Medium modification of the jet properties

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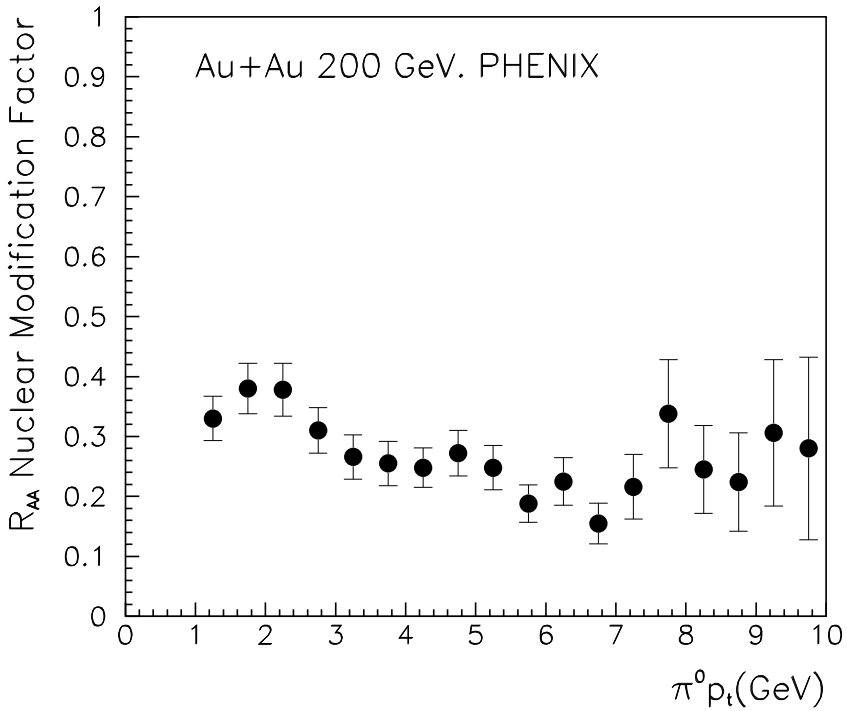
- Motivation. $\longrightarrow$ Medium properties.
- Medium-induced gluon radiation.
  - Heavy quarks
- Jet shapes in nuclear collisions.

Jet quenching (inclusive particle)



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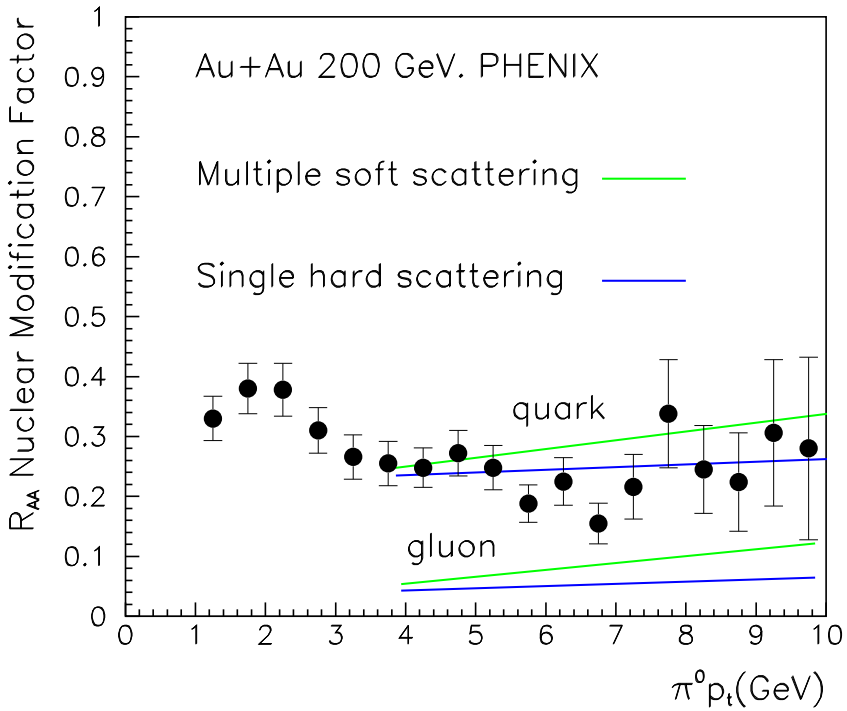

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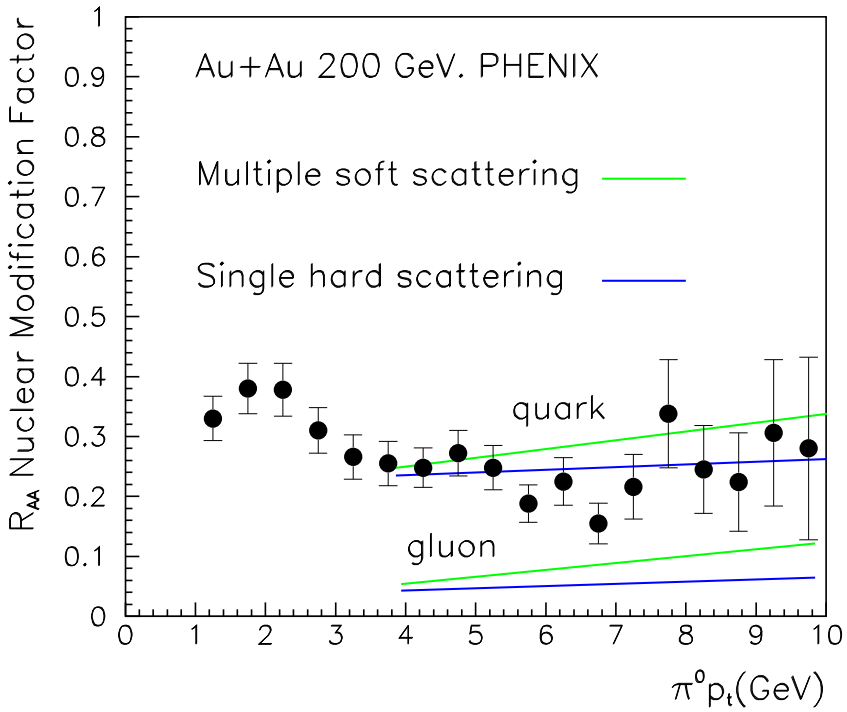
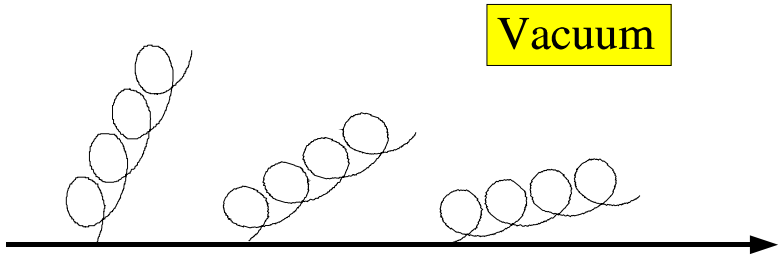


- ⇒ Several groups also describe these data (Gyulassy, Levai, Vitev, Wang, ...)
- ⇒ Smallest values of p_t are in the limit of applicability of the calculations.
- ⇒ Slope and magnitude of the effect are ok.

See poster by Heli 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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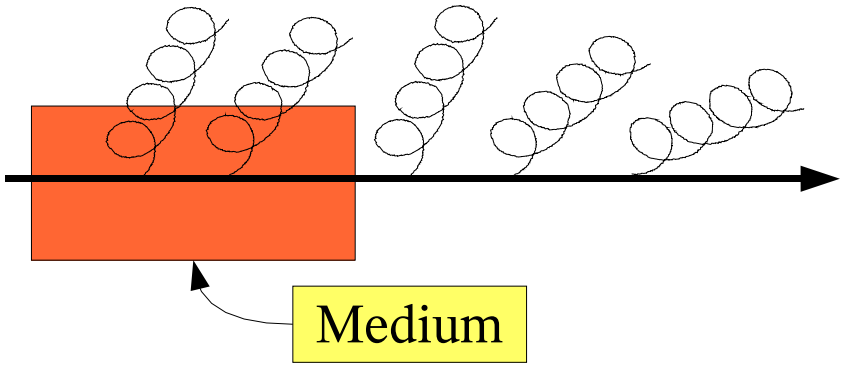
- Gluon radiation modified when the particle traverses a medium: medium-induced gluon radiation.



Probe to study medium properties.

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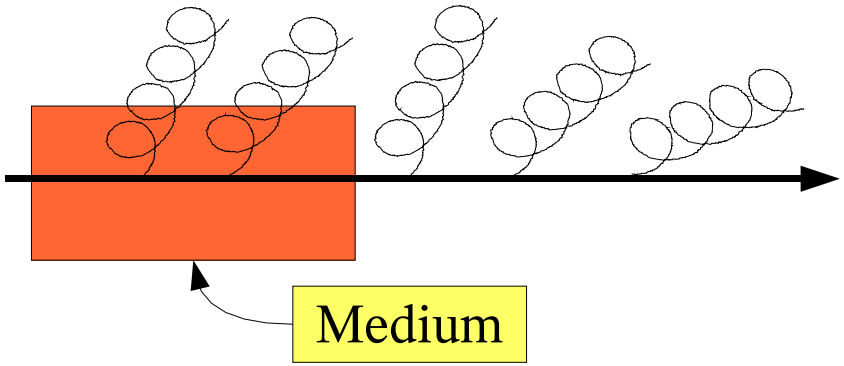
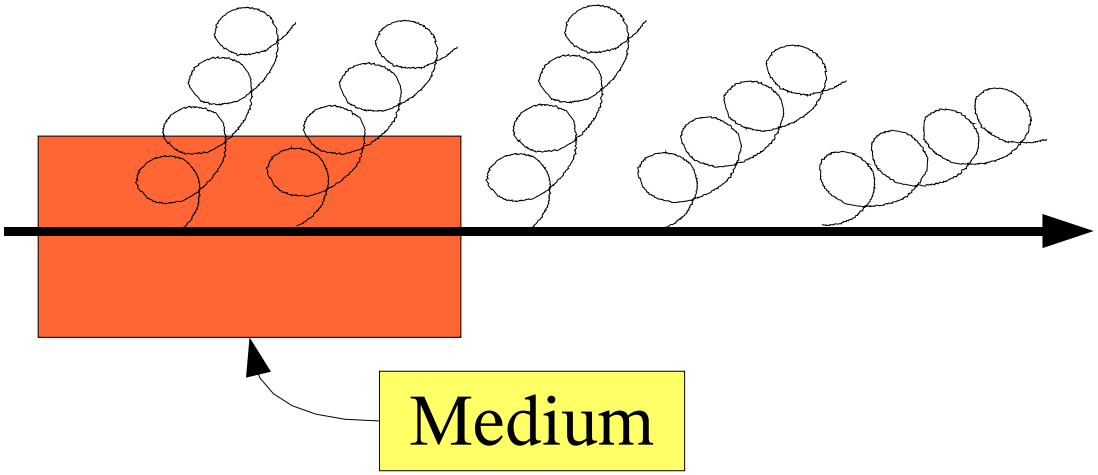


Probe to study medium properties.

- In the same framework that describes inclusive particle suppression:
  - Heavy quarks.
  - Jet properties $\rightarrow$ access to dynamics.

Jets



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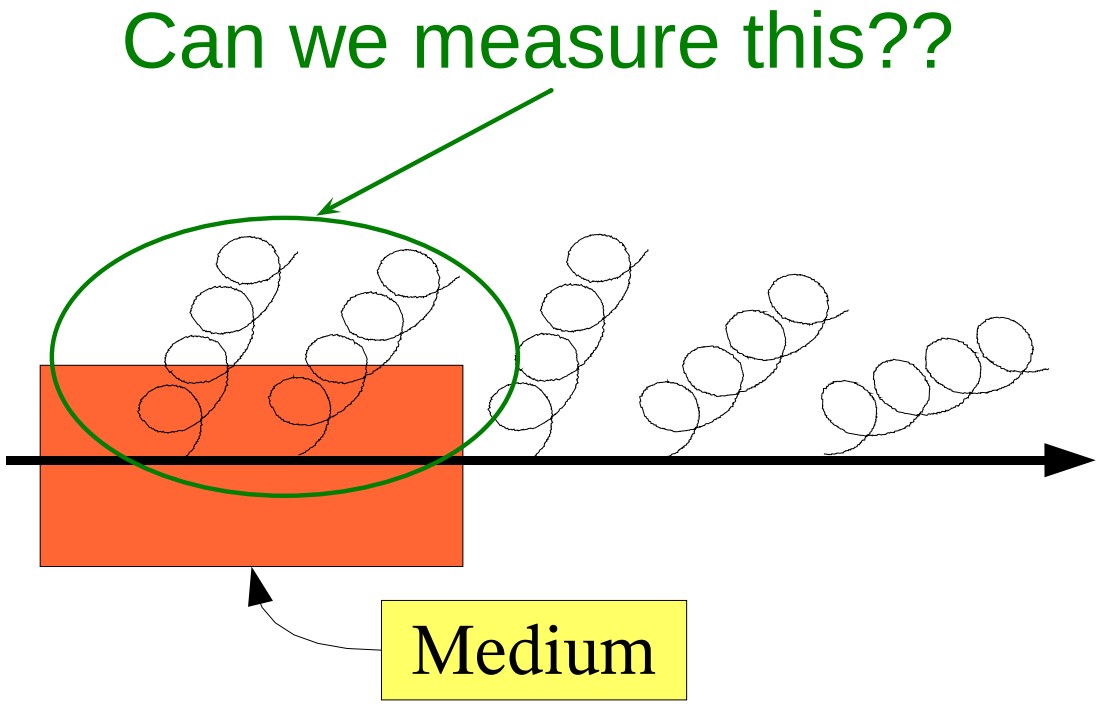
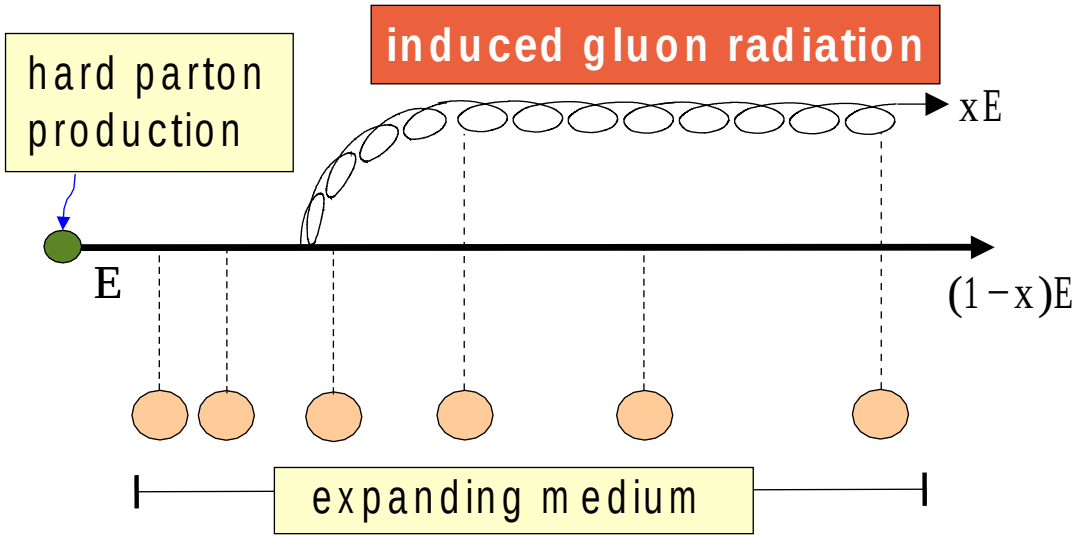
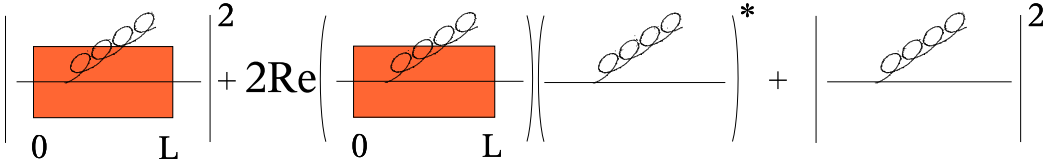


Medium–induced gluon radiation.



For media of finite length

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



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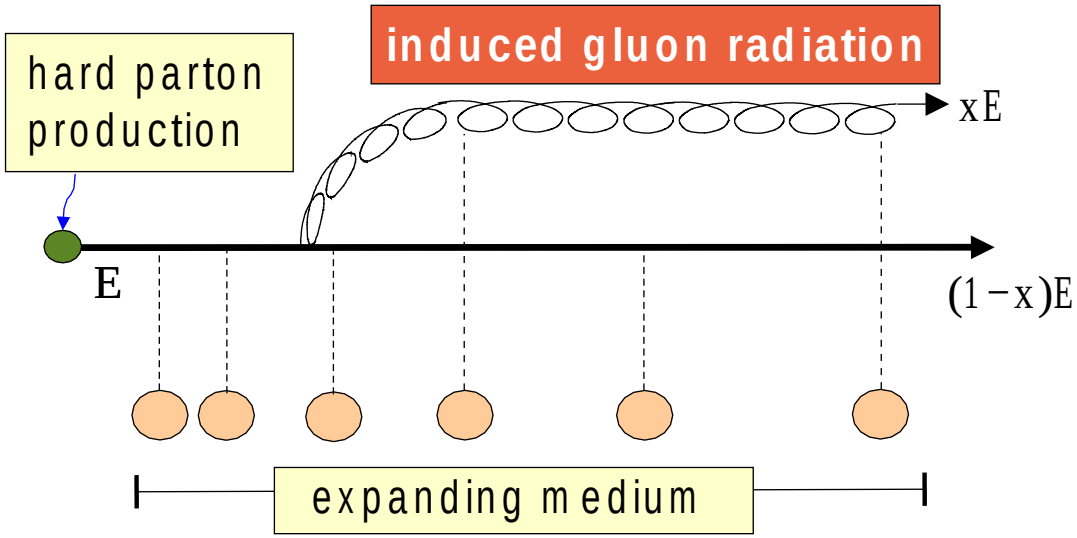

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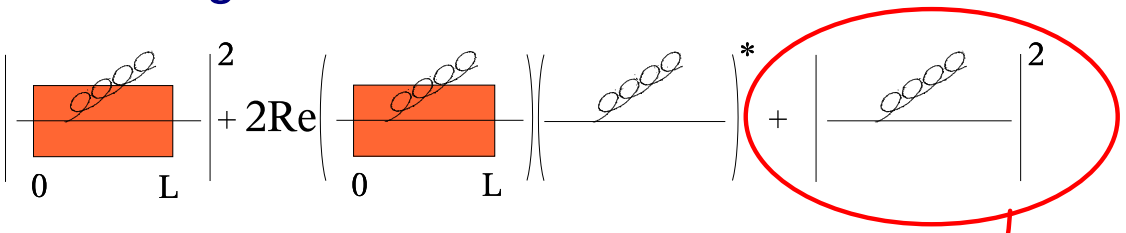


The medium induced gluon radiation

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

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

Coherent radiation

Coherence effects are important in high energy multiple scattering processes. For a gluon emitted with energy ω and $k_\perp$,

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

Medium $\longrightarrow$ transport coefficient $\hat{q} \simeq \frac{\mu^2}{\lambda}$, transverse momentum μ^2 per mean free path λ. So,

$$k_\perp^2 \sim \frac{l_{coh}}{\lambda}\mu^2 \Longrightarrow k_\perp^2 \sim \hat{q}L \qquad (\text{for } l_{coh} = L)$$

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

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

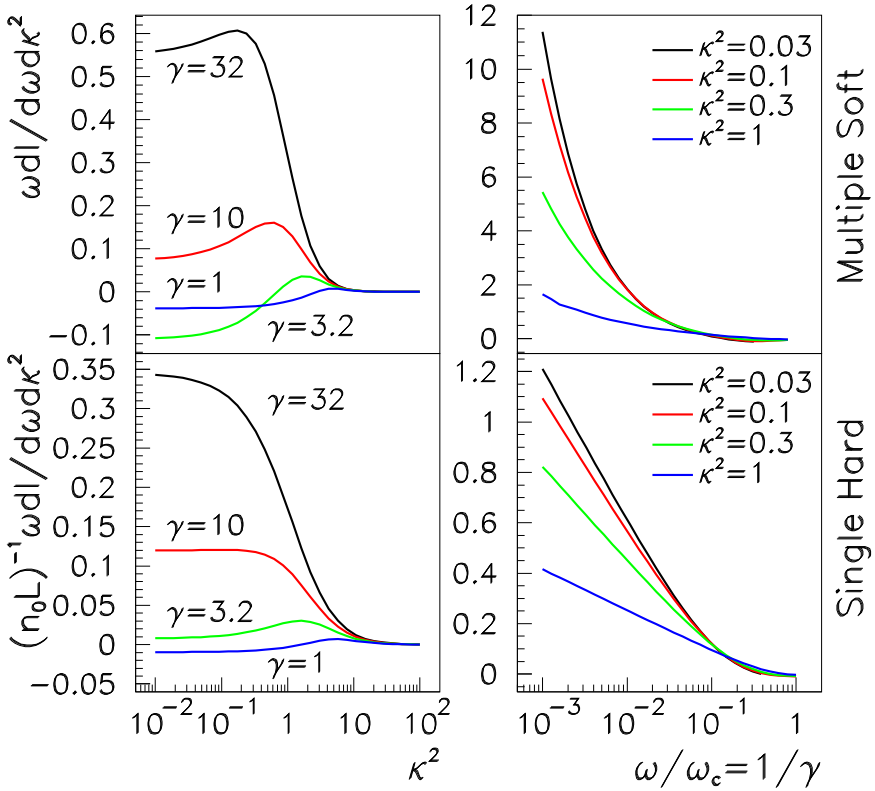
gluon emitted when $\varphi \gtrsim 1 \Longleftrightarrow$ radiation suppressed for $\kappa^2 \lesssim \omega/\omega_c$

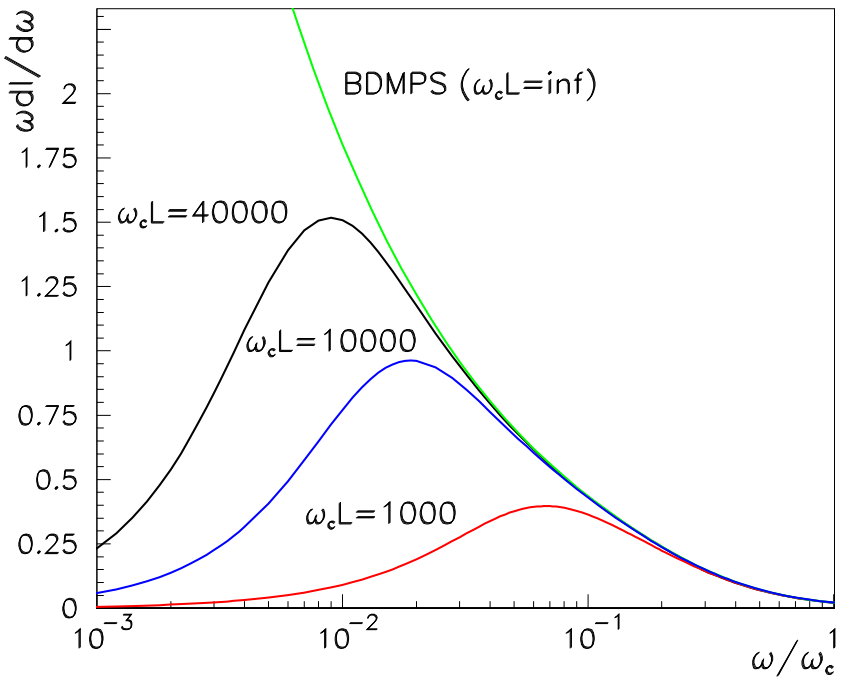
In cold nuclear matter: $Q_{sat}^2 = \hat{q}L \Longrightarrow \kappa^2 = \frac{k_\perp^2}{Q_{sat}^2}$

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

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

Infrared safe.

Heavy Quarks

- In the vacuum, small-angle radiation suppressed $\longrightarrow$ dead cone effect

$$\frac{1}{k_\perp^2} \quad \rightarrow \quad \frac{k_\perp^2}{\left(k_\perp^2 + \frac{\omega}{E} m^2\right)^2}$$

- Dokshitzer-Kharzeev PLB519 (2001) 199 same factor for medium-induced radiation taking

$$k_\perp^2 \sim \sqrt{\hat{q}\omega}$$

- Recent developments (2003):
  - Djordjevic and Gyulassy, PLB560, 37; PRC68, 034914; nucl-th/0310076
  - Zhang, Wang and Wang, nucl-th/0309040
  - Armesto, Salgado and Wiedemann, hep-ph/0312106

Heavy Quarks

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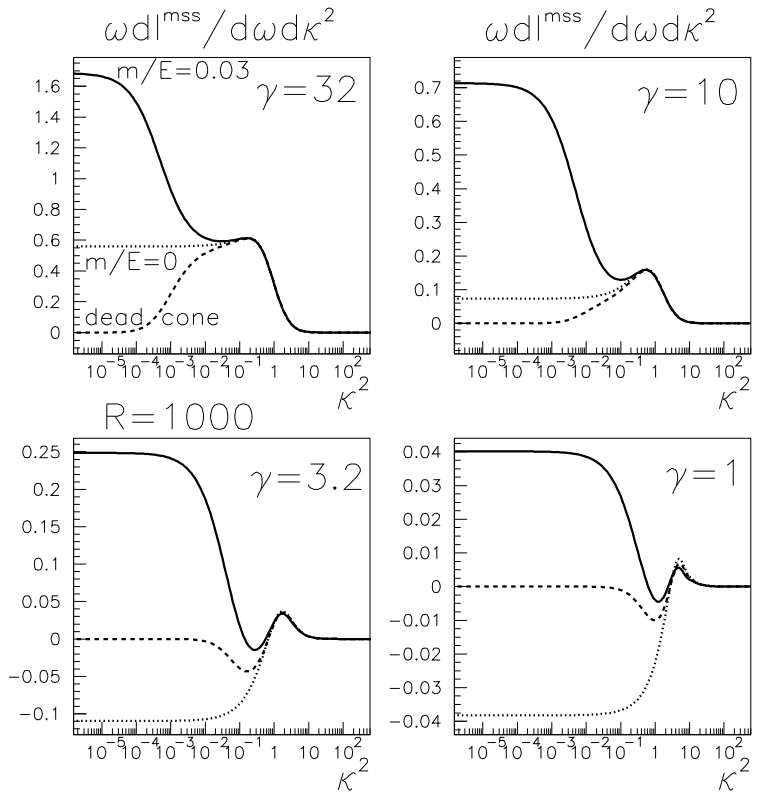
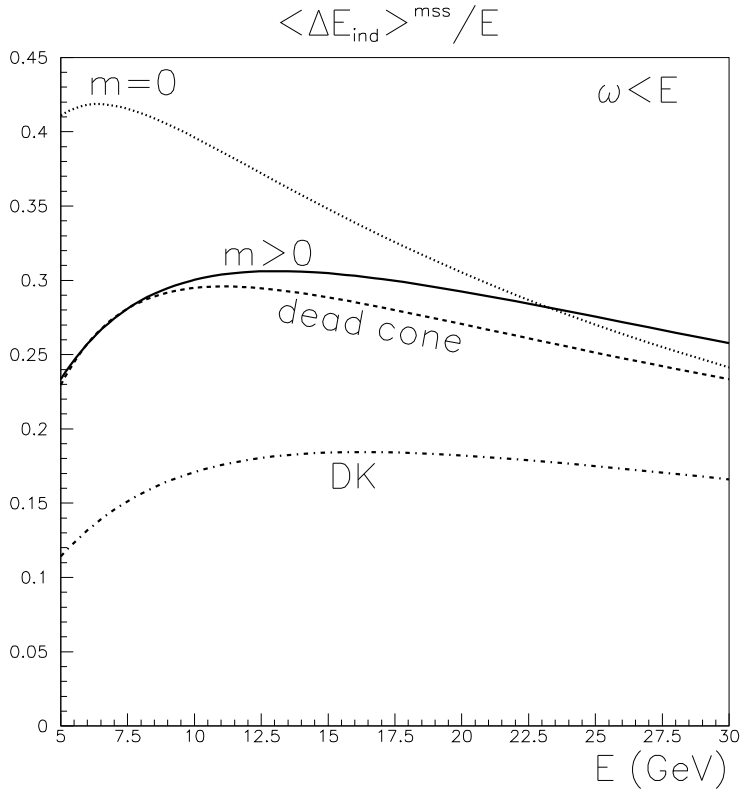


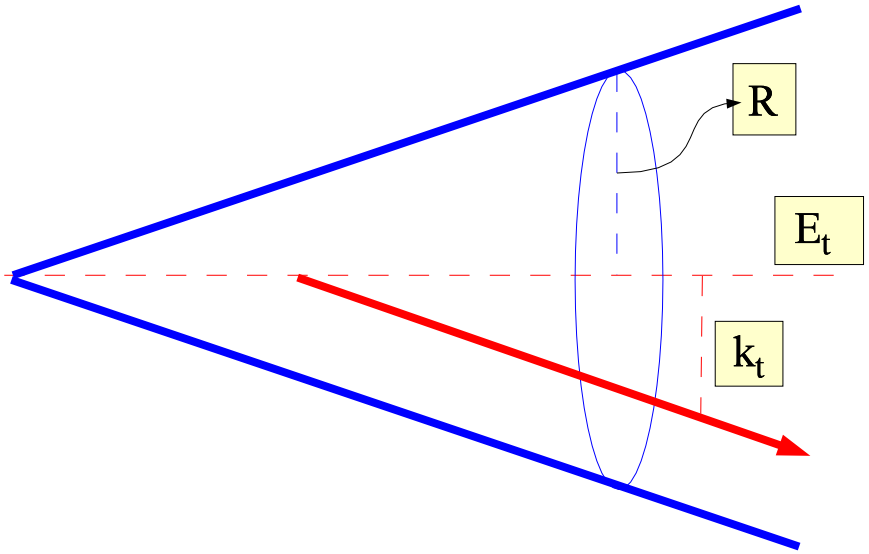
The dead cone is filled!



Smaller suppression than for light quarks, but not negligible.

Jet shapes

With the ω and $k_\perp$-differential spectrum it is, in principle, possible to compute the medium-effects on jet observables.



Jet shapes

$\rho(R)$, fraction of the jet energy inside a cone $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

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

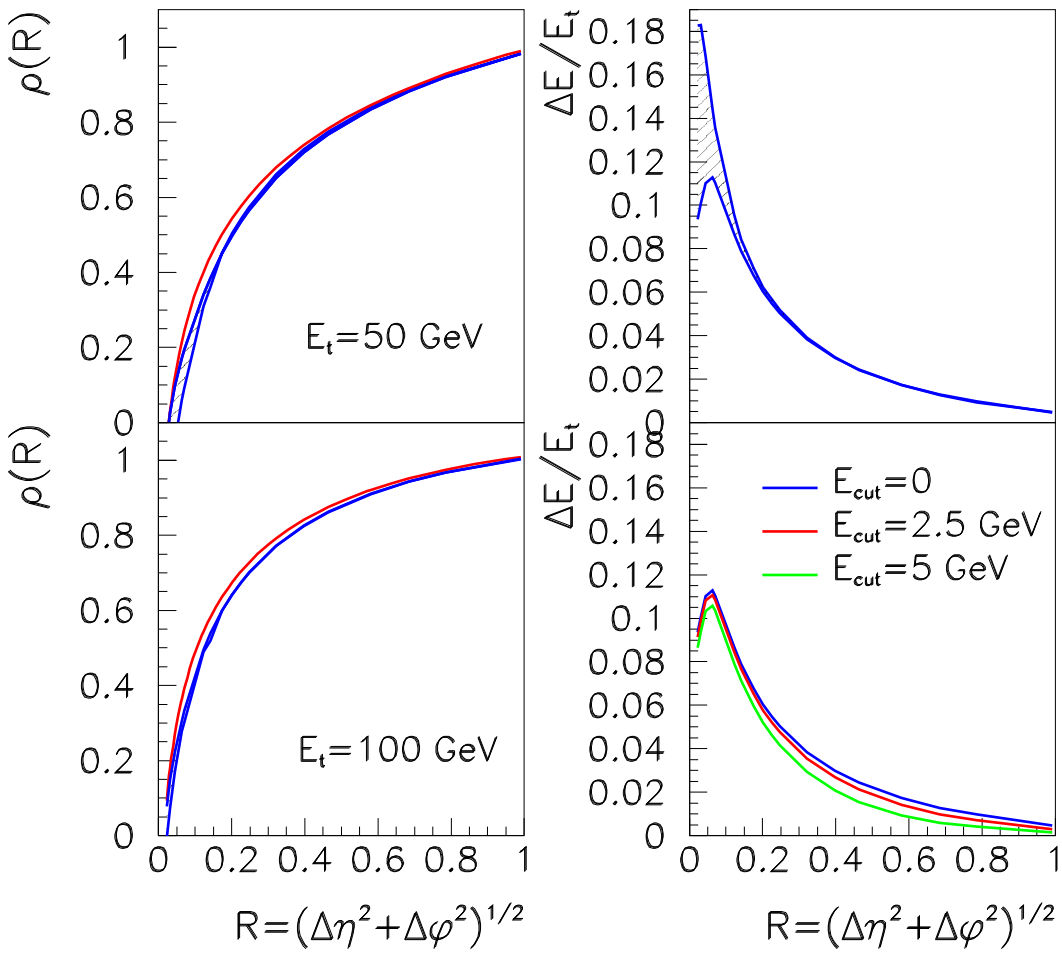
$$\rho_{\rm med} = \rho_{\rm vac} - \frac{\Delta E_t(R)}{E_t(R=1)} + \frac{\Delta E}{E_t}(1 - \rho_{\rm vac}(R))$$

Small modification → can jet energy be determined experimentally above background??

Scaling with number of collisions for large cone angle.

Small sensitivity to IR cuts!

(Salgado, Wiedemann hep-ph/0310079)



Vacuum D0 data: Fermilab-PUB-97/242-E

Gluon multiplicity inside the jet.

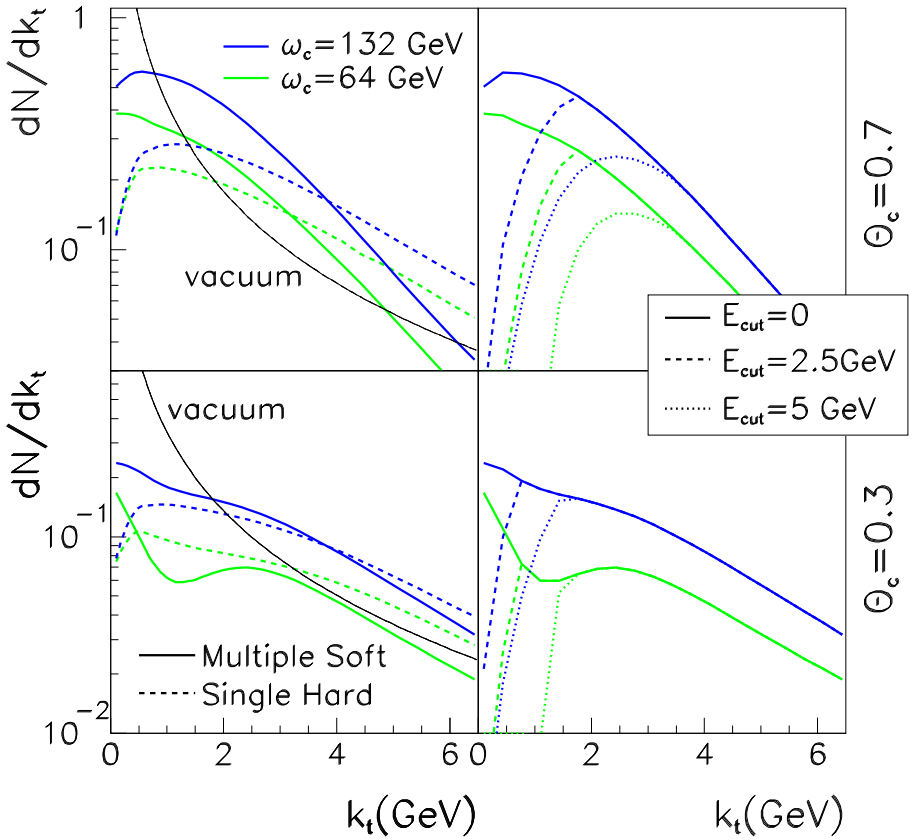
The characteristic angular distribution of the medium–induced gluon radiation could be better observed in the quantity

$$\frac{dN^{\rm jet}}{dk_\perp} = \int_{k_\perp/sin\theta_c}^{E} d\omega \frac{dI}{d\omega dk_\perp}$$

For the vacuum we simply use

$$\frac{dI_{\rm vac}}{d\omega dk_\perp} \sim \frac{1}{\omega}\frac{1}{k_\perp}$$

Needs a more quantitative analysis.

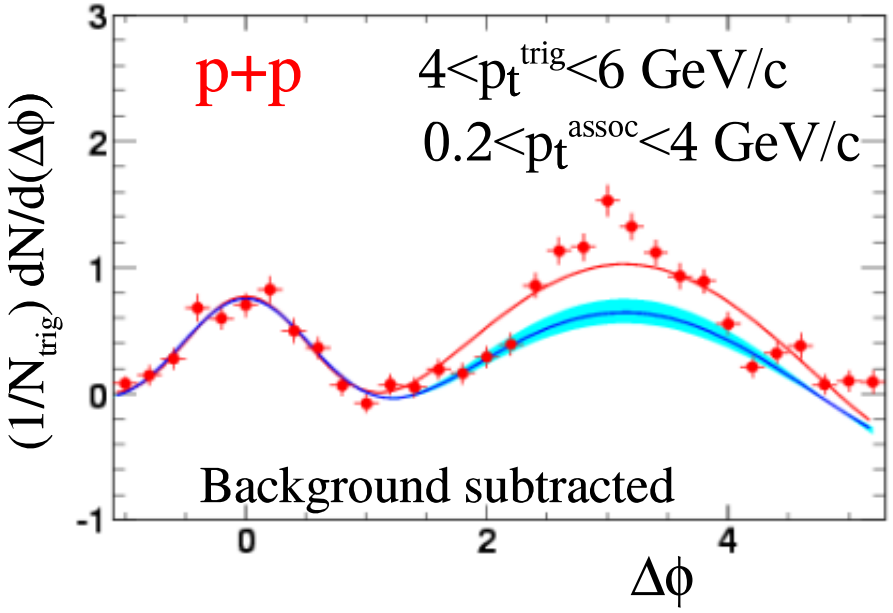


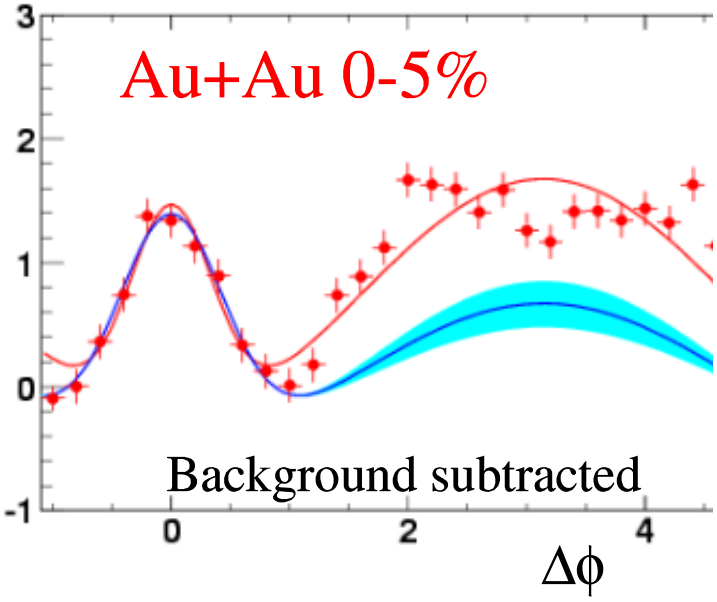
(100 GeV jet)

But, effect based mainly on kinematics!

News from RHIC (from Mike Miller's Wednesday talk)

STAR preliminary





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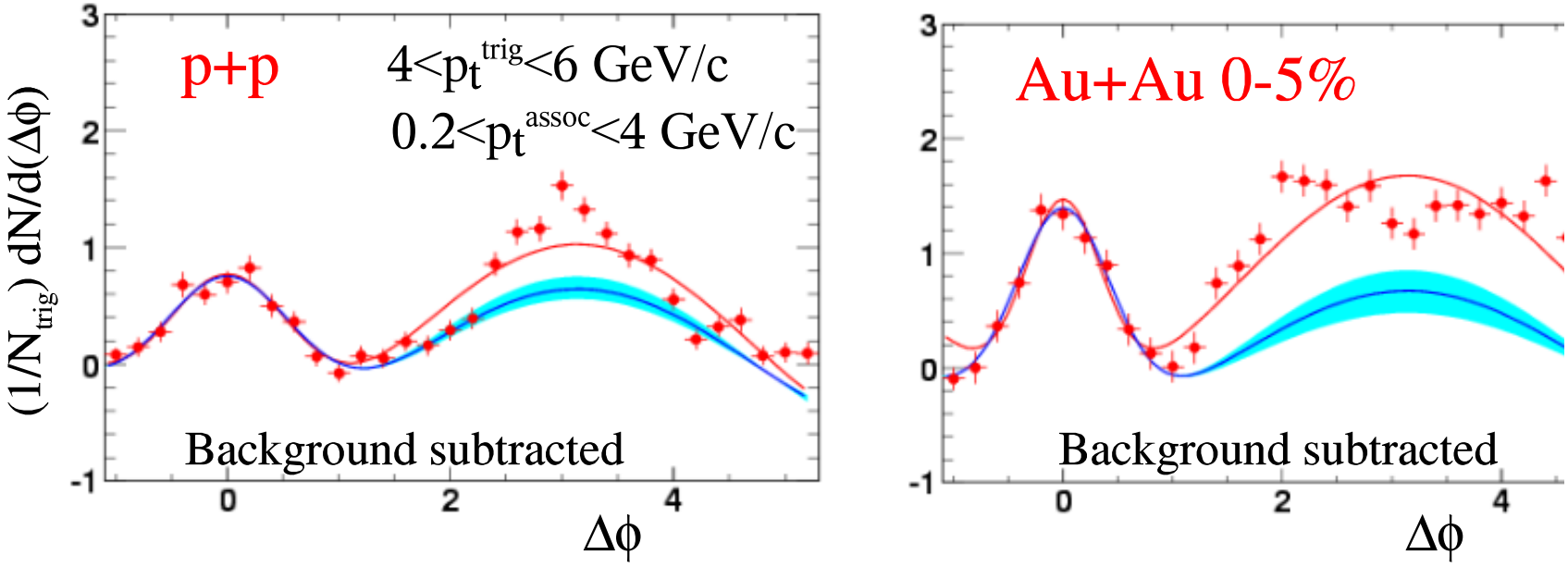

⇒ In qualitative agreement with PHENIX results

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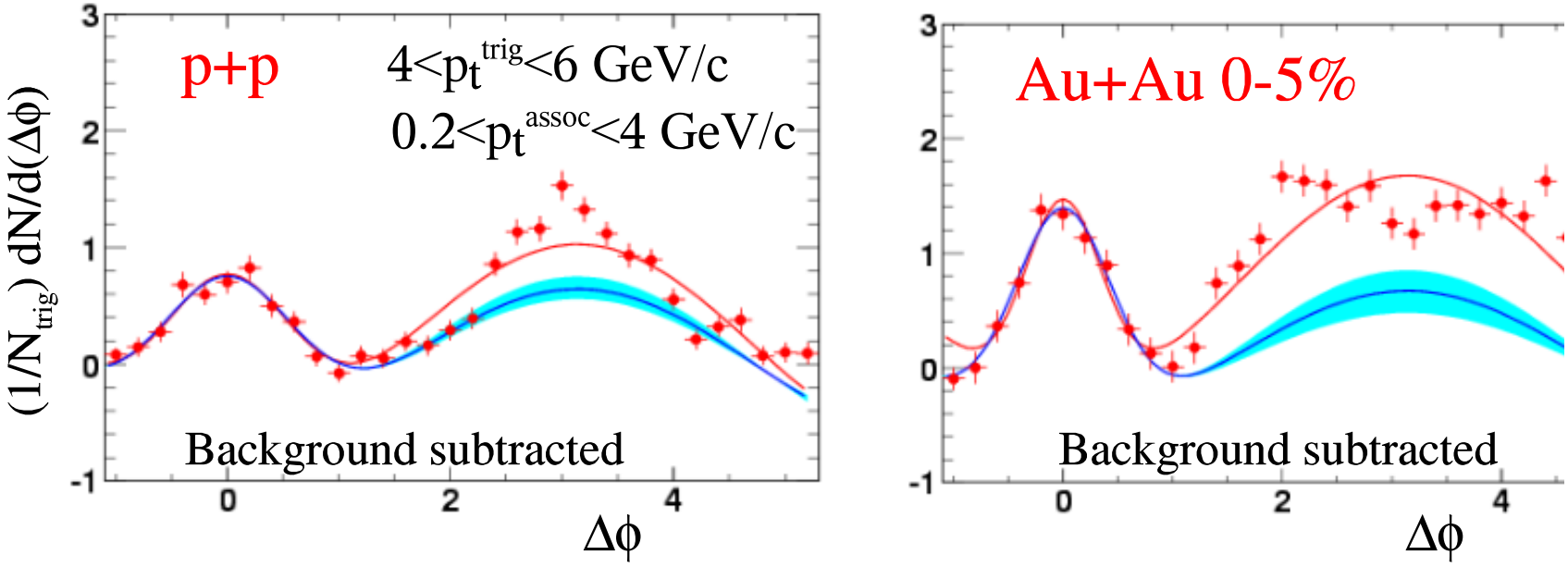

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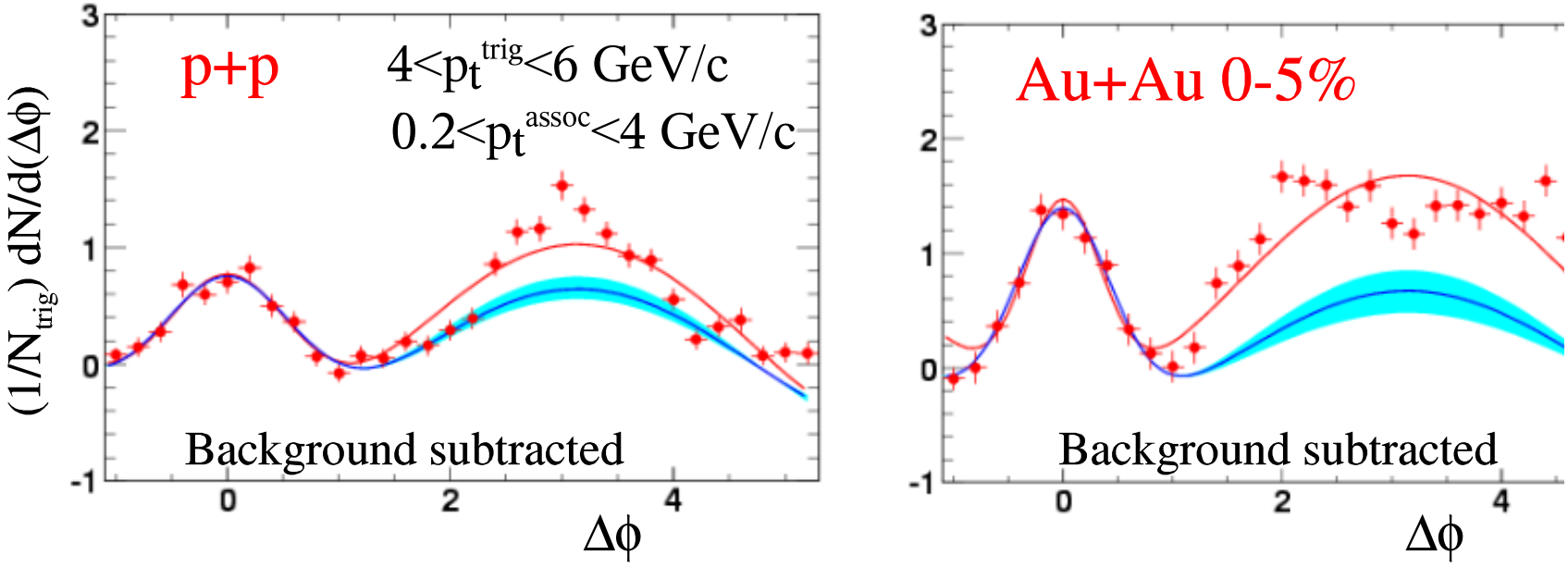

- In qualitative agreement with PHENIX results
- Also in qualitative agreement with theoretical expectations
- However, not directly comparable with our results in previous slide: thermalization?

Conclusion

- RHIC high-p_t results strongly point to a final state effect in central AuAu. In agreement with jet-quenching interpretation.
- Medium–induced gluon radiation computed
  - ω and k_t-differential: Radiative energy-loss $\Longleftrightarrow$ k_t-broadening.
  - k_t-integrated spectrum: Small IR-sensitivity.
- Jet shapes $\rightarrow$ Measure jets above background?
  - Small effect in the azimuthal redistribution of jet energy.
  - k_t-differential spectrum inside the jets could be a clean observable.

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