

# **Heavy-ions physics at collider energies**

## **– Lecture II –**

**France-Asia Particle Physics School**

Les Houches, 23-25 Sept. 2008

**David d'Enterria**

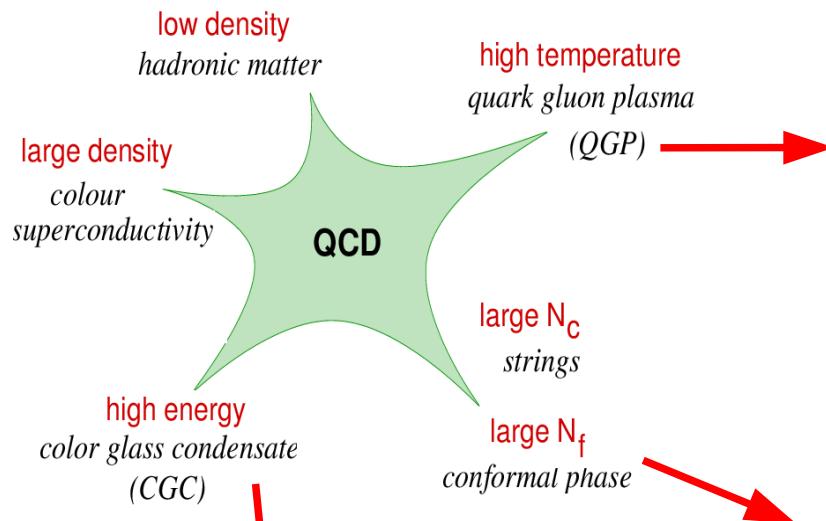


Massachusetts  
Institute of  
Technology

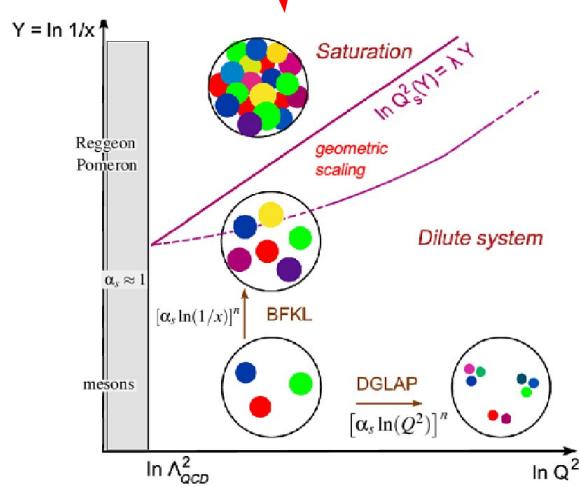
# 6 big HEP questions for the LHC

- 👉 “Mass generation” problem: What is the origin of elementary particle masses ? Higgs mechanism ? other physics ?
- 👉 “Flavour” problem: Why so many types of matter particles ?  
Origin of baryon asymmetry in the Universe ?
- 👉 “Hierarchy”, “fine tuning” problem: Why large ( $10^{16}!$ ) difference between EW & gravity (Planck) scales ? strings ? extra-dims ?
- 👉 “Dark matter” problem: ~1/4 matter in universe invisible. SUSY ?
- 👉 “QCD in non-perturbative regime” : Why quark confinement ?  
HE hadronic cross-sections ? Gauge-String duality (AdS/CFT) ?
- 👉 “Highest-energy cosmic-rays” : Sources/nature of CRs at  $10^{20}$  eV?

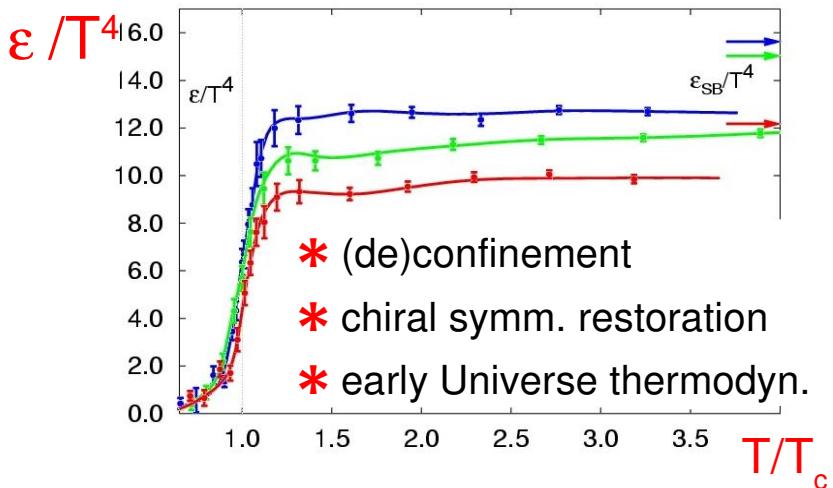
# QCD matter: physics menu & theoretical tools



## ■ High-density QCD at small-x: CGC

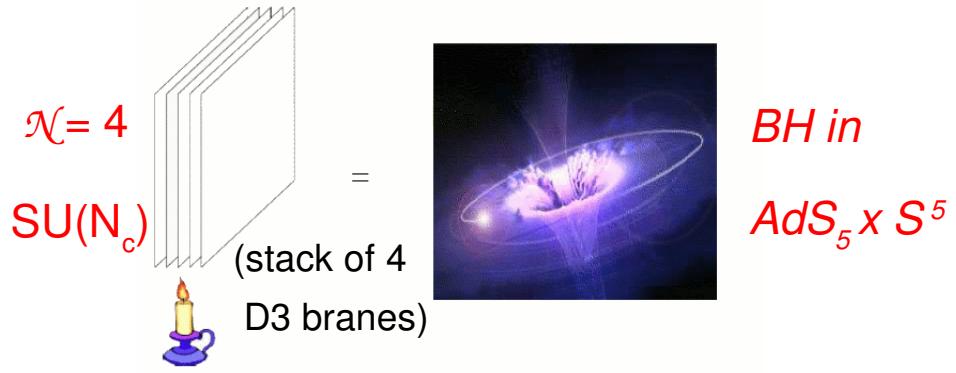


## ■ Lattice QCD at high-T: QGP



## ■ Gauge-gravity duality: AdS/QCD

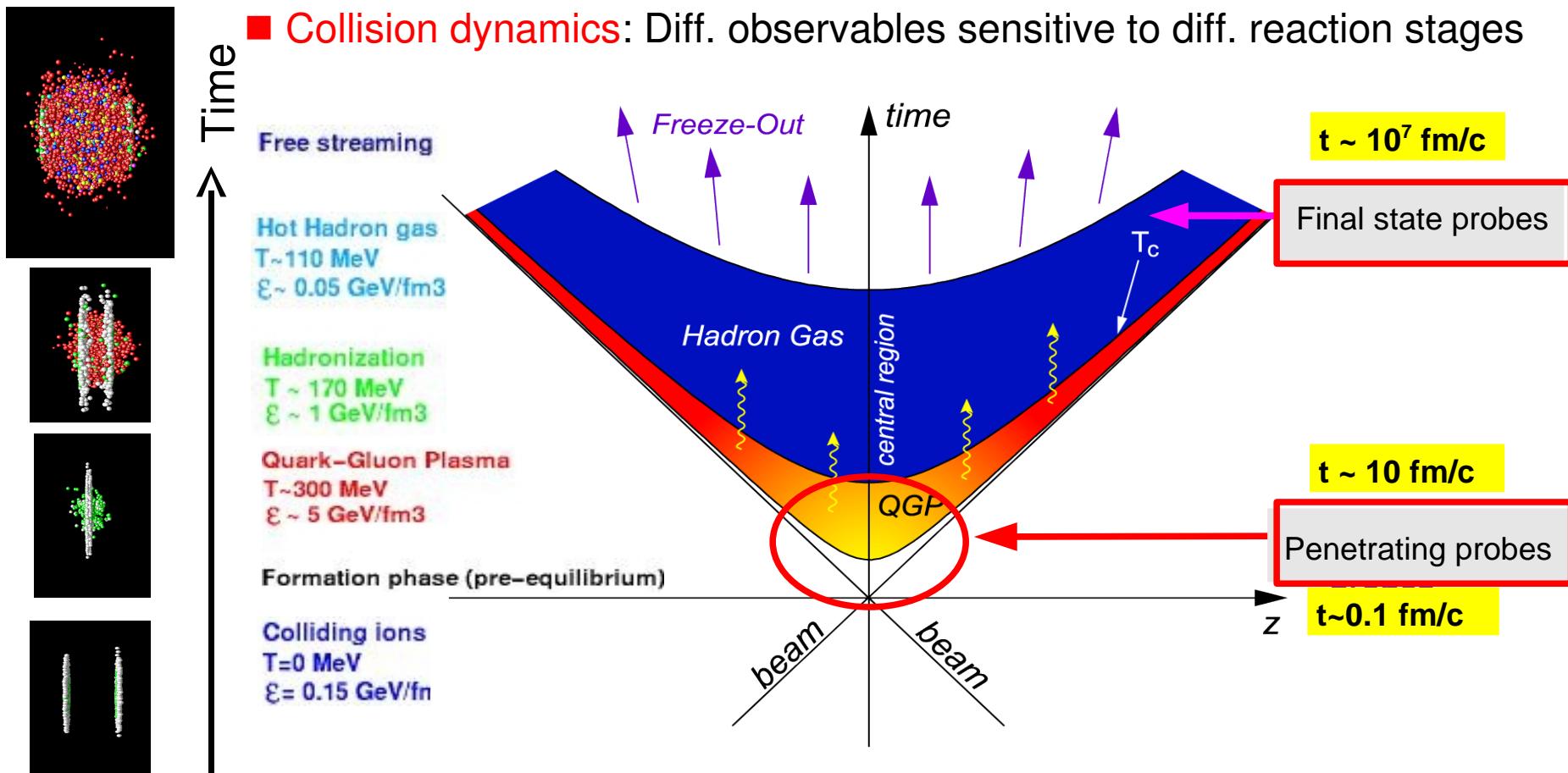
$$\mathcal{L} = \frac{1}{2g_{\text{YM}}^2} \text{Tr}(F_{\mu\nu}F^{\mu\nu}) + i\text{Tr}(\bar{\psi}\gamma^\mu D_\mu\psi) \quad \leftrightarrow \quad ds^2 = \frac{r^2}{R^2}(-dt^2 + d\vec{x}^2) + \frac{R^2}{r^2}d\Omega_5^2$$



Thermal gauge theory = black hole in anti de-Sitter space

# The "Little Bang" in the lab.

- High-energy **nucleus-nucleus collisions**: fixed-target ( $\sqrt{s}=20$  GeV, SPS) or colliders ( $\sqrt{s}=200$  GeV, RHIC;  $\sqrt{s}=5.5$  TeV, LHC)
- Expanding QGP: volume  $\sim O(10^3 \text{ fm}^3)$  for times  $\sim 0.1\text{-}10 \text{ fm/c}$
- Collision dynamics: Diff. observables sensitive to diff. reaction stages



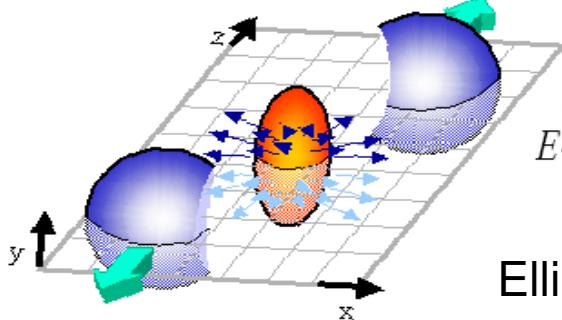
# Plan of lectures

- 1<sup>st</sup> {
- Introduction
    - High-energy nucleus-nucleus collisions **physics programme**: confinement, chiral symmetry, early Universe thermodyn., low-x QCD ...
    - Colliders & **Experiments**: RHIC(Au-Au@200 GeV), LHC(PbPb@5.5 TeV)
  - Study of **many-body QCD (thermo)dynamics**:
    - Soft probes:
      - (1)  $dN_{ch}/d\eta \Rightarrow$  Colour-Glass-Condensate – gluon  $xG_A(x, Q^2)$
      - (2) Low  $p_T$   $\pi/K/p$  spectra  $\Rightarrow$  QCD Equation-of-State
      - (3) **Elliptic flow**  $\Rightarrow$  QCD medium viscosity, AdS/CFT test-bed
    - Hard probes:
      - (1) “**Jet quenching**”  $\Rightarrow$  Parton density,  $\langle \hat{q} \rangle$  transport coefficient
      - (2) Direct (thermal) photons  $\Rightarrow$  QCD critical temperature ( $T_{crit}$ )
      - (3) Quarkonia suppression  $\Rightarrow$  QCD critical  $\varepsilon_{crit}, T_{crit}$
- 2<sup>nd</sup> {

# **Soft QGP probes (IV): Elliptic flow**

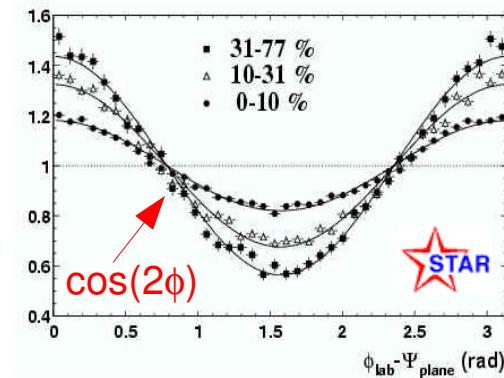
# Elliptic flow (RHIC)

- Lens-shaped spatial anisotropy (overlap) in non-central collisions translates into boosted momentum emission along react. plane:



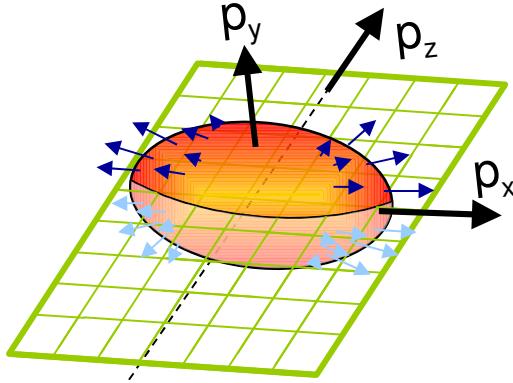
$$E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_{RP})] \right)$$

Elliptic flow  $v_2$  = 2<sup>nd</sup> Fourier coefficient



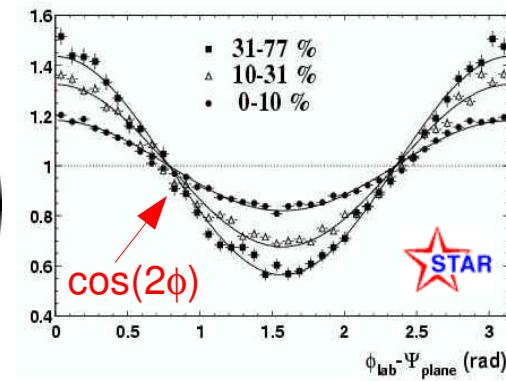
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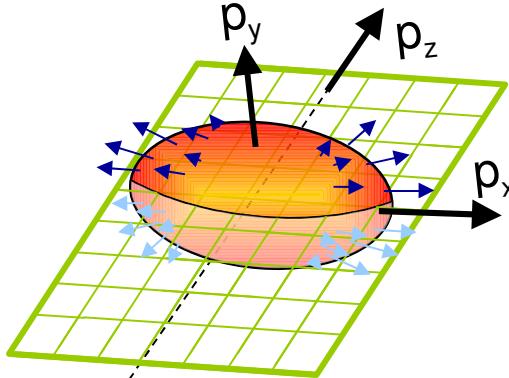
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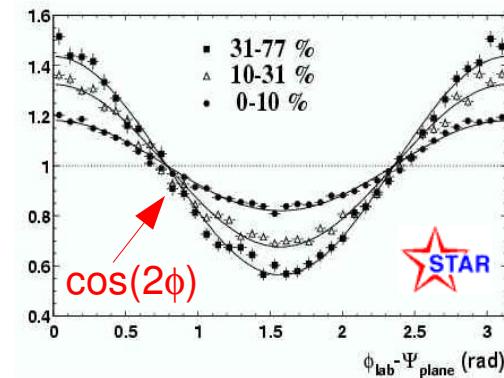
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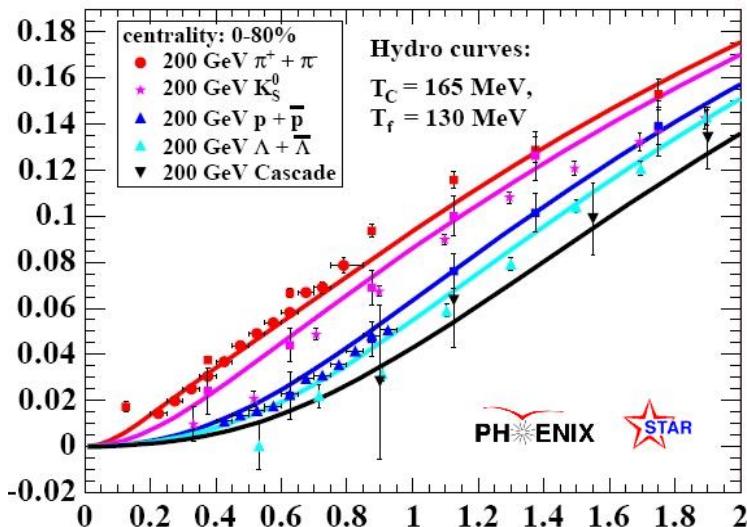


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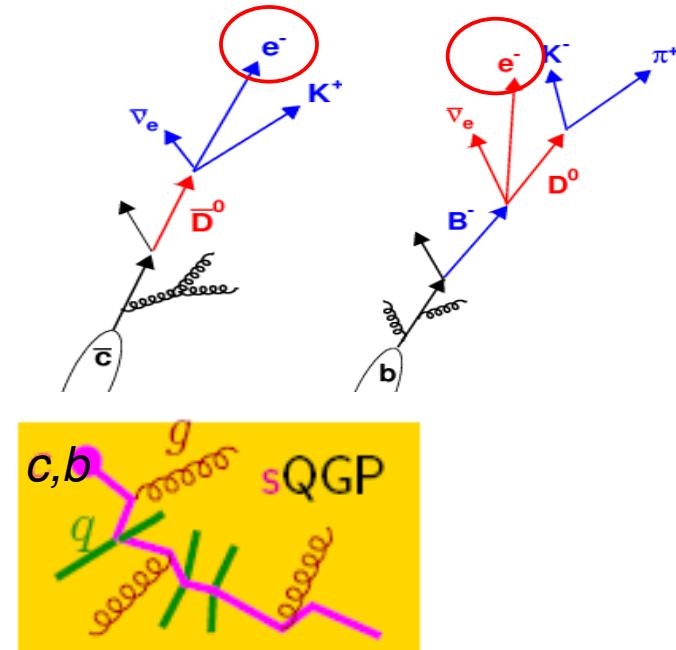
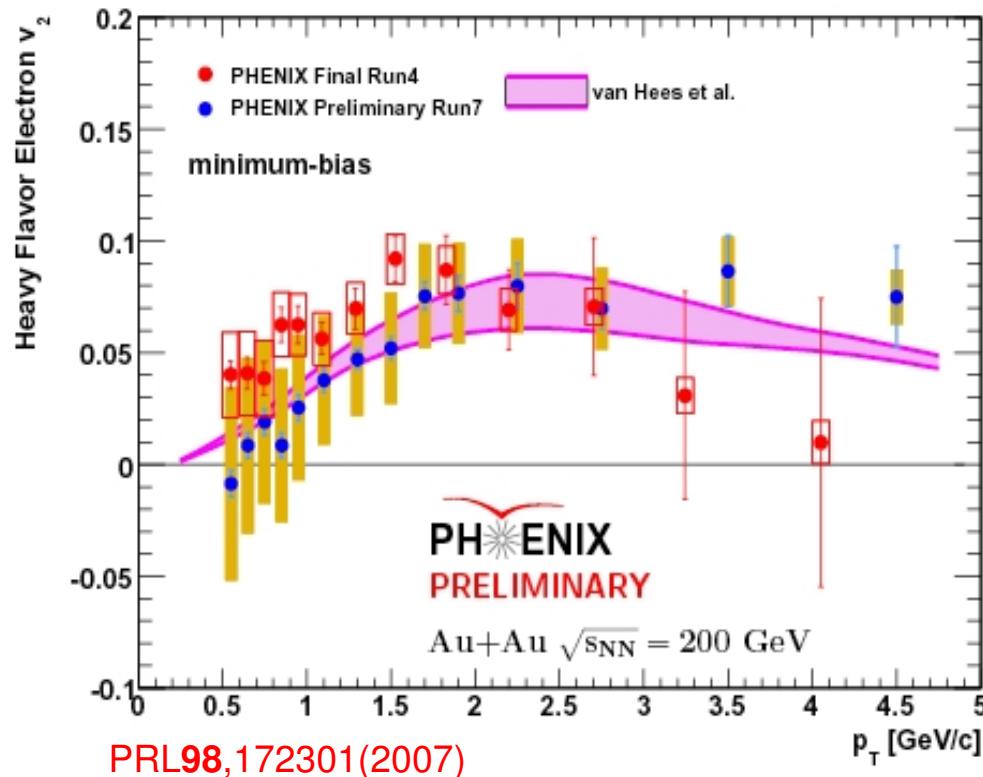
- Large  $v_2$  signal (~20%) for all hadrons well described by ideal hydrodynamics:



- ⇒ Strong partonic pressure grads.
- ⇒ Large & fast parton rescattering:  
very fast thermalization.
- ⇒ Low viscosity (no “internal dissipation”)

# Elliptic flow (RHIC)

- Large  $v_2$ -parameter of decay  $e^\pm$  from D,B mesons too:



- Even heavy-quarks flow collectively with medium !
- The plasma at RHIC is “strongly coupled” (sQGP) !

# sQGP: most ideal fluid known !

- “Perfect fluid” (=non-viscous) relativistic hydrodynamics:

Fastly thermalized ( $\tau_0 = 0.6 \text{ fm/c}$ ) QGP with  $\varepsilon_0 \sim 30 \text{ GeV/fm}^3$   
 reproduces radial & elliptic flows:

$$\partial_\mu T^{\mu\nu} = 0 \quad (\text{5 eqs. w/ 14 unknowns})$$

$$\partial_\mu N_i^\mu = 0, \quad i = B, S, \dots$$

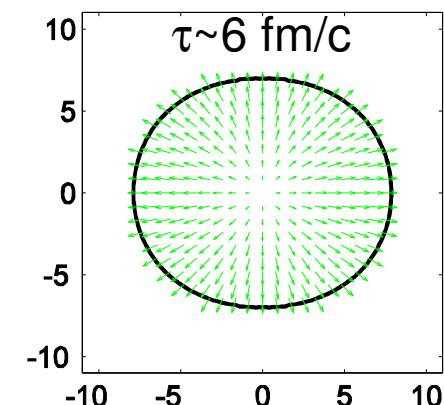
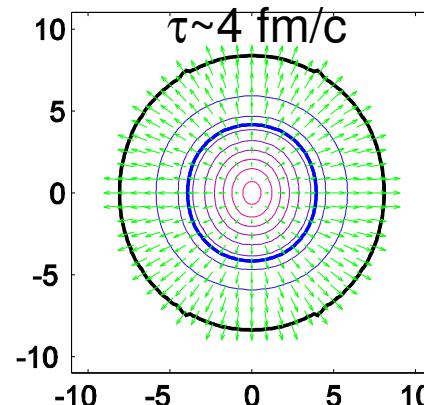
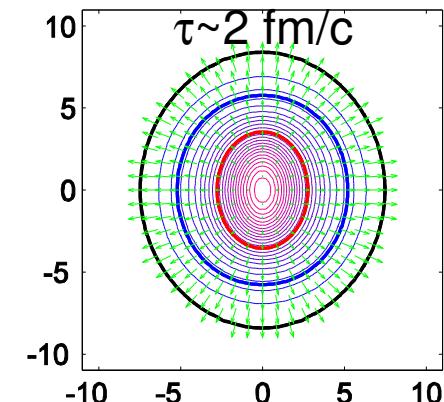
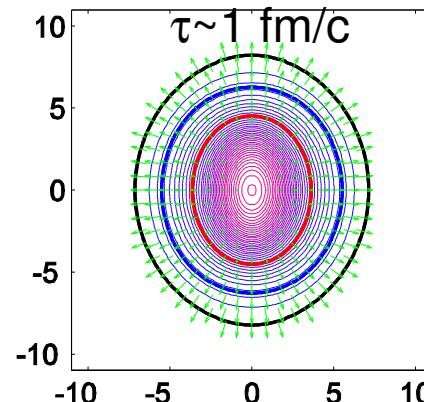
$T^{\mu\nu}$  is energy-momentum tensor

$N_i^\mu$  is charge 4-current ,  $u^\mu$ : collective 4-veloc. field

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - Pg^{\mu\nu}$$

$$N^\mu = n u^\mu$$

$P = P(\varepsilon, n) \rightarrow$  latt. QCD Equation-of-State



# sQGP: most ideal fluid known !

- Relativistic hydrodynamics with **non-zero viscosity  $\eta$** :

shear-stress term modifies expansion rate:  $v_2(p_T)$  strongly **reduced** !

$$T^{\mu\nu} = T_0^{\mu\nu} + \eta(\nabla^\mu u^\nu)$$

$$\partial_\mu T^{\mu\nu} = 0 \quad (5 \text{ eqs. w/ 14 unknowns})$$

$$\partial_\mu N_i^\mu = 0, \quad i = B, S, \dots$$

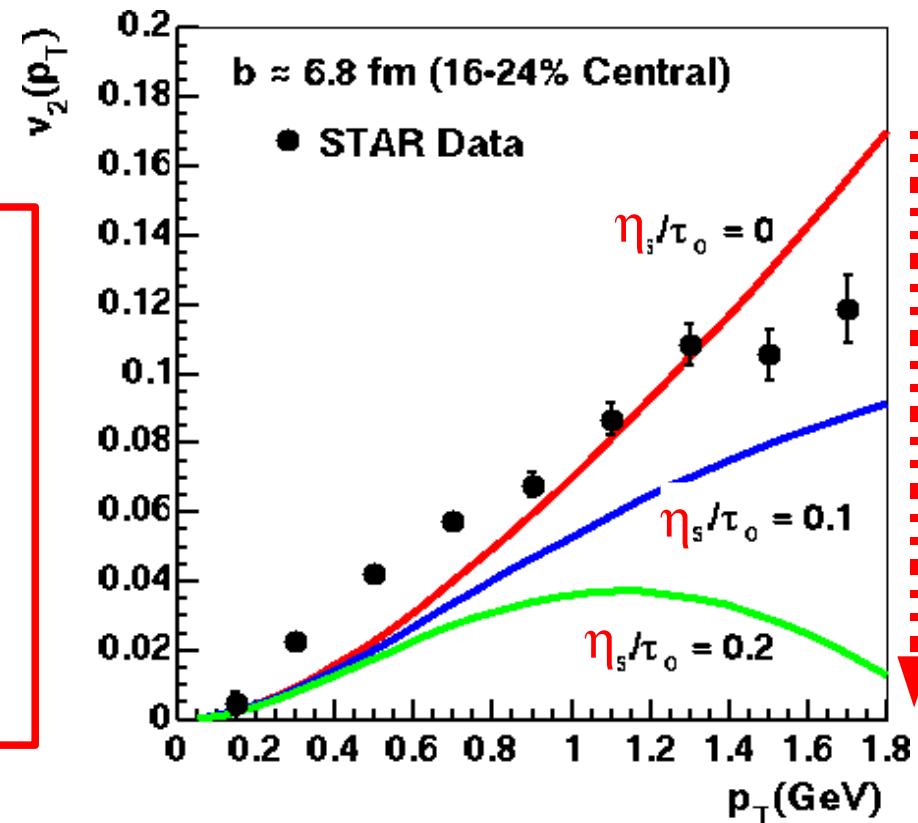
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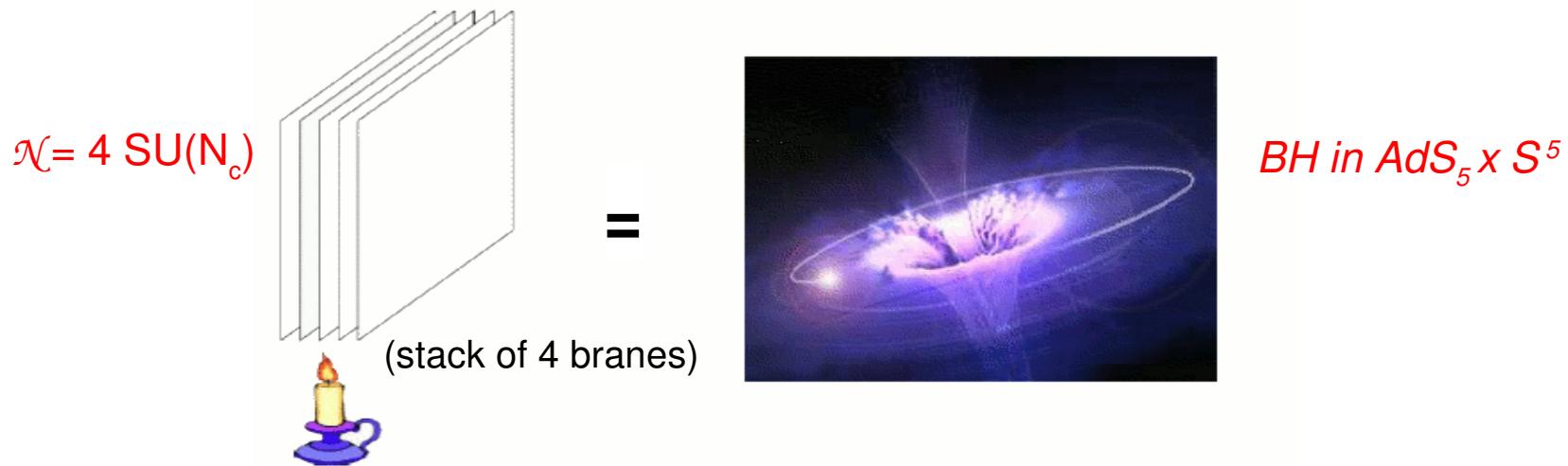
$P = P(\varepsilon, n) \rightarrow$  latt. QCD Equation-of-State



# SQGP: AdS/CFT correspondence

- Strongly-coupled theories (QCD-like) can be studied analytically solving equations-of-motion/thermodynamics in simpler 5-D gravity duals.

$$\mathcal{L} = \frac{1}{2g_{\text{YM}}^2} \text{Tr}(F_{\mu\nu}F^{\mu\nu}) + i\text{Tr}(\bar{\psi}\gamma^\mu D_\mu\psi) \quad \longleftrightarrow \quad ds^2 = \frac{r^2}{R^2}(-dt^2 + d\vec{x}^2) + \frac{R^2}{r^2}d\Omega_5^2$$



Duality relation between couplings:  $g_{\text{SYM}}^2 = 4\pi g_{\text{st}}$      $g_{\text{SYM}}^2 N_c = \left(\frac{R}{l_{\text{st}}}\right)^4$

- Key point: find the “dictionary” that relates both sides of duality for a given observable e.g.: Hawking T  $\Leftrightarrow$  QGP T:  $T_H = r_0/4\pi R^2$

# sQGP: AdS/CFT applications

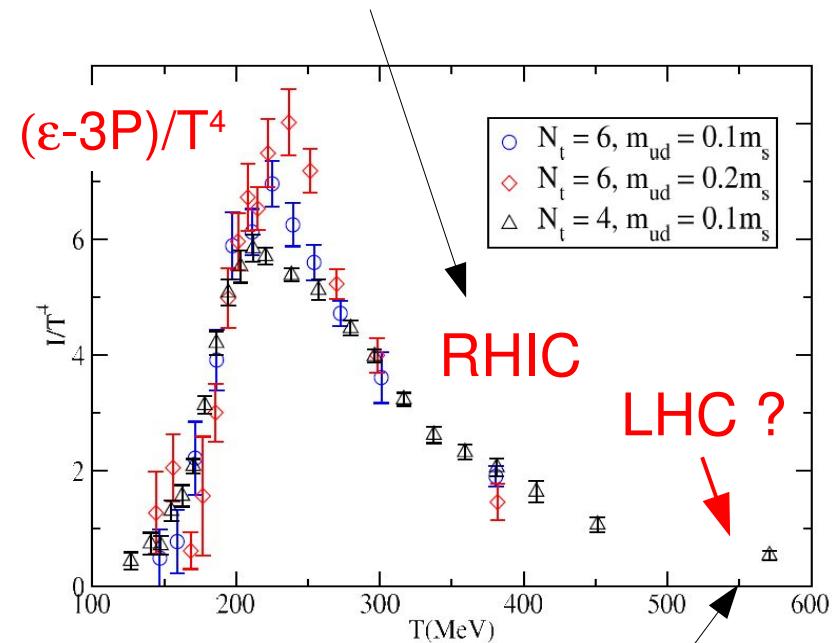
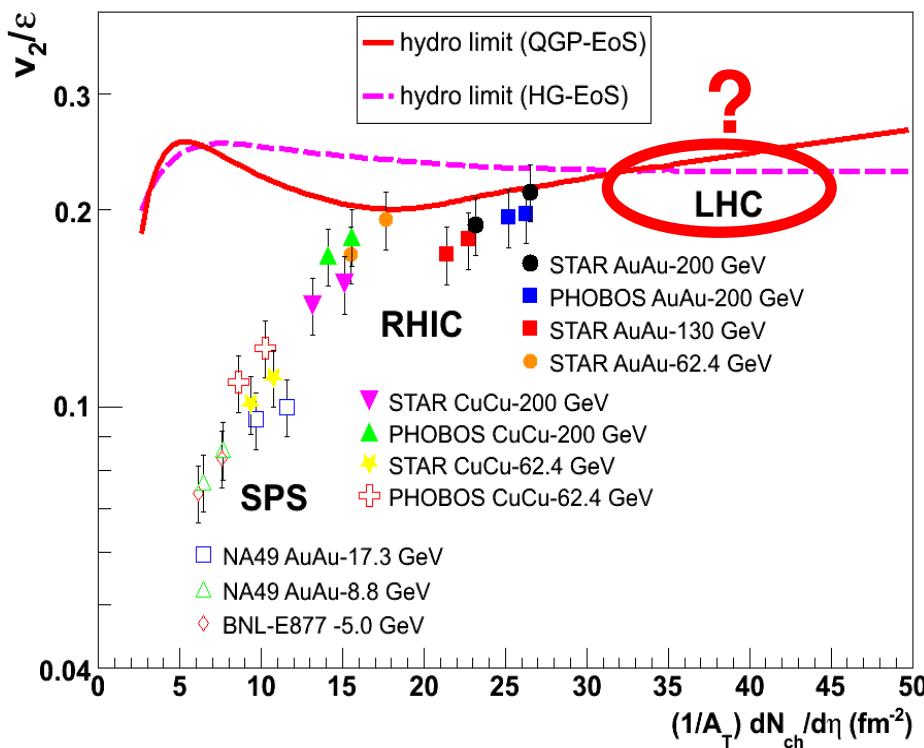
- AdS/CFT gives access to **dynamical (transport) QCD** quantities.
- Large **differences** (degrees of freedom, conformality, ...) **between** QCD & SYM “wash out” at finite-temperature:
  - Universal shear **viscosity  $\eta$  bound** ( $\sim \sigma_{\text{abs}}$  of soft gravitons in BH):  $\eta/s > 1/4\pi$   
[Kovtun&Son&Starinets, PRL94:111601,2005]
  - **Quenching parameter  $\hat{q}$**  (Wilson loop from strings):  $\hat{q}_{\text{SYM}} \approx 26.69 \sqrt{\alpha_{\text{SYM}} N_c} T^3$   
[Liu&Rajagopal&Wiedemann, PRL97, 182301, 2006]
  - **Heavy-Q diffusion coefficient D** (Wilson loop from strings):  $D_{\text{SYM}} \simeq \frac{1.0}{2\pi T} \left( \frac{1.5}{\alpha_{\text{SYM}} N} \right)^{1/2}_{\text{pQCD}}$   
[Herzog, Gubser, Casalderrey-Solana, ...]
  - virtual/real  **$\gamma$  emission rates** (thermal spectral functions), ...  
[Kovtun, Teaney, ...]

# Elliptic flow at the LHC ?

## ■ Collective azimuthal anisotropy

( $v_2$  parameter) in Pb-Pb 5.5 TeV ?

◆ null-viscosity fluid as at RHIC ?  
 (⇒ AdS/QCD applicable)



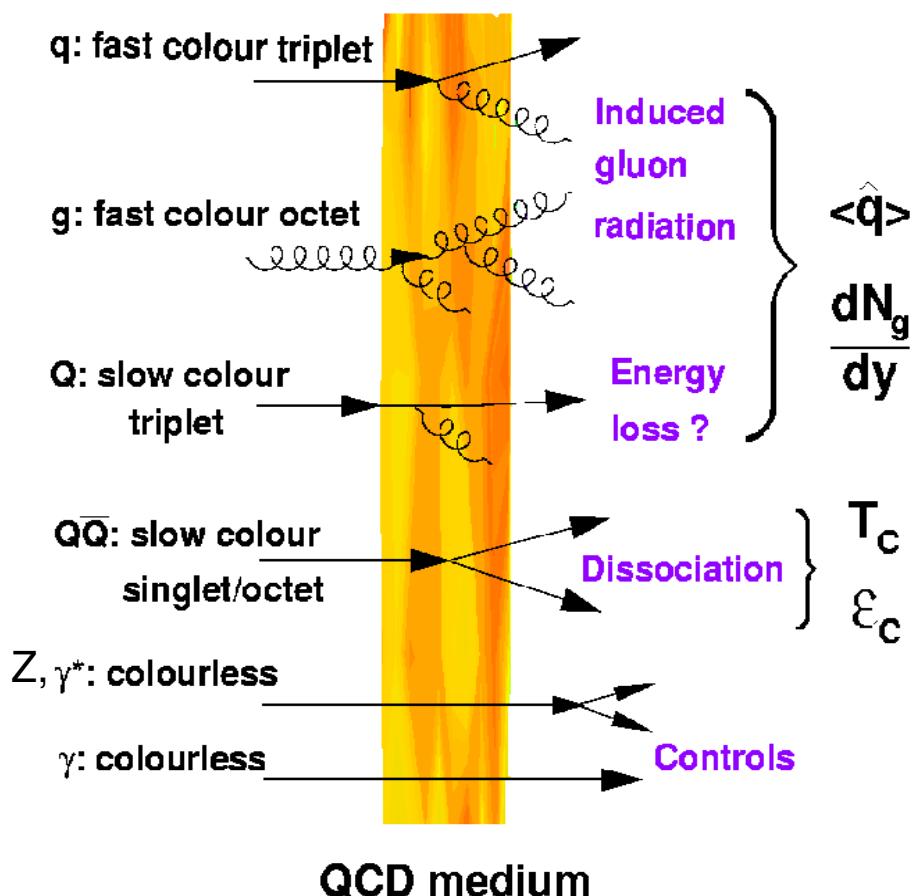
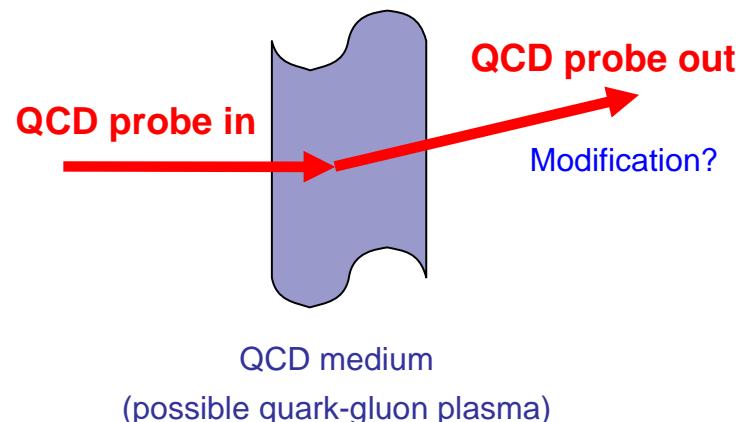
◆ weakly interacting (high viscosity)  
 quark-gluon “gas” (latt.-QCD) ?

# **Hard QGP probes**

# Hard tomographic probes of QCD matter

## ■ Hard-probes of QCD matter:

- ◆ jets,  $\gamma$ ,  $Q\bar{Q}$  ... well controlled experimentally & theoretically (pQCD).
- ◆ self-generated in collision at  $\tau < 1/Q \sim 0.1$  fm/c.
- ◆ tomographic probes of hottest & densest phases of medium.



# Nuclear modification factor

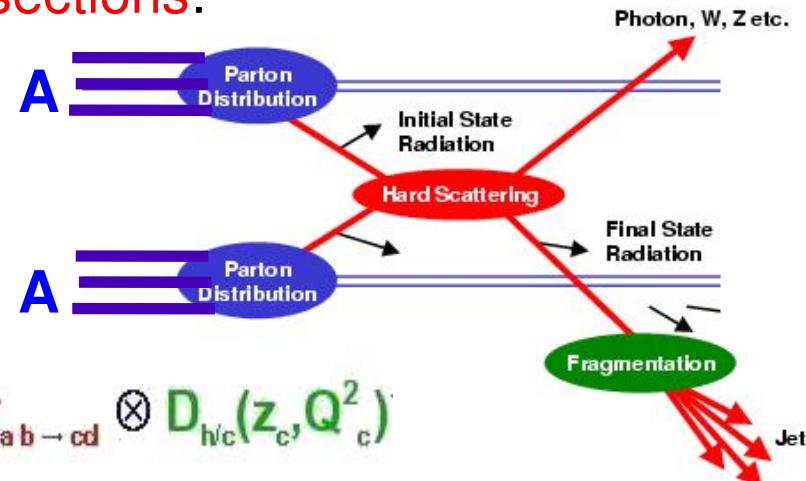
## ■ Factorization theorem for hard cross-sections:

A-A = superposition of p-p collisions

i.e. nuclear PDF = sum of “free” partons:

$$f_{a/A}(x, Q^2) = A f_{a/p}(x, Q^2)$$

$$d\sigma_{AB \rightarrow hX} = A^2 \cdot f_{a/A}(x_a, Q^2_a) \otimes f_{b/B}(x_b, Q^2_b) \otimes d\sigma_{ab \rightarrow cd} \otimes D_{h/c}(z_c, Q^2_c)$$

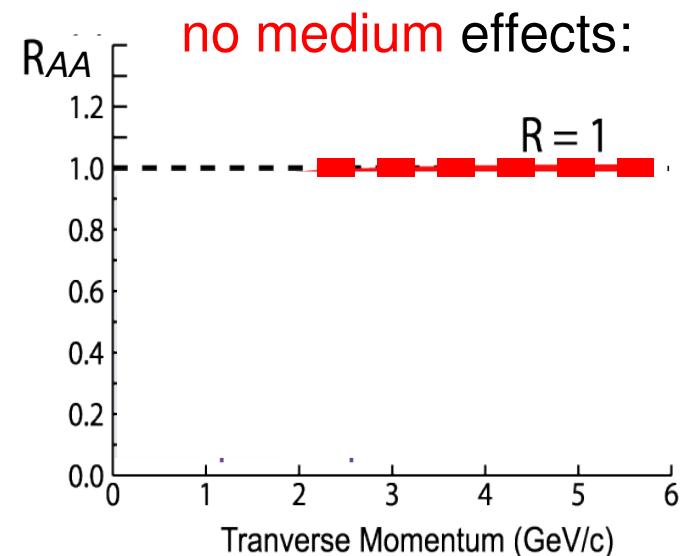


## ■ Nuclear modification factor:

$d\sigma(A-A)/d\sigma(p-p) \propto$  “QCD medium”/“QCD vacuum”

$$R_{AA}(p_T) = \frac{d^2 N_{AA} / dy dp_T}{\langle N_{coll}(b) \rangle \times d^2 N_{pp} / dy dp_T}$$

Number of p-p collisions:  $\sim A^2$



# Nuclear modification factor

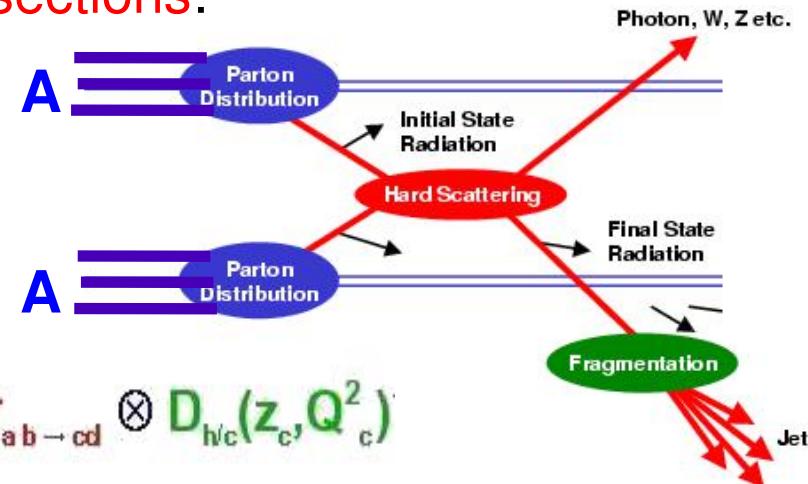
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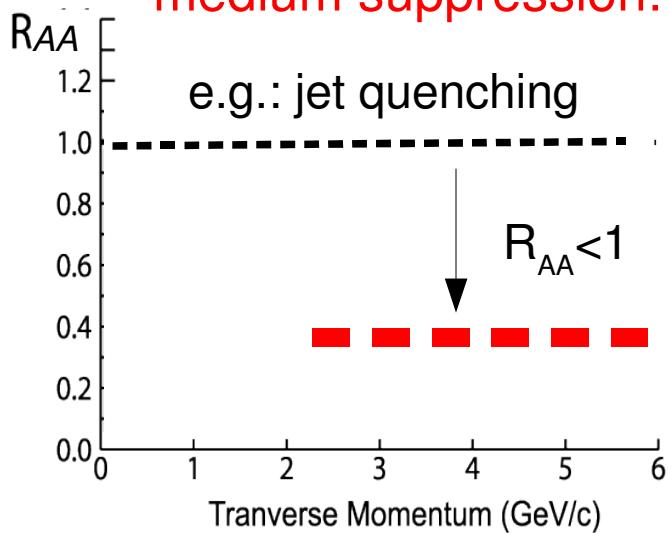
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Number of p-p collisions:  $\sim A^2$

medium suppression:

e.g.: jet quenching



# Nuclear modification factor

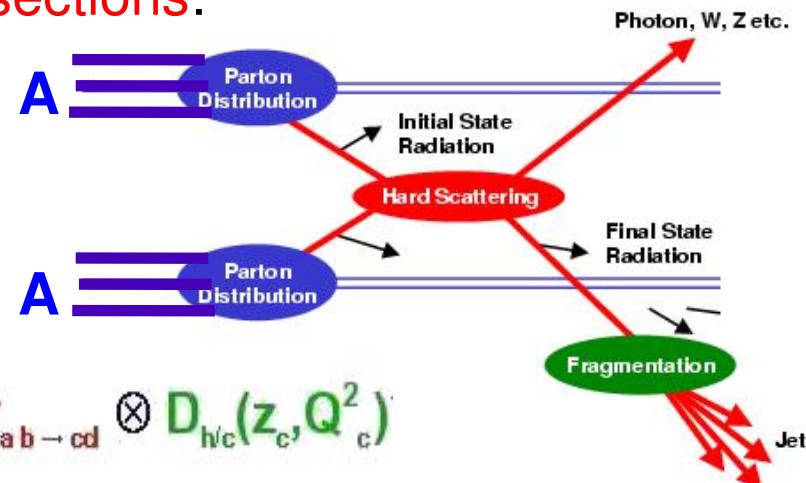
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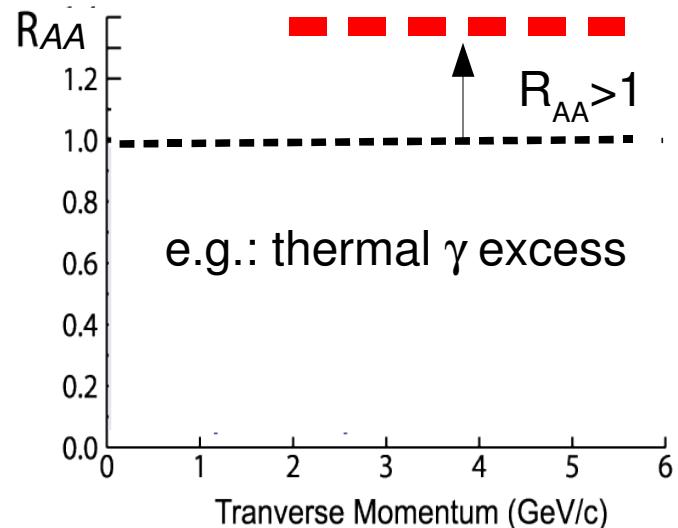
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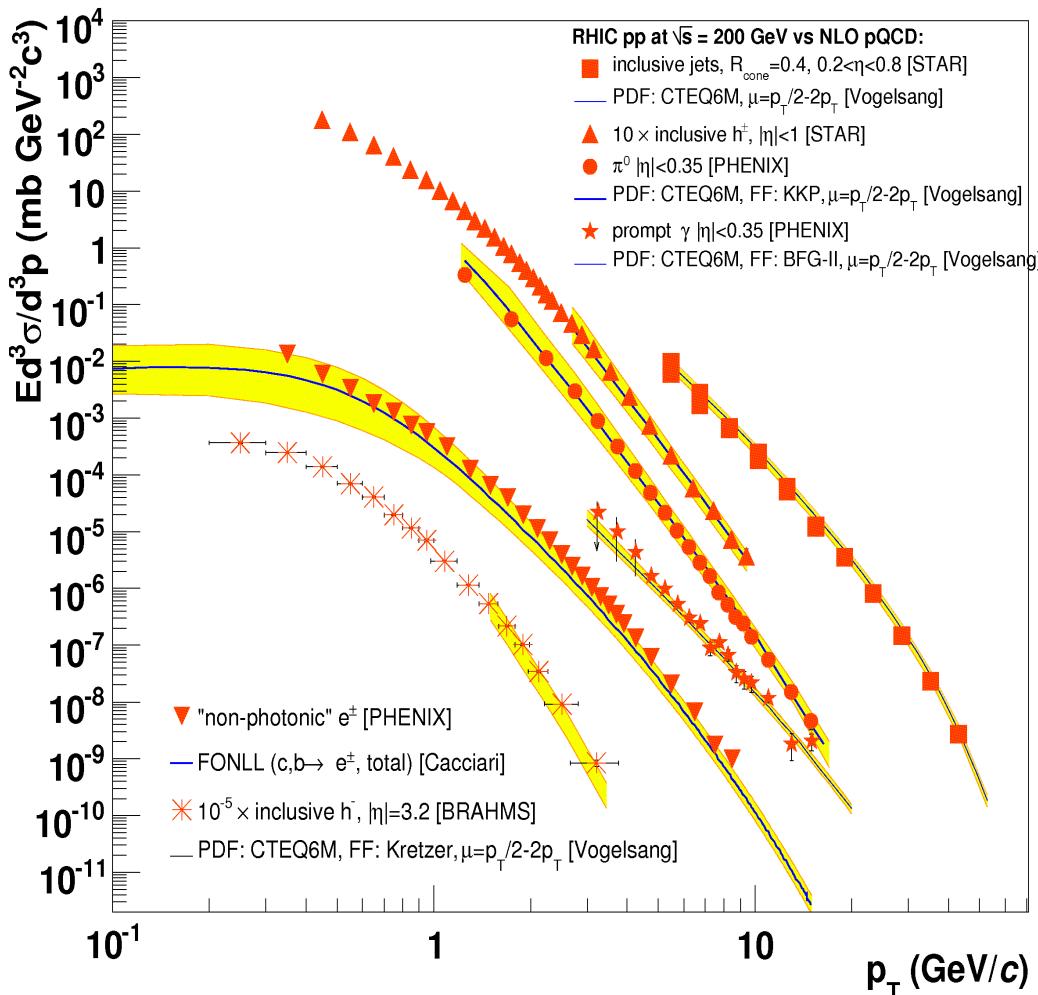
Number of p-p collisions:  $\sim A^2$

medium enhancement:



# Hard probes: p-p reference under control

- Jets, high- $p_T$  hadrons,  $\gamma$ , heavy-Q ... well controlled experimentally & theoretically (pQCD):

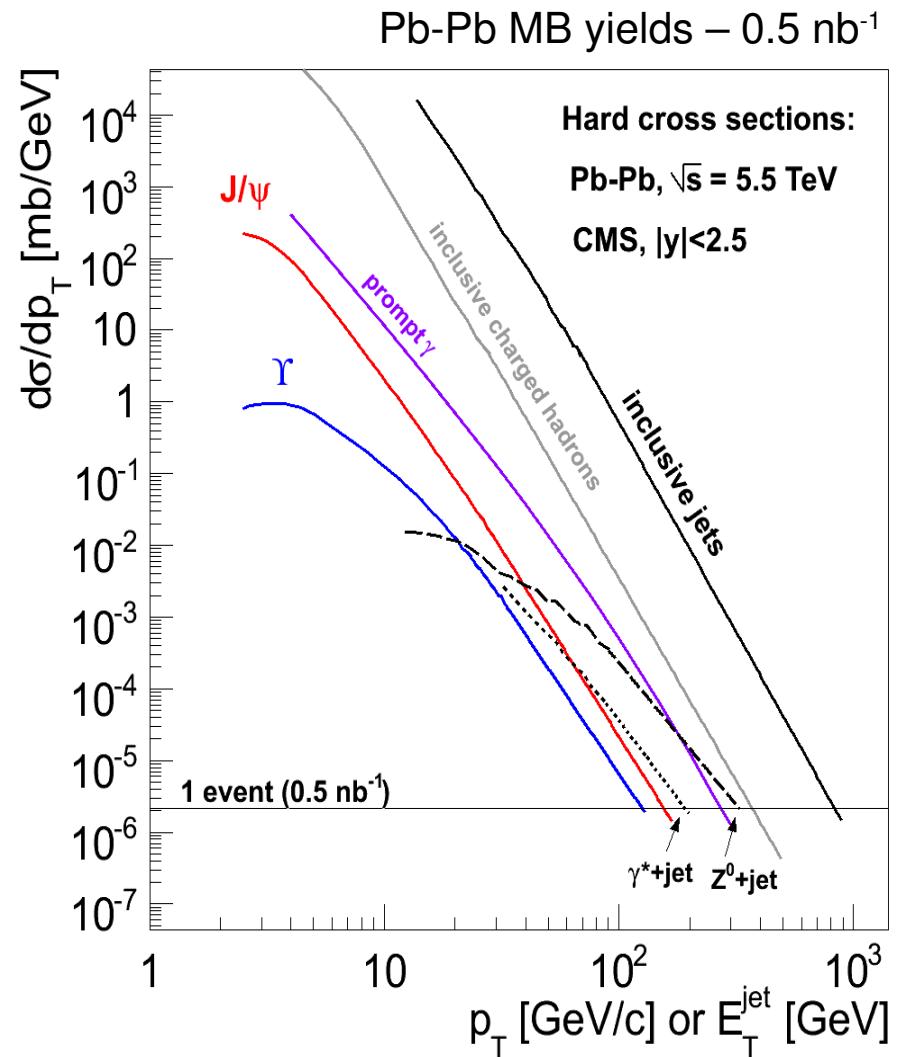
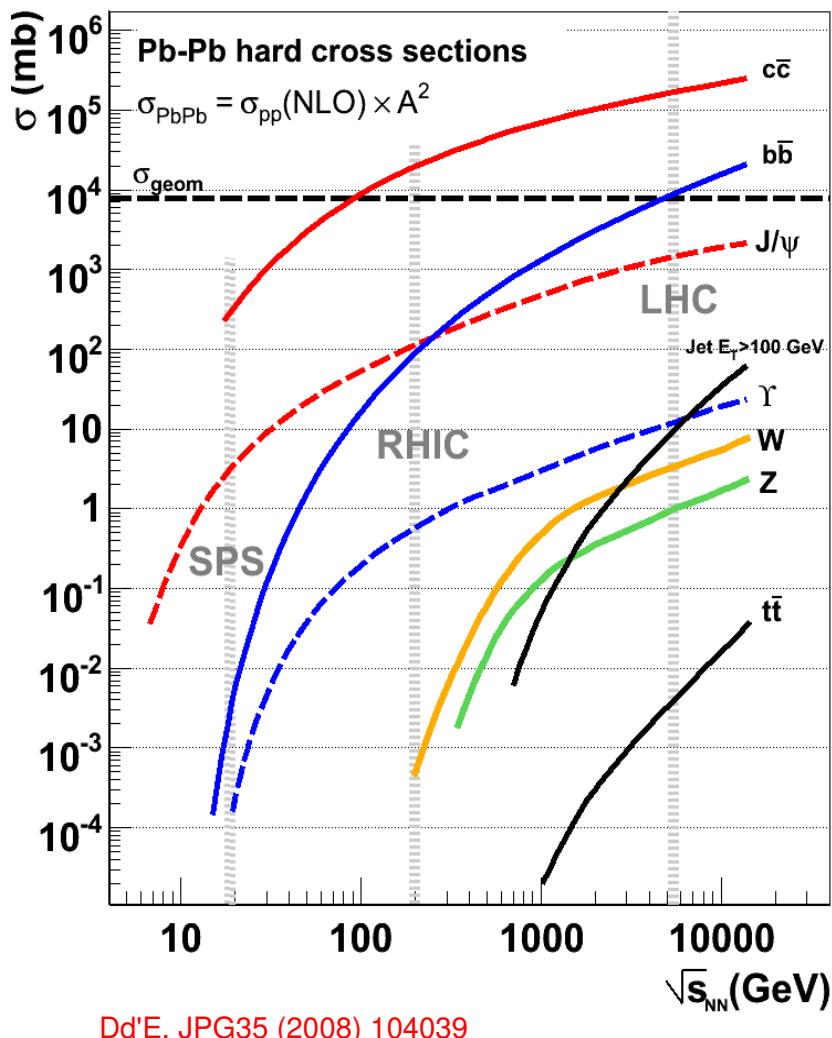


$p+p \Rightarrow X$ ,  $\sqrt{s}=200$  GeV  
NLO pQCD  
reproduces well  
all data

DdE, JPG34 (2007) S53-S81

# Hard probes cross-sections (RHIC,LHC)

- Large cross-sections (large stats.) at the LHC:



# **Hard QGP probes (I): “Jet quenching”**

# “Jet quenching” $\Rightarrow$ QGP density

- Hard partons lose energy by multiple non-Abelian (=gluon) radiation in the traversed **dense medium**
- Parton **energy loss**  $\propto$  medium properties:

$$\Delta E \propto \alpha_s^3 C_R \frac{1}{A_\perp} \frac{dN^g}{dy} L \propto (\text{gluon density})$$

$$\langle \Delta E \rangle \propto \alpha_s C_R \langle \hat{q} \rangle L^2 \propto (\text{transport coeffic.})$$

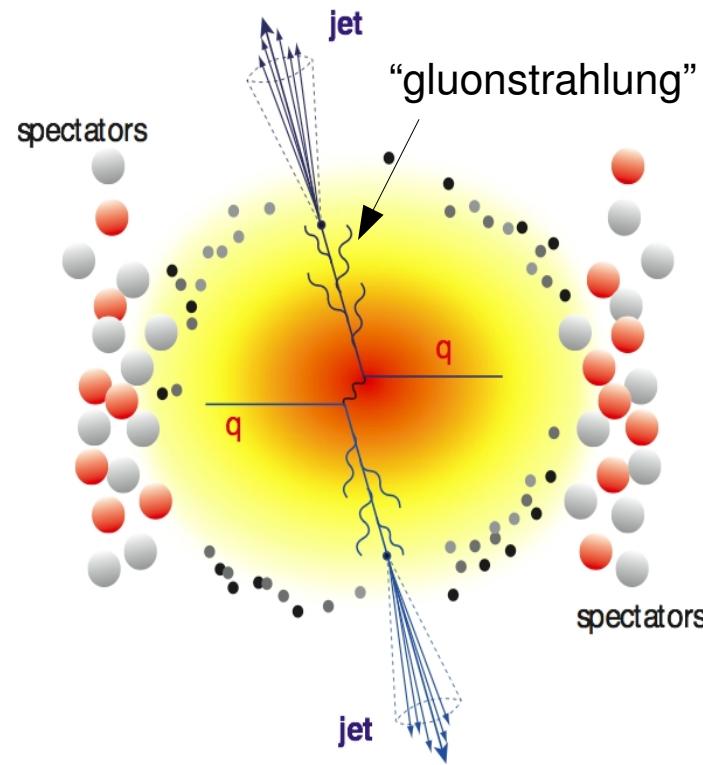
- Flavor-dependent energy loss:

$$\Delta E_{\text{loss}}(g) > \Delta E_{\text{loss}}(q) > \Delta E_{\text{loss}}(Q)$$

↑  
(color factor)      ↑  
(mass effect)

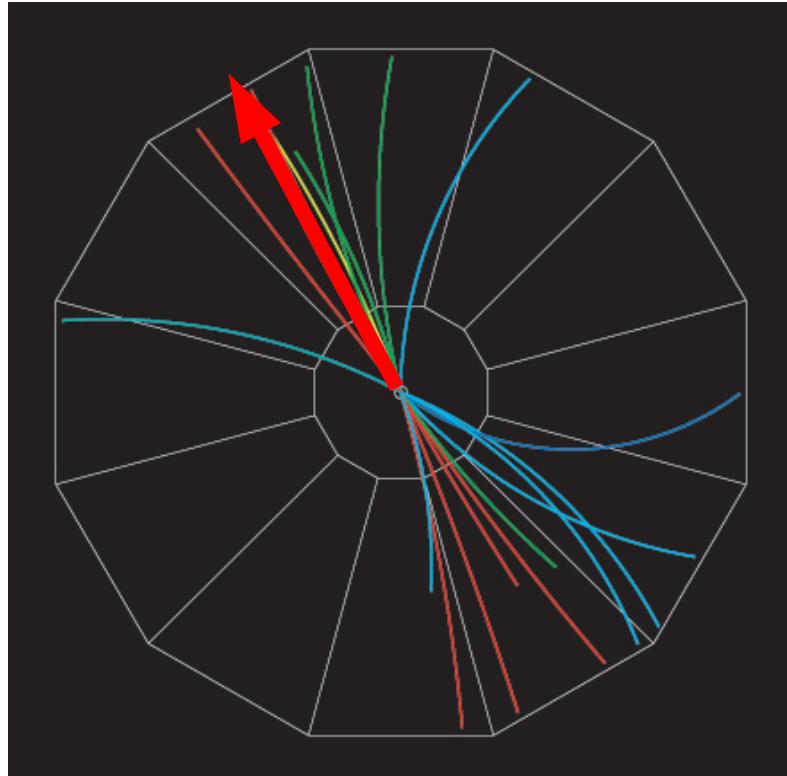
- Phenomenological implications:

- (1) **Suppression** of high  $p_T$  leading hadrons  $\rightarrow$  seen at RHIC
- (2) Disappearance of back-to-back **dijets** (“monojets”)  $\rightarrow$  seen @ RHIC
- (3) Modified energy/particle flow within jet (**modified FF**)  $\rightarrow$  seen(?) @ RHIC,LHC

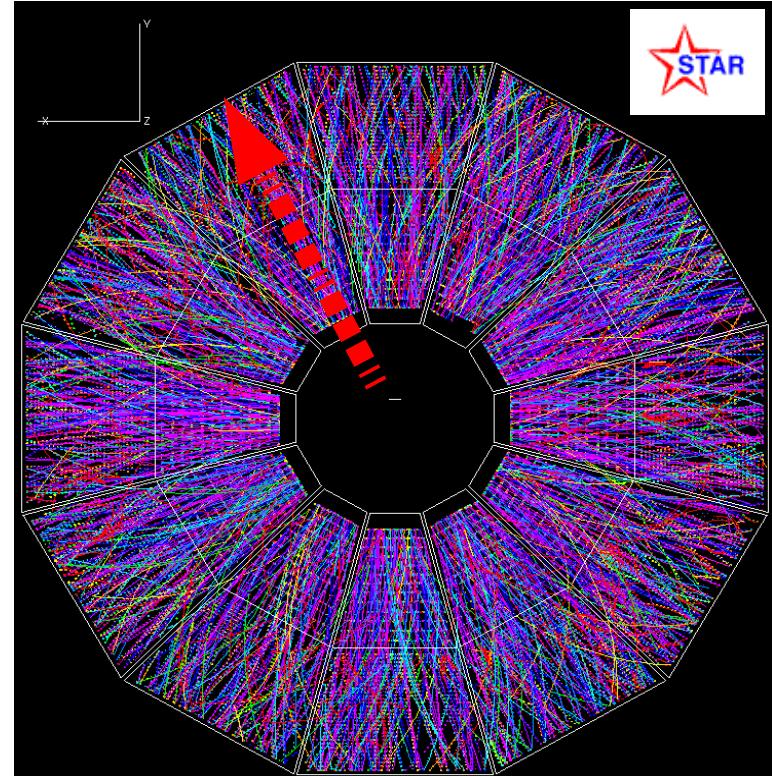


# Jet quenching in nucleus-nucleus collisions (I)

- Study **energy modifications** suffered by the highest  $p_T$  hadrons (“leading” hadron of the jet) in AA compared to pp:



$p+p \rightarrow \text{jet+jet}$  [ $\sqrt{s} = 200 \text{ GeV}$ ]



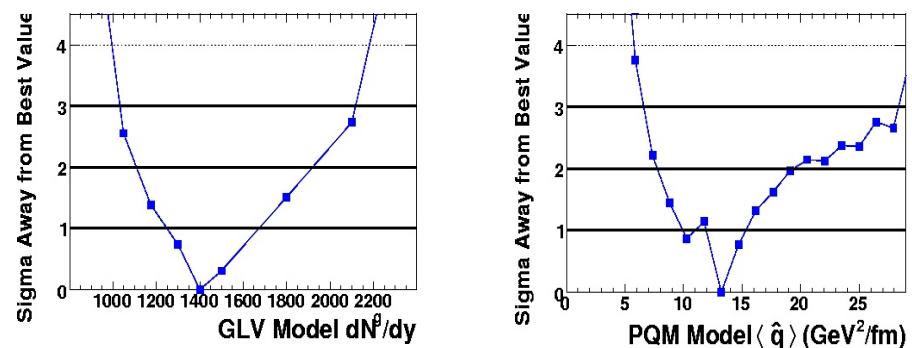
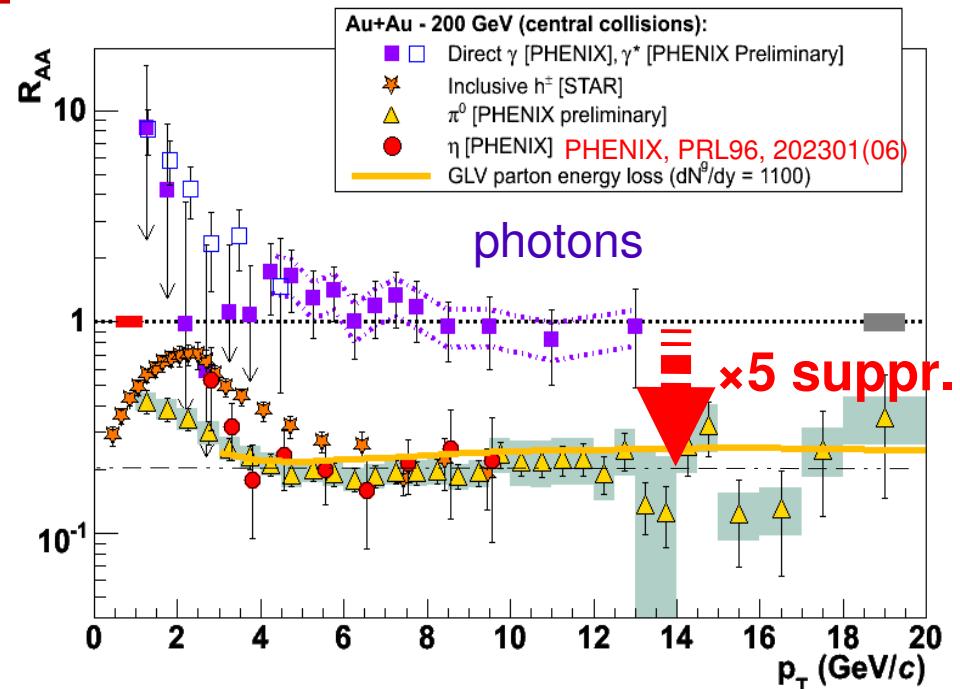
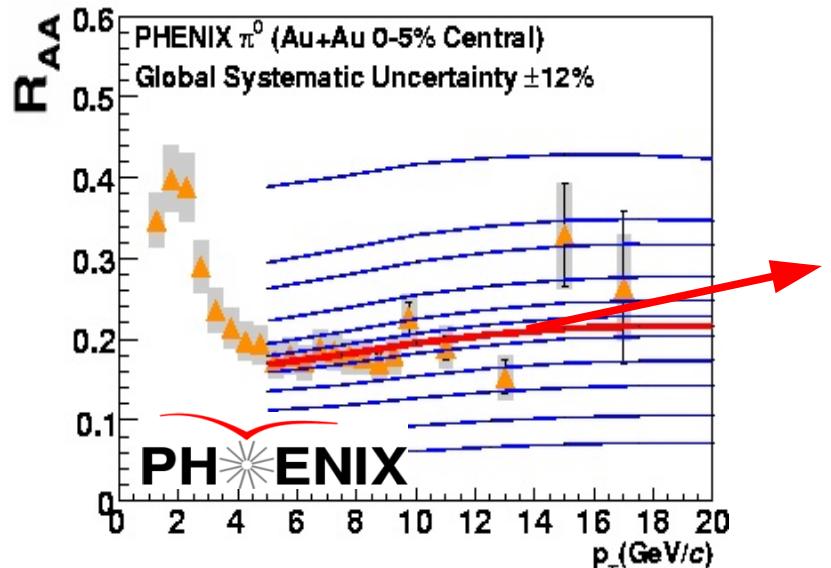
$\text{Au+Au} \rightarrow X$  [ $\sqrt{s_{NN}} = 200 \text{ GeV}$ ]

# High- $p_T$ leading hadron suppression (RHIC)

- High- $p_T$  hadrons suppressed.  
Photons unsuppressed !

$R_{AA}$  = "QCD medium"/"QCD vacuum"

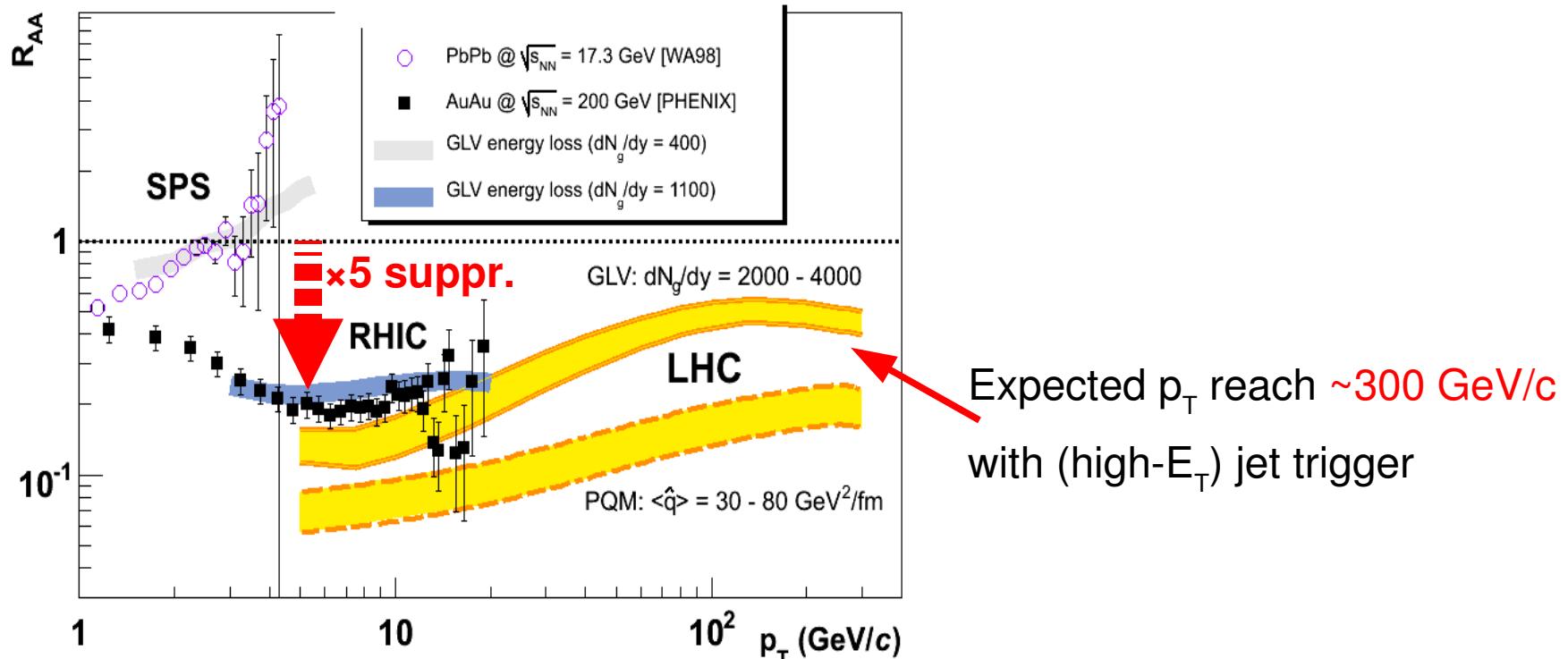
- Medium properties via model comparison:



Initial medium density:  $dN_g/dy \sim 1400$   
Transport coeffic.:  $\langle \hat{q} \rangle \sim 14$  GeV $^2$ /fm

# High- $p_T$ leading hadron suppression (LHC)

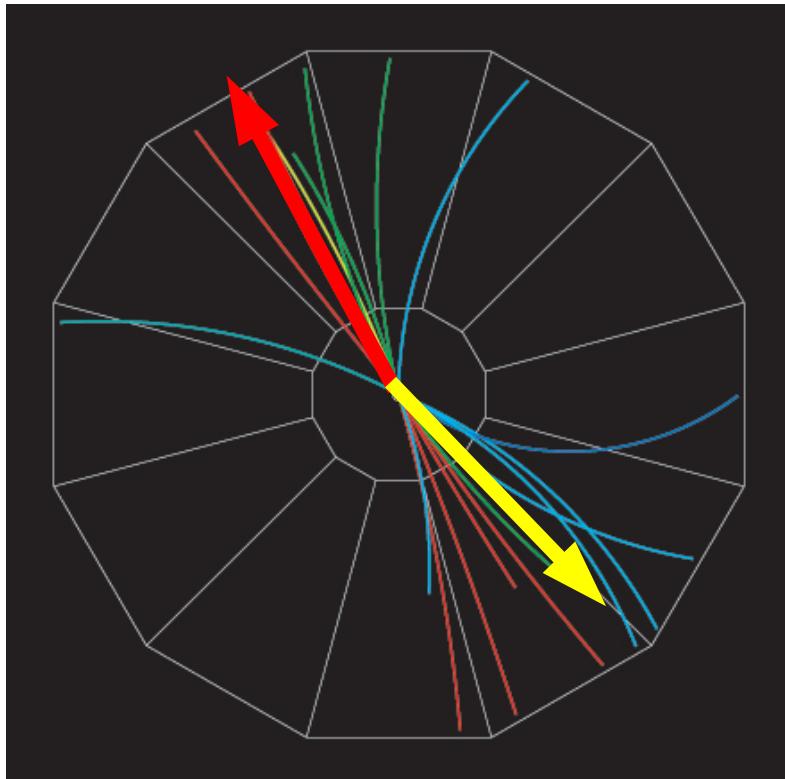
- Nuclear modification factor at the LHC:



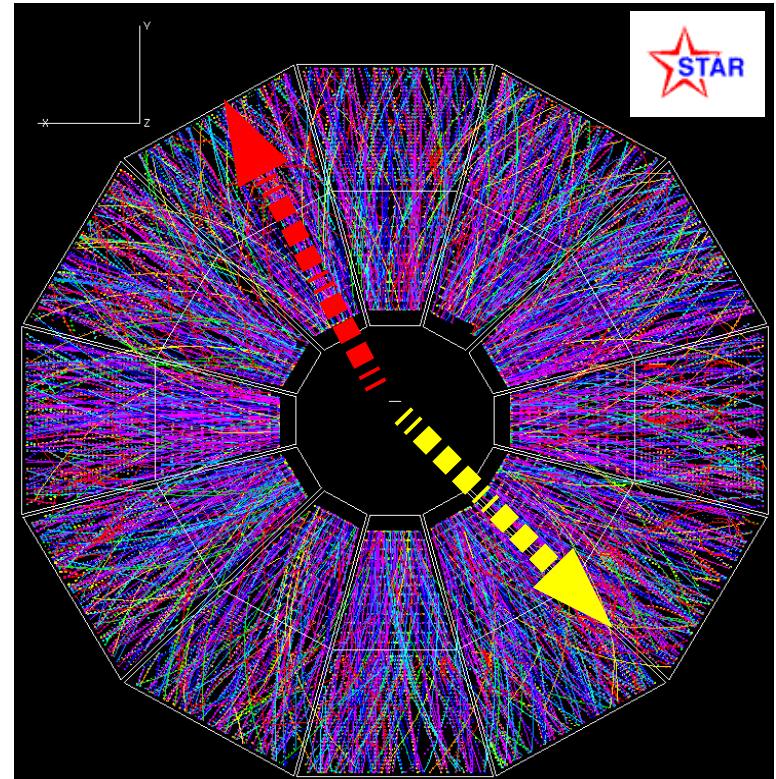
- Strong discrimination power for parton energy loss models:
  - Initial parton medium density:  $dN_g/dy \sim 2000-4000$
  - Medium transport coefficient:  $\langle \hat{q} \rangle \sim 10-100$  GeV $^2$ /fm

# Jet quenching in nucleus-nucleus collisions (II)

- Study the azimuthal correlations in A-A relative to p-p between highest  $p_T$  hadron (“trigger”) & any other “associated” hadron:



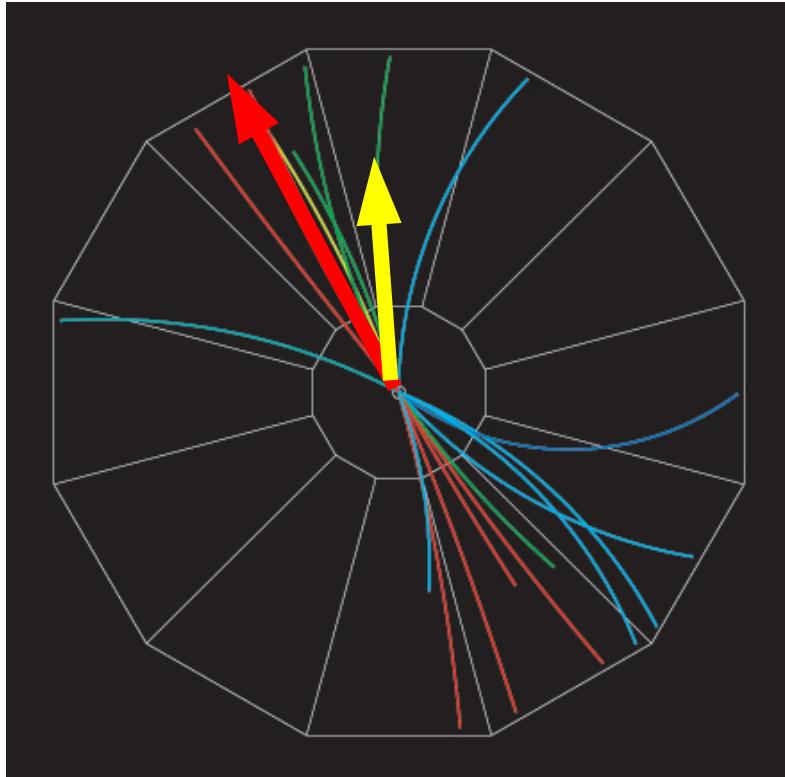
$p+p \rightarrow \text{jet+jet}$  [ $\sqrt{s} = 200 \text{ GeV}$ ]



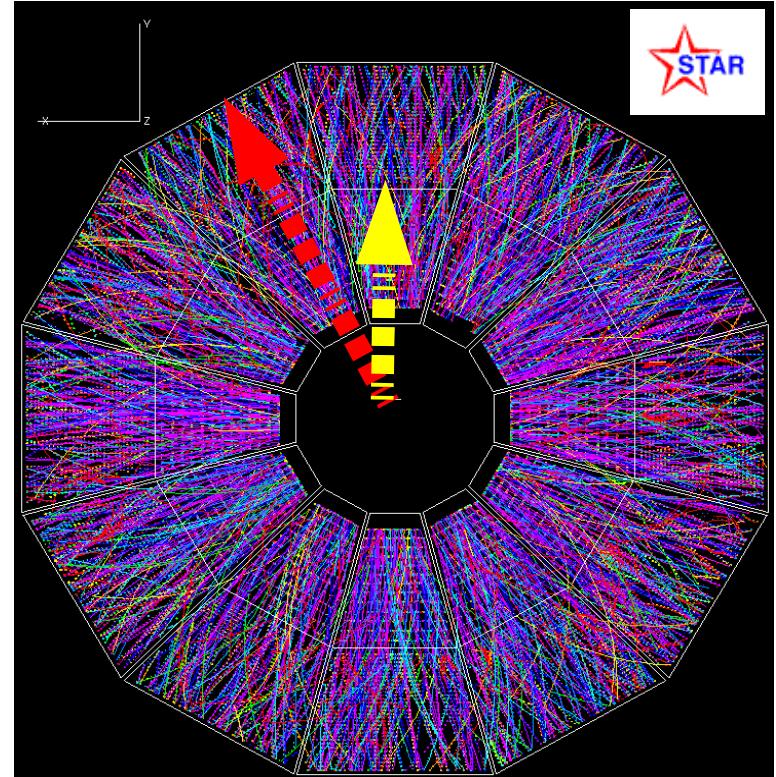
$\text{Au+Au} \rightarrow X$  [ $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$ ]

# Jet quenching in nucleus-nucleus collisions (II)

- Study the **azimuthal correlations** in A-A relative to p-p between highest  $p_T$  hadron (“trigger”) & any other “associated” hadron:



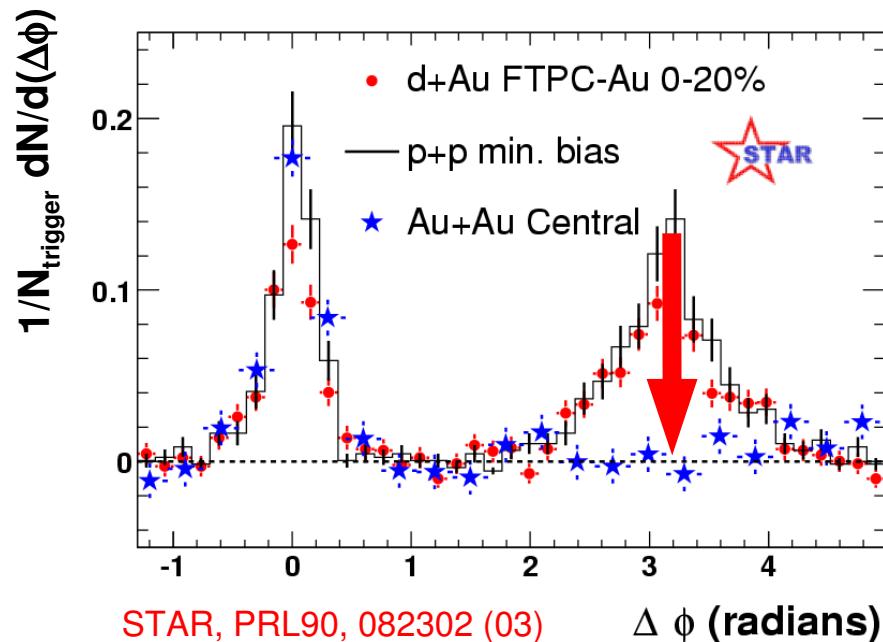
$p+p \rightarrow \text{jet+jet}$  [ $\sqrt{s} = 200 \text{ GeV}$ ]



$\text{Au+Au} \rightarrow X$  [ $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$ ]

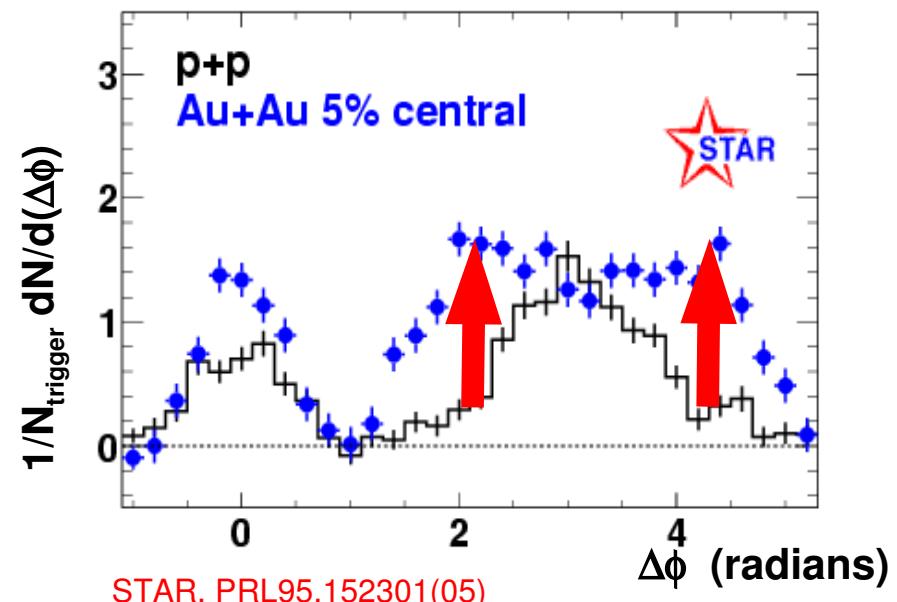
# Au-Au high- $p_T$ dihadron $\Delta\phi$ correlations (RHIC)

- Strongly modified away-side  $\Delta\phi$  correlations:
- Away-side peak disappears:  
“monojet”-like topology:
- “Jet remnants” reappear at lower  $p_T$   
as a broader/softened structure:



$$p_{T \text{trigg}} = 4 - 6 \text{ GeV}/c$$

$$p_{T \text{assoc}} > 2 \text{ GeV}/c$$



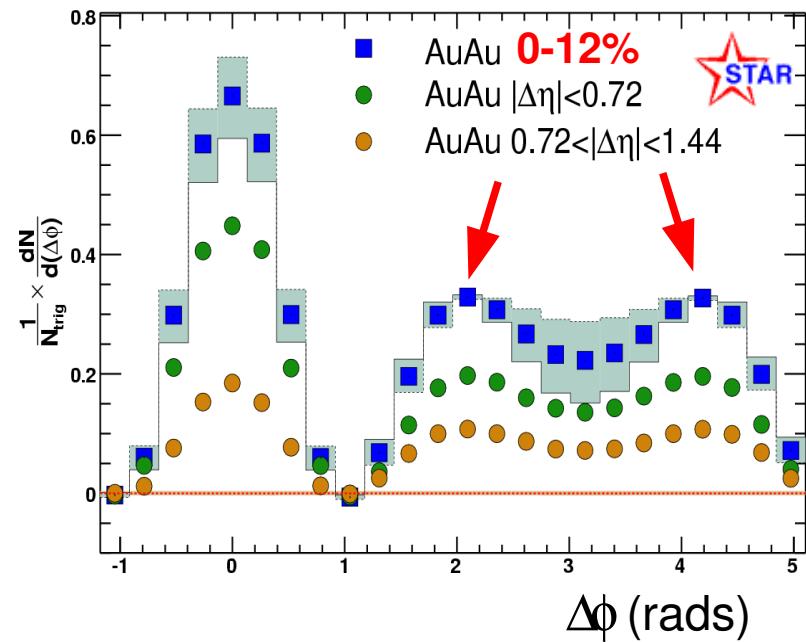
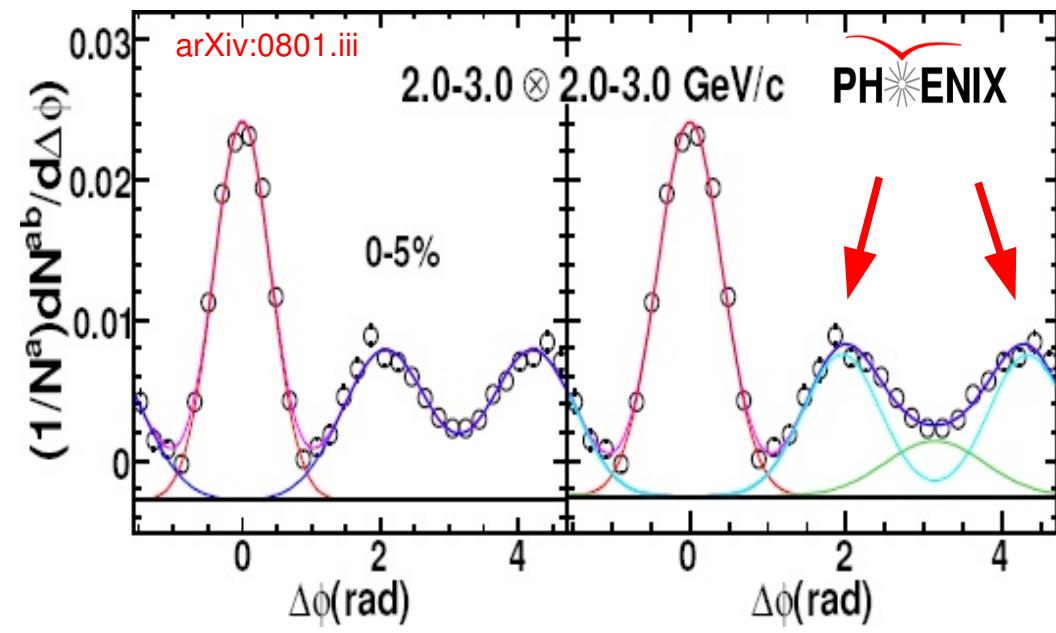
$$p_{T \text{trigg}} = 4 - 6 \text{ GeV}/c$$

$$p_{T \text{assoc}} = 0.15 - 4 \text{ GeV}/c$$

# Au-Au high- $p_T$ dihadron $\Delta\phi$ correlations (RHIC)

- Strongly modified away-side  $\Delta\phi$  correlations:
  - Away-side “dip” at  $\Delta\phi$
  - Excess of activity (“double peak”, “shoulders”)

at:  $\Delta\phi \pm 1.1$  rad



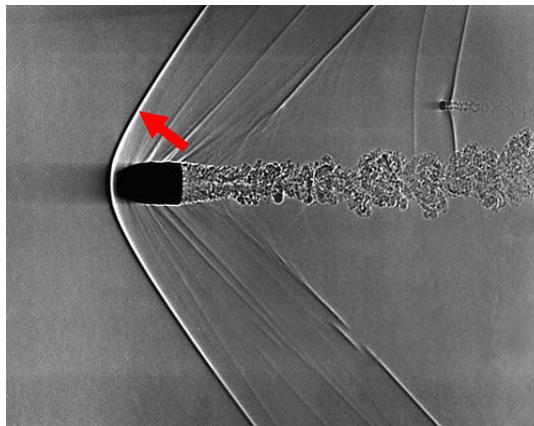
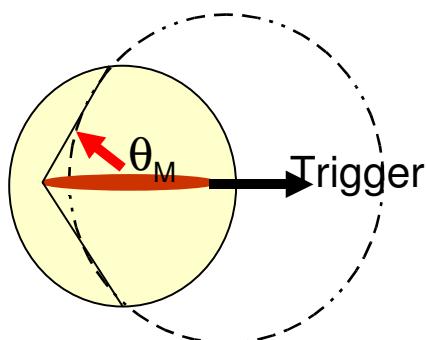
# Au-Au high-p<sub>T</sub> dihadron Δϕ correlations (RHIC)

- Strongly modified away-side Δϕ correlations:

Preferential angle at  $\Delta\phi \pm 1.1 \text{ rad}$

- Conical flow = Mach cone ?

- Cerenkov radiation ?



Quenched-jet generates a “shock-boom” while propagating supersonically ( $v > v_s$ ) through medium.

Speed-of-sound accessible from angle  $\theta_M$

$$\cos \theta_M = c_s$$

[hep-ph/0411315 Casalderrey, Shuryak, Teaney](#)

[nucl-th/0406018 Stoecker](#)

[hep-ph/0503158 Muller, Ruppert](#)

[nucl-th/0503028 A. K. Chaudhuri](#)

Quenched-jet radiates at fixed angle when traversing the medium at  $v > c$ .

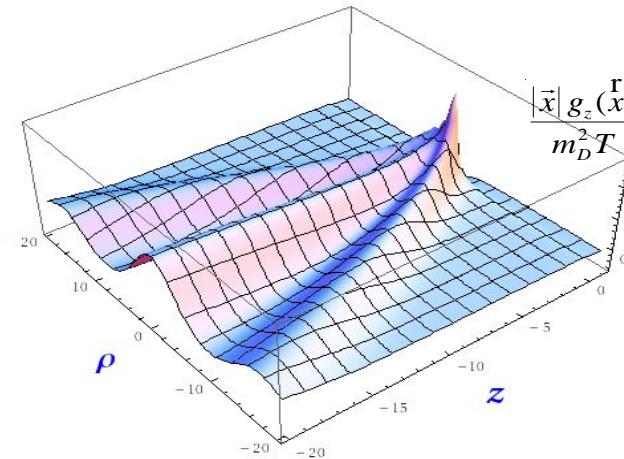
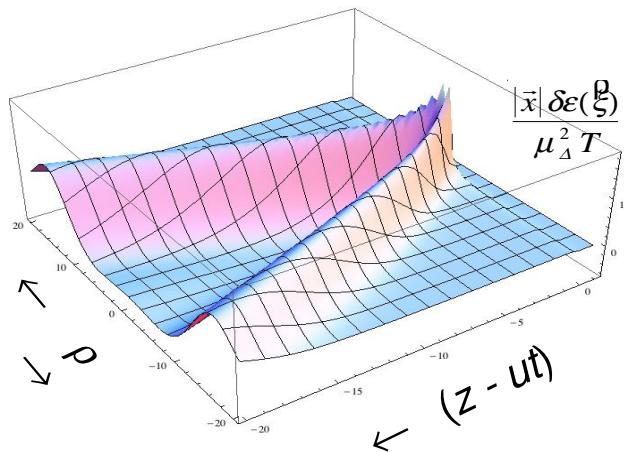
Gluon **dielectric coefficient** accessible:

$$\cos(\theta_c) \approx \frac{1}{\sqrt{\epsilon}} \approx \frac{1}{n}$$

I. Dremin;  
V. Koch,  
A. Majumder,  
X-N. Wang  
[nucl-th/0507063](#)  
David d'Enterria (MIT)

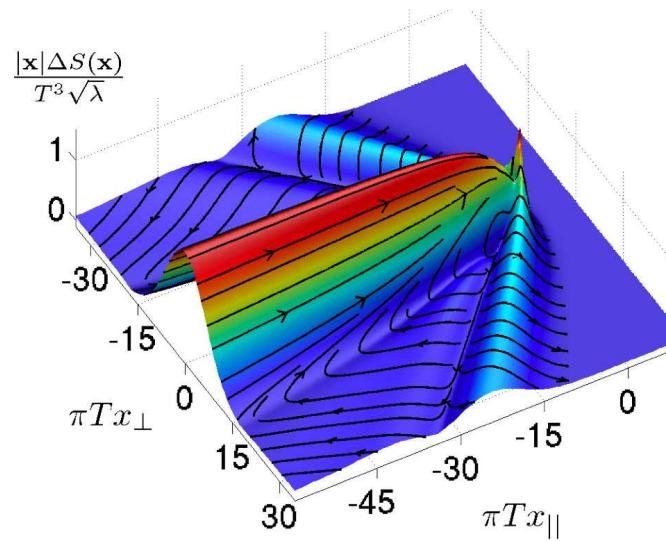
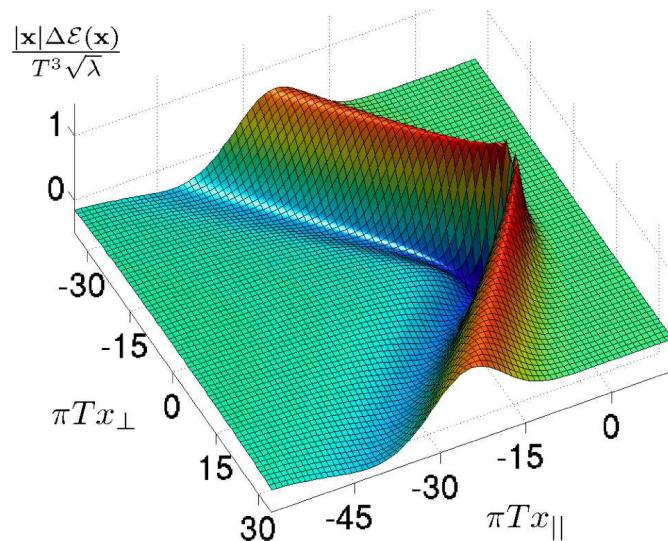
# “Mach cone”: supersonic parton in sQGP

pQCD vs. N=4 SYM



$$u = 0.99955 c$$

R.B. Neufeld  
(preliminary)

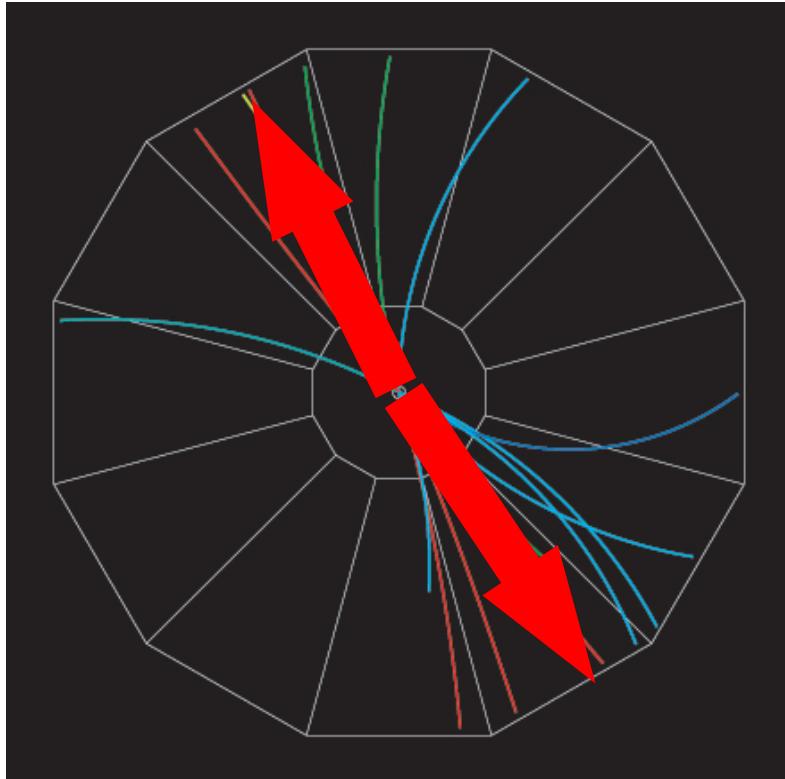


Chesler &  
Yaffe arXiv:  
0712.0050

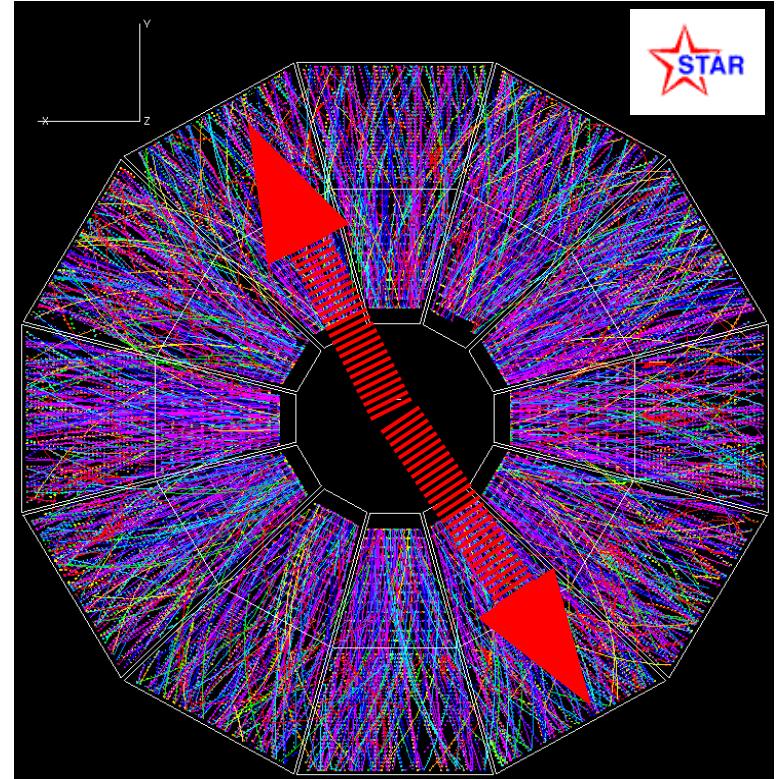
$$u = 0.75 c$$

# Jet quenching in nucleus-nucleus collisions (II)

- Full jet reconstruction:



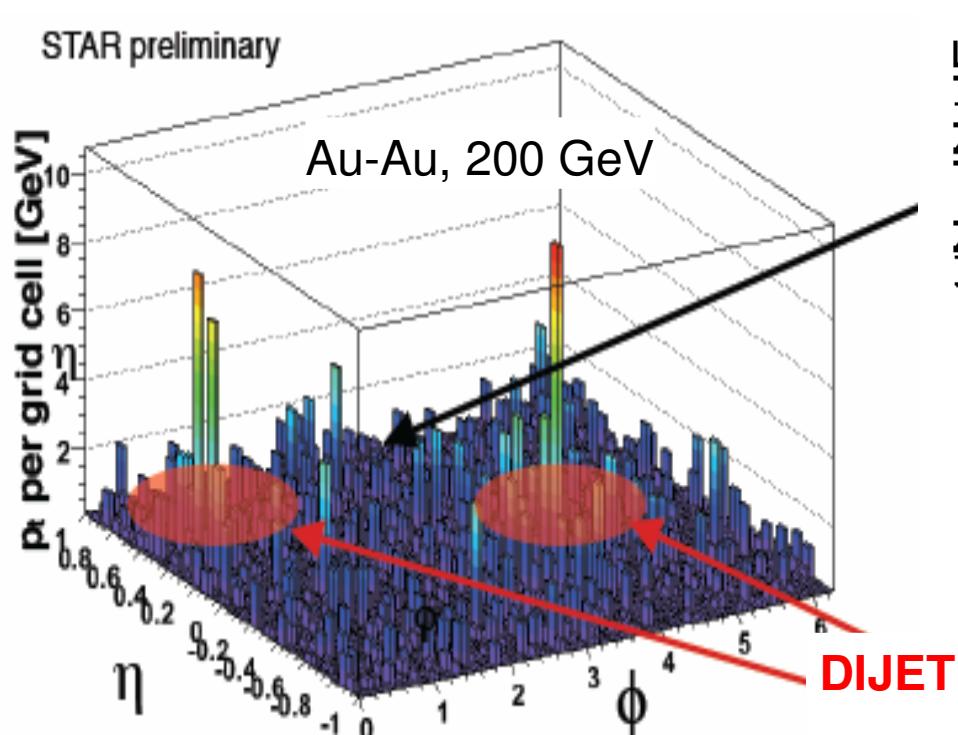
$p+p \rightarrow \text{jet+jet}$  [ $\sqrt{s} = 200$  GeV]



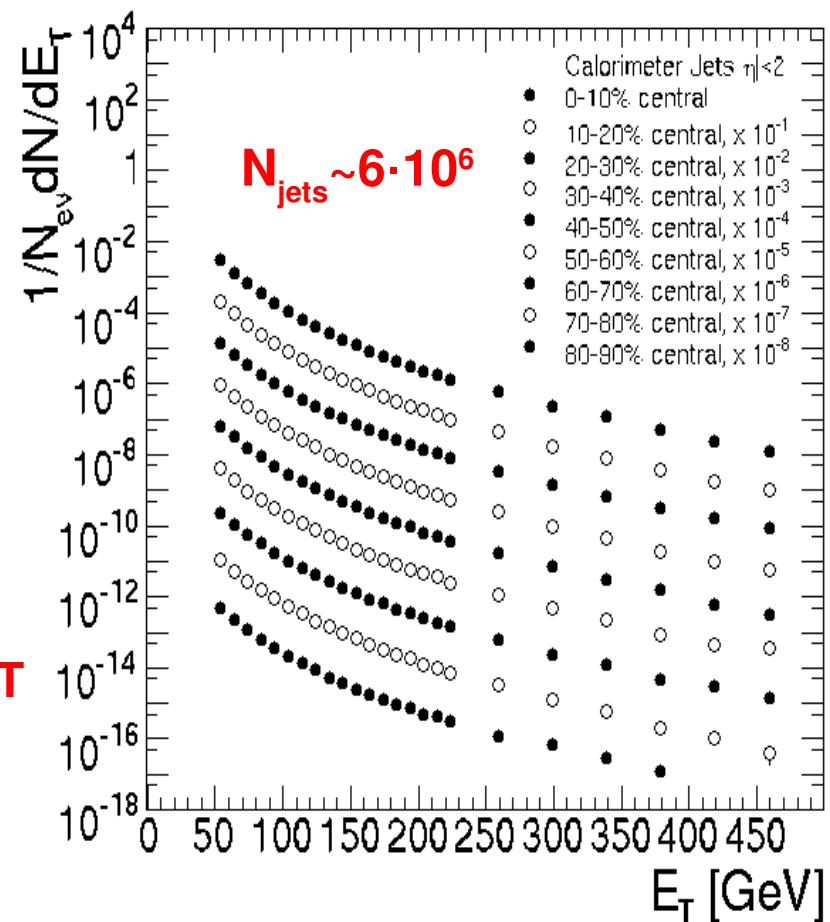
$\text{Au+Au} \rightarrow X$  [ $\sqrt{s_{\text{NN}}} = 200$  GeV]

# Full jet reconstruction in A-A (RHIC, LHC)

- RHIC: First jets measurements by STAR (Au-Au, 200GeV).
- LHC: jet spectra up to  $E_T \sim 0.5$  TeV (PbPb, 0.5 nb<sup>-1</sup>, HLT-triggered).



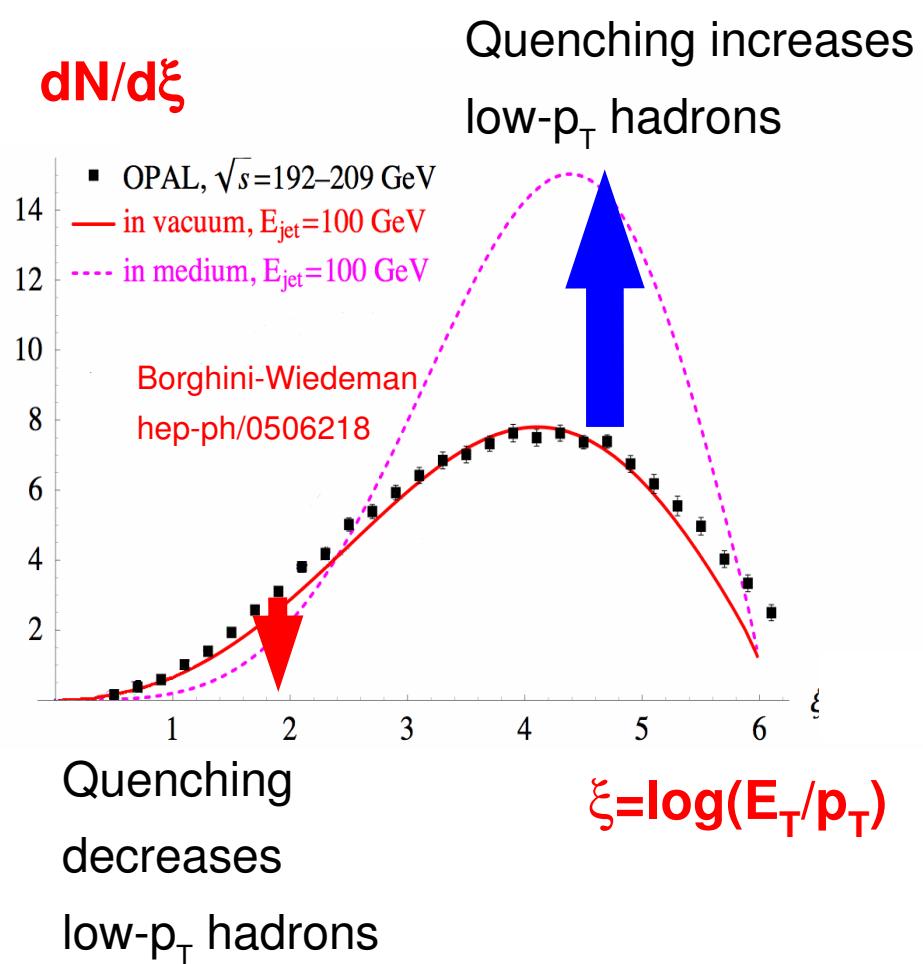
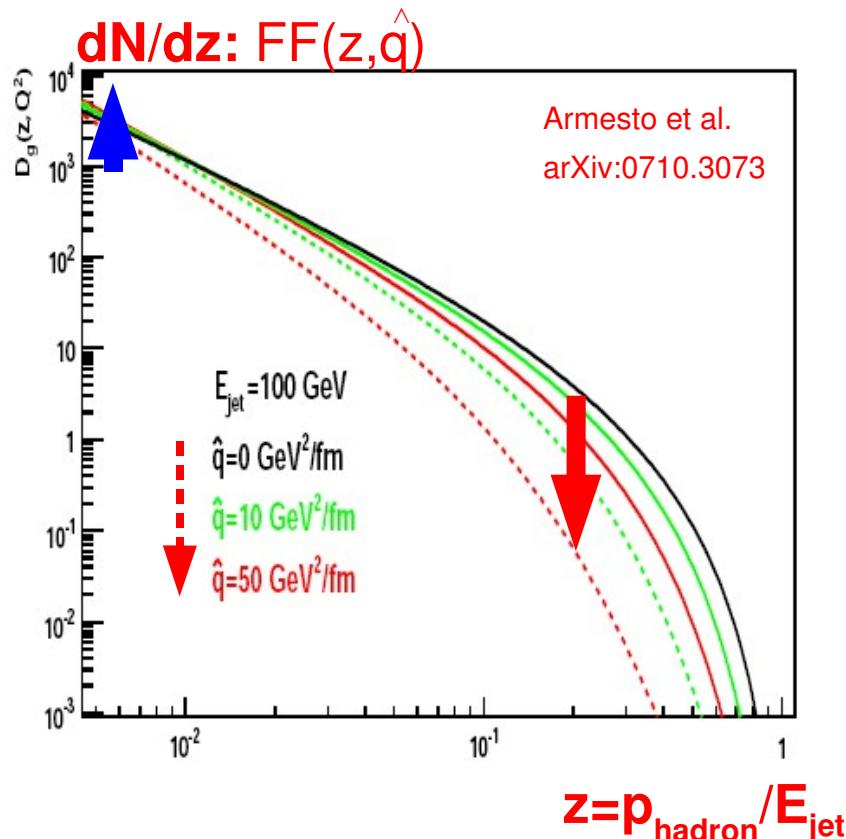
Jörn Putschke, BNL Theory Seminar, Sept. 2008



- Detailed studies of medium-modified (quenched) jet FF possible.

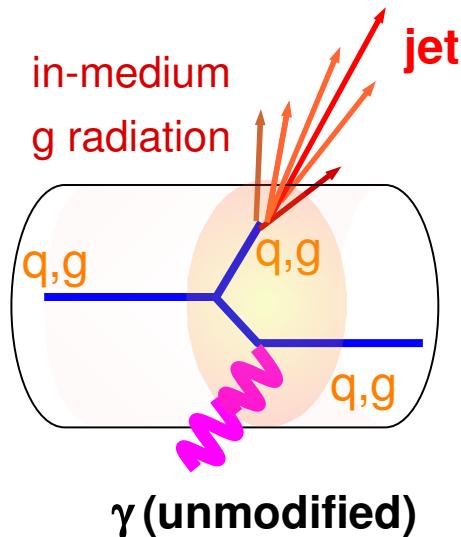
# Medium-modified Fragmentation Functions (FFs)

- “Jet quenching”: Radiative energy loss in a hot/dense QGP **shifts parton energy from high-z to low-z** hadrons: leading-hadron suppression.



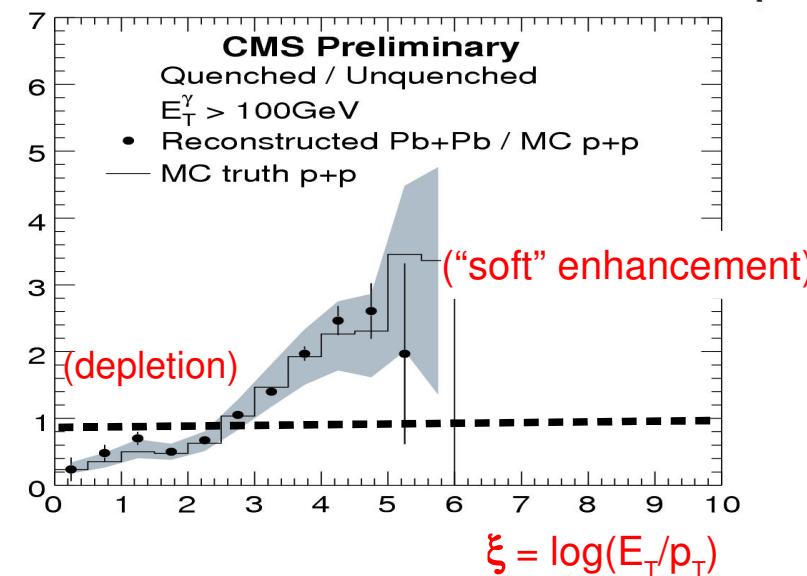
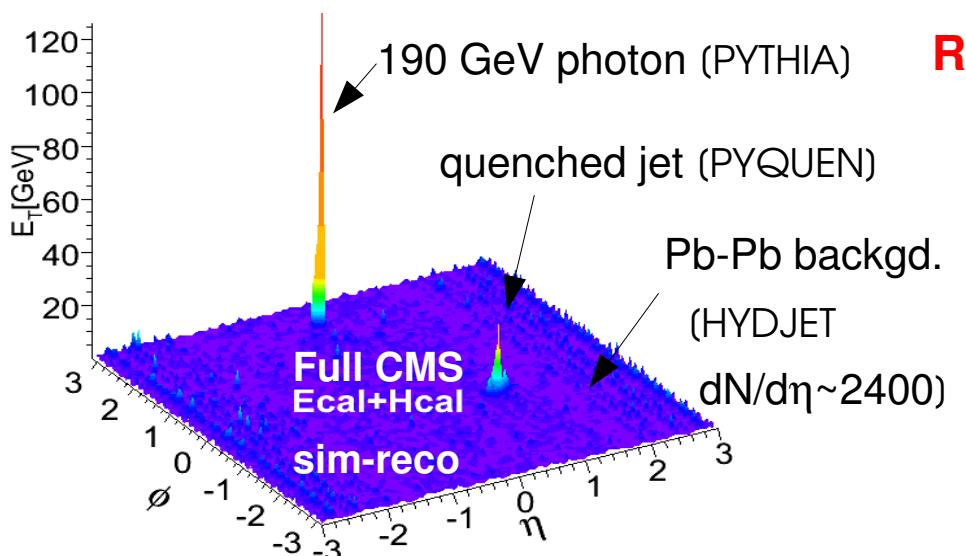
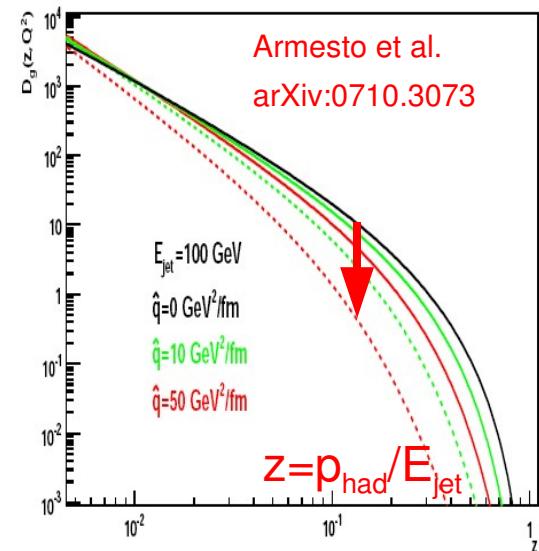
# $\gamma$ -jet, Z-jet (LHC)

■ Fragmentation Functions (FFs) via jet balanced with gauge bosons:



FFs depend on medium transport coefficient  $\hat{q}$ :

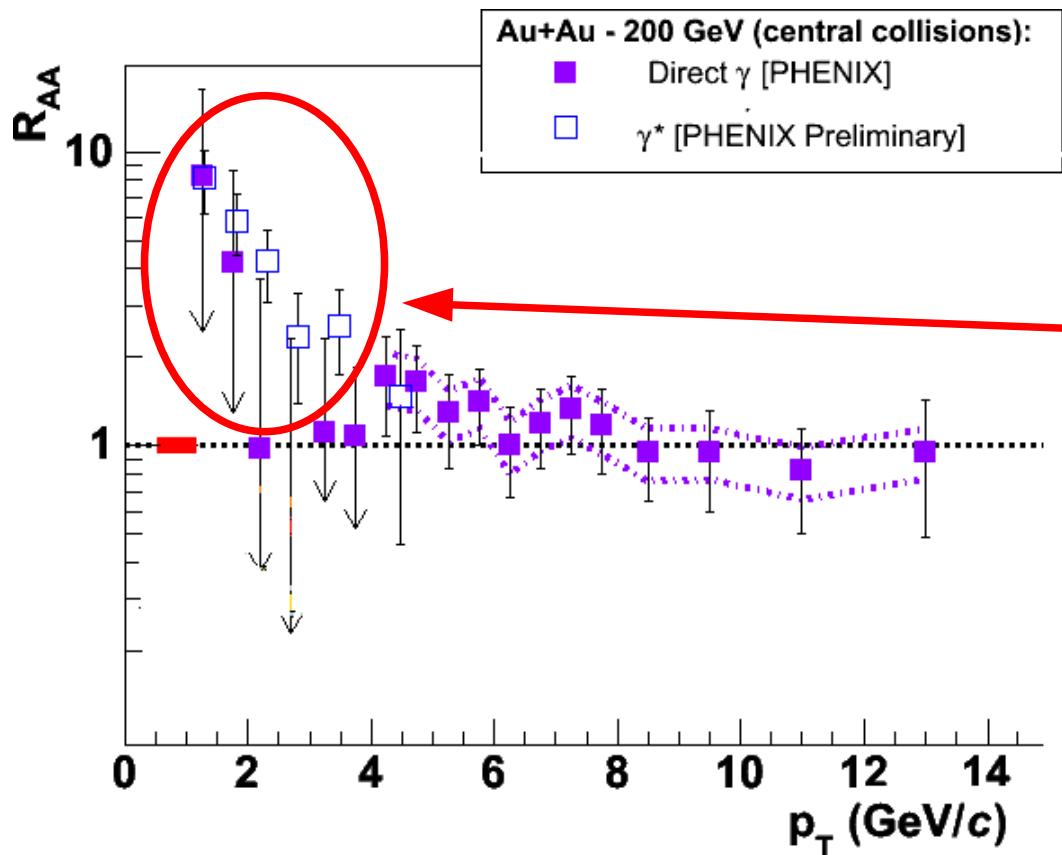
$$\text{FF}(z, \hat{q}): dN/dz, dN/d\xi$$



# **Hard QGP probes (II): Direct photons**

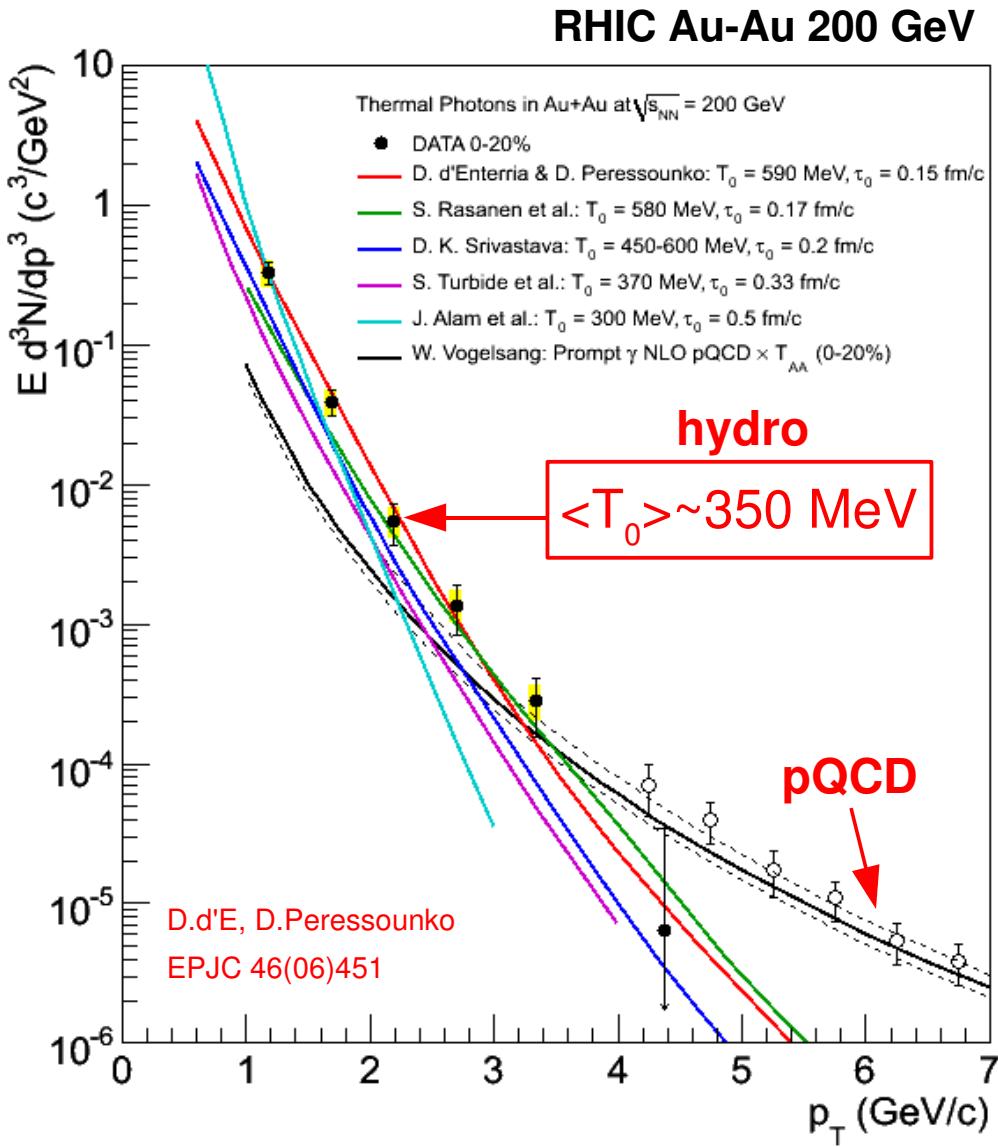
# Direct photon excess (RHIC)

RHIC Au-Au 200 GeV



- PHENIX observes extra direct- $\gamma$  production above p-p (pQCD) at  $p_T \sim 1-4$  GeV/c.

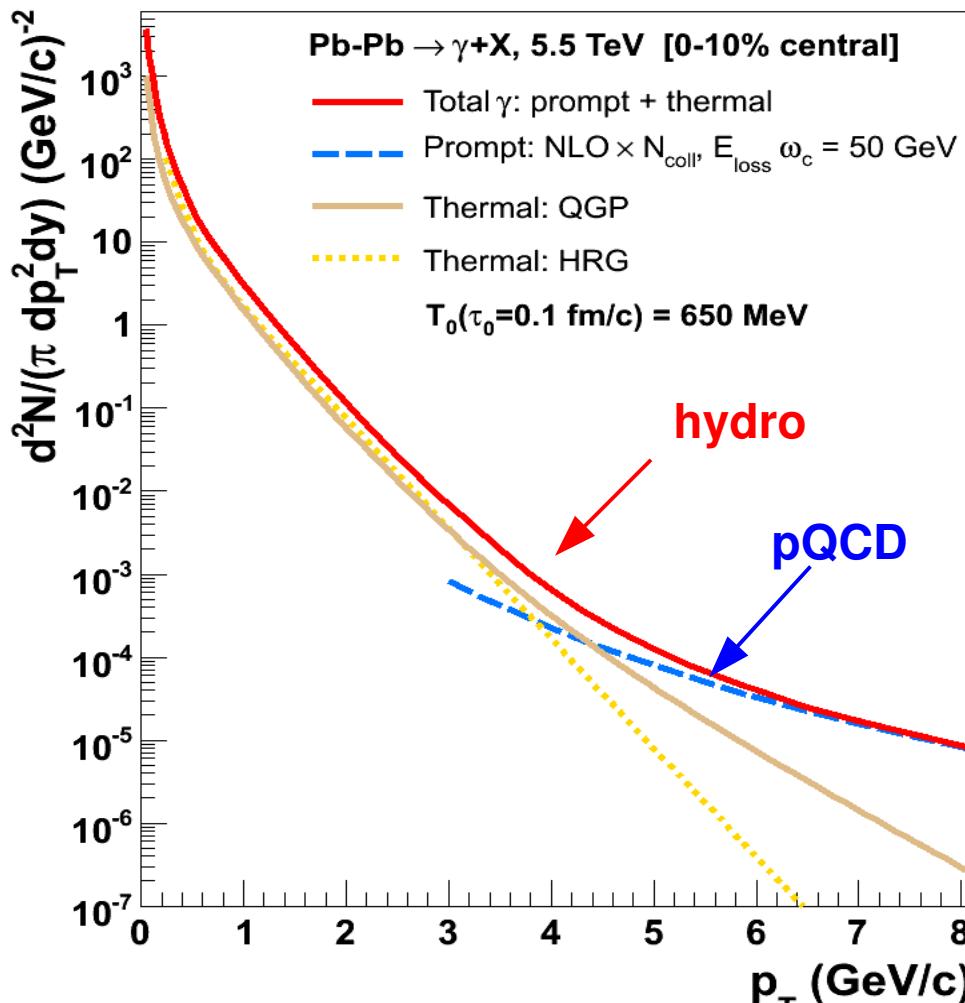
# Thermal photon radiation ? (RHIC)



- Hydrodynamical (thermal photons) models vs PHENIX  $\gamma$  excess:
  - D.d'E. & D.Peressounko  
 $T_0=590\text{MeV}$ ,  $\tau_0=0.15\text{fm/c}$
  - S. Rasanen et al.  
 $T_0=580\text{MeV}$ ,  $\tau_0=0.17\text{fm/c}$
  - D. K. Srivastava  
 $T_0=450\text{-}600\text{MeV}$ ,  $\tau_0=0.2\text{fm/c}$
  - S. Turbide et al.  
 $T_0=370\text{MeV}$ ,  $\tau_0=0.33\text{fm/c}$
  - J. Alam et al.  
 $T_0=300\text{MeV}$ ,  $\tau_0=0.5\text{fm/c}$
- All models require QGP radiating at temperatures  $T \sim 2 T_{\text{crit}}$ .

# Thermal+Prompt photon (LHC)

- Photon spectra: hydro + NLO pQCD predictions



Pb-Pb @ 5.5 TeV ( $\langle b \rangle \sim 3 \text{ fm}$ )

$$\varepsilon_0 \propto s_0^{-4} \sim 650 \text{ GeV/fm}^3$$

$$T_0 = 770 \text{ MeV} (\langle T_0 \rangle \sim 500 \text{ MeV})$$

$$\tau_0 = 0.1 \text{ fm}/c$$

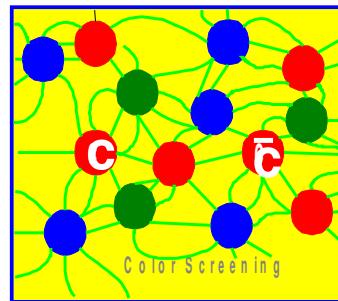
- Thermal photon radiation expected in range  $p_T \sim 1-5 \text{ GeV}/c.$

# **Hard QGP probes (III): Quarkonia suppression**

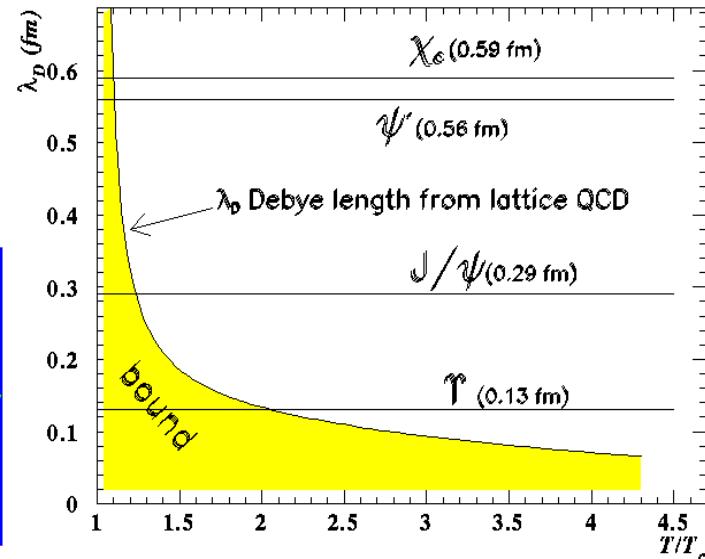
# QQbar suppression $\Rightarrow$ Color screening

## ■ Heuristic argument [Matsui-Satz 1986]:

- Colour screening in a deconfined plasma “dissolves” QQbar bound state
  - Different bound states “melt” at different temperatures due to their different binding radius:
- QQbar: QGP “thermometer”



Screening length  $\lambda_D$  vs.  $T$ :

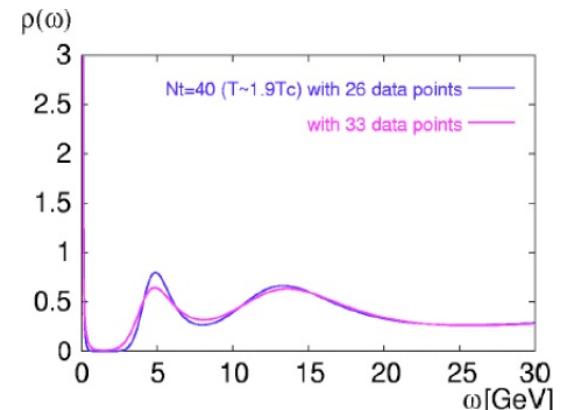
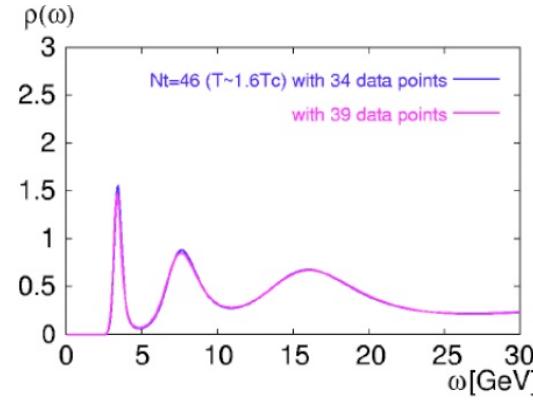


## ■ Lattice QCD calculations (quarkonia spectral functions):

$\Psi'$ ,  $\chi_c$  dissolve around  $T_c$

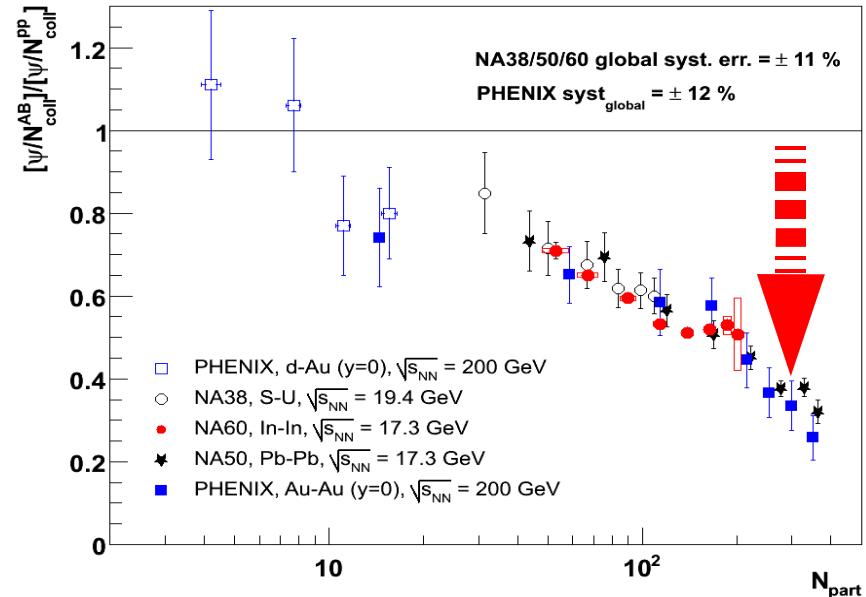
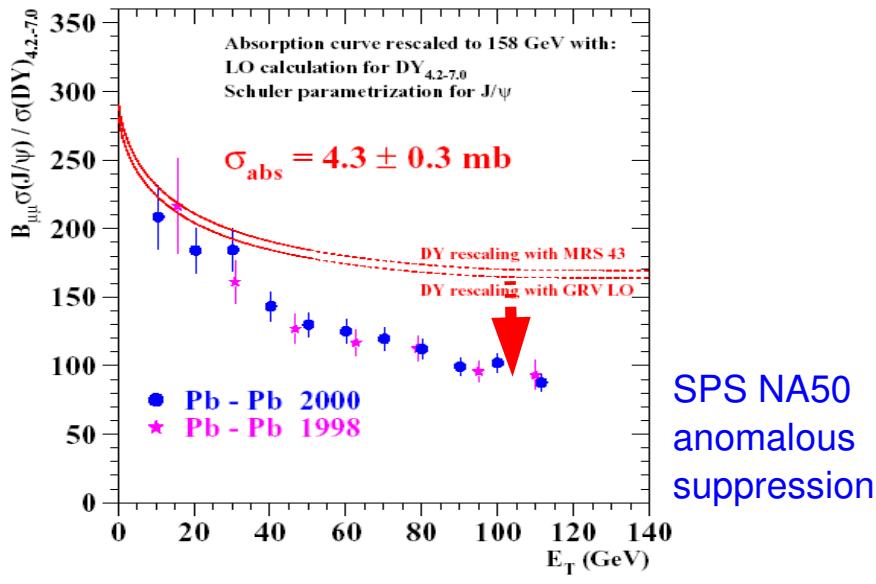
$J/\psi$  survives up to  $\sim 2T_c$

$\Upsilon$  survives up to  $\sim 4T_c$



# J/ $\psi$ suppression (SPS, RHIC)

- J/ $\psi$  suppression vs. centrality ( $N_{\text{part}}$ ):



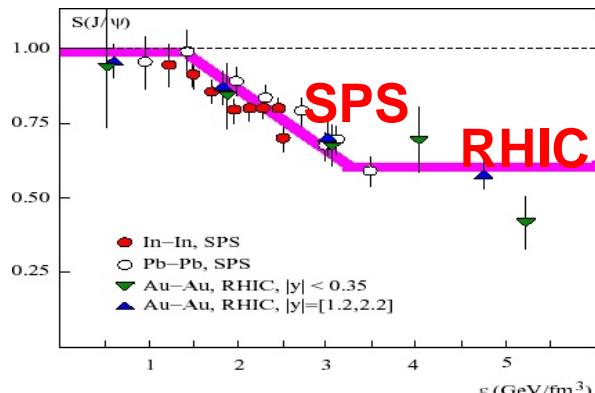
- Same suppression observed at RHIC ( $T \sim 400 \text{ MeV}$ ) & SPS ( $T \sim 200 \text{ MeV}$ ) !?

Recombination: ccbar regeneration ( $\sim 10$  ccbar pairs in central AuAu) compensates for screening

Sequential dissociation: Only  $\psi'$  and  $\chi_c$  ( $\sim 40\%$  feed-down J/ $\psi$ ) suppressed.  
Direct J/ $\psi$  survives at RHIC  $\Rightarrow T_0 < \sim 2 \cdot T_c$

# J/ $\psi$ , $\Upsilon$ suppression (LHC)

■ J/ $\psi$ : enhancement or suppression ?

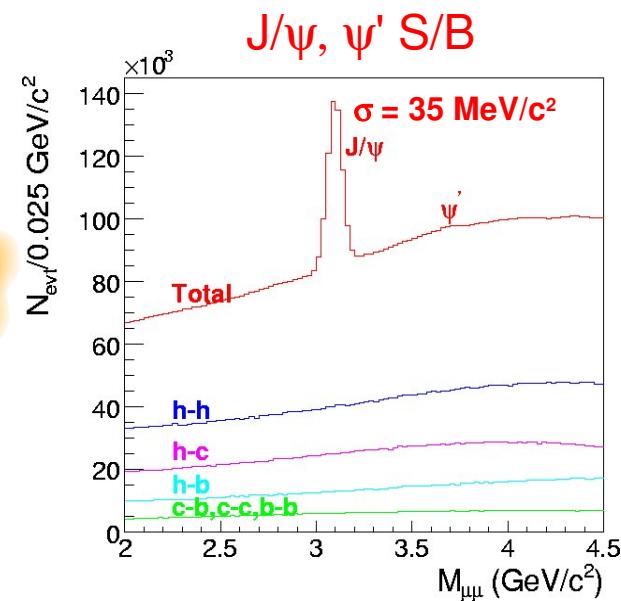


*Energy Density*

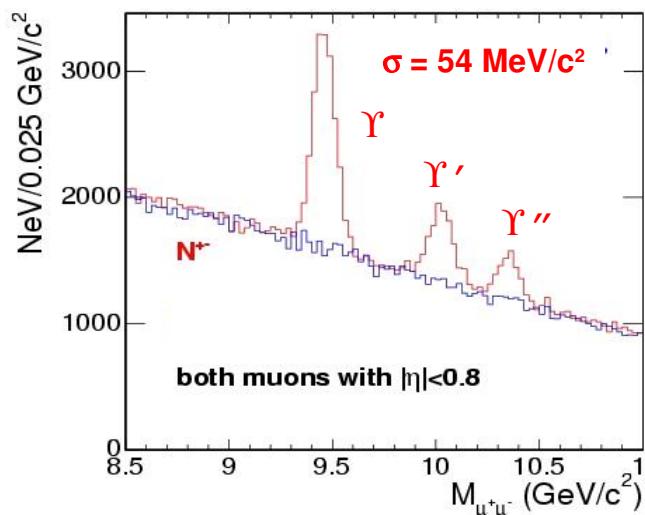
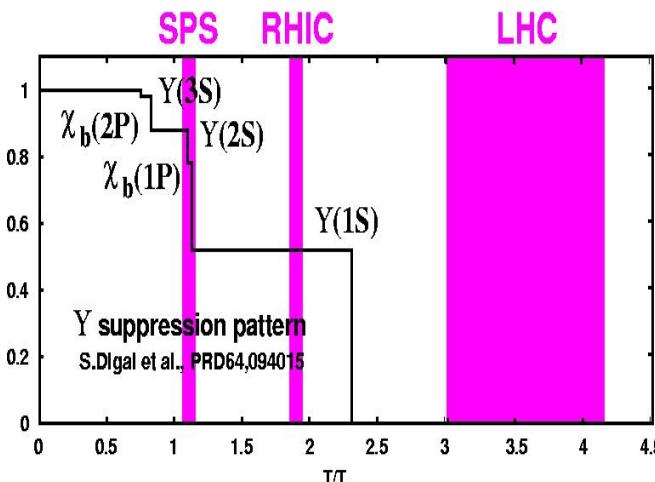
regeneration ?

LHC

suppression ?



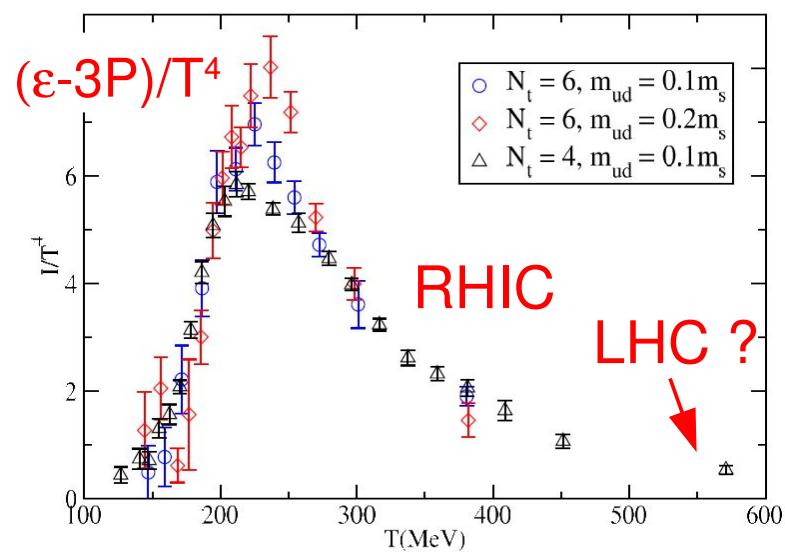
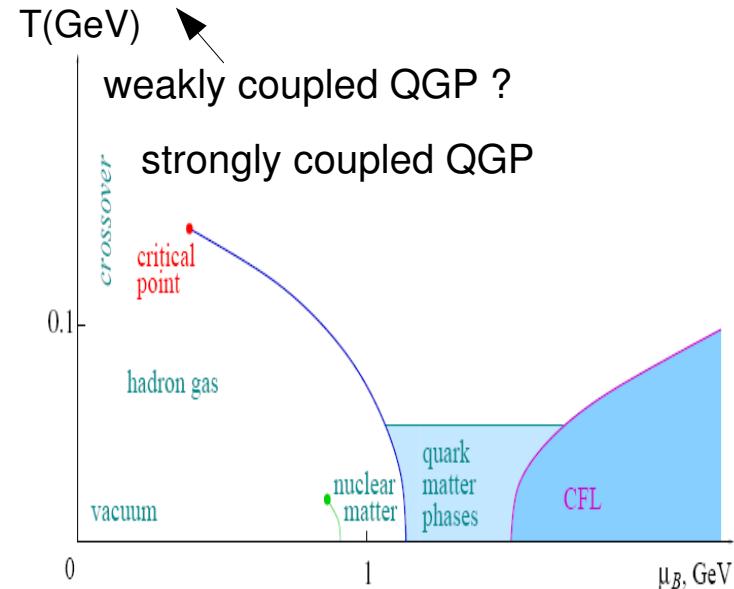
■ Bottomonia: sequential suppression ?



■ Large stats.  
available:  
 $O(10^5)$  J/ $\psi$   
 $O(10^4)$   $\Upsilon$

# Summary

- High-energy heavy-ion collisions study QCD in **extreme** conditions of  $p, T, \text{small-}x$
- SPS: close to phase boundary ( $T_0 \sim 200$  MeV)  
J/ $\Psi$  suppressed, ( $\rho$  broadened, ...)
- RHIC: Initial-state = **saturated gluon xG** (CGC)  
Strongly-coupled QGP (large partonic flows):  
low viscosity/entropy ( $\sim 1/4\pi$  ?)  
  
Dense QCD system ( jet quenching ):  
 $dN_g/dy \sim 1000$ ,  $\langle \hat{q} \rangle \sim 14$  GeV $^2/\text{fm}$   
  
Hot medium (J/ $\Psi$  suppressed, thermal?  $\gamma$ )  
 $T_0 \sim 2 \cdot T_c \sim 400$  MeV
- LHC: Hottest/densest matter in the lab ever.  
weakly-coupled QGP ?  
stronger CGC effects ? ...



# **Backup slides**