The heavy-ion programme at the LHC

“Taller d'Altes Energies” 2010

Univ. de Barcelona, 6 Sept. 2010

David d'Enterria

CERN

Unsolved questions in particle physics

1. Mass generation problem : What is the origin of the SM elementary particle masses ? Higgs boson ? other mechanism ?

2. Hierarchy / fine-tuning problem: What stabilizes m_{Higgs} up to m_{Planck} (10^{16} orders-of-magnitude !?) ? SUSY ? extra-dimensions ? ...?

3. Dark matter problem : ~1/4 universe = invisible matter. SUSY ? ...?

4. Flavour problem : Origin of matter-antimatter asymmetry in the Universe ? Why so many types of matter particles ?

5. QCD in strongly-interacting regime : Why quark confinement ? high-energy hadronic x-sections ? Gauge-String duality (AdS/CFT) ?

6. Highest-energy cosmic-rays : Sources/nature of CRs at 10^{20} eV ?

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my topic today

6. Highest-energy cosmic-rays : Sources/nature of CRs at 10^{20} eV ?

Solving the unsolved at the LHC: 7 experiments

1. Mass generation problem:

(Higgs boson)

ATLAS CMS

2. Hierarchy, fine tuning:

3. Dark matter problem:

(SUSY, Beyond SM)

ATLAS CMS LHCb MoEDAL

4. Flavour problem:

(CP-violation, B-physics)

LHCb ATLAS CMS

5. non-perturbative QCD:

(QGP, total x-section, ...)

ALICE ATLAS CMS TOTEM

6. Highest-energy cosmic-rays:

LHCf ALICE ATLAS CMS TOTEM

Overview

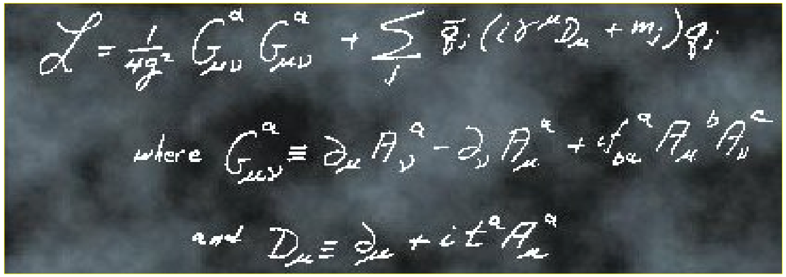
- Introduction:
  - - High-energy nucleus-nucleus collisions: Physics motivations
  - - Experiments: RHIC (Au-Au@200 GeV), LHC (Pb-Pb@5.5 TeV)
- Probes of many-body quantum chromo (thermo)dynamics:

Observable (type)	Medium property	Theoretical tool
dN/dη multiplicity (soft)	gluonic struct. $xG(x,Q^2)$	Color-Glass-Condensate
dN/dp$_T$ spectra (soft)	Equation-of-State P(V,T)	(Hydro), Lattice QCD
dN/dΔφ elliptic flow (soft)	shear viscosity η	(Hydro), AdS/CFT
Jet quenching (hard)	transport coefficient $<\hat{q}>$	(Hydro), pQCD
γ enhancement (intermed.)	critical temperature T_{crit}	(Hydro), Lattice QCD
$Q\bar{Q}$ suppression (hard)	critical energy density ε_{crit}	(Hydro), Lattice QCD

- Summary

Many-body dynamics of quarks & gluons

- QCD = Quantum-field theory with very rich dynamical content: asymptotic freedom,confinement, (approx.) χ-symmetry, non-trivial vacuum, $U_A(1)$ anomaly, CP-problem, ...



$$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_j (i\gamma^\mu D_\mu + m_j) q_j$$

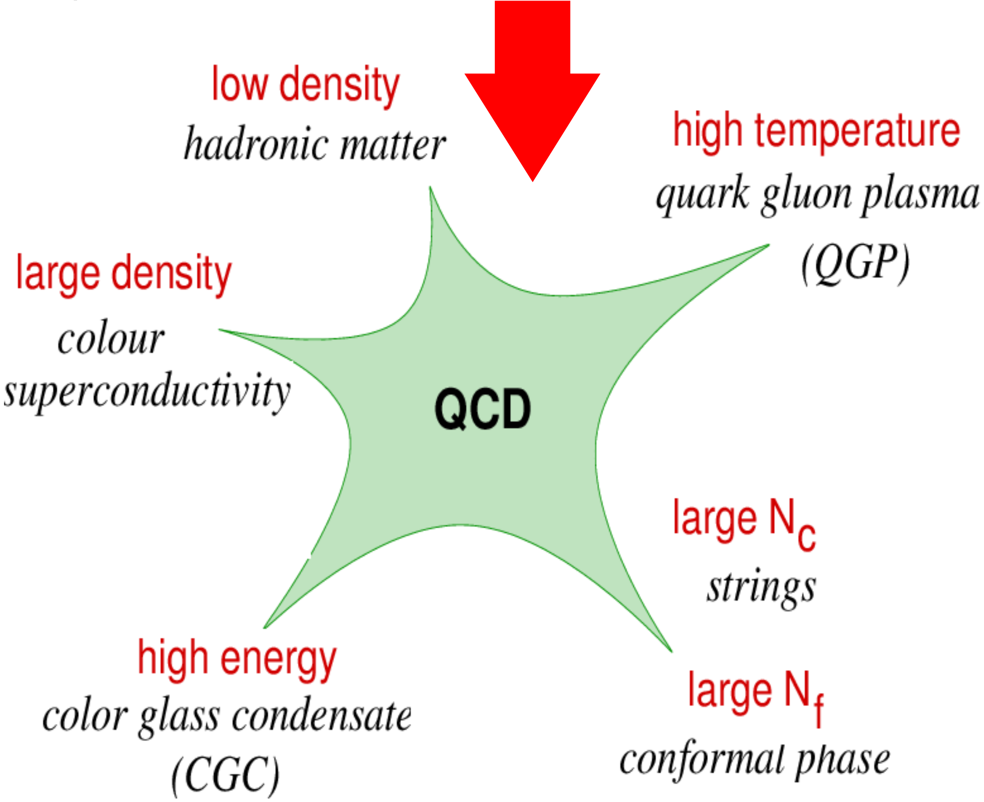
where $G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + f^a_{bc} A^b_\mu A^c_\nu$

and $D_\mu \equiv \partial_\mu + i t^a A^a_\mu$

$g^2(Q^2) \sim 4\pi / [\beta_0 \log(Q^2/\Lambda^2)]$, Λ~0.2 GeV

- QCD = the only sector of SM whose collective behaviour can be studied in the lab: phase transition(s), thermalization of fundamental fields, ...

- QCD = very diverse many-body phenomenology at various limits:



QCD

low density
hadronic matter

high temperature
quark gluon plasma (QGP)

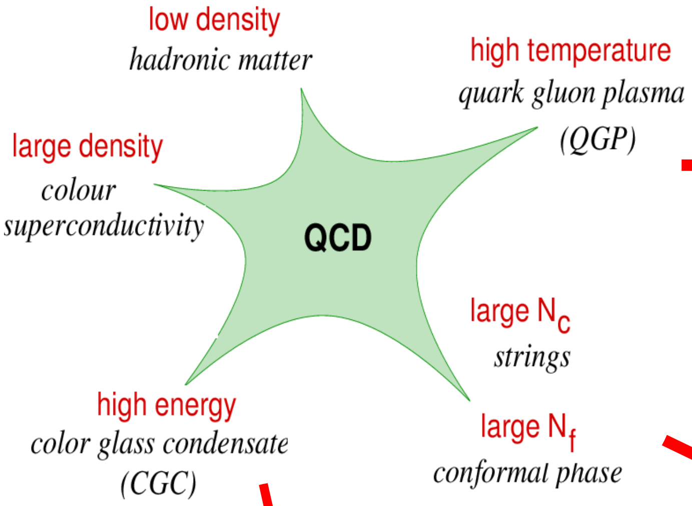
large density
colour superconductivity

large N_c
strings

high energy
color glass condensate (CGC)

large N_f
conformal phase

QCD matter: physics menu



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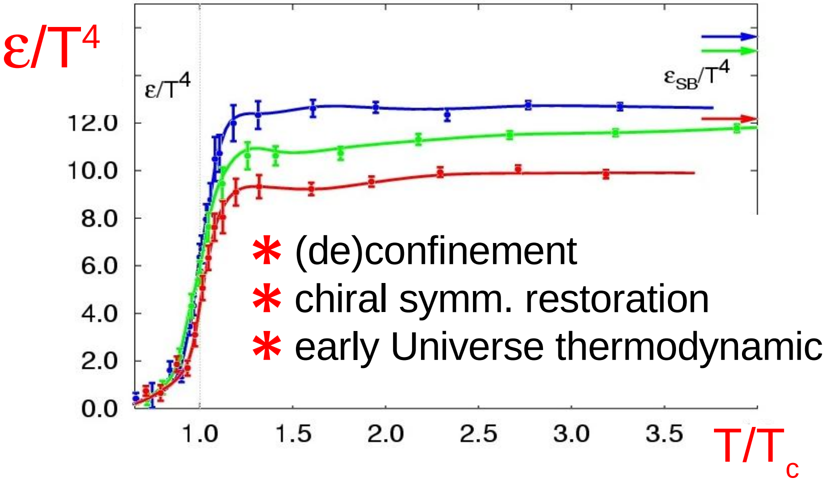
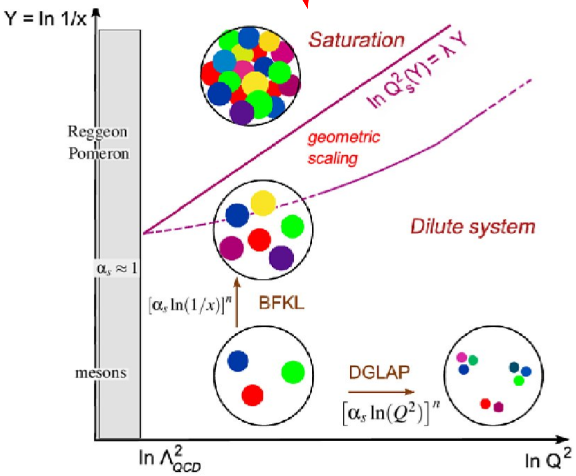
- Lattice QCD at high-T: **QGP**



* (de)confinement
* chiral symm. restoration
* early Universe thermodynamics

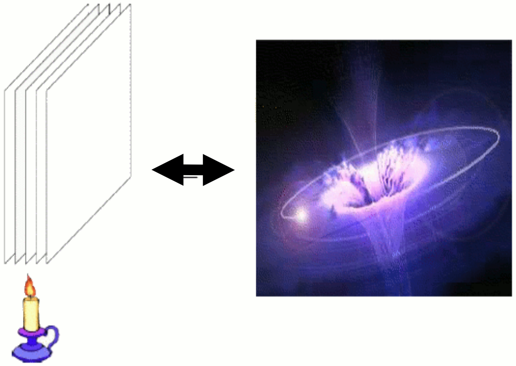
- High-density QCD at small-x: **CGC**



- Gauge-gravity duality: **AdS/CFT**

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

$\mathcal{N}$= 4 SYM
plasma in 4-D

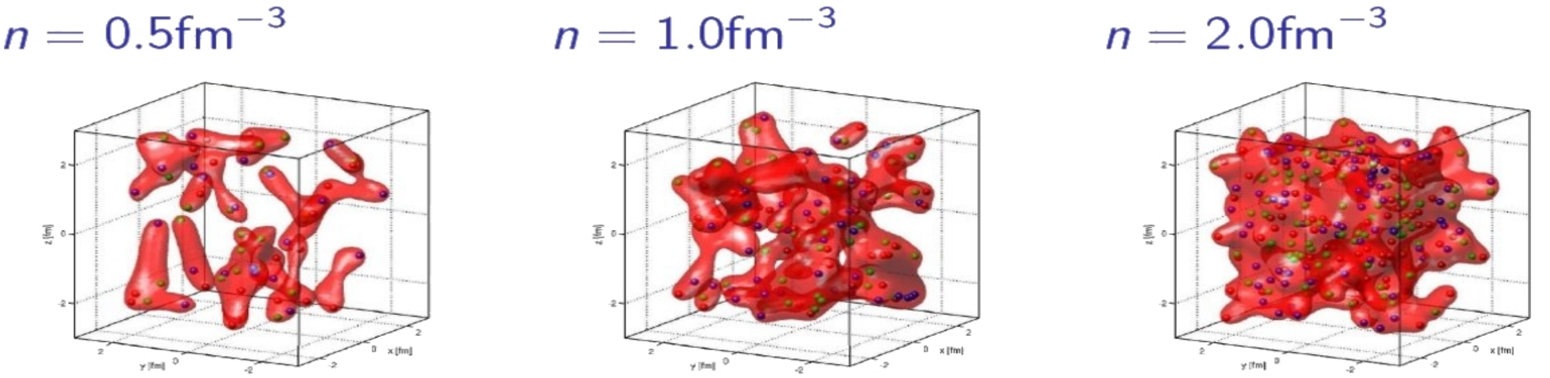


Black-hole in 5-D

* QGP transport coeffics: viscosity, diffusivity, ...

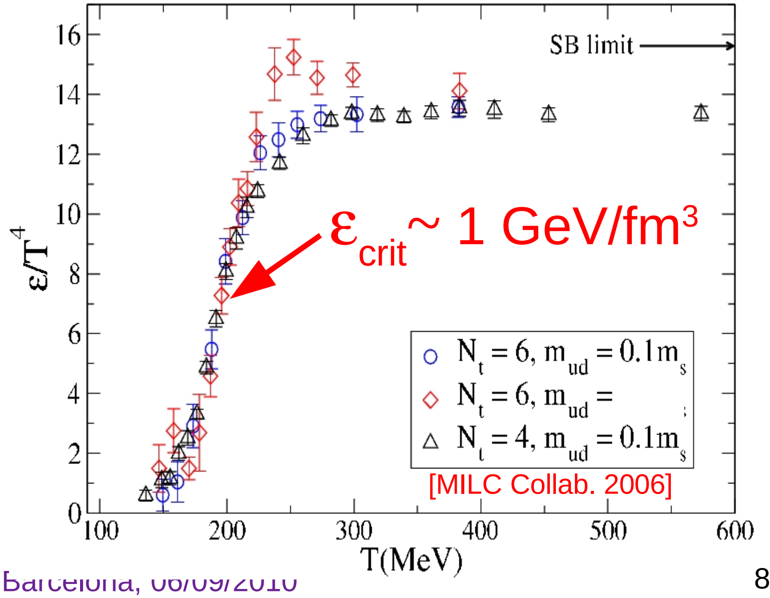
Topic I: Study of (bulk) deconfinement ...

- Increase of parton # density (n) ⇒ bulk deconfined state:



Color-neutral clusters Increasing overlap with n Color-connected system at n_{crit}

- Energy density vs. temperature (lattice QCD Equation-of-State):



$\varepsilon_{crit} \sim 1\ \text{GeV/fm}^3$

[MILC Collab. 2006]

Deconfinement transition:

- Sharp rise of ε at T_{crit}~0.2 GeV

- Sudden increase of degrees of freedom:

$\varepsilon \propto g_{eff} T^4$

g_{eff} (hadrons) = 3 (pions)

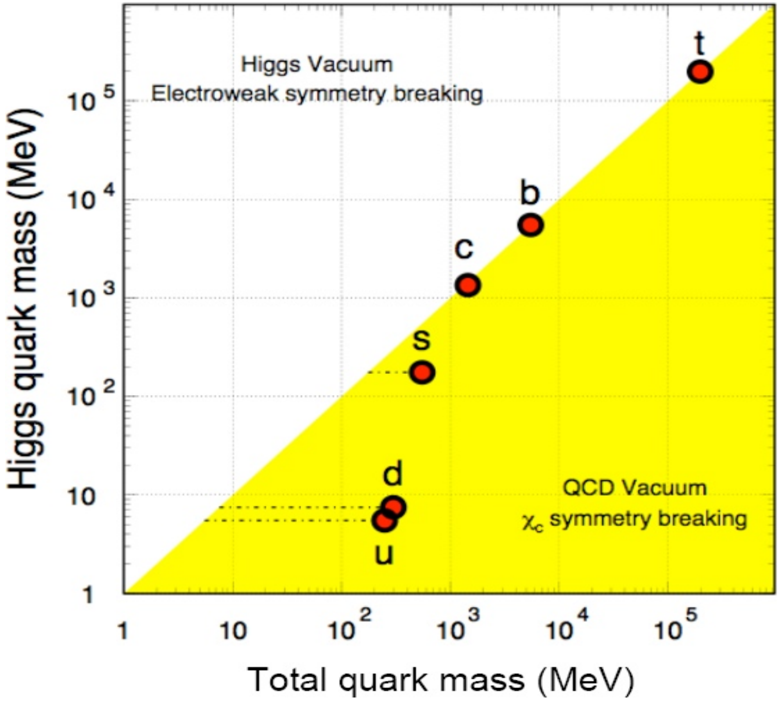
g_{eff} (QGP) ~ 47 (gluons,quarks)

= 2(spin)*8(color) + (7/8)*
[2*3(flavour)*3(color)*2(spin)]

Topic I: ... and origin of (visible) mass

- QCD (= χ-symm breaking) not (!) Higgs (= EWK-symm breaking) is truly responsible for the "origin of (baryon) mass" (~4% of all mass in Univ.):

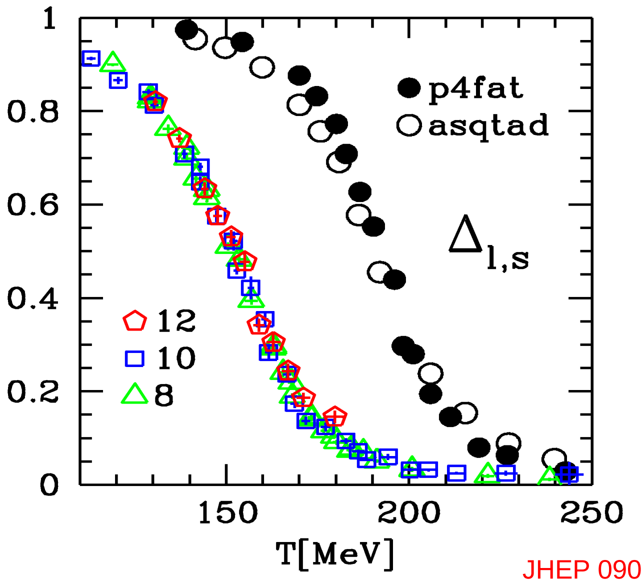
- Quark masses at T=0:



~98% of the u,d masses generated dynamically (gluons) in the QCD confining potential

- Quark masses at T≠0:

$<\bar{q}q>_{norm}$ in latt-QCD



JHEP 0906(09)088

Chiral transition: light-q recover bare mass at T_{crit}~0.15-0.2 GeV

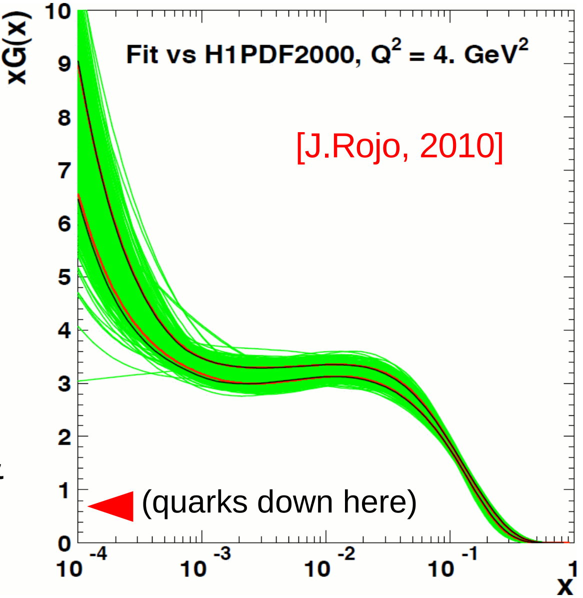
Topic 2: Gluon saturation

- Gluons dominate low-x hadronic wave-function:
- Radiation controlled by QCD evolution eqs.:

  Q^2 - DGLAP: $F_2(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n$, $Q_0^2 \sim 1$ GeV^2

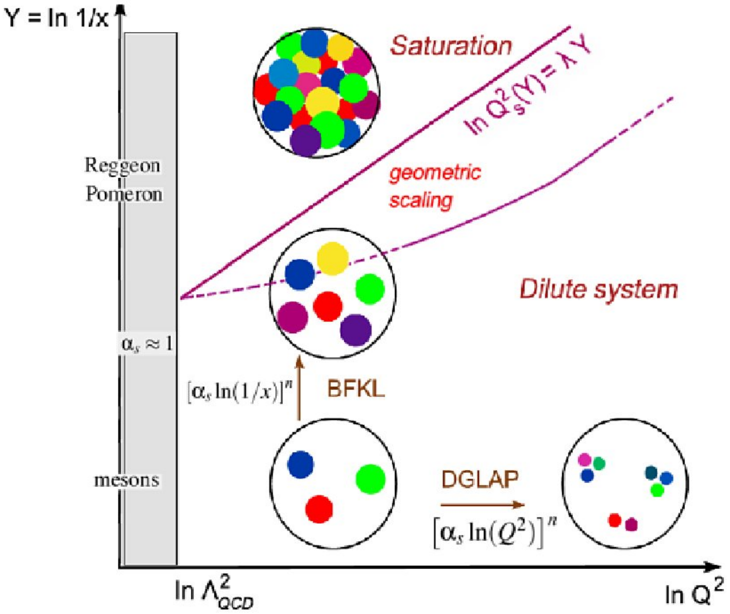
  x - BFKL: $F_2(x) \sim \alpha_s \ln(1/x)^n$

  Linear eqs. (single parton radiation/splitting) cannot work at very low-x: Unitarity violated (even for $Q^2 >> \Lambda^2$), collinear & k_T factorization breakdown.

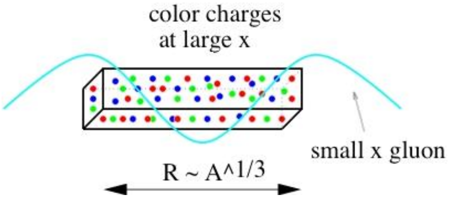


[J.Rojo, 2010]

(quarks down here)



- Gluons overlap below "saturation scale" $Q_s(x)$
- Color Glass Condensate = EFT describes hadrons as classical fields below Q_s
- Saturation effects enhanced in nuclei:



Large # of partons per transverse area

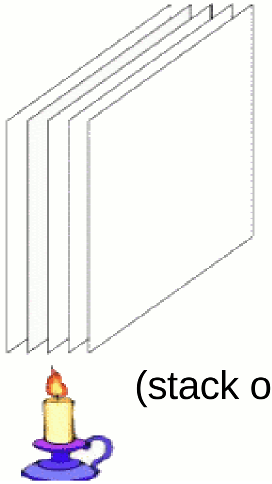
$Q_s^2 \sim A^{1/3} \sim 6$

Topic 3: AdS/CFT correspondence

- Strongly-coupled 4-D theories (QCD-like) can be studied analytically from eqs-of-motion/thermodynamics in simpler 5-D gravity duals.

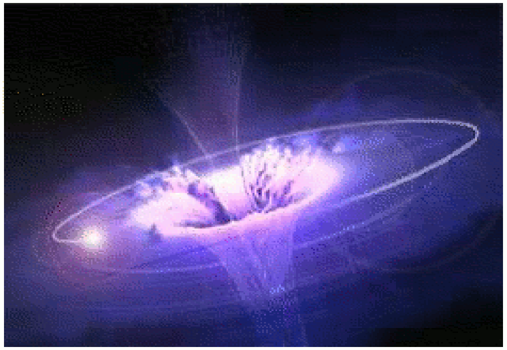
$$\mathcal{L} = \frac{1}{2g^2_{\rm YM}}\mathrm{Tr}(F_{\mu\nu}F^{\mu\nu}) + i\mathrm{Tr}(\bar{\psi}\gamma^\mu D_\mu\psi) \longleftrightarrow ds^2 = \frac{r^2}{R^2}(-dt^2 + d\vec{x}^2) + \frac{R^2}{r^2}d\Omega_5^2$$

𝒩=4 SYM plasma in 4-Dims



(stack of 4 branes)

=



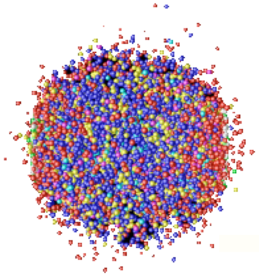
Black-Hole in AdS$_5$x S^5

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

- Guess the holography "dictionary" that relates both sides of duality for a given observable, e.g. BH Hawking T ⇔ QGP T ($T_H = r_0/4\pi R^2$)
- Large differences between QCD & SYM (extra SUSY degrees of freedom, no running-coupling, no confinement) "wash out" at finite-T.

QCD matter studies via heavy-ion collisions

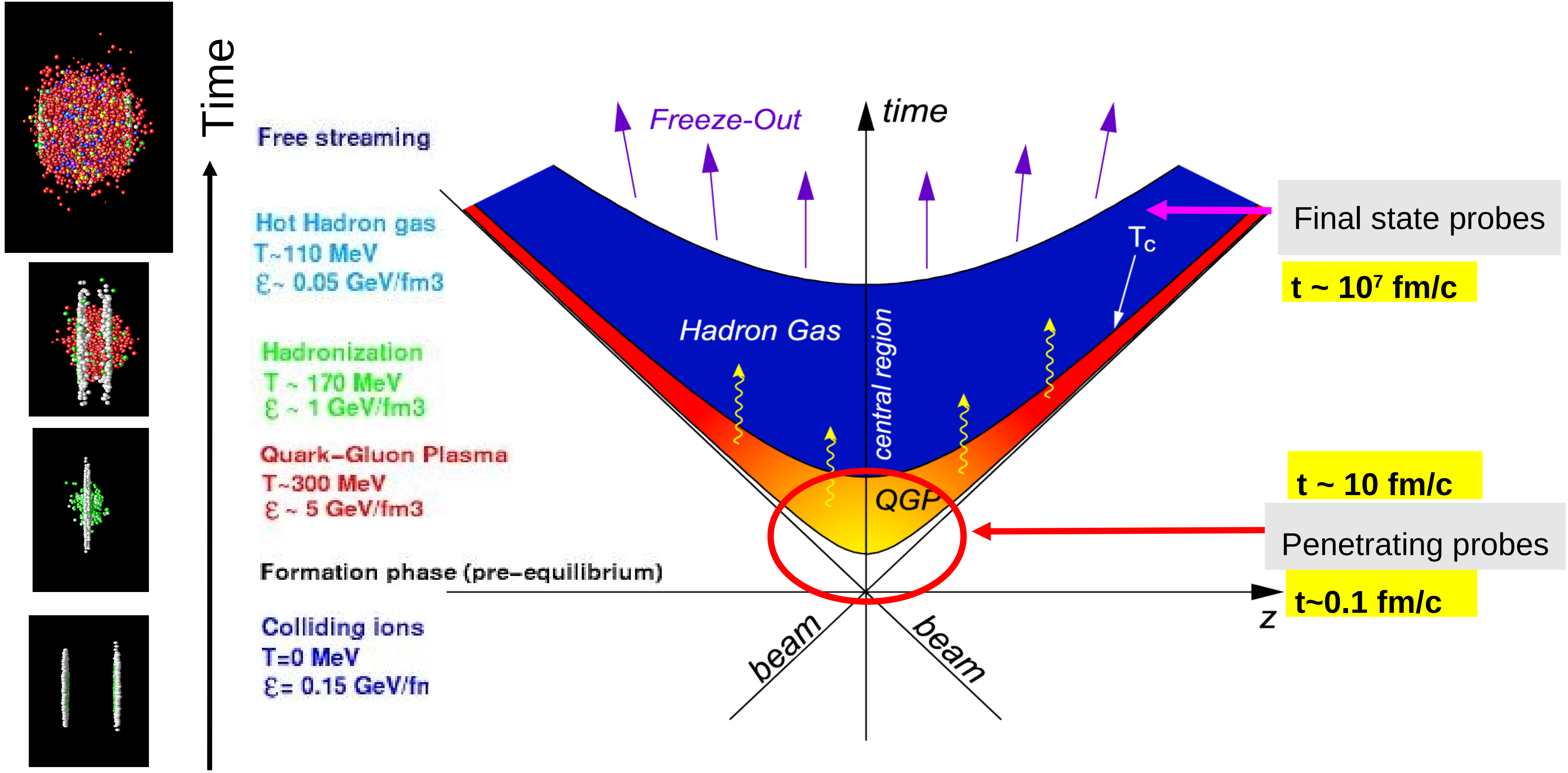
The "Little Bang" in the lab.



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~$\mathcal{O}(10^3\ \text{fm}^3)$ for times ~ 0.1-10 fm/c

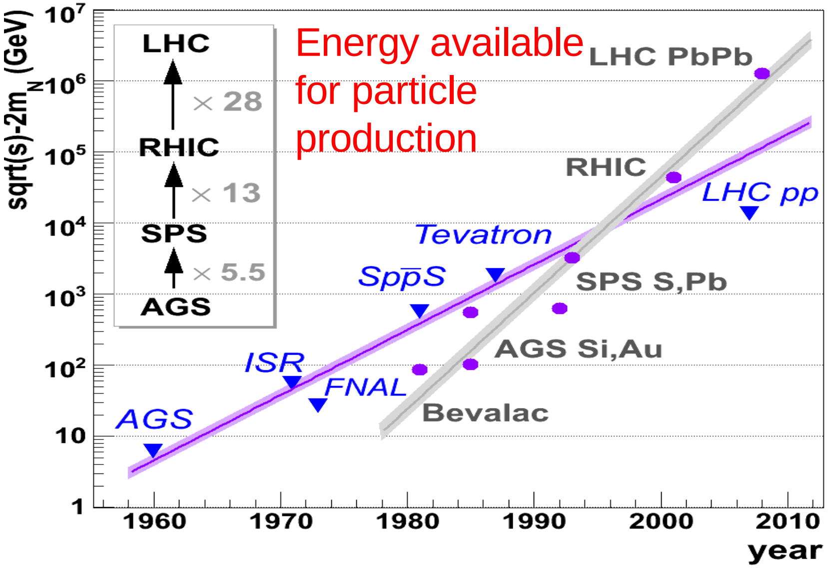
Collision dynamics: Diff. observables sensitive to diff. reaction stages



Energy densities in A-A collisions

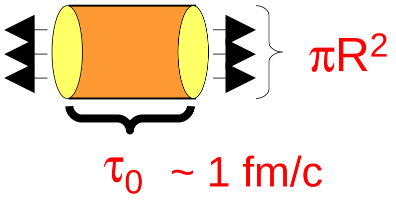
- T.D. Lee [Rev. Mod. Phys. 47 (1975) 267]:

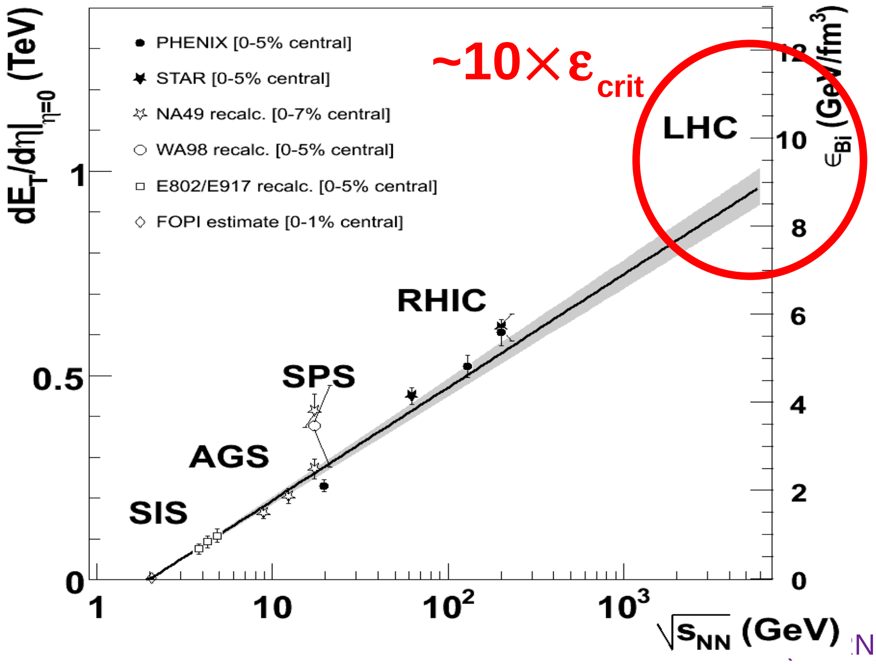
> *"In HEP we've concentrated on experiments in which we distribute a higher & higher amount of energy into a region with smaller & smaller dimensions. In order to study the question of 'vacuum' (...) we should investigate 'bulk' phenomena by distributing high energy over a relatively large volume."*



- Energy density "Bjorken estimate" (longitudinally expanding plasma):

$$\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$$

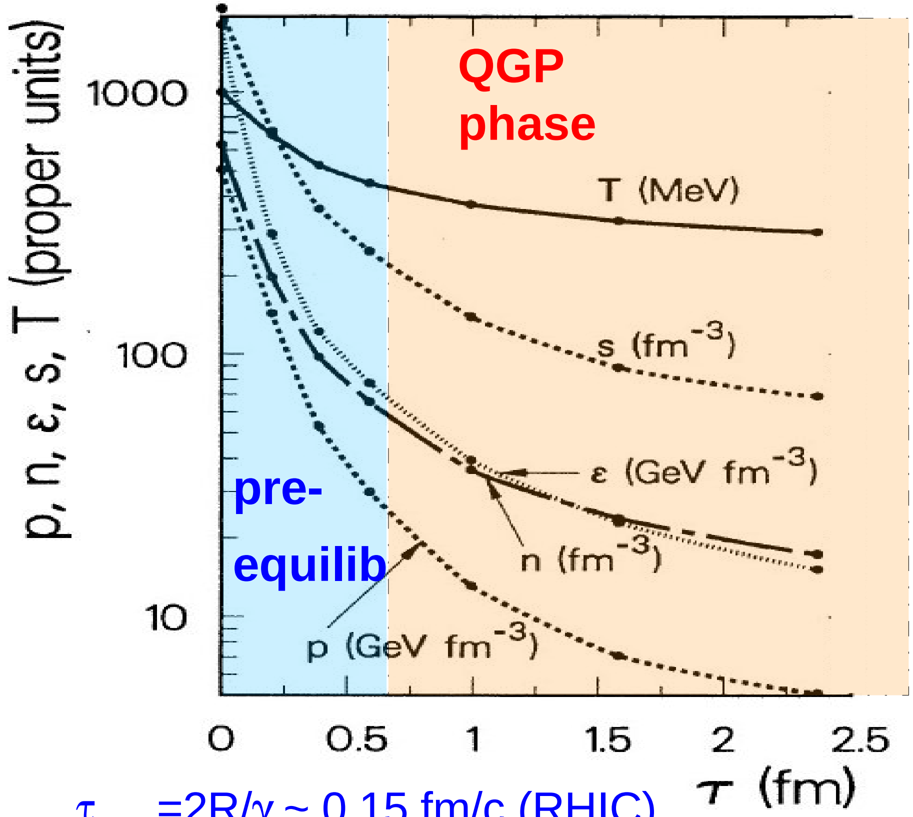




QCD fluid-dynamics

- After collision, medium expands ($\beta_L \approx 1$, $\beta_T > 0.5$) & cools within $\tau \sim 15$ fm/c.
- Power-law evolution of thermo-dynamical properties: $T \sim 1/\tau^{1/3}$, $\varepsilon \sim 1/\tau^{4/3}$,...

(longitudinal 1-D expansion)



$\tau_{cross} = 2R/\gamma \sim 0.15$ fm/c (RHIC)
$\sim 5 \cdot 10^{-3}$ fm/c (LHC)

- Relativistic fluid-dynamics needed to extract initial QGP properties:

Local conservation of energy-momentum tensor & other currents:

$$\begin{aligned} \partial_\mu T^{\mu\nu} &= 0 \\ \partial_\mu N_i^\mu &= 0, \quad i = B, S, \ldots \end{aligned}$$

Ideal (non-viscous) fluid tensor & charges:

$$\begin{aligned} T^{\mu\nu} &= (\epsilon + P) u^\mu u^\nu - P g^{\mu\nu} \\ N^\mu &= n u^\mu \end{aligned}$$

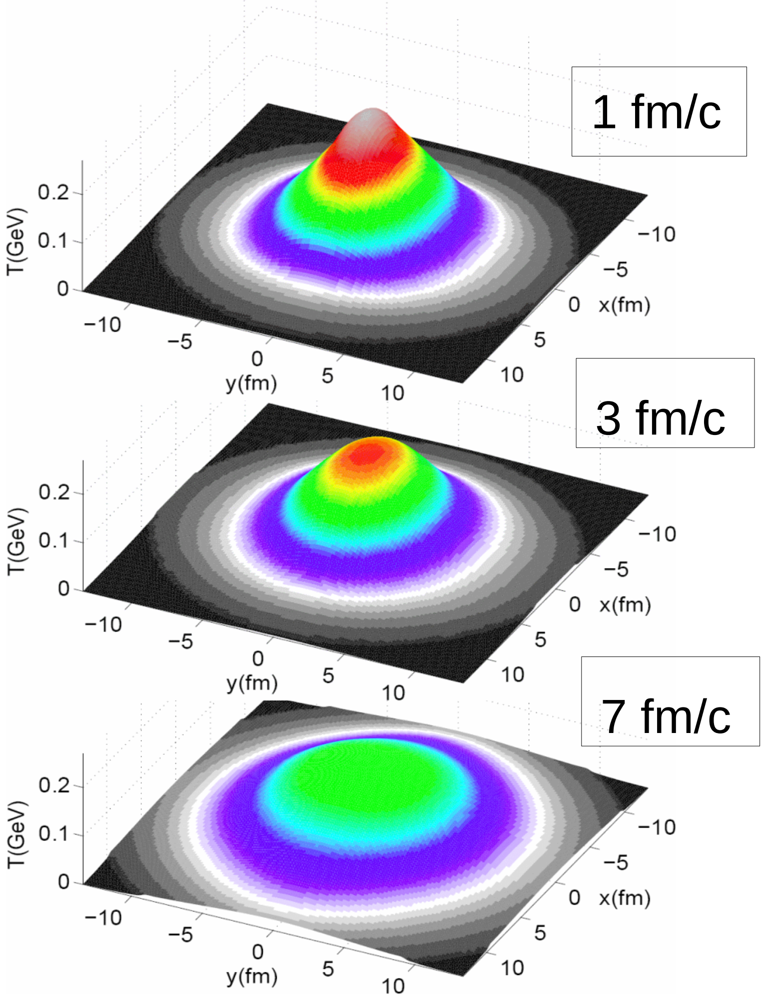
(u^μ: fluid velocity)

Equation-of-State (parton relativ. gas):

$$\varepsilon = 3 \cdot P \propto g_{\rm eff} \cdot T^4$$ (Stefan-Boltzmann)

3-D viscous QCD fluid-dynamics

- After collision, medium expands ($\beta_L \approx 1$, $\beta_T > 0.5$) & cools within $\tau \sim 15$ fm/c.
- Relativistic 3-D (viscous) fluid-dynamics needed to extract initial QGP properties



Local conservation of energy-momentum tensor & other currents:

$$\begin{aligned} \partial_\mu T^{\mu\nu} &= 0 \\ \partial_\mu N_i^\mu &= 0, \quad i = B, S, \ldots \end{aligned}$$

Viscous fluid tensor & charges:

$$\begin{aligned} T^{\mu\nu} &= (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu} + \Pi^{\mu\nu} \\ N^\mu &= n u^\mu \end{aligned}$$

($\Pi^{\mu\nu}$: shear-stress)

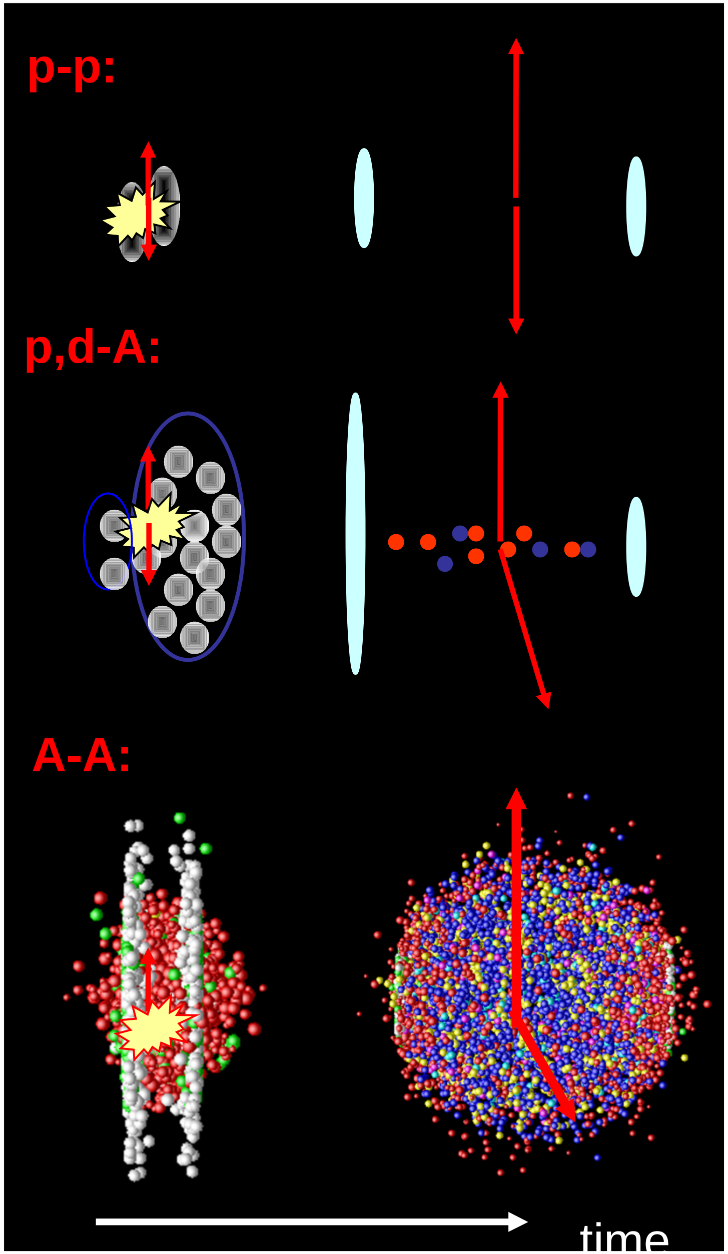
Equation-of-State (parton relativ. gas):

$$\varepsilon = 3 \cdot P \propto g_{\rm eff} \cdot T^4$$

(Stefan-Boltzmann)

Heavy-Ion Experiments

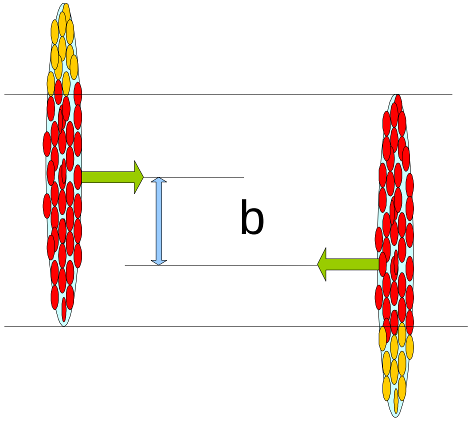
proton-proton & proton-nucleus baselines



p-p = “QCD vacuum” (reference)

p,d-A = “cold QCD medium” (control)

A-A = “hot & dense QCD matter”



Plasma volume
dialed varying
impact parameter b
(“centrality”)

Relativistic Heavy-Ion Collider (RHIC) @ BNL

- Specifications:

3.83 km circumference

2 independent rings:

  - 120 bunches/ring
  - 106 ns crossing time

A-A collisions @ $(\sqrt{s}_{NN})_{max}$ = 200 GeV

Lumi: ~10^{27} cm^{-2} s^{-1} (~6 kHz,~6 mo./year)

p-p @ $\sqrt{s}_{max}$= 500 GeV

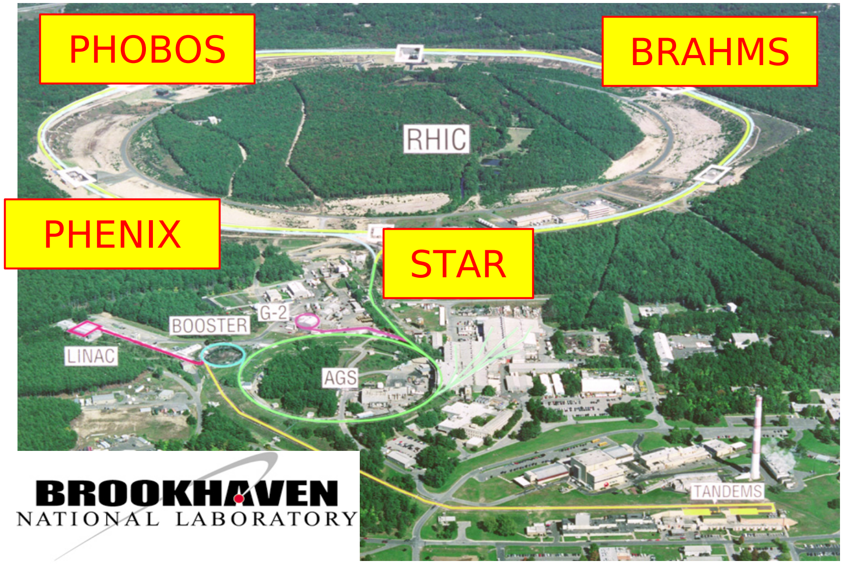
p,d-A @ $\sqrt{s}_{max}$= 200 GeV

- 4 experiments:

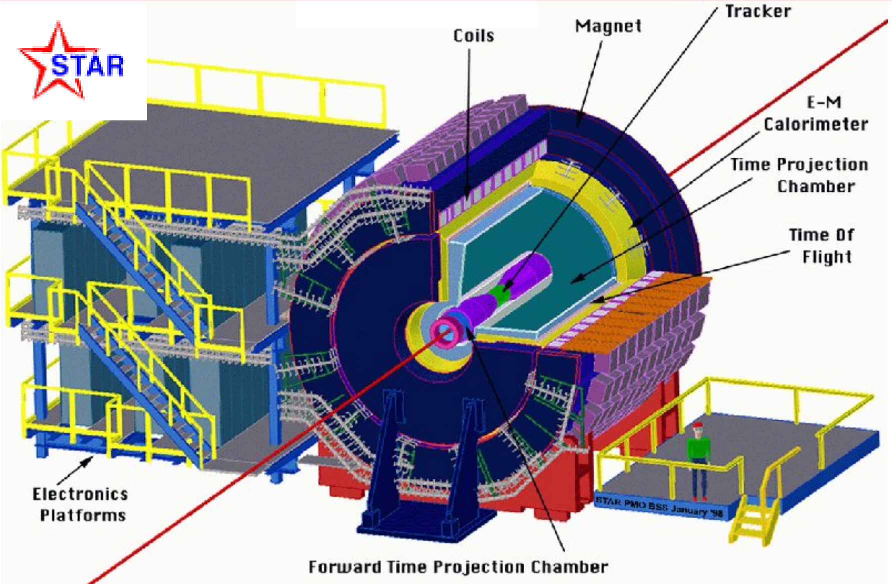
PHENIX, STAR (BRAHMS, PHOBOS)

- Runs 1 - 7 (2000 – 2010):

Au-Au,Cu-Cu @ $\sqrt{s}_{NN}$ = 4 – 200 GeV
d-Au @ $\sqrt{s}_{NN}$ = 200 GeV
p-p, p↑-p↑ @ $\sqrt{s}$ = 22 – 500 GeV

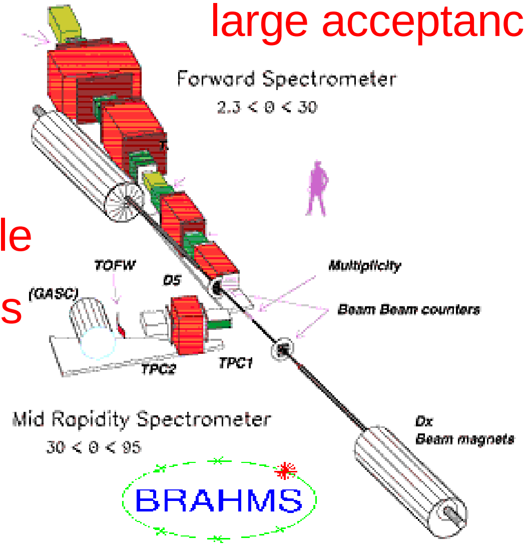


RHIC experiments



TPCs, Si, calorimeters,

large acceptance

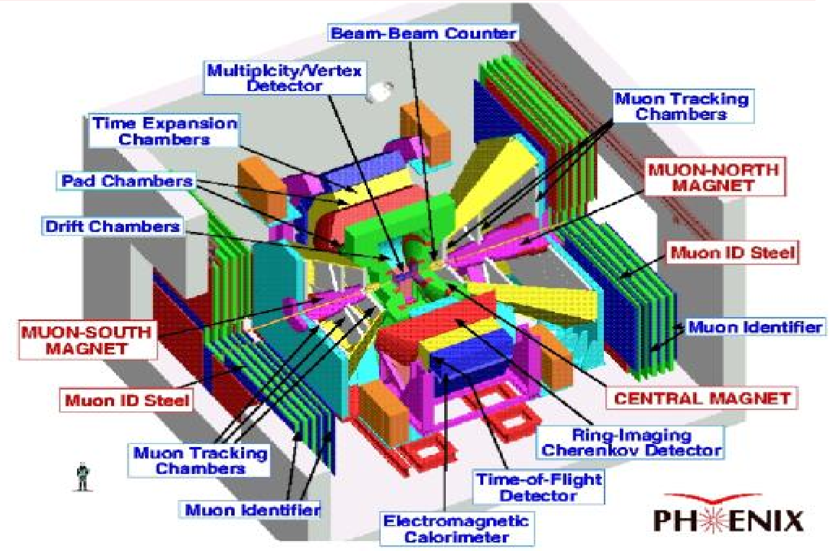


2 magn. dipole

spectrometers

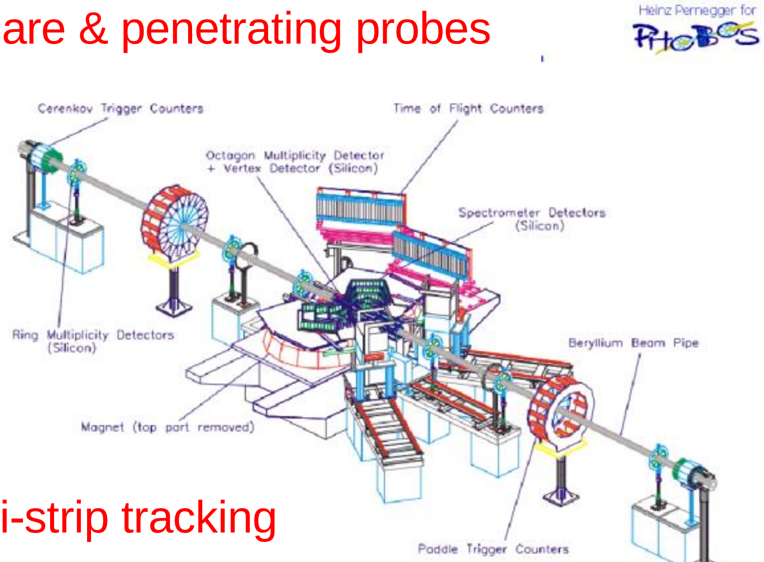
in “fix-target”

config.



Hadrons, e,μ,γ. High-rate DAQ.

Rare & penetrating probes

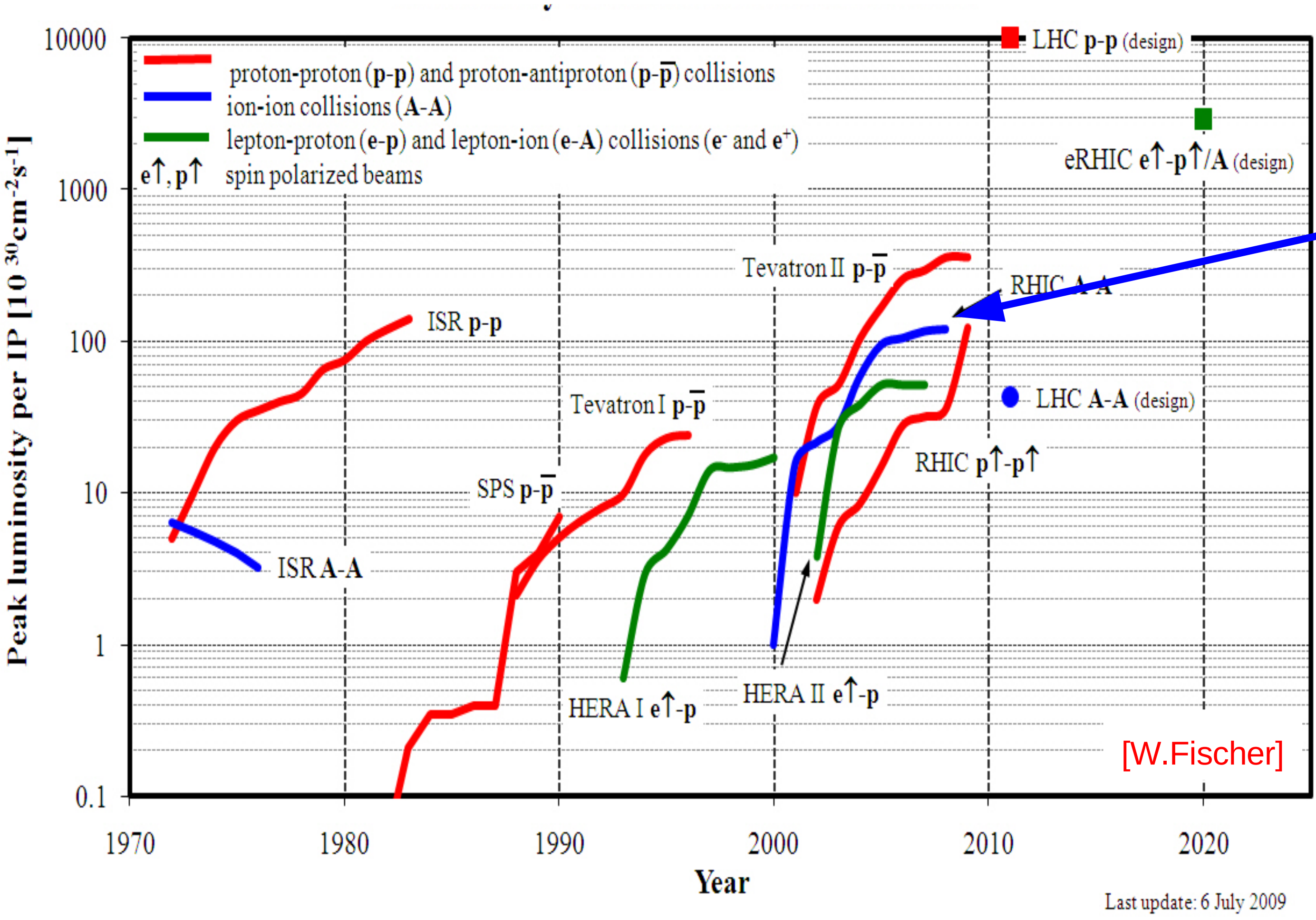


Si-strip tracking

PMT-based TOF

RHIC luminosities

- Peak luminosities: $\mathcal{L}_{\text{equiv-pp}} = A^2 \times \mathcal{L}_{AA} \sim 200^2 \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1} \sim 10^{32}\ \text{cm}^{-2}\text{s}^{-1}$
- Max. integrated luminosities: $\int \mathcal{L}dt \sim 400\ \text{pb}^{-1}$ (A-A), 150 pb^{-1} (p↑-p↑)



[W.Fischer]

- Recent 1st-ever measurements in heavy-ion colls.:

⇒Jets (to 50 GeV)

⇒Upsilon

Large Hadron Collider (LHC) @ CERN

- Specifications:

  1 ring: 26.7 km circumference
  8.33 T superconducting coils
  25 ns crossing time

Pb-Pb @ $\sqrt{s_{NN}}$= 5.5 TeV

Lumi: 10^{27} cm^{-2} s^{-1} (~7 kHz, 1mo./year)

p-p collisions @ $\sqrt{s_{NN}}$ = 14 TeV

Lumi: 10^{34} cm^{-2} s^{-1} (~600 MHz, 8 mo./year)

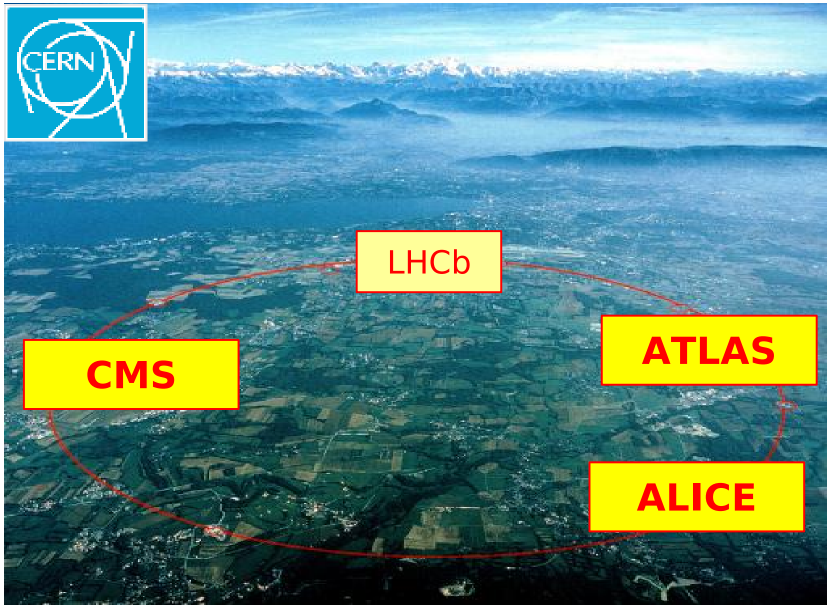
p,d-Pb @ $\sqrt{s_{NN}}$ = 8.8 TeV

- 3 experiments:

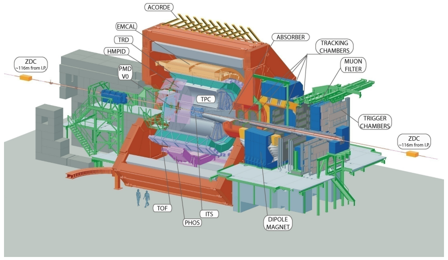
  ALICE, ATLAS, CMS

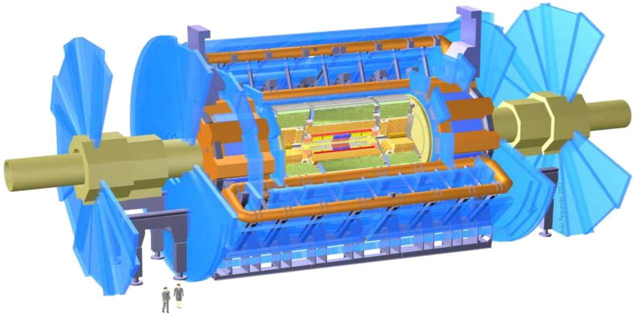
- Run planning:

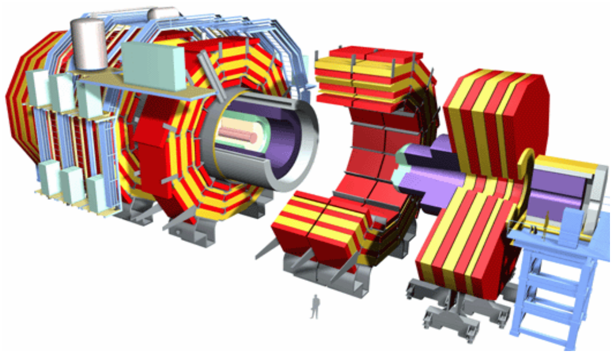
  p-p @7-14 TeV (2010, ...)
  Pb-Pb @ 2.76-5.5 TeV (2010, ...)
  p-Pb @ 8.8 TeV (2015?)



LHC heavy-ion experiments







ALICE: dedicated HI experiment

People: largest community (~1000)

$|\eta|<1$: Tracking (TPC+ITS+TRD)

Calorimetry (EMCal,PHOS)

$\eta=2.5-4$: Muon spectrometer.

0.5 T solenoid magnet

Strongest capabilities:

low-p_T, light-quark PID, ...

ATLAS & CMS: multipurpose (pp+HI) program

People: ~50/2000 (ATLAS), ~120/2500 (CMS)

$|\eta|< 2.5$: Tracking, muons

$|\eta|< 5$: EM/HAD Calorimetry

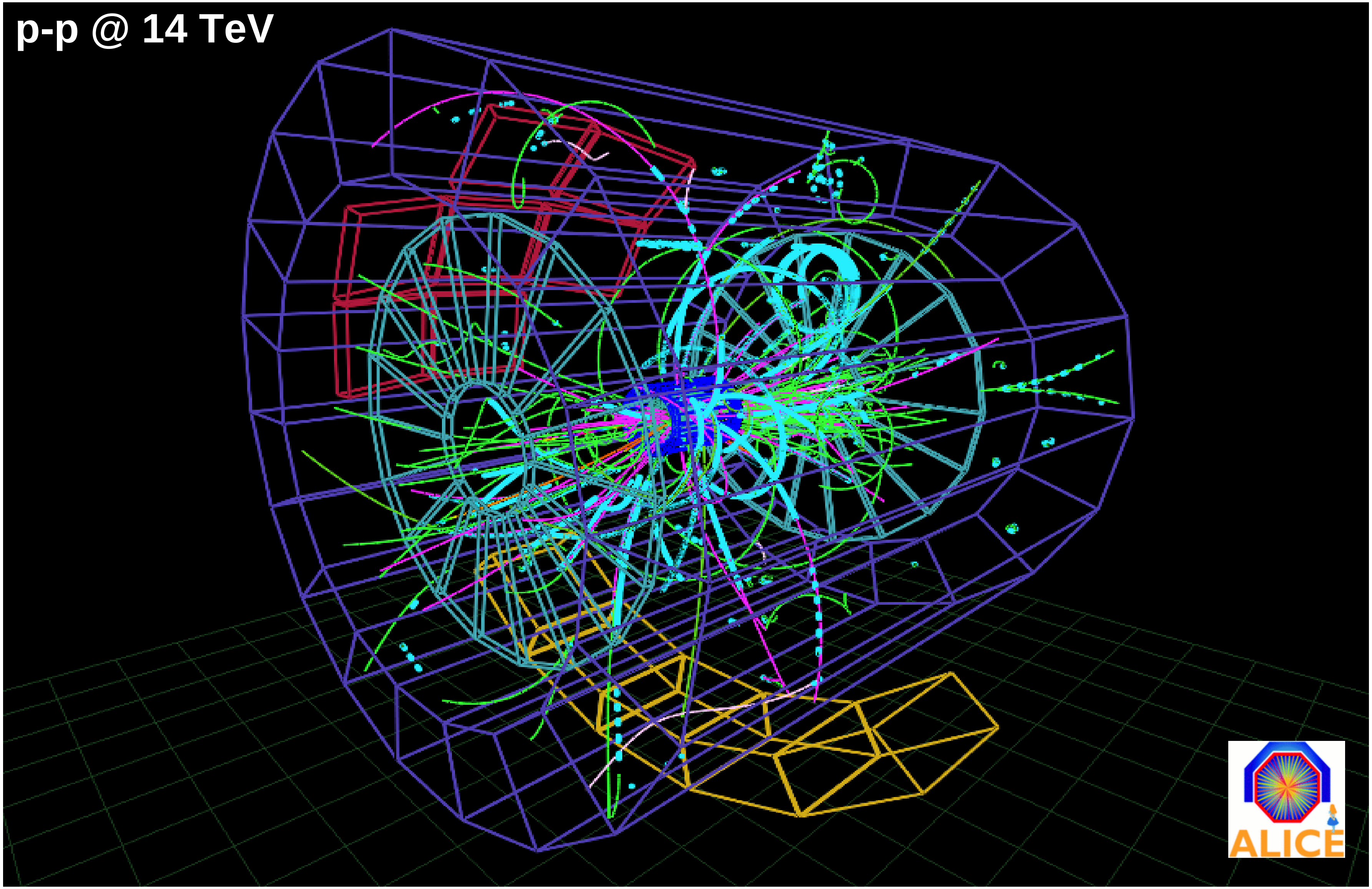
$\eta=5-6.6$: Forward calorimetry (CMS)

4 T (CMS), 2 T (ATLAS) mag. field

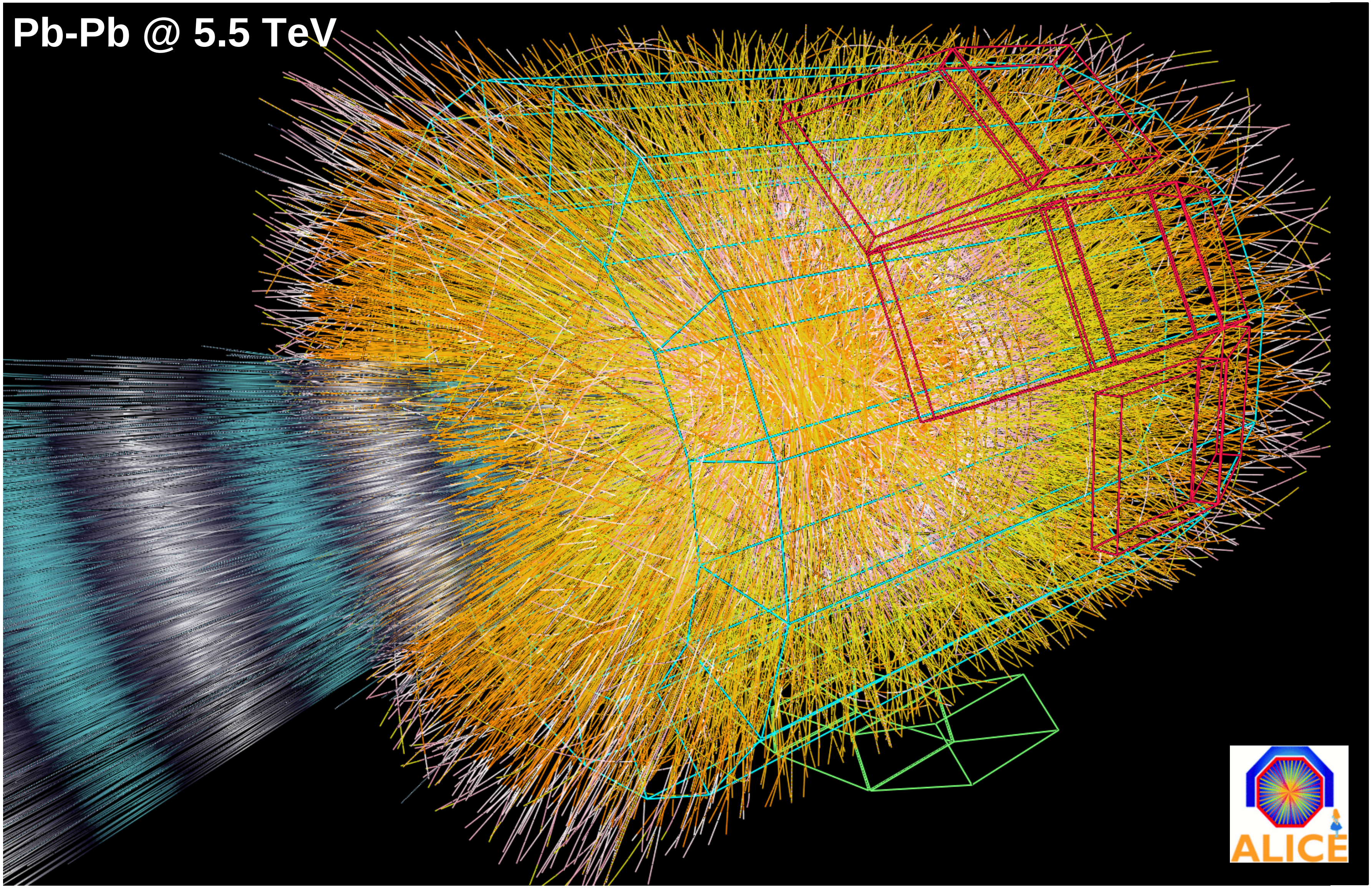
Strongest capabilities:

hard-probes, full jet reco, heavy-Q jet PID

ALICE event display: p-p @ 14 TeV



ALICE event display: Pb-Pb @ 5.5 TeV



Quark-gluon matter probes:

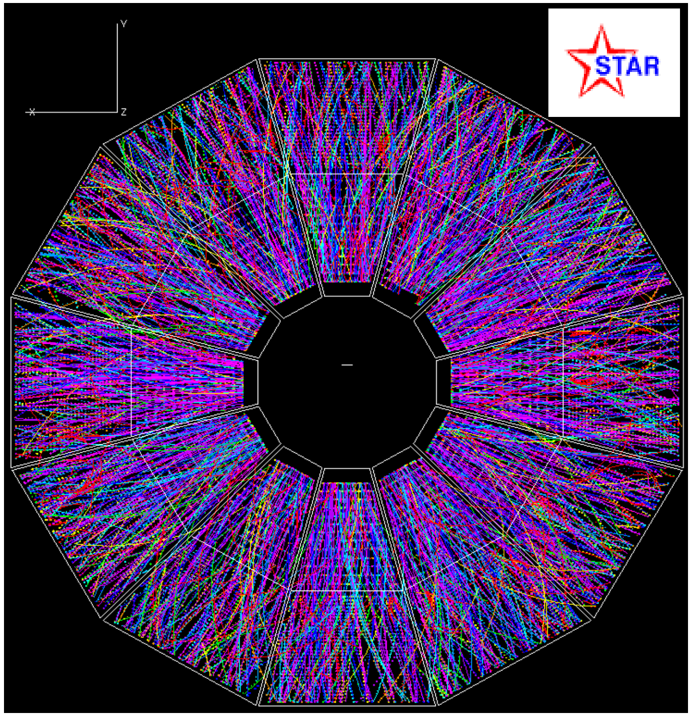
Observable (type)	Medium property	Theoretical tool
$dN/d\eta$ multiplicity (soft)	gluonic struct. $xG(x,Q^2)$	Color-Glass-Condensate
dN/dp_T spectra (soft)	Equation-of-State $P(V,T)$	(Hydro), Lattice QCD
$dN/d\Delta\phi$ elliptic flow (soft)	shear viscosity η	(Hydro), AdS/CFT
Jet quenching (hard)	transport coefficient $<q>$	(Hydro),pQCD,AdS/CFT
γ enhancement (intermed.)	critical temperature T_{crit}	(Hydro), Lattice QCD
QQ suppression (hard)	critical energy density ε_{crit}	(Hydro), Lattice QCD

Quark-gluon matter probes (1)

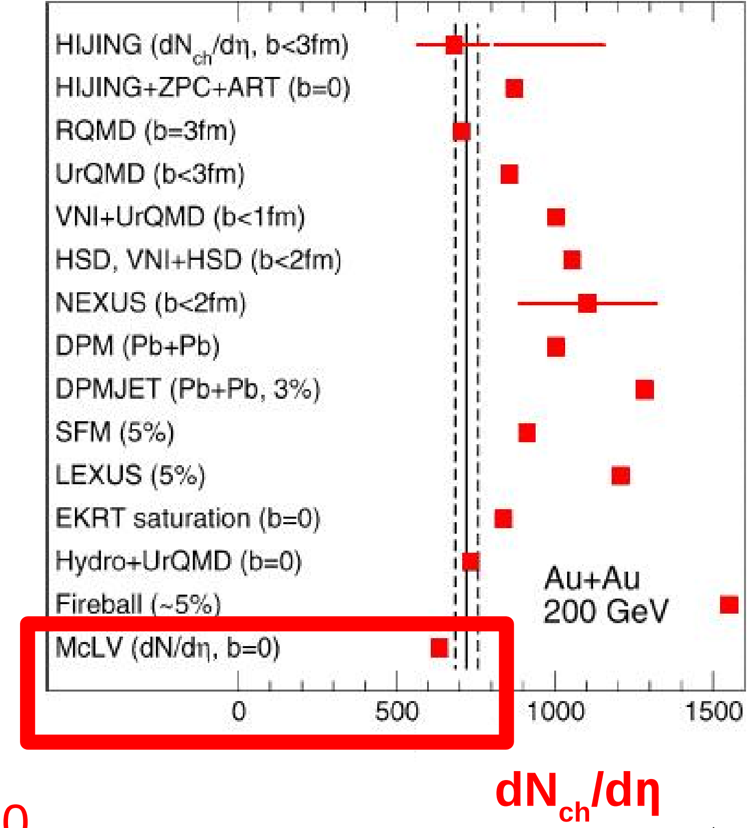
Observable (type)	Medium property	Theoretical tool
$dN/d\eta$ multiplicity (soft)	**gluonic struct. $xG(x,Q^2)$**	**Color-Glass-Condensate**
dN/dp_T spectra (soft)	Equation-of-State $P(V,T)$	(Hydro), Lattice QCD
$dN/d\Delta\phi$ elliptic flow (soft)	shear viscosity η	(Hydro), AdS/CFT
Jet quenching (hard)	transport coefficient $<q>$	(Hydro),pQCD,AdS/CFT
γ enhancement (intermed.)	critical temperature T_{crit}	(Hydro), Lattice QCD
QQ suppression (hard)	critical energy density ε_{crit}	(Hydro), Lattice QCD

Total Au-Au hadron multiplicity (RHIC)

- AuAu (200 GeV) 0-5% central collisions:

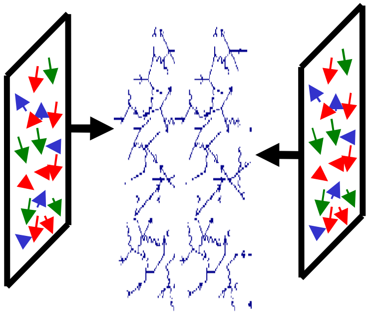


Armesto-Pajares IJMP-A 14 (2000) 2019



~ 650 charged hadrons per unit rapidity at y=0

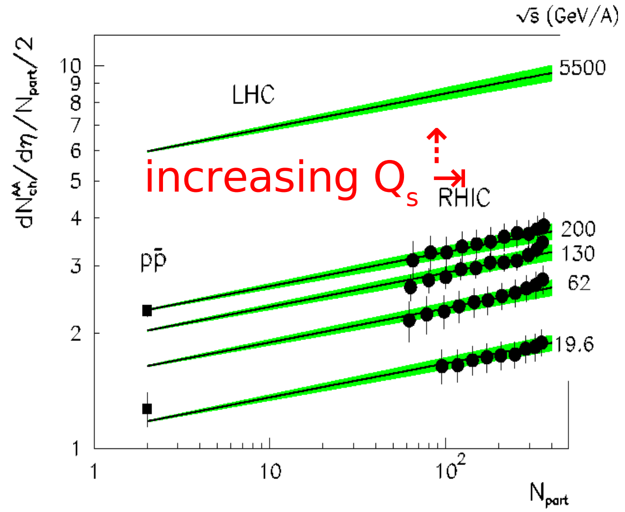
- Most hadrons from semihard partons w/ Q_s~1.5 GeV
- Low multiplicity predicted by saturation models due to reduced incoming parton flux (gg→g)



Total Pb-Pb hadron multiplicity (LHC)

- Final A-A hadron multiplicity ∝ Initial # of released gluons with $p_T \sim Q_s \propto xG \propto A^{1/3}\times(\sqrt{s})^{\lambda}$:

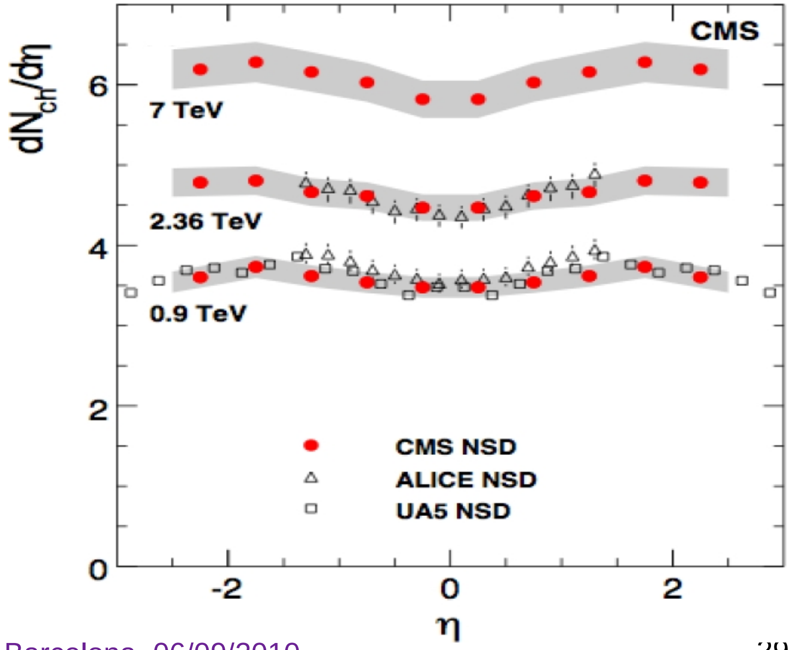
  CGC: $dN_{ch}/d\eta \propto A^{1/3}\times(\sqrt{s})^{\lambda}$, with $\lambda\sim0.25$

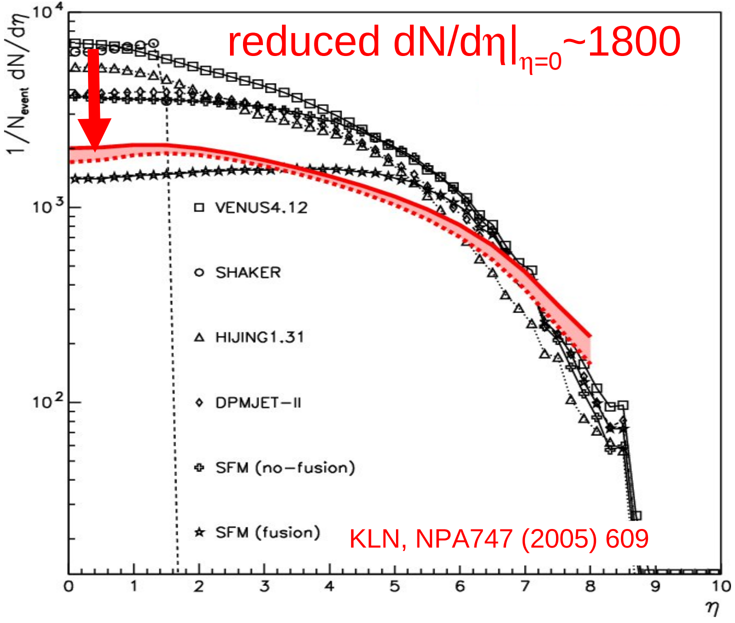


increasing Q_s

- $dN_{ch}/d\eta$: 1st LHC measurement (Si trackers):

p-p at 0.9, 2.36, 7 TeV





Gluon saturation ⇒ reduced $dN/d\eta|_{\eta=0}\sim1800$

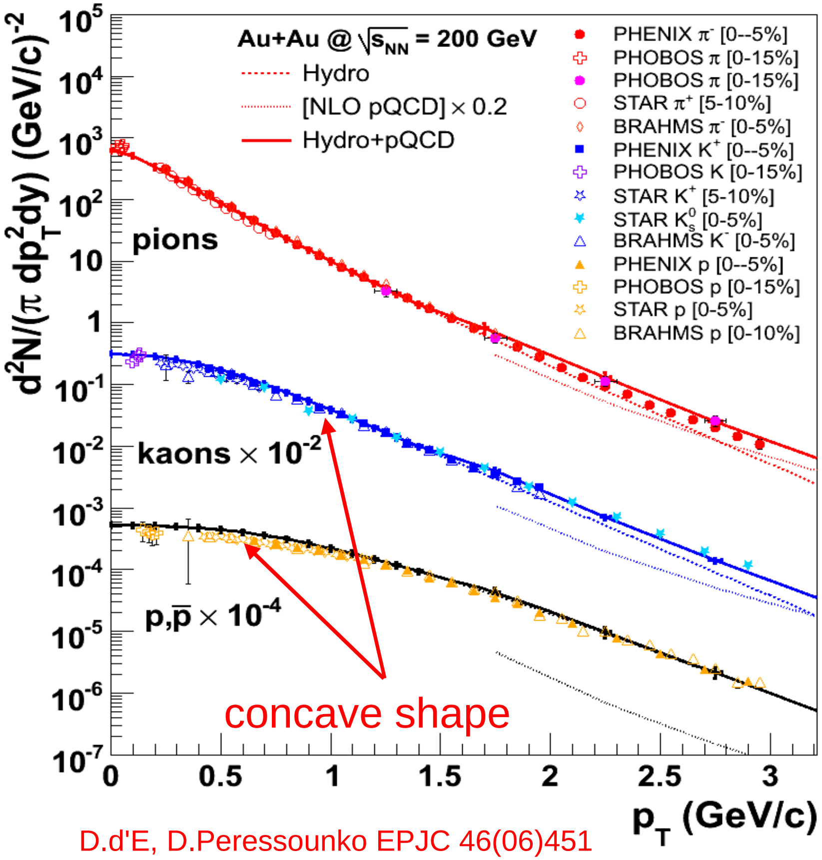
KLN, NPA747 (2005) 609

Quark-gluon matter probes (2)

Observable (type)	**Medium property**	**Theoretical tool**
dN/dη multiplicity (soft)	gluonic struct. $xG(x,Q^2)$	Color-Glass-Condensate
dN/dp$_T$ spectra (soft)	**Equation-of-State P(V,T)**	**(Hydro), Lattice QCD**
dN/dΔϕ elliptic flow (soft)	shear viscosity η	(Hydro), AdS/CFT
Jet quenching (hard)	transport coefficient <q>	(Hydro),pQCD,AdS/CFT
γ enhancement (intermed.)	critical temperature T_{crit}	(Hydro), Lattice QCD
QQ suppression (hard)	critical energy density ε_{crit}	(Hydro), Lattice QCD

Soft hadron spectra (RHIC)

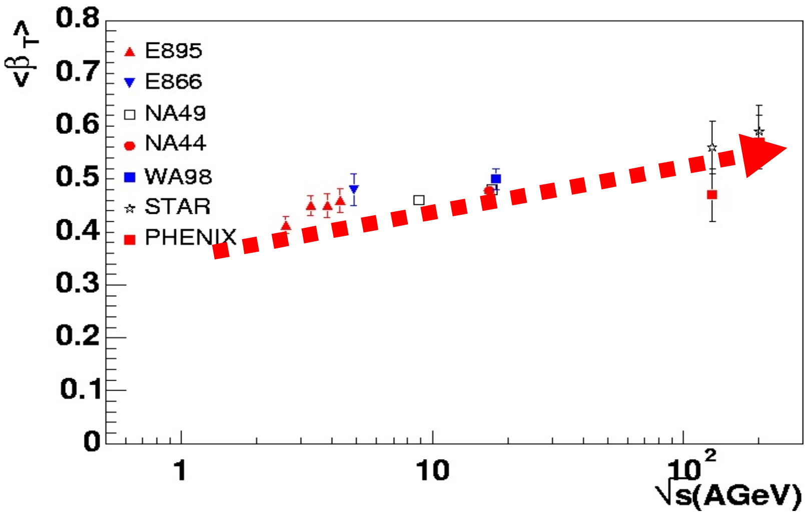
- Single hadron ($\pi^{\pm}$, $K^{\pm}$, p, pbar) p_T spectra up to ~2 GeV/c boosted for increasing centrality, with a (mass-dependent) collective radial flow:



concave shape

D.d'E, D.Peressounko EPJC 46(06)451

Strong radial collective flow built-up at freeze-out: $\langle\beta_T\rangle \approx$ 0.6



Expansion rate depends on EoS:

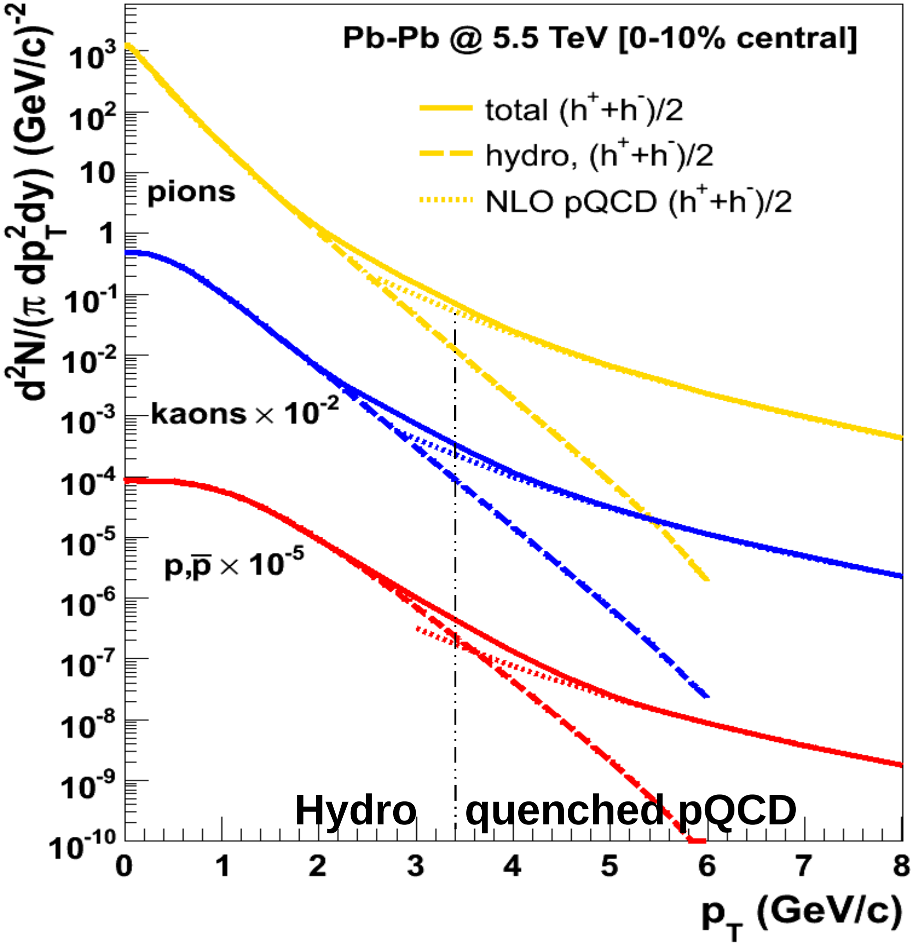
$$\frac{\partial u^{\mu}}{\partial t} = \frac{c_s^2}{1+c_s^2} \cdot \frac{\nabla^{\mu}\varepsilon}{\varepsilon} \quad \text{with} \quad c_s^2 = \frac{\partial P}{\partial \varepsilon} = \frac{1}{3}$$

- “Explosive” behaviour reproduced in hydro:

QGP EoS (ε_0~30 GeV/fm^3) & fast thermalization (τ_0~0.6 fm/c)

Soft hadron spectra (LHC)

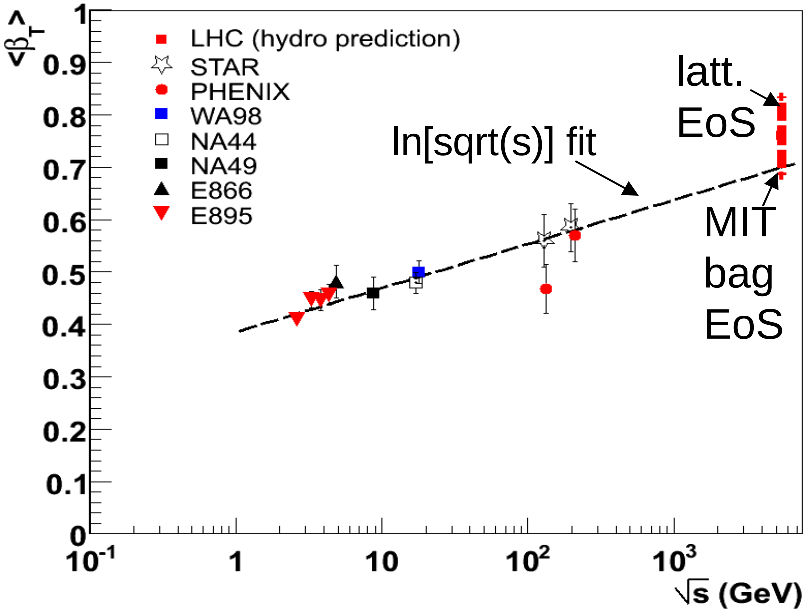
- LHC plasma starts hotter & denser: Larger transverse pressure expected
- “Hydrodynamics predictions for ε_0~650 GeV/fm^3 at τ_0~0.1 fm/c:



Arleo-DdE-Peressounko JPG 35 (08)054001

Collective expansion velocity

of inclusive hadrons: $<\beta_T> \approx$ 0.75

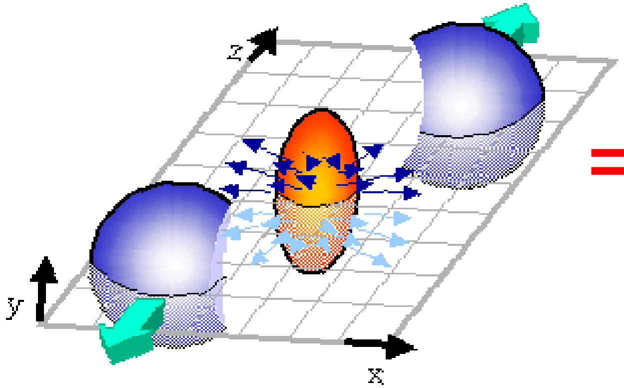


Quark-gluon matter probes (3)

Observable (type)	**Medium property**	**Theoretical tool**
dN/dη multiplicity (soft)	gluonic struct. xG(x,Q^2)	Color-Glass-Condensate
dN/dp_T spectra (soft)	Equation-of-State P(V,T)	**(Hydro), Lattice QCD**
dN/d$\Delta\phi$ elliptic flow (soft)	**shear viscosity η**	**(Hydro), AdS/CFT**
Jet quenching (hard)	transport coefficient <q>	(Hydro),pQCD,AdS/CFT
γ enhancement (intermed.)	critical temperature T_{crit}	(Hydro), Lattice QCD
QQ suppression (hard)	critical energy density ε_{crit}	(Hydro), Lattice QCD

Elliptic flow: azimuthal anisotropies

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



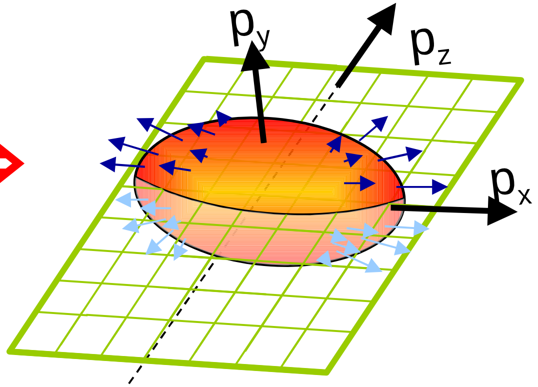
⇒

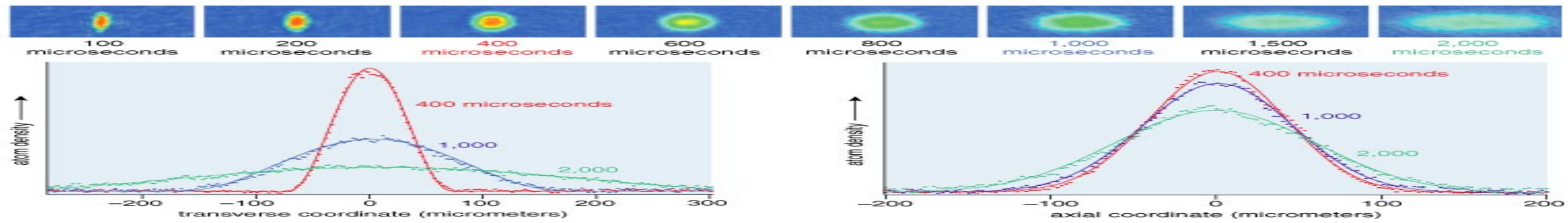
Strong initial-state pressure gradients

⇔

large & fast parton rescatterings

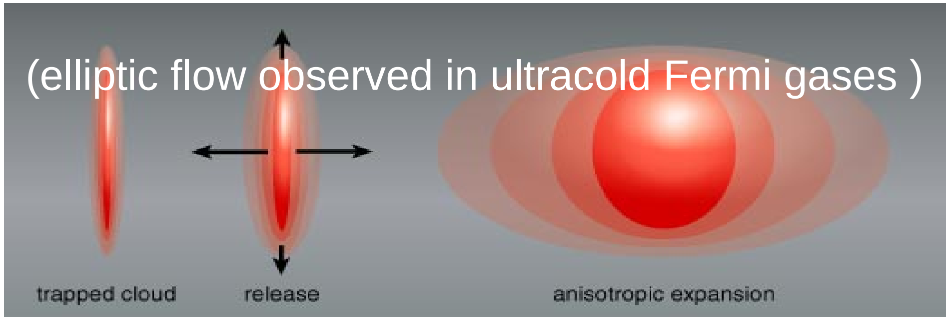
⇒





t=100 μs

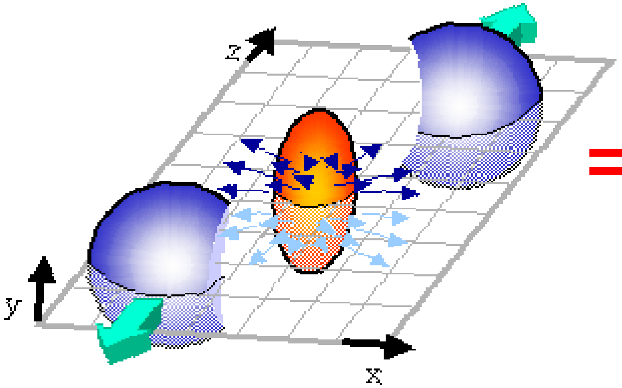
t=2000 μs


(elliptic flow observed in ultracold Fermi gases)

M. Gehm et al. Sci 298 (02)2179

Elliptic flow: azimuthal anisotropies

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



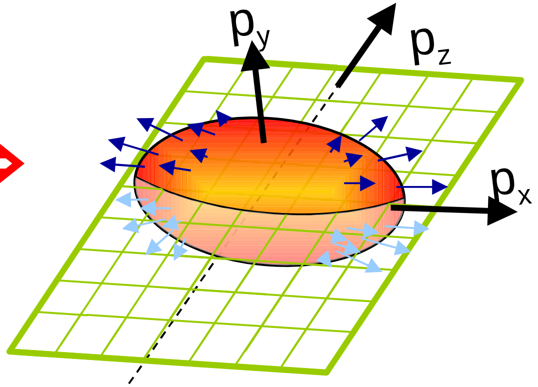
⇒

Strong initial-state pressure gradients

⇔

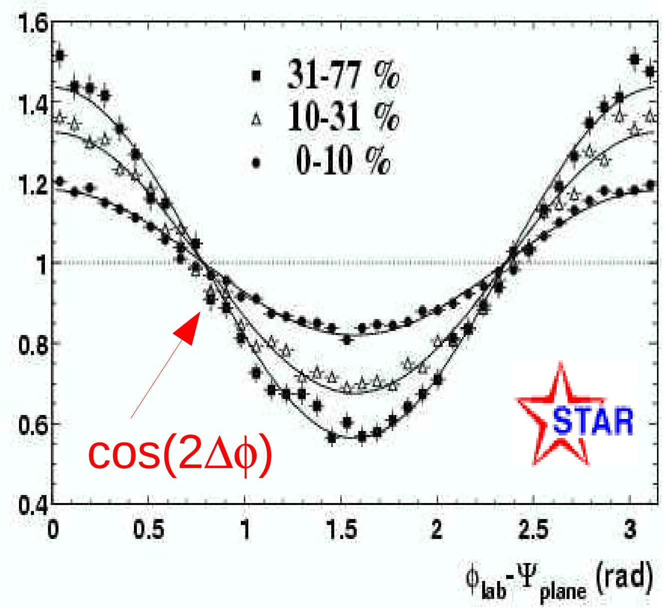
large & fast parton rescatterings

⇒



- Elliptic flow v_2 = 2nd Fourier coeff. azimuth distrib.

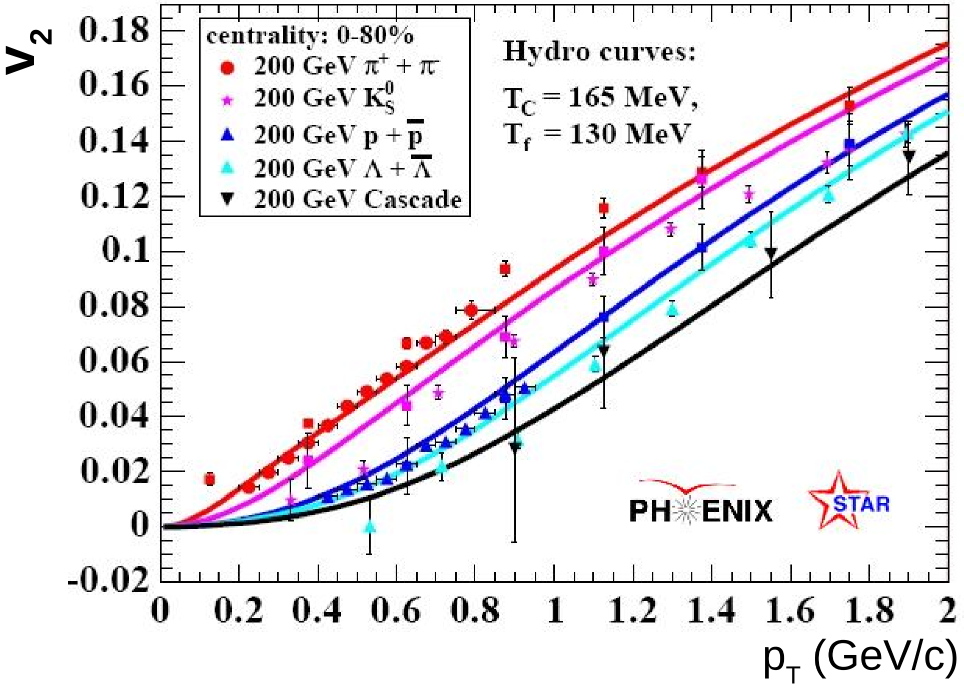
$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1+2\sum_{n=1}^{\infty}\boxed{v_n}cos[n(\phi-\Phi_{RP})]\right)$$

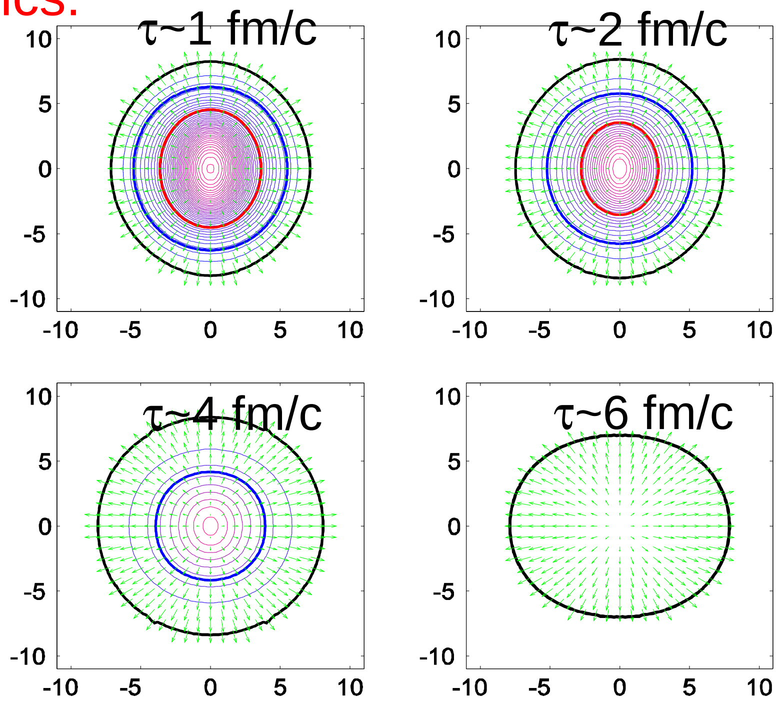


- v_2 is very sensitive to medium viscosity

Strong elliptic flow (RHIC): QGP = perfect fluid ?

- Large v_2 signal (~20%) for all hadrons well described by “perfect fluid” (= non-viscous) relativistic hydrodynamics:





Kolb-Heinz,Huovinen,Teaney, ...

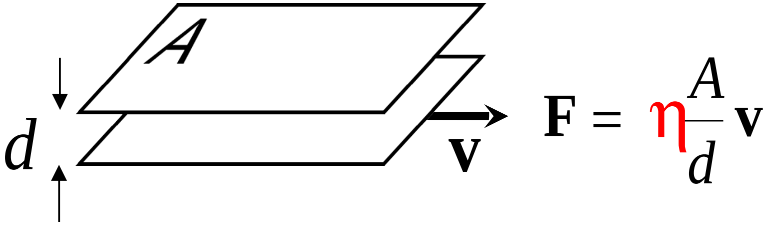
⇒ Initial conditions: τ_0= 0.6 fm/c, ε_0~30 GeV/fm^3

⇒ Lattice QCD (QGP → hadron gas) Equation-of-State

⇒ Zero viscosity (no “internal dissipation”) term in equations.

Minimum universal viscosity from AdS/CFT

- (Shear) Viscosity ~ "internal friction" of a fluid: η~ 1/(fluidity):



$$F = \eta \frac{A}{d} v$$

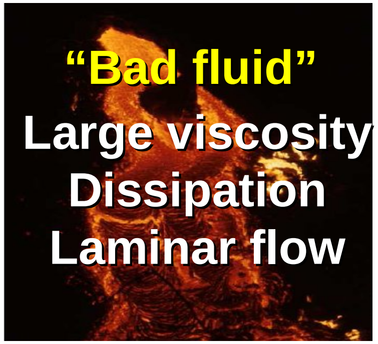
η: resistance to flow gradients

"Good fluid"

Small viscosity

No dissipation

Turbulent flow



"Bad fluid"

Large viscosity

Dissipation

Laminar flow

Microscopically: $\eta = \frac{1}{T}\int d^4x \langle T_{xy}(x) T_{xy}(0) \rangle$ (hard to compute in lattQCD !)

- Minimum viscosity/entropy ratio possible: $\boxed{\eta/s \geq 1/4\pi(\hbar/k_B)}$

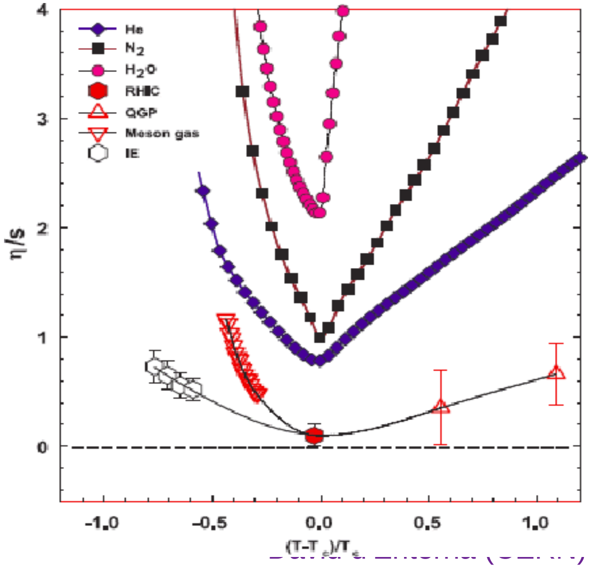
  AdS/CFT "universal bound" (see next slide)

  [Kovtun-Starinets-Son, PRL94,111601(2005)]

- Only 3 classes of quantum fluids known

  to have $\eta/s < (\hbar/k_B)$!

1) Strongly-coupled Bose fluids (liquid ^{4}He) T_{crit}~ 5 K
2) Strongly-correlated ultracold Fermi gases T_{crit}~10^{-6} K
3) Quark-Gluon-Plasma T_{crit}~10^{12} K



Viscosity from AdS/CFT correspondence

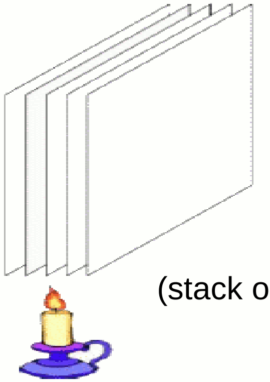
- Certain gauge-theories in Minkowski space can be obtained as limits in the 4-D boundary of simpler 5-D string dual theories:

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

(Conformal gauge theory) (Anti-de-Sitter curved space)

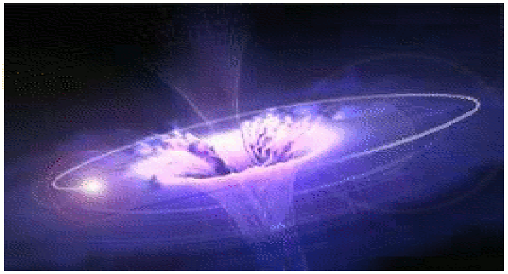
- Duality relation between couplings: $g^2_{SYM} = 4\pi g_{\rm st}$ $g^2_{SYM} N_c = \left(\frac{R}{l_{\rm st}}\right)^4$
- "Easy" case: strongly-coupled QFT ↔ classical gravity

$\mathcal{N}$=4 SYM plasma in 4-dimensions



(stack of 4 branes)

=



Black-Hole in $AdS_5 x\ S^5$

- Dual thermodynamics: BH Hawking T ⇔ SYM plasma: $T_H = r_0\hbar/\pi R^2$
- Dual transport coeffic.: Graviton BH $\sigma_{\rm absorption}$ ⇔ SYM viscosity/entropy
- KSS "universal bound": $\boxed{\eta/s \geq 1/4\pi(\hbar/k_B)}$

Kovtun-Starinets-Son, PRL94(05)111601

Viscous relativistic fluid-dynamics

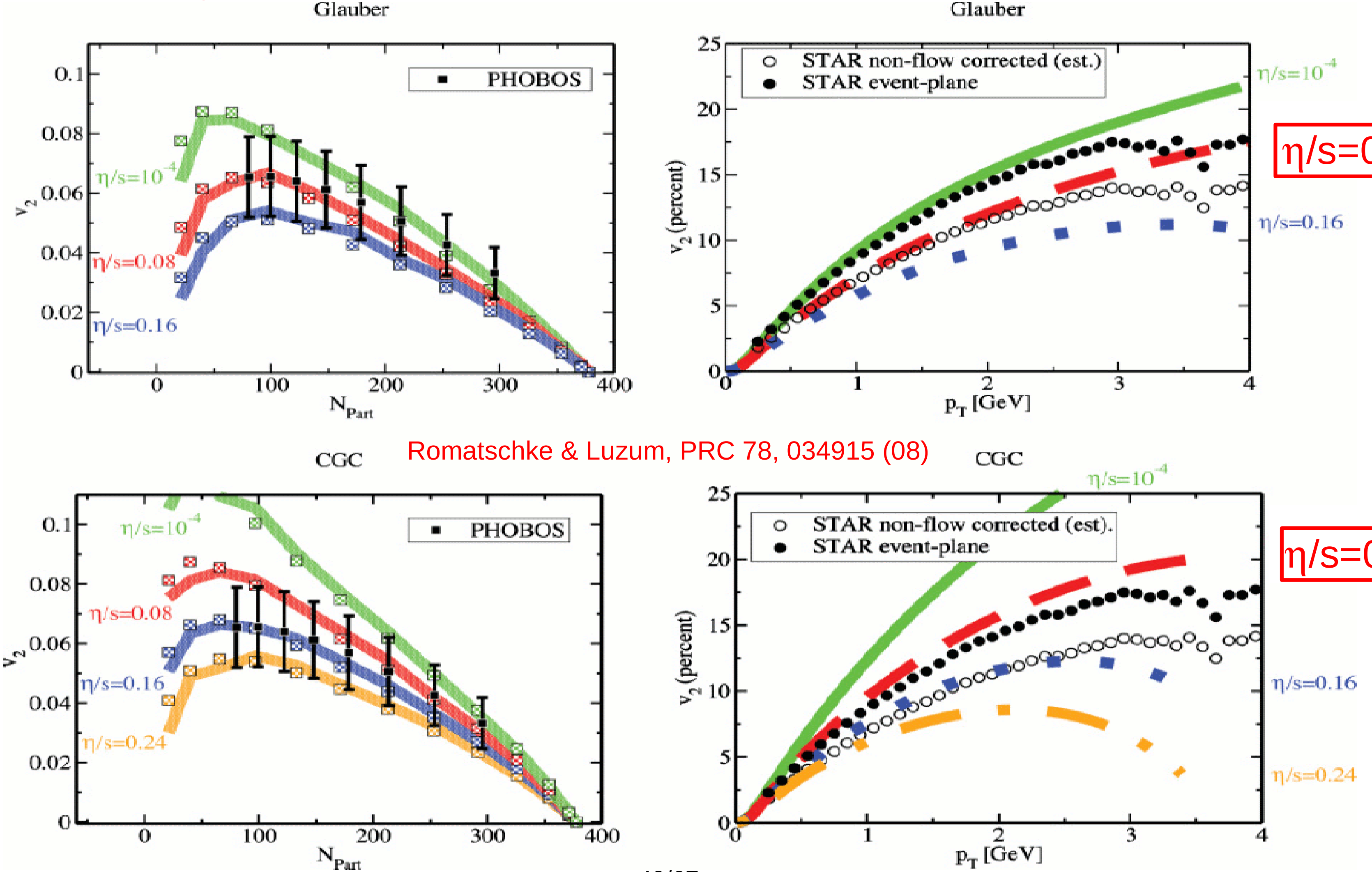
- Relativistic hydrodynamics equations with non-zero viscosity η (theoretical “tour de force”) ...

$$
\begin{aligned}
\tau_{\Pi}\,\dot{\Pi} + \Pi &= \Pi_{\mathrm{NS}} + \tau_{\Pi q}\, q\cdot\dot{u} - \ell_{\Pi q}\,\partial\cdot q - \zeta\,\hat{\delta}_{0,1}\,\Pi\,\theta \\
&\quad + \lambda_{\Pi q}\, q\cdot\nabla\alpha + \lambda_{\Pi\pi}\,\pi^{\mu\nu}\sigma_{\mu\nu} + \hat{\delta}_{0,2}\,\Pi^2 + \hat{\epsilon}_0\, q\cdot q + \hat{\eta}_0\,\pi^{\mu\nu}\pi_{\mu\nu} \\
\tau_q\,\Delta^{\mu\nu}\dot{q}_\nu + q^\mu &= q^\mu_{\mathrm{NS}} - \tau_{q\Pi}\,\Pi\,\dot{u}^\mu - \tau_{q\pi}\,\pi^{\mu\nu}\,\dot{u}_\nu \\
&\quad + \ell_{q\Pi}\,\nabla^\mu\Pi - \ell_{q\pi}\,\Delta^{\mu\nu}\,\partial^\lambda\pi_{\nu\lambda} + \tau_q\,\omega^{\mu\nu}\,q_\nu - \frac{\kappa}{\beta}\hat{\delta}_{1,1}\,q^\mu\,\theta \\
&\quad - \lambda_{qq}\,\sigma^{\mu\nu}\,q_\nu + \lambda_{q\Pi}\,\Pi\,\nabla^\mu\alpha + \lambda_{q\pi}\,\pi^{\mu\nu}\,\nabla_\nu\alpha \\
&\quad + \hat{\delta}_{1,2}\,\Pi\,q^\mu + \hat{\eta}_1\,\pi^{\mu\nu}\,q_\nu \\
\tau_\pi\,\dot{\pi}^{<\mu\nu>} + \pi^{\mu\nu} &= \pi^{\mu\nu}_{\mathrm{NS}} + 2\,\tau_{\pi q}\,q^{<\mu}\dot{u}^{\nu>} \\
&\quad + 2\,\ell_{\pi q}\,\nabla^{<\mu}q^{\nu>} + 2\,\tau_\pi\,\pi_\lambda{}^{<\mu}\omega^{\nu>\lambda} - 2\,\eta\,\hat{\delta}_{2,1}\,\pi^{\mu\nu}\,\theta \\
&\quad - 2\,\tau_\pi\,\pi_\lambda{}^{<\mu}\sigma^{\nu>\lambda} - 2\,\lambda_{\pi q}\,q^{<\mu}\nabla^{\nu>}\alpha + 2\,\lambda_{\pi\Pi}\,\Pi\,\sigma^{\mu\nu} \\
&\quad + \hat{\delta}_{2,2}\,\Pi\,\pi^{\mu\nu} - \hat{\eta}_2\,\pi_\lambda{}^{<\mu}\pi^{\nu>\lambda} - \hat{\epsilon}_2\,q^{<\mu}q^{\nu>}
\end{aligned}
$$

P.Romatschke-Baier, D.Teaney, U.Heinz-Song, A.Muronga ...

Elliptic flow: very small viscosity

- Inclusion of shear stress, $T^{\mu\nu} = T_0^{\mu\nu} + \boxed{\eta\langle\nabla^\mu u^\nu\rangle}$ modifies expansion rate: $v_2(p_T, N_{part})$ strongly reduced !



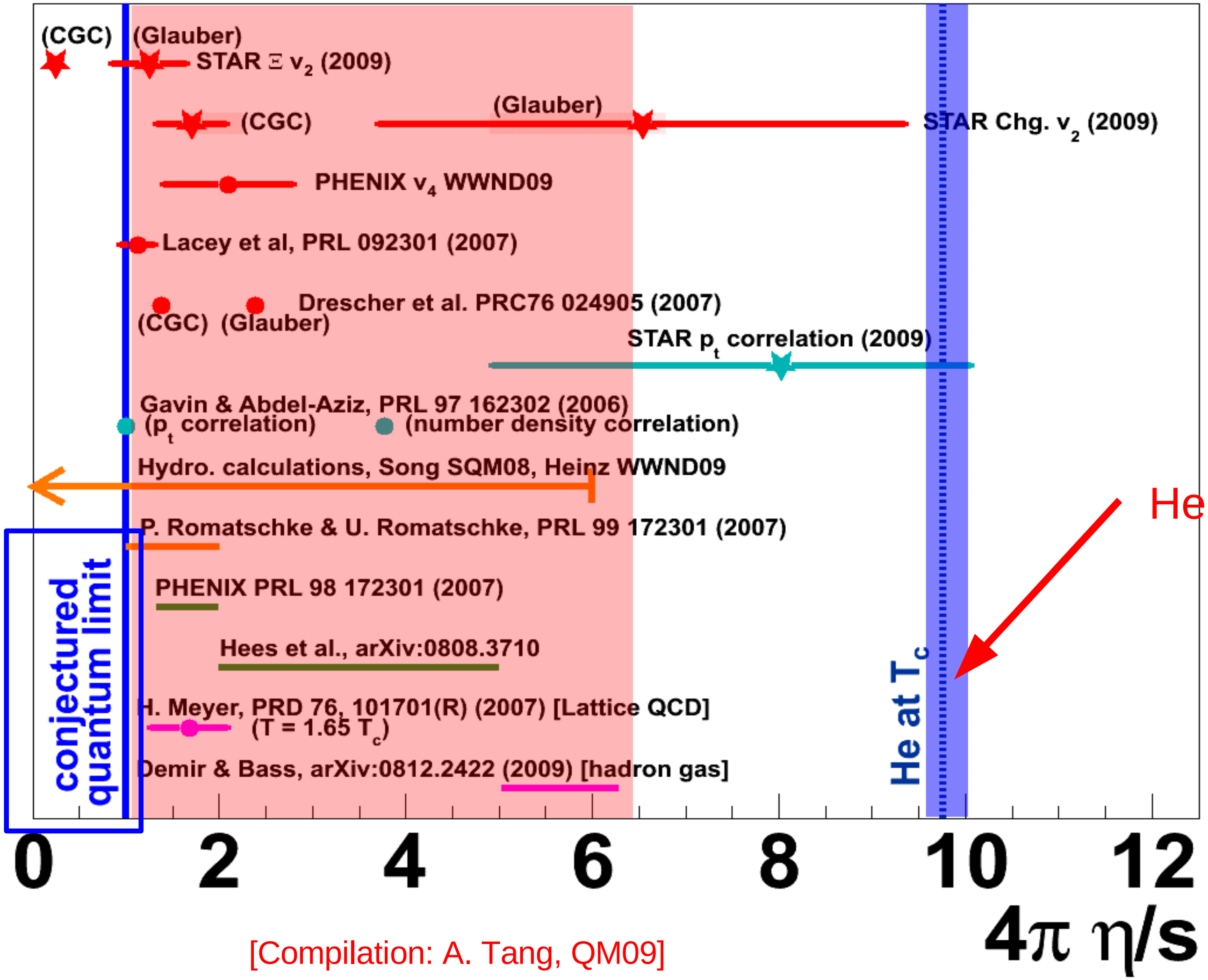
η/s=0.08

η/s=0.08

Romatschke & Luzum, PRC 78, 034915 (08)

QGP viscosity constraints from RHIC data

- QGP is the best perfect-fluid known ! $\eta/s < 6\cdot(\hbar/k_B)/4\pi$

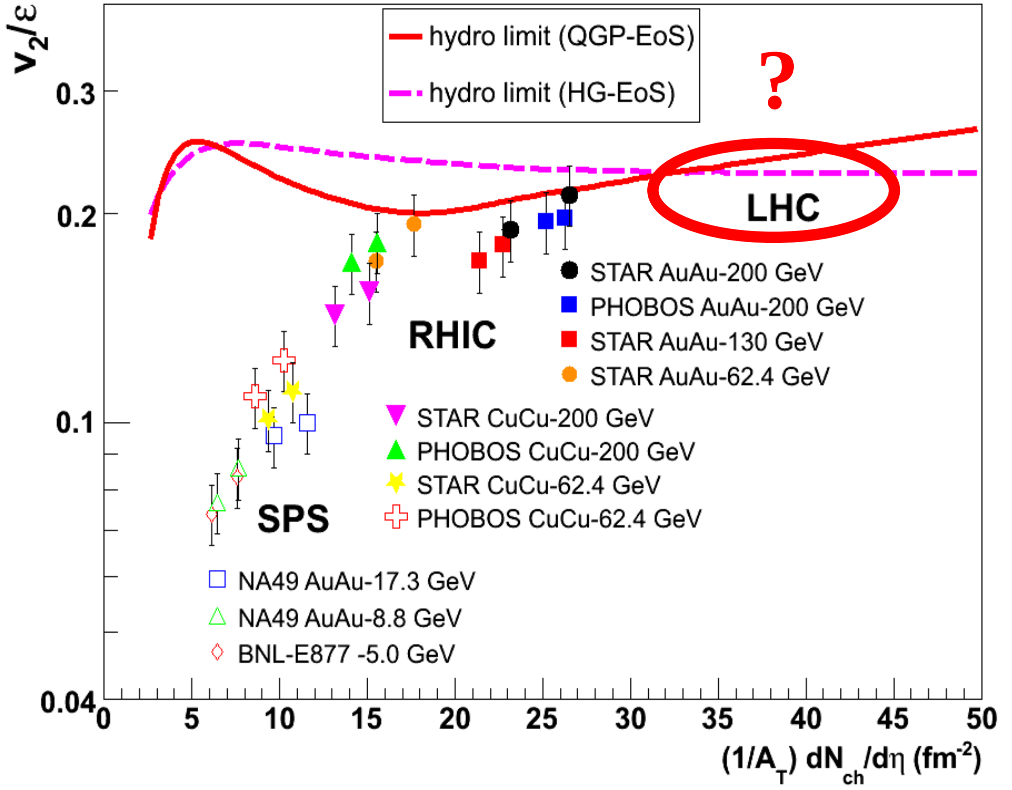


He-4 is here ...

[Compilation: A. Tang, QM09]

Elliptic flow (LHC)

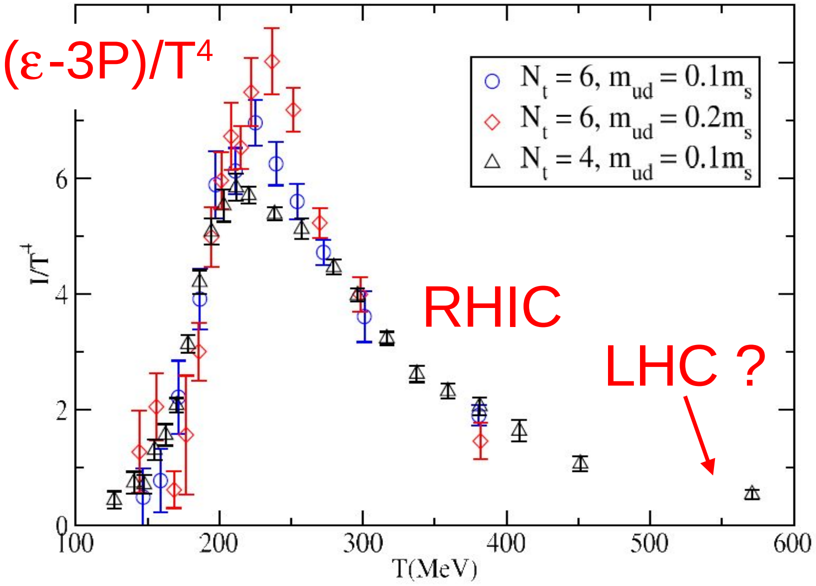
- Collective azimuthal anisotropy (v_2 parameter) in Pb-Pb 5.5 TeV ?



◆ null-viscosity fluid as at RHIC ?

⇒ AdS/CFT applicable ...

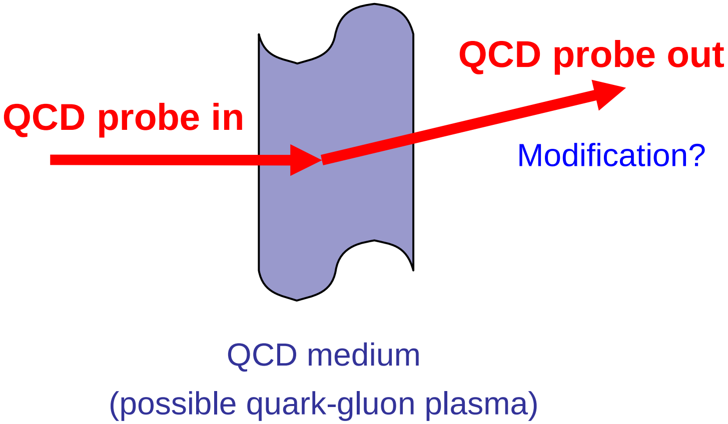
◆ weakly interacting (high viscosity) quark-gluon "gas" from latt.-QCD ?

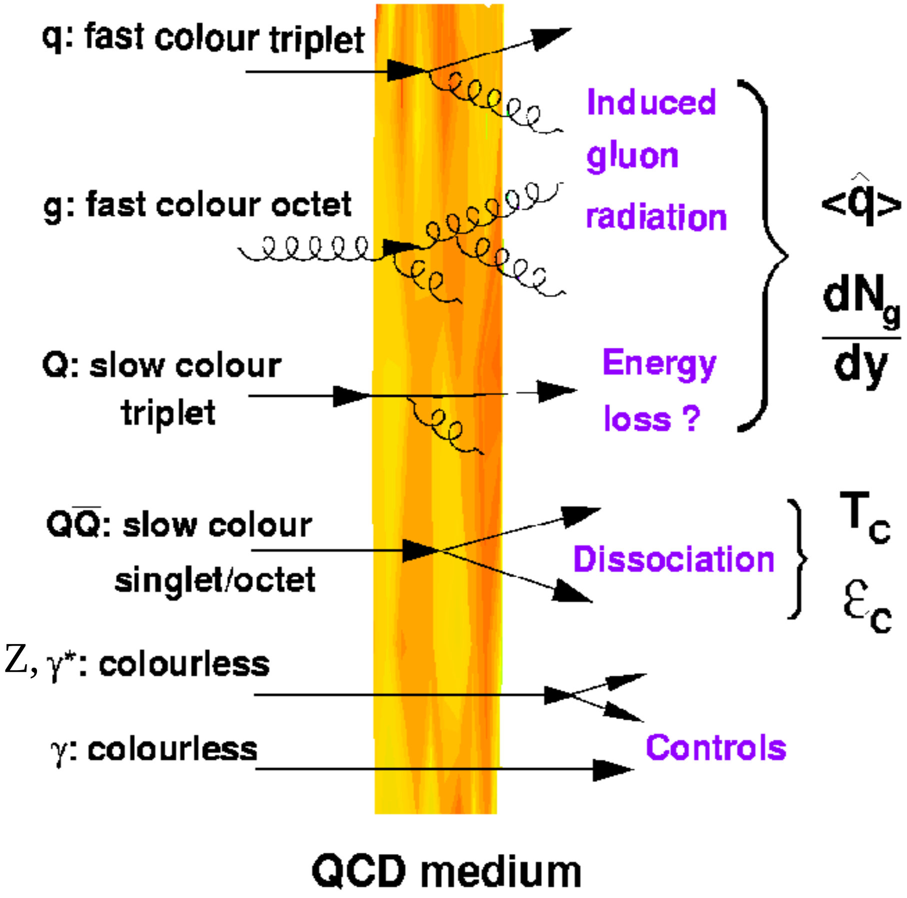


Hard QGP probes

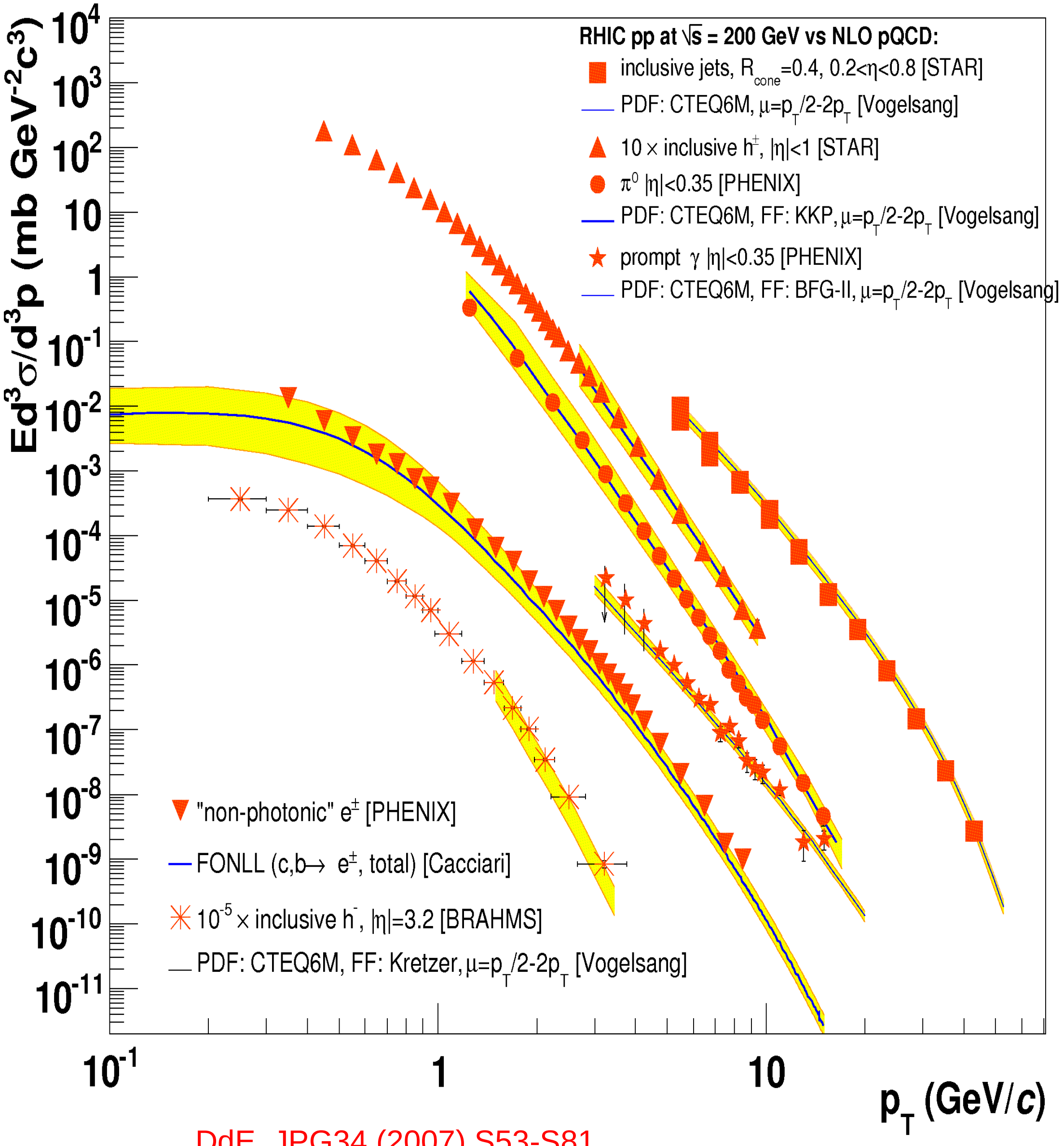
Hard "tomographic" probes of QCD matter

- Hard-probes of QCD matter:
  - jets, γ, $Q\overline{Q}$ ... well controlled experimentally & theoretically (pQCD)
  - self-generated in collision at $\tau<1/Q\sim0.1$ fm/c,
  - tomographic probes of hottest & densest phases of medium .





RHIC “QCD vacuum” (p-p) references vs. pQCD



DdE, JPG34 (2007) S53-S81

p-p ⇒ X ,√s = 200 GeV

- Jets, high-p_T hadrons, prompt-γ, heavy-Q ...

  High-quality measurements

  within p_T~2-45 GeV/c

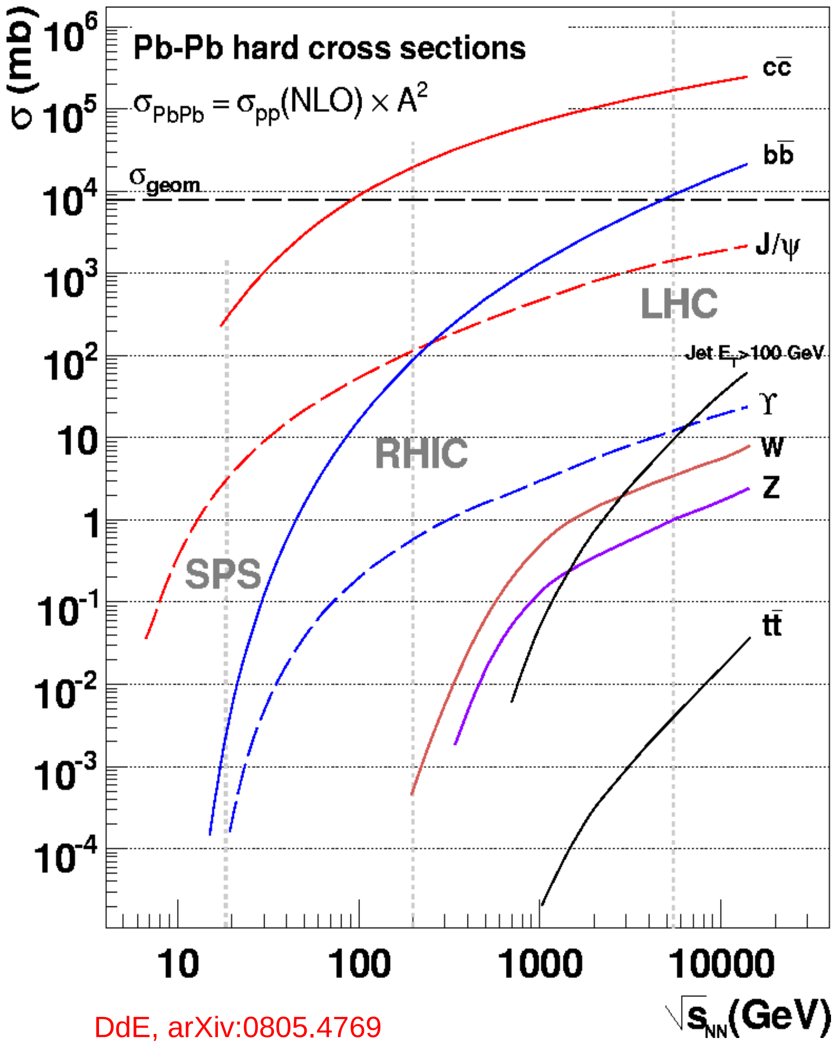
- NLO [1], NLL [2] pQCD + recent PDFs, FFs in good agreement with all data.

[1] W. Vogelsang *et al.*

[2] M. Cacciari *et al.*

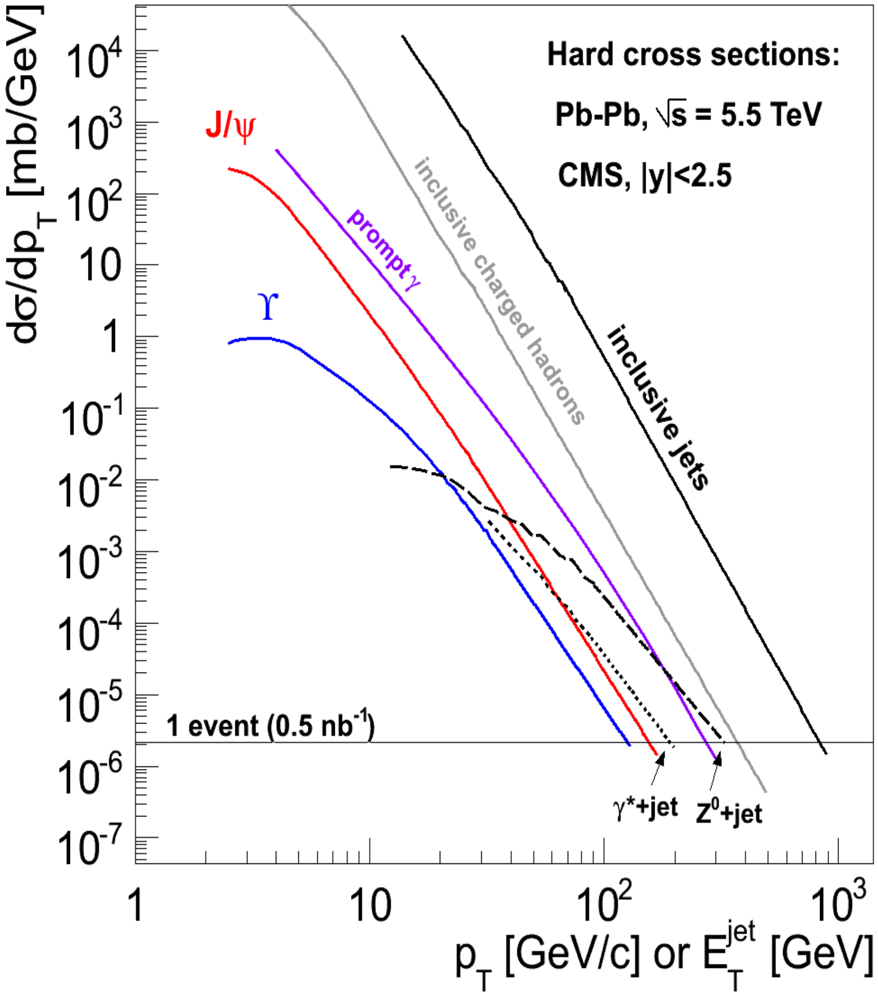
Hard probes cross-sections (LHC)

- Huge cross-sections (large statistics & p_T reach) at the LHC:



DdE, arXiv:0805.4769

Pb-Pb MB yields – 0.5 nb^{-1}

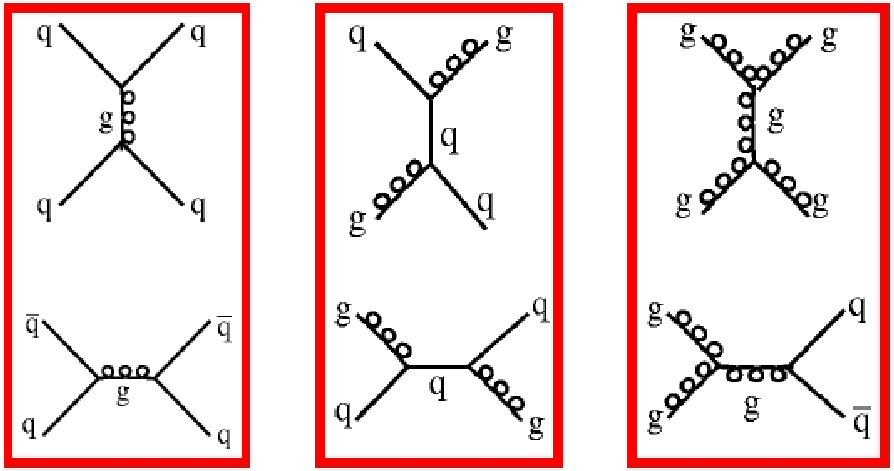


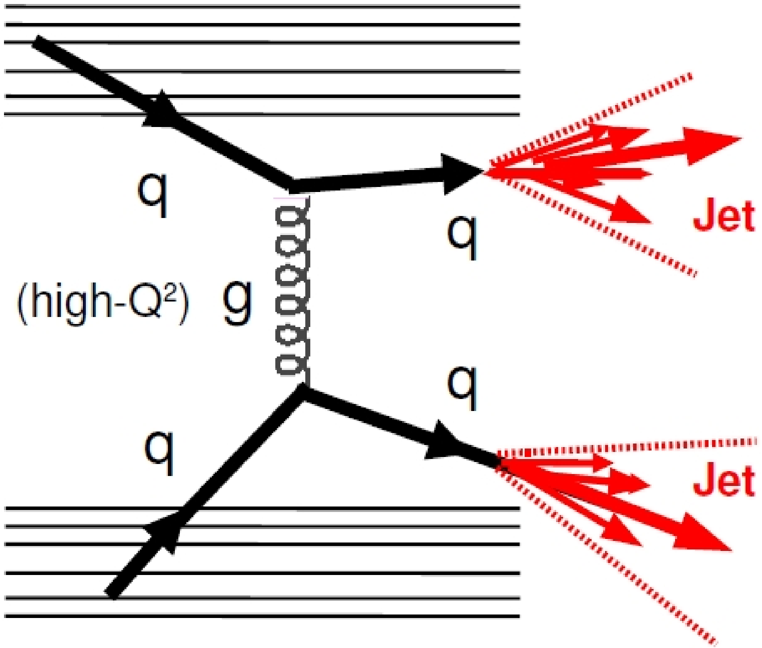
Quark-gluon matter probes (4)

Observable (type)	Medium property	Theoretical tool
dN/dη multiplicity (soft)	gluonic struct. $xG(x,Q^2)$	Color-Glass-Condensate
dN/dp$_T$ spectra (soft)	Equation-of-State P(V,T)	(Hydro), Lattice QCD
dN/dΔφ elliptic flow (soft)	shear viscosity η	(Hydro), AdS/CFT
Jet quenching (hard)	**transport coefficient <q>**	**(Hydro), pQCD**
γ enhancement (intermed.)	critical temperature T_{crit}	(Hydro), Lattice QCD
QQ suppression (hard)	critical energy density ε_{crit}	(Hydro), Lattice QCD

Jets in hadronic collisions

- Jet = high-p_T parton (quark, gluon) produced in a hard scattering process: qq, qg, gg (or in the decay of a heavy particle)
- Jet production processes (leading order):



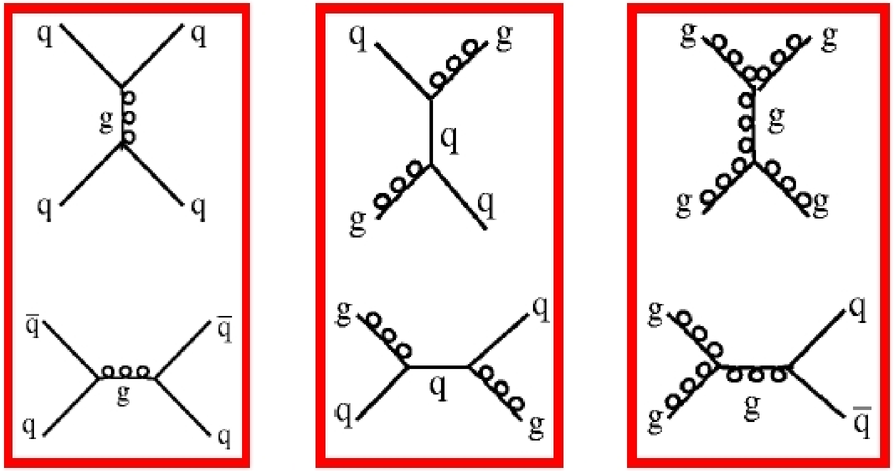


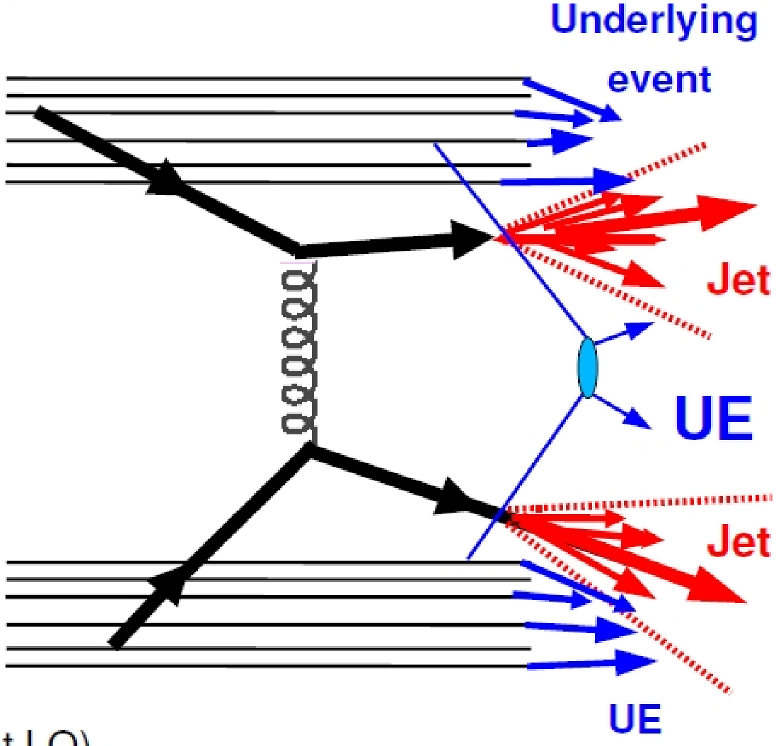
Jet balanced back-to-back by another jet, a prompt γ, ... (at LO).

- Jet (real life): Collimated spray of hadrons in a cone ($R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ ~0.4-1.) with total 4-momentum of original fragmenting parton.

Jets in hadronic collisions

- Jet = high-p_T parton (quark, gluon) produced in a hard scattering process: qq, qg, gg (or in the decay of a heavy particle)
- Jet production processes (leading order):



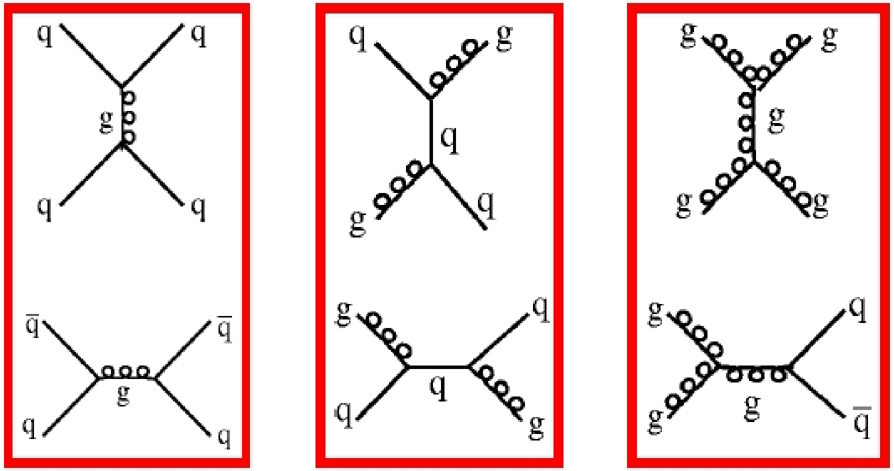


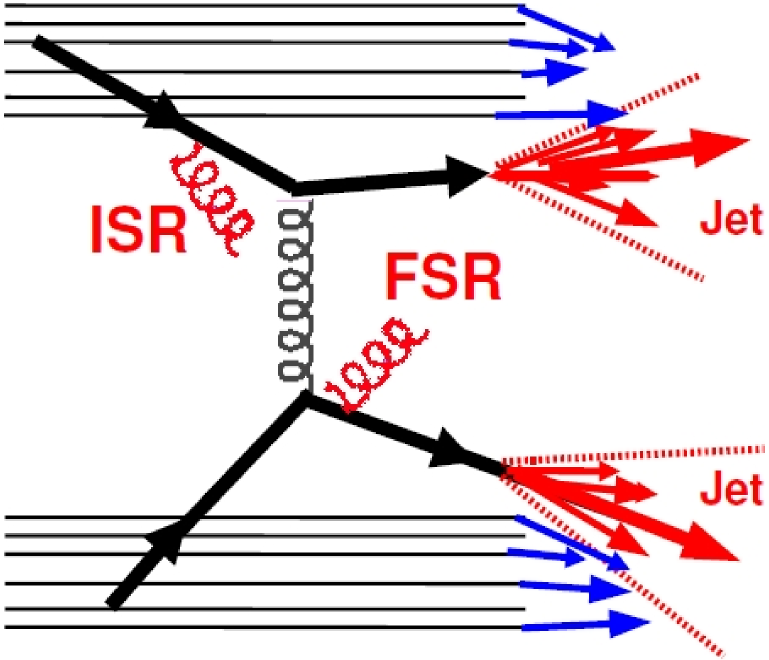
Jet balanced back-to-back by another jet, a prompt γ, ... (at LO).

- Jet (real life): Collimated spray of hadrons in a cone ($R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ ~0.4-1.) with total 4-momentum of original fragmenting parton.

Jets in hadronic collisions

- Jet = high-p_T parton (quark, gluon) produced in a hard scattering process: qq, qg, gg (or in the decay of a heavy particle)
- Jet production processes (leading order):



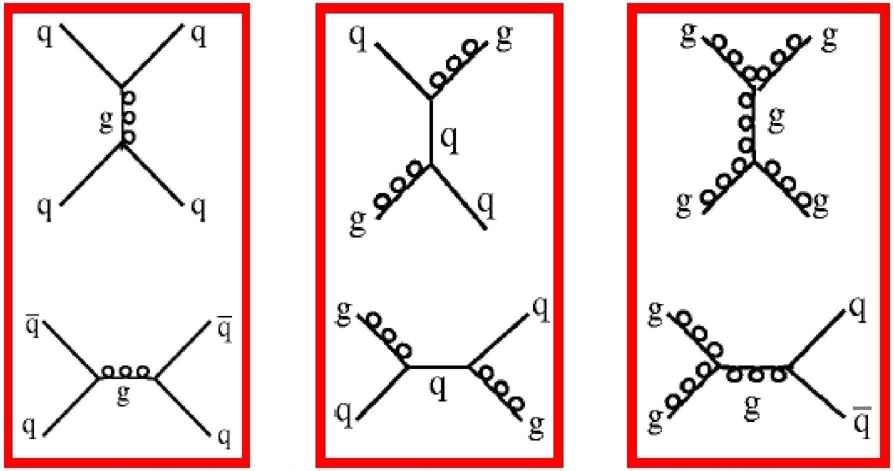


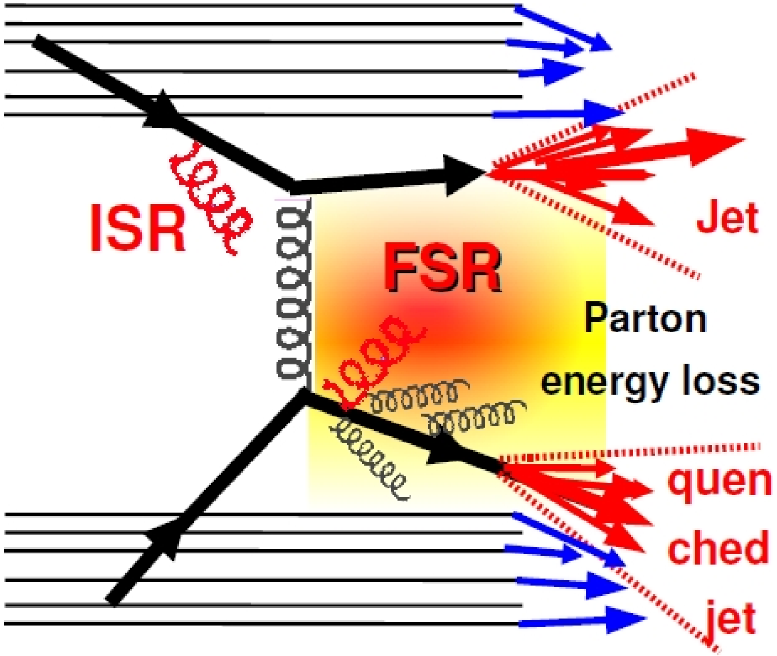
Jet balanced back-to-back by another jet, a prompt γ, ... (at LO).

- Jet (real life): Collimated spray of hadrons in a cone ($R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ ~0.4-1.) with total 4-momentum of original fragmenting parton.

Jets in nuclear collisions

- Jet = high-p_T parton (quark, gluon) produced in a hard scattering process: qq, qg, gg (or in the decay of a heavy particle)
- Jet production processes (leading order):



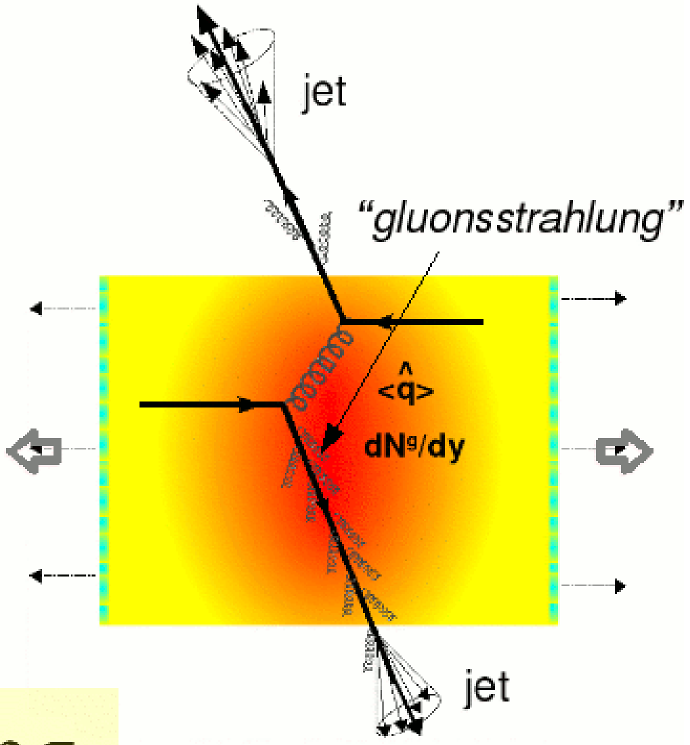


Jet balanced back-to-back by another jet, a prompt γ, ... (at LO).

- Jet (real life): Collimated spray of hadrons in a cone ($R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ ~0.4-1.) with total 4-momentum of original fragmenting parton.

"Jet quenching" = tomographic QGP probe

- Parton radiative energy loss: multiple gluon radiation off the produced hard parton induced by the dense QCD medium:



- Energy loss ➠ Medium properties:

$$\Delta E_{\mathrm{GLV}} \propto \alpha_S^3 C_R \frac{1}{A_\perp} \frac{dN^g}{dy} L$$

$$\langle \Delta E \rangle_{\mathrm{BDMPS}} \propto \alpha_S C_R \langle \hat q \rangle L^2$$

$\propto$ ($\hat q$, gluon density, $L^{(2)}$)

- $\hat q$ transport coefficient:

medium "scattering power" $\hat q \equiv m_D^2/\lambda = m_D^2 \rho \sigma$

parton-parton x-section

medium density

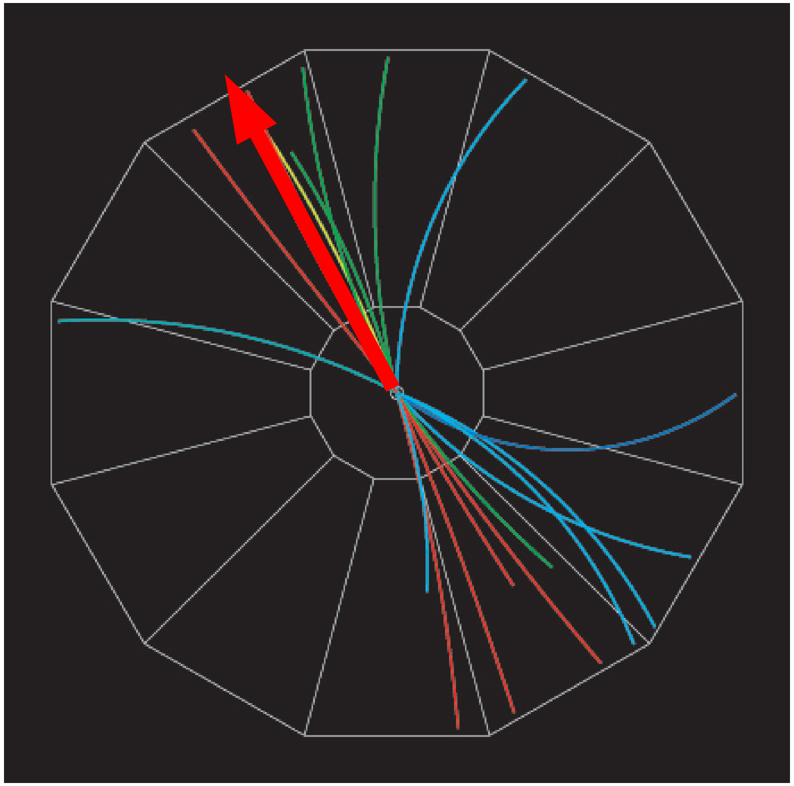
Debye mass ~ gT

- Flavour-dependent energy loss: $\Delta E_{loss}(g) > \Delta E_{loss}(q) > \Delta E_{loss}(Q)$

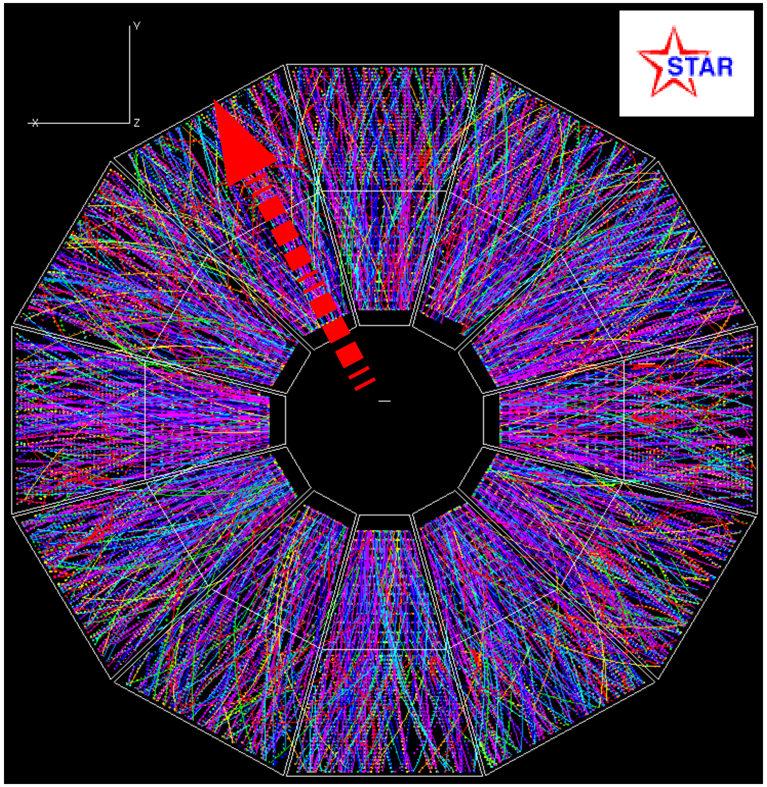
(color factor) (dead-cone effect)

Jet quenching at RHIC (I): high-p_T hadrons

- Study energy modifications suffered by the high p_T hadrons ("leading" hadron of the jet) in A-A compared to p-p:



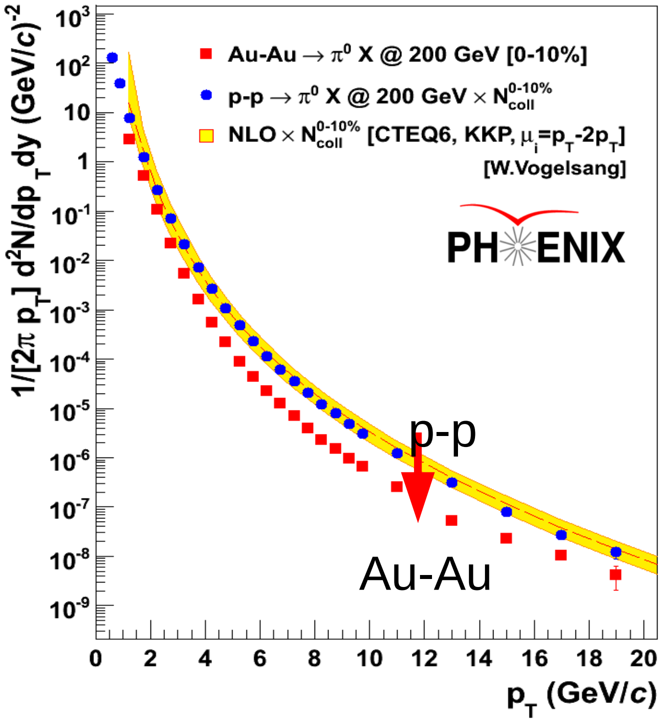
p+p →jet+jet [√s = 200 GeV]

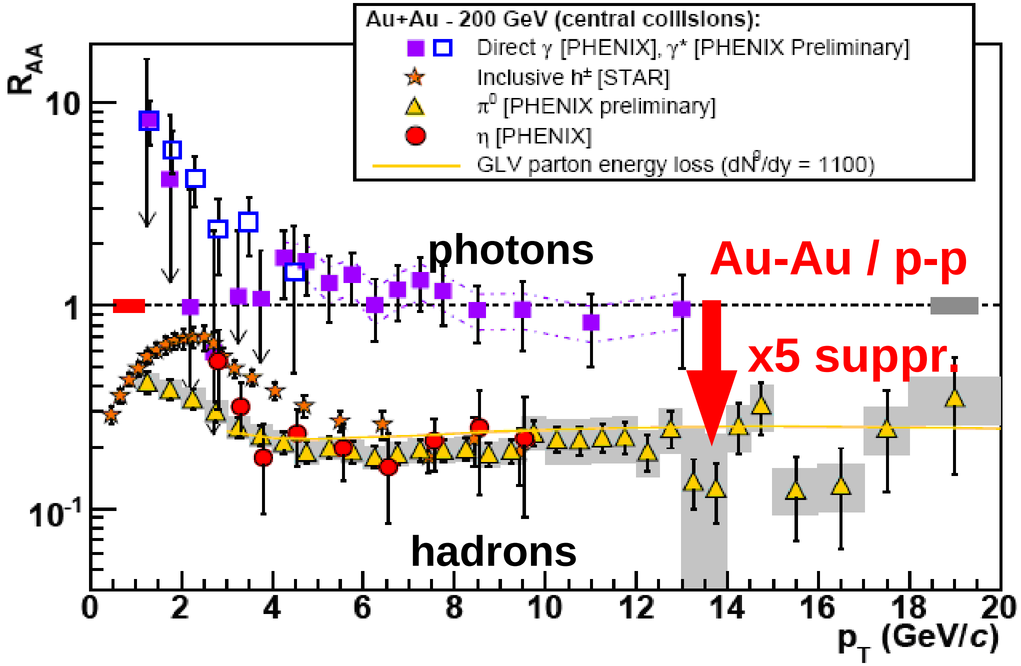


Au+Au → X [$\sqrt{s_{NN}}$ = 200 GeV]

Jet quenching at RHIC (II): high-p_T hadrons

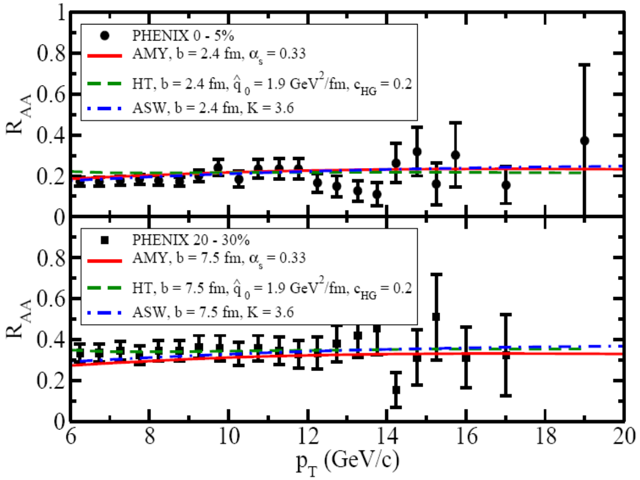
- All high-p_T hadrons quenched (but not photons) !





- Derived medium properties (within 3-D hydro model):

  QGP very dense & opaque to colored particles !



$\langle\hat{q}\rangle$=4-13 GeV²/fm

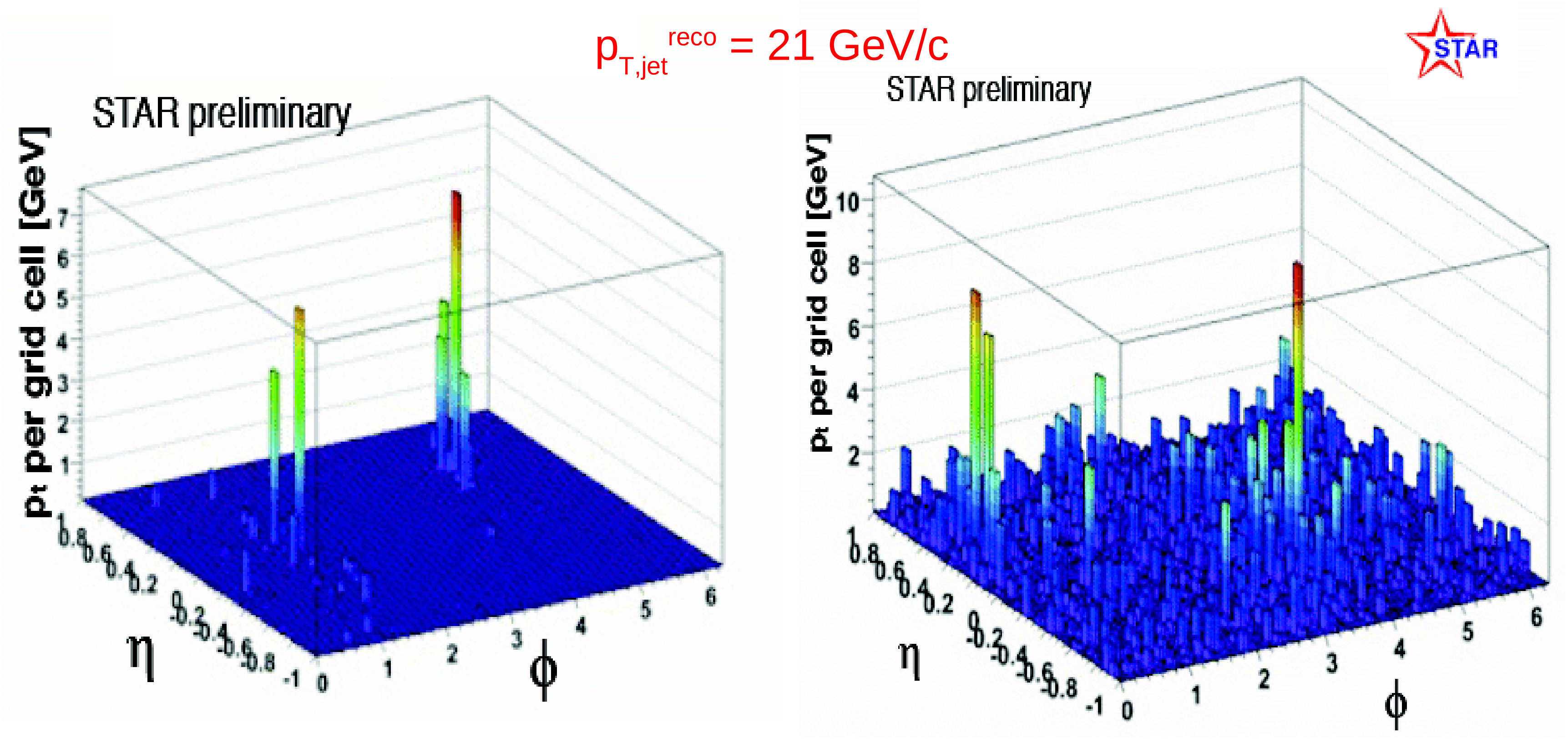
dN^g/dy~1400±200

S. Bass et al.
PRC79 (2009)024901

Jet quenching at RHIC (III): full jet reconstruction

- Study jet modifications (energy, shape, FFs) in A-A compared to p-p:

p+p →jet+jet [$\sqrt{s_{NN}}$ = 200 GeV] Au+Au → jet+jet



$p_{T,jet}^{reco}$ = 21 GeV/c

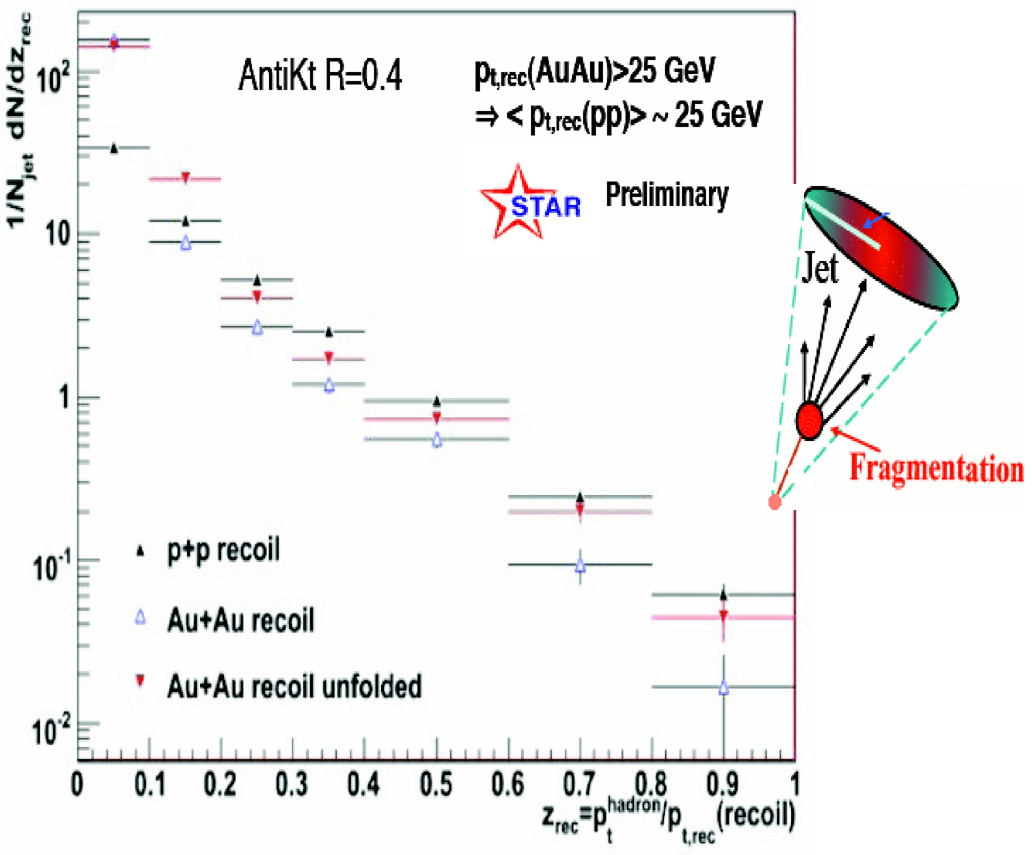
- Full jet reco complicated (but feasible): huge A-A underlying evt.:

$\langle p_T^{bkg} \rangle$ ~ 45 GeV in R=0.4 cone (S/B~0.5 for a p_T=20 GeV jet)

Jet quenching at RHIC (IV): fragmentation functions

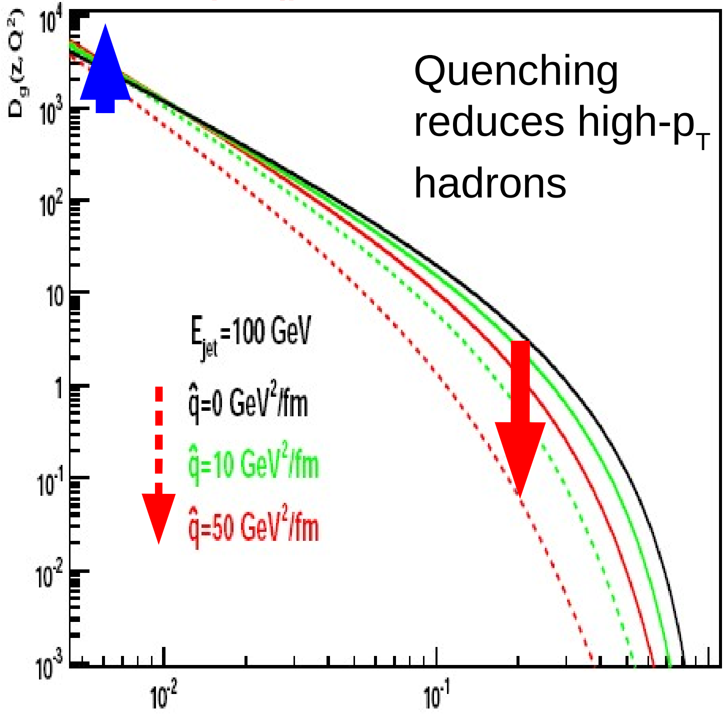
- Detailed studies of medium-modified fragmentation fcts. accessible.
- Radiative E_{loss} shifts partons from high-z to low-z: sensitive to $<\hat{q}>$

z=p(hadron)/p(parton)



Putschke,Salur,Ploskon,Bruna, QM'09

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



Quenching reduces high-p_T hadrons

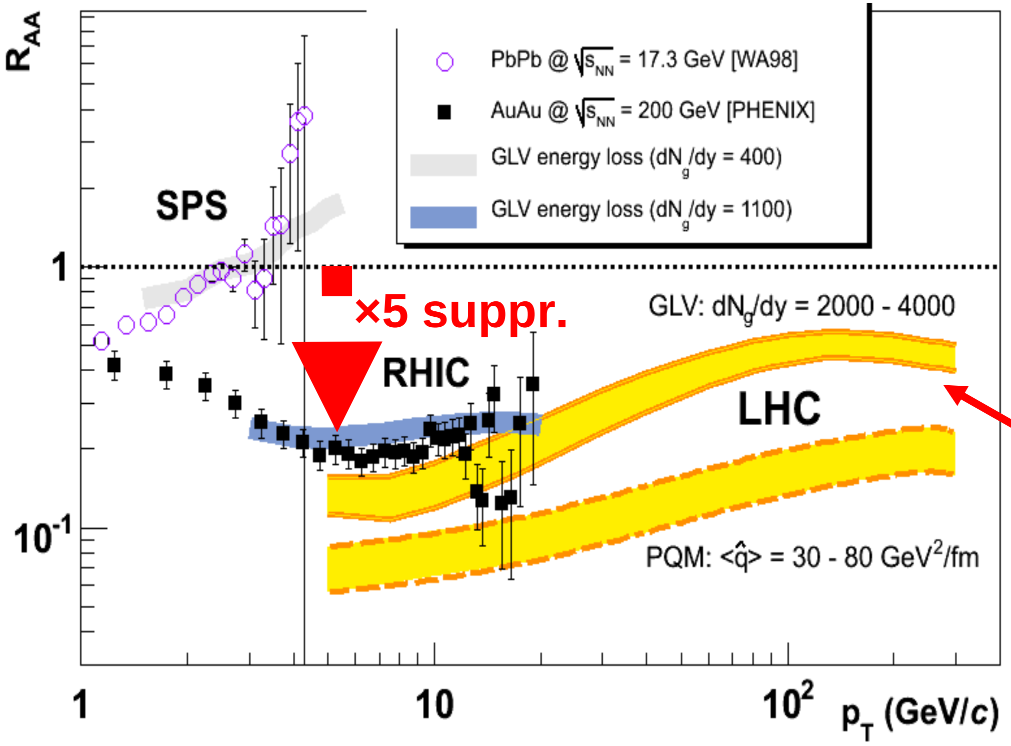
Quenching increases low-p_T hadrons

$z=p_{hadron}/E_{jet}$

Armesto et al. arXiv:0710.3073

High-p_T hadron suppression (LHC)

- Nuclear modification factor (= AA-yield / pp-yield) at the LHC:

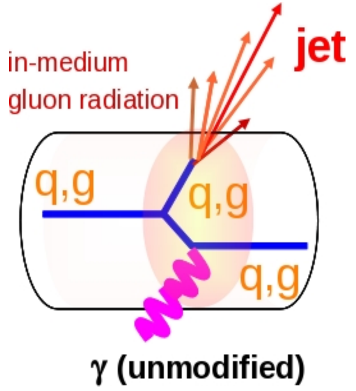


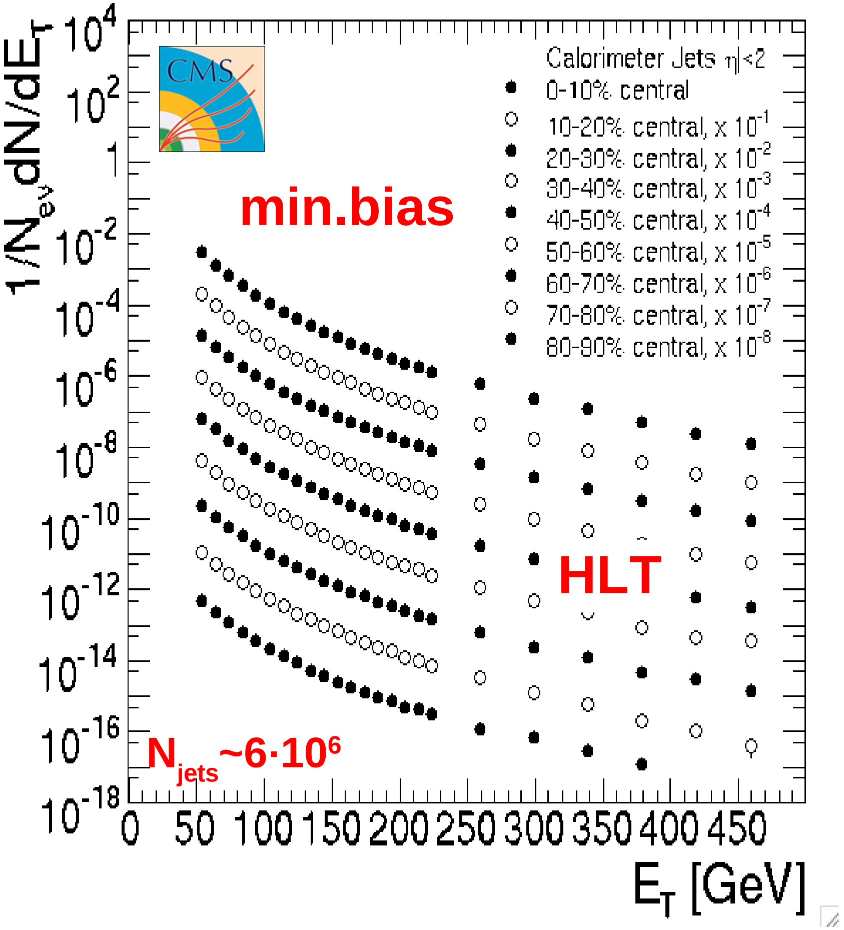
Expected p_T reach ~300 GeV/c with (high-E_T) jet trigger

- Strong discrimination power for parton energy loss models:
  - Initial parton medium density: $dN_g/dy \sim O(2\text{-}4 \cdot 10^3)$
  - Medium transport coefficient: $\langle\hat{q}\rangle \sim O(10\text{-}100)$ GeV^2/fm

Jet, γ - jet reconstruction (LHC)

- Jet reconstruction, backg-subtraction & corrections: complicated but doable
- Jet spectra up to E_T~ 0.5 TeV
- γ - jet: medium-modified (quenched) jet FF possible.



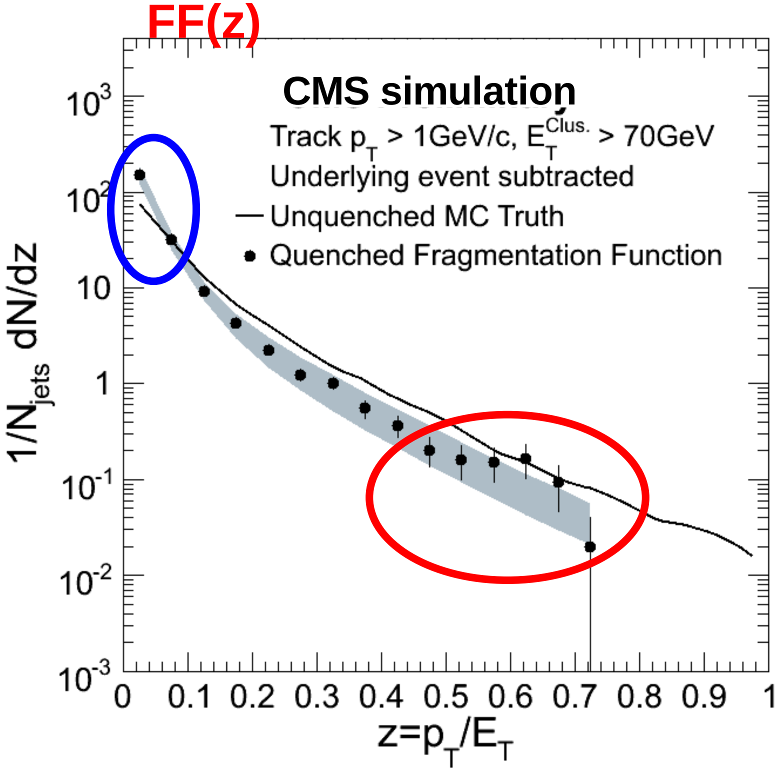


min.bias

HLT

N_{jets}~$6\cdot10^6$

FF(z)



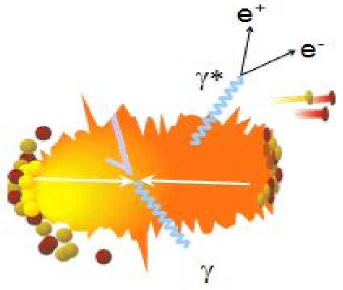
Quark-gluon matter probes (5)

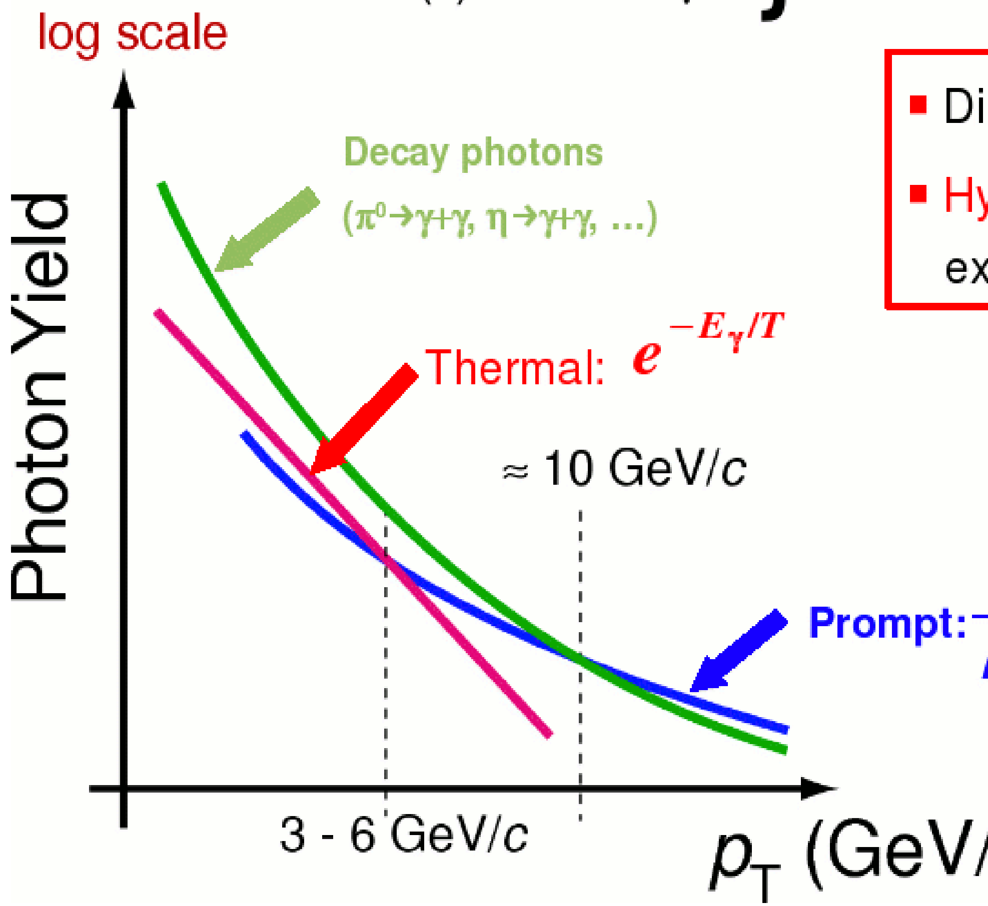
Observable (type)	Medium property	Theoretical tool
dN/dη multiplicity (soft)	gluonic struct. $xG(x,Q^2)$	Color-Glass-Condensate
dN/dp$_T$ spectra (soft)	Equation-of-State P(V,T)	(Hydro), Lattice QCD
dN/dΔφ elliptic flow (soft)	shear viscosity η	(Hydro), AdS/CFT
Jet quenching (hard)	transport coefficient <q>	(Hydro), pQCD
γ enhancement (intermed.)	**critical temperature T_{crit}**	**(Hydro), Lattice QCD**
QQ suppression (hard)	critical energy density ε_{crit}	(Hydro), Lattice QCD

Thermal photon radiation = QGP temperature

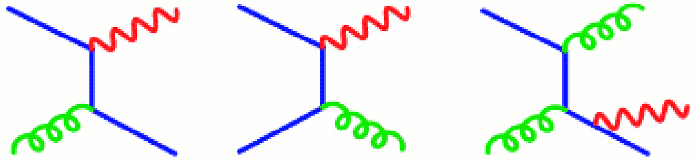
- Three sources: (i) Hadron decay γ → Background

  (ii) Prompt γ
  (ii) Thermal γ } → Direct photon signal





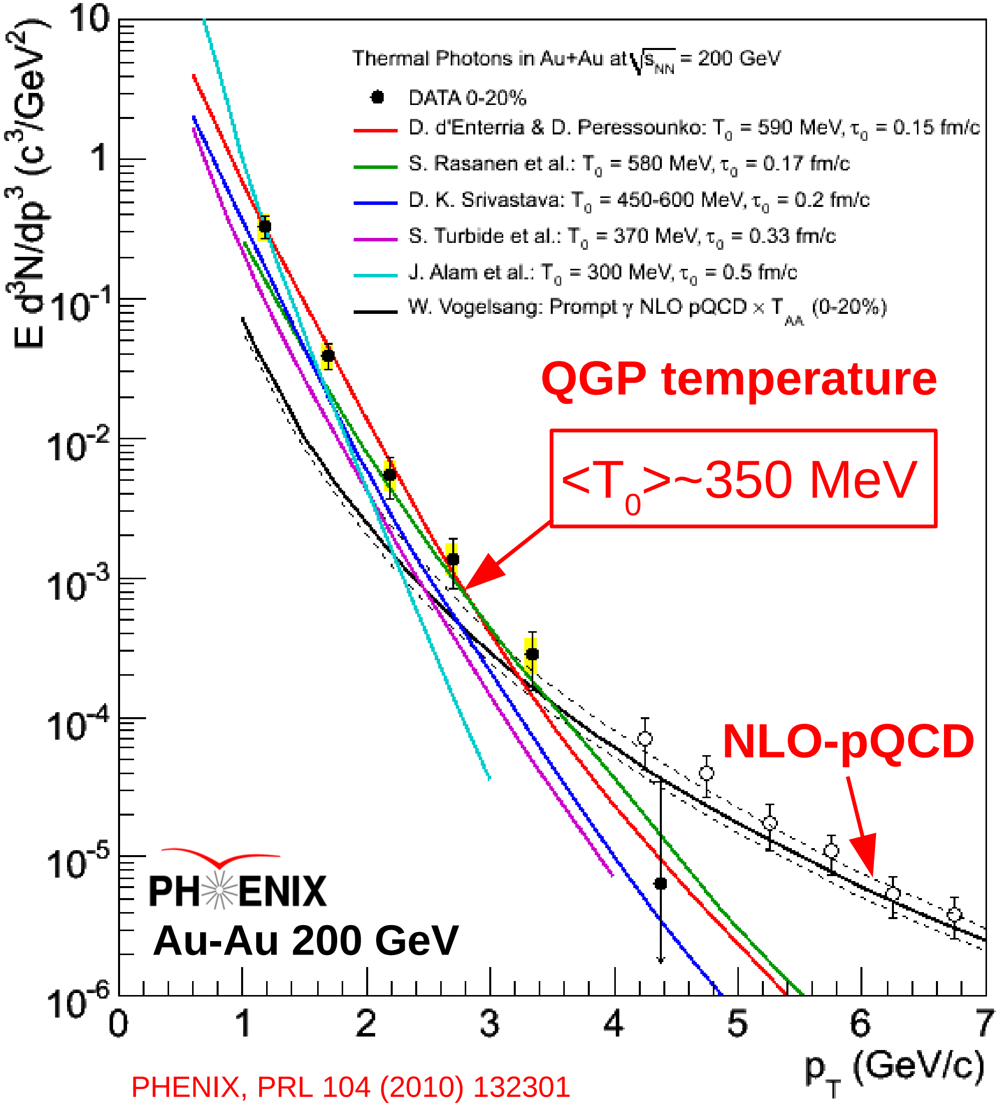
- Direct measure of the medium T
- Hydro model needed to relate expo slope to temperature.



- Initial parton-parton colls.
- Measurable in p-p.
- Computable in pQCD.

Thermal photon radiation from QGP

- Hydrodynamical models vs. Au-Au γ,γ^* excess over p-p & pQCD:

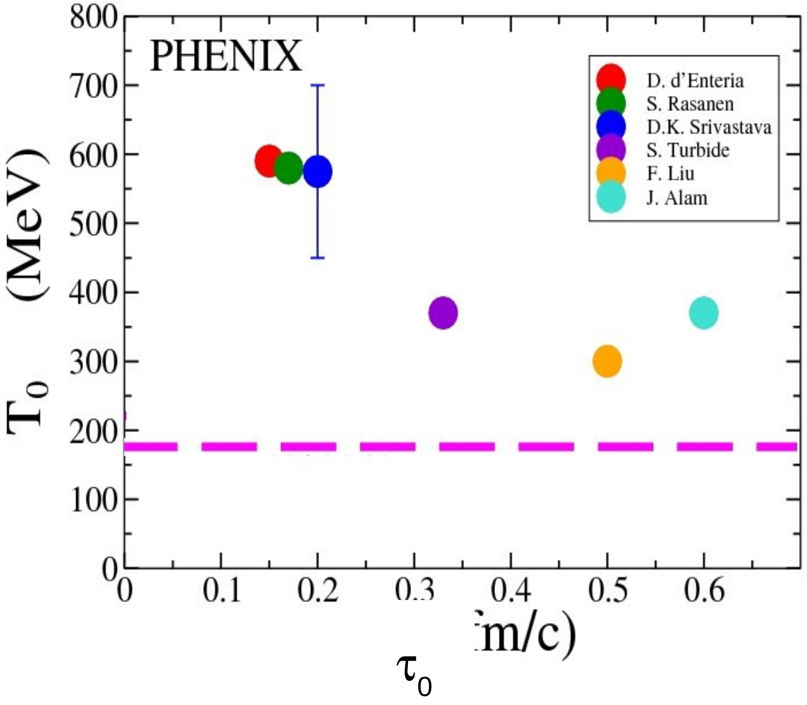


QGP temperature

$<T_0>$~350 MeV

NLO-pQCD

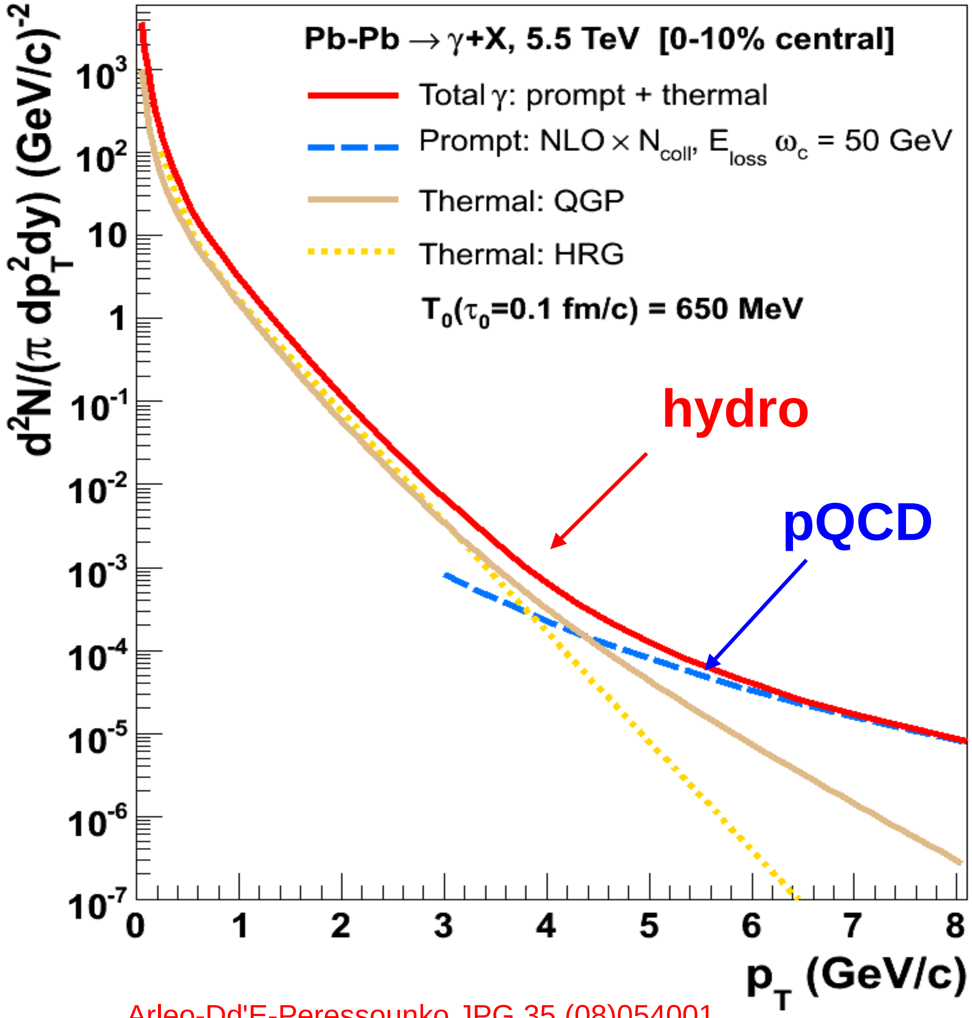
PHENIX, PRL 104 (2010) 132301
D.d'E, D.Peressounko, EPJC46 (2006) 451



- Initial derived temperatures: T_0=0.3-0.6 GeV well above latt. QCD T_{crit}~ 0.17-0.19 GeV

Thermal+Prompt photon (LHC)

- Photon spectra: hydro + NLO pQCD predictions:



Arleo-Dd'E-Peressounko JPG 35 (08)054001

Pb-Pb @ 5.5 TeV (<b>~3 fm)

$\varepsilon_0 \propto s_0^{4/3}$ ~ 650 GeV/fm^3

T_0=770 MeV (<T_0> ~500 MeV)

τ_0=0.1fm/c

- Thermal photon radiation dominates at p_T~1-5 GeV/c.

Quark-gluon matter probes (6)

Observable (type)	Medium property	Theoretical tool
dN/dη multiplicity (soft)	gluonic struct. $xG(x,Q^2)$	Color-Glass-Condensate
dN/dp$_T$ spectra (soft)	Equation-of-State P(V,T)	(Hydro), Lattice QCD
dN/dΔφ elliptic flow (soft)	shear viscosity η	(Hydro), AdS/CFT
Jet quenching (hard)	transport coefficient <q>	(Hydro), pQCD
γ enhancement (intermed.)	critical temperature T_{crit}	(Hydro), Lattice QCD
QQ suppression (hard)	**critical energy density ε_{crit}**	**(Hydro), Lattice QCD**

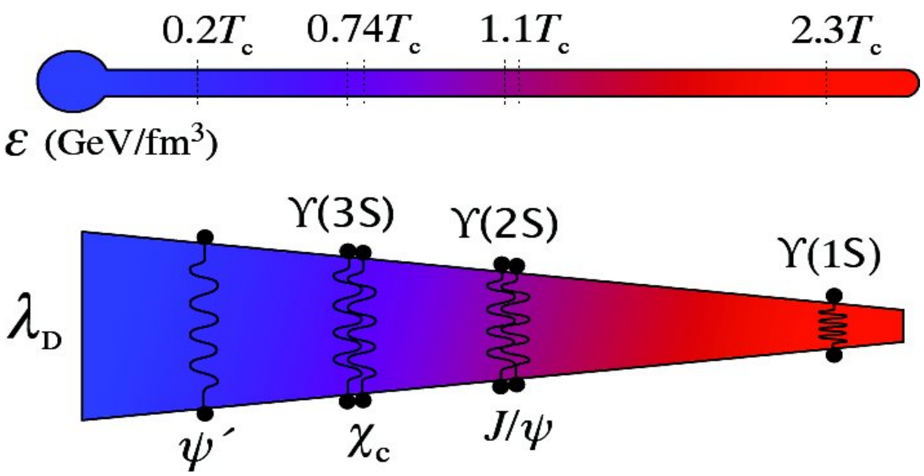
QQbar suppression = Color screening

- Heuristic argument [Matsui-Satz 1986]:

  - Colour screening in a deconfined plasma dissolves QQbar.

  - Different bound states “melt” at different temperatures due to their different binding radius:
  QQbar: QGP “thermometer”

Screening Debye length λ_D vs. T:

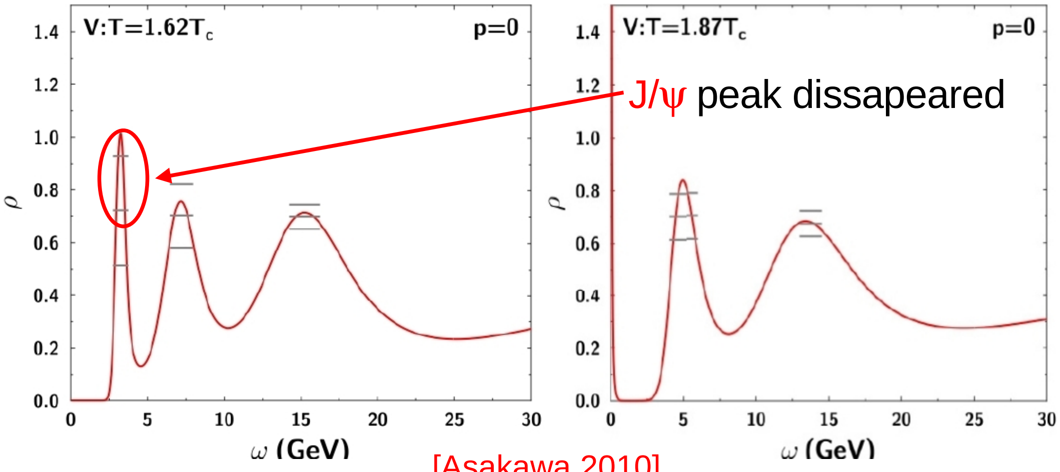


- Lattice QCD calculations (quarkonia spectral functions):

ψ', χ_c dissolve around T_c

J/ψ dissolves at ~1.5-2T_c

Υ survives up to ~4T_c



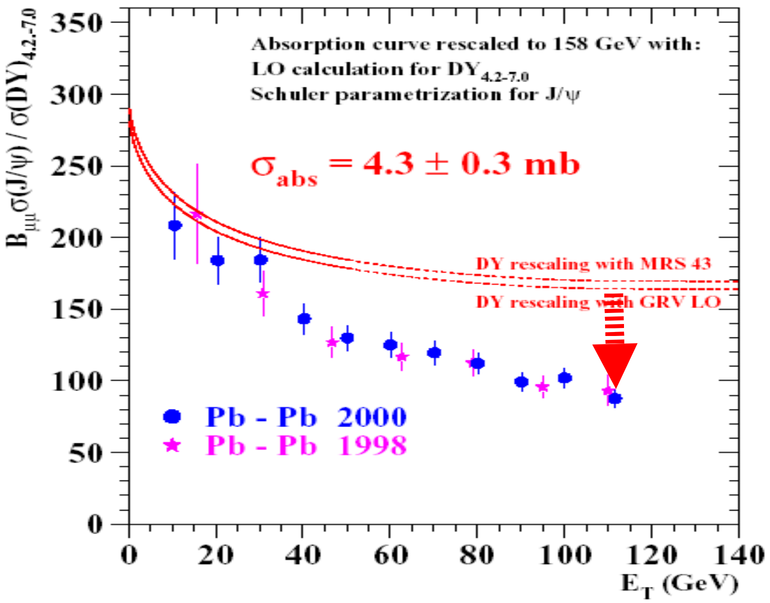
J/ψ peak dissapeared

[Asakawa 2010]

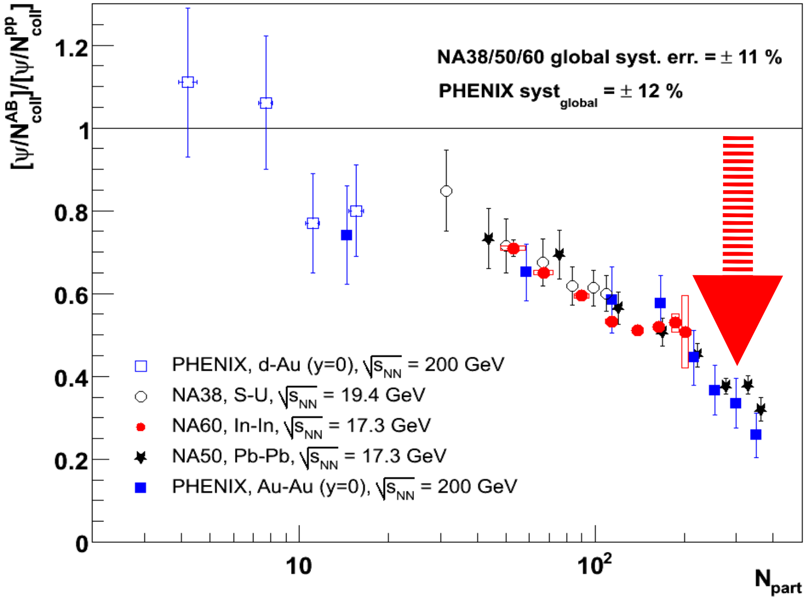
J/ψ suppression (SPS, RHIC)

- J/ψ suppression vs. collision centrality (N_{part}):

SPS: √s~20 GeV



RHIC: √s=200 GeV



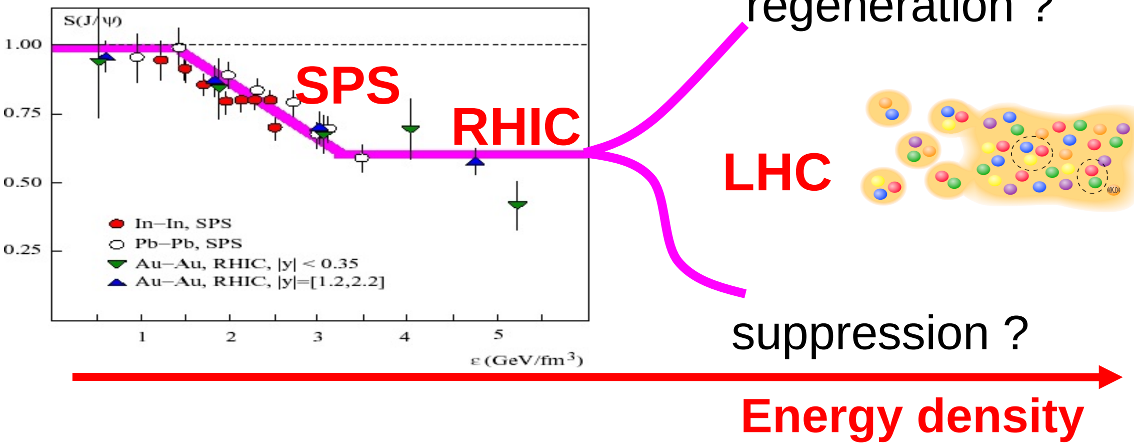
- Same suppression observed at RHIC (T~400 MeV) & SPS (T~200 MeV) !?

Charm recombination ? ccbar regeneration (~10 ccbar pairs in central AuAu) compensates for screening

Sequential dissociation ? Only ψ’ and χ_c (~40% feed-down J/ψ) suppressed. Direct J/ψ survives at RHIC ⇒ T_0<~2·T_c

J/ψ, ϒ suppression (LHC)

- J/ψ: enhancement or suppression ?

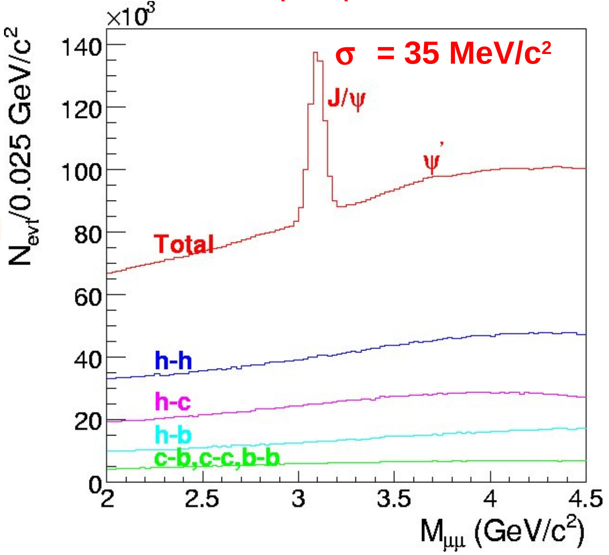


regeneration ?

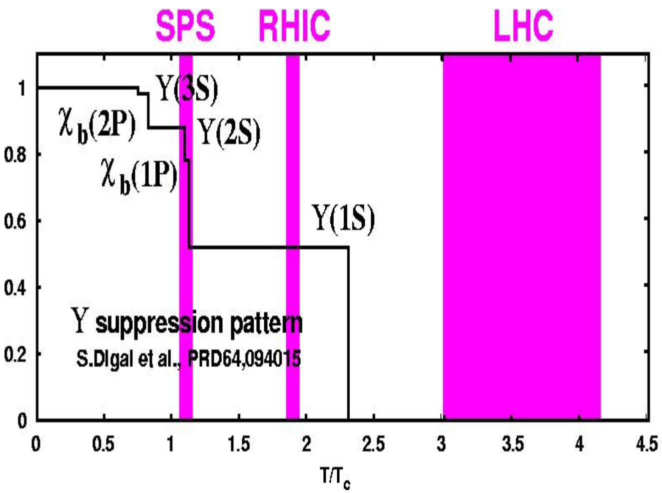
suppression ?

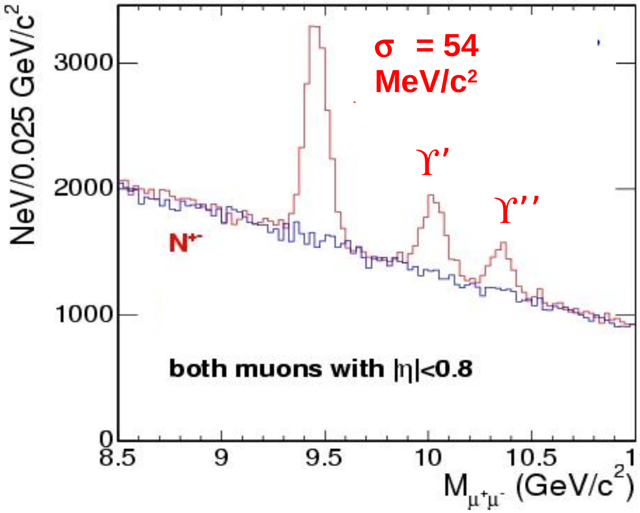
Energy density

J/ψ, ψ' S/B



- Bottomonia: sequential suppression ?





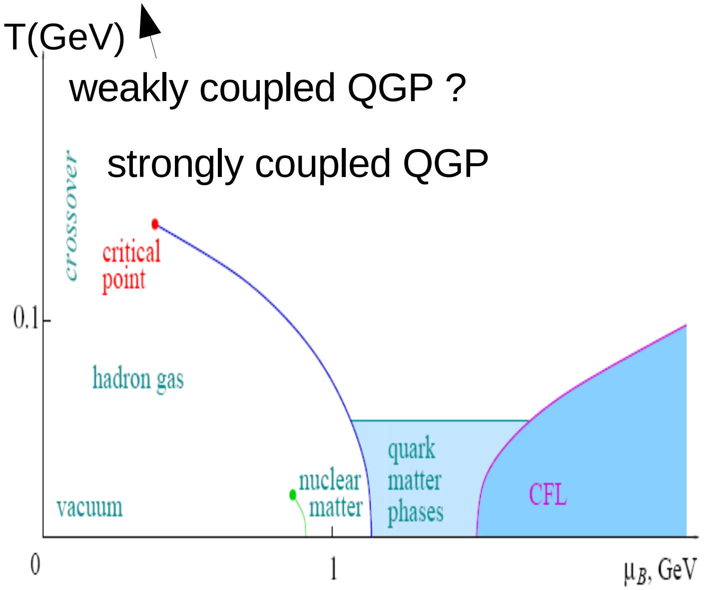
- Large stats. available:

  O(10^5) J/ψ

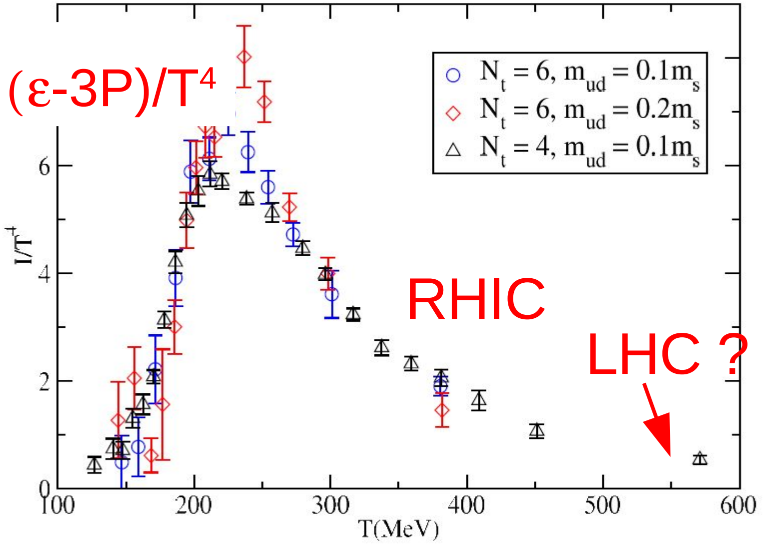
  O(10^4) Υ

Summary

- High-energy heavy-ion collisions study QCD in extreme conditions (ρ,T,small-x)
- SPS: close to phase boundary (T_0~200 MeV)
  J/Ψ suppressed, (ρ broadened, ...)
- RHIC: Initial-state = saturated gluon xG (CGC)
  Strongly-coupled QGP (large partonic flows):
  lowest viscosity/entropy <6/4π
  Very dense system (“jet quenching”):
  dN_g/dy~1000, <$\hat{q}$>~10 GeV^2/fm
  Hot medium (J/Ψ suppressed, thermal γ)
  T_0~2·T_c~400 MeV
- LHC: Hottest/densest matter in the lab ever.
  weakly-coupled QGP ?
  stronger CGC effects ? ...



LattQCD interaction measure:



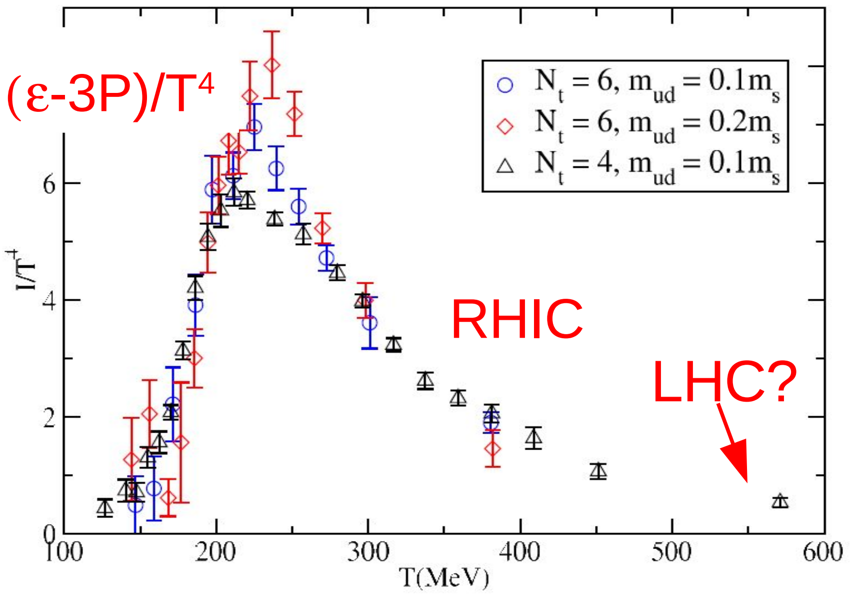
Backup slides

LHC: new frontier for QGP/CGC studies

- QGP: hotter, denser, bigger, longer-lived

	SPS	RHIC	LHC	
$\sqrt{s_{NN}}$ (GeV)	17	200	5500	X 28
dN_{ch}/dy	500	650	1500	x 2-3
τ^0_{QGP} (fm/c)	1	0.2	0.1	faster
T/T_c	1.1	1.9	3.0-4.2	hotter
ε (GeV/fm³)	~5	~10	~20	denser
τ_{QGP} (fm/c)	≤2	2-4	≥10	longer
τ_f (fm/c)	~10	20-30	30-40	
V_f(fm³)	few 10^3	few 10^4	few 10^5	bigger

weakly-interacting QGP ?



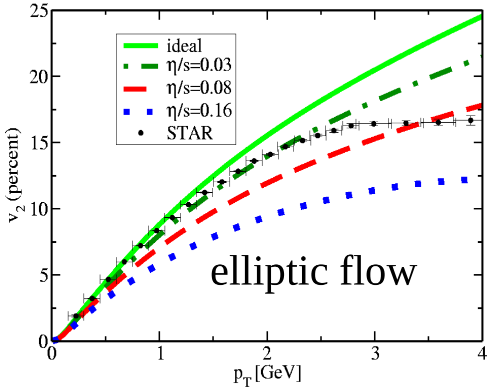
- Very large pQCD cross-sections (copious "tomographic" QGP probes).
- Very low-x = $2p_T/\sqrt{s}\cdot e^{y}$~10^{-4}-10^{-5} (30-45 times smaller than @ RHIC). Saturation scale (Q_s) x4 larger

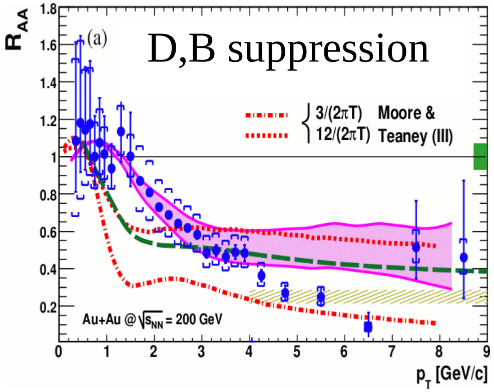
AdS/CFT: QGP applications

- The Quark-Gluon-Plasma @ RHIC is “strongly coupled”:

Strong parton flows consistent w/ ideal hydro (viscosity η~0)

Large heavy-Q (& light-q) E_{loss} (very opaque medium)





- AdS/CFT gives access to real-time (transport) QCD quantities.
- Large differences between QCD & SYM “wash out” at finite-T:

- Universal shear viscosity η bound (~ σ_{abs} of soft gravitons in BH): η/s > 1/4π

  [Kovtun&Son&Starinets, PRL94:111601,2005]

- Quenching parameter qhat (Wilson loop from strings): $\hat{q}_{\mathrm{SYM}} \approx 26.69\sqrt{\alpha_{\mathrm{SYM}} N_c}\,T^3$

  [Liu&Rajagopal&Wiedemann, PRL97, 182301, 2006]

- Heavy-Q diffusion coefficient D (Wilson loop from strings): $D_{SYM}\; D \simeq \frac{6.0}{2\pi T}\left(\frac{1.5}{\alpha_s N_c}\right)^2\;{}_{pQCD}$

  [Herzog, Gubser, Casalderrey-Solana, ...]

- virtual/real γ emission rates (thermal spectral functions), ...

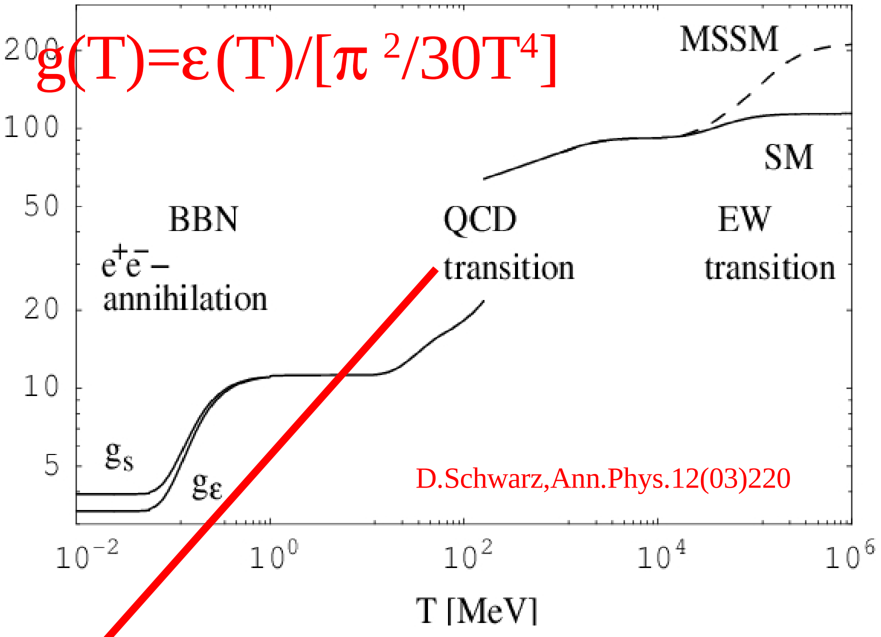
  [Kovtun, Teaney, ...]

QCD transition in the primordial Universe

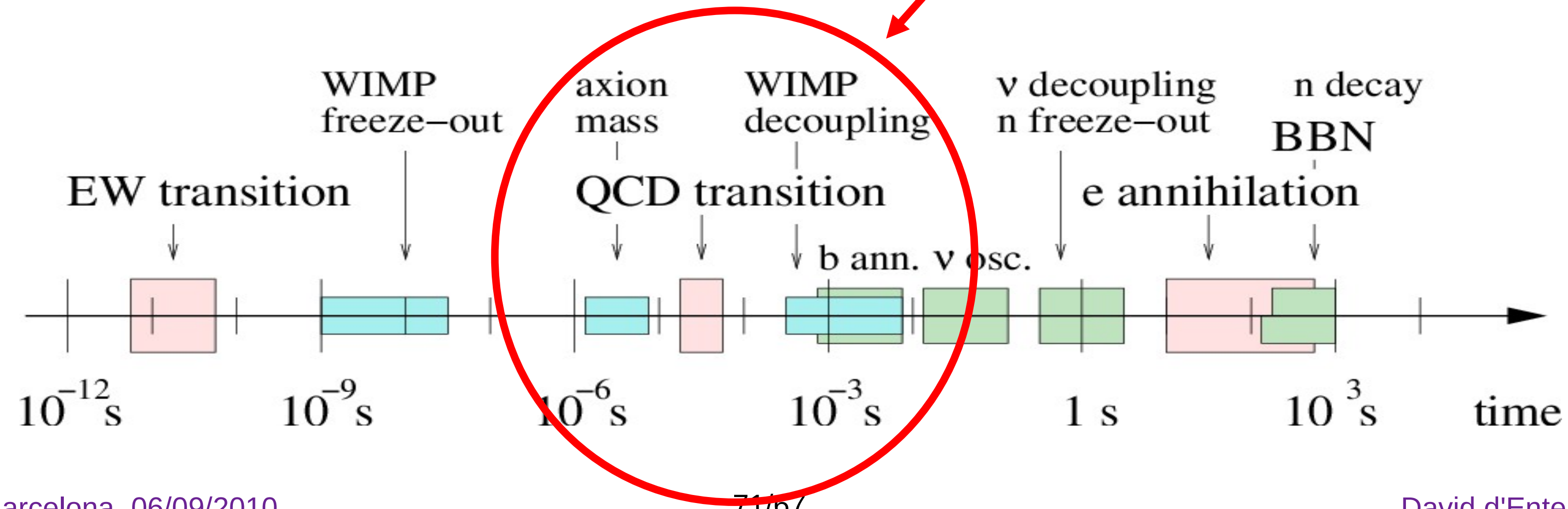
- The QGP was already produced ~13.7 (-10 μs) Gyears ago: Most important event between EW (or SUSY) transition and Big-Bang Nucleosynthesis:

- QCD phase-transition = backgd. role for most of DM relic densities

effective degrees of freedom vs T


$g(T)=\varepsilon(T)/[\pi^2/30T^4]$

D.Schwarz,Ann.Phys.12(03)220



“AdS/QGP” connection: basics

- Anti-de-Sitter(AdS)/Conformal-Field-Theory(CFT) correspondence

Strongly-coupled gauge theories in 4-D brane (CFT in our flat space)

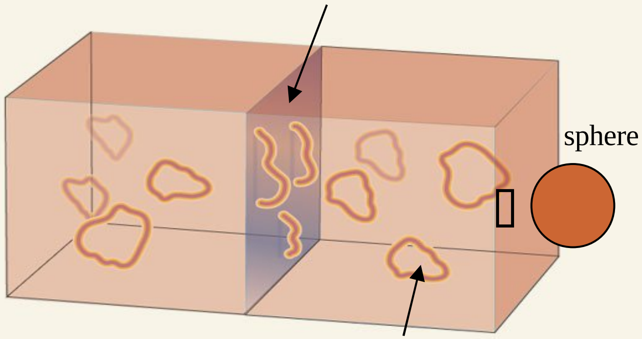
EQUIVALENT to

weakly-coupled gravity theories in 5-D neg. curved space-time (AdS)

- Maldacena's holographic conjecture,1998:

4-D $\mathcal{N}$= 4 SUSY Yang-Mills SU(N_c) ⇔ IIB string theory (supergravity) in $AdS_5 x S^5$

Gauge: fields (open strings) in 4-D brane



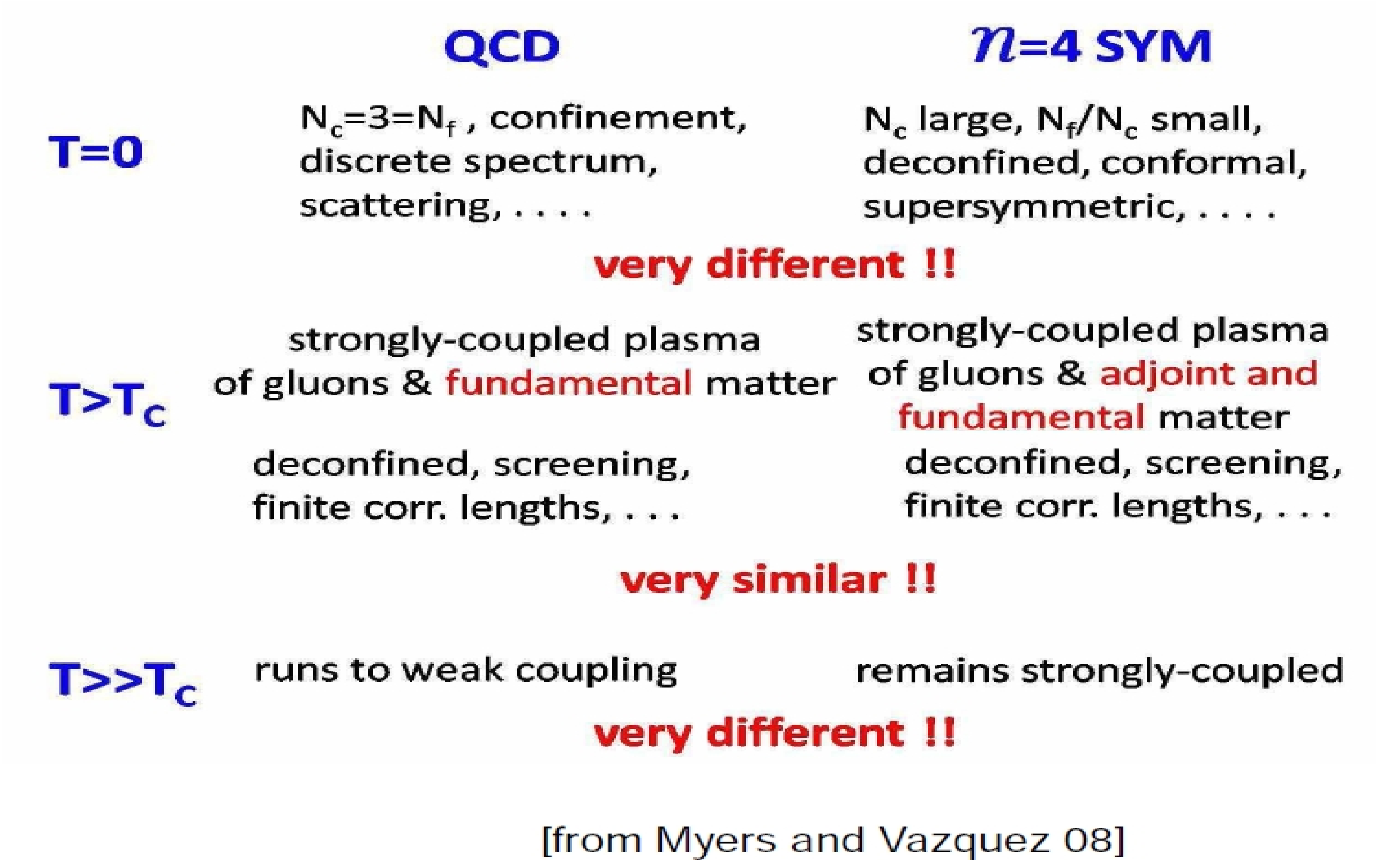
Dual: closed strings in 5-D AdSxS^5 space

Conjecture: Gauge (AdS boundary/horizon) & dual are same theory seen at diff. values of coupling (radial dir. r)

“Technicalities”:

- Gauge sector: 2 params. (g_{YM},N_c), large 't Hooft coupling ($g^2_{YM}N_c$ >> 1), conformal (no runn. coupling), supersymm. (gauge field, 4 Weyl fermions, 6 real scalars), $\mathcal{N}$=4 (four copies of D=4 brane)
- Gravity dual: SUGRA (supersymm. to match gauge side), fields (massless: gravitons, ...; massive string excitats.), 5 extra scalars (S^5 sphere), 2 parameters (string tension $1/\ell_s^2$, string coupling g_{st}), small curvature limit (R/ℓ_s>>1, classical Einstein GR)

QCD versus N=4 SYM



	QCD	**$\mathcal{N}$=4 SYM**
T=0	N_c=3=N_f , confinement, discrete spectrum, scattering, ...	N_c large, N_f/N_c small, deconfined, conformal, supersymmetric, ...
	very different !!	
T>T_C	strongly-coupled plasma of gluons & fundamental matter deconfined, screening, finite corr. lengths, . . .	strongly-coupled plasma of gluons & adjoint and fundamental matter deconfined, screening, finite corr. lengths, . . .
	very similar !!	
T>>T_C	runs to weak coupling	remains strongly-coupled
	very different !!	

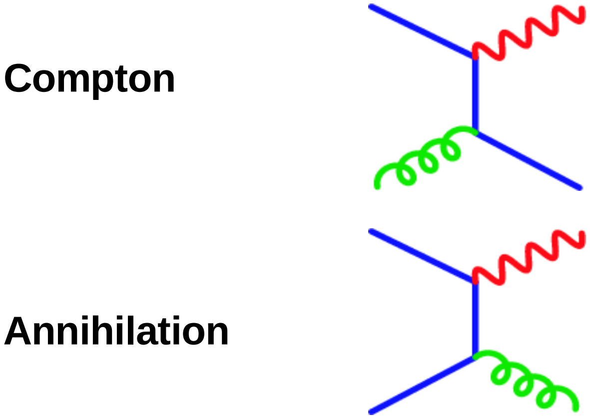
[from Myers and Vazquez 08]

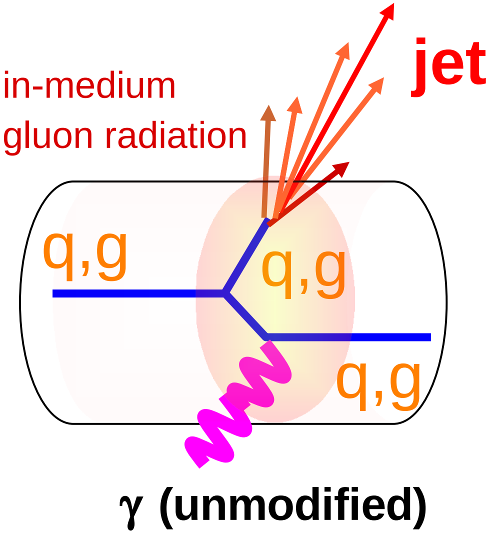
Heavy-ion experiments @ LHC

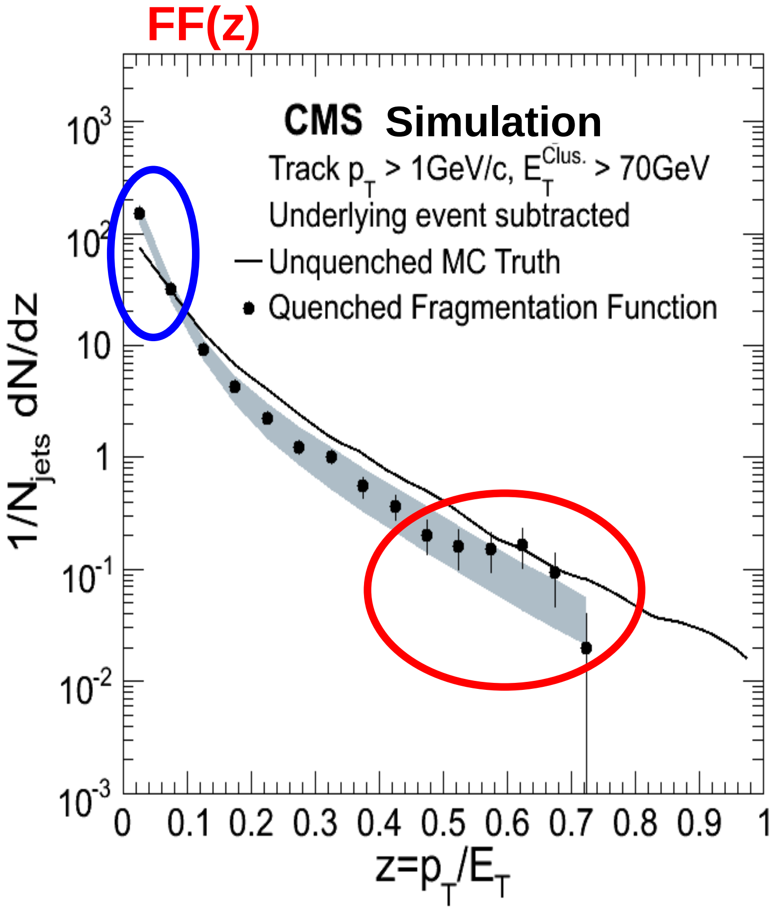
γ – jet, Z–jet (LHC)

- Jet-energy loss & Frag. Functions via jet balanced with gauge bosons:

Photon-jet LO diagrams (back-to-back):







Pb-Pb reaction centrality

- Centrality = crucial parameter to determine PbPb collision overlap: volume, particle/energy density of “fireball”.
- E_{tot},E_T in CASTOR or HF = monotonic functions of impact parameter (b)

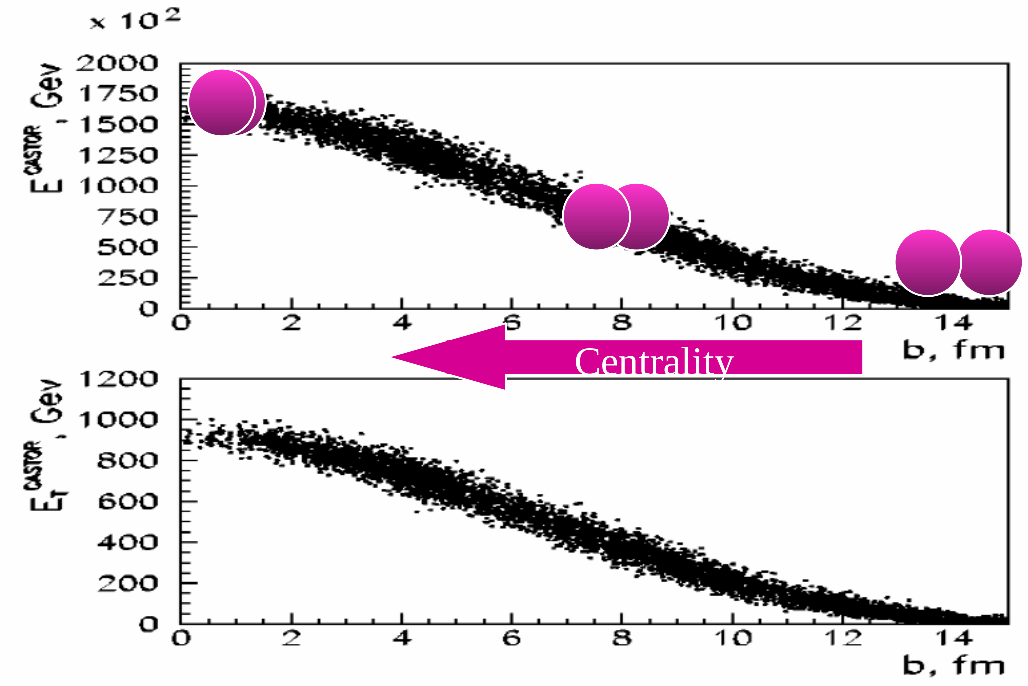
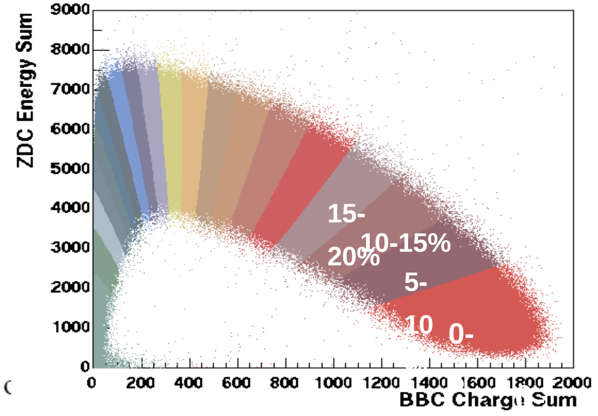


Figure 3: The distributions of energy and transverse energy deposited in CASTOR as a function
the impact parameter, *b*, for the highest energy Pb-Pb collisions at the LHC.

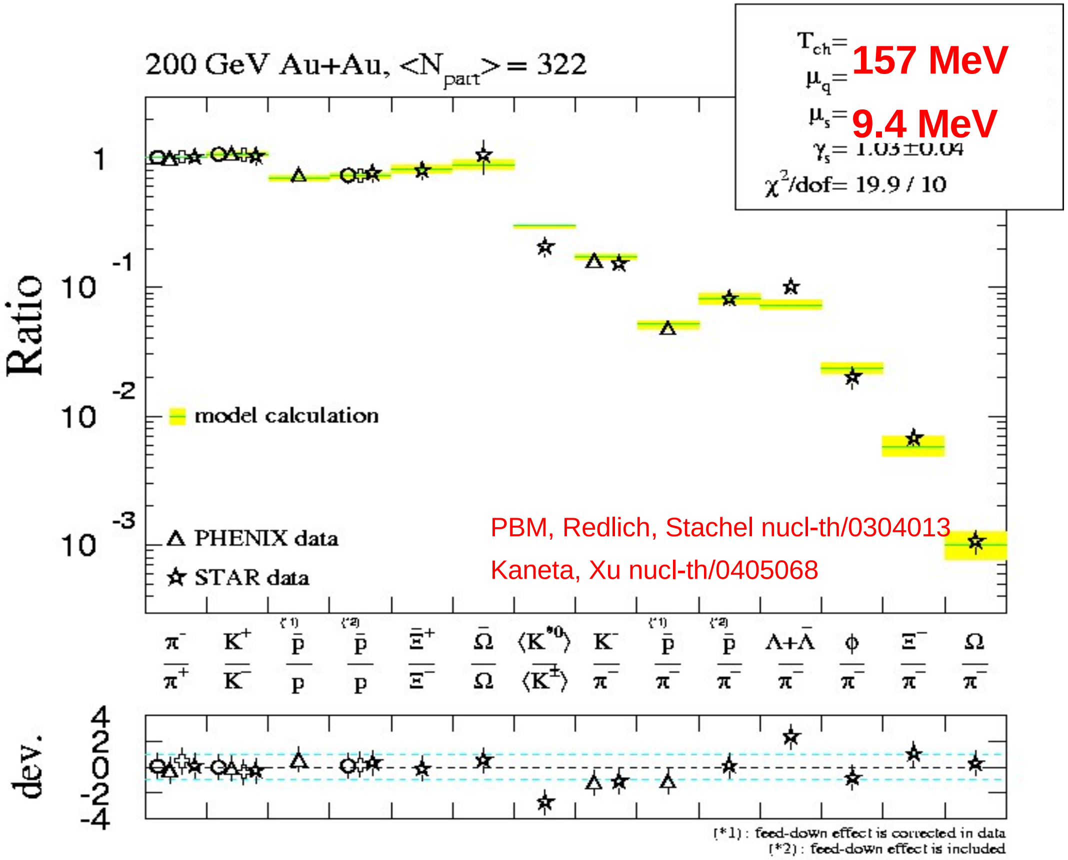
ZDC vs BBC @ RHIC



- NB: Correlation of CASTOR E_{tot} with ZDC E_{tot} will provide yet more accurate determination of the event centrality (default method at RHIC).

Ratios of particle yields

- Ratios of hadron yields consistent w/ system at chemical equilibrium at hadronization ($T_{chem.freeze-out}$ ~ T_{crit}) :



PBM, Redlich, Stachel nucl-th/0304013
Kaneta, Xu nucl-th/0405068

- Assume grand canonical distrib. described by T and μ:

$$dN \sim e^{-(E-\mu)/T} d^3p$$

- 1 ratio (e.g. $\bar{p}/p$) determines μ/T

$$\bar{p}/p \sim e^{-(E+\mu)/T}/e^{-(E-\mu)/T} = e^{-2\mu/T}$$

- 2nd ratio (e.g. K/pi) provides T,μ
- All other hadronic yields and ratios predicted

- Hadron composition (even for strange had., γ_s=1) “fixed” at hadronization