

# Recherche du plasma de quarks et de gluons au RHIC

A la suite du programme ions lourds effectué auprès du SPS au CERN, la mise en service récemment du collisionneur RHIC, fonctionnant à des énergies environ dix fois supérieures, ouvre de nouvelles perspectives sur la recherche et l'étude du plasma de quarks et de gluons...

**Frédéric Fleuret**  
**Laboratoire Leprince-Ringuet**

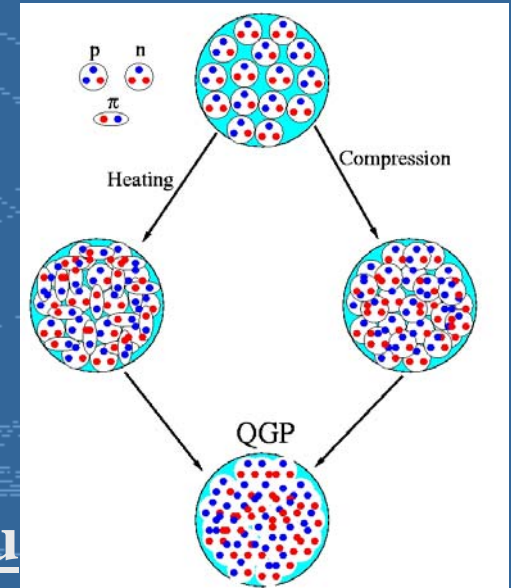
# Recherche du plasma de quarks et de gluons au RHIC

- **Introduction**
  - La prédiction théorique
  - Le contexte expérimental
- **Le RHIC et ses expériences**
  - La machine
  - Les expériences
  - PHENIX
- **Résultats récents**
  - Collisions Au-Au au RHIC
  - Collisions d-Au au RHIC

# PQG : la prédiction théorique

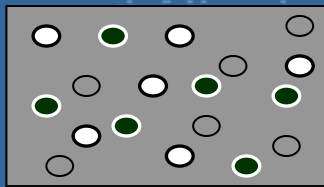
- QCD : Le déconfinement

- Prédiction : à une densité (température) suffisamment élevée, une transition de phase devrait apparaître.



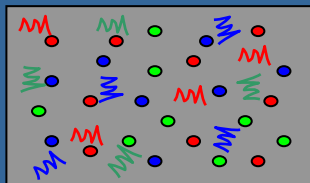
- La transition de phase : QCD sur réseau

Gaz de pions



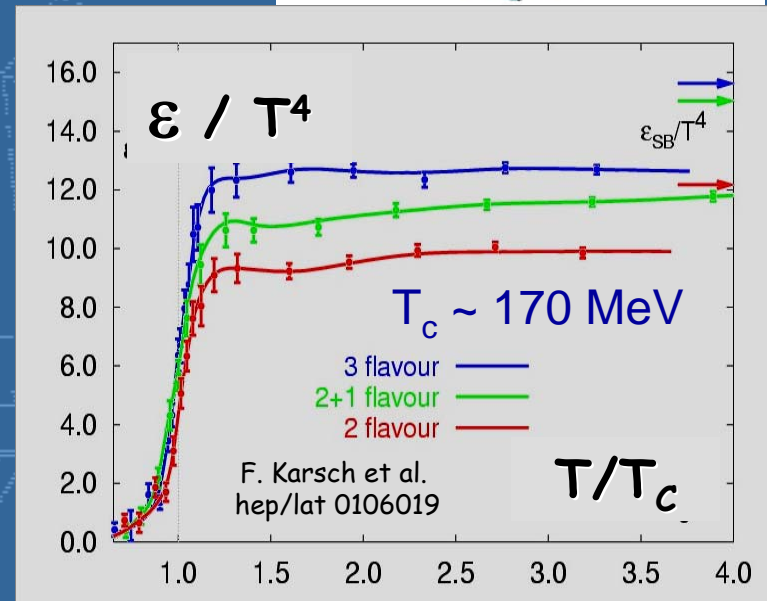
$$N_{\text{d.o.f}} = 3$$

PQG



$$N_{\text{d.o.f}} = 37$$

(2-saveurs)

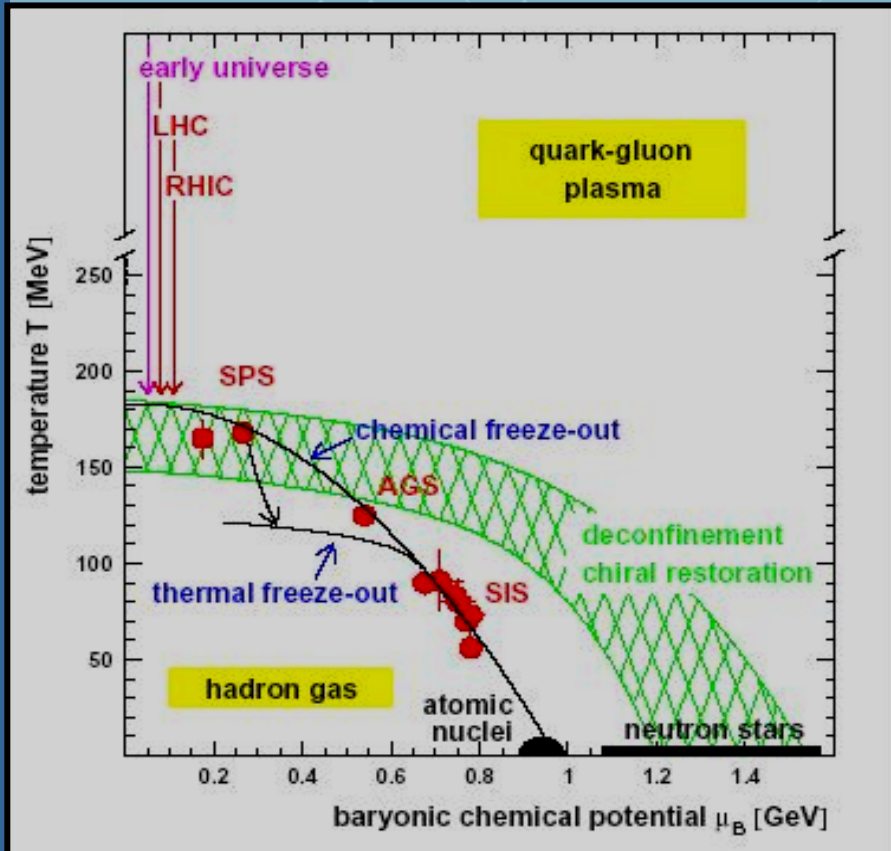
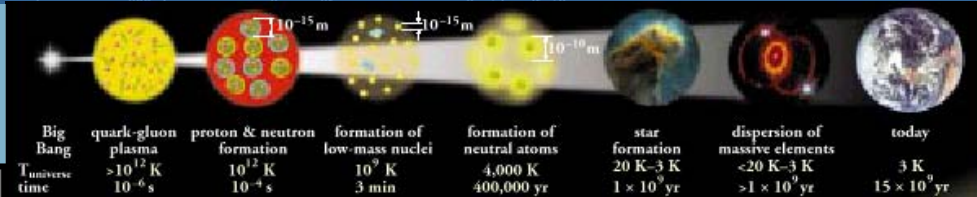


# PQG : la prédiction théorique

- Le diagramme de phase

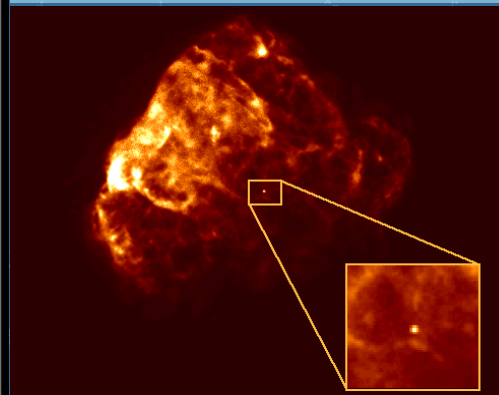
## Big Bang

- haute température ( $10^{12}$  K)
- $10^{-6}$  s. : Plasma  $\rightarrow$  matière confinée



## Etoiles à neutron

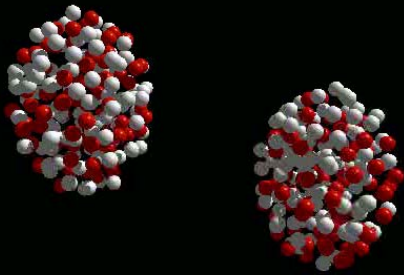
- effondrement d'étoile
- forte densité de matière
- (5 à 10 fois la densité nucléaire classique)
- matière confinée  $\rightarrow$  plasma



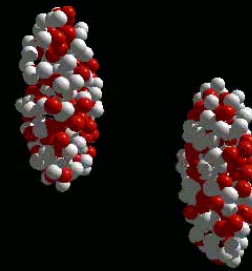
# PQG : le contexte expérimental

- Historique

BNL - AGS 4 GeV



CERN - SPS 20 GeV



BNL - RHIC 200 GeV



CERN - LHC 5 TeV



CIBLE  
FIXE

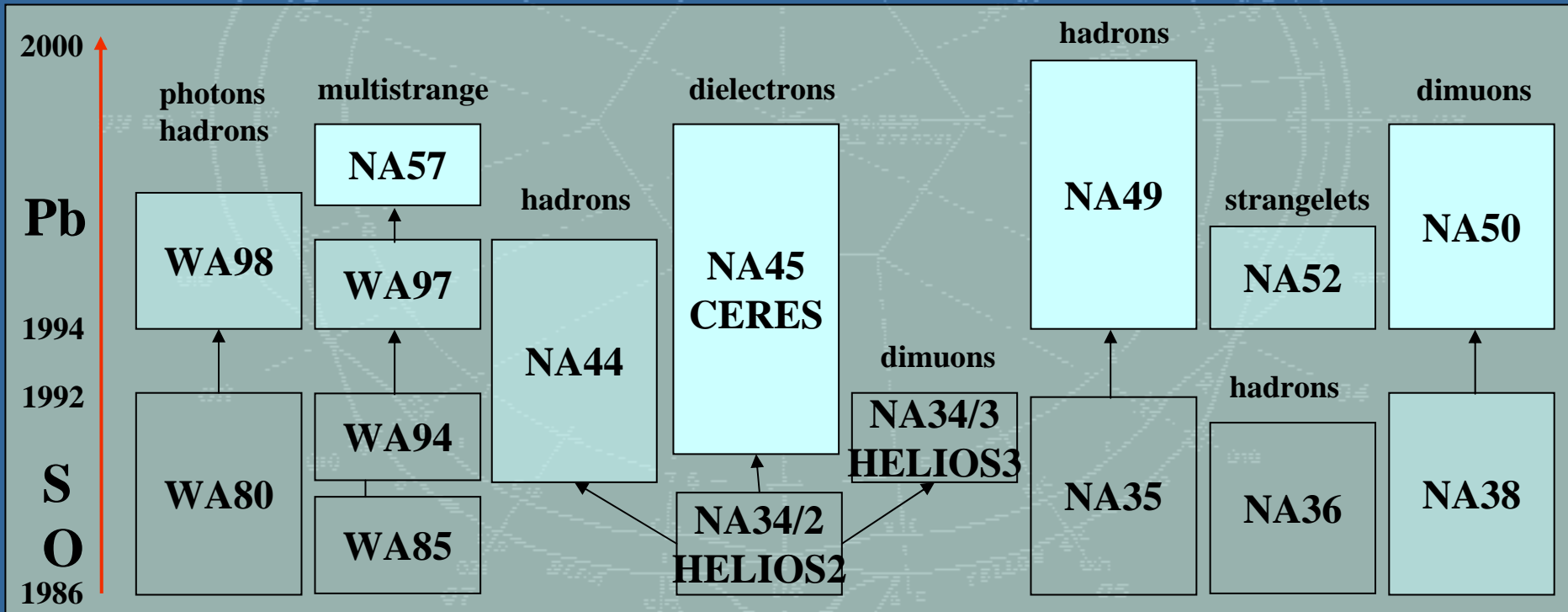
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# PQG : le contexte expérimental

- 15 ans de recherche au CERN
    - 1986 - 1987 : Oxygène @ 60 & 200 GeV/nucléon
    - 1987 - 1992 : Soufre @ 200 GeV/nucléon
    - 1994 - 2000 : Plomb @ 40, 80 & 158 GeV/nucléon
- + pp et pA pour des études de référence



# PQG : le contexte expérimental

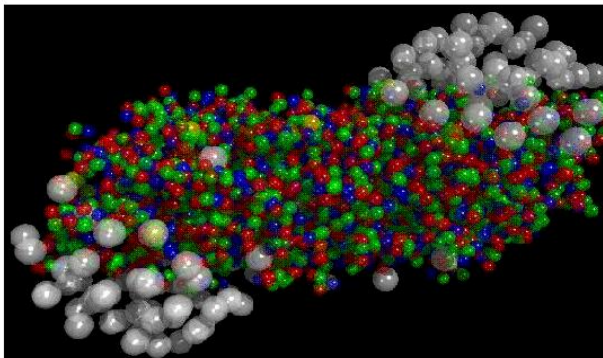
- 15 ans de recherche au CERN : bilan



Organisation Européenne pour la Recherche Nucléaire  
European Organization for Nuclear research  
Laboratoire Européen pour la Physique des Particules  
European Laboratory for Particle Physics  
Europäisches Laboratorium für Teilchenphysik  
Laboratorio europeo per la fisica delle particelle

PRESS RELEASE

## New State of Matter created at CERN



At a special seminar on 10 February, spokespersons from the experiments on CERN\* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.

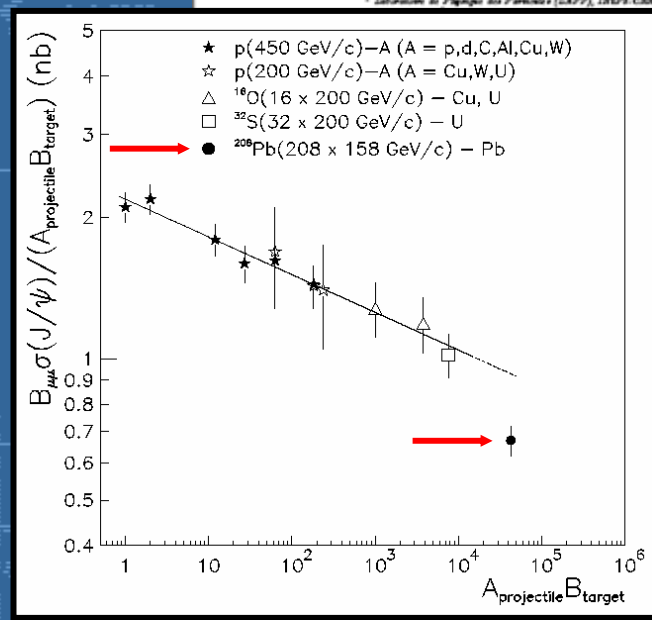
### Anomalous $J/\psi$ suppression in Pb-Pb interactions at 158 GeV/c per nucleon

**NAM Collaboration**

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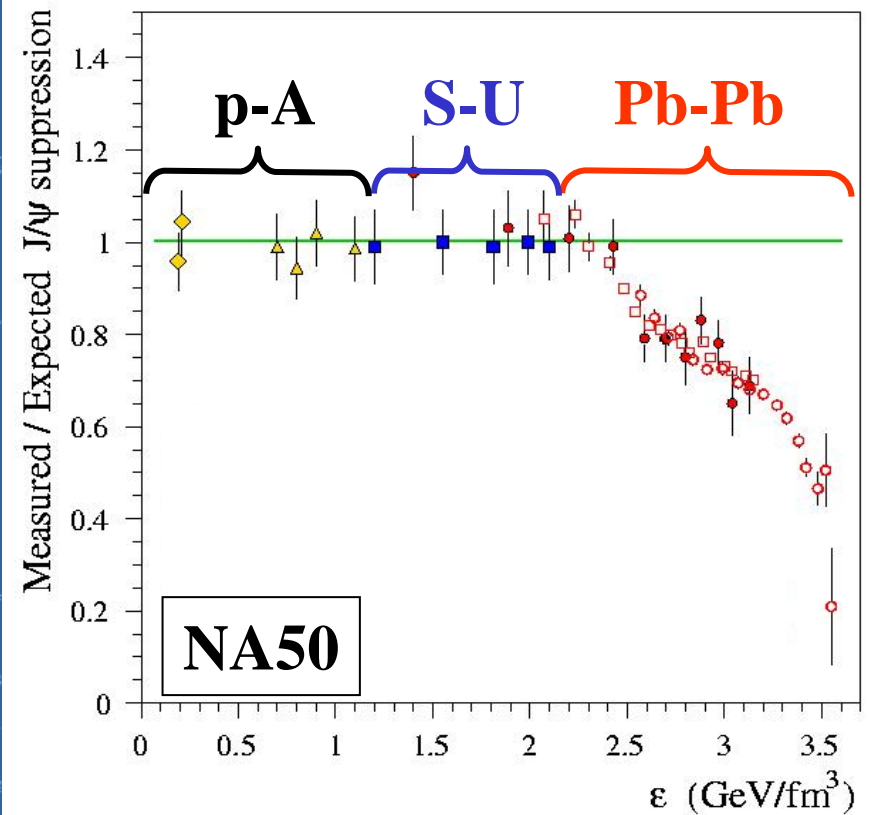
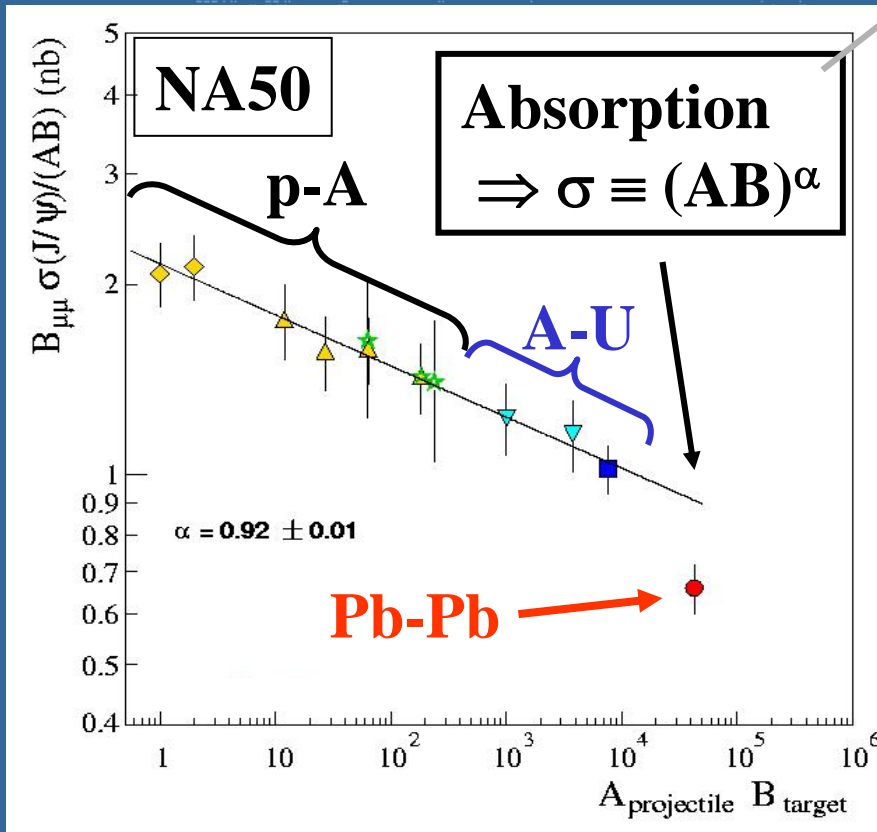
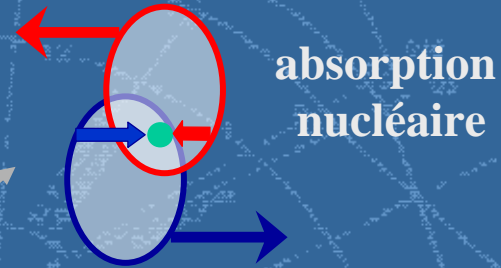
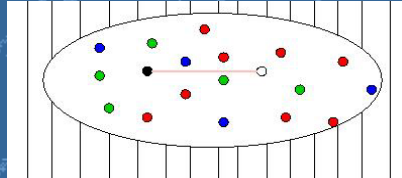
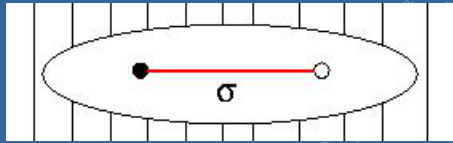


# PQG : le contexte expérimental

- NA50 : suppression du  $J/\psi$

quarkonium

écranage





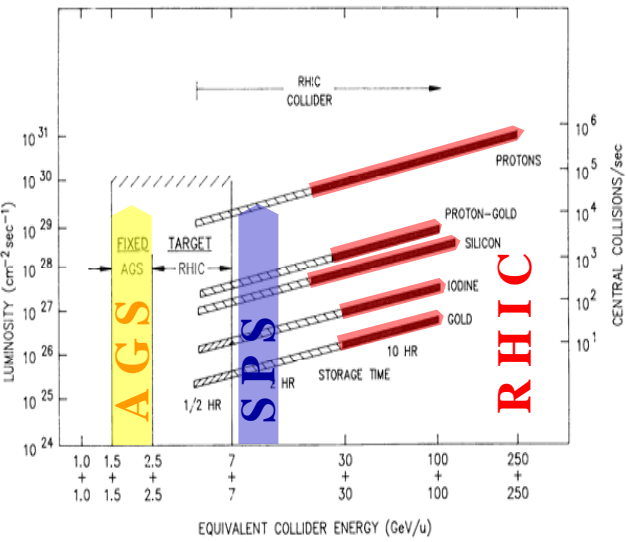
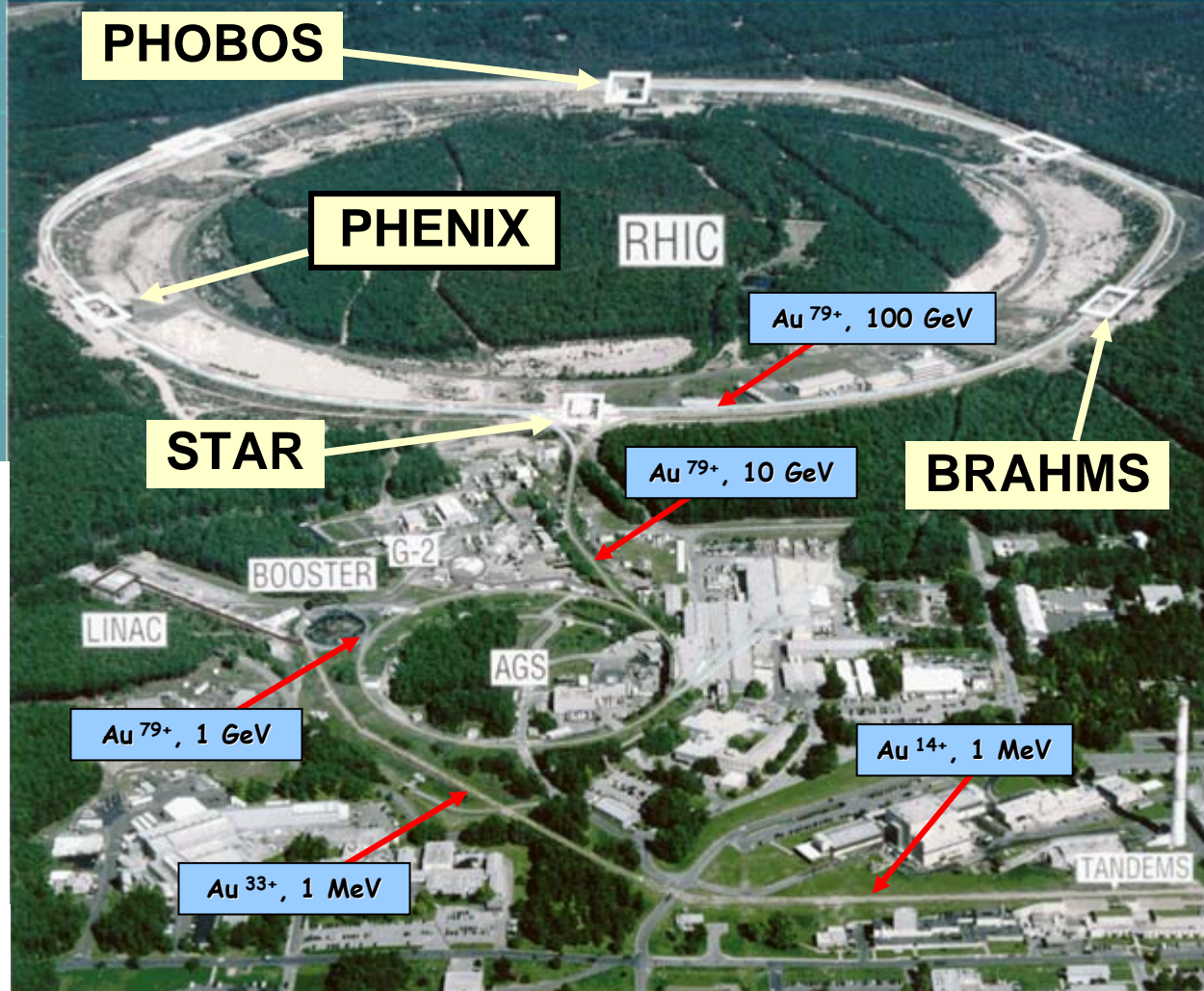
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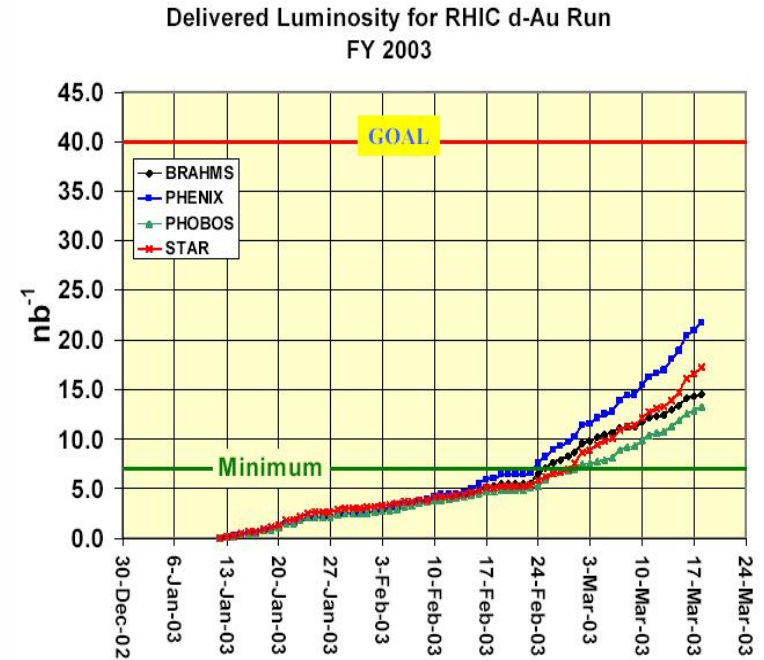
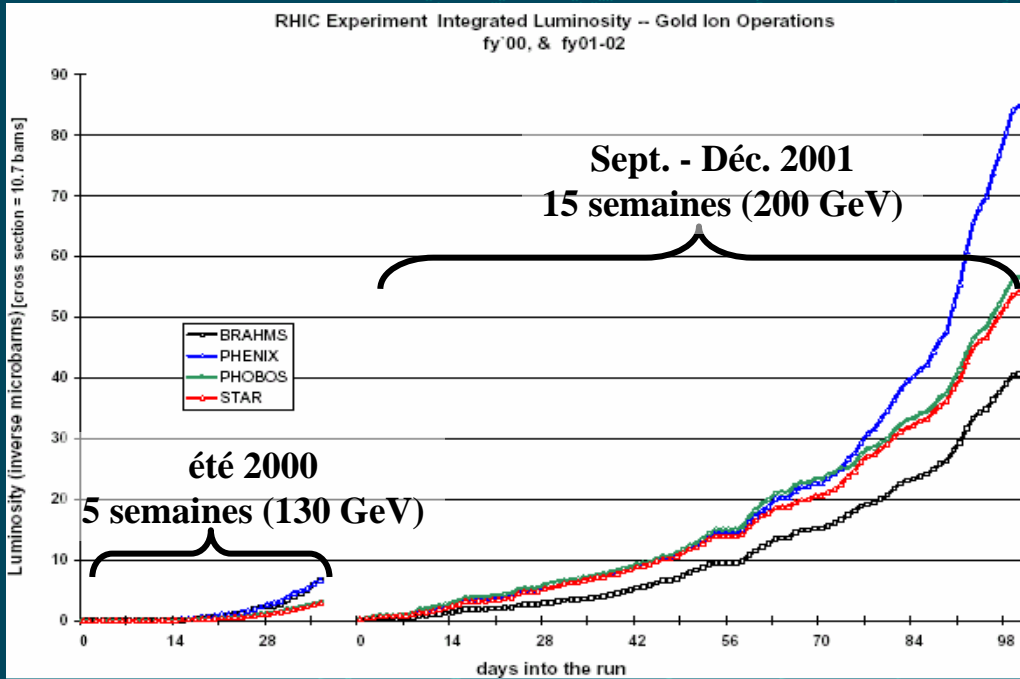
# Le RHIC

- La machine : Relativistic Heavy Ion Collider

- 3,9 km circonférence
- de p+p (polarisés)
  - $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
  - jusqu'à 500 GeV
- à Au+Au
  - $2 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$
  - 200 GeV/nucléon



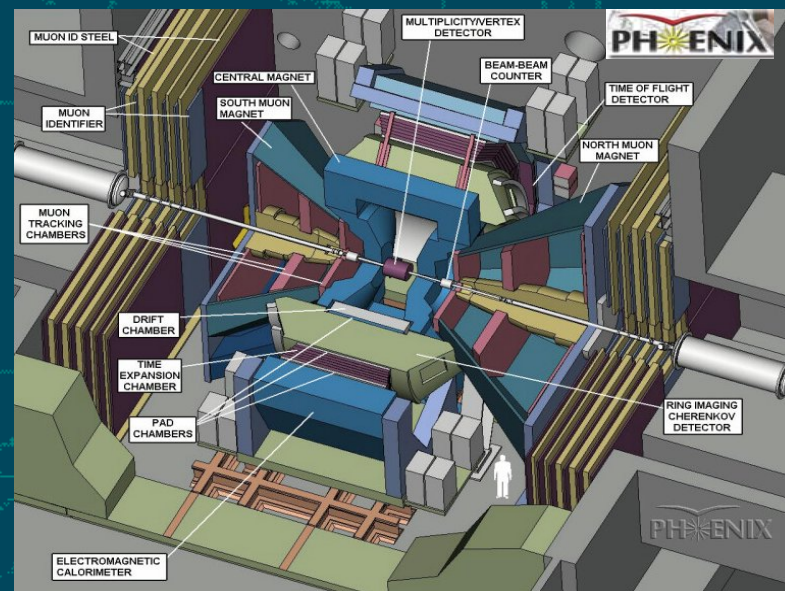
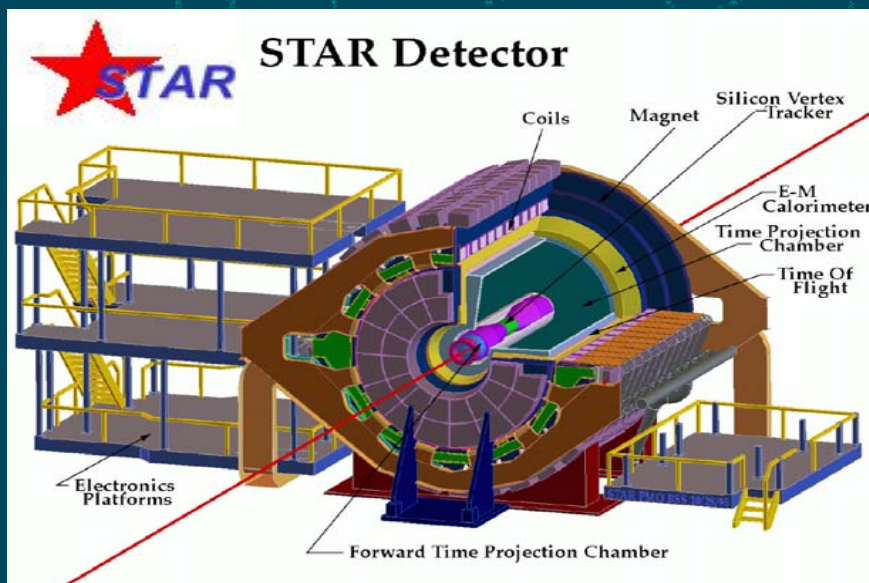
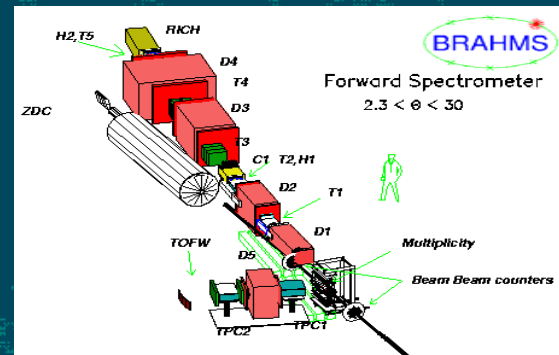
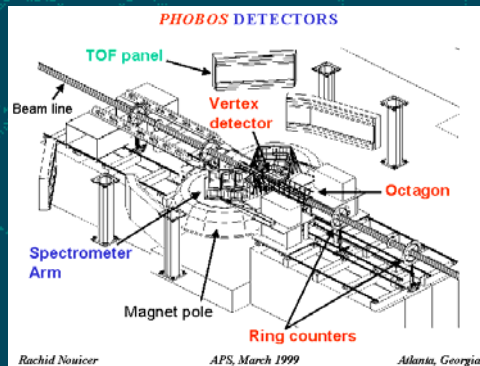
## • Luminosités



- **Run I :**
  - 5 semaines
  - Au-Au @ 130 GeV
- **Run II :**
  - 15 semaines
  - Au-Au @ 200 GeV
- **Run III :**
  - 9 semaines
  - d-Au @ 200 GeV

	<u>attendue</u>	<u>obtenue</u>
	20 $\mu\text{b}^{-1}$	1 $\mu\text{b}^{-1}$
	300 $\mu\text{b}^{-1}$	24 $\mu\text{b}^{-1}$
	10 $\text{nb}^{-1}$	2.7 $\text{nb}^{-1}$

- Les expériences
  - Deux petites et deux grandes



## • La collaboration

### • 12 countries

**Brazil (1)**

**China (3)**

**France (5)**

**Germany (1)**

**Hungary (3)**

**India (2)**

**Israel (1)**

**Japan (10)**

**Korea (6)**

**Russia (5)**

**Sweden (1)**

**USA (18)**

### • 56 institutions

### • ~ 450 participants

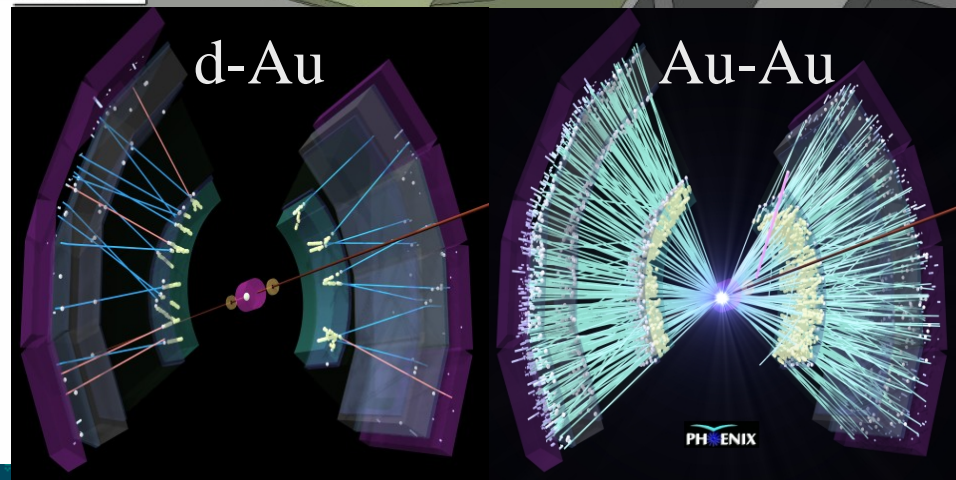
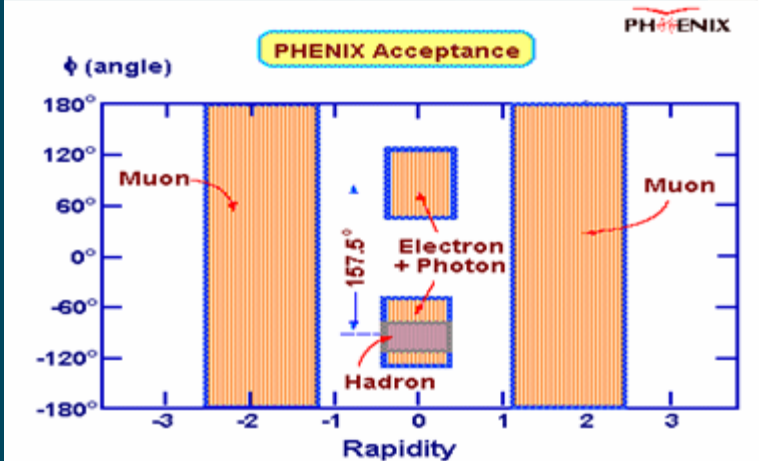
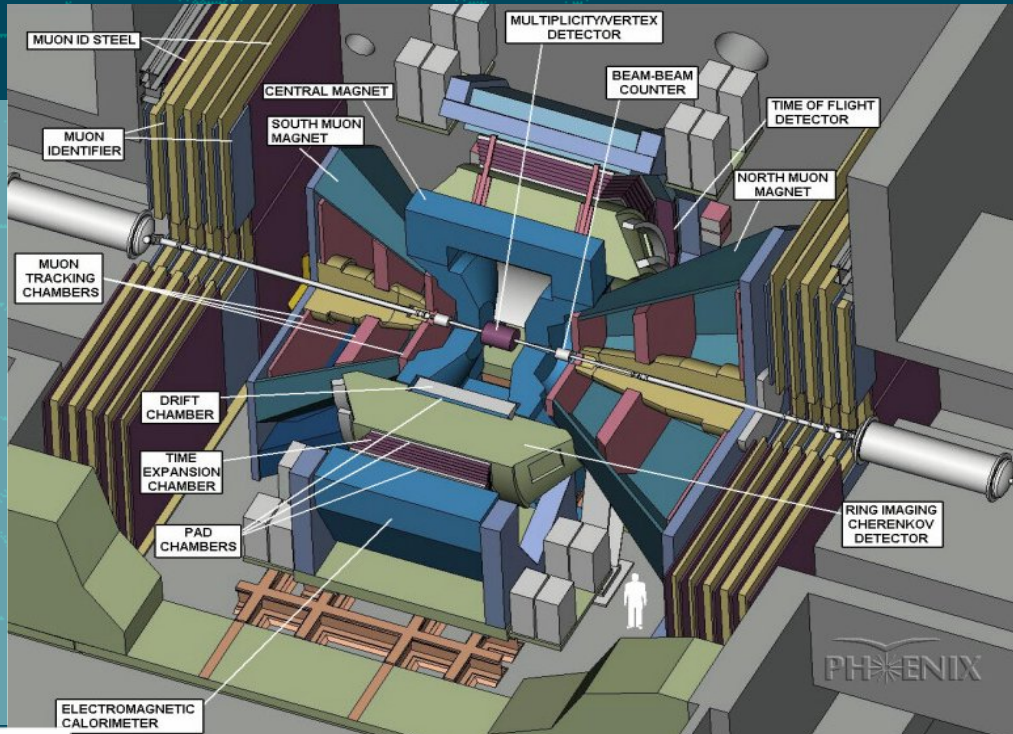
<b>Brazil</b>	<b>University of São Paulo, São Paulo</b>
<b>China</b>	<b>Academia Sinica, Taipei, Taiwan</b> <b>China Institute of Atomic Energy, Beijing</b> <b>Peking University, Beijing</b>
<b>France</b>	<b>LPC, University de Clermont-Ferrand, Clermont-Ferrand</b> <b>Dapnia, CEA Saclay, Gif-sur-Yvette</b> <b>IPN-Orsay, Université Paris Sud, CNRS-IN2P3, Orsay</b> <b>LLR, Ecole Polytechnique, CNRS-IN2P3, Palaiseau</b> <b>SUBATECH, Ecole des Mines at Nantes, Nantes</b>
<b>Germany</b>	<b>University of Münster, Münster</b>
<b>Hungary</b>	<b>Central Research Institute for Physics (KFKI), Budapest</b> <b>Debrecen University, Debrecen</b> <b>Eötvös Loránd University (ELTE), Budapest</b>
<b>India</b>	<b>Banaras Hindu University, Banaras</b> <b>Bhabha Atomic Research Centre, Bombay</b>
<b>Israel</b>	<b>Weizmann Institute, Rehovot</b>
<b>Japan</b>	<b>Center for Nuclear Study, University of Tokyo, Tokyo</b> <b>Hiroshima University, Higashi-Hiroshima</b> <b>KEK, Institute for High Energy Physics, Tsukuba</b> <b>Kyoto University, Kyoto</b> <b>Nagasaki Institute of Applied Science, Nagasaki</b> <b>RIKEN, Institute for Physical and Chemical Research, Wako</b> <b>RIKEN-BNL Research Center, Upton, NY</b> <b>University of Tokyo, Bunkyo-ku, Tokyo</b> <b>Tokyo Institute of Technology, Tokyo</b> <b>University of Tsukuba, Tsukuba</b> <b>Waseda University, Tokyo</b>
<b>S. Korea</b>	<b>Cyclotron Application Laboratory, KAERI, Seoul</b> <b>Kangnung National University, Kangnung</b> <b>Korea University, Seoul</b> <b>Myong Ji University, Yongin City</b> <b>System Electronics Laboratory, Seoul Nat. University, Seoul</b> <b>Yonsei University, Seoul</b>
<b>Russia</b>	<b>Institute of High Energy Physics, Protovino</b> <b>Joint Institute for Nuclear Research, Dubna</b> <b>Kurchatov Institute, Moscow</b> <b>PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg</b> <b>St. Petersburg State Technical University, St. Petersburg</b>
<b>Sweden</b>	<b>Lund University, Lund</b>



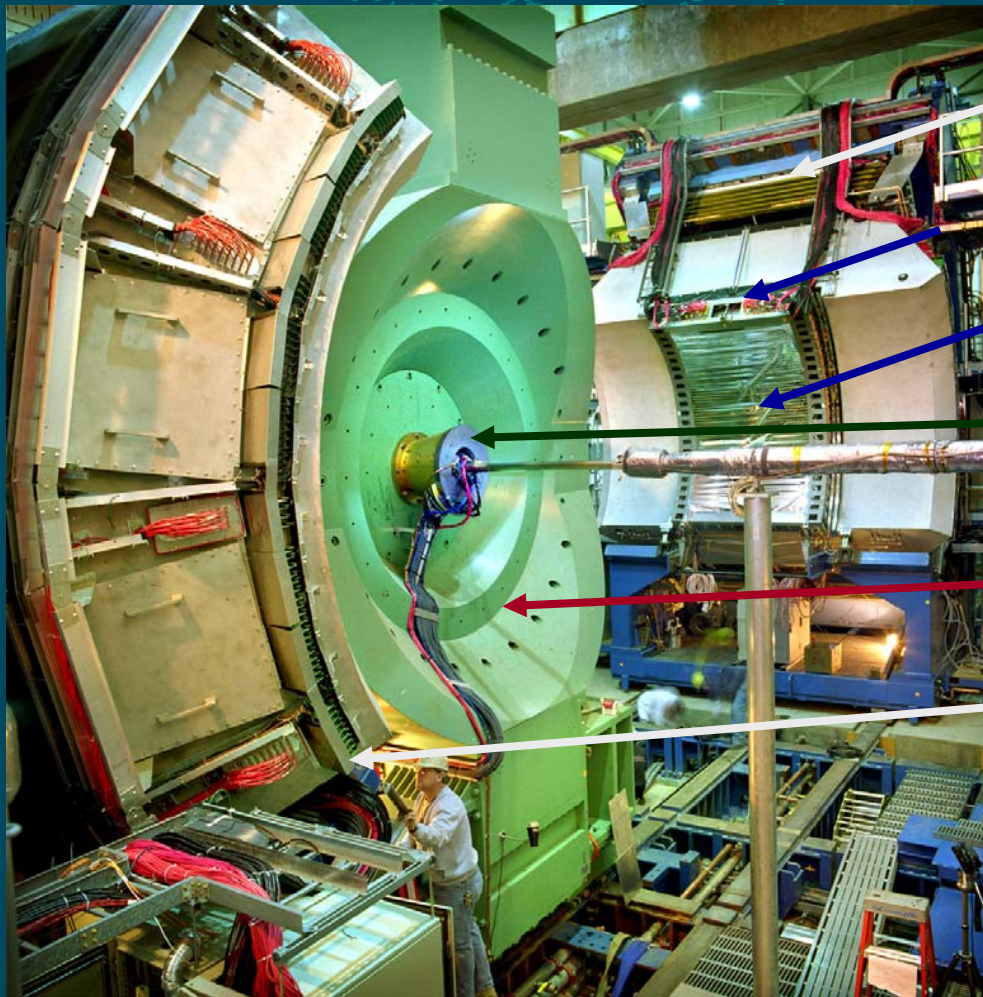
**USA** **Abilene Christian University, Abilene, TX**  
**Brookhaven National Laboratory, Upton, NY**  
**University of California - Riverside, Riverside, CA**  
**University of Colorado, Boulder, CO**  
**Columbia University, Nevis Laboratories, Irvington, NY**  
**Florida State University, Tallahassee, FL**  
**Georgia State University, Atlanta, GA**  
**University of Illinois Urbana Champaign, IL**  
**Iowa State University and Ames Laboratory, Ames, IA**  
**Los Alamos National Laboratory, Los Alamos, NM**  
**Lawrence Livermore National Laboratory, Livermore, CA**  
**University of New Mexico, Albuquerque, NM**  
**New Mexico State University, Las Cruces, NM**  
**Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY**  
**Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY**  
**Oak Ridge National Laboratory, Oak Ridge, TN**  
**University of Tennessee, Knoxville, TN**  
**Vanderbilt University, Nashville, TN**

## • Le détecteur

- $e, \gamma, h$  (Central Arms)
  - $|\eta| < 0.35, \Delta\phi = \pi$
  - $p_T > 0.2 \text{ GeV}/c$  (charged particles)
- $\mu$  (Muon Arms)
  - $1.2 < |\eta| < 2.4, \Delta\phi = 2\pi$
  - $p_{tot} > 2 \text{ GeV}/c$
- Interaction and vertex detectors
  - Beam-Beam Counters ( $3.0 < |\eta| < 3.9$ )
  - Zero-Degree Calorimeters ( $|\eta| > 6.2$ )



- Le détecteur



East Carriage

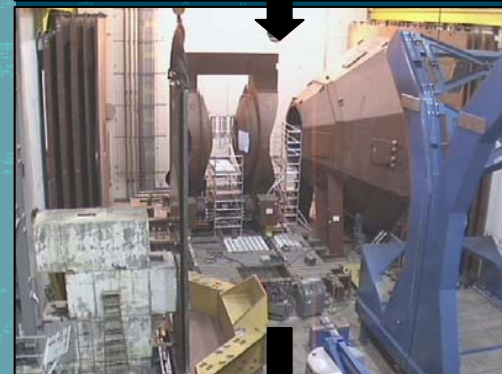
Ring Imaging  
Cerenkov

Drift Chamber

Beam-Beam  
Counter

Central Magnet

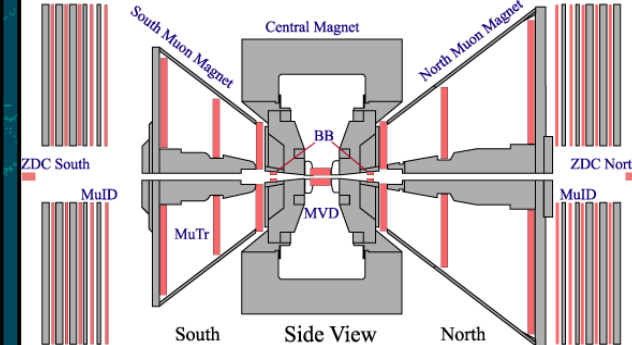
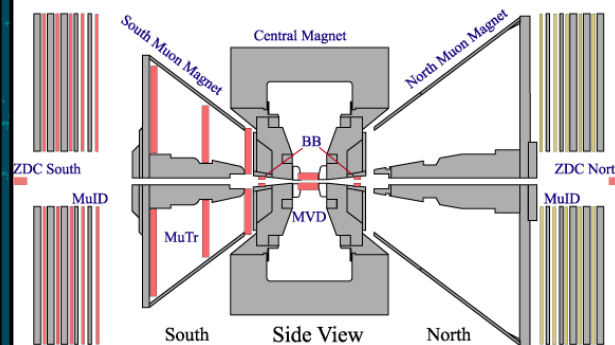
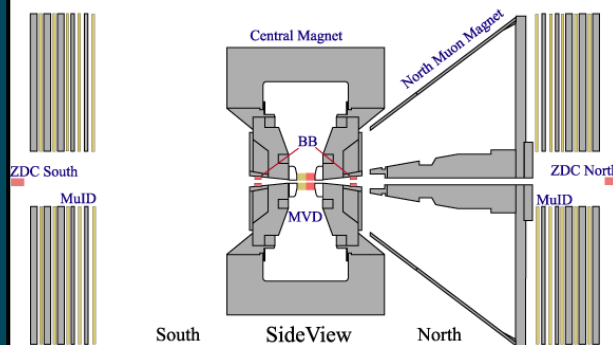
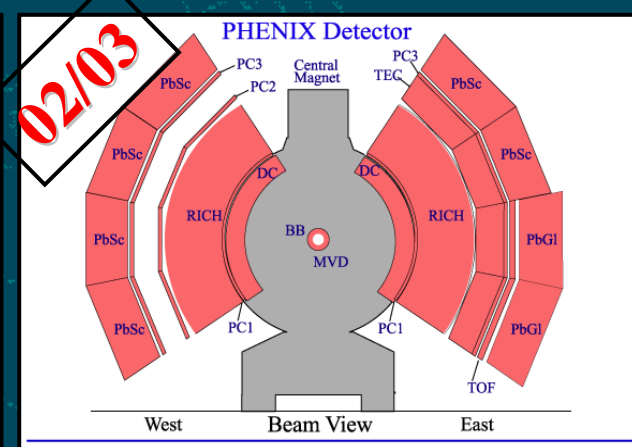
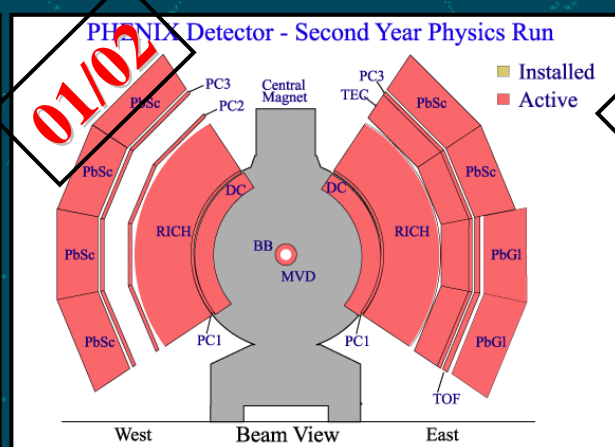
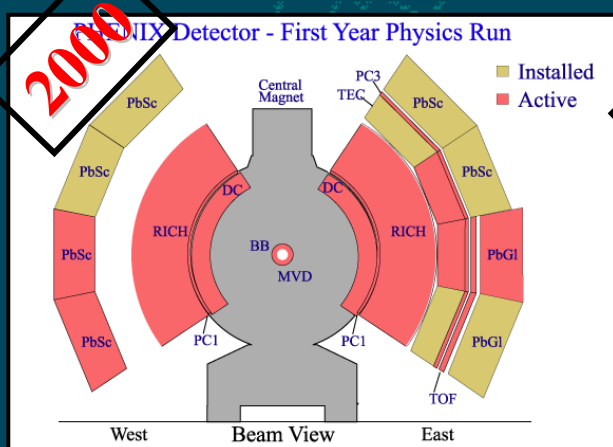
West Carriage



- Historique

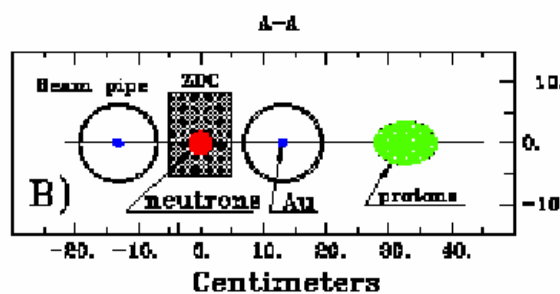
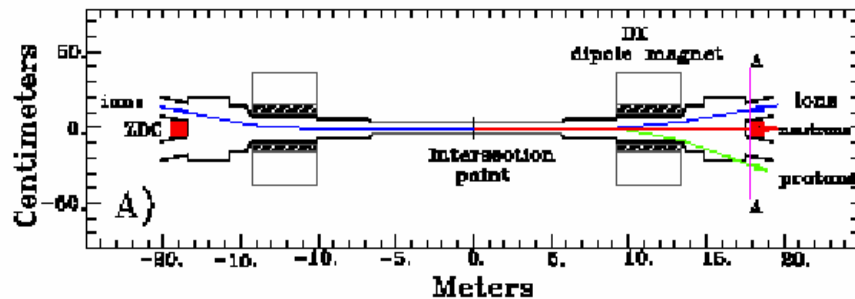
- Contribution française :

- Production, installation de l'électronique du bras nord
- Maintenance des deux bras dimuons (nord & sud)





## Mesure de la centralité : BBC vs. ZDC



### BBC

Beam Beam Counter  
measures charged  
particle multiplicity  
within  $3.0 < |\eta| < 3.9$

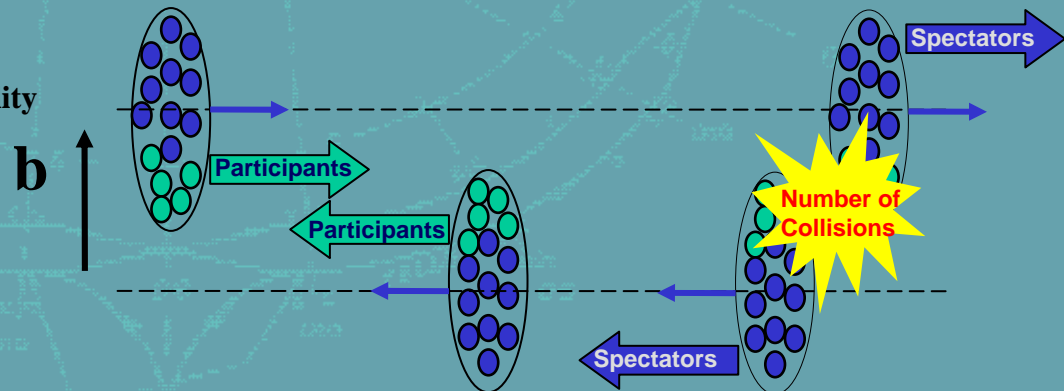
### ZDC

Zero Degree Calo  
measures neutron  
multiplicity at beam  
rapidity.

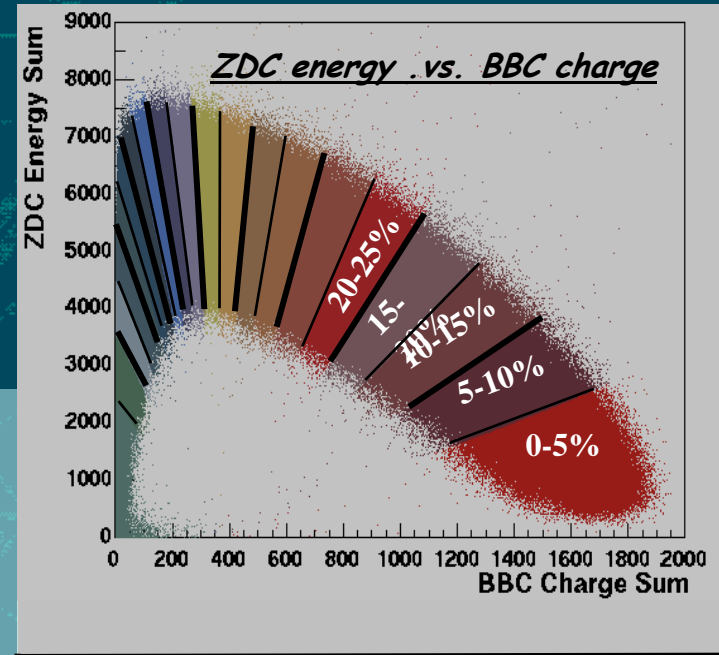


### Centrality measurement

- Use ZDC vs. BBC information to define centrality
- Use Glauber modeling to extract  $N_{\text{participants}}$ 
  - Impact parameter
  - Number of participants/spectators
  - Number of collisions

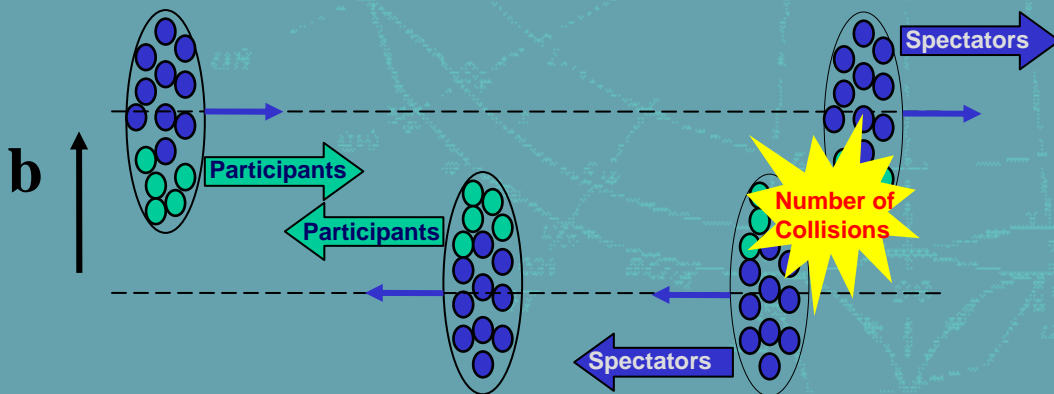


- Mesure de la centralité
  - BBC .vs. ZDC



- Centrality measurement

- Use ZDC.vs.BBC information to define centrality
- Use Glauber modeling to extract  $N_{\text{participants}}$ 
  - Impact parameter
  - Number of participants/spectators
  - Number of collisions



centrality	b (fm)	$N_{\text{part}}$	$N_{\text{coll}}$
0-5%	2,3 ± 0,9	353 ± 19	1091 ± 102
20-25%	7,1 ± 0,5	181 ± 16	422 ± 65
90-95%	14,5 ± 0,3	4.1 ± 2.5	2.8 ± 2.2

# Recherche du plasma de quarks et de gluons au RHIC

- **Introduction**
  - La prédiction théorique
  - Le contexte expérimental
- **Le RHIC et ses expériences**
  - La machine
  - Les expériences
  - PHENIX
- **Résultats récents**
  - Collisions Au-Au au RHIC (01/02)
  - Collisions d-Au au RHIC (02/03)

# Résultats récents

- Collisions Au-Au au RHIC

- Conditions initiales

- Densité d'énergie

- L'explosion finale

- Gel chimique
    - Gel thermique

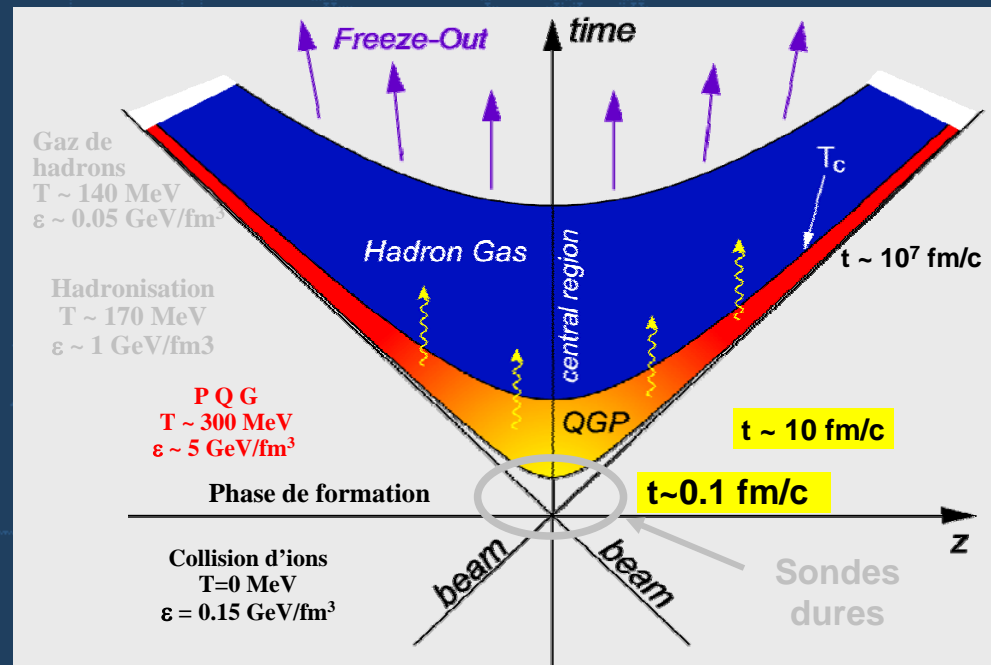
- Signer le déconfinement

- Suppression du  $J/\psi$
    - Jet quenching

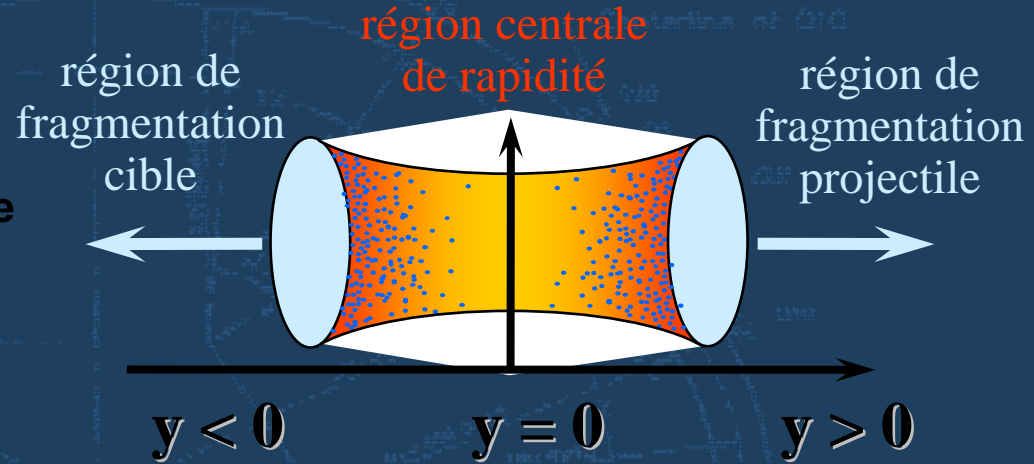
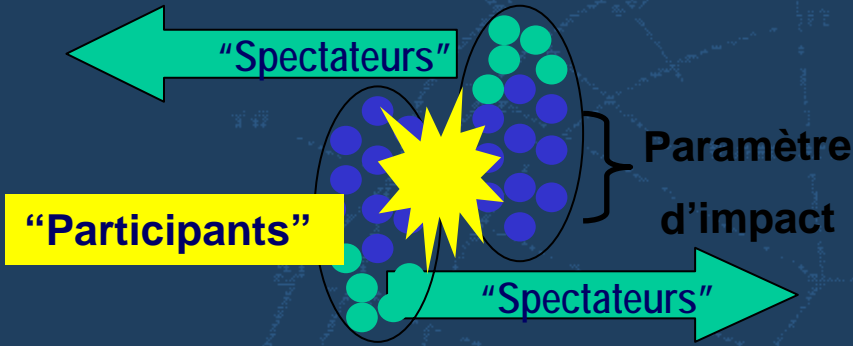
- Collisions d-Au au RHIC

- Premiers résultats sur la production de hadrons

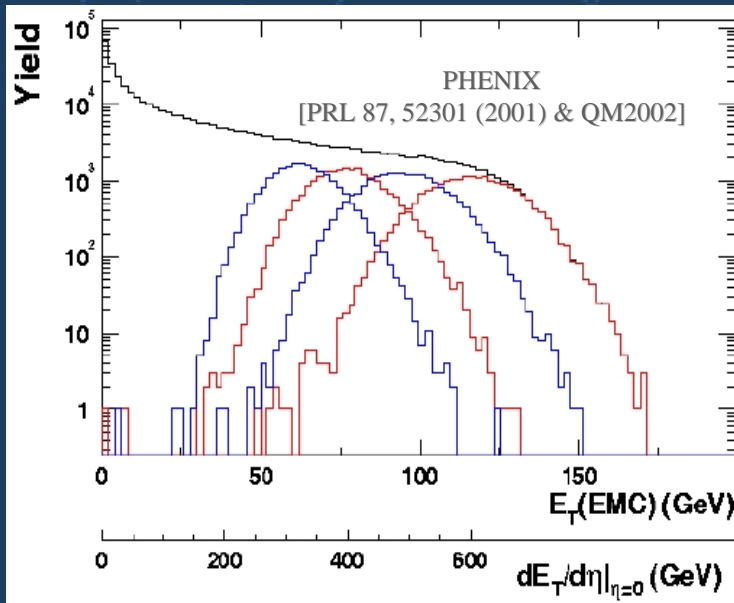
- Tester la production du  $J/\psi$



# Densité d'énergie



- Collisions Au-Au



Formule de Bjorken :

$$\varepsilon = \frac{dE_T}{dy} \Bigg|_{y=0} \frac{1}{S_{\perp} \tau}$$

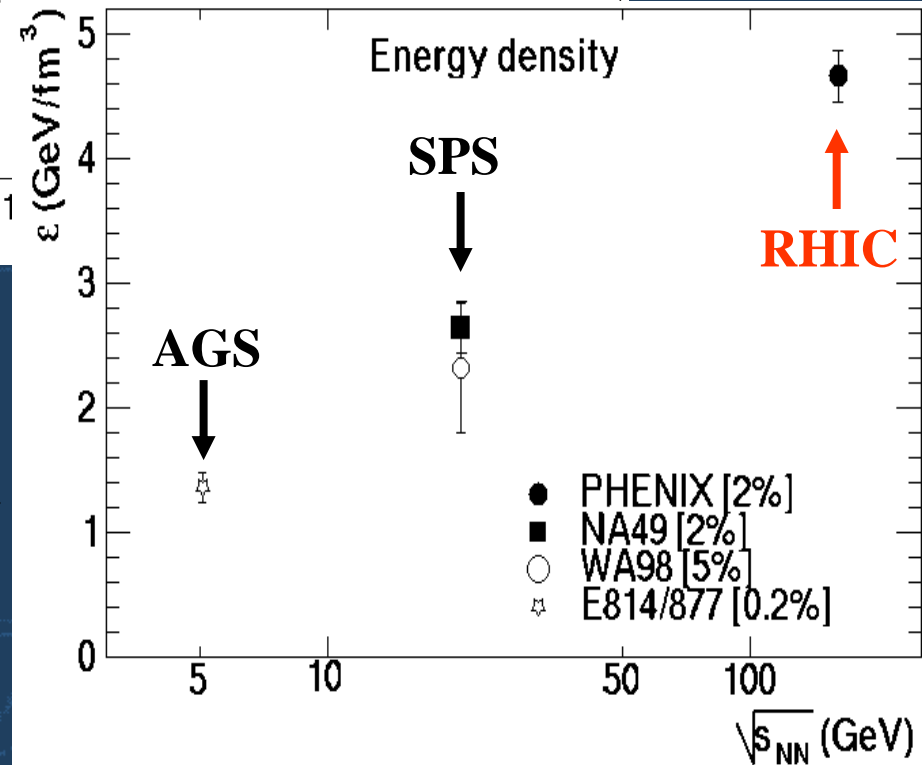
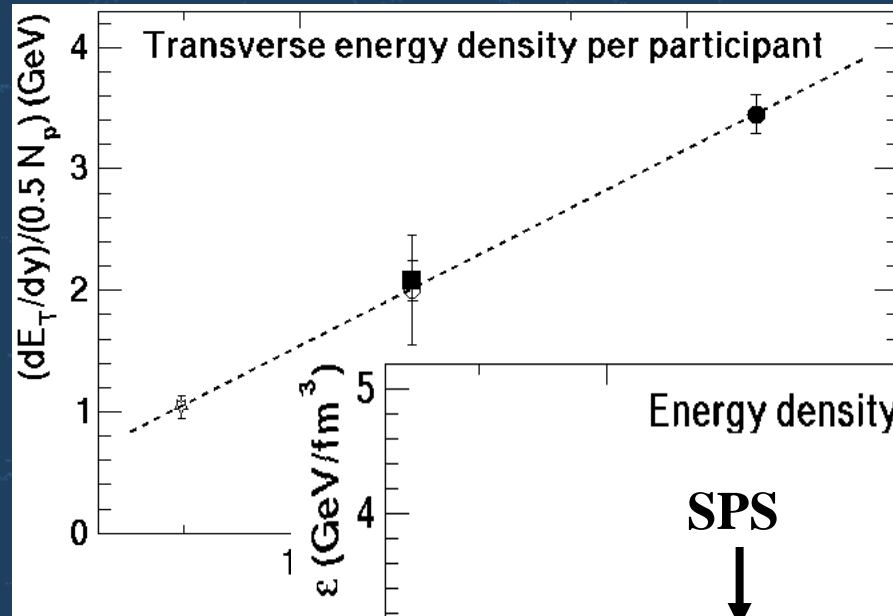
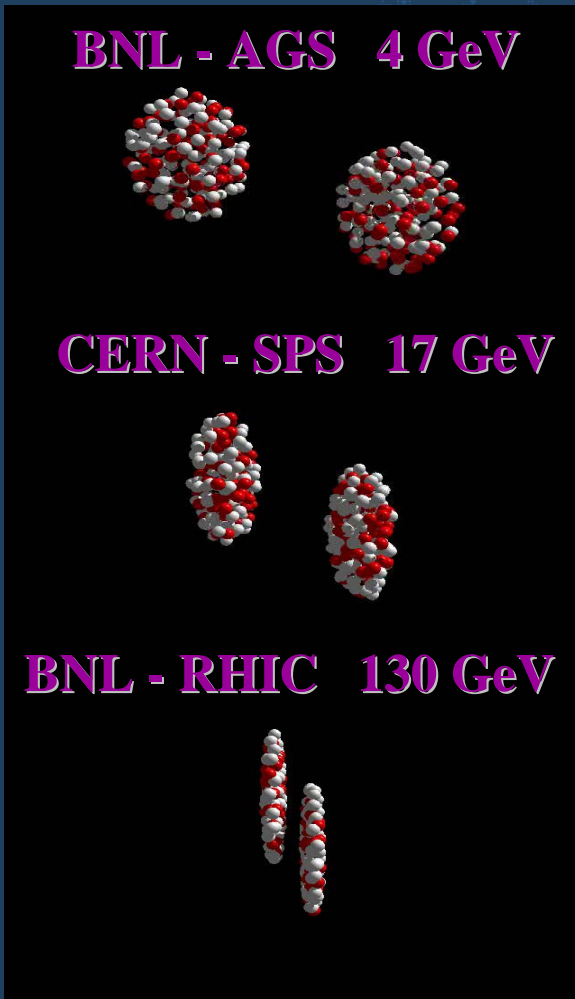
$\tau$  temps de formation de 0.1 à 1 fm/c

rayon nucléaire  $1.18 A^{1/3}$  fm

$\varepsilon > 5 \text{ GeV/fm}^3$

# Densité d'énergie

- Comparaison AGS/SPS/RHIC



# Résultats récents

- Collisions Au-Au au RHIC

- Conditions initiales
  - densité d'énergie

- L'explosion finale

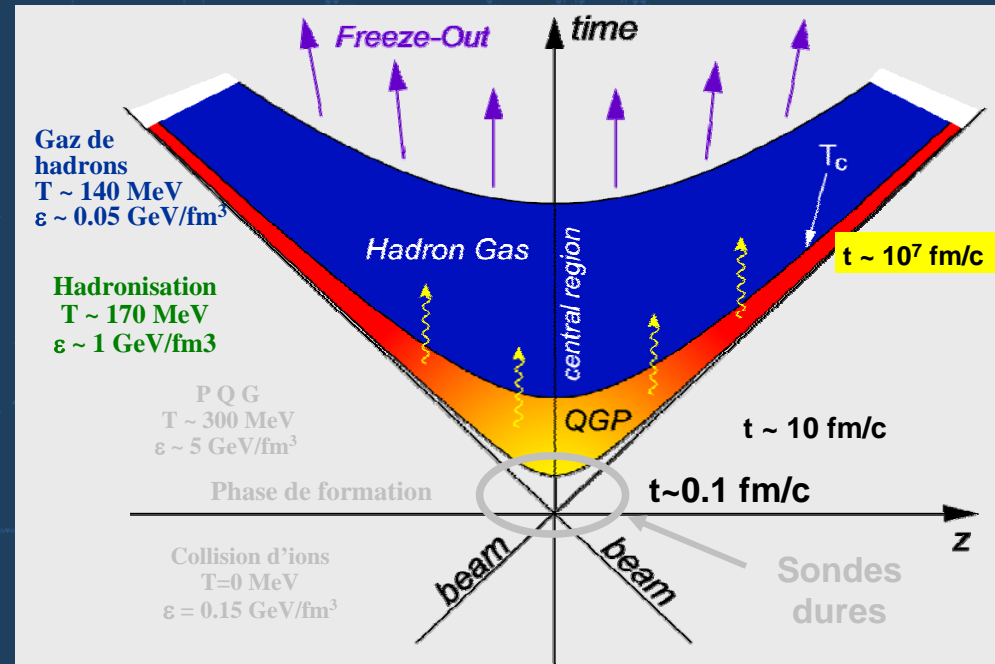
- Gel chimique
- Gel thermique

- Signer le déconfinement

- Suppression du  $J/\psi$
- Jet quenching

- Collisions d-Au au RHIC

- Premiers résultats sur la production de hadrons
- Tester la production du  $J/\psi$



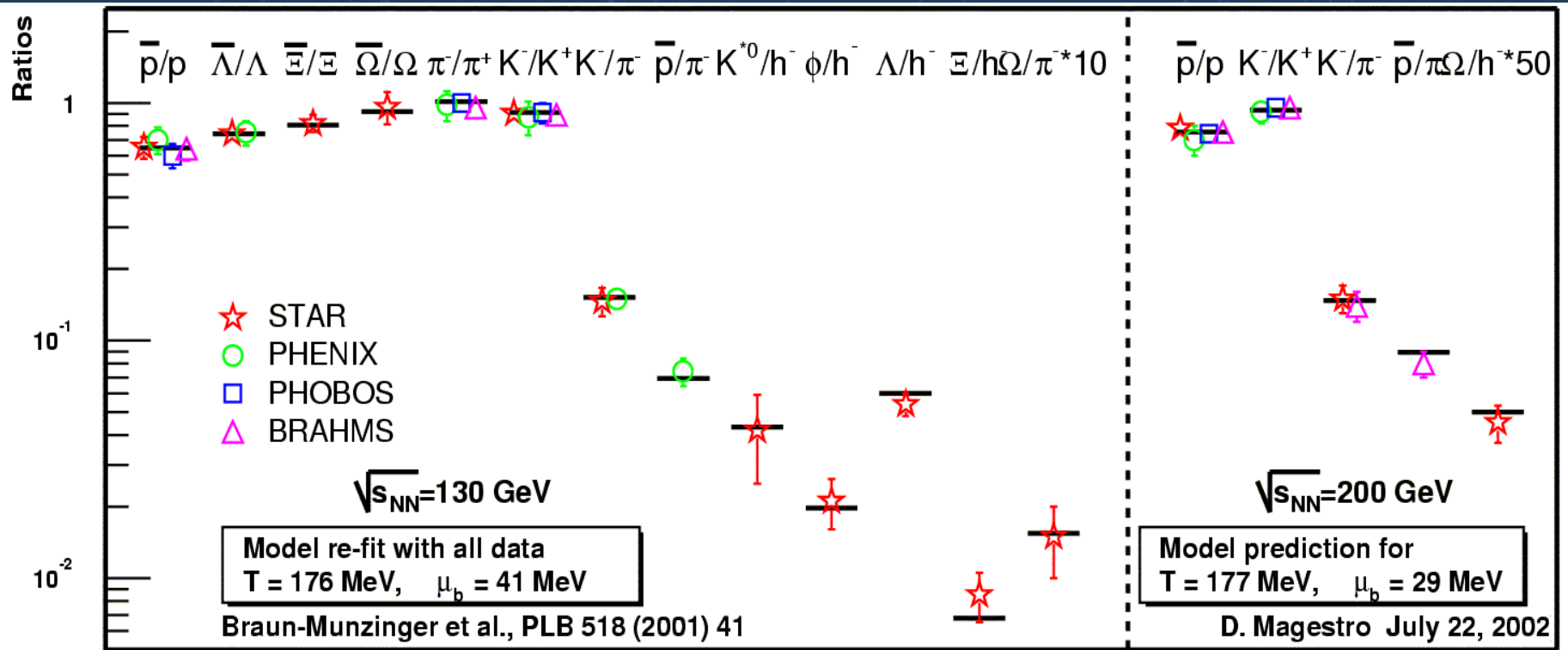
# Gel chimique

- Collisions Au-Au

density of the particles of species  $i$  in an equilibrated fireball:

$$n_i = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}$$

with particle density  $n_i$ , spin degeneracy  $g_i$ ,  $\hbar = c = 1$ , momentum  $p$ , total energy  $E$  and chemical potential  $\mu_i = \mu_B B_i - \mu_S S_i - \mu_{I_3} I_i^3$ .



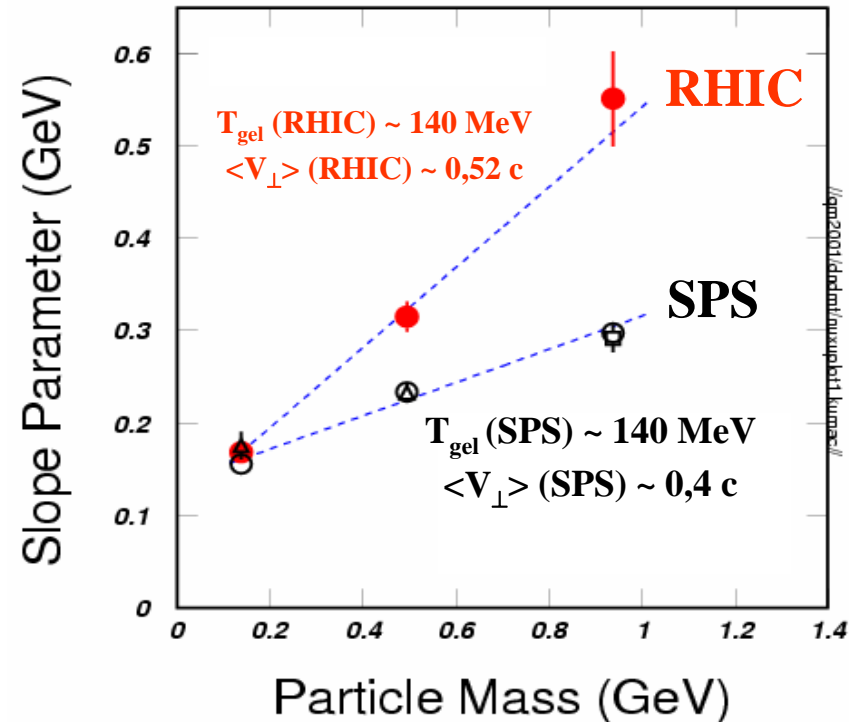
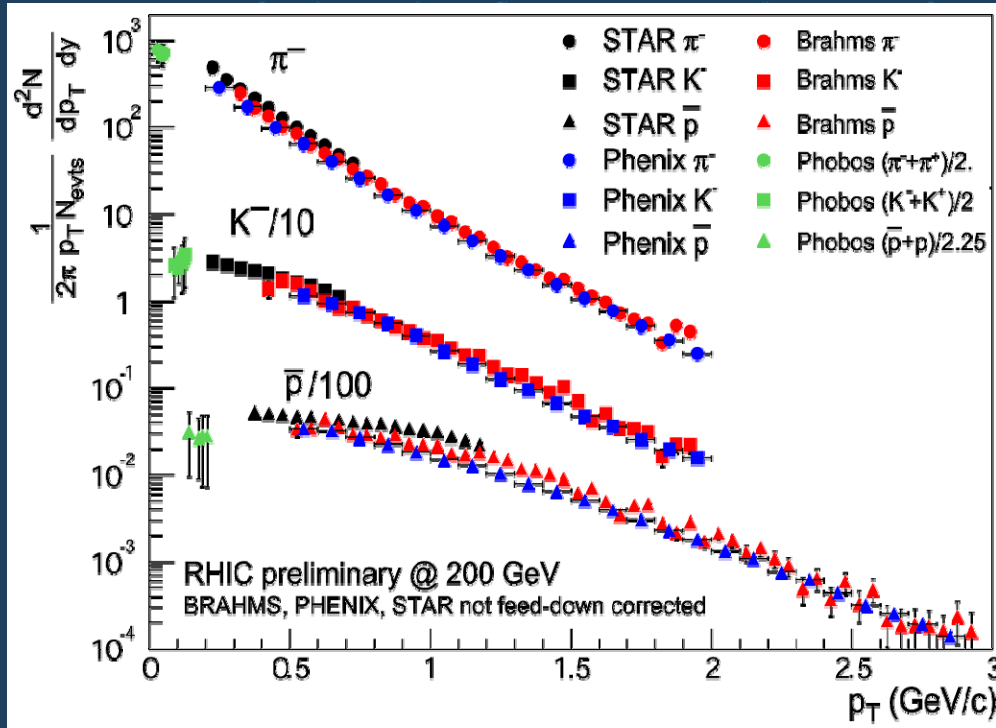


# Gel thermique

- Comparaison SPS/RHIC

- Mesurer les spectres d'émission des hadrons
- flot radial plus important à RHIC → plus forte pression

$$T = T_{\text{gel}} + \frac{1}{2} m \langle V_{\perp} \rangle^2$$



# Résultats récents

- Collisions Au-Au au RHIC

- Conditions initiales

- Densité d'énergie

- L'explosion finale

- Gel chimique
- Gel thermique

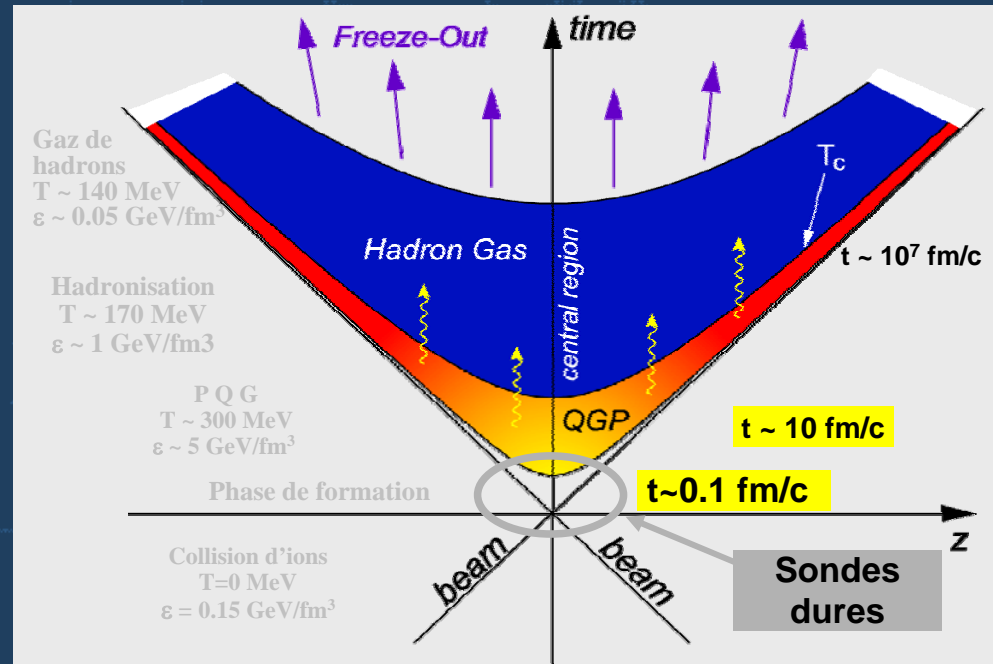
- Signer le déconfinement

- Suppression du  $J/\psi$
- Jet quenching

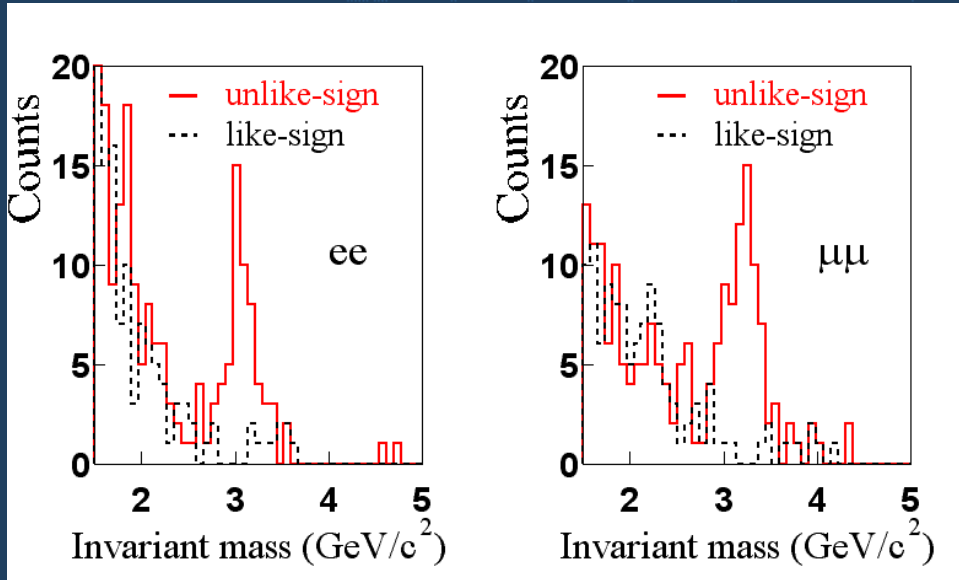
- Collisions d-Au au RHIC

- Premiers résultats sur la production de hadrons

- Tester la production du  $J/\psi$



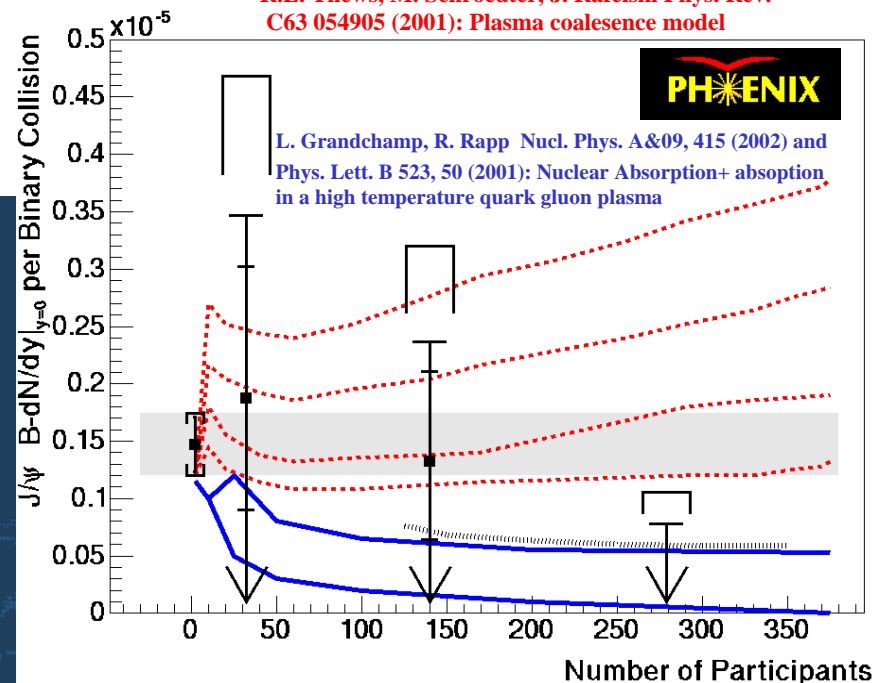
# Suppression du J/ψ



← Données p-p (200 GeV)

centralité	centralité	centralité
40-90%	20-40%	0-20%
$N_{\text{coll}}=45$	$N_{\text{coll}}=296$	$N_{\text{coll}}=779$

R.L. Thews, M. Schroedter, J. Rafelski Phys. Rev. C63 054905 (2001): Plasma coalescence model



Données Au-Au (200 GeV) →

**Manque de statistique**

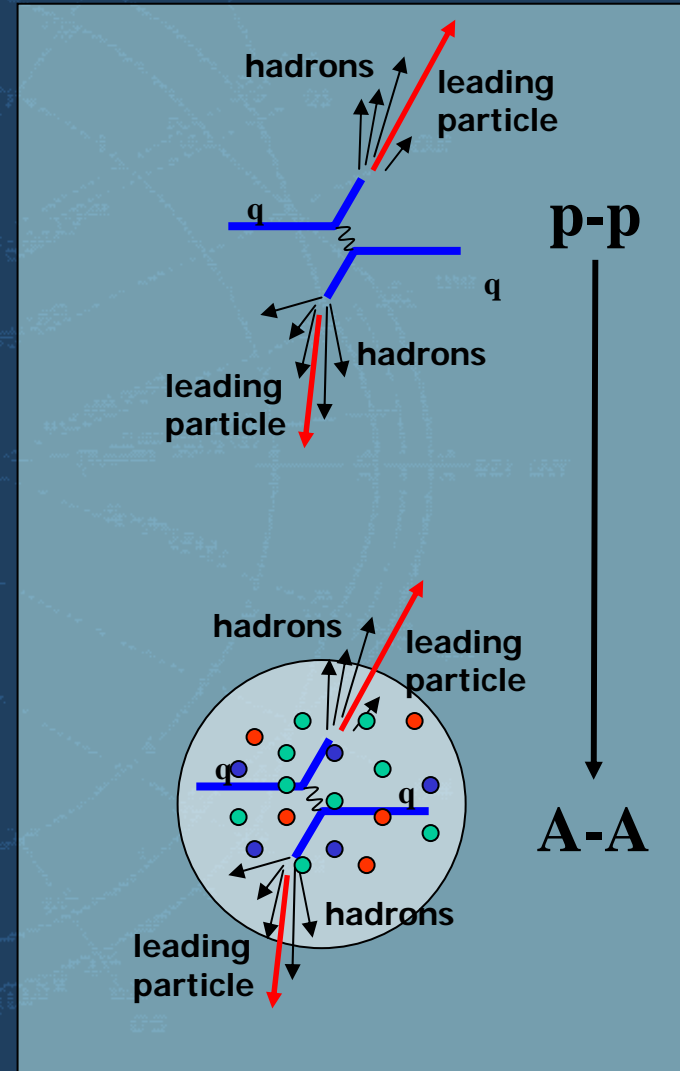
# Production de hadrons à grand $P_T$

## – Pourquoi ?

- Dans la matière colorée, les partons sont susceptibles de perdre une quantité importante d'énergie par rayonnement de gluons

## – Conséquences

- Atténuation ou absorption des jets : « jet quenching »
- Suppression des hadrons de grand  $P_T$

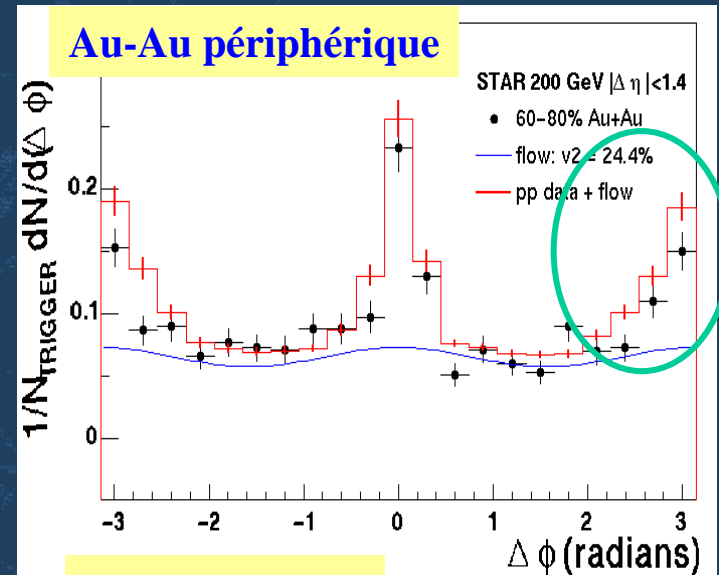


# Production de hadrons à grand $P_T$

- Jet quenching

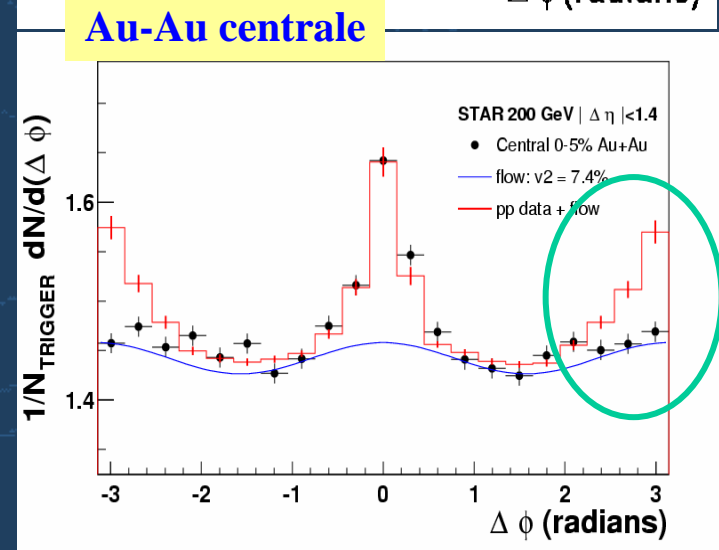
Corrélation angulaire entre une particule de  $p_T > 4$  GeV et les autres ( $p_T > 2$  GeV)

Accord or+or avec p+p (+ flow) en collisions périphériques...



Désaccord

En collisions centrales...



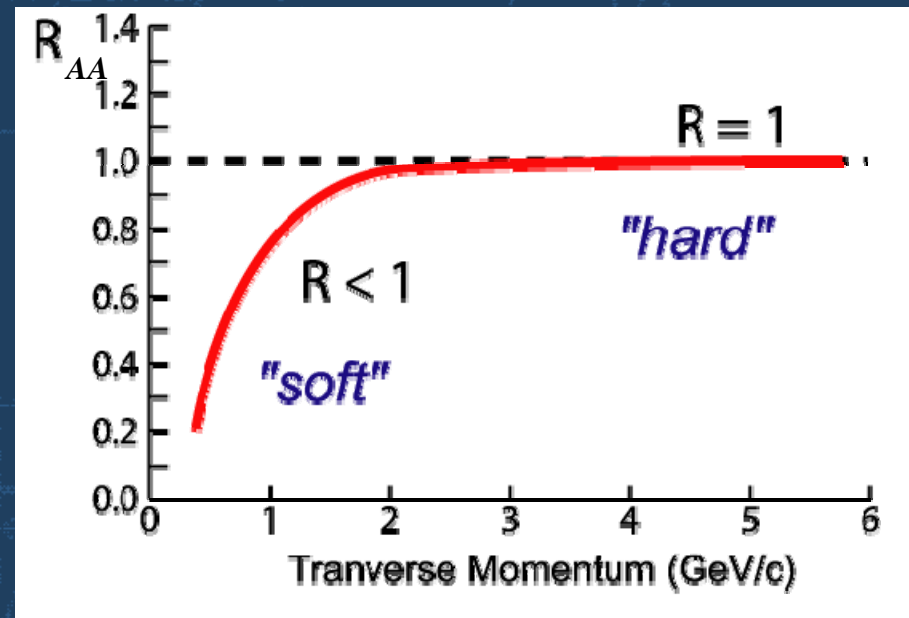
# Production de hadrons à grand $P_T$

- Spectres des hadrons
  - Comparer Au-Au et nucléon-nucléon :

$$R_{AA}(p_T) = \frac{d^2 N^{AA} / dp_T d\eta}{T_{AA} d^2 \sigma^{NN} / dp_T d\eta}$$

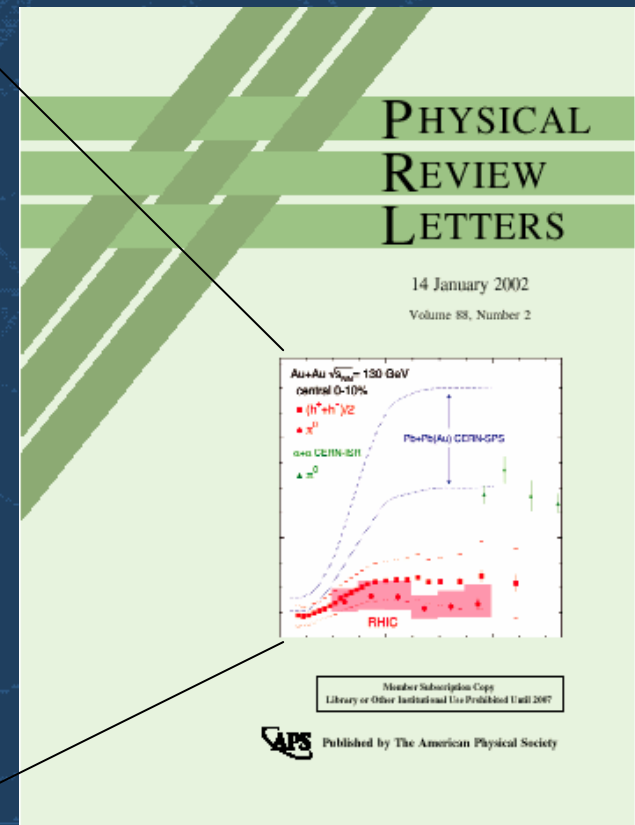
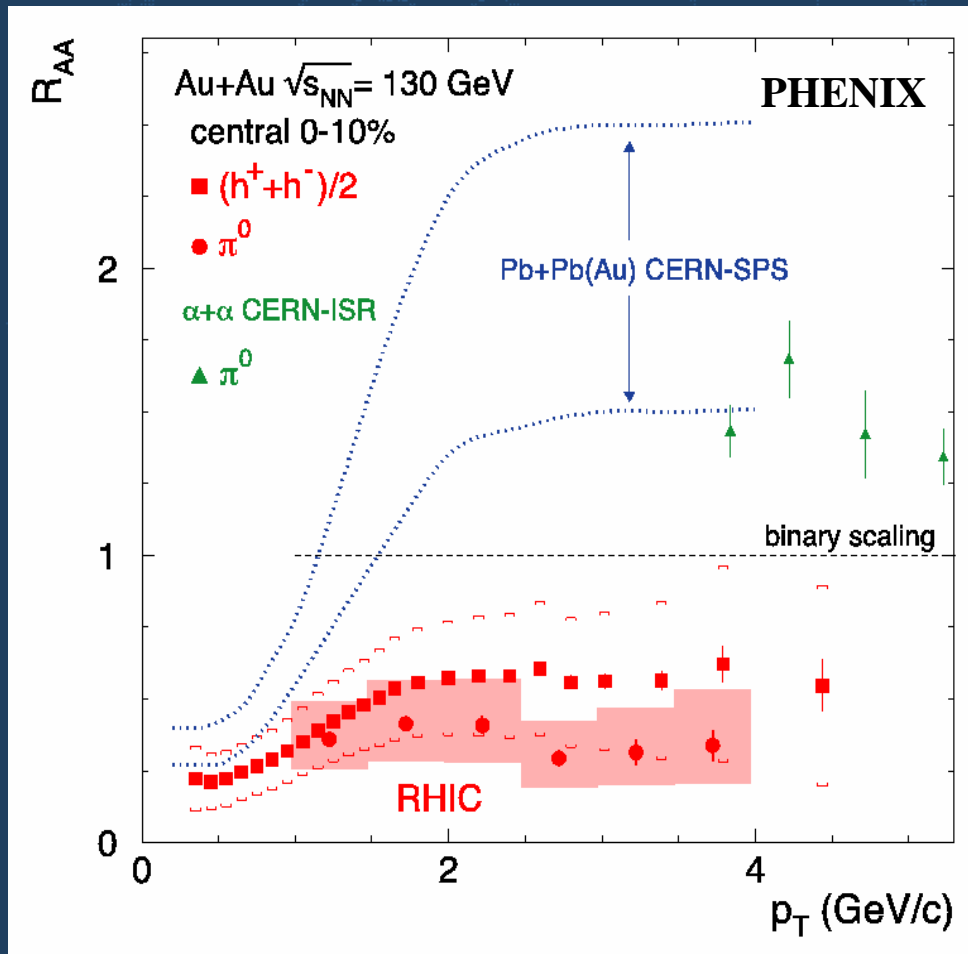
Section efficace  
Nucléon-nucléon

- Pas d'effet :
  - $R_{AA} < 1$  à bas  $P_T$
  - $R_{AA} = 1$  à grand  $P_T$
- Suppression
  - $R_{AA} < 1$  à grand  $P_T$



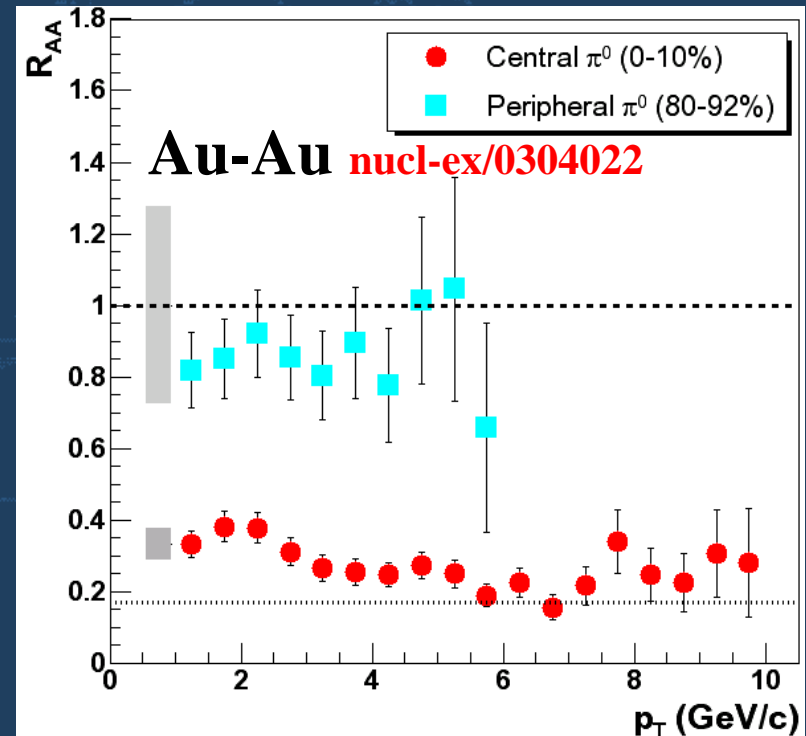
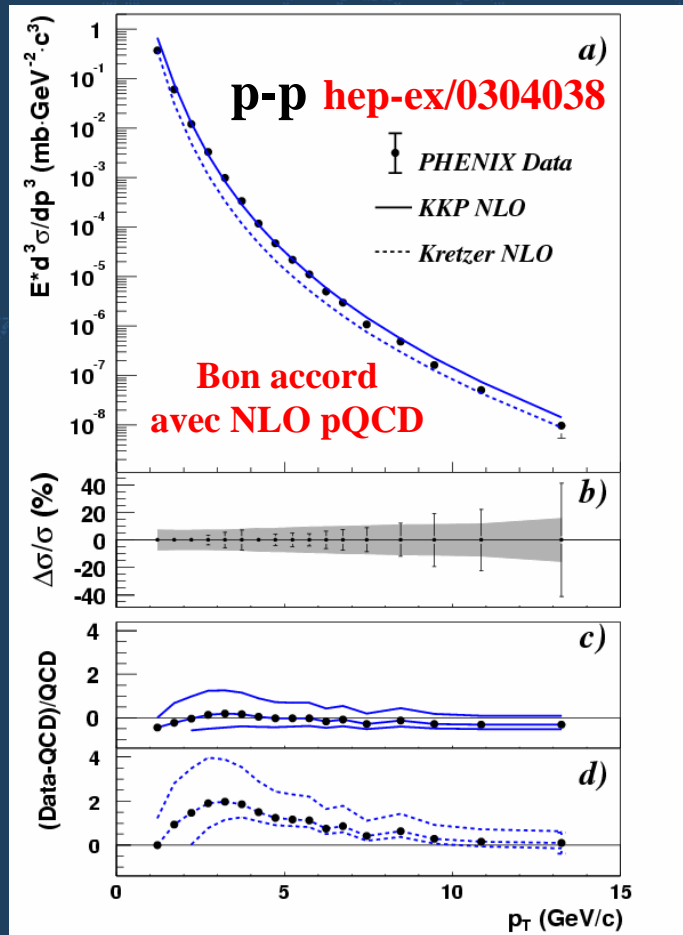
# Production de hadrons à grand $P_T$

- Spectres des hadrons (Au-Au à 130 GeV)



# Production de hadrons à grand $P_T$

- Spectres des  $\pi^0$  (p-p et Au-Au à 200 GeV)

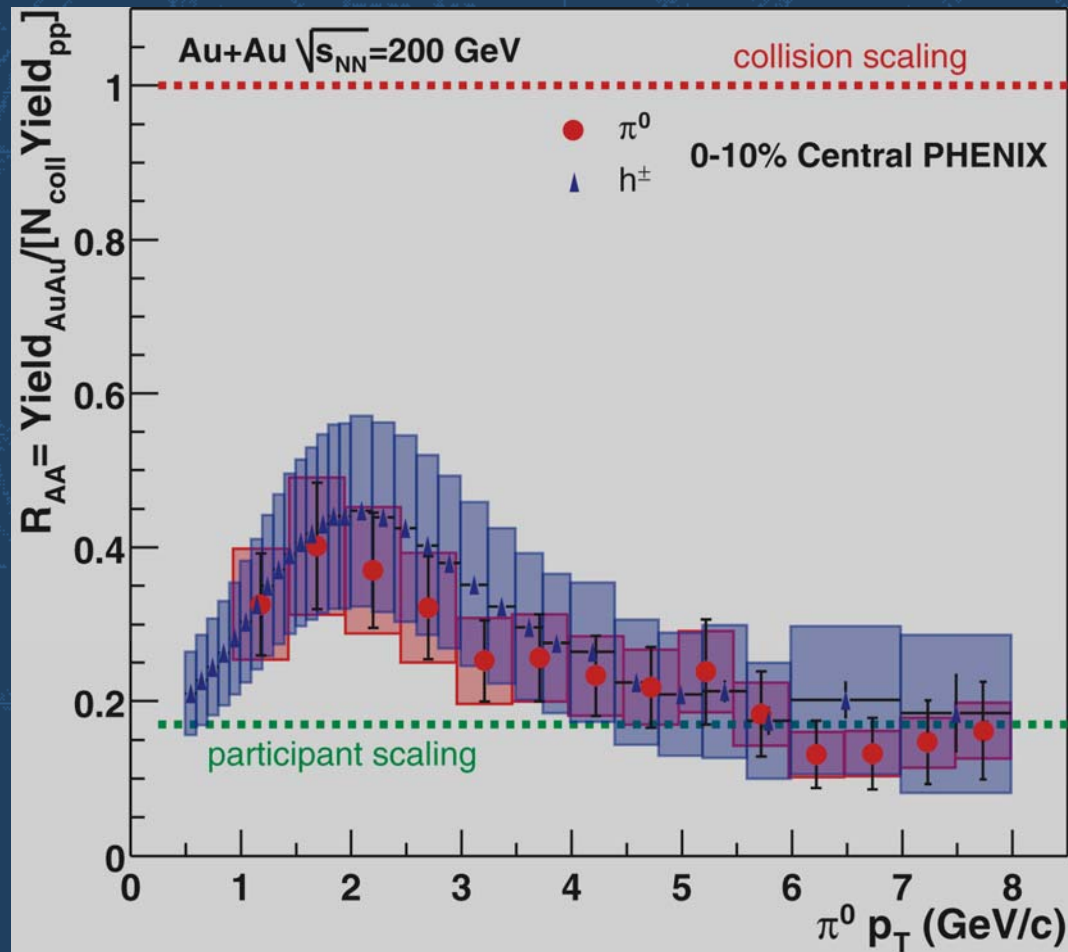


$$R_{AA} = \frac{\text{Yield}_{\text{AuAu}} / \langle N_{\text{binary}} \rangle_{\text{AuAu}}}{\text{Yield}_{pp}}$$



# Production de hadrons à grand $P_T$

- Spectres des hadrons (Au-Au à 200 GeV)
  - Même comportement  $h^\pm/\pi^0$



# Production de hadrons à grand $P_T$

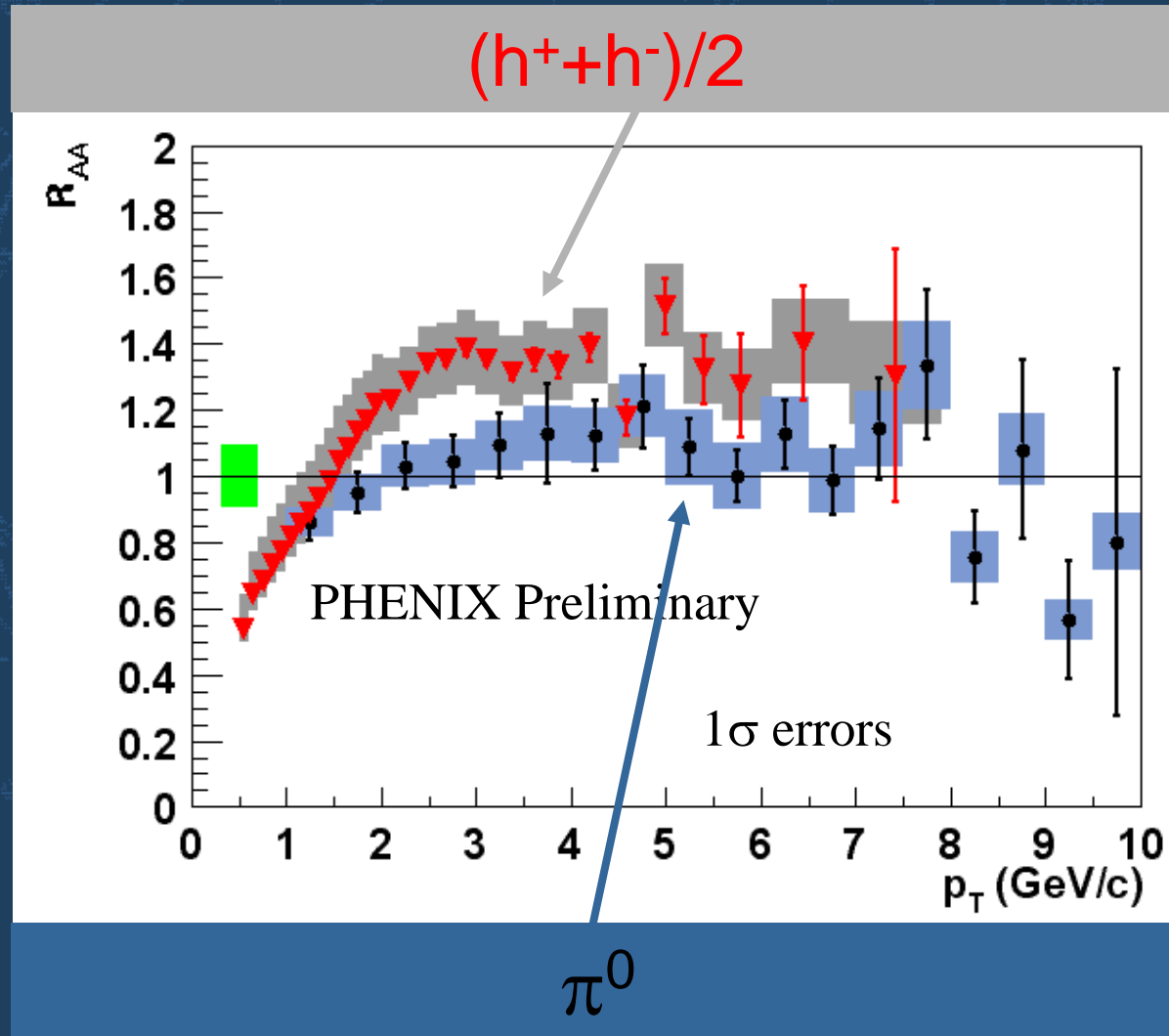
- Origine de la suppression
  - Effets dans l'état initial ?
    - Modification des PDF dans le noyau : shadowing ou anti-shadowing
  - Effets dans l'état final ?
    - Perte d'énergie du parton dans le milieu via le rayonnement de freinage gluonique
- Vérification
  - d-Au à 200 GeV

# Résultats récents

- Collisions Au-Au au RHIC
  - Conditions initiales
    - Densité d'énergie
  - L'explosion finale
    - Gel chimique
    - Gel thermique
  - Signer le déconfinement
    - Suppression du  $J/\psi$
    - Jet quenching
- Collisions d-Au au RHIC
  - Premiers résultats sur la production de hadrons
  - Tester la production du  $J/\psi$

# Production de hadrons à grand $P_T$

- Collisions d-Au



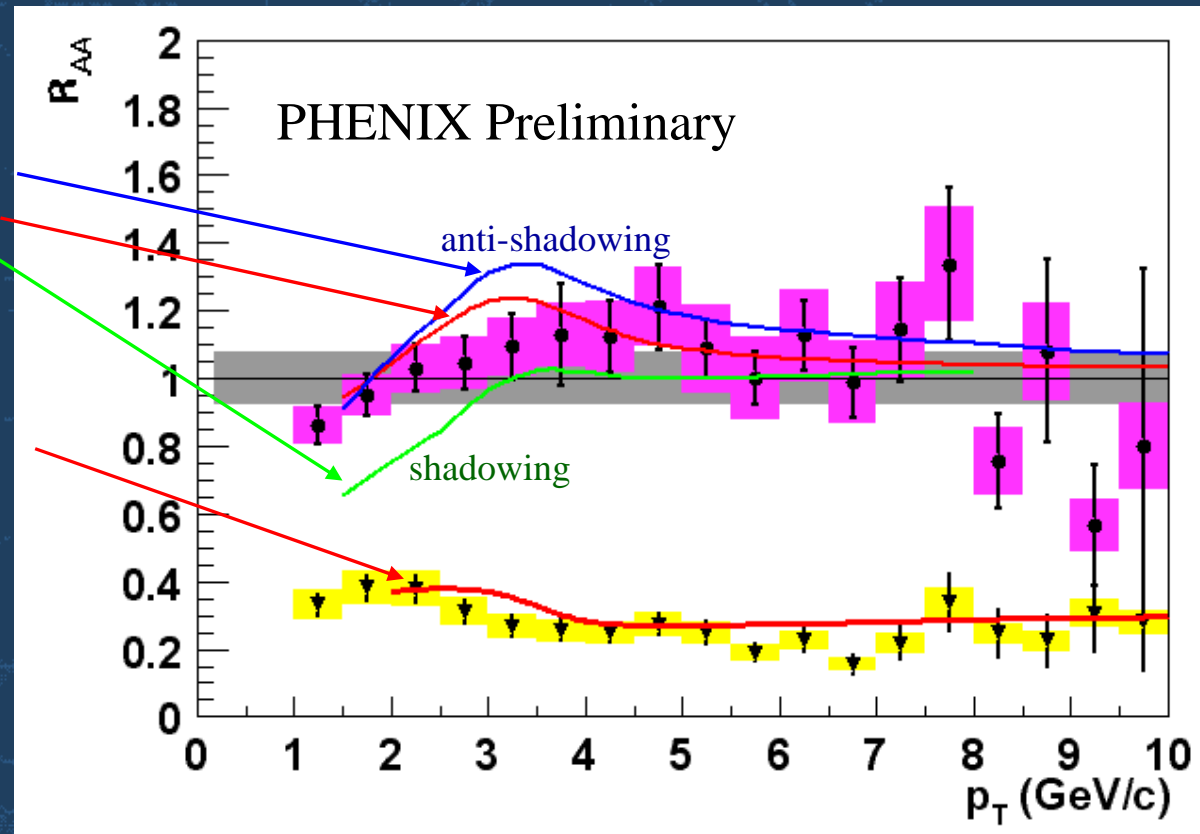
# Production de hadrons à grand $P_T$

- Bilan : Collisions Au-Au et d-Au

Prédictions théoriques:

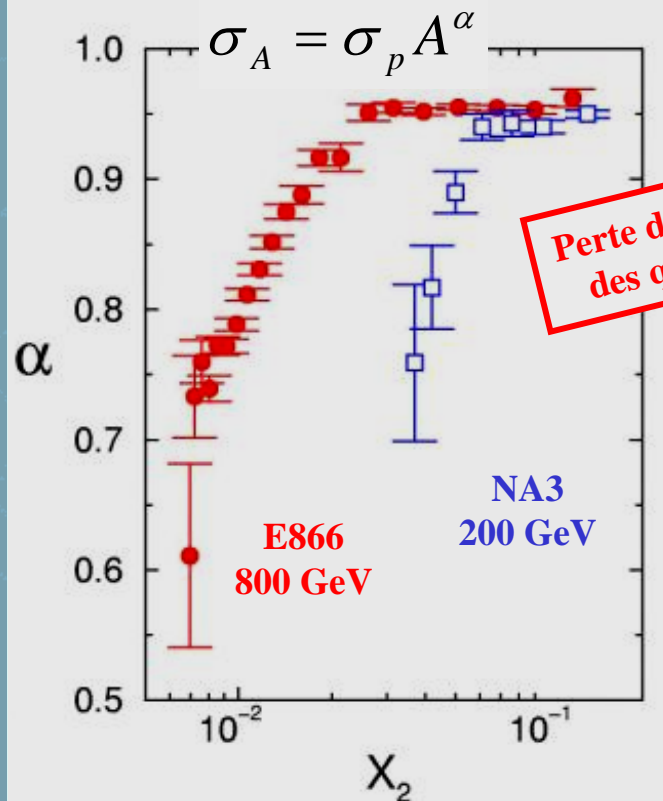
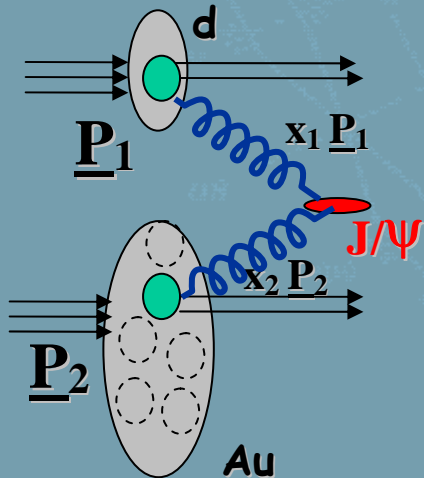
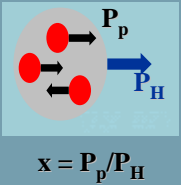
d+Au: I. Vitev, nucl-th/0302002

Au+Au: I. Vitev and M. Gyulassy, hep-ph/0208108, to appear in Nucl. Phys. A; M. Gyulassy, P. Levai and I. Vitev, Nucl. Phys. B 594, p. 371 (2001).

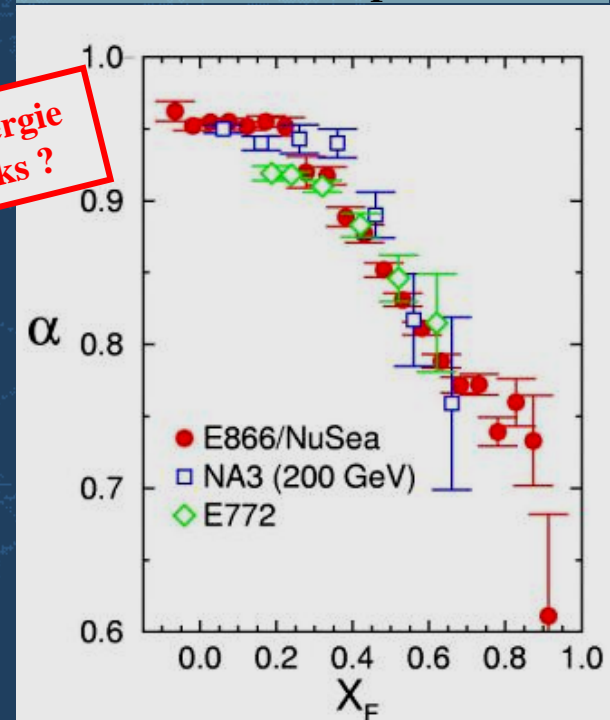
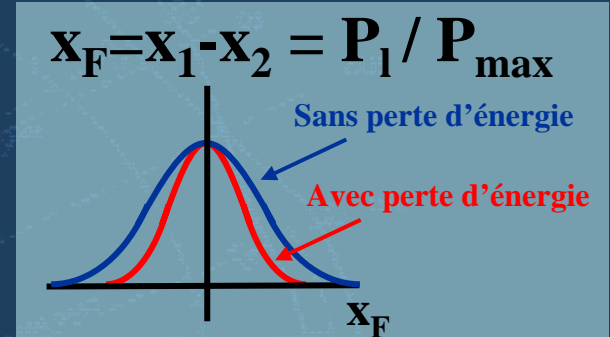


# Tester la production du J/ψ

- Résultats Fermilab et CERN

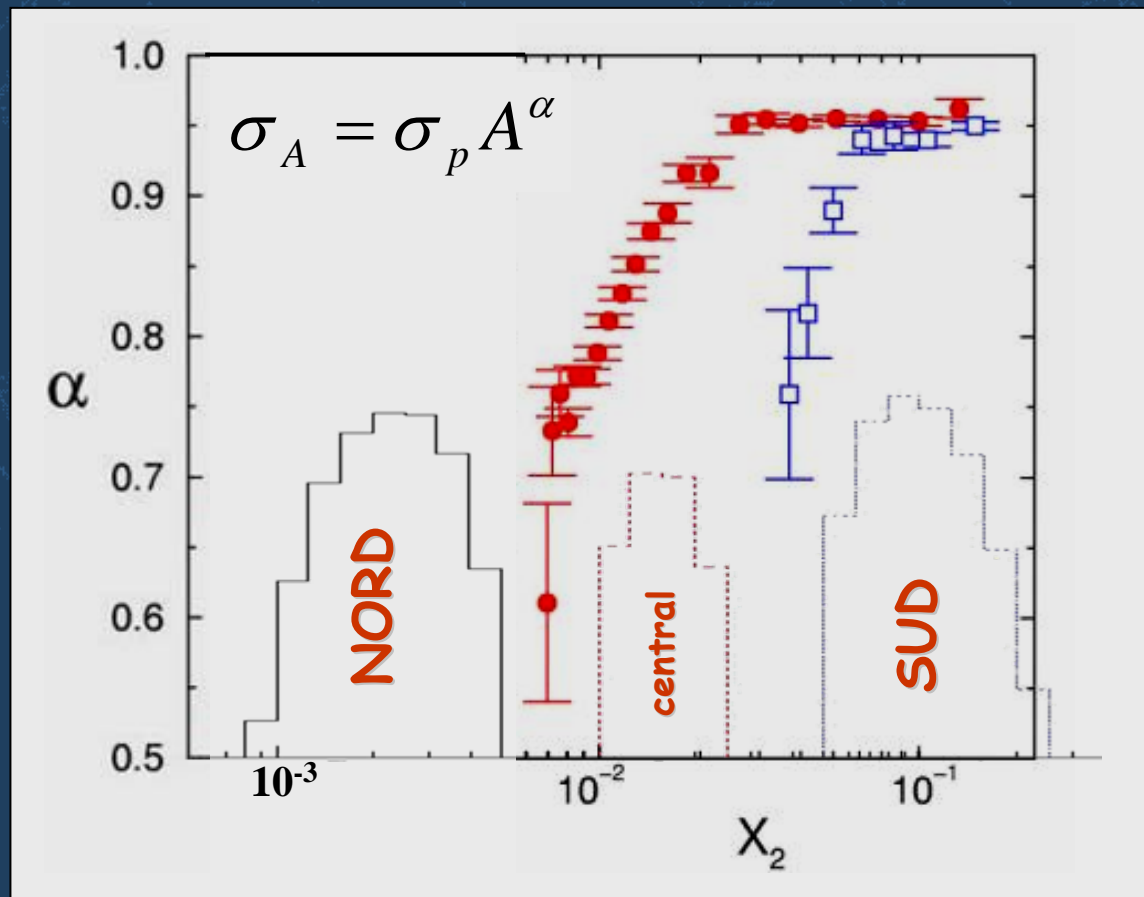


Perte d'énergie des quarks ?



# Tester la production du $J/\psi$

- Production de  $J/\psi$  au RHIC
  - Acceptance de PHENIX

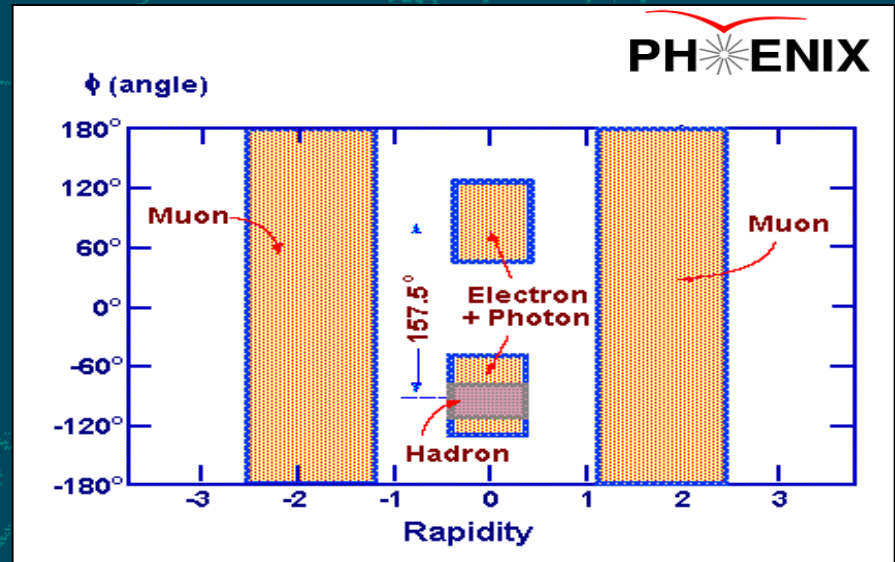
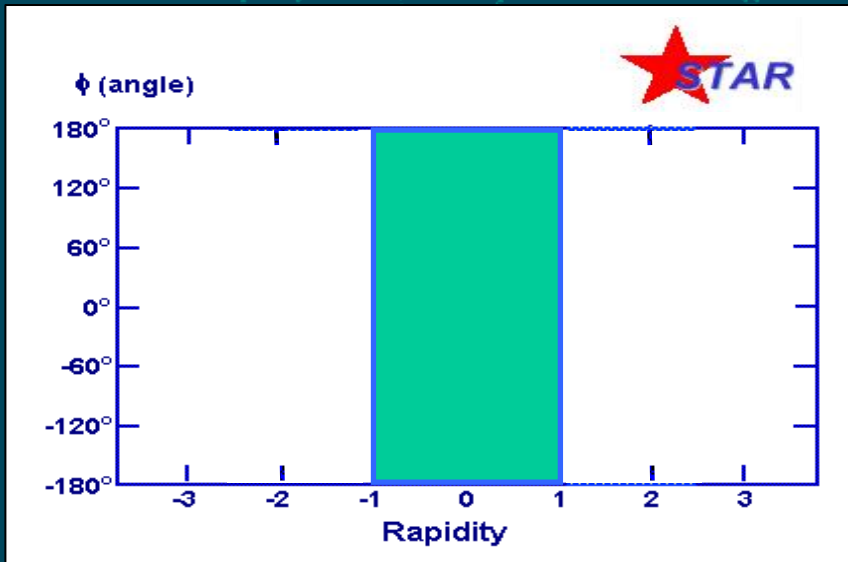
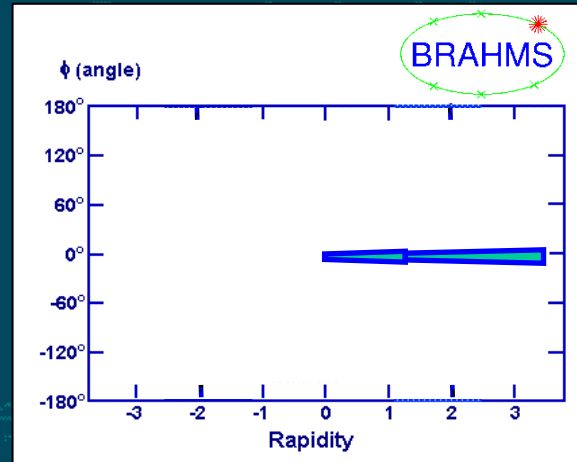
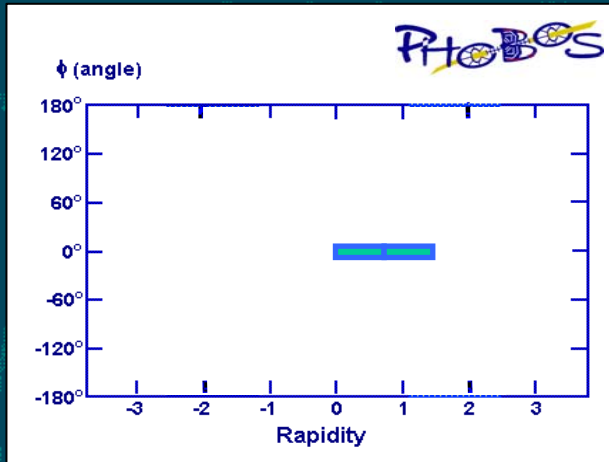


# Conclusion

- **Au RHIC depuis 2001**
  - **Données p-p, Au-Au, d-Au**
  - **Résultats inattendus à grand  $P_T$**
  - **Pas de conclusion sur la suppression du  $J/\psi$**
- **Automne 2003**
  - **Nouvelle prise de données Au-Au**
- **Futur**
  - **Systemes plus légers ....**

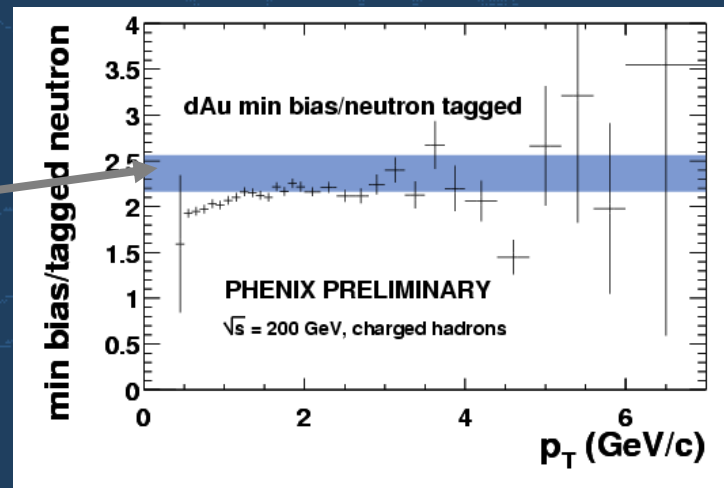
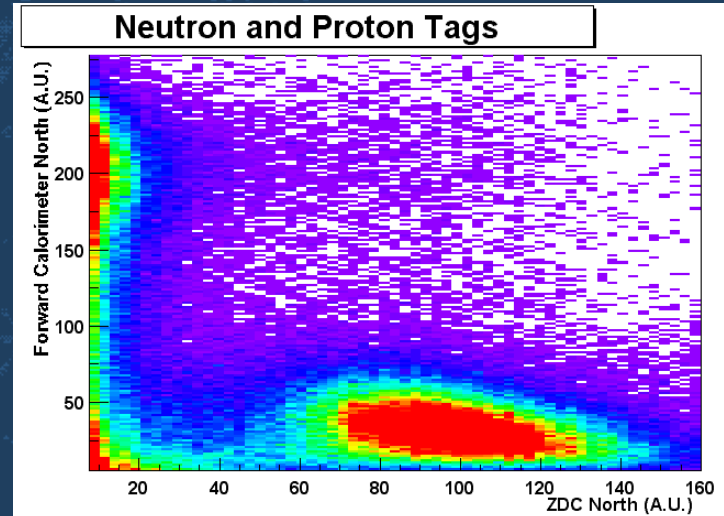
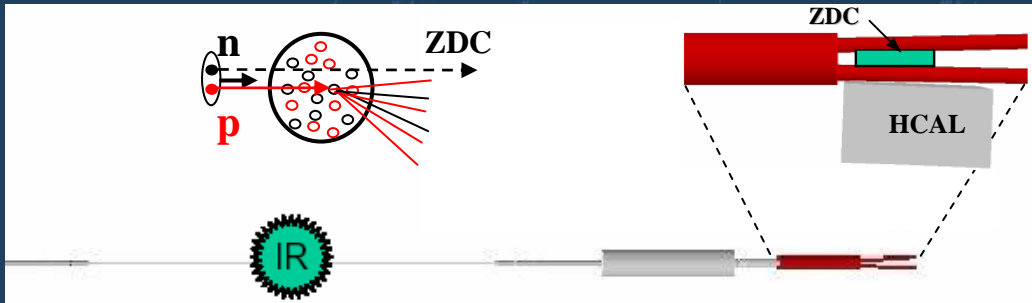


- Les acceptances



# Production de hadrons à grand $P_T$

- Collisions d-Au : centralité



$$\langle N_{\text{coll}} \rangle = 8.5 \pm 0.7 / 3.6 \pm 0.4$$

Pas de dépendance en centralité  
observée !

# PQG : la prédiction théorique

- QCD : Liberté asymptotique

- Potentiel à courte distance

$$V_{short} = -\frac{4}{3} \frac{\alpha_s(r)}{r} \quad \lim_{r \rightarrow 0} \alpha_s(r) = 0$$

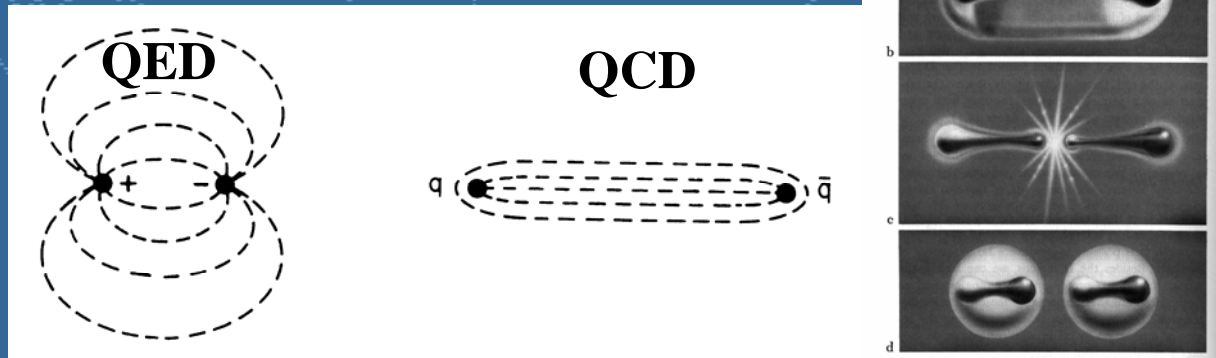
- Validité de la théorie des perturbations

- QCD : Confinement

- À des échelles de l'ordre de la taille des hadrons ( $\sim 1$  fm), les méthodes perturbatives perdent leur validité

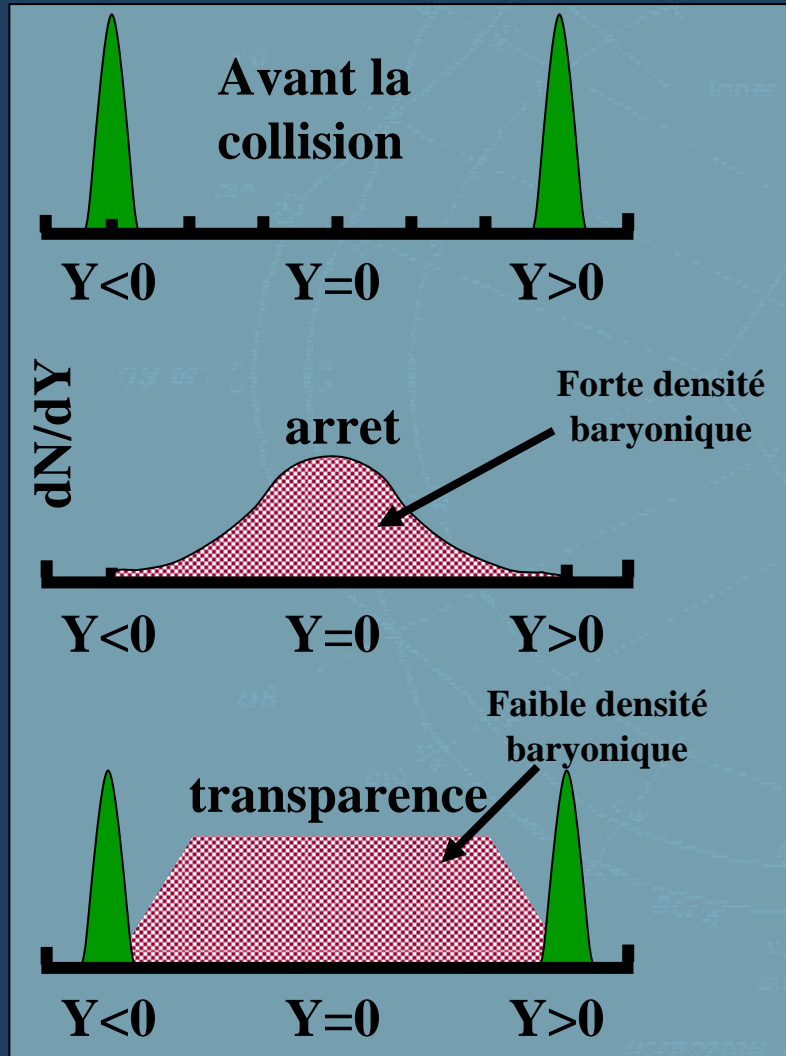
- La corde

$$V_{long} = kr \quad \text{avec } k \sim 1 \text{ GeV/fm}$$

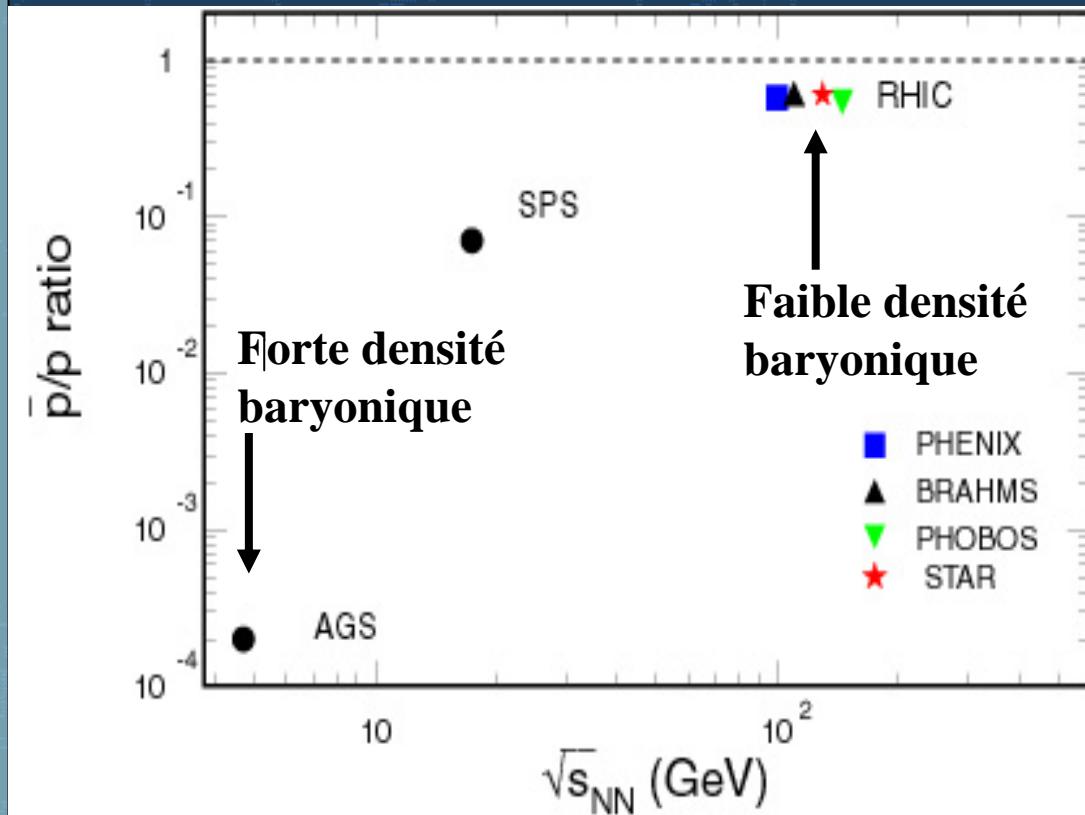


# Transparence

- Comparaison AGS/SPS/RHIC



La mesure du rapport  $\bar{p}/p$  traduit la transparence de la collision



# Multiplicité

- Collisions Au-Au

- $dn_{ch}/d\eta|_{\eta=0} \rightarrow 670$  (mesurés par les 4 expériences)
- $N_{total} \sim 6000$  particules !

