Are jets suppressed at RHIC?

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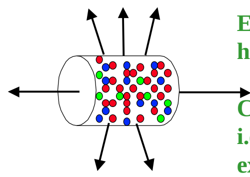
outline

- Experimental high p_T probes
- High p_T results at RHIC
  - Single particle spectra
  - Particle correlations
  - Differences from pp and lower $\sqrt{s}$
- Conventional explanations?
- Systematics:
  - Particle type
  - Centrality dependence
- p_T range of hard vs. soft processes
- Can we answer the question?

Experiments ask: did something new happen?

- Study collision dynamics (via final state)

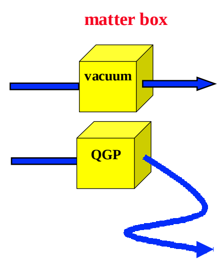


Equilibrium?
hadron spectra, yields

Collective behavior
i.e. pressure and expansion?
elliptic, radial flow

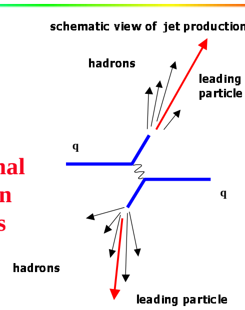
- Probe the early (hot) phase

Particles created early in predictable quantity interact *differently* with QGP and normal matter
fast quarks, J/Ψ, strange quark content, thermal radiation



My favorite probe: fast partons traversing plasma

Jets in heavy ion collisions: observed via fast leading particles or azimuthal correlations between the leading particles



But, before they create jets, the scattered quarks radiate energy in the colored medium

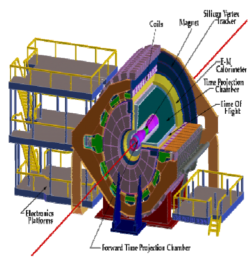
→ decreases their momentum
→ fewer high p_t particles
→ "jet quenching"

High p_T measurements done by the two large experiments

STAR

Hadronic Observables over a Large Acceptance
Event-by-Event Capabilities

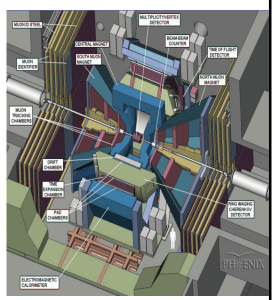
Solenoidal magnetic field
Large Time-Projection Chamber
Silicon Tracking, RICH, EMC, TOF



PHENIX

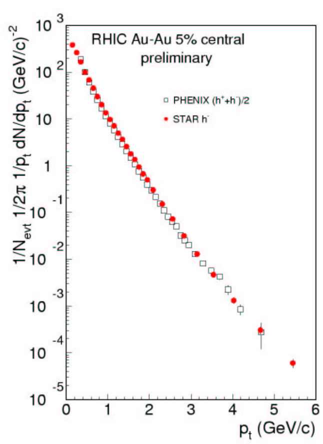
Electrons, Muons, Photons
hadrons to high p_T
Rare Probes: J/ψ, high-p_T

Two central spectrometers with tracking + electron/photon PID
Two forward muon spectrometers

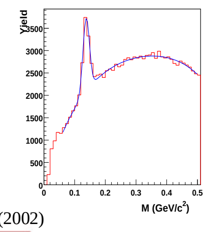


Inclusive p_t spectra of charged particles

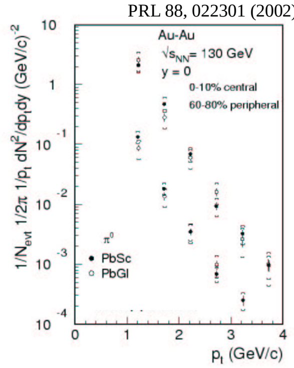
- p_t data from PHENIX + STAR agree well:
  - p_t range to 6 GeV (>6 orders of magnitude)
  - well above what was reached at the SPS



π^0's
p_T>2 GeV,
asym<0.8
in PbSc



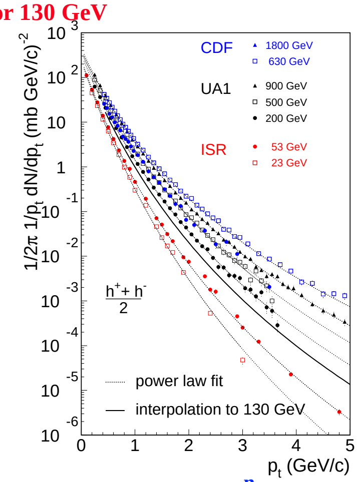
PRL 88, 022301 (2002)



excellent agreement!

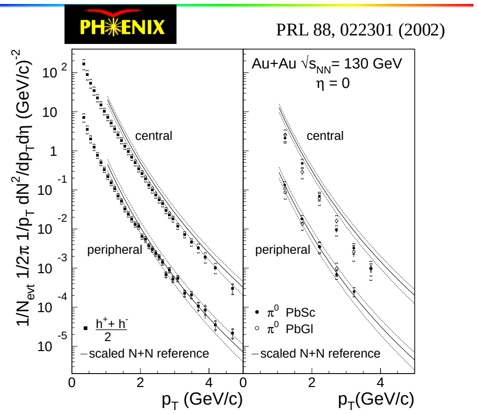
look at inclusive p_t distribution

- **p-p data available over wide range of √s, but not for 130 GeV**



power law: $\sigma_{pp} = d^2N/dp_t^2 = A\,(p_0+p_t)^{-n}$
interpolate A, p_0, n to 130 GeV

Both $h^{\pm}$ & π^0 below p+p



Peripheral collisions (60-80% of σ_{geom}):

~ p-p scaled by <N bin coll> = 20 ± 6

central (0-10%):

shape different (more exponential)

below scaled p-p!

(<N bin coll> = 905 ± 96)

Nuclear modification factor

- **We measure** $$\text{Yield}_{A\text{-}A} = \frac{1}{N_{evt}} \cdot \frac{d^2N}{2\pi \cdot p_T \cdot d_{p_T} d\eta}$$
- **Create ratio to check scaling with NN**

$$R_{A-A}(p_T) = \frac{\text{Yield}_{A-A}}{\langle N_{binary} \rangle \cdot \text{Yield}_{N-N}}$$

If no nuclear effects R_{AA} should be 1
at high p_T when hard scattering dominates

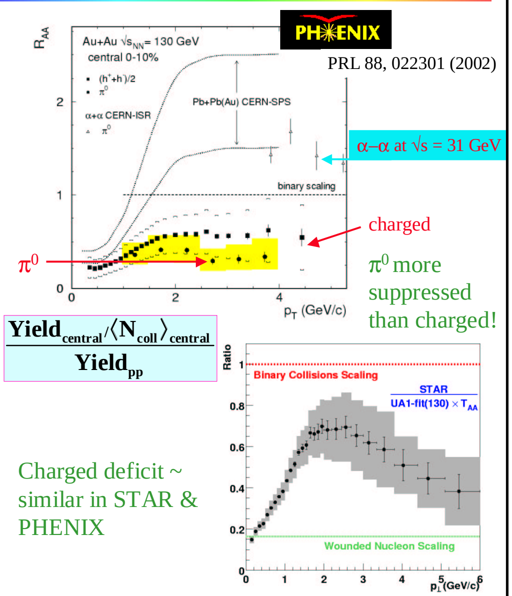
Departures from 1 measure nuclear effects

R_{AA} > 1 from k_T broadening and multiple scattering

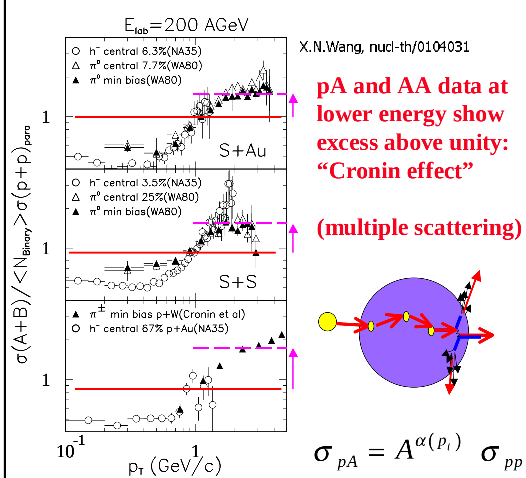
R_{AA} < 1 from energy loss

R_{AA} < 1 in regime of soft physics

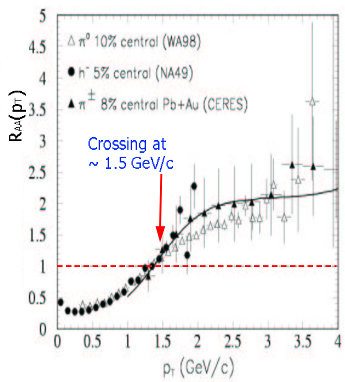
A deficit is observed in central collisions!



Known effects



In Pb + Pb at CERN

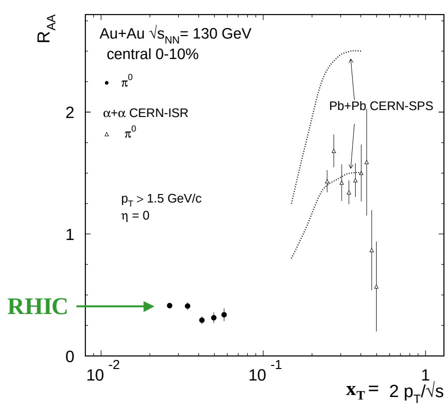


From compilation of X.N. Wang

→parton energy loss, if any, is overwhelmed by initial state soft multiple scattering!

Is SPS-RHIC comparison fair?

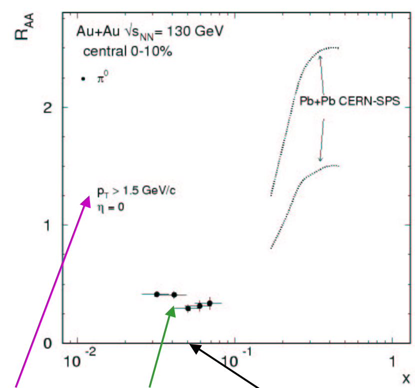
- Same p_t implies different x!



if $p_{T(had)} / p_{T(jet)} \sim 1$
then $x_T \sim$ x(parton) at y=0

more realistic fragmentation function

Thanks to X.N. Wang



to exclude known soft physics regime

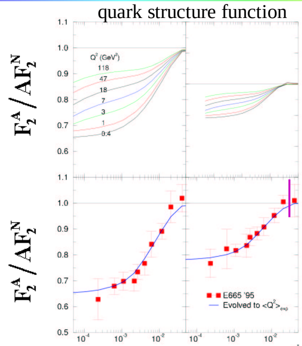
z range indicated by horizontal bar: answer is not very different

P_T = 3 GeV/c (is a safer boundary for hard processes)

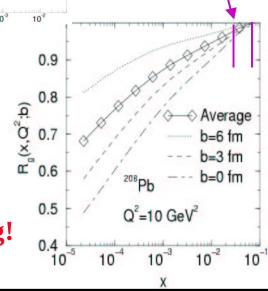
Shadowing at RHIC?

Zheng Huang, Hung Jung Lu, Ina Sarcevic: Nucl.Phys.A637:79-106,1998 (hep-ph/9705250)

quark structure function



Shadowing of structure functions small in RHIC x range!!



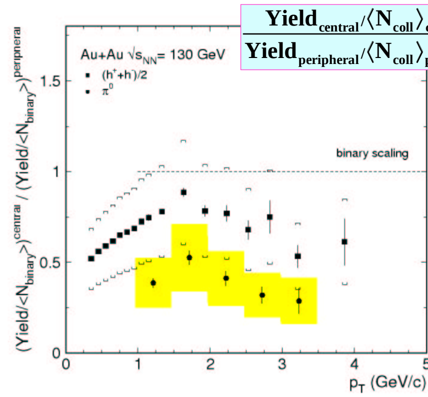
Gluon shadowing should be even less

p_t comparison OK

deficit ≠ shadowing!

Different systematics: peripheral collision reference

$$\frac{\mathrm{Yield}_{central}/\langle N_{coll}\rangle_{central}}{\mathrm{Yield}_{peripheral}/\langle N_{coll}\rangle_{peripheral}}$$

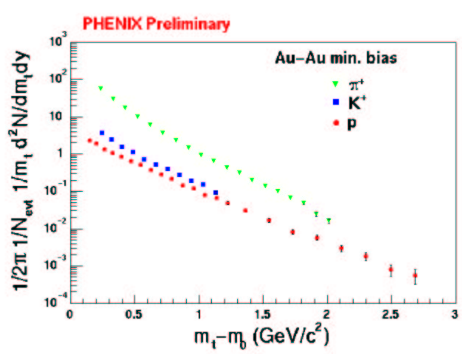


deficit remains

$$\langle N_{binary}\rangle_{central} = 905 \pm 96$$
$$\langle N_{binary}\rangle_{peripheral} = 20 \pm 6$$

is π/h smaller in central vs. peripheral?!

Separate charged hadron spectrum

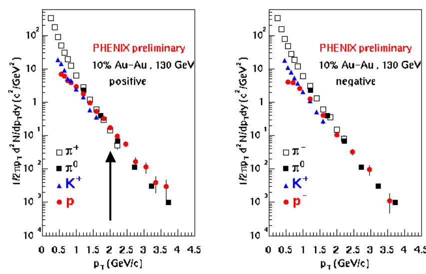


$$m_T^2 = p_T^2 + m_0^2$$

Protons are flatter → velocity boost?
gluon saturation?

Many high p_t baryons!

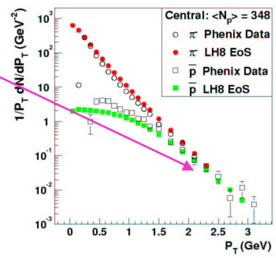
nucl-ex/0203015



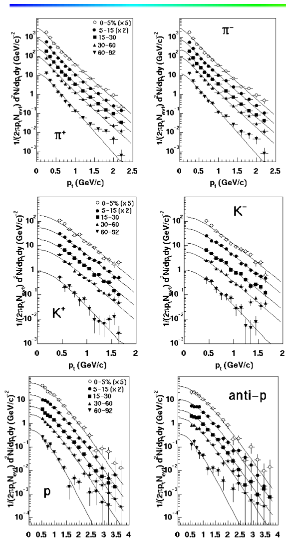
not the expected jet fragmentation function D(z)!

hydrodynamical calculation agrees with data

Teaney, Lauret, Shuryak
nucl-th/01100037

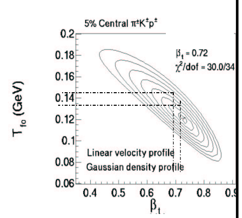


hydrodynamic analysis of spectra



PHENIX Preliminary

Simultaneous fit to m_T-m_0 < 1 Gev/C

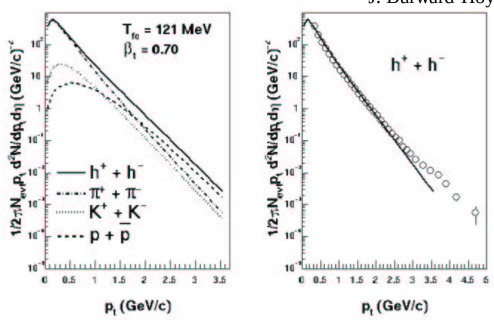


PHENIX Preliminary

T = 122±4 MeV
β_t = 0.72 ±0.01
χ^2/dof = 30.0/40.0

Extrapolate soft component using hydrodynamics

J. Burward-Hoy



Calculate spectra using hydro parameters

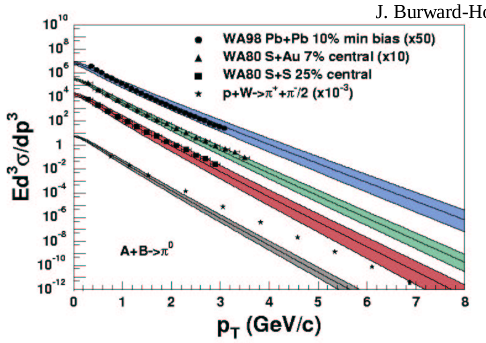
$h^+ + h^- = \Sigma\ \pi, K, p$

Compare sum to measured charged particle p_T spectrum

- Hydrodynamic flow modifies p_t threshold where hard physics starts to dominate
- physics is soft (thermal) until $p_t \geq 3$ GeV/c

Similar hydro analysis at SPS

J. Burward-Hoy



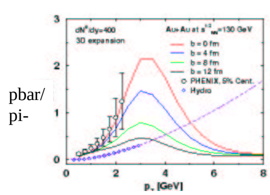
Available data really do not extend to hard regime!
So (at the moment) RHIC owns hard scattering

note

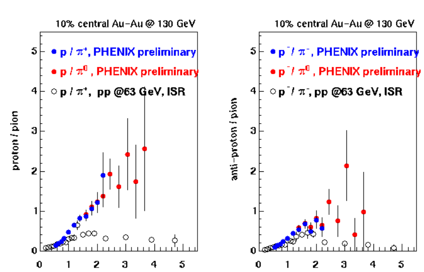
- **Transverse expansion and hydrodynamic flow are not the only possible explanation of the spectra**
- ***~ m_T scaling expected if gluon saturation***
  Schaffner-Bielich, McLerran, et al.
- **This is also a thermal (i.e. soft) effect**
  If it predicts the shape of the spectra, also can be used to define threshold for jets
  conclusion will be ~ similar to that from hydrodynamic extrapolation!

hard/soft boundary is species dependent

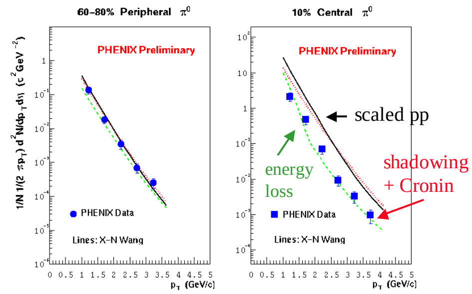
- **hydro boosts baryons to higher pt**
- **Jet quenching should reduce π yield (by ~3-5)**
  baryons less depleted as less likely to be leading particles in fragmenting jet



Vitev & Gyulassy
nucl-th/0104066



Is there energy loss at RHIC?

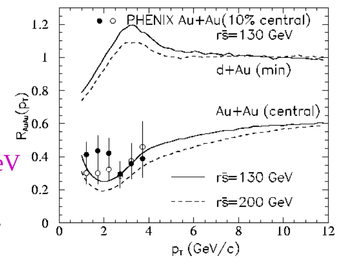


<dE/dx> = 0.25 GeV/fm

but system is not static!

With expansion:
<dE/dx> ~7.3 GeV
At 10 GeV/c

X.N. Wang & E. Wang, hep-ph/0202105

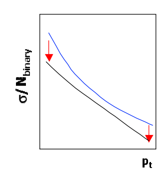


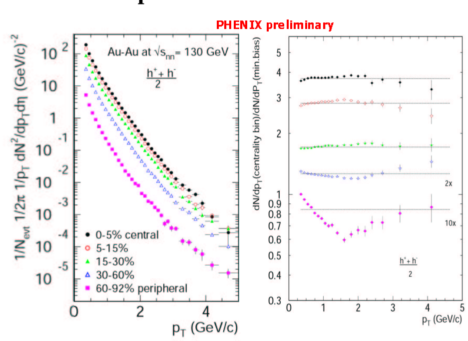
Centrality dependence of spectra

- **See a continuous shape evolution**

  peripheral coll:
  pronounced power law

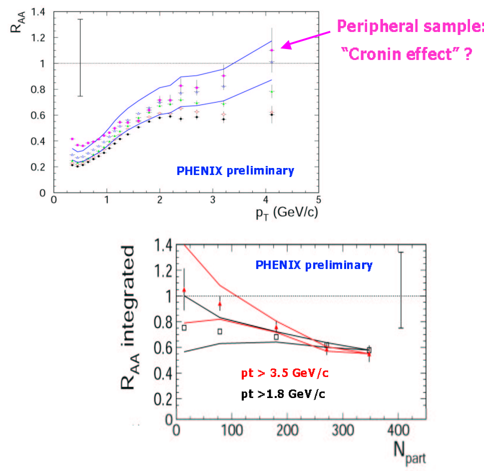
  central collisions:
  spectrum becomes more exponential



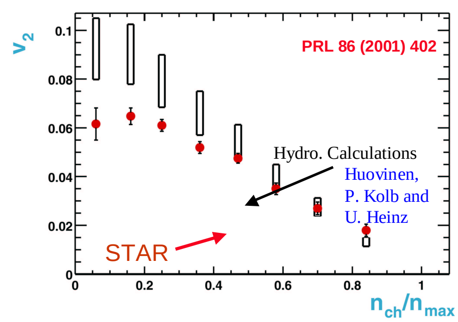


Centrality evolution of R_{AA}

- Deficit of high p_T particles increases gradually with centrality



Insights from correlations



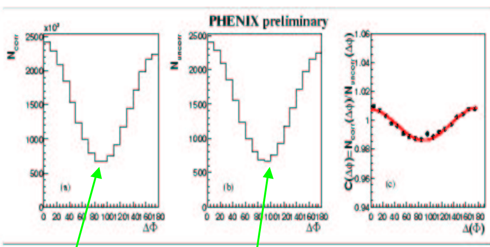
At low p_t v2 measures elliptic flow * → early pressure buildup & equilibration

But at high p_t dominant process changes

* Also measured by PHOBOS, PHENIX

Can also get v_2 from correlations

PHENIX (and PHOBOS) measure correlation function in azimuthal angle



$\Delta\phi$ from same event

$\Delta\phi$ from mixed events

$C(\Delta\phi)$ = ratio

$$dN/d(\Delta\phi) \propto [1 + 2\lambda_1 \cos(\Delta\phi) + 2\lambda_2 \cos(2\Delta\phi)]$$

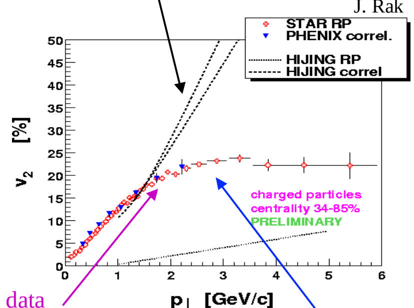
$$\lambda_2 \to v_2$$

Impose p_T threshold & see jet correlations

At high p_T

Correlation method on HIJING picks out back-to-back particles from jets

J. Rak



For data correlation & reaction plane methods agree

Hydrodynamics no longer dominates

jet correlations weak or missing!
Reaction plane results a mystery...

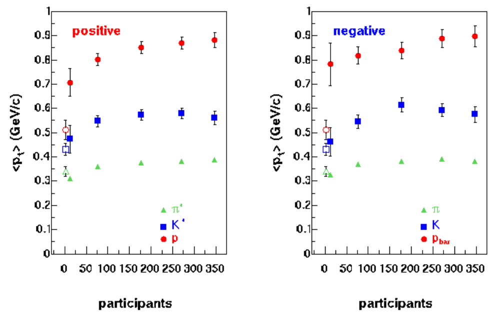
Conclusions

- New behavior at RHIC!
  - Suppression of high p_T particles
    - data are correct, it's not shadowing
  - Large v2 which saturates at high p_T
- Data are consistent with jet quenching
  - Jet-like tail decreases with centrality
  - *Sure looks like jets go away…*
- But p_T range is limited
  - barely out of the soft regime
  - soft regime is extended
    - either by transverse expansion
    - or gluon saturation
- Significant uncertainties in p+p and peripheral reference spectra

So, are jets quenched?

- My personal opinion:
  - *…yes…*
- *But data do not yet offer appropriate standard of proof!*
- Coming this year
  - measured p-p reference spectrum
  - verify jet quenching at higher p_T
  - back-to-back correlations at high p_T
  - near-side correlations
    - (first results in P. Jacobs' talk)
- energy loss vs. no hard scattering: not clear from the data
- Ultimate goal: measure energy transport in the plasma!

<p_t> increases with centrality

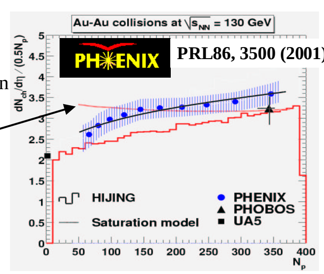


Expect such a trend from radial flow
but also from partonic multiple scattering
and gluon saturation

don't know whether final or initial state effect

Centrality dependence of charged particle production

Aside: it is possible that gluon density sufficient for saturation. EKRT version ruled out by data, but others are consistent...

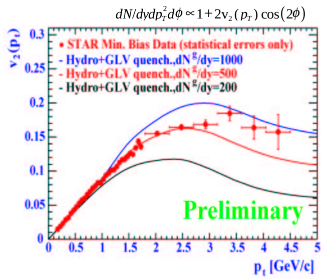


Fit with $dN^{ch}/d\eta|_{\eta=0} = A \times N^{part} + B \times N^{bin}$

Find
A = 0.88 ± 0.28   B = 0.34 ± 0.12
soft: scales with Npart
hard: has an additional component scaling with Ncoll

hard processes are becoming significant!

hard/soft competition as probe

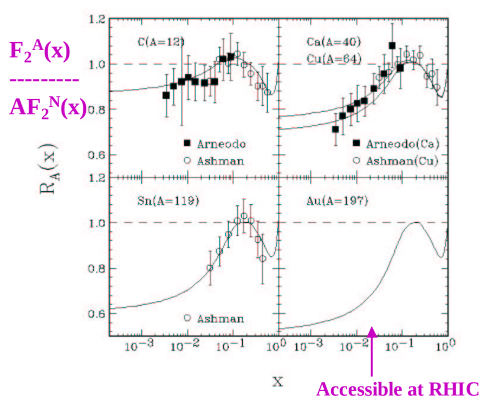


Above p_t ~ 1.5 GeV/c, hydrodynamic flow in the reaction plane has competition from hard processes, which are not correlated with that plane

so look for disappearance of elliptic flow depends on amount of energy loss!

Nuclear effects in initial stage

- **Structure functions are modified in nuclei**
- **Shadowing in small-x region**
  due to high parton density from superposition of all the nucleons



Hydrodynamics-inspired fit

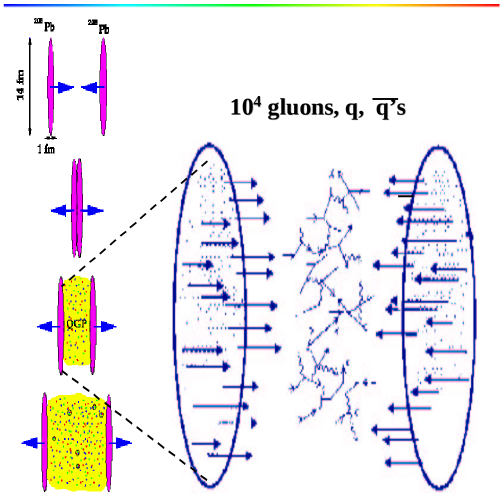
$$\frac{dN}{m_T dm_T} = A\int m_T\, f(\xi) K_1\left(\frac{m_T \cosh(\rho)}{T_{FO}}\right) I_0\left(\frac{p_T \sinh(\rho)}{T_{FO}}\right)\xi d\xi$$

$$\xi = \frac{r}{R};\ \rho = \tanh^{-1}(\beta_s \xi^n)$$

$$\beta_s \equiv SurfaceVelocity$$

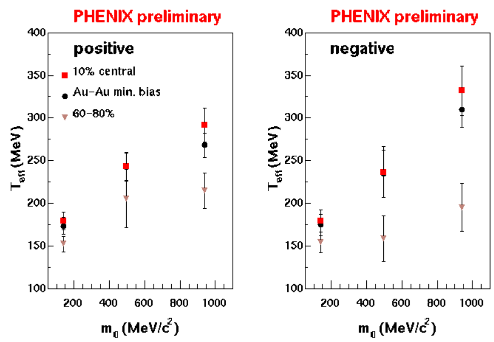
$$T_{FO} \equiv FreezeOutTemperature$$

Hard scattering and collision evolution



Initial collision probability given by nuclear structure functions

Measure radial expansion



$T_{eff} = T_{fo} + m\langle\beta_{radial}\rangle^2$

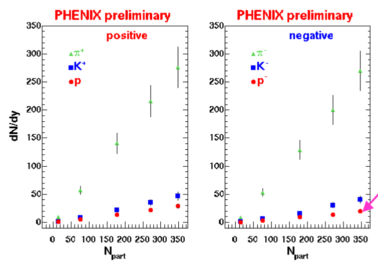
T_{fo} = 140 - 150 MeV

β_{radial} = 0.5 - 0.6 (higher for central collisions)

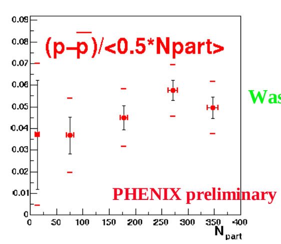
was 0.4 at lower energy

less flow in peripheral collisions!

baryon yields

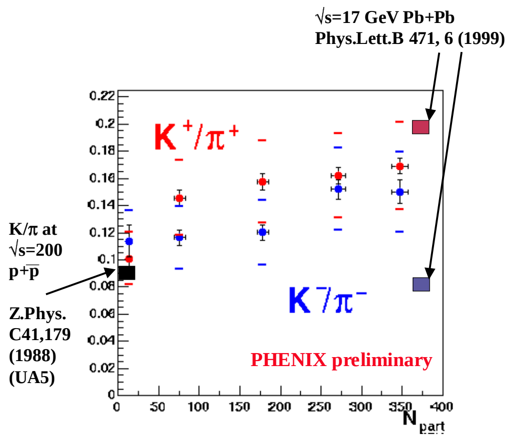


antiproton dN/dy = 20!



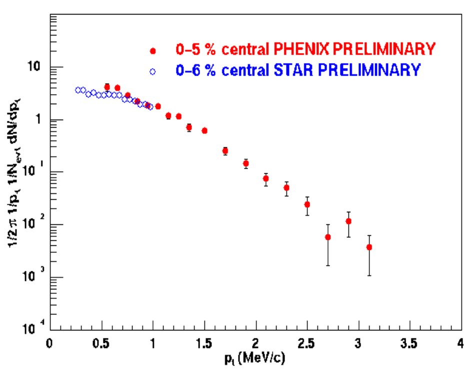
Was 0.18 at SPS

strangeness production



Both K+/π+ and K-/π– increase with Npart
Peripheral collisions near pp value
K+/π+ and K-/π– do not diverge as at SPS,AGS

Compare PHENIX and STAR pbar slopes

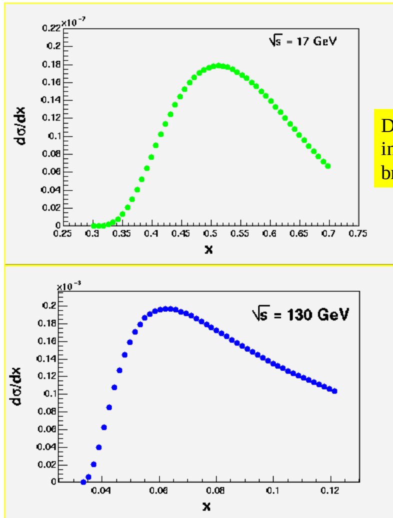


Mt spectra agree, but are NOT exponential
∴ slope depends on where you fit!
Should use better functional form (Boltzmann)
→ radial expansion!

For RHIC and CERN

Thanks to Xin-Nian Wang!

For p_t = 4 GeV/c hadron from jet fragmentation, what is x distribution of parent parton?

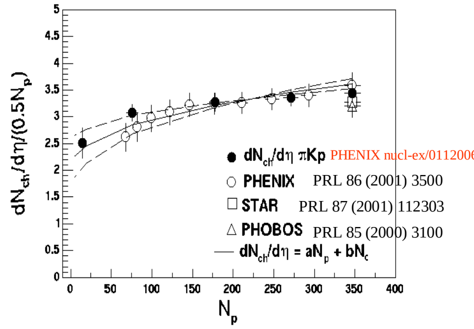


Does not include kt broadening

From Xin-Nian's calculation

- **For CERN energy**
  <z> ~ 0.87
  distribution is fairly symmetric
- **for RHIC**
  peak z ~ 1
  long tail to higher x parent parton
    i.e. tail to smaller z
    estimate with z range 0.7-1.0
- **remake x plot**

charged particle multiplicity



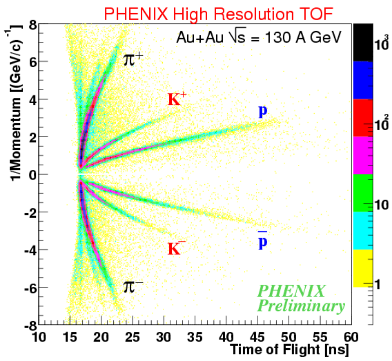
Goal of experiments at RHIC

- **Collide Au + Au ions at high energy**
  130 GeV/nucleon c.m. energy in 2000
  √s = 200 GeV/nucleon in 2001+

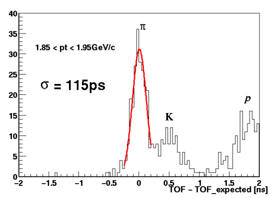
- **Achieve highest possible temperature and density**
  as existed ~1 μsec after the big bang

- **Study the hot, dense matter**
  do the nuclei dissolve into a quark gluon plasma?
  what are its properties?
  energy transport?
  gluon saturation?

Separate charged hadron spectrum



Measure momentum & flight time calculate particle mass



"hard" vs. "soft" processes

- Soft physics : thermal
  - system with T ~ 200 MeV
  - collective flow boosts p_t spectra
- Hard processes
  - happen early
  - create useful probes of the system
    - J/ψ, charm, jets → QGP signals
  - calculable via pQCD
    - sensitive to parton distribution evolution
    - i.e. gluon saturation
- Theoretical tools very different
  - Gyulassy/Wang: boundary 1-2 GeV/c

$$\sigma \quad (s) = \sigma_{jet}(s) + \sigma_{soft}(s)$$

from parton structure functions — from Glauber model

Experimental challenge: constrain which to be used where!