Mesure de la température du Plasma de Quarks et de Gluons

Au RHIC avec l'expérience PHENIX

1. Plasma de Quarks et de Gluons
2. Smoking guns
3. Température

Plasma de Quarks et de Gluons

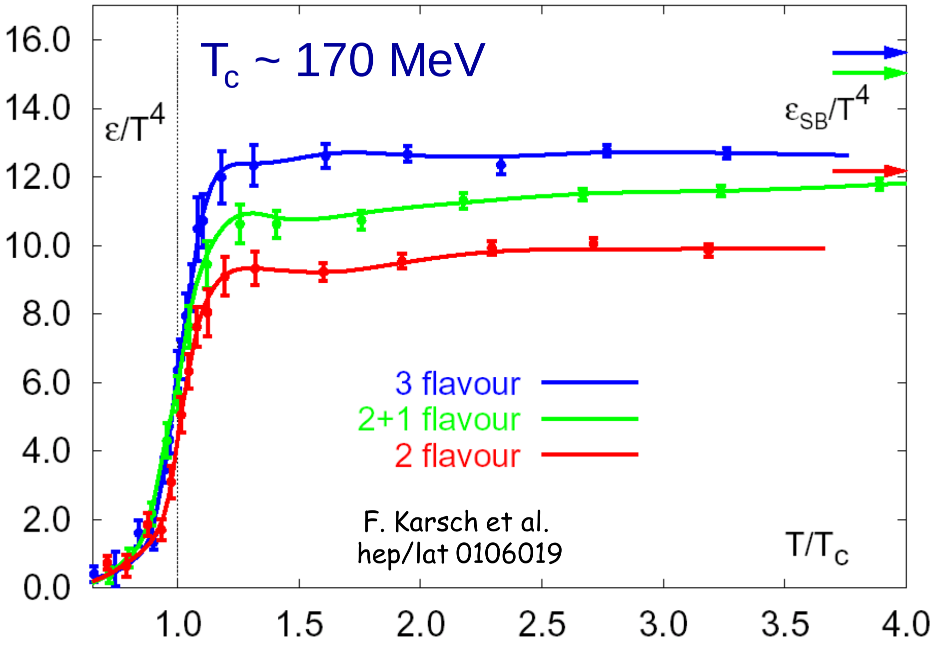
Déconfinement

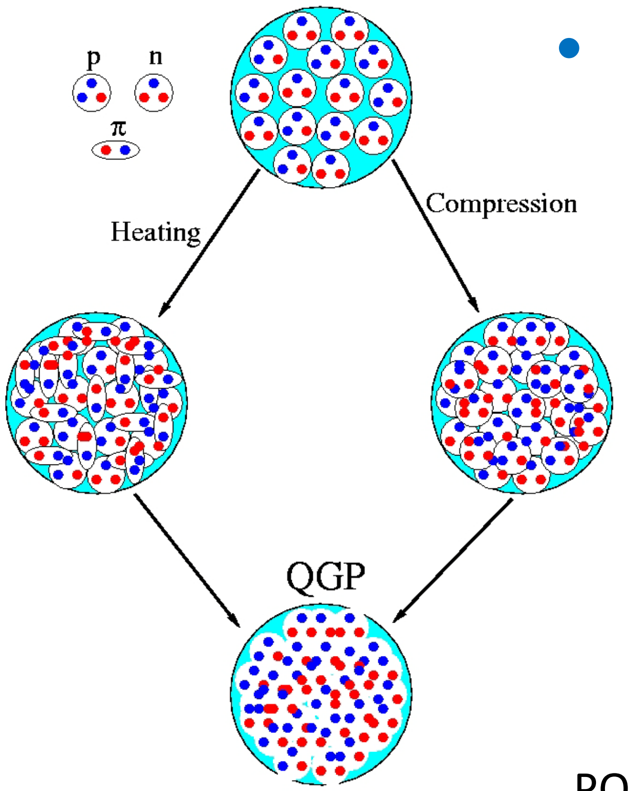
Collisions d’ions lourds

Centralité

Plasma de Quarks et de Gluons

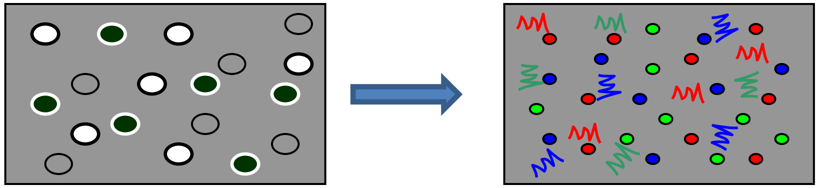
- **Le déconfinement**
  - Prédiction : à une densité (température) suffisamment élevée, une transition de phase devrait apparaître.
  - QCD sur réseau :





Gaz de pions
$N_{d.o.f} = 3$

PQG
$N_{d.o.f} = 37$
(2 saveurs)

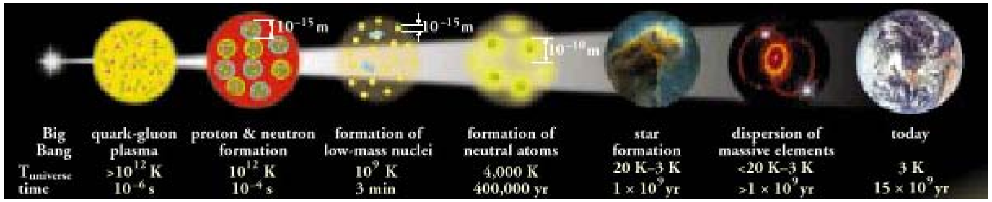


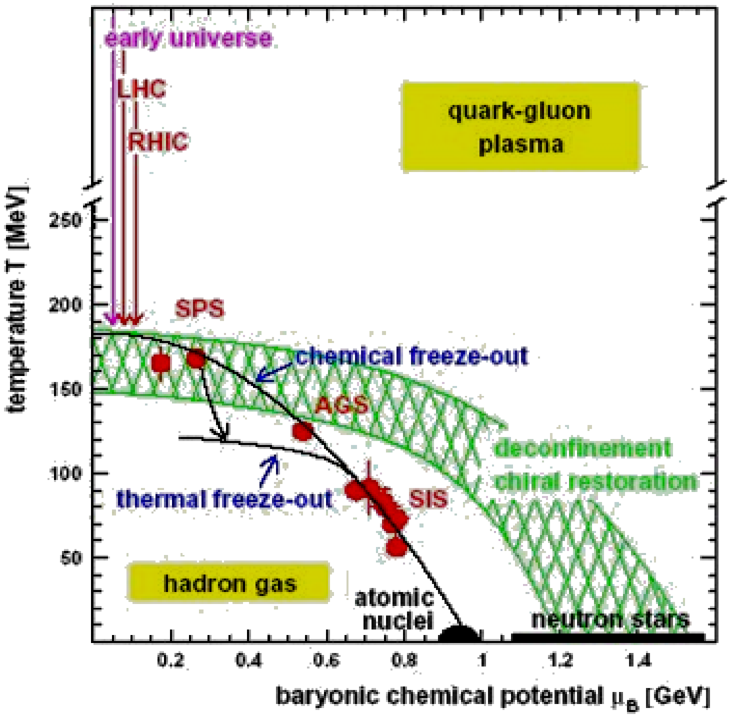
Plasma de Quarks et de Gluons

• Le diagramme de phase

Big Bang

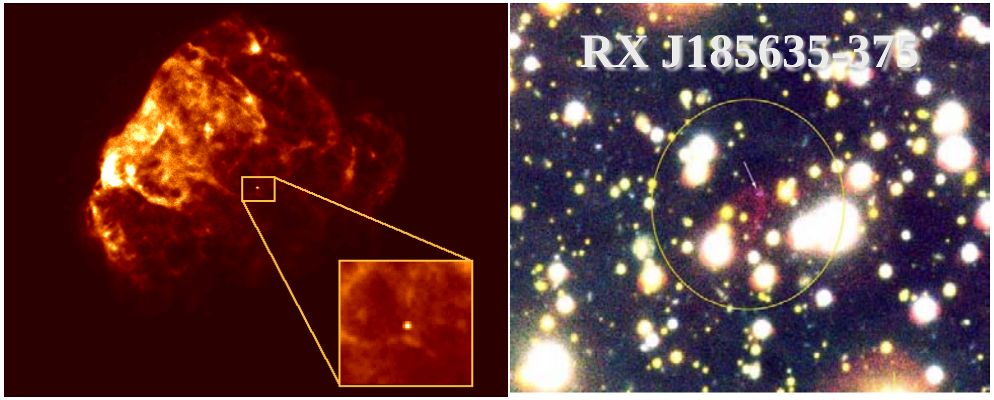
- ➢ haute temperature (10^{12} K)
- ➢ 10^{-6} s. : Plasma → matière confinée





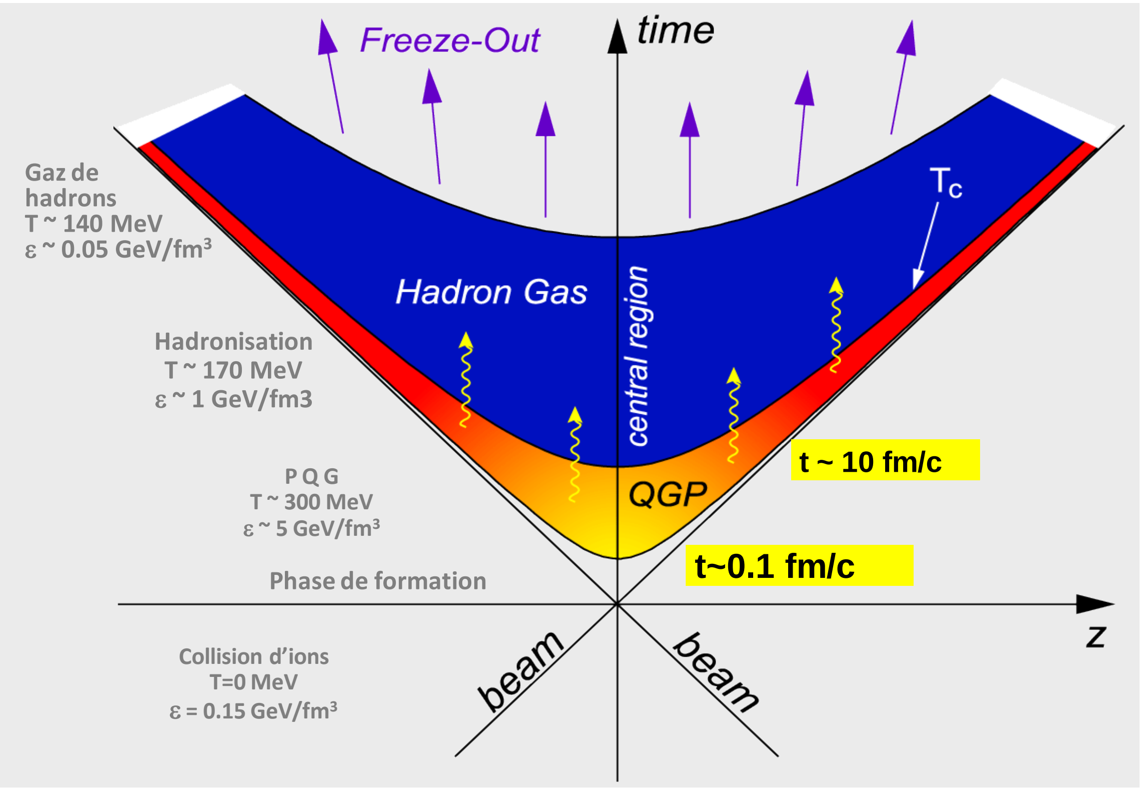
Cœur des étoiles à neutron

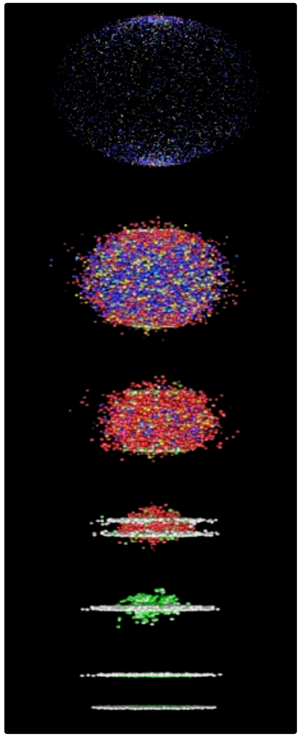
- ➢ Effondrement d'étoile
- ➢ Grande densité de matière
  (5 à 10 fois la densité nucléaire standard)
- ➢ Matière confinée → plasma



Plasma de Quarks et de Gluons

- **Expérimentalement : collisions d'ions lourds**
  - Gros noyaux ➔ volume + thermalisation
  - Grande énergie ➔ densité critique

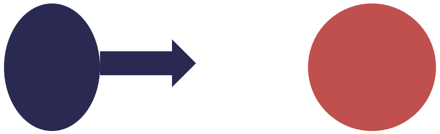




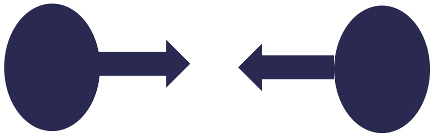
Plasma de Quarks et de Gluons

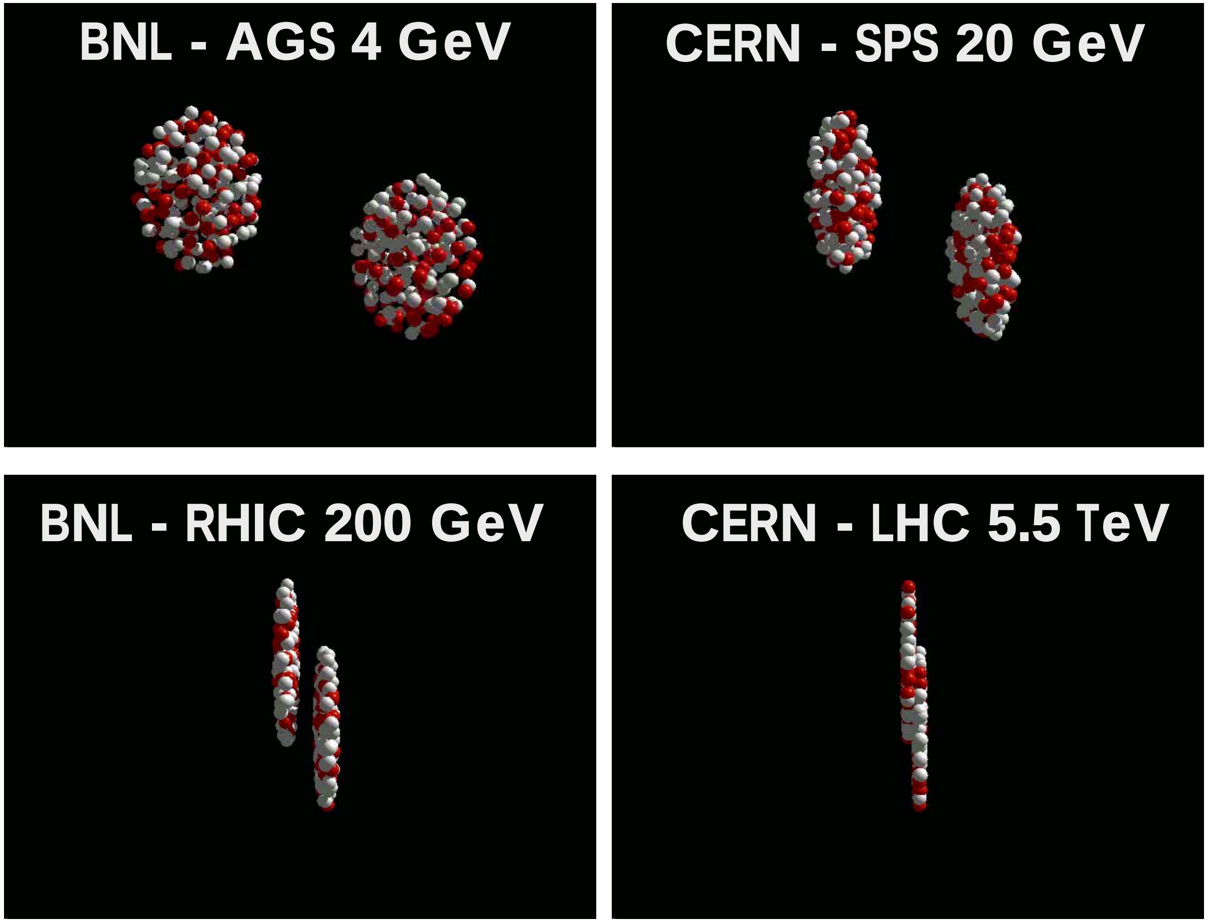
- Expérimentalement : collisions d’ions lourds

Expériences
Cibles fixes



Expériences
collisionneurs

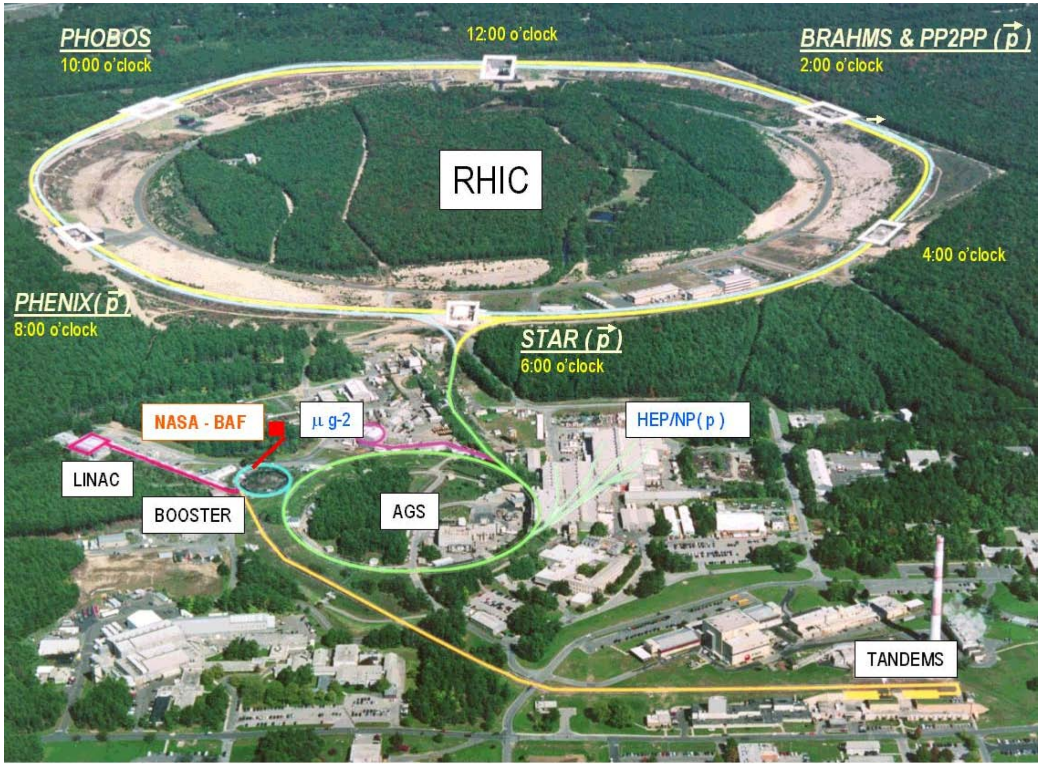




Le RHIC

Deux programmes de recherche

- Plasma de Quarks et de Gluons : **ions lourds** jusqu'à √s = 200 GeV
- Structure en spin du nucléon : **protons polarisés** jusqu'à √s = 500 GeV

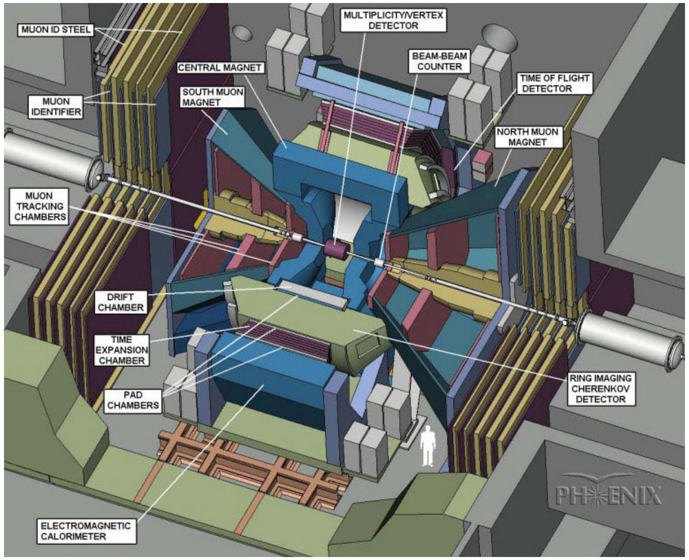


- p+p ➔ la référence
- d+Au ➔ étude des effets froids (shadowing, saturation,…)
- Au+Au ➔ étude des effets chauds (QGP)

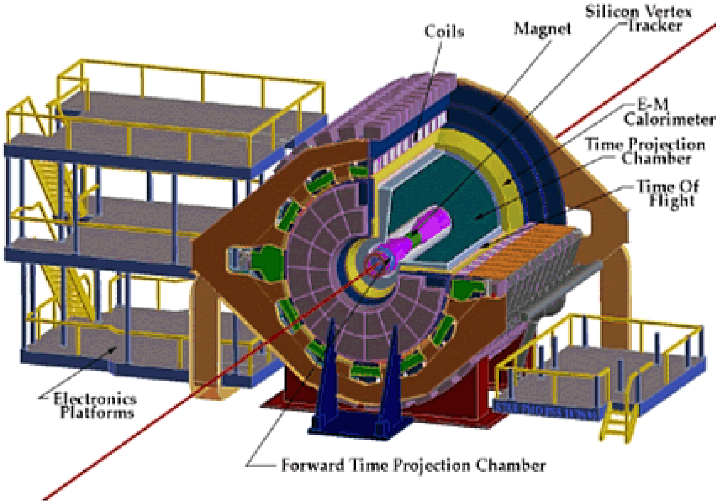
Campagne	Espèces	Énergie (GeV)	Luminosité intégrée (Phenix)
2000/2001	Au+Au	130	1,0 μb^{-1}
2001/2002	Au+Au p+p	200 200	24,0 μb^{-1} 0,15 pb^{-1}
2002/2003	d+Au p+p	200 200	2,74 nb^{-1} 0,35 pb^{-1}
2003/2004	Au+Au Au+Au	200 62	241 μb^{-1} 9 μb^{-1}
2004/2005	Cu+Cu Cu+Cu Cu+Cu p+p	200 62 22.5 200	3 nb^{-1} 0,19 nb^{-1} 2,70 μb^{-1} 3,80 pb^{-1}
2005/2006	p+p p+p	200 62	10,7 pb^{-1} 0,1 pb^{-1}
2006/2007	Au+Au	200	810 μb^{-1}
2007/2008	d+Au p+p	200 200	80 nb^{-1} 5,2 pb^{-1}
2008/2009	p+p p+p	200 500	8,6 pb^{-1} 13 pb^{-1}
2009/2010	Au+Au Au+Au Au+Au Au+Au	200 62 39 7,7	1,3 nb^{-1} 0,11 nb^{-1} 40 μb^{-1} 0,26 μb^{-1}

PHENIX & STAR

- PHENIX
  - Central rapidity |y|<0.35
    - Tracking (DC, PC)
    - EM calorimeter
    - TOF
    - RICH
  - Muon spectrometers 1.2<|y|<2.2
  - Measures everything

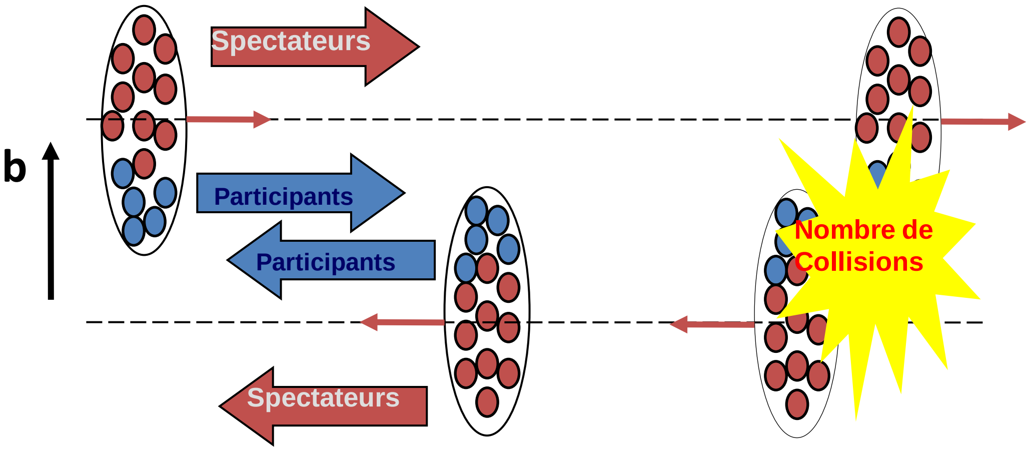


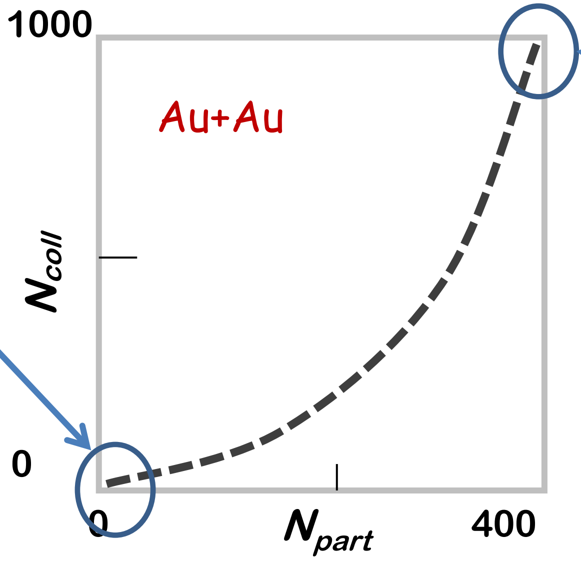
- STAR
  - Large TPC
  - Silicon vertex tracker
  - EM calorimeter
  - Time of flight
  - Track ~2000 charged particles in |η|<1



Centralité

- **Principe**
  - N_{part} = nombre de nucléons participant
  - N_{coll} = nombre de collisions nucléon-nucléon





Petit paramètre d'impact b

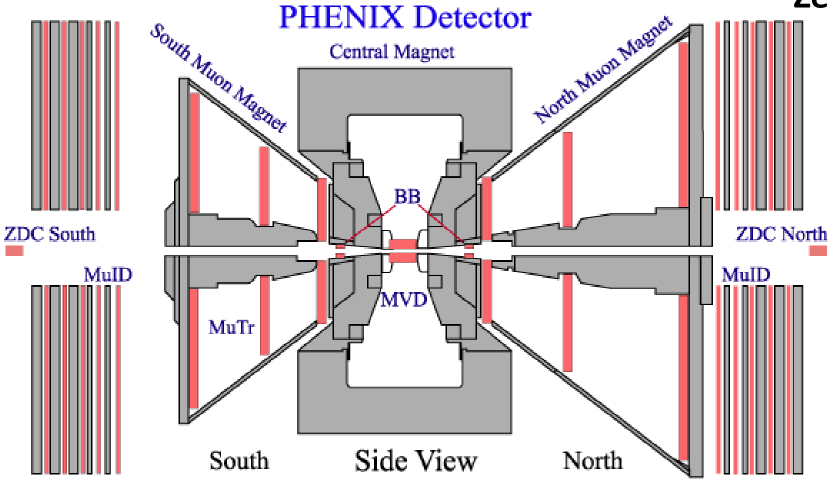
Grand paramètre d'impact

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

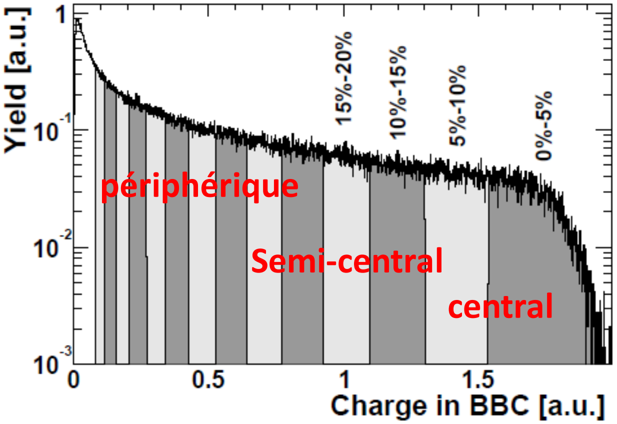
Centralité

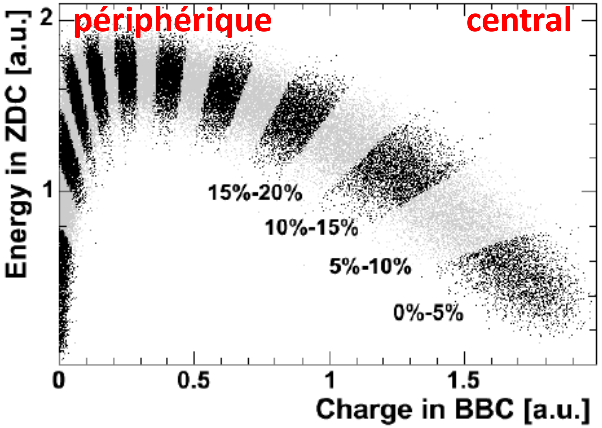
- **Mesure**

Beam Beam Counter (z=±1.5 m)



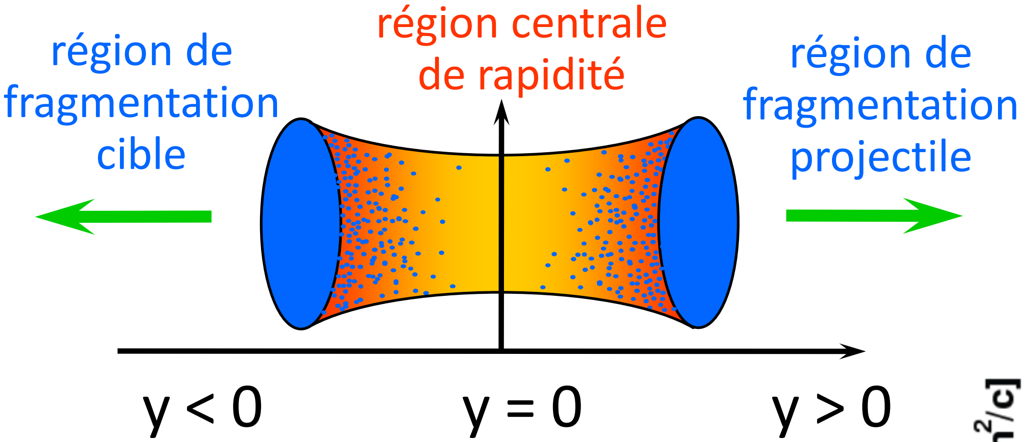
Zero Degree Calorimeter (z=±20m)





Cent.	b (fm)	N_{part}	N_{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

Densité d'énergie



région de fragmentation cible

région centrale de rapidité

région de fragmentation projectile

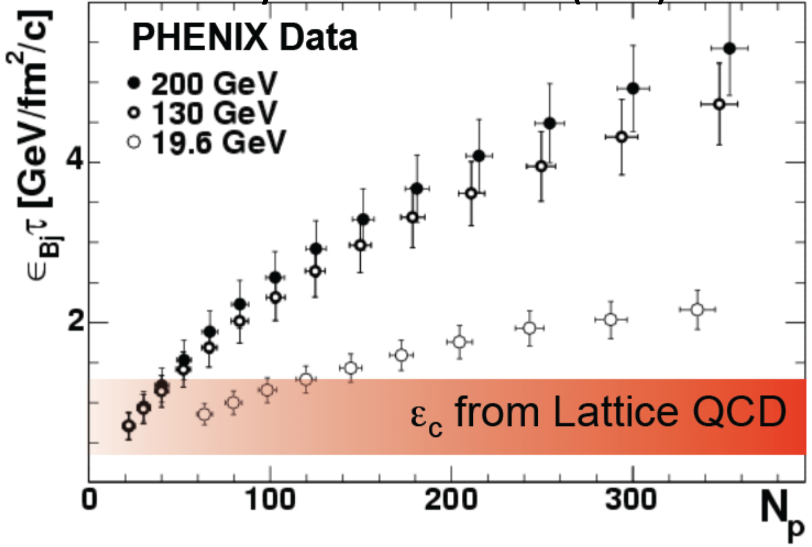
y < 0

y = 0

y > 0

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

Phys. Rev. C71:034908 (2005)



Smoking guns

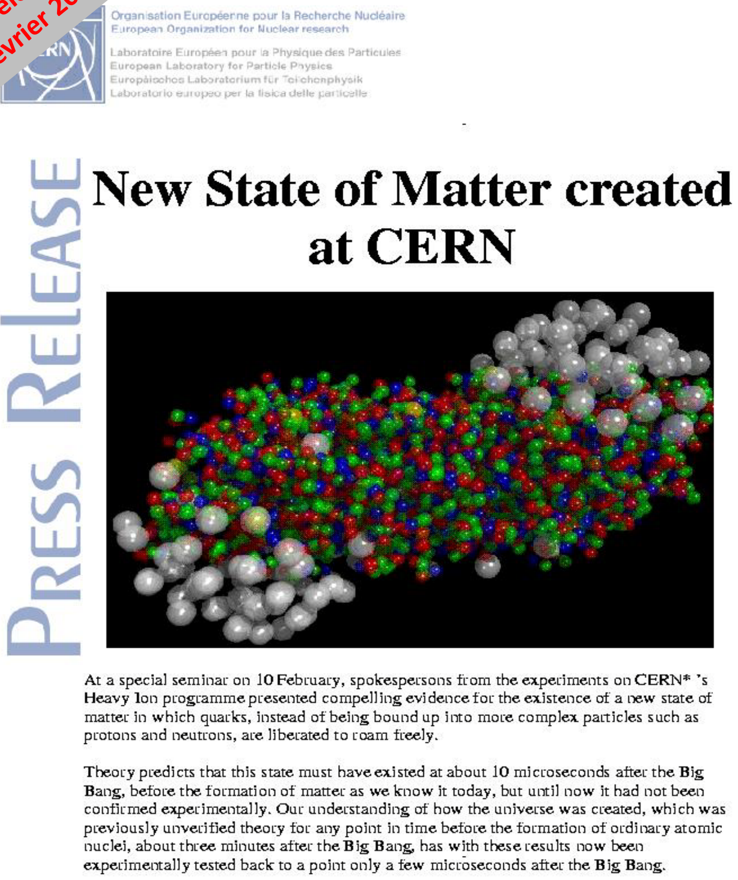
Au SPS : suppression du J/Ψ

Au RHIC : le liquide parfait

Smoking guns

- **Au SPS : suppression du J/Ψ**

Press release
10 février 2000



Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear research

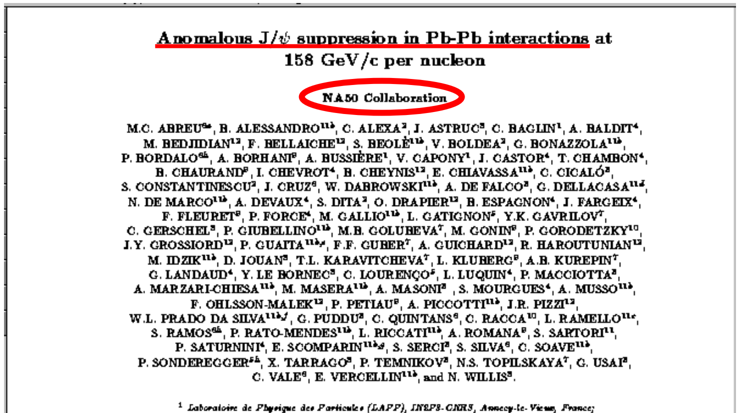
Laboratoire Européen pour la Physique des Particules
European Laboratory for Particle Physics
Europäisches Laboratorium für Teilchenphysik
Laboratorio europeo per la fisica delle particelle

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.

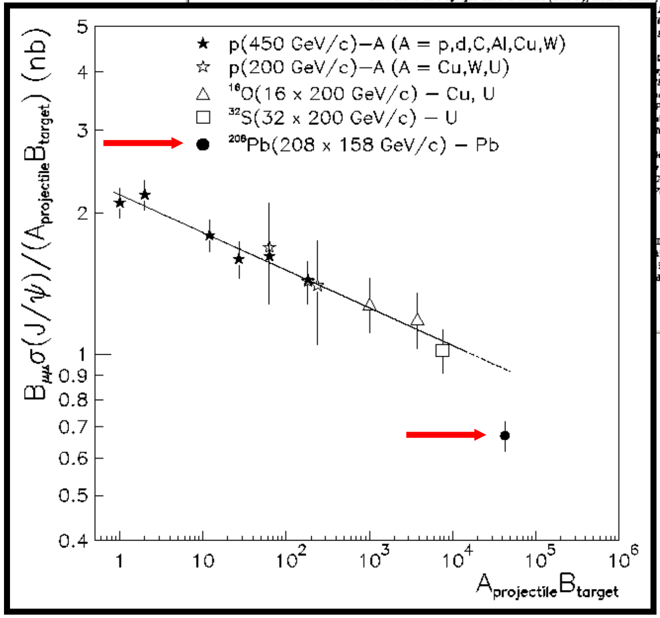


Anomalous J/ψ suppression in Pb-Pb interactions at 158 GeV/c per nucleon

NA50 Collaboration

M.C. ABREU[6a], B. ALESSANDRO[11b], C. ALEXA[2], J. ASTRUC[8], C. BAGLIN[1], A. BALDIT[4], M. BEDJIDIAN[12], F. BELLAICHE[12], S. BEOLÈ[11b], V. BOLDEA[2], G. BONAZZOLA[11b], P. BORDALO[6h], A. BORHANI[9], A. BUSSIÈRE[1], V. CAPONY[1], J. CASTOR[4], T. CHAMBON[4], B. CHAURAND[9], I. CHEVROT[4], B. CHEYNIS[12], E. CHIAVASSA[11b], C. CICALÓ[3], S. CONSTANTINESCU[2], J. CRUZ[6], W. DABROWSKI[11b], A. DE FALCO[3], G. DELLACASA[11d], N. DE MARCO[11b], A. DEVAUX[4], S. DITA[2], O. DRAPIER[12], B. ESPAGNON[4], J. FARGEIX[4], F. FLEURET[9], P. FORCE[4], M. GALLIO[11b], L. GATIGNON[5], Y.K. GAVRILOV[7], C. GERSCHEL[8], P. GIUBELLINO[11b], M.B. GOLUBEVA[7], M. GONIN[9], P. GORODETZKY[10], J.Y. GROSSIORD[12], P. GUAITA[11b,e], F.F. GUBER[7], A. GUICHARD[12], R. HAROUTUNIAN[12], M. IDZIK[11b], D. JOUAN[8], T.L. KARAVITCHEVA[7], L. KLUBERG[9], A.B. KUREPIN[7], G. LANDAUD[4], Y. LE BORNEC[8], C. LOURENÇO[5], L. LUQUIN[4], P. MACCIOTTA[3], A. MARZARI-CHIESA[11b], M. MASERA[11b], A. MASONI[3], S. MOURGUES[4], A. MUSSO[11b], F. OHLSSON-MALEK[12], P. PETIAU[9], A. PICCOTTI[11b], J.R. PIZZI[12], W.L. PRADO DA SILVA[11b,f], G. PUDDU[3], C. QUINTANS[6], C. RACCA[10], L. RAMELLO[11c], S. RAMOS[6h], P. RATO-MENDES[11b], L. RICCATI[11b], A. ROMANA[9], S. SARTORI[11], P. SATURNINI[4], E. SCOMPARIN[11b,g], S. SERCI[3], S. SILVA[6], C. SOAVE[11b], P. SONDEREGGER[5h], X. TARRAGO[8], P. TEMNIKOV[3], N.S. TOPILSKAYA[7], G. USAI[3], C. VALE[6], E. VERCELLIN[11b], and N. WILLIS[8].

[1] *Laboratoire de Physique des Particules (LAPP), IN2P3-CNRS, Annecy-le-Vieux, France;*



Smoking guns

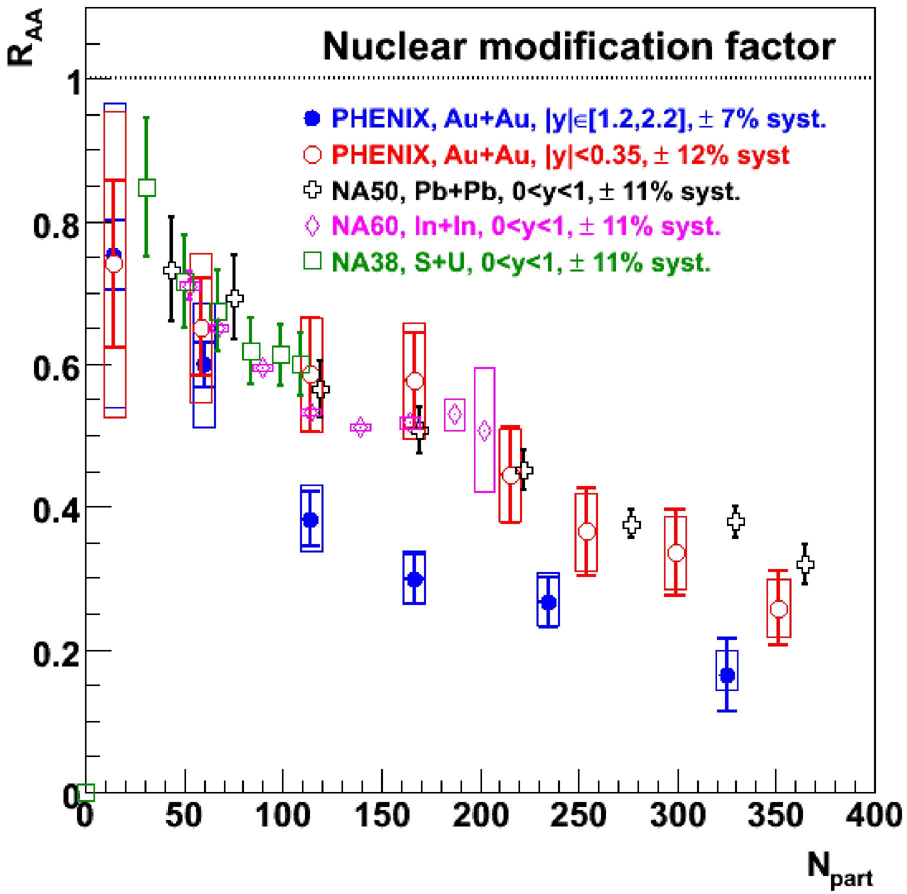
- Suppression du J/Ψ au RHIC

$$R_{AA} = \frac{dN_{AA}}{< N_{coll} > \times dN_{pp}}$$

Rapport de modification nucléaire
si pas d'effets nucléaires, $R_{AA} = 1$

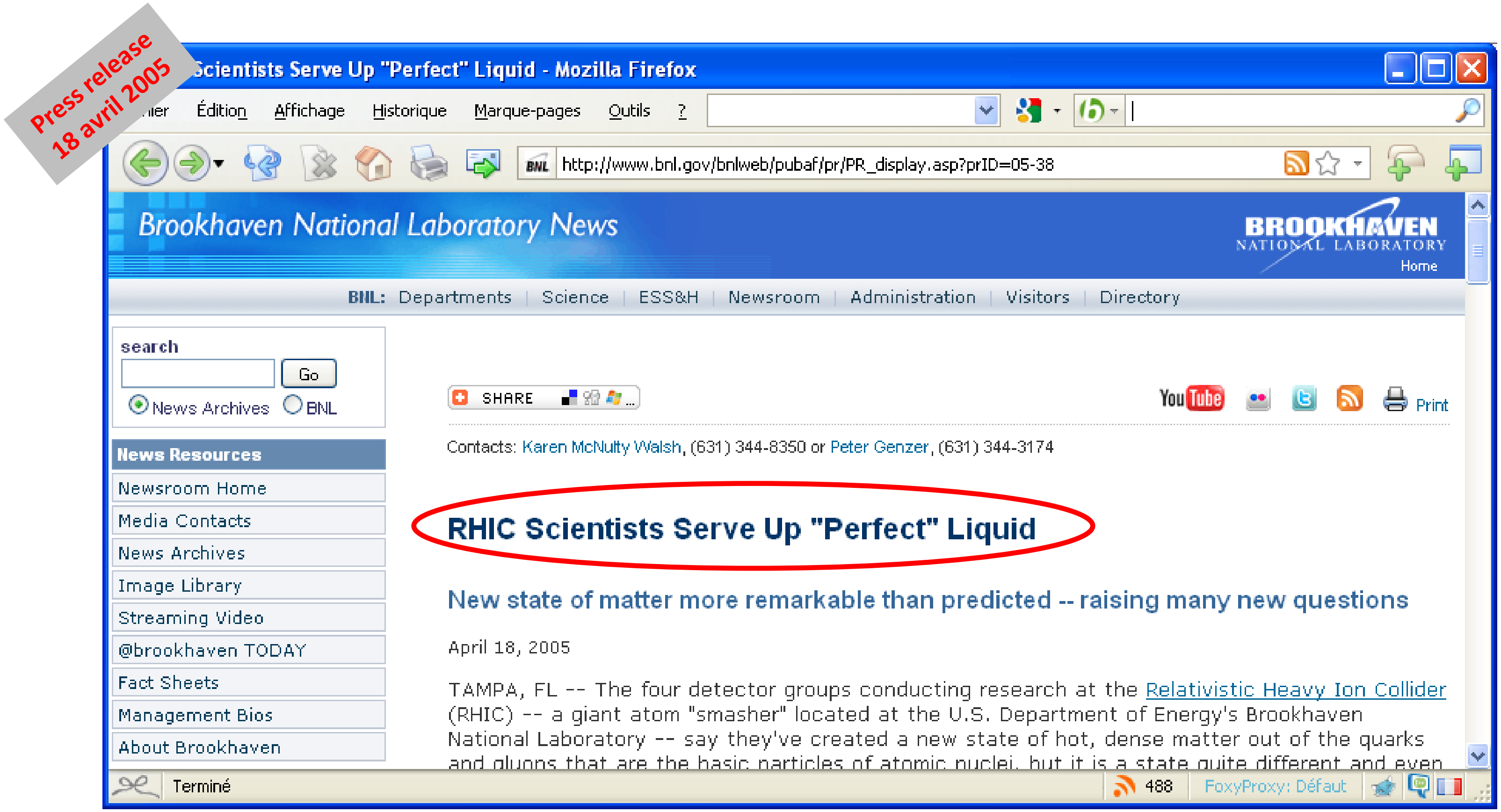
- Suppression similaire à même rapidité
- **Interprétation difficile encore aujourd'hui.**

  Plusieurs possibilités :
  - Recombinaison
  - Suppression séquentielle
  - Contribution des effets froids
- Intérêt de mesurer les quarkonia au LHC



Smoking guns

- Au RHIC : le liquide parfait
  - Jet quenching (opacité)
  - Flot elliptique (collectivité)



Press release
18 avril 2005

Contacts: Karen McNulty Walsh, (631) 344-8350 or Peter Genzer, (631) 344-3174

RHIC Scientists Serve Up "Perfect" Liquid

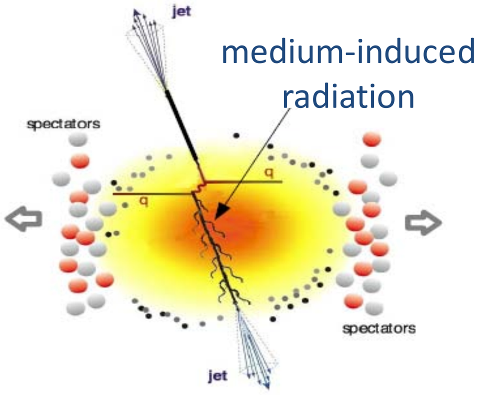
New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even

Smoking guns

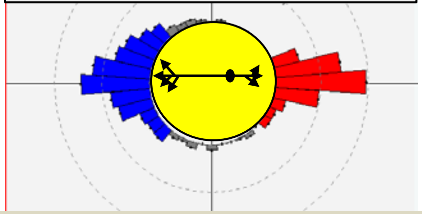
- **Au RHIC : jet quenching**



p+p

$p_T^{trig} > 4$ GeV/c

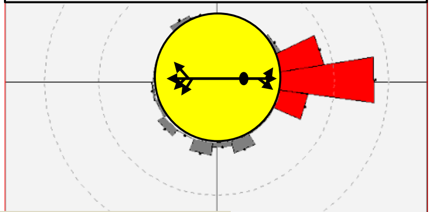
2 GeV/c $< p_T^{assoc} < p_T^{trig}$



Au+Au

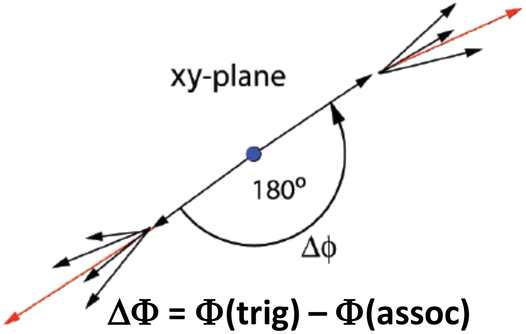
$p_T^{trig} > 4$ GeV/c

2 GeV/c $< p_T^{assoc} < p_T^{trig}$

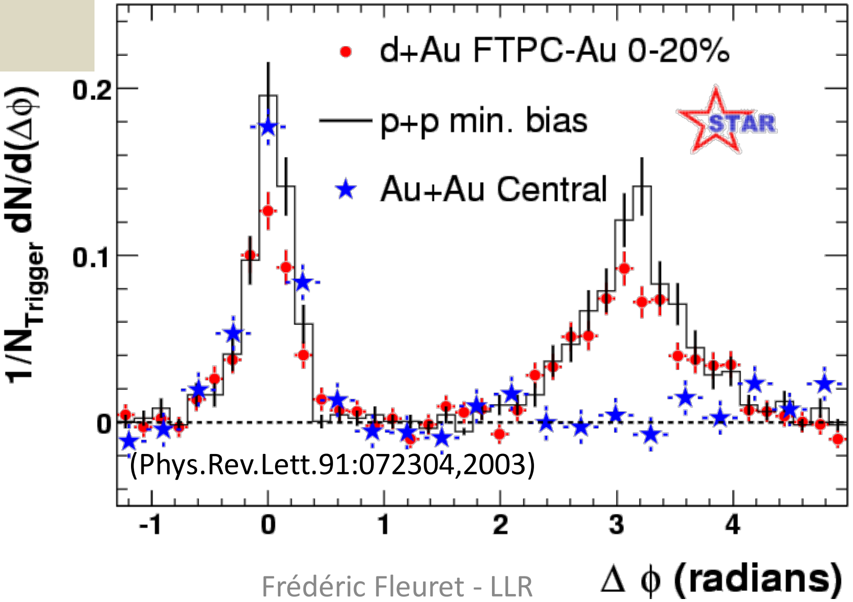


1. Perte d'énergie dans le milieu

2. Corrélations angulaires



$\Delta\Phi = \Phi(\mathrm{trig}) - \Phi(\mathrm{assoc})$



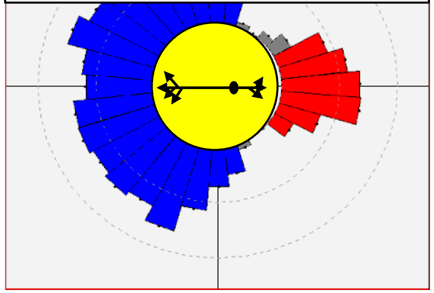
(Phys.Rev.Lett.91:072304,2003)

3. Où va l'énergie ?

Au+Au

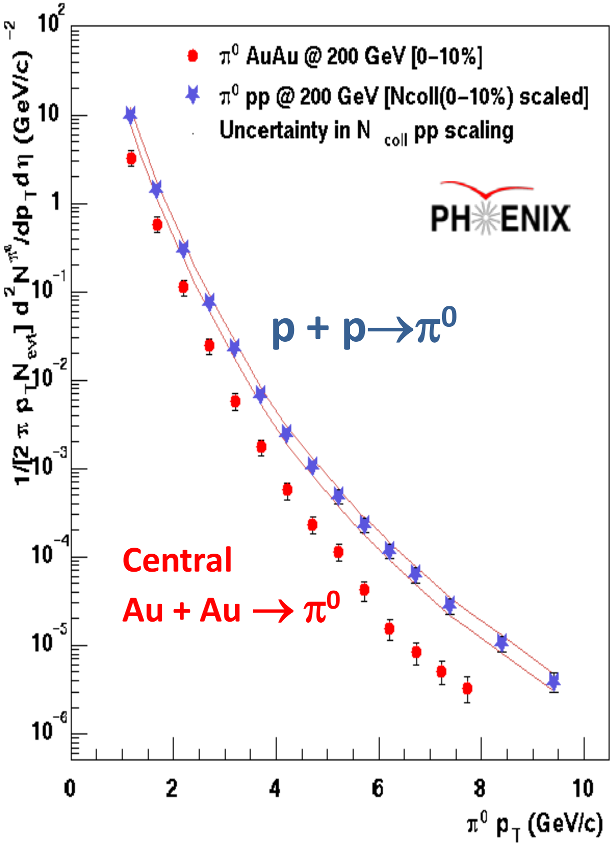
$p_T^{trig} > 4$ GeV/c

0.2 GeV/c $< p_T^{assoc} < p_T^{trig}$



Smoking guns

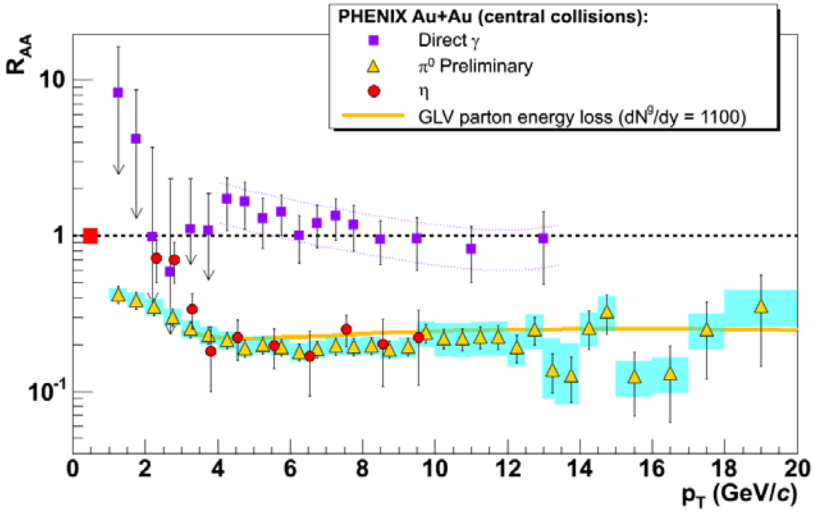
- **Au RHIC : jet quenching**



$$R_{AA} = \frac{dN_{AA}}{< N_{coll} > \times dN_{pp}}$$

Rapport de modification nucléaire

Pas d'effets nucléaires ➔ $R_{AA} = 1$



Très forte suppression

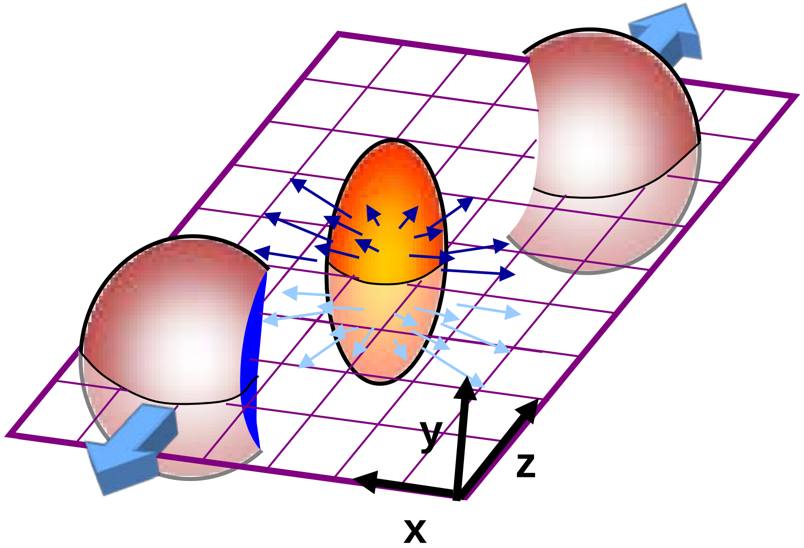
➔Milieu très opaque

➔ plus opaque qu'un gaz

➔ **un liquide**

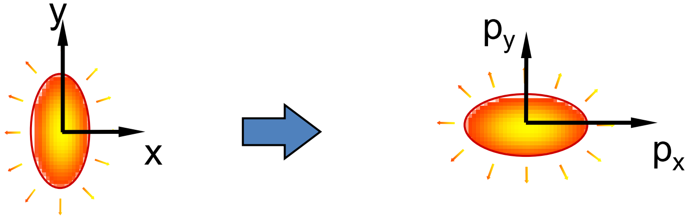
Smoking guns

- ## Au RHIC : flot elliptique

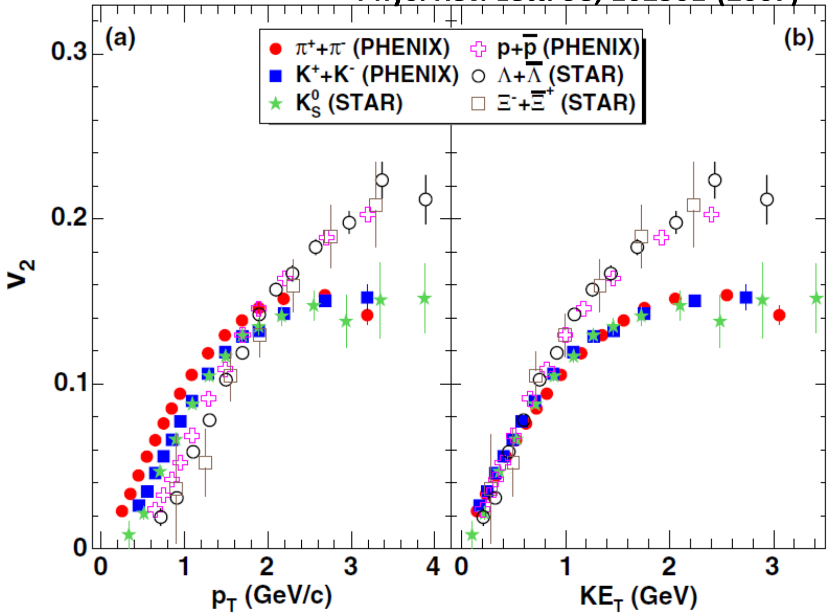


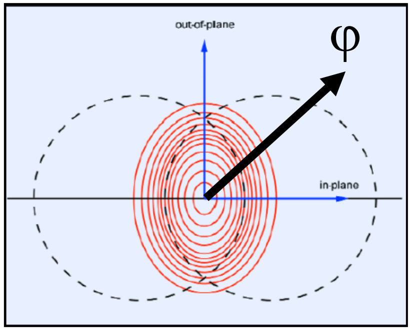
Dans un milieu fortement interagissant (thermalisé)

- **Anisotropie spatiale → anisotropie impulsionnelle** (gradient de pression plus important dans le plan de réaction)



Phys. Rev. Lett. 98, 162301 (2007)





$$\frac{dN}{d\varphi dp_T} = 1 + v_2(p_T)\cos(2\varphi)$$

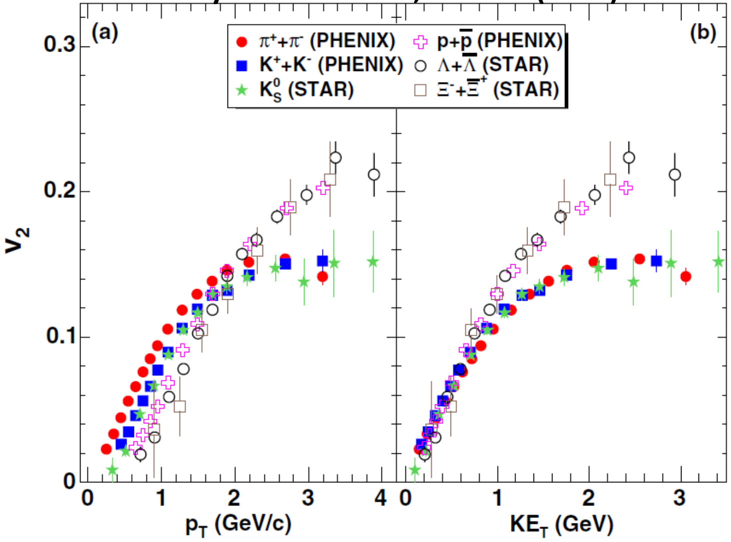
$$v_2 = \frac{\langle p_x{}^2\rangle - \langle p_y{}^2\rangle}{\langle p_x{}^2\rangle + \langle p_y{}^2\rangle}$$

V2>0 → flot dans le plan de réaction

V2<0 → flot hors du plan de réaction

Smoking guns

- Au RHIC : flot elliptique



Phys. Rev. Lett. 98, 162301 (2007)

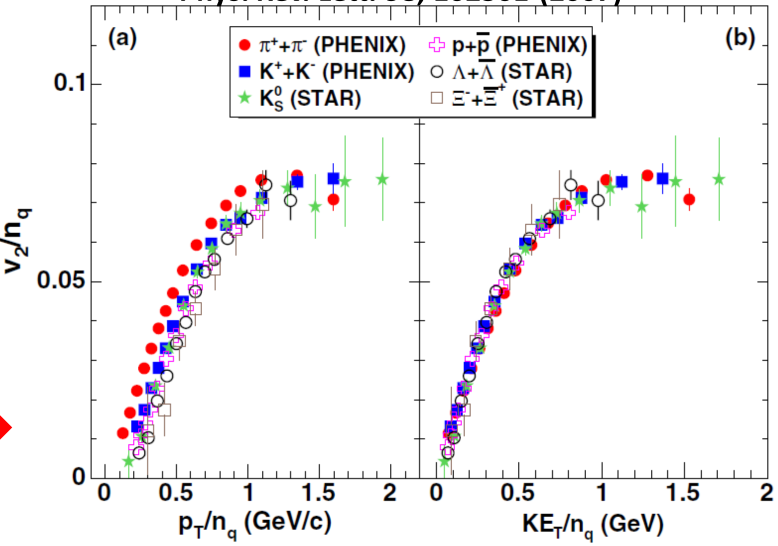
V_2 des hadrons

n_q = nombre de quarks de valence

$v_2 \rightarrow v_2/n_q$

$p_T \rightarrow p_T/n_q$

$KE_T \rightarrow KE_T/n_q$



Phys. Rev. Lett. 98, 162301 (2007)

V_2 des quarks de valence

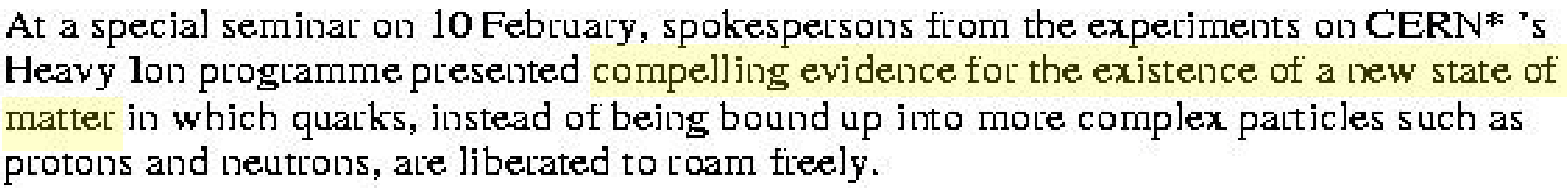
Comportement similaire des hadrons → **Comportement universel des partons**

↓

mouvement collectif

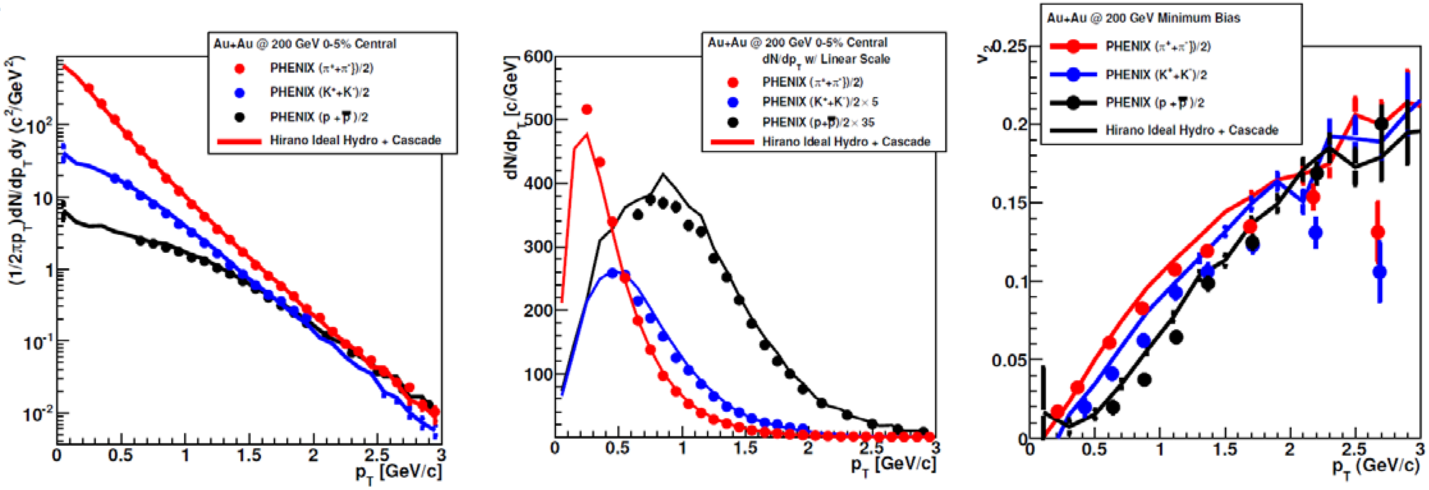
Résumé

- ## Au SPS :

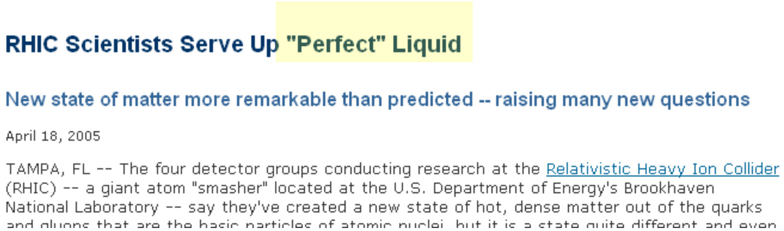


At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

- ## Au RHIC :



Données reproduites par modèles hydrodynamiques (zéro viscosité) + cascade hadronique



RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even

- ## Au RHIC : température ?

Température

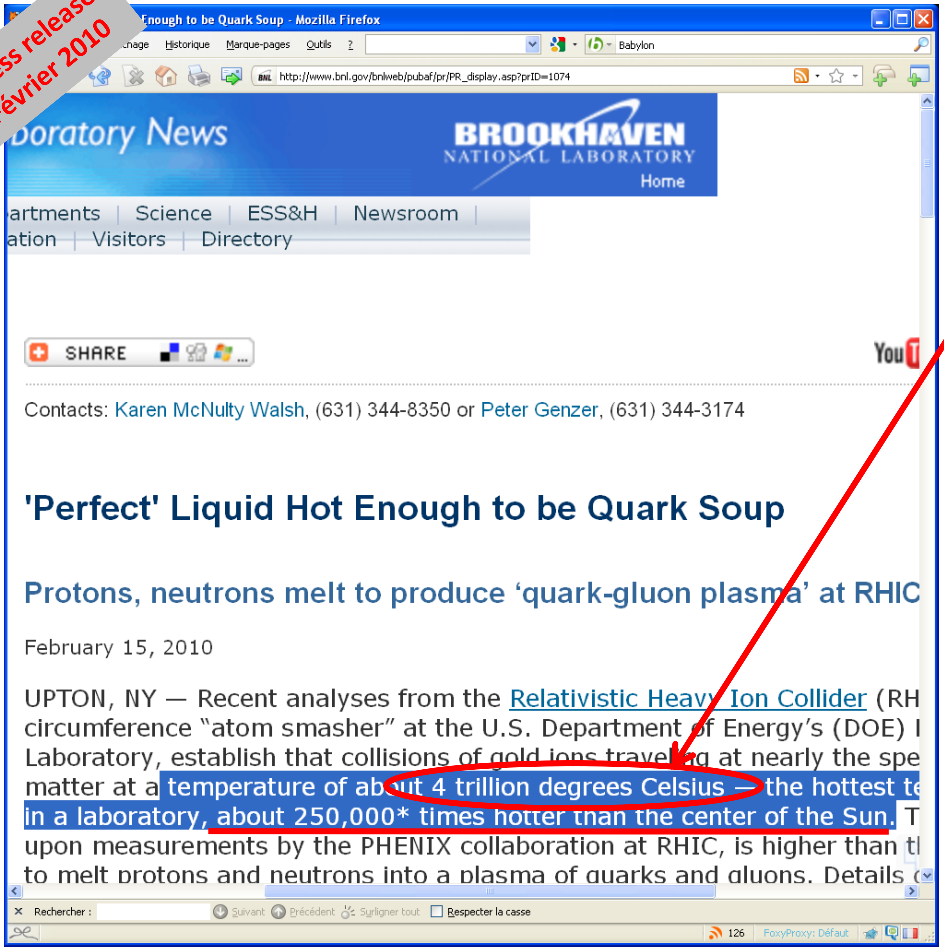
Mesure des photons thermiques

Mesure des photons virtuels

Température

- Perfect liquid hot enough to be quark soup

Press release
Février 2010



Contacts: Karen McNulty Walsh, (631) 344-8350 or Peter Genzer, (631) 344-3174

'Perfect' Liquid Hot Enough to be Quark Soup

Protons, neutrons melt to produce 'quark-gluon plasma' at RHIC

February 15, 2010

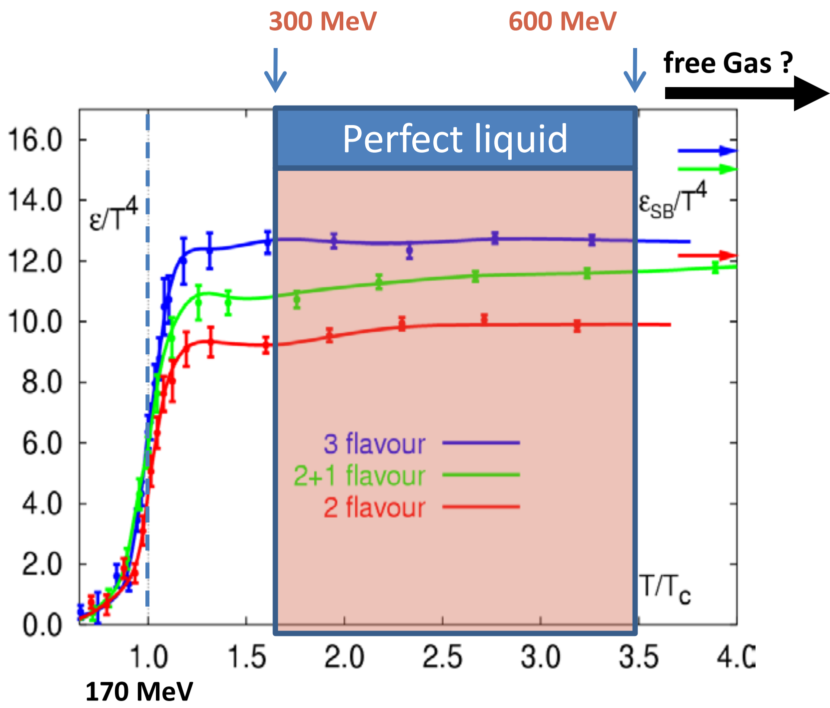
UPTON, NY — Recent analyses from the Relativistic Heavy Ion Collider (RH
circumference "atom smasher" at the U.S. Department of Energy's (DOE) I
Laboratory, establish that collisions of gold ions traveling at nearly the spe
matter at a temperature of about 4 trillion degrees Celsius — the hottest te
in a laboratory, about 250,000* times hotter than the center of the Sun. T
upon measurements by the PHENIX collaboration at RHIC, is higher than tl
to melt protons and neutrons into a plasma of quarks and gluons. Details c

(Phys.Rev.Lett.104:132301,2010)

Hydro fits ➔ T_{ini} ~ 300 – 600 MeV

(k_B ~ 8.6 10^{-5} eV K^{-1})

T ~ 4 – 8 10^{12} K



Température

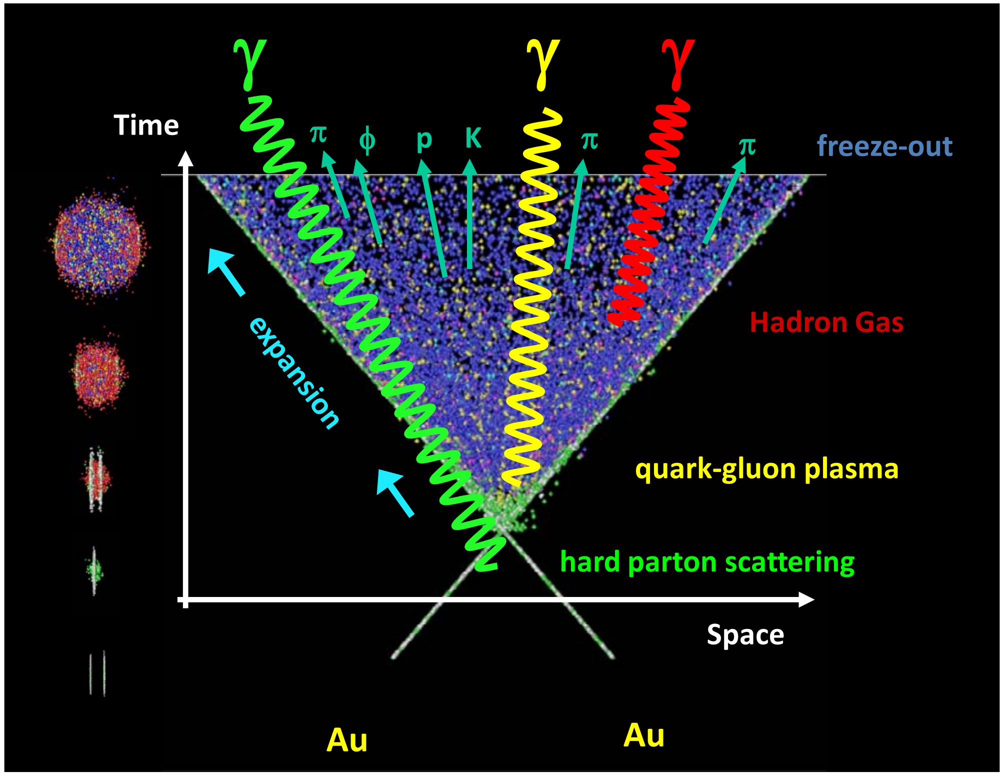
- Comment mesurer la température ?
  - En mesurant les photons
    - Émission de radiation thermique
    - La température peut être mesurée avec les spectres d'émission

Hard parton scattering
High pT photons (> 6 GeV)

QGP photons
Low pT photons (1 – 3 GeV)

Hadron gas photons
Very low pT photons (<2 GeV)

Mesurer les photons
En p+p : obtenir la référence
En d+Au : effets froids
En Au+Au : obtenir la température



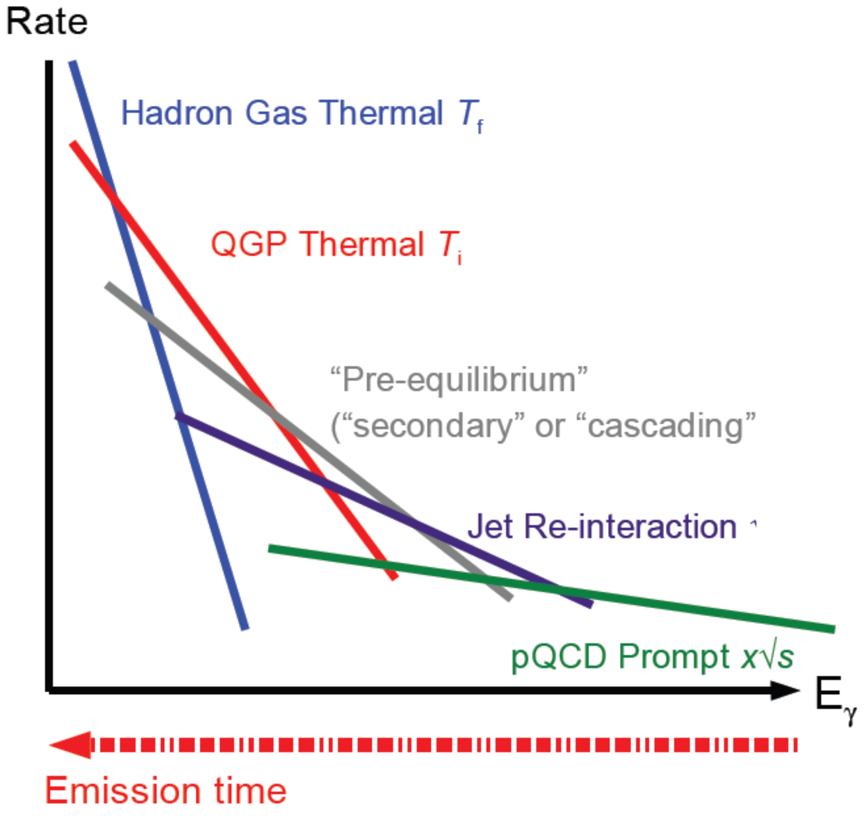
Mesurer les photons

• Dans les collisions A+A

- High p_T photons (p_T>6 GeV) : **non thermal**
  - **Initial parton-parton scattering**: as in p+p
  - not affected by Hot and Dense Matter ➔ test the theoretical description of A+A collisions with pQCD

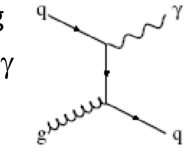
- Low p_T photons (p_T < 3 GeV) : **thermal**
  - **Come from the thermalized medium**
  - Carry information about the initial temperature of the Quark Gluon Plasma
  - Thermal photons are created in the QGP as well as in the hadron gas over the entire lifetime of these phases ➔ test hydro models

- Low and intermediate p_T (up to 6 GeV)
  - **Interaction of the quarks and gluons** from the hard scattering processes **with the QGP**
  - $q_{hard} + g_{QGP} \rightarrow q + g$
  - g get a large fraction of the momentum of q_{hard}



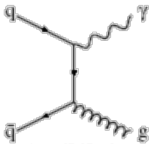
Photons directs : la référence

- Collisions p+p
  - **Direct photons**
    - Compton scattering
      - q + g → q + γ



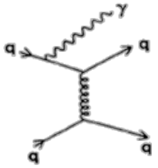
Compton Scattering

    - qq annihilation
      - q + q → g + γ

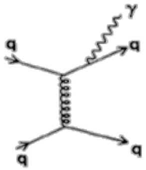


Annihilation

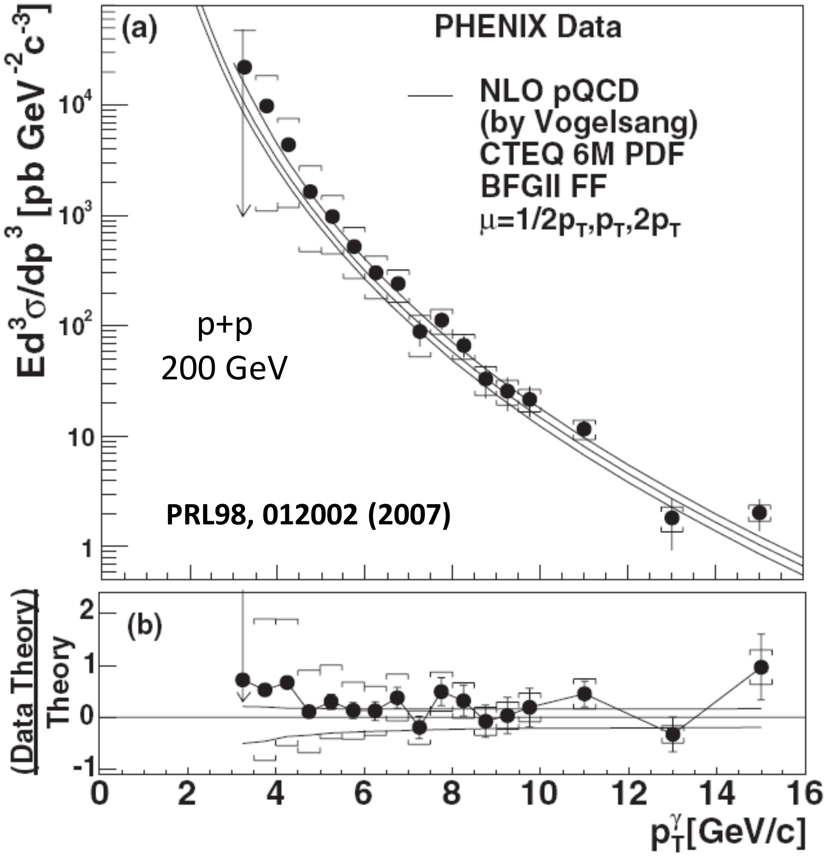
    - Bremsstrahlung (intial state)



  - **Fragmentation photons**
    - Brem. From final state partons



  - Final state **hadron decay** (background)
    - π^0, η, K^0,… → γ + γ



p+p
200 GeV

PRL98, 012002 (2007)

Measured p+p yield compatible with NLO pQCD calculations

Les photons thermiques

- ## La mesure

direct photons are measured as « excess » above hadron decay photons

$$R_\gamma = \frac{\left(\frac{\gamma}{\pi^0}\right)_{measured}}{\left(\frac{\gamma}{\pi^0}\right)_{background}} \approx \frac{\gamma_{measured}}{\gamma_{background}}$$

Direct photons candidates : obtained after rejecting photons pairs falling within 110<$M_{\gamma\gamma}$<170 MeV/c² (π^0) and 500<$M_{\gamma\gamma}$<620 Mev/c² (η)

$$\left(\frac{\gamma}{\pi^0}\right)_{measured}$$

Direct photons candidates (from data)

π^0 from data

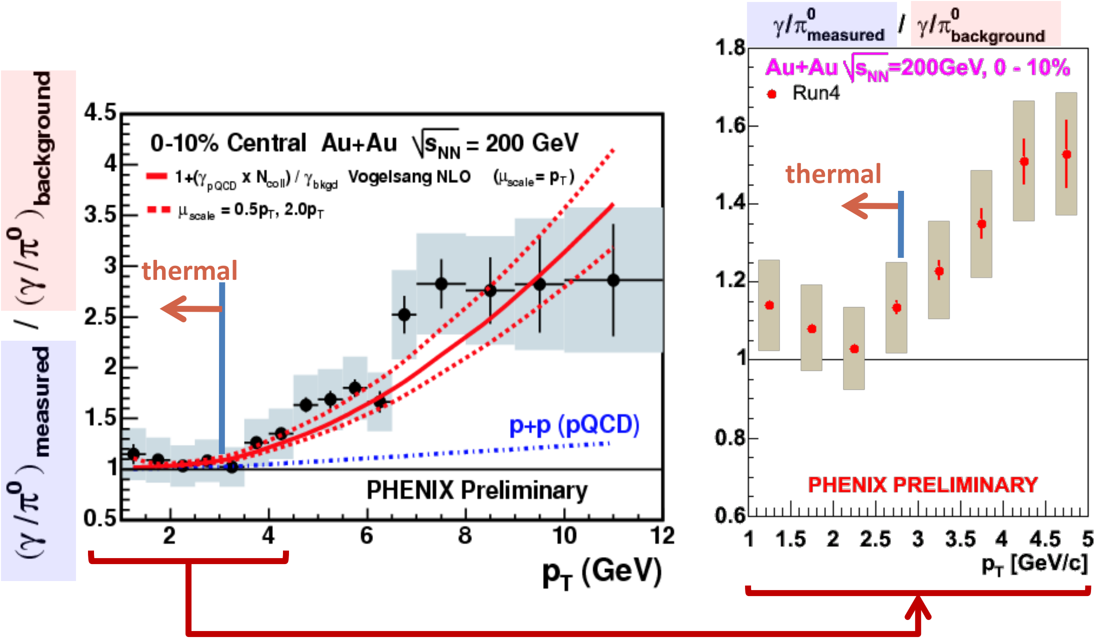
$$\left(\frac{\gamma}{\pi^0}\right)_{background}$$

background photons

π^0 from MC

From Monte Carlo : take a parametrization of measured π^0 as input and propagate the particles through detectors

background photons = remaining photons (from π^0) after all cuts

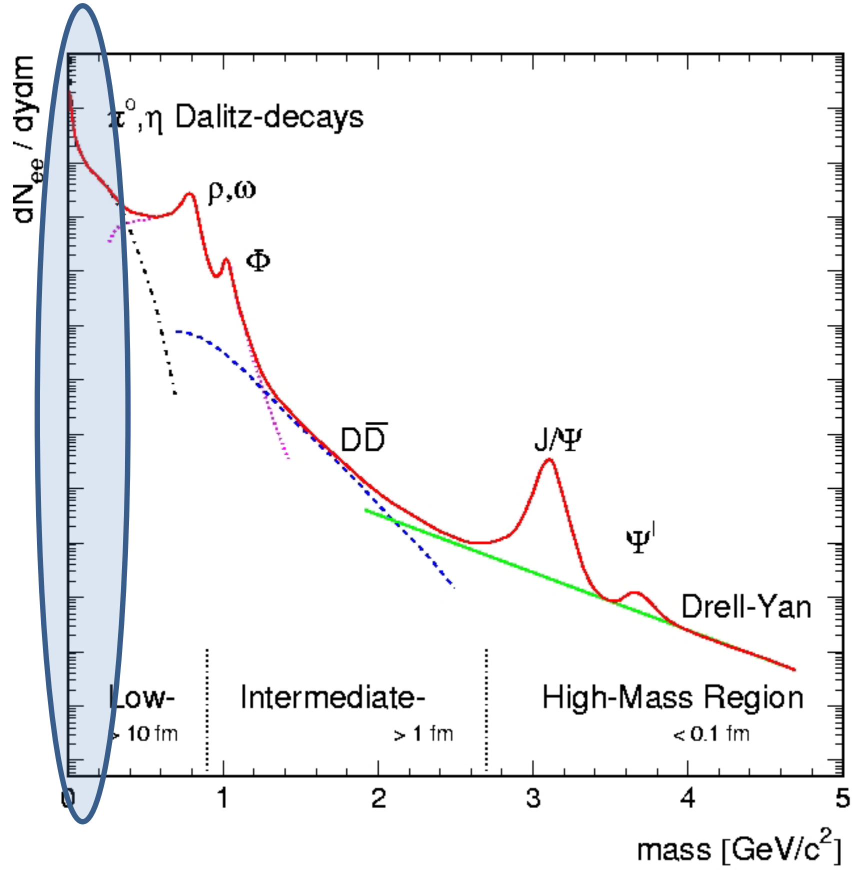


Difficult to measure below p_T<3 GeV/c

(the yield of thermal photons is only 1/10 of that of hadron decay photons)

Mesure alternative

- Les photons virtuels « quasi réels »

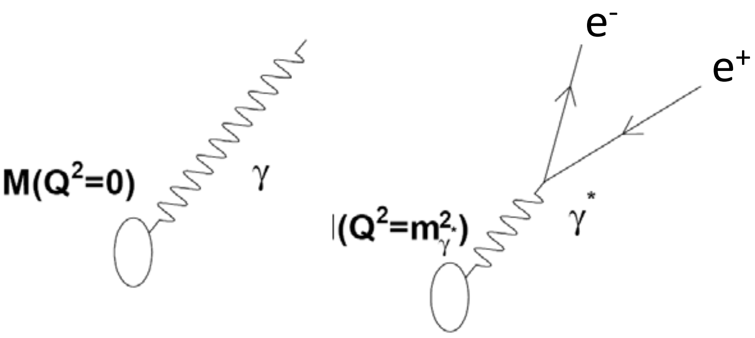


- **les sources de photons réels devraient aussi pouvoir émettre des photons virtuels**
- **à m→0, la production des photons virtuels est la même que celle des photons réels**
- **la production des photons réels peut être mésurée à partir des photons virtuels qui sont observés à basse masse en e^+e^-**
- **le BdF provenant des désintégrations de hadrons peut être fortement réduit.**
- **meilleure résolution en énergie, identification, …**

Mesure alternative

- **Les photons virtuels « quasi réels »**

Source of real photon should also be able to emit virtual photon



$$\frac{d^2N_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)SdN_\gamma$$

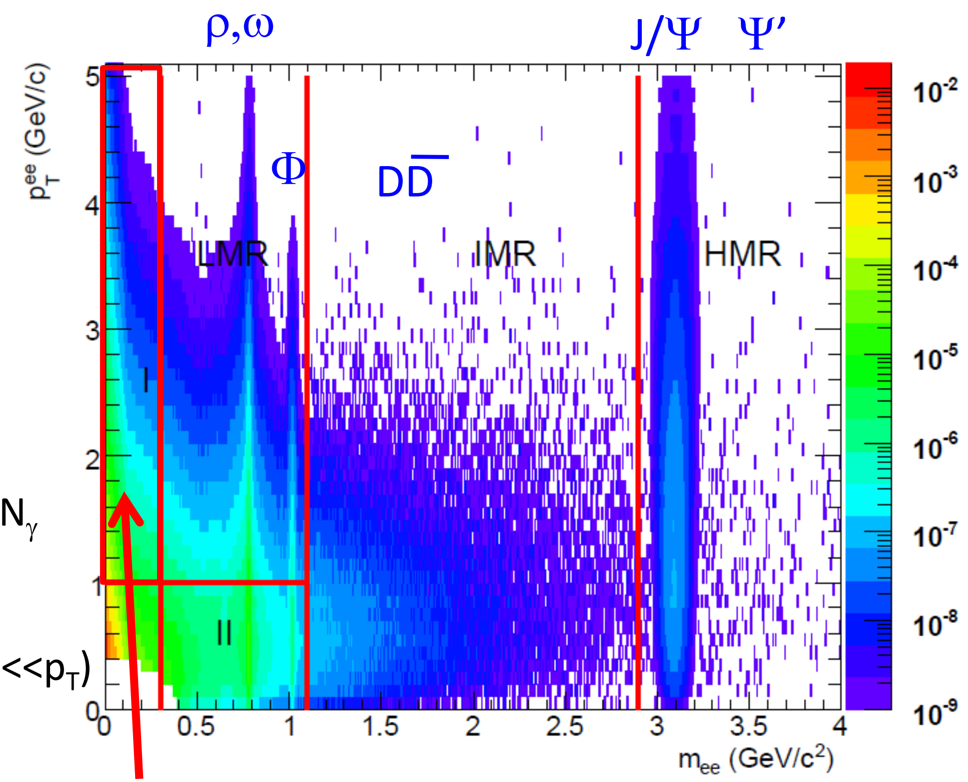
$$\downarrow$$

$S(m_{ee},p_T) = dN_{\gamma^*}(m_{ee})/dN_\gamma$

S = process (direct γ, π^0, η, …)dependent factor

- **Hadron dalitz decay : $S^h(m_{ee})=0$** for $m_{ee}>m_h$
- **Direct photon : $S^\gamma(m_{ee}) \rightarrow 1$** when $m_{ee}/p_T \rightarrow 0$ ($m_{ee} << p_T$)

(See arXiv : 0912.0244 (appendix B) for more details)



LMR I (Low Mass Region I)

($M_{ee}/p_T \rightarrow 0$) $p_T^{ee} >> M_{ee}$ → « quasi real » photons

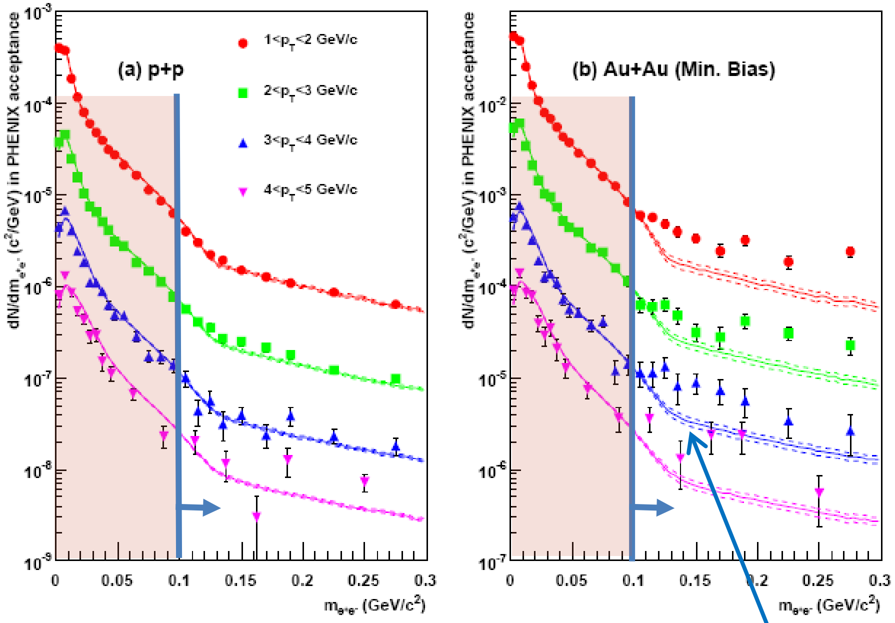
Mesure des γ^* « quasi réels »

- Mesurer les paires d'électrons

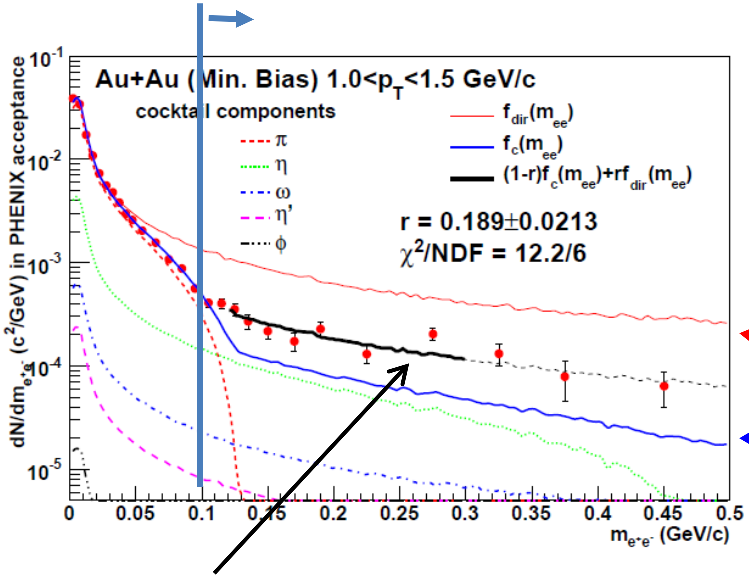
Look at $100 < M_{ee} < 300$ MeV

Several p_T bins

Remove (dalitz) $\pi^0 \rightarrow e^+e^-\gamma$ ➔ $M_{ee} > 135$ MeV/c²



Cocktail
(π,η,ω,ρ,..)



$f_{dir}(M_{ee})$ = expected shape from direct photon spectrum normalized to the data for mee<30 MeV/c²

$f_c(M_{ee})$ = cocktail mass distribution normalized to mee<30 MeV/c²

(Note : for m_{ee}<30 MeV/c² $S^{\pi^\circ}=S^\gamma\sim1$ ➔ identical shape for f_{dir} and f_c)

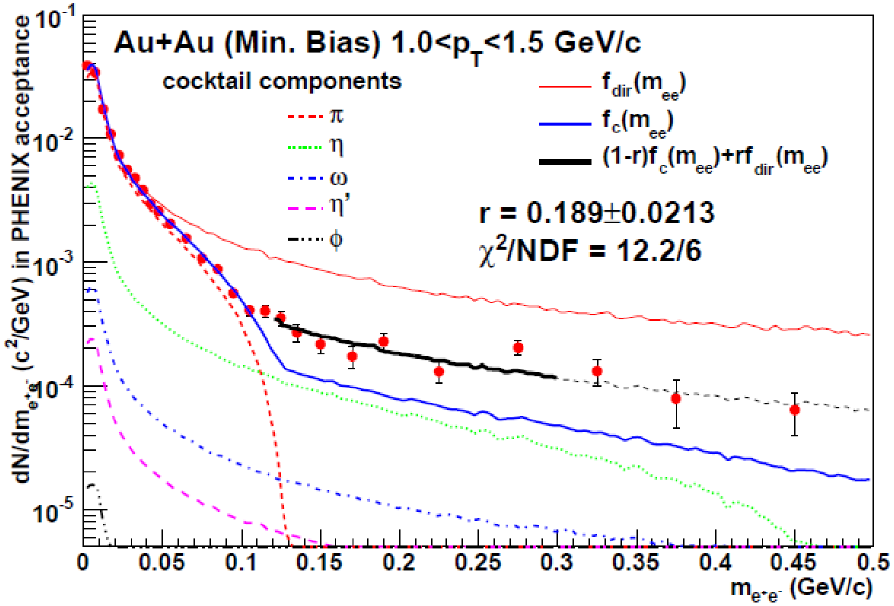
$f_{tot}=(1-r)\,f_c(M_{ee}) + r\,f_{dir}(M_{ee})$

r = fraction of direct photons = direct/inclusive

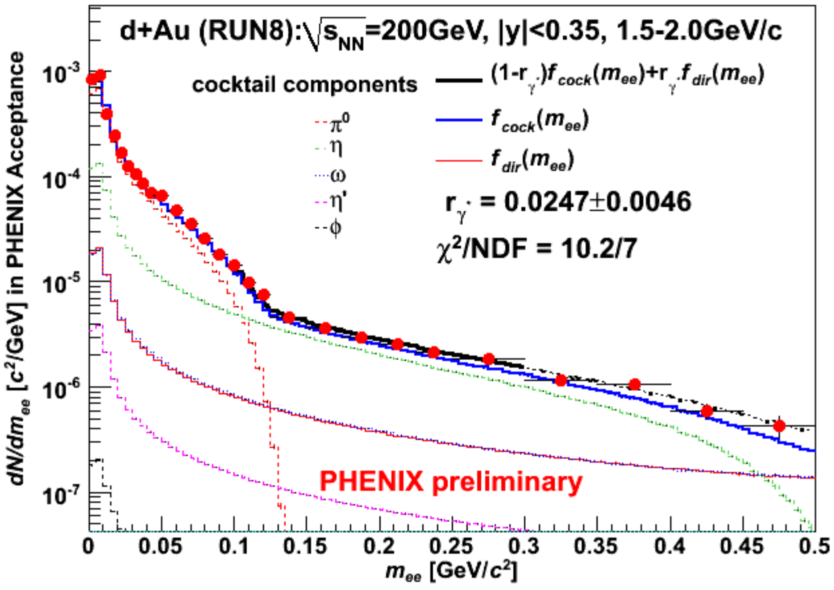
Mesure des γ^* « quasi réels »

- Comparaison Au+Au et d+Au

Au+Au



d+Au



Fraction de photons directs :

-r_{AuAu} = 0.189 ±0.0213

-r_{dAu} = 0.0247±0.0046

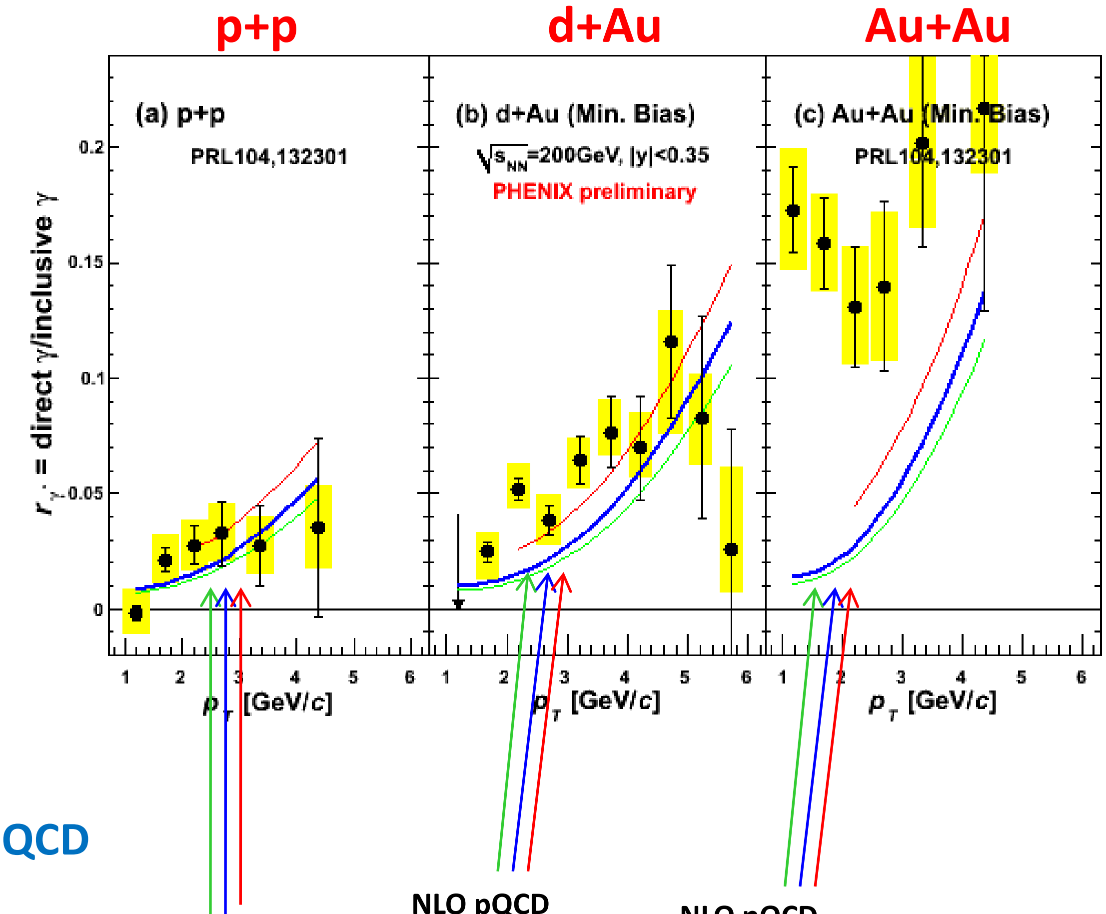
$r_{AuAu} \sim 10 \times r_{dAu}$

Fraction de photons directs

- **En fonction de p_T**

- Several pT bins:
- $1.0 < p_T < 1.5$ GeV/c
- $1.5 < p_T < 2.0$ GeV/c
- $2.0 < p_T < 2.5$ GeV/c
- $2.5 < p_T < 3.0$ GeV/c
- $3.0 < p_T < 4.0$ GeV/c
- $4.0 < p_T < 5.0$ GeV/c

- **p+p consistent with NLO pQCD**
- **d+Au : small excess above NLO pQCD**
- **Au+Au : large excess above NLO pQCD**



NLO pQCD calculations

NLO pQCD calculations ×T_{dAu}

NLO pQCD calculations ×T_{AuAu}

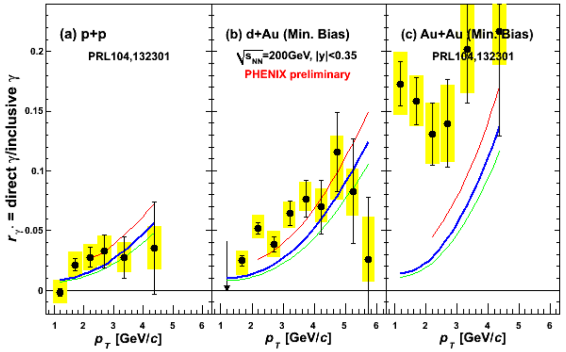
T_{AA} = glauber nuclear overlap function

Spectre des photons directs

- **Détermination du spectre**

Fraction de photons directs

$$r = \frac{\gamma^{\mathrm{dir}}}{\gamma^{\mathrm{incl}}} = \frac{dN_\gamma^{\mathrm{dir}}}{dN_\gamma^{\mathrm{incl}}}$$



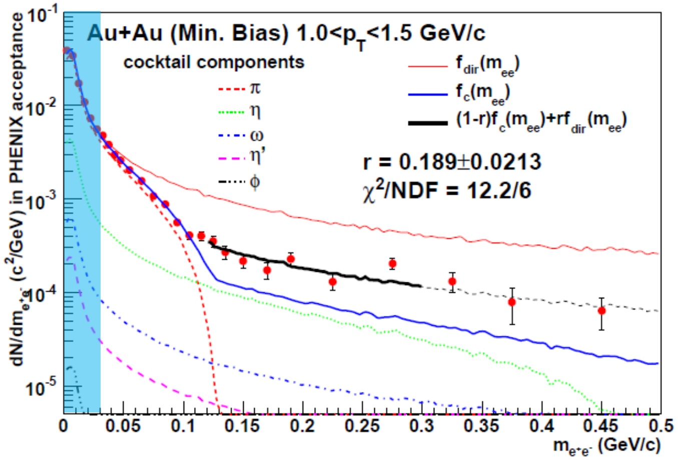
$$dN_\gamma^{\mathrm{dir}} = r \times dN_\gamma^{\mathrm{incl}} = r \times N_{ee}^{\mathrm{data}} \times \frac{dN_\gamma^{c}}{dN_{ee}^{c}}$$

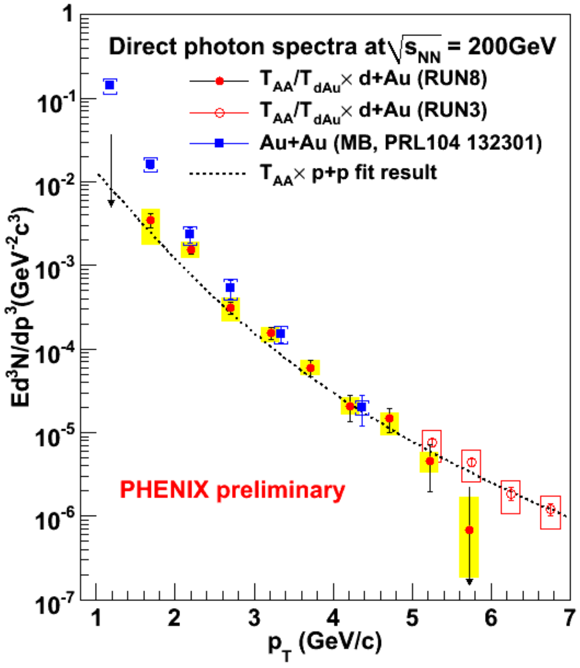
Measured e+e- yield for $m_{ee} < 30$ MeV/c²

Normalized cocktail e+e- yield For $m_{ee} < 30$ MeV/c²

Photon yield from normalized cocktail for $m_{ee} < 30$ MeV/c²

to take S (the process dependent factor) into account

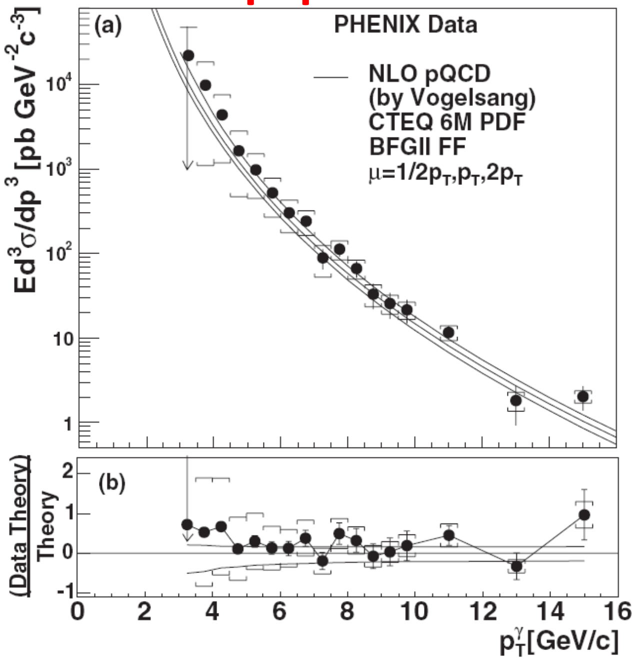




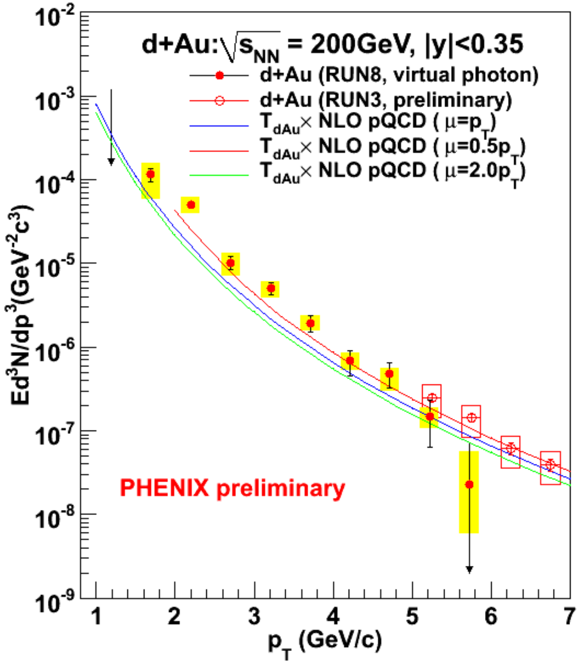
Spectre des photons directs

- **Comparaisons p+p, d+Au, Au+Au**
  - p+p : compatible with NLO pQCD calculation
  - d+Au : Hint of an enhancement, probably due to a nuclear effect
  - Au+Au : excess at low p_T ➔ thermal photons

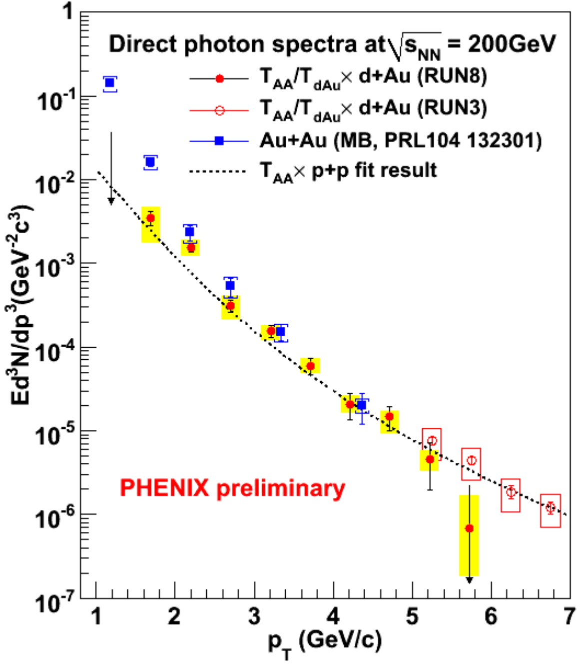
p+p



d+Au



Au+Au



Spectre des photons directs

- **Détermination de la température**

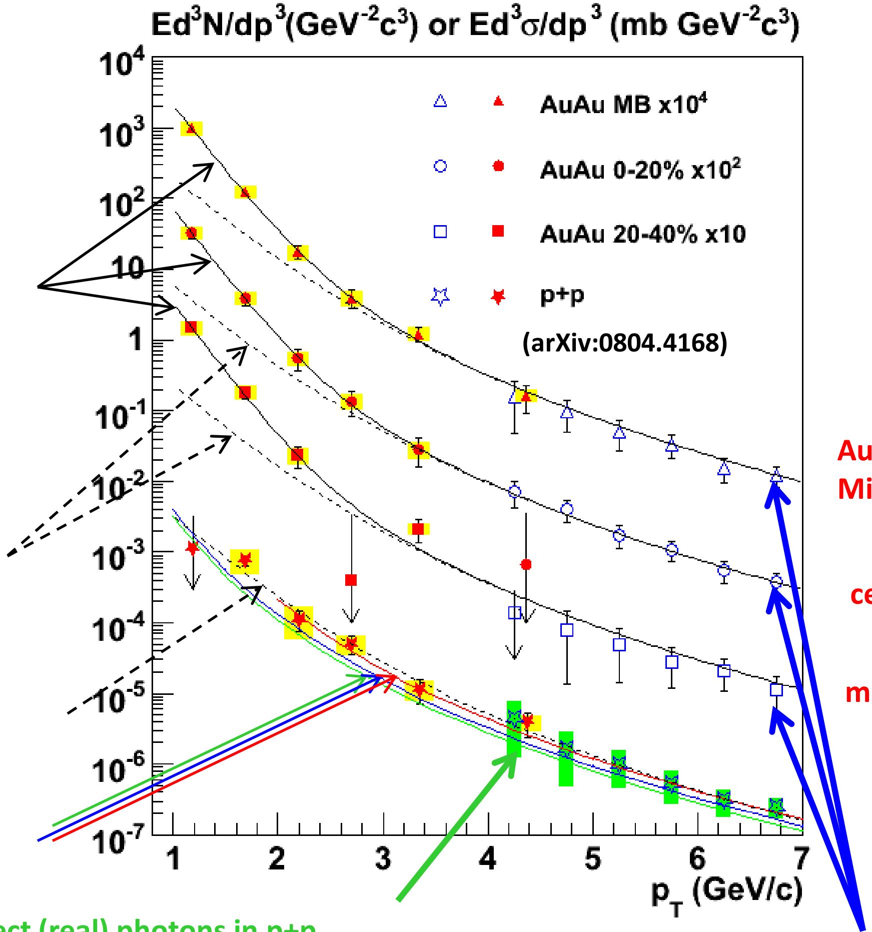
Fit = exponential + (MPLF×T_{AA})

$$= Ae^{-p_T/T} + (\text{MPLF}\times T_{AA})$$

Cent	dN/dy (pT>1GeV)	Slope (MeV)
0-20%	1.50±0.23±0.35	221±19±19
20-40%	0.65±0.08±0.15	217±18±16
MinBias	0.49±0.05±0.11	233±14±19

T = 221 ±19±19 MeV

Phys. Rev. Lett. 104, 132301 (2010)



Exponential + MPLF on p+p × T_{AA}

MPL Fit on p+p × T_{AA}

Modified Power Law Fit on p+p

NLO pQCD calculations

Au+Au Min bias

central

mid

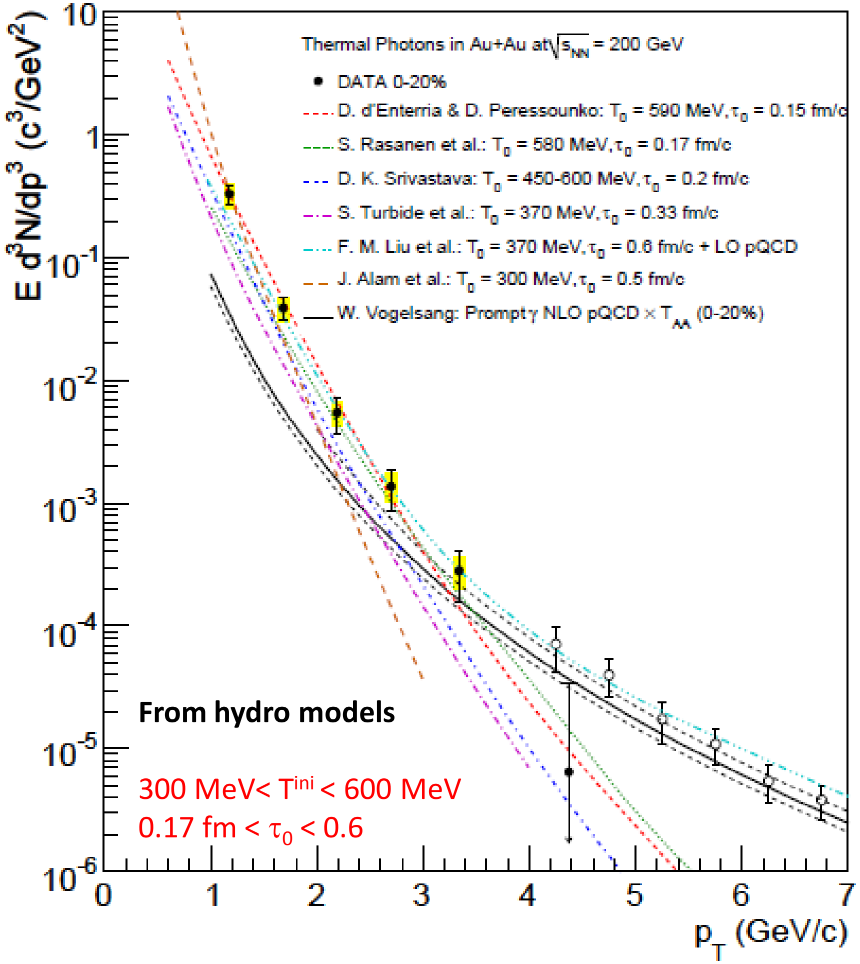
p+p

Direct (real) photons in p+p
Phys. Rev. Lett. 98, 012002 (2007)

Direct (real) photons in Au+Au
Phys. Rev. Lett. 94, 232301 (2005)

Températures

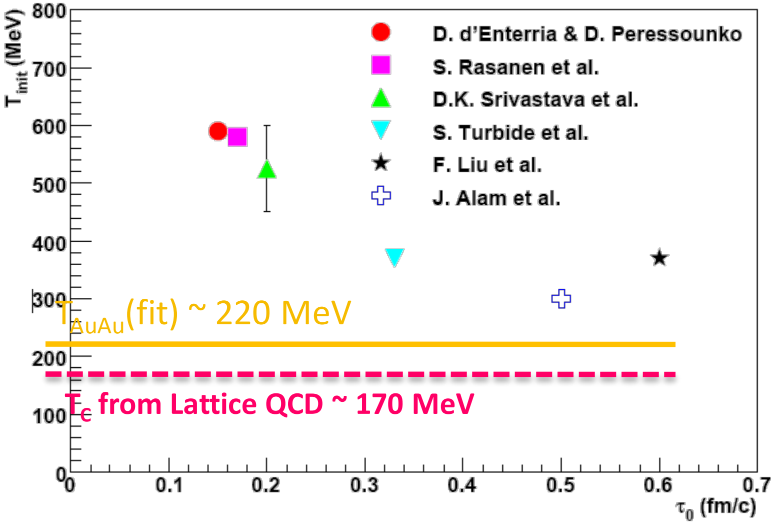
- **Modèles hydrodynamiques**



From hydro models

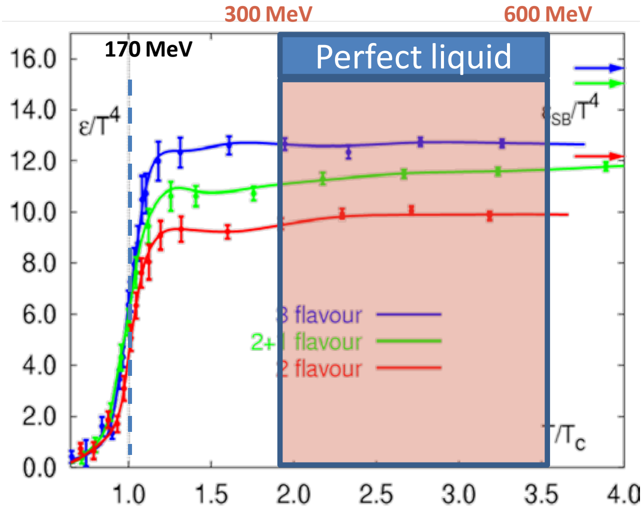
300 MeV< T^{ini} < 600 MeV

0.17 fm < τ_0 < 0.6



T_{AuAu}(fit) ~ 220 MeV

T_c from Lattice QCD ~ 170 MeV



300 MeV

600 MeV

170 MeV

Perfect liquid

Conclusion

- **Au RHIC**
  - Résultats : liquide parfait
    - Jet quenching → opacité
    - Flot elliptique → collectivité
    - Température → 300 à 600 MeV

  - Futur (à partir de 2011)
    - Installation d'un détecteur de vertex
    - Accès à la physique des saveurs lourdes (open charm, open beauty)

- **Au LHC**
  - Pb+Pb à 5,5 TeV