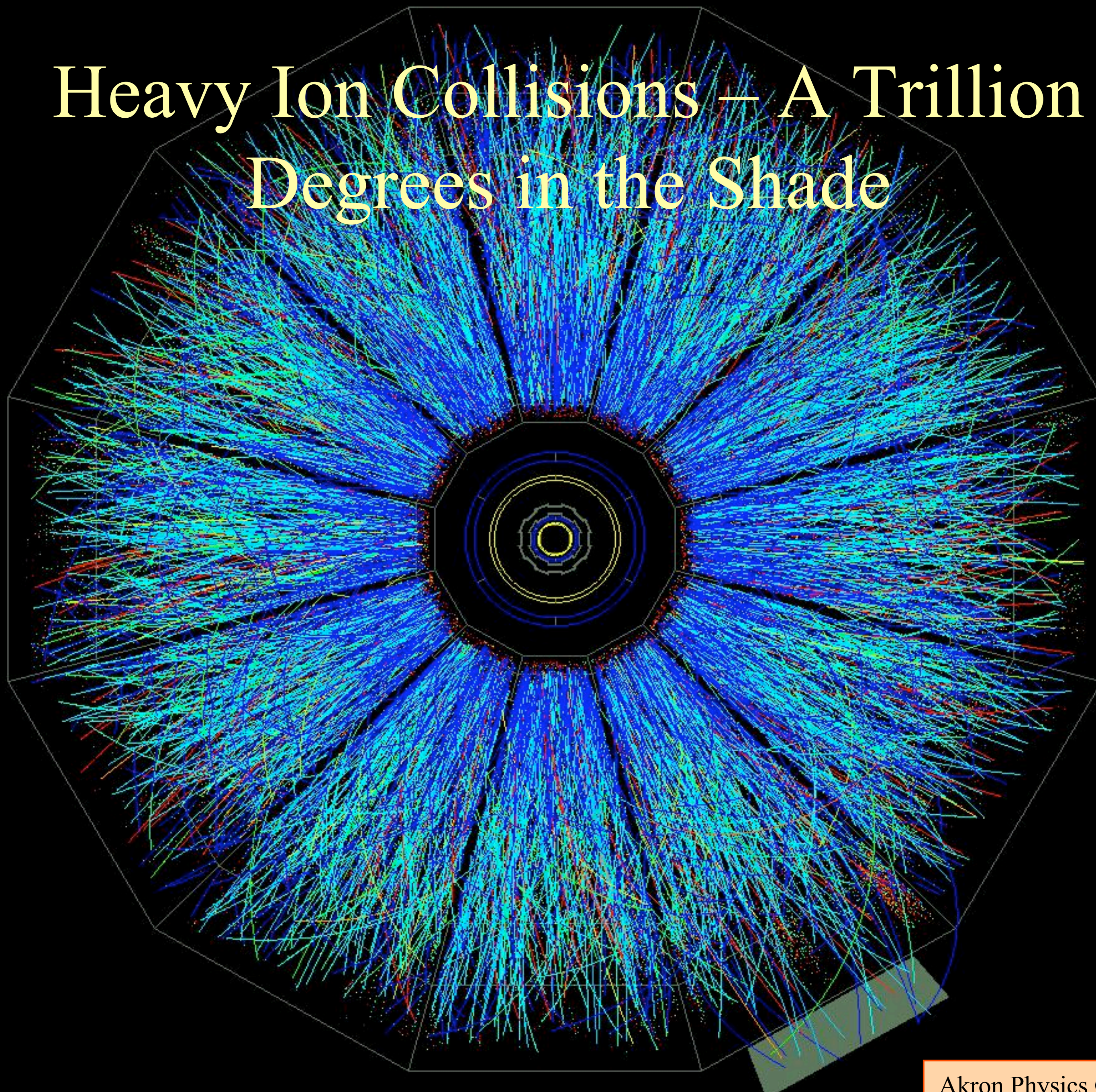
Heavy Ion Collisions – A Trillion Degrees in the Shade



Outline

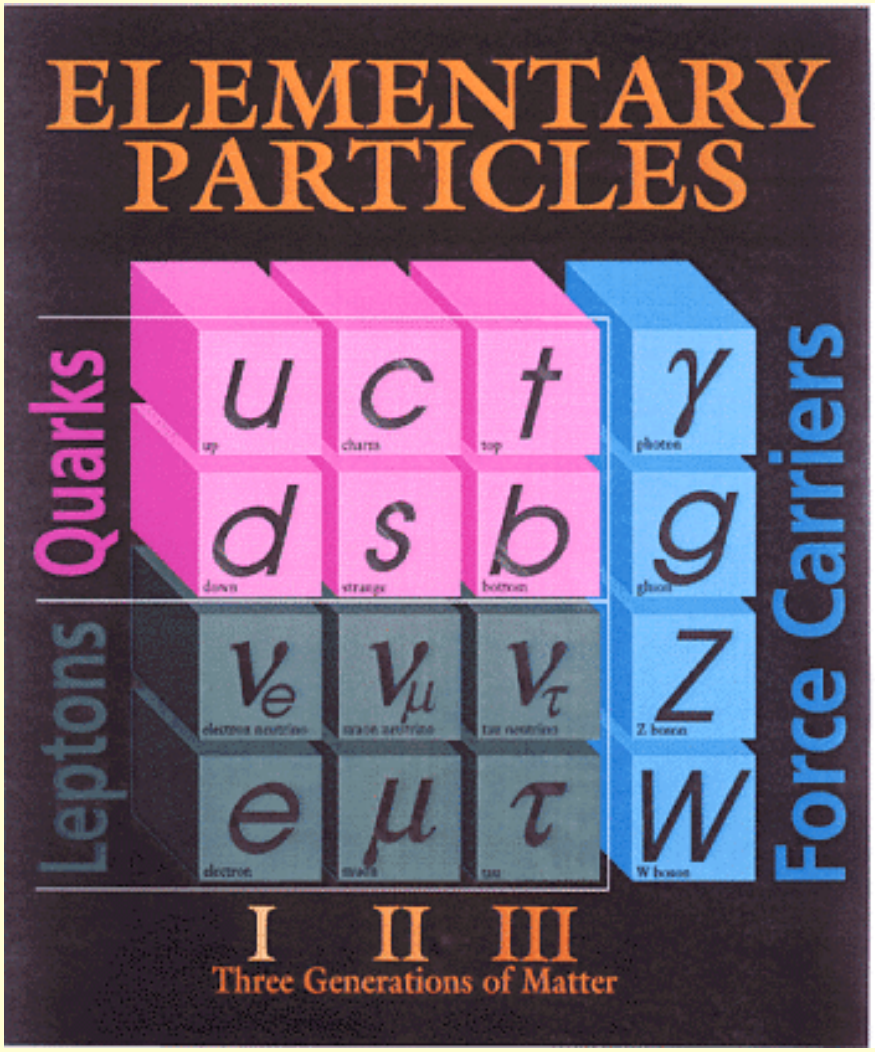
- Why collide heavy nuclei at high energy?
- RHIC: Machine and experiments
- Physics from the first ten years of RHIC
  - Soft physics
  - Hard physics

"In high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions.

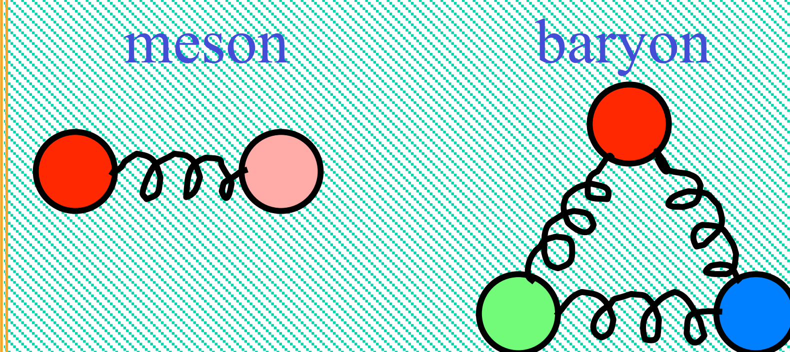
In order to study the question of 'vacuum', we must turn to a different direction; we should investigate some 'bulk' phenomena by distributing high energy over a relatively large volume."

T.D. Lee (Nobel Laureate – Parity violation)
Rev. Mod. Phys. 47 (1975) 267.

Quantum Chromodynamics



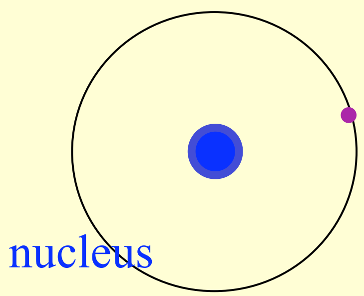
1) Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.
2) Gluons hold quarks together to from hadrons:



3) Gluons and quarks, or partons, typically exist in a color singlet state: ***confinement***.

An analogy… and a difference!

An atom has substructure – we want to study its constituents and their interactions

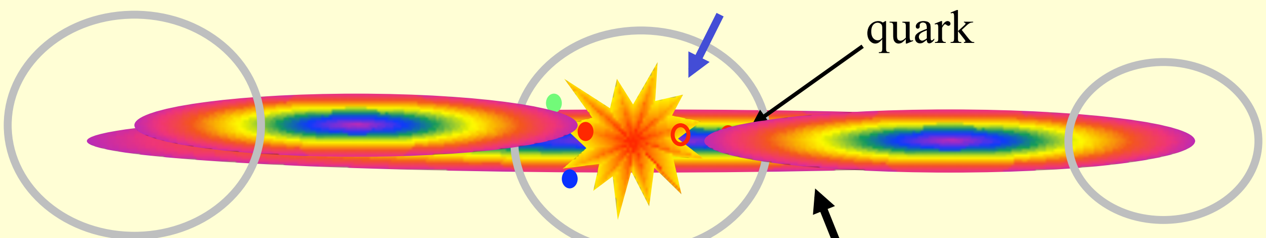


Separate constituents: EM interaction vanishes & we can study constituents/interactions separately

Imagine our understanding of atoms or QED if we could not isolate charged objects!!

Confinement: fundamental & crucial (but *not* well-understood!) feature of QCD
colored objects (partons) have ∞ energy in normal vacuum

would love to study **deconfined** partonic system!



But how?

- Use feature of **asymptotic freedom**
  - Bring nucleons as close as possible
    - Strong force gets weaker
    - Partons would be free to move around
- A '**phase transition**' to parton '**plasma**' should occur

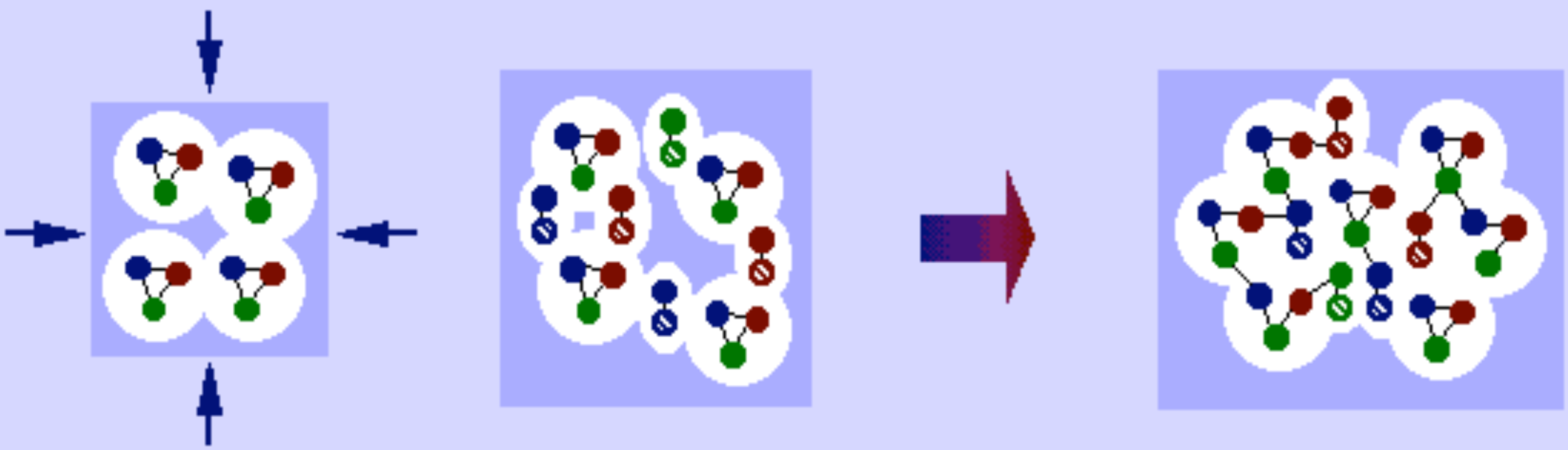
Phase Transitions

- What is a phase transition ?

A process in which a system changes,
over a negligible range of temperature or pressure,
from one state into another which has different properties.

Examples:

Water → Steam
Ice → Water
Nuclear Matter → Quark-Gluon Plasma ?



Compression + Heating (creation of pions) → Quark-Gluon Plasma

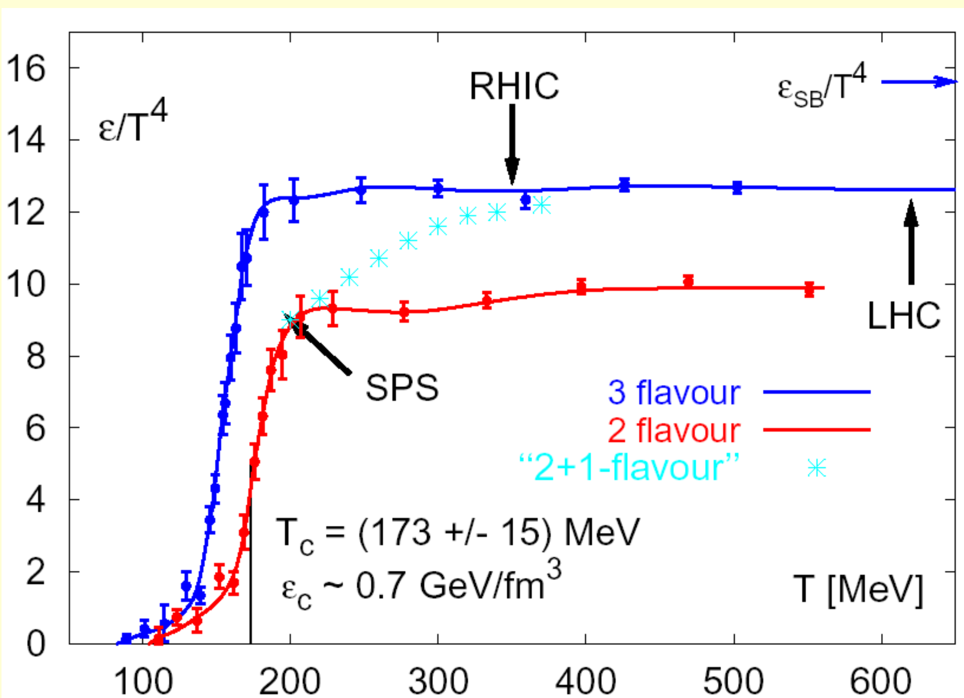
P.G.Jones@bham.ac.uk

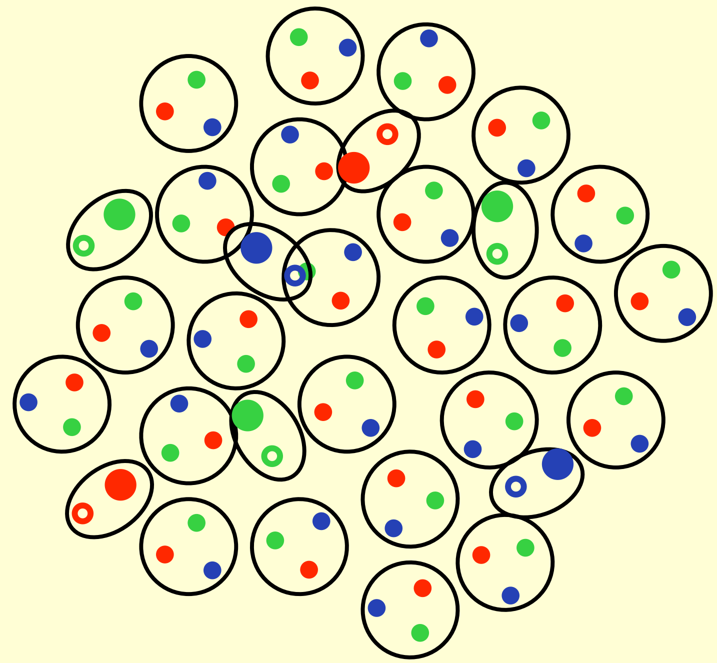
Collective Phenomenology & QGP

Present understanding of
Quantum Chromodynamics (QCD)

- heating
- compression

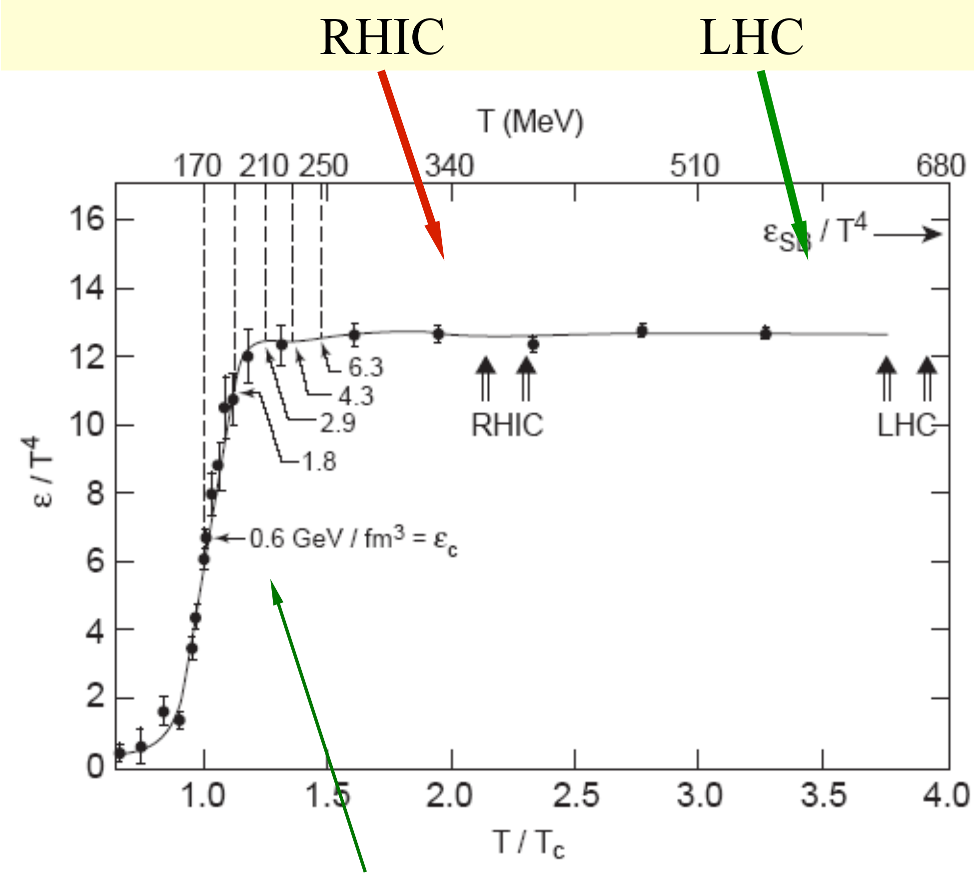
→ *deconfined color matter !*





Hadronic Matter / Nuclear Matter / Quark Gluon Plasma
(confined) / deconfined !

QCD on Lattice



Lattice calculations predict
$T_C \sim 160 \pm 20$ MeV

1) Large increase in ε, a fast cross cover !

2) Does not reach ideal, non-interaction S. Boltzmann limit !

⇒ many body interactions
⇒ Collective modes
⇒ Quasi-particles are necessary

Y. Aoki, Z. Fodor, S.D. Katz, K.K. Szabo, PLB643 46(06); hep-lat/0609068
*Z. Fodor et al, **JHEP** 0203:014(02)*
Z. Fodor et al, hep-lat/0204029
*C.R. Allton et al, PR**D66**, 074507(02)*
F. Karsch, Nucl. Phys. A698, 199c(02).

The Phase Diagram

TWO different phase transitions at work!

Deconfinement transition

– Particles roam freely over a large volume

Chiral transition

– Masses change (vanish)

10^{12} °K

Calculations show that these occur at approximately the same point

Two sets of conditions:

High Temperature

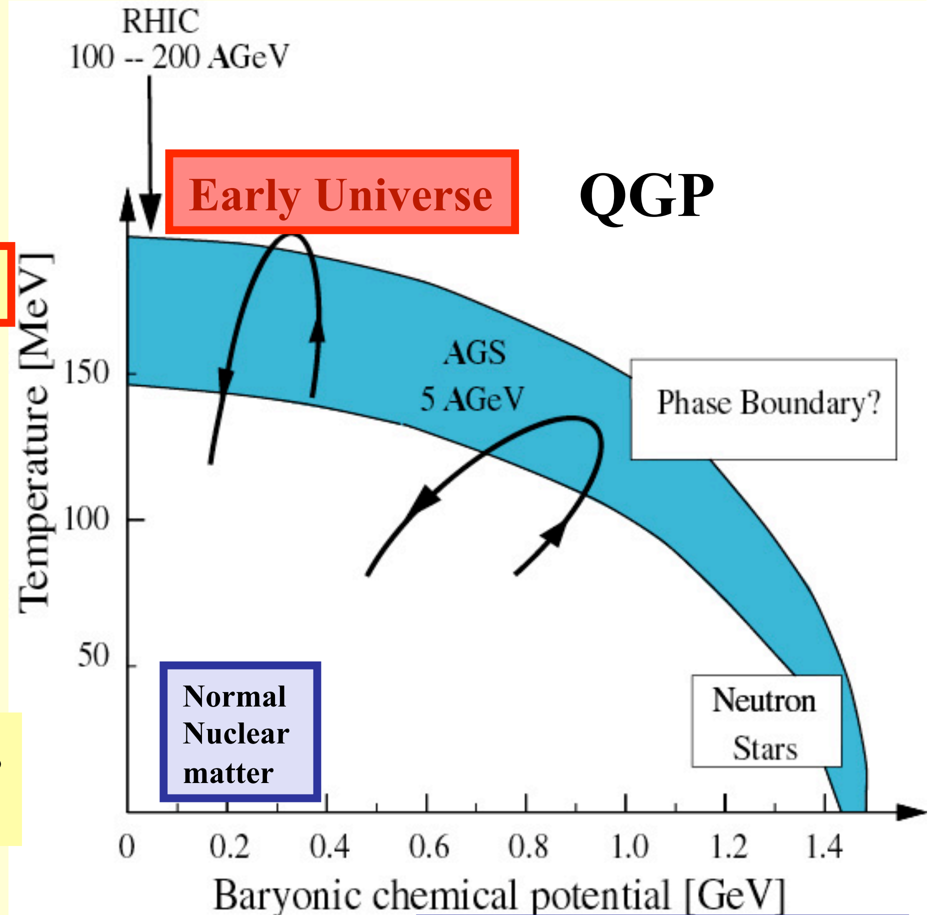
High Baryon Density

Nuclear Collisions can do both

Lattice QCD calc. Predict:

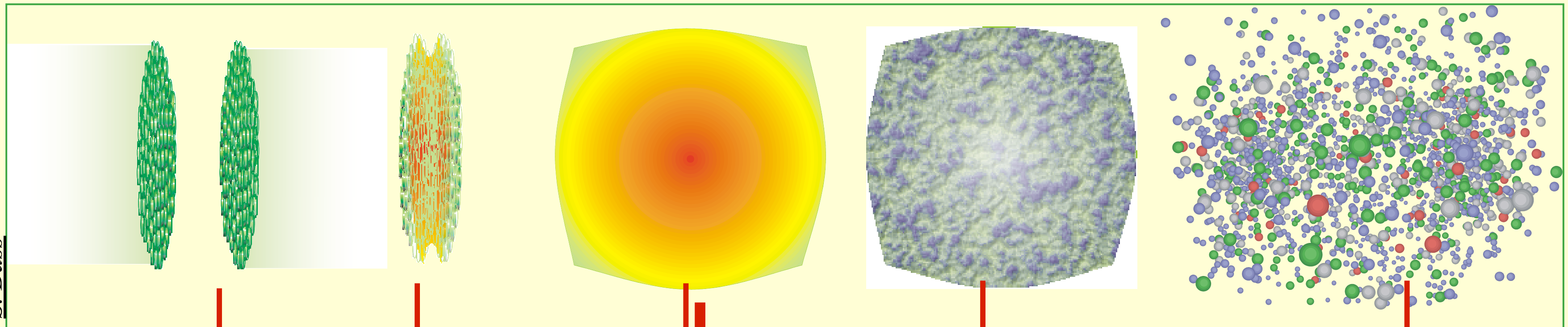
$T_c \sim 150\text{-}170$ MeV

$\varepsilon_c \sim 1$ GeV/fm^3



Density - "Compress"

High-energy Nuclear Collisions



S. Bass

Initial conditions

Initial high Q^2 interactions

Parton matter - QGP - The hot-QCD

Hadronization and Freeze-out

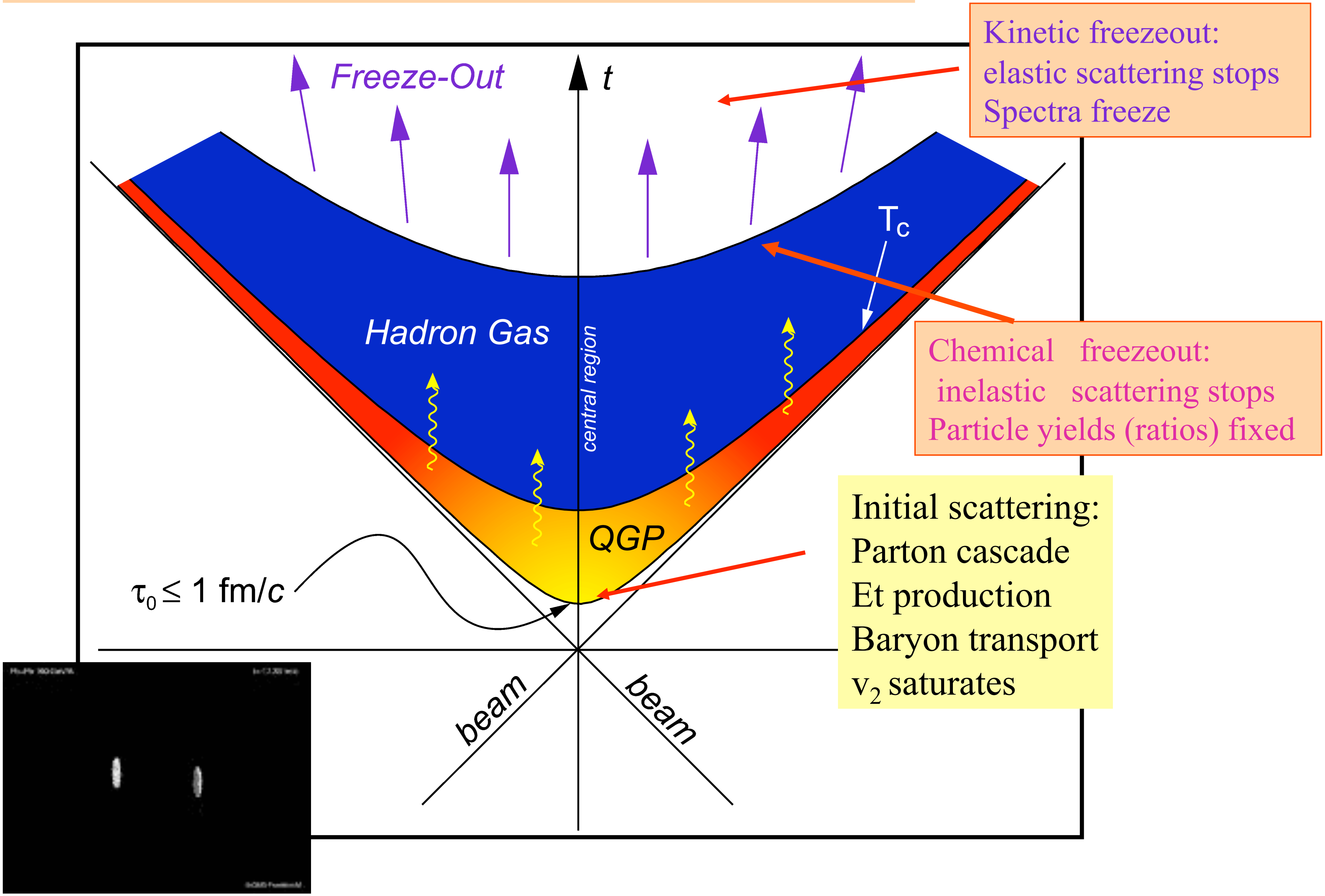
Experimen…

- **Energy**
- **Collecti**
- Charm - productions plus the combination (1) and (2)

(1) Hard scattering production - QCD prediction
(2) Interactions with medium - deconfinement/thermalization
(3) Initial parton density

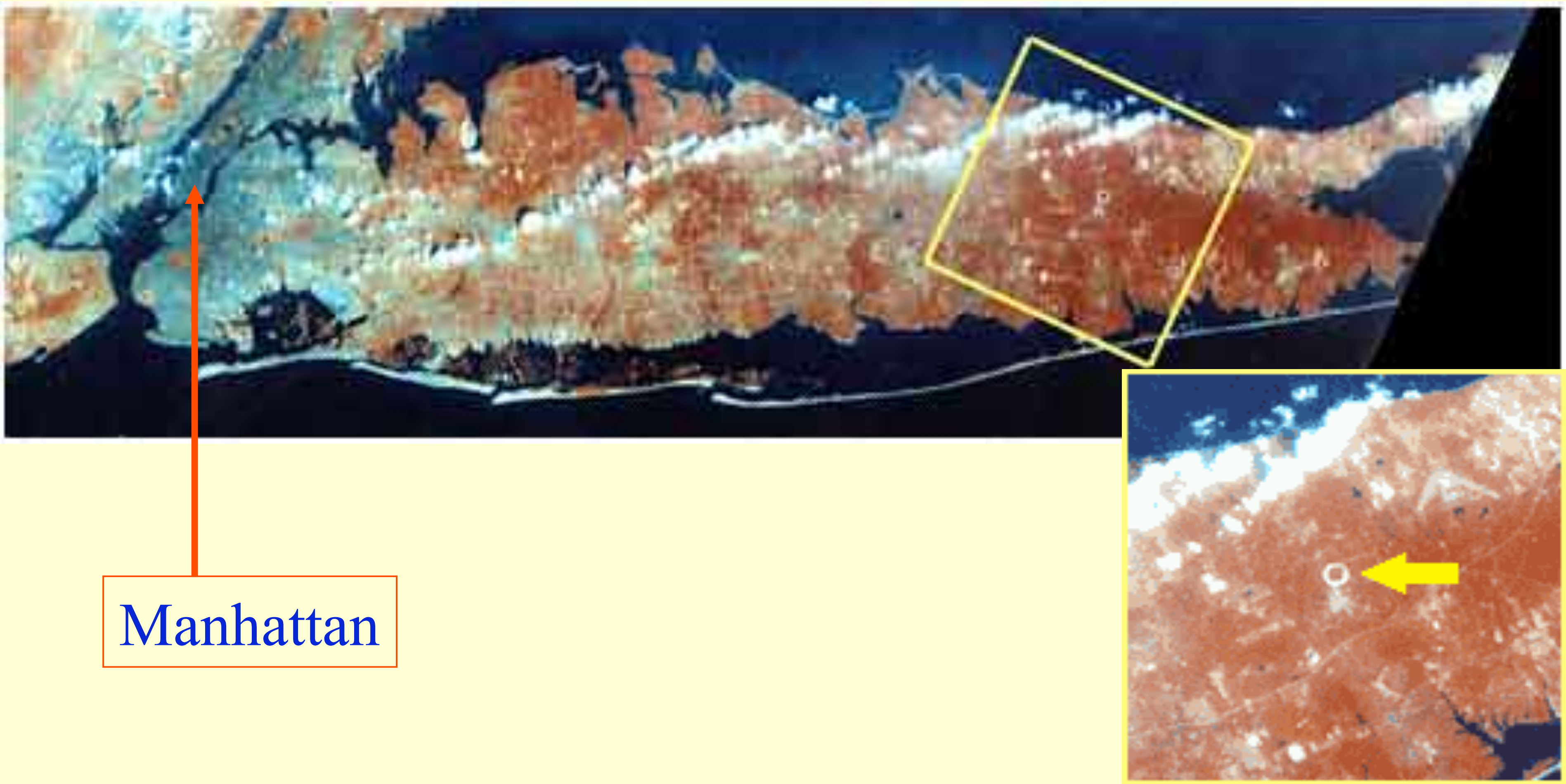
(1) Initial condition in high-energy nuclear collisions
(2) Cold-QCD-matter, small-x, high-parton density - parton structures in nucleon / nucleus

The ‘Little Bang’ in the Laboratory



Crossing a New Threshold

Relativistic Heavy Ion Collider



"Big Bang machine could destroy Earth" -The Sunday Times – July '99

the risk of such a catastrophe is essentially zero. – B.N.L. – Oct '99

Apocalypse2 – ABC News – Sept '99

features

A black hole ate my planet – New Scientist

Could physicists accidentally make killer black holes or lethal strange matter that would swallow the Earth? At least there'd be no one left to say sorry to, says Robert Matthews

UH-OH, the mad scientists are at it again. In their determination to extract nature's secrets, physicists in America have built a machine so powerful it has raised fears that it might cause The End of The World As We Know It.

most dangerous event in human history: - ABC News – Sept '99

No… the experiment will not tear our region of space to subatomic shreds.

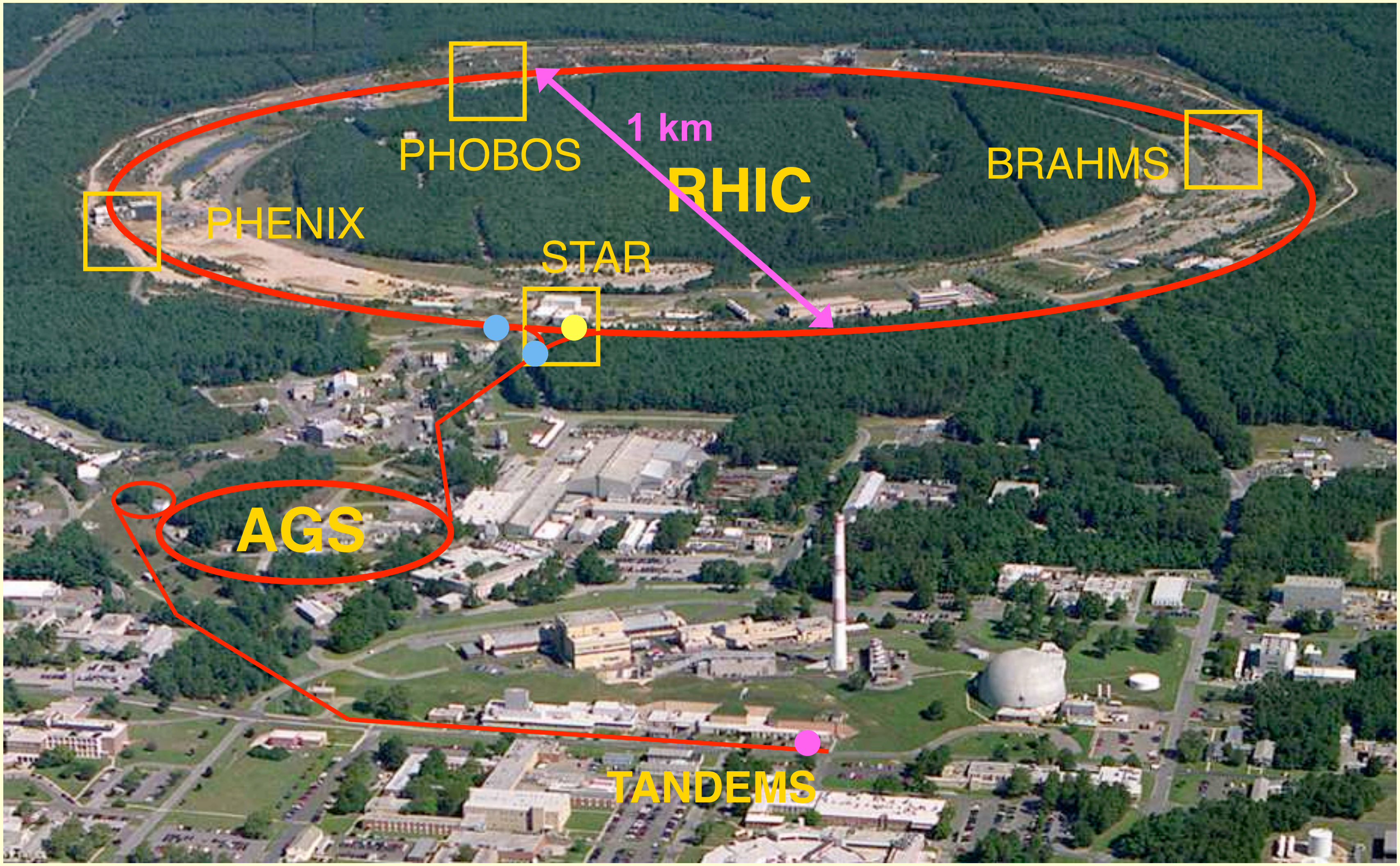
- Washington Post – Sept '99

Will Brookhaven Destroy the Universe? – NY Times – Aug '99

REVIEW OF SPECULATIVE 'DISASTER SCENARIOS' AT RHIC.
W. Busza, R.L. Jaffe, J. Sandweiss, F. Wilczek, Sep 1999

Rev.Mod.Phys.72 (2000) and **hep-ph/9910333**

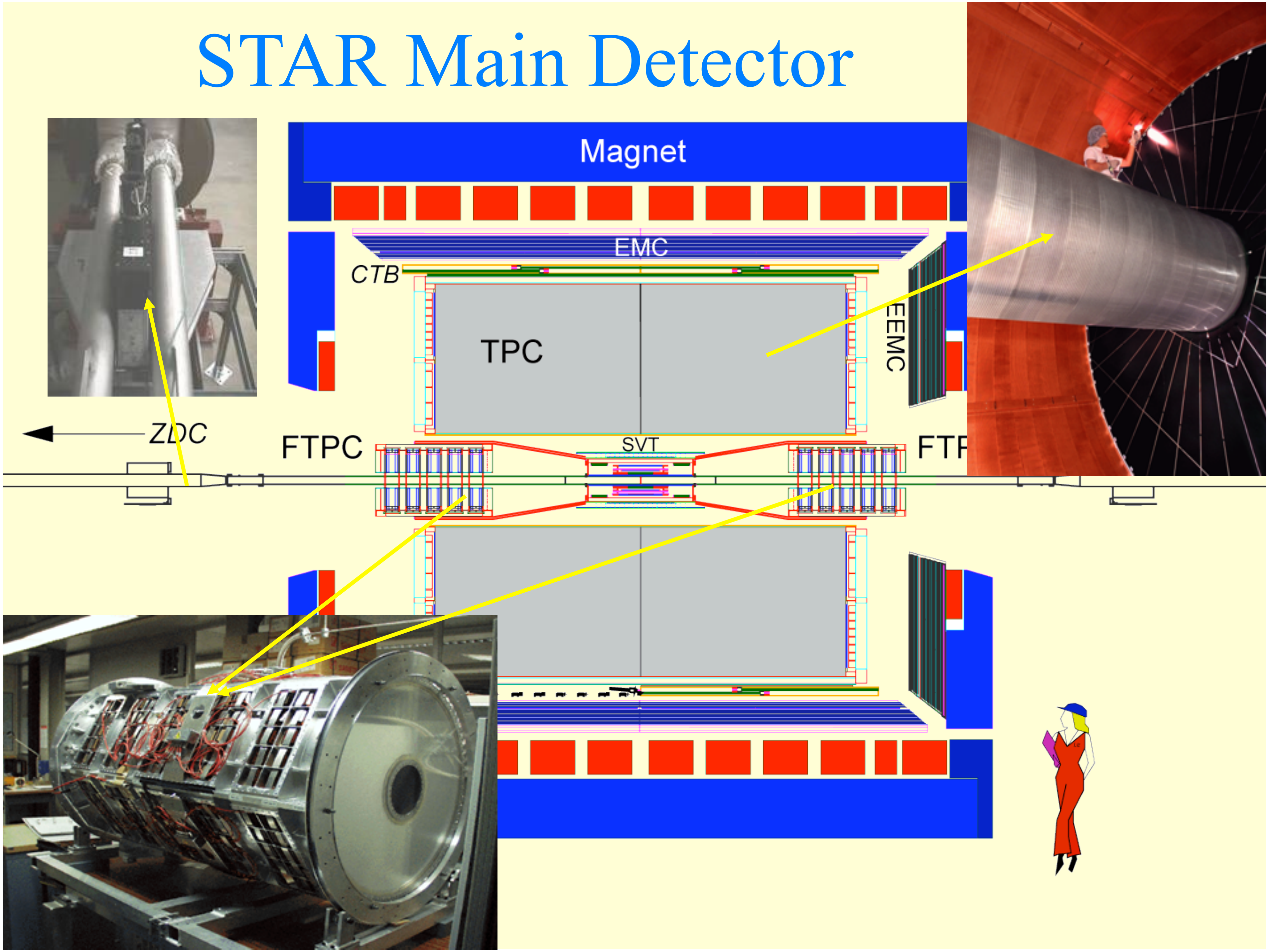
RHIC & its experiments



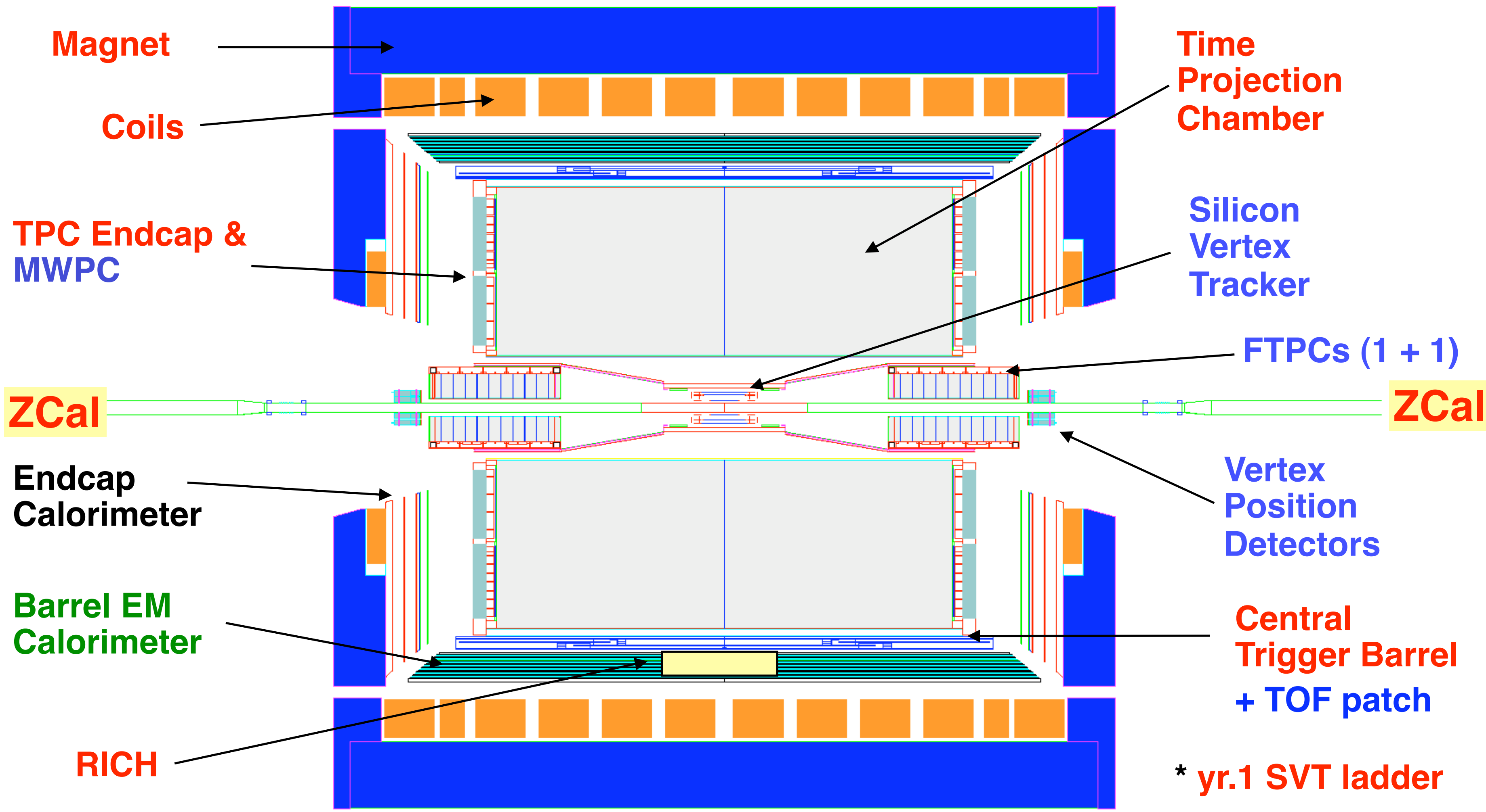
The STAR experiment

STAR ~500 Collaborators

STAR Main Detector

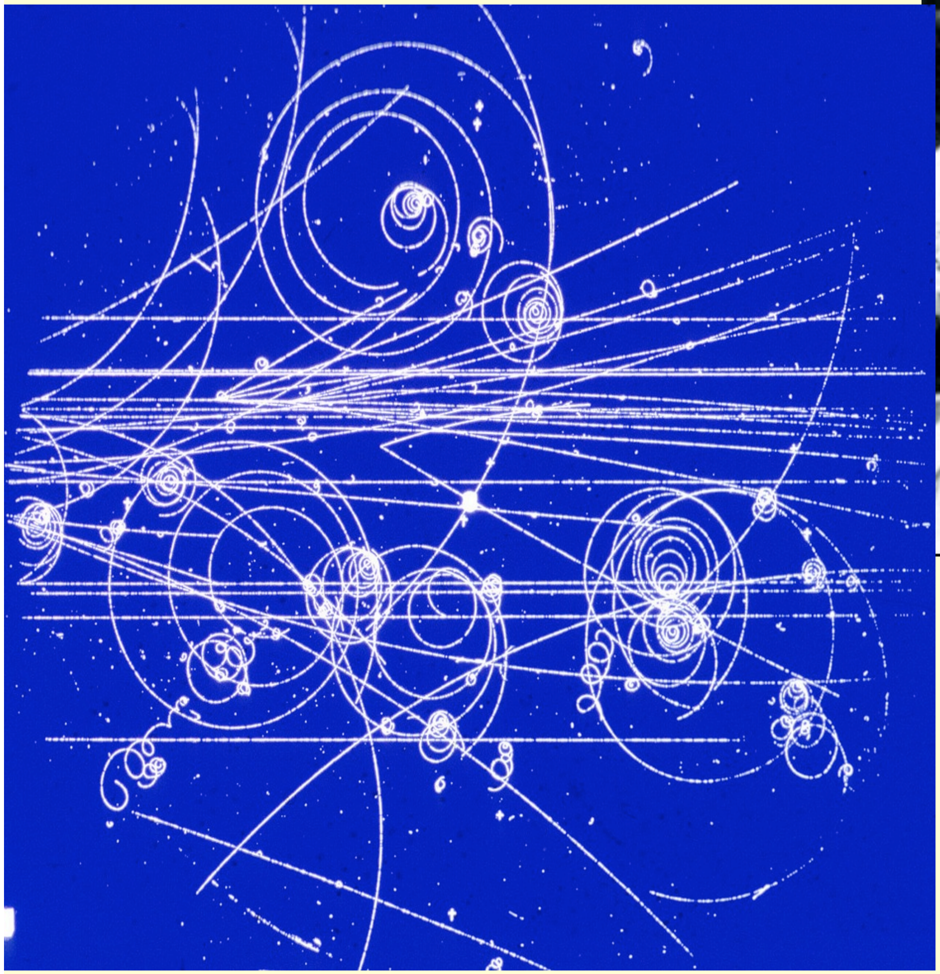


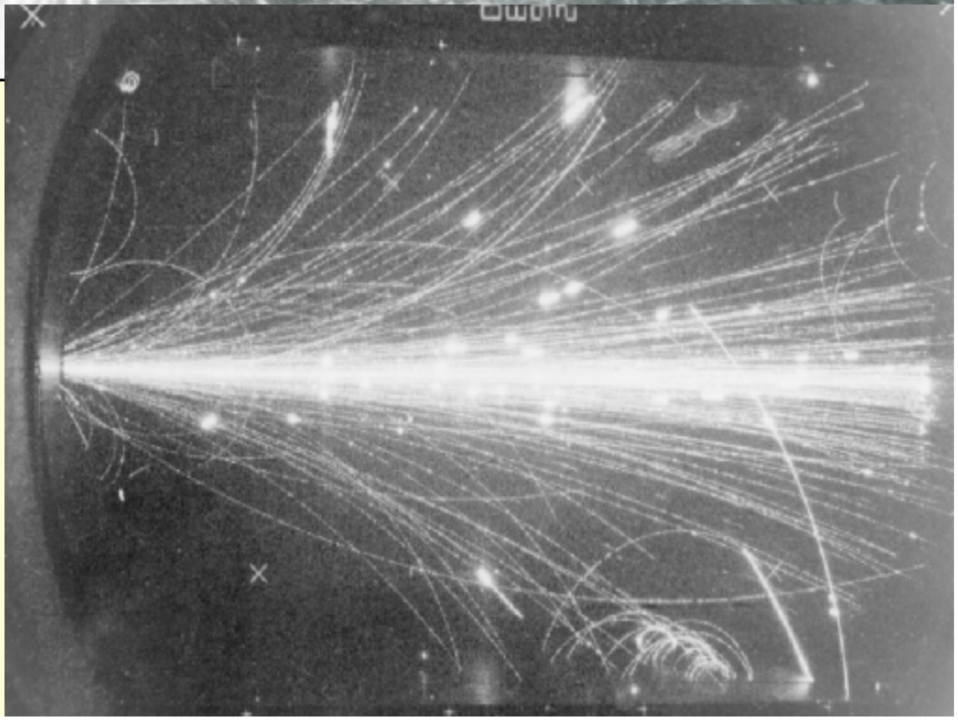
The STAR Detector



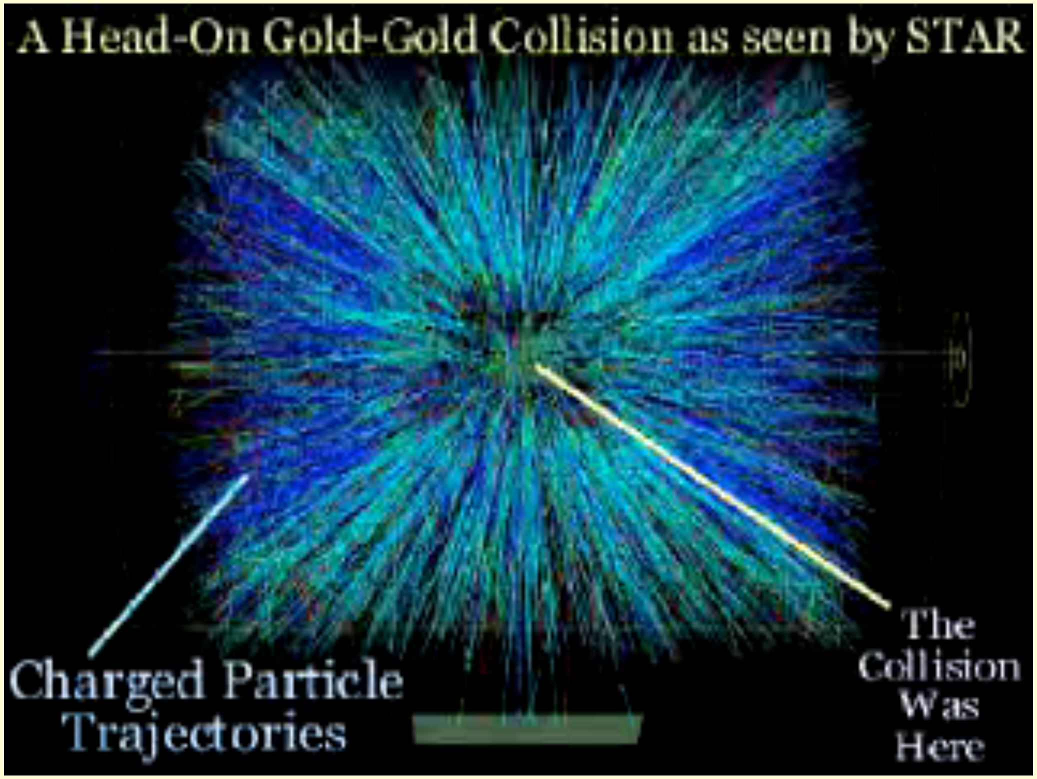
1st year (130 GeV), 2nd year (200 GeV)

Older tracking detectors: 2-D projections

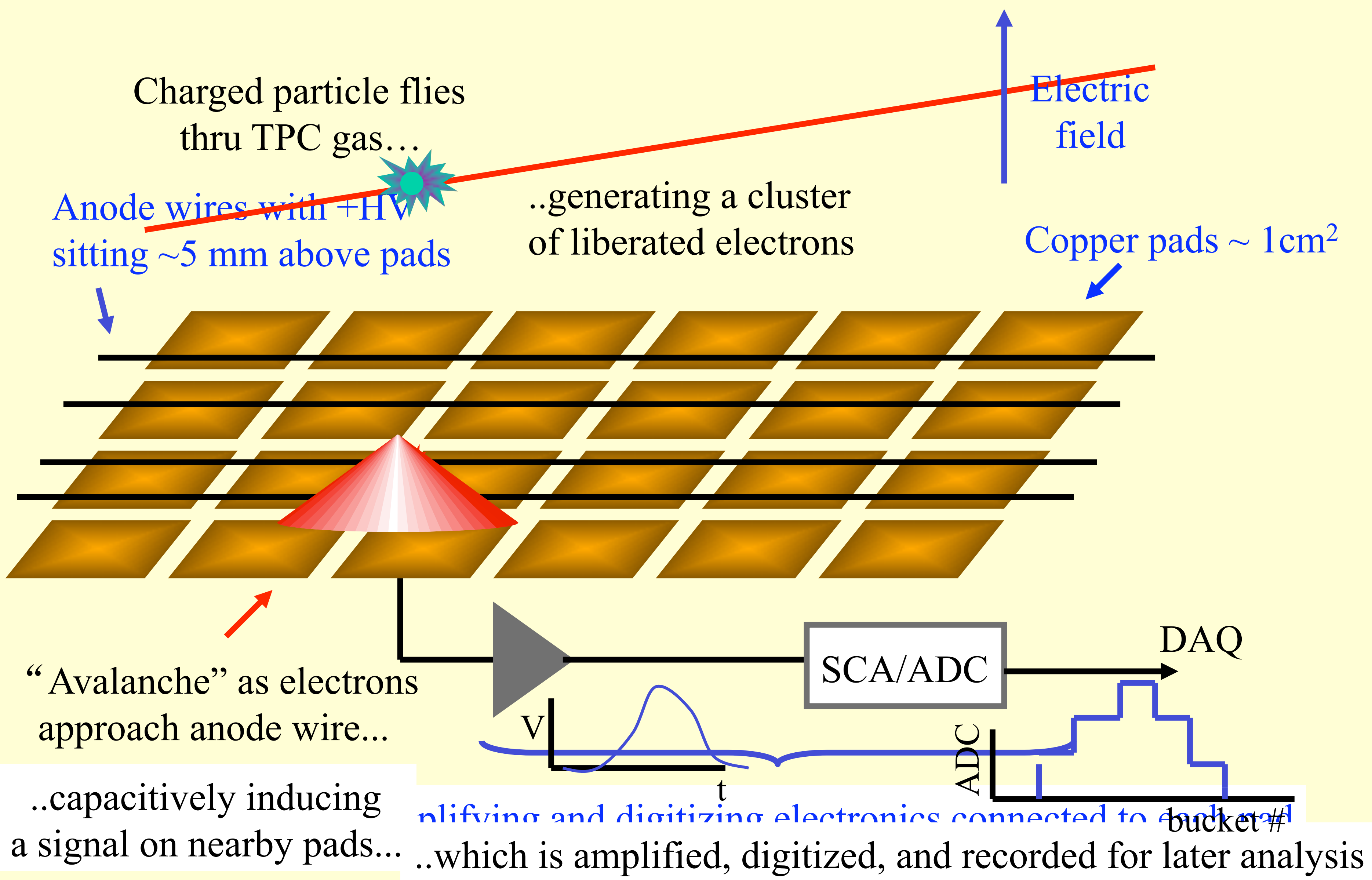




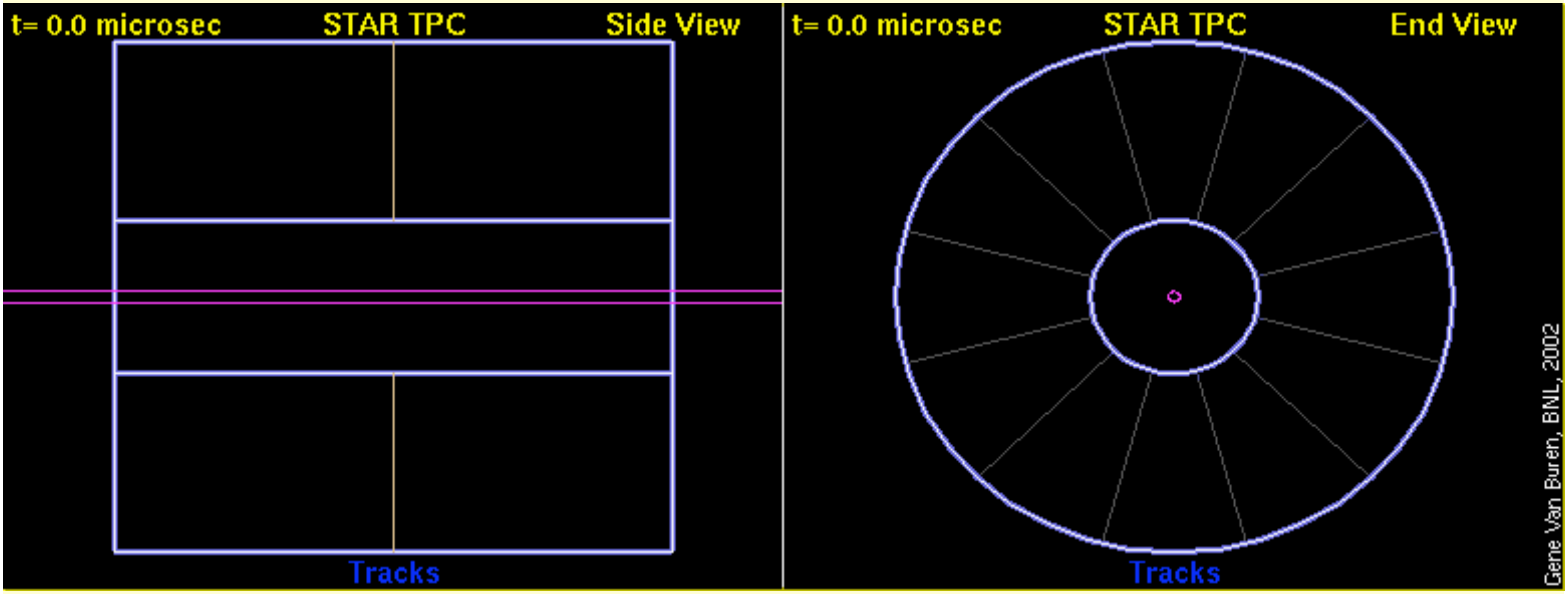
TPC - true tracking in 3-D



Operation of a Time Projection Chamber



Getting z-coord from drift time in TPC

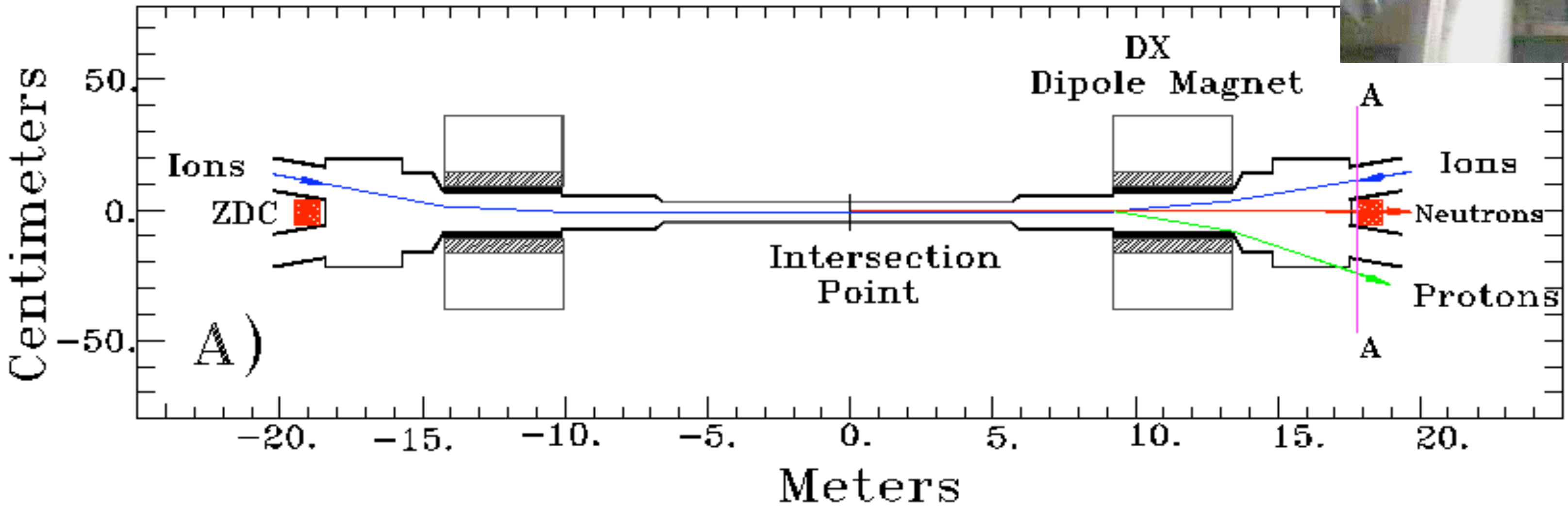


STAR ZDC

- Each of the RHIC experiments has a pair of Zero Degree Calorimeters for beam monitoring, triggering, and locating interaction vertices.

- ZDCs detect neutrons emitted along beam directions and measure their total energy (multiplicity) .

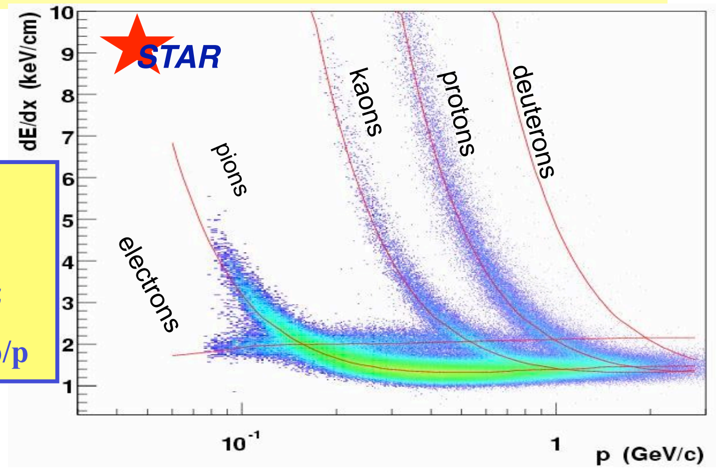
- *Baseline ZDCs have no <u>transverse segmentation,</u>* which motivates upgrade.



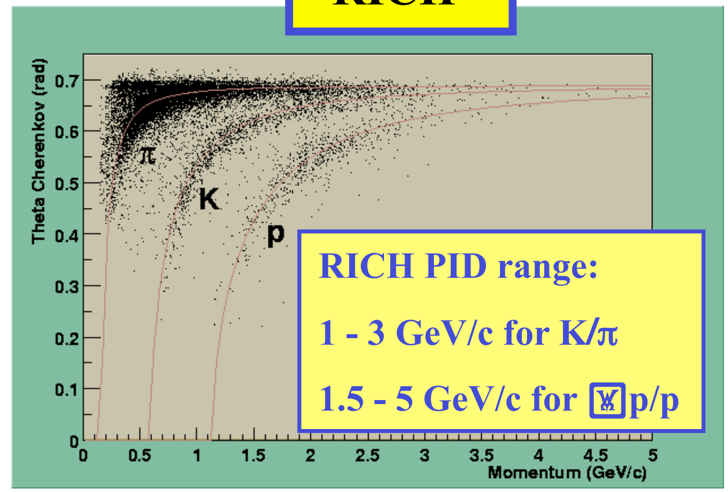
Particle ID in STAR

dE/dx

dE/dx PID range:
[σ (dE/dx) = .08]
p → ~ 0.7 GeV/c for K/π
→ ~ 1.0 GeV/c for ☒p/p



RICH

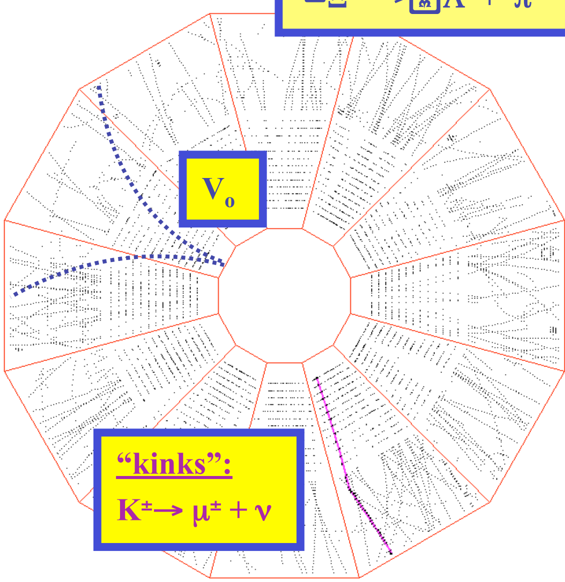


RICH PID range:
1 - 3 GeV/c for K/π
1.5 - 5 GeV/c for ☒p/p

Topology

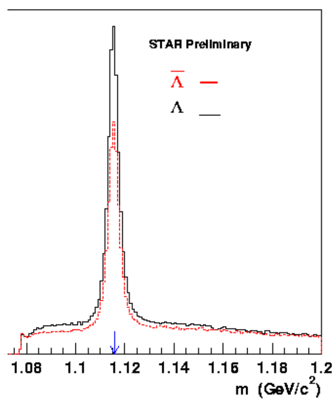
Decay vertices

$K_s \rightarrow \pi^+ + \pi^-$ $\Lambda \rightarrow p + \pi^-$
☒Λ → ☒p + π^+ $\Xi^- \rightarrow \Lambda + \pi^-$
☒Ξ^+ → ☒Λ + π^+ $\Omega \rightarrow \Lambda + K^-$



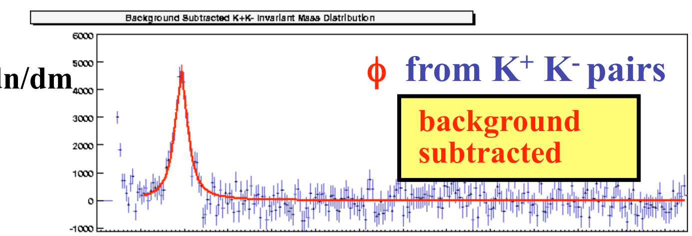
V_o

"kinks":
$K^\pm \rightarrow \mu^\pm + \nu$



Combinatorics

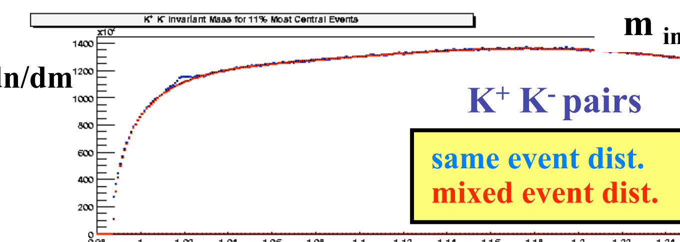
$K_s \rightarrow \pi^+ + \pi^-$ $\phi \rightarrow K^+ + K^-$
$\Lambda \rightarrow p + \pi^-$ $\bar{\Lambda} \rightarrow$ ☒p + π^+
[$\rho \rightarrow \pi^+ + \pi^-$]   [$\Delta \rightarrow p + \pi^-$]



ϕ from $K^+ K^-$ pairs

background subtracted

m inv

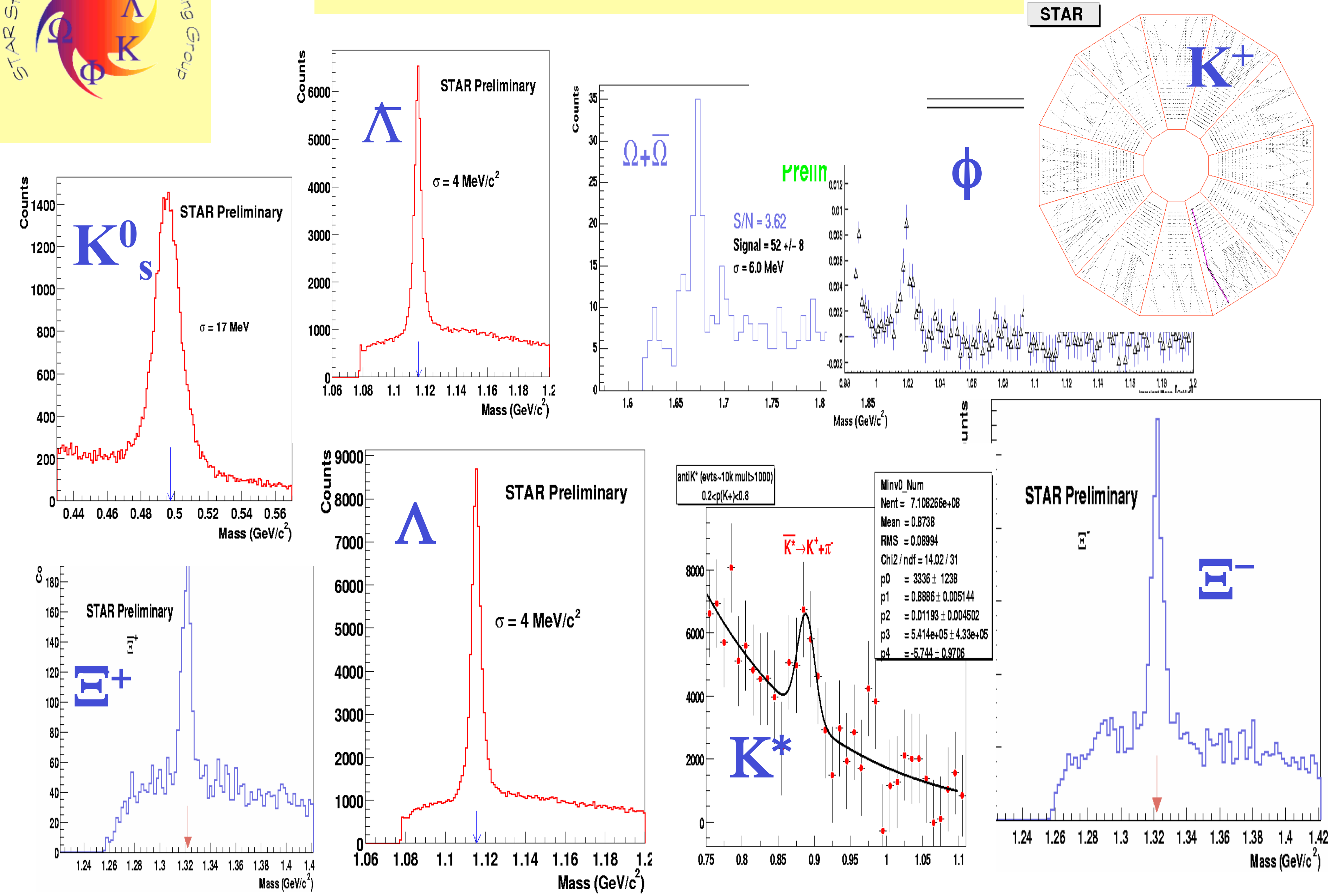


$K^+ K^-$ pairs

same event dist.
mixed event dist.

m inv

STAR STRANGENESS



How to Observe QGP in Nuclear Collisions

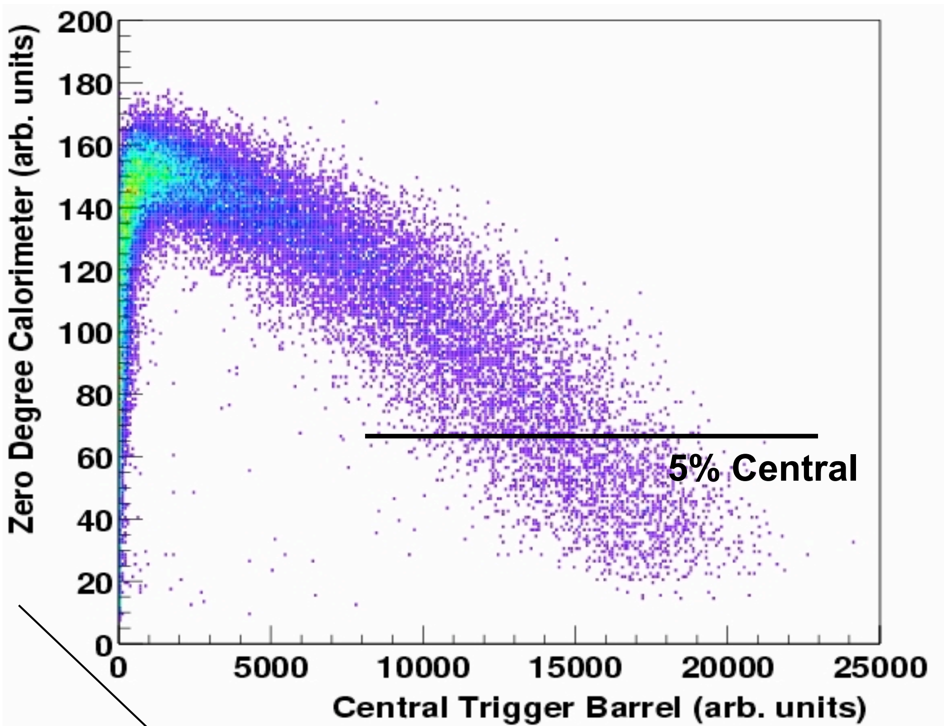
- Nuclear collisions are highly dynamic, no first-principles theory
- Emphasis shifts – Experience and Surprises
- Some tools to distinguish deconfined QGP from dense hadron gas:
  - High energy density: interaction of jets with medium
  - High temperature: direct photons
  - Quasi-equilibrium at early stage: flow
  - Rapid equilibration, mass shifts: strangeness enhancement
  - Threshold behavior: must be able to turn effects off

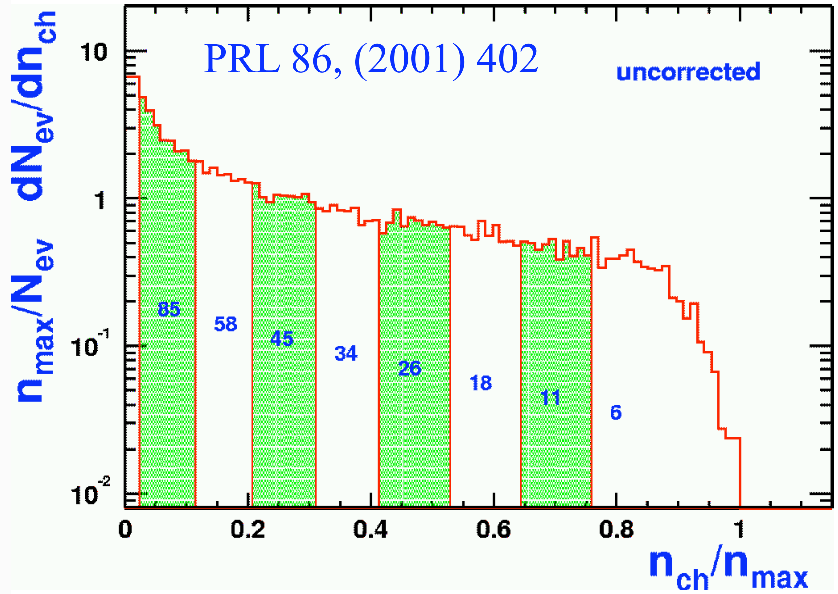
    ⇒$\sqrt{s}$, centrality of collision, mass of system

    ⇒Need p-p, d-Au reference data or central/peripheral event selection

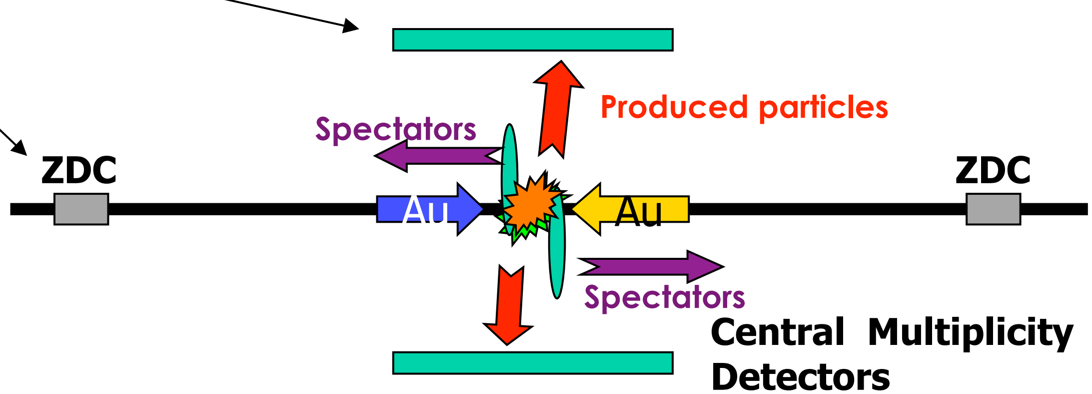
QGP must emerge as most reasonable picture from many different observables simultaneously

Event (Centrality) Selection





n_{ch} = primary tracks in $|\eta| < 0.75$



Soft Physics: $p_T < 2$ GeV/c

Goal: Characterize the bulk of the event

What do we know (or we think we do)?

- **High apparent energy density ~5 GeV/fm3 (lattice phase transition ~1 GeV/fm3, cold matter ~ 0.16 GeV/fm3)** PRL 86, 112303 (2001)

Bjorken Energy Density

- Bjorken '83: ideal 1+1 D relativistic hydrodynamics
- boost invariance $\Rightarrow \eta \sim 0$

$$\varepsilon = \frac{1}{\pi R^2 \tau} \frac{dE_T}{dy} \approx \frac{1}{\pi R^2 \tau} \langle p_T \rangle \frac{3}{2} \frac{dN_{ch}}{d\eta} \quad (R \sim A^{1/3}, \tau = 1 \text{ fm/c})$$

Central Au+Au @ $\sqrt{s_{NN}}$=130:

- PHENIX E_T: ε = 4.6 GeV/fm^3 *(nucl-ex/0104015)*
- STAR charged particles: ε ~ 4.5 GeV/fm^3

Compare NA49 Pb+Pb@SPS: ε ~ 3 GeV/fm^3 (τ = 1 fm/c)

Critical issues:

- Has equilibrium been achieved? (i.e. hydrodynamics valid?)
- If so, what is formation time τ?

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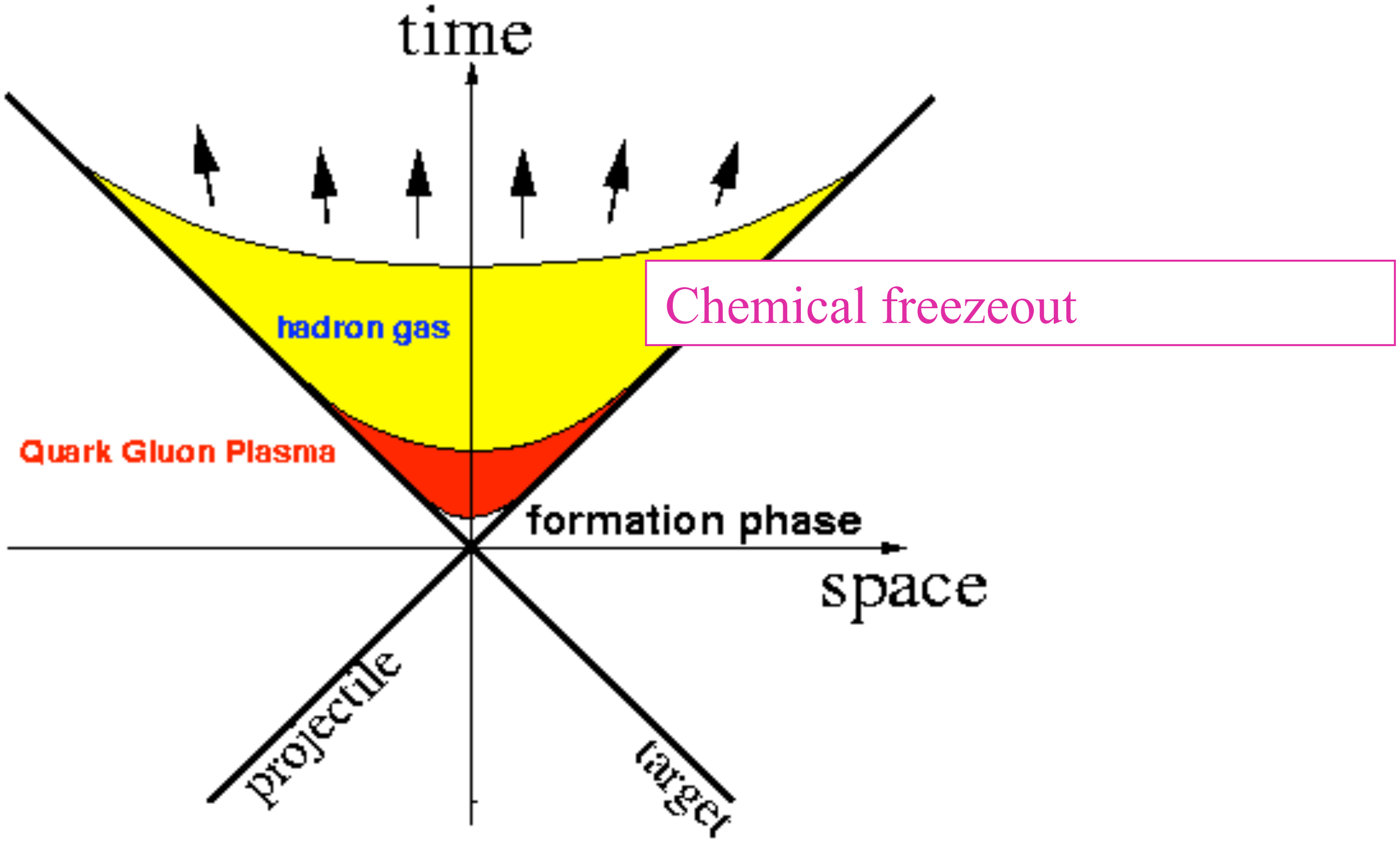
•**Chemical equilibrium(?): T~175 MeV, μ_B<40 MeV ⇒ near lattice phase boundary** PRC **66**, 061901(R) (2002); PRL **89**, 092301 (2002); PRC **65**, 041901(R) (2002); nucl-ex/0211024; nucl-ex/0206008

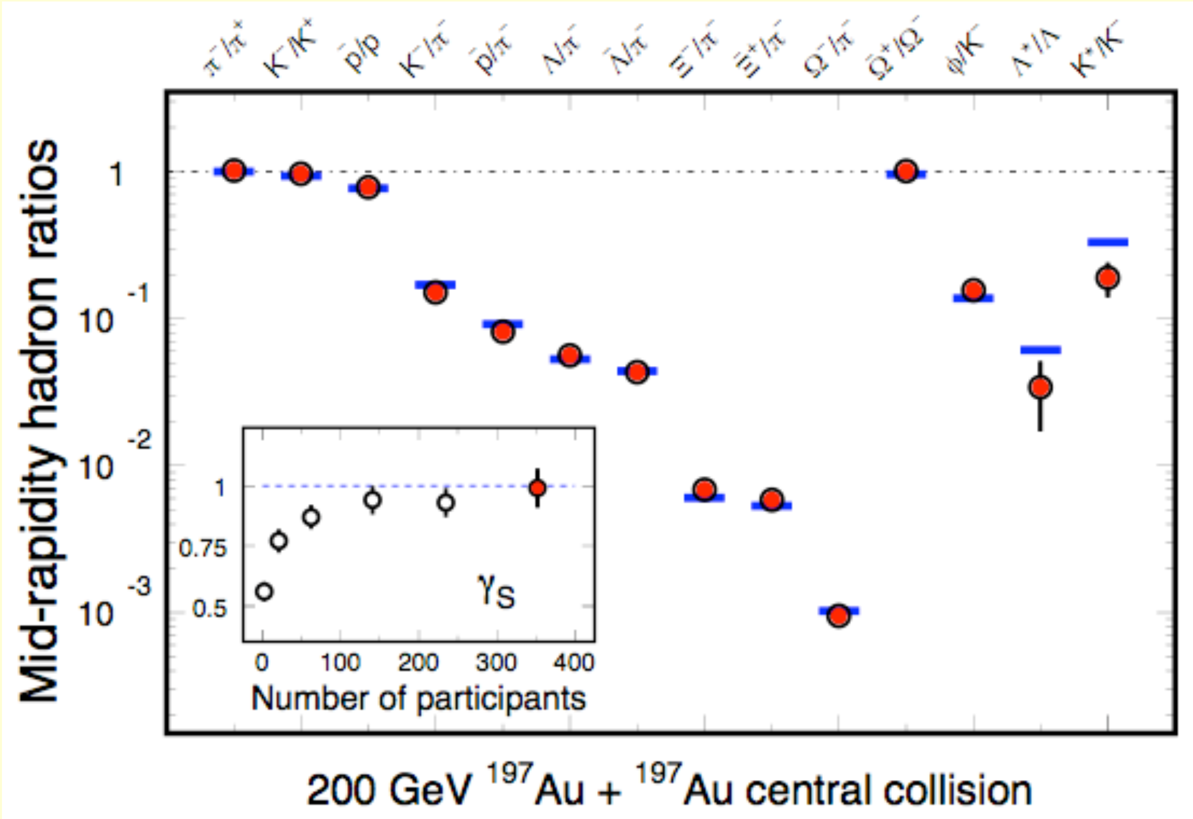
Particle Ratios in Central Collisions



Simple thermal model:

- Partition fn, spectrum of hadrons
- Parameters T, μ_B, μ_s
- Fit to ratios of antiparticle/particles: $\pi, K, p, \Lambda, \Xi, K^*_0$

Yields Ratio Results



data

Thermal model fits

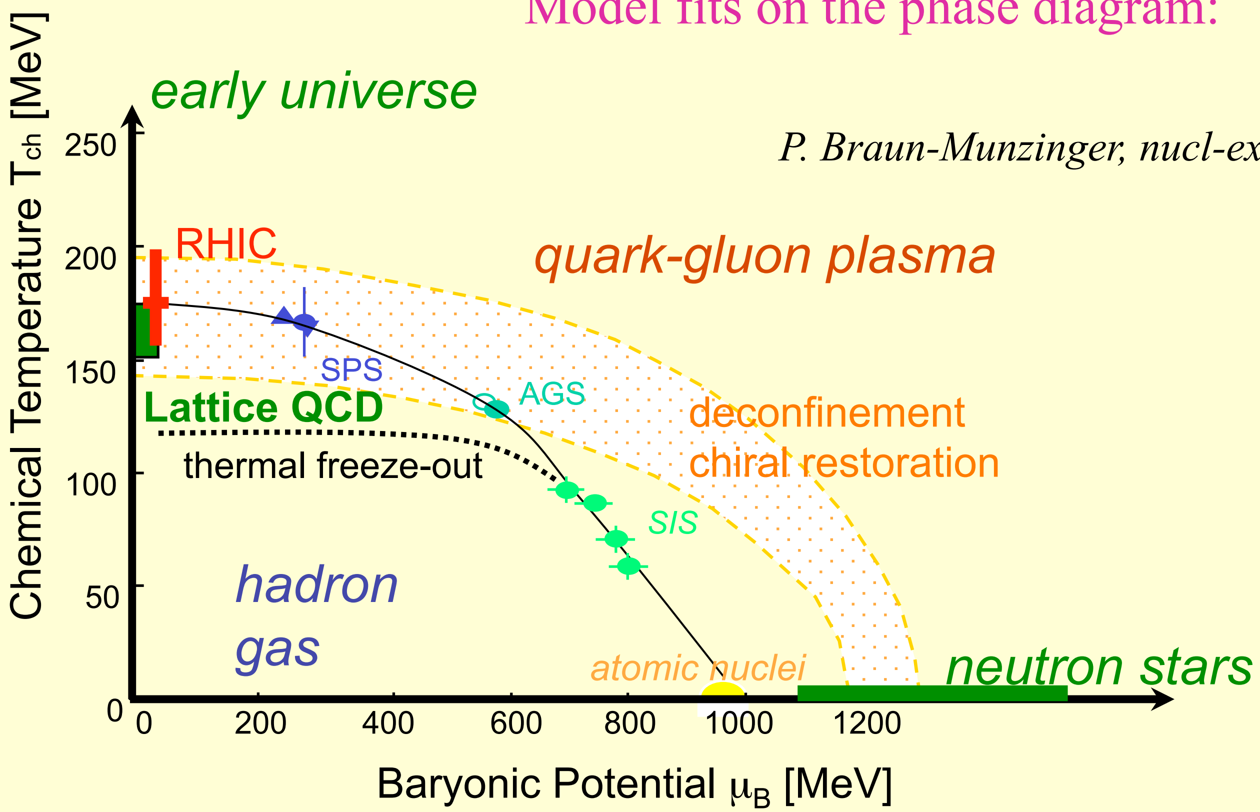
T_{ch} = 163 ± 4 MeV

μ_B = 24 ± 4 MeV

- In central collisions, thermal model fit well with $\gamma_S = 1$. **The system is thermalized at RHIC.**
- Short-lived resonances show deviations. **There is life after chemical freeze-out.** RHIC white papers - 2005, Nucl. Phys. *A757*, STAR: p102; PHENIX: p184.

Phase Diagram at Chemical Freezeout

Put parameters from Thermal Model fits on the phase diagram:



- parameters near phase boundary
- (strangeness) equilibration time for hadronic gas very long (~50 fm/c)
- do we have more direct evidence of early equilibration?

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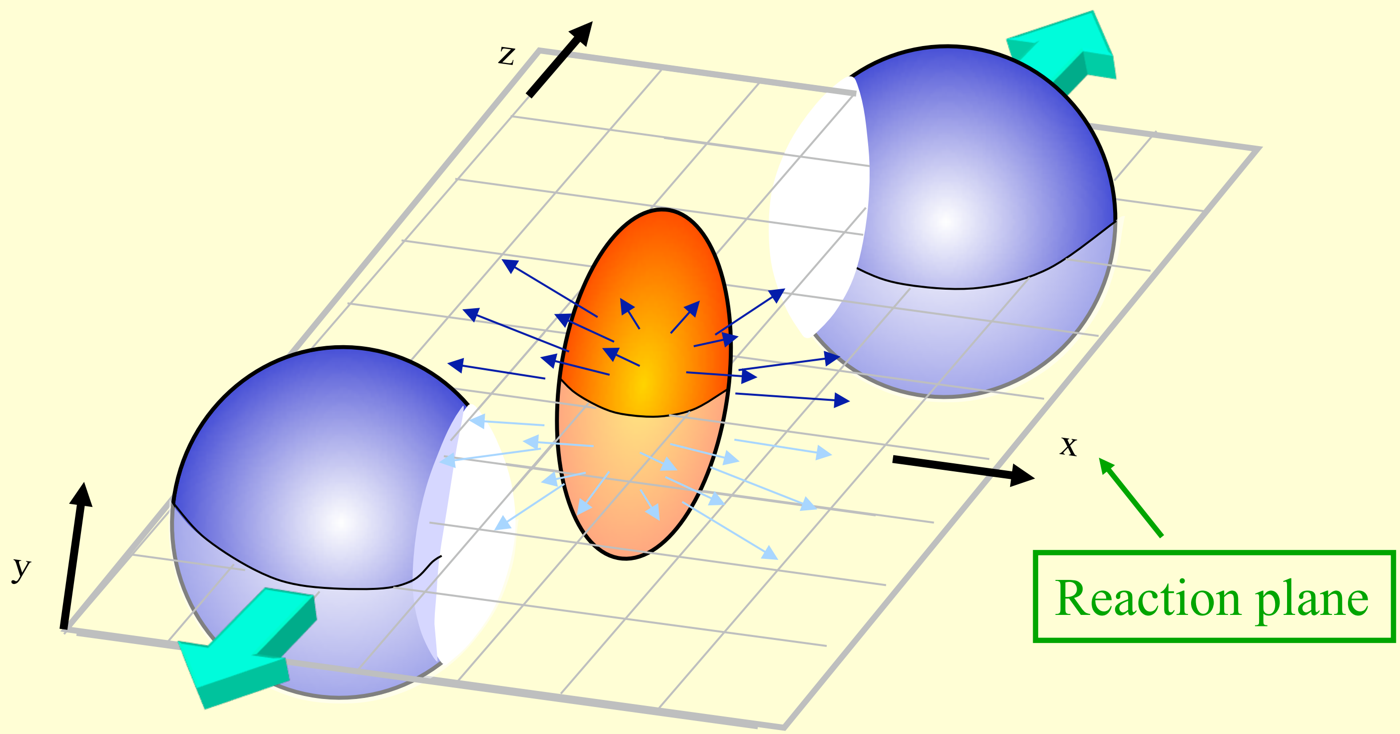
• **Hydrodynamics works well** PRL **90**, 032301 (2003); PRC **66**, 034904 (2002); PRL **89**, 132301 (2002); PRL **87**, 182301 (2001); PRL **86,** 402 (2001)

(With some trouble with HBT correlations)

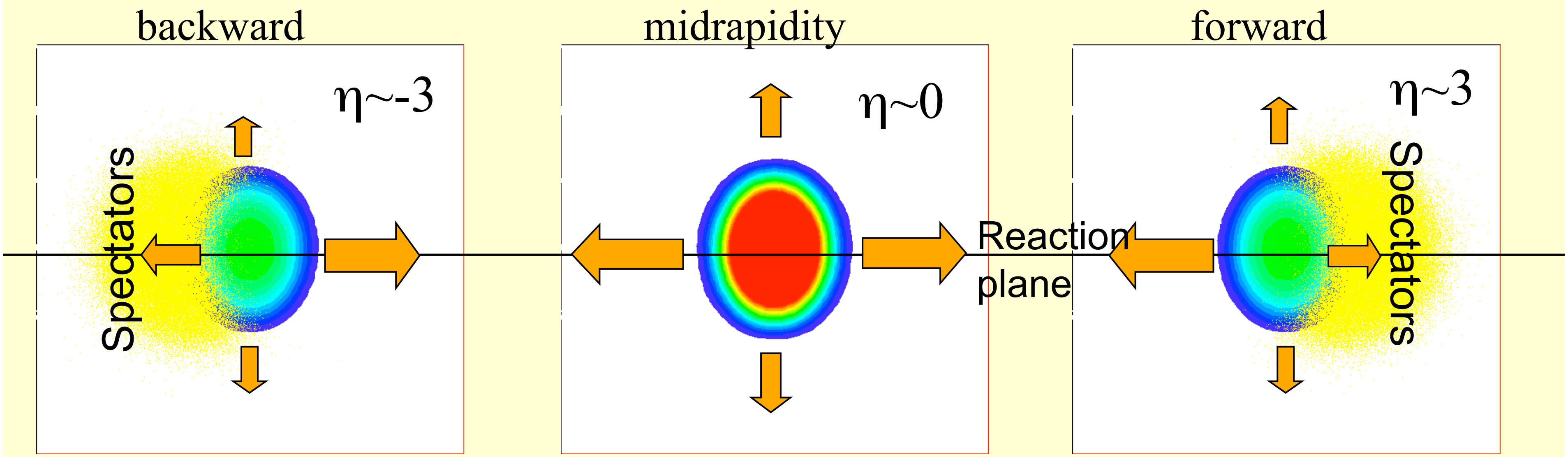
Geometry of Heavy Ion Collisions

Non-central Collisions



Elliptic Flow

Anisotropic flow: v1, v2, v4



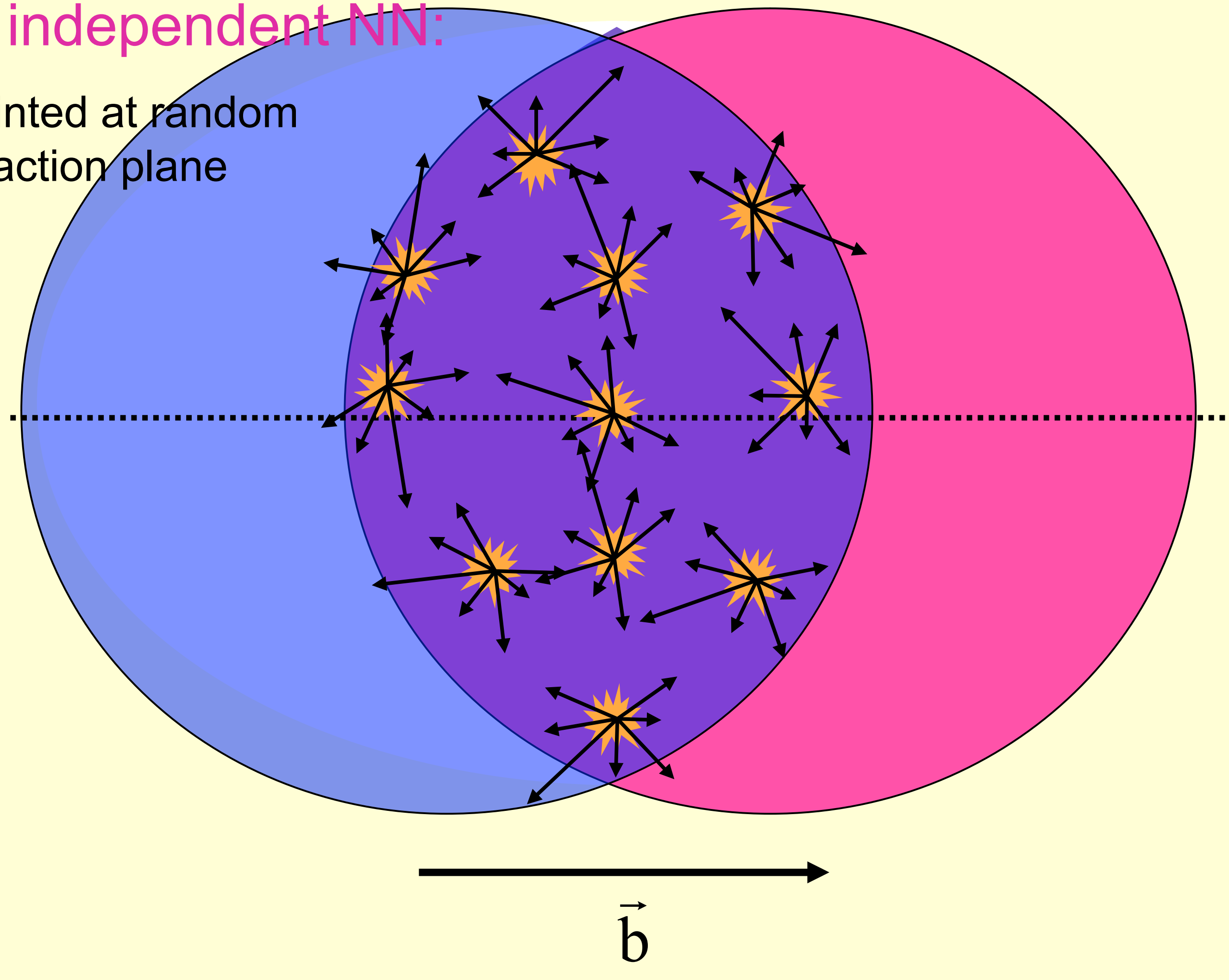
$$\frac{dN}{dY p_T dp_T d\varphi} = \frac{dN}{dY p_T dp_T} \frac{1}{2\pi} \left(1 + 2v_1 \cos\varphi + 2v_2 \cos 2\varphi + 2v_4 \cos 4\varphi + \ldots\right)$$

Directed flow Elliptic flow

Time evolution at finite b

1) Superposition of independent NN:

momenta pointed at random
relative to reaction plane



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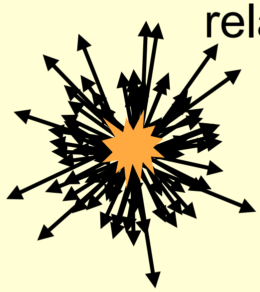
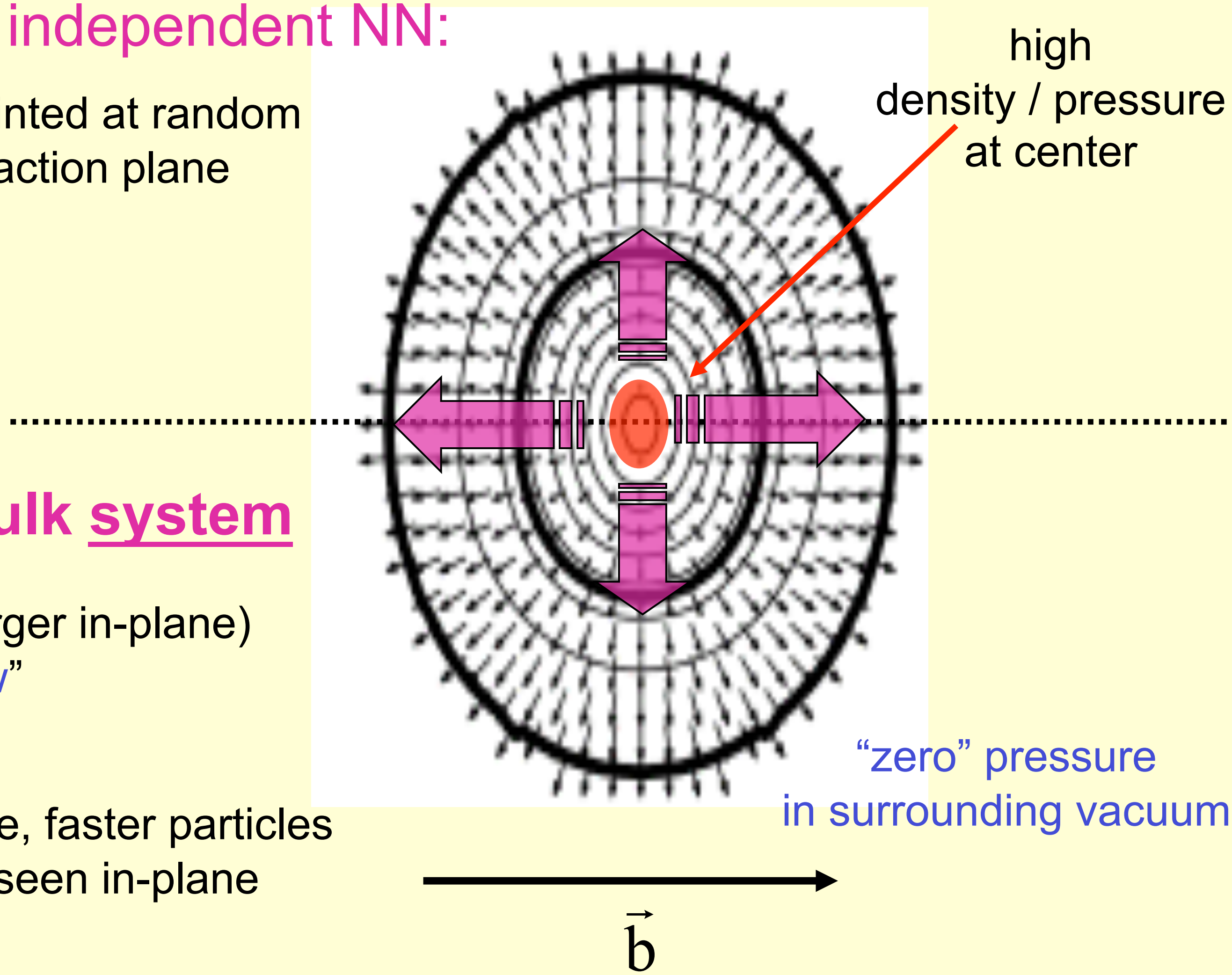
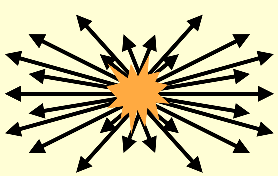


high
density / pressure
at center



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

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



more, faster particles
seen in-plane

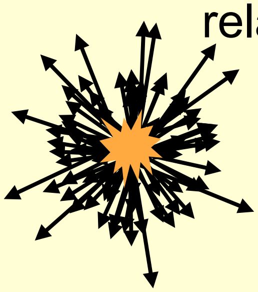
"zero" pressure
in surrounding vacuum

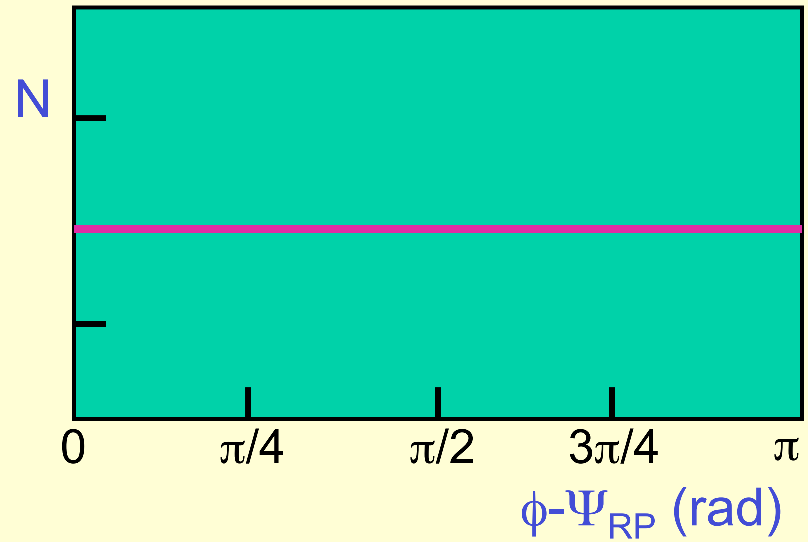
$\vec{b}$

Time evolution at finite b

1) Superposition of independent NN:

momenta pointed at random
relative to reaction plane





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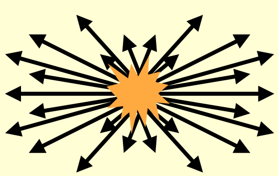
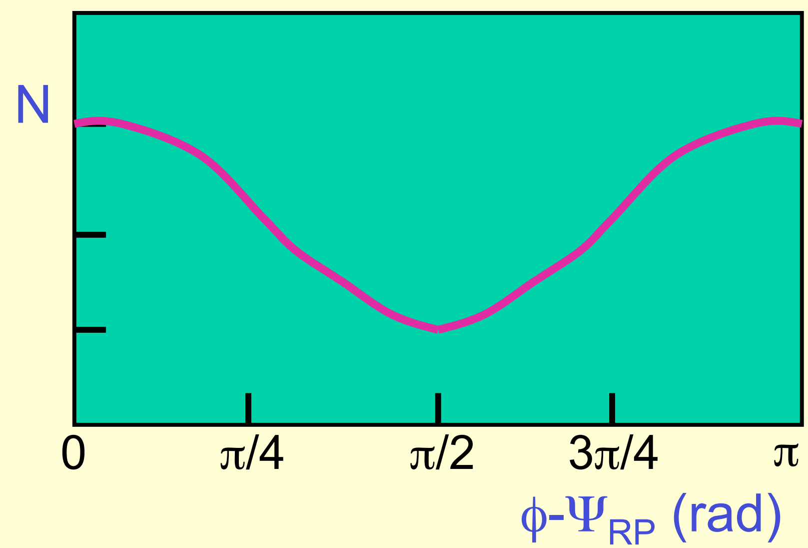
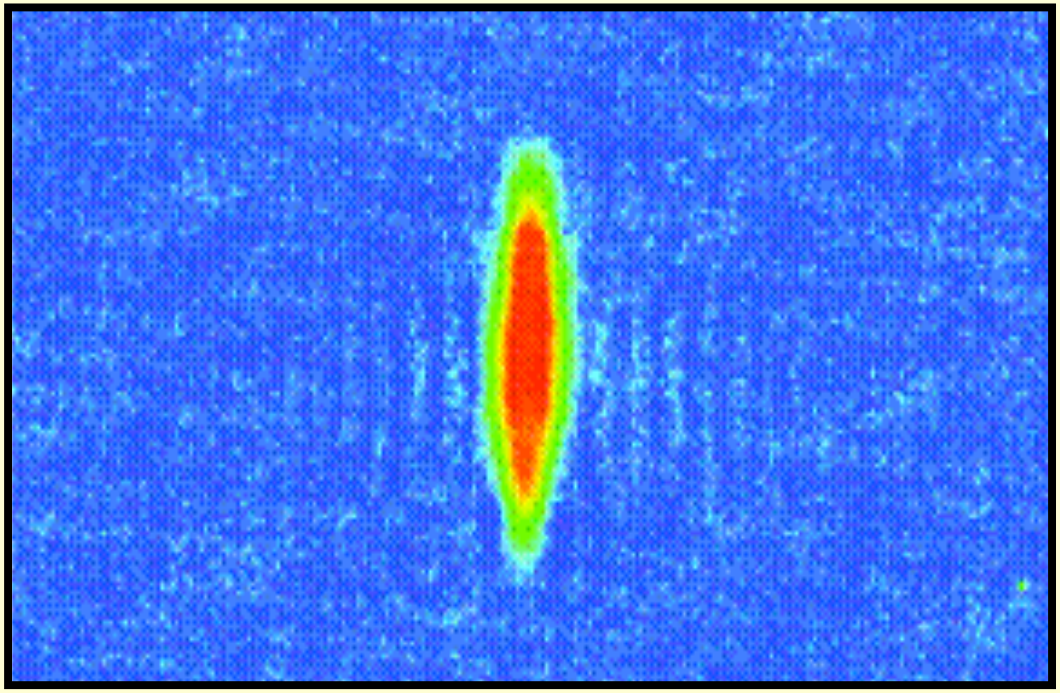
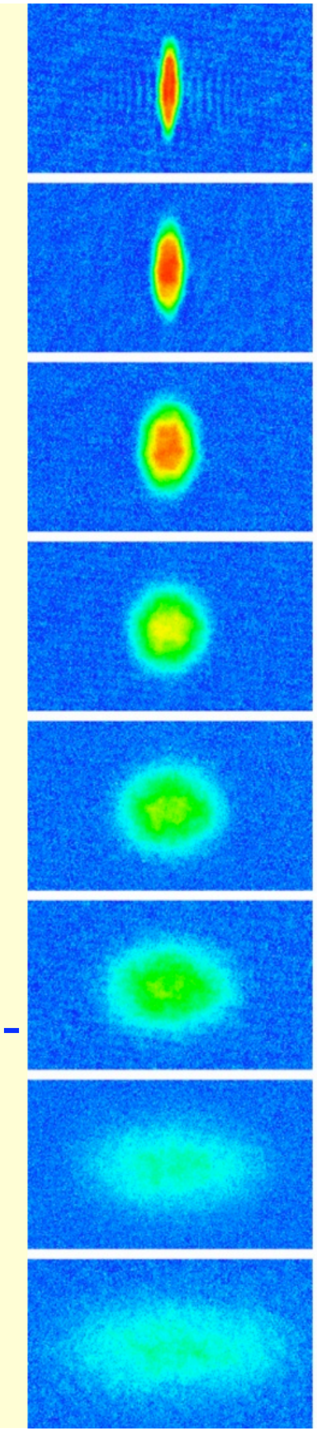


more, faster particles
seen in-plane



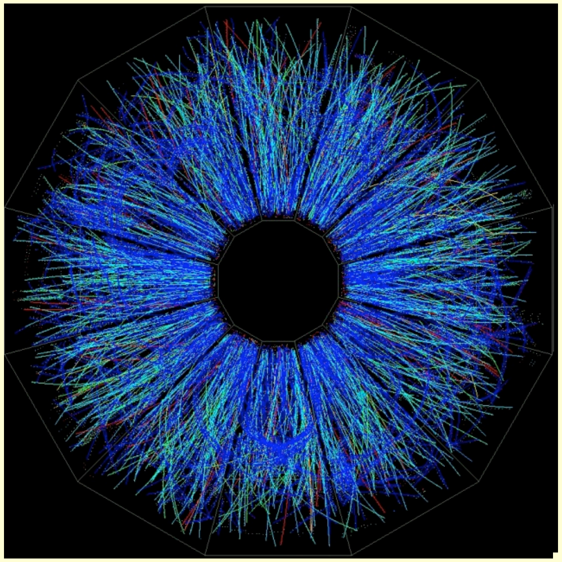
Elliptic Flow: ultra-cold Fermi-Gas





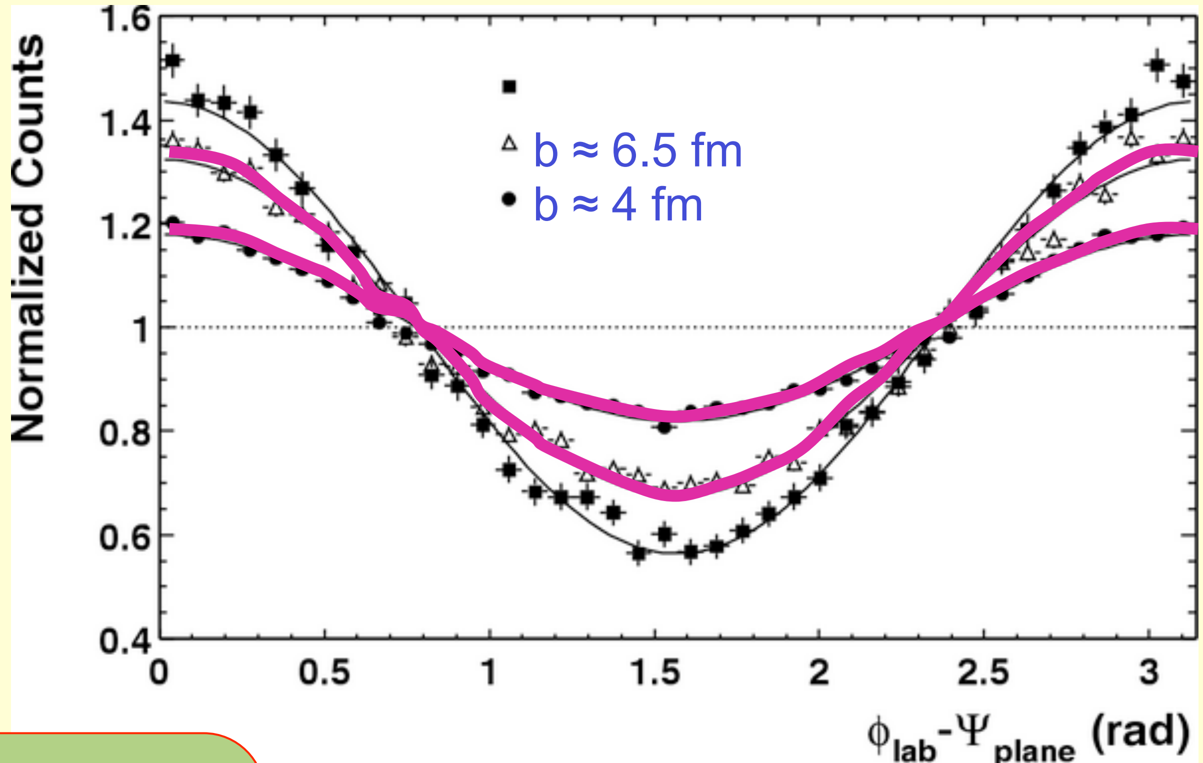
- Li-atoms released from an optical trap exhibit elliptic flow analogous to what is observed in ultra-relativistic heavy-ion collisions
- ➢ Elliptic flow is a general feature of strongly interacting systems!

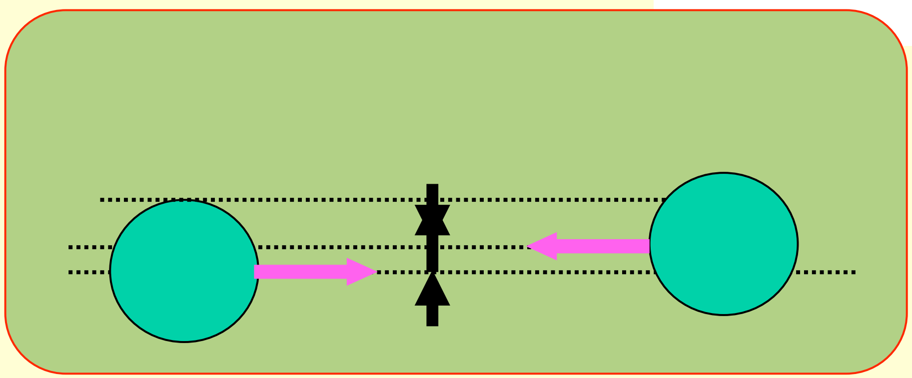
Resulting azimuthal distributions

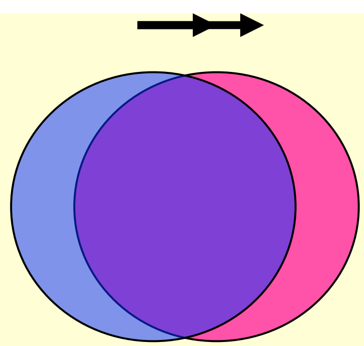


mid“central” collisions

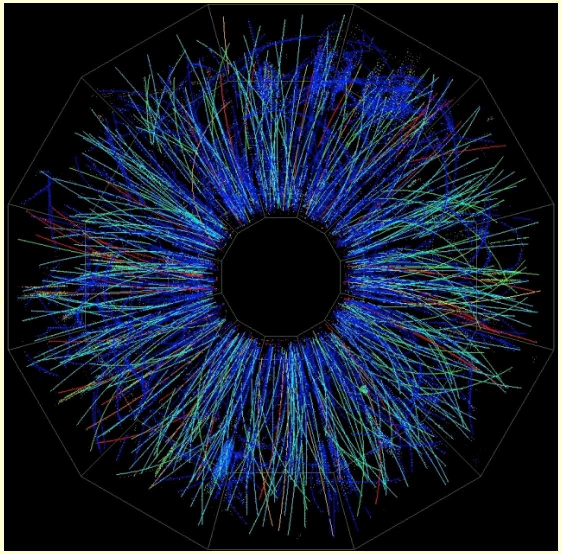
STAR, PRL**90** 032301 (2003)



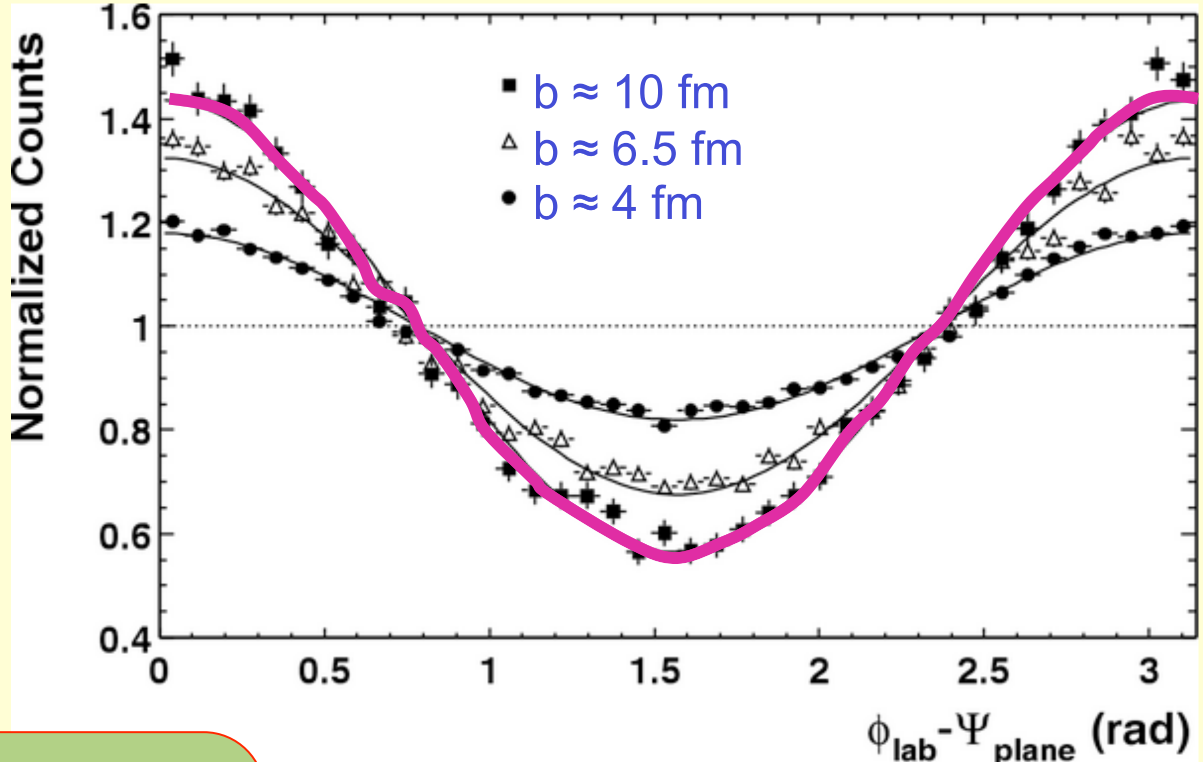




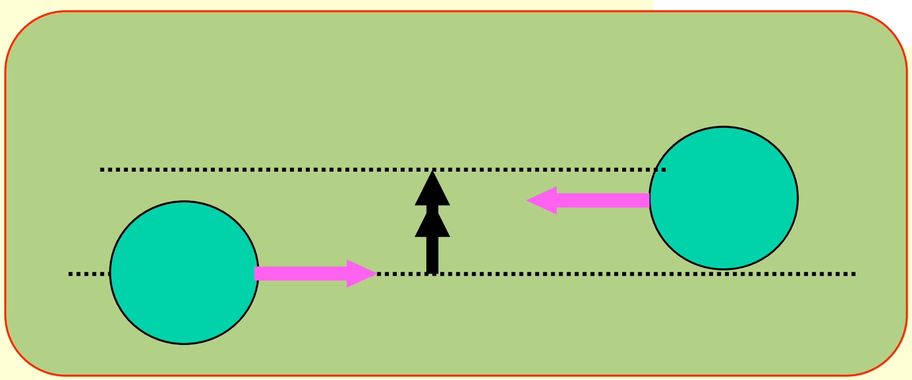
Resulting azimuthal distributions

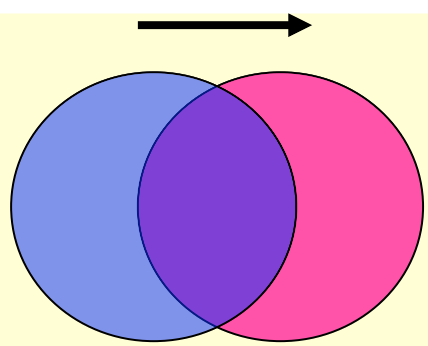


STAR, PRL**90** 032301 (2003)



peripheral collisions



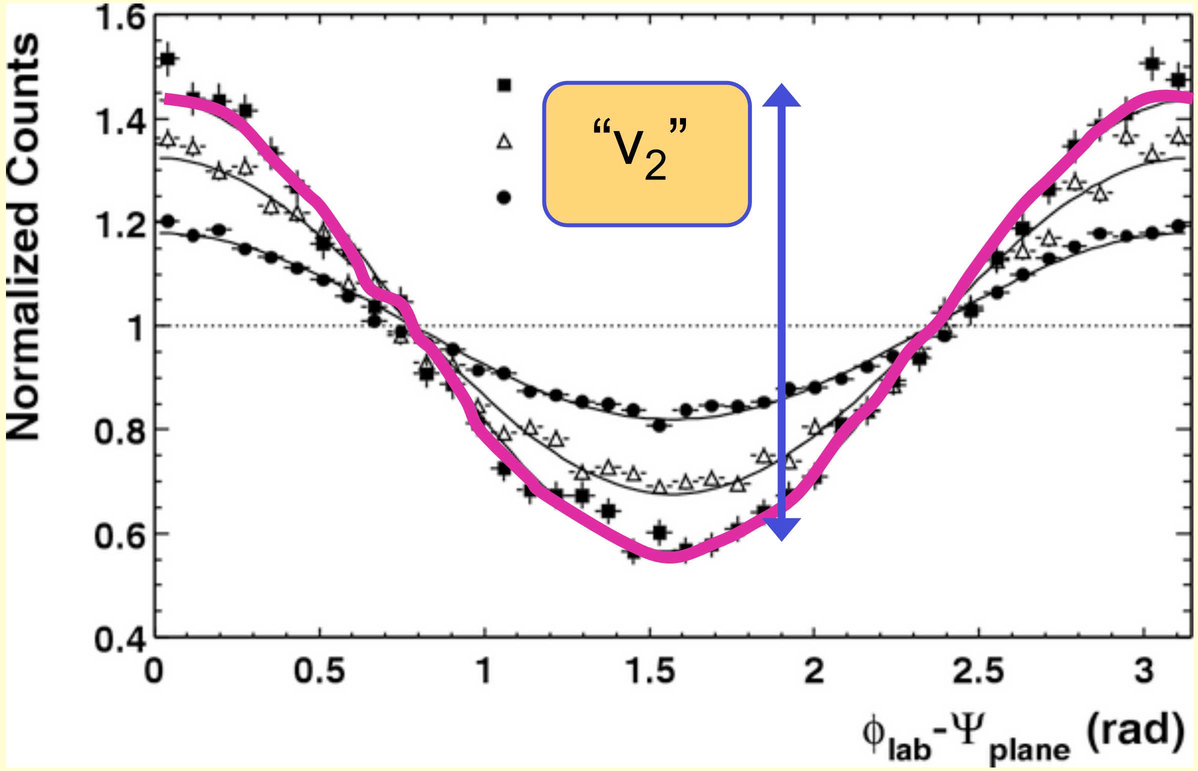


Elliptic flow

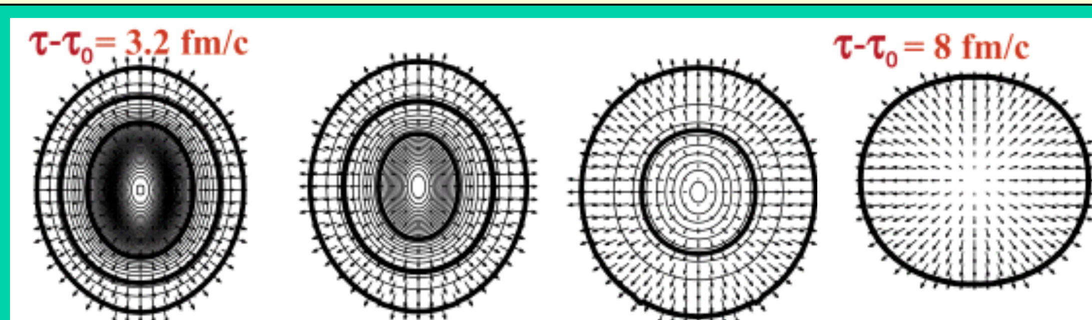
observed momentum anisotropy is largely elliptic deformation; its amplitude is denoted v2

RHIC v_2 reaches large values yielded by hydro (unlike lower energies)

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

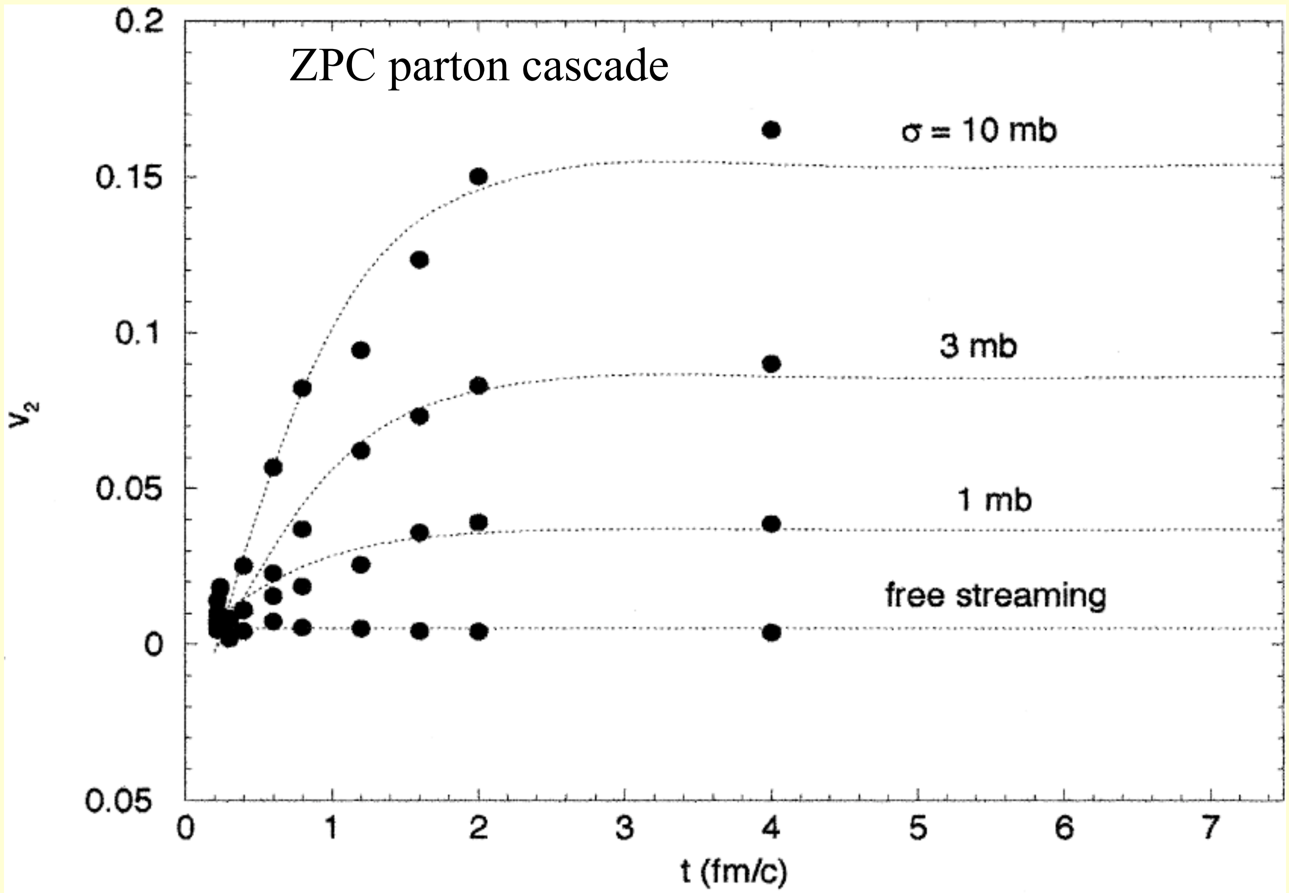


Hydrodynamic calculation of system evolution



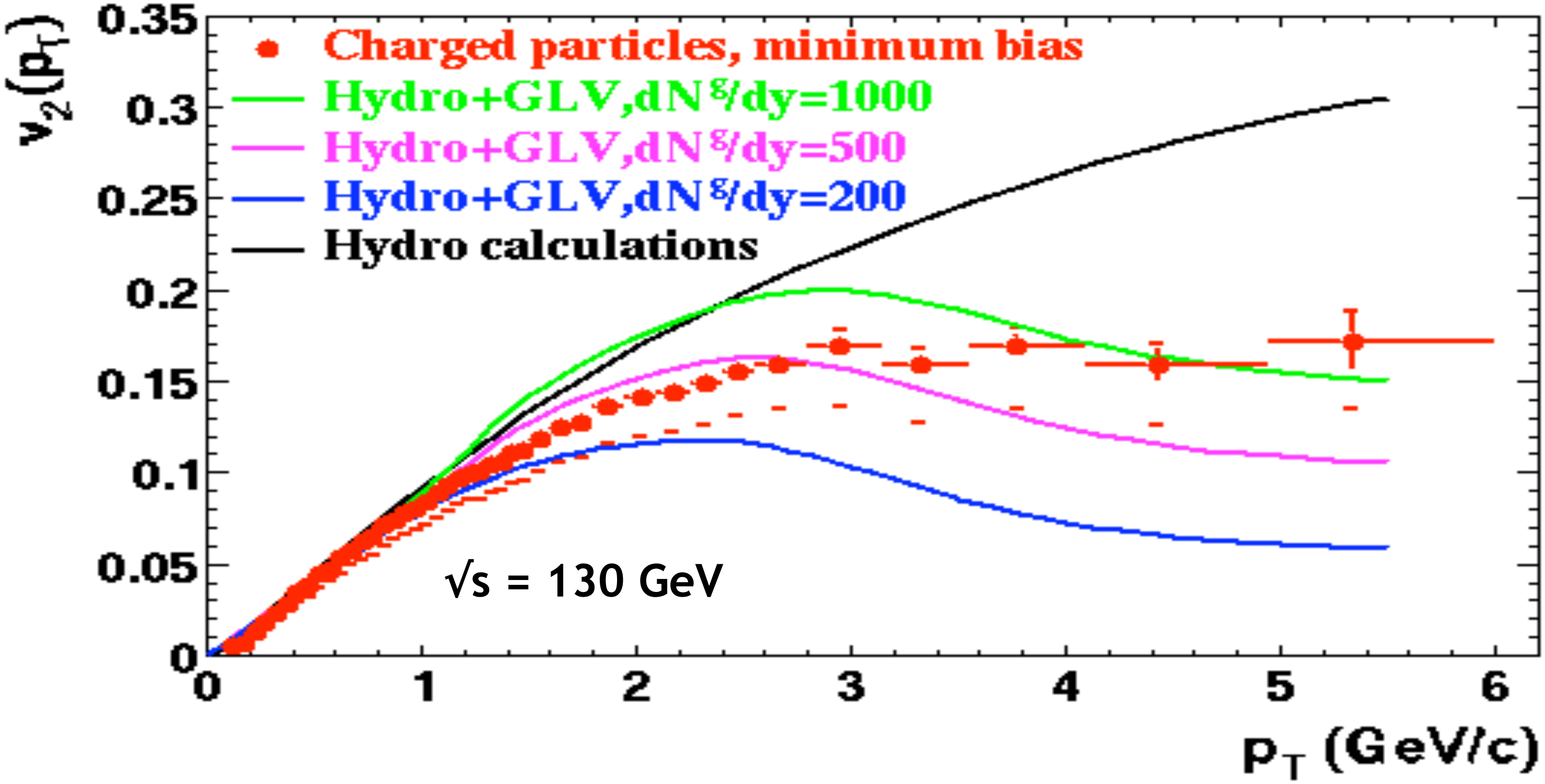
Elliptic flow - sensitive to early stages

Zhang, Gyulassy, Ko, Phys. Lett. **B 455,** 45 (1999)



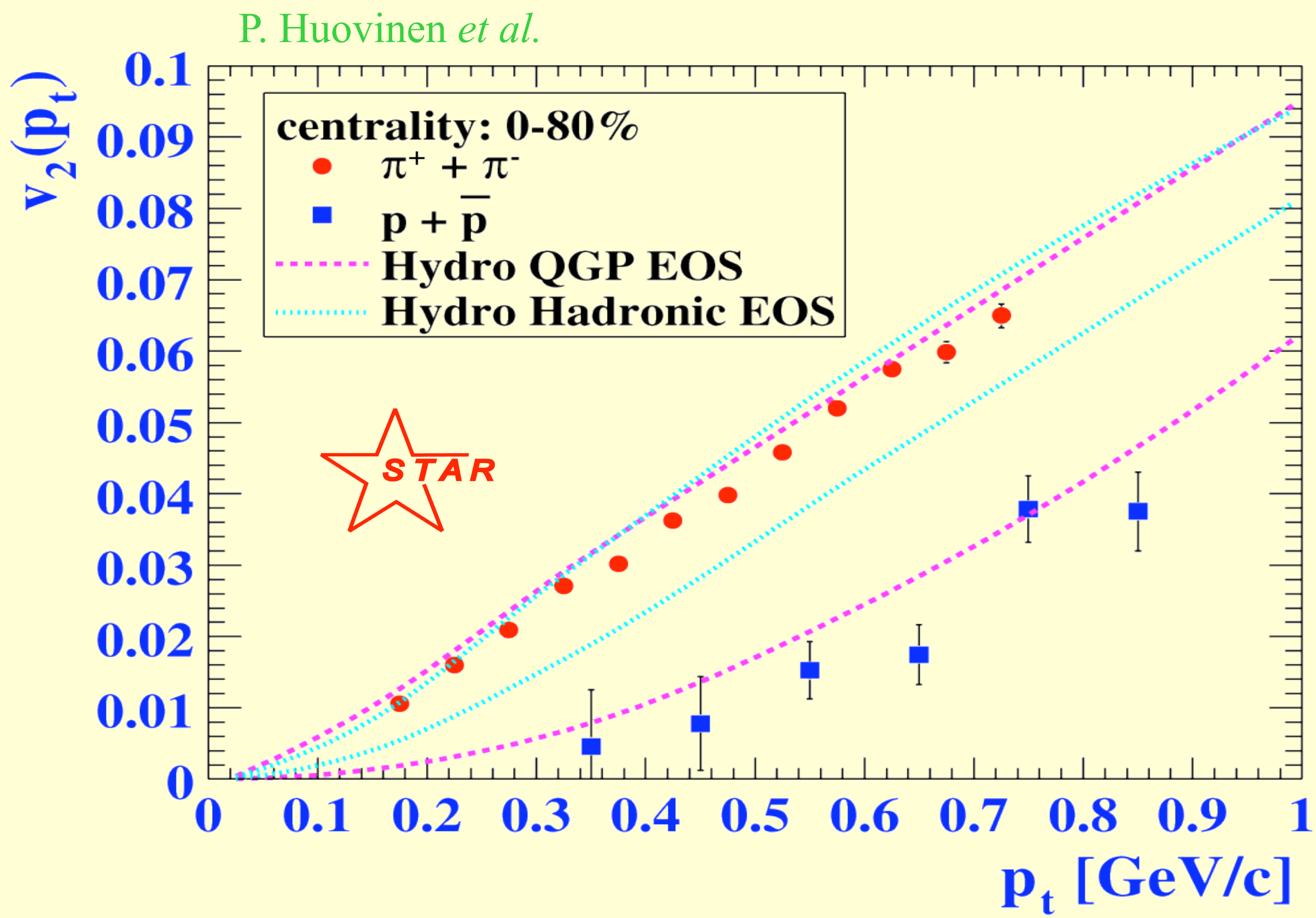
Azimuthal anisotropy of leading hadrons

PRL 90, 032301 (2003)

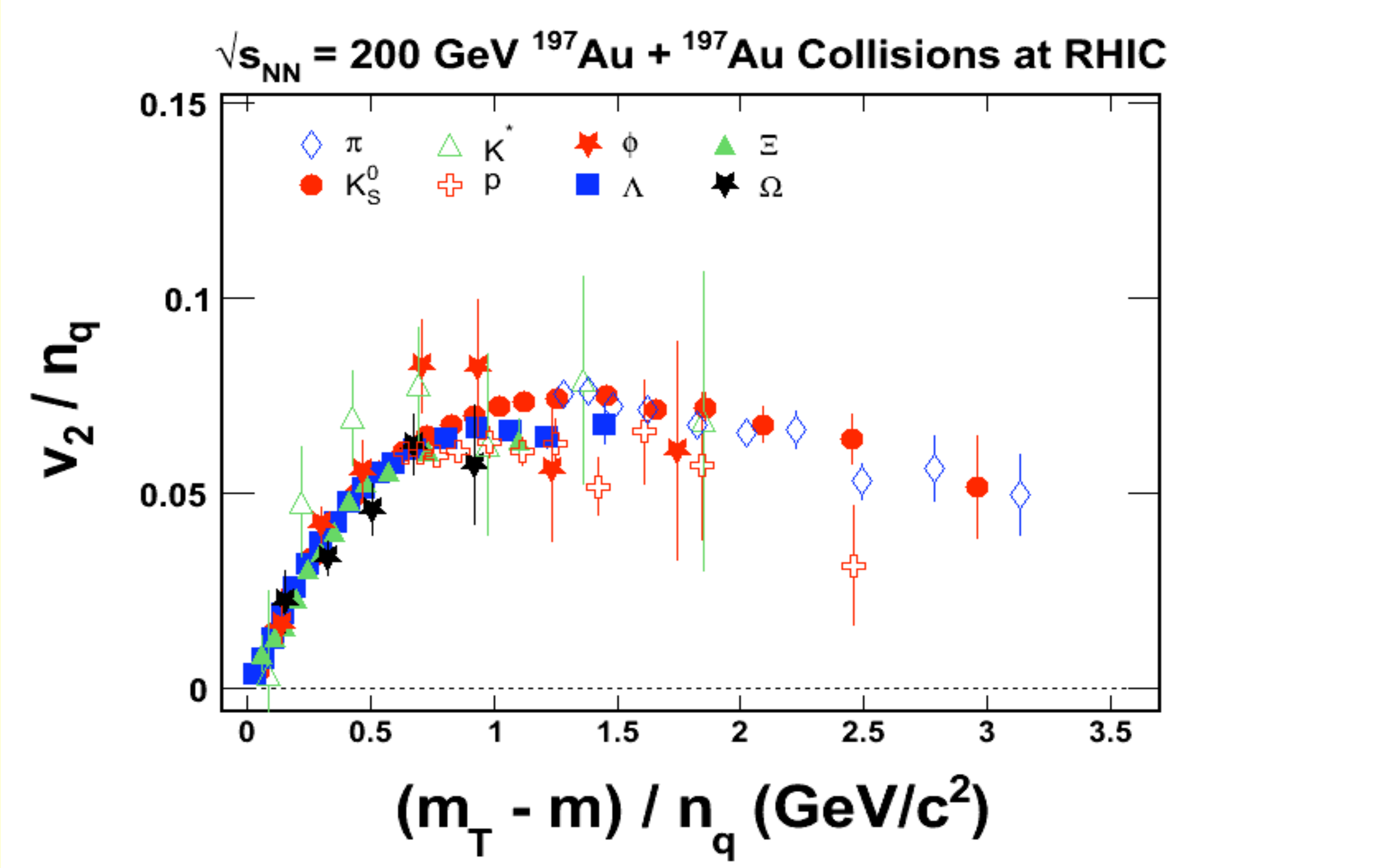


- p_T<2 GeV: detailed agreement with hydrodynamics
- p_T >4 GeV: flattening of data

Elliptic flow - sensitive to QGP/Hadronic EOS

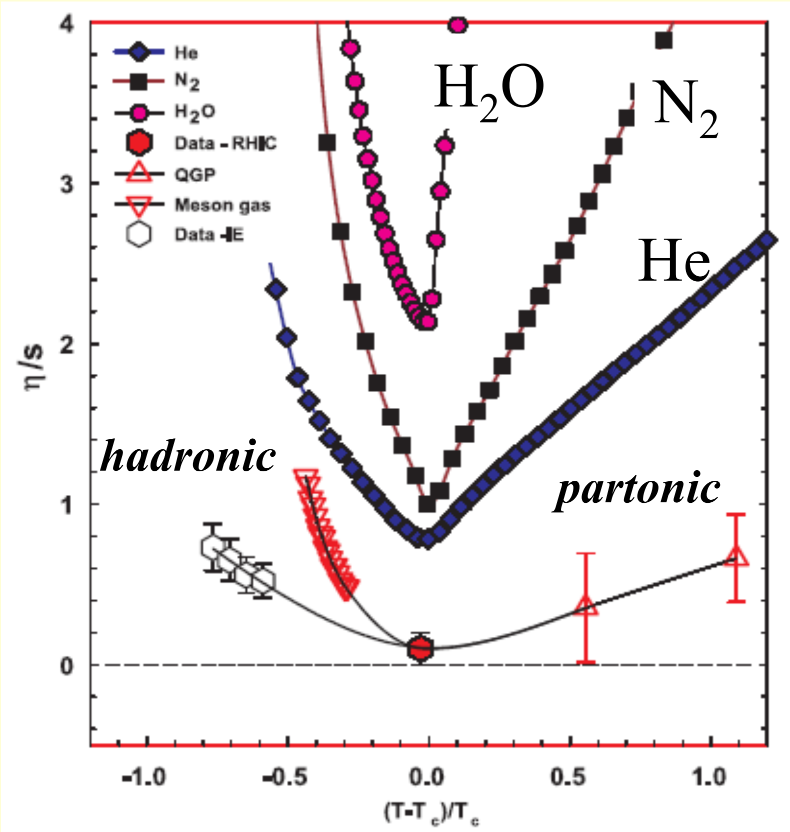


The bottom line:



It produces copious mesons and baryons with yield ratios and flow properties that suggest their formation via coalescence of valence quarks from a hot thermal bath.

Viscosity and the Perfect Fluid



Caption: The viscosity to entropy ratio versus a reduced temperature.

Lacey et al. PRL **98**:092301(07)
hep-lat/0406009
hep-ph/0604138

The universal tendency of flow to be dissipated due to the fluid's ***internal friction*** results from a quantity known as the **shear viscosity**. All fluids have non-zero viscosity. The larger the viscosity, the more rapidly small disturbances are damped away.

Quantum limit: $\eta/s_{AdS/CFT} \sim 1/4\pi$

pQCD limit: ~ 1

At RHIC: ideal ($\eta/s = 0$) hydrodynamic model calculations fit to data ⇒

Perfect Fluid at RHIC?!

APS top physics story in 2005

Soft Physics: p_T< 2 GeV/c

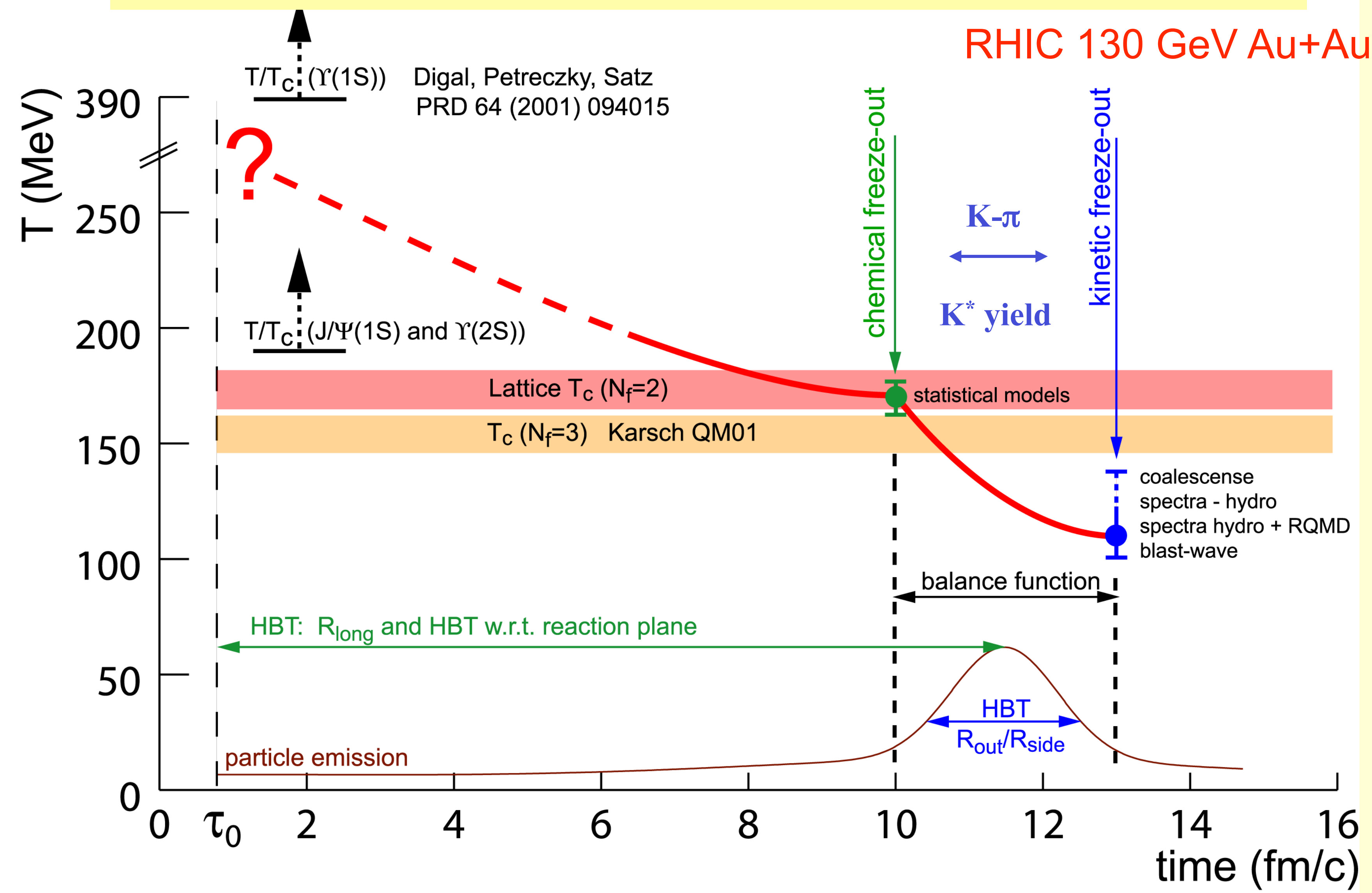
Goal: Characterize the bulk of the event

<u>What do we know (or we think we do)?</u>

- Baryon/antibaryon ratios ~0.6-1 close to baryon-free PRL 86, 4778 (2001)
- High apparent energy density ~5 GeV/fm3 (lattice phase transition ~1 GeV/fm3, cold matter ~ 0.16 GeV/fm3) PRL 86, 112303 (2001)
- Chemical equilibrium: T~175 MeV, μ_B<40 MeV ⇒ near lattice phase boundary PRC **66**, 061901(R) (2002); PRL **89**, 092301 (2002); PRC **65**, 041901(R) (2002); nucl-ex/0211024; nucl-ex/0206008
- **Hydrodynamics works well** PRL **90**, 032301 (2003); PRC **66**, 034904 (2002); PRL **89**, 132301 (2002); PRL **87**, 182301 (2001); PRL **86**, 402 (2001) **(With some trouble with HBT correlations)**
- **Explosive dynamics - Huge radial flow**

Overall picture: system appears to be in equilibrium but explodes and hadronizes rapidly ⇒ high initial pressure

Low-p_T dynamics — one (naïve?) interpretation: rapid evolution and a "flash"



Disclaimer: all numbers (especially time) are approximate

Hard Physics: $p_T > 2$ GeV/c

Goal: Penetrating probes

What do we know so far?

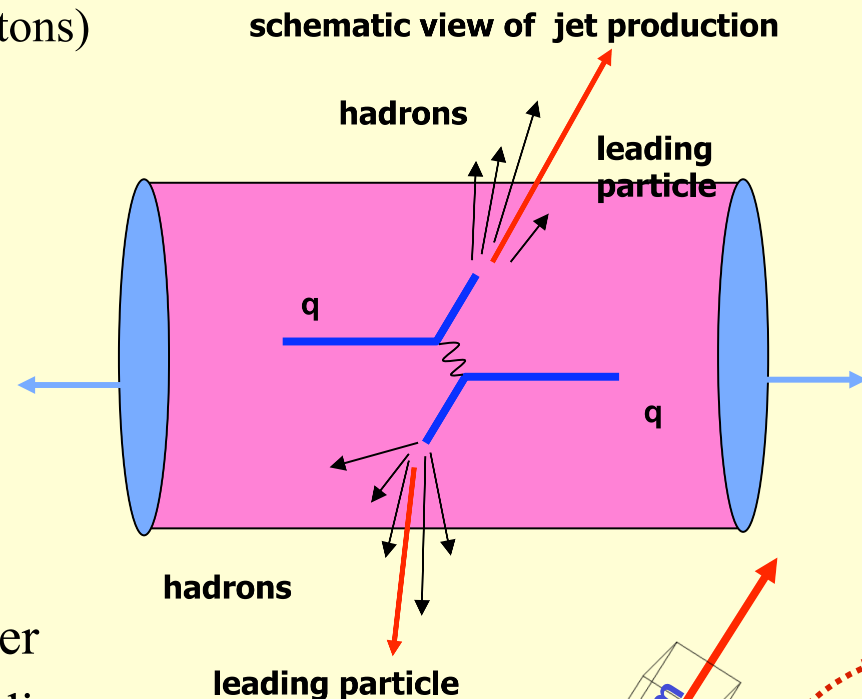
- **Leading Hadron Suppression in Central Collisions** PRL 89, 112303 (2001)

New with Heavy Ions at RHIC/LHC

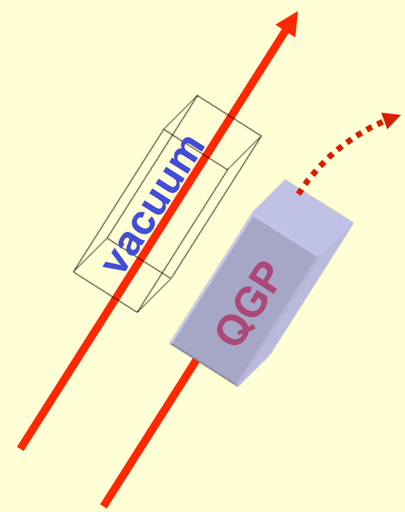
- New opportunity for heavy ion physics → *Hard Parton Scattering*
  - $\sqrt{s_{NN}}$ = 130 GeV at RHIC vs $\sqrt{s_{NN}}$ = 17 GeV at CERN SPS
- Jets and mini-jets (from hard-scattering of partons)
  → 30 - 50 % of particle production

  → high p_t leading particles

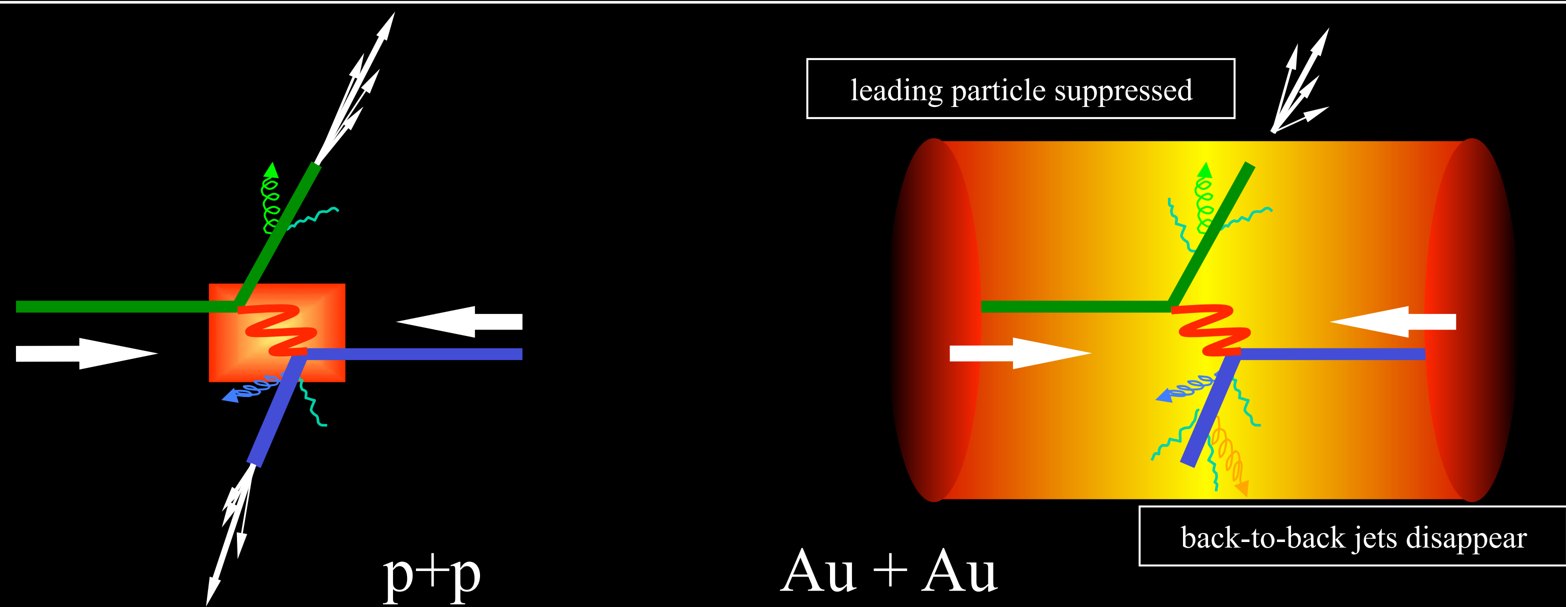
  → azimuthal correlations
- Extend into perturbative regime
  - Calculations reliable

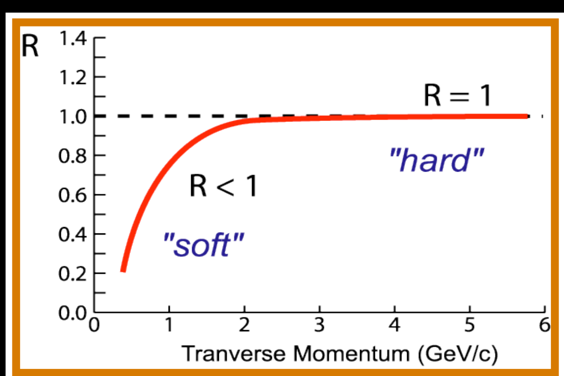


- Scattered partons propagate through matter radiate energy (~ GeV/fm) in colored medium
  - interaction of parton with partonic matter
  - suppression of high p_t particles
    aka "parton energy loss" or "jet quenching"
  - suppression of angular correlation



Energy Loss in A+A Collisions



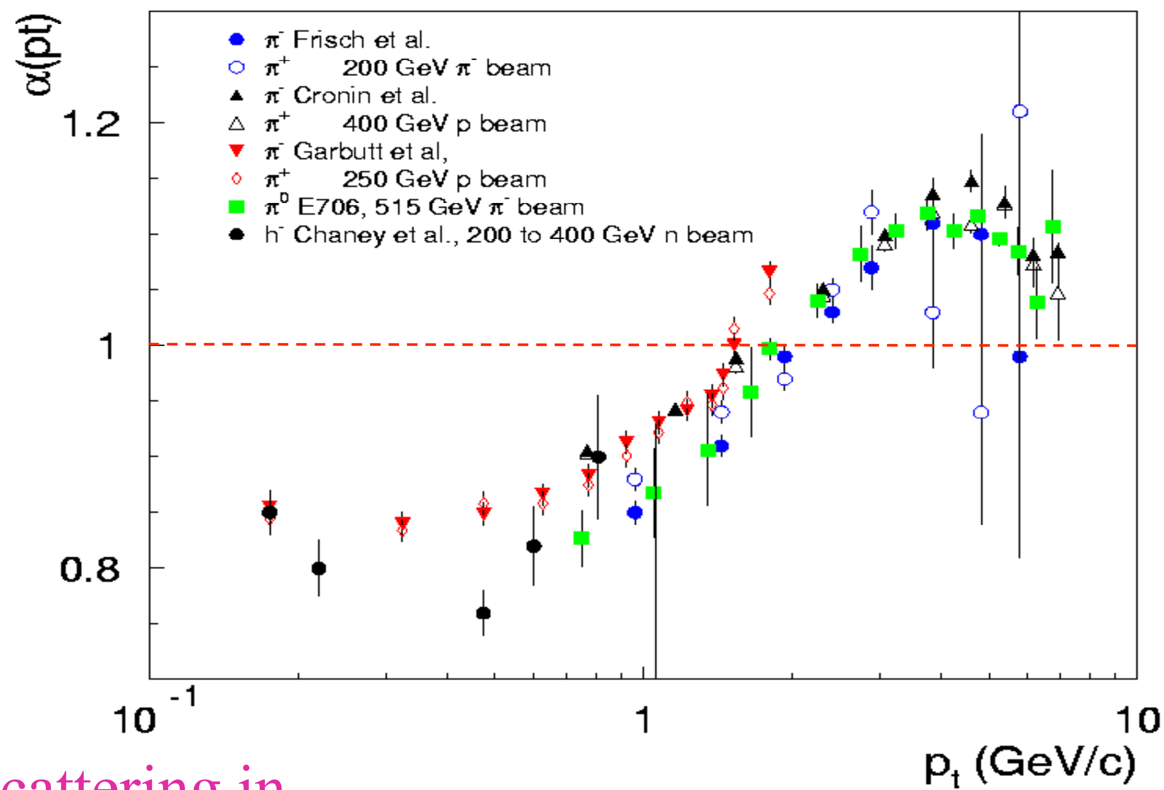


Nuclear Modification Factor:

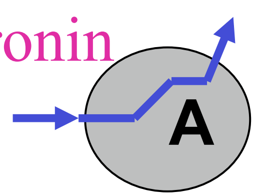
$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$

Leading Hadrons in Fixed Target Experiments

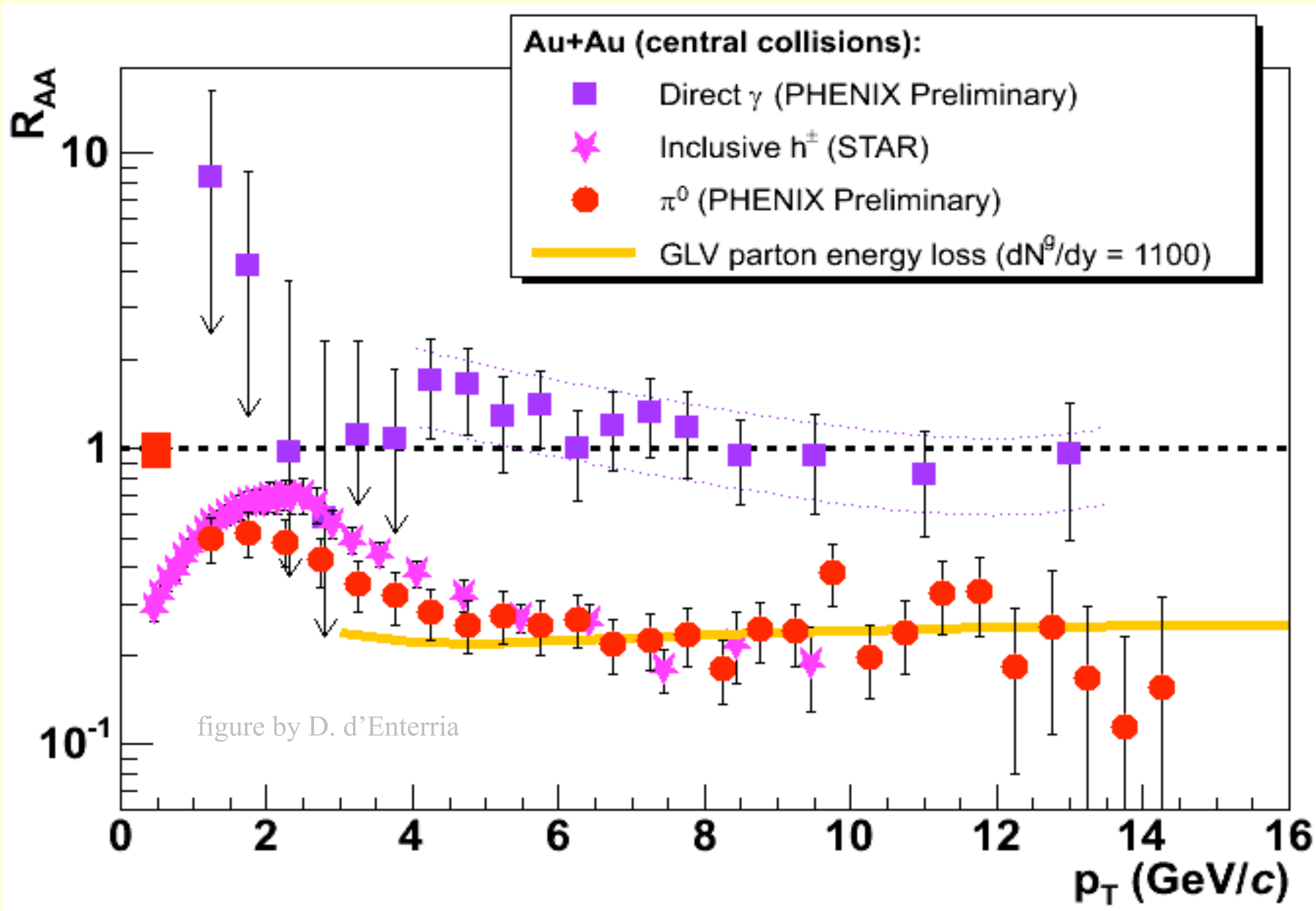
p+A collisions: $\sigma_{pA} = A^{\alpha(p_t)} \sigma_{pp}$



Multiple scattering in initial state("Cronin effect")

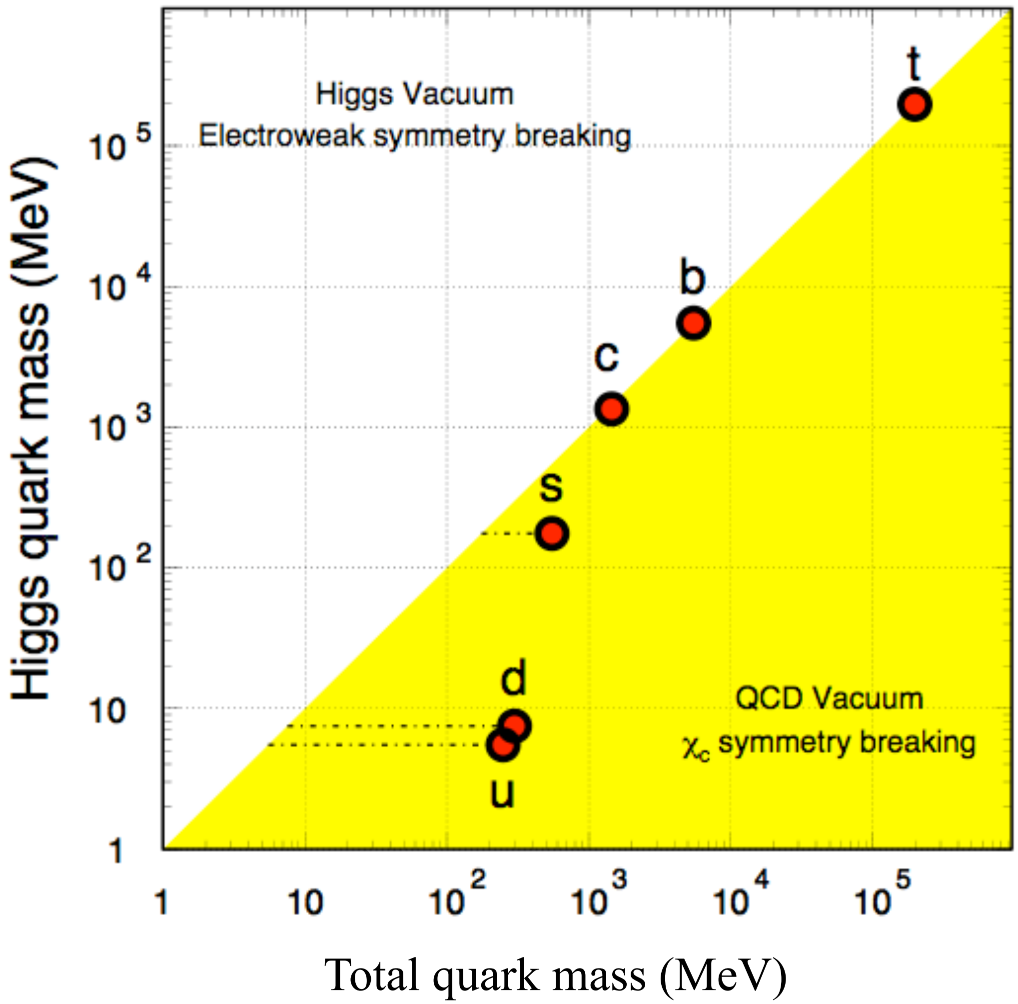


Leading Hadron Suppression: Data



It is highly opaque to colored probes– quarks and gluons – but not to photons

Quark Masses



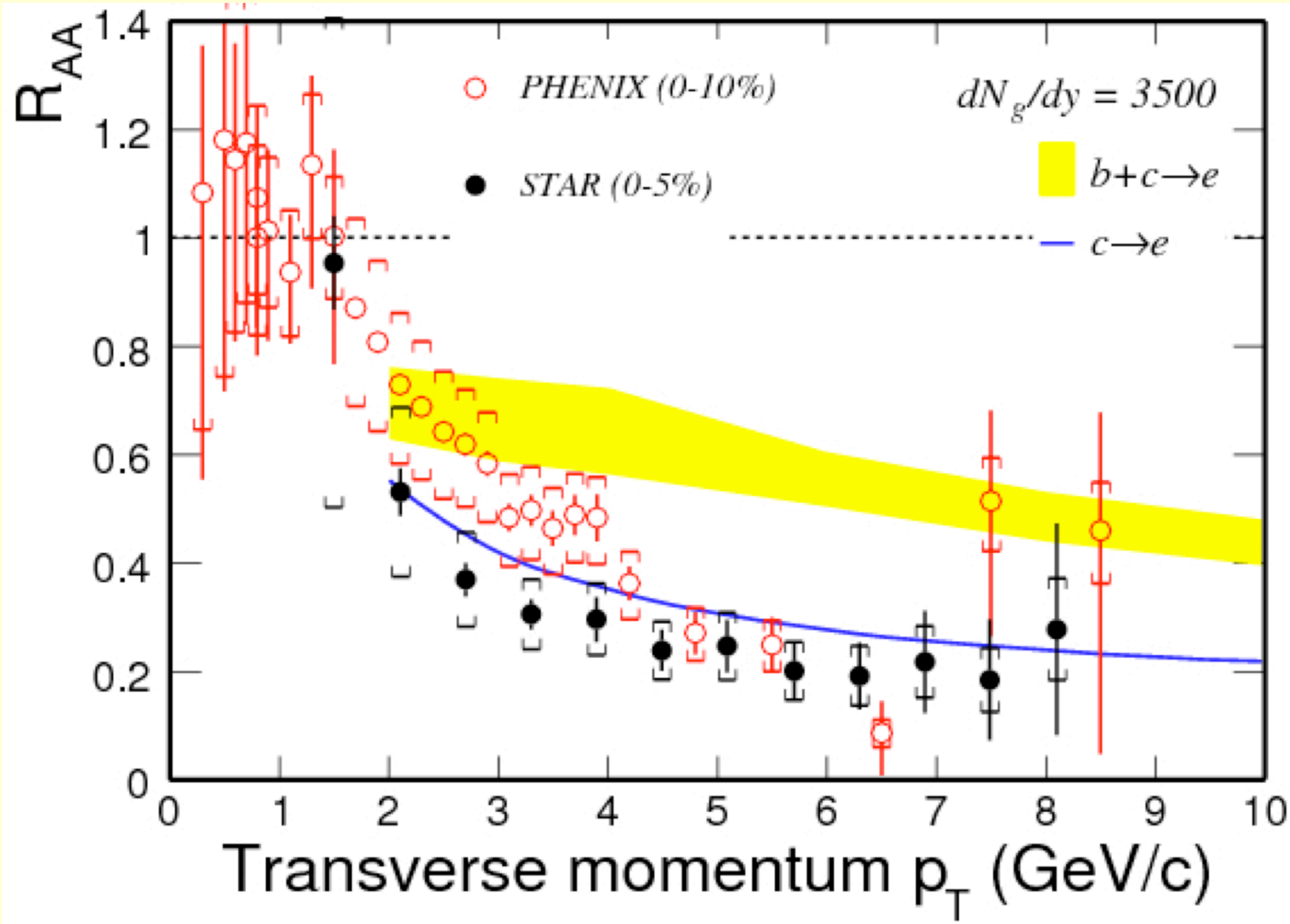
- Higgs mass: electro-weak symmetry breaking. (current quark mass)
- QCD mass: Chiral symmetry breaking. (constituent quark mass)

⇨ Strong interactions do not affect heavy-quark masses.

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

⇨ Test pQCD predictions at RHIC, including the effect of color factors.

Heavy Flavor



Hard Physics: p_T> 2 GeV/c

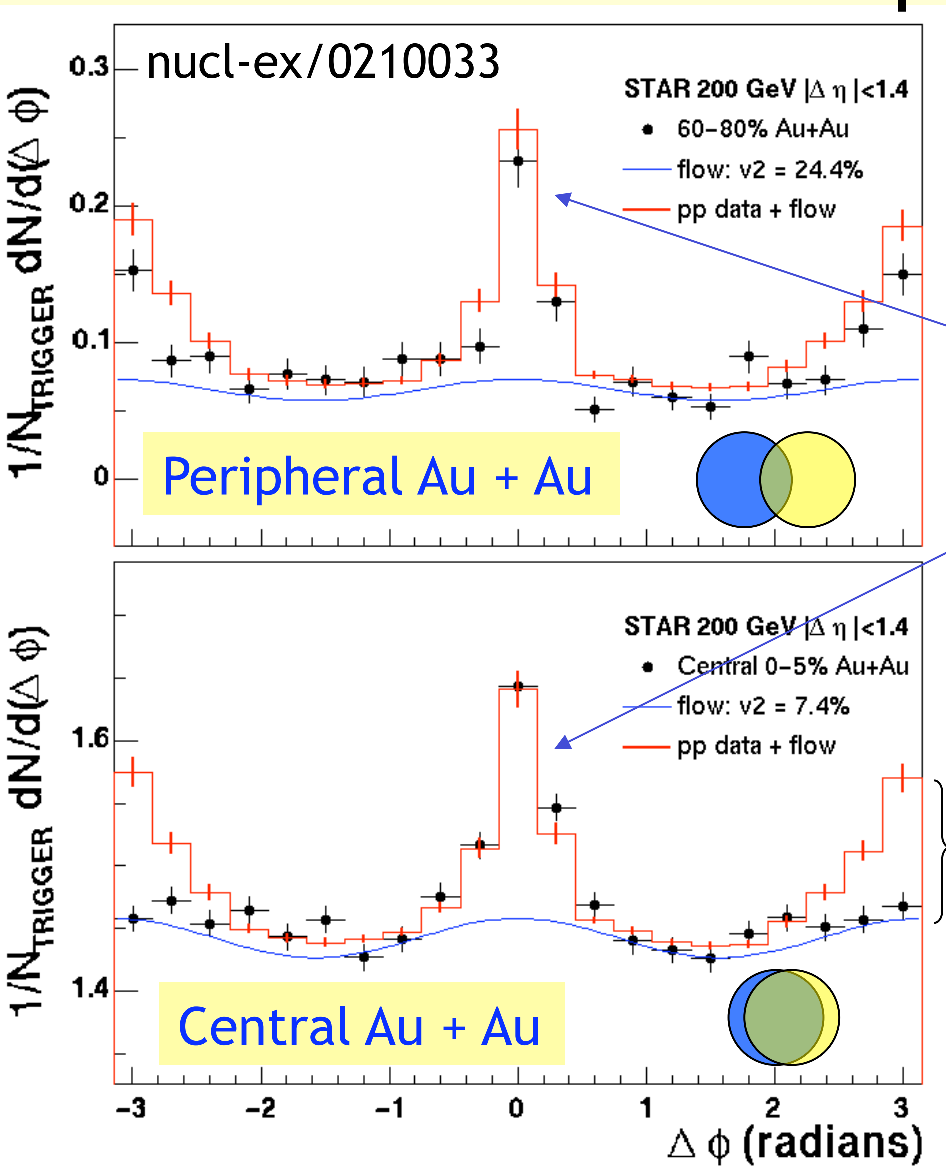
Goal: Penetrating probes

<u>What do we know so far?</u>

- How hard is hard?
- Leading Hadron Suppression in Central Collisions PRL 89, 112303 (2001)
- Elliptic flow saturation with p_T PRL **90**, 032301 (2003); nucl-ex/0210026
- Even with strange mesons/baryons
- **Disappearance of away side jet in central Au+Au collisions** nucl-ex/0210033

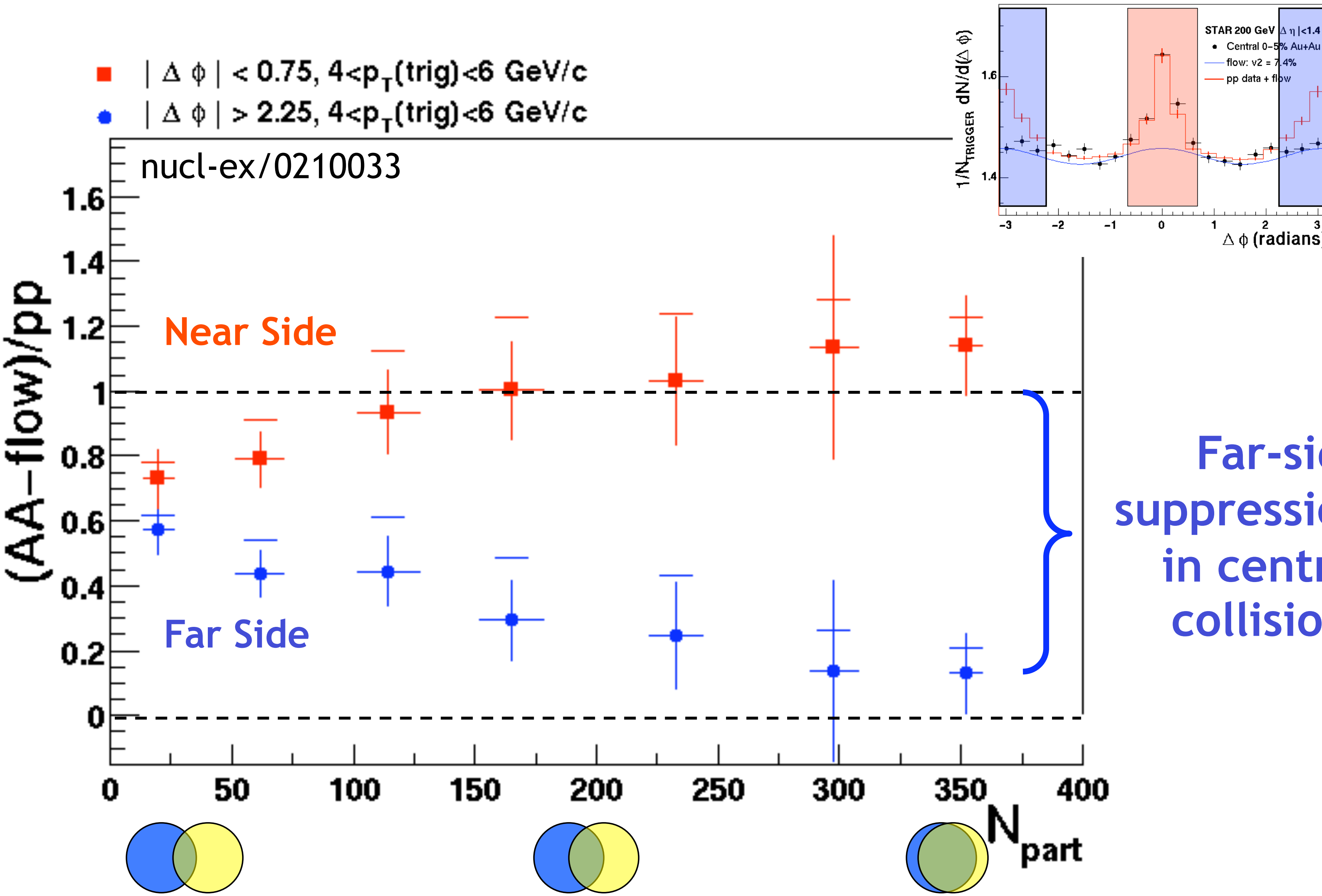
High p_T Azimuthal Correlations

Ansatz: Au+Au = p+p + Elliptic Flow



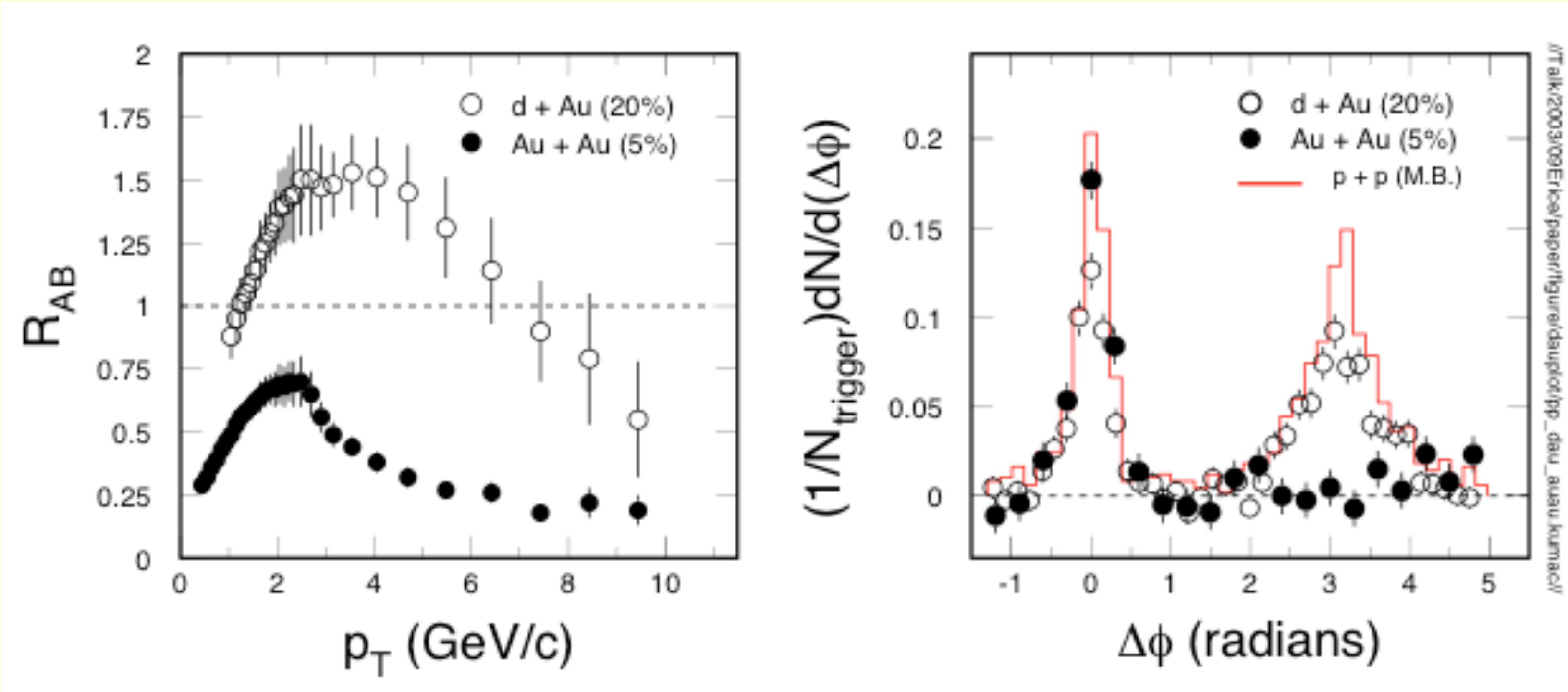
- Near-side correlation shows jet-like signal in central/peripheral Au+Au
- Away-side correlation suppressed in central Au+Au

Suppression of jets on the Far Side…



Far-side suppression in central collisions

Bottom line



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

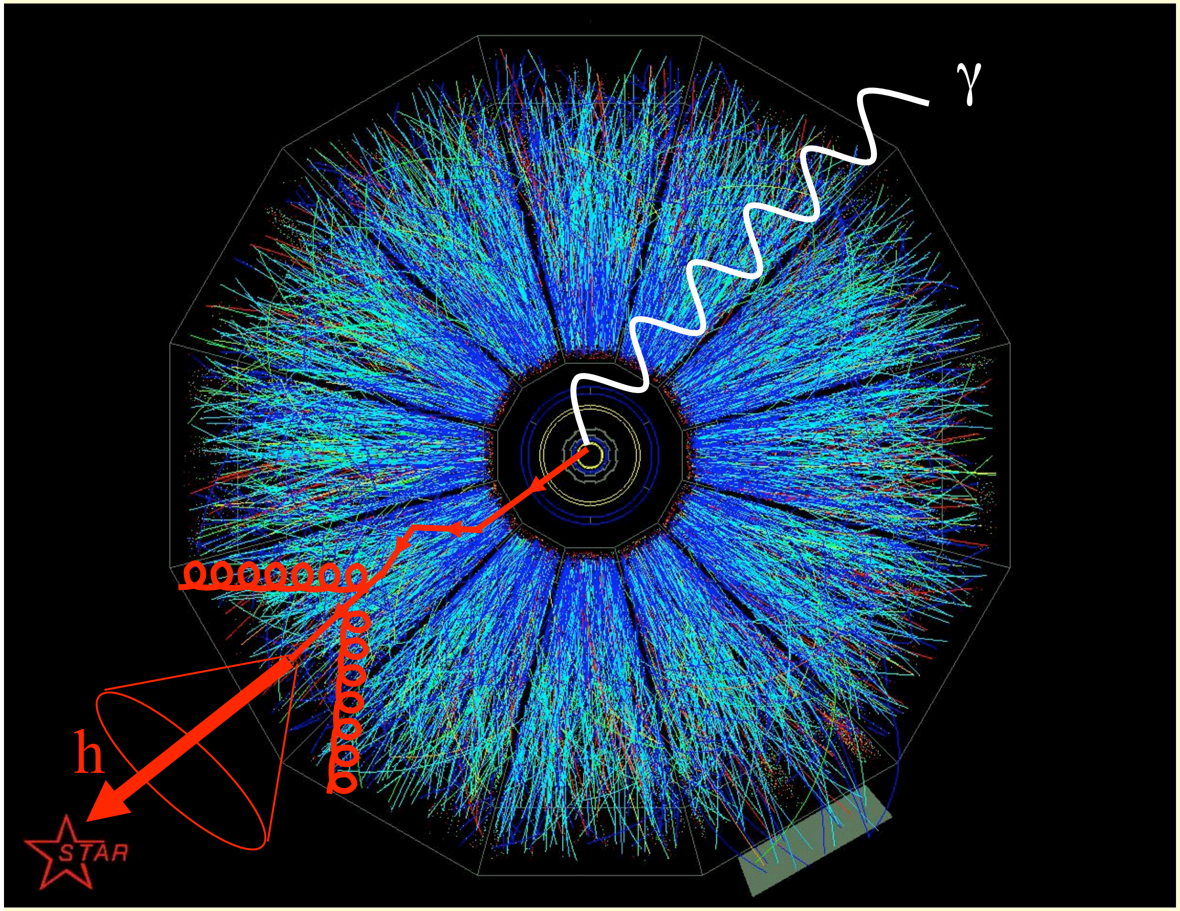
Energy density at RHIC: ε > 5 GeV/fm^3 ~ 30ε_0

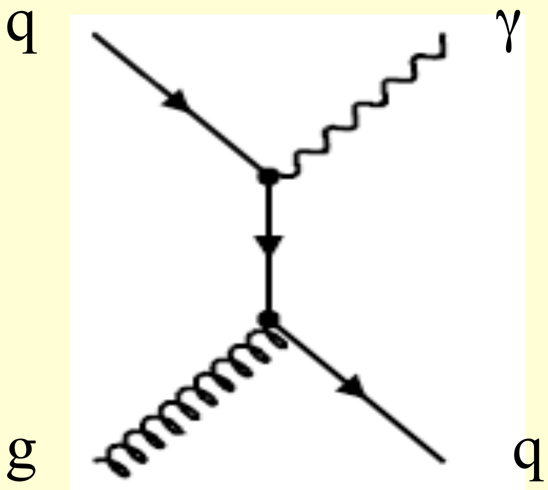
Parton energy loss: Bjorken 1982

("**Jet quenching**") Gyulassy & Wang 1992

…

γ-Jet: Golden Probe of QCD Energy Loss

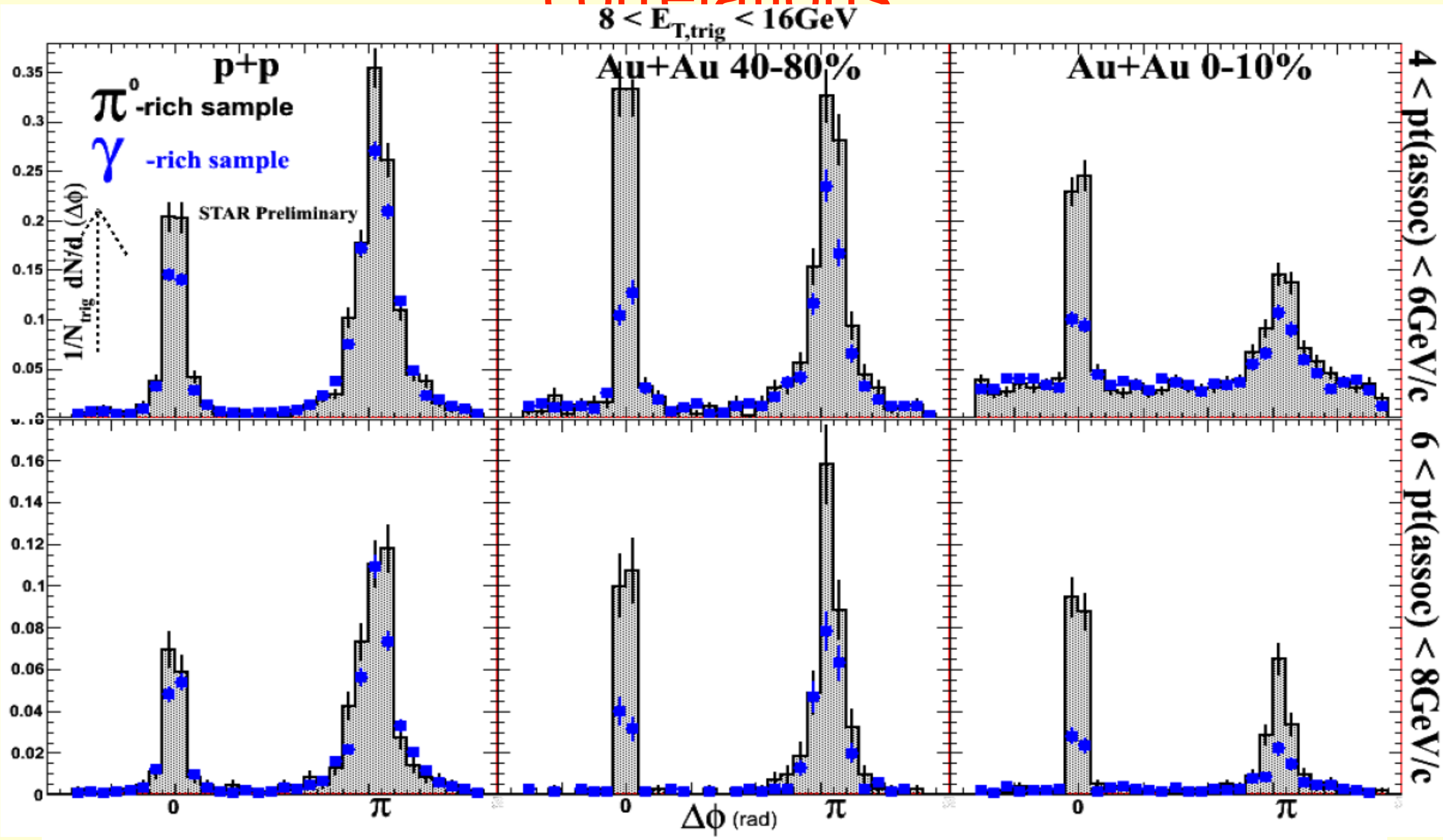




QCD analog of
Compton Scattering

- γ emerges unscathed from the medium
  - This probe is valuable for comparison with di-hadron correlations
  - It provides fully reconstructed kinematics: measure real fragmentation function D(z)

First results on high-p_T di-hadron,γ-hadron correlations

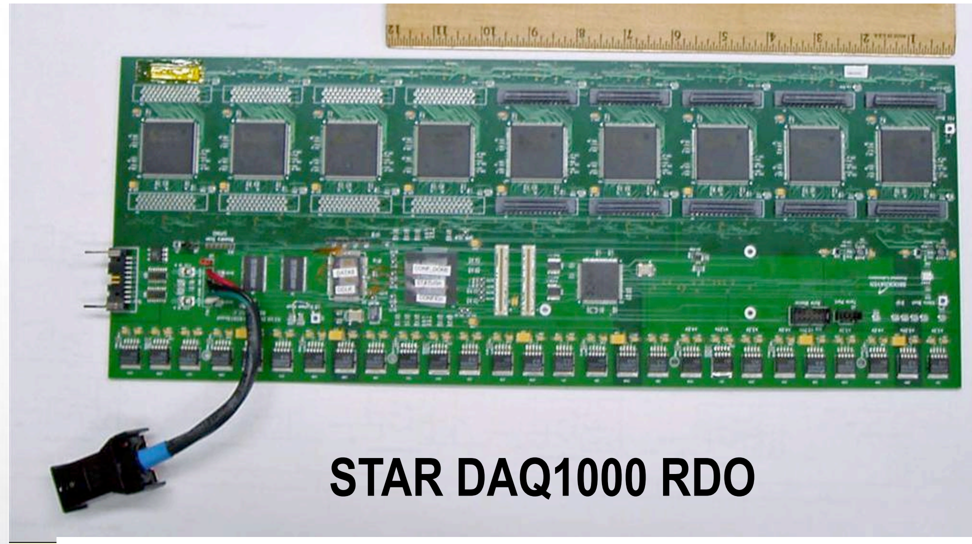


First steps to precision study with high luminosity at RHIC

See J. Kapitan, P156

The next step

Full prototype TPC sector now in operation and working flawlessly



Collaboration Plan:

Increase of DAQ rate to1000 times design by Run 9 leveraging CERN/ALICE Altro chip development (thank you)

Construction of HFT in time for full operation in Run 12 (Fall 2011)

END