Recent Results on Properties of QCD Matter at RHIC

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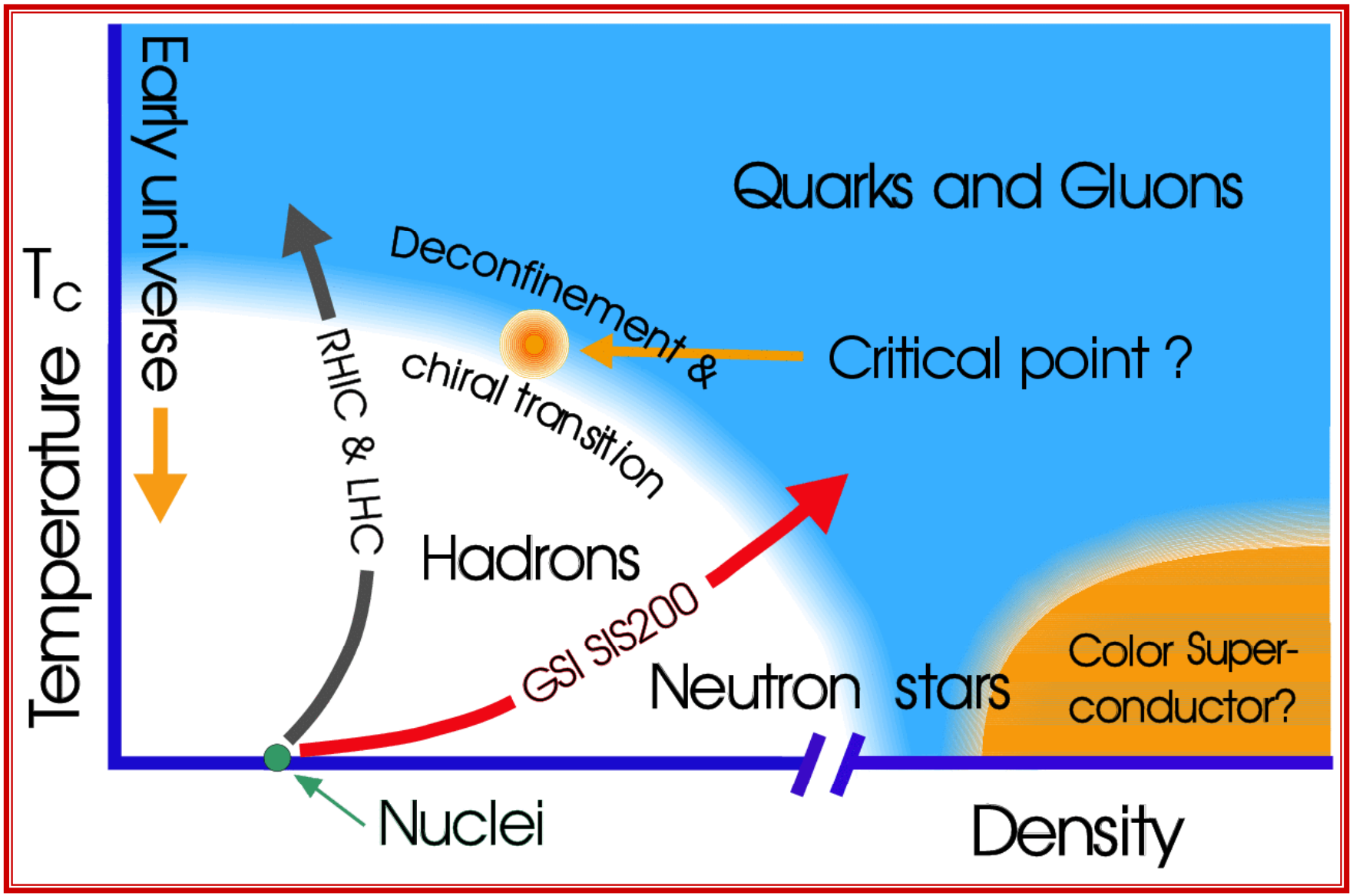
Quark-Hadron Phase Transition



Nucleus-Nucleus Collisions and Volcanic Eruption

Volcanic high p_T -- Strombolian eruption

Volcanic mediate p_T – Spatter (clumps)

Volcanic low p_T – Bulk matter flows

1) Initial Temperature

2) Viscosity

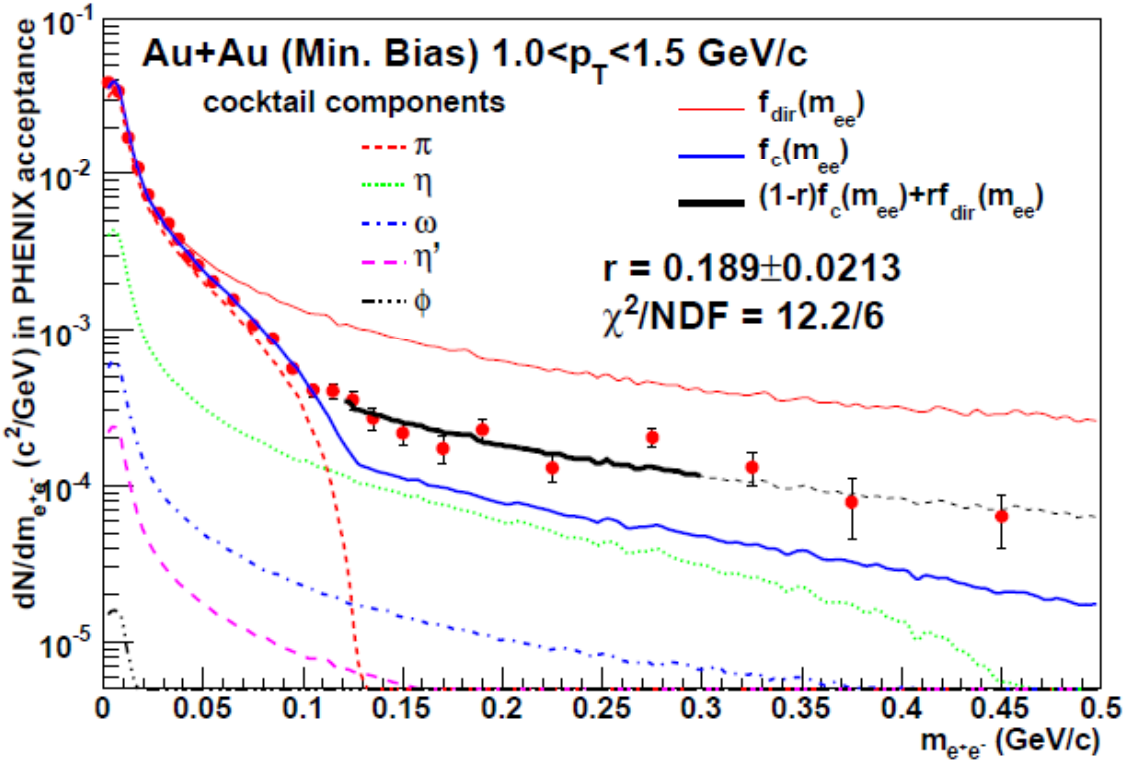
3) Bulk Matter Hadronization

Extract Thermal Radiation from Virtual γ* (di-electrons) Yield

Direct γ^*/inclusive γ^* from fitting the following function:

$$f_{data}(M_{ee}) = (1-r)\cdot f_{cocktail}(M_{ee}) + r \cdot f_{direct}(M_{ee})$$

r = direct γ^*/inclusive γ^*

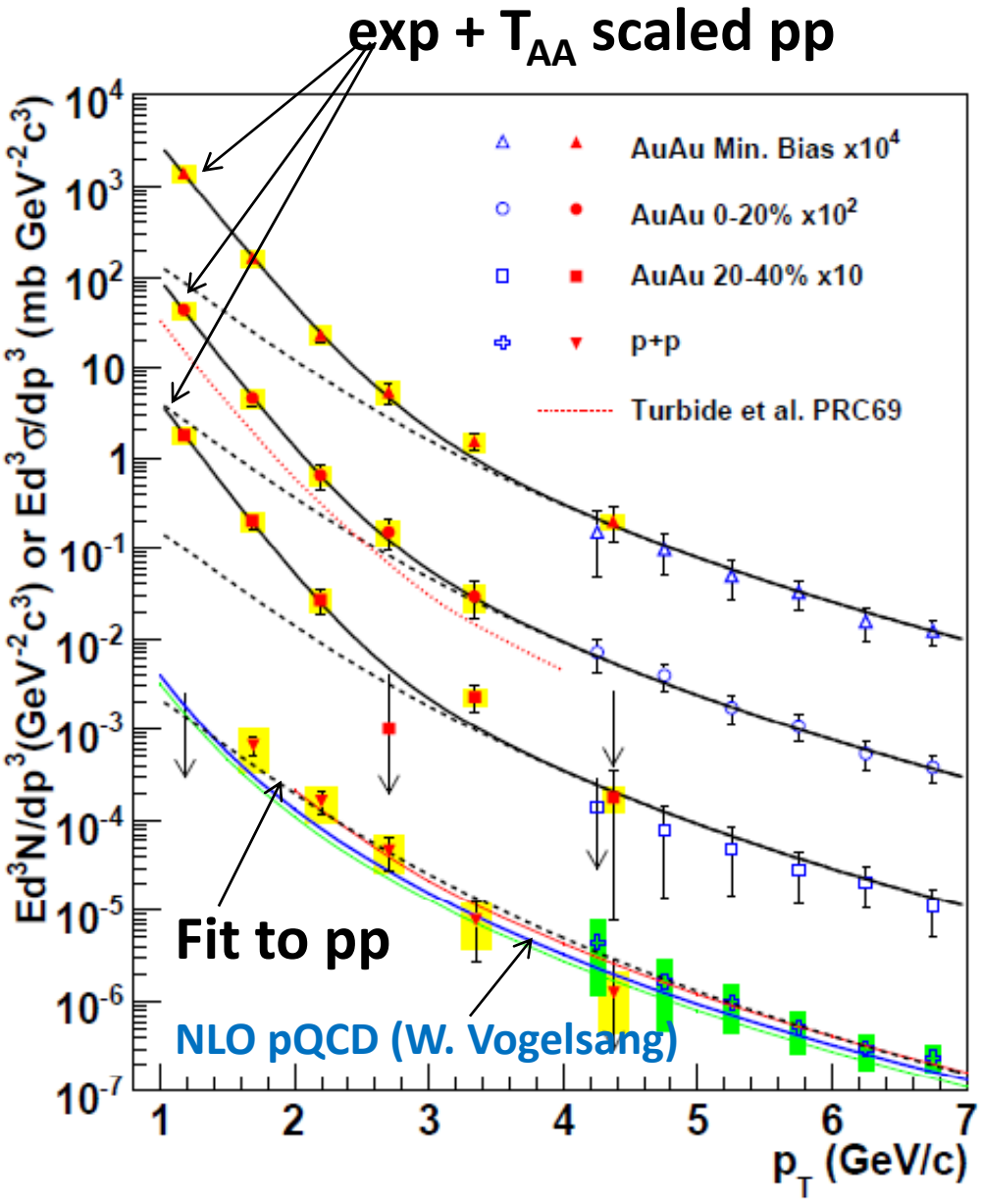


- **Fit in 120-300MeV/c² (insensitive to π^0 yield)**
- **The mass spectrum follows the expectation for m > 300 MeV**

→ $S(m) = dN_{\gamma^*}/dN_{\gamma} \sim 1$

A. Adare et al., PRL 104, 132301 (2010)

The Partonic Matter at RHIC is very Hot initially (T>300 MeV)



- Direct photon measurements
  - real (p_T>4GeV)
  - virtual (1<p_T<5GeV)
- p+p data consistent with pQCD down to p_T=1GeV/c
- Au+Au data require source other than pQCD for p_T < 2.5 GeV/c
- The source could be
  $T_{AuAu} = 221 \pm 19^{stat} \pm 19^{syst}$ MeV (time averaged)
- Theoretical calculations put T_{init} 300-600 MeV range.

The Partonic Matter at RHIC Flows Hydrodynamically

Ideal Hydrodynamics -- shear viscosity $\eta = 0$

Strongly Interacting Matter
→ η/s = shear viscosity/entropy

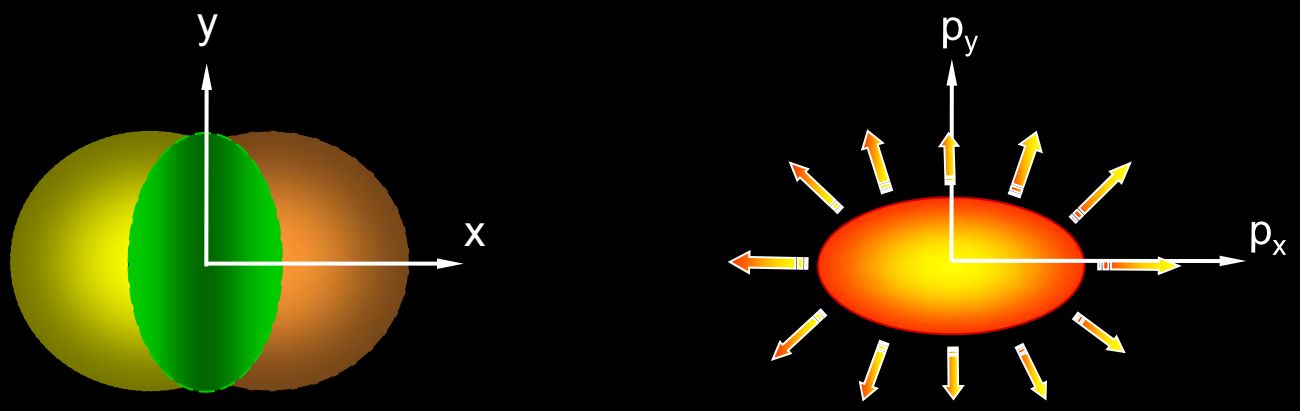
Povtun, Son and Starinets
PRL94 111601 (2005)
quantum limit η/s =1/4π for N=4
supersymmetric Yang-Mills theory

Is this limit universal?

Great for string theorists!
AdS/CFT calculations
-- almost like QCD
-- can be tested experimentally

Elliptic Flow Parameter v_2

coordinate-space-anisotropy ⇔ momentum-space-anisotropy

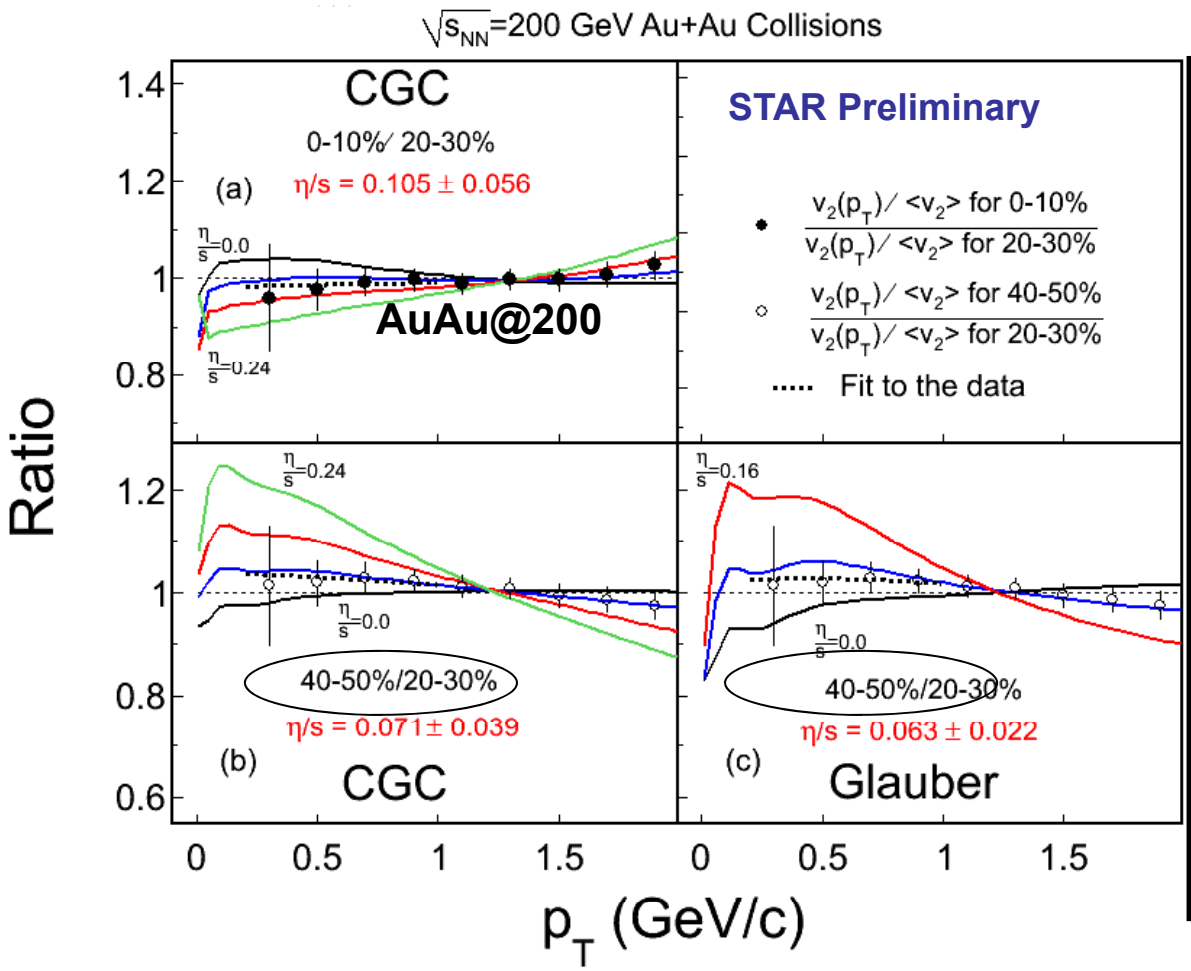


Initial/final conditions, dof, EOS

$$\frac{dN}{p_t dp_t dy d\varphi} = \frac{1}{2\pi}\frac{dN}{p_t dp_t dy}\left[1+\sum_{i=1} 2v_i \cos(i(\varphi-\Psi_R))\right]$$

Extraction of η/s relies on viscous hydrodynamic calculations

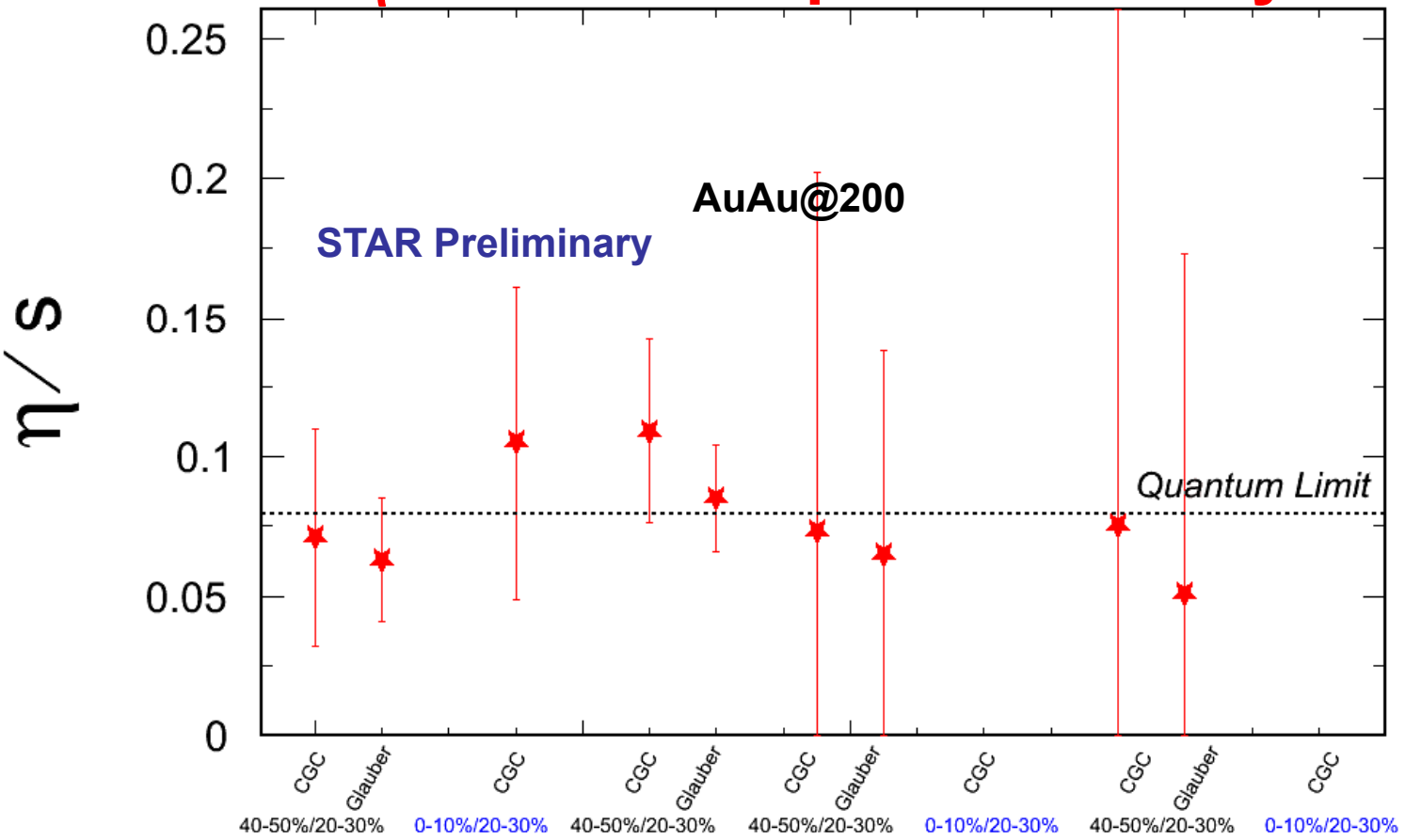
Assuming -- η/s does not depend on the collision centrality significantly.



- Data: v_2{FTPC}
- Fit range: $0.15 < p_T < 1$ GeV/c
- Less dependence on the initial geometrical shapes
- The shape change at p_T>1 GeV/c is dominated by q-hat – parton energy loss

[1]K. Dusling, G. Moore and D. Teaney, arXiv:0909.0754

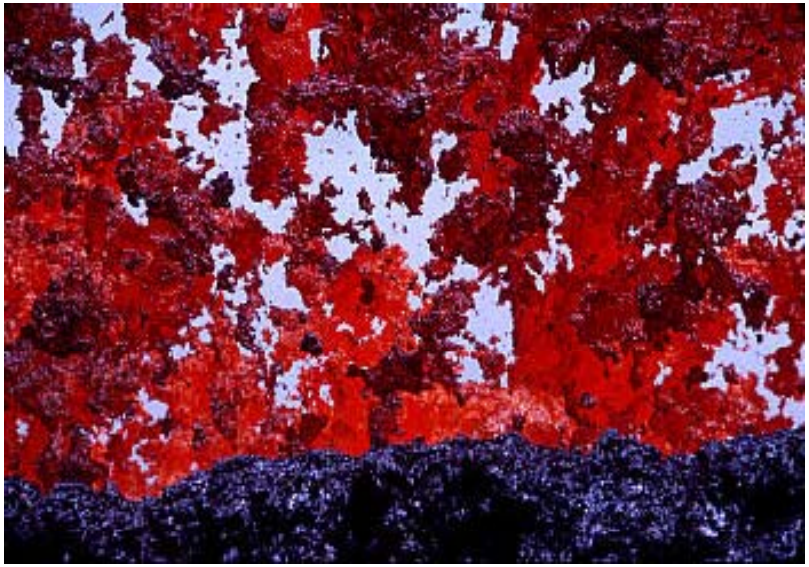
Strongly Interacting Partonic Matter @RHIC
small η/s --- almost perfect fluidity



Different exp method for v_2 calculations

- **Less dependence on the initial geometrical shapes**
- **η/s: (0.5~2)/(4π)**

Hadronization of Bulk Partonic Matter → Coalescence



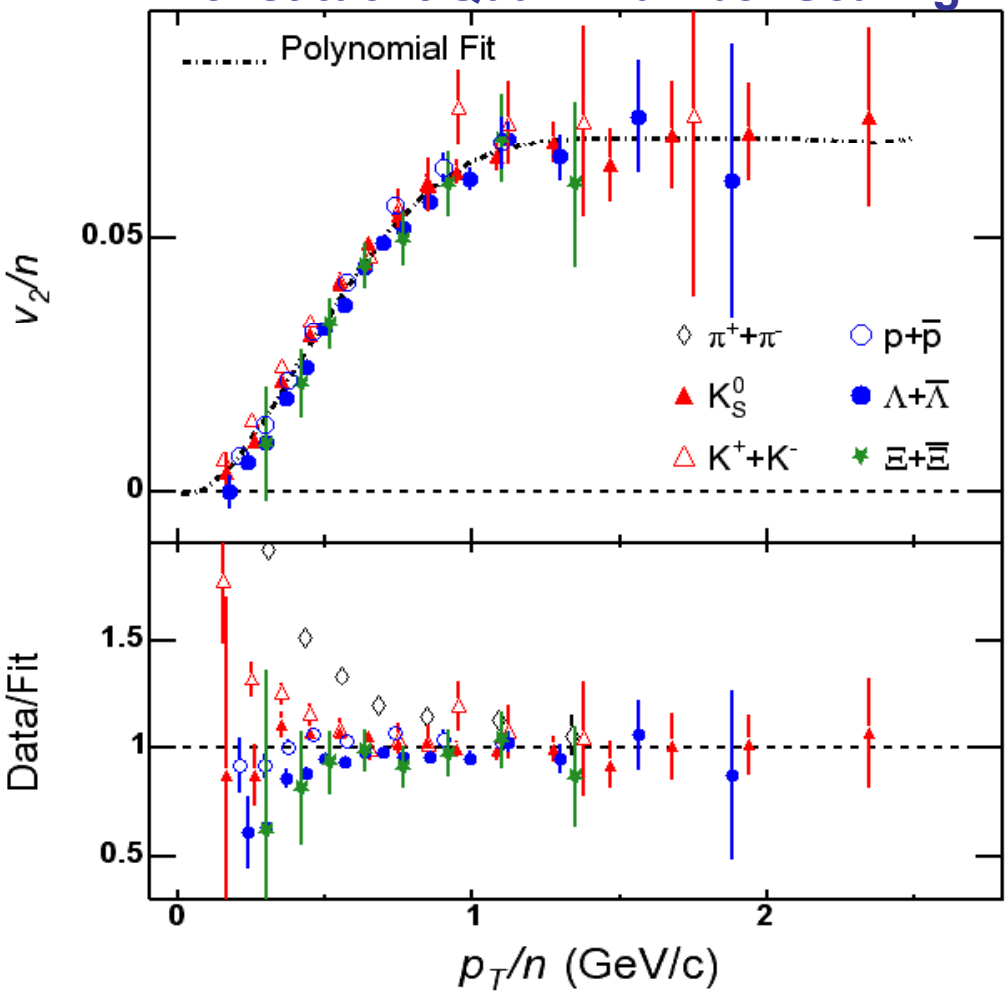
Volcanic mediate p_T – Spatter (clumps)

Partons at hadronization have a v_2

→ Collectivity

Deconfinement !

Constituent Quark Number Scaling



Quark Coalescence – (ALCOR-J.Zimanyi et al, AMPT-Lin et al, Rafelski+Danos, Molnar+Voloshin …..)

Quark Recombination – (R.J. Fries et al, R. Hwa et al)

Multi-Parton Dynamics for Bulk Matter Hadronization

Essential Features:

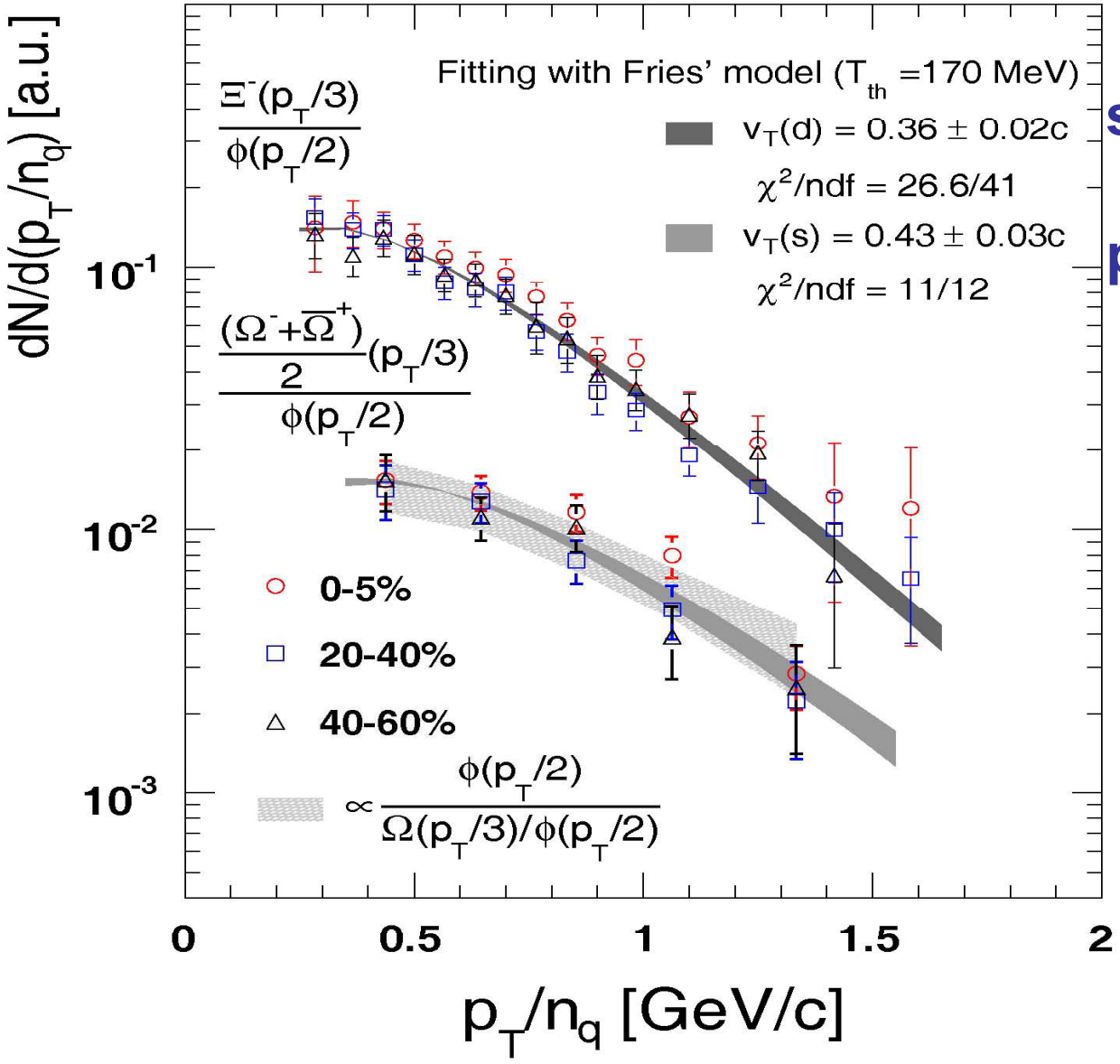
Traditional fragmentation → particle properties mostly determined by the leading quark !

Emerging picture from RHIC data (R_{AA}/R_{CP} and v_2) → all constituent quarks are almost equally important in determining particle properties !

v_2 of hadron comes from v_2 of all constituent quarks !

The fact that in order to explain the v_2 of hadrons individual constituent quarks (n=2-meson,3-baryon) must have a collective elliptic flow v_2 and the hadron v_2 is the sum of quark v_2 → **Strong Evidence for Deconfiement !**

Strange and down quark distributions

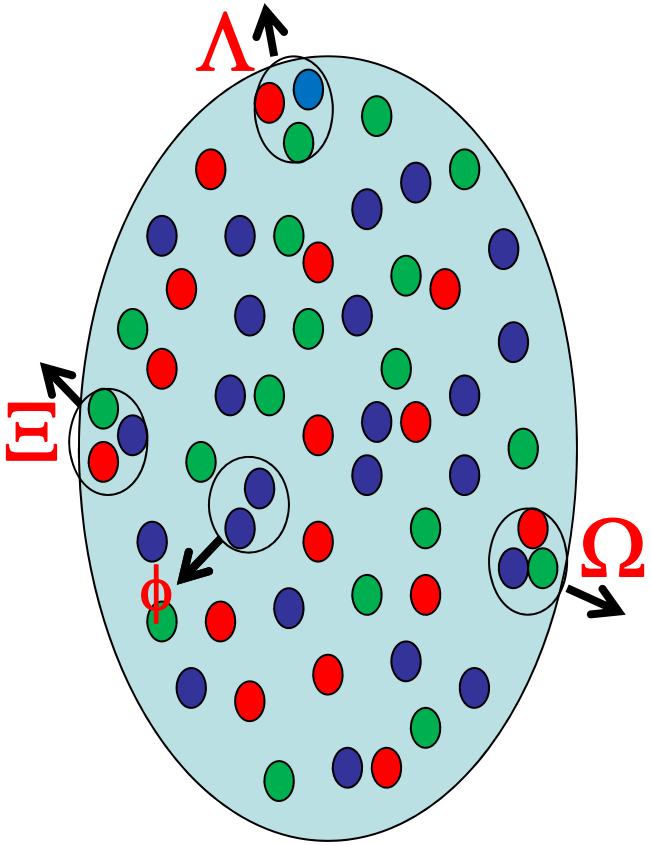


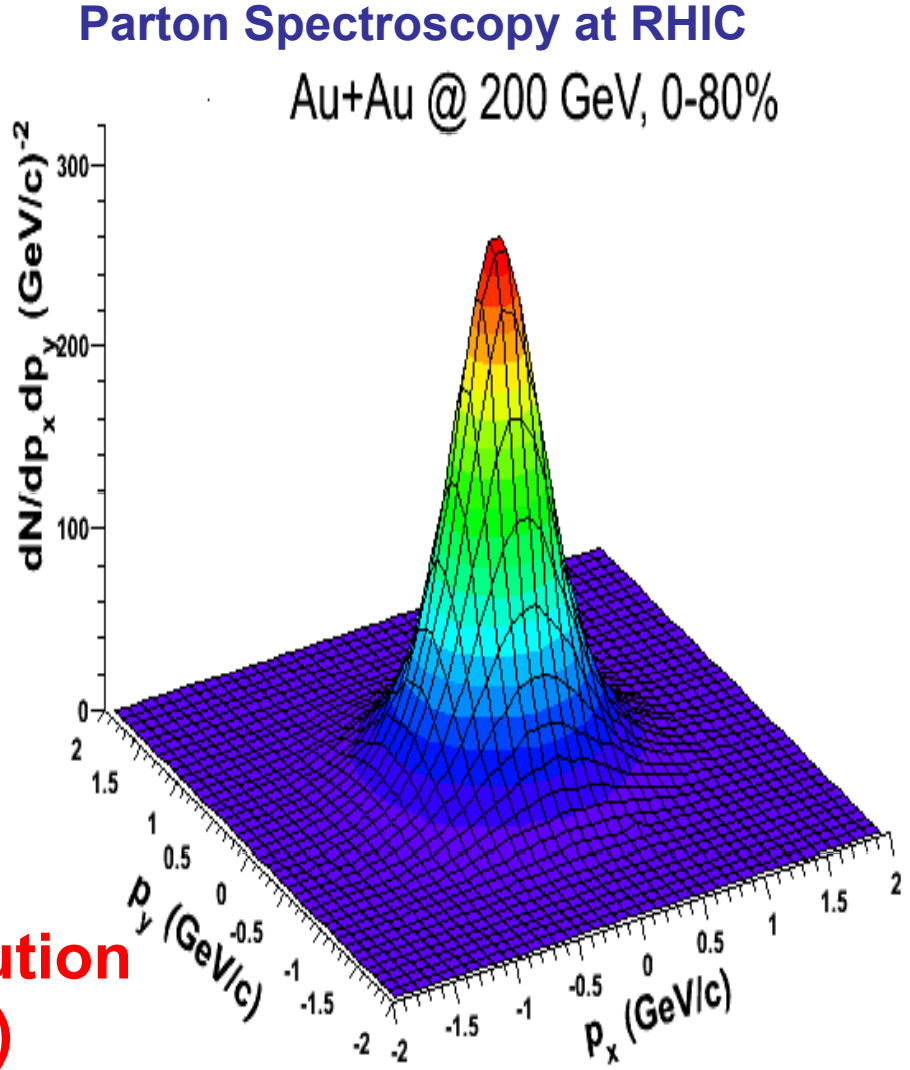
s distribution harder than d distribution perhaps related to different s and d quarks in partonic evolution

Independent Test – ϕ/s should be consistent with s quark distribution

Yes !

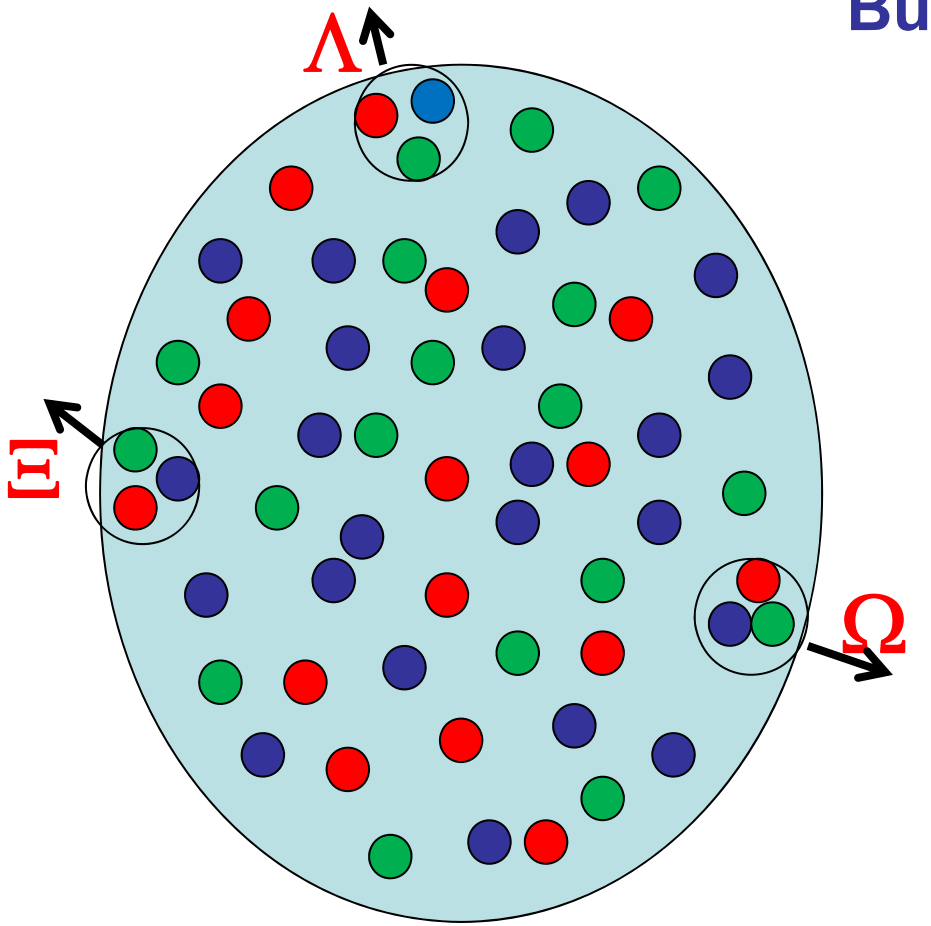
Effective Parton Distribution in the Drop at Hadronization





Use particle emission to measure parton pT distribution and angular anisotropy (v_2) in the dense parton drop !!

Summary



Central Au+Au Collisions at RHIC
Bulk Partonic Matter --

1) Initially very Hot
T above 300 MeV

2) parton collectivity
v_2 and
hydro expansion
Deconfined matter
with parton DOF

3) η/s small – near the limit
$1/4\pi$ for N=4
supersymmetric Y-M theory

Discoveries from Unexpected Areas?!

RHIC -- Frontier for bulk partonic matter formation
(quark clustering and rapid hadronization)
-- Factory for exotic particles/phenomena

Potential exotic particles/phenomena:

tetra- penta-quark states (particle and anti-part)

di-baryons

H – (Λ–Λ, uuddss)

[Ω–Ω] (ssssss)

strange quark matter

meta-stable Parity/CP odd vacuum bubbles

disoriented chiral condensate

……

$^{3}_{\Lambda}\overline{\mathrm{H}}$ signal from the data

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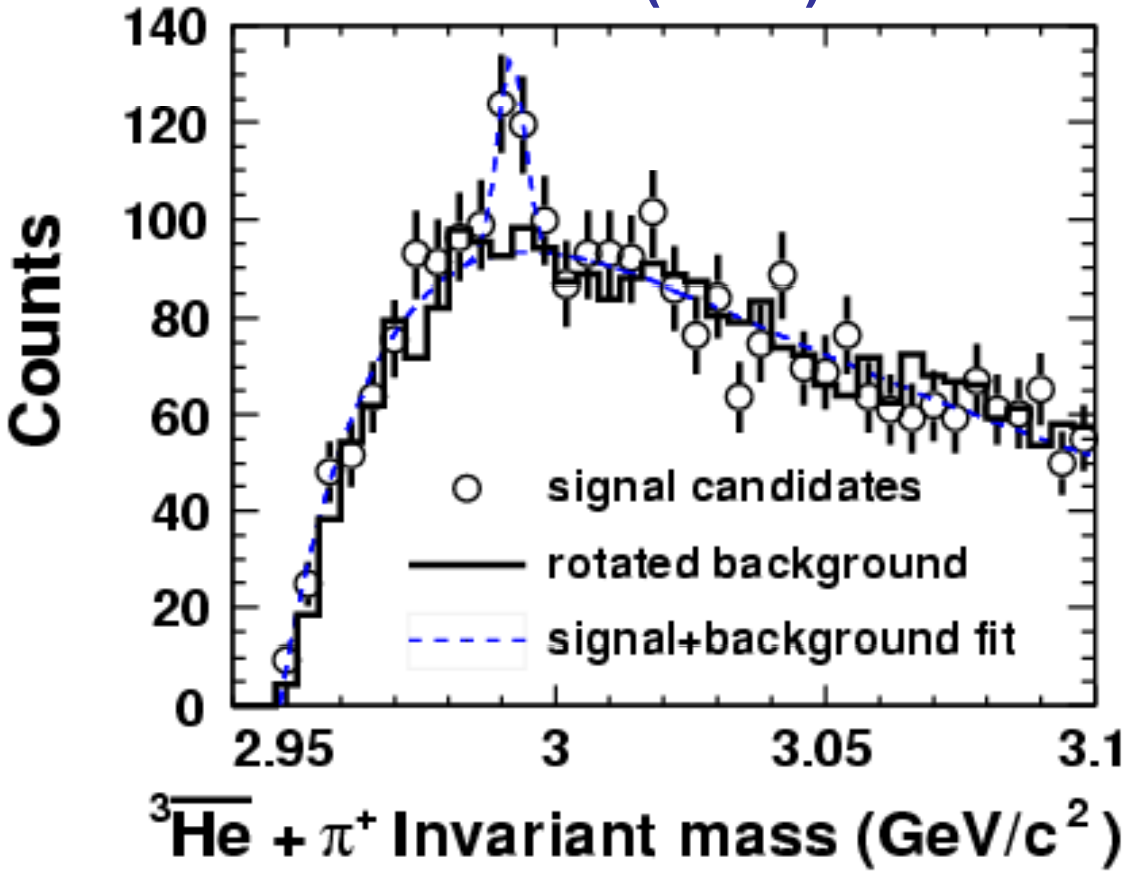
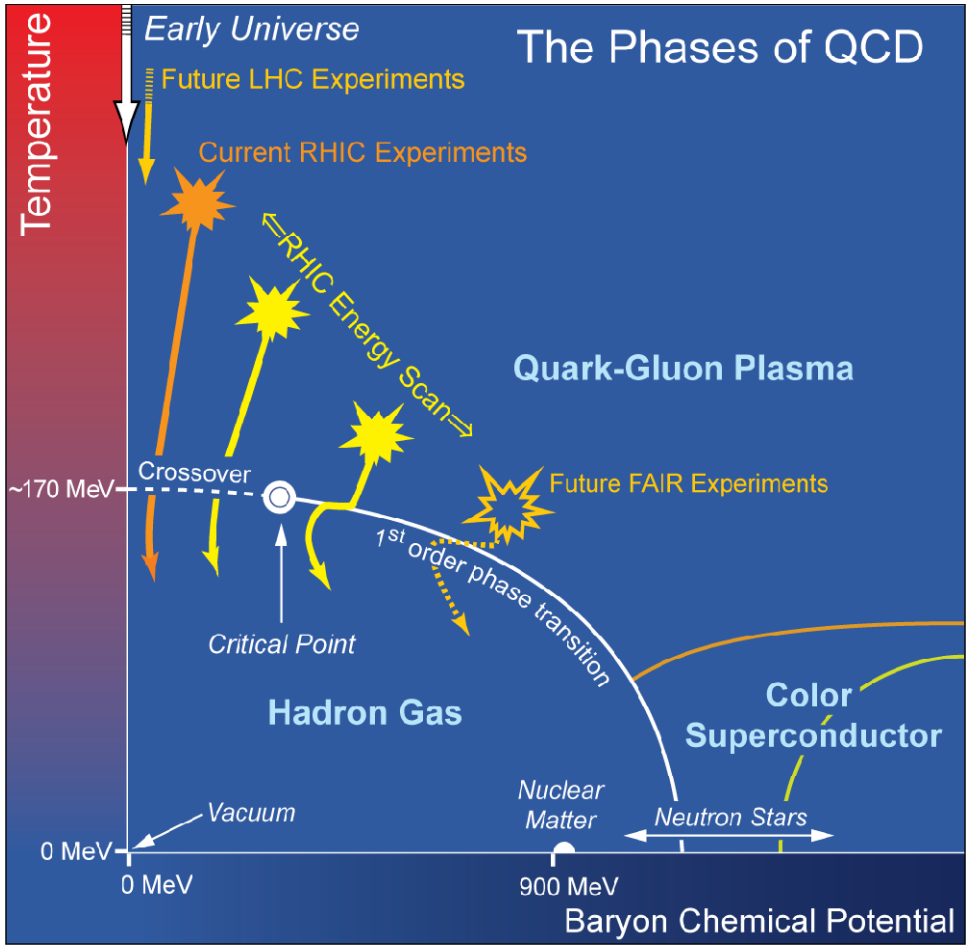


★ **Signal observed from the data (bin-by-bin counting): 70±17;**

Mass: 2.991±0.001±0.002 GeV; Width (fixed): 0.0025 GeV.

Au+Au: 89M MB events and 22M central collision events.

Near Future Perspective



Is there a critical point in the QCD phase diagram?
-- RHIC low energy scan

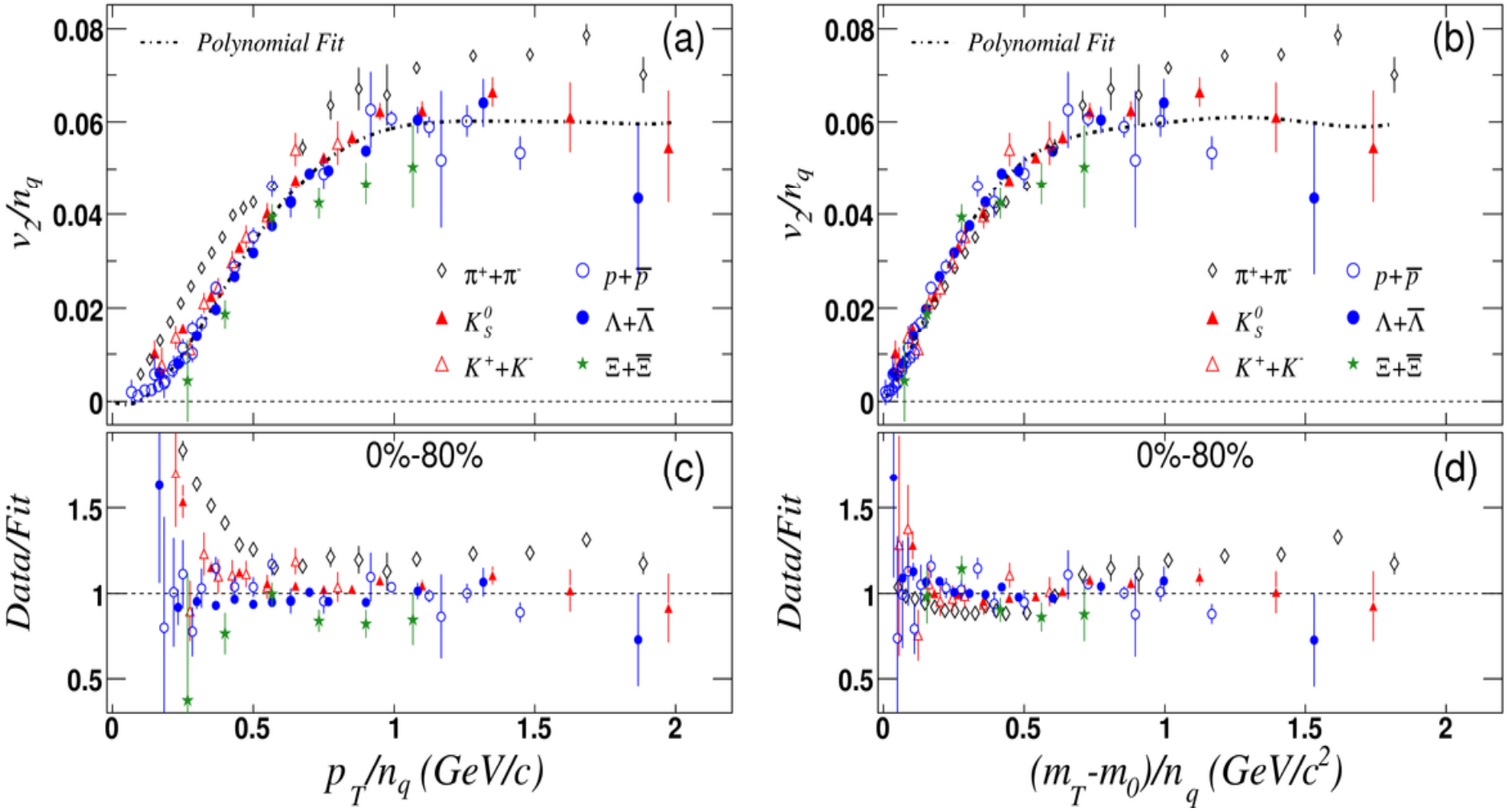
Initial conditions for partonic evolutions?
-- Color Glass Condensate

Heavy Quark flavored QGP
-- detector upgrade for charm/bottom

Flavor tagged parton energy loss in dense matter

End

Constituent Quark Scaling



Parton P_T Distributions at Hadronization

If baryons of p_T are mostly formed from coalescence of partons at $p_T/3$ and mesons of p_T are mostly formed from coalescence of partons at $p_T/2$

$$s = \frac{\Omega(p_T/3)}{\phi(p_T/2)}$$

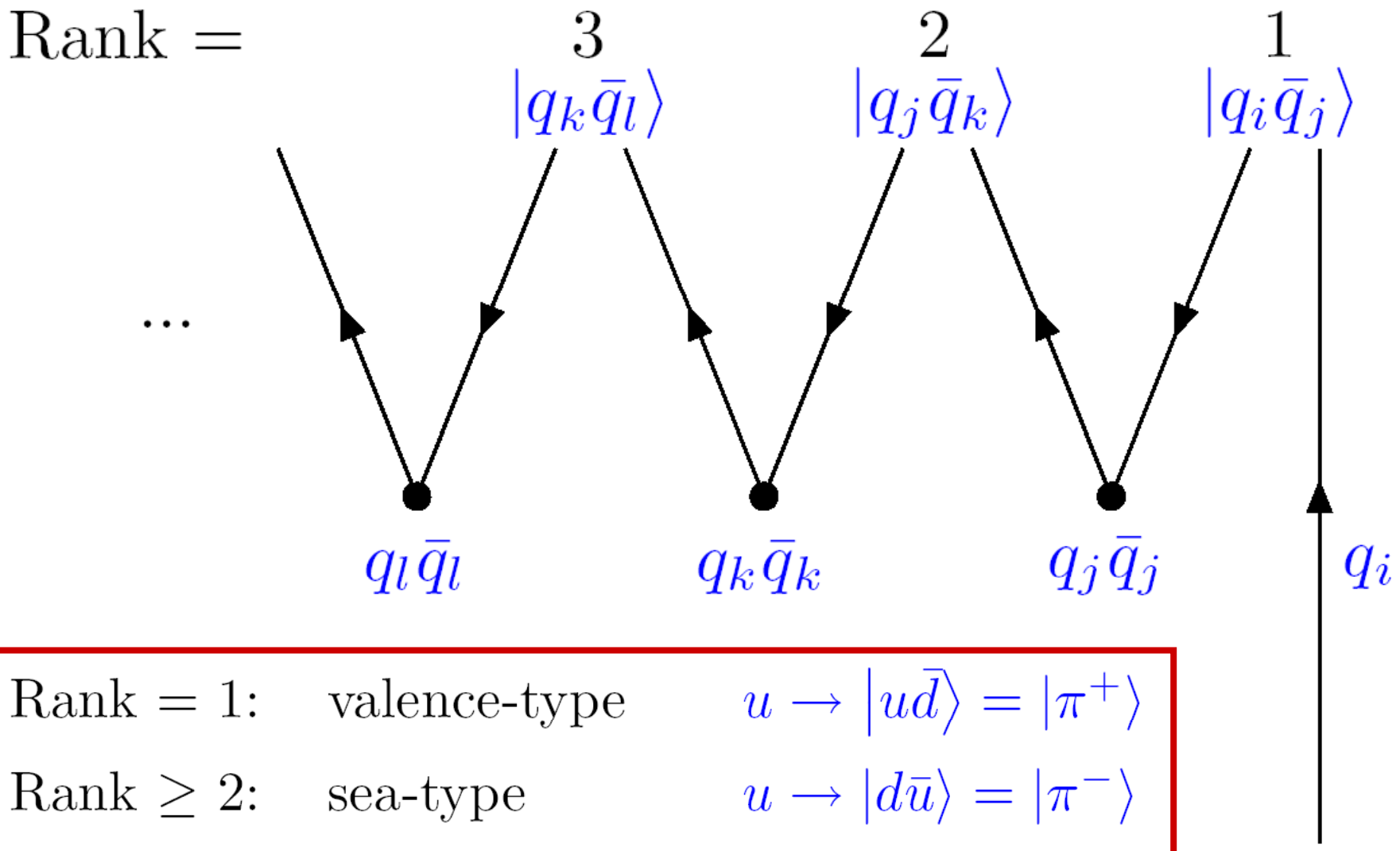
$$d = \frac{\Xi(p_T/3)}{\phi(p_T/2)}$$

Ω and ϕ particles have no decay feeddown contribution !

Ξ decay contribution is small

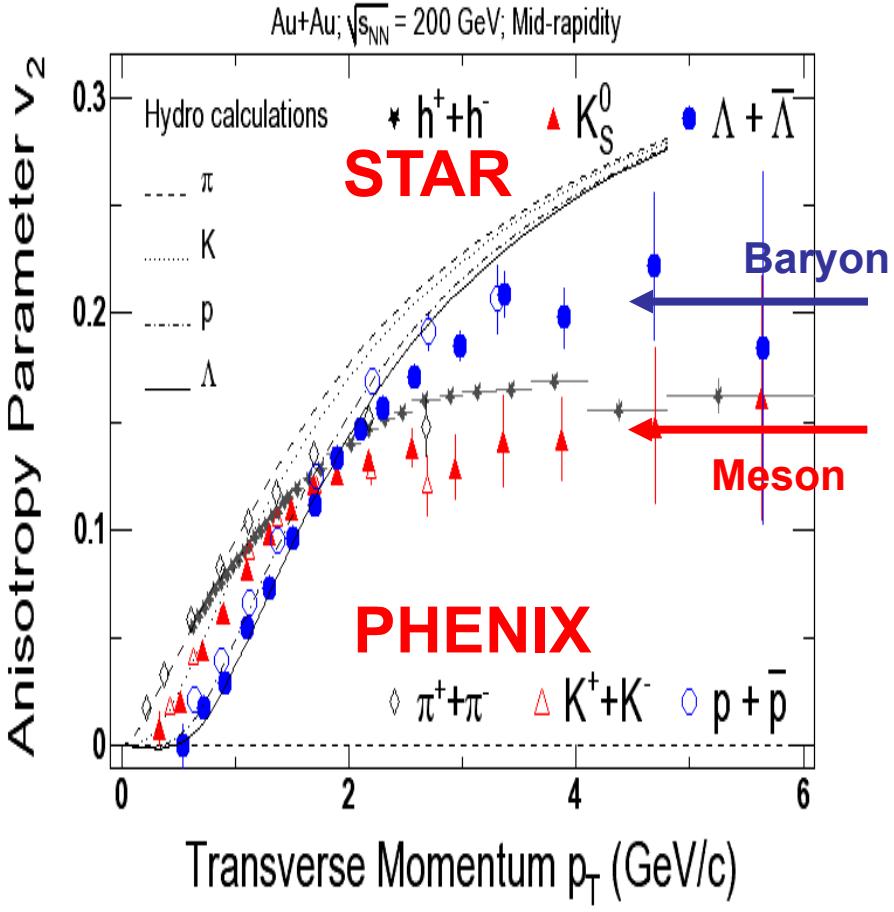
These particles have small hadronic rescattering cross sections

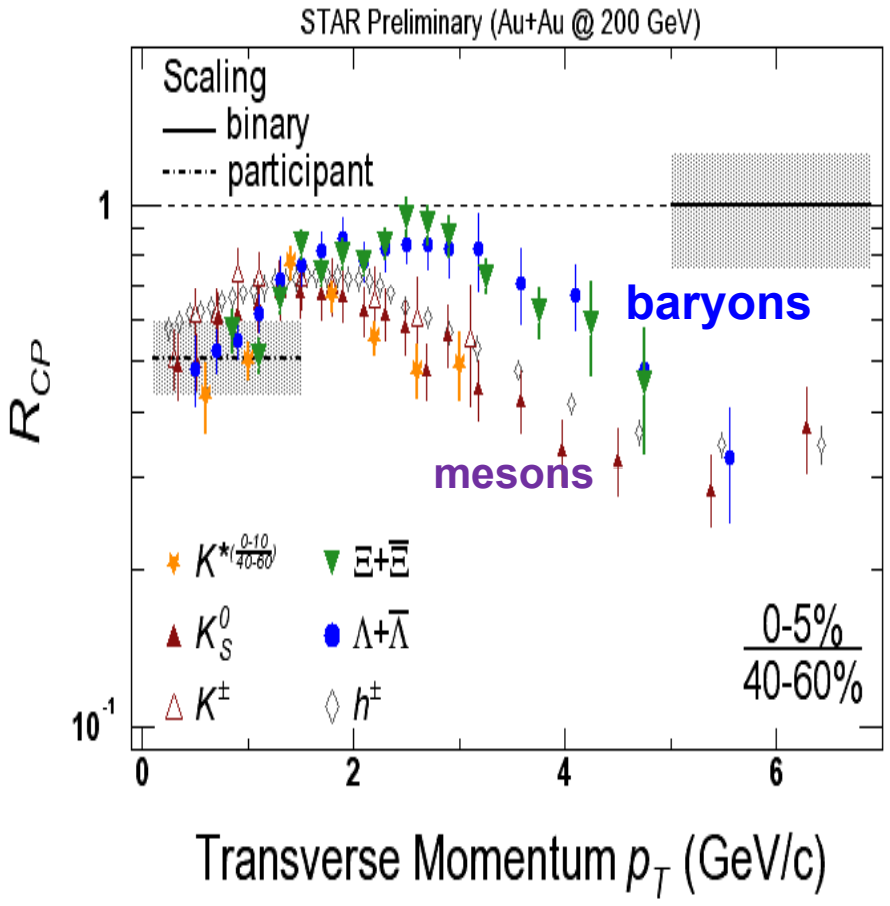
The Field & Feynman picture of cascade fragmentation



Rank $= 1$:	valence-type	$u \to \|u\bar{d}\rangle = \|\pi^+\rangle$
Rank ≥ 2:	sea-type	$u \to \|d\bar{u}\rangle = \|\pi^-\rangle$
$q_i \neq s$:	$s\bar{s}$ suppression	$u \to \|u\bar{s}\rangle = \|K^+\rangle$

Constituent Quark Scaling



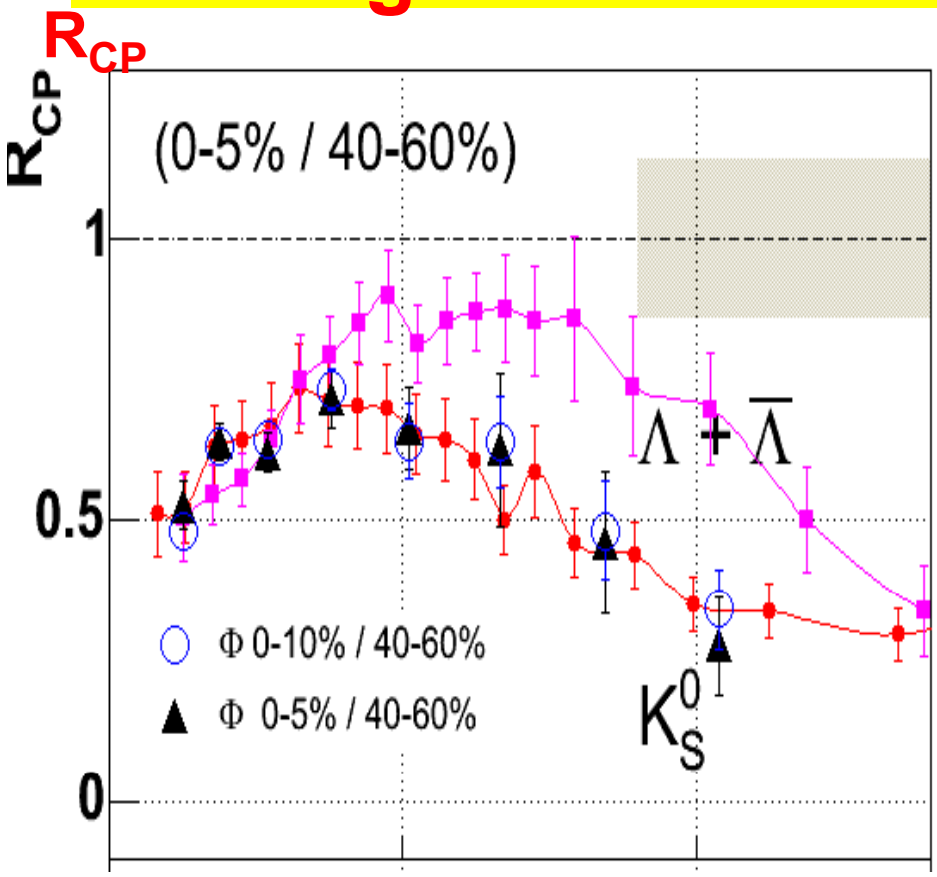


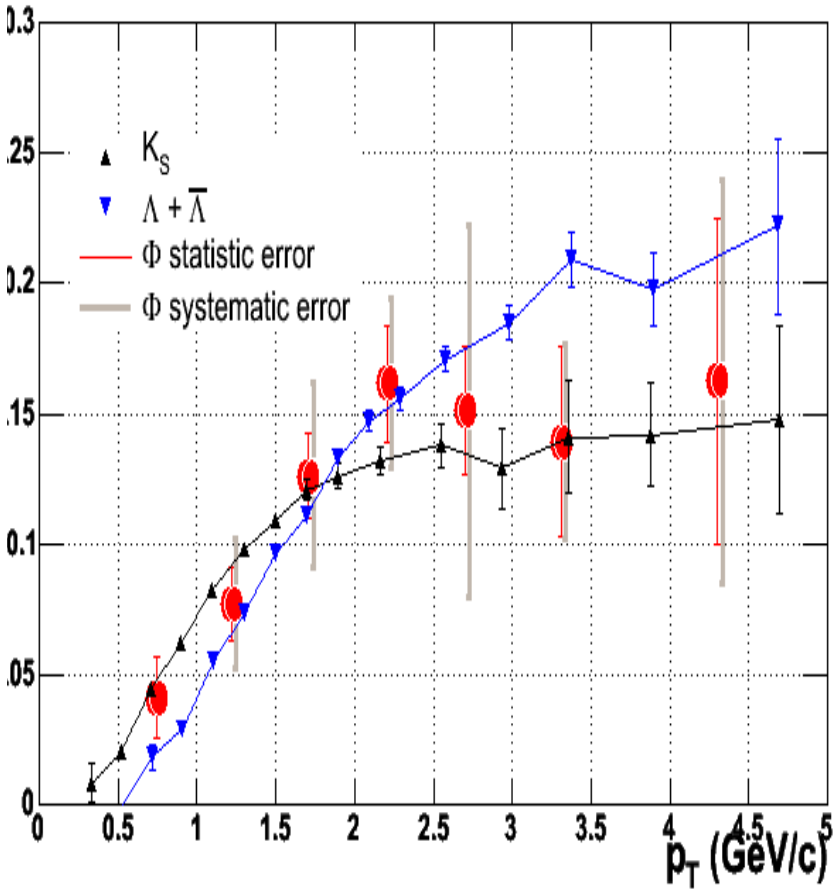
Constituent (n) Quark Scaling

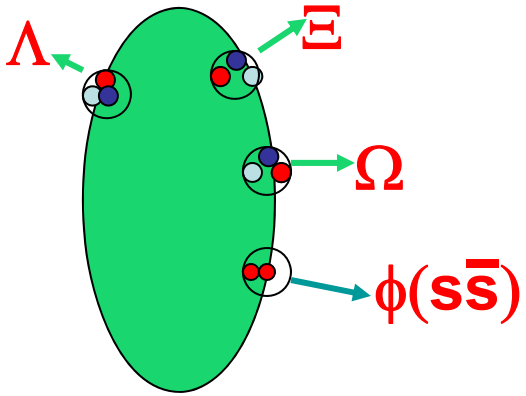
-- Meson n=2 and Baryon n=3 grouping

Saturation of v_2 at Intermediate p_T

Strangeness from Bulk Partonic Matter







Constituent Quark Number Scaling
-- Hadronization through quark clustering
-- Effective DOF – constituent quarks
quasi-hadrons at T_c ?
Lattice QCD picture?