Heavy ion collisions phenomenology overview

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

→ **Increase energy density**

simple systems

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Collective properties of the fundamental interactions

→ **Increase <u>extended</u> energy density**

“less simple” systems

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Collective properties of the fundamental interactions

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"less simple" systems

What are the building blocks and how they organize?

- Spectroscopy
- Heavy-ion collisions

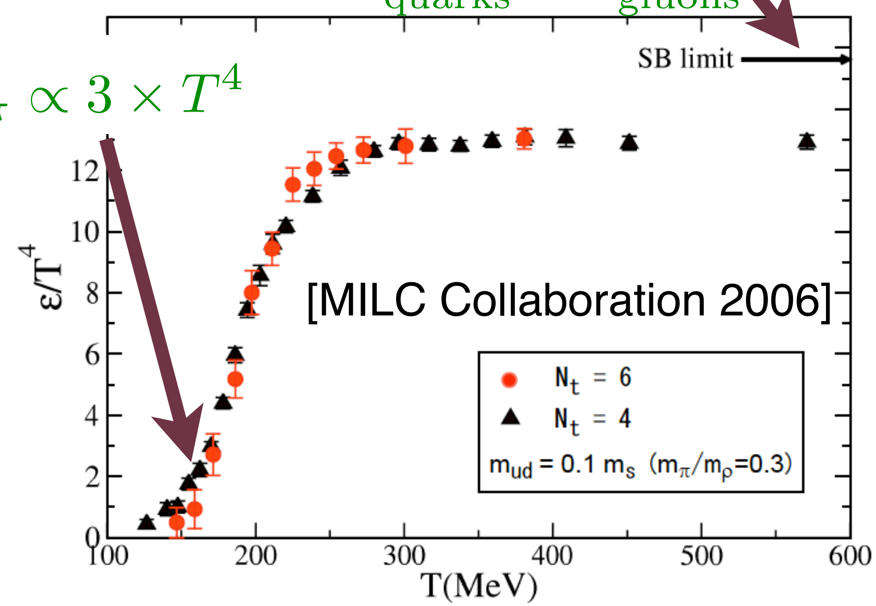
QCD has a rich dynamical structure

- ⇛ Two broken symmetries in the QCD vacuum
  - confinement
  - chiral symmetry is broken
- ⇛ Restored at high-temperatures ⟵ asymptotic freedom

Equation of state

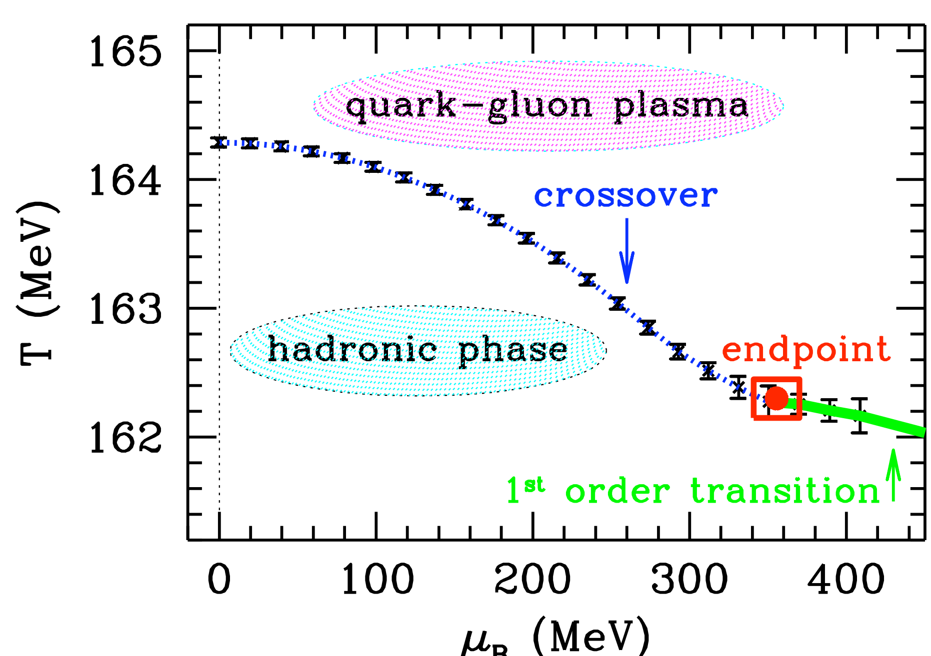
$$P_{QGP} \propto (\underbrace{2 \times 2 \times 3}_{\text{quarks}} + \underbrace{2 \times 8}_{\text{gluons}}) \times T^4$$

$P_\pi \propto 3 \times T^4$



Phase diagram

[Fodor, et al. 2004]



What do we expect to learn?

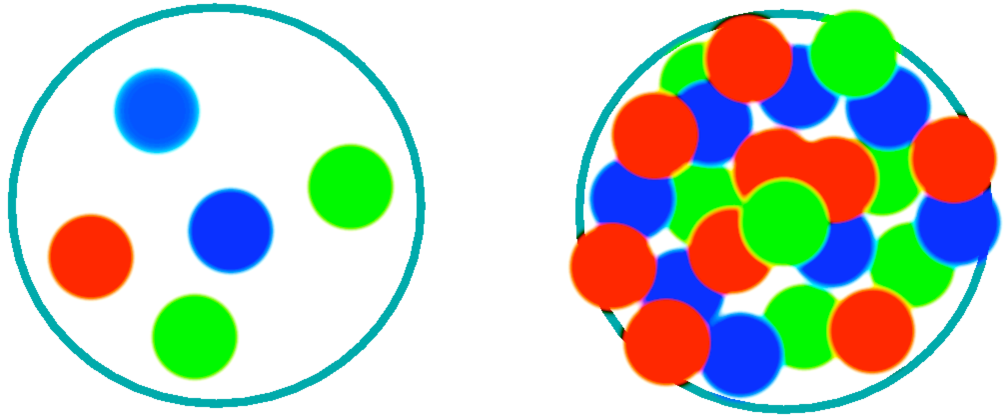
Specific questions in heavy-ion collisions

- ⇛ 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?

(high-density) Initial state

Saturation of partonic densities: picture

Saturation scale when interaction probability becomes $\mathcal{O}(1)$



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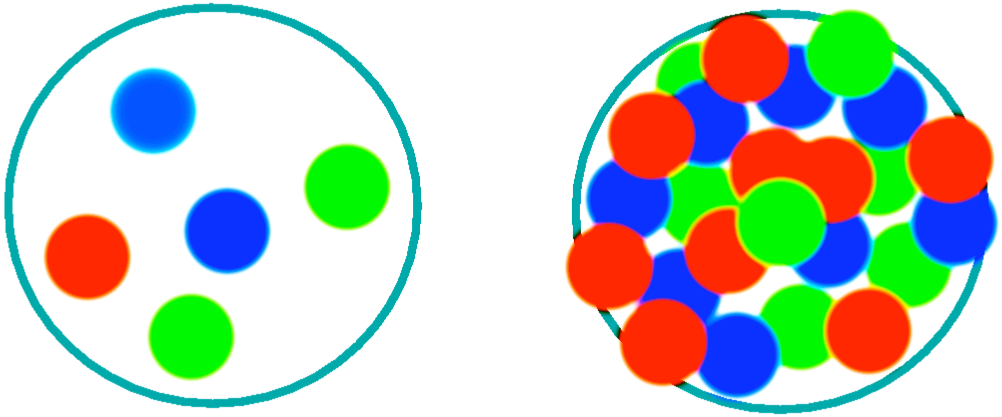

transverse area of the gluon

$$\alpha_s \frac{1}{Q^2_{\rm sat}} A N_g(x, Q^2_{\rm sat}) \sim \pi R_A^2$$

transverse area of the nucleus

$$R_A \sim A^{1/3}$$

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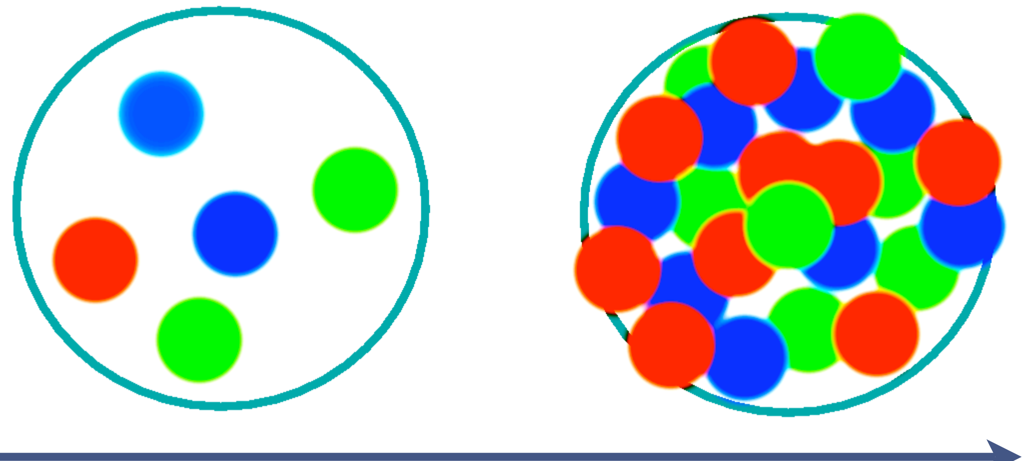


increasing energy (decreasing x)

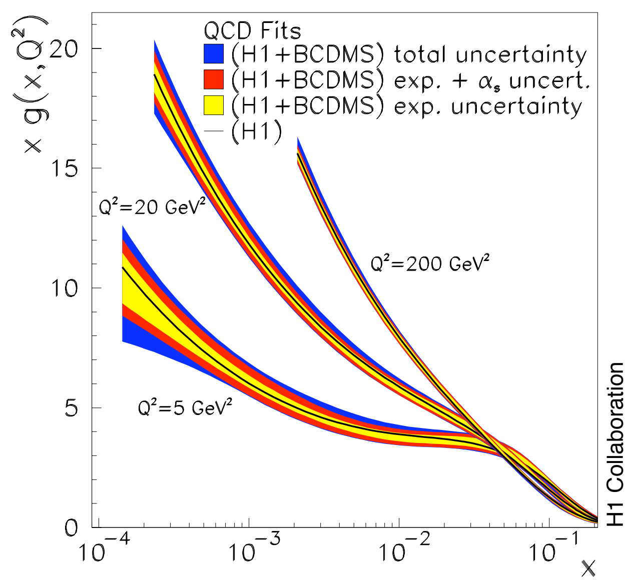
transverse area of the gluon

$$\alpha_s \frac{1}{Q^2_{\rm sat}} A N_g(x, Q^2_{\rm sat}) \sim \pi R_A^2$$

transverse area of the nucleus

$$R_A \sim A^{1/3}$$

$$N_g \sim \frac{1}{x^\lambda} \quad \Longrightarrow \quad Q^2_{\rm sat} \sim \frac{A^{1/3}}{x^\lambda}$$

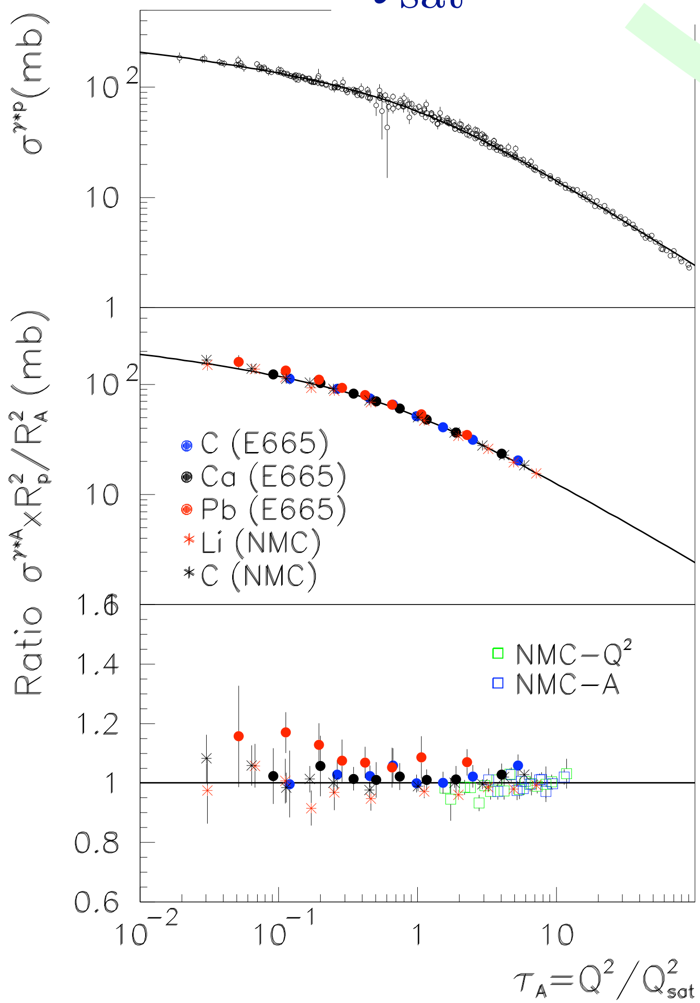


Strong fields and large occupation numbers.
Semiclassical approach possible:
Color Glass Condensate

Geometric scaling and data

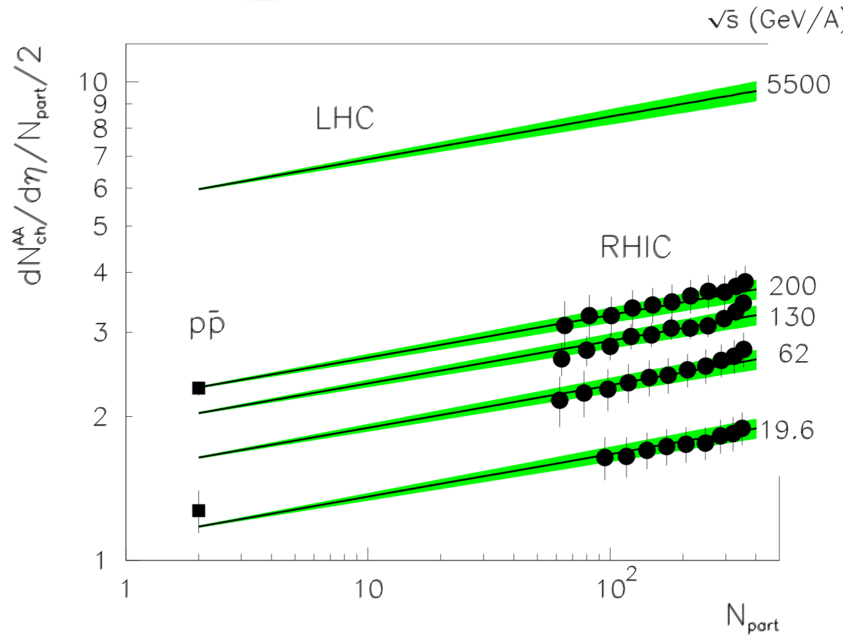
$$Q^2_{\rm sat} \propto x^{-\lambda} A^{1/3\delta}$$

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



Stasto, Golec-Biernat, Kwiecinski 2001

Armesto, Salgado, Wiedemann 2004



Kharzeev, Levin, McLerran, Nardi 2000...

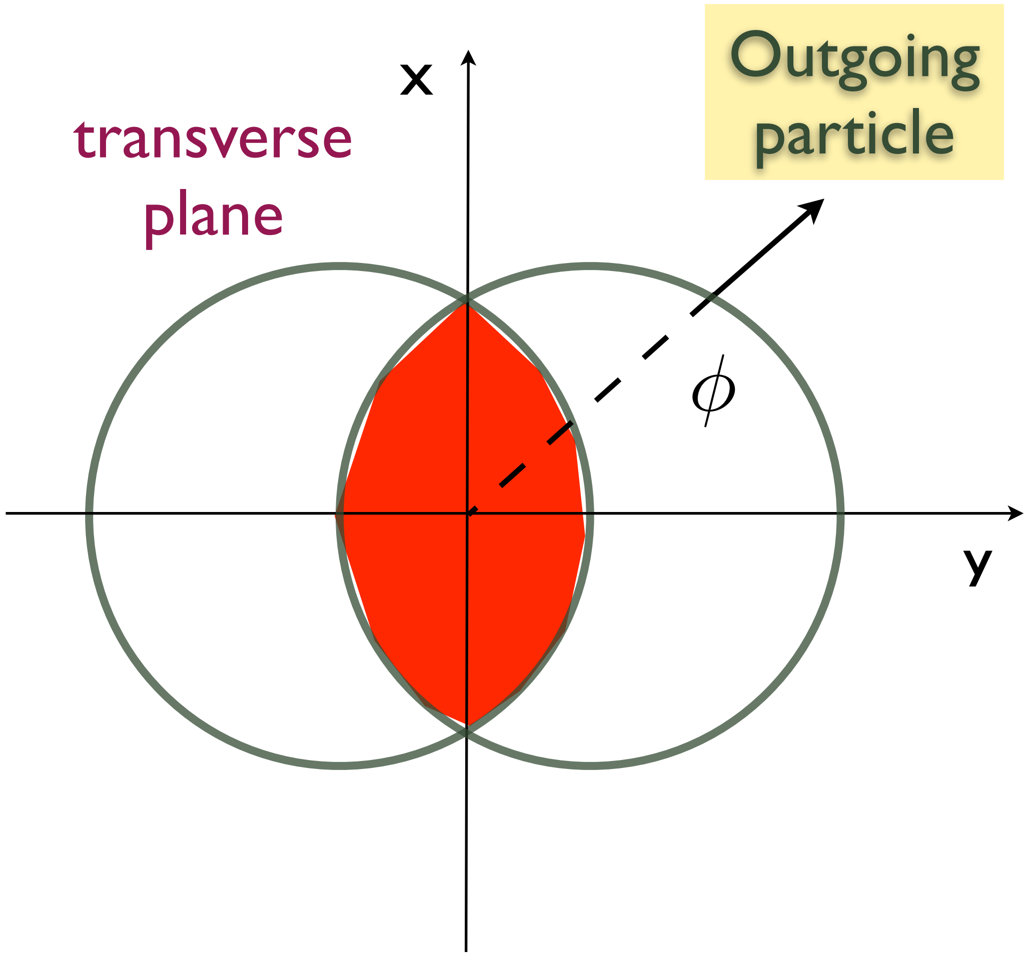
Armesto, Salgado, Wiedemann 2004

Checks of hydrodynamical evolution (thermalization)

The essential measurement for hydro

⇛ Recall the Euler equation

$$\frac{d\beta}{dt} = -\frac{c^2}{\epsilon + P}\nabla P$$



The essential measurement for hydro

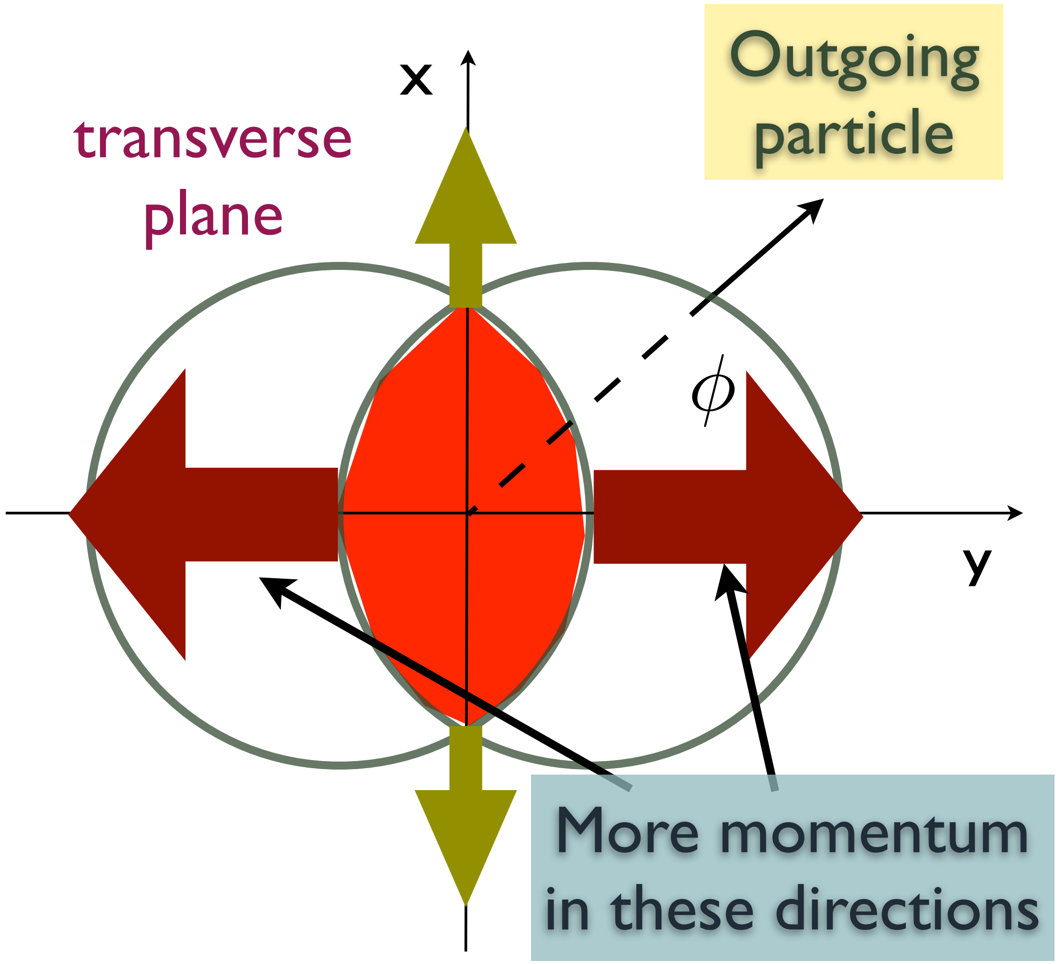
⇛ Recall the Euler equation

$$\frac{d\beta}{dt} = -\frac{c^2}{\epsilon + P}\nabla P$$

$$\epsilon = 3P \quad \Longrightarrow \quad \nabla_x P < \nabla_y P$$

⇛ Elliptic flow normally measured by the second term in the Fourier expansion

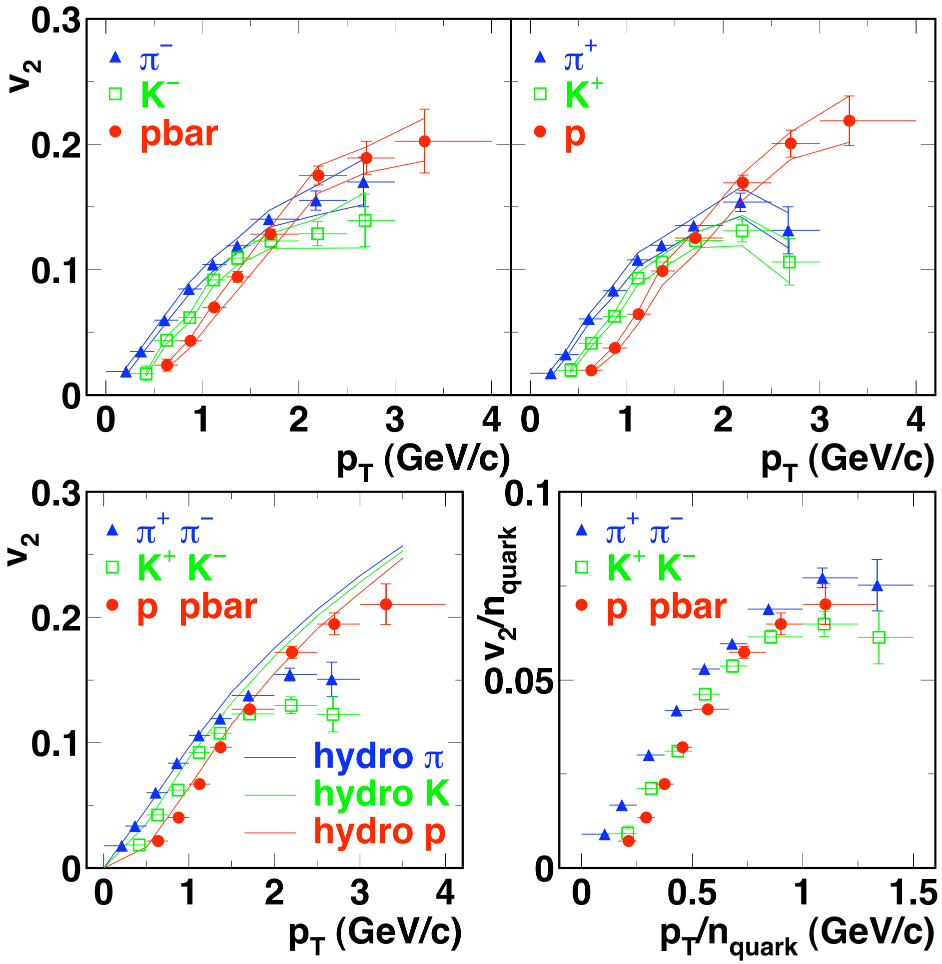
$$\frac{dN}{d\phi} \propto 1 + 2\,v_2 \cos(2\phi)$$



Initial conditions at thermalization time need to be given (ex. CGC)

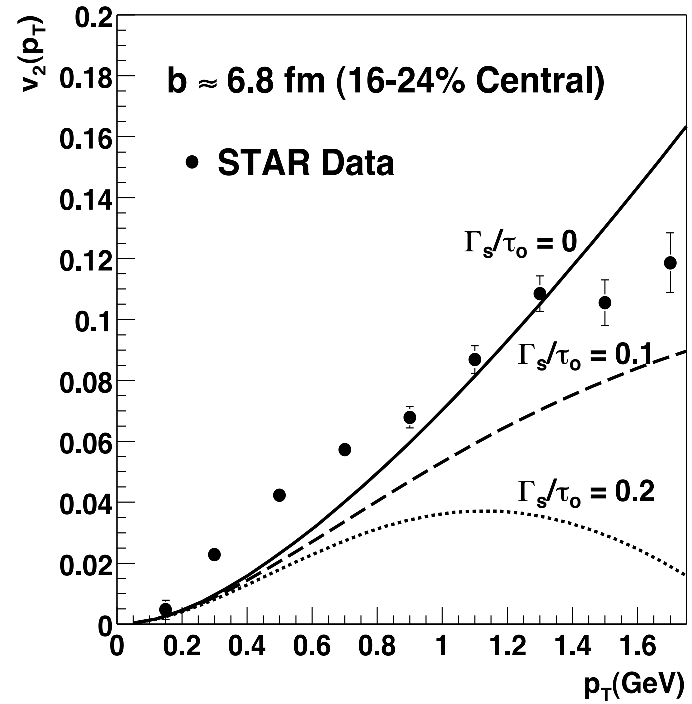
One of the first measurements at RHIC

Large elliptic flow compatible with ideal hydrodynamics



[data: STAR]

The effect of viscosity



[Teaney 2003]

Two important results

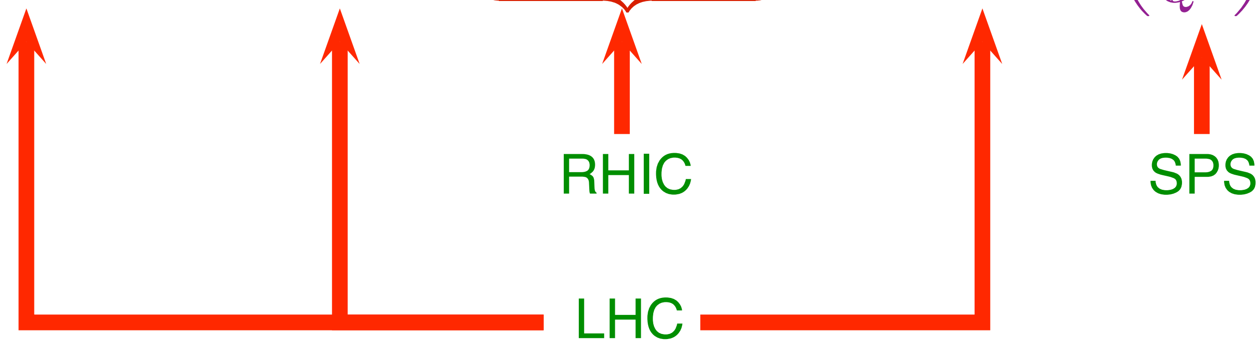
- Initial time for the evolution is very small
- Viscosity (non-perfect fluid behavior) is small

Hard Probes

Hard probes in heavy-ion collisions

- 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

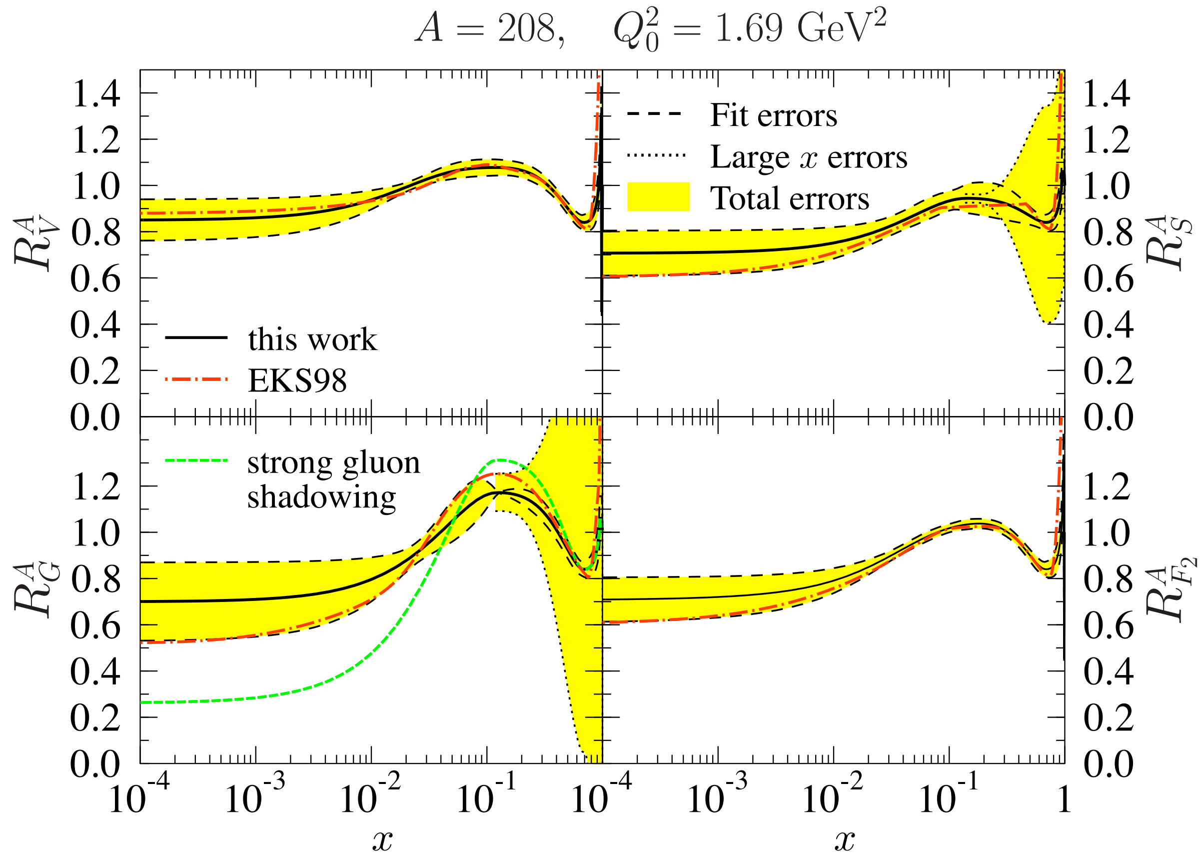
$$\sigma^{pp\to h} = f_p(x_1, Q^2) \otimes f_p(x_2, Q^2) \otimes \underbrace{\sigma(x_1, x_2, Q^2)} \otimes D(z, Q^2) + \left(\frac{1}{Q^2}\right)^n$$



- The extension of the medium modifies the long-distance terms
  - New evolution equations for $f_A(x, Q^2); D(z, Q^2)$
- Kinematical access to evolution: large-Q^2, small-x $\longrightarrow$ LHC

Nuclear PDFs: uncertainties

PDFs determined by a global DGLAP fit



[Eskola, Kolhinen, Paukkunen, Salgado 2007]

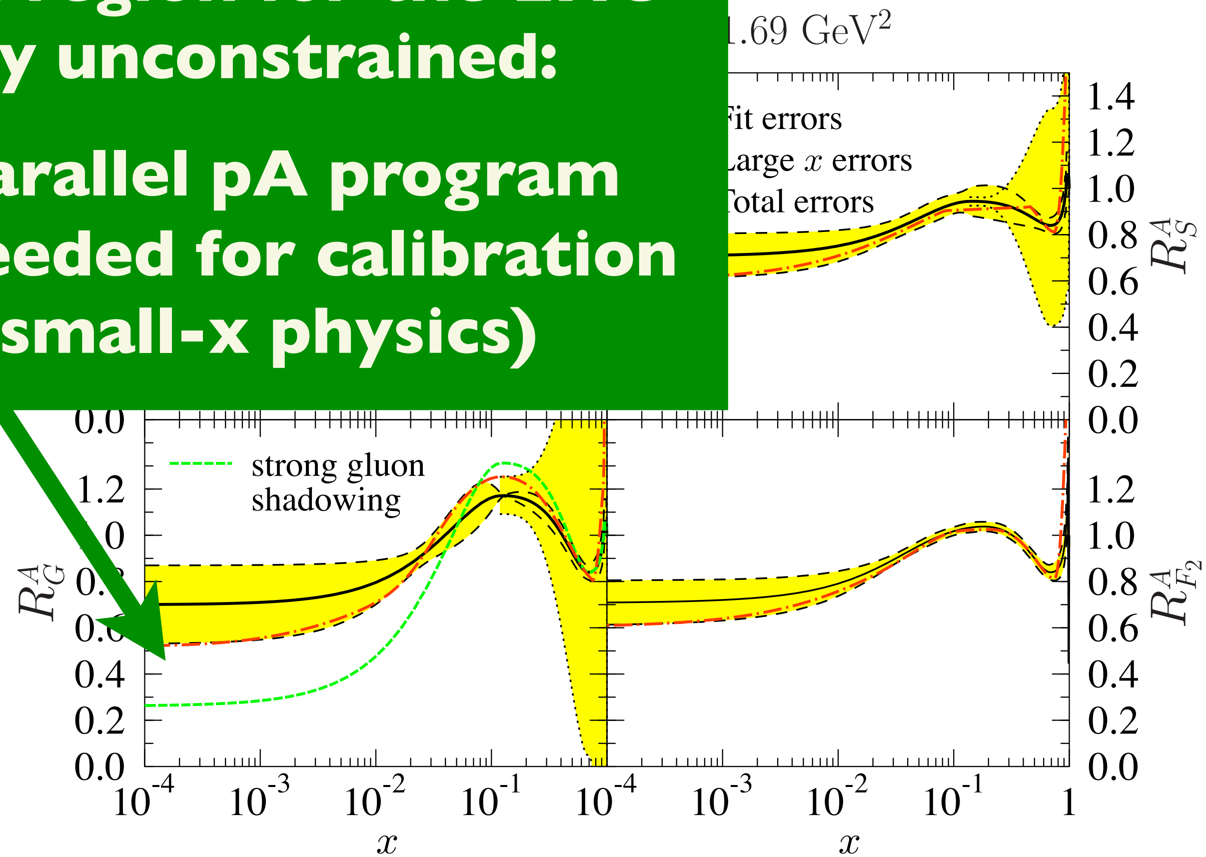
[Other sets: De Florian, Sassot 2004; Frankfurt, Guzey, Strikman 2005; Hirai, Kumano, Nagai 2007]

Nuclear PDFs: uncertainties

obal DGLAP fit

Relevant region for the LHC largely unconstrained:

⟶ a parallel pA program will be needed for calibration (and small-x physics)



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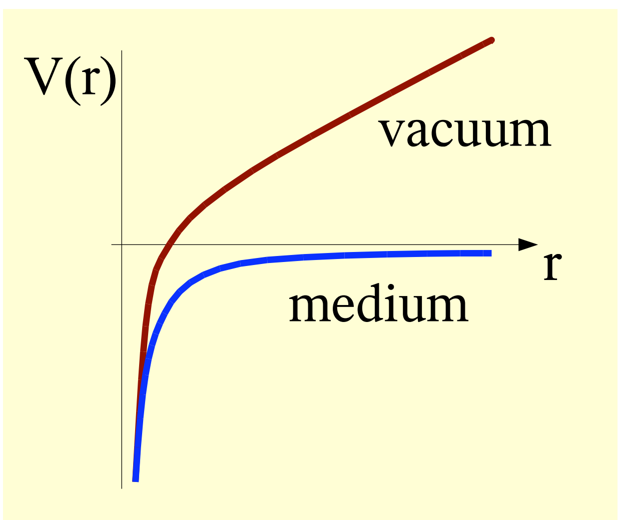
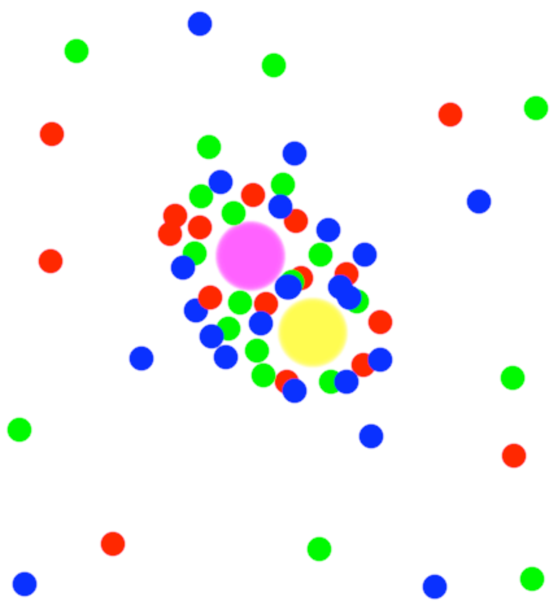
A conceptually simple example, J/Ψ suppression

- A J/Ψ is a $c\bar{c}$ bound state.

$$\sigma^{hh\to J/\Psi} = f_i(x_1,Q^2)\otimes f_j(x_2,Q^2)\otimes\sigma^{ij\to[c\bar{c}]}(x_1,x_2,Q^2)\langle\mathcal{O}([c\bar{c}]\to J/\Psi)\rangle$$

- The potential is screened by the medium
  - The long-distance part is modified $\langle\mathcal{O}([c\bar{c}]\to J/\Psi)\rangle \to 0$
- The J/Ψ production is suppressed [Matsui, Satz 1986]





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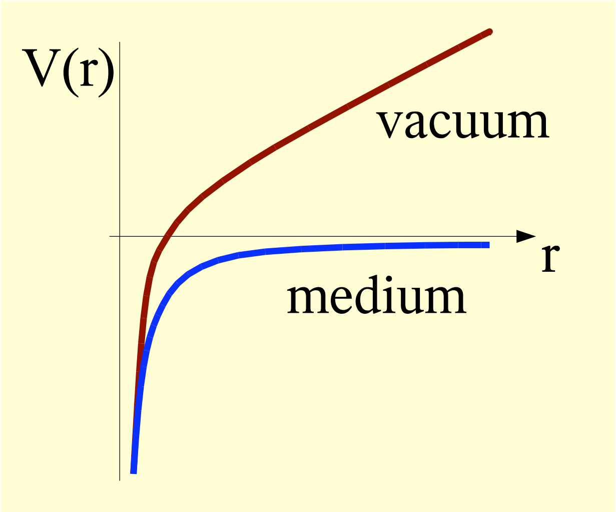
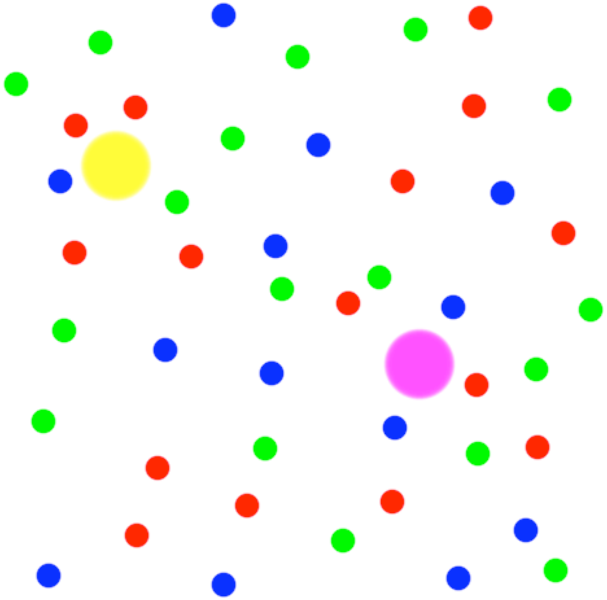
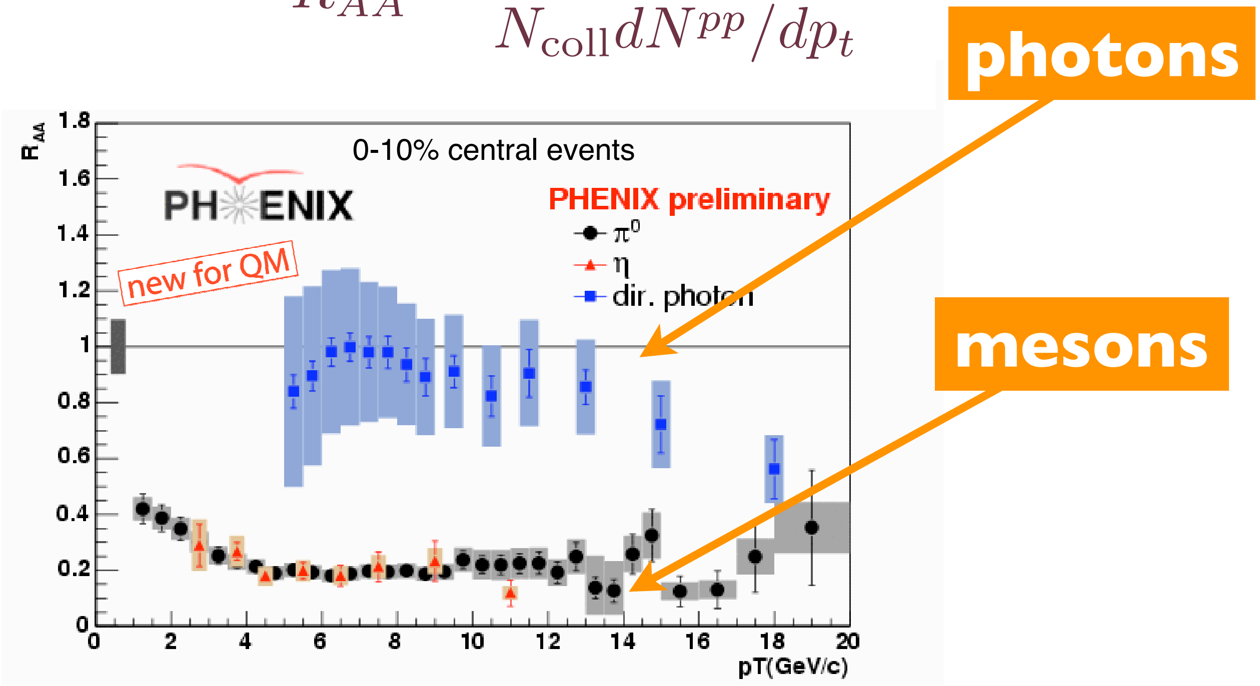




Effects on high-p_t particles

$$R_{AA} = \frac{dN^{AA}/dp_t}{N_{\rm coll}dN^{pp}/dp_t}$$



Photons don't interact with the medium quarks and gluons do

Effects on high-p_t particles

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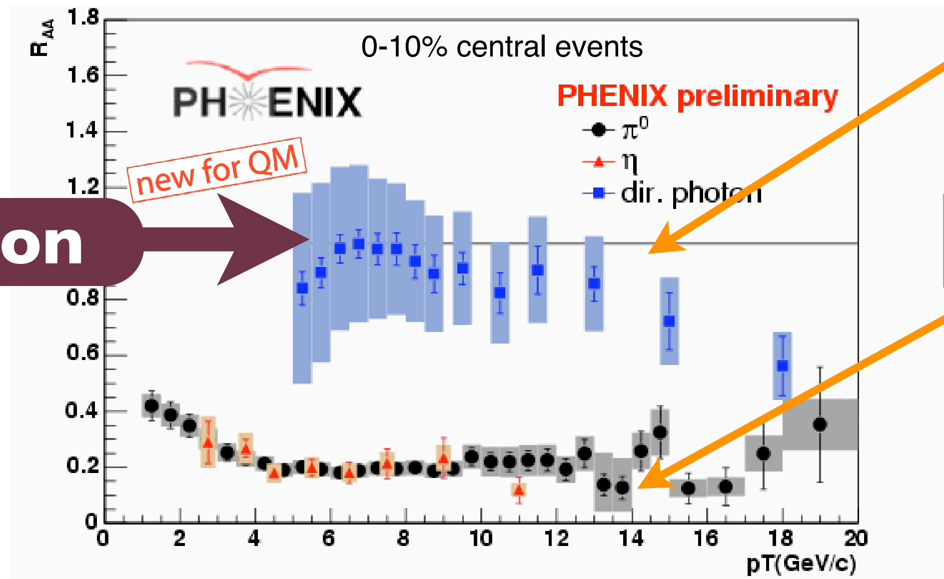
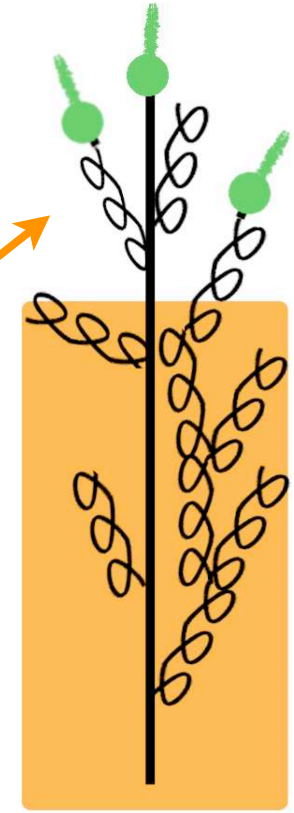
Calibration



photons

mesons

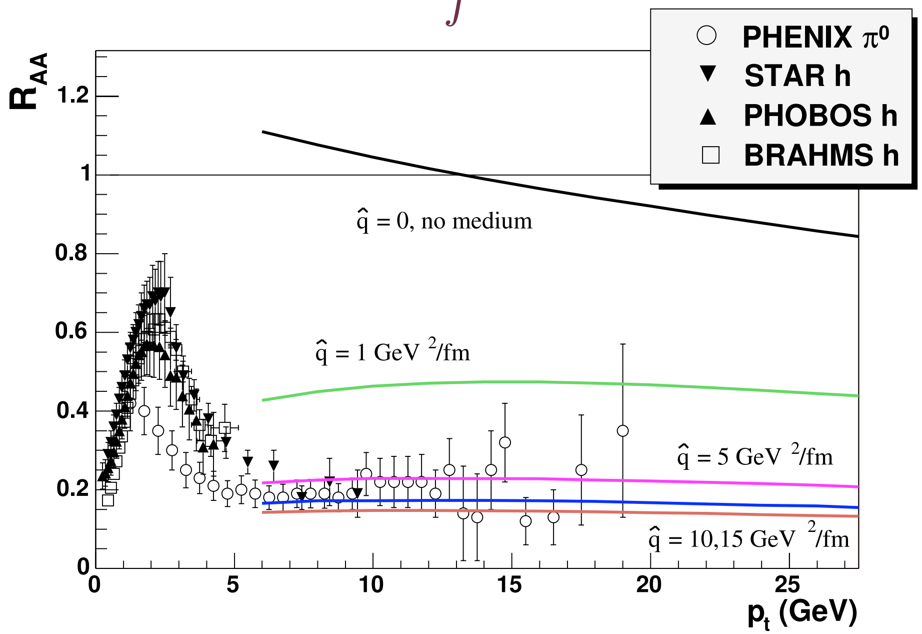


Photons don't interact with the medium quarks and gluons do

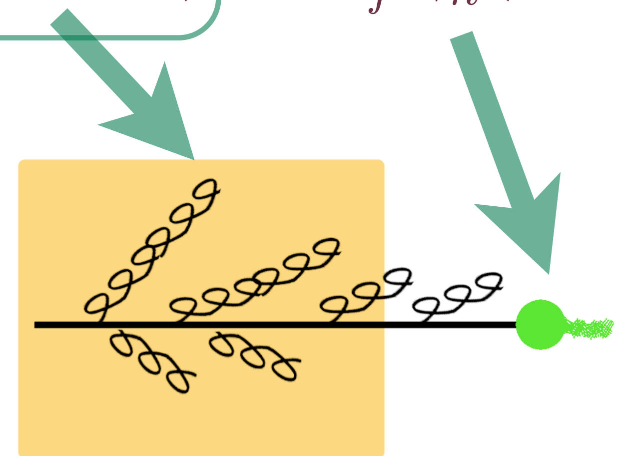
⇛ Well calibrated and abundant probes of the medium

The inclusive particle suppression

$$d\sigma_{\rm med}^{AA\to h+X} = \sum_f d\sigma_{\rm vac}^{AA\to h+X} \otimes P_f(\Delta E, L, \hat{q}) \otimes D_{f\to h}^{(\rm vac)}(z,\mu_F)$$



[Eskola, Honkanen, Salgado, Wiedemann 2005]



⇛ Transport coefficient

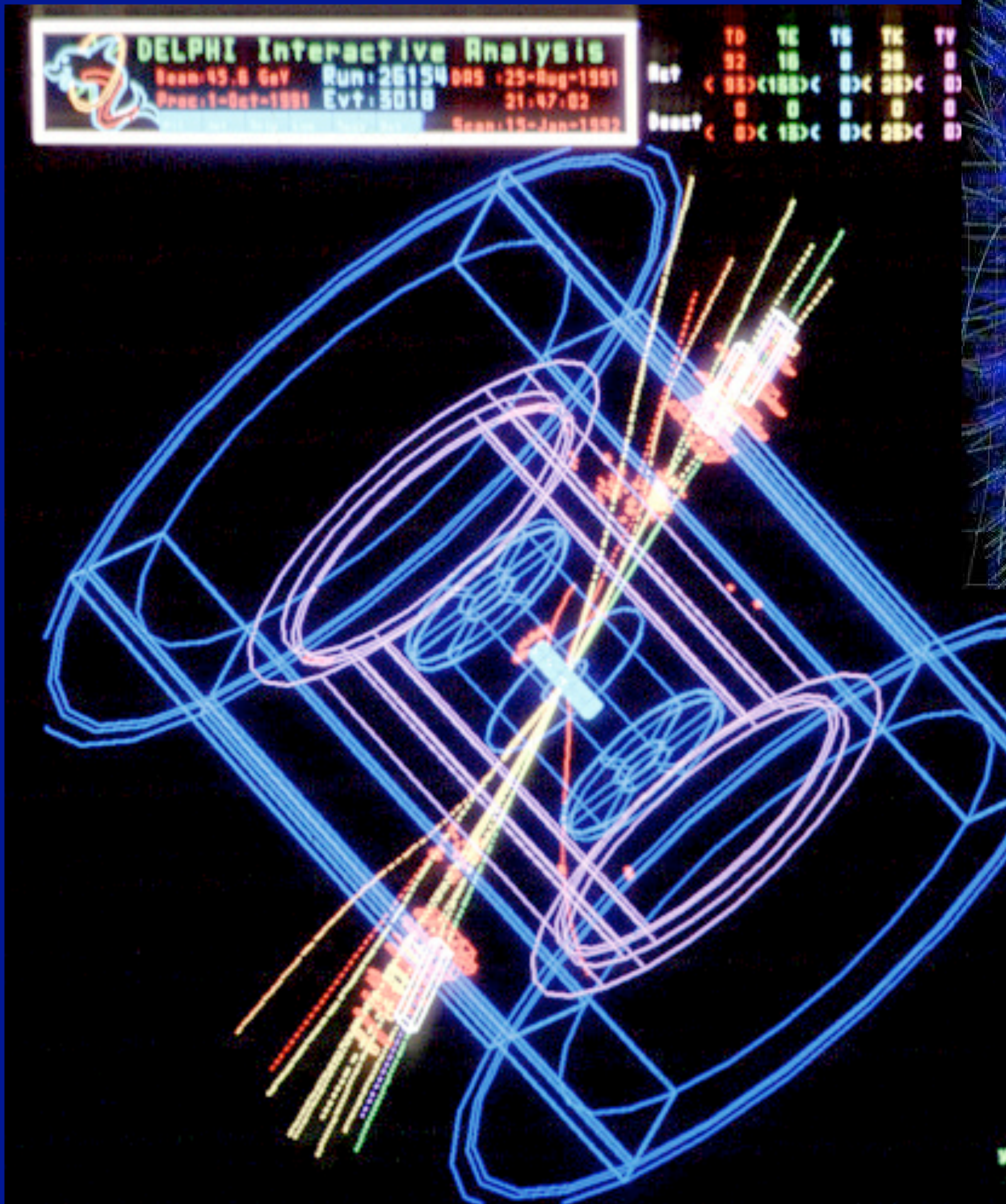
$$\hat{q} \simeq \frac{\langle k_\perp^2 \rangle}{\lambda} \propto n(\xi)\sigma$$

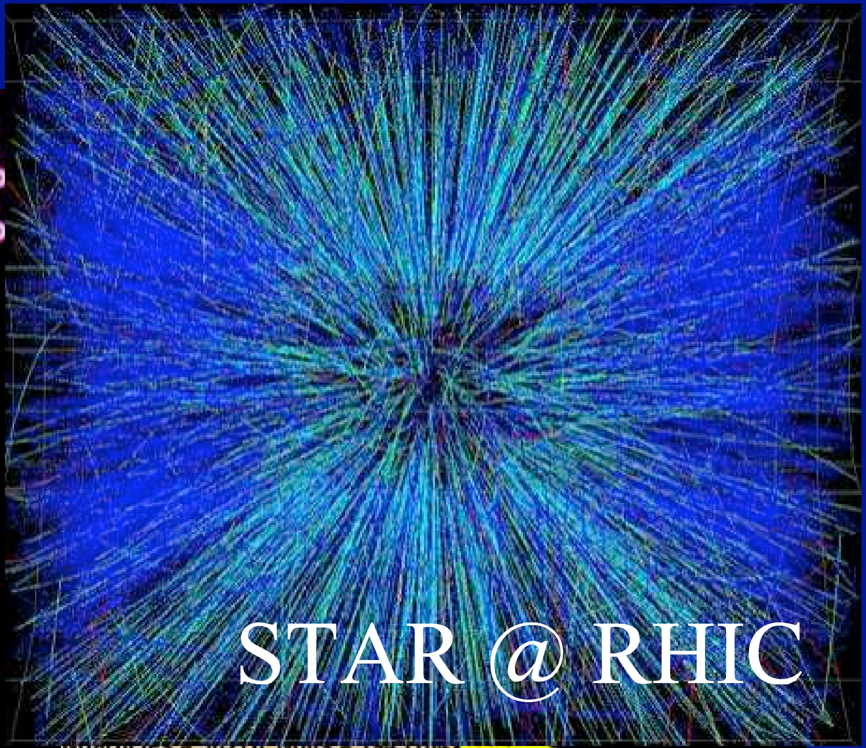
⇛ Data favors a large transport coefficient

$$\hat{q} \simeq 5\ldots15\ {\rm GeV}^2/{\rm fm}$$

[Gyulassy, Levai, Vitev 2002; Arleo 2002; Dainese, Loizides, Paic 2004; Wang, Wang 2005; Drees, Feng Jia 2005; Turbide, Gale, Jeon, Moore 2005; Renk, Ruppert, Nonaka, Bass 2007...]

Jets in HIC





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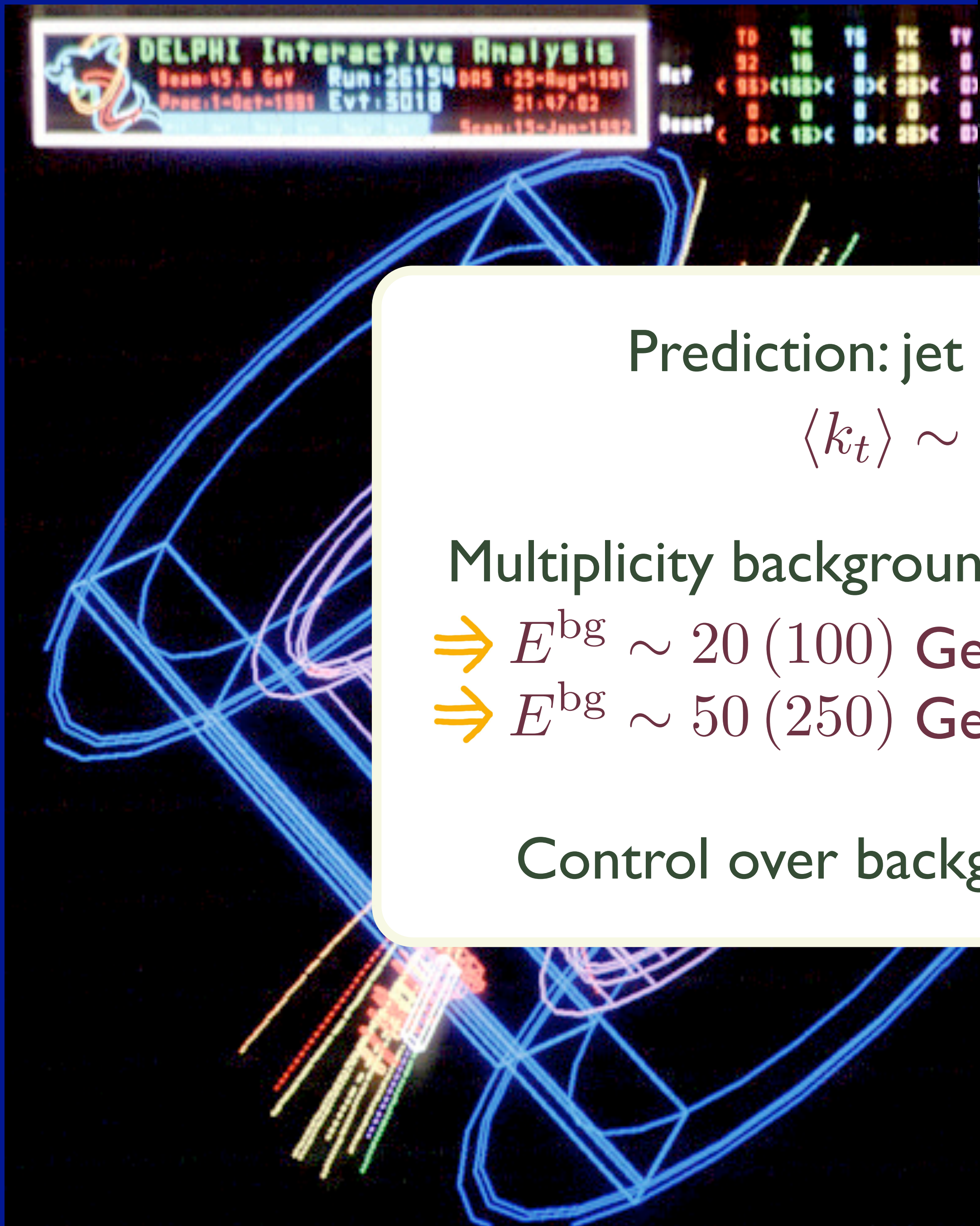
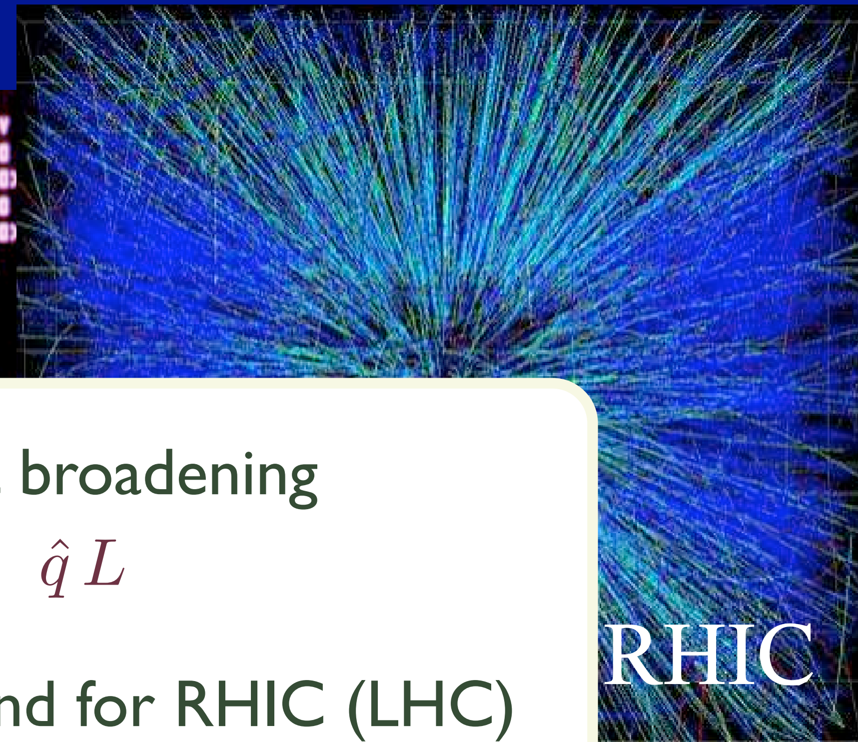
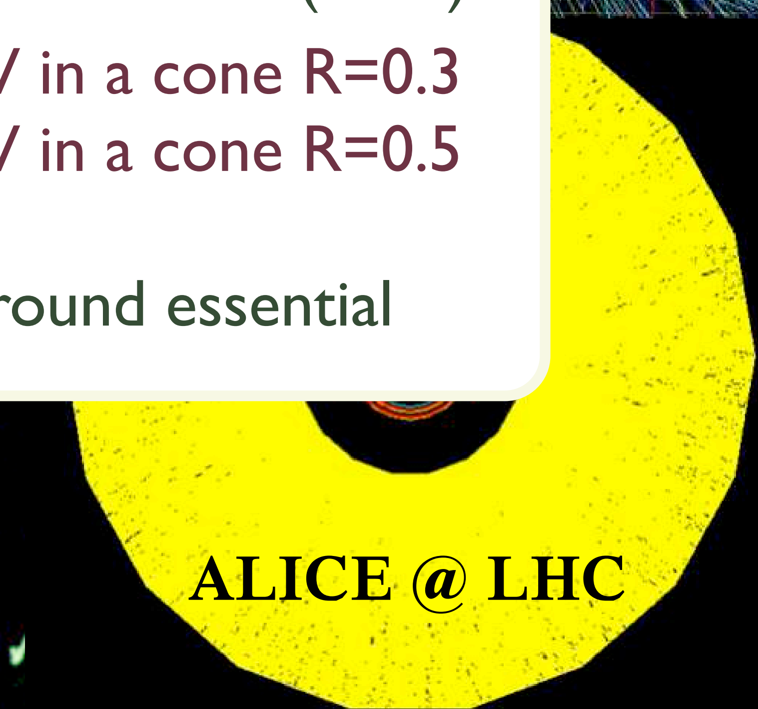






Prediction: jet broadening

$$\langle k_t \rangle \sim \hat{q}\, L$$

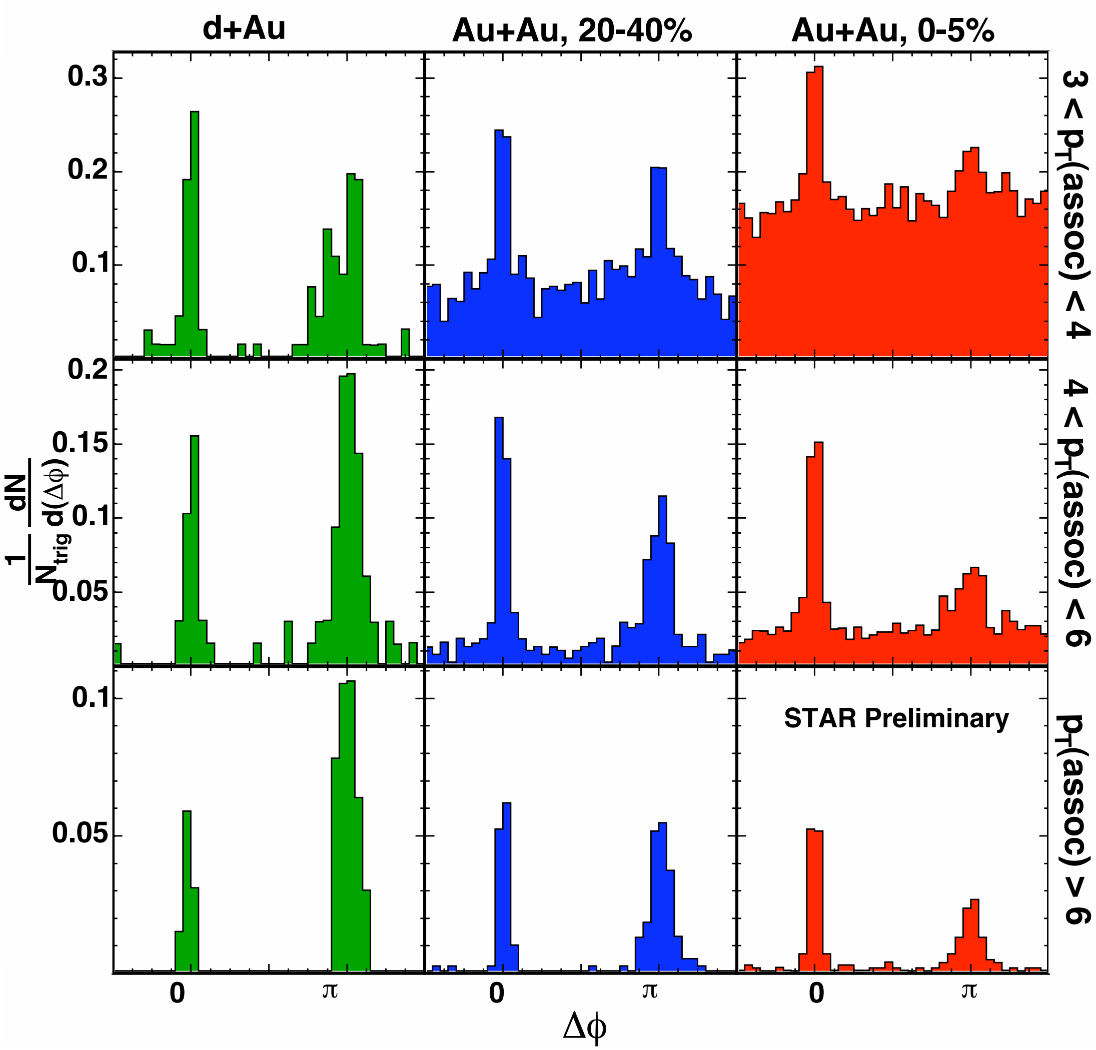
Multiplicity background for RHIC (LHC)

$\Rightarrow E^{\rm bg} \sim 20\,(100)$ GeV in a cone R=0.3

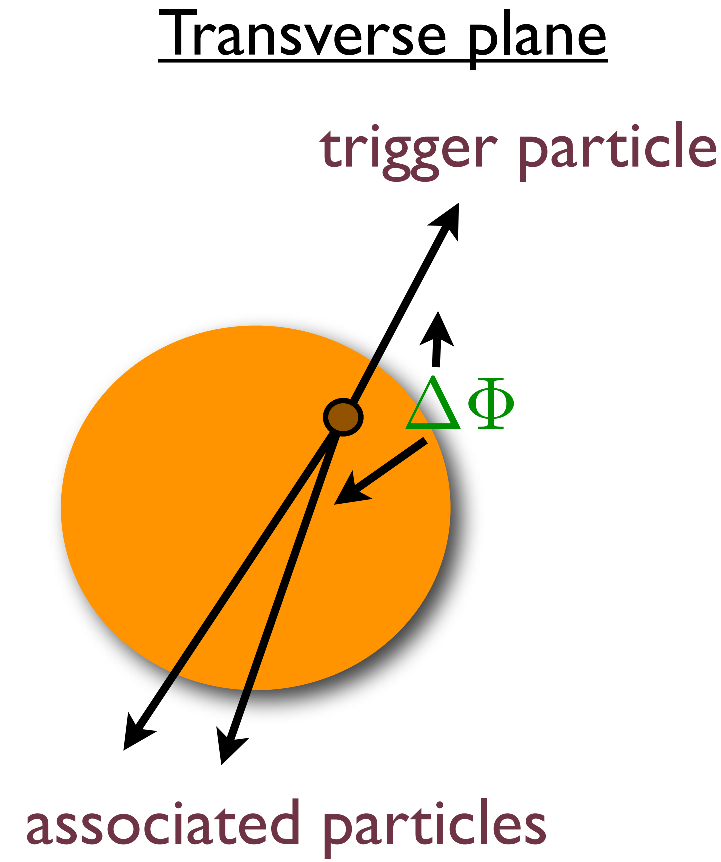
$\Rightarrow E^{\rm bg} \sim 50\,(250)$ GeV in a cone R=0.5

Control over background essential

RHIC: two particle correlations



[STAR 2006]



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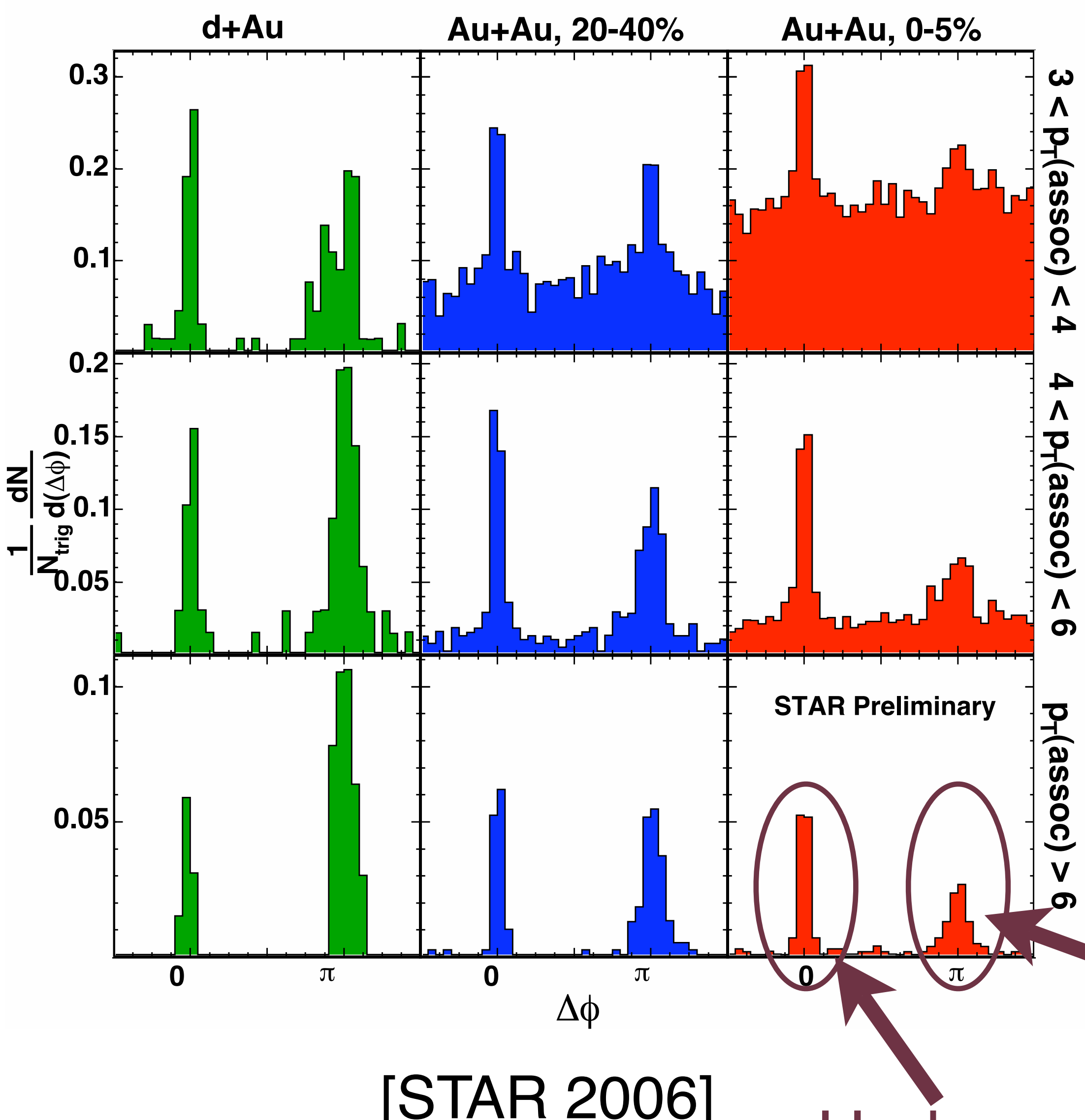
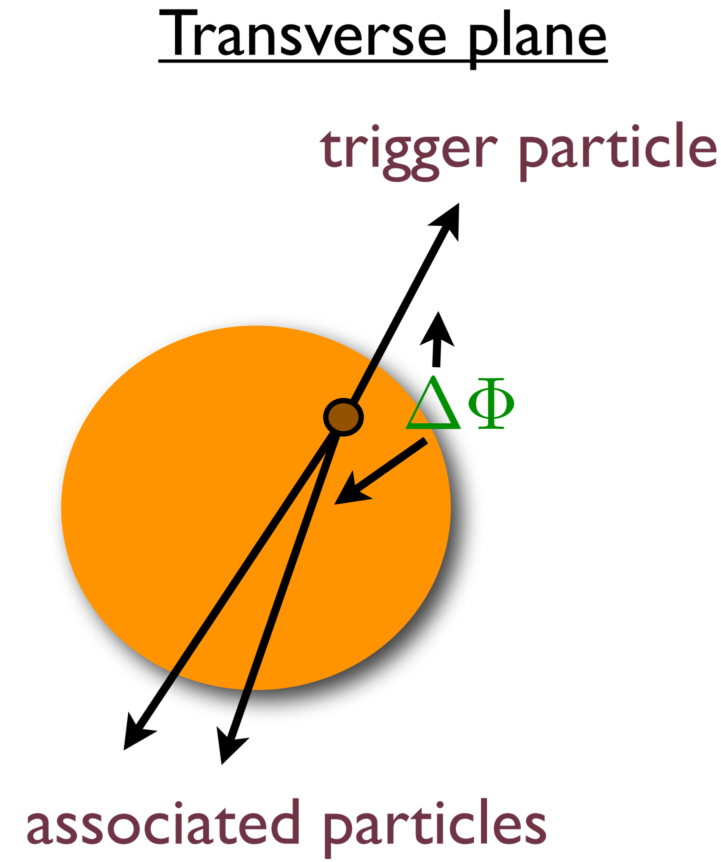
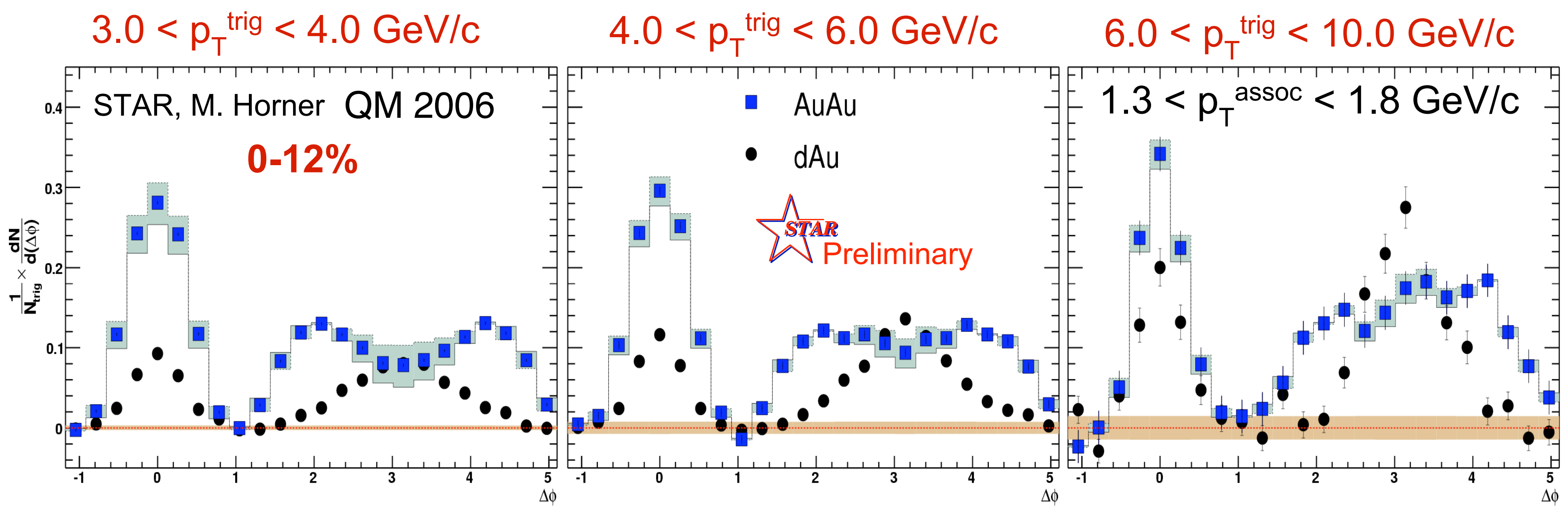




Removing the cut-off at RHIC

[Similar results for PHENIX and also SPS (Ceres)]



⇒ Nontrivial angular dependences in the away side

- Large broadening
- Two-peaks when $p_t^{\rm trigg} \sim p_t^{\rm assoc}$

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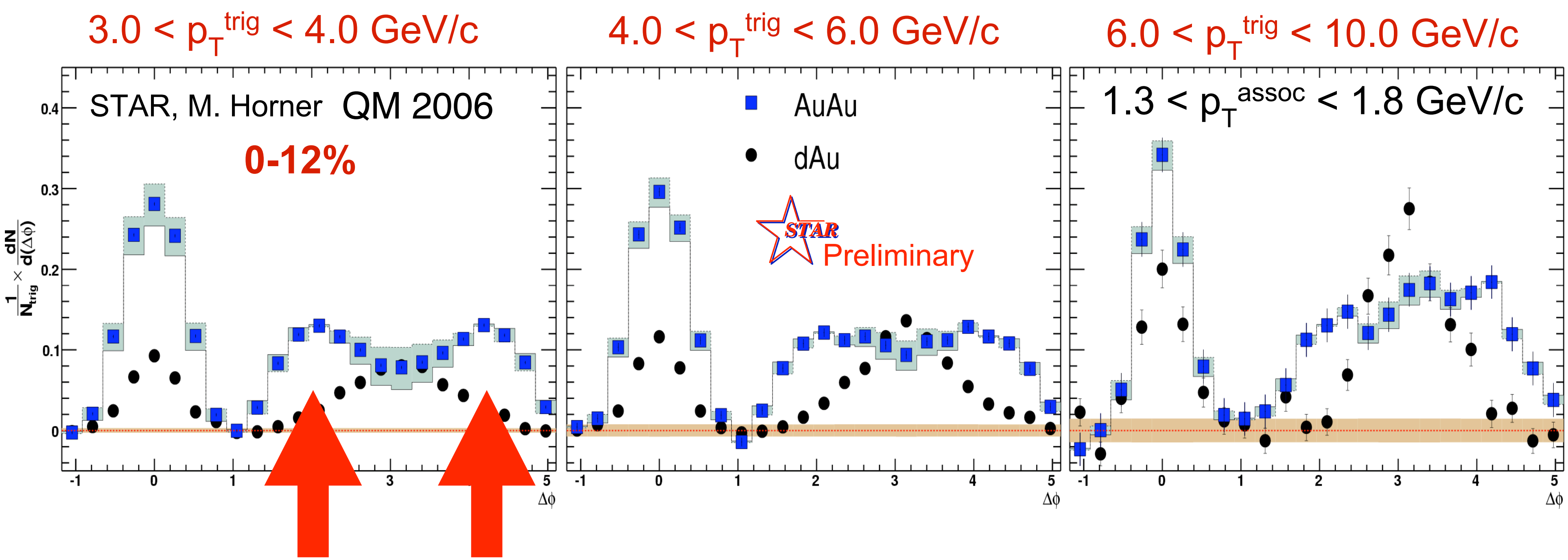

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Interpretations: two opposite assumptions

All lost energy is transferred to the medium

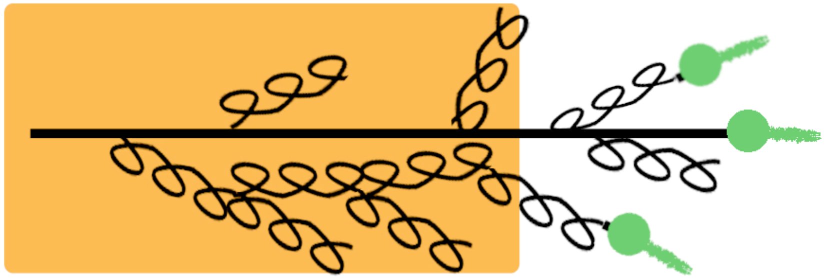
- Hydro evolution

  [Satarov, Stoecker, Mishustin 2005; Casalderrey-Solana, Shuryak, Teney 2005....]

- Colored wakes

  [Muller, Ruppert, Renk 2006, Chakraborty, Mustafa, Thoma 2006...]

Negligible energy transferred: Energy loss by radiation



- Medium-induced gluon radiation

  [Polosa, Salgado 2007]

- Cherenkov radiation

  [Dremin 1979, 2005; Koch, Majumder, Wang 2006]

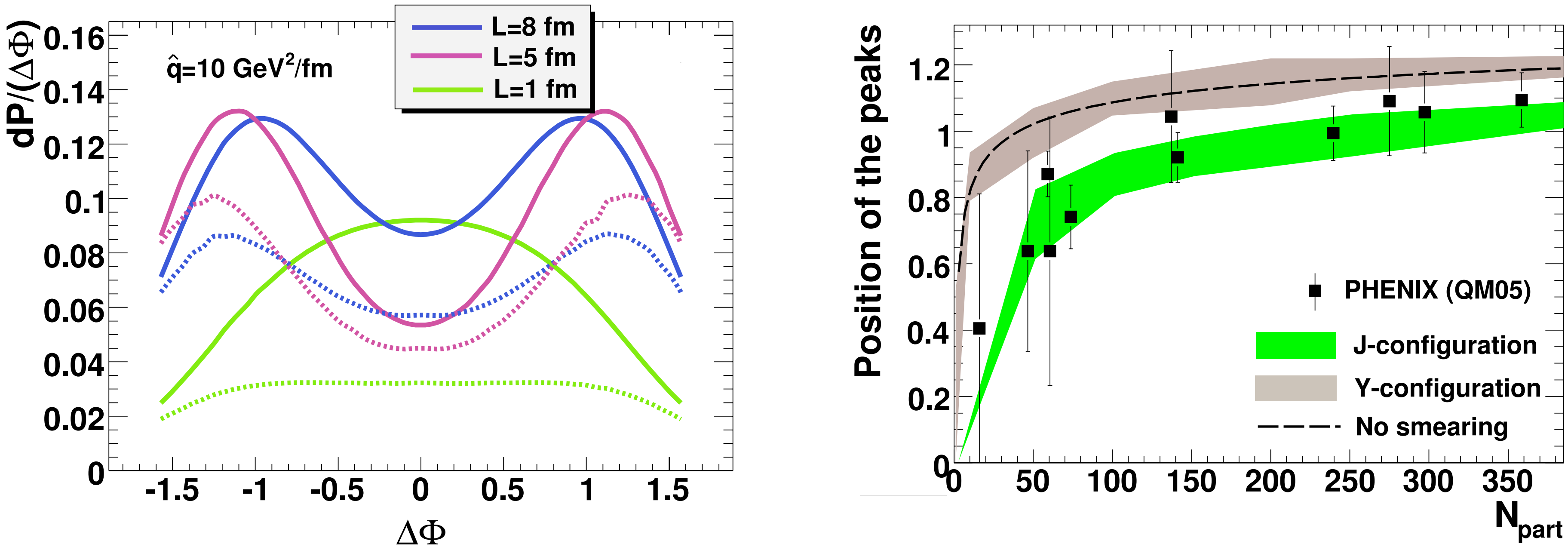
Parton shower for opaque media

⇒ When $p_t \sim \omega \lesssim \hat{q}^{1/3} \sim 3$ GeV $\longrightarrow$ Large $\hat{q}$ needed

- totally coherent limit and large angle radiation

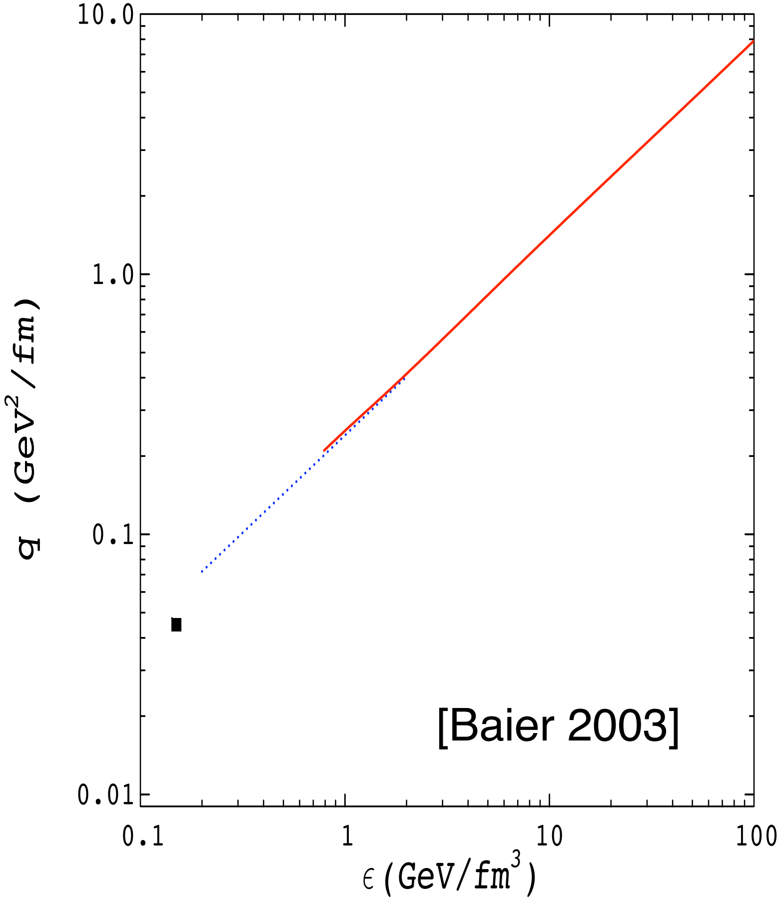
⇒ Probability of only one splitting has non-trivial angular dependence

$$d\mathcal{P} = dz\, d\theta\, \frac{\alpha_s C_R}{16\pi^2}\, E\, L\, \sin\theta\, \cos\theta \exp\left\{-\frac{\alpha_s C_R}{16\pi}\, E\, L\, \cos^2\theta\right\}$$



[Polosa, Salgado 2007]

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



⇛ Transport coefficient for an ideal quark-gluon gas

$$\hat{q}_{\rm ideal\ gas} \simeq \frac{72}{\pi}\xi(3)\alpha_s^2 T^3 \simeq 2\epsilon^{3/4}$$

[Baier and Schiff 2006]

⇛ Fits to the data

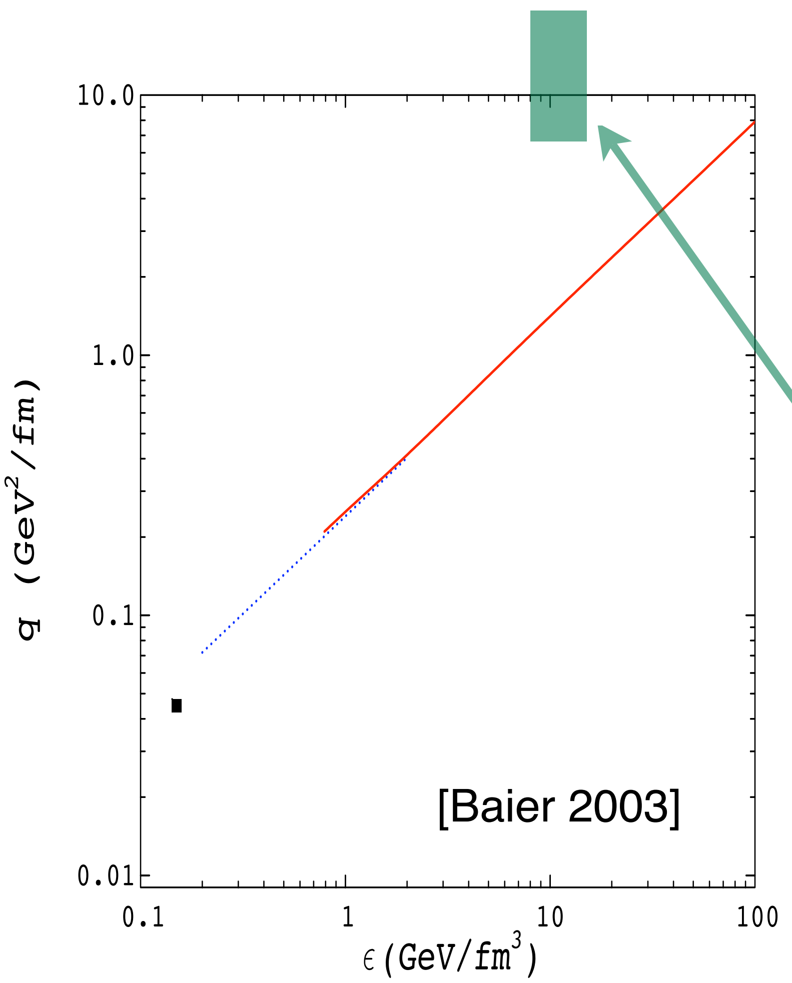
$\hat{q} > 5\ \hat{q}_{\rm ideal\ gas}$ [Eskola et al. 2004]

$\hat{q} \simeq 4.2\ \hat{q}_{\rm ideal\ gas}$ [Renk et al. 2007]

⇛ Geometry plays a crucial role

⇛ Model of the medium? sQGP?

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



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- Geometry plays a crucial role
- Model of the medium? sQGP?

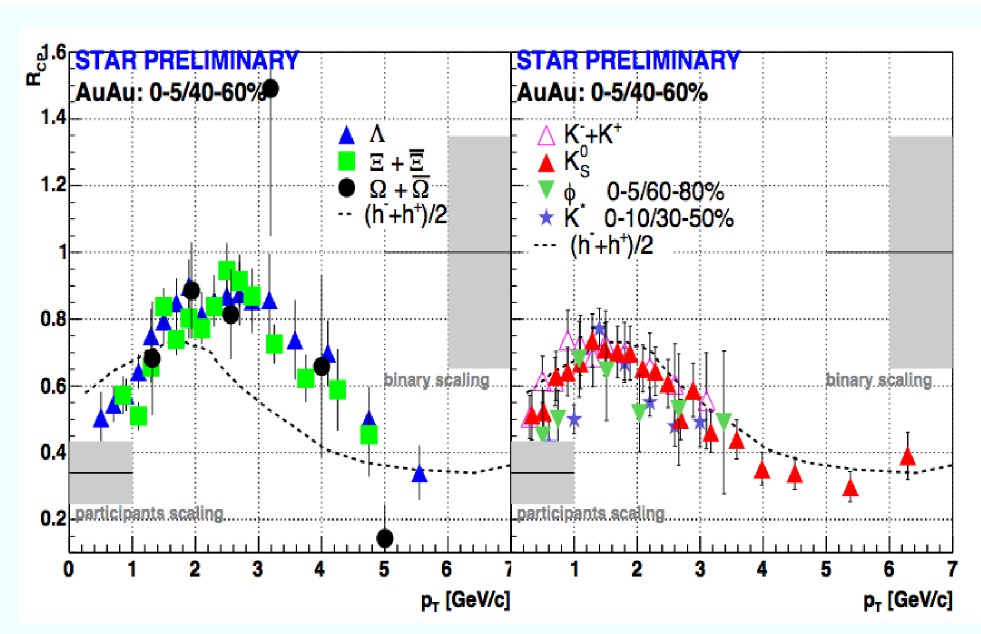
What is the order of magnitude of the NLO correction?

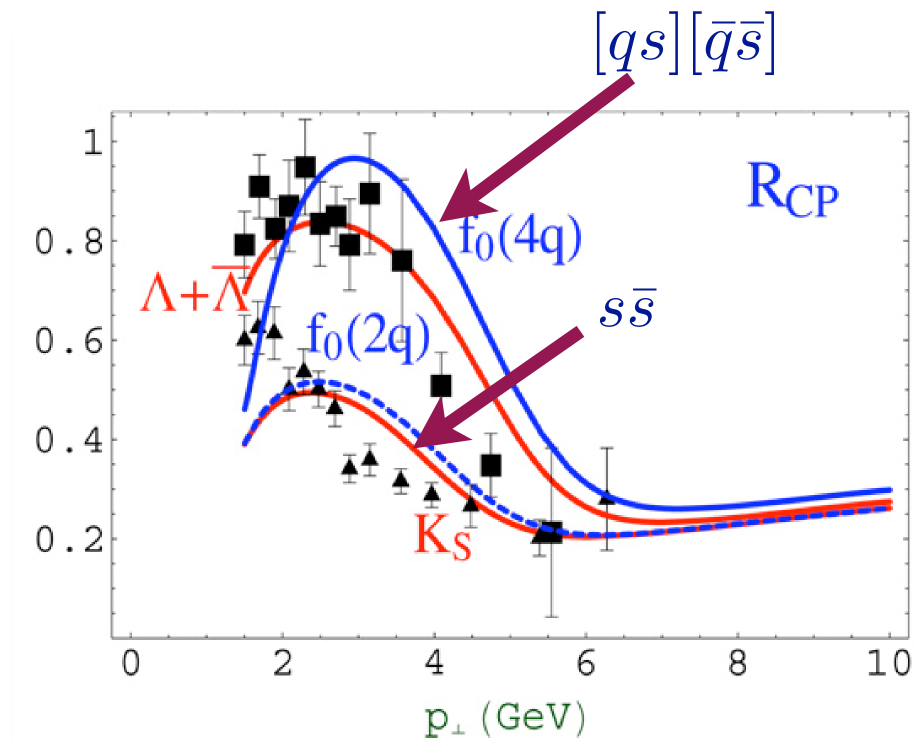
What are the degrees of freedom?

- Above 3Tc quark and gluon quasiparticles (pert. QCD)
- Below 3Tc (where experiments are)
  - Possible existence of bound states (lattice)
  - Large Interaction cross sections (viscosity, jet quenching)
  - Still unclear → several proposals
  - Ideal fluid formed by colored bound states, diquarks...?
  - Strongly coupled Quark Gluon Plasma (sQGP)?

Exotic meson spectroscopy and HIC

Baryon/meson hierarchy of suppressions observed at RHIC



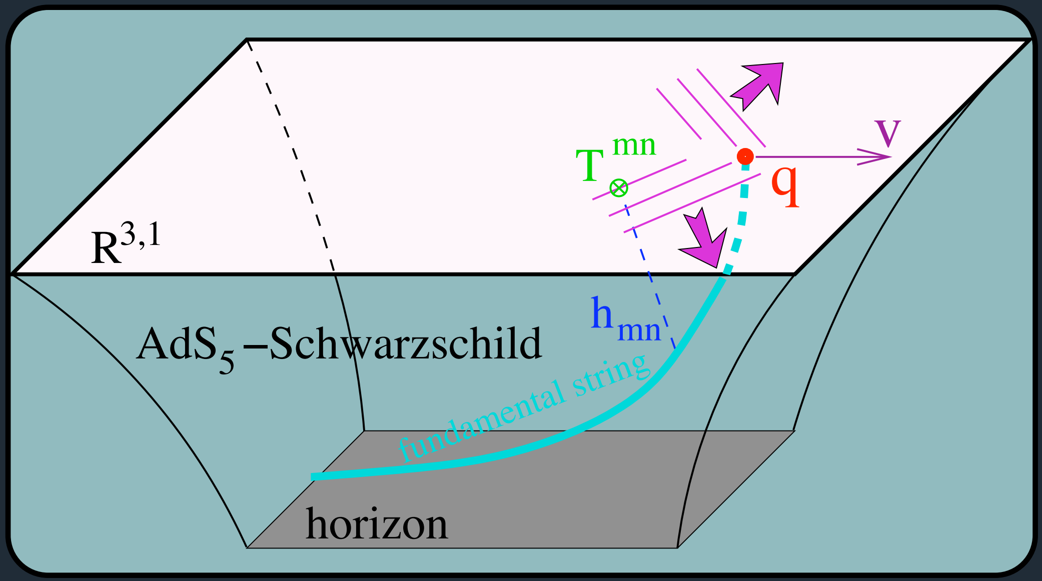


A nice possibility for a clean measurement of the exotic structure

$$f_0(980) = s\bar{s} \quad \text{OR} \quad [qs][\bar{q}\bar{s}] \; ?$$

[Maiani, Polosa, Riquer, Salgado (2007)]

[Nonaka, Muller, Asakawa, Bass, Fries 2004; Chen, Ko, Liu, Nielsen, Greco, Lee, Liu 2004, 2007]



The String Theory connection...

The observables

⇛ Applied to the jet quenching parameter:

$$\langle W^A(\mathcal{C})\rangle \simeq \exp\left[-\frac{1}{4\sqrt{2}}\hat{q}r^2L_-\right]$$

$$\hat{q} = 4.5,\ 10.6,\ 20.7\ \mathrm{GeV}^2/\mathrm{fm}$$

$$T = 300,\ 400,\ 500\,\mathrm{MeV}$$

[Liu, Rajagopalan, Wiedemann; Armesto, Edelstein, Mas...2006]

⇛ The viscosity-to-entropy ratio

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

$\eta \propto$ area of horizon
$s \propto$ area of horizon

Universal lower bound?

[Kovtun, Son, Starinets 2003]

⇛ The hydrodynamic behavior

↘ Bjorken hydrodynamics (and more)

[Janik, Peschanski 2006; Kovchegov, Taliotis 2007...]

⇛ Shock waves; heavy quark energy loss; bound states....

[Gubser; Herzog, Karch, Kovtun, Kozcaz, Yaffe; Casalderrey-Solana, Teaney.... 2006]

The observables

⇒ Applied to the jet quenching parameter:

$$\langle W^A(\mathcal{C})\rangle \simeq \exp\left[-\frac{1}{4\sqrt{2}}\hat{q}r^2L_-\right]$$

$$\hat{q} = 4.5,\ 10.6,\ 20.7\ \mathrm{GeV}^2/\mathrm{fm}$$
$$T = 300,\ 400,\ 500\,\mathrm{MeV}$$

[Liu, Rajagopalan, Wiedemann; Armesto, Edelstein, Mas...2006]

⇒ The viscosity-to-entropy ratio

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

$\eta \propto$ area of horizon
$s \propto$ area of horizon

Universal lower bound?

[Kovtun, Son, Starinets 2003]

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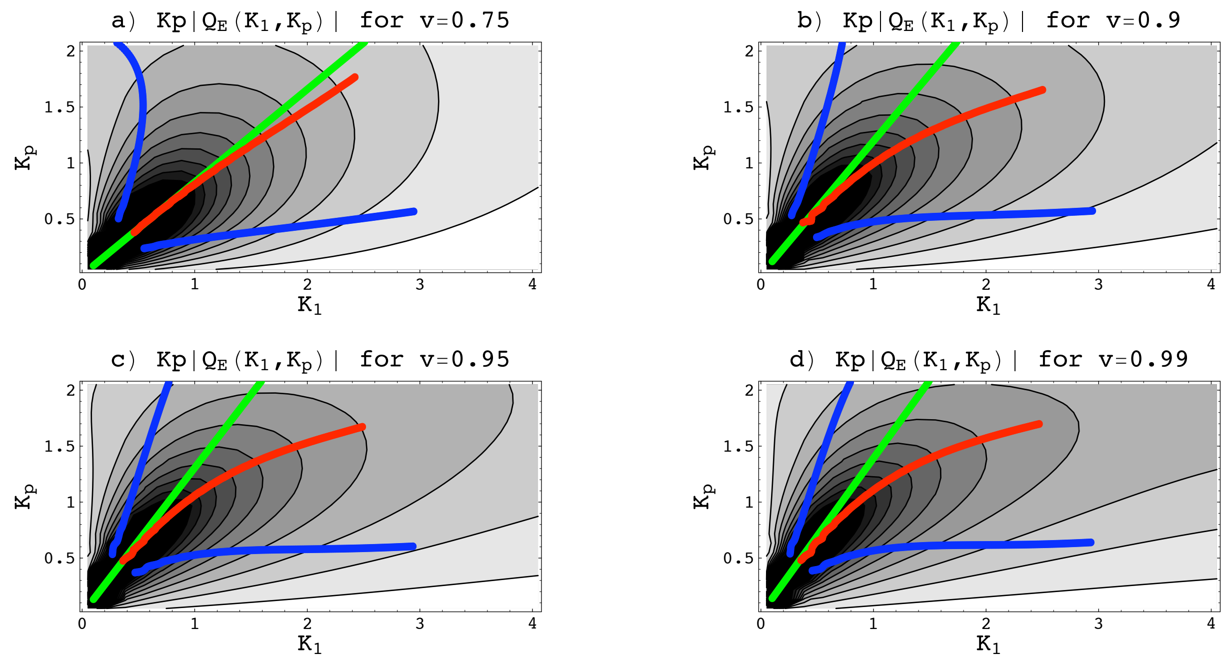
Shock waves and AdS/CFT

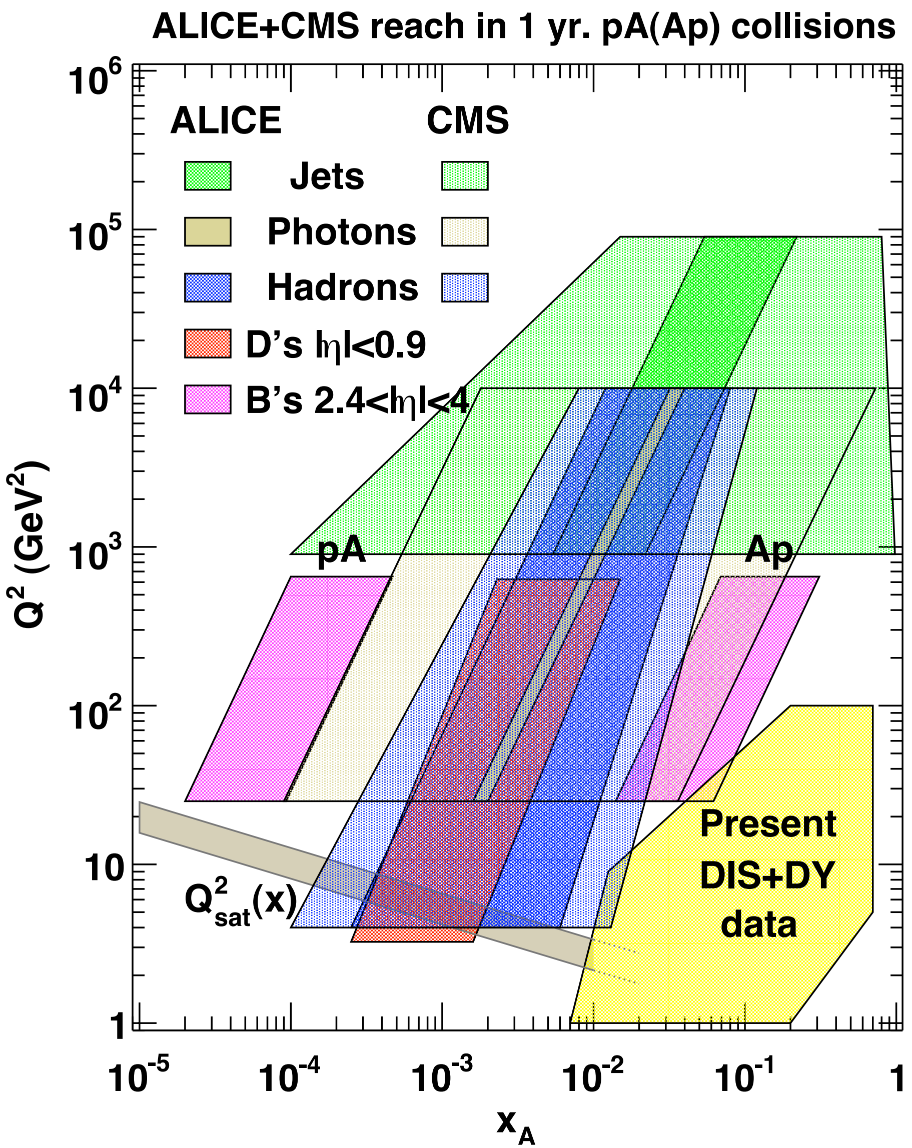
$T^{\mu\nu}$ computed for a quark moving with constant velocity in a medium



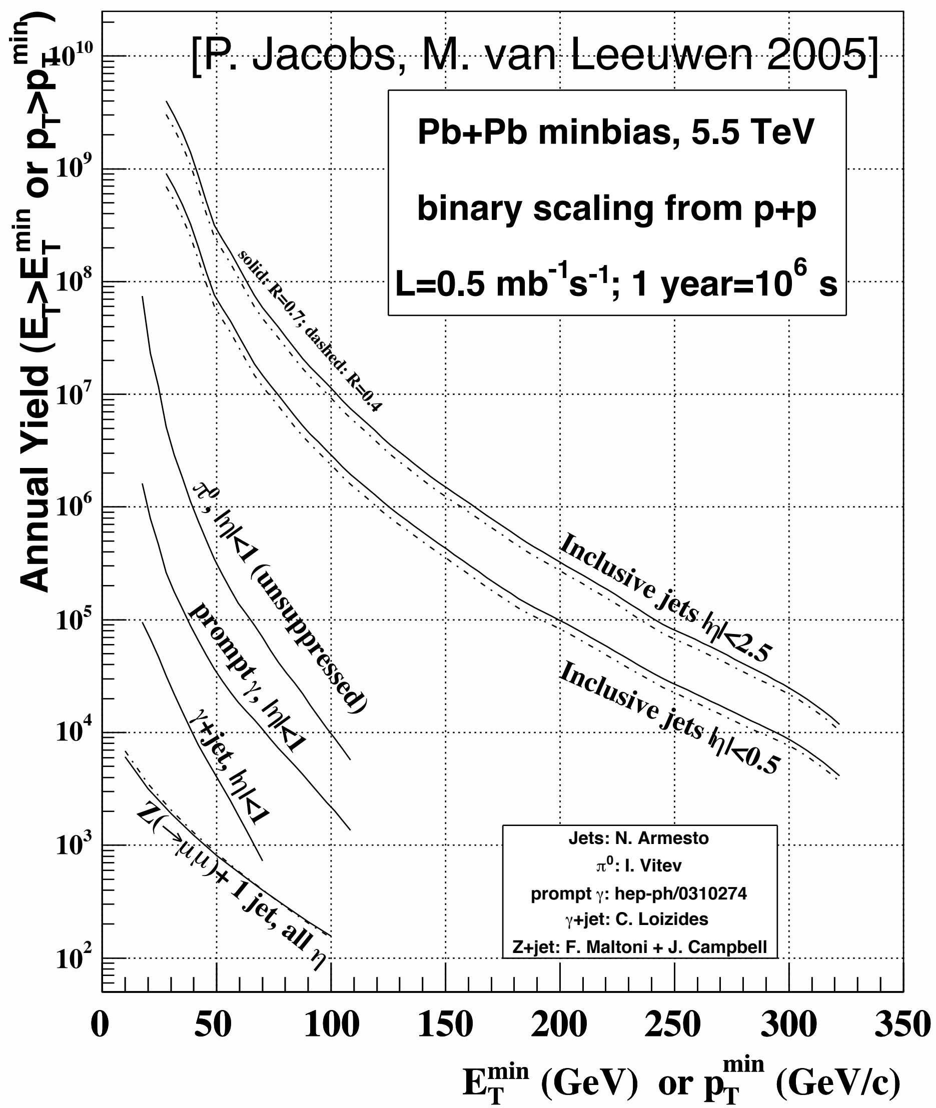
Yet, despite the potential stumbling blocks, it is exciting to see a simple type IIB string theory construction approaching quantitative comparisons with a data-rich experimental field.

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

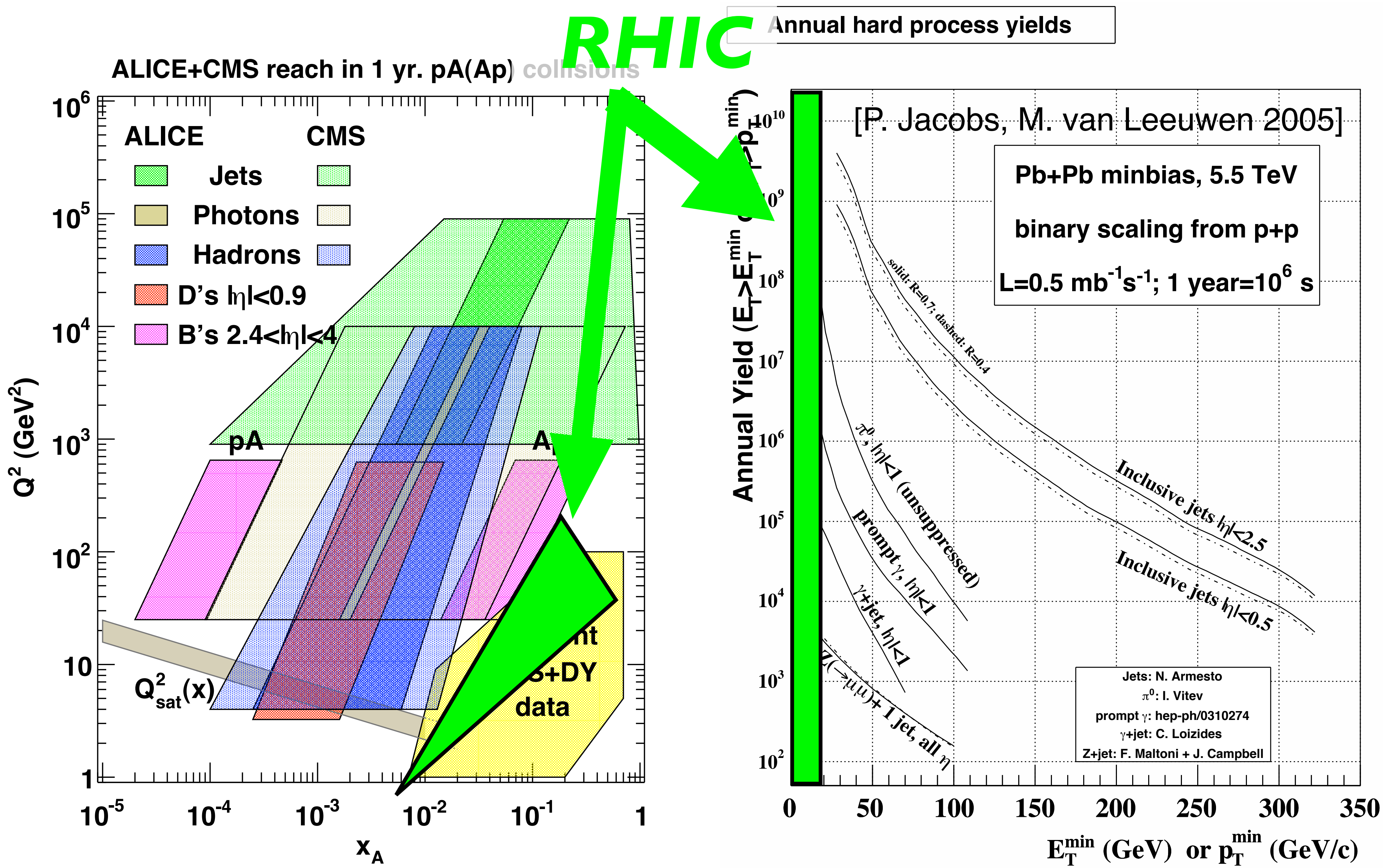
New regimes at the LHC



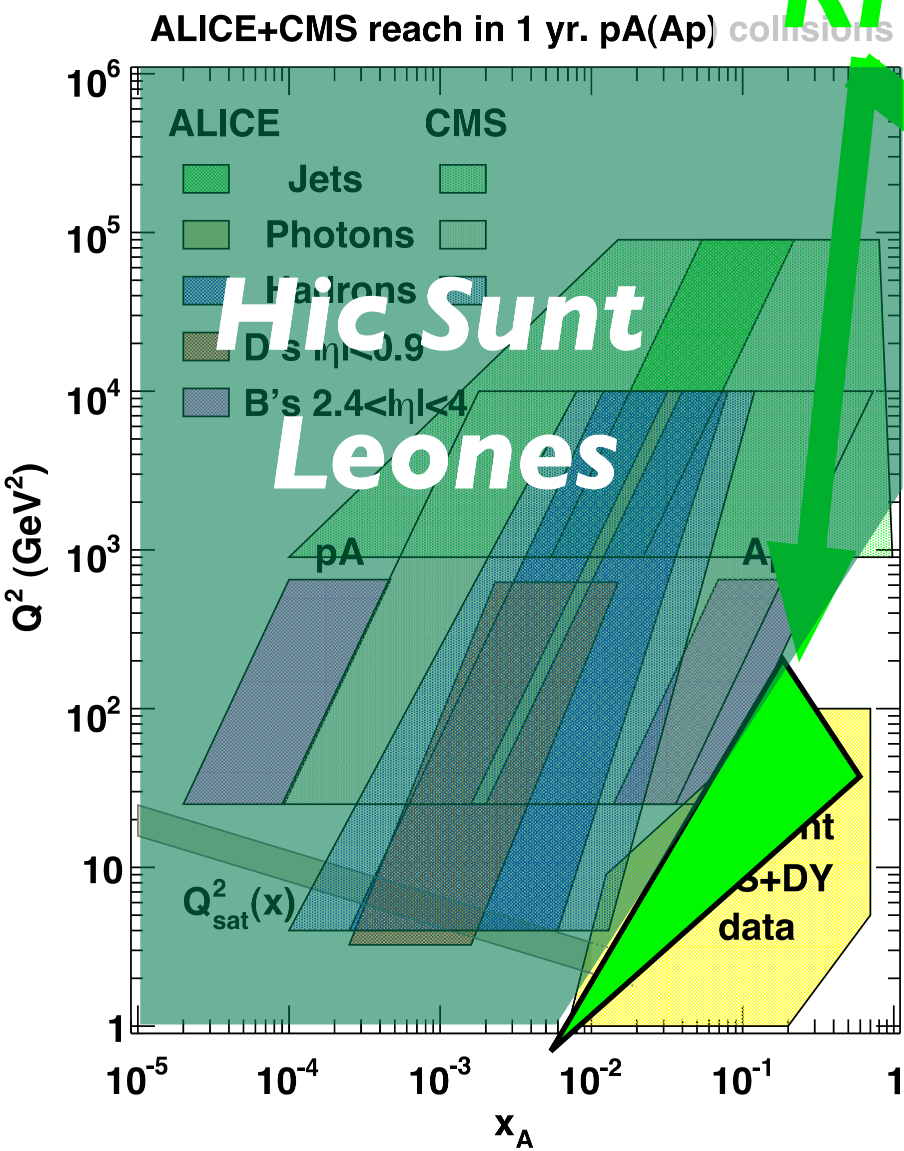
Annual hard process yields

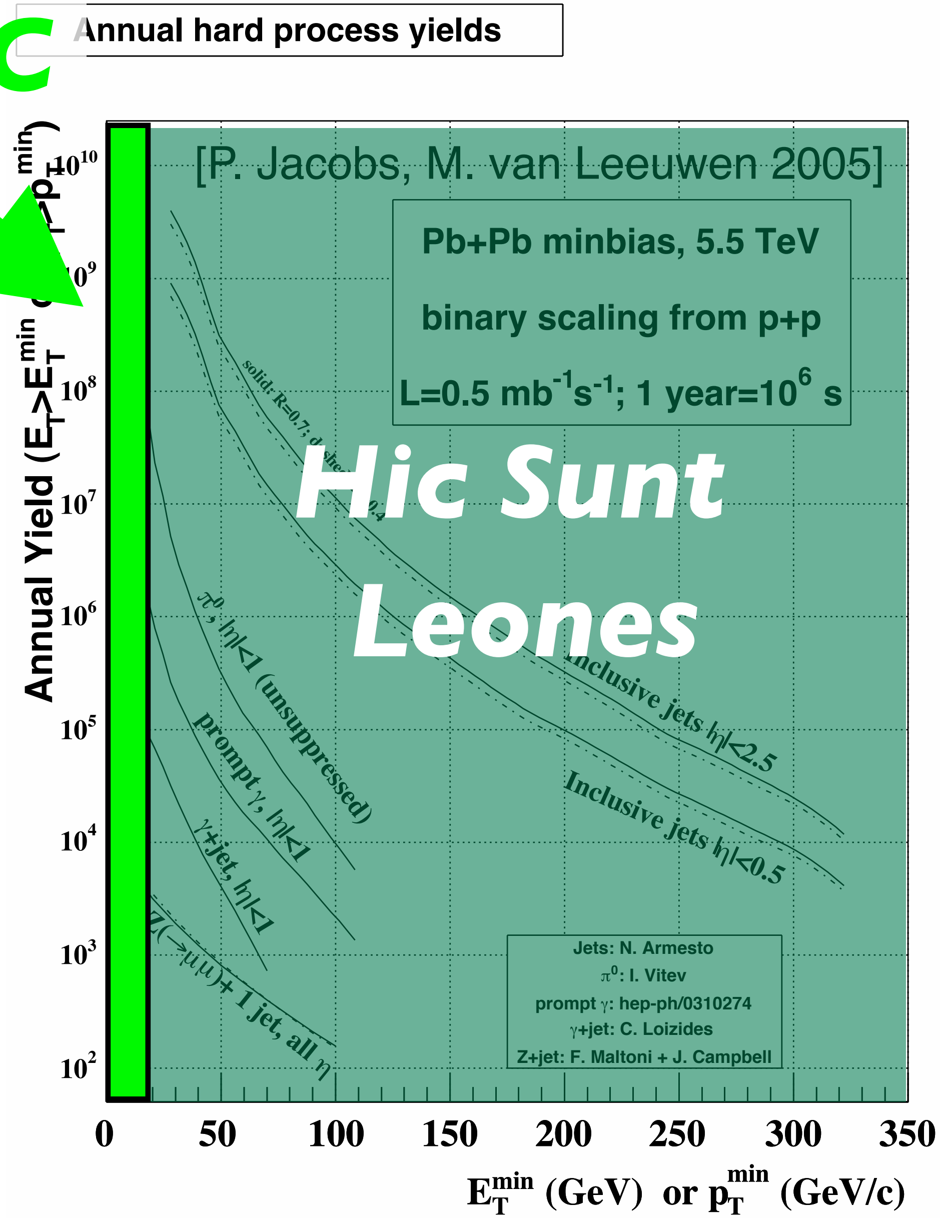


New regimes at the LHC



New regimes at the LHC





Summary

- ⇛ Developing paradigm from experimental data+theory
  - Early themalization and ideal fluid behavior
  - Very dense medium
  - Strongly coupled quark-gluon plasma → perfect liquid ?
- ⇛ What are the relevant degrees of freedom (building blocks)?
  - Not a free gas of quarks and gluons in present experiments
  - Quasiparticles? bound (colored) states?
- ⇛ Different fields are contributing to these developments
  - String-theory computations (attempt to) face experimental data

- ⇛ LHC: new regimes of QCD where in-medium evolution dominates