The core-corona model

or

Is the Centrality Dependence of Observables in ultrarelativistic Heavy Ion Collisions more than a Core-Corona Effect?

inspired by the first multiplicity results in CuCu
motivated first to explain strangeness enhancement
then used to extract the physics of EPOS simulations
finally compared to all available observables

- Multiplicities
- $\langle p^i_t \rangle$, elliptic flow v_2 (v_2^i)
- spectra of identified particles

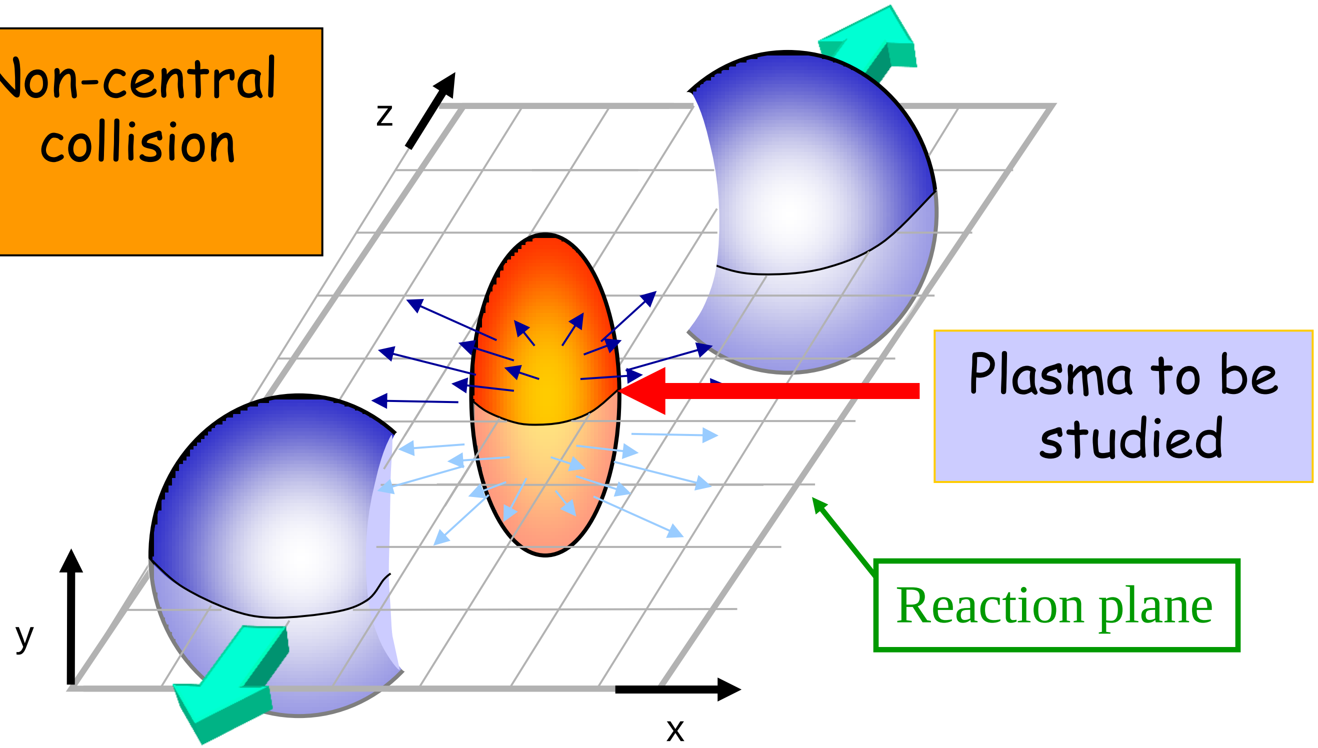
-> interior of neutron starts, early univerese

Precursors: droplet model (Werner+Aichelin), Manninen+Becattini...

in collaboration with C. Schreiber M. Gemard and K. Werner

Geometry of a Heavy-Ion Collision

Non-central collision

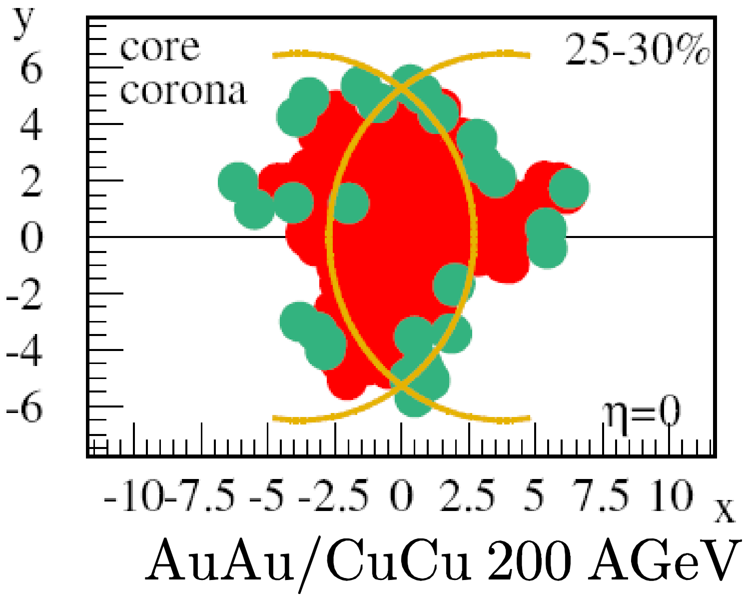


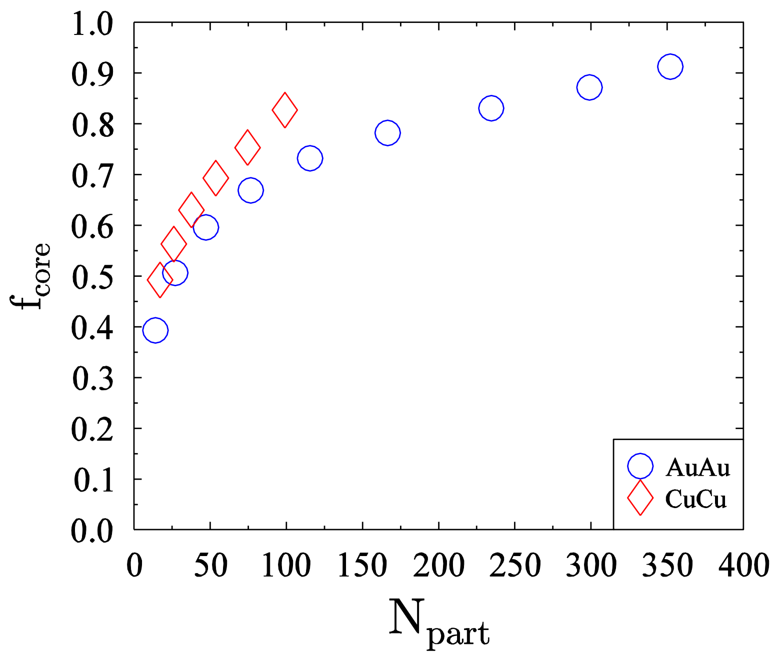
Number of participants (Npart): number of incoming nucleons (participants) in the overlap region

In equilibrium:

Multipl / Npart =const,
independent of b and hadrons species
Experimentally not seen

Centrality Dependence of Hadron Multiplicities





In reality more complicated (EPOS)
-shape fluctuations, finite particle number
-some of the participants scatter only once (cannot equilibrate)
→separation of core and corona

Core – corona model

Assumption:
Nucleons with 1 initial coll: corona
Nucleons with more: core

Calculated in Glauber Model

Basic assumptions:

Core nucleons equilibrate completely

Corona nucleons fragment like nucleons in pp collisions

In the measured momentum range core and corona nucleons do not interact
-> EPOS

Measured multiplicities, $\langle p_t \rangle$, v_2, spectra are superpositions of core and corona with a rel. fraction given by geometry

M^i (Npart) follows a very simple law:

$$M^i(N_{\text{part}}) = N_{\text{part}}\left[f(N_{\text{core}}) \cdot M^i_{\text{core}} + (1 - f(N_{\text{core}})) \cdot M^i_{\text{corona}}\right]$$

$$M^i_{\text{corona}} = \frac{1}{2}\frac{dn^i}{dy}|^{pp}_{y=0}$$

$$M^i_{\text{core}} = \frac{1}{N_{\text{part}}}\frac{dn^i}{dy}|_{y=0} \text{ from stat. model or most central HI collision}$$

$$1 - f(N_{\text{core}}) = \text{fraction of nucleons which have scattered only once}$$

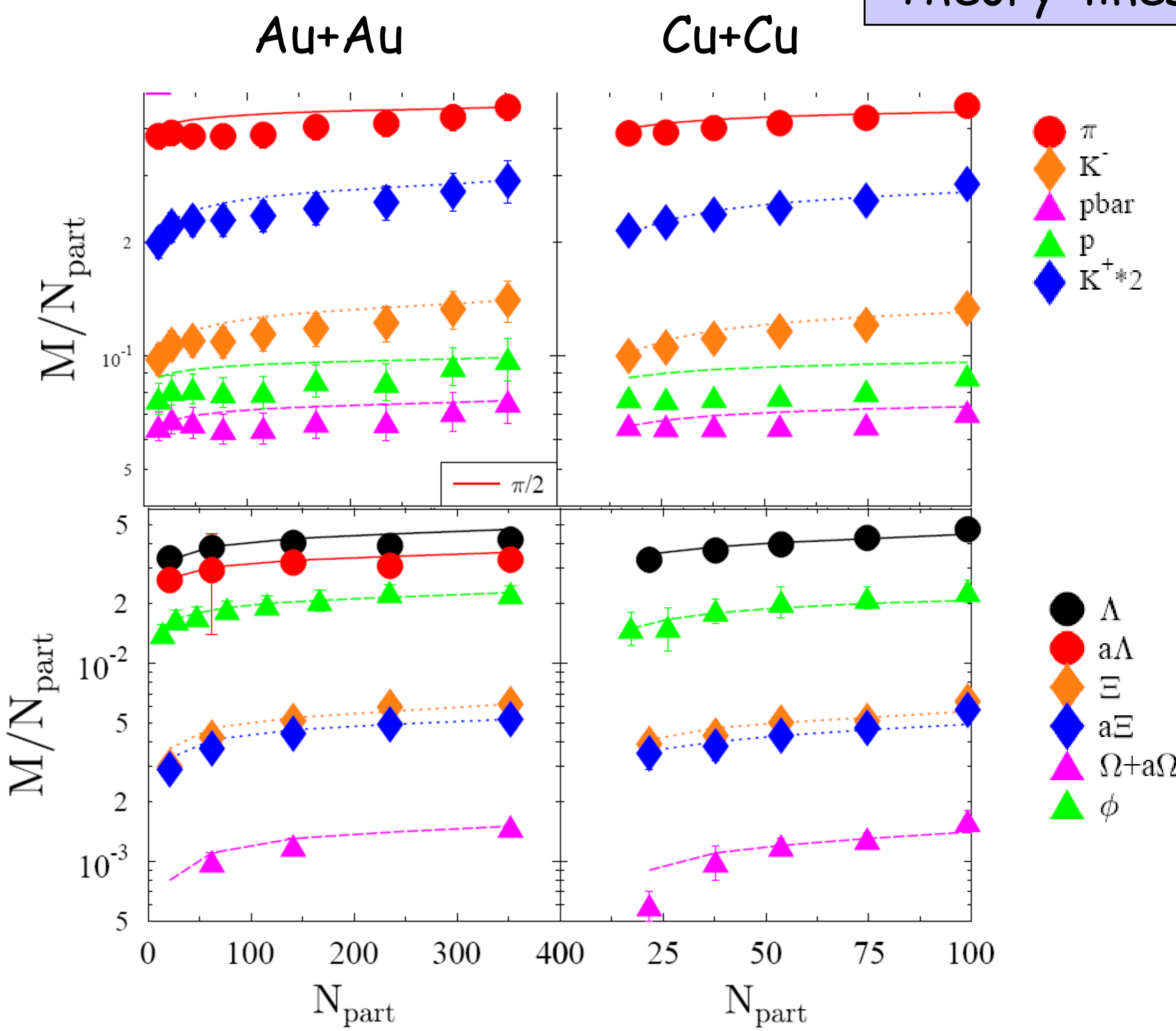
$$(\rightarrow \text{Glauber})$$

Calculation for Cu+Cu without any further input

Phys.Rev.C79:064907

200 AGeV

Theory=lines



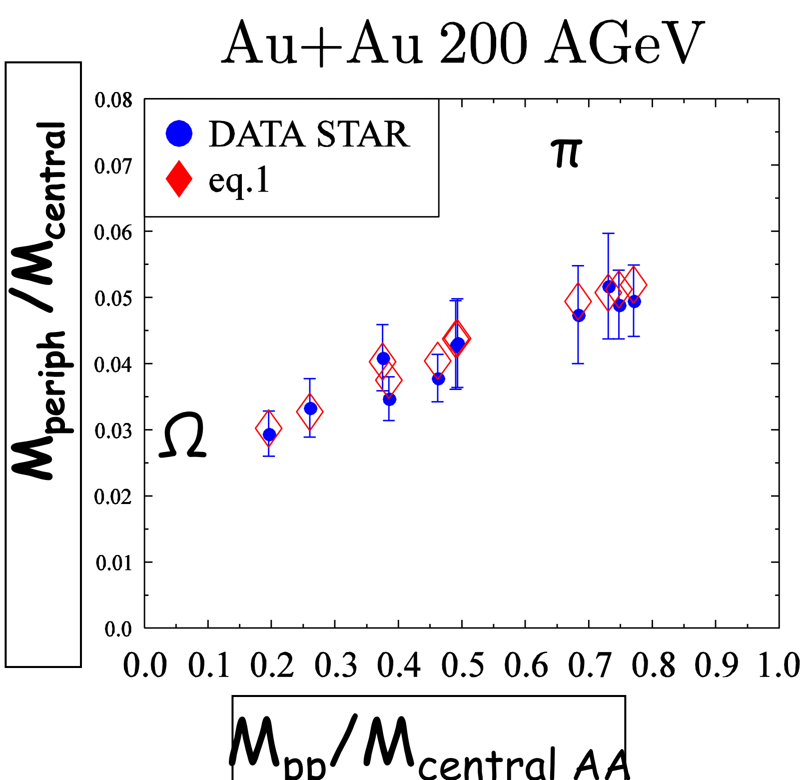
works for
non strange
and for
strange
hadrons
at 200
(and 62 and
17.3) AGeV

Cu+Cu: completely predicted from Au+Au and pp

Further confirmation of the core-corona effect

strong correlation between multiplicity ratios
peripheral/central and pp/central
for all hadrons (strange and non-strange)

Such a correlation is neither expected in statistical nor in hydro models

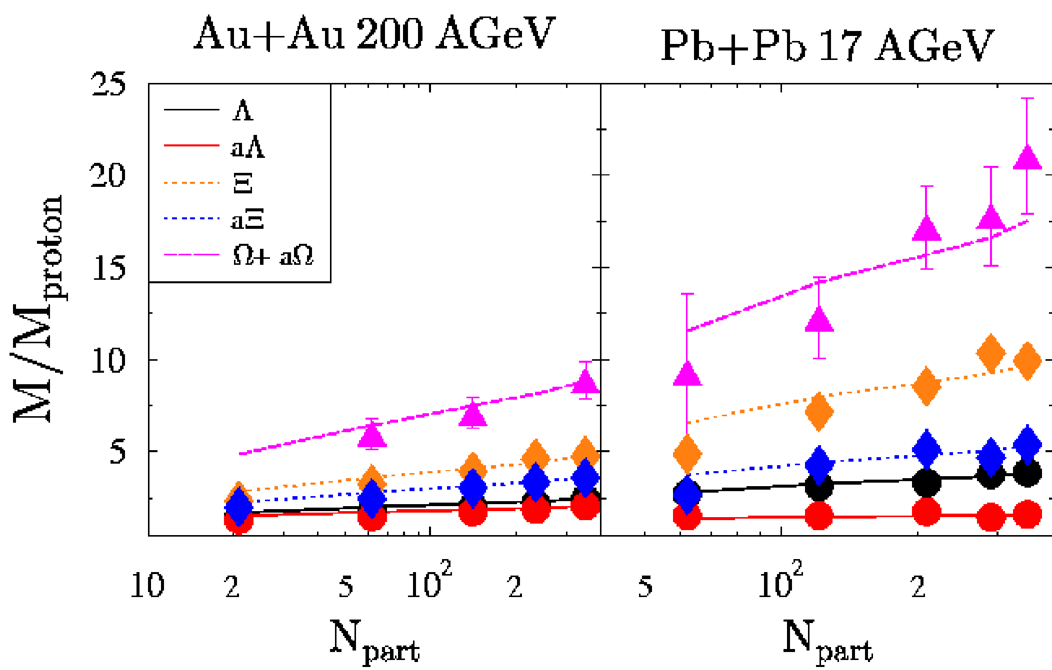


Core-Corona Model reproduces quantitatively this correlation

This model explains among other things

STRANGENESS ENHANCEMENT

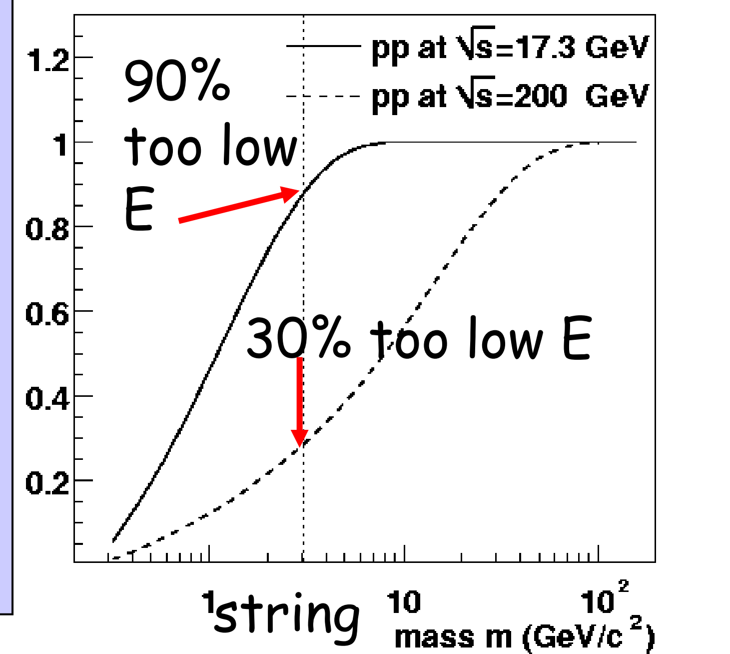
in particular that the enhancement at SPS is larger than at RHIC



Strangeness enhancement in HI is in reality strangeness suppression in pp

Fraction of strings with $E<2m_\Omega$

PRD 65, 057501 (2002)



- Central M^i / N_{part} same in Cu+Cu and Au+Au (pure core)
- very peripheral same in Cu+Cu and Au+Au (pp)
  → increase with N_{part} stronger in Cu+Cu

- all particle species follow the same law

  → Φ is nothing special (the strangeness content is not considered in this model)
  → Strangeness enhancement is in reality strangeness suppression in pp (core follows stat model predictions)

- works for very peripheral reactions (N_{core} =25). The formation of a possible new state is not size dependent

Light hadrons insensitive to properties of matter prior to freeze out

Dynamical Variables

Can we go further and investigate also kinematical variables like $\langle p_T(N_{part})\rangle$, $v_2(N_{part})$ or even single particle spectra ?

Yes, if we make an additional (strong) assumption:

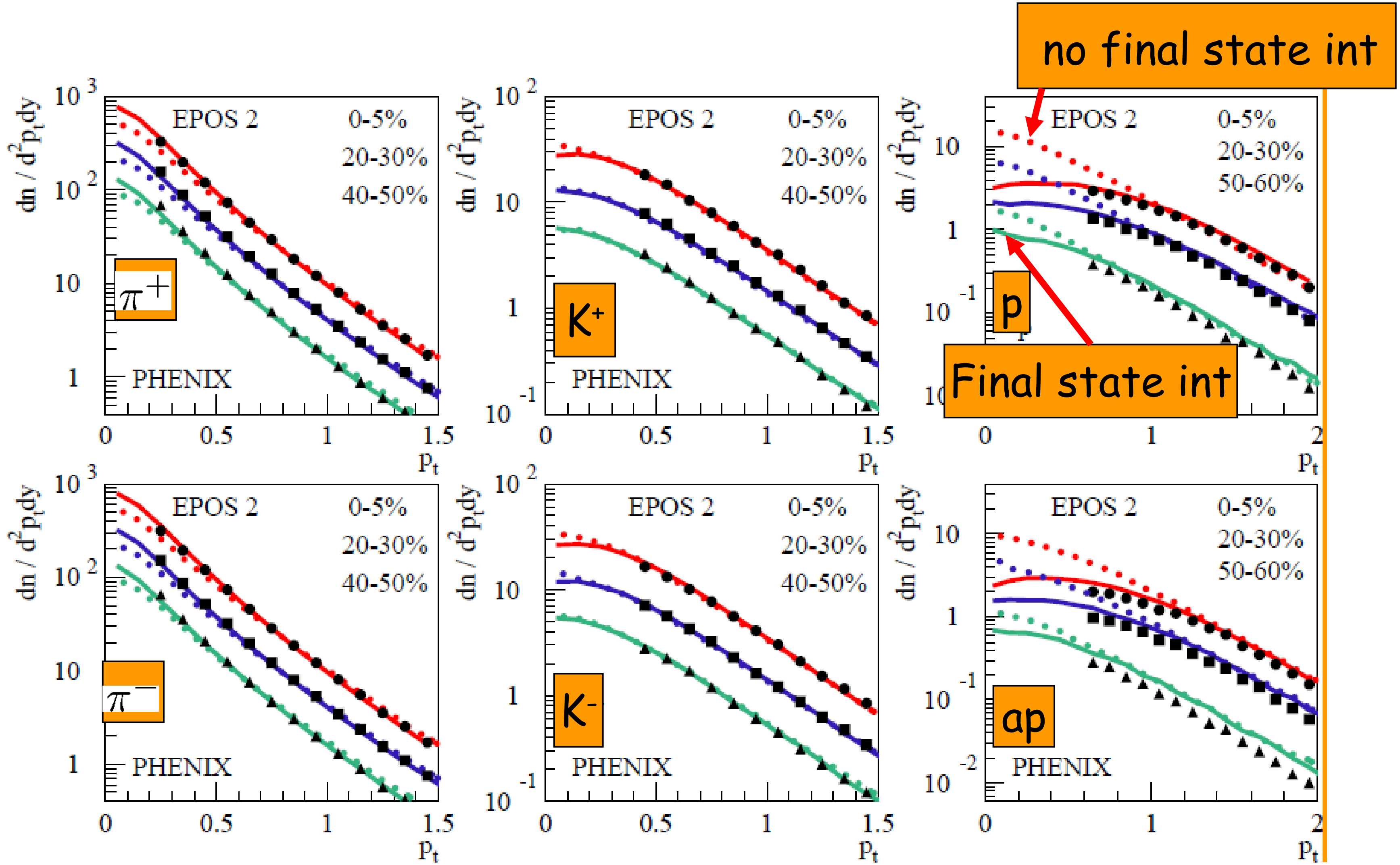
$\langle p_T \rangle$ of corona hadrons depends on the particle type.
Therefore interactions among corona hadrons change their momentum

$\langle p_T \rangle$ is different for corona and core hadrons
Therefore interactions between core and corona hadrons change their momentum

If the core corona model works:
improbable that core hadrons interact with corona hadrons

EPOS gives evidence that this is indeed the scenario.

Is this compatible with event generator results?



Yes, there is final state interaction but only at low p_T where no data exist

$v_2 =< \frac{px^2-py^2}{px^2+py^2} >$ as a function of centrality has a long history

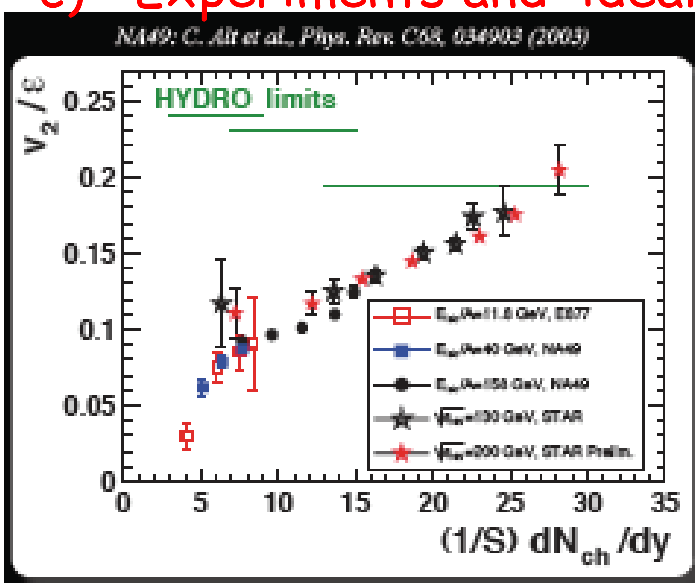
a) In ideal hydrodynamics:

v_2/ε ($\epsilon = \frac{x^2-y^2}{x^2+y^2}$ eccentricity in coordinate space) is independent of the geometry if v_2 is caused by ε

b) All RHIC and SPS data points (for heavy systems) fall on a common line if plotted as: v_2/ε as a fct of 1/SdN/dy

1/S dN/dy = measures the particle density

c) Experiments and ideal hydro results do not agree



Snellings QM09

Hydrodynamics describes many features in central collisions

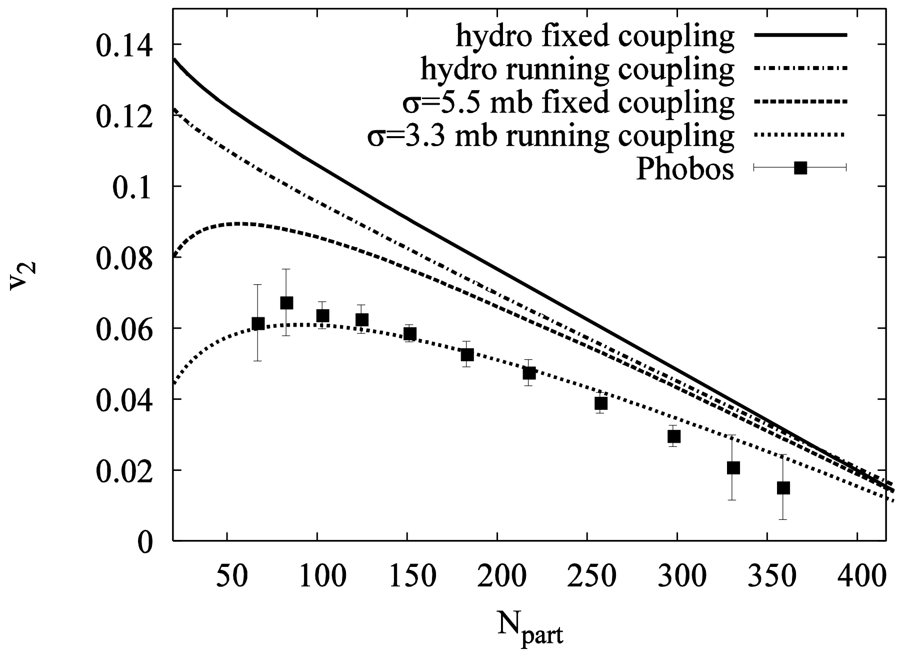
therefore

Centrality dependence points toward the need of viscous hydro (which in the limit of large dN/dy agrees with ideal hydrodynamics)

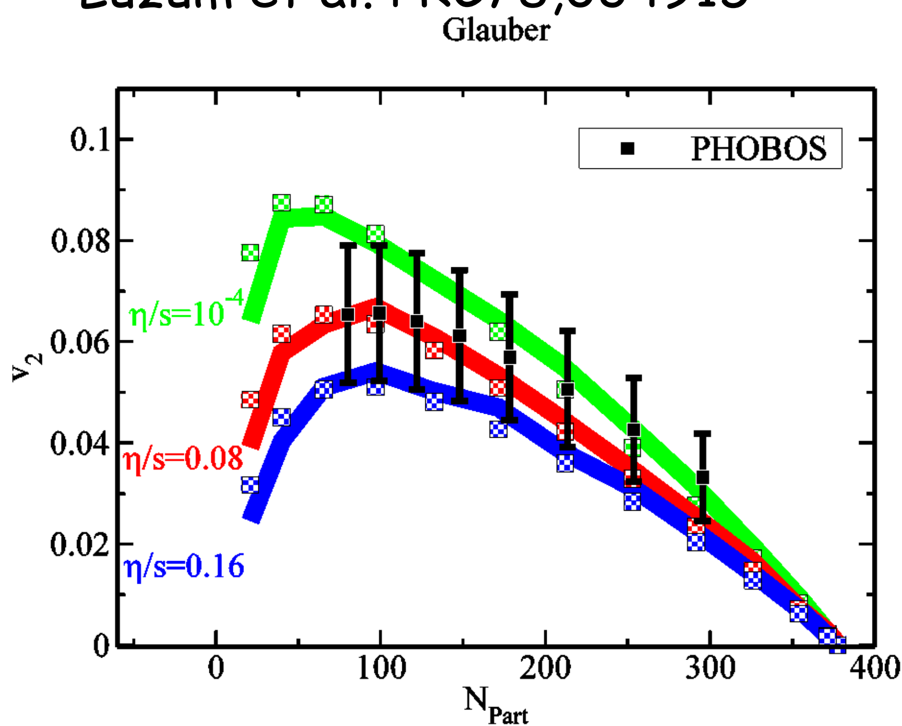
Viscous Hydro fits the viscosity to the centrality dependence of v_2

The other way around: Centrality dependence of v_2 allows for the determination of the viscosity

Drescher et al. PRC76,024905

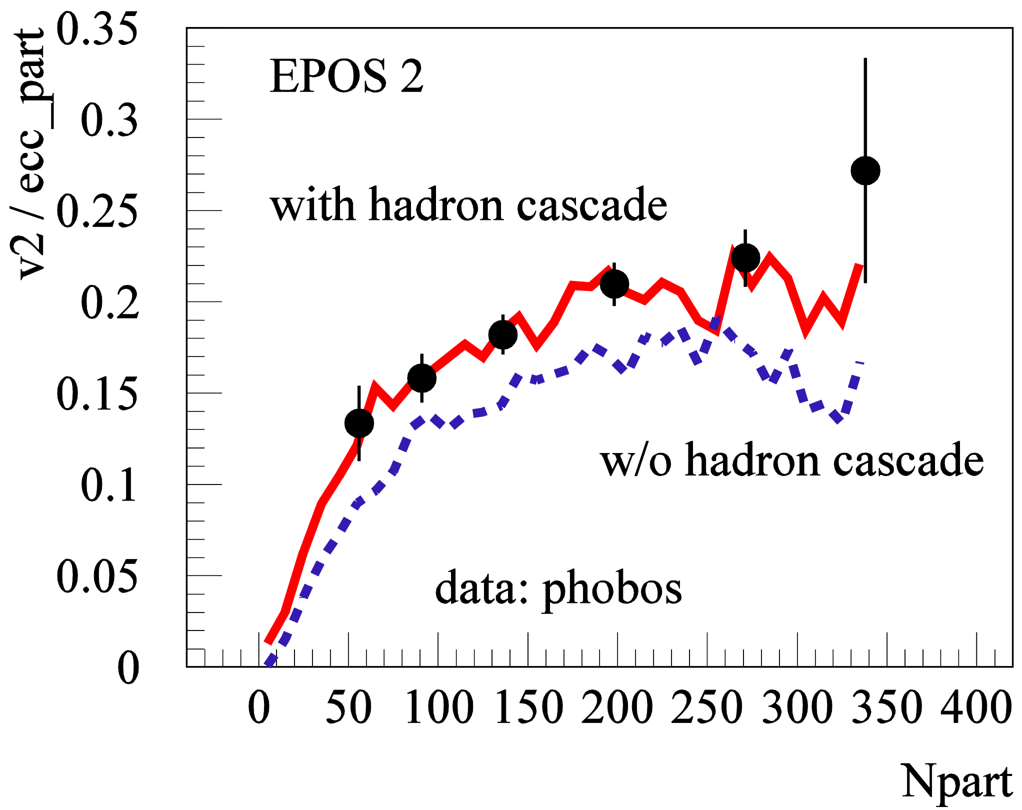


Luzum et al. PRC78,034915



BUT

EPOS: Ideal hydro describes the data if core- corona is taken into account



viscosity and core-corona give about the same effect

Surprising?

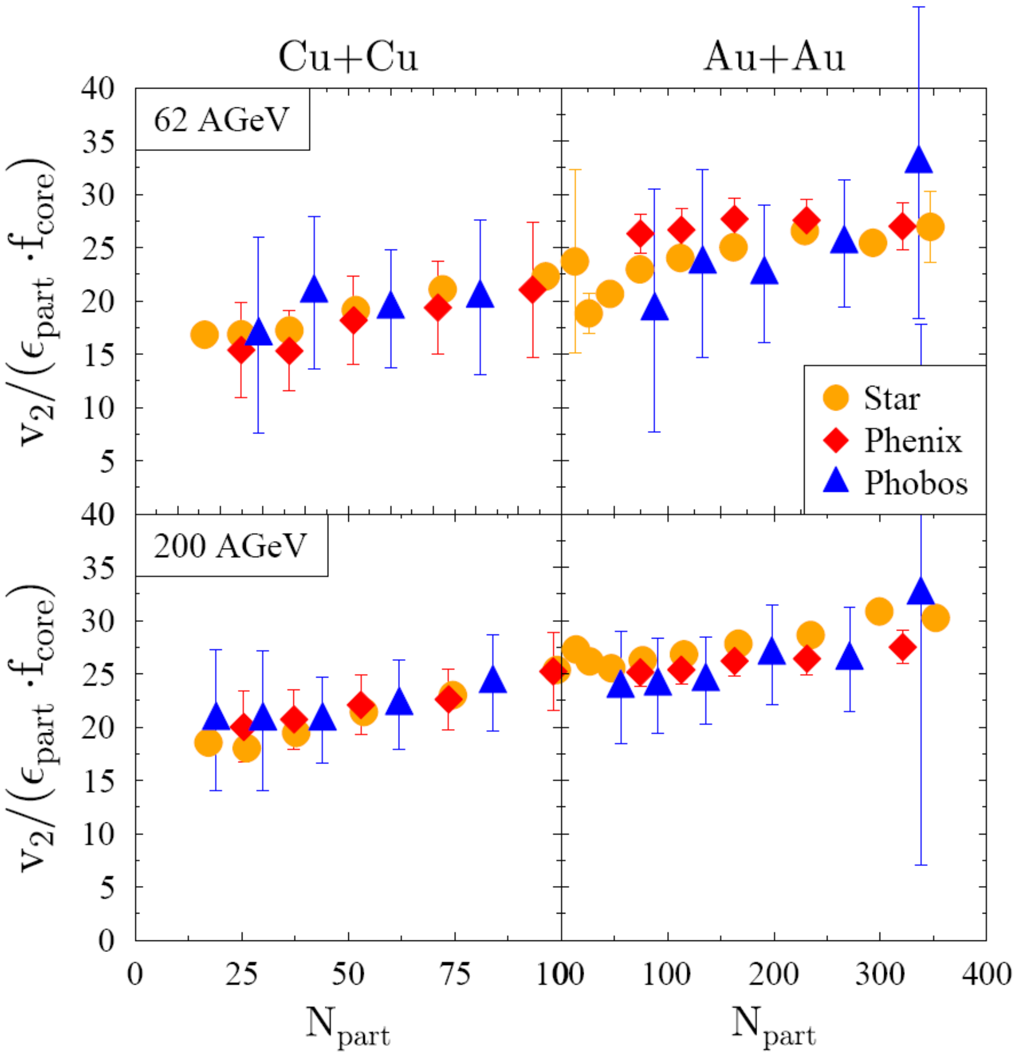
Not really

Hydrodynamics: core and corona particles are treated the same way: the fact that corona particles are not in equilirium with the rest is therefore expressed as viscosity

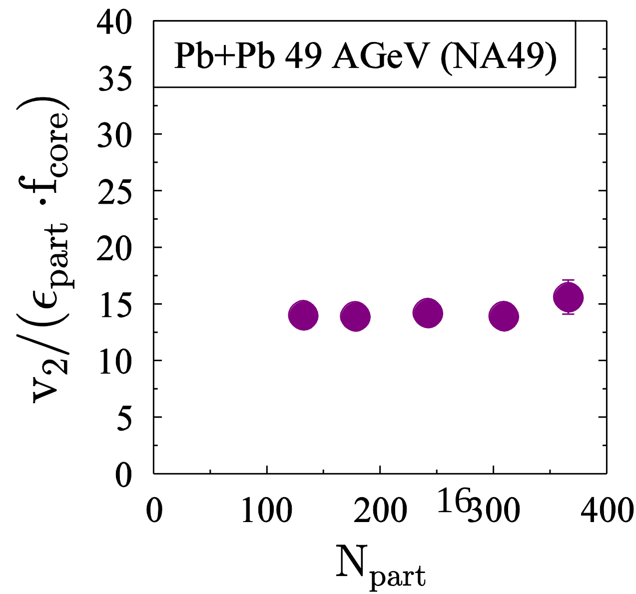
Core-corona:
Core in complete equilibrium
Corona like in pp.
Non equilibrium effect comes from mixture of two components, depends on centrality

Core-corona model: Only core particles develop elliptic flow
(corona part. fragment like pp)

$v_2/\varepsilon(N_{part}) = (v_2/\varepsilon)^{ideal\ hydro}\ f_{core}(N_{part})$



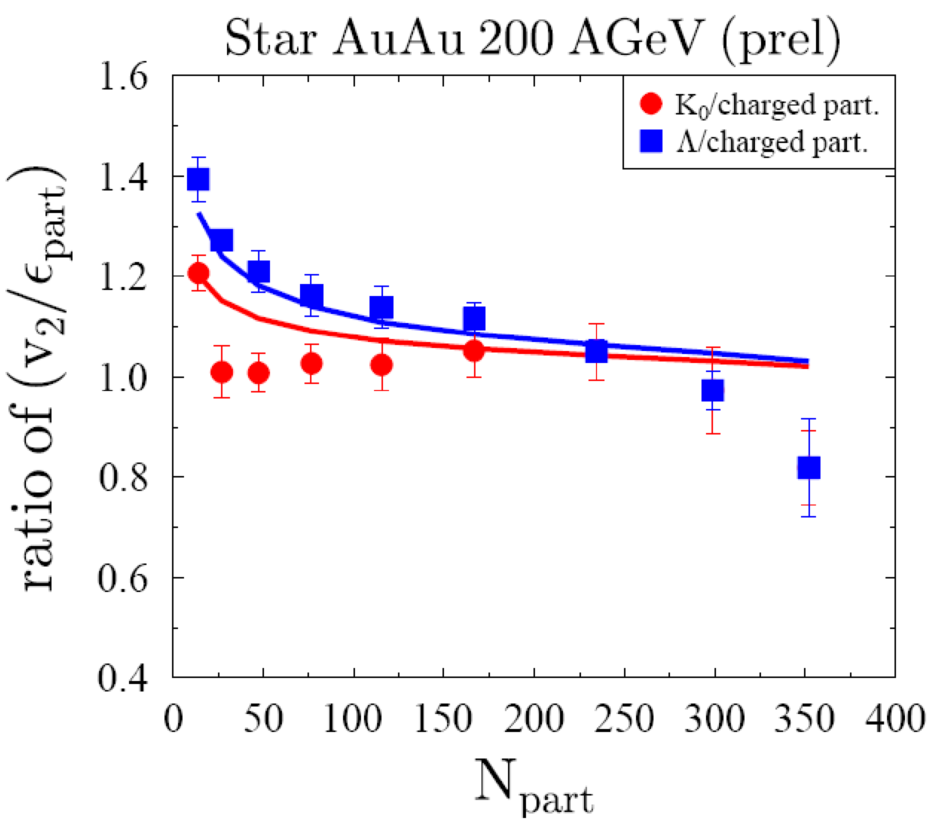
All data compatible with a straight line and hence with the core-corona assumption
No free parameter (viscosity)



Possibility to distinguish between viscosity and core-corona?

v_2 of identified particles:
Ratio of v_2 dependents multiplicity of identified part. on b
Ratio of v_2 in hydro not

Less corona particles -> v_2 larger



Up to now analysis done for two particles:

Good agreement for Λ
less good for K_0

Deviation at central collision not understood

more data needed

What is the difference between

Viscous hydro	core-corona

no surface effects

Time evolution of all particles identical with finite viscosity

v_2/ε depends on centrality via (Drescher & Ollitrault PRC76, 024905)

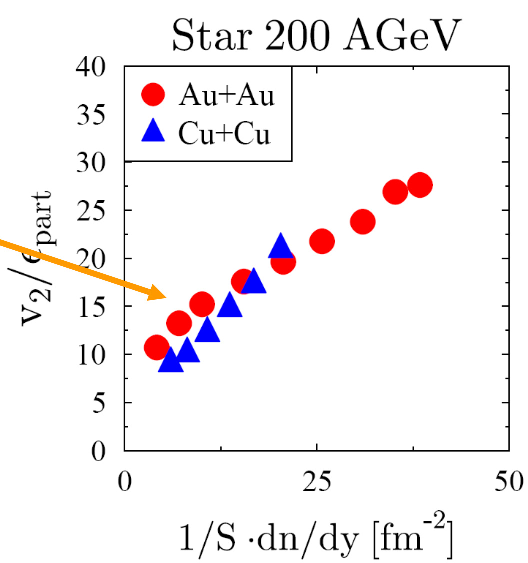
$$\frac{v_2}{\epsilon}(N_{part}) = \frac{v_2^{hydro}}{\epsilon}\frac{1}{1+\frac{K(N_{part})}{K_0}}$$

$$\frac{1}{K} = \frac{\sigma}{S}\frac{dN}{dy}c_s(E_{beam})$$

Parameters:
$(v_2/\varepsilon)^{hydro}$
K_0
c_s (E_{beam})

Distinction between surface and core (critical energy dens.)
core = ideal hydro (visc = 0)
corona = pp

$$\frac{v_2}{\epsilon}(N_{part}) = f_{core}\frac{v_2^{hydro}}{\epsilon}$$



Parameters:
$(v_2/\varepsilon)^{hydro}$
(f_{core} same as for multiplicities or $\langle p_t \rangle$)

Average p_T

$$\langle p_T \rangle = f^i_{core}(Npart)\langle p_T\rangle_{core} + (1-f^i_{core}(Npart))\langle p_T\rangle_{corona}$$

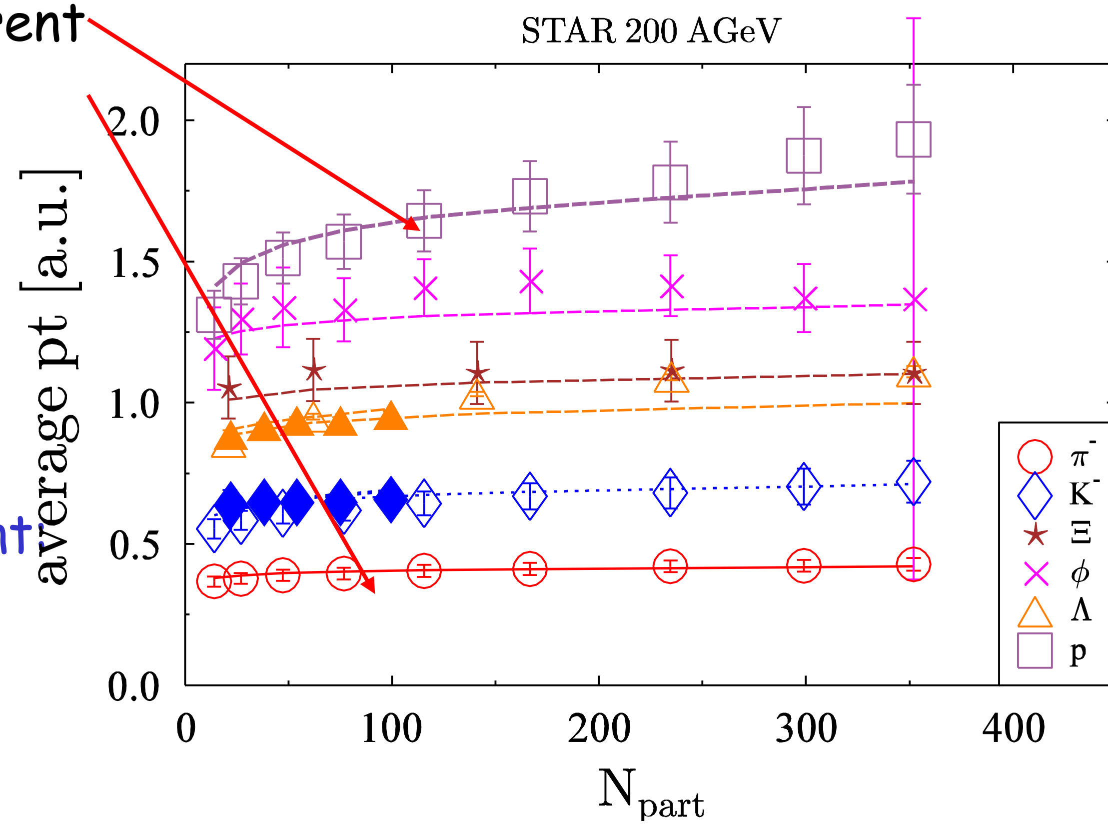
Strong dependence

For p $\langle p_T\rangle_{pp}$ and $\langle p_T\rangle_{central}$ different
For π $\langle p_T\rangle_{pp}$ similar to $\langle p_T\rangle_{central}$
K^+ in between

$\langle p_t\rangle_{exp}$ also
reproduced by core-corona

Centrality dep. of
$\langle p_T(\Phi)\rangle$ and $\langle p_T(p)\rangle$ very different

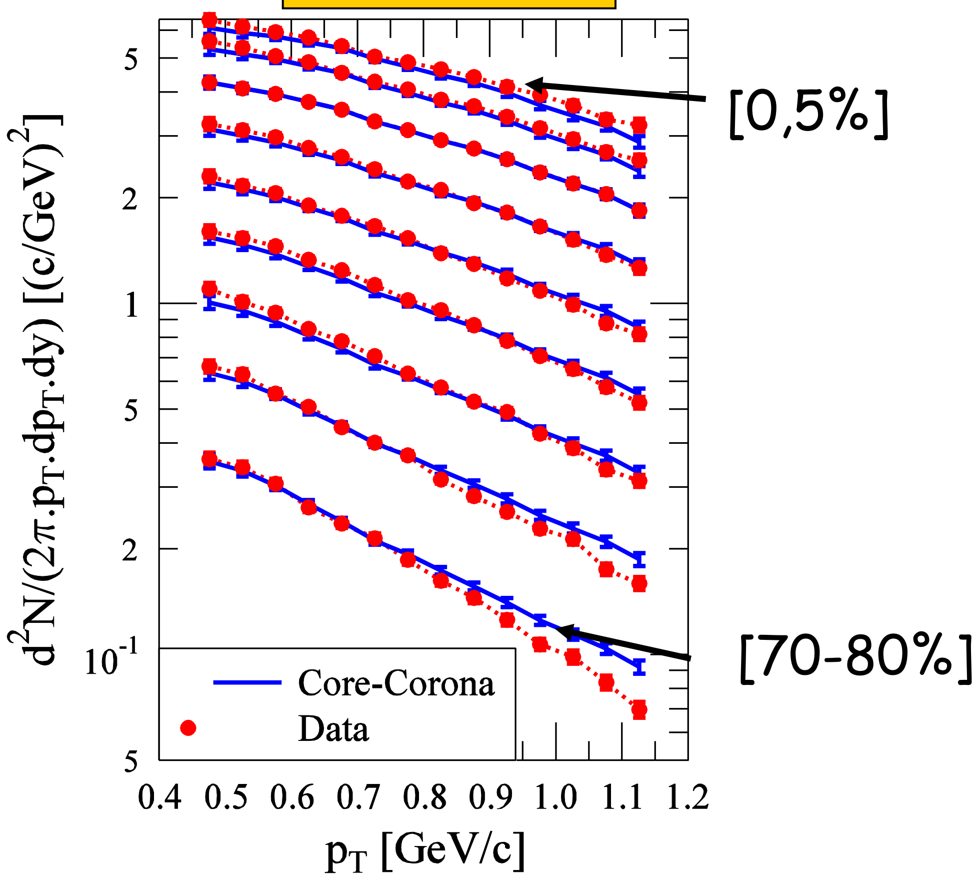
Centrality dep. of
$\langle p_T\rangle$ due to core-corona and
not necessarily due to
collective flow



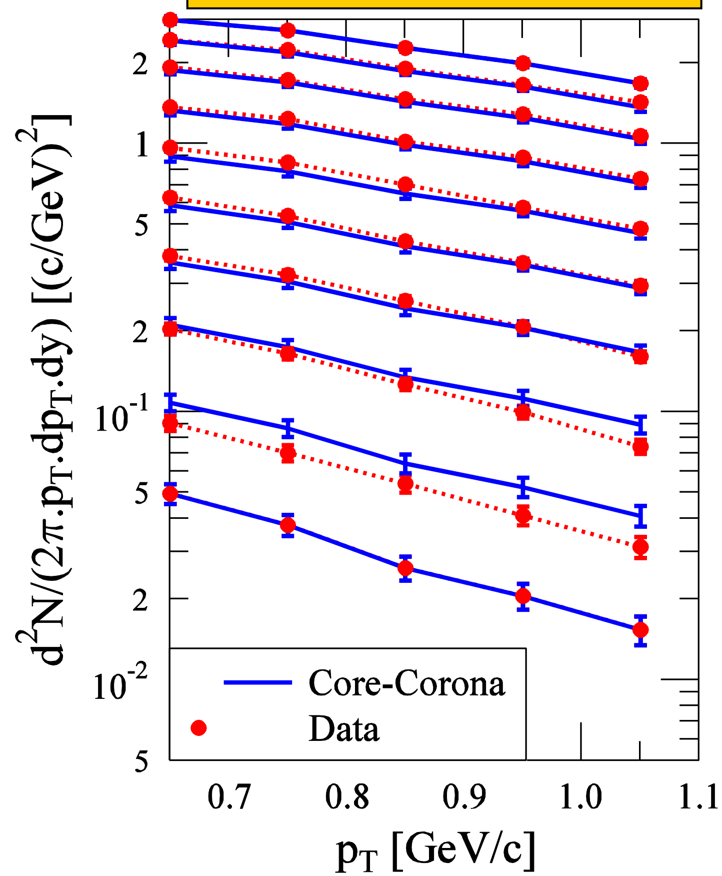
Single particle spectra (protons)

$$\frac{d^2N}{p_t dp_t dy}(N_{part}) = f^i_{core}(N_{part})\frac{d^2N}{p_t dp_t dy}|_{core} + (1 - f^i_{core})\frac{d^2N}{p_t dp_t dy}|_{pp}$$

STAR

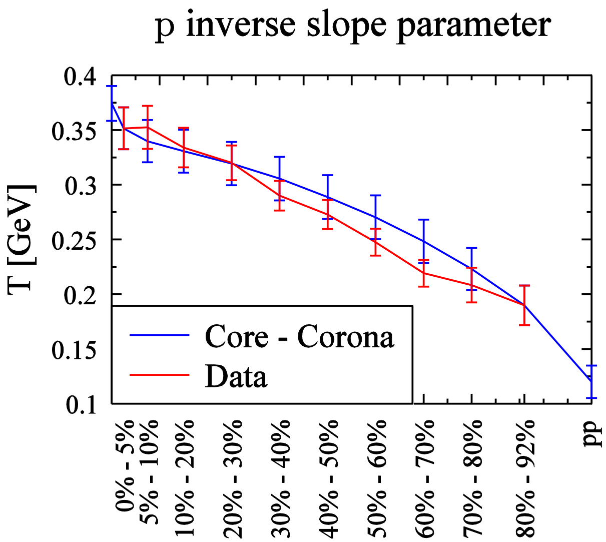


PHENIX

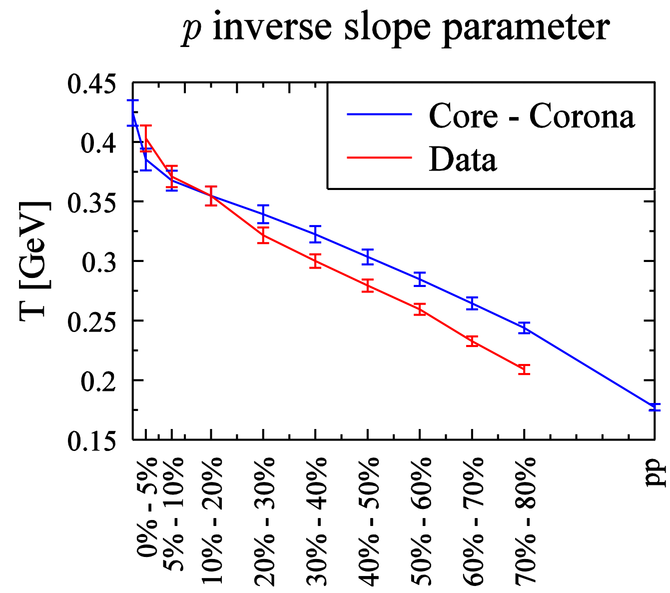


Core-corona agrees almost within errorbars with exp spectra

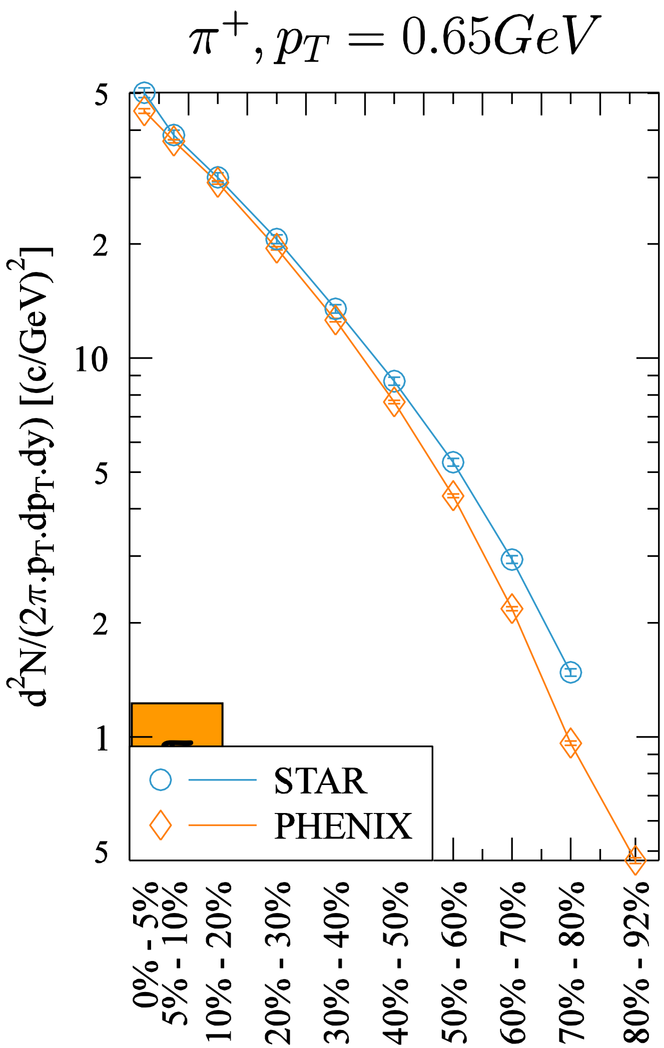
STAR



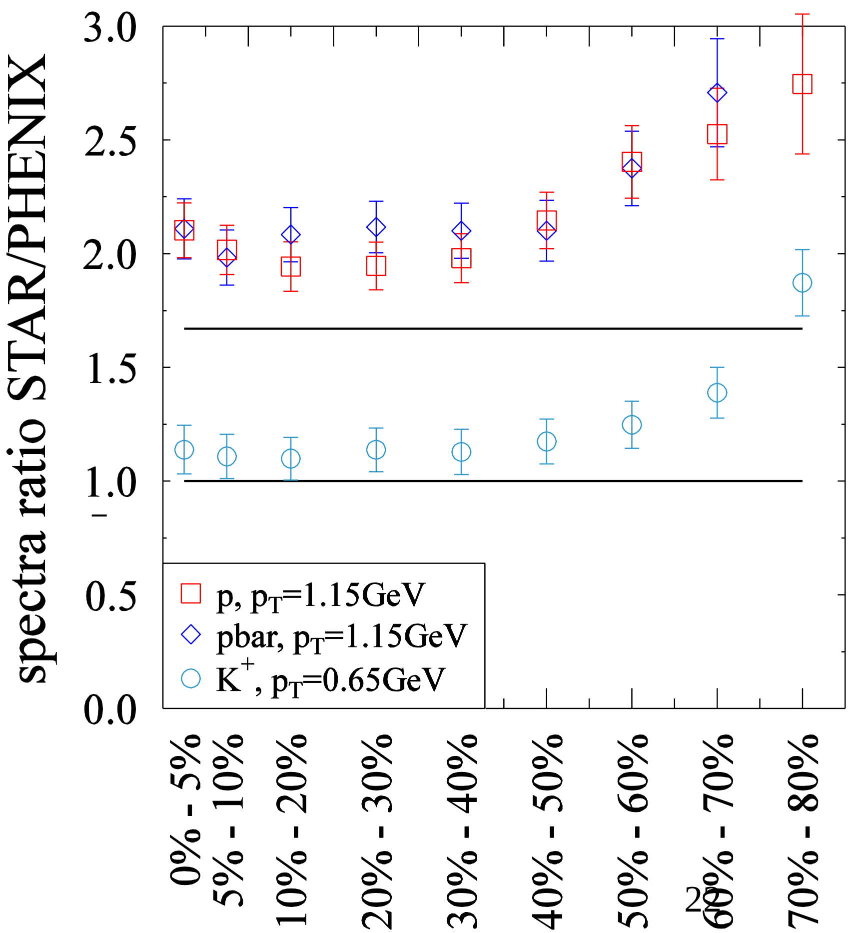
PHENIX



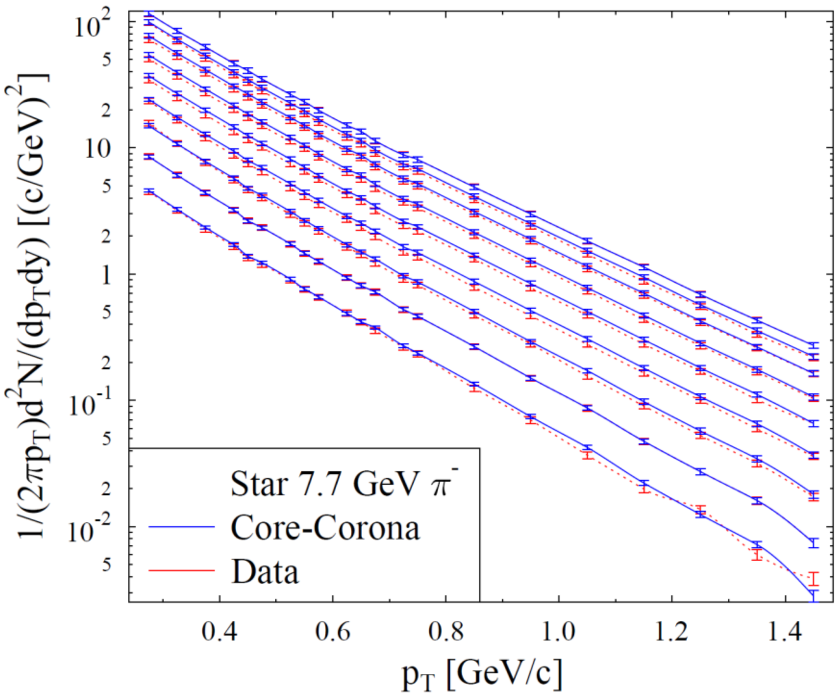
Not at all trivial: slope chance by a factor of 2 from central -> peripheral



STAR and PHENIX data do not agree
Therefore the core and corona parameters are different



Hopefully task force finds a solution



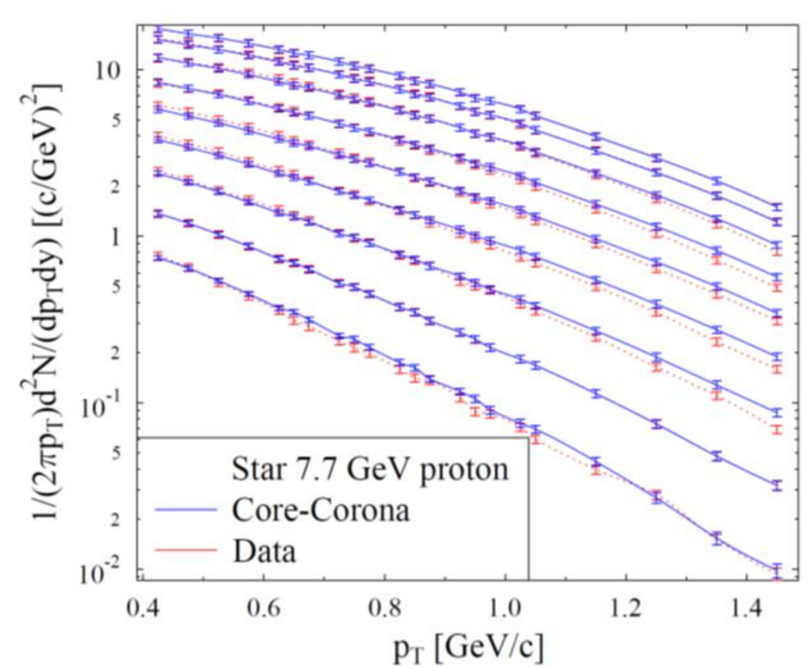
.and at other energies:

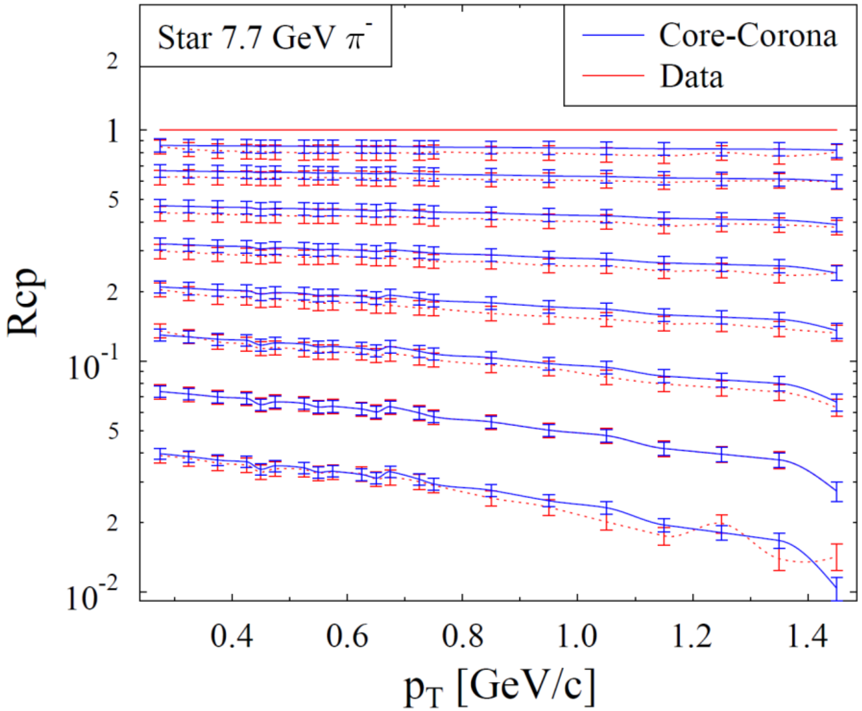
Star energy scan data 7.7 GeV

most peripheral bin replaces spectrum in pp

To take just two particles:

π^- and proton: well reproduced





Physics content best visible by

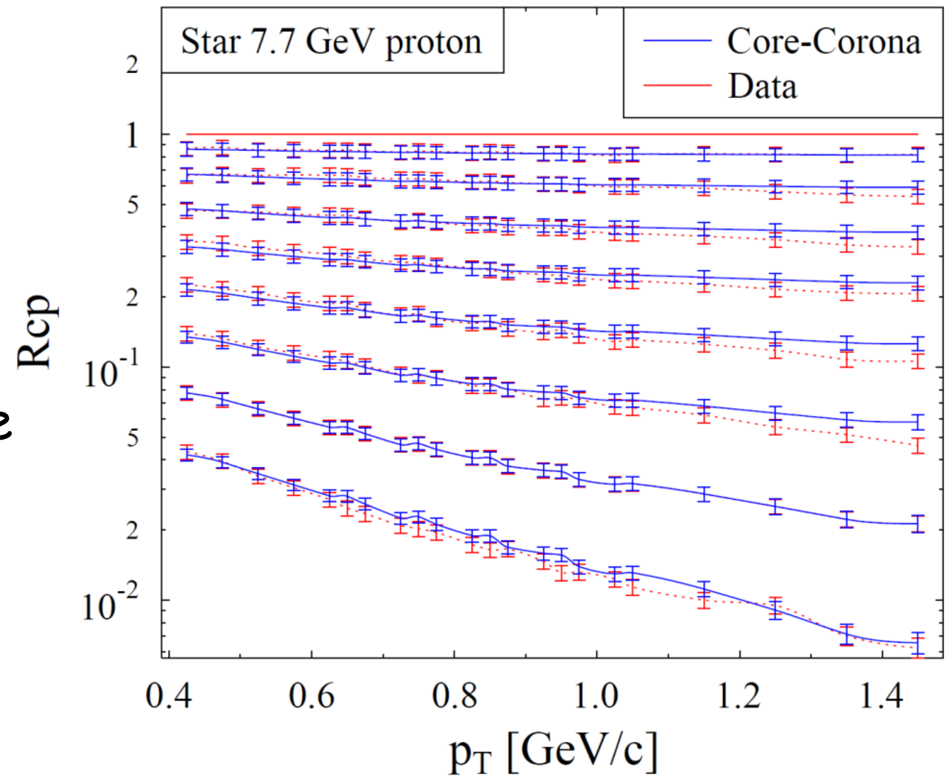
R_{cp} = division of the spectra by the most central spectra

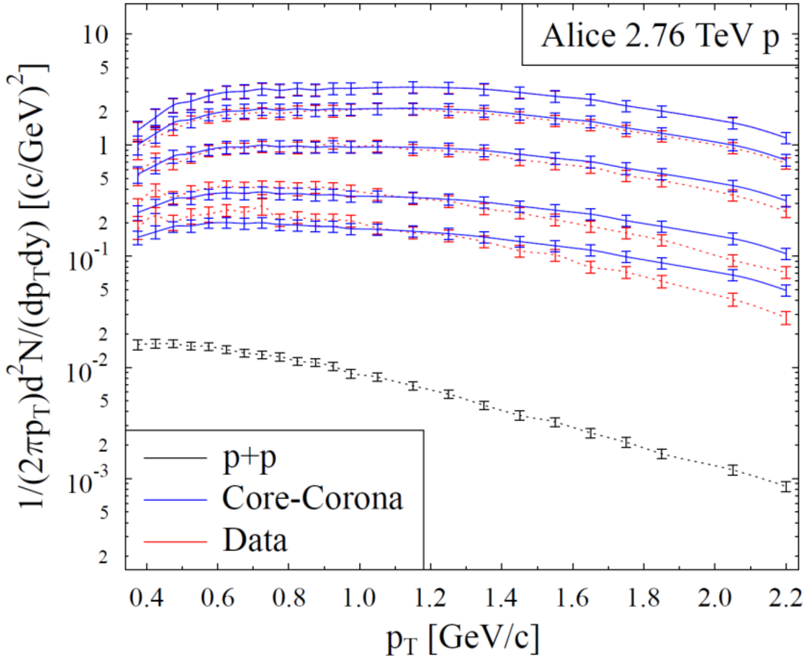
Changes of the slopes become visible

R_{cp} (p_T) well reproduced for all centrality bins.

R_{cp} (p_T) specific to the particle type:

π factor of three
p factor of 10



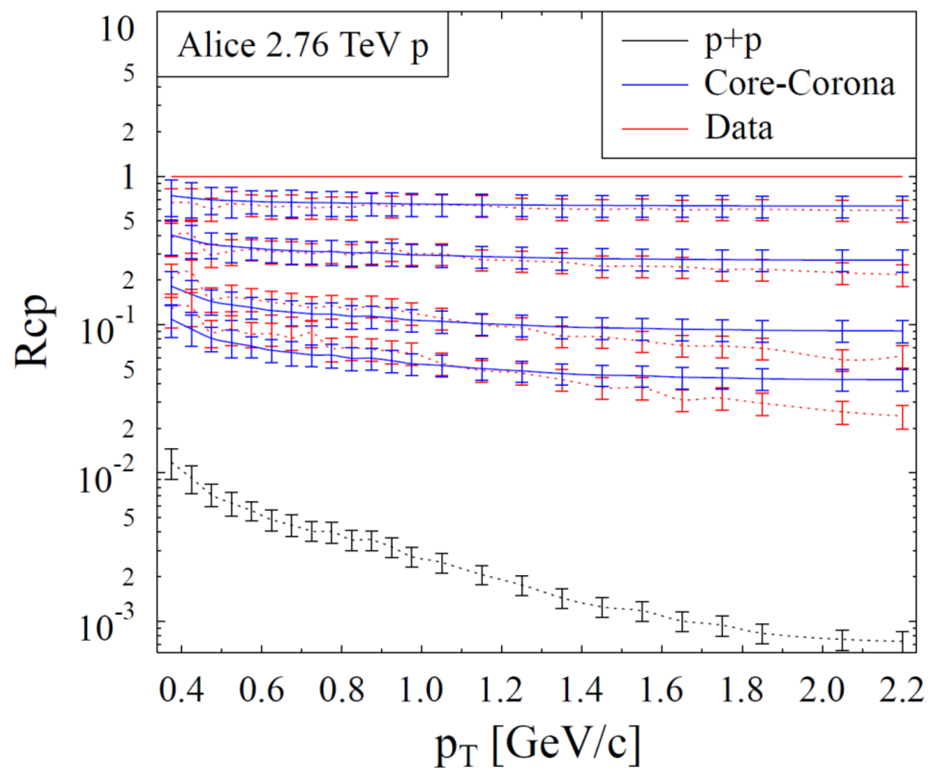


and the other extreme:

Alice data at 2.76 TeV

Also well reproduced:

No data for very peripheral bins yet



Conclusions

Core - corona model inspired by first CuCu results, checked against EPOS and developed to make this physics more transparent.

V_2, M^i ,$\langle p^i_T \rangle$ and spectrum in central collisions and pp is the only input

Predicts quantitatively all experimental results on centrality dependence at midrapidity:

-M^i (Npart) of all hadrons i from SPS to RHIC (strangeness enhancement)
-v_2/ε (Npart) of charged particles from SPS to RHIC
-$\langle p^i_T \rangle$ (Npart) of hadrons i from SPS to RHIC
-single particle spectra
-the experimental observation of correlations
between peri/central and pp/central for multiplicities and $\langle p_T \rangle$

In short: central and pp collisions is all what we need

This is much more than we expected in view of its simplicity
(improvement difficult due to large experimental error bars)

Conclusion on the Physics

The fact that the centrality dependence of all observables is described by this simple model may suggest that it describes the essential features of the reaction.
If this were the case:

What we see in the detector is a superposition of two independent contributions:
A corona contribution with properties identical to pp
A core contribution whose properties are independent of N_{part} even for very small N_{part} (≈20)
The observed centrality dependence is due to the N_{part} dependence of the ratio of both contributions
During the expansion
the average $\langle p_T \rangle$ of each hadron species does not change
The spectra remain a superposition
-> very little final state int. after hadron formation above p_T>.4 GeV
When we have understood central AA and pp, we have understood all

Conclusion with respect to other models

The core-corona models shows (as experiment)

correlations between pp and peripheral heavy ion reactions

for multiplicities and $\langle p_T \rangle$

which is alien to hydrodynamics.

It reproduces the centrality dependence of v_2 without using viscosity

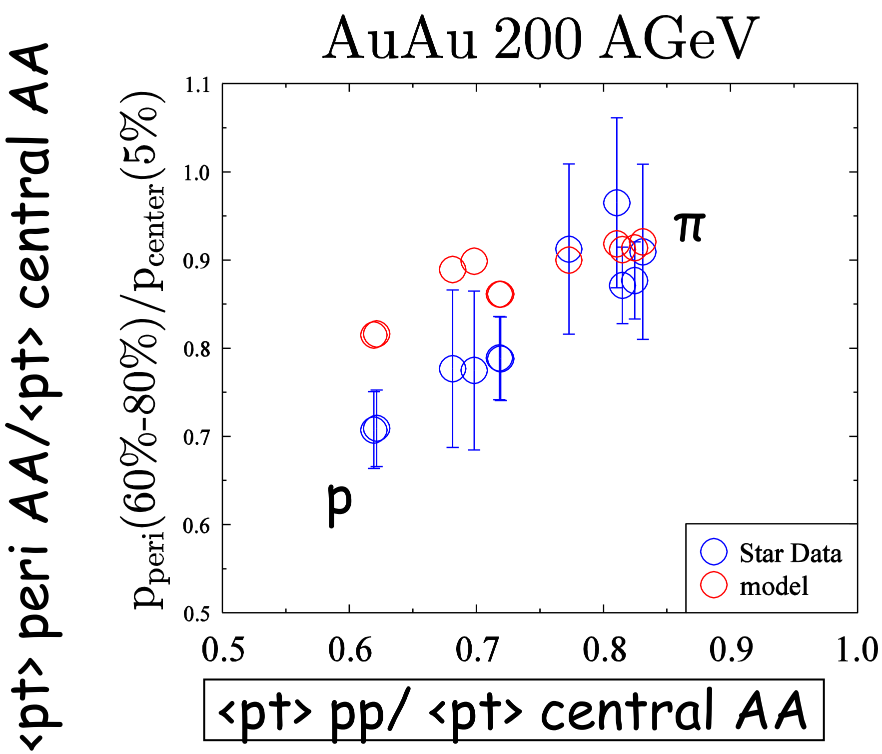
$v_2 = v_2 / f_{core}$

In the core-corona model the centrality dependence of $\langle p_T \rangle$ is given by the difference of $\langle p_T \rangle$ in pp and central heavy ion reactions.

Particles with similar masses (as p,Φ,Λ) show a quite different centrality dependence of $\langle p_T \rangle$.

This questions whether collective flow, derived from blast wave fits, is really the origin of the mass dependence of $\langle p_T \rangle(N_{part})$.

Correlation between peripheral AA and pp collisions



Data as core - corona model:

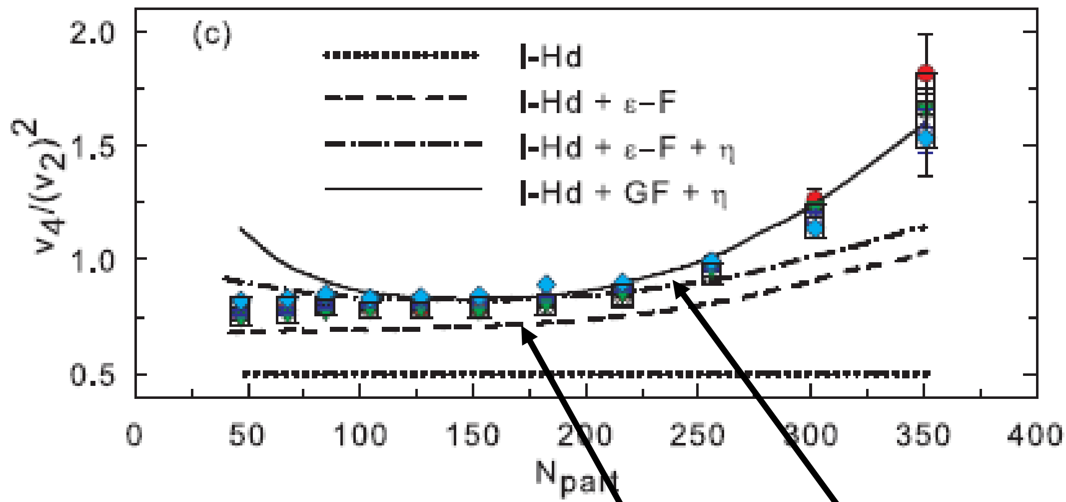
$$\frac{<p_t(AA\ peri)>}{<p_t(AA\ centr)>} \propto \frac{<p_t(pp)>}{<p_t(AA\ centr)>}$$

Such a correlation is unknown in hydro

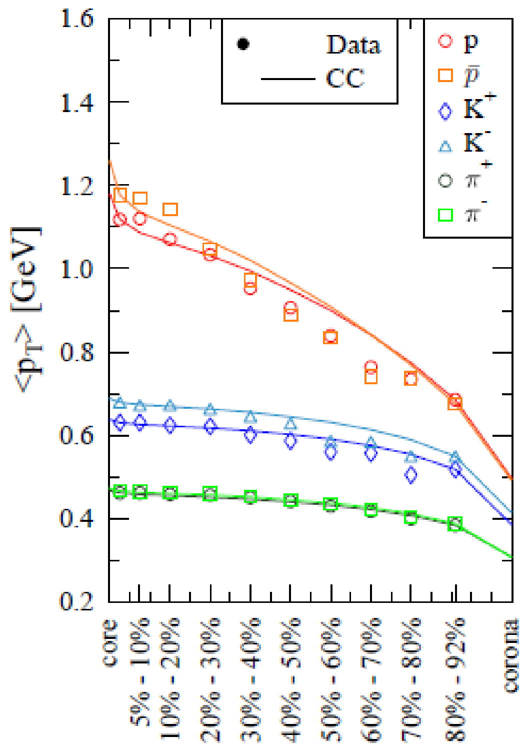
Problem: pp data are not very precise

Can v_4 help?

Phenix, arXiv:1003:5586



Determined mostly by ε fluctuations
Little difference between ideal and viscous hydro



(b)PHENIX

The core-corona model predicts
that the centrality dependence
has nothing to do with a collective flow

It is merely due to the difference of
$\langle p_T \rangle$ in pp and central AA