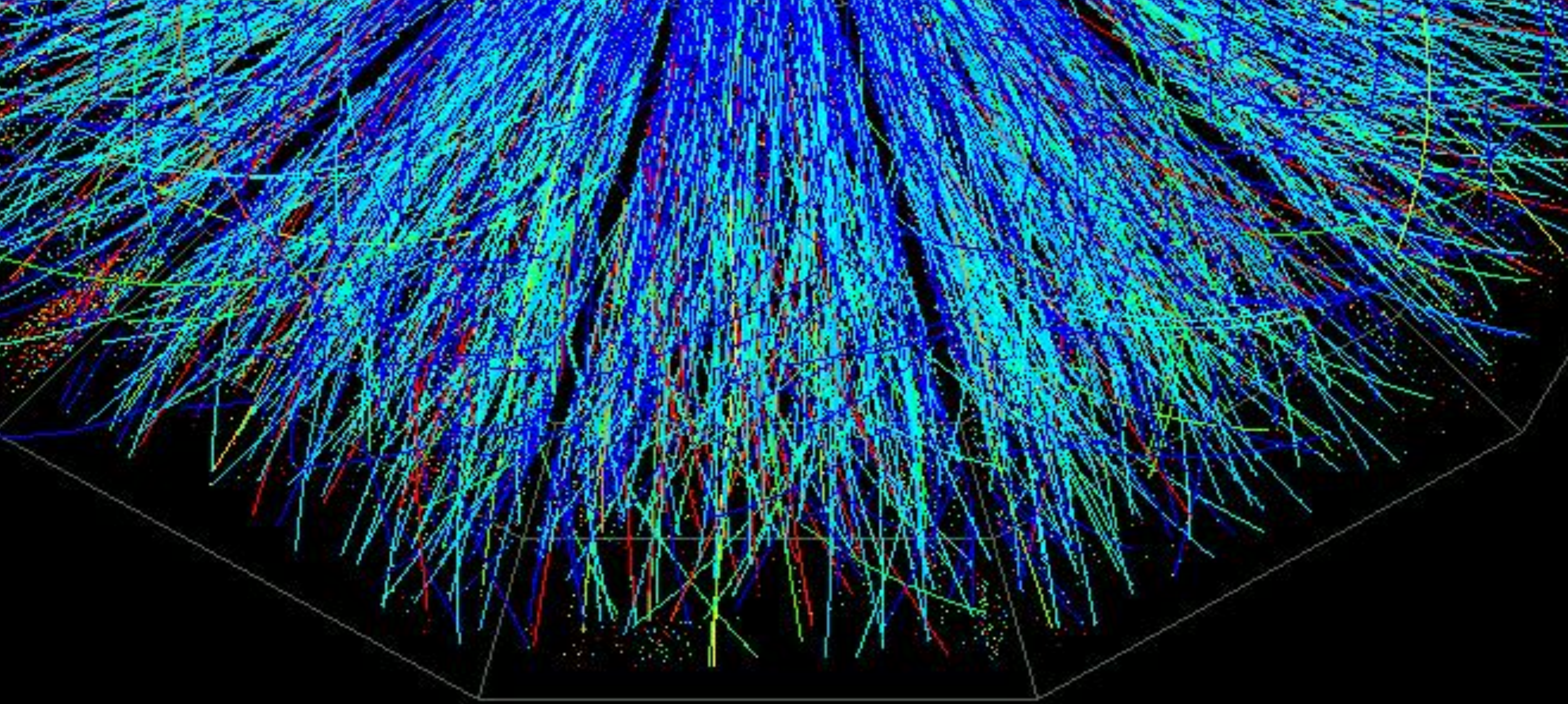


Probing QCD Phase Diagram with Heavy-Ion Collision Experiments

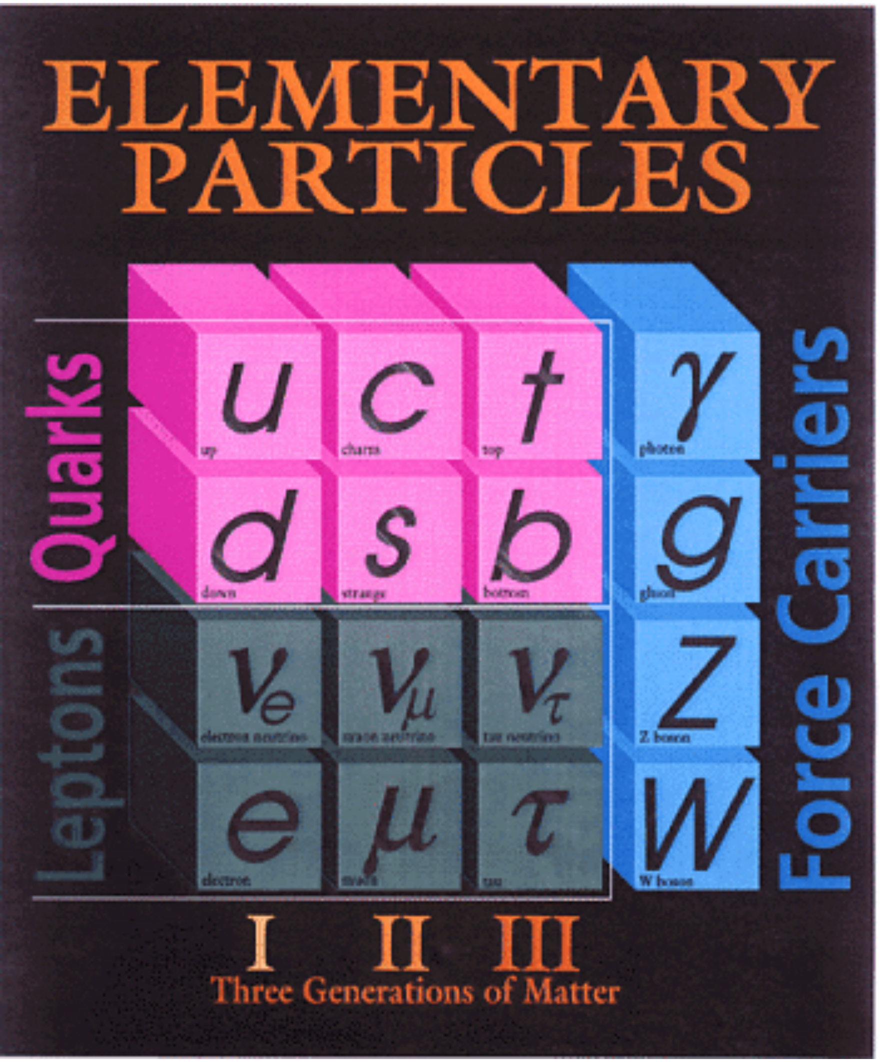
Grazyna Odyniec

Lawrence Berkeley National Laboratory

53rd Karpacz Winter School on Theoretical Physics, Karpacz, February 26 – March 4, 2017

- Refresher from lecture I :

Today: Standard Model



Everything in the Universe is found to be made from 12 basic building blocks called fundamental particles, governed by four fundamental forces

Two basic types: quarks and gluons
Four basic forces: strong, weak, electromagnetic and gravitational

Our best understanding of how these twelve particles and three forces (out of 4, omitting gravity) are related to each other is encapsulated in the Standard Model of particles and forces

QCD* predicted a new phase of strongly interacting matter :

i.e. in special circumstances of enormous high temperature and pressure -> deconfinement: i.e. hadrons would "melt up" to a large medium of interacting q and g

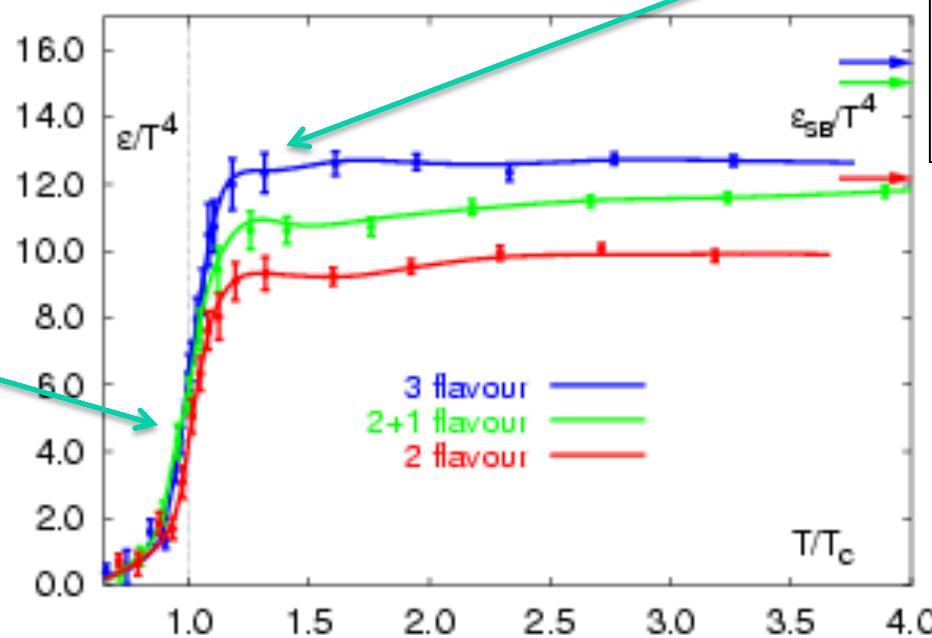
-> *Quark Gluon Plasma*

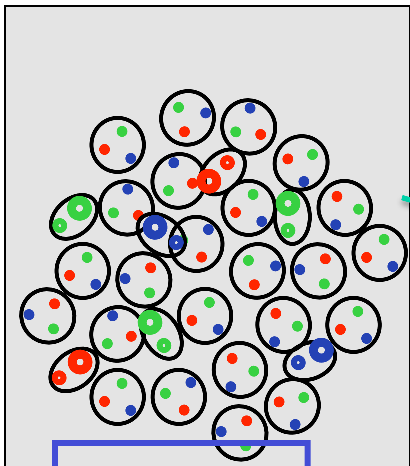
Cosmology: quark-hadron transition in early Universe

*also early phenomenological consideration predicted phase transition

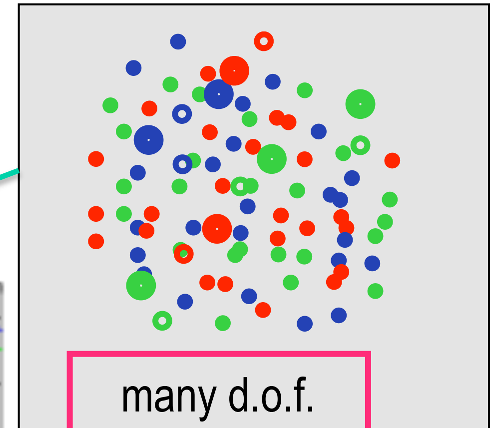
QCD predictions: Phase Transition

Energy density





few d.o.f.
→**confined**



many d.o.f.
→**deconfined**

Temperature

Large increase in energy density at **T_C ~ 170 MeV** (➔ **154 MeV**)
Not reached the non-interacting S.B. limit
Change of number of degree of freedom (on jump)

F. Karsch et al. Nucl. Phys. ***B524****, 123(02). Z. Fodor et al,* ***JHEP*** *0203:014(02).*

practical question:

- How can we find QGP ?
  - high-energy nuclear collisions
  - RHIC

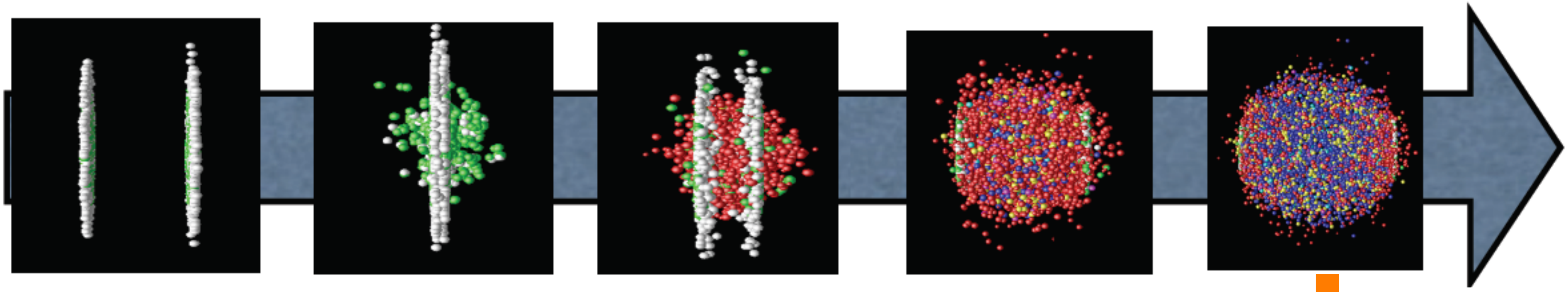
“Mini-Bang” in the lab

Let’s go for the Mini-Bang:

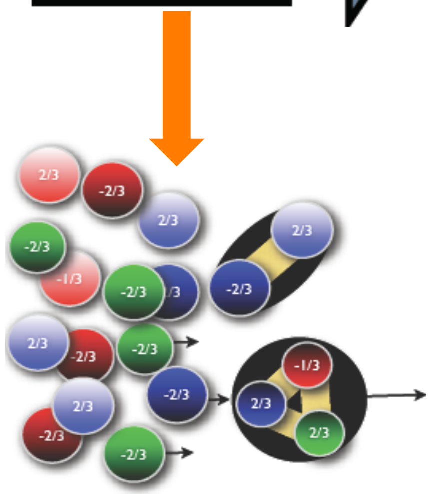
- We need a system that is small so that we can accelerate it to very high speeds: ~ 99.9% of the speed of light.
- But we need a **system** (i.e. a chunk of matter and not just a single particle) so that the system can follow simple rules of thermodynamics and form a new state of matter in a particular phase.
- We use heavy ions (e.g. a Gold ion which is made of 197 protons and neutrons). It is tiny (about a 10^{-14} m in diameter) but it is a finite volume that can be exposed to pressure and temperature.

We try to force matter we know (e.g. our Gold nucleus) though a phase transition to a new state of matter, predicted also by the Big-Bang model, called a Quark-Gluon Plasma

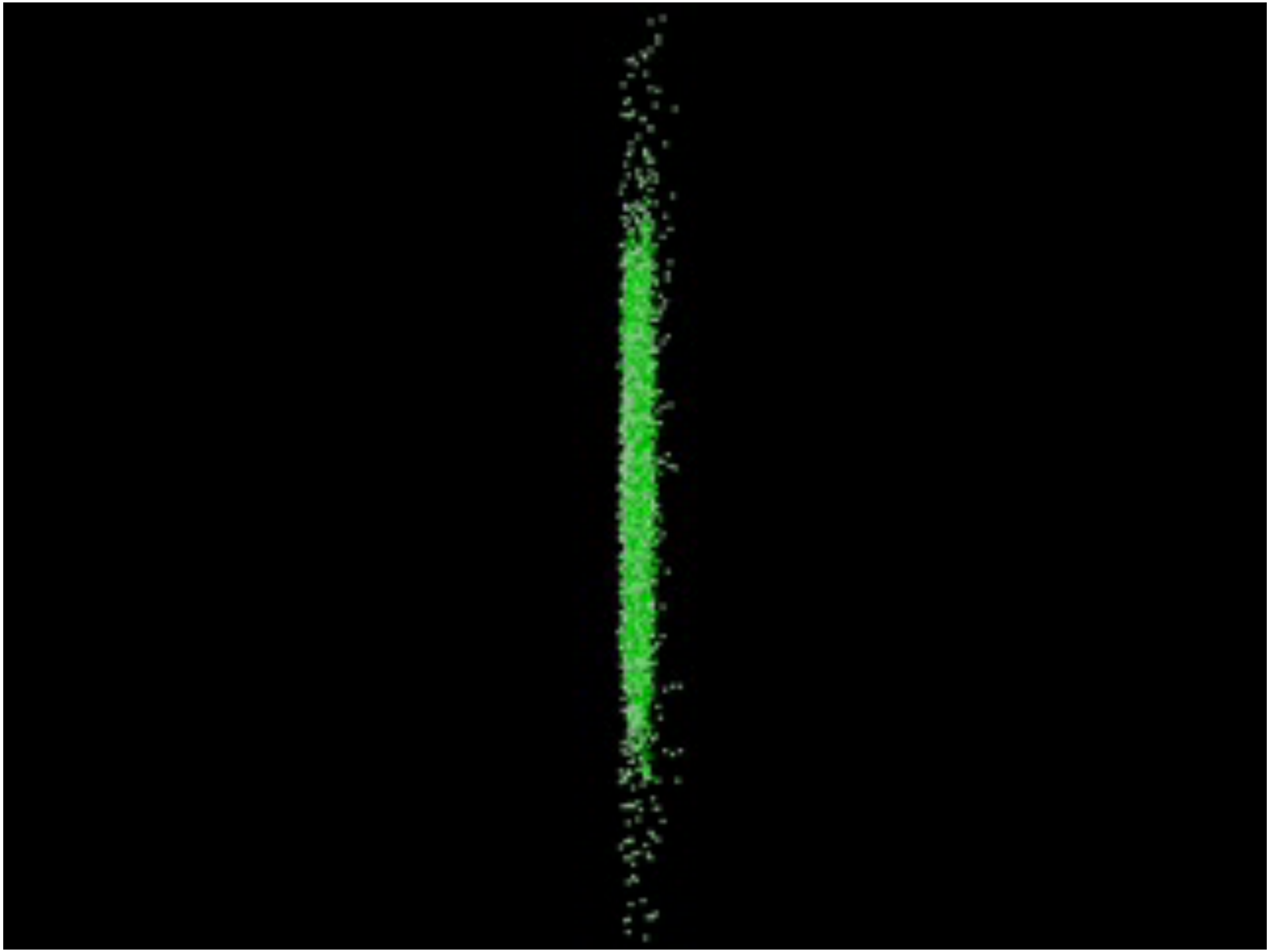
Evolution of quark gluon plasma



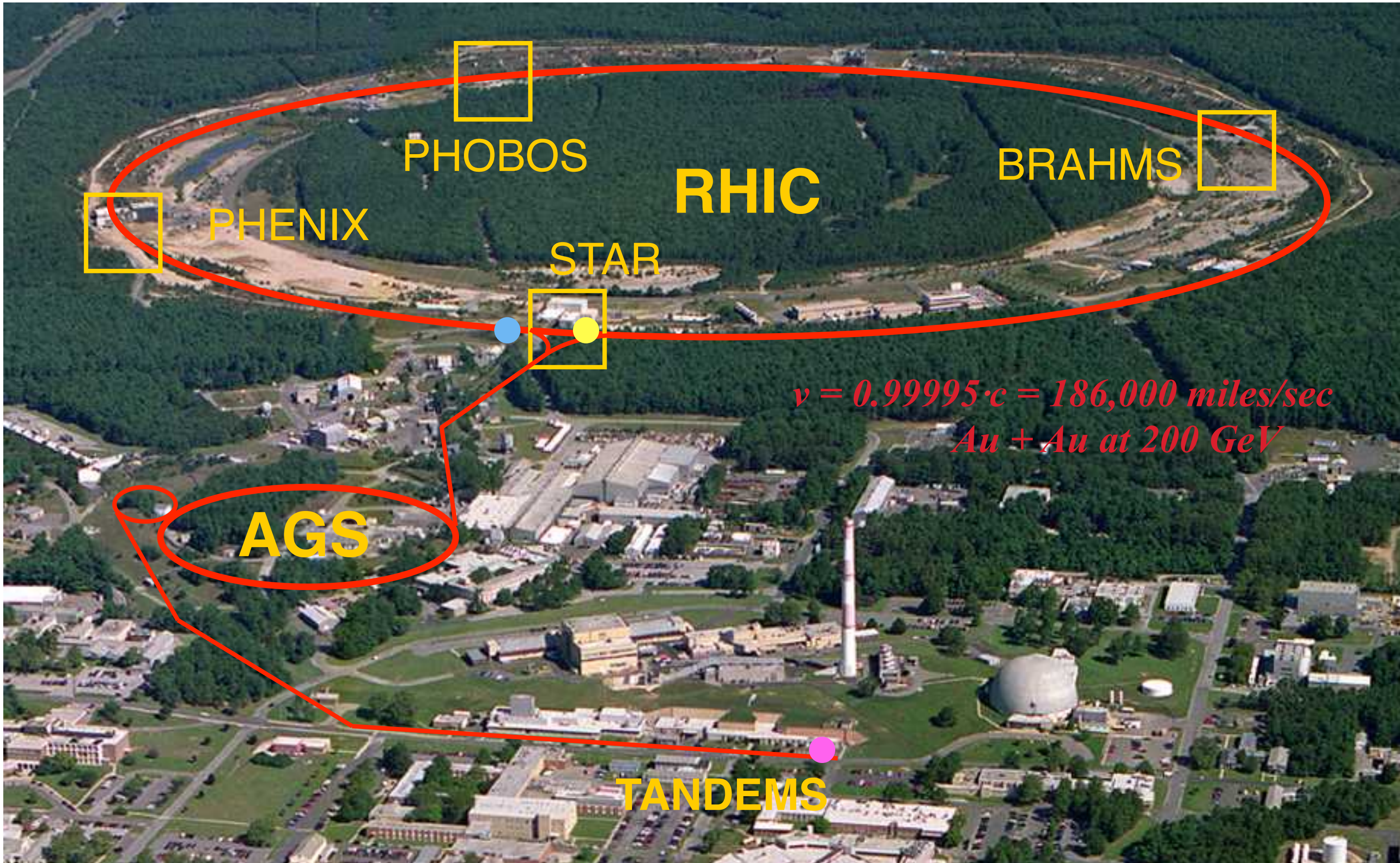
Collision time ~ 10^{-22} seconds



All particles flow
as if frozen out from
a flowing soup of
constituent quarks

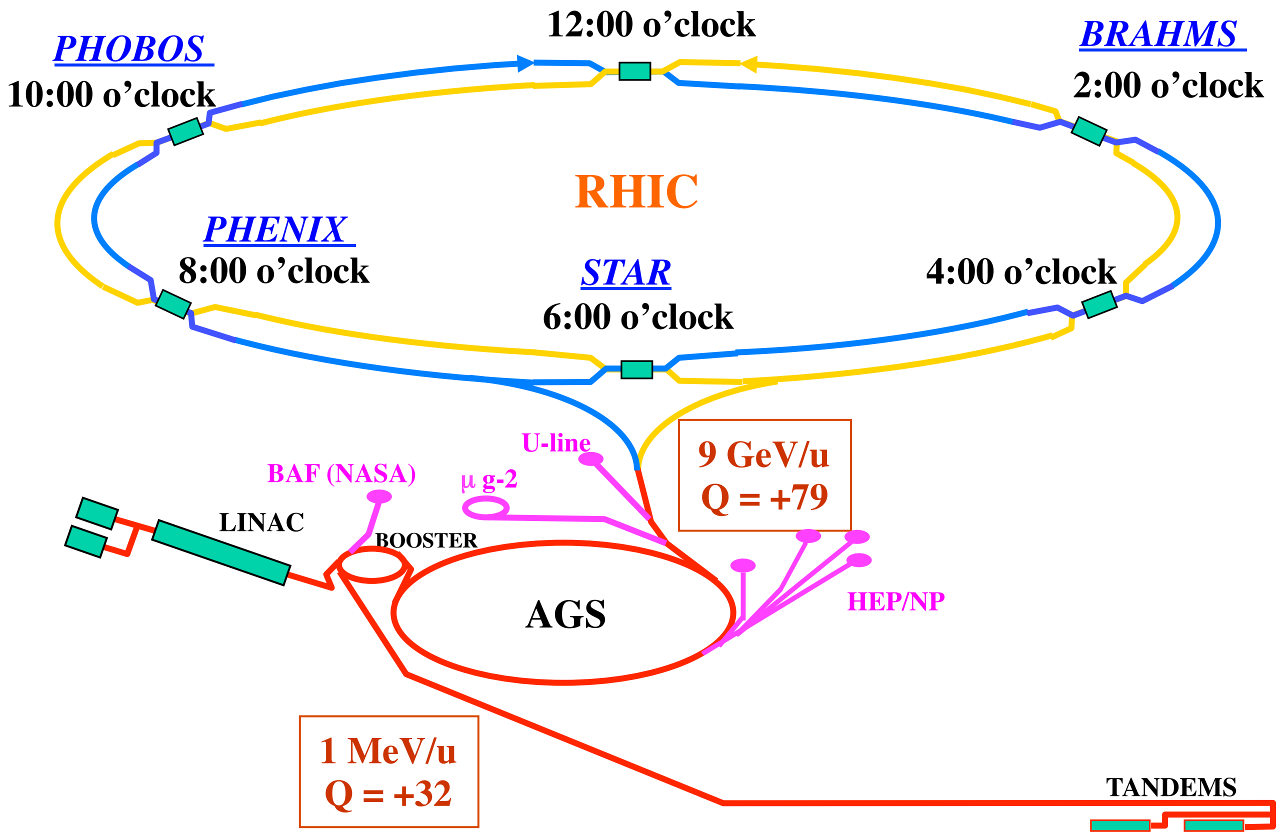


Relativistic **H**eavy **I**on **C**ollider (RHIC)
Brookhaven National Laboratory (BNL), Upton, NY



Animation M. Lisa

Relativistic Heavy Ion Collider (RHIC)

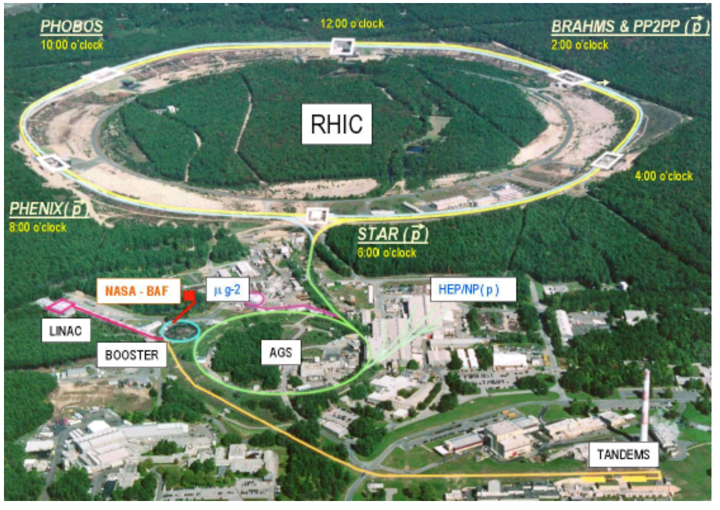


- 2 concentric rings of 1740 superconducting magnets
- 3.8 km circumference
- counter-rotating beams of ions from *p* to Au
- max center-of-mass energy: AuAu 200 GeV, pp 500 GeV

So, we know:
what …
how …
where …

- Lecture II

RHIC – the QCD Collider - Main Specifications



RHIC is an intersecting storage ring and particle accelerator

Two independent rings each 3.834 km circumference (yellow and blue)
Hexagonally shaped rings

Can collide: any nuclear species on any other: p+p to Au=Au

p-beams are polarized !

Max Energy: p+p: $\sqrt{s}$ = 500 GeV

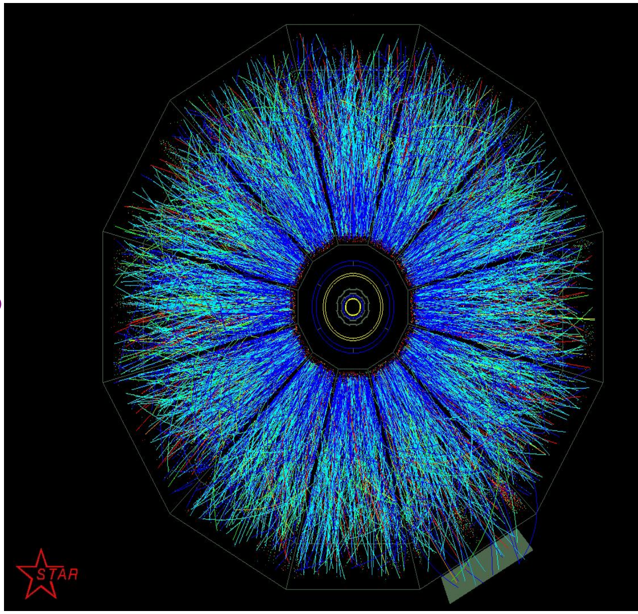
Au+Au $\sqrt{s}_{NN}$ = 200 GeV

Originally 4 experiment, presently two: STAR and PHENIX

What do we have to measure ?

- In Au+Au: Au = 79 protons+118 neutrons = 197 nucleons -> 394 nucleons total
- after collision : ~ 10,000 particle debris !
- measured particles: e, p, π, K, ϕ, Λ, ρ, Ξ, Ω, d, J/Ψ, Y, B, …
- Many particles contain s-quarks, some even c- and b-quarks
- Energy converts to matter, but does the matter go though a phase transition ?

- the only thing to do is to check the make-up of debris:
  - which particles have been formed ?
  - how many of them ?
  - are they emitted statistically (Boltzmann distribution)?
  - what are their kinematics (speed, momentum, angular distributions)?
  - are they correlated in coordinate or momentum space ?
  - do they move collectively ?
  - do some of them “melt” ?
  - …



ROAD MAP: What do we measure in collider experiments, and how ?

<u>**Inner detectors**</u>:

- particles come from the vertex, they have to traverse certain detectors but should not change their properties when traversing the inner detectors.

DETECT but don't DEFLECT !!!

- Inner detectors have to be very thin (low radiation length): easy with gas (TPC), challenge with solid state materials (vertex detectors)
- Measurements:
  - Momentum and charge via high resolution tracking detectors (for example TPC) in magnetic field
  - PID via dE/dx in TPC and time of flight in TOF
  - PID of decay particles via topology

<u>**Outer detectors**</u>:

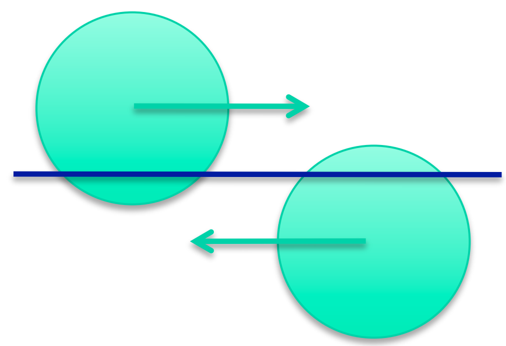
- Particles should stop in the outermost detectors
- Other detector has to be thick and of high radiation length (e.g. Pb/Scint calorimeter)
- Measurements:
  - Deposited energy for event and specific particles
  - e/h separation via shower profile
  - Photon via shower profile

ROAD MAP: design guidelines …

- The "Plan":
  - Consistent framework for describing most of the observed phenomena
  - Avoid single-signal detectors
  - "Specialized" detectors but keep considerable overlap for comparison and cross-checks
  - Expect the unexpected
    - Preserve high-rate and triggering capabilities
    - Maintain flexibility as long as $'s allow

ROAD MAP: How do we know what happened ?

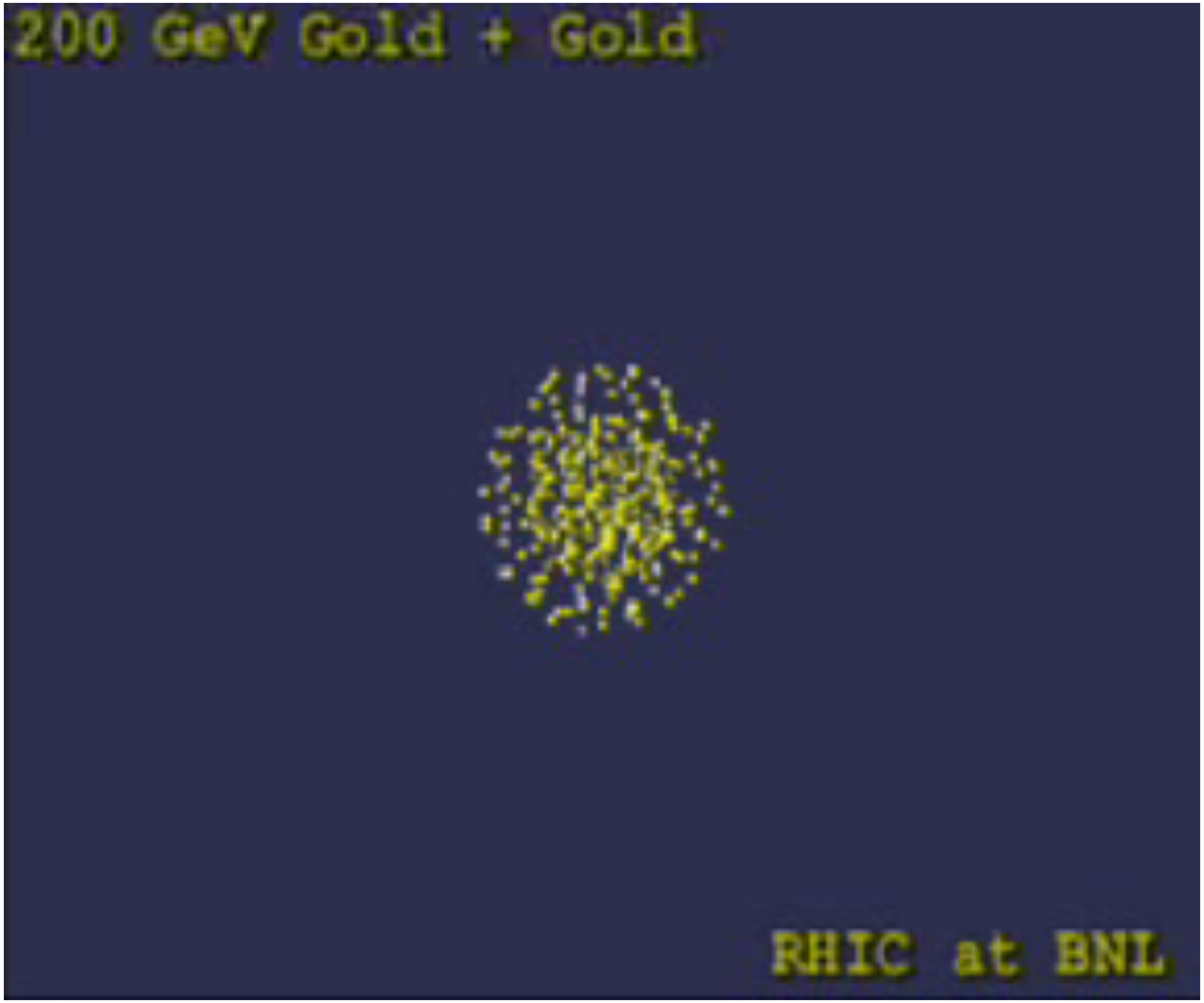
- We have to compare to a system that definitely did not go through a phase transition (a reference collisions)
- Two options:
  - a proton-proton collisions, compared to a Au+Au collisions, do not generate a big enough volume for formation of a plasma phase 
  - a peripheral Au+Au collisions, compared to a central ones, do not generate enough energy and volume for formation of a plasma phase



So, Au+Au not enough, our detectors need to deal with p+p (p+A) as well

You must run simulations ! (obligatory)

side view

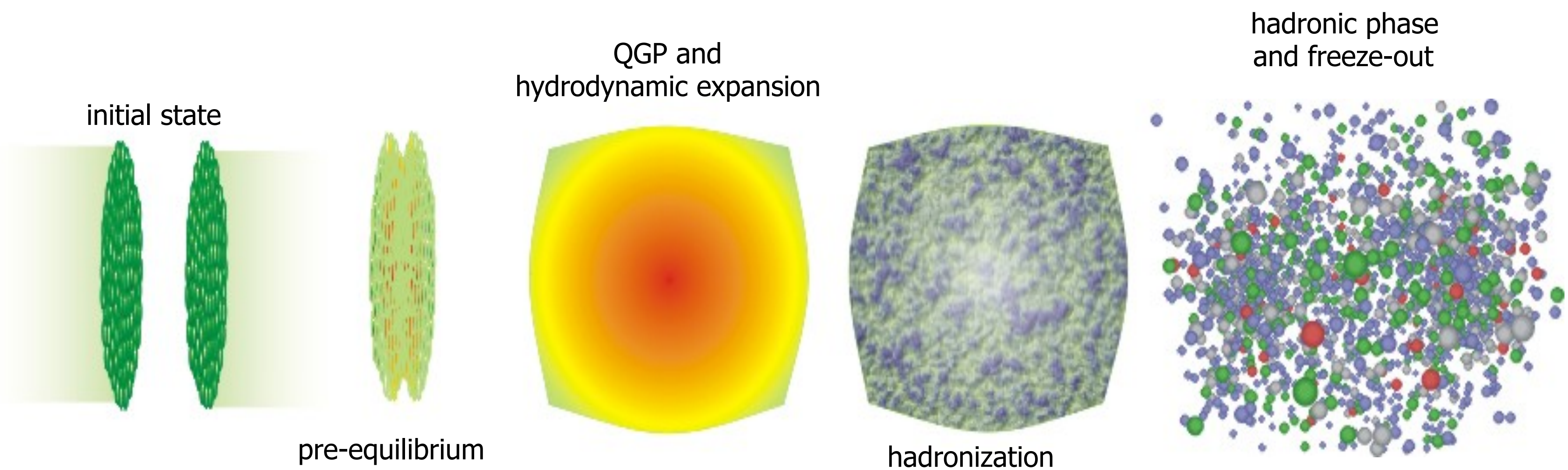


front view

The importance of simulations can not be overstated

Must know what to expect and design detectors accordingly (+ unexpected)

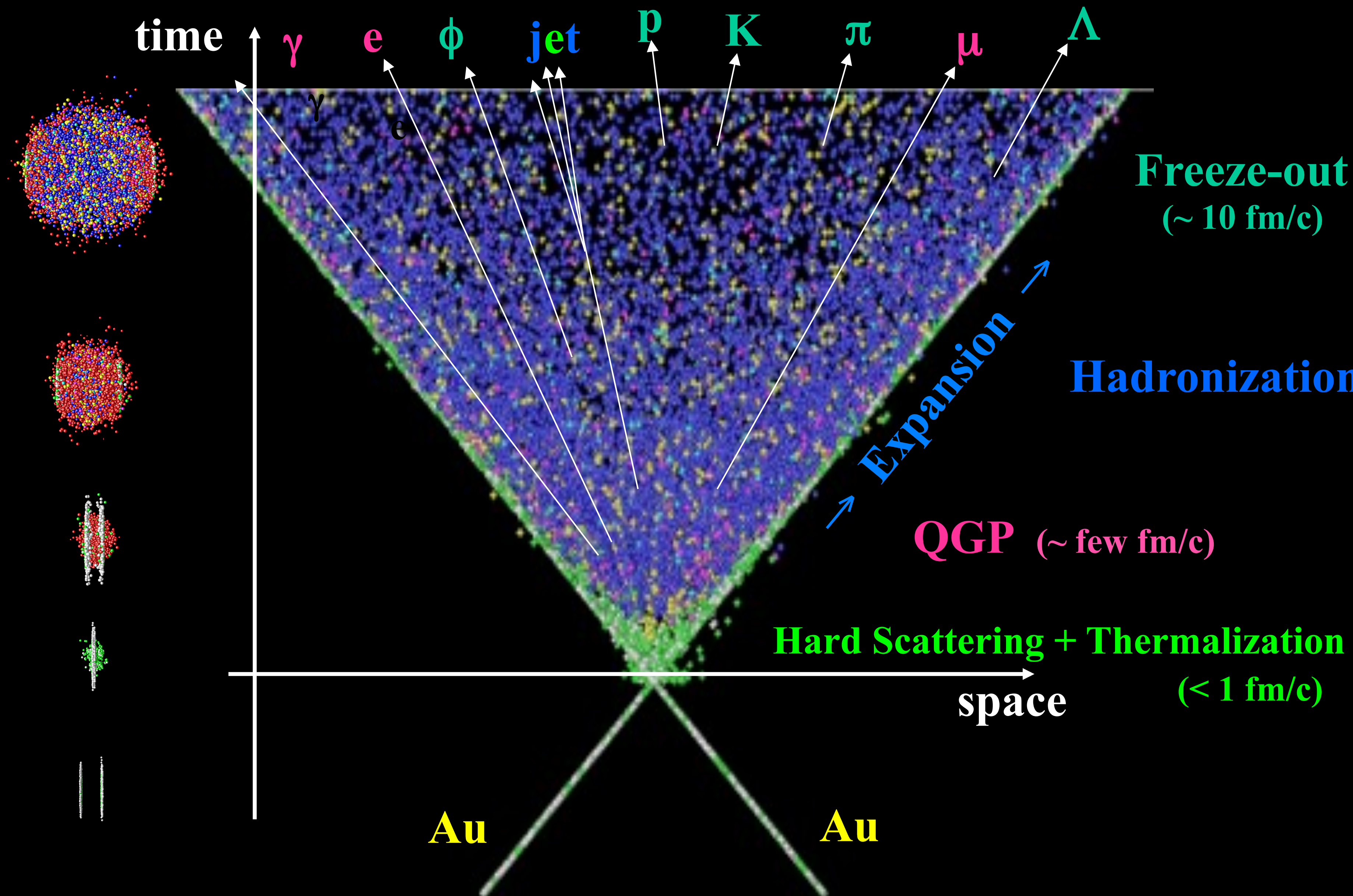
Stages of high energy nucleus-nucleus collisions



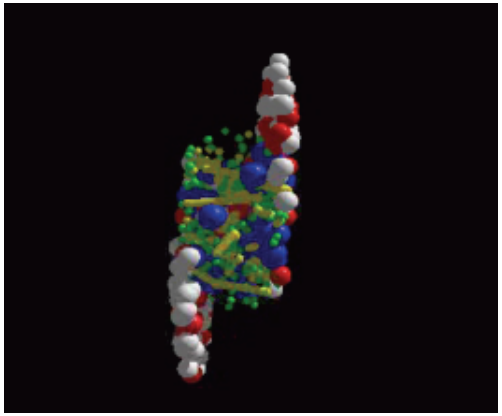
Physics:

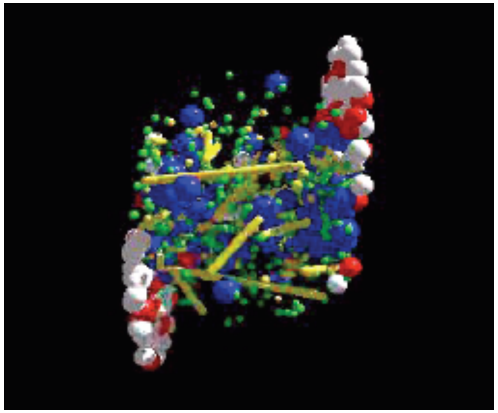
1) Parton distributions in nuclei
2) Initial conditions of the collision
3) a new state of matter – Quark-Gluon Plasma and its properties
4) hadronization

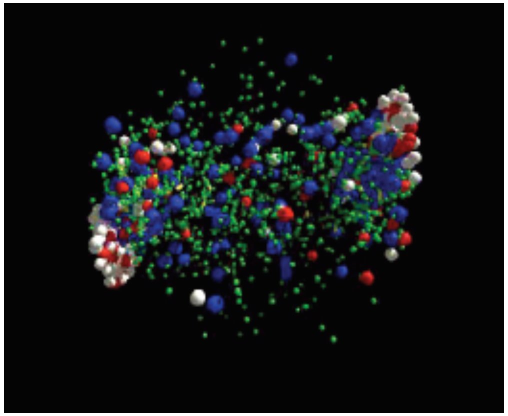
Space-time Evolution of RHIC Collisions



Probes from different stages of the collision





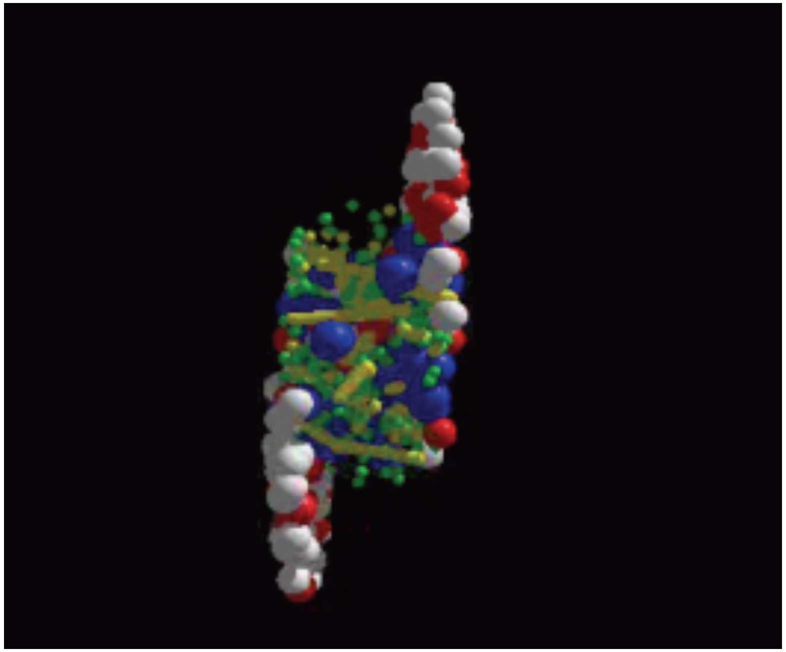


Early stage probes: hydrodynamic flow from initial spatial asymmetry

Dense matter probes: Jet traversing dense matter (“tomography”)

Final stage probes: produced particles, thermalization, hadrochemistry

Early stage probes:
hydrodynamic flow from initial spatial asymmetry



need to remind important terms:

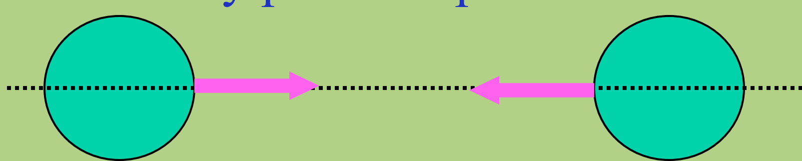
Impact parameter & Reaction plane

Impact parameter vector $\vec{b}$:
- $\perp$ beam direction
- connects centers of colliding nuclei

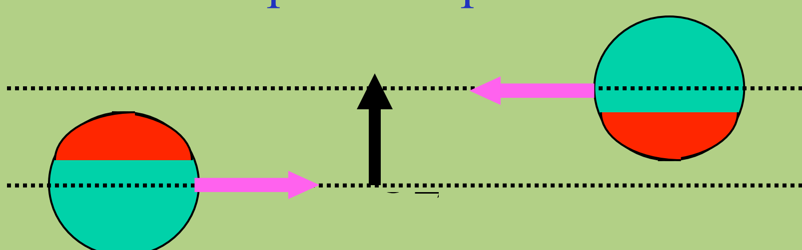
Reaction plane:

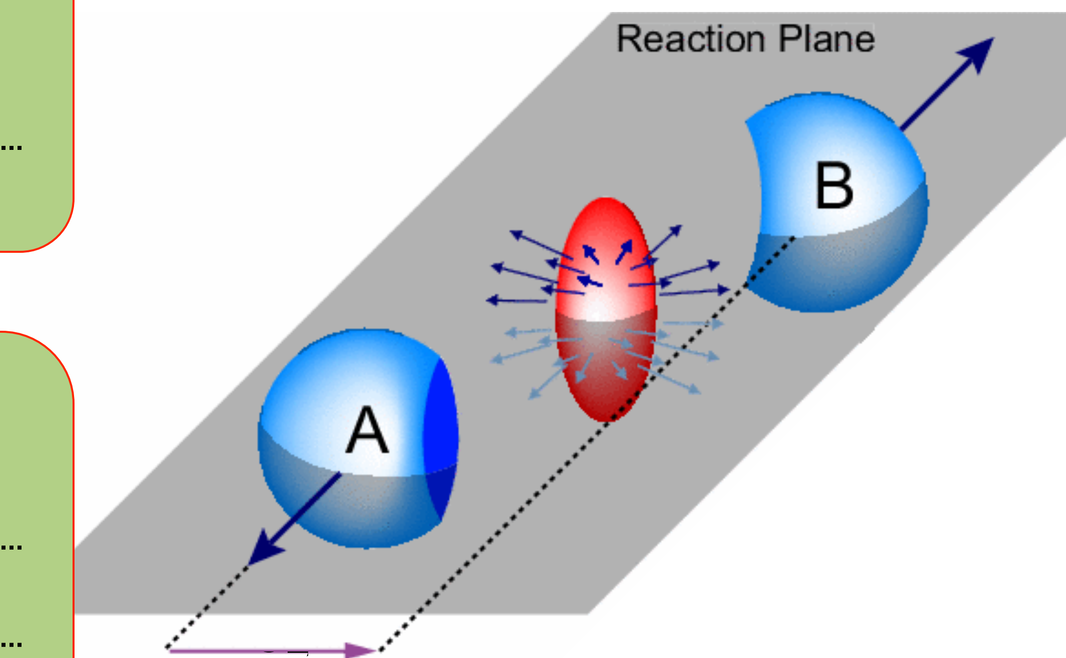
spanned by beam direction and $\vec{b}$

b = 0 -> "central collision"
many particles produced



"peripheral collision"
fewer particles produced



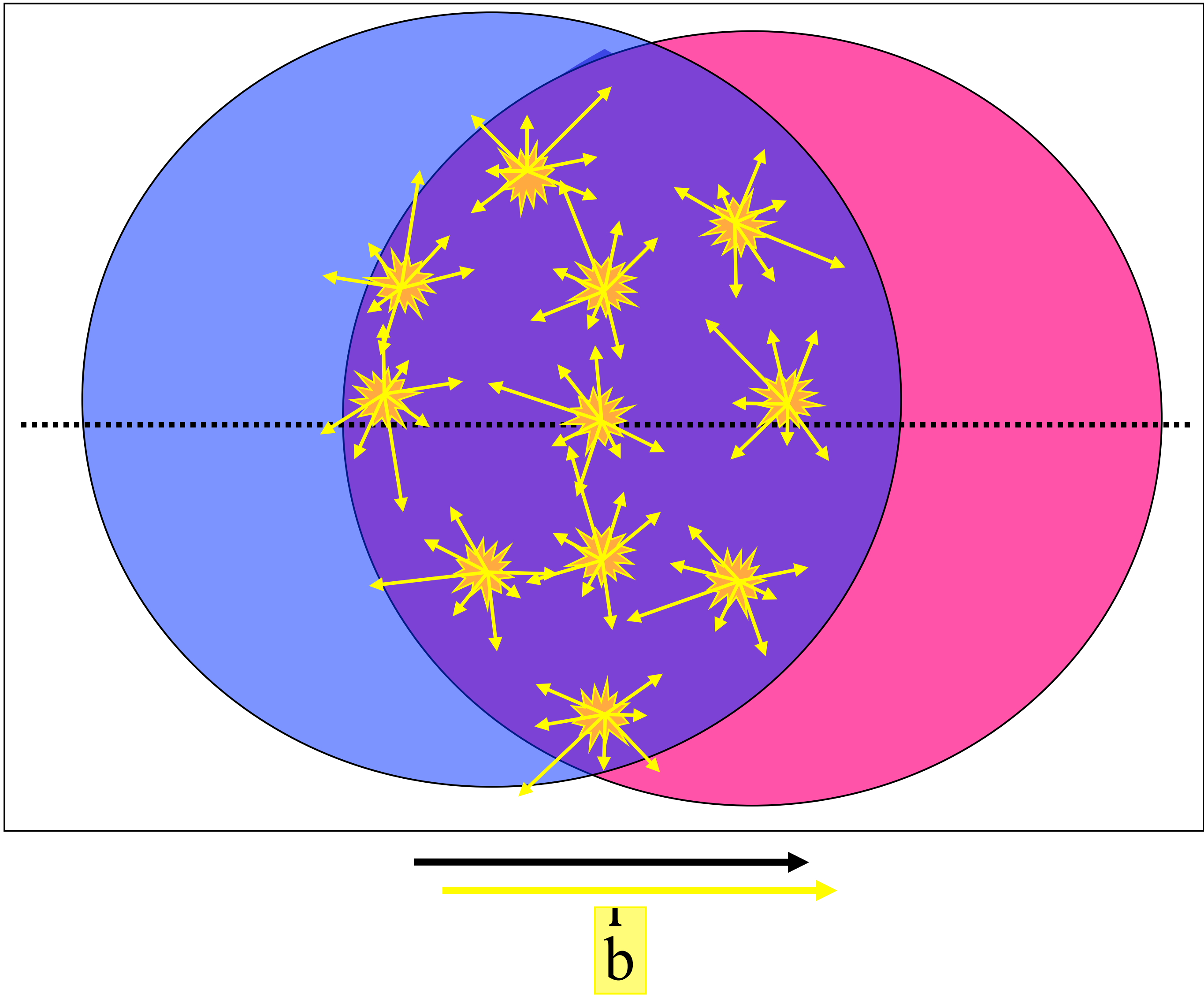


we can not control impact parameter $\vec{b}$!

How do RHIC collisions evolve?

1) Superposition of **independent p+p**:

momenta random relative to reaction plane

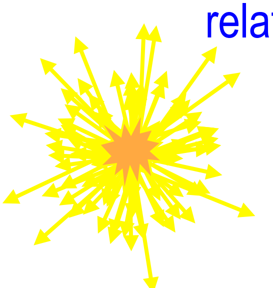


OR

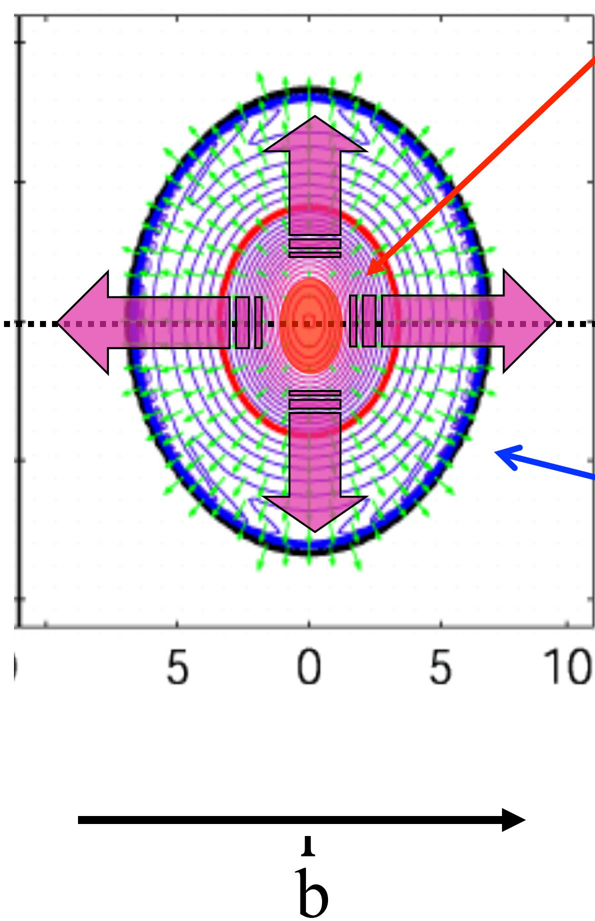
How do RHIC Collisions Evolve?

1) Superposition of independent p+p:

momenta random
relative to reaction plane



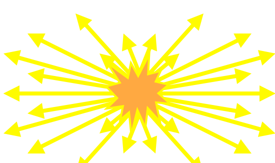
High density
pressure
at center



"zero" pressure in
surrounding vacuum

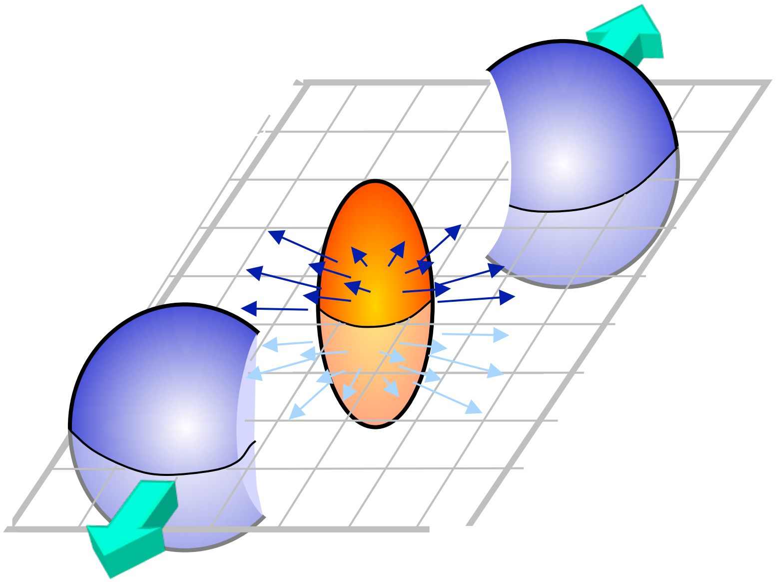
2) Evolution as a **bulk system**

Pressure gradients (larger in-plane) push bulk
"out" → "flow"

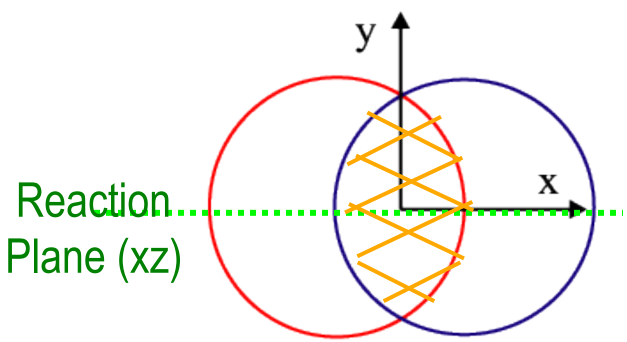


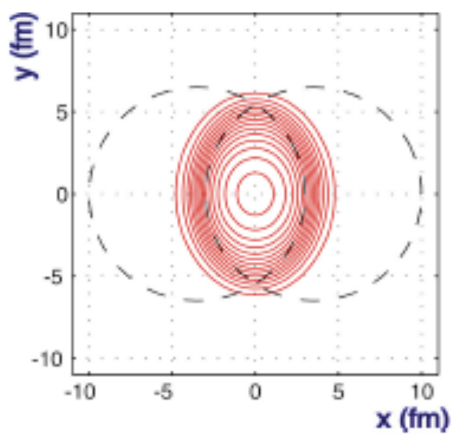
more, faster particles seen
in-plane

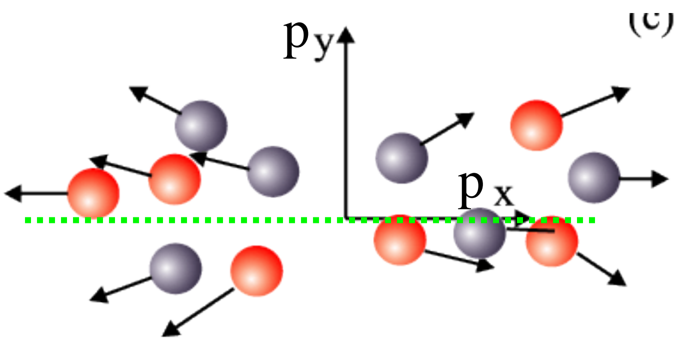
2) Evolution as a **bulk system:**



Early pressure in system
- Azimiuthal anizotropy of emission
→ Elliptic Flow!







Almond shape overlap region
in coordinate space

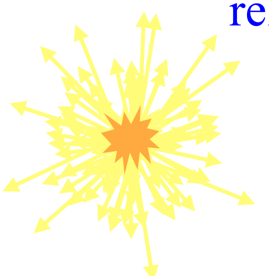
interactions/
rescattering

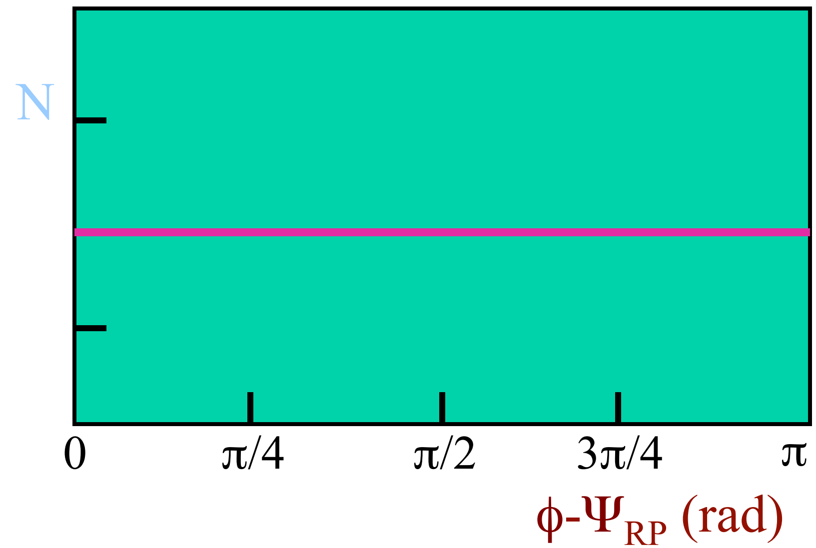
azimuthal anisotropy
in momentum space

How do RHIC Collisions Evolve?

1) Superposition of independent p+p:

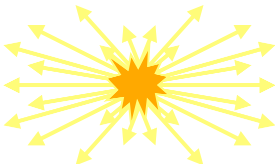
momenta random
relative to reaction plane



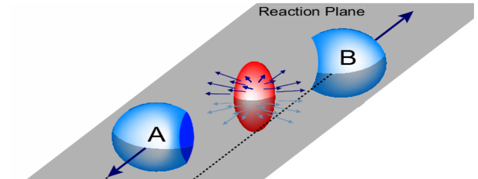


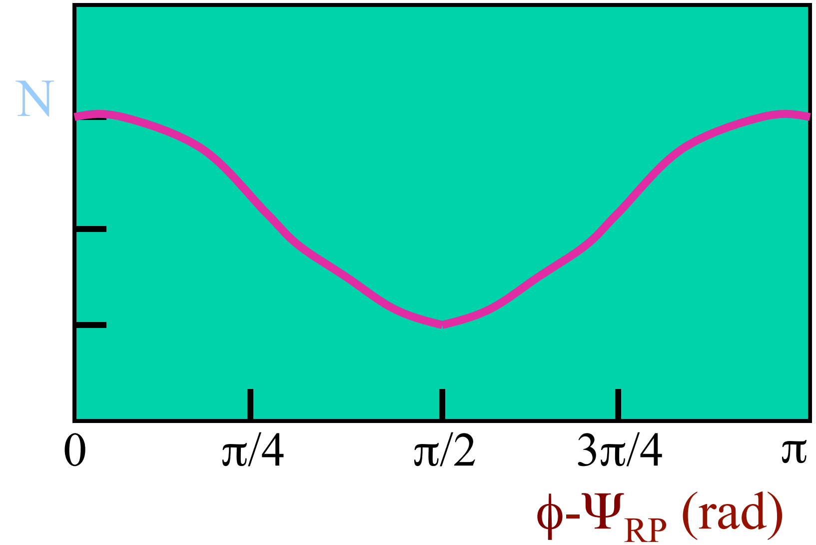
2) Evolution as a **bulk** **<u>system</u>**

Pressure gradients (larger in-plane) push
bulk "out" → "flow"

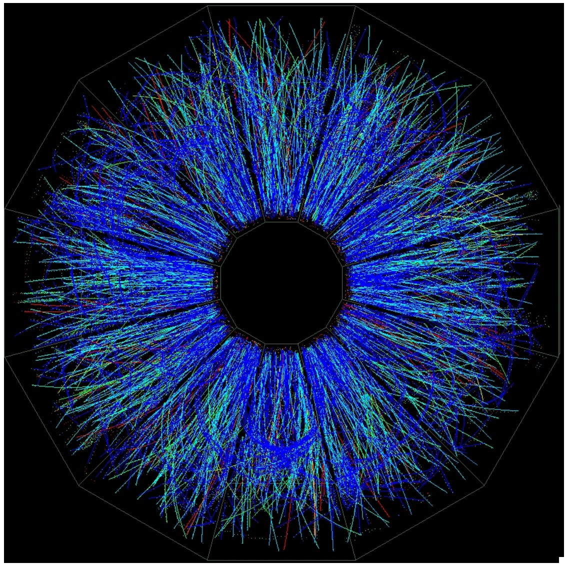


more, faster particles
seen in-plane



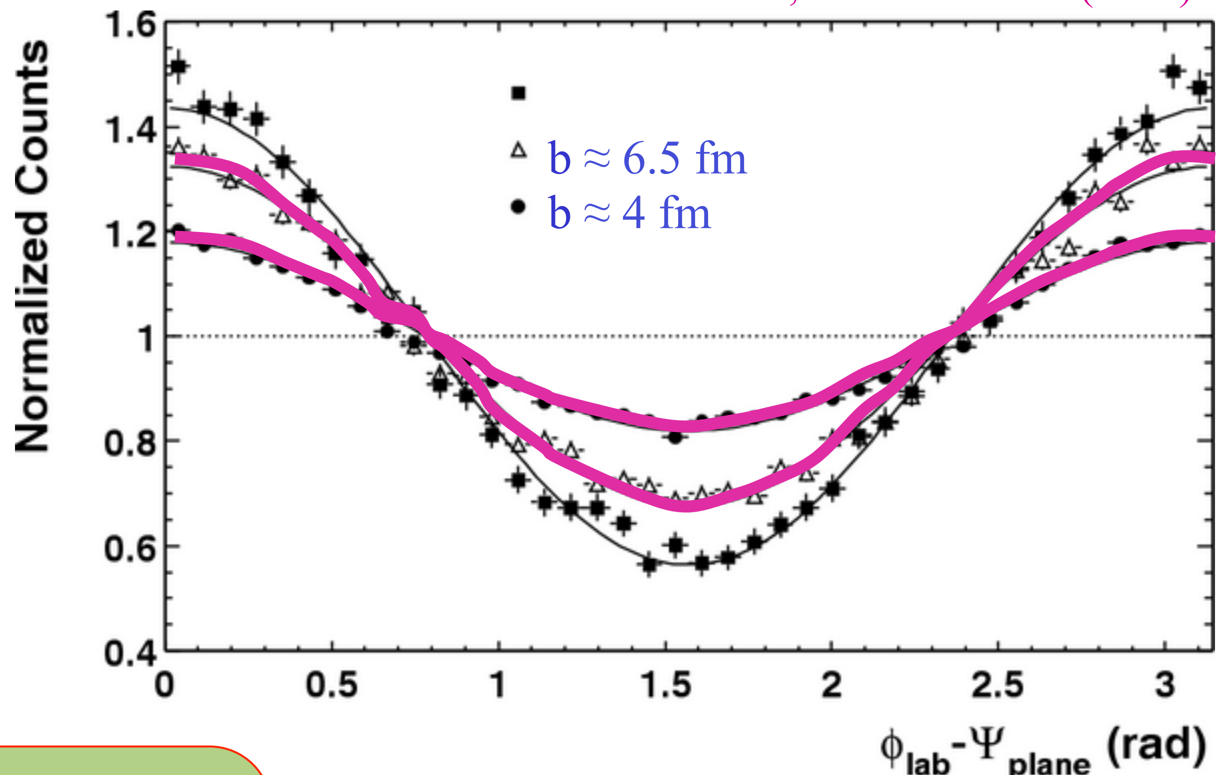


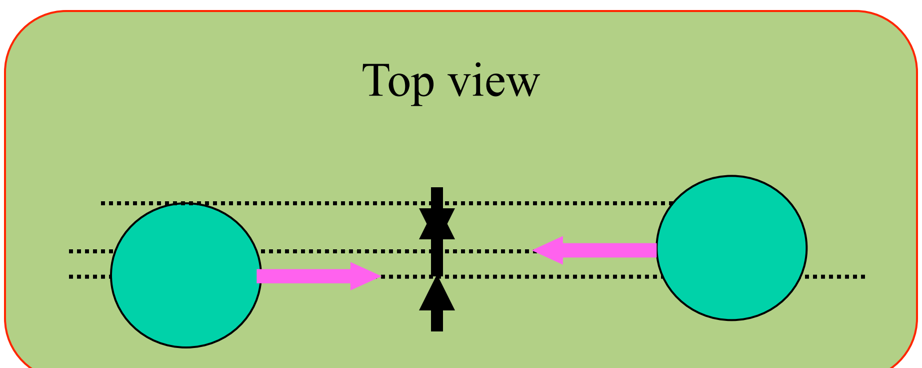
“First Day” Physics at RHIC - Azimuthal Distributions

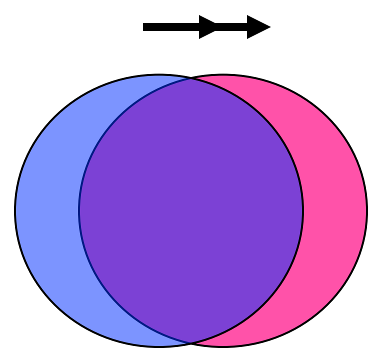


midcentral collisions
‘central’ collisions

STAR, PRL90 032301 (2003)

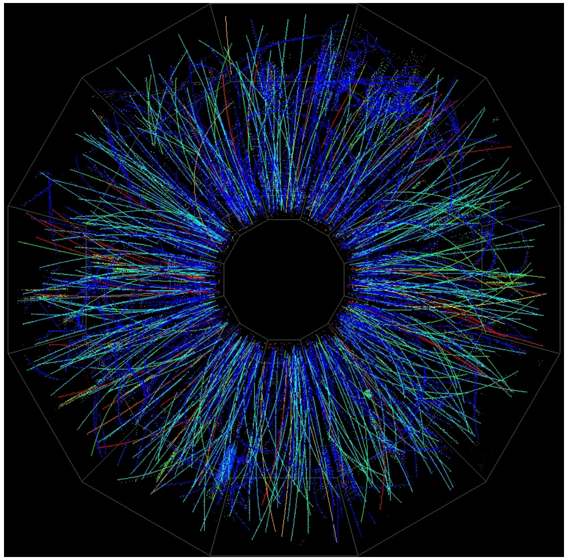




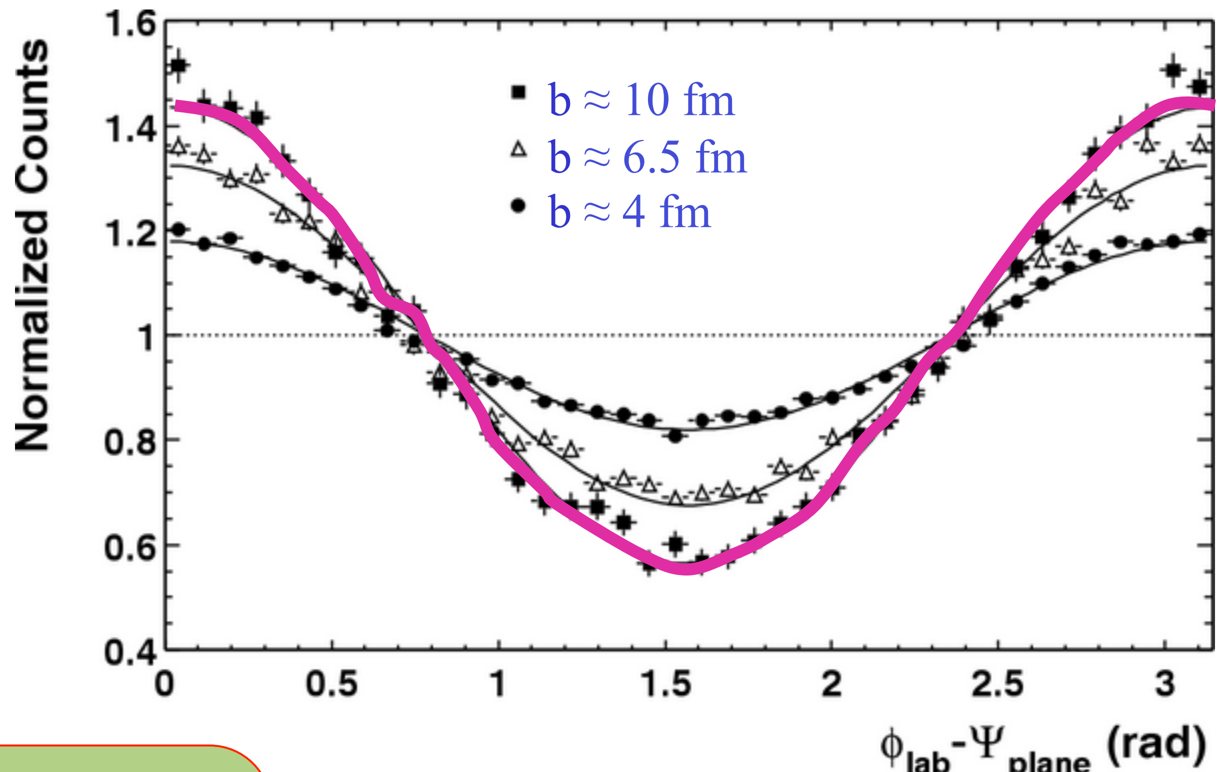


Beams-eye view

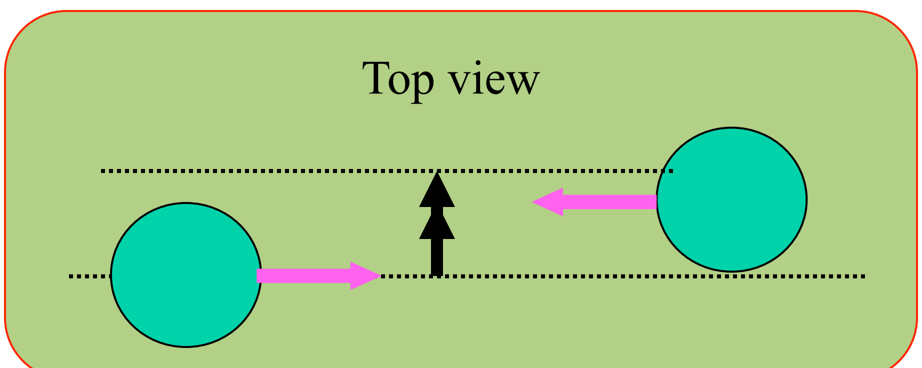
"First Day" Physics at RHIC - Azimuthal

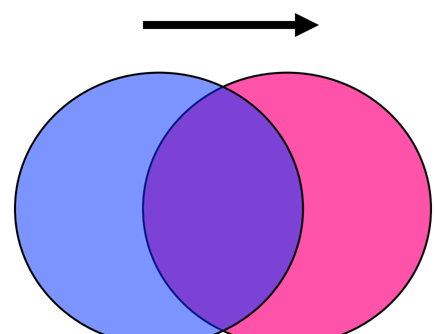


STAR, PRL**90** 032301 (2003)



peripheral collisions

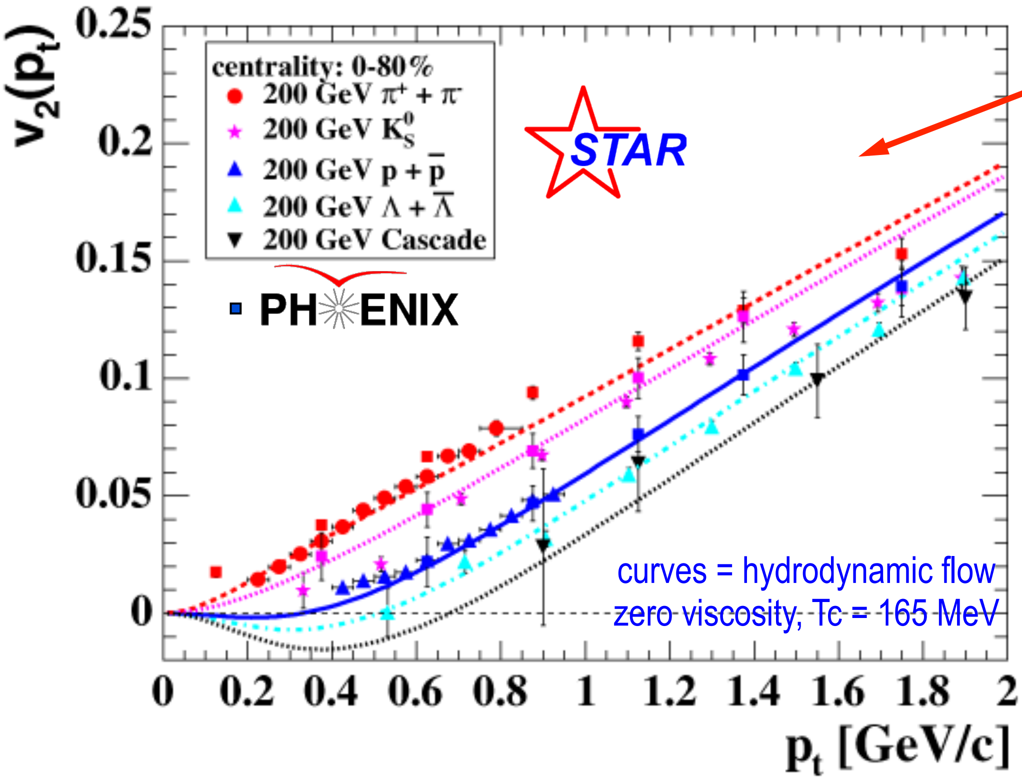


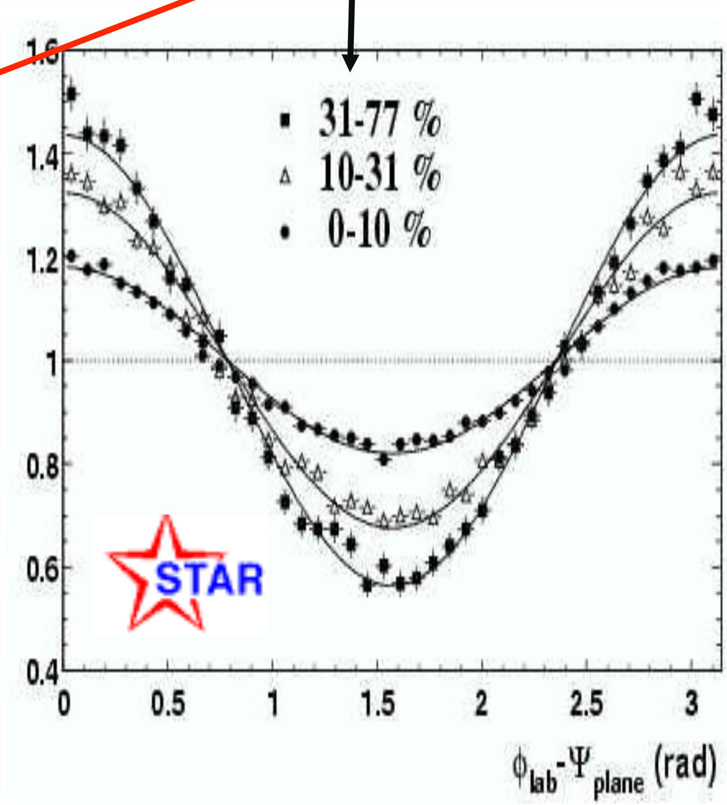


Beams-eye view

Elliptic flow – indicator for early thermalization

- Azimuthal asymmetry of charged particles: $dn/d\phi \sim 1 + 2\,v_2(p_T)\cos(2\phi) + \ldots$





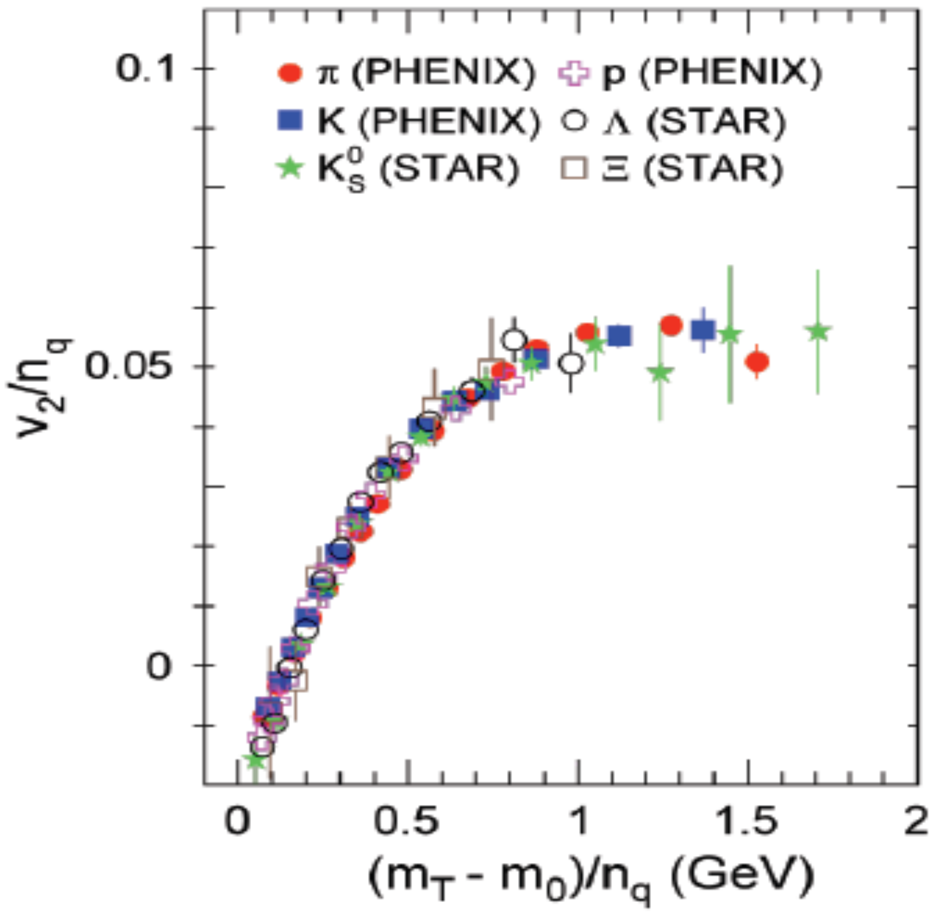
The "fine structure" $v_2(p_T)$ for different mass particles shows good agreement with ideal (zero viscosity) hydrodynamics -> "perfect fluid"

Huge asymmetry found at RHIC

-massive effect in azimuthal distribution w.r.t. reaction plane

- factor 3:1 peak to valley from 25% v_2

Quark number scaling - partonic degrees of freedom



Scaling flow parameters by quark content n_q (baryons=3, mesons=2) resolves meson-baryon separation of final state hadrons – coalescence / recombination mechanism

flow developed in pre-hadronic stage

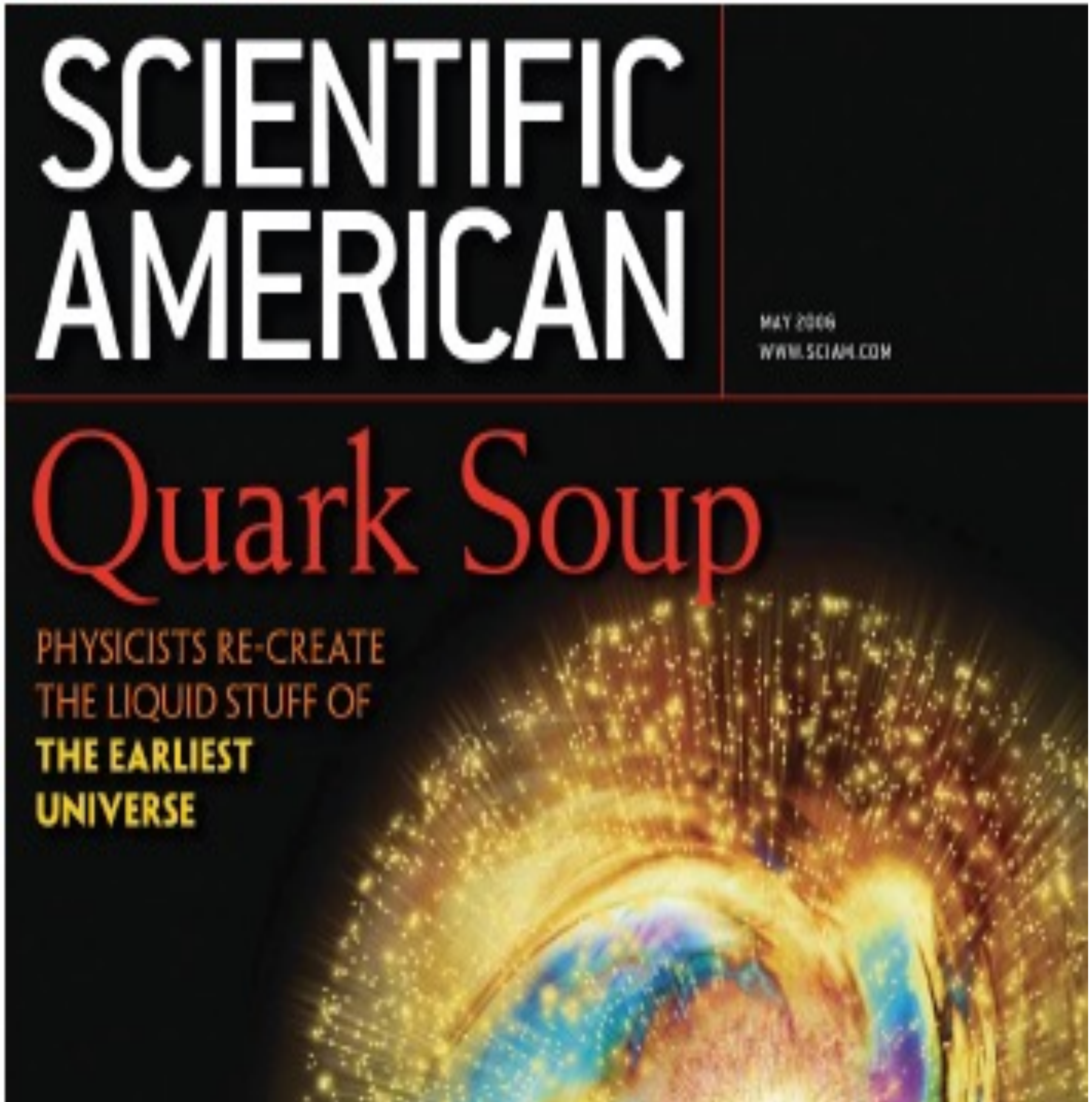
DECONFINEMENT at RHIC

So,
if baryons and mesons form from independently flowing quarks then quarks are deconfined (for a brief moment, ~ 10^{-12} s, then hadronization takes place)

Particles flow collectively and are thermally distributed at universal hadronization temperature T = ~ 160 MeV

So, we established that partonic hot and dense matter was formed in the early stage of collision, what happens next ?

Killer question: QGP ?
How do we probe hot QCD matter ?
What are those signatures we are after ?

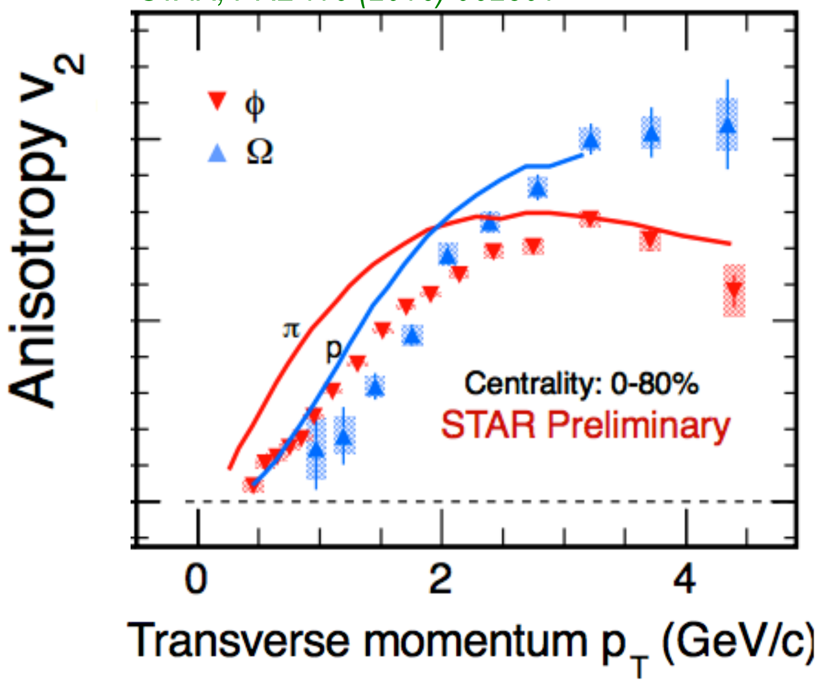


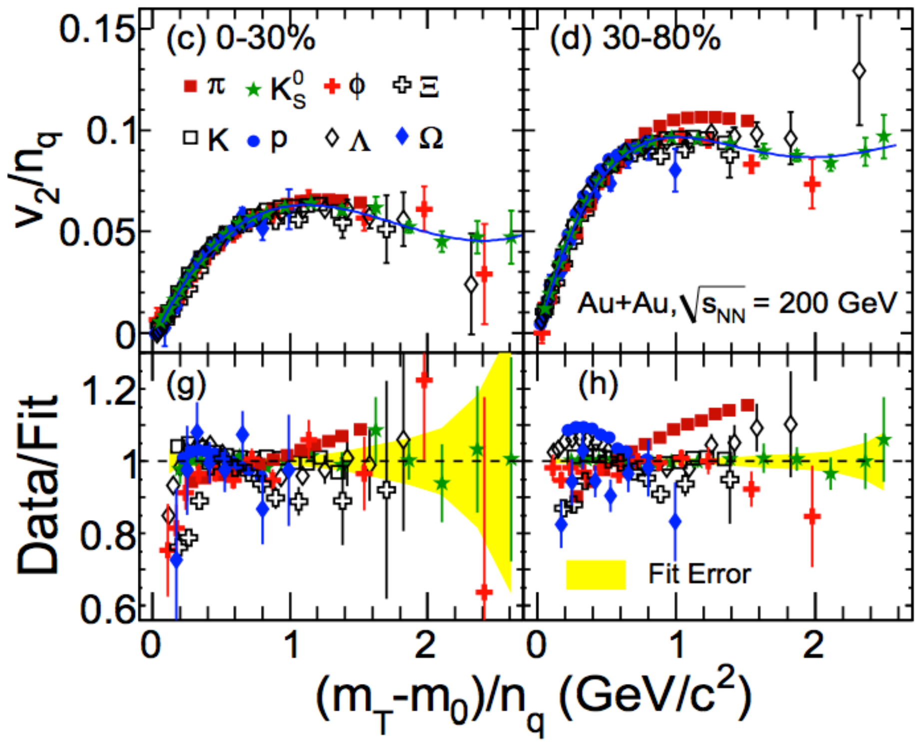
The American Institute of Physics announced the RHIC quark-gluon liquid as the top physics story of 2005 !

see http://www.aip.org/pnu/2005/

Partonic collectivity - Fast forward … 2016

STAR, PRL 116 (2016) 062301





- Precision measurements of multi-strange (ϕ, Ξ, Ω) particles show

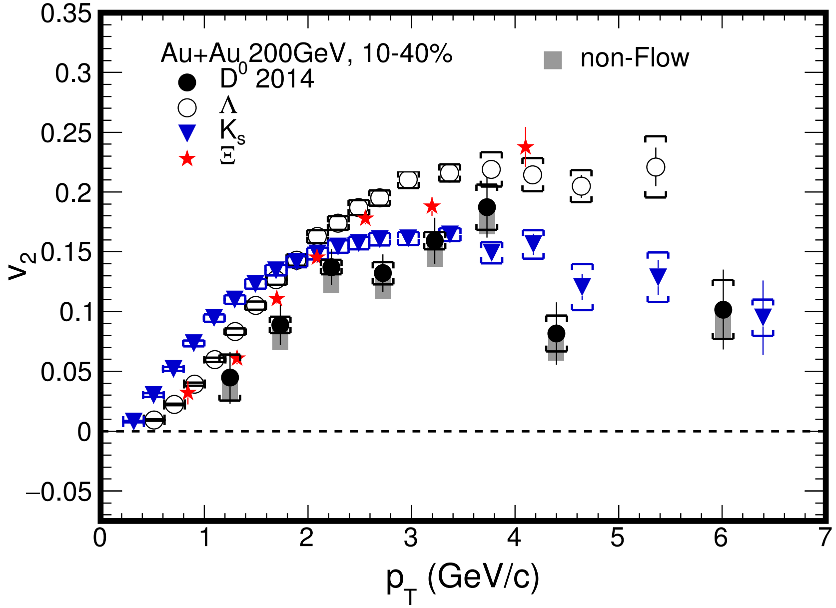
  $v_2(\Omega) \sim v_2(\Xi) \sim v_2(p)$, $v_2(\phi) \sim v_2(\pi)$

- Number-of-Constituent-Quark scaling holds within 10%

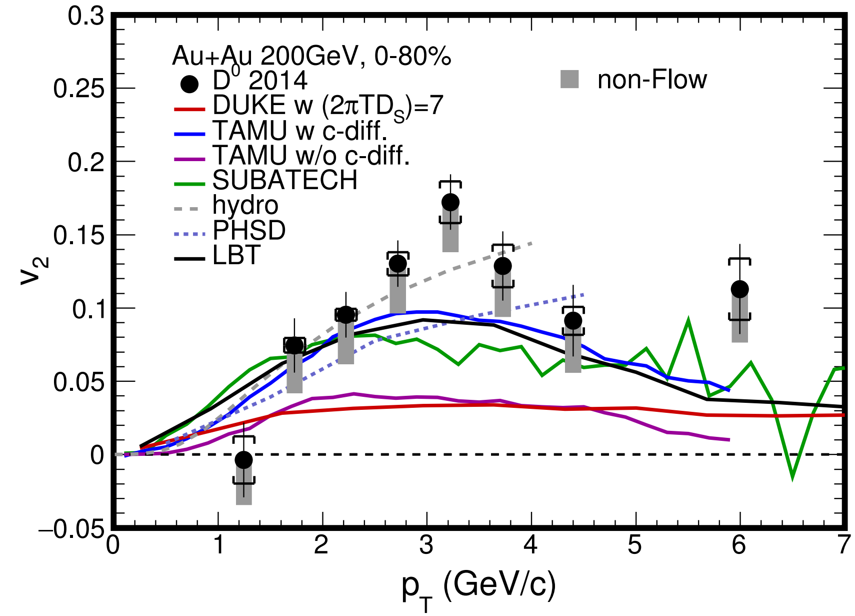
  strange quark: thermalized and flows!

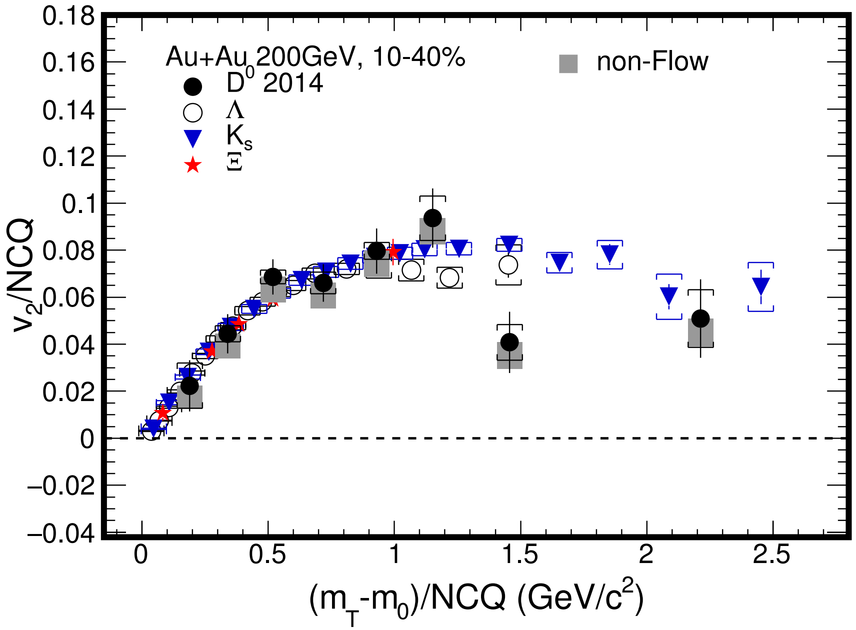
Does charm quark flow ? More sensitivity to medium transport properties

STAR, submitted to PRL



QM 2017, Chicago





- Significant charm hadron v_2 at p_T>1.5 GeV/c
- v_2/n_q vs. $(m_T-m_0)/n_q$: D^0 mesons flow similar to light hadrons

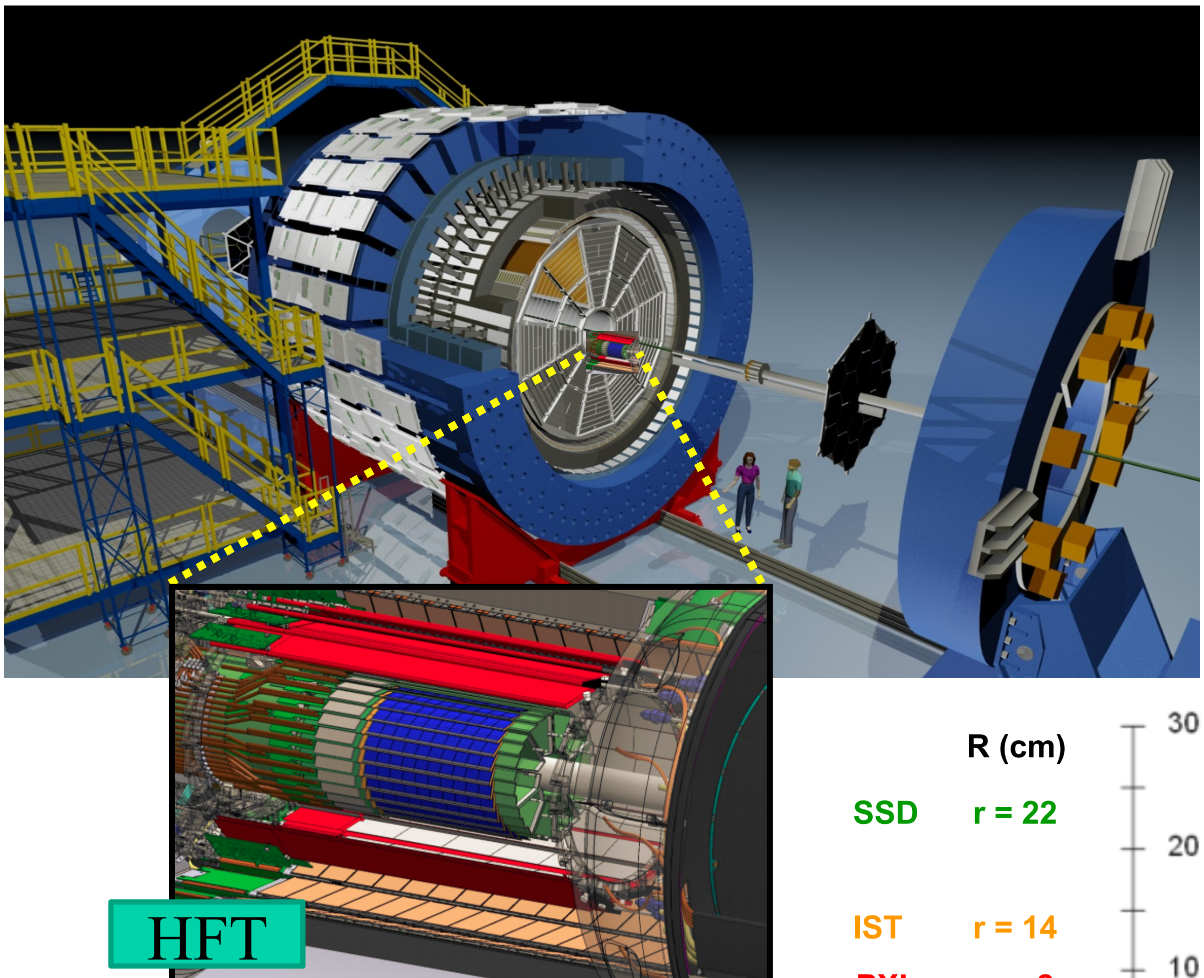
  - charm quark thermalized in the medium !
  - similar observation at LHC

digression

How did we do it ? STAR HFT Upgrade

Extend the measurement capabilities in the *heavy flavor* domain, good probe to QGP:

- Direct topological reconstruction of charm hadrons (e.g. $D^0 \rightarrow K\,\pi,\;\; c\tau \sim 120\ \mu\mathrm{m}$)



Need to resolve displaced vertices in high multiplicity environment

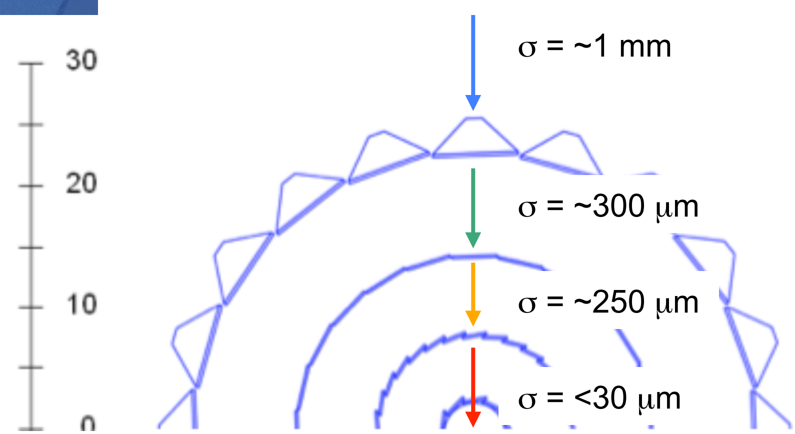
TPC – Time Projection Chamber (main tracking detector in STAR)

HFT – Heavy Flavor Tracker

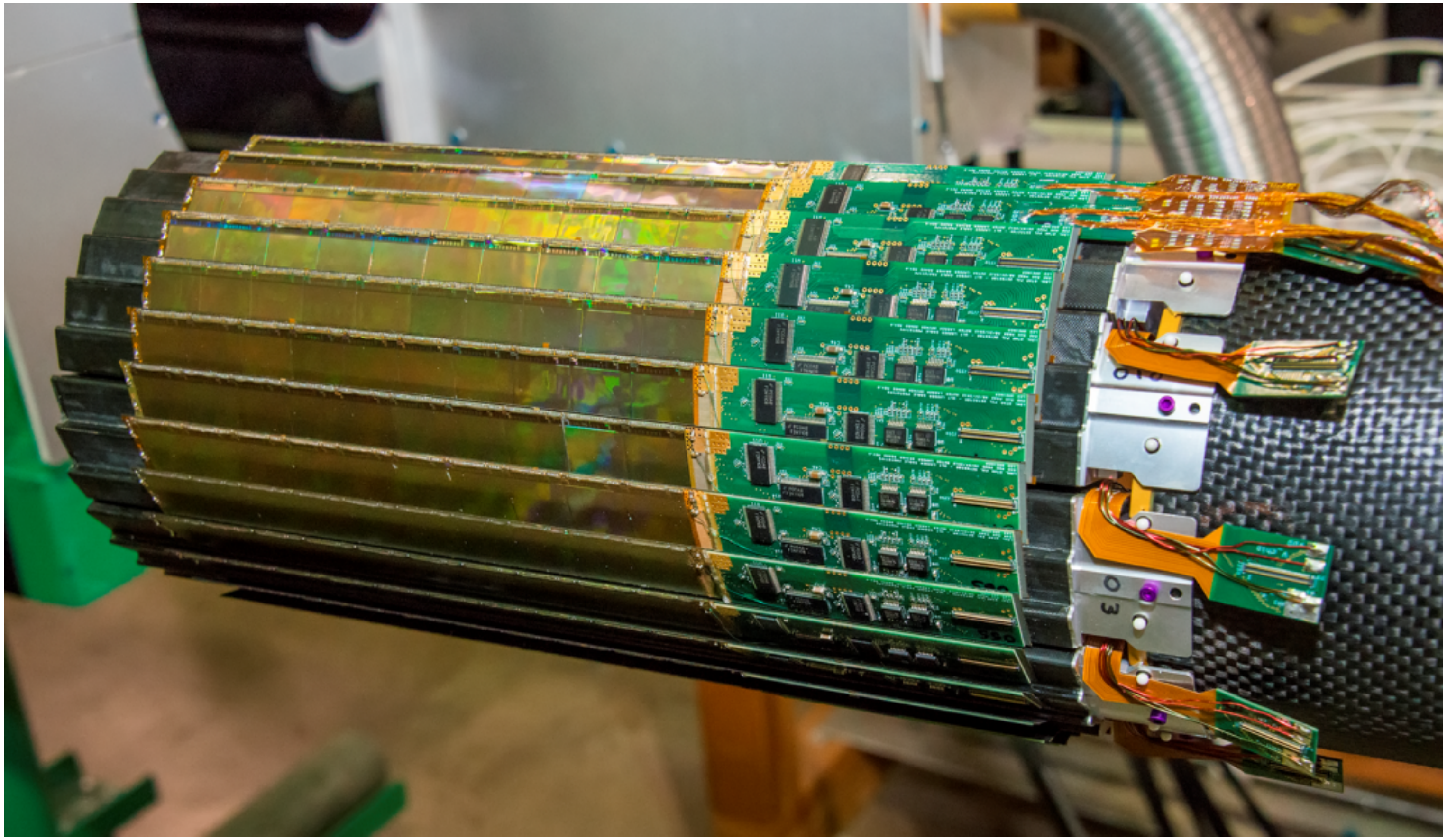
- **SSD – Silicon Strip Detector**
- **IST – Intermediate Silicon Tracker**
- **PXL – Pixel Detector**

Tracking inwards with gradually improved resolution:

	R (cm)
SSD	**r = 22**
IST	**r = 14**
PXL	**r_2 = 8**
	r_1 = 2.8



STAR HFT !



MAPS Vertex Detector HFT for STAR

First application of Monolithic Active Pixel Sensors (MAPS) in a collider experiment. Detector originated and developed in LBNL, completed in 2014, on time and under budget (14M project, 9M spent at LBNL)

End of digression

RHIC was built to discover QGP and to explore QCD phase diagram !

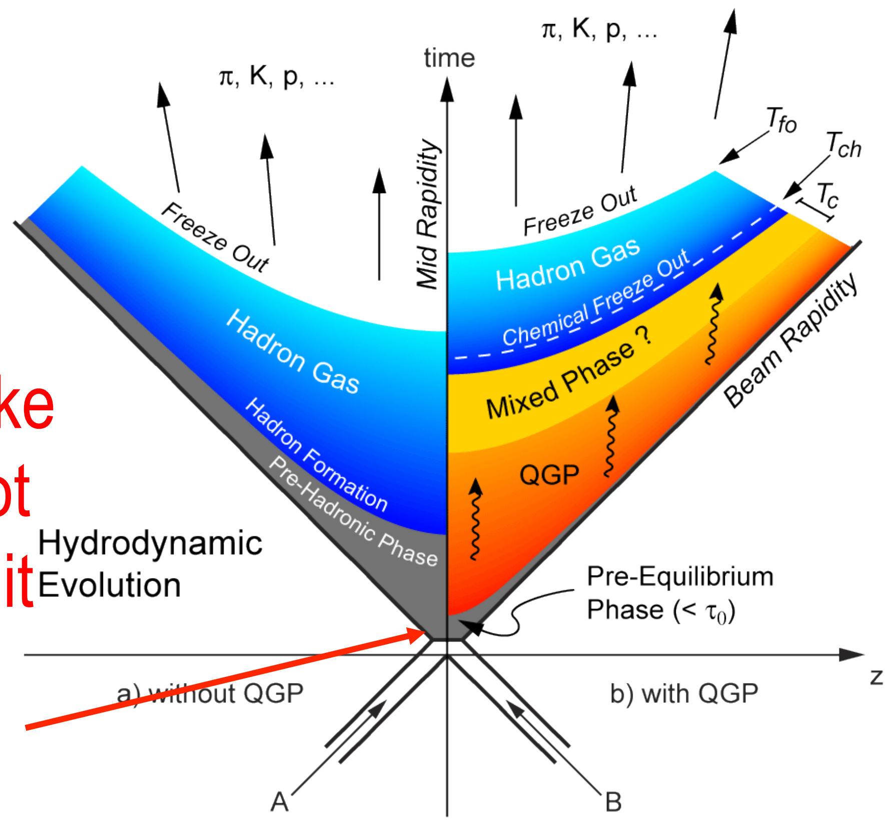
- RHIC was built to create and investigate strongly interacting matter (in laboratory setting):

so hot $\longrightarrow$ "melt" ?

QCD: HG $\longrightarrow$ QGP

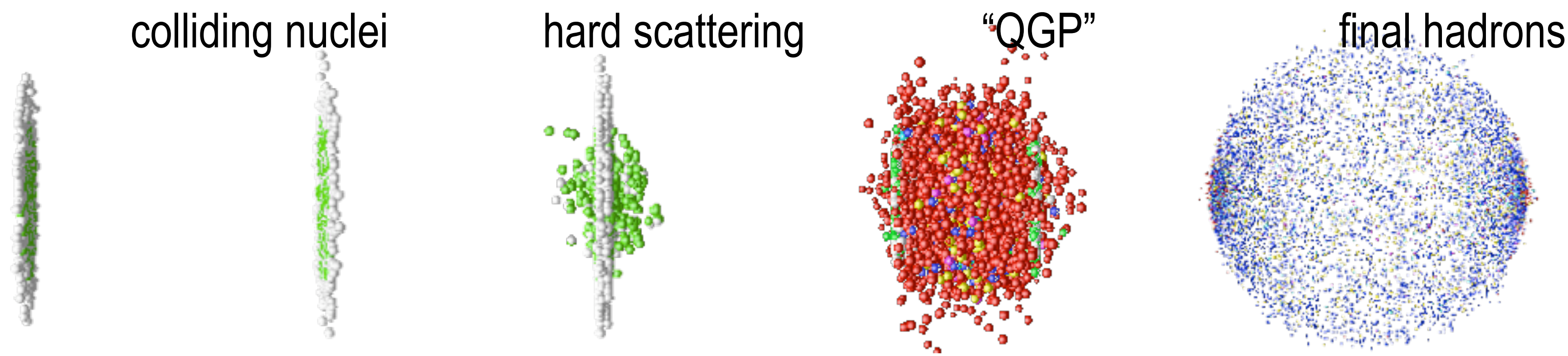
HI collisions = best opportunity to make unique matter in lab, but they must not only create the matter but also probe it

left or right ?

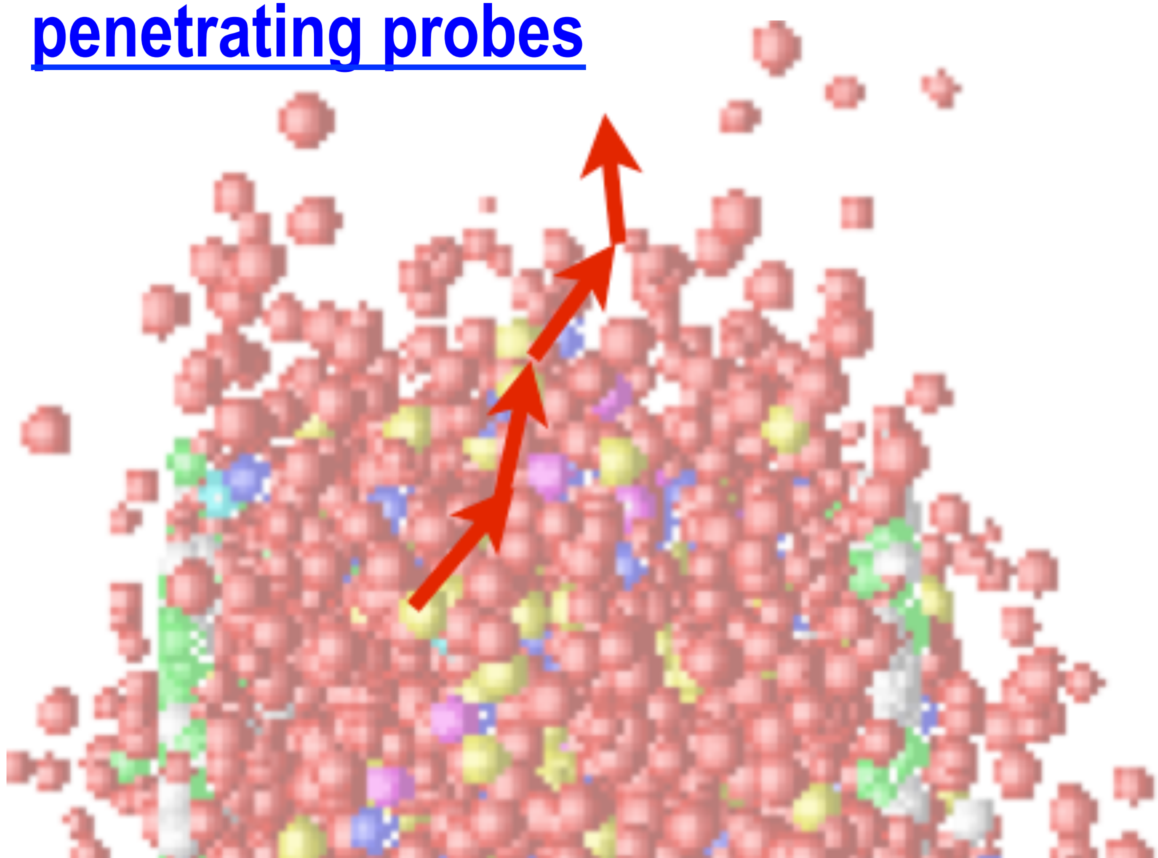


penetrating probes !

penetrating probes need to be created here and need to survive



Hard probes ⟷ **penetrating probes**



HARD PROBES !!
Jets and heavy flavor

- “Hard” processes when there is:
  - high momentum transfer Q^2
  - high mass m
  - high transverse momentum p_{Tg}

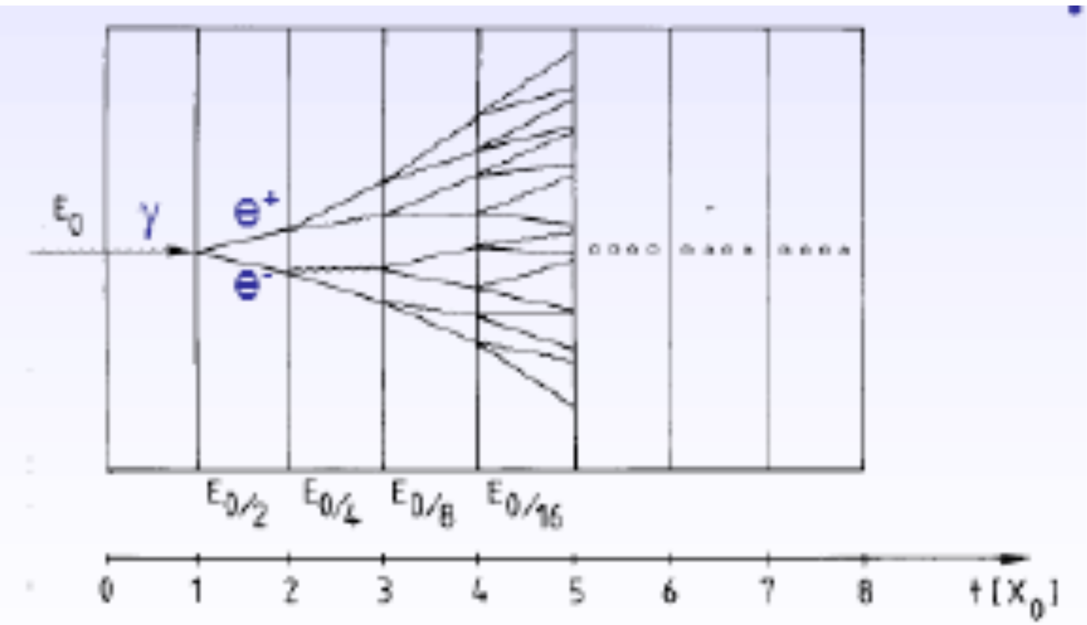
  Hard processes can be calculated using perturbative QCD

  - *Since m>>0 for heavy quark production it is a “hard” process even at low p_T*

Detour:

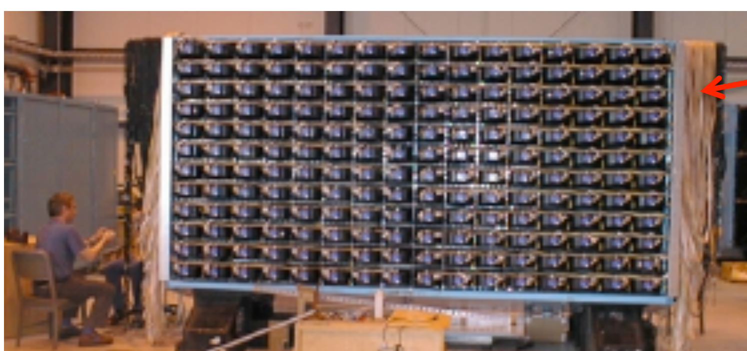
EMCal

Calorimetry= energy measurement by total absorption, usually combined with spatial absorption: $\delta E/E \sim 1/\sqrt{E}$

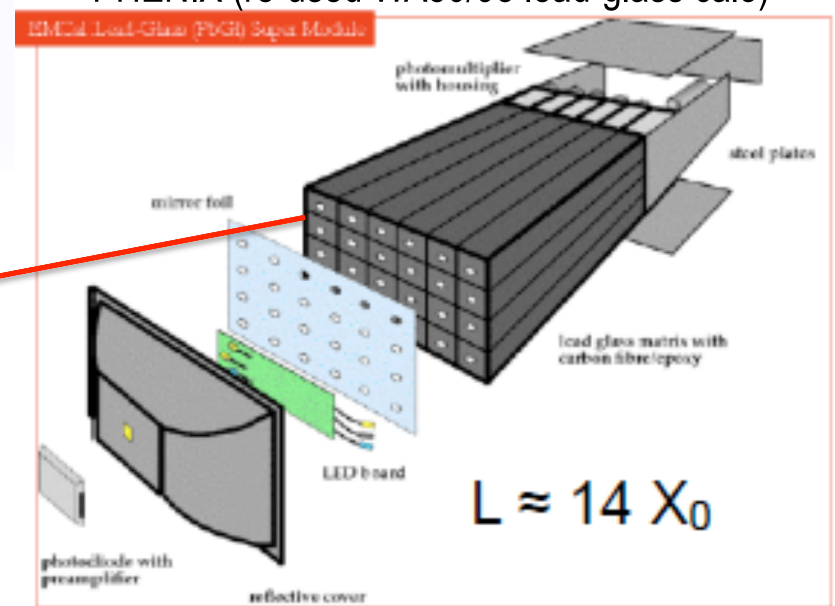


EM shower:

- above 10 MeV (γ,e)
- pair production $\gamma \rightarrow e^+e^-$
- bremsstrahlung: $e \rightarrow e\gamma$
- characterized by radiation length X_o

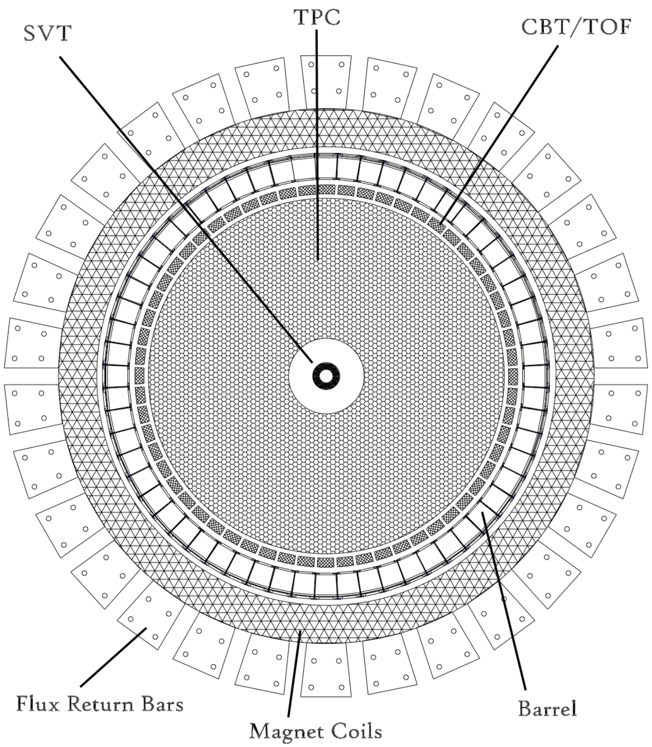


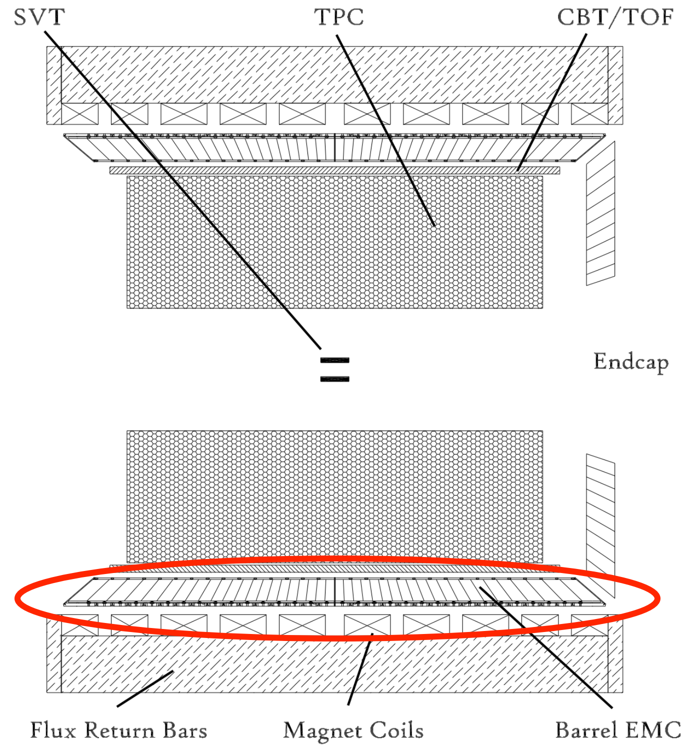
PHENIX (re-used WA80/98 lead-glass calo)



STAR EMCal: Barrel + End Cups

BEMC (barrel): 1<η<+1 + full azimuth (as TPC), 120 modules (60 in ϕ, 2 in η)
each module is segmented into 4800 towers (0.05 $\Delta\phi$ and 0.05 $\Delta\eta$)





Radiation Length X_0 = It is both the mean distance over which a high-energy electron loses all but 1/e of its energy by bremsstrahlung, and 7/9 of the mean free path for pair production by a high-energy photon

End of detour

Paradigm:

- We accelerate nuclei to high energies with intend of utilization of beam energy to drive a phase transition to QGP
- Created system lasts only ~10 fm/c
- Collision must not only utilize the energy effectively, but generate the signatures of the new phase for us

- I make an artificial distinction as follows:

Medium: bulk of the particles, dominated by soft production and possibly exhibiting some phase

Probe: particles whose production is calculable, measurable, and thermally incompatible with (distinct from) the medium

The importance of the control measurement(s) can not be overstated !

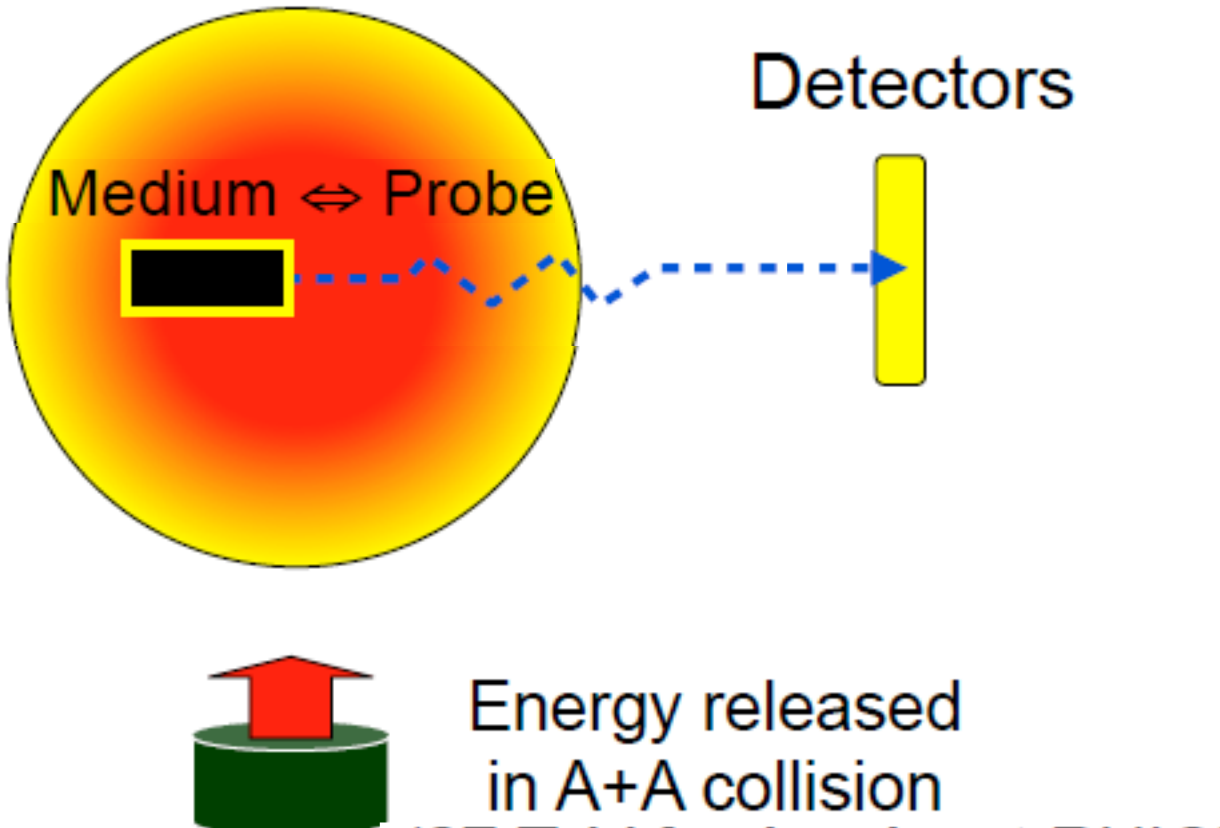
Control measurement (s) !

Matter we want to study

Hard Probes

Self-generated probes

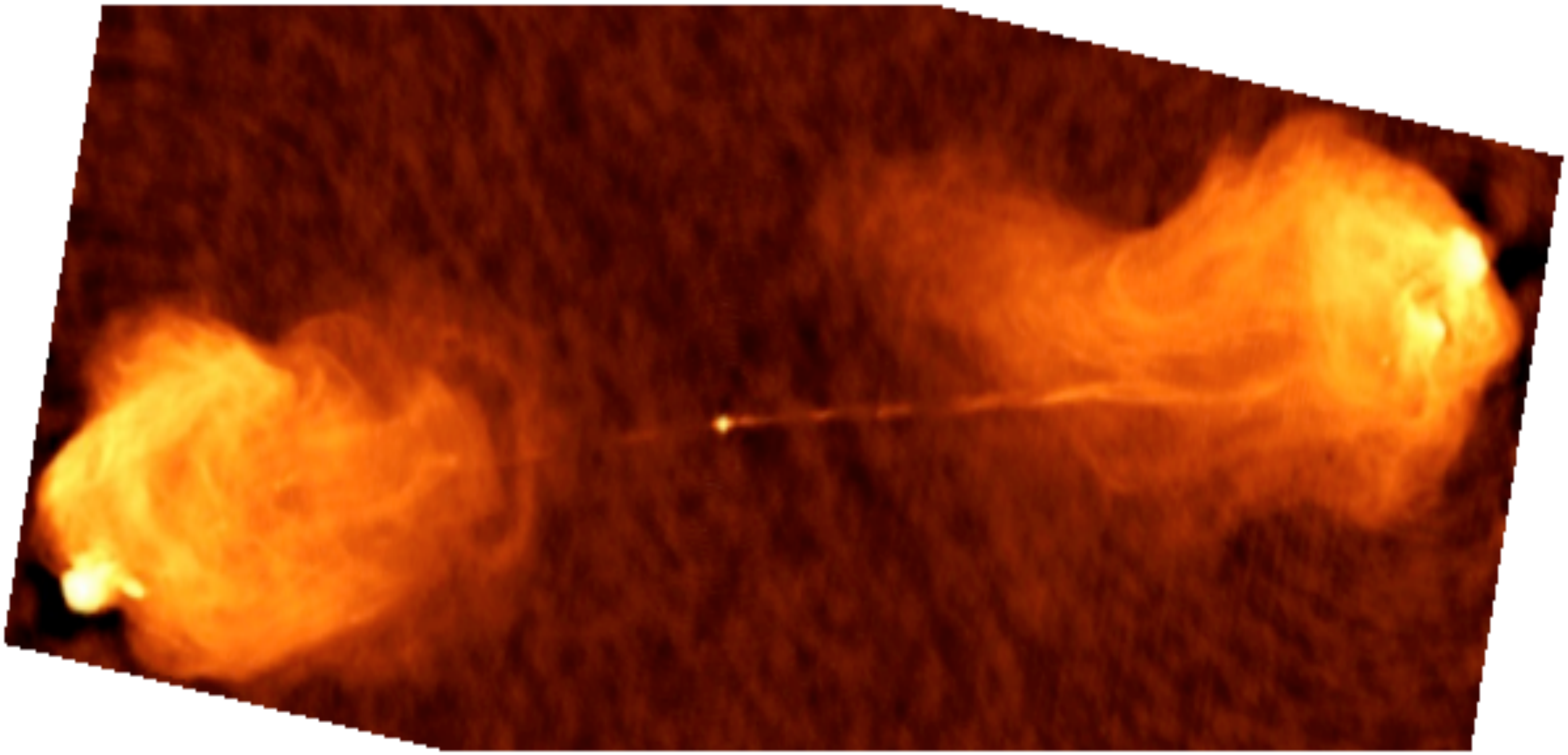
- Photons
- Partons (q, g)
- Quarkonia (J/ψ, Υ)



- Jets… what is this ?

No !

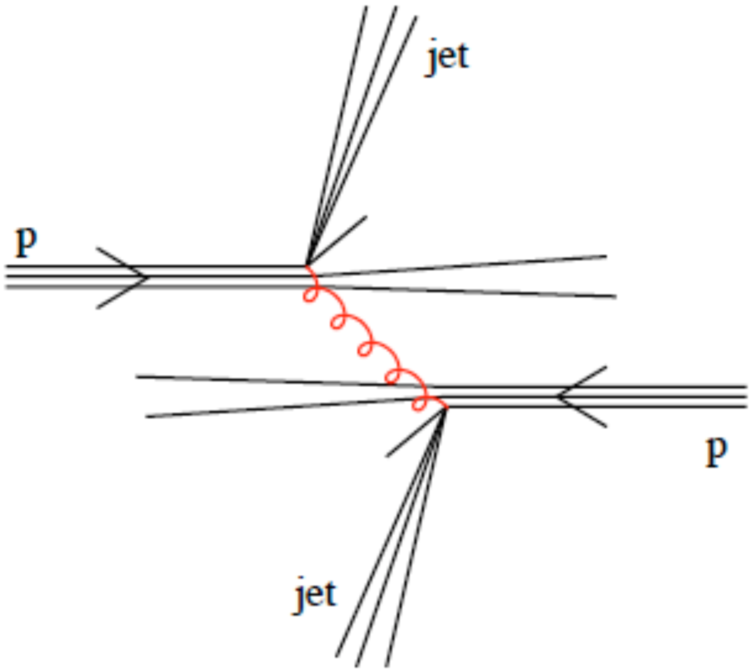
What is jet ?



Cool picture (radio image) of two jets shoot out of the center of active galaxy Cygnus A …
…but also not what we mean

What is jets ?

fragmented, hard-scattered partons



partons (q,g) do not exist in free form due to color confinement

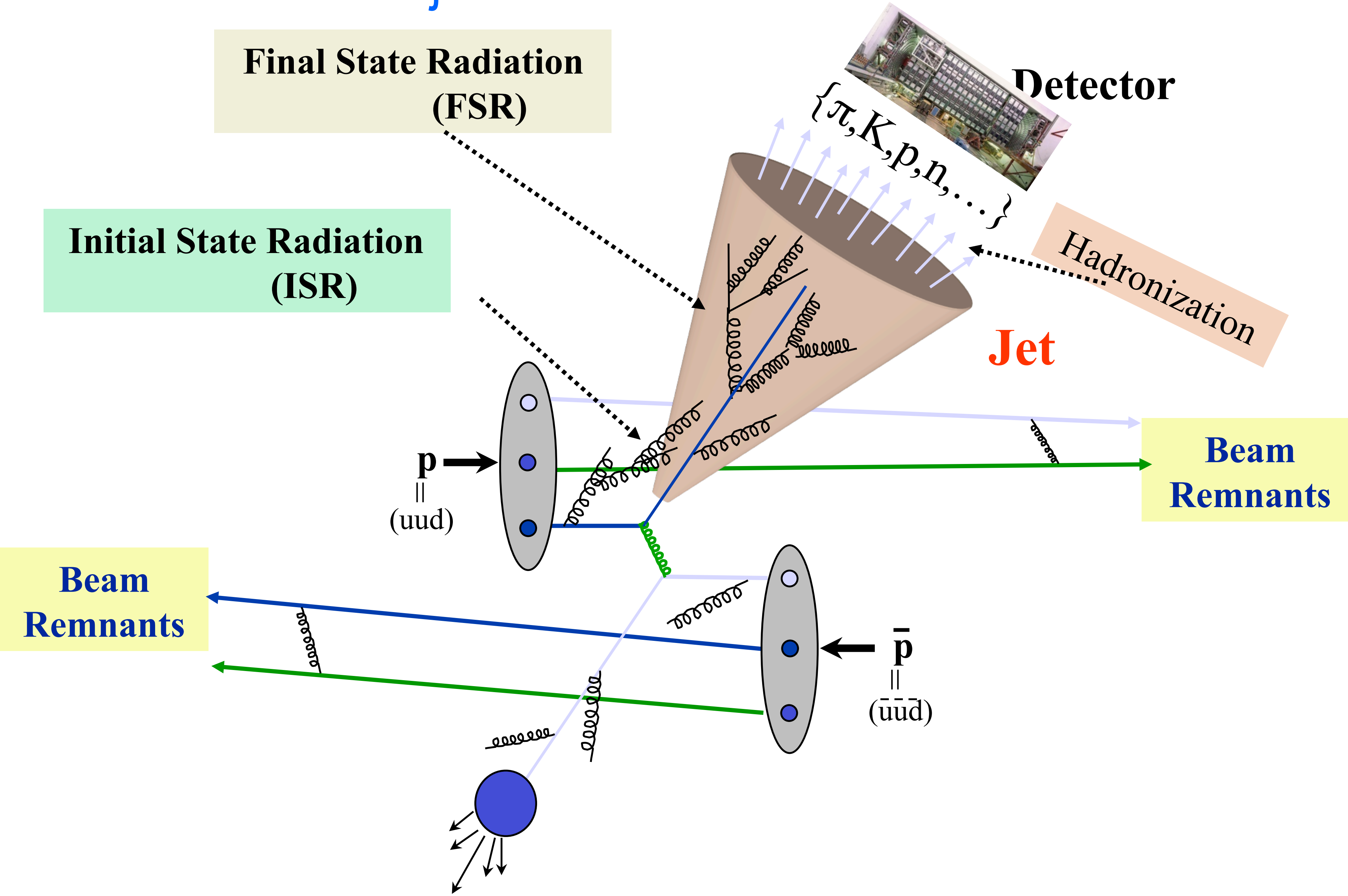
parton that leaves vicinity of interaction fragments into hadrons (~narrow cone of hadrons)

partons could be only studied via jet measurements in a particle detectors

most jets - back-to-back pair production via elementary hard process

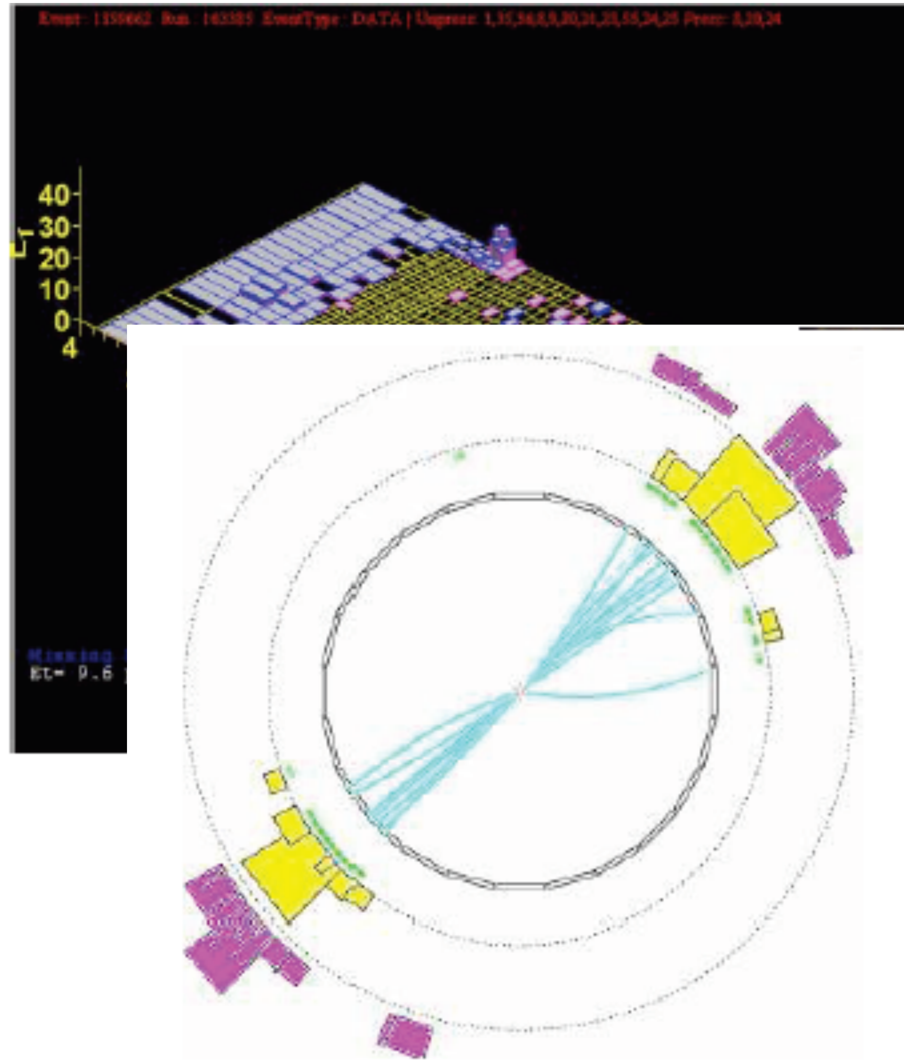
can be calculated using perturbative theory

jets in hadronic collision…



Jets in hadronic collisions

Delphi 1992

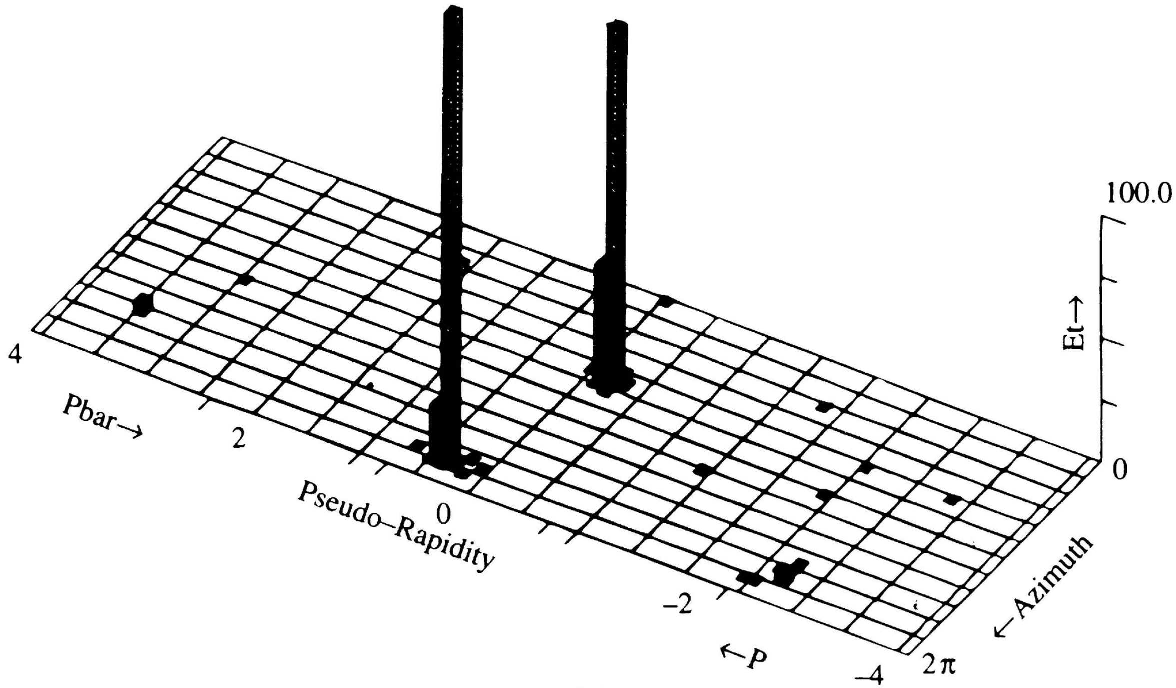


CDF two-jet event

Jets are everywhere in QCD !
This is our window on partons, but
not the same as partons

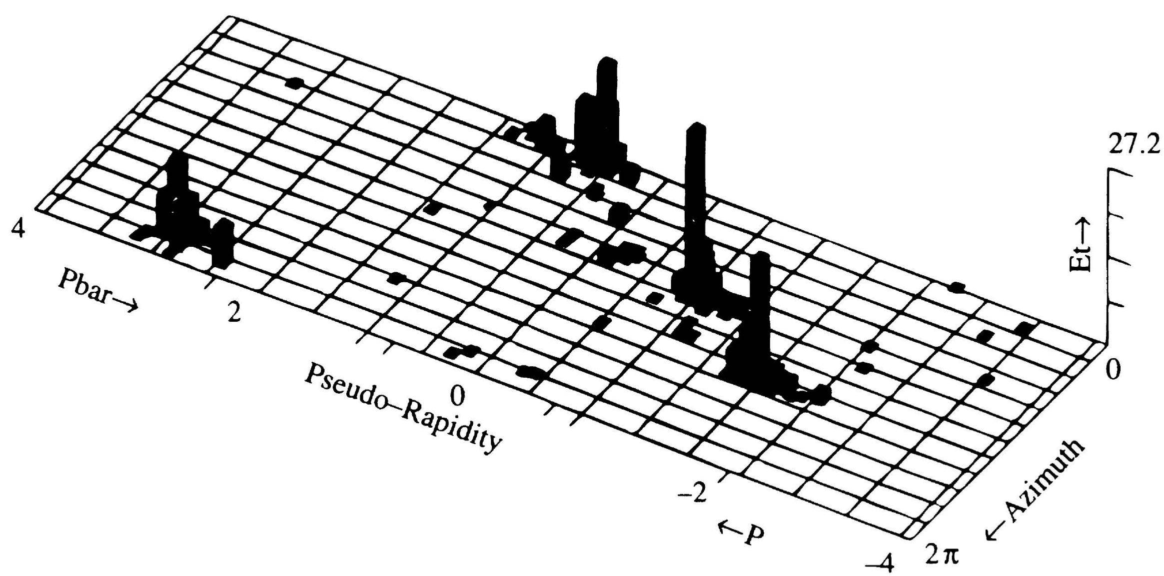
High Energy
p+p collisions:

You can 'see'
jets clearly



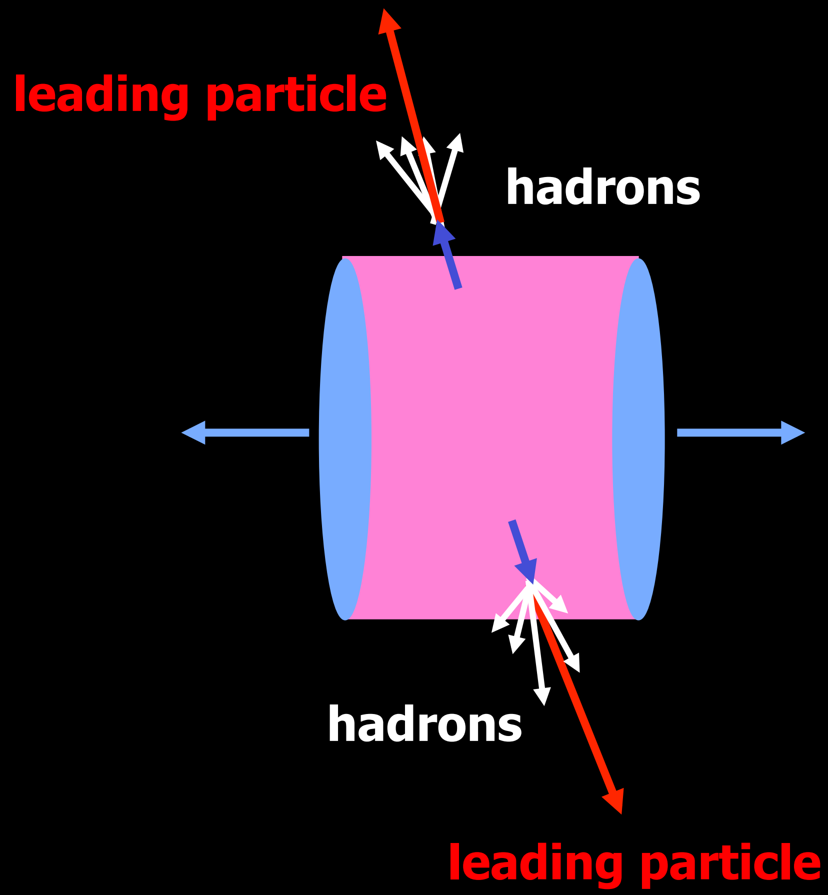
(a)

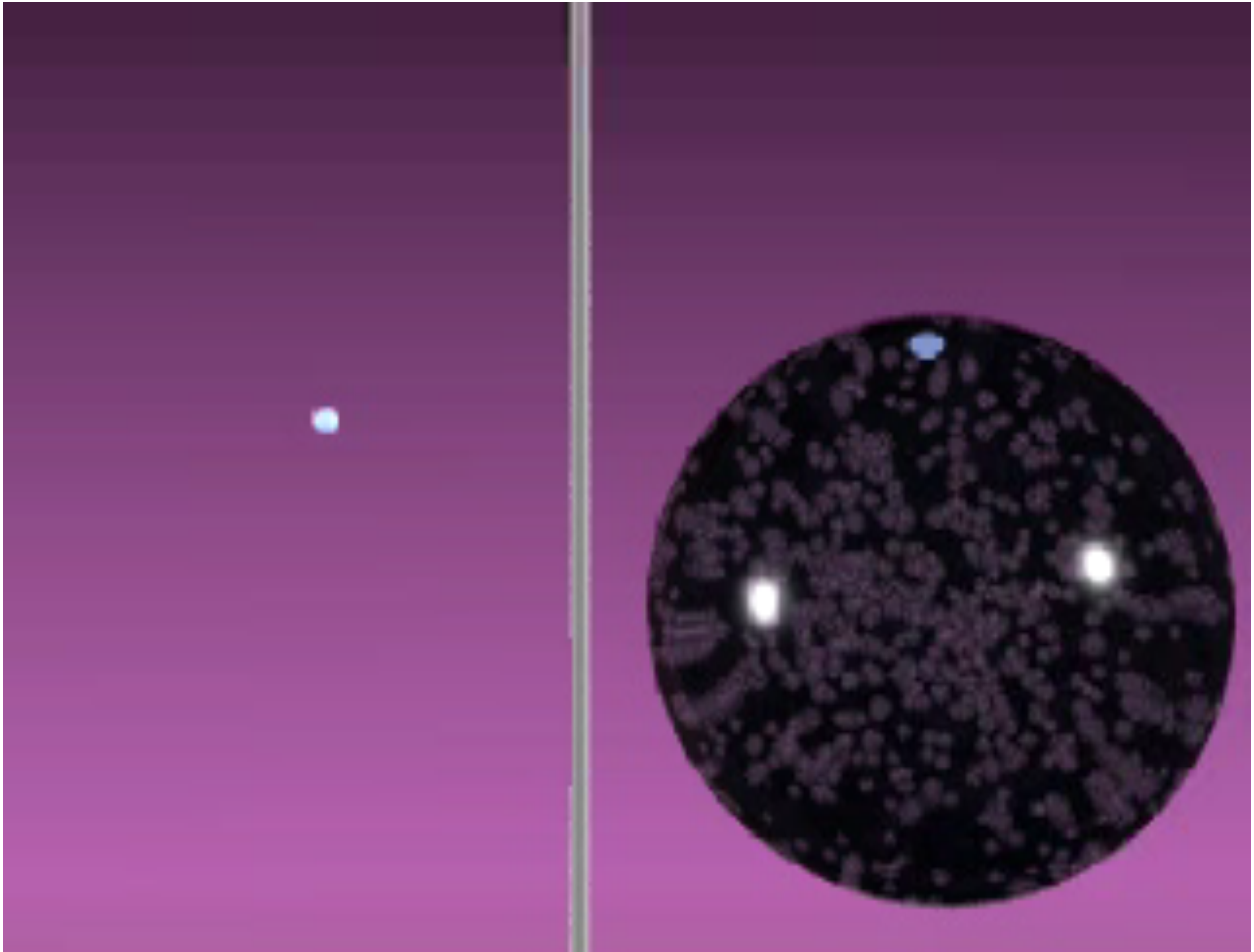
4 jets event
possible !



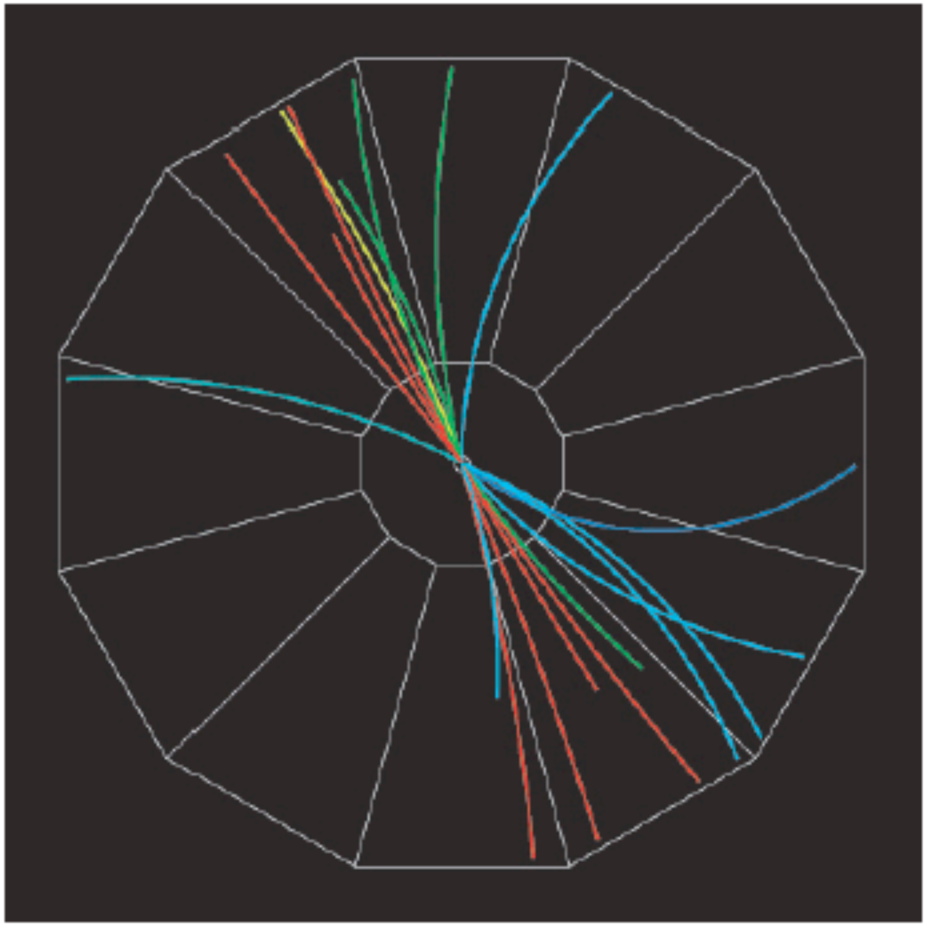
(b)

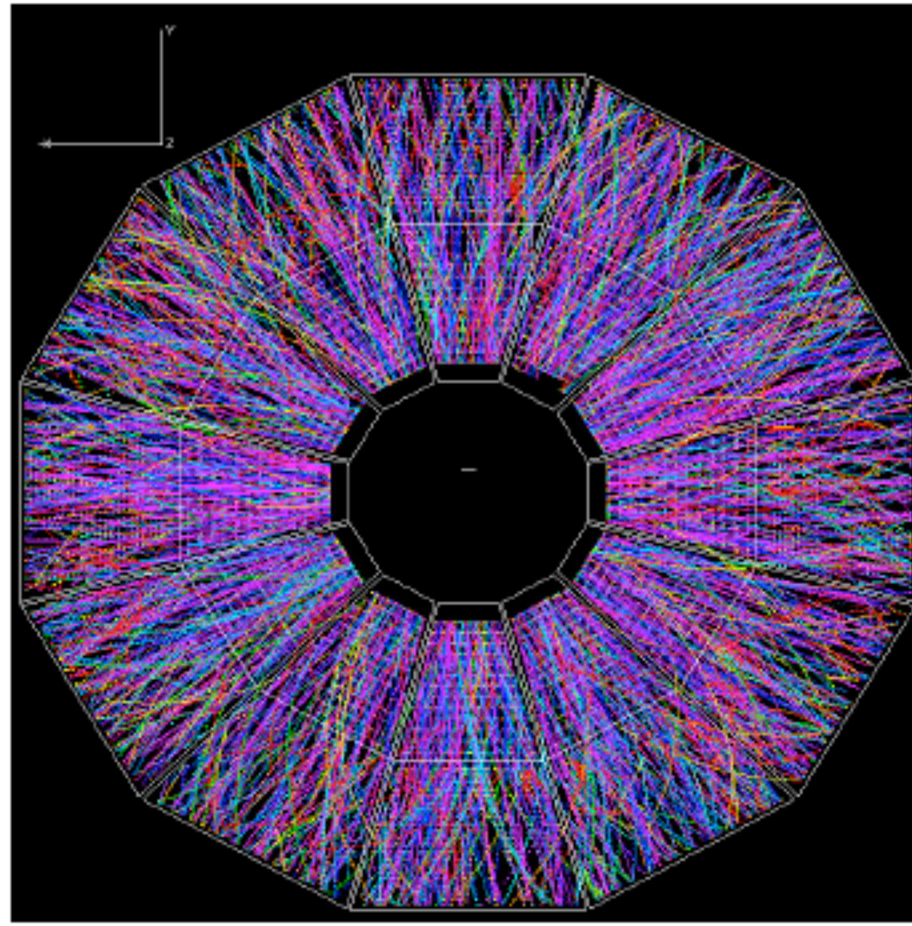
Jets in A+A:





Seeing jets …

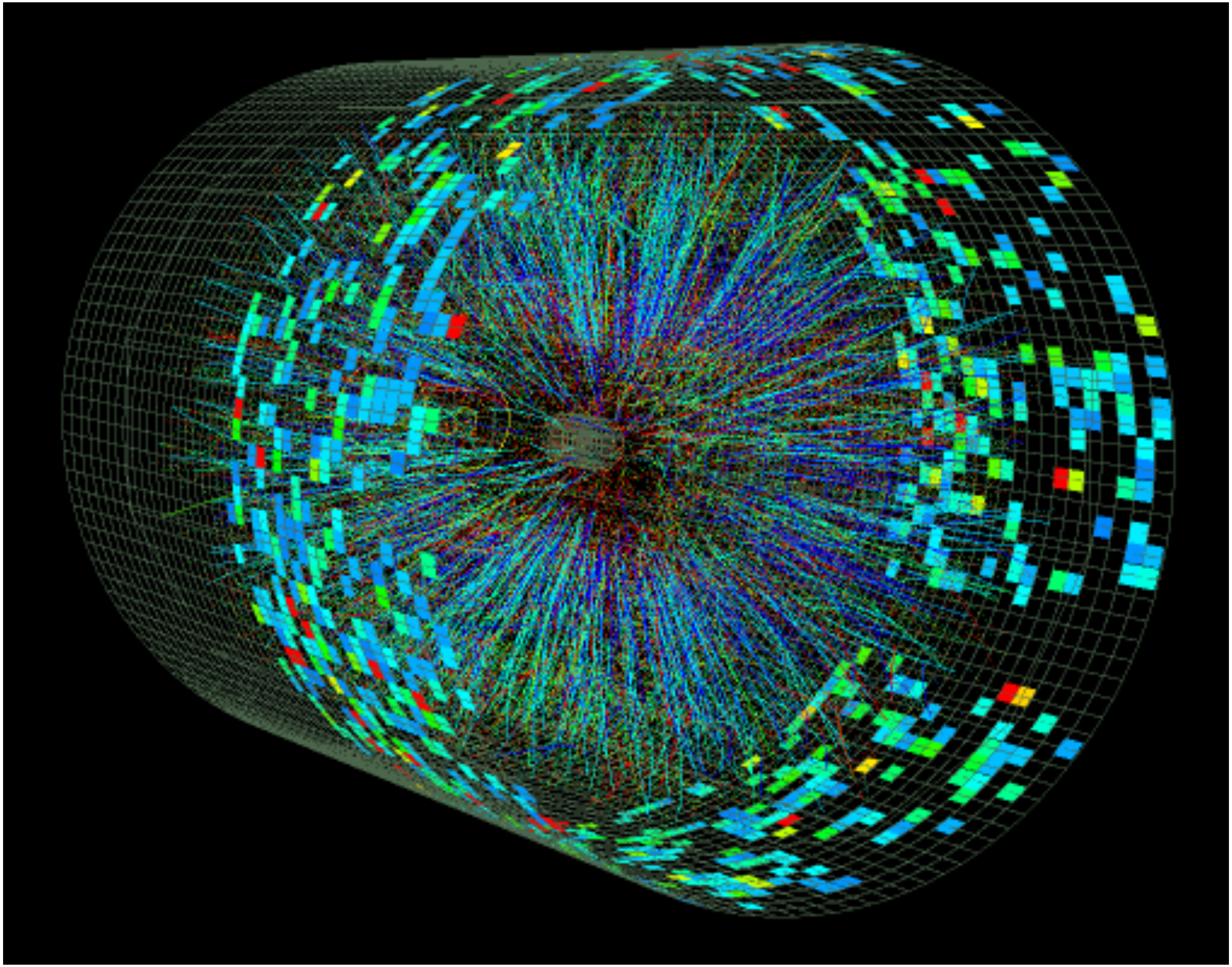




Jets are what you see
clearly 2 jets here !

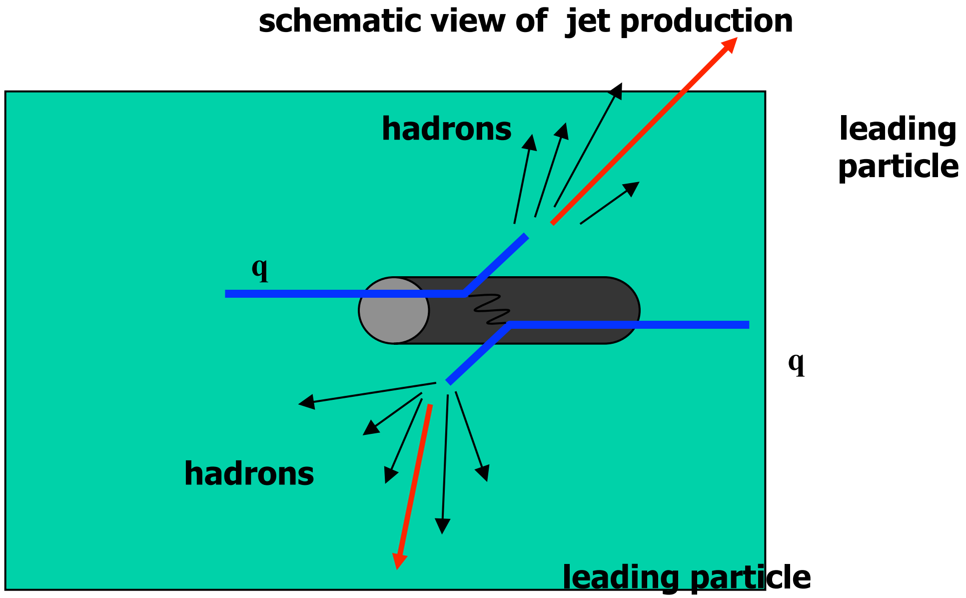
What about Au+Au (at 200 GeV) ?

How STAR detectors see it



q/g jets as probe of hot medium

What do we measure ?
Jets from hard scattered quarks observed via:
- fast **leading particles**
 or
- **azimuthal correlations** between the leading particles



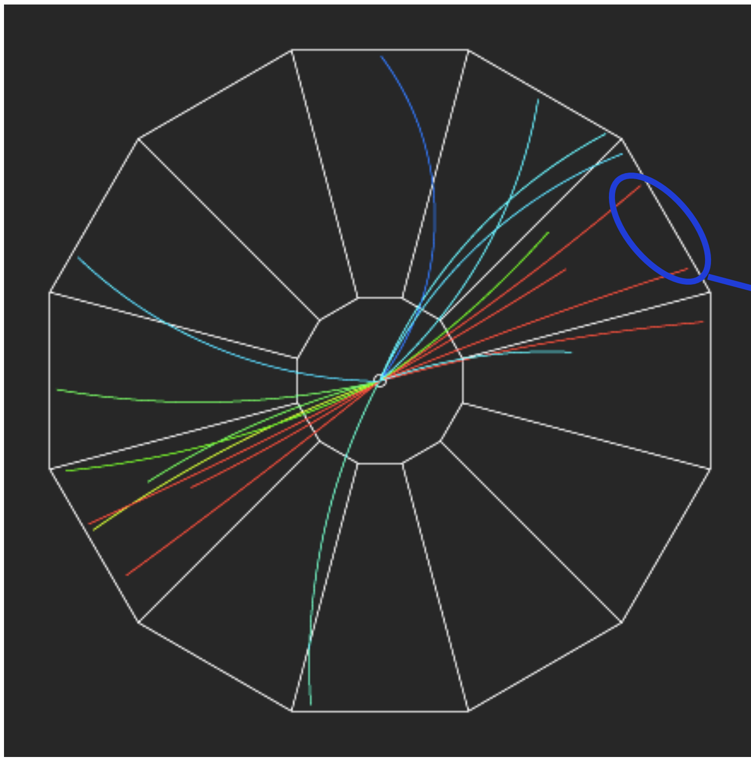
However, before they create jets, the scattered quarks radiate energy (~ GeV/fm) in the colored medium

→decreases their momentum (fewer high p_T particles)
→"kills" jet partner on other side

jet quenching

Jets in p+p collisions at RHIC

p+p → dijet

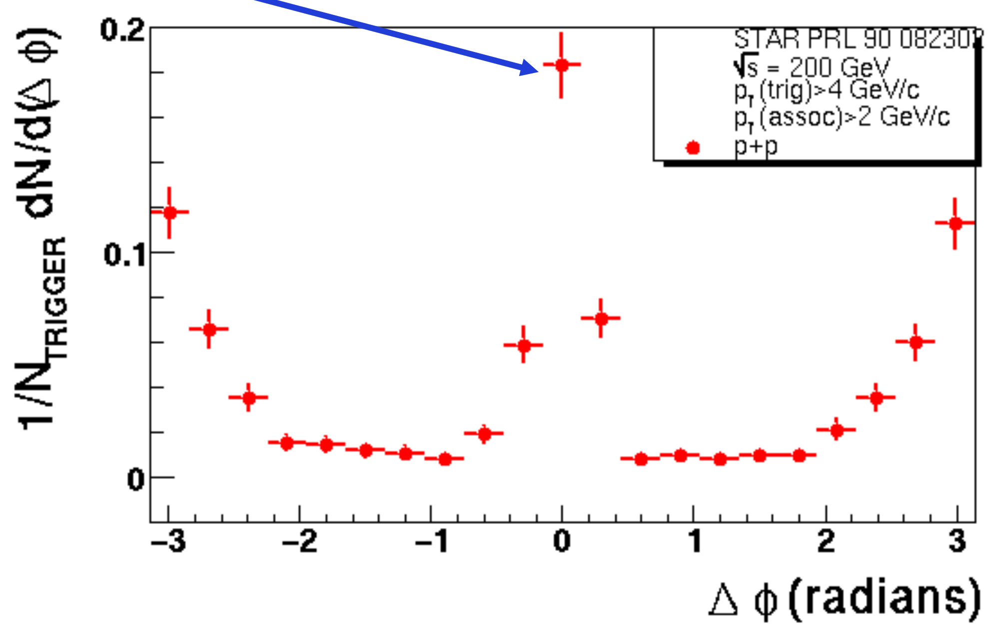


Two-particle azimuthal correlations:

•p+p events with high p_T track (biased jet finder)

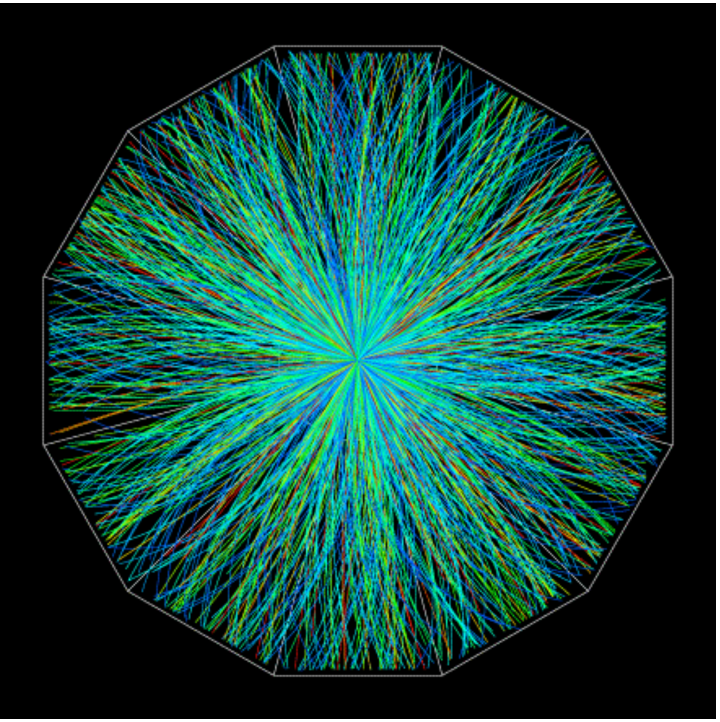
•$\Delta\phi$ distribution of other tracks (p_T>2 GeV/c) in these events

•normalize to the # triggers …



Jets in Au+Au collisions at RHIC

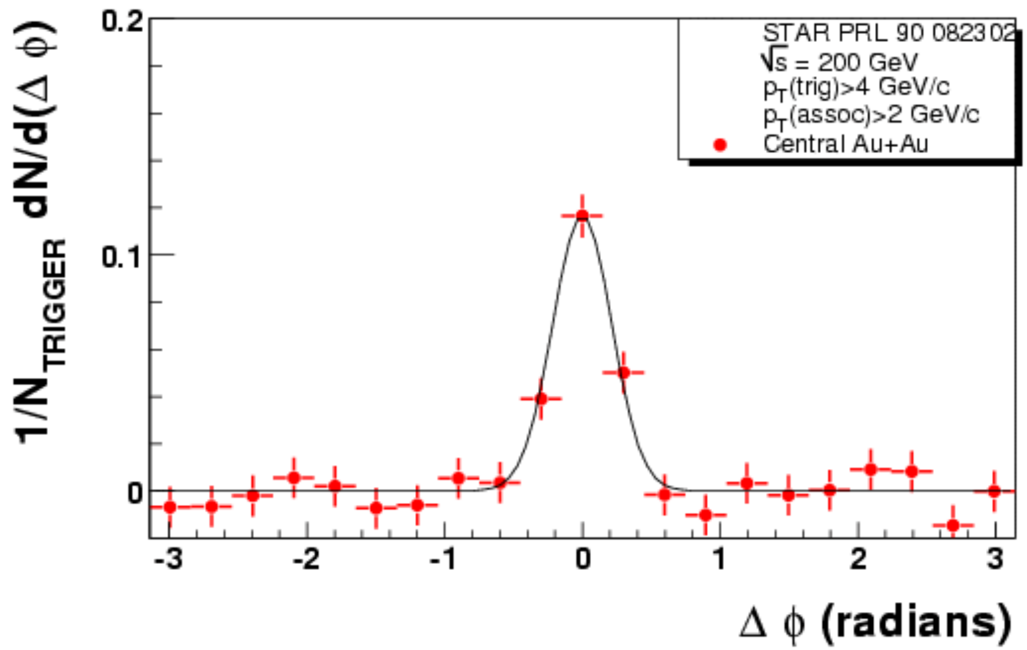
Au+Au→4000 particles



STAR PRL 90, 032301
STAR PRL 90, 082302

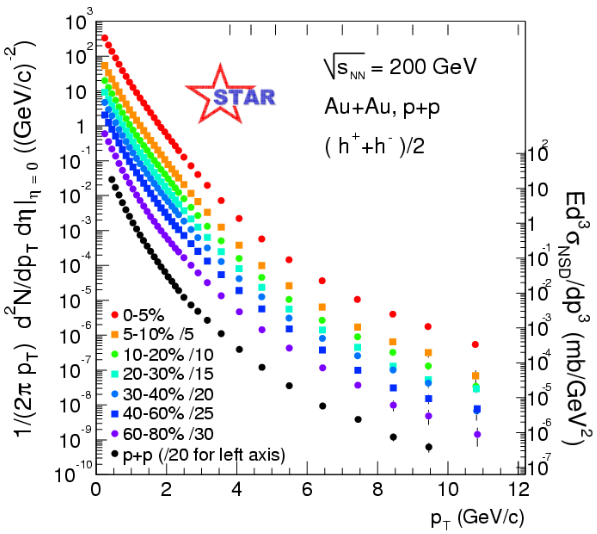
First direct evidence for et production in nucleus-nucleus collisions

- Au+Au events with high p_T track (*minimally* biased jet finder)
- $\Delta\phi$ distribution of other tracks in these events
- normalize to the # triggers …

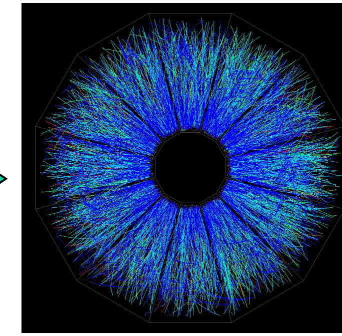


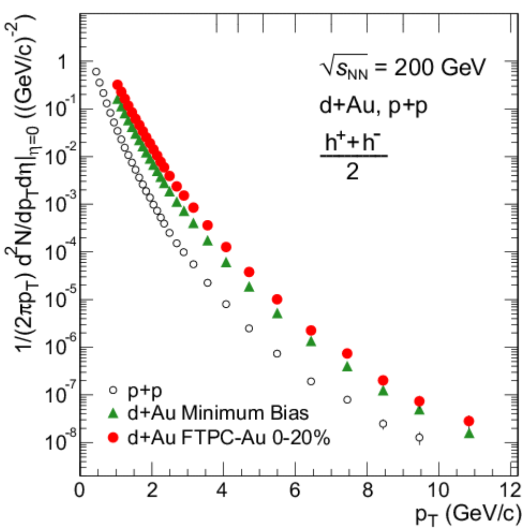
second peak is gone !

Observable to study effect of jets through medium



Jets in collisions like this





X N_{bin}

$$R_{AB} = \frac{1}{T_{AB}(b)} \frac{d^2N^{AB}/dp_T d\eta}{d^2\sigma^{pp}/dp_T d\eta}$$

It measures the deviation of the nucleus-nucleus collision at a given impact parameter from a superposition of pp collision.

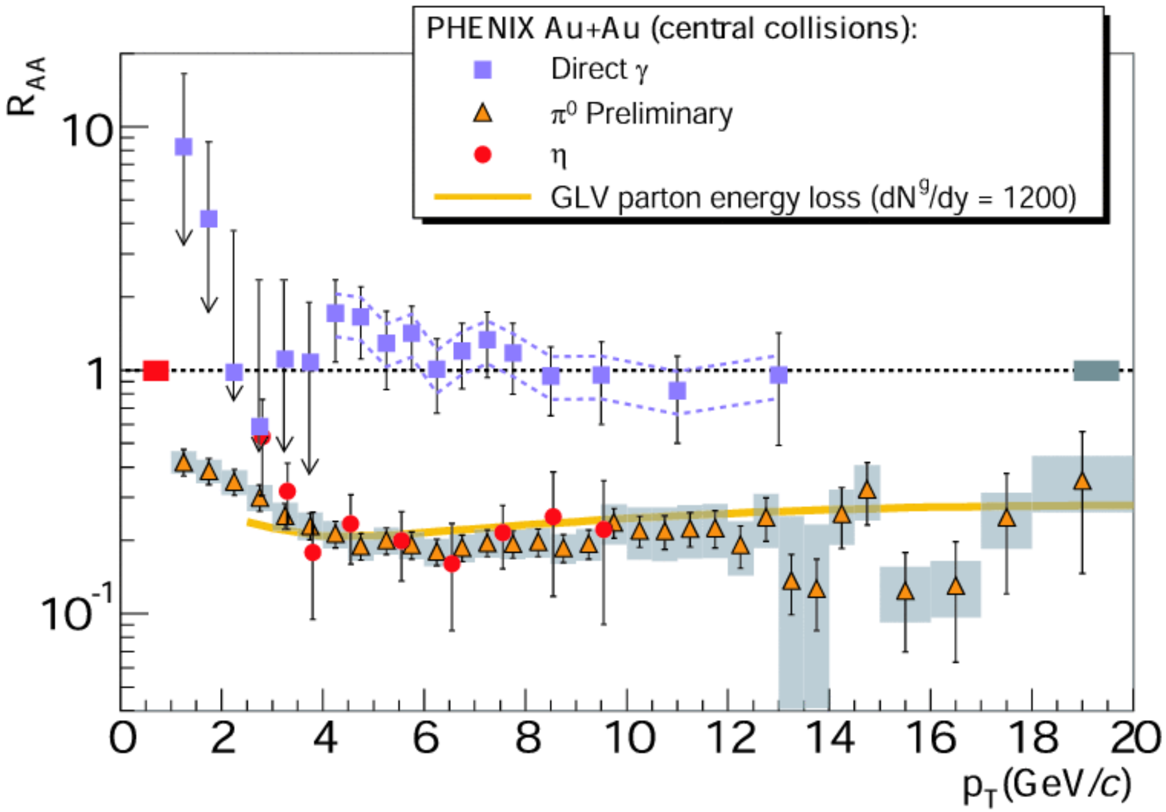
If at high p_T:

$R_{AB} = 1 \rightarrow$ no nuclear effects

$R_{AB} > 1 \rightarrow$ enhanced hadron production in AuAu

$R_{AB} < 1 \rightarrow$ suppressed hadron production in AuAu

Light hadron production in AA (jets I)



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

Photons (color-neutral)
Jets (color-charged)

Hadron production suppressed ~5x relative to pp - dense medium formed

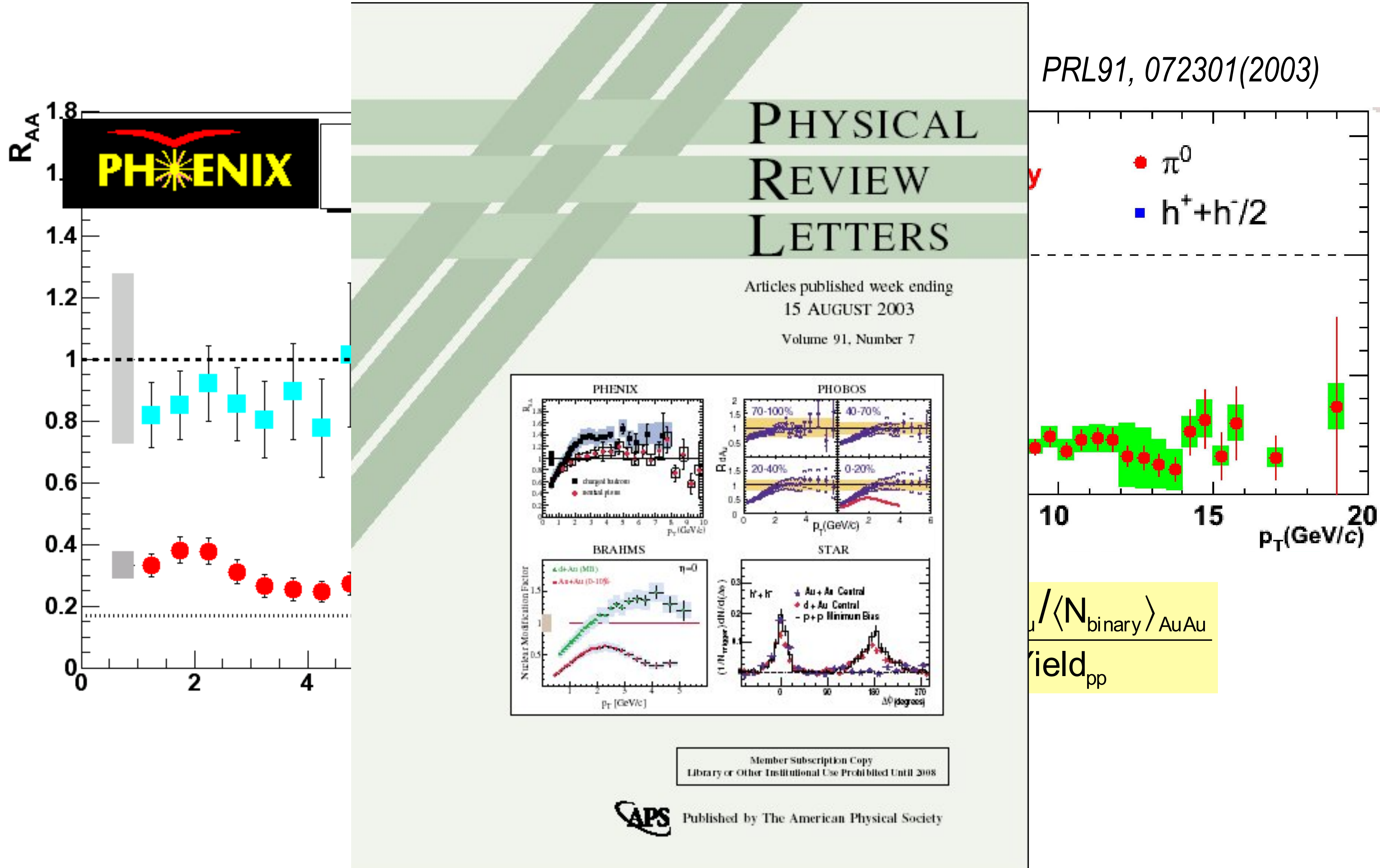
$\pi 0$ and η mesons suppressed by similar levels – energy loss at partonic level.

Photons NOT suppressed. They do not interact strongly. Suppression due to interactions with medium.

colored objects lose energy, photons don't

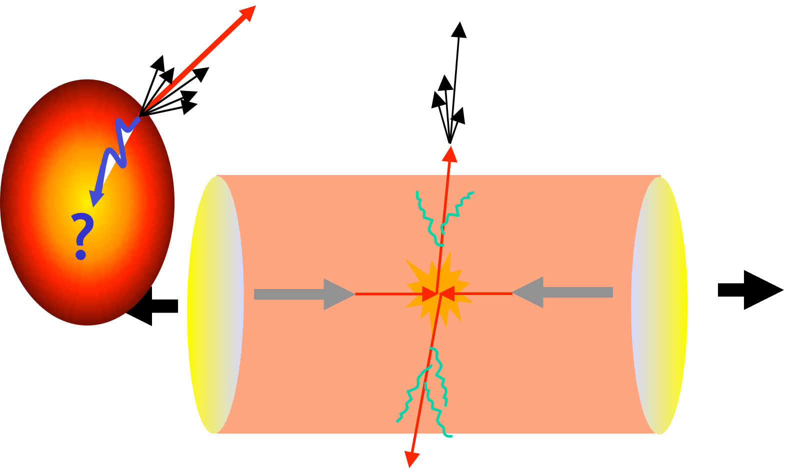
Au-Au √s = 200 GeV: high p_T suppression!

PRL91, 072301(2003)

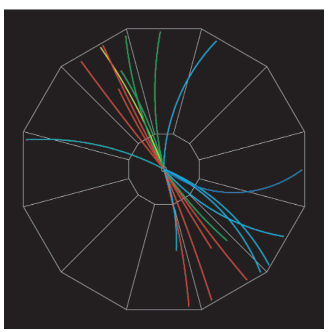


Effect is real…seen by ALL 4 experiments…Final or Initial State Effect ??

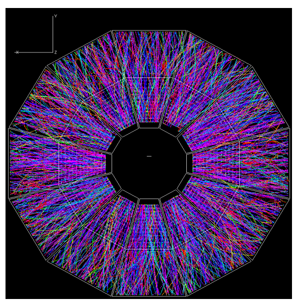
Azimuthal di-hadron correlations



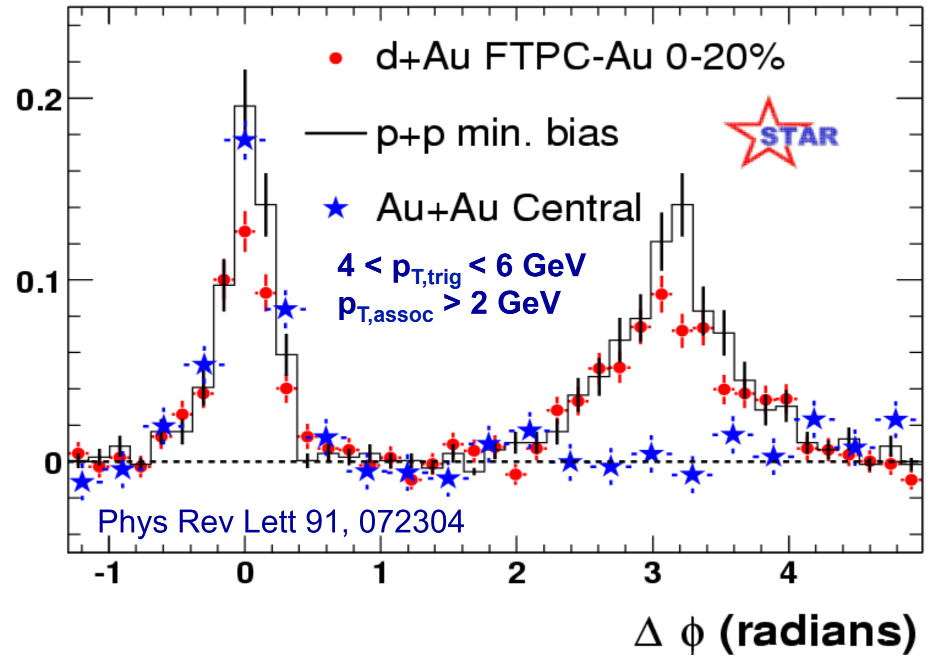
p+p



Au+Au



Need to subtract background in Au+Au



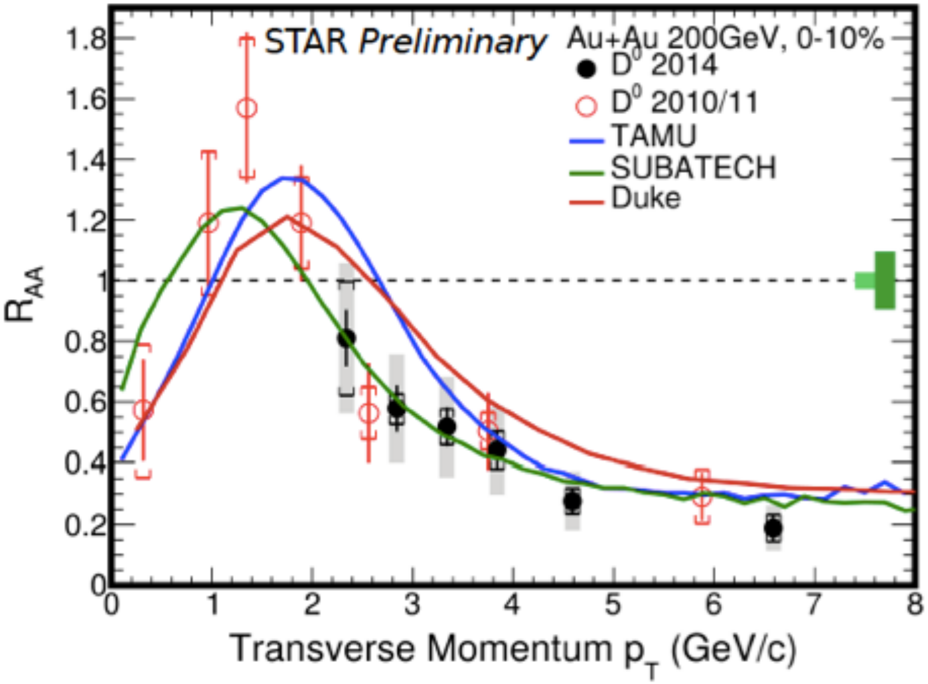
2002 result (year 2):

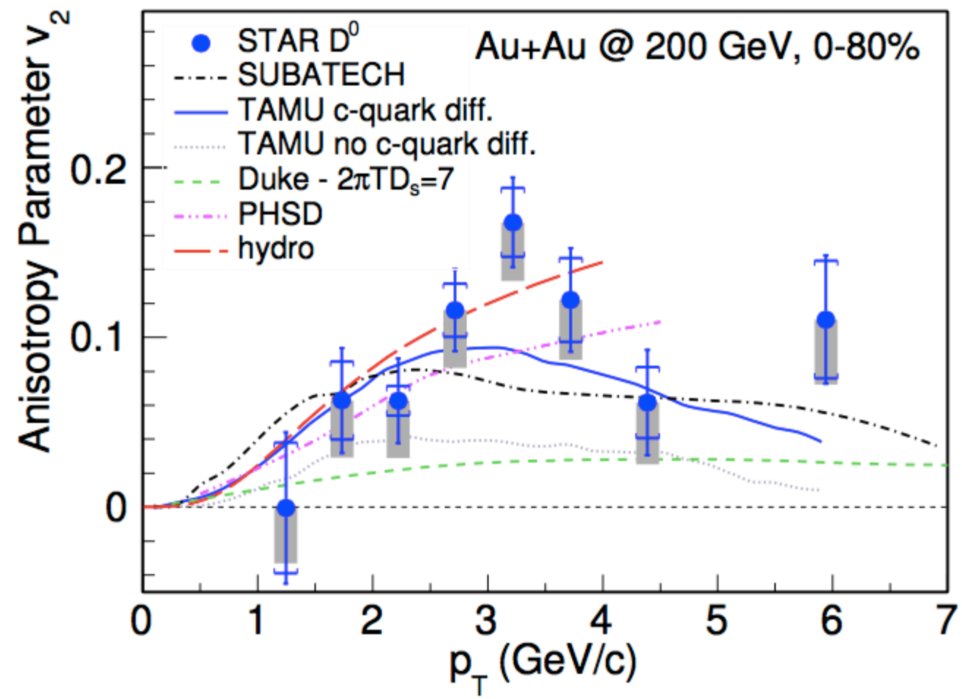
No modification of near side

Strong suppression of away side

No measurable away-side yield; cannot quantify suppression

Fast forward 2016/2017 – look at heavier quarks - D^0 R_{AA}

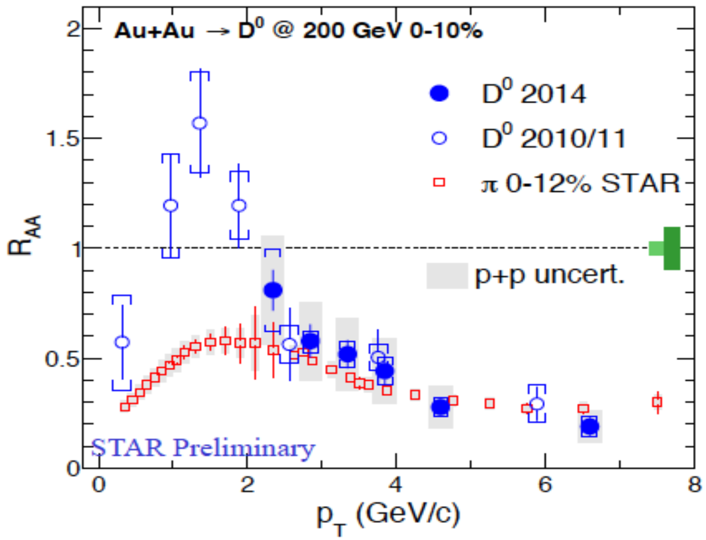


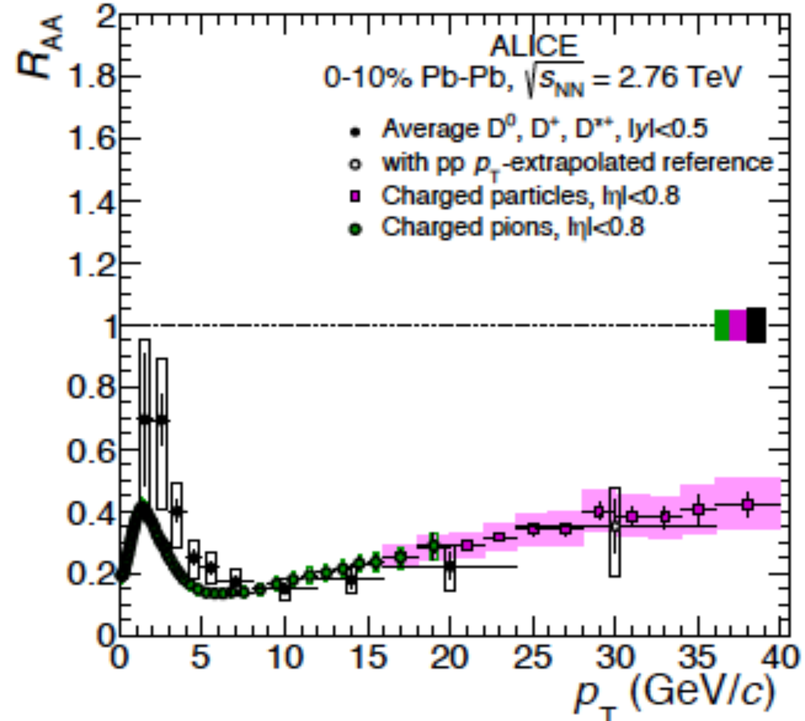


- Charm quarks at RHIC show
  - significant suppression at high p_T, $R_{AA}(D) \sim R_{AA}(h)$
  - significant flow at low-intermediate p_T, $v_2(D) \sim v_2(h)$ vs. m_T-m_0
- Models with a diffusion coefficient $2pT\boldsymbol{D_s} \sim 2$-$12$ describe both D^0 R_{AA} and v_2
  - *differences between models to be settled*
- Future measurements:
  - Λ_c, D_s, bottom production

even heavier

arXiv: 1509.06888





c, b quarks have higher mass than u, d, s

- Surprise - charm behaves as u, d, s! charm is a light quark!
- How about heavier bottom quark?
- First hints at LHC and RHIC that b is less suppressed…
- But is it really true? (upgraded detectors will tell!)

Exciting new physics :
perfect liquid
suppression of jets
....
QGP !

Thanks !

Questions ?

my e-mail: G_Odyniec@lbl.gov