Heavy Ions Collisions and the search for the Quark-Gluon Plasma

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1. QCD matter. The final state in HIC.
2. The first stages and before. The initial state in HIC.
3. Signals for the QGP formation.
4. Experimental/Theoretical status.
   - ⇛ RHIC
   - ⇛ LHC

Summary I+II

- QCD vacuum:
  Confinement & chiral symmetry breaking
- Theory $\longrightarrow$ Different phases exist!
- Order of the transition depends on quarks masses. For realistic masses, most probably crossover at $\mu_B = 0$.

Initial state effects

- Multiple scattering and coherence effects necessary to describe heavy ion collisions
- Large multiplicities in HIC
  - High densities created
- Non-linear terms in the evolution equations appear.

3. Signals of QGP formation

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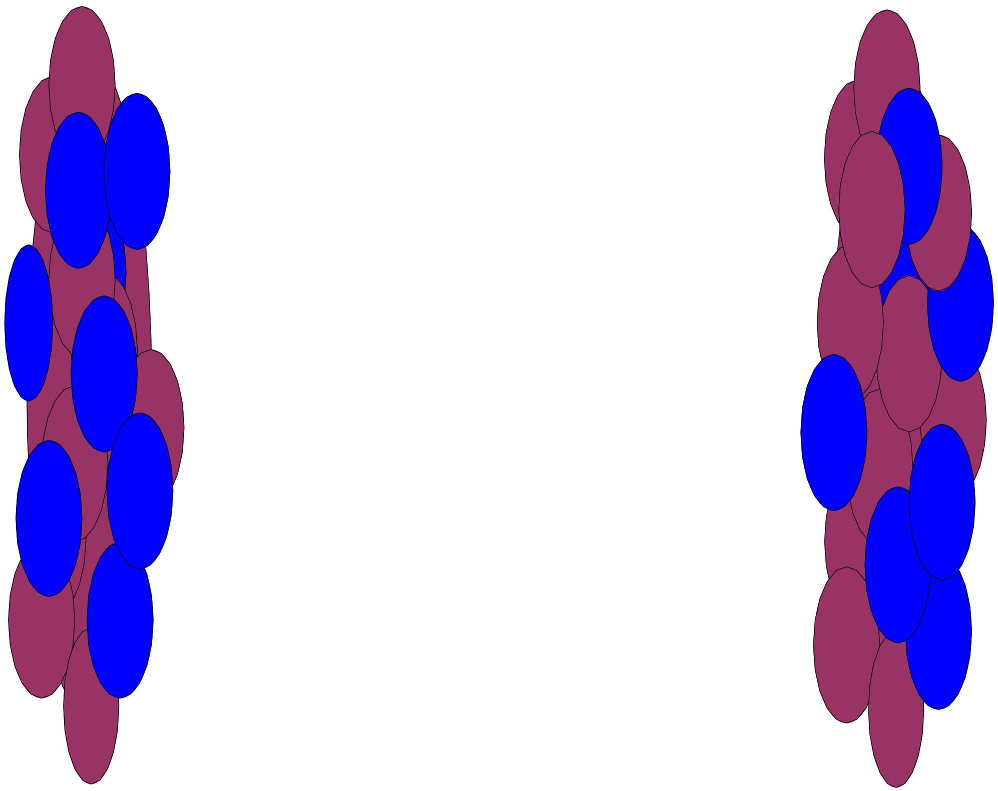
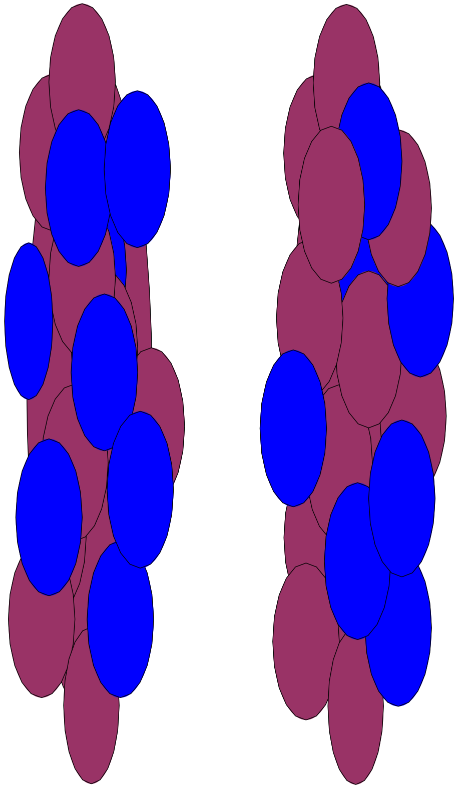
Final state effects

High-energy heavy ion collisions



Before the collision: Lorentz-contracted nuclei

High-energy heavy ion collisions



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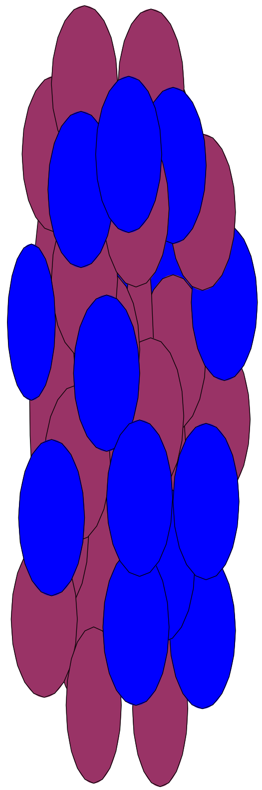
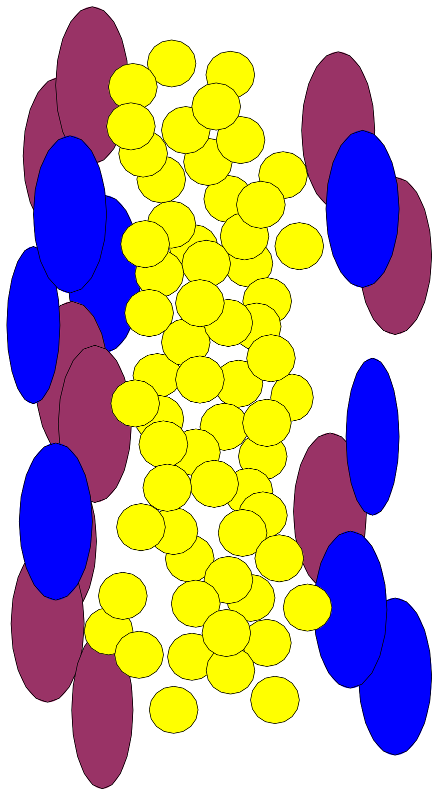


at $t = 0$ most of the energy in the central region

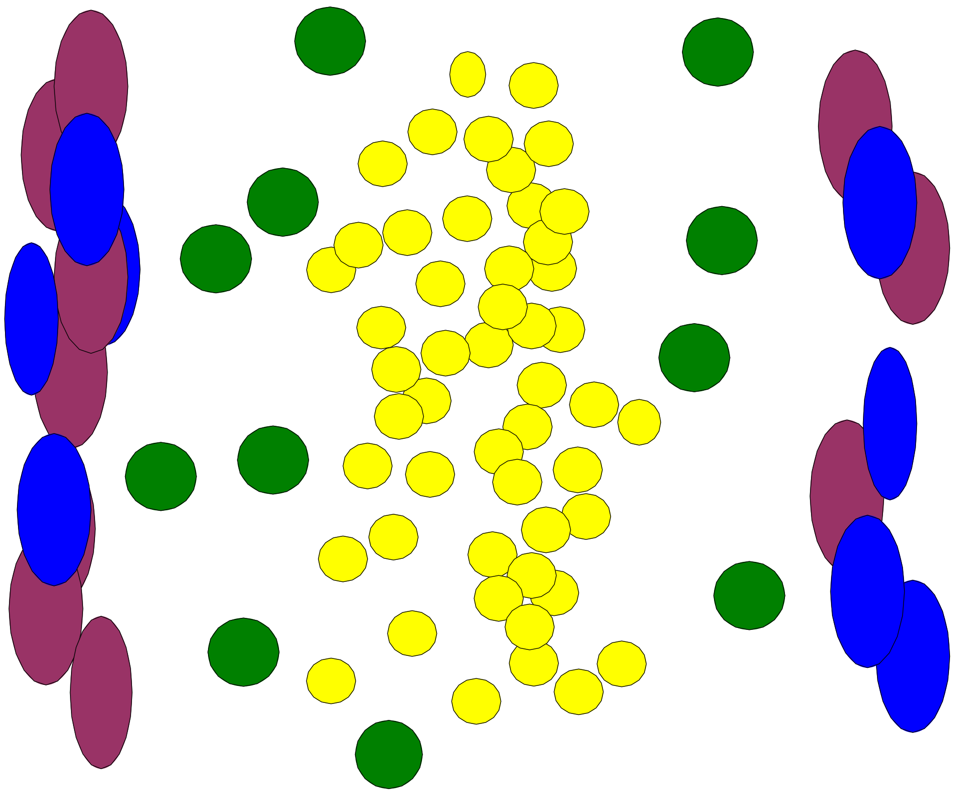
Initial state

High-energy heavy ion collisions



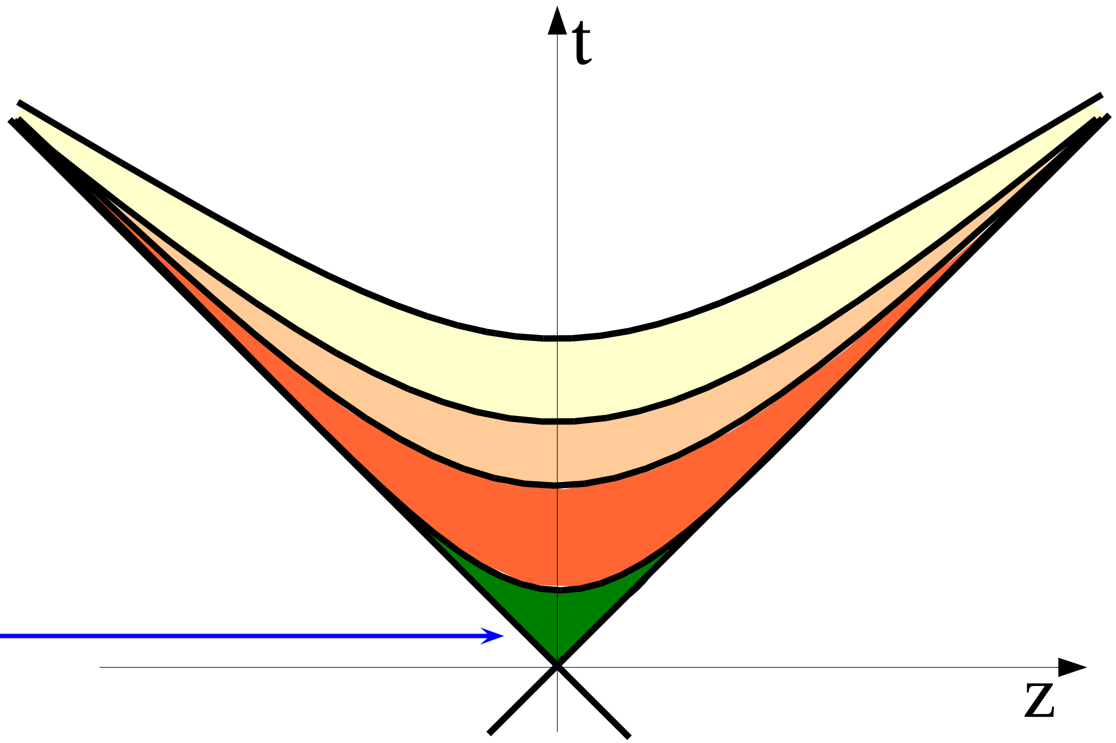
First $\sim 0.1 \div 0.3$ fm. Quark gluon plasma formation

High-energy heavy ion collisions



Expansion and hadronization

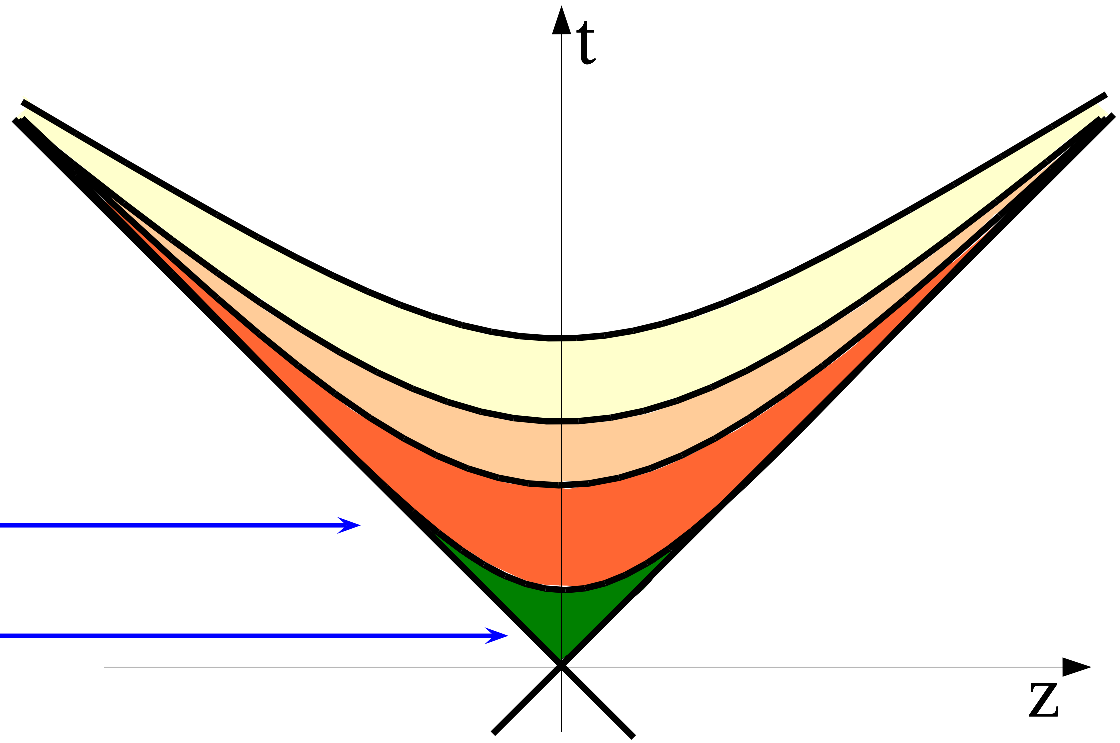
"Canonical" space-time picture



⇒ production and thermalization

Transitions: lines of constant proper time τ.

"Canonical" space-time picture



⇛ QGP

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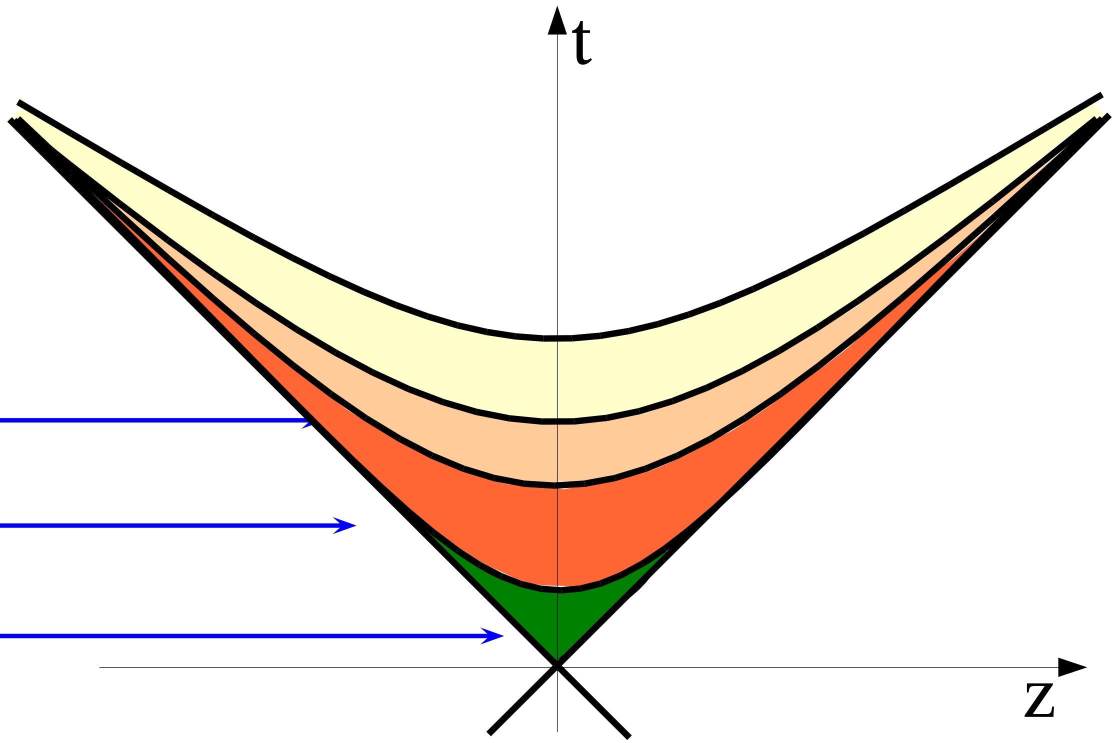
- ⇛ mixed phase??
- ⇛ QGP
- ⇛ production and thermalization



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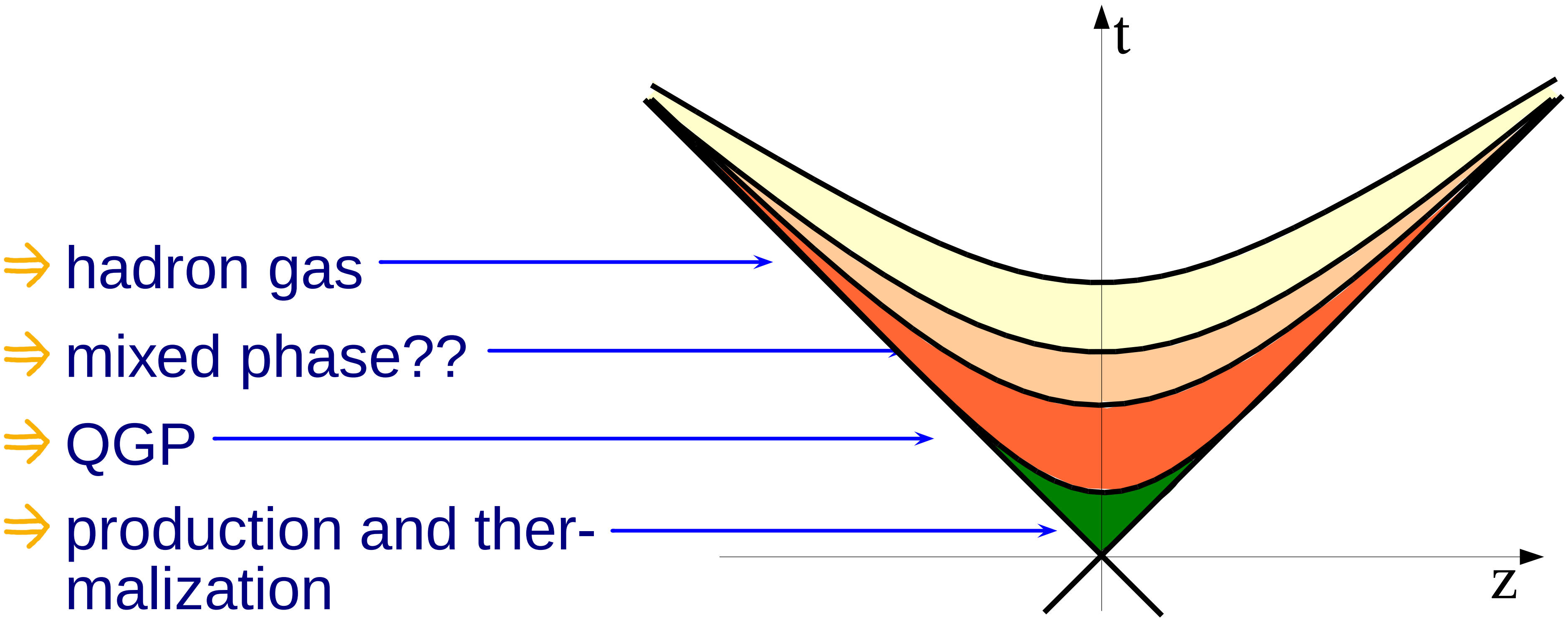
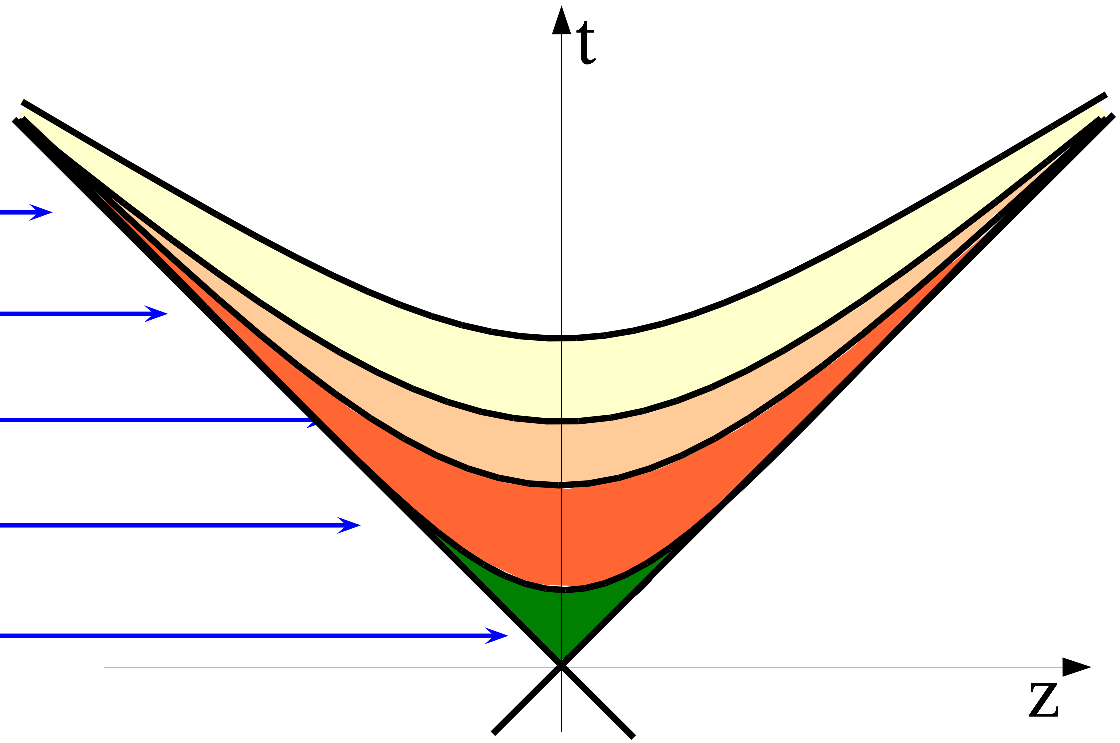


Transitions: lines of constant proper time τ.

"Canonical" space-time picture

- ⇒ freeze-out
- ⇒ hadron gas
- ⇒ mixed phase??
- ⇒ QGP
- ⇒ production and thermalization



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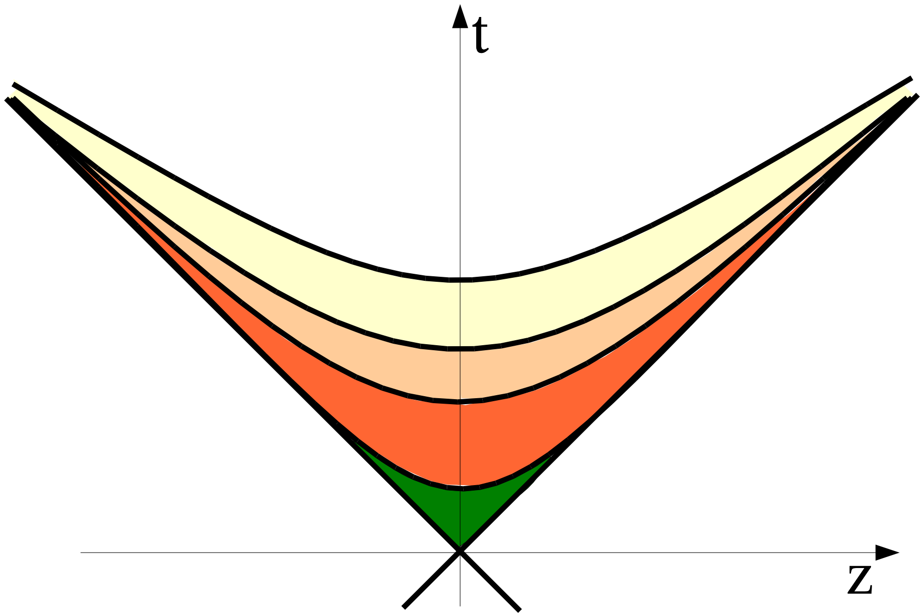
Characterization of the medium

The medium (or media?!), if formed, has a very short lifetime. In order to study its properties some (indirect) signals are proposed

⇒ Soft (bulk) signatures:

- Strangeness enhancement
- Flows
- Particle composition
- ...



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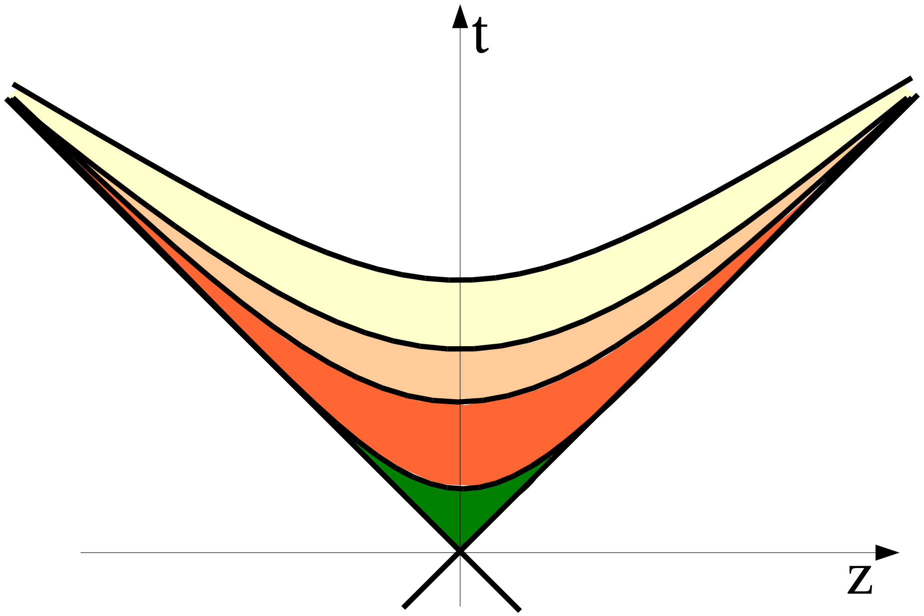
  - J/Ψ suppression
  - Jet quenching



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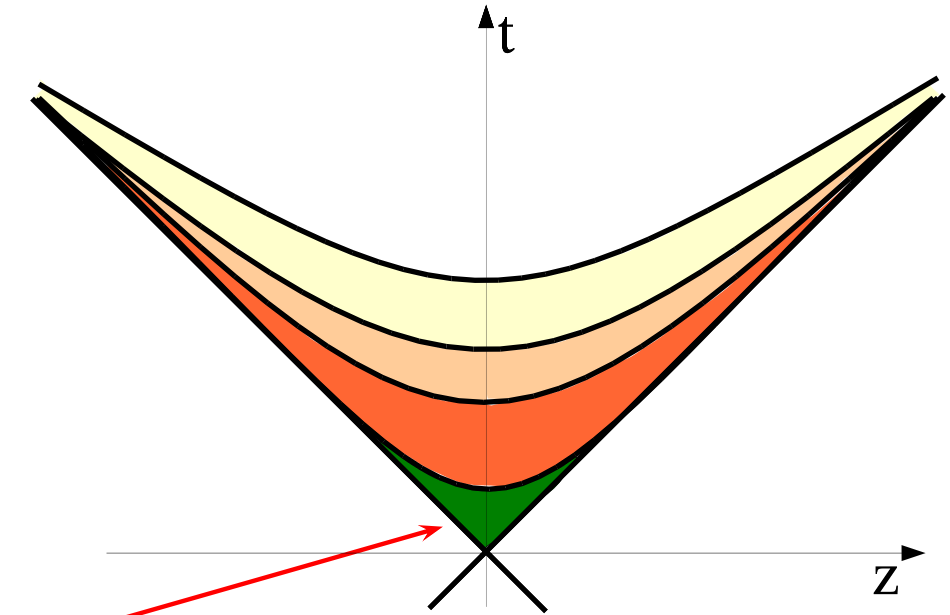
  Produced at the early ($\tau \sim 1/Q$) stages



Soft probes

Strangeness enhancement

In order to produce strangeness,in a medium with broken chiral symmetry one needs

$$m_{K^+} + m_{K^-} \sim 1GeV$$

In a medium in which chiral symmetry is restored, the energy is just the sum of the strange quark mass,

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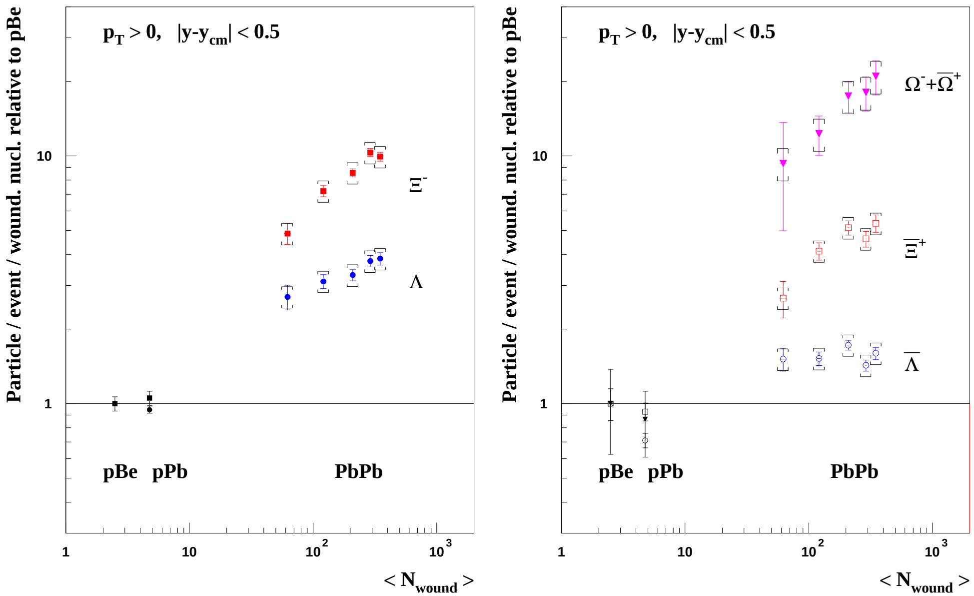


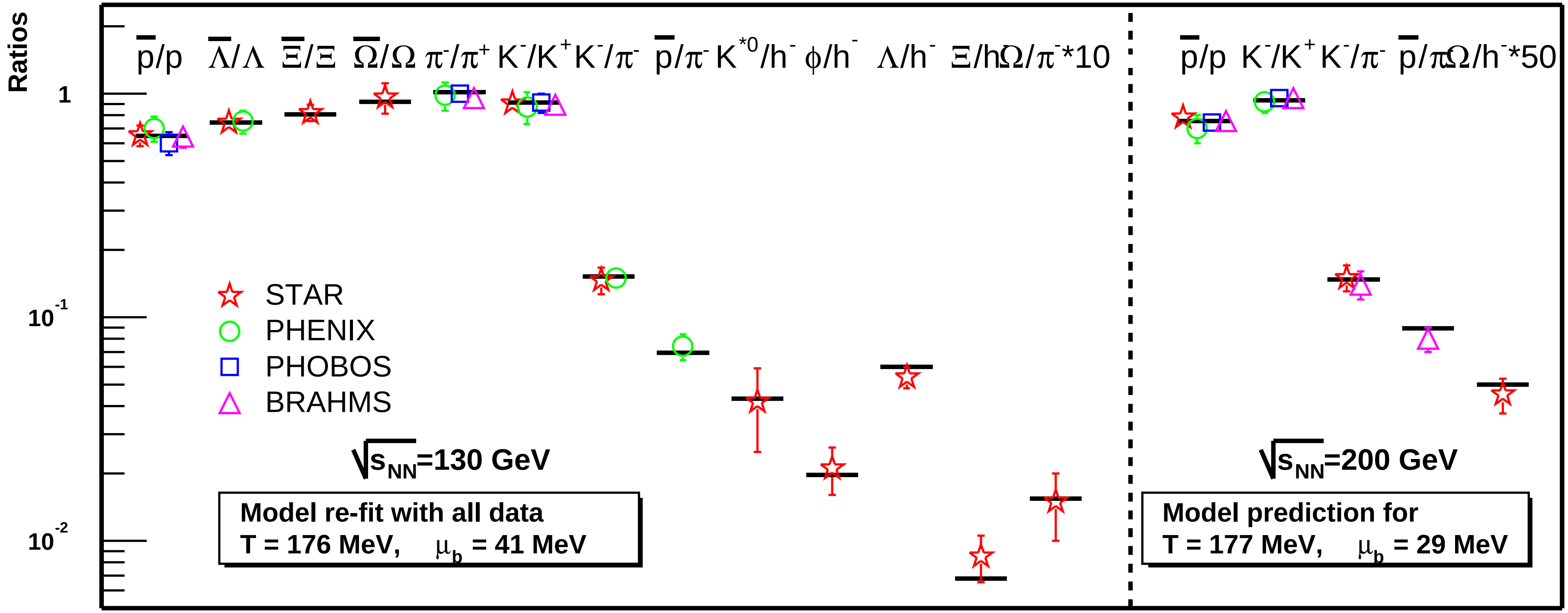
Strange baryons enhancement by NA57 ($\sqrt{s}$=17.3 GeV)

Statistical description of particle yields

Assuming an ideal gas of particles, the number densities are

$$n_i = -\frac{T}{V}\frac{\partial \ln Z}{\partial \mu_i}\frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp[(E_i-\mu_i)/T]\pm 1}$$

Only two independent parameters, μ_B and T (+some assumptions)



Braun-Munzinger et al., PLB 518 (2001) 41 D. Magestro (updated July 22, 2002)

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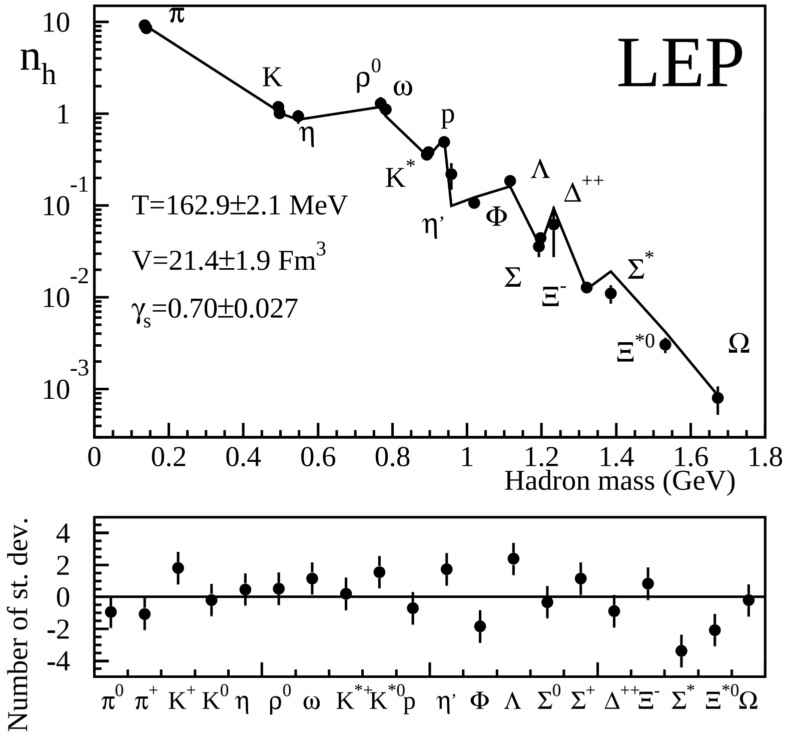
However, it also works for e^+e^-...



[Becattini 1995]

Collective flow

⇛ In a non-relativistic fluid, the fluid acceleration is given by Euler's eq.

$$\frac{d\beta}{dt} = -\frac{1}{\rho}\nabla P \qquad \left[\ \frac{d\beta}{dt} = -\frac{c^2}{\epsilon + P}\nabla P \quad \rightarrow \quad \text{relativistic}\right]$$

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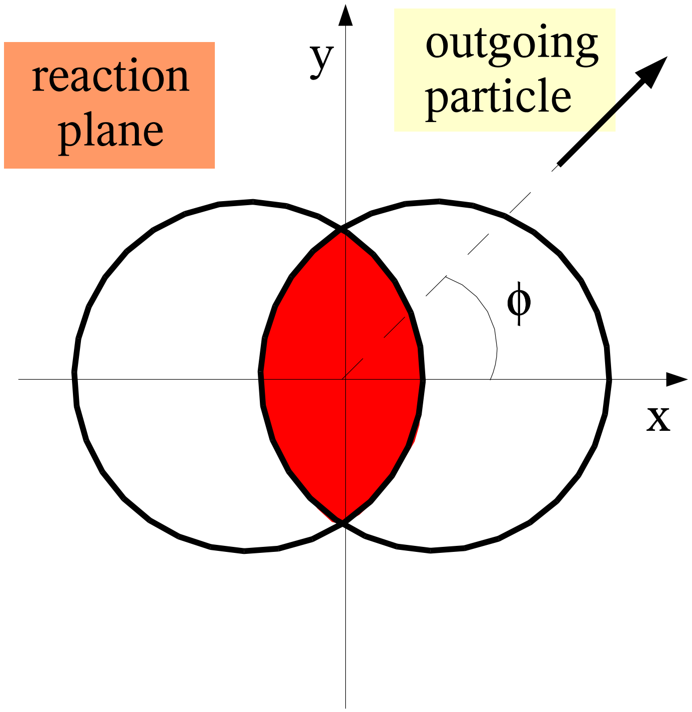
- Initial condition in a HIC has gradients of energy density. This translates into gradients of the pressure and, by evolution, flow.
  - Relation between the initial distribution of energy and flow(s).

Elliptic flow

Gradients are more easily produced in asymmetric media: Changing the centrality of the collision.

⇛ Reaction plane defined by the impact parameter and the collision axis.



Elliptic flow

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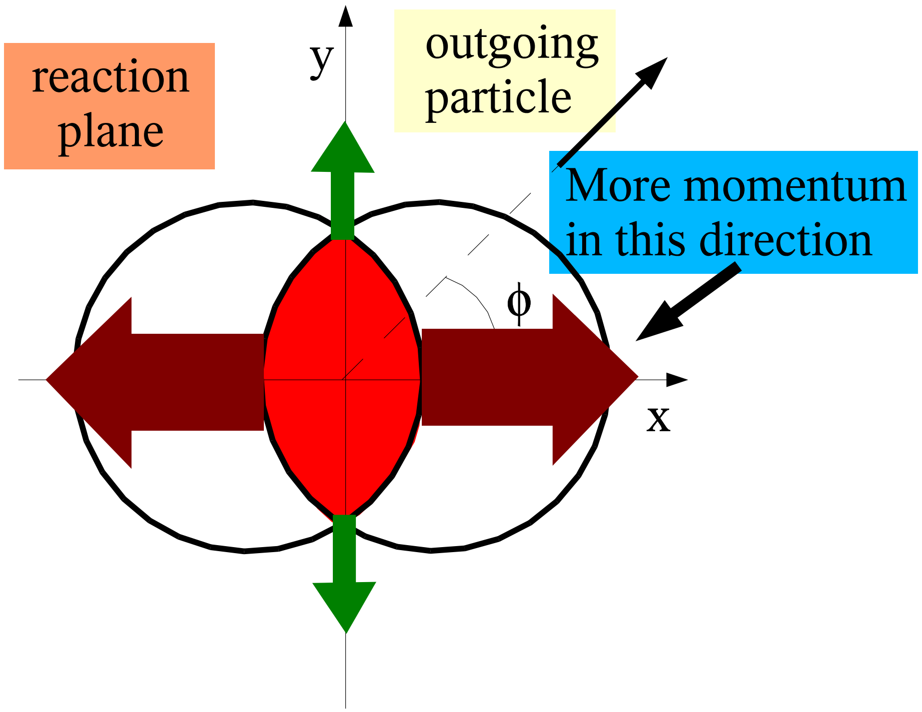
- ⇛ Reaction plane defined by the impact parameter and the collision axis.
- ⇛ Doing the Fourier expansion of the number of particles in the reaction plane

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n\phi)$$

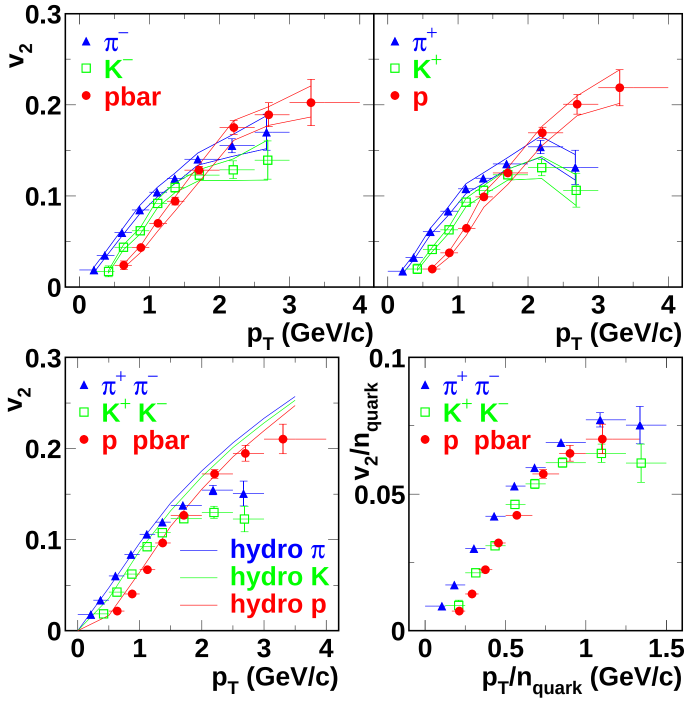
v_n characterize the strength of the anisotropic flow.

- ⇛ v_2 elliptic flow.



Elliptic flow

Elliptic flow has measured at RHIC (one of the main signals)



[STAR data]

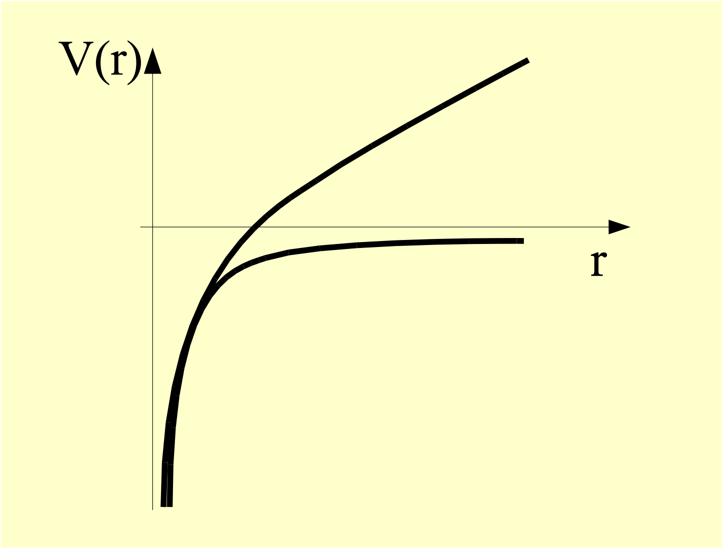
⇒ Comparison with hydrodynamical calculations

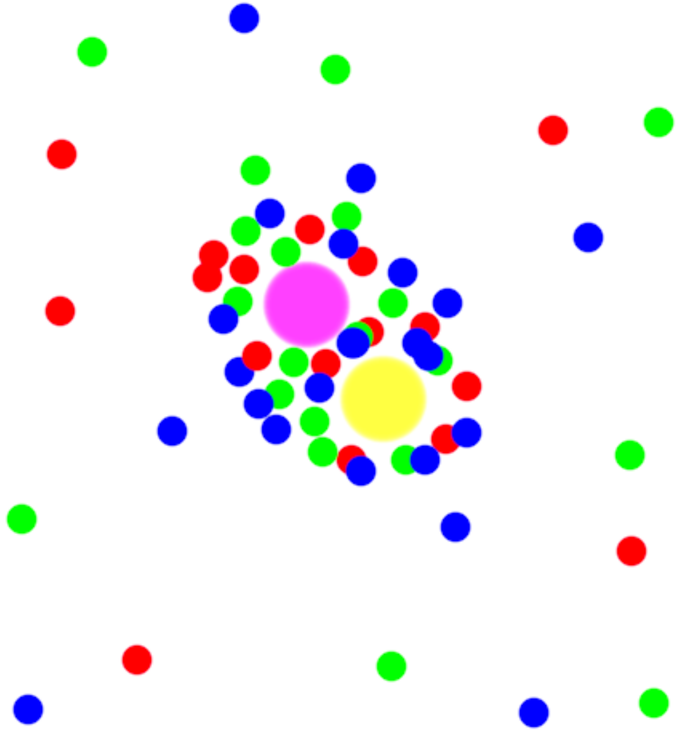
⇒ The main interest of elliptic flow is that it is very difficult to generate without strong final state interactions/thermalization.

Hard Probes

J/Ψ suppression

- A J/Ψ is a bound $c\bar{c}$ state.
- We have seen that the potential between two quarks is screened in the medium.
- In this case, the $c\bar{c}$ pair is diluted in the medium and the production of bound states is suppressed.





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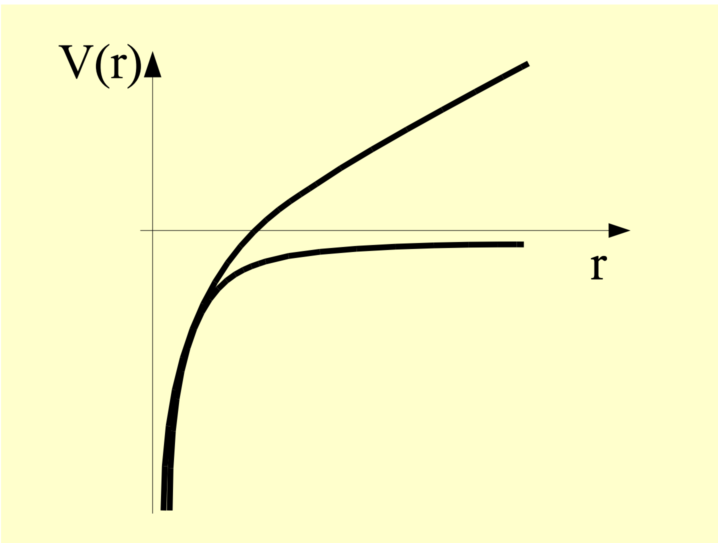
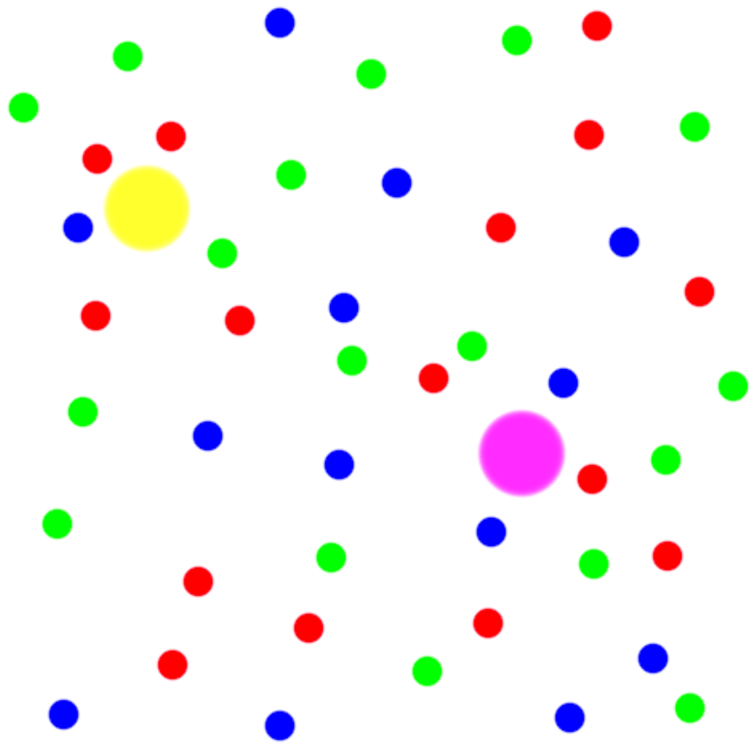
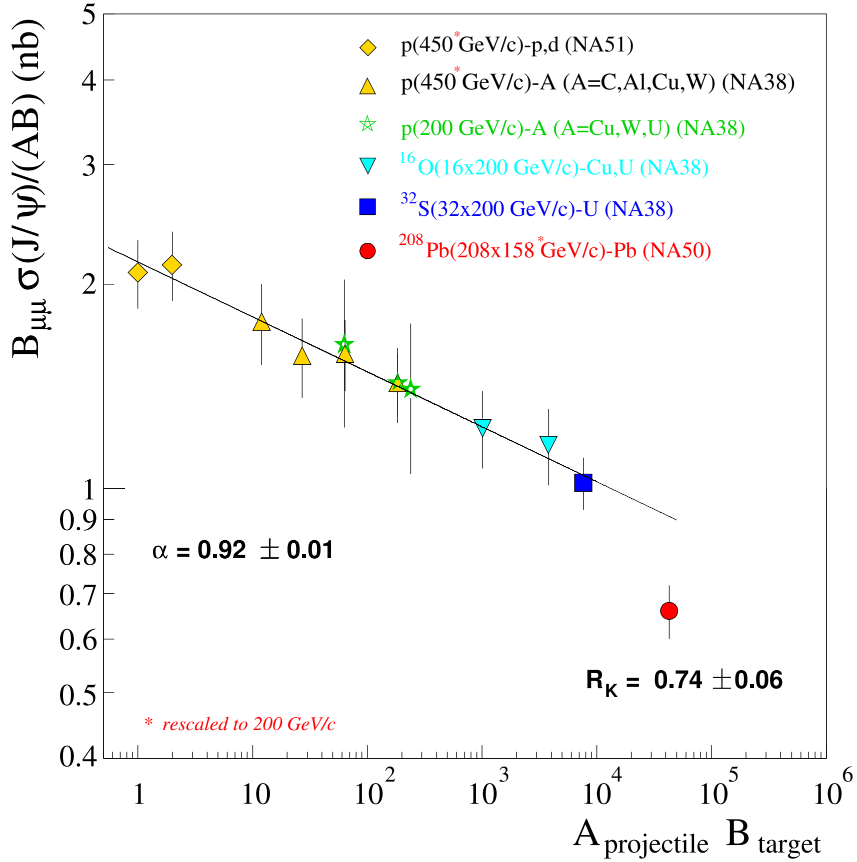


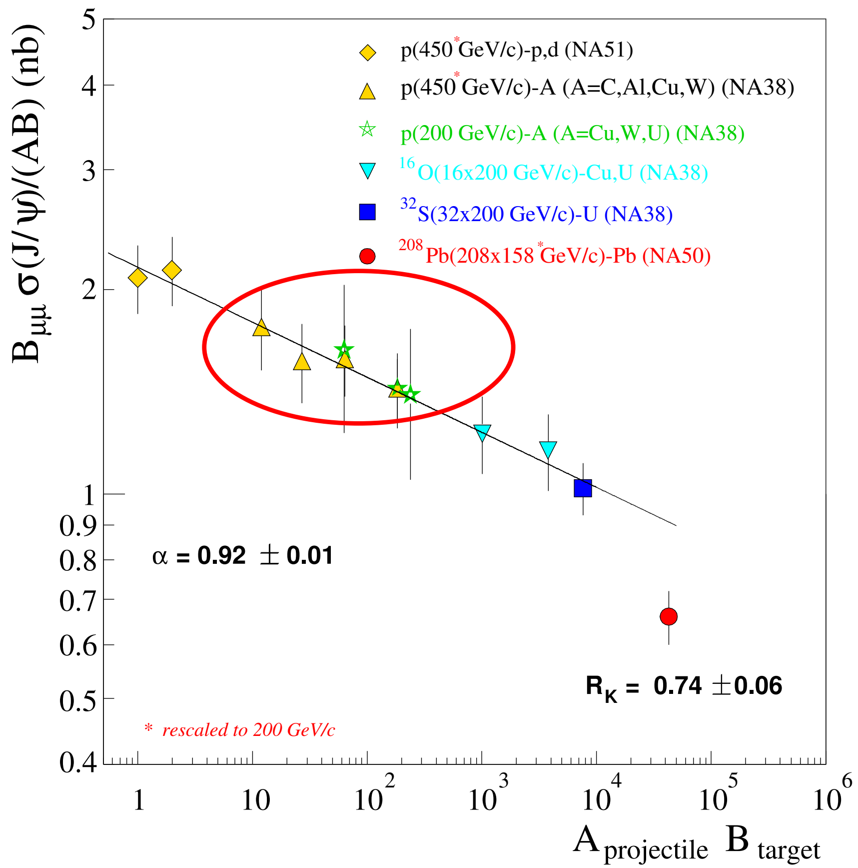


J/Ψ suppression II



⇛ J/Ψ suppression measured at CERN (NA50).

J/Ψ suppression II



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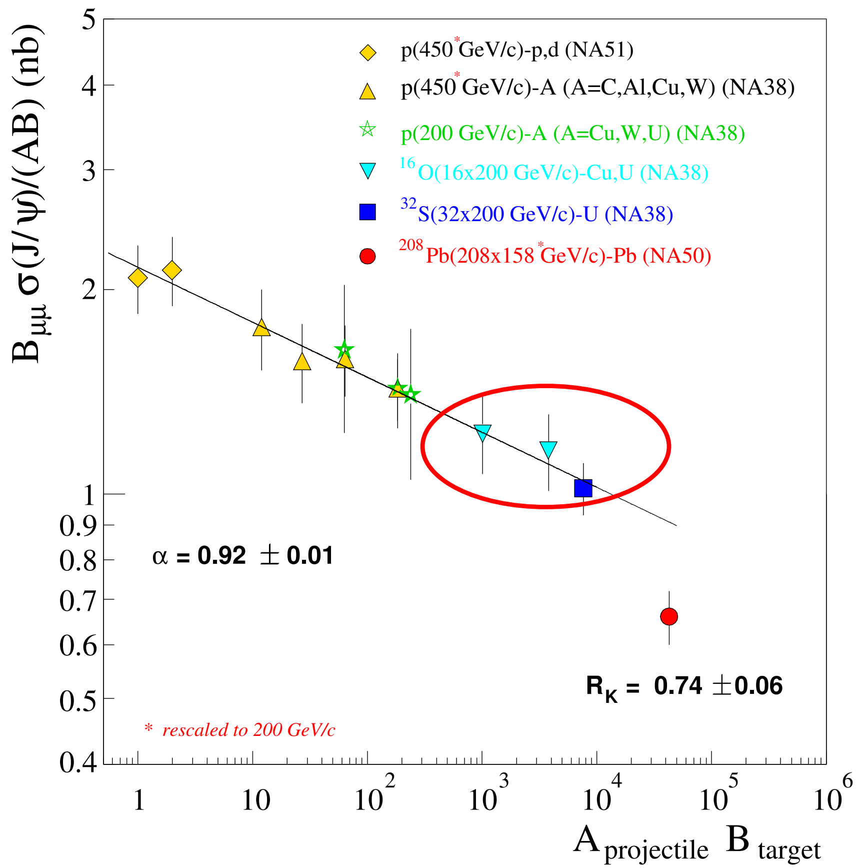

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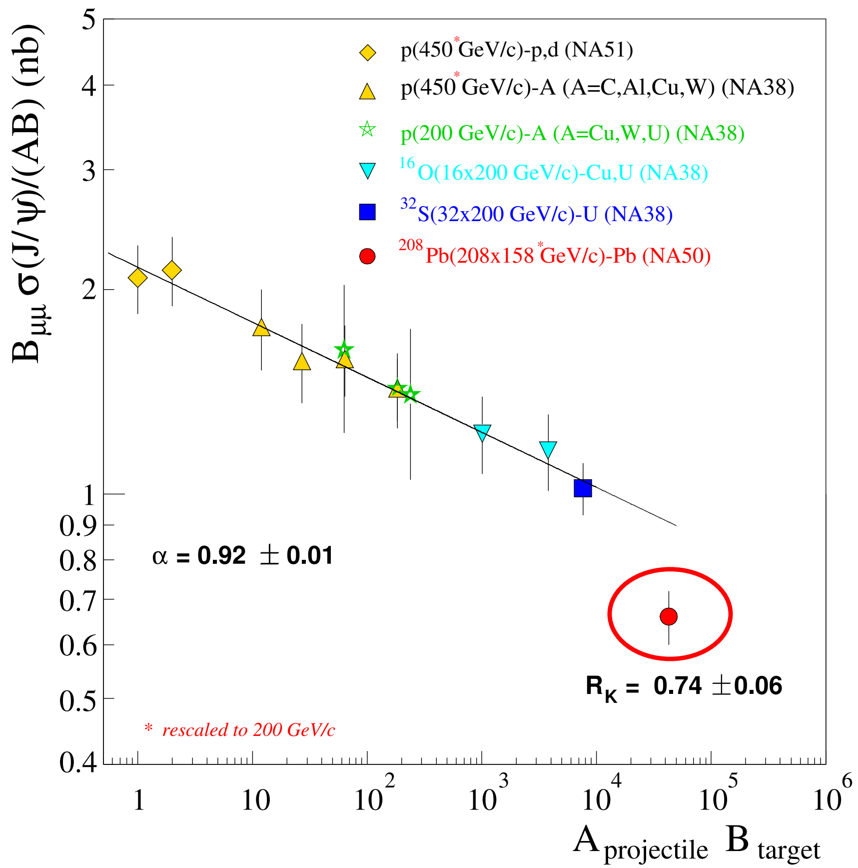

- J/Ψ suppression measured at CERN (NA50).
- pA collisions $\rightarrow$ nuclear absopt. (multiple scattering $c\bar{c}$-A)
- OCu, OU, SU $\rightarrow$ nuclear absoption.
- PbPb ”anomalous suppression”
  - hadronic or partonic origin?

Lattice results not yet determinant on whether J/Ψ dissociates at T_c or above. Other $c\bar{c}$ states, as ψ' or χ_c, could dissociate bellow T_c.

Jet quenching

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- Suppose a particle entering a medium or created inside the medium

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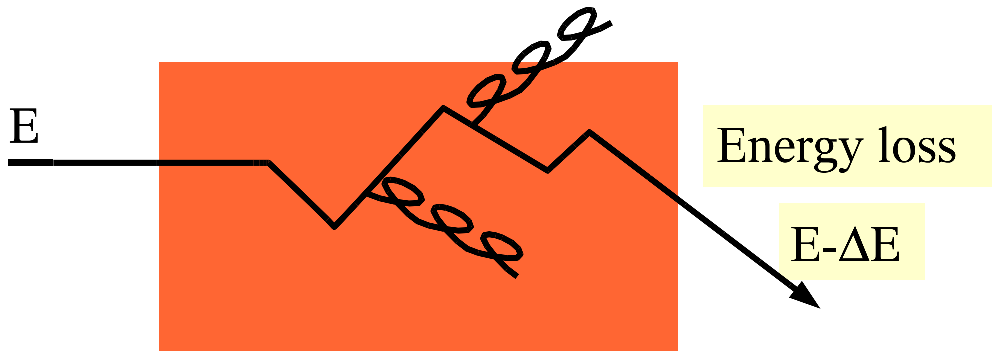
- The particle looses energy while traveling through the medium
  - by scattering with the medium
  - by radiation



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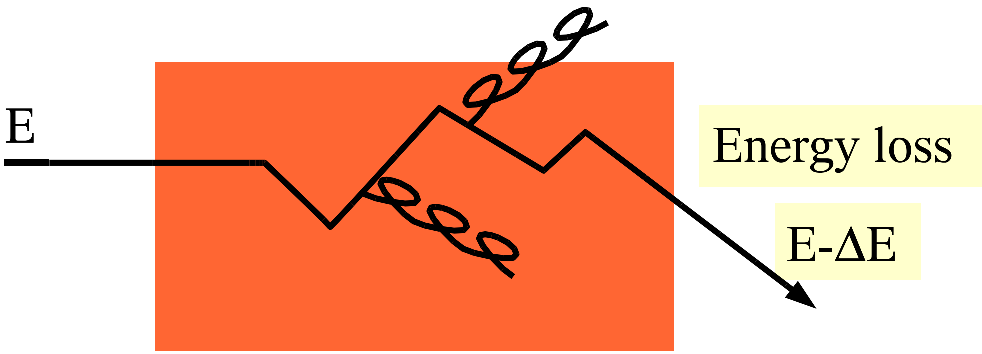

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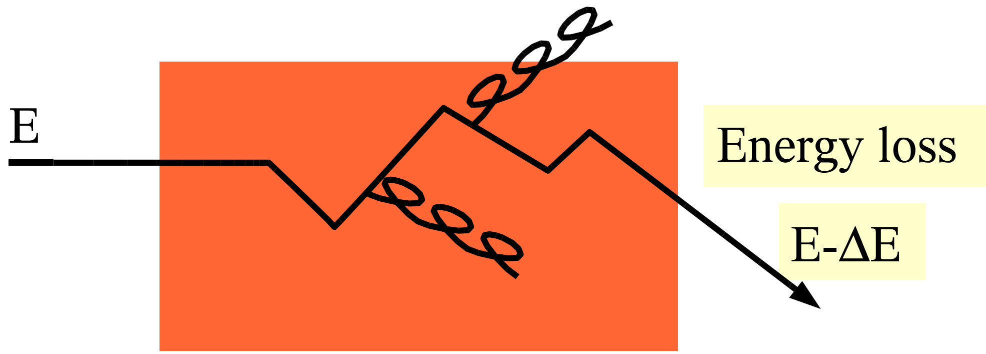
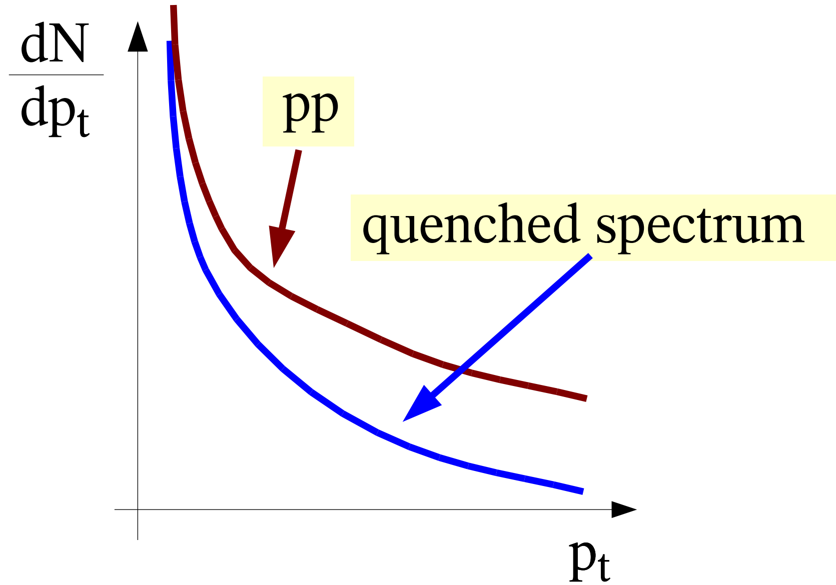
- A high-p_t particle produced inside a medium will lose energy while escaping it $\longrightarrow$ spectrum suppressed at large p_t.

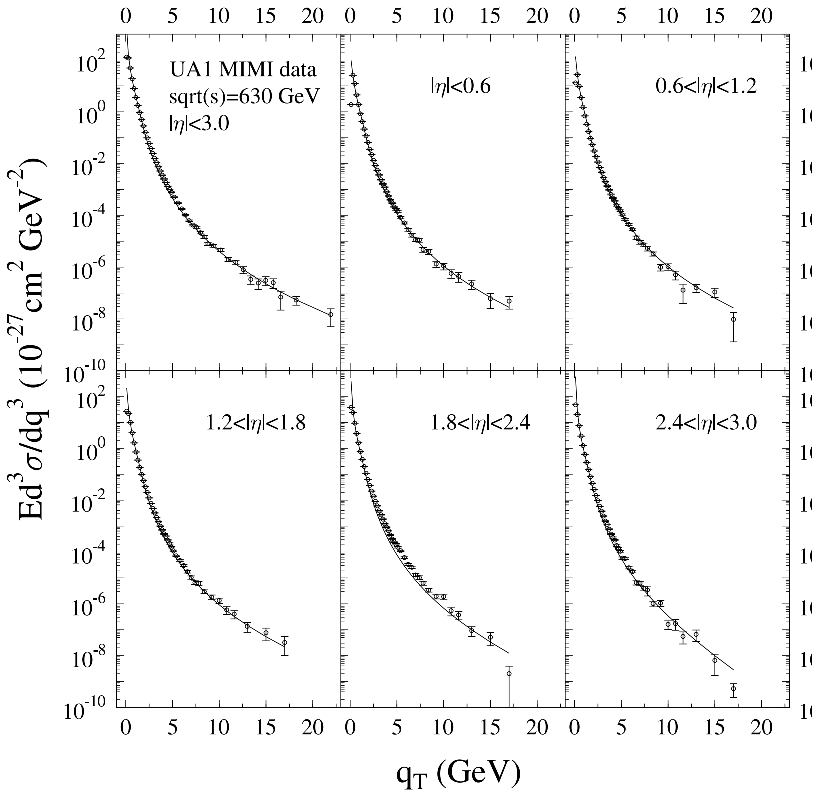




High-p_t production in pp: pQCD

QCD factorization formula:

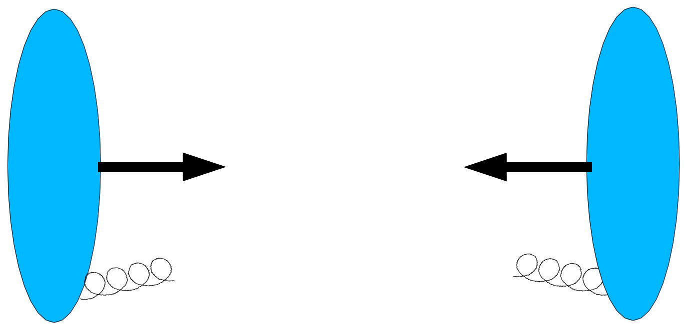
$$\frac{d\sigma^h_{pp}}{dp_t^2 dy} \sim \sum_{i,j} x_1 f_i^p(x_1, Q^2) \otimes x_2 f_j^p(x_2, Q^2) \otimes \frac{d\sigma^{ij\to k}}{d\hat{t}} \otimes D_{k\to h}(z, \mu_F^2)$$



(Eskola and Honkanen: Nucl.Phys. **A713** (2003) 167)

Space-time picture

Before the collision, initial state: nuclear PDF's.



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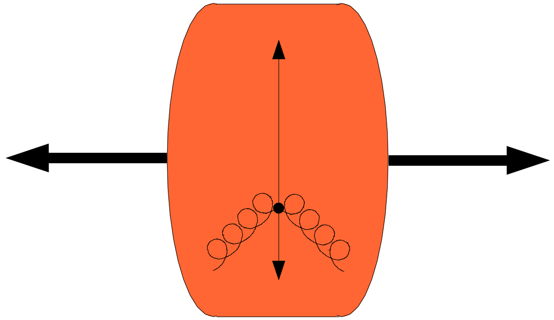
Space-time picture

At $t \sim 0$



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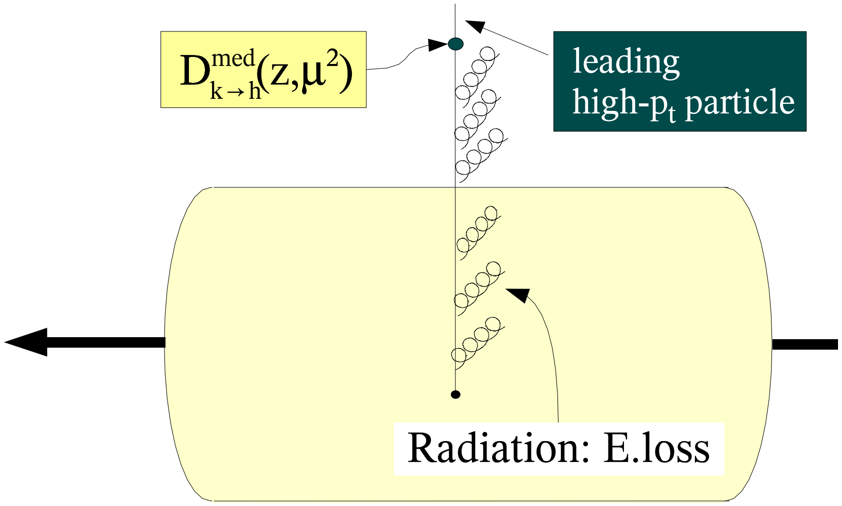
Space-time picture

Evolution.



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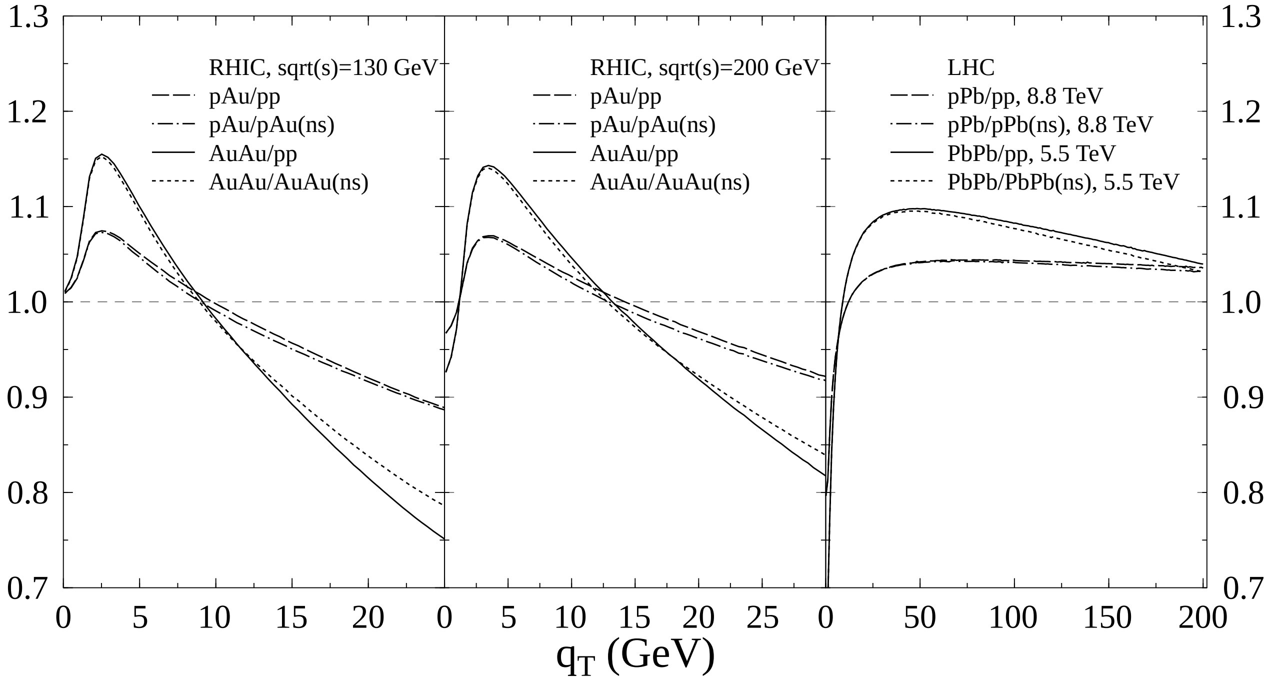
Effects of nuclear PDF.

Nuclear effects in PDF produce small changes in high–p_t particle production at RHIC and LHC, at most 25 % .

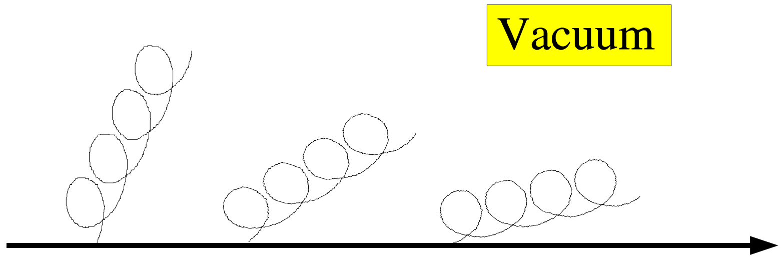


Computed using EKS98 nPDF's.

[Eskola and Honkanen]

Matter affects evolution.

⇛ A quark or gluon (traveling in vacuum) with virtuality Q^2 will radiate gluons to become on-shell: DGLAP-like evolution.



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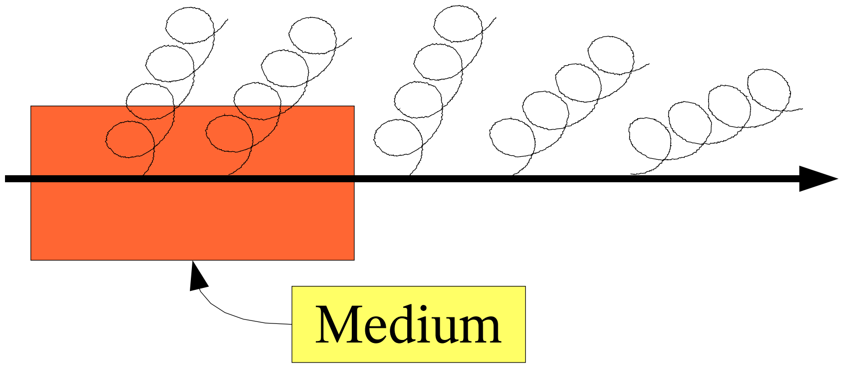

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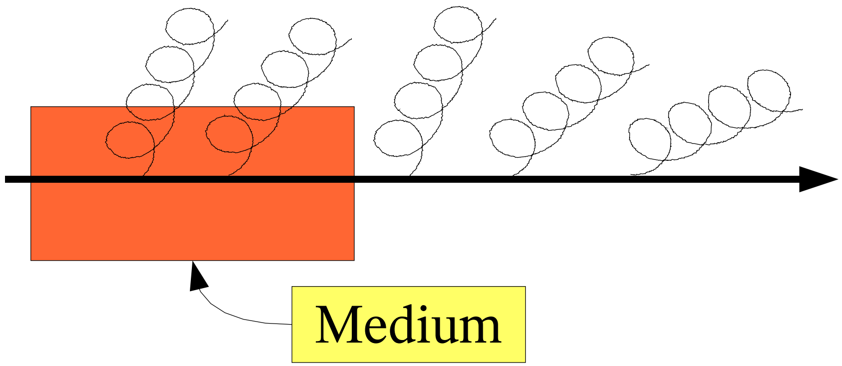
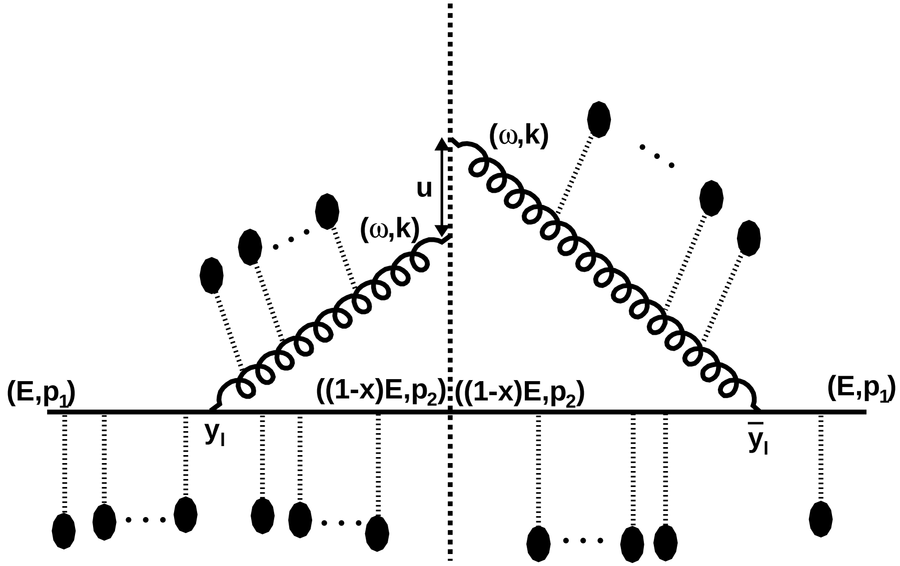


⇛ Where to look?

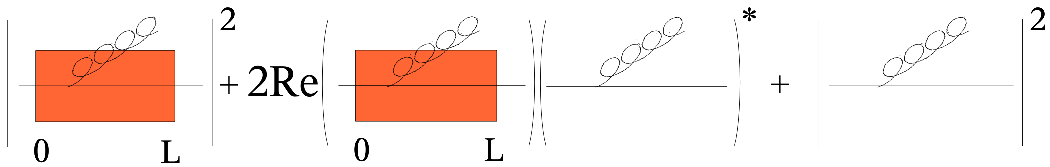
- Inclusive particle (suppression).
- Jets: Jetshapes... $\longrightarrow$ LHC

Medium–induced gluon radiation.



For media of finite length

$$\omega \frac{dI^{tot}}{d\omega dk_\perp^2} =$$



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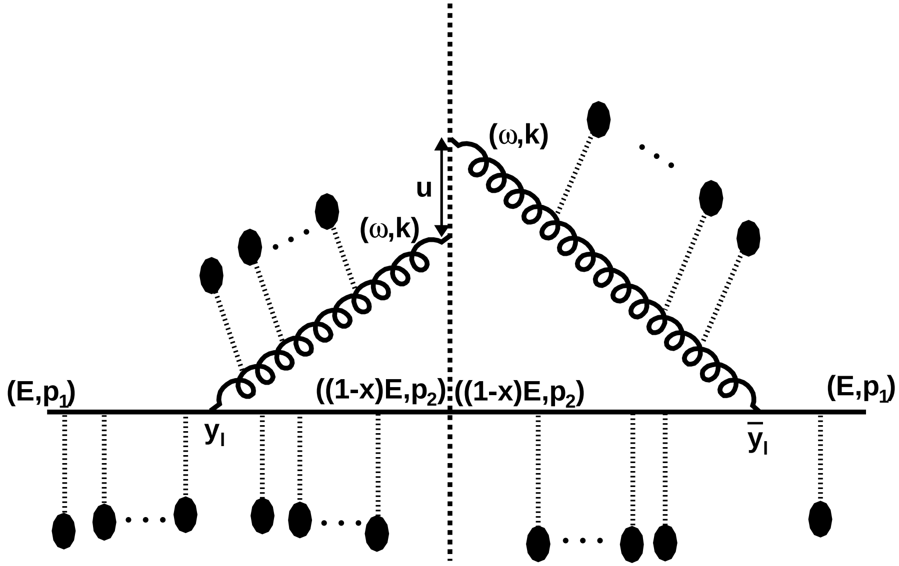

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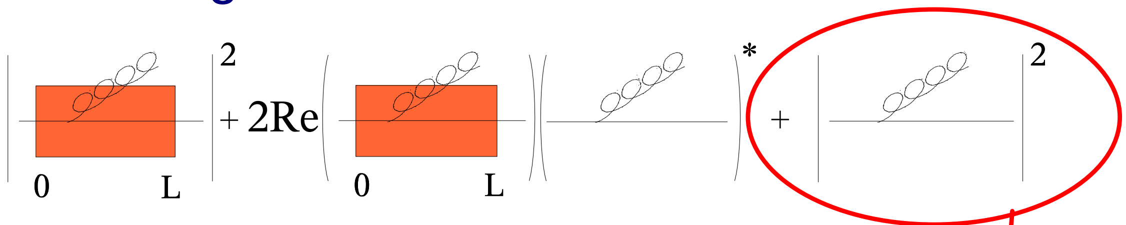

The medium induced gluon radiation

$$\omega \frac{dI}{d\omega dk_\perp^2} = \omega \frac{dI^{tot}}{d\omega dk_\perp^2} - \omega \frac{dI^{vac}}{d\omega dk_\perp^2}$$

Medium: L (length) and $\hat{q}$ (transport coefficient).

Double differential spectrum

High energy approximation $\longrightarrow$ multiple scattering. The final result is

$$\omega \frac{dI}{d\omega d\mathbf{k}_\perp} = \frac{\alpha_s C_R}{(2\pi)^2 \omega^2} 2\mathrm{Re} \int_{\xi_0}^{\infty} dy_l \int_{y_l}^{\infty} d\bar{y}_l \int d\mathbf{u}\, e^{-i\mathbf{k}_\perp \cdot \mathbf{u}}\, e^{-\frac{1}{2}\int_{\bar{y}_l}^{\infty} d\xi\, n(\xi)\, \sigma(\mathbf{u})}$$

$$\times \frac{\partial}{\partial \mathbf{y}} \cdot \frac{\partial}{\partial \mathbf{u}} \int_{\mathbf{y}=0=\mathbf{r}(y_l)}^{\mathbf{u}=\mathbf{r}(\bar{y}_l)} \mathcal{D}\mathbf{r} \exp\left[i \int_{y_l}^{\bar{y}_l} d\xi \frac{\omega}{2} \left(\dot{\mathbf{r}}^2 - \frac{n(\xi)\sigma(\mathbf{r})}{i\,\omega} \right) \right].$$

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Two approximations

- Multiple soft scattering $n(\xi)\sigma(\mathbf{r}) = \frac{\hat{q}(\xi)}{2}\mathbf{r}^2$. The path integral reduces to a harmonic oscillator of imaginary frequency.
- Single hard scattering First order in the opacity expansion parameter $n(\xi)\sigma(\mathbf{r})$.A Yukawa cross section is usually taken for the cross section $\sigma(\mathbf{r})$
  - Expansion in the number of scatterings

Coherent radiation

Two phases appear: quark and emitted gluon

$$\varphi_E = \left\langle \frac{k_\perp^2}{2E}\,\Delta z \right\rangle \qquad \varphi = \left\langle \frac{k_\perp^2}{2\omega}\,\Delta z \right\rangle \Longrightarrow l_{coh} \sim \frac{\omega}{k_\perp^2}$$

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Let us define $\quad \kappa^2 \equiv \frac{k_\perp^2}{\hat{q}L}\ ,\ \omega_c = \frac{1}{2}\hat{q}L^2$

So, the phase for $\Delta z = L \longrightarrow \ \varphi \sim \kappa^2 \ \frac{\omega_c}{\omega}$

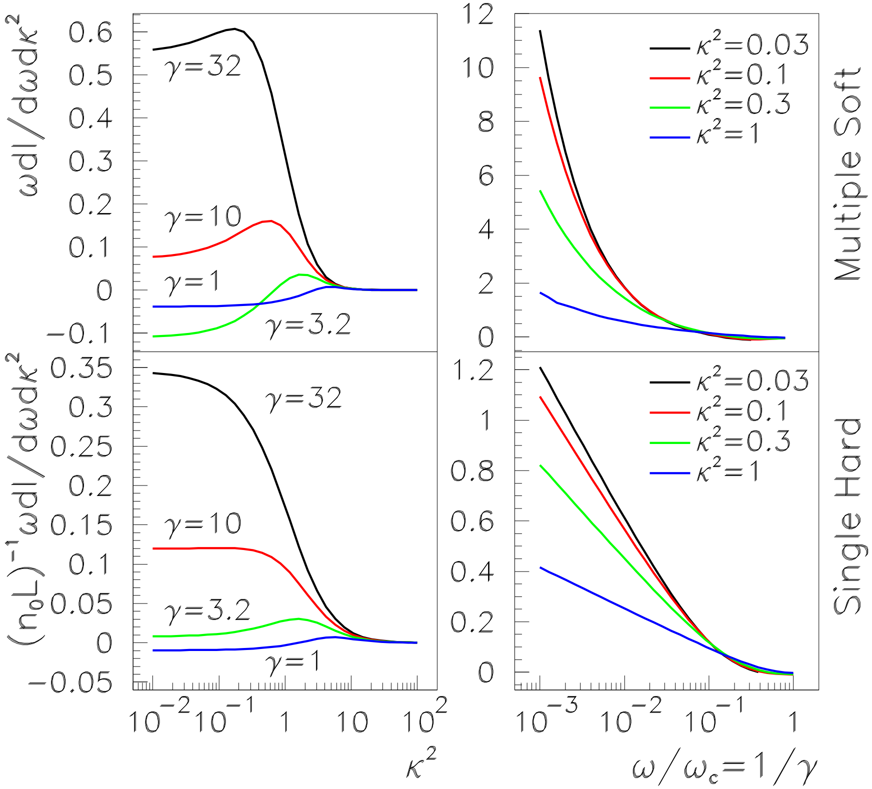
gluon emitted when $\varphi \gtrsim 1 \Longleftrightarrow$ radiation suppressed for $\kappa^2 \lesssim \omega/\omega_c$

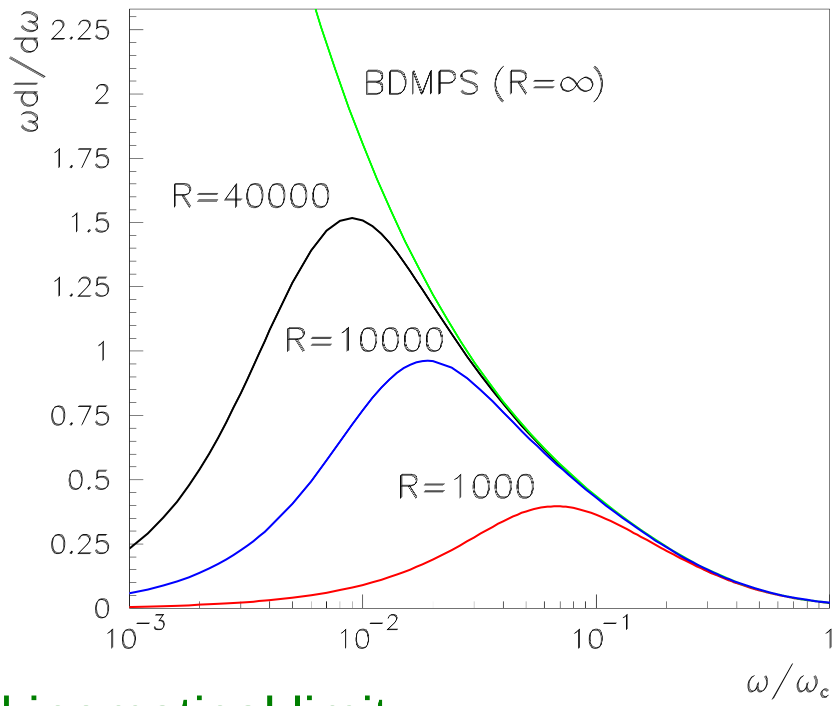
In cold nuclear matter: $Q_{sat}^2 = \hat{q}L \Longrightarrow \kappa^2 = \frac{k_\perp^2}{Q_{sat}^2}$

Gluon energy distributions for quark jets

$$\kappa^2 = \frac{k_\perp^2}{\hat{q}L} \;,\; \omega_c = \frac{1}{2}\hat{q}L^2$$

$$\omega\frac{dI}{d\omega} = \int_0^\omega dk_\perp \omega \frac{dI}{d\omega dk_\perp}$$





Plateau at small $\kappa \longleftrightarrow$ coherence

gluons $\Longrightarrow$ factor N_c/C_F larger

kinematical limit

$k_\perp \leq \omega \implies R = \omega_c L$ finite

Infrared safe.

Properties of the spectrum

- For gluon emission, we have the restriction $k_\perp \leq \omega$.
- Coherence, $k_\perp^2 \lesssim \hat{q}L$. $\Longrightarrow$ spectrum suppressed for

$$\omega^2 \lesssim k_\perp^2 \sim \hat{q}L \qquad \Longleftrightarrow \qquad \left(\frac{\omega}{\omega_c}\right)^2 \lesssim \frac{2}{R}\,, \qquad R = \frac{1}{2}\hat{q}L^3\,.$$

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$\longrightarrow$ Formation time effects suppress IR region.

- Removing this limit ($R \to \infty$)

$$\lim_{R\to\infty} \omega \frac{dI(\omega)}{d\omega} = \frac{\alpha_s C_R}{\pi} \ln\left[\cosh^2 \sqrt{\frac{\omega_c}{2\omega}} - \sin^2 \sqrt{\frac{\omega_c}{2\omega}}\right]\,.$$

[Baier, Dokshitzer, Mueller, Peigné, Schiff]

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[Baier, Dokshitzer, Mueller, Peigné, Schiff]

- The total energy loss:

$$\lim_{R\to\infty} \omega \frac{dI(\omega)}{d\omega} \xrightarrow[\omega<\omega_c]{} \sqrt{\frac{\omega_c}{\omega}} \qquad \Longleftrightarrow \qquad \boxed{\Delta E = \int d\omega\, \omega \frac{dI(\omega)}{d\omega} \sim \omega_c \sim \hat{q}L^2}$$

Medium-modified fragmentation functions I

- For large-p_t the hadronization takes place outside the medium
- Model: (Wang, Huang, Sarcevic, PRL 77 2537)

$$D_{h/q}^{(\mathrm{med})}(z,Q^2) = \int_0^1 d\epsilon\, P_E(\epsilon)\, \frac{1}{1-\epsilon}\, D_{h/q}(\frac{z}{1-\epsilon},Q^2)\,.$$

- $P(\epsilon)$ probability that the hard parton loses a fraction of energy ϵ.
- Independent gluon emission approx.: (BDMS, JHEP 0109:033)

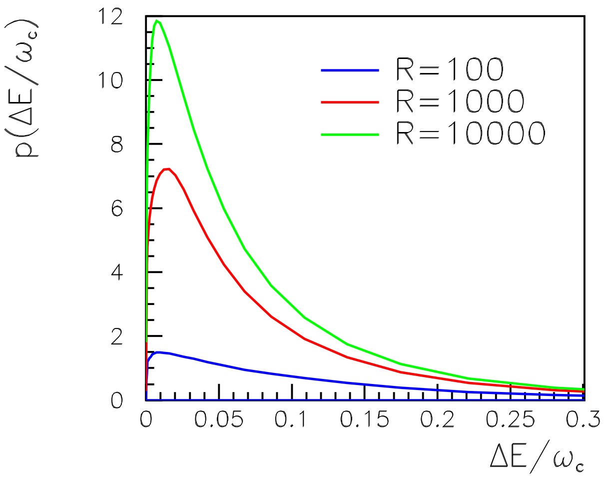
$$P_E(\epsilon) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega}\right] \delta\left(\epsilon - \sum_{i=1}^{n} \frac{\omega_i}{E}\right) \exp\left[-\int d\omega \frac{dI}{d\omega}\right]\,.$$

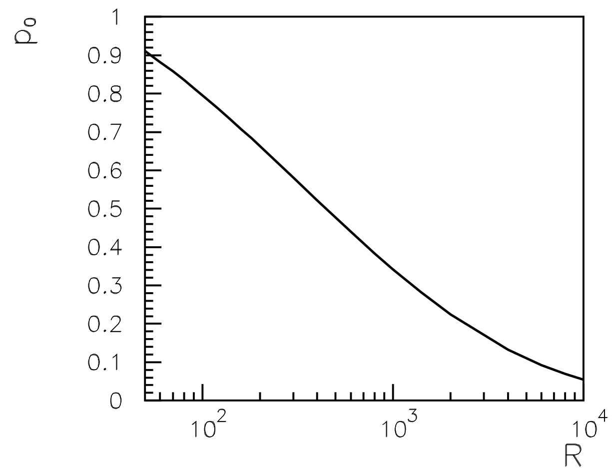
$$P(\epsilon) = p_0\delta(\epsilon) + p(\epsilon)$$

  - $p_0 \Rightarrow$ no E.loss
  - $p(\epsilon) \Rightarrow$ sum for $n \geq 1$.

Medium-modified FF II

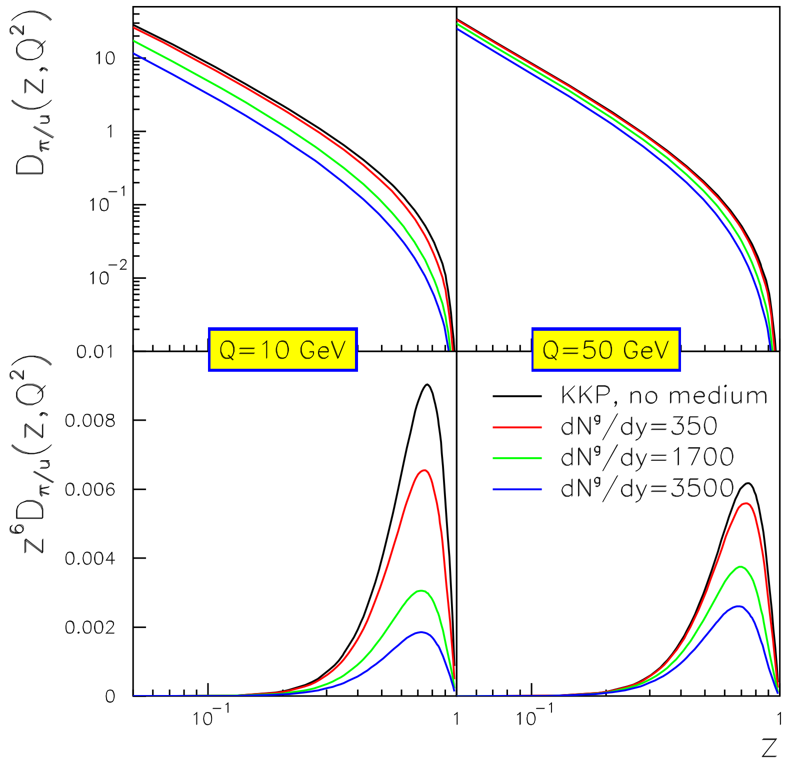
Quenching weights for quarks.





Tabulated: http://home.cern.ch/csalgado

$$R = \frac{\hat{\bar{q}}}{2} L^3 = \frac{L^2}{R_A^2} \frac{dN^g}{dy}$$



Suppression of $\sim$ 5 for $p_t \sim 5 \div 7$ GeV $\Longrightarrow$ R$\sim$ 2000.

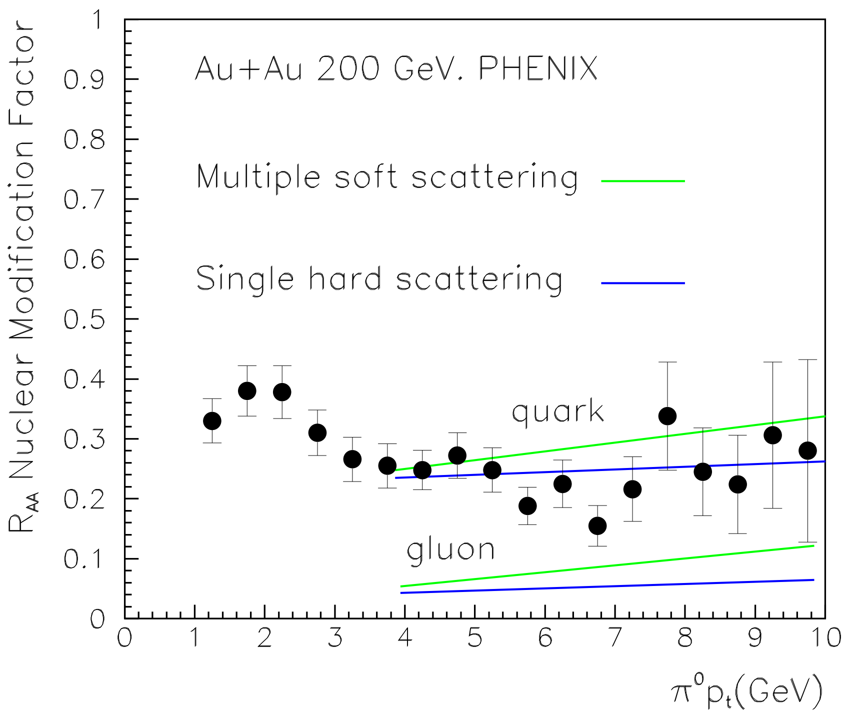
Comparison with PHENIX data.

- At RHIC, particles with $p_t \lesssim 10$ GeV have been measured.
- Ratio with proton-proton:

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

$R_{AA} = 1 \Rightarrow$ no effect.

- A factor of 5 suppression for central AuAu collisions.
- Smallest values of p_t are in the limit of applicability of the calculations.



- Can be described with $dN^g/dy \sim 1000 \div 2000$.
- Some estimates [X-N Wang]

$$\epsilon|_{\tau \sim 0.2 fm/c} \sim 15 GeV/fm^3$$

Summary III

- In order to characterize the created medium (indirect) signals are necessary.
  - Soft: strangeness enhancement, particle ratios, flows
  - Hard: J/Ψ suppression, jet quenching
- Hard probes specially interesting as
  - they are created at very short times $\sim 1/Q$
  - can be described by perturbative QCD
- All these effects have been measured in nucleus-nucleus collisions, however, they can also be produced by
  - Nuclear effects in the initial state (shadowing...)
  - Interaction with a confined medium (pion gas...)
- Study proton-nucleus collisions as a control experiment.