Collective Flow of QCD – matter at Highest Collider Energies

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Quark Gluon Plasma

Source: Michael Turner, *National Geographic (1996)*

Quark Gluon Plasma:

(a) Deconfined and

(b) thermalized state of quarks and gluons

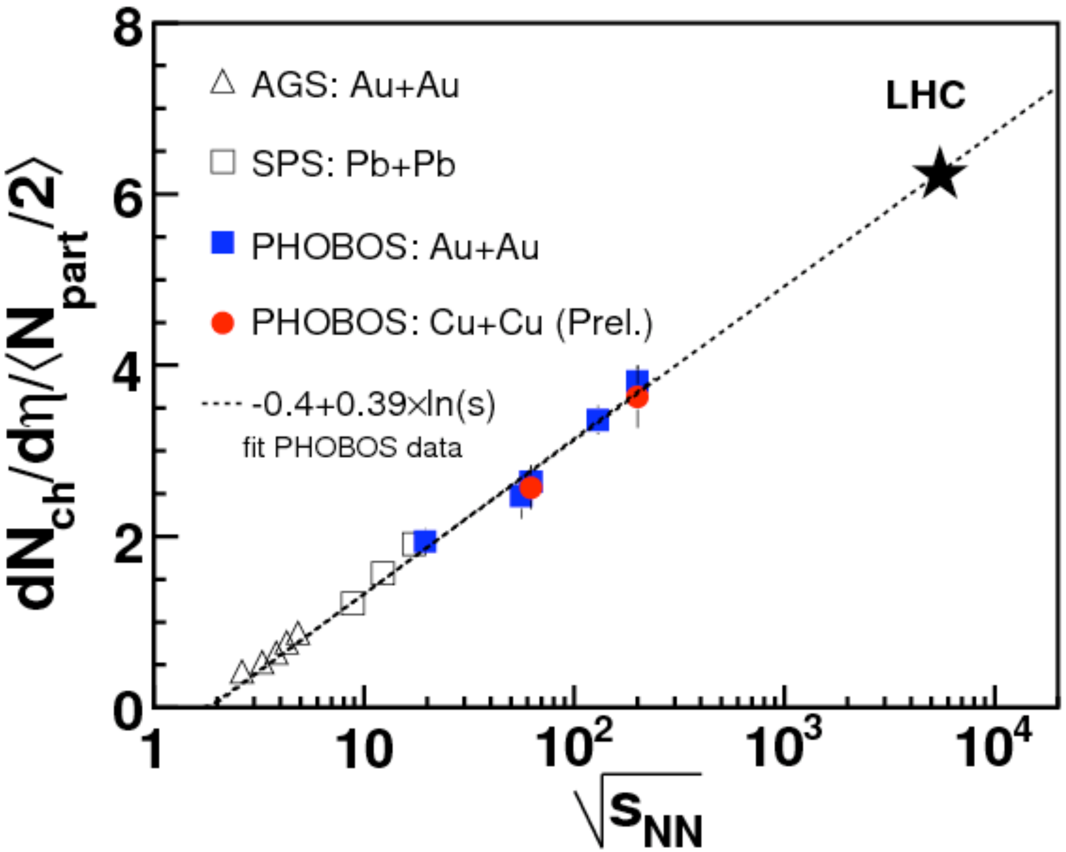
→ Study partonic EOS at LHC
(?) Probe thermalization using heavy-quarks

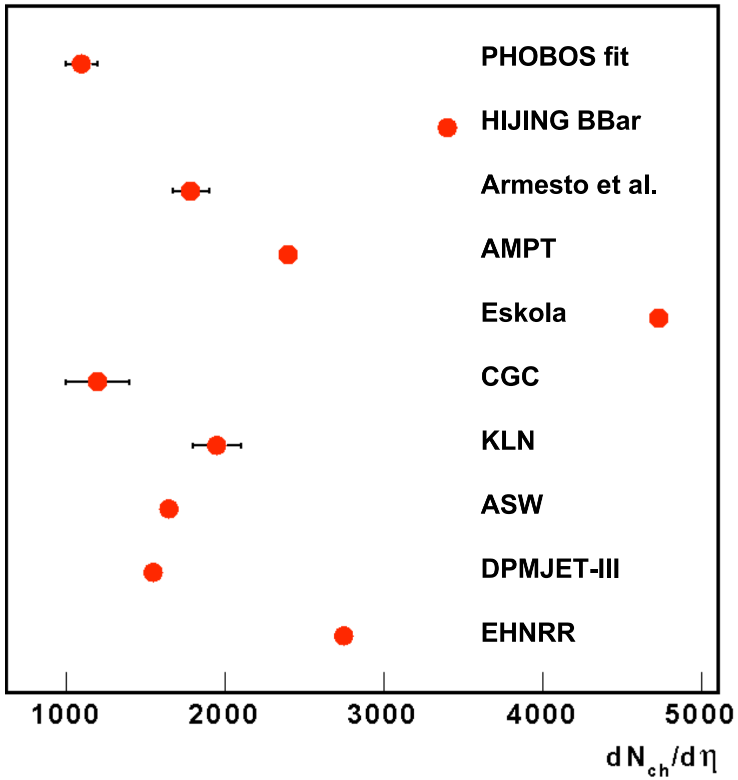
Outline

Identify and study QCD bulk-matter with partonic degrees of freedom:

- Transverse Radial and Elliptic Flow:
  - some results from RHIC
  - some estimates for LHC
- Heavy – quark collectivity
- Summary

Mid – rapidity Densities





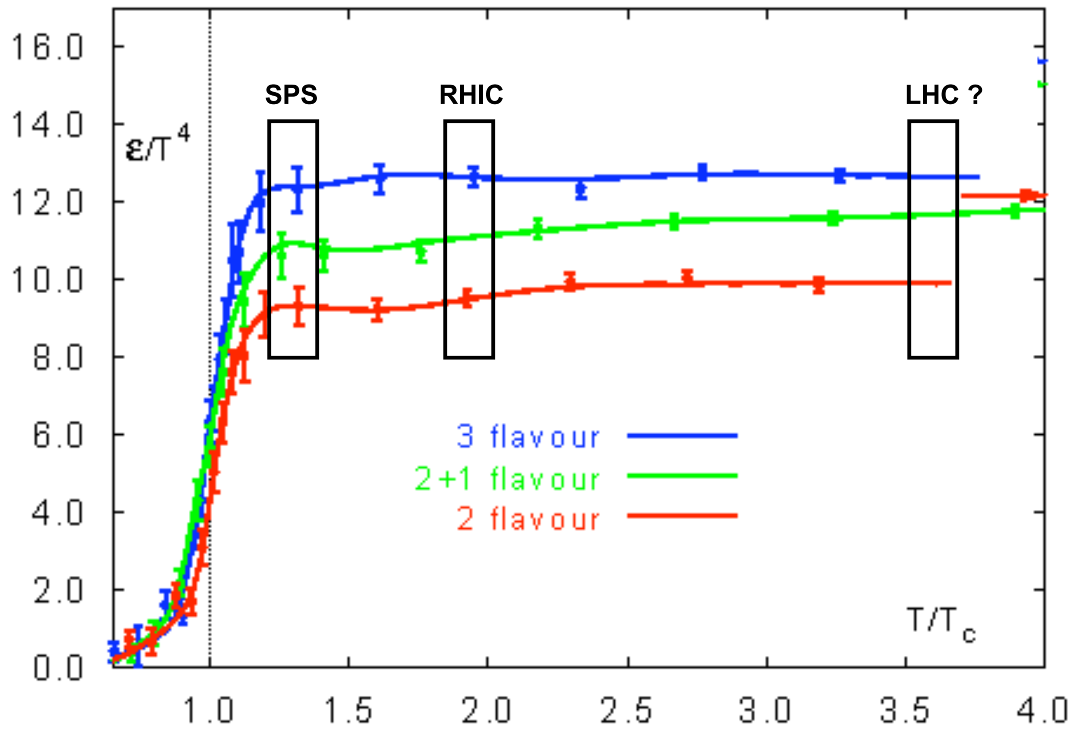
- at LHC, dN/dη ≈ 1000 – 2000 (detectors designed for 8000)
- estimate energy density

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

PHOBOS compilation: W. Busza, SQM07.

Theory points: HI at LHC – last call for predictions, CERN, May 2007.

EoS from Lattice QCD



1) Large increase in ε !

→ Large increase in Ndof: Hadrons vs. partons

2) T_C ~ 160 MeV

3) Boxes indicate max. initial temperatures

→ Longest expansion duration at LHC

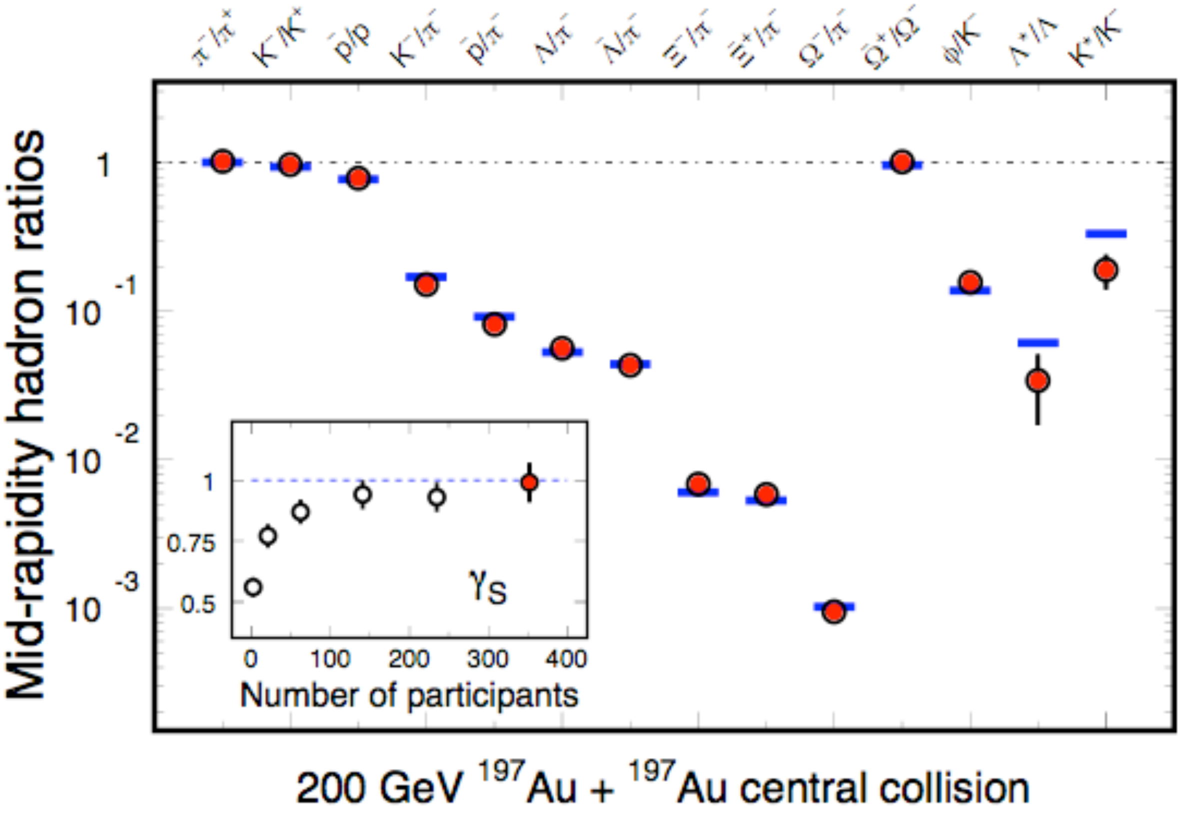
→ Expect large partonic collectivity at LHC

Z. Fodor et al, JHEP 0203:014(02)

C.R. Allton et al, hep-lat/0204010

F. Karsch, Nucl. Phys. A698, 199c(02).

Hadron Yield – Ratios



1) At RHIC:

T_{ch} = 160 ± 10 MeV

μ_B = 25 ± 5 MeV

2) γ_S = 1.

➠ **The hadronic system is thermalized at RHIC.**

3) Short-lived resonances show deviations.

➠ **There is life after chemical freeze-out.**

RHIC white papers - 2005, Nucl. Phys. A757, STAR: p102; PHENIX: p184;
Statistical Model calculations: P. Braun-Munzinger *et al.* nucl-th/0304013.

Pressure, Flow, ...

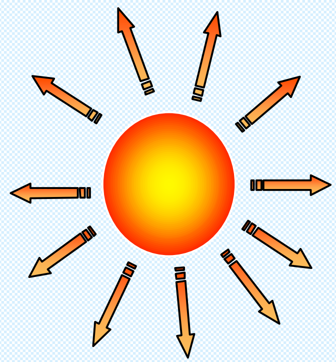
Thermodynamic identity

σ – entropy p – pressure
U – energy V – volume
$\tau = k_B T$, thermal energy per dof

$$\tau d\sigma = dU + p dV$$

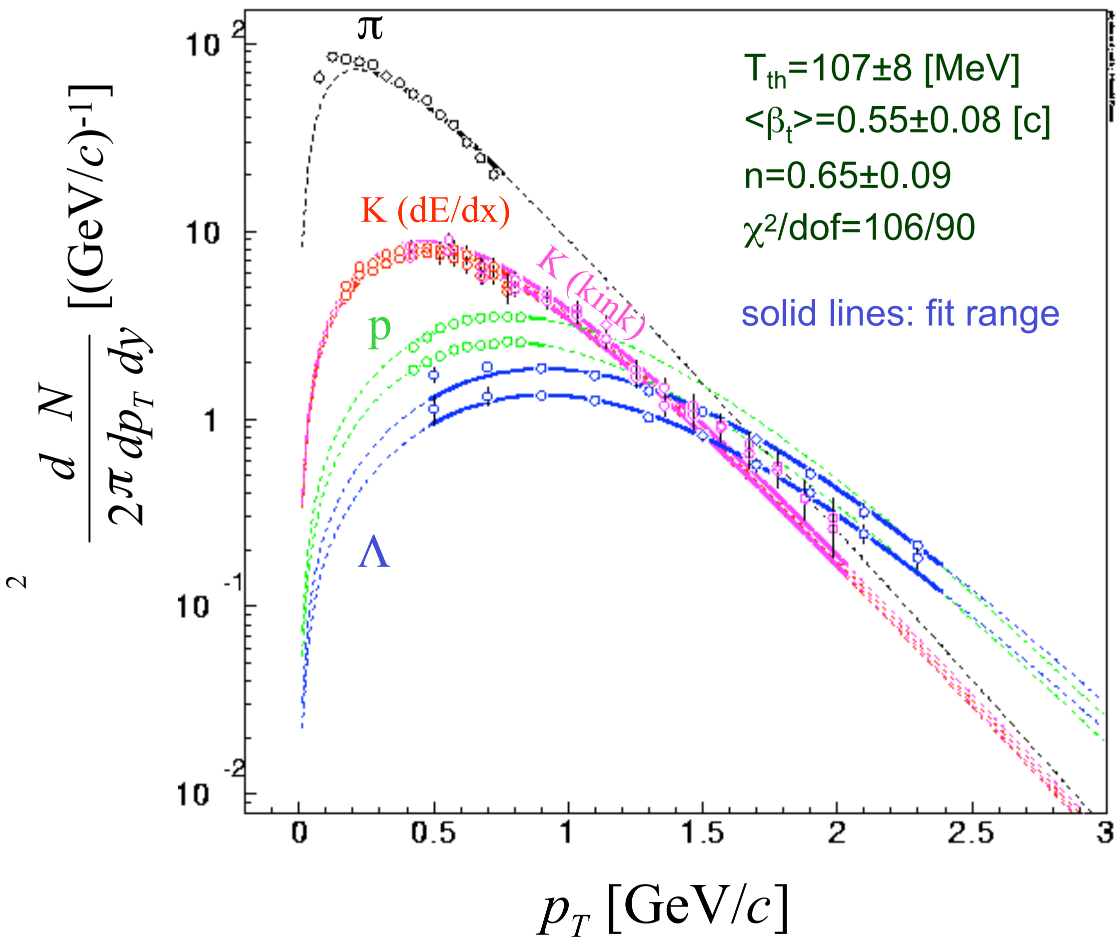
In A+A collisions, ***interactions among constituents*** *and* density distribution lead to:

pressure gradient $\Rightarrow$ collective flow



$\Leftrightarrow$ number of degrees of freedom (dof)
$\Leftrightarrow$ Equation of State (EOS)
$\Leftrightarrow$ cumulative – *partonic* + *hadronic*

Momentum Distributions*

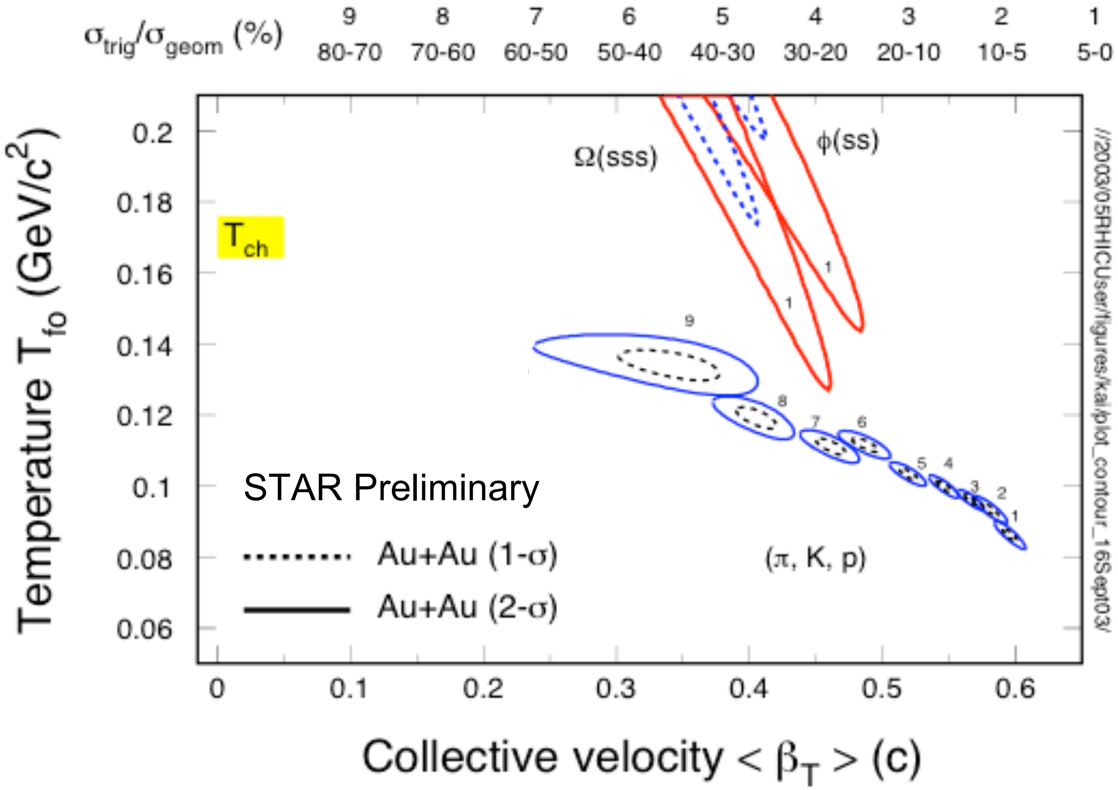


- Typical mass ordering in inverse slope from light π to heavier Λ
- Two-parameter fit describes yields of
  π, K, p, Λ
- T_{th} = 90 ± 10 MeV
- $\langle\beta_t\rangle$ = 0.55 ± 0.08 c

→ ***Disentangle collective motion from thermal random walk***

*Au+Au @130 GeV, STAR

Kinetic Freeze-out at RHIC



1) Multi-strange hadrons φ and Ω freeze-out earlier than (π, K, p)
⇨⇨ Collectivity prior to hadronization

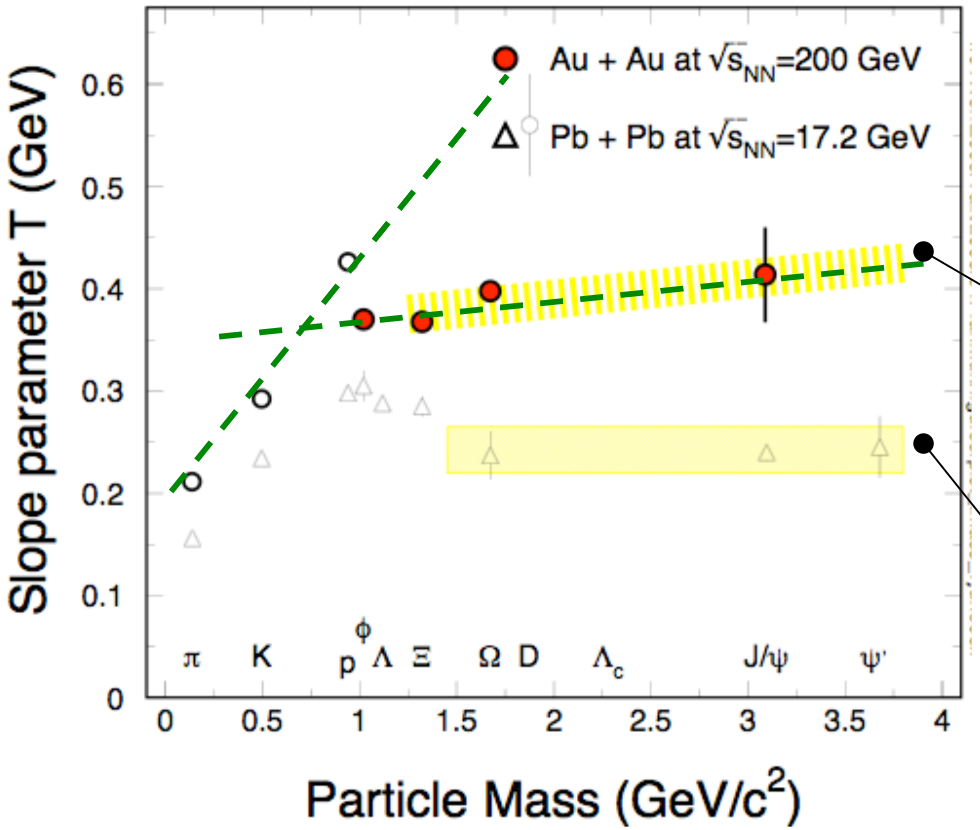
2) Sudden single freeze-out*: Resonance decays lower T_{fo} for (π, K, p)
⇨⇨ Collectivity prior to hadronization

⇨ **Partonic Collectivity**

STAR Data: Nucl. Phys. A757, (2005 102),

*A. Baran, W. Broniowski and W. Florkowski, Acta. Phys. Polon. B 35 (2004) 779.

Slope Parameter Systematics



$$f = A \bullet \exp\left(-m_T / T_{slope}\right)$$

RHIC results:
Collective motion for multi-strange and charm hadrons!

$\langle \beta_p \rangle \geq 0.2c$

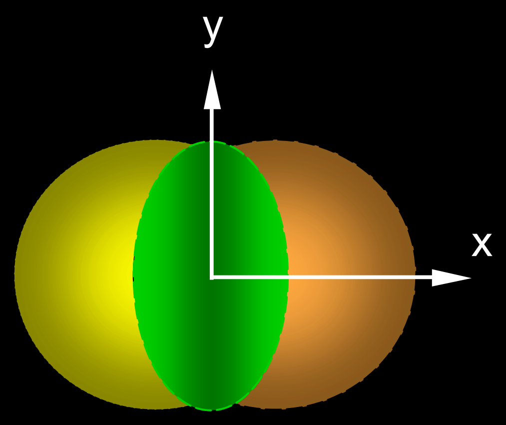
SPS results:
No collective motion for multi-strange and charm hadrons!

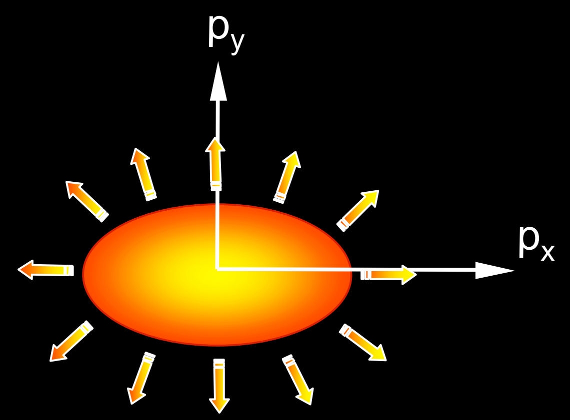
At RHIC, φ, Ξ, Ω, and J/ψ show collective motion in 200 GeV Au + Au central collisions!

PHENIX (π, K, p, J/ψ): PRC69, 034909(04), QM05; STAR (φ, Ξ, Ω): QM05.

Anisotropy Parameter v_2

coordinate-space-anisotropy ⇔ momentum-space-anisotropy



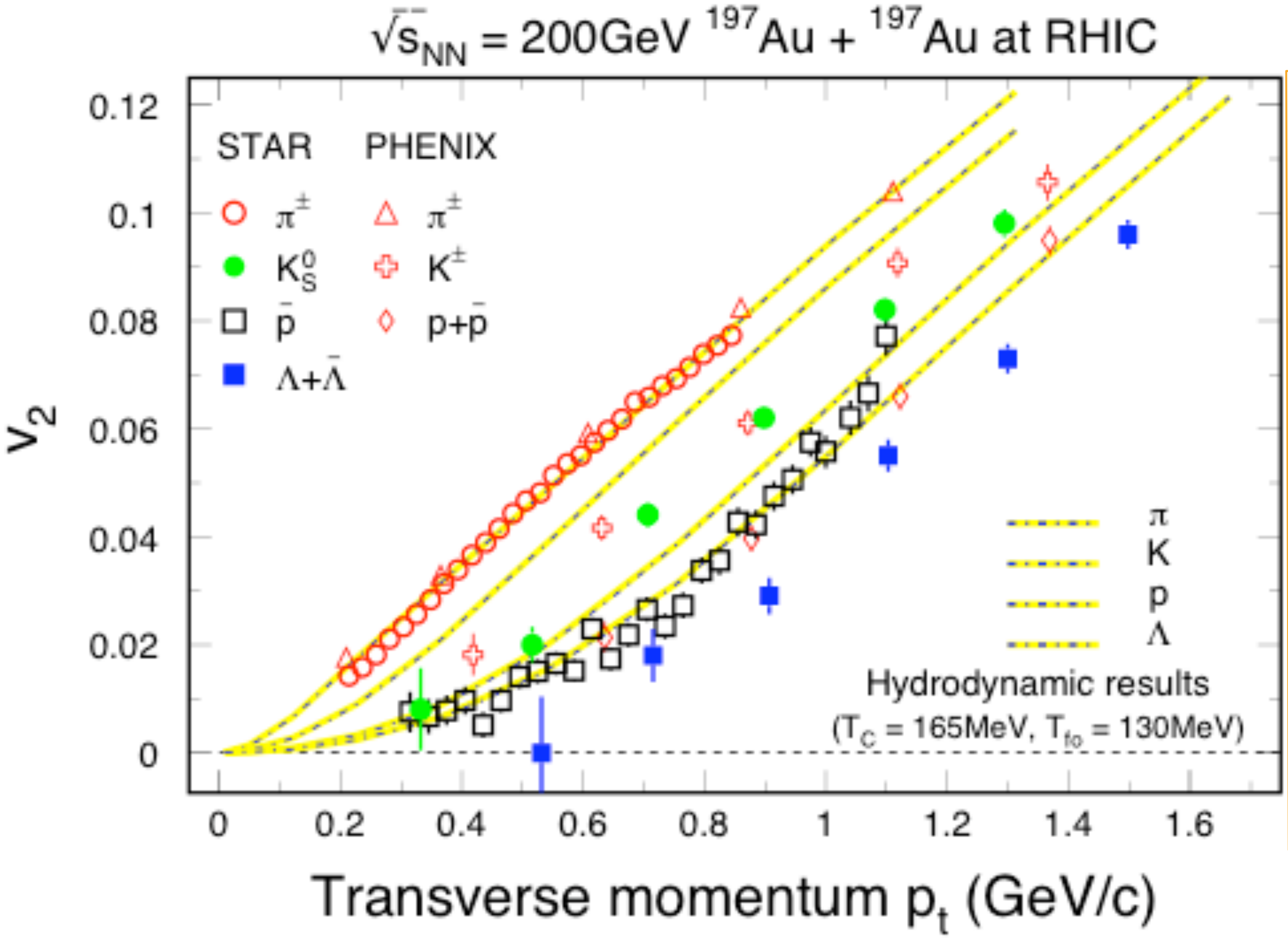


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freed

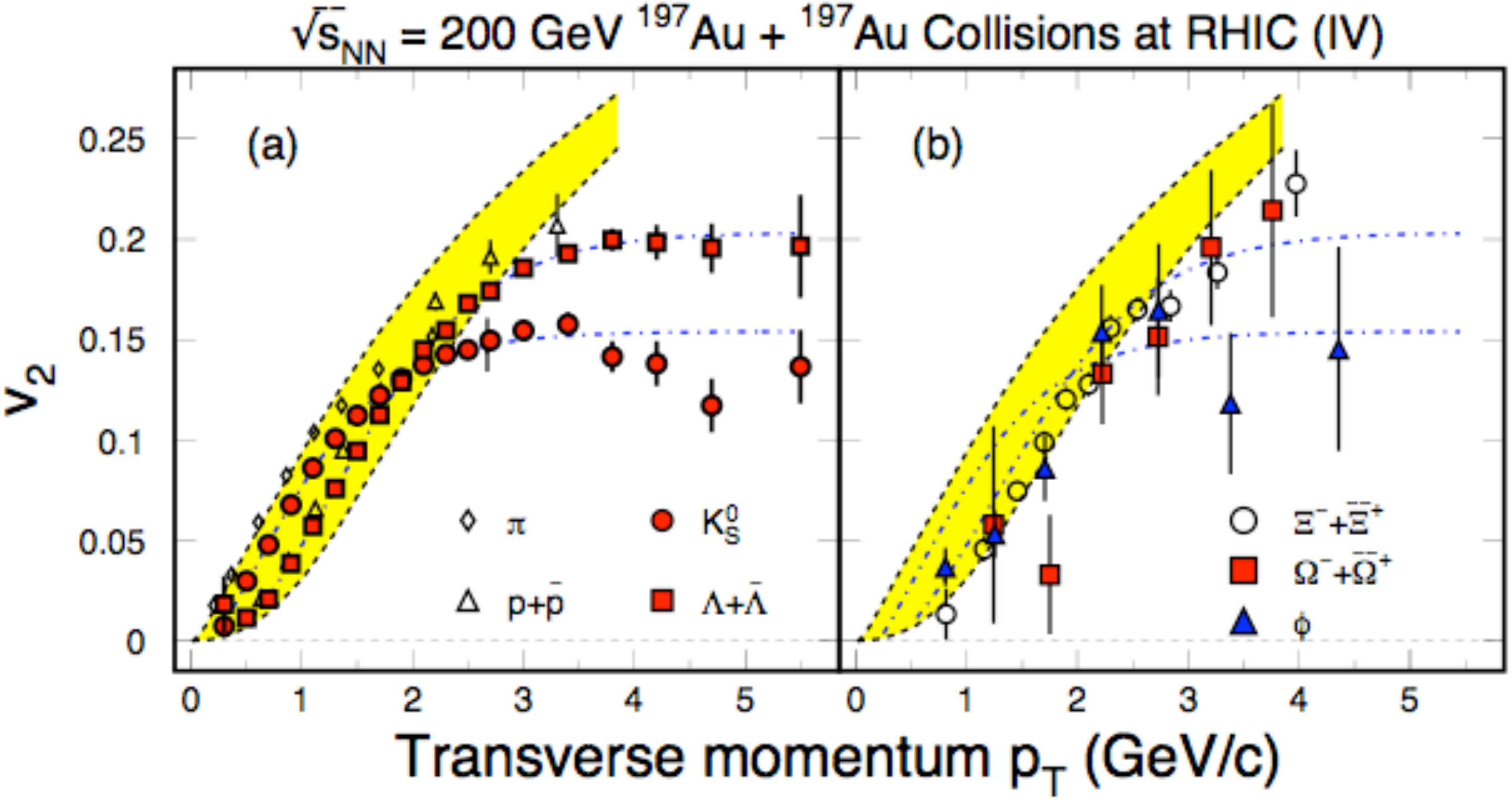
v_2 in the Low-p_T Region



P. Huovinen, private communications, 2004

- Minimum bias data! At low p_T, model result fits mass hierarchy well!
- Details do not work, need more flow in the model!

v_2 of Multi-strange Hadrons
ϕ and Ω



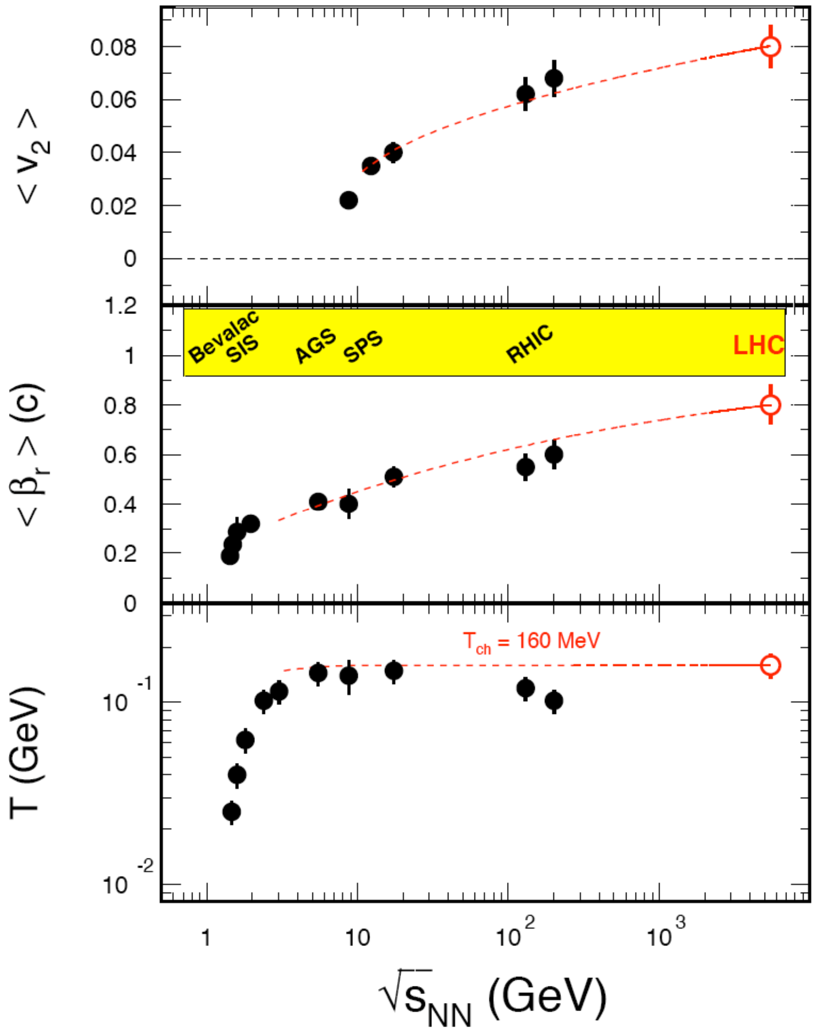
Strange-quark flow – partonic collectivity at RHIC!

NB: $\Phi \rightarrow K^+ + K^-$ (BR 49%)

$\Phi \rightarrow e^+ + e^-$ (BR 0.03%)

QM05 conference: M. Oldenburg; nucl-ex/0510026.

Collectivity – Energy Dependence



- Collectivity parameters $<\beta_T>$ and $<v_2>$ increase with energy
- Two extreme scenarios:

(a) $T_{fo} \approx T_{ch}$ AND $\beta_T \approx 0.8$

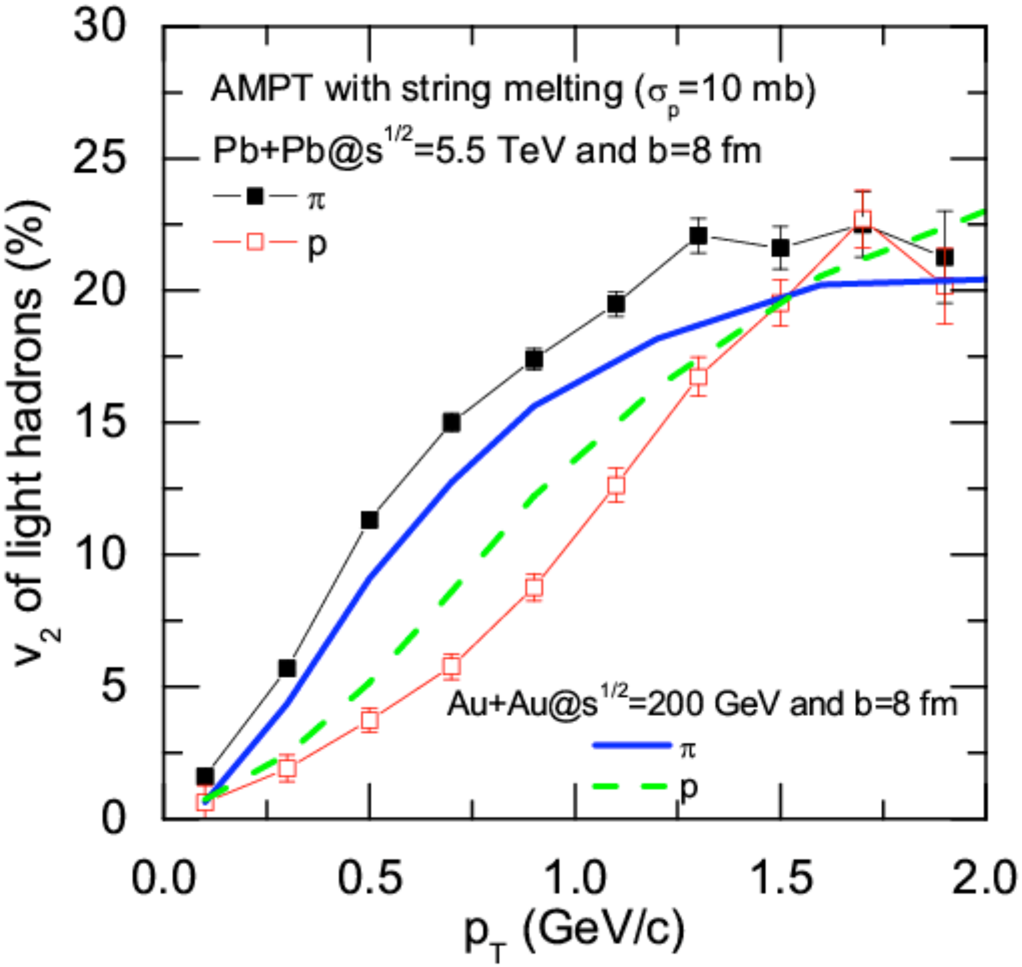
→ ***pure partonic collectivity at LHC!***

(b) $T_{fo} \approx T_{ch}$, $\beta_T \approx 0.3$

→ ***no collectivity, no QGP !***

K.S., ISMD07, arXiv:0801.1436/\[nucl-ex].

Elliptic Flow at LHC



"Elliptic flow is larger for pions but smaller for protons at LHC than at RHIC".

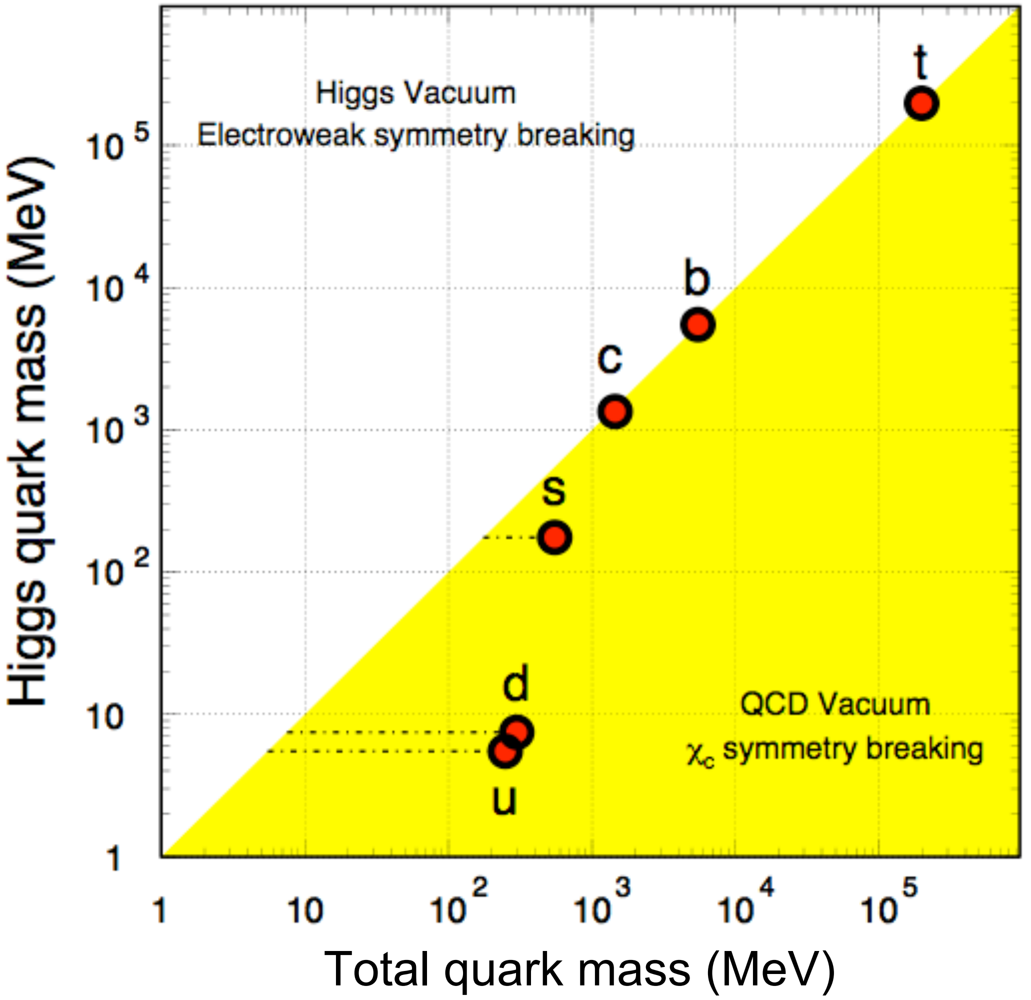
→ ***This is expected from simple, hydro-like blast-wave fits !***

→ ***larger collective flow: mass ordering more pronounced !***

→ ***sensitive to partonic EOS !***

Theory points: C.M. Ko – last call for predictions, CERN, May 2007.

Quark Masses



1) Higgs mass: electro-weak symmetry breaking (current quark mass).
2) QCD mass: Chiral symmetry breaking (constituent quark mass).

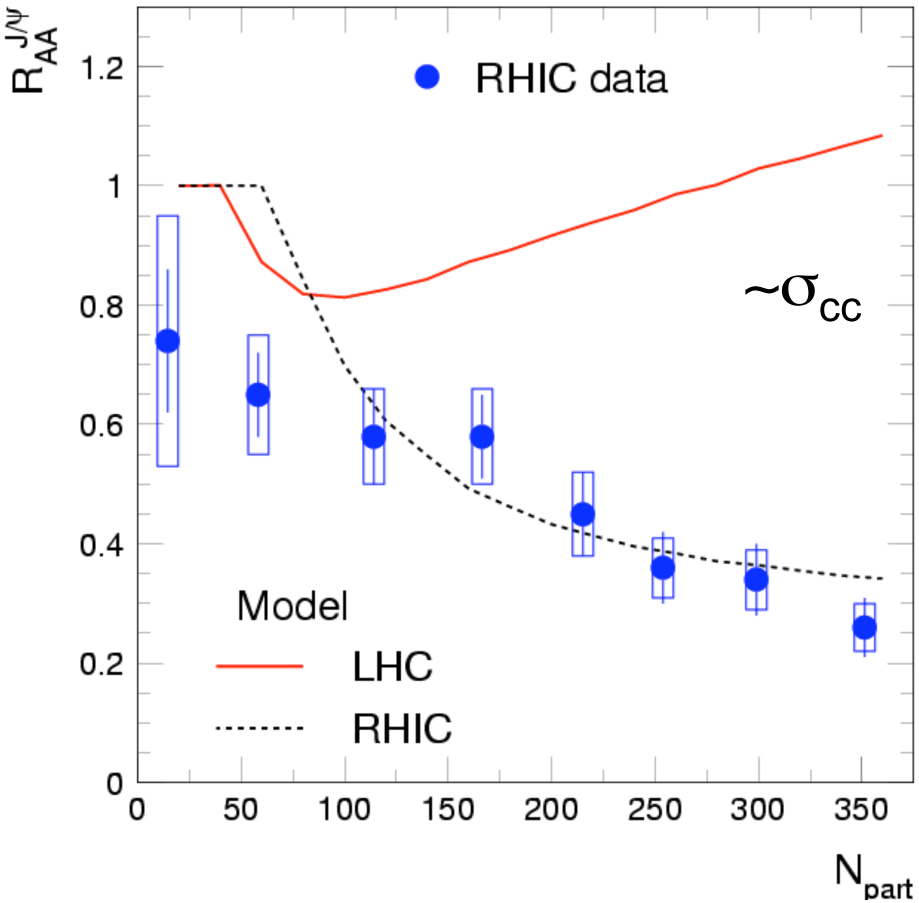
⇨ Strong interactions do not affect heavy-quark masses.

⇨ Important tool for studying properties of the hot/dense medium at RHIC and LHC.

⇨ Test pQCD predictions at RHIC and LHC.

X. Zhu, M. Bleicher, K.S., H. Stoecker, N. Xu et al., PLB 647 (2007) 366.

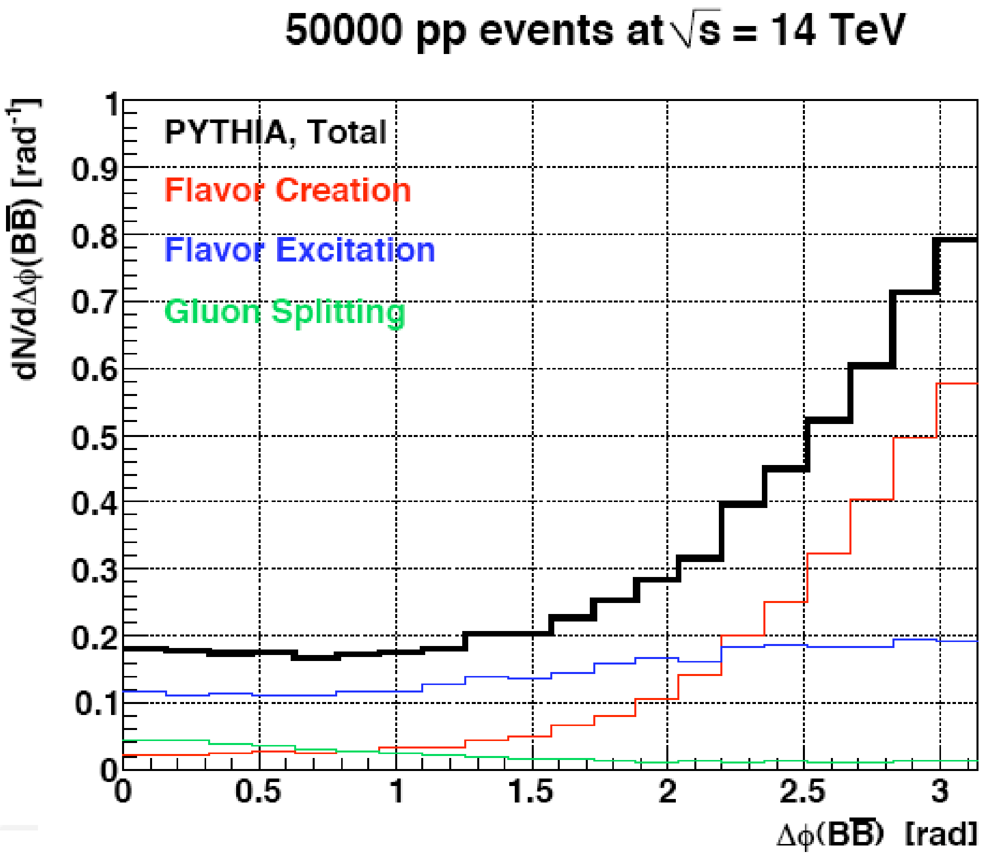
Predictions for LHC

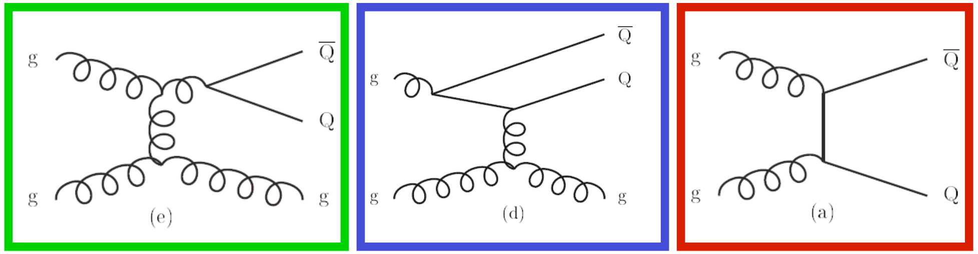


- large charm production at LHC
- strong regeneration of J/ψ
- striking centrality dependence
- ***Signature for QGP formation !***
- Initial conditions at LHC ?
- ***Need to measure total charm production in PbPb !***
- Also: check ψ'/ψ ratio vs stat. model predictions

A. Andronic et al., Phys. Lett. B 652 (2007) 259.

Beauty Correlations





b-bbar are correlated

- Pair creation: back to back
- Gluon splitting: forward
- Flavor excitation: flat

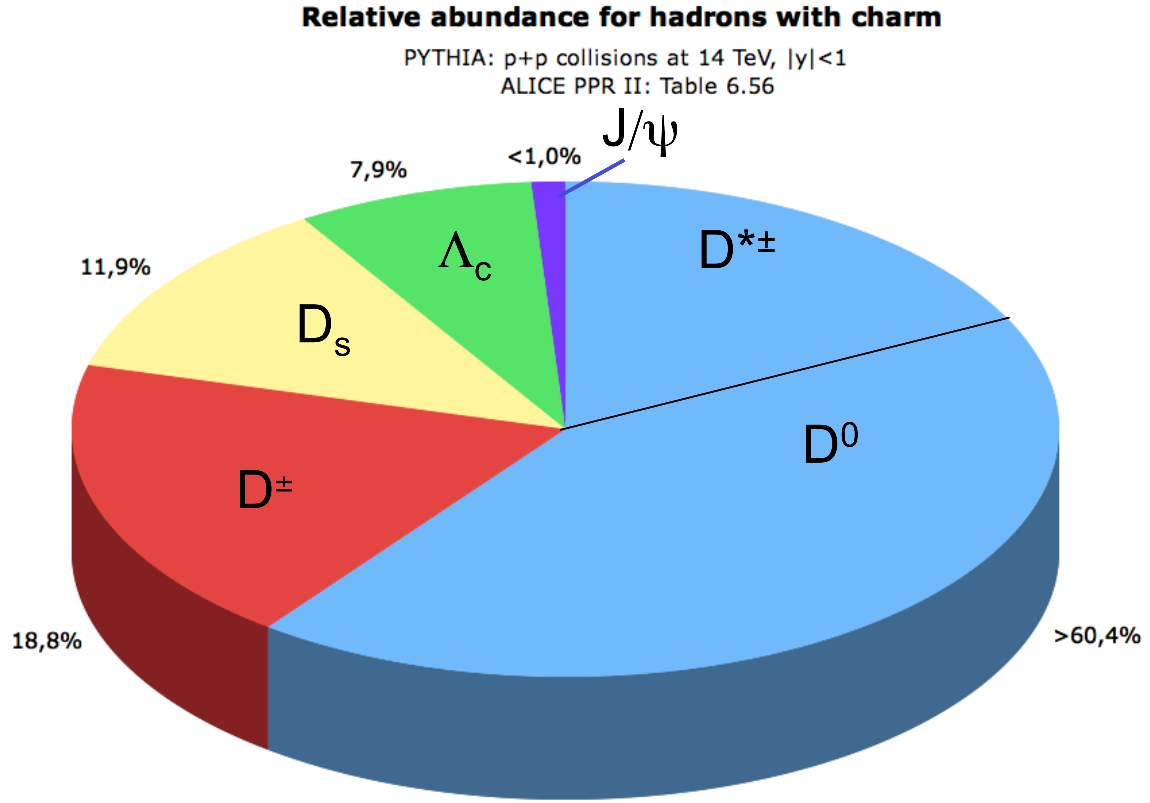
Correlations vanish

→ ***frequent interactions among partons !***

→ ***probe light-quark thermalization !***

Pythia calcs.: G. Tsiledakis.

Where does all the charm go?



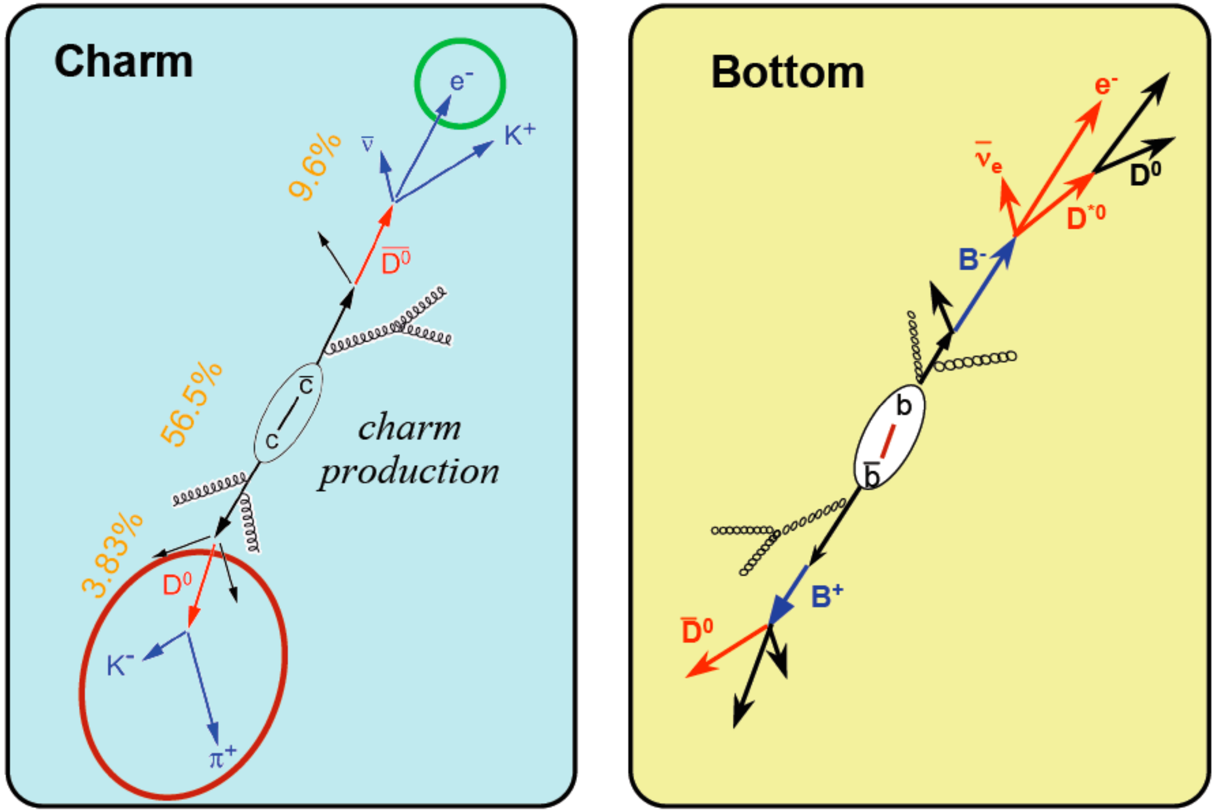
- Measure open-charm mesons, e.g. D^0 and D^* to address:

  (a) total charm production

  (b) heavy-quark collectivity

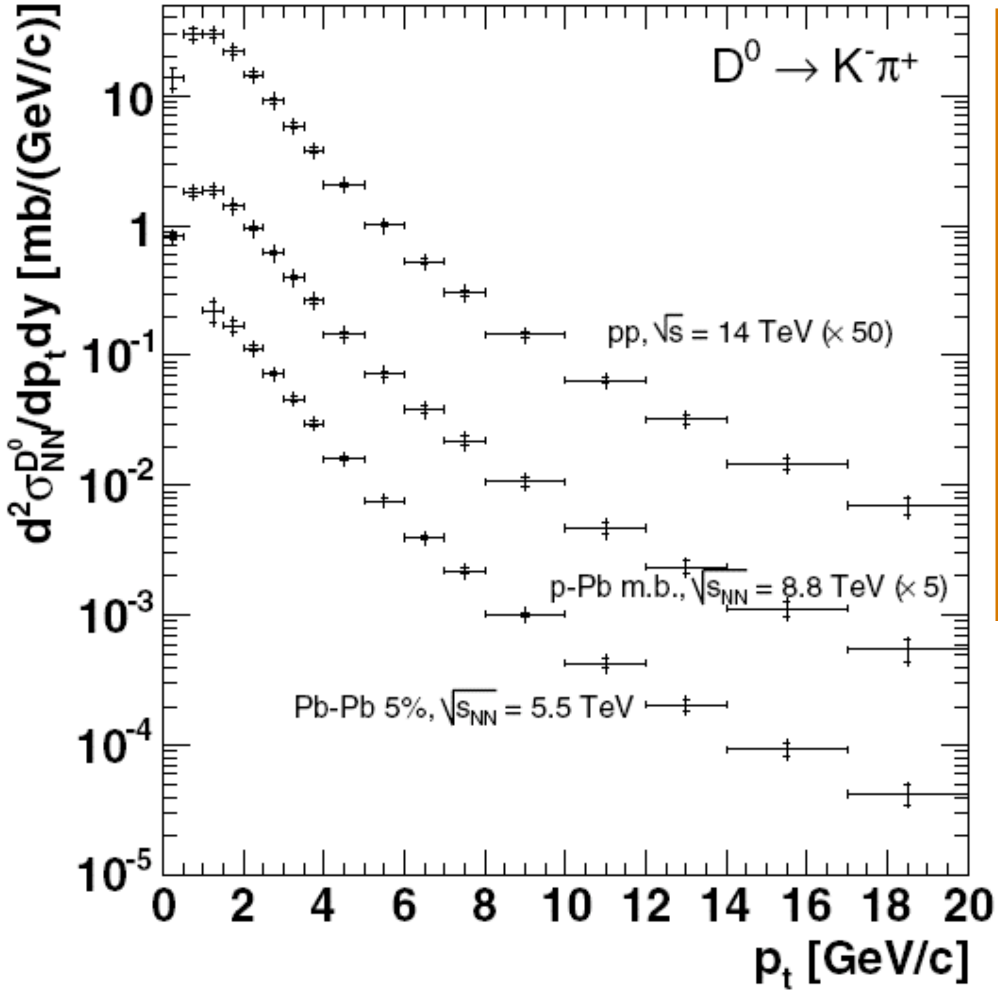
Statistics plot: H. Yang and Y. Wang.

How to measure Heavy-Quark Production



- Measure
  - single e ⇒ total (c+b) production
  - D^0 and D^* ⇒ heavy quark collectivity and total c (+b) cross section
  - B → J/ψ + X, B^+, Λ_b ⇒ disentangle c and b !

D^0 – Meson Performance



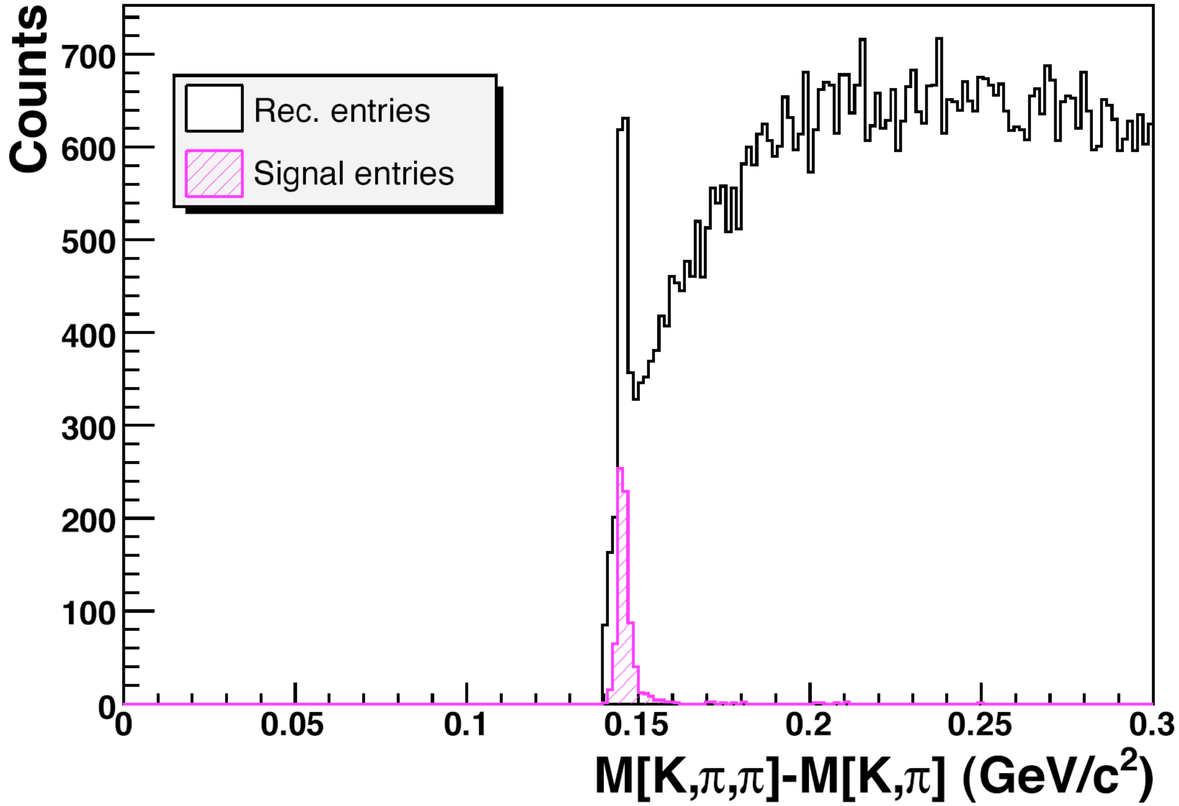
- Measure secondary vertex
  → Direct reconstruction of D^0

→ precise measurement of total heavy-quark yield

→ address heavy – quark collectivity !

ALICE: PPR.vol.II, J. Phys. G 32 (2006) 1295.

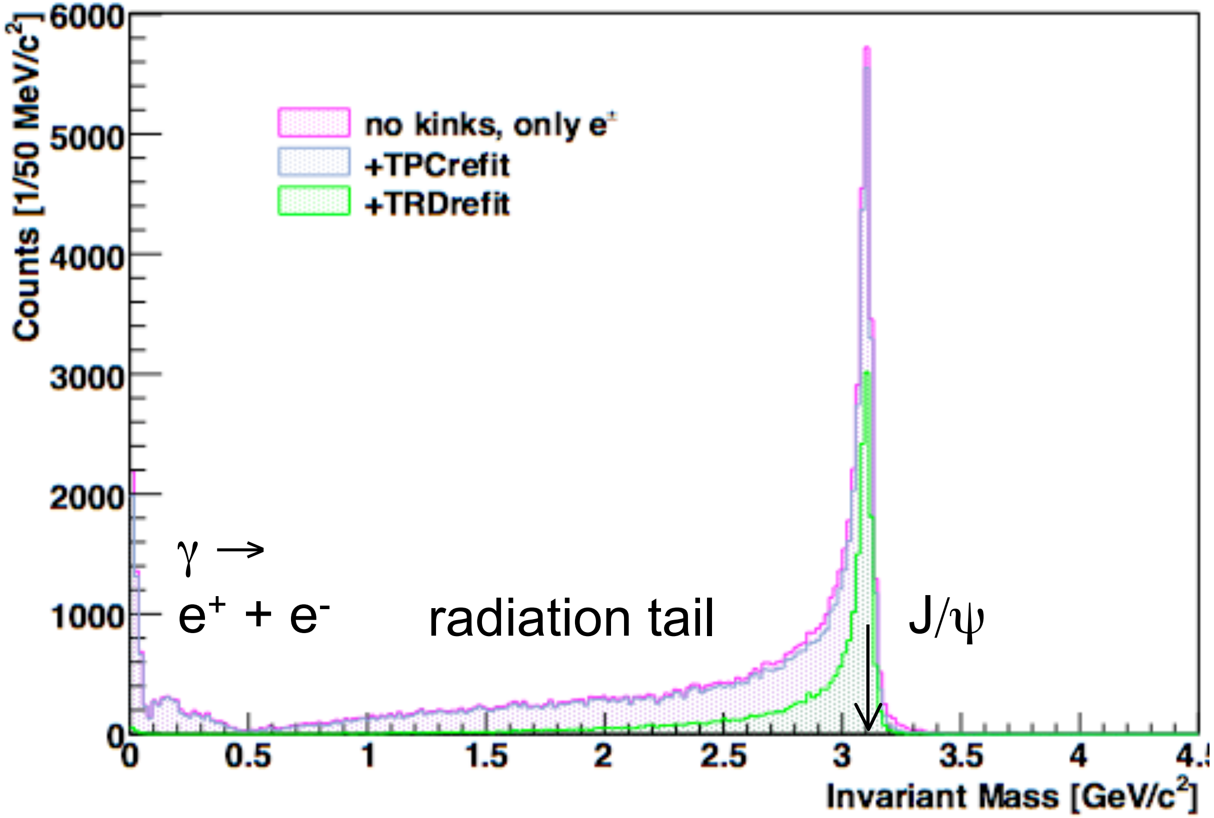
D*– meson Identification



- $D^{*+} \rightarrow D^0 + \pi^+$
- Identify D^{*+} through $\Delta M[D^{*+} - D^0]$
- Subtract resonance decay to D^0
- Two different methods to address total charm production

D*± analysis: Yifei Wang, Heidelberg

J/ψ – Identification



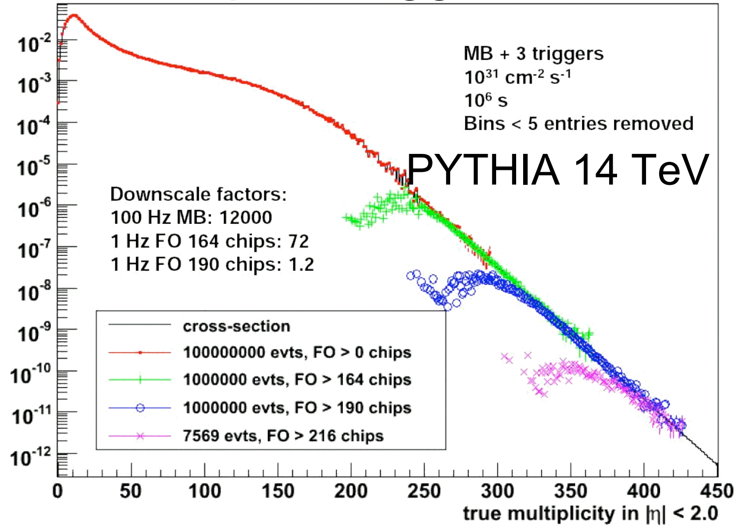
- J/ψ → $e^+ + e^-$
- Identify through invariant mass
- e → e + γ leads to signal loss (30%)
- $e^\pm$-pairs form photon conversion at low inv. Mass

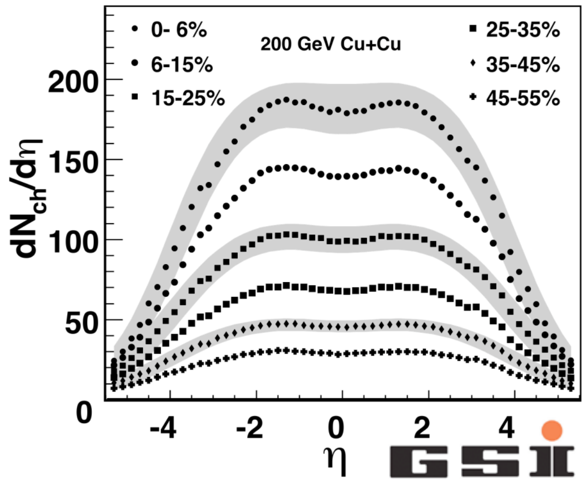
J/ψ analysis: Dirk Krumbhorn, Heidelberg
Also: Wolfgang Sommer, Frederik Kramer, Frankfurt

Collectivity in p+p @ 10 TeV ?

- At RHIC, global observables scale with multiplicity
- p+p @10TeV, $dN_{ch}/d\eta$ up to 100
- Similar to mid-central Cu+Cu collisions at top RHIC energy
- Look for collectivity in p+p @ LHC !

ALICE pixel trigger:





ALICE MC data: A. Dainese, HP2008;
PHOBOS multiplicity: nucl-ex 0709.4008;
Z. Chajecki and M. Lisa, arXiv:0807.3569 [nucl-th].

Summary

- Bulk properties at LHC:

  $T_{ch} \approx 160 \pm 10$ MeV, $\mu_B \approx 0 - 5$ MeV

  $T_{fo} \approx T_{ch} \rightarrow$ all collectivity from partonic stage

  $\langle\beta_T\rangle = 0.8 \pm 0.05$ (c), $\langle v_2\rangle \approx 0.08$

- In Pb+Pb (p+p) measure spectra, correlations and v_2 of:

  D^0, $D^{*\pm}$, D^+, D_s, J/ψ, ψ', Λ_b, Υ

  to ***identify and characterize QGP !***

- ALICE with ITS, TPC, TRD and ToF

  is well suited for these studies