IFAE 2010
IX EDIZIONE DEGLI INCONTRI DI FISICA DELLE ALTE ENERGIE
Roma, 7-9 Aprile, 2010

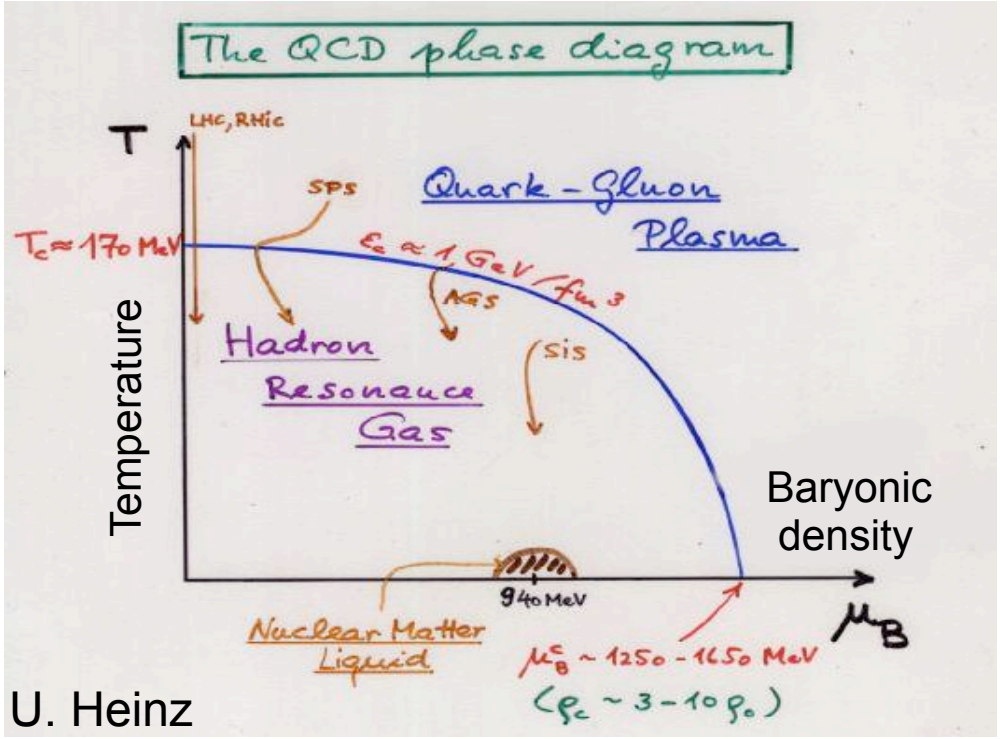
Rassegna sulla fisica degli ioni pesanti

Andrea Dainese
INFN – Padova

High-density QCD with high-energy nucleus-nucleus collisions

- Hot and dense QCD matter
- What we learnt at SPS and RHIC
- Perspectives for LHC (Pb-Pb run next November!)

Physics of hot and dense QCD matter



U. Heinz

QCD phase diagram:

Hadronic matter exists in different states

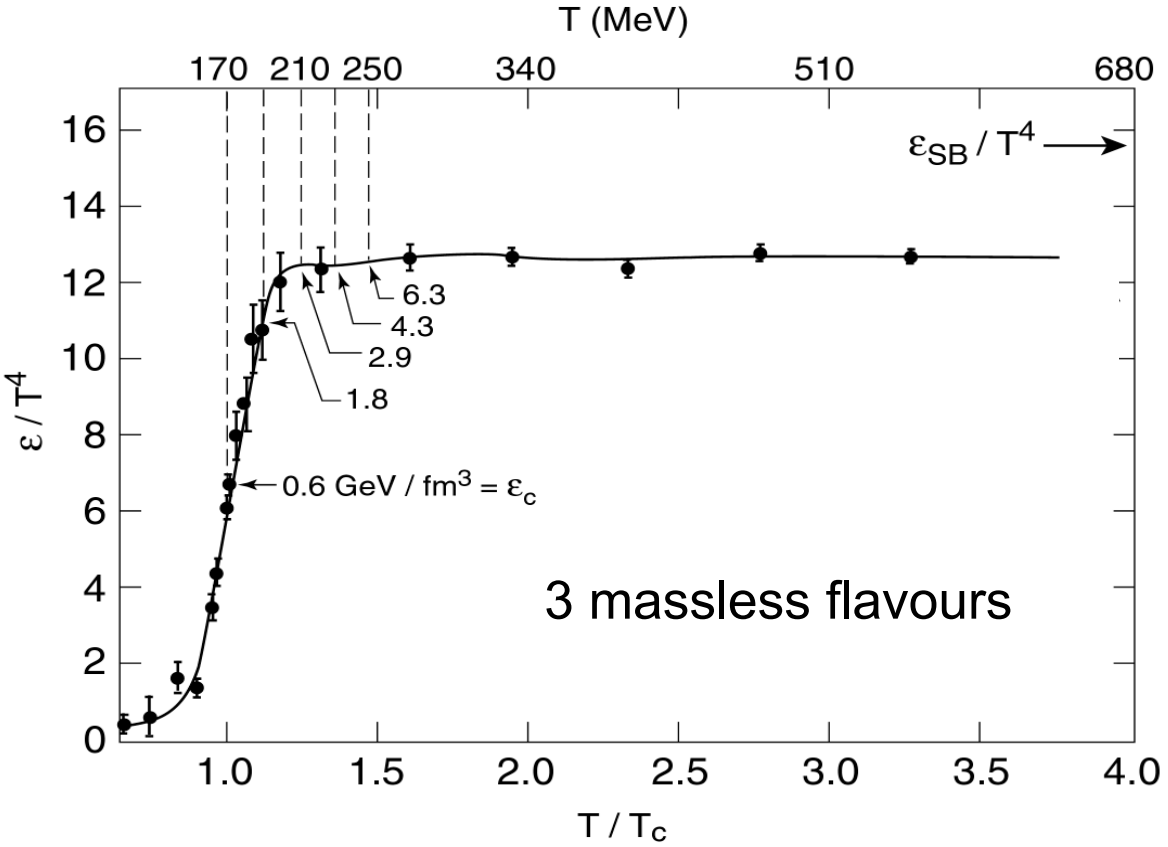
At high energy density (high temperature and/or high density) hadronic matter undergoes a **phase transition** to the *Quark-Gluon Plasma (QGP)*

- *a state in which colour confinement is removed*
- *and chiral symmetry is restored*
- *a high-density QCD medium of "weakly"-interacting gluons*

Physics of hot and dense QCD matter

Lattice QCD estimates the phase transition at:

temp. $T_c \sim 170$ MeV and energy density $\varepsilon_c \sim 1$ GeV/fm$^3 \sim 5\ \varepsilon_{nucleus}$



$$\frac{\varepsilon}{T^4} \propto n_{\text{degrees of freedom}}$$

phase transition:

pion gas → *QGP*

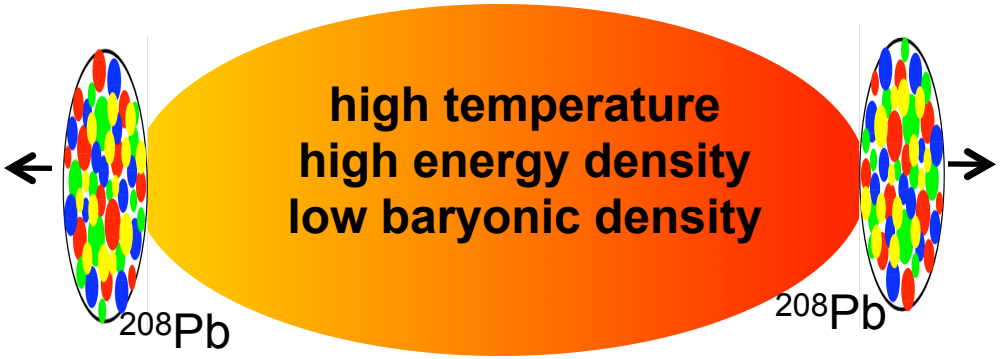
$n_{\text{d.o.f.}}$: 3 → 47

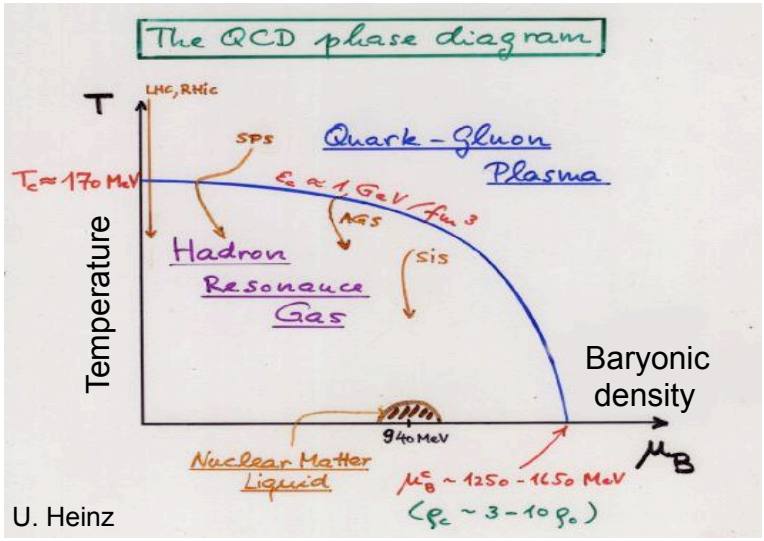
→ M.D'Elia talk

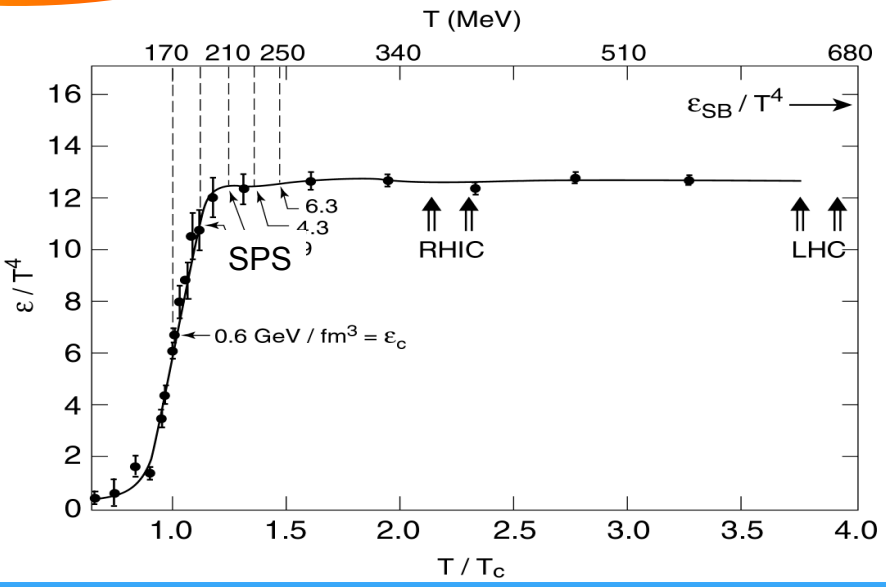
→ ***from hadronic to partonic degrees of freedom***

The Little Bang in the lab

- QCD phase transition (QGP → hadrons) at $t_{Universe}$ ~ 1 μs at μ_B=0
- In **high-energy heavy-ion** collisions **large energy densities** (> 2–3 GeV/fm^3) are reached over **large volumes** (> 1000 fm^3)

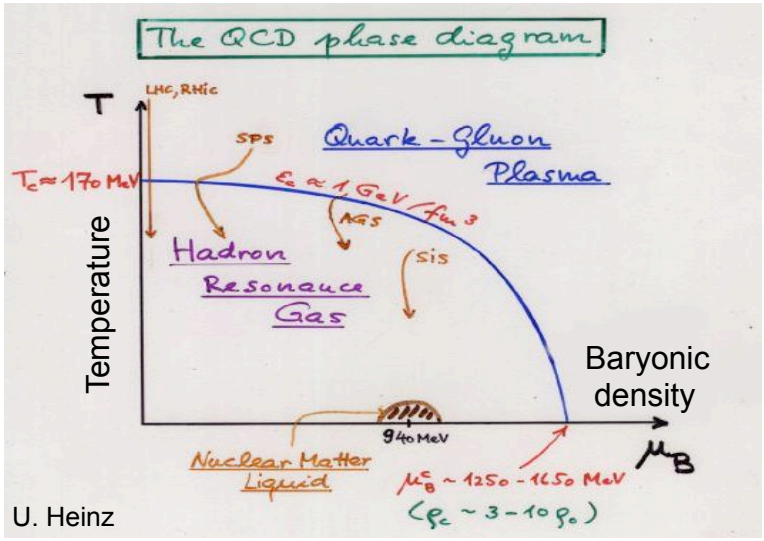


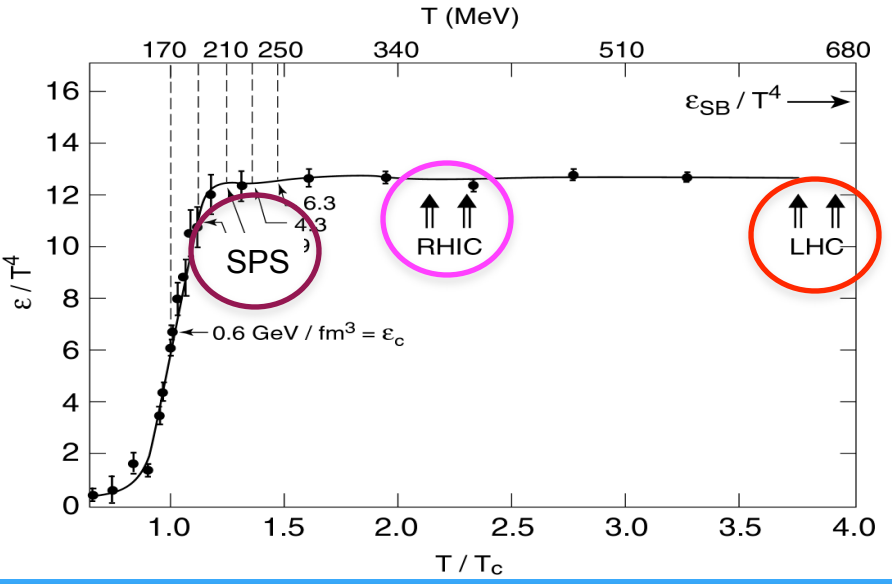




The Little Bang in the lab

- QGP evidence at **CERN-SPS** (up to: Pb-Pb, $\sqrt{s_{NN}} = 17\ \mathrm{GeV}$)
- First QGP properties at **BNL-RHIC**, Au-Au, $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$
- Next step: **LHC** with Pb-Pb, $\sqrt{s_{NN}} = 2.75 - 5.5\ \mathrm{TeV}$





CERN-SPS ('90s): a glimpse of the new QCD medium

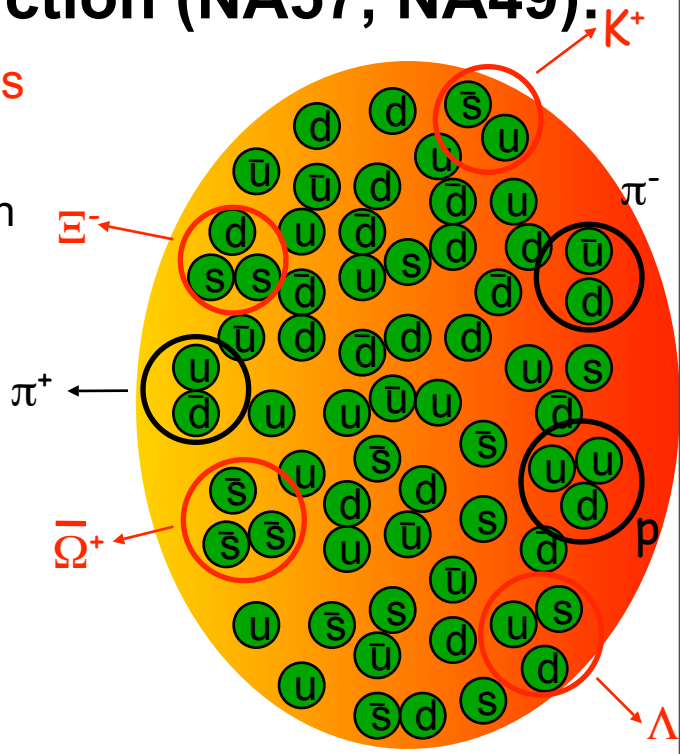
- > 1990: fixed target Pb-Pb collisions at $\sqrt{s}$ = 17 GeV
- Energy density ε up to 3 GeV/fm^3 (> ε_c ~ 1 GeV/fm^3)
- Experiments observe the two historical signatures of the QGP formation:

Enhancement of strange baryon production (NA57, NA49):

- restoration of χ symmetry → increased production of s
  - s mass in QGP back to current value ~ 150 MeV ~ T_c
  - → copious production of s-sbar pairs by gluon-gluon fusion

  [Rafelski: PR88 (1982) 331]
  [Rafelski-Müller: PRL48 (1982) 1066]
- deconfinement → stronger effect for multi-strange
  - can be built recombining s quarks
  - strangeness enhancement increasing with strangeness content

  [Koch, Müller & Rafelski: PR142 (1986) 167]



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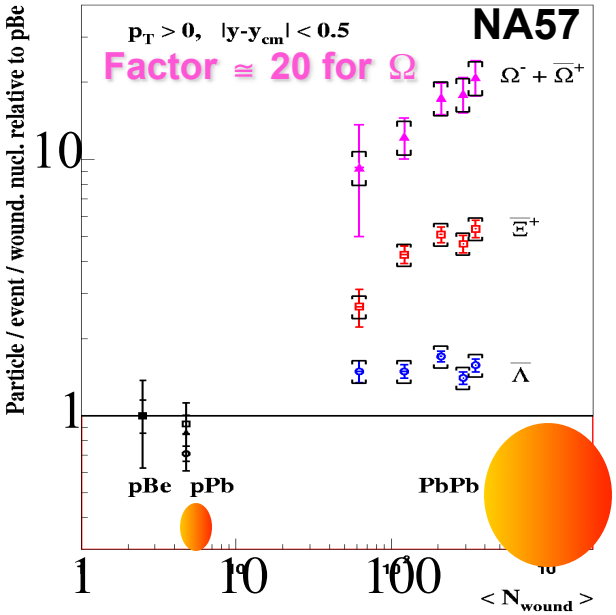

number of participant nucleons

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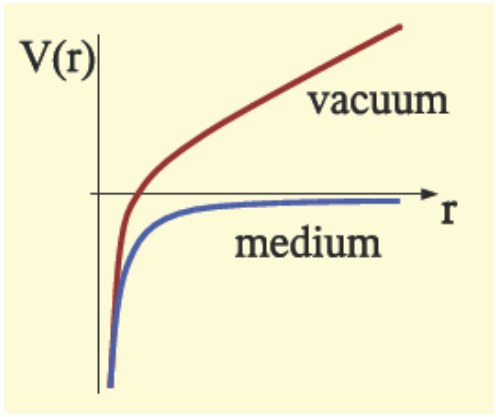
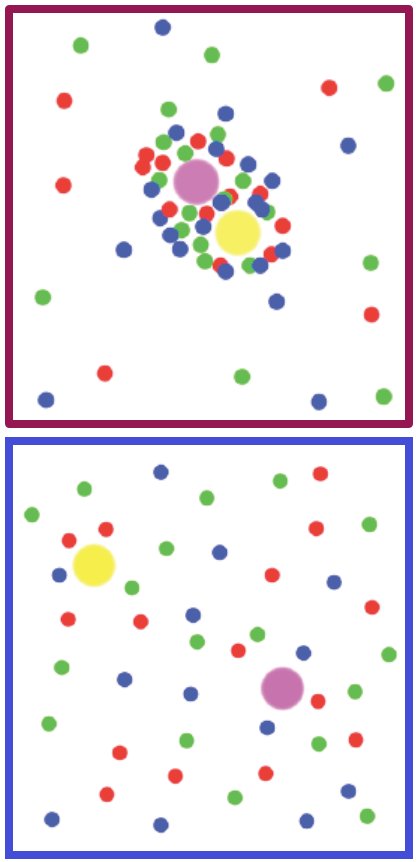
Suppression of J/ψ yield (NA50, NA60):

- The high colour charge density of the deconfined medium screens the interaction of c anf cbar
- Interaction potential screend beyond the Debye length λ_D
- Quarkomium states with r > λ_D do not bind
- Their yield is suppressed

for T ~ 200 MeV:

λ_D ~ 0.1 – 0.2 fm > r_ψ and $r_{\chi c}$





T.Matsui and H.Satz, 1986

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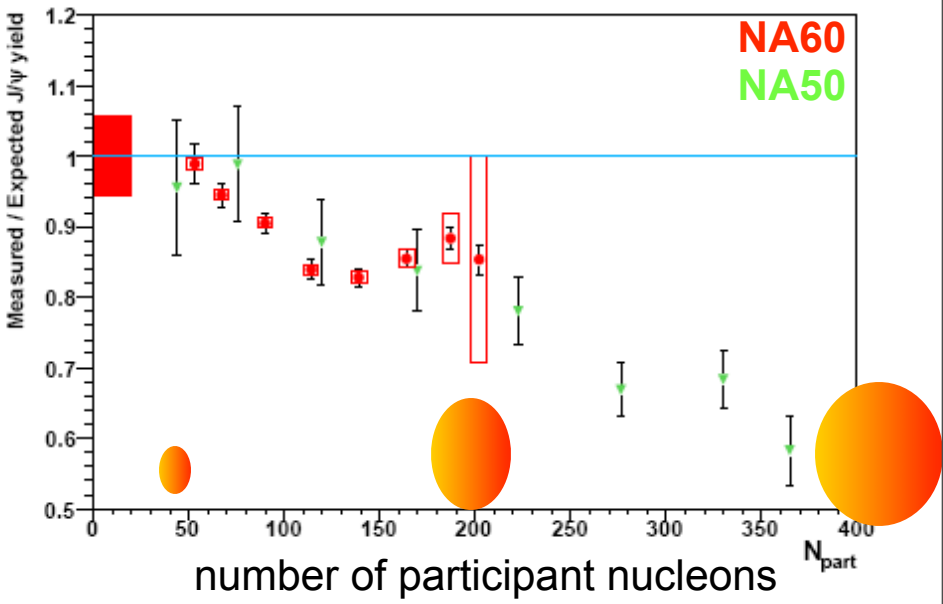
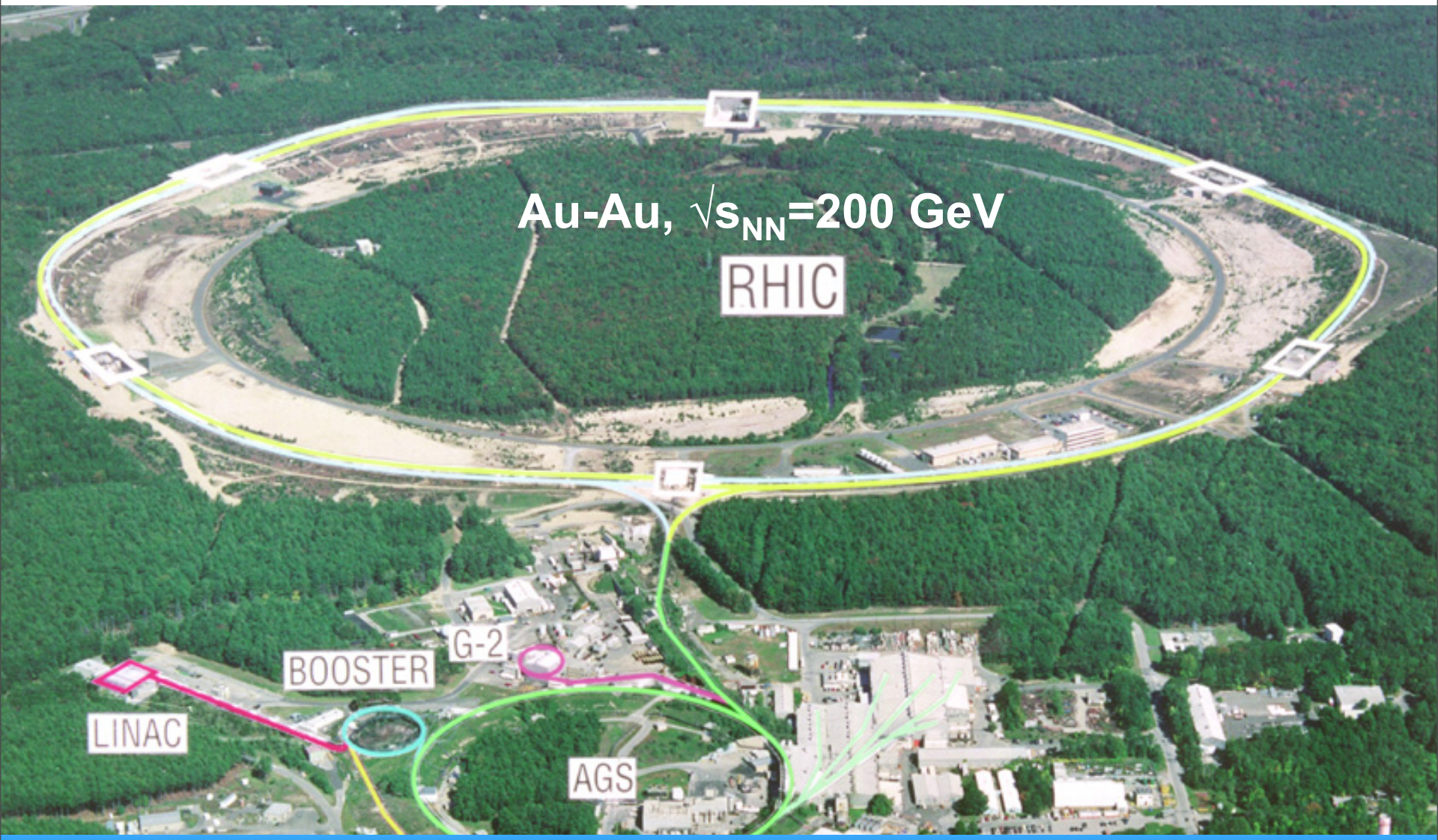


BNL-RHIC (2000s): beginning of the collider era



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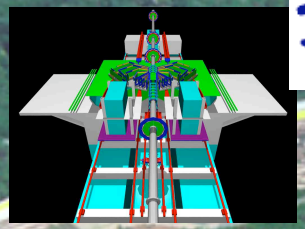
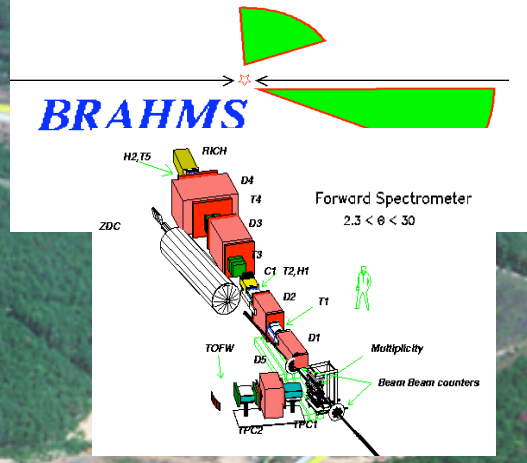
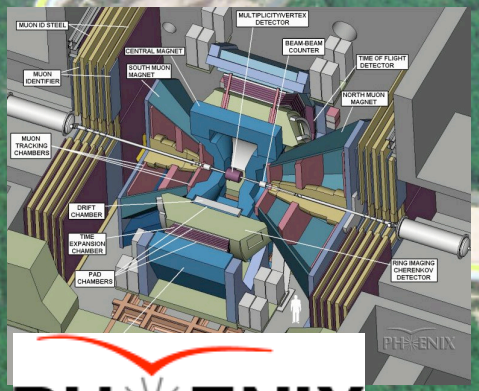


PHOBOS



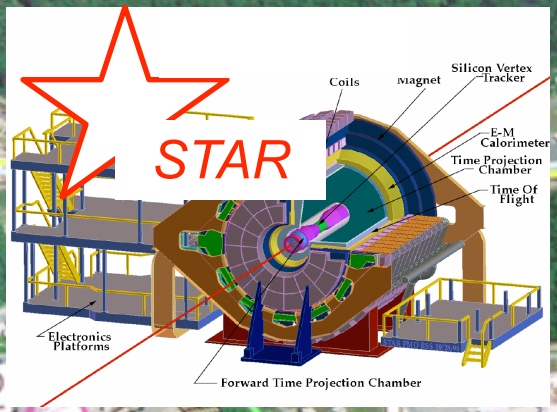
Au-Au, $\sqrt{s_{NN}}$=200 GeV

RHIC



PHENIX

STAR



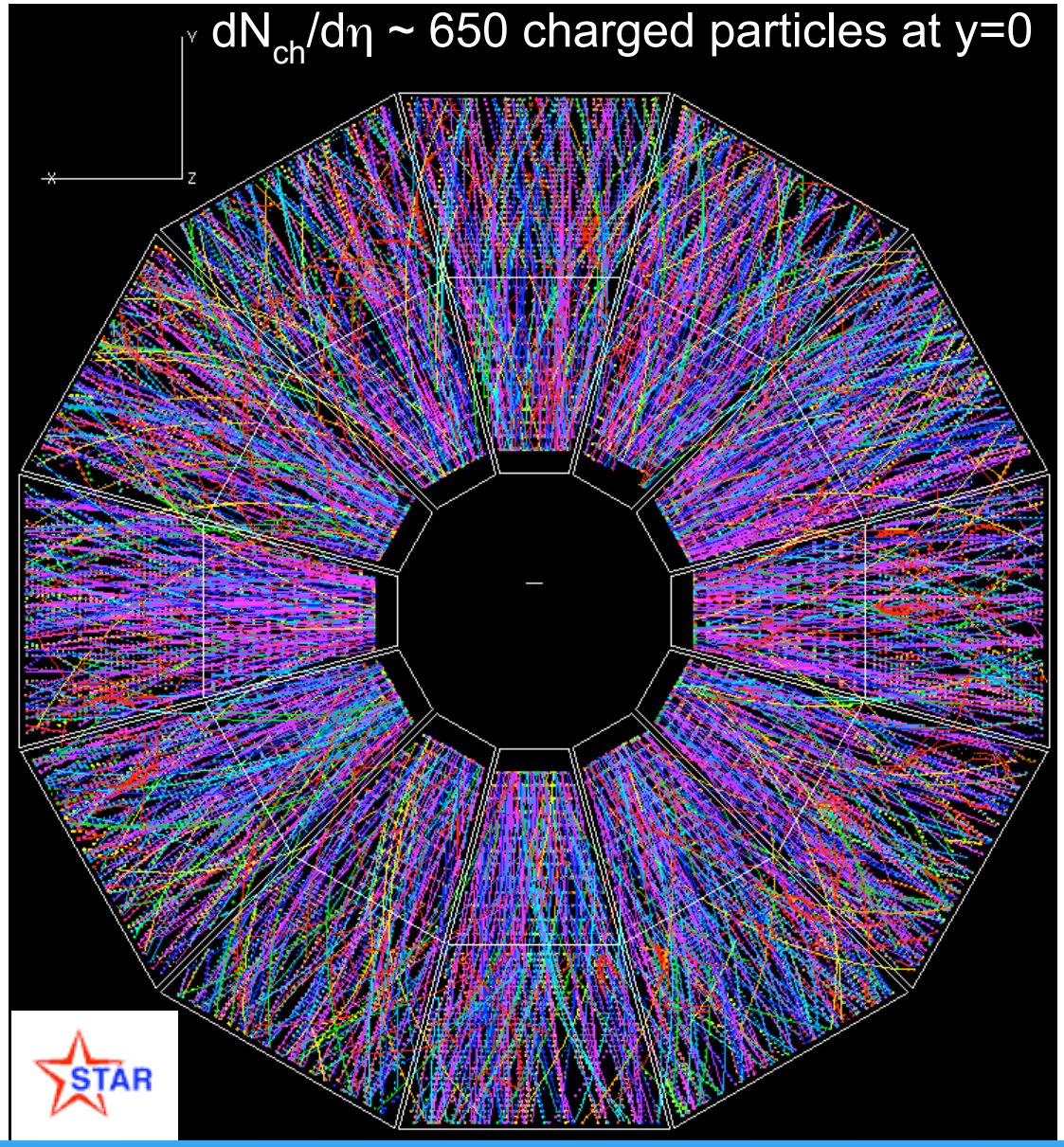
G-2

BOOSTER

LINAC

AGS

Central Au-Au 200 GeV in STAR TPC



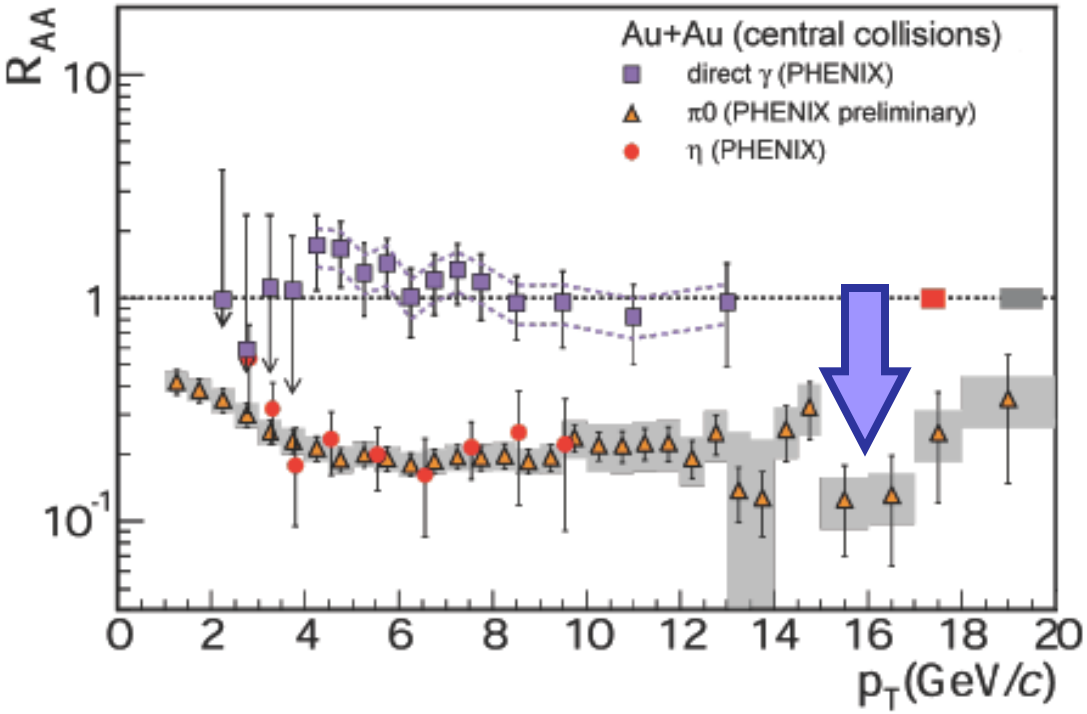
BNL-RHIC (2000s): first properties of the QCD medium

- > 2000: Au-Au collisions at $\sqrt{s}$ = 200 GeV
- Energy density up to 5-15 GeV/fm^3
- Major findings of the 4 RHIC experiments in a nut-shell:
  - **Jet quenching**: hard partons lose energy due to interaction with the medium
  - **Strong collective flow**, well described by hydro-dynamical models
  - **Quark recombination** dominates over fragmentation in hadron production at intermediate momenta

Jet quenching at RHIC: high-p_T suppression

- *Nuclear modification factor* of p_T distributions:

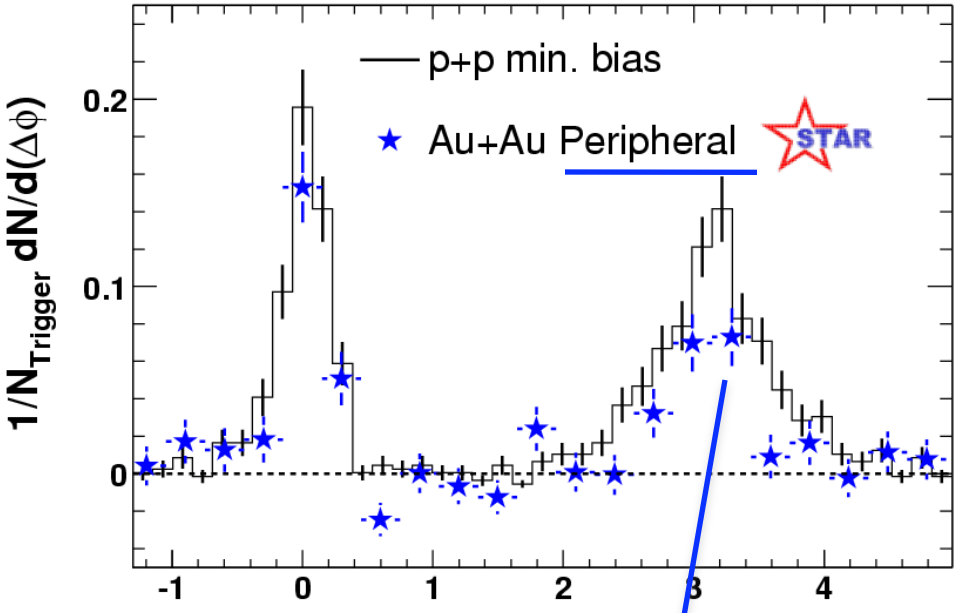
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \times \frac{d^2N_{AA}/dp_T d\eta}{d^2N_{pp}/dp_T d\eta}$$



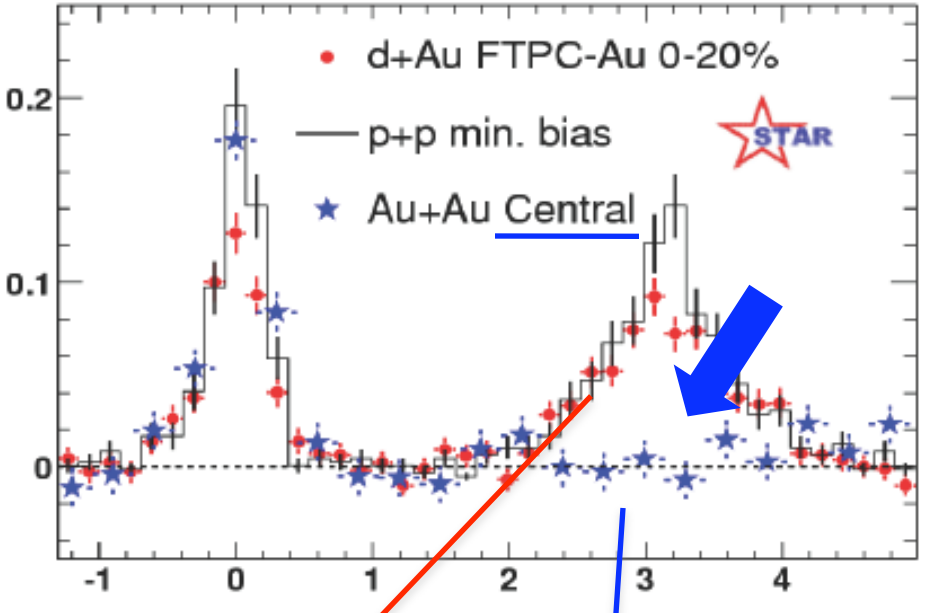
little/no suppression for photons (blind to QCD medium)

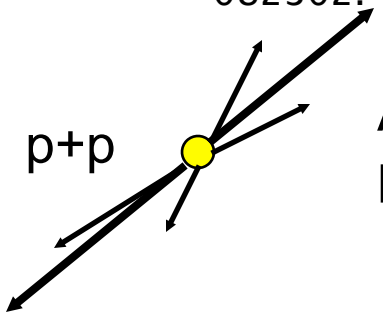
factor 5 suppression for pions!

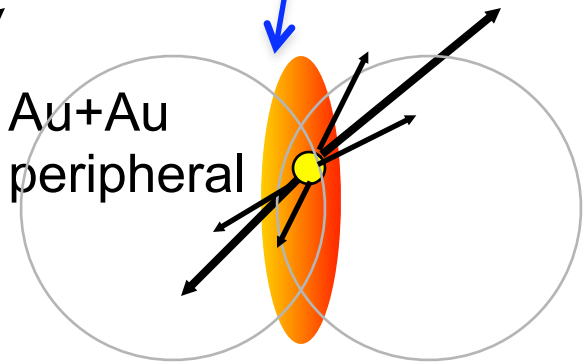
Jet quenching at RHIC: away-side jet suppression

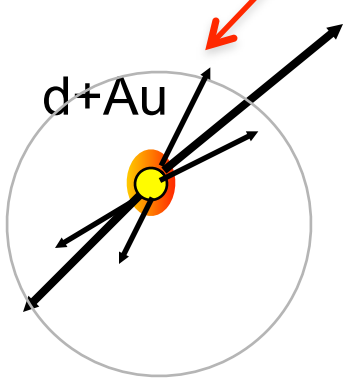


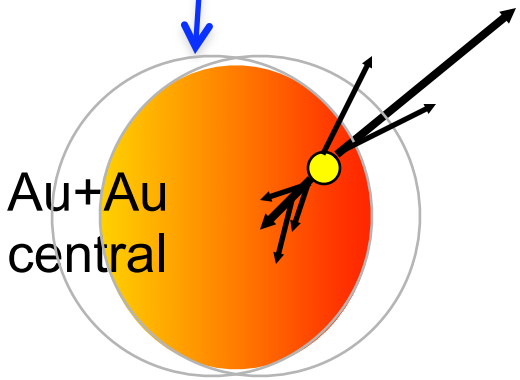
STAR Coll., PRL 90 (2003) 082302.





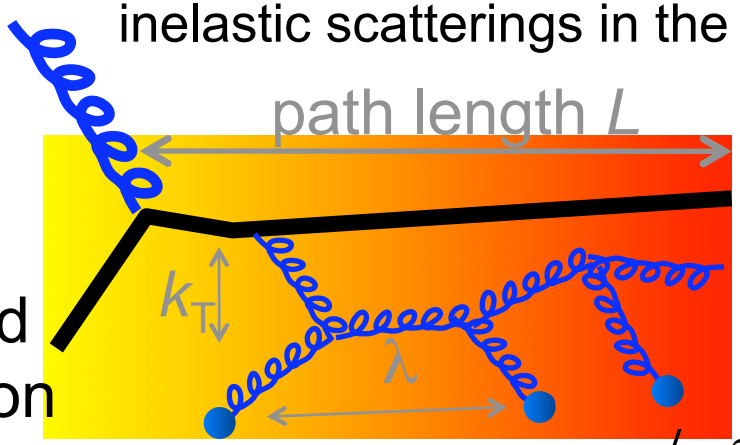






Parton QCD Energy Loss

- Partons travel ~4 fm in the high **colour**-density medium
- Energy loss, mainly by ***medium-induced gluon radiation***
  - Coherent wave-function gluon acummulates k_T due to multiple inelastic scatterings in the medium → it decoheres and is radiated



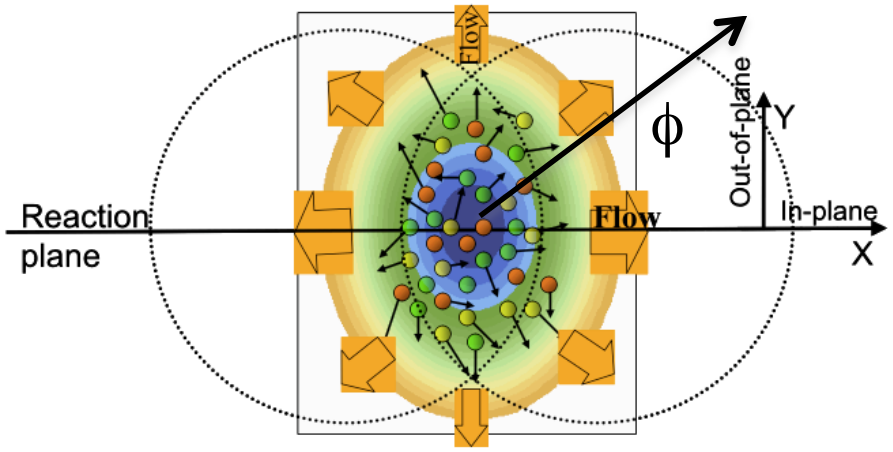
$$\langle \Delta E \rangle \propto \alpha_s \, C_R \, \hat{q} \, L^2$$

$$\langle \Delta E \rangle \propto \hat{q} = \frac{\langle k_T^2 \rangle}{\lambda} \propto$$ gluons volume-density and interaction cross section

Hard partons probe the medium properties

Gyulassy, Pluemer, Wang, Baier, Dokshitzer, Mueller, Peigne', Schiff, Levai, Vitev, Zhakarov, Salgado, Wiedemann, …

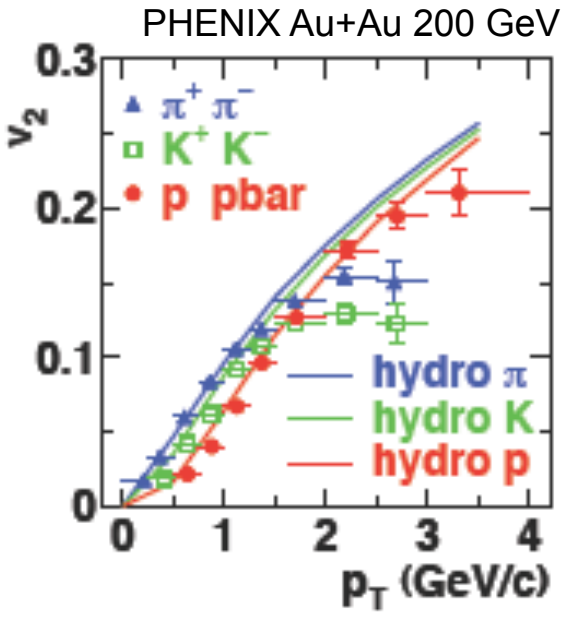
Collectivity at RHIC: elliptic flow



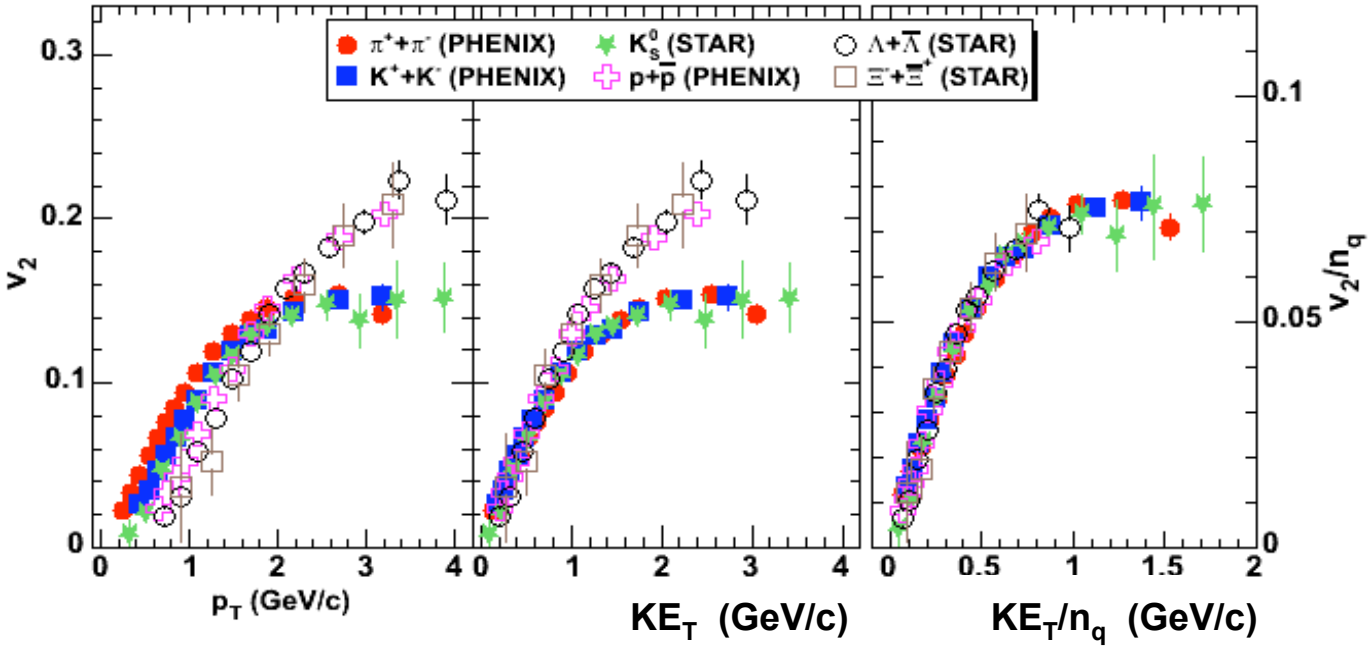
- Medium geometry asymmetric in non-central collisions
- Hydro-dynamic models:
  - expansion under azimuth-dep. pressure gradient
  - results in azimuth-dep. momentum distributions

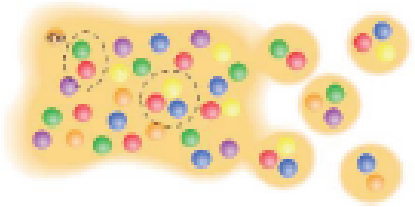
- Measured by the elliptic flow parameter $v_2(p_T) = \langle\cos(2\phi)\rangle(p_T)$

→ At low p_t well-described by hydro-dynamic calculations



Collectivity at RHIC: flow and recombination





- Clear separation between mesons and baryons for p_t > 2 GeV/c
- Well explained within hadronization-by-recombination scenario:
  - collective flow is built in the partonic phase
  - partons recombine into hadrons

  → $p_T^{hadron} = n_{quarks} \times p_t^{parton}$; $v_2^{hadron} = n_{quarks} \times v_2^{parton}$

Heavy-ion Physics at the LHC

LHC: factor 15-30 jump in $\sqrt{s}$ w.r.t. RHIC

Central collisions	SPS	RHIC	LHC
√s (GeV)	17	200	2750-5500
T / T_c	>1	~2	~4
ε (GeV/fm³)	3	5-10	15- 60
V_f(fm³)	10^3	$7x10^3$	$2x10^4$
τ_{QGP} (fm/c)	< 1	1.5- 4.0	4-10

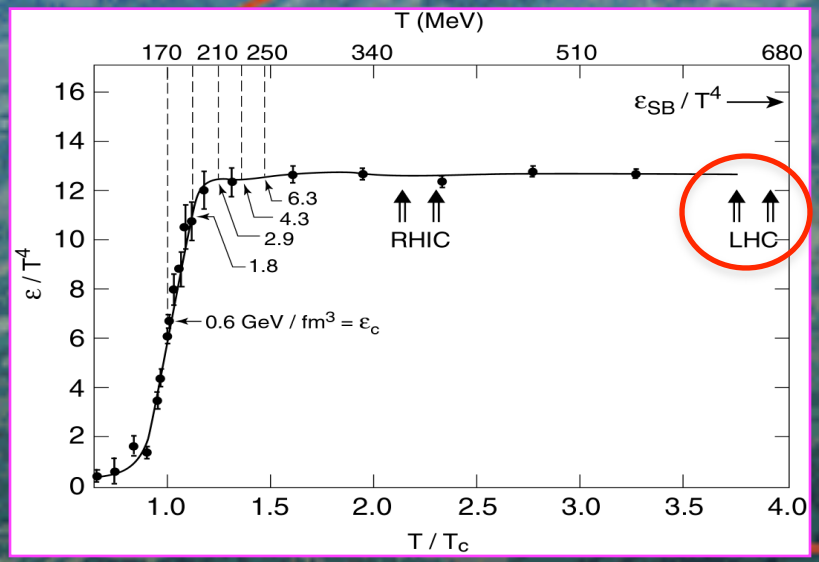
× 3 - 6

× 3

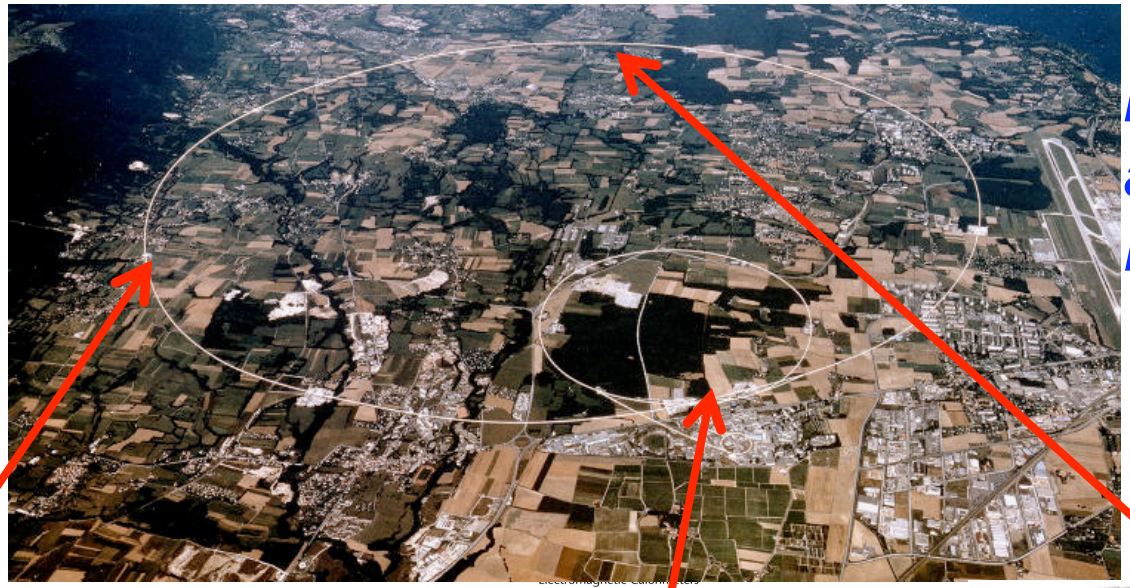
produce & study:

hotter
bigger
longer-lived

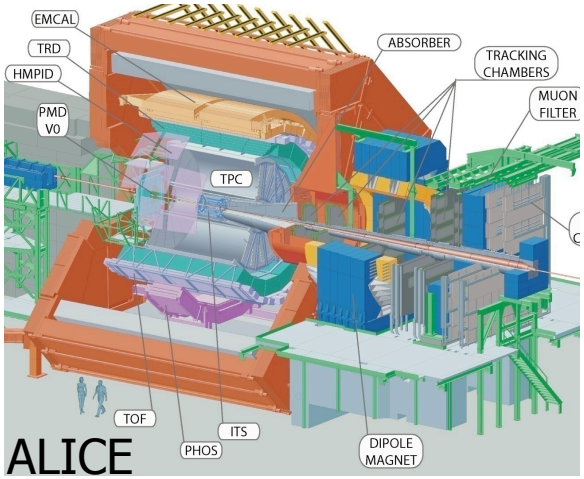
"fire-balls" of QCD medium

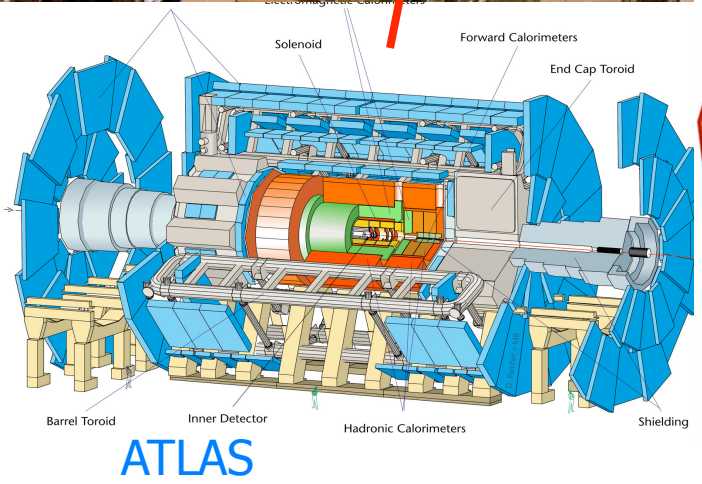


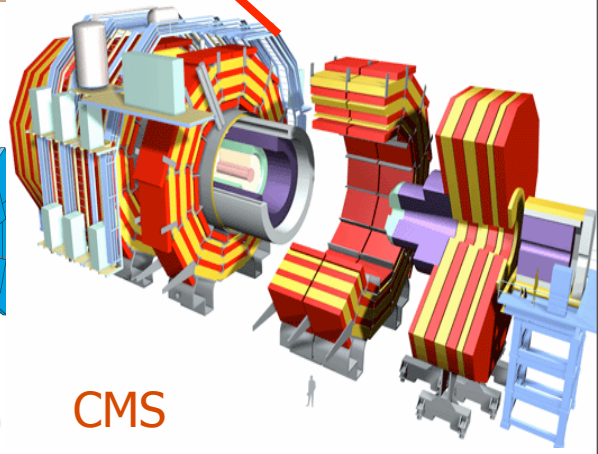
Heavy-ion experiments at the LHC



Pilot Pb-Pb run at 2.75 TeV Nov 2010





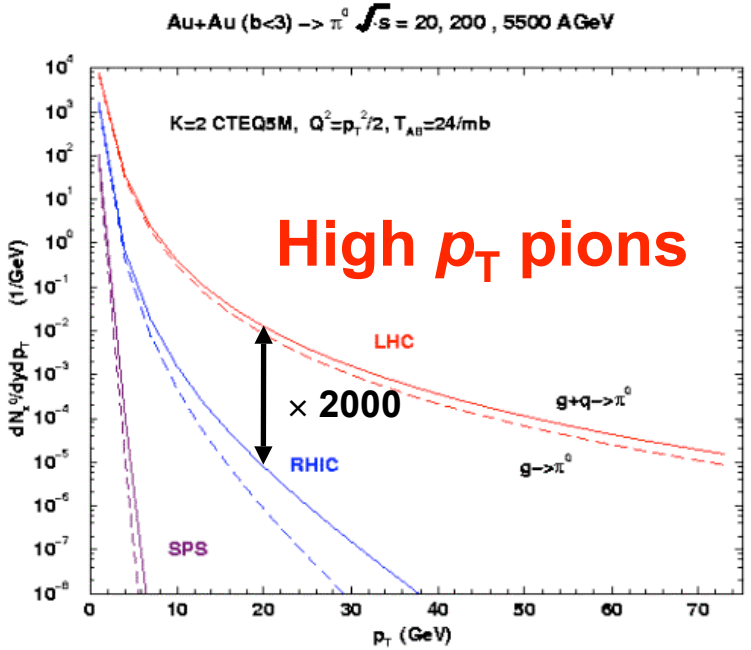


LHC: a Hard Probes machine

Large hard cross sections

→ New probes of the medium:

- high-E_T jets
- b quarks
- medium-blind bosons γ, W, Z^0



Jets at the LHC (Pb-Pb 5.5 TeV):

E_T	2 GeV	20 GeV	100 GeV	200 GeV
	100/event	1/event	10^6/month	$4x10^4$/month

Heavy quarks:

	RHIC	LHC	
charm	10	100	×10
beauty	0.05	5	×100

w.r.t. RHIC

Hard Probes at the LHC: heavy quarks

q: colour triplet

u,d,s: m~0, C_R=4/3

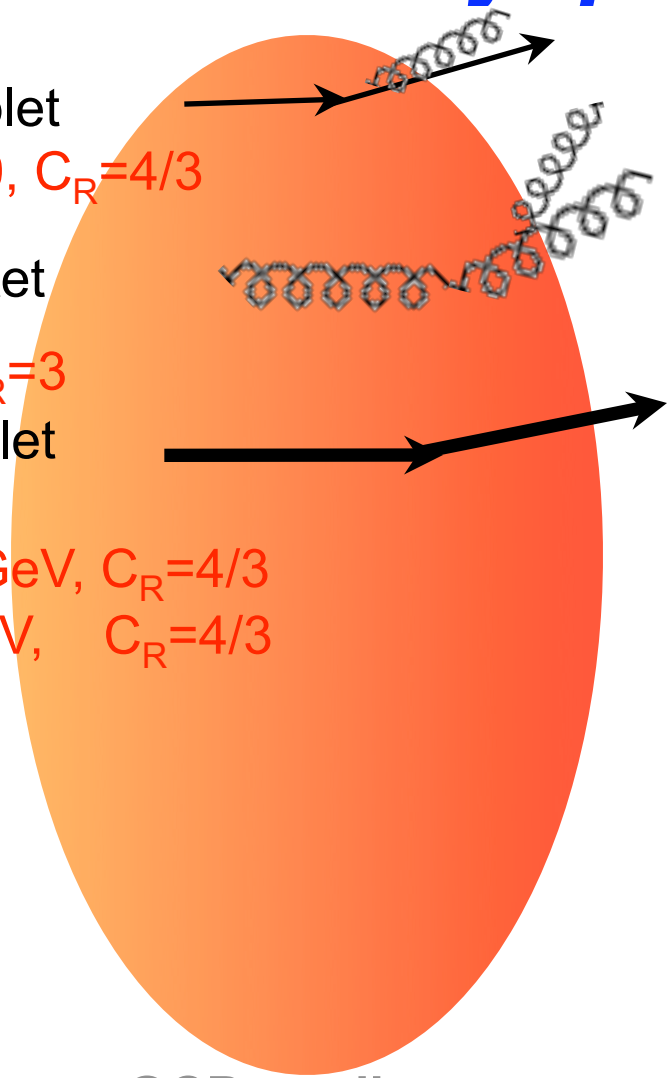
g: colour octet

g: m=0, C_R=3

Q: colour triplet

c: m~1.5 GeV, C_R=4/3

b: m~5 GeV, C_R=4/3



Parton Energy Loss

$$\Delta E(\varepsilon_{QGP}; C_R, m, L)$$

for heavy quarks, gluon radiation suppressed at small angles, $\theta < m_Q/E_Q$ (dead cone effect)

Gluonsstrahlung probability

$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

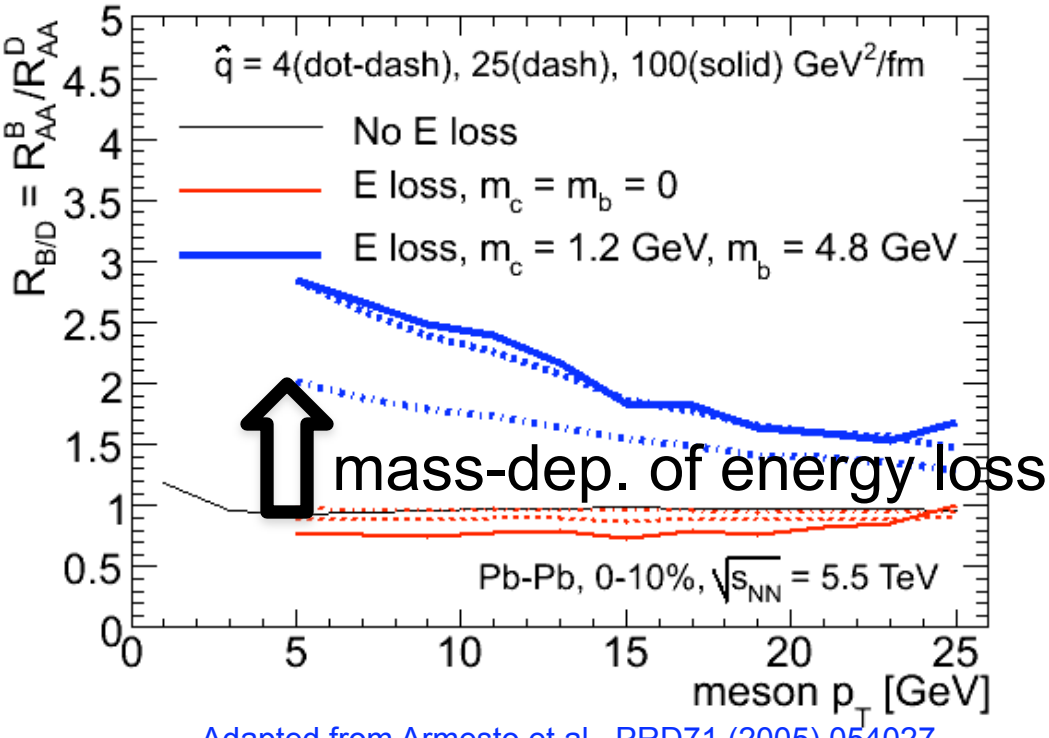
$$\Delta E_g > \Delta E_{c \approx q} > \Delta E_b$$

$$R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$$

Dokshitzer and Kharzeev, PLB 519 (2001) 199
Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003

Hard Probes at the LHC: heavy quarks

$$R_{B/D}(p_t) = R^B_{AA}(p_t) \big/ R^D_{AA}(p_t)$$



Adapted from Armesto et al., PRD71 (2005) 054027

- Compare c and b: same colour charge
- Mass effect → Enhancement of factor ~2 for b wrt c
- ***Fundamental test of the QCD E-loss paradigm***

Hard Probes at the LHC: boson-calibrated jets

q: colour triplet

g: colour octet

Q: colour triplet

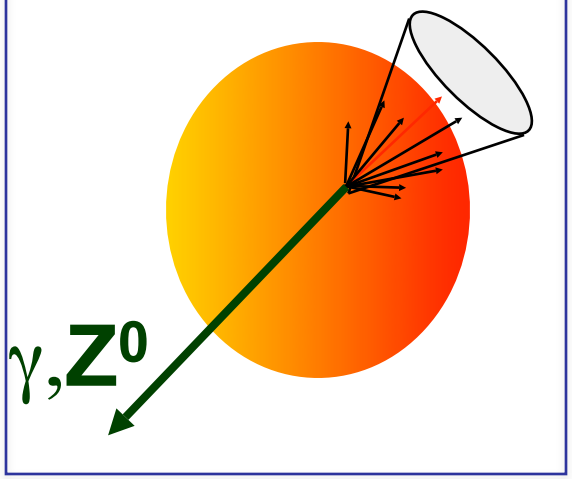
Real photon: colourless

Virtual photon/W: colourless

Medium-blind (no QCD int.)
→ calibration tool

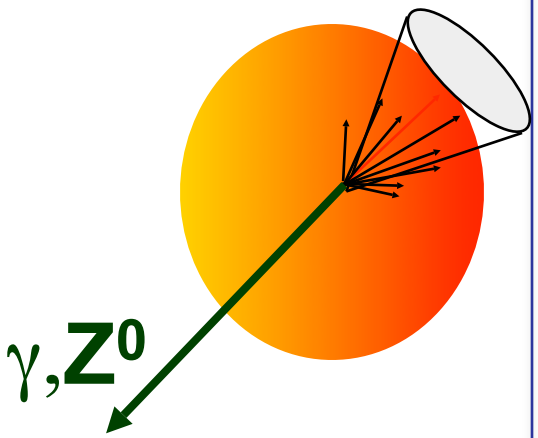
QCD medium

Unique tool:
$E^{\gamma/Z} = E^{\text{hard parton}}$!



Medium-modified Jet Fragmentation Function via γ-jet correlations

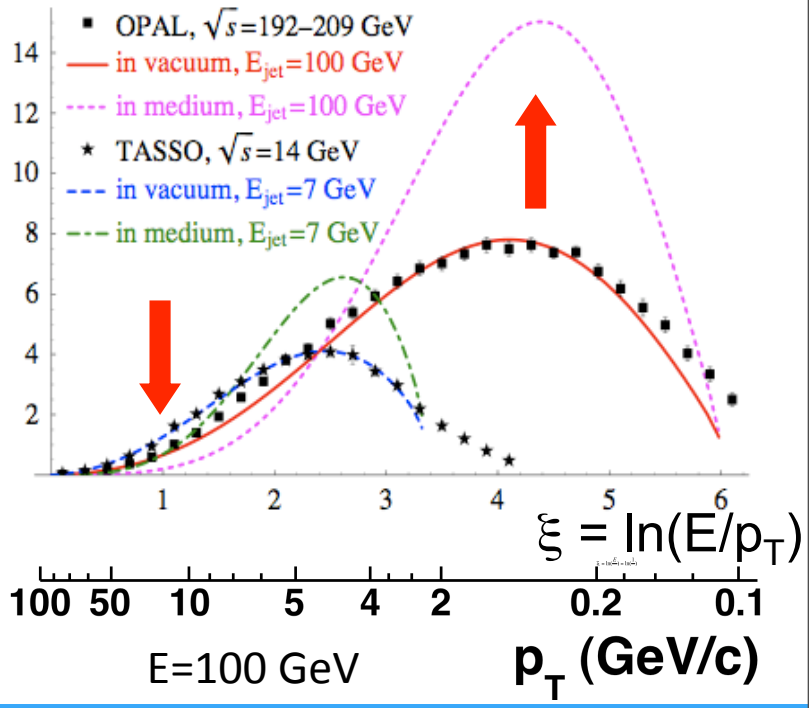
Unique tool:
$E^{\gamma/Z} = E^{\text{hard parton}}$!



Effects of the medium (energy loss):

- Decrease of leading particle p_T
- Increase of number of low momentum particles
- Increase of p_T relative to jet axis (j_T)

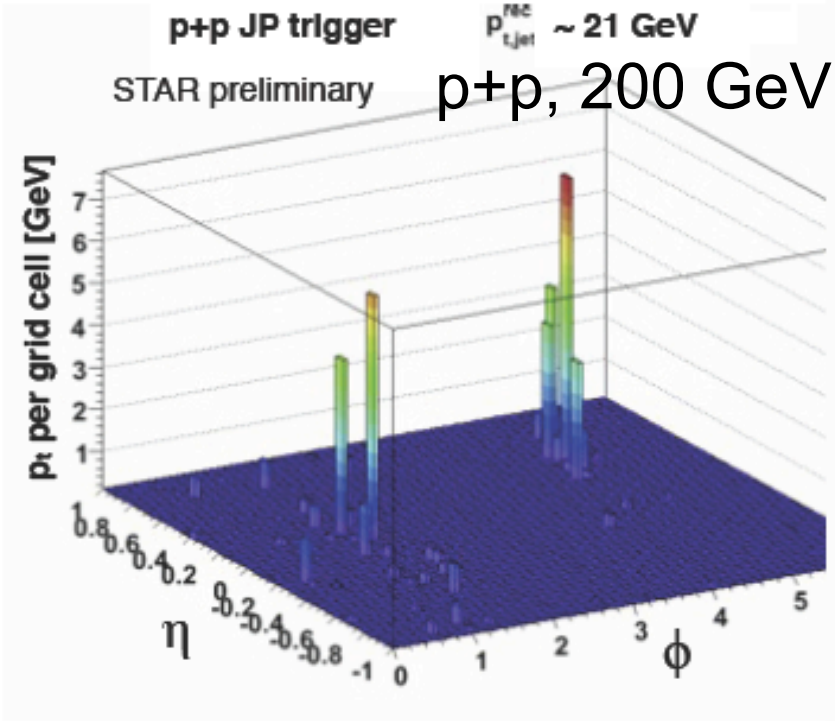
Borghini,Wiedemann, hep-ph/0506218

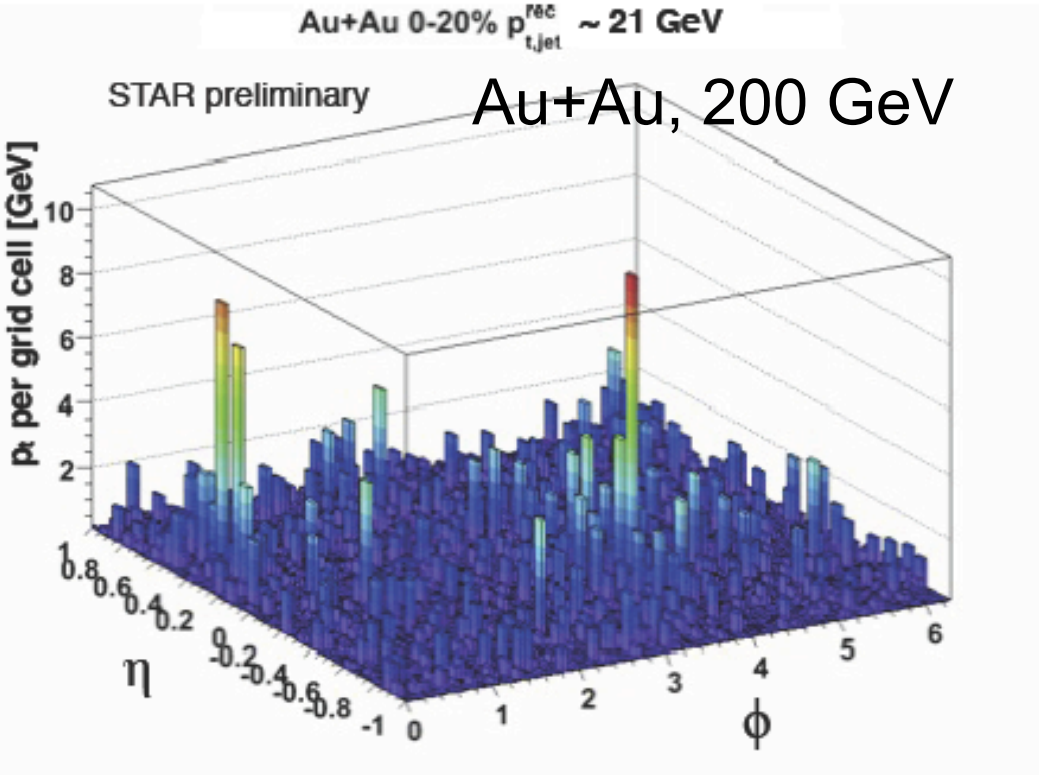


- Study jet FF($\xi=\ln(E^{\gamma}/p_T)=\ln(1/z)$):
- Search for depletion at low ξ ($z\to1$)
- Then, high-ξ ($z\to0$) enhancement

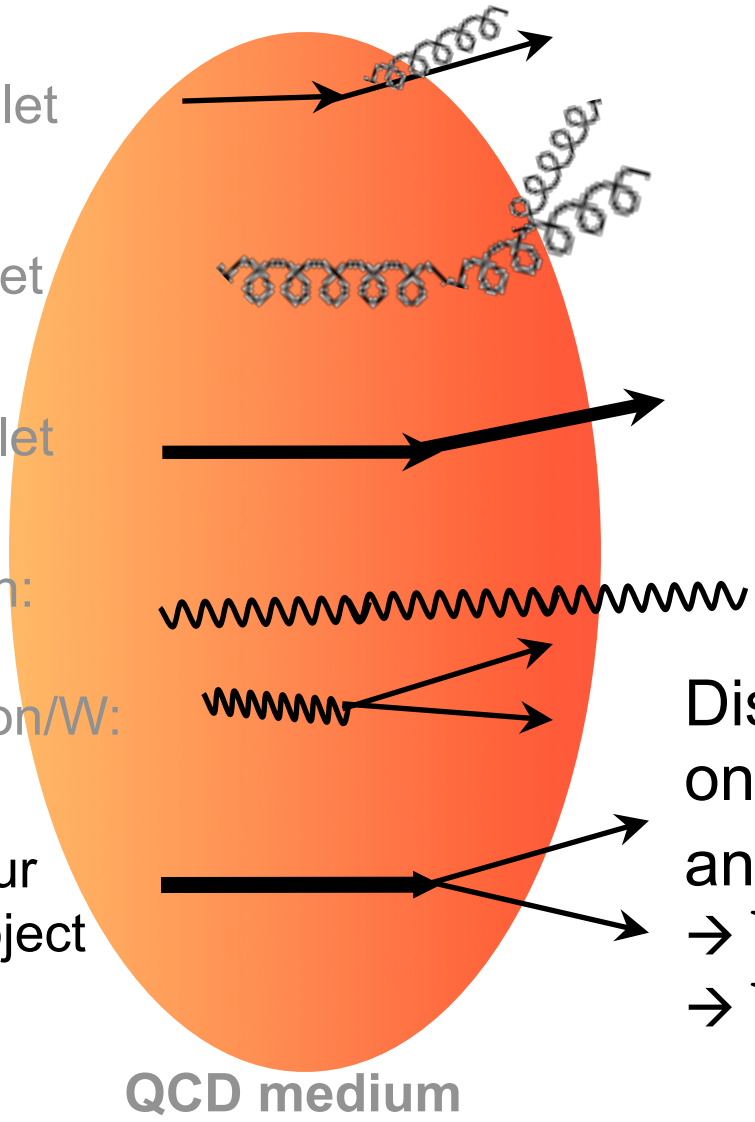
Towards full jet reconstruction in heavy-ion collisions

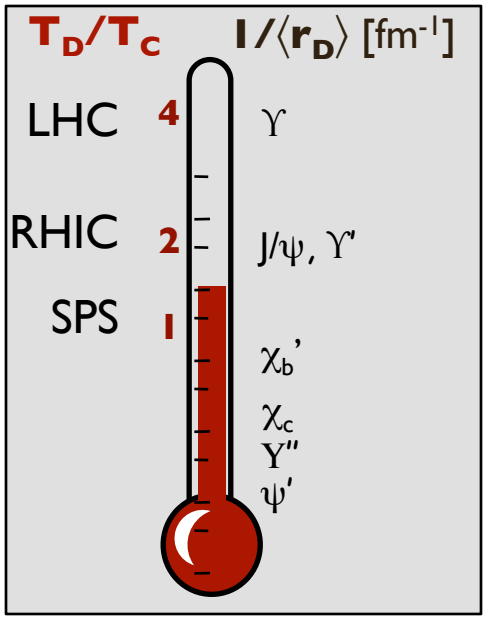
- Very challenging in high-multiplicity environment
  - Background subtraction is crucial





Hard Probes at the LHC: Quarkonia as a thermometer



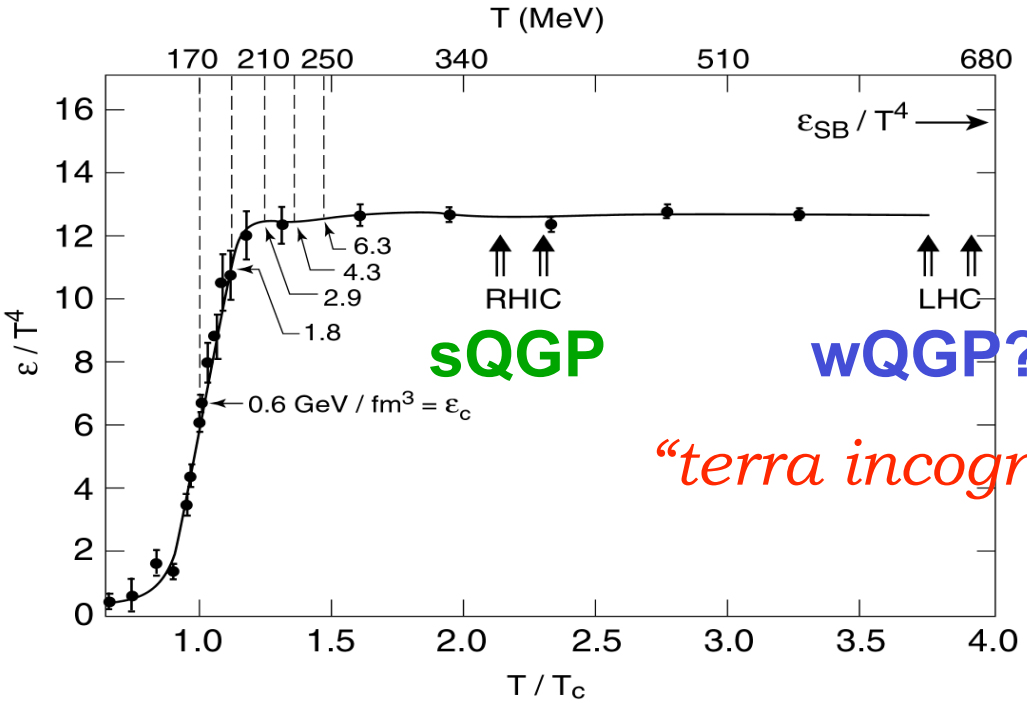


Dissociation pattern depends on binding energy T_D (~$1/r_D$) and medium temperature T

→ Υ would dissociate at LHC (4 T_C)

→ Υ' T_D ~ J/ψ T_D

Ultimate goal: characterize medium properties



sQGP

wQGP?

"terra incognita"

JET QUENCHING → ε

QUARKONIA SUPPRESSION (and thermal γs) → T

Summary

- Heavy-ion physics addresses:
  - limits of colour confinement
  - QCD in extended high-density systems
- SPS and RHIC: first properties of QCD medium
  - colour-deconfined (charmonium suppression)
  - partonic (strangeness enhancement, recombination)
  - dense (jet quenching)
  - hydro-dynamic (collective flow)
- The LHC: ideal to explore these new territories of QCD
  - higher energy, temperature
  - copious hard probes
  - last but not least, the LHC detectors