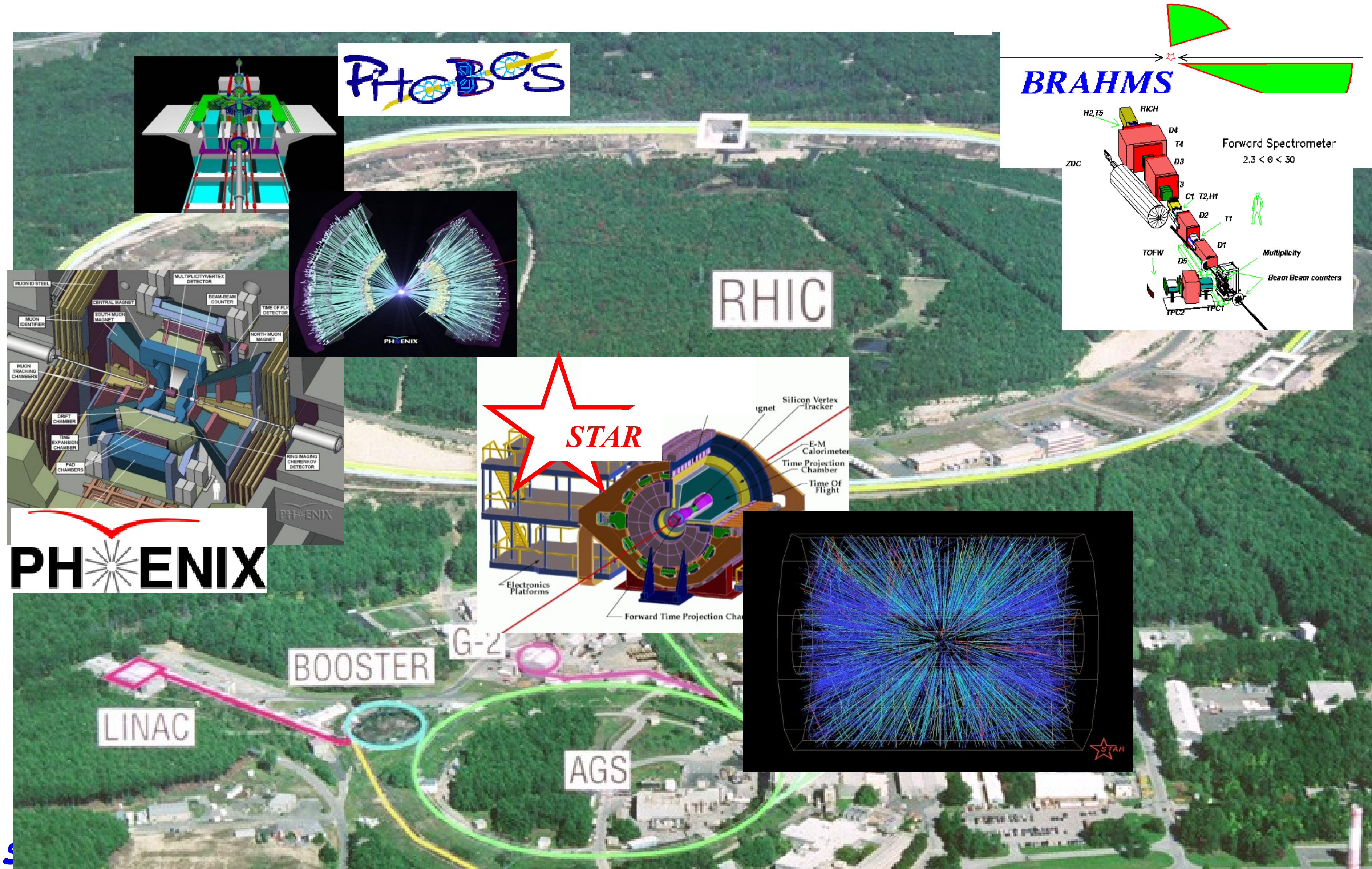
Outline of Lectures

- **What have we done?**
  - Energy Density
  - Initial Temperature
  - Chemical & Kinetic Equilibrium
  - System Size
- **Is There a There There?**
  - The Medium & The Probe
  - High Pt Suppression
  - Control Experiments: γ_{direct}, W, Z
- **What is It Like?**
  - Azimuthally Anisotropic Flow
  - Hydrodynamic Limit
  - Heavy Flavor Modification
  - Recombination Scaling
- **Is the matter exotic?**
  - Quarkonia, Jet Asymmetry, Color Glass Condensate

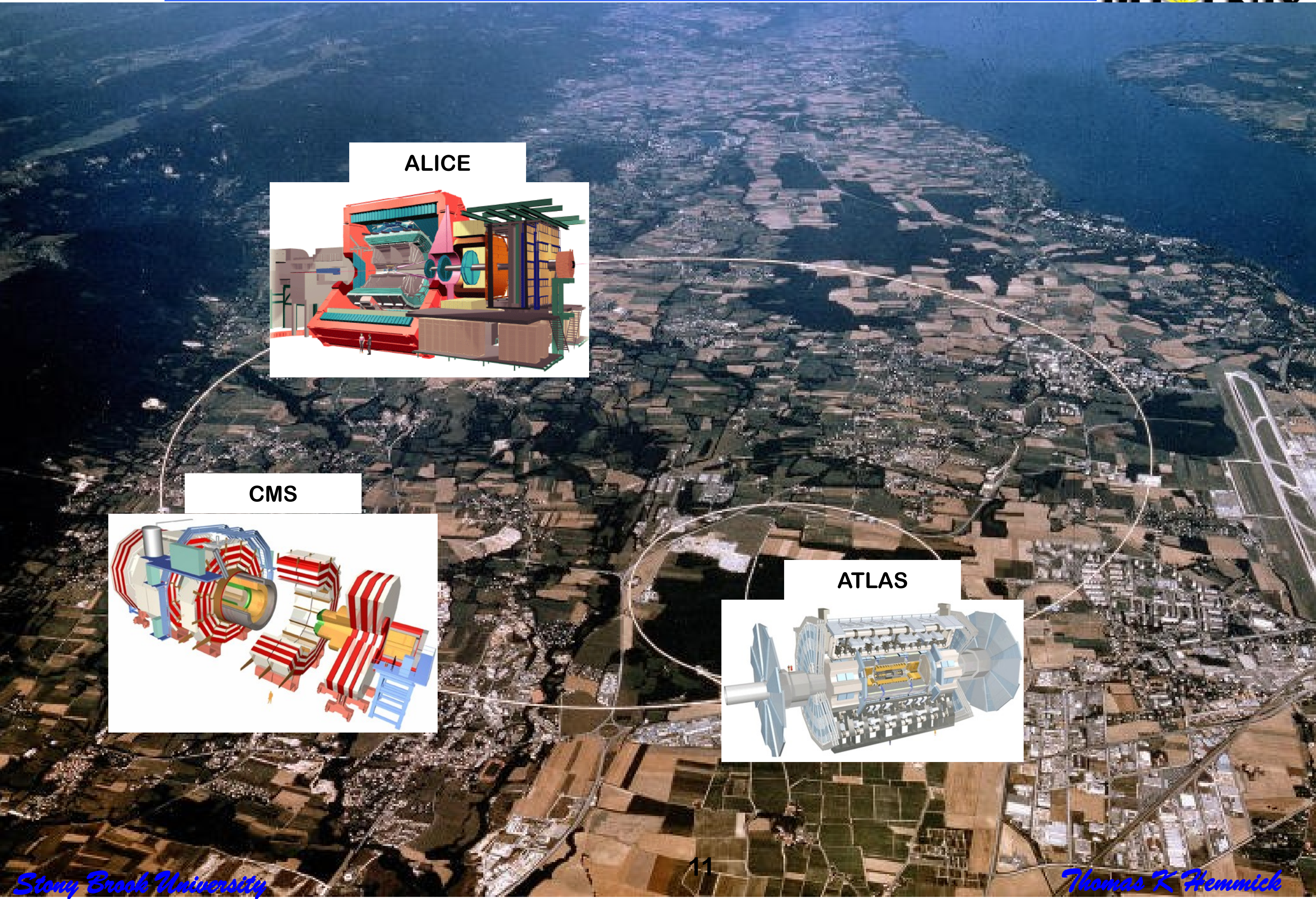
Lecture 1

Lecture 2

RHIC Experiments

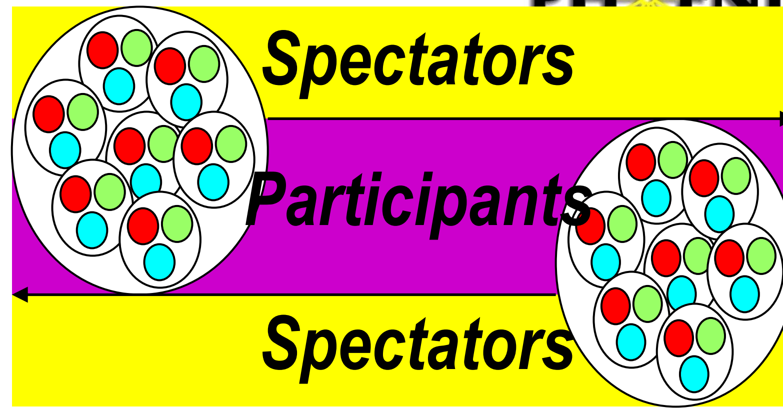


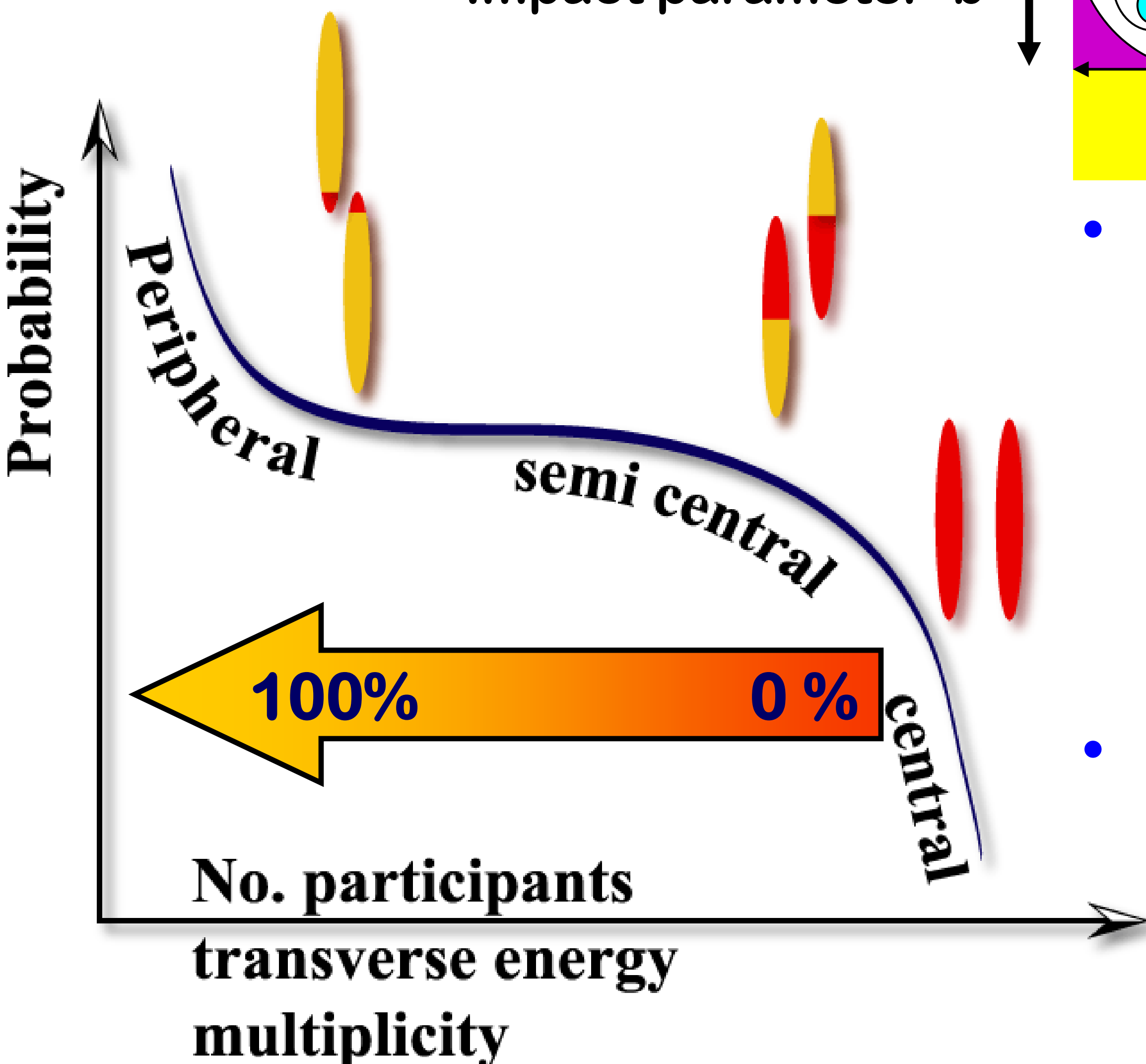
LHC Experiments



Collisions are not all the same

Impact parameter b

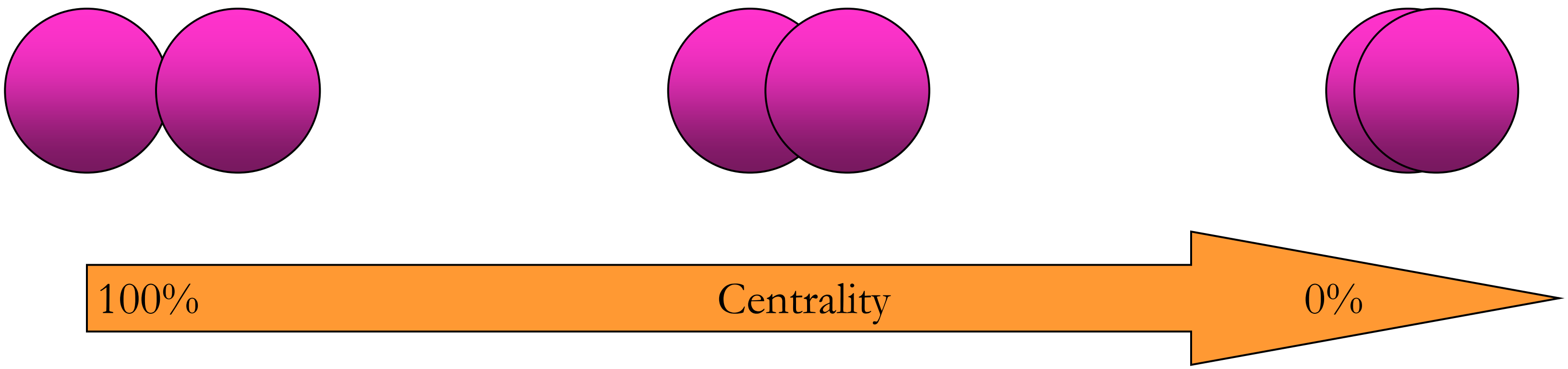




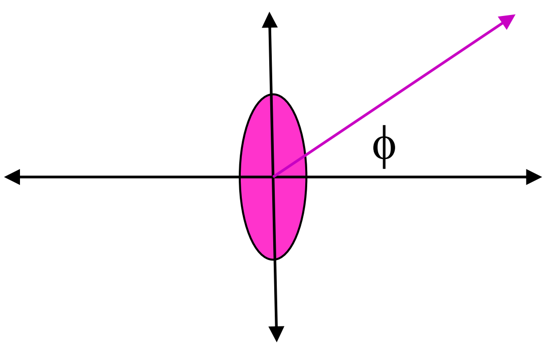
- Small impact parameter (b~0)
  - High energy density
  - Large volume
  - Large number of produced particles
- Measured as:
  - Fraction of cross section "centrality"
  - Number of participants
  - Number of nucleon-nucleon collisions

Terminology

Peripheral Collision | Semi-Central Collision | Central Collision



- **Centrality and Reaction Plane determined on an Event-by-Event basis.**
- **N_{part}= Number of Participants**
  - **2 → 394**



Reaction Plane

- **Fourier decompose azimuthal yield:**

$$\frac{d^3N}{d\phi \, dp_T \, dy} \propto \left[1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + \ldots\right]$$

What have we done? Energy Density

Overly Simplified: Particles don't even have to interact!

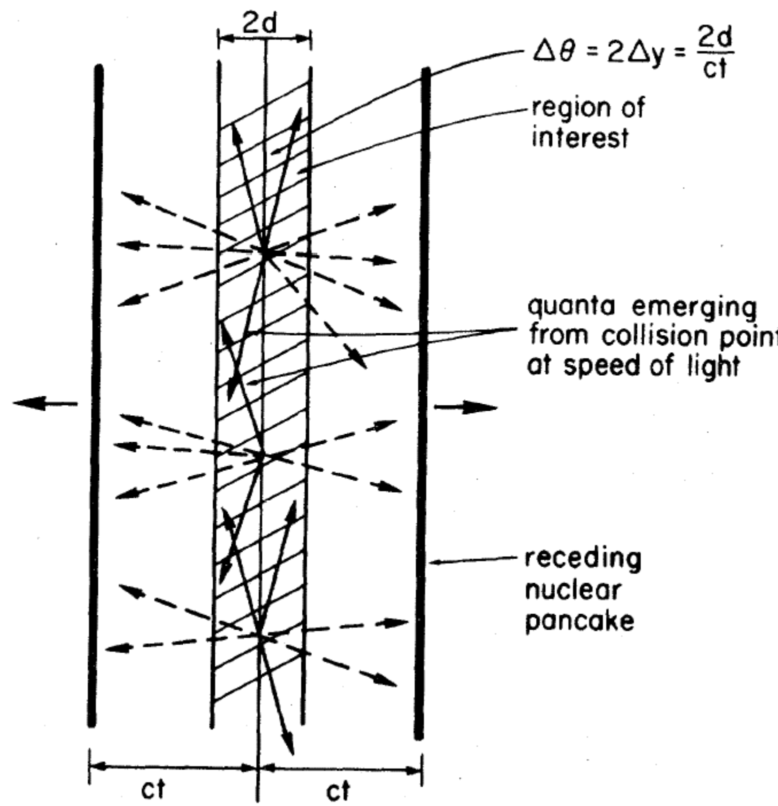
- **Let's calculate the Mass overlap Energy:**

$$\langle \varepsilon \rangle = 2\rho_0 \gamma^2 = 3150 \frac{GeV}{fm^3} \qquad \rho_0 = 0.14 \frac{GeV}{fm^3}; \gamma_{RHIC} = 106$$

- **Bjorken Energy Density Formula:**

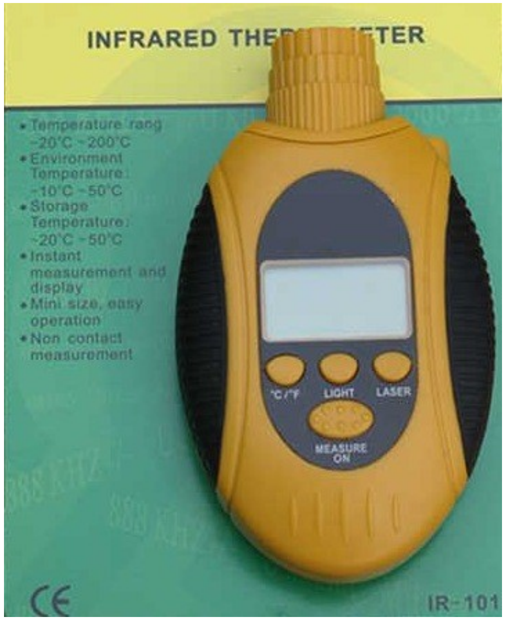
$$\langle \varepsilon_{BJ}(t_{form}) \rangle = \frac{1}{t_{form} A} \frac{dE_T(t_{form})}{dy}$$

Assumed **Measured**

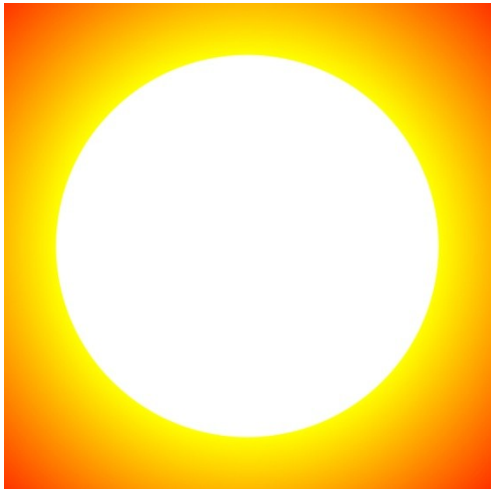


- **RHIC: $\varepsilon\tau$ = 5.4 +/- 0.6 GeV/fm²c**
  LHC: $\varepsilon\tau$ = 16 GeV/fm²c

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!

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Real versus Virtual Photons

Direct photons $\gamma_{direct}/\gamma_{decay}$ ~ 0.1 at low p_T, and thus systematics dominate.

Number of virtual photons per real photon:

$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)S$$

Hadron decay:

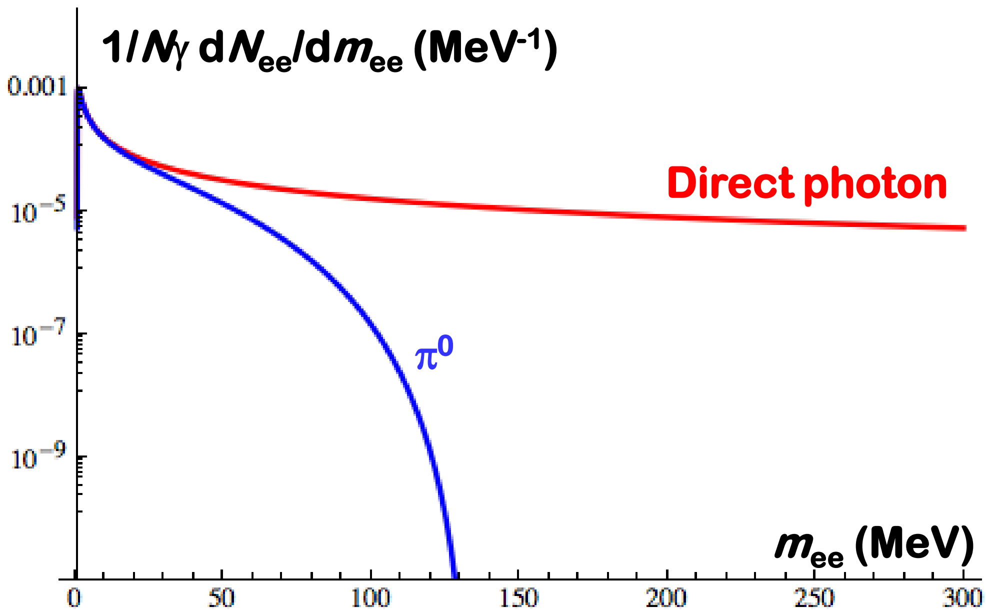
$$S = |F(m_{ee}^2)|^2\left(1-\frac{m_{ee}^2}{M_h^2}\right)^3$$

form factor

Point-like process:

$$S \approx 1$$

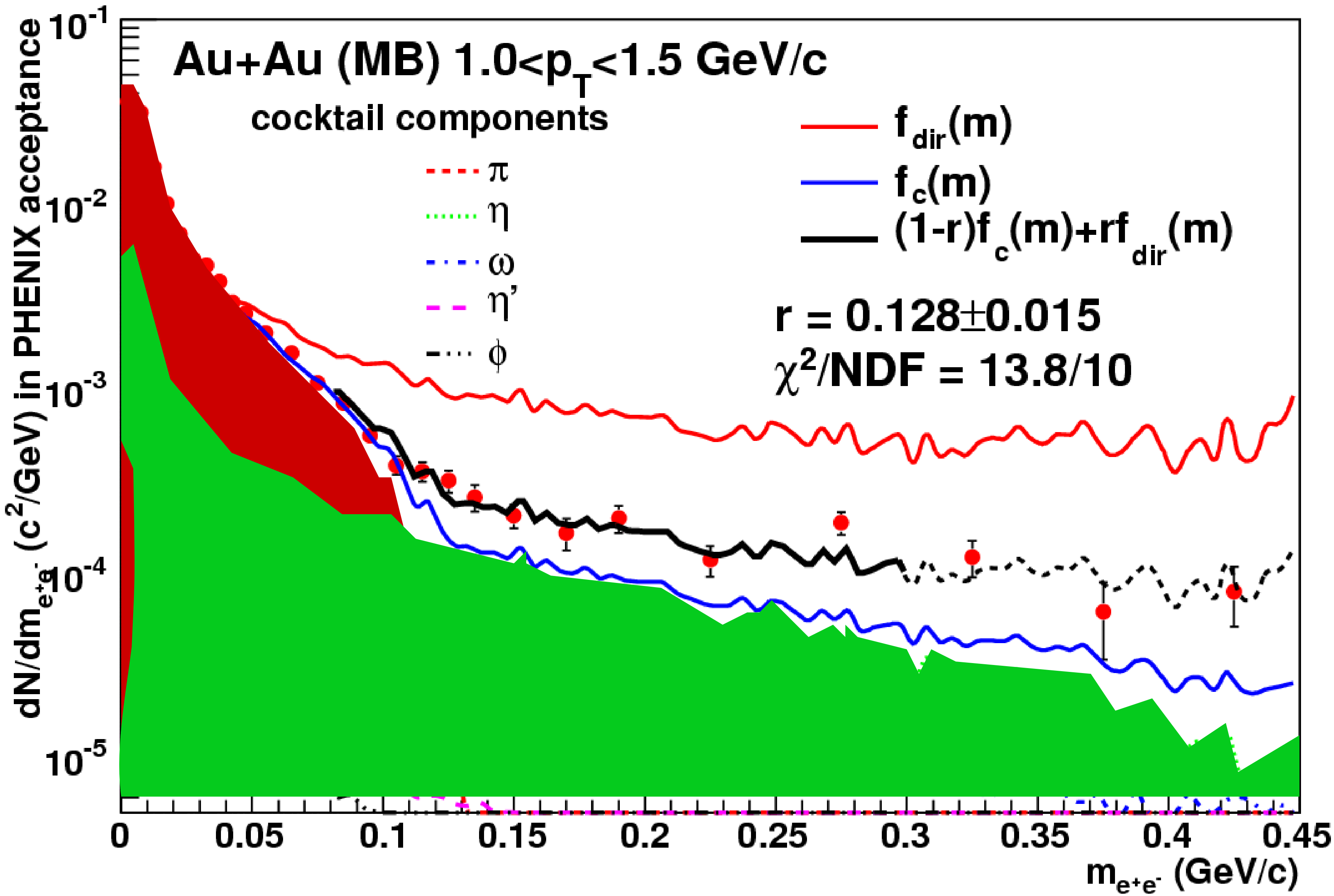
$$(\text{for } p_T^{ee} \gg m_{ee})$$



About 0.001 virtual photons with $m_{ee} > M_{pion}$ for every real photon

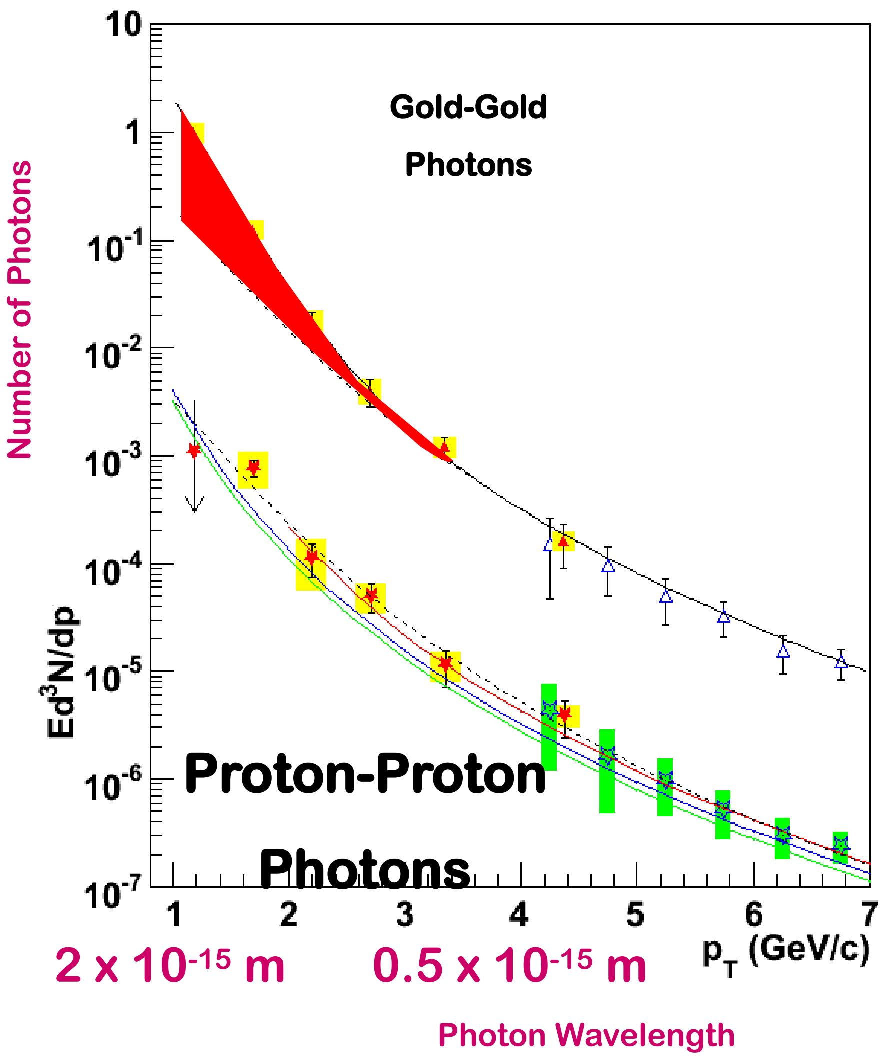
Avoid the π^0 background at the expense of a factor 1000 in statistics

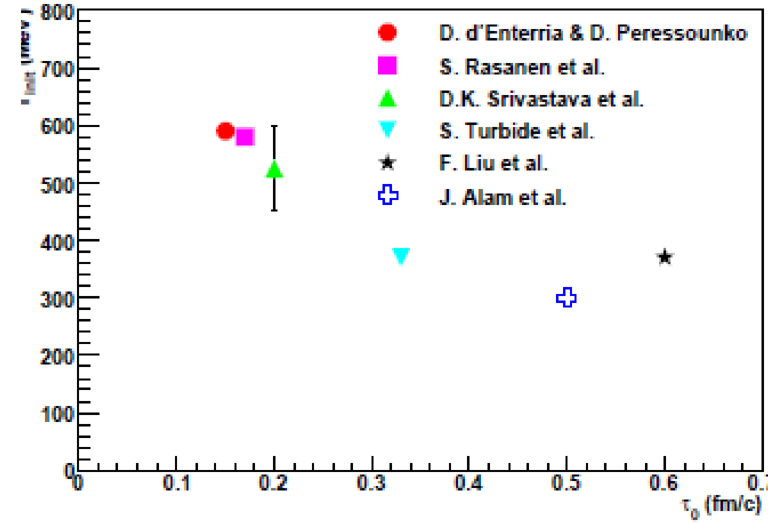
Observation of Direct Virtual Photons



Experimental Result

T_i = 4-8 trillion Kelvin





Emission rate and distribution consistent with equilibrated matter

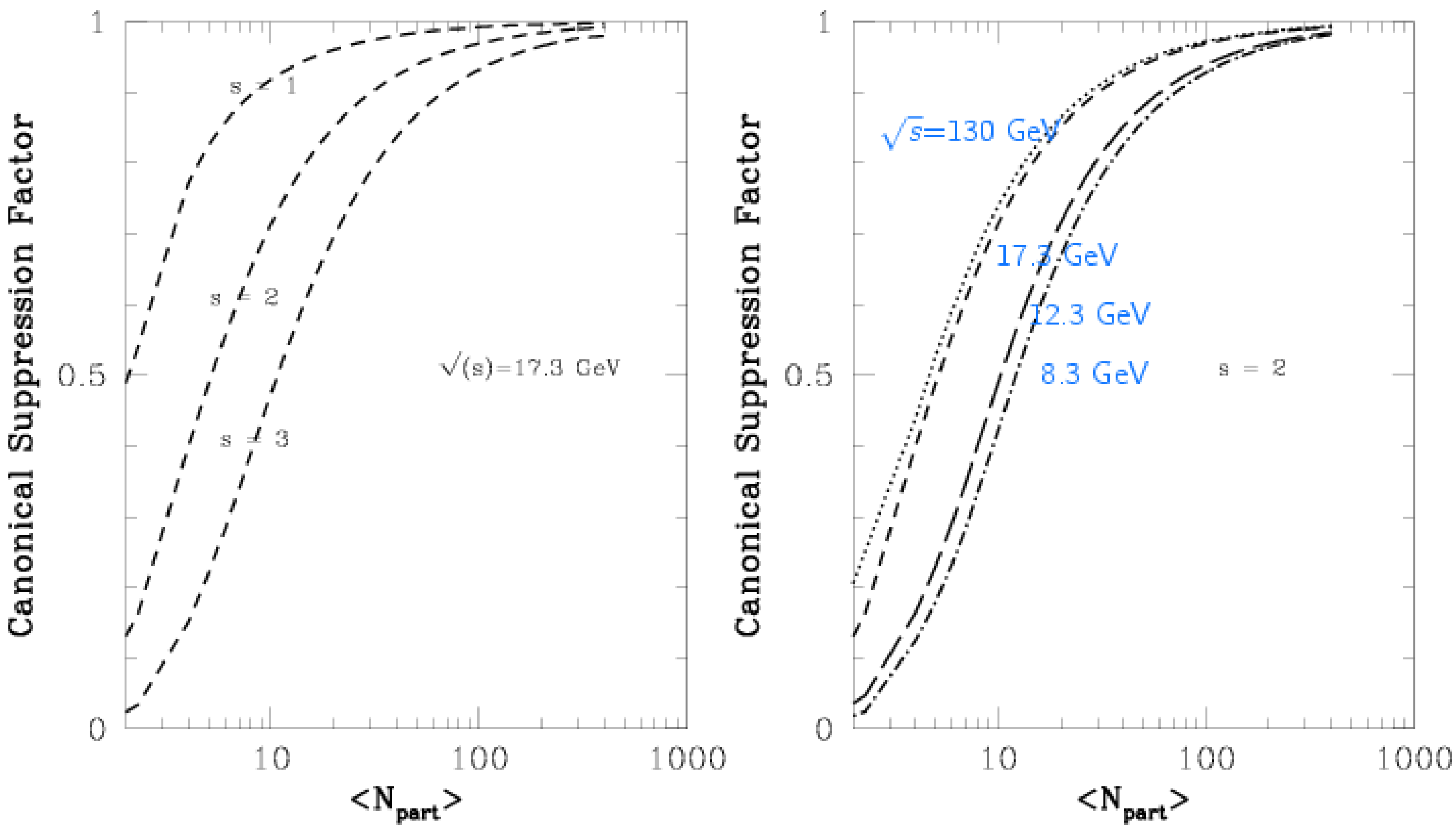
T~300-600 MeV

Thermal Equilibrium

- **We'll consider two aspects of thermal predictions:**
  - **Chemical Equilibrium**
    - Are all particle species produced at the right relative abundances?
  - **Kinetic Equilibrium**
    - Energetic sconsistent with common temperature plus flow velocity?
- **Choose appropriate statistical ensemble:**
  - **Grand Canonical Ensemble**: In a large system with many produced particles we can implement conservation laws in an averaged sense via appropriate chemical potentials.
  - **Canonical Ensemble**: in a small system, conservation laws must be implemented on an EVENT-BY-EVENT basis. This makes for a severe restriction of available phase space resulting in the so-called "Canonical Suppression."
  - **Where is canonical required:**
    - low energy HI collisions.
    - high energy e+e- or hh collisions
    - Peripheral high energy HI collisions

Chem Eql: Canonical Suppression

Tounsi and Redlich, hep-ph/0211159



for $N_{part} \geq 60$ Grand Canonical ok to better 10%

Canonical Suppression is likely the driving force behind "strangeness enhancement"

Thermal or Chemical yields

- As you know **the formula for the number density of all species:**

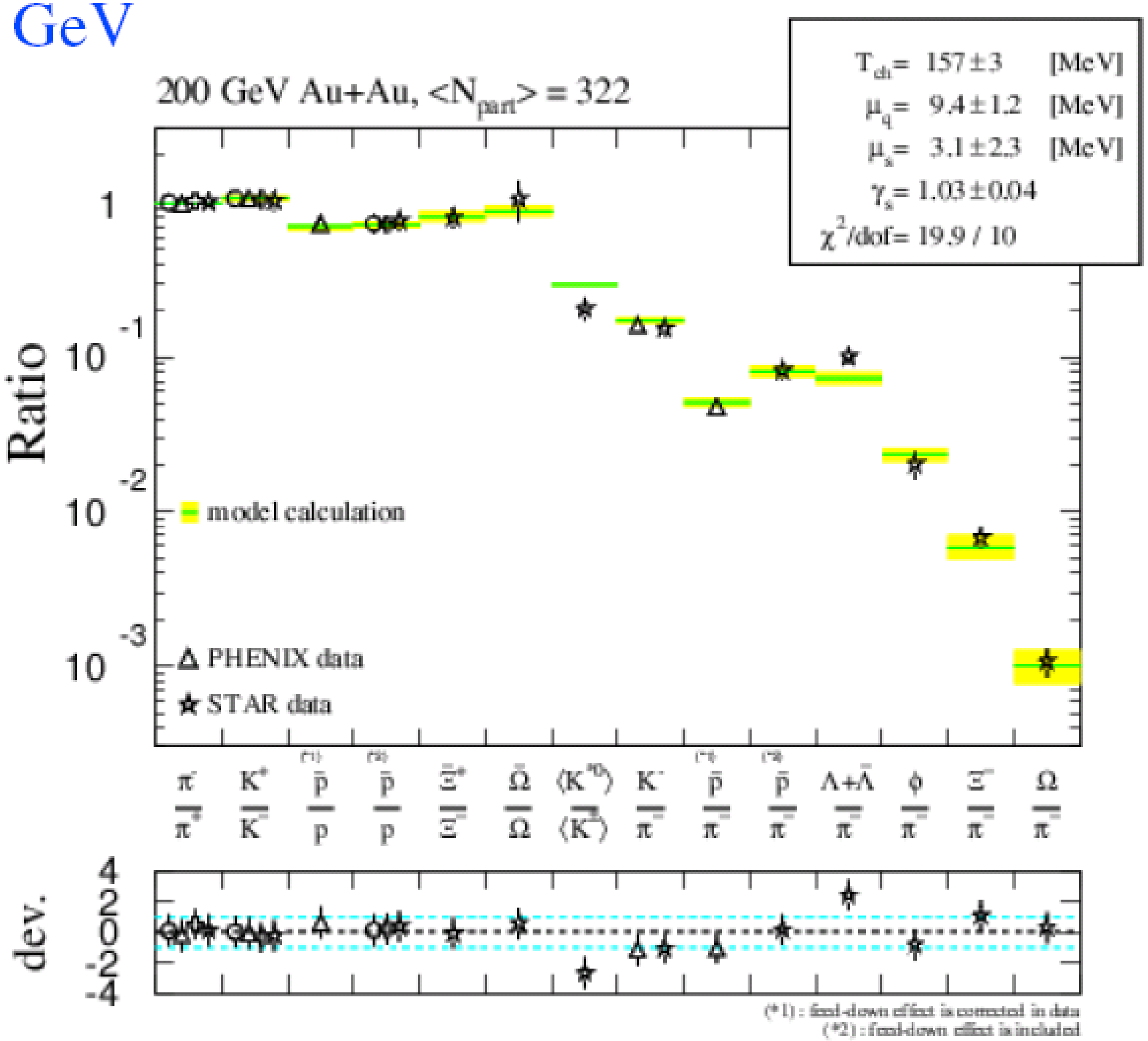
$$n_i^0 = \frac{g_i}{2\pi^2}\int \frac{p^2\,dp}{e^{\left(E-\mu_B B_i-\mu_s S_i-\mu_3 I^3\right)/T} \pm 1}$$

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

- Given the temperature and all m, on determines the equilibruim number densities of all various species.
- The ratios of produced particle yields between various species can be fitted to determine T, μ.

Chemical Equilibrium Fantastic

200 GeV



Simple 2-parameter fits to chemical equilibrium are excellent.

Description good from AGS energy and upward.

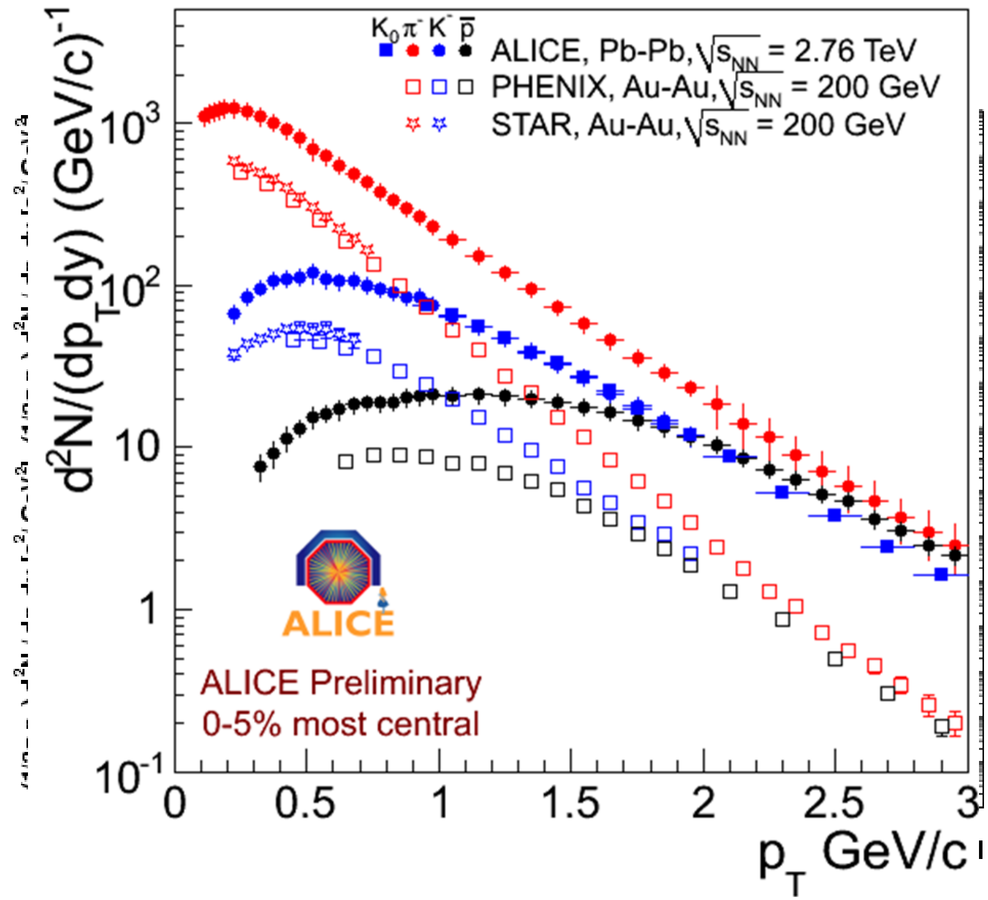
Necessary, but not sufficient for QGP

Kinetic Equil: Radial Flow

- As you know for any interacting system of particles expanding into vacuum, radial flow is a natural consequence.
  - During the cascade process, one naturally develops an ordering of particles with the highest common underlying velocity at the outer edge.
- This motion complicates the interpretation of the momentum of particles as compared to their temperature and should be subtracted.
  - Although 1st principles calculations of fluid dynamics are the higher goal, simple parameterizations are nonetheless instructive.
- Hadrons are released in the final stage and therefore measure “FREEZE-OUT” Temp.

Radial Flow in Singles Spectra

- **Peripheral:**
  - Pions are concave due to feeddown.
  - K,p are exponential.
  - Yields are MASS ORDERED.
- **Central:**
  - Pions still concave.
  - K exponential.
  - p flattened at left
  - Mass ordered wrong (p passes pi !!!)



Underlying collective VELOCITIES impart more momentum to heavier species consistent with the trends

Decoupling Motion: Blast Wave

- **Let's consider a Thermal Boltzmann Source:**

$$\frac{d^3N}{dp^3} \propto e^{-E/T};\ E\frac{d^3N}{dp^3} = \frac{d^3N}{m_T dm_T d\phi dy} \propto Ee^{-E/T} = m_T \cosh(y) e^{-m_T \cosh(y)/T}$$

- **If this source is boosted radially with a velocity β_{boost} and evaluated at y=0:**

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto m_T I_0\left(\frac{p_T \sinh(\rho)}{T}\right) K_1\left(\frac{m_T \cosh(\rho)}{T}\right)$$

where $$\rho = \tanh^{-1}(\beta_{boost})$$

- **Simple assumption: uniform sphere of radius R and boost velocity varies linearly w/ r:**

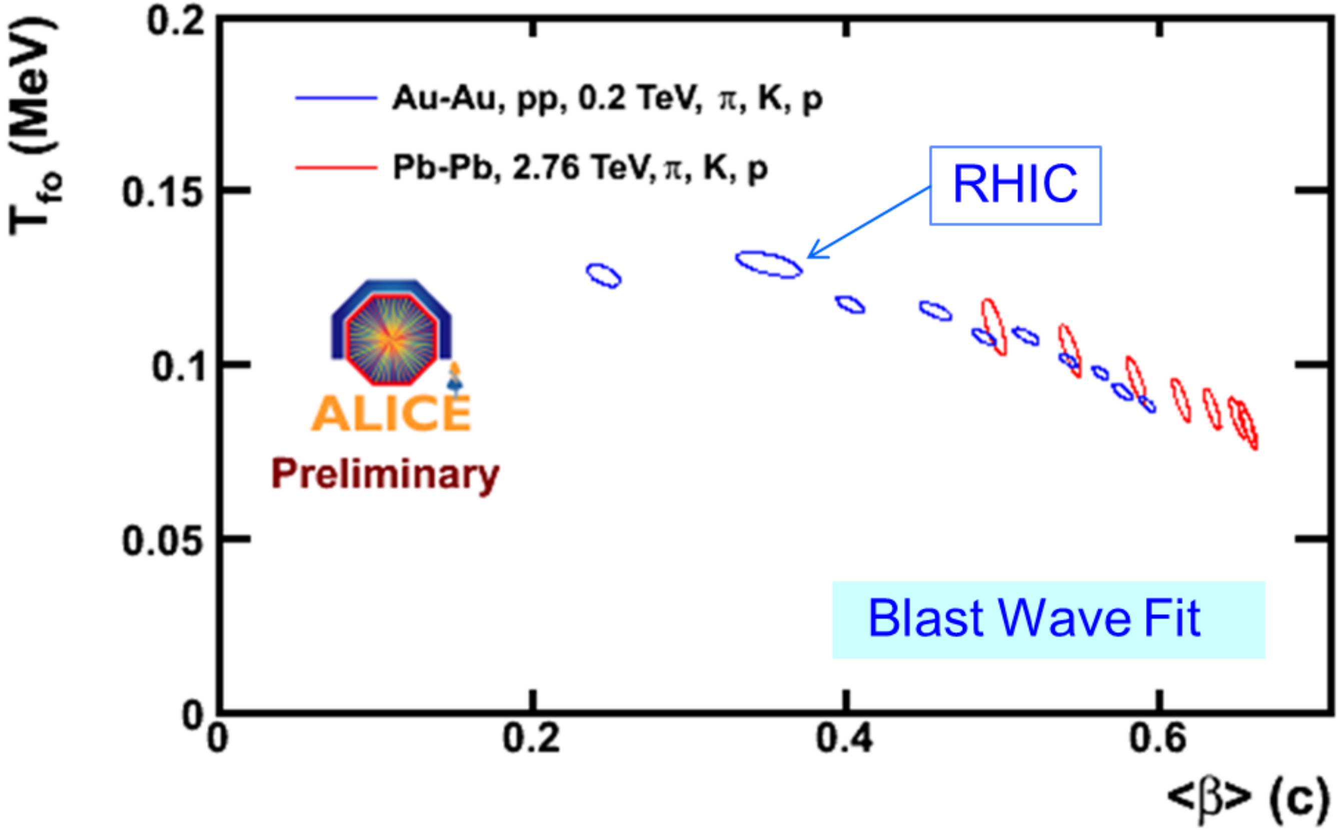
$$\frac{1}{m_T}\frac{dN}{dm_T} \propto \int_0^R r^2 dr m_T I_0\left(\frac{p_T \sinh(\rho)}{T}\right) K_1\left(\frac{m_T \cosh(\rho)}{T}\right)$$

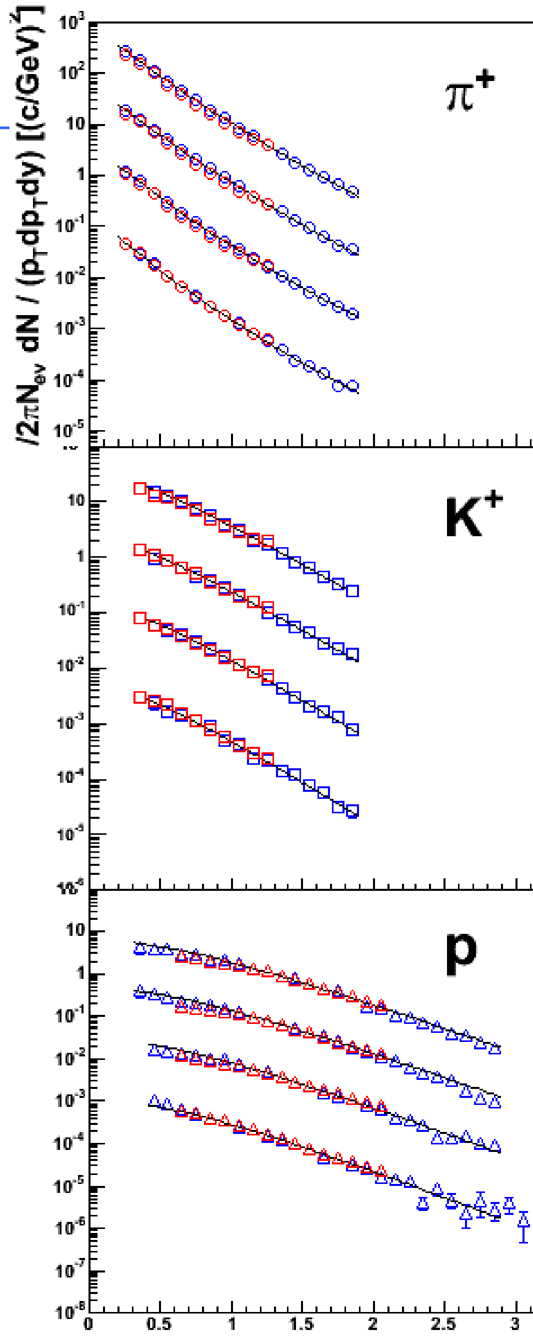
$$\rho(r) = \tanh^{-1}\left(\beta_T^{MAX}\frac{r}{R}\right)$$

Blast Wave Fits

Fit AuAu spectra to blast wave model:

- β_S (surface velocity) drops with dN/dη
- T (temperature) almost constant.





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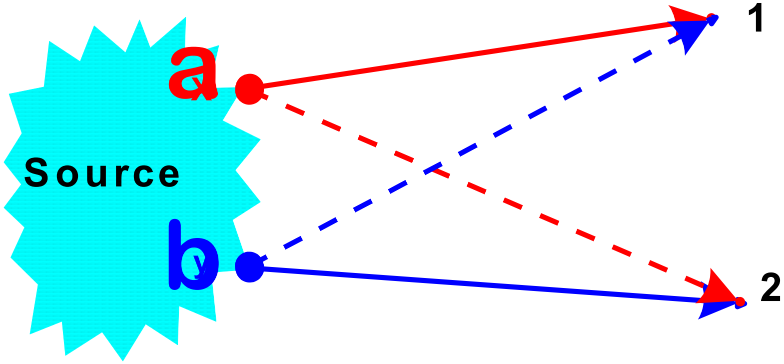
Intensity Interferometry

- All physics students are taught the principles of amplitude interferometry:
  - The probability wave of a single particle interferes with itself when, for example, passing through two slits.
- Less well known is the principle of intensity interferometry:
  - Two particles whose origin or propagation are correlated in any way can be measured as a pair and exhibit wave properties in their relative measures (e.g. momentum difference).
  - Correlation sources range from actual physical interactions (coulomb, strong; attractive or repulsive) to quantum statistics of identical bosons or fermions.
- Measurement of two-particle correlations allows access space-time characteristics of the source.

Boson Correlations



- Consider two particles emitted from two locations (a,b) within a single source.
- Assume that these two are detected by detector elements (1,2).

- The two paths (a→1,b→2) and (a→2,b→1) are indistinguishable and form the source of the correlation:

$$A = \frac{1}{\sqrt{2}}\left(e^{ik_1^\mu (r_1 - r_a)^\mu} e^{ik_2^\mu (r_2 - r_b)^\mu} + e^{ik_1^\mu (r_1 - r_b)^\mu} e^{ik_2^\mu (r_2 - r_a)^\mu}\right)$$

$$I = |A|^2 = 1 + \left\{ e^{i(k_2 - k_1)^\mu (r_a - r_b)^\mu} + c.c. \right\}$$

- The intensity interference between the two point sources is an oscillator depending upon the relative momentum $q = k_2 - k_1$, and the relative emission position!

Integrate over Source

- **The source density function can be written as**

$$E_p \frac{dN}{d^3p} = \int d^4x\, S(x,p)$$

- **We define the 2-particle correlation as:**

$$C(p_1,p_2) = \frac{E_1 E_2 dN/(d^3p_1 d^3p_2)}{(E_1 dN/d^3p_1)(E_2 dN/d^3p_2)}\,.$$

- **To sum sources incoherently, we integrate the intensities over all pairs of source points:**

$$C(\boldsymbol{q},\boldsymbol{K}) = 1 \pm \frac{\left|\int d^4x\, S(x,K)\, e^{iq\cdot x}\right|^2}{\int d^4x\, S(x,K+\frac{1}{2}q)\ \int d^4y\, S(y,K-\frac{1}{2}q)} \approx 1 \pm \left|\frac{\int d^4x\, S(x,K)\, e^{iq\cdot x}}{\int d^4x\, S(x,K)}\right|^2$$

- **Here q,K are the 4-momentum differences and sums, respectively of the two particles.**

Famous Naïve Mistakes

- If S(x,K) = ρ(x)Π(K), the momentum dependence cancels!

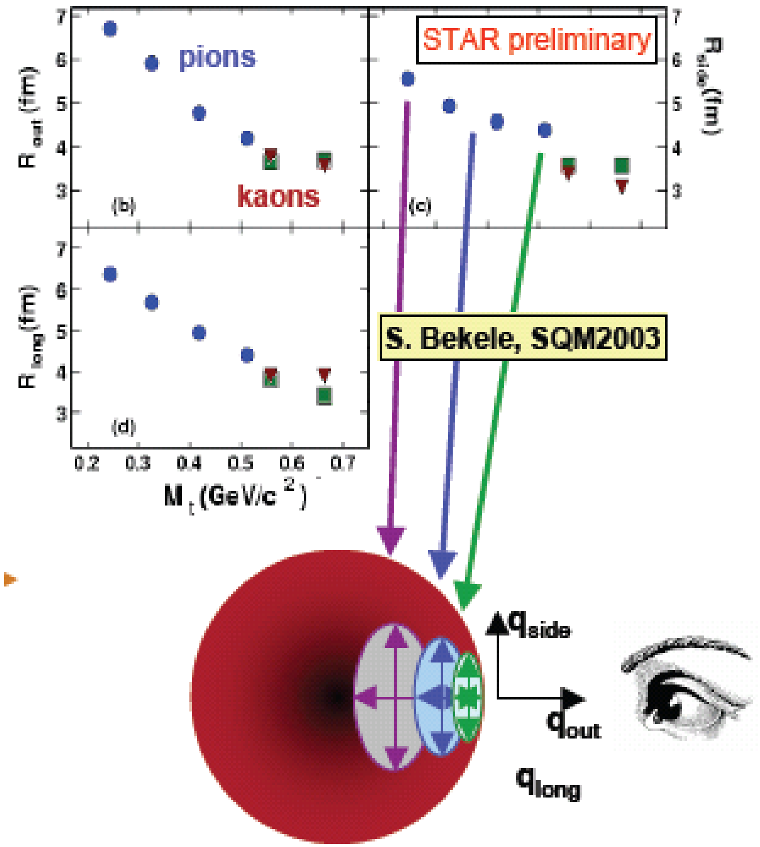
$$C(q,K) = 1 \pm \left| \frac{\int d^4x\rho(x)\Pi(K)e^{iq\cdot x}}{\int d^4x\rho(x)\Pi(K)} \right|^2 = 1 \pm \left| \frac{\int d^4x\rho(x)e^{iq\cdot x}}{\int d^4x\rho(x)} \right|^2$$

  - No. If the source contains any collective motions (like expansion), then there is a strong position-momentum correlation .
- Gee…the correlation function is simply the Fourier Transform of S(x,K). All we need do is inverse transform the C(q,K) observable!!
  - Um…no. Particles are ON SHELL.
- Must use parameterized source.

$$C(q,K) = 1 \pm \lambda(K)\exp\left(-R_s^2(K)q_s^2 - R_o^2(K)q_o^2 - R_l^2(K)q_l^2\right)$$

Building Intuition

- The "under-measure" of the source size for a flowing source depends upon the flow velocity:
  - Higher flow velocity, smaller source.
- We expect that the measured Radius parameters from HBT would drop with increasing K (or K_T).



$$R_o^2(K) = \langle \tilde{x}_o^2 \rangle - 2\beta_T \langle \tilde{x}_o t \rangle + \beta_T^2 \langle t^2 \rangle$$

$$R_s^2(K) = \langle \tilde{x}_s^2 \rangle$$

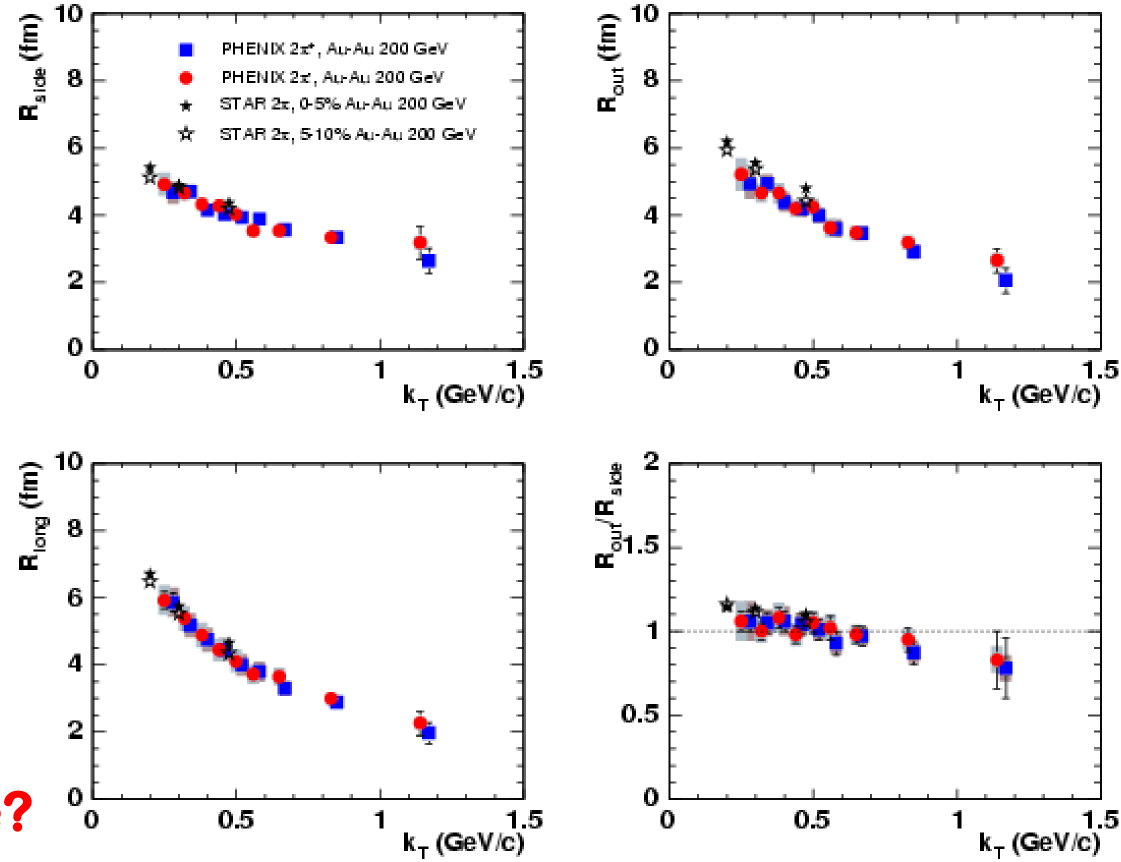
$$R_l^2(K) = \langle \tilde{z}^2 \rangle \quad \left(= \tau^2 + t^2\right)$$

Some Results

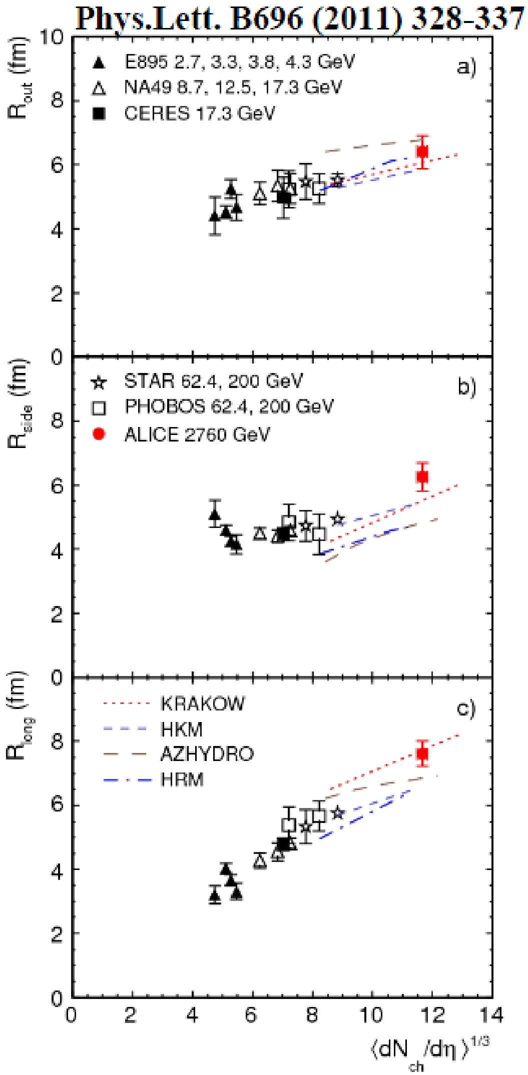
- R(Au) ~ 7 fm, R(HBT)<6 fm
  - No problem, its only a homogeneity length…
- R(k_T) drops with increasing k_T
  - Just as one expects for flowing source…
- R_{out}~R_{side}
  - Surprising!

$$\Delta \tau = \sqrt{R^2_{Out} - R^2_{Side}}$$

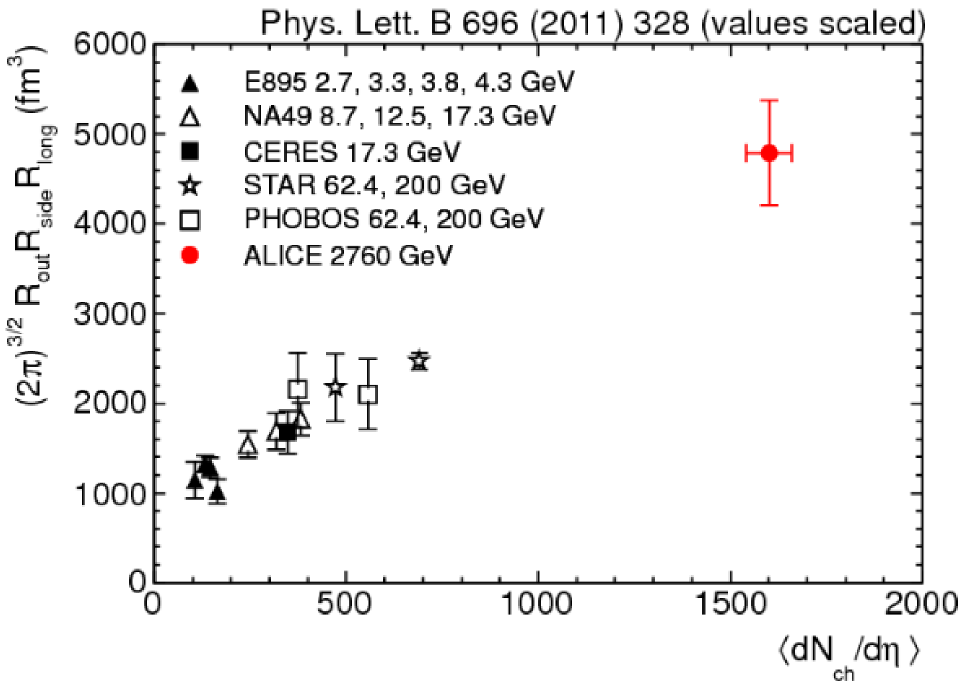
  - Vanishing emission time?



Scaling with Multiplicity



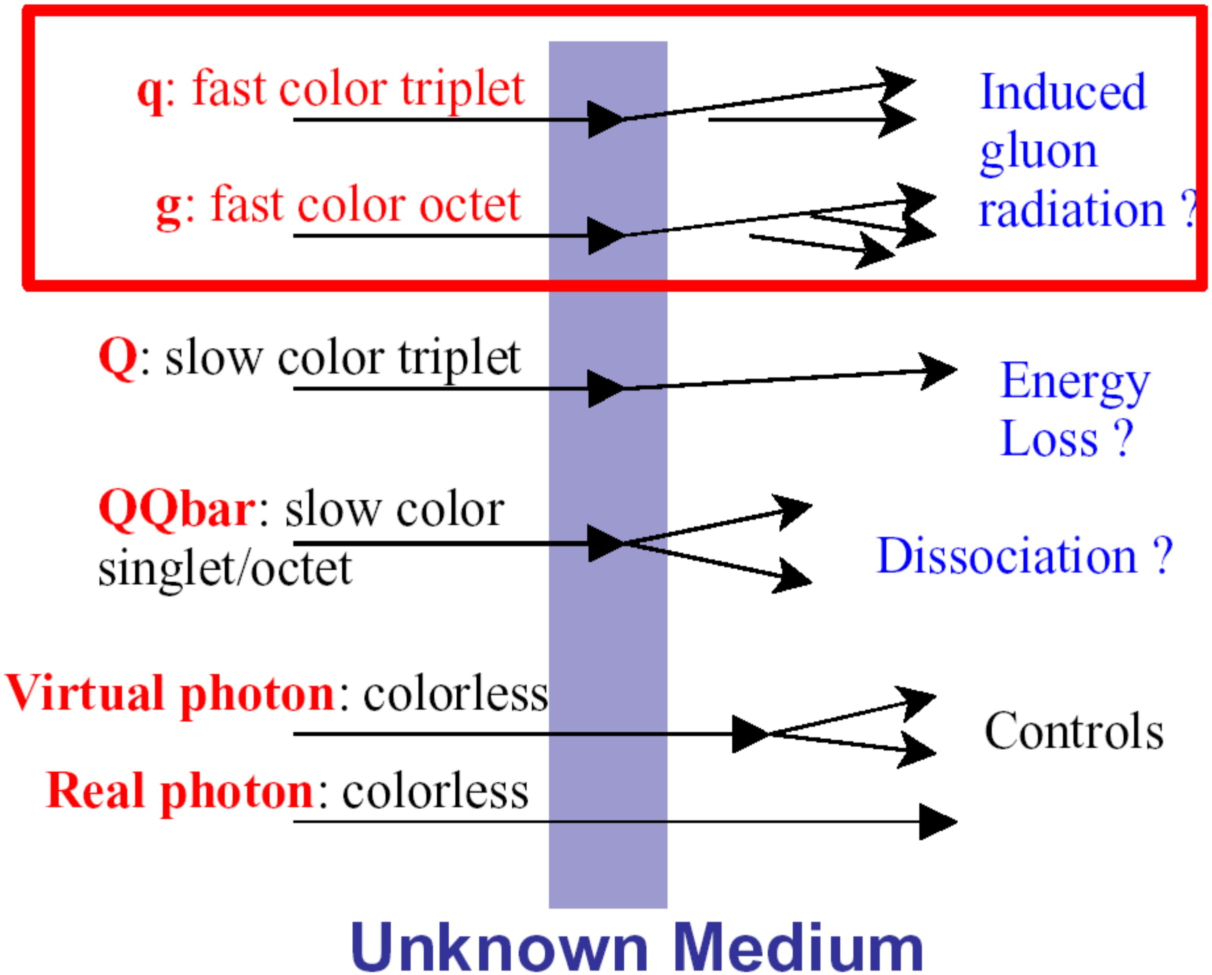
- Increase of the radii with $dN_{ch}/d\eta$ for central collisions consistent with models
- Increase of the "homogeneity volume" over most central RHIC by a factor of ~2



Is There a There There?

- We accelerate nuclei to high energies with the hope and intent of utilizing the beam energy to drive a phase transition to QGP.
- The collision must not only utilize the energy effectively, but generate the signatures of the new phase for us.
- I will make an artificial distinction as follows:
  - Medium: The bulk of the particles; dominantly soft production and possibly exhibiting some phase.
  - Probe: Particles whose production is calculable, measurable, and thermally incompatible with (distinct from) the medium.
- The medium & probe paradigm will establish whether there is a there there.

The Probes Gallery:



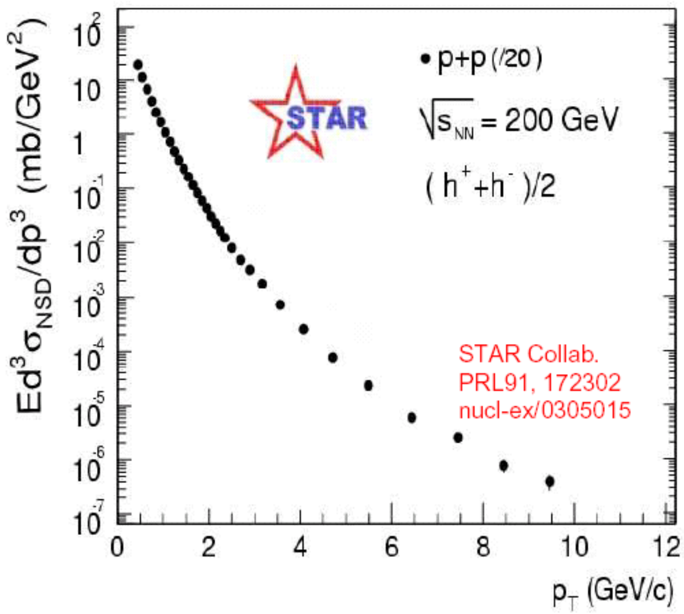
Jet Suppression

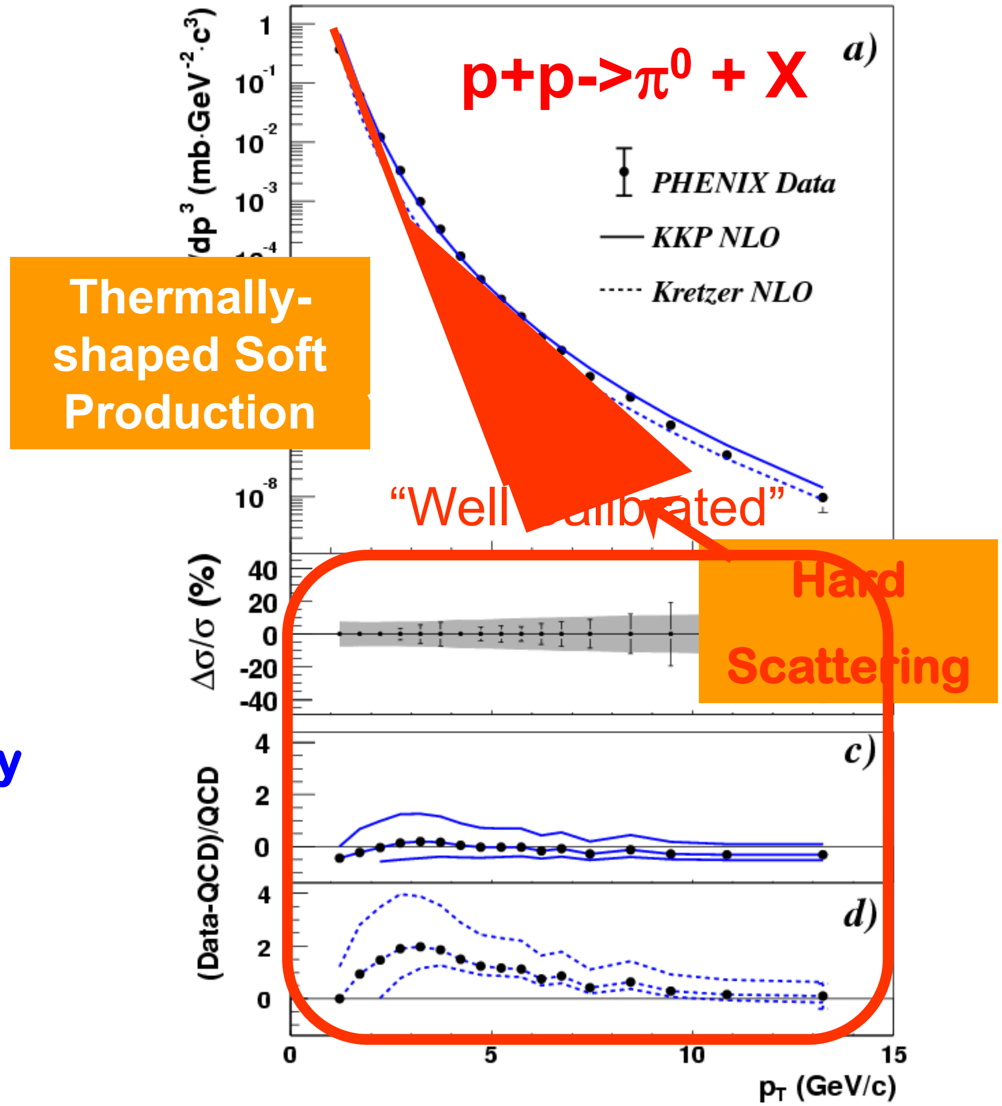
charm/bottom dynamics

J/Ψ & Y

Colorless particles
CONTROL

Calibrating the Probe(s)





- **Measurement from elementary collisions.**
- **"The tail that wags the dog" (M. Gyulassy)**

hep-ex/0305013 S.S. Adler et al.

R_{AA} Normalization

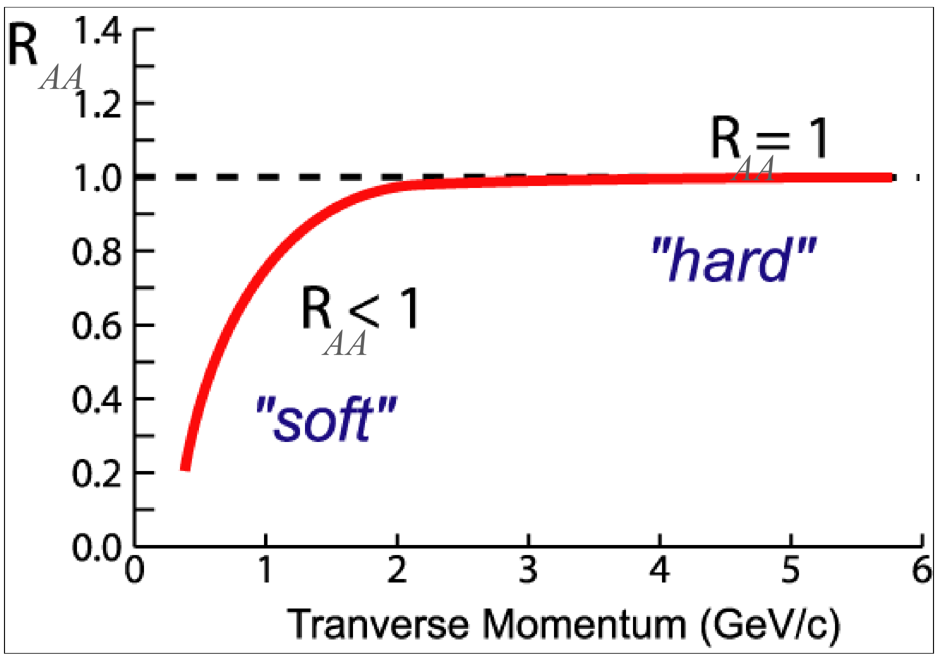
1. Compare Au+Au to nucleon-nucleon cross sections
2. Compare Au+Au central/peripheral

Nuclear Modification Factor:

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

nucleon-nucleon cross section

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



If no "effects":

$R_{AA} < 1$ in regime of soft physics

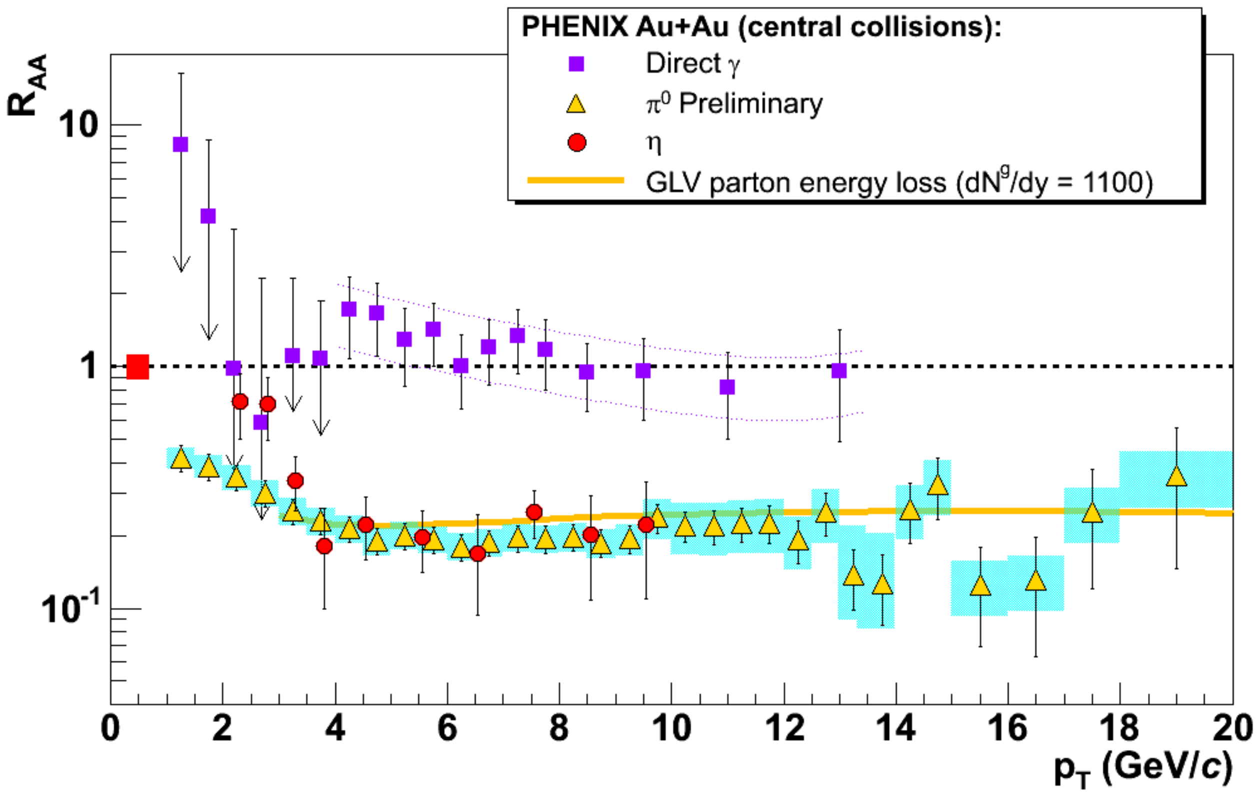
$R_{AA} = 1$ at high-p_T where hard scattering dominates

Suppression:

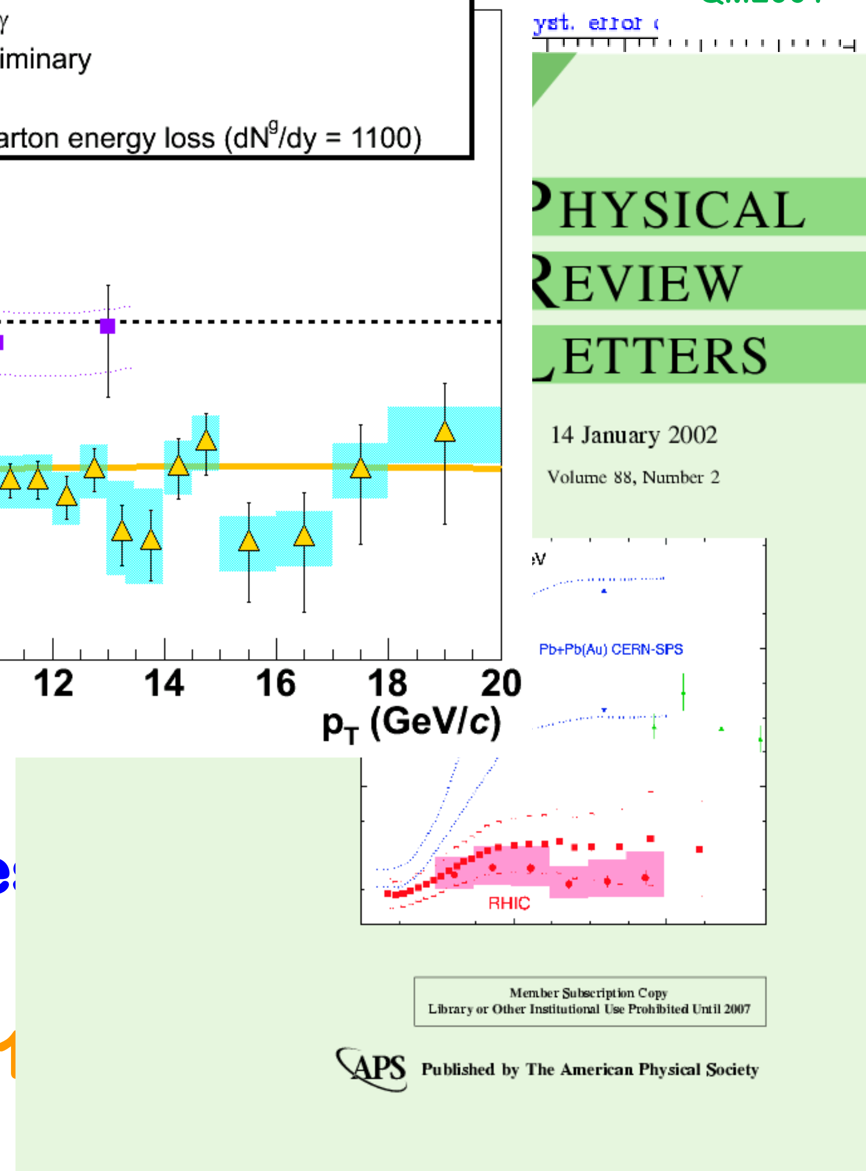
$R_{AA} < 1$ at high-p_T

Discovered in RHIC-Year One

Observed
―――――
Expected

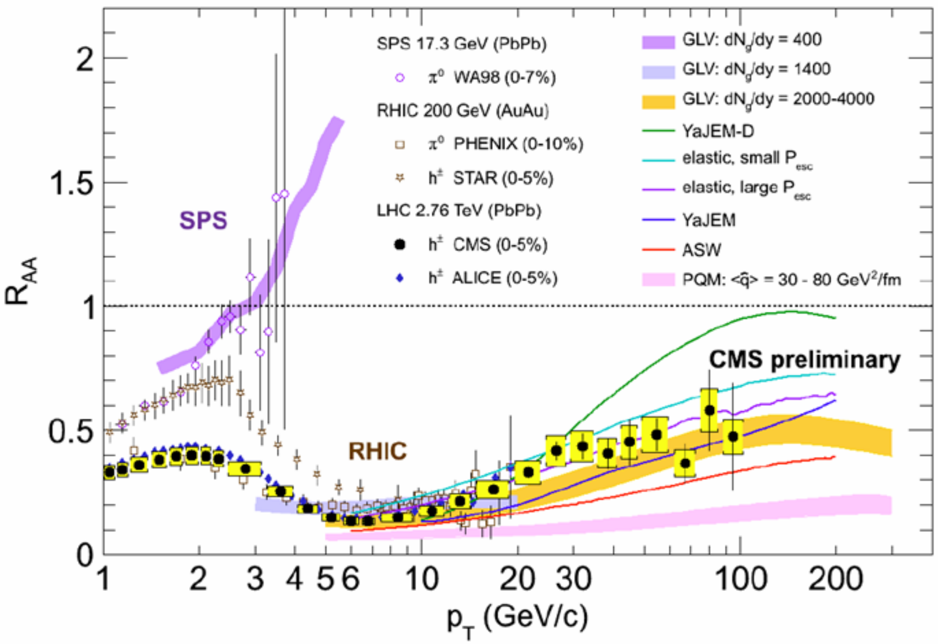


QM2001

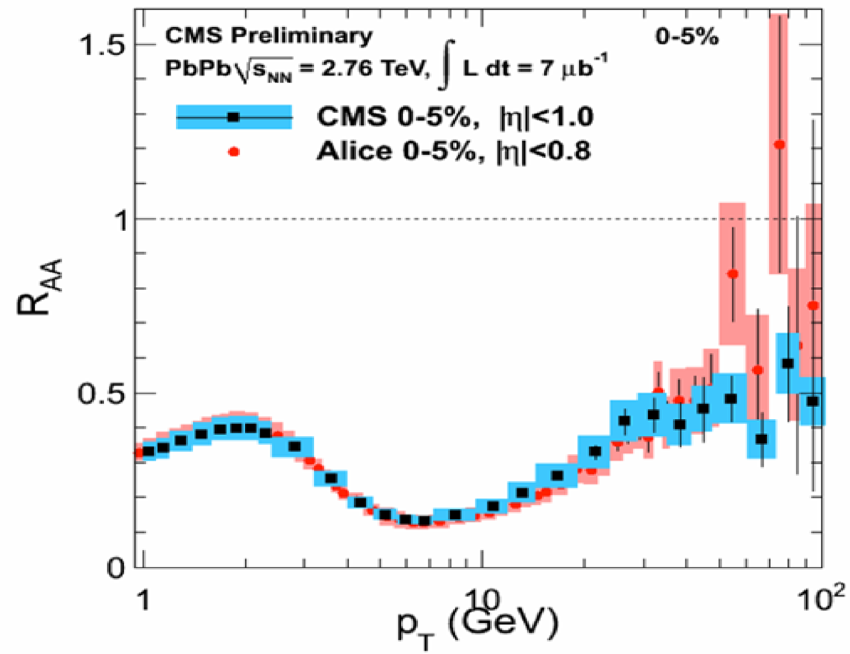


- **Quark-containing particle**
- **Photons Escape!**
- **Gluon Density = dN_g/dy ~ 1**

Suppression Similar @LHC



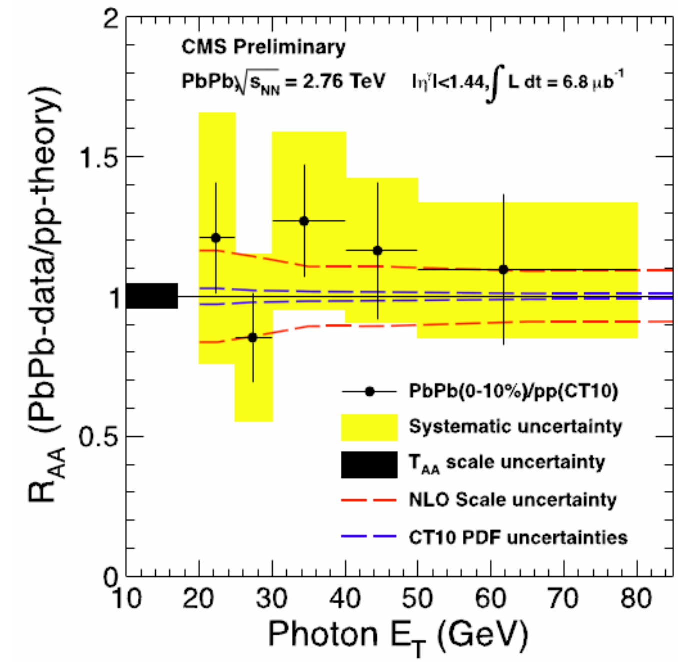
Strong constraint on the parton energy loss models

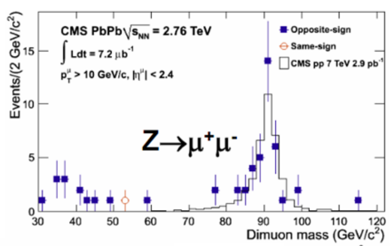


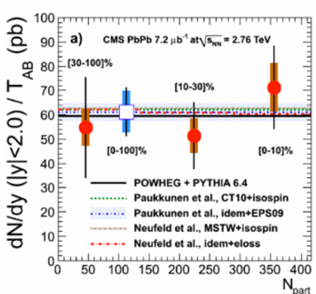
- Suppression of high momentum particles similar at RHIC and LHC.
- Both are well beyond the phase transition.

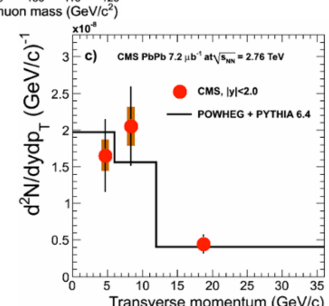
Control Measures for R_{AA}

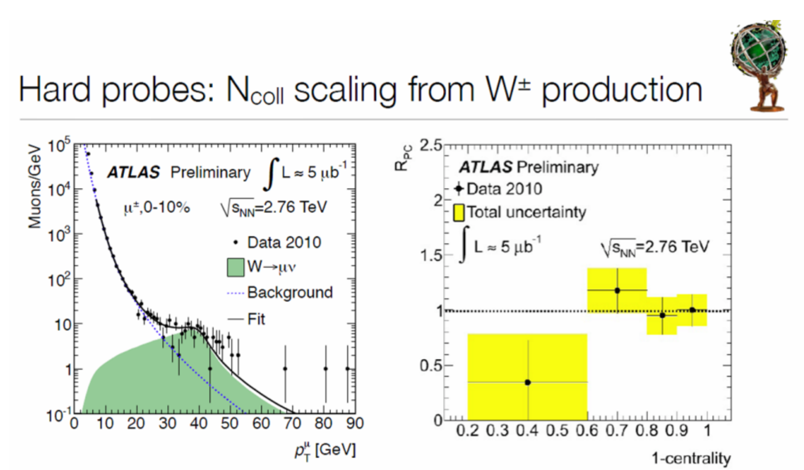
- R_{AA} intrinsically scales the pp reference by $\langle N_{coll} \rangle$ as the denominator.
- Validity of this for colorless probes should be established.
- At RHIC was use direct photons at large p_T.
- At LHC, there are more:
  - γ_{direct}
  - W
  - Z



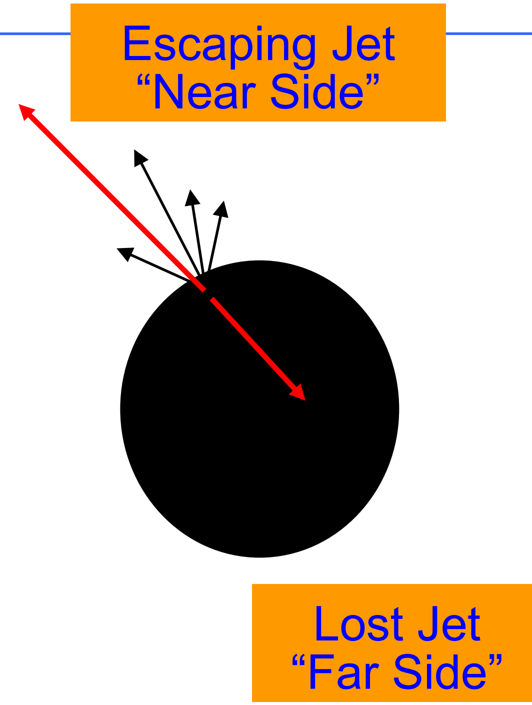






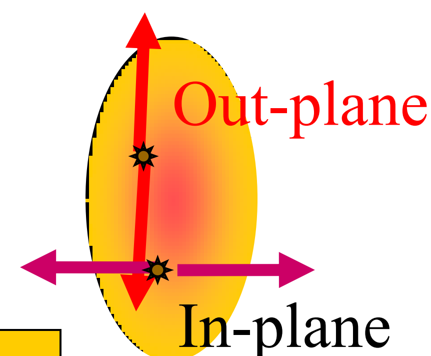


Jet Tomography



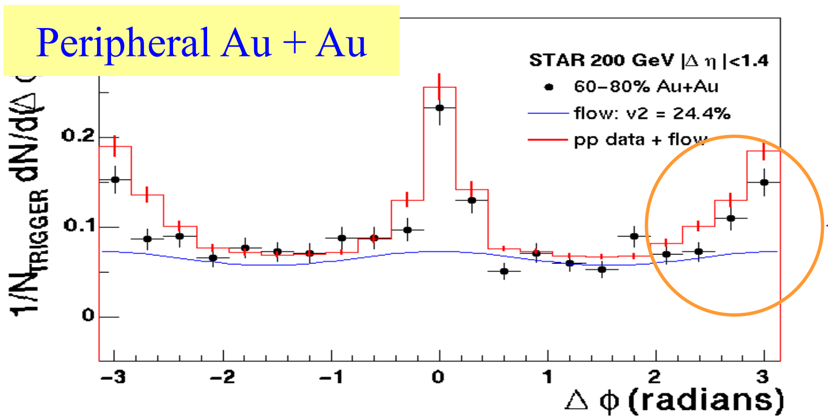
- **Tomography, a fancy word for a shadow!**
- **Jets are produced as back-to-back pairs.**
- **One jet escapes, the other is shadowed.**
- **Expectation:**
  - **"Opaque" in head-on collisions.**
  - **"Translucent" in partial overlap collisions.**

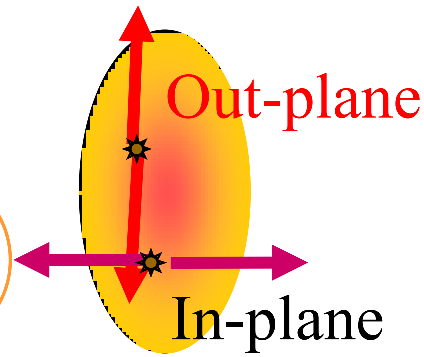
X-ray pictures are shadows of bones

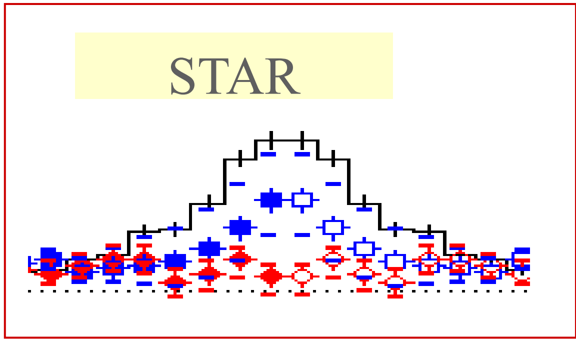


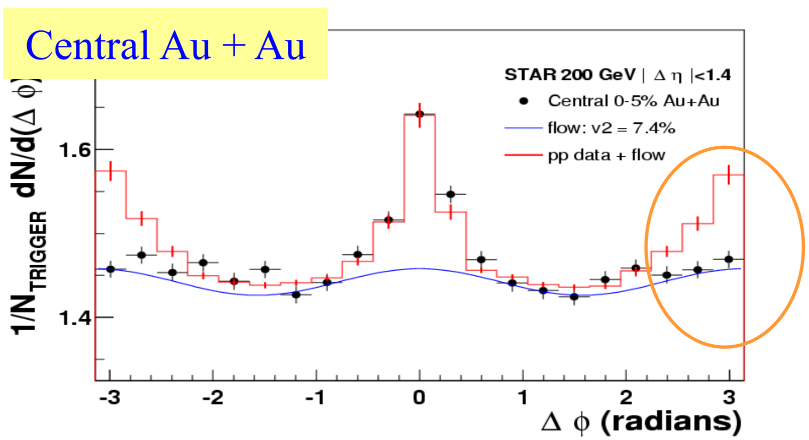
Can Jet Absorption be Used to "Take an X-ray" of our Medium?

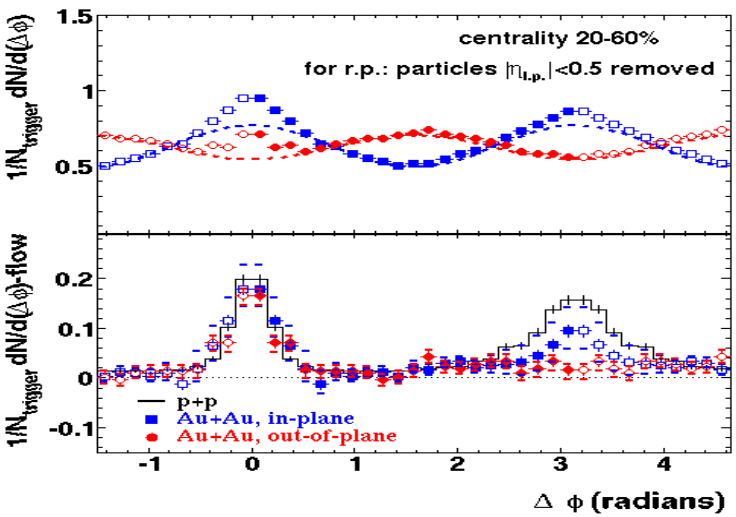
Back-to-back jets





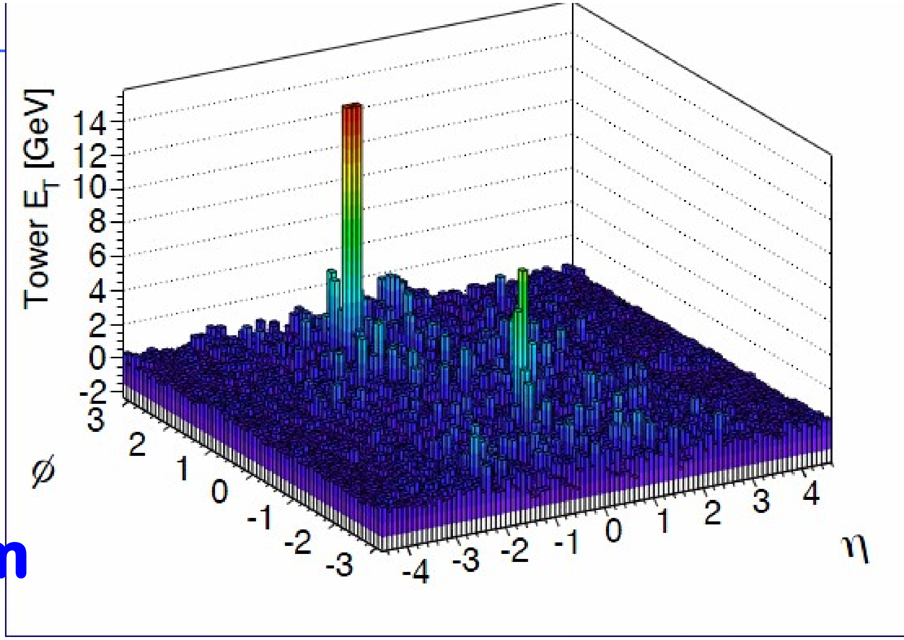






- **Given one "jet" particle, where are it's friends:**
  - **Members of the "same jet" are in nearly the same direction.**
  - **Members of the "partner jet" are off by 180°**
- **Away-side jet gone (NOTE: where did the energy go?)**

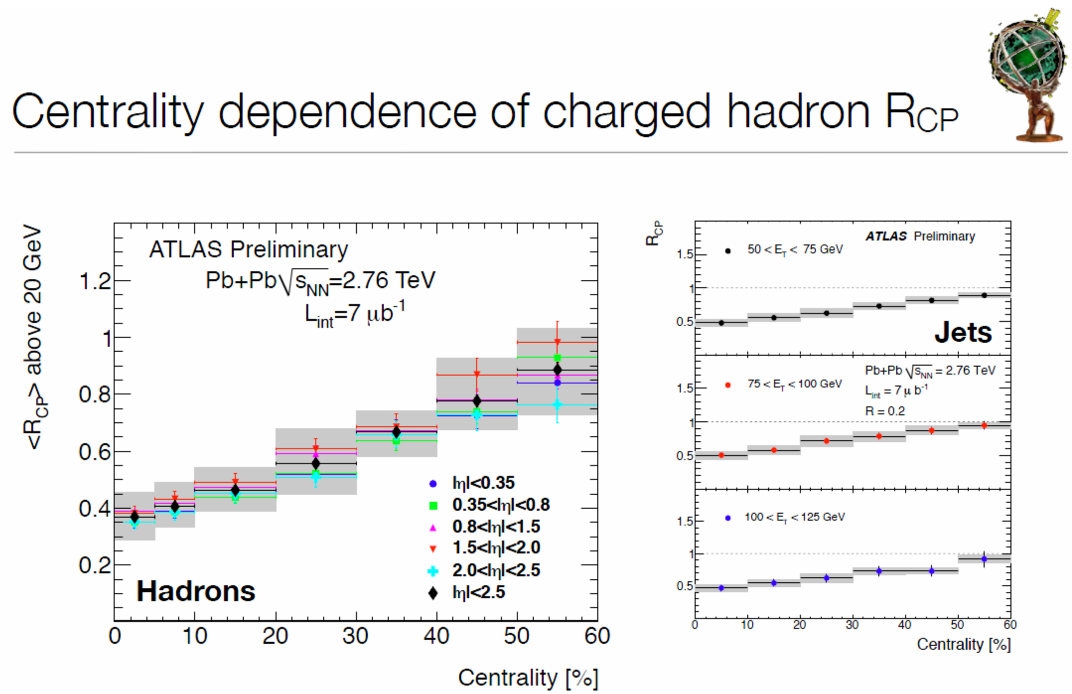
Singles to Jets

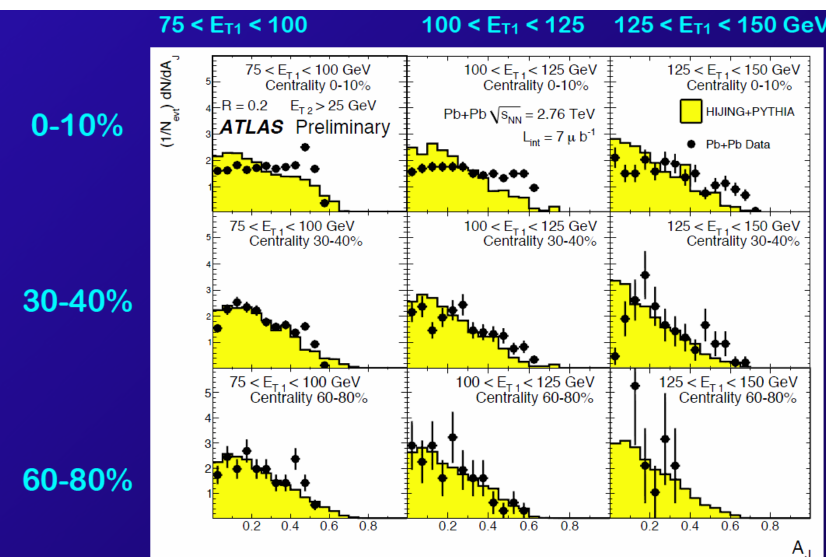


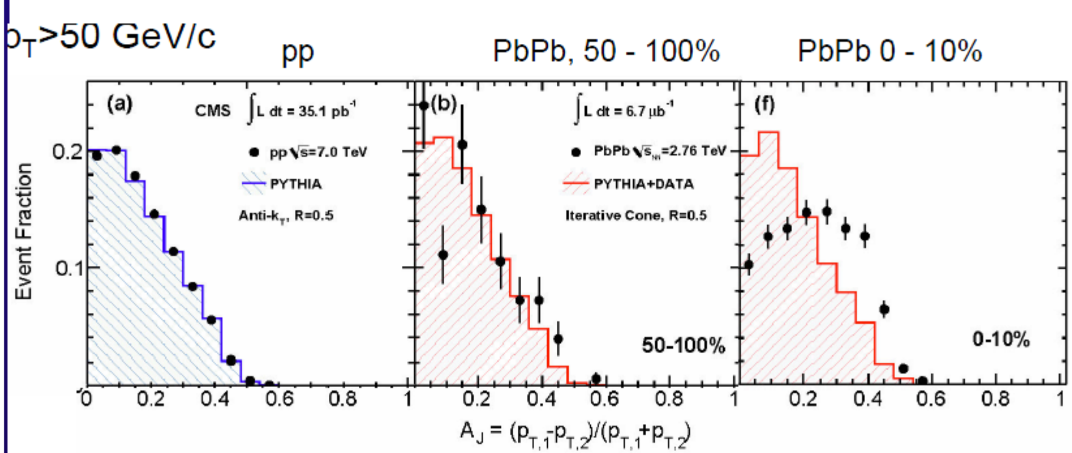
- Parton pairs are created at the expected rate (control measure).
- Parton pairs have a "k_T" due to initial state motion.
- Partons interact with medium (E-loss,scattering?)
- Fragment into Jets either within or outside the medium.
- To be Learned:
    - E-loss will created R_{AA}\{Jets\} < 1.
    - Scattering will make back-to-back correl worse (higher "k_T")
    - Fragmentation function modification possible.

Moving from Singles to Jets…

- **LHC shows loss of Jets similar to loss of hadrons.**
- **Huge Asymmetry signal in ATLAS and CMS.**
- **Must understand the nature of this loss…**

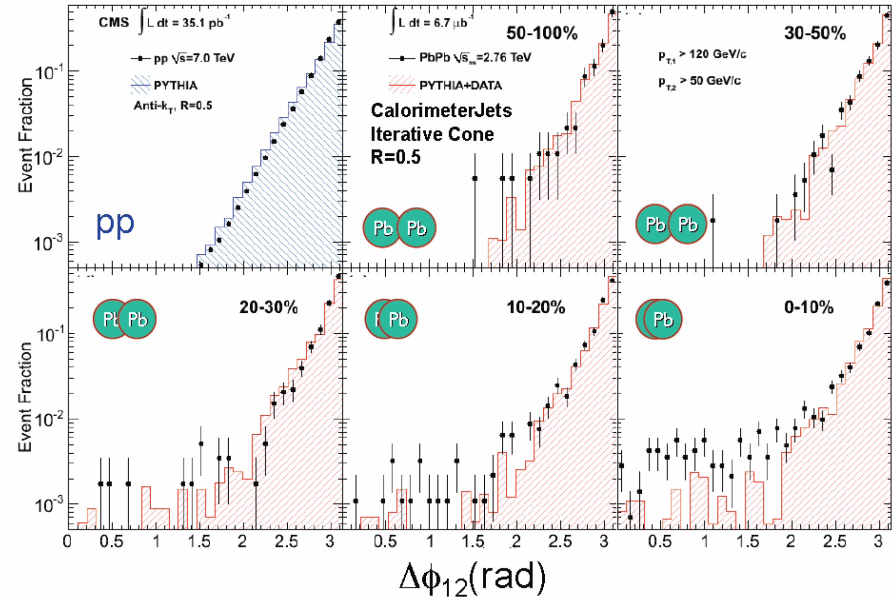


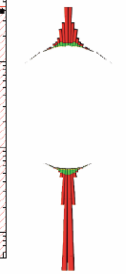


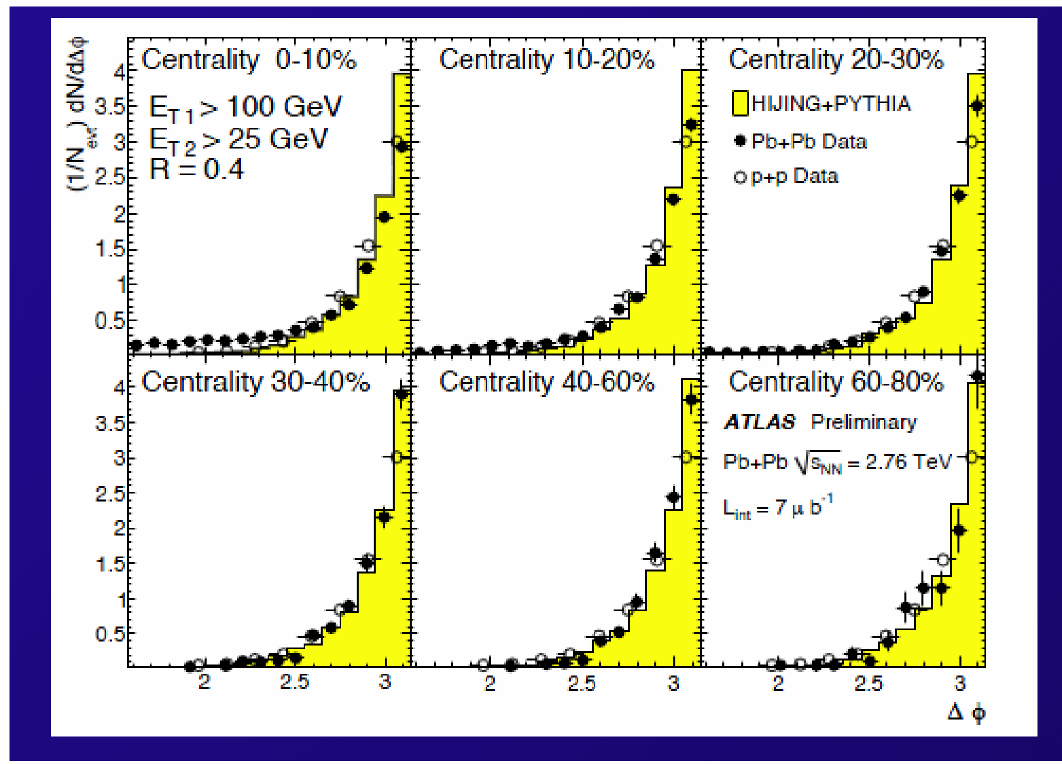


Jet Direction

- **Overwhelmingly, the direction of the Jets seems preserved.**
- **This is a shock…**
- **How can you lose a HUGE amount of longitudinal momentum and not have a “random walk” that smears back-to-back.**
- **Top Puzzle from LHC.**







Summary Lecture 1

- Heavy Ion collisions provide access to the thermal and hydrodynamic state of QCD.
- RHIC and LHC both provide sufficient energy to create the form of matter in the "plateau" region.
- The matter is opaque to the propagation of color charge while transparent to colorless objects.
- Coming in Lecture #2:
  - The medium behaves as a "perfect fluid".
  - Fluid is capable of altering motion of heavy quarks (c/b).
  - Descriptions from string theory (AdS/CFT duality) are appropriate.
  - Indications of yet another new phase of matter (Color Glass Condensate) are beginning to emerge.