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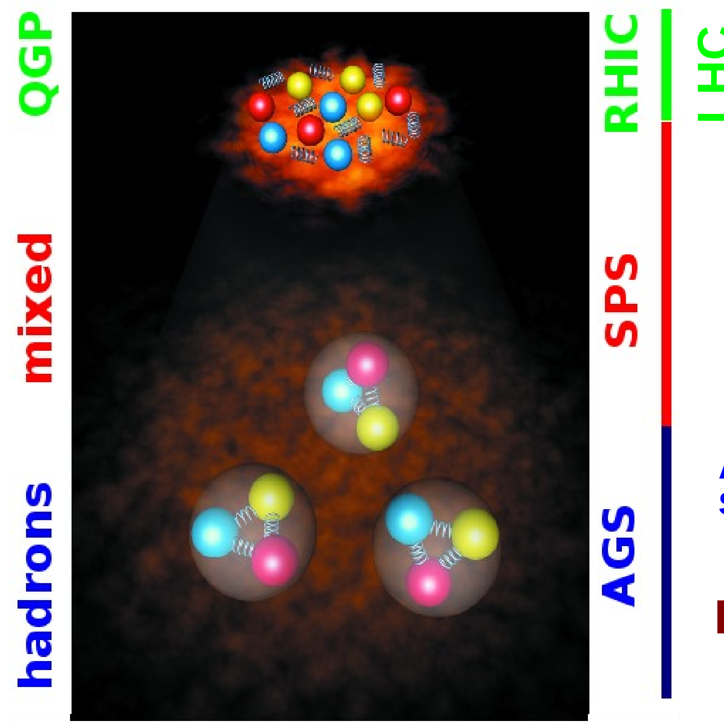
Hot strong matter

XXII. International Workshop on Deep-Inelastic Scattering and Related Subjects

Warsaw, 28 April - 2 May 2014

Phases of water



Large Hadron Collider (CERN)

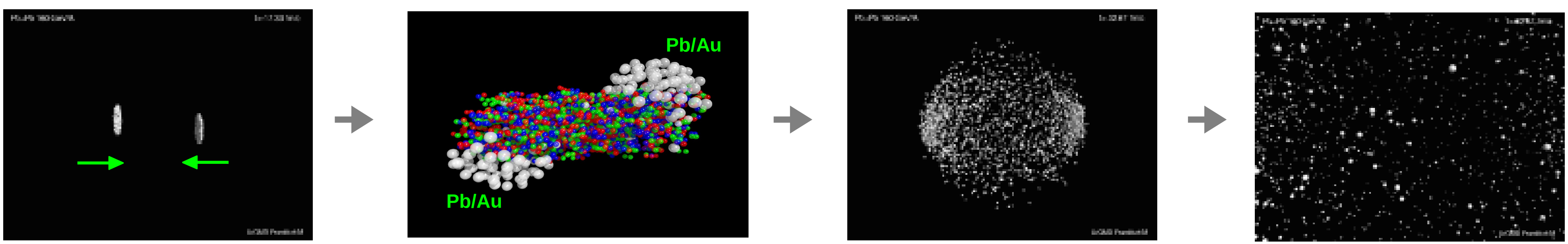
Relativistic Heavy Ion Collider (BNL)

Super Proton Synchrotron (CERN)

Alternating Gradient Synchrotron (BNL)

Phases of strongly interacting matter

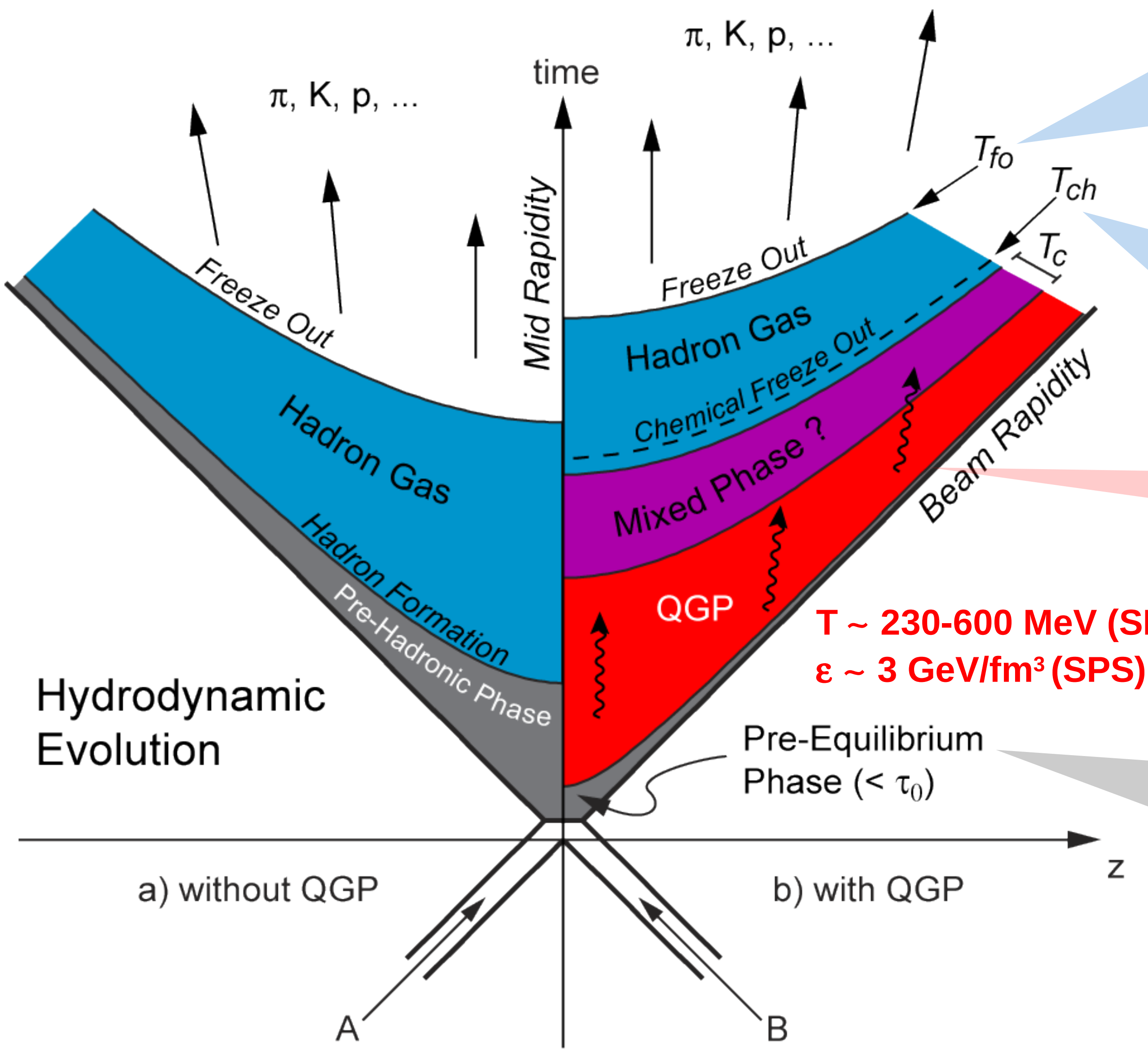
Why do we want to study heavy ion collisions at high energies?



We want to produce and analyze properties of quark-gluon plasma (QGP) and properties of transition between QGP and HG

Quark-gluon plasma – a system of deconfined quarks and gluons; existed probably after Big Bang

Space-time evolution of heavy ion collision



$T \sim$ 90-140 MeV, $\varepsilon \sim$ 0.05 GeV/fm^3
thermal freeze-out –
particles momenta fixed
(end of elastic interactions);
decays still possible

$T \sim$ 150-170 MeV, $\varepsilon \sim$ 0.6 GeV/fm^3
chemical freeze-out –
chemical composition fixed
(end of inelastic interactions)

QGP life-time before hadronization ~ few fm/c

$T \sim$ 230-600 MeV (SPS-LHC)
$\varepsilon \sim$ 3 GeV/fm^3 (SPS), ε > 5/15 GeV/fm^3 (RHIC/LHC)

parton formation and thermalization
formation time $\tau_0 \sim$ 1 fm/c at top SPS and ~ 0.6 fm/c at top RHIC energies

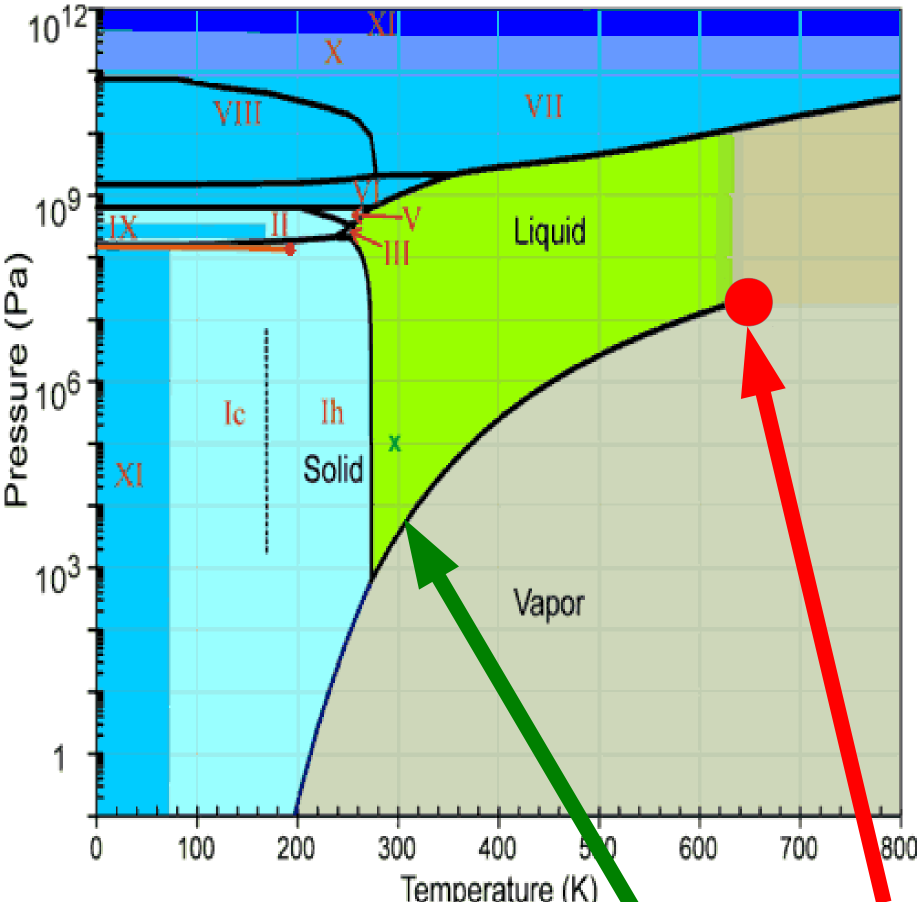
normal nuclear matter
$T \cong$ 0 MeV, $\varepsilon \cong$ 0.16 GeV/fm^3

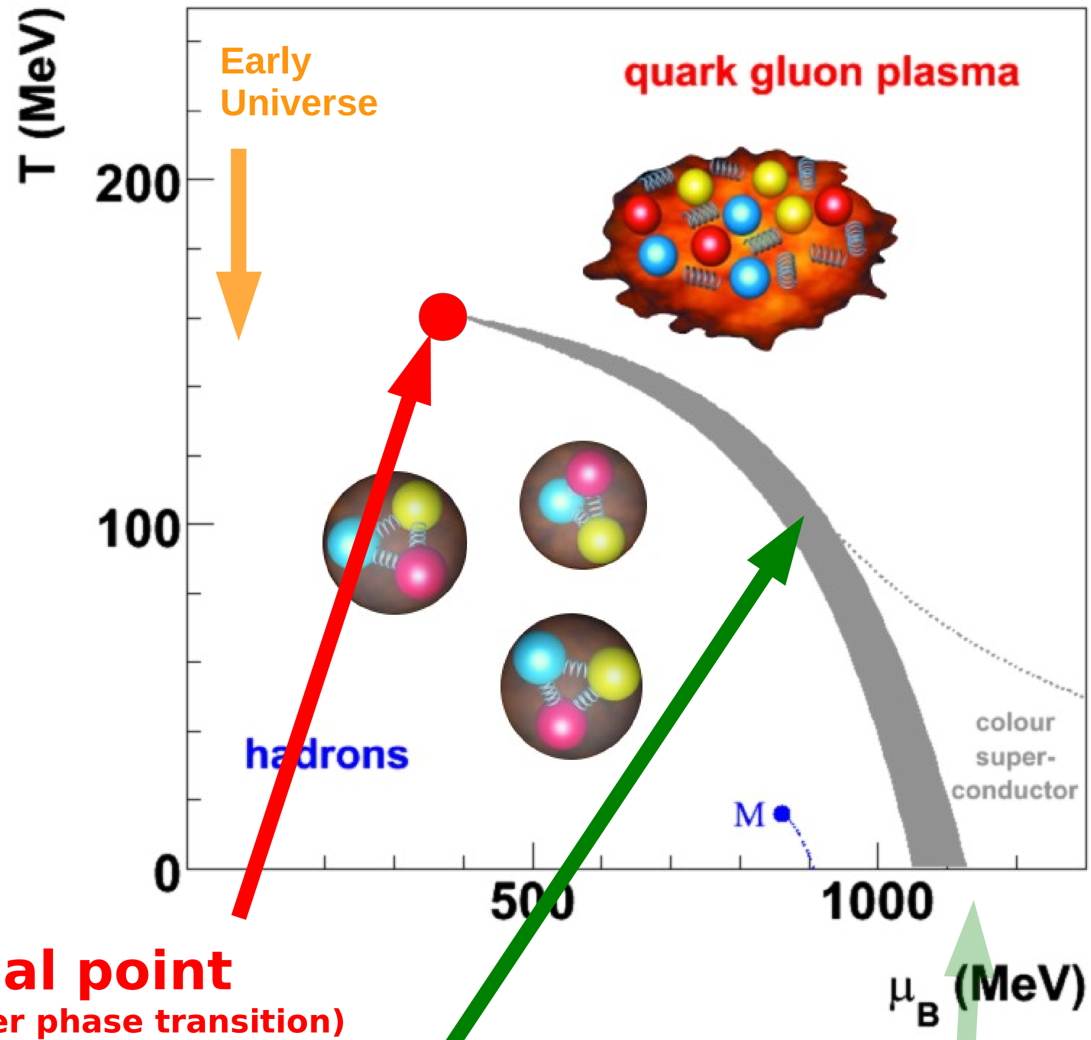
Temperature decreases during expansion $\Rightarrow T_{chem} \geq T_{therm}$

K. Grebieszkow, DIS 2014

Phase diagram of water is well established

The properties of the transition between hadron gas and QGP still need to be discovered





critical point
(2[nd] order phase transition)

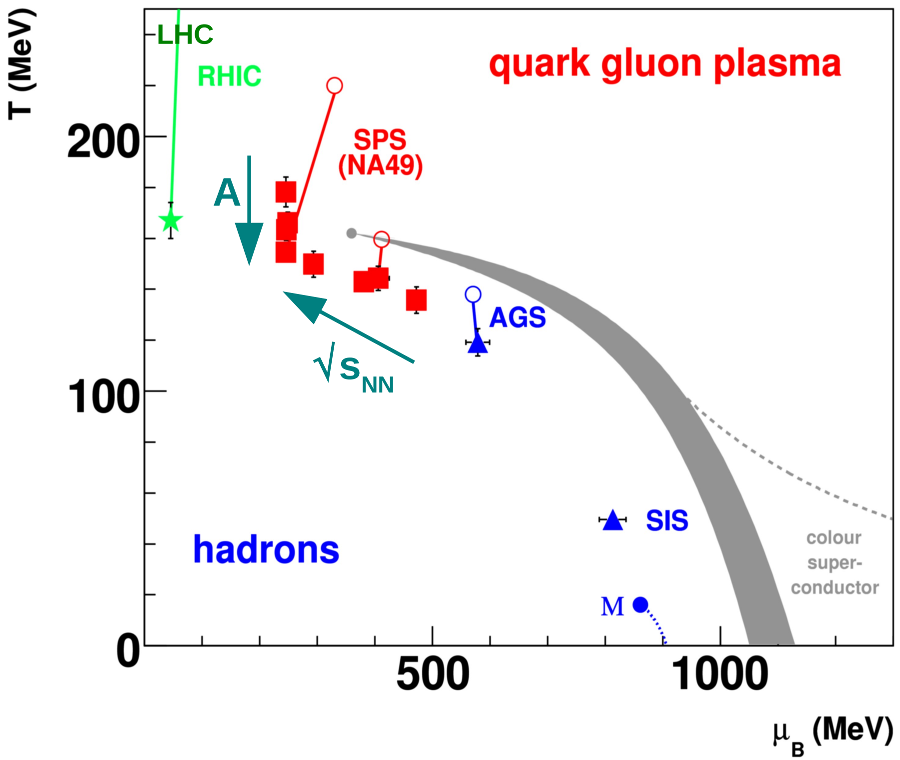
1[st] order phase transition

μ_B - reflects net baryon density

neutron stars ~ 4-10ρ_0
ρ_0 ~ 10^{14} g/cm^3 (normal nucl. matt.)
T ~ 10^5 – 10^9 K

K. Grebieszkow, DIS 2014

Very interesting region of the phase diagram covered by CERN SPS



Open symbols: early stages

Full symbols: chemical freeze-out points

CP should be searched above the energy of the onset of deconfinement

E_{CP} > $E_{OD} \cong$ 30*A* GeV (NA49 data)

30*A* GeV $\Leftrightarrow$ $\sqrt{s_{NN}}$=7.6 GeV

1. Evidence for **onset of deconfinement** (kink, horn, step) **is observed by NA49** at **$\sqrt{s_{NN}} \cong$ 7.6 GeV** (PR C77, 024903 (2008))

2. **Critical point** of strongly interacting matter may be located at SPS energies

- **(T^{CP}, μ_B^{CP}) = (162(2), 360(40)) MeV**

(Fodor, Katz, JHEP 0404, 050 (2004))

μ_B^{CP} = 360 MeV $\Leftrightarrow$ $E_{CP} \cong$ 50*A* GeV ($\sqrt{s_{NN}}$=9.7 GeV)

(Beccatini, Manninen, Gaździcki, PR C73, 044905 (2006))

- **$(T^{CP}/T_c, \mu_B^{CP}/T^{CP})$ = (~0.96, ~1.8) (μ_B~290 MeV),** T_c – cross-over temp. at μ_B = 0

(Datta, Gavai, Gupta, NP A904-905, 883c (2013))

- **(T^{CP}, μ_B^{CP}) = (0.927(5)T_c, 2.60(8)T_c) = (~157, ~441) MeV**

(Li et al. RIKEN-BNL Workshop, Oct. 4, 2011, http://www.bnl.gov/fcrworkshop/)

http://foundwalls.com/wp-content/uploads/2012/05/desert-sand-hot-dune.jpg

Jet quenching as a signature of hot and dense matter

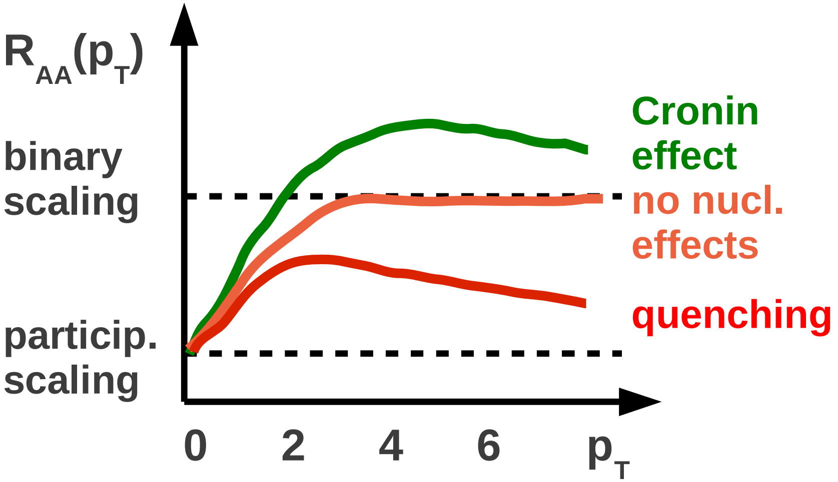
Suppression of high p_T particles predicted in: Bjorken, FERMILAB-PUB-82-59-THY; Bjorken, PR D27, 140 (1983); Wang et al. PRL 68, 1480 (1992); Gyulassy et al. PL B243, 432 (1990)

To compare p_T spectra in p+p, p+A, A+A:

Nuclear Modification Factor R

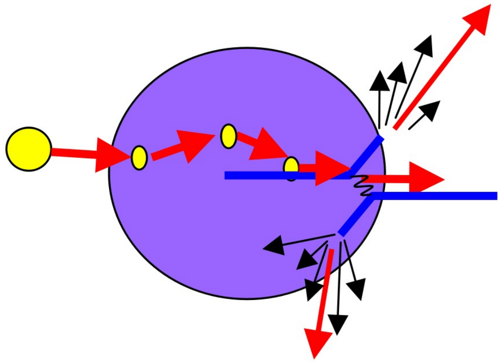
$$R_{AA}(p_T)=\frac{1}{N_{coll}^{AA}}\frac{(Invariant\ yield)_{AA}}{(Invariant\ yield)_{pp}}$$

$$R_{CP}(p_T)=\frac{N_{coll}^{PERIPH}}{N_{coll}^{CENTRAL}}\frac{(Invariant\ yield)_{CENTRAL}}{(Invariant\ yield)_{PERIPH}}$$



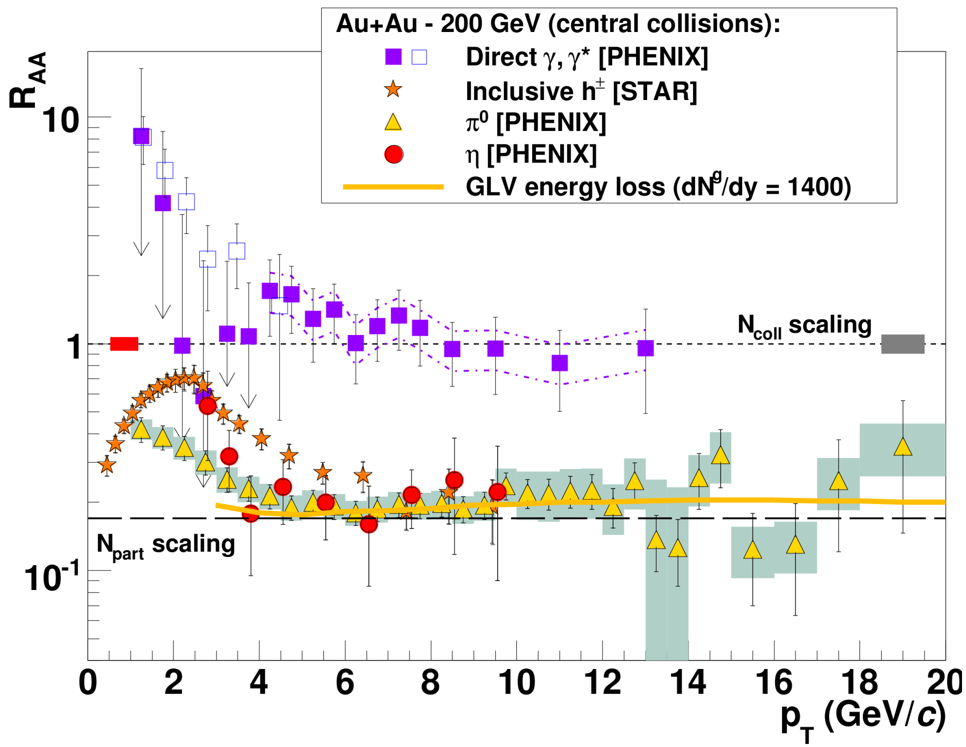
Expected:

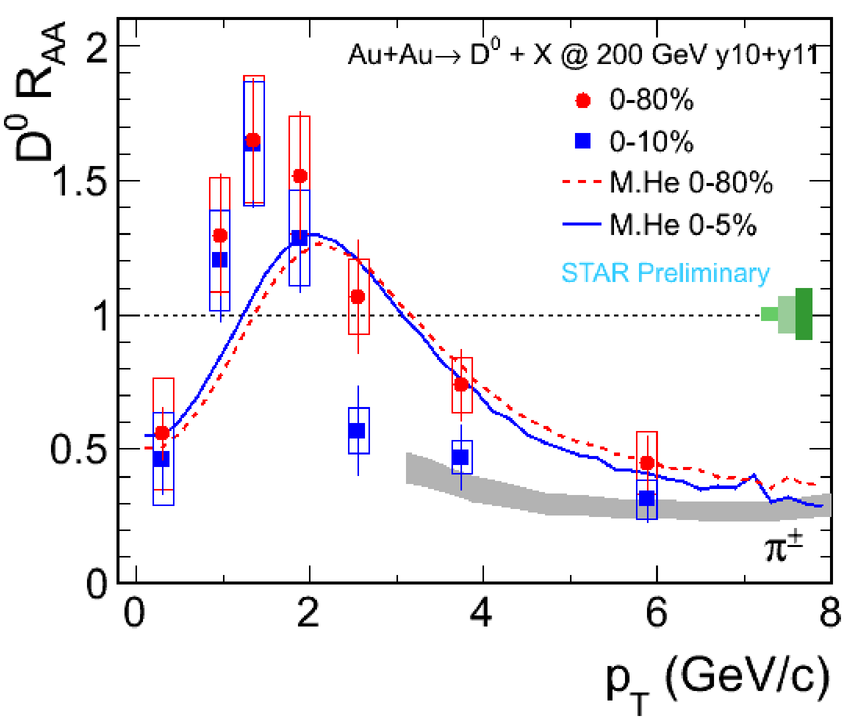
- Soft processes (low p_T) → participant scaling ($R_{AA} < 1$)
- Hard processes (high p_T) → binary collisions (N_{coll}) scaling ($R_{AA} = 1$)



Cronin effect (in p+A, d+Au, etc.) → probably due to initial elastic multiple low-momentum scattering of the parton (from projectile nucleon) on target nucleons. Before the final hard parton+parton interaction the projectile parton already has got $p_T \neq 0$.

d'Enterria, NP A827, 356c (2009)





top RHIC, central Au+Au

- Strong suppression (factor 5), but
- not seen for photons (they do not interact strongly with the medium) ⇒ observed **suppression is a final state effect** (interpreted as **parton energy loss while traveling through hot and dense medium**)

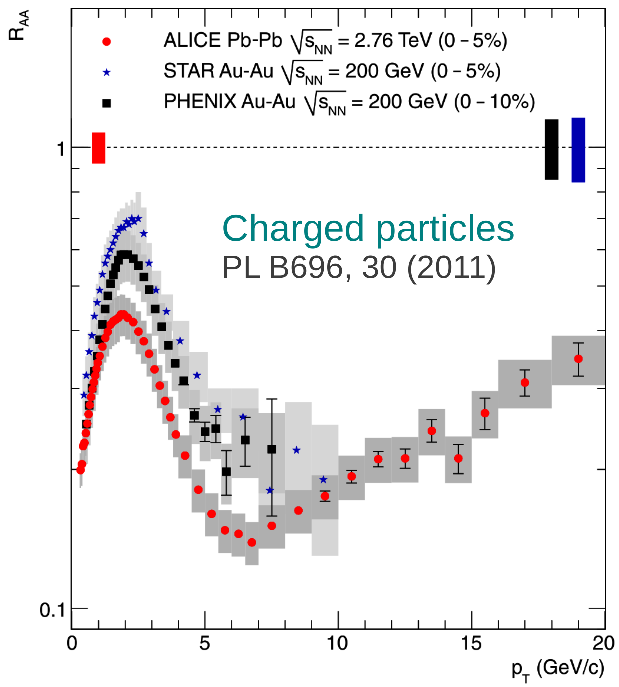
Gluon density in the medium (y - rapidity)
$dN^g/dy \approx 1400 \Leftrightarrow T \approx 400$ MeV
(d'Enterria, NP A827, 356c (2009))

Expected energy losses (for E_{parton}= const.) due to induced gluon radiation in dense color medium:
$\Delta E_{rad}(g) > \Delta E_{rad}(q_{light}) > \Delta E_{rad}(c) > \Delta E_{rad}(b)$

But at top RHIC **suppression seems to be similar for light and heavy particles**

QM2012 slides (Dong, Tlusty, Xie) and NP A904-905, 639c (2013); final results in STAR, arXiv:1404.6185v1
similar behaviour in U+U at 193 GeV →
Trzeciak (for STAR), WWND 2014

LHC, Pb+Pb

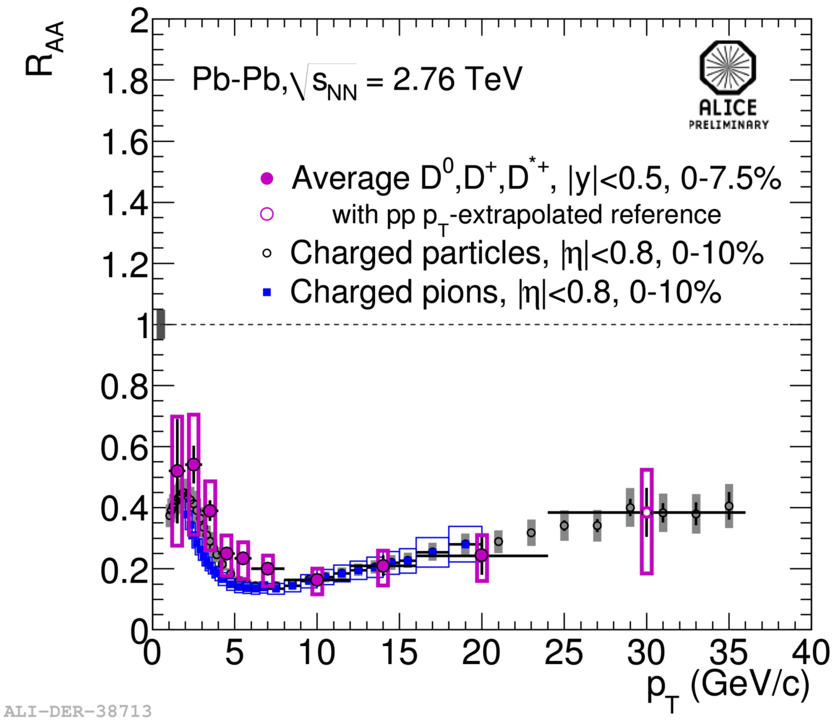


- **Suppression** (at min. p_T=6-7 GeV/c) **stronger than at RHIC**
- Heavy **D mesons suppressed on similar level as charged particles but suppression of beauty smaller**
  $R_{AA}(D) \sim R_{AA}(\pi) \le R_{AA}(B \to J/\psi)$

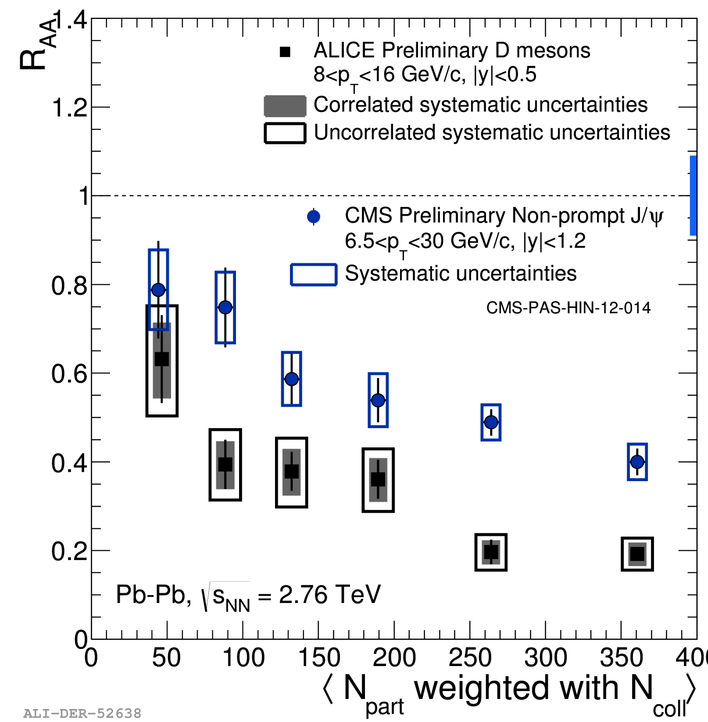
$\Delta E(c) > \Delta E(b) \quad \rightarrow \quad R_{AA}(D) < R_{AA}(B)$

Indication of larger energy loss for charm than for beauty

Andronic (for ALICE), JPCS 455, 012002 (2013); Mischke, arXiv:1301.7550

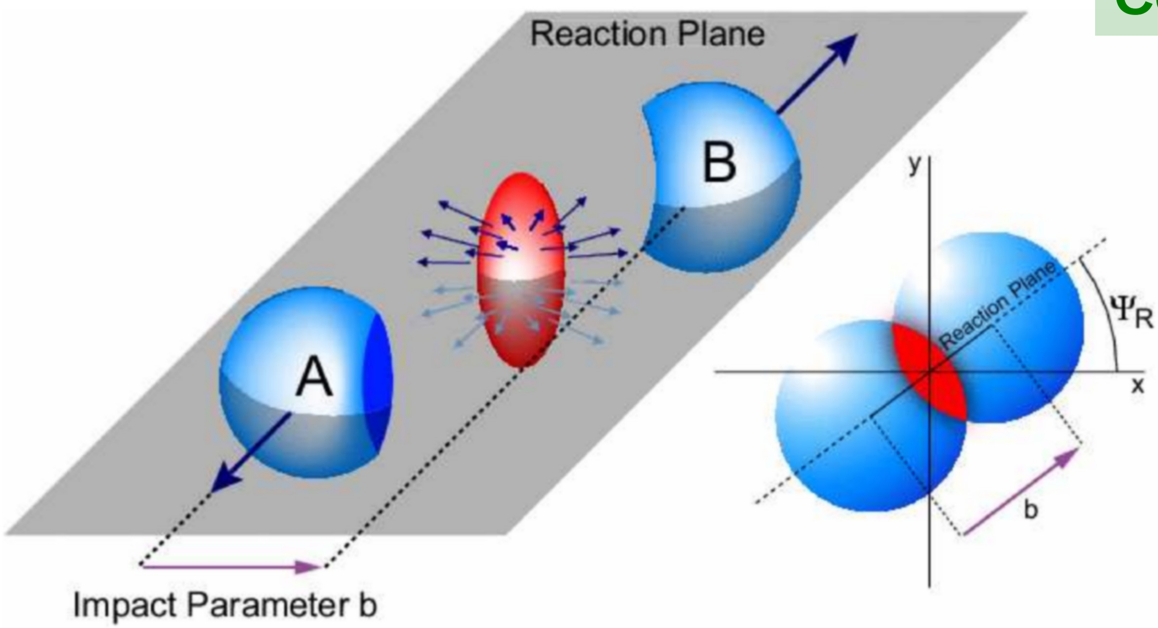


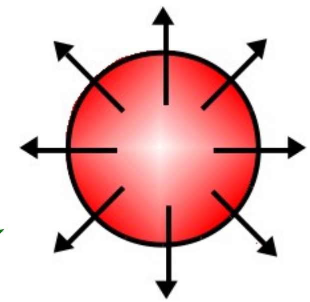
Non-prompt J/psi – from B decays



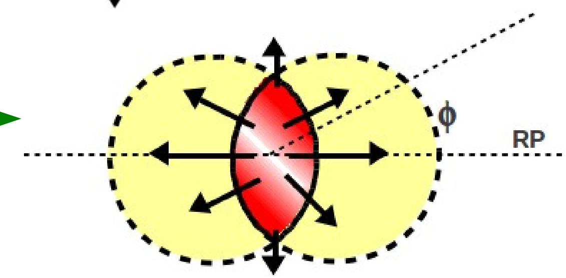
Jena (for ALICE), WWND 2014; Grelli (for ALICE), arXiv:1310.7366v1

Collectivity in A+A collisions





$$\phi = atan\frac{p_y}{p_x}$$



- For central collisions (b=0 fm) → radial flow only
- For non-central collisions (b≠0) → flow is anisotropic (directed flow v_1, elliptic flow v_2, higher harmonics)

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1 + 2v_1\cos(\phi - \Phi_R) + 2v_2\cos[2(\phi - \Phi_R)] + \ldots\right)$$

isotropic emission (1 represents radial flow)

directed flow

elliptic flow

$$v_n = \langle \cos[n(\phi - \Phi_R)] \rangle$$

Initial spatial anisotropy + rescattering → pressure gradients → **anisotropy in momentum space** (more particles in-plane than out-plane)

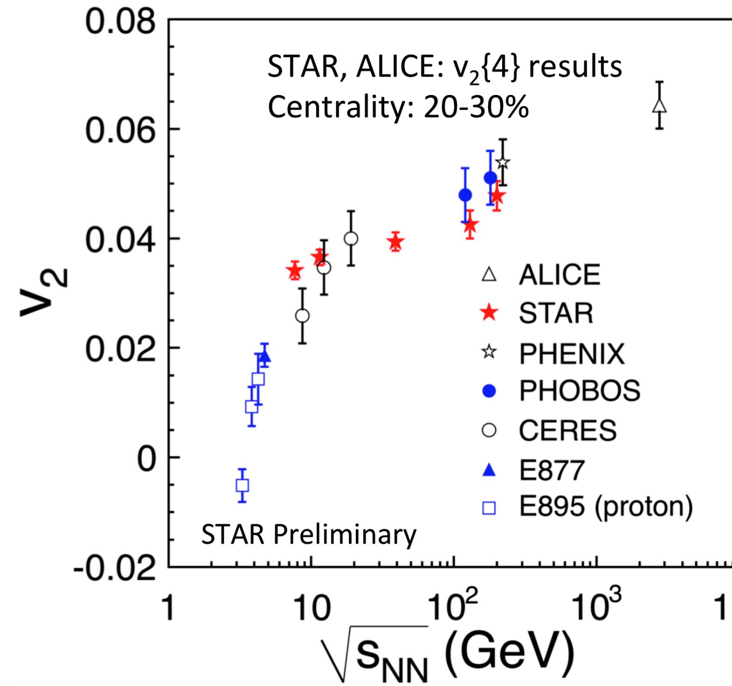
(p_T integrated) **elliptic flow grows with energy...**

… and for higher energies scales with the number of constituent quarks (n_q)
– "NCQ scaling"

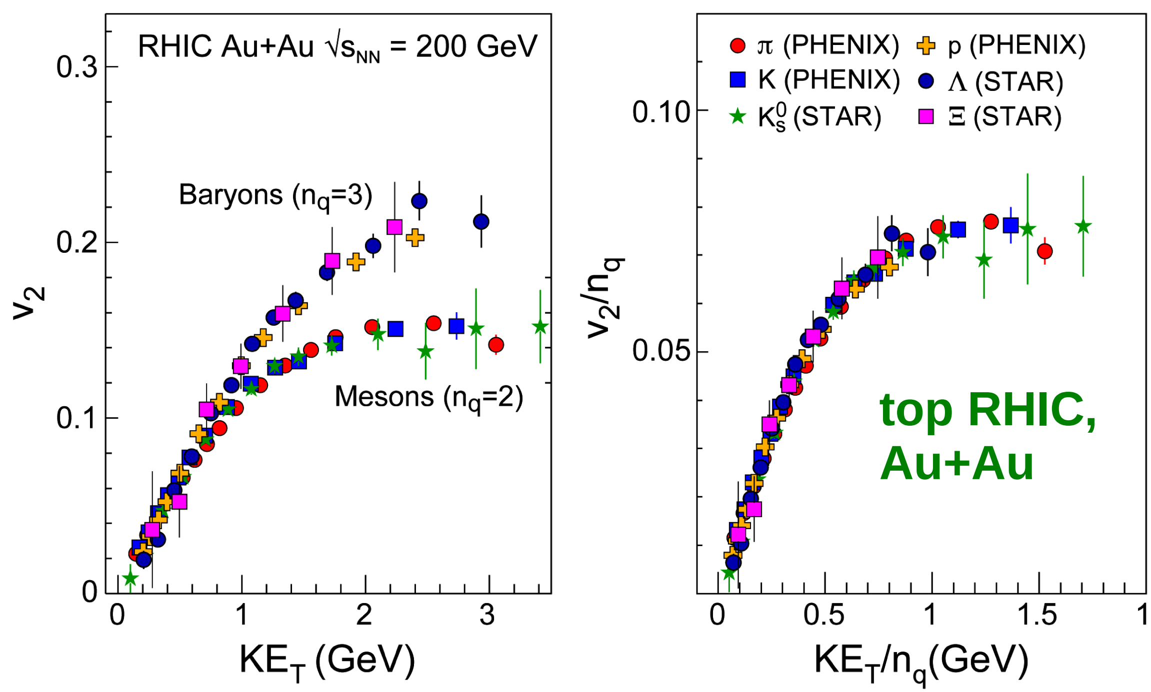
In coalescence models of hadronization (they assume QGP phase!) v_2^q – elliptic flow of quark, then:

$v_2^{MESON}(p_T) \approx 2v_2^q(p_T/2)$

$v_2^{BARION}(p_T) \approx 3v_2^q(p_T/3)$



Sumbera, ISMD 2012 (slides)



Heinz, Phys. Scripta 78, 028005 (2008) [arXiv:0805.4572]

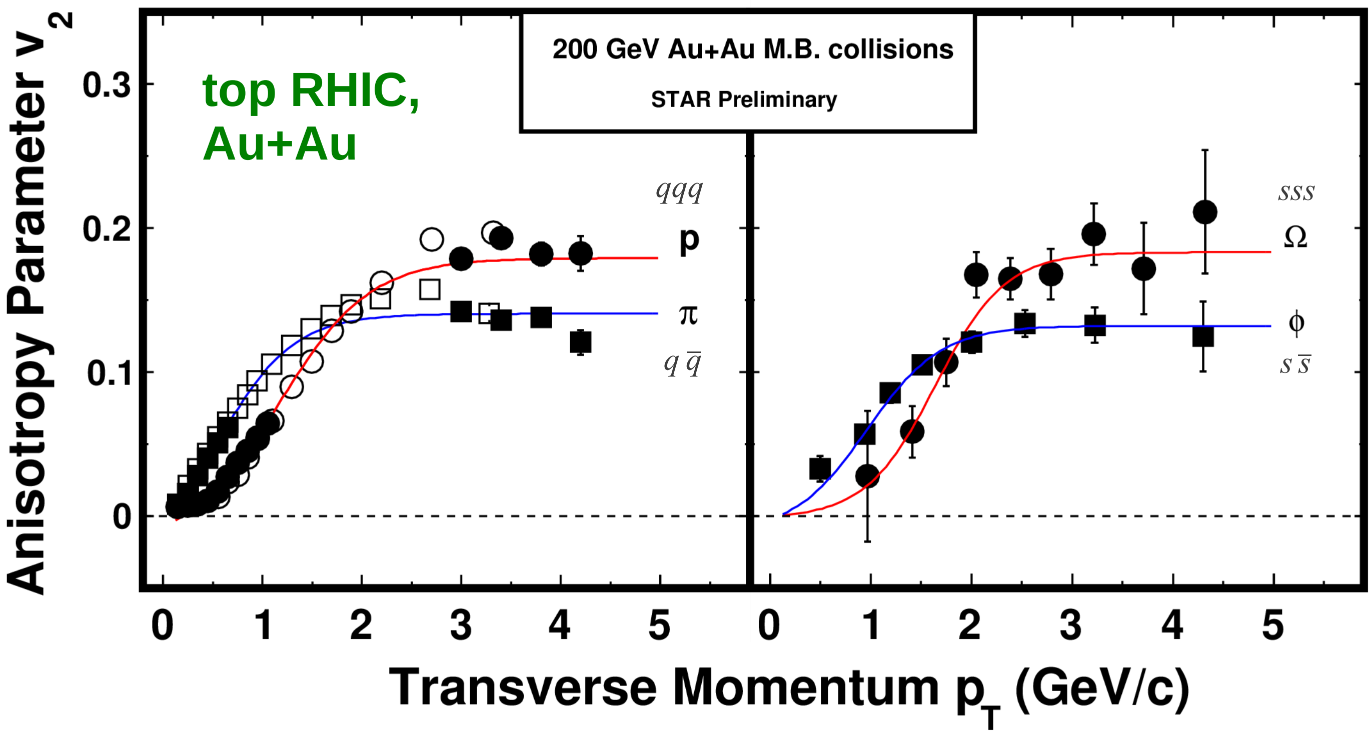
top RHIC, Au+Au

v_2 scales with n_q – proof of **partonic collectivity** (flow is originally developed on quark level; quarks flow in QGP)

partonic collectivity – **key QGP signature at top RHIC energies**

$$KE_T = m_T - m = \sqrt{m^2 + p_T^2} - m$$

Elliptic flow of heavier ('*s*') flavours



Shi (for STAR),
NP A830, 187c (2009)

ϕ mesons are as heavy as protons but their v_2 is as for π mesons $\rightarrow n_q$ is important ! Not mass

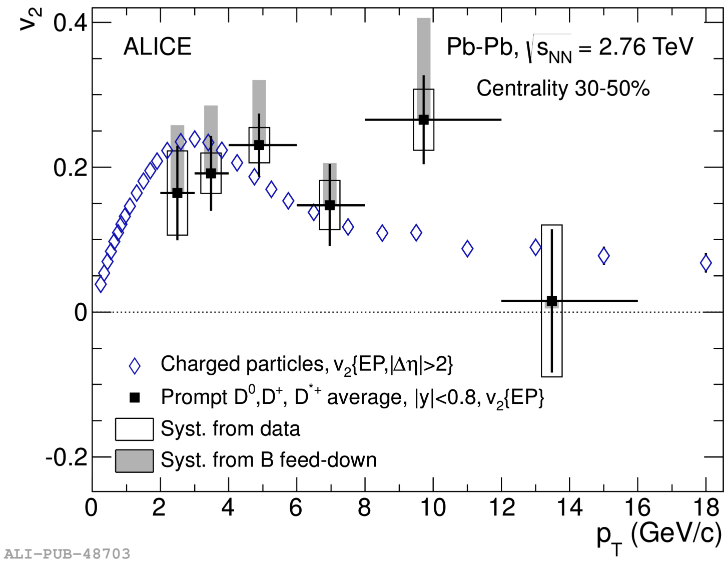
's' quarks flow similarly to light 'u' and 'd' quarks $\Rightarrow$ argument for partonic collectivity (developed mostly in deconfined phase)

ϕ and Ω particles have small cross sections for hadronic interactions and probably freeze-out earlier → promising observable of the early stage (they should be less affected by later stage hadronic interactions). Thus results suggest that the significant part of collectivity was developed in partonic stage

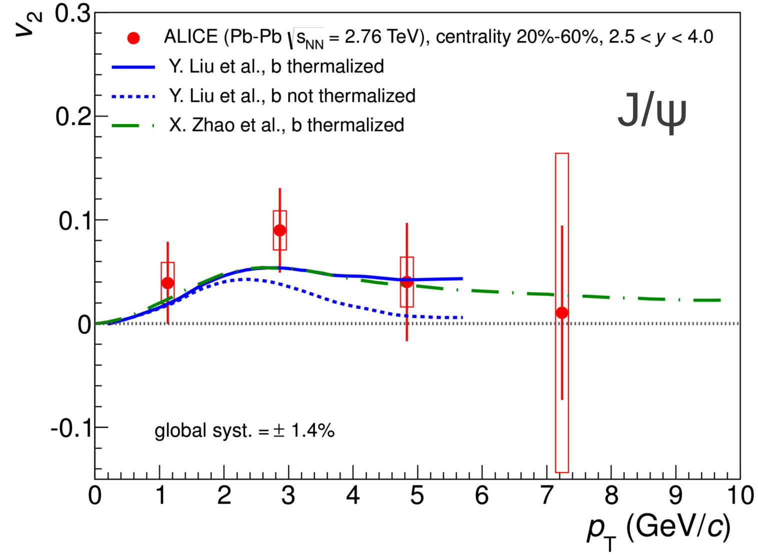
Elliptic flow of heavy flavours

LHC, Pb+Pb

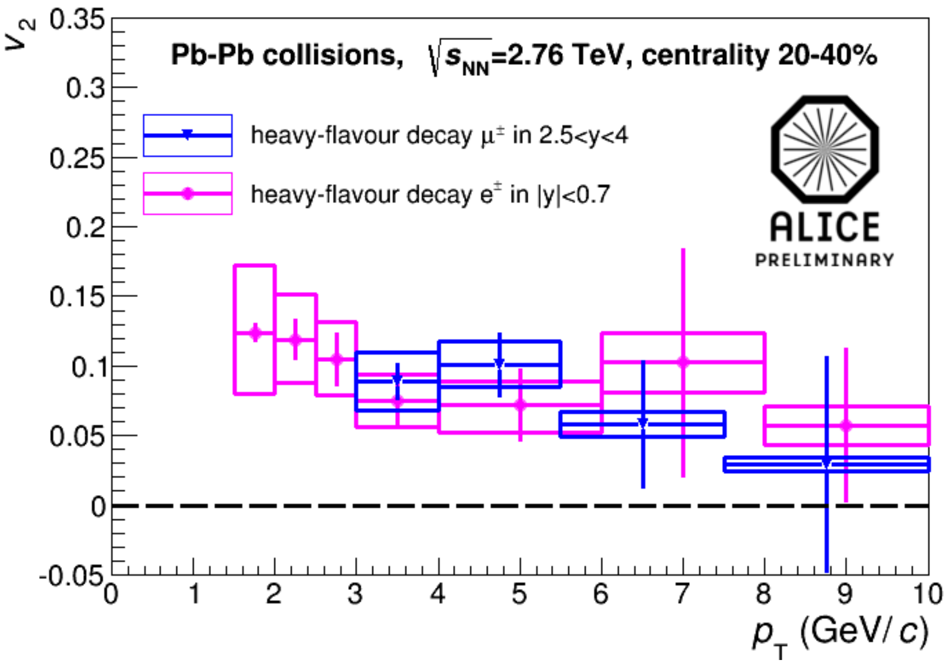
PRL 111, 102301 (2013)



PRL 111, 162301 (2013)



Lines – transport models: J/psi dissociation and regeneration



LaPointe (for ALICE), WWND 2014;
LaPointe (for ALICE), arXiv:1401.6858

- Flow of D mesons similar to that for light particles → charm quarks participate in the collective flow of the expanding medium
- Hidden charm (J/ψ) $v_2 > 0$ (at RHIC ≈ 0)
- Heavy-flavour decay $\mu^\pm$ and $e^\pm$ (from 'c' and 'b' decays) also experience anisotropic expansion of the medium ($v_2 > 0$)

Heavy quarks may also flow with matter !
Like stones flowing with the stream

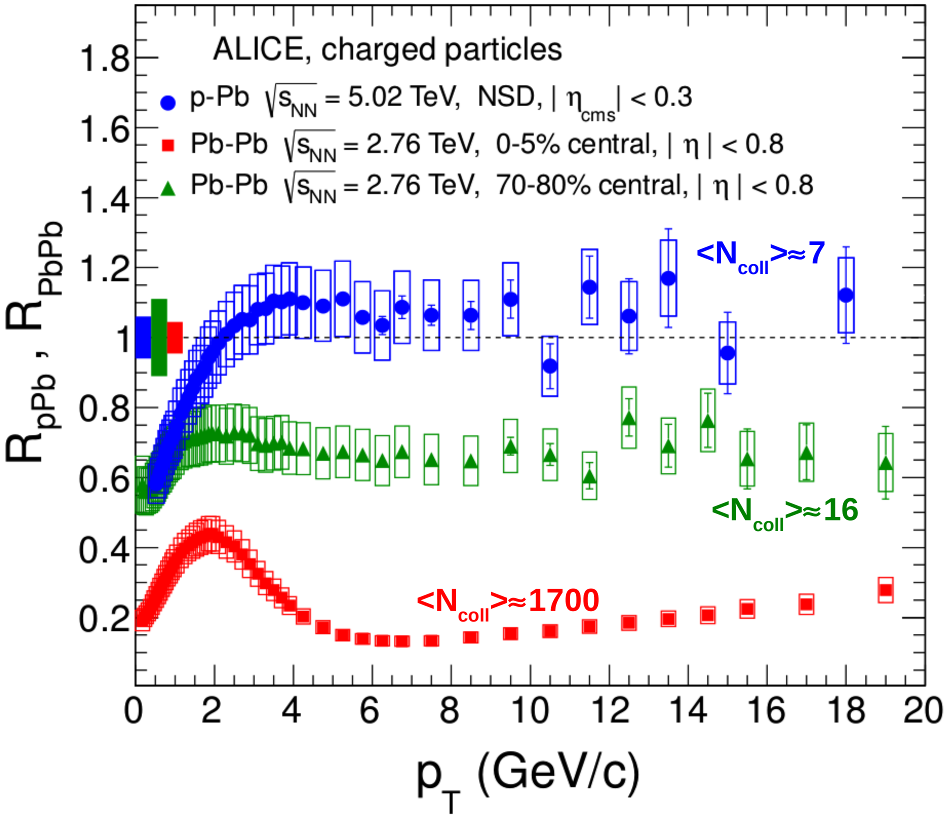
http://www.piterpanzerwwii.com.pl/czolg-t-100/

At LHC and top RHIC energies QGP is produced in heavy systems: Pb+Pb, Au+Au

What about light and intermediate mass systems ??

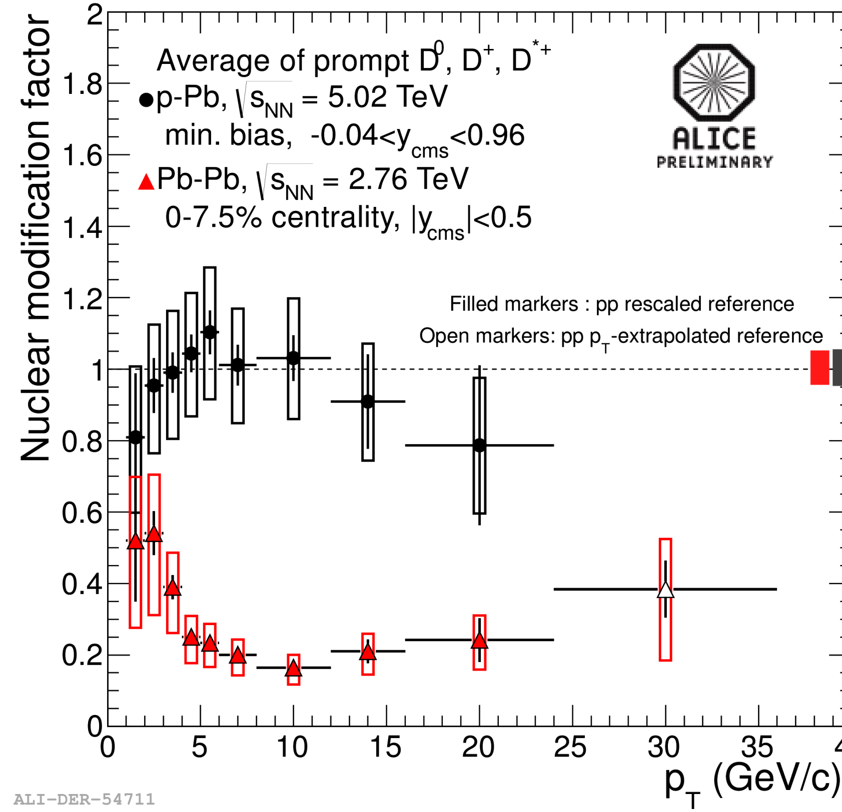
http://pl.123rf.com/photo_2550393_czarny-ptak-piorko-na-bialym-tle.html

PRL 110, 082302 (2013)



- **Suppression** of high p_T particles **seen even in peripheral Pb+Pb** where $\langle N_{coll} \rangle$ is only twice higher than $\langle N_{coll} \rangle$ in p+Pb
- Charged particles in **p+Pb do not show suppression** (similar observation for d+Au at top RHIC energy); in ALICE $R_{pPb} \approx 1$ up to $p_T \approx 50$ GeV/c (Verweij, WWND 2014)

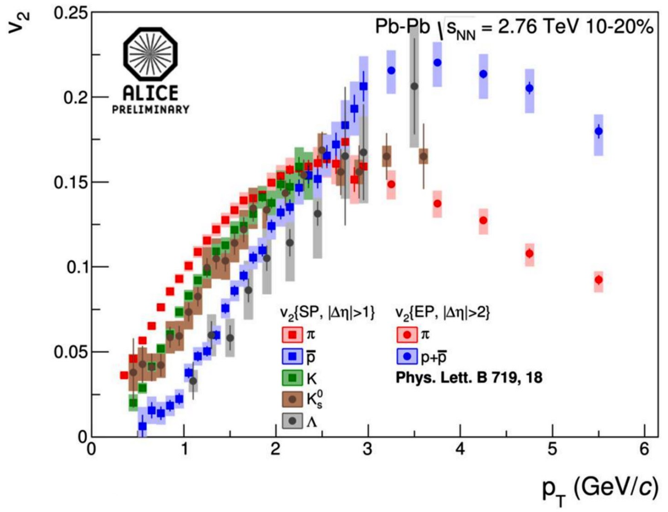
LHC, Pb+Pb and p+Pb



Grelli (for ALICE), arXiv:1310.7366v1

- Heavy D mesons in p+Pb collisions also do not show suppression
- **Suppression of high p_T particles in** central and peripheral **Pb+Pb** is not due to initial-state effects, but rather **due to final state interactions in a hot medium** (QGP opaque to energetic partons)

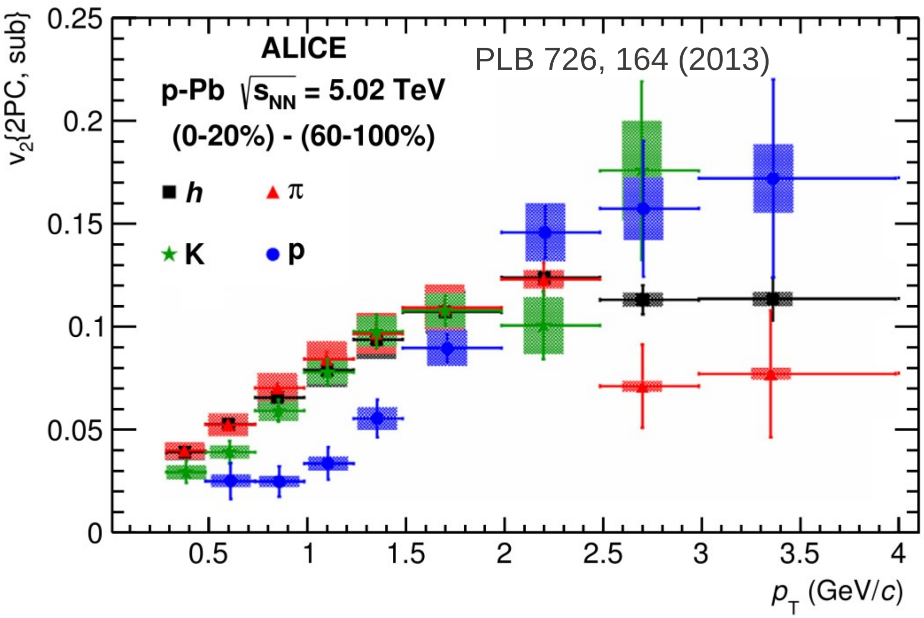
LHC, Pb+Pb



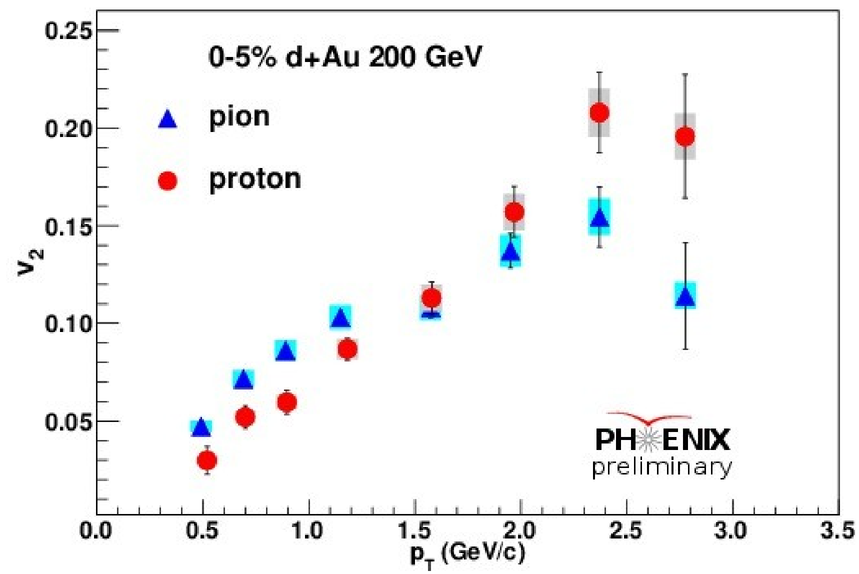
Evidence of collective flow in small systems

- **Mass ordering of v_2 in Pb+Pb** (and Au+Au at top RHIC) qualitatively reproduced (at lower p_T) by hydrodynamical models (not shown) and understood as **due to radial flow**; hydro: $v_2 \sim (p_T - \langle v_T \rangle m_T)/T$
- Qualitatively **similar behaviour in high multiplicity p+Pb** (and d+Au) **collisions. Does p+Pb** (d+Au) **flow ?**

LHC, central p+Pb



top RHIC, central d+Au



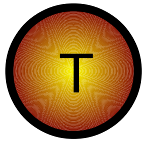
Orjuela-Koop (for PHENIX), WWND 2014

Another evidence of radial flow in p+Pb → increase of $\langle p_T \rangle$ with increasing particle mass (see Loizides, arXiv:1308.1377v2); the same behaviour is well known in Pb+Pb (PR C88, 044910 (2013)) and reproduced by hydrodynamical models. For radial flow: $\langle p_T \rangle_{(m)} \sim m\, v_T$

Static source

$T_{(slope)} = T_{freeze\text{-}out(fo)}$

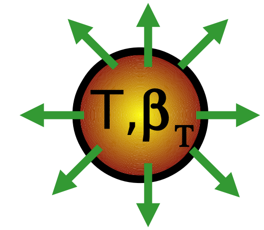
(thermal freeze-out)



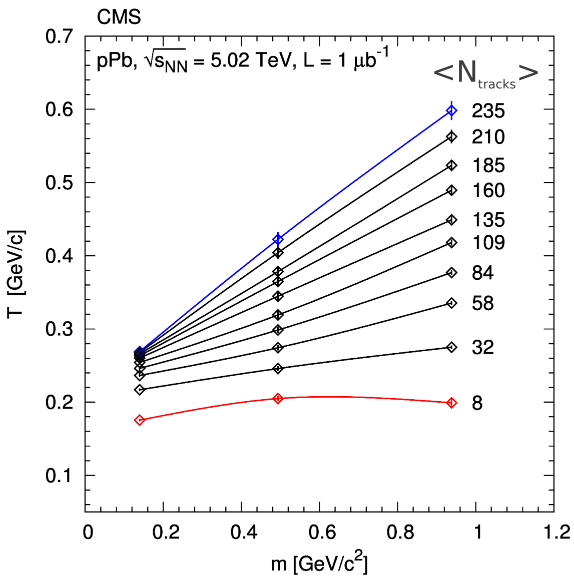
Expanding source

$T_{(slope)} \approx T_{freeze\text{-}out(fo)} + ½\, m_i \langle v_T \rangle^2$

(example for non relativistic case: $p_{T\,i} \ll m_i$)



CMS, arXiv:1307.3442v1

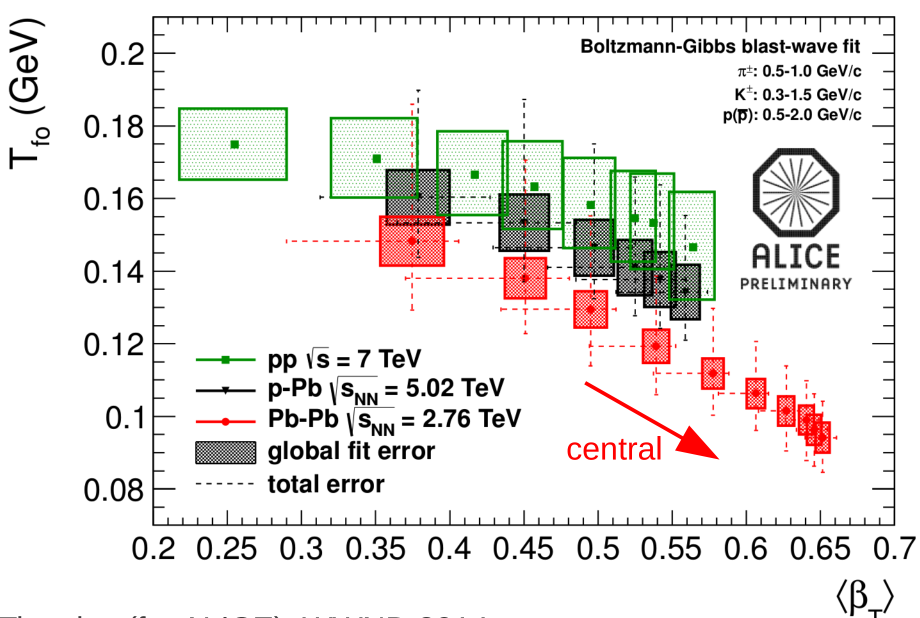


Boltzmann-type distribution: $dN/dp_T \propto p_T \exp(-m_T/T)$

Flow like behaviour (increase of T with mass)
becomes much stronger for highest multiplicities

… more precisely:

Thermal freeze-out parameters (T_{fo}, $\langle\beta_T\rangle$) fitted within **Blast Wave model** (Schnedermann et al., PR C48, 2462 (1993); see also ALICE (Pb+Pb): PR C88, 044910 (2013))



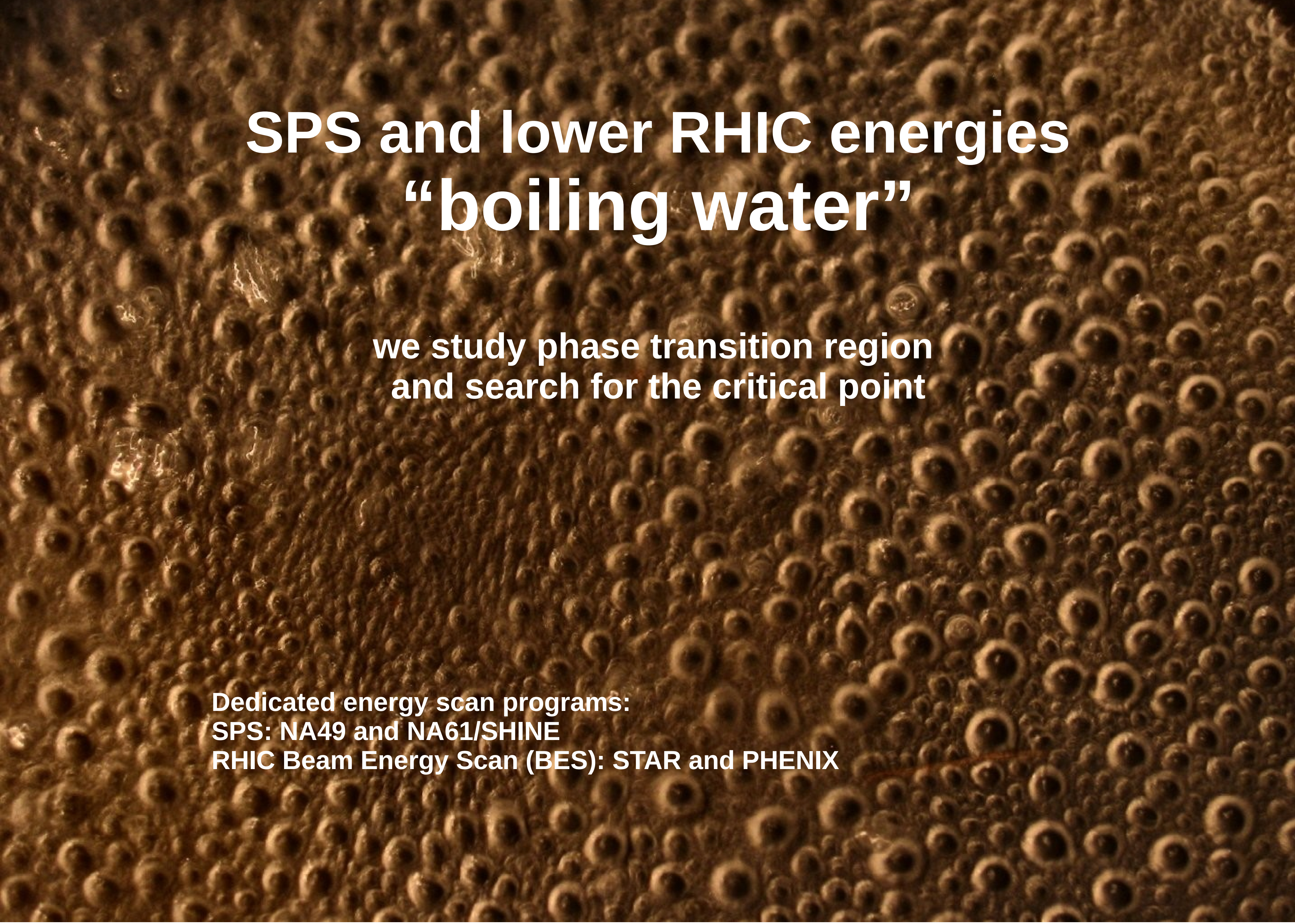
Timmins (for ALICE), WWND 2014

$$\frac{1}{p_T}\frac{dN}{dp_T} \propto \int_0^R r\,dr\, m_T\, I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right)$$

I_0, K_1 - modified Bessel functions

$\rho(r) = \tanh^{-1} \beta_T(r)$; $\beta_T(r) \equiv \beta_{T\,(surf)}(r/R)^n$ R – fireball radius

- Pb+Pb (central): $\langle\beta_T\rangle$=0.65c (10% higher than at RHIC)
- Central p+Pb: $\langle\beta_T\rangle$~0.5c; similar values in p+p
  → **sign of collectivity in p+Pb and p+p ?**

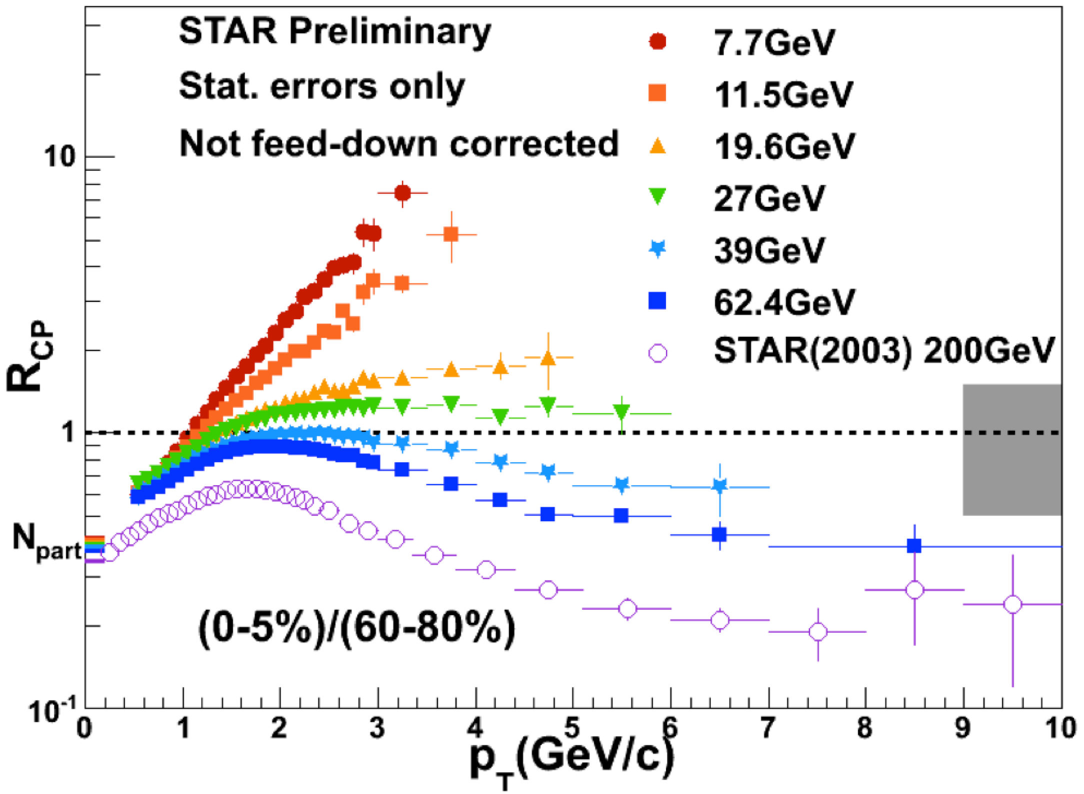


SPS and lower RHIC energies
“boiling water”

we study phase transition region and search for the critical point

Dedicated energy scan programs:
SPS: NA49 and NA61/SHINE
RHIC Beam Energy Scan (BES): STAR and PHENIX

http://soul-amp.blogspot.com/2008/01/boiling-water-photo-weird-photos-of.html



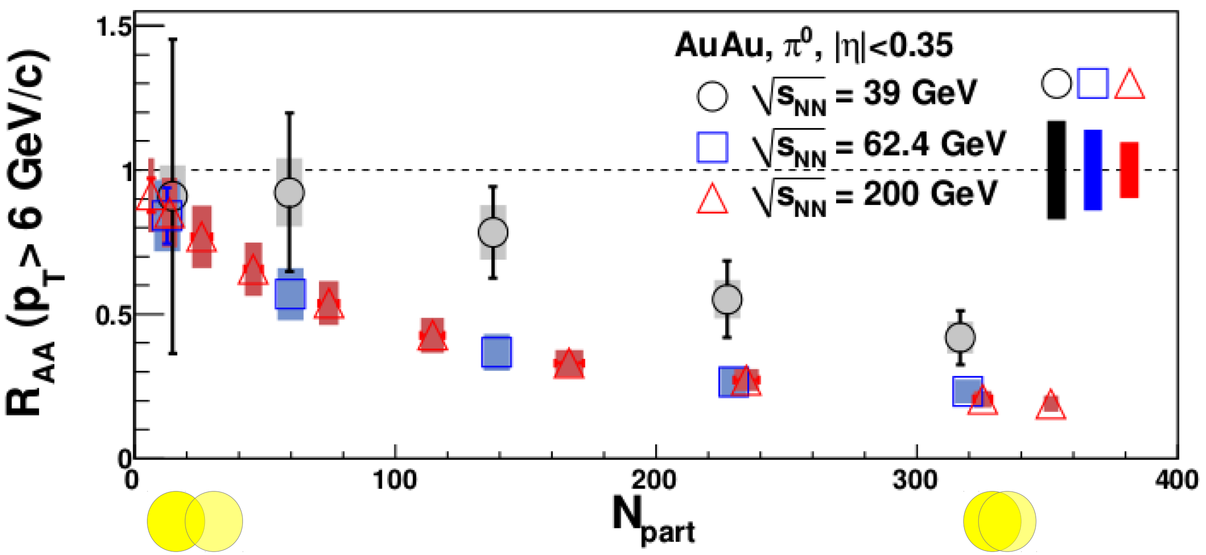
Kumar (for STAR), MPL A28, 1330033 (2013) [arXiv:1311.3426]

RHIC STAR BES, Au+Au

R_{CP} for charged hadrons: **jet quenching disappear** at lower energies (absence of dense medium)→ **"turn-off" of QGP signature**

Partonic effects become less important at lower energies and cold nuclear matter effects (Cronin) start to dominate

See also HIJING results (Sumbera (for STAR), arXiv:1312.2718) with jet quenching off

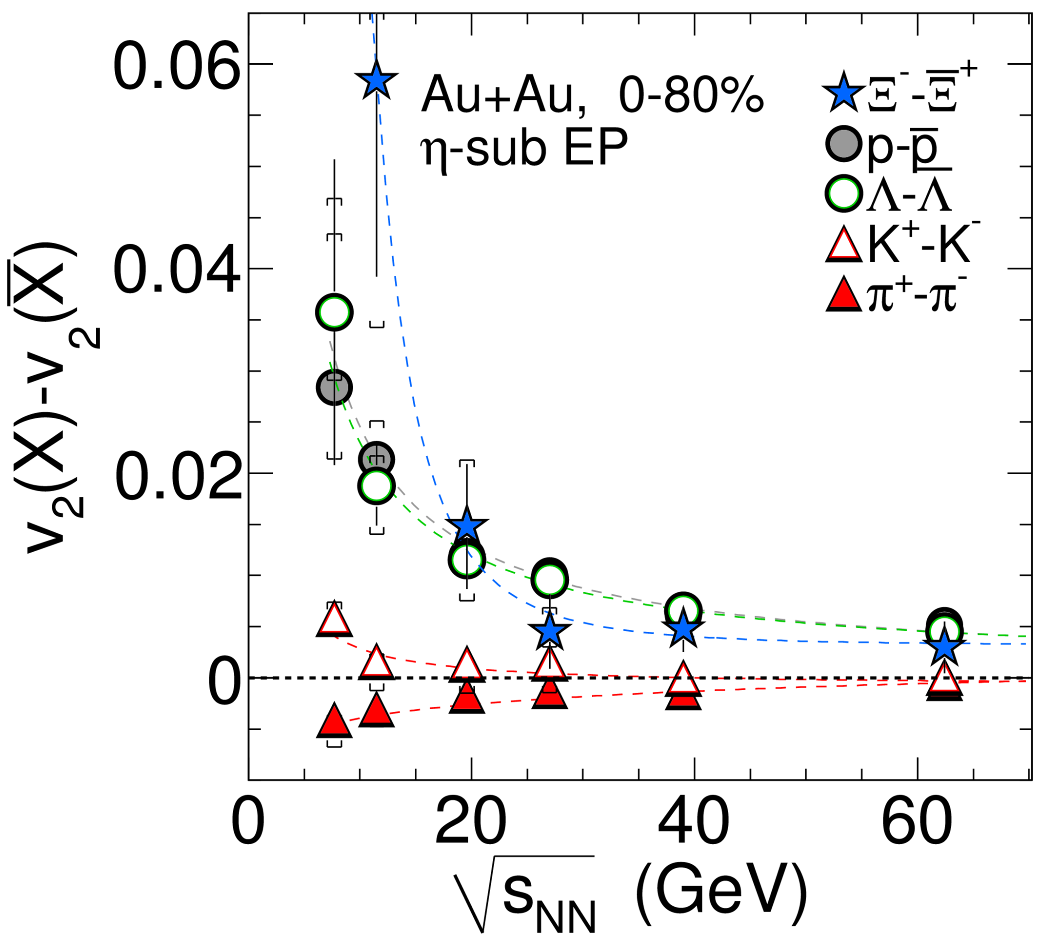


RHIC PHENIX BES, Au+Au

R_{AA} for neutral pions: suppression of high p_T (> 6 GeV/c) neutral pions similar at $\sqrt{s_{NN}}$=200 and 62.4 GeV and smaller at 39 GeV

Mitchell (for PHENIX), PoS CPOD 2013, 003 [arXiv:1308.2185]

Observation of breaking of NCQ scaling at lower energies
as a new method of **estimation of the onset of deconfinement energy?**



RHIC STAR BES, Au+Au

For lower energies difference between v_2 of particle and antiparticle →

”turn-off” of QGP signature

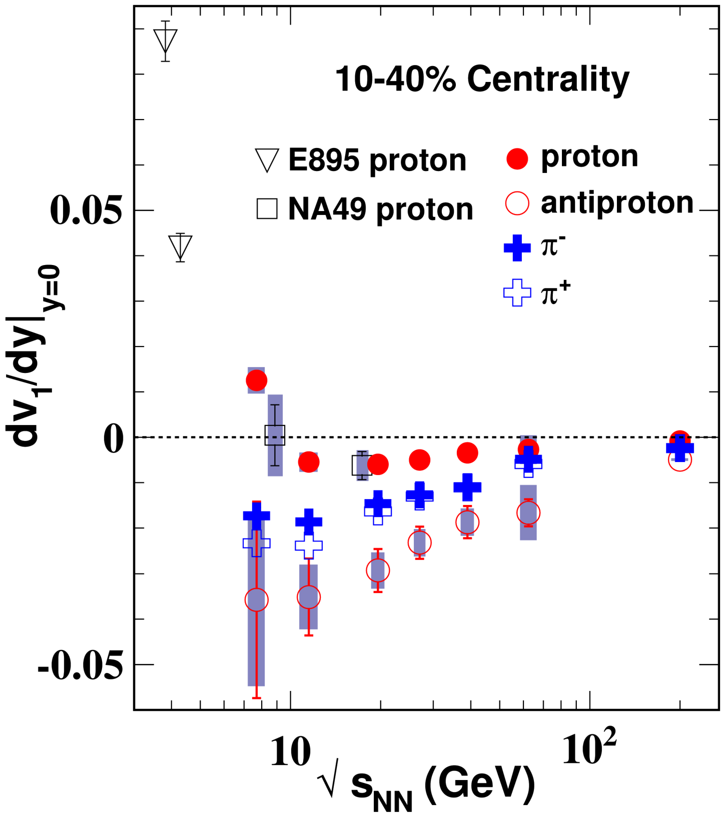
Breaking of partonic collectivity at lower energies may be interpreted as a change of degrees of freedom in the system

departing from QGP region ?

STAR, PRL 110, 142301 (2013)

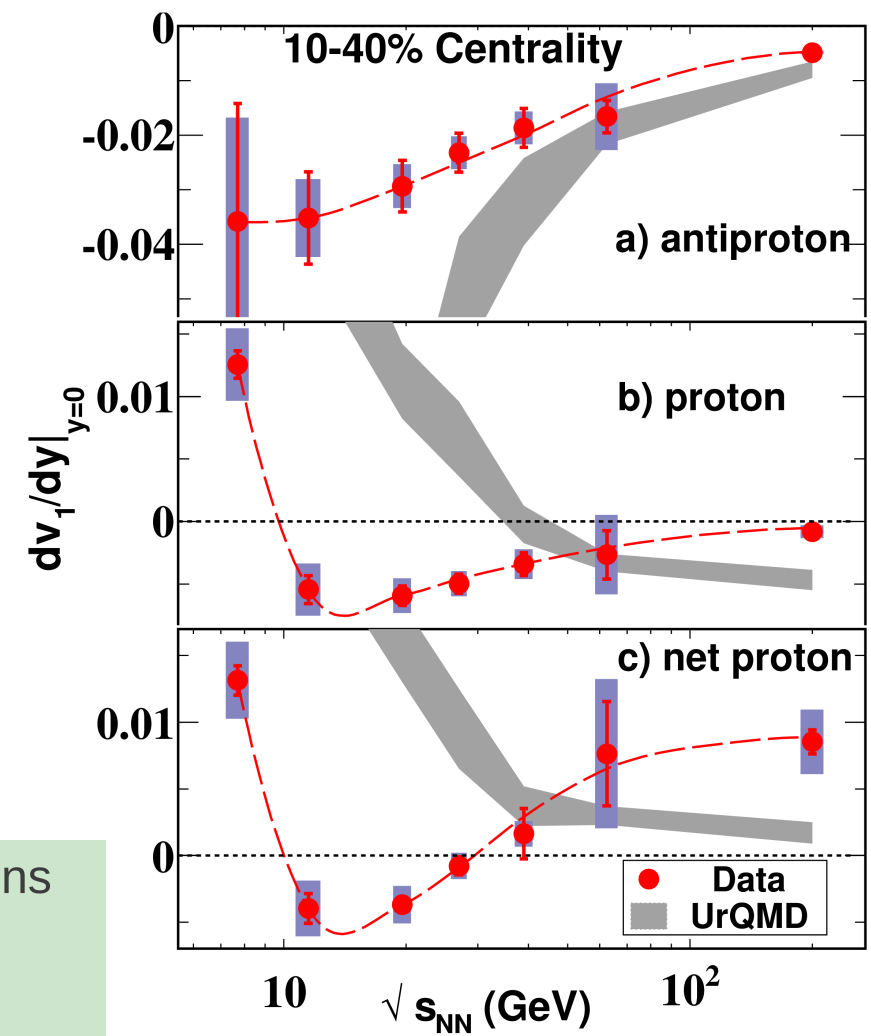
v_2 scaling with n_q – favors partonic degrees of freedom
breaking of v_2 scaling with n_q – favors hadronic degrees of freedom

Directed flow v_1 was considered to be **sensitive to 1st order phase transition** (softening of EOS) Csernai, Rohrich, PL B458, 454 (1999); Stoecker, NP A750, 121 (2005); Brachmann et al. PR C61, 024909 (2000).
Expected: **non-monotonic behaviour** (positive → negative → positive) **of proton dv_1/dy as a function of beam energy - "collapse of proton flow"**



$$y = \frac{1}{2}\ln\frac{E+p_L}{E-p_L}$$

RHIC STAR BES, Au+Au



STAR, arXiv:1401.3043v2, accepted by PRL

- v_1 slopes always negative for pions and anitiprotons
- **v_1 slopes for protons and net-protons** change signs at lower energies and **show minimum at 10-20 GeV** (15 GeV planned in BES-II)

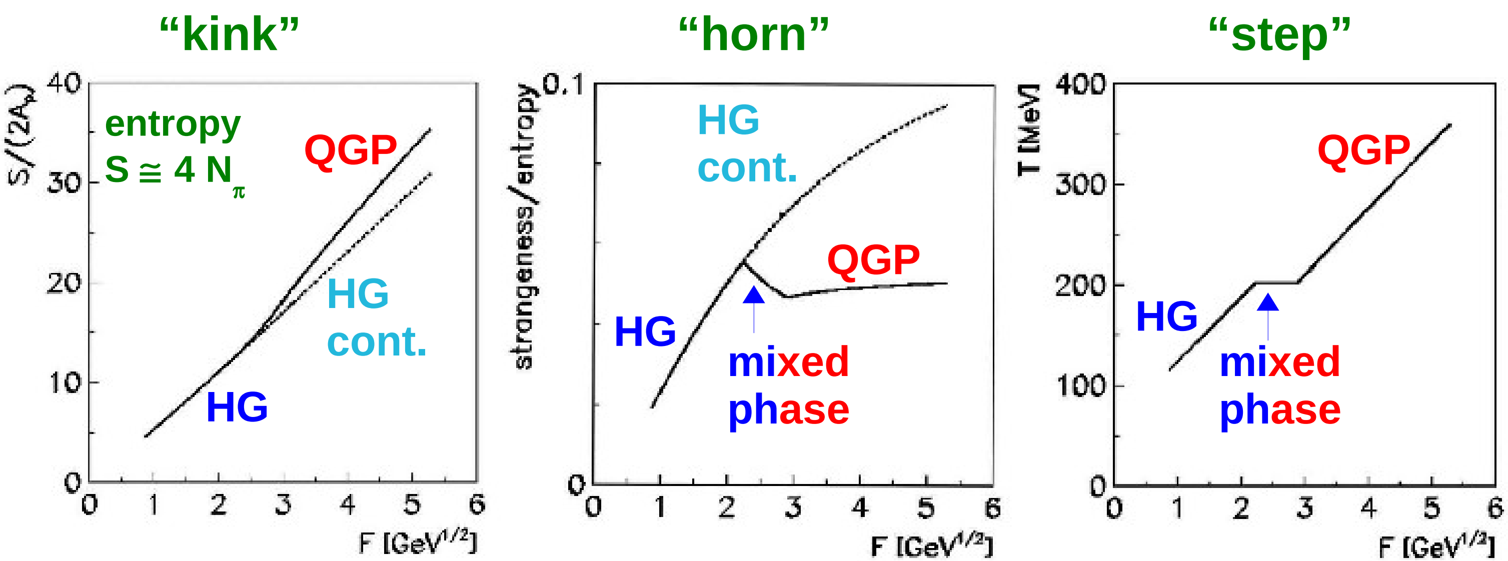
→ **consistent with hydro models with 1st order PT**

Can we estimate the energy threshold for deconfinement even more precisely ?

(the lowest energy sufficient to create a partonic system)

Motivation: **S**tatistical **M**odel of the **E**arly **S**tage (SMES)

Gaździcki, Gorenstein, Acta Phys. Polon. B30, 2705 (1999)



Fermi variable

$$F \equiv \left[\frac{\left(\sqrt{s_{NN}} - 2m_N\right)^3}{\sqrt{s_{NN}}} \right]^{1/4}$$

$$F \simeq \sqrt{\sqrt{s_{NN}}}$$

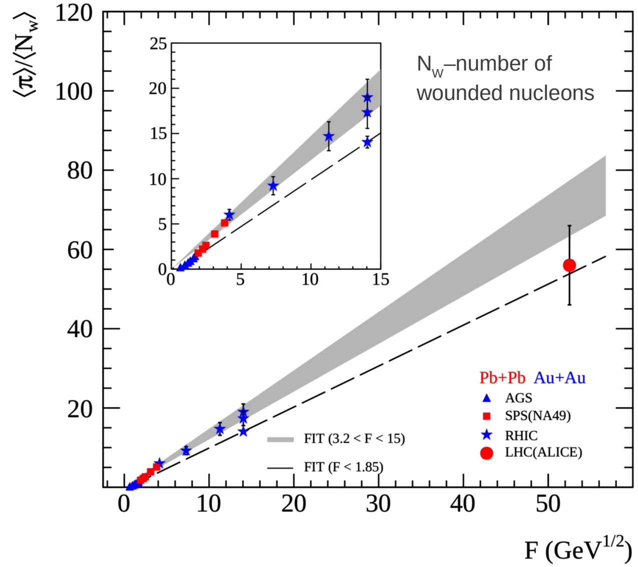
- 1^{st} order phase transition to QGP between top AGS and top SPS energies $\sqrt{s_{NN}} \approx 7$ GeV
- number of internal degrees of freedom (*ndf*) increases HG $\rightarrow$ QGP (activation of partonic degrees of freedom)
- total entropy and total strangeness are the same before and after hadronization (cannot decrease QGP $\rightarrow$ HG)
- mass of strangeness carriers decreases HG $\rightarrow$ QGP ($m_{\Lambda, K, \ldots} > m_s$)
- constant temperature and pressure in mixed phase

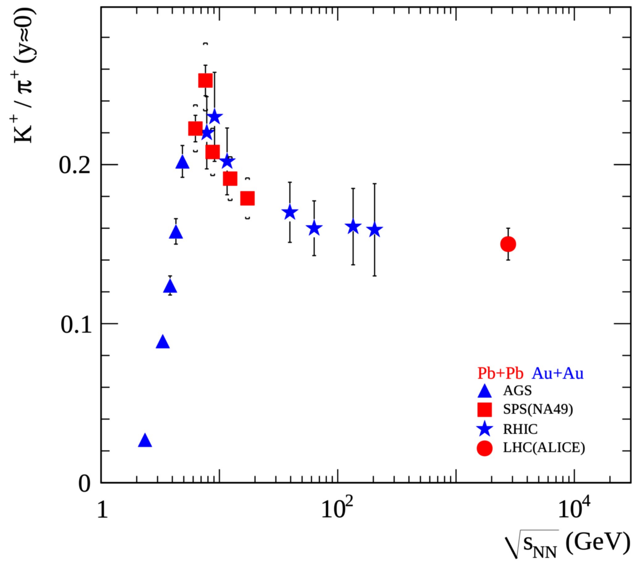
Onset of deconfinement in NA49 (PR C77, 024903 (2008))

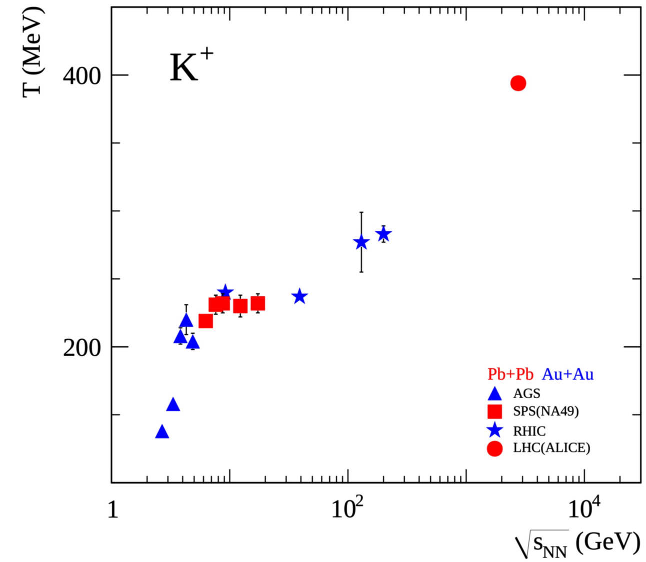
Verification of NA49 results and interpretation by STAR and ALICE

APP B43, 609 (2012); for details see Rustamov https://indico.cern.ch/conferenceDisplay.py?confId=144745

E_{beam} = 30*A* GeV ⇔ $\sqrt{s_{NN}}$ = 7.6 GeV







Kink: increased entropy
Pions measure early stage entropy. In **SMES** (APP B30, 2705 (1999)): **$\langle\pi\rangle/N_w \sim (ndf)^{1/4}$**
Change of slope around 30*A* GeV; no change of slope in p+p data (not shown)

$$\langle\pi\rangle = 1.5(\langle\pi^+\rangle + \langle\pi^-\rangle)$$

$$F \simeq \sqrt{\sqrt{s_{NN}}}$$

⟨π⟩ at LHC was estimated based on ALICE N_{ch} measurement

Horn: decrease of strangeness carrier masses (rise → saturation) **and of strangeness to entropy ratio** (step down)
Sharp peak observed at 30*A* GeV (not seen in p+p)

Step: constant *T* and *p* in mixed phase
Inverse slope of m_T spectra: strong rise at AGS, plateau at SPS, rise towards RHIC

STAR BES points confirm NA49 mesurements;
LHC point supports the interpretation

http://www.piterpanzerwwii.com.pl/czolg-t-100/

The signatures of the onset of deconfinement energy are seen at middle SPS energies for heavy systems: Pb+Pb, Au+Au

What about light and intermediate mass systems ??

http://pl.123rf.com/photo_2550393_czarny-ptak-piorko-na-bialym-tle.html

NA61/SHINE heavy ion program (part I)

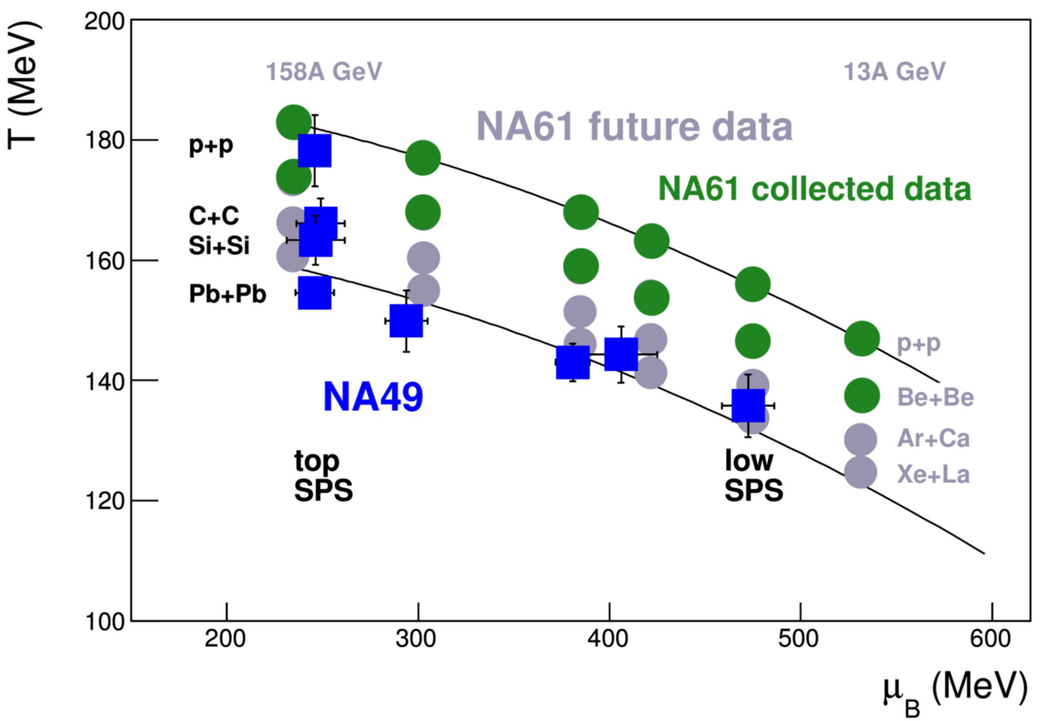
SHINE – SPS Heavy Ion and Neutrino Experiment

Successor of the NA49 experiment

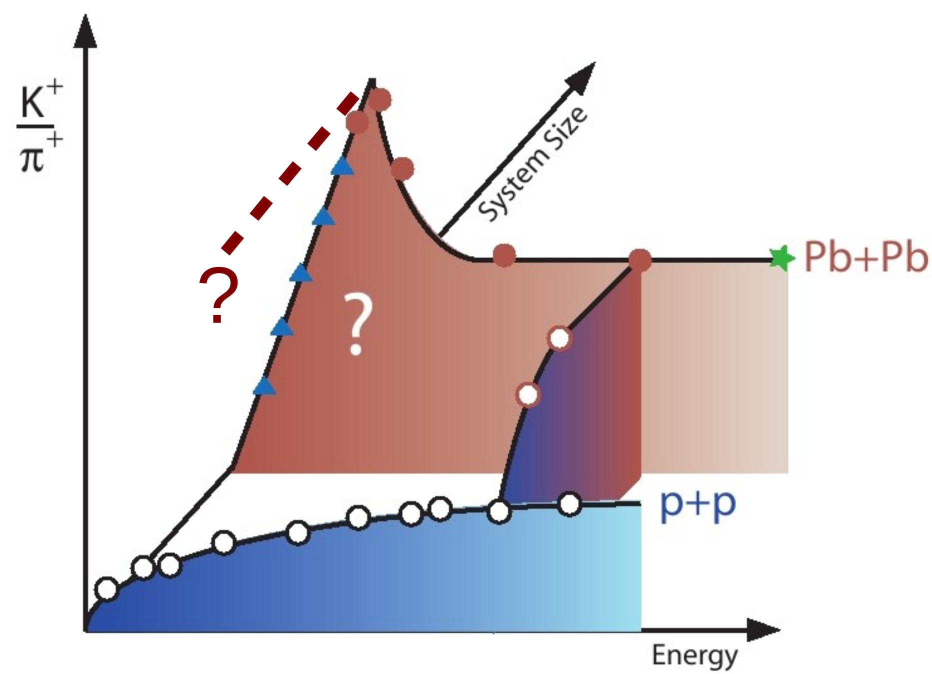
Comprehensive scan in the whole SPS energy range (E_{beam}= 13*A*-158*A* GeV ⇔ $\sqrt{s_{NN}}$=5.1-17.3 GeV) with **light and intermediate mass nuclei**

Study of the properties of the onset of deconfinement

Search for the **onset of the horn / kink / step, etc. in collisions of light nuclei**; additional analysis of fluctuations and correlations (azimuthal, particle ratios, etc.)



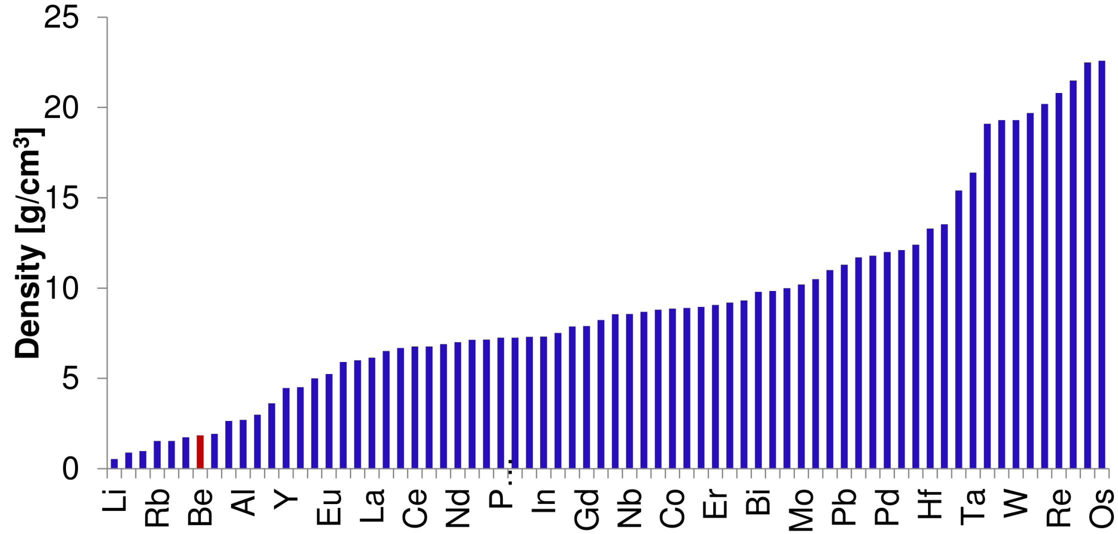
Estimated (NA49) and expected (NA61) chemical freeze-out points according to PR C73, 044905 (2006)



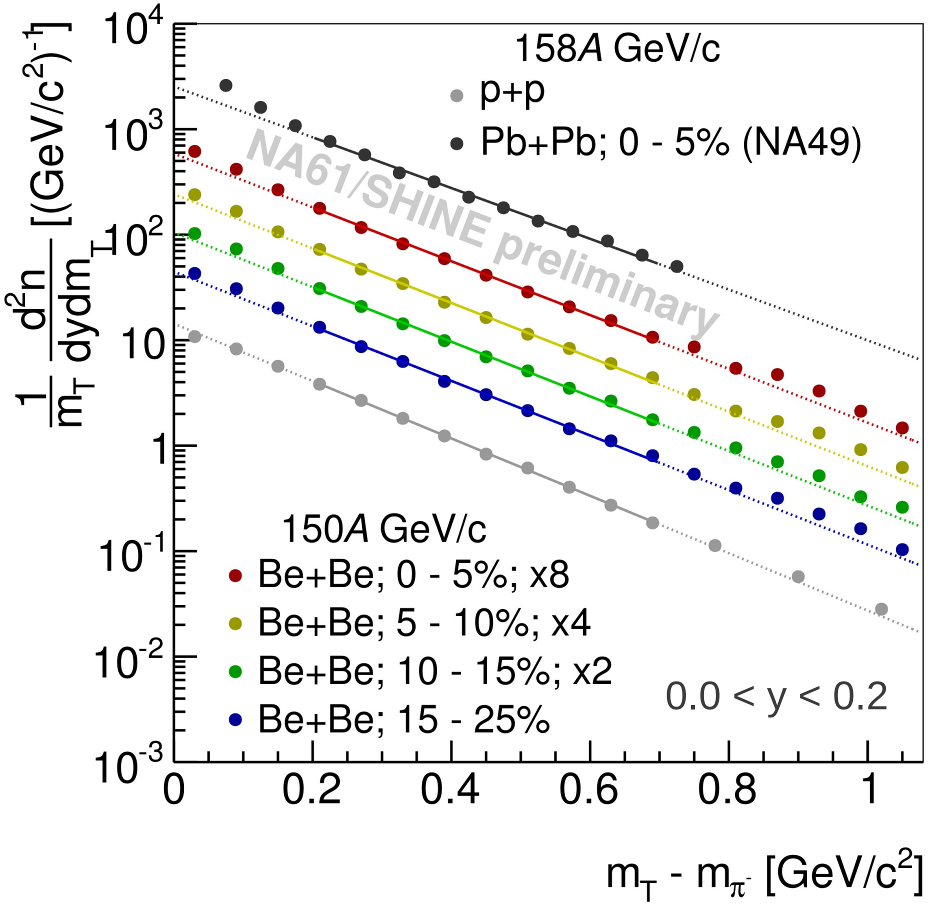
First A+A results from NA61:

Is Beryllium heavy?

Compared to other metals by the density of the solid state Beryllium is quite light



top SPS, Be+Be



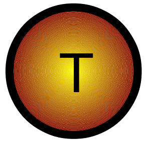
Transverse mass spectra of π^- mesons

- p+p spectra are exponential
- Convex shape of Pb+Pb and Be+Be spectra
- Spectra fitted in the range:
  $0.2 < m_T - m_\pi < 0.7$ GeV/c^2

$$\frac{dn}{dm_T} = A\, m_T \exp\left(\frac{-m_T}{T}\right)$$

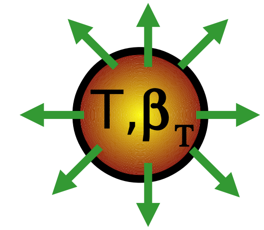
Kaptur (for NA61), X Polish Workshop on Relativistic Heavy-Ion Collisions (XII 2013)

Static source



$T_{(slope)} = T_{freeze\text{-}out}$
(thermal freeze-out)

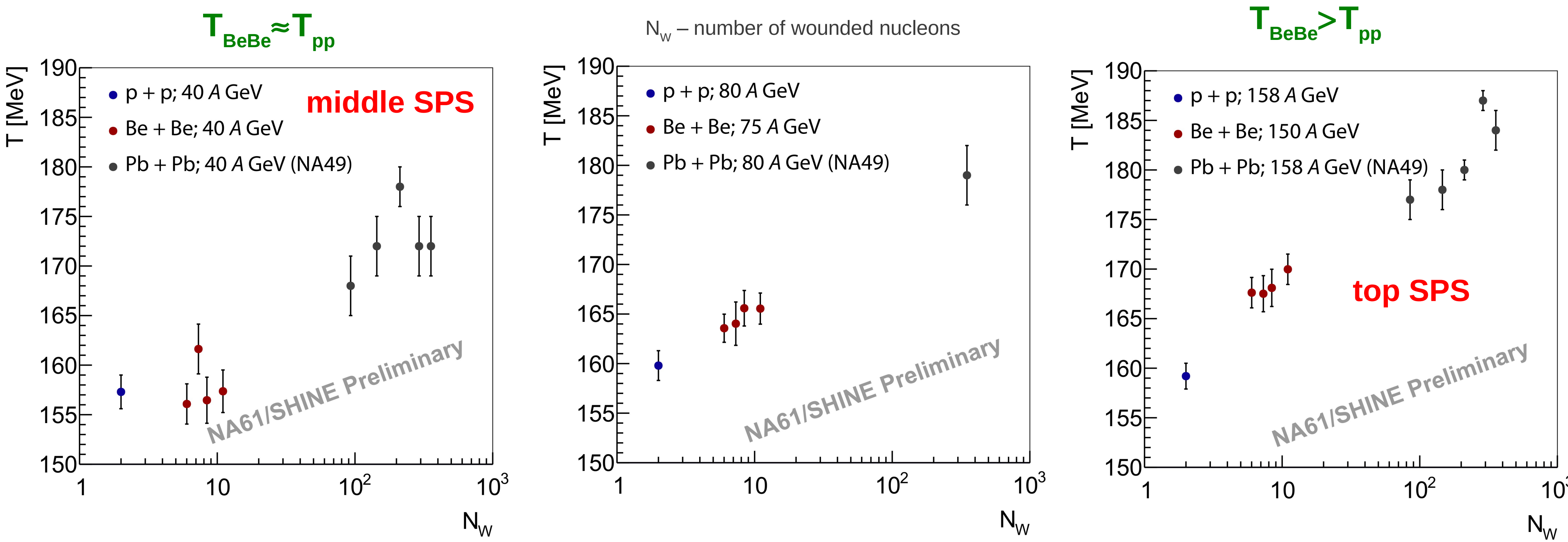
Expanding source



$T_{(slope)} = T_{freeze\text{-}out}$ + effect of radial flow

Inverse slope parameter (T) of transverse mass spectra of π^- mesons

- T at the top SPS is significantly larger in Be+Be than in p+p ⇒ **possible evidence of transverse collective flow in Be+Be collisions at higher SPS energies**
- Beryllium looks heavy at 150*A* GeV/c (top SPS)



Kaptur (for NA61), X Polish Workshop on Relativistic Heavy-Ion Collisions (XII 2013)

Analysis of other particles (K, p, etc.) → coming soon → BW fits
Analysis of other observables (kink, horn, step) → coming soon

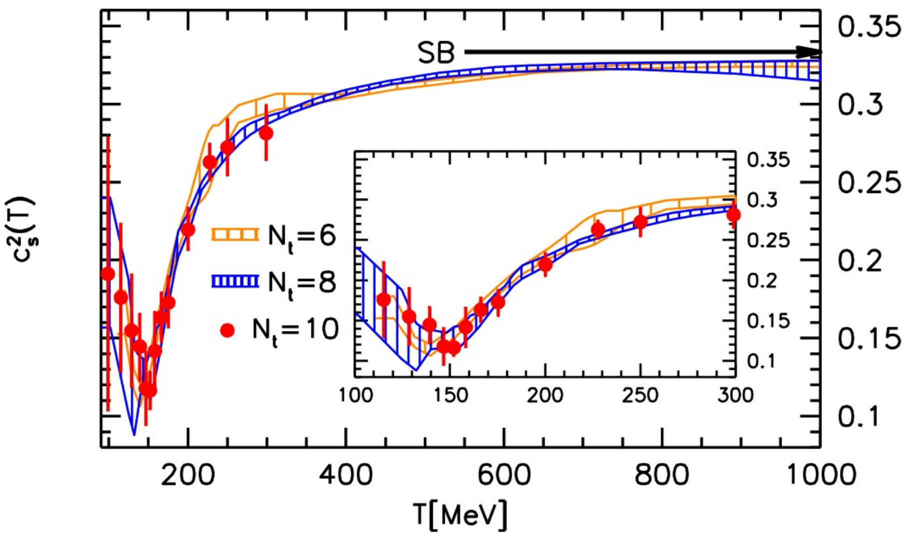
Lattice results - minimum of sound velocity (softest point of EOS) close to the temperature of QGP ↔ hadron gas transition

$c_s^2 = dp / d\varepsilon$

p - pressure

ε - energy density

Borsanyi et al.
JHEP 1011, 077 (2010)



"Dale" plot → studying the properties of the onset of deconfinement

Eur. Phys. J. C (2014) 74:2794

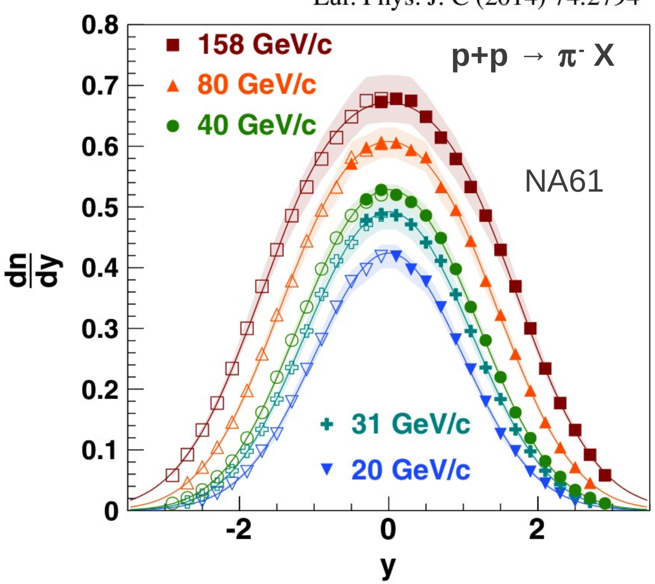
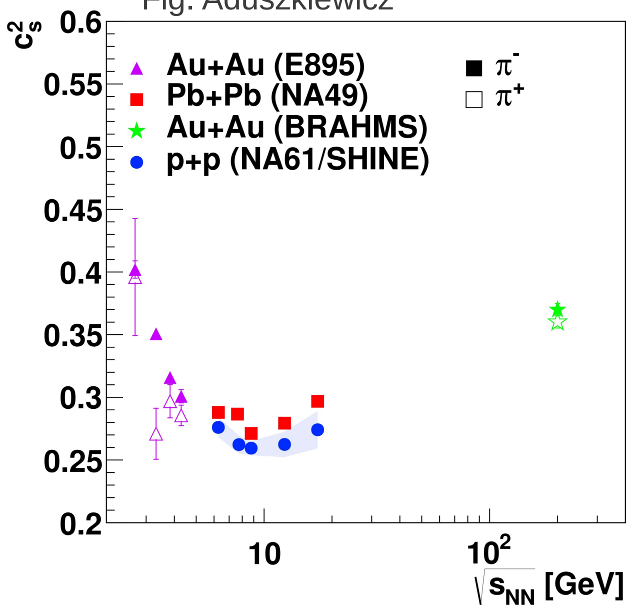


Fig. Aduszkiewicz



Hydrodynamical Landau model
Shuryak, Yad. Fiz. 16, 395 (1972):

$$\sigma_y^2(\pi^-) = \frac{8}{3}\frac{c_s^2}{1-c_s^4}\ln\left(\sqrt{s_{NN}}/2m_p\right)$$

- **Minimum in Pb+Pb at middle SPS energies**
- **The dale may be present also in p+p reactions !**

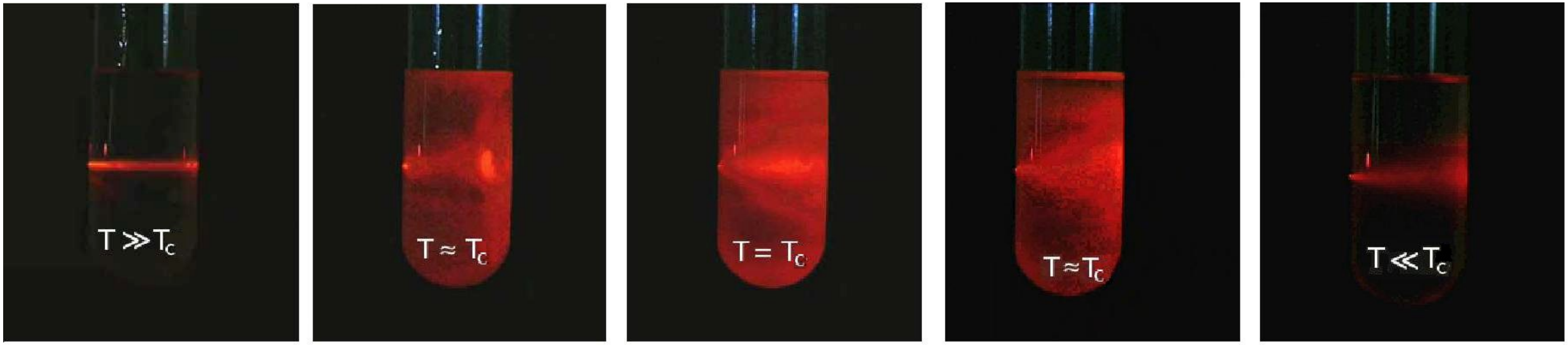
Looking for the **critical point**
- The Holy Grail of modern heavy ion physics

Fluctuations and correlations can help to locate the critical point of strongly interacting matter

Analogy to critical opalescence – **enlarged fluctuations close to the critical point**. For strongly interacting matter maximum of CP signal expected when freeze-out happens near CP

Critical opalescence is observed in most liquids (including water)

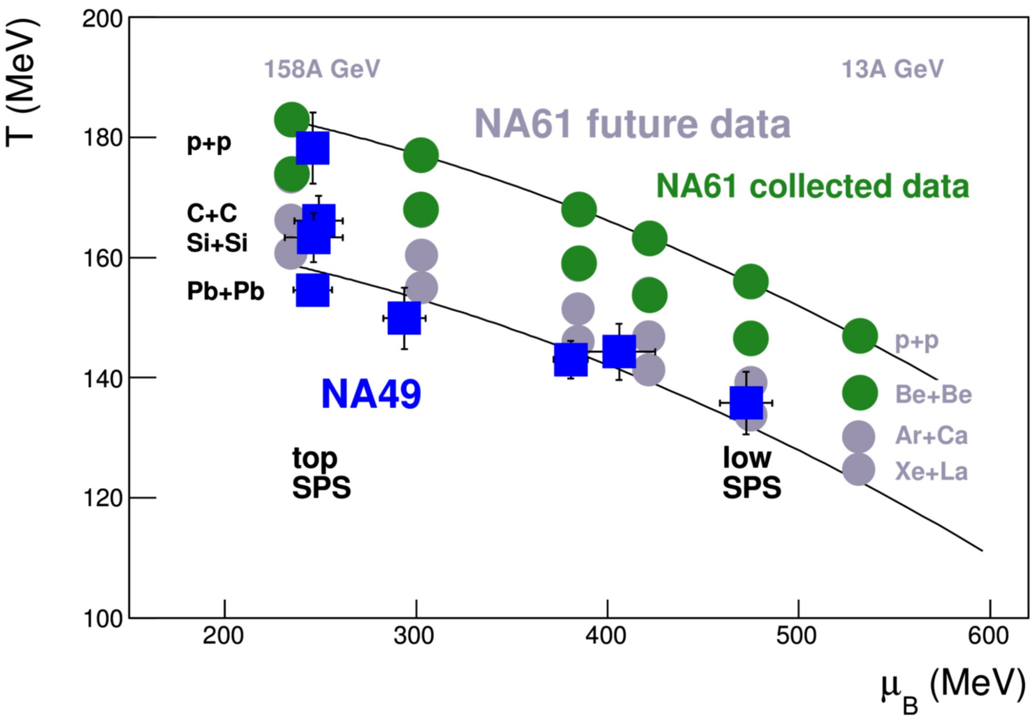
"As the fluid cools down under conditions such that it passes near the end point of the boiling transition, it goes from transparent to opalescent to transparent as the end point is approached and then passed. This non-monotonic phenomenon is due to scattering of light on critical long wavelength density fluctuations (...)"
Stephanov, Rajagopal, Shuryak, PR D60, 114028 (1999)



http://www.msm.cam.ac.uk/doitpoms/tlplib/solid-solutions/videos/laser1.mov

RHIC BES studied: net-charge and net-proton fluctuations (STAR, arXiv:1402.1558; Mohanty, 1402.3818), p_T correlations, particle ratio (chemical) fluctuations (Sahoo, WWND 2014) → no clear non-monotonic behaviour, no clear evidence of CP in the energy scan of Au+Au collisions

NA61/SHINE heavy ion program (part II)

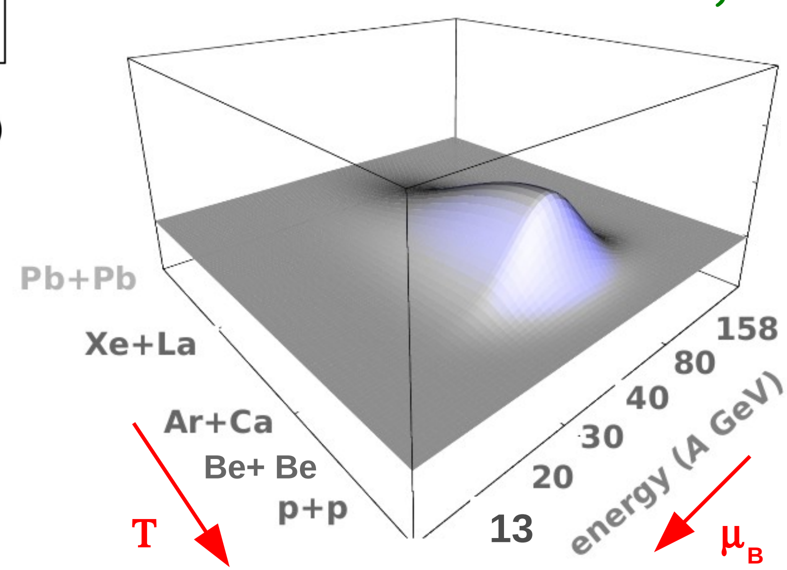


Search for the critical point

Search for a maximum of CP signatures (**hill of fluctuations**): fluctuations of N, average p_T, etc., intermittency, when system freezes out close to CP

CP signal

ω, Φ_{pT}, ...



Non-monotonic dependence of critical point signal on control parameters (energy, centrality)

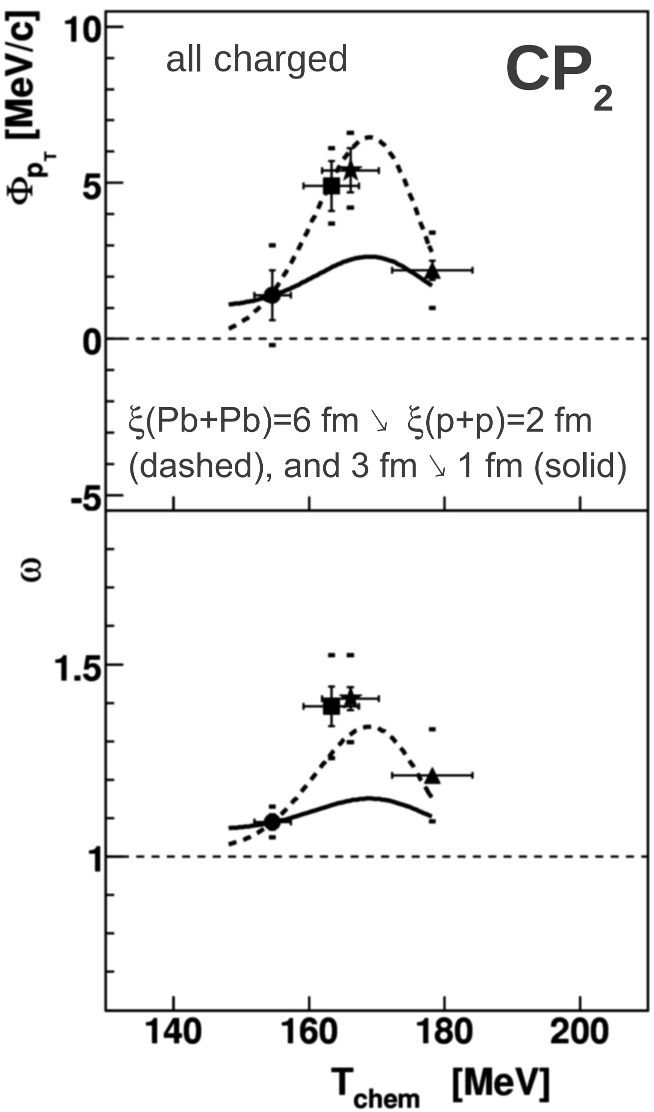
K. Grebieszkow, DIS 2014

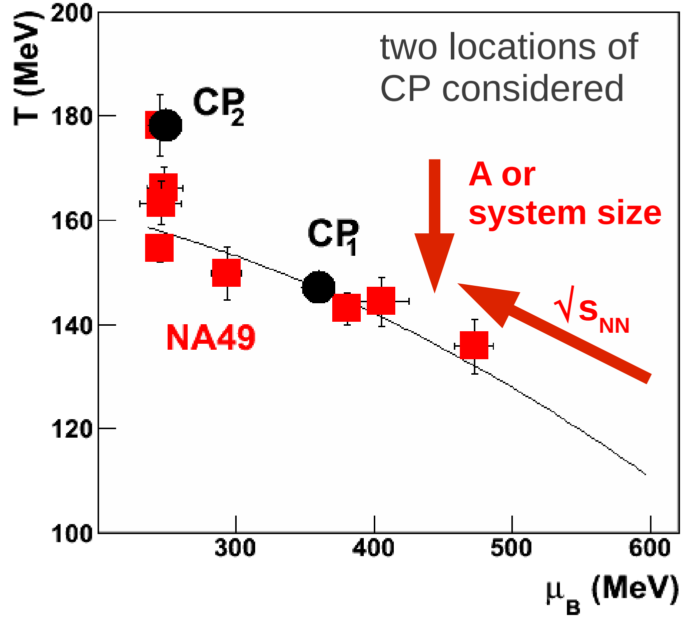
Average p_T and multiplicity fluctuations: dependence on phase diagram coordinates

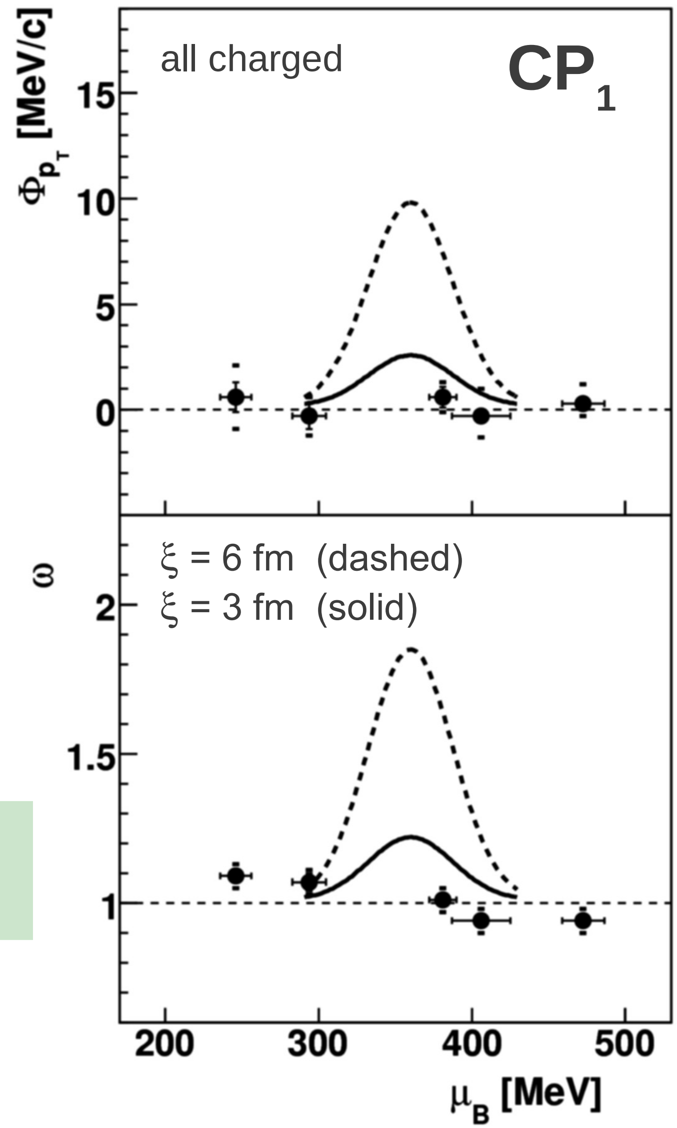
Φ_{p_T} – measures event-by-event p_T fluctuations (Φ_{p_T}=0→no fluct. / correlations; strongly intensive)

ω – scaled variance (variance / mean) of multip. distrib. (ω=0→no fluct., ω=1→Poisson; intensive)

http://www.ujk.edu.pl/homepages/mryb/10thworkshop/files/slides/grebieszkow.pdf → other measures in NA49 and NA61





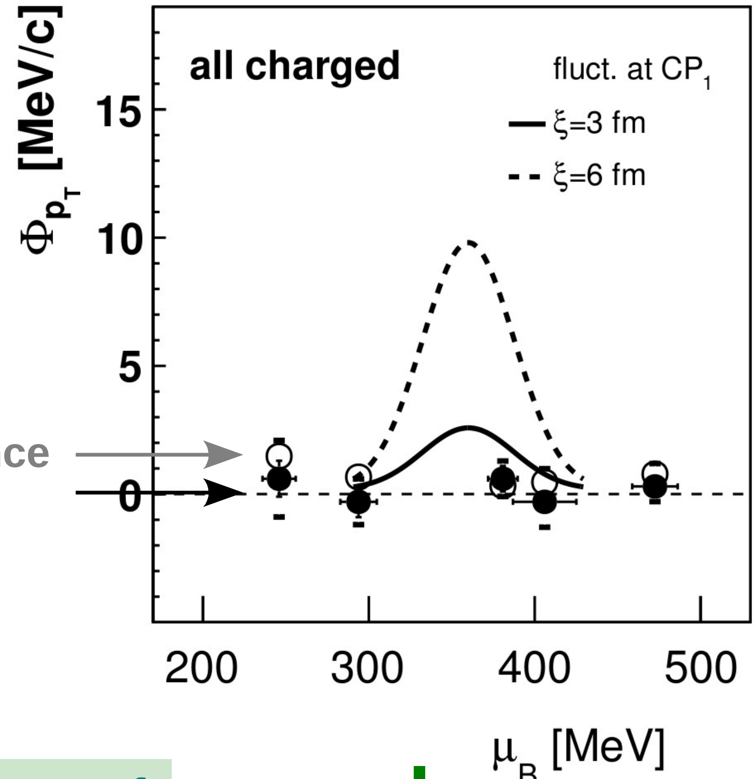


Maximum of Φ_{pT} and ω observed for C+C and Si+Si

Data are consistent with the CP_2 predictions

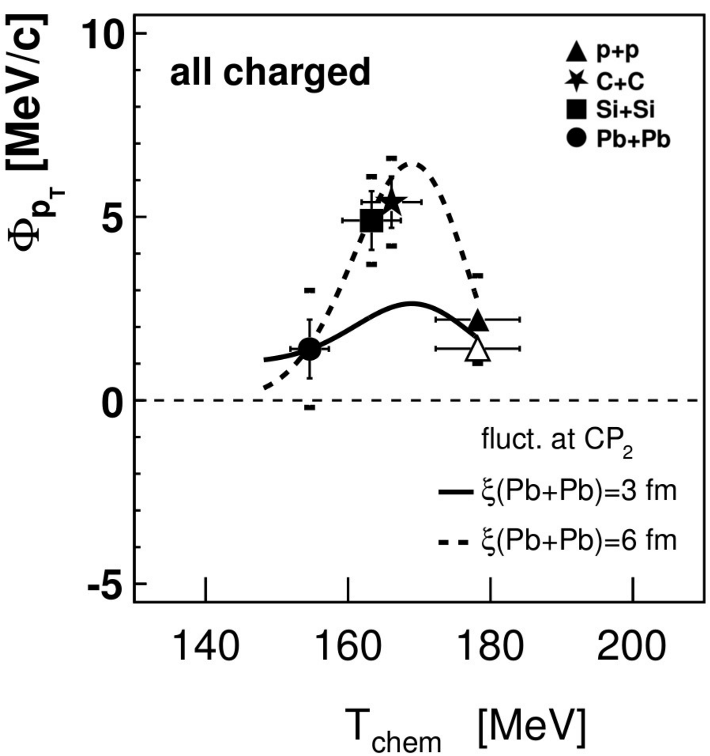
NA49: forward-rapidity region;
see NP A830, 547C (2009) for details

Comparison of p_T fluctuations between p+p and Pb+Pb collisions (NA49: PR C79, 044904 (2009)) in the NA49 phase-space cuts.
No significant difference is observed



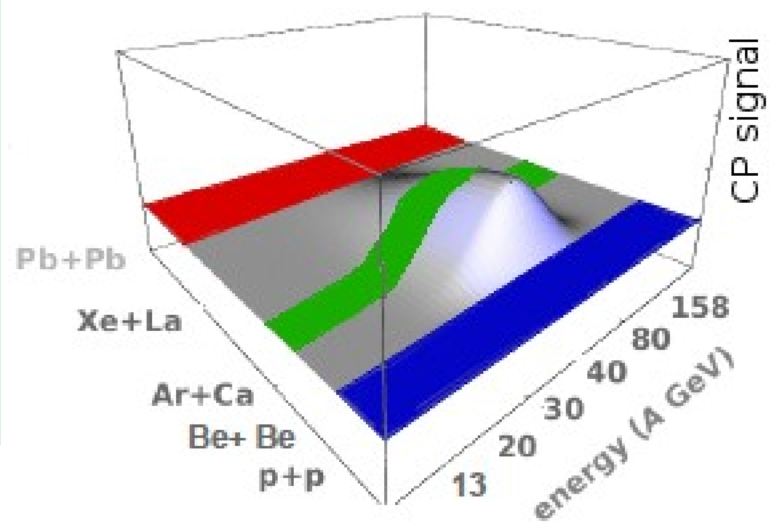
NA61: p+p in NA49 acceptance
NA49: 7.2% Pb+Pb

Seyboth (for NA49 and NA61), arXiv:1402.4619; Grebieszkow (for NA49 and NA61), X Polish Workshop on Relativistic Heavy-Ion Collisions (XII 2013)

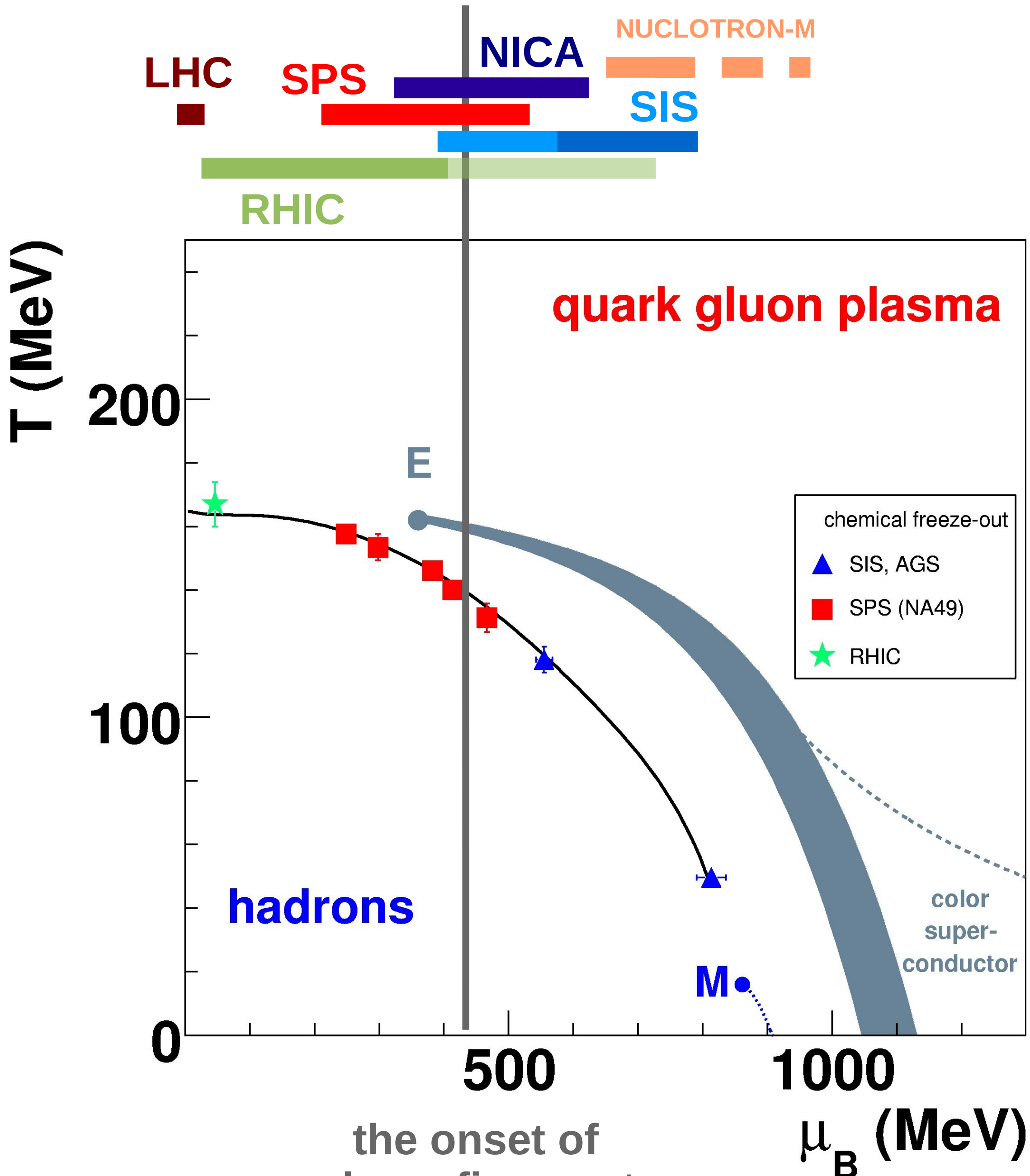


No indications of critical point in the energy scan of Pb+Pb (NA49) **and p+p** (NA61)

We are waiting for the results from Be+Be, Ar+Ca, and Xe+La



Heavy ion programs



the onset of deconfinement

New period in the experimental study of A+A collisions at the SPS energy range started in 2009 with the p+p energy scan of NA61/SHINE at the CERN SPS

CERN **SPS** (NA61)
BNL **RHIC** (STAR, PHENIX)
JINR **NUCLOTRON-M** (BM@N)
JINR **NICA** (MPD)
GSI **FAIR SIS-100/300**
(**HADES+CBM, CBM**)

2009(11) ↗
2009 ↗
2010 ↗
2015 ↗
2017 ↗
2018/19(2025?) ↗

K. Grebieszkow, DIS 2014

Summary:

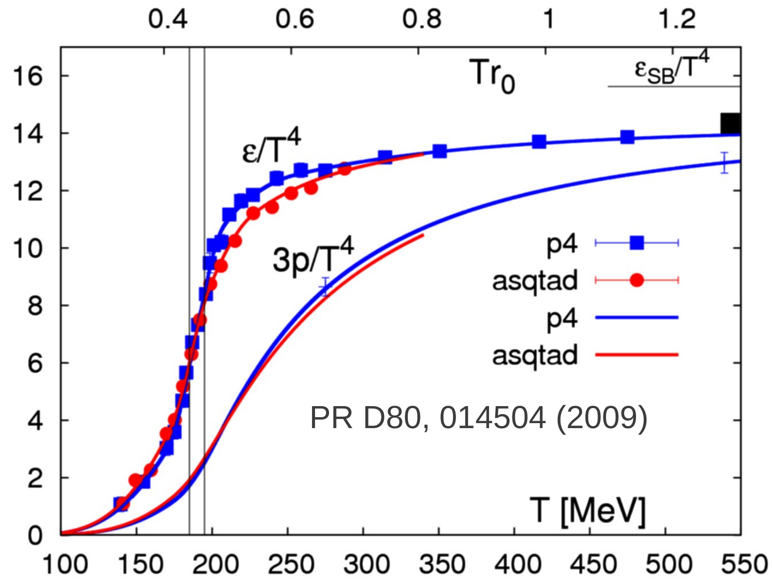
- **LHC, top RHIC energies → studying properties of QGP**
  - The existence of **QGP in Au+Au / Pb+Pb** collisions **at high energies** is well established, but
  - Some interesting measurements suggesting that collectivity may be present also in high multiplicity p+p and p(d)+A collisions ⇒ **p+p and p(d)+A is not only boring reference to A+A interactions!** Radial flow can be present also in light Be+Be system at higher SPS energies!

- **SPS, RHIC Beam Energy Scan energies → studying transition region ...**
  - Several observables (RHIC BES and NA49→dv_1/dy, NCQ scaling of v_2, R_{AA}, kink, horn, step, dale, etc.) showing that the **energy threshold for deconfinement in Pb+Pb / Au+Au collisions is located close to middle SPS energies**
  - Very interesting to **check** whether QGP may be also created **in smaller systems** → energy scan with small and intermediate mass systems in NA61

- **… and looking for the critical point**
  - **Fluctuations of average p_T, multiplicity, multiplicity of low mass $\pi^+\pi^-$ pairs and protons** (see NA49: PR C81, 064907 (2010) and arXiv:1208.5292v2 for the last two) **tend to a maximum in Si+Si collisions at top SPS**. It might be connected with CP at SPS energies → strong motivation for future experiments
  - It is the beginning of the story! Much more effort is needed both from experimental (corrections, proper measures of fluctuations, etc.) and theoretical (lattice, models with predicted magnitudes of fluctuation measures at CP) side

Back-up slides

Theory (lattice calculations at $\mu_B = 0$)



More recent results:

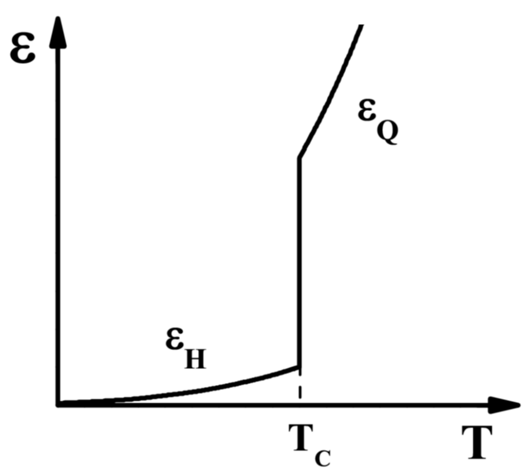
T_c = 154 ± 8(stat.) ± 1(sys.) MeV (HotQCD),

T_c = 155 ± 3(stat.) ± 3(sys.) (Wuppertal-Budapest)

NP A904-905, 318c (2013); NP A904-905, 270c (2013)

ε/T^4 ~ # degrees of freedom

1st order PT



Experiment (Bjorken model)

For central collisions:

$$\varepsilon_{Bj} = \frac{energy}{volume} \approx \frac{1}{\pi R^2 \tau_0} \left[\frac{dE_T}{dy}\right]_{y^*=0}$$

$$R = 1.12\, A^{1/3}$$

$$[dE_T/dy]_{y^*=0} = \langle m_T \rangle [dN/dy]_{y^*=0}$$

thus: $$\varepsilon_{Bj} \approx \frac{\langle m_T \rangle}{\pi R^2 \tau_0} \left[\frac{dN}{dy}\right]_{y^*=0}$$

top SPS $\varepsilon_{Bj}\tau \approx$ 3.2 GeV/(fm²c)

for **$\tau_0 \approx$ 1 fm/c** $\Rightarrow \varepsilon_{Bj} \approx$ 3.2 GeV/fm³

top RHIC $\varepsilon_{Bj}\tau \approx$ 5 GeV/(fm²c)

for $\tau_0 \approx$ 1 fm/c $\Rightarrow \varepsilon_{Bj} \approx$ 5 GeV/fm³

for **$\tau_0 \approx$ 0.6 fm/c** $\Rightarrow \varepsilon_{Bj} \approx$ 9 GeV/fm³

LHC $\varepsilon_{Bj}\tau \approx$ 15-16 GeV/(fm²c)

for $\tau_0 \approx$ 1 fm/c $\Rightarrow \varepsilon_{Bj} \approx$ 15-16 GeV/fm³

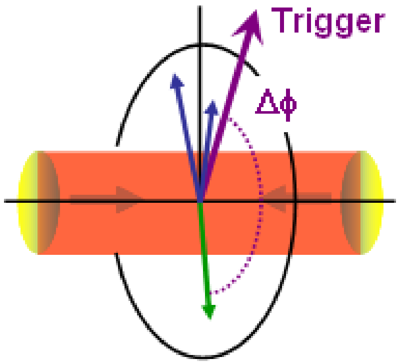
for **$\tau_0 \approx$ 0.6 fm/c** (hydro describ. spectra PR C85, 064915 (2012))

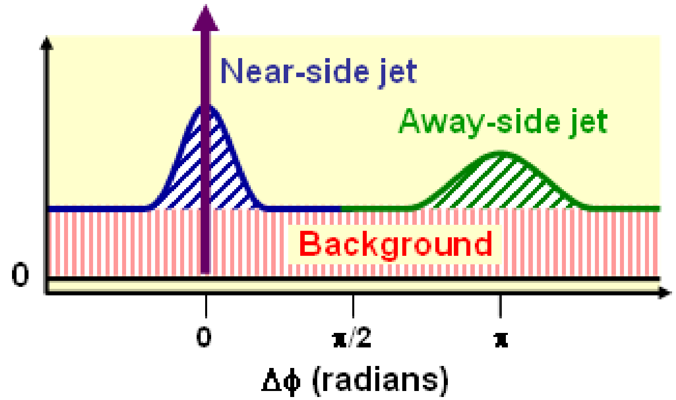
$\Rightarrow \varepsilon_{Bj} \approx$ 25-27 GeV/fm³

for **$\tau_0 \approx$ 0.3 fm/c** $\Rightarrow \varepsilon_{Bj} \approx$ 50-53 GeV/fm³

Jet quenching as a signature of hot and dense matter

Two-particle correlations in azimuthal angle (left)

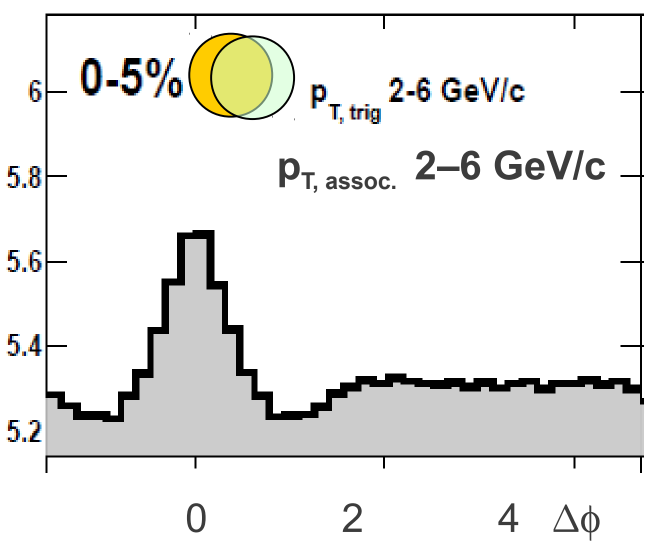




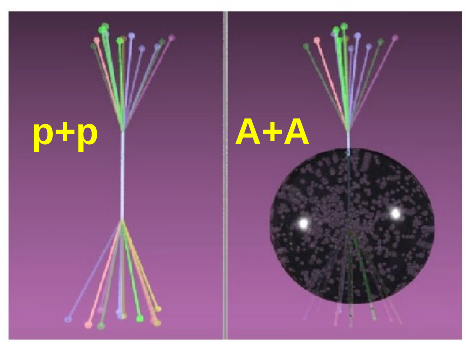
Trigger particle (high p_T) combined with *associated* particles and $\Delta\phi$ calculated for each pair

seen at top RHIC and LHC

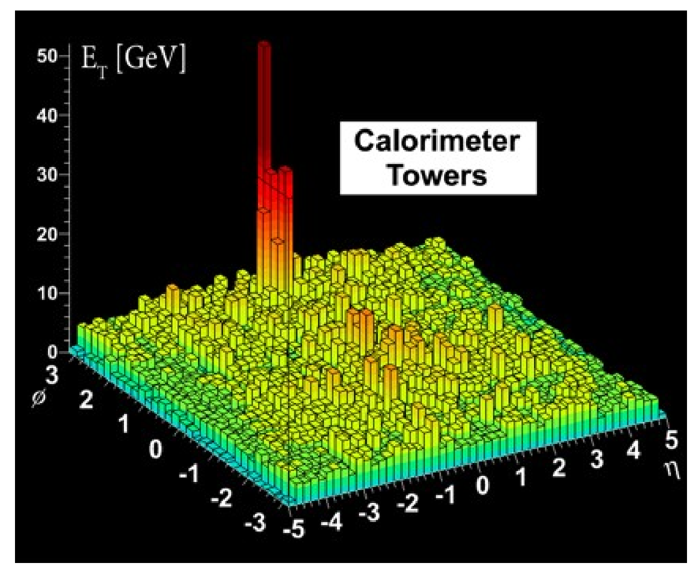
Disappearance (= p_T reduction!) **of away-side jet** due to parton passage trough dense and hot medium; effect not seen in d+Au and p+p (not shown here)



ALICE, central Pb+Pb at $\sqrt{s_{NN}}$=2.76 TeV



PRL 105, 252303 (2010)



ATLAS, central Pb+Pb at $\sqrt{s_{NN}}$=2.76 TeV

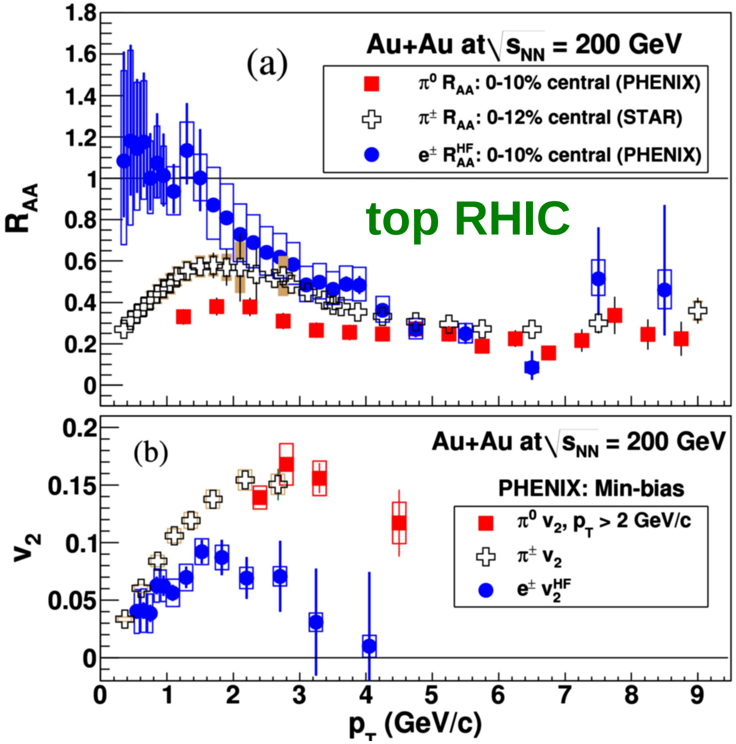
<u>Direct</u> (w/o 2-part. corr.) observation of jet quenching at LHC

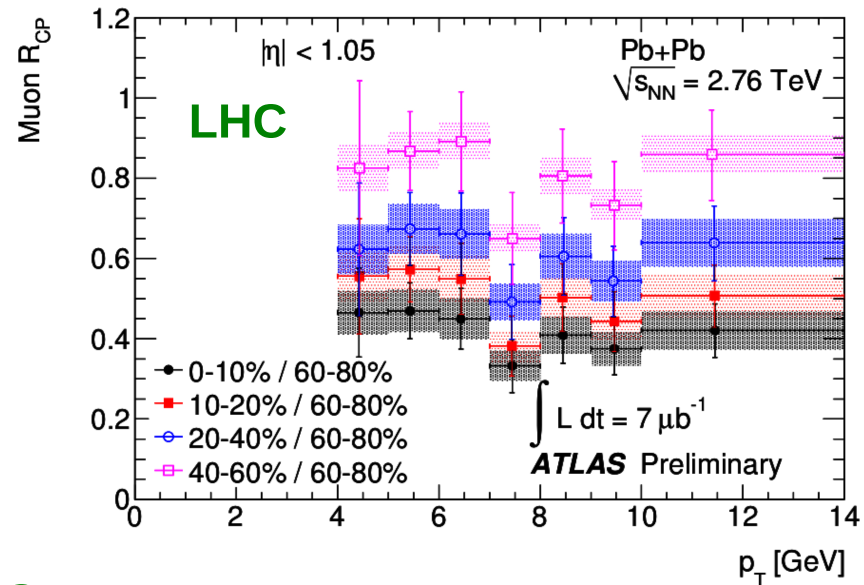
Electrons / muons from HF decays

(from semi-leptonic decays of D and B mesons

i.e. $D^0 \rightarrow e^+ K^- \nu_e$)

Nouicer, arXiv:0901.0910

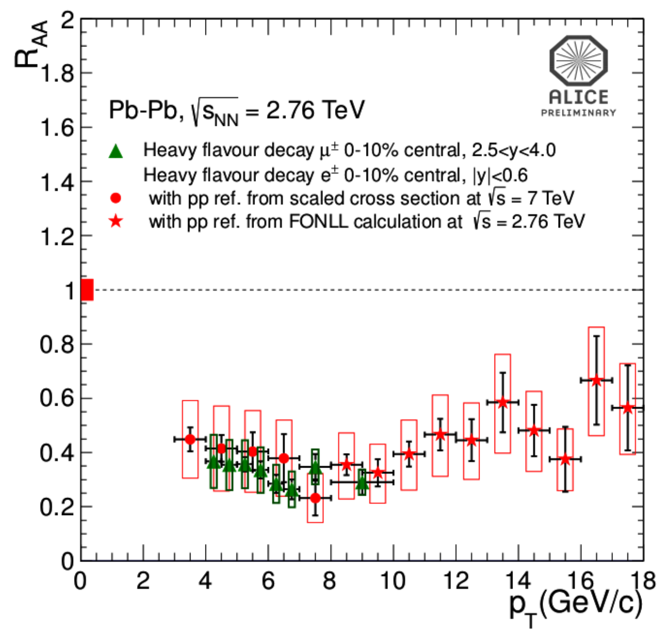




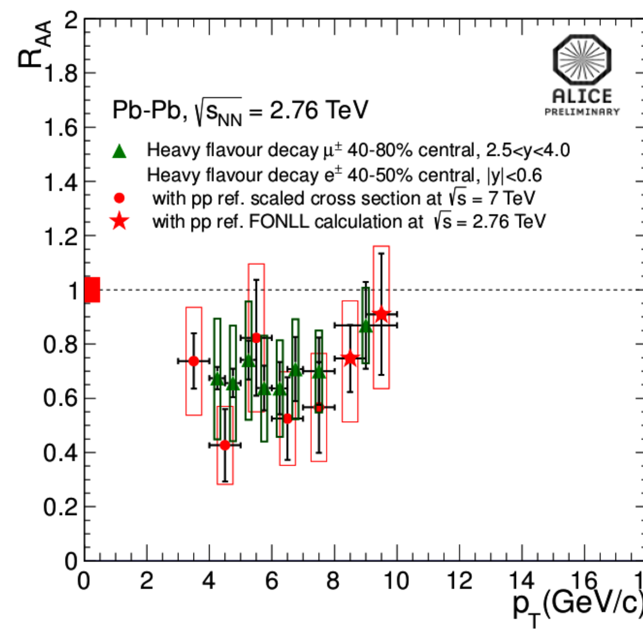
Rossi, EPJ Web Conf. 60, 03003 (2013) [arXiv:1308.2973]

LHC

LaPointe (for ALICE), arXiv:1401.6858



ALI-DER-36791



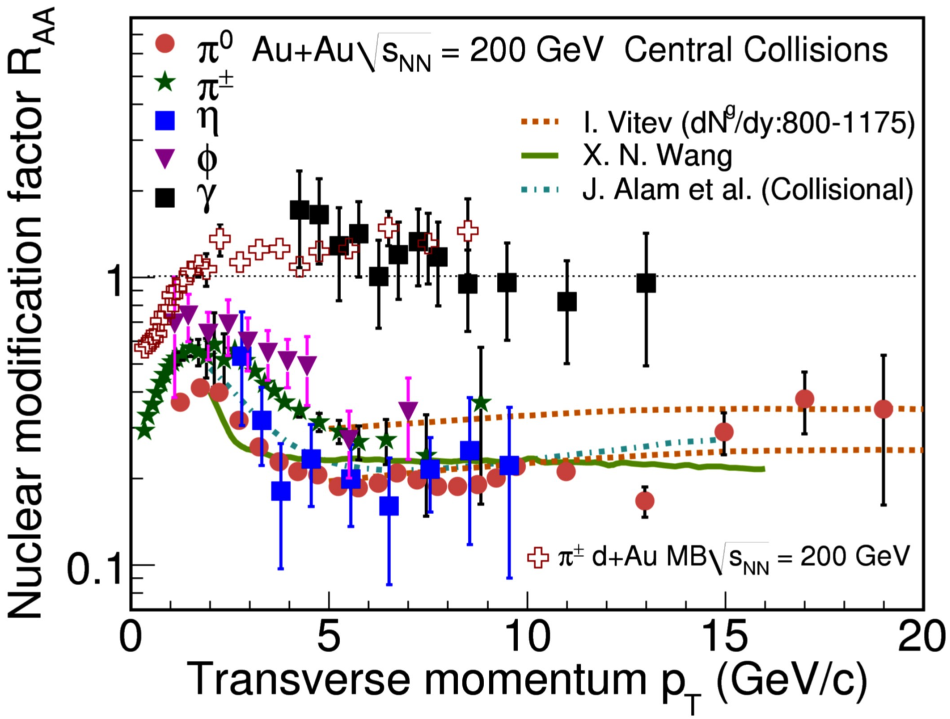
ALI-DER-53851

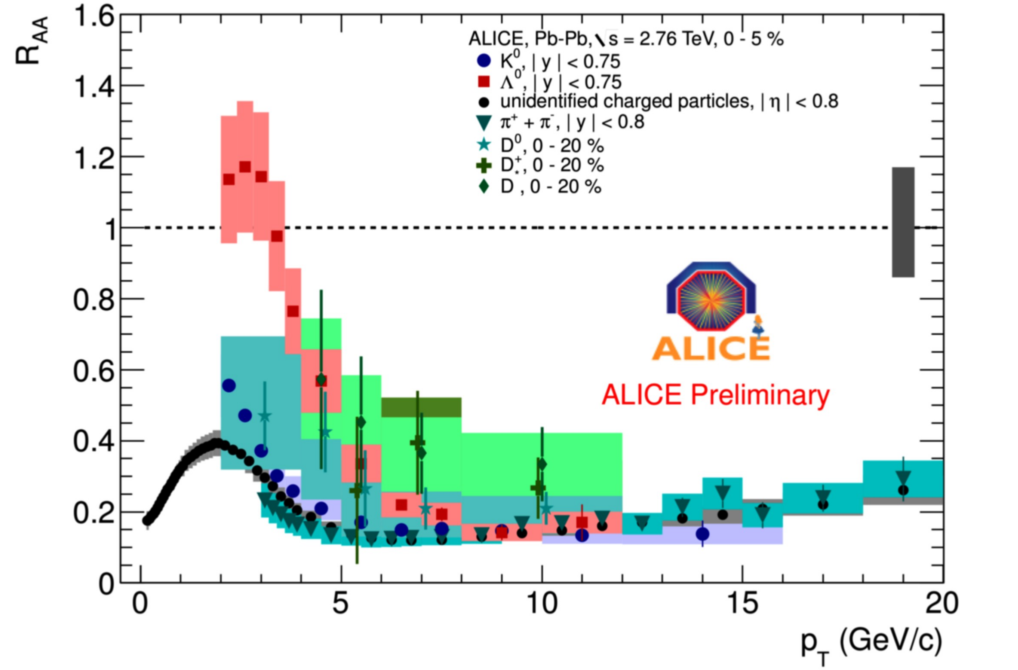
Mohanty, New J.Phys. 13, 065031 (2011) [arXiv:1102.2495]

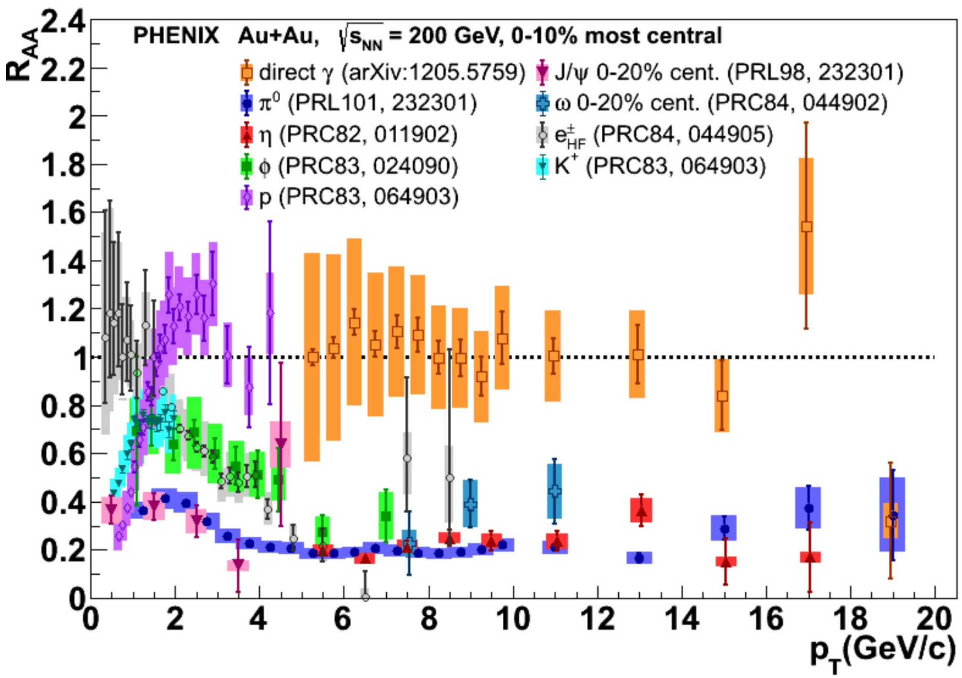
RHIC

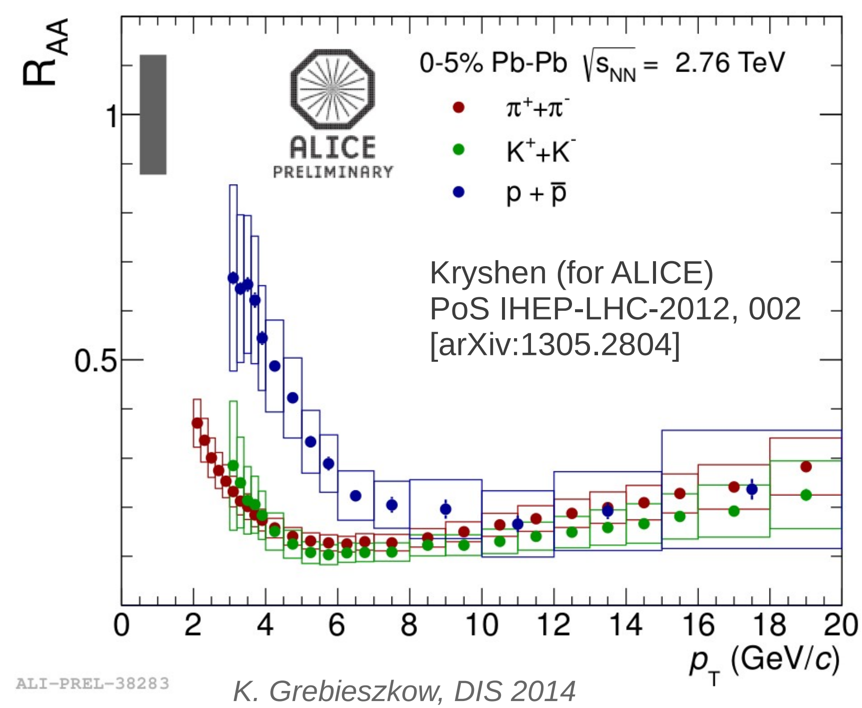
LHC

Kharlov (for ALICE), PoS IHEP-LHC-2011, 013 [arXiv:1203.2420]









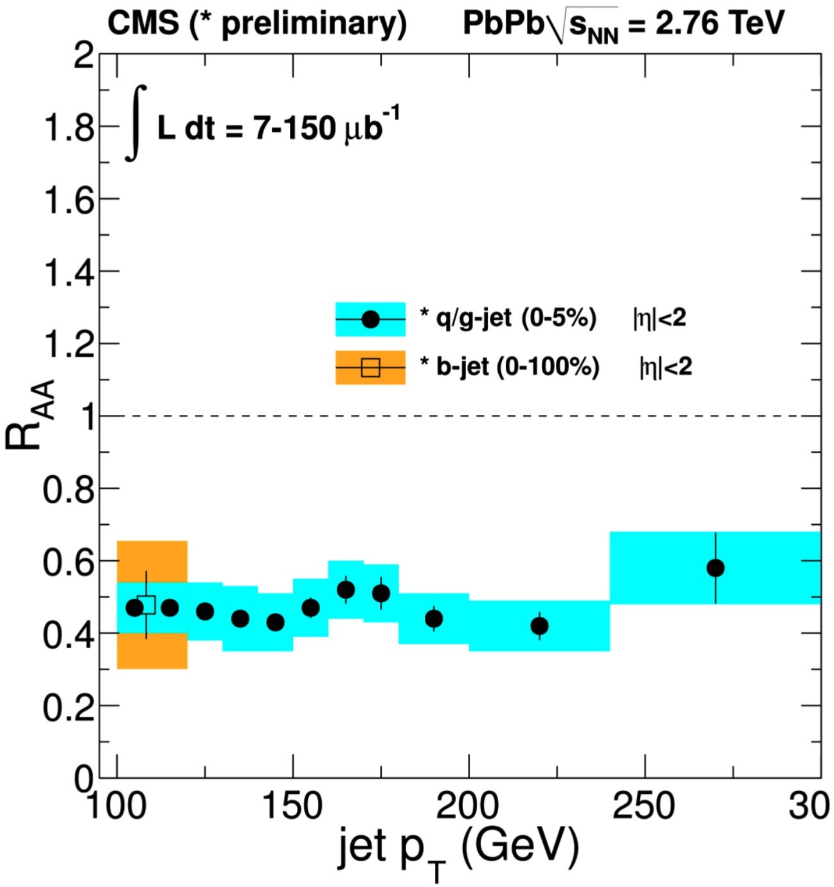
Kryshen (for ALICE)
PoS IHEP-LHC-2012, 002
[arXiv:1305.2804]

K. Grebieszkow, DIS 2014

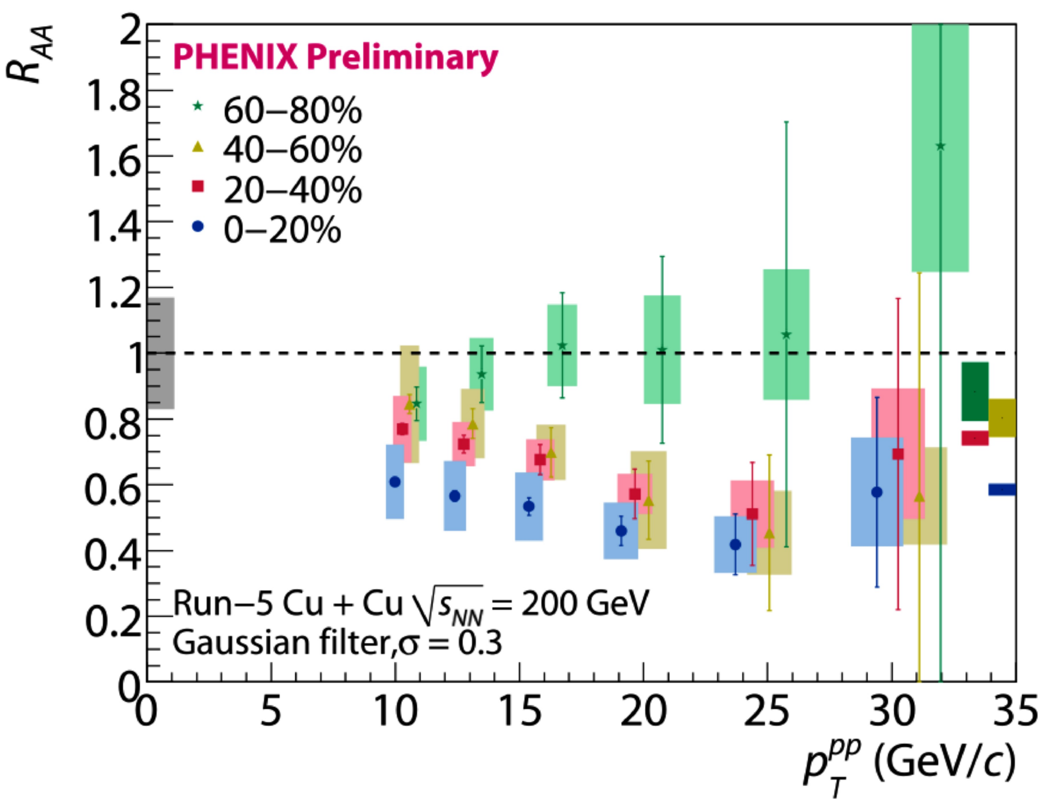
Full jet reconstruction; R_{AA} of jets

LHC   RHIC

arXiv:1212.6722 (without 'b'); Mischke, Zimanyi Winter School, XII 2012



Tserruya, arXiv:1212.6722



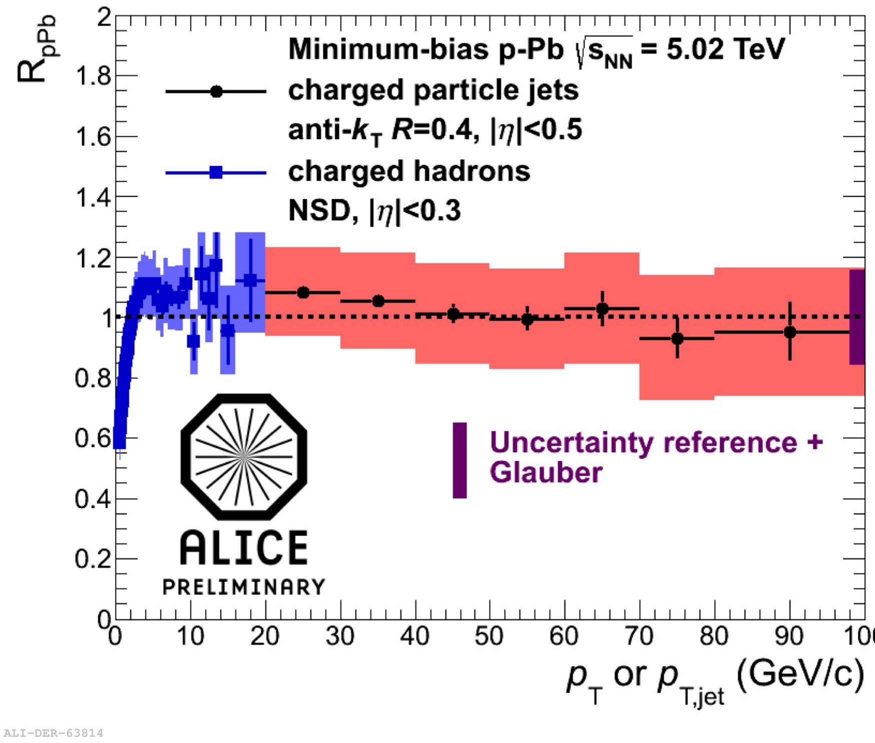
- **Quenching of whole jets on similar level at RHIC** (→ see central Cu+Cu) **and LHC. Suppression factor ≈ 2 (R_{AA} close to 0.5)**

- Reminder: suppression of high p_T particles (R_{AA} for hadrons, not jets) was about a factor of 5 for top RHIC (R_{AA} at high p_T was close to 0.2) and for LHC about a factor of 7 in minimum of R_{AA} and factor of 2 after increase of R_{AA} (for p_T of hadrons ≈ 100 GeV/c, see CMS results)

Suppression of hadrons and jets at LHC

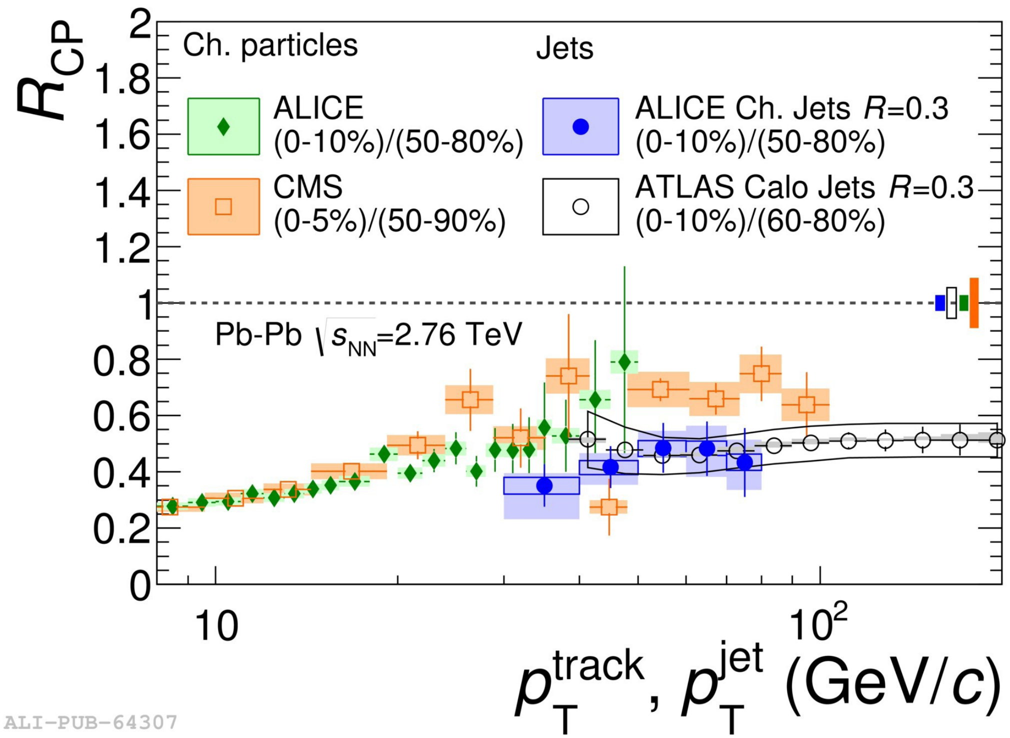
Verweij (for ALICE), WWND 2014

p+Pb



Pb+Pb

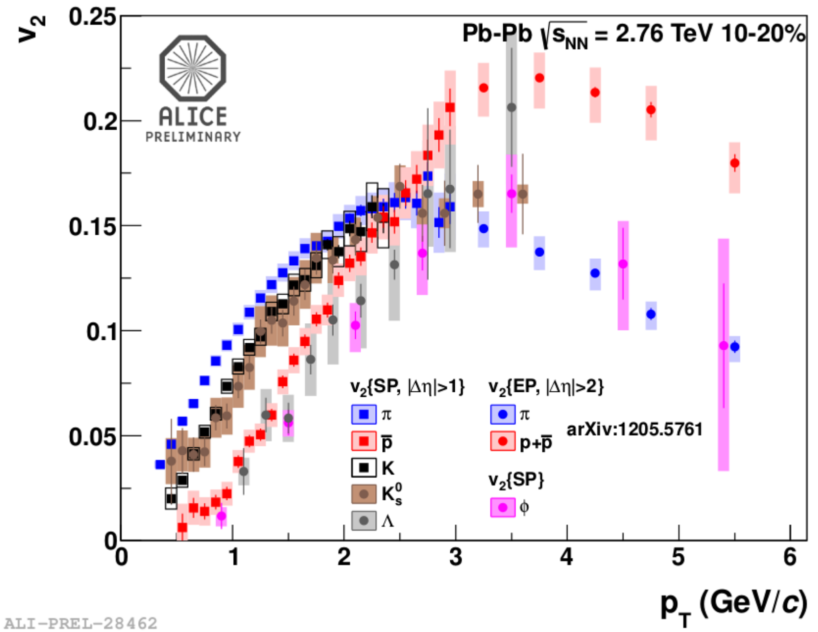
JHEP 1403, 013 (2014)

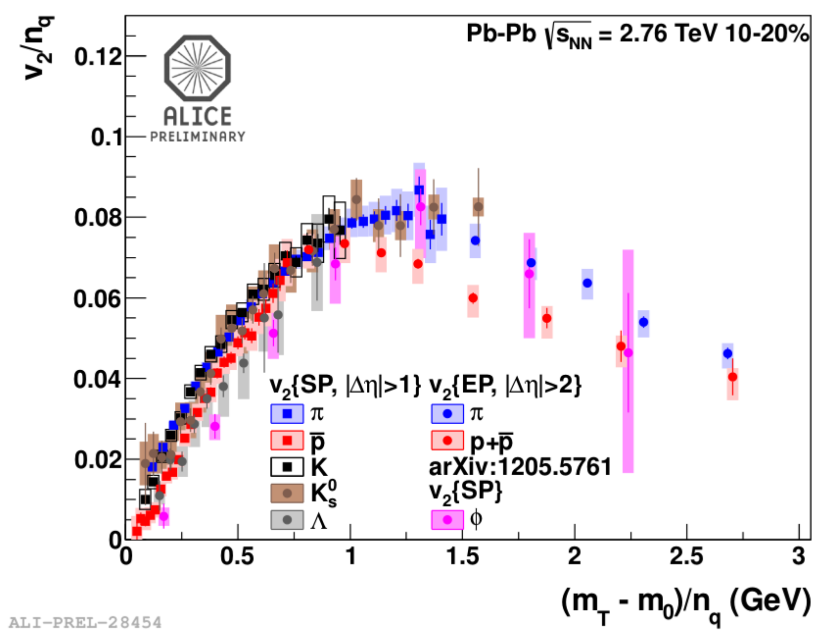


- No suppression in p+Pb
- Strong suppression in Pb+Pb

Jet suppression in heavy ion collisions is not initial state effect

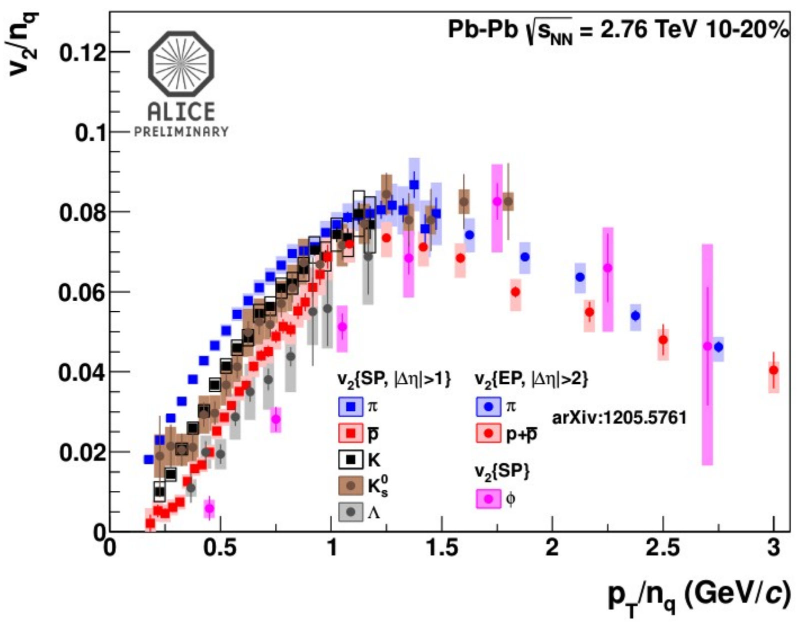
v_2 scaling with n_q at LHC looks a bit worse than at RHIC ...

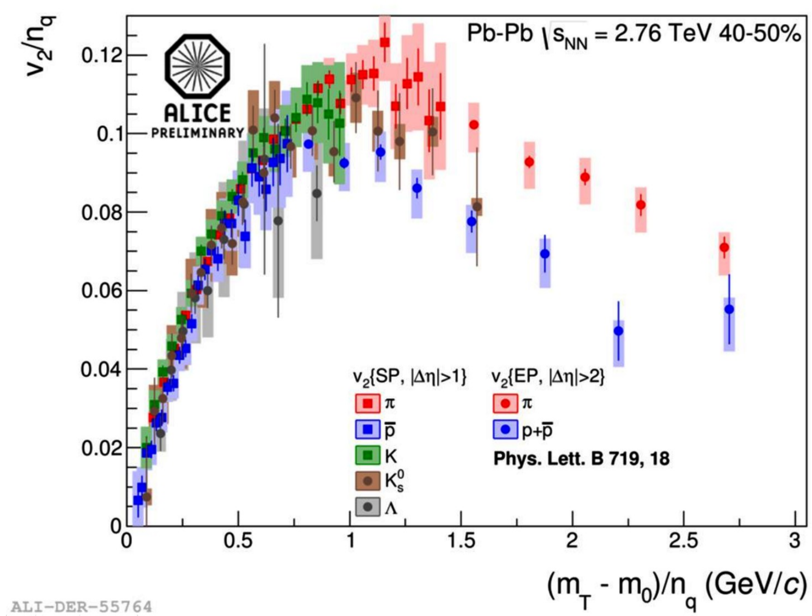




Kryshen (for ALICE), PoS IHEP-LHC-2012, 002 [arXiv:1305.2804]

Voloshin (for ALICE) NP A904-905, 90c (2013) [arXiv:1211.5680]

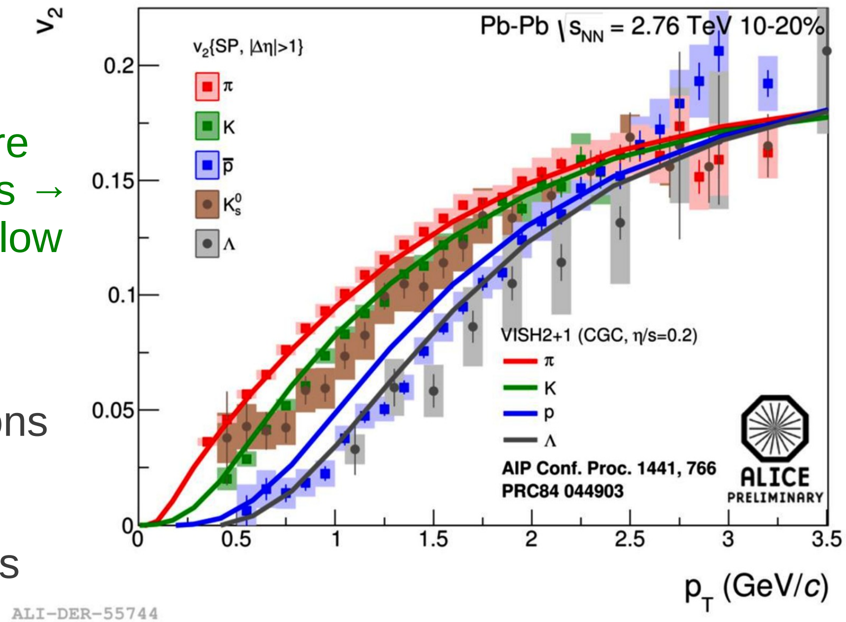


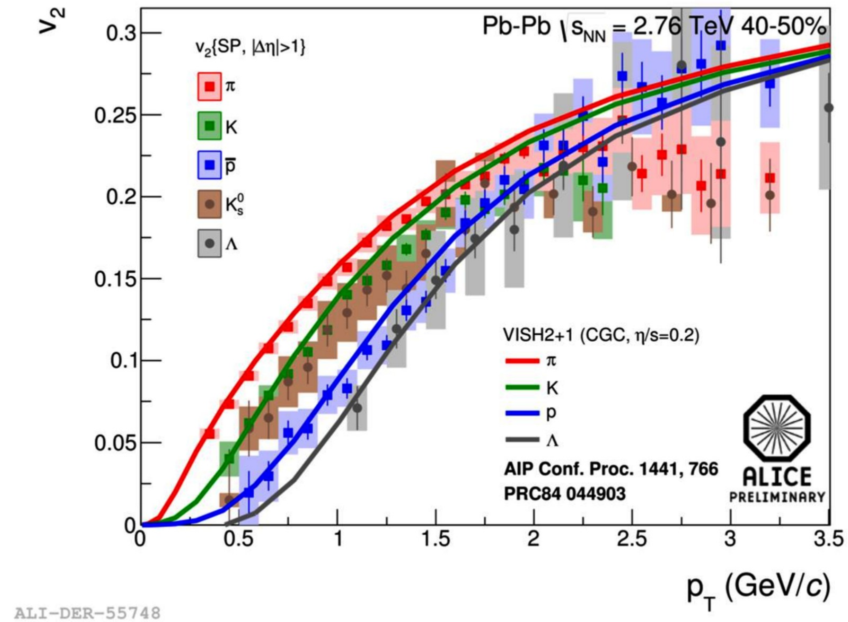


Noferini (for ALICE) WPCF 2013; and Zhou (for ALICE) arXiv:1309.3237

Mass splitting stronger for more central collisions → stronger radial flow

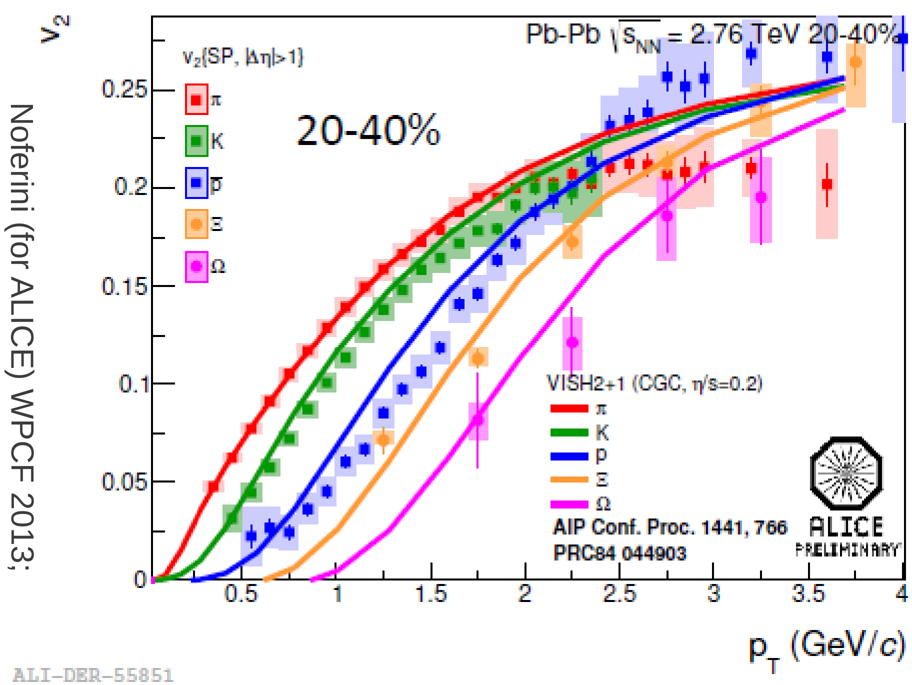
Stronger radial flow but pure hydro calculations do not describe well the most central collisions





Hydro → U. W. Heinz, C. Shen, and H. Song, **AIP Conf. Proc. 1441**, 766-770 (2012)

Noferini (for ALICE) WPCF 2013; Zhou (for ALICE), arXiv:1309.3237

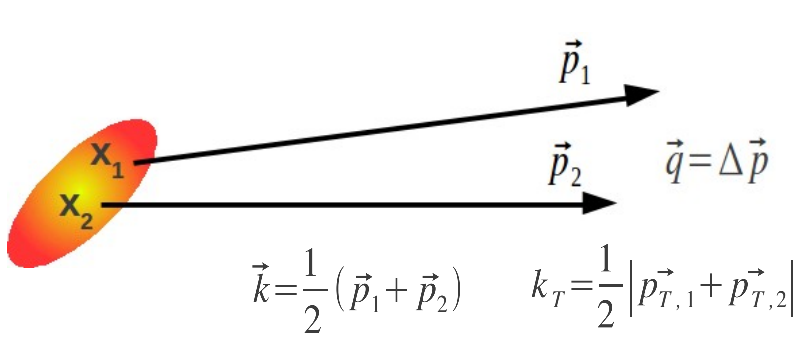


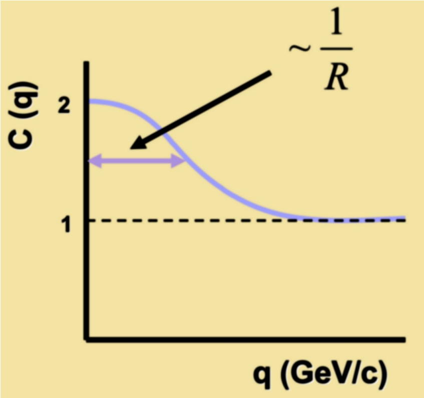
Viscous hydro model (VISH2+1, CGC initial condition with η/s = 0.20) quantitatively reproduce the mass splitting of v_2 (better in peripheral collisions). In central collisions overestimation of proton v_2 → proton might freeze-out later (with larger radial flow); **results suggest also important role of hadronic interactions in reproducing proton v_2**

→see VISHNU hybrid model = (2+1)D viscous hydrodynamics + microscopic hadronic transport model when **baryon and anti-baryon annihilation** processes (below a switching temperature of 165 MeV) are included, Song, Bass, Heinz, arXiv:1311.0157)

A possible evidence of radial flow was observed also in high multip. p+p collisions !

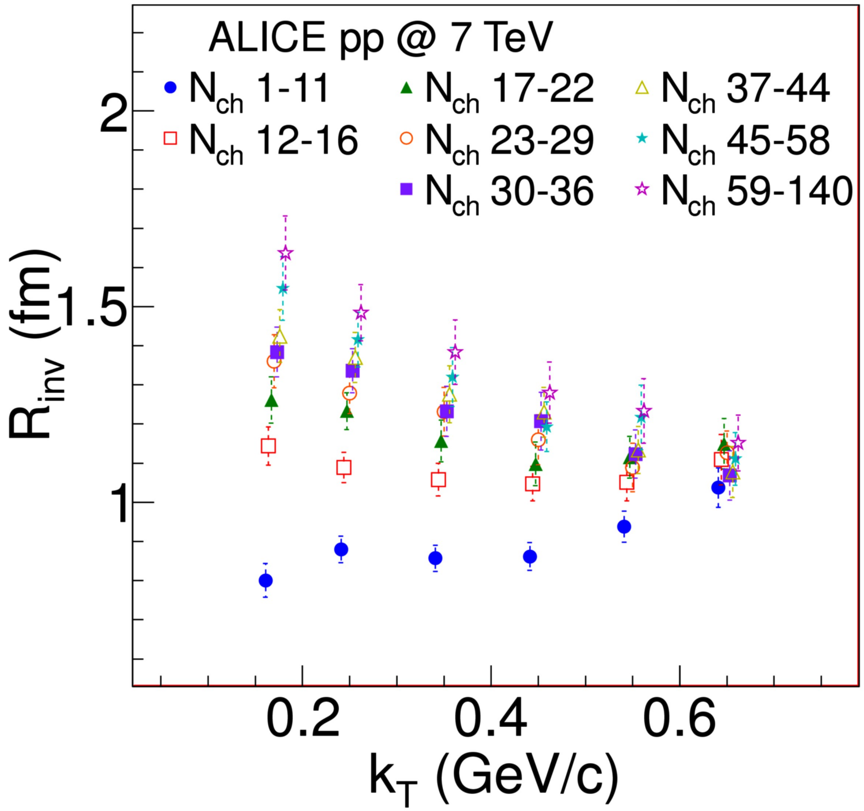
Source radii from **femtoscopy** (HBT) **analysis** → Hunbury, Brown, Twiss, Nature 178, 1046 (1956)





C(q) – correlation function for identical bosons (i.e. $\pi^-\pi^-$); pairs from the same event divided by uncorrelated pairs (mixed event pairs)

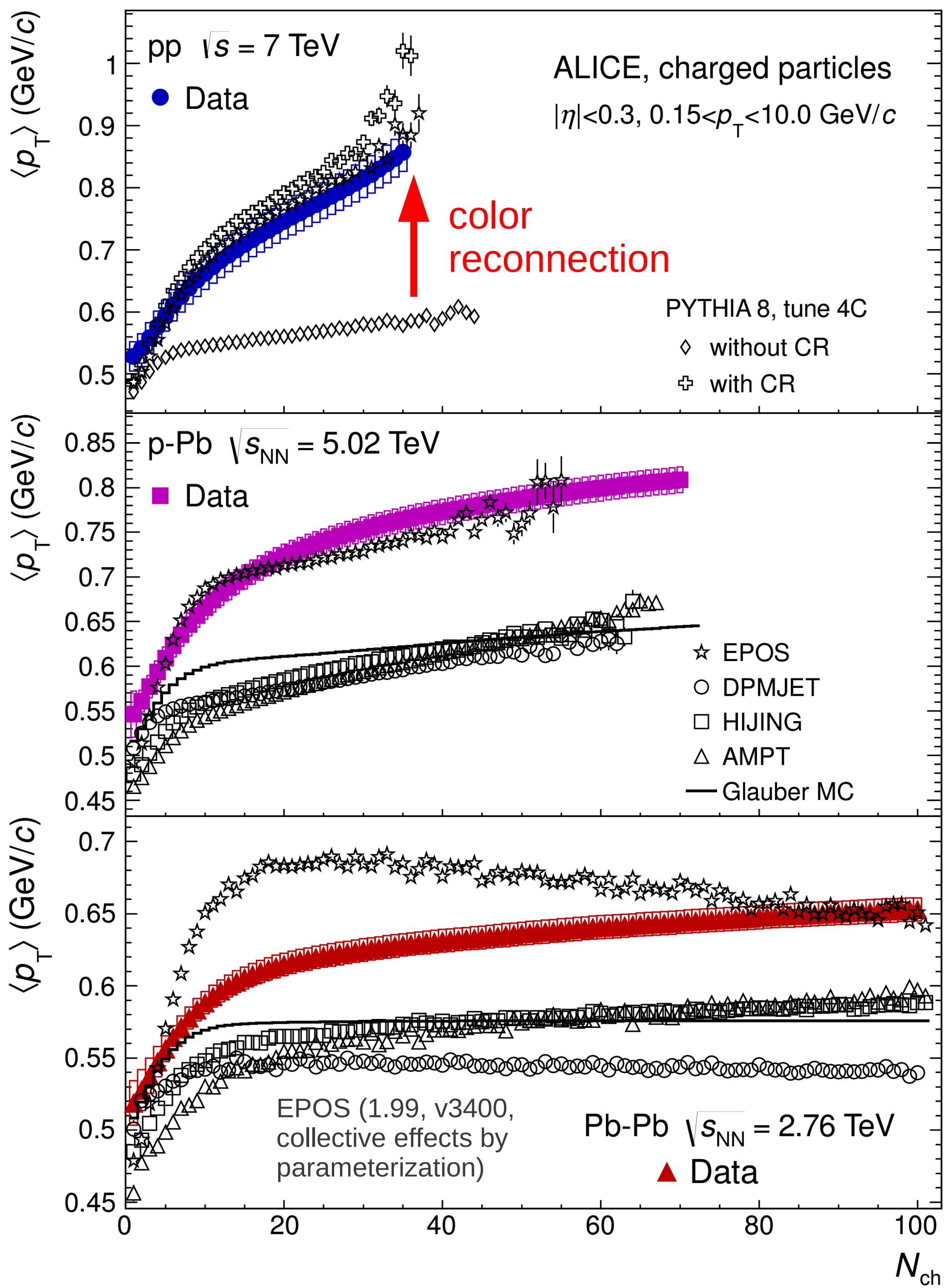
Miśkowiec (for ALICE) PoS WPCF2011, 001 [arXiv: 1204.1224]



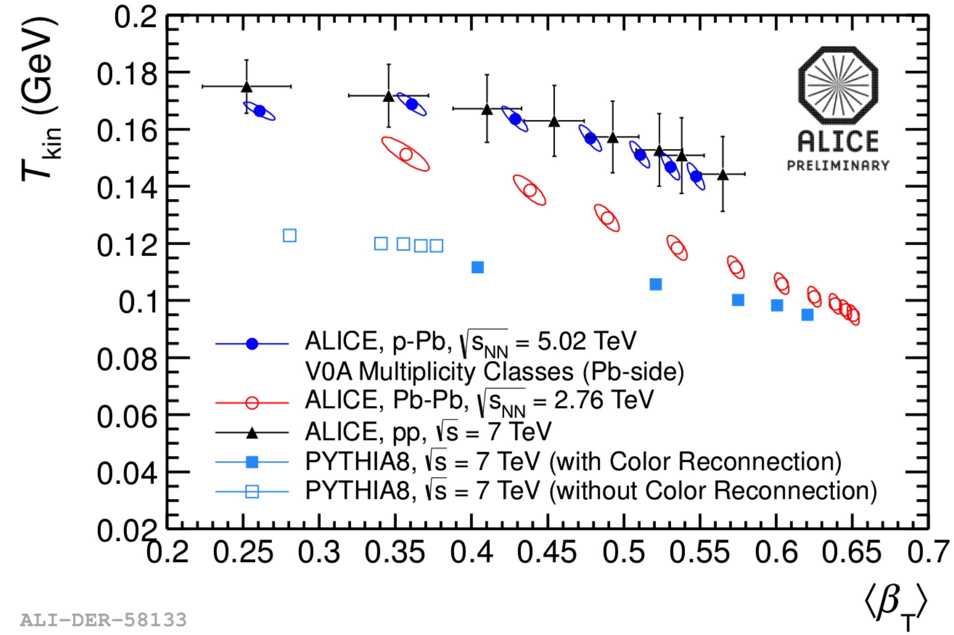
- **Decrease of HBT radii with increasing k_T in A+A was interpreted as due to transverse collective expansion**: faster particles (higher momenta) show regions of smaller sizes → expansion
- At LHC such behaviour seen for high multiplicity p+p events ! **Collectivity developed in high multiplicity p+p collisions at LHC ?**

Such effects seen also in 0-10% central d+Au at top RHIC → see Mwai (for PHENIX), WWND 2014

ALICE, PL B727, 371 (2013)



Velasquez (for ALICE), arXiv:1404.4354



Color reconnection (CR) – color string formation between final partons from independent hard scatterings → see T. Sjostrand, arXiv:1310.8073

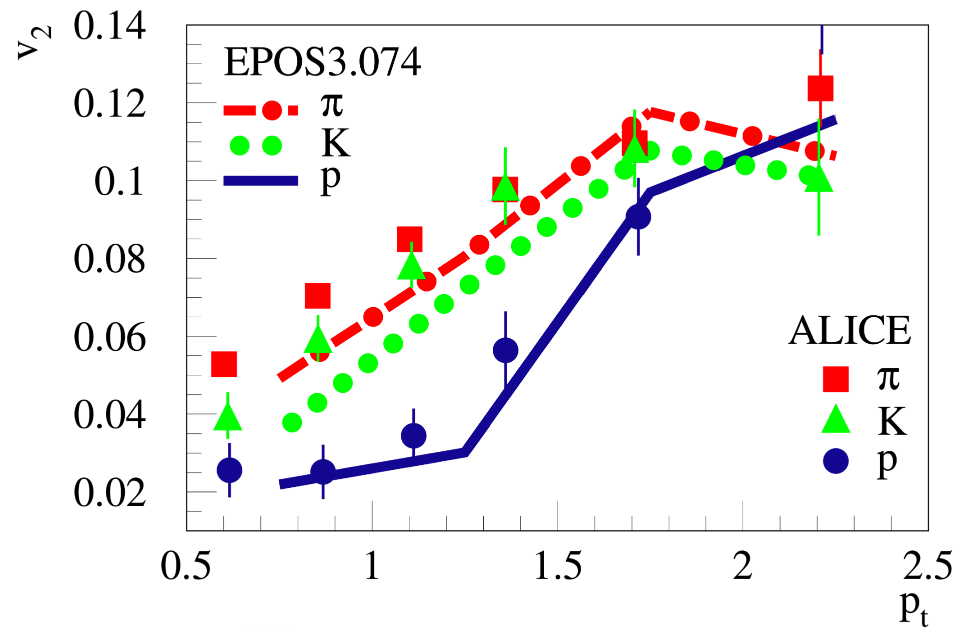
Unlike hydrodynamics, CR mechanism acts on a microscopic level, and therefore does not require formation of thermalized medium in a small system

CR can mimic "flow-like" trends seen in p+p data

Note: CR = coherent effects between strings = some form of collectivity

EPOS3, B. Guiot, Y. Karpenko, T. Pierog, K. Werner
arXiv:1312.1233 , arXix:1307.4379

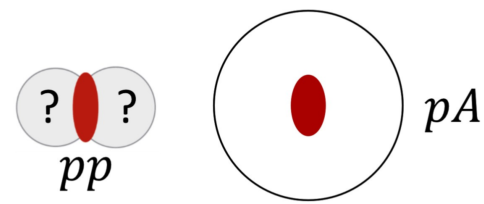
- ☐ Initial conditions:
  Gribov-Regge multiple scattering approach,
  elementary object = Pomeron = parton ladder,
  using saturation scale $Q_s \propto N_{part}\,\hat{s}^{\lambda}$
- ☐ Core-corona approach
  to separate fluid and jet hadrons
- ☐ Viscous hydrodynamic expansion, $\eta/s = 0.08$
- ☐ Statistical hadronization, final state hadronic cascade

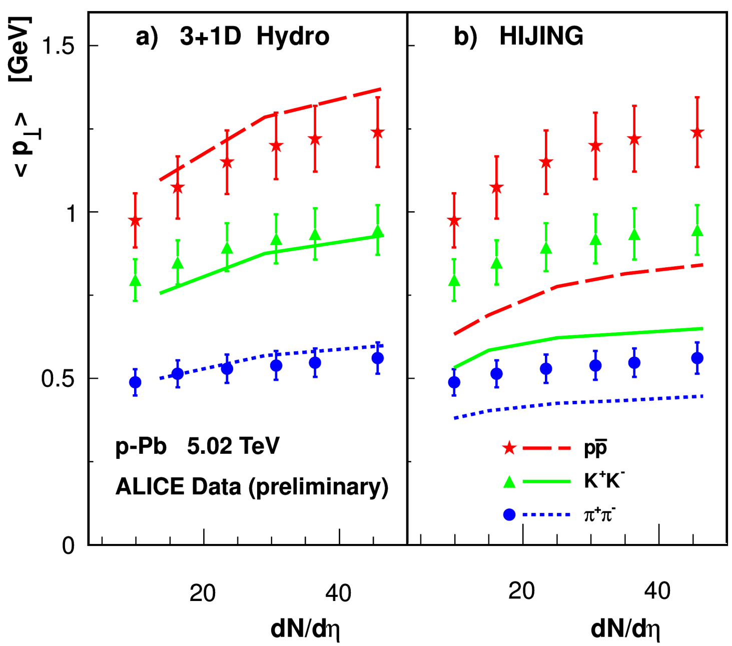


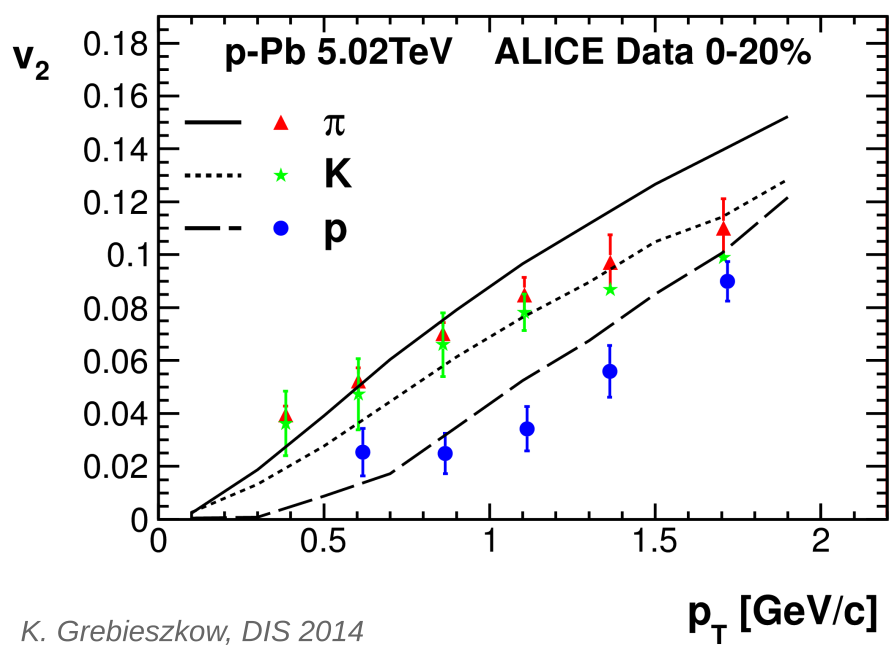
Werner, WWND 2014

p+Pb, 5.02 TeV
Mass splitting (as in Pb+Pb) due to flow

Perhaps we can apply hydrodynamics to high-multiplicity p+p and p+A collisions. The interaction region is small but dense.

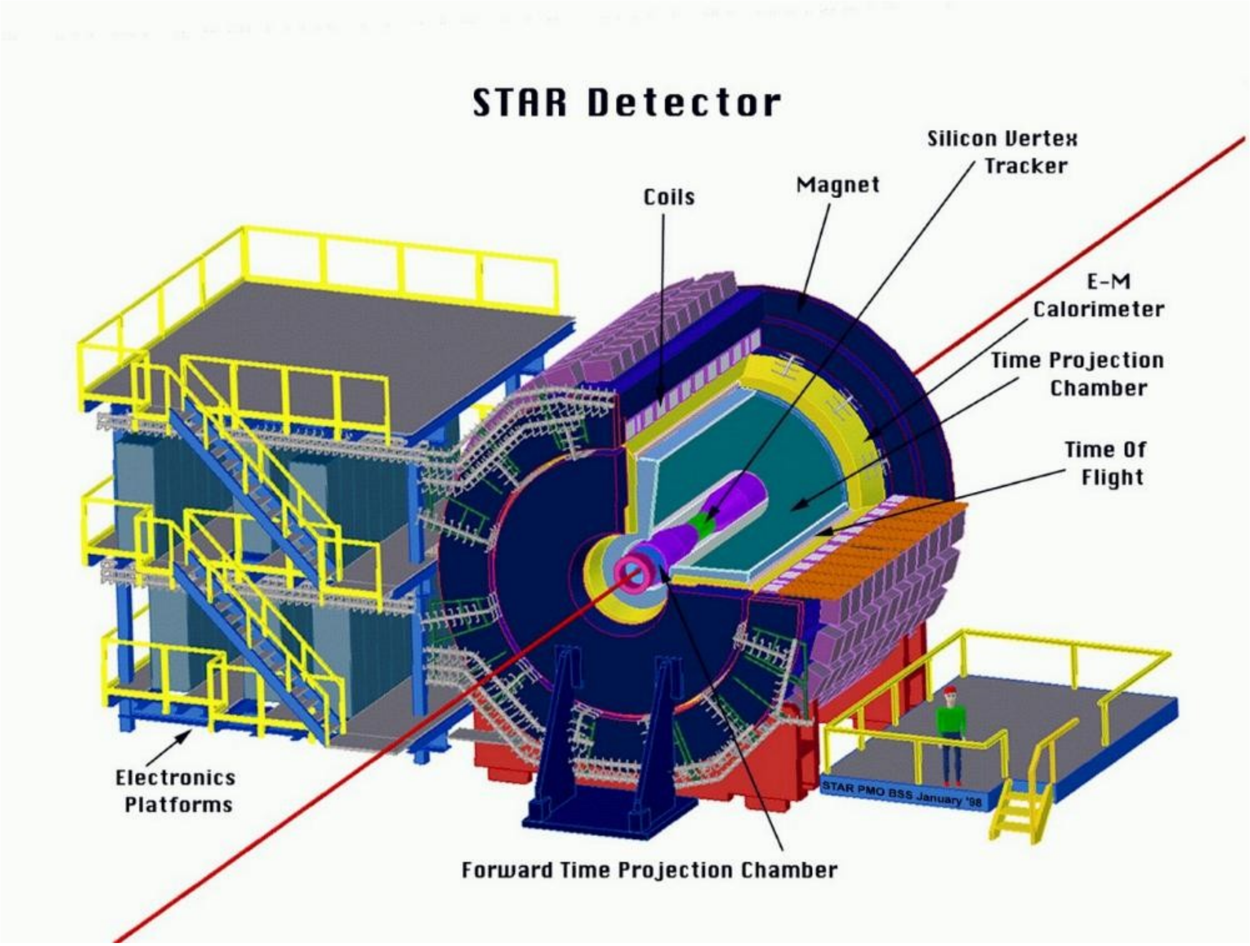






Bozek, Broniowski, arXiv:1401.2367

K. Grebieszkow, DIS 2014



- **Time Projection Chamber** inside Magnet; measurement of dE/dx and p. **Time of Flight** detectors. **Silicon Vertex Tracker** for measuring short-living particles. **Electro-Magnetic Calorimeter.**
- **Uniform acceptance, independent of energy.**

Taken in STAR (old + BES-I)

Au+Au at $\sqrt{s_{NN}}$=7.7, 11.5, 19.6, 27, 39, 62.4, 130, 200 GeV

Cu+Cu at $\sqrt{s_N}$ =22.5, 62.4, 200 GeV

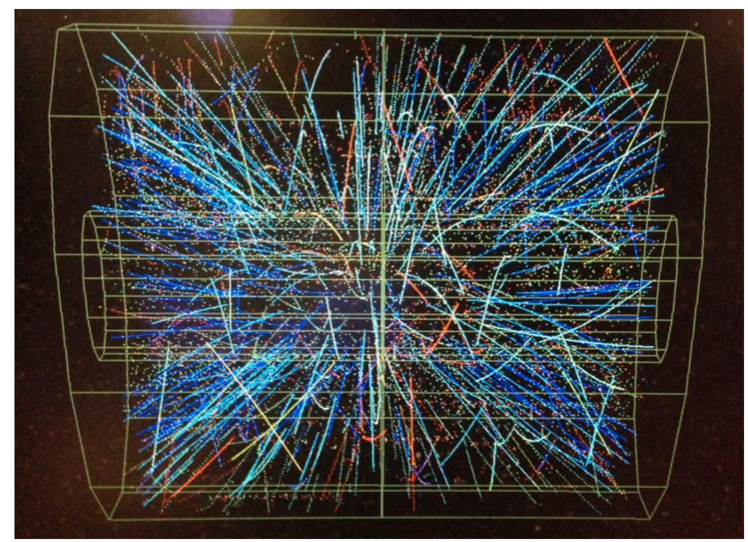
Planned in STAR BES-II (collider mode):

Au+Au at $\sqrt{s_{NN}}$=7.7, 11.5, 15, 19.6 GeV (high stat.)

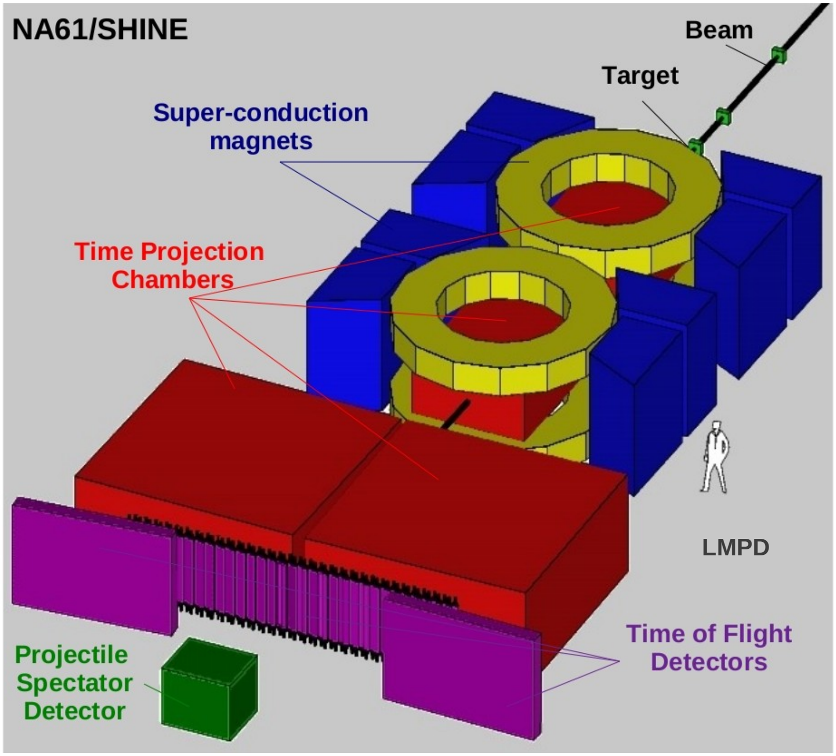
Planned in STAR BES-II (fixed target mode):

Au+Au at $\sqrt{s_{NN}}$=3, 3.5, 4, 4.5 GeV

Kumar (for STAR), arXiv:1311.3426; Lisa, WPCF 2013; Mitchell, CPOD 2013



STAR; Au+Au at $\sqrt{s_{NN}}$= 14.5 GeV (2014)
Sun, WWND 2014



- Four large volume **Time Projection Chambers (TPCs)**: VTPC-1, VTPC-2 (inside superconducting magnets), MTPC-L, MTPC-R; measurement of dE/dx and p. **Time of Flight (ToF)** detector walls.

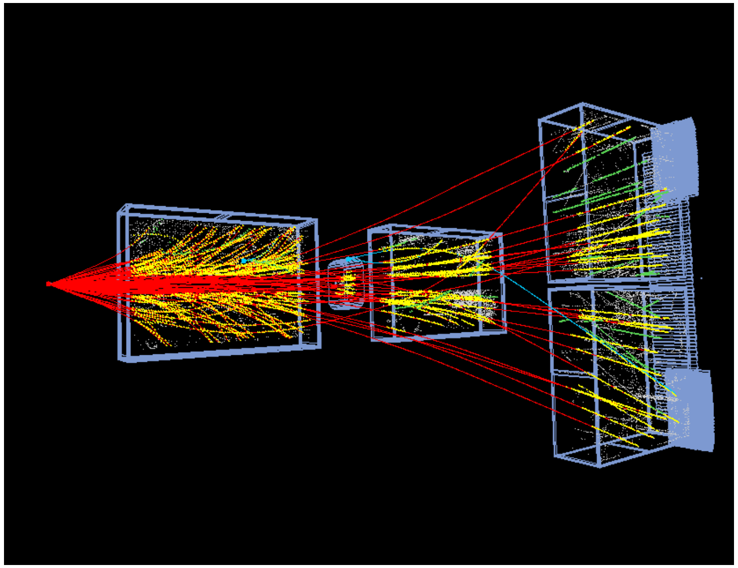
- **Projectile Spectator Detector (PSD)** for centrality measurement (energy of projectile spectators) and determination of reaction plane; **resolution of 1 nucleon (!)** in the studied energy range (important for fluctuation analysis).

Taken in NA49:
p+p, C+C, Si+Si, Pb+Pb (MB) at $\sqrt{s_{NN}}$=17.3 GeV
central Pb+Pb at $\sqrt{s_{NN}}$=6.3, 7.6, 8.7, 12.3, 17.3 GeV

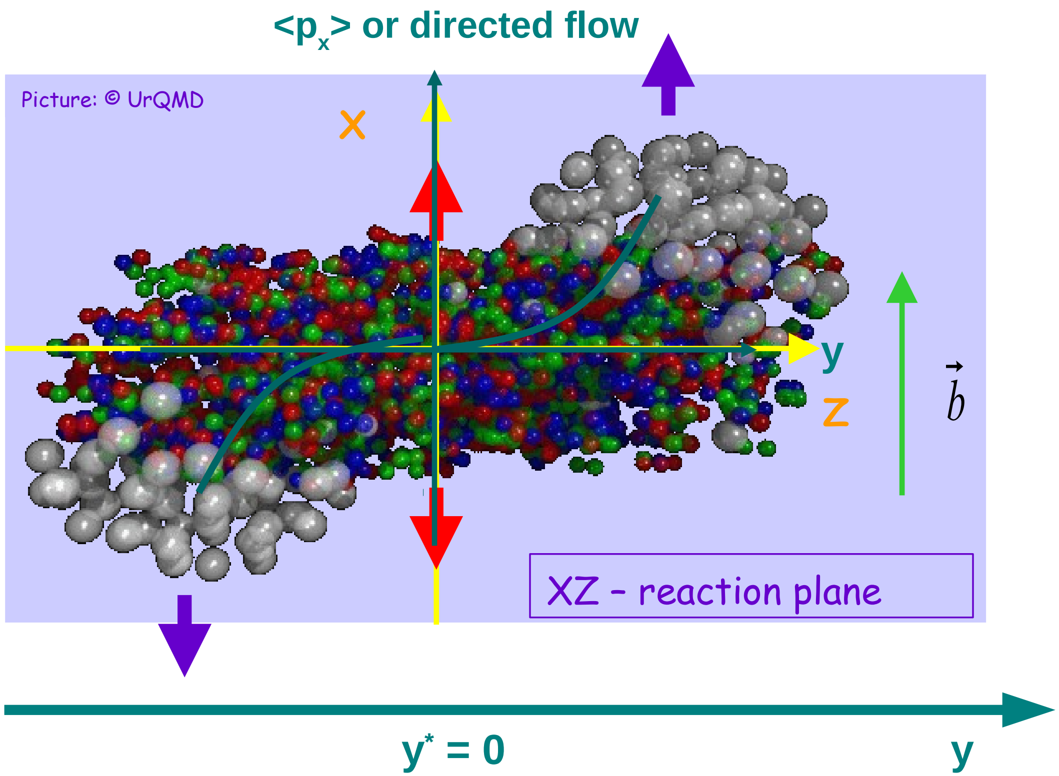
Taken in NA61 (successor of NA49):
p+p at $\sqrt{s_{NN}}$=5.1, 6.3, 7.7, 8.8, 12.3, 17.3 GeV
Be+Be at $\sqrt{s_{NN}}$=5.1, 6.2, 7.6, 8.7, 11.8, 16.7 GeV

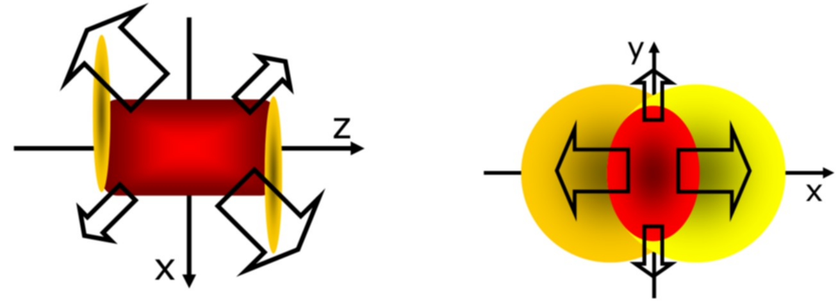
Planned in NA61:
Ar+Ca at $\sqrt{s_{NN}}$=5.1, 6.3, 7.6, 8.8, 12.3, 17.3 GeV
Xe+L at $\sqrt{s_{NN}}$=5.1, 6.3, 7.6, 8.8, 12.3, 17.3 GeV

Planned (needs approval) in NA61:
Pb+Pb at $\sqrt{s_{NN}}$=5.1, 6.3, 7.6, 8.8, 12.3, 17.3 GeV (high stat.)



NA61; Be+Be at $\sqrt{s_{NN}}$= 16.7 GeV



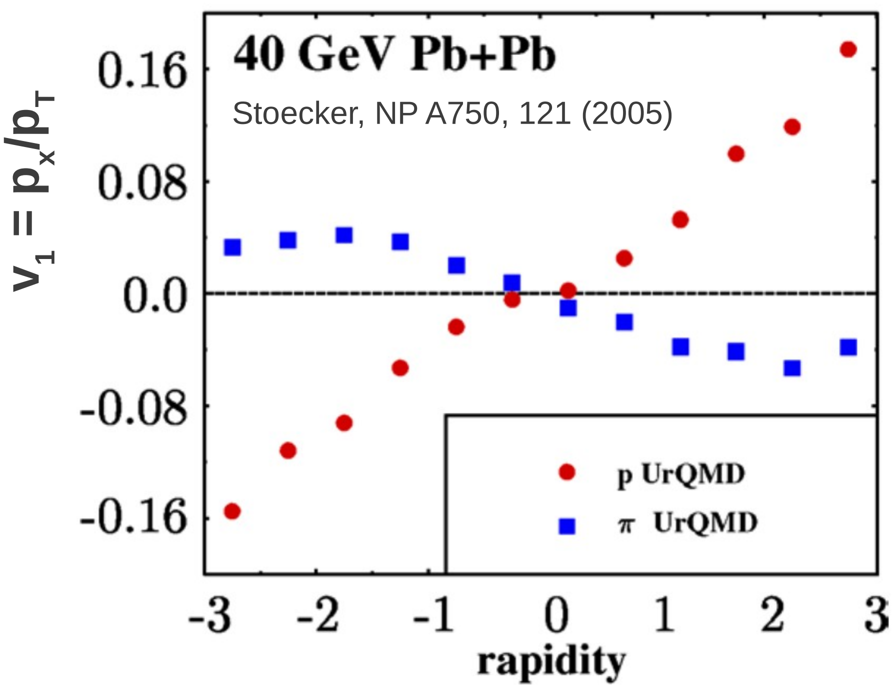


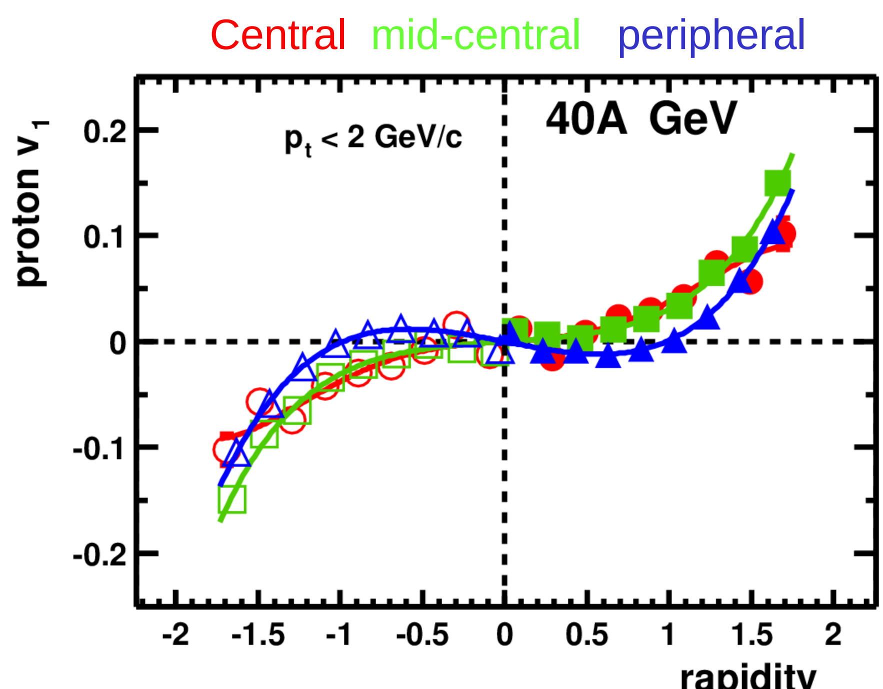
(a) First harmonic v_1 (b) Second harmonic v_2

$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle, \text{ where } p_T = \sqrt{p_x^2 + p_y^2}$$

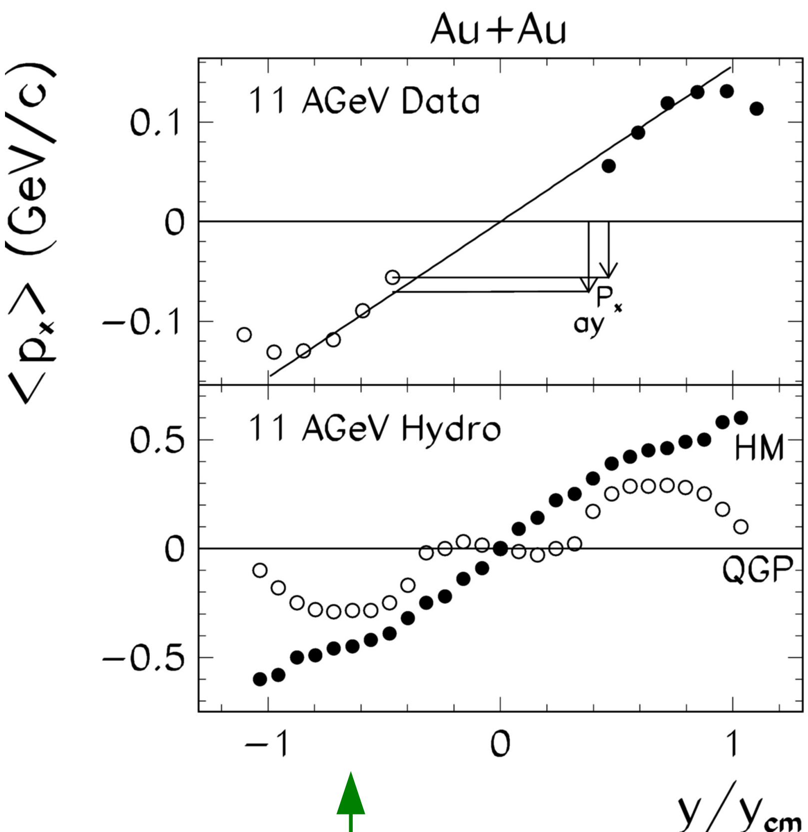
$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

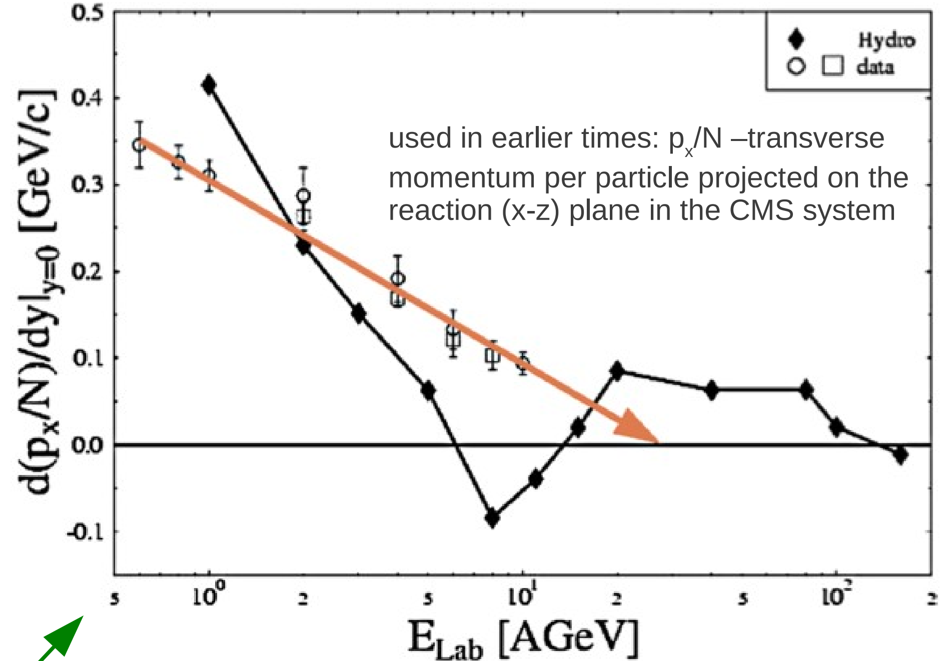
Protons “antiflow” in NA49 (around midrapidity); not seen in UrQMD (left; no PT)
NA49: PR C68, 034903 (2003)





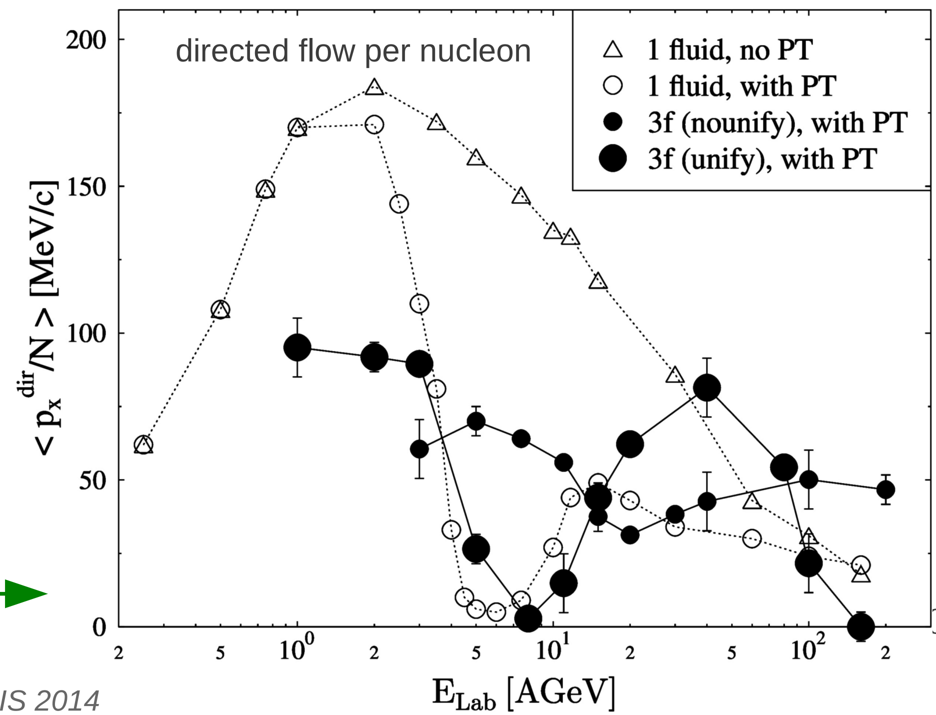
Predictions of hydrodynamical models



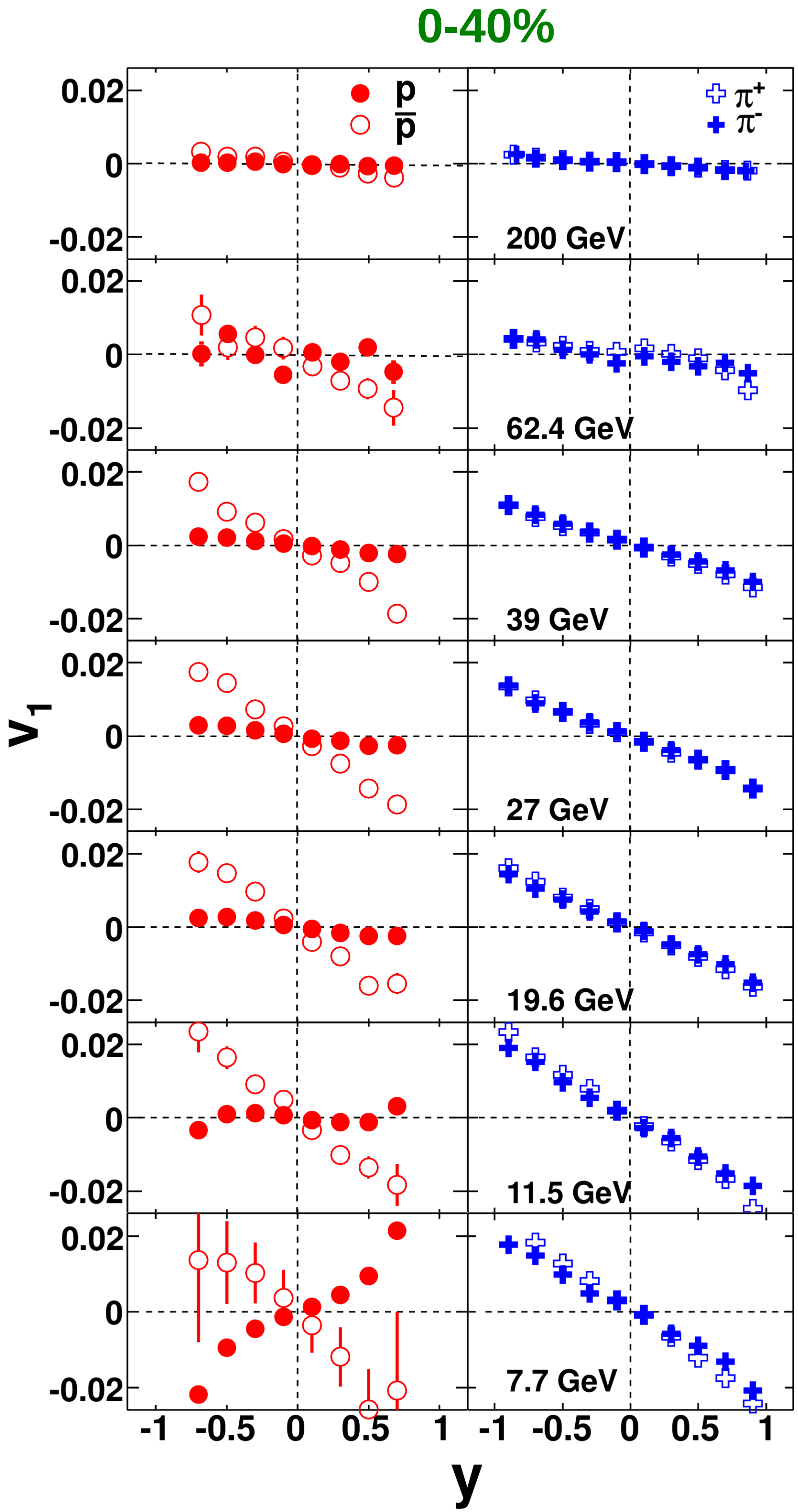


SIS and AGS data (protons) compared to three-fluid hydro calculations. Stoecker, NP A750, 121 (2005)

Directed flow from ideal hydrodynamics with Hadronic (HM) and QGP EOS. “Antiflow” (neg. slope) wiggle in the proton flow visible in case of 1st order PT. Csernai, Rohrich, PL B458, 454 (1999)



$<p_x^{dir}/N>$ for Au+Au at b=3 fm. Triangles are for purely hadronic EOS, circles are for EOS with PT. Solid lines - three-fluid model, with (large circles) or without (small circles) dynamical unification.
Brachmann et al. PR C61, 024909 (2000)



STAR, arXiv:1401.3043

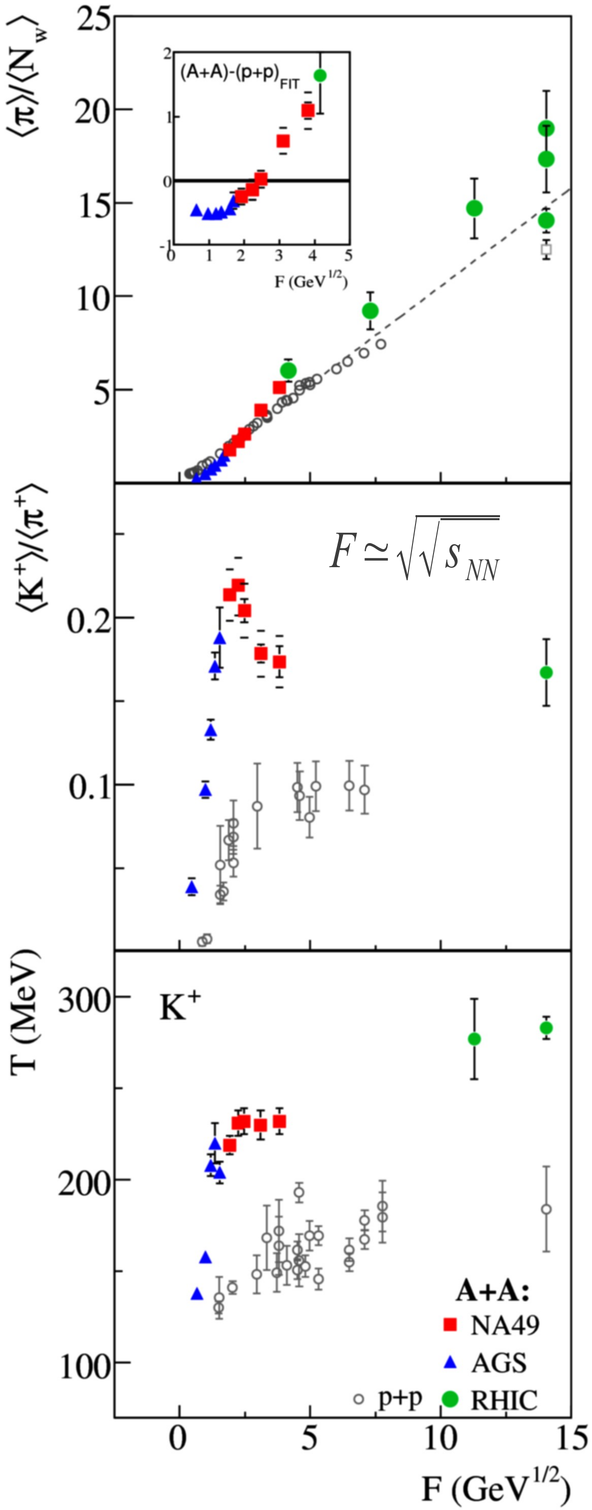
"The energy dependence of proton dv_1/dy involves an interplay between v_1 of protons associated with baryon number transported from the initial beam rapidity to the vicinity of mid-rapidity, and the directed flow of protons from particle-antiparticle pairs produced near mid-rapidity. (...)

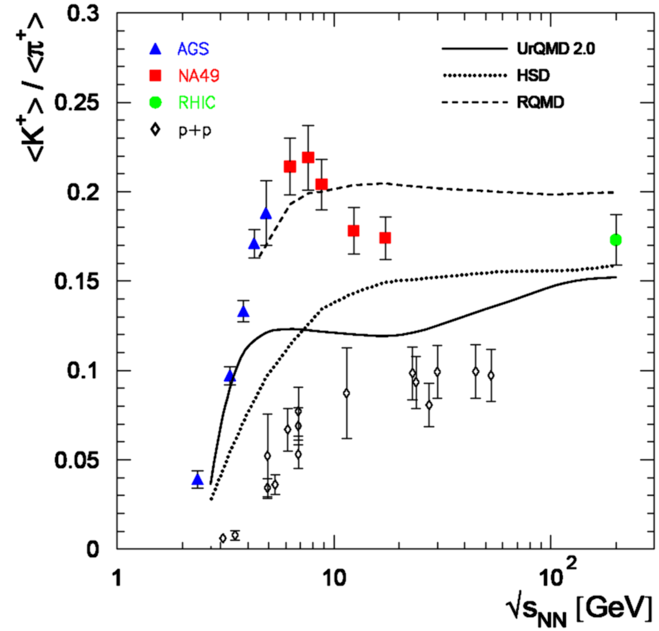
Assuming antiproton directed flow as a proxy for the directed flow of pair produced protons, the proposed net-proton slope can be constructed from

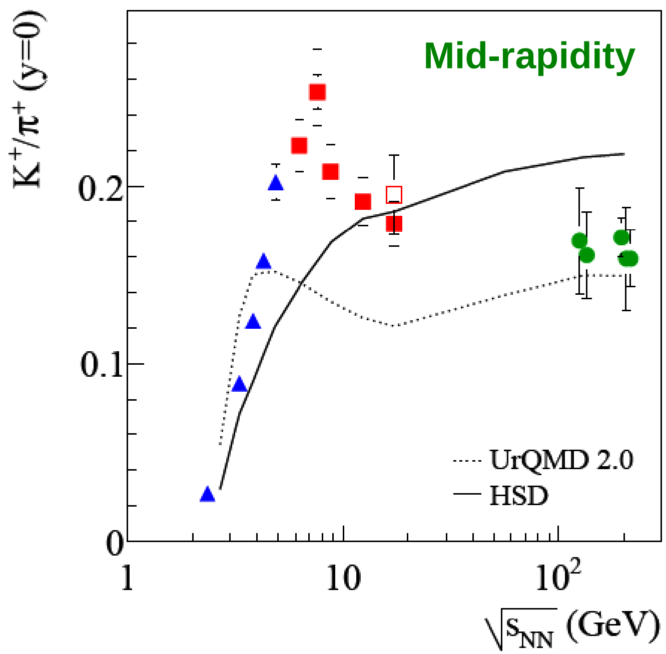
$$[v_1(y)]_p = r(y)[v_1(y)]_{anti\text{-}p}+[1-r(y)]\ [v_1(y)]_{net\text{-}p}$$

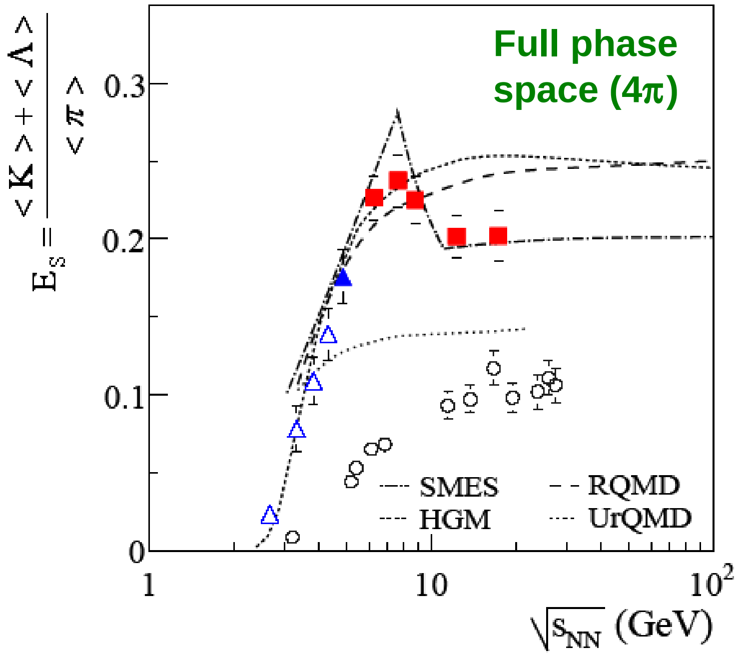
where r(y) is the observed rapidity dependence of the ratio of antiprotons to protons at each beam energy."

E_s - strangeness to entropy









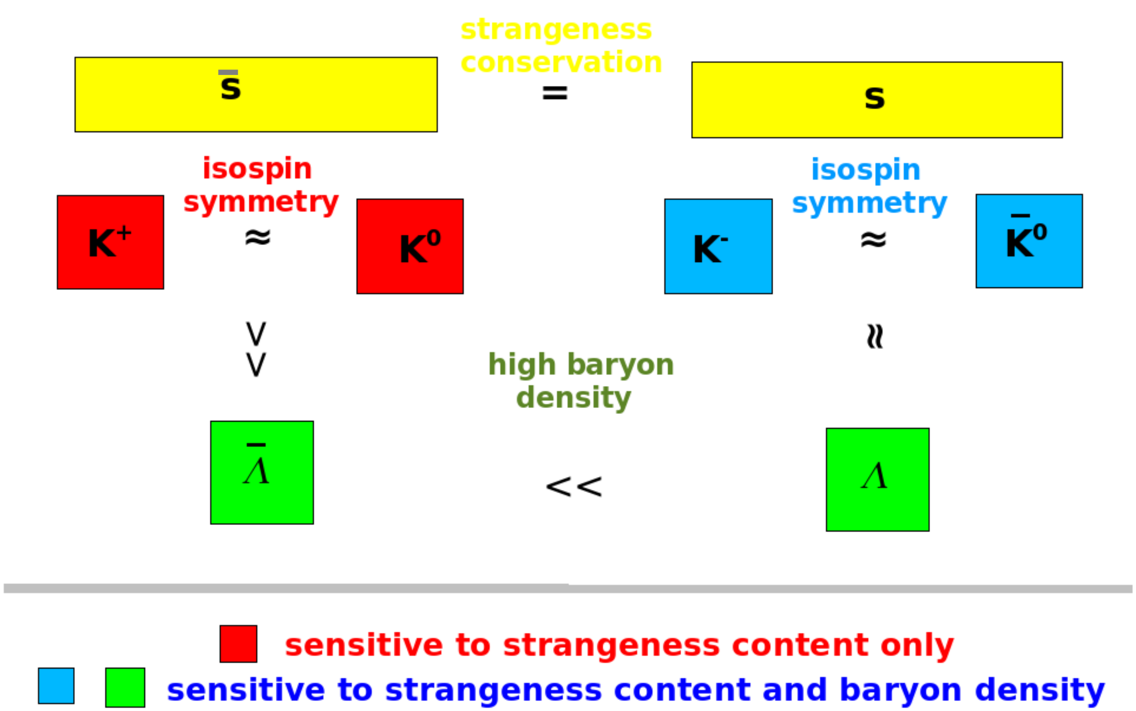
→ Effect on ⟨K^+⟩/⟨π^+⟩ even more pronounced at mid-rapidity

E_S calculated from π, K and Λ yields in 4π. Proposed as a measure of strangeness to entropy ratio (SMES)

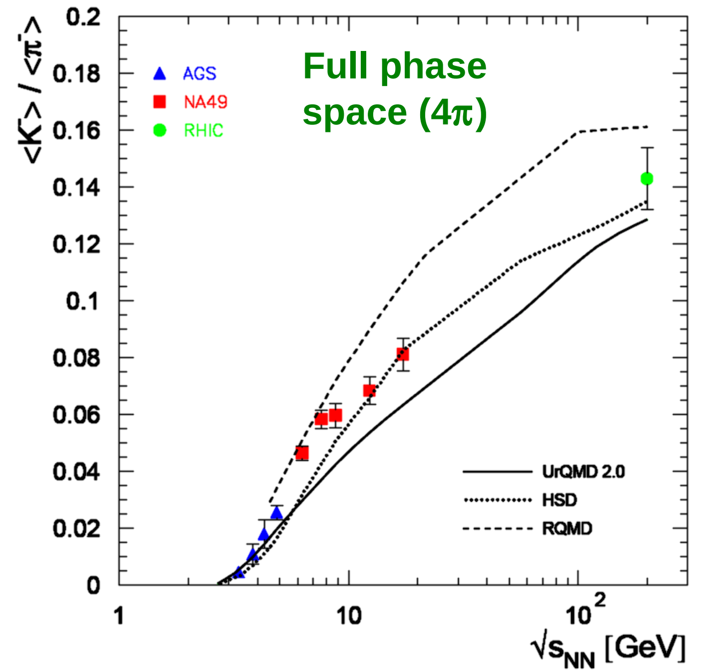
→ E_s shows distinct peak at 30*A* GeV

→ Described (predicted) only by model assuming phase transition (SMES)

main strangeness carriers



Λ (ud**s**)
K^+ (u **anty-s**)
K^- (anty-u **s**)
K^0 (d **anty-s**)
anty-K^0 (anty-d **s**)



Difference in ⟨K^+⟩ and ⟨K^-⟩ production due to different sensitivity to baryon density. At SPS energies lambdas have significant influence on total strangeness production (anti-lambdas not)

$$\bar{s} \rightarrow K^+, K^0$$
$$s \rightarrow K^-, \bar{K}^0, \Lambda$$

⟨K^+⟩/⟨π^+⟩ proportional to strangeness/entropy

⟨K^-⟩/⟨π^-⟩ additionally sensitive to baryon density

Thermal (hadron gas) models

$$n_i = \frac{N}{V} = \frac{(2J_i+1)(2I_i+1)}{2\pi^2} \int_0^\infty \frac{p^2\,dp}{\exp[(E_i-\mu_i)/T] \pm 1 \; {}^{(FD)}_{(BE)}} \qquad \mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3i}$$

Particle yields (π, K, p, Λ, etc.) **or ratios of yields** at mid-rapidity or at 4π acceptance are used as **input to thermal model.** After implementation of conservation laws (baryon number, strangeness, charge, etc.) **fit parameters are T_{ch} and μ_B** (event. also fireball volume in case of yields)

Horn in the hadron gas model (Andronic, Braun-Munzinger, Stachel, NP A772, 167 (2006))

Parametrization of T_{ch}, μ_B as a function of energy; **relative maximum in $\langle K^+\rangle/\langle\pi^+\rangle$ ratio as a consequence of saturating T_{ch} and decreasing μ_B with increasing energy** (Limiting temperature reached somewhere at SPS)

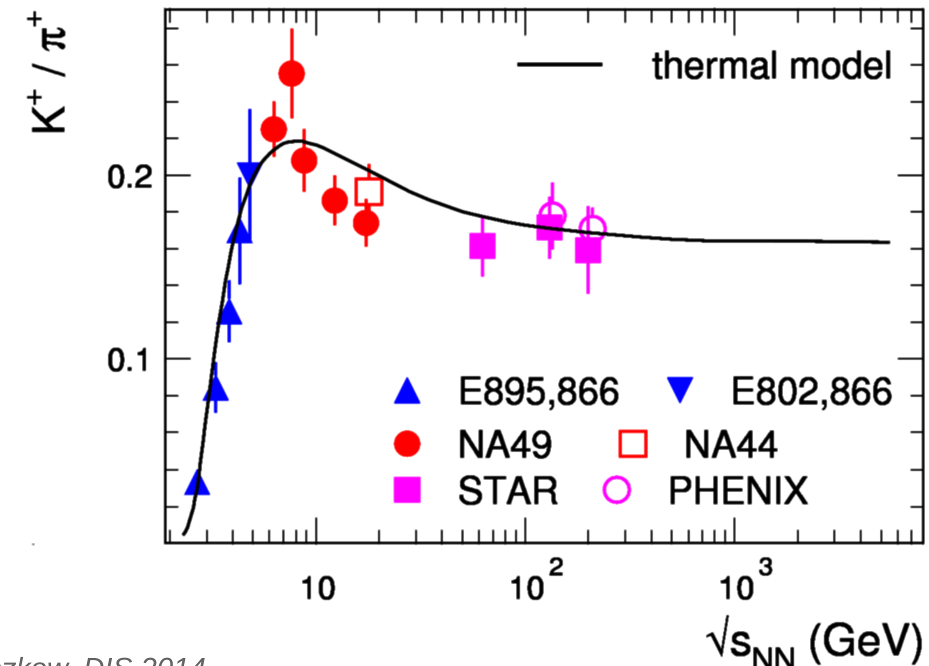
$\rightarrow$ So far problems: HGM overestimated relative kaon yields from 30*A* GeV on

Extended version of hadron gas model

(arXiv:0812.1186; APP B40, 1005 (2009))

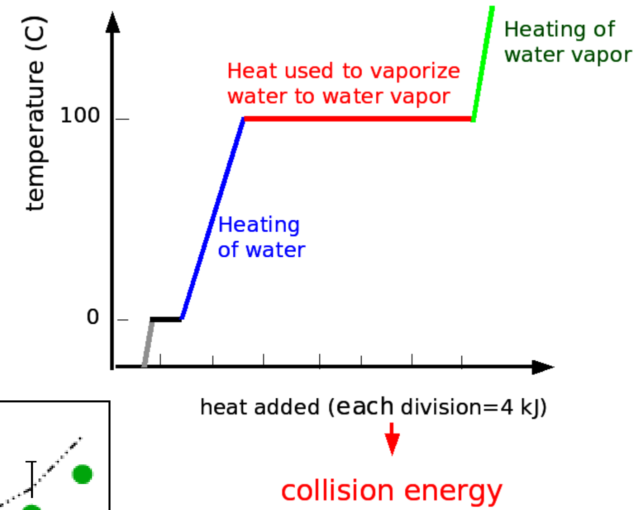
Inclusion of (not measured) higher-mass resonances in the model spectrum improves description of K/π data: These resonances feed-down predominantly into pions $\rightarrow$ increased pion yield

Warning: in this HGM extension unmeasured states are included!

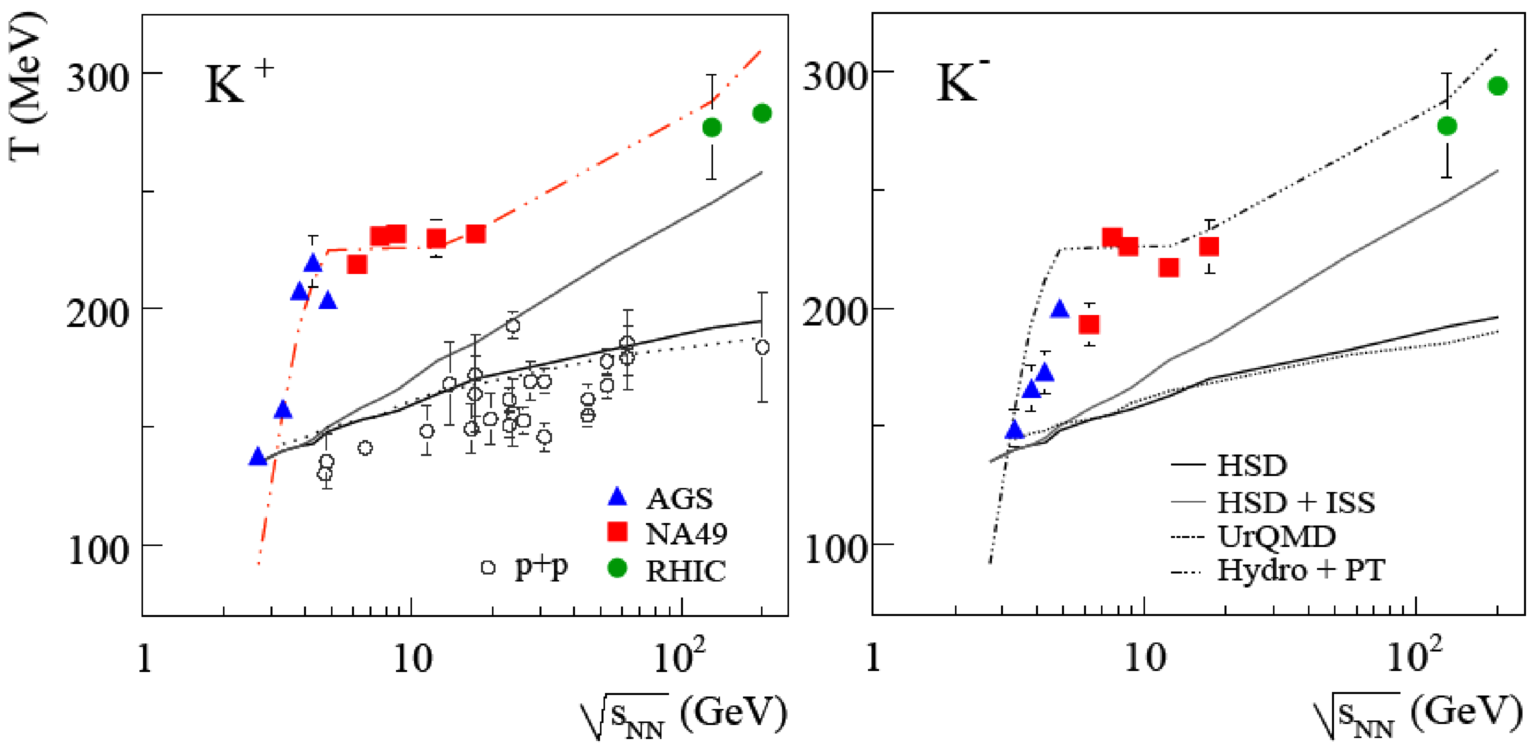


Step: constant *T* and *p* in mixed phase

(NA49, PR C77, 024903 (2008))



Kaon inverse slopes (T)



Transverse mass spectra

$$\frac{dn}{m_T\, dm_T} = C \exp\left(-\frac{m_T}{T}\right)$$

fits close to mid-rapidity

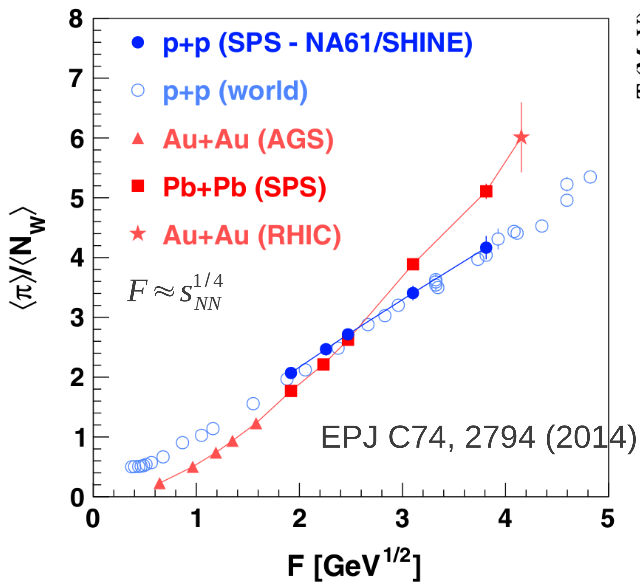
→ **Inverse slope: strong rise at AGS, plateau at SPS, rise towards RHIC**
(not seen in p+p)

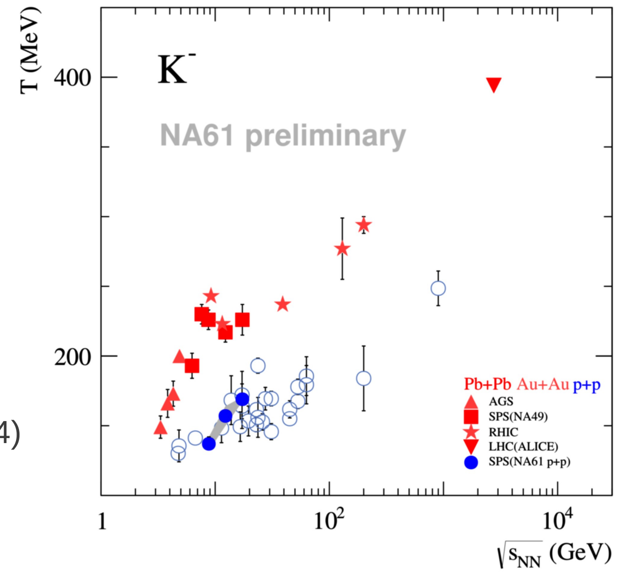
→ Consistent with constant temperature and pressure in mixed phase (latent heat) – SMES;
Gorenstein et al., PL B567, 175 (2003)

→ **Models without phase transition do *not* reproduce the data**

→ **Hydro model with deconfinement phase transition at SPS describes data**
(Hama et al., Braz. J. Phys. 34, 322 (2004))

Kink and step plots – studying the properties of the onset of deconfinement

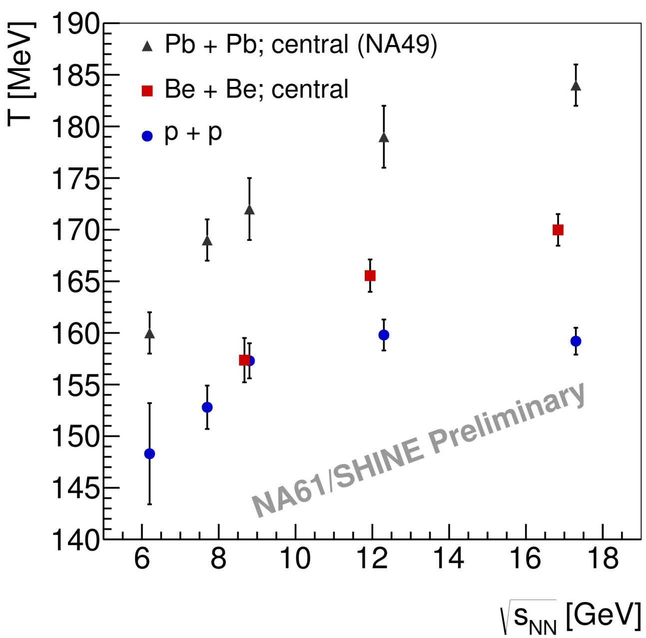




Grebieszkow, PoS CPOD2013, 004

- π multiplicity at the SPS energies increases faster in central Pb+Pb than in p+p collisions (**kink**). The two dependences cross at about 40*A* GeV
- Inverse slope parameters T of m_T spectra at the SPS energies show different behavior in central Pb+Pb (**step**) than in p+p (smooth increase)

NA61 precision sufficient to study properties of the onset of deconfinement



Inverse slope parameter of transverse mass spectra of π^- mesons

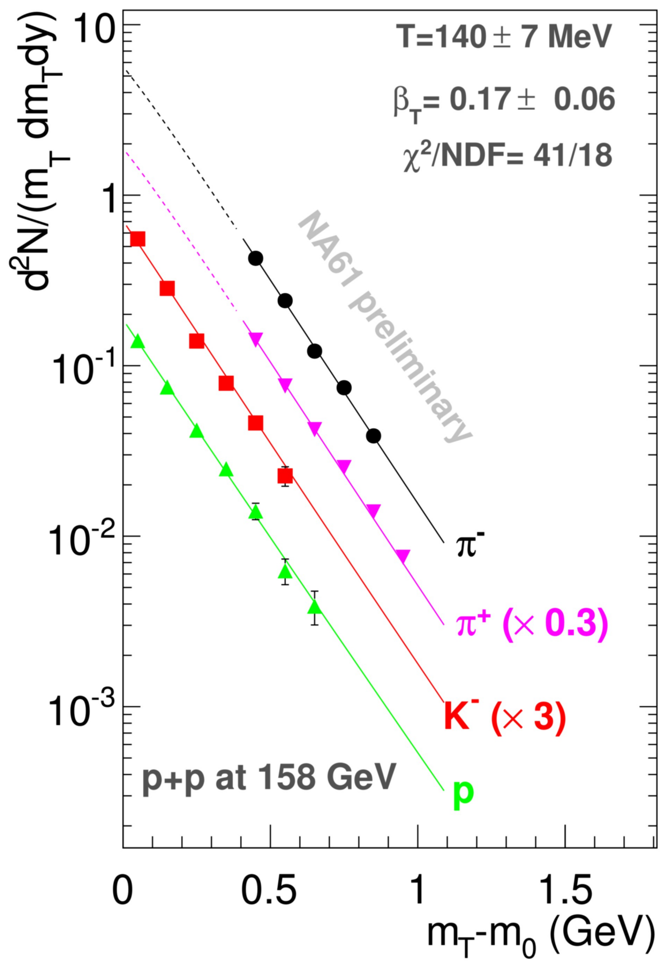
Beryllium looks heavy at 150*A* GeV/c !

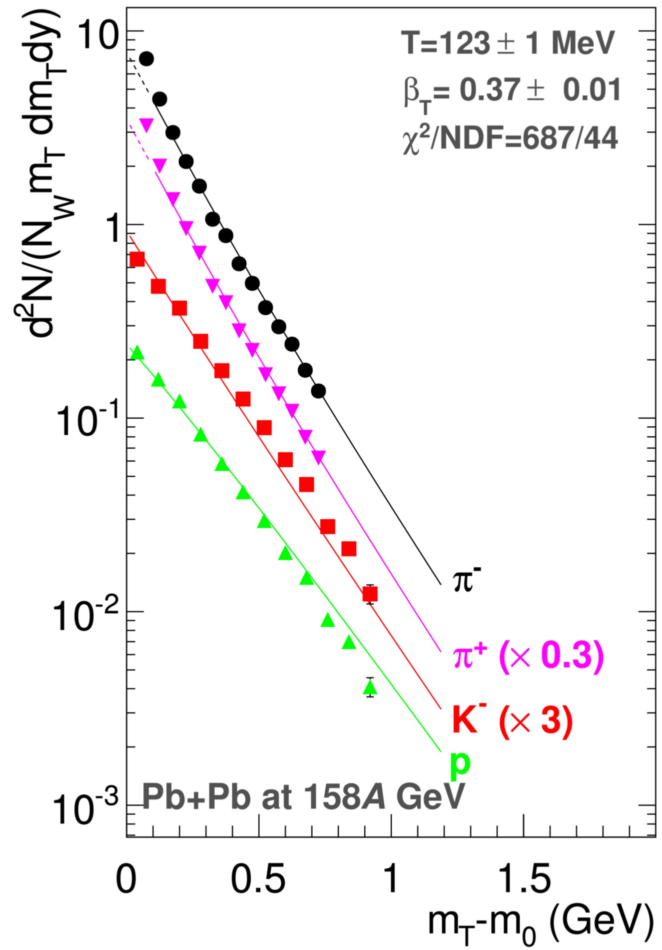
Energy dependence of T parameter in Be+Be similar to Pb+Pb

Kaptur (for NA61), X Polish Workshop on Relativistic Heavy-Ion Collisions (XII 2013)

$$\frac{dN_i}{m_T dm_T dy} = A_i m_T K_1\left(\frac{m_T \cosh\rho}{T}\right) I_0\left(\frac{p_T \sinh\rho}{T}\right)$$
$$\rho = atanh\,\beta_T$$

Schnedermann, Sollfrank, Heinz, PR C48, 2462 (1993)

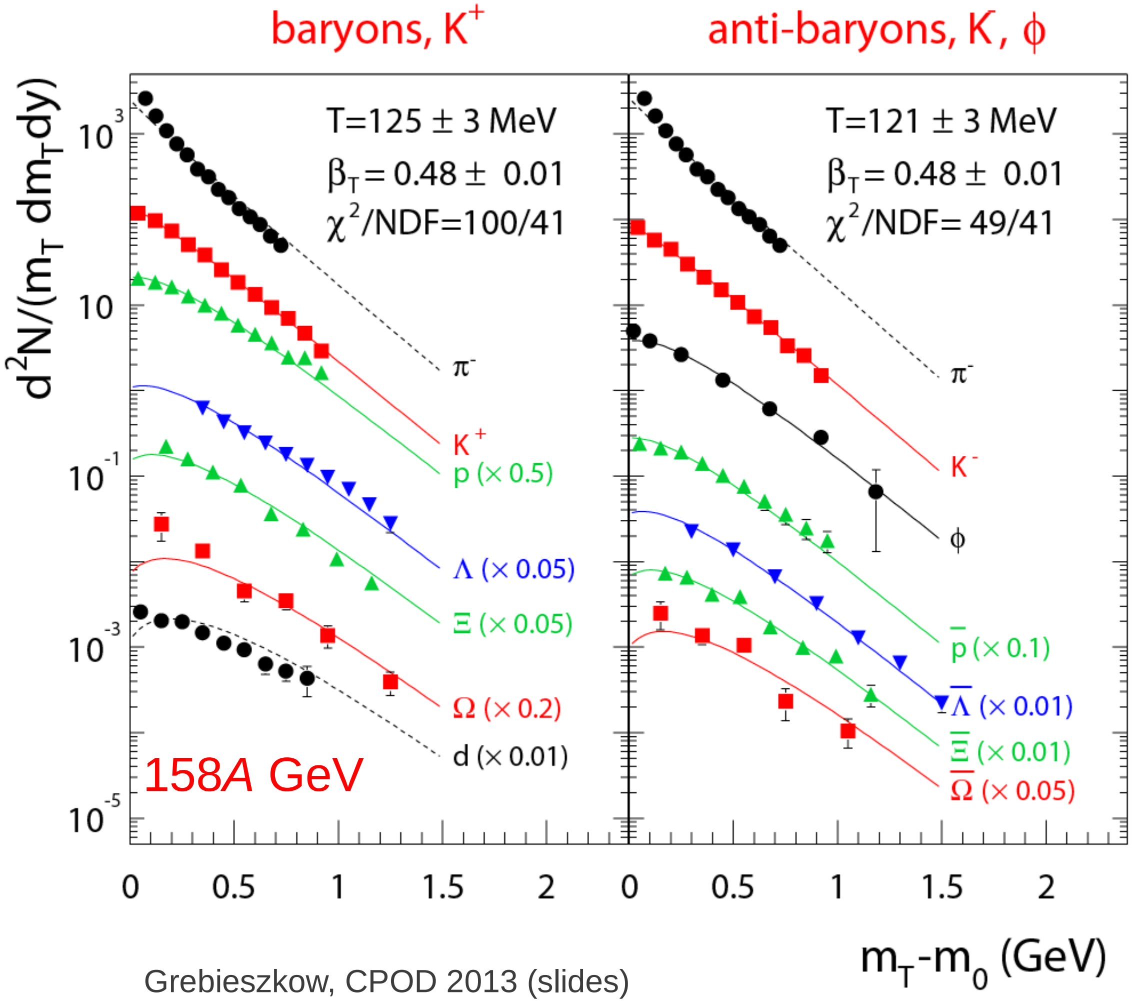




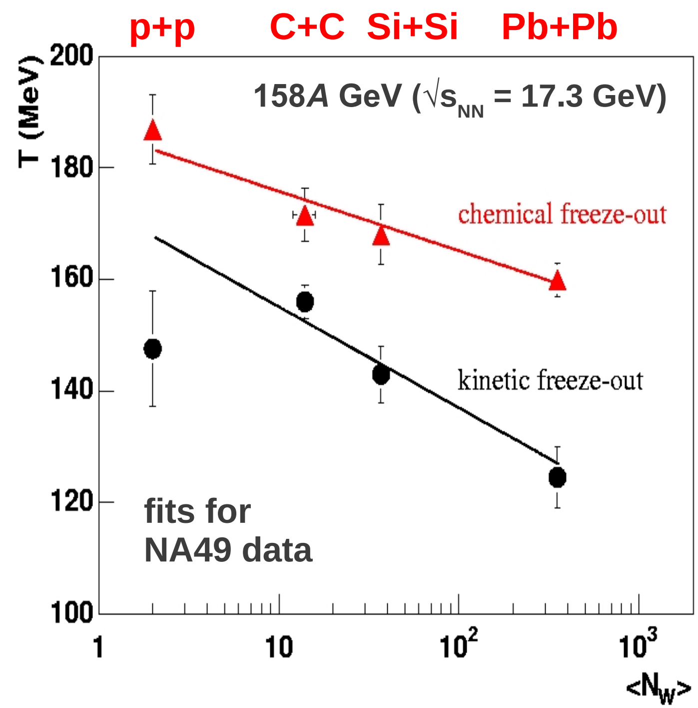
$$\frac{1}{p_T}\frac{dN}{dp_T} = \frac{1}{m_T}\frac{dN}{dm_T}$$

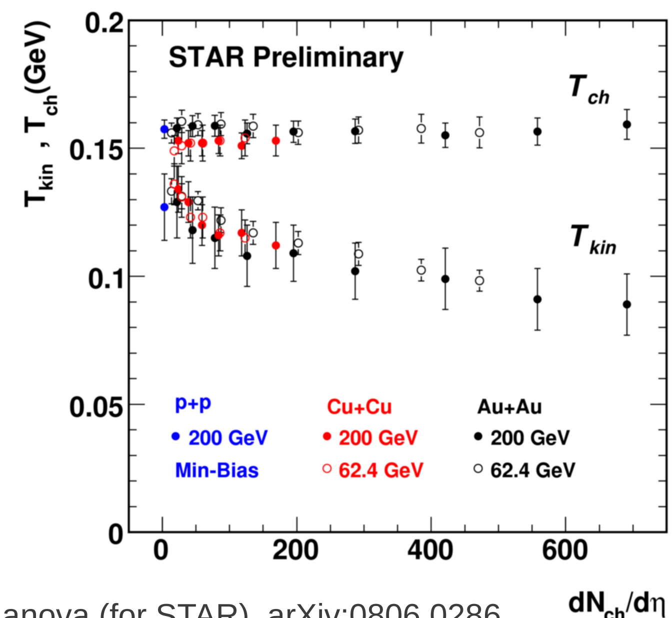
Grebieszkow,
PoS CPOD2013, 004

Transverse mass spectra are approximately exponential in p+p interactions. In central Pb+Pb collisions the exponential dependence is modified by the transverse flow.

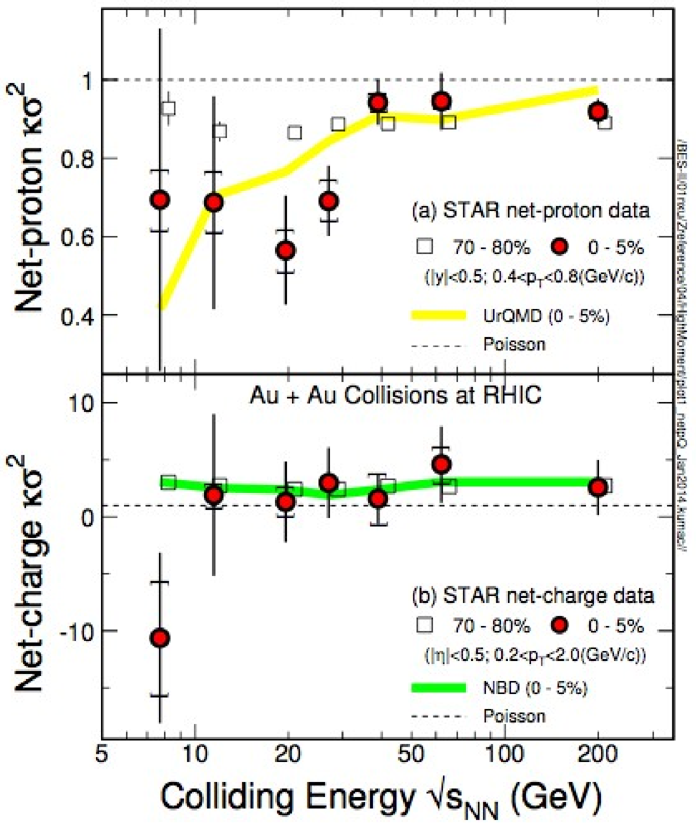


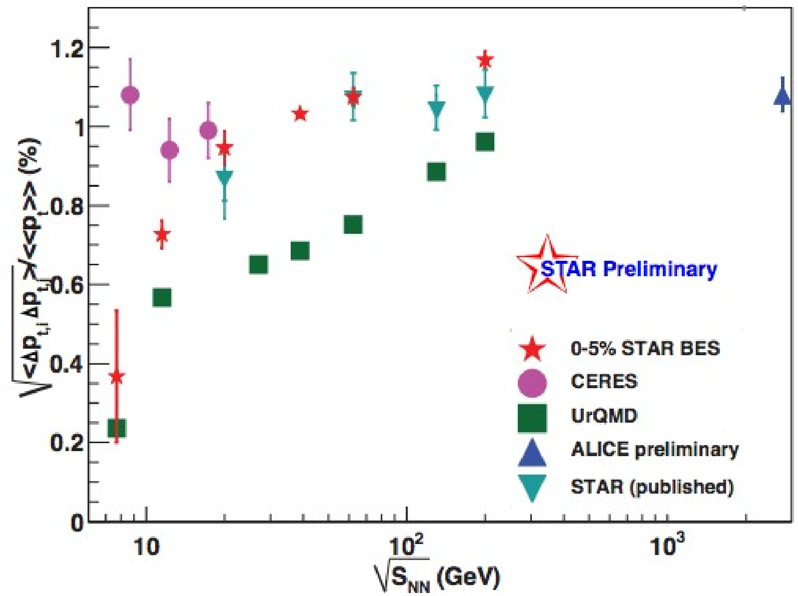
Grebieszkow, CPOD 2013 (slides)





Iordanova (for STAR), arXiv:0806.0286





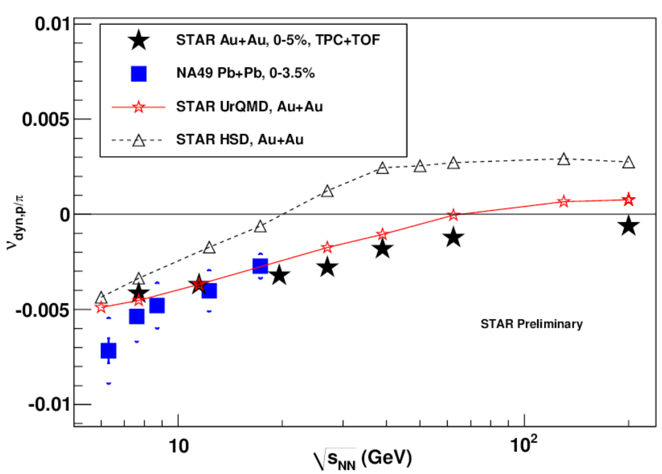
RHIC
STAR BES

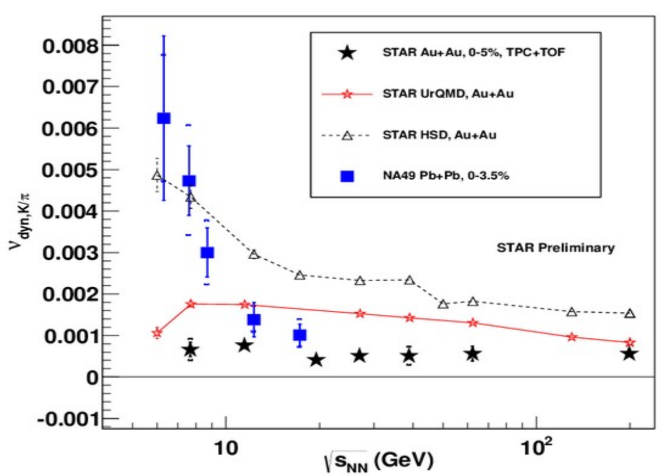
Sahoo (for STAR),
WWND 2014

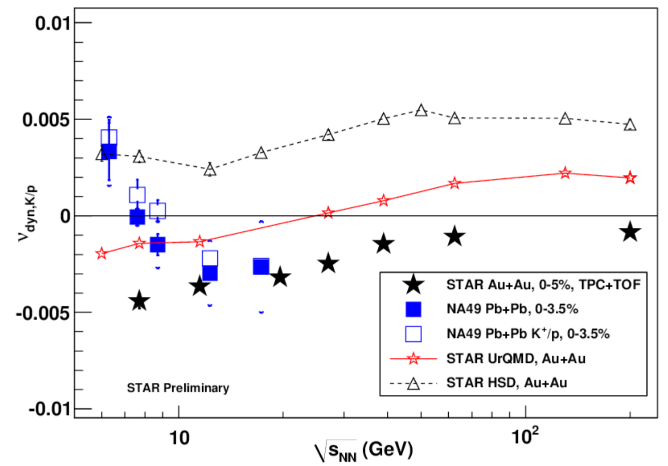
$$\langle \Delta p_{t,i} \Delta p_{t,j} \rangle = \frac{1}{N_{event}} \sum_{k=1}^{N_{event}} \frac{C_k}{N_k(N_k-1)}\, , \quad C_k = \sum_{i=1}^{N_k} \sum_{j=1, i \neq j}^{N_k} \left(p_{t,i} - \langle\langle p_t \rangle\rangle\right)\left(p_{t,j} - \langle\langle p_t \rangle\rangle\right)$$

$$\nu_{\mathrm{dyn}}^{M-N} = \frac{\langle M(M-1)\rangle}{\langle M^2 \rangle} + \frac{\langle N(N-1)\rangle}{\langle N^2 \rangle} - 2\frac{\langle MN \rangle}{\langle M \rangle \langle N \rangle}$$

where M and N are multiplicities of different particles species

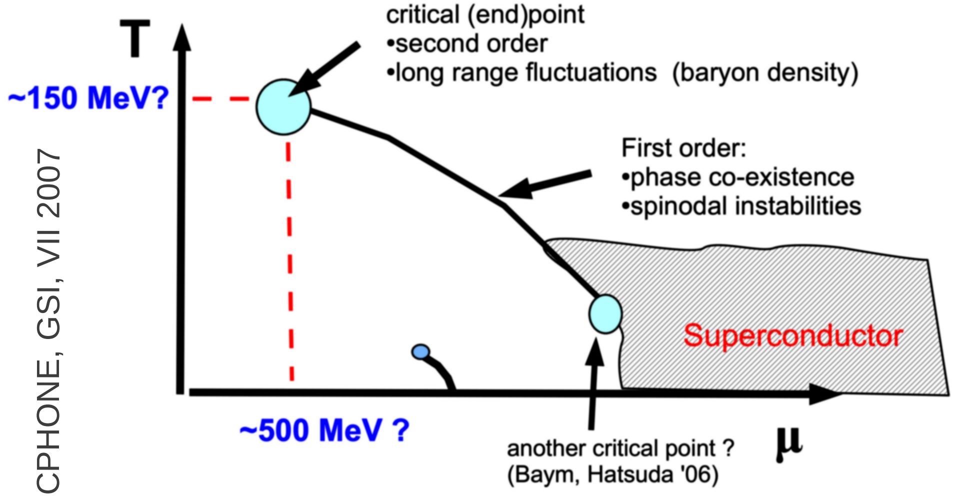






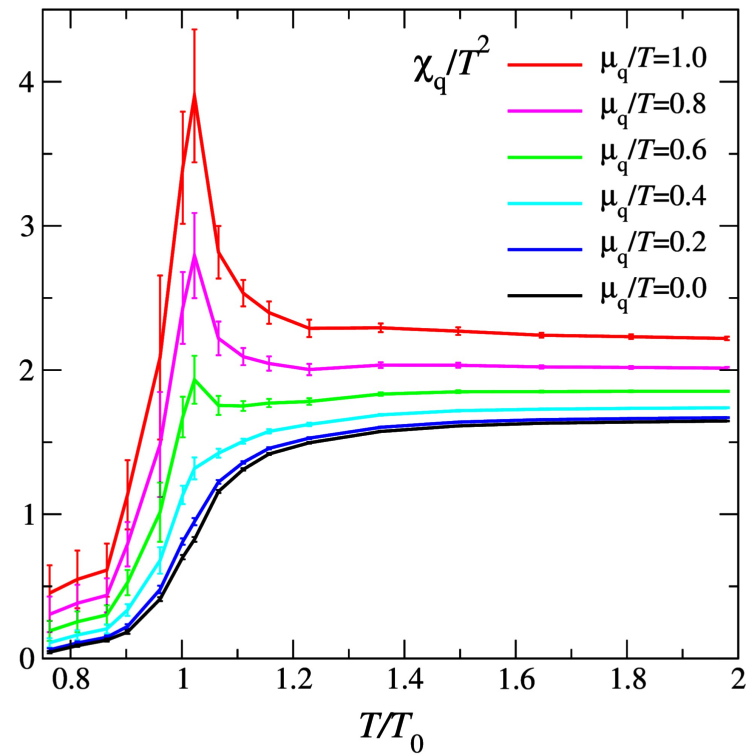
K. Grebieszkow, DIS 2014

CPHONE, GSI, VII 2007

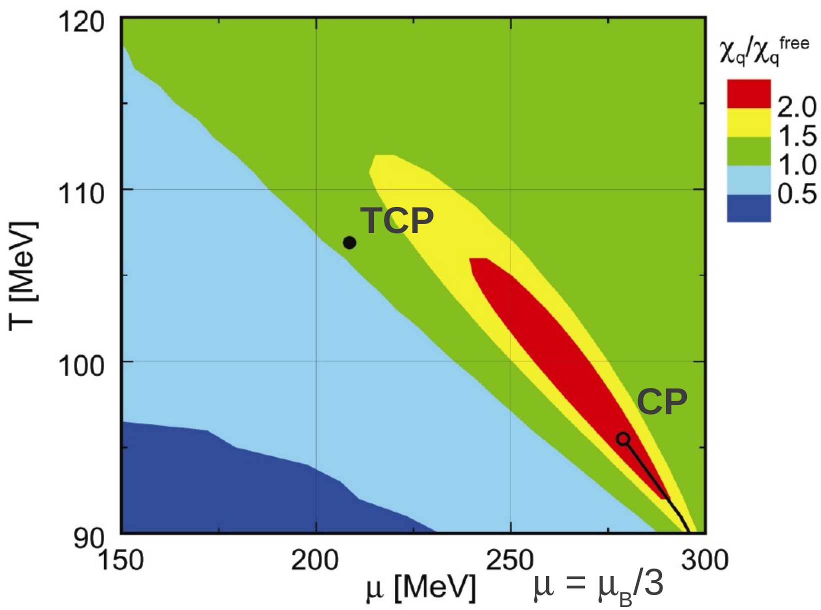


For strongly interacting matter long range baryon density fluctuations expected

A picture supported by lattice calculations



Hatta, Ikeda PR D67, 014028 (2003)



Baryon density fluctuations appear to diverge for some critical value of the baryochemical potential

Effect of critical point extends over a critical region with $\sigma(\mu_B)$ and $\sigma(T)$ $\Rightarrow$ we do not need to hit precisely the critical point because **a large region can be affected!**

Allton, PR D68, 014507 (2003)
quark number susceptibility: $\chi_q \equiv \partial n_q/\partial \mu_q$,
T_0 – critical temperature for $\mu_q = 0$ ($\mu_B = 3\mu_q$)

- **Scaled variance ω of multiplicity distribution**
  - Intensive measure
  - For Poisson N distribution ω=1
  - In **M**odel of **I**ndependent **S**ources $\omega(N_s$ sources$) = \omega(1$ source$) + \langle n\rangle\omega_{Ns}$

    <n> - mean multiplicity from a single source; ω_{Ns} - fluctuations in N_s

$$\omega = \frac{\langle N^2\rangle - \langle N\rangle^2}{\langle N\rangle}$$

ω is strongly dependent on N_s fluctuations (it is intensive but not strongly intensive)

- **Φ_x measure** (ZP C54, 127 (1992)) **of fluct. ($x=p_T$, ϕ, Q)**
  - In MIS: $\Phi_x(N_s$ sources$) = \Phi_x(1$ source$)$
  - For **I**ndependent **P**article **M**odel (not corr. emission) $\Phi_x=0$
  - In superposition model **Φ_x is independent of N_s and N_s fluctuations (strongly intensive)**

$z_x = x - \bar{x}$; $\bar{x}$ - inclusive average

event variable $Z_x = \sum_{i=1}^{N}(x_i - \bar{x})$

$$\Phi_x = \sqrt{\frac{\langle Z_x^2\rangle}{\langle N\rangle}} - \sqrt{\overline{z_x^2}}$$

- **Intermittency in low mass $\pi^+\pi^-$ pair density fluctuations in p_T space**
  - Proper mass window and multiplicity required
  - Mixed events used as reference
  - **Power-law behavior** from σ mode expected: $\Delta F_2 \sim (M^2)^{\phi_2}$
  - Critical QCD prediction ϕ_2 = 2/3

2D transv. momentum factorial moments:

$$F_p(M) = \frac{\langle \frac{1}{M^2}\sum_{i=1}^{M^2} n_i(n_i-1)\dots(n_i-p+1)\rangle}{\langle \frac{1}{M^2}\sum_{i=1}^{M^2} n_i\rangle^p}$$

M^2 - number of cells in p_T space of di-pion

$\vec{p}_{T,\pi\pi} = \vec{p}_{T,\pi^+} + \vec{p}_{T,\pi^-}$

n_i - number of reconstruc. di-pions in i-th cell

$\Delta F_2(M)$ - combinatorial background subtracted (by use of mixed events) second factorial moment

Critical point predictions for multiplicity and transverse moment. fluctuations

Magnitude of fluctuations at CP from Stephanov, Rajagopal, Shuryak PR D60, 114028 (1999)
with correlation length ξ = min ($c_1 A^{1/3}$, $c_2 A^{1/9}$) =
min (limit due to finite system size, limit due to finite life time)

(M. Stephanov, private communication)

where c_1 and c_2 are fixed such that

- ξ(Pb+Pb) = 6 fm and ξ(p+p) = 2 fm (c_1 = 2, c_2 = 3.32)
- ξ(Pb+Pb) = 3 fm and ξ(p+p) = 1 fm (c_1 = 1, c_2 = 1.66)

Width of CP region in (T, μ_B) plane based on Hatta, Ikeda PR D67, 014028 (2003)

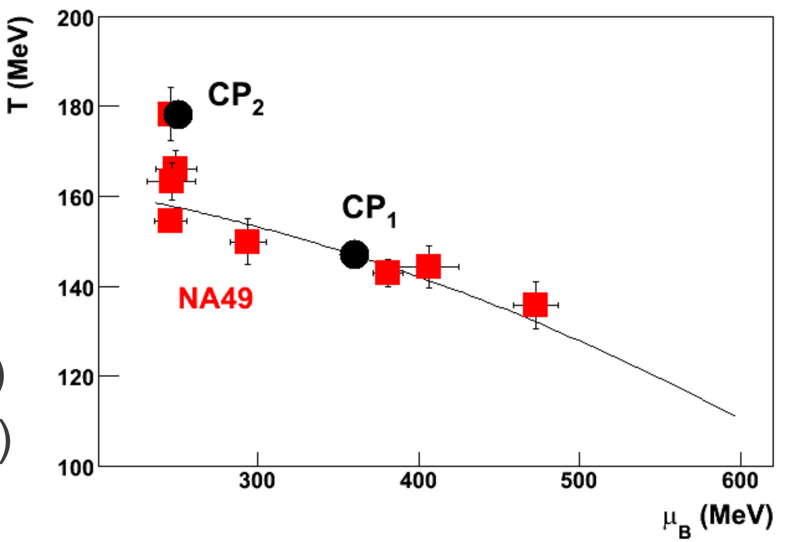
$\sigma(\mu_B) \approx 30$ MeV and $\sigma(T) \approx 10$ MeV

Chemical freeze-out parameters, T(A,$\sqrt{s_{NN}}$) and μ_B(A,$\sqrt{s_{NN}}$) from Beccatini et al. PR C73, 044905 (2006)

Location of the Critical Point:
two examples considered

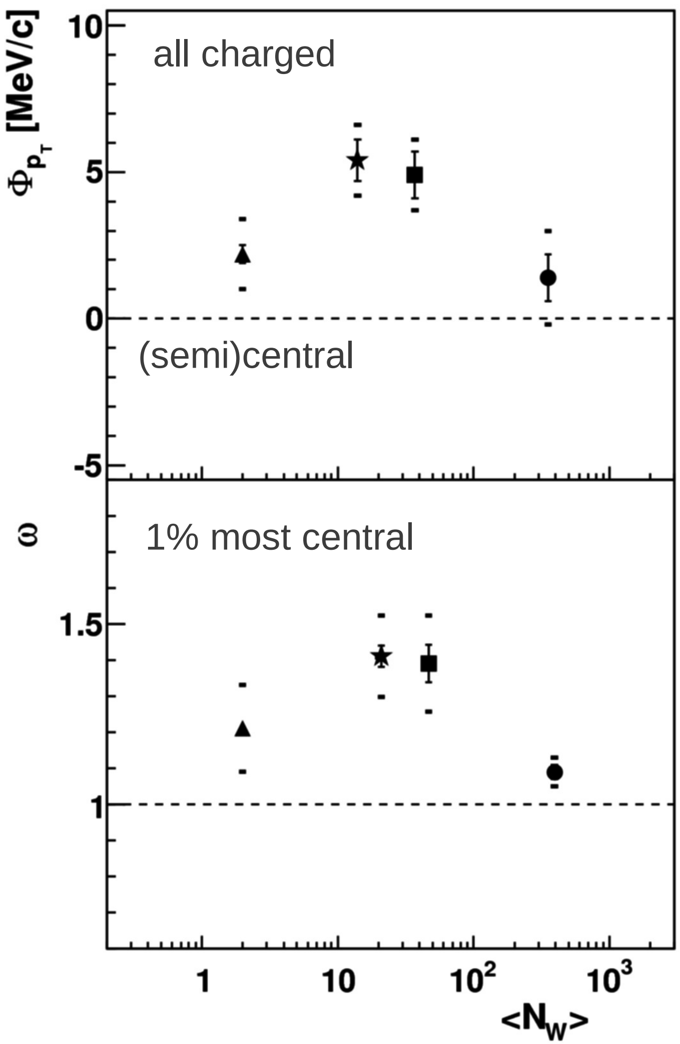
- $\mu_B(CP_1)$ = 360 MeV (Fodor, Katz JHEP 0404, 050 (2004))
  $T(CP_1) \approx 147$ (chemical freeze-out temperature T_{chem}
  for central Pb+Pb at μ_B = 360 MeV)

- $\mu_B(CP_2) \cong 250$ MeV (μ_B for A+A collisions at 158A GeV)
  $T(CP_2)$ = 178 MeV (T_{chem} for p+p collisions at 158 GeV)



System size dependence (p+p, C+C, Si+Si, and Pb+Pb) of average p_T and multiplicity fluctuations at 158*A* GeV

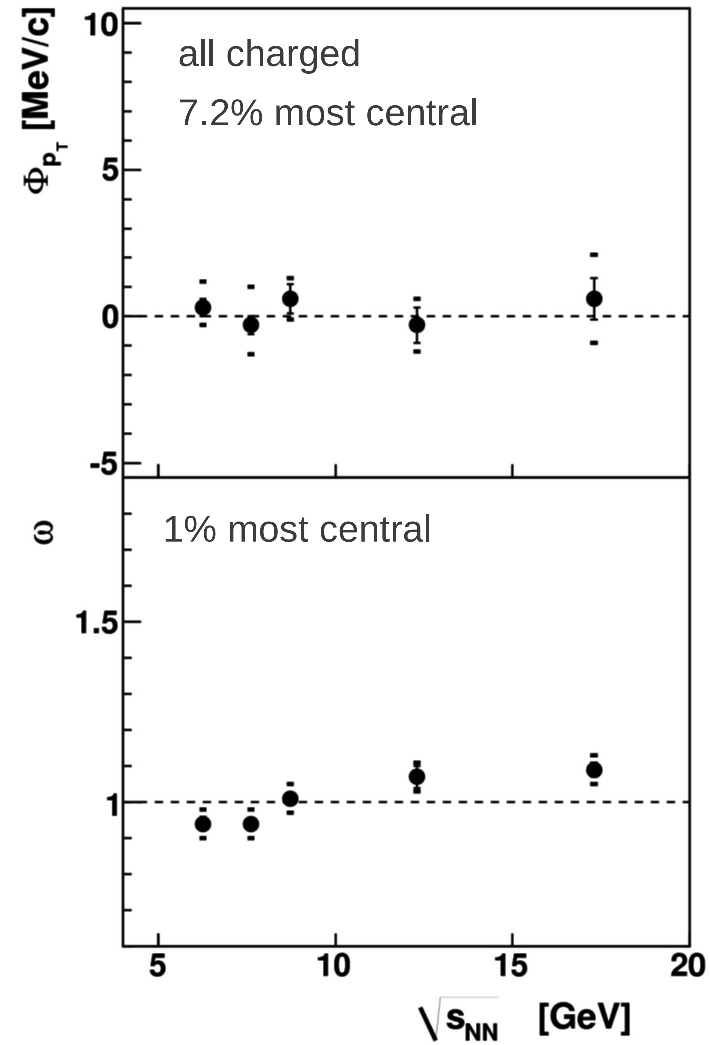
Energy dependence of average p_T and multiplicity fluctuations for central Pb+Pb



- **Maximum of Φ_{pT} and ω for C+C and Si+Si at 158*A* GeV**
- **No significant energy dependence**

Forward-rapidity, limited azimuthal acceptance

upper left: PR C70, 034902 (2004)
lower left: p+p – PR C75, 064904 (2007); Pb+Pb – PR C78, 034914 (2008); C+C, Si+Si - B. Lungwitz, PhD thesis
upper right: PR C79, 044904 (2009)
lower right: PR C78, 034914 (2008)

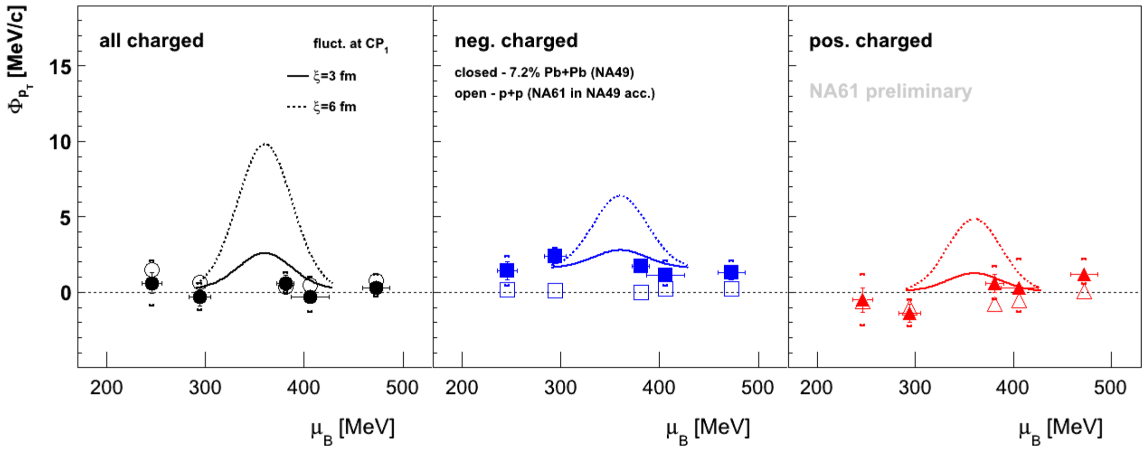


K. Grebieszkow, DIS 2014

For energy dependence of Φ_{pT} important cut on y^*_p to get rid of artificial effect of event-by-event centrality fluctuations while studying only forward-rapidity → for details see separate paper KG, PR C76, 064908 (2007)

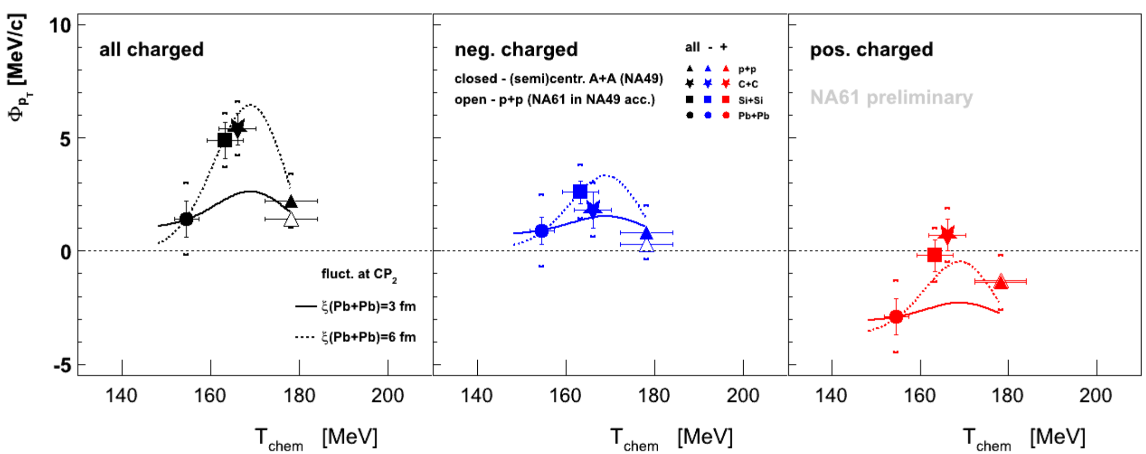
Comparison of p_T fluctuations for NA49 A+A and NA61 p+p collisions

in the same (NA49) acceptance



- **Forward-rapidity**
  $1.1 < y_\pi < 2.6$;
  $y_p < y_{beam} - 0.5$
- **Common** (for all energies) **limited azimuthal angle**

Similar behaviour for Pb+Pb and p+p; difference only for negatively charged particles



- **Forward-rapidity**
  $1.1 < y_\pi < 2.6$
- **Wide azimuthal angle** –
  nearly as available at 158*A* GeV

Details of CP predictions (curves) for Φ_{pT}
→ NP A830, 547C (2009)

Grebieszkow (for NA61 and NA49), X Polish Workshop on Relativistic Heavy-Ion Collisions, (XII 2013)

Pion-pion intermittency analysis

The analog of critical opalescence is detectable through intermittency analysis in transverse momentum space (power-law behavior of factorial moments expected)

Idea: σ-field fluctuations at the critical point
(density fluctuations of zero mass σ-particles produced in abundance at CP)

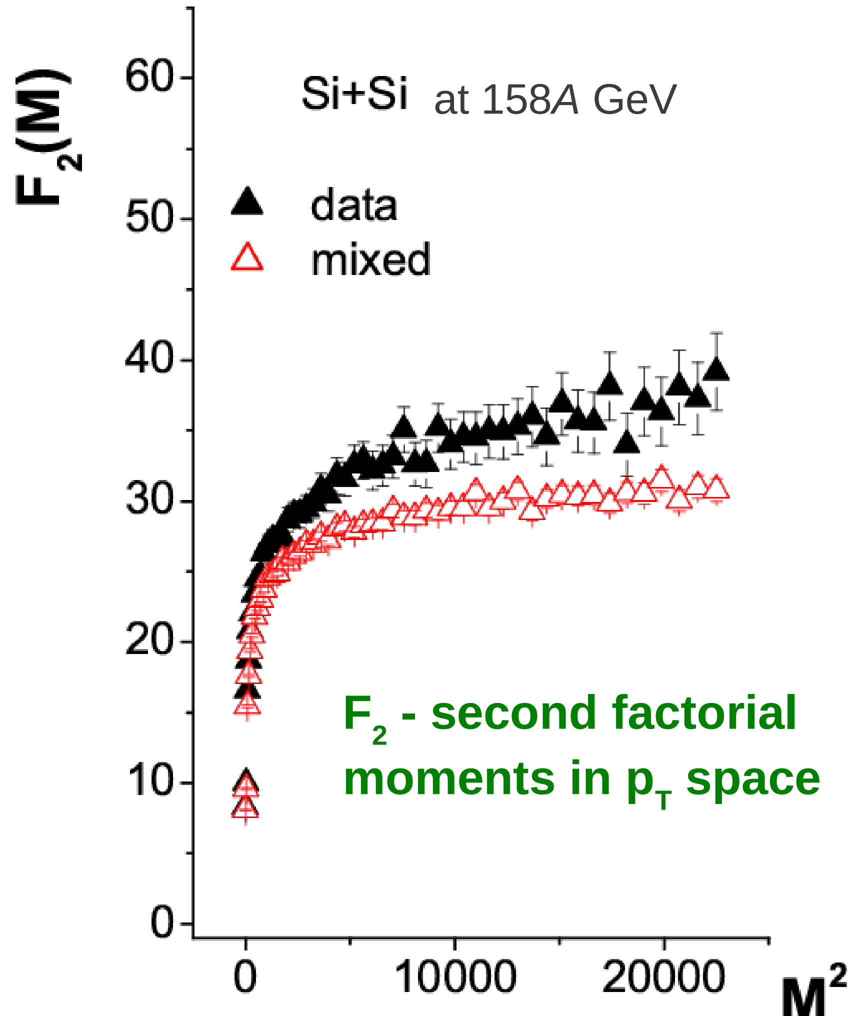
Antoniou et al. NP A761, 149 (2005),
Anticic et al., PR C81, 064907 (2010)

Why:

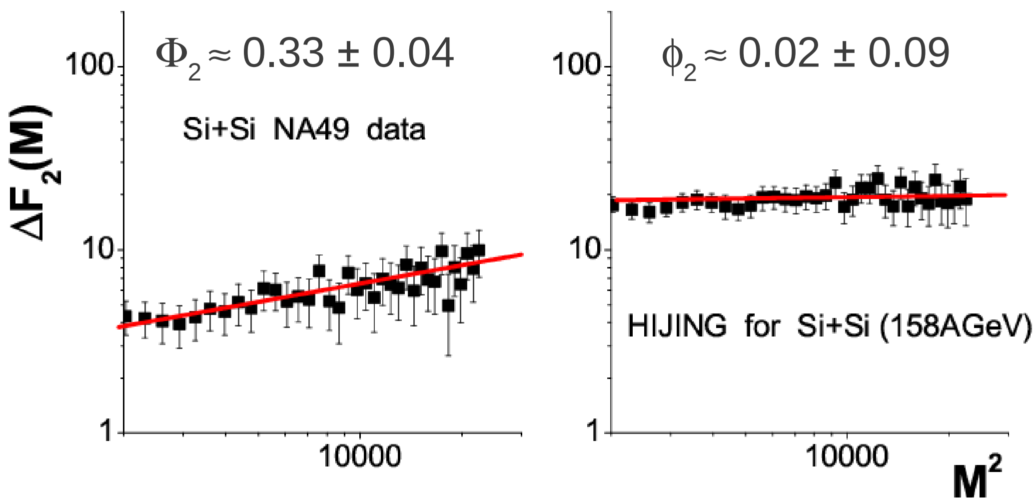
- σ at $T<T_c$ may reach the two-pion threshold ($2m_\pi$) and decay into two pions, thus density fluctuations of di-pions with $m_{\pi+\pi-}$ close to $2m_\pi$ incorporate σ-field fluctuations at CP
- local density fluctuations expected both in configuration and momentum space

Method: Intermittency analysis in p_T space of reconstructed di-pions ($\pi^+\pi^-$ pairs) with invariant mass just above $2m_\pi$

For each event **all possible pairs** with $m_{\pi+\pi-}$ in small kin. window above two-pion threshold:



System size dependence of di-pion intermittency signal at 158*A* GeV

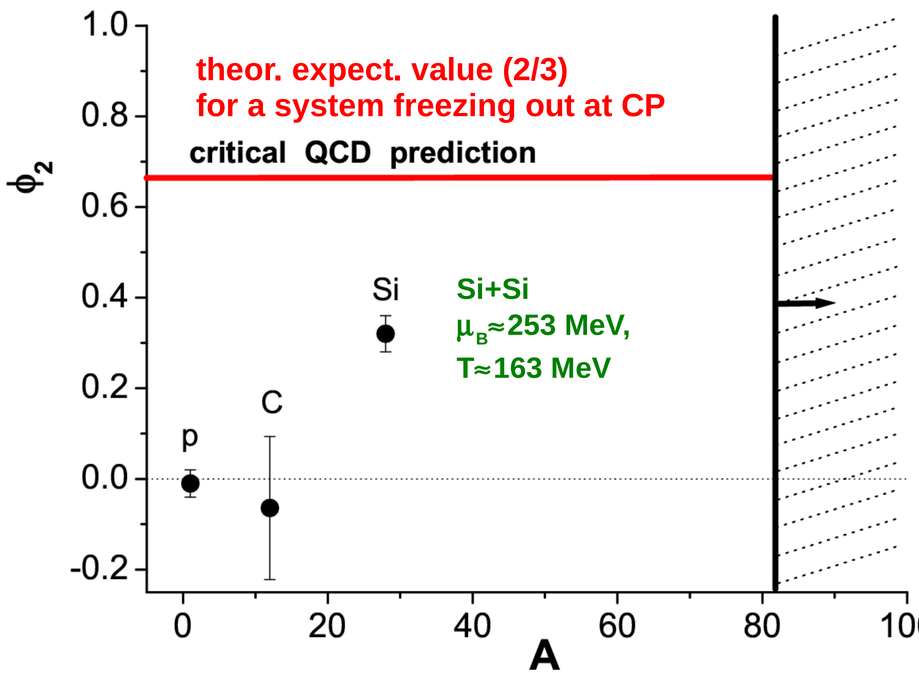


ΔF_2 - combinatorial background subtracted moments in p_T space

$$\Delta F_2 \sim (M^2)^{\phi_2}$$

For Si+Si ΔF_2 measures fluctuations which are much higher than those from HIJING

Anticic et al., PR C81, 064907 (2010)



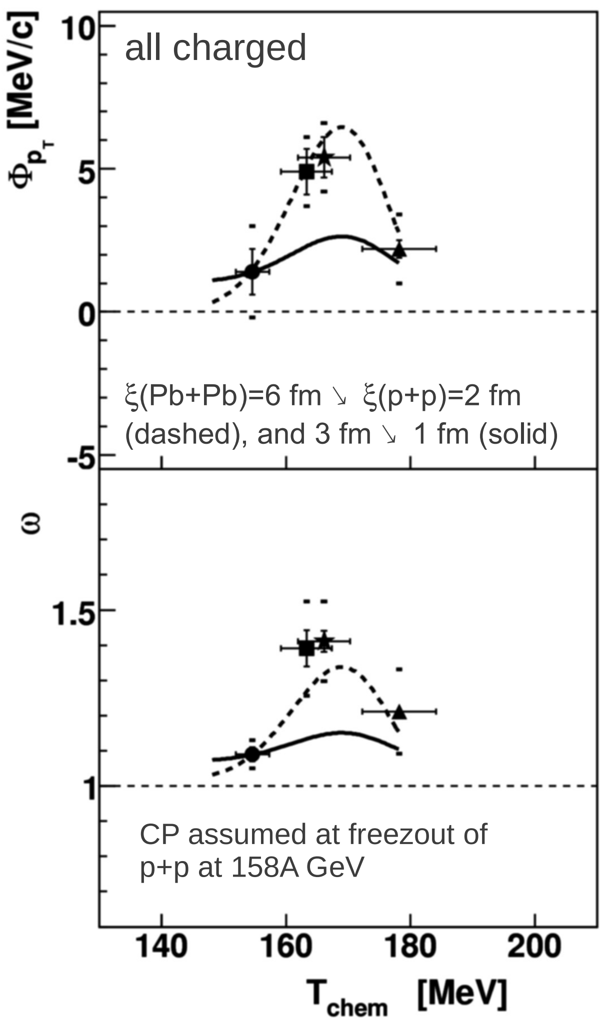
Values of ϕ_2 for p+p, C+C (0-10%), and Si+Si (0-10%)

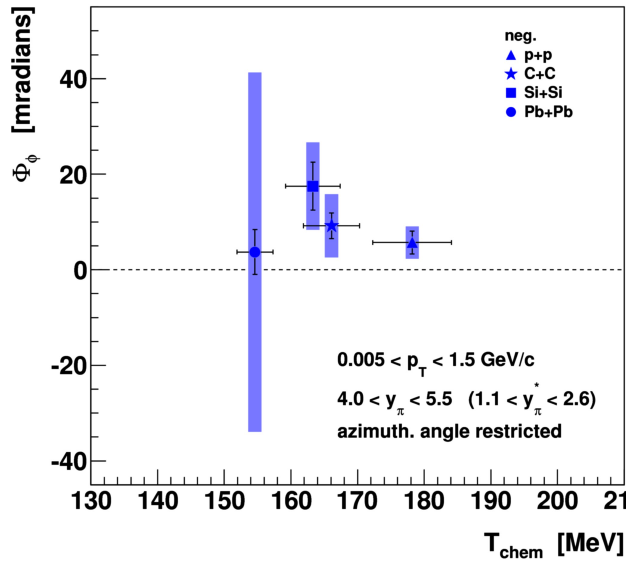
Fluctuations in the freeze-out state of Si+Si system approaching in size the prediction of critical QCD (the remaining departure, $\phi_{2,max} \approx 0.33 \pm 0.04$ instead of 2/3, may be due to freezing out at a distance from CP)

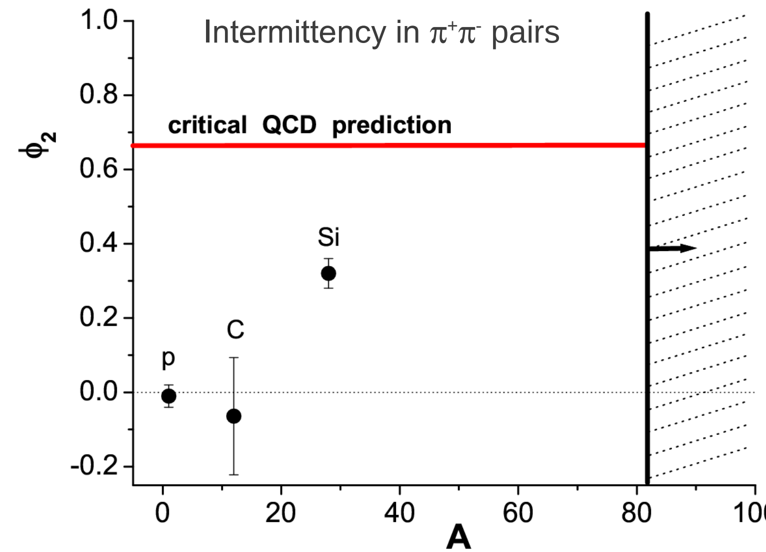
… (net)proton intermittency analysis to be published soon

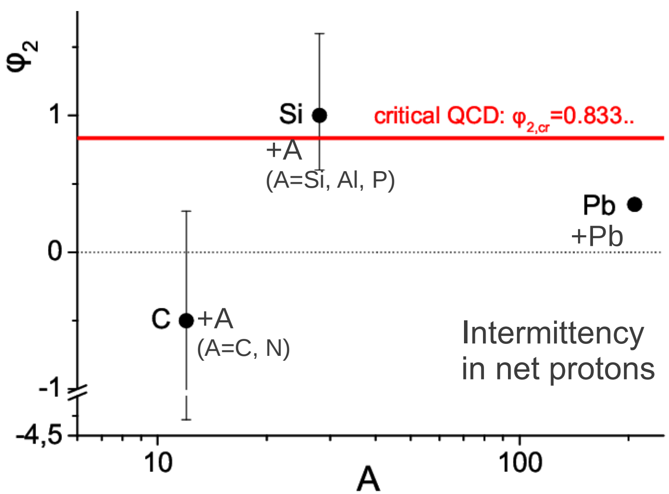
Summary of critical point search in NA49

System size dependence (p+p, C+C, Si+Si, Pb+Pb) of fluctuations at 158*A* GeV









Fluctuations of
- average p_T
- multiplicity
- average azimuthal angle (?)
- multiplicity of $\pi^+\pi^-$ pairs
- net-proton density

tend to a maximum in Si+Si (Si+A) collisions at 158*A* GeV

→ **strong motivation for future experiments**

NP A830, 547C (2009);
APP B43, 609 (2012);
arXiv:1208.5292v2