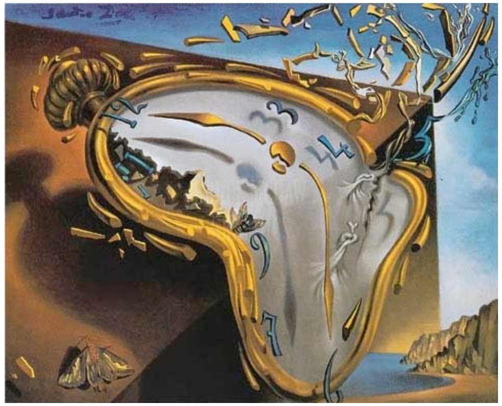


"Reloj blando en el momento de su primera explosión" (1954)
Salvador Dalí

SOFT PHYSICS AT THE LHC

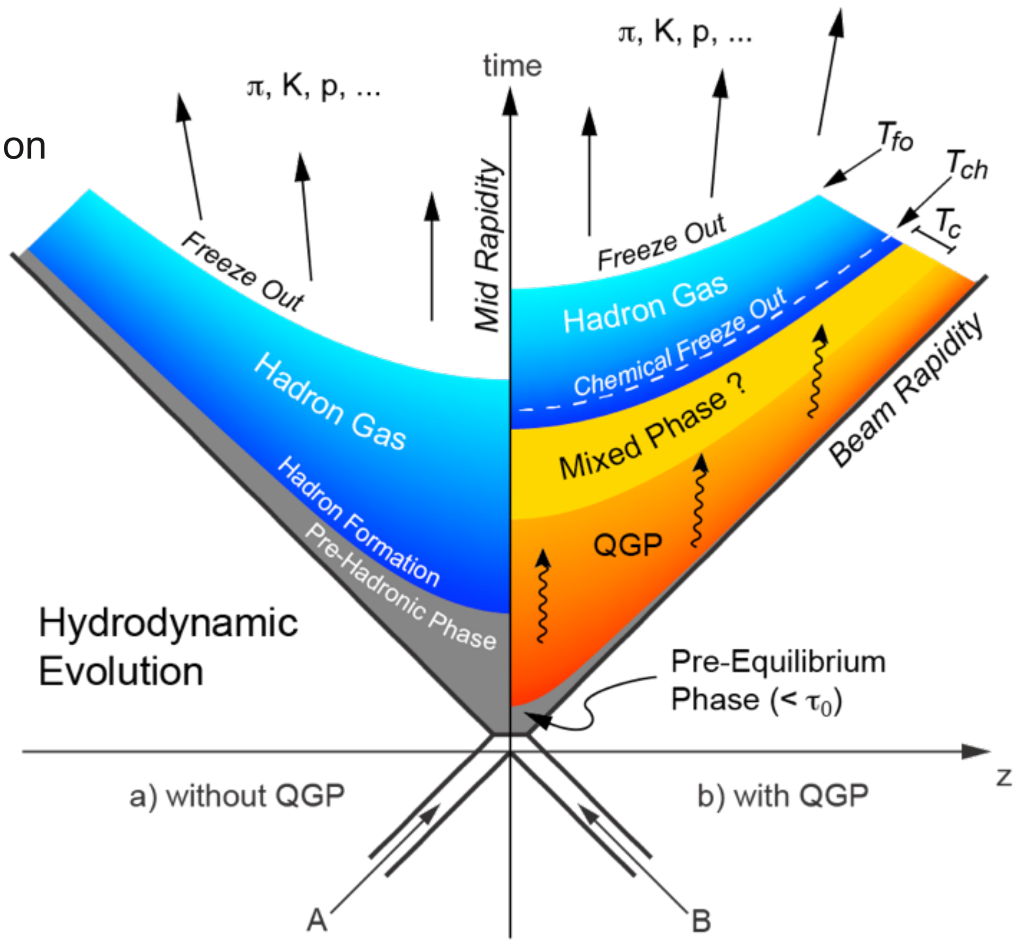
Boris HIPPOLYTE (IPHC, Université de Strasbourg)

OUTLINE

- Evolution of the system in heavy-ion collisions
  - ➡ paradigm of binary scaling in pp vs. collective effects in AA
- Soft physics (global) observables:
  - ➡ size of the system(s)
  - ➡ flavour content and hadro-chemistry
  - ➡ intermediate p_T and “in-medium” hadronisation
  - ➡ radial flow
  - ➡ hadronic phase
- Summary

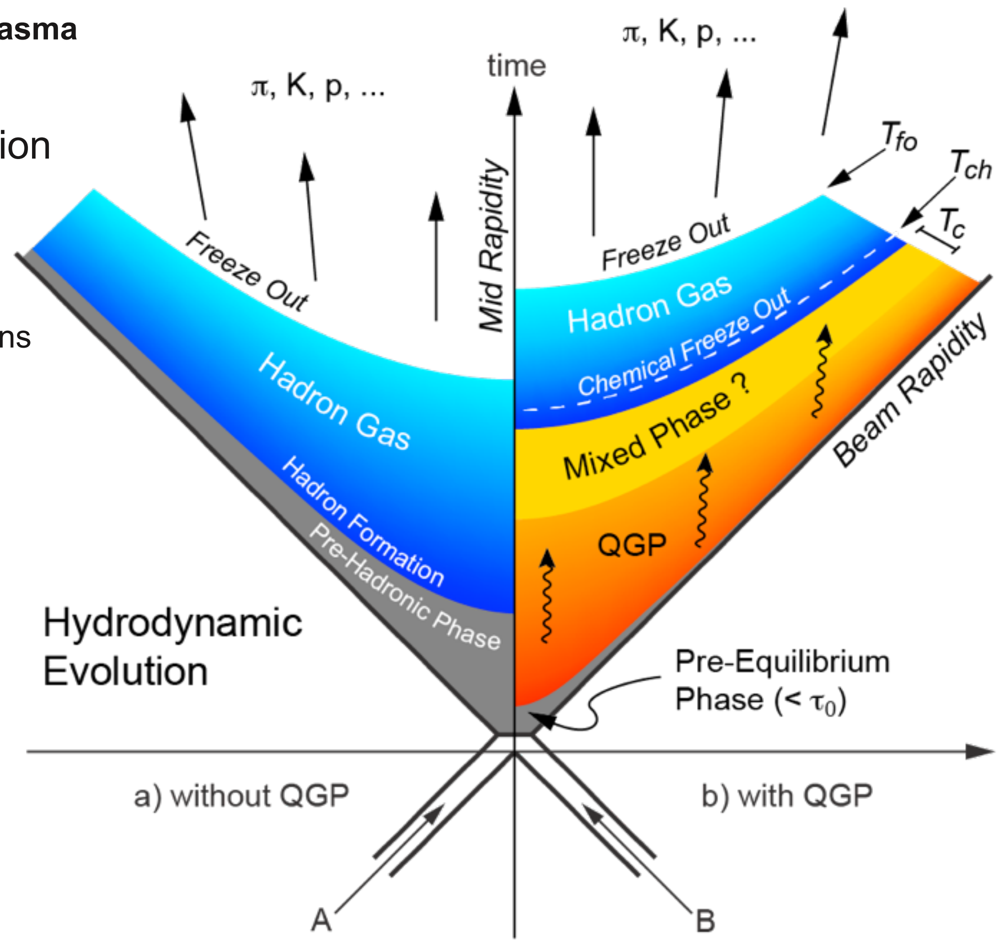
EVOLUTION OF THE SYSTEM FOR HEAVY-ION COLLISIONS

- Initial pre-equilibrium state
- Hard parton scattering(s) & jet production
- QGP formation
- QGP expansion and cooling
- Phase transition
- Hadronic Phase



EVOLUTION OF THE SYSTEM FOR HEAVY-ION COLLISIONS

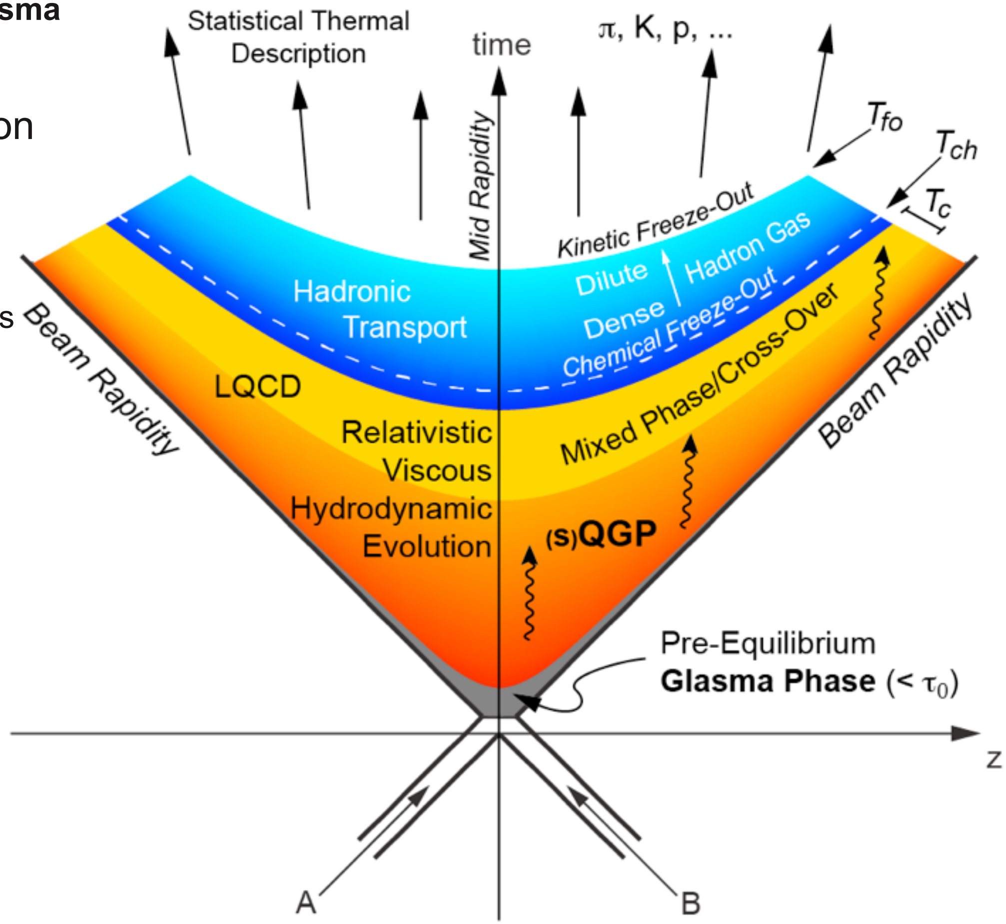
- Initial pre-equilibrium state
  - ➡ gluonic fields (Color Glass Condensate) **Glasma**
- Hard parton scattering(s) & jet production
- QGP formation
  - ➡ thermalisation of **strongly** interacting partons
- QGP expansion and cooling
  - ➡ **3D+1** relativistic **viscous** hydrodynamics
- Phase transition
  - ➡ Lattice QCD, **Cross-Over**
- Hadronic Phase
  - ➡ Chemical freeze-out
  - ➡ Rescattering then kinetic freeze-out.



EVOLUTION OF THE SYSTEM FOR HEAVY-ION COLLISIONS

- Initial pre-equilibrium state
  - ➡ gluonic fields (Color Glass Condensate) **Glasma**
- Hard parton scattering(s) & 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
  - ➡ Rescattering then kinetic freeze-out.

for LHC energies



FINAL STATE AND GLOBAL PROPERTIES OF THE MEDIUM

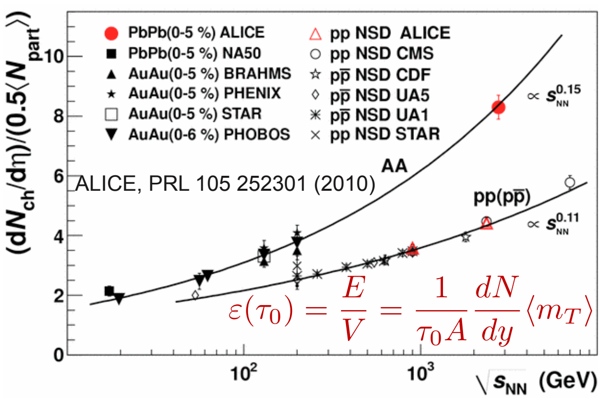
- the A-A system at the LHC is **denser**, **larger** and **longer** lived than at RHIC

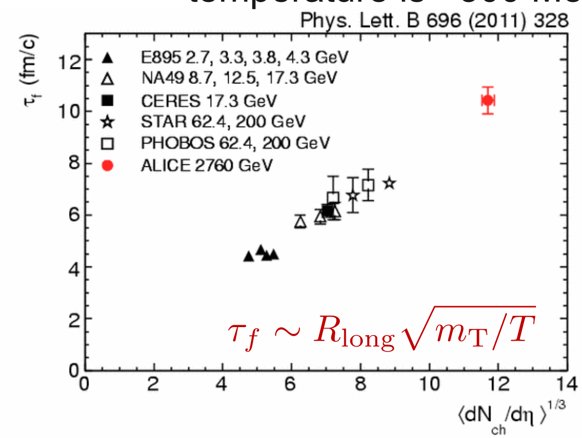
➡ energy density is ~10 GeV/fm^3 (3x RHIC)

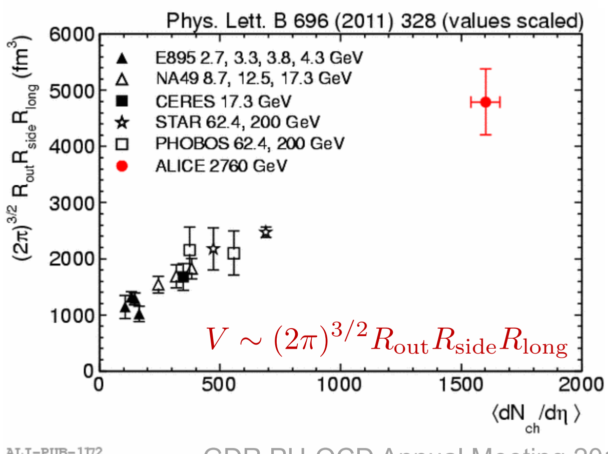
➡ volume is ~4800 fm^3 (2x RHIC)

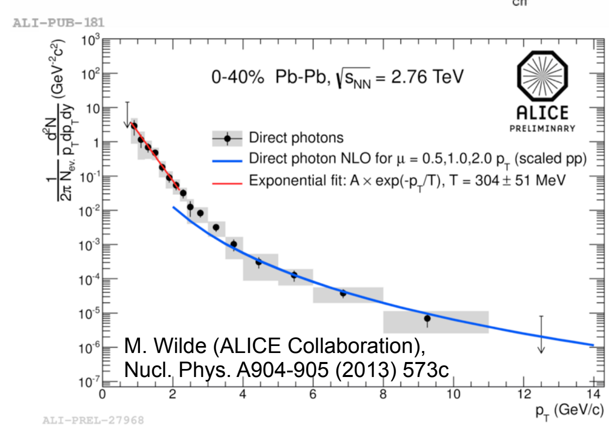
➡ lifetime is ~10 fm/*c* (+20% RHIC)

➡ temperature is ~300 MeV (+30% RHIC)









GdR PH-QCD

FINAL STATE AND GLOBAL PROPERTIES OF THE MEDIUM

- comparison of pp and p-A collisions with multiplicity similar to peripheral A-A

“Freeze-out radii extracted from three-pion cumulants in pp, p–Pb and Pb–Pb collisions at the LHC”
ALICE Collaboration, Phys. Lett. B739 (2014) 139

Multiplicity intervals: $\langle N_{\rm pions}\rangle$ and $\langle N_{\rm ch}\rangle$

	Pb–Pb data			p–Pb data			pp data		
$N^{\rm rec}_{\rm pions}$	⟨Cent⟩	$\langle N_{\rm pions}\rangle$	$\langle N_{\rm ch}\rangle$	Fraction	$\langle N_{\rm pions}\rangle$	$\langle N_{\rm ch}\rangle$	Fraction	$\langle N_{\rm pions}\rangle$	$\langle N_{\rm ch}\rangle$
[3,5)	-	-	-	0.10	-	-	0.23	4.0	4.6
[5,10)	-	-	-	0.20	8.5	9.8	0.31	7.7	8.6
[10,15)	-	-	-	0.18	15	17	0.12	13	15
[15,20)	-	-	-	0.14	20	23	0.05	18	20
[20,30)	77%	26	36	0.17	29	33	0.03	24	27
[30,40)	73%	37	50	0.07	40	45	0.003	34	37
[40,50)	70%	49	64	0.03	51	57	1×10^{-4}	44	47
[50,70)	66%	66	84	0.01	63	71	-	-	-
[70,100)	60%	95	118	-	-	-	-	-	-
[100,150)	53%	142	172	-				-	-
[150,200)	48%	213	253	-					-
[200,260)	43%	276	326	-					-
[260,320)	38%	343	403	-					-
[320,400)	33%	426	498	-					-
[400,500)	28%	534	622	-					-
[500,600)	22%	654	760	-				-	-
[600,700)	18%	777	901	-	-	-	-	-	-
[700,850)	13%	931	1076	-	-	-	-	-	-
[850,1050)	7.4%	1225	1413	-	-	-	-	-	-
[1050,2000)	2.6%	1590	1830	-	-	-	-	-	-

3 systems overlap

$$p < 1.0\ {\rm GeV}/c$$
$$p_{\rm T} > 0.16\ {\rm GeV}/c$$
$$|\eta| < 0.8$$

FINAL STATE AND GLOBAL PROPERTIES OF THE MEDIUM

- comparison of pp and p-A collisions with multiplicity similar to peripheral A-A

“Freeze-out radii extracted from three-pion cumulants in pp, p–Pb and Pb–Pb collisions at the LHC”
ALICE Collaboration, Phys. Lett. B739 (2014) 139

$R_{\rm inv}$ from 3-pion cumulant (QS) correlation function
Gaussian expansion (but also exponential and Edgeworth)

Usual Gaussian 2-part QS correlation

$$C_2^{\rm QS}(q) = 1 + \lambda\, E_{\rm w}^2(R_{\rm inv}\, q)\, e^{-R_{\rm inv}^2 q^2}$$

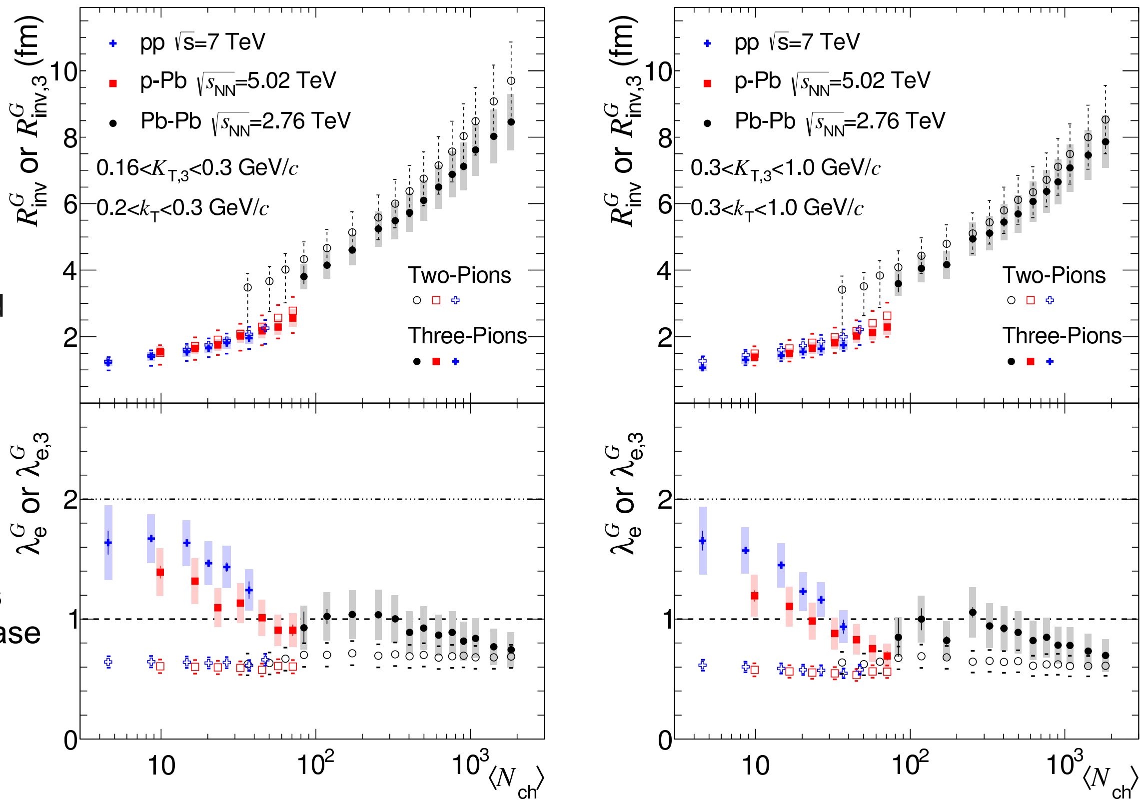
Deviations from Gaussian (E_w = 1)
noticeable non gaussian features

Extension to 3 identified pions
lower non femtoscopic background

From Edgeworth fits:
$R_{\rm inv}$ of p-Pb (5-15%) > $R_{\rm inv}$ of pp
$R_{\rm inv}$ of Pb-Pb (35-55%) > $R_{\rm inv}$ of p-Pb

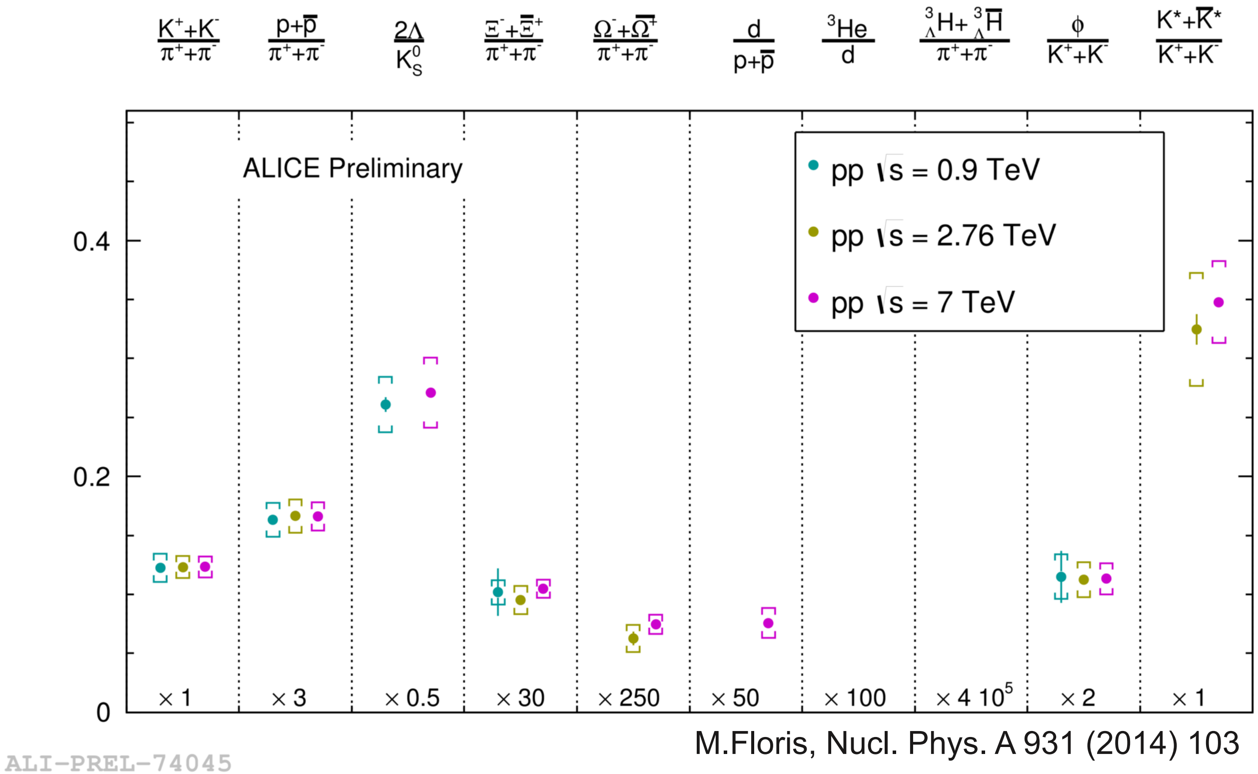
Compatibility with CGC initial conditions (IP-Glasma) with no hydrodynamics phase

More differential analyses needed…



FLAVOUR CONTENT AND HADRO-CHEMISTRY

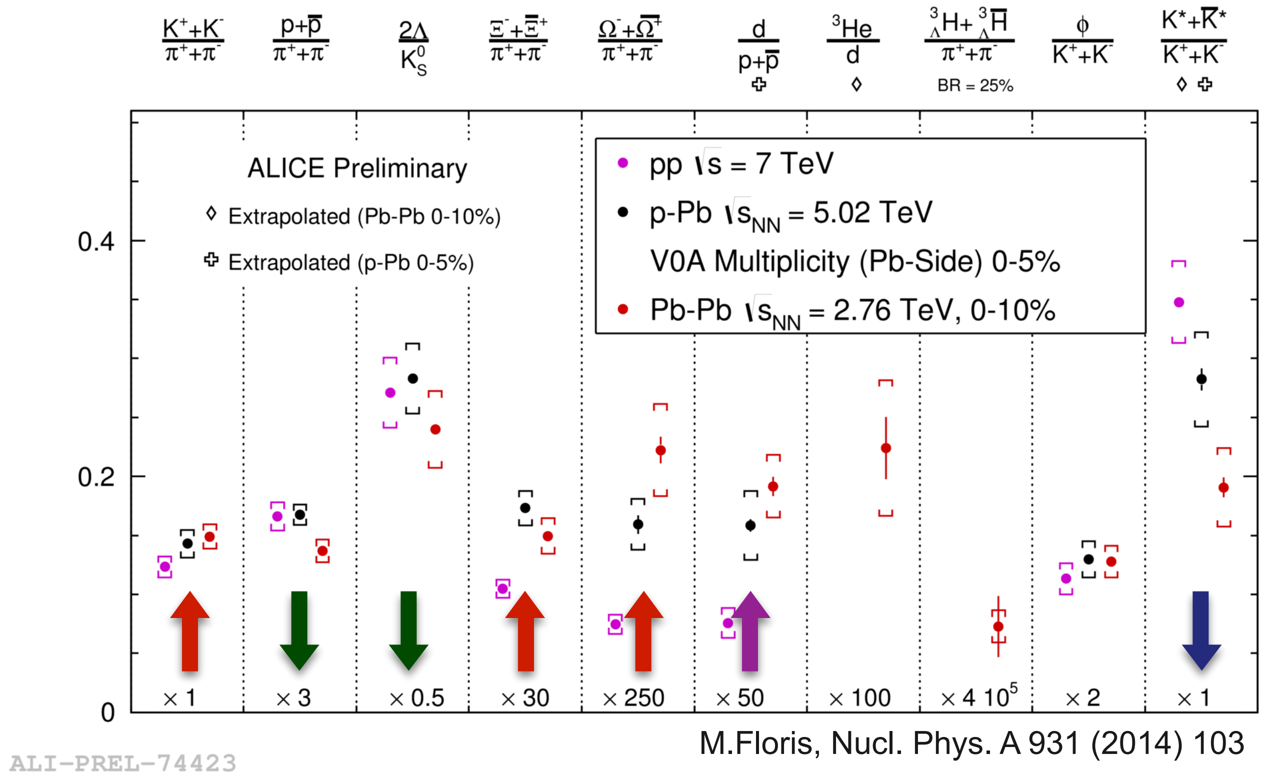
- light flavours (u, d and s)
- energy dependence of hadron ratios for pp (baseline)



- p_T integrated ratios measured in pp collisions
- show no significant energy dependence at the LHC

FLAVOUR CONTENT AND HADRO-CHEMISTRY

- light flavours (u, d and s)
- system dependence of hadron ratios for pp, p-Pb et Pb-Pb



strangeness enhancement

deuteron enhancement

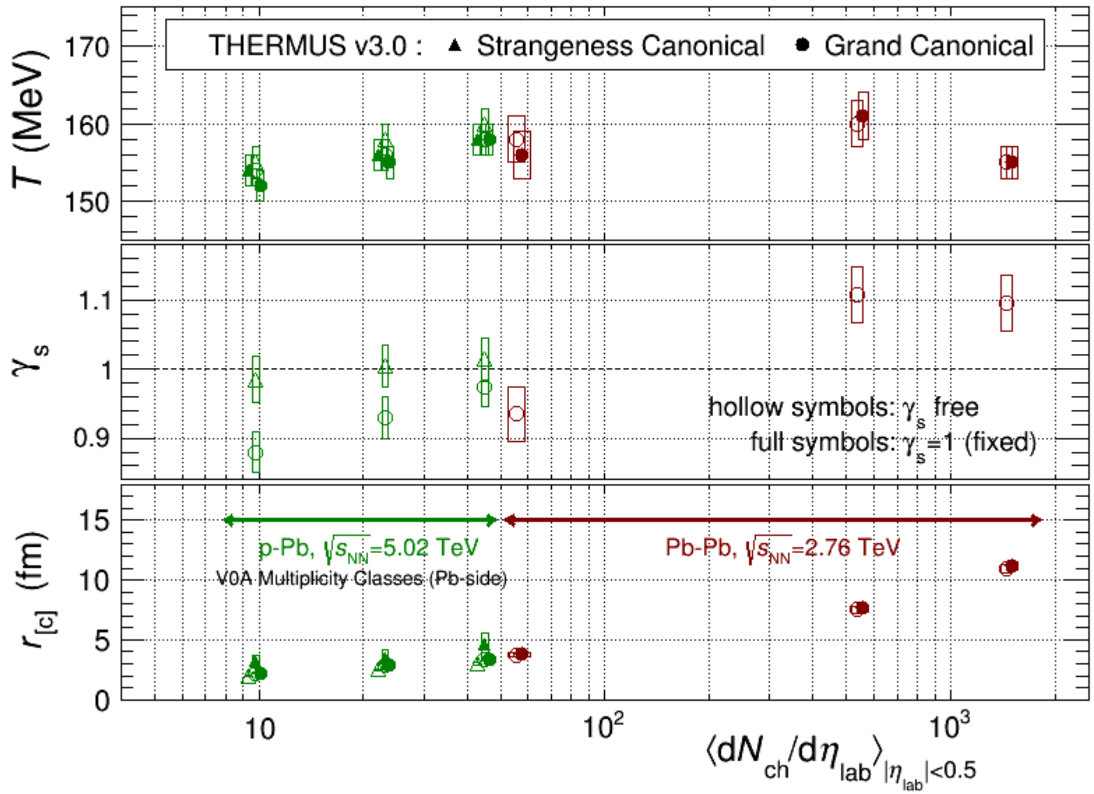
no ϕ but K* suppression

small baryon suppression ?

- evolution as expected from statistical thermal model (GC)
- suppression from re-interaction in the hadronic phase ?

FLAVOUR CONTENT AND HADRO-CHEMISTRY

- light flavours (u, d and s)
- extraction of global parameters using statistical thermal model



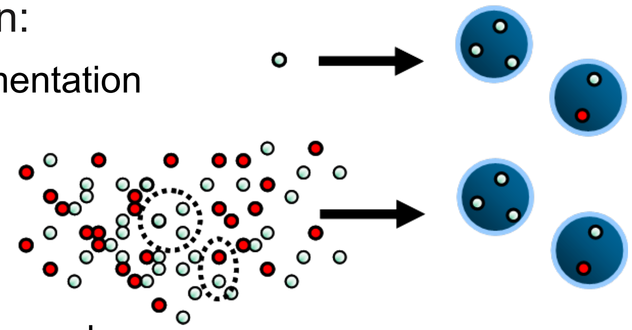
- using THERMUS v3.0 (latest version with charm, beauty and hyper-nuclei)
- *"THERMUS -- A Thermal Model Package for ROOT",* S. Wheaton, J. Cleymans and M. Hauer, Comput. Phys. Commun. 180 (2009) 84-106

INTERMEDIATE P_T AND "IN-MEDIUM" HADRONISATION

- Fragmentation vs. Recombination:

Hadronisation of 1 parton: fragmentation

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

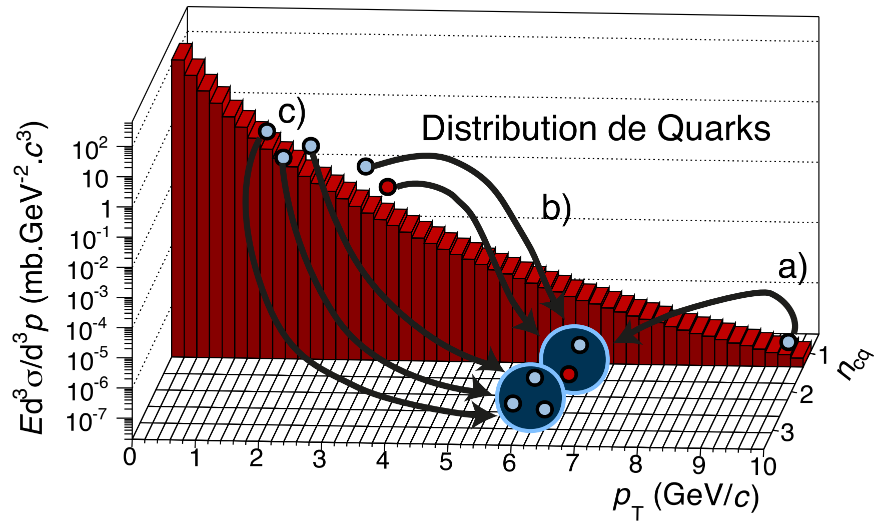


Dilute partonic system
High virtualities

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)

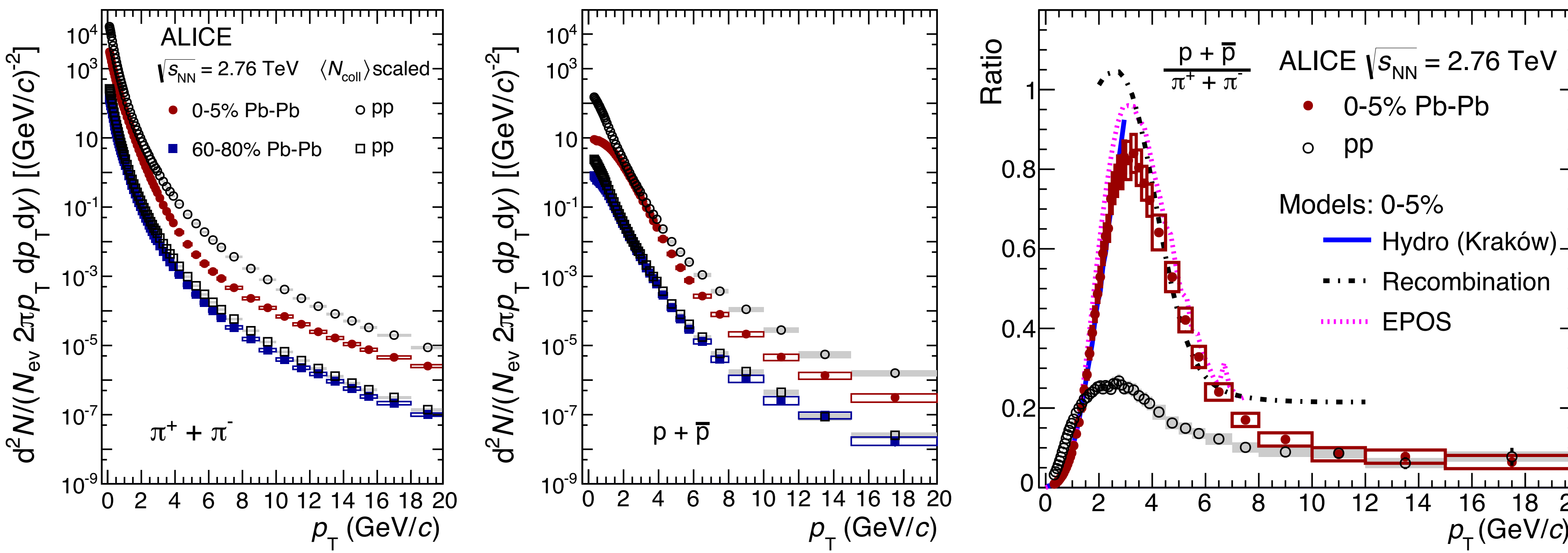
➡ fully compatible with an explosive system and "sudden hadronisation" ?

➡ validate recombination with light quarks before invoking it for heavy flavours...

INTERMEDIATE P_T AND "IN-MEDIUM" HADRONISATION

- observed for light flavour (pions and protons)

ALICE Collaboration, Phys. Lett. B736 (2014) 196



➡ comparison of A-A p_T spectra with binary scaled pp ones

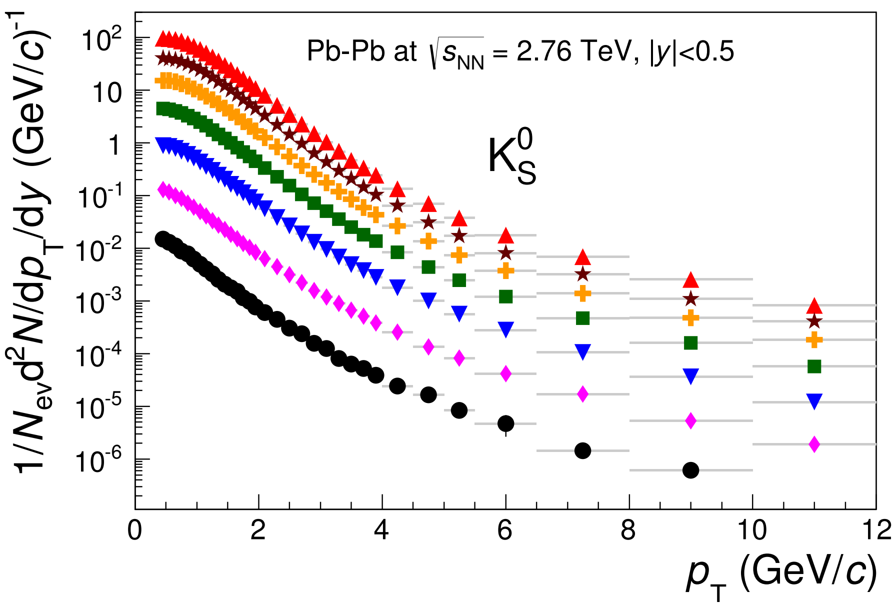
➡ suppression in central A-A collisions at high p_T

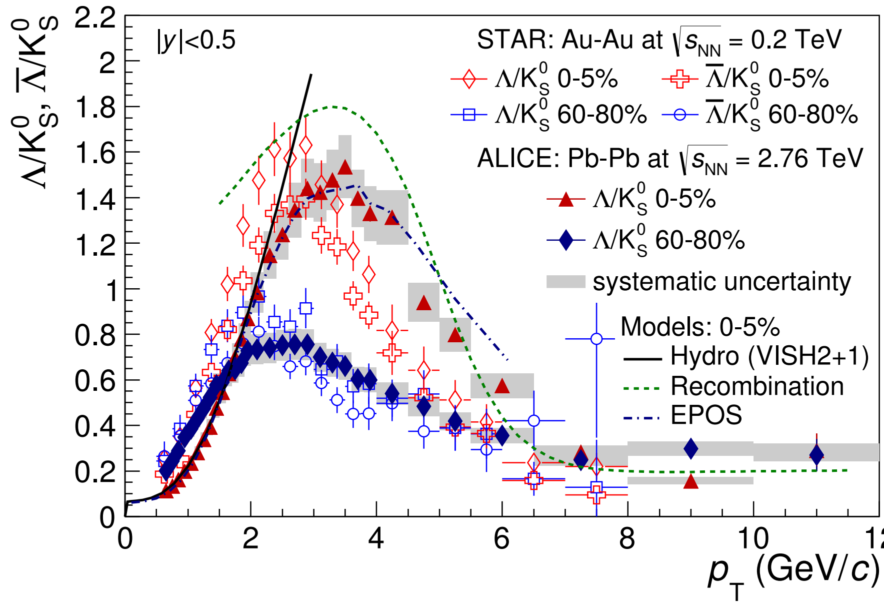
➡ harder p_T spectra in pp collisions for pions

INTERMEDIATE P_T AND "IN-MEDIUM" HADRONISATION

- observed for strangeness (K^0_s and Λ)

ALICE Collaboration, Phys. Rev. Lett. 111 (2013) 22, 222301





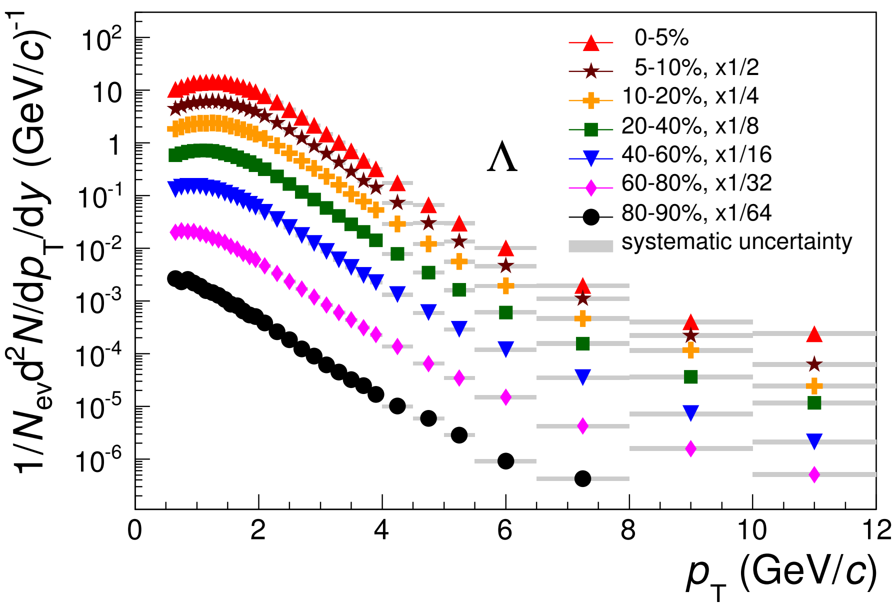
➡ evolution of A-A p_T spectra as a function of centrality

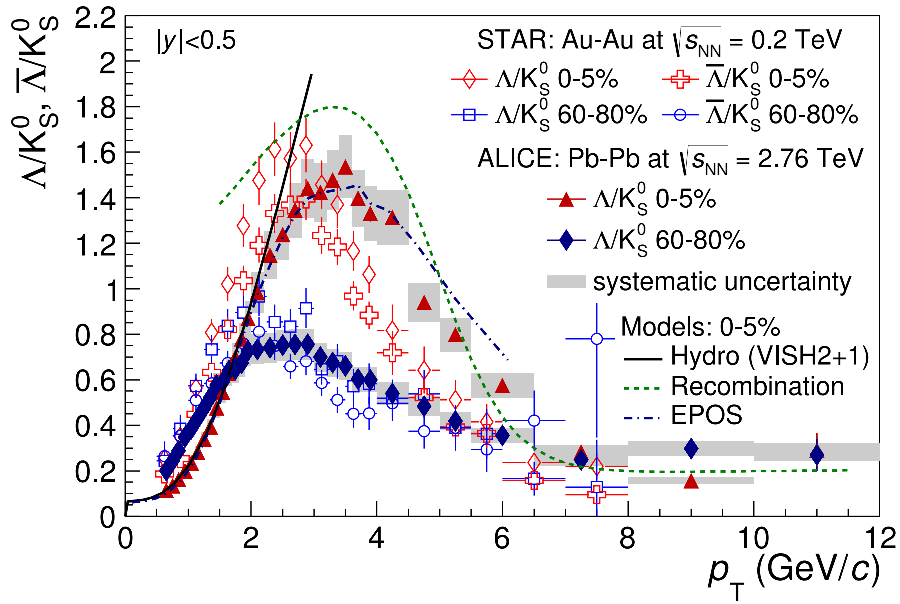
➡ ratio: increase from radial flow… decrease compared to recombination models

INTERMEDIATE P_T AND "IN-MEDIUM" HADRONISATION

- observed for strangeness (K^0_s and Λ)

ALICE Collaboration, Phys. Rev. Lett. 111 (2013) 22, 222301



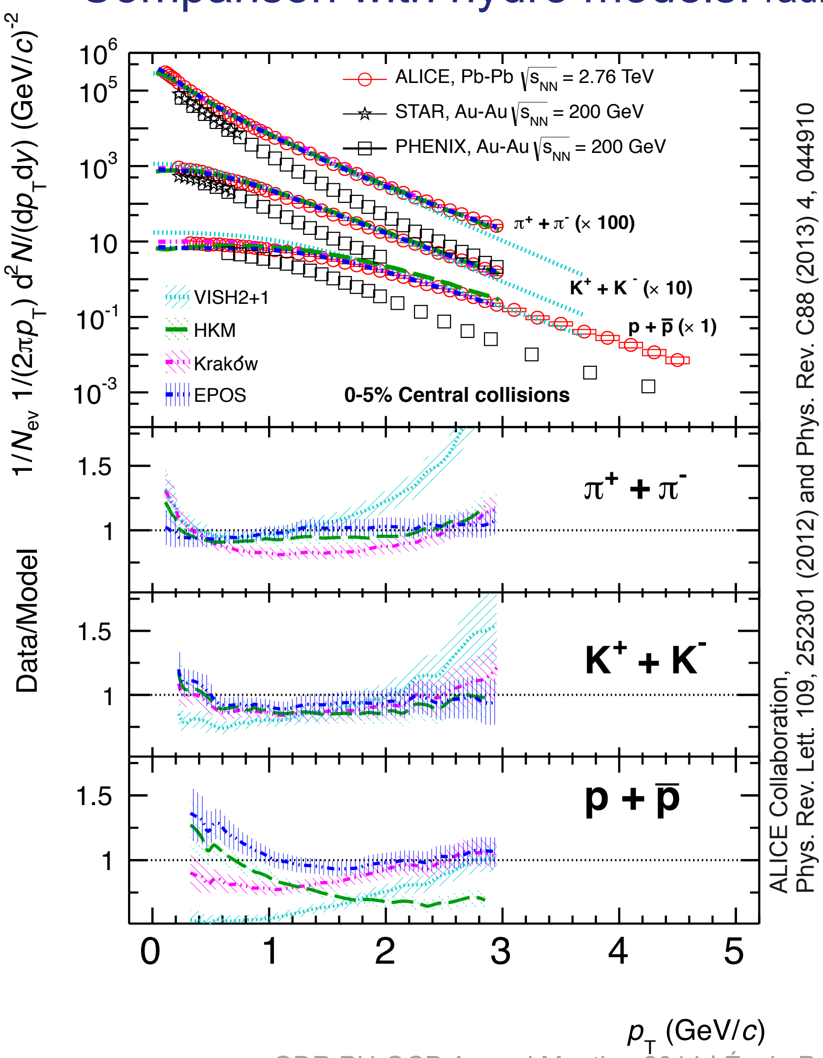


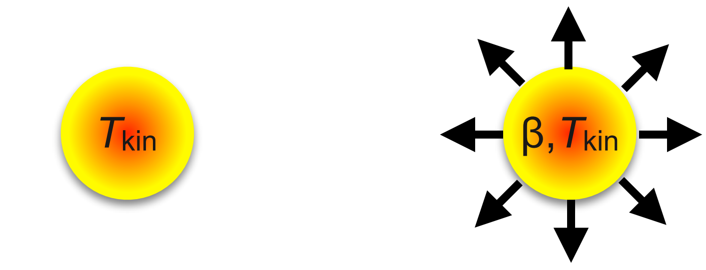
➡ evolution of A-A p_T spectra as a function of centrality

➡ ratio: increase from radial flow… decrease compared to recombination models

IDENTIFIED P_T SPECTRA AND HADRONIC RESCATTERING

- Comparison with hydro models: radial flow and kinetic freeze-out temperature T_{kin}





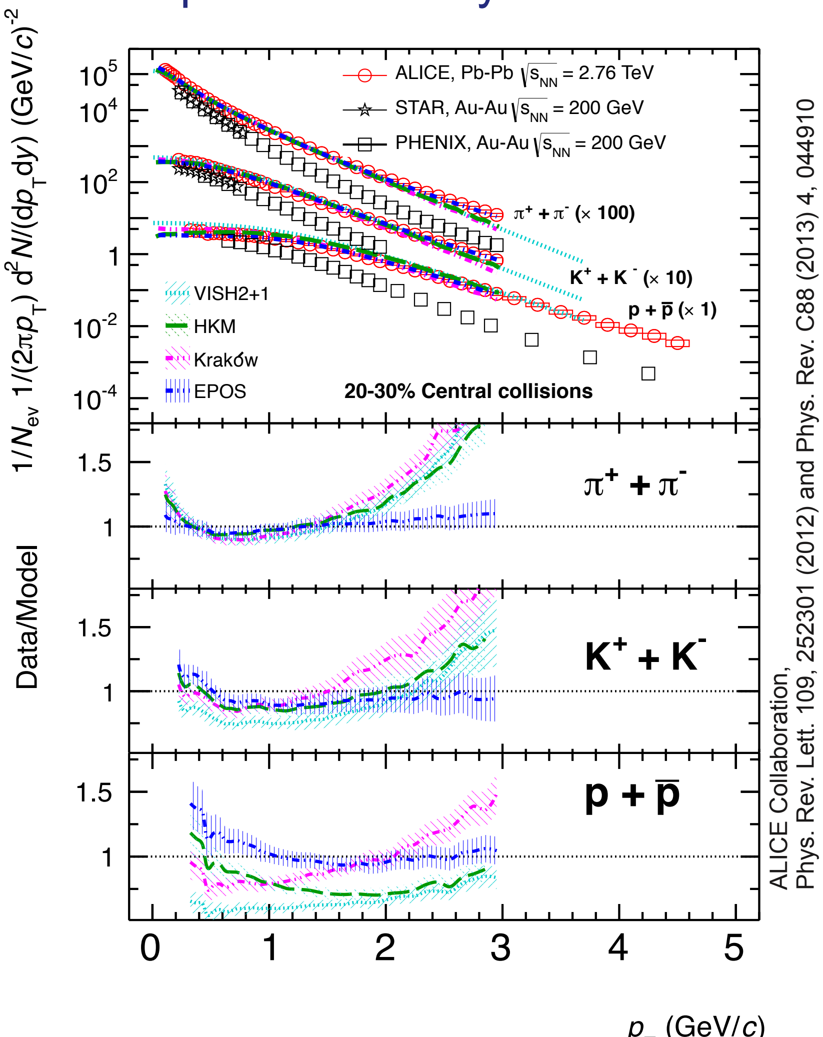
Large radial flow in top central events:
<β_T> = 0.65 ± 0.02 (~10% higher w.r.t. RHIC)
increases with centrality

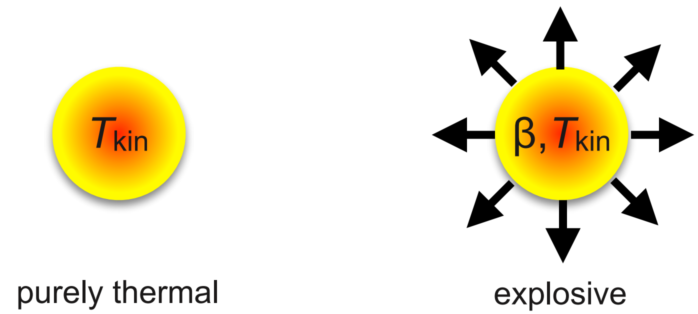
T_{kin}= 95 MeV (same as RHIC within errors)
decreases with centrality

model comparisons:
- VISH2+1 (viscous hydro)
- HKM (hydro+UrQMD)
- Kraków (viscous corr., lower the effective T_{ch})
- EPOS (hydro+UrQMD)

IDENTIFIED P_T SPECTRA AND HADRONIC RESCATTERING

- Comparison with hydro models: radial flow and kinetic freeze-out temperature T_{kin}





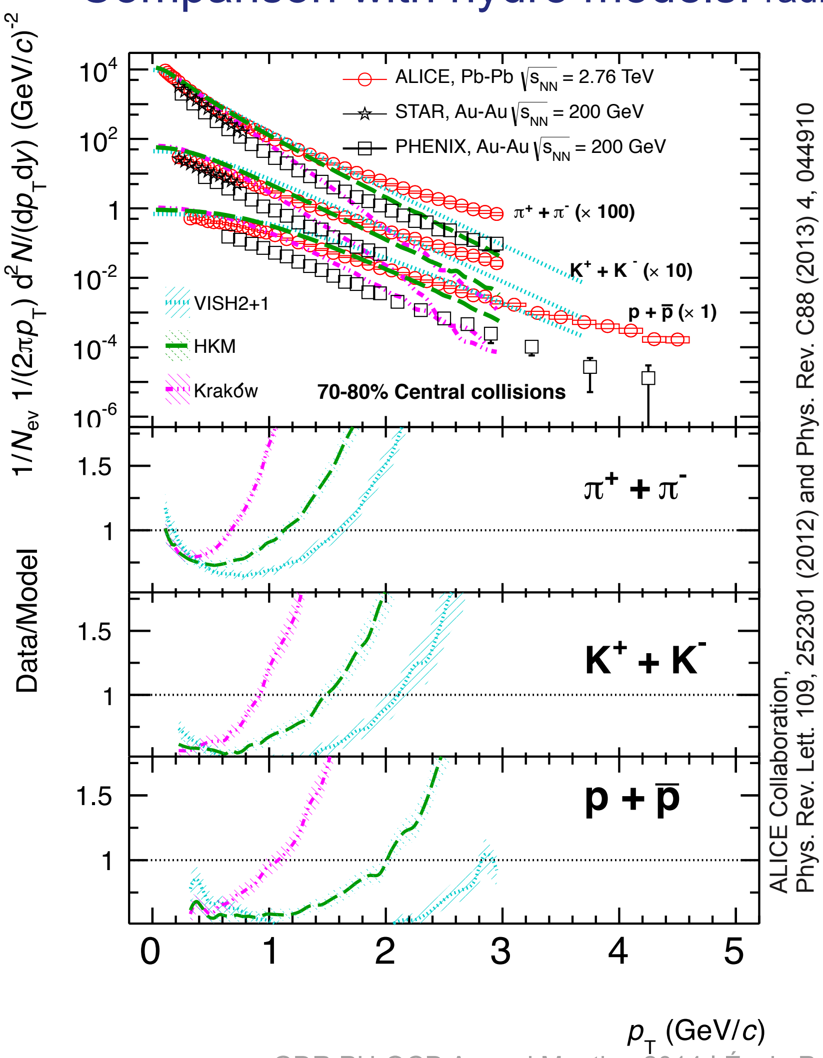
Large radial flow in top central events:
$\langle\beta_T\rangle = 0.65 \pm 0.02$ (~10% higher w.r.t. RHIC)
increases with centrality

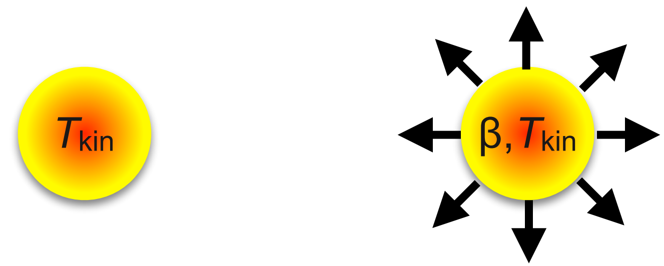
T_{kin}= 95 MeV (same as RHIC within errors)
decreases with centrality

model comparisons:
- VISH2+1 (viscous hydro)
- HKM (hydro+UrQMD)
- Kraków (viscous corr., lower the effective T_{ch})
- EPOS (hydro+UrQMD)

IDENTIFIED P_T SPECTRA AND HADRONIC RESCATTERING

- Comparison with hydro models: radial flow and kinetic freeze-out temperature T_{kin}





purely thermal

explosive

Large radial flow in top central events:
$\langle\beta_T\rangle$ = 0.65 ± 0.02 (~10% higher w.r.t. RHIC)
increases with centrality

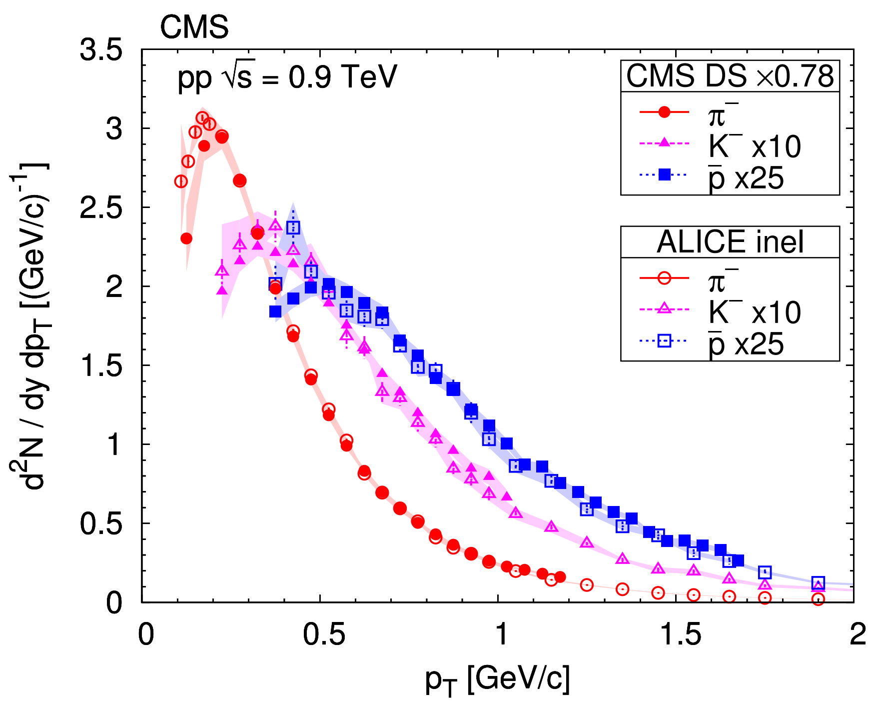
T_{kin}= 95 MeV (same as RHIC within errors)
decreases with centrality

model comparisons:
- VISH2+1 (viscous hydro)
- HKM (hydro+UrQMD)
- Kraków (viscous corr., lower the effective T_{ch})
- EPOS (hydro+UrQMD)

➡ the more peripheral the events are,
the more challenging for the models !

REFERENCE COLLIDING SYSTEM(S) AND COMPARISONS

- the shapes of p_T spectra in A-A are compared to pp collisions
  - ➡ check consistency for ranges with overlapping PID capabilities



CMS Collaboration, Eur. Phys.J. C72 (2012) 2164

ALICE Collaboration, Eur. Phys.J. C71 (2011) 1

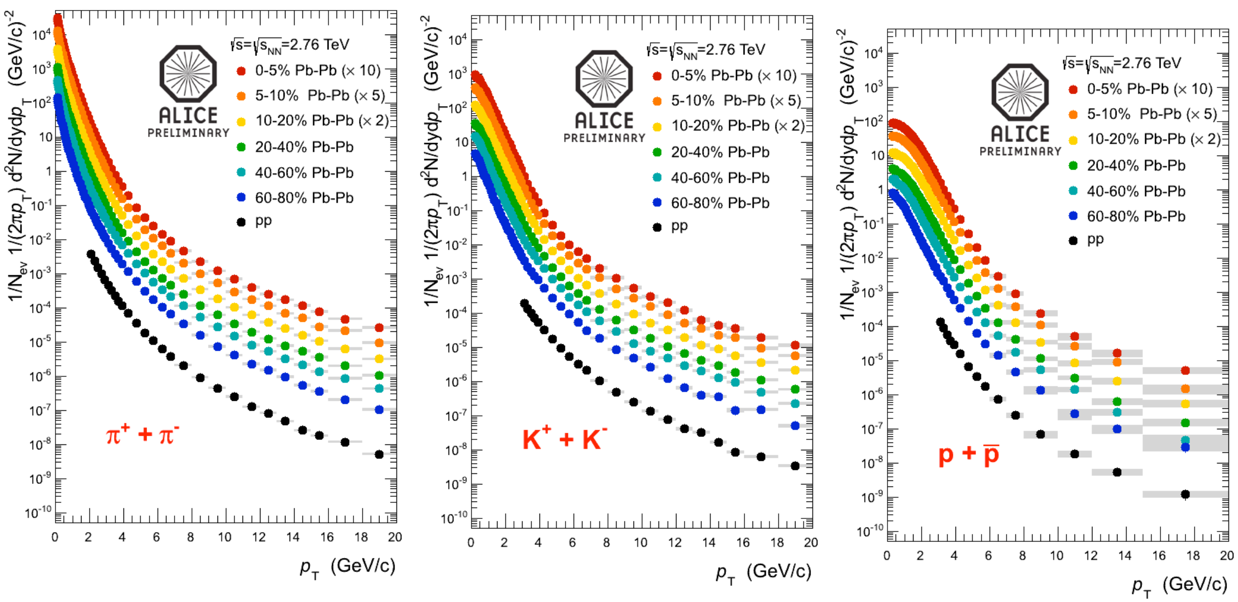
➡ within the same experiment when several PID detectors are available

➡ between different experiments, e.g. CMS and ALICE for light-flavour hadrons at very low p_T

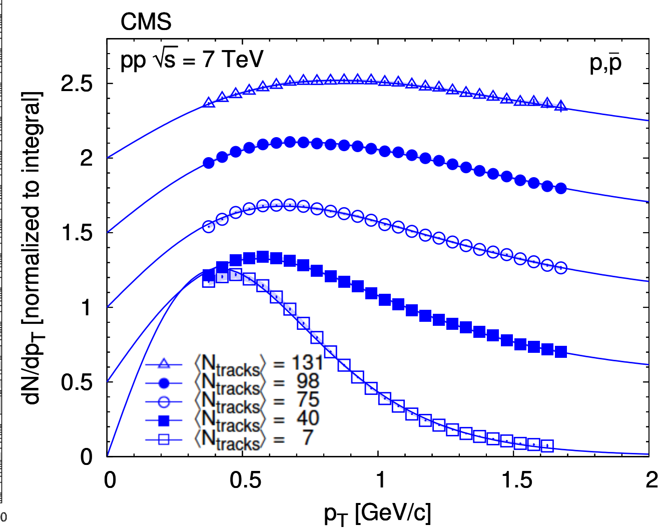
Excellent agreement between the different measurements !

REFERENCE COLLIDING SYSTEM(S) AND COMPARISONS

- the shapes of p_T spectra in A-A are compared to pp collisions
  - ➡ check consistency for ranges with overlapping PID capabilities
    for instance CMS and ALICE for light flavoured hadrons at very low p_T
  - ➡ minimum bias pp often used as one reference for Pb-Pb



A.Ortiz Velasquez (for the ALICE Collaboration), Nucl. Phys. A904-905 (2013) 763c

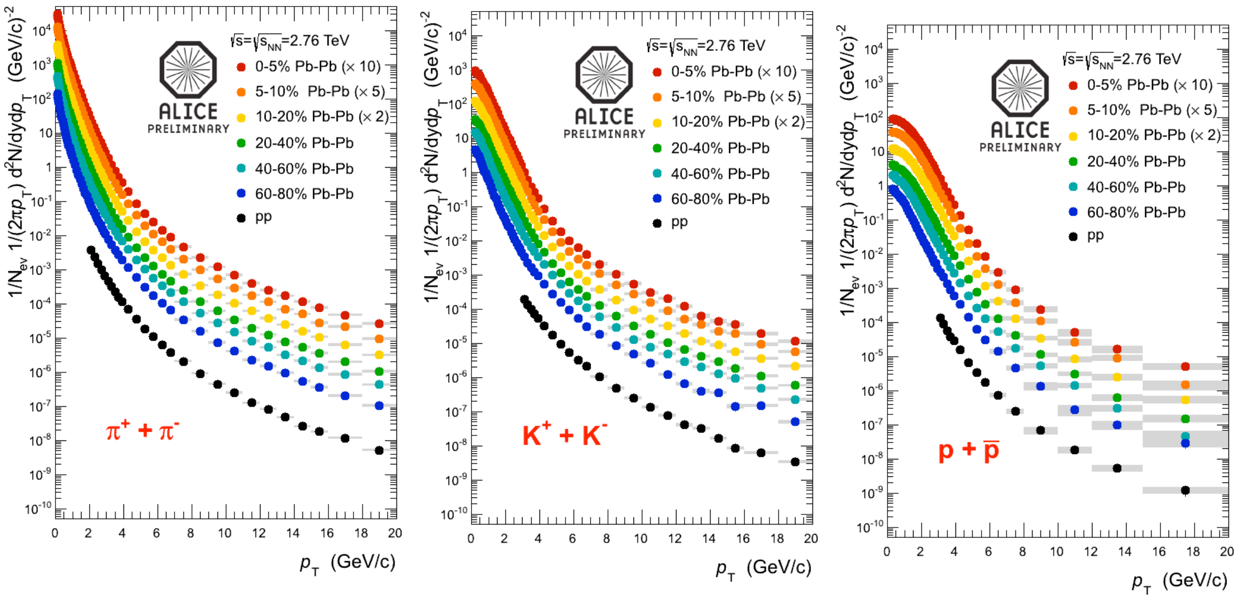


CMS Collaboration, Eur. Phys.J. C72 (2012) 2164

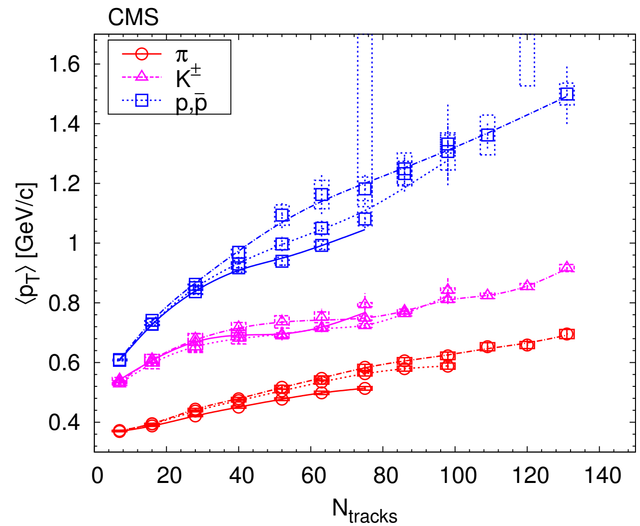
Caution: in pp, the p_T spectra shape changes more as a function of multiplicity than as a function of colliding energy...

REFERENCE COLLIDING SYSTEM(S) AND COMPARISONS

- the shapes of p_T spectra in A-A are compared to pp collisions
  - ➡ check consistency for ranges with overlapping PID capabilities
    for instance CMS and ALICE for light flavoured hadrons at very low p_T
  - ➡ minimum bias pp often used as one reference for Pb-Pb



A.Ortiz Velasquez (for the ALICE Collaboration), Nucl. Phys. A904-905 (2013) 763c



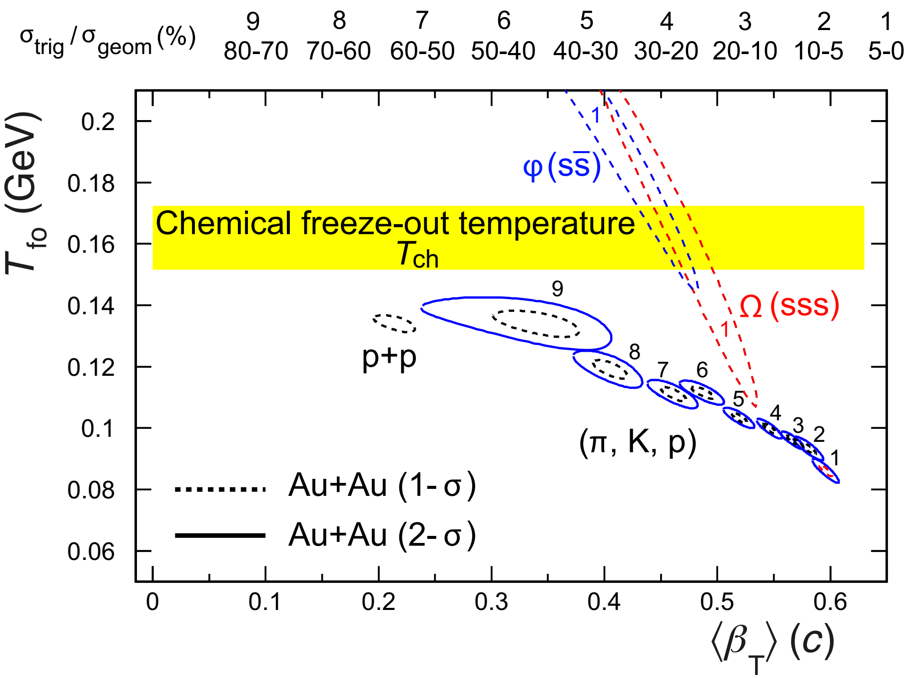
CMS Collaboration, Eur. Phys.J. C72 (2012) 2164

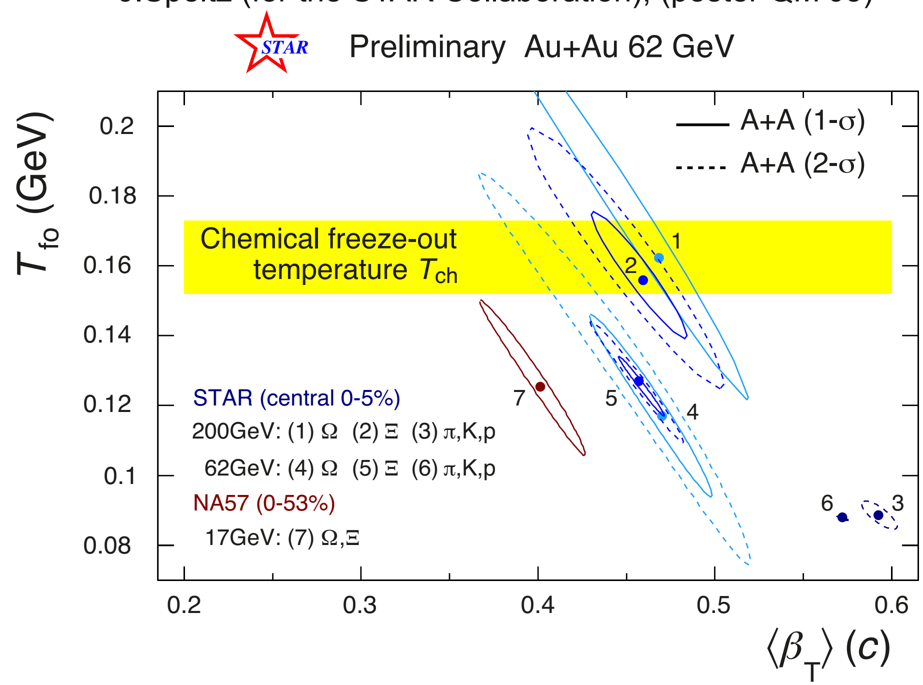
Caution: in pp, the p_T spectra shape changes more as a function of multiplicity than as a function of colliding energy...

COOLING AND HADRONIC PHASE

- Dense then dilute hadronic phase (3D+1 hydro + UrQMD results)
- Systematics on radial flow and kinetic freeze-out temperature T_{kin}
  - ➡ blast-wave parametrisation (as seen before…with known caveats...)
  - ➡ from top RHIC…

STAR Collaboration, Nucl. Phys. A757 (2005) 102
J.Speltz (for the STAR Collaboration), (poster QM'05)



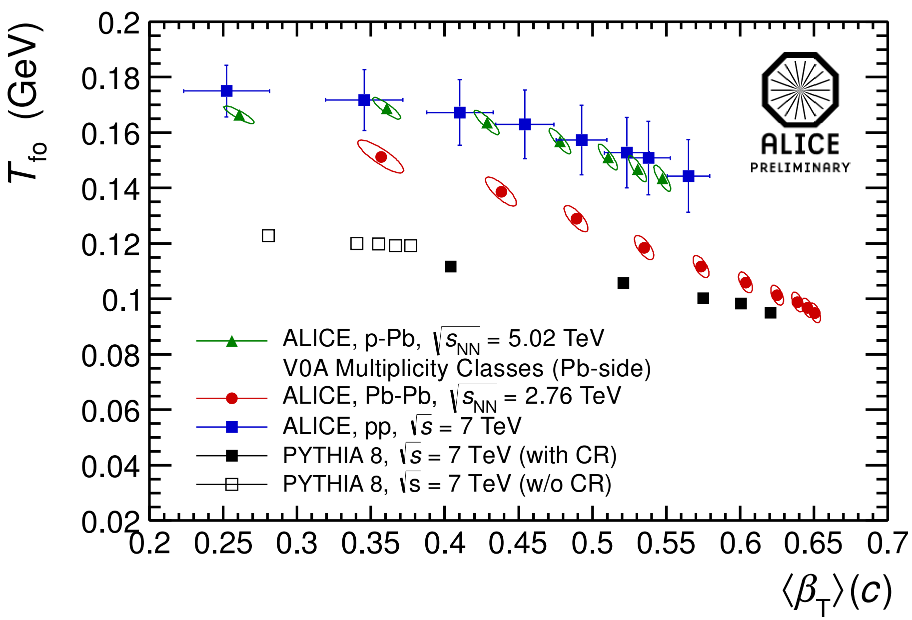


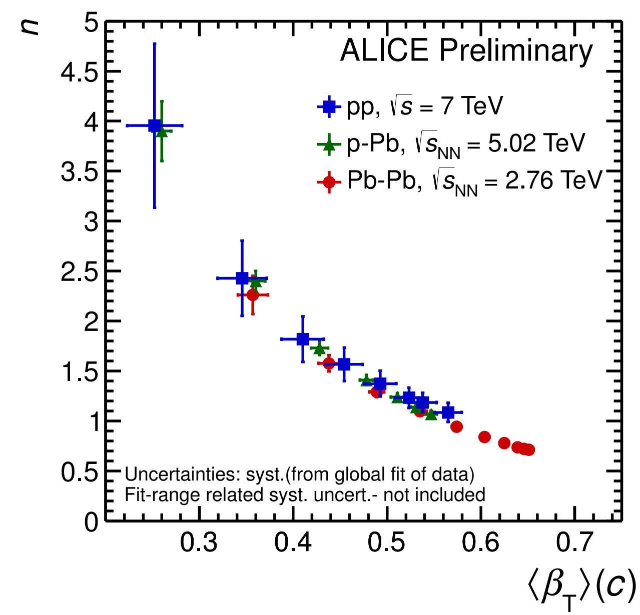
Caution: ~10 years ago, LQCD calculations T_c ~165 MeV

COOLING AND HADRONIC PHASE

- Dense then dilute hadronic phase (3D+1 hydro + UrQMD results)
- Systematics on radial flow and kinetic freeze-out temperature T_{kin}
  - ➡ blast-wave parametrisation (as seen before…with known caveats...)
  - ➡ from top RHIC… to LHC energies:

C.Andrei (for the ALICE Collaboration), Nucl. Phys. A 931 (2014) 888





Caution: now, LQCD calculations

T_{c}= 155 ± 3 (stat.) ± 3 (syst.) MeV (**)
T_{c}= 154 ± 8 (stat.) ± 1 (syst.) MeV (°°)

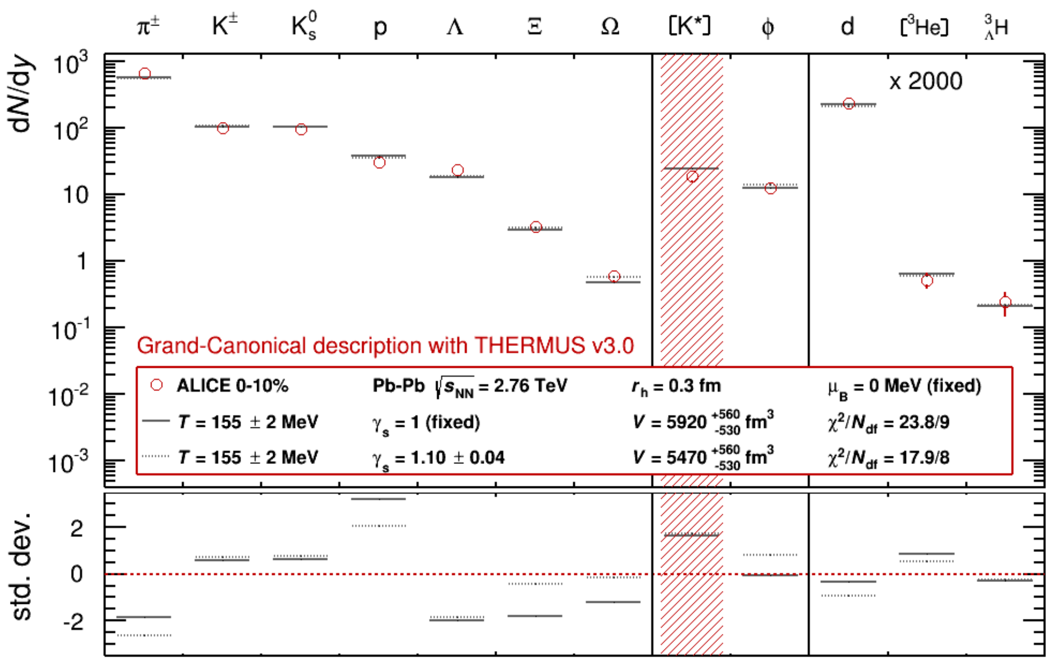
** S. Borsanyi *et al.*, JHEP 1009, 073 (2010)   °° A. Bazavov *et al.*, Phys. Rev. D 85, 054503 (2012)

GdR PH-QCD

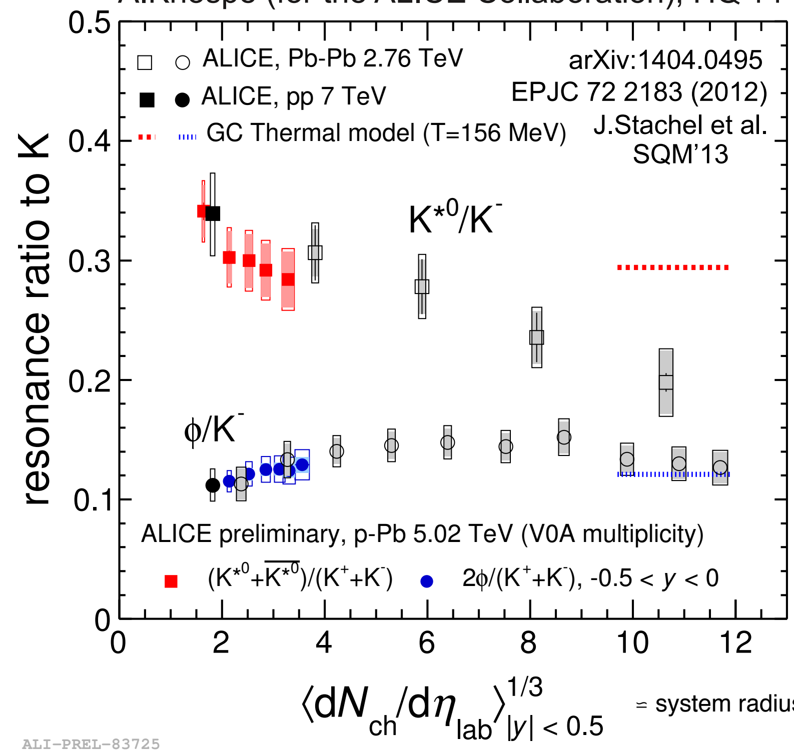
HADRONIC PHASE AND RESCATTERING AT THE LHC

- suppression for K*
- thermal yields for ϕ … and (hyper) nuclei

K* τ = 4.16 fm/c
ϕ τ = 46.3 fm/c



F.Bellini (for the ALICE Collaboration), QM'14
A.Knospe (for the ALICE Collaboration), HQ'14



Explosive system with little (no ?) effect on resonance and (hyper) nuclei yields

SUMMARY

- System produced in pp, p-A and A-A at the LHC:
  - ➡ System created in A-A collisions at the LHC is denser, hotter and longer lived
  - ➡ Evolution with similarities… but also differences
  - ➡ More differential analyses needed for isolating unambiguously collective effects
  - ➡ Question: are pp (multiplicity), p-A good reference systems ?
- Flavour content and hadro-chemistry at the LHC:
  - ➡ T_{ch} (parameter) corresponds to T_c (LQCD) and $\gamma_s = 1$ for A-A … and p-A
  - ➡ Strangeness enhancement still valid… but yields in p-Pb (and pp) are increasing
- Probing "in-medium" hadronisation at intermediate p_T
  - ➡ Baryon/meson increase essentially from radial flow (recombination ?)
- Radial flow and kinetic freeze-out evolution for pp and p-A (vs energy)
  - ➡ Interpretation using Blast-wave parametrisation: cooling and flow build-up
- Hadronic phase and rescattering at the LHC
  - ➡ Explosive system with little (no ?) effect on resonance and (hyper) nuclei yields