Heavy Ions theory overview

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LHC days in Split

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Fundamental interactions

Searches – Higgs, SUSY, extra-dimensions...

pp @ LHC, LC??

↑

Increase energy density

Fundamental interactions

Searches – Higgs, SUSY, extra-dimensions...

pp @ LHC, LC??

Increase energy density

Increase extended energy density

AA @ RHIC and LHC

Collective properties

of the fundamental interactions

How?

Specific questions in heavy-ion collisions

- What is the initial state of the system and how is it produced?
  - What is the structure of the colliding objects?
  - What is the asymptotic limit of QCD?
- What is the mechanism of thermalization?
  - How is thermal equilibrium reached?
  - What is the temperature of the created system?
- What are the properties of the produced medium?
  - How to measured them? – signals
  - What is the relation with lattice QCD?

Hard Probes

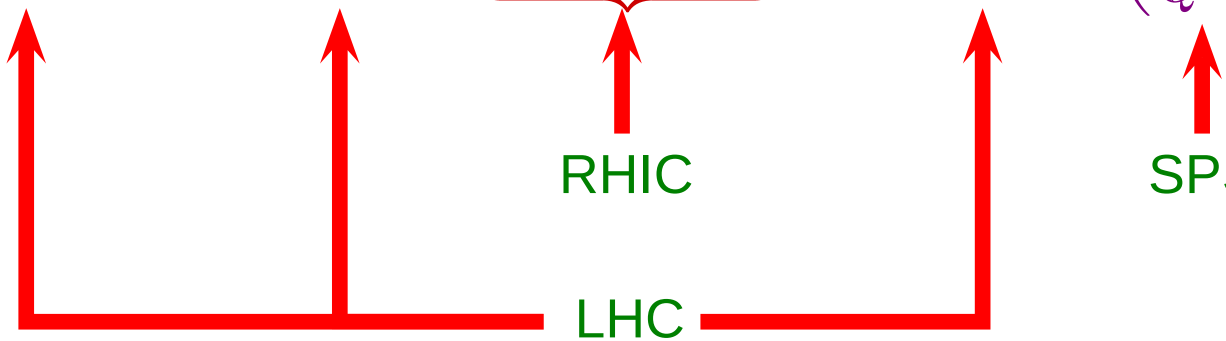
Provide a general framework

to answer these questions

Hard probes: heavy ion experiments

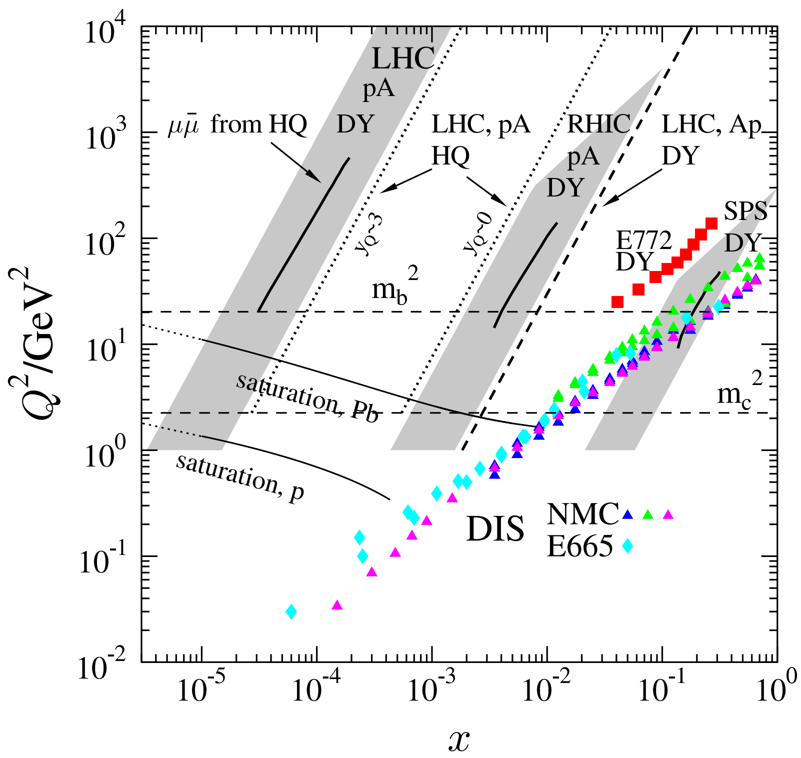
- SPS $\sqrt{s} = 20$ GeV ($Q \sim 1$ GeV) $\longrightarrow$ marginal access to HP
- RHIC $\sqrt{s} = 200$ GeV ($Q \sim 10$ GeV) $\longrightarrow$ access to HP
- LHC $\sqrt{s} = 5500$ GeV ($Q \gtrsim 100$ GeV) $\longrightarrow$ HP and QCD evolution

$$\sigma^{pp\to h} = f_p(x_1, Q^2) \otimes f_p(x_2, Q^2) \otimes \underbrace{\sigma(x_1, x_2, Q^2)} \otimes D(z, Q^2) + \left(\frac{1}{Q^2}\right)^n$$



- $Q^2 \gg 1 \implies$ short distances pieces not affected by the medium
- Modification of long-distance parts $f_p(x, Q^2)$ and $D(z, Q^2)$
  - new dynamics (evolution eqs.) $\longrightarrow$ properties of the medium.

Kinematical regions studied

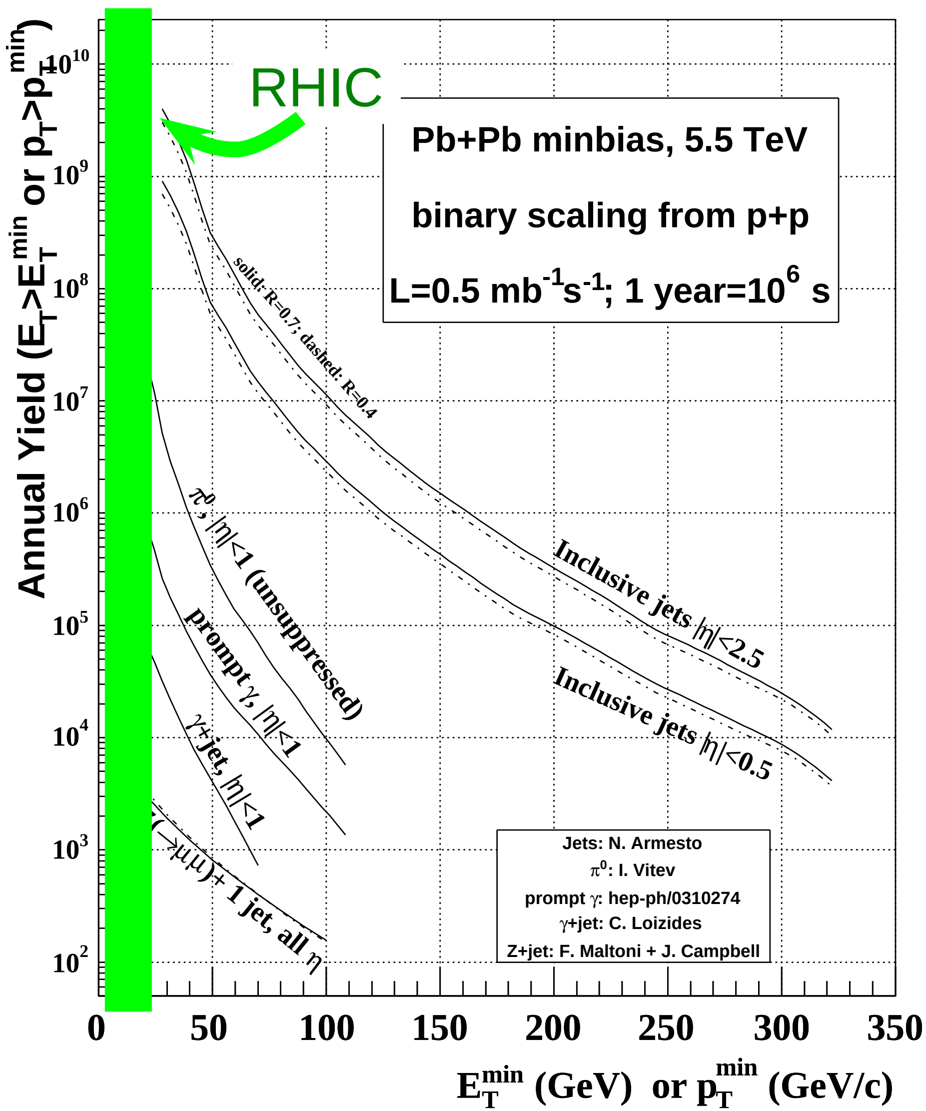


Eskola *et al.* hep-ph/0302170

⇛ New regimes at the LHC

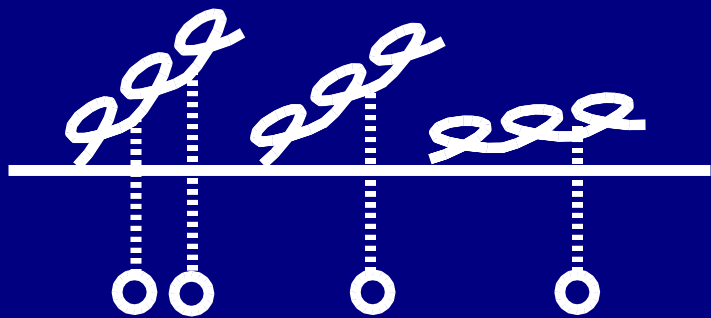
➷ In-medium QCD-evolution

Annual hard process yields



P. Jacobs, M. van Leeuwen 2005

QCD at high densities

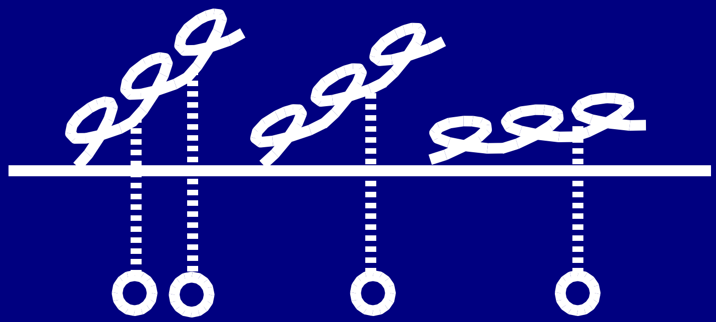


$\longrightarrow$ New (non-linear) ev. equations

parton distributions: saturation

$\longrightarrow$ Jet shapes modified

QCD at high densities



$\longrightarrow$ New (non-linear) ev. equations parton distributions: saturation

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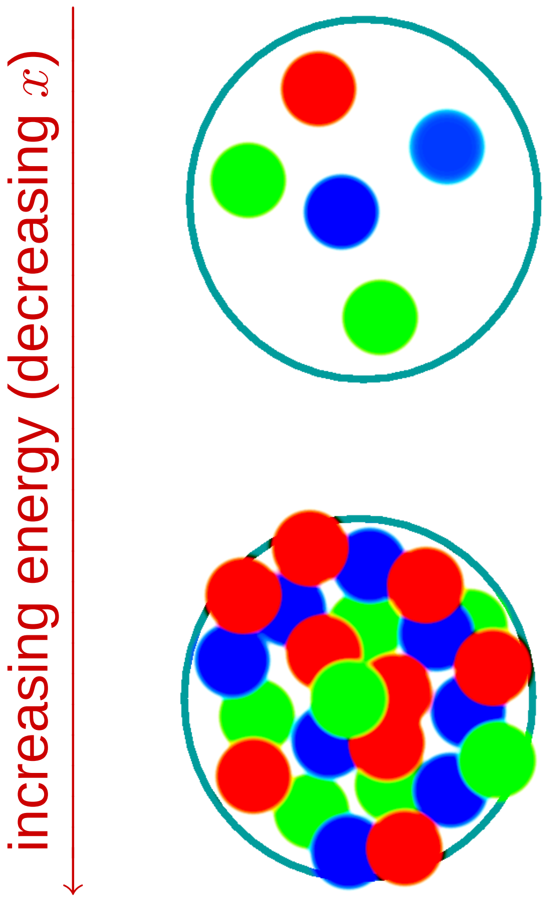
Saturation of partonic densities

Saturation scale $Q_{\rm sat}$ when interaction probab. $\mathcal{O}(1)$

$$\alpha_S(Q^2_{\rm sat})xg(x,Q^2_{\rm sat})/Q^2_{\rm sat}\pi R^2 \sim 1$$



- ⇛ Large occupation numbers $n \sim 1/\alpha_S$
  - Semiclassical approach
- ⇛ Weak coupling $\alpha_S(Q^2_{\rm sat})$, $Q_{\rm sat} \gg \Lambda_{\rm QCD}$
- ⇛ QCD-evolution modified by non-linear terms: B-JIMWLK, Kovchegov equations
  - Geometric scaling

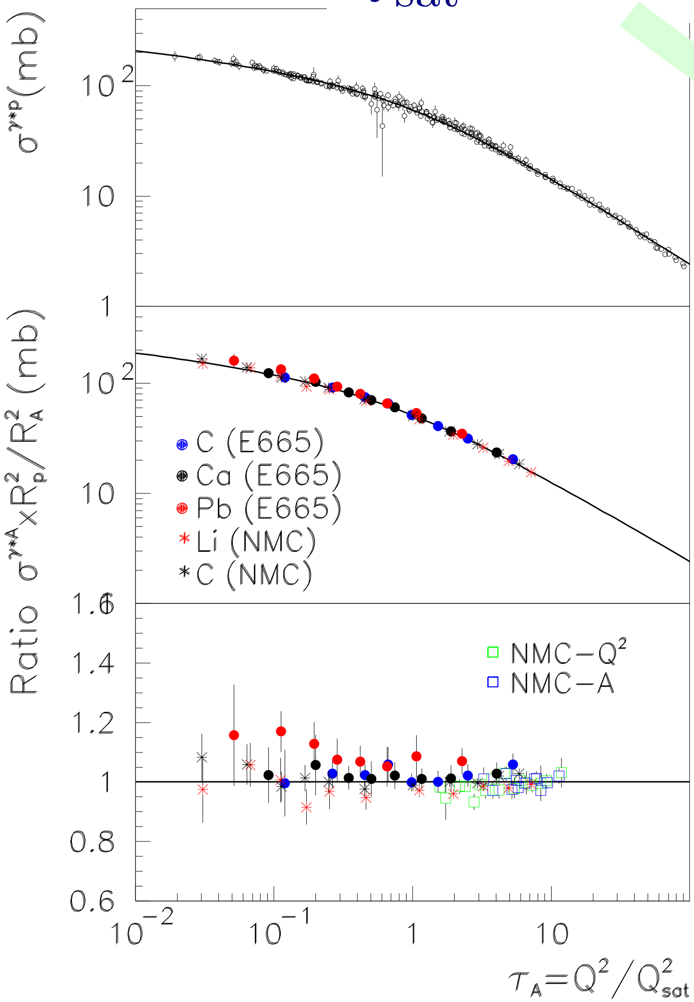
Observables

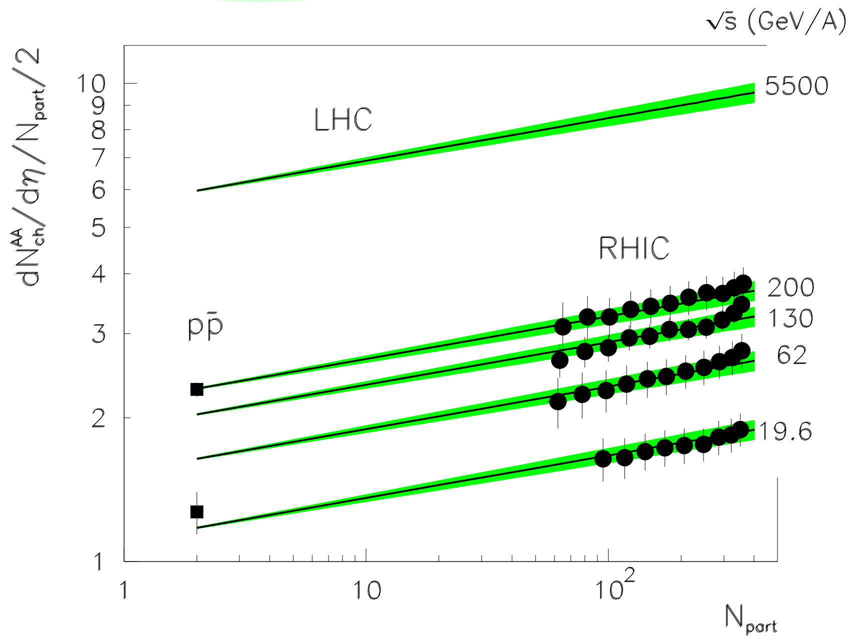
- ⇛ Multiplicities in nucleus-nucleus
- ⇛ Proton-nucleus collisions
- ⇛ Correlations

Geometric scaling and data

$$Q^2_{\rm sat} \propto x^{-\lambda} A^{1/3\delta}$$

$$\frac{1}{N_{\rm part}} \frac{dN^{AA}}{d\eta}\bigg|_{\eta\sim 0} = N_0 \sqrt{s}^{\lambda} N_{\rm part}^{\frac{1-\delta}{3\delta}}$$





Stasto, Golec-Biernat, Kwiecinski 2001

Armesto, Salgado, Wiedemann 2004

Kharzeev, Levin, McLerran, Nardi 2000...

Armesto, Salgado, Wiedemann 2004

Saturation and data

- Main properties of the CGC compatible with experimental data
  - saturation scale
  - scaling solution
  - suppression at forward rapidity (small-x)
- Accident??

++ Provides a general framework

- Initial conditions for the dense medium
- Fast thermalization? $\tau_0 \sim \frac{1}{Q_{\rm sat}} \sim$ 0.2 fm at RHIC
  - Strong fields $\Longrightarrow$ Unruh (thermal) radiation [Kharzeev and Tuchin (2005)]
- Other approaches predict slower thermalization times:
  - bottom-up thermalization [Baier, Mueller, Schiff and Son (2001)]
  - Plasma instabilities [Mrowczynski 1994; Arnold, Lenaghan, Moore 2003; Romatschke, Strickland 2003...]

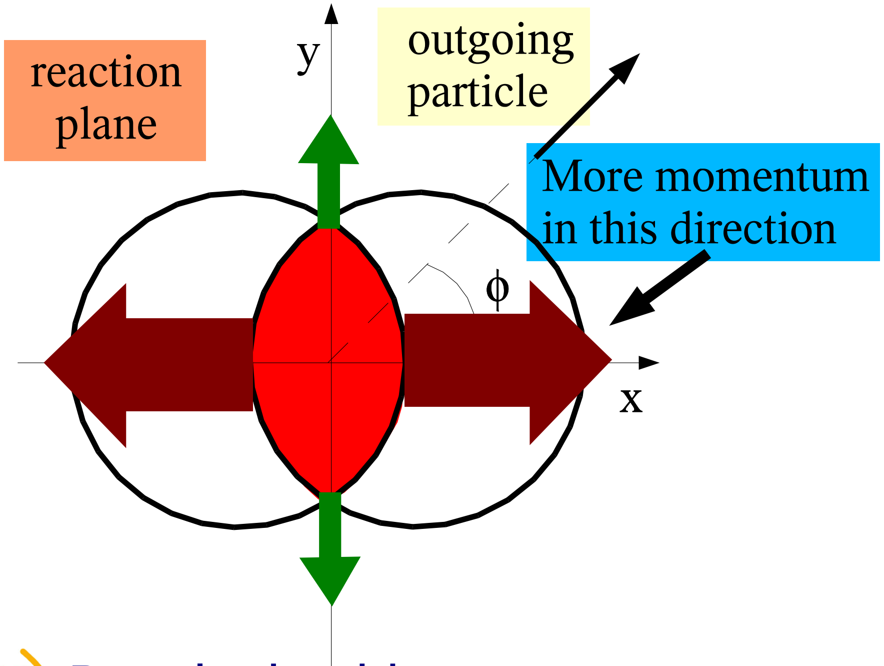
Hydrodynamics

as a check of themalization

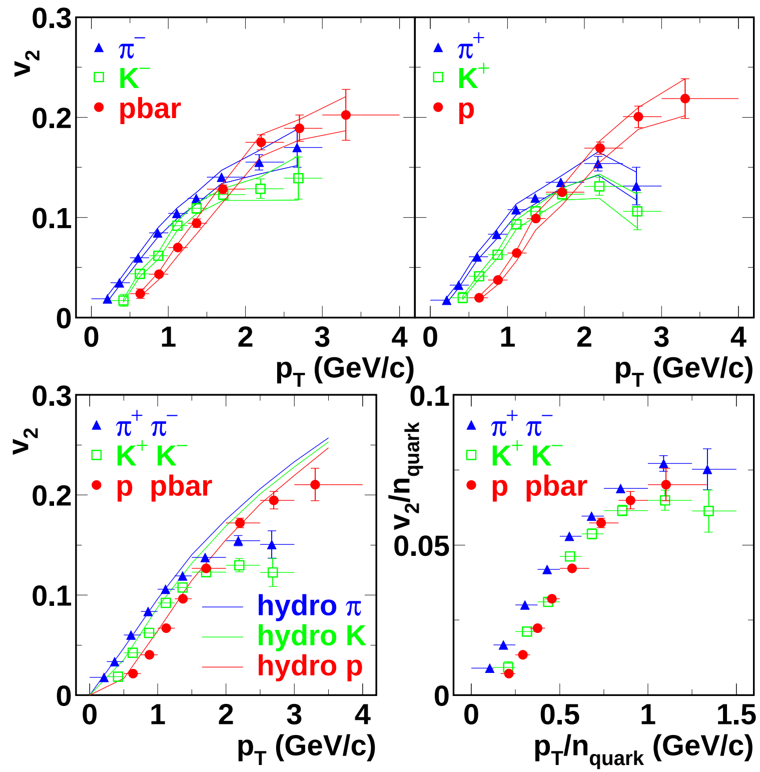
Description of the medium as a fluid

⇛ In a fluid, the acceleration is given by the Euler equation

$$\frac{d\beta}{dt} = \frac{1}{\rho}\nabla P \quad \text{for an ideal gas} \quad \epsilon = 3P$$



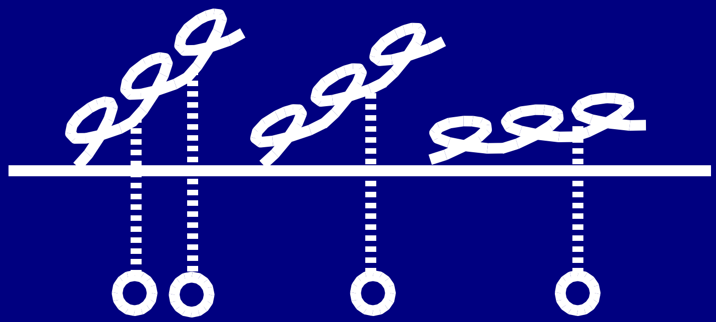
Full hydrodynamical simulation



⇛ Developing idea

- Early thermalization $\tau_0 < 1$fm
- Ideal liquid

QCD at high densities



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parton distributions: saturation

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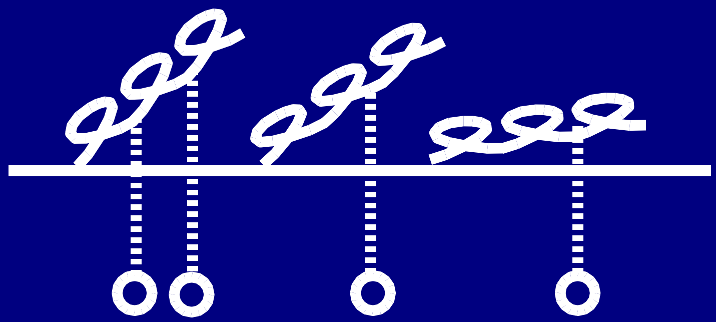

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Why high-p_t?

Different scales studied

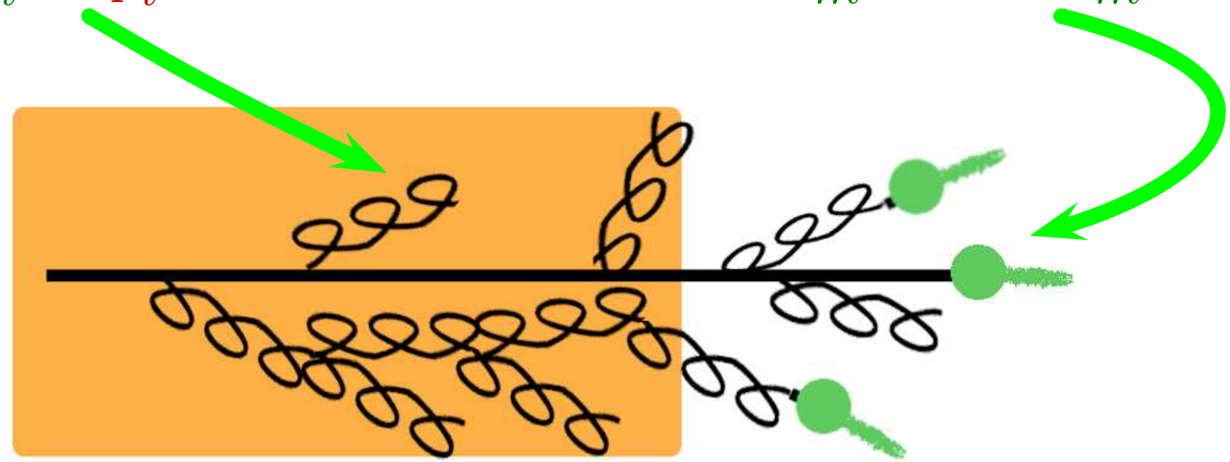
Unique property of jet quenching as a probe of the medium

Radiation formation time

$$t_{\rm form} \sim \frac{\omega}{k_t^2} \sim \frac{1}{p_t^{\rm assoc} \sin\theta}$$

Hadronization time

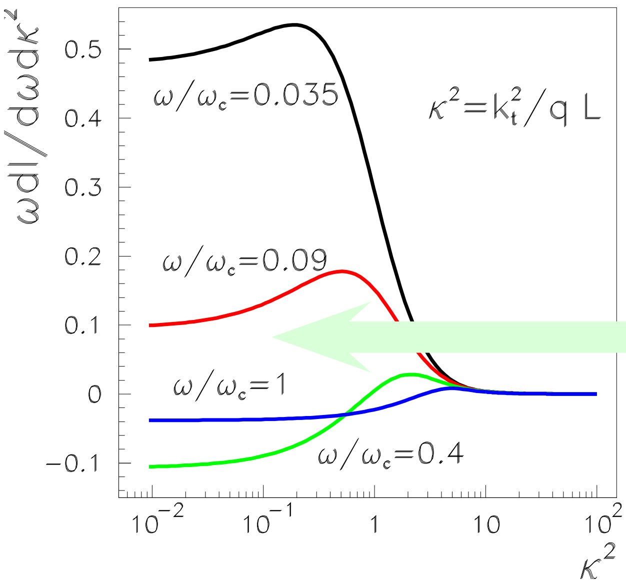
$$t_{\rm had} \sim \frac{E}{m} R_{\rm had} \sim \frac{p_t^{\rm lead}}{m} R_{\rm had}$$

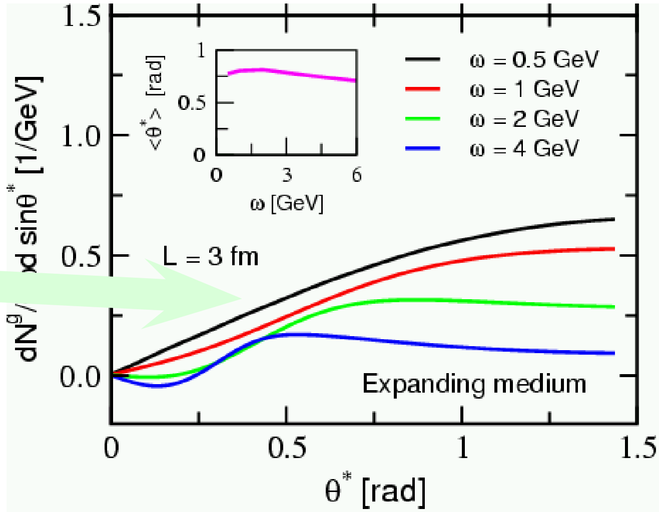


- ⇒ $t_{\rm form} \leq L \Longrightarrow$ shower in a medium
- ⇒ $R_{\rm had}$ not known for a medium
- ⇒ Intermediate $p_t \longrightarrow$ interplay radiation–thermalization–hadronization
- ⇒ Which part of the spectrum is thermalized?

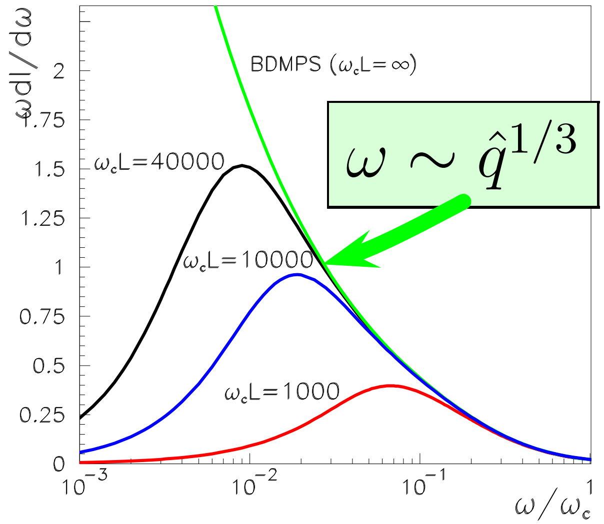
The Medium-induced gluon radiation spectrum

[BDMPS (1996); Zakharov (1997); Wiedemann (2000); GLV (2000)]





Coherence/
Formation time



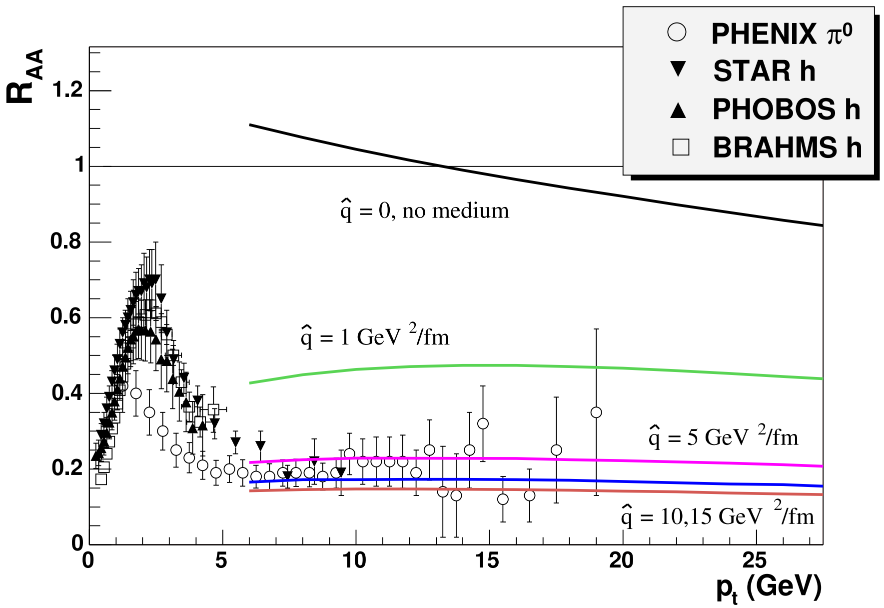
⇒ Medium: transport coefficient

$$\hat{q} \simeq \frac{\langle k_t^2 \rangle}{\lambda} \propto n(\xi)$$

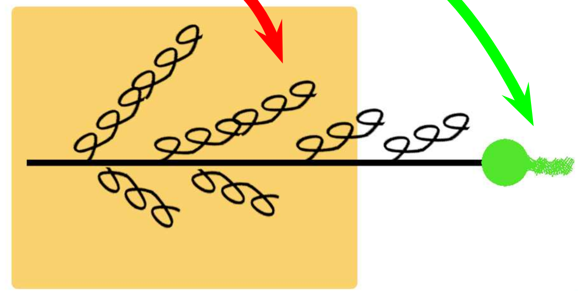
- High-p_t suppression: $\Delta E \sim \alpha_S \hat{q}\, L^2$
- Jet-broadening: $k_t^2 \sim \Delta E/\alpha_S L$ BDMPS 97

R_{AA} for light mesons at RHIC

$$d\sigma^{AA\to h+X}_{(\text{med})} = \sum_f d\sigma^{AA\to f+X}_{(\text{vac})} \otimes \boxed{P_f(\Delta E, L, \hat{q})} \otimes D^{(\text{vac})}_{f\to h}(z, \mu_F^2)\,.$$



[Eskola, Honkanen, Salgado, Wiedemann (2004)]



⇛ Multiple emission: Poisson distribution

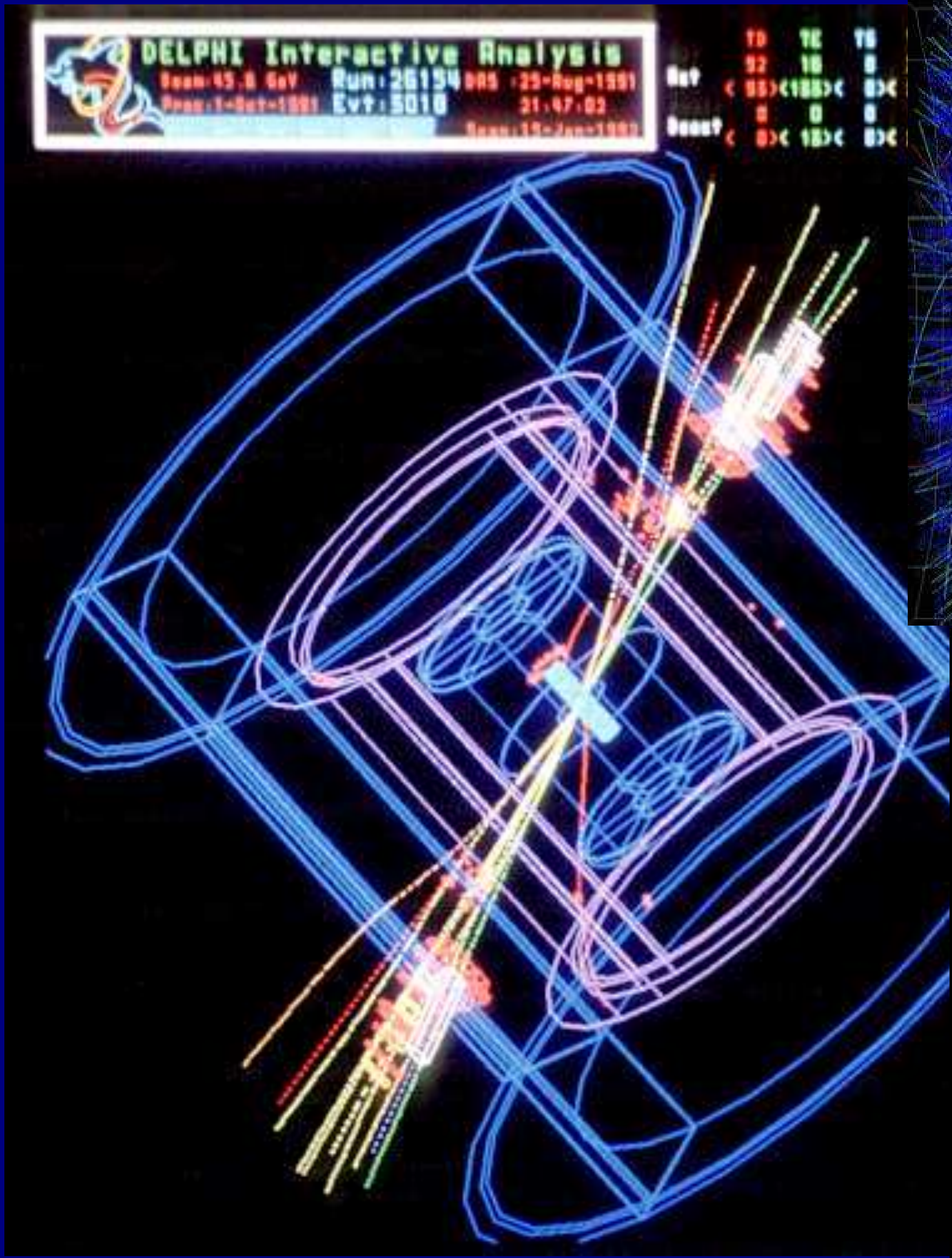
⇛ Hadronization in vacuum at high-p_t

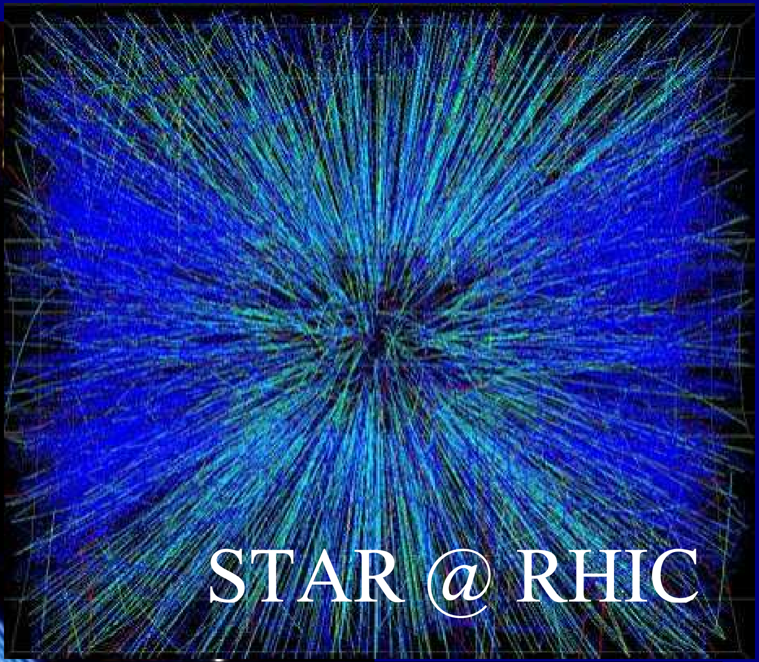
⇛ Data favors a large time-averaged transport coefficient

$$\hat{q} \sim 5 \ldots 15 \frac{GeV^2}{fm}$$

[Gyulassy, Levai, Vitev 2002; Arleo 2002; Dainese, Loizides, Paic 2004; Wang, Wang 2005; Drees, Feng, Jia 2005; Turbide, Gale, Jeon, Moore 2005...]

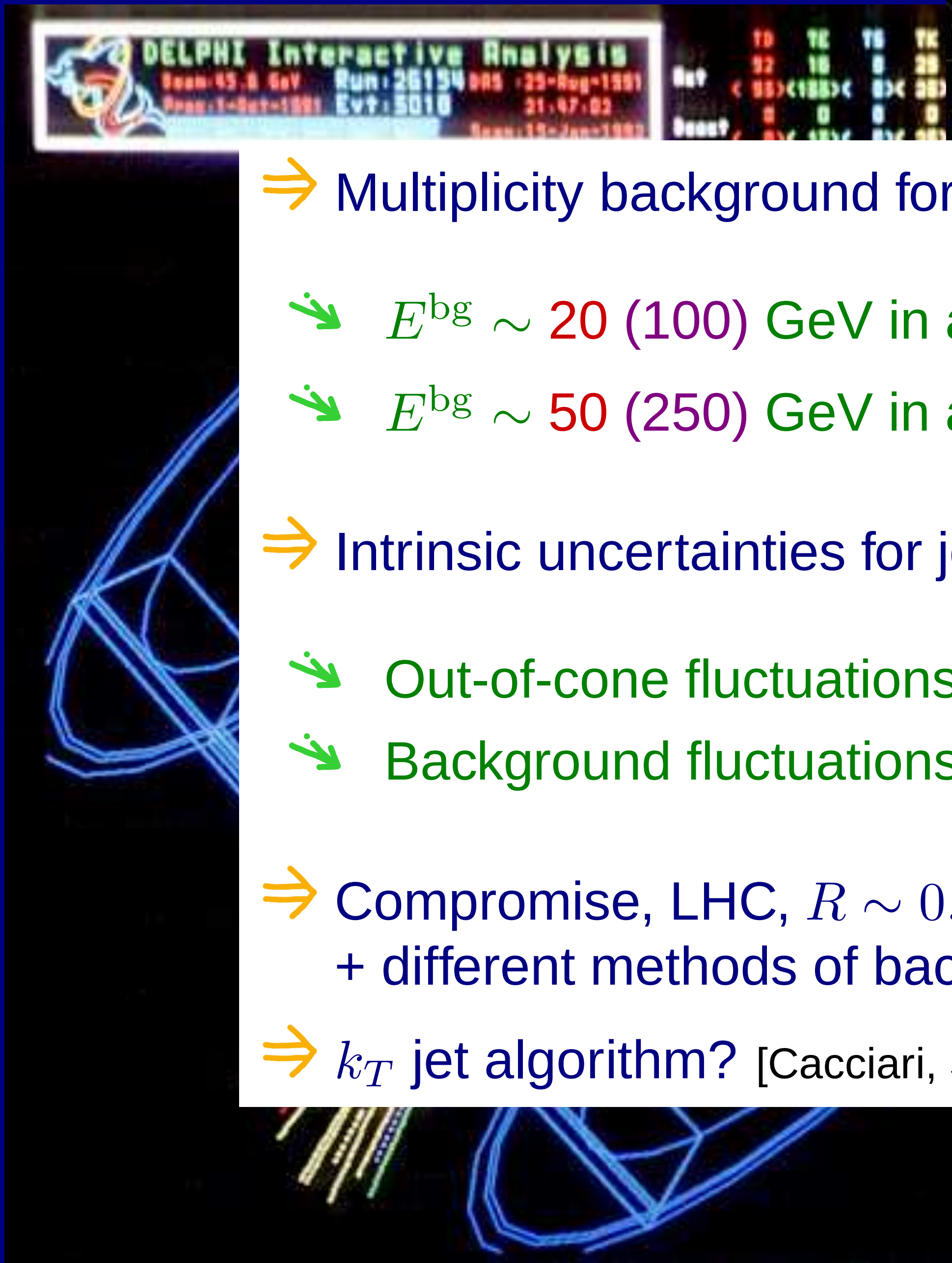
Jets in HIC?

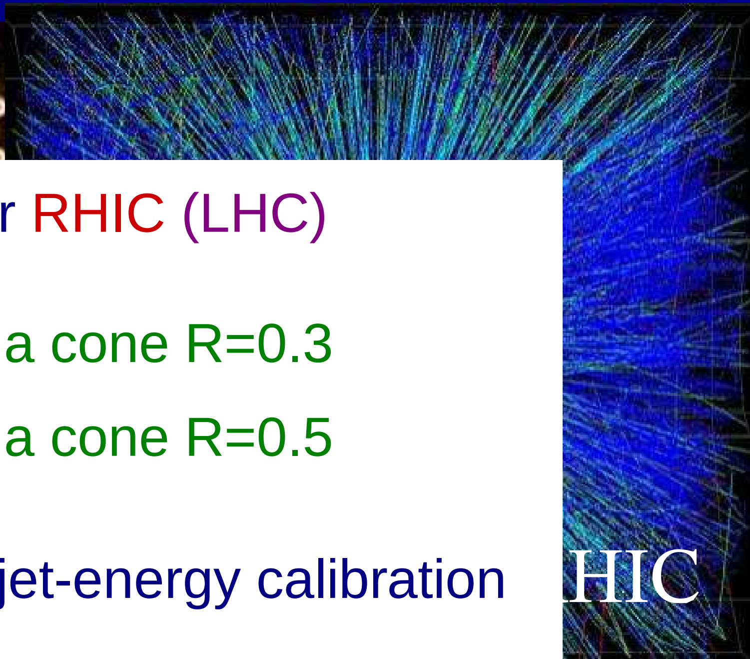

DELPHI Interactive Analysis

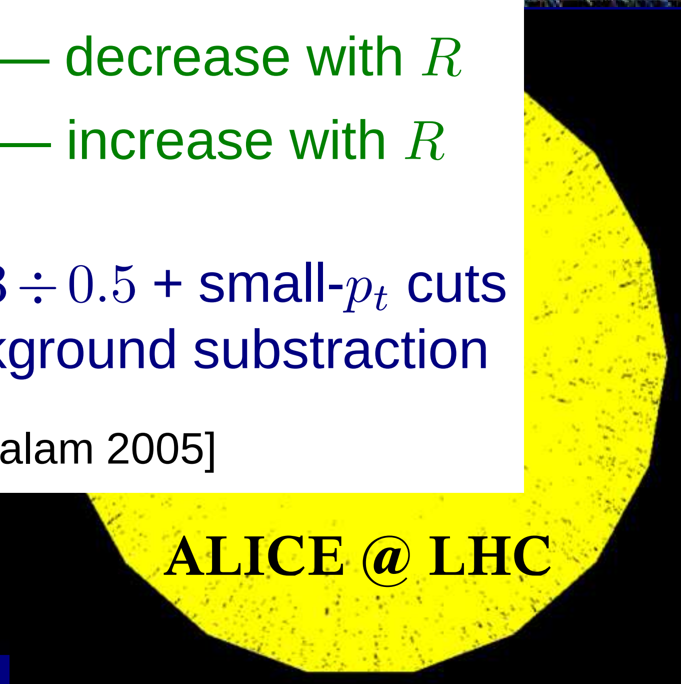

STAR @ RHIC


Alice event: 0, Run:0
Nparticles = 36276 Nhits = 19431047
ALICE @ LHC

Jets in HIC?







⇛ Multiplicity background for RHIC (LHC)

- $E^{\rm bg} \sim$ 20 (100) GeV in a cone R=0.3
- $E^{\rm bg} \sim$ 50 (250) GeV in a cone R=0.5

⇛ Intrinsic uncertainties for jet-energy calibration

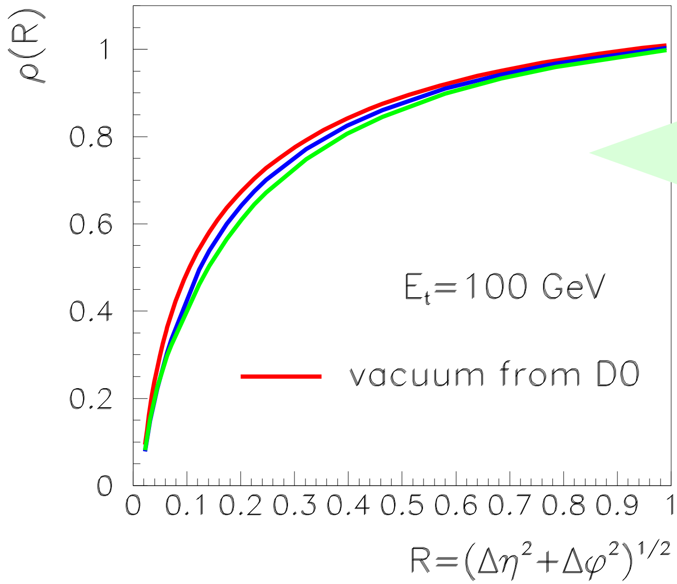
- Out-of-cone fluctuations — decrease with R
- Background fluctuations — increase with R

⇛ Compromise, LHC, $R \sim 0.3 \div 0.5$ + small-p_t cuts + different methods of background substraction

⇛ k_T jet algorithm? [Cacciari, Salam 2005]

Jet heating at the LHC

Medium-modification of jet shapes, E_t=100 GeV [Salgado, Wiedemann 2004]



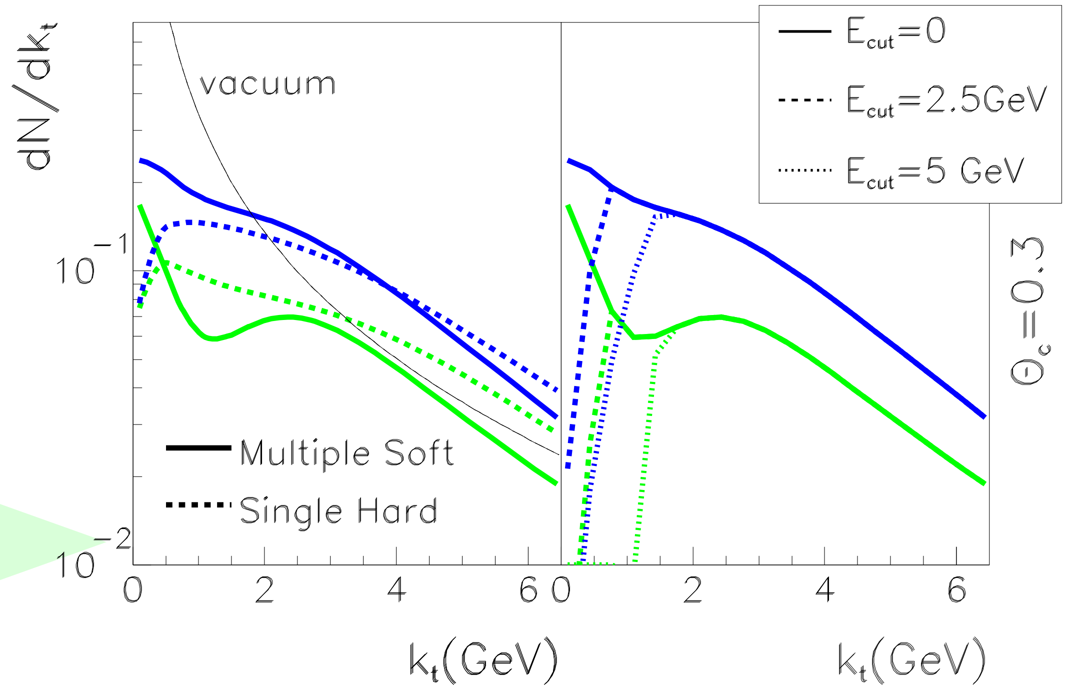
⇛ Fraction of the energy inside a cone $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

$$\rho(R) = \frac{1}{N_{\rm jets}} \sum_{\rm jets} \frac{E_t(R)}{E_t(R=1)}$$

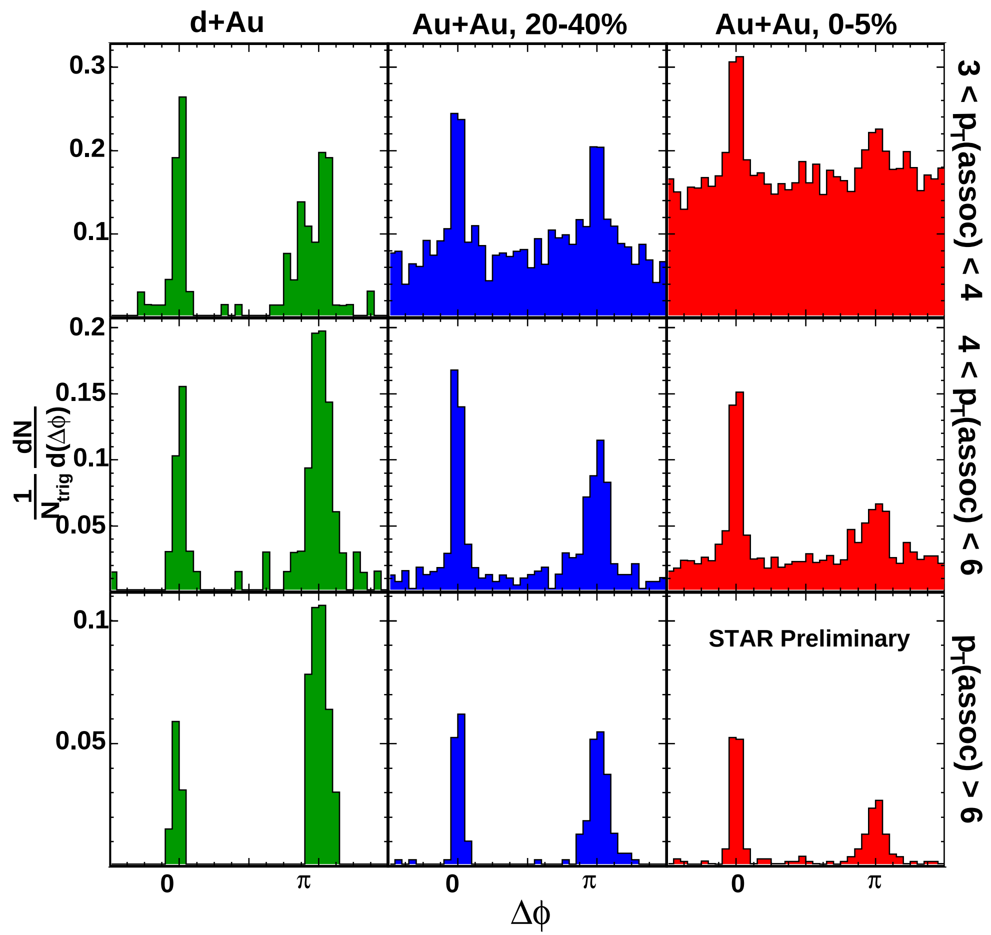
⇛ Jet energy calibration for $R \sim 0.3$

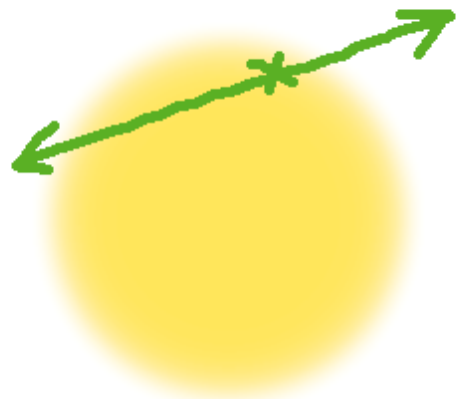
⇛ k_t-dependence of the multiplicity inside a cone

⇛ Large broadening



News from RHIC





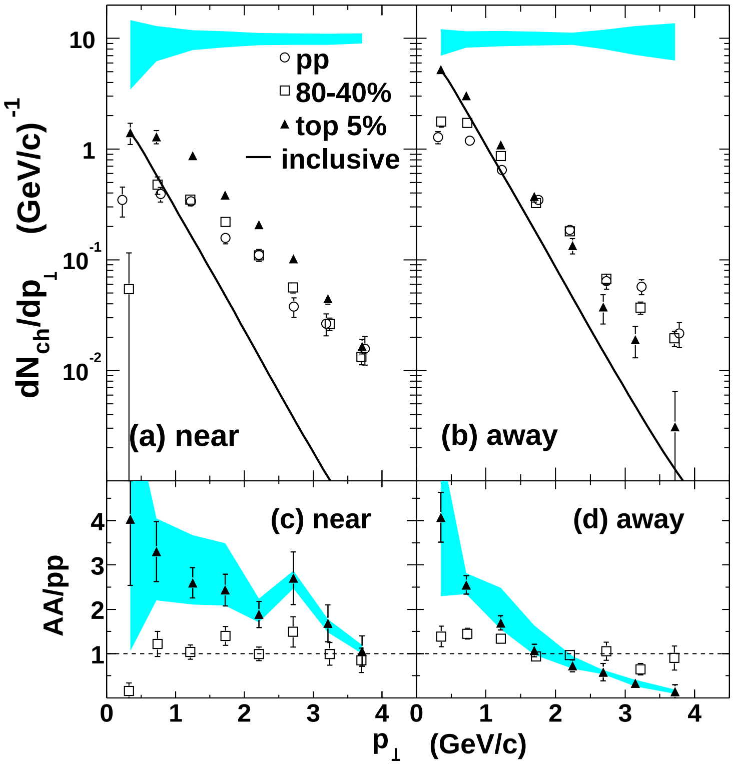
$p_t^{\rm trigg} > 8$ GeV, No background substranction

[STAR: D. Magestro QM05]

⇛ Data can be understood in the formalism [Dainese, Loizides 2005]

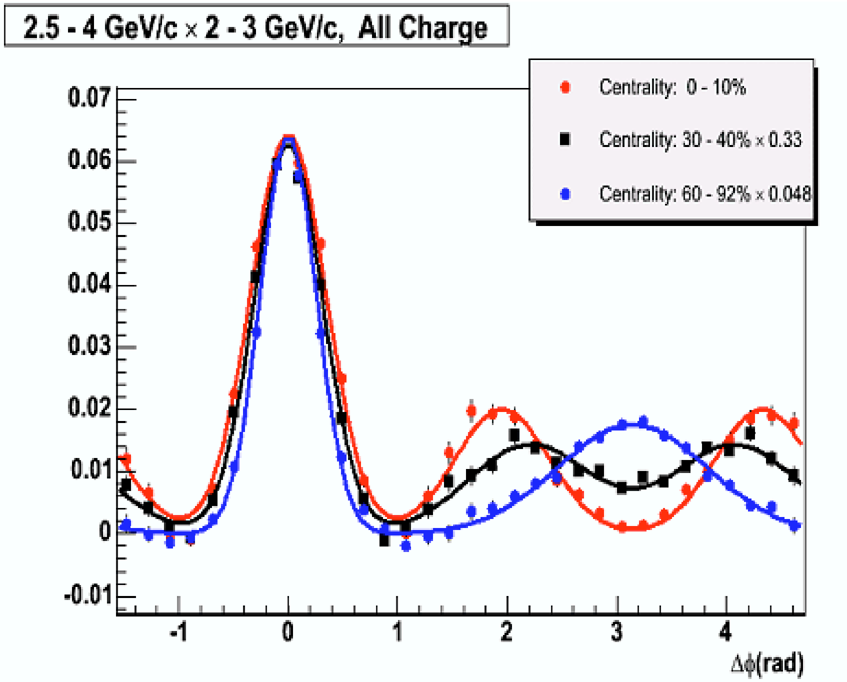
Removing the cut-off at RHIC

Interplay between the soft bulk and high-p_t



[STAR Collaboration 2005]

$4 \le p_t^{\rm trig} \le 6$ GeV



[PHENIX Collaboration 2005]

⇛ Associated particles are softer

⇛ Large broadening (two-peaks?) in the away side

Removing the cut-off at RHIC: Interpretations

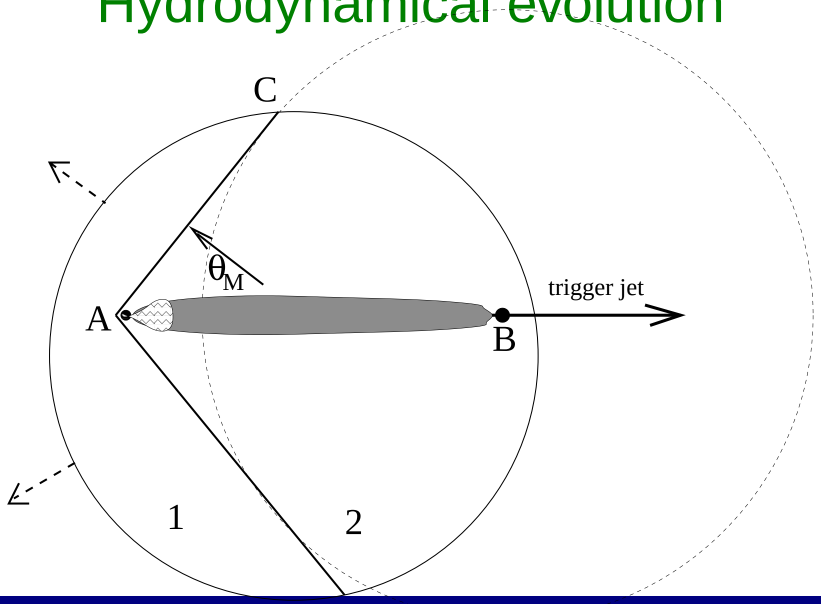
- Shock waves: measure sound velocity in the medium

  [Satarov,Stoeker,Mishustin 2005; Casalderrey-Solana,Shuryak,Teaney 2004; Ruppert,Muller 2005]

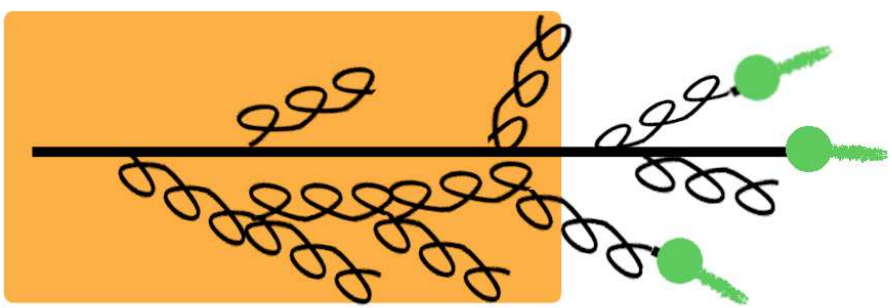
- Gluon radiation
  - Cherenkov radiation [Dremin 2005; Koch, Majumder, Wang 2005]
  - Parton shower for opaque media [Polosa, Salgado 2006]

Two opposite assumptions

All energy transferred to medium:
Hydrodynamical evolution



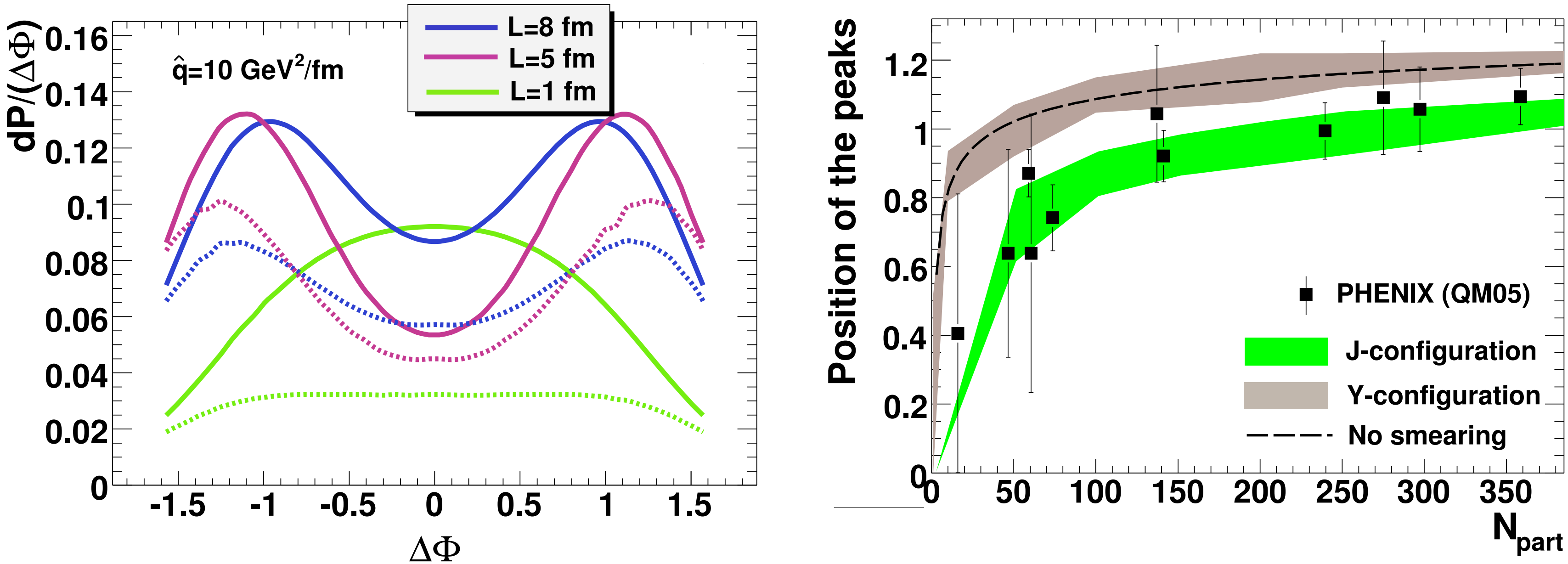
Negligible energy transferred:
Energy loss is radiated as gluons



Parton Shower for opaque media

⇛ Probability of one splitting for $\omega \lesssim \hat{q}^{1/3} \simeq$ 3 GeV [coherent limit]

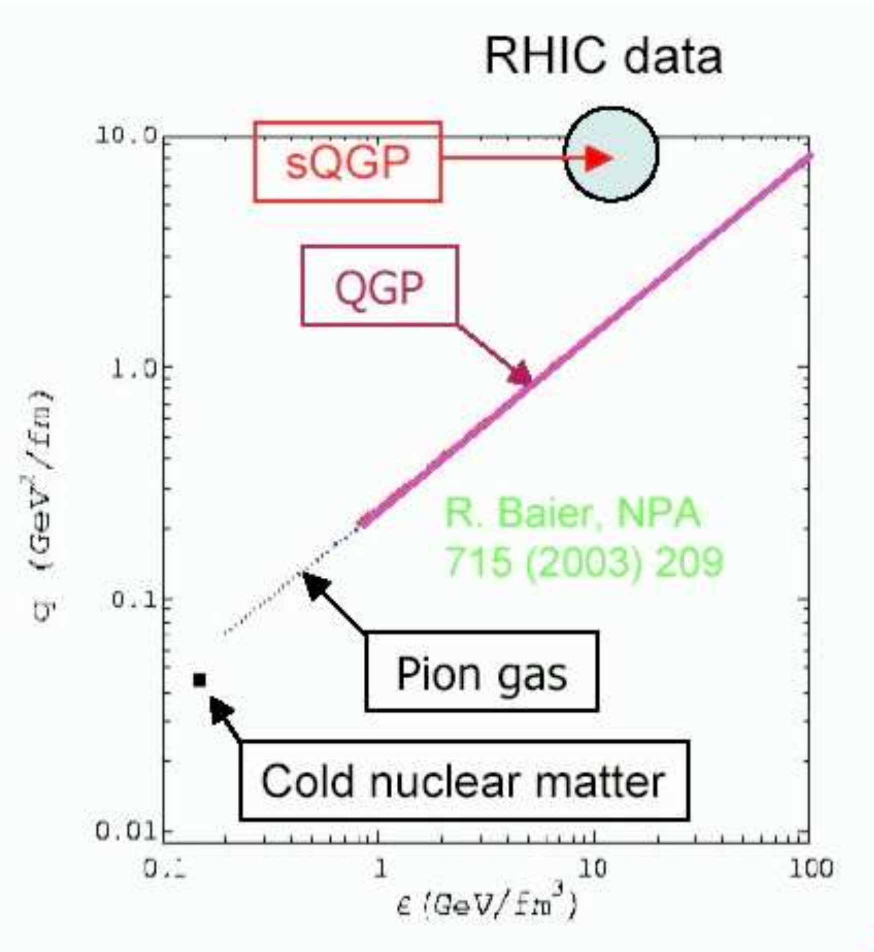
$$\left.\frac{d\mathcal{P}(\Phi,z)}{dz\,d\Phi}\right|_{\eta=0} = \frac{\alpha_s C_R}{16\pi^2}\,E\,L\,\cos\Phi\,\exp\left\{-E\,L\,\frac{\alpha_s C_R}{16\pi}\cos^2\Phi\right\}$$



[Polosa, Salgado hep-ph/0607295]

⇛ A perturbative mechanism, the medium-induced gluon radiation, is able to reproduce the observed 2-peak structure in the away side jet.

Interpretation of the value of $\hat{q}$



$\Rightarrow$ Opacity problem

$$\hat{q} = c\,\epsilon^{3/4}, \; c^{QGP}_{\text{ideal}} \simeq 2$$

$$\boxed{c > 5c^{QGP}_{\text{ideal}}}$$

Why??

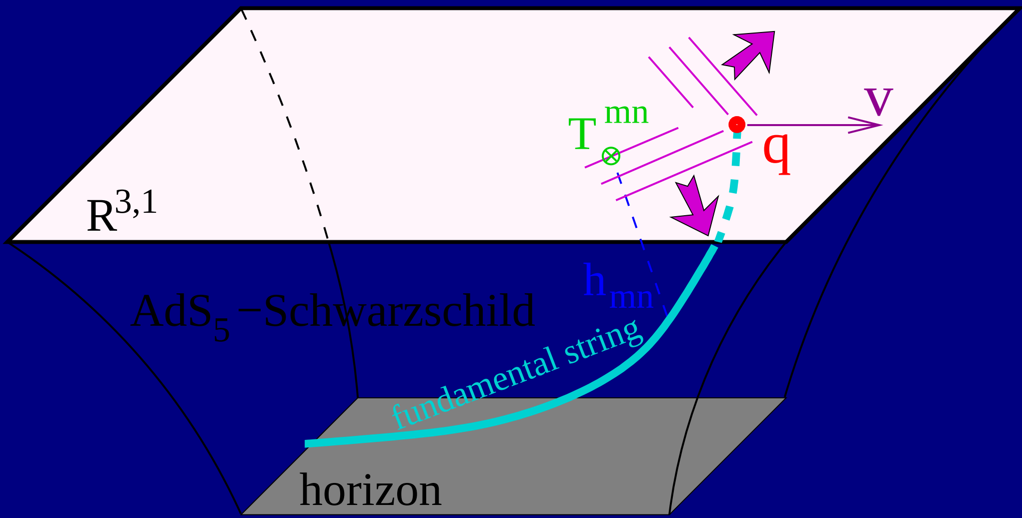
$\Rightarrow$ Interaction much stronger than in an ideal gas

- sQGP hypothesis

$\Rightarrow$ $\hat{q}$ sensitive to flow $\hat{q}(T^{\mu\nu})$

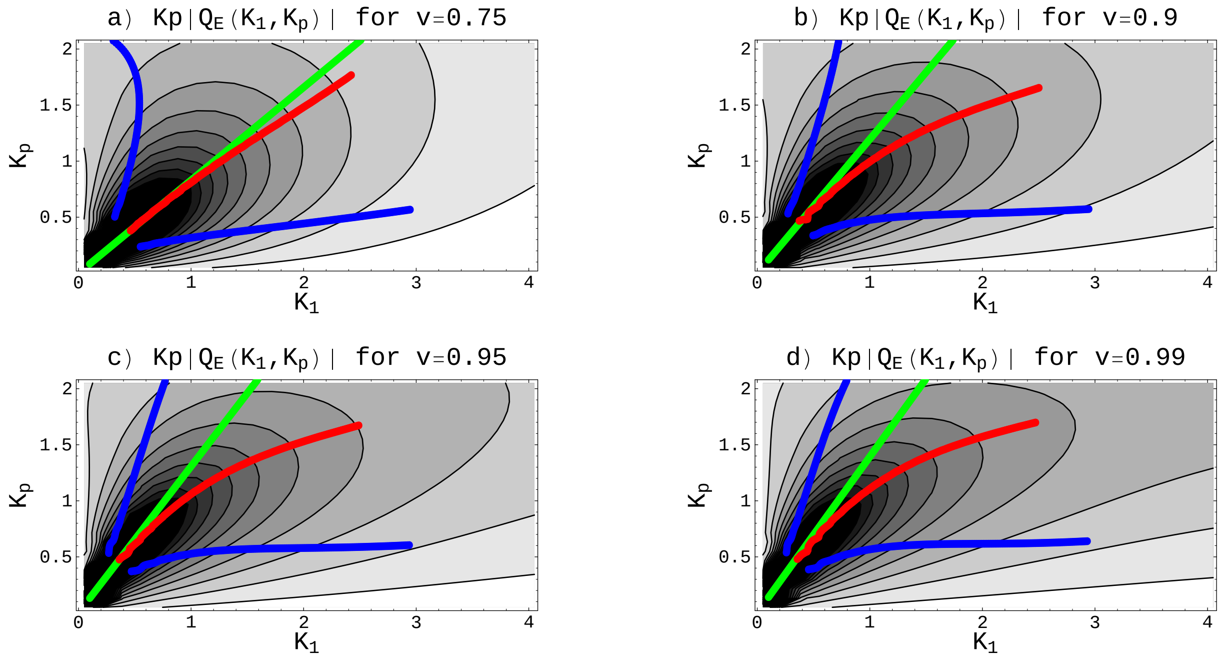
$\Rightarrow$ Theory needs to be improved

The AdS/CFT correspondence and HIC observables



Shock waves and AdS/CFT

$T^{\mu\nu}$ computed for a quark moving with constant velocity in a medium



Yet, despite the potential stumbling blocks, it is exciting to see a simple type IIB string theory construction approaching quantitative comparisons with a data-rich experimental field.

[Friess, Gubser, Michalogiorgakis, Pufu hep-th/0607022]

The transport coefficient $\hat{q}$ in AdS/CFT

- $\hat{q}$ defined by the small-distance behavior of the expectation value of two Wilson lines

$$\langle \mathrm{Tr}[W^{A^+}(\mathbf{y}) W^A(\mathbf{x})] \rangle \approx \exp\left\{ -\frac{1}{4} \hat{q} L^- (\mathbf{x} - \mathbf{y})^2 \right\}$$

- Use AdS/CFT correspondence

$$\hat{q}_{\mathrm{SYM}} = \frac{\pi^{3/2} \Gamma(\frac{3}{4})}{\sqrt{2}\Gamma(\frac{5}{4})} \sqrt{\lambda} T^3 \approx 18.87 \sqrt{\alpha_{\mathrm{SYM}} N_c} T^3$$

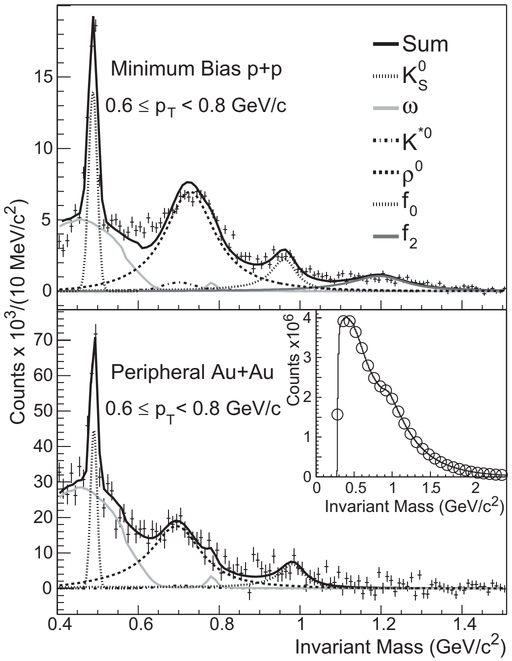
- $\hat{q}$ measures T, not energy density
- Putting some numbers ($N_c = 3$, $\alpha_{\mathrm{SYM}} = \frac{1}{2}$)

$$\hat{q} = 3.2,\ 7.5,\ 14.7\,\mathrm{GeV}^2/\mathrm{fm} \quad \text{for} \quad T = 300,\ 400,\ 500\,\mathrm{MeV}$$

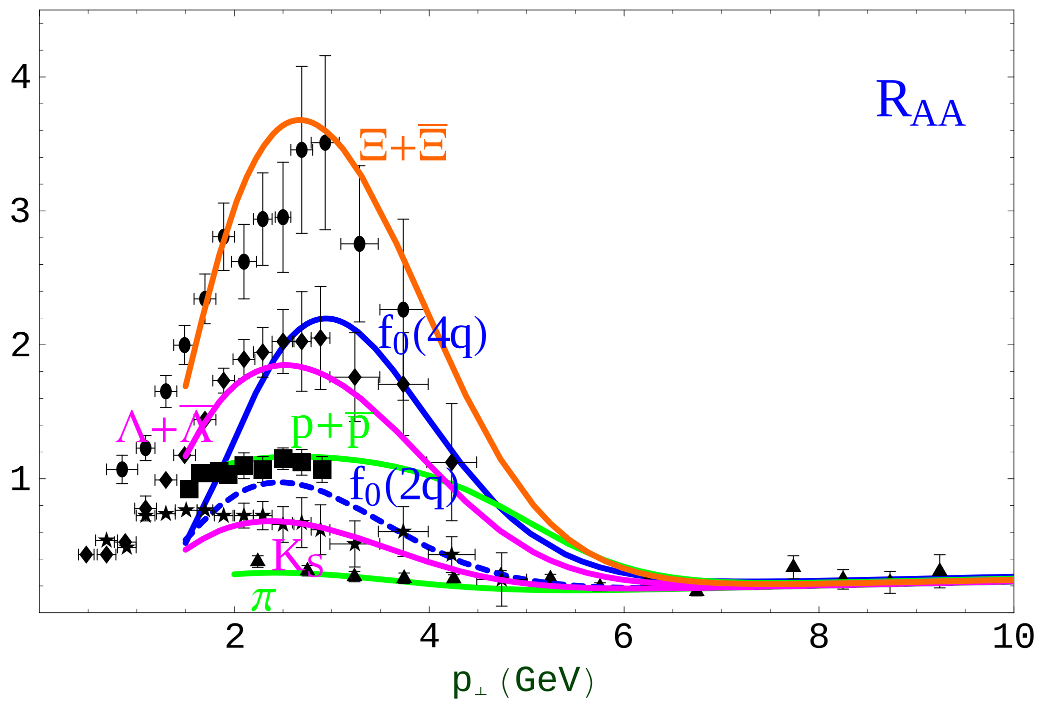
[Liu, Rajagopal, Wiedemann hep-ph/0605178]

f_0 resonance at high-p_t

⇛ A strong probe for the quark structure of f_0: $[qq][\bar{q}\bar{q}]$ vs $q\bar{q}$



[STAR 2003]



[Maiani, Polosa, Riquer, Salgado 2006]

⇛ Measure v_2 for $f_0(980)$ [Nonaka et al. (2003) for pentaquarks]

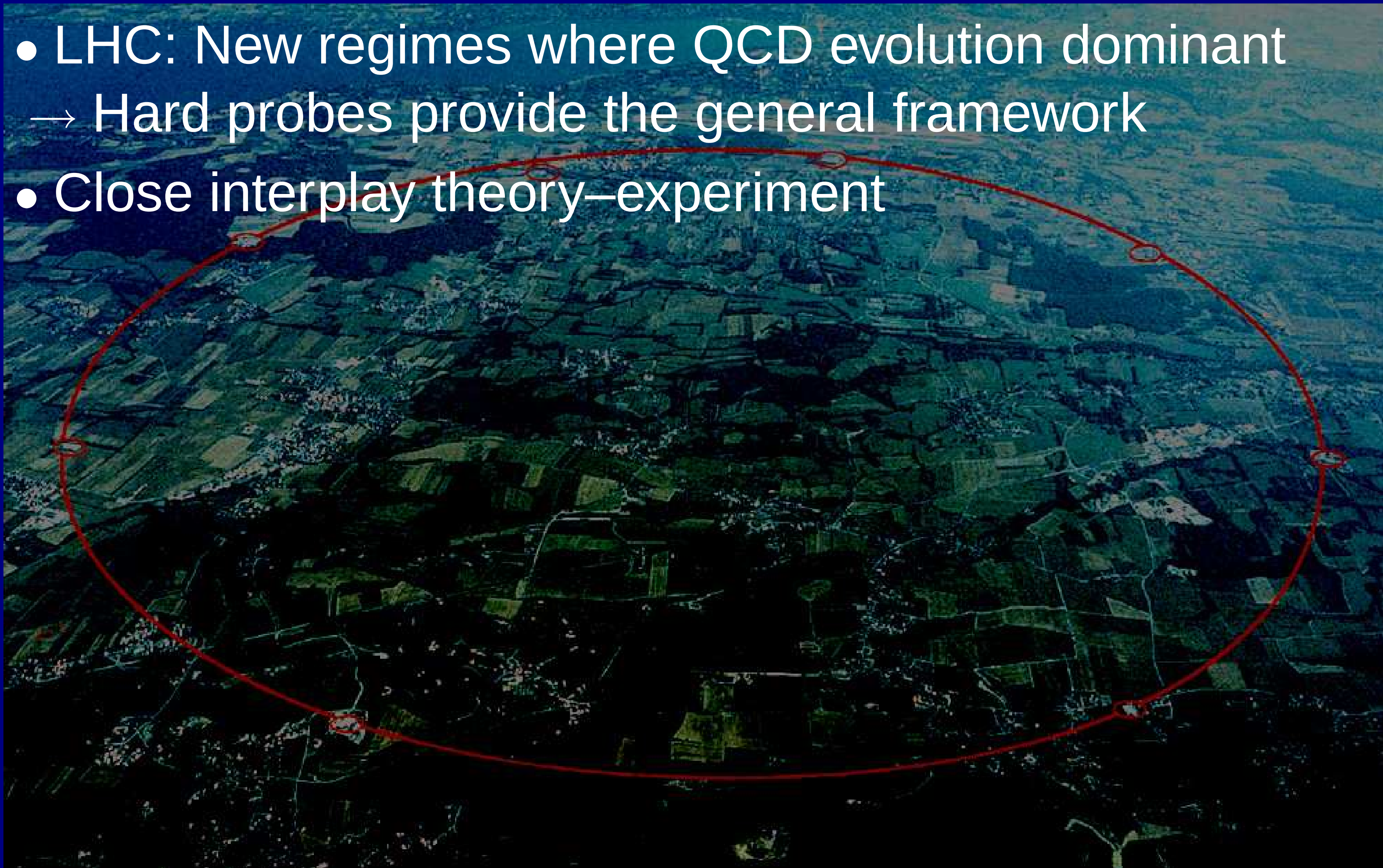
⇛ Measure R_{CP} and R_{AA} for $f_0(980)$

Perspectives for the future

- LHC: New regimes where QCD evolution dominant

$\rightarrow$ Hard probes provide the general framework

- Close interplay theory–experiment



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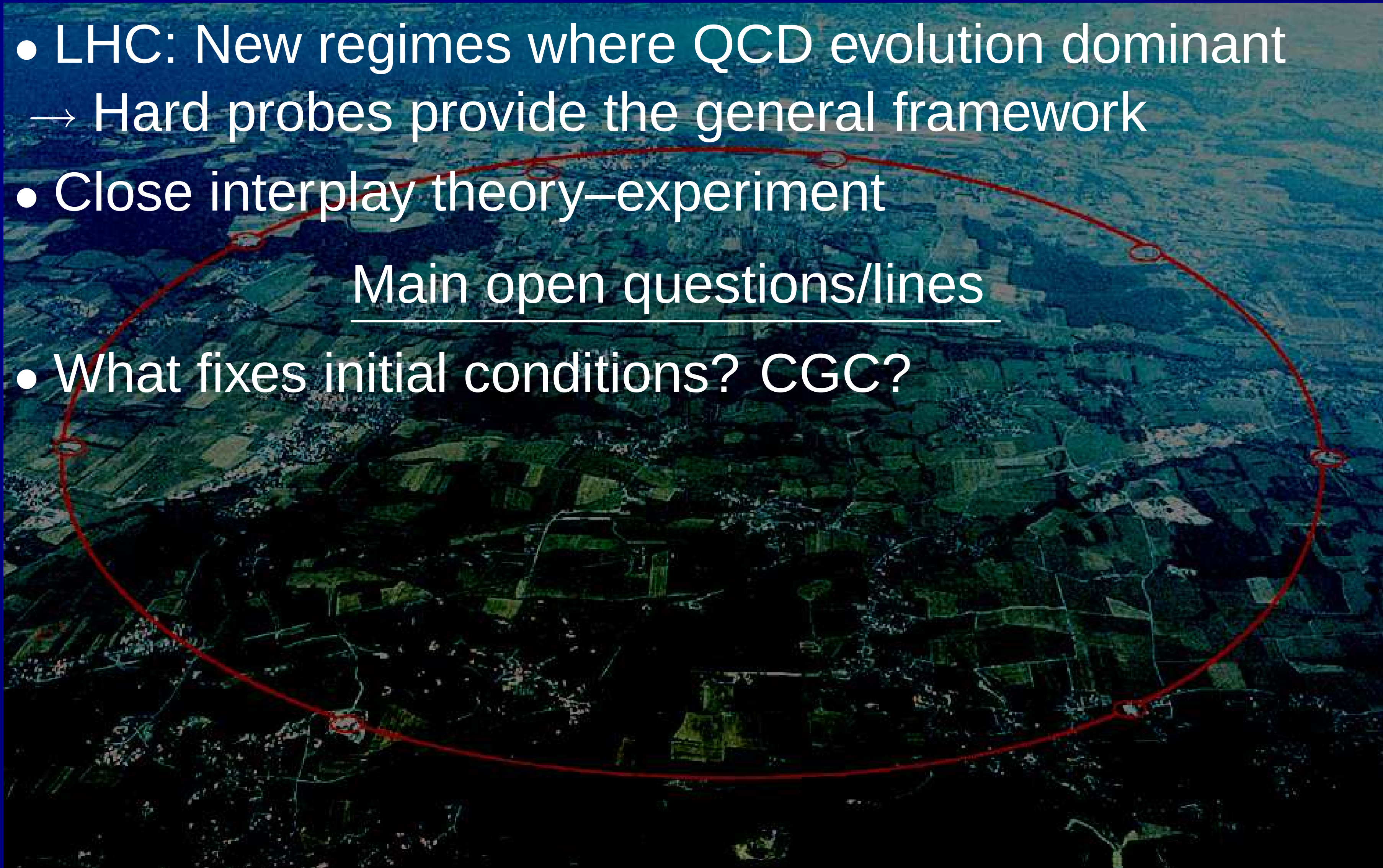

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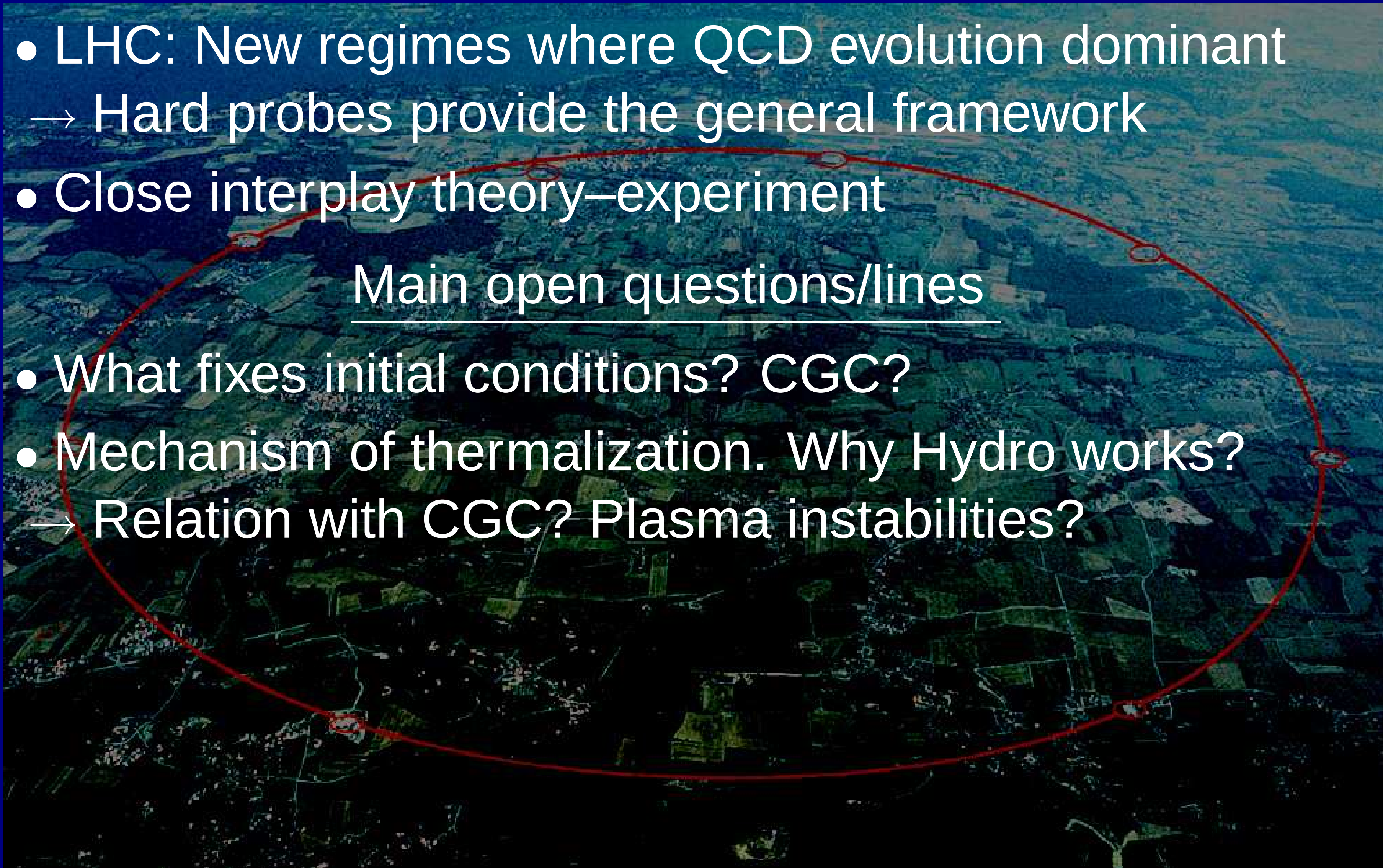

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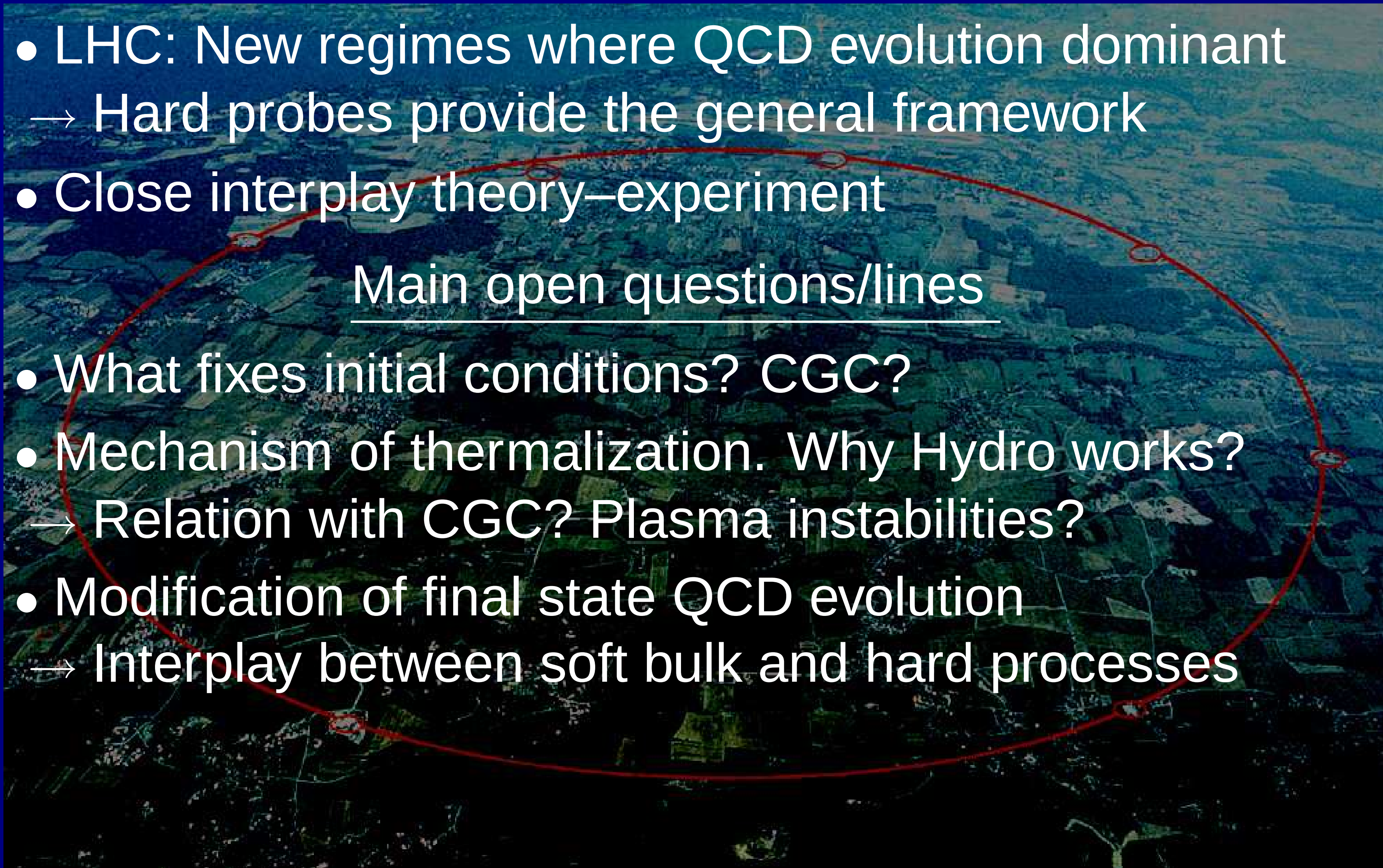

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$\rightarrow$ Interplay between soft bulk and hard processes

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- Modification of final state QCD evolution

$\rightarrow$ Interplay between soft bulk and hard processes

- What is the nature of the (created) medium?
- Ample new window for first principle calculations