



ALICE au LHC: la  
thermodynamique de la  
matière en interaction forte

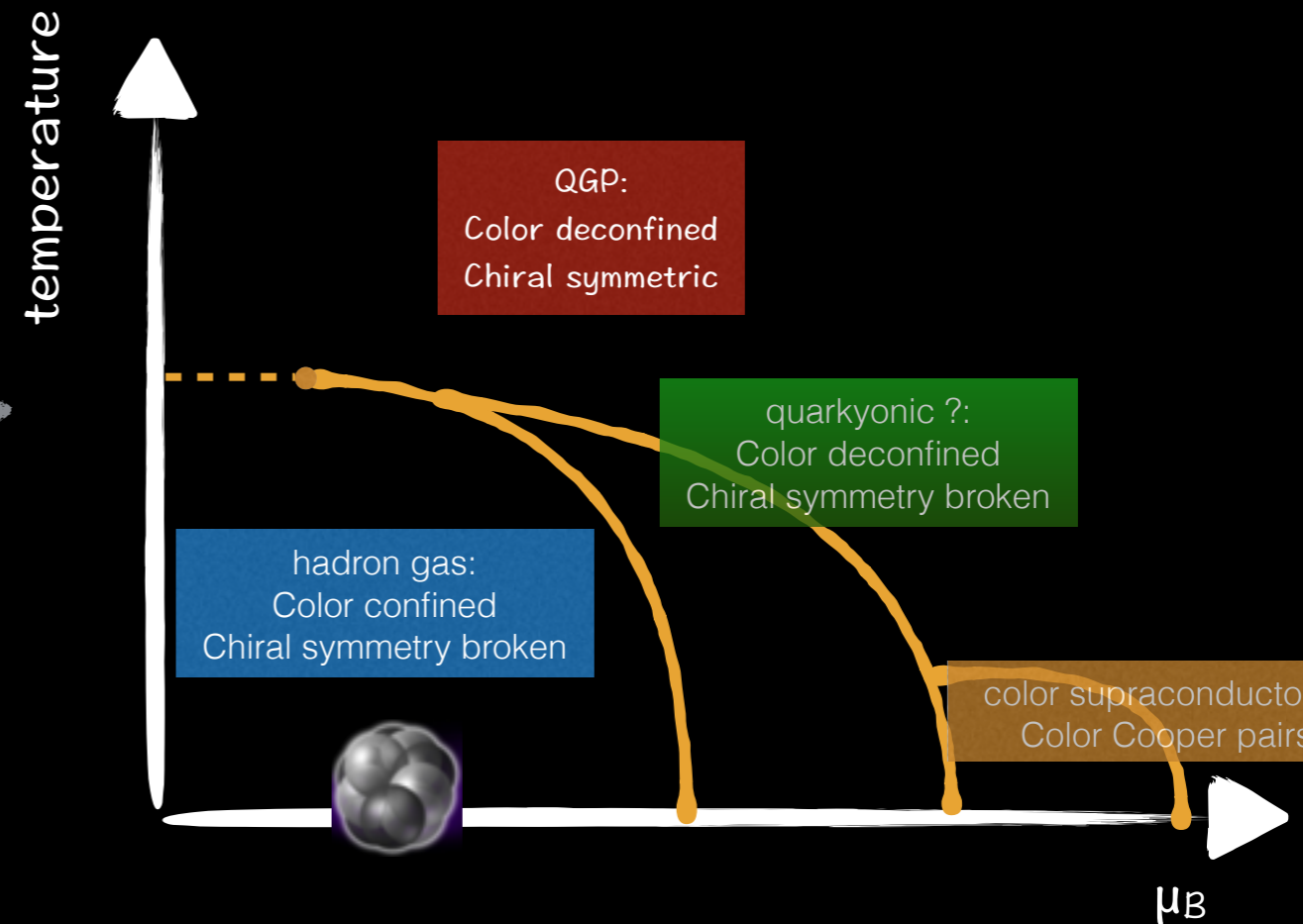
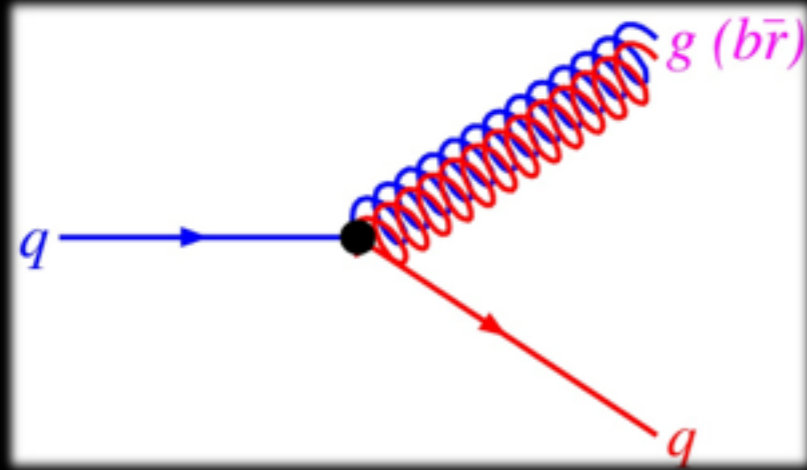
« In high-energy physics we have concentrated on experiments in which we distributed a higher and higher amount of energy into a region with smaller and smaller dimensions. In order to study the question of 'vacuum' we must turn in a different direction; we should investigate some bulk phenomena by distributing high energy over a relatively large volume »

*-T.D. Lee, Rev. Mod. Phys. 47 (1975)*

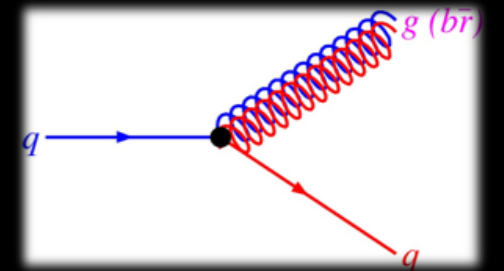
# Rappel

Les objectifs scientifiques du programme ions lourds au  
LHC

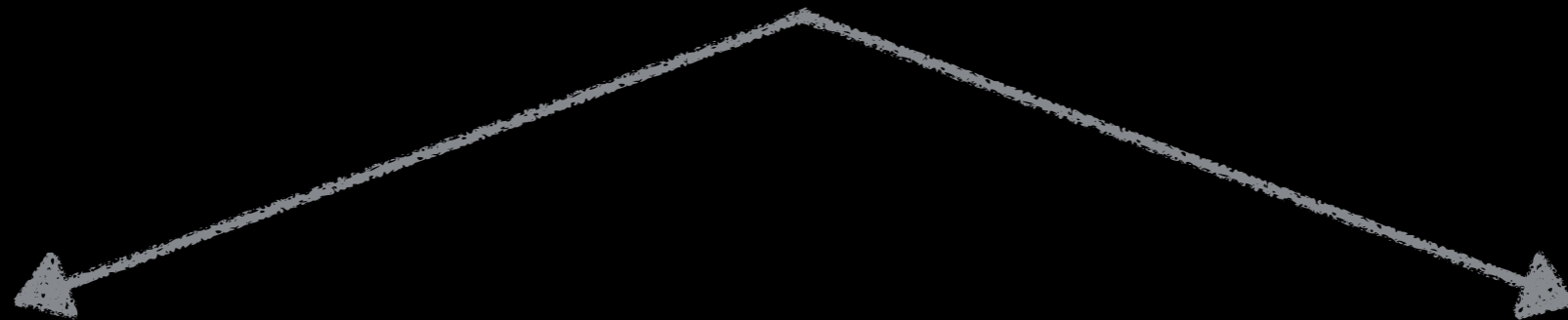
# Thermodynamique de la matière en interaction forte



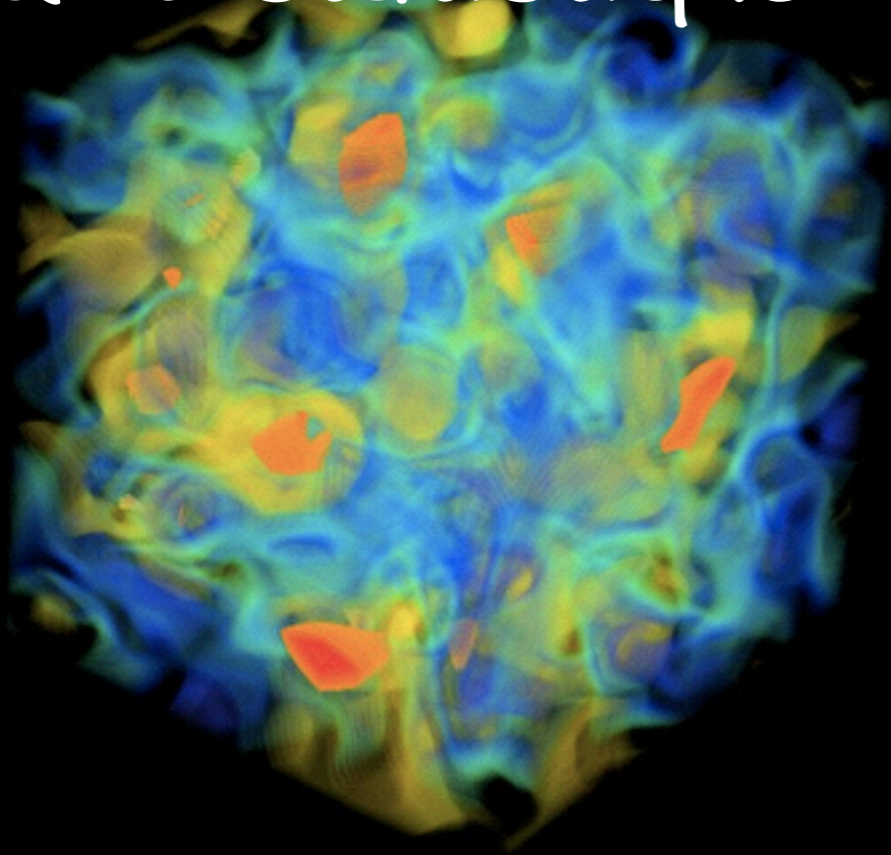
Comment la complexité de la matière émerge de la dynamique de l'interaction forte



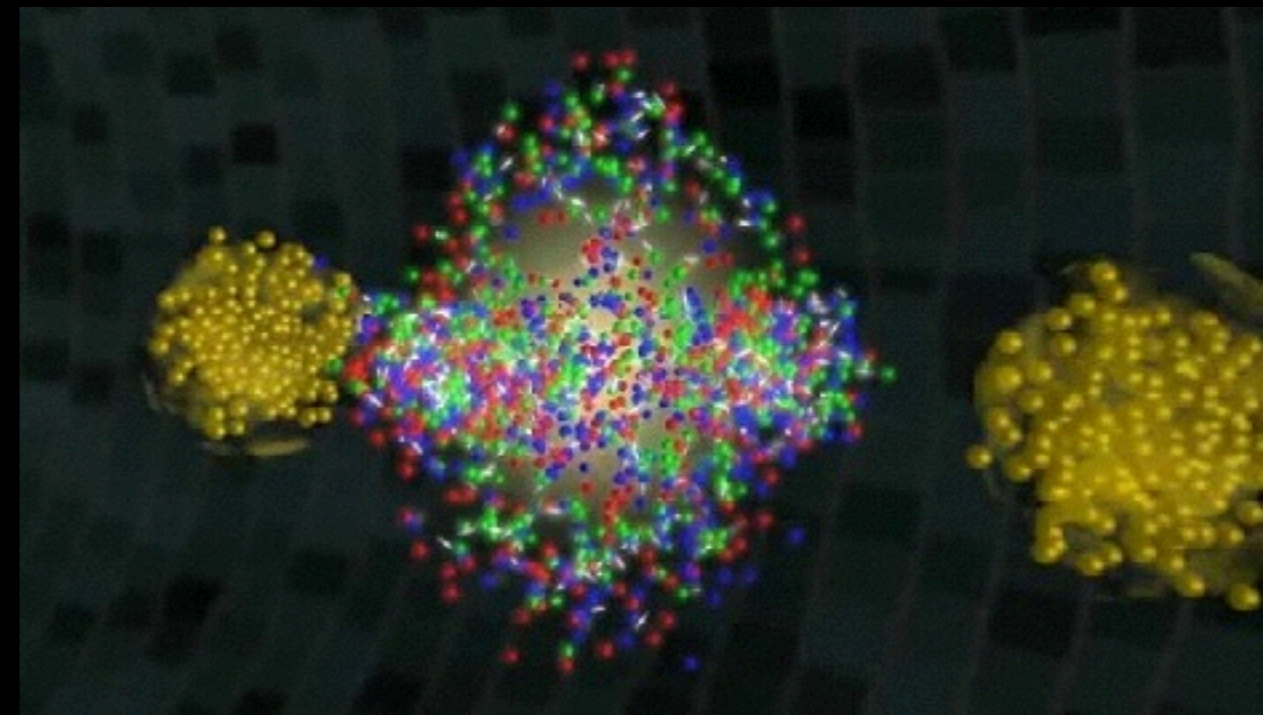
# Thermodynamique de la matière et interaction forte



QCD statistique



collisions ions lourds



# Les faits établis: exp

- Aux températures du LHC la matière a les propriétés d'un liquide\* parfait\*\*

## The Quark-Gluon Plasma, a nearly perfect fluid

■ L. Cifarelli<sup>1</sup>, L.P. Csernai<sup>2</sup> and H. Stöcker<sup>3</sup> - DOI: 10.1051/epn/2012206

■ <sup>1</sup> Dipartimento di Fisica, Università di Bologna, 40126 Bologna, Italy;

■ <sup>2</sup> Department of Physics and Technology, University of Bergen, 5007 Bergen, Norway;

■ <sup>3</sup> GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany

We are living in interesting times, where the World's largest accelerator, the Large Hadron Collider, has its most dominant successes in Nuclear Physics: collective matter properties of the Quark-Gluon Plasma (QGP) are studied at a detail which is not even possible for conventional, macro scale materials.

\* en interaction forte

\*\* non-dissipatif

# QGP

- est fortement couplé
- possède un libre parcours moyen très petit
- démontre un important degré de collectivité
- absorbe une fraction significative des partons de haute énergie

▶  $v_2, v_n$

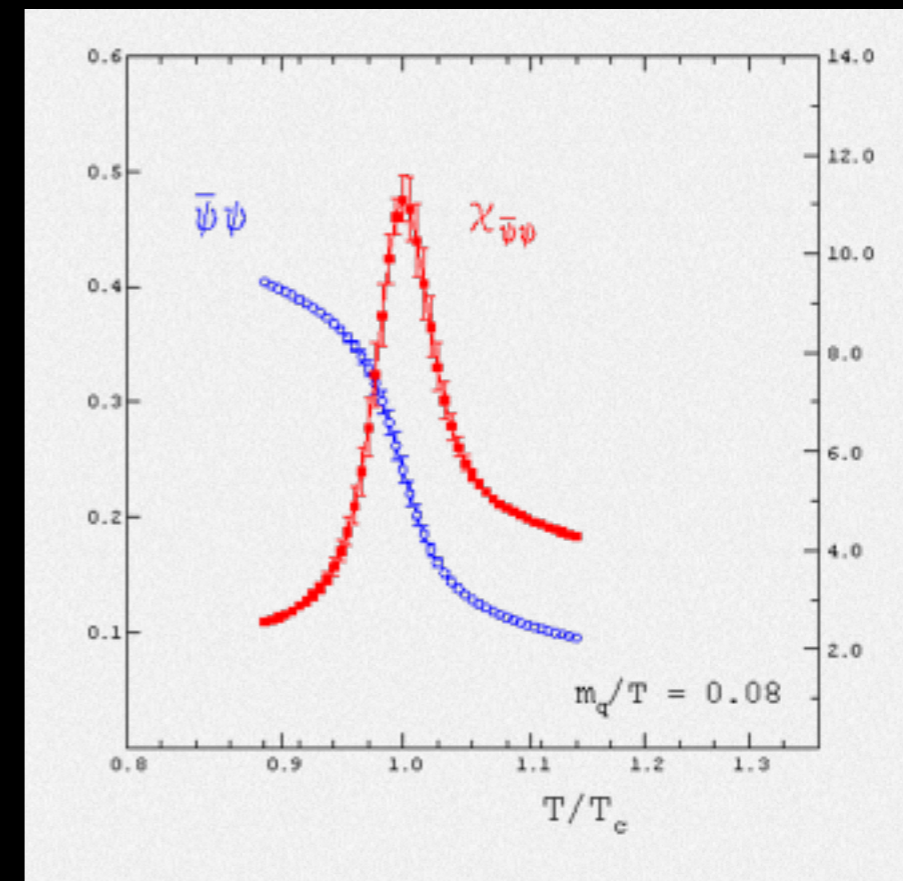
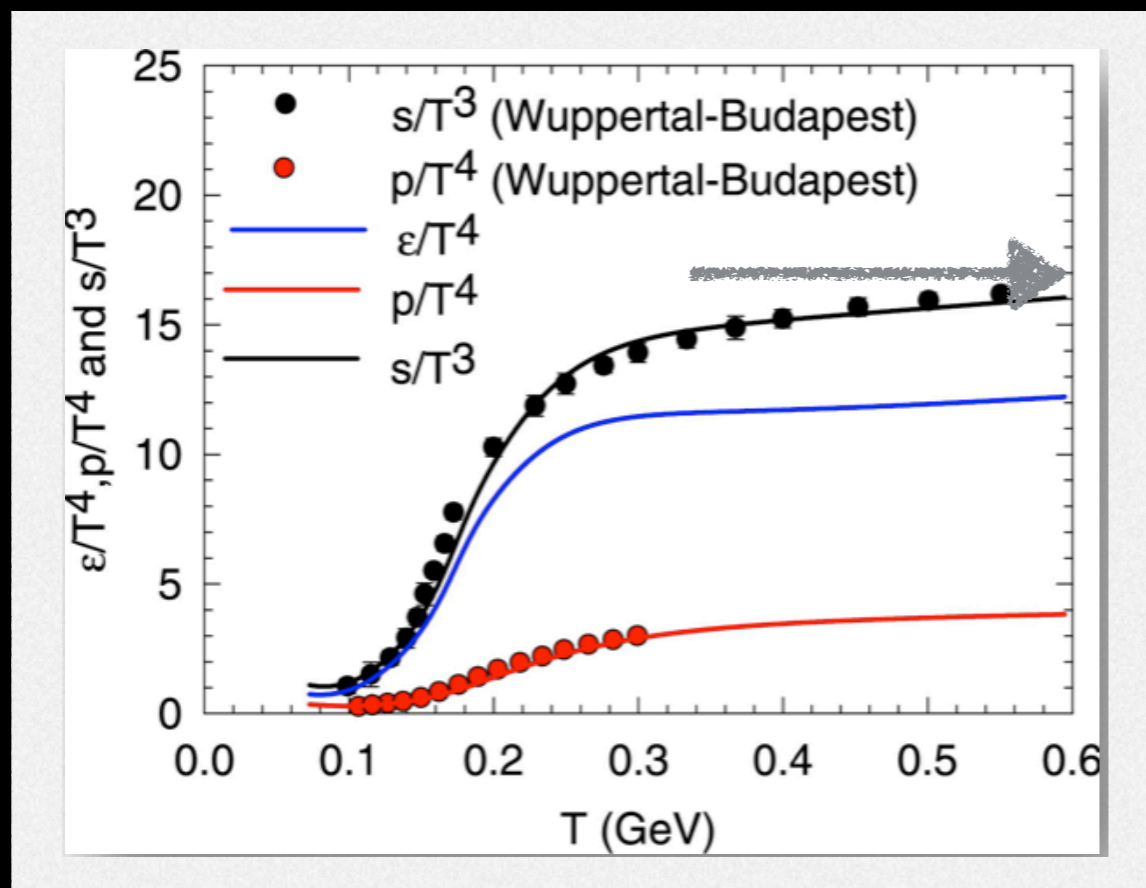
▶  $\eta/S$

▶  $\beta, v_n$

▶  $R_{AA}$

# Les faits établis: théorie

- transition **douce**\* d'un gas de hadrons vers QGP ( $Z_3$  symétrie); symétrie chirale **restaurée**\*\*



\* pas une transition de phase, pas SB

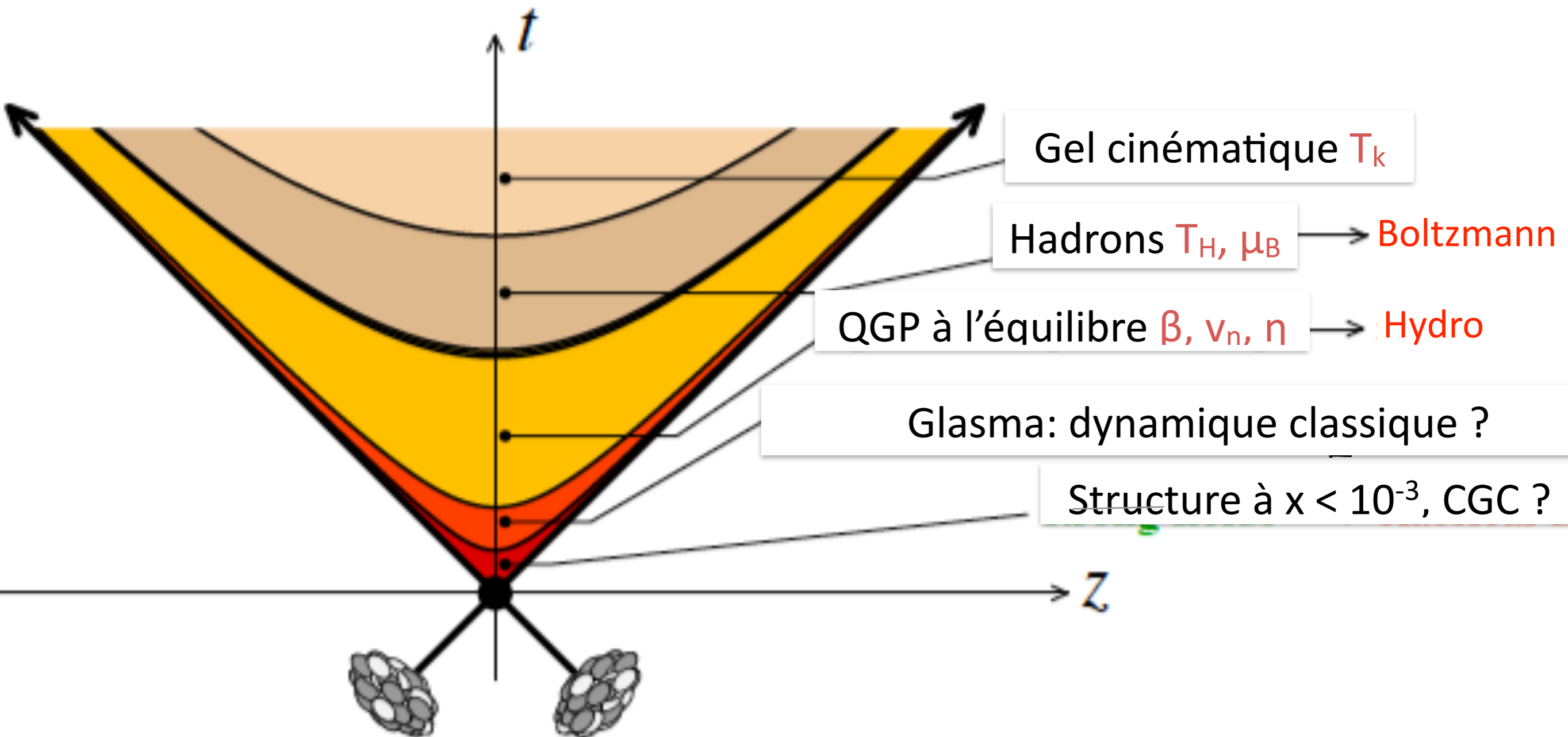
\*\* les quarks retrouvent leur masse intrinsèque (Higgs)



Dernières Nouvelles:  $T_C = 154 \pm 9 \text{ MeV}$

*-A. Bazavov et al., Phys. Rev. D90 (2014) 094503*

... ça se corse !



# Le mandat de ALICE

Etablir les propriétés fondamentales de la matière en interaction forte et à haute énergie au travers de mesures de **precision, complètes\***

\*  $p_t \sim T \oplus PID \oplus p_t \gg \Lambda_{\text{QCD}}$



# Stratégie standard

- Grand et dense: physique des ions lourds
- Petit et dilué: mesures de référence

# Stratégie standard

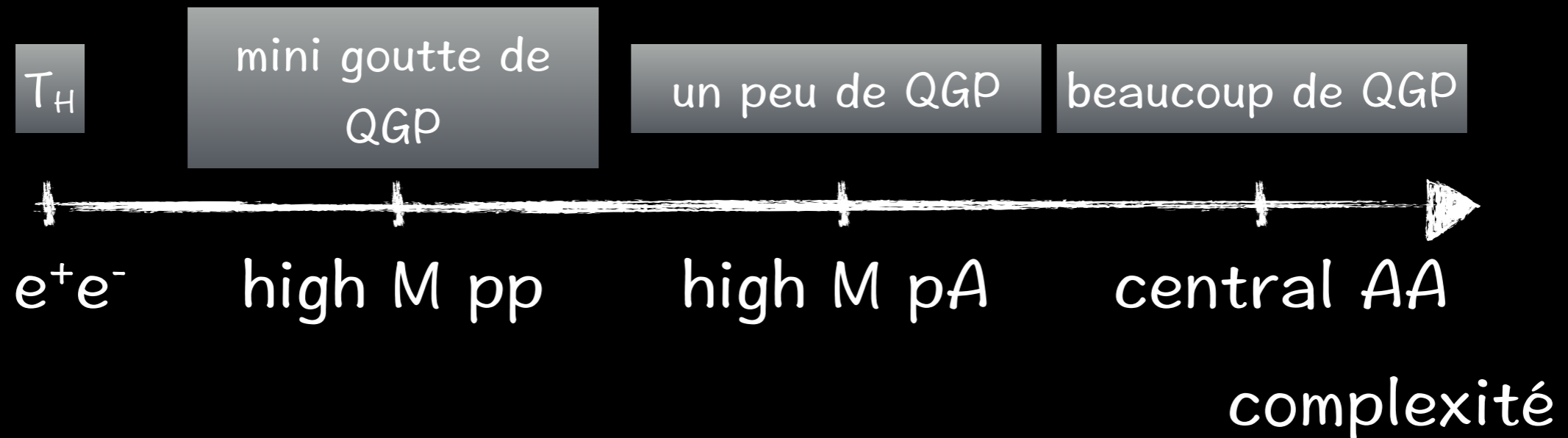
- Grand et dense: physique des ions lourds
  - ▶  $AA \rightarrow p\text{QCD} + N\text{pdf} + FF + \text{collectivité}$
- Petit et dilué: mesures de référence
  - ▶  $pp \rightarrow p\text{QCD} + \text{pdf} + FF$
  - ▶  $pA \rightarrow p\text{QCD} + N\text{pdf} + FF$

# Mais ... High M pp/pA

- production des particules
- spectres
- rayons HBT
- Ridges
- suppression des quarkonia

# Vers un nouveau paradigme

- Collectivité partout !



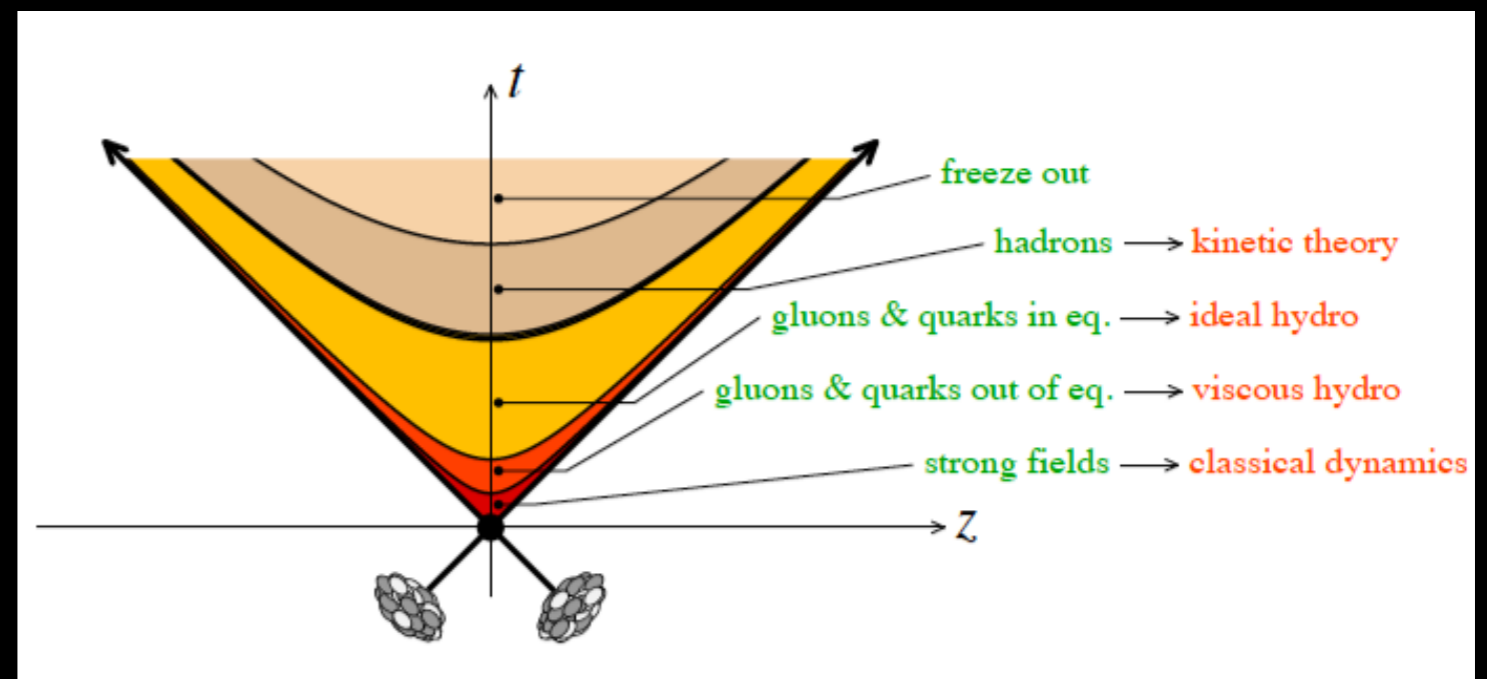
Une approche expérimentale et théorique cohérente de QCD statistique de  $e^+e^-$  à AA



# Questions ouvertes

# Questions...

- IS à LHC: champs classiques de gluons ? faiblement ou fortement couplés ?
- dynamiques: de IS vers un liquide hydro en 0.5 fm/c
- DoF: un milieu sans quasi-particules ? tout près de  $T_H$  ? hadronisation ?



soft:  $p_T \sim T, \Lambda_{\text{QCD}}$

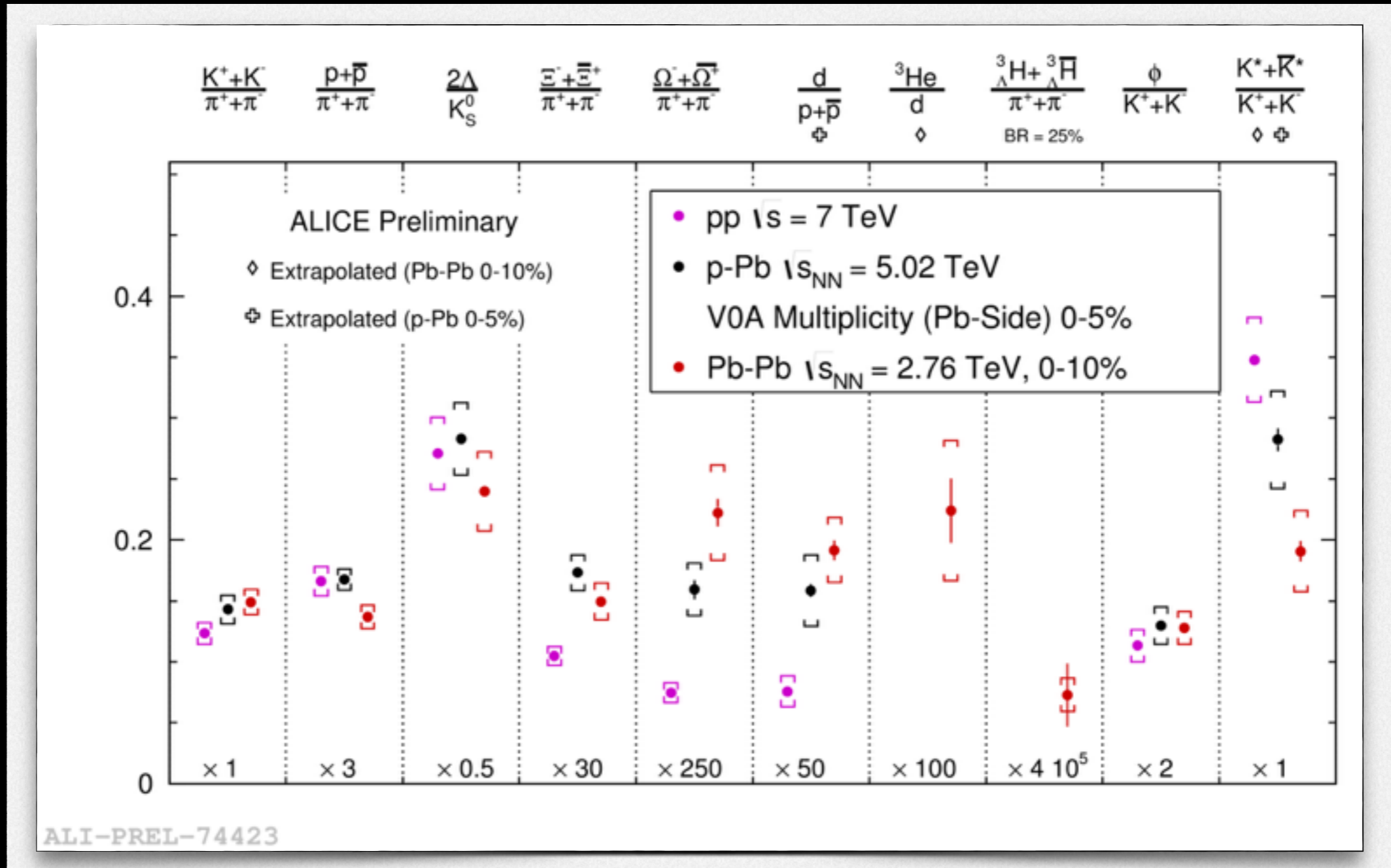
teste le milieu

# QGP-hadronization, ...nucléosynthèse



Sarah Szabo

# production de hadrons



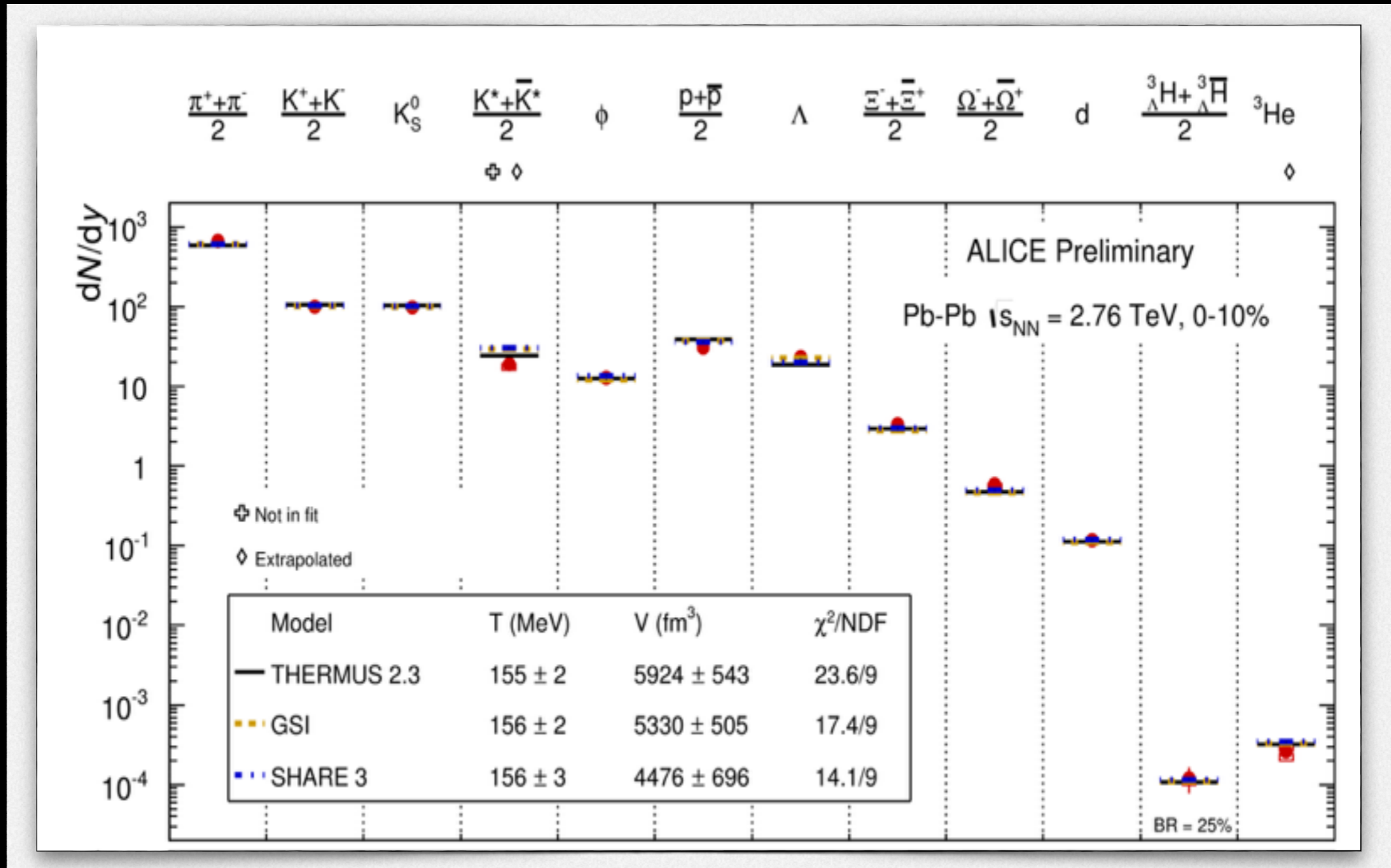
augmentation S,  
suppression K\*

OK

suppression p  
augmentation d

???

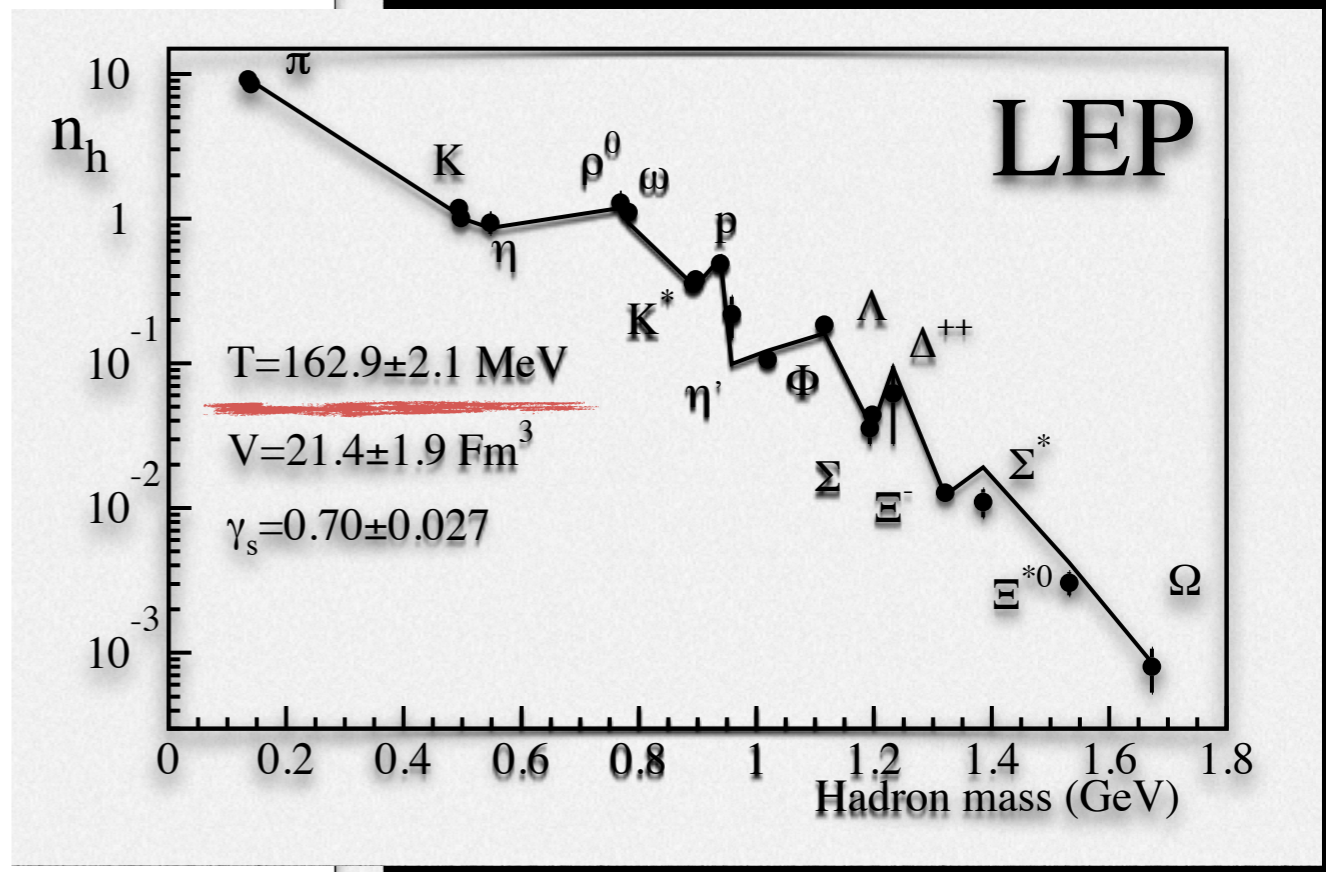
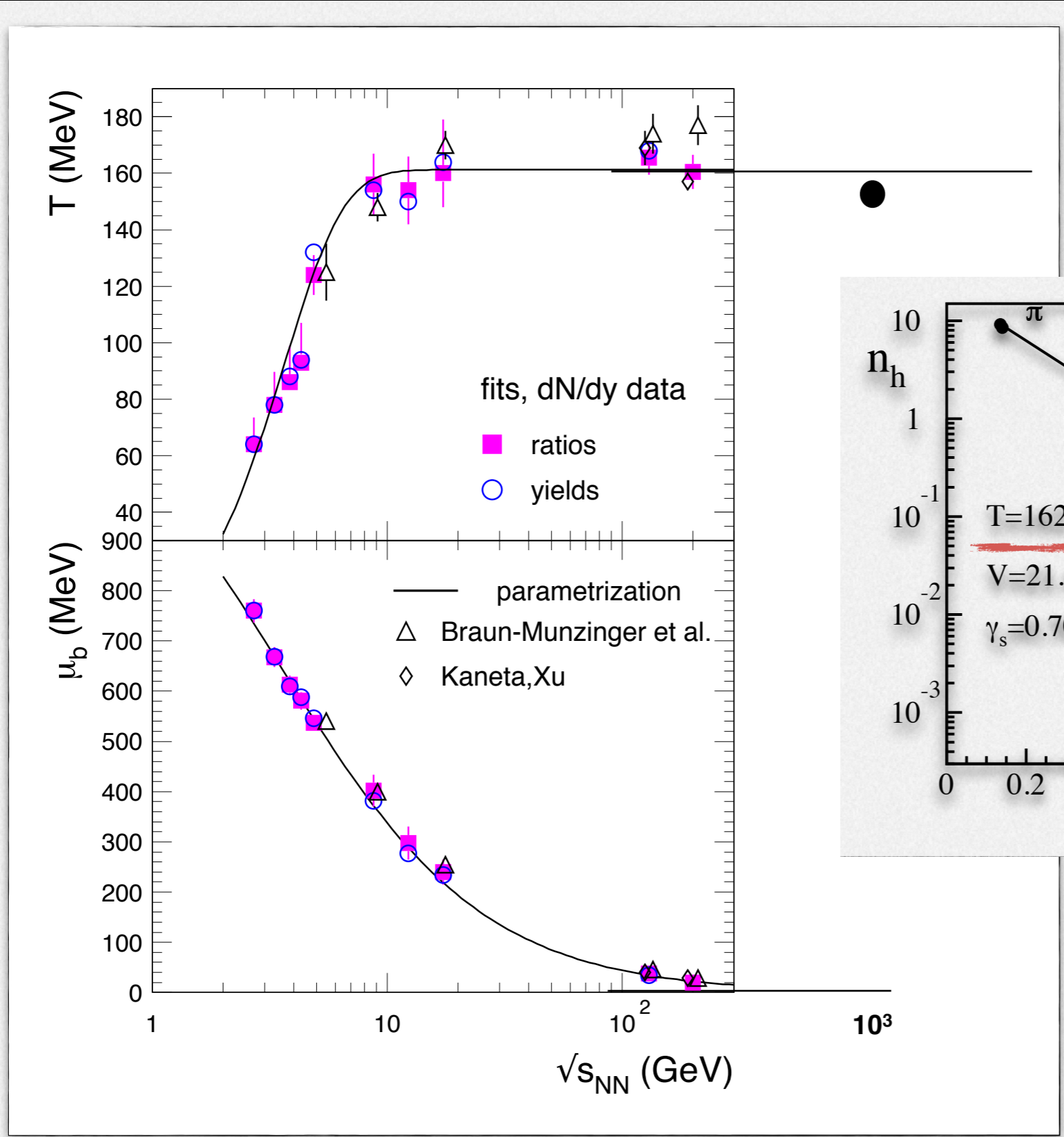
# production de hadrons



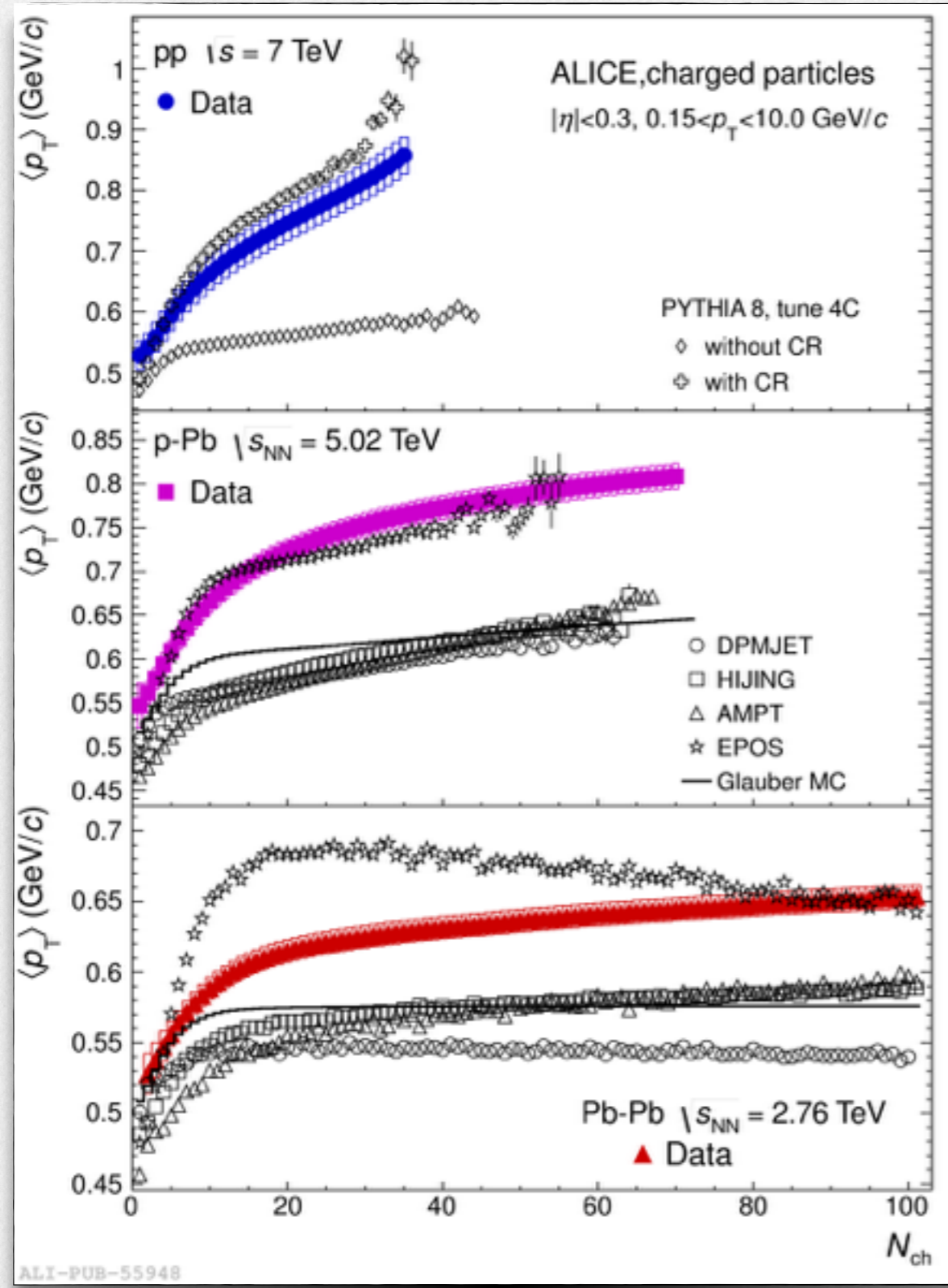
7 ordres de grandeur !  
 p, d, noyaux !!  
 T<sub>H</sub> = 155 MeV !!!

# production de hadrons

$T_H = 155 \text{ MeV} !!! !!!!!$   
Baryons S lourds invisibles ?



# $\langle p_t \rangle$ vs M



pp:  $\neq$  superposition incohérente d'interactions multiples de partons (CR)

pA:  $\neq$  superposition incohérente de collisions pp (EPOS + hydro)

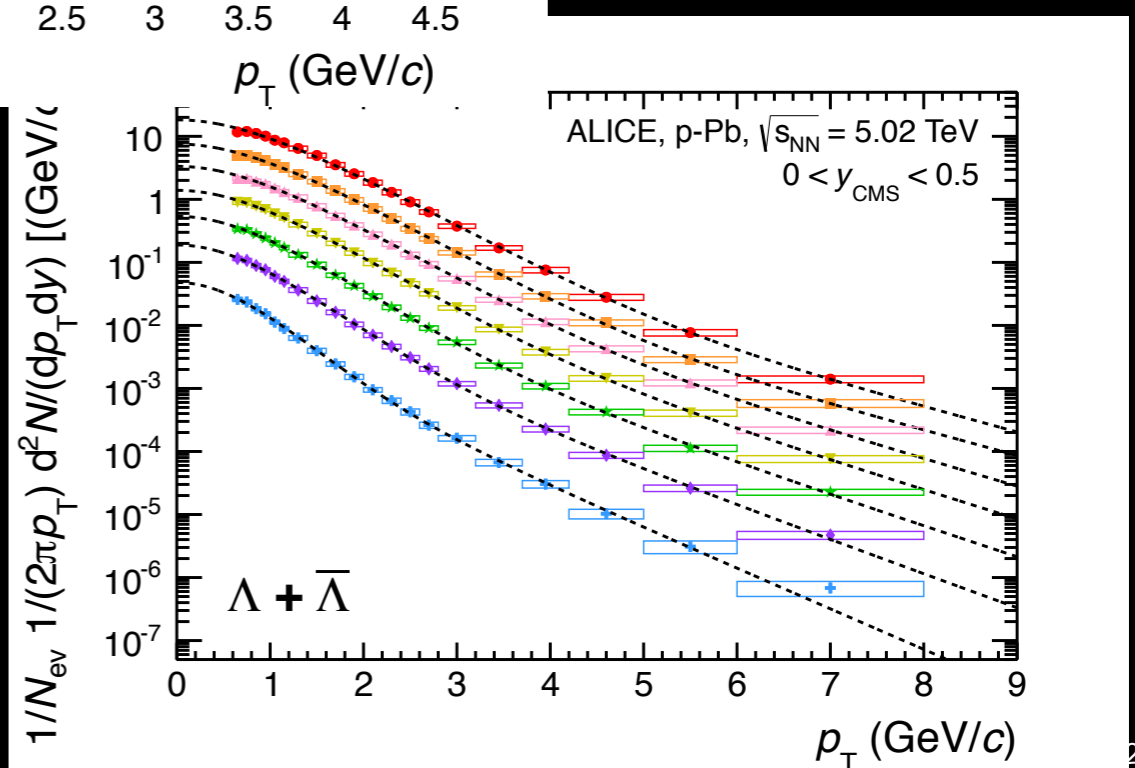
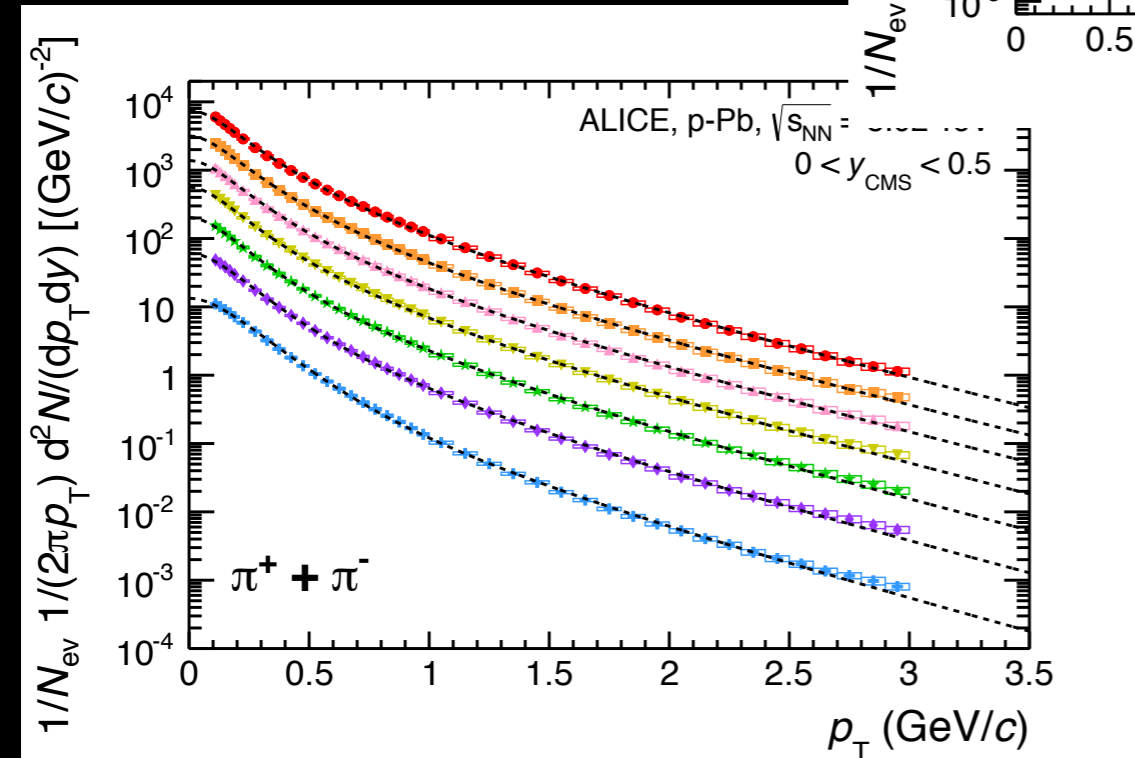
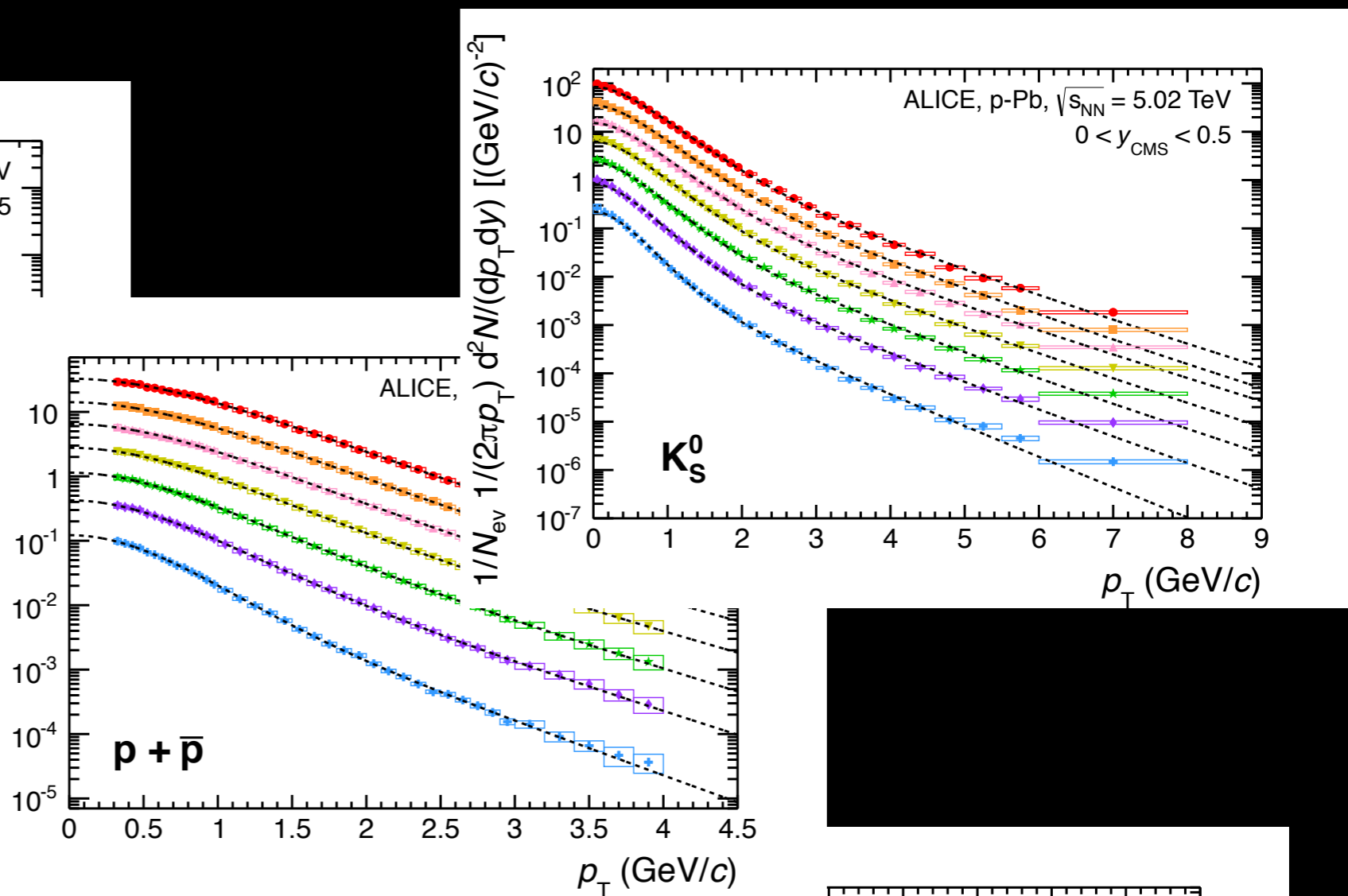
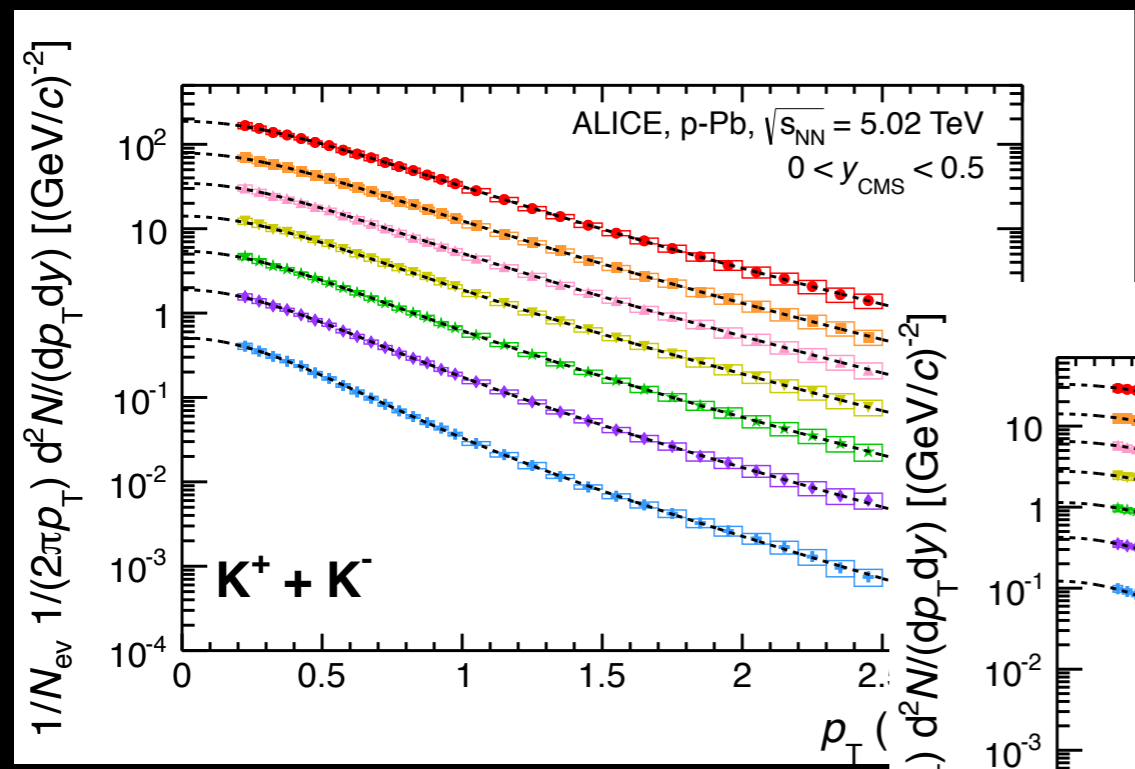
collectivité partout ?  
Modèles !



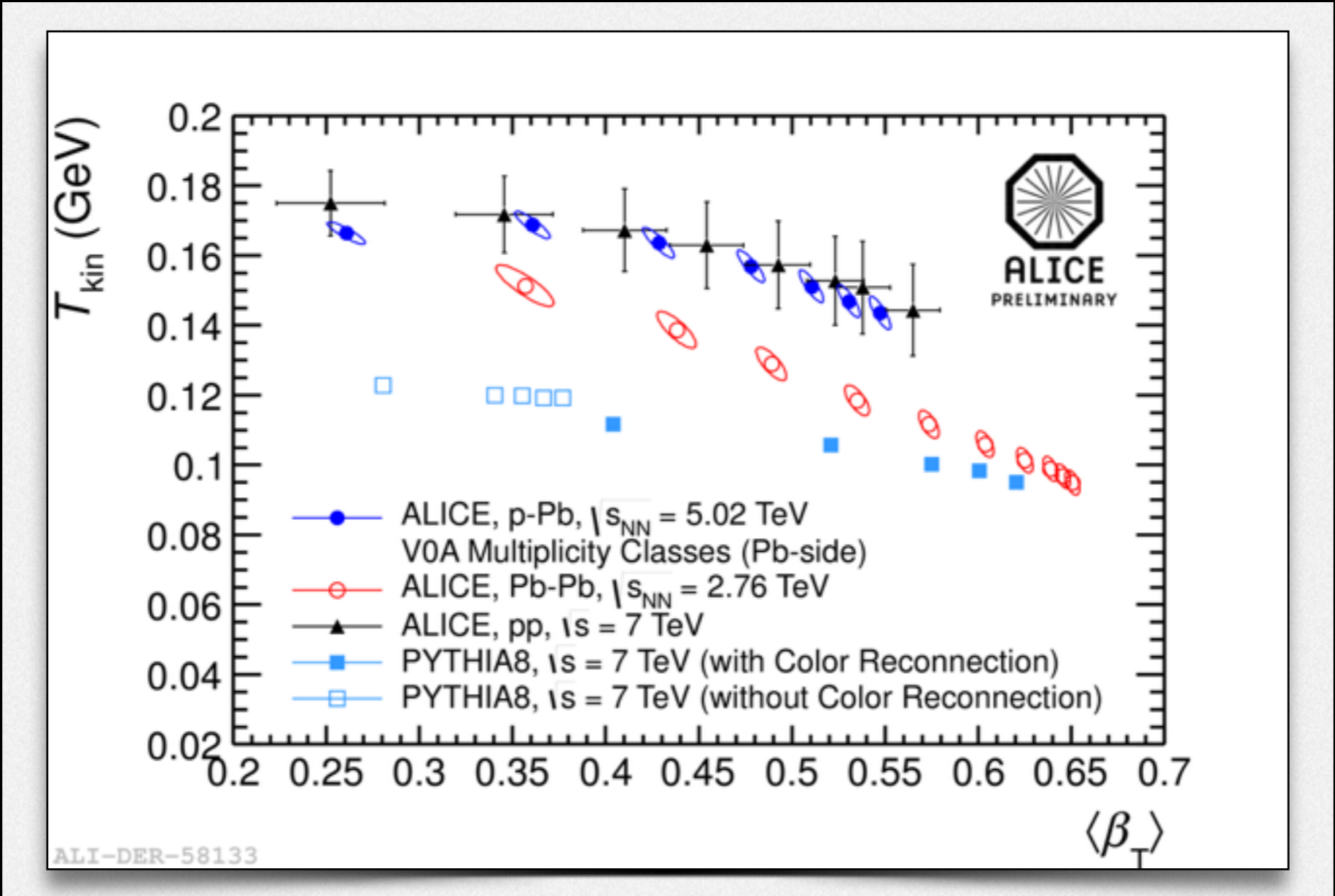
# Ta Panta Rhei (Τα Πάντα ρεῖ )



# Blue shift: flow radial



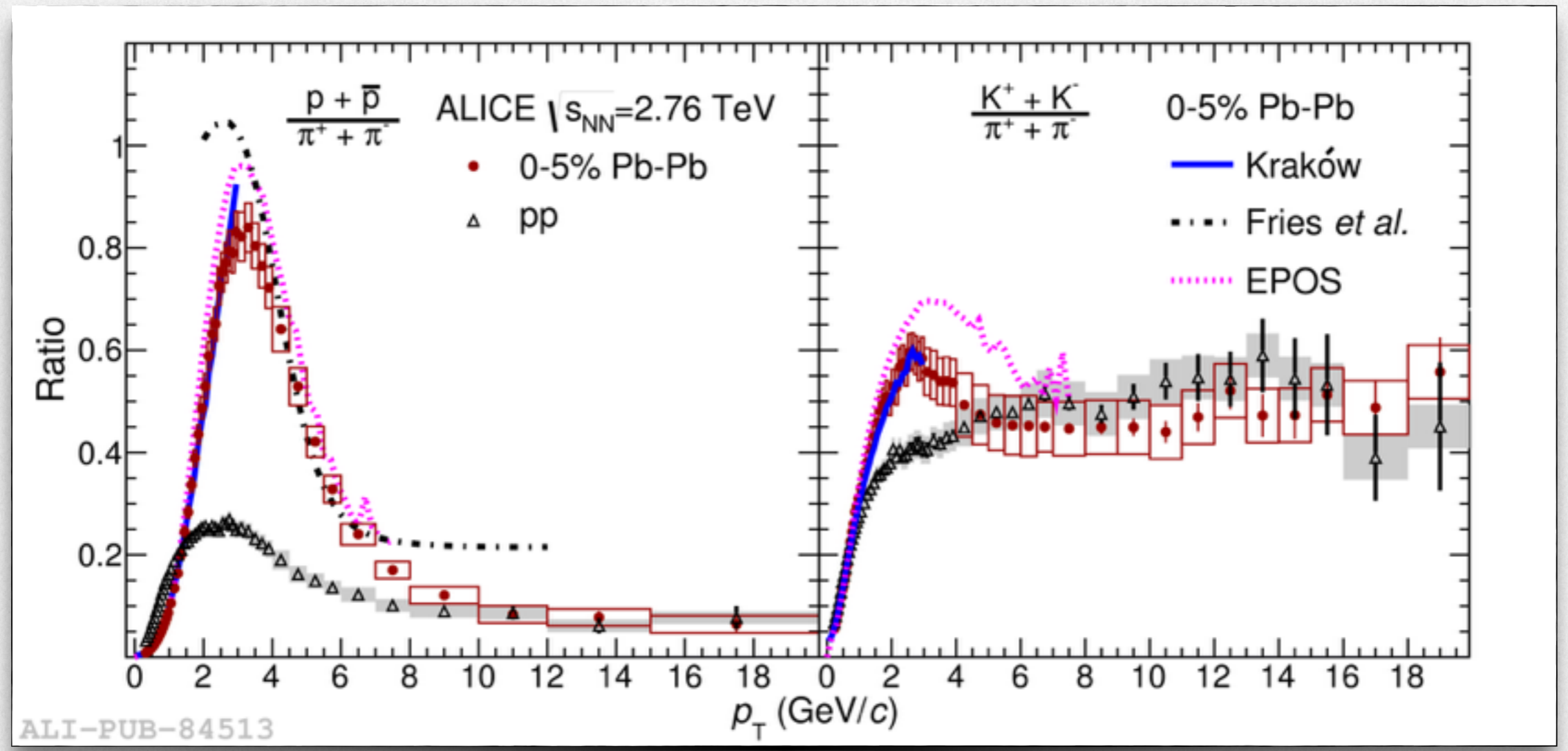
# Flow radial



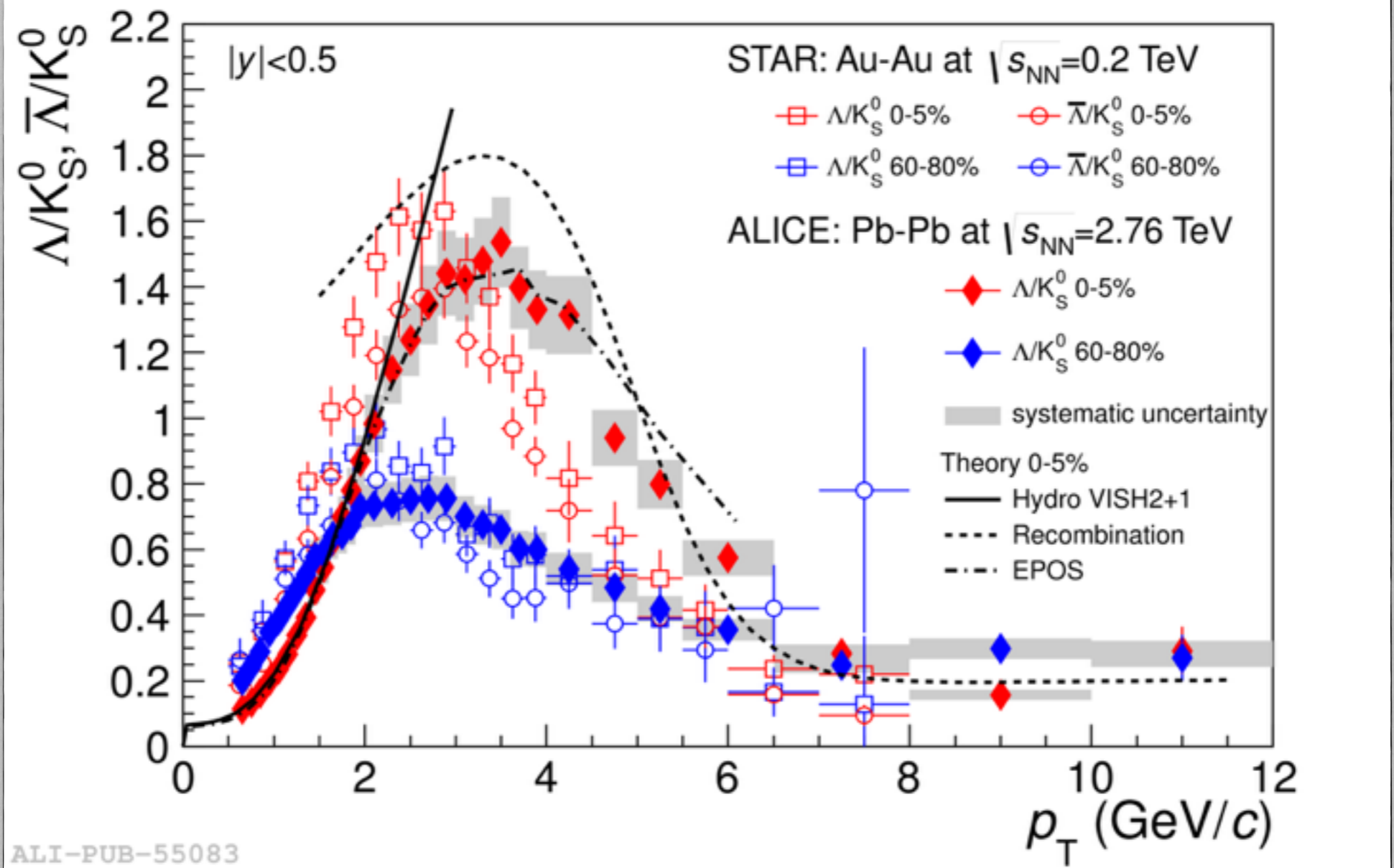
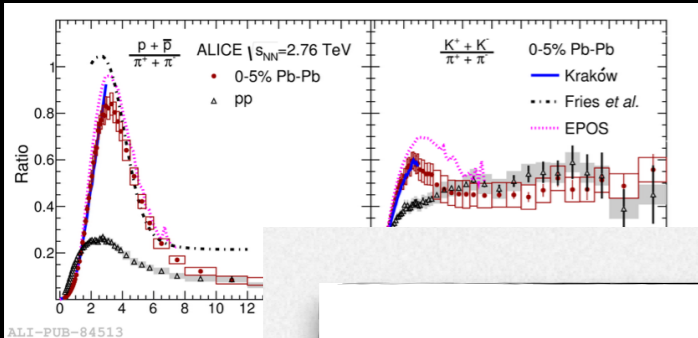
p-Pb and pp: gradient radial (plus fort)!

p-p: mécanisme FS singe flow radial !!

# Baryon & Meson léger

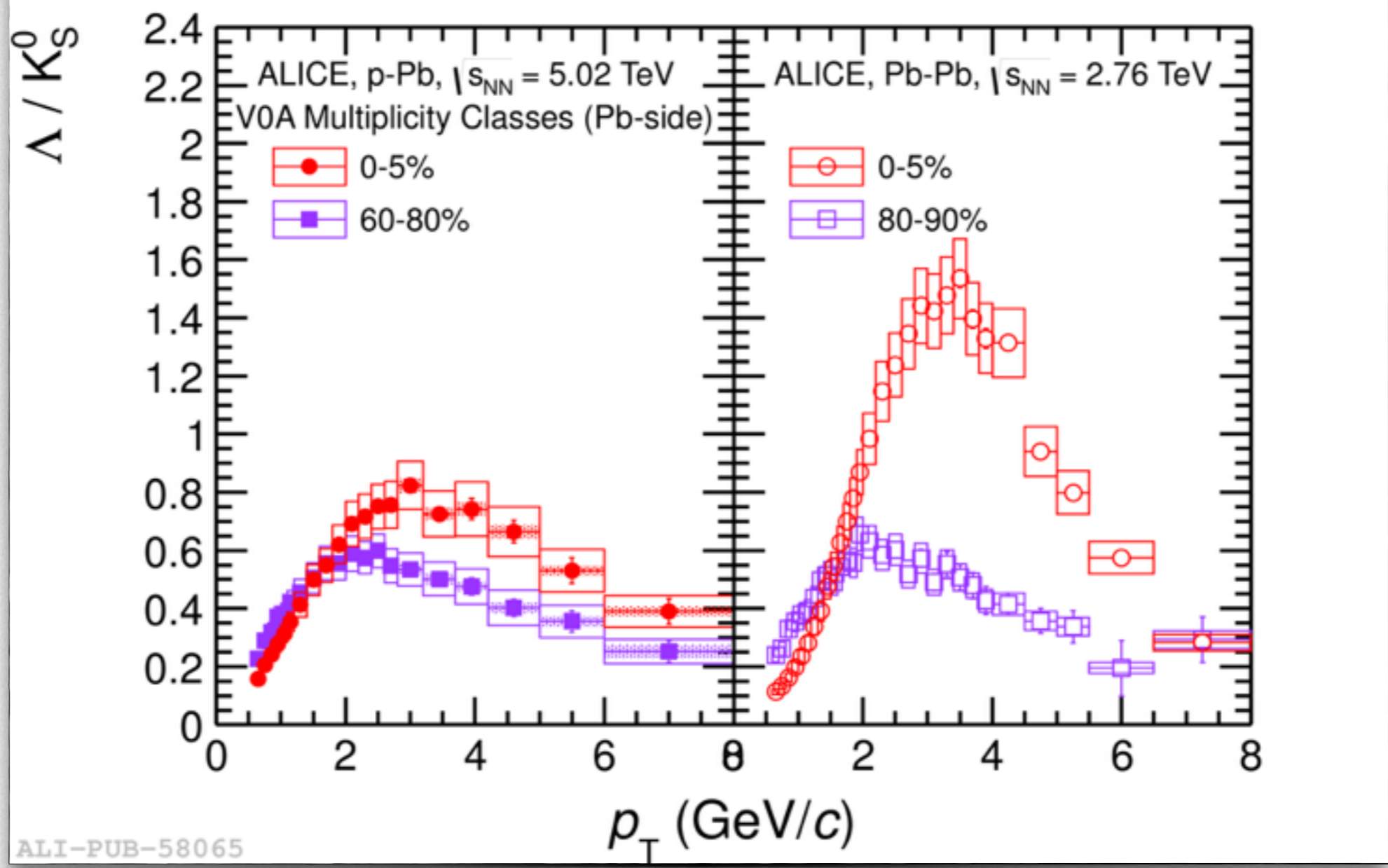
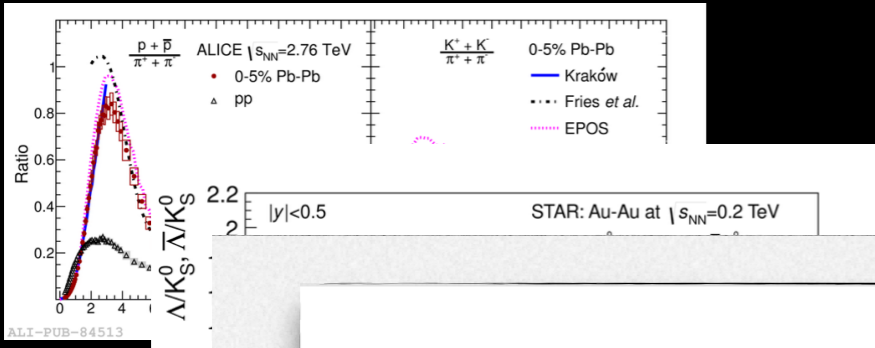


# Baryon & Meson étrange

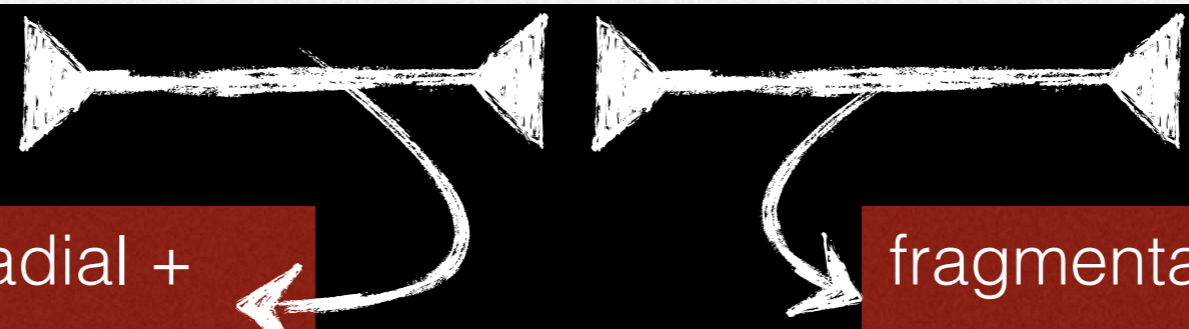
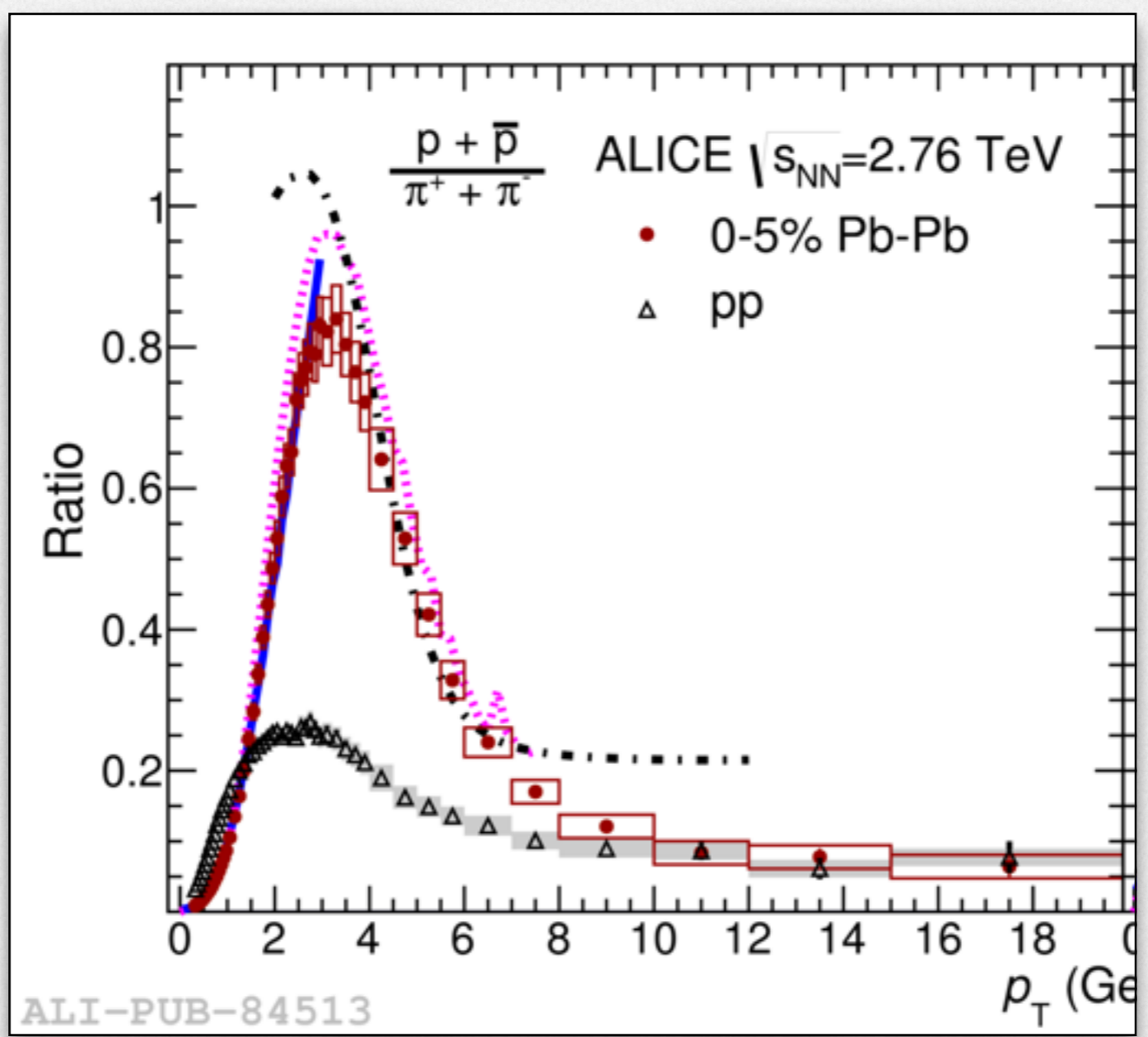
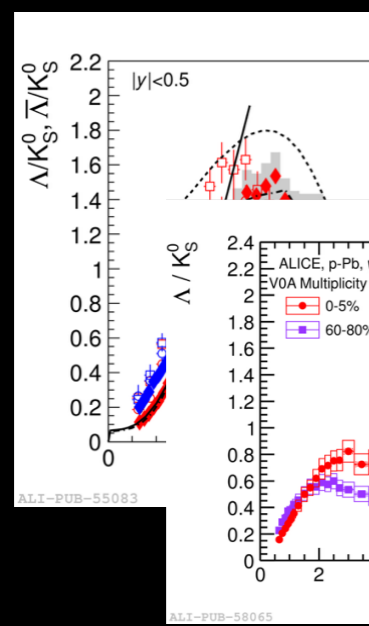


# Baryon & Meson

pPb pareil !



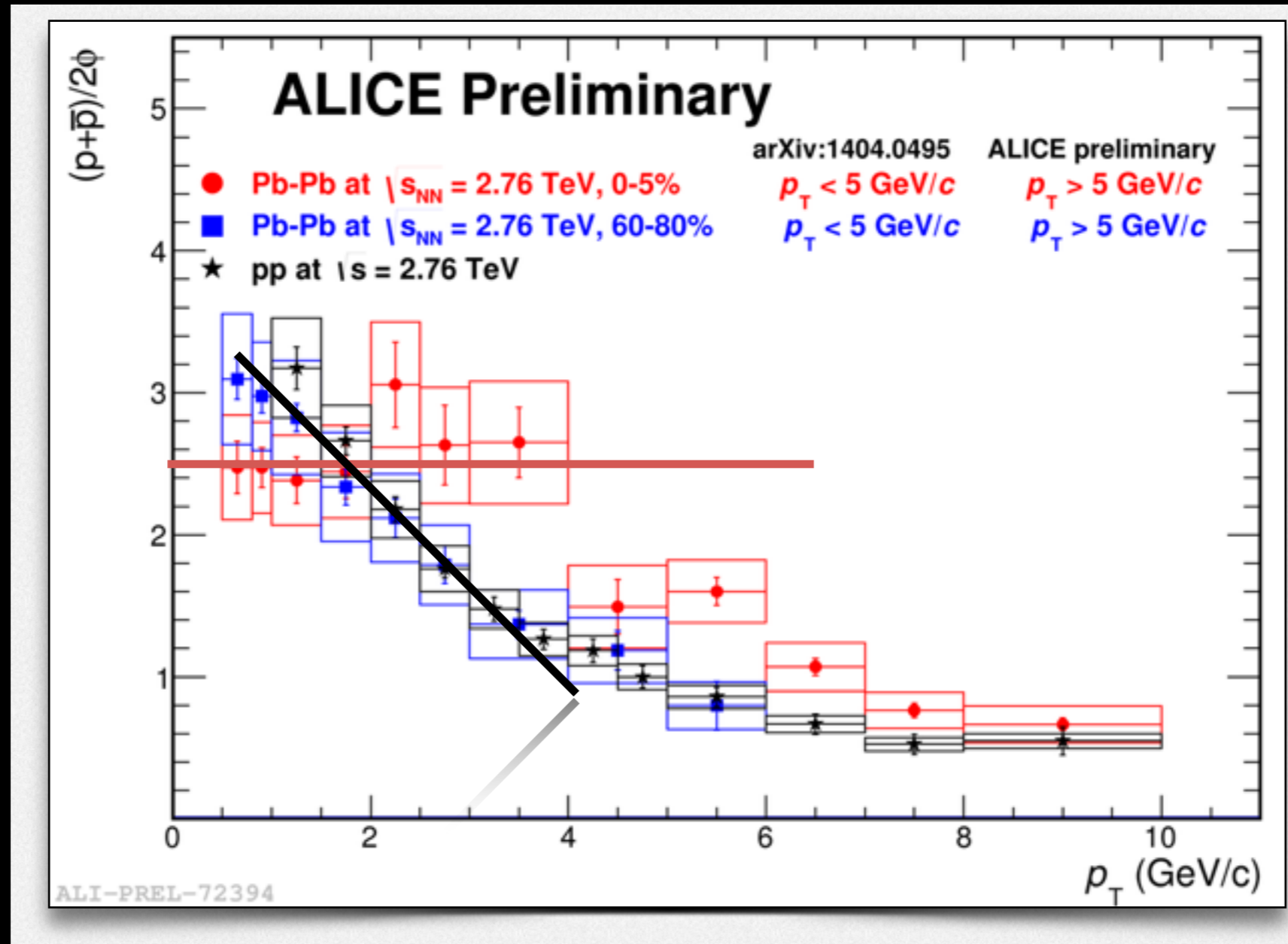
# Baryon & Meson



effets collectifs: flow radial + coalescence ?

fragmentation jet dans le vide: pQCD

## Baryon &amp; Meson



effets collectifs: flow radial +  
~~coalescence ?~~

Masse plutôt que # quark

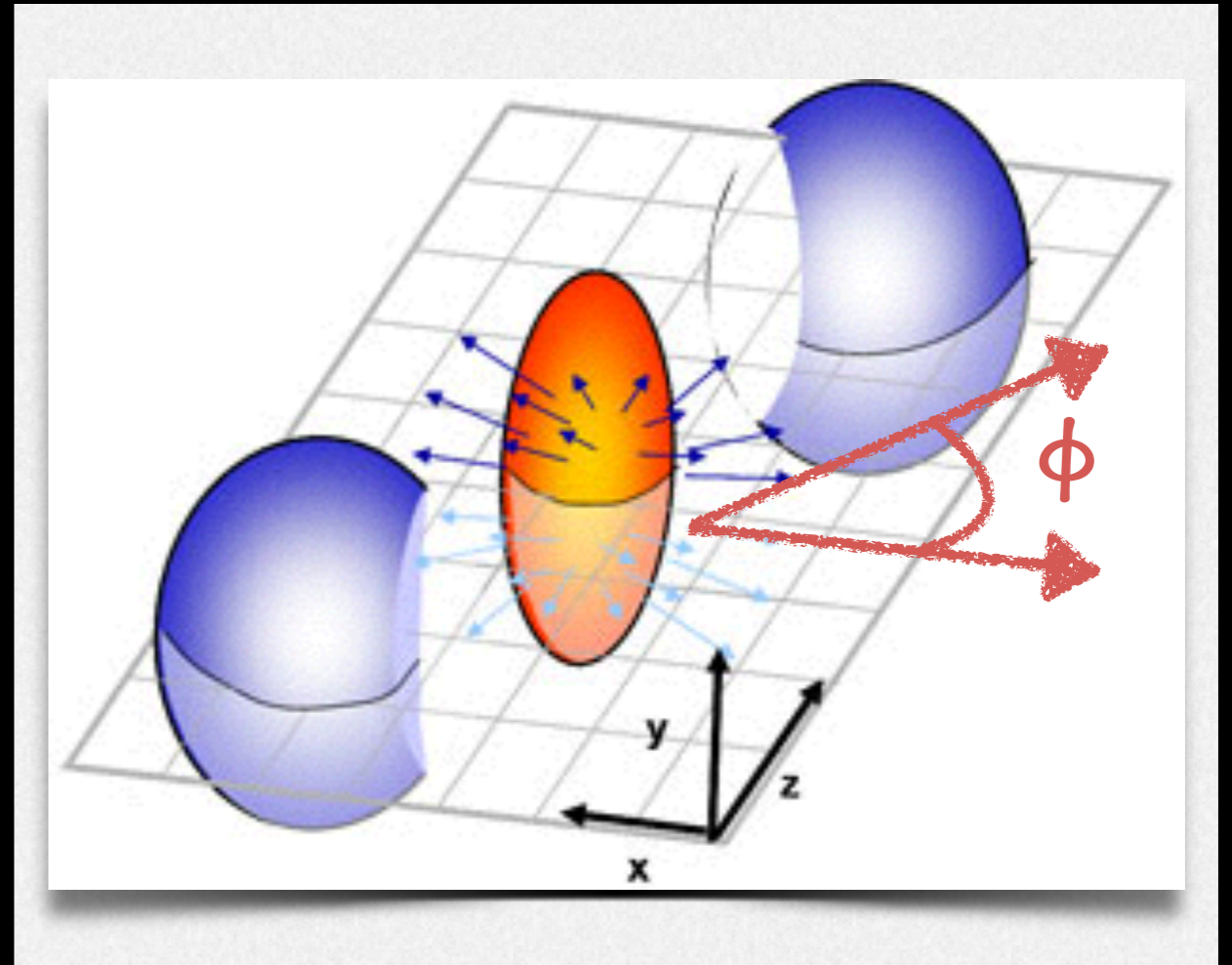


# Heavy-ion collisions 4 Hydrodynamics

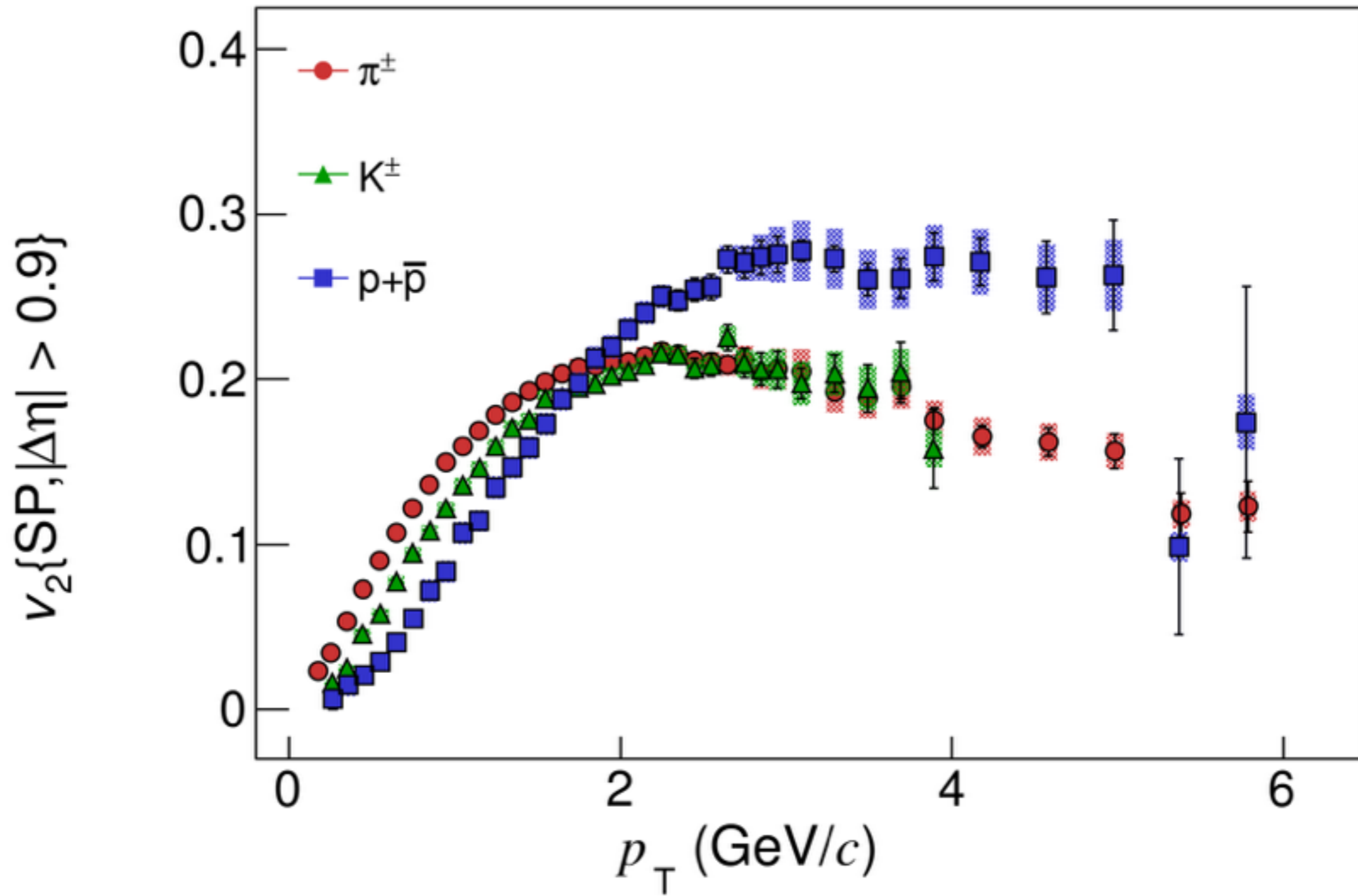
$\varepsilon_2$  : géométrie  
(paramètre d'impact)

liquide + dissipation  
minimale

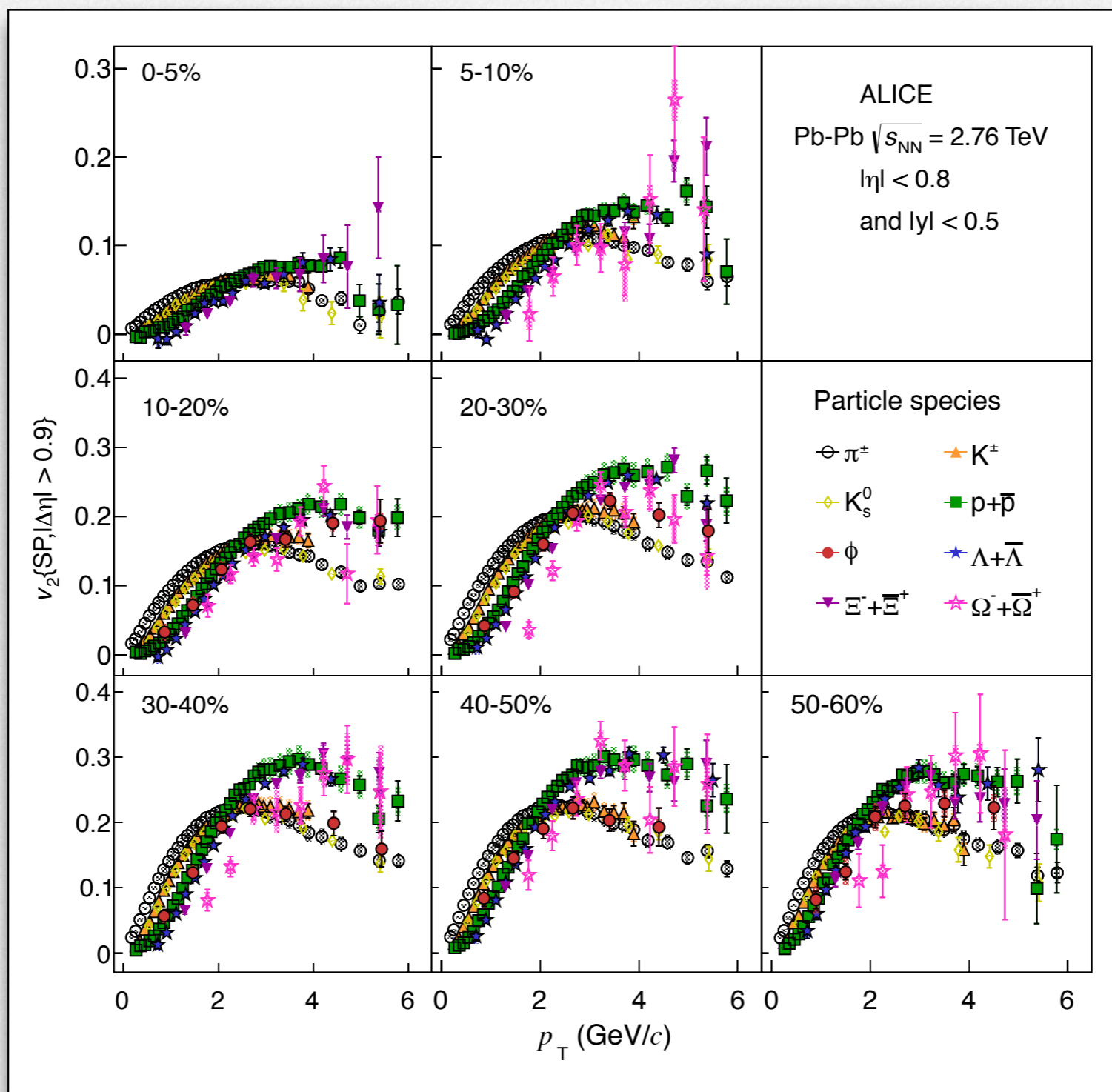
$v_2$  : dans l'espace des  
impulsions



ALICE 50-60% Pb-Pb  $\sqrt{s_{NN}} = 2.76$  TeV

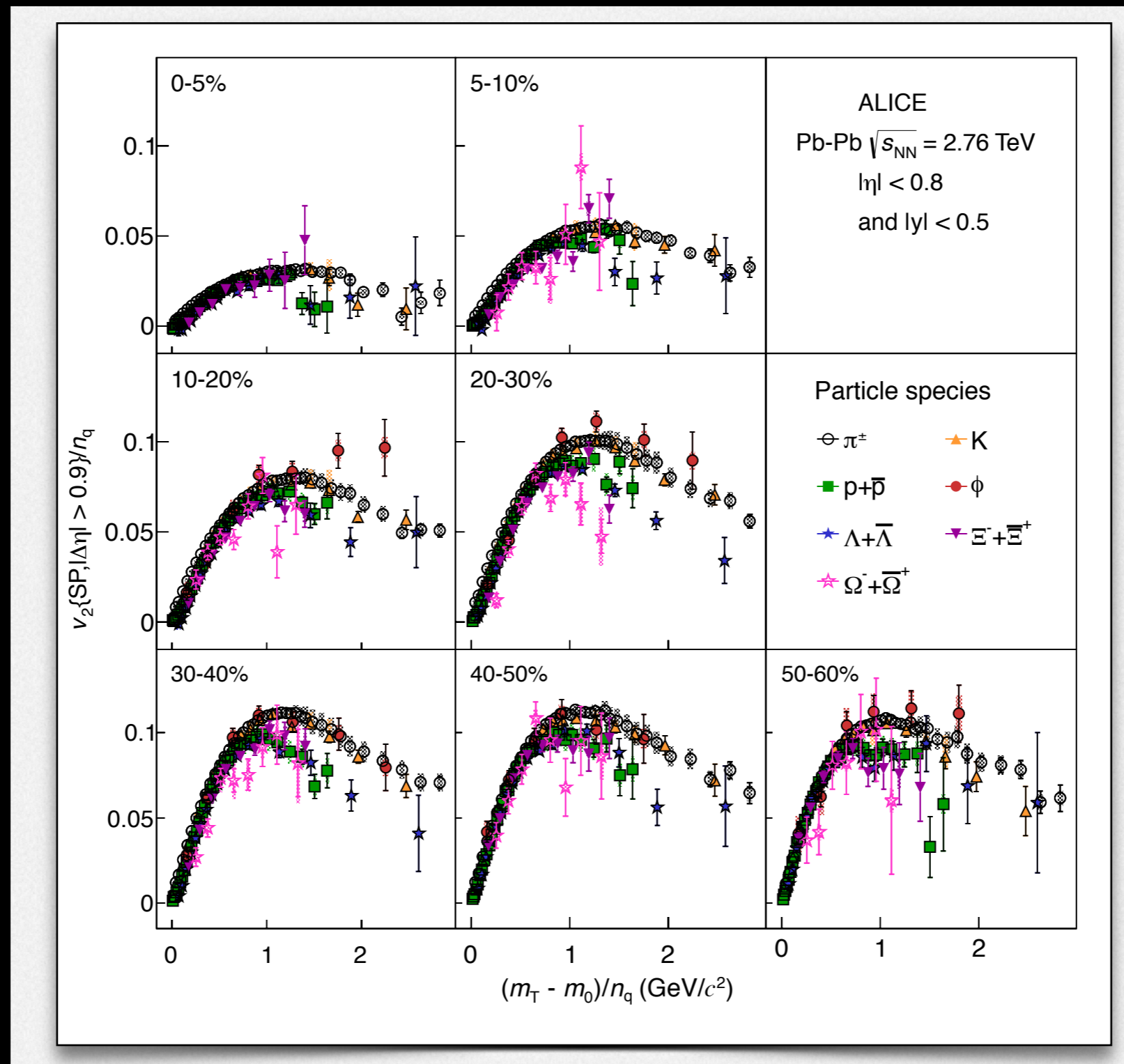


## Flow elliptique



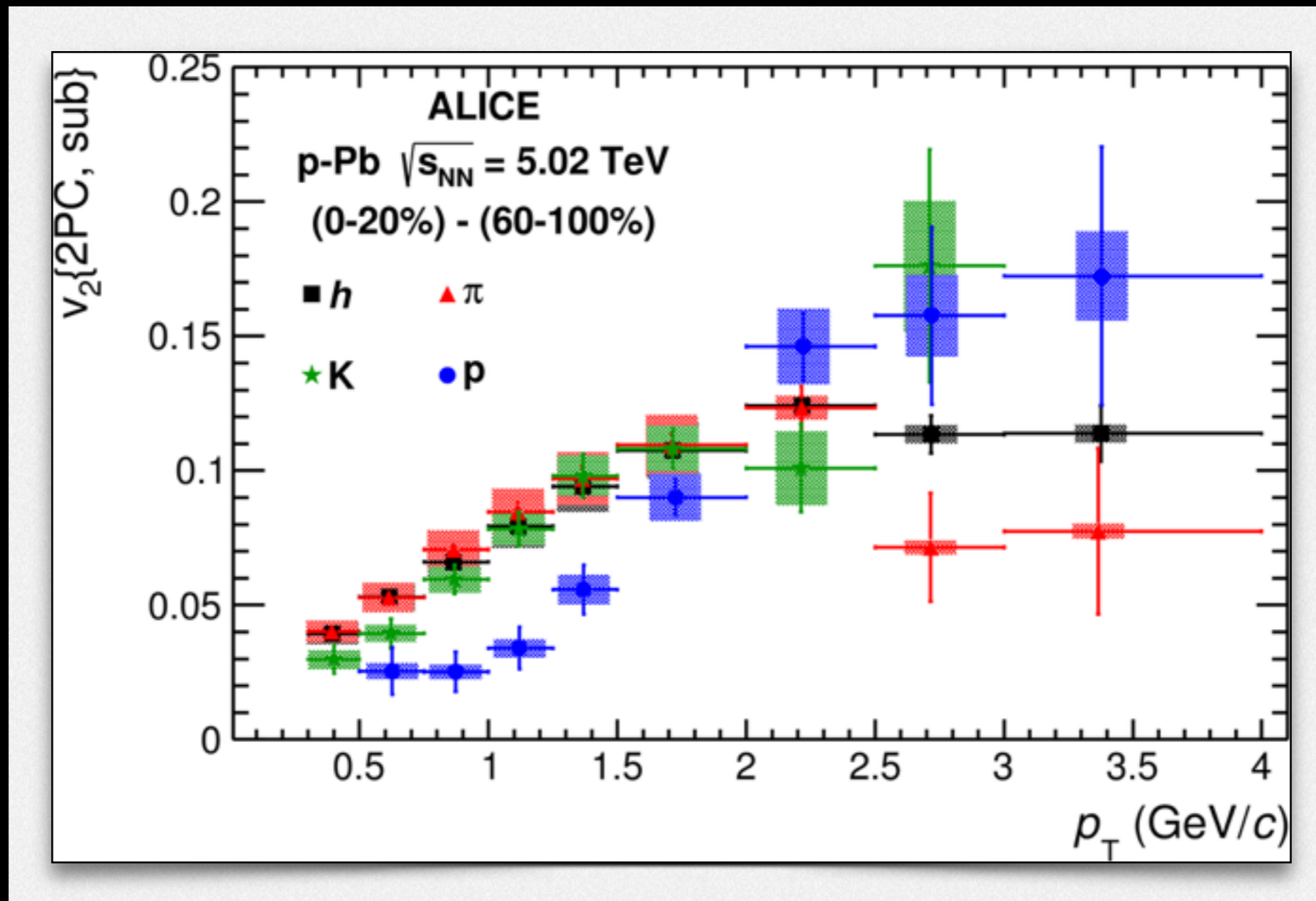
hadronization par coalescence de  $q \rightarrow q$  DoF à  $T > T_H$ ?

## Flow elliptique



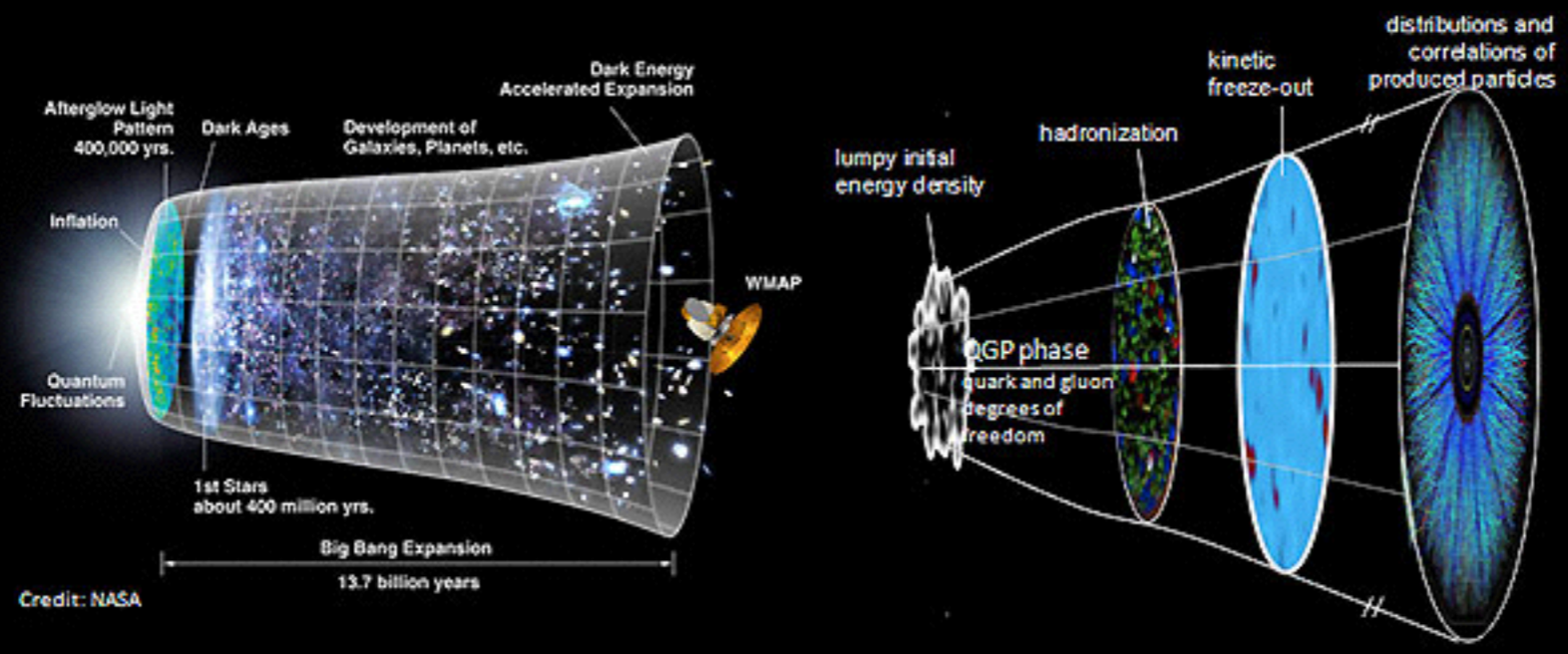
~~hadronization par coalescence de  $q \rightarrow q$  DoF à  $T > T_H$ ?~~

## Flow elliptique



pPb: flow hydro, pareil ! le succès gênant de hydro

# The Big (Bang) story

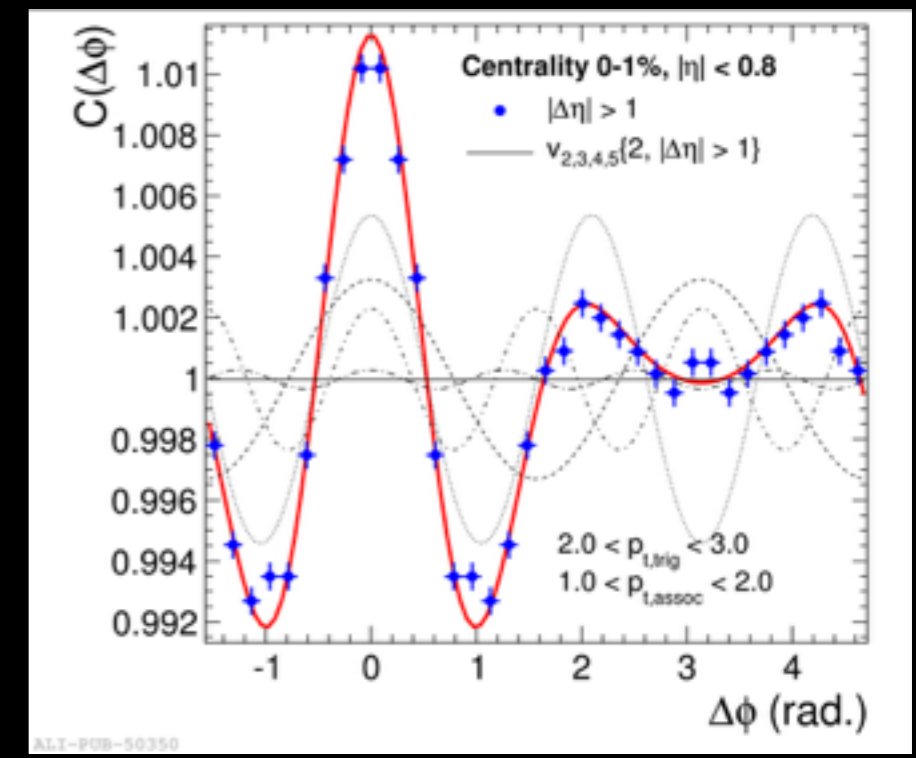
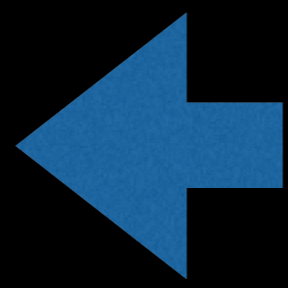


Dissipation in the perfect liquid is minimal:

QGP transparent aux fluctuations quantiques dans IS

hydro non dissipatif  
+ dynamique des  
champs classiques

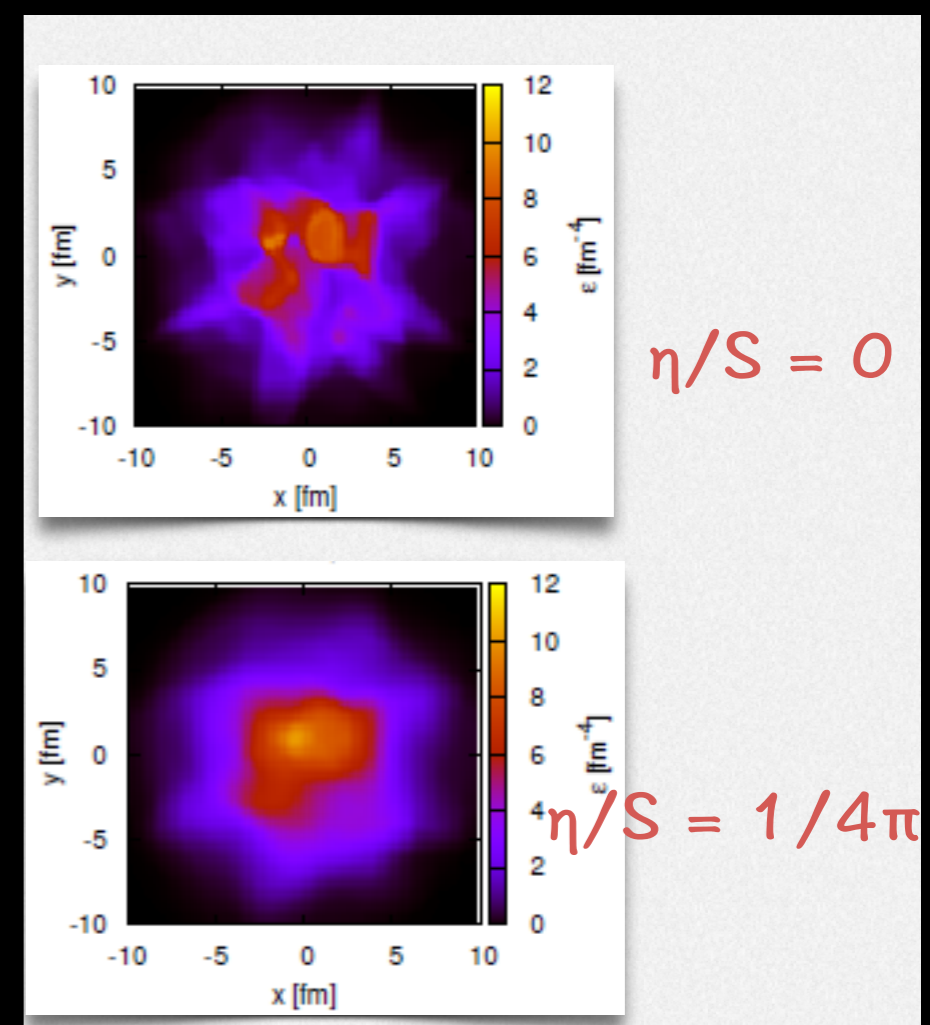
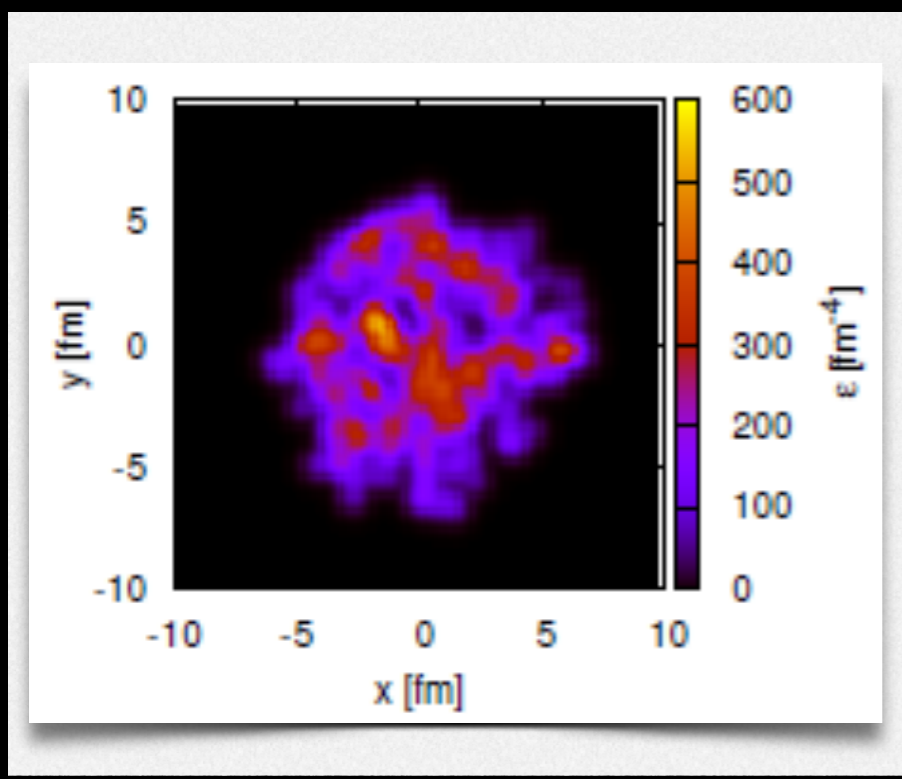
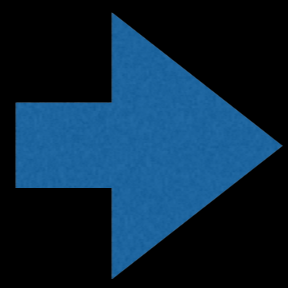
IS: pure champ de  
jauge faiblement  
couplé +  
fluctuations  
quantiques



Dissipation in the perfect liquid is minimal:

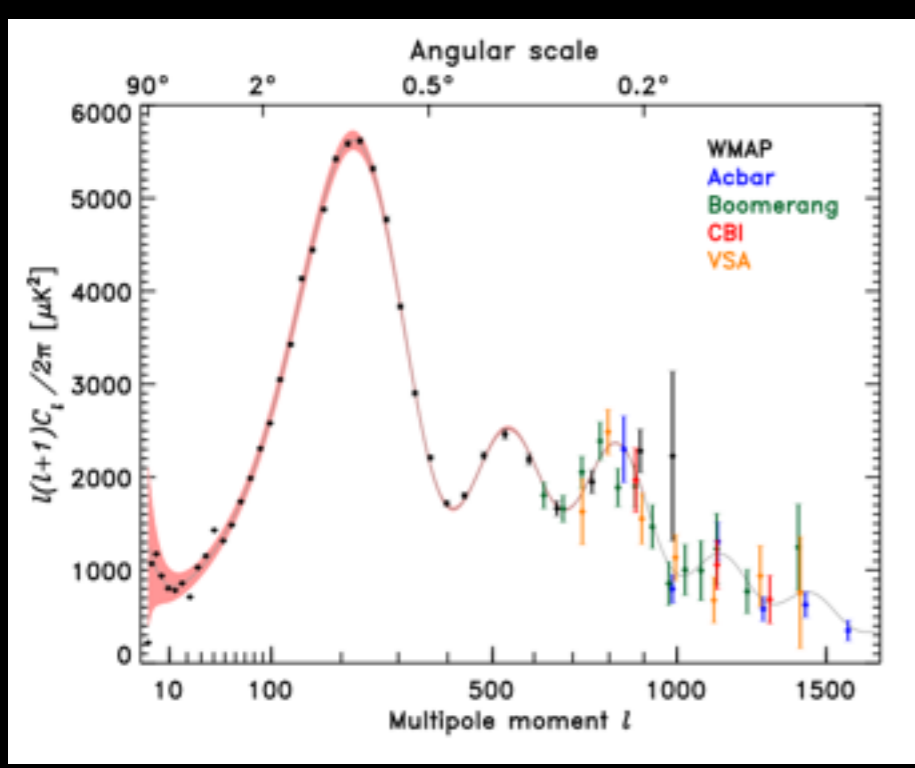
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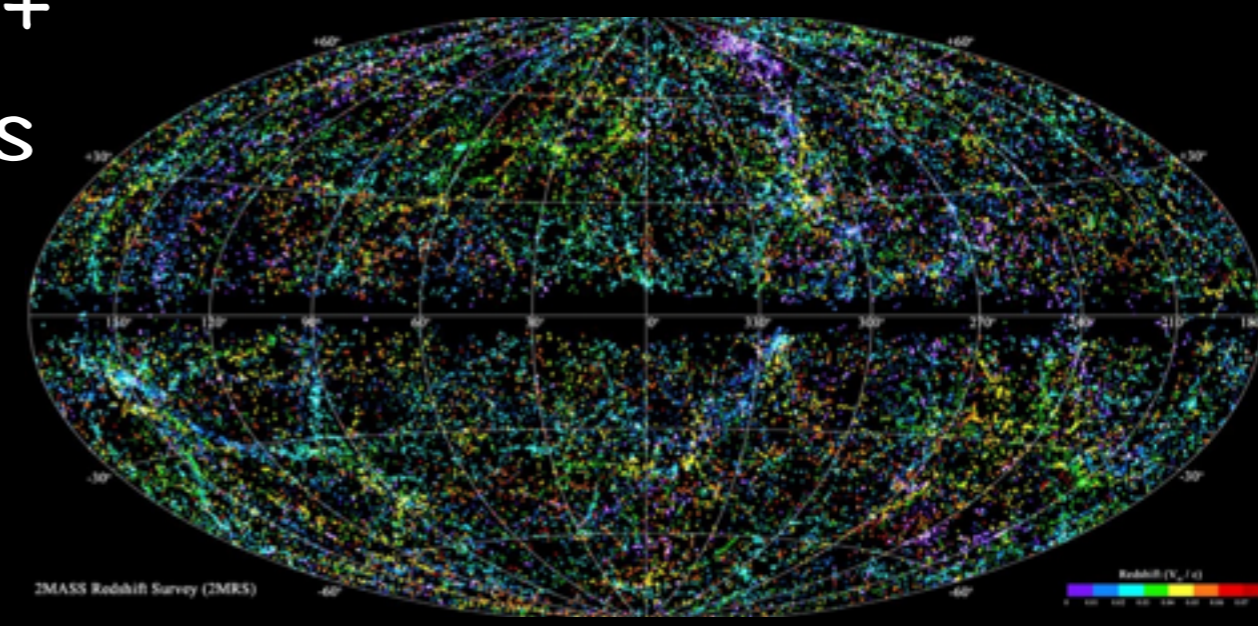
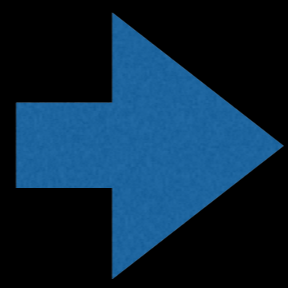




## Analyse des fluctuations permet d'accéder aux propriétés du matériau



### BB modèle + paramètres

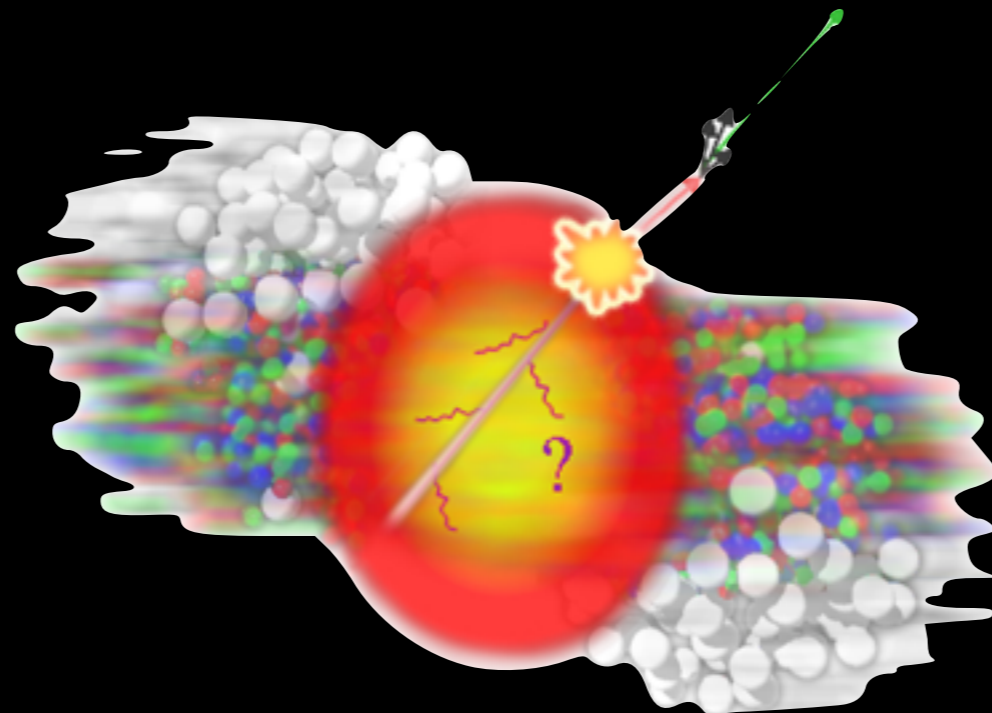


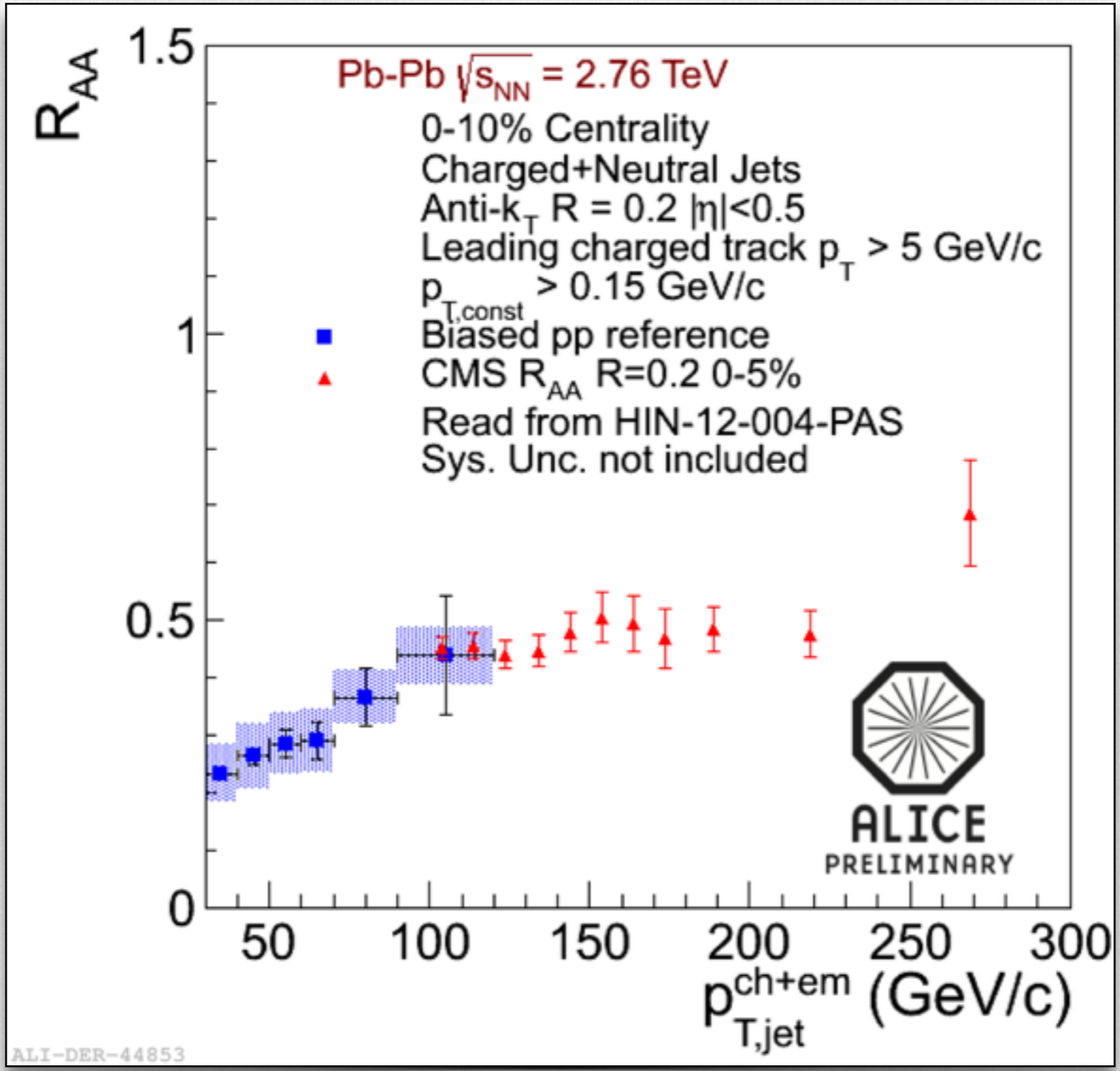
hard:  $p_T, m_T \gg T, \Lambda_{\text{QCD}}$

sonde QGP à grande résolution (DoF)

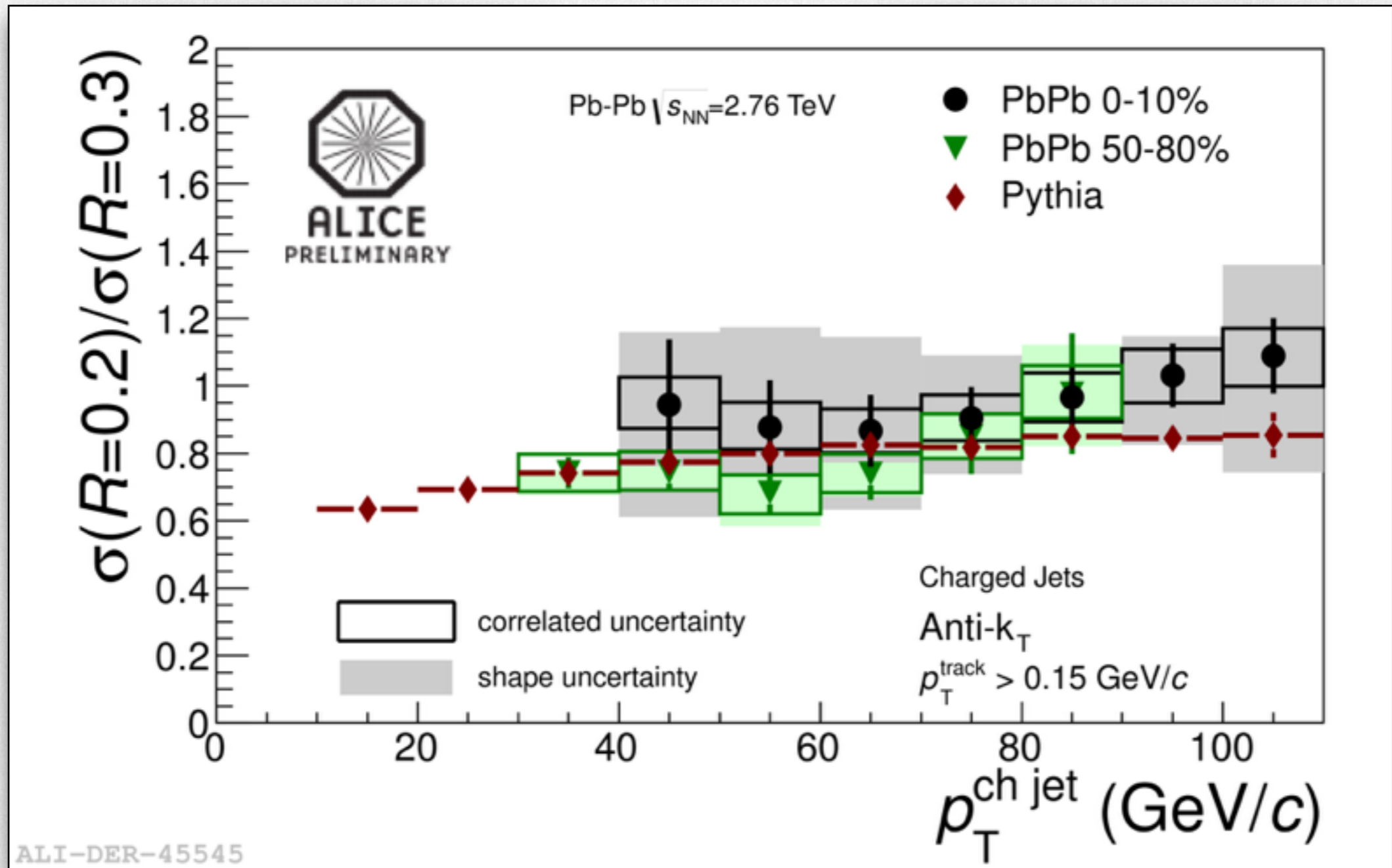
hard:  $p_T, m_T \gg T, \Lambda_{\text{QCD}}$

Transport de partons dans QGP: couleur, saveur, masse





jets « perdent de l'énergie »

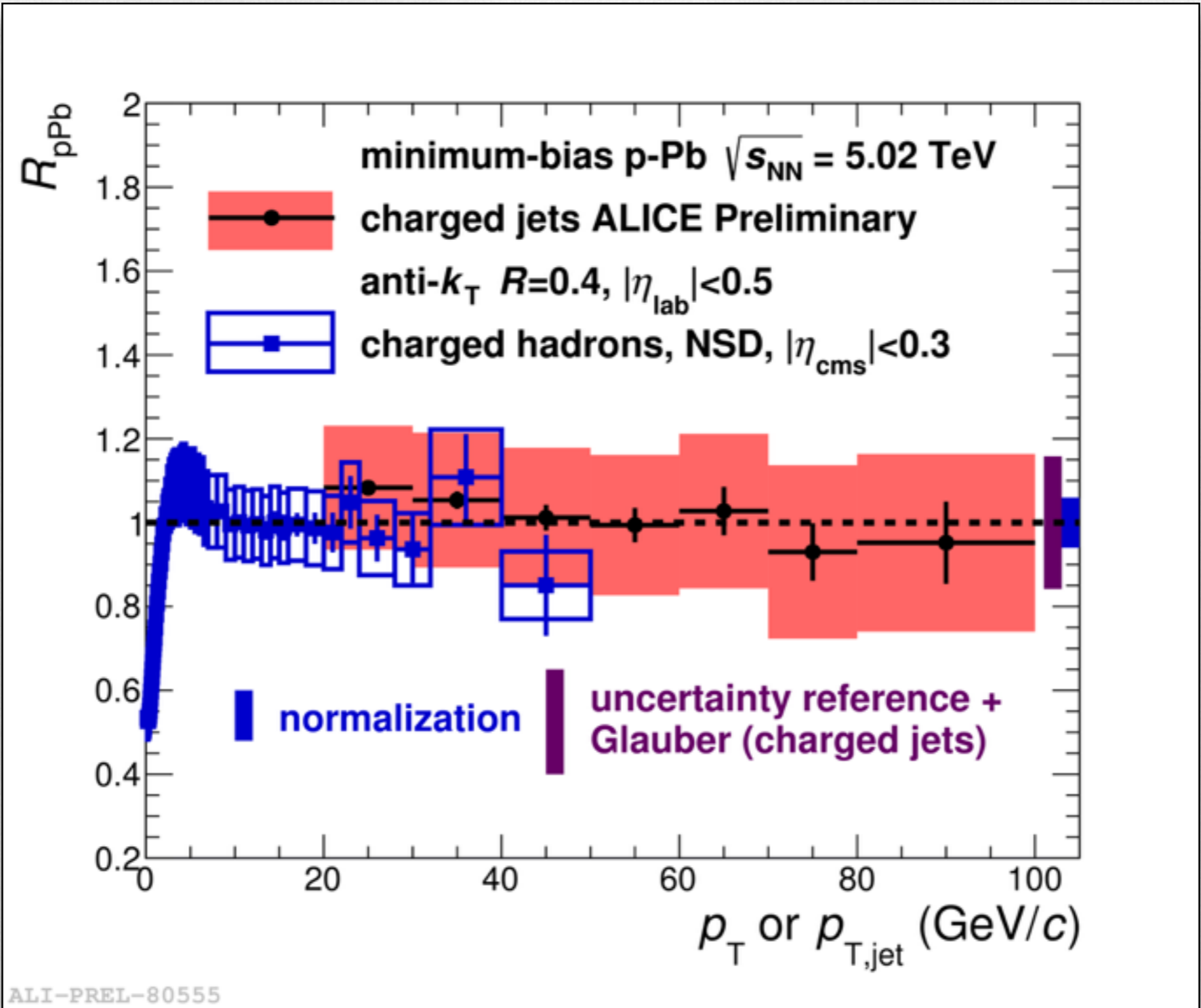


ALI-DER-45545

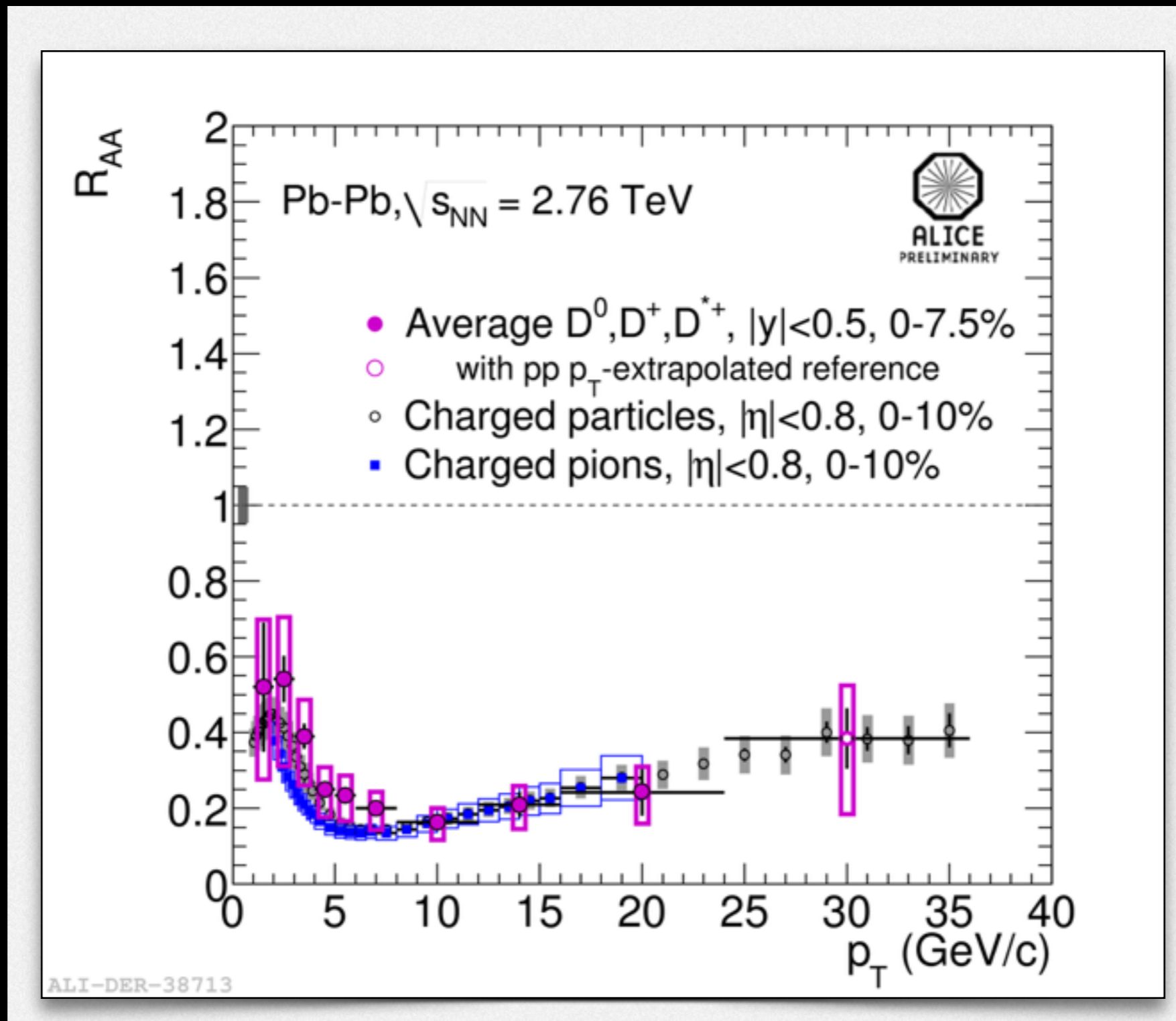
Où est rayonnée l'énergie perdue ?

$$\hat{q} = f(\sqrt{s}, T, E_{\text{jet}}, L_{\text{milieu}})$$

- ▶ Quelles contraintes quantitatives sur les propriétés du milieu ?
- ▶ Théorie et expérience: même langage ?
- ▶ Existe-t-il une approche expérimentale pour discriminer aspect perturbatif et couplage fort ?

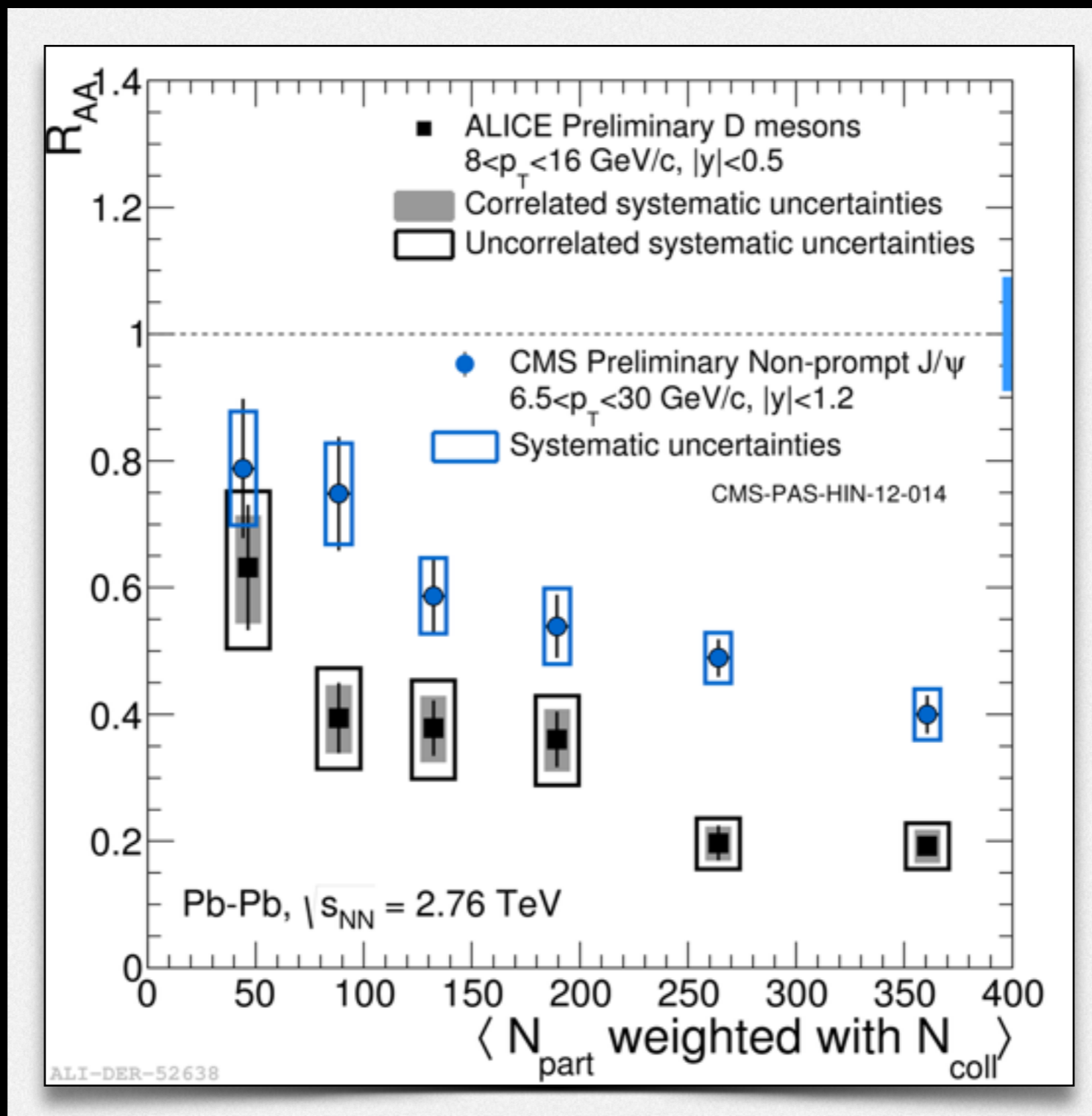


Pas d'effet de milieu FS dans pPb ??

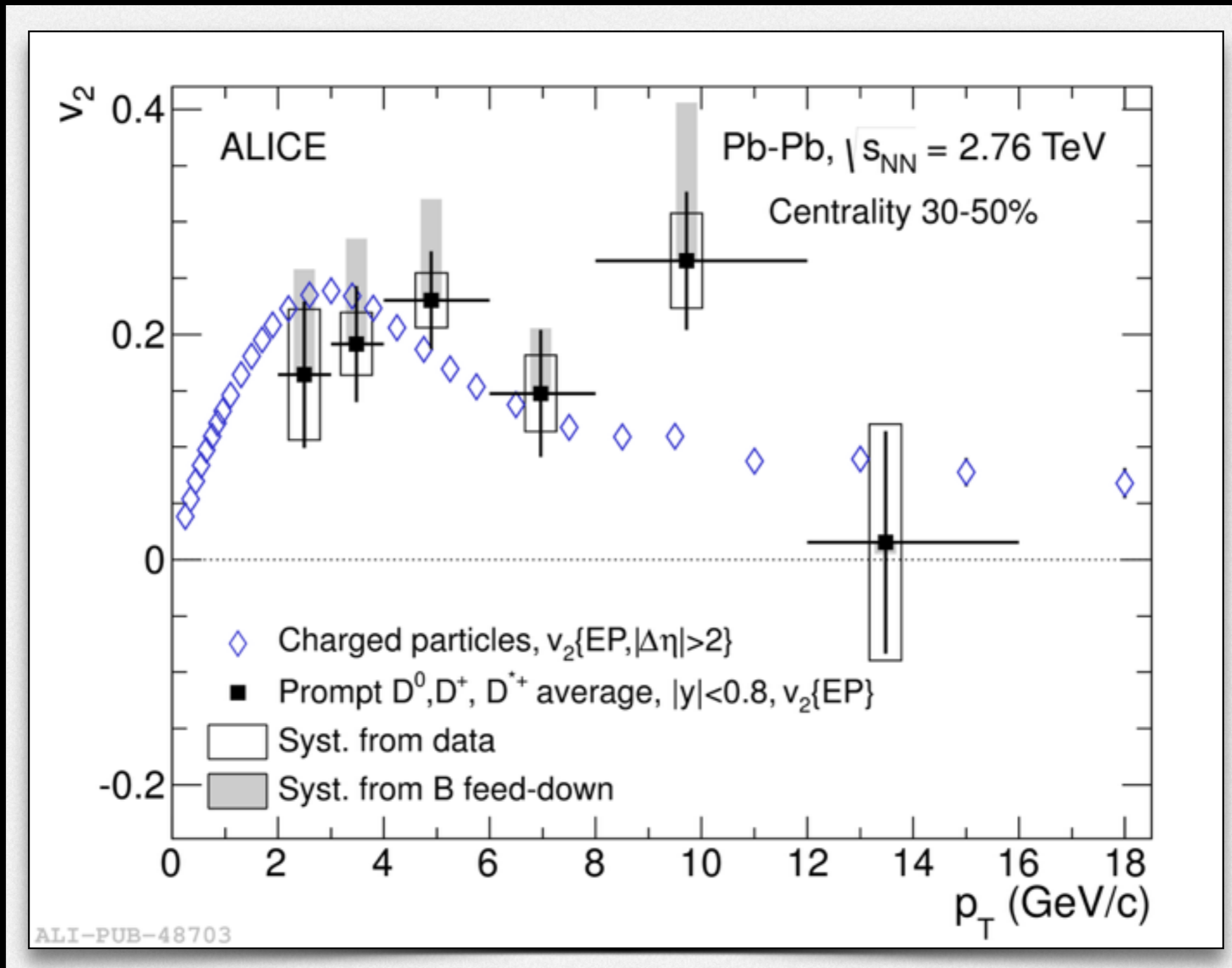


Effet charge de couleur (g vs q) ?

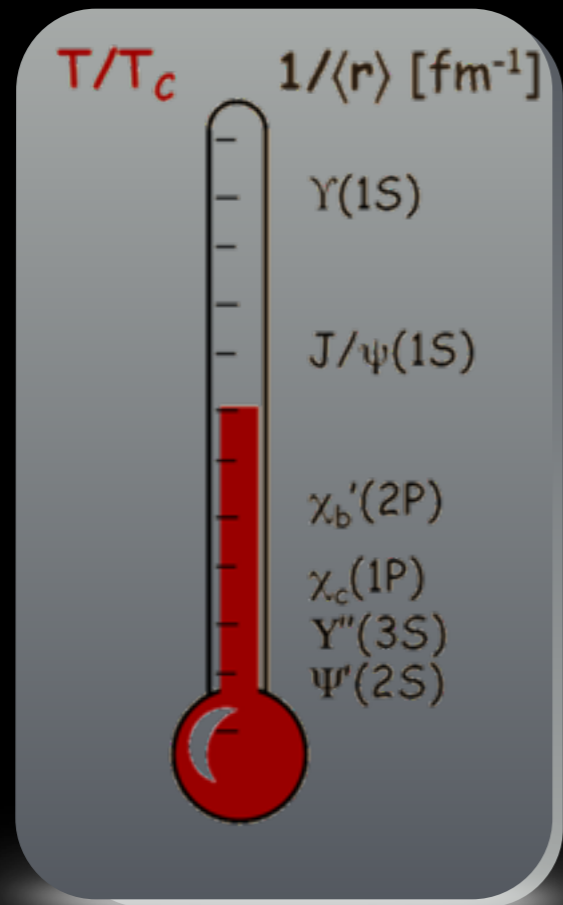




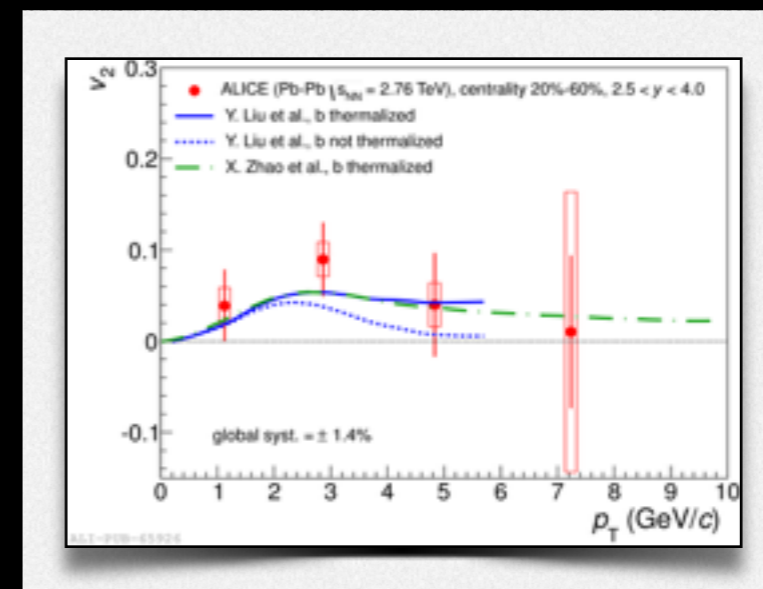
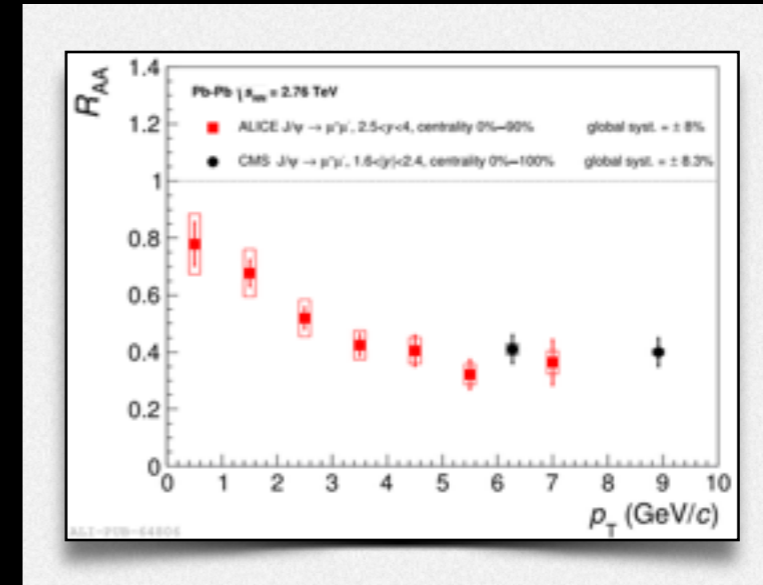
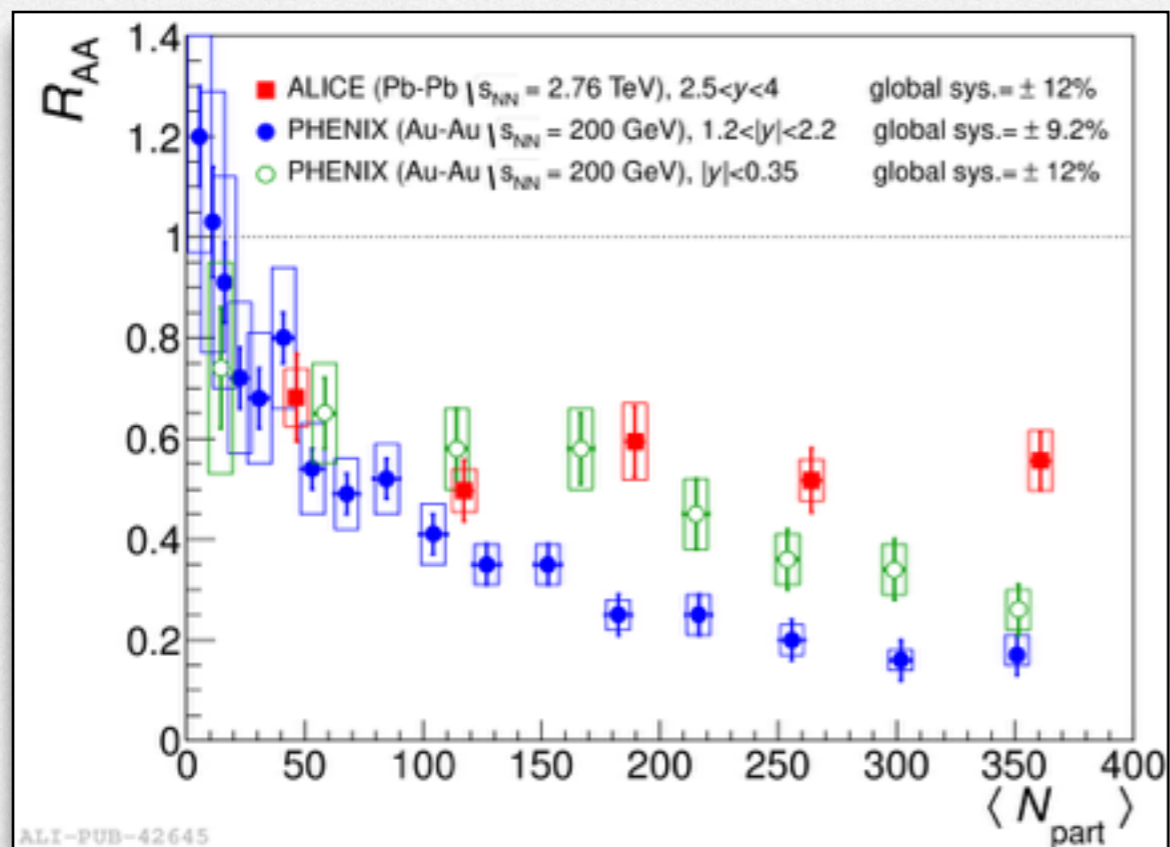
Radiatif ou collisions ?



Flow ? coalescence ?



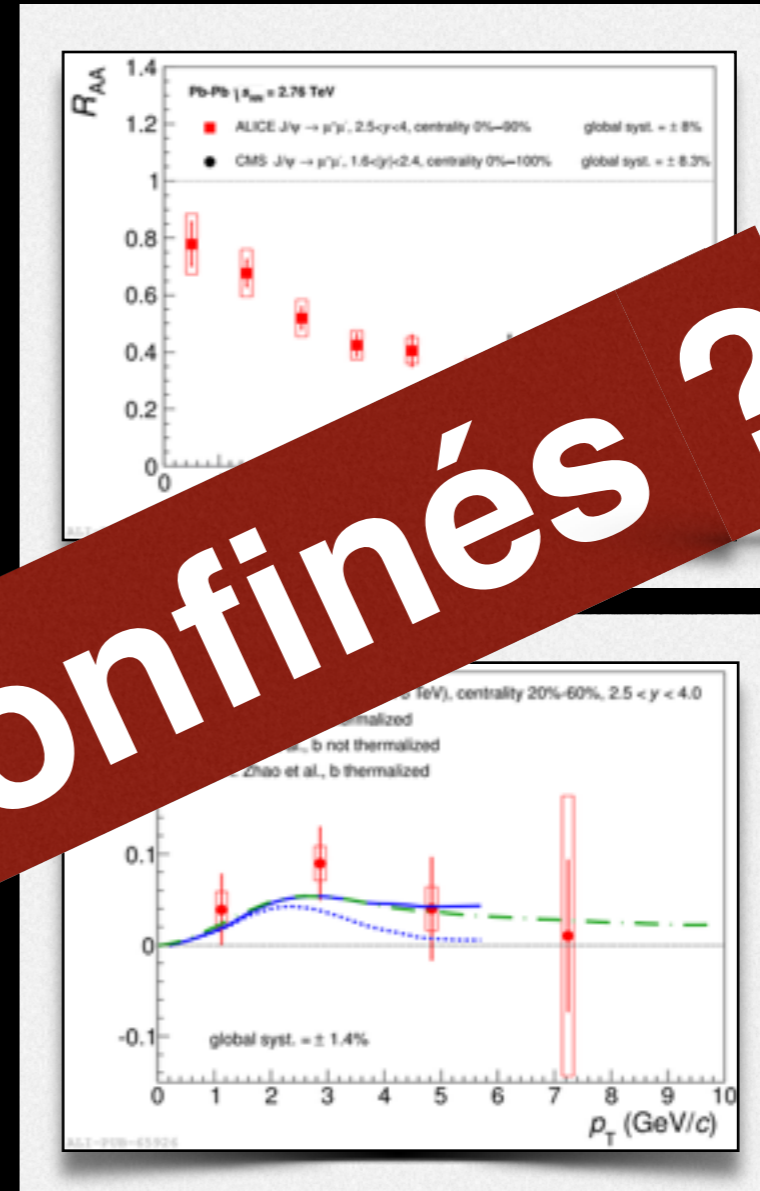
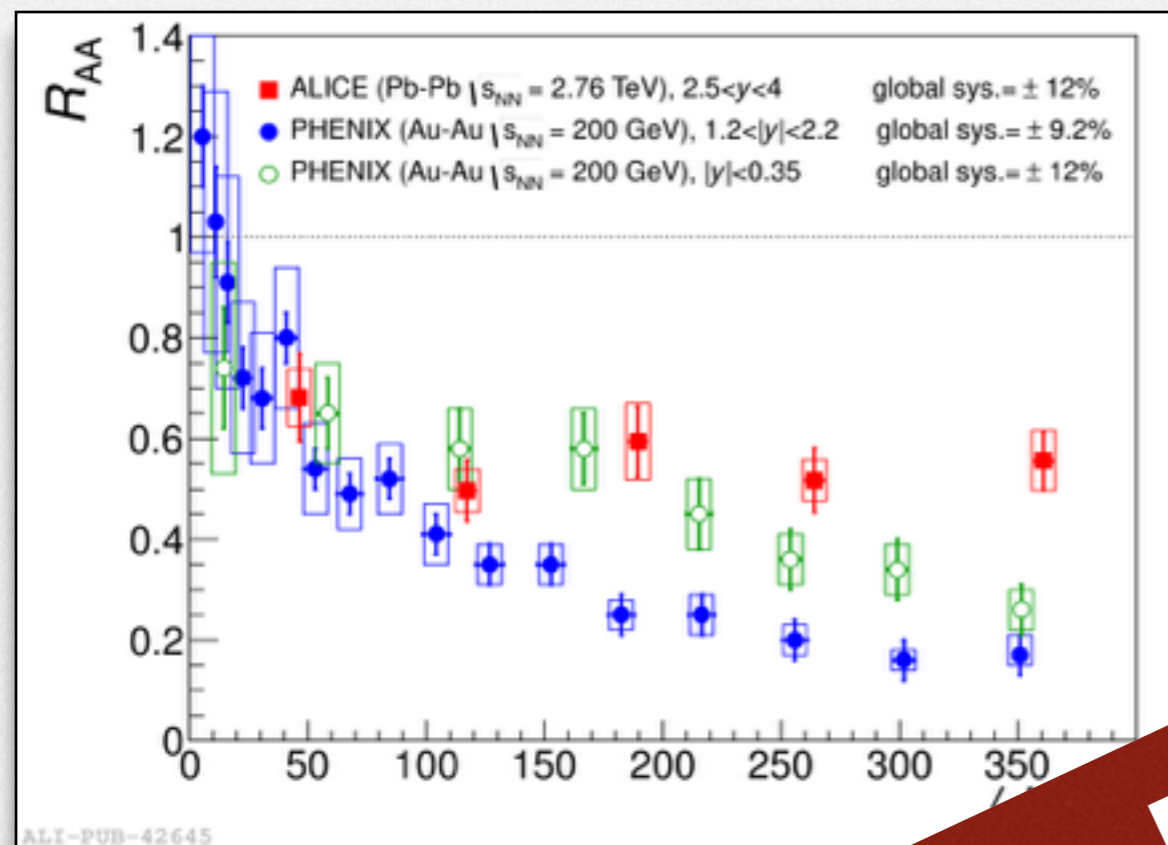
la saga quarkonia ...



processus dur  $\oplus$  écrantage de couleur  $\oplus$  coalescence

► c déconfinés dans **QGP**  $\rightarrow$  hadronisation statistique ?

► destruction/création continues dans **QGP**  $\rightarrow$  gel ?



# Quarks déconfinés ?

processus  $\oplus$  écrantage de couleur  $\oplus$  coalescence

▶ c déconfinés dans **QGP**  $\rightarrow$  hadronisation statistique ?

▶ destruction/création continues dans **QGP**  $\rightarrow$  gel ?

... et pour conclure

## Un nouveau chapitre du manuel de référence QCD

- ▣ La physique de l'équilibre dans QCD
- ▣ Comment est réalisée une dissipation minimale ?
- ▣ De quoi est fait le QGP ?

« It is made of quarks and gluons .... »

- *Frank Wilczek, QM2014* -