Explore the QCD Phase Diagram

Nu Xu
Lawrence Berkeley National Laboratory

Many Thanks to the Organizers

Outline

1) Introduction

2) Recent experimental data
- **High p_T results**
- Partonic collectivity at RHIC

3) Outlook
- Heavy quark measurements
  ➔ ***thermalization***
- RHIC beam energy scan
  ➔ ***QCD tri-critical point***

Physics Goals at RHIC

- Identify and study the properties of the matter (EOS) with partonic degrees of freedom.

- Explore the QCD phase diagram.

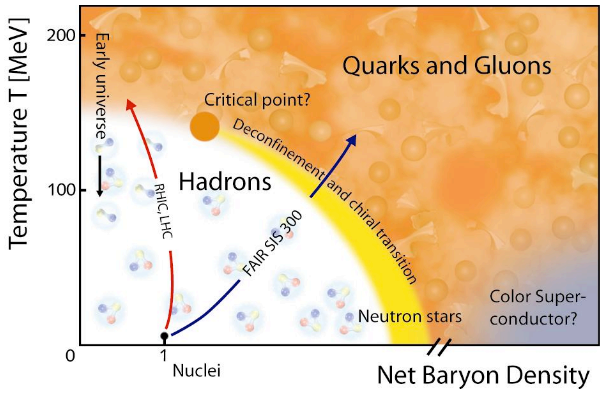
Bulk Properties:

(1) Spectra and anisotropies
(2) Correlation and fluctuations
(3) Heavy quark hadron collectivity
(4) …

Penetrating Properties:

(1) Leading hadron spectra
(2) Jets production
(3) High p_T triggered correlations
(4) Heavy quark production …

STAR Physics Focus

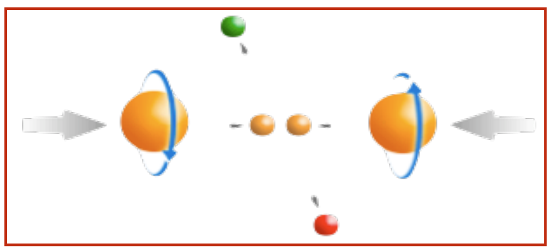


1) Heavy-ion program

- Study ***medium properties, EoS***
- pQCD in hot and dense medium

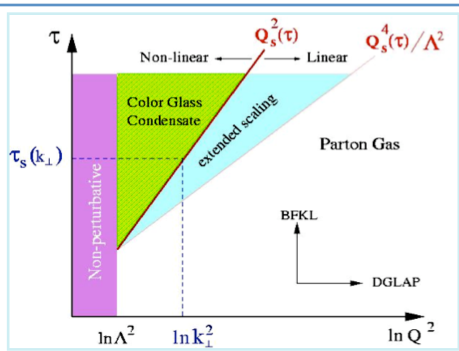
2) RHIC beam energy scan

- Search for ***critical point***
- Chiral symmetry restoration



Polarized spin program

- Study ***proton intrinsic properties***

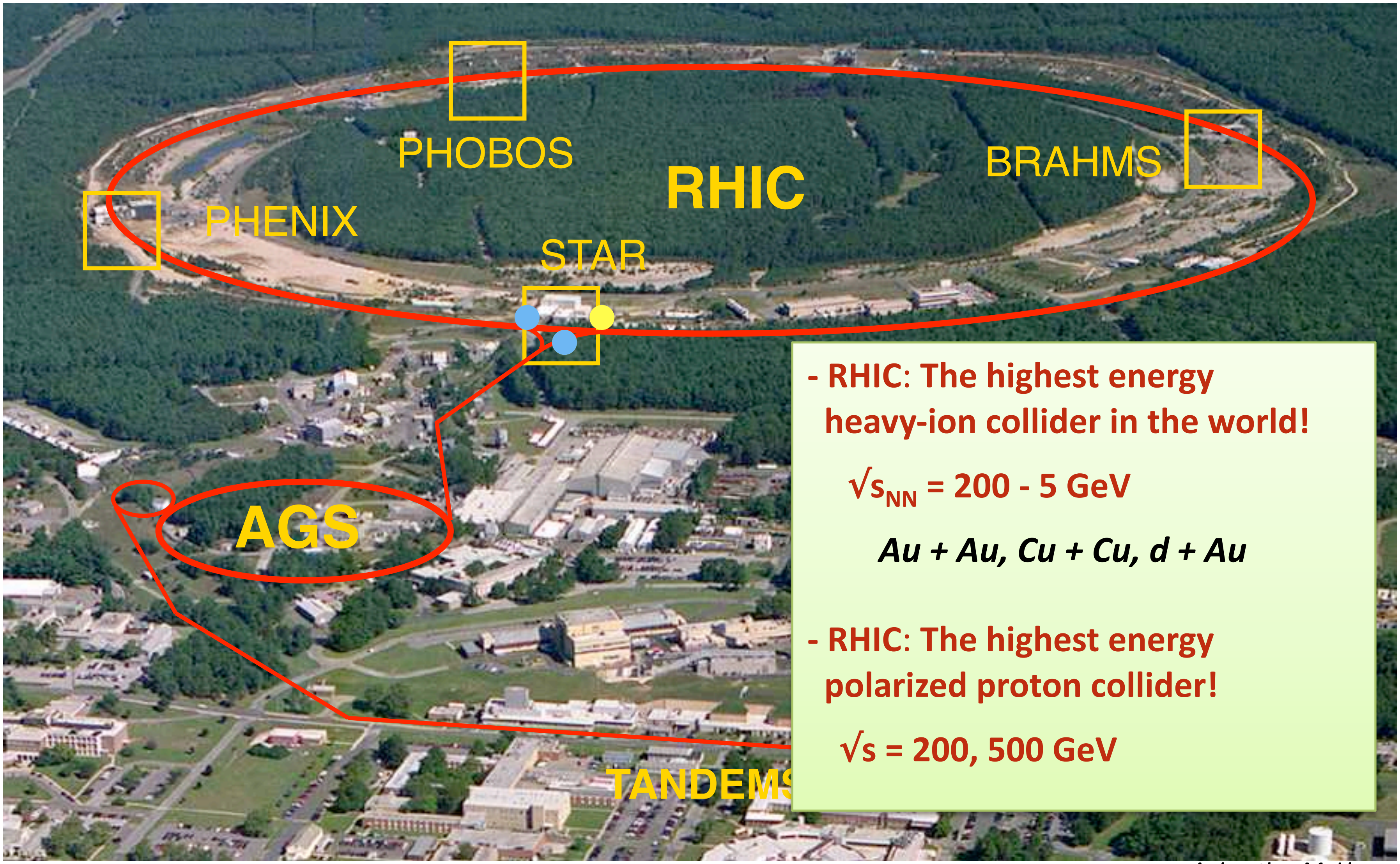


Forward program

- Study low-x properties, search for ***CGC***
- Study elastic (inelastic) processes (pp2pp)
- Investigate ***gluonic exchanges***

Relativistic **H**eavy **I**on **C**ollider (RHIC)

Brookhaven National Laboratory (BNL), Upton, NY



- RHIC: The highest energy heavy-ion collider in the world!

$\sqrt{s_{NN}}$ = 200 - 5 GeV

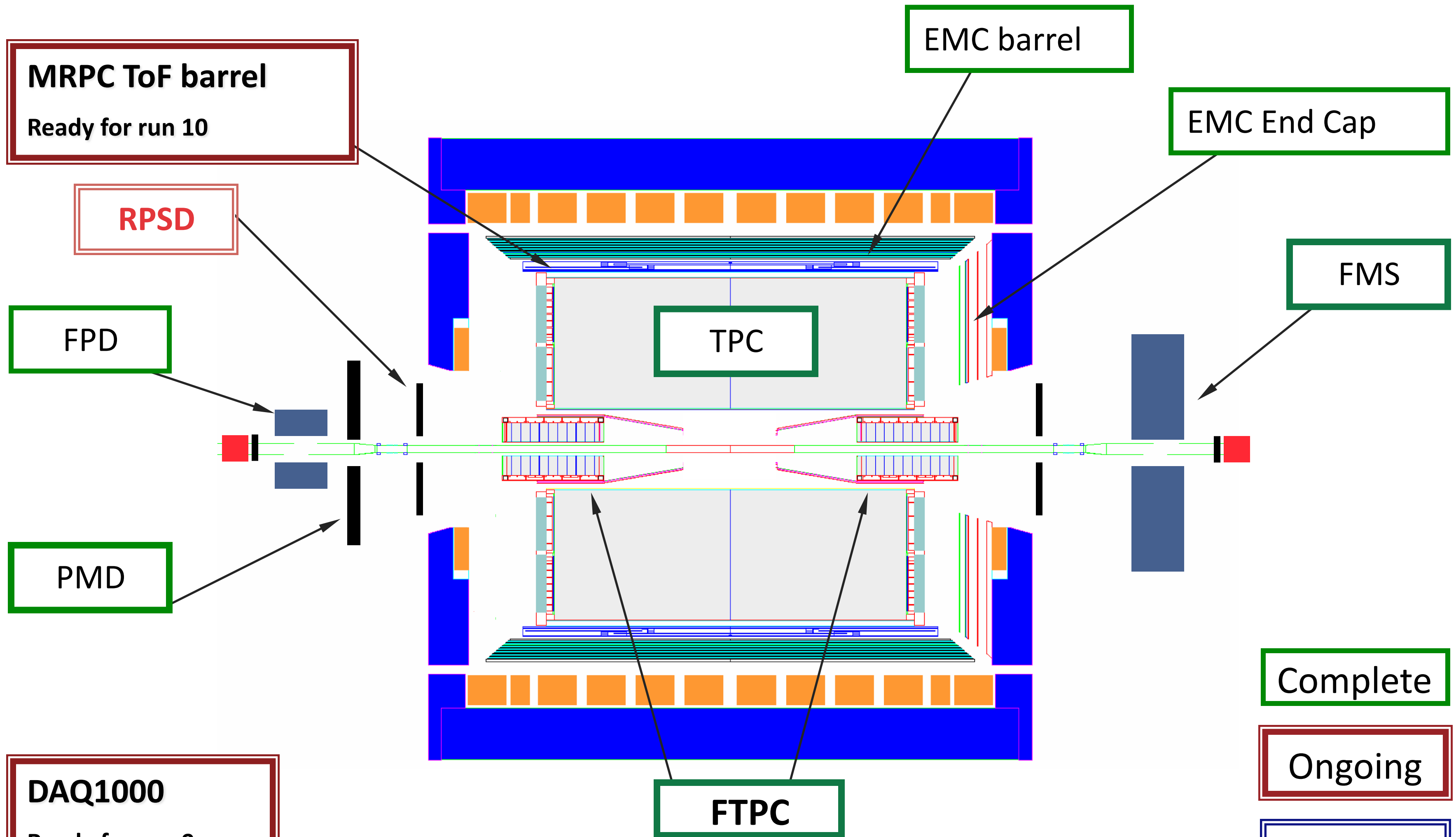
Au + Au, Cu + Cu, d + Au

- RHIC: The highest energy polarized proton collider!

$\sqrt{s}$ = 200, 500 GeV

Animation M. Lisa

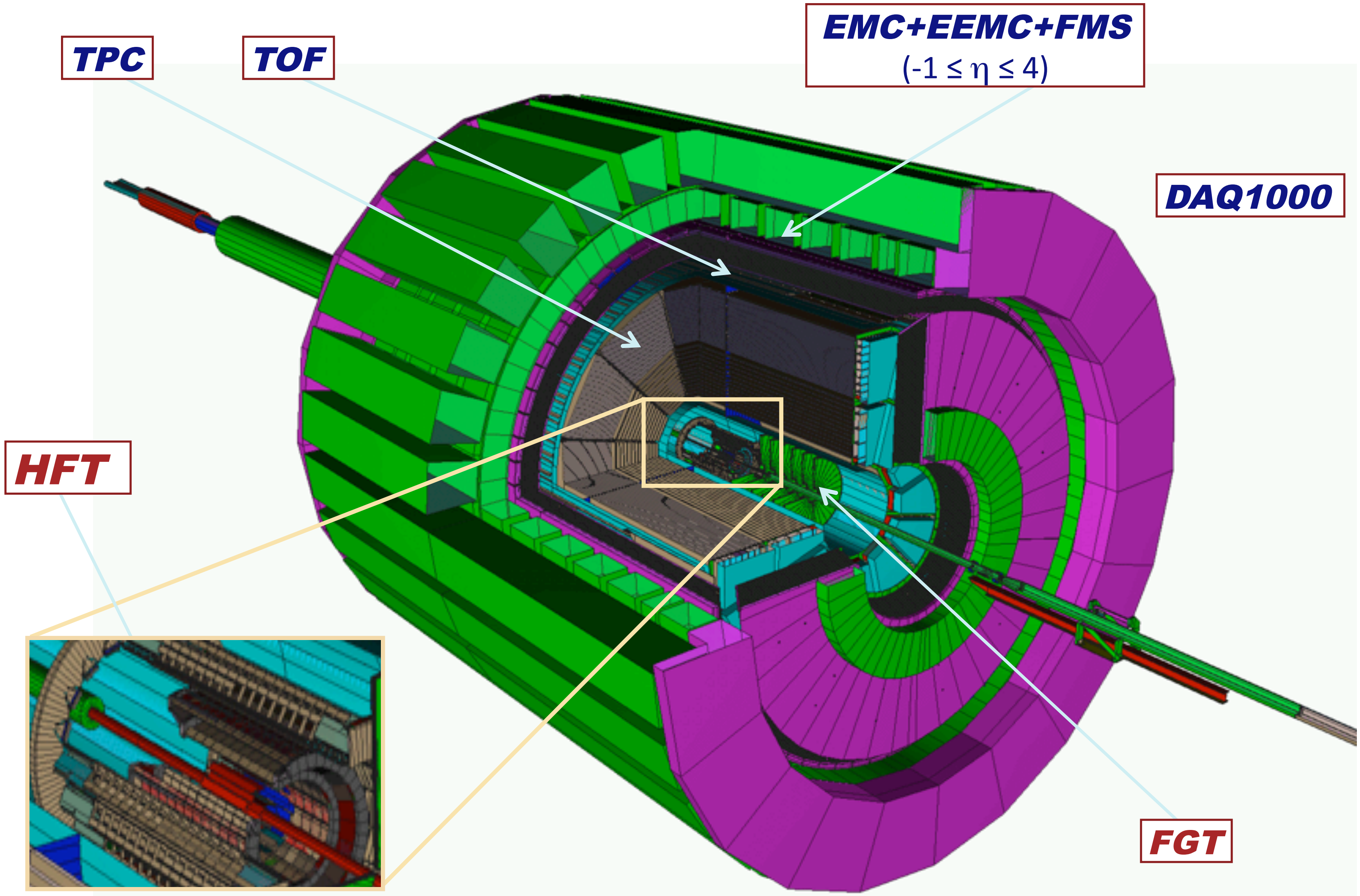
STAR Detector



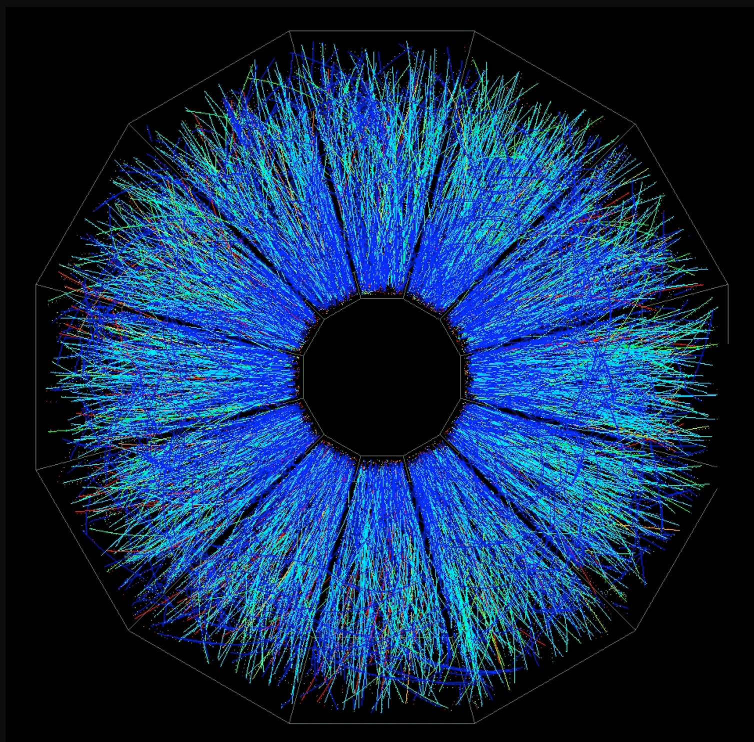
Full azimuthal particle identification!

$e, \pi, \boldsymbol{\rho}, K, \boldsymbol{K^*}, p, \boldsymbol{\varphi}, \Lambda, \Delta, \Xi, \Omega, D, \Lambda_C, \boldsymbol{J/\psi}, \boldsymbol{Y} \ldots$

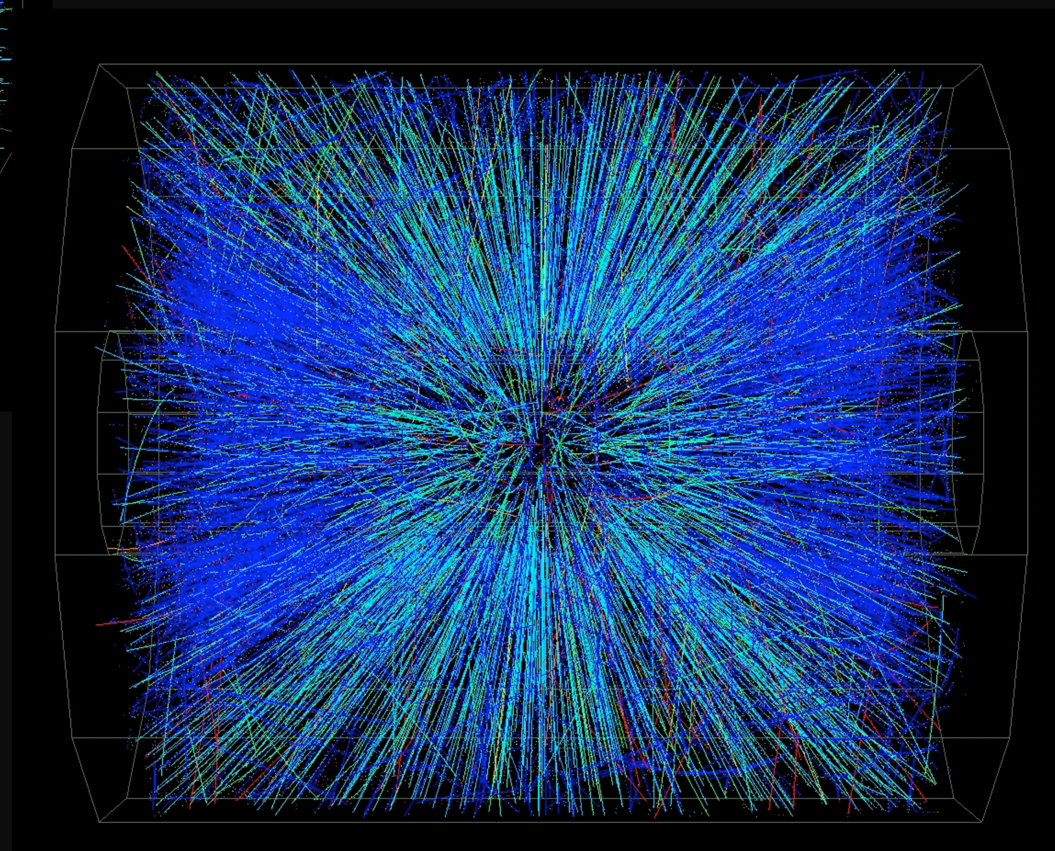
STAR Detectors: *Full 2π particle identification!*



Au + Au Collisions at RHIC



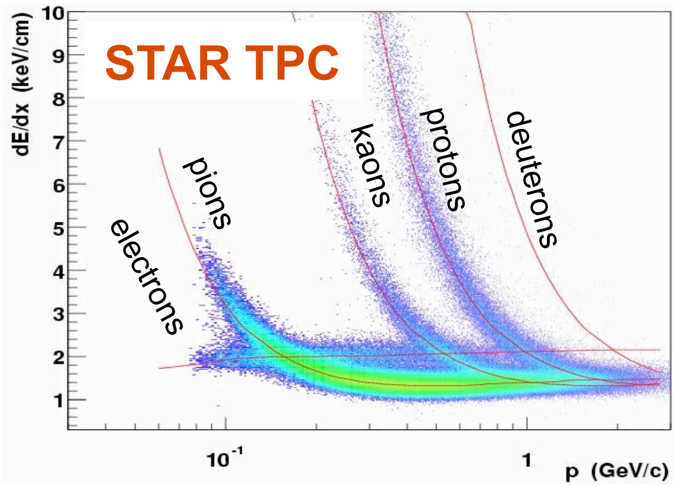
Central Event

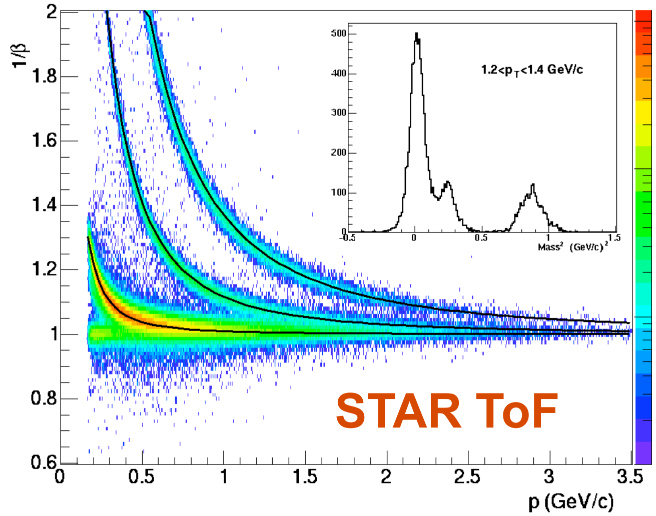


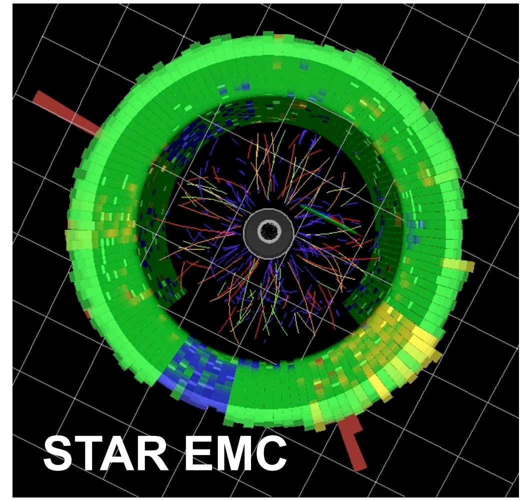
STAR

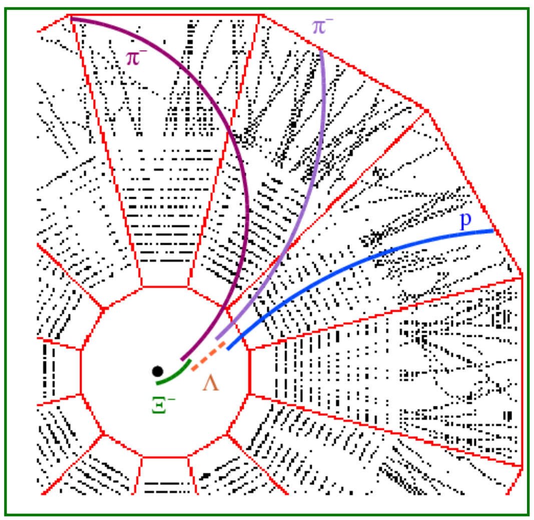
(real-time Level 3)

Particle Identification at STAR

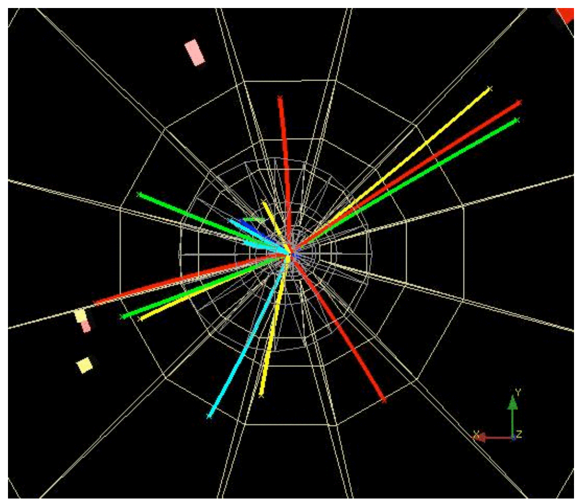




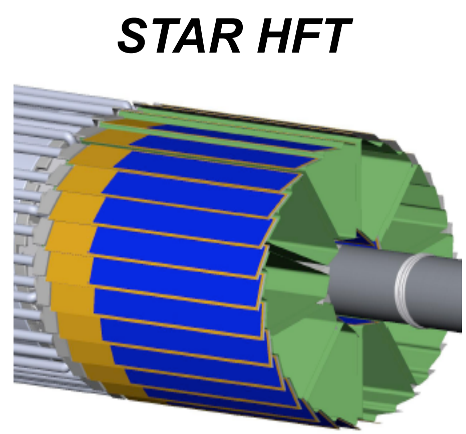




Strange hadrons

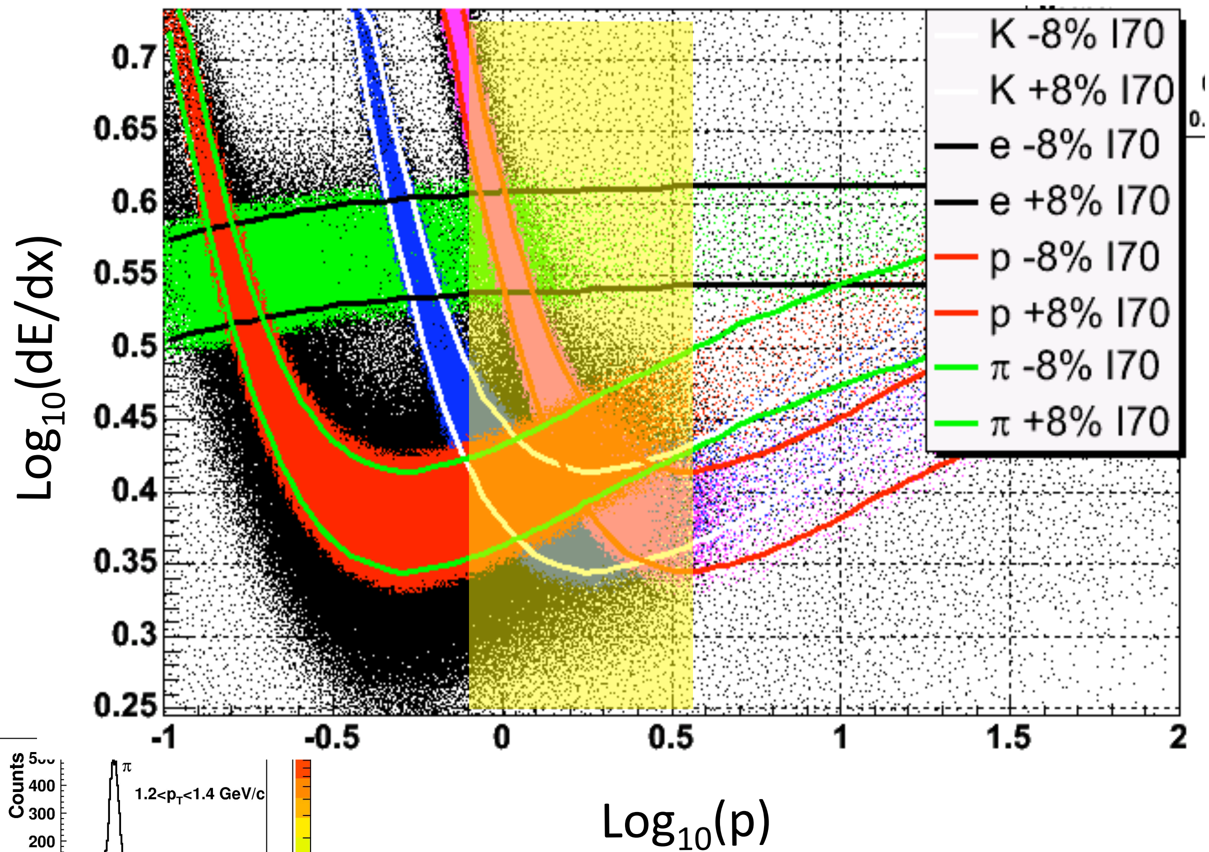


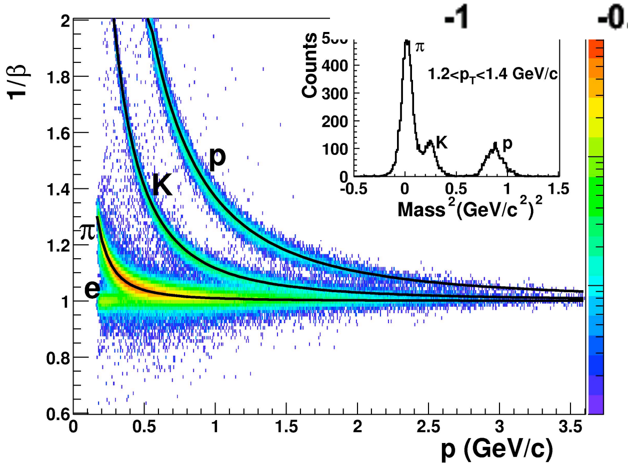
Jets



Heavy quark hadrons

Light Hadron PID at Large p_T

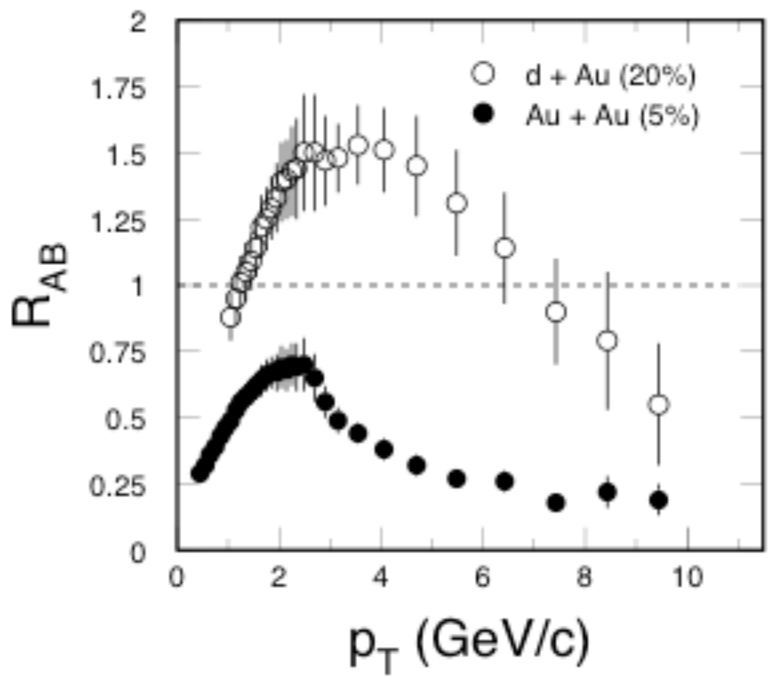


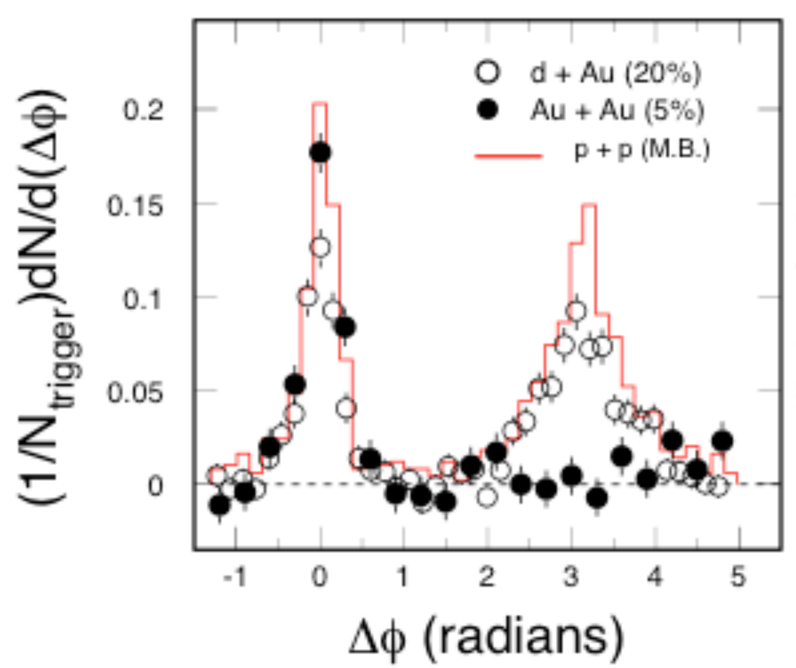


1)	Low p:	TPC
2)	$0.2 < p_T < 5$ GeV/c	ToF
3)	> 5 GeV/c	TPC

(dE/dx at relativistic rise extends PID beyond $p_T \sim 10$ GeV/c)

Suppression and Correlation





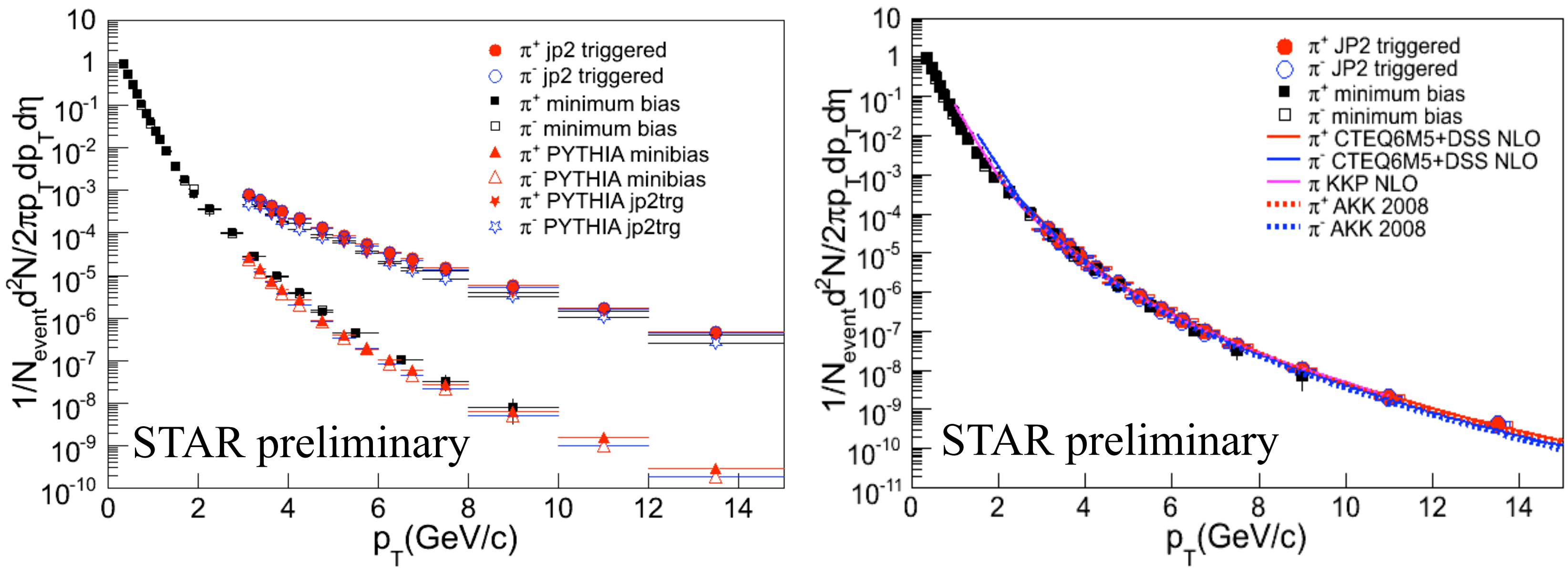
In central Au+Au collisions: hadrons are suppressed and back-to-back 'jets' are disappeared. Different from p+p and d+Au collisions.

Energy density at RHIC: ε > 5 GeV/fm^3 ~ 30ε_0

Parton energy loss:	Bjorken	1982
"**Jet quenching**":	Gyulassy & Wang	1992

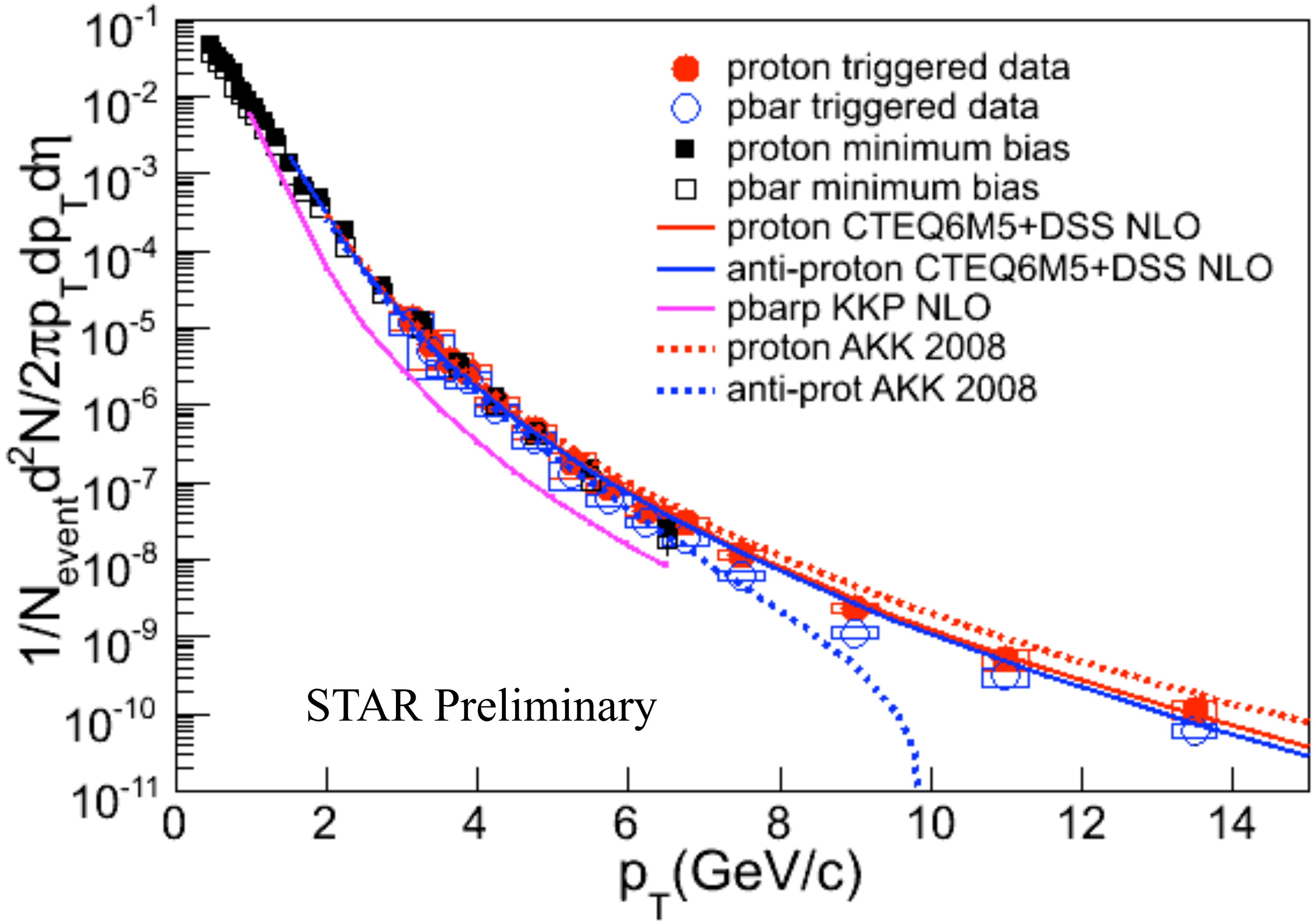
...

High p_T Results of pion Spectra



PYTHIA (V6.205, MSEL=1) and GEANT are used to get trigger efficiency to correct spectra in triggered events.

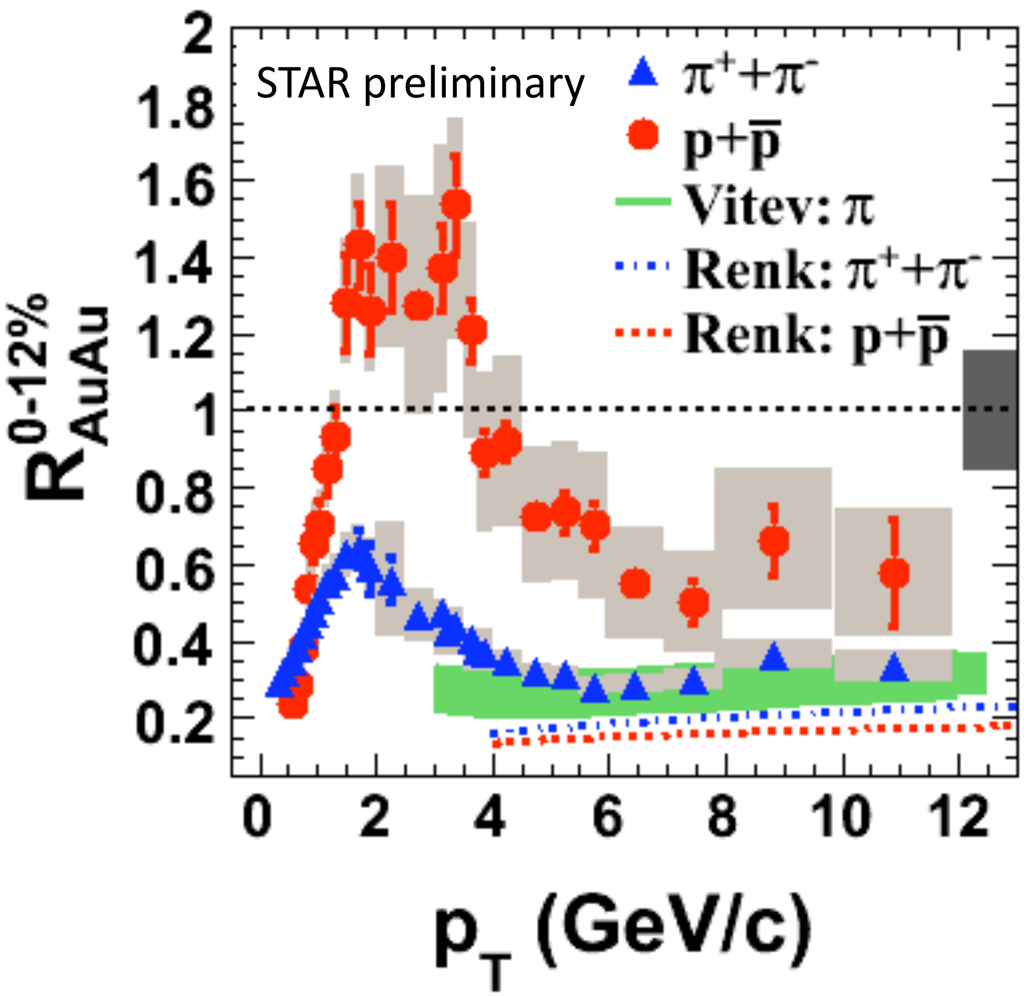
High p_T Results for proton Spectra



p+p collisions at RHIC:

pQCD based calculations provide a reasonable fit to data

pion and proton R_{AA} at High p_T



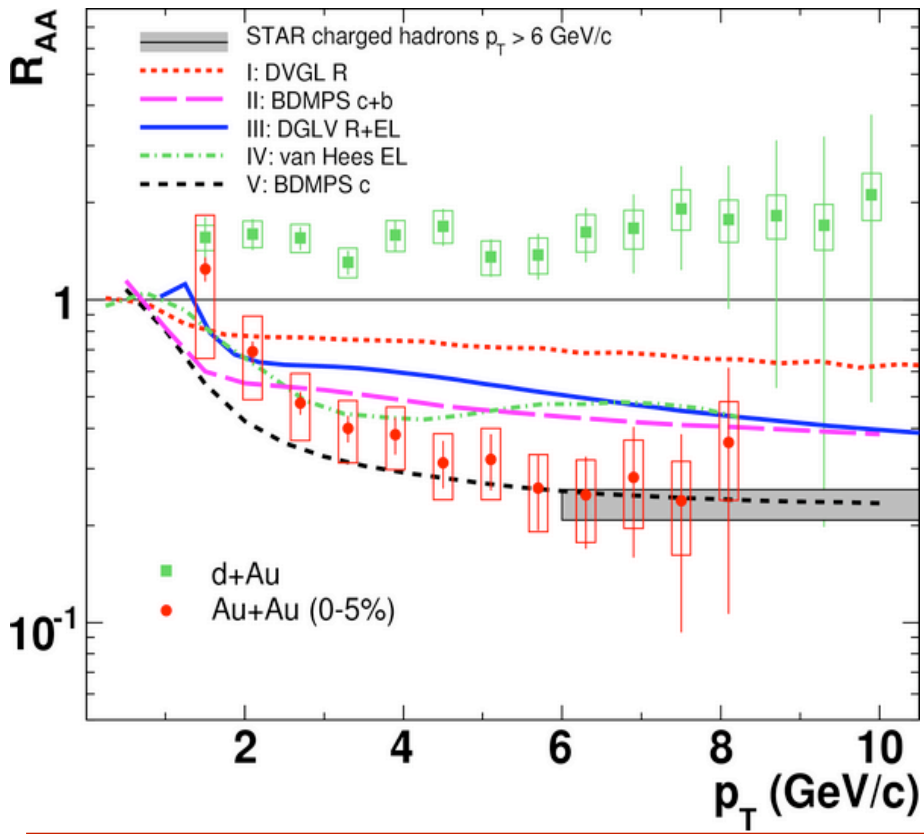
(1) STAR PID up to $p_T \sim 12$ GeV/c

(2) At the highest p_T $R_{AA}(\pi) \leq R_{AA}(p)$

$\Rightarrow$ No ***color factor*** effects!

Heavy Flavor Energy Loss

STAR PRL, 98, 192301 (2007)



1) Non-photonic electrons decayed from - charm and beauty hadrons

2) At $p_T \geq 6$ GeV/c,

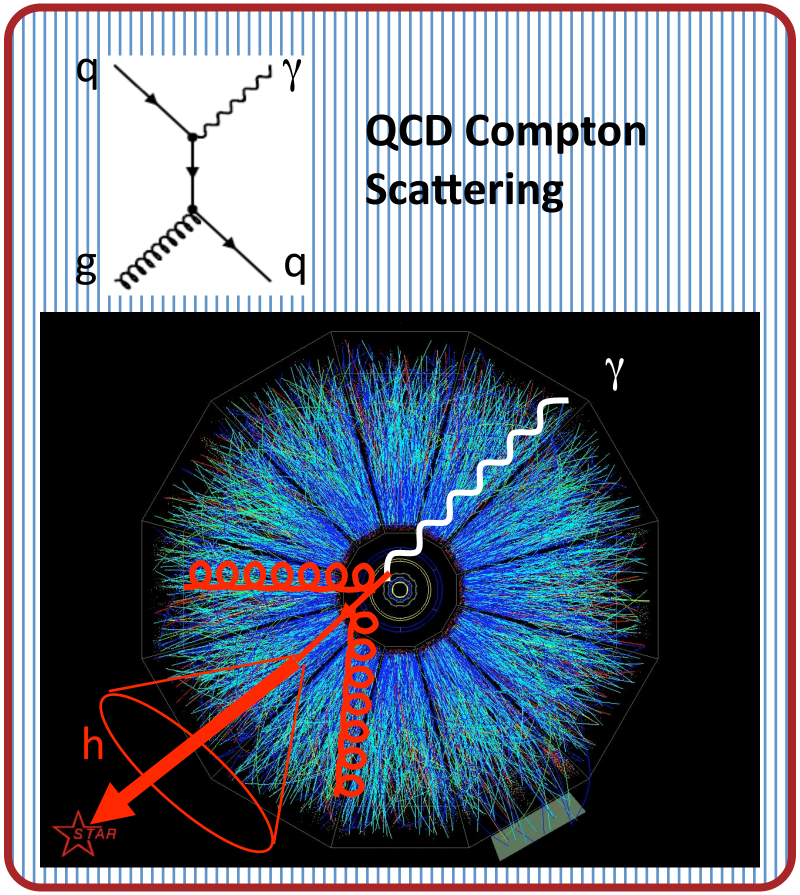
R_{AA}(n.e.) ~ R_{AA}($h^{\pm}$)!

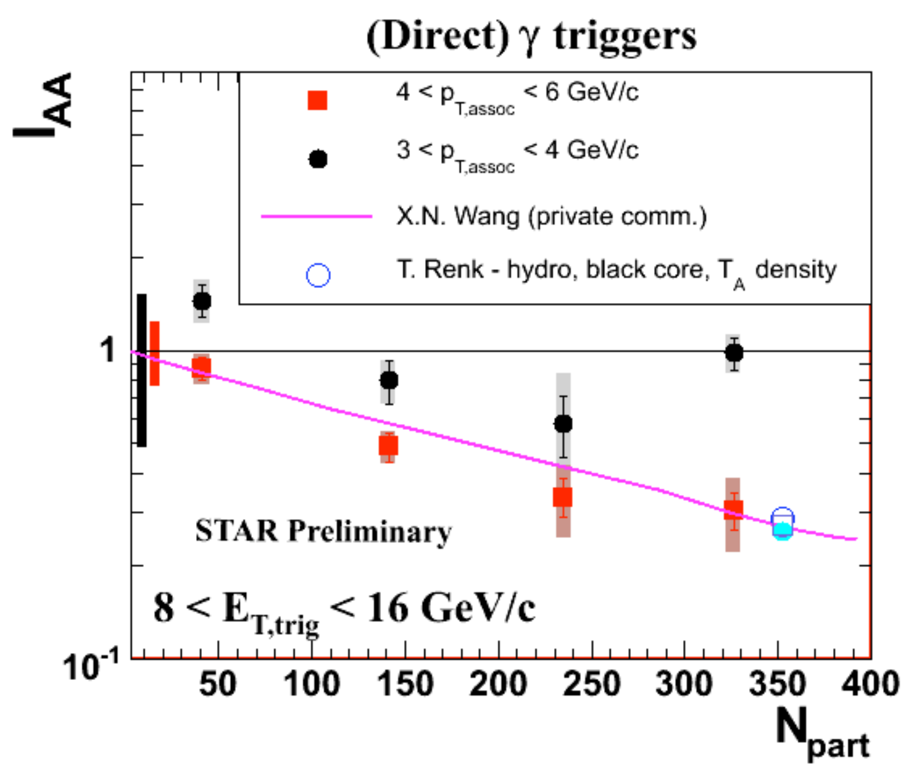
contradicts to naïve pQCD predictions

Surprising results -
- challenge our understanding of the energy loss mechanism
- force us to RE-think about the collisional energy loss
- **Requires direct measurements of C- and B-hadrons.**

γ-Jet Measurement in STAR

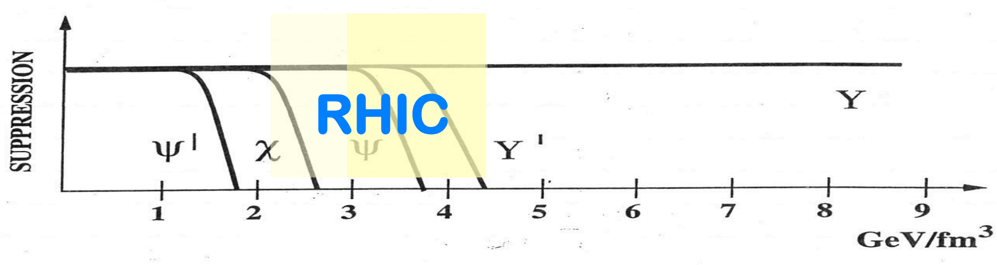
"Golden Probe" of QCD Energy Loss





- This probe is valuable for comparison with di-hadron correlations
- Goal: Full reconstructed kinematics: real fragmentation function D(z)

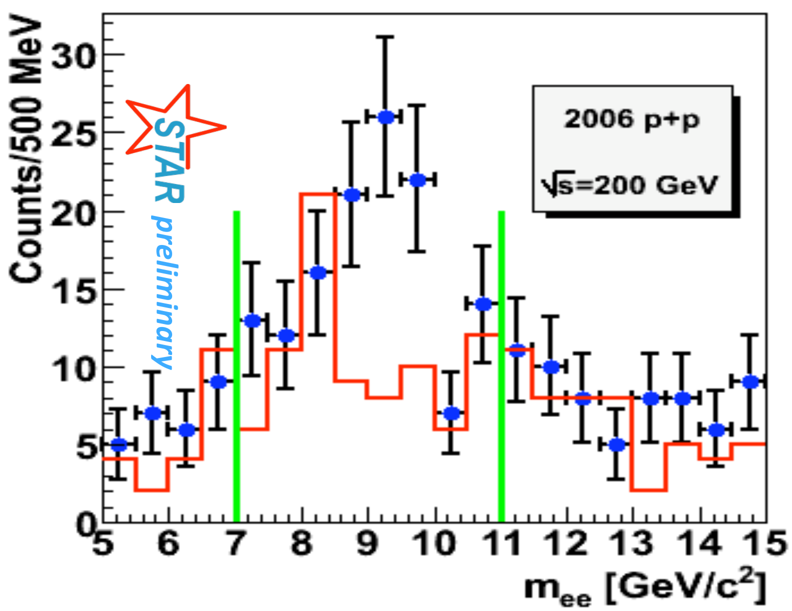
High Mass: Υ



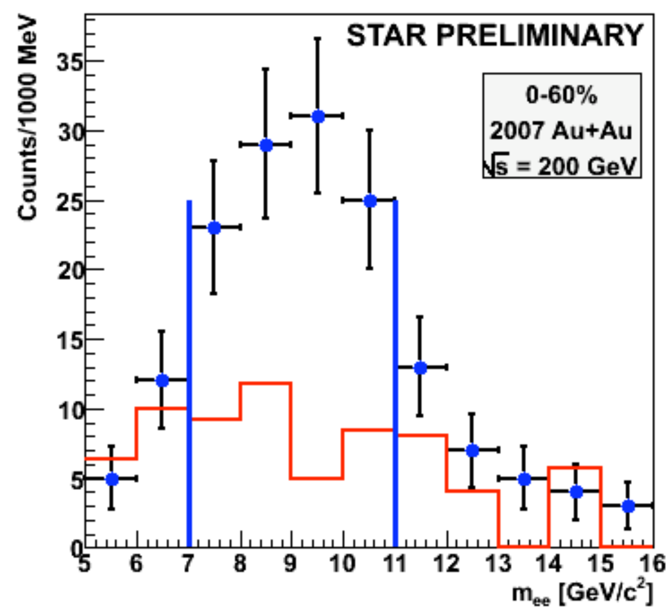
Sequential dissociation of quarkonia is sensitive to energy density of plasma

Υ (1S+2S+3S) $\longrightarrow$ e^+e^-

Run 6: 200 GeV p+p



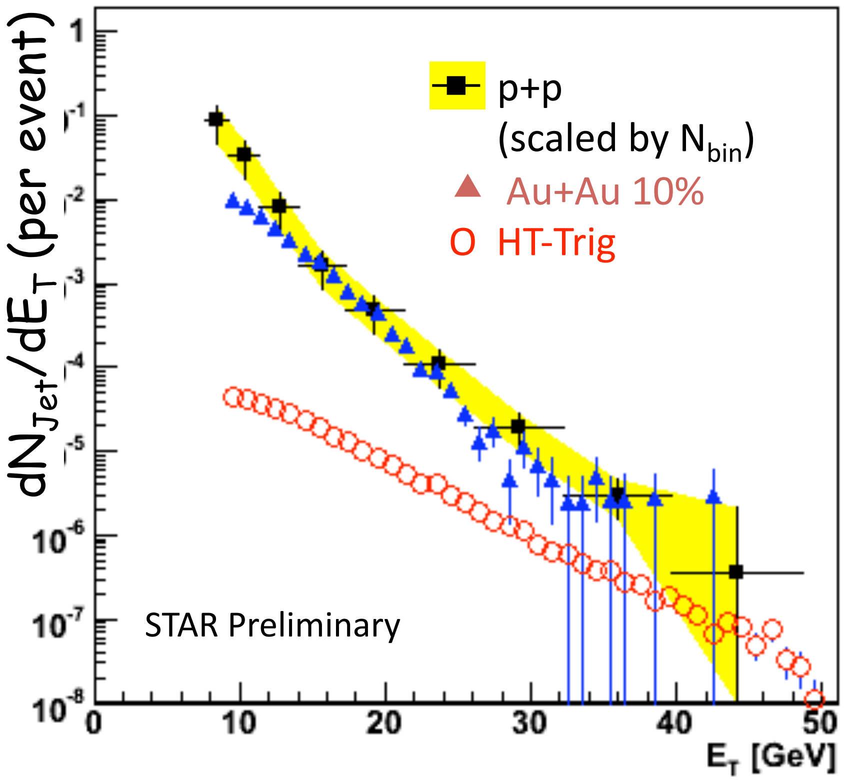
Run 7: 200 GeV Au+Au



STAR high p_T topological electron trigger works!

pQCD calculations are consistent with data!

Reconstructed Jet in Au+Au



Leading Order High Seed Cone(LOHSC)
R=0.4, p_T = 1 GeV/c, seed = 4.6 GeV/c
Statistical errors only.

MB-Trig: Good agreement with N_{bin} scaled p+p collisions

HT-Trig: Large trigger bias persists at least to 30 GeV.

Relative normalization systematic uncertainty: ~50%

Resolution effect corrected assuming Pythia fragmentation.

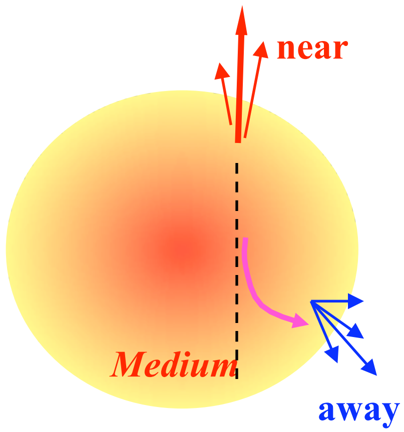
Further statistics of MB is needed to assess the bias in HT Trigger.

First step towards jet reconstruction in heavy ion collisions.

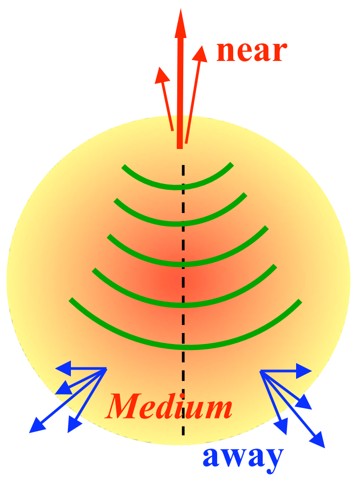
Search for Mach Cone

with Three Particle Correlations

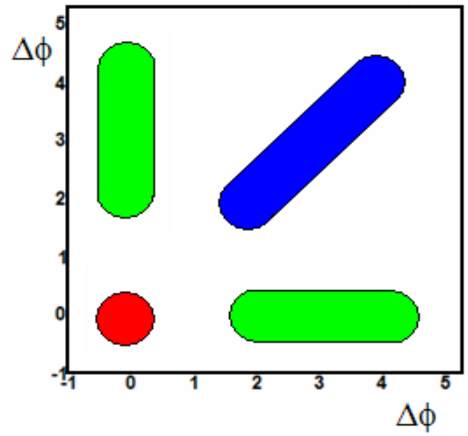
STAR: sub. to PRL, arXiv: 0805.0622

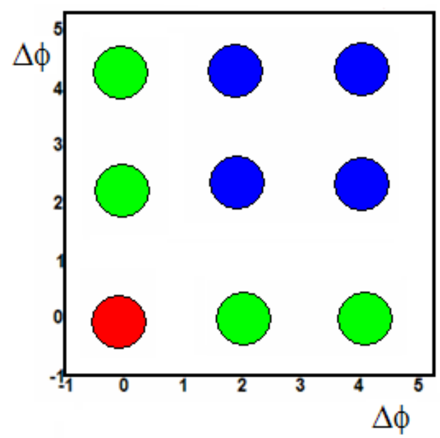


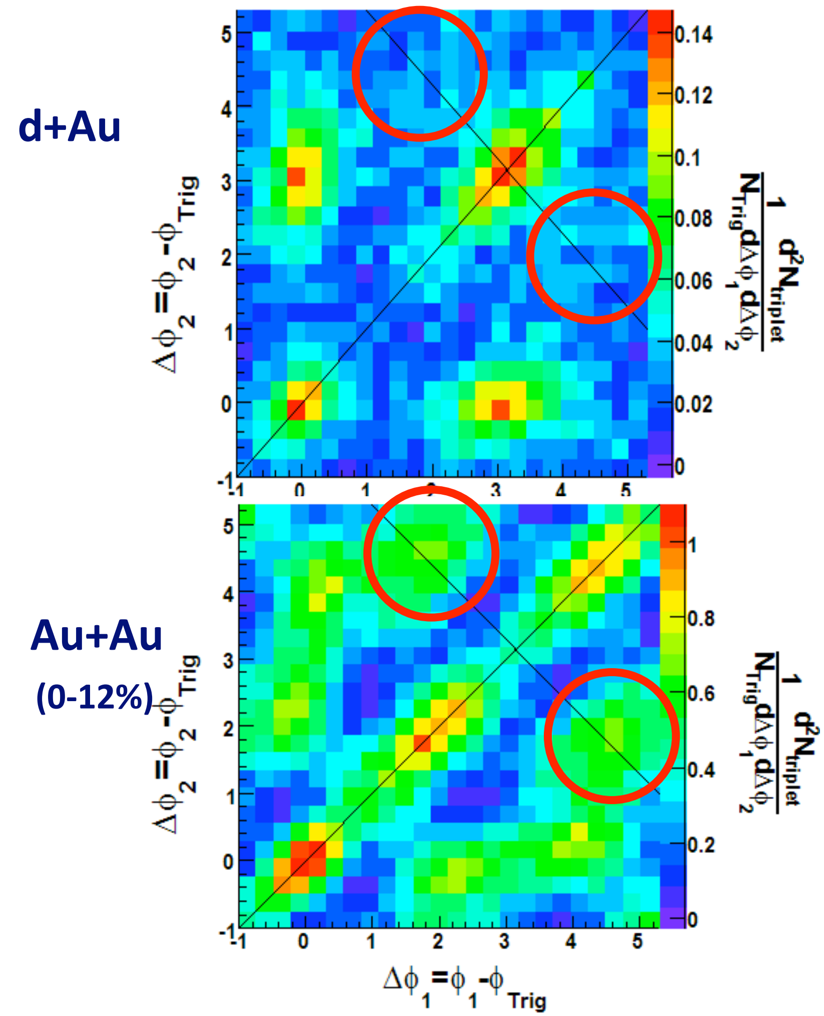
deflected jets



Conical Emission





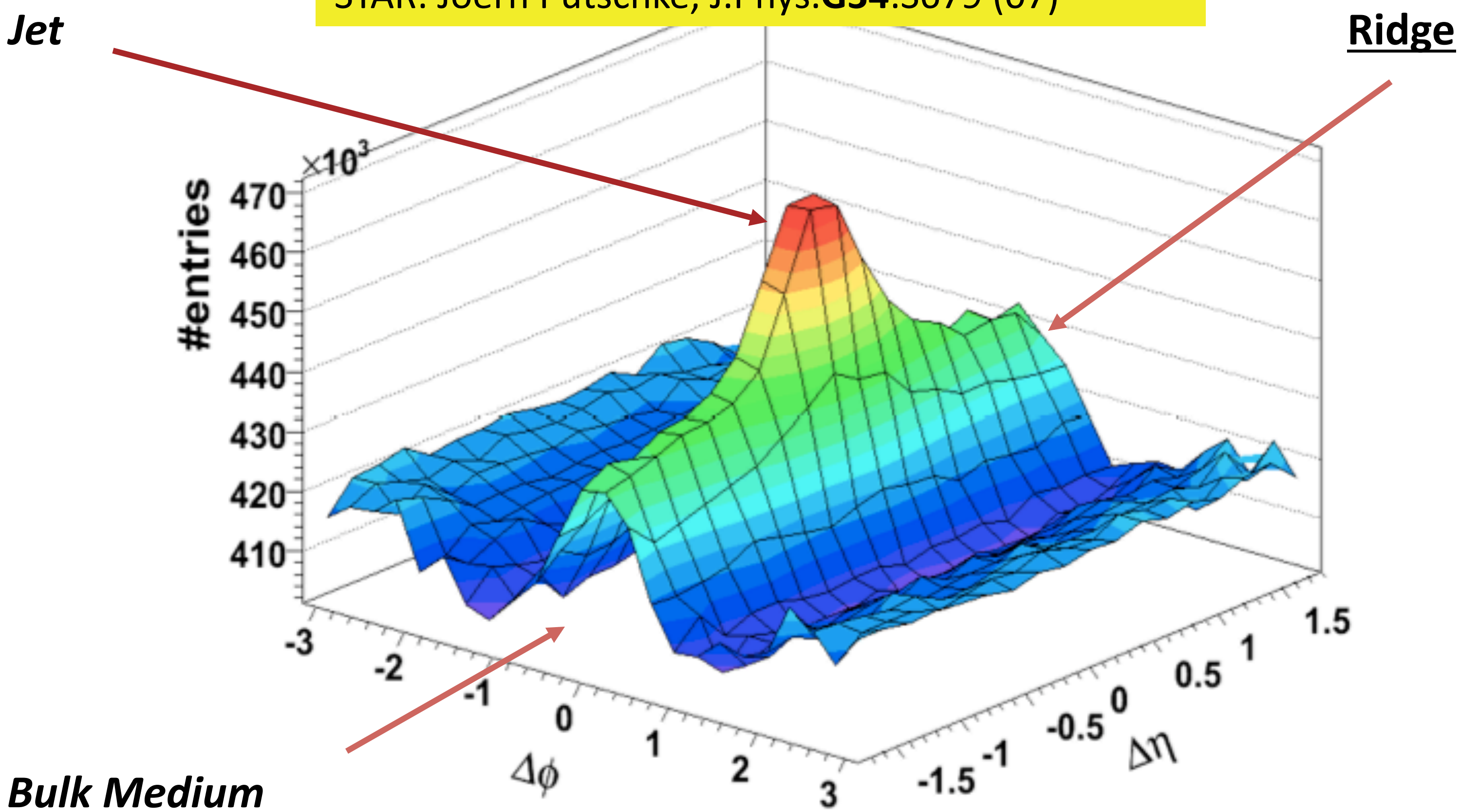


$$\boxed{\cos\vartheta^{Mach} = \sqrt{p/\varepsilon}}$$

"Evidence of conical emission …"

The Ridge from STAR

STAR: Joern Putschke, J.Phys.**G34**:S679 (07)

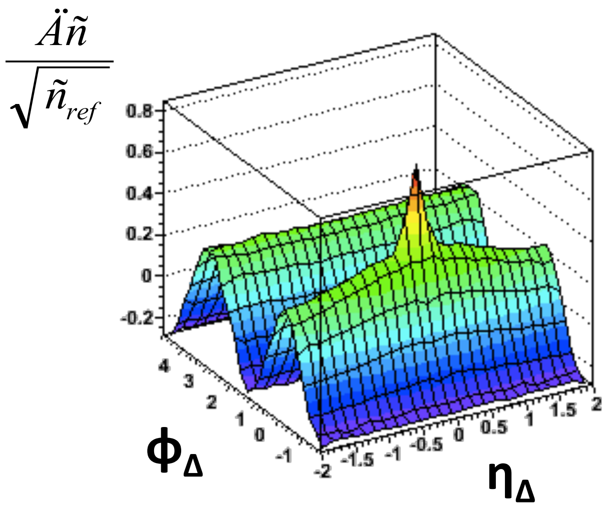


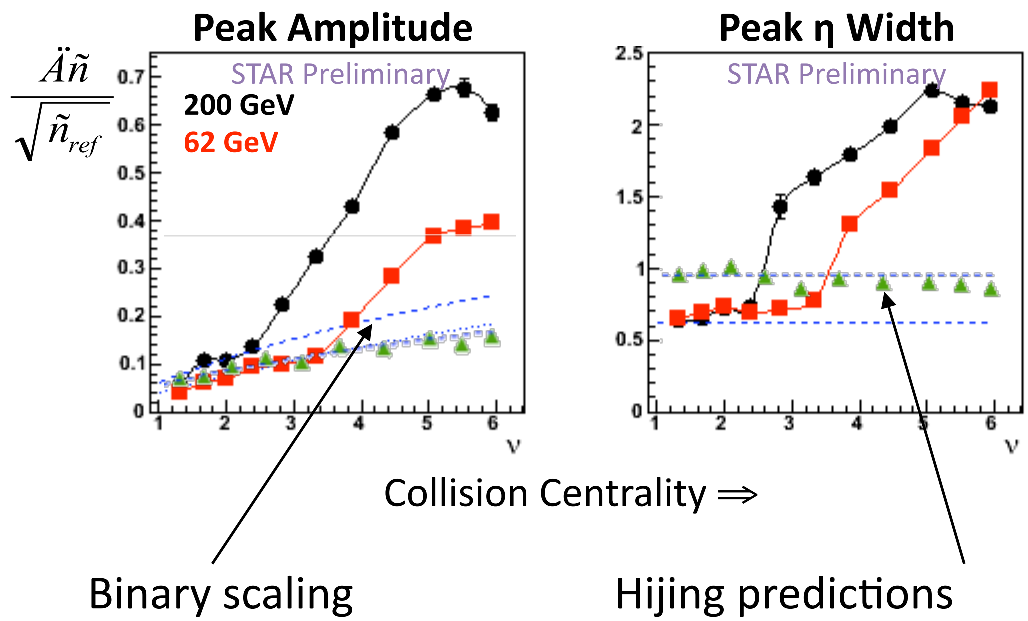
Rich underlying physics: jet, bulk, jet-medium interaction, medium responses,…

N. Armesto et al.; R. Hwa; A. Majumder, et al.; E. Suryak; S. Voloshin; C.Y. Wong

Not fully understood.

Two Particle Correlations





1) Amplitude and η widths: ***sharp transition***

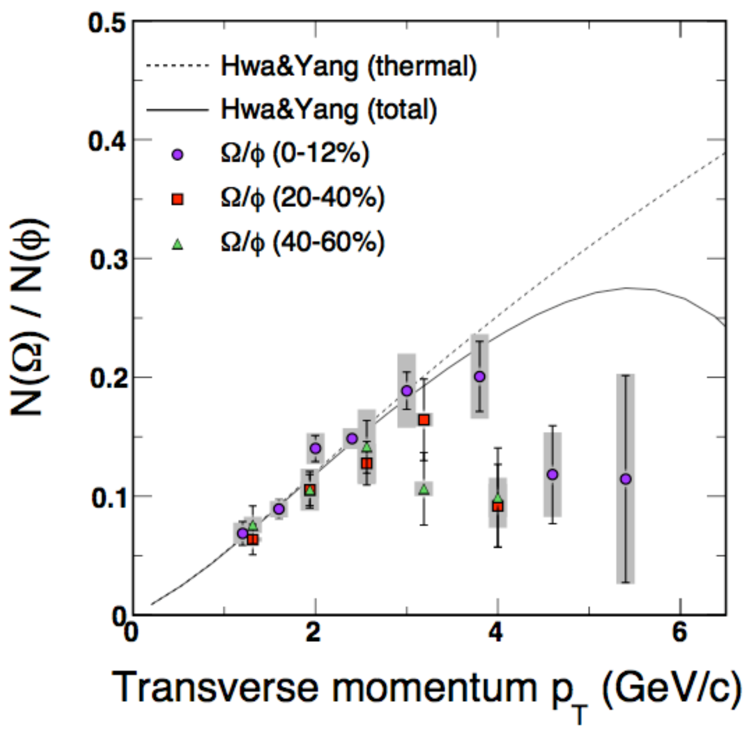
2) Deviations from binary scaling: ***physics unique to HI collisions***

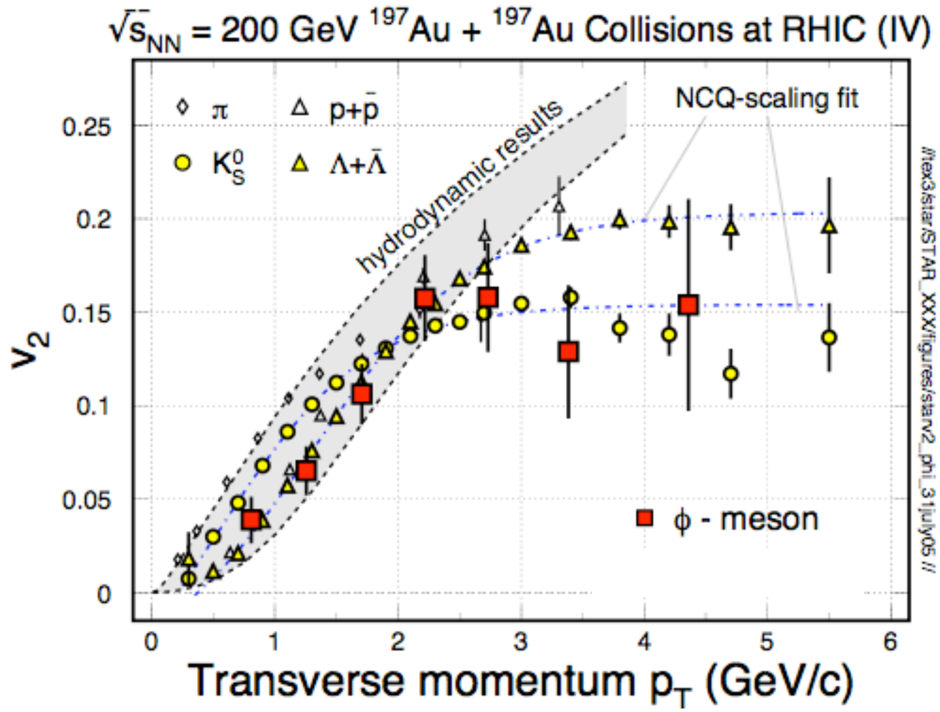
3) The observed correlation: ***Hijing under predicted*** the correlation

4) Inconsistent with the medium thermalization(?)

Modification of energetic 'jets' in the medium!

ϕ -meson Flow: Partonic Flow





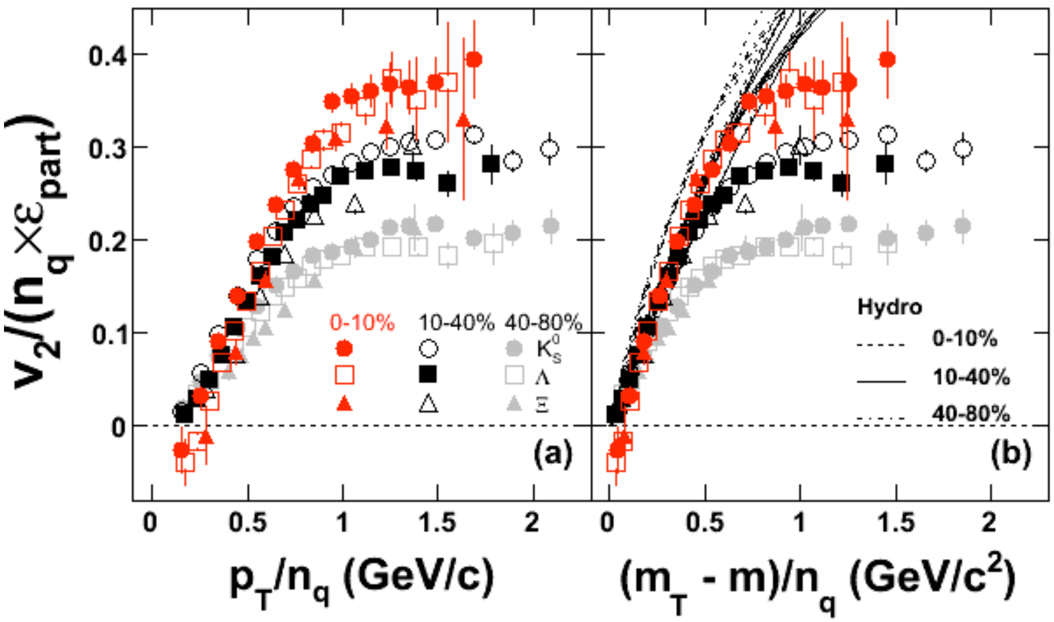
"ϕ-mesons are produced via coalescence of seemingly thermalized quarks in central Au+Au collisions. This observation implies *hot and dense matter with partonic collectivity* has been formed at RHIC"

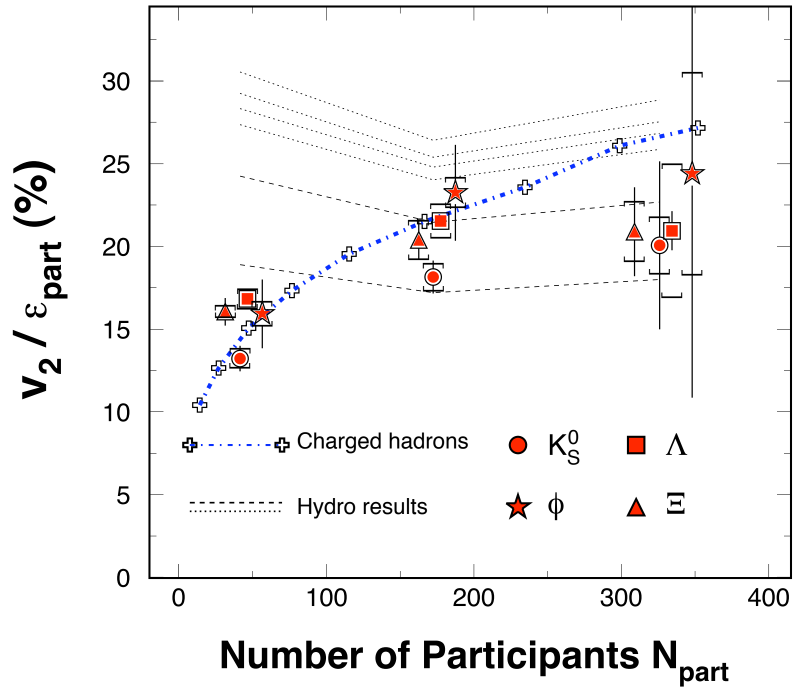
STAR: Phys. Rev. Lett. ***99*** (2007) 112301// * STAR, Duke, TAMU
** OZI rule

Centrality Dependence

*STAR: Phys. Rev. **C77**, 54901(2008)*

200 GeV Au+Au





*S. Voloshin, A. Poskanzer, PL **B474**, 27(00).*

D. Teaney, et. al., nucl-th/0110037

- Larger v_2/ε_{part} indicates stronger flow in more central collisions.
- NO ε_{part} scaling.
- The observed n_q-scaling does not necessarily mean thermalization.

sQGP and the QCD Phase Diagram

200 GeV Au+Au collisions at RHIC, strongly interacting matter formed:

- **Jet energy loss: R_{AA}**
- **Strong collectivity: v_0, v_1, v_2**
- **Hadronization via coalescence: n_q-scaling**

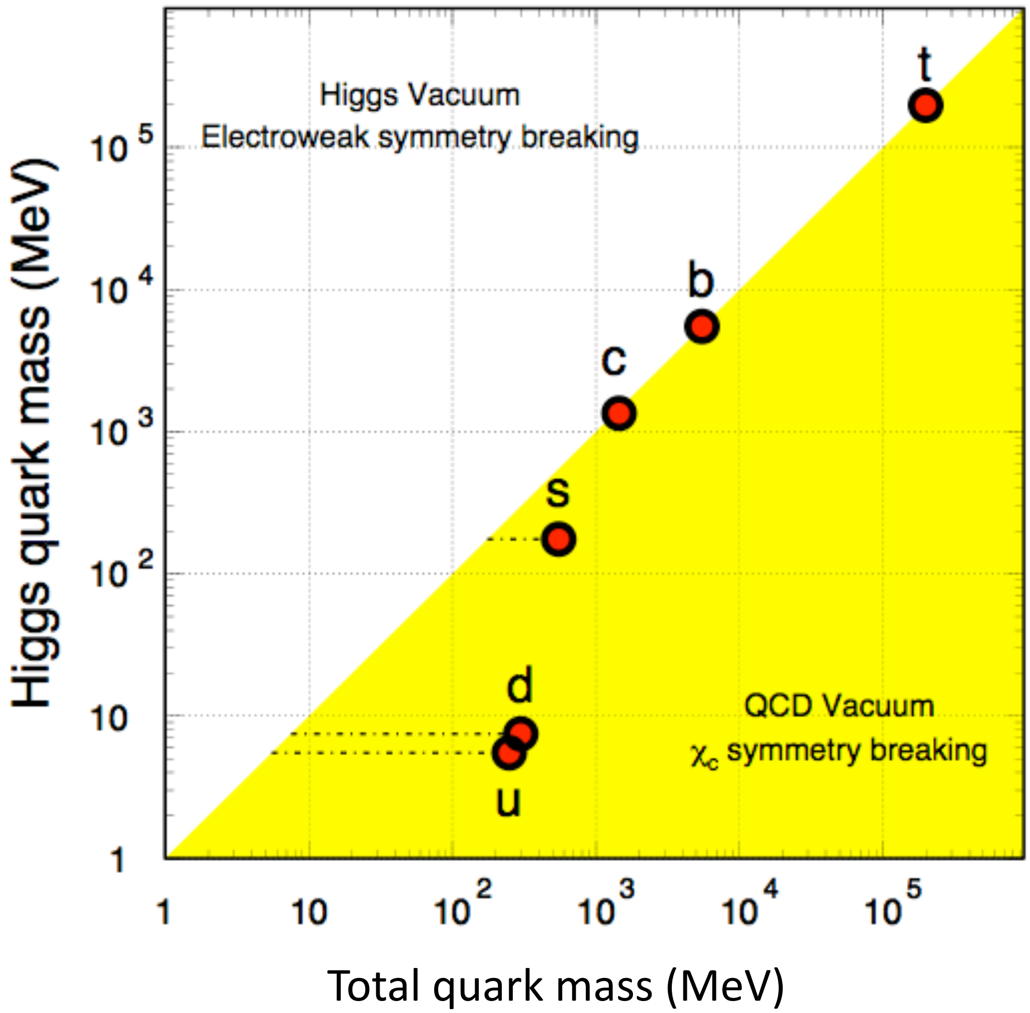
Questions:

Has the thermalization reached, or how large is the η at RHIC?

When (at which energy) does this transition happen?

What does the QCD phase diagram look like?

Quark Masses



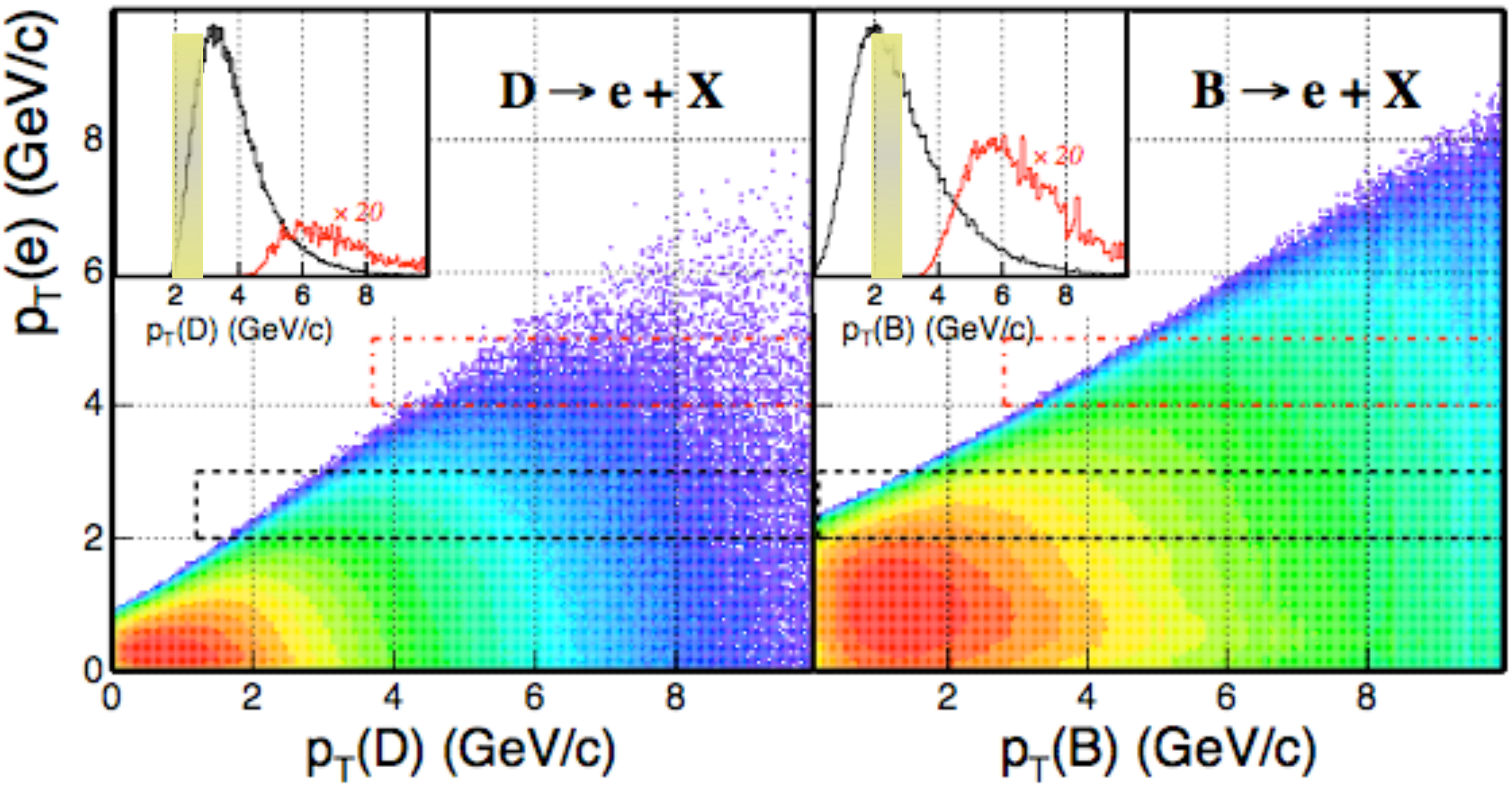
1) Higgs mass: electro-weak symmetry breaking. (current quark mass)
2) QCD mass: Chiral symmetry breaking. (constituent quark mass)

⇨ New mass scale compared to the excitation of the system.

⇨ Important tool for studying properties of the hot/dense medium at RHIC.

⇨ Test pQCD predictions at RHIC.

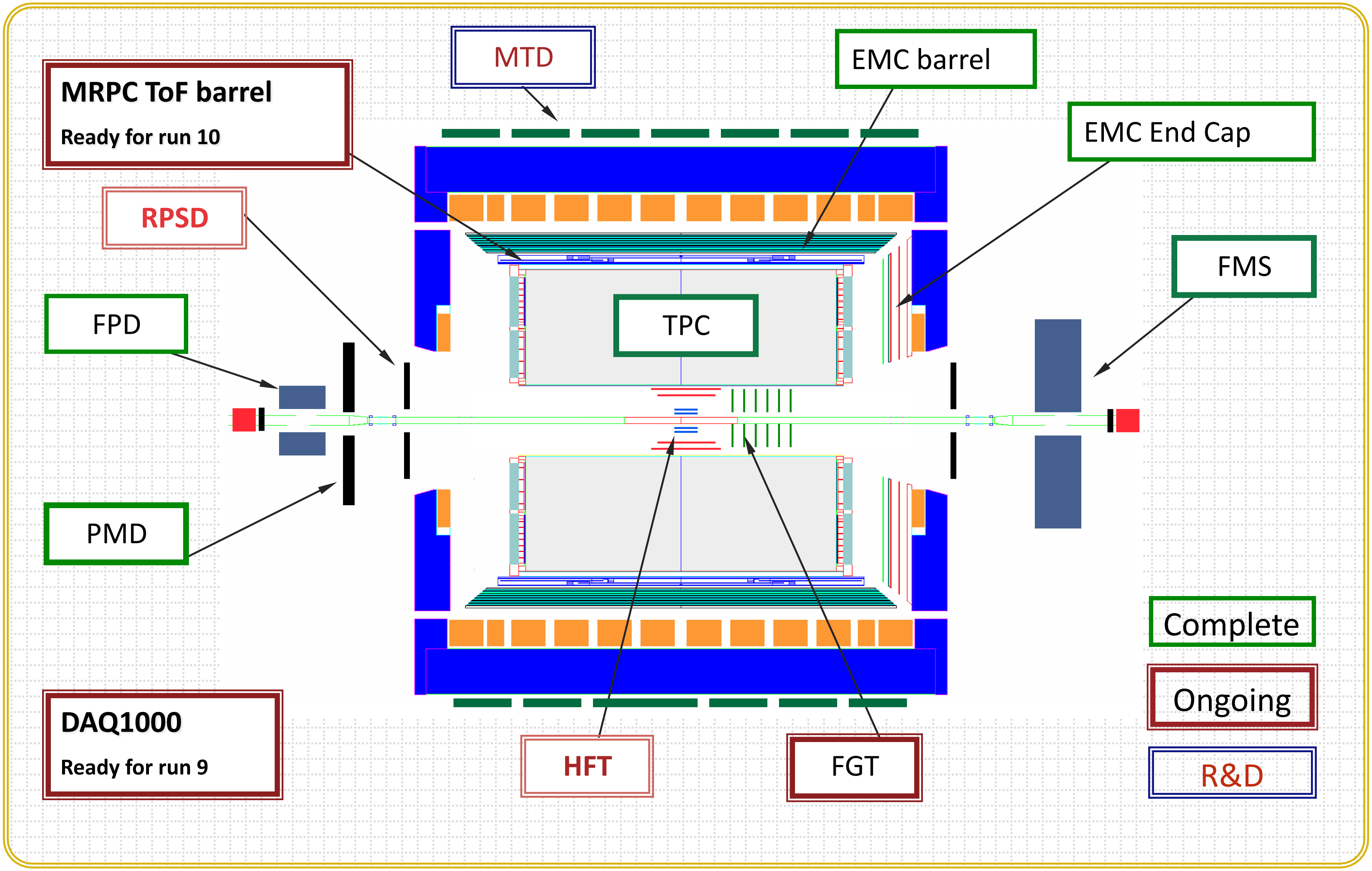
Decayed e p_T vs. b- and c-hadron p_T



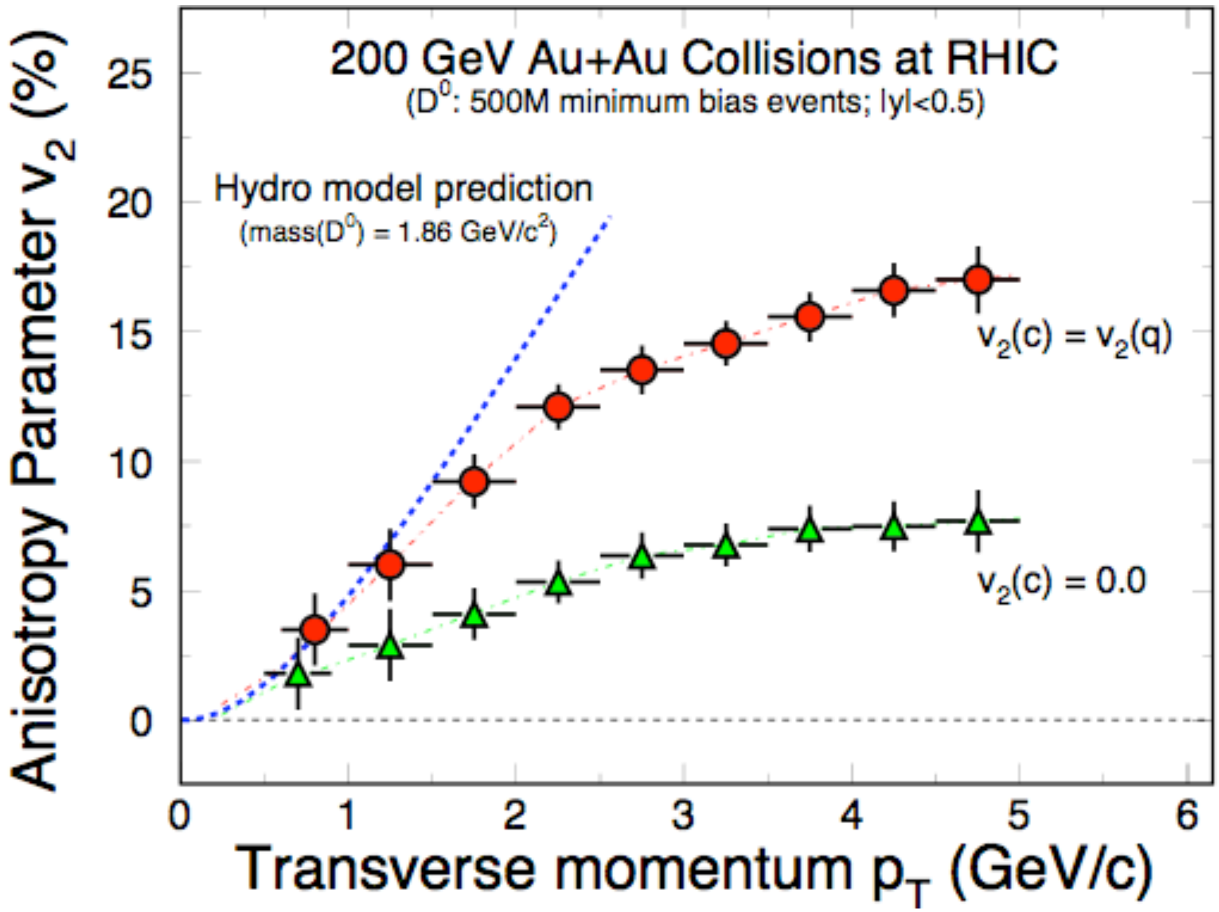
Key: ***Directly reconstructed heavy quark hadrons!***

Pythia calculation   Xin Dong, USTC October 2005

STAR Detector

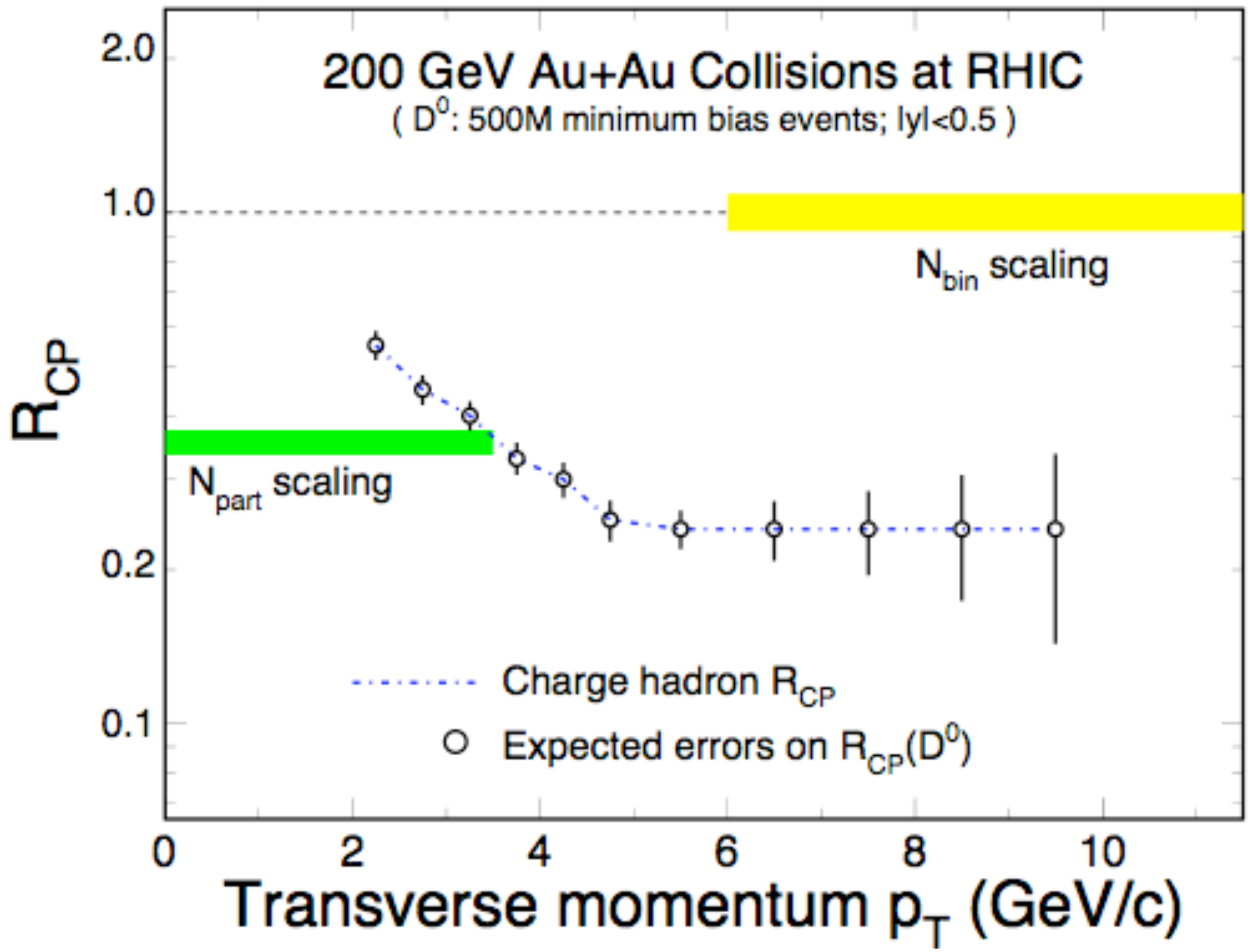


Charm Hadron v_2



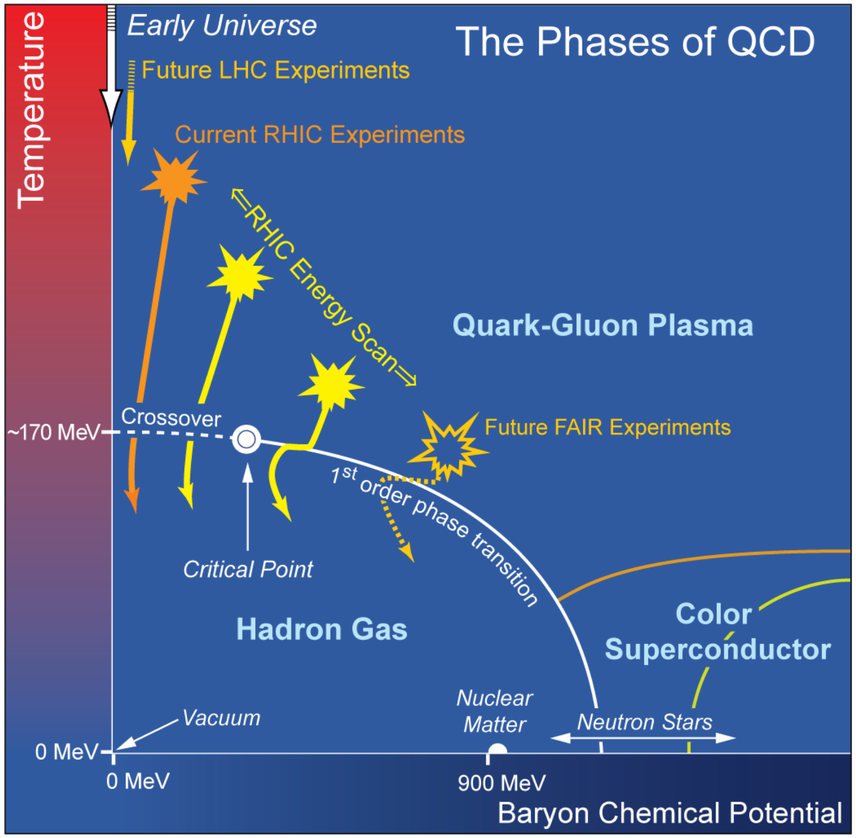
- 200 GeV Au+Au minimum biased collisions (500M events).
- Charm collectivity ⇨ drag/diffusion constants ⇨ ***medium properties!***

Charm Hadron R_{CP}



- 200 GeV Au+Au minimum biased collisions (|y|<0.5 500M events).
- Charm R_{AA} ⇨ ***energy loss mechanism, e.g. collisional vs. radiative!***

The QCD Critical Point



- LGT prediction on the transition temperature T_C is robust.

- LGT calculation, universality, and models hinted the existence of the critical point on the QCD phase diagram* at finite baryon chemical potential.

- Experimental evidence for either the critical point or 1st order transition is important for our knowledge of the QCD phase diagram*.

*** Thermalization has been assumed**

*M. Stephanov, K. Rajagopal, and E. Shuryak, PRL **81**, 4816(98)*
*K. Rajagopal, PR **D61**, 105017 (00)*

- http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf