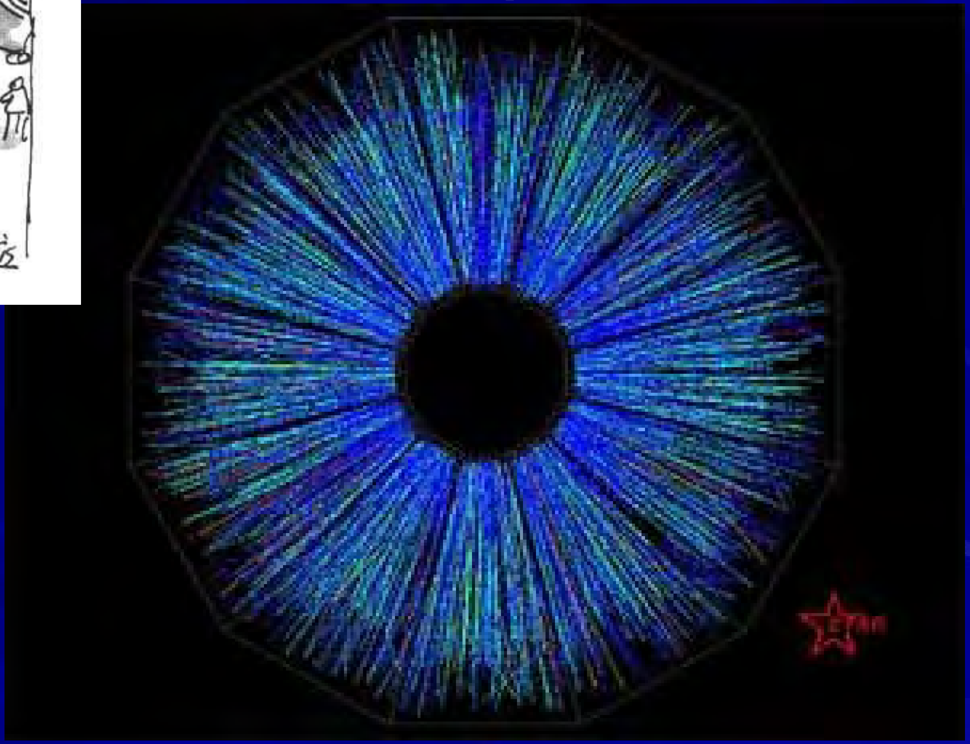
An Introduction to High Energy Heavy Ion Physics

- What is high energy heavy ion physics
  - QCD and the Quark Gluon Plasma
  - Heavy ion collisions and experiments
- Results from RHIC
  - Bulk physics: stopping, particle production, flow
  - Jets and heavy quarks
- Outlook
  - New theoretical tools
  - LHC and ALICE
- 2nd talk will focus on ALICE and the TPC

What is high energy heavy ion physics

1 small bang in the STAR experiment



QCD at high energies

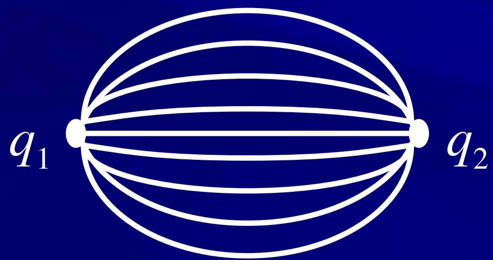
- Low energy QCD (the universe today)
  - Confinement
    - Nucleons (hadrons) are relevant degrees of freedom
  - Chiral symmetry is spontaneous broken by vacuum condensates
    - Chiral partners have different mass, pion is “goldstone boson”
  - Lattice QCD (the strong coupling constant is large).
- High energy QCD (early universe <10^{-6} s after big bang)
  - Deconfinement (Quark Gluon Plasma)
    - Quarks and gluons are relevant degrees of freedom
  - Chiral symmetry restored
    - Chiral partners have similar mass
  - Perturbative QCD, Color Glass Condensate (gluon saturation)
    - NEW! Anti-de-Sitter/Conformal Field Theories (weakly coupled string theory <-> strongly coupled non-perturbative “QCD”)

Confinement

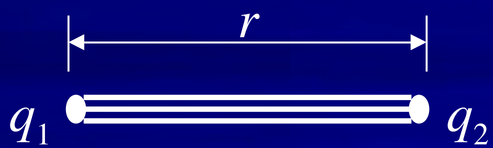
- The strong interaction potential
  - Compare the potential of the strong & e.m. interaction

$$V_{em} = -\frac{c}{r} \qquad V_s = -\frac{c'}{r} + kr \qquad c, c', k \text{ constants}$$

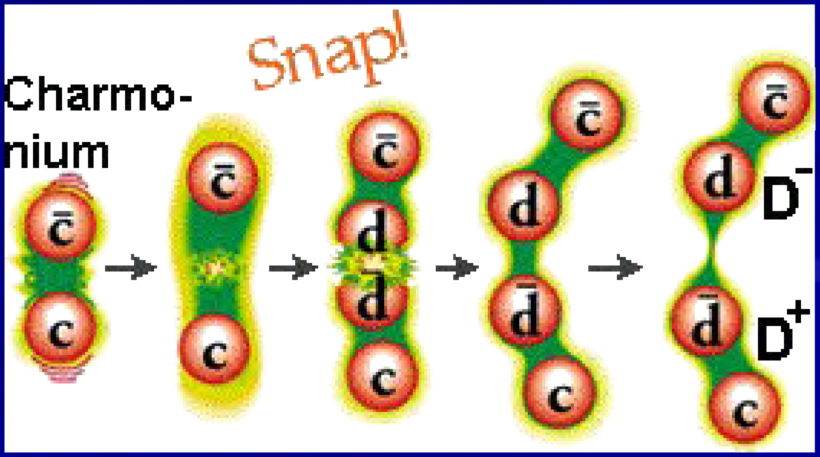
  - Confining term arises due to the self-interaction property of the colour field. k~1GeV/fm~10 tons!



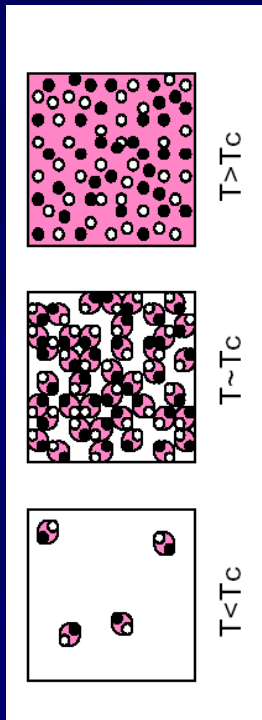
a) QED or QCD ($r < 1$ fm)

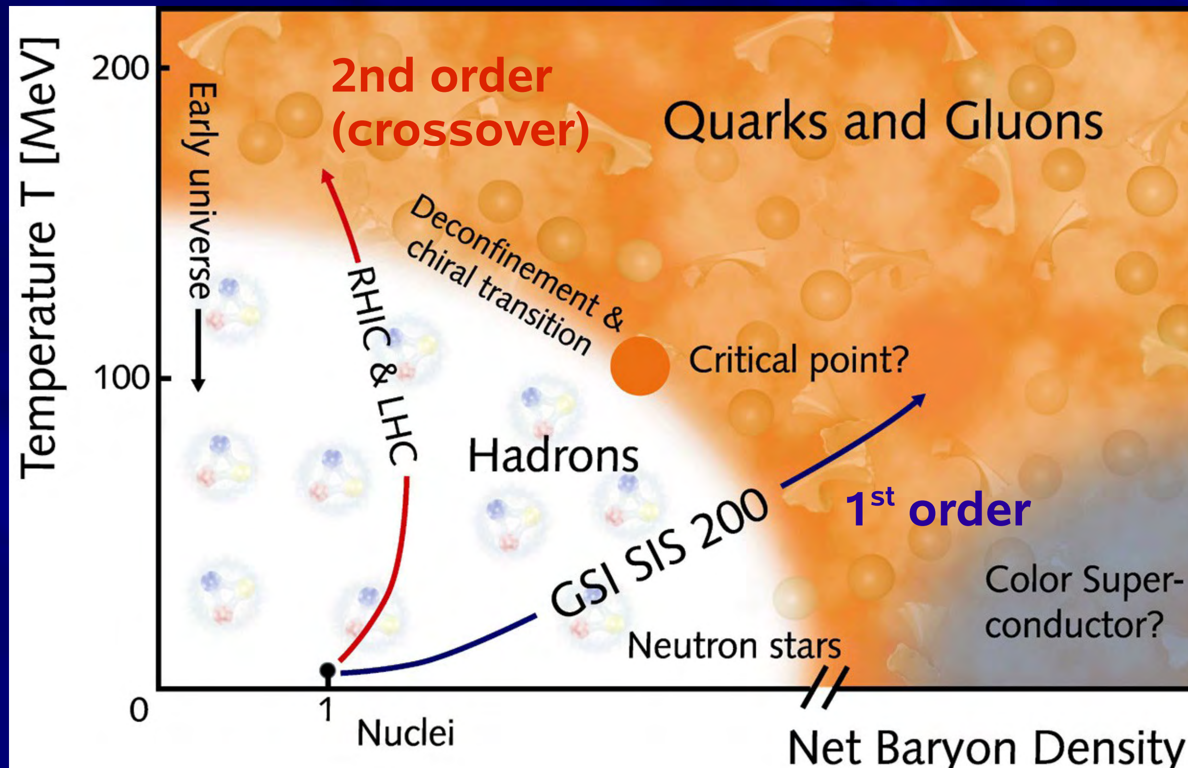


b) QCD ($r > 1$ fm)



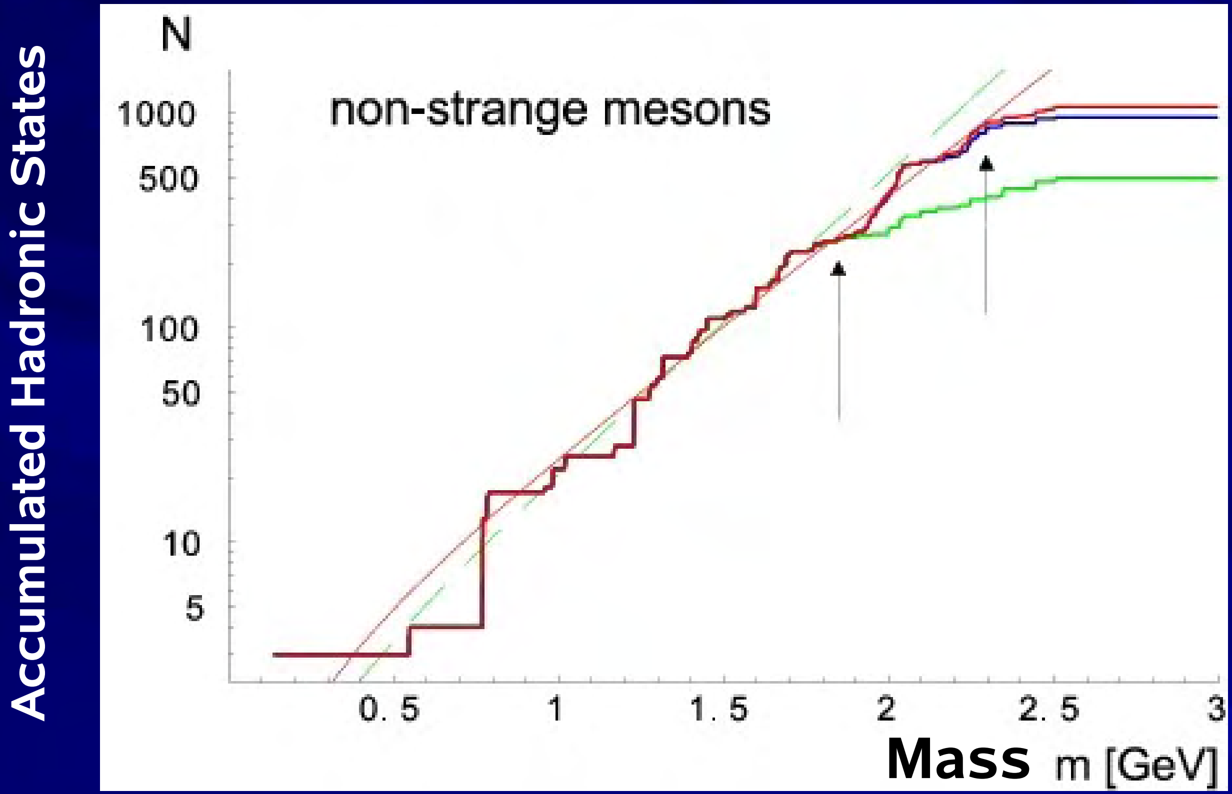
Schematic QCD phase diagram





- At high temparures (T>170MeV) and/or net-baryon densities ($\sim\rho_{proton}$) we expect a phase transition to a phase where the quarks and gluons are deconfined:
  The Quark Gluon Plasma (QGP)

The Hagedorn temperature

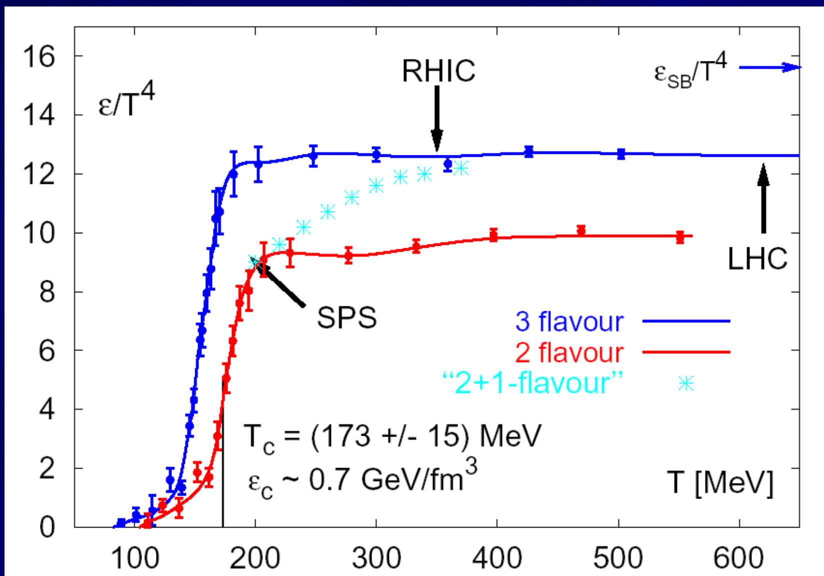


The number of hadronic states experimentally observed increaseses exponential with the mass within the observable region.
In a statistical model they are populated proportional to: exp(-m/T)

- If this exponential growth continues, as proposed by Hagedorn, there is a limiting temperature for hadronic matter where the energy density becomes infinite (if there was no phase transition). $T_{Hagedorn}$ = 200-300 MeV.

Lattice QCD results (Numerical non-perturbative)

QCD energy denisty

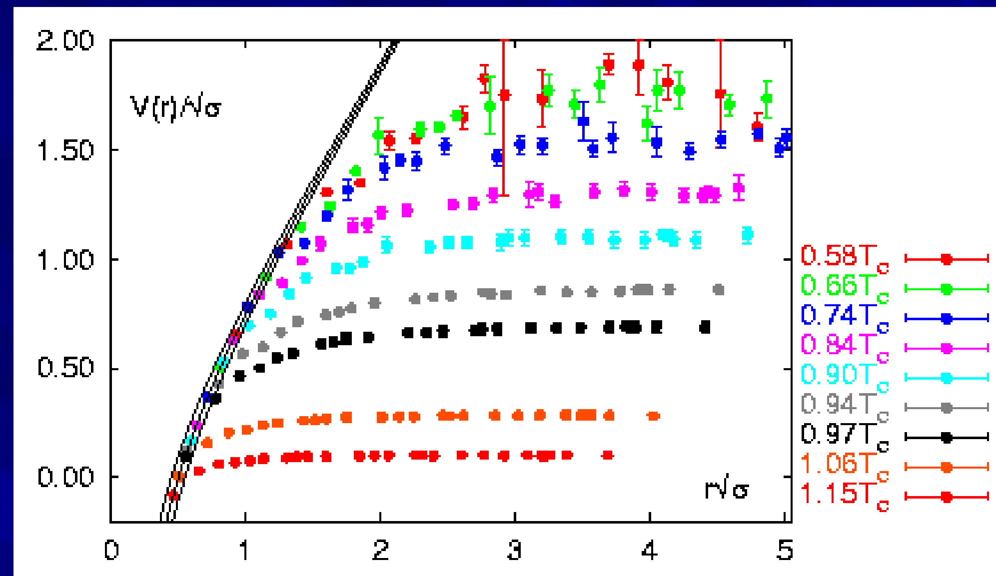


$$\epsilon_{QCD} = \frac{\pi^2}{30}\left(2\times 8 + \frac{7}{8}2\times 2\times 3\times 3\right)T^4$$

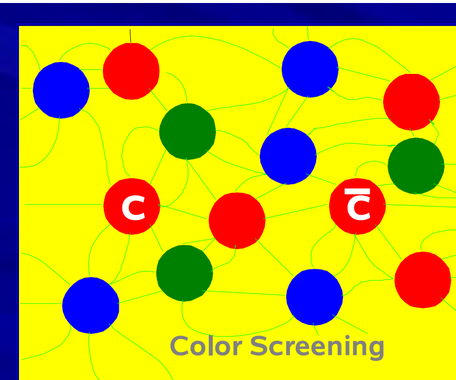
Gluon spin and color

(Anti+)quark spin, color and flavor

Heavy quark potential

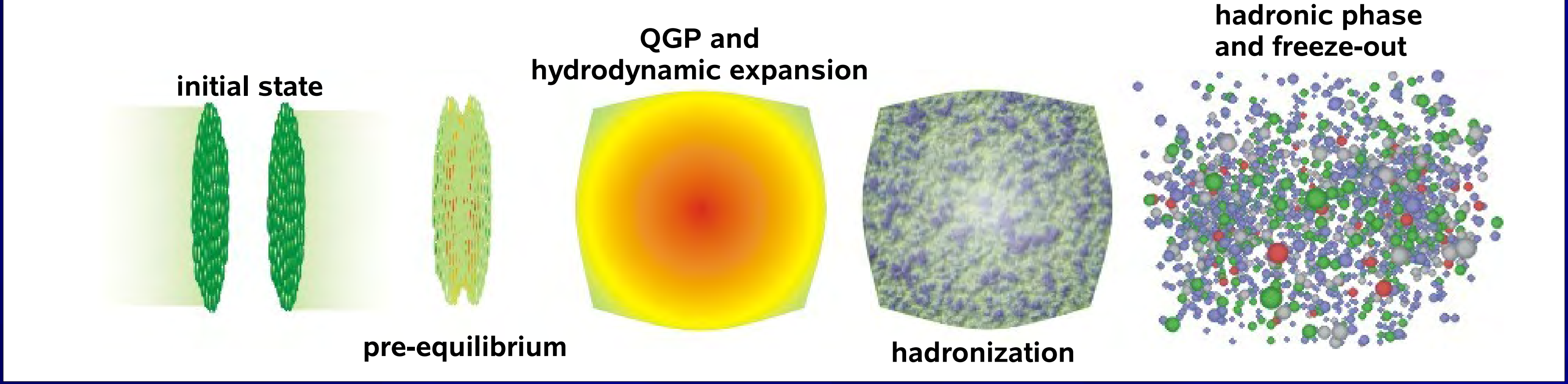


At T~Tc the strong potential is screened so e.g. c+c-bar states can disassociate.



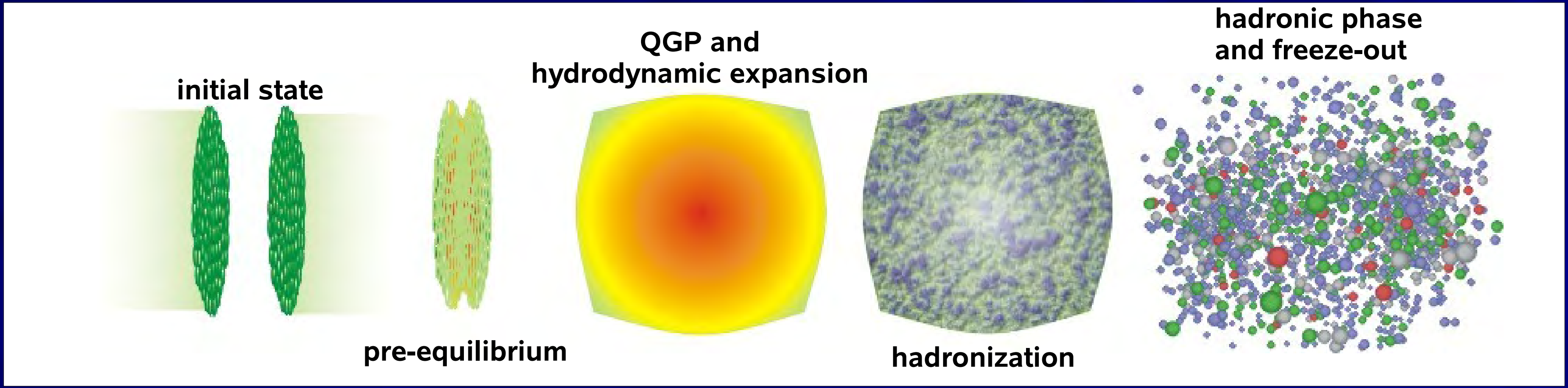
Heavy ion collisions: The study of high energy QCD

The evolution of a heavy ion collision



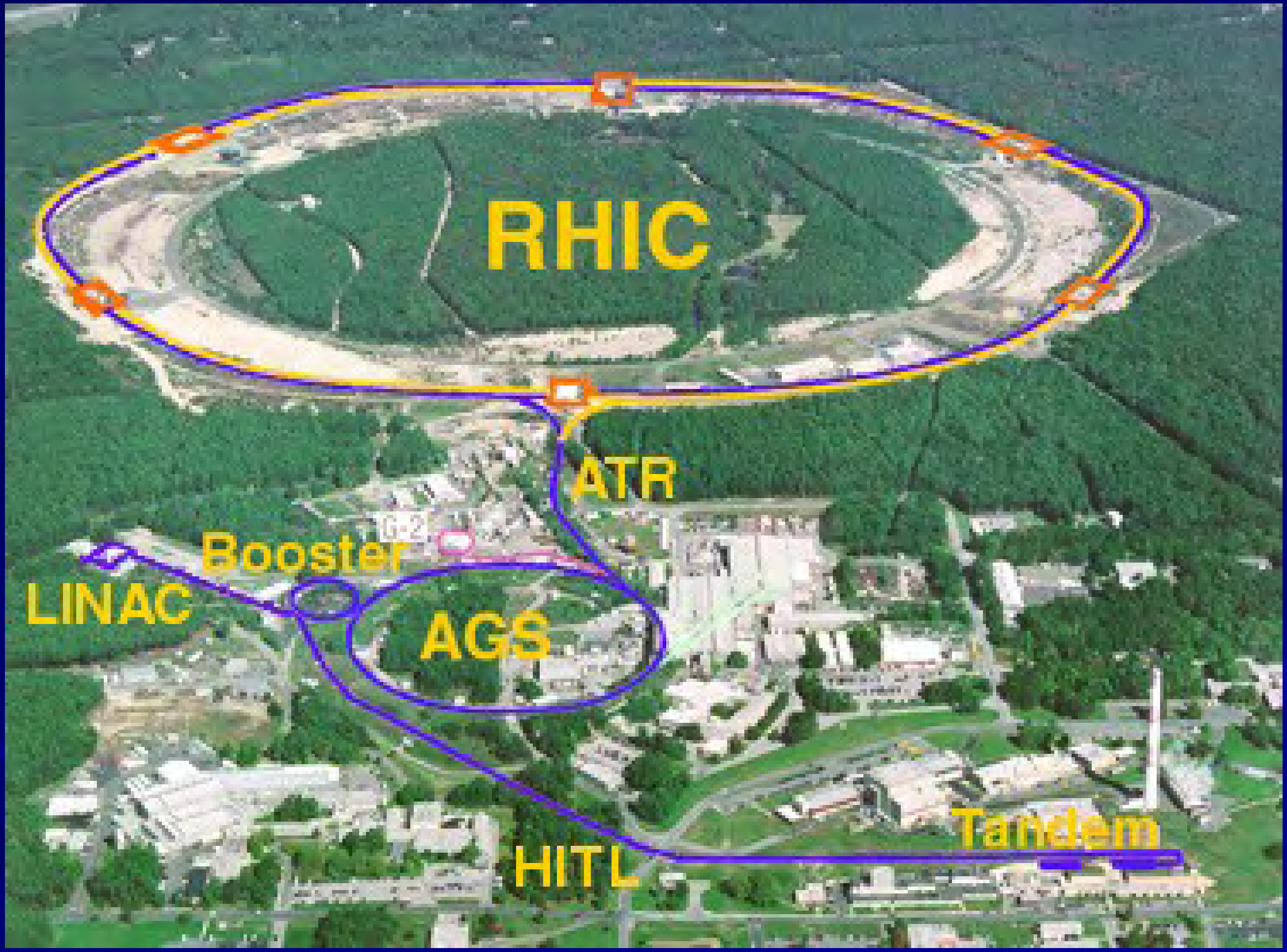
- By colliding heavy ions it is possible to create a large (»1fm^3) zone of hot and dense QCD matter
- Exerimentally only the final state particles are observed
  - NB! Photons and leptons can act as probes of early stages
- Theoretically LQCD only describes a stationary thermalized state. NEED dynamical model description(s)!

Theoretical descriptions of heavy ion collisions



- Some examples of ingredients:
  - Hard processes (jets): perturbative QCD
  - Initial state: Color glass condensate / Glasma
  - Hydrodynamic expansion
  - Hadronization: Statistical a la Hagedorn.
  - Lund string model for soft physics
- Most models are phenomenological, so a large degree of tuning is possible!

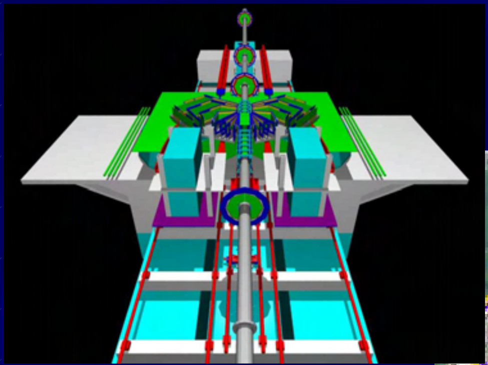
The Relativistic Heavy Ion Collider (RHIC)

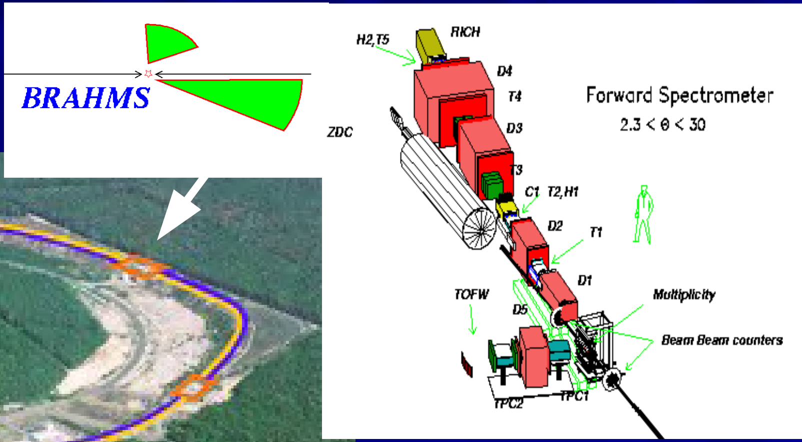


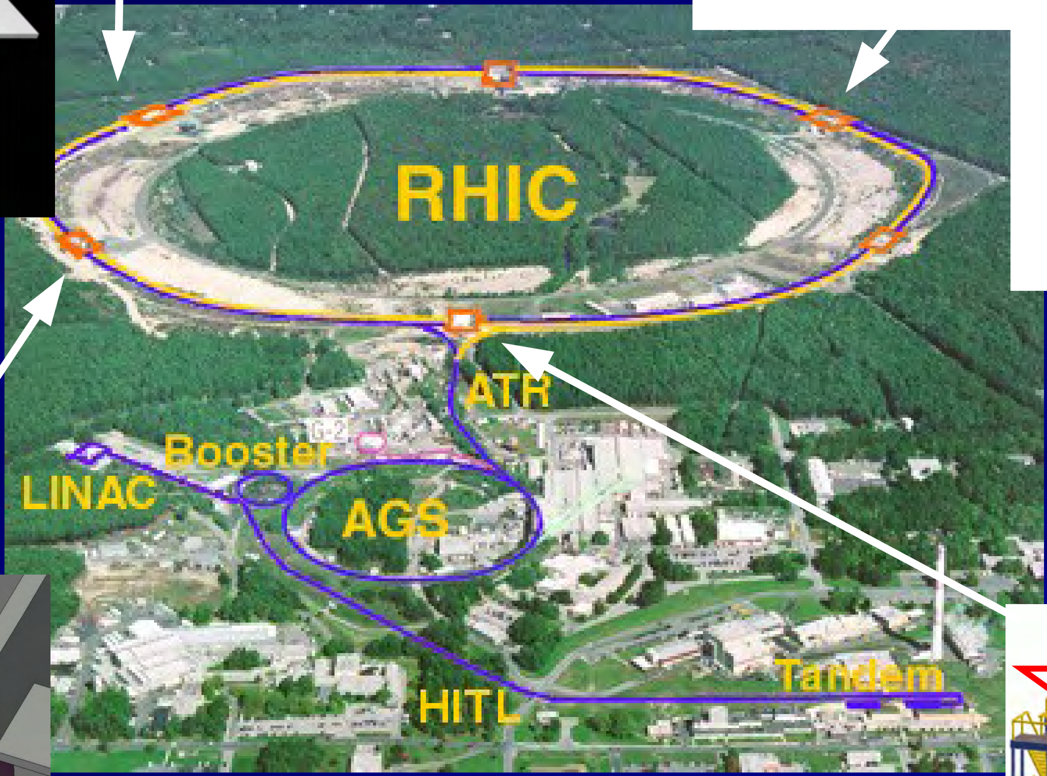
RHIC is the first heavy ion collider in the world. Operational since 2000. Max beam energy: $\sqrt{s_{NN}}$=200GeV

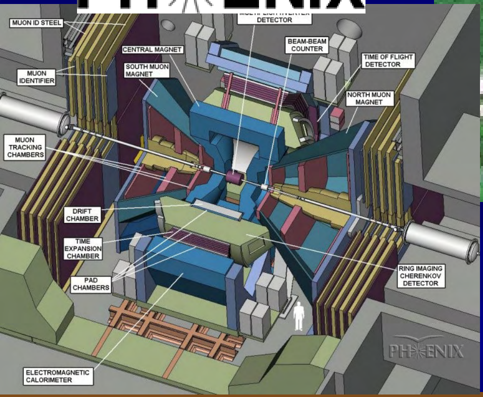
2 independent rings (good for d+Au).

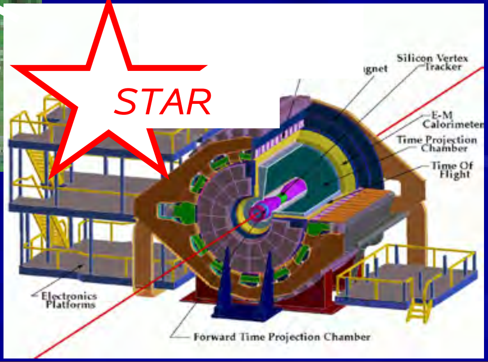
The 4 experiments at RHIC





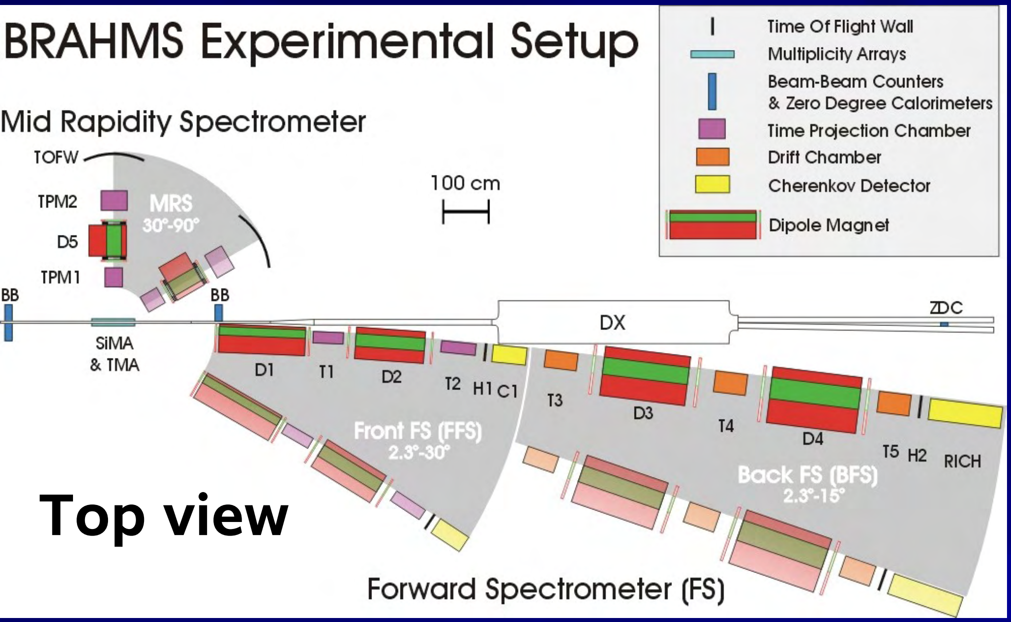


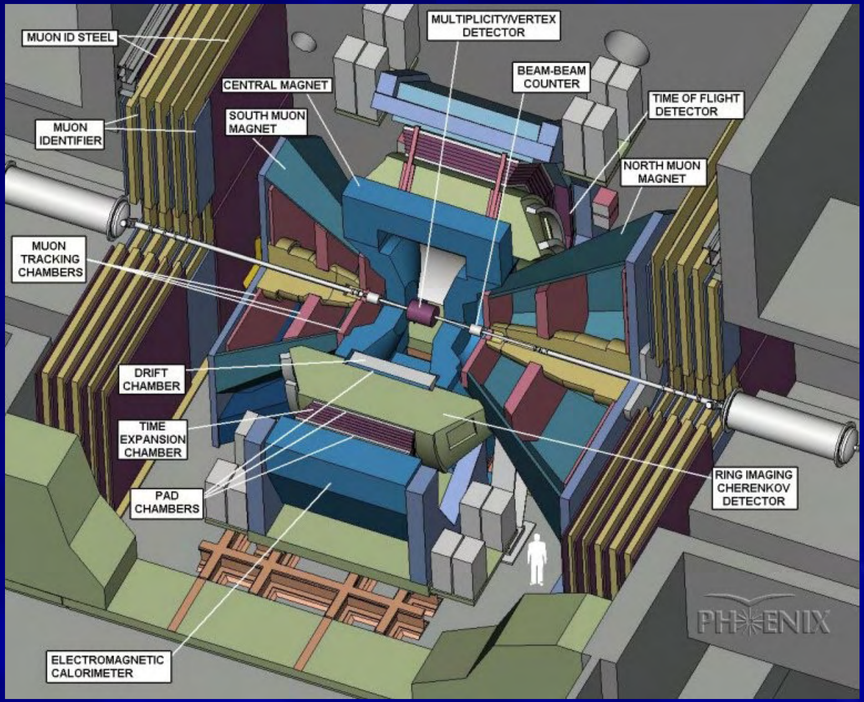




Lund group

Examples of experiments: BRAHMS and PHENIX



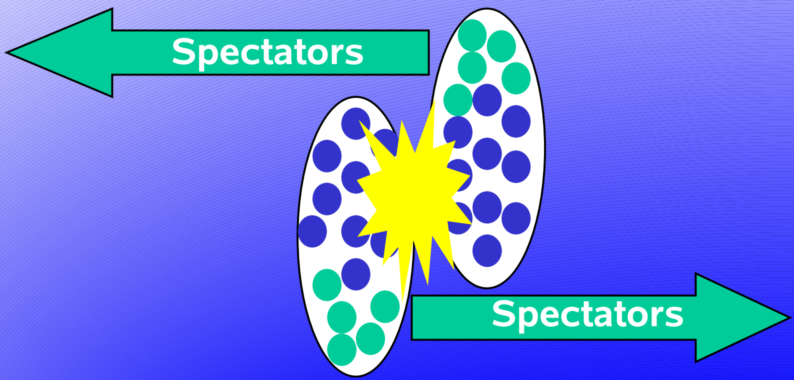


BRAHMS (50 people):
Specialized detector
Combining many settings allows charged π, K, p to be meaured over large rapidity range: 0 < y < 3.5

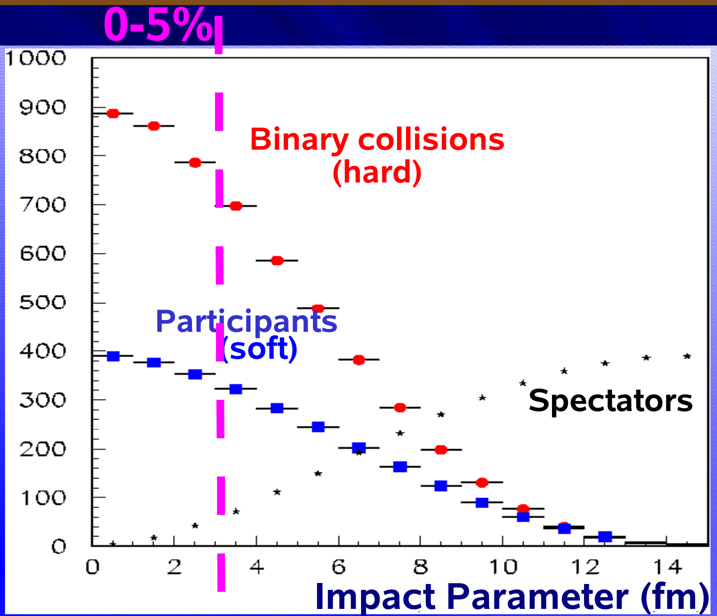
PHENIX (300 people):
General purpose detector
Big acceptance around y=0
Measures charged hadrons and photons and leptons
Lund group built pad chambers

Heavy Ion Jargon

- Centrality (ex. for Au+Au):



Participants = 2*197 - Spectators

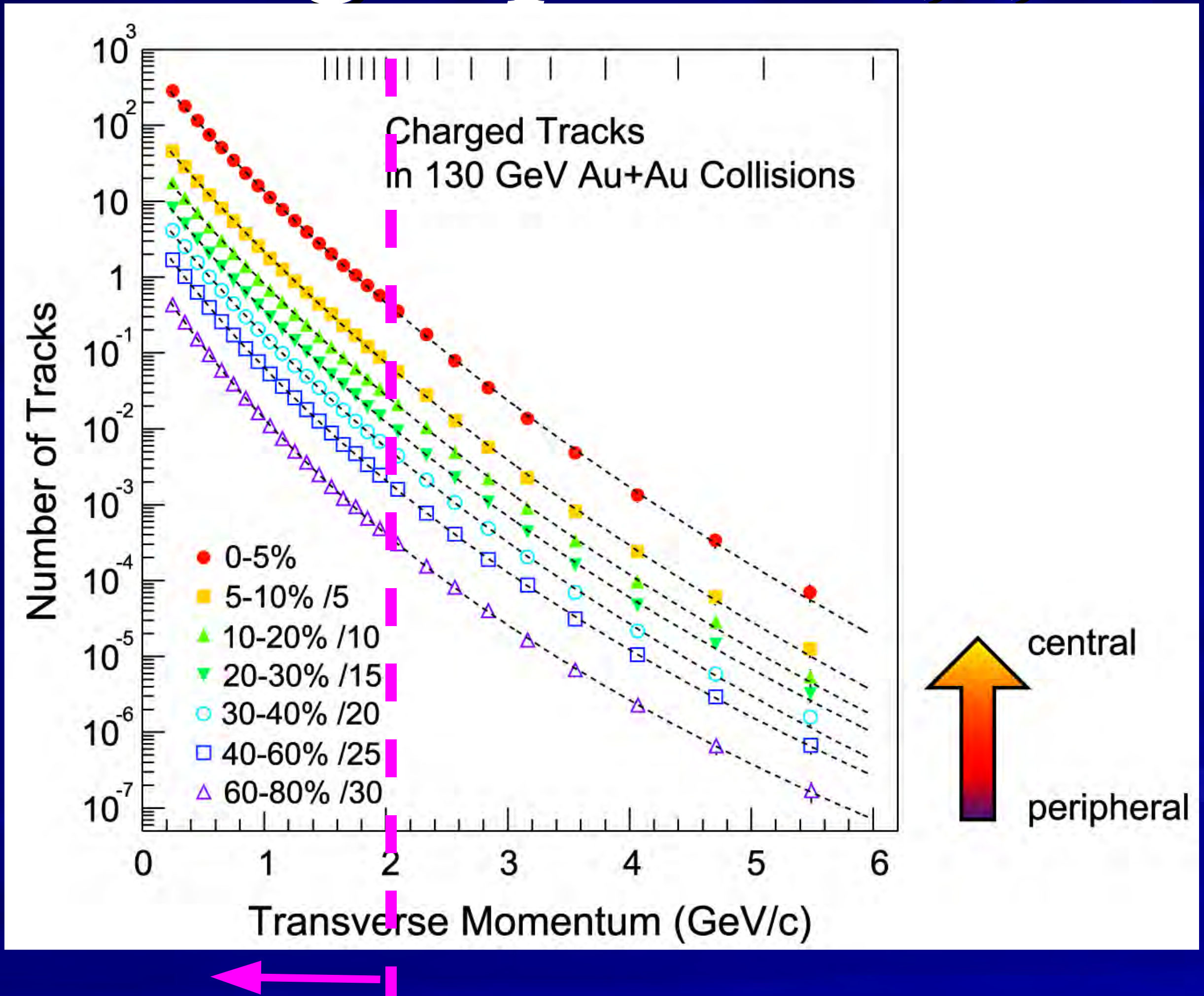


- Rapidity (Boost invariant) & Pseudo-rapidity (No PID):

$$y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right) \qquad \eta = -\log\left[\tan\left(\frac{\theta}{2}\right)\right]$$

- Accelerators: AGS (BNL), SPS (CERN), RHIC (BNL), LHC (CERN). $\sqrt{s_{NN}}$ = 5, 17, 200, 5500 GeV

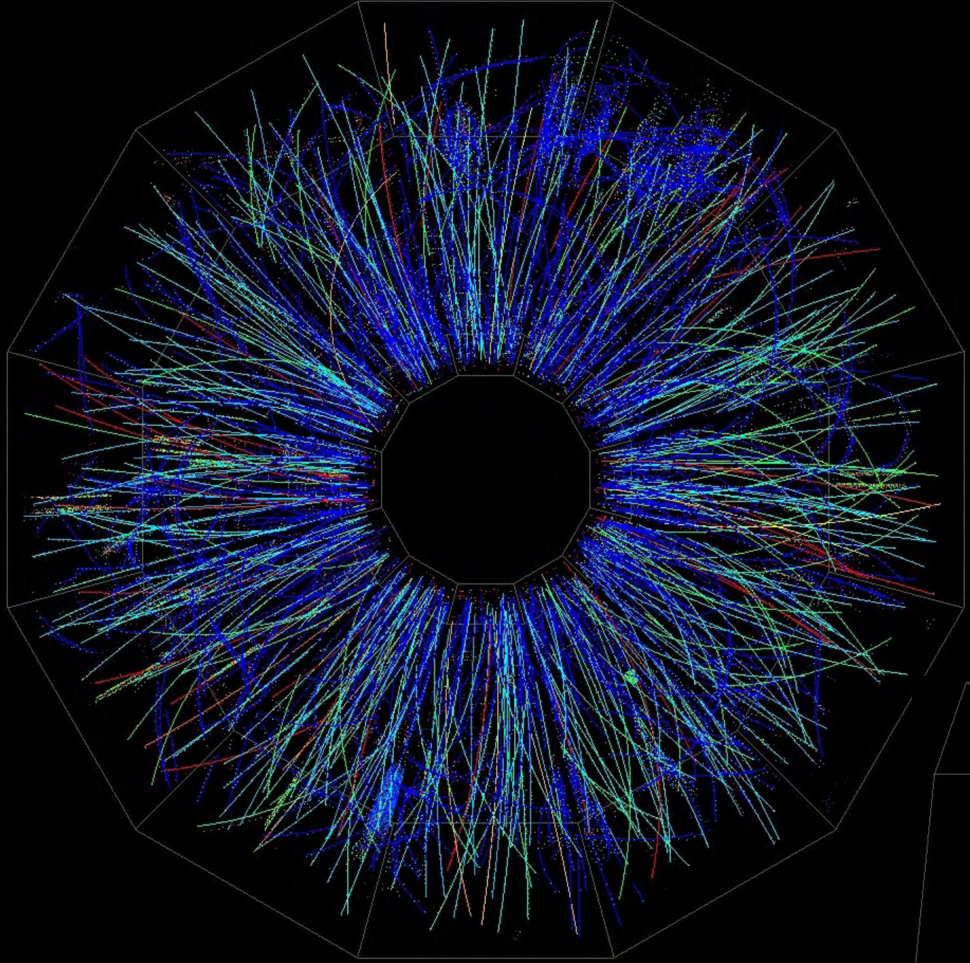
Soft physics: p_T<2GeV/c and light quarks:u,d,s

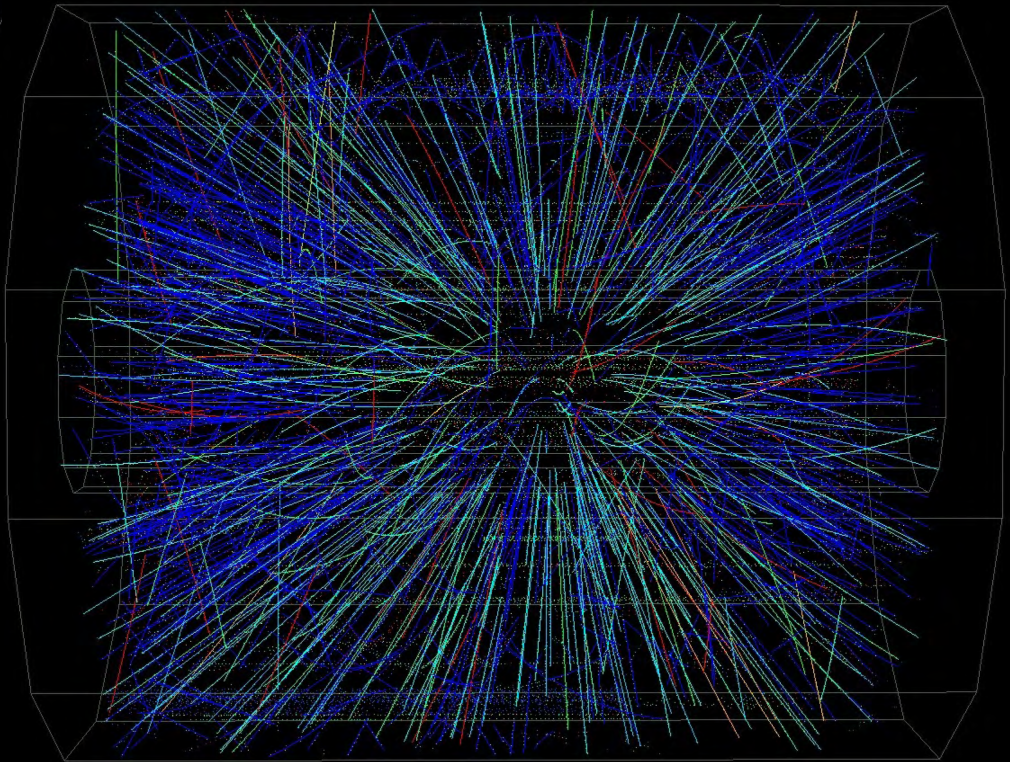


99% of particles

Peripheral Event

From real-time Level 3 display.





color code ⇒ energy loss

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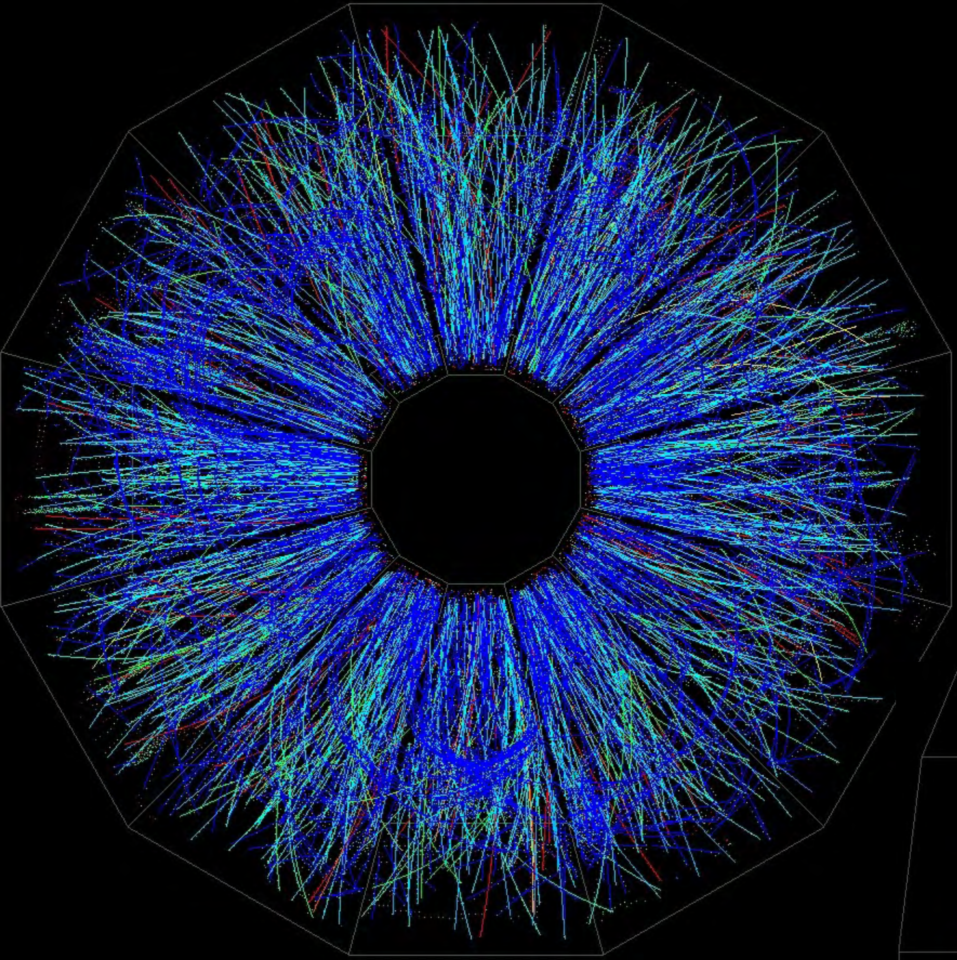
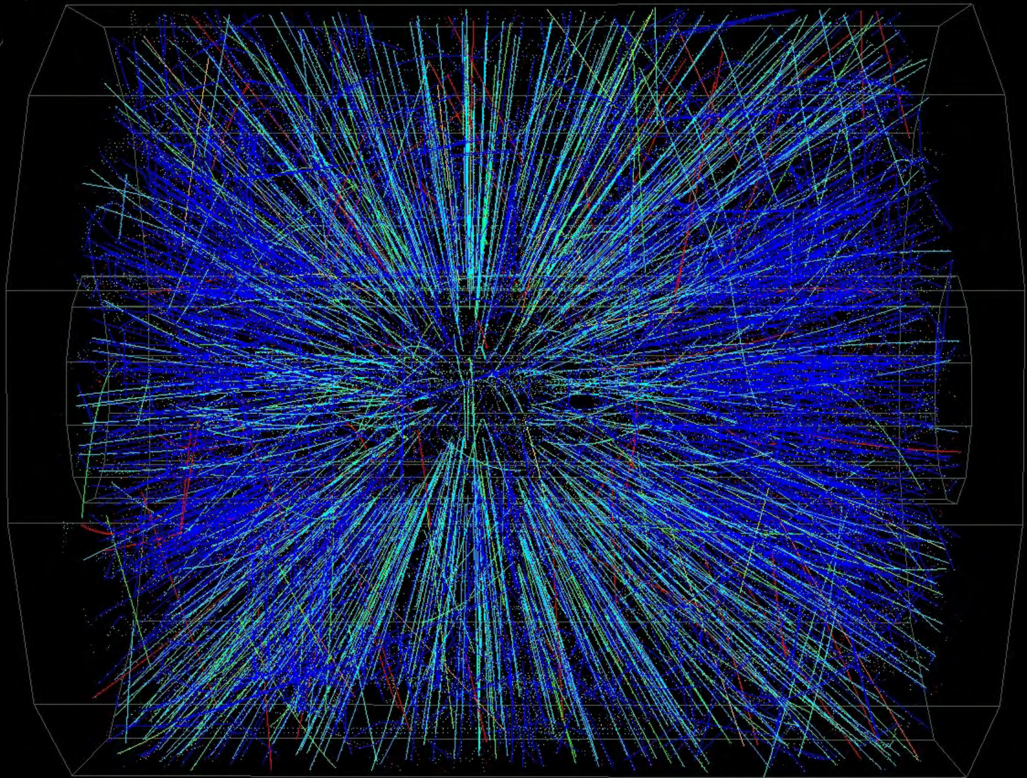


Mid-Central Event

From real-time Level 3 display.



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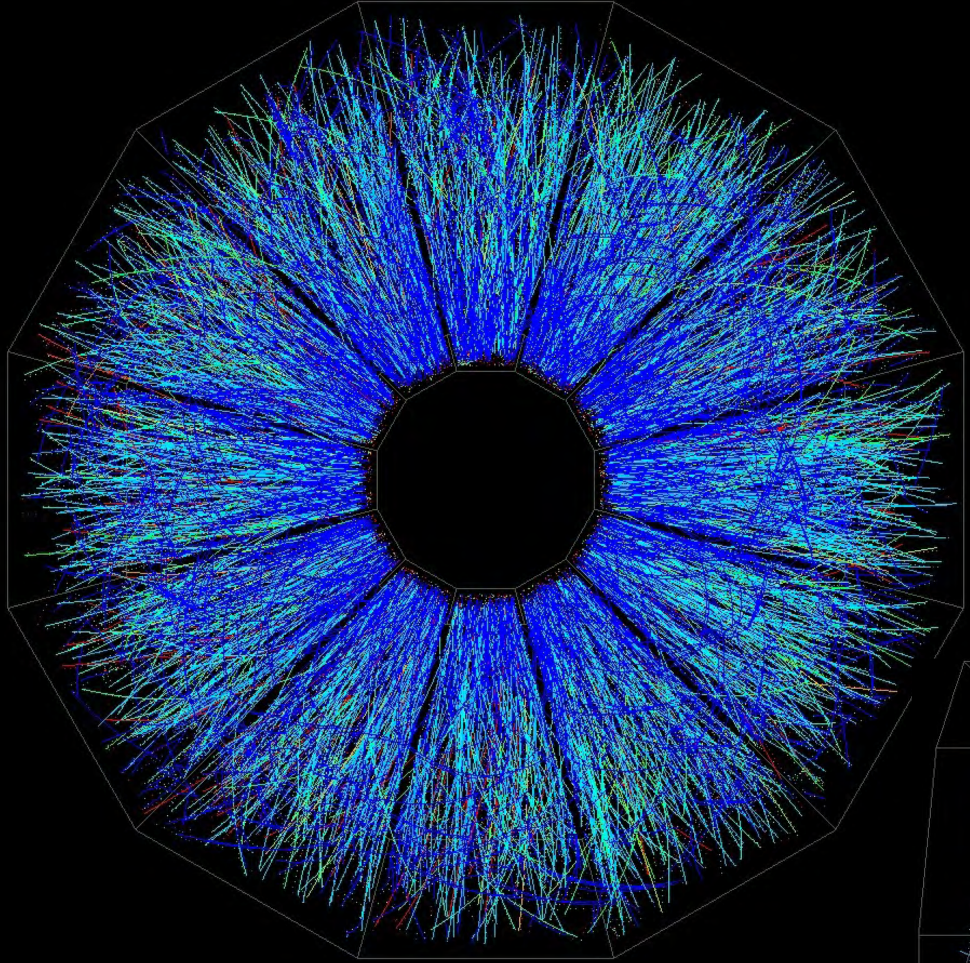
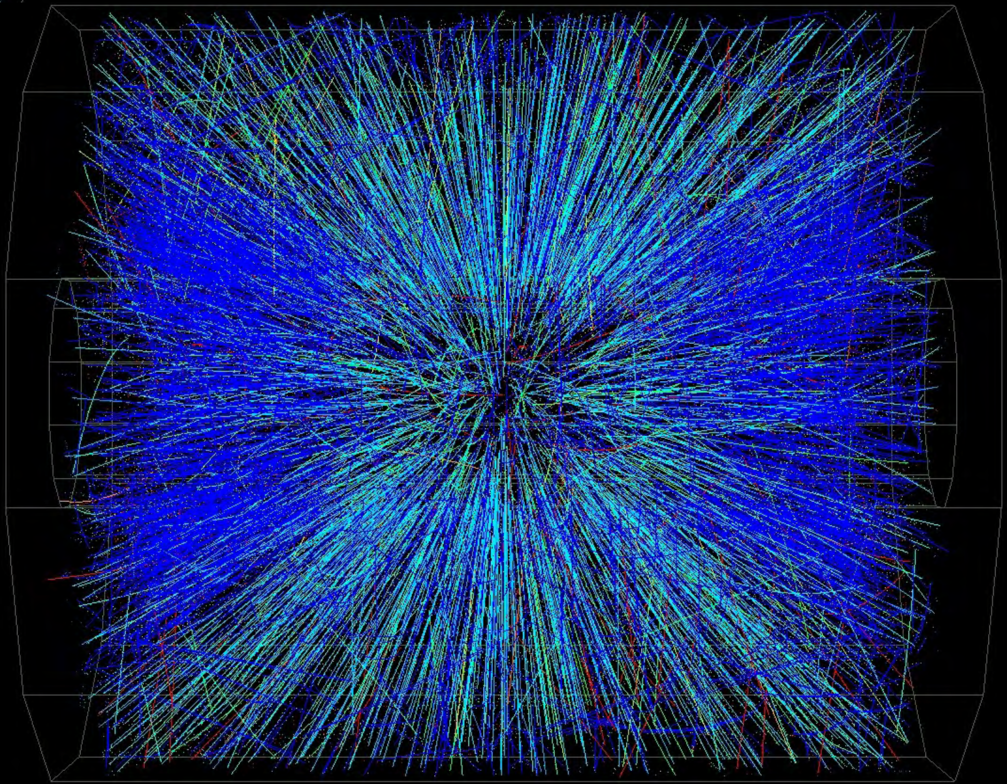
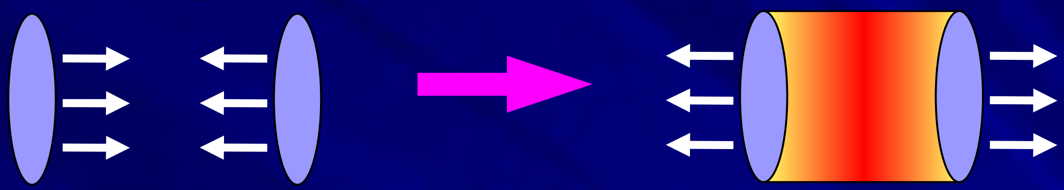


Central Event

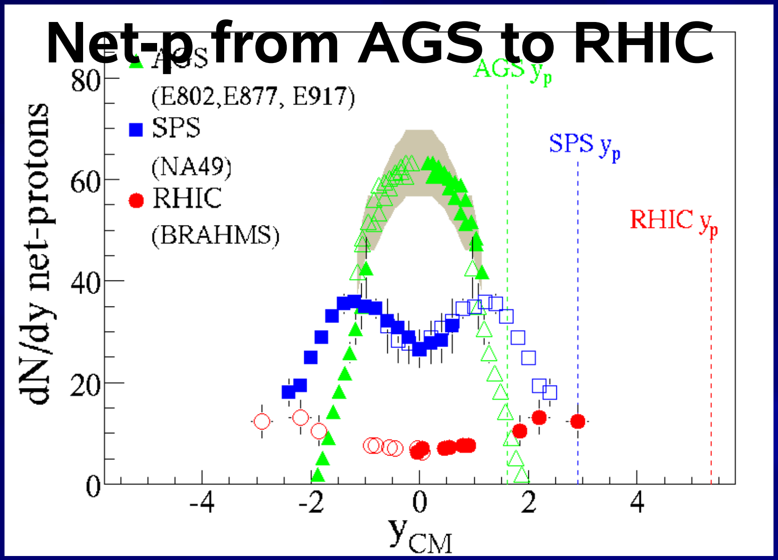
From real-time Level 3 display.

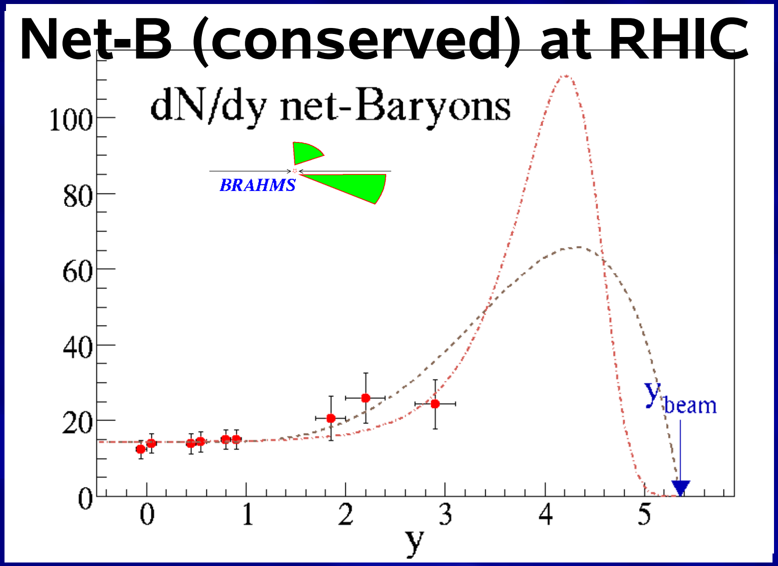


Nuclear Stopping
Creating hot and dense matter



Net-protons= Protons - Anti-protons



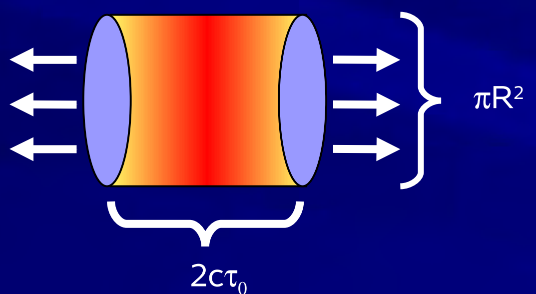


- Due to baryon number conservation the kinetic energy loss of the incoming nuclei can be determined.
- Extrapolating to beam rapidity one finds that ~75% of the energy is available for particle production

"Measured" initial energy density

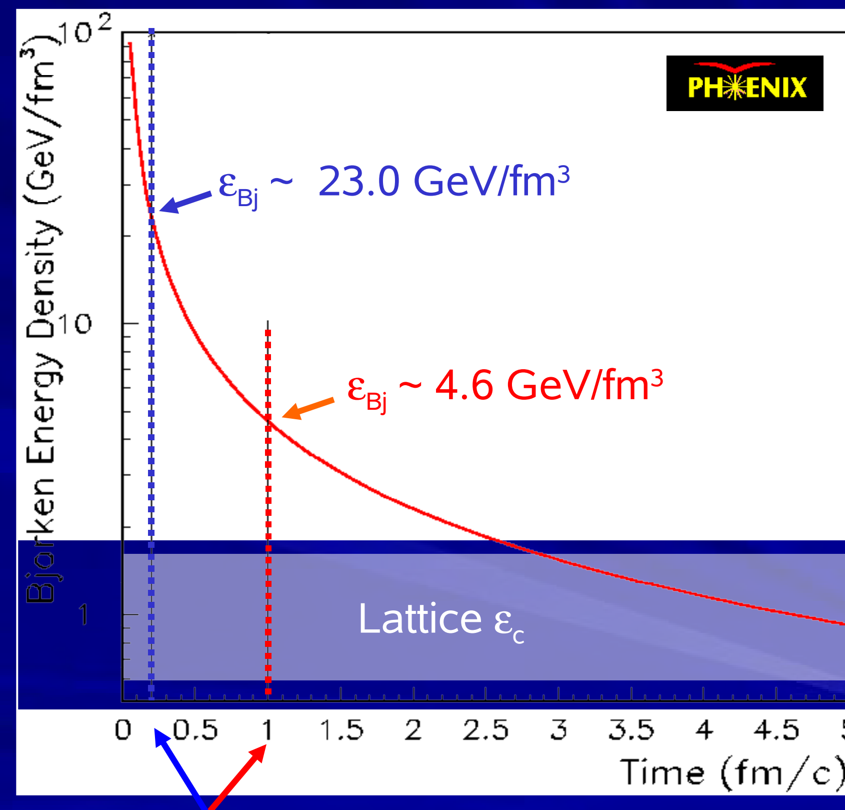
Bjorkens hydrodynamic formula for thermalized energy density in terms of measured transverse energy E_T

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{c\tau_0} \left(\frac{dE_T}{dy} \right)$$



PHENIX: Central Au Au yields

$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\, GeV$$



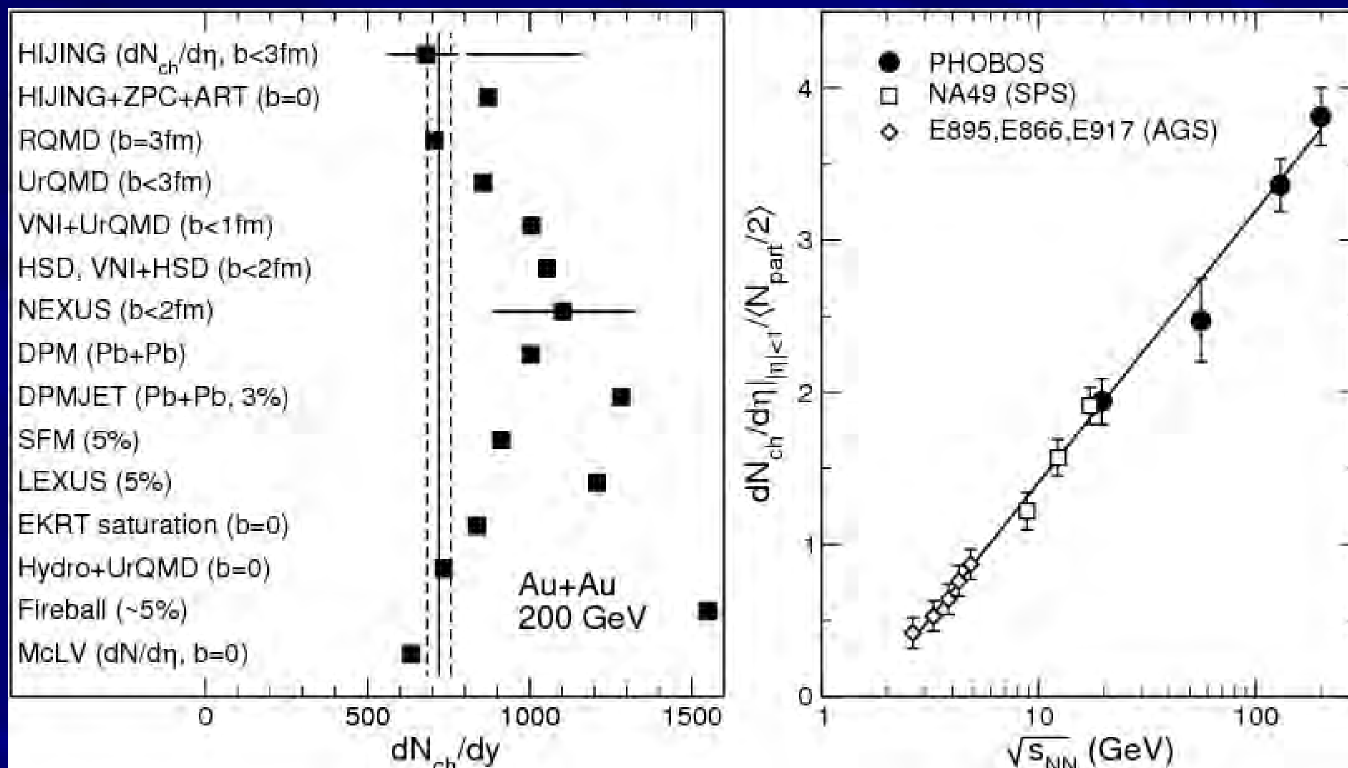
Formation(thermalization) time ?

Charged multiplicity $dN_{ch}/d\eta$ at mid-rapidity (η~0) vs models

Model predictions at $\sqrt{s_{NN}}$=200GeV **$dN/d\eta$ $\sqrt{s_{NN}}$**

Lund strings →

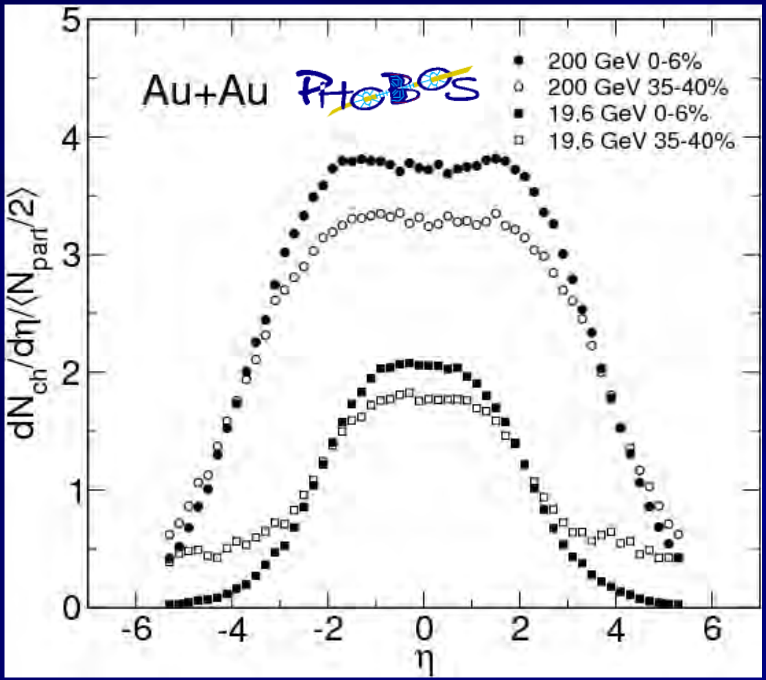
Gluon saturation (final state!) →

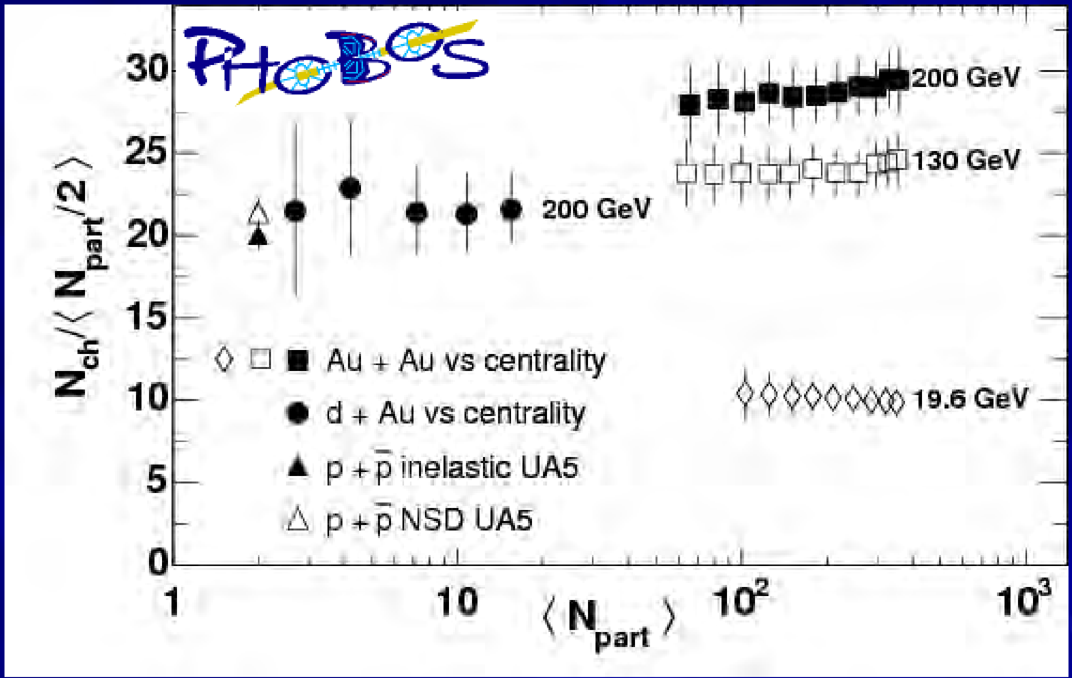


- Model predictions before RHIC generally overpredicted $dN/d\eta$. Data shows simple power law increase: $dN/d\eta \sim k1 * \sqrt{s_{NN}}^{k2}$ with no signs of discontinuity (no bump)

Charged particle multiplicity scaling with Npart

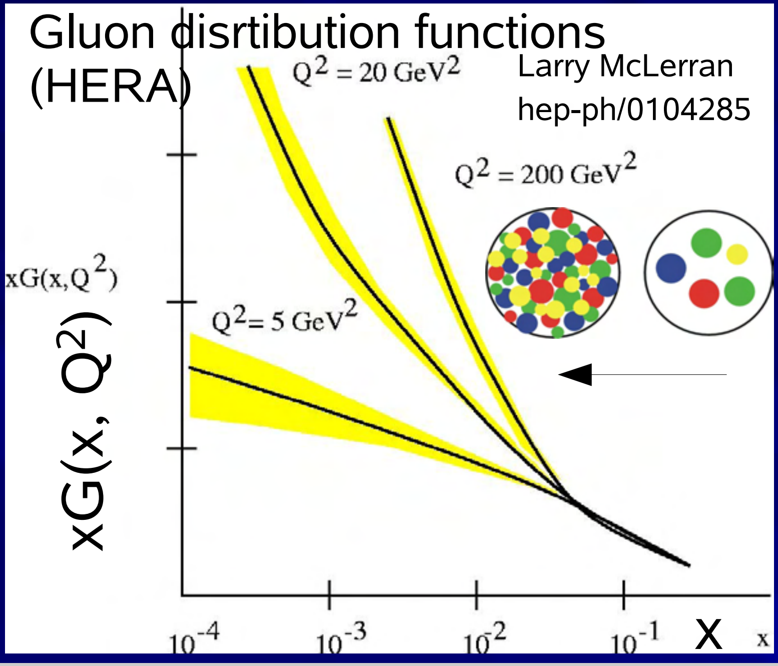
$dN_{ch}/d\eta$ norm. to Npart/2 | **N_{ch} norm. to Npart/2 vs Npart**

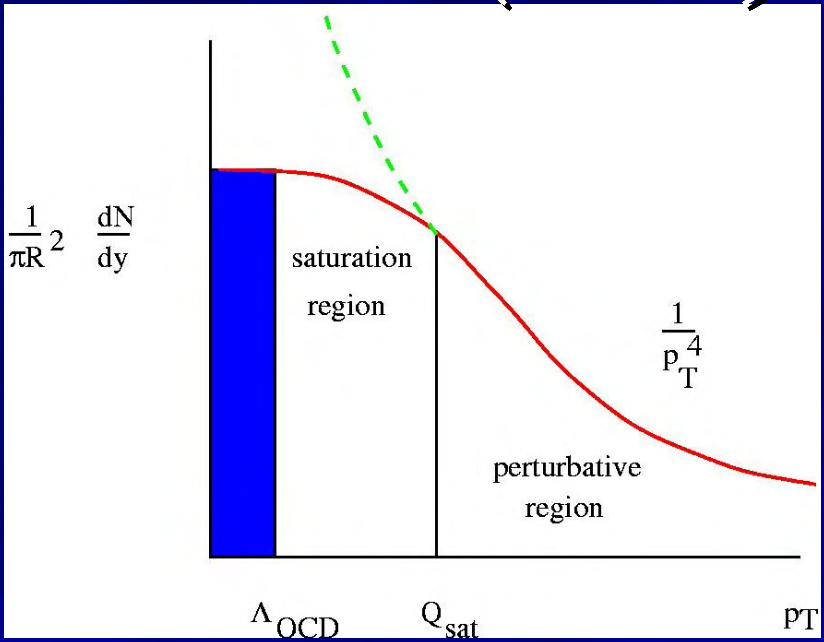




- Charged multiplicity per Npart is almost flat
- Why is there no effect of multiple binary collisions?
  - Energy momentum conservation?
  - Or gluon saturation?

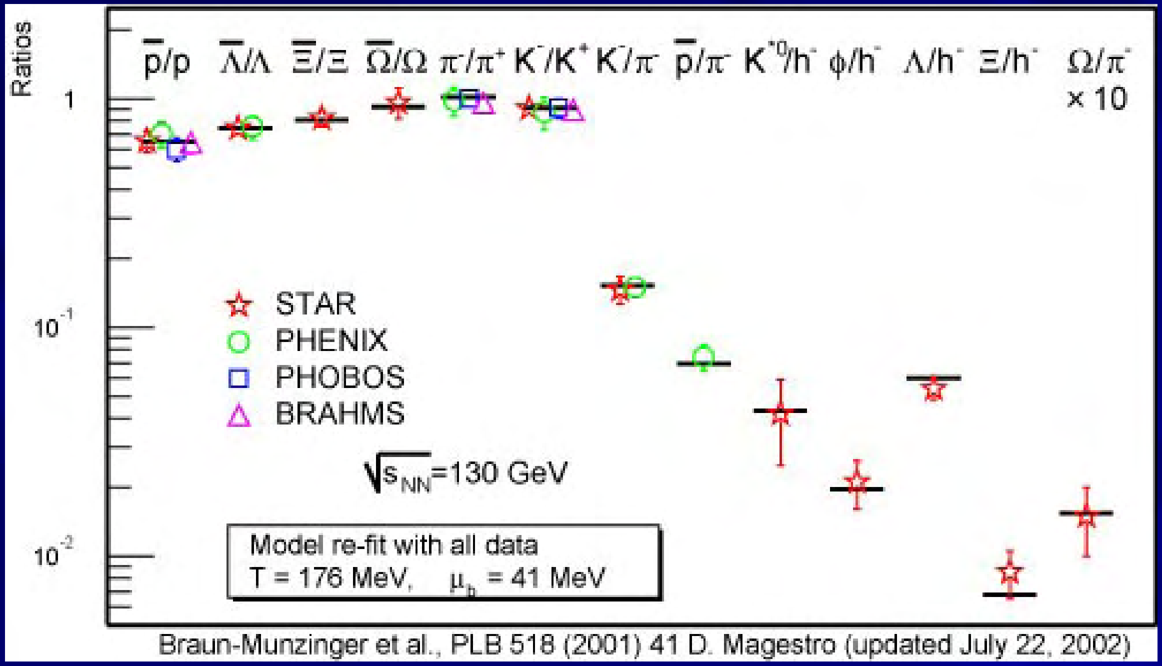
Gluon Saturation: Color Glass Condensate (CGC)

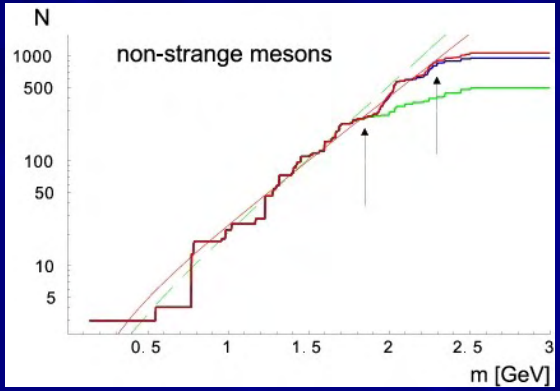




- **With increasing energy/momentum resolution the number of (small-x) partons in a hadron/nucleus grows rapidly (dominate soft physics)**
- **At the saturation scale Q_s partons begin to overlap in the transverse area of the nucleus (~$A^{1/3}$), which prevents further growth of the parton density**
- **Color-Glass-Condensate (initial state): The many partons can be treated as semi-classical fields so initial condition at RHIC/LHC can be calculated**
- **Is this the general state of very high energy nucleons and nuclei?**

Identified particle ratios: T and μ_B at freezeout

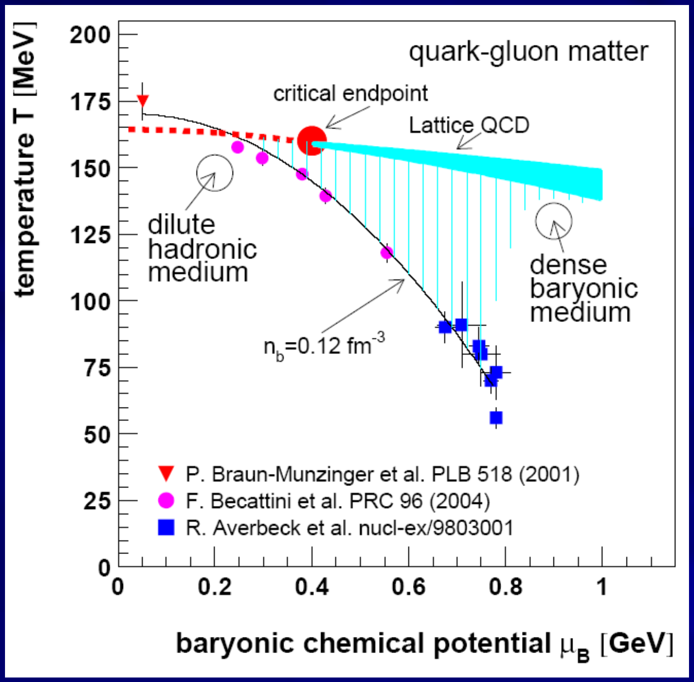


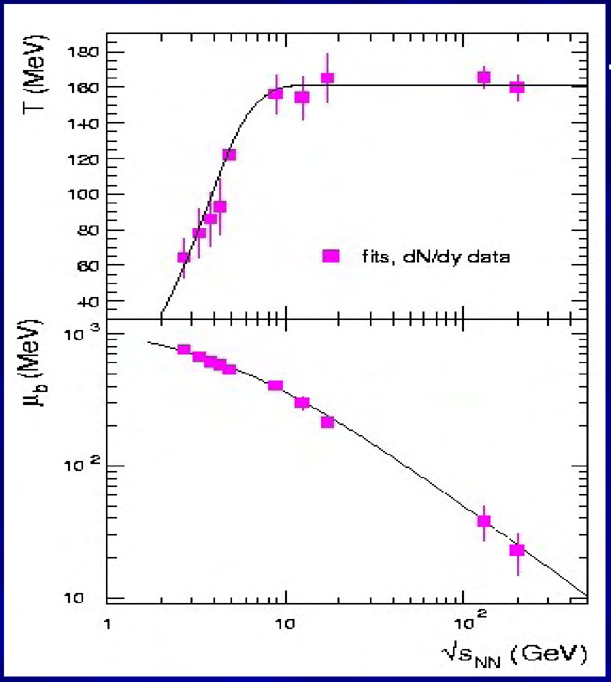


1. Generate hadrons with weights: $\exp(-(m+\mu_B)/T)$
2. Decay strongly
3. Compare to data

- Particle ratios are well described by statistical models when decay from hadronic resonances are taken into account (only QCD input are the masses and decays)
- The temperature is consistent with what we expect from Lattice QCD calculations for the transition temperature

The QCD phase diagram with the measured T and μ_B





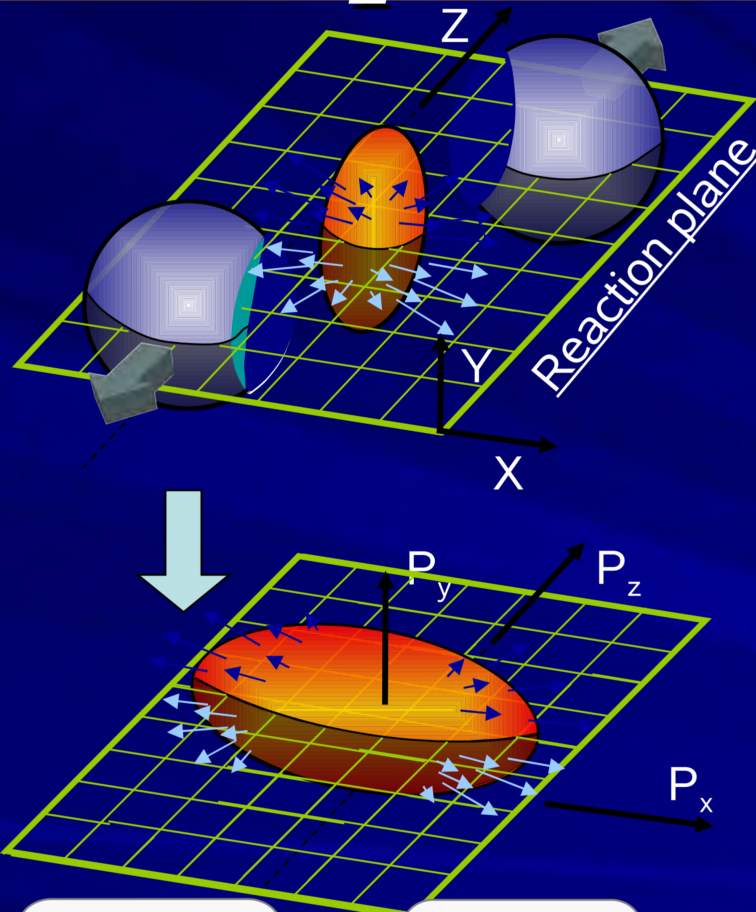
T_{lim} = 161 ± 4 MeV

A. Andronic,
P. Braun-Munzinger,
J. Stachel,
nucl-th/0511071

Because of the simple beam-energy systematics statistical models have predictive power!

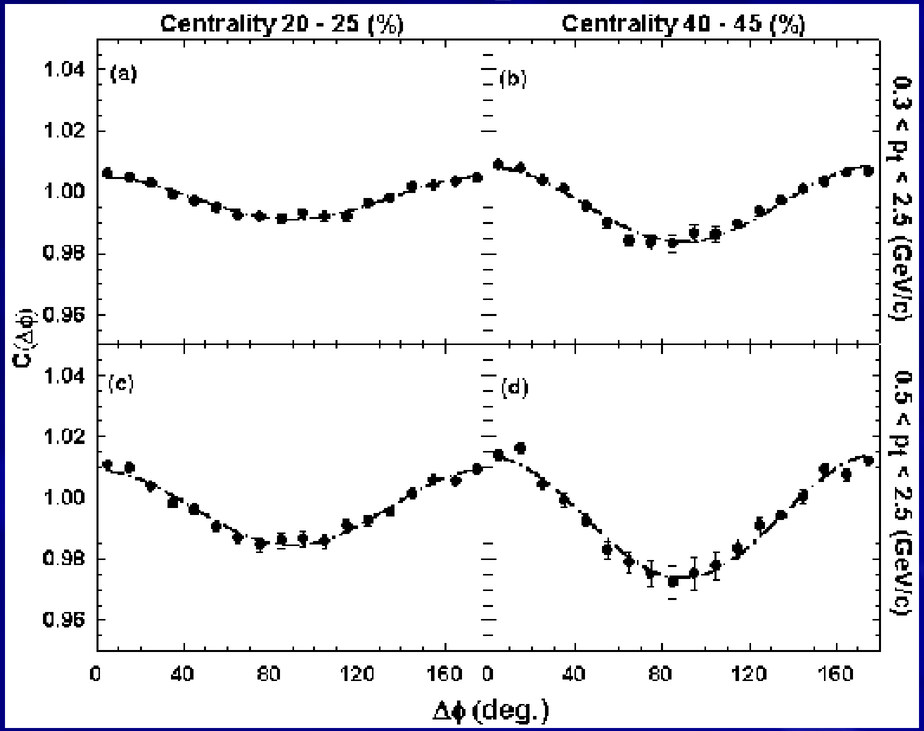
- The statistical description of particle rations is also good for lower energies: AGS and SPS
- The temperature saturates at T~160 MeV indicating that the system has crossed the phase boundary
- <u>But p+p ratios can be described with a similar (canonical) formalism and T! So it is a hadronization attribute!(?)</u>

Elliptic flow (v2) unique in heavy ion collisions



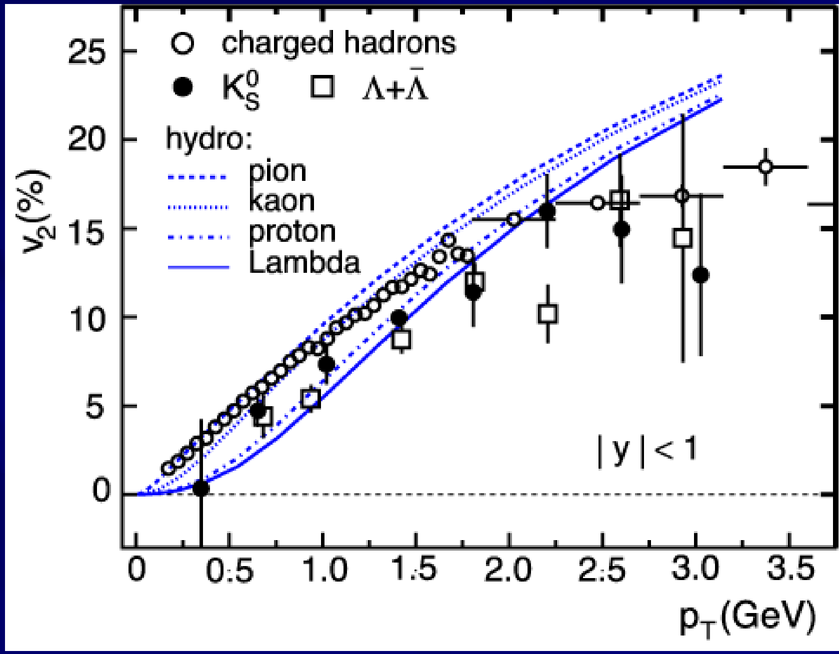
Fourier decomposition:

$dN/d\phi = 1 + 2\,V_2\cos(2\,\Delta\phi)$



Initial spatial anisotropy → Strong pressure gradients → v_2 Azimuthal anisotropy → **Sensitivity to early expansion**

v2 at RHIC: Maximal flow and low viscosity



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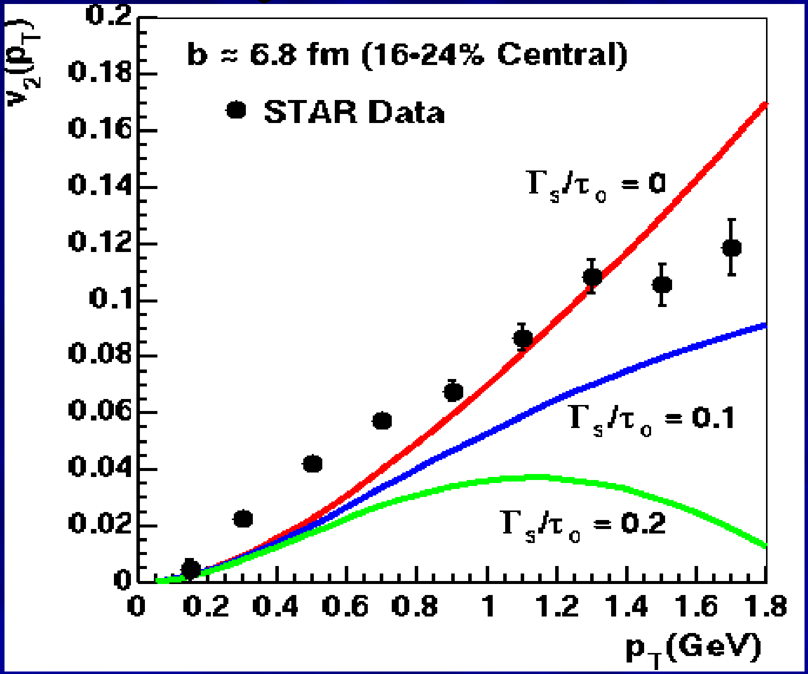


Phys. Rev., 2003, C68, 034913

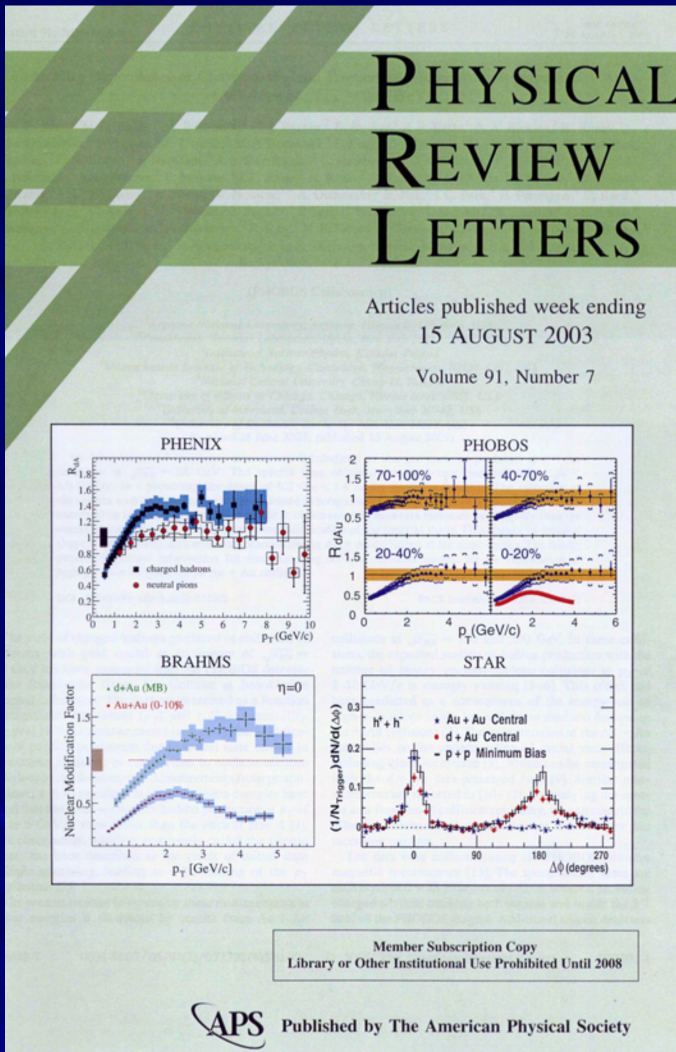
- Hydrodynamic predicts v2 (for p_T<2GeV/c)
- Strong interactions are really strong => use hydro
- <u>To generate high flow one needs early interactions</u>
- Low viscosity => Perfect fluid
- Where is QCD dynamics? v2 not very sensitive to EOS.

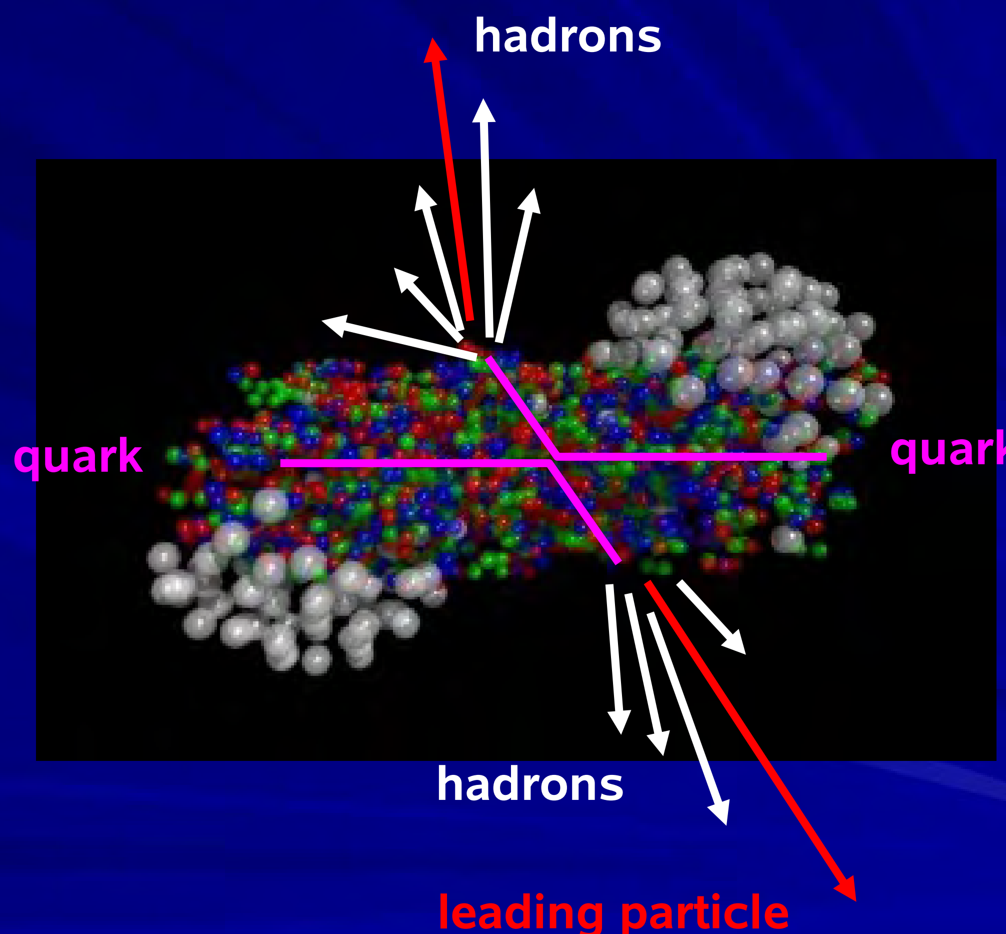
Summary of soft results

- The system created at RHIC
  - 75% of kinetic energy goes into the system (stopping)
  - Initial energy density > Lattice requirement (transverse energy)
  - System interacts early and strong – thermalization? (v2)
  - Tchemical ~ Lattice phase transition T (particle ratios)
- The matter created at RHIC does not behave as a weakly interacting gas, but as a strongly interacting perfect liquid: QGP -> sQGP

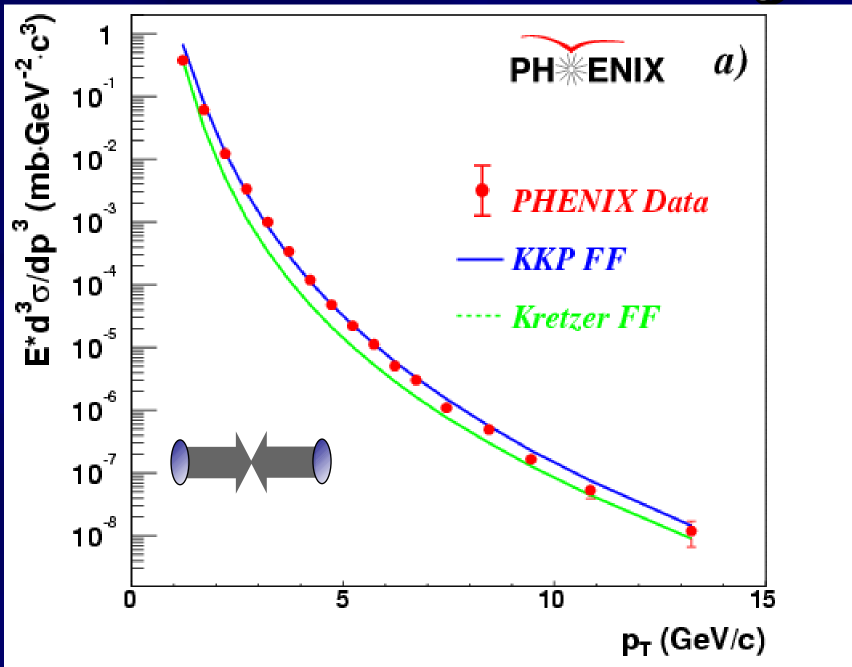
- **There are indications that system has been in plasma phase but no smoking gun!**

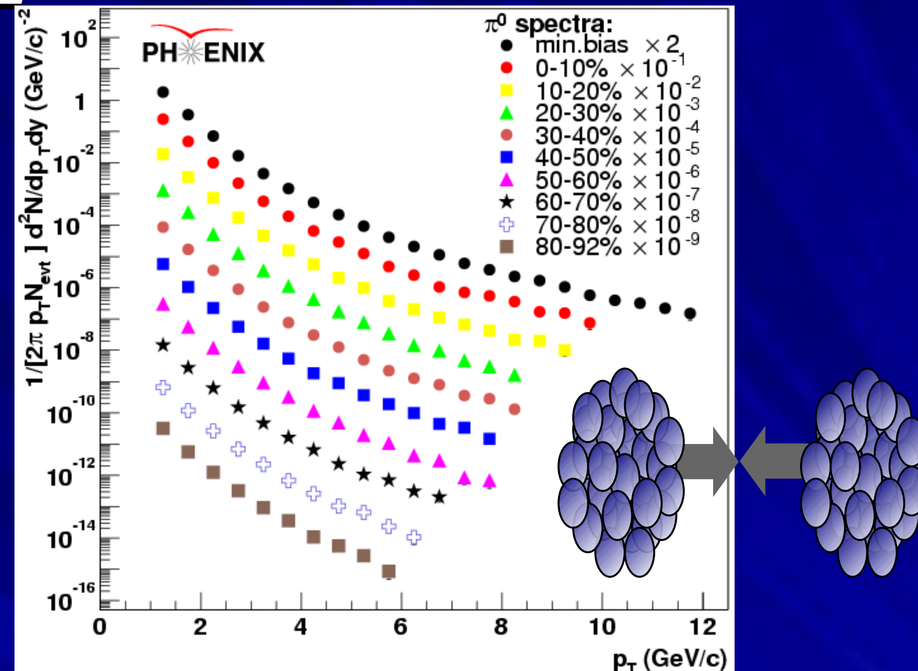
Hard probes (pQCD): p_T>2GeV and heavy quarks:



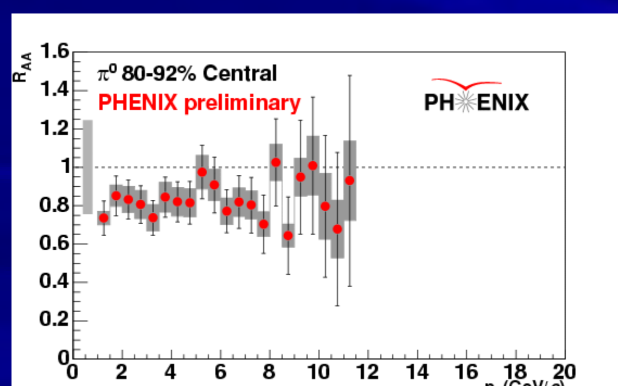


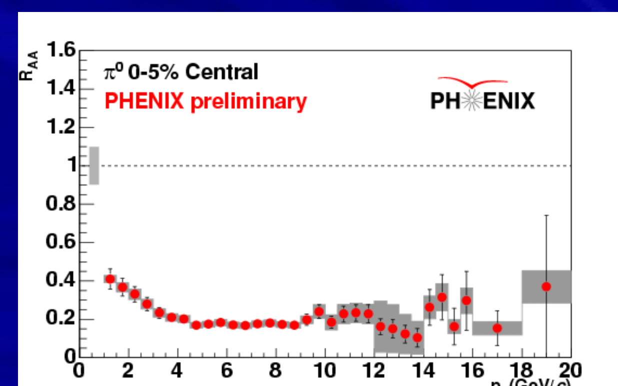
The nuclear modification factor for pions



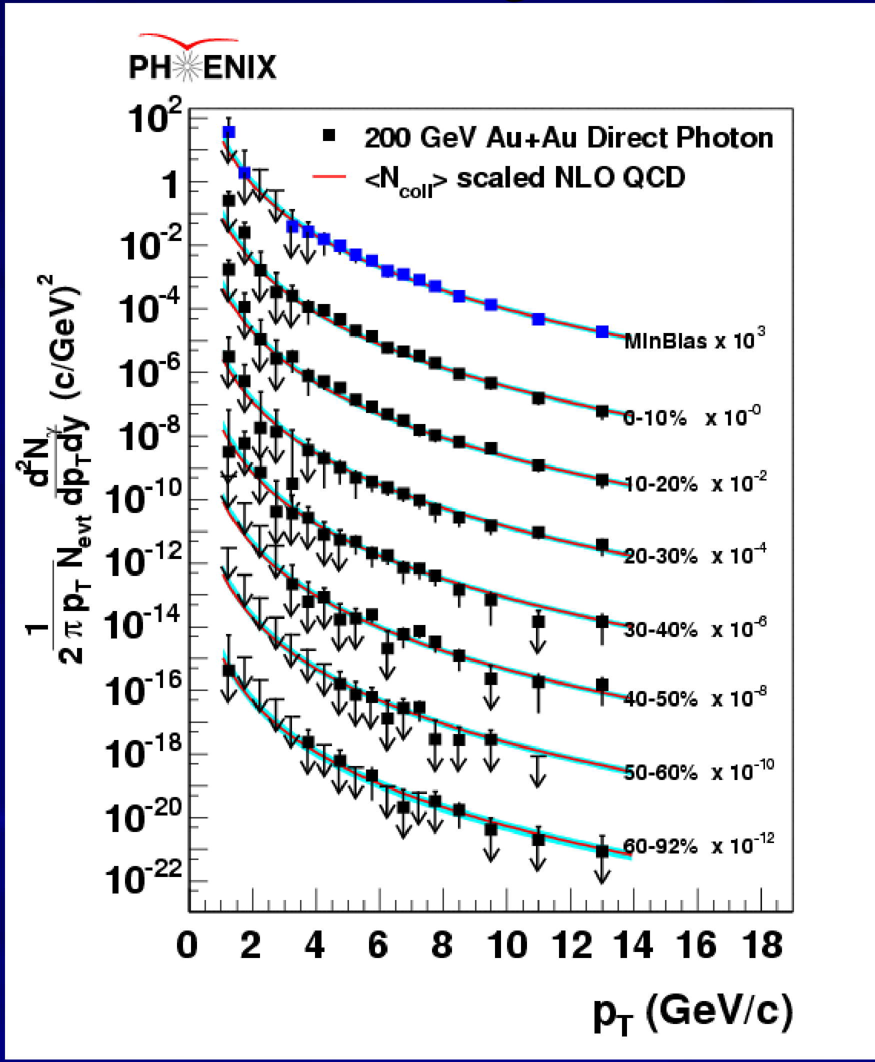


$$R_{AA} = \frac{d^2 N^{AA} / d\, p_T\, dy}{\langle N_{bin} \rangle d^2 N^{NN} / d\, p_T\, dy}$$

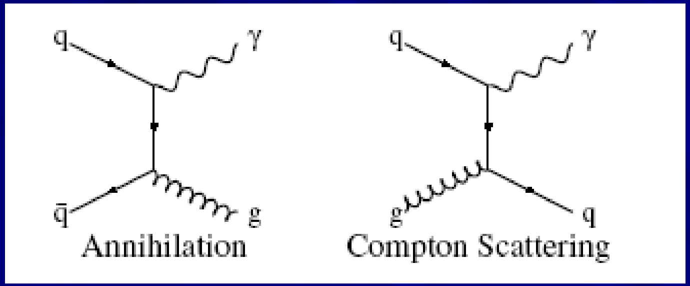




The nuclear modification factor for direct photons

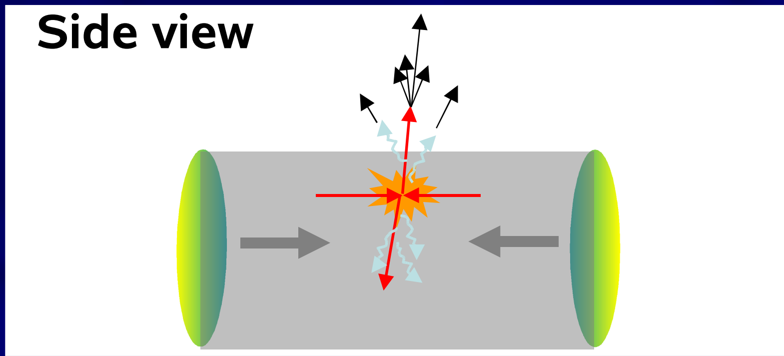


Source of direct photons

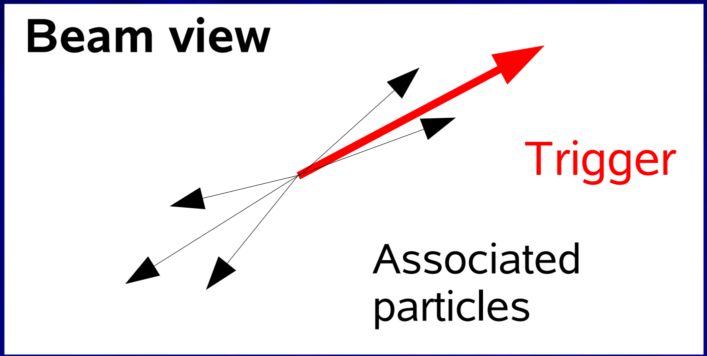


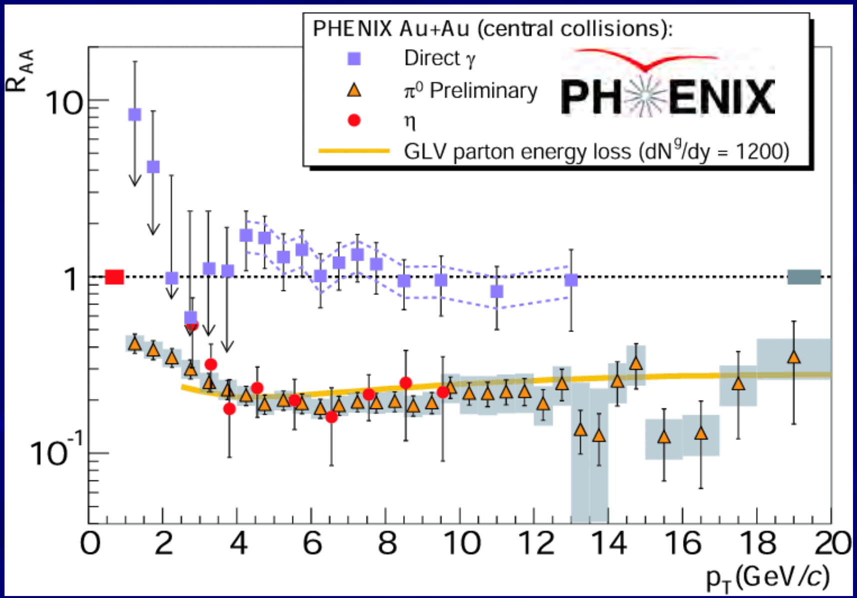
- Direct photons does not interact with final state hadronic matter!
- At low pT photons are dominantly decay photons e.g. $\pi^0 \rightarrow 2\gamma$
- Direct photons confirm binary scaling of hard processes!

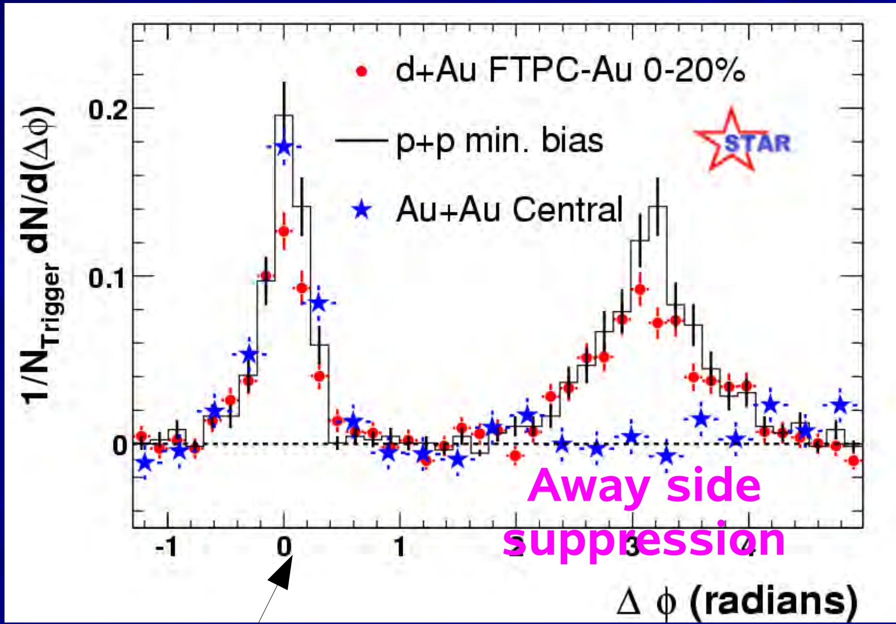
Disappearance of the away side jet indicates final state effect



Most jets are created back to back!



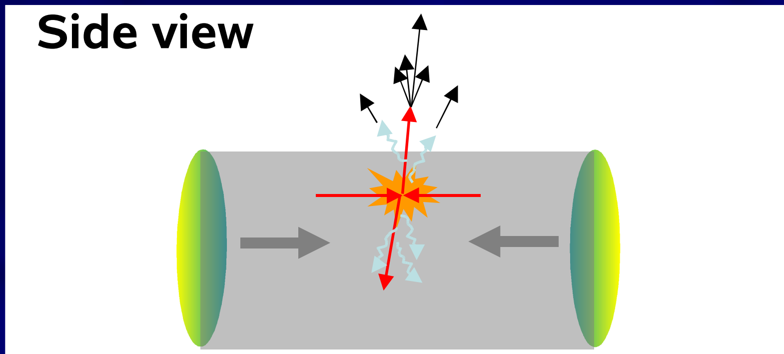




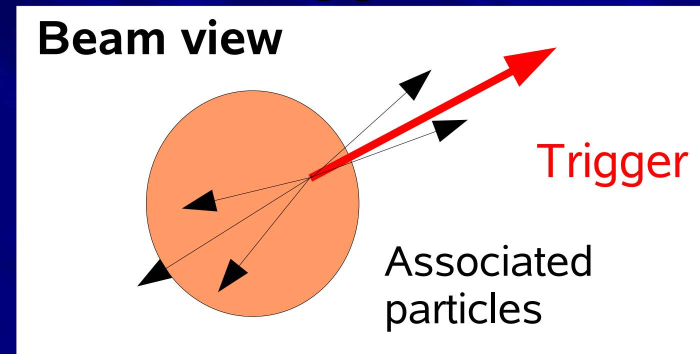
4 < p_T(trig) < 6 GeV/c

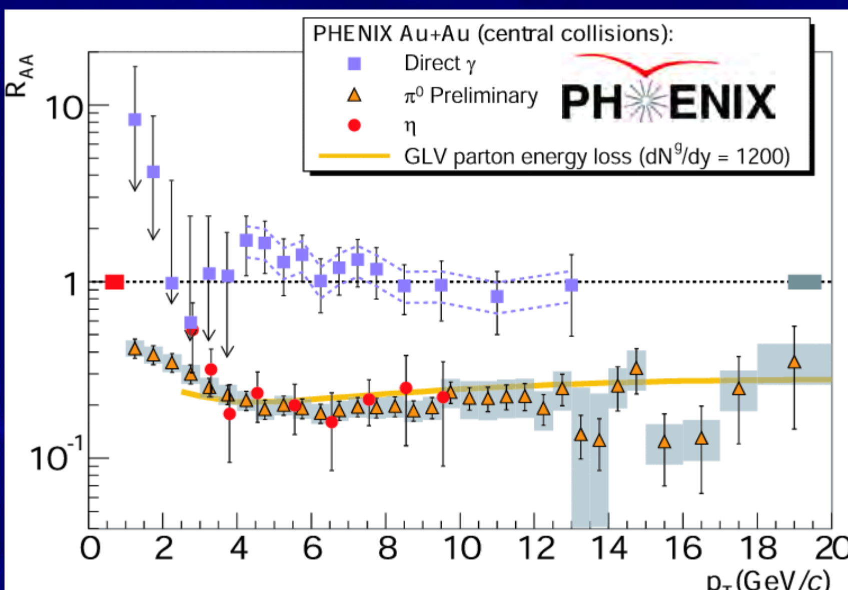
p_T(assoc) > 2 GeV/c

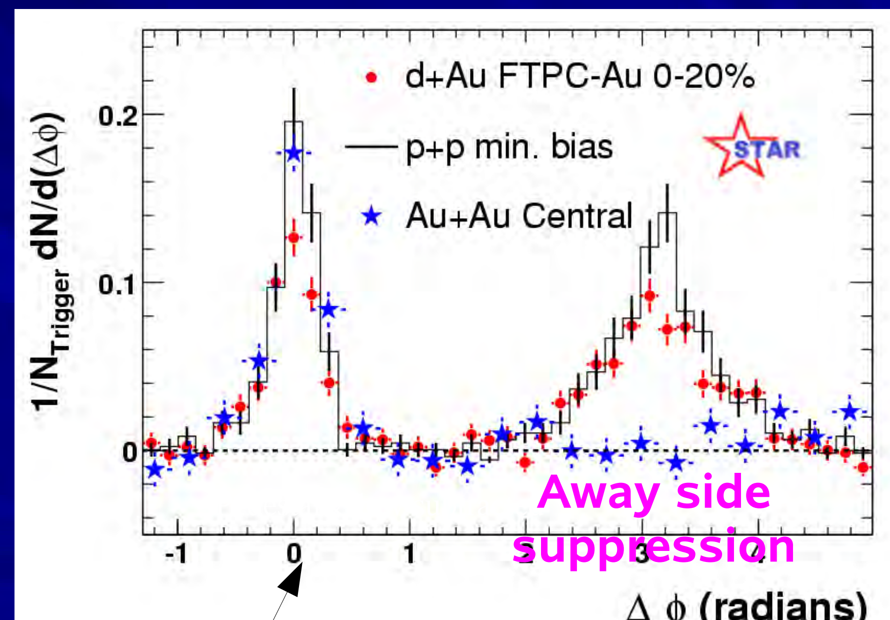
Disappearance of the away side jet indicates final state effect



Most jets are created back to back!



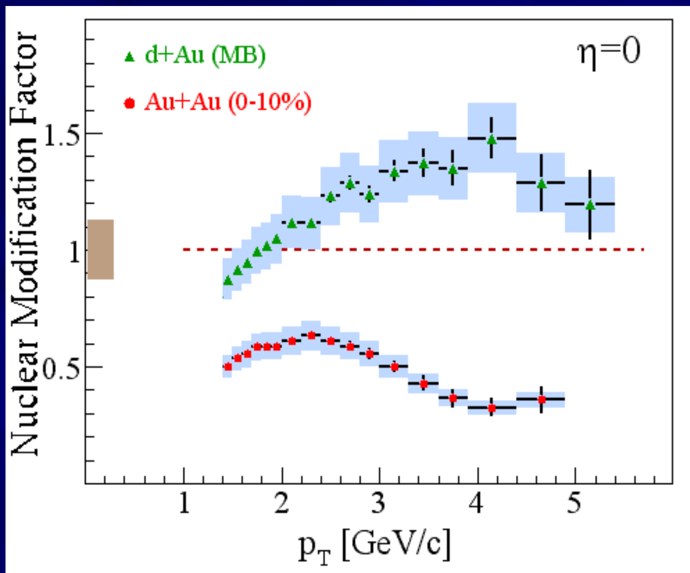


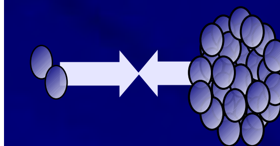


$4 < p_T(\text{trig}) < 6$ GeV/c

$p_T(\text{assoc}) > 2$ GeV/c

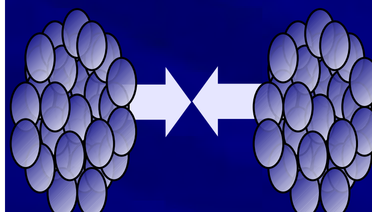
Au+Au vs d+Au
Hot vs cold nuclear matter



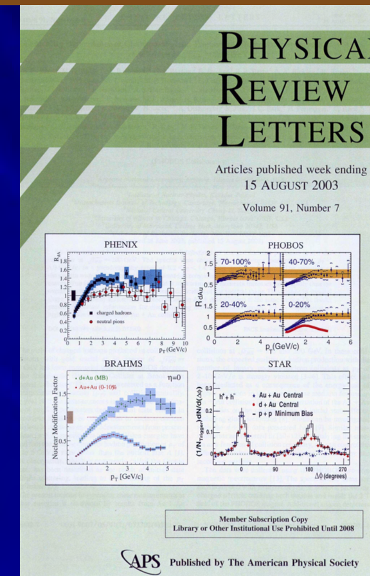


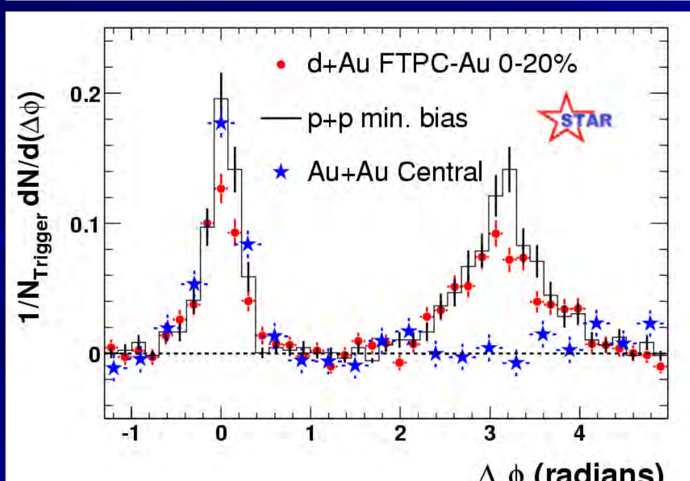
d+Au

Au+Au



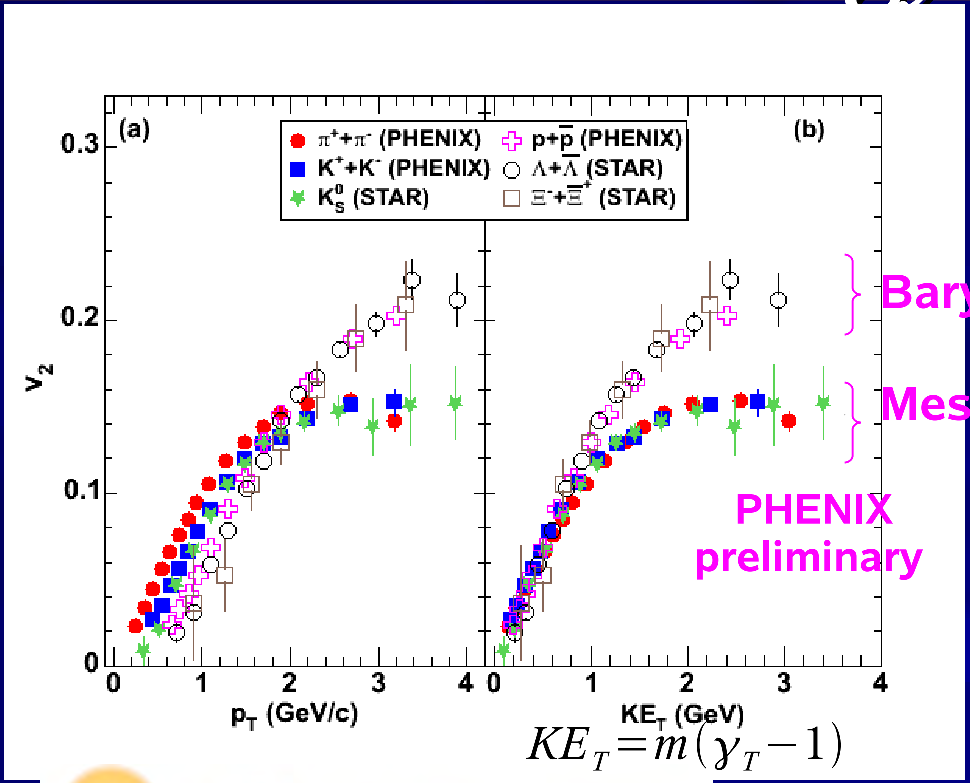
All 4 experiments published together in PRL:



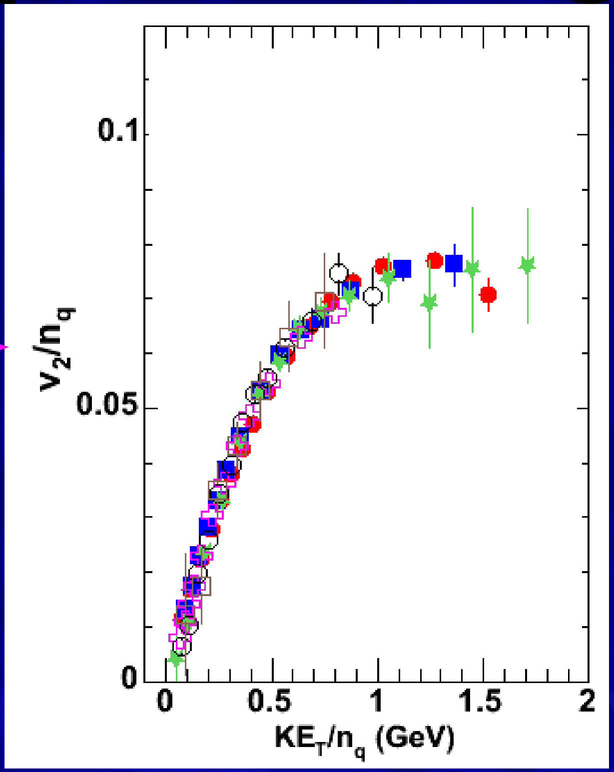


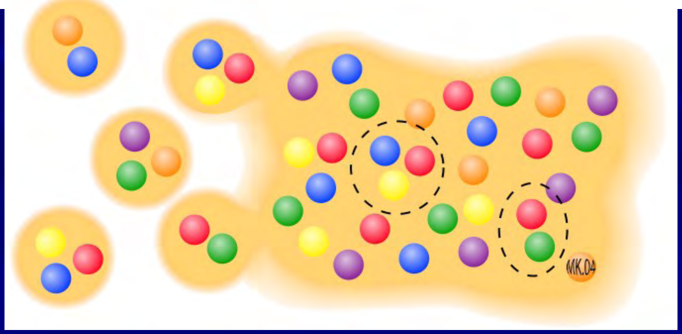
No suppression seen in d+Au
→Final state effect not seen at lower energy!
Quarks and gluons loose/radiate energy as they propagate through the dense medium!
They probe the created matter

Elliptic flow at high pT: kinetic energy and quark scaling



$$KE_T = m(\gamma_T - 1)$$

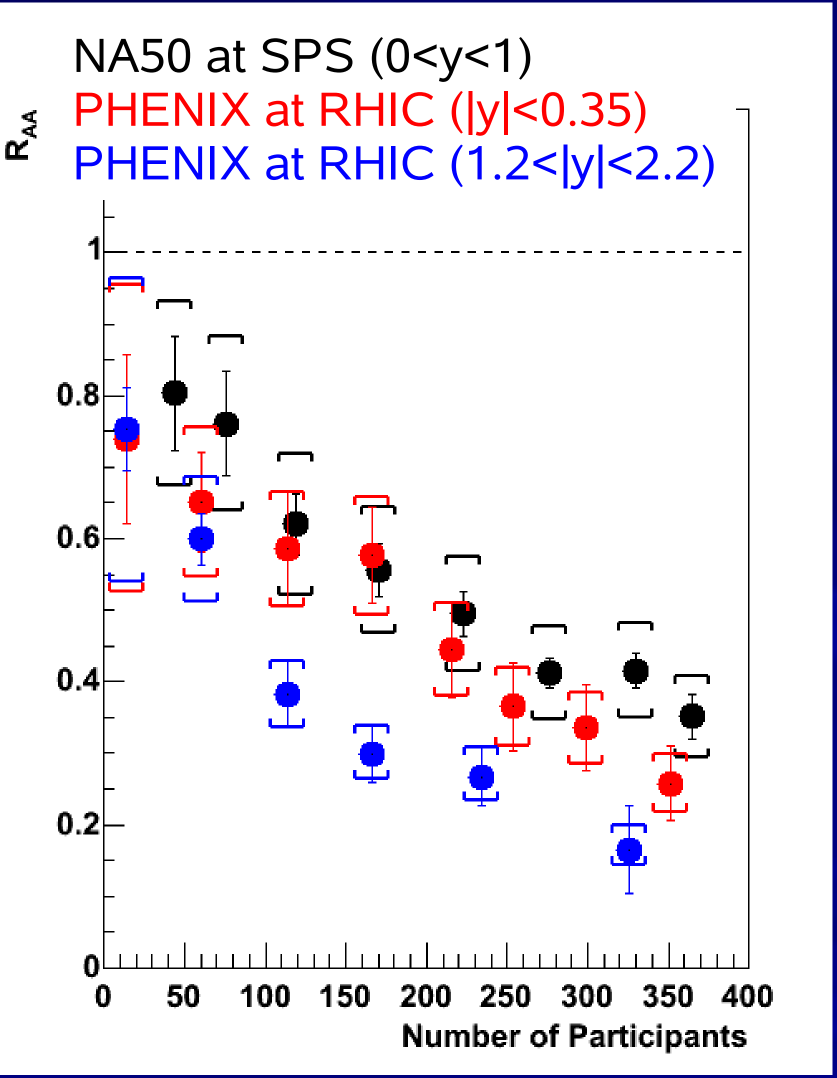




Quark recombination into hadrons ?

Quark degrees of freedom?

J/Ψ (c+c-bar) suppression at SPS and RHIC

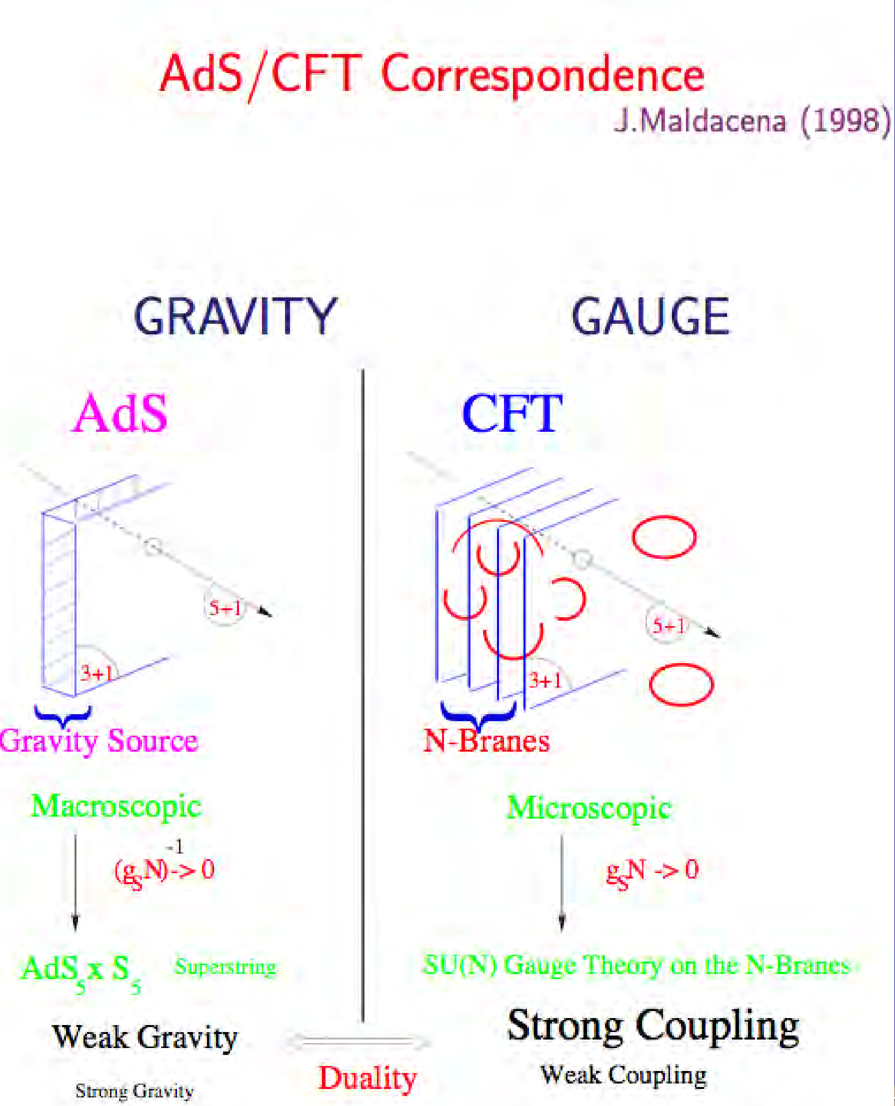


- Suppression patterns are remarkably similar at SPS and RHIC when measured with the nuclear modification factor R_{AA}
- Cold matter suppression (absorption) larger at SPS, hot matter suppression (screening) larger at RHIC, balance?
- c+c-bar recombination cancels additional suppression at RHIC?
- LHC will give the answer(?)

Summary of hard physics

- High p_T jets are suppressed indicating that they suffer a large energy loss in the medium
  - Medium is dense and strongly interacting
- Quark degrees of freedom
- J/ψ puzzle: Suppression pattern similar at SPS and RHIC
- Upgrade of RHIC to RHIC-II (higher luminosity) and upgrades of experiments with new detectors e.g. vertex
  - Focus on direct photons and direct ID of heavy quarks (c, b)
- Problem: QGP or not QGP is a question for theorists
  - Need better theory!

New theoretical tool?: String theory can describe QCD



Robi Peschanski EPS Manchester 07

High Energy Heavy Ion - test laboratory for string theory?

- Shear viscosity (prediction of low viscosity – universal limit?)
  "Viscosity in Strongly Interacting Quantum Field Theories from Black Hole Physics" *P.K. Kovtun, D.T. Son, and A.O. Starinets*
- Quenching parameter
  "Calculating the jet quenching parameter from AdS/CFT" *Liu, Rajagopal, and Wiedemann*
- Thermal particle production
  Unruh mechanism, black hole radiation,… *Karzeev, Satz*

Conclusions

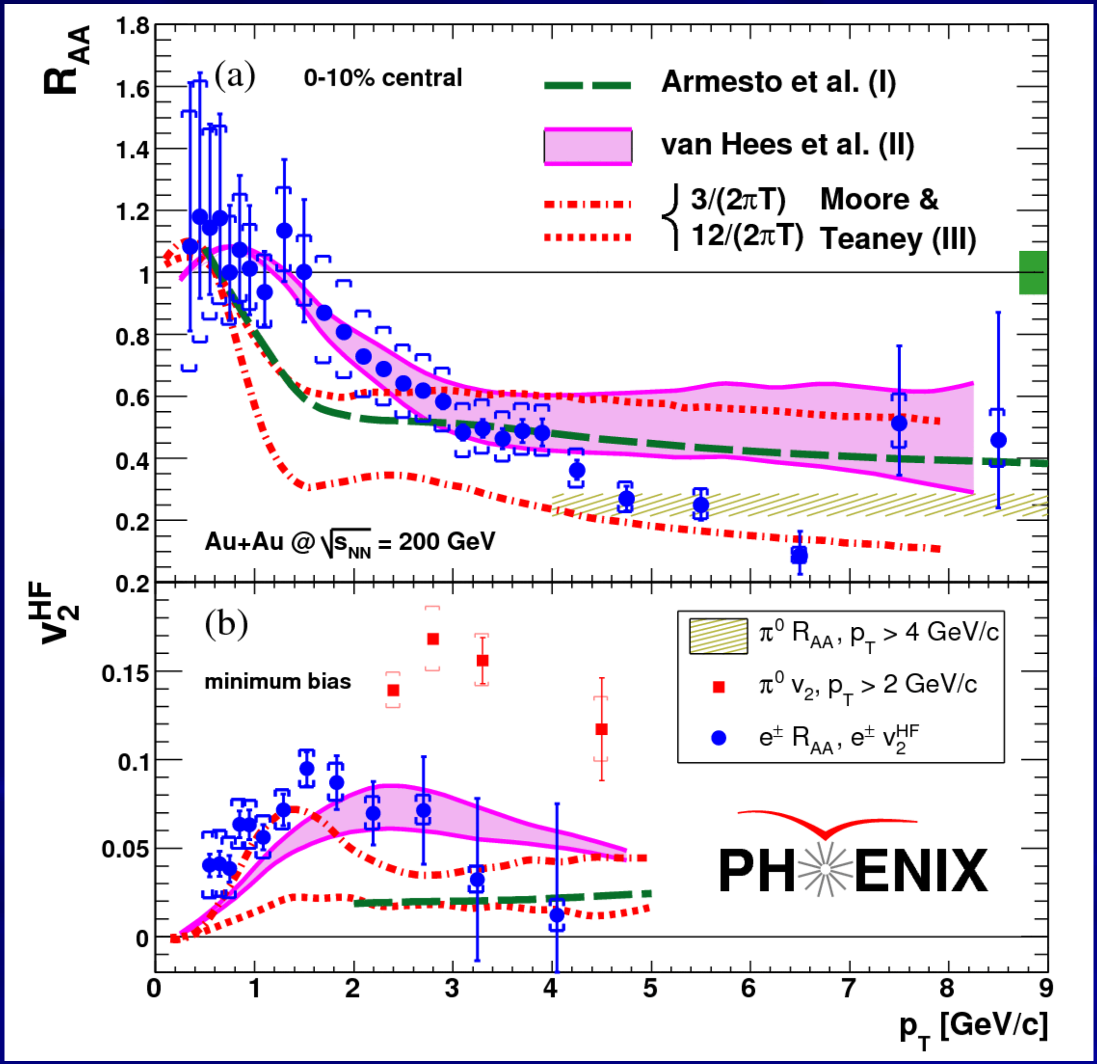
- A new phase of QCD matter has been observed at RHIC and it has been possible to determine some of the properties
  - The energy density and temperature is consistent with LQCD predictions for a QGP
  - The matter created is interacting early and strong
  - It is interacting so strong that it absorbs jets
  - It shows quark degrees of freedom (recombination?)
- Questions for LHC
  - Will elliptic flow be higher than hydro at LHC?
  - What will the suppression patter be for light hadrons, heavy quarks and for fully reconstructed jets at LHC
  - Recombination model predicts very large effects at LHC where there are many more mini jets
  - And possible new effects!

LHC and ALICE

To boldly go where no man or woman has gone before...

Backup slides

Heavy Quark (c, b) Energy Loss and Flow in Au+Au



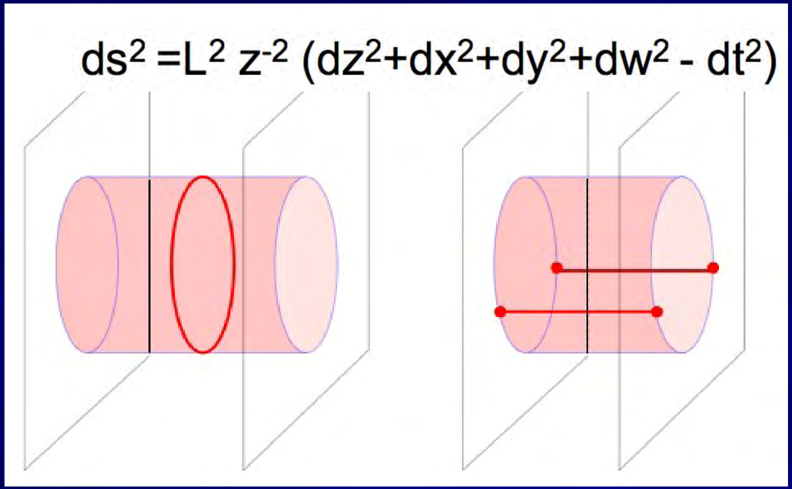
Indirectly measured: Measure single electron spectra and correct for background.

No suppression at low pT Suppression observed for pT>3 GeV/c (smaller than for light quarks)

Heavy quarks also has elliptic flow

Heavy quarks interact with the medium! Further information / constraints for theory

5d Anti de-Sitter space ↔ Conformal FT (QCD like)



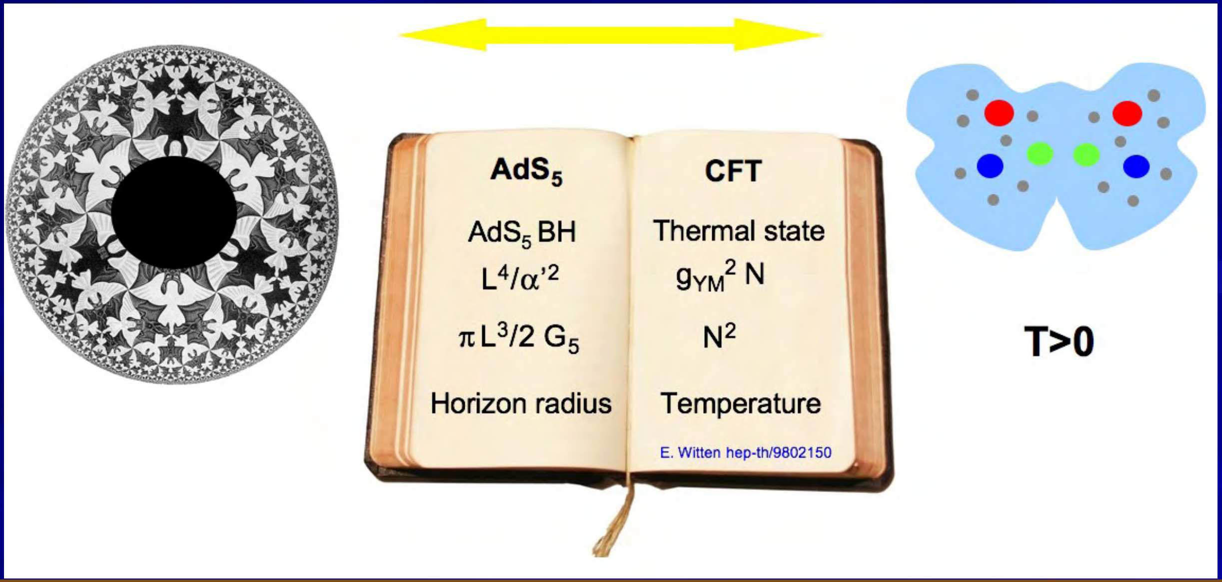
J. Maldacena 1998 (top cite +4800)

Close String ⇔ 1-loop Open String

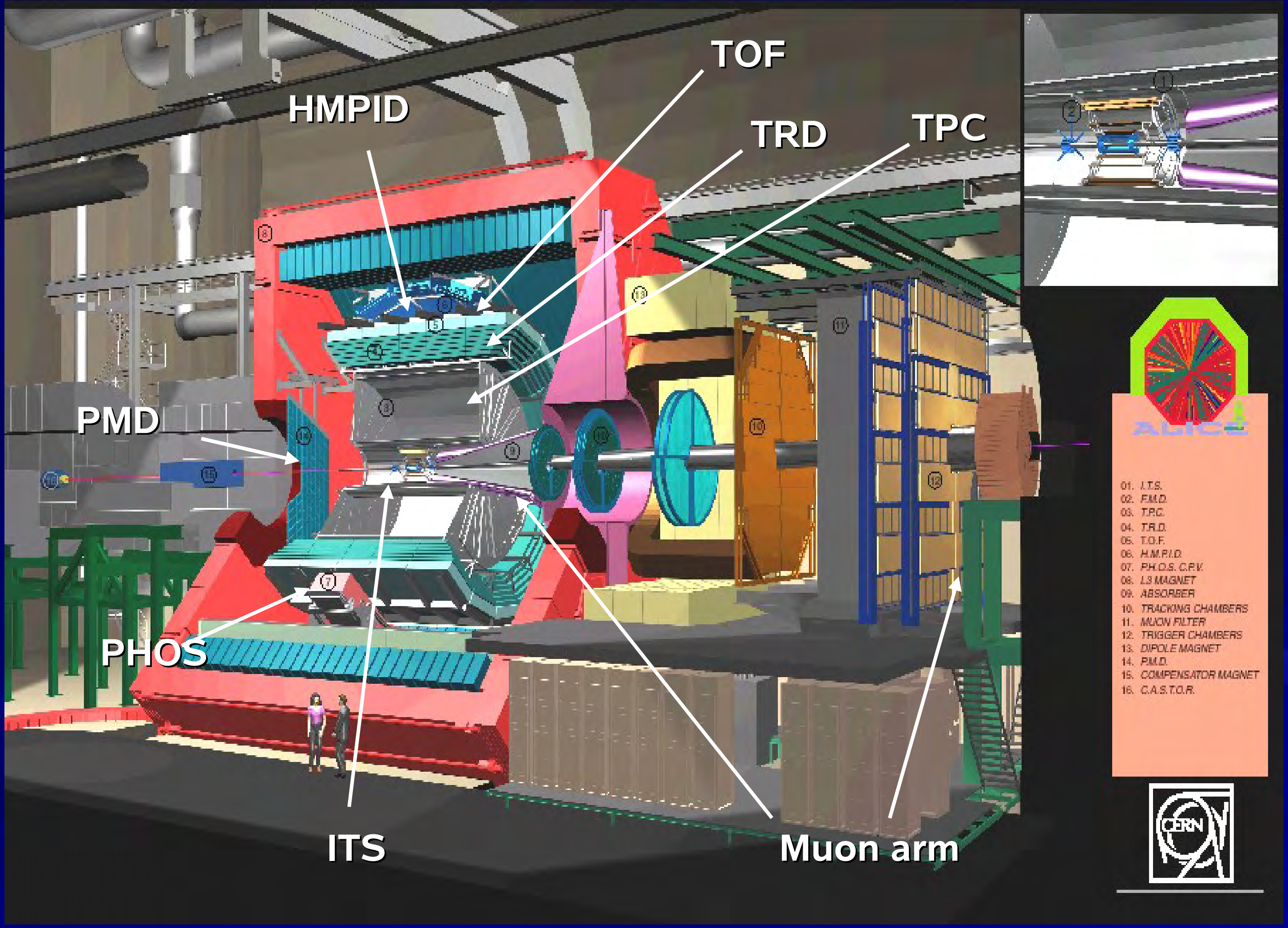
Endpoint of an open string on the boundary ⇔ Massive particle

Gravity ⇒ Gauge theory

Large/small dist. ⇒ AdS/CFT corresp.



The ALICE experiment at LHC



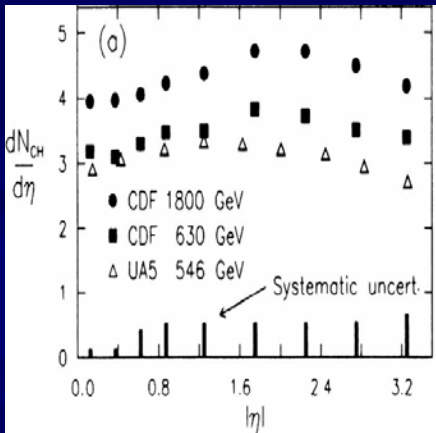
Global detectors:
V0
T0
FMD

Combines the **best of STAR:** TPC and full azimuthal coverage **and PHENIX:** Photon/lepton detectors **and also has:** inner tracker

Proton-proton physics with ALICE (from June 2008)

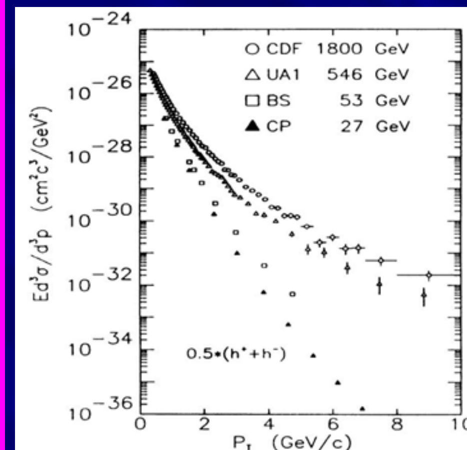
- The first physics with ALICE will be proton-proton collisions:
  - Provides "reference" data to understand heavy-ion collisions.
  - Genuine proton-proton physics where ALICE is unique or competitive
    - low momentum cutoff – due to low magnetic field and small material budget
    - particle identification – unique in central region at LHC
    - ALICE reach p_T up to ~100GeV/c, ensuring overlap with other LHC experiments
  - Proton data taking at several centre-of-mass energies (0.9 TeV?, 2.4 TeV?, 5.5 TeV? and 14 TeV)
- Physics programme: interplay of non-perturbative *vs*. perturbative physics
  - Min. bias events global properties, constraints for underlying event in high P_T signals, pileup in rare triggers
  - Multi-parton interactions (high multiplicity pp events)
  - Heavy Flavours (b and c quarks) [TRD, muon arm and TPC/ITS]
  - Jet physics
  - Collision energy dependence of all the above

First p+p measurements with ALICE (and the TPC)



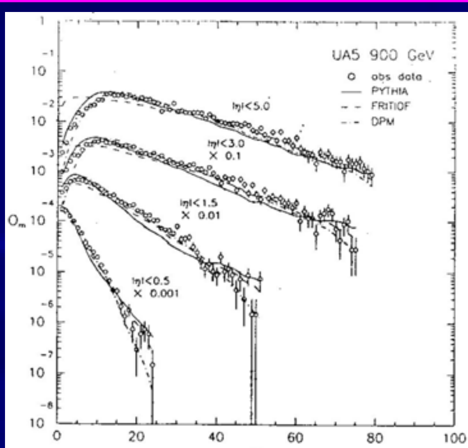
Pseudorapidity density dN/dη

CDF:
Phys. Rev.
D41, 2330 (1990)



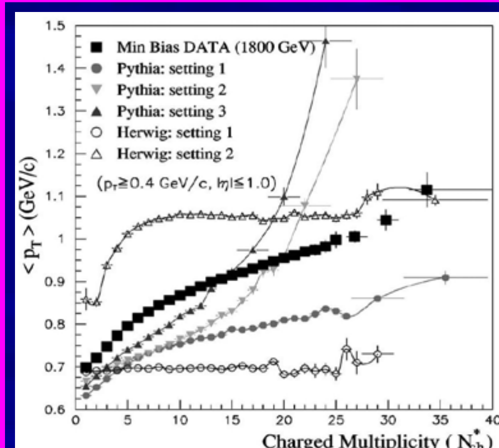
p_T spectrum Charged tracks

CDF:
Phys. Rev. Lett.
51, 1819 (1988)



Multiplicity distribution

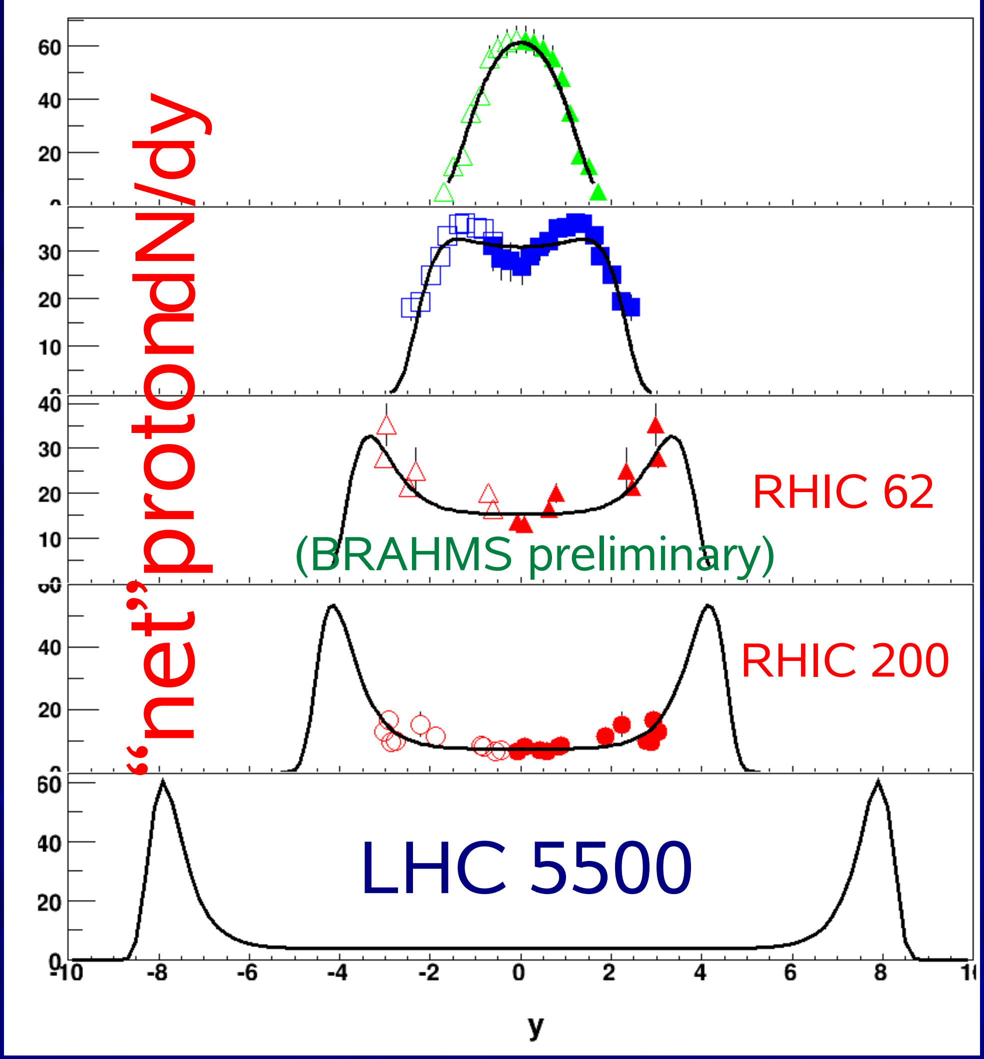
UA5:
Z. Phys
43, 357 (1989)



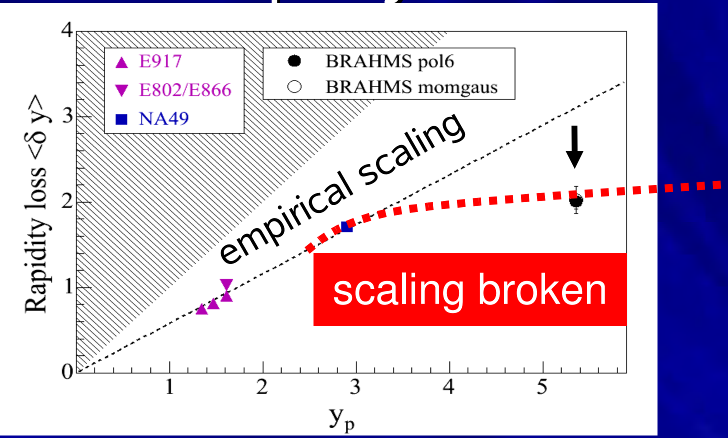
Mean p_T vs multiplicity

CDF:
Phys. Rev.
D65,72005(2002)

Extrapolated stopping From AGS to LHC



- The extrapolation is based on the saturation of the rapidity loss:

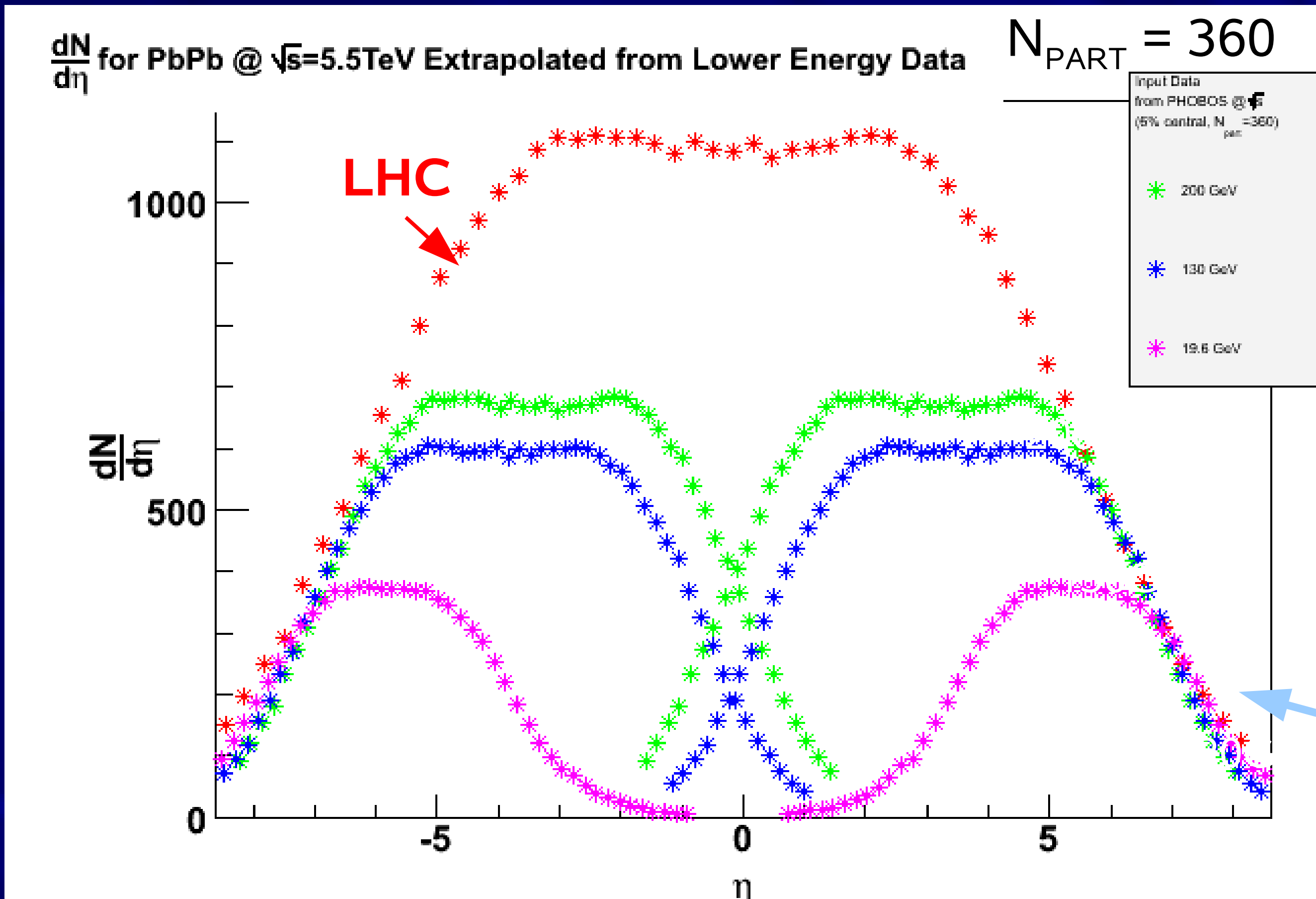


- And that the fit function (which is a Gauss in p_z):

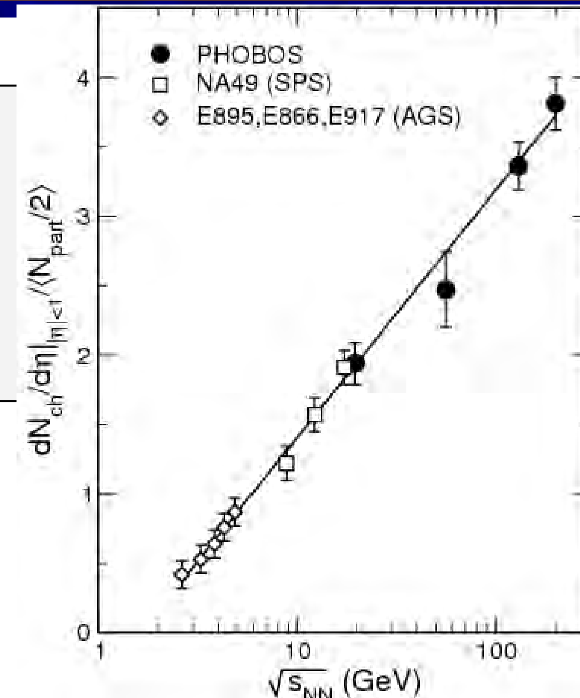
$$\sum_{\pm} \exp\left[-\frac{\left(m_N \sinh(y) \pm \langle p_z \rangle\right)^2}{2\sigma_{pz^2}}\right]$$

describes data so far.

Extrapolated charged particle multiplicities from RHIC

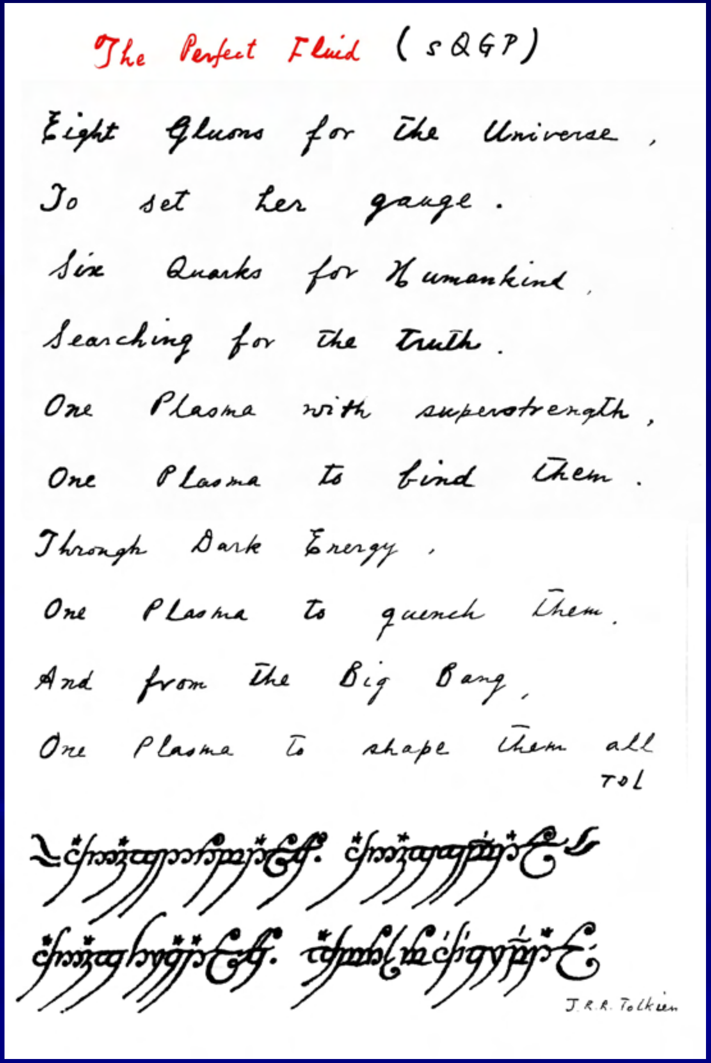


Rapidity shifted AuAu Data from PHOBOS



Limiting fragmentation (same shape when plotted as η-y_{beam})

Results from RHIC

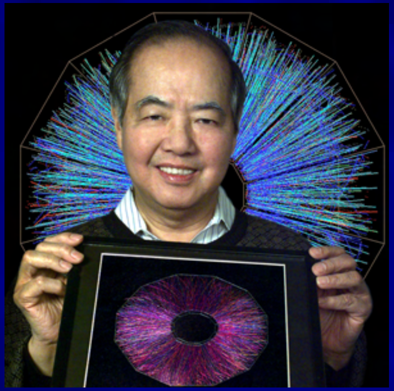


The Perfect Fluid (sQGP)

Eight Gluons for the Universe,
To set her gauge.
Six Quarks for Humankind,
Searching for the truth.
One Plasma with superstrength,
One Plasma to find them.
Through Dark Energy,
One Plasma to quench them.
And from the Big Bang,
One Plasma to shape them all
TDL

J.R.R. Tolkien

T.D. Lee at QM06



A more detailed overview of the results from RHIC can be found in the experimental "white papers" from RHIC:

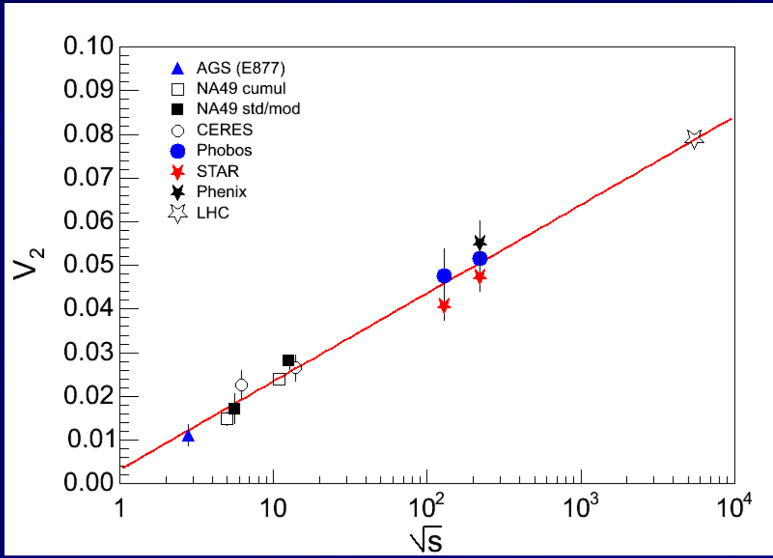
Nuclear Physics A757, August 2005

AIP: The Perfect Liquid at RHIC

Top physics story of 2005

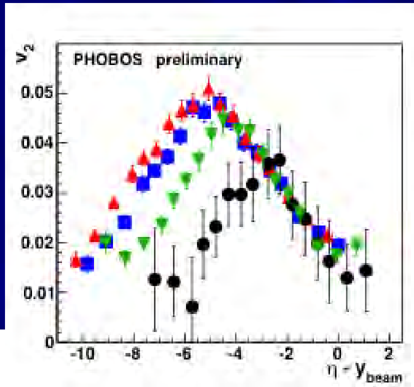
Extrapolated elliptic flow (v2) at LHC

Energy dependence of v2

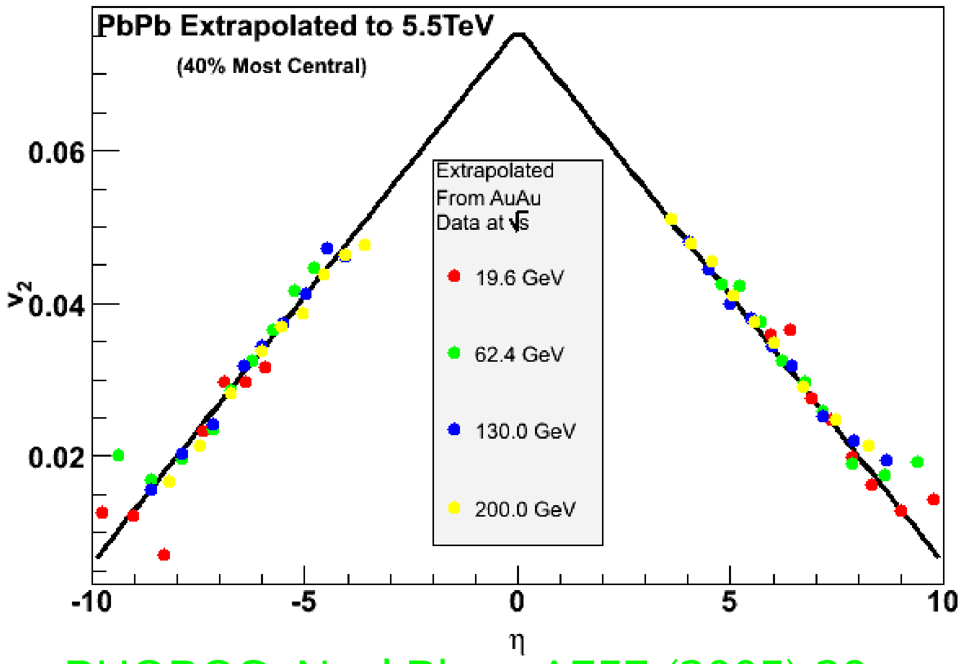


Compilation of data from

Phys. Rev. C68 (2003) 034903



Elliptic Flow also shows limiting fragmentation



PHOBOS, Nucl.Phys. A757 (2005) 28

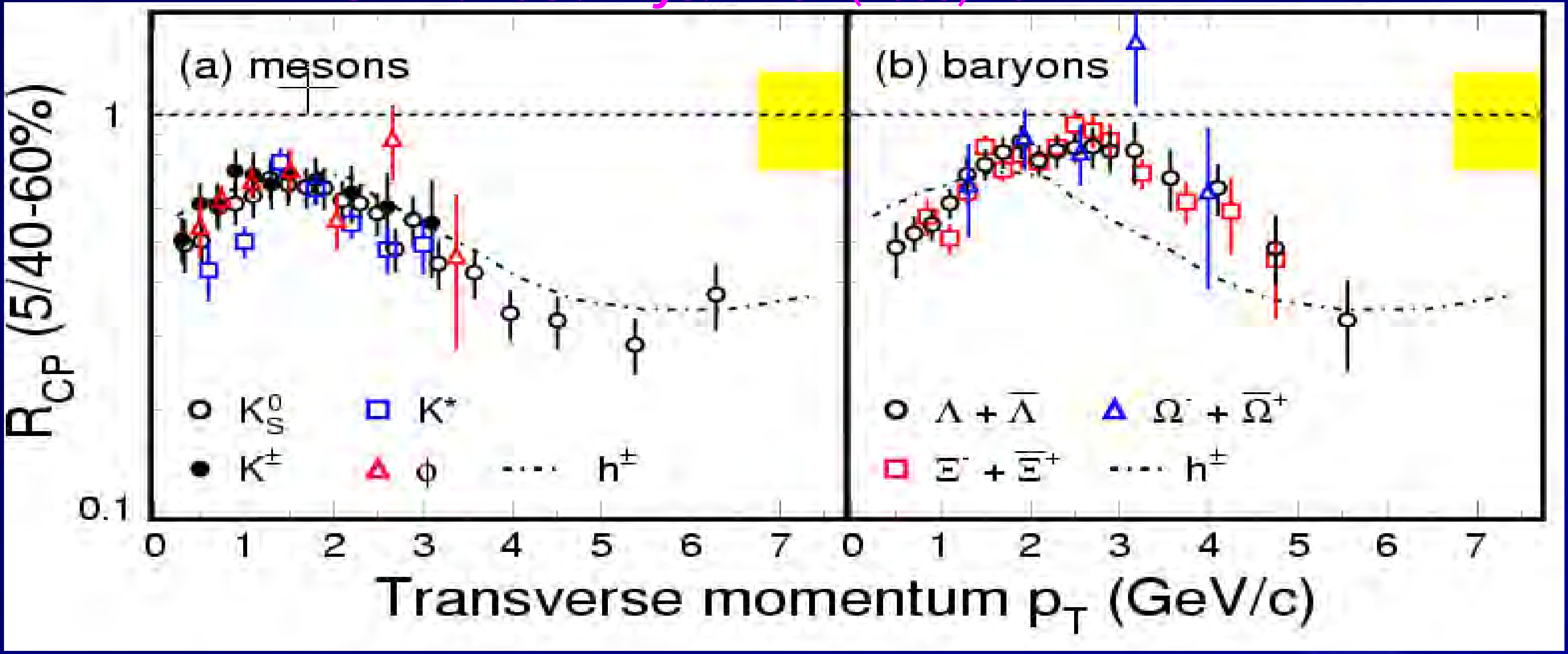
Summary and conclusion

- Results from RHIC shows that the system formed is dense and strongly interacting
- High p_T partons and heavy quarks looses energy through interaction with the medium so that medium properties can be determined

- There are many naïve predictions for LHC based on experimentally observed scaling that if broken could give first indications of new physics
- Hard physics systematics from RHIC-II and LHC will provide more information on the mechanism of suppression and properties of the medium

R_{cp} Scaling - Comparison of peripheral and central yields

STAR: Nucl. Phys. A 757 (2005) 102



Two groups (2<pT<6GeV/c):

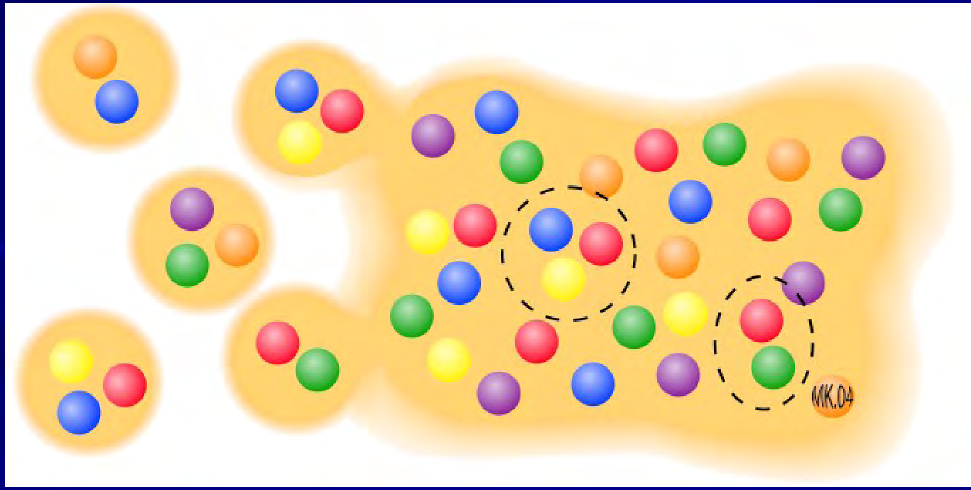
π, Ks, K±, K*, ϕ ⇦ mesons

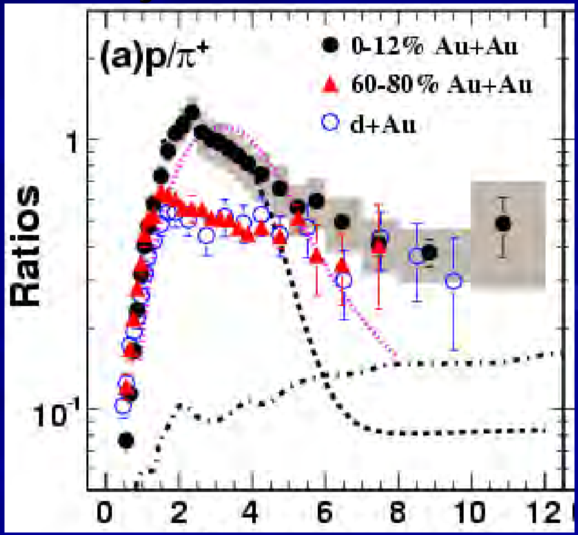
p, Λ, Ξ, Ω ⇦ baryons

Rcp splitting between baryons and mesons comes naturally in the recombination approach (next slide)

Recombination at LHC(?)

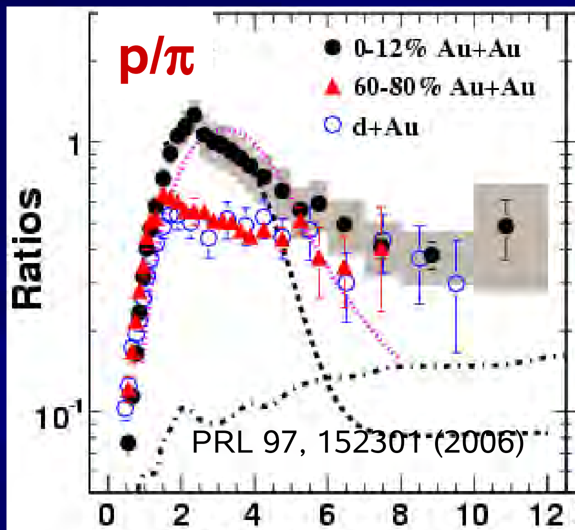
- Normal pQCD particle production
  - 1 parton → many partons → many hadrons
- Recombination allows the many partons from different quarks to recombine! $p = \sum p_{partons}$ (Baryon p > Meson p)
- Njets increases at LHC => recombination region should cahnge. Hwa and Yang (nucl-th/0603053) predicts $p/\pi \sim 10$ out to $p_T \sim 20$GeV/c with no associated jet structure!





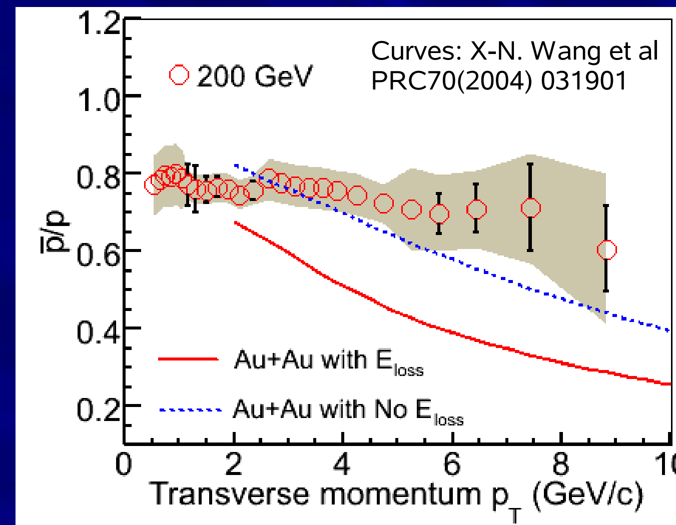
Quark vs gluon energy loss (modified QM summary slide)

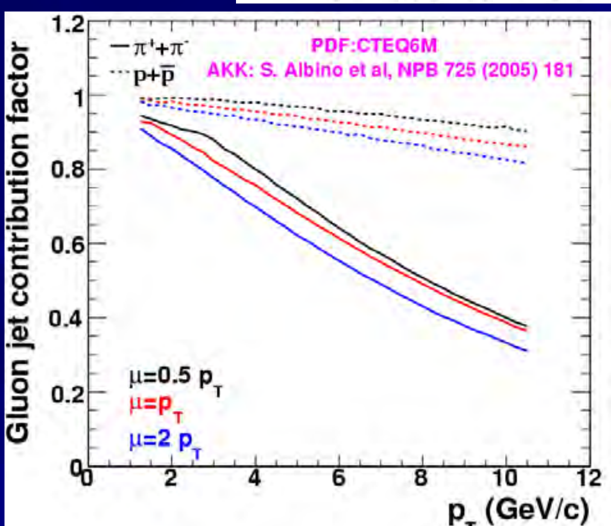
STAR, L. Ruan



p_T (GeV/c)

STAR, B. Mohanty





- If jet quenching is due to radiative energy loss, gluons loose more energy than quarks
- Model calculations very interesting:
  - 90% of p from gluons
  - 40% of pi from gluons
- Conclusions depends a lot on our p+p production model/understanding