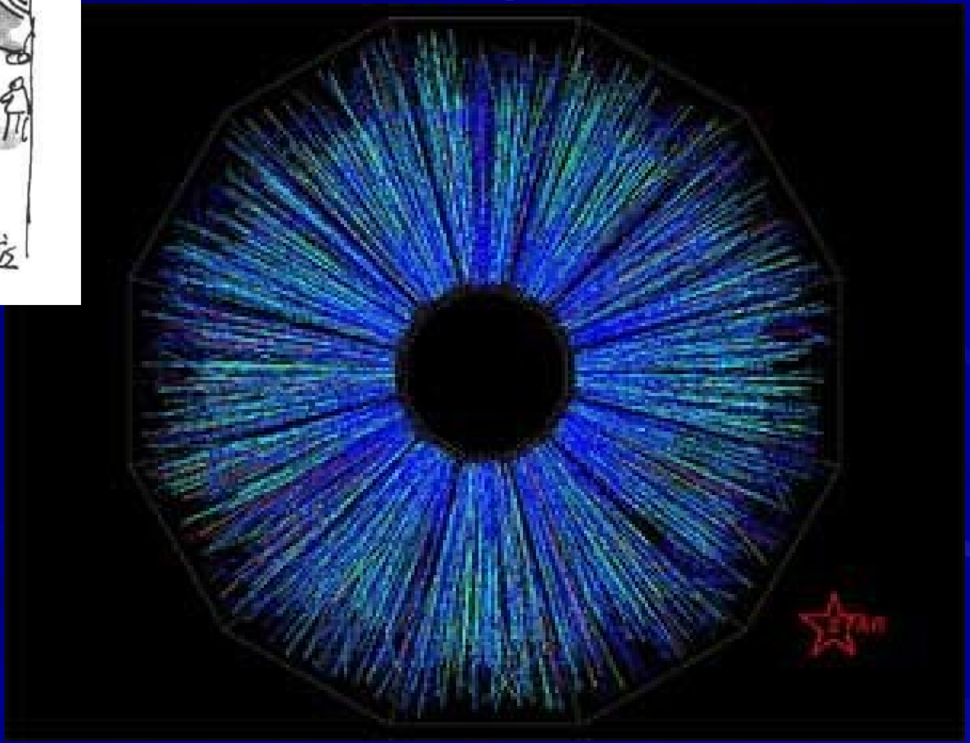
An experimentalists overview of high energy heavy ion physics

- An introduction to 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 (Jan Rak will tell much more)
- What to expect at LHC
  - First p+p physics
  - A+A expectations
- Conclusions

Thanks for all the “borrowed” figures/slides!

An introduction to high energy heavy ion physics

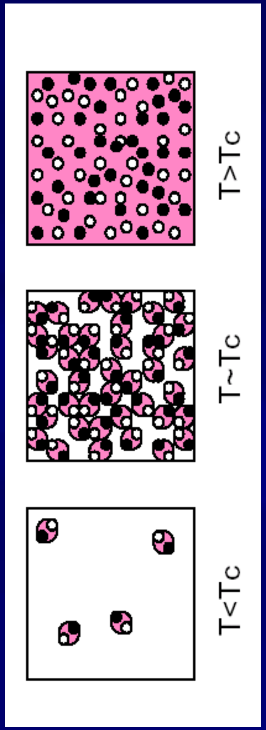
1 small bang in the STAR experiment

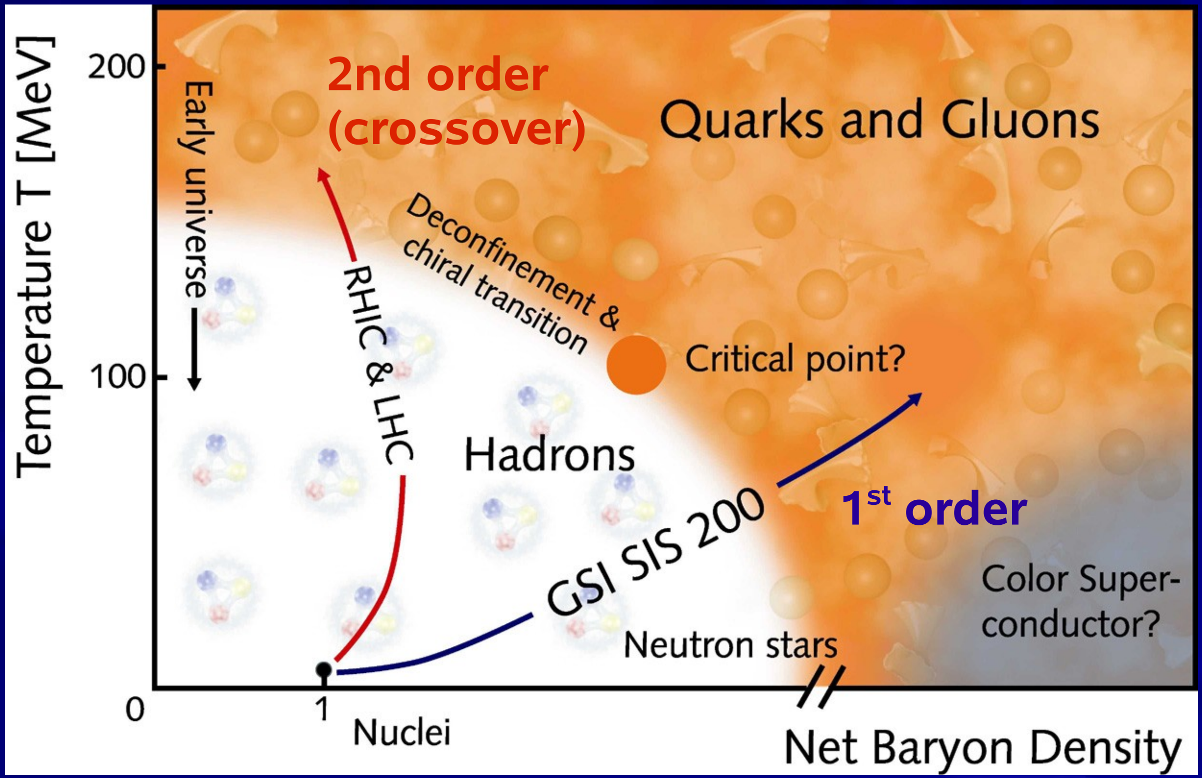


QCD at high energies

- 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”)

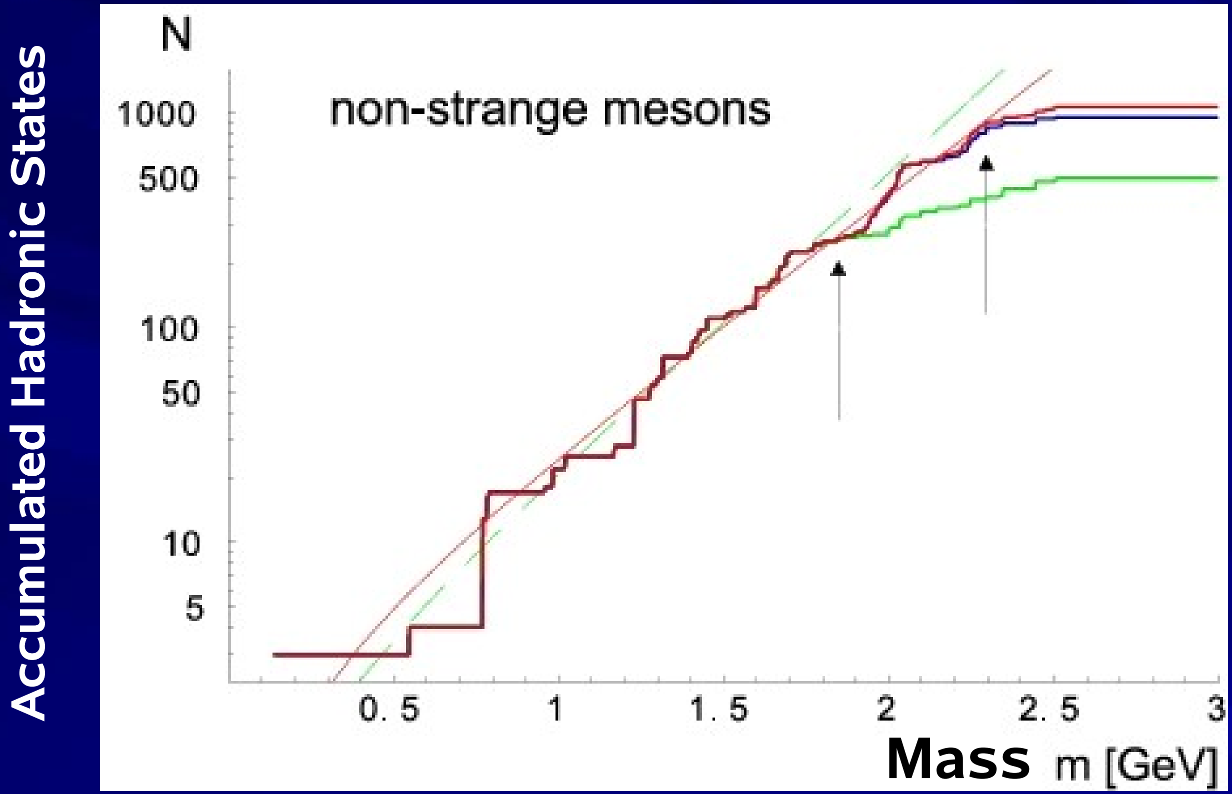
Schematic QCD phase diagram





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

The Hagedorn temperature

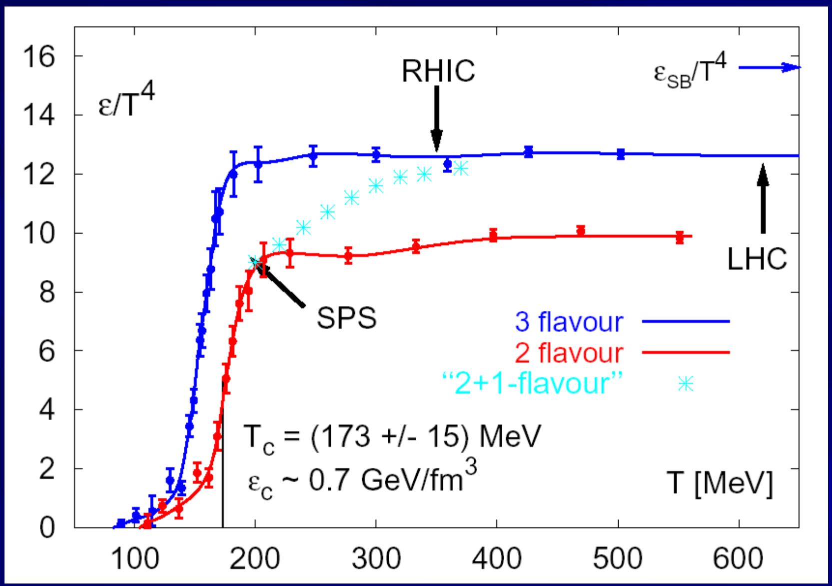


The number of hadronic states experimentally observed increaseses exponential with the mass withing the observable region.
In a statistical model they are populated proportional to:
exp(-m/T)

- 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

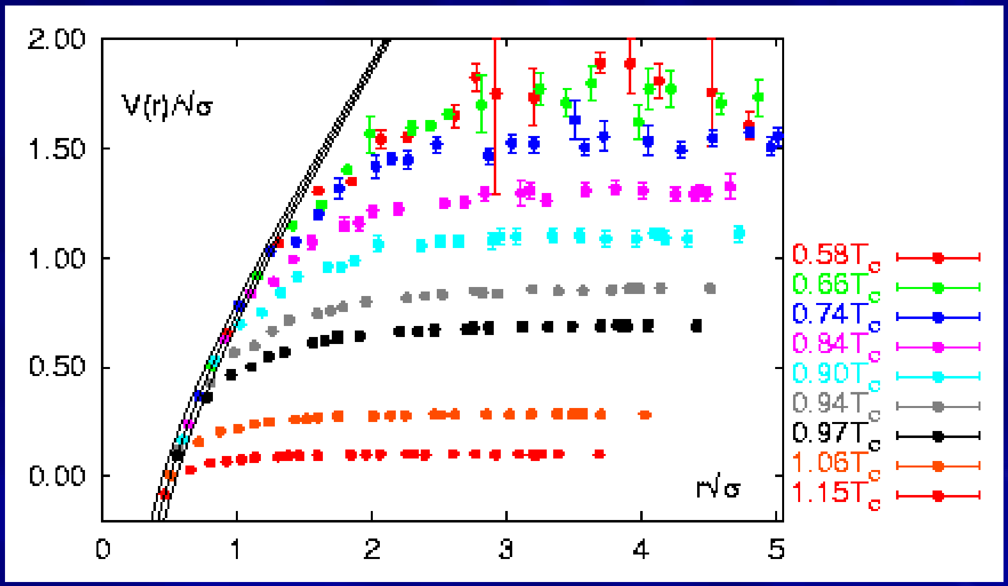


$$\epsilon_{QCD} = \frac{\pi^2}{30}\left(2\times 8 + \frac{7}{8} 2\times 2\times 3\times 3\right) T^4$$

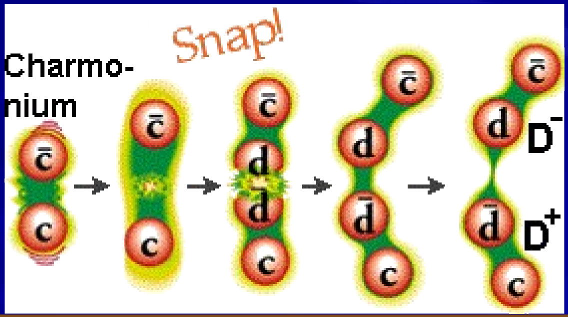
Gluon spin and color

(Anti+)quark spin, color and flavor

Heavy quark potential

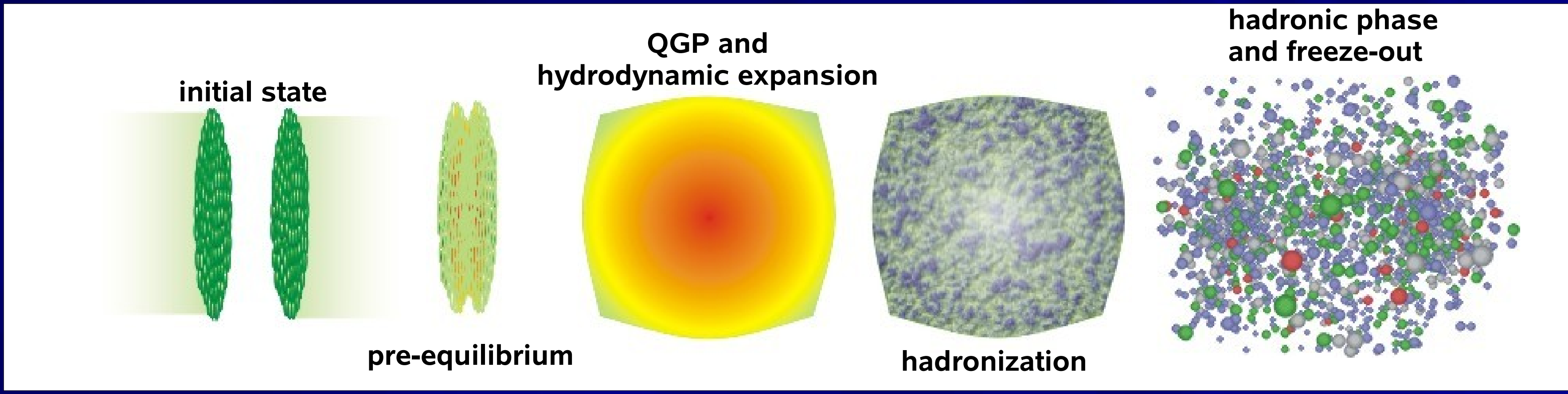


At T~Tc the strong potential is screened so e.g. c+c-bar states can disassociate.



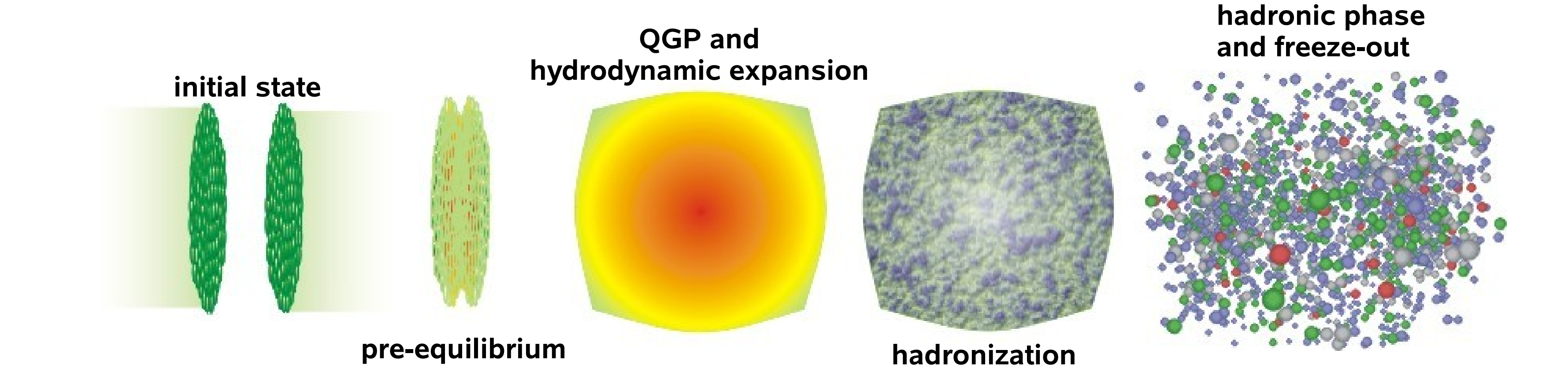
Heavy ion collisions: The study of high energy QCD

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)!

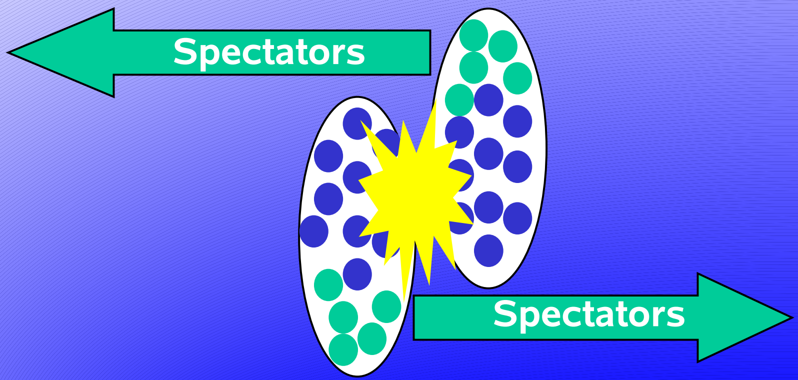
A theoretical description of heavy ion collisions

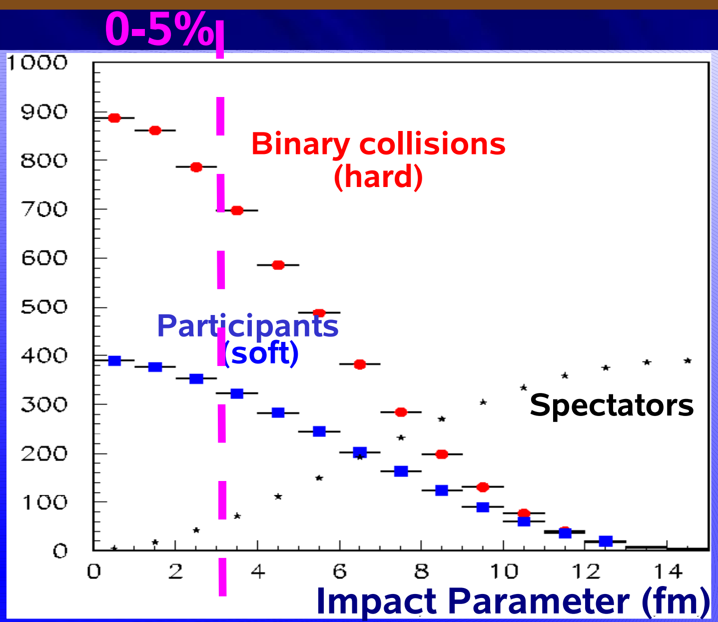


- Some examples of ingredients:
  - Hard processes (jets): perturbative QCD
  - Hydrodynamic expansion: Bjorken, Landau.
  - Hadronization: Statistical a la Hagedorn.
- Alternative descriptions:
  - Color glass condensate (initial conditions from gluon saturation)
  - Lund string model (describes well p+p with phenomenolgical strings). Basis of Hijing model.

Heavy Ion Jargon

- Centrality (ex. for Au+Au):





Participants = 2*197 - Spectators

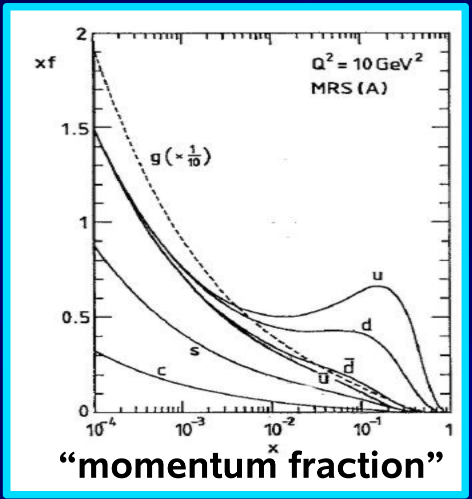
- Rapidity (Boost invariant) & Pseudo-rapidity (No PID):

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

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

pQCD jet calculations in p+p collisions

Example of pdf:

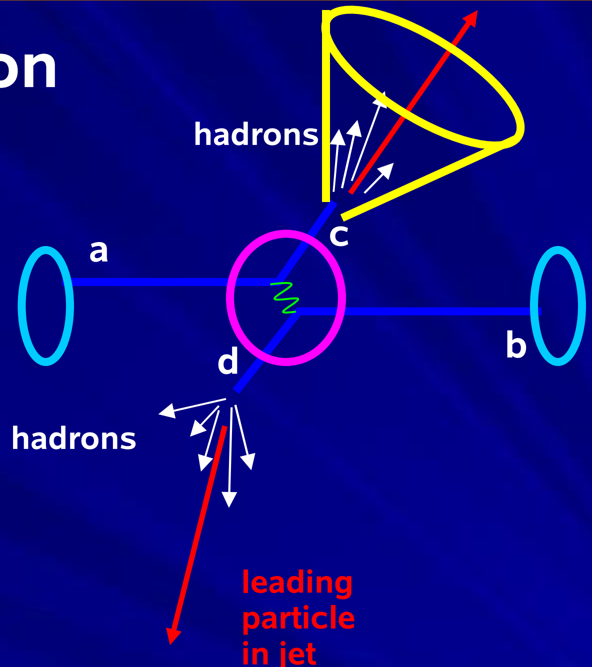


Jet: A localized collection of hadrons from a fragmenting parton

Parton Distribution Functions

Hard-scattering cross-section

Fragmentation Function



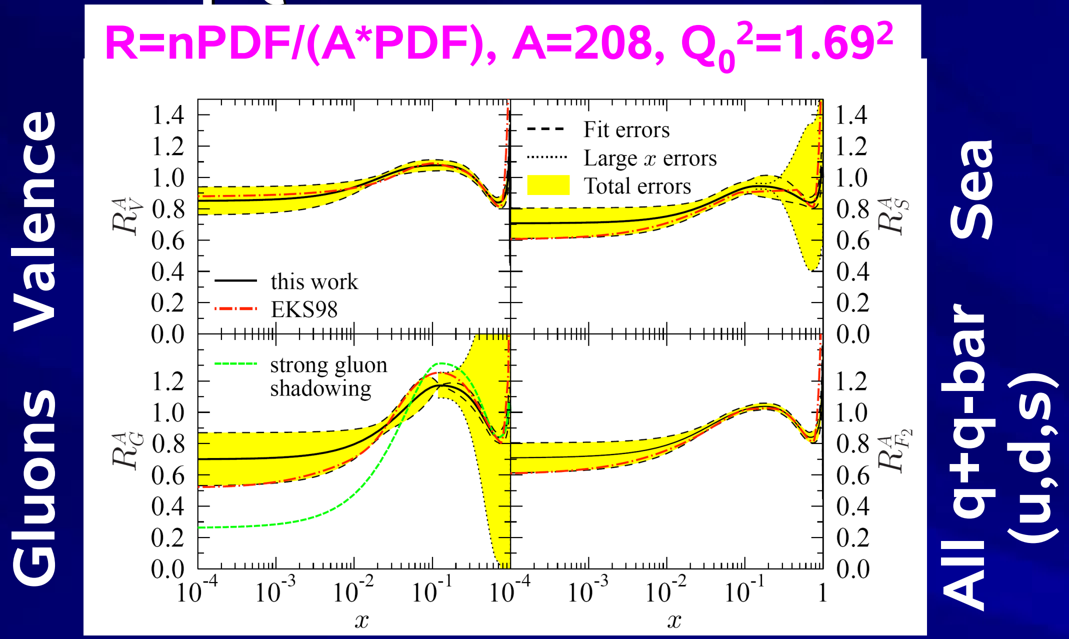
High p_T (> 2.0 GeV/c) hadron production in pp collisions:

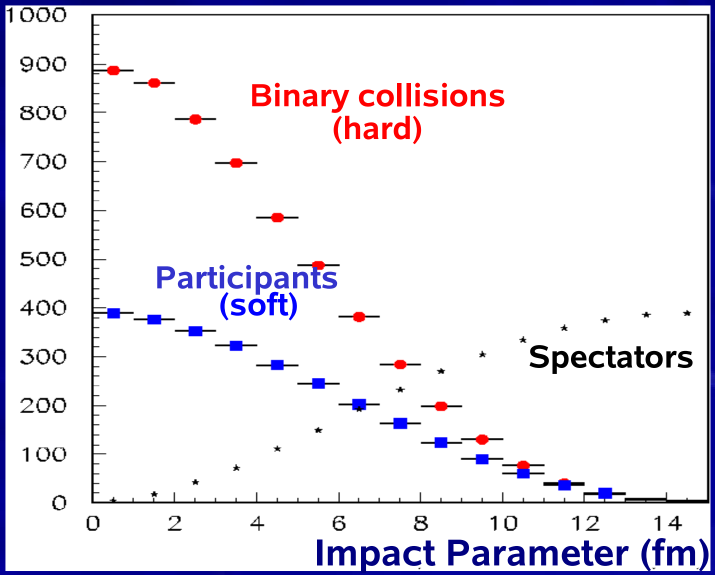
"Collinear (no intrinsic p_T) factorization"

$$\frac{d\sigma^h_{pp}}{dy d^2 p_T} = K \sum_{abcd} \int dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \frac{d\sigma}{d\hat{t}}(ab \to cd) \frac{D^0_{h/c}}{\pi z_c}$$

pQCD calculations in A+A collisions

- For pQCD calculations in A+A collisions one has to **scale the cross section with Nbin** and **use nuclear PDFs**



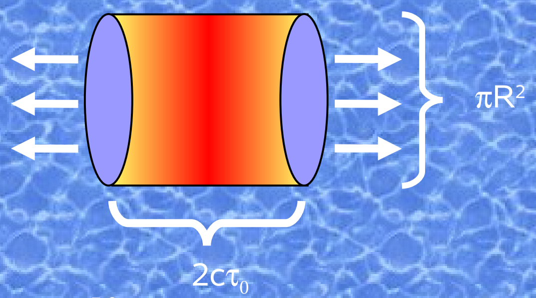


- The nuclear modification factor compares p+p and A+A:

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

Bjorken vs Landau hydrodynamics

Bjorken: Transparent boost invariant initial conditions

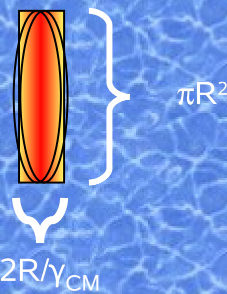


=>No gradient
=>expansion is trivial
dN/dy is flat!
Due to energy conservation:

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

Theorists →
← Experimentalists

Landau: Full stopping initial conditions

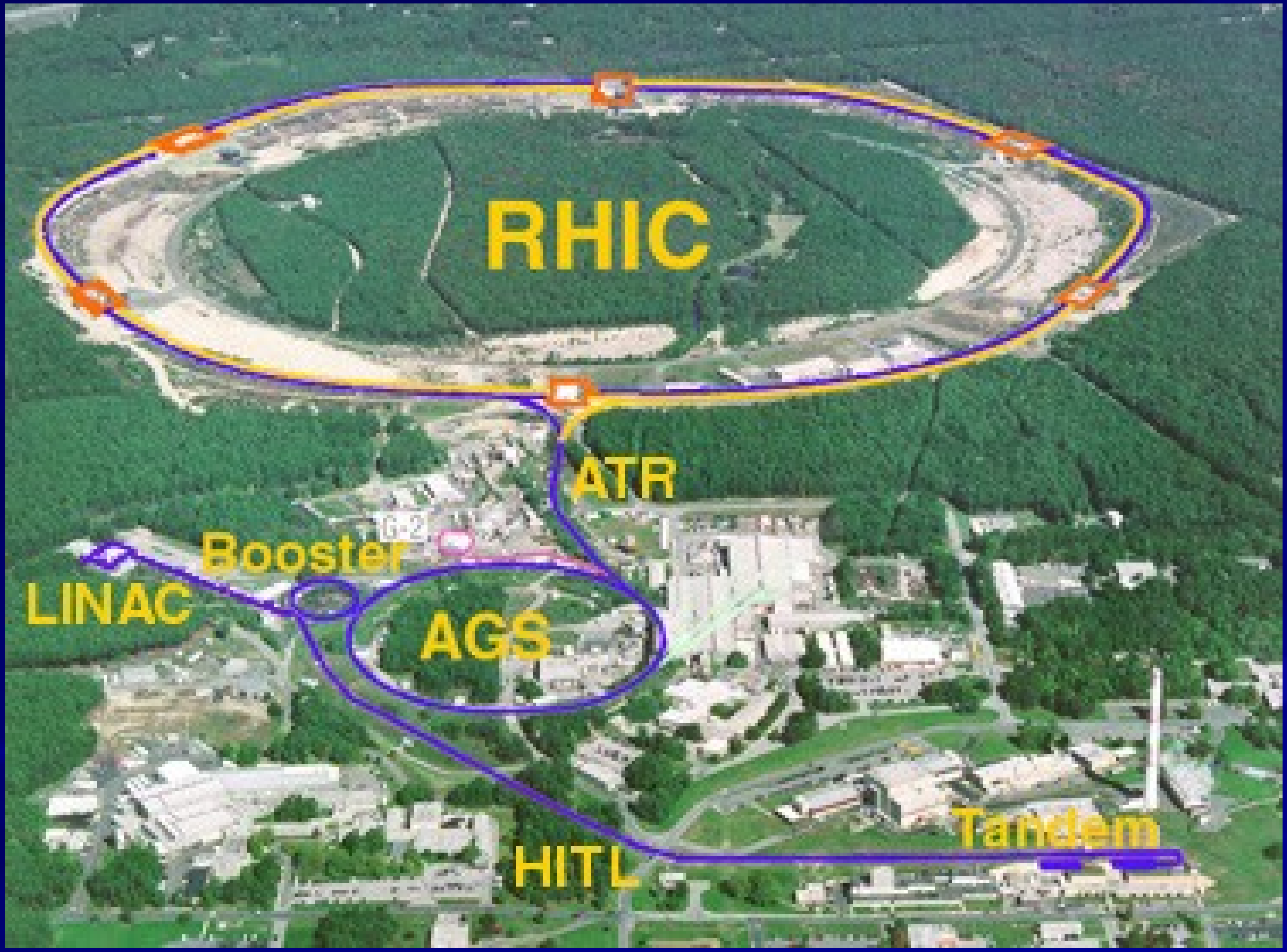


Strong longitudinal gradient drives expansion
dN/dy is gaussian with σ:

$$\sigma^2 = \log\left(\frac{\sqrt{s}}{2 m_p} \right)$$

Originally a model of p+p.
Also predicts Npart scaling and limiting fragmentation.

The Relativistic Heavy Ion Collider (RHIC)

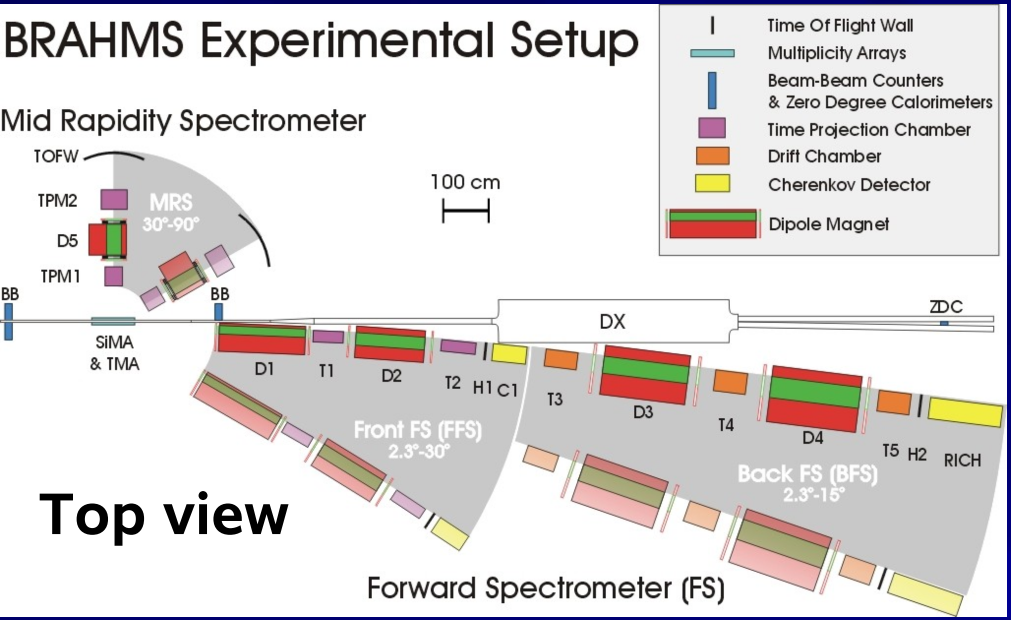


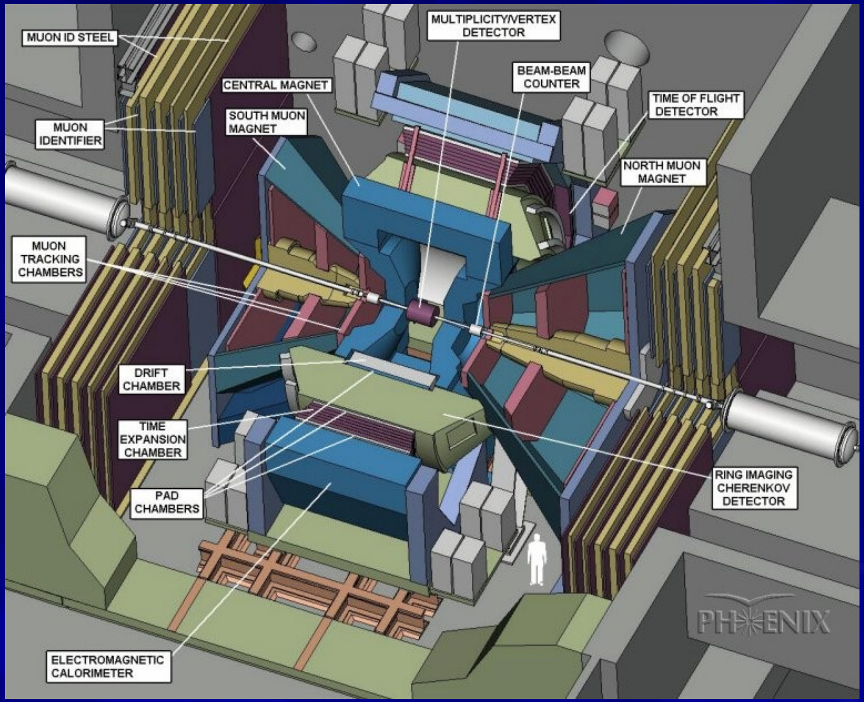
RHIC is the first heavy ion collider in the world.
Operational since 2000.
Max beam energy: $\sqrt{s_{NN}}$=200GeV

2 independent rings (good for d+Au).

The 4 experiments at RHIC

Examples of experiments: BRAHMS and PHENIX

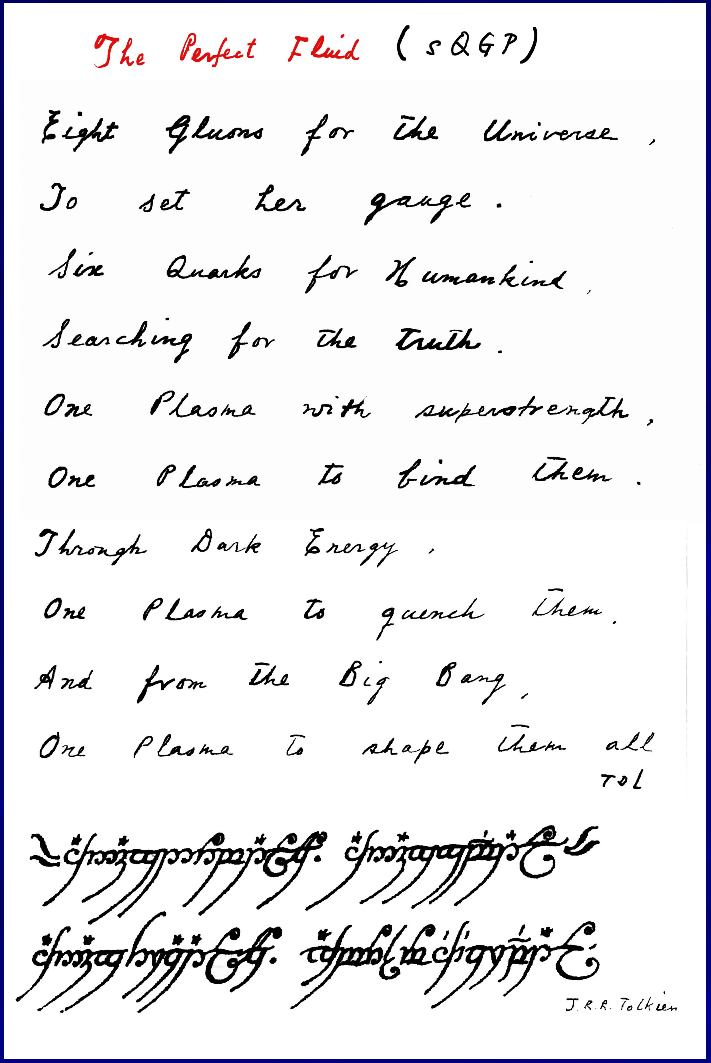




BRAHMS (50 people):
Specialized detector
Combining many settings allows charged π, K, p to be meaured over large rapidity range: $0 < y < 3.5$

PHENIX (300 people):
General purpose detector
Big acceptance around y=0
Measures charged hadrons and photons and leptons (electrons and muons)

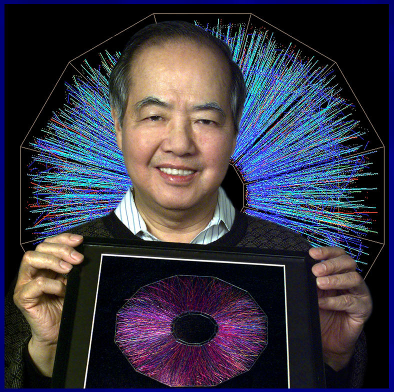
Results from RHIC


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



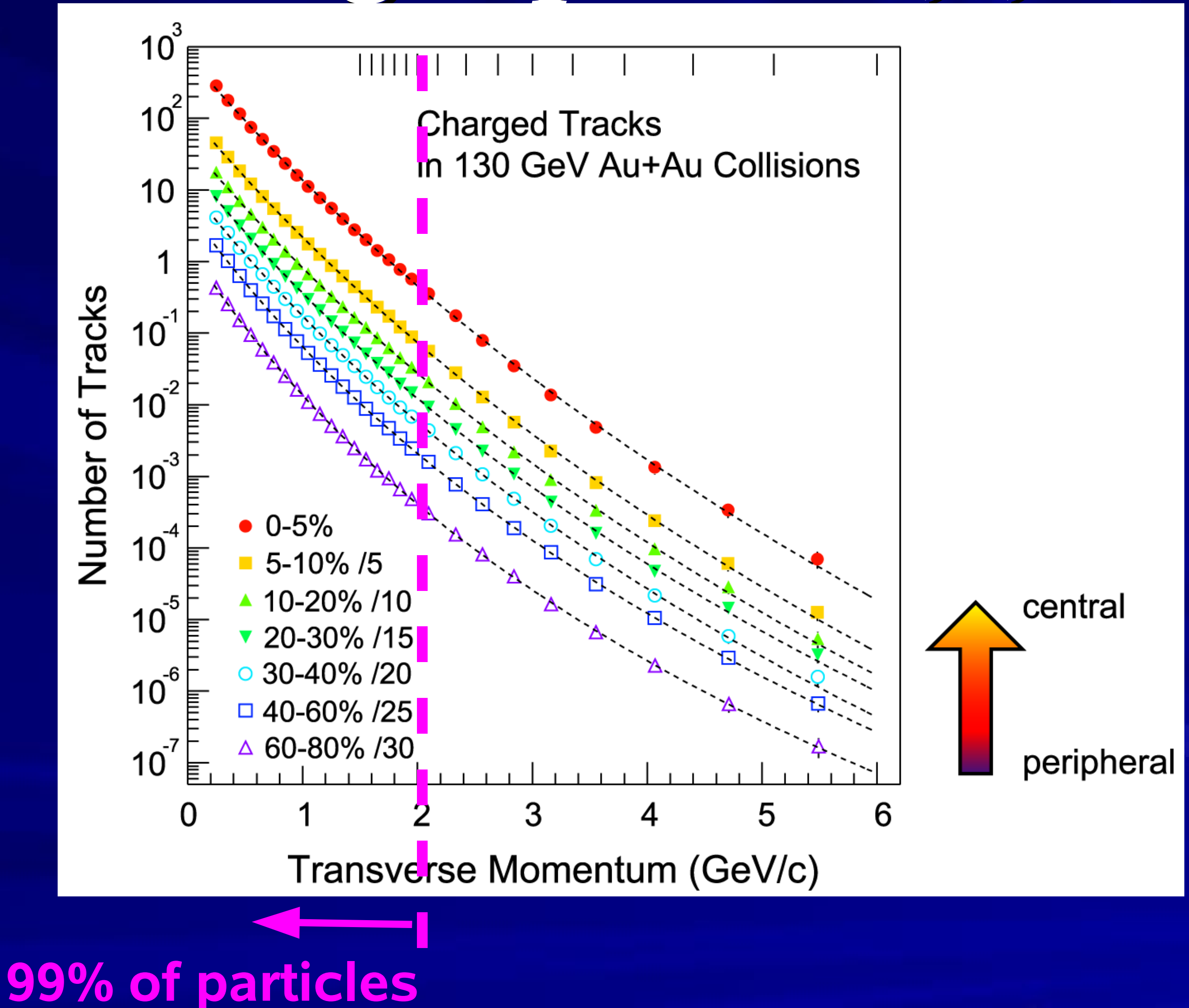
A more detailed overview of the results from RHIC can be found in the experimental "white papers" from RHIC:

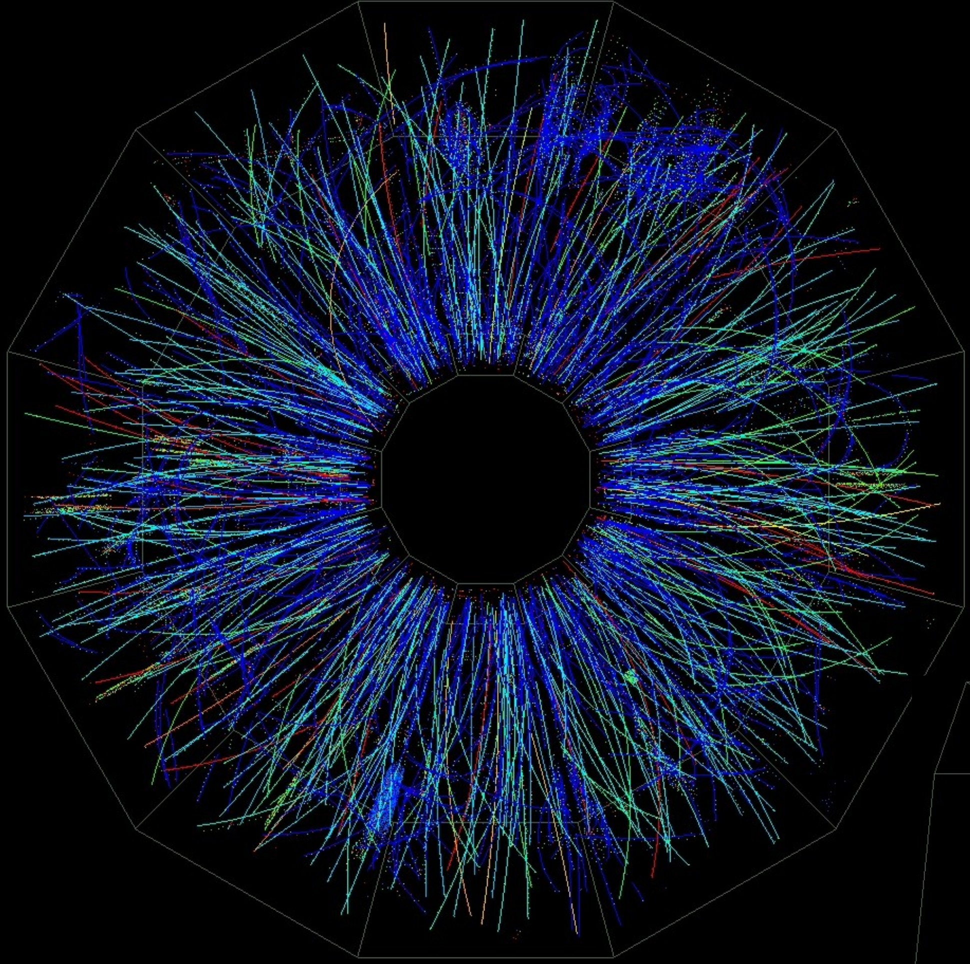
Nuclear Physics A757, August 2005

AIP: The Perfect Liquid at RHIC

Top physics story of 2005

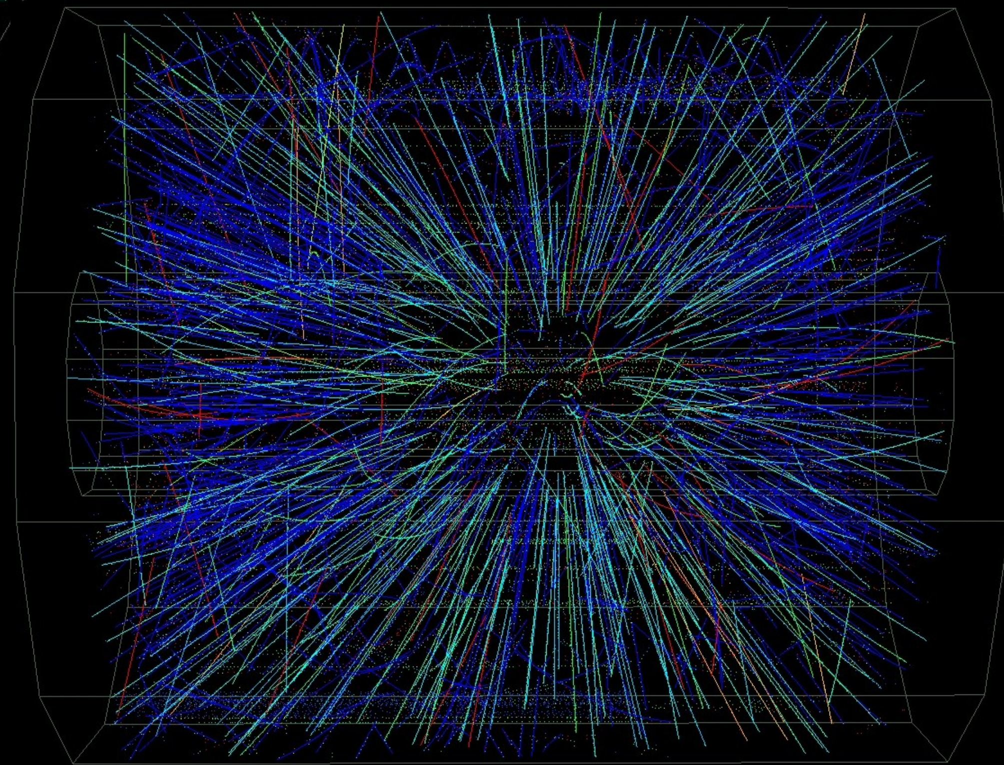
Soft physics: p_T<2GeV/c and light quarks:u,d,s





Peripheral Event

From real-time Level 3 display.



color code $\Rightarrow$ energy loss

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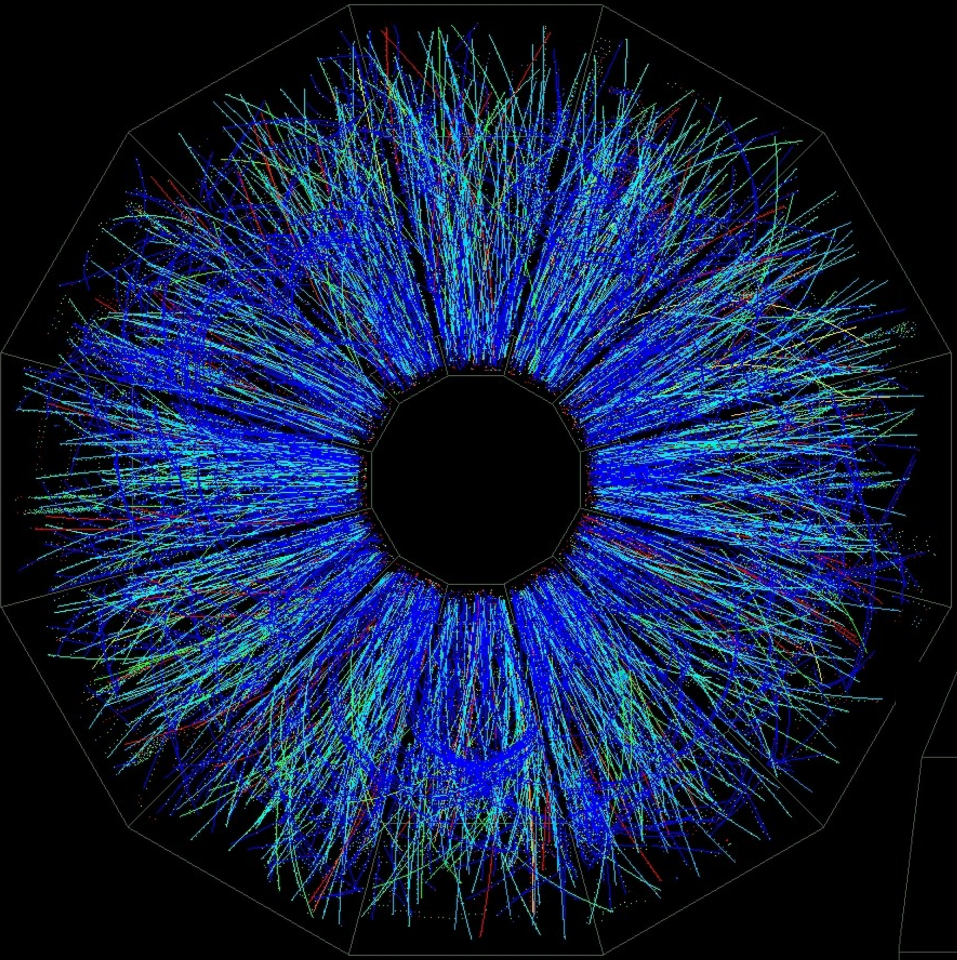
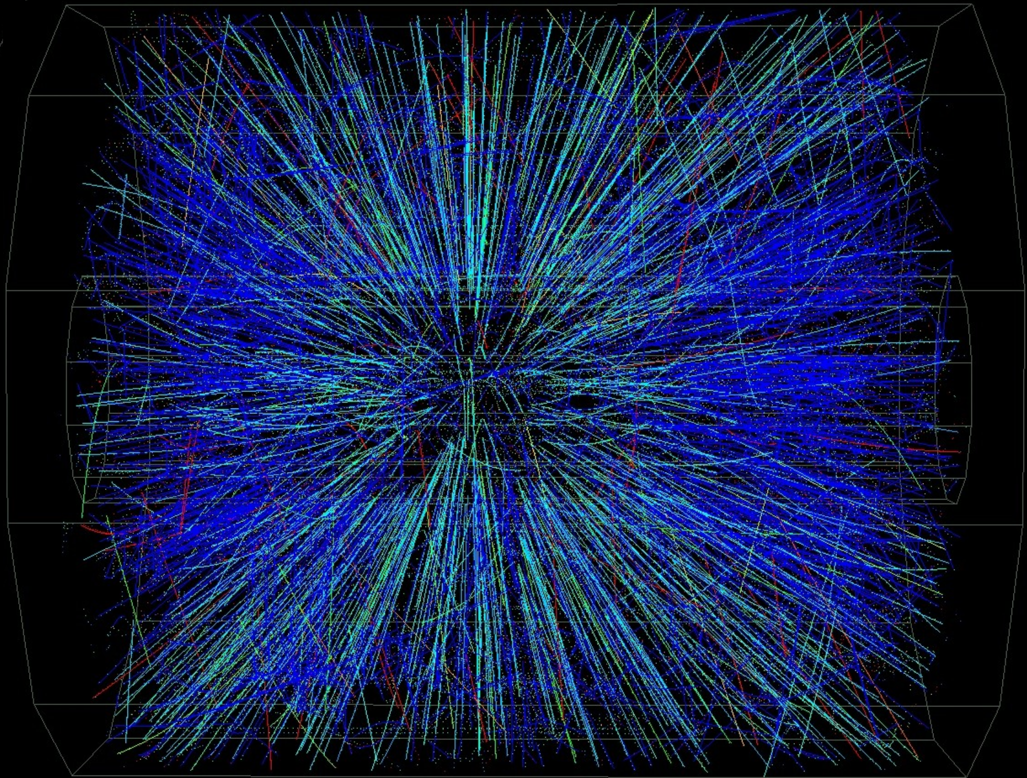


Mid-Central Event

From real-time Level 3 display.



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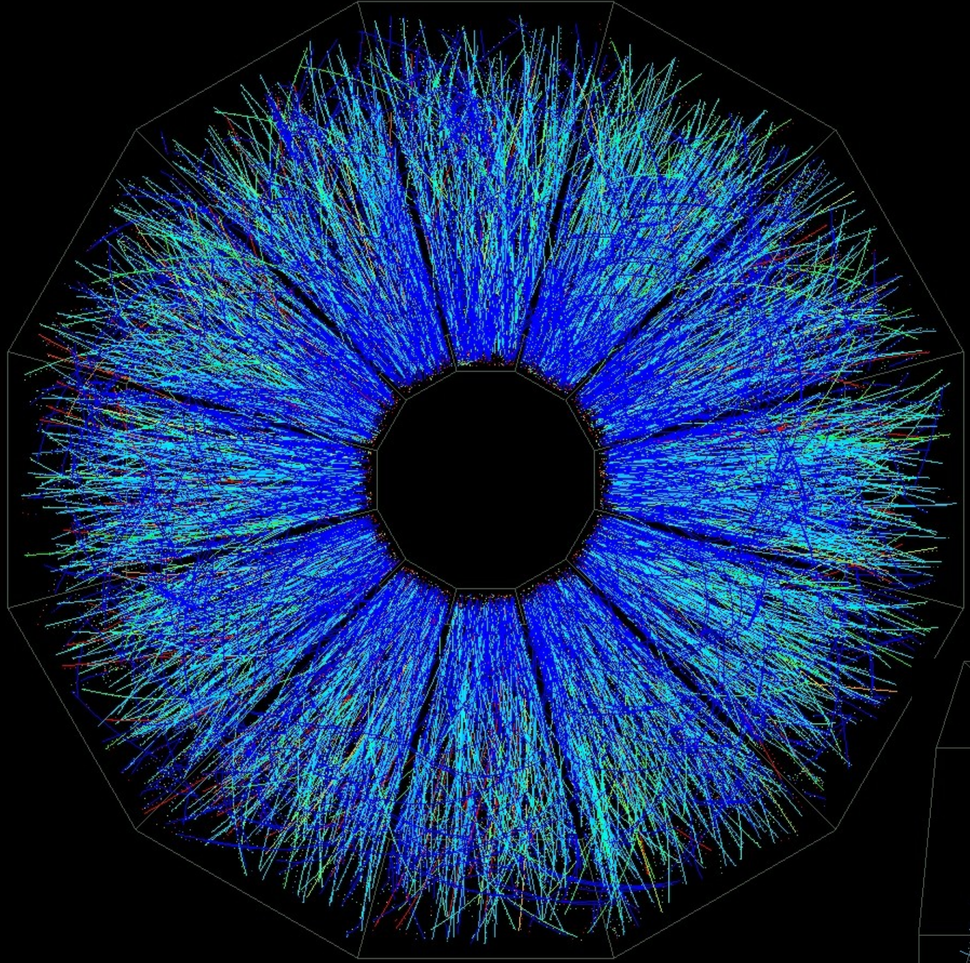
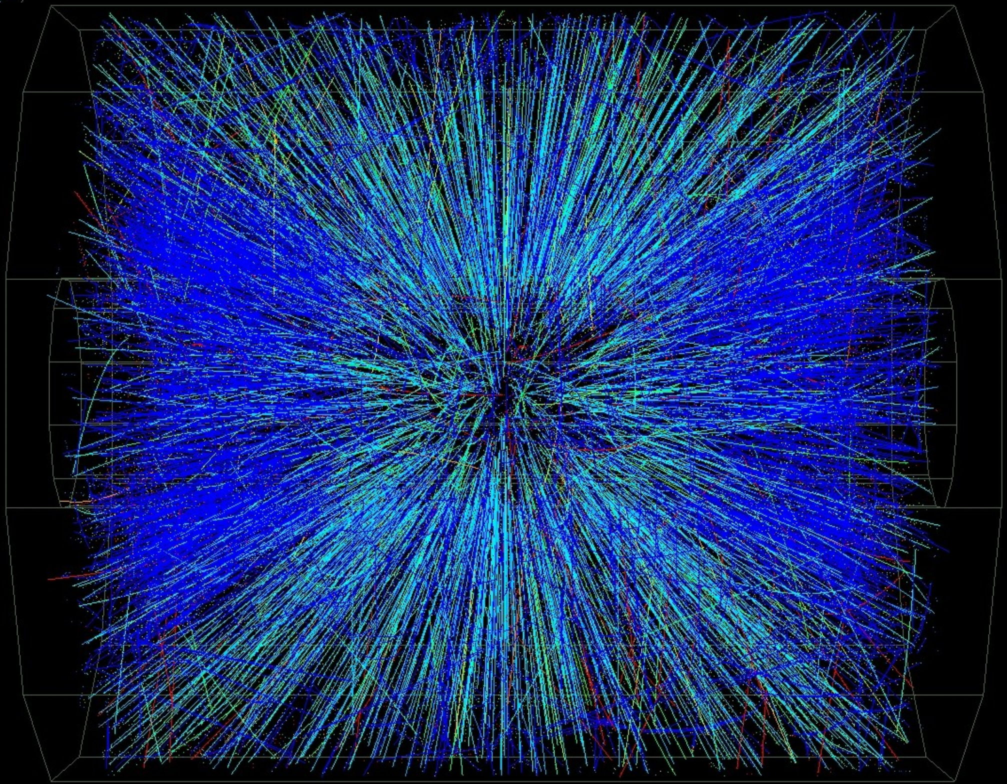


Central Event

From real-time Level 3 display.



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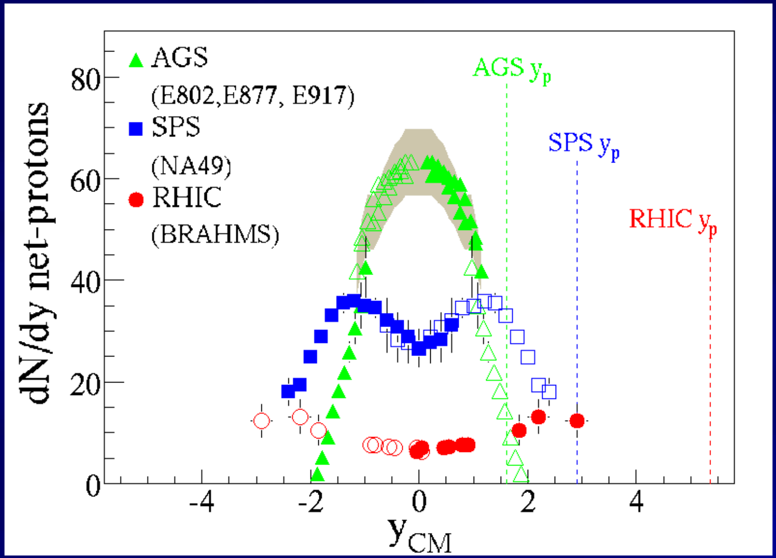
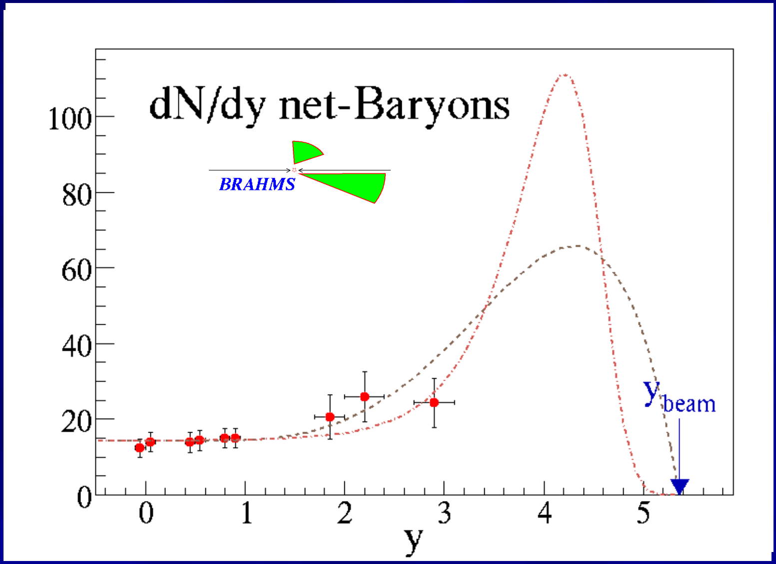
Stopping
Creating hot and dense matter

Net-p from AGS to RHIC | **Net-B (conserved) at RHIC**

Net-protons=
Protons - Anti-protons



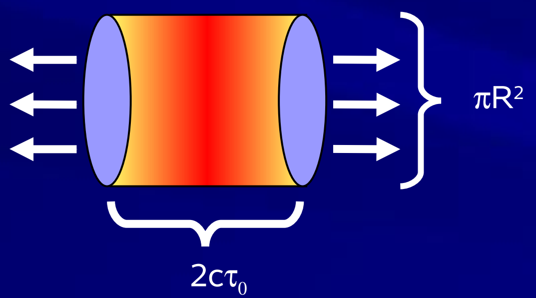


- Due to baryon number conservation the kinetic energy loss of the incoming nuclei used to create the hot and dense zone of matter can be determined.
- Extrapolating to beam rapidity one finds that ~75% of the energy is available for particle production and that the rapidity loss is around 2 (twice that in p+p)

“Measured” energy density

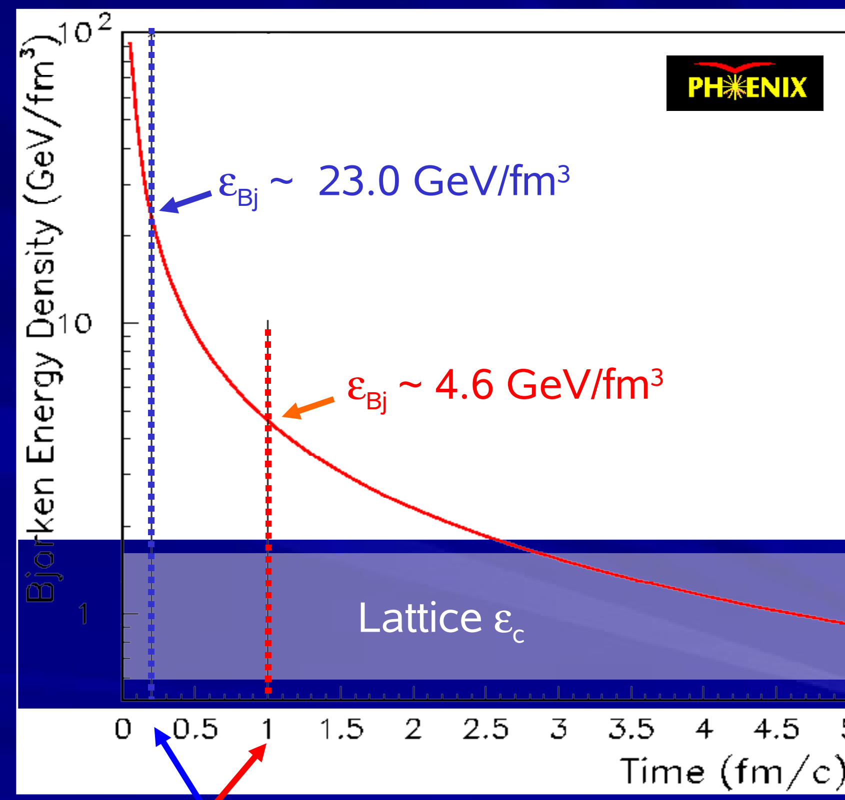
Bjorken formula for thermalized energy density in terms of measured transverse energy E_T

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



PHENIX: Central Au Au yields

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



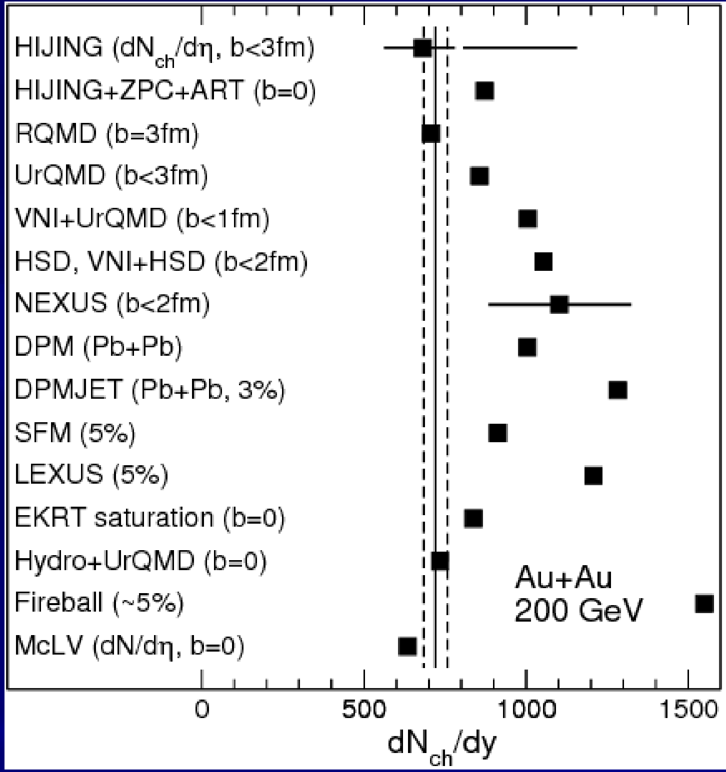
Formation(thermalization) time ?

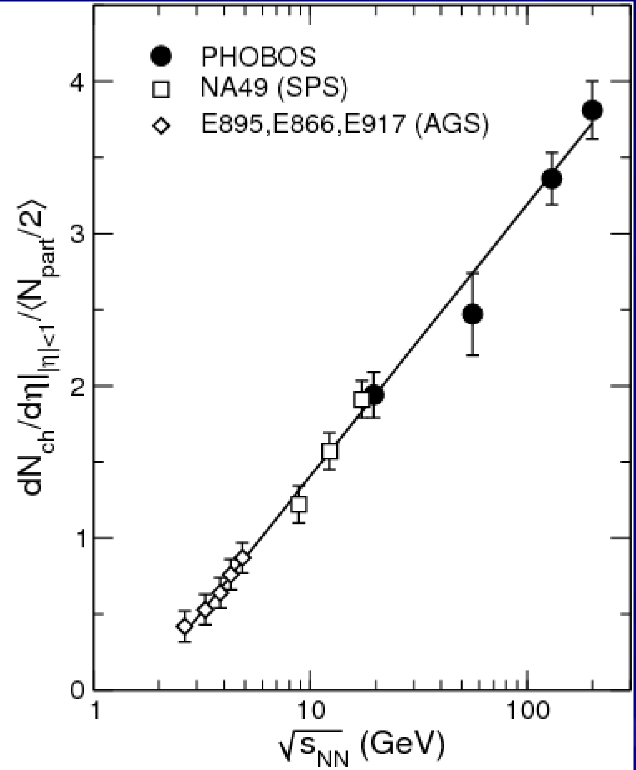
Charged multiplicity $dN_{ch}/d\eta$ at mid-rapidity ($\eta\sim0$) vs models

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

Lund strings →

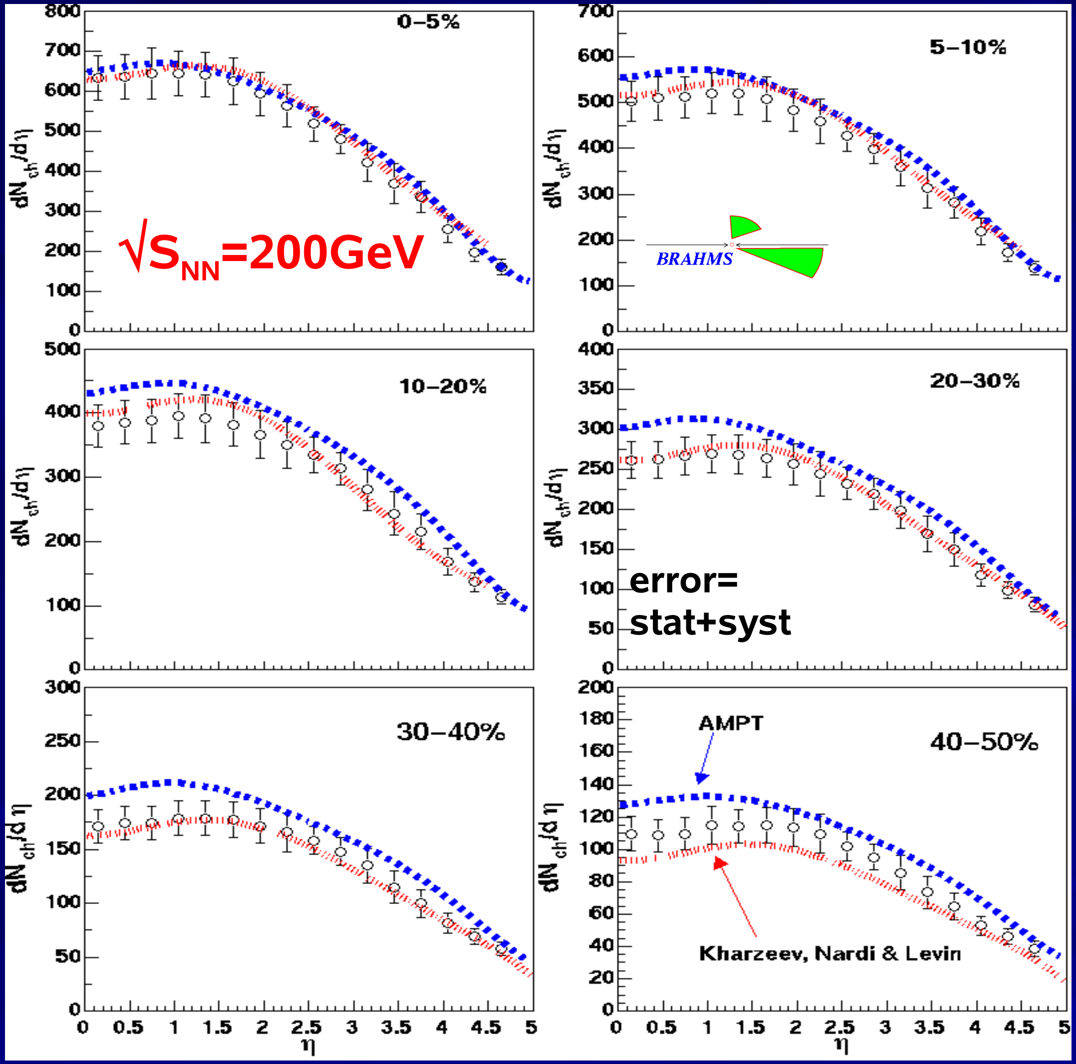
Gluon saturation (final state!) →





- Real model predictions generally overestimated $dN/d\eta$, while data indicates simple power law extrapolation:
  $dN/d\eta \sim k1*\sqrt{s_{NN}}^{k2}$ with no signs of discontinuity

Charged particle multiplicities compared to models

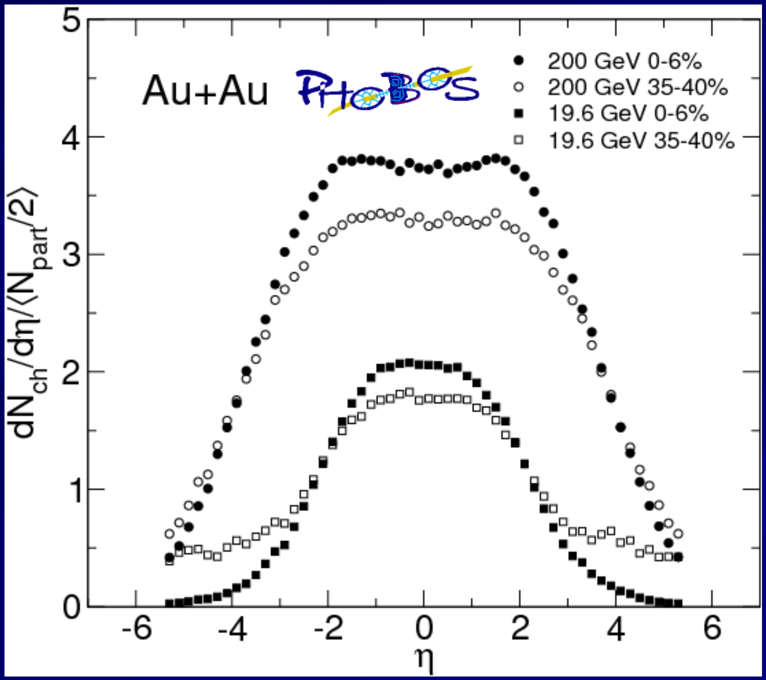


- In central collisions more than 5000 charged particles are produced!
- The model curves are both predictions <u>after</u> $\sqrt{s_{NN}}$=130 GeV was known

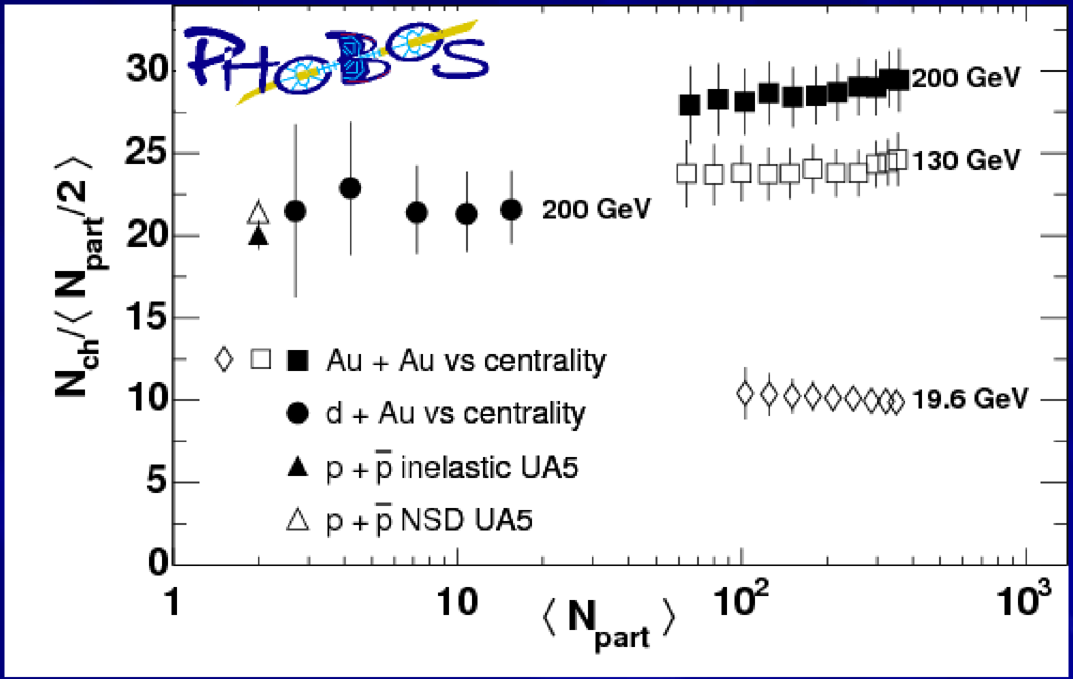
AMPT (Hijing based Lund string model)
High density QCD gluon saturation
Kharzeev and Levin, PLB523(2001)79

Charged particle multiplicity scaling with Npart

$dN_{ch}/d\eta$ norm. to Npart/2

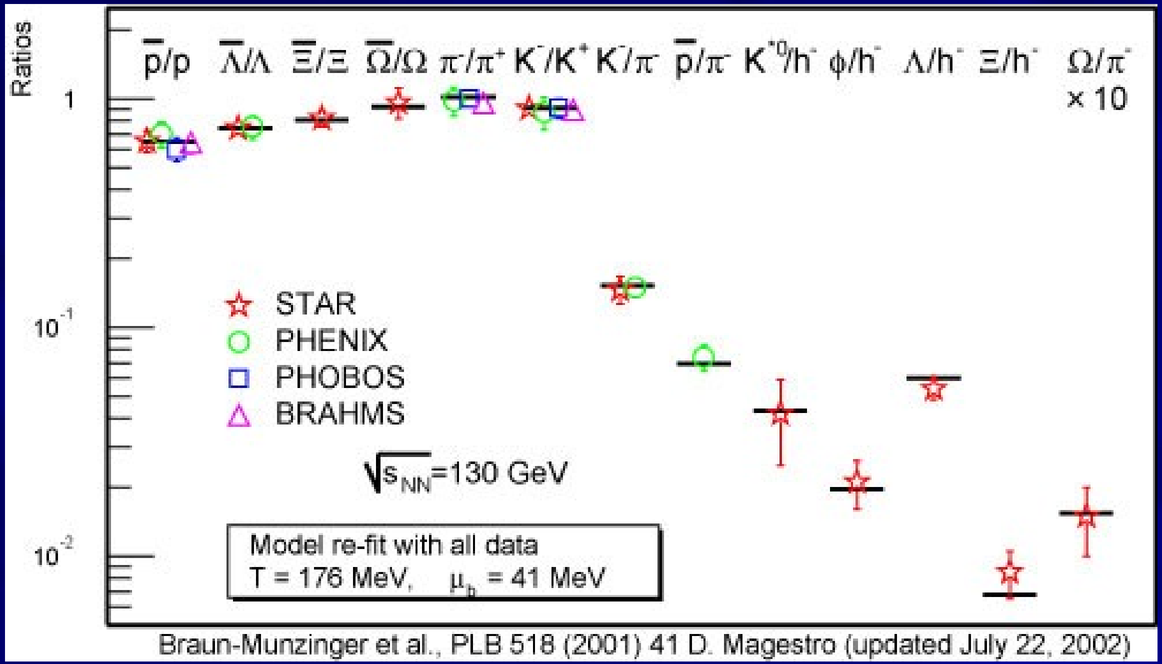


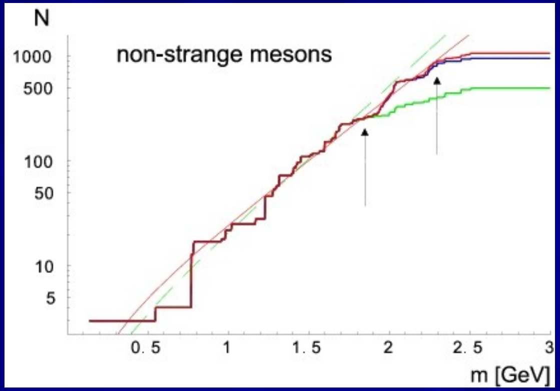
N_{ch} norm. to Npart/2 vs Npart



- Total charged particle multiplicity per Npart is almost independent of centrality (Npart scaling)! (effect of multiple collisions?)

Identified particle ratios: T and μ_B at freezeout

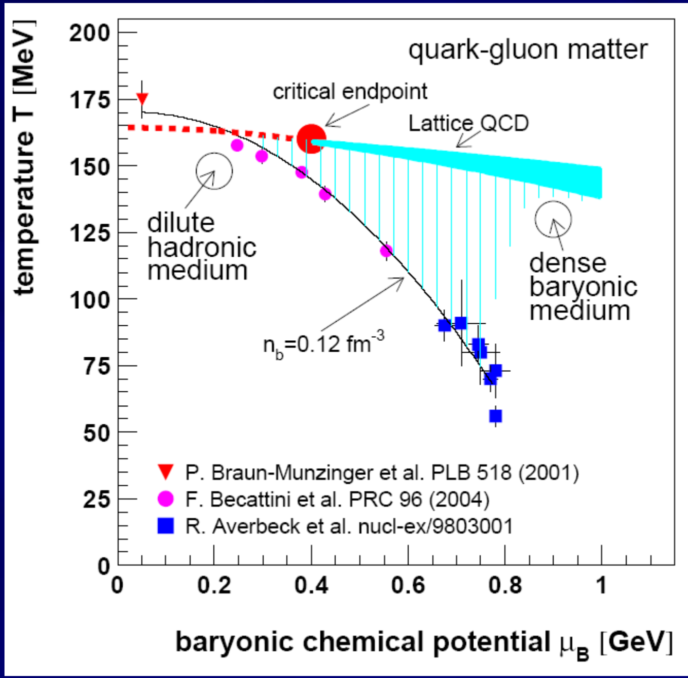


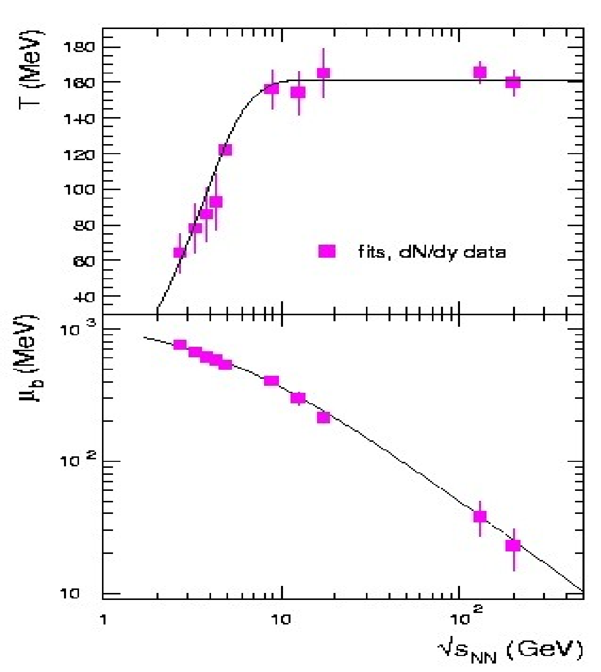


1. Generate hadrons with weights: $\exp(-(m+\mu_B)/T)$
2. Decay strongly
3. Compare to data

- 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





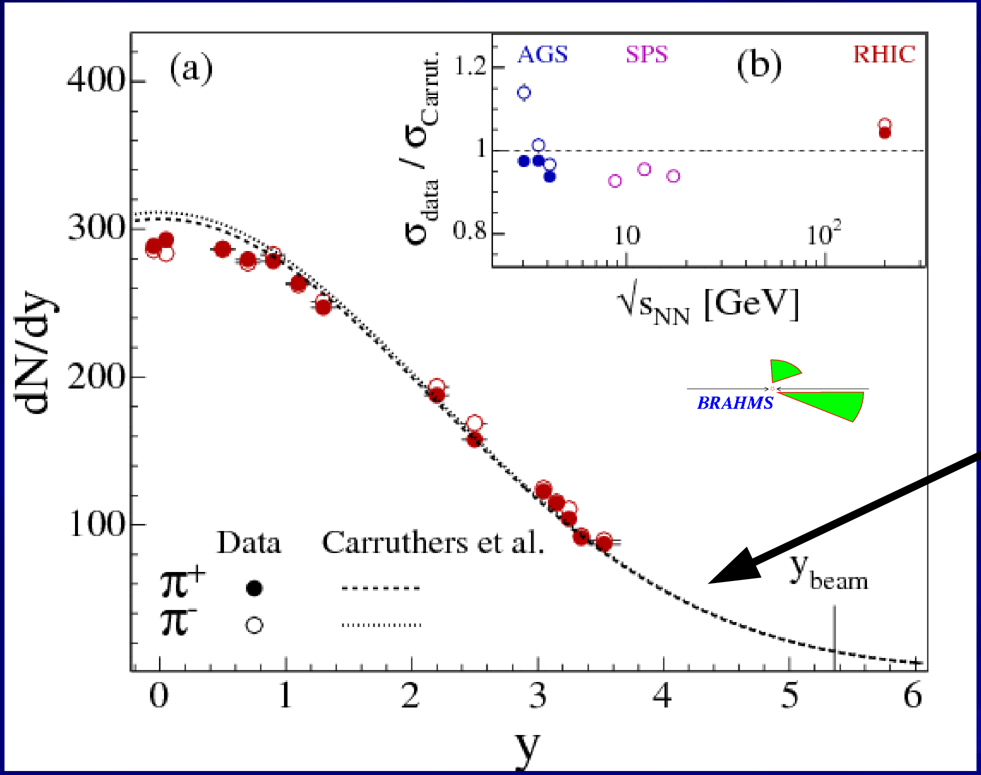
T_{lim} = 161 ± 4 MeV

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
- But p+p ratios can be described with a similar (canonical) formalism and T! So it is a hadronization attribute.

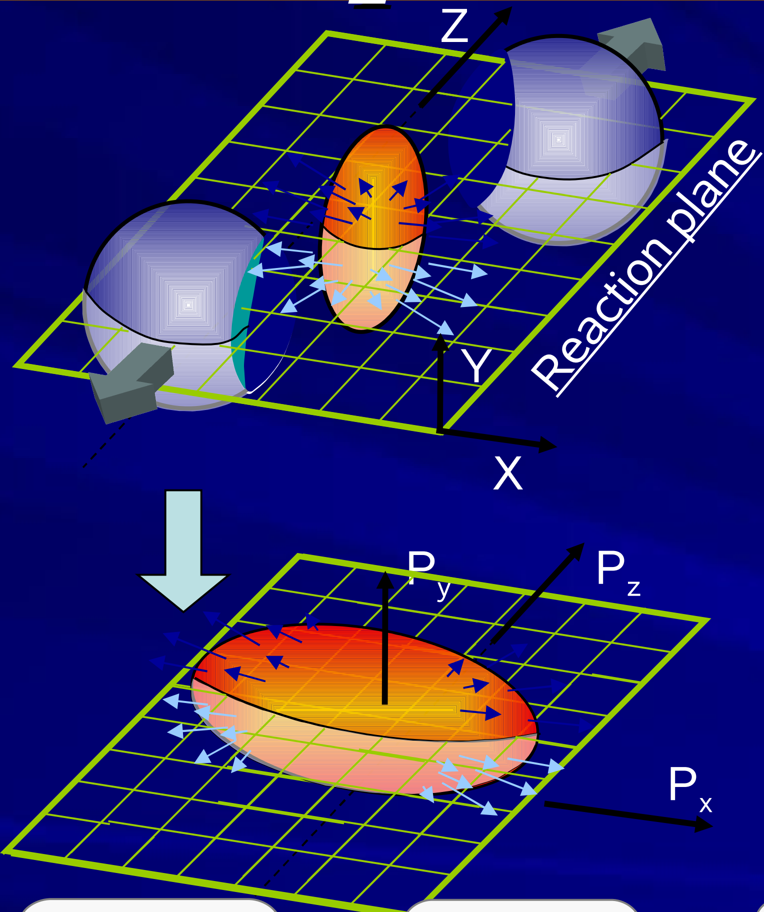
Pion rapidity distributions: Bjorken(flat) vs Landau(Gauss)



$$\sigma^2 = \ln\left(\frac{\sqrt{s}}{2m_p}\right)$$

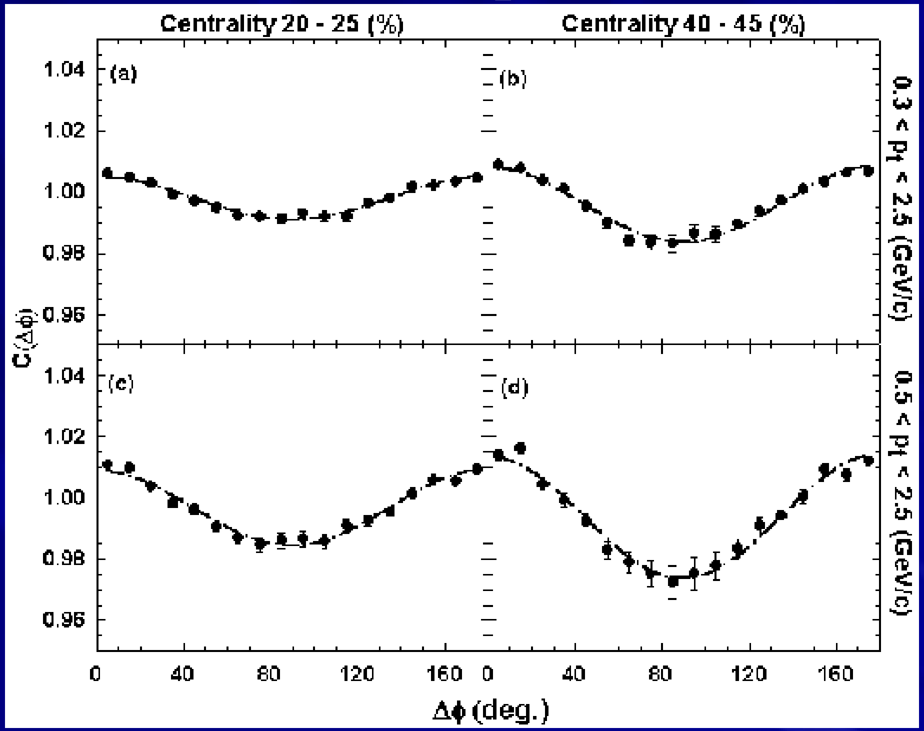
- Pion rapidity spectra are Gaussian (not boost invariant) and the width is consistent with the Landau/Carruthers prediction (for pp!) within 5%
- This is also true for AGS and SPS data

Elliptic flow (v2) unique in heavy ion collisions



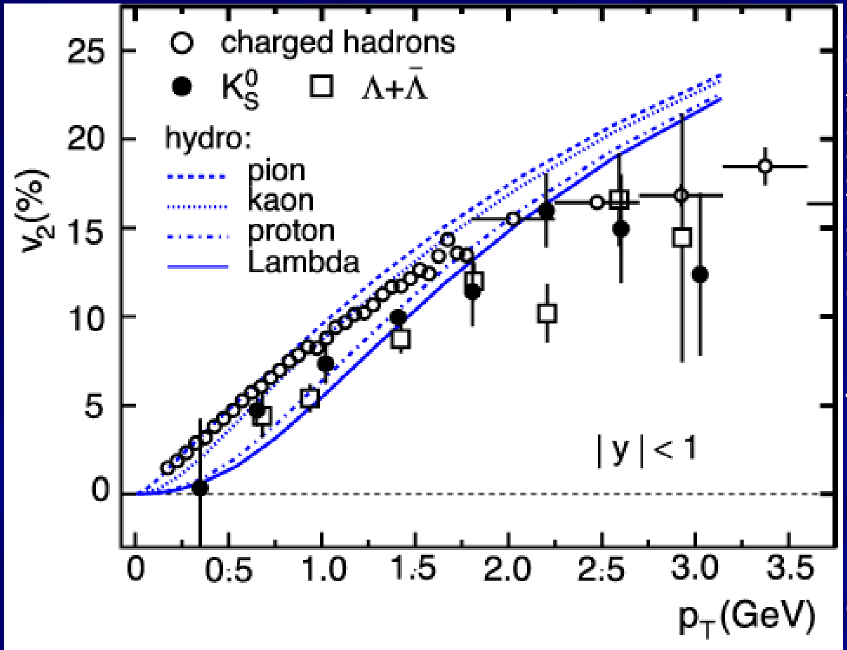
Fourier decomposition:

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



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

v2 at RHIC



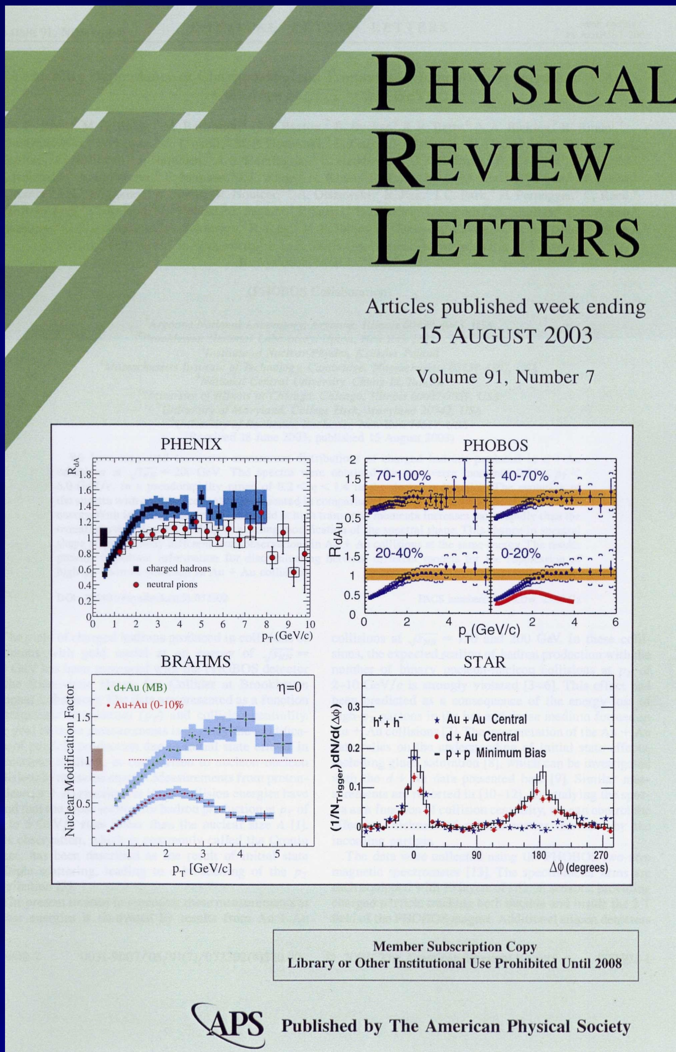
STAR, J. Phys. G 28 (2002) 20

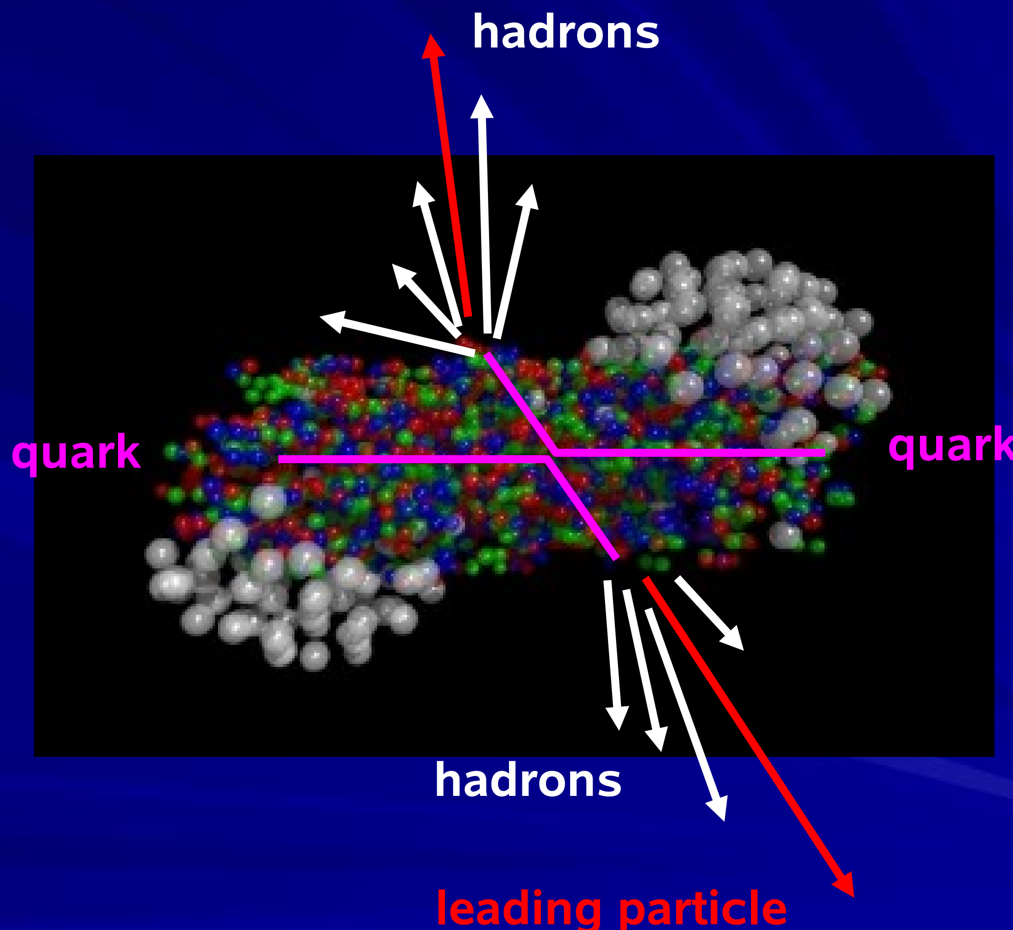
- Hydrodynamic predicts v2 (for p_T<2GeV/c)
  - Mass difference comes from velocity/flow at freezeout
  - v2 at AGS and SPS is below hydro limit
- Strong interactions are really strong => use hydro
- Where is QCD dynamics?

Summary of soft results

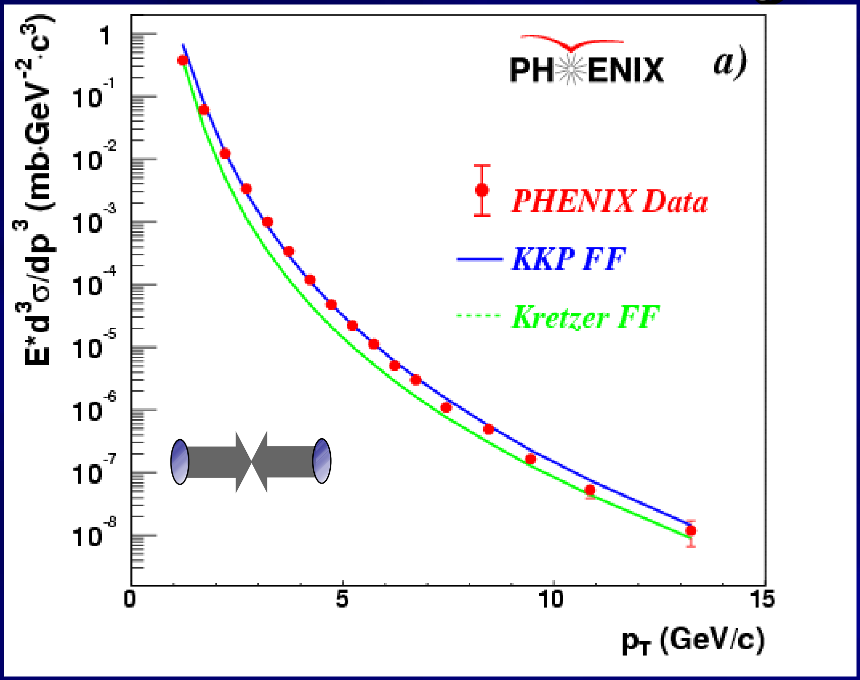
- The system created at RHIC
  - 75% of kinetic energy goes into the system (stopping)
  - Initial energy density > Lattice requirement (transverse energy)
  - System interacts early and strong – thermalization? (v2)
  - Tchemical ~ Lattice phase transition T (particle ratios)
- Surprisingly simple systematic as a function of centrality and beam energy
- **There are indications that system has been in plasma phase but no smoking gun!**

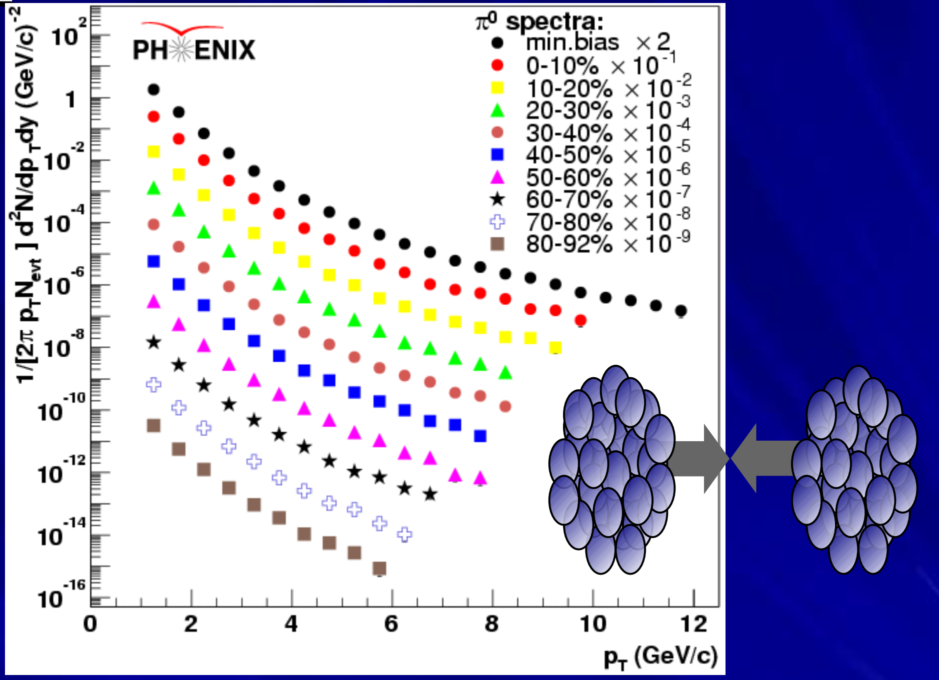
Hard probes:
p_T>2GeV and heavy quarks:



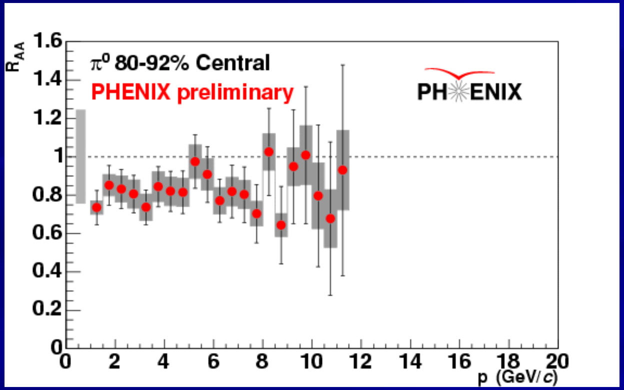


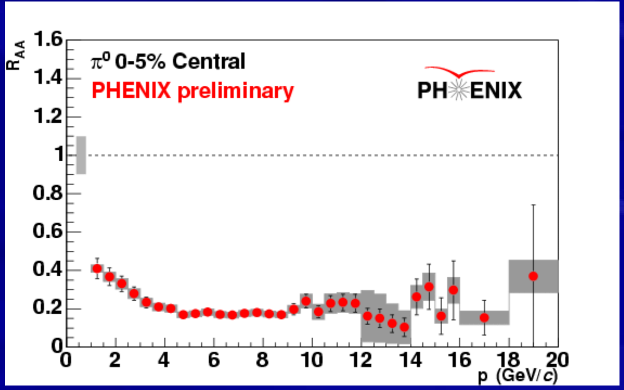
The nuclear modification factor for pions



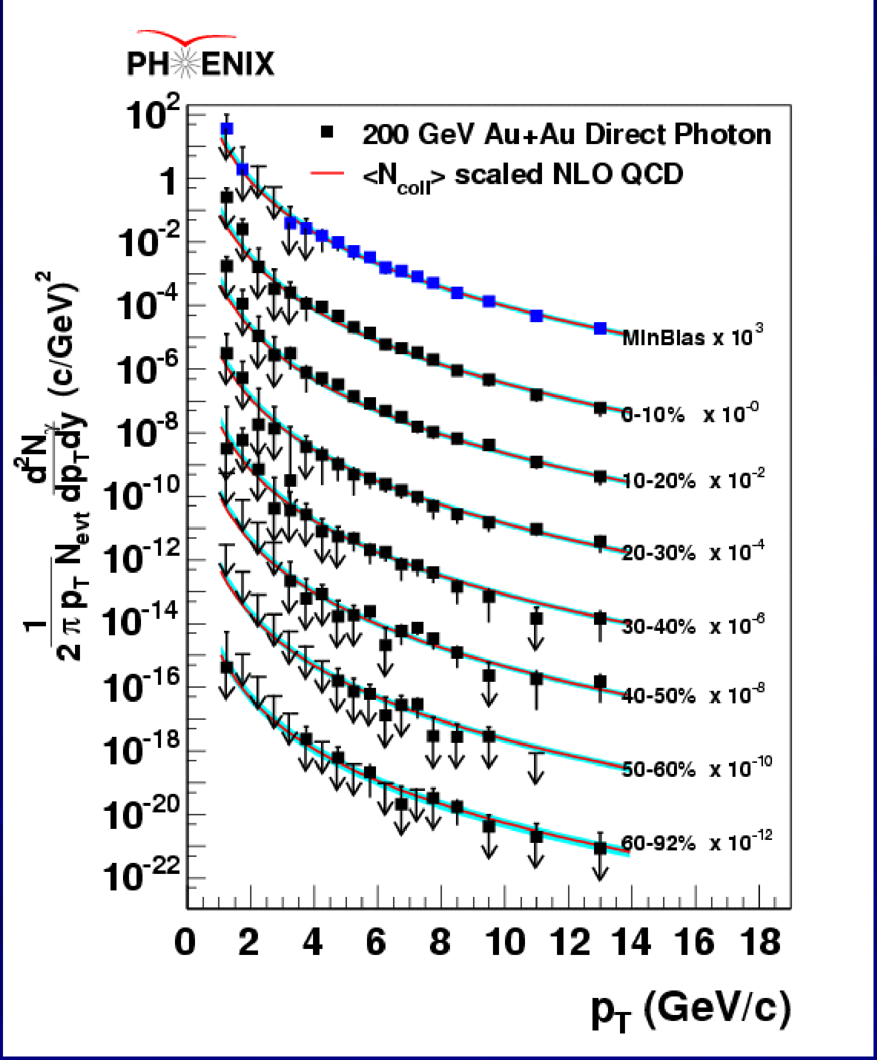


$$R_{AA} = \frac{d^2 N^{AA} / d\, p_T\, dy}{\langle N_{bin} \rangle d^2 N^{NN} / d\, p_T\, dy}$$

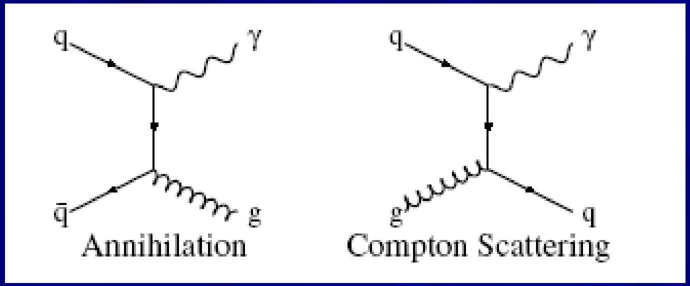




The nuclear modification factor for direct photons

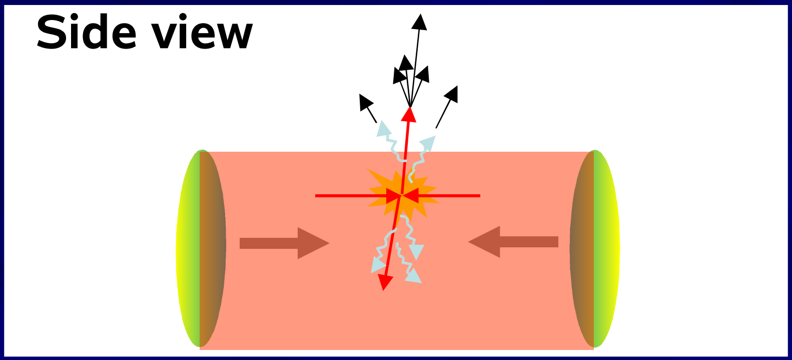


Source of direct photons

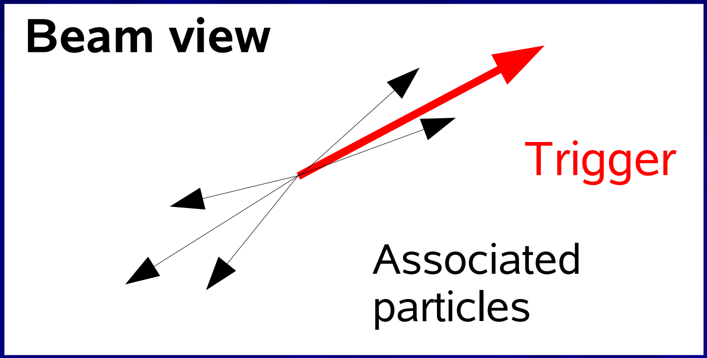


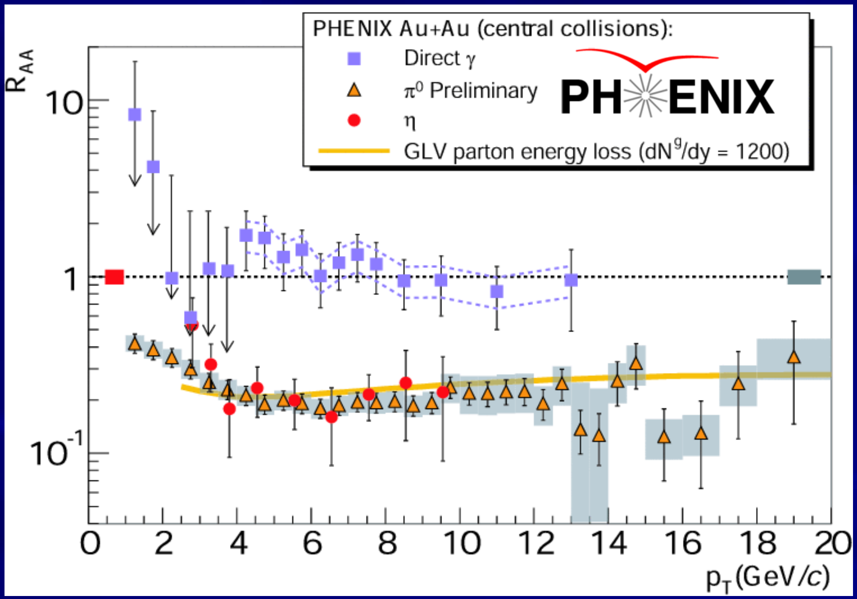
- Direct photons does not interact with final state hadronic matter!
- At low pT photons are dominantly decay photons e.g. $\pi^0 \rightarrow 2\gamma$
- Direct photons confirm binary scaling of hard processes!

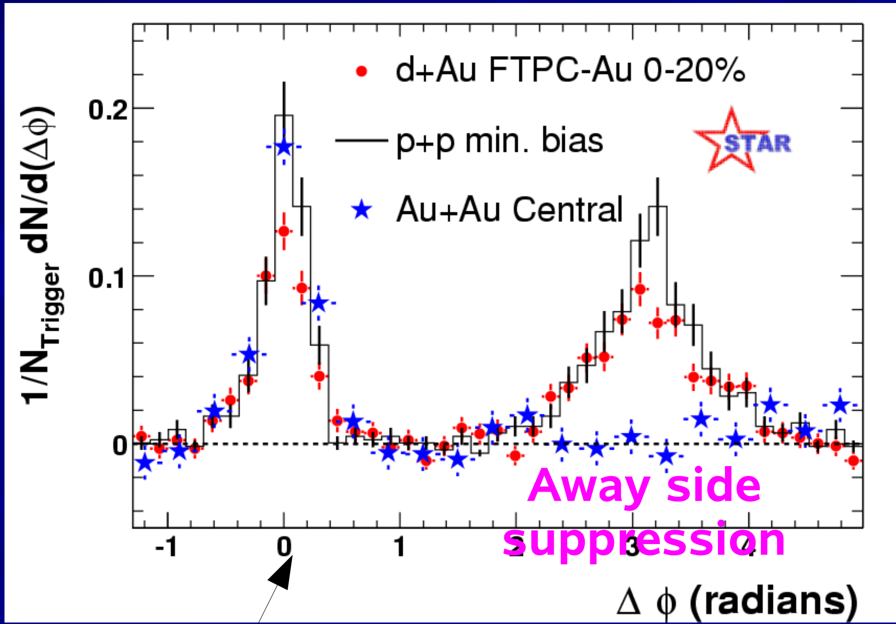
Disappearance of the away side jet indicates final state effect



Most jets are created back to back!



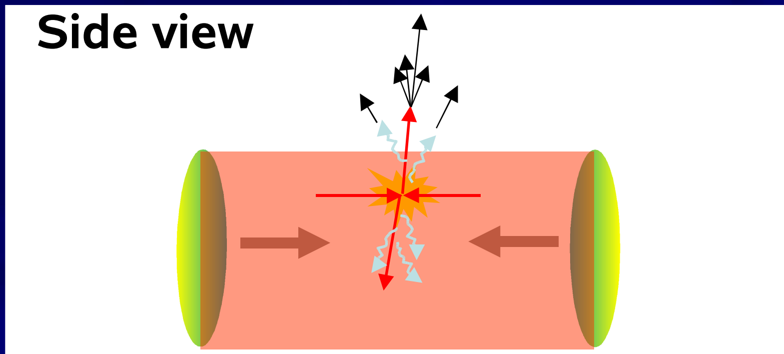




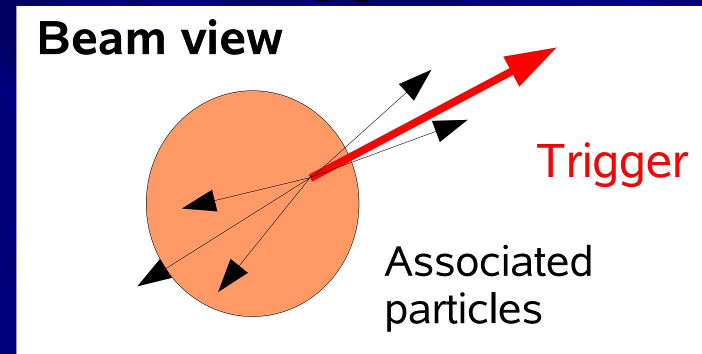
$4 < p_T(\text{trig}) < 6$ GeV/c

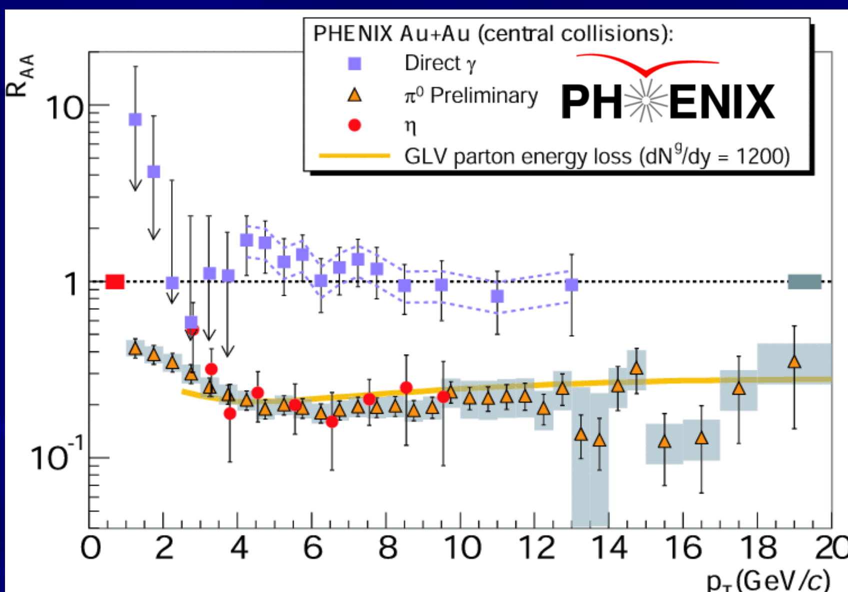
$p_T(\text{assoc}) > 2$ GeV/c

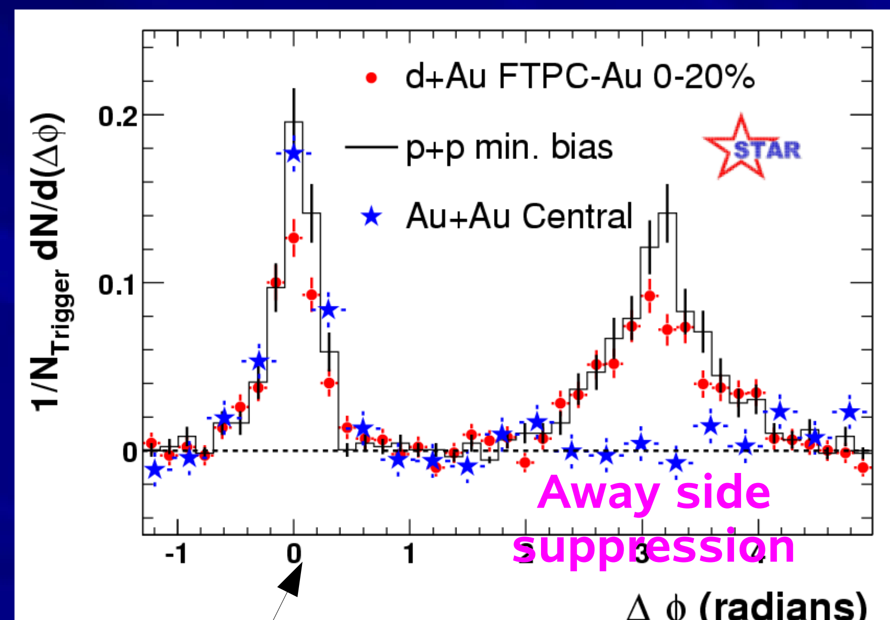
Disappearance of the away side jet indicates final state effect



Most jets are created back to back!



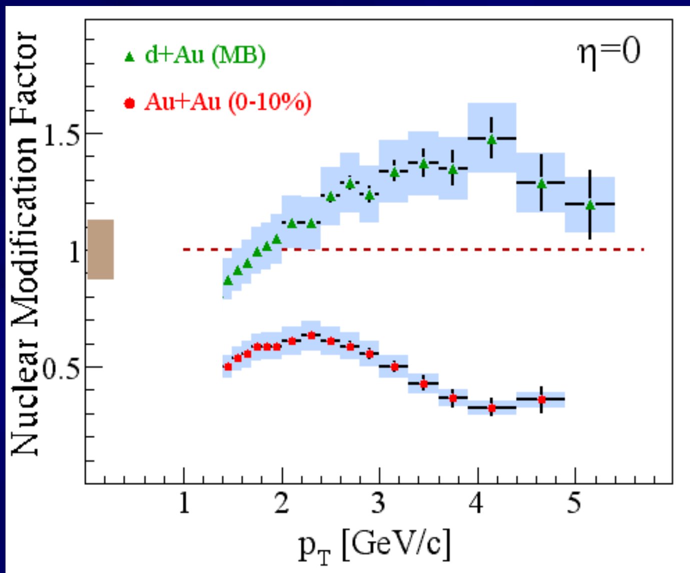


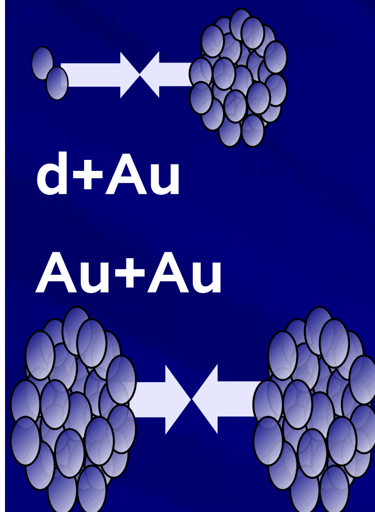


4 < p_T(trig) < 6 GeV/c

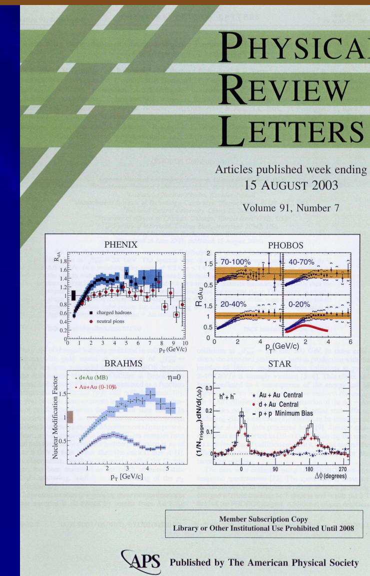
p_T(assoc) > 2 GeV/c

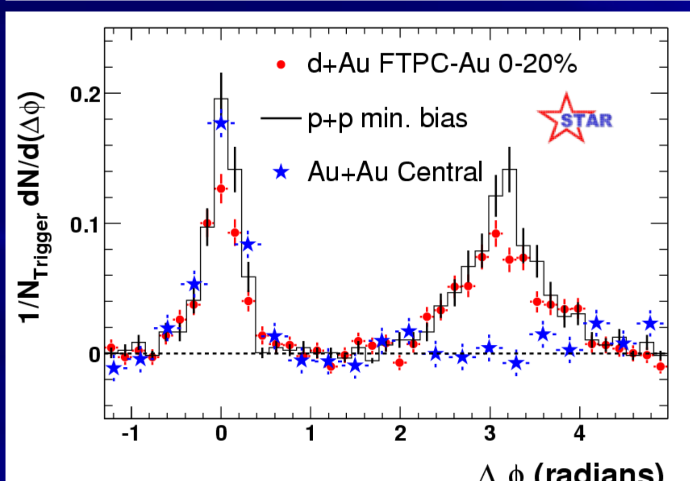
Au+Au vs d+Au
Hot vs cold nuclear matter





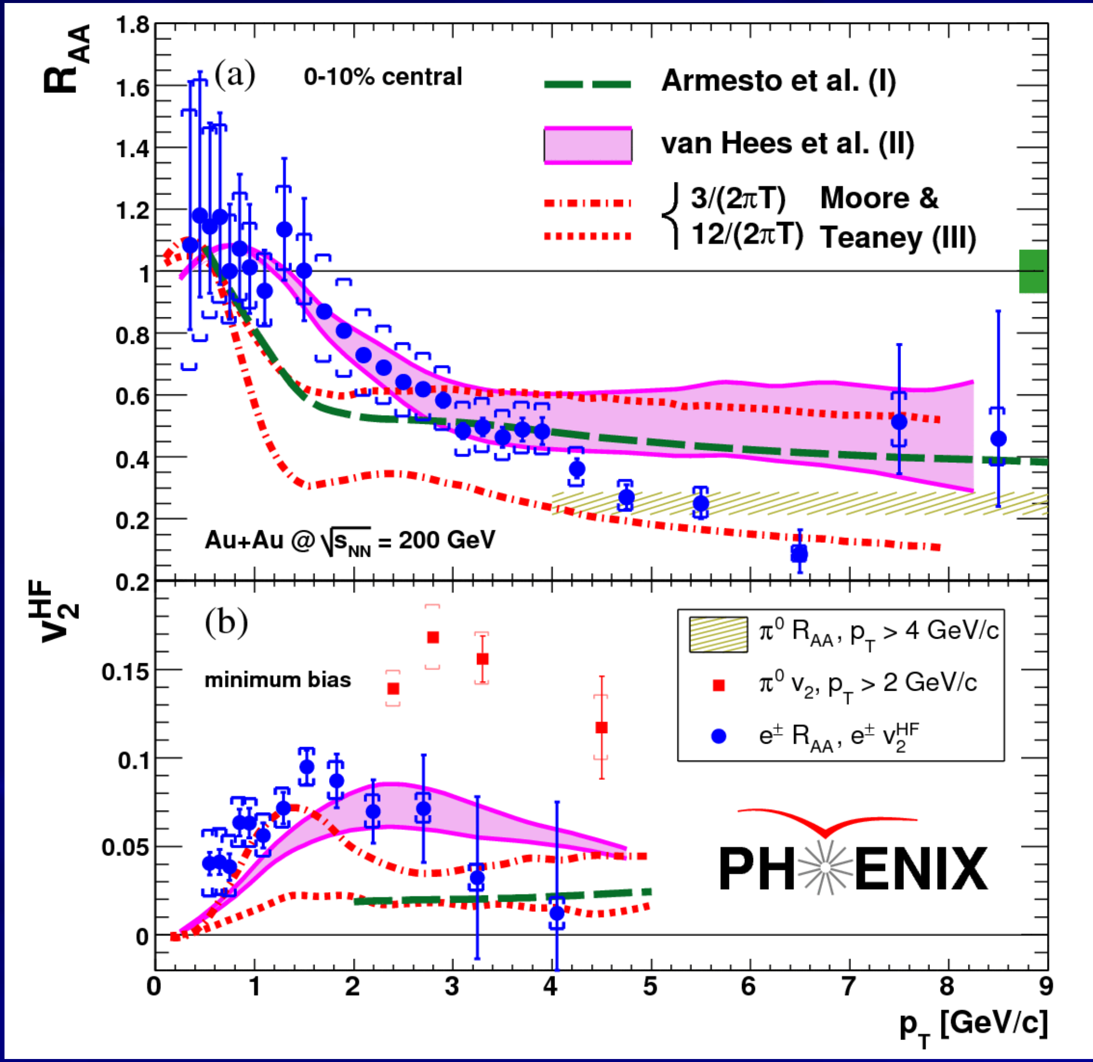
All 4 experiments published together in PRL:





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

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



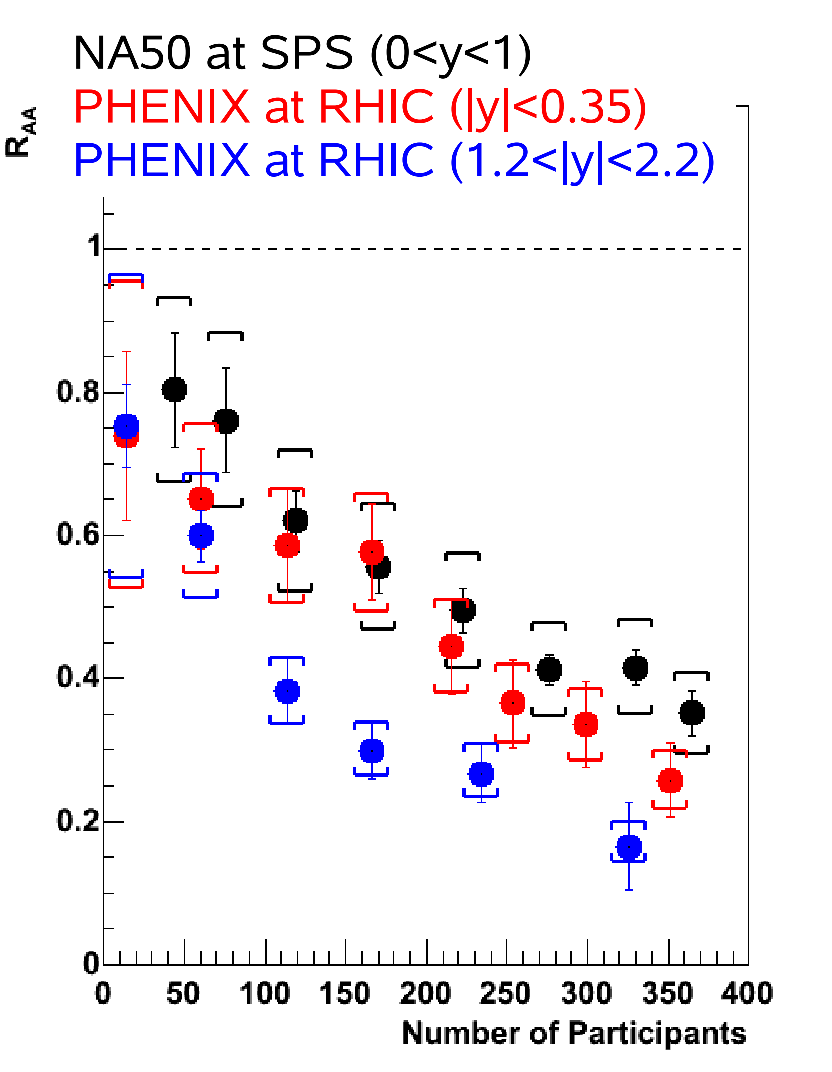
Indirectly measured: Measure single electron spectra and correct for background.

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

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(?)

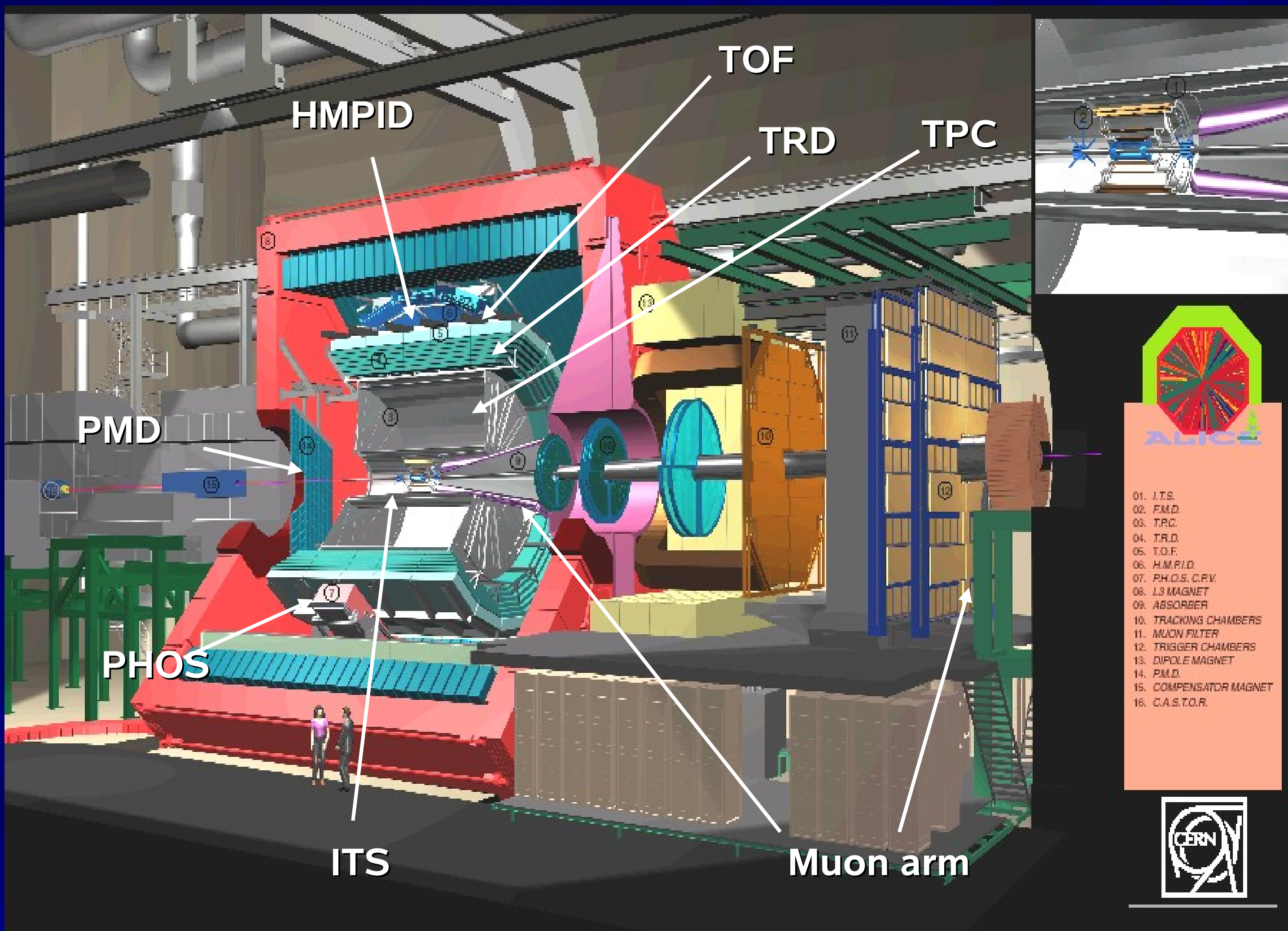
Summary of hard physics

- High p_T jets are suppressed indicating that they suffer a large energy loss in the medium
  - Medium is dense and strongly interacting
- Heavy quarks are flowing and suppressed
  - They also interact with the medium
- 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)

What to expect at LHC as seen from the RHIC generation

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

The ALICE experiment at LHC



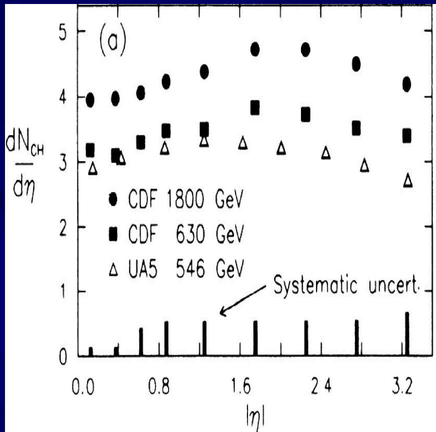
Global detectors:
V0
T0
FMD

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)

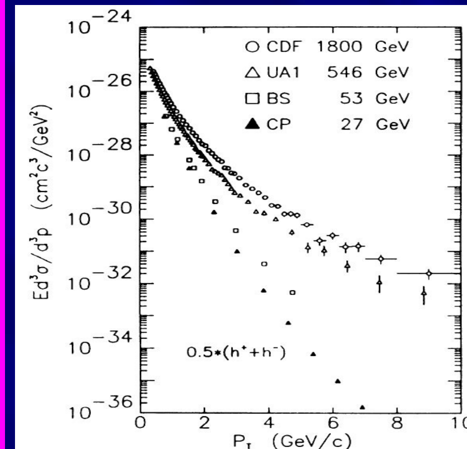
- The first physics with ALICE will be proton-proton collisions:
  - Provides “reference” data to understand heavy-ion collisions.
  - Genuine proton-proton physics where ALICE is unique or competitive
    - low momentum cutoff – due to low magnetic field and small material budget
    - particle identification – 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)



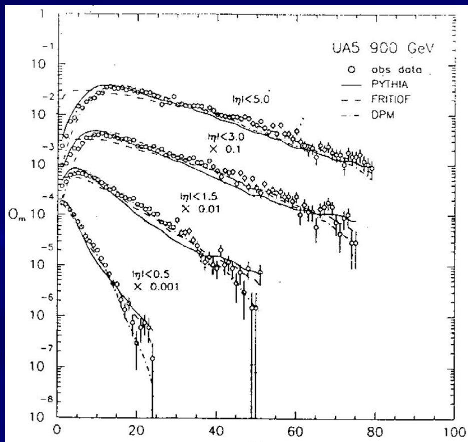
Pseudorapidity density dN/dη

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



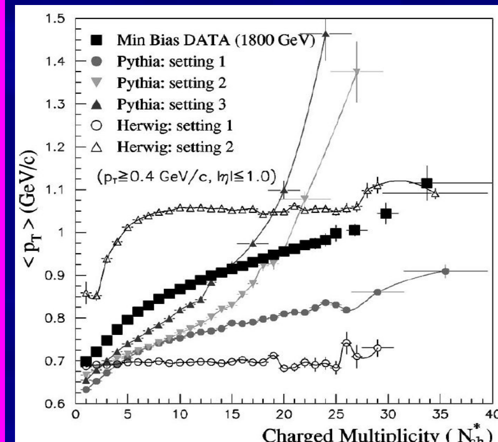
p_T spectrum Charged tracks

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



Multiplicity distribution

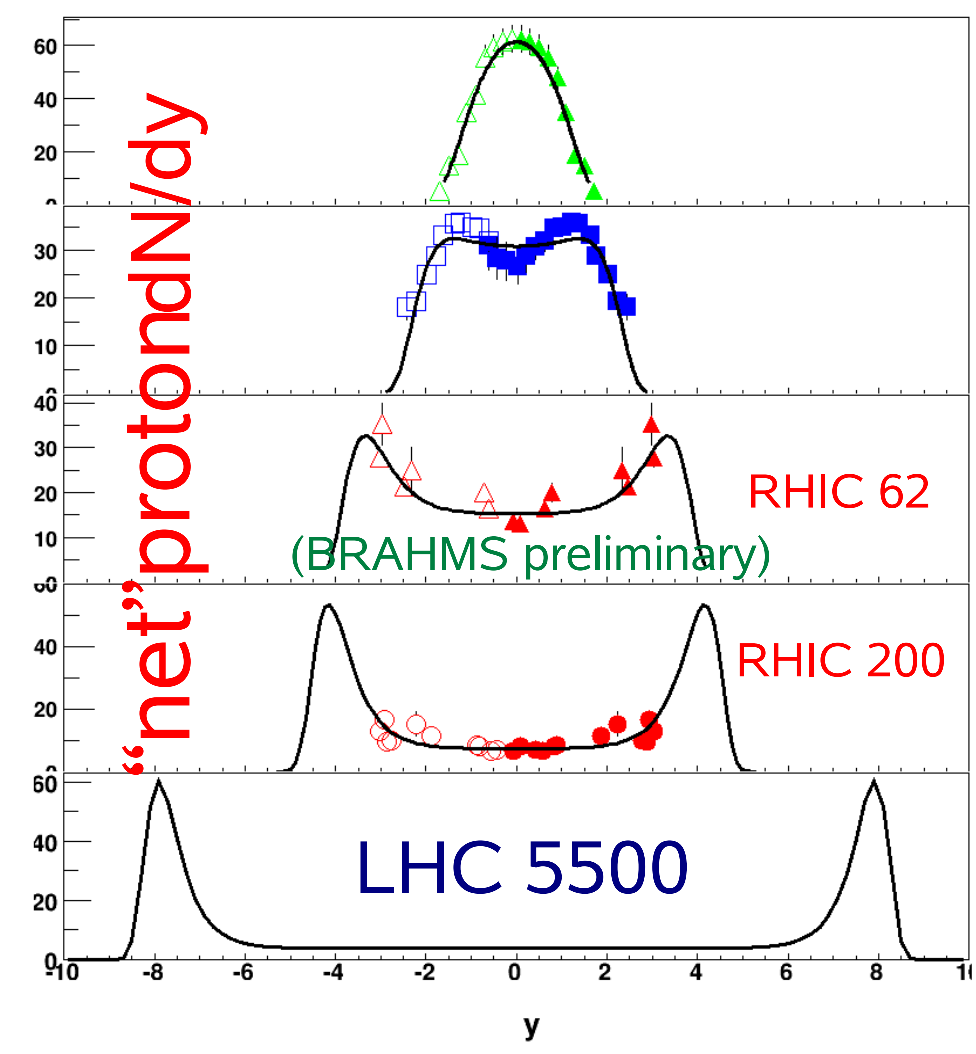
UA5:
Z. Phys
43, 357 (1989)



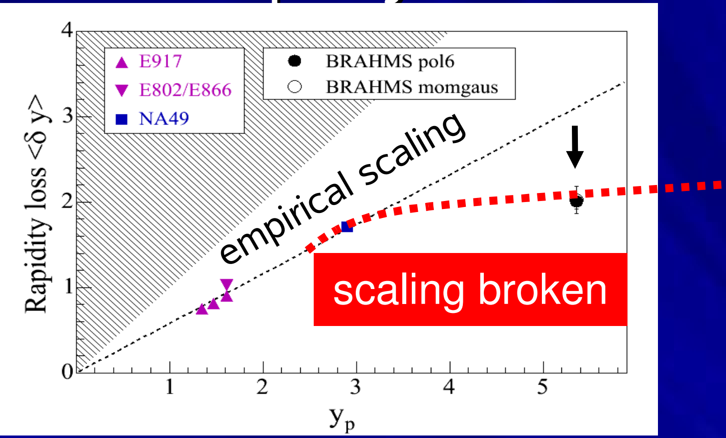
Mean p_T vs multiplicity

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

Extrapolated stopping From AGS to LHC



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



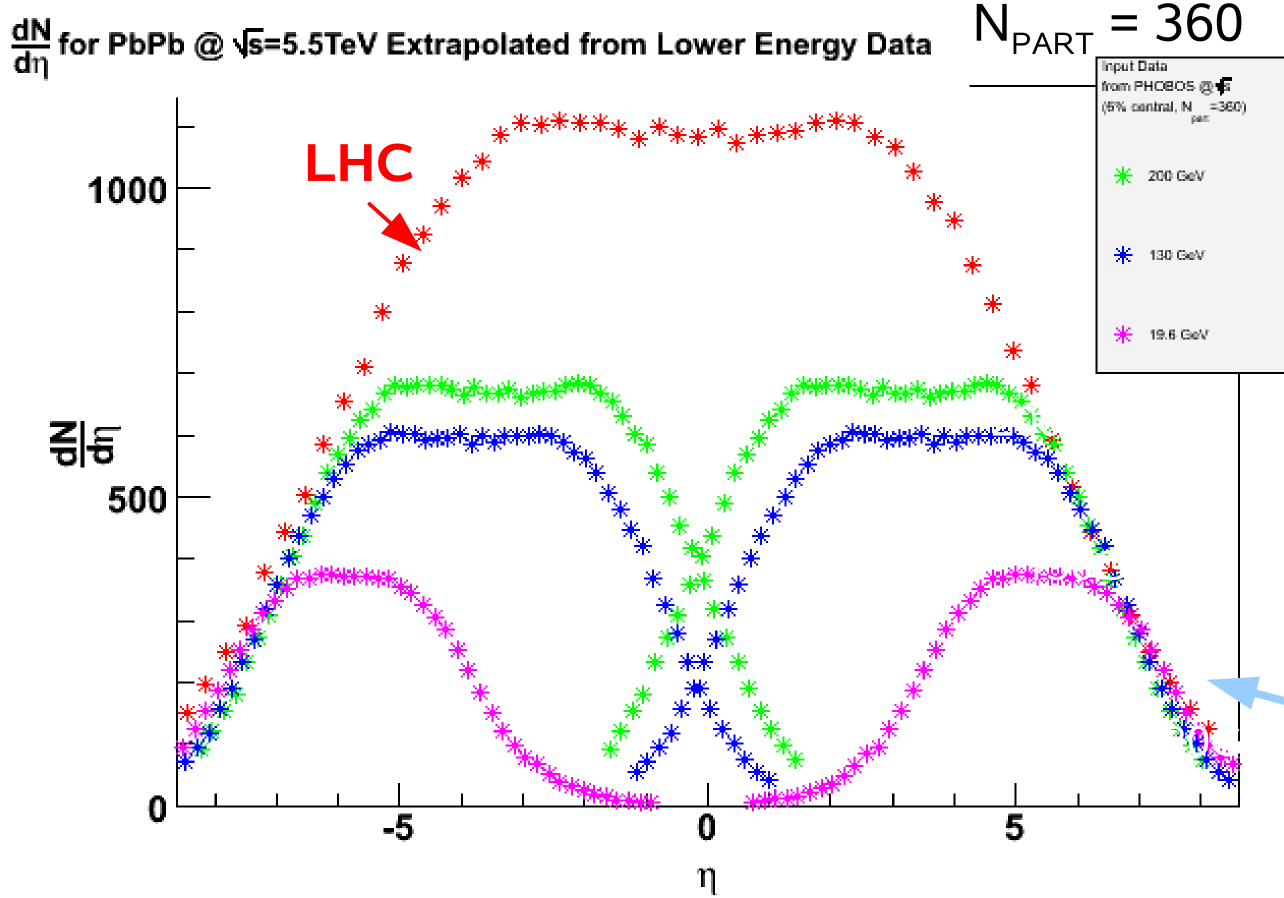
- And that the fit function (which is a Gauss in p_z):

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

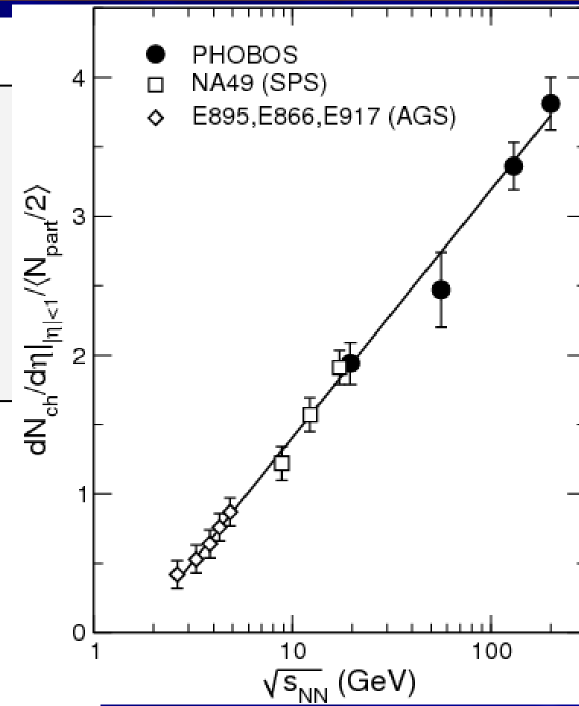
describes data so far.

Extrapolated charged particle multiplicities from RHIC

N_{PART} = 360



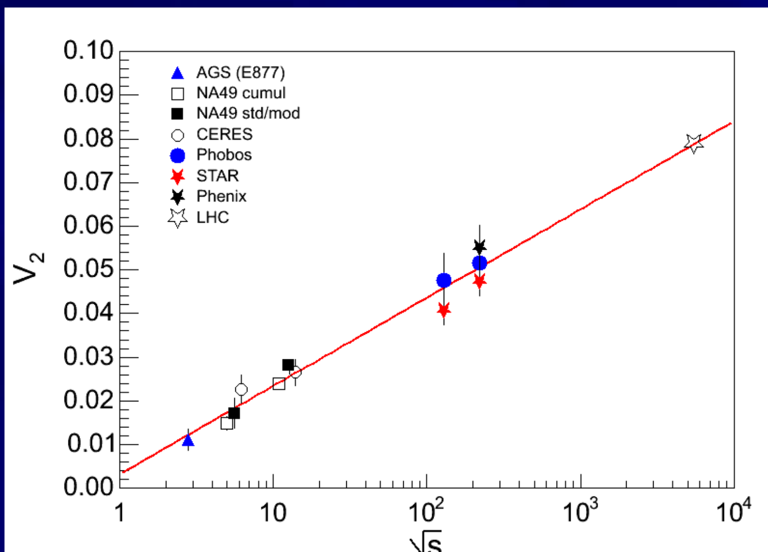
Rapidity shifted AuAu Data from PHOBOS



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

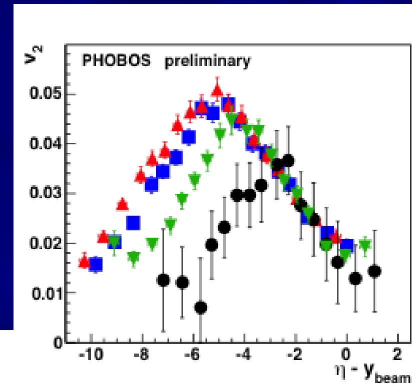
Extrapolated elliptic flow (v2) at LHC

Energy dependence of v2

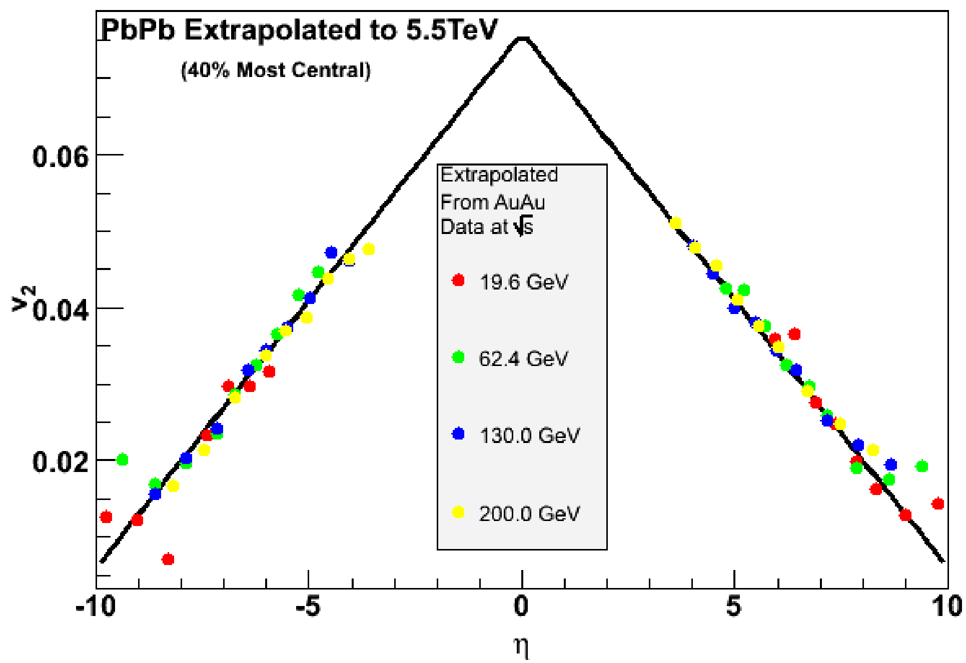


Compilation of data from

Phys. Rev. C68 (2003) 034903



Elliptic Flow also shows limiting fragmentation



PHOBOS, Nucl.Phys. A757 (2005) 28

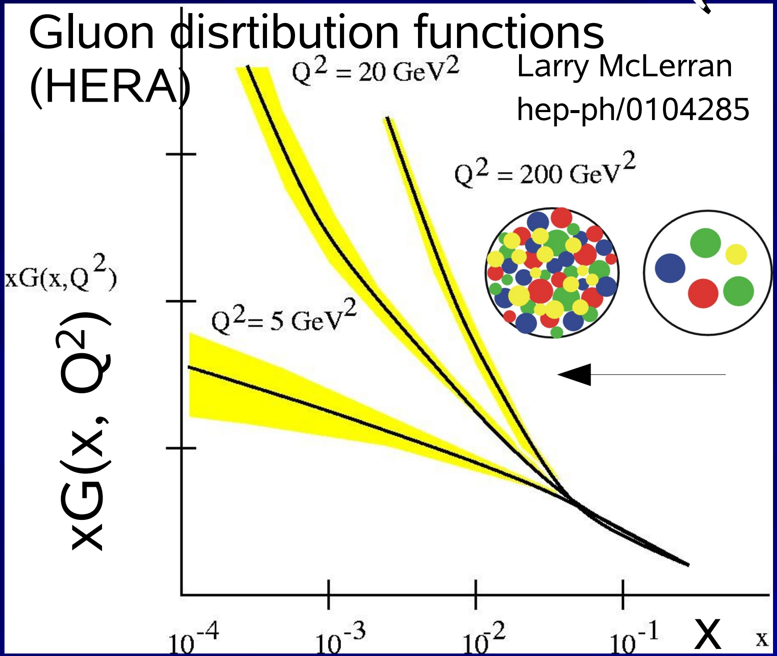
Summary and conclusion

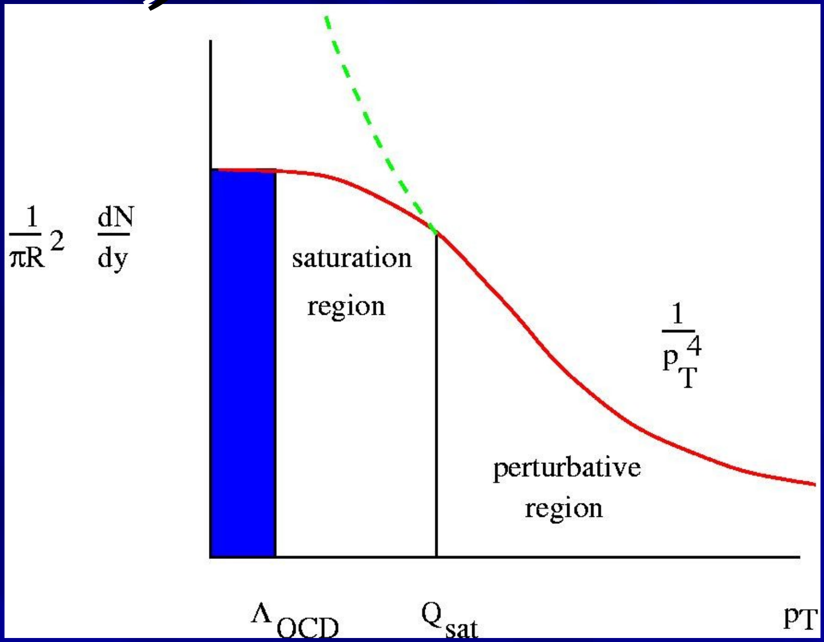
- Results from RHIC shows that the system formed is dense and strongly interacting
- High p_T partons and heavy quarks looses energy through interaction with the medium so that medium properties can be determined

- 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

Backup slides

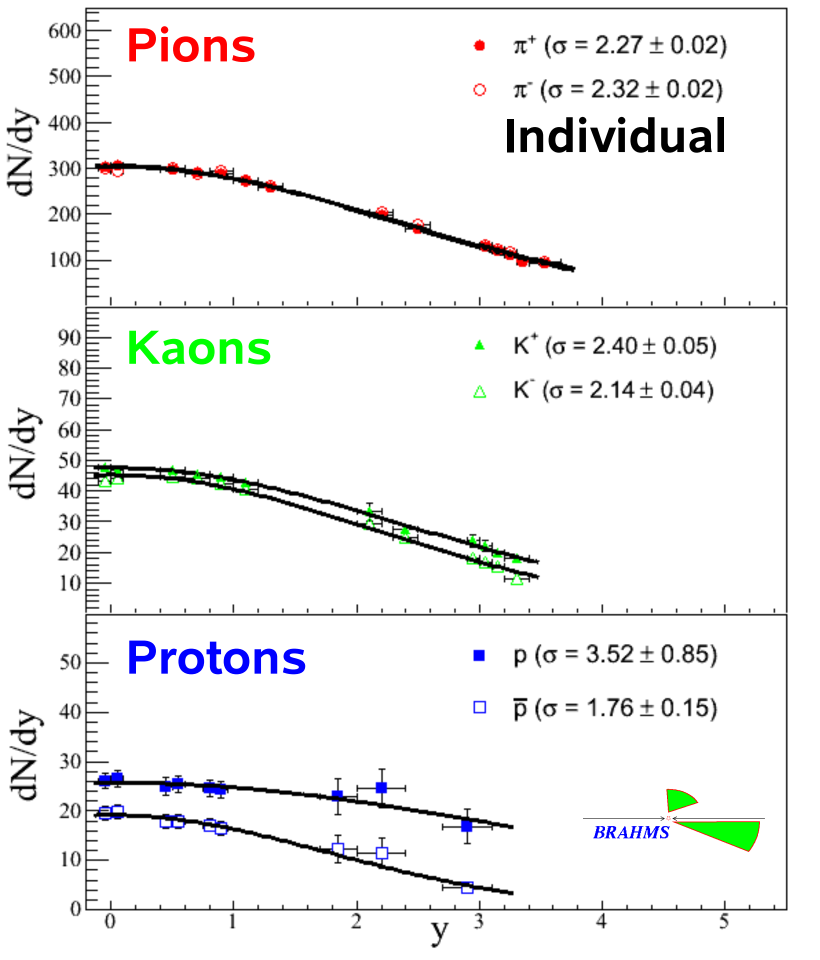
The Color Glass Condensate (CGC)

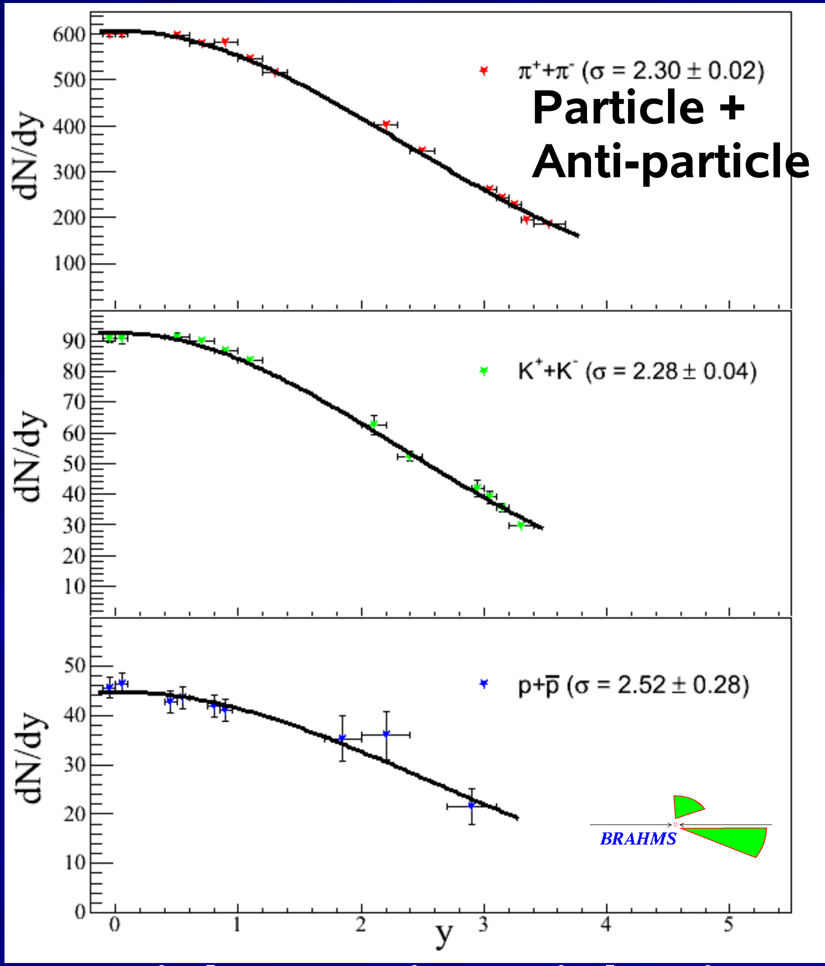




- With increasing energy/momentum resolution the number of (small-x) partons in a hadron/nucleus grows rapidly (dominate soft physics)
- At the saturation scale Q_s partons begin to overlap in the transverse area of the nucleus ($\sim A^{1/3}$), which prevents further growth of the parton density
- Color-Glass-Condensate: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

Does other dN/dy behave as Landau hydro?

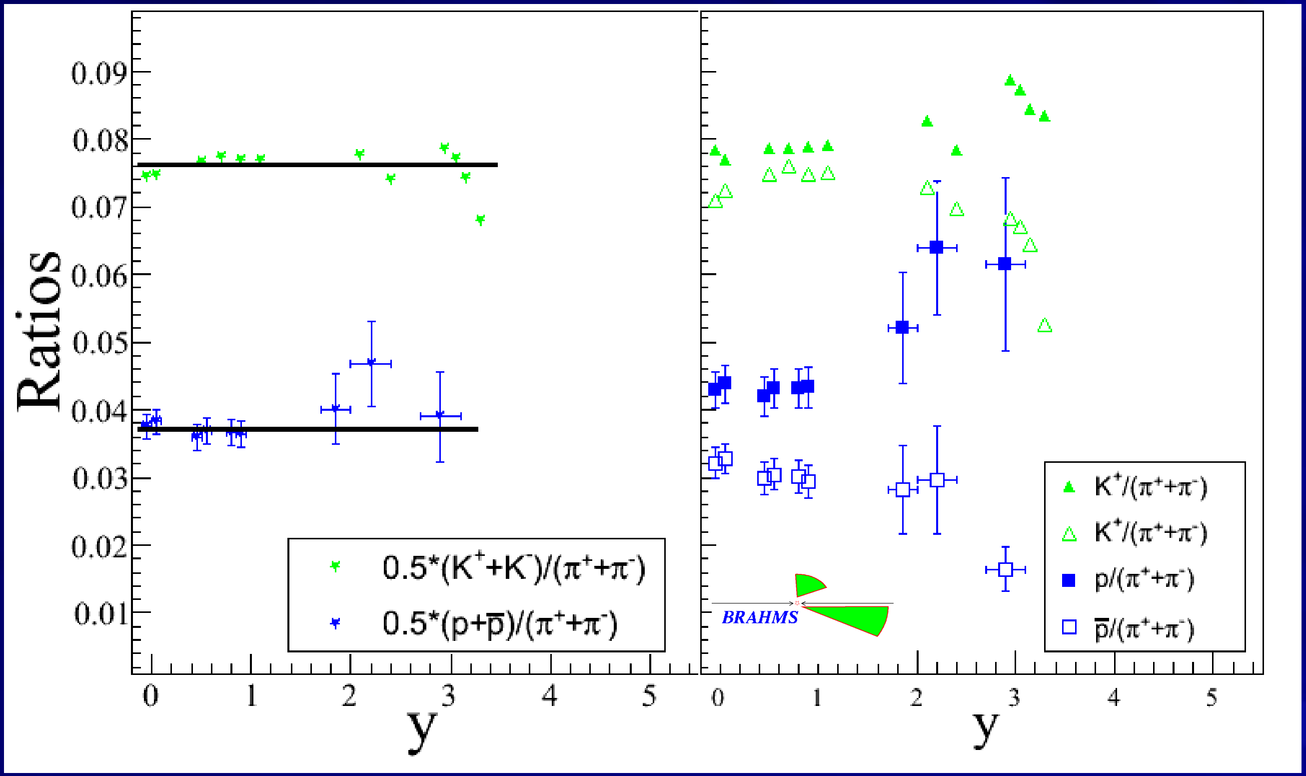




Ordering of individual sigmas:
p-bar < K^- < π^+ < π^- < K^+ < p

Particle + anti-particle sigmas are similar and ~Landau

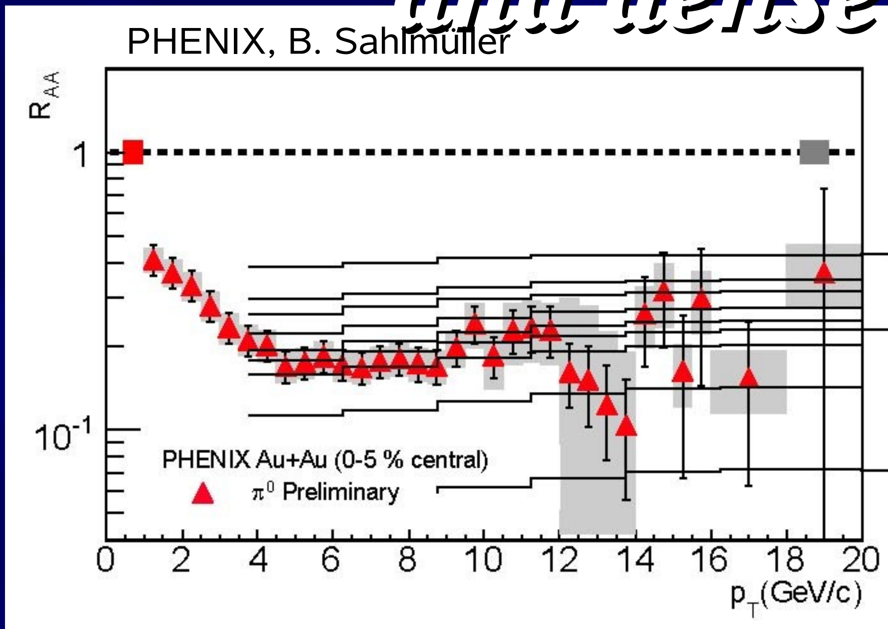
T and μB vs rapidity

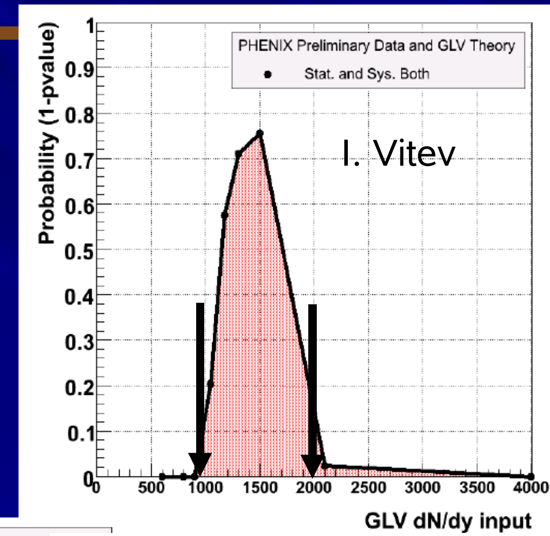


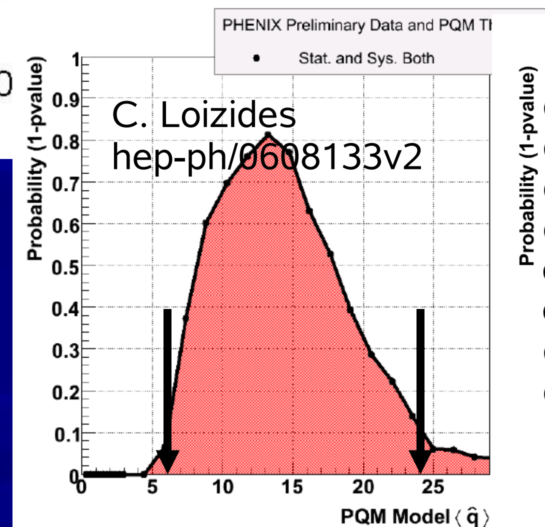
For small chemical potentials (μ<T):
exp(-μ/T)+exp(μ/T)
(=2cosh(μ/T))
~1-μ/T + 1+μ/T~2
i.e. constant

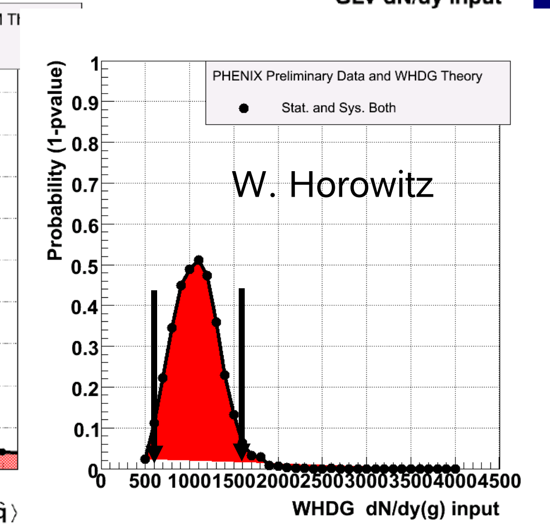
- The chemical freezeout temperature seems to be independent of rapidity so that it is only the baryon chemical potential which changes

R_{AA} for π^0 as a probe of the hot and dense medium









Use R_{AA} to extract medium density:

I. Vitev: $1000 < dN_g/dy < 2000$

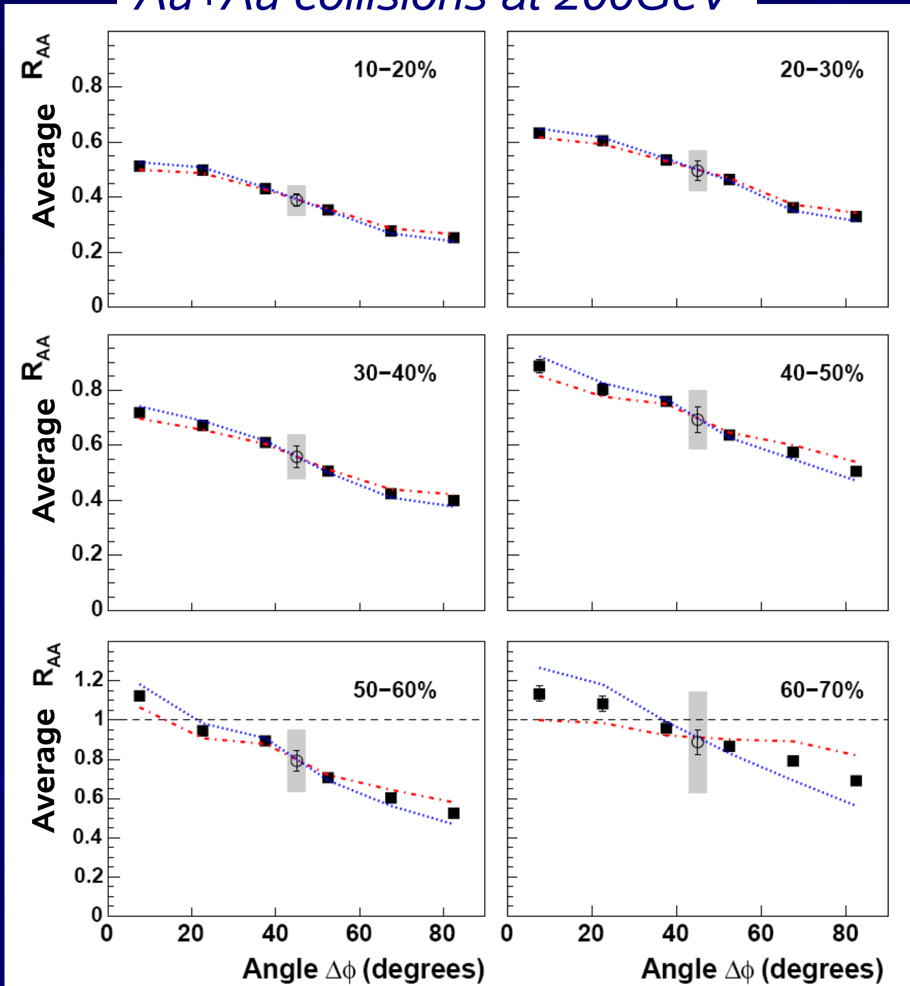
W. Horowitz: $600 < dN_g/dy < 1600$

C. Loizides: $6 < \hat{q} < 24$ GeV²/fm

Statistical analysis to make optimal use of data

Average R_{AA} vs. Reaction Plane

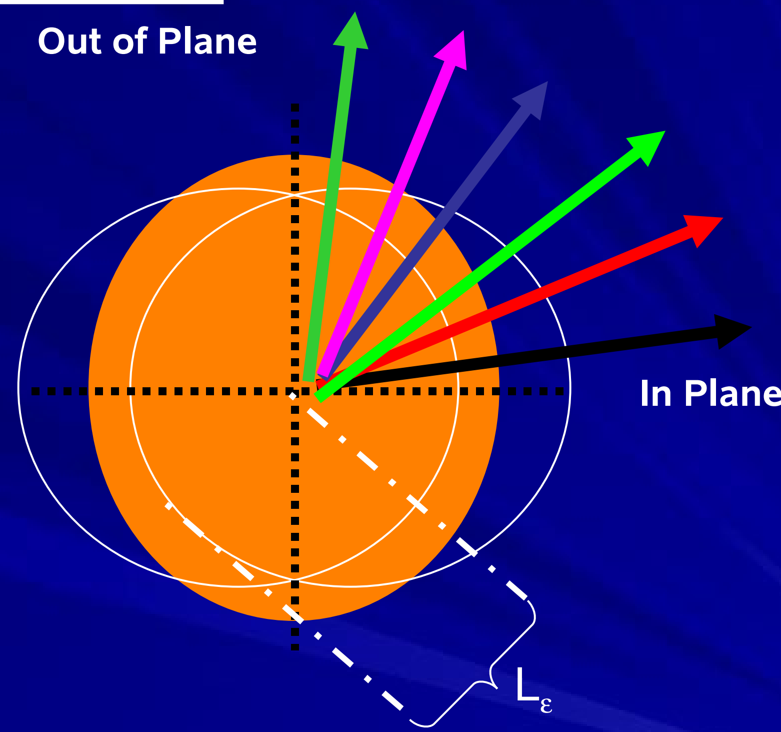
Au+Au collisions at 200GeV



$3<p_T<5$ GeV/c

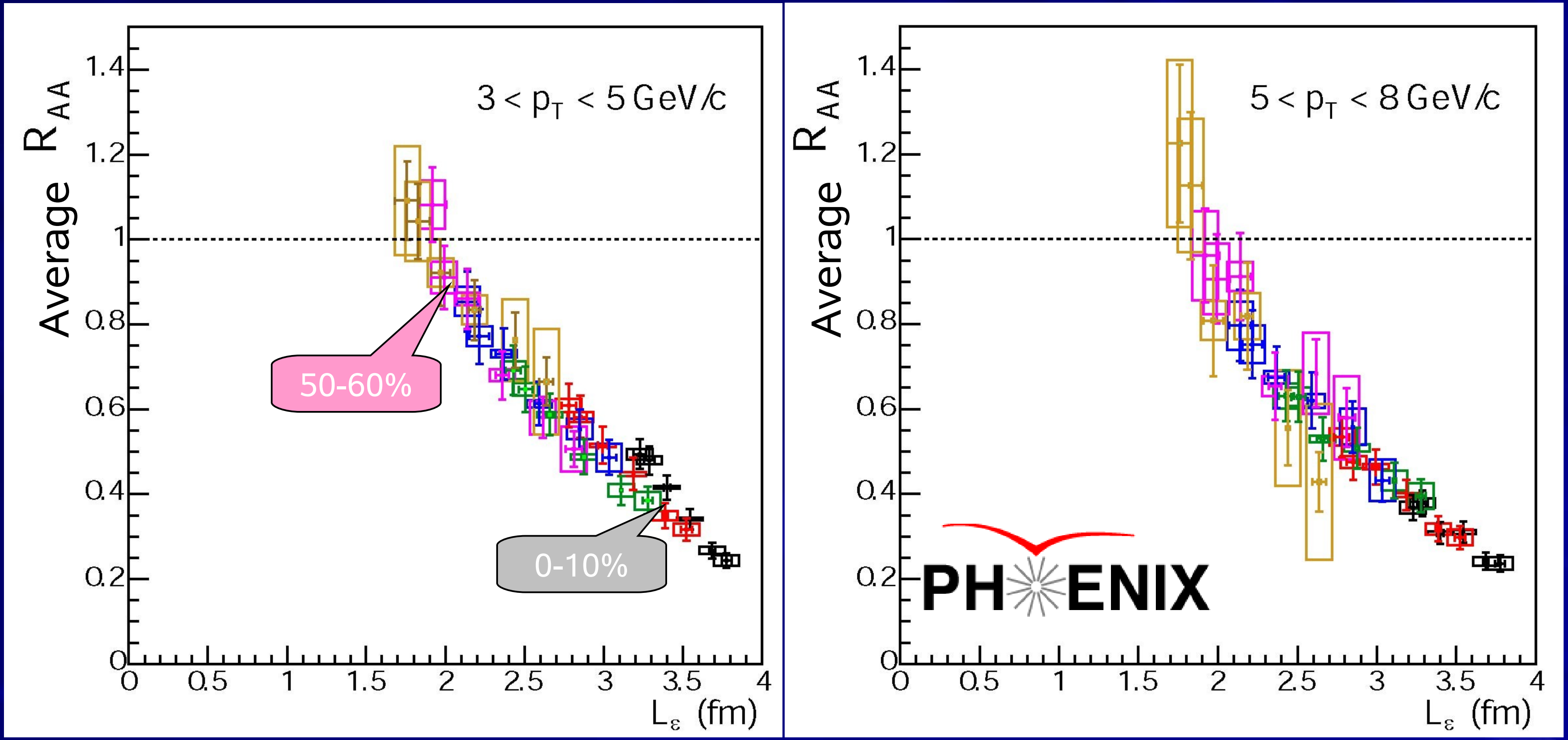
PHENIX

nucl-ex/0611007
(submitted to Phys. Rev. C.)



In plane emission shows no energy loss in peripheral bins.

Model challenge:
R_{AA} L_ε Dependence



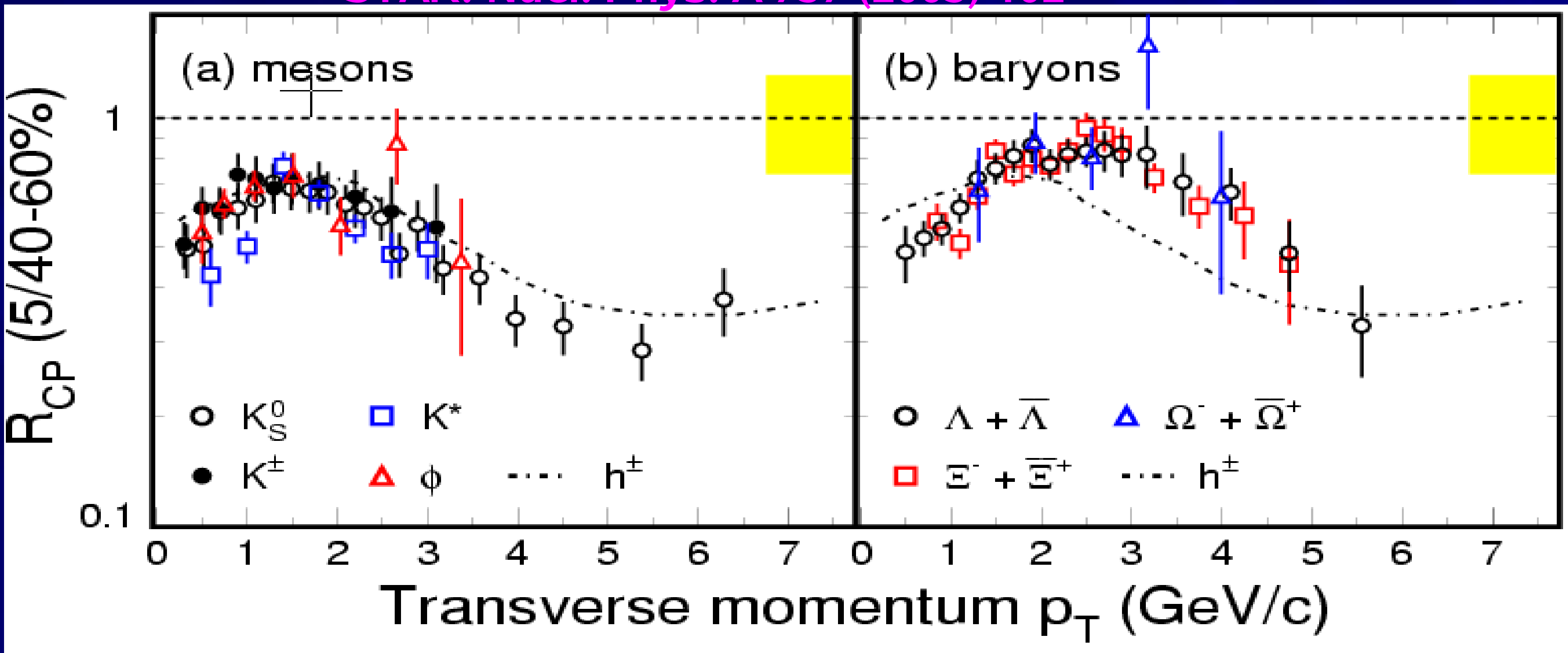
L_ε = matter thickness calculated in Glauber model (not the same as matter seen!)

nucl-ex/0611007
(submitted to Phys. Rev. C.)

Little/no energy loss for L_ε < 2 fm (formation time?)

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

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



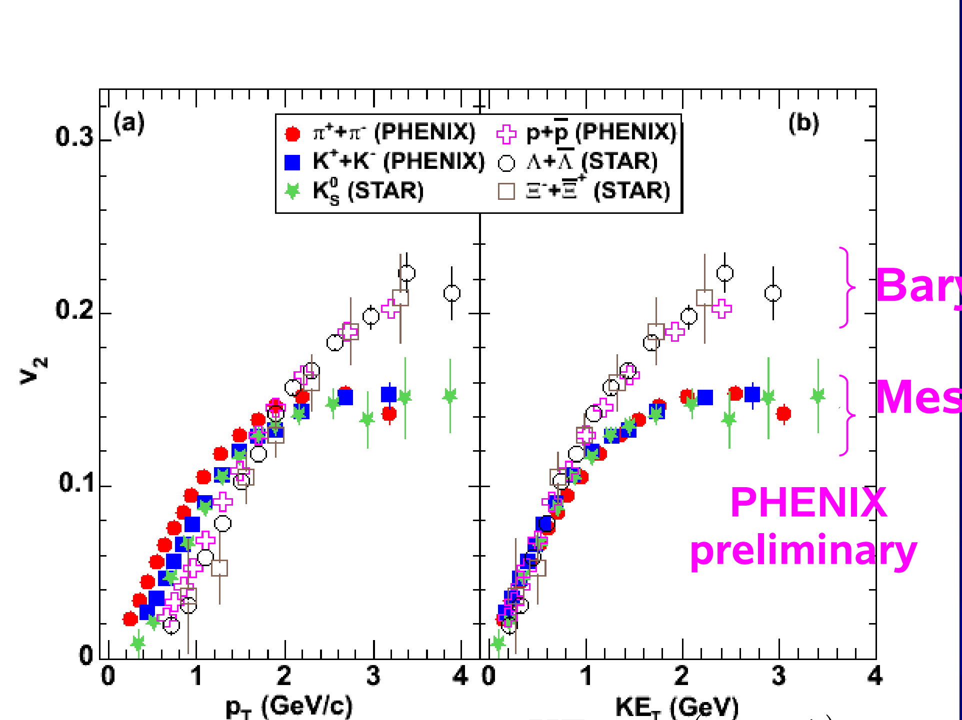
Two groups (2<pT<6GeV/c):

π, Ks, K±, K*, ϕ ⇦ mesons

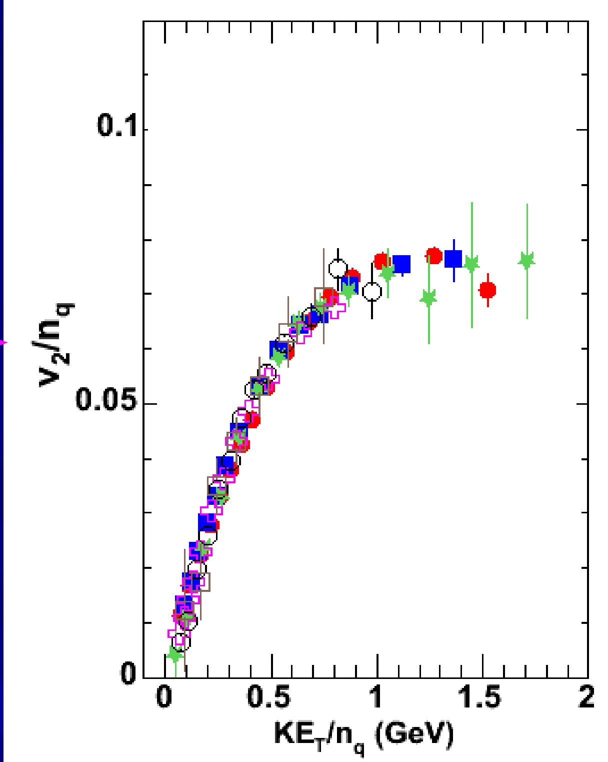
p, Λ, Ξ, Ω ⇦ baryons

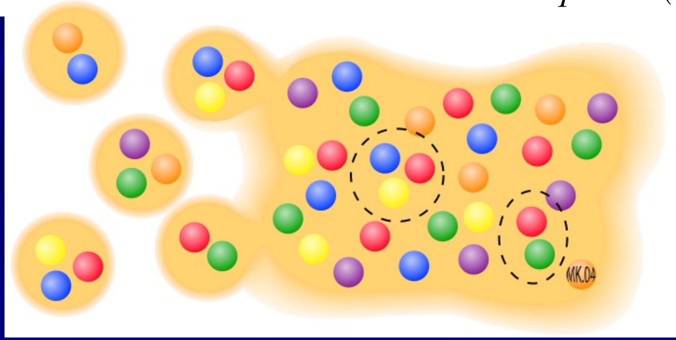
Rcp splitting between baryons and mesons comes naturally in the recombination approach (next slide)

Elliptic flow at high pT: kinetic energy and quark scaling



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



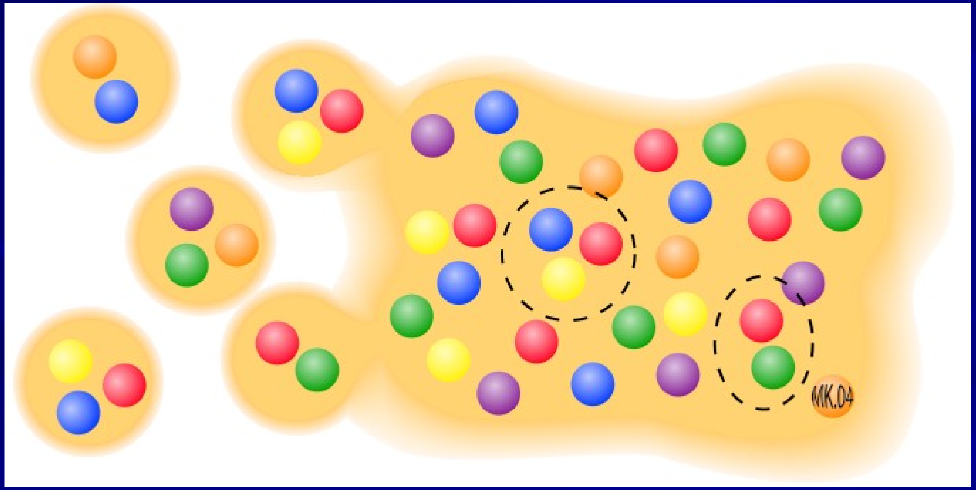


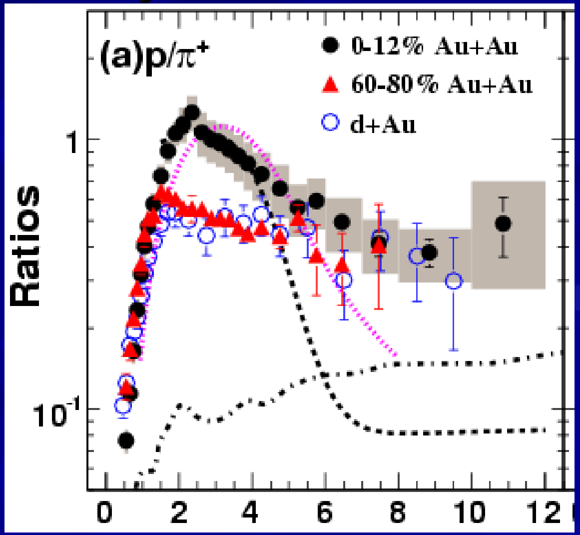
Quark recombination into hadrons ?

Quark degrees of freedom?

Recombination at LHC(?)

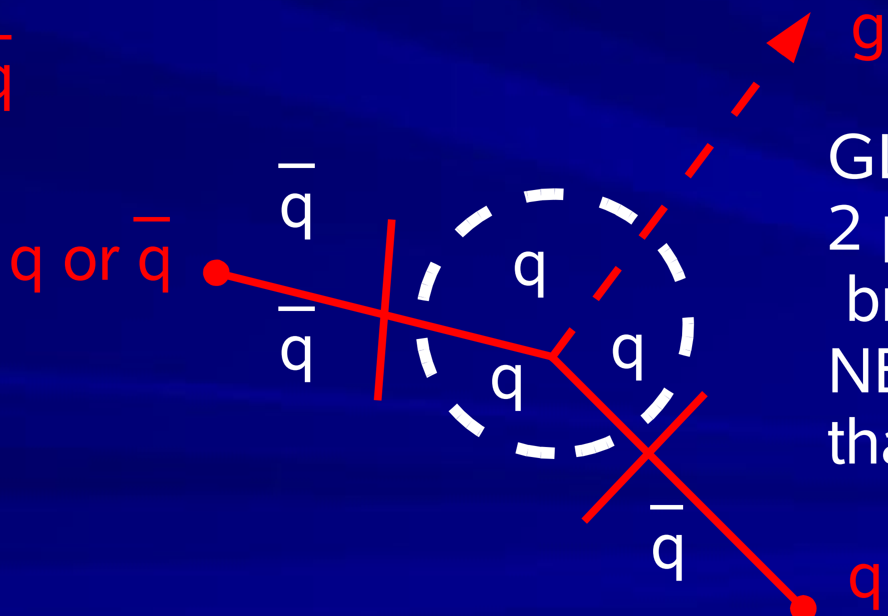
- Normal pQCD particle production
  - 1 parton → many partons → many hadrons
- Recombination allows the many partons from different quarks to recombine! $p = \sum p_{partons}$ (Baryon p > Meson p)
- Njets increases at LHC => recombination region should cahnge. Hwa and Yang (nucl-th/0603053) predicts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





Baryon production in quark and gluon jets in string models.

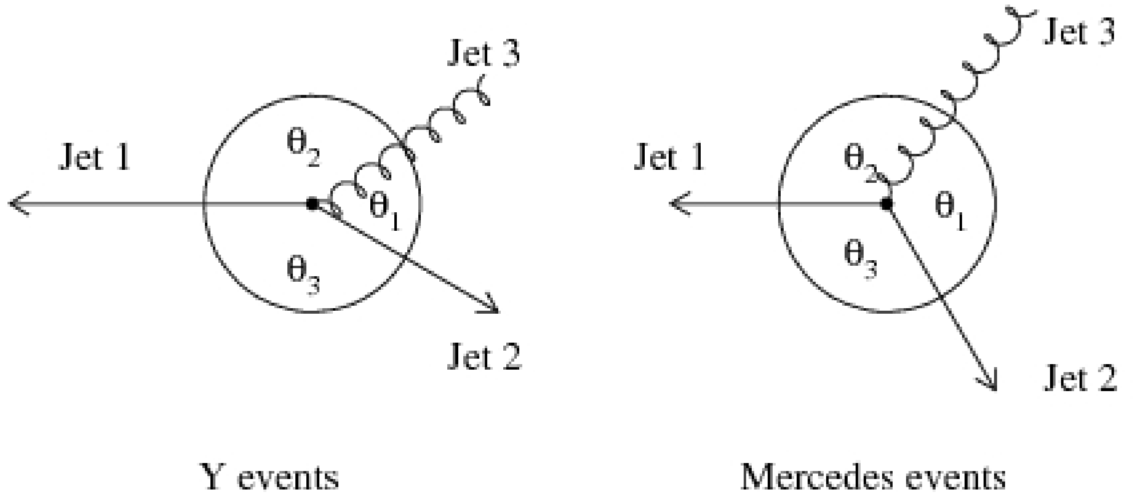
QUARK JET:
Needs diquark (q q - $\bar{q}\,\bar{q}$) string break to make a leading baryon.
(suppressed by 1/10 vs q-q breaking)



GLUON JET (KINK):
2 possibilities for diquark breaking => 2/10
NB! gluon jets are softer than quark jets

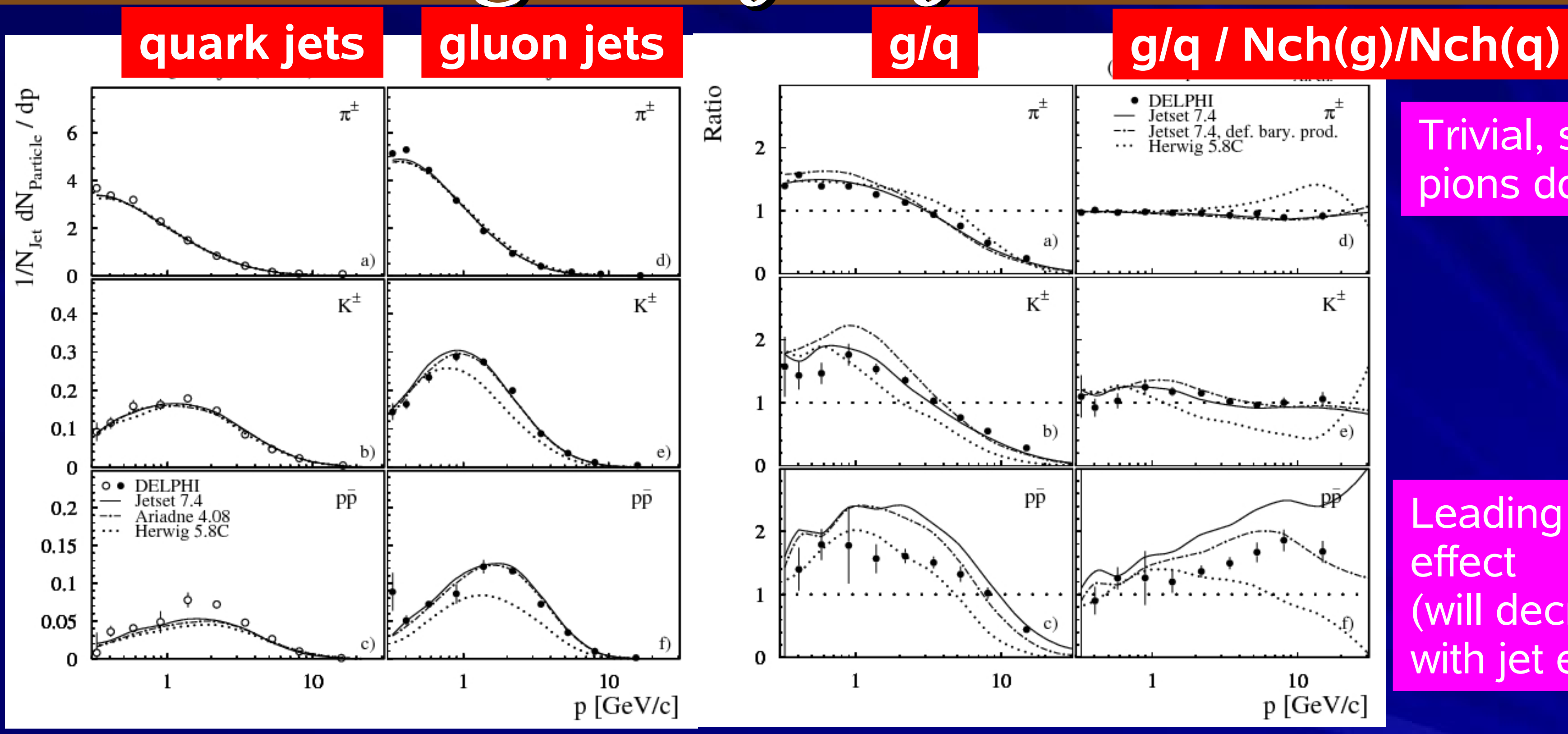
Delphi results on quark and gluon jets *(Eur. Phys. J C17(2000)207)*

3 jet events: e^+-e^- -> Z^0 -> q + q-bar + g



- Select Y-events
  - Require 150-15 deg < $\theta_{2,3}$ < 150+15 deg
  - Ignore jet1
  - Compare identified particle yield in quark (jet2) and gluon (jet3)
- This ensures that quark and gluon have similar kinematics
  - Gluon jet is identified by angle or history assigment (?)

Identified particles in quark and gluon jets from Υ events



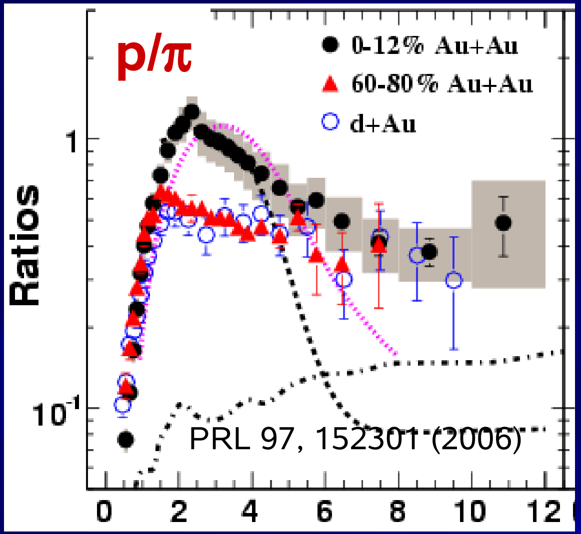
Trivial, since pions dominate

Leading baryon effect
(will decrease with jet energy!)

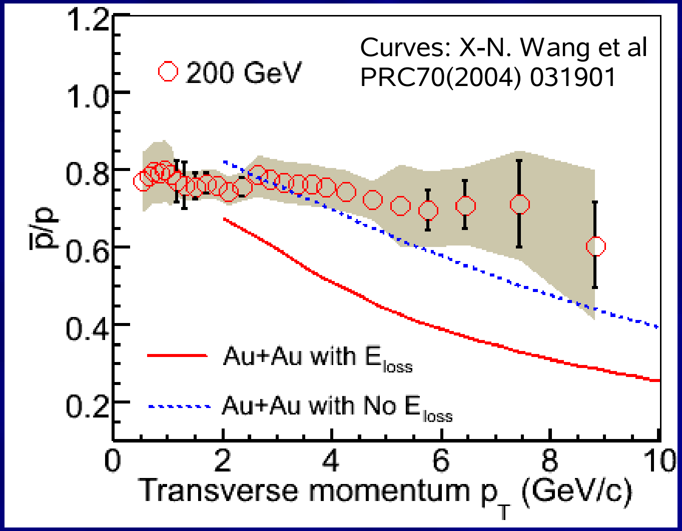
- Enhanced overall particle prod. in gluon jets (NB! but less at high p)
- Baryon production is enhanced wrt charged particle production, but mostly at high p where gluon particle productions is suppressed!

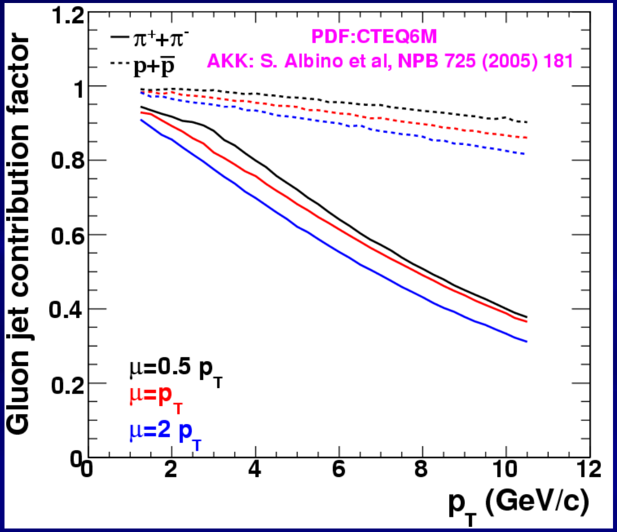
Quark vs gluon energy loss (modified QM summary slide)

STAR, L. Ruan



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