High-density QCD in heavy ion collisions

Carlos A. Salgado
Università di Roma "La Sapienza" and INFN Roma

Cracow School of Theoretical Physics
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carlos.salgado@cern.ch http://csalgado.web.cern.ch/

Summary I

- ⇛ QCD vacuum:
  Confinement & chiral symmetry breaking
- ⇛ Other states of matter possible?
- ⇛ Theory $\longrightarrow$ Different phases exist!

(for small μ_B)
Lattice + perturbative + models

- ⇛ Transition hadron gas $\leftrightarrow$ quark gluon plasma.
- ⇛ Order of the transition depends on quarks masses. For realistic masses, most probably crossover at $\mu_B = 0$.
- ⇛ Properties close to T_c different from a gas: Strongly coupled QGP? Indications of bound states above T_c
- ⇛ Heavy ion collisions experiments attempt to study this region.

2. Heavy-ion collisions and collective behavior in QCD

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?

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Today's talk

Where?

- SPS at CERN.
  - Have collided pA at $p_{\rm lab} = 450$ GeV/c, SU at $p_{\rm lab} = 200$ AGeV/c and PbPb at $p_{\rm lab} = 158$ AGeV/c.
  - The program is almost finished now
- RHIC at BNL
  - pp, dAu, AuAu and CuCu at $\sqrt{s} = 20 \ldots 200$ AGeV
  - RHIC II will improve detectors for rare processes and enhance statistics
- LHC at CERN
  - Will collide PbPb at $\sqrt{s} = 5500$ AGeV also pPb or dPb (under discussion) at $\sqrt{s} = 8200$
  - ALICE is a dedicated HI experiment
  - CMS and ATLAS have own programs of heavy ion collisions

Initial state of the system

The nuclear structure at high energies

⇛ We want to know the structure of the colliding system at high energies - and eventually the initial state of the medium

The nuclear structure at high energies

- We want to know the structure of the colliding system at high energies - and eventually the initial state of the medium
- Let us start by a simpler one: dipole-nucleus collision

High-energy variables

- Light-cone variables

$$x^{\pm} = x_0 \pm x_3 \qquad p^{\pm} = p_0 \pm p_3$$

- So that, the scalar product

$$p \cdot x = \frac{1}{2}(p^{+}x^{-} + x^{-}x^{+}) - \mathbf{p}_{\perp} \cdot \mathbf{x}_{\perp}$$

- Rapidity

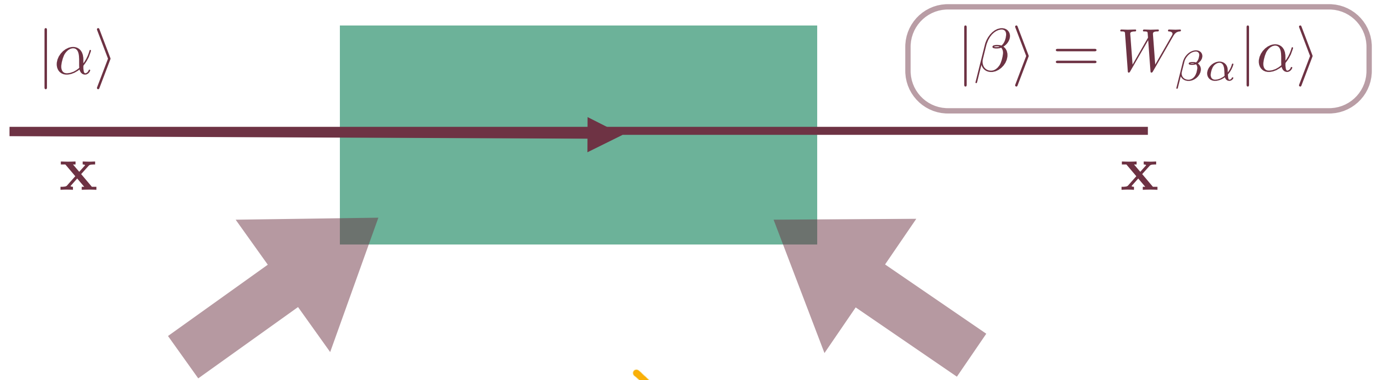
$$y = \frac{1}{2} \ln \left[\frac{p_0 + p_3}{p_0 - p_3} \right] = \frac{1}{2} \ln \left[\frac{p^{+}}{p^{-}} \right]$$

- Boost is just adding a factor $\rightarrow$ *additive velocity*

$$y' = y + y_{\beta} \quad \Longrightarrow \quad y_{\beta} = \frac{1}{2} \ln \left[\frac{1 + \beta}{1 - \beta} \right]$$

Particle propagation in matter: Eikonal limit

- At high energies → Eikonal approximation $E \gg k_\perp$



- Particle does not change its direction of propagation
- The medium rotates the color of the probe

$$W(\mathbf{x}) = P\,\exp\left\{i\int dz^- T^a A_a^+(\mathbf{x},z^-)\right\}$$ Wilson line

- Recoil is neglected → medium is a background field

[See e.g. A. Kovner Lectures Zakopane 2005]

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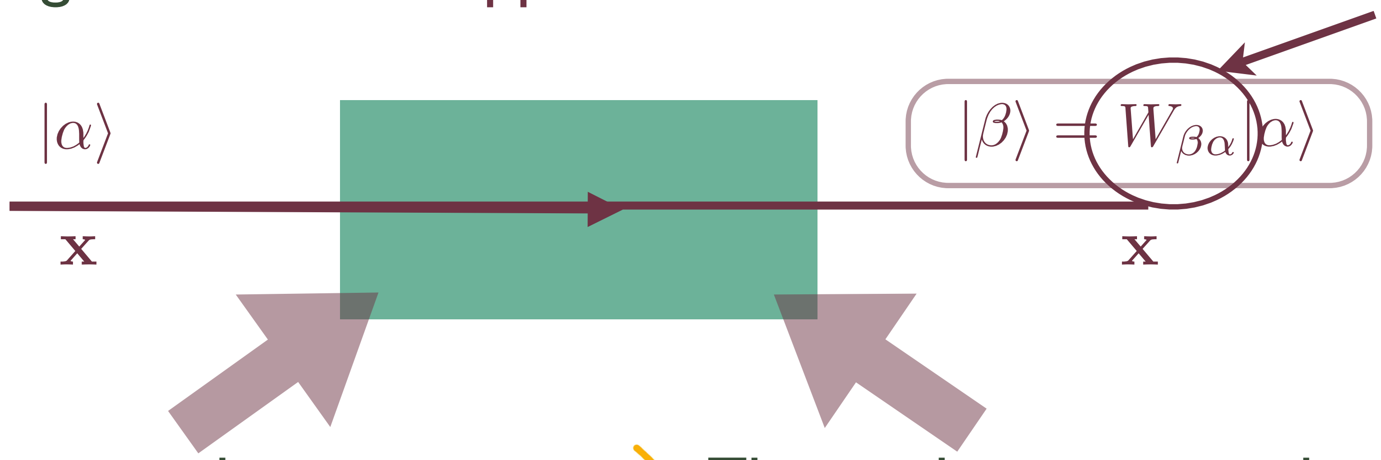

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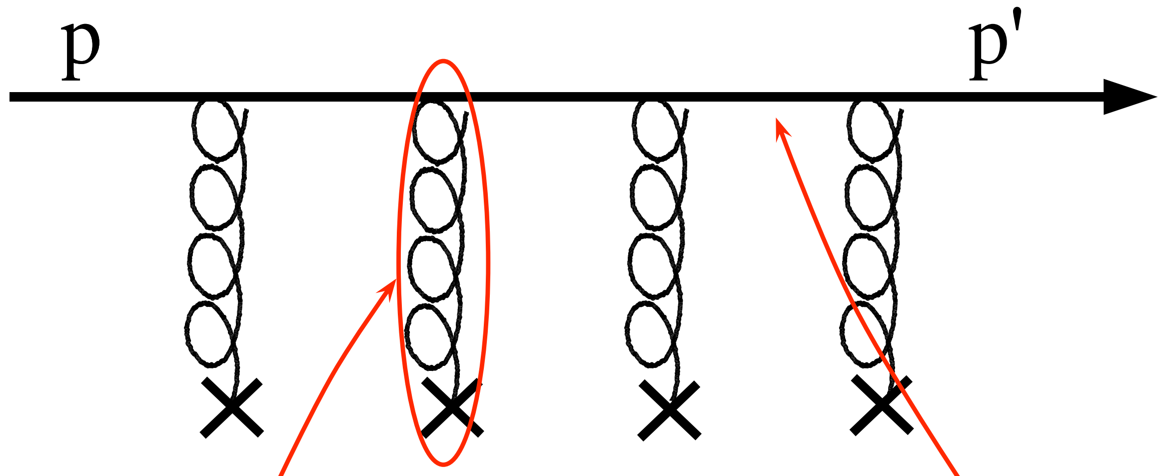
A simple derivation

Multiple potential scattering

[See e.g. A. Hebecker Phys. Rep. 331 (2000) 1]



$$\int d^4x A^\mu(x) \exp\{ix(k_i - k_{i+1})\}$$

Potentials

$$\frac{1}{k_i^2 + i\epsilon}$$

Propagators

A simple derivation

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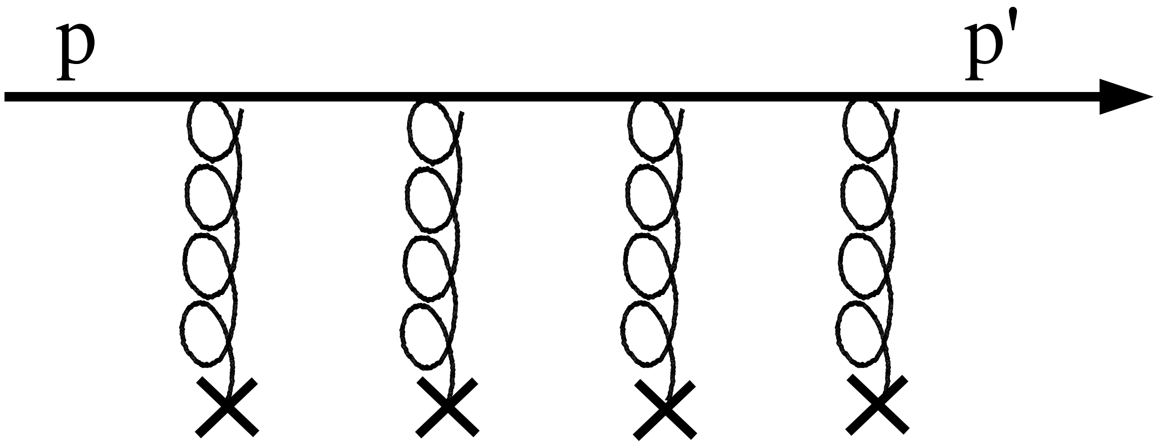

The contribution of two scatterings to the S-matrix is

$$S_2(p', p) = \int \frac{d^4k}{(2\pi)^4} \left\{ -ig(k_\mu + p'_\mu) \int d^4x_2 A^\mu(x_2) \mathrm{e}^{ix_2(p'-k)} \right\}$$
$$\frac{i}{k^2 + i\epsilon} \left\{ -ig(p_\mu + k_\mu) \int d^4x_1 A^\mu(x_1) \mathrm{e}^{ix_1(k-p)} \right\}$$

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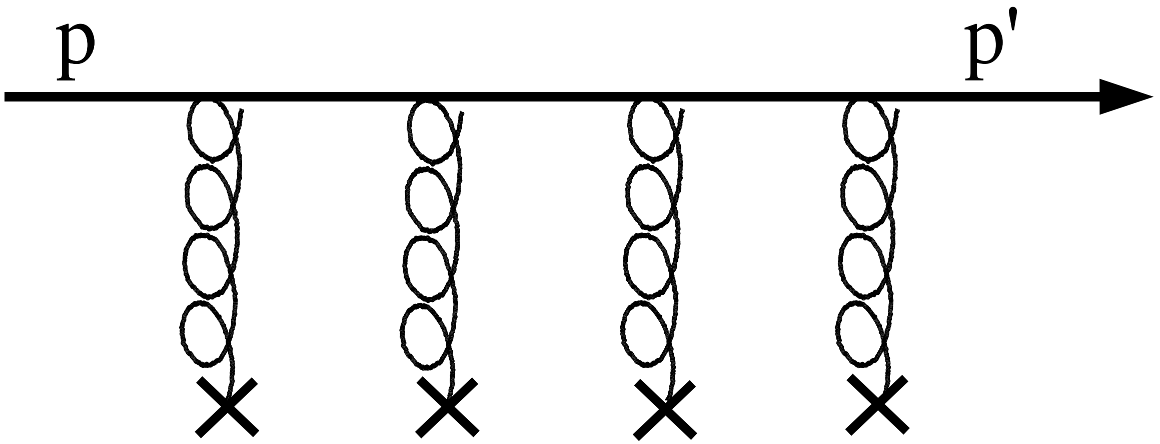

The high-energy limit ($p_+ \to \infty$) gives

$$S_2 = 2\pi\delta(p'_+ - p_+)2p_+ \int \frac{d^2\mathbf{k}_\perp}{(2\pi)^2} \int d^3\mathbf{x_1}\,[-igA_-(\mathbf{x_1})] \int d^3\mathbf{x_2}\,[-igA_-(\mathbf{x_2})] \times$$

$$\times \exp\{i\mathbf{k}_\perp(\mathbf{x_{1\perp}} - \mathbf{x_{2\perp}})\} \exp\{i(\mathbf{x_{2\perp}p_{2\perp}} - \mathbf{x_{1\perp}p_{1\perp}})\}$$

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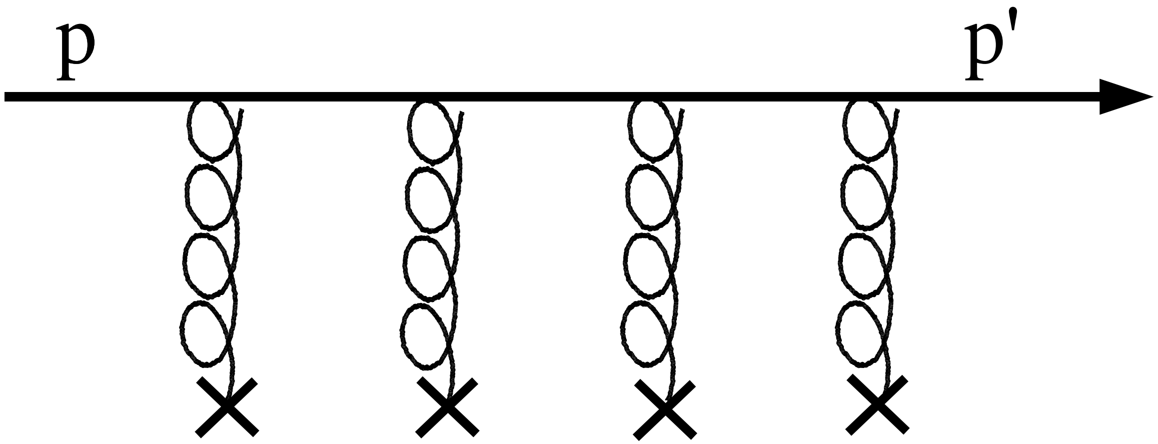

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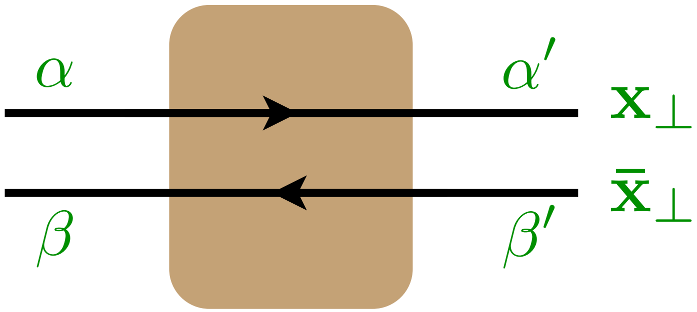
[Ex. check these formulas]

$$S = \int d^2\mathbf{x}_\perp \mathrm{e}^{-i\mathbf{x}_\perp(\mathbf{p}'_\perp - \mathbf{p}_\perp)} \boxed{P\exp\left\{-\frac{ig}{2}\int dx_+ A_-(x_+, x_\perp)\right\}}$$

Particle propagation in matter II: the dipole

⇛ Each propagation is a Wilson line at the relevant (fixed) transverse position



$$W(\mathbf{x}) = \mathcal{P} \exp \left[i \int dx^- A^+(\mathbf{x}_\perp, x^-) \right]$$

⇛ So, the S-matrix

$$|\alpha'; \beta'\rangle \equiv S_{\alpha'\beta'\alpha\beta} |\alpha; \beta\rangle = W_{\alpha'\alpha}(\mathbf{x}_\perp) W^\dagger_{\beta'\beta}(\bar{\mathbf{x}}_\perp) |\alpha; \beta\rangle$$

⇛ Total probability of interaction (cross-section w/ needed factors)

$$P^{q\bar{q}}_{\mathrm{tot}} = \left\langle 2 - \frac{2}{N_C} \mathrm{Tr} \left[W(\mathbf{x}_\perp) W^\dagger(\bar{\mathbf{x}}_\perp) \right] \right\rangle$$

[Ex. check these formulas, use e.g. the optical theorem]

What are the $\langle \ldots \rangle$??

⇛ All the medium properties are encoded in the medium-averages of the Wilson lines.

⇛ Several prescriptions used

↘ Saddle-point approximation → opaque medium, many scatterings

$$\frac{1}{N}\text{Tr}\left\langle W(\mathbf{x}_\perp)W^\dagger(\bar{\mathbf{x}}_\perp)\right\rangle \approx \exp\left\{-\frac{1}{8}Q_{\rm sat}(\mathbf{x}_\perp-\bar{\mathbf{x}}_\perp)^2\right\}$$

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- Opacity expansion → small medium, few scatterings

$$\frac{1}{N}\mathrm{Tr}\left\langle W(\mathbf{x}_\perp)W^\dagger(\bar{\mathbf{x}}_\perp)\right\rangle \approx 1-\int dx^- n(x^-)\sigma(\mathbf{x}_\perp-\bar{\mathbf{x}}_\perp)$$

- ....

[See e.g. Kovner and Wiedemann, PRD64 (2001)114002; A. Hebecker Phys. Rep. 331 (2000) 1]

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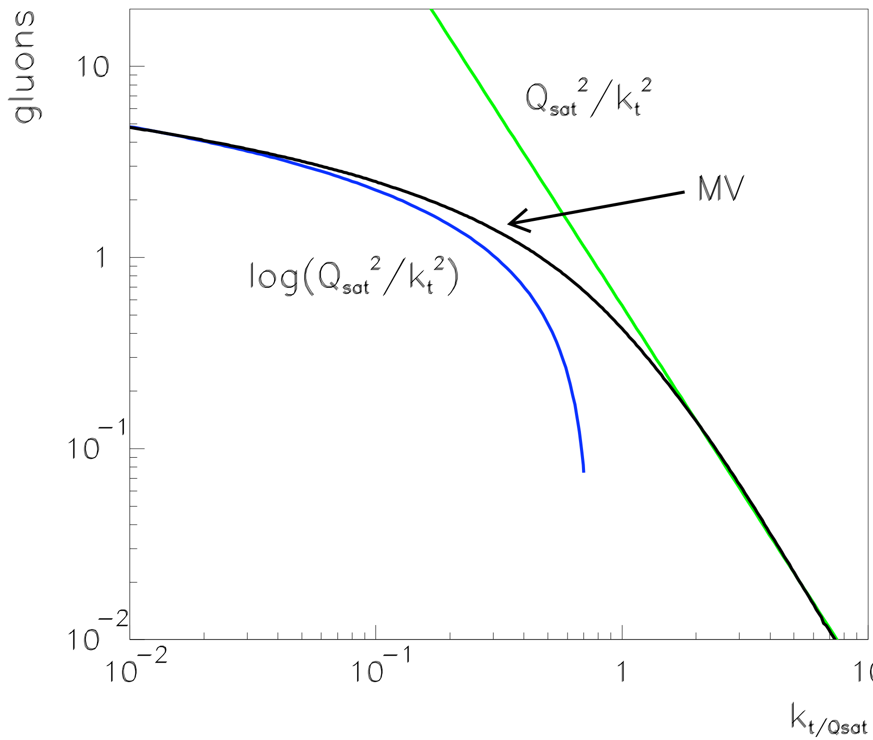
All together: the gluon distribution

⇛ The dipole 'counts' the number of gluons, of a given size r, in the nucleus, so the (unintegrated) gluon distribution:

$$N(r) = 1 - \exp\left[-\frac{1}{8}Q_{\rm sat}^2 r^2\right] \quad \Longrightarrow \quad \phi(k) = \int \frac{d^2r}{2\pi r^2} e^{i\mathbf{r}.\mathbf{k}} N(r)$$

[up to logs: McLerran, Venugopalan 1994]



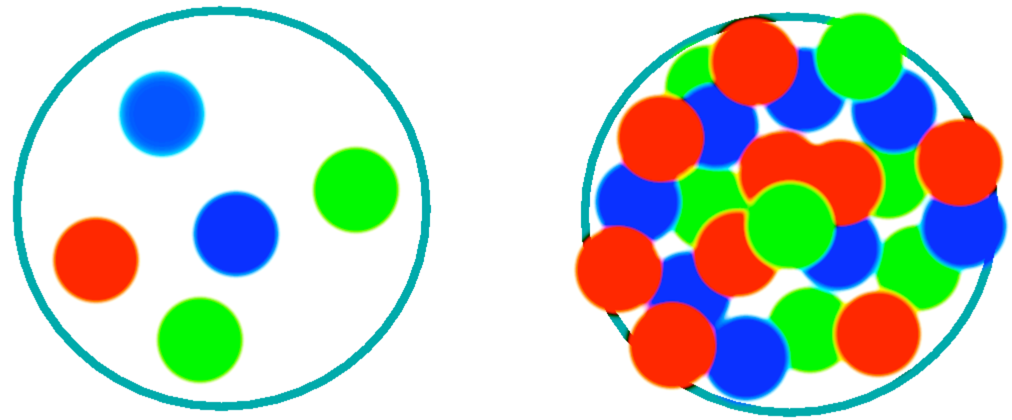
Two important consequences:

- Saturation scale cuts-off the small momentum region
- Geometric scaling:

$$\phi = \phi(k^2/Q_{\rm sat}^2)$$

Saturation of partonic densities: picture

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



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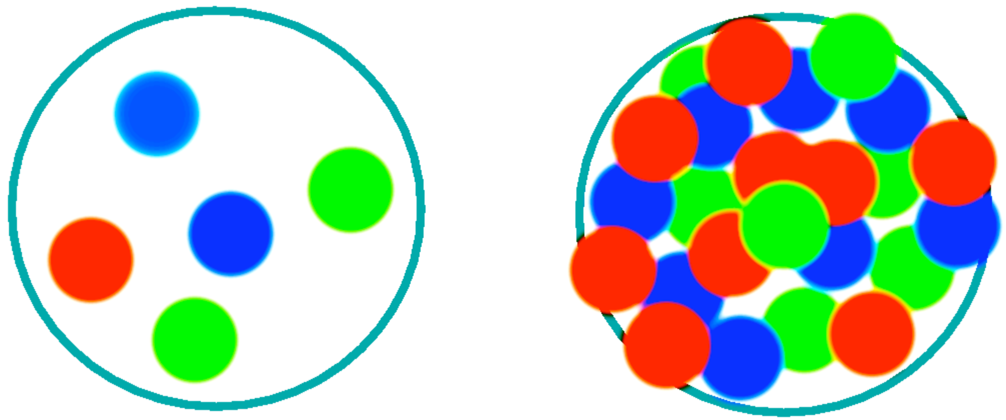

transverse area of the gluon

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

transverse area of the nucleus

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

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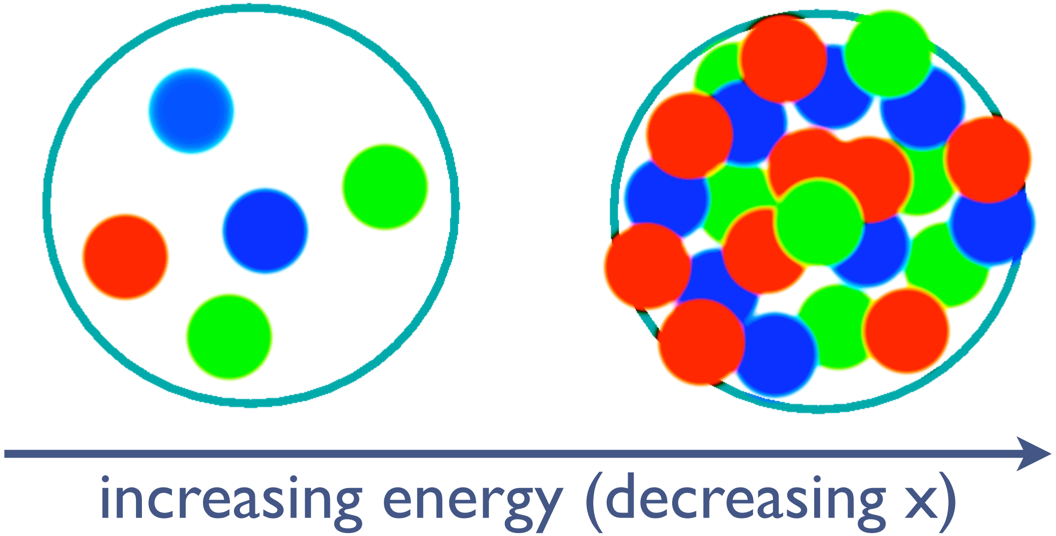

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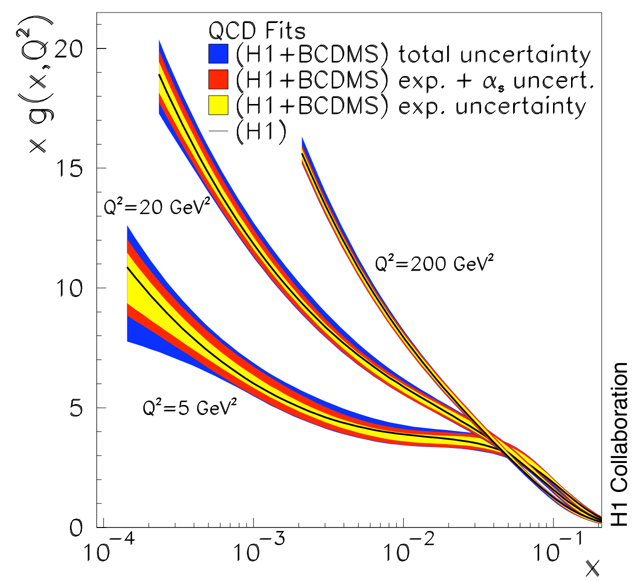
$$N_g \sim \frac{1}{x^\lambda} \quad \Longrightarrow \quad Q_{\rm sat}^2 \sim \frac{A^{1/3}}{x^\lambda}$$



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

Geometric scaling in lepton-hadron data

⇛ All lepton-proton data with $x \leq 0.01$ only function of

$$\tau_p = \frac{Q^2}{Q^2_{\rm sat}}; \quad Q^2_{\rm sat} = \frac{x^{-\lambda}}{R_0^2}$$

Stasto, Golec-Biernat, Kwiecinski 2001

⇛ Scaling in lepton-nucleus

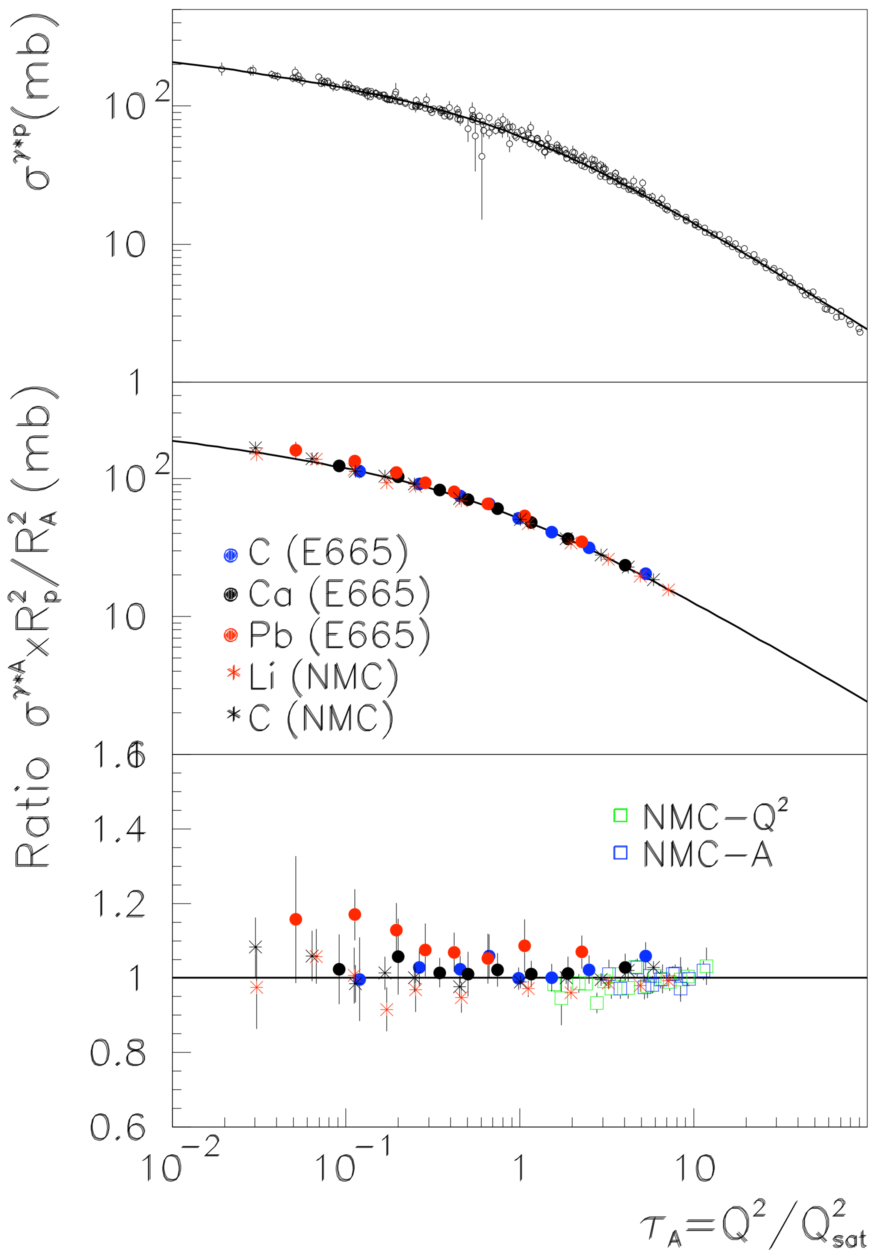
$$Q^2_{\rm sat,A} = Q^2_{\rm sat,p} \left(\frac{A R_p^2}{R_A^2} \right)^{1/\delta}$$

$$\lambda \sim 0.3; \quad \delta \sim 0.8$$

Exercise: Check this scaling for BK eq. Help:

$$\sigma_{T,L}^{\gamma^* h}(x, Q^2) = \int d^2\mathbf{r} \int_0^1 dz |\Psi_{T,L}^{\gamma^*}|^2 \, \sigma_{\rm dip}^h(\mathbf{r}, x) \, .$$

[see Phys. Rev. Lett 94 (2005) 022002]



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⇒ Scaling in lepton-

$$Q^2_{\rm sat,A} = Q^2_{\rm sat,p}$$

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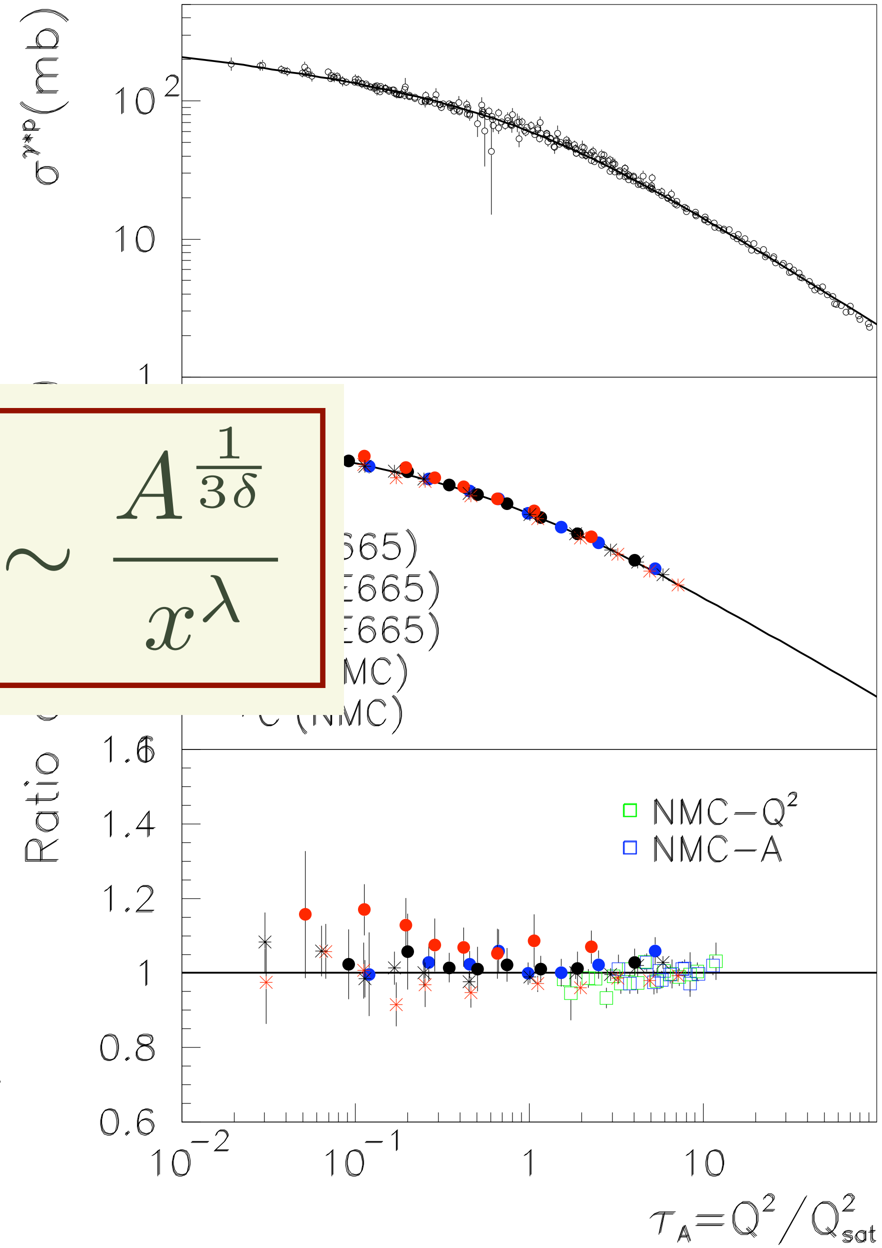
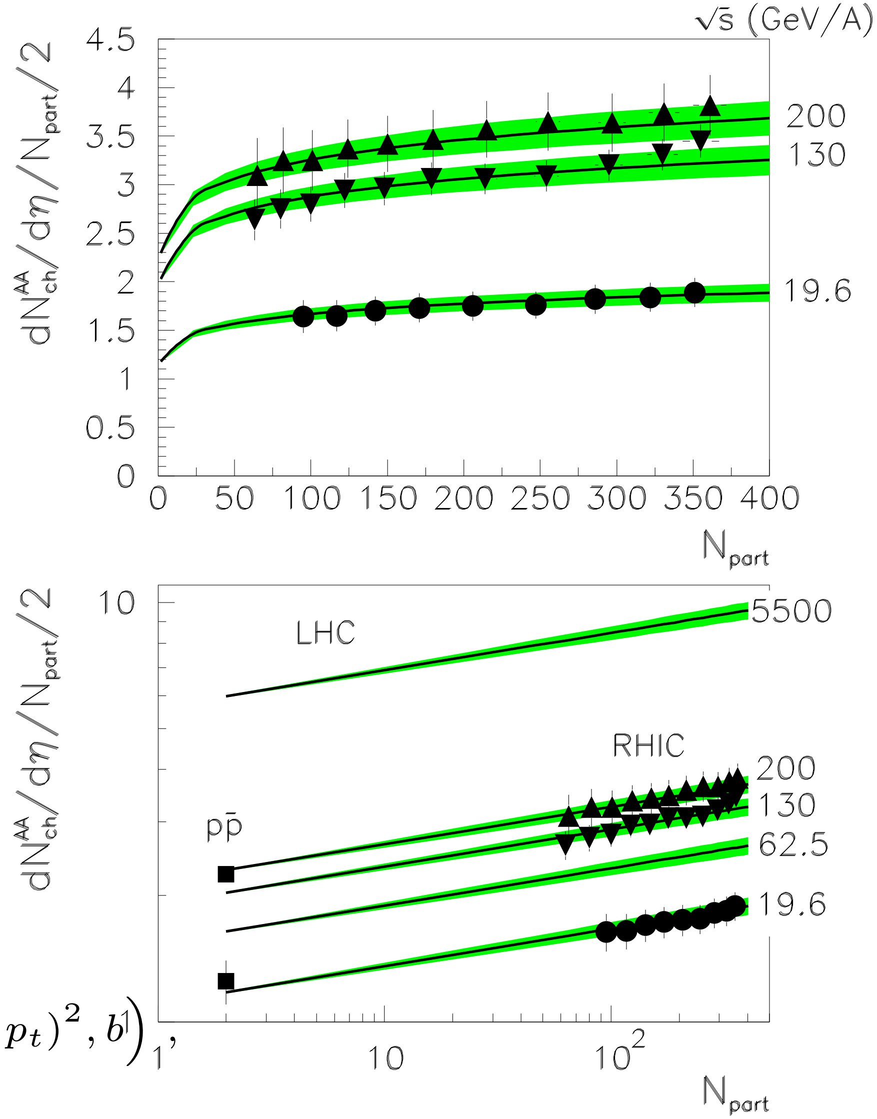


Multiplicities and geometric scaling

- ⇒ Multiplicity = number of produced particles
- ⇒ Assuming the same scaling for particle production in AA collisions

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



- ➘ Energy and centrality dependence fixed by lepton-proton/nucleus data

Exercise: Check this formula. Use

$$\frac{dN_g^{AB}}{dy\,dp_t^2\,d^2b} \propto \frac{\alpha_S}{p_t^2}\int d^2k\,\phi_A(y,k^2,b)\,\phi_B\left(y,(k-p_t)^2,b\right),$$

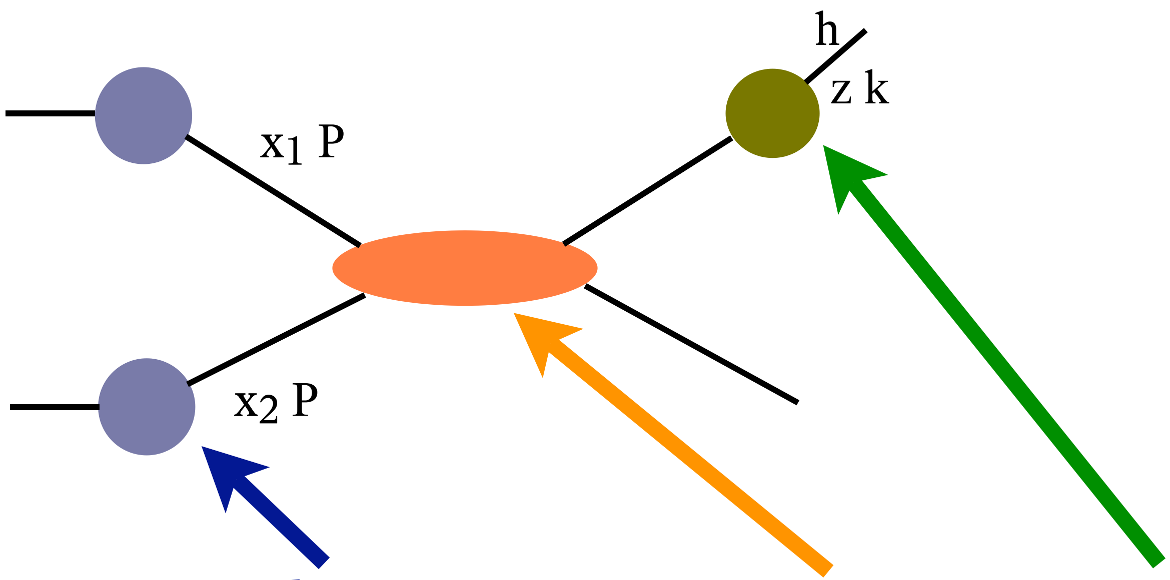
[see Phys. Rev. Lett 94 (2005) 022002]

[More in Wit Busza's talks]

Characterizing the final state: Hard Probes

Hard probes

- ⇛ Remember, asymptotic freedom $\alpha_S(Q^2) \to 0$ for $Q^2 \to \infty$
- ⇛ A typical hard cross section expands in powers of $\alpha_S(Q^2)$



$$\sigma^{AB\to h} = N_{\rm coll} \underbrace{f_A(x_1,Q^2) \otimes f_B(x_2,Q^2)}_{\text{Long distance}} \otimes \underbrace{\sigma(x_1,x_2,Q^2)}_{\text{Short dist.}} \otimes \underbrace{D(z,Q^2)}_{\text{Long dist.}}$$

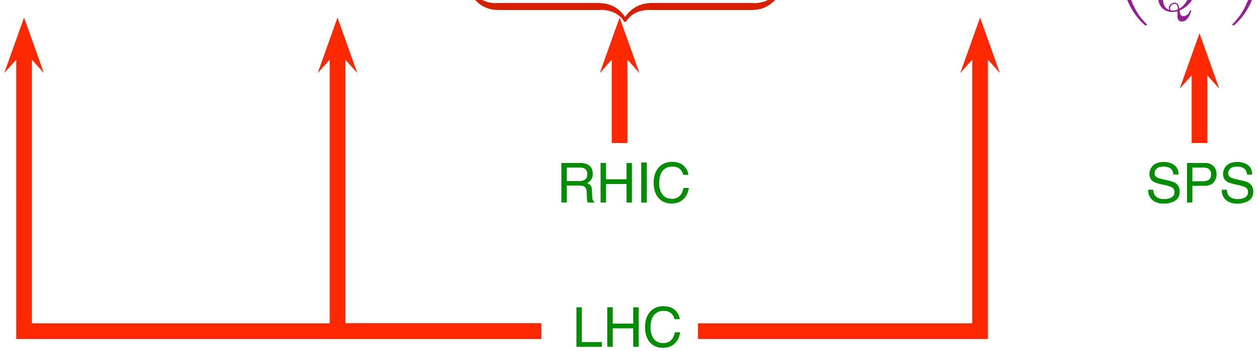
Long and short distance separation: factorization

Extension of the medium modifies the long distance parts

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

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



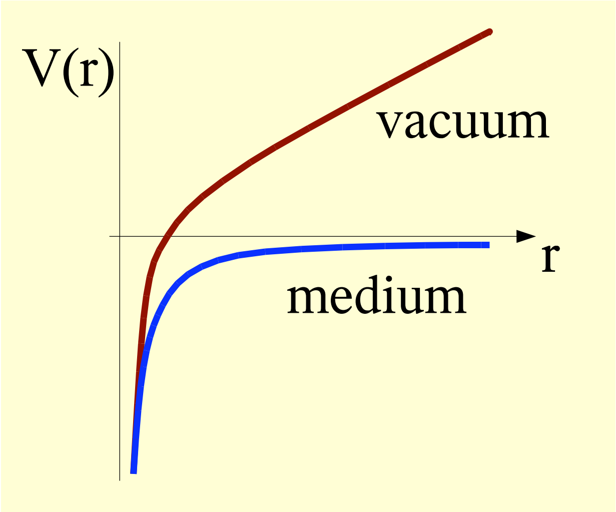
- QCD $\longrightarrow$ field theory $\longrightarrow$ quantum corrections (evolution equations)
- $Q^2 \gg 1 \implies$ short distances
  - But we want to study extended objects
    $\implies$ QCD-evolution in long-distance parts $f_p(x, Q^2)$ and $D(z, Q^2)$

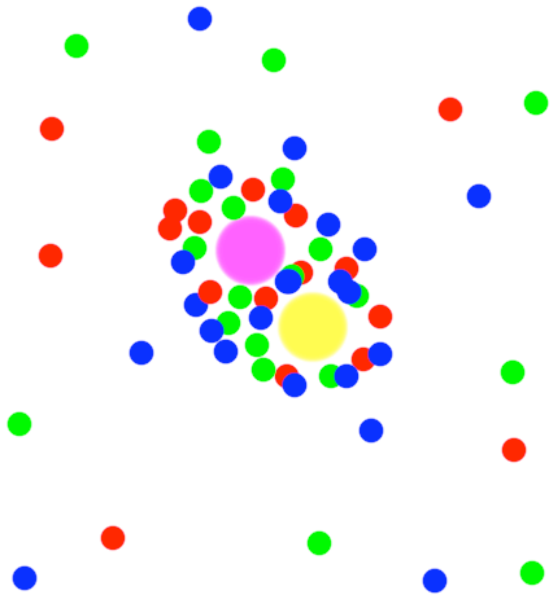
A 'simple' example, J/Ψ suppression

- 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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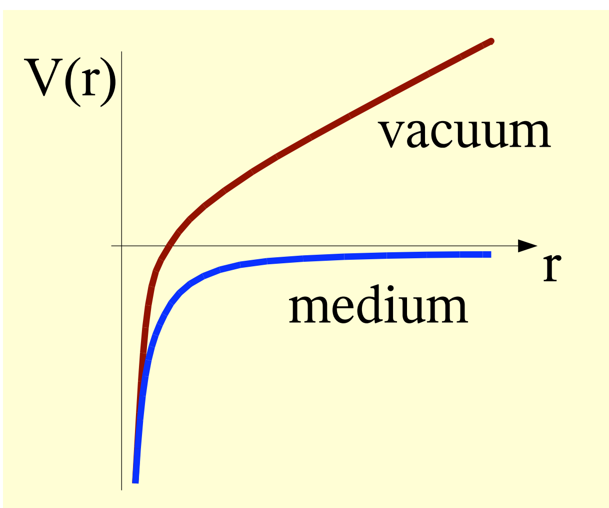
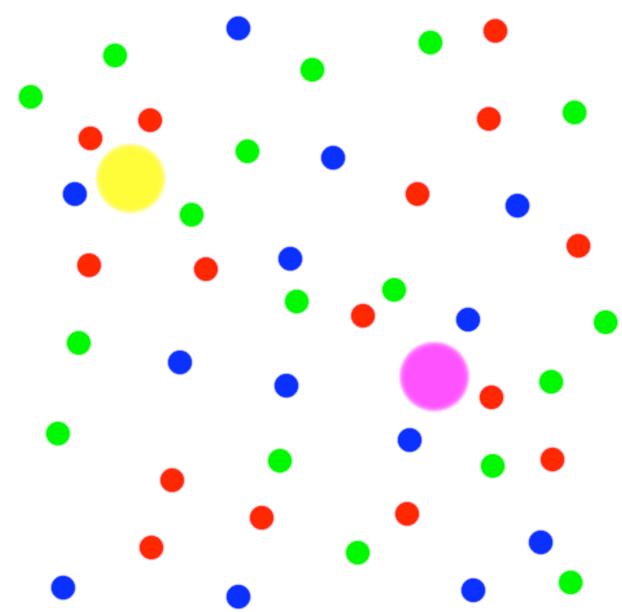
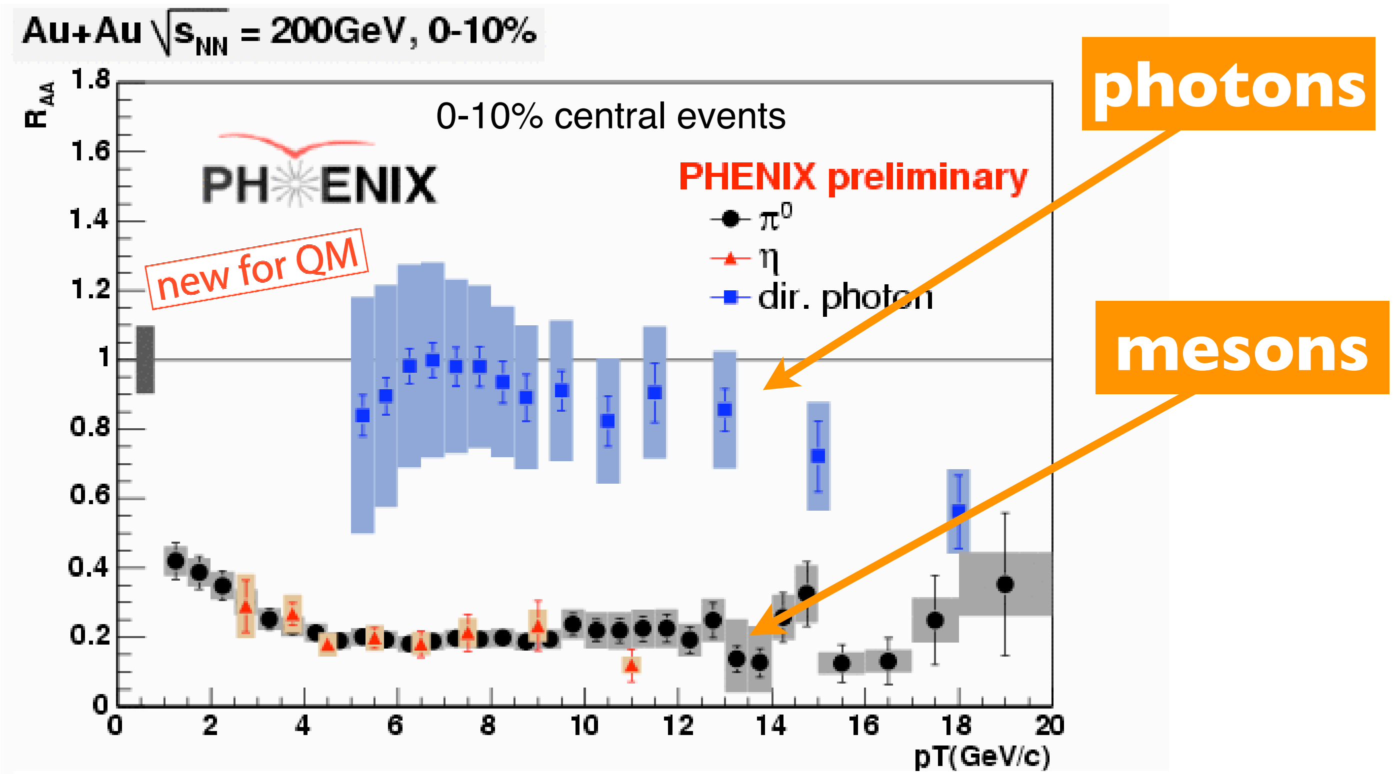




Effects on high-p_t particles

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



Photons don't interact (no effect) quarks and gluons do (suppression)

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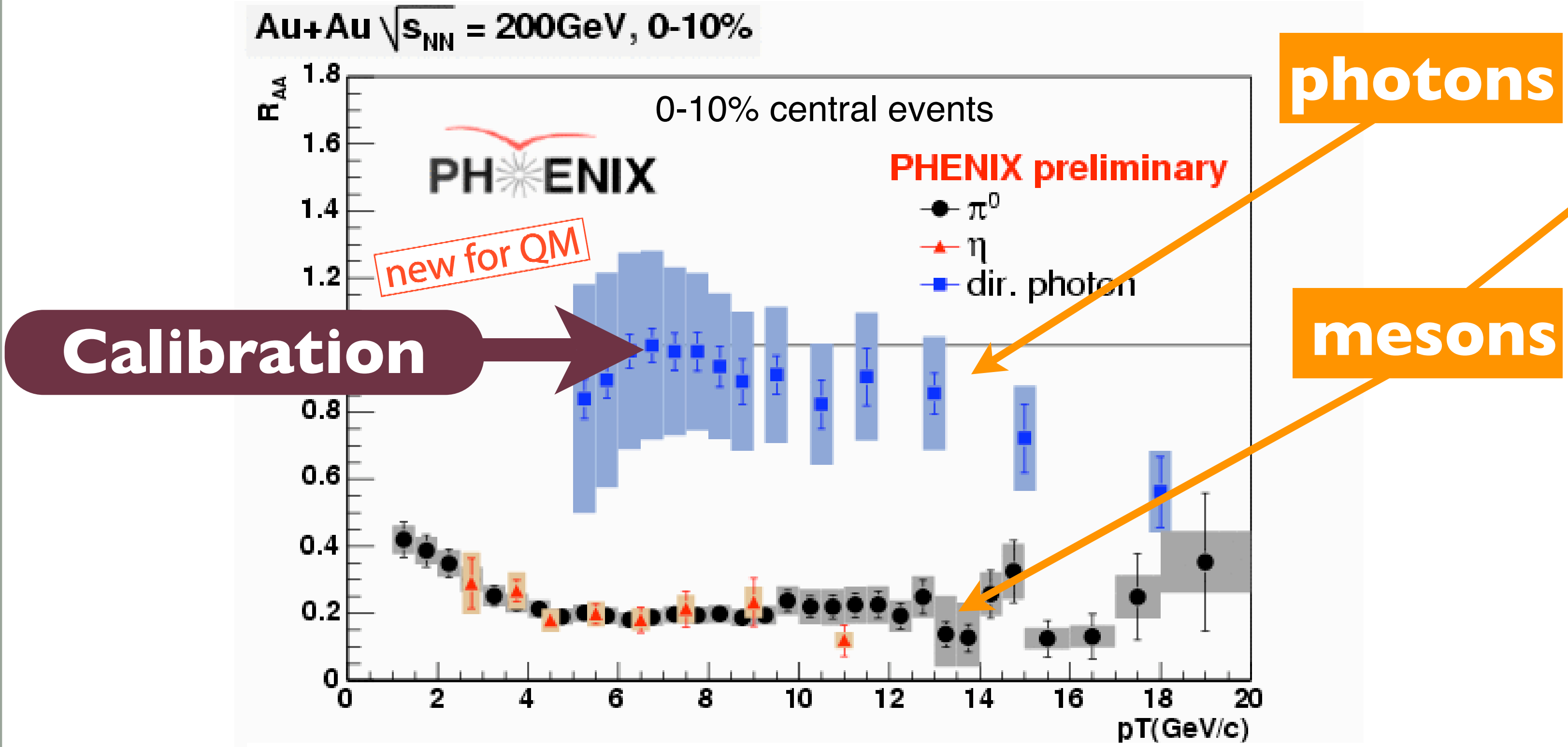

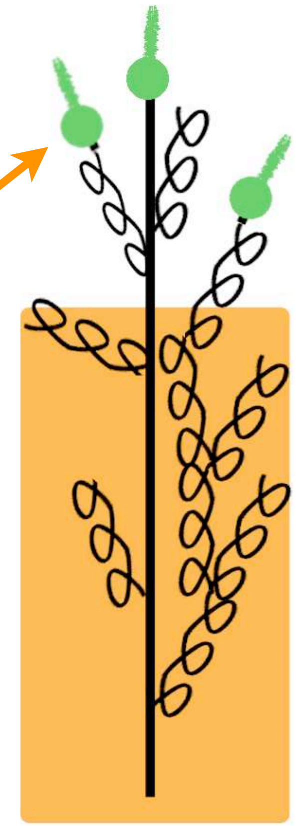

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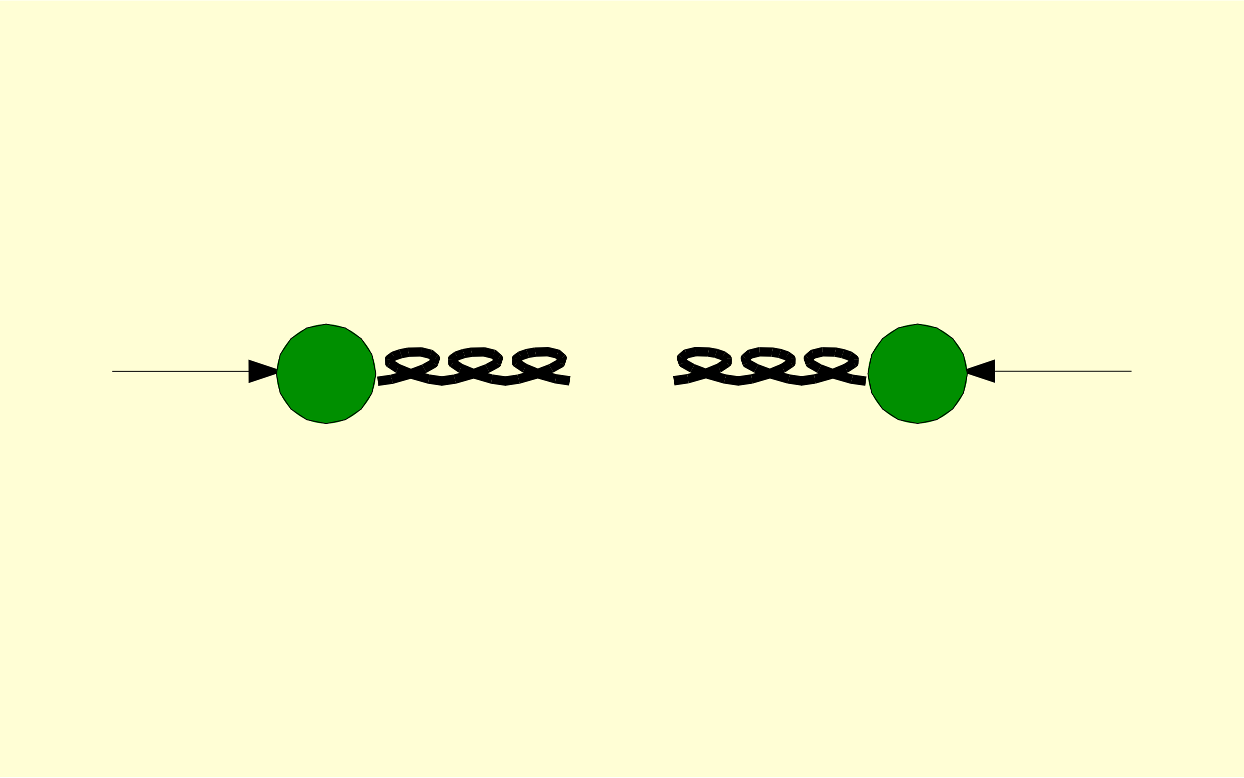

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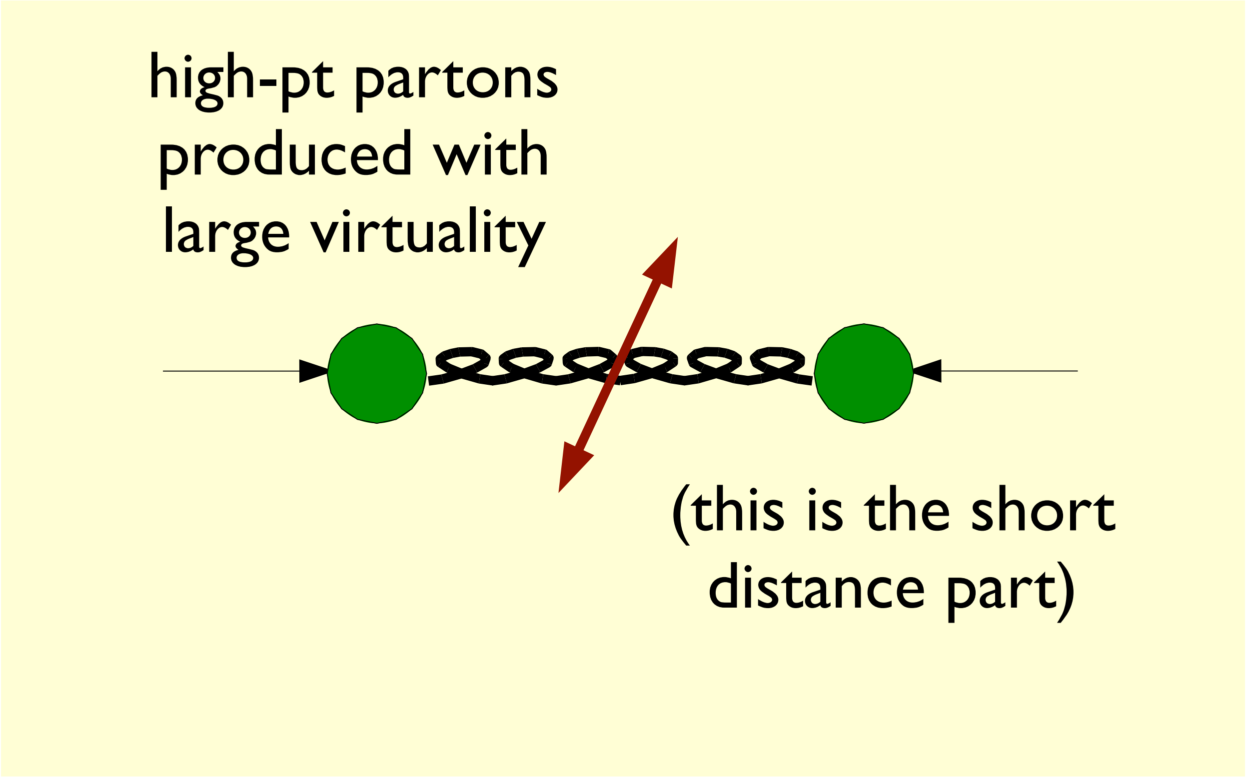

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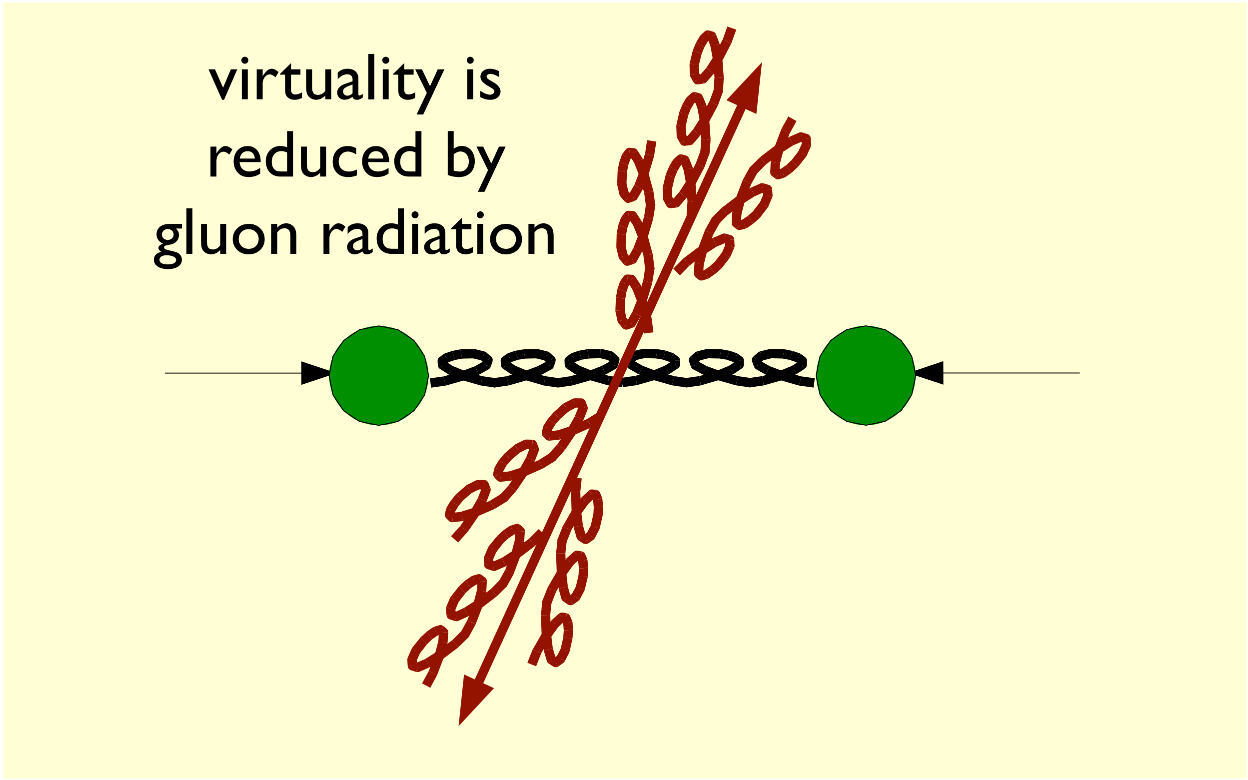

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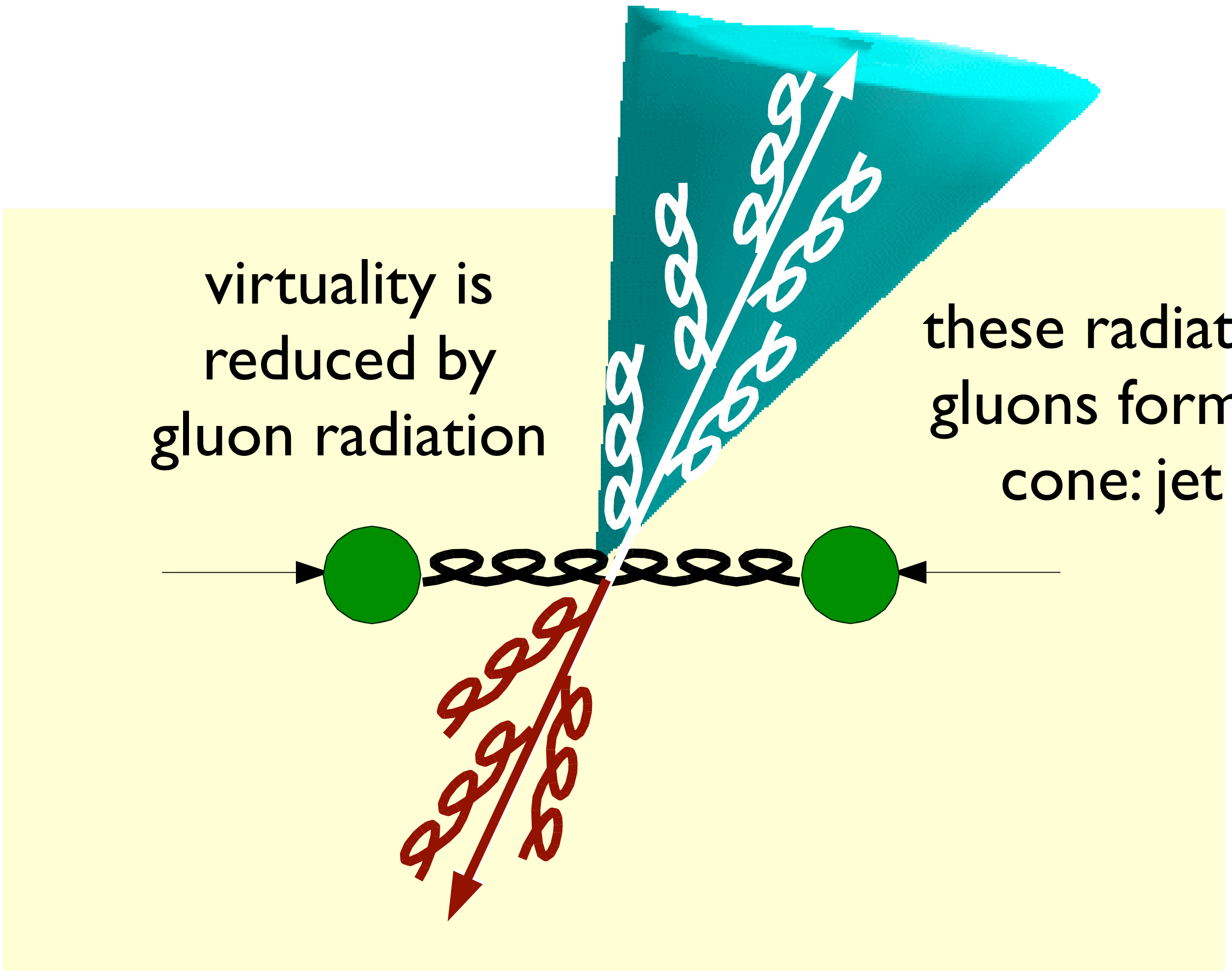
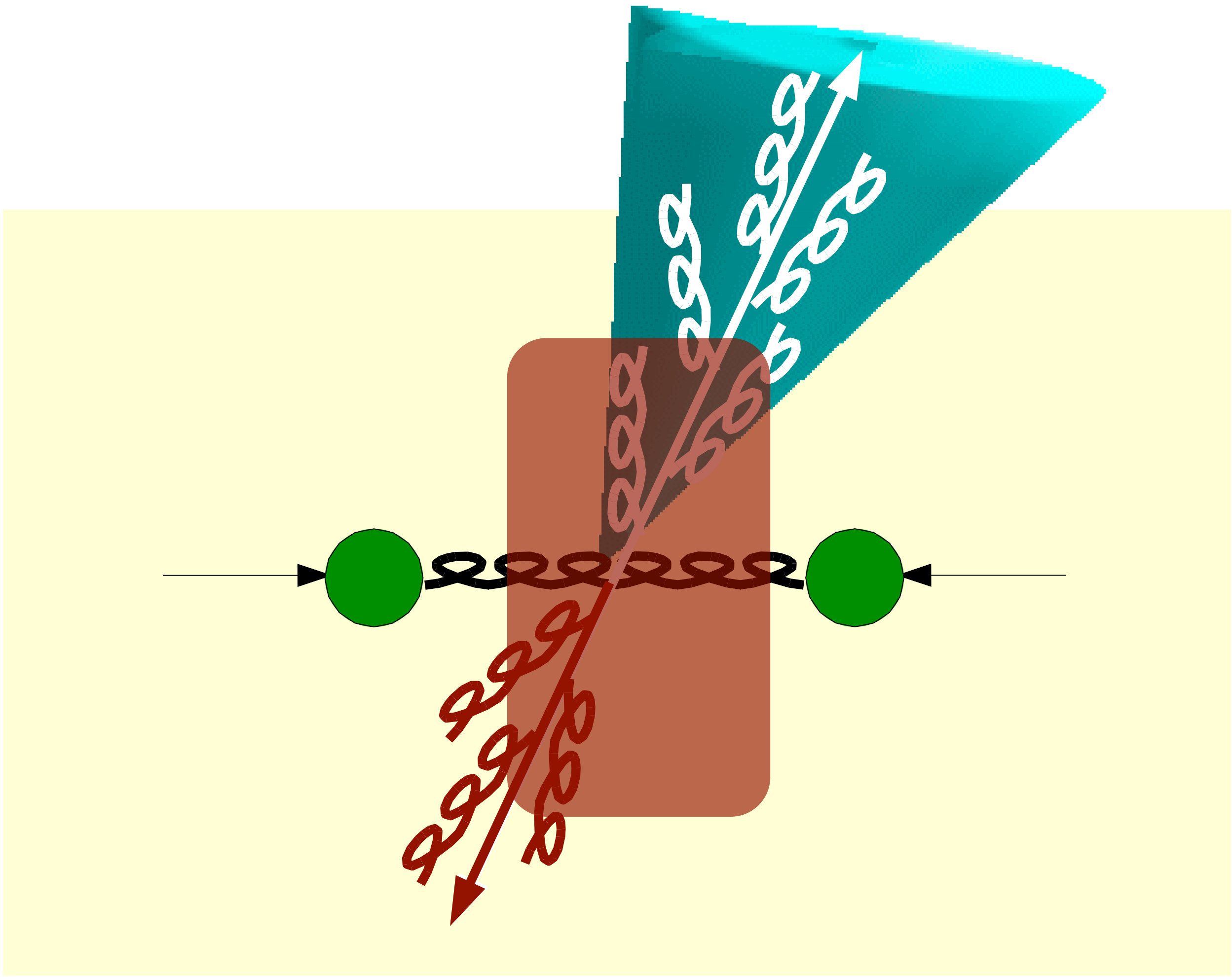
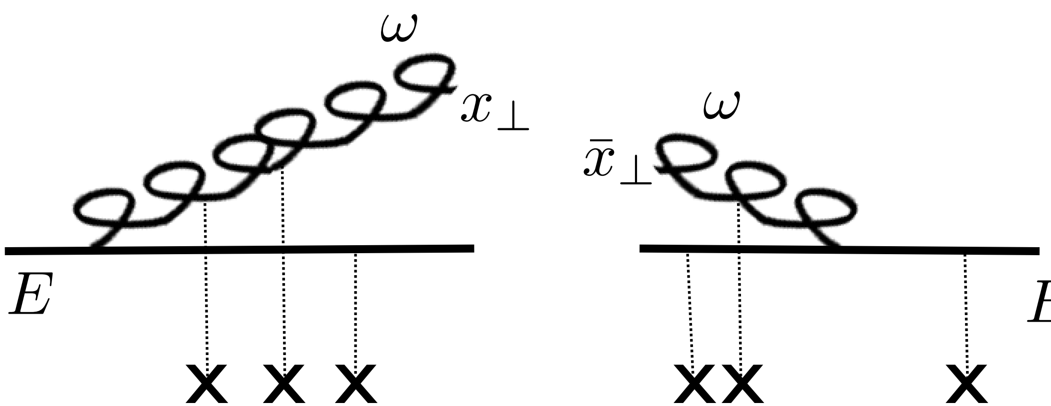


Jet quenching



What happens when this evolution takes place in the medium created in the collision??

Medium-induced gluon radiation



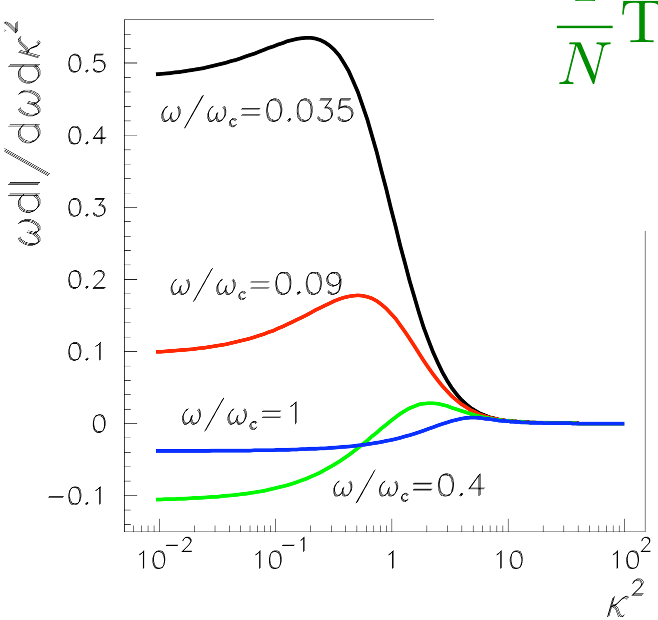
<u>Compute gluon bremsstrahlung in a medium</u>

⇛ High energy approximation

$$E \gg \omega \gg k_\perp$$

⇛ Same formalism as initial state but Wilson lines for gluons

$$\frac{1}{N}\mathrm{Tr}\left\langle W^A(\mathbf{x}_\perp)W^{A\dagger}(\bar{\mathbf{x}}_\perp)\right\rangle \approx \exp\left\{-\frac{1}{4}\hat{q}L(\mathbf{x}_\perp-\bar{\mathbf{x}}_\perp)^2\right\}$$



⇛ Two main predictions

- Energy loss $\Delta E \sim \alpha_s \hat{q} L^2$
- Jet broadening $\langle k_t \rangle \sim \hat{q} L$

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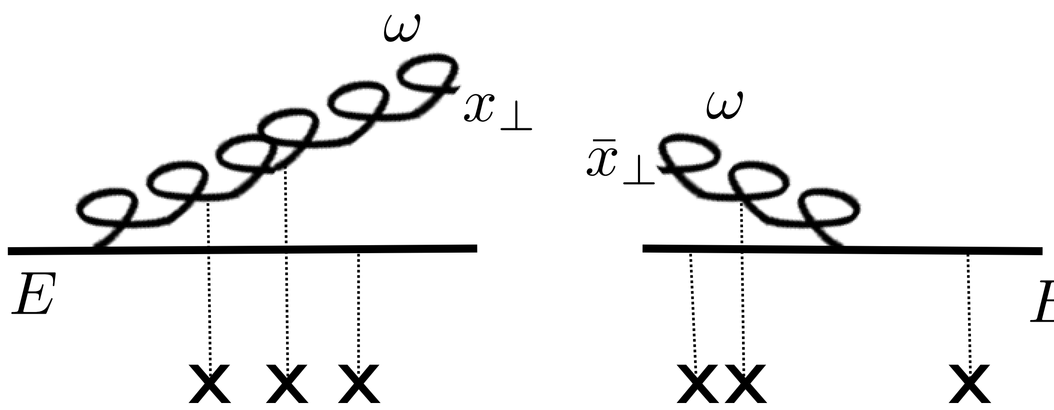

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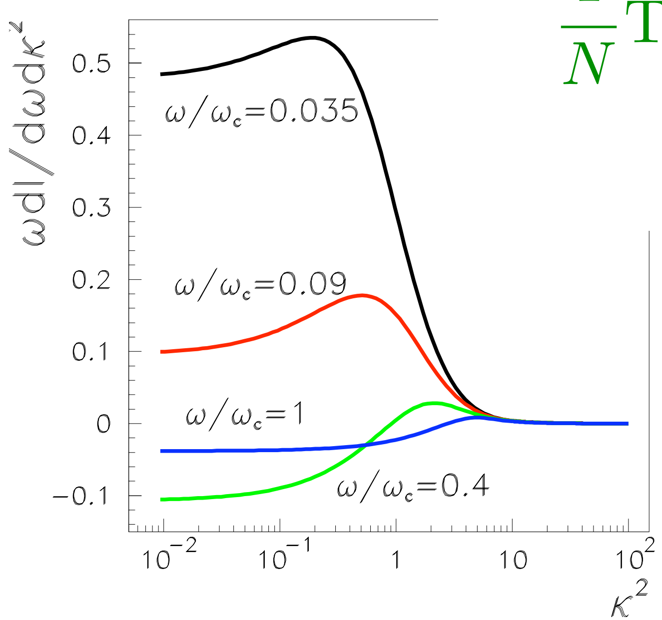
transport coefficient



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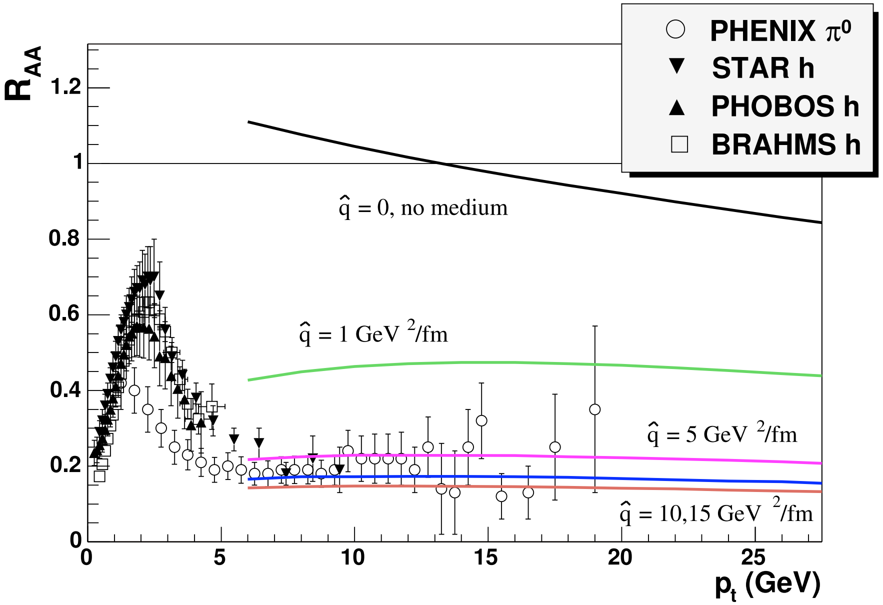
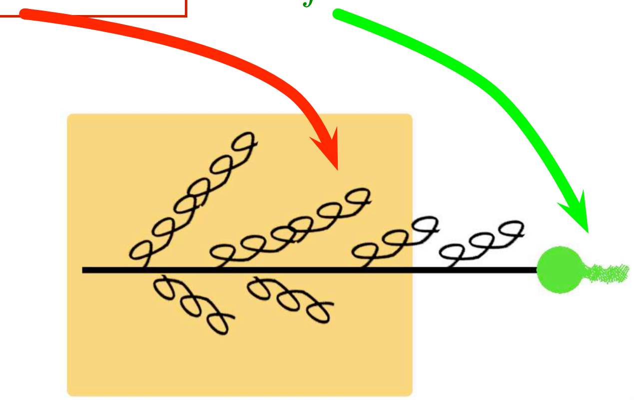
Description of the suppression

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



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



⇒ Multiple emission: Poisson distribution

⇒ Hadronization in vacuum at high-p_t

⇒ Data favors a large time-averaged transport coefficient

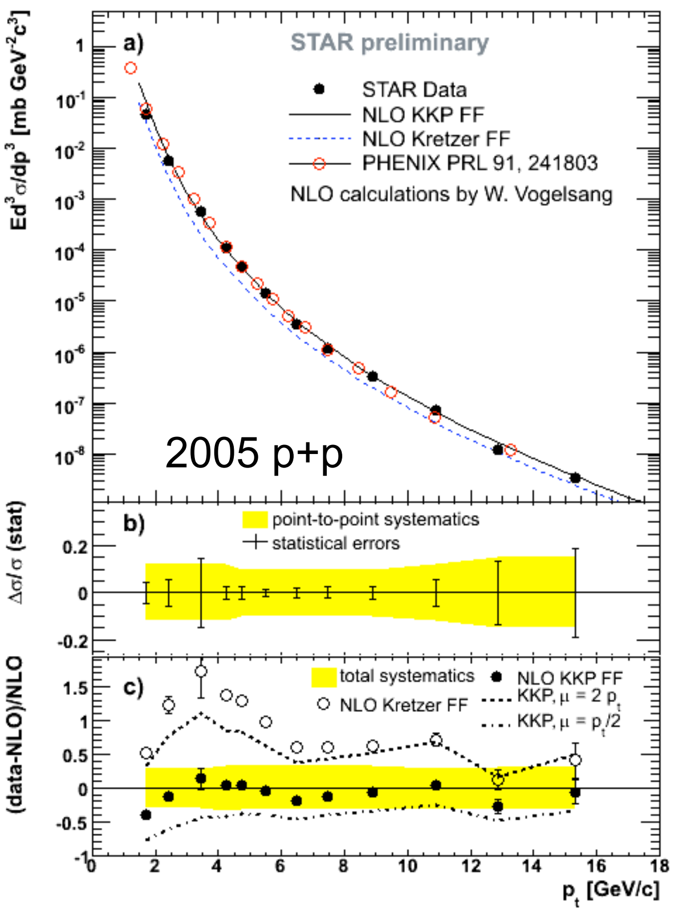
$$\boxed{\hat{q} \sim 5\ldots15\frac{GeV^2}{fm}}$$

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

Calibration of the probes

proton-proton

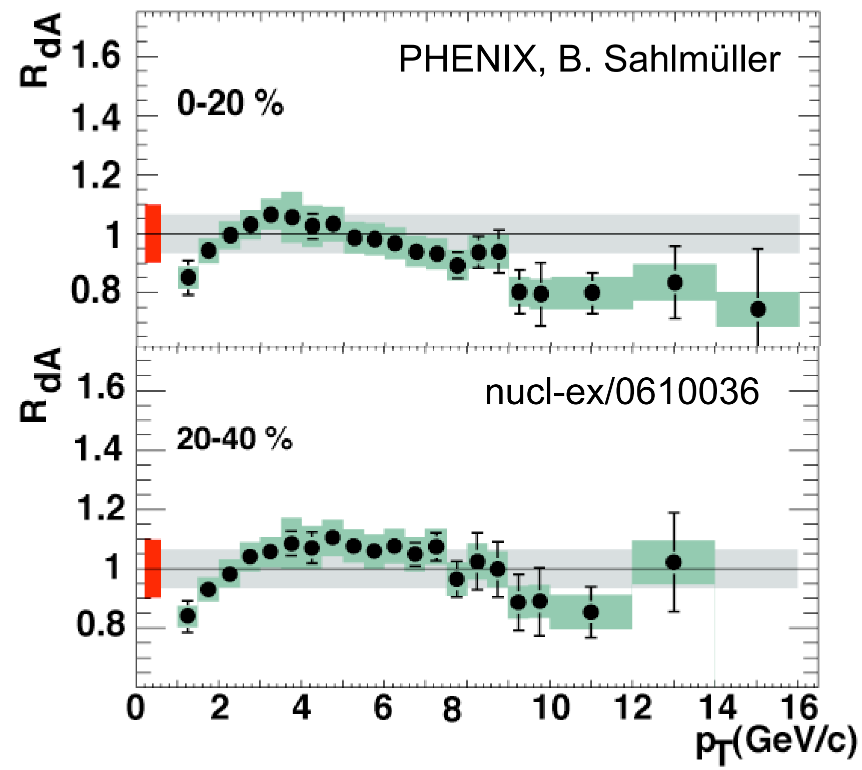
M. Russcher



STAR gearing up γ, π^0 in p+p, d+Au

Good agreement with NLO pQCD and PHENIX

$$R_{dA} = \frac{dN^{dA}/dp_t}{N_{\mathrm{coll}} dN^{pp}/dp_t}$$



Measures Cronin, initial state effects

[Marco van Leeuwen QM06]

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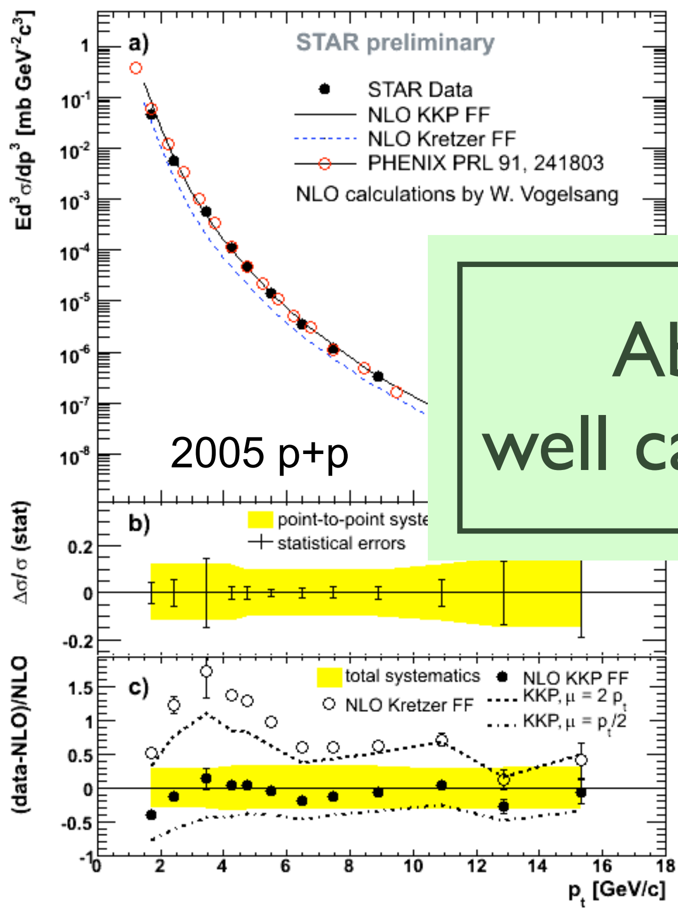

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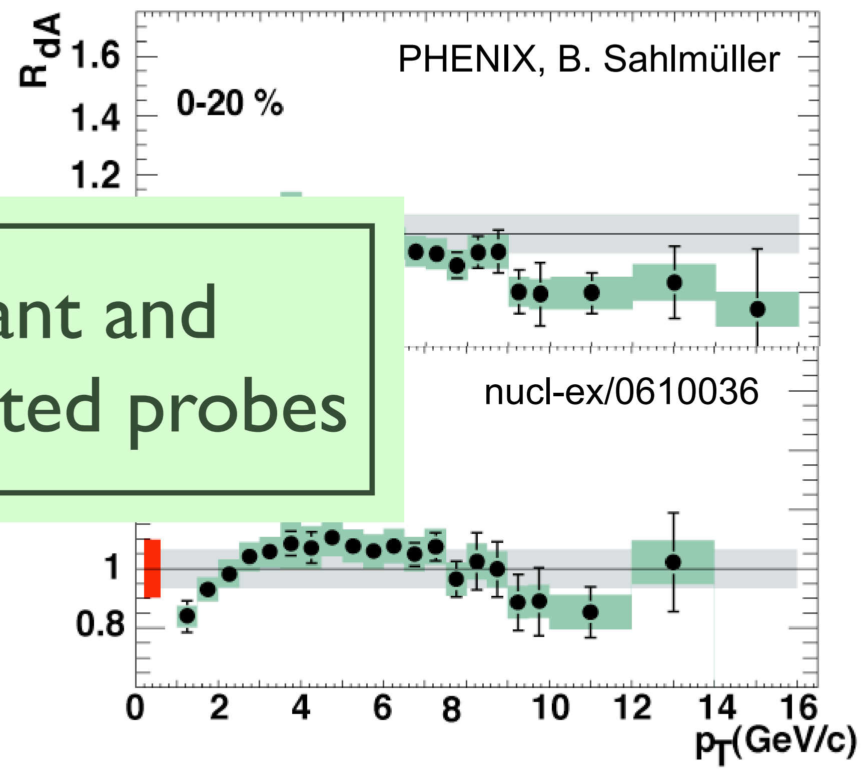
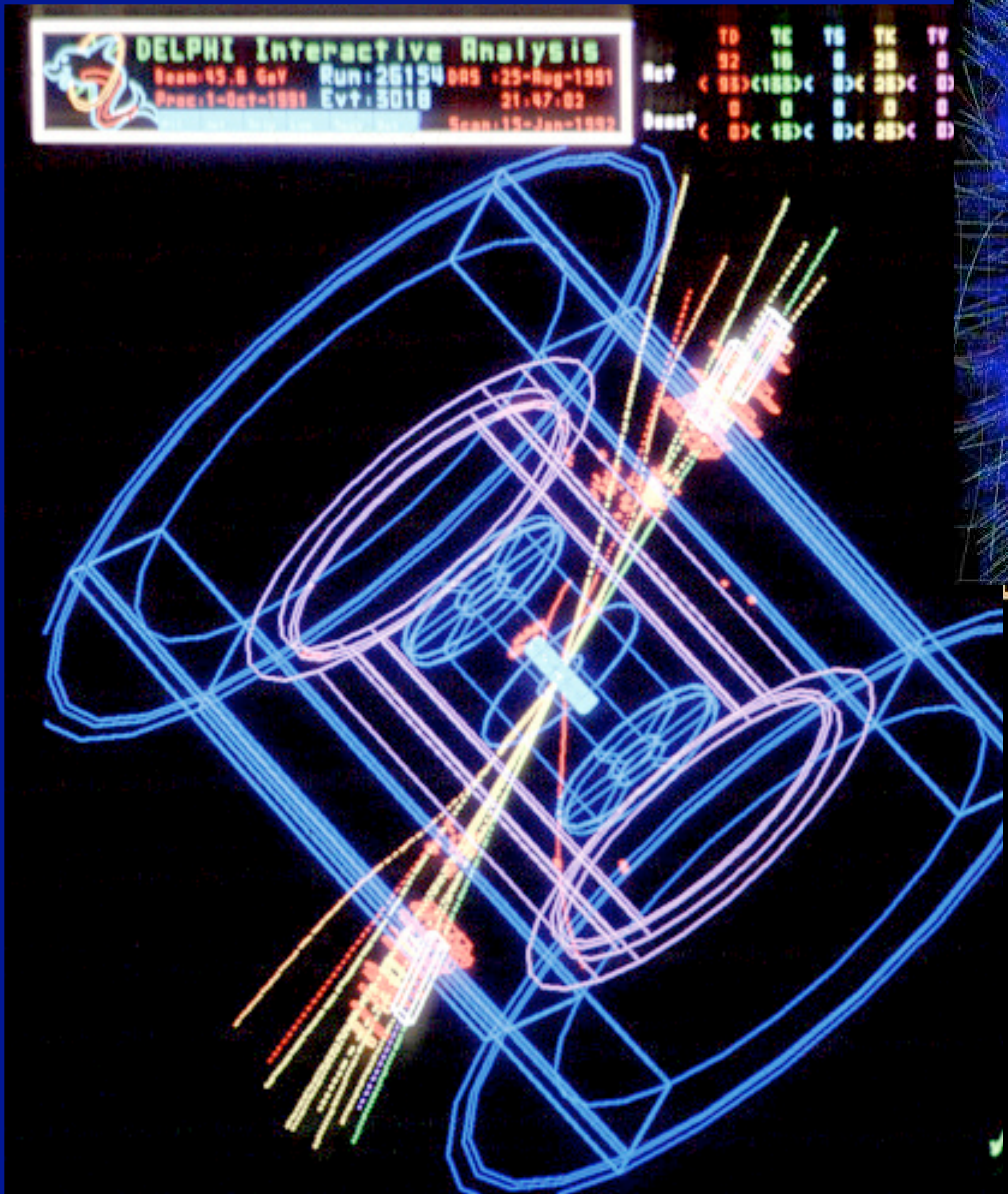


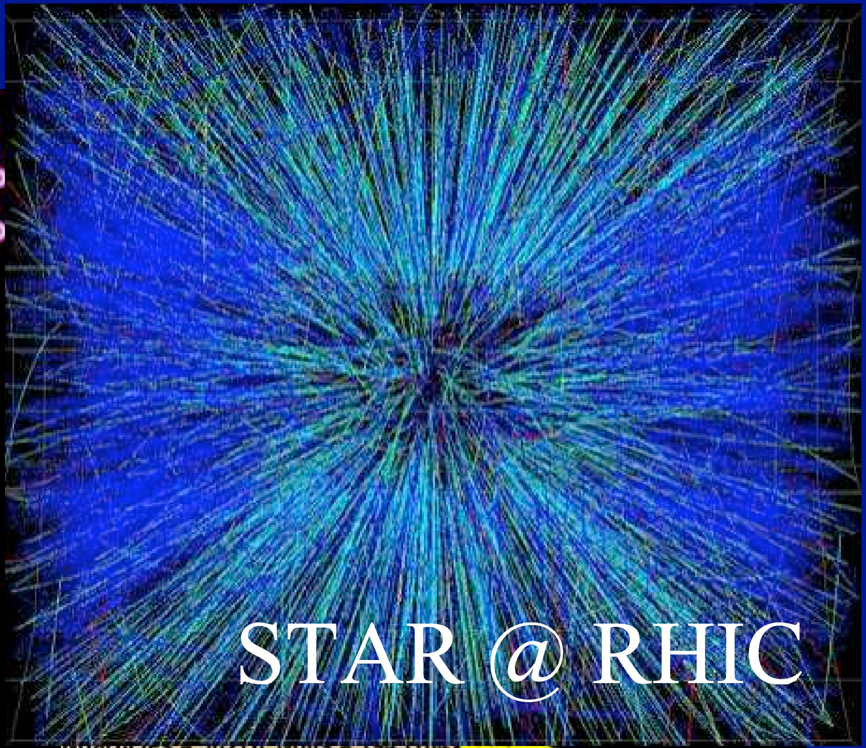
Abundant and well calibrated probes

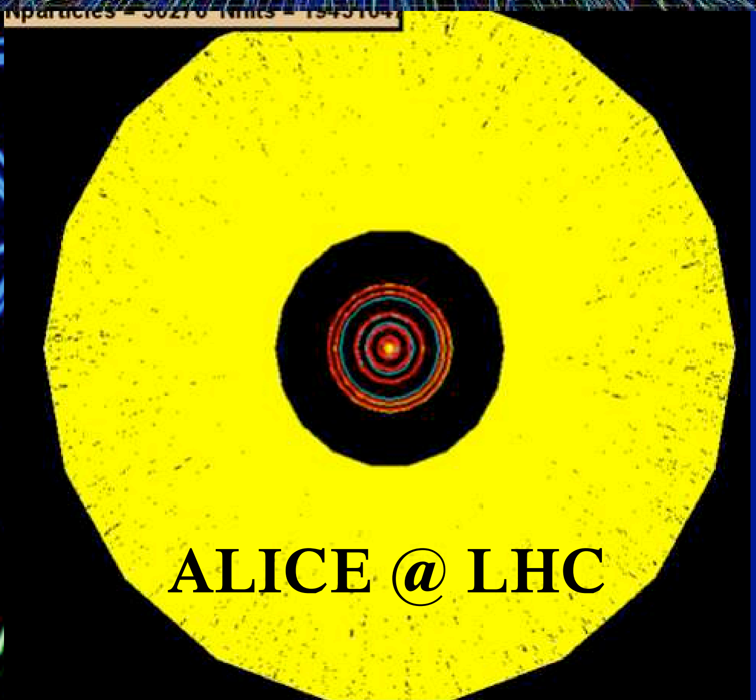
Measures Cronin, initial state effects

[Marco van Leeuwen QM06]

Jets in HIC



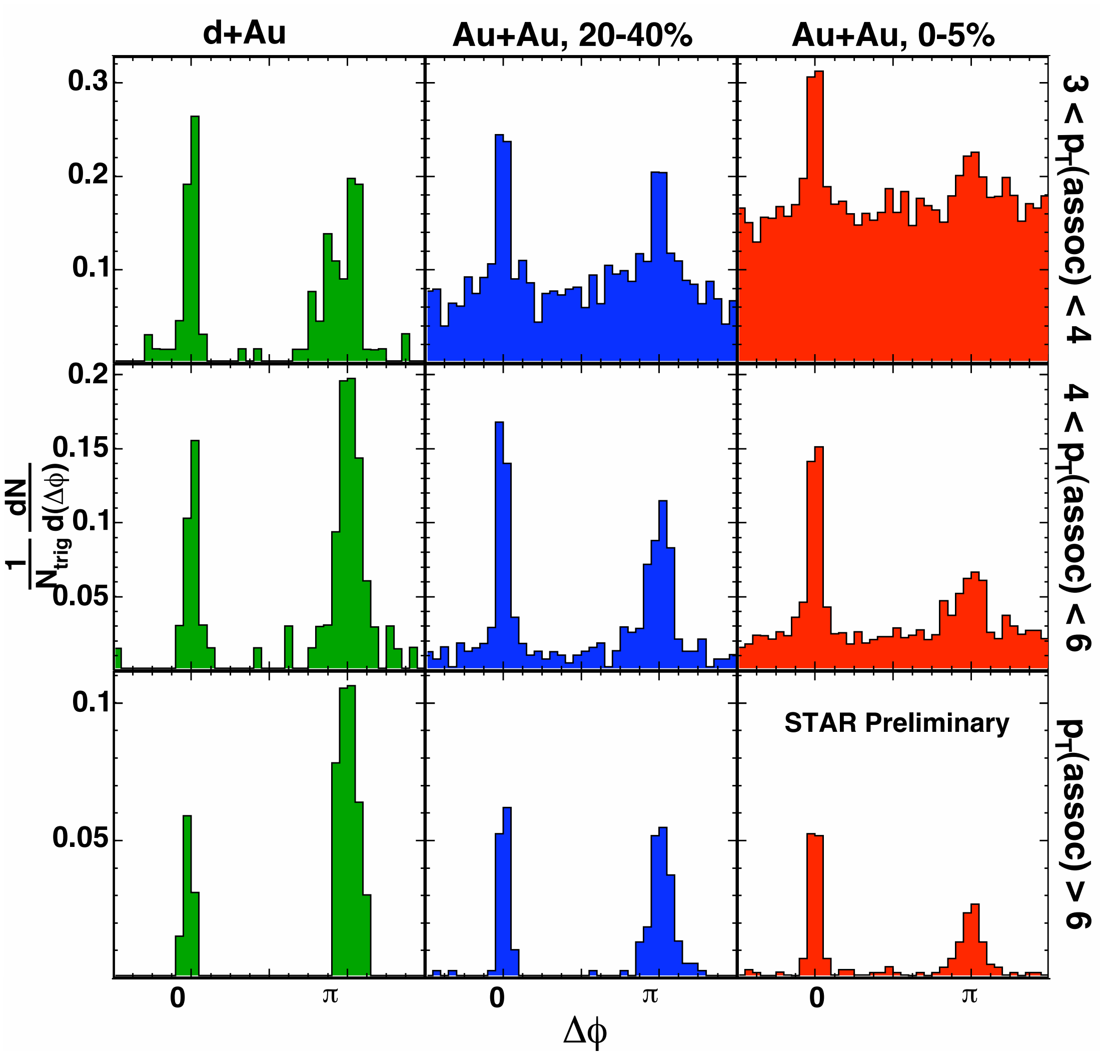




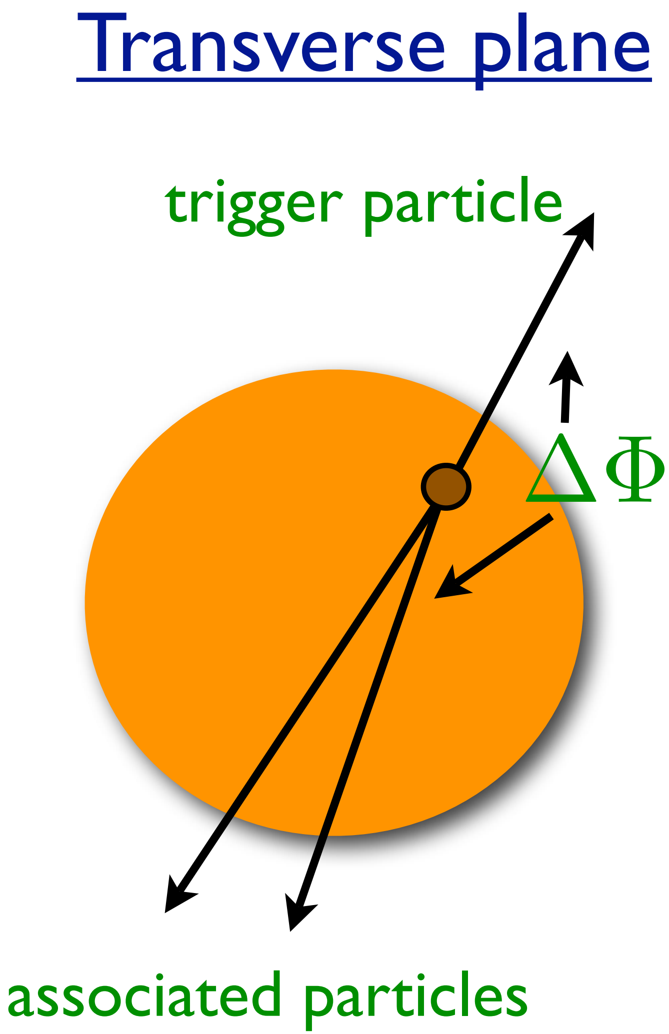
Jets in HIC

Not possible at RHIC first results from LHC expected for 2009-2010

RHIC: two particle correlations

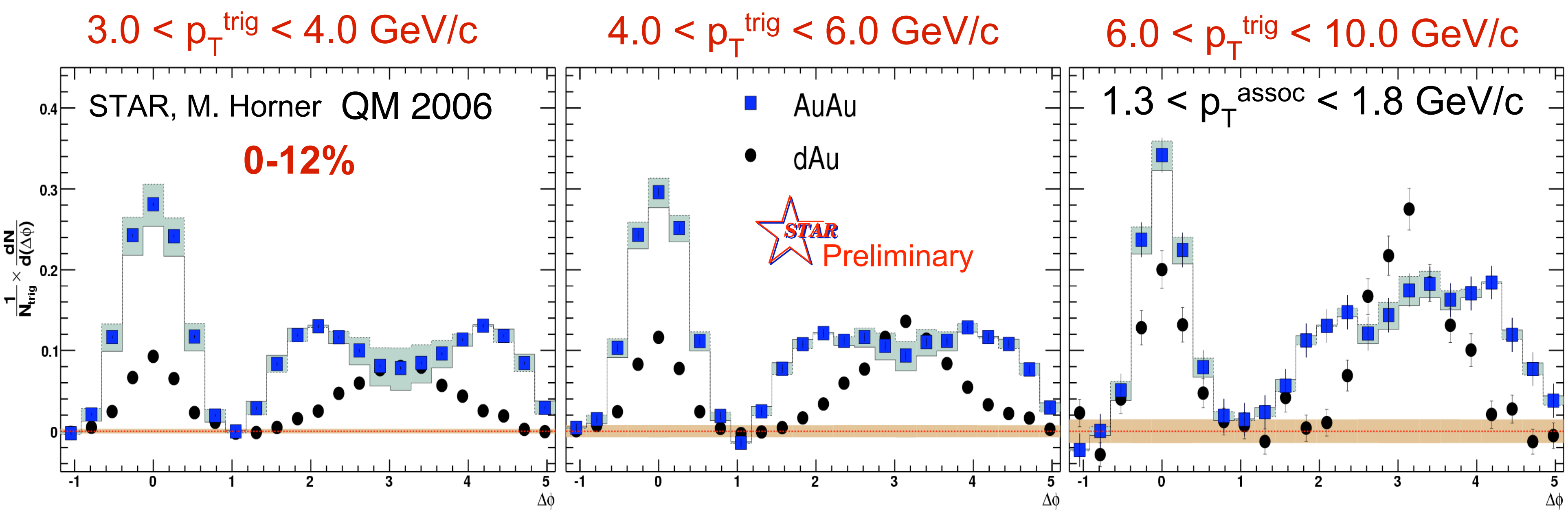


[STAR 2006]



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 $p_t^{trigg} \sim p_t^{assoc}$

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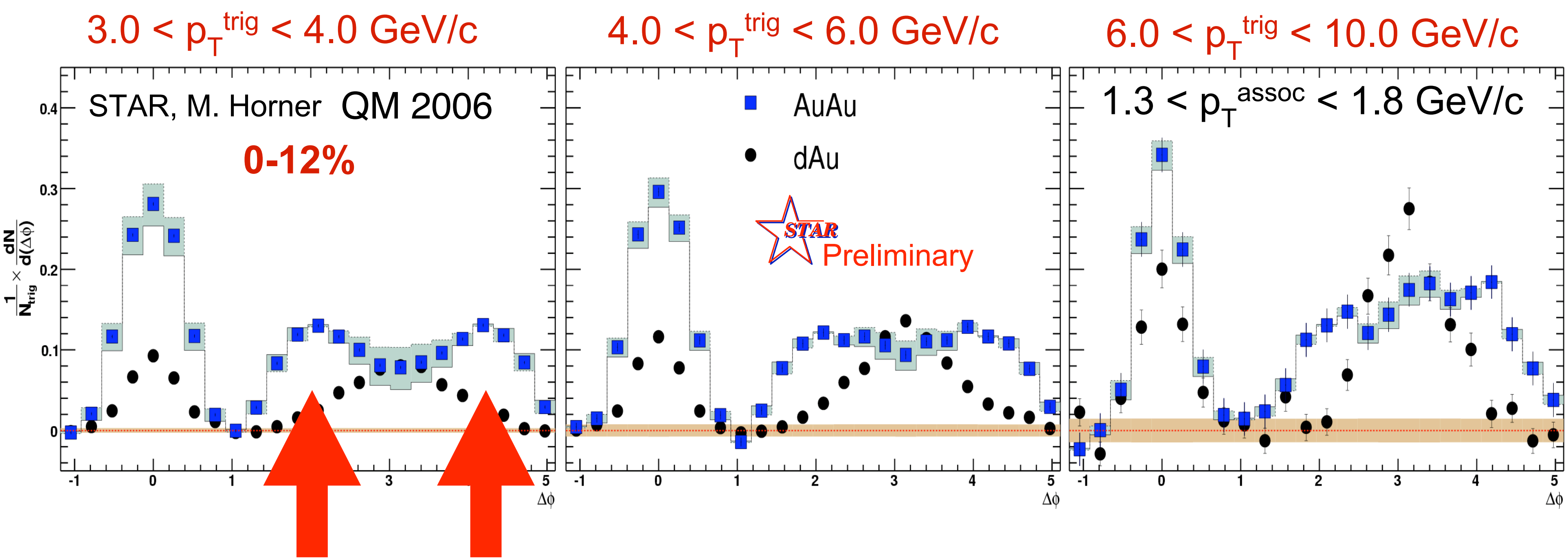

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- All energy deposited in the medium +hydrodynamical evolution
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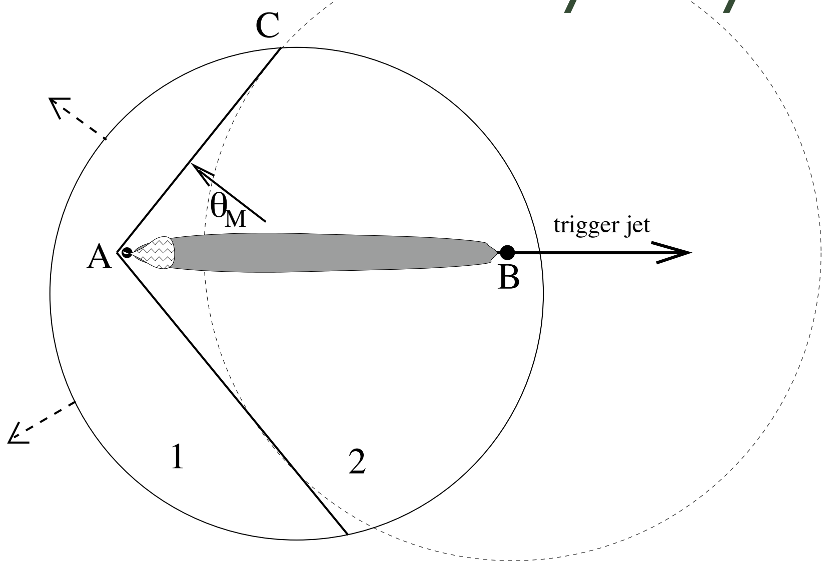
A way to understand the energy deposition in the medium

Interpretations...

Shock waves in hydrodynamical medium

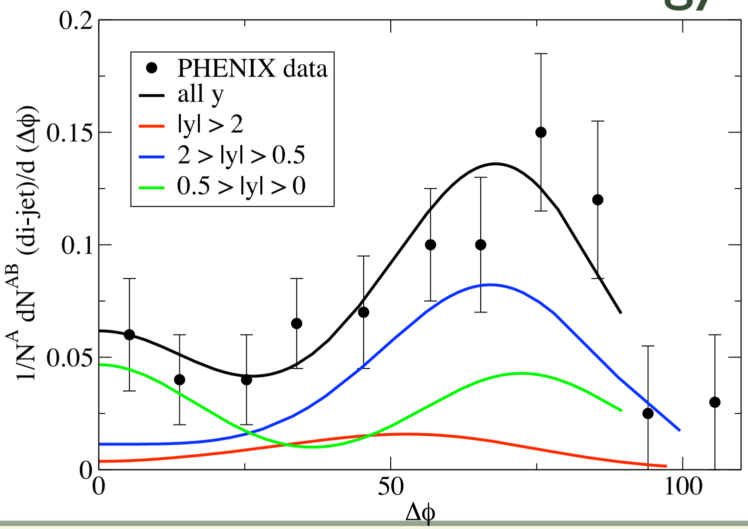


⇛ A hydrodynamical medium produces shock waves IF the energy is deposited fast enough

[Casalderrey-Solana, Shuryak, Teaney; Stoeker; Muller, Renk, Ruppert; Manuel, Mannarelli ...]

⇛ Also Cherenkov radiation proposed

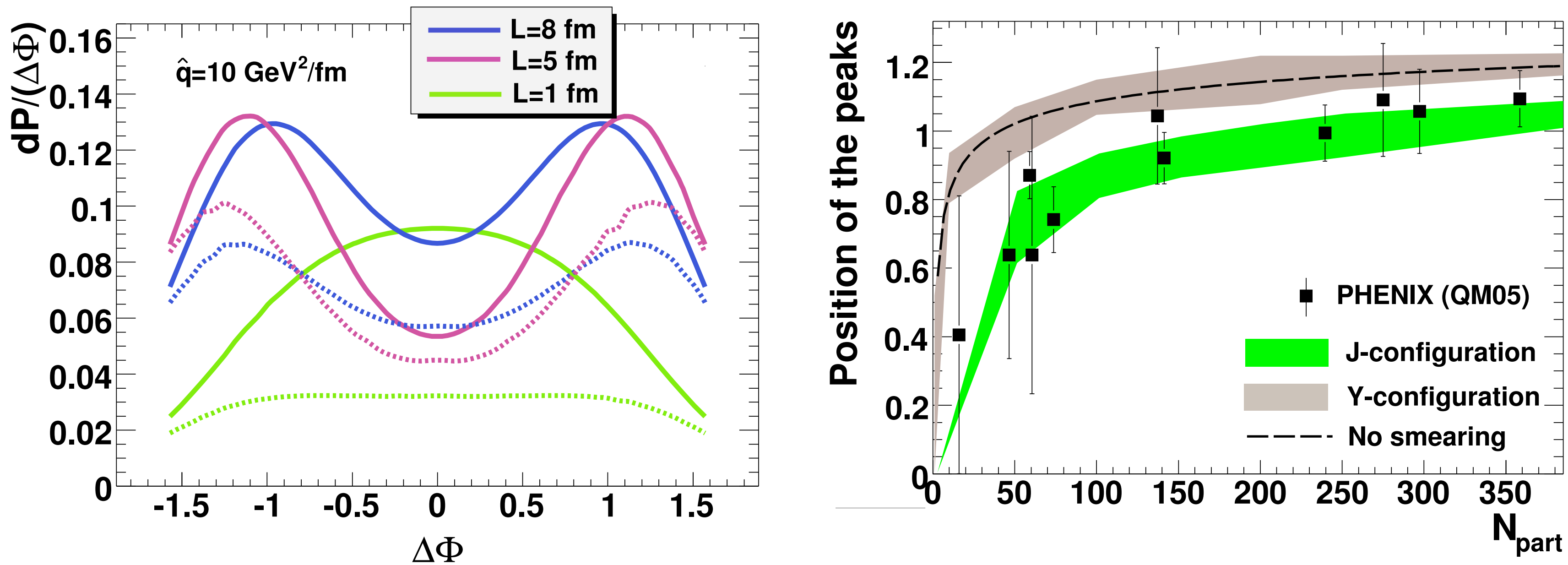
[Dremin; Majumder, Wang]



Jet shapes in opaque media

⇛ The probability of only one splitting

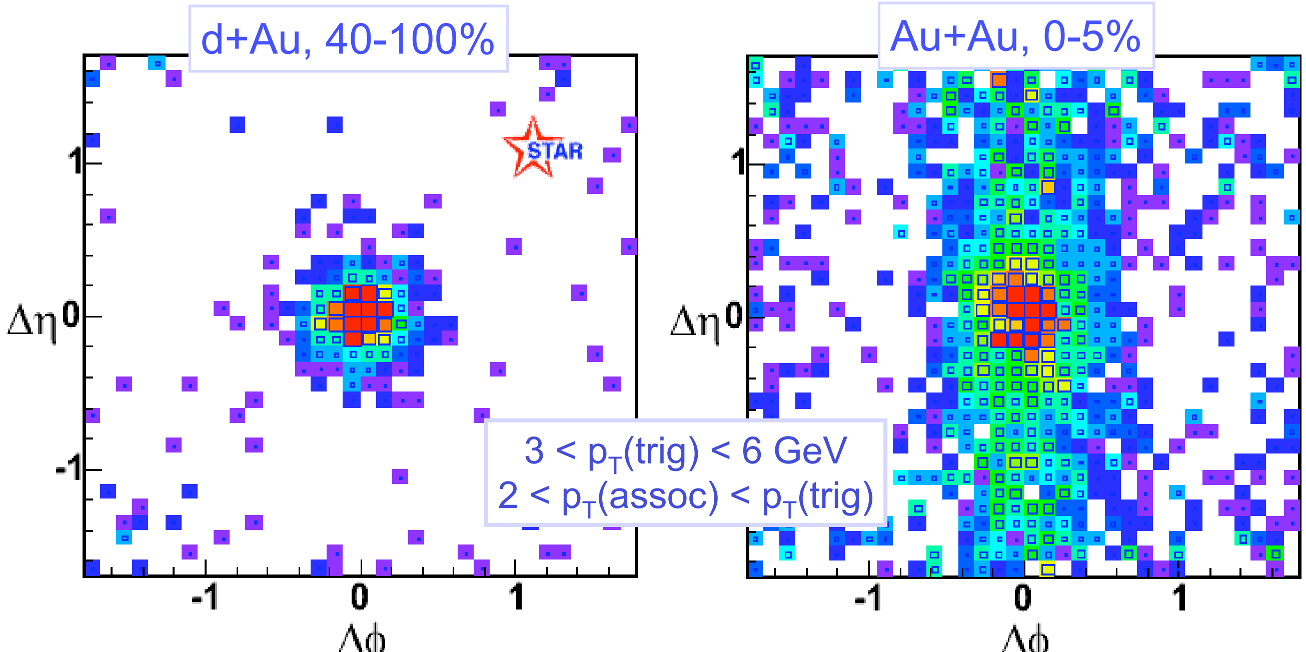
$$d\mathcal{P} = dz\, d\theta\, \frac{\alpha_s C_R}{8\pi}\, E\, L\, \sin\theta\, \cos\theta\, \exp\left\{-\frac{\alpha_s C_R}{16\pi}\, E\, L\, \cos^2\theta\right\}$$



[Polosa, Salgado hep-ph/0607295]

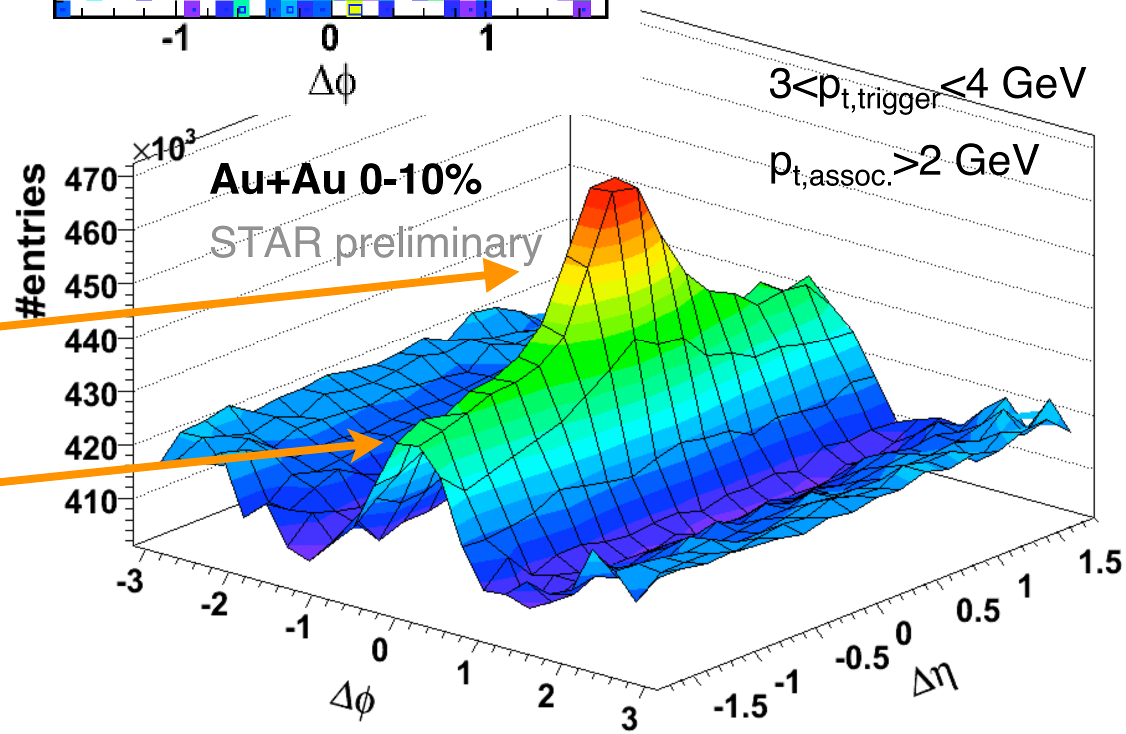
⇛ A perturbative mechanism, the medium-induced gluon radiation, is able to reproduce the observed 2-peak structure in the away side jet.

The 'ridge'



[Dan Magestro HP04]

Near side correlations gaussian+ridge



- ⇒ Gaussian similar to vacuum fragmentation
- ⇒ Ridge similar to bulk

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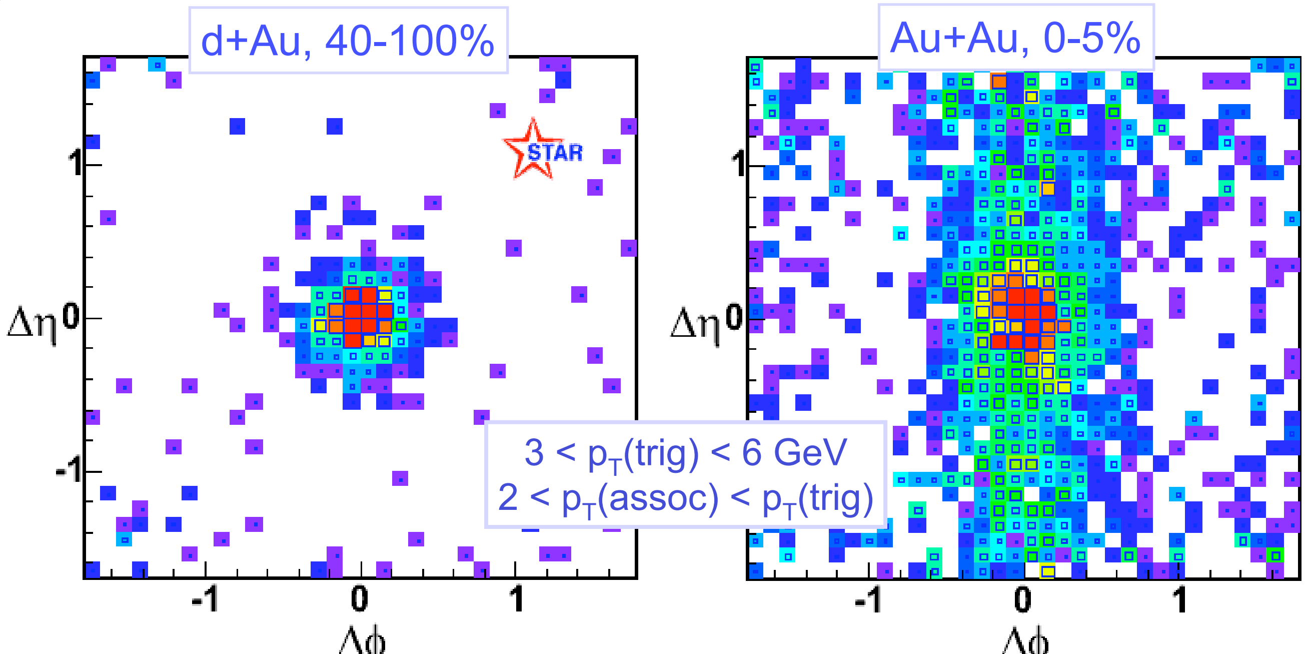
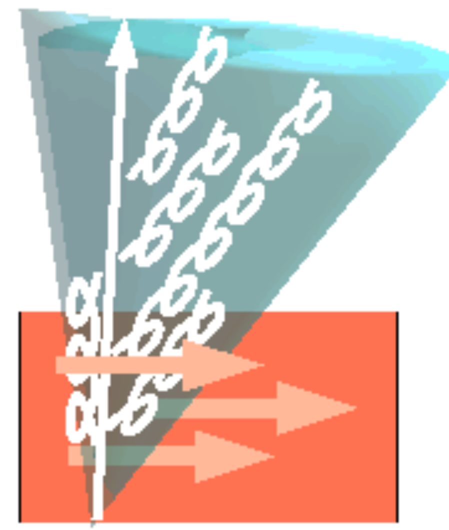
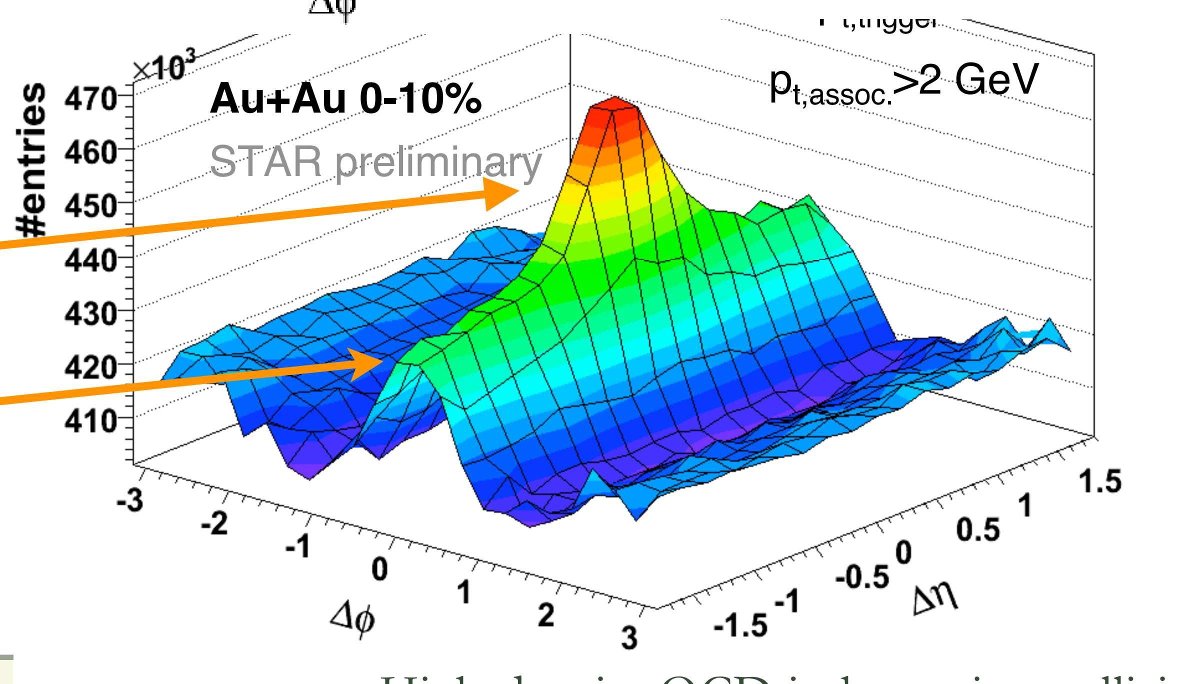


[Dan Magestro HP04]

[Armesto, Salgado, Wiedemann 2004]





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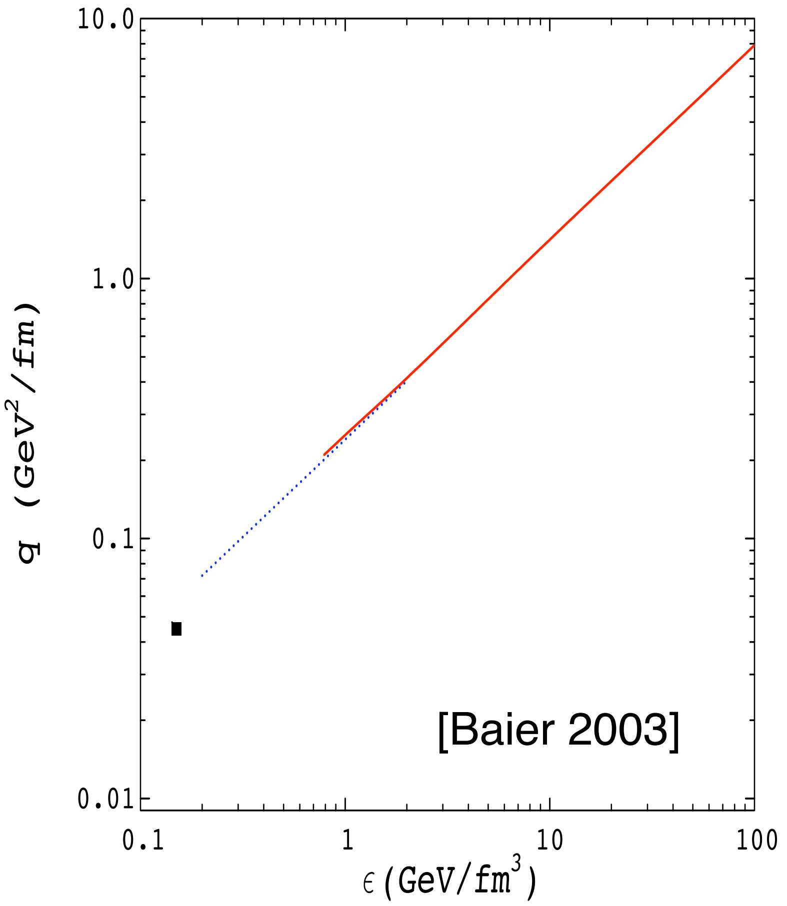
Interpretation of the value of $\hat{q}$



- Transport coefficient for an ideal quark-gluon gas

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

[Baier and Schiff 2006]

- Fits to the data

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

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

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

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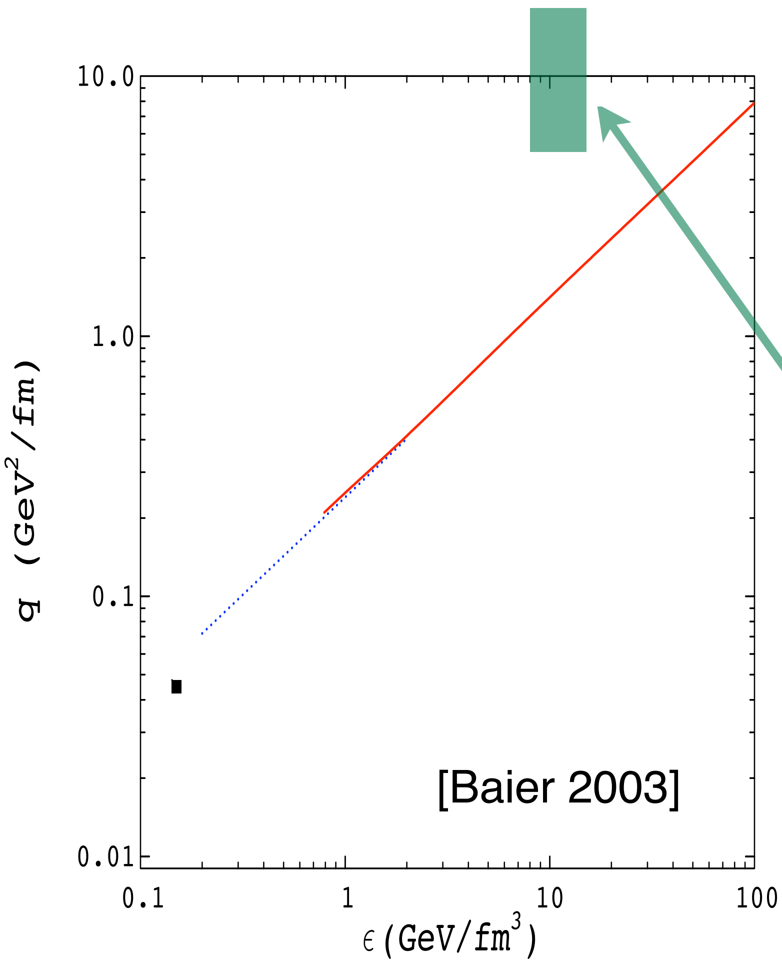

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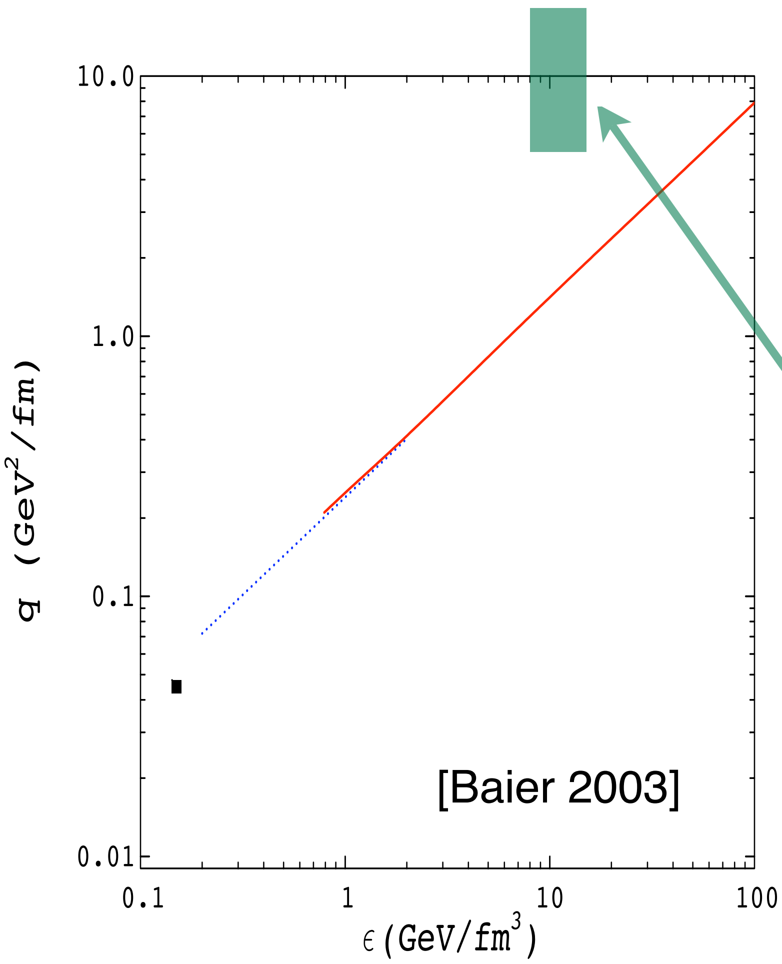

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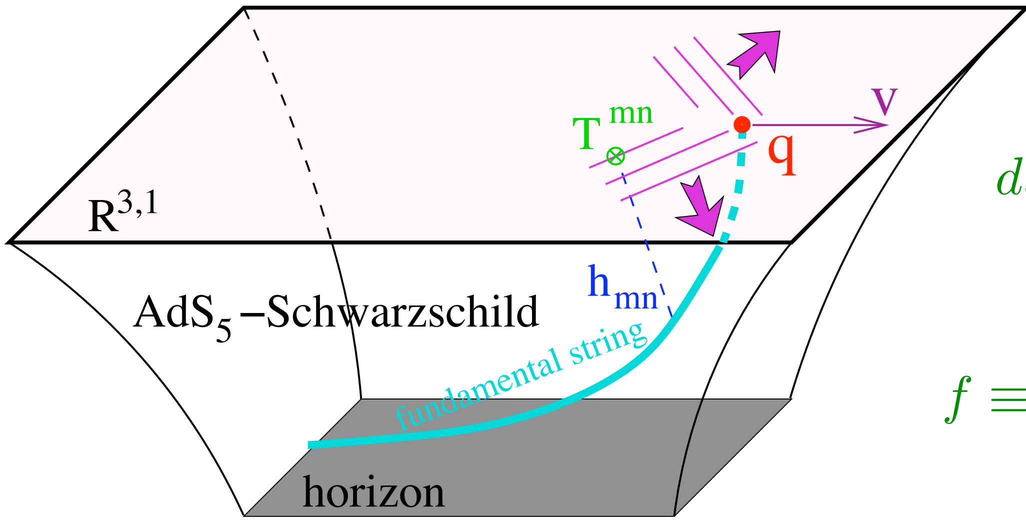
What is the order of magnitude of the NLO correction?

Some new developments...
The String Theory connection

The AdS/CFT correspondence



⇛ Define a metric in 4+1 dimensions with a black hole

$$ds^2 = f dt^2 + \frac{r^2}{R^2}(dx_1^2 + dx_2^2 + dx_3^2) + \frac{1}{f} dr^2$$

$$f \equiv \frac{r^2}{R^2}\left(1 - \frac{r_0^4}{r^4}\right)$$

black hole horizon at $r = r_0$

⇛ Dual to a thermal $\mathcal{N} = 4$ super YM theory at finite temperature

$$T = \frac{r_0}{\pi R^2}$$

(Hawking temperature)

⇛ Ex. compute the Wilson loop = compute the action for the string

$$\langle W^F(\mathcal{C})\rangle = \mathrm{e}^{-S(\mathcal{C})} \qquad S = \frac{1}{2\pi\alpha'}\int d\sigma d\tau \sqrt{\det g_{\alpha\beta}}$$

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

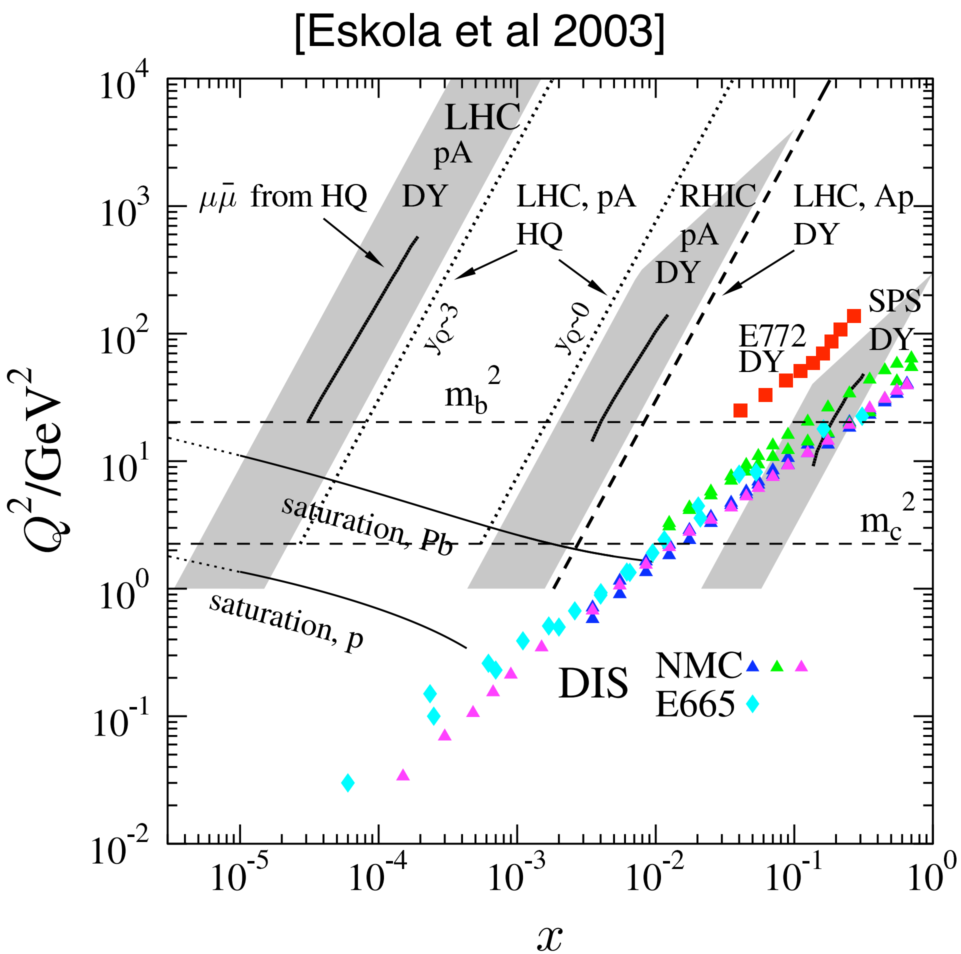
→ Bjorken hydrodynamics recovered (and more)

[Heller, Surowka: seminars; Janik, Peschanski 2006; Kovchegov, Taliotis 2007...]

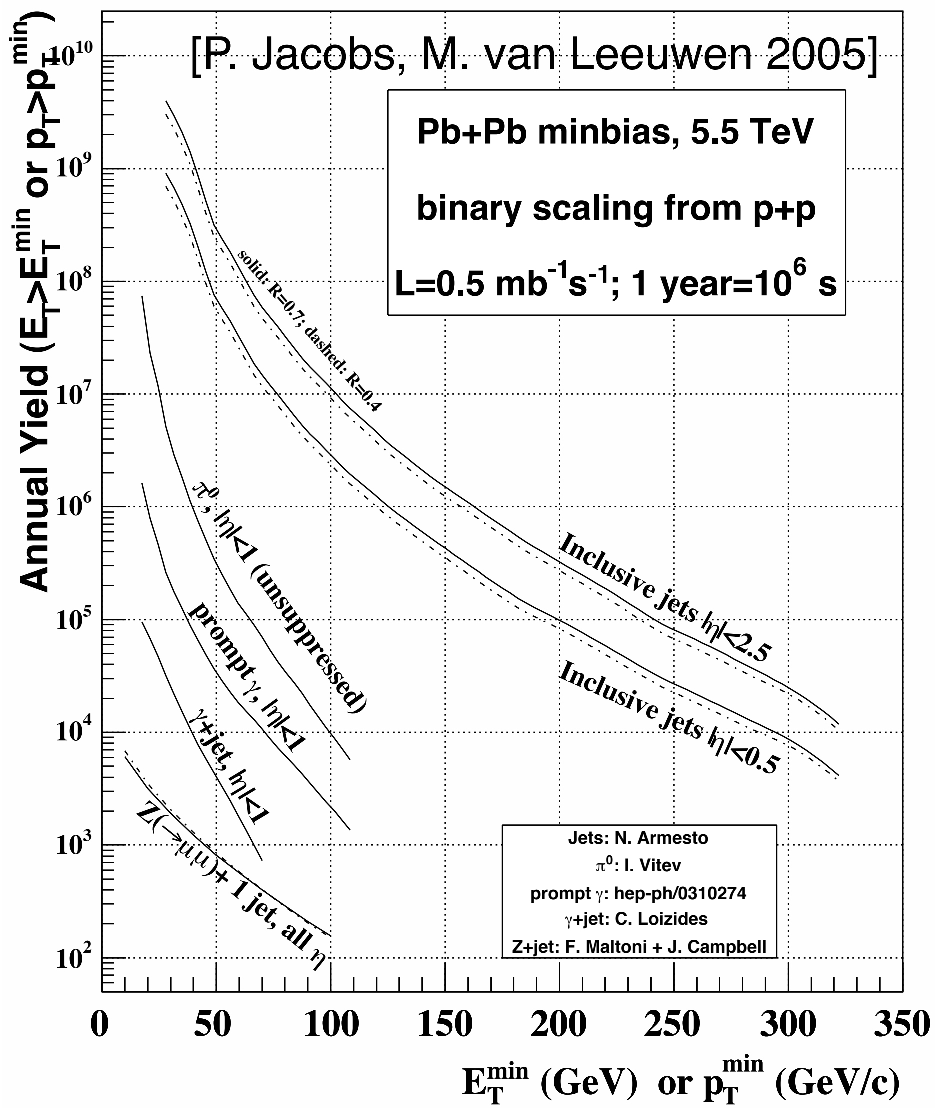
⇛ Shock waves; heavy quark energy loss; bound states....

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

New regimes at the LHC



Annual hard process yields



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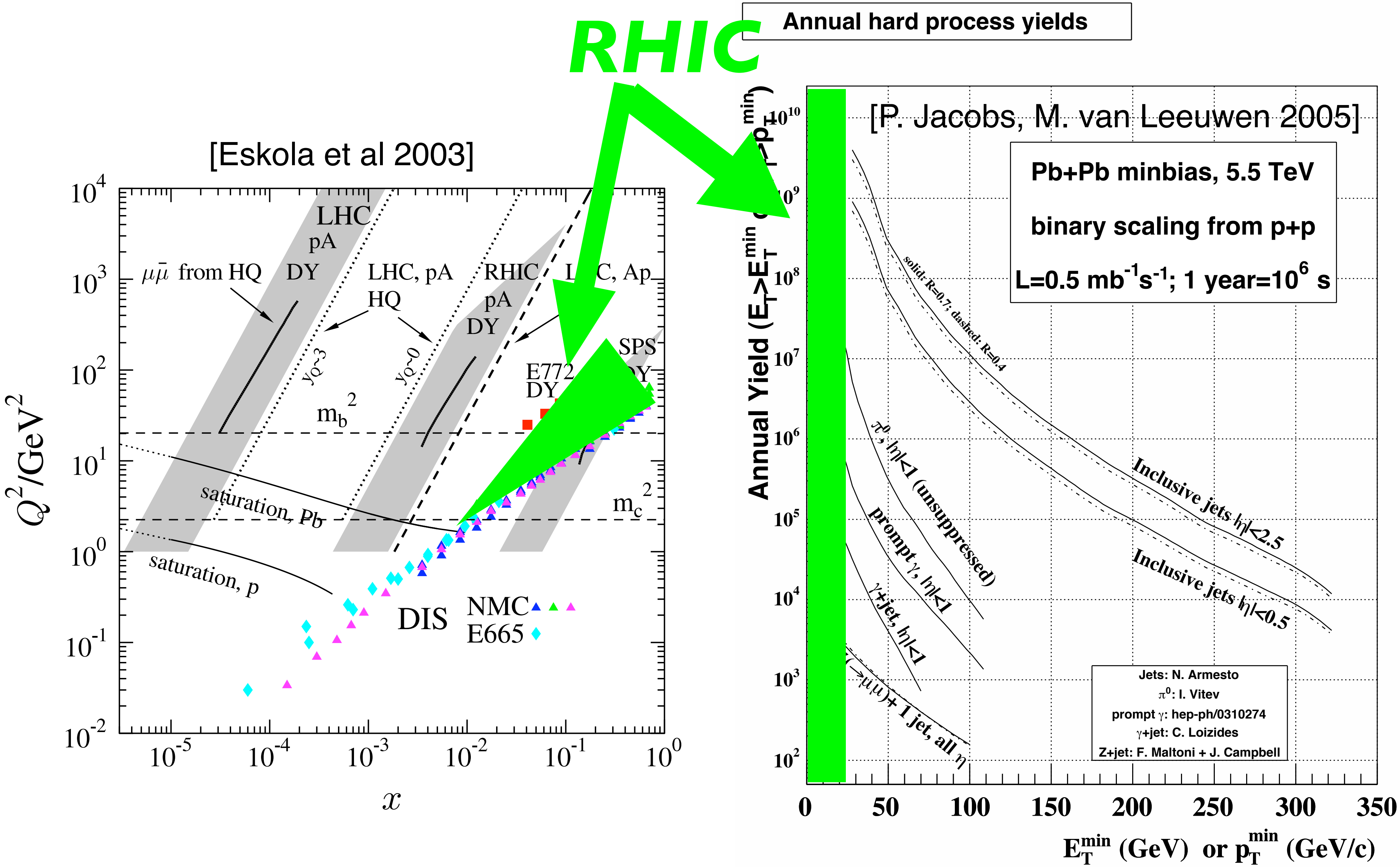

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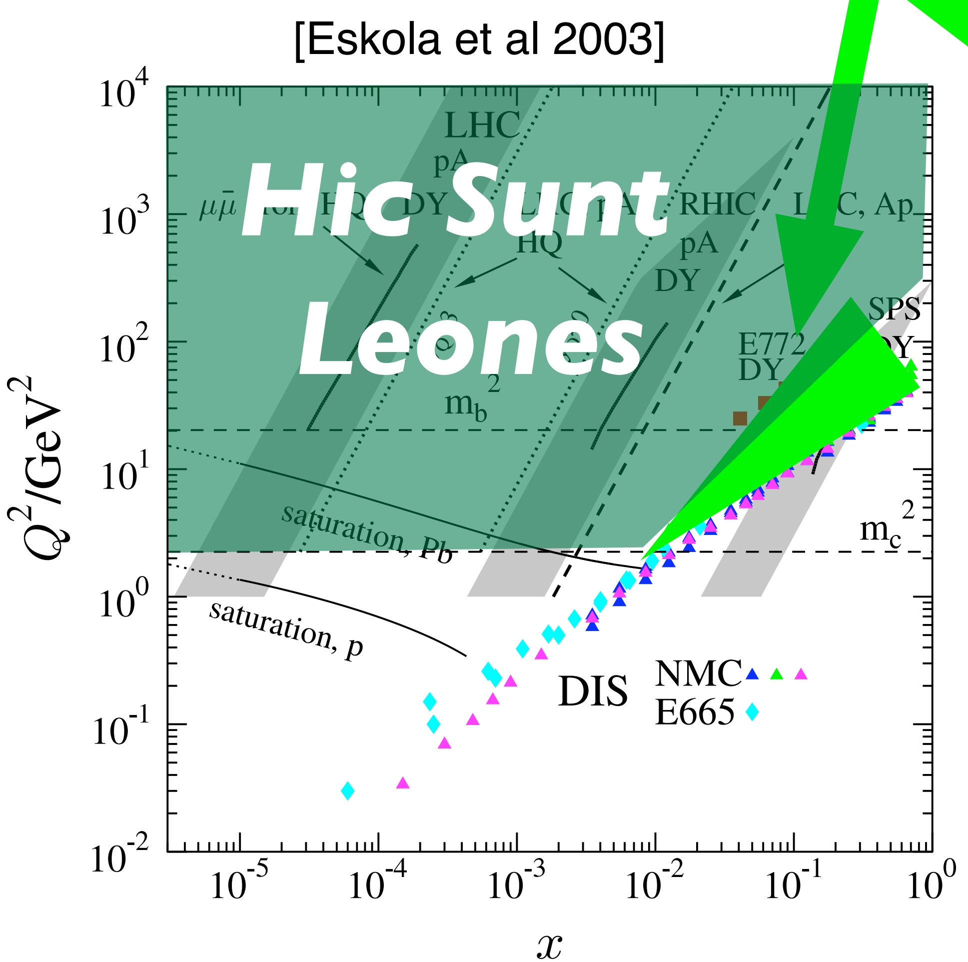

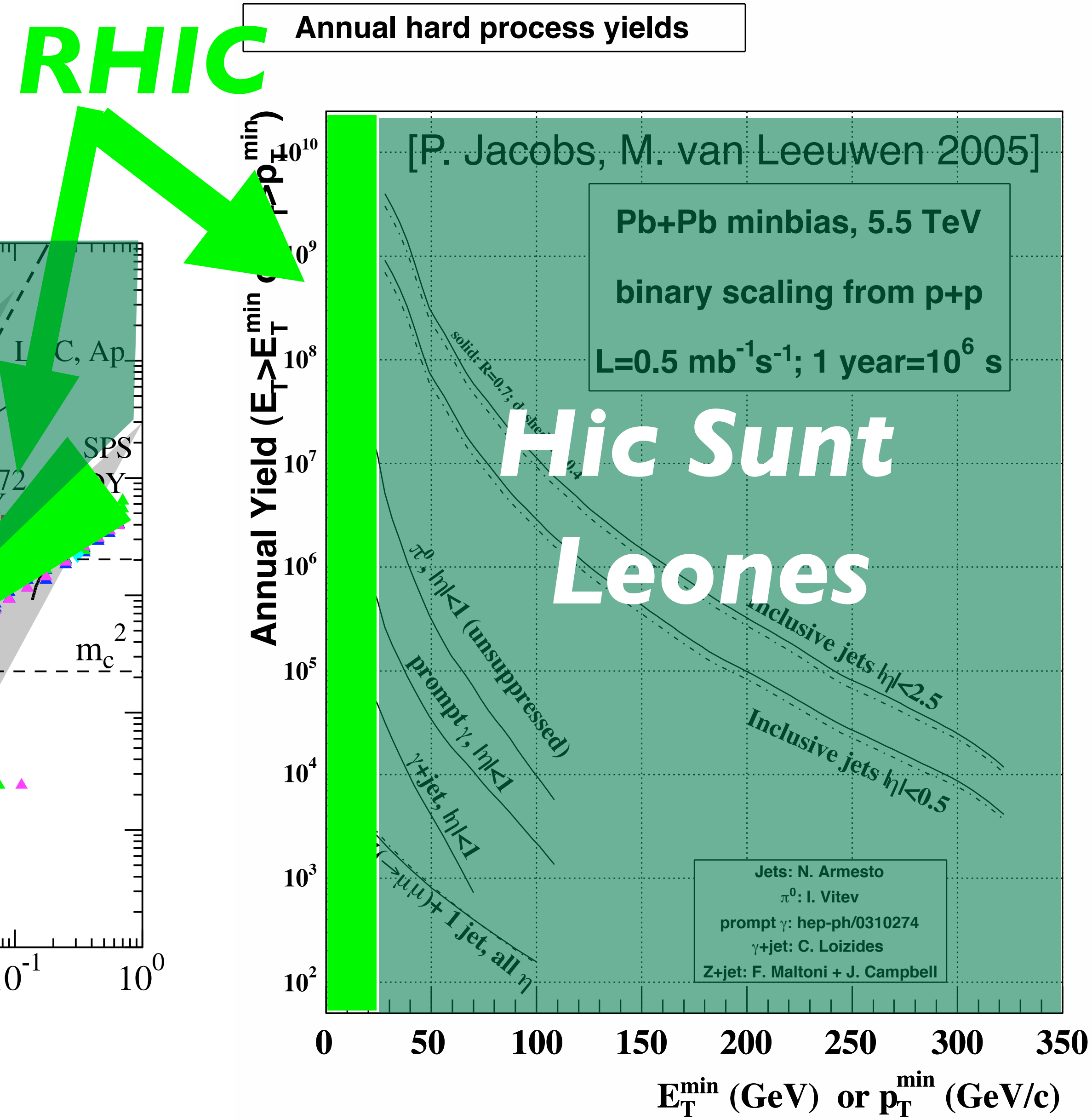

Summary

- HIC to study collective properties of fundamental interactions
- Initial state probably dominated by strong color fields
  - Semiclassical approach
  - Hints from experimental data - definite checks at the LHC
- Hard Probes ideal tools to characterize the medium
  - Jet quenching: Medium modification of jet structures
  - Interplay between hydrodynamical behavior and jet development
- Different fields are contributing to these developments
  - String-theory computations (try to) face experimental data
- LHC will explore completely new regimes of QCD