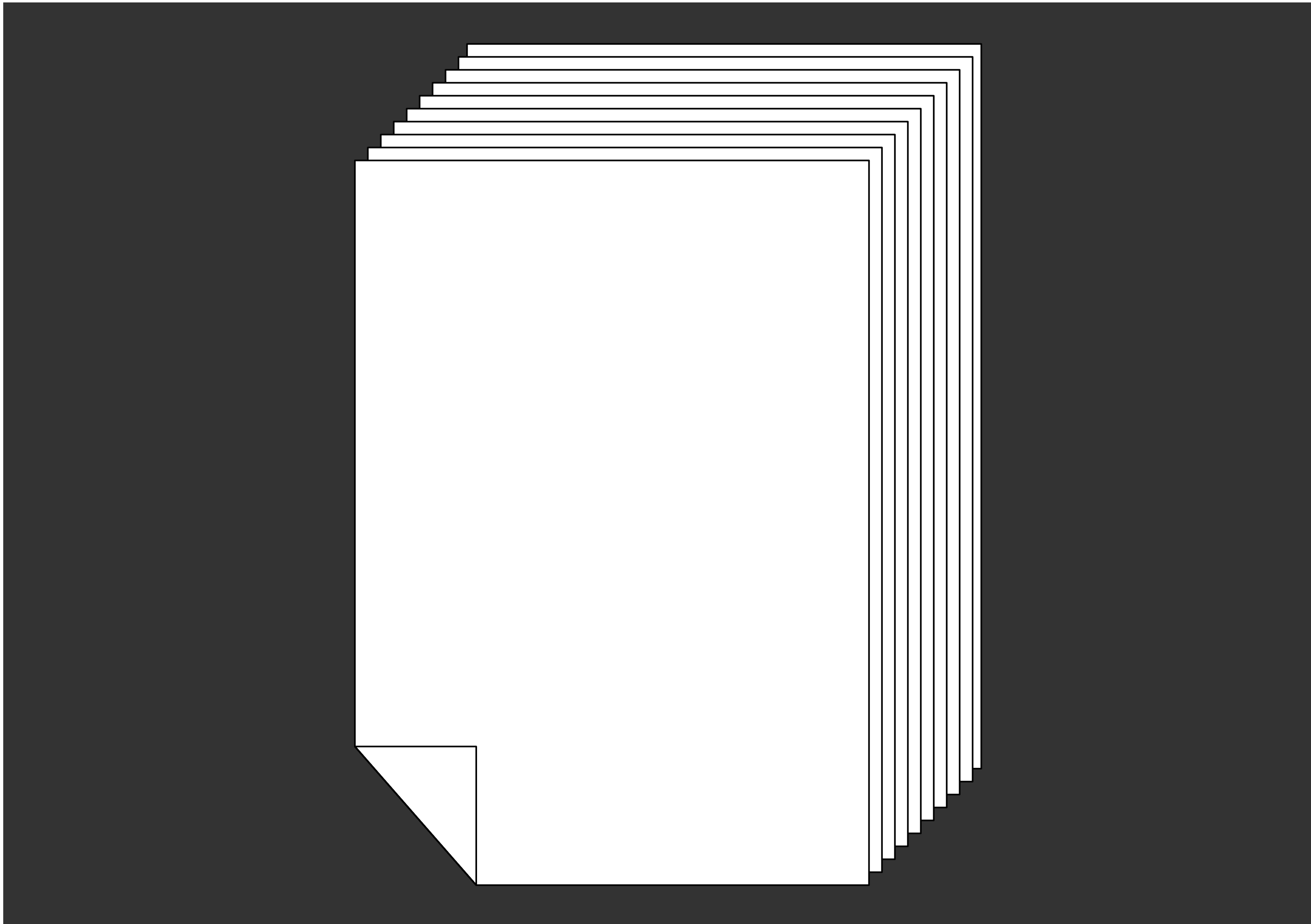


Conclusions physiques du White Paper

- Densité d'énergie et particules chargées
  - Densité d'énergie → 15 GeV/fm^3
  - Particules chargées → saturation des gluons dans l'état initial ?
- Thermalisation
  - Production d'étrangeté en accord avec l'hypothèse d'un équilibre chimique.
  - Le flot elliptique observé indique un haut degré de collectivité.
  - Pas d'image consistante de la dynamique de la collision.
- Binarité
  - Effet Cronin en dAu → CGC ?
  - Binarité des photons directs et du charme en AuAu → compatible avec CGC ?
- Suppression à grand pT
  - Suppression des hadrons croissante avec la centralité → milieu dense
  - Hypothèse d'un milieu dense confirmée par les corrélations angulaires
- Production des hadrons
  - Différence de comportement protons/pions
  - Étude du méson Φ → différence de comportement pas liée à la différence de masse
  - Observation d'un flot partonique → différence de comportement liée au nombre de quarks
  - Corrélations des jets incompatibles avec modèles de recombinaison

Les données du White Paper

- Les périodes de prise de données
  - Le rapport porte sur les données des runs 01 – 02 – 03.
  - Pour les résultats des runs 04/05 → QM05

Run	Year	Species	$s^{1/2}$ [GeV]	∫Ldt	N_{tot}	p-p Equivalent	Data Size
01	2000	Au+Au	130	1 μb^{-1}	10M	0.04 pb^{-1}	3 TB
02	2001/2002	Au+Au	200	24 μb^{-1}	170M	1.0 pb^{-1}	10 TB
		p+p	200	0.15 pb^{-1}	3.7G	0.15 pb^{-1}	20 TB
03	2002/2003	d+Au	200	2.74 nb^{-1}	5.5G	1.1 pb^{-1}	46 TB
		p+p	200	0.35 pb^{-1}	6.6G	0.35 pb^{-1}	35 TB
04	2003/2004	Au+Au	200	241 μb^{-1}	1.5G	10.0 pb^{-1}	270 TB
		Au+Au	62	9 μb^{-1}	58M	0.36 pb^{-1}	10 TB
05	2004/2005	Cu+Cu	200	3.06 nb^{-1}	1.1B		
		Cu+Cu	62	190.2 μb^{-1}	425M		
		p+p	200	3.78 pb^{-1}			

Les articles/auteurs du White Paper

~35 articles et preprints

- First measurement of the dependence of the charged particle pseudo-rapidity density (Adcox *et al.*, 2001a) and the transverse energy (Adcox *et al.*, 2001b) on the number of participants in Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV; systematic study of the centrality and $\sqrt{s_{NN}}$ dependence of $dE_T/d\eta$ and $dN_{ch}/d\eta$ (Adler *et al.*, 2004g).
- Discovery of suppressed production for π^0's and charged particles at high p_T in Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV (Adcox *et al.*, 2002g) and a systematic study of the scaling properties of the suppression (Adcox *et al.*, 2003); extension of these results to much higher transverse momenta in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (Adler *et al.*, 2003e, 2004a).
- Co-discovery (together with BRAHMS (Arsene *et al.*, 2003), PHOBOS (Back *et al.*, 2003) and STAR (Adams *et al.*, 2003a)) of absence of high-p_T suppression in d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (Adler *et al.*, 2003g).
- Discovery of the anomalously large proton and anti-proton yields at intermediate transverse momentum in Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV through the systematic study of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ spectra (Adcox *et al.*, 2002a); study of the scaling properties of the proton and anti-proton yields in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (Adler *et al.*, 2003d);
- Measurement of Λ's and $\bar{\Lambda}$'s in Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV (Adcox *et al.*, 2002d); measurement of ϕ's at $\sqrt{s_{NN}}$ = 200 GeV (Adler *et al.*, 2004l); measurement of deuteron and anti-deuteron spectra at $\sqrt{s_{NN}}$ = 200 GeV (Adler *et al.*, 2004e).
- Measurement of Hanbury-Brown-Twiss (HBT) correlations in $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs in Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV (Adcox *et al.*, 2002h) and 200 GeV (Adler *et al.*, 2004f), establishing that the "HBT puzzle" of $R_{\mathrm{out}} \approx R_{\mathrm{side}}$ extends to high pair momentum.
- First measurement of single electron spectra in Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV, suggesting that charm production scales with the number of binary collisions (Adcox *et al.*, 2002e); measurement of centralty dependence of charm production in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (Adler *et al.*, 2004h).
- Sensitive measures of charge fluctuations (Adcox *et al.*, 2002f) and fluctuations in mean p_T and transverse energy per particle (Adcox *et al.*, 2002b; Adler *et al.*, 2004d) in Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV and 200 GeV.
- Measurements of elliptic flow for charged particles from Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV (Adcox *et al.*, 2002c) and 62 GeV to 200 GeV (Adler *et al.*, 2004m) and identified charged hadrons from Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (Adler *et al.*, 2003c).
- Extensive study of hydrodynamic flow, particle yields, ratios and spectra from Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV (Adcox *et al.*, 2004) and 200 GeV (Adler *et al.*, 2004b).
- First observation of J/ψ production in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (Adler *et al.*, 2004c).
- Measurement of the nuclear modification factor for hadrons at forward and backward rapidities in d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (Adler *et al.*, 2004k).
- First measurement of the jet structure of baryon excess in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (Adler *et al.*, 2004n).
- First measurement of elliptic flow of single electrons from charm decay in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (Adler *et al.*, 2005b).
- First measurement of direct photons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (Adler *et al.*, 2005c).
- Measurement of crucial baseline data on π^0 spectra (Adler *et al.*, 2003f), direct photon producion (Adler *et al.*, 2005a), and J/ψ production (Adler *et al.*, 2004i) in $p+p$ collisions at $\sqrt{s}$ = 200 GeV.
- First measurement of the double longitudinal spin asymmetry A_{LL} in π^0 production for polarized p+p collisions at $\sqrt{s}$ = 200 GeV (Adler *et al.*, 2004j).

Writing Group
Yasuyuki Akiba (chair)
Brian Cole
ShinIchi Esumi
Barbara Jacak
Jamie Nagle
Craig Ogilvie
Richard Seto
Paul Stankus
Mike Tannenbaum
Itzhak Tserruya
--
Stefan Bathe (scientific secretary)

PHENIX :
~500 collaborateurs
• 60 institutions
PHENIX France :
~ 25 collaborateurs
• 5 labos français

Le plan du White Paper

Abstract

Extensive experimental data from high-energy nucleus-nucleus collisions were recorded using the PHENIX detector at the Relativistic Heavy Ion Collider (RHIC). The comprehensive set of measurements from the first three years of RHIC operation includes charged particle multiplicities, transverse energy, yield ratios and spectra of identified hadrons in a wide range of transverse momenta (p_T), elliptic flow, two-particle correlations, non-statistical fluctuations, and suppression of particle production at high p_T. The results are examined with an emphasis on implications for the formation of a new state of dense matter. We find that the state of matter created at RHIC cannot be described in terms of ordinary color neutral hadrons.

I. Densité d'énergie et particules chargées
II. Thermalisation
III. Binarité
IV. Suppressions à grand p_T
V. Production des hadrons

I. Densité d'énergie et particules chargées

de l'étude des conditions initiales

A prerequisite for creating a quark-gluon plasma is producing a system with sufficiently large energy density. From both elementary estimates [22] and from extensive numerical studies in lattice QCD [11,10], the required density is known to be on the order of 1 GeV/fm^3. Establishing that this energy density is created in RHIC collisions is a basic ingredient in establishing the creation of a QGP at RHIC.

1. Densité d'énergie
2. Distribution des particules chargées

I. Densité d'énergie et particules chargées

de l'étude des conditions initiales

1. Estimation de la densité d'énergie

– Formule de Bjorken

$$\varepsilon_{Bj}(\tau_0) = \frac{1}{\pi R^2 \tau_0} \frac{dE_T}{dy}$$

– habituellement τ_0 = 1 fm/c :
- AGS (AuAu) → ε_{Bj} = 1.5 GeV/fm^3
- SPS (PbPb) → ε_{Bj} = 2.9 GeV/fm^3
- **RHIC (AuAu) → ε_{Bj} = 5.4 GeV/fm^3**

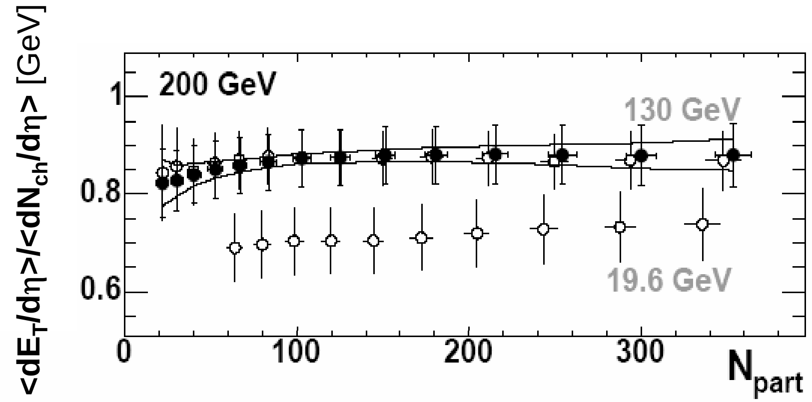


Fig. 6. The ratio of transverse energy density in pseudorapidity to charged particle density in pseudorapidity, at mid-rapidity; shown as a function of centrality, represented by the number of nucleons participating in the collision, N_{part}, for three different RHIC beam energies [67].

– Estimation de τ_0 au RHIC

$$\tau_0 = \hbar / m_T$$

$$\frac{dE_T}{dy} = \langle m_T \rangle \frac{dN}{dy}$$

$$\Rightarrow \langle m_T \rangle = \frac{dE_T(\tau_0)/dy}{dN(\tau_0)/dy} \approx \frac{dE_T/d\eta}{dN/d\eta} = \frac{dE_T/d\eta}{dN_{ch}/d\eta} \times \frac{dN_{ch}/d\eta}{dN/d\eta} \approx 0.85 \times \frac{2}{3} \approx 0.57 \text{ GeV}$$

$\langle m_T \rangle$ ~ 0.57 GeV → τ_0 ~ 0.35 fm/c

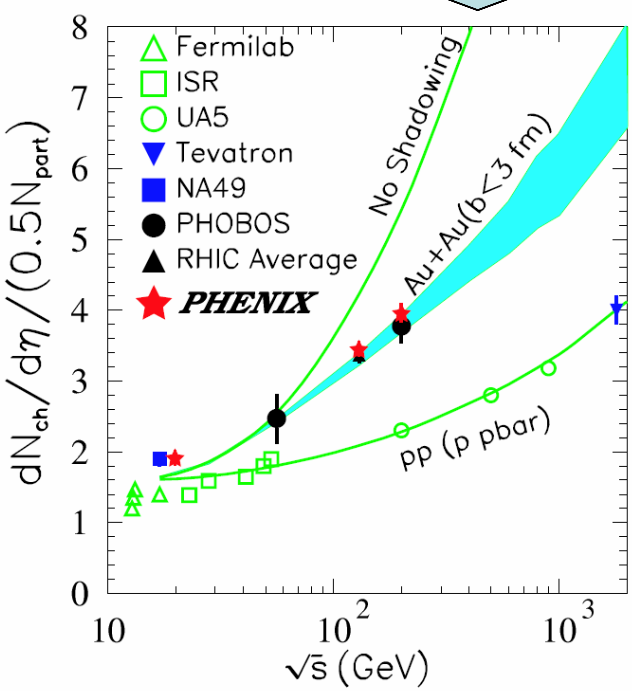
Collisions centrales → dET/dη ~ 600 GeV → ε_{Bj}~15 GeV/fm^3

I. Densité d'énergie et particules chargées

de l'étude des conditions initiales

2. Distribution des particules chargées

Extrapolation pp → AuAu sans modification des pdf

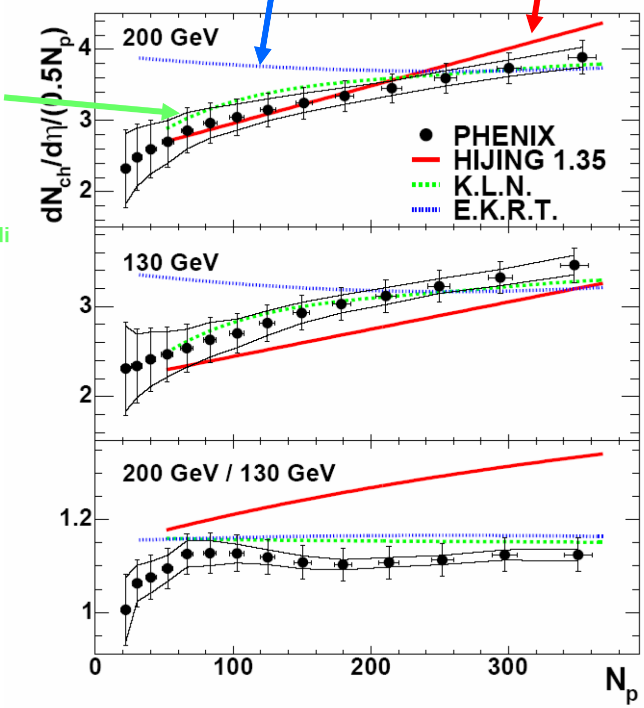


Li, Wang, Phys. Lett. B527 (2002) 85

Saturation des gluons dans l'état initial
Kharzeev-Levin-Nardi

Saturation dans l'état final

pQCD



Modification des pdf dans les noyaux
Saturation des gluons dans l'état initial → CGC ?

I. Densité d'énergie et particules chargées

de l'étude des conditions initiales

- Conclusions

• The peak energy density in created secondary particles is at least 15 GeV/fm^3, and this is most likely an underestimate. This is well in excess of the ~1 GeV/fm^3 required, according to lattice QCD predictions, to drive a QCD transition to QGP.

• Pre-RHIC expectations that E_T and charged particle production would be dominated by factorized pQCD processes were contradicted by data, which showed only very modest increases with centrality and beam energy. A new class of models featuring initial-state gluon saturation compares well with RHIC multiplicity and E_T data, and are also consistent with our Bjorken-style arguments for estimating energy densities at early times.

II. Thermalisation
de l'étude du milieu produit

A key question is whether the matter formed at RHIC is thermalized, and if so when in the collision was equilibration achieved. If thermalization is established early then evidence for strong transverse expansion can be potentially related to the equation of state of the dense matter produced at RHIC.

1. Équilibre chimique

2. Expansion collective

3. Flot elliptique

4. Comparaison avec des modèles hydrodynamiques

II. Thermalisation
de l'étude du milieu produit

1. Équilibre chimique

– La production des particules étranges permet de tester l'équilibre chimique.

– Les rapports K/π

- Augmentent avec la centralité
- Plus vite que p/π
- **Évolution attendue par les modèles statistiques**

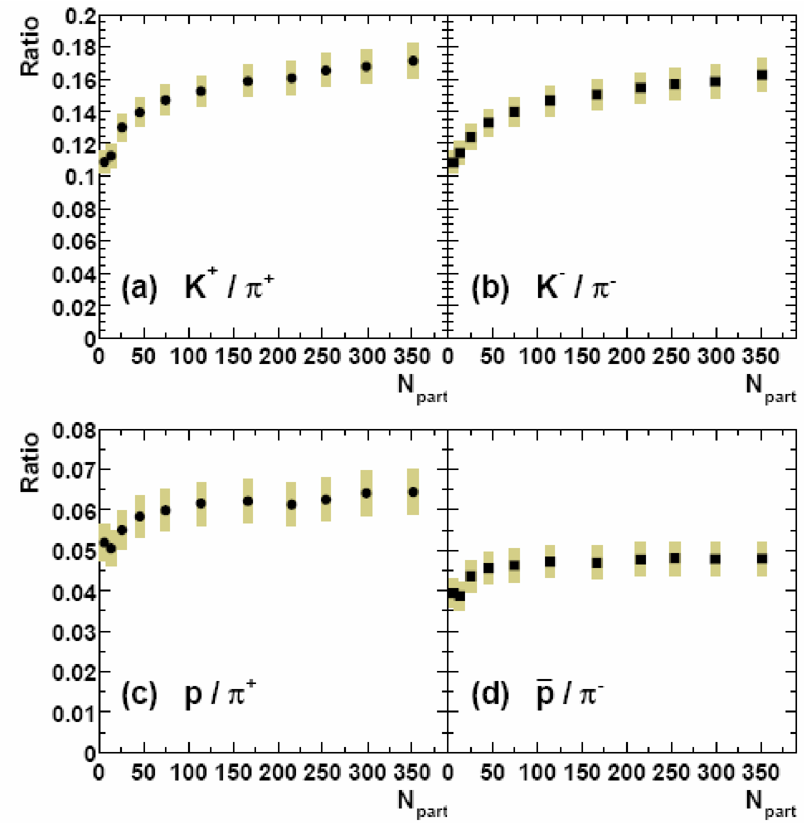


Fig. 9. Centrality dependence of particle ratios for (a) K^+/π^+, (b) K^-/π^-, (c) p/π^+, and (d) $\bar{p}/\pi^-$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [54].

II. Thermalisation

de l'étude du milieu produit

1. Équilibre chimique

– Dans les collisions AuAu (200 GeV) centrales

- Les rapports d'abondance sont décrits par des modèles thermiques (Kaneta et Xu)

- γ_S=étrangeté mesurée/étrangeté attendue (plein équilibre)

- **On « mesure » :**
  - **Tch=157 ± 3 MeV**
  - **γ_S=1.03 ± 0.04**

– Note : γ_S ~1 pour AGS et SPS

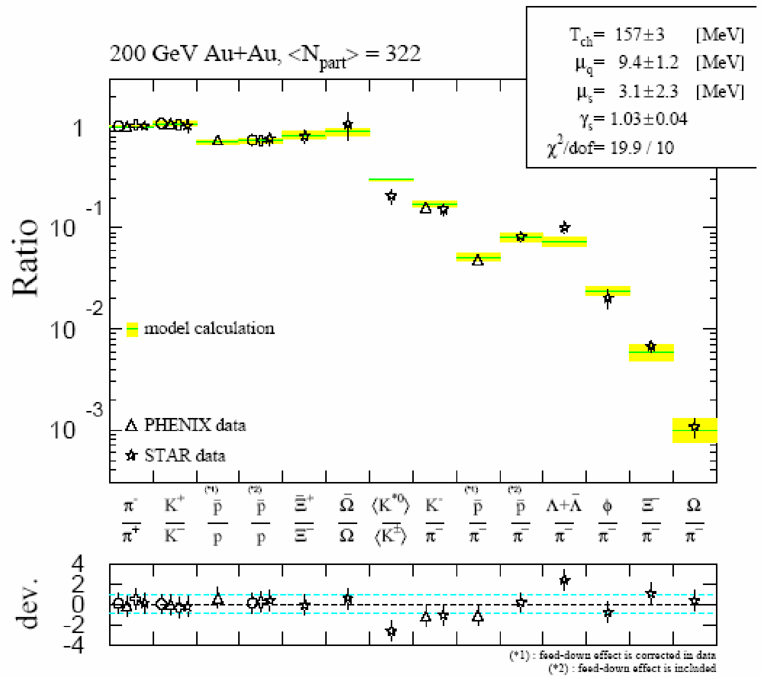
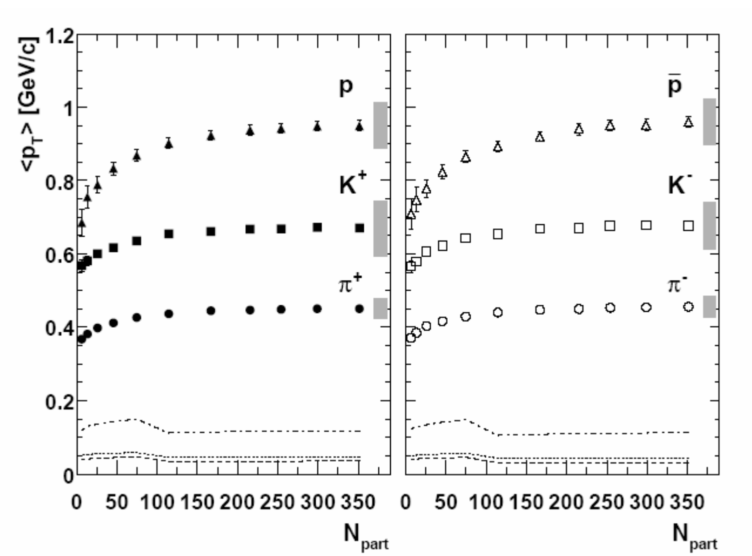


FIG. 10 Comparison of PHENIX (triangles), STAR (stars), BRAHMS (circles), and PHOBOS (crosses) particle ratios from central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at mid-rapidity. The thermal model descriptions from Kaneta (Kaneta and Xu, 2004) are also shown as lines. See Kaneta (Kaneta and Xu, 2004) for the experimental references.

II. Thermalisation

de l’étude du milieu produit

2. Expansion collective
   - <pT> augmente plus fortement pour les protons
   - Consistant avec une expansion collective → <pT> (m grand) > <pT> (m petit)



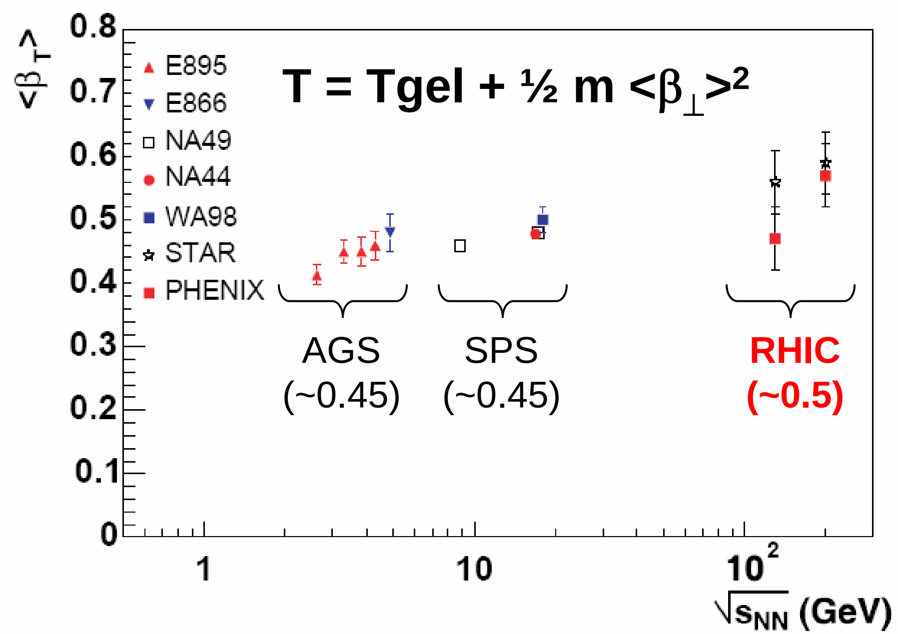
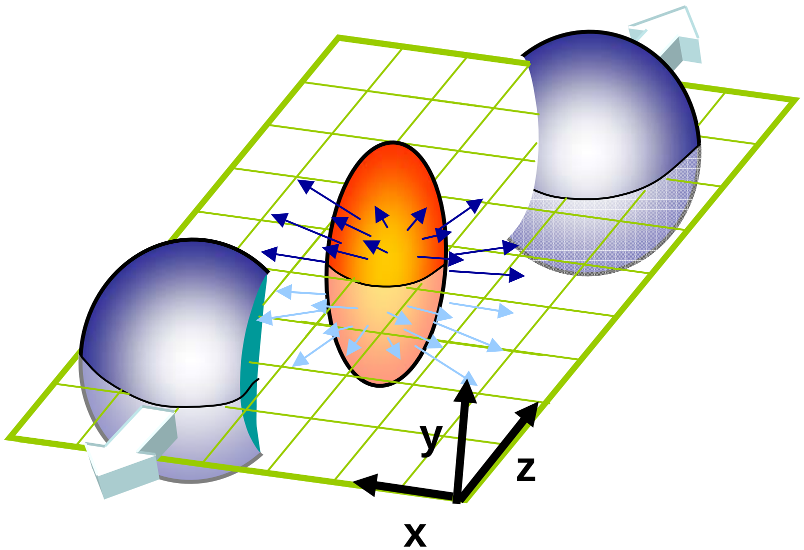
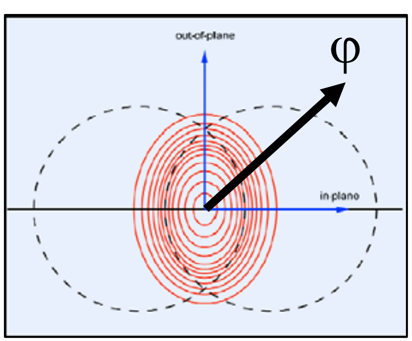


Fig. 13. Beam-energy dependence of the extracted mean transverse expansion velocity as a function of beam energy from simultaneous fits to spectra of different mass [97,98,99,100,101,48,102].

II. Thermalisation
de l’étude du milieu produit

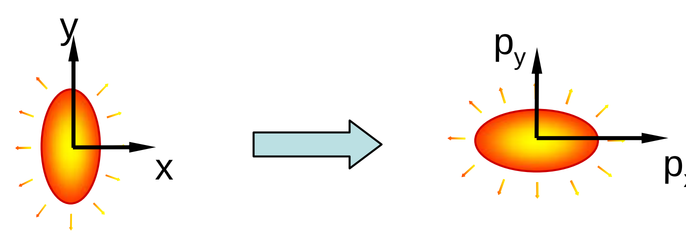
3. Flot elliptique





Dans un milieu fortement interagissant (thermalisé)

- Gradient de pression plus important dans le plan de la réaction
- Anisotropie spatiale → anisotropie impulsionnelle



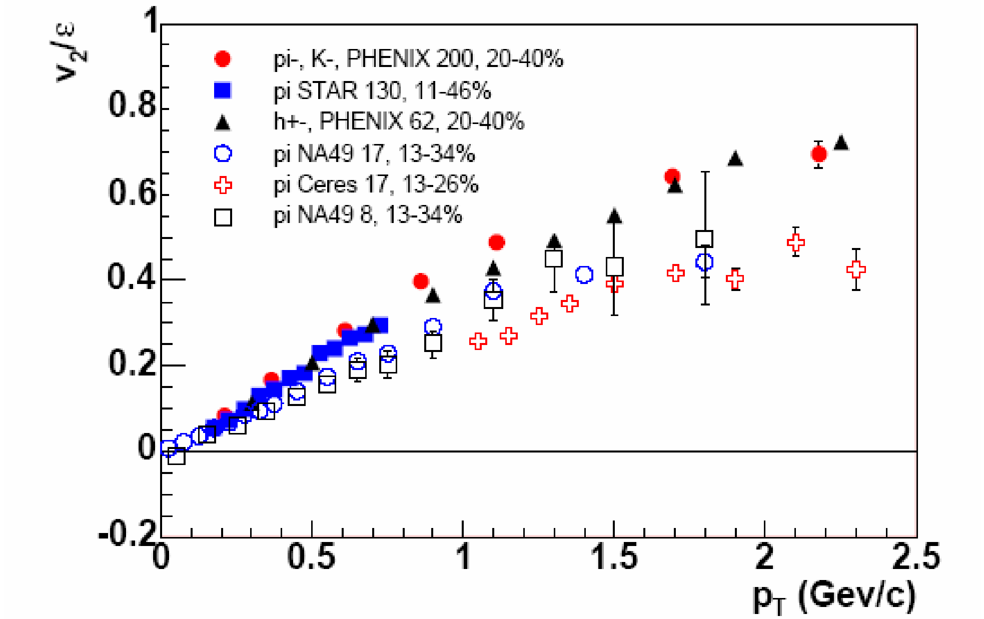
$$\frac{dN}{d\varphi dp_T} = 1 + v_2(p_T)\cos(2\varphi) \qquad v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

V2>0 → flot dans le plan de réaction
V2<0 → flot hors du plan de réaction

II. Thermalisation

de l'étude du milieu produit

3. Flot elliptique



- $v_2>0$ → flot dans le plan de la réaction
- $v_2(RHIC) > v_2(SPS)$
- v_2 reproduit par certains modèles hydrodynamiques
  - τ_{therm} ~1fm/c
  - $\varepsilon_{init.}$>10 GeV/fm^3
  - ε_{therm}~5GeV/fm^3

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

L'excentricité spatiale dépend de la géométrie et du type de noyau

→ Modèle de Glauber

→ Pour comparer différentes espèces, normaliser v_2 par l'excentricité

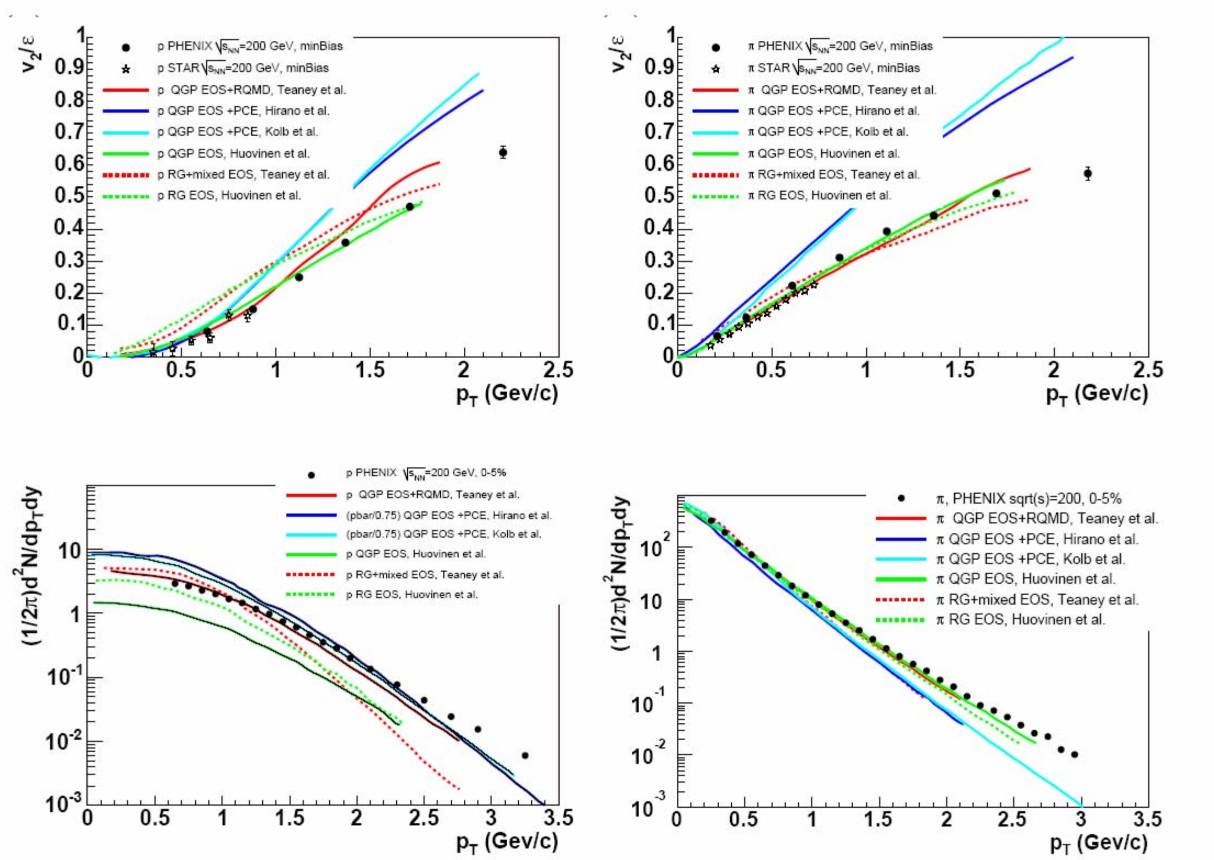
II. Thermalisation

de l'étude du milieu produit

4. Comparaison avec les modèles hydrodynamiques

Avec QGP

Sans QGP



Un seul modèle reproduit « raisonnablement » les données :

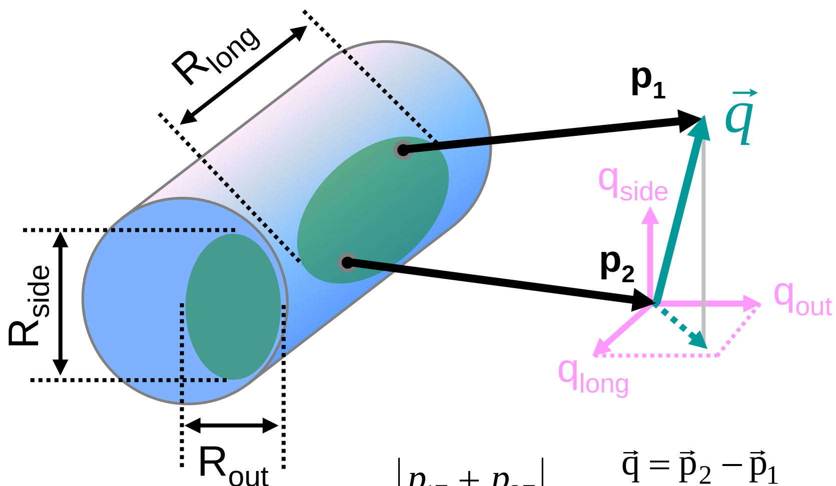
QGP Teaney et al.

Modèle sans viscosité
(viscosité≠0 réduit v_2)

II. Thermalisation

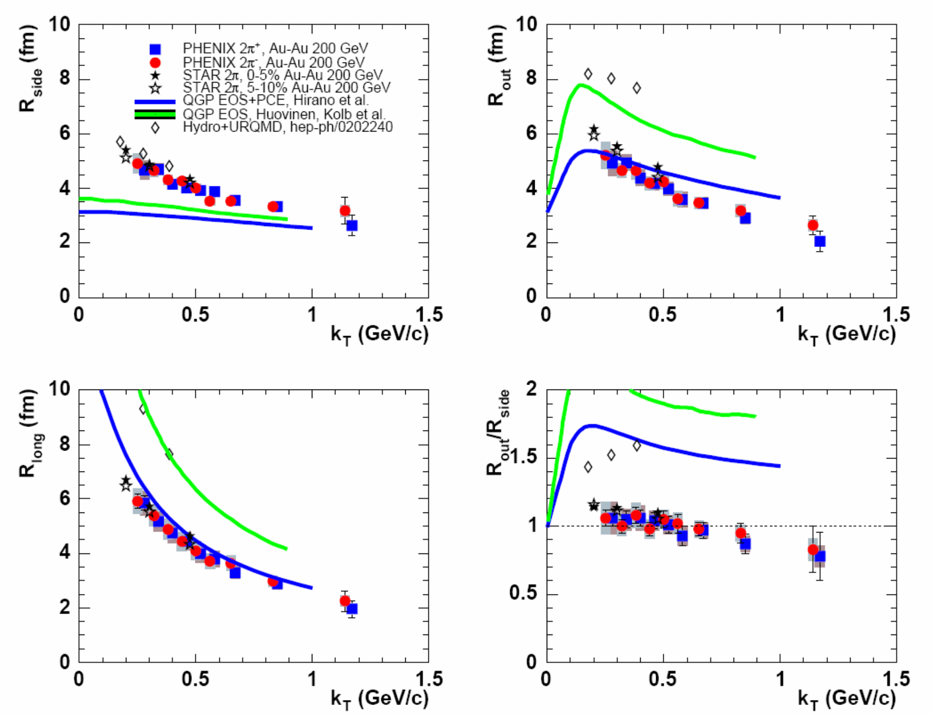
de l'étude du milieu produit

4. Comparaison avec les modèles hydrodynamiques : HBT



$$k_T = \frac{|p_{1T} + p_{2T}|}{2} \qquad \vec{q} = \vec{p}_2 - \vec{p}_1$$

$$C_2 = 1 + \lambda \exp(-R_{\text{side}}^2 q_{\text{side}}^2 - R_{\text{out}}^2 q_{\text{out}}^2 - R_{\text{long}}^2 q_{\text{long}}^2)$$



- QGP Teaney ne fournit pas de prédiction pour HBT
- Deux autres modèles hydrodynamiques sont présentés → ne reproduisent pas les données

II. Thermalisation

de l'étude du milieu produit

- Conclusions

- The measured yields and spectra of hadrons are consistent with thermal emission from a strongly expanding source.
- Strangeness is fully saturated at RHIC, consistent with full chemical equilibrium.
- The scaling of v_2 with eccentricity shows that collective behavior is established early in the collision.
- Elliptic flow is stronger at RHIC than at the SPS, since the measured slope of $v_2(p_T)$ for pions is 50% larger at RHIC.
- The measured proton $v_2(p_T)$ is less than that for pions at low p_T; the small magnitude of the proton v_2 at low p_T is reproduced by hydro models that include both a QGP and hadronic phase.
- However several of the hydro models that reproduce the proton $v_2(p_T)$ fail for the pion $v_2(p_T)$.
- The HBT source parameters, especially the small value of R_{long} and the ratio $R_{\mathrm{out}}/R_{\mathrm{side}}$, suggest that the mixed phase is too long-lived in the current hydro calculations.

Hence we currently do not have a consistent picture of the space-time dynamics of reactions at RHIC as revealed by spectra, v_2, and HBT. The lack of a

III. Binarité

de l’étude des interactions dans l’état initial

- Processus proportionnels au nombre de collisions binaires ?

$$R_{CP} = \frac{dN^{centrale} / < N_{coll}^{centrale} >}{dN^{périphérique} / < N_{coll}^{périphérique} >}$$

RCP = 1 ←→ proportionnel

Production de π_0 dans les collisions pp
Données décrites par pQCD

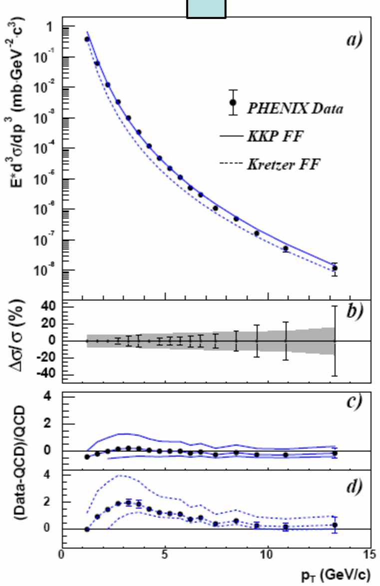


Fig. 27. PHENIX π^0 invariant cross section at mid-rapidity from $p+p$ collisions at $\sqrt{s} = 200$ GeV, together with NLO pQCD predictions from Vogelsang [151,152]. a) The invariant differential cross section for inclusive π° production (points) and the results from NLO pQCD calculations with equal renormalization and factorization scales of p_T using the “Kniehl-Kramer-Pötter” (solid line) and “Kretzer” (dashed line) sets of fragmentation functions. b) The relative statistical (points) and point-to-point systematic (band) errors. c,d) The relative difference between the data and the theory using KKP (c) and Kretzer (d) fragmentation functions with scales of $p_T/2$ (lower curve), p_T, and $2p_T$ (upper curve). In all figures, the normalization error of 9.6% is not shown [60].

Production de π_0 dans les collisions dAu
→ **Interactions dans l’état initial**

Color Glass Condensate ?

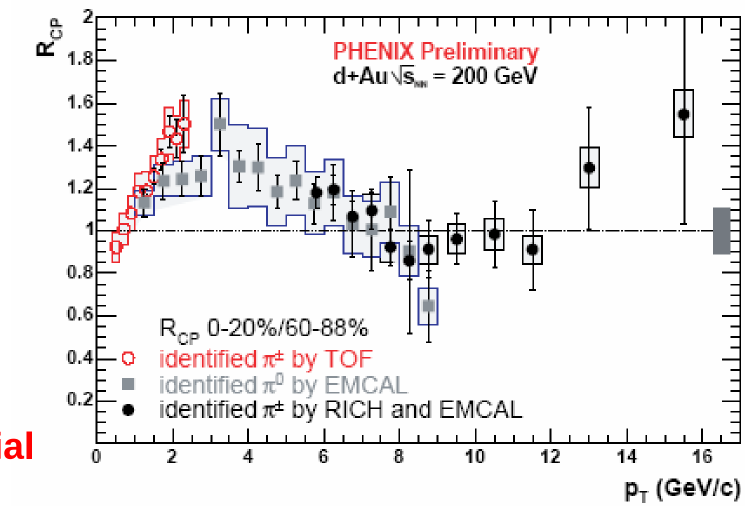
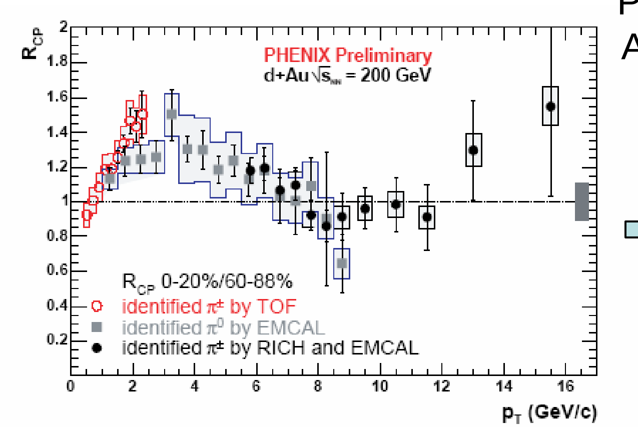


Fig. 32. Cronin effect in R_{CP}, the ratio of point-like scaled central to peripheral collisions for pions in d+Au at $\sqrt{s_{NN}} = 200$ GeV[167]. Data points for low p_T are $\pi^\pm$ identified by Time of Flight (TOF). Data at medium p_T are for π^0 identified by reconstruction in the Electromagnetic Calorimeter (EMCAL). Highest p_T data are for $\pi^\pm$ identified by a count in the Ring Imaging Cerenkov Counter (RICH) and a deposited energy/momentum and shower shape in the EMCAL inconsistent with those of a photon or electron. The shaded band on the right represents the overall fractional systematic uncertainty due to N_{coll}.

III. Binarité

de l'étude des interactions dans l'état initial

- Color glass condensate ?



RCP anormal
En dAu

Production de photons directs en AuAu proportionnelle au nombre de collisions

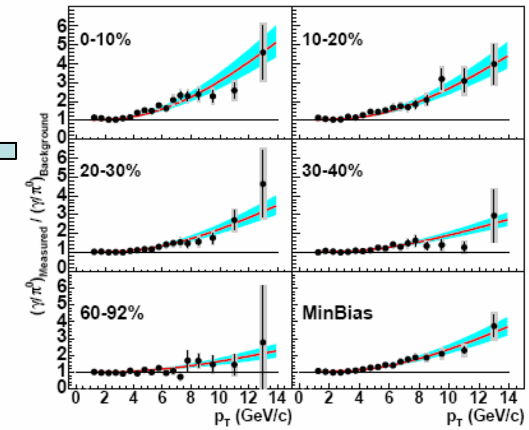


Fig. 33. PHENIX direct photon measurements relative to the background for for minimum bias and for five centralities of Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (0-10% is the most central). Statistical and total errors are indicated separately on each data point by the vertical bar and shaded region, respectively. The curves represent a pQCD calculation of direct photons in $p+p$ collisions from Vogelsang [169,170,171,172] scaled to Au+Au assuming pure point-like (N_{coll}) scaling, with no suppression. The shaded region around the curves indicate the variation of the pQCD calculation for scale changes from $p_T/2$ to $2p_T$, plus the $\langle N_{coll} \rangle$ uncertainty [73].

Production de charme en AuAu proportionnelle au nombre de collisions

The color glass condensate (CGC) provides an alternative view of the initial state of a nucleus at RHIC in which coherence of gluons due to non-linear gluon-gluon fusion can produce a Cronin-like effect, depending on the initial conditions and the kinematic range covered. However, at the present writing, there is no CGC description of the initial state nuclear structure function which reproduces the observed Cronin effect for pions in d+Au collisions and the observed binary scaling for both direct photon production and the total charm yield in Au+Au collisions.

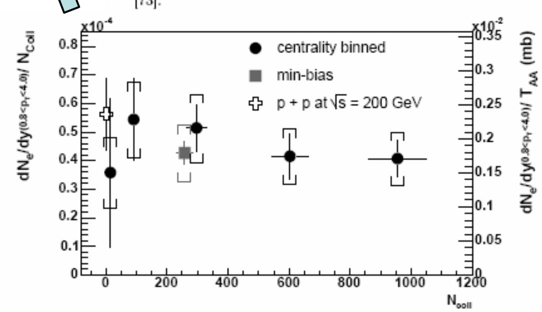


Fig. 34. Non-photonic electron yield ($0.8 < p_T < 4.0$ GeV/c), dominated by semi-leptonic charm decays, measured in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV scaled by N_{coll} as a function of N_{coll}. The right-hand scale shows the corresponding electron cross section per NN collision in the above p_T range. The yield in $p+p$ collision at 200 GeV is also shown [57].

IV. Suppression à grand pT

de l'étude de signatures (sondes) directes

To study the initial properties of the matter created in heavy ion collisions we need a probe that is already present at earliest times and that is directly sensitive to the properties of the medium. Partons resulting from hard scatterings during the initial crossing of the two nuclei in A+A collisions provide such a probe.

Energetic partons propagating through a dense medium are predicted to lose energy [173,174,175,176,177,178,179,180,181] thus producing a suppression in the yield of high-p_T hadrons produced from the fragmentation of these partons.

1. Suppression des hadrons
2. Corrélations angulaires

IV. Suppression à grand pT

de l'étude de signatures (sondes) directes

1. Suppression des π_0 dans les collisions centrales AuAu

Production de π_0 dans les collisions pp
Données décrites par pQCD

$$< T_{AB} >_{cent} = \frac{< N_{coll} >_{cent}}{\sigma_{NN}}$$

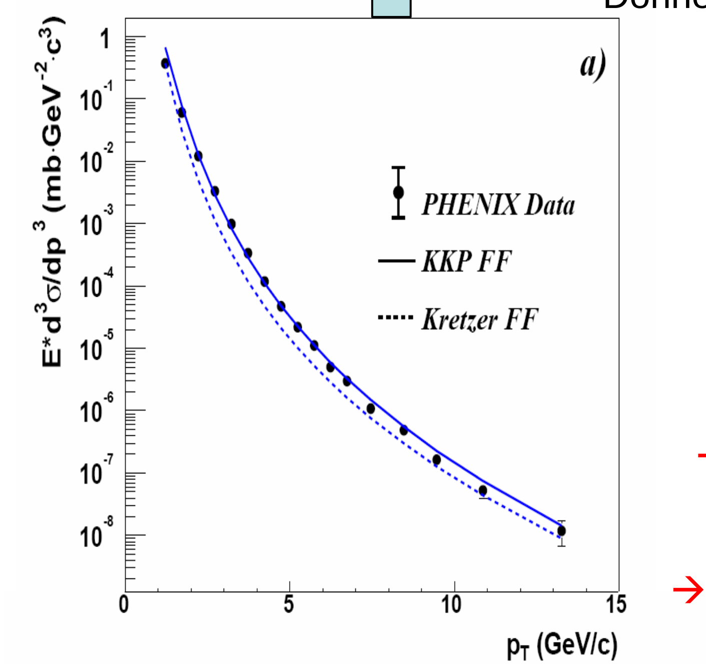


Fig. 27. PHENIX π^0 invariant cross section at mid-rapidity from $p+p$ collisions at $\sqrt{s}$ = 200 GeV, together with NLO pQCD predictions from Vogelsang [151,152].

Production de π_0 dans les collisions AuAu

→Proportionnelle en AuAu périphériques

→Forte suppression en AuAu centrales

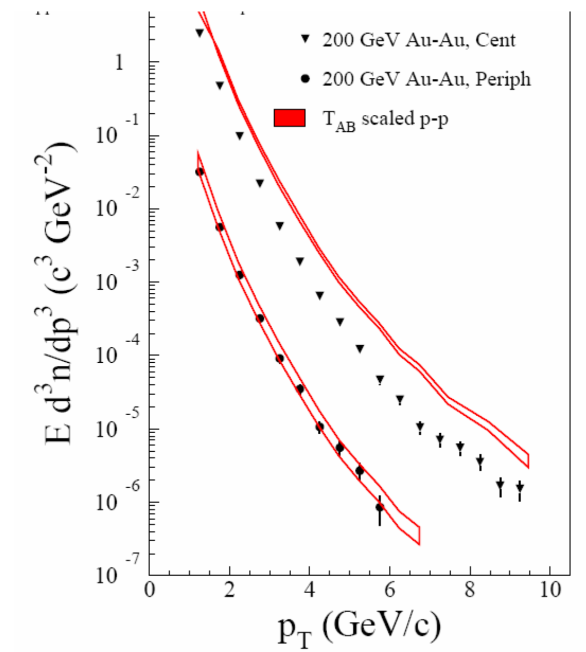


Fig. 35. π^0 p_T spectra in 200 GeV Au+Au collisions [49] compared to a T_{AB} scaling of the 200 GeV $p+p$ π^0 differential cross section [60]. The central data were obtained with a 0–10% centrality cut while the peripheral data were obtained with an 80–92% cut.

IV. Suppression à grand pT

de l'étude de signatures (sondes) directes

1. Suppression des π_0 dans les collisions centrales AuAu

– $$R_{AB} = \frac{dN_{AB}}{< N_{coll} > \times dN_{NN}}$$

– dAu min bias
  - Léger défaut à bas p_T → les processus mous (bas p_T) ne sont pas proportionnels à T_{AB}
  - Léger excès à grand p_T → effet Cronin.

– AuAu périphériques
  - Léger défaut comparer à dAu (mais compatible)

– **AuAu centrales**
  - **Très forte suppression (~ x5)**

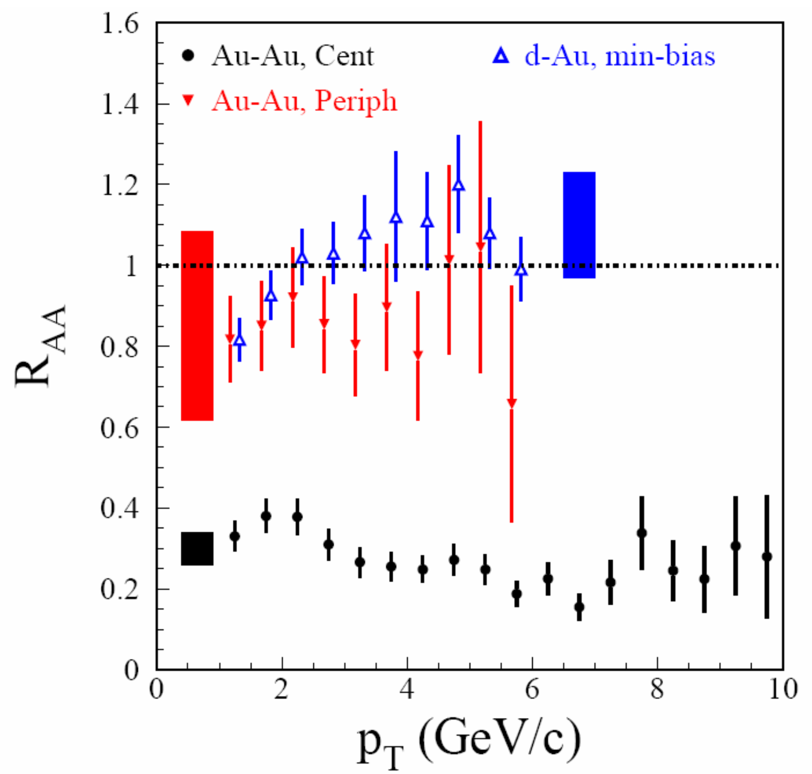
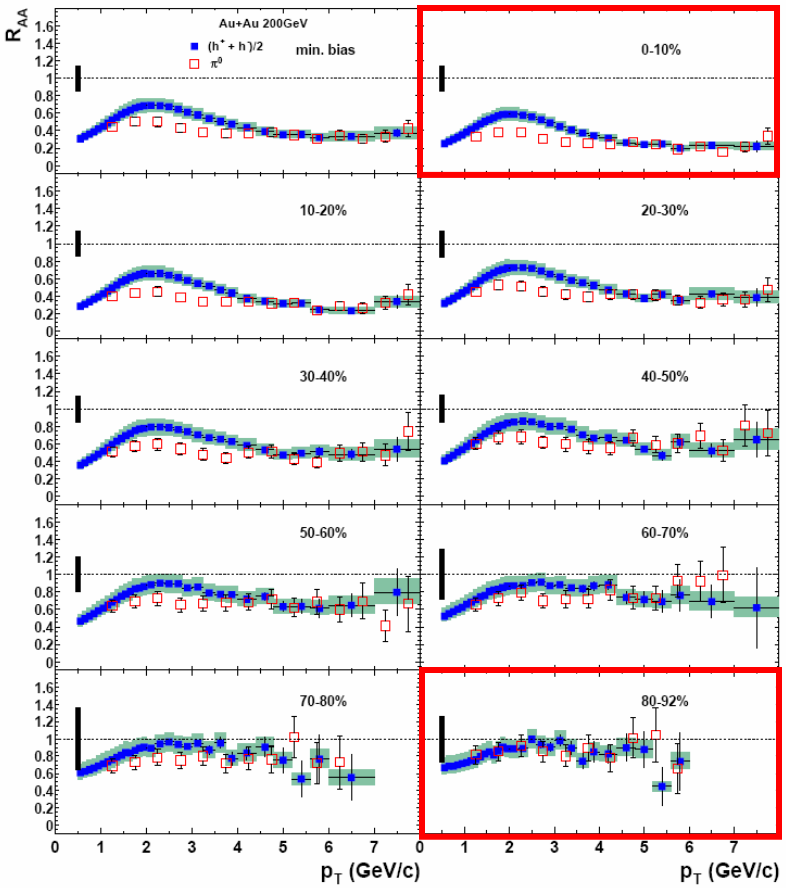


Fig. 36. π^0 $R_{AA}(p_T)$ for central (0–10 %) and peripheral (80–92 %) Au+Au collisions [49] and minimum-bias d+Au collisions [64]. The shaded boxes on the left show the systematic errors for the Au+Au R_{AA} values resulting from overall normalization of spectra and uncertainties in T_{AB}. The shaded box on the right shows the same systematic error for the d+Au points.

IV. Suppression à grand pT

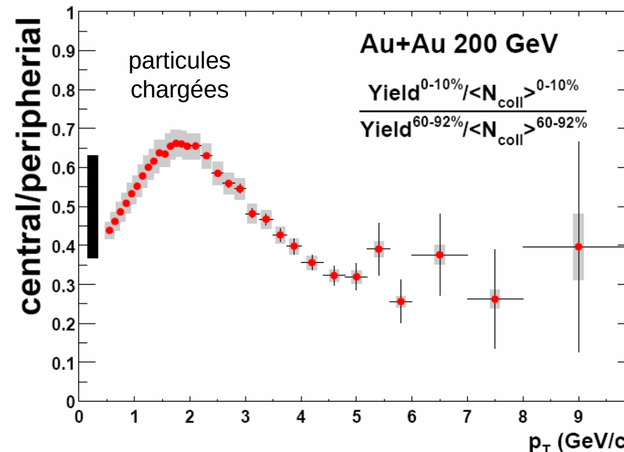
de l'étude de signatures (évidences) directes

1. Suppression en fonction de la centralité



Les plus centrales

Les plus périphériques



La suppression augmente avec la centralité

Note 1 : plus forte suppression des π_0, comparés aux hadrons chargés, vers les p_T intermédiaires → contribution des protons (cf. production des hadrons)

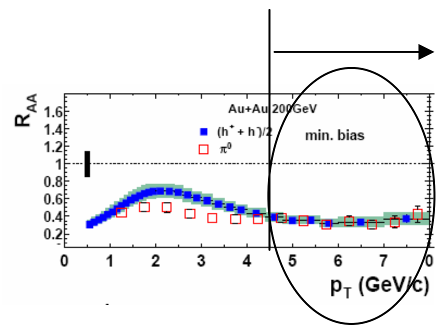
Note 2 : la suppression est constante pour p_T>4.5 GeV/c

→

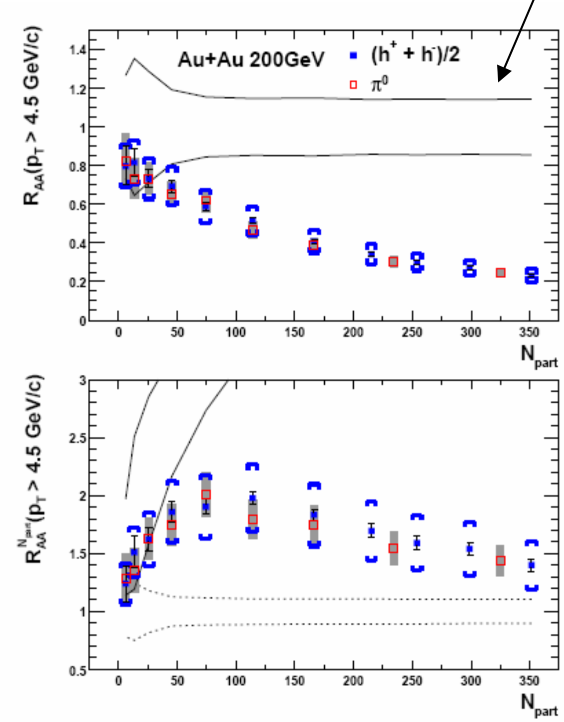
IV. Suppression à grand pT

de l'étude de signatures (évidences) directes

1. Suppression en fonction de la centralité
   – Pour chaque tranche de centralité
     - Intègre le spectre pour pT>4.5 GeV/c
     - Représente la dépendance en fonction de N_{part}



T_{AB} scaling



R_{AA}

R_{AA} par participant

The initial rise and subsequent decrease of $R_{AA}^{N_{\rm part}}$ with increasing $N_{\rm part}$ suggests that the high-p_T hadron yield in Au+Au collisions has no simple dependence on $N_{\rm part}$. The observation that the high-p_T yields initially increase proportional to T_{AB} demonstrates that in the most peripheral Au+Au collisions the hard-scattering yields are consistent with point-like scaling.

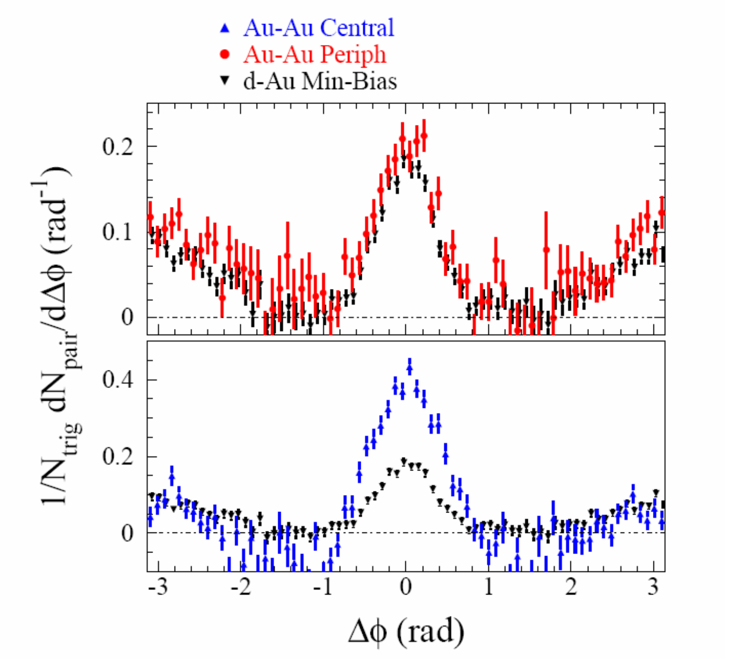
Fig. 38. Top panel: R_{AA} vs. $N_{\rm part}$ obtained from p_T-integrated ($p_T > 4.5$ GeV/c) Au+Au π^0 and charged-hadron spectra. The band indicates the systematic error bands on a hypothetical T_{AB} scaling of the $p+p$ p_T-integrated cross section. Bottom panel: π^0 and charged hadron yield per participant vs. $N_{\rm part}$ divided by the same quantity in $p+p$ collisions ($R_{AA}^{N_{\rm part}}$). The solid band shows the same band as in the top panel expressed in terms of yield per participant pair while the dashed band indicates the systematic error bands around a hypothetical $N_{\rm part}$ scaling. Both plots are from [53].

IV. Suppression à grand pT
de l'étude de signatures (évidences) directes

2. Corrélations angulaires

a reasonable way to check the assumption that high-p_T hadron production in Au+Au collisions is due to hard scattering is to directly observe the angular correlations between hadrons in the jets.

- Particule « déclenchante » = $2.5 < p_T < 4$ GeV/c
- Particule « associée » = $1.0 < p_T < 2.5$ GeV/c
- $\Delta\Phi$ = angle azimuthal (déclenchante,associée)
- Interprétation :
  - $\Delta\Phi = 0 \rightarrow$ hadrons issus du même jet
  - $\Delta\Phi = \pi \rightarrow$ hadrons issus de jets différents
- Résultats :
  - dAu et AuAu périph sont en accord
  - AuAu centrales montrent un défaut de hadrons dans le jet opposé.



IV. Suppression à grand pT

de l'étude de signatures (évidences) directes

- Conclusions

The observed suppression of high-p_T particle production at RHIC is a unique phenomenon that has not been previously observed in any hadronic or heavy ion collisions at any energy. The suppression provides direct evidence that Au+Au collisions at RHIC have produced matter at extreme densities, greater than ten times the energy density of normal nuclear matter and the highest energy densities ever achieved in the laboratory. Medium-induced energy loss, predominantly via gluon bremsstrahlung emission, is the only currently known physical mechanism that can fully explain the magnitude and p_T dependence of the observed high-p_T suppression.

V. Production des hadrons

de l’étude de l’hadronisation

One could conclude that a quark-gluon plasma had been formed if one had conclusive evidence of hadronization occurring from a thermal distribution of quarks and gluons.

1. Baryons et anti-baryons
2. Le méson Φ
3. Modèle hydrodynamique/recombinaison
4. Les corrélations des jets

V. Production des hadrons

de l’étude de l’hadronisation

1. Baryons et anti-baryons

Rapports (anti)proton/pion
dans la région 2 < pT < 5 augmentation d’un facteur ~3 entre collisions centrales et collisions périphériques.

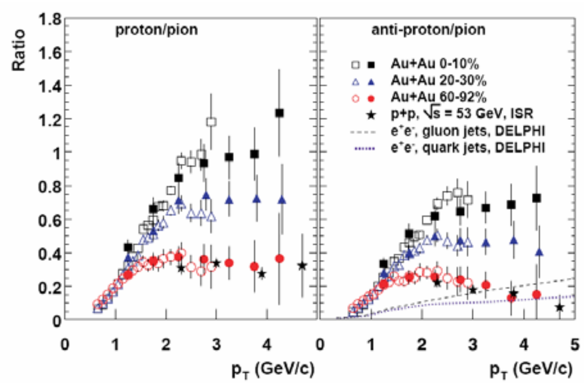
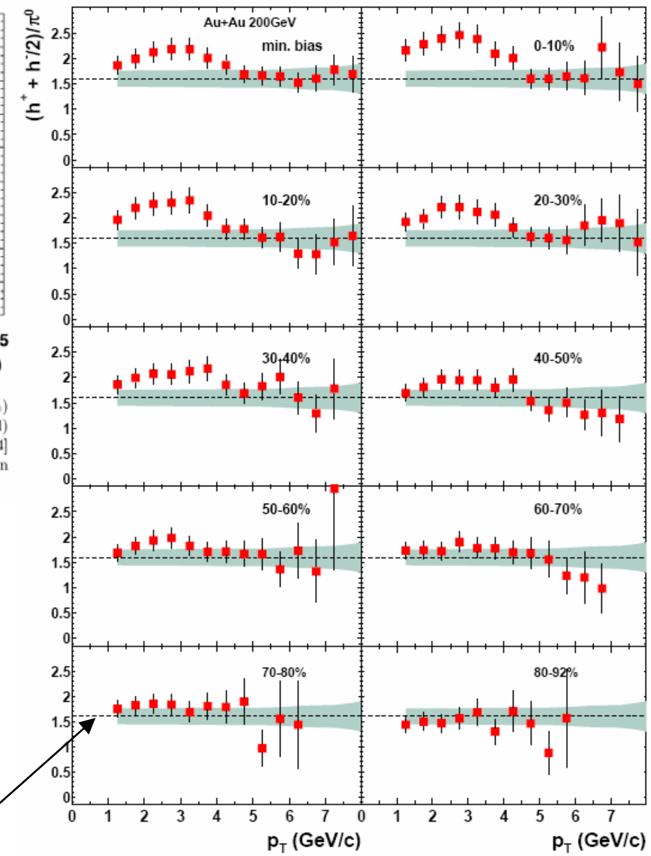


Fig. 44. p/π (left) and $\bar{p}/\pi$ (right) ratios for central (0–10%), mid-central (20–30%) and peripheral (60–92%) Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV[52]. Open (filled) points are for $\pi^{+/-}$ (π^0), respectively. Data from $\sqrt{s} = 53$ GeV $p+p$ collisions [224] are shown with stars. The dashed and dotted lines are $(\bar{p}+p)/(\pi^+ + \pi^-)$ ratio in gluon and in quark jets [225].

Rapports hadron chargés/π_0

- Forte augmentation pour pT∈ [2:5]
- Retour vers p+p pour pT>5
- l’effet augmente avec la centralité



mesuré en p+p

Fig. 45. Charged hadron to π^0 ratio for different centrality classes for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV[53]. Error bars represent the quadratic sum of statistical and point to point systematic errors. The shaded band shows the normalization error common to all centrality classes. The line at 1.6 is the h/π ratio measured in $p+p$ collisions at $\sqrt{s} = 53$ GeV [224] and e+e- collisions [225].

- Effet dû à la masse des hadrons ?
- Effet baryon-méson ?

V. Production des hadrons

de l'étude de l'hadronisation

2. Le méson Φ

Le Φ :

- C'est un méson ➔ π_0
- M ~ 1 GeV ➔ proton

On observe :

- $R_{CP}(\Phi) = R_{CP}(\pi_0)$
- $R_{CP}(\Phi) \neq R_{CP}$(proton+antiproton)

L'effet n'est pas dû à la masse

Effet baryon-méson ?

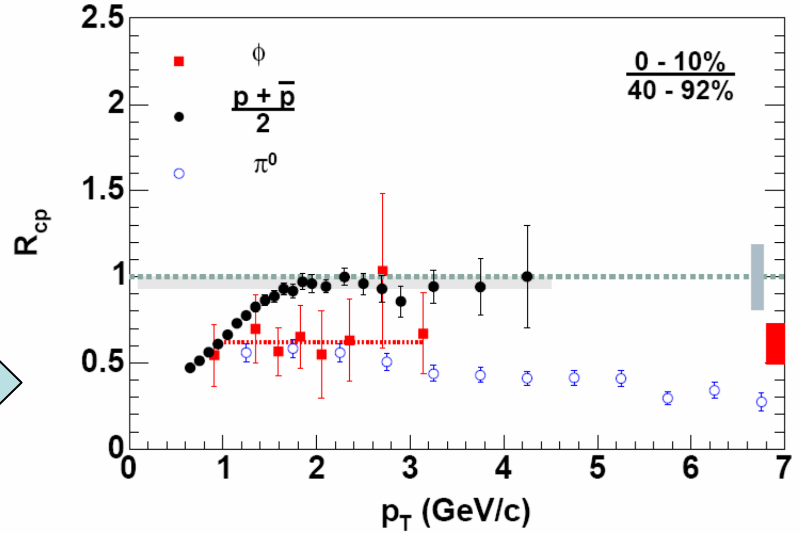


Fig. 48. The R_{CP} of the ϕ as measured in the KK channel, compared to the protons and pions for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV[69].

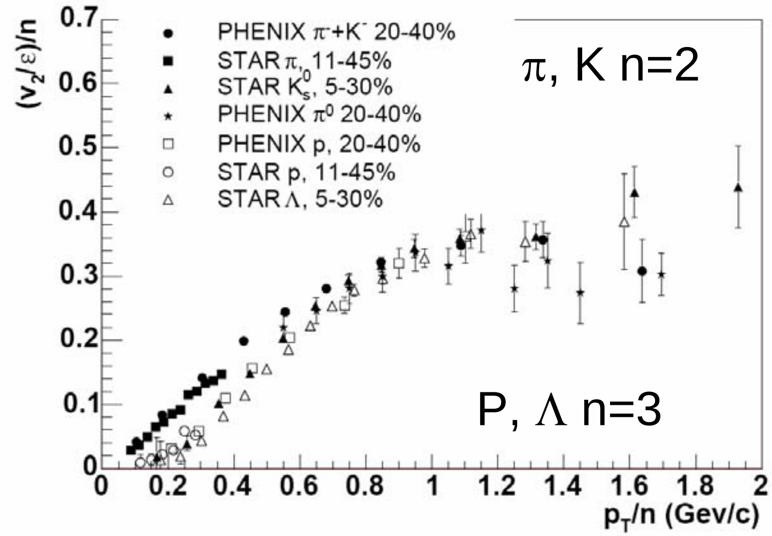
V. Production des hadrons

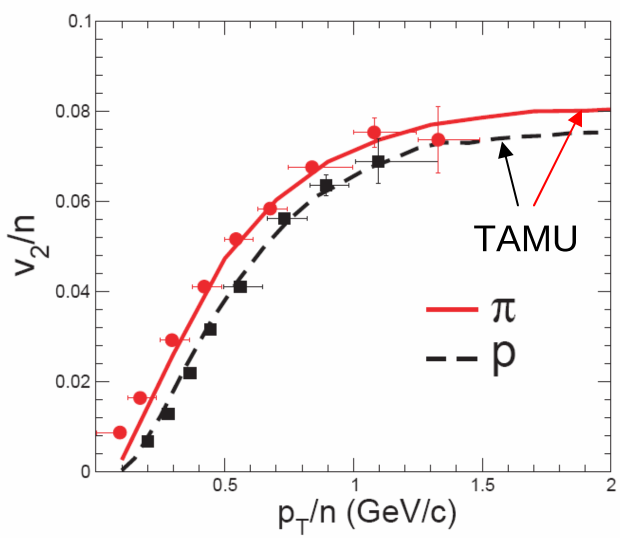
de l'étude de l'hadronisation

3. Modèle hydrodynamique/recombinaison

Effet baryon (n_{quarks}=3)/méson (n_{quarks}=2) ?

Flot partonique observé
dans les données





Flot partonique reproduit
par un modèle de
recombinaison

Compatibilité hydrodynamique/recombinaison ?

V. Production des hadrons

de l’étude de l’hadronisation

3. Modèle hydrodynamique/recombinaison

Hydrodynamique :

QGP Teaney décrit le rapport p/π jusqu’à 2 GeV

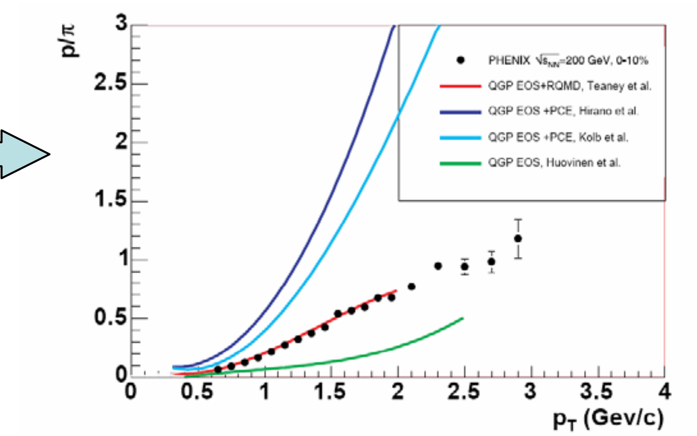


Fig. 52. p/π ratios for central (0–10%) Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV[52] compared to hydrodynamic models [106,107,117,118,119].

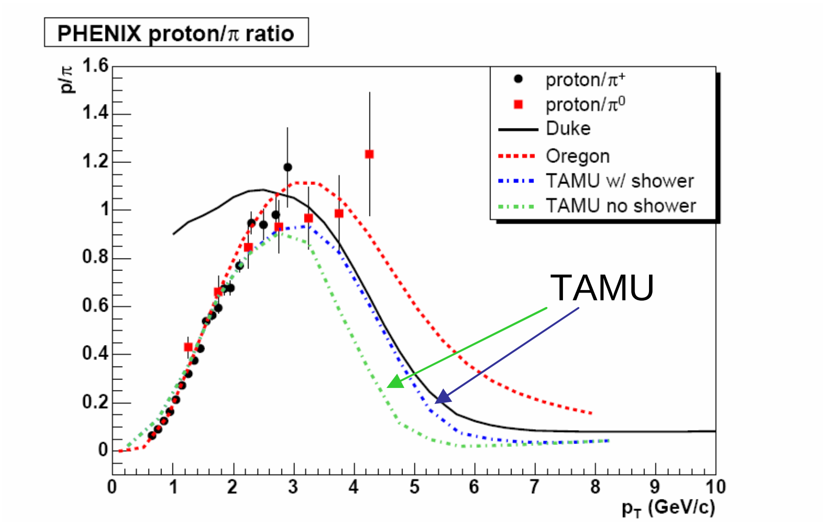


Fig. 53. The proton to pion ratio measured by PHENIX for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV[52]. Several comparisons to recombination models as mentioned in the text are shown.

Recombinaison :

Prédit que le flot collectif des hadrons doit suivre le flot collectif de leur quarks constituants

V. Production des hadrons

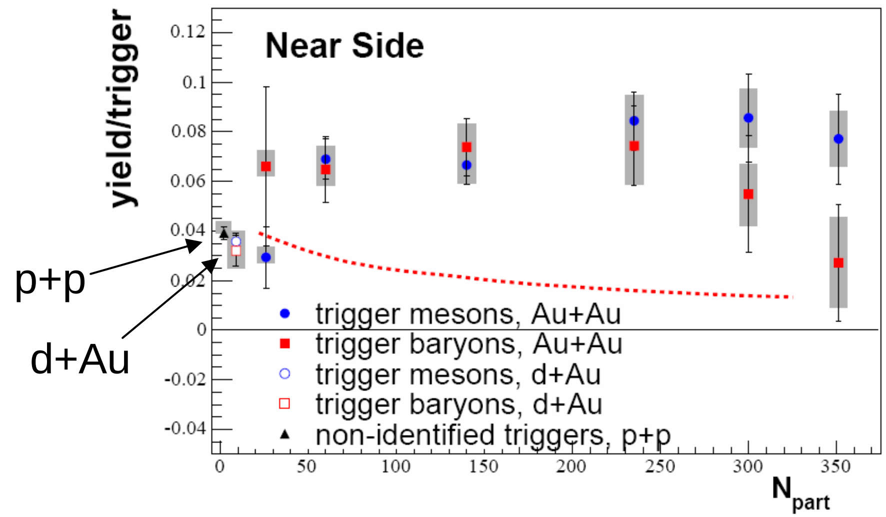
de l'étude de l'hadronisation

4. Corrélations des jets

A crucial test of the origin for the enhanced (anti)proton to pion ratio is to see if baryons in this intermediate p_T regime exhibit correlations characteristic of the structure of jets from hard-scattered partons.

Mesure des jets :

- Compter le nombre de hadrons chargés (particules associées) dans un cône autour de la particule déclenchante
- particules déclenchantes : 2.5 < pT < 4
- particules associées : 1.7 < pT < 2.5



- Comportement similaire p+p et d+Au
- 2× plus de particules produites en AuAu → le processus de fragmentation est modifié par le milieu
- Dans les modèles de recombinaison, on s'attend à une baisse de « yield/trigger » (ligne pointillée)

V. Production des hadrons

de l'étude de l'hadronisation

- Conclusions

The large (anti) baryon to pion excess relative to expectations from parton fragmentation functions at intermediate $p_T = 2 - 5$ GeV/c remains one of the most striking unpredicted experimental observations at RHIC. The data clearly indicate a new mechanism other than universal parton fragmentation as the dominant source of baryons and anti-baryons at intermediate p_T in heavy ion collisions. The boosting of soft physics, that dominates hadron production at low p_T, to higher transverse momentum has been explored with the context of hydrodynamic and recombination models. However, investigations into these intermediate p_T baryons reveals a near-angle correlation between particles, in a fashion characteristic of jet fragmentation. If instead these baryons have a partonic hard scattering followed by fragmentation source, this fragmentation process must be significantly modified. It is truly remarkable that these baryons have a large v_2 (typically 20%) indicative of strong collective motion and also a large "jet-like" near-side partner yield. At present, no theoretical framework provides a complete understanding of hadron formation in the intermediate p_T region.

Conclusions du White Paper

- Densité d'énergie et particules chargées
  - Densité d'énergie → 15 GeV/fm3
  - Particules chargées → saturation des gluons dans l'état initial ?
- Thermalisation
  - Production d'étrangeté en accord avec l'hypothèse d'un équilibre chimique.
  - Le flot elliptique observé indique un haut degré de collectivité.
  - Pas d'image consistante de la dynamique de la collision.
- Binarité
  - Effet Cronin en dAu → CGC ?
  - Binarité des photons directs et du charme en AuAu → compatible avec CGC ?
- Suppression à grand pT
  - Suppression des hadrons croissante avec la centralité → milieu dense
  - Hypothèse d'un milieu dense confirmée par les corrélations angulaires
- Production des hadrons
  - Différence de comportement protons/pions
  - Étude du méson Φ → différence de comportement pas liée à la différence de masse
  - Observation d'un flot partonique → différence de comportement liée au nombre de quarks
  - Corrélations des jets incompatibles avec modèles de recombinaison

Les futures mesures

de l'intérêt de continuer

- Supression à grand p_T et physique des jets
  - Augmenter la statistique
  - Atteindre de plus grand p_T
- Production du J/Ψ
  - Jusqu'ici, shadowing mesuré en dAu, mais pas assez de statistique en AuAu
  - 1er résultats attendus avec les données AuAu (2004) et CuCu (2005) → QM05.
  - Résultats à grande statistique avec les données AuAu (2008).
- Production du charme
  - Flot du charme
  - Perte d'énergie du charme dans un milieu dense
- Di-leptons de basse masse
  - Tester la restauration de la symétrie chirale (r,F,w/cf CERES au CERN)
  - Nouveau détecteur pour réduire le bruit de fond.
- Radiation thermique
  - Mesure des photons directs
  - Données 2004 → grande (suffisante ?) statistique