(Some) Bulk Properties at RHIC

Many thanks to organizers !

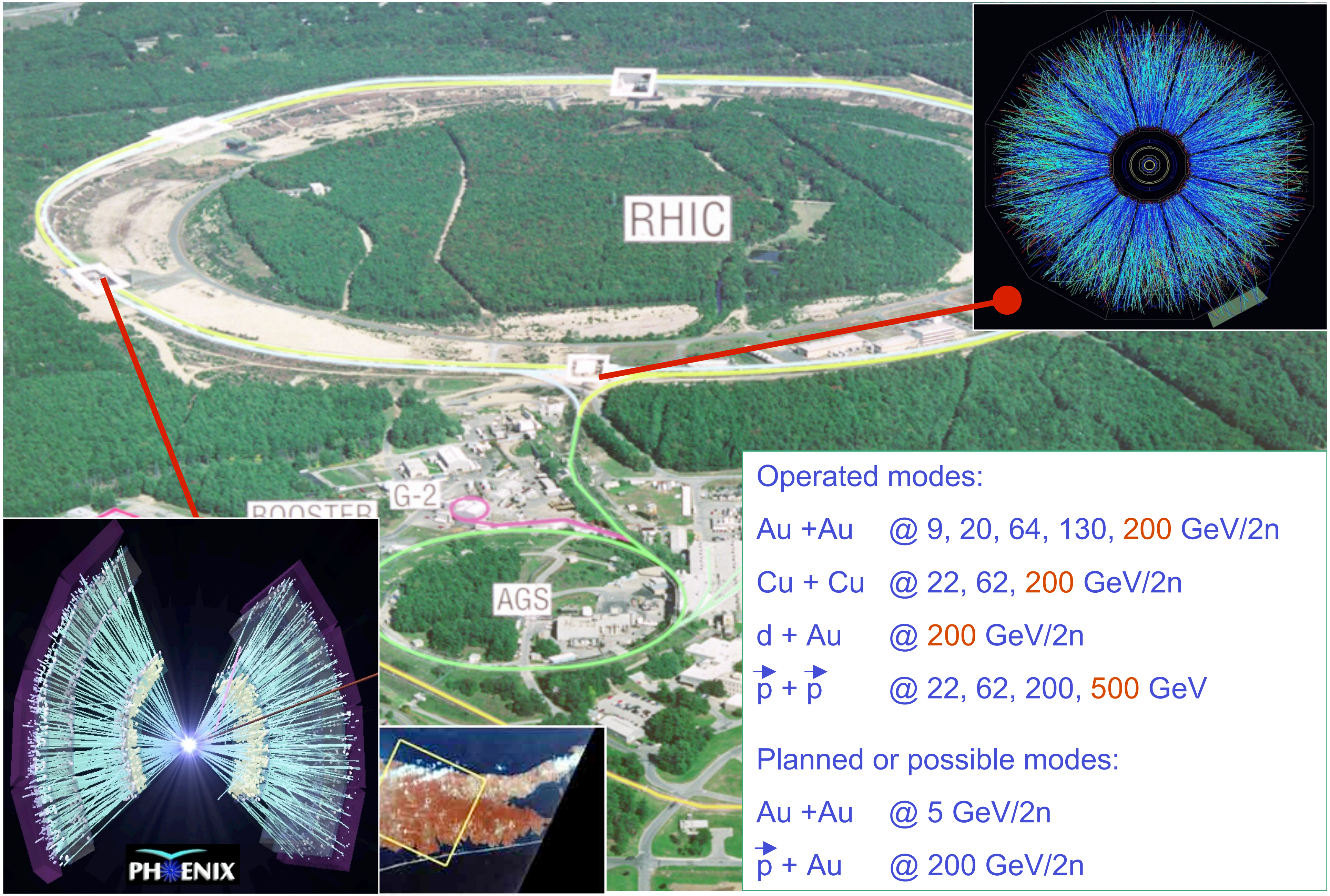
Kai Schweda, University of Heidelberg / GSI Darmstadt

HELMHOLTZ ASSOCIATION

GSI

Outline

- Introduction
- Collectivity at RHIC
  - transverse radial flow
  - tranverse elliptic flow
  - extracting η/s
- Heavy – quark dynamics
- Summary



Operated modes:

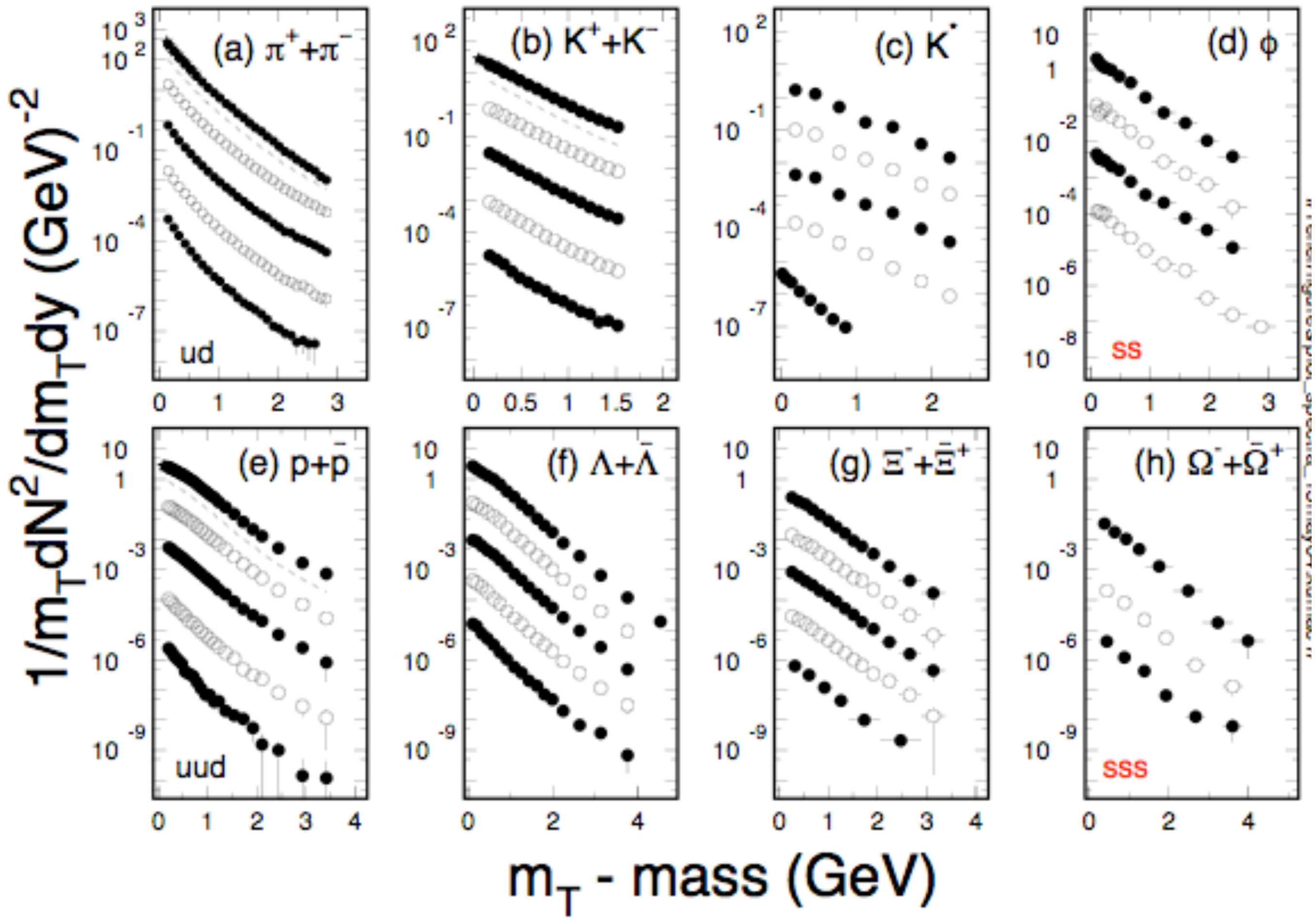
Au +Au	@ 9, 20, 64, 130, 200 GeV/2n
Cu + Cu	@ 22, 62, 200 GeV/2n
d + Au	@ 200 GeV/2n
$\vec{p} + \vec{p}$	@ 22, 62, 200, 500 GeV

Planned or possible modes:

Au +Au	@ 5 GeV/2n
$\vec{p}$ + Au	@ 200 GeV/2n

Hadron spectra from RHIC

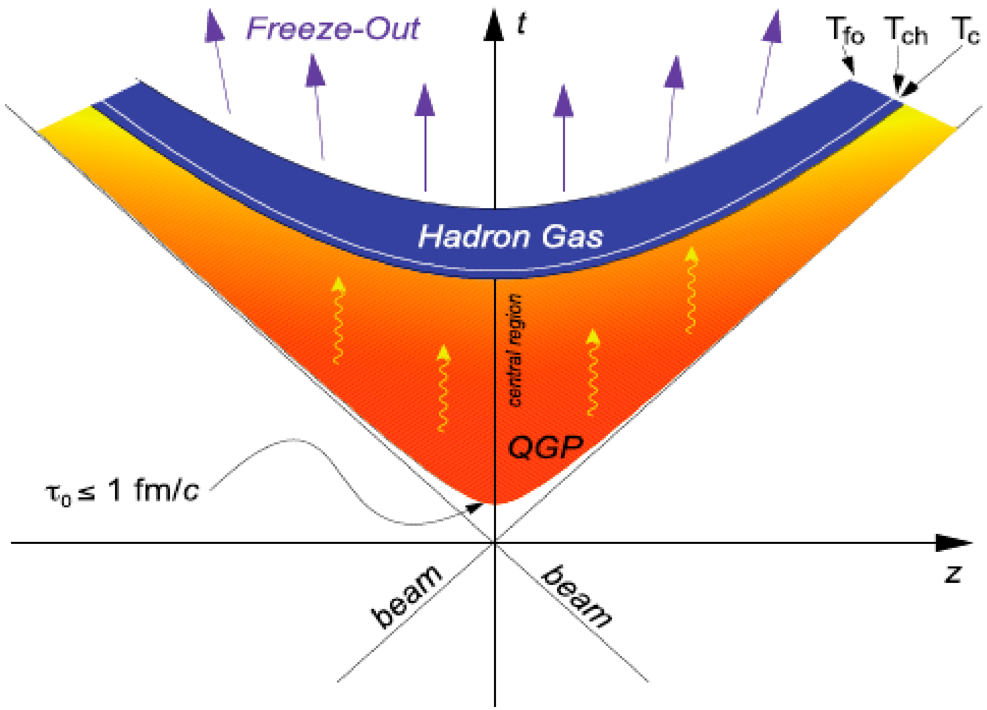
p+p and Au+Au collisions at 200 GeV



Full kinematic **reconstruction** of (multi-) **strange hadrons** in large acceptance of STAR

White papers - STAR: Nucl. Phys. A757, p102.

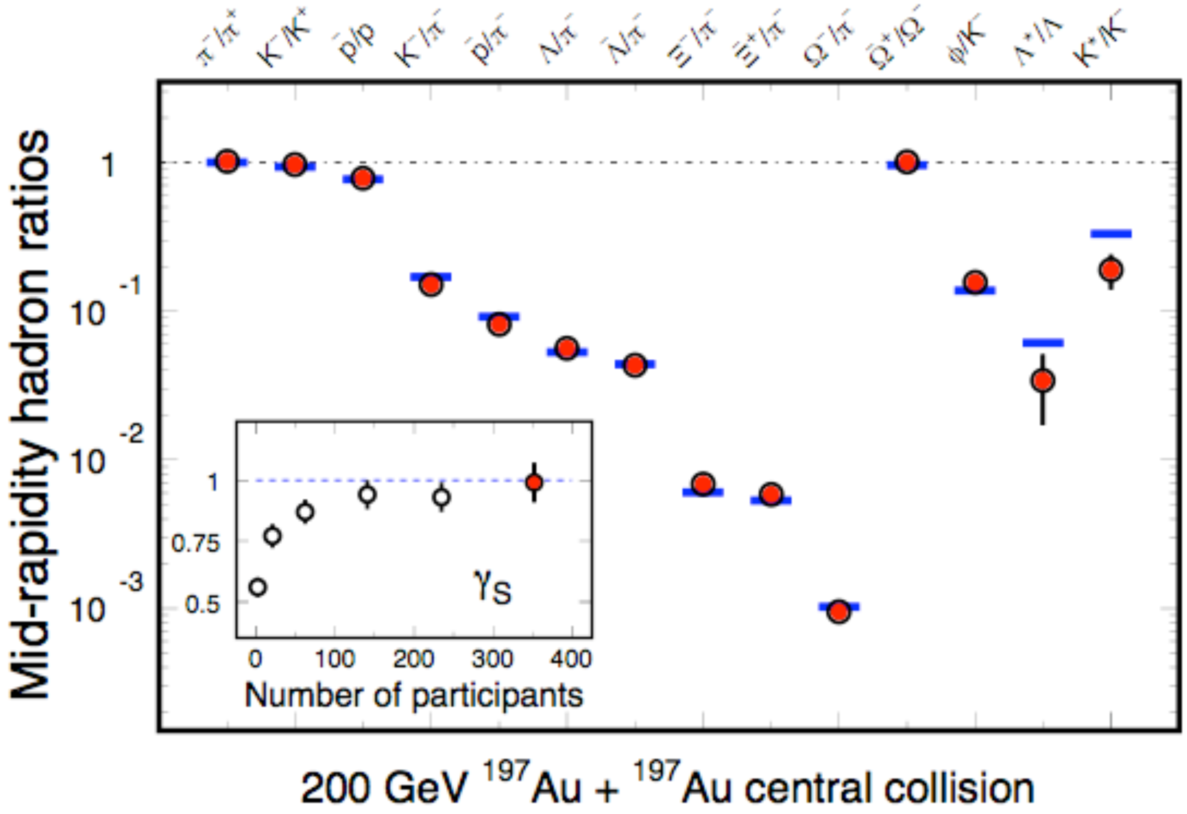
HI - Collision History



- $T_{c(ritical)}$: quarks and gluon ⇒ **hadrons**
- $T_{ch(emical)}$: **hadron abundancies** freeze out
- T_{fo}: **particle spectra** freeze out

Plot: R. Stock, arXiv:0807.1610 [nucl-ex].

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, ...

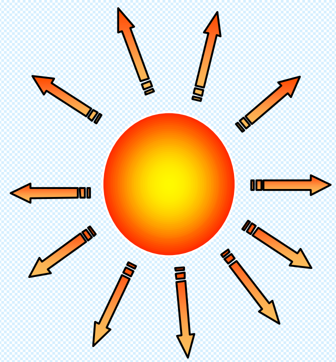
Thermodynamic identity

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:

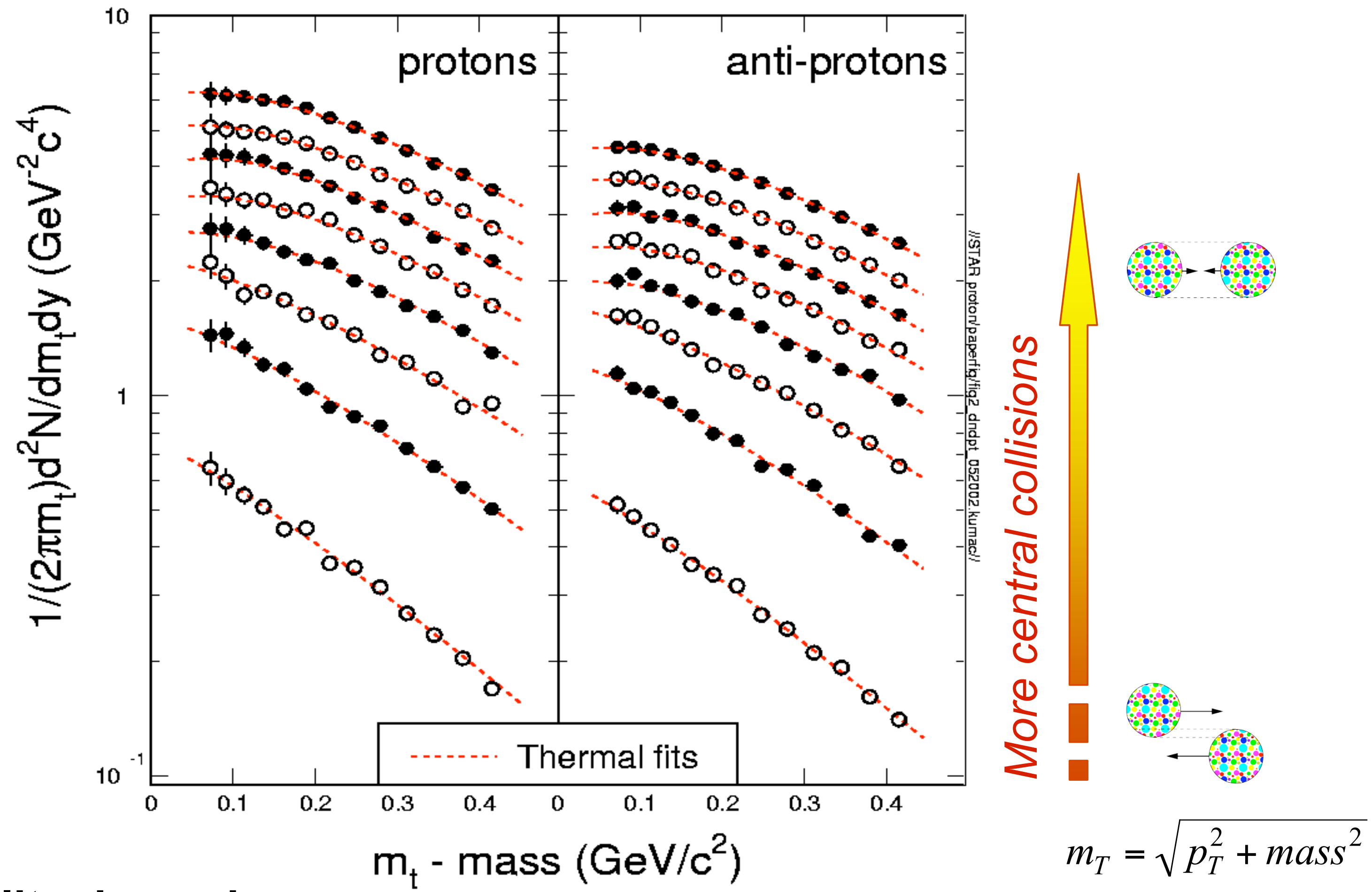
pressure gradient $\Rightarrow$ collective flow



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

(anti-)Protons From RHIC

Au+Au@130GeV



$m_T = \sqrt{p_T^2 + mass^2}$

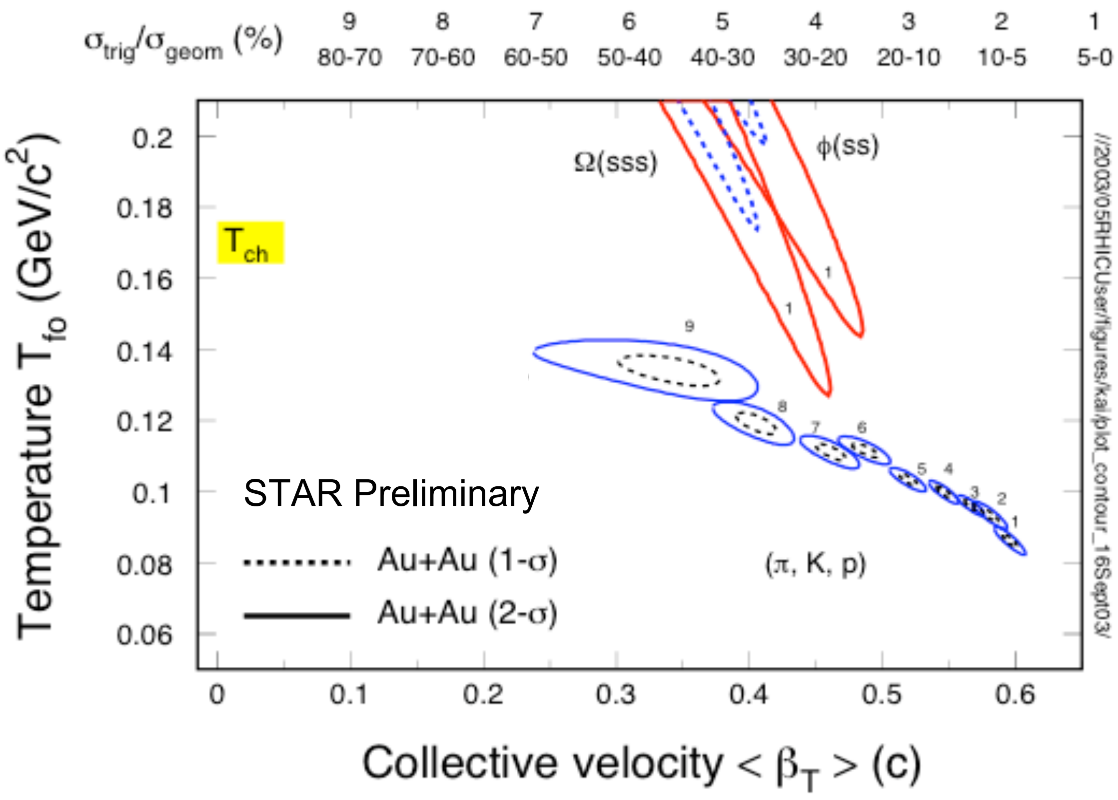
Centrality dependence:

- spectra at low momentum de-populated, become flatter at larger momentum

➠ ***stronger collective flow in more central coll.!***

STAR: Phys. Rev. C70, 041901(R).

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

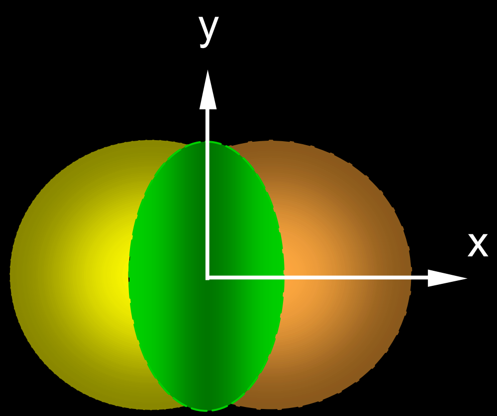
⇨ **Partonic Collectivity ?**

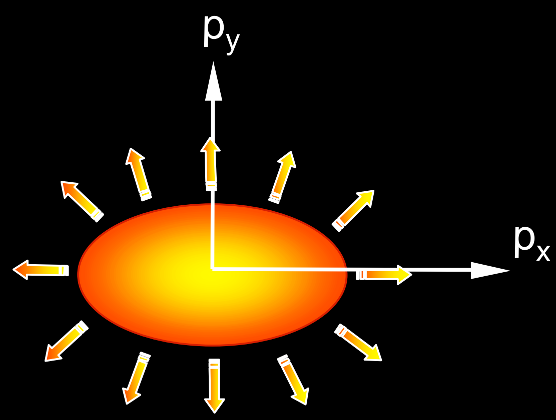
STAR Data: Nucl. Phys. A757, (2005 102),

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

Anisotropy Parameter v_2

coordinate-space-anisotropy ⇔ momentum-space-anisotropy



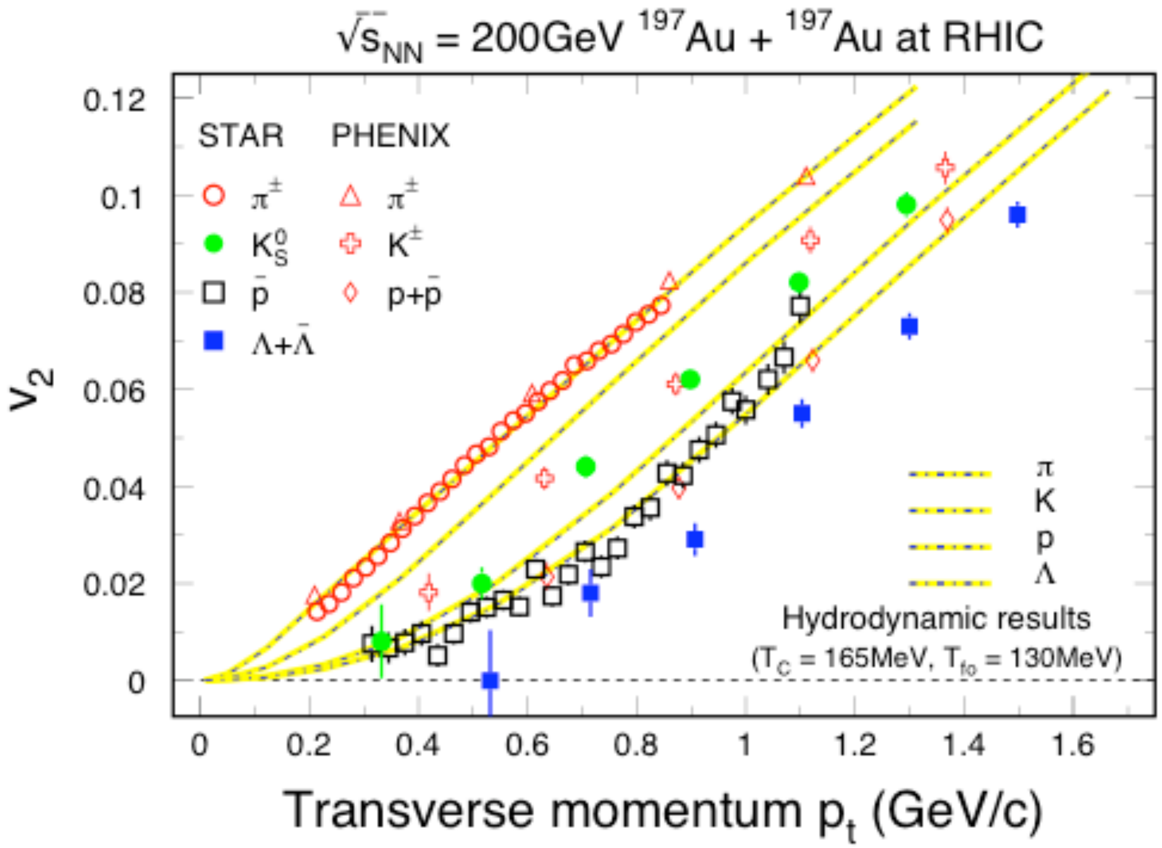


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

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

Initial/final conditions, EoS, degrees of freedom

v_2 in the Low-p_T Region



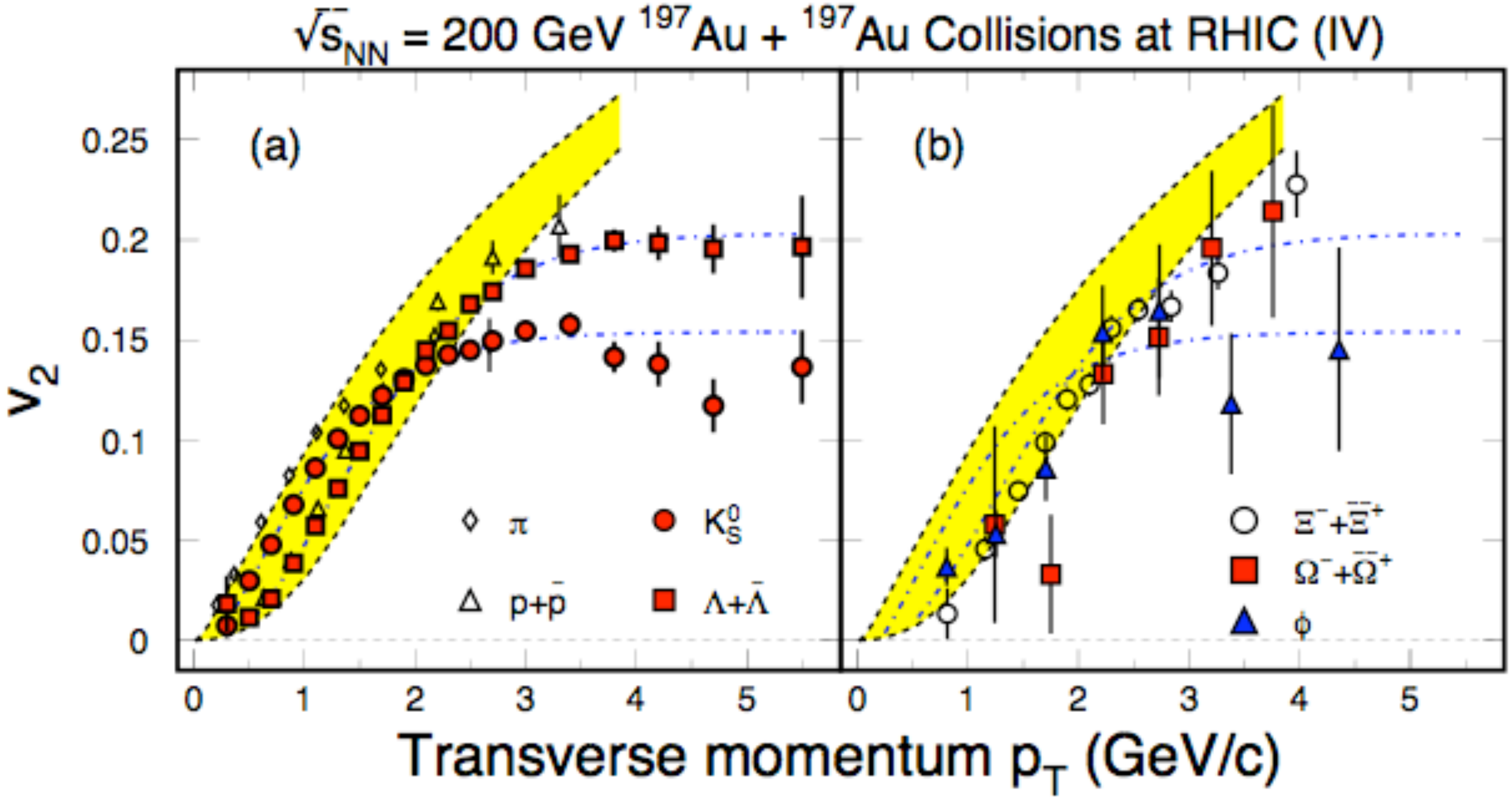
P. Huovinen, private communications, 2004

- v_2 approx. linear in p_T, **mass ordering** from **light** π to **heavier** Λ

➠ ***characteristic of hydrodynamic flow !***

➠ ***sensitive to equation of state***

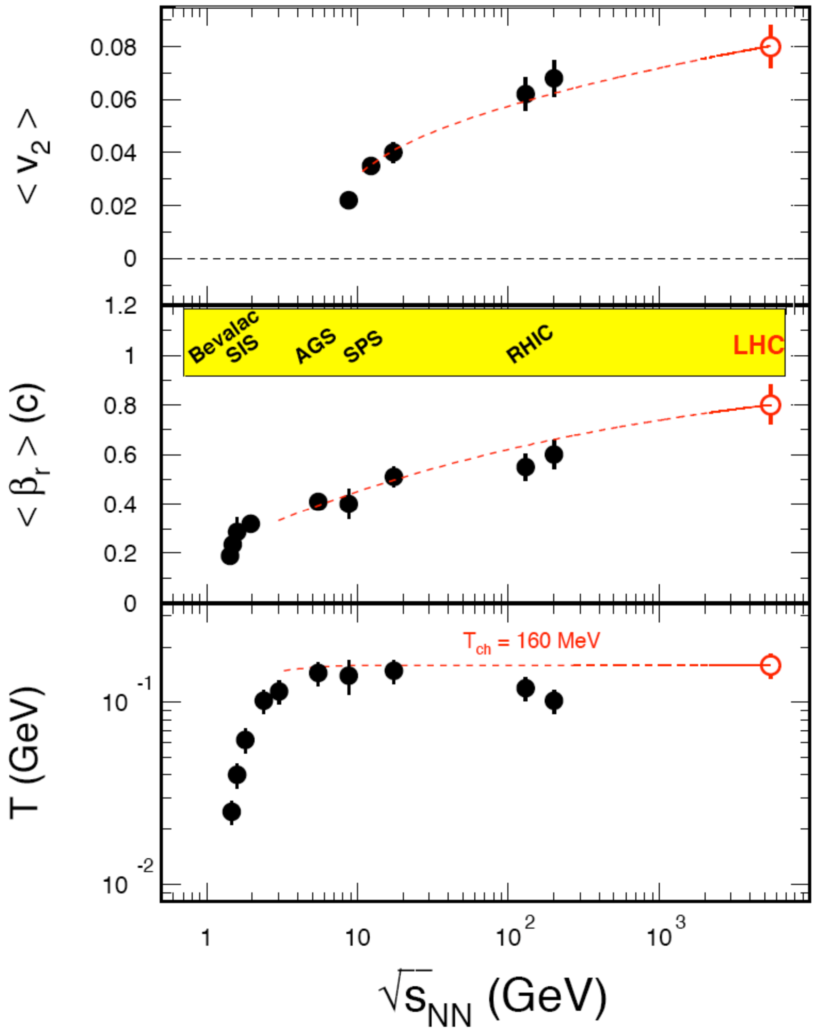
v_2 of ϕ and multi-strange Ω



➢ ***Strange-quark flow - partonic collectivity at RHIC !***

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

Collectivity – Energy Dependence



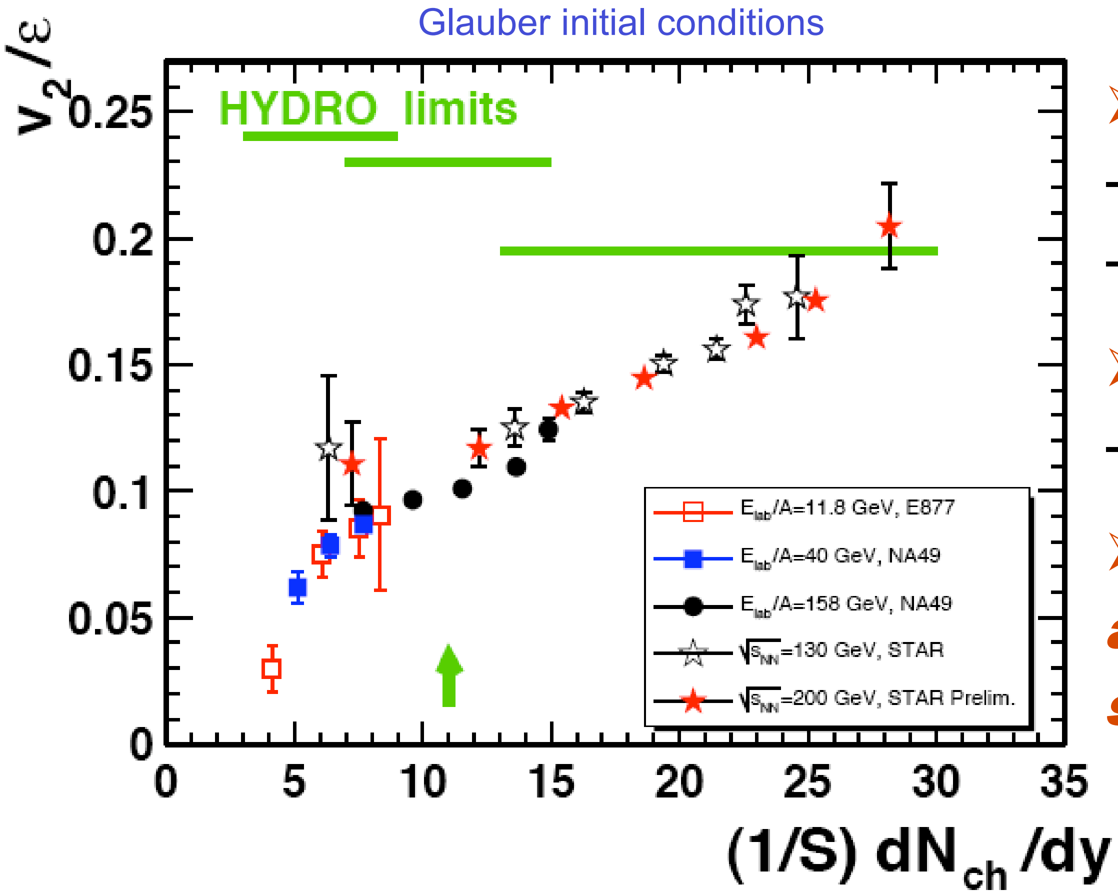
- **Collectivity parameters** $<\beta_T>$ and $<v_2>$ **increase** with collision energy
- ***strong collective expansion at RHIC !***

  $<\beta_T>_{RHIC} \approx 0.6$
- expect ***strong partonic expansion at LHC***,

  $<\beta_T>_{LHC} \approx 0.8$, $T_{fo} \approx T_{ch}$

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

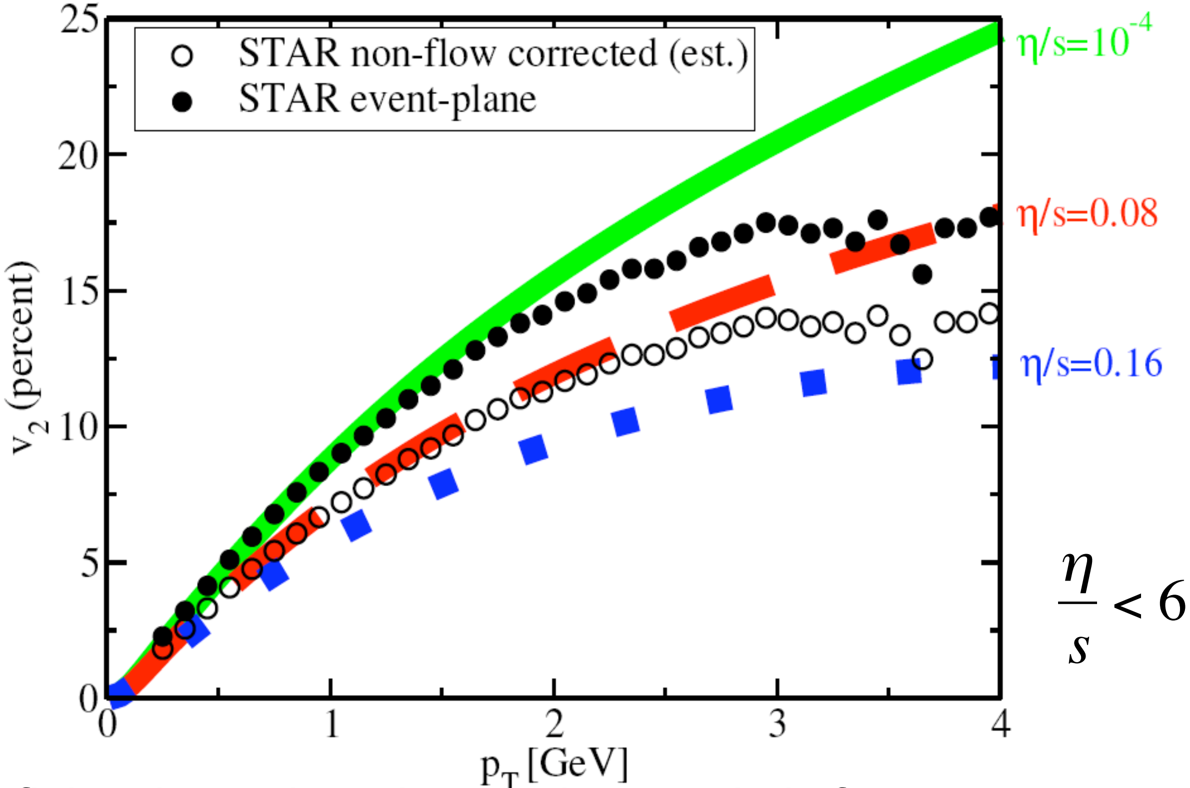
Elliptic Flow vs Collision Energy



- Centrality dependence:
  - initial eccentricity ε
  - overlap area S
- Collision energy dep.:
  - multiplicity density dN_{ch}/dy
- ***in central collisions at RHIC, hydro-limit seems reached !***

NA49, Phys. Rev. C68, 034903 (2003);
STAR, Phys. Rev. C66, 034904 (2002);
Hydro-calcs.: P. Kolb, J. Sollfrank, and U. Heinz, Phys. Rev.C62, 054909 (2000).

Non-ideal Hydro-dynamics



$$\frac{\eta}{s} < 6/4\pi$$

- finite shear viscosity η reduces elliptic flow
- many caveats, e.g.:
  - initial eccentricity ε (Glauber, CGC, …)
  - equation of state
  - hadronic contribution to η/s

cf. talks by D. Fernandez-Fraile and D. Rischke

M.Luzum and R. Romatschke, PRC 78 034915 (2008); P. Romatschke, arXiv:0902.3663.

Partonic Collectivity at RHIC

1) Copiously produced hadrons freeze-out π,K,p:

T_{fo} = 100 MeV, β_T = 0.6 (c) > β_T(SPS)

2) Multi-strange hadrons freeze-out:

T_{fo} = 160-170 MeV (~ T_{ch}), β_T = 0.4 (c)

3) Multi-strange v_2:

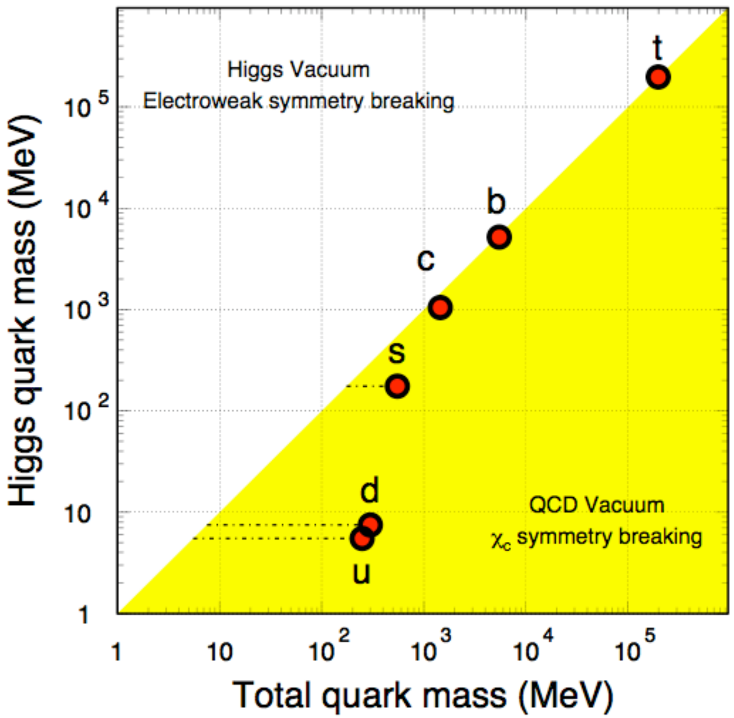
ϕ and multi-strange hadrons Ξ and Ω do flow!

4) Model - dependent η/s: (0?),1 - 10 x $1/4\pi$

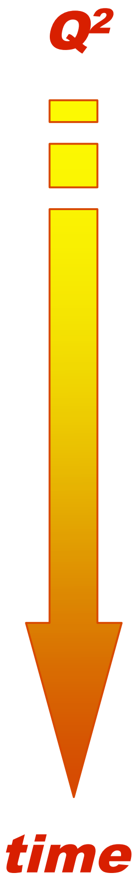
Deconfinement &

Partonic (u,d,s) Collectivity !

Heavy – flavor: a unique probe



X. Zhu, M. Bleicher, S.L. Huang, K.S., H. Stöcker, N. Xu, and P. Zhuang, PLB 647 (2007) 366.

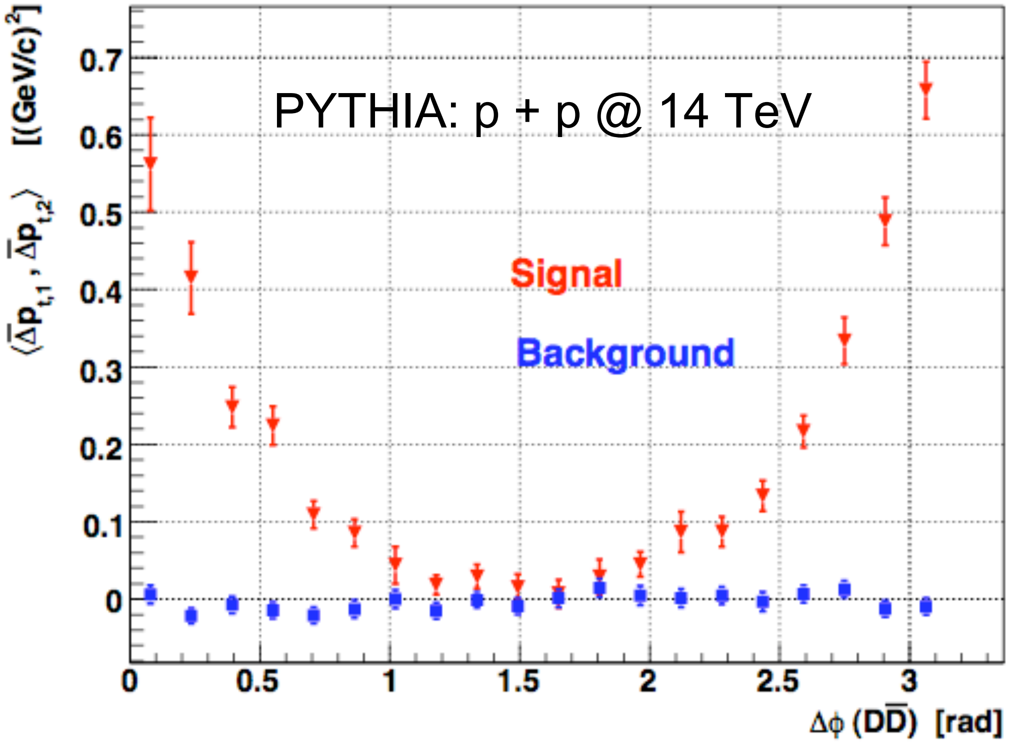


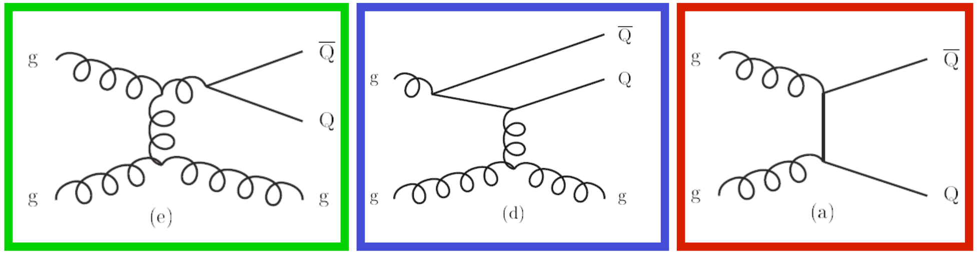
$m_{c,b} >> \Lambda_{QCD}$: new scale

$m_{c,b} \approx$ const., $m_{u,d,s} \neq$ const.

- **initial conditions:**
  - $\sigma_{c\bar{c}}$, $\sigma_{b\bar{b}}$
  - test pQCD, μ_R, μ_F
  - probe gluon distribution
- **early partonic stage:**
  - diffusion (γ), drag (α), flow
  - probe thermalization
- **hadronization:**
  - chiral symmetry restoration
  - confinement
  - statistical coalescence
  - J/ψ enhancement / suppression

Heavy – quark Correlations



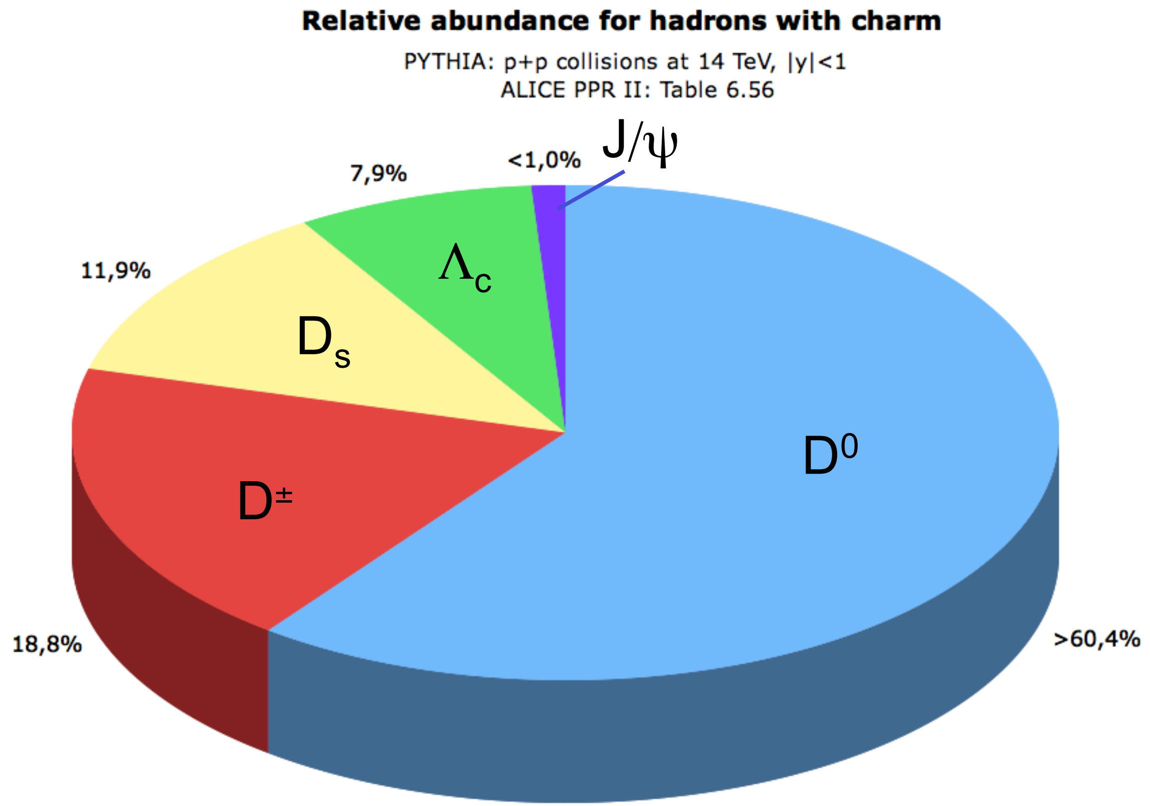


X. Zhu, M. Bleicher, S.L. Huang, K.S., H. Stöcker, N. Xu, and P. Zhuang, PLB 647 (2007) 366.
G. Tsildeakis, H. Appelshäuser, K.S., J. Stachel, arXiv: 0908.0427.

- **c-cbar** mesons are **correlated**
  - **Pair creation**: back to back
  - **Gluon splitting**: forward
  - **Flavor excitation**: flat
- Exhibits **strong correlations !**
- **Baseline** at **zero**: clear measure of **vanishing correlations !**

→ ***probe thermalization among partons !***

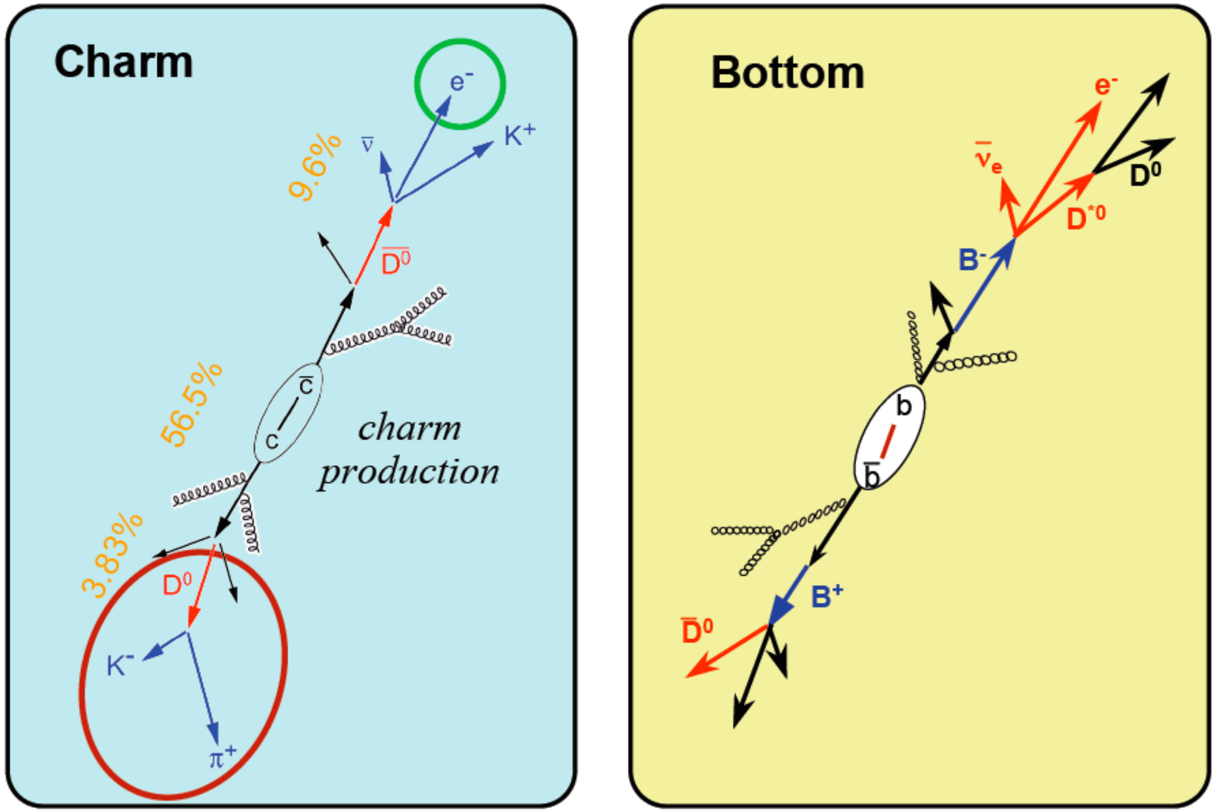
Where does all the charm go?



- Total charm cross section: open charm hadrons, e.g. D^0, D^*, Λ_c, … or c,b → e(μ) + X
- Hidden-charm mesons, e.g. J/ψ carry ~ 1 % of total charm

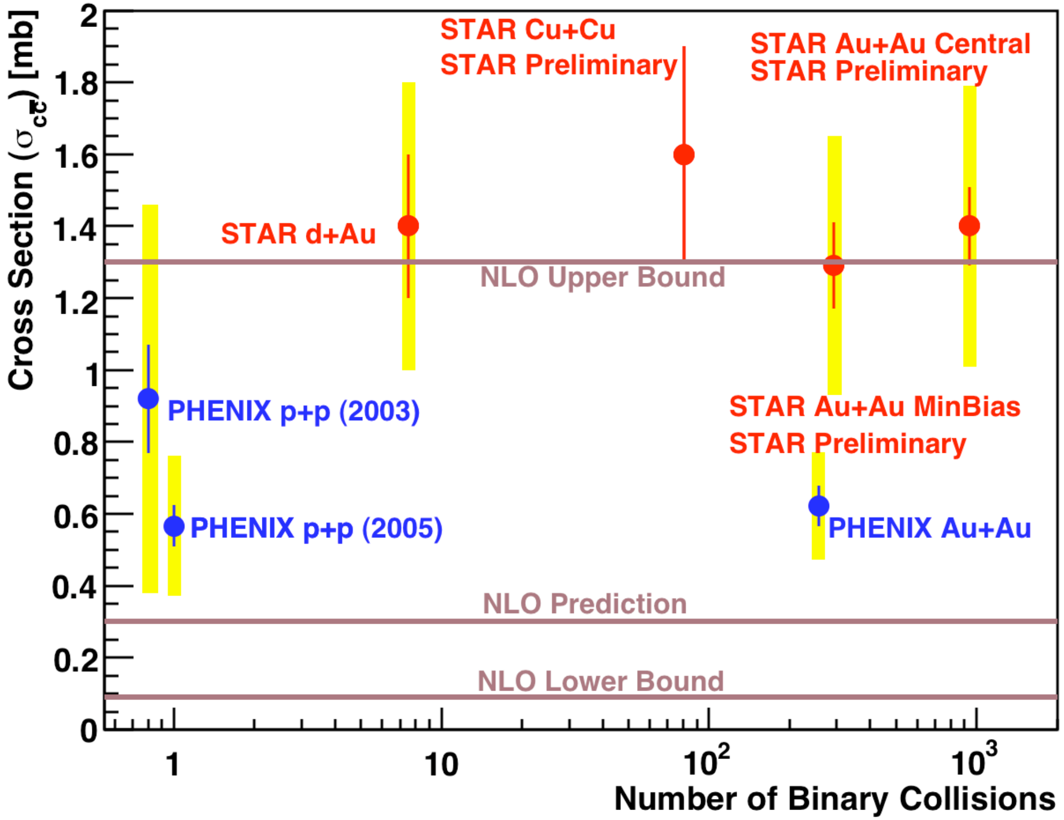
Statistics plot: H. Yang and Y. Wang, U Heidelberg.

How to measure Heavy-Quark Production



- e.g., D^0, $c\tau$ = 123 μm
- displaced decay vertex is signature of heavy-quark decay
- need precise pointing to collision vertex

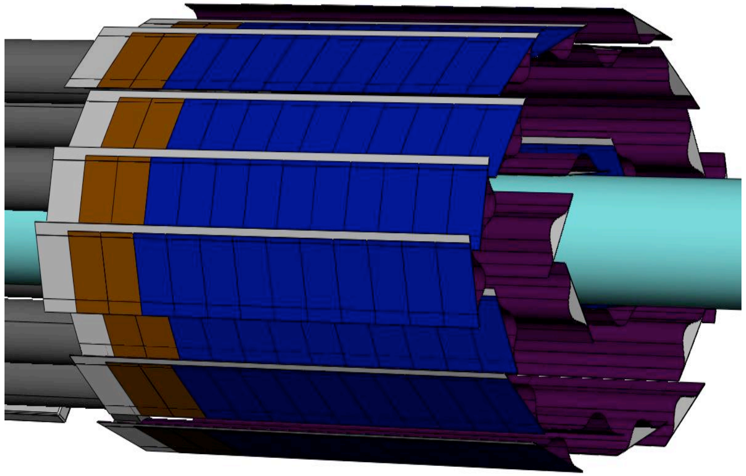
Heavy – Flavor production at RHIC

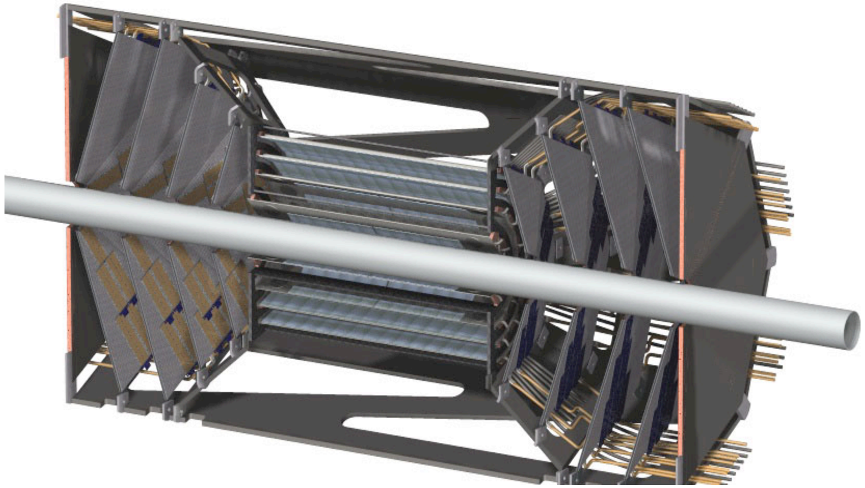


- large discrepancy between STAR and PHENIX: factor > 2 (!)
- need Si-vertex upgrades (> 2011)
- large theoretical uncertainties (factor > 10)
- Measure charm production at RHIC, LHC, FAIR and provide input to theory:
  - gluon distribution,
  - scales μ_R, μ_F

Plot: J. Dunlop (STAR), QM2009, Open Heavy-flavor in heavy-ion collisions,
Calcs: R. Vogt,Eur. Phys. J. C, s10052-008-0809-x (2008),
M. Cacciari, 417th Heraeus Seminar, Bad Honnef (2008).

STAR and PHENIX Si - Upgrades





STAR MicroVertex Tracker

Active pixel sensors (APS)
Two layers of thin silicon

- **Full open charm measurements**
- **Full resonance measurements with both hadron and lepton decays**

PHENIX Silcon Vertex Tracker

2 layers of pixel sensors (ALICE-type)
2 layers of thin silicon strip

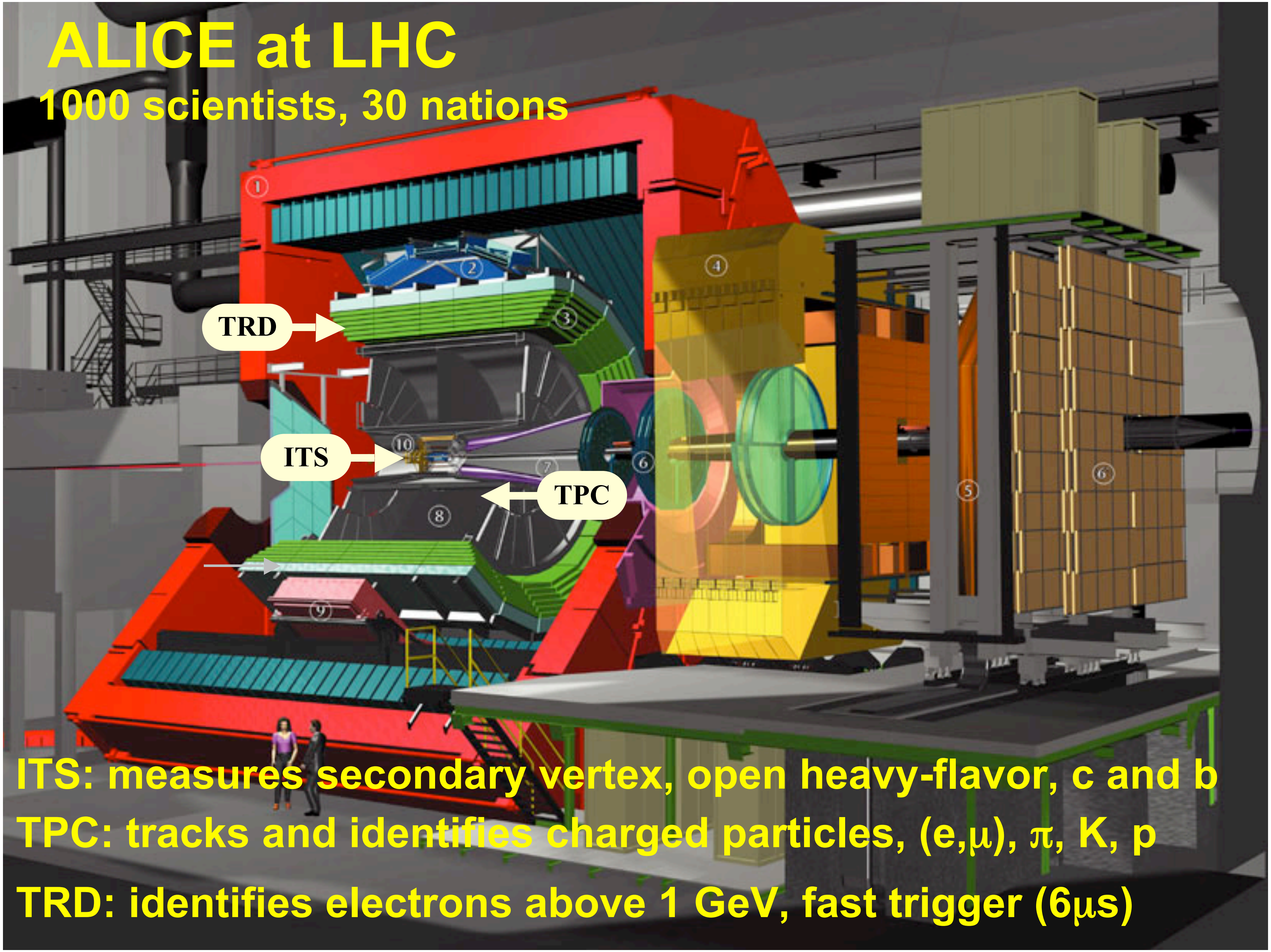
- **Full open charm measurements**

➢ ***High-statistics Au+Au collisions @ 200GeV: 2012****

*T. Roser, RHIC Retreat, Mystic, CT, July 2009.

ALICE at LHC

1000 scientists, 30 nations



ITS: measures secondary vertex, open heavy-flavor, c and b

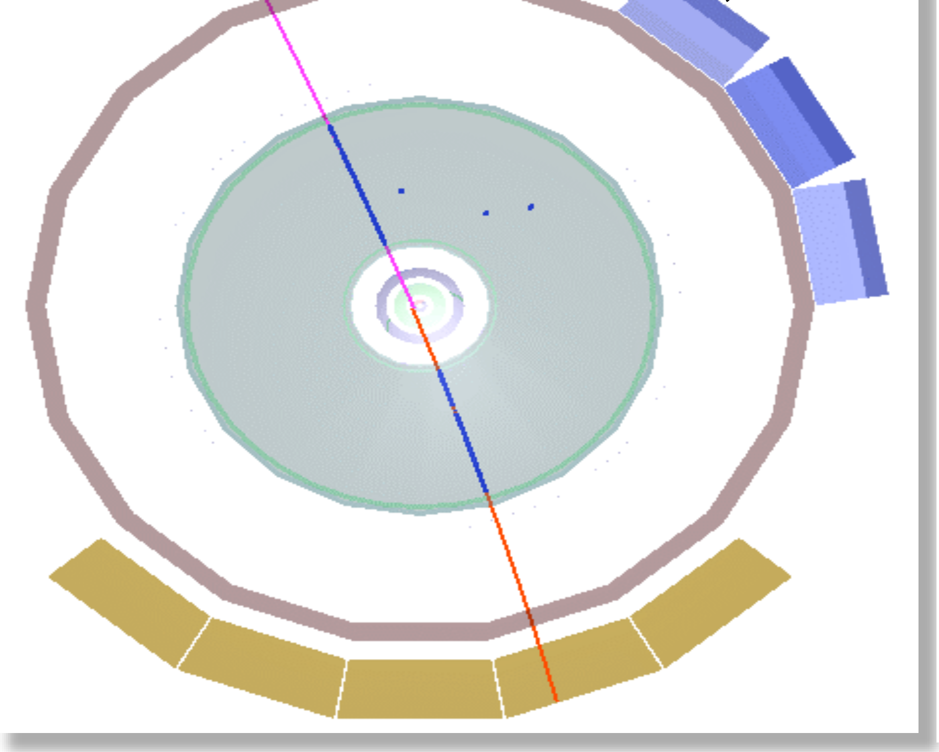
TPC: tracks and identifies charged particles, (e,μ), π, K, p

TRD: identifies electrons above 1 GeV, fast trigger (6μs)

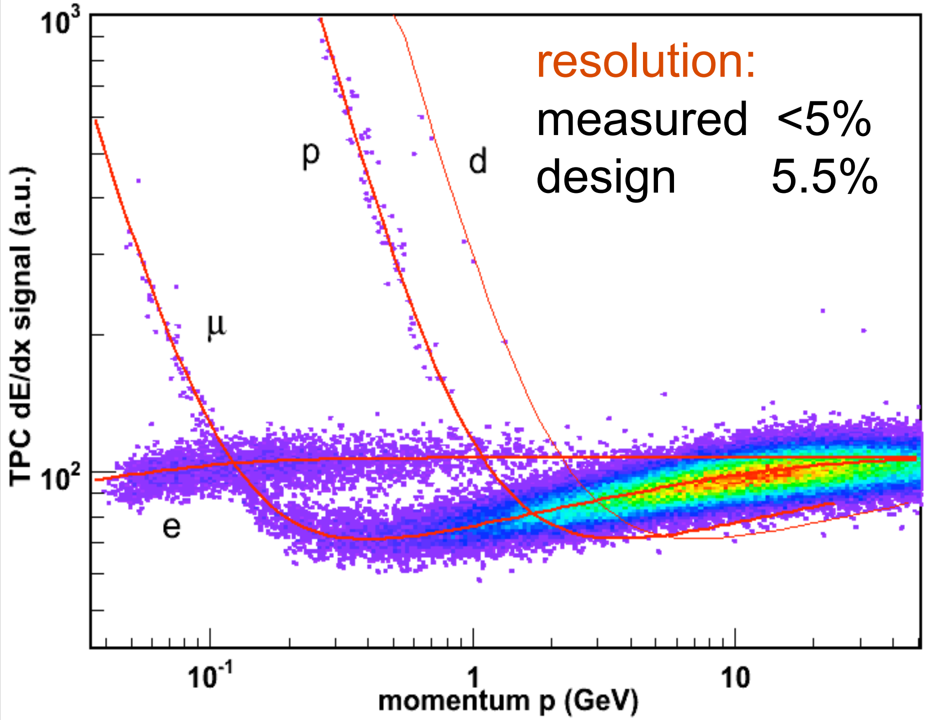
TPC commissioning

– TPC installed in ALICE, running continuously May-October 2008, and since Aug 2009
– 60 million events (cosmics, krypton, and laser) recorded

transverse momentum resolution, B=0.5 T

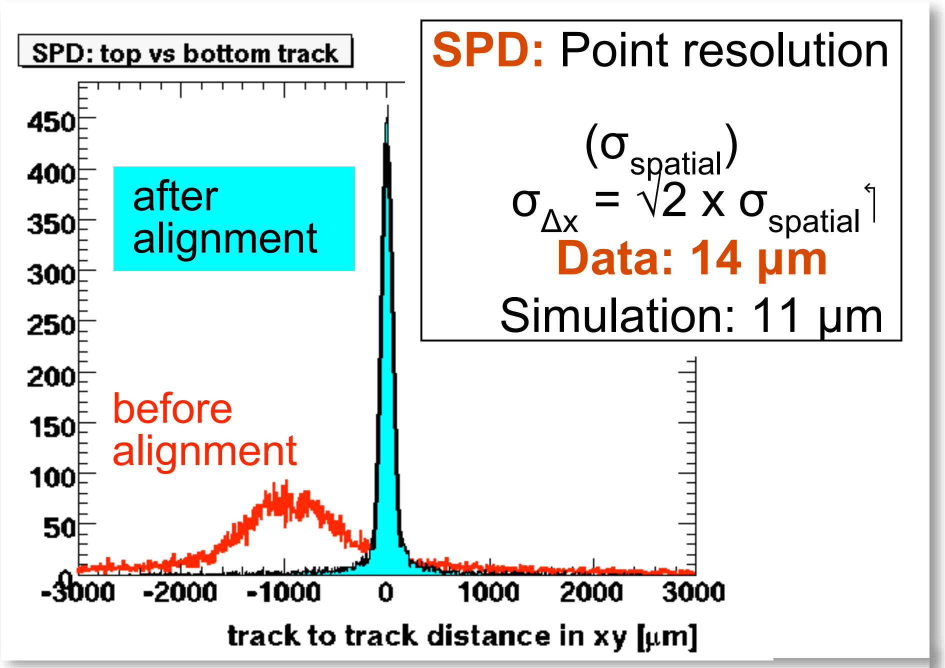


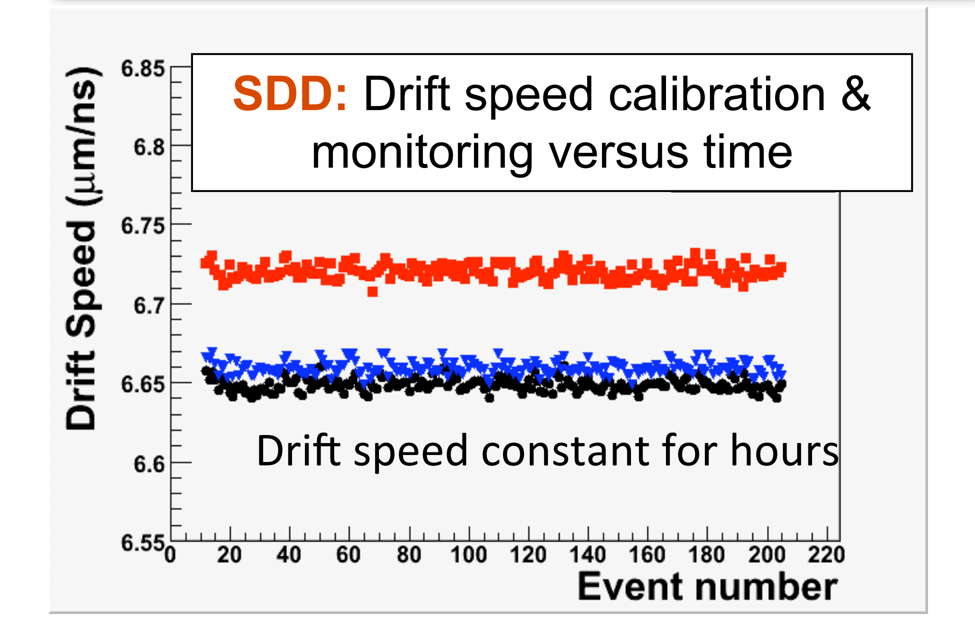
particle identification via dE/dx

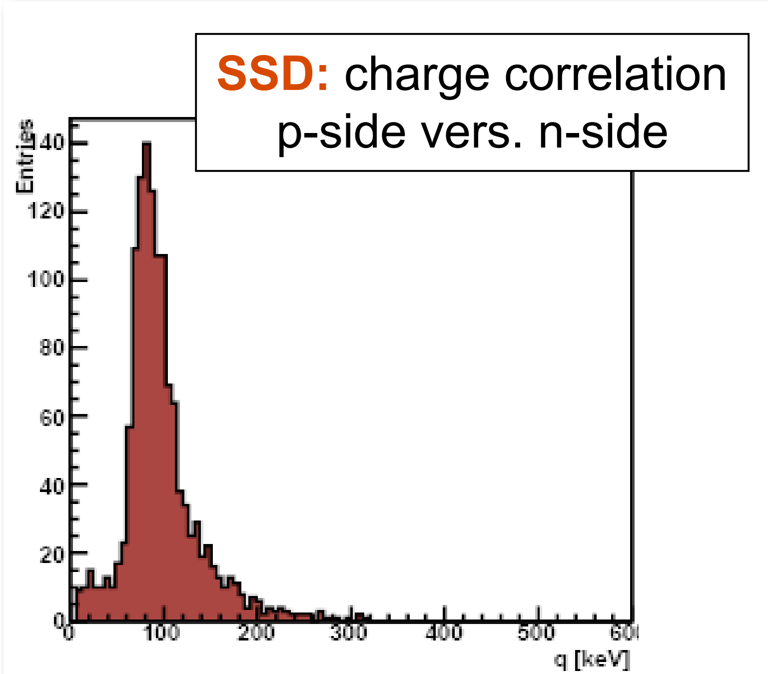


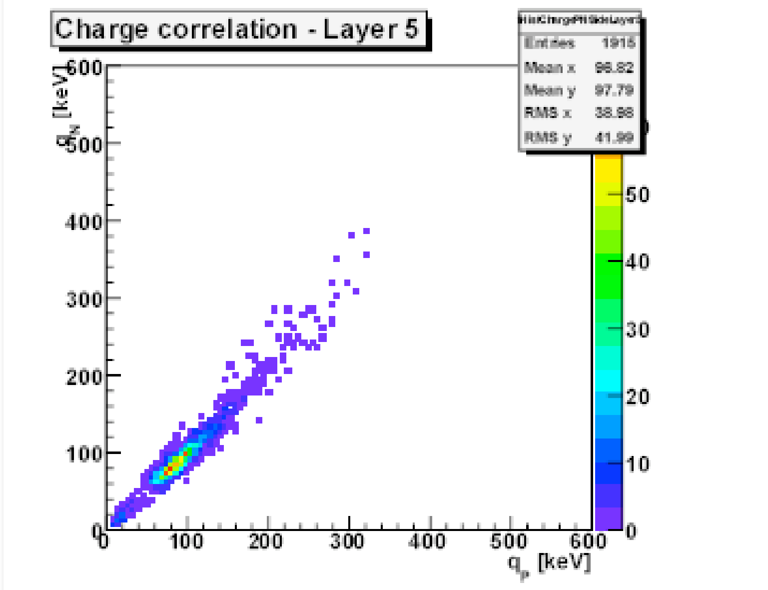
- **performance at design, TPC ready for collisions**

ITS: installed & commissioned









Summary

- Strong collective expansion at RHIC

  $\langle v_{coll} \rangle = 0.6\ c$, $\langle v_2 \rangle = 0.07$

- Small $\eta/s < 10 \times 1/4\pi$

- Large uncertainty (exp. and theory) in $\sigma_{c\bar{c}}$ at RHIC

  need Si - upgrades

- Measure spectra, correlations and v_2 of:

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

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

- ***ALICE @ LHC ready for Physics !***