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

4. Experimental/theoretical status

Experiments

- 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.
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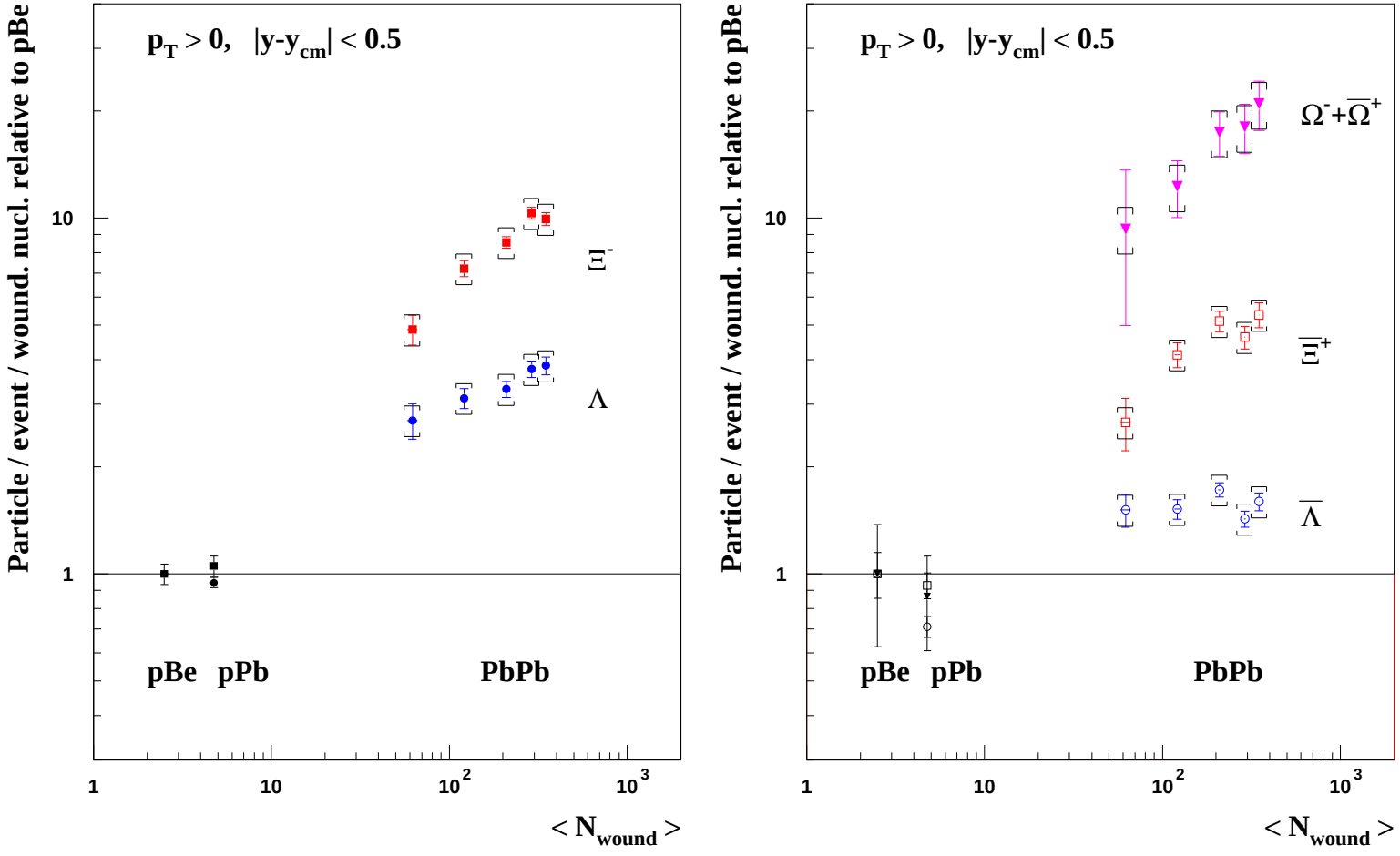
- LHC at CERN
  - Will collide PbPb at $\sqrt{s} = 5500$ AGeV (also pPb and smaller systems possible)

Pre-RHIC

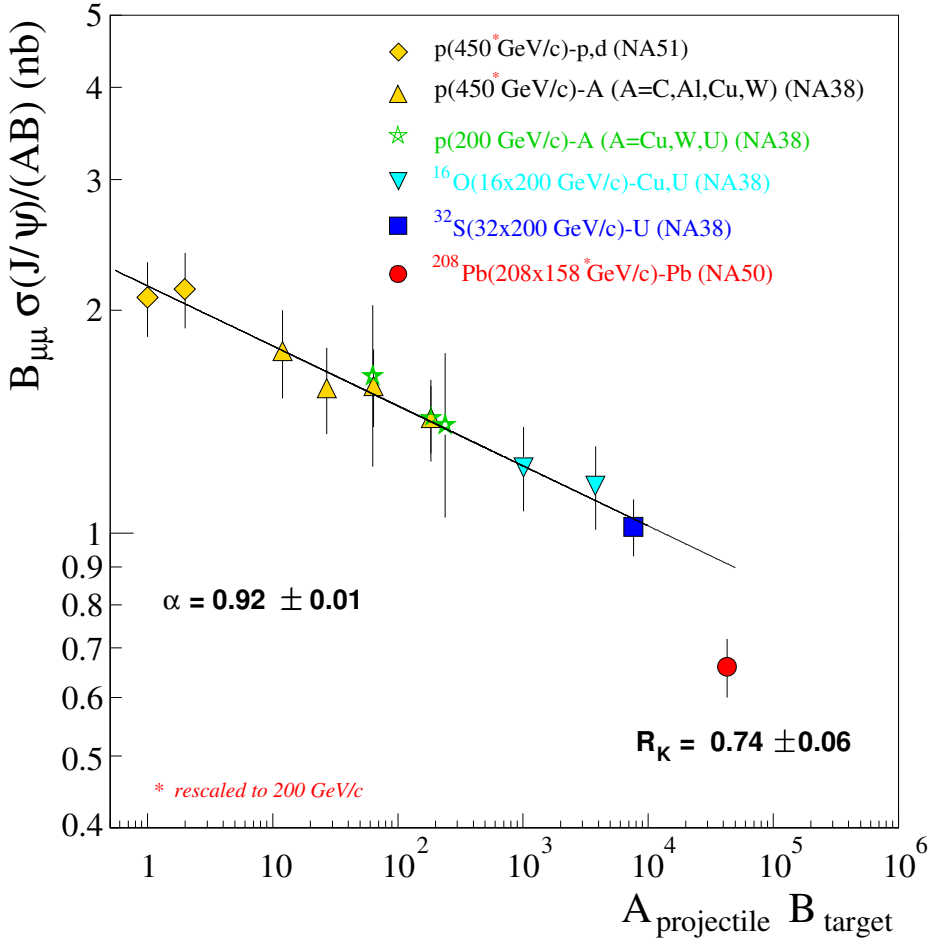
Reference???

Strangeness enhancement



Enhancement also present in pA (not shown)

J/Ψ suppression



Suppression also present in pA collisions.

Main problem for SPS

Effects present in pA collisions

Initial state effects

RHIC: two main signals

Elliptic flow

Jet quenching

Elliptic flow

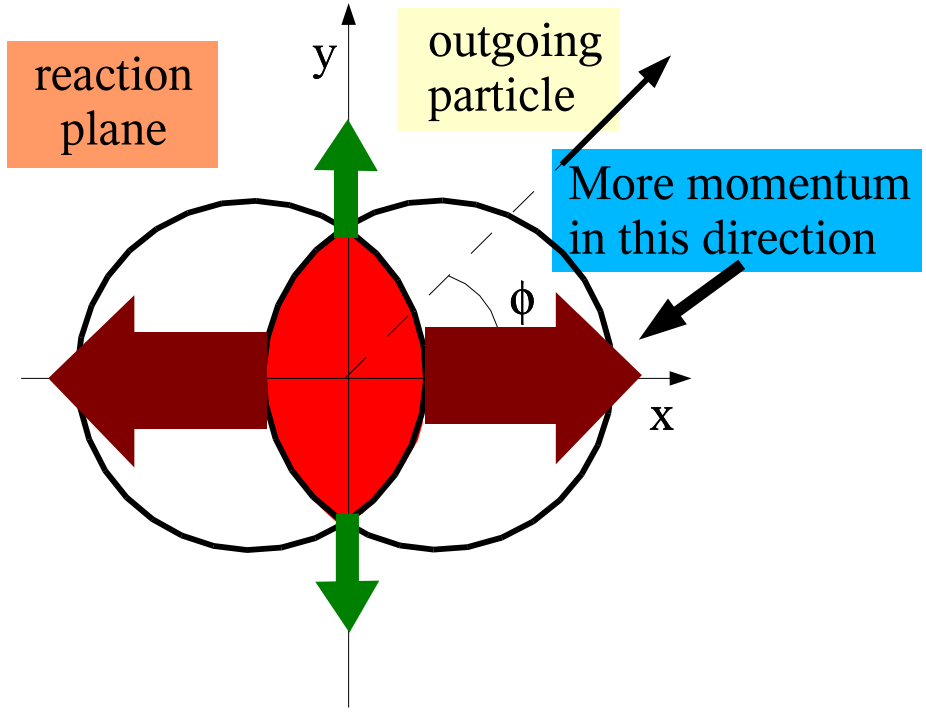
Gradients are more easily produced in asymmetric media: Changing the centrality of the collision.

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

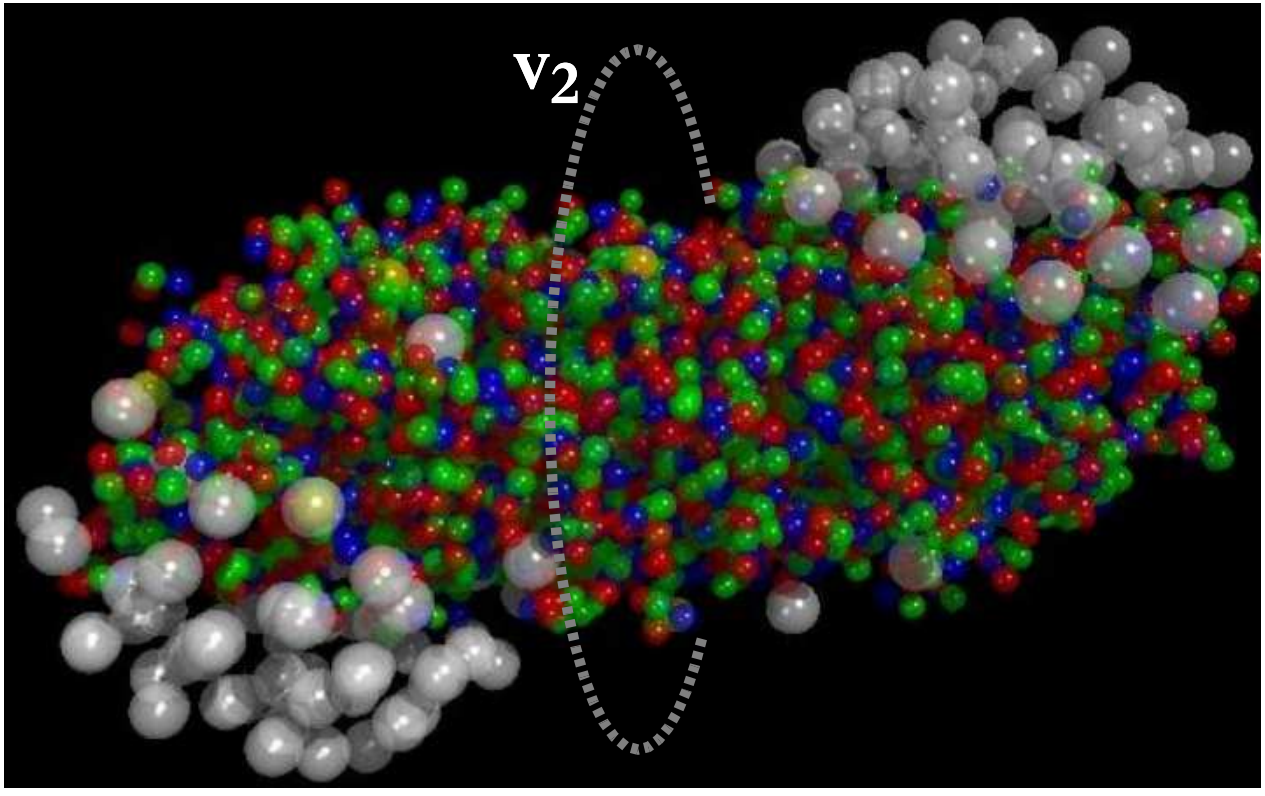
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n\phi)$$

v_n characterize the strength of the anisotrotropic flow.

- ⇛ v_2 elliptic flow.

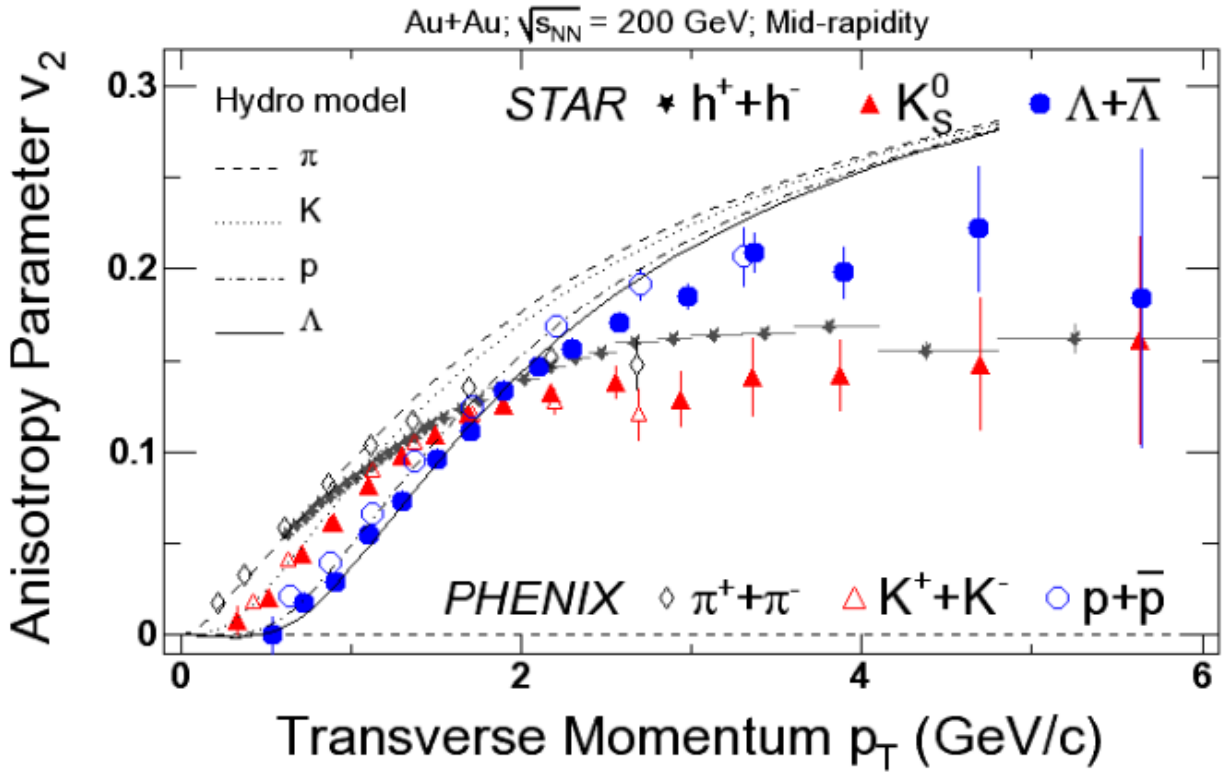


Elliptic flow



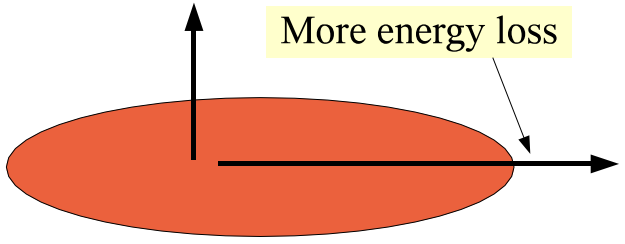
- ⇛ Peripheral collisions produce very asymmetric media with gradients of energy density $\longrightarrow$ pressure.
- ⇛ This produces elliptic flow

Elliptic flow at high-p_t



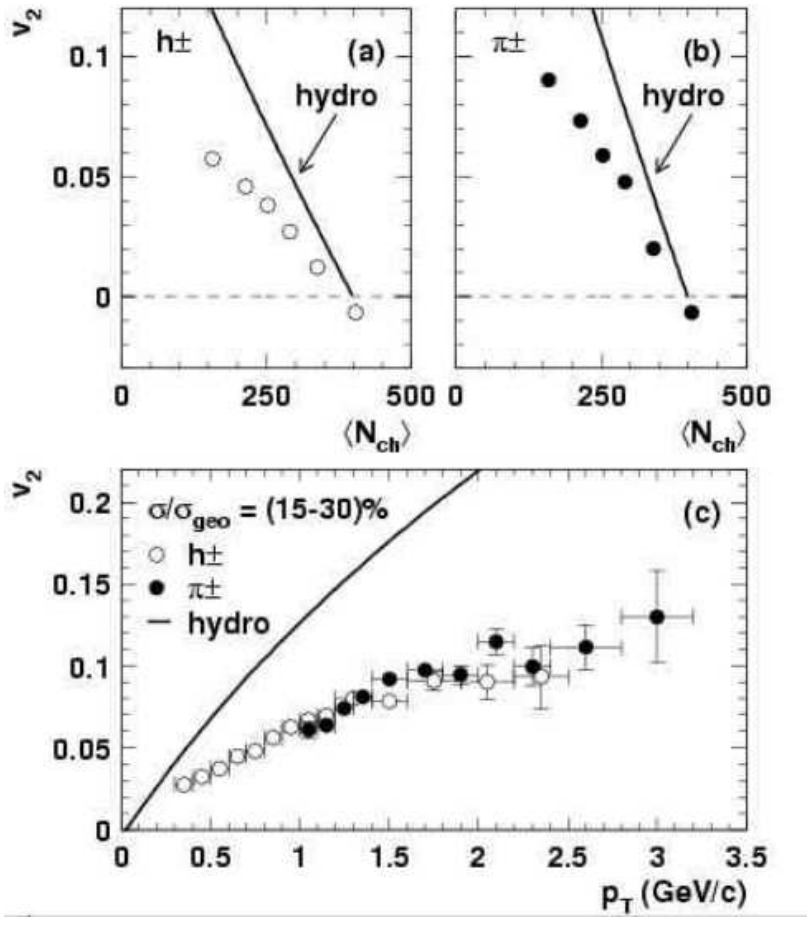
⇛ Hydrodynamical models can reproduce data for small$-p_t$.

⇛ Large-p_t perhaps energy loss:



Elliptic flow at SPS

Elliptic flow



Smaller than hydrodynamical expectations.

Is this a QGP?

⇒ For a QGP we need a thermalized partonic medium.

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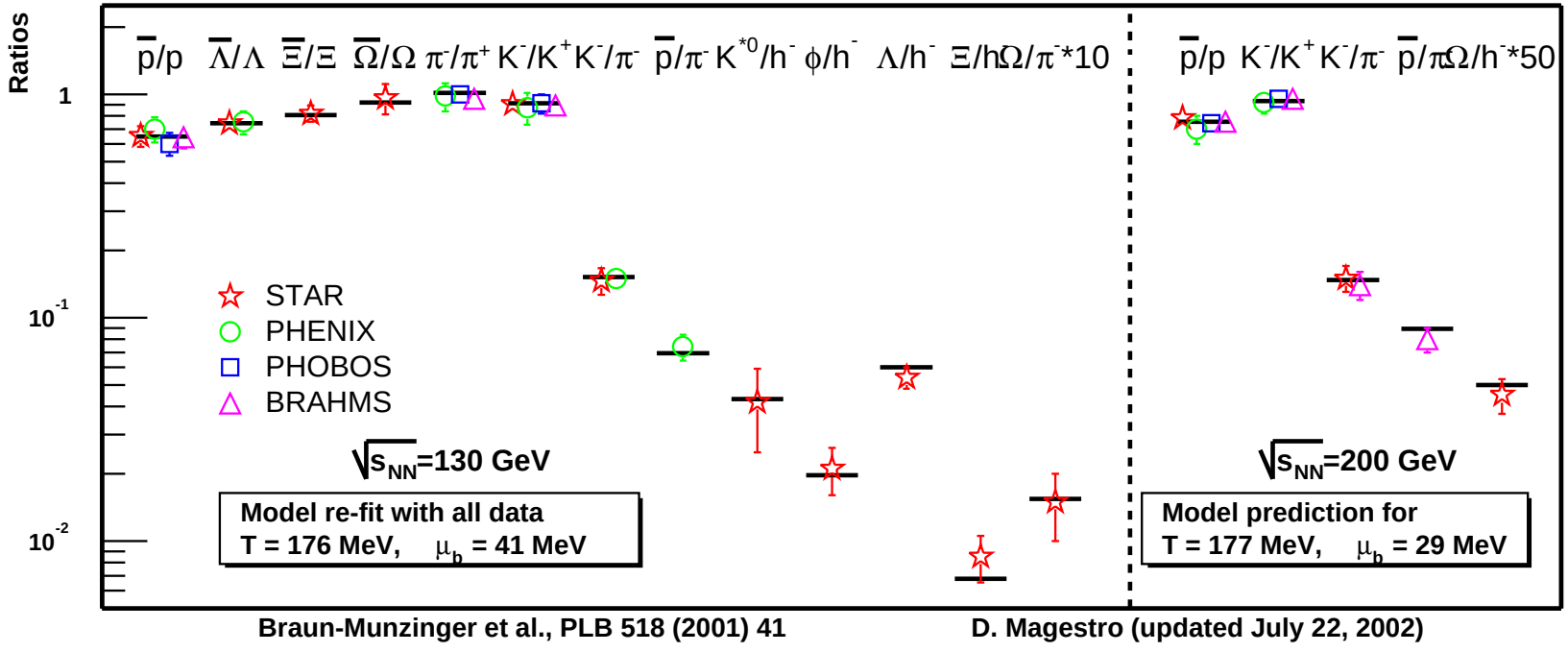
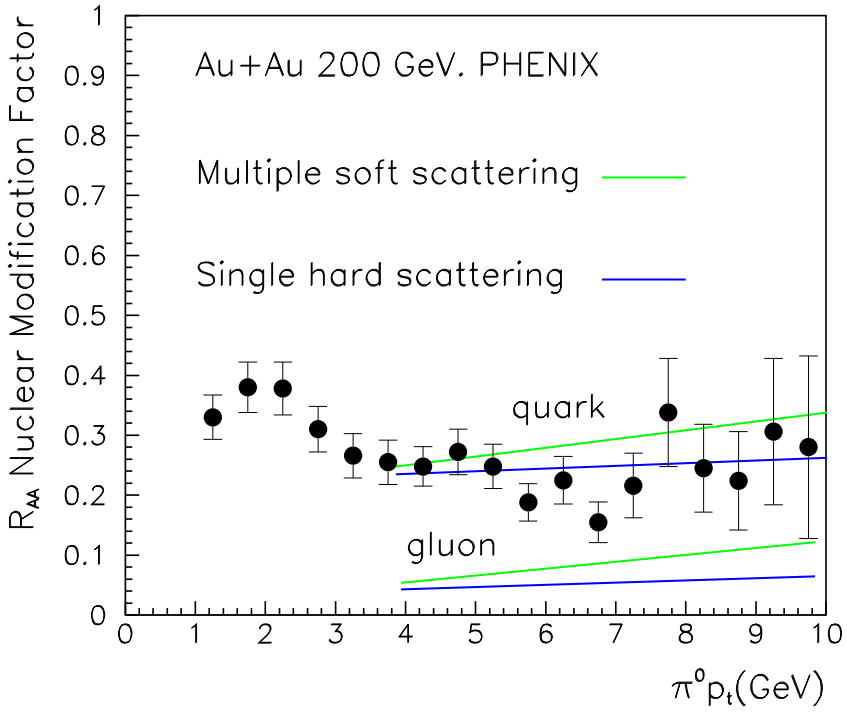


⇛ In favor of thermalization, but calculations done for a hadronic gas.

High-p_t particle production

High-p_t particle suppression has been proposed as a signal of QGP formation $\longrightarrow$ jet quenching.



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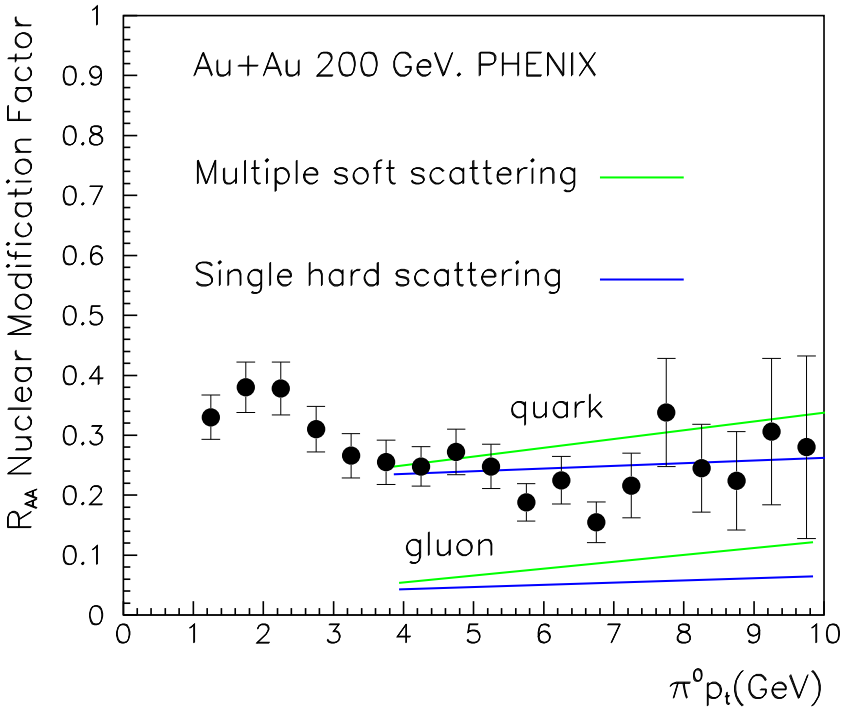

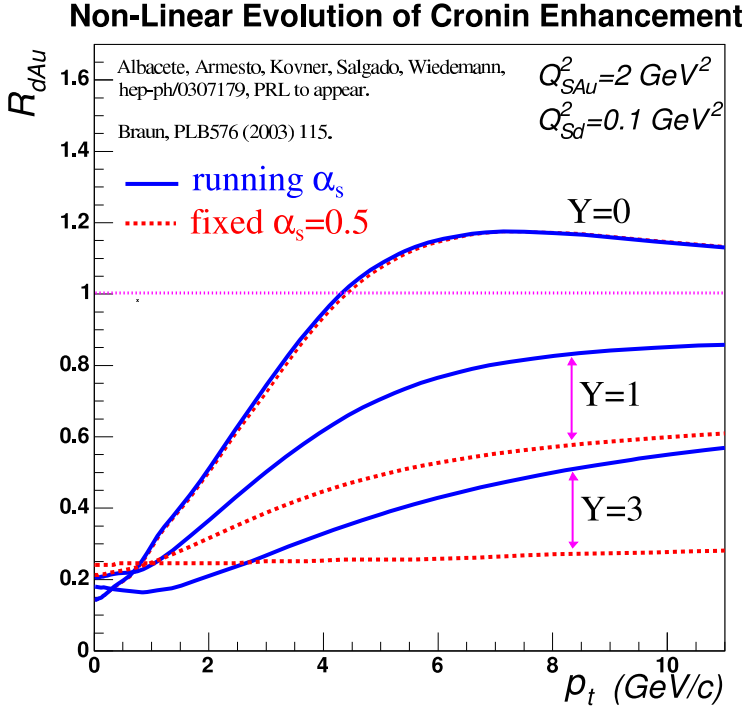

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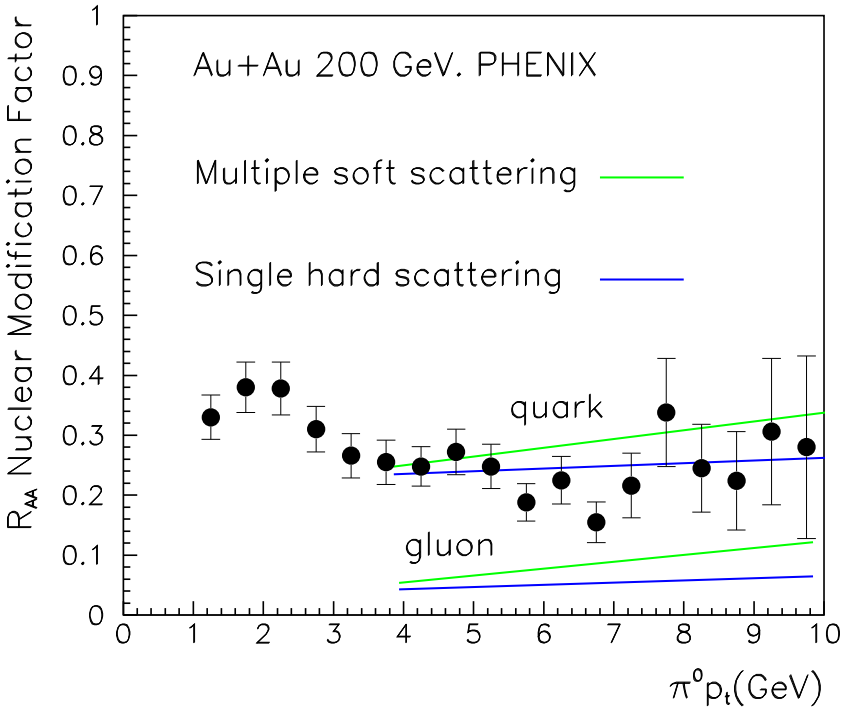
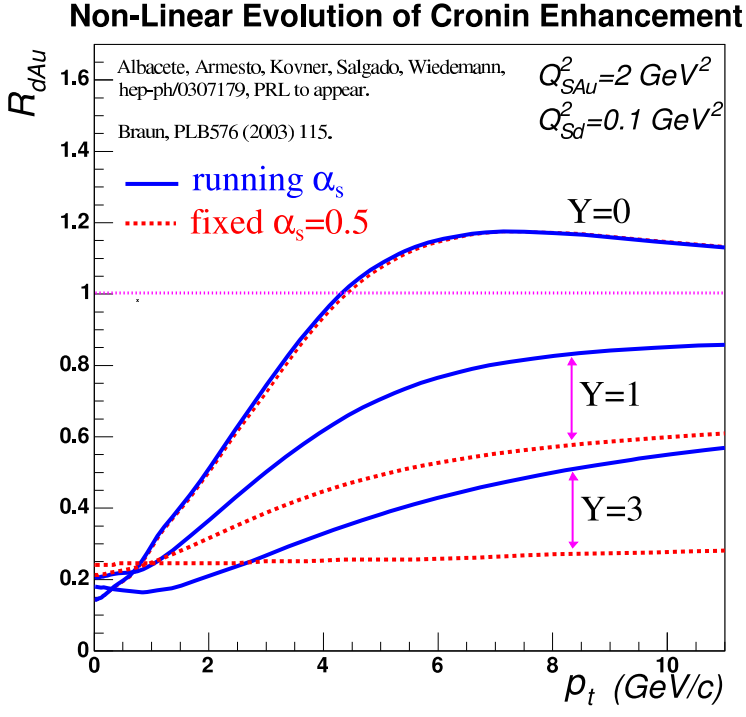




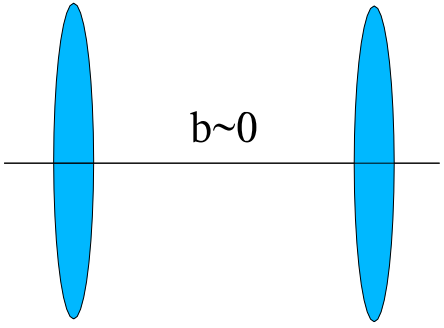
Is this suppression in central AuAu an initial of final state effect?

dAu collisions in RHIC

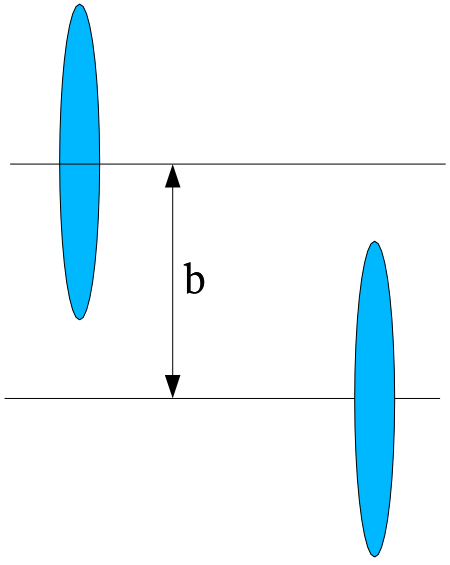
In order to answer this question $\longrightarrow$ deuteron-gold collisions at RHIC

- $\Rightarrow$ In dAu no dense final state is created
- $\Rightarrow$ All the effects are initial state effects and will be present in AuAu as well

Recall centrality



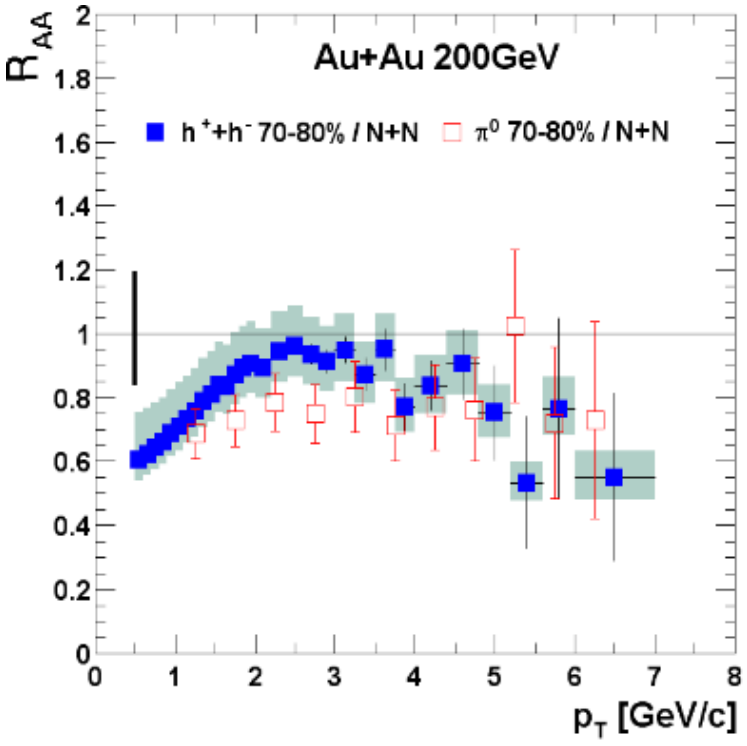
Central collision

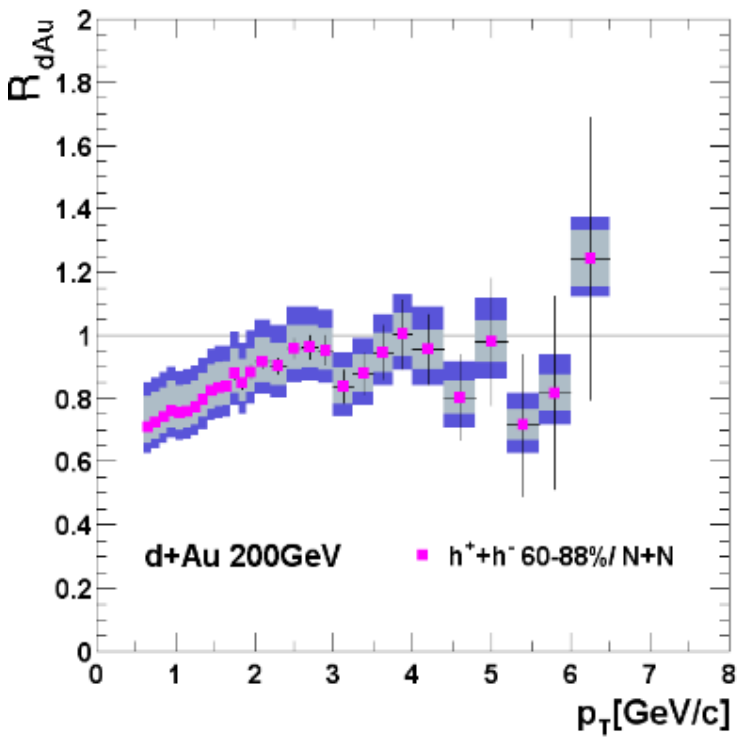


Peripheral collision
No/small effects.

High-p_t I: Inclusive particle spectra

$$R_{AA(dA)} = \frac{1}{N_{\rm coll}} \frac{dN^h_{AA(dA)}/dp_t}{dN^h_{pp}/dp_t}$$





Centrality dependence

Peripheral collisions scale with $N_{\rm coll}$ for $p_t \gtrsim 2$ GeV/c.

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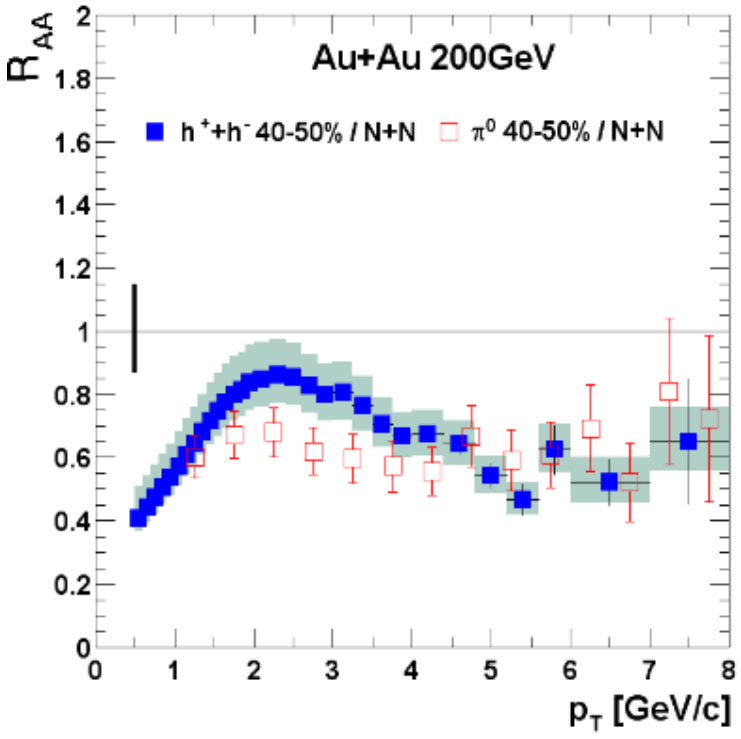

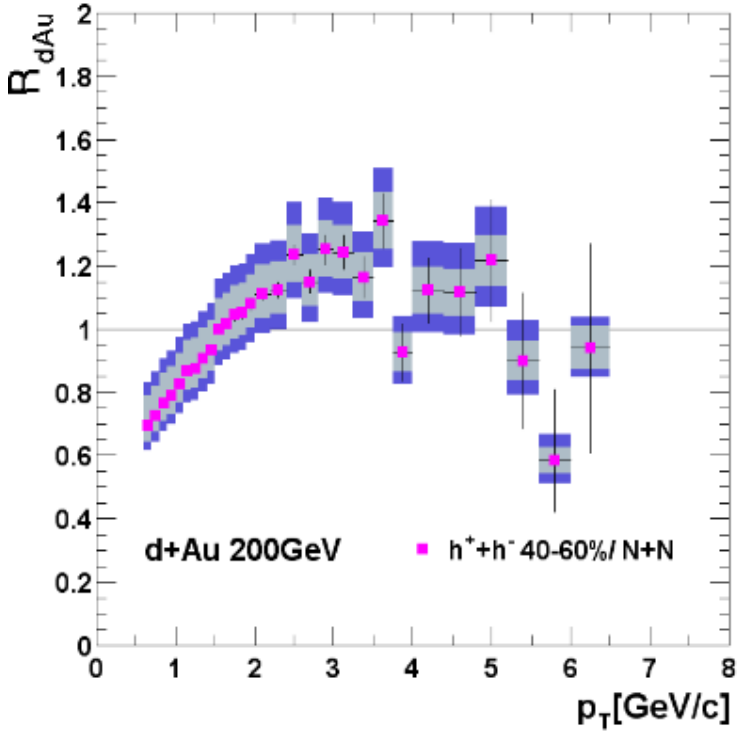

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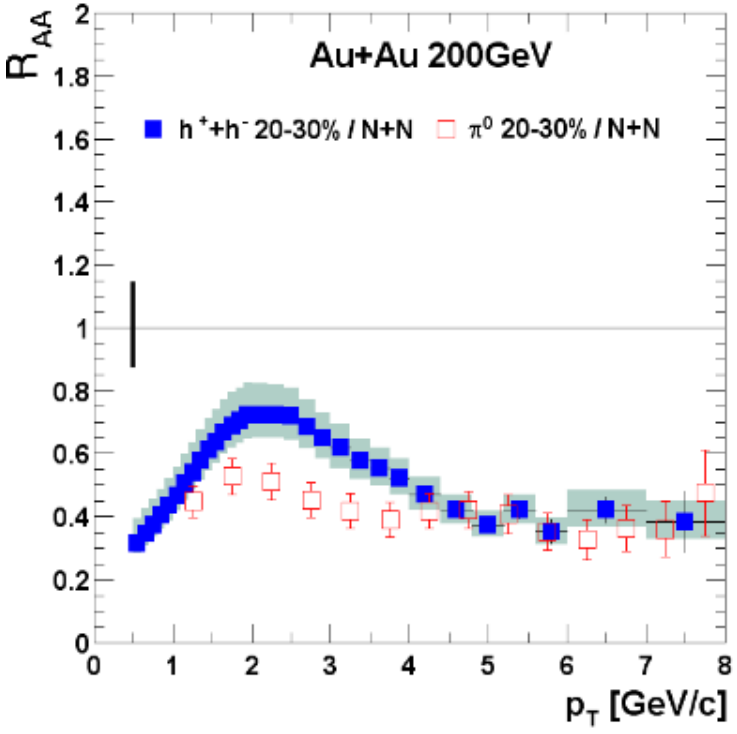

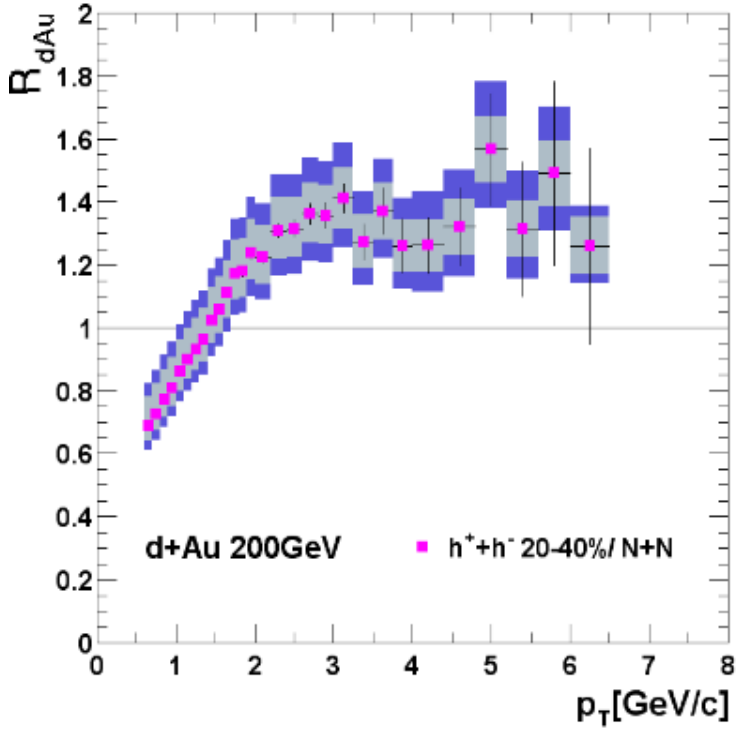

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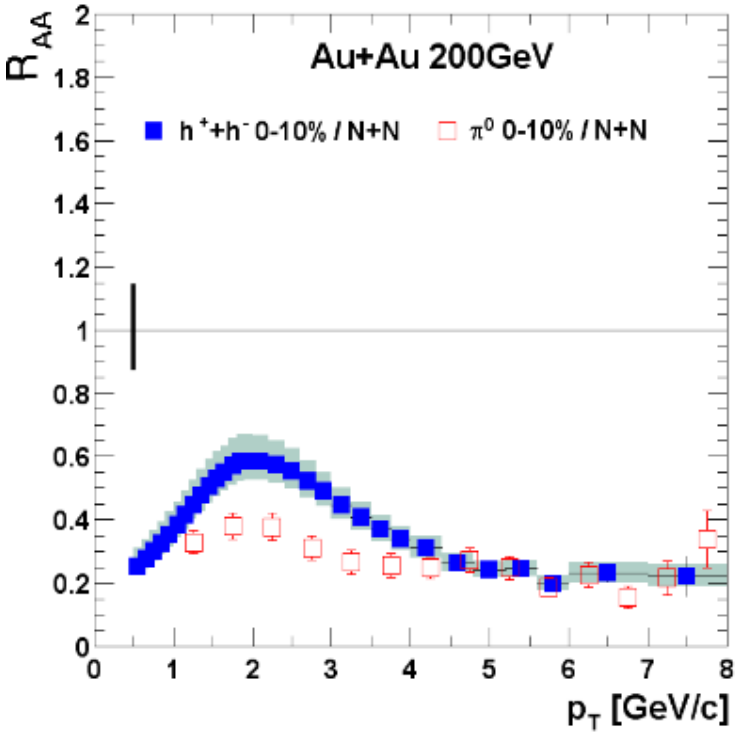
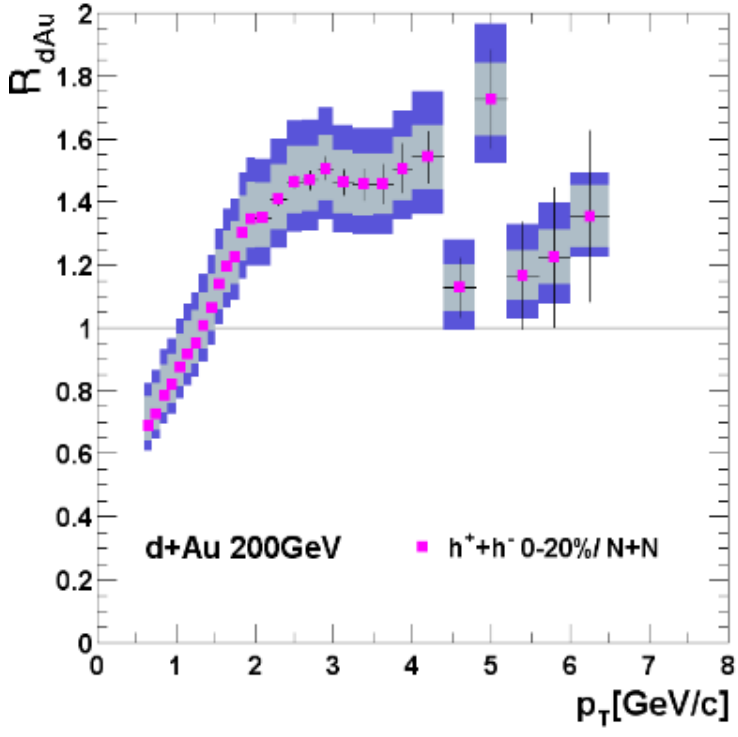




Centrality dependence

Suppression in AuAu due to final state.

Ok, the effect is opposite in AA and pA

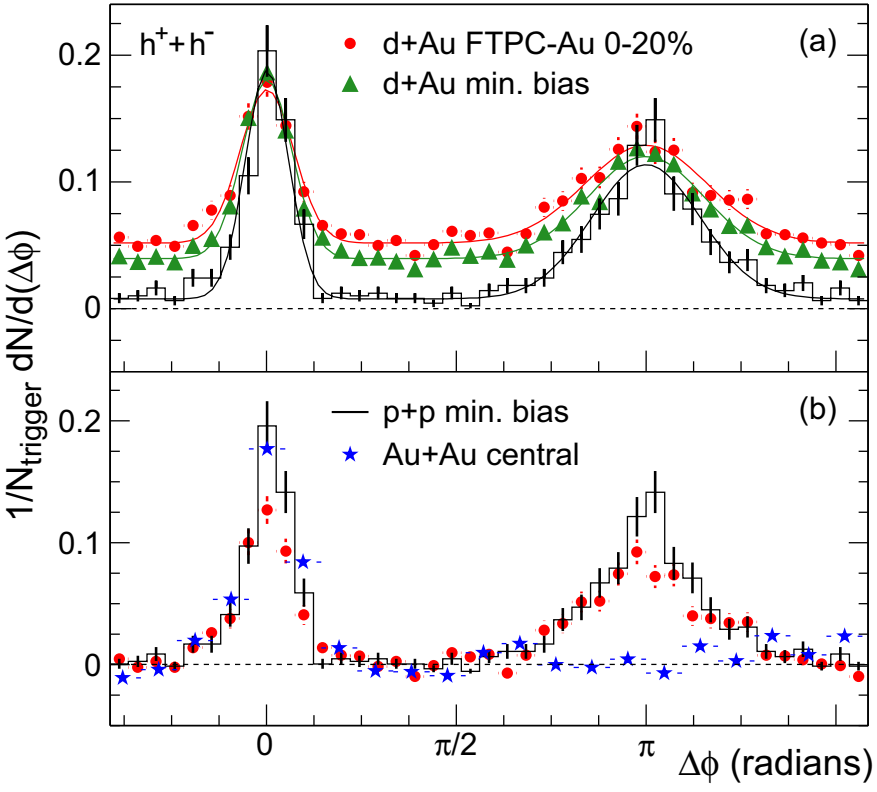
(for the first time!)

High-p_t II: back-to-back correlations.

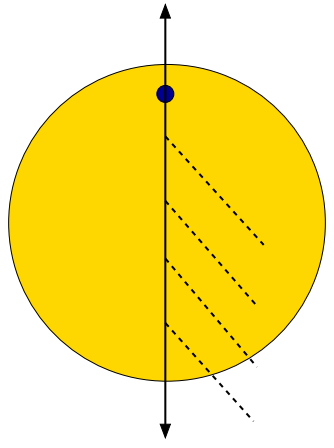
⇛ Azimuthal distributions ($0< |\Delta\eta| <1.4$, $4< p_T^{trig} <6$ GeV/c).

⇛ Typical of jet production.

STAR data (PRL 91 (2003) 072304)



Particles produced close to the surface are less suppressed. (Notice that $\Delta E \sim L^2$)



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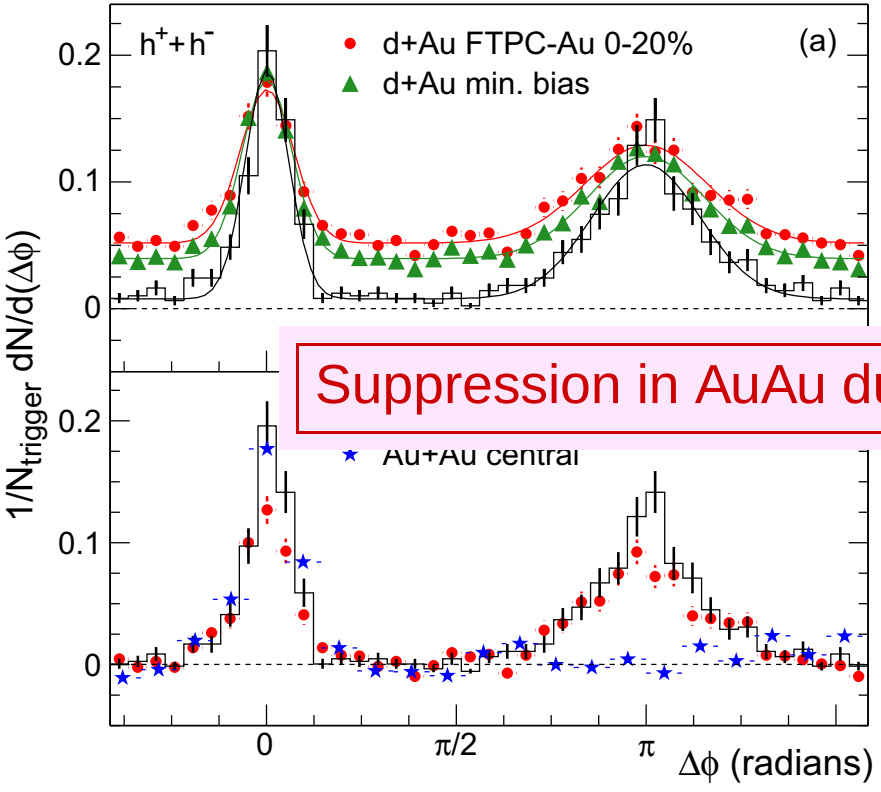

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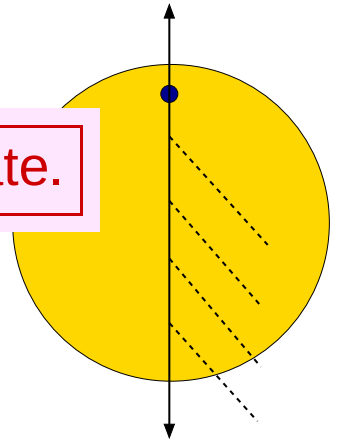

Jet quenching interpretation

Can this (final state) effect be described by energy loss by medium-induced gluon emision (previous lecture)
We assumed

⇒ The high-p_t quark or gluon hadronizes outside the medium

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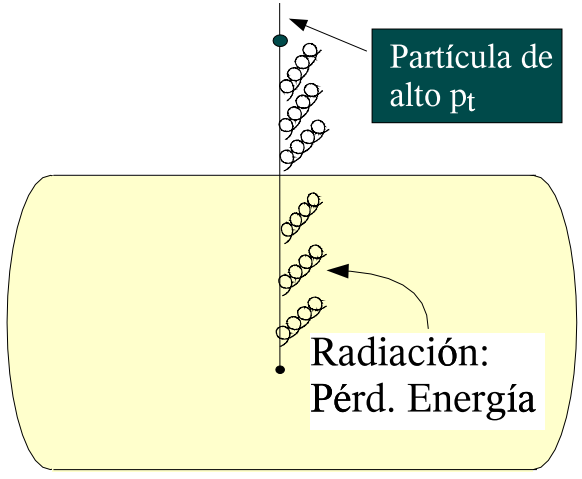

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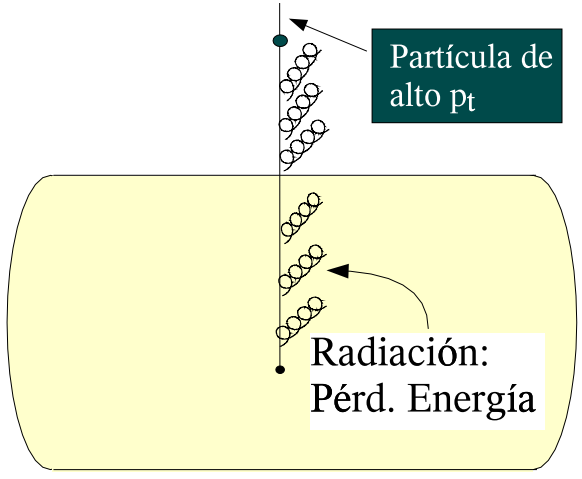
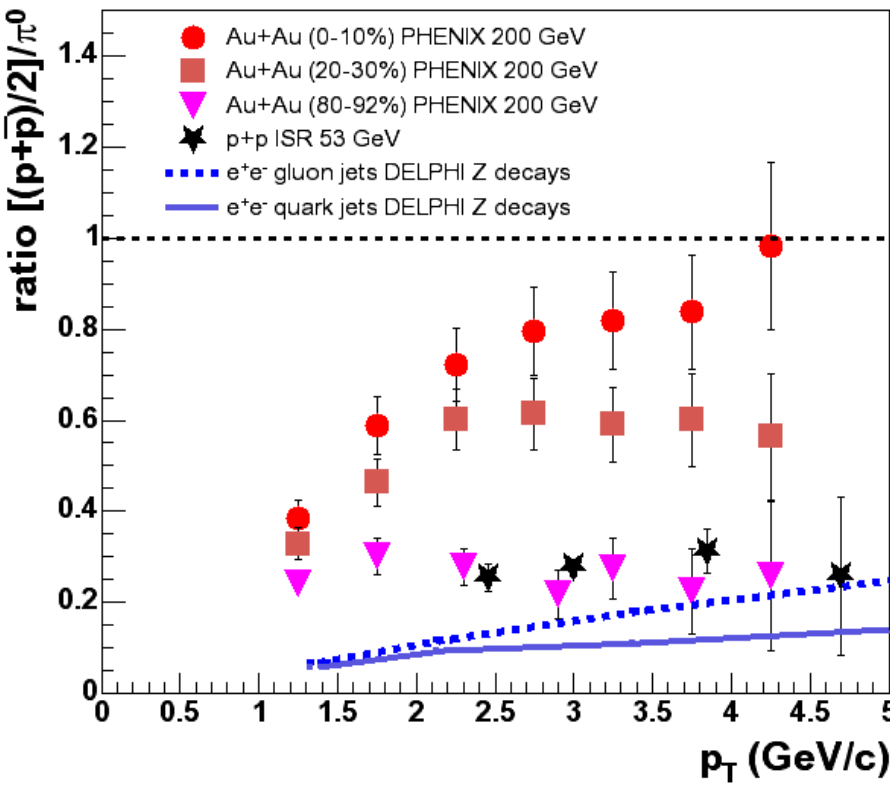
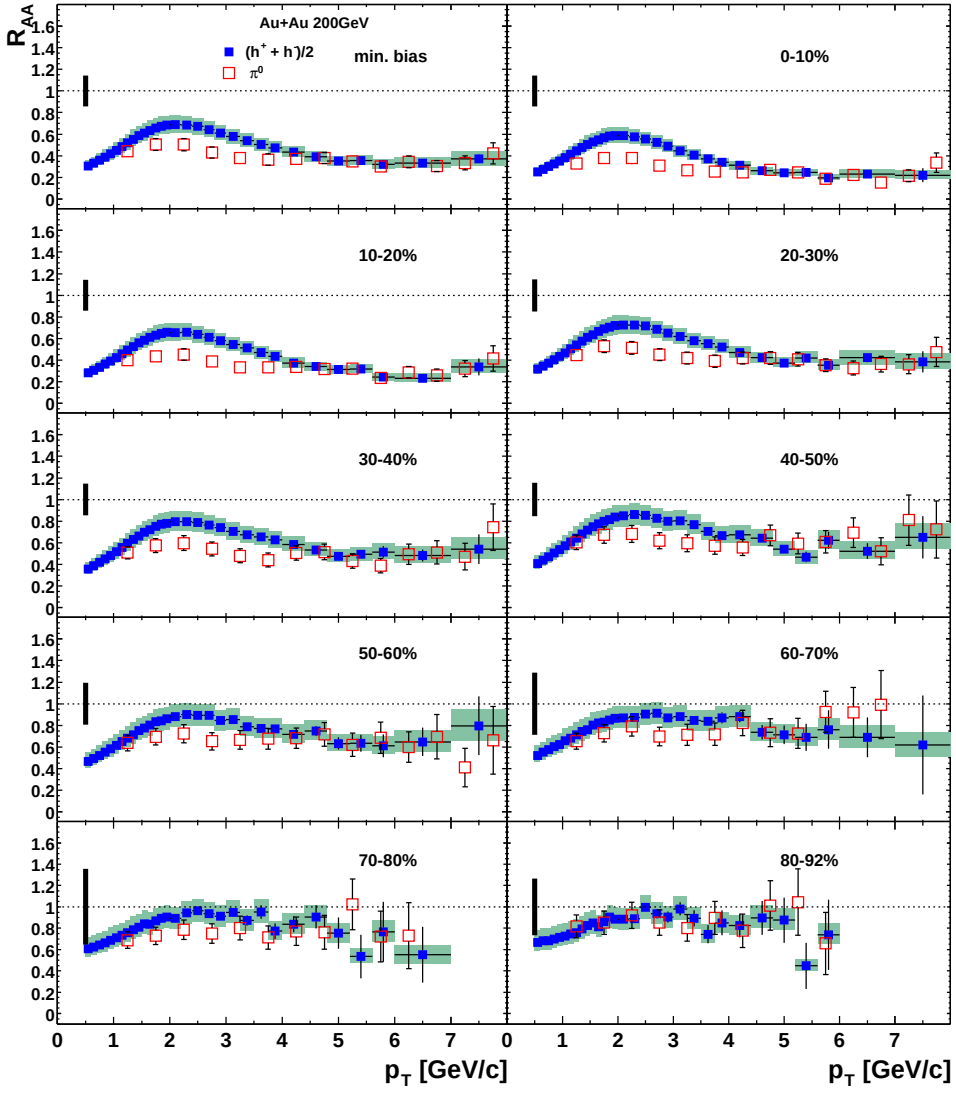


⇛ $\Delta E \ll E \longrightarrow$ the particle looses a small fraction of its energy in the medium

Baryon/meson ratio for large p_t





⇛ More protons than pion produced at $p_t \sim 4$ GeV

⇛ For $p_t \gtrsim 5$ GeV independent fragmentation is valid.

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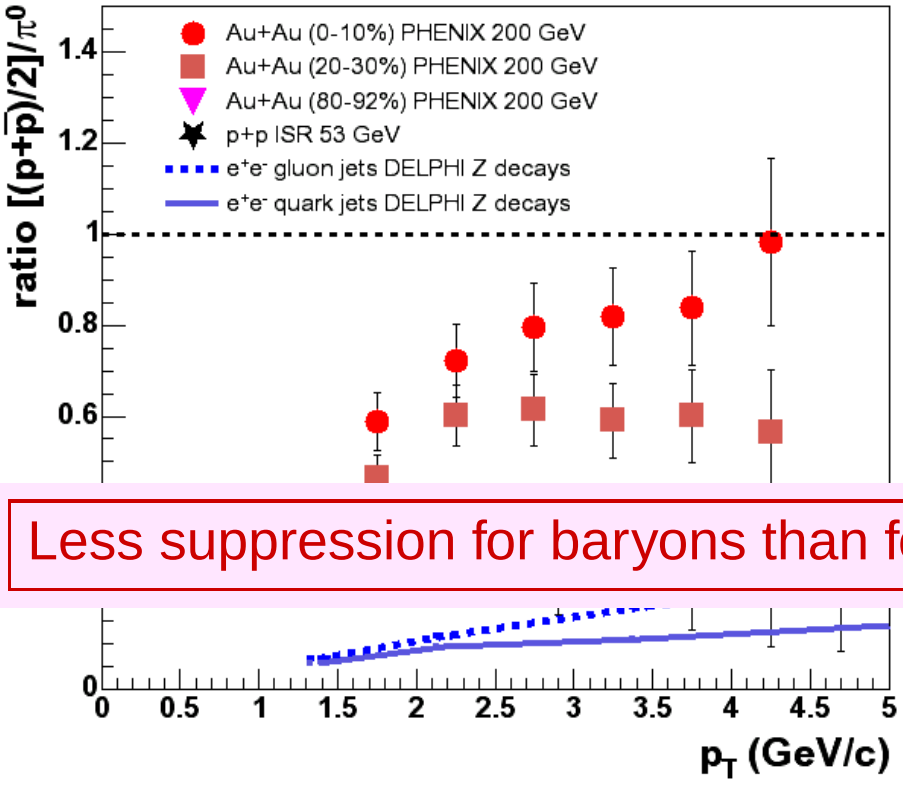

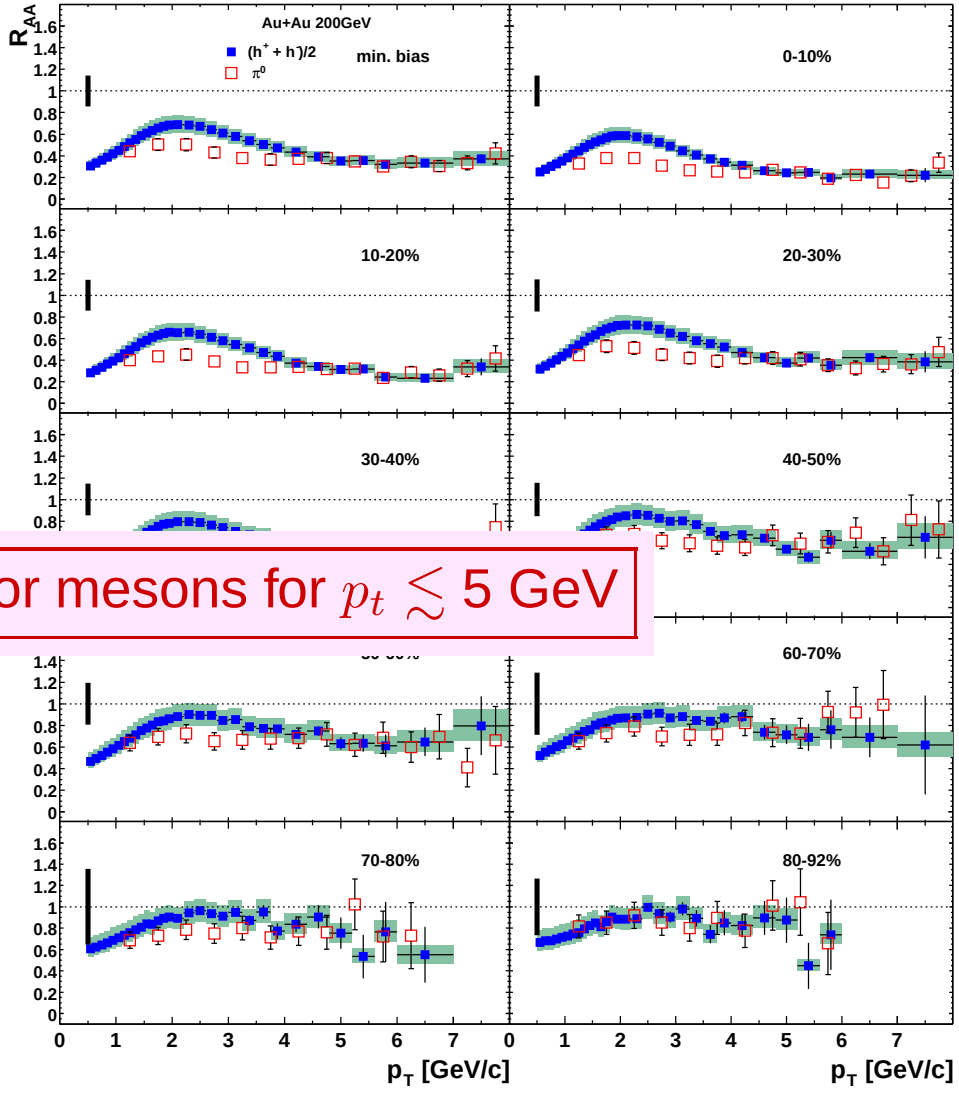

Less suppression for baryons than for mesons for $p_t \lesssim 5$ GeV

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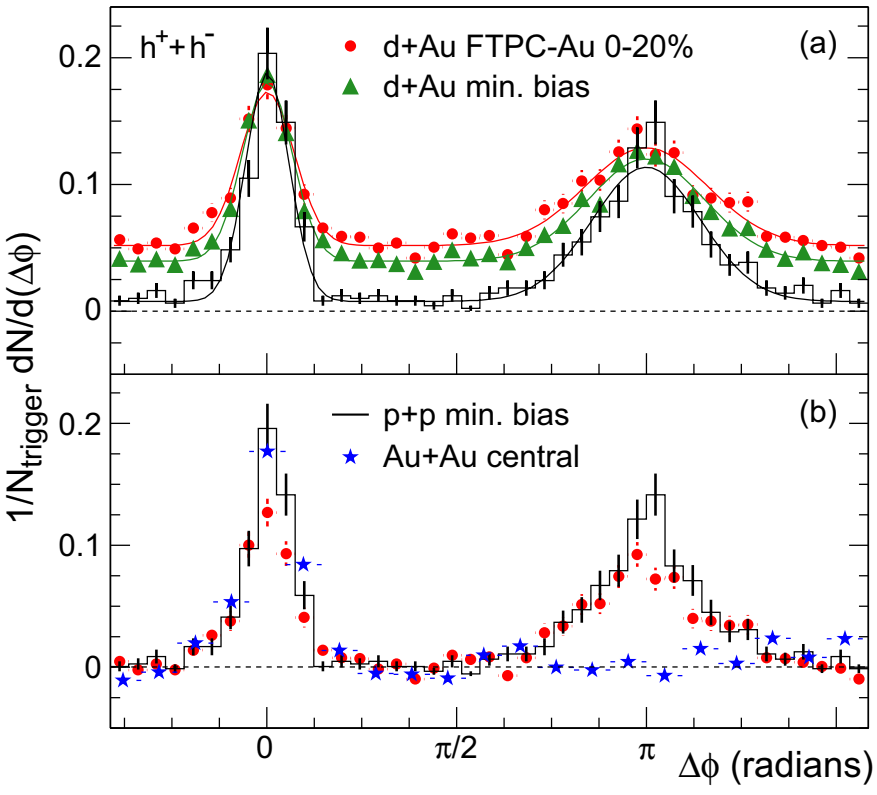
Back to back correlations

Let us come back to the back-to-back correlations



⇛ pp data suggest a dijet interpretation (a $q\bar{q}$ produced in a hard collision hadronizes in the vacuum)

For central AuAu

⇛ The high-p_t particle dissapears in the backwards hemisphere.

⇛ All the energy has been lost! Remember $\Delta E \sim L^2$

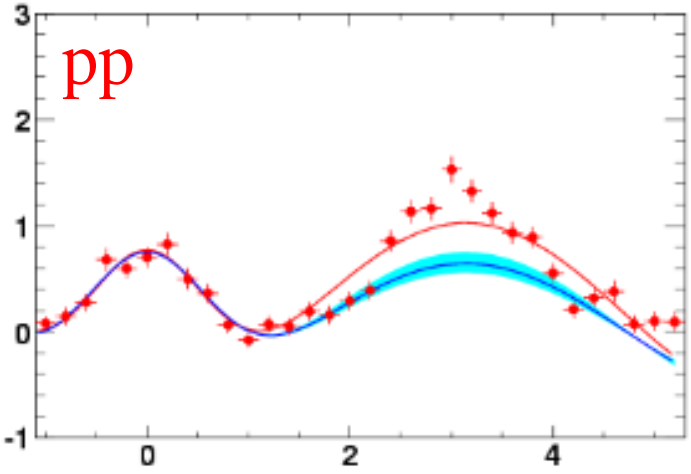
⇛ Thermalization of the high-p_t particles??

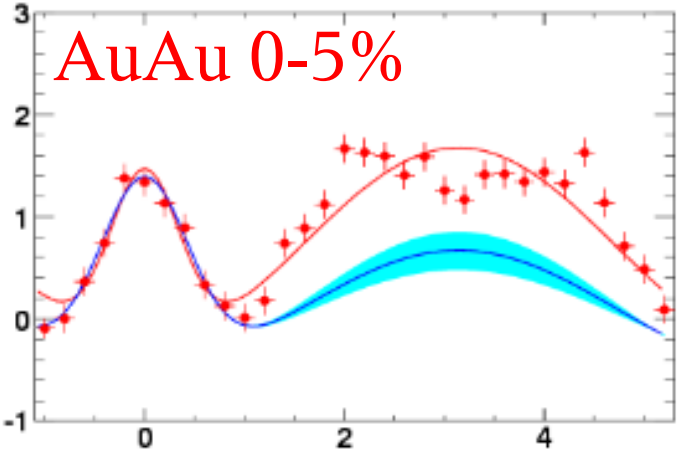
Calculations in the actual form cannot be applied

Where does this energy go

The associated particles in the previous plot were in the range $2 < p_t^{assoc} < 4$ GeV. Removing the lower limit ($0.15 < p_t^{assoc} < 4$ GeV)

Star preliminary





The 'lost energy' reapears in the backwards hemisphere

- ⇛ This energy is softer in central AuAu than in pp.
- ⇛ The backward-hemisphere signal in pp is jet-like, while in central AuAu is not $\longrightarrow$ thermalization??
- ⇛ This opens the possibility of studying jet properties in heavy ion collisions experiments. (Small p_t up to now, though...)

Is there thermalization??

- Elliptic flow, main signal in favor of thermalization
  - Drawback: needs inputs for initial state and equation of state.
  - Hadronization can change flow by a large amount.

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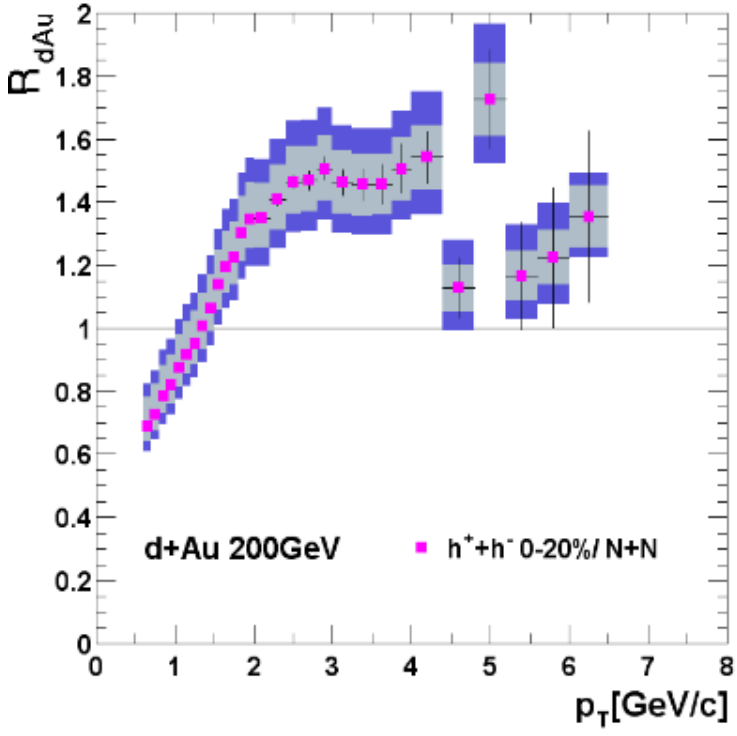
  - Thermalization at the partonic or hadronic stage?
- Total dissapearance of backwards jet
  - Strong final state interactions.
  - Has the hard parton thermalized in the medium?

High-p_t particle production in dAu

Saturation approaches predicted a suppression of high-p_t particle production. Is this ruled out?



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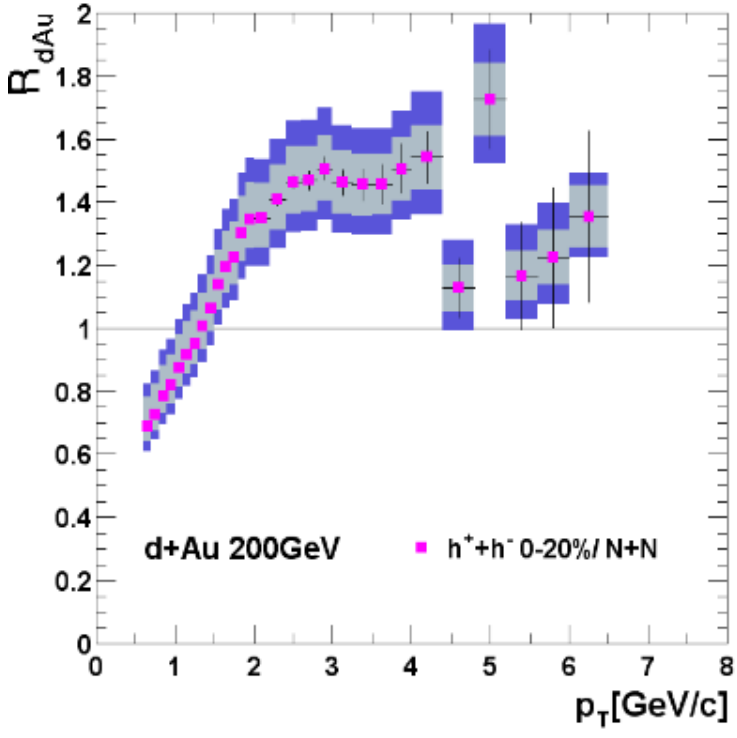

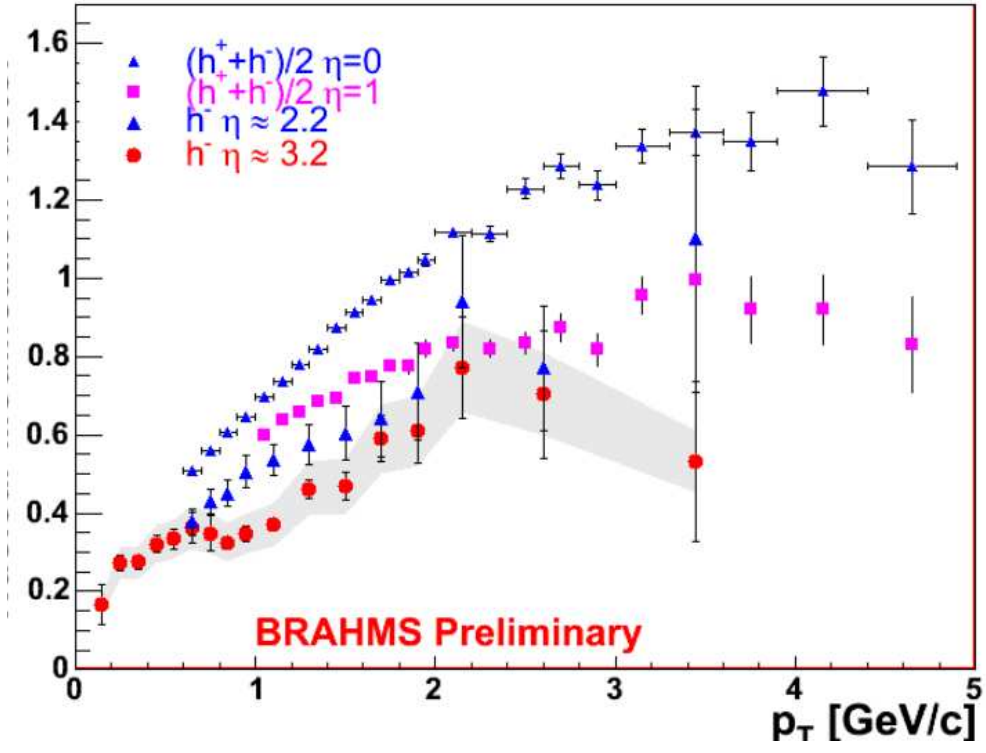

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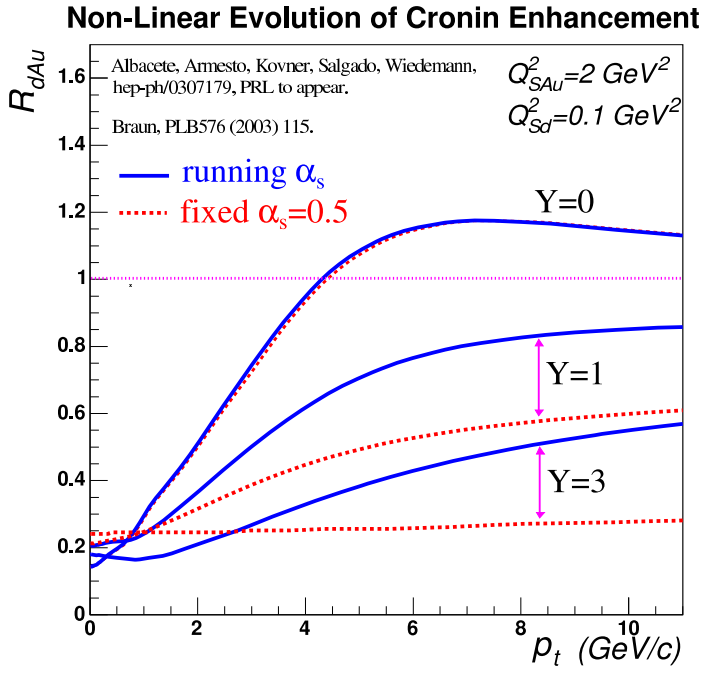

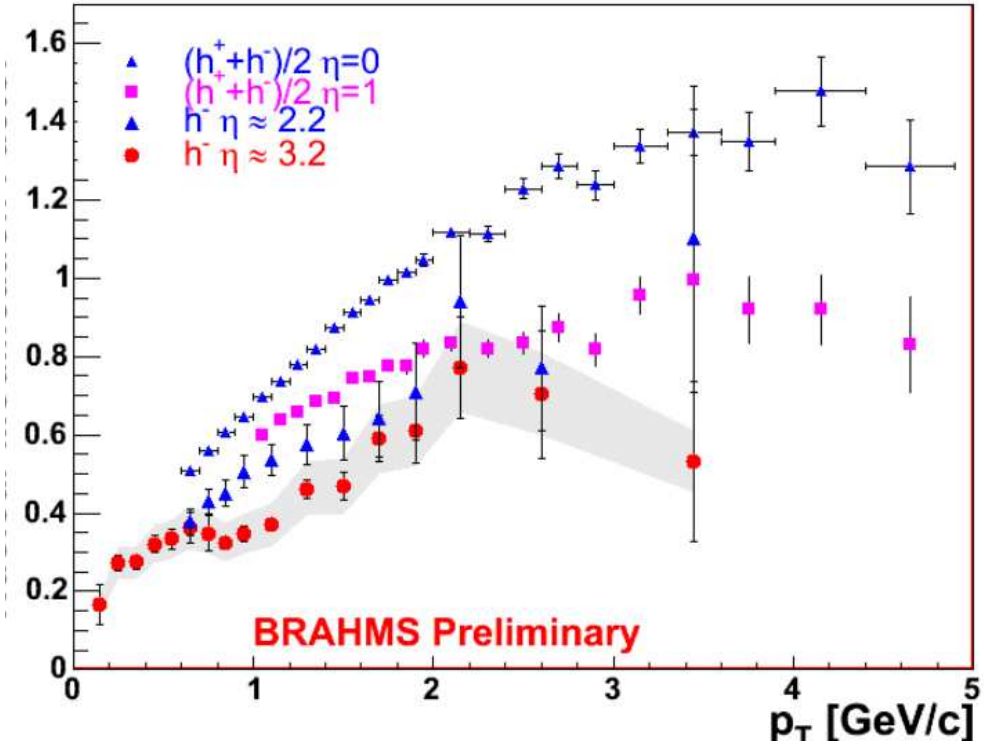

⇛ Go to large rapidity to study smaller-x ($y \sim \ln 1/x$)

⇛ Strong suppression: first indication of low-x evolution in HIC??

What do we think we have learned

- A dense state has been created at RHIC.
  - This state has strong interactions (jet quenching) far from ideal gas?
  - Most probably partonic interactions (suppression depends only on the particle being a meson or baryon and not on the mass)

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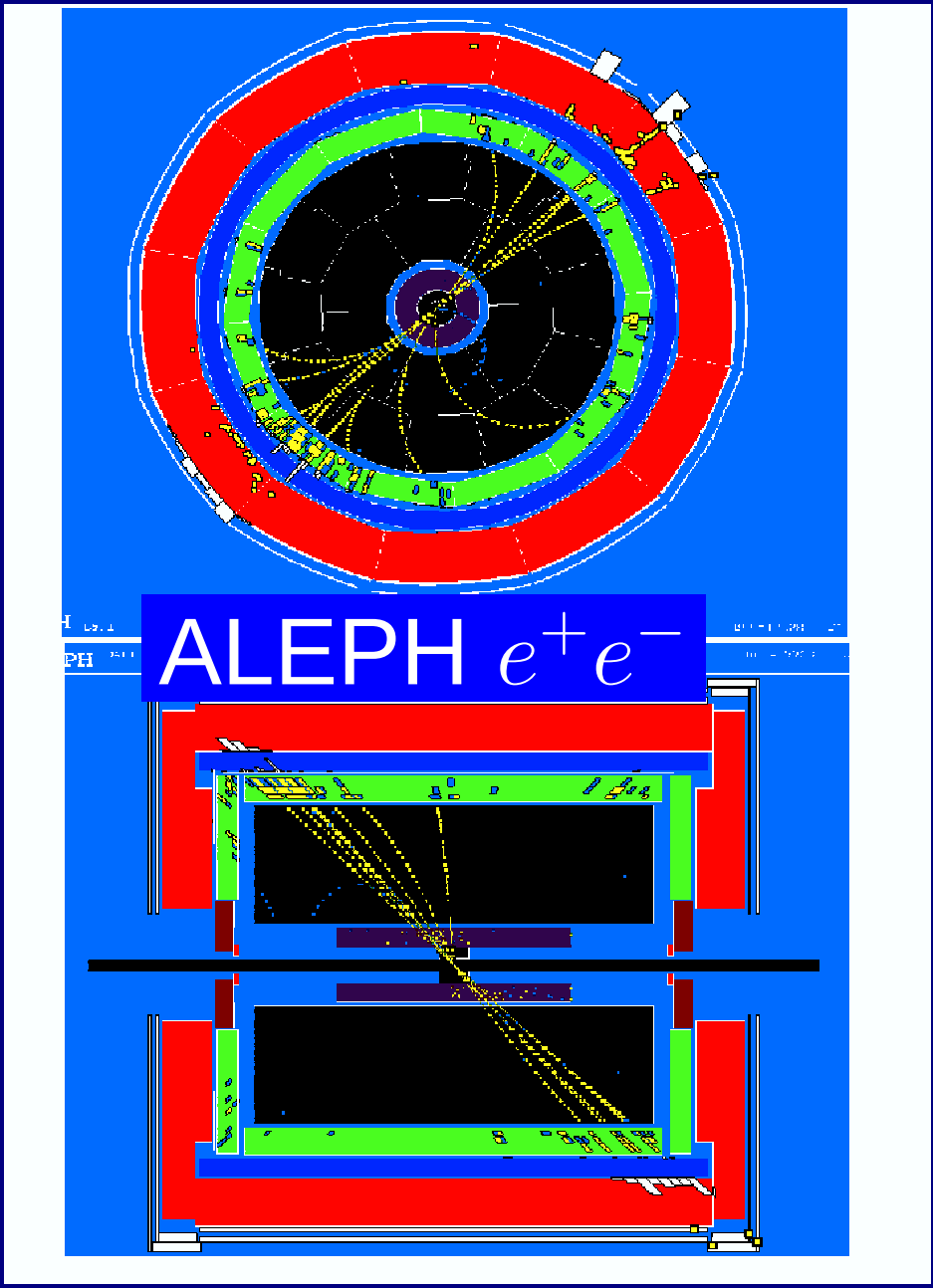
- Results of high-p_t suppression at large rapidity (small-x) in dAu possibly caused by small-x evolution equations.

Future: LHC

Jets in HIC???



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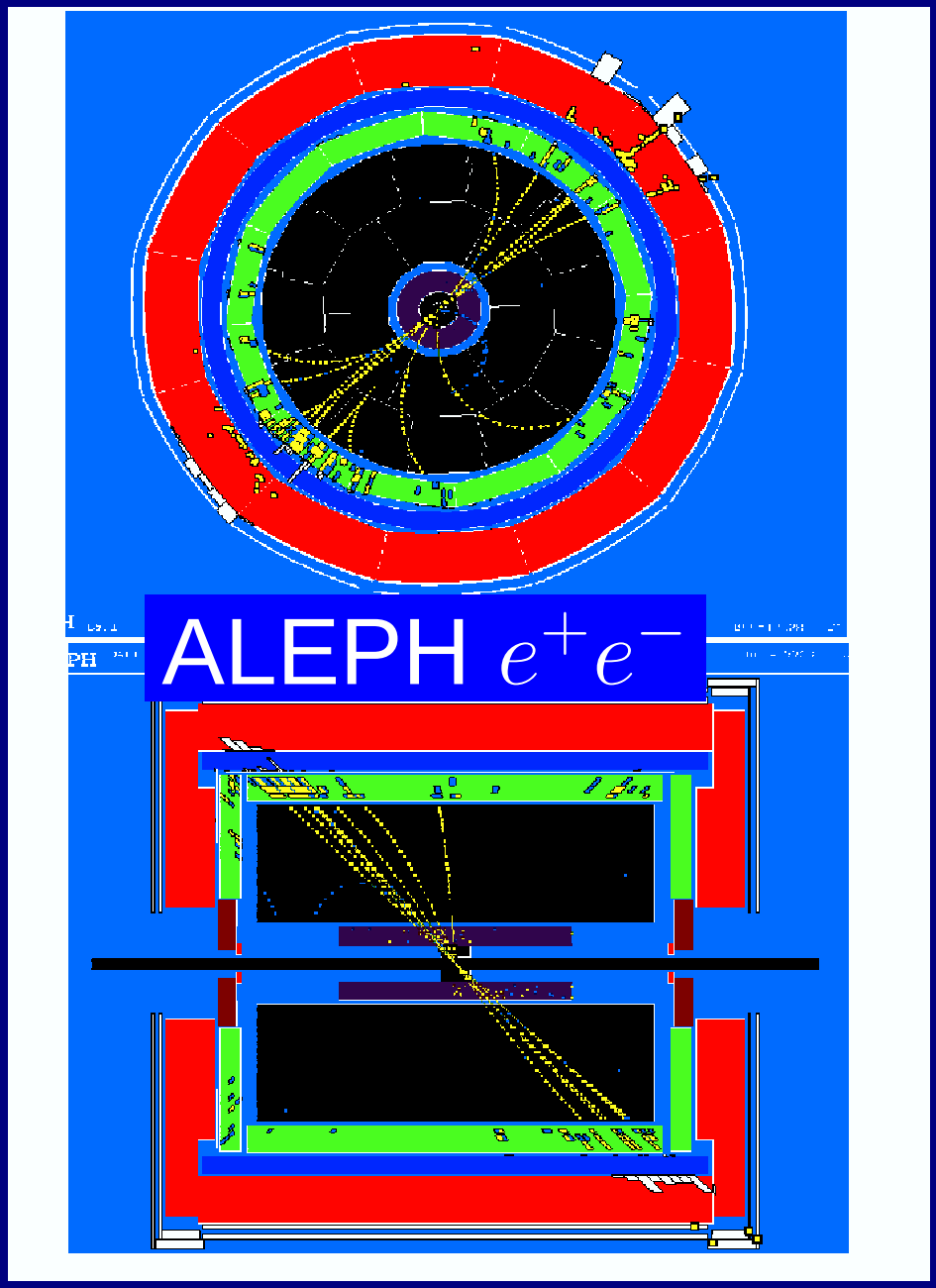

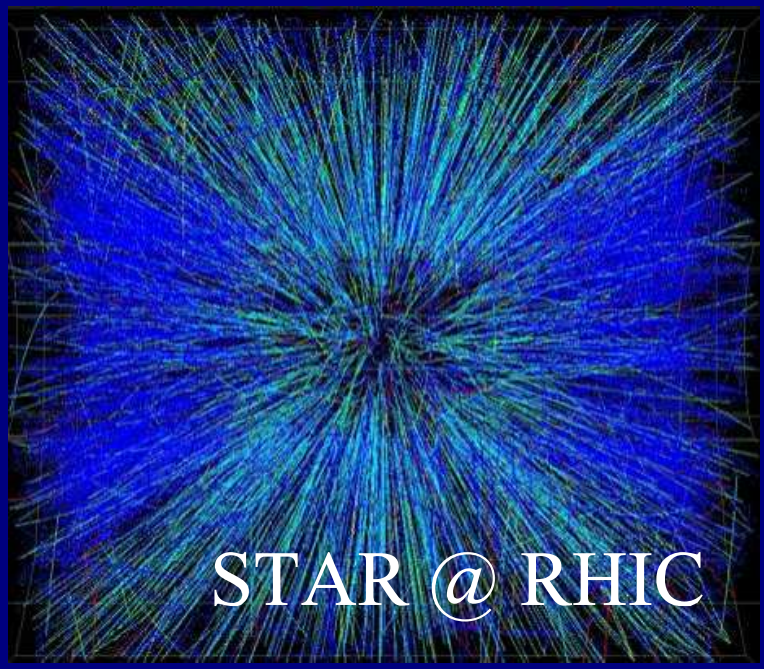

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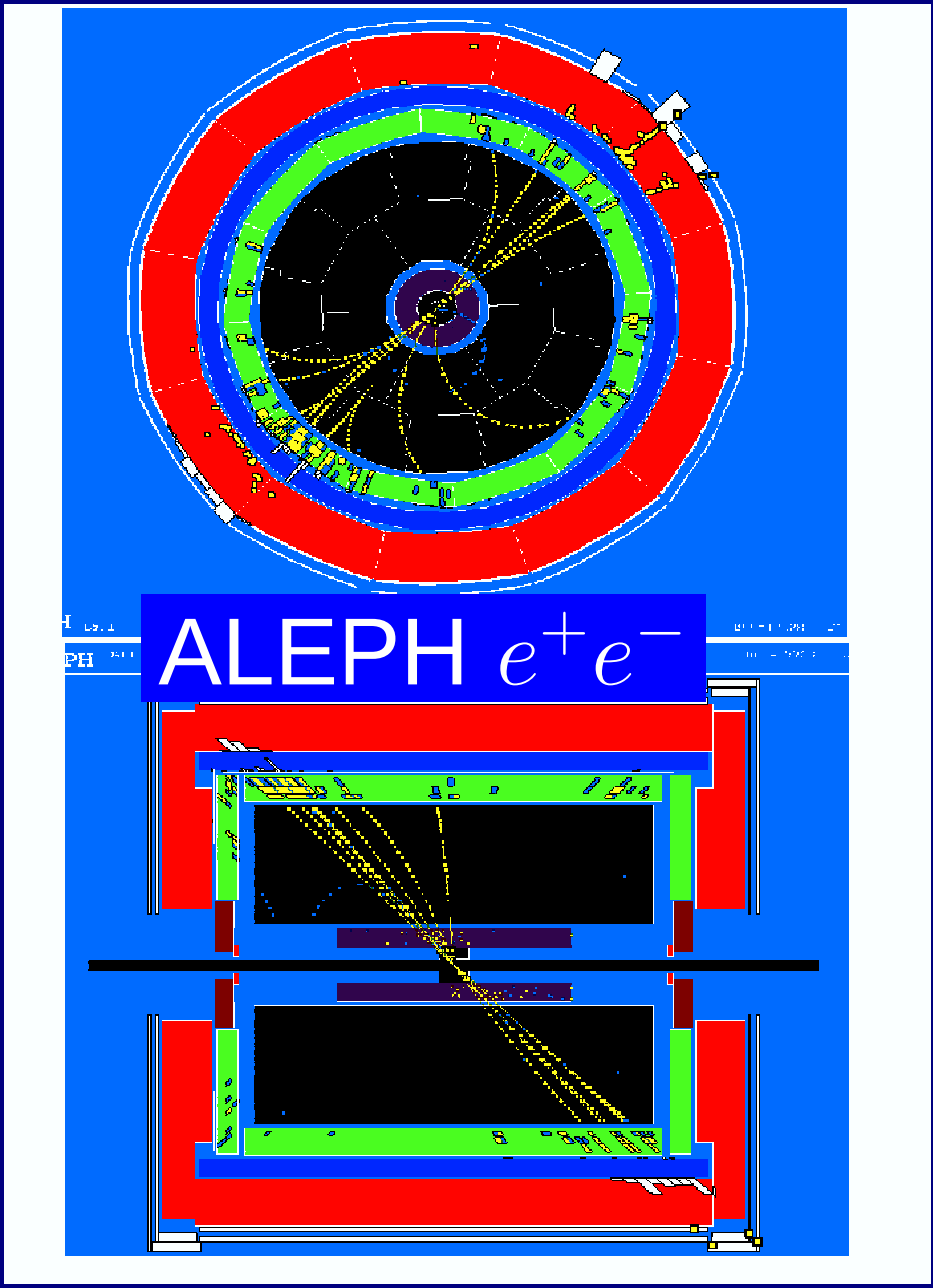
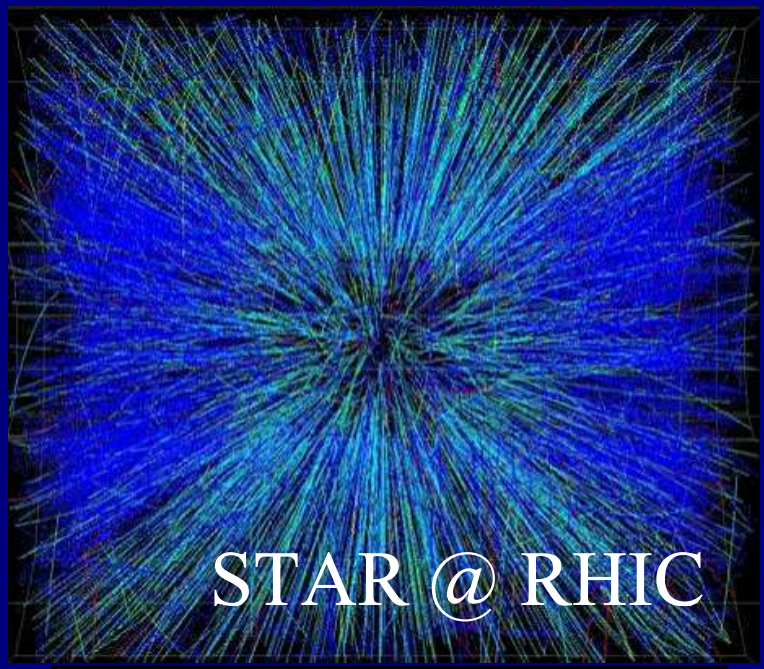
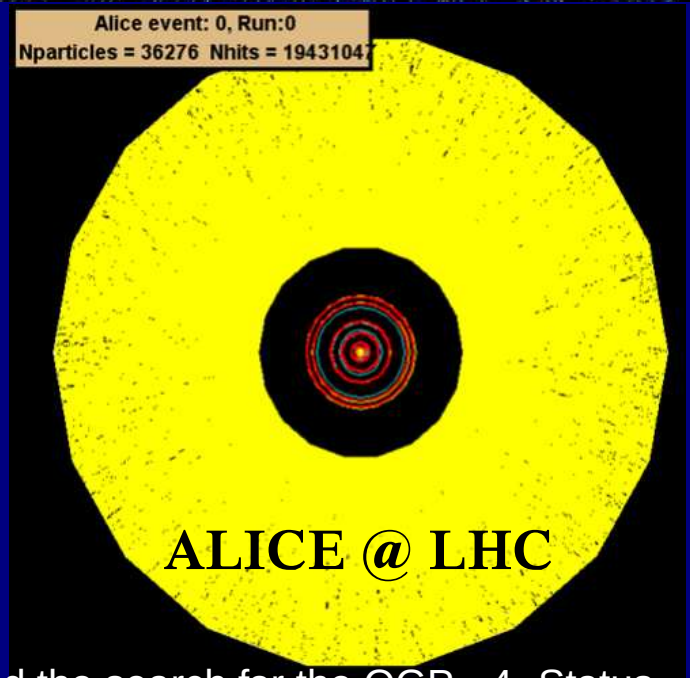
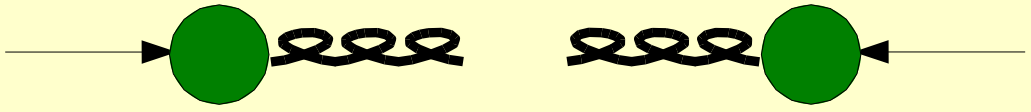

ALEPH e^+e^-


STAR @ RHIC


Alice event: 0, Run:0
Nparticles = 36276 Nhits = 1943104
ALICE @ LHC

What is a jet?



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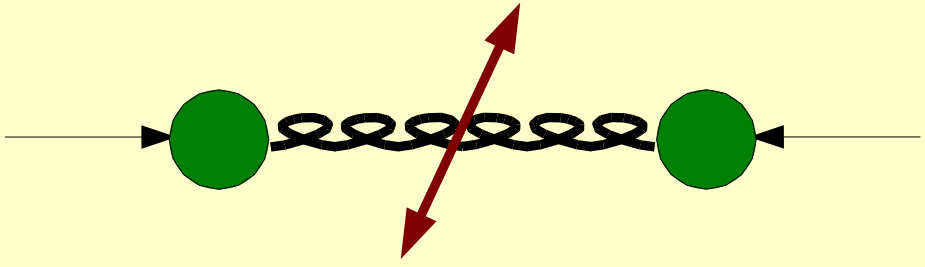
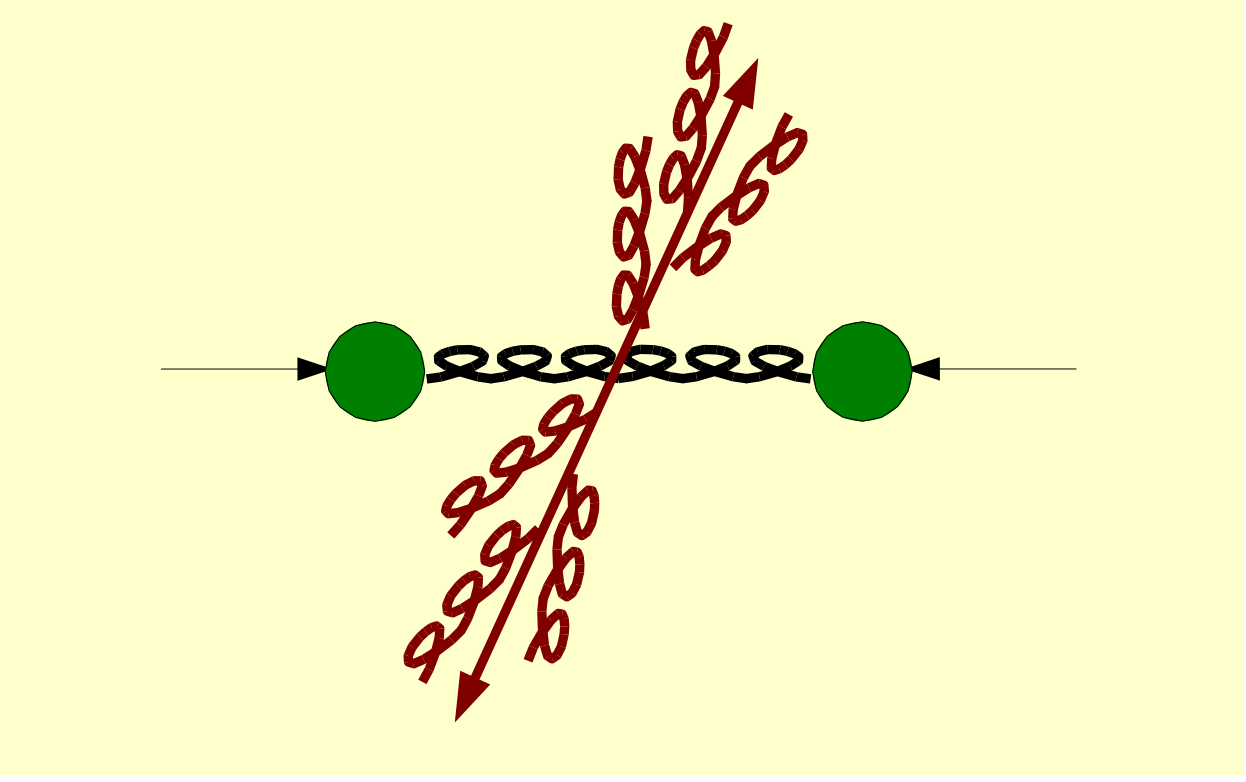


What is a jet?



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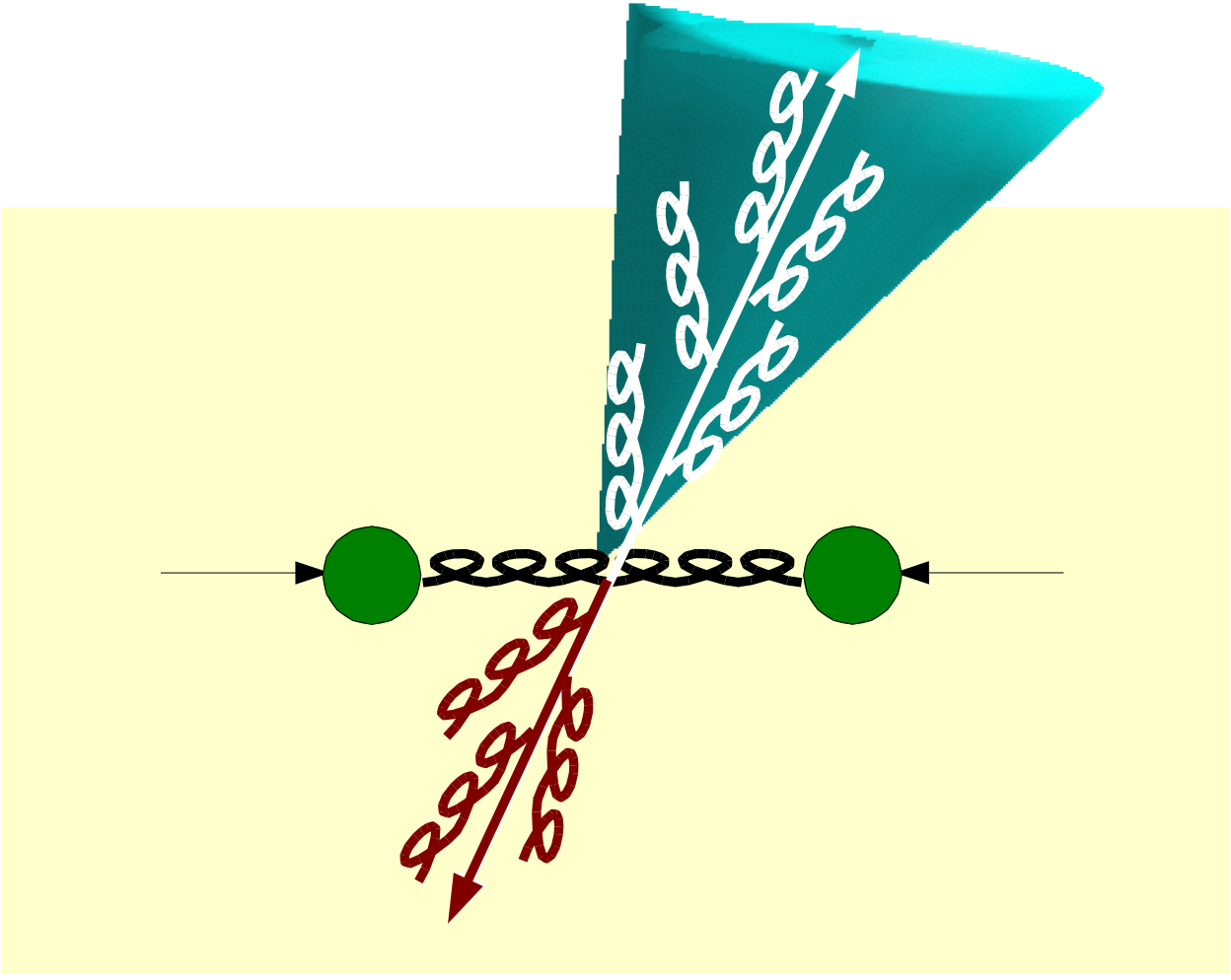

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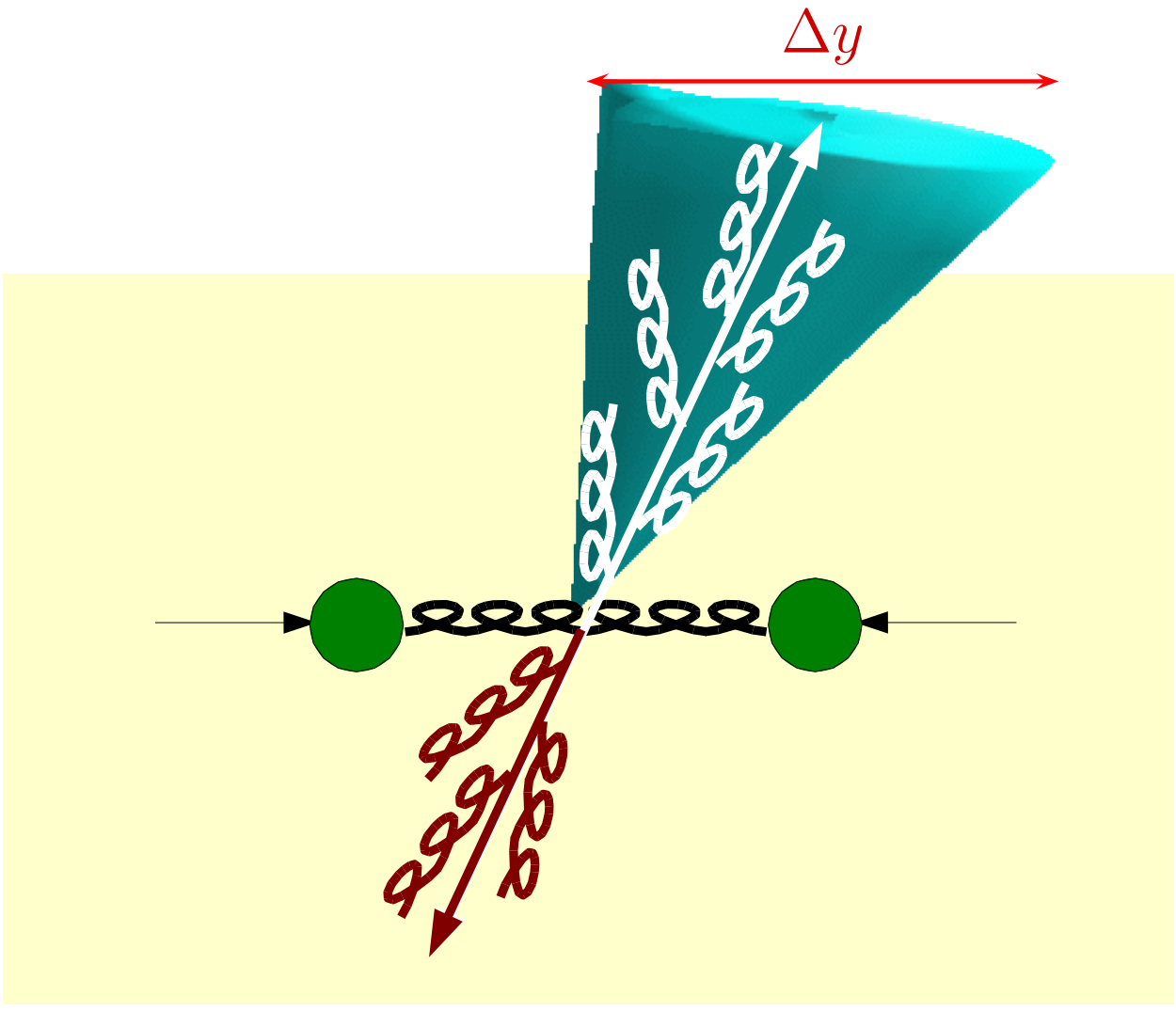

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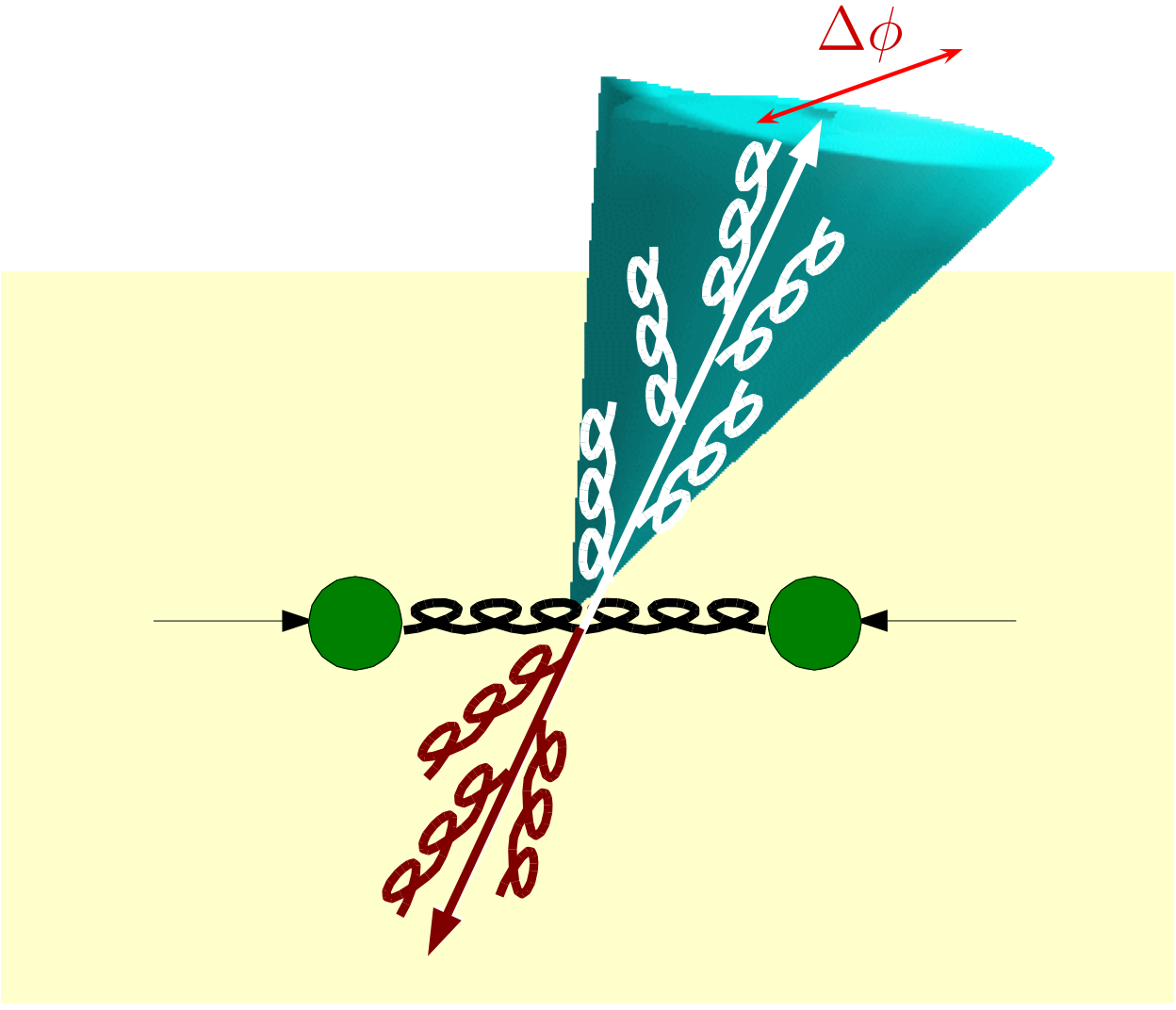


Jet shapes

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

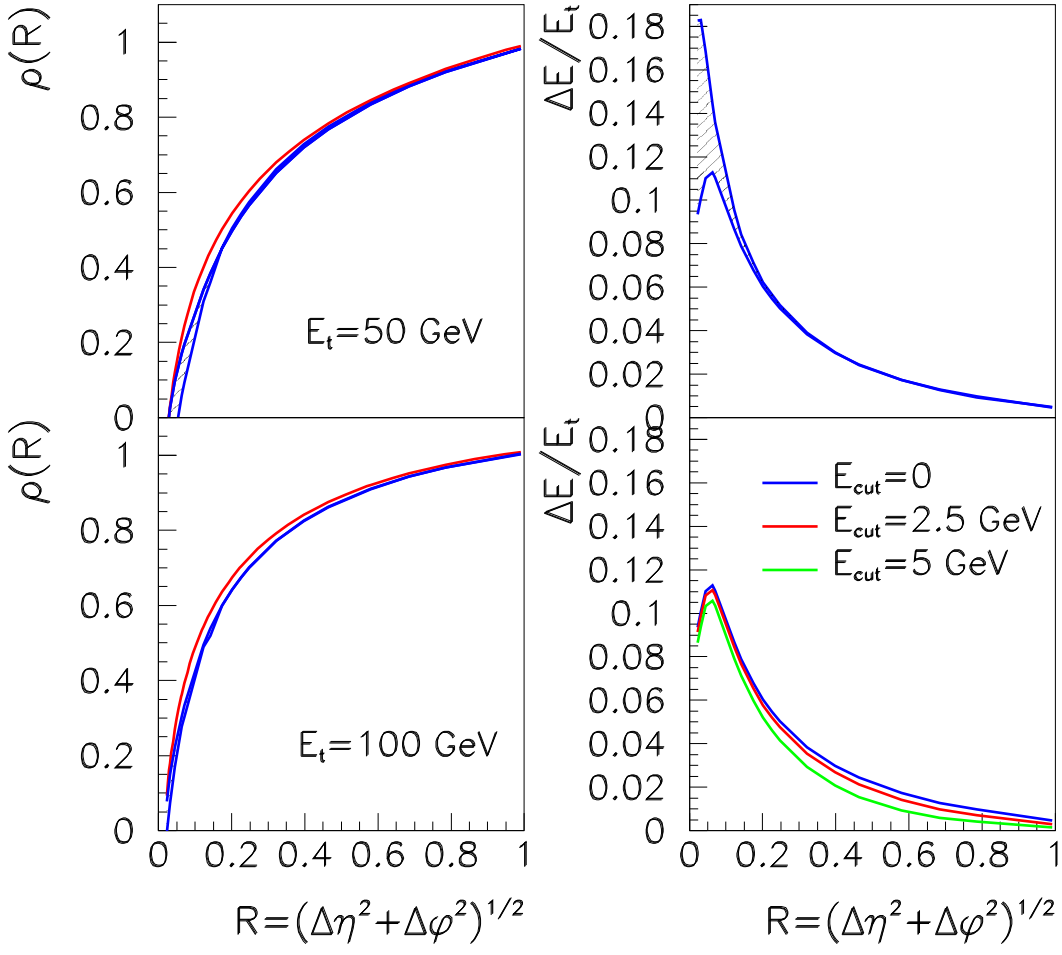
$$\rho_{\rm vac}(R) = \frac{1}{N_{\rm jets}} \sum_{\rm jets} \frac{E_t(R)}{E_t(R=1)}$$

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

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)



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

Gluon multiplicity inside the jet.

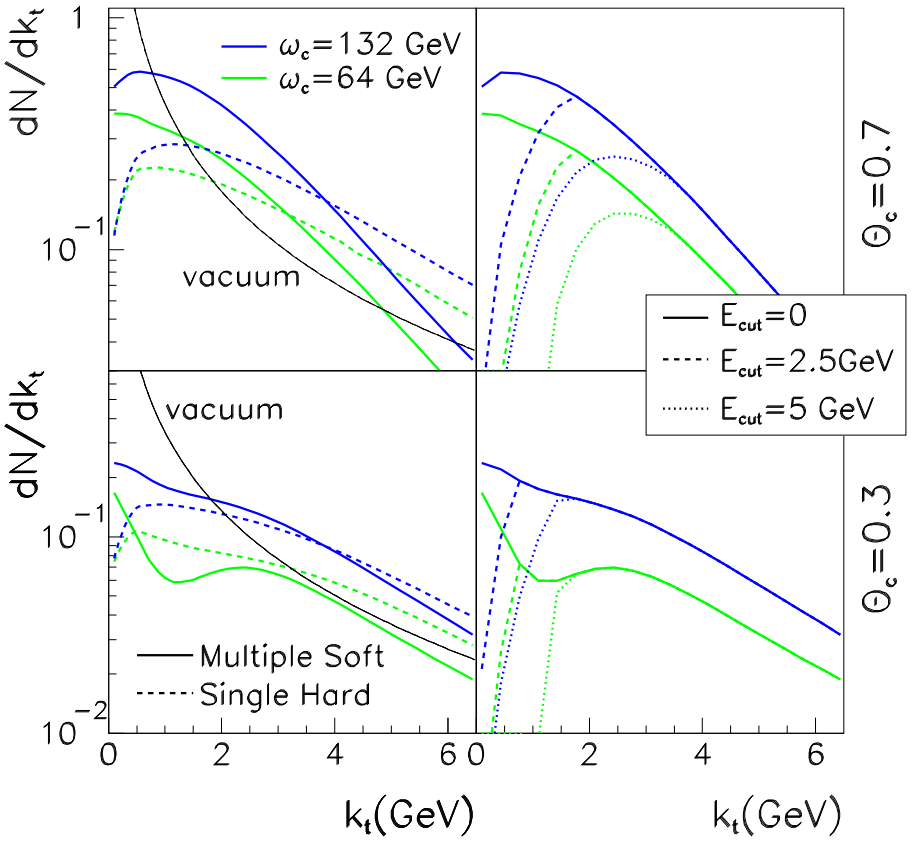
The characteristic angular distribution of the medium–induced gluon radiation could be better observed in the quantity

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

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.

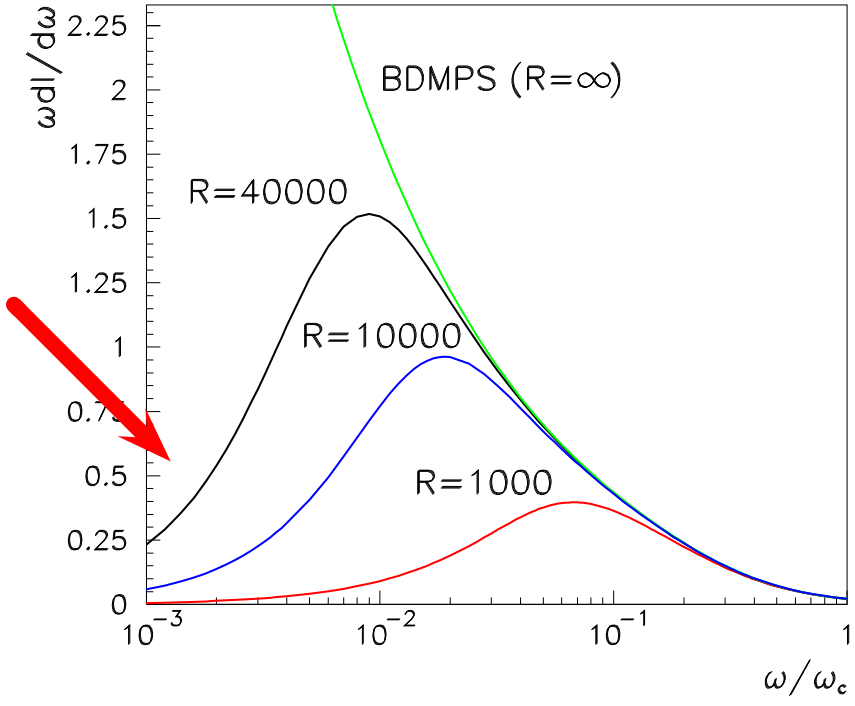


(100 GeV jet)

But, effect based mainly on kinematics.

IR cuts

⇒ The fact that the results show small sensitivity to IR cuts is due to the shape of the spectrum



⇒ As we have seen, this is due to formation time effects.

Summary

- QCD calculations predict states of deconfined matter where the chiral symmetry is restored.
  - Order of the transition depends on quark masses and μ_B.
- Knowledge about the initial state effects essential to interpret experimental data.
  - Give information about properties of the medium (energy density...)
  - Fixes the reference for QGP effects.
- New experimental data from RHIC indicates
  - High density medium created, perhaps $\epsilon \sim 15$ GeV/fm^3 (lattice $\epsilon_c \sim$ 1GeV/fm^3). Probably thermalized at the parton level
  - Jet quenching and elliptic flow are the main signals
- Future: LHC will produce much larger densities ($\sim 2 \div 5$ times larger) and abundant jets
  - Study jet production in HIC $\longrightarrow$ DIS with the medium