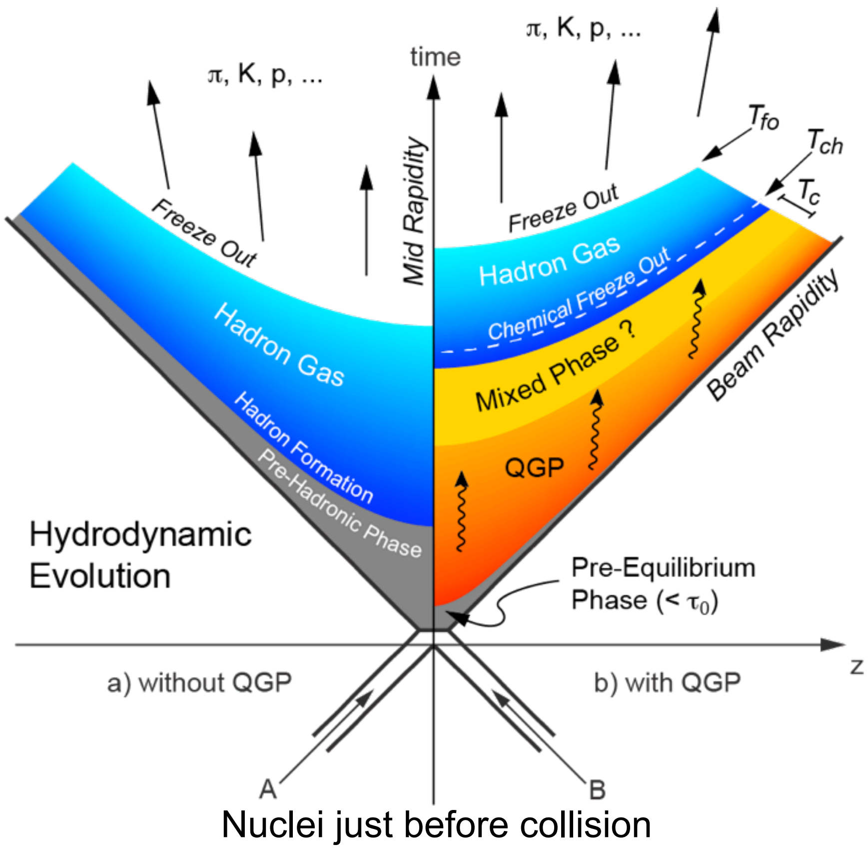
PROBING THE (S)QGP WITH STRANGENESS

Boris HIPPOLYTE (IPHC - Université de Strasbourg)

OUTLINE

- evolution of the system in heavy-ion collisions
- the importance of the references: pp, pA, dA...
- to be in chemical equilibrium or not to be (?)
- news from strangeness enhancement front
- hadronisation: recombination vs. fragmentation
  - ➡ baryon/meson ratio
  - ➡ fluid-dynamics: v_2 and constituent quark scaling
- radial flow and rescattering in the hadronic phase
- tomography
- summary (more a “wish-list”)

EVOLUTION OF THE SYSTEM CREATED IN H-I COLLISIONS



- Initial pre-equilibrium state
- hard parton scattering & jet production
- QGP formation
- QGP expansion and cooling
- Phase transition:
- Hadronic Phase:
  - ➡ chemical freeze-out
  - ➡ rescattering then kinetic freeze-out.

With hadronic states, many observables can be studied in order to characterise the properties of the Quark Gluon Plasma

Probing the whole evolution of the system with the strange hadrons created in heavy-ion collisions: jet flavour content, R_{AA}, strange particle flow, resonances, multi-strange (with low hadronic x-section)...

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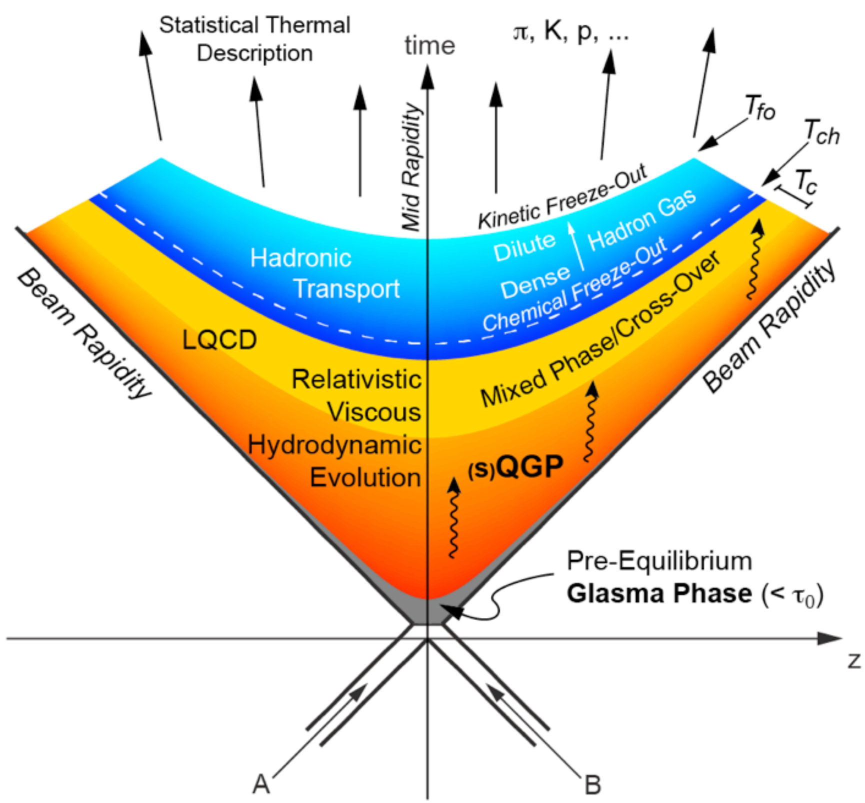

- Initial pre-equilibrium state
  - ➡ gluonic fields (Color Glass Condensate) **Glasma**
- hard parton scattering & jet production
- QGP formation
  - ➡ thermalisation of **strongly** interacting partons
- QGP expansion and cooling
  - ➡ **3D+1** relativistic **viscous** hydrodynamics
- Phase transition:
  - ➡ Lattice QCD, **Cross-Over**
- Hadronic Phase:
  - ➡ chemical freeze-out
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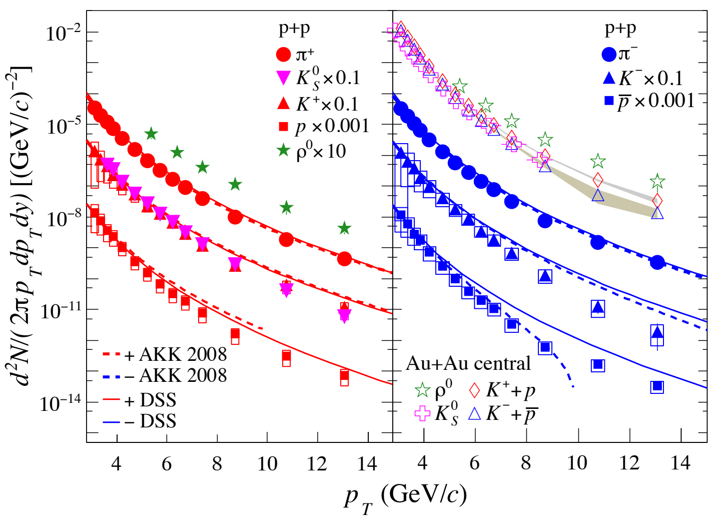
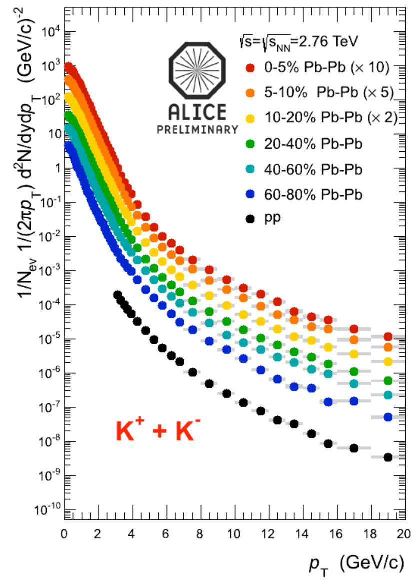
REFERENCE COLLIDING SYSTEM(S) AND COMPARISONS

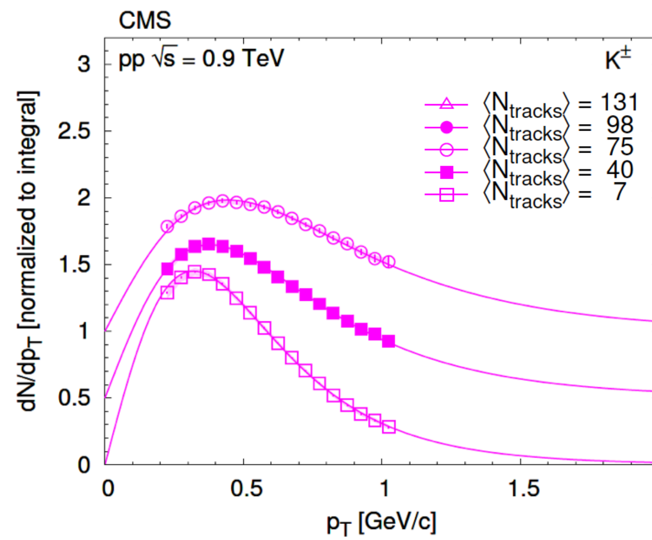
- the shapes of p_T spectra in AA are compared to pp, p/dA collisions
  - ➡ minimum bias pp are very often used a reference for AA
  - ➡ spectra are precisely measured up to high p_T and vs. beam energy



STAR Collaboration,
PRL 108 (2012) 072302, arXiv:1110.0579



M. Ivanov (ALICE Collaboration),
NPA 904-905 2013 (2013) 162c



CMS Collaboration, CMS-FSQ-12-014,
EPJC 72 (2012) 2164, arXiv:1207.4724

- ➡ p_T-spectra shapes change more vs. multiplicity than vs. colliding energy;
- ➡ not only p_T-spectra and $\langle p_T \rangle$ but p_T ratios (see forthcoming talks);
- ➡ difficulties for models, not only kaons (strangeness) but protons (baryons);
- ➡ good references ? collective effects ? (e.g. color reconnection in PYTHIA, initial boost in EPOS...)

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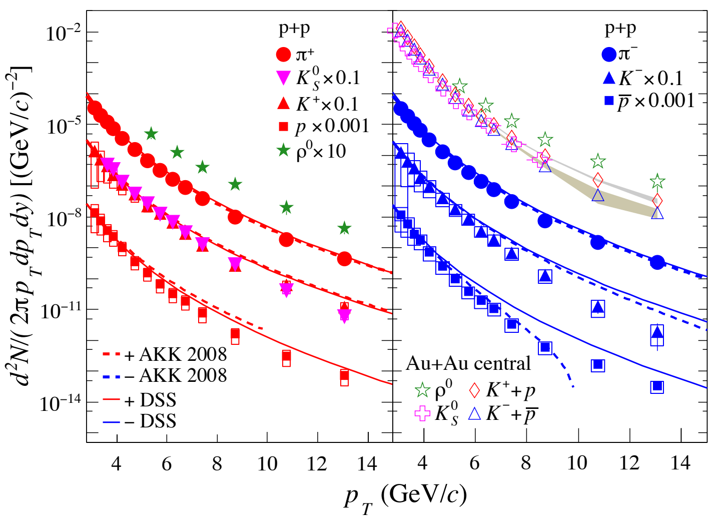

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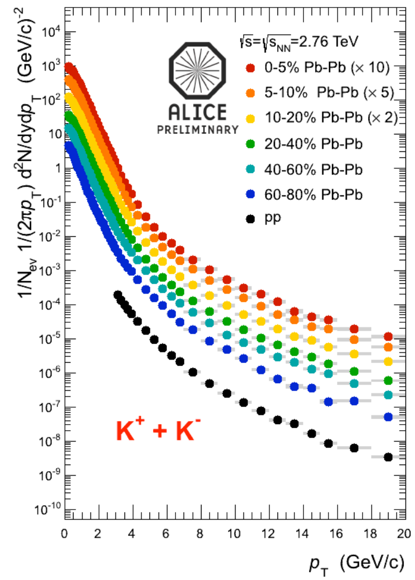

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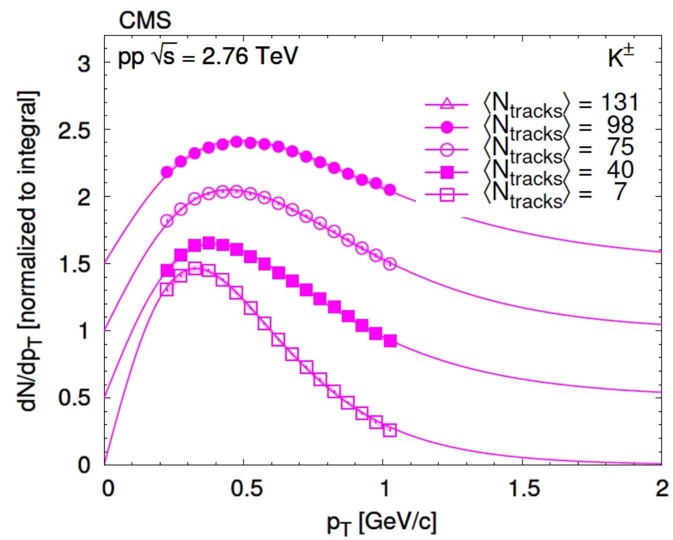

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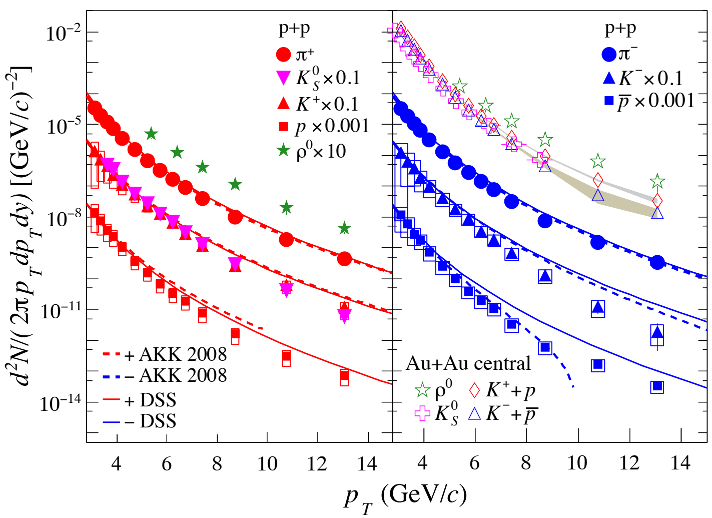

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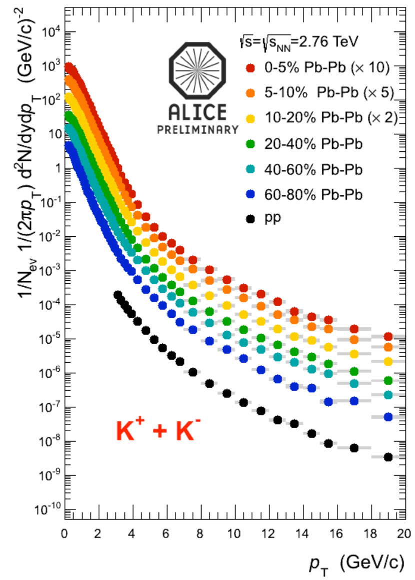

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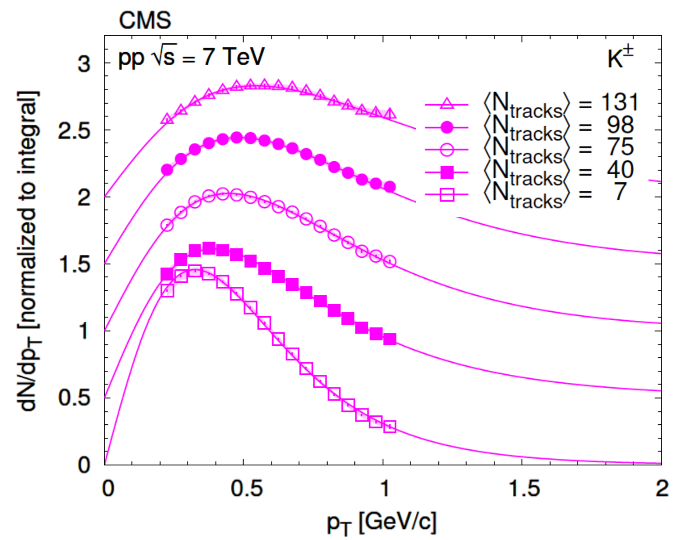

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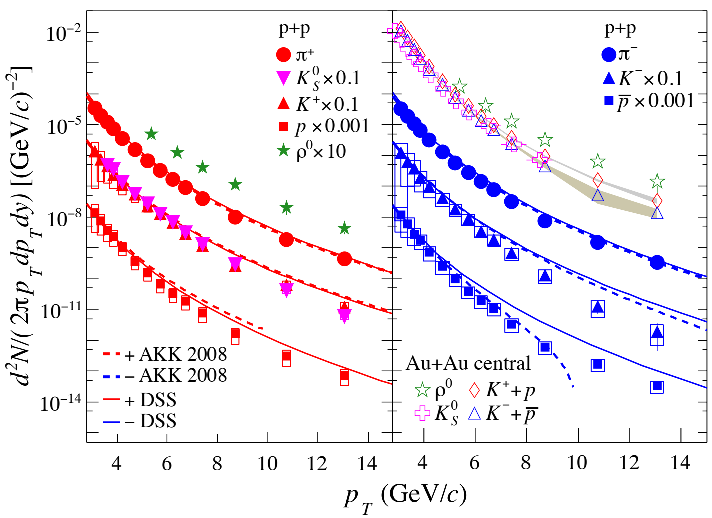

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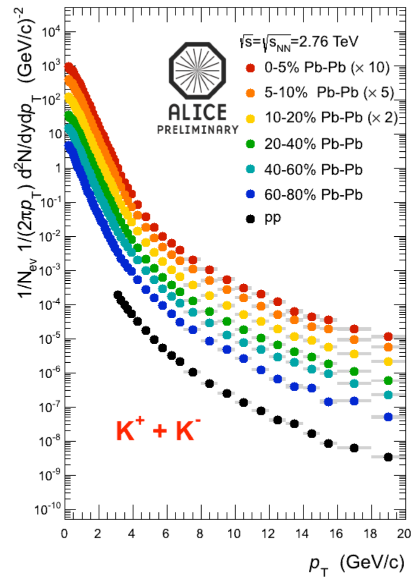

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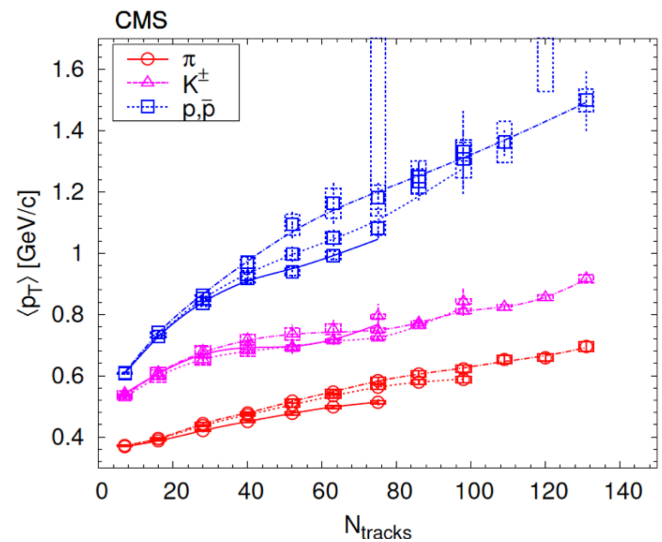

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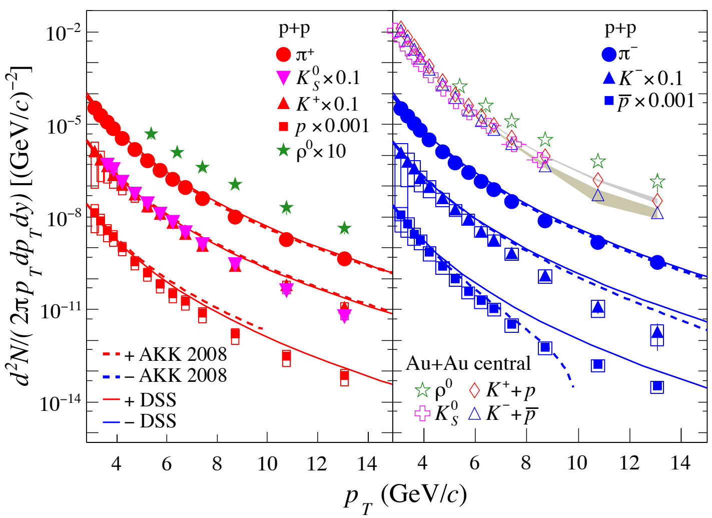

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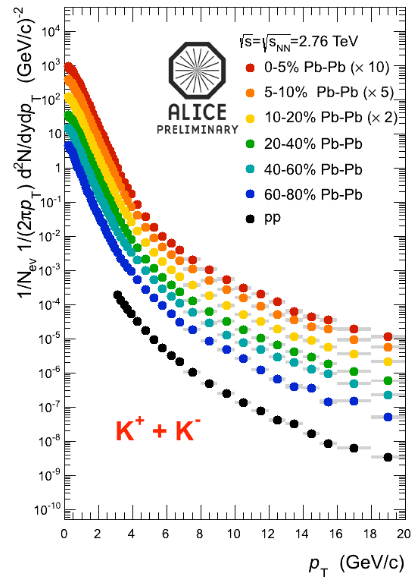

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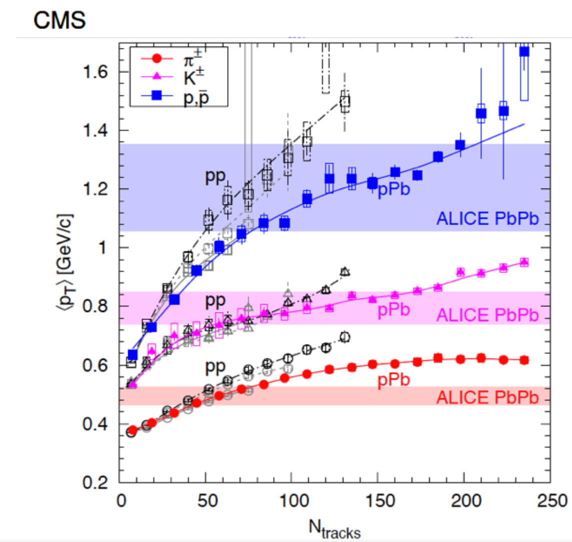

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+ arXiv:1307.3442 (pPb)

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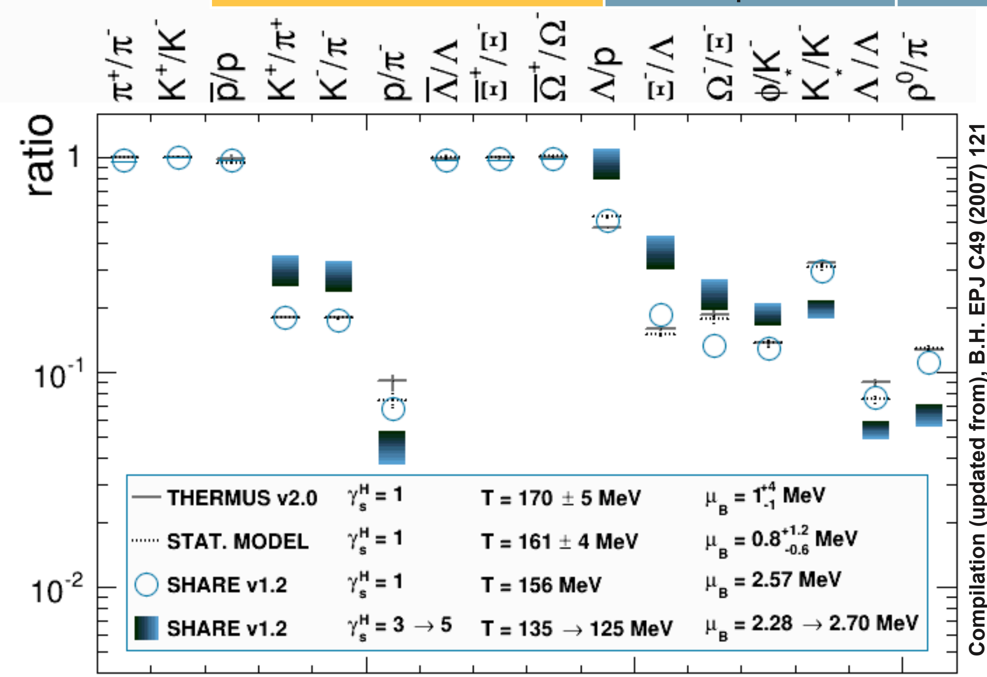
SQM 2013 BIRMINGHAM

TO BE IN EQUILIBRIUM OR NOT TO BE

- mid-rapidity p_T-integrated production of hadrons: description by statistical thermal models
  - Baryo-chemical potential μ_B
  - Chemical freeze-out temperature T_{ch}
  - Strangeness (non-)equilibrium parameter: γ_s

➡ Question: equilibration and saturation of strangeness (partonic / hadronic phases)

2006 predictions:	Equilibrium	A. Andronic *et al.*, Nucl. Phys. A772 (2006) 167
		I. Kraus *et al.*, J.Phys.G32 (2006) S495
	Non Equilibrium	J. Rafelski *et al.*, Eur. J. Phys. C45 (2006) 61



Estimates for LHC energies:
Equilibrium vs. Non Eq. particle ratios

➡ "explosive" system

➡ eq. vs. non-eq. driven by K/π

➡ low p/π lower T_{ch}

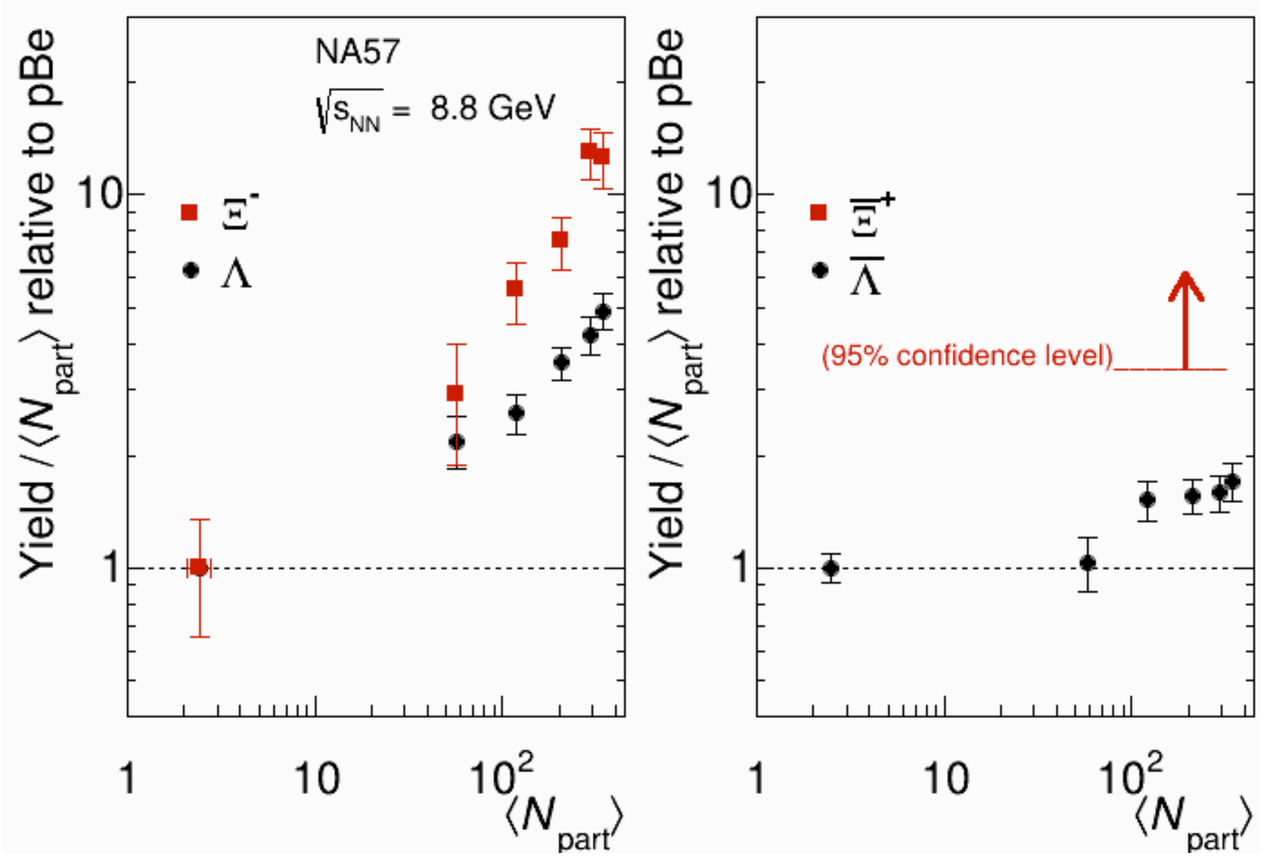
➡ $p\bar{p}$ annihilation but small p/π centrality dep.

➡ agreement LQCD: T_c ~155 MeV

➡ flavour dependence for T_c ?

STRANGENESS ENHANCEMENT

- From Pb-Pb to Au-Au to Pb-Pb: SPS (x2) to RHIC...



➡ see ALICE talks for the final (not "preliminary") enhancement at 2.76 TeV

➡ is pp a good reference ? is <N_{part}> the proper scale ?

➡ any saturation for the strange baryon production ?

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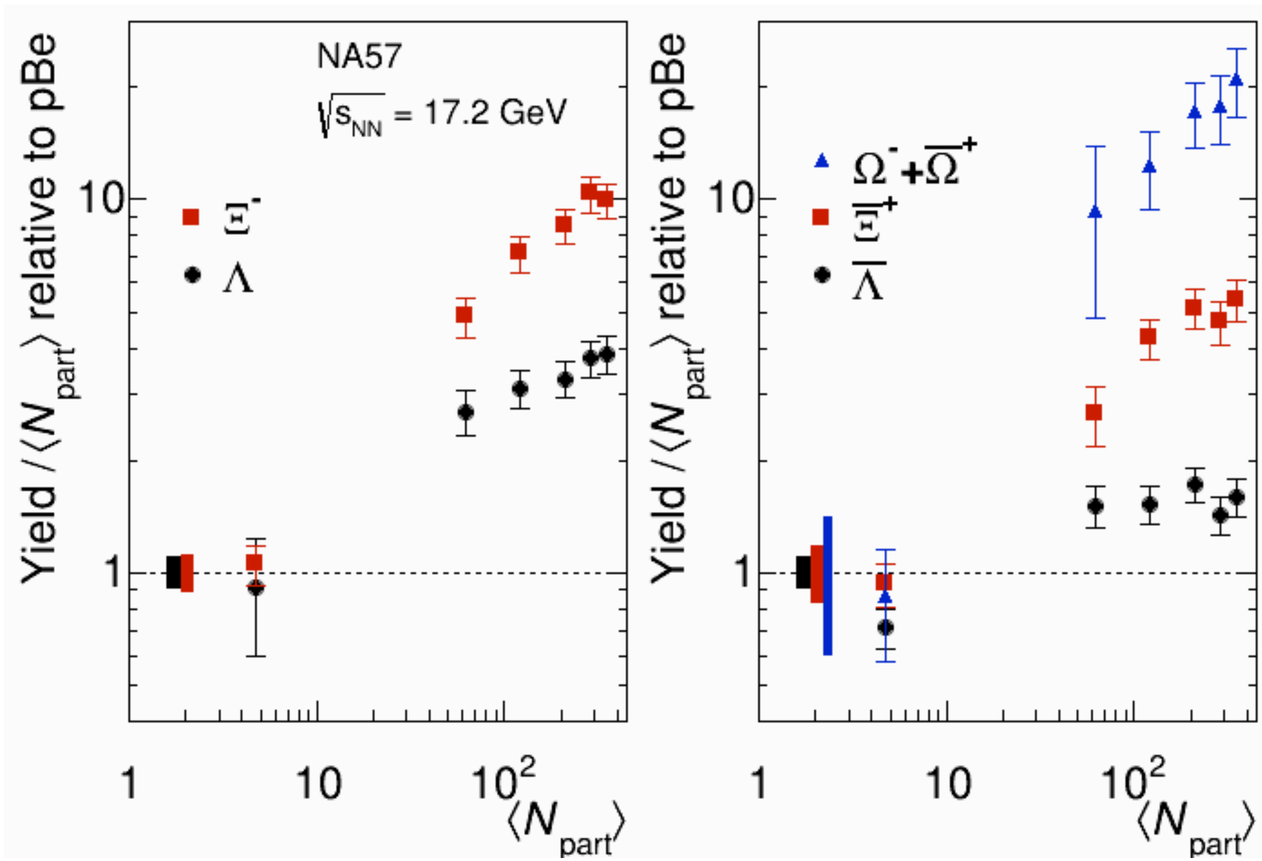

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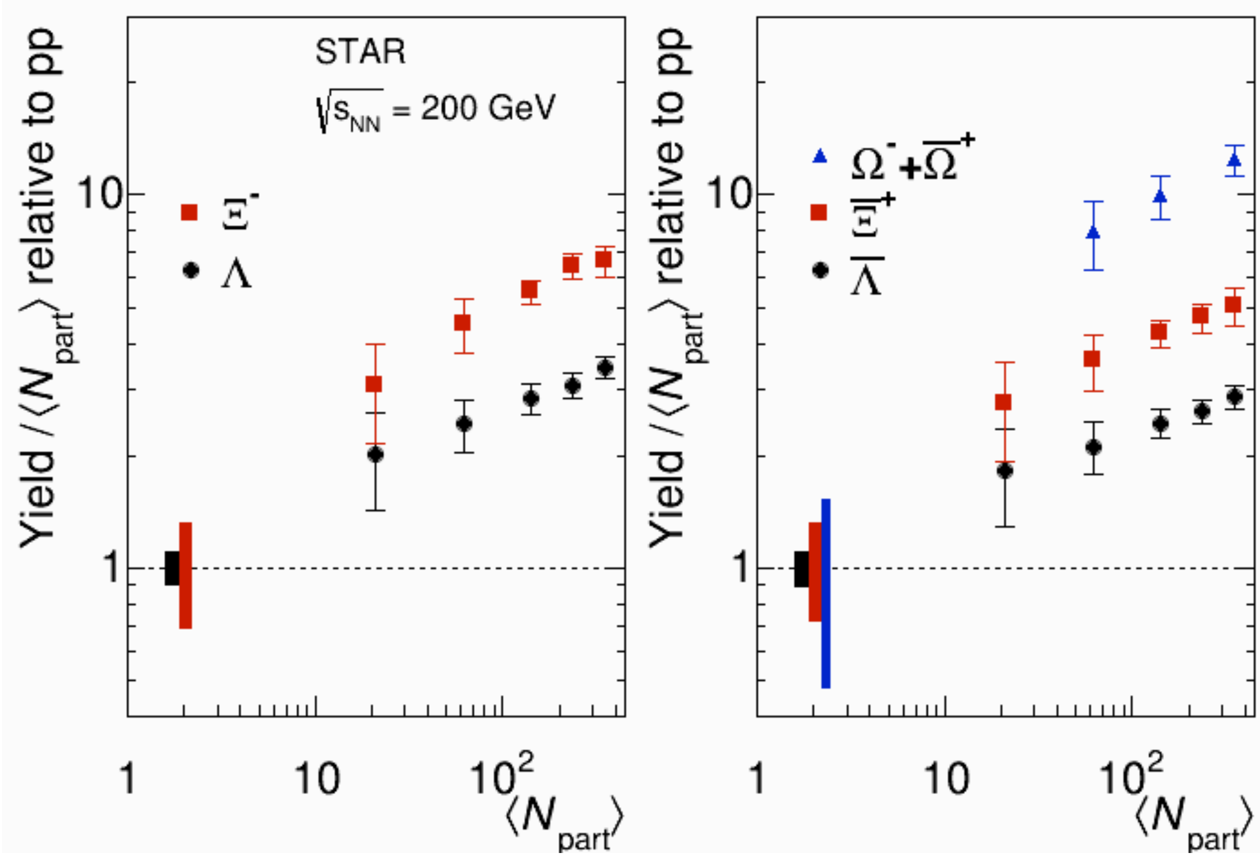

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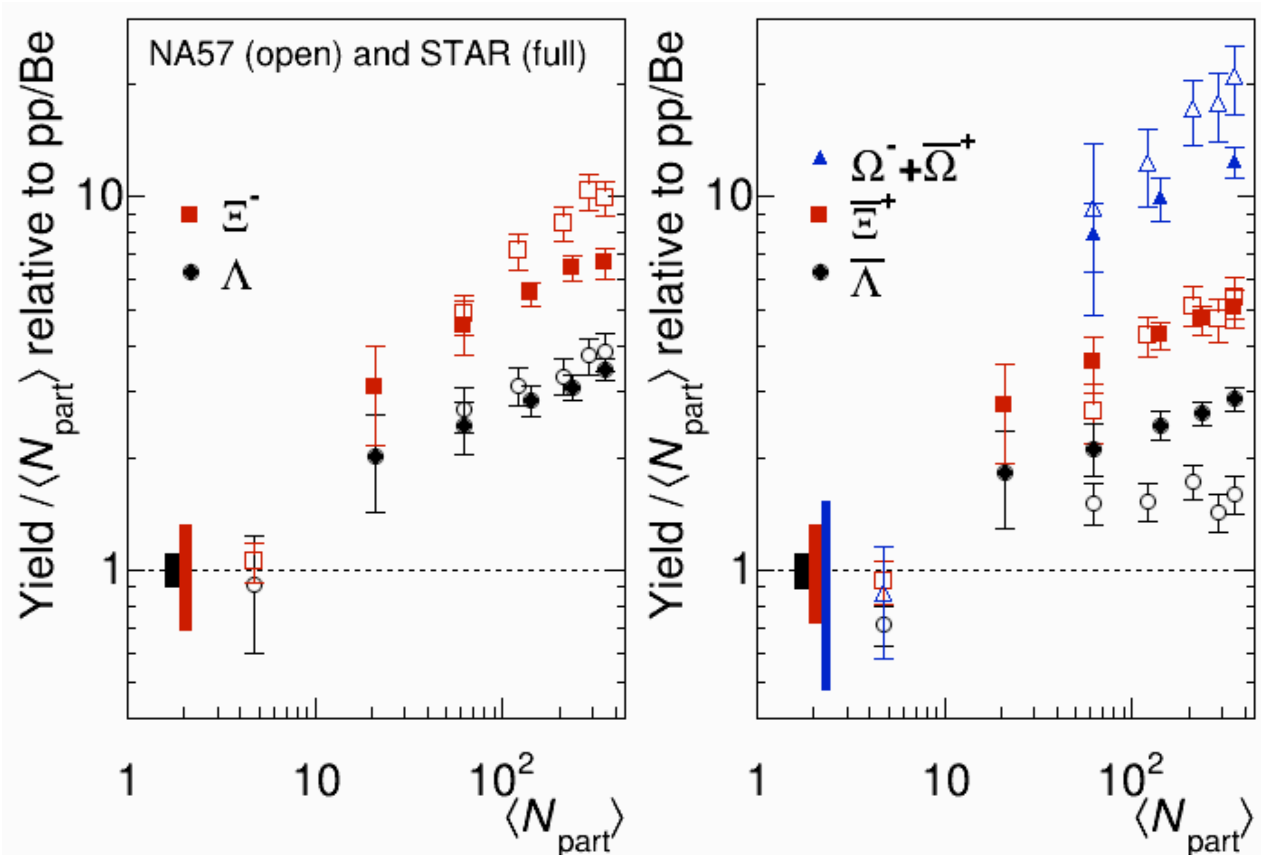

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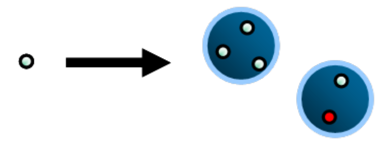
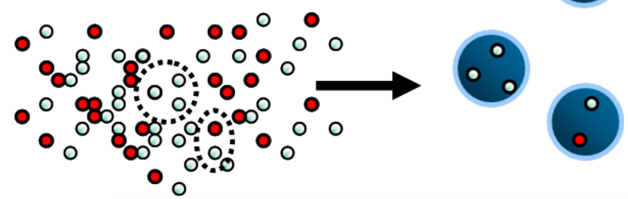
HADRONISATION: RECOMBINATION vs. FRAGMENTATION

Hadronisation of 1 parton: fragmentation



Dilute partonic system
High virtualities

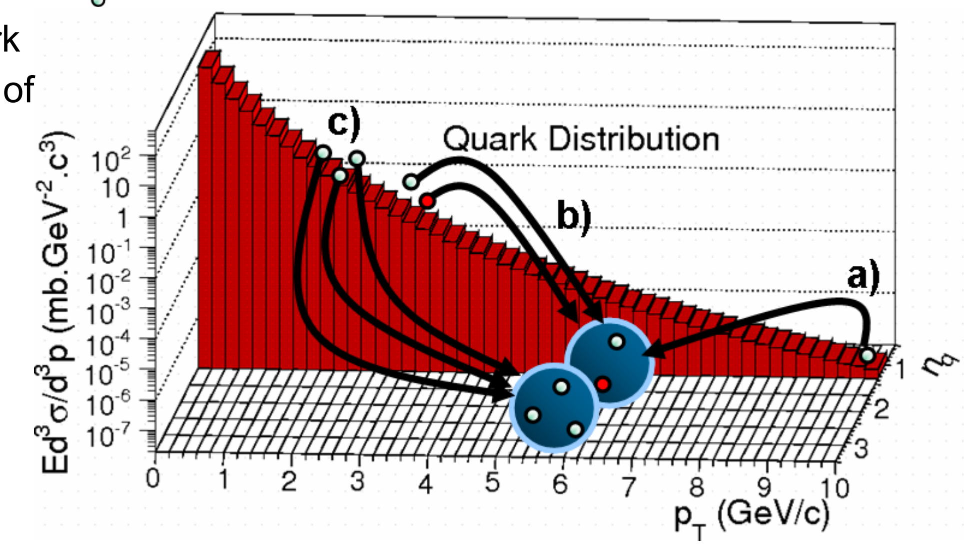
If phase space is filled with partons: hadronisation via recombination/coalescence



Dense partonic system
Low virtualities

The in vacuo fragmentation of a high p_T quark competes with the in medium recombination of lower momentum quarks

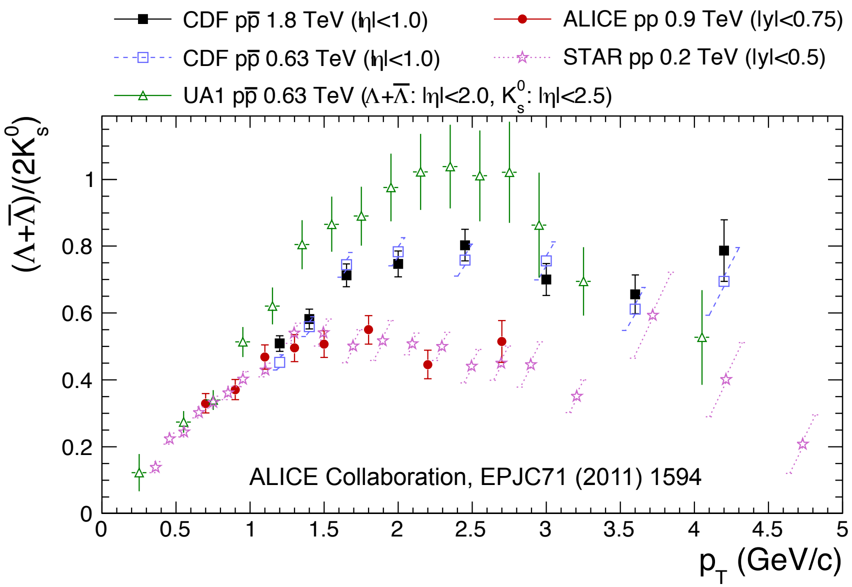
a) 6 GeV/c pion from 1x 10 GeV/c quark fragmentation
b) 6 GeV/c pion from 2x 3 GeV/c quark recombination
c) 6 GeV/c proton from 3x 2 GeV/c quark recombination

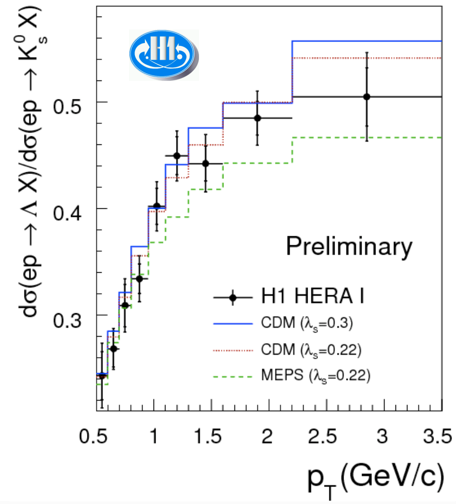


Baryon/Meson ratios
Constituent Quark Scaling (e.g. v_2)
Correlations via Soft+Hard contributions

- ➡ "...requires the assumption of a thermalized parton phase... (which) may be appropriately called a quark-gluon plasma." Fries *et al.*, PRC 68, 044902 (2003)
- ➡ fully compatible with an explosive system and "sudden hadronisation" ?
- ➡ validate recombination with light quarks before invoking it for heavy flavours...

BARYON /MESON RATIOS: SYSTEM DEPENDENCE

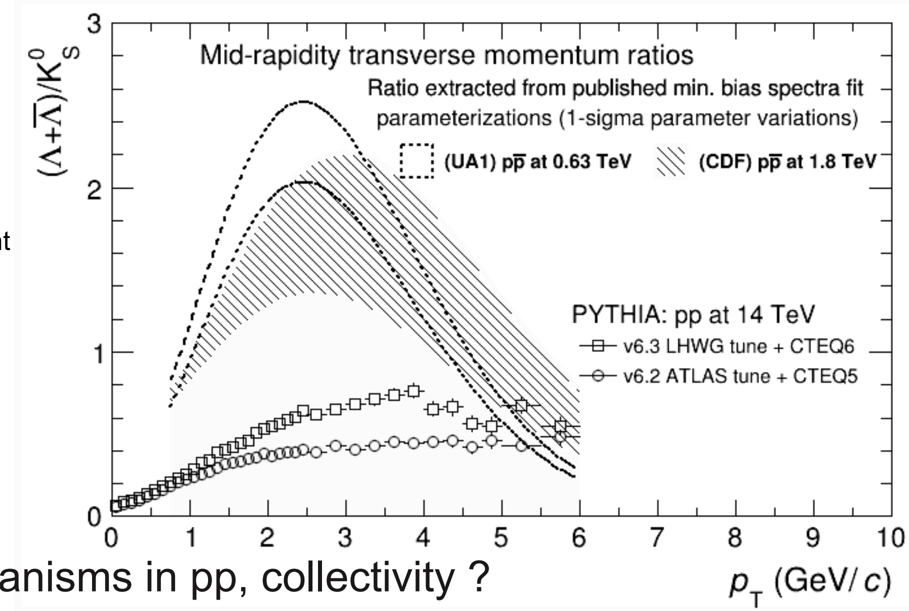




Important evolutions for the soft sector:

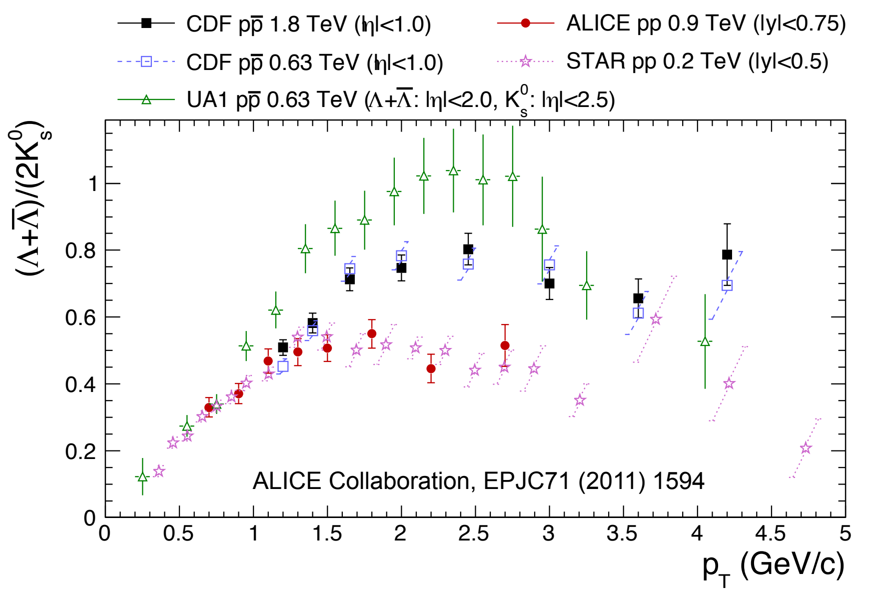
PYTHIA: **v6.2 ⇨ v6.3/4** Multiple Parton Interactions (M.P.I) treatment
(part.-part. interactions and isr/fsr)
Interleaved pT-ordered showers
color reconnection annealing

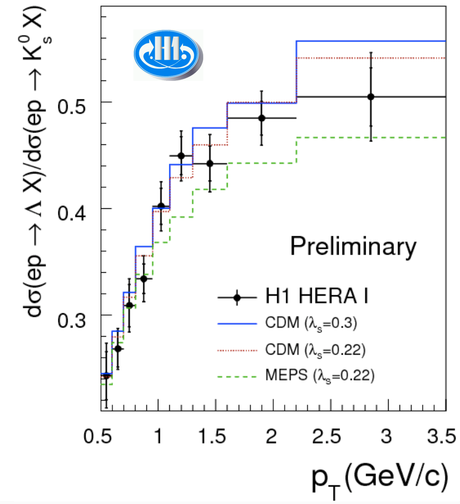
PDF: **CTEQ5 ⇨ CTEQ6** Gluon distribution function
(visible at low Q^2)

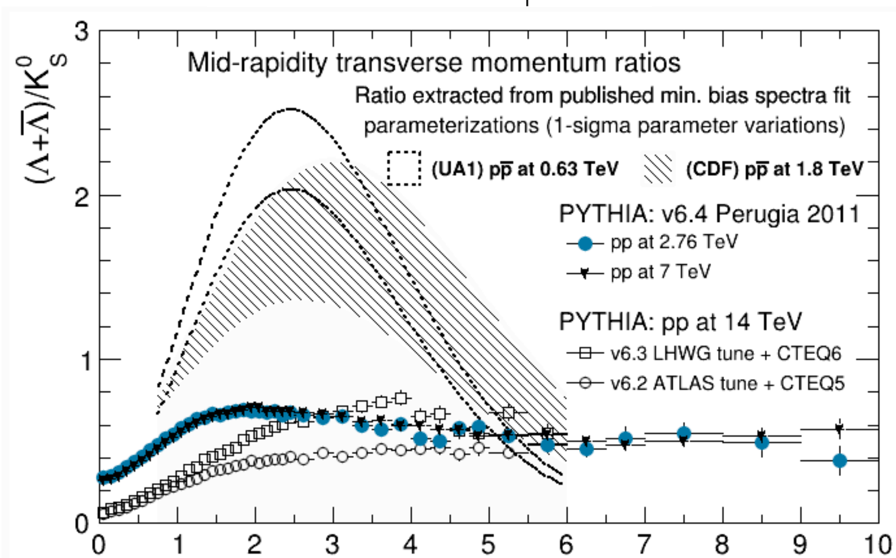


➡ baryon / strangeness creation mechanisms in pp, collectivity ?

BARYON /MESON RATIOS: SYSTEM DEPENDENCE







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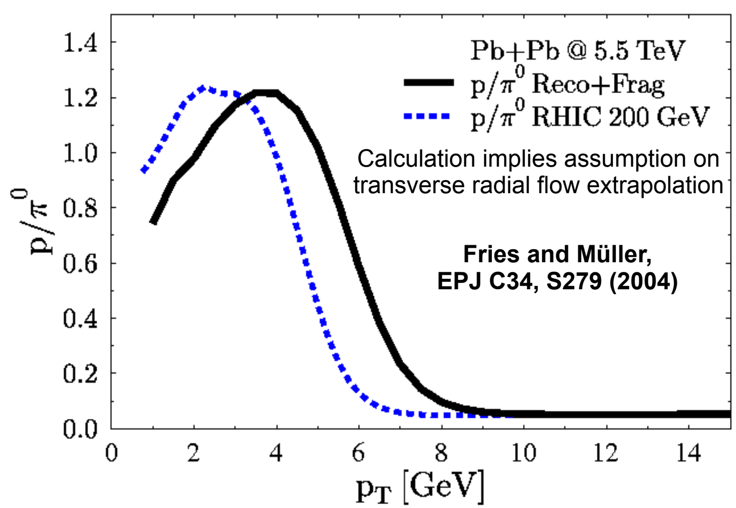
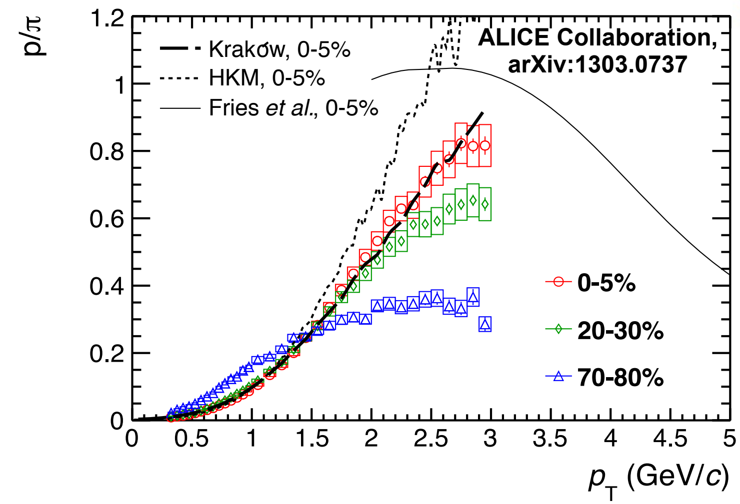
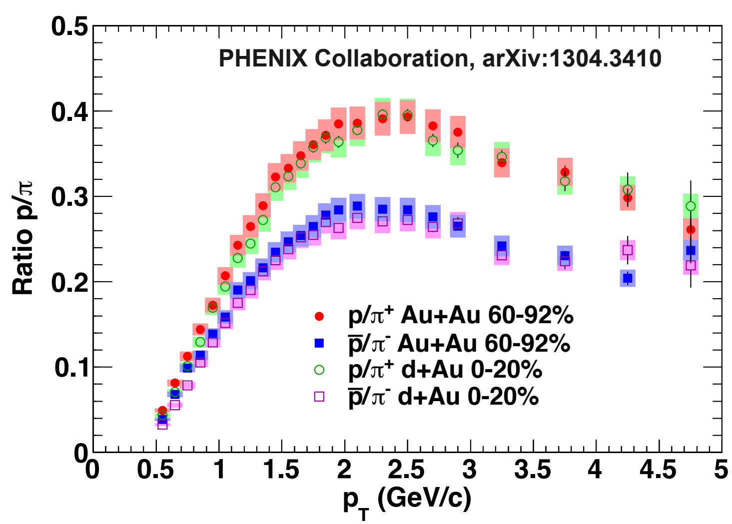
p_T (GeV/ c)

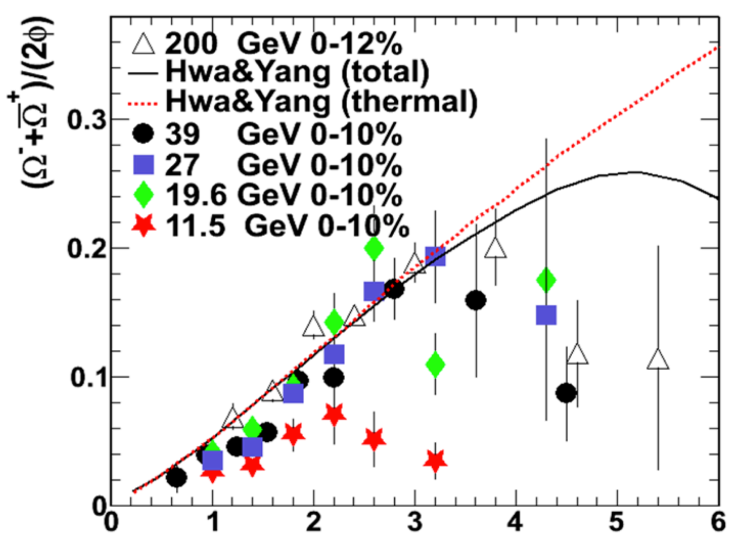
BARYON /MESON RATIOS: ENERGY DEPENDENCE





Amplitude for mixed ratio predicted to be the same at LHC than for RHIC but the turnover and limit are shifted to higher p_T



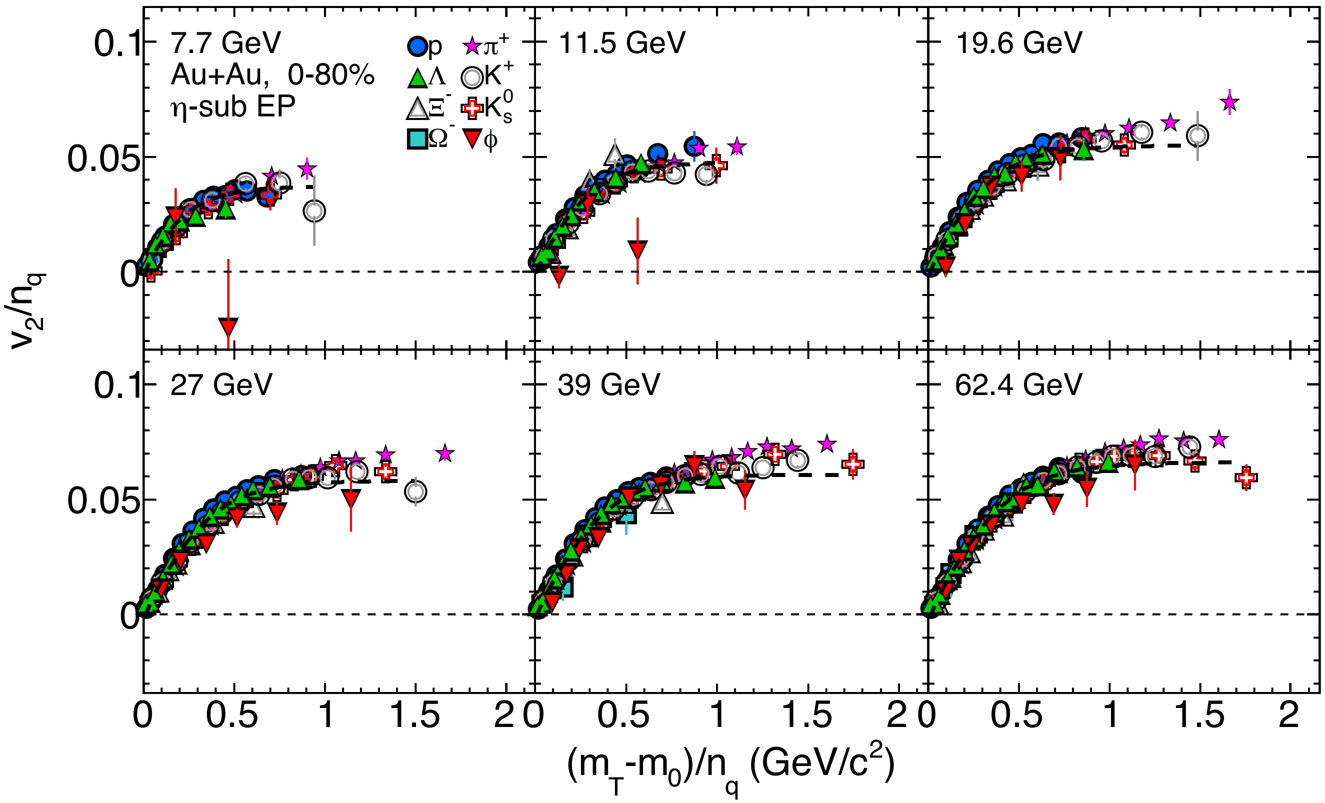


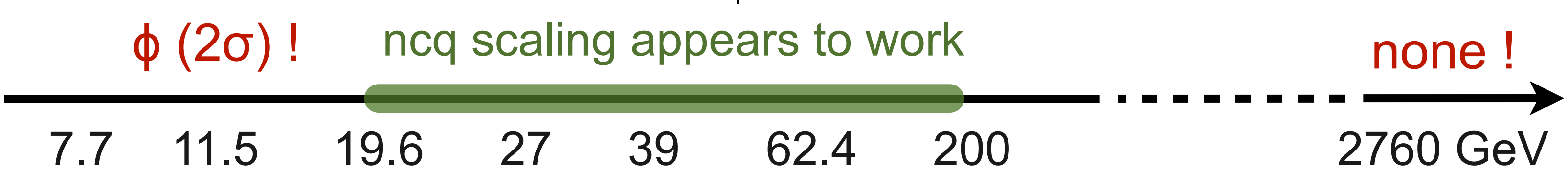
X.Zhang (STAR Collaboration), NPA 904-905 (2013) 543c

FLUID-DYNAMICS: AZIMUTHAL ANISOTROPY

- v_2+PID ! probing mass and constituent quark dependence **RHIC**

STAR Collaboration, PRC 88 (2013) 14902





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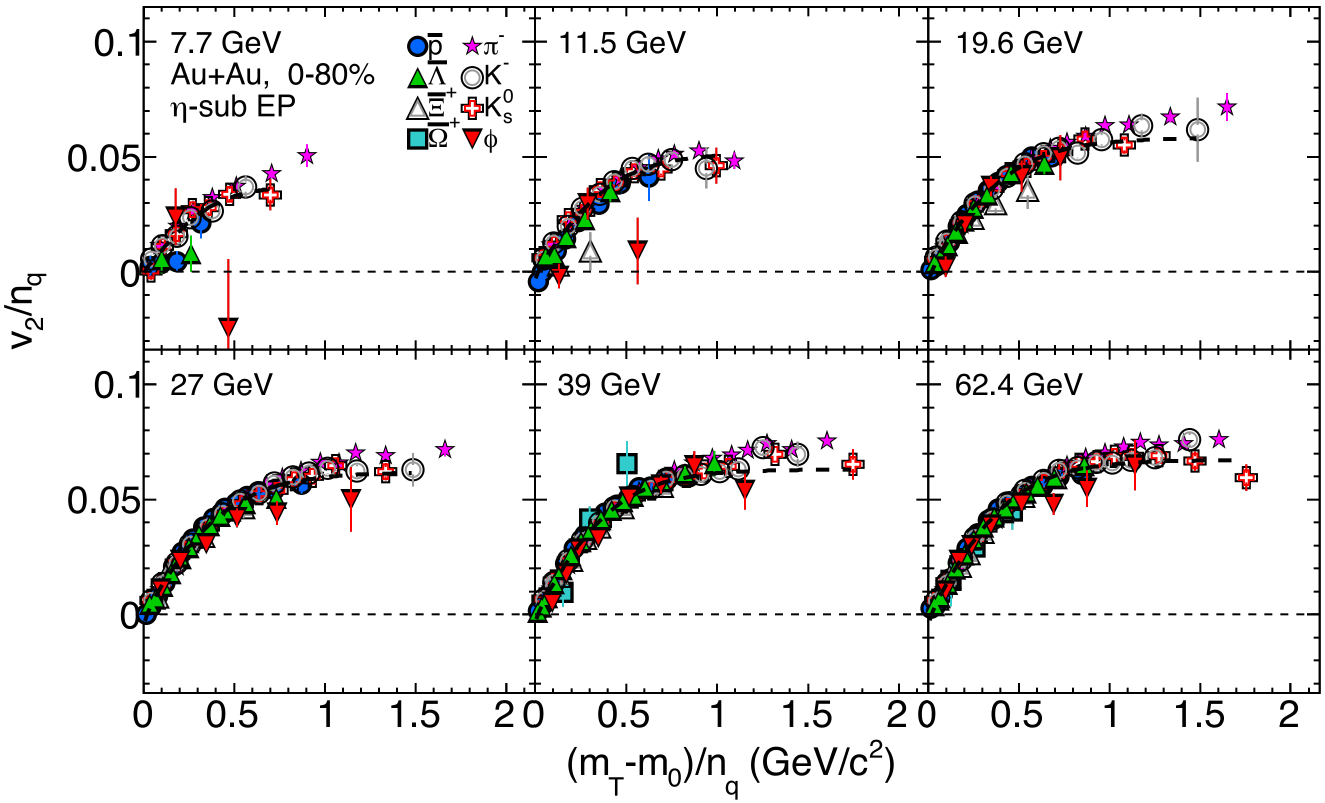
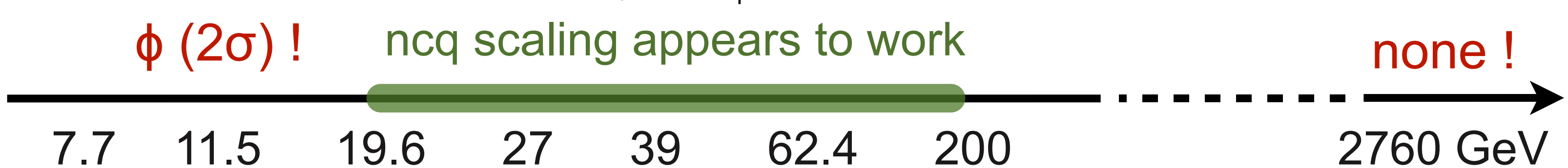
STAR Collaboration, PRC 88 (2013) 14902

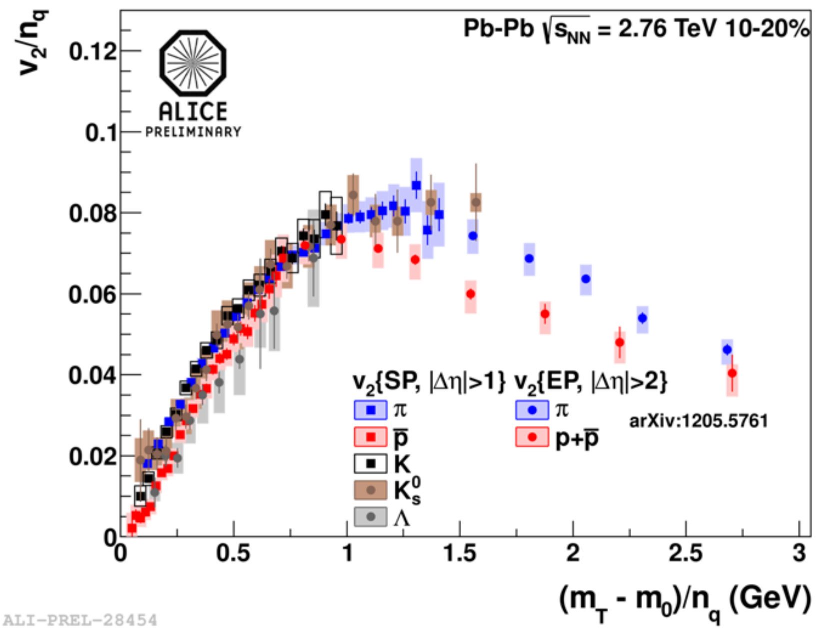


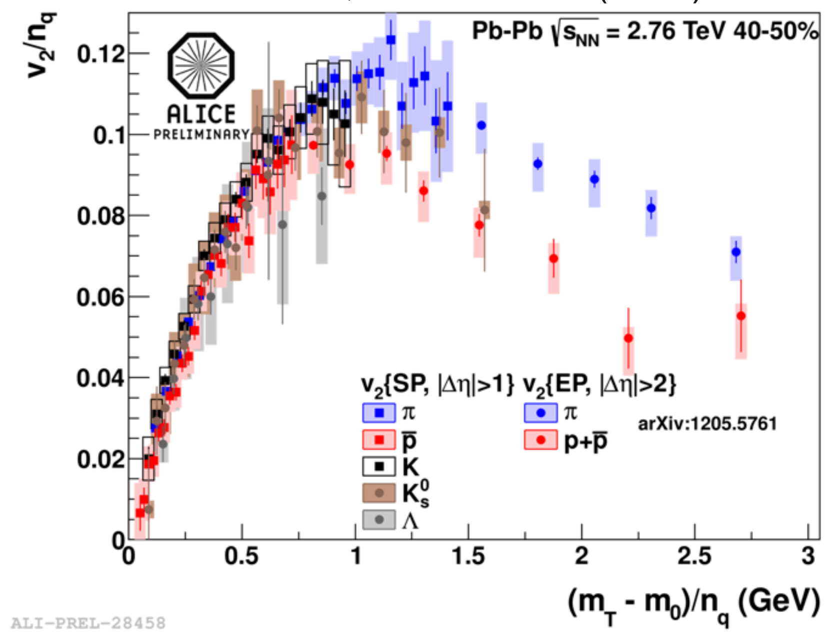


FLUID-DYNAMICS: AZIMUTHAL ANISOTROPY

- v_2+PID ! probing mass and constituent quark dependence **LHC**

F. Noferini, NPA 904-905 (2013) 483c





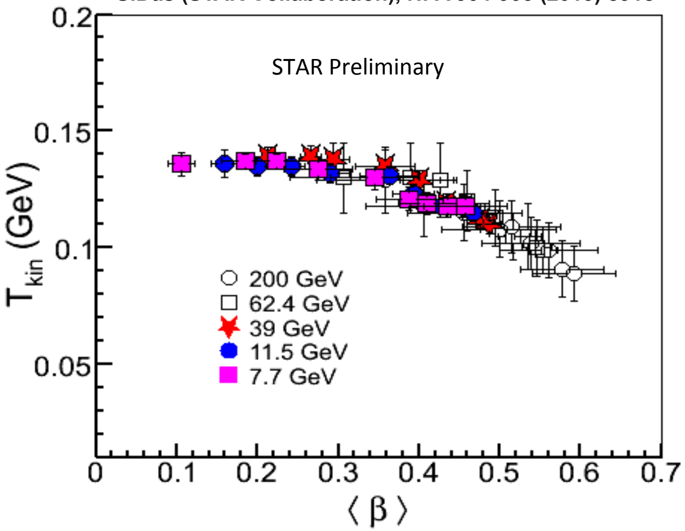
➡ splitting of baryon and mesons

➡ leaving very little (no) room for ncq scaling at the LHC...

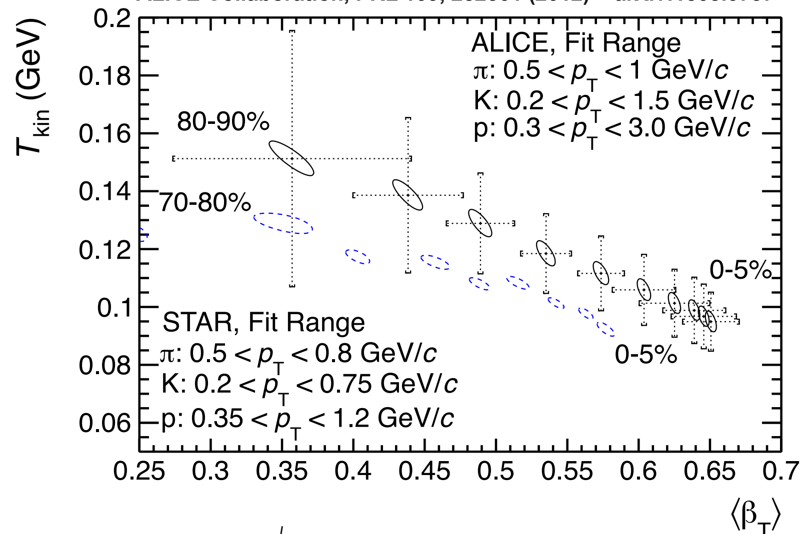
COOLING AND RESCATTERING

- Dense then dilute hadronic phase (3D+1 hydro + UrQMD results) !
- Systematics on radial flow and kinetic freeze-out temperature T_{kin}
  - ➡ blast-wave parametrisation (with known caveats...)
  - ➡ top RHIC to LHC energies (5% central): increase of $<\beta_T>$ by 10% (0.60*c* to 0.65*c*) constant T_{kin} ~ 95 MeV

S.Das (STAR Collaboration), NPA 904-905 (2013) 891c



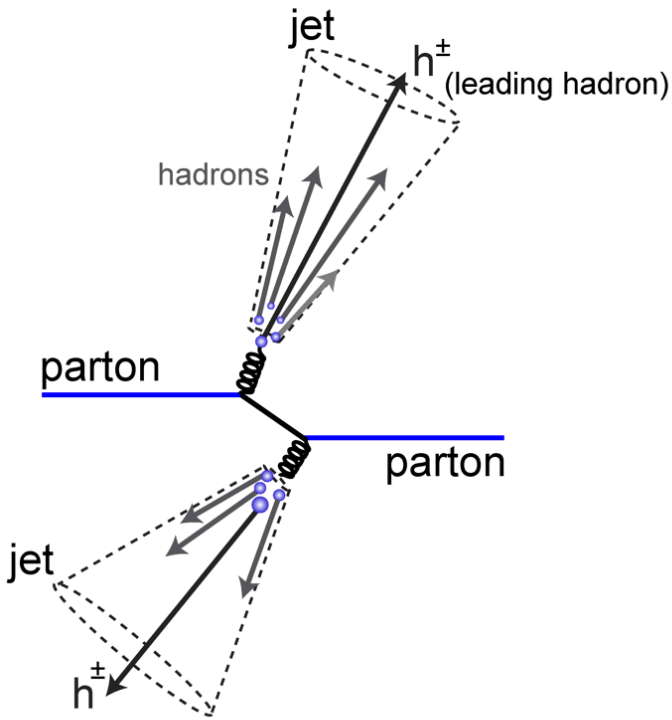
ALICE Collaboration, PRL 109, 252301 (2012) + arXiv:1303.0737



- ➡ radial flow increase from most peripheral collisions at $\sqrt{s_{NN}}$ = 7.7 GeV to most central Au-Au events at $\sqrt{s_{NN}}$ = 200 GeV and Pb-Pb events at $\sqrt{s_{NN}}$ = 2.76 TeV;
- ➡ additional information from strangeness (including resonance) studies.

TOMOGRAPHY: PROBING THE OPACITY OF THE QGP

- use energetic partons produced during the early stages of the collision
  - ➡ fragmentation in vacuum
  - ➡ propagation with energy loss in the coloured medium: flavour dependence
  - ➡ colourless probes for benchmarking



experimentally:

1) $$R_{AA}(p_T) = \frac{1}{\langle N_{coll}\rangle}\frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{1}{\langle T_{AA}\rangle}\frac{dN_{AA}/dp_T}{d\sigma^{inel}_{pp}/dp_T}$$

2) Hadron angular correlations: $$\frac{1}{N_{trig}}\frac{d^2N_{assoc}}{d\Delta\eta\, d\Delta\varphi} = \frac{S(\Delta\eta\Delta\varphi)}{B(\Delta\eta\Delta\varphi)}$$

(S) same event and (B) different events

3) Gamma-jet angular correlations

differentially:

- ➡ several reference systems (pp , pA, dA)
- ➡ light (strangeness) and heavy flavour dependence
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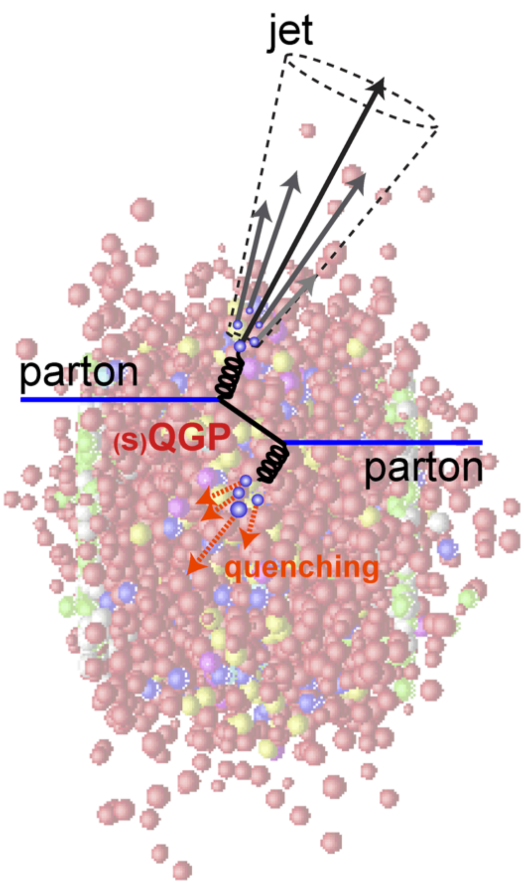

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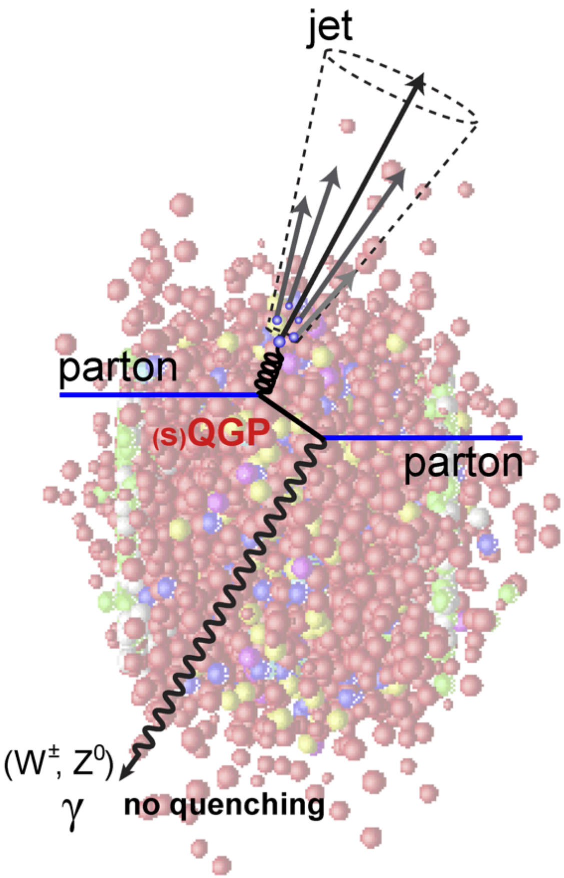

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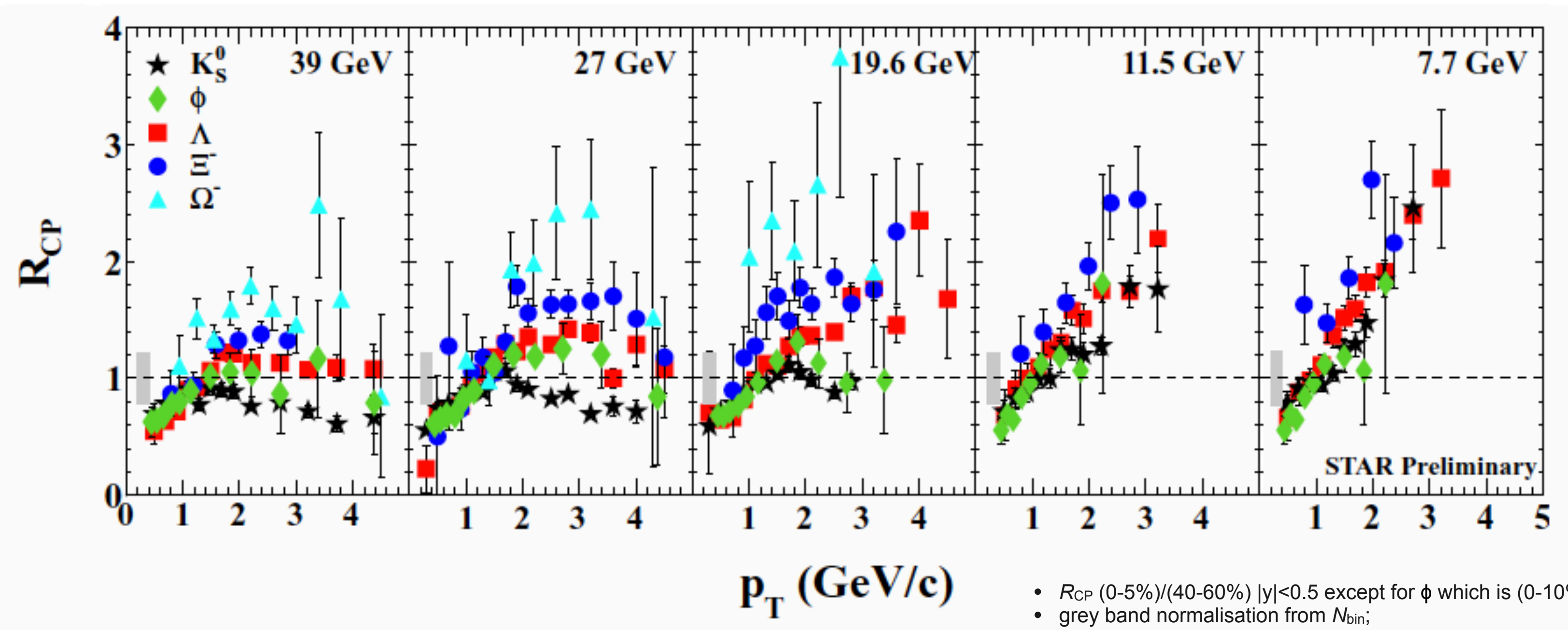
IDENTIFIED R_{CP} AT RHIC (BEAM ENERGY SCAN)

X.Zhang (STAR Collaboration), NPA 904-905 (2013) 543c



- R_{CP} (0-5%)/(40-60%) |y|<0.5 except for ϕ which is (0-10%)/(40-60%);
- grey band normalisation from N_{bin};
- statistical uncertainties only.

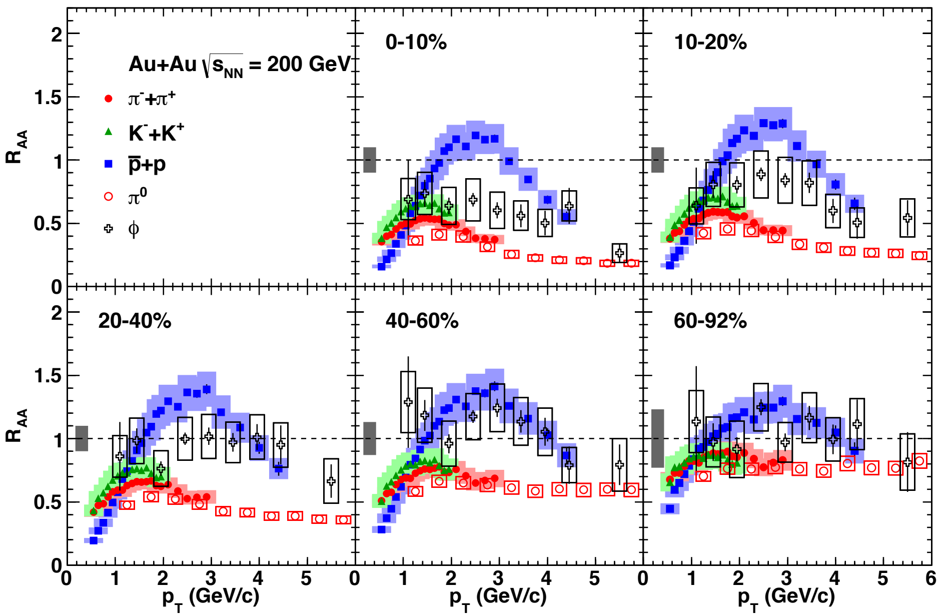
➡ not unity nor clear species splitting below 19.6 GeV

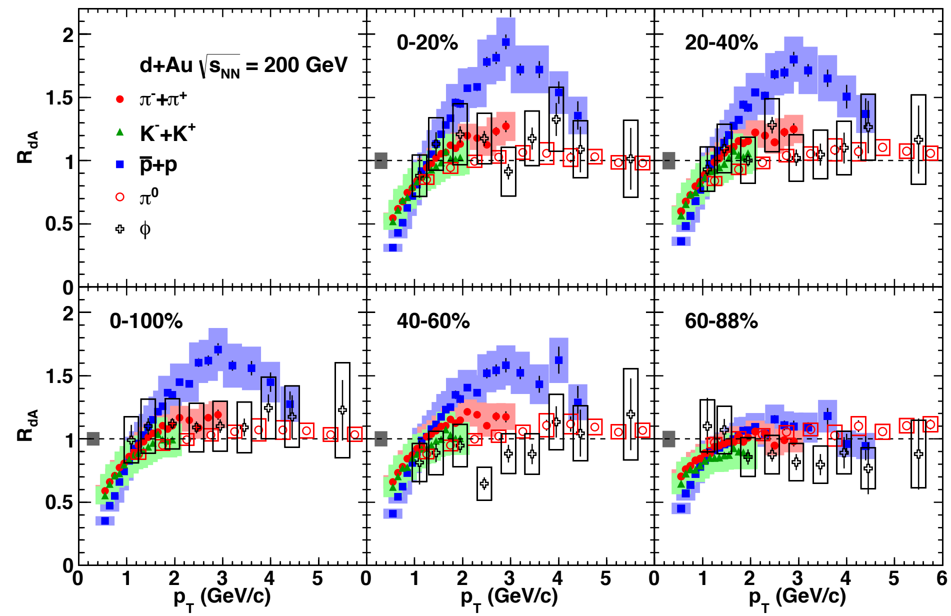
➡ suppression for K^0_s above 27 GeV

➡ enhancement for baryons

IDENTIFIED R_{AA} AND R_{dA} AT RHIC (200 GeV)

PHENIX Collaboration, arXiv:1304.3410





- ➡ separation between ϕ and proton
- ➡ no high p_T suppression but clear baryon enhancement for dA
- ➡ consistent with no suppression in dA for the ϕ

SUMMARY: STRANGENESS (WORK-)SHOPPING LIST

- comparison of (pid) p_T spectra with 3D+1 hydro + UrQMD
- more results on reference colliding systems (pp, pA, dA)
- more constrains for coalescence/recombination mechanism
- constructive discussion on equilibrium vs non equilibrium for strangeness
- for (multi-)strange and resonances:
  - ➡ kinetic freeze-out parameters
  - ➡ azimuthal anisotropy coefficients (up to high p_T)
- tomography (R_{AA}, 2-part angular and gamma-jet/s-hadron correlations):
  - ➡ flavour / system (AA, pp, pA, dA) / energy (RHIC BES to LHC) / centrality dependence

Many thanks for your attention !

Thanks a lot to the organisers for the invitation...