Color charge dependence of energy loss at RHIC

Bedanga Mohanty
(for the STAR Collaboration)
Lawrence Berkeley National Laboratory

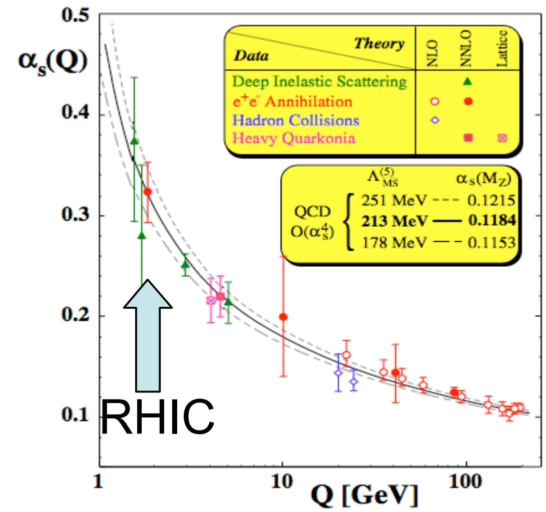
Outline

- Introduction
  - What are color factors in QCD ?
  - What should be the effect of color charge on E_{loss} ?
  - What are the experimental observables to see this effect ?
- Search for color charge effect at RHIC
- Physics possibilities regarding the observations at RHIC
- Future measurements
- Summary

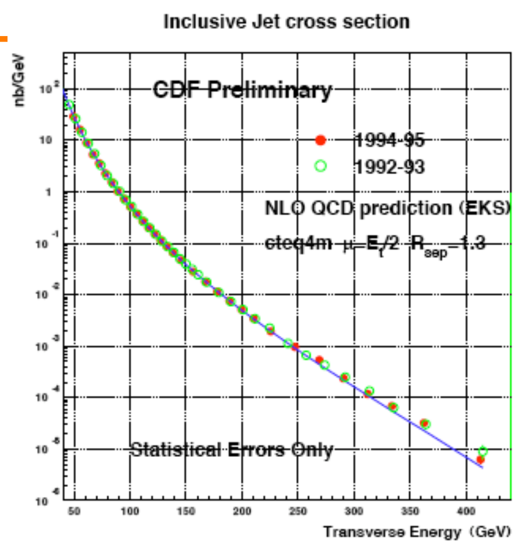
Introduction

- Quantum chromodynamics (QCD) is the theory of color charge (strong interactions)
- Many quantities can be calculated in perturbative QCD with a free parameter, the strong coupling strength
- Another key ingredient of QCD is the underlying gauge group
- QCD is a gauge theory with SU(3) as underlying gauge group. This can be tested by measurement of color factors

The running of QCD coupling



S. Bethke, Nucl. Phys. Proc. Suppl 121 (2003) 74



Jet cross section

What are color factors ?

Introduction - Color factors

- Consider a Lie group of dimension N_c.
- For $SU(N_c)$, the color factors are

  $C_A = N_c$, $C_F = (N_c^2-1)/2N_c$ and $T_F = 1/2$

  A and F represent adjoint and fundamental representations

- Technically they are the eigen values of the Casimir operator of the gauge group

- For QCD : $N_c = 3$, $C_A = 3$, $C_F = 4/3$

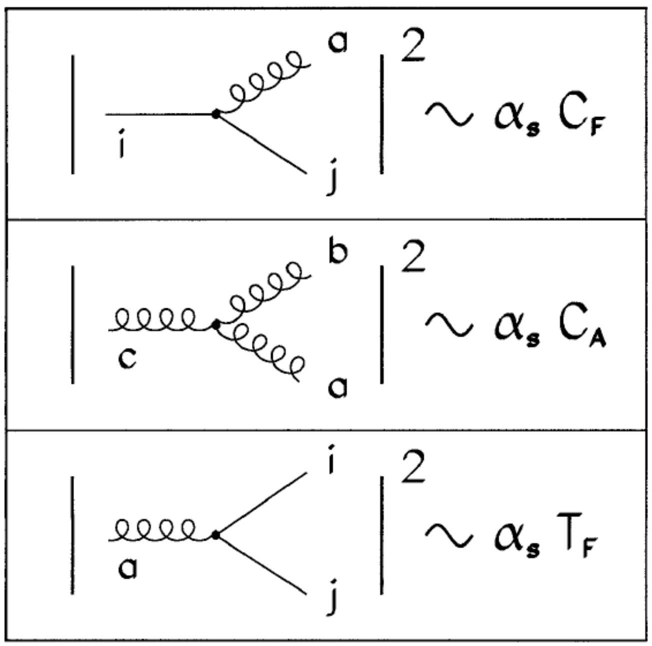
  Quarks are represented by Dirac fields in the fundamental rep of SU(3)

  Gluons lie in the adjoint rep of SU(3); 8 generators so 8 gluons

What is the physical picture for the color factors ?

Physical picture - Color factors

- Color factors are related to fundamental couplings of the theory :
- C_F - determines coupling strength of a gluon to a quark,
- C_A - related to the gluon self coupling (fundamental property of QCD arising due to non-Abelian nature of the theory)
- T_F - strength of splitting of a gluon into a quark pair



$$= \sum_{\alpha} \left(T^{\alpha} T^{\alpha} \right)_{ij} = C_F \delta_{ij}$$

$$= \sum_{\alpha\beta} \left(f^{\beta\alpha\delta} f^{\gamma\alpha\delta} \right) = C_A \delta^{\beta\gamma}$$

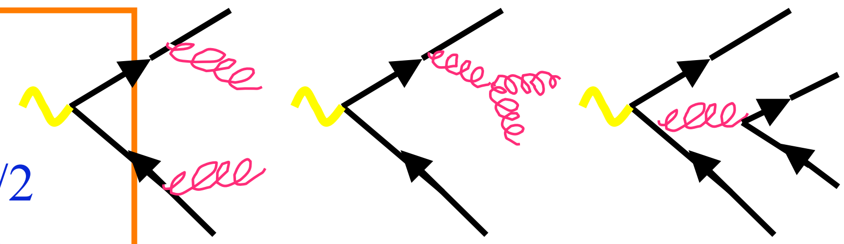
QCD : For SU(3) :
$N_c = 3$
$C_A = 3$, $C_F = 4/3$

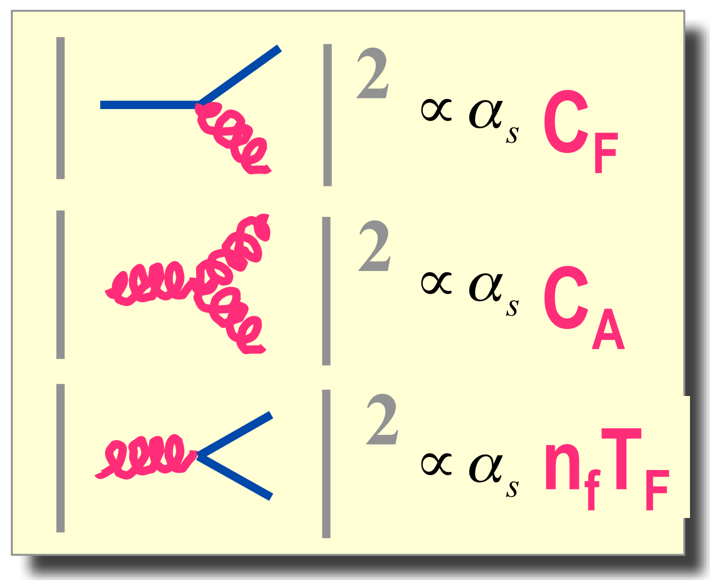
- i,j represent fermion field indices and a,b (α,β) gauge field indices
- T : Generators and f : Structure constants

Can we experimentally determine color factors ?

Experimental determination of Color factors

- All of the three basic vertices are present in four jet production in e^+e^- collisions
- Since each diagram involves spin-1 or spin-1/2 particles in different configurations. So each graph results in a different angular distributions in the final states.
- The observed jet angular distributions are then fitted to theoretical predictions with C_A, C_F, T_F as free parameters.





What are the experimental results ?

Results on Color factors and QCD gauge group

- Results from L3, OPAL and ALEPH experiments

ALEPH : Z. Phys. C 76 (1997) 1

L3 : Note 1805 (1995)

OPAL: Eur. J. Phys. C 20 (2001) 601

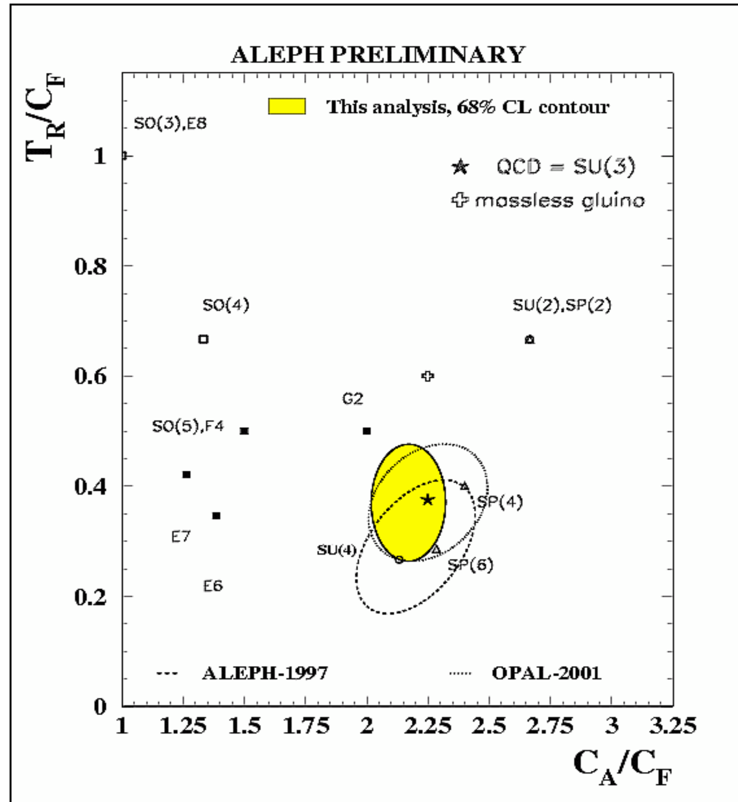
- For SU(N_c), the color factors are
  $C_A = N_c$,
  $C_F = (N_c^2-1)/2N_c$
  and $T_F = 1/2$

For SU(3) : $N_c = 3$
$C_A = 3$, $C_F = 4/3$

$\alpha_s(M_Z) = 0.119 \pm 0.006 \pm 0.022$

$C_A = 2.93 \pm 0.14 \pm 0.49$

$C_F = 1.35 \pm 0.07 \pm 0.22$

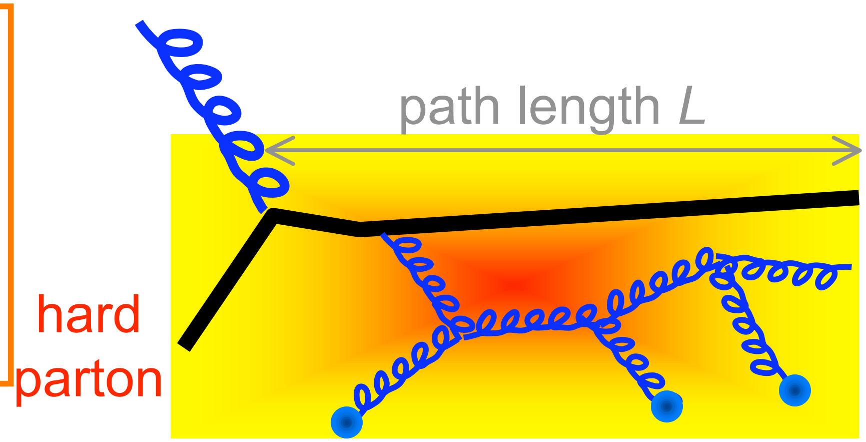


What this has to do with E_{loss} at RHIC ?

- SU(3) is the gauge group for QCD

The color factors and E_{loss} in heavy ion collisions

- One of the mechanism of parton energy loss is through medium induced gluon radiation
- Average energy loss in most models ~ BDMPS or GLV



$$\langle \Delta E \rangle \propto \alpha_s \, C_R \, \hat{q} \, L^2$$

BDMPS : Nucl. Phys. B 483 (1997) 291
GLV : PRL 85 (2000) 5535

Strong force coupling constant

Color factor: 4/3 for quarks and 3 for gluons

Medium transport coefficient --- gluon density and momenta

Path length

$$\frac{\Delta E_g}{\Delta E_q} \sim 9/4$$

Can this effect be seen in heavy-ion collisions ?

Experimental observables sensitive to color charge effect

$$\frac{\Delta E_g}{\Delta E_q} \sim 9/4$$

Energy loss : High p_T region has to be probed

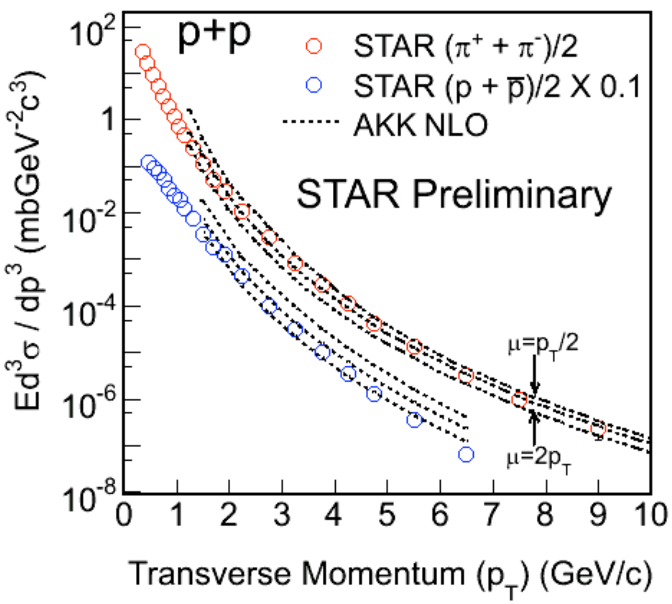
Look for difference in Nuclear Modification Factors (R_{AA} or R_{CP}) between particles dominantly coming from gluon jets and quark jets

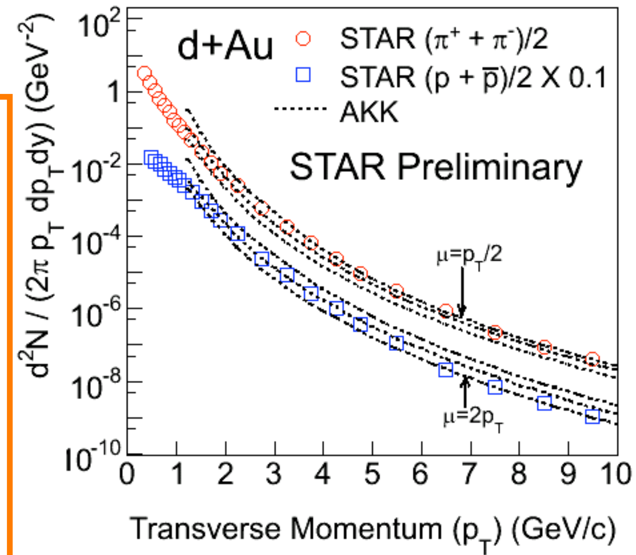
Question is :

How to know which particles are produced dominantly from gluon jets and which are produced from quark jets ?

It is not very clear if this ~2 difference will remain after hadronization of the partons. However model calculation shows this effect should be observable.
But most model calculations do not use the current knowledge of fragmentation function from RHIC data!

NLO pQCD calculations and RHIC data

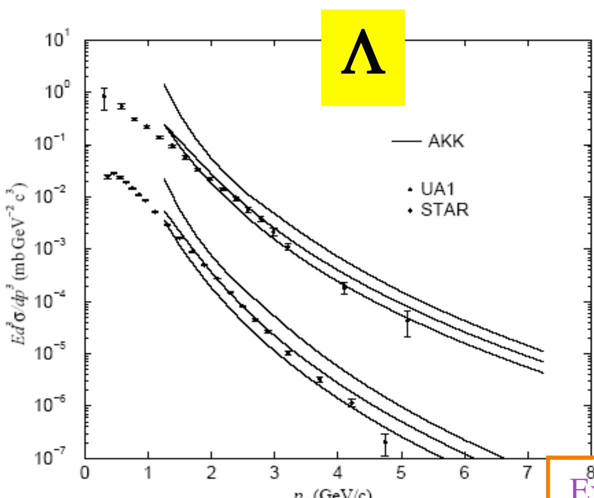


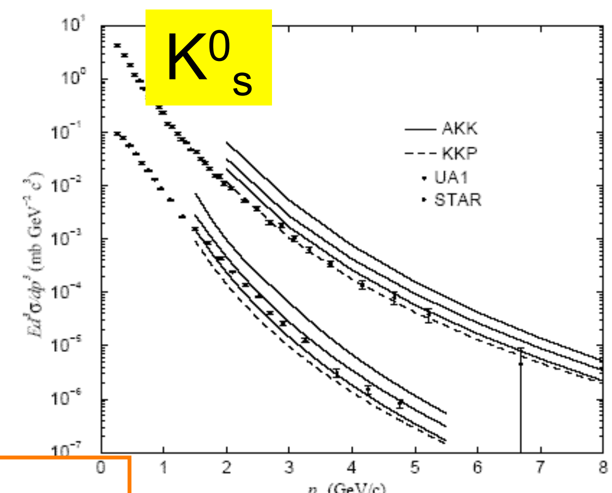


π, p,K and Λ production at high p_T well explained by NLO pQCD calculations with AKK fragmentation function.

AKK FF uses recent light flavor separated e^+e^- data from OPAL Collaboration.

First time baryon production reasonably well described by NLO pQCD

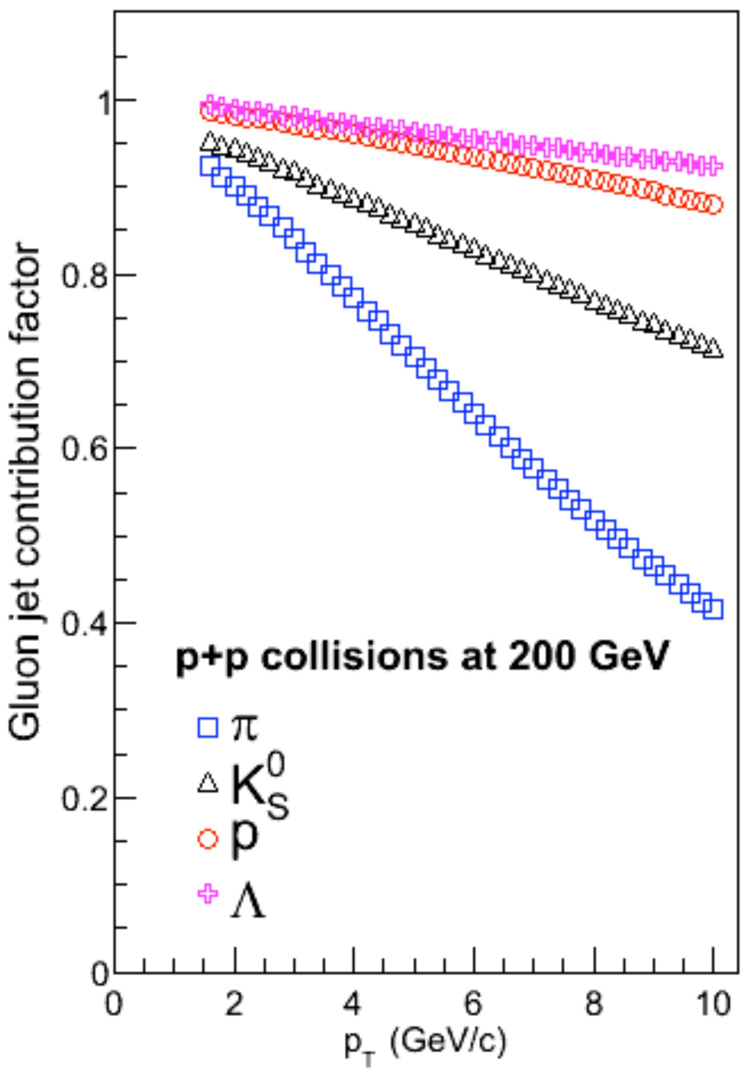




Expt : PLB 637 (2006) 161, nucl-ex/0607033
Theory : S. Albino et al., Nucl. Phys. B 597 (2001) 337

Experimental Observable - I

NLO PQCD calculations with AKK FF



Gluon jet contribution factor increases as we go from π, K,p and Λ

If $\langle \Delta E \rangle \propto \alpha_s \, C_R \, \hat{q} \, L^2$

and $\frac{\Delta E_g}{\Delta E_q} \sim 9/4$

Then

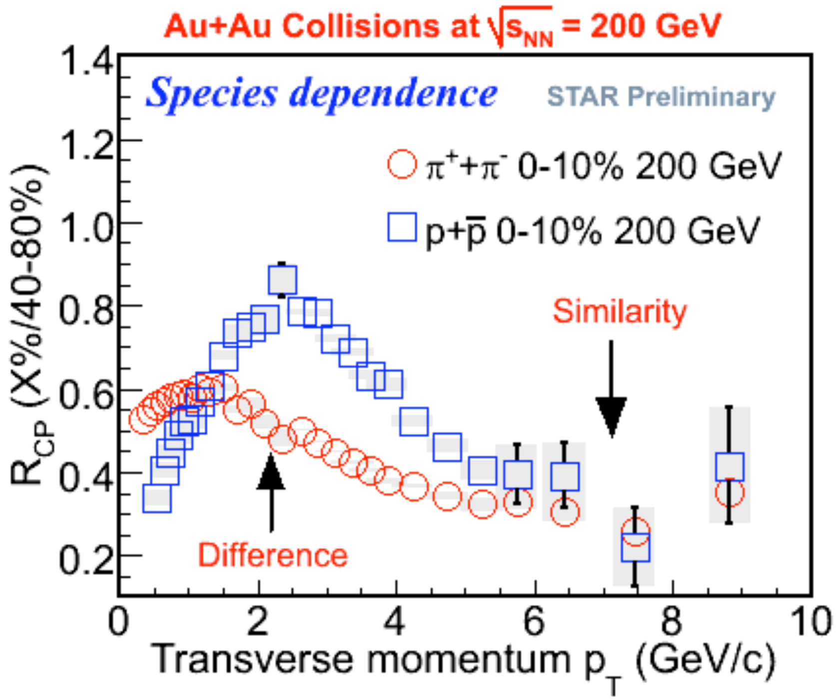
at high p_T for same beam energy, collision species and collision centrality the NMF for

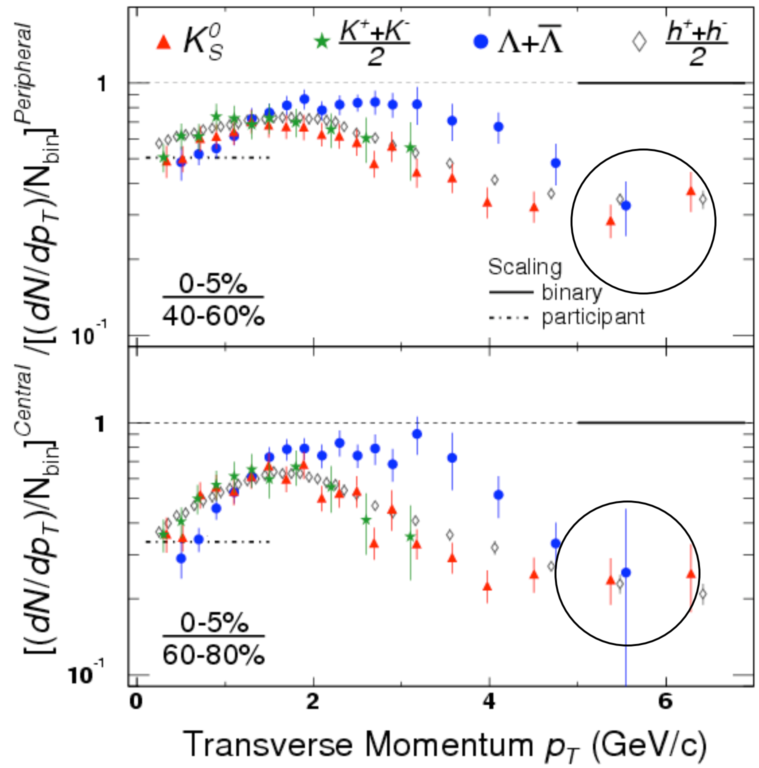
RCP(π) > RCP (p)

and

RCP (K) > RCP (Λ)

Experimental Results at RHIC - I





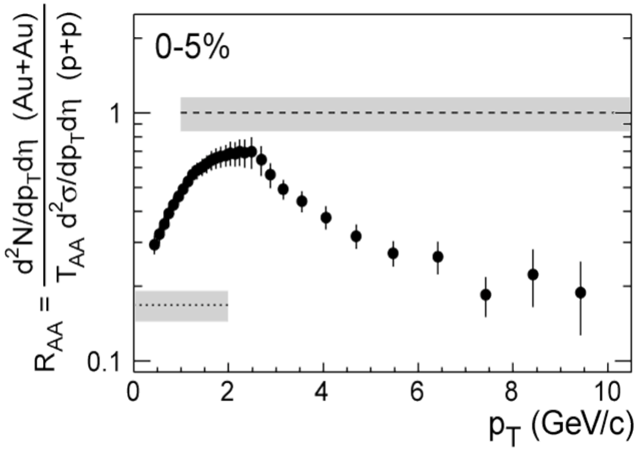
Observation at high p_T :

- RCP(π) ~ RCP (p) and
- Comparison of RCP (K) and RCP (Λ) need more statistics and higher p_T range

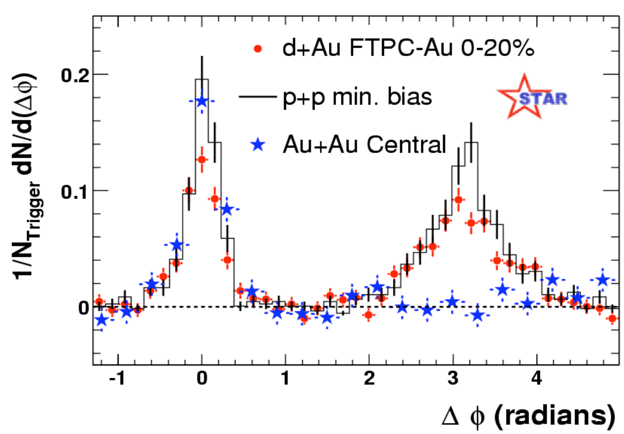
No difference observed in R_{CP} which is suppose to reflect E_{loss}

Does it mean similar E_{loss} of partons ?

Experimental Observable - II



STAR : PRL 91 (2003) 172302
PRL 91 (2003) 072304



In Au+Au collisions there is a dense medium where gluons loose more energy than quarks. Anti-protons are mostly coming from gluon jets.

and

In p+p and d+Au collisions no such dense medium -

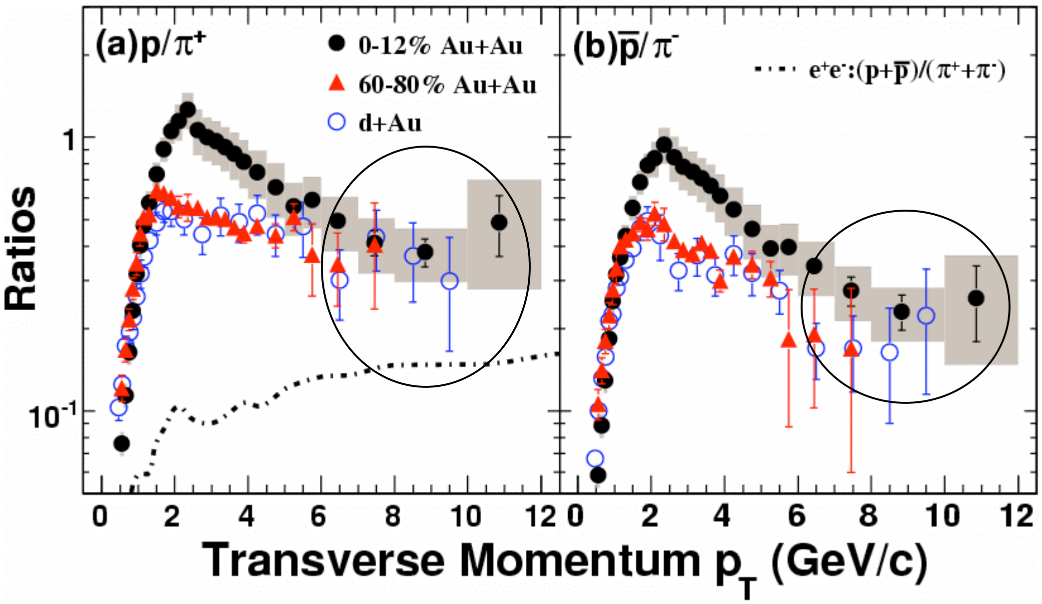
Then at high p_T for same beam energy,

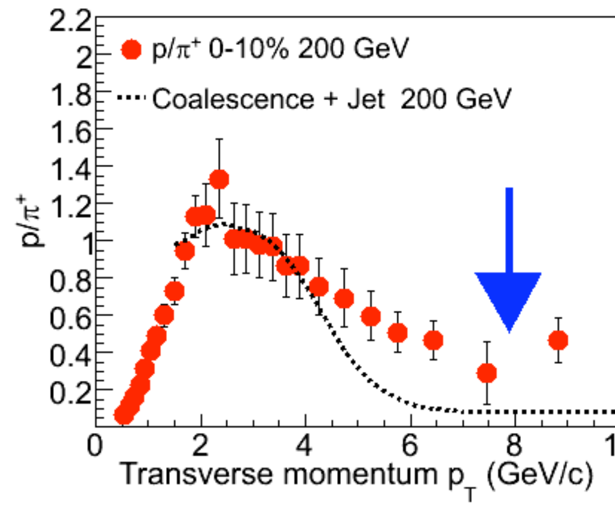
pbar/ π (Au+Au) < pbar/π (p+p or d+Au)
Λ/K^0_s (Au+Au) < Λ/K^0_s (p+p or d+Au)

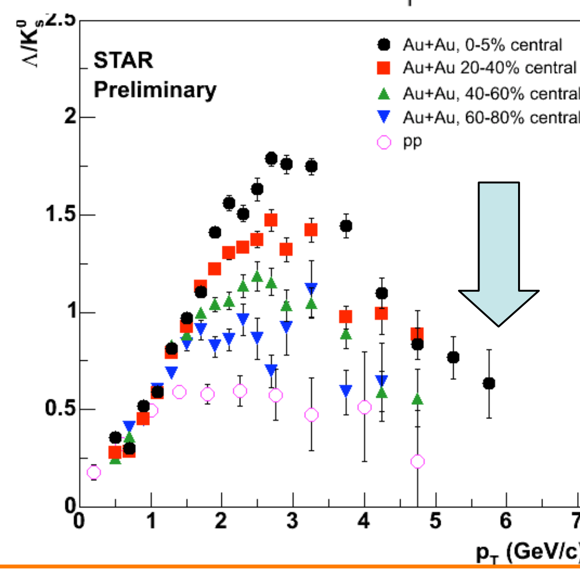
And

pbar/p (Au+Au) < pbar/p (p+p or d+Au)
$\bar{\Lambda}/\Lambda$ (Au+Au) < $\bar{\Lambda}/\Lambda$ (p+p or d+Au)

Experimental Results at RHIC - II





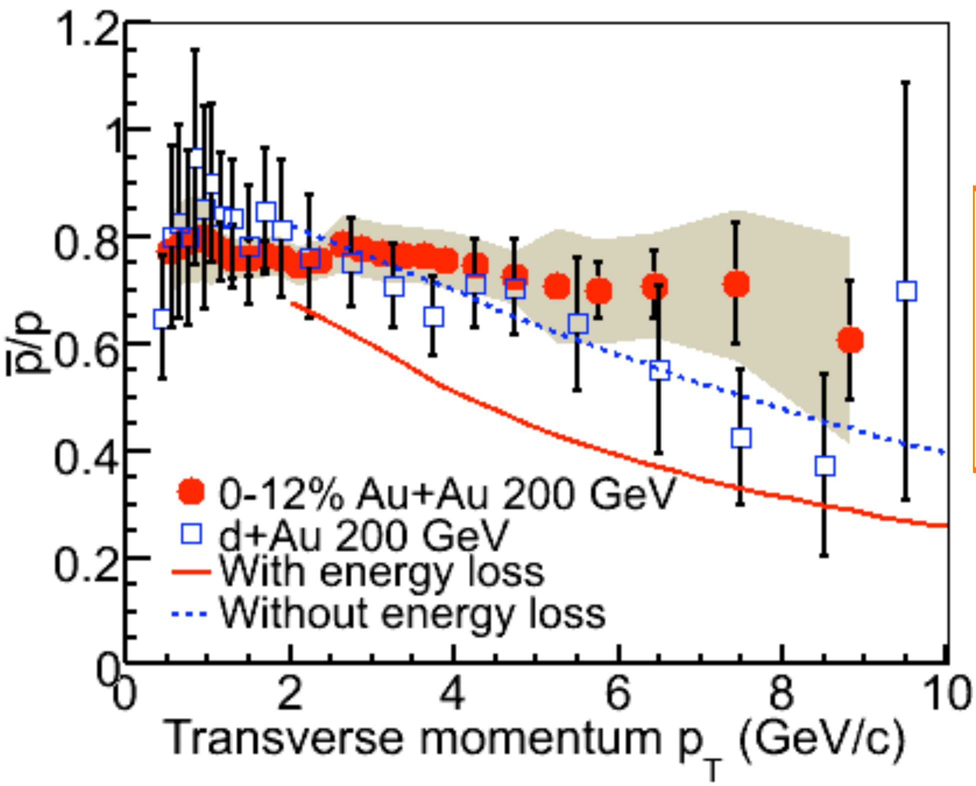


Observation at high p_T :

- p/π (Au+Au) ~ p/π (d+Au)
- Ratios way above jet quenching calculations
- For the Λ/K^0_s (Au+Au) and Λ/K^0_s (p+p) we need more statistics to conclude

p,π : PRL 97 (2006) 152301
Λ,K : nucl-ex/0601042
Theory : Fries et al, PRC 68 (2003) 044902

Experimental Results at RHIC - II



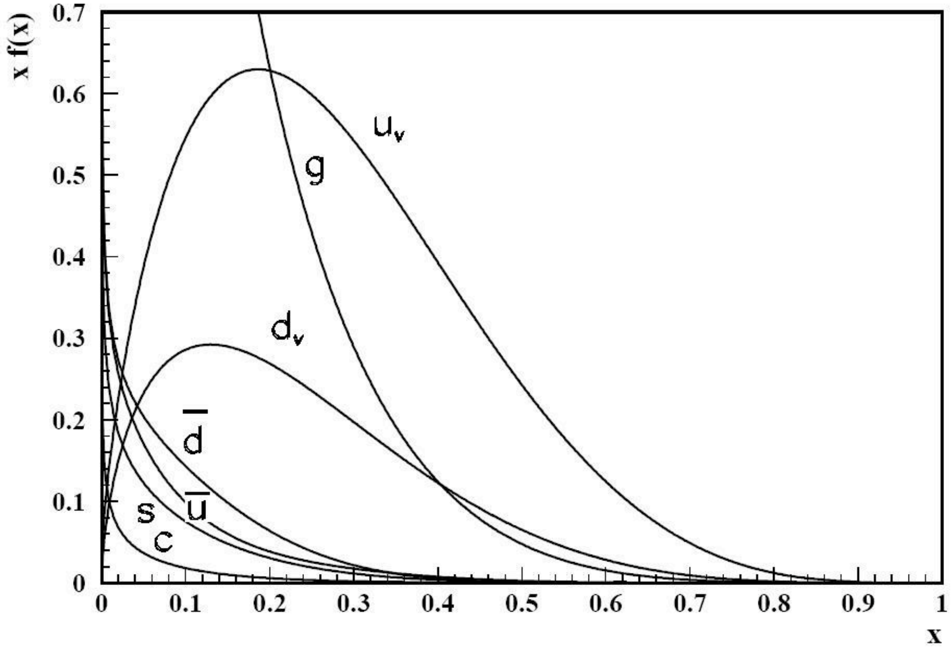
Observation at high p_T :

- pbar/p (Au+Au) >~ pbar/p (d+Au)
- pbar/p (Au+Au) > models with E_{loss}

AuAu : PRL 97 (2006) 152301
dAu : PLB 637 (2006) 161
Theory : X. N. Wang - PRC 70 (2004) 031901

We do not observe the naively expected lower ratios for Au+Au collisions due to difference in E_{loss} of quarks and gluons

Experimental Observable - III



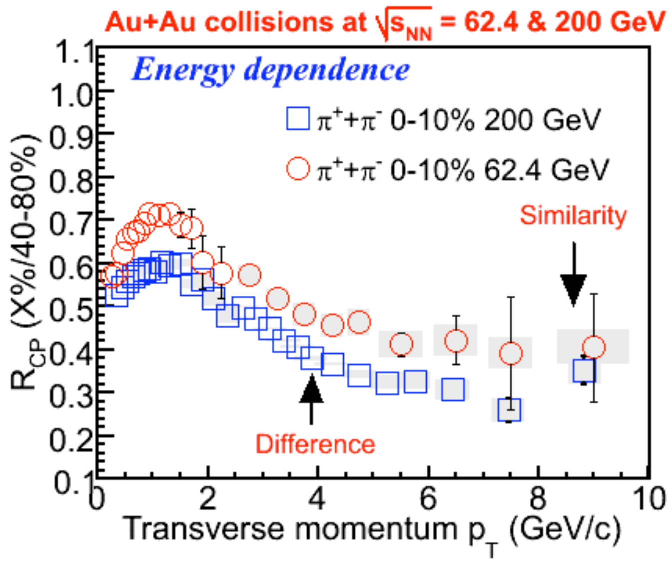
Proton - parton distribution function

$x_T = 2p_T/\sqrt{s_{NN}}$

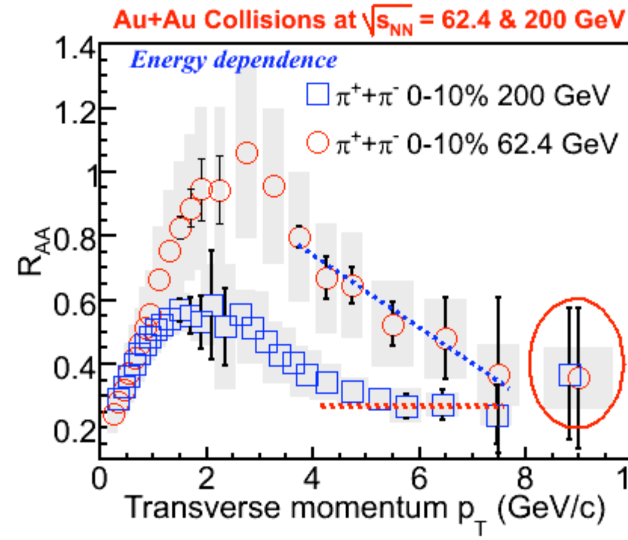
At p_T = 10 GeV
62.4 GeV : $x_T \sim 0.32$
200 GeV : $x_T \sim 0.1$

- Probing quark dominated jet production at lower energy to gluon dominated jet production at higher energy
- Then beam energy dependence of high p_T nuclear modification factor can in principle probe the color charge effect.

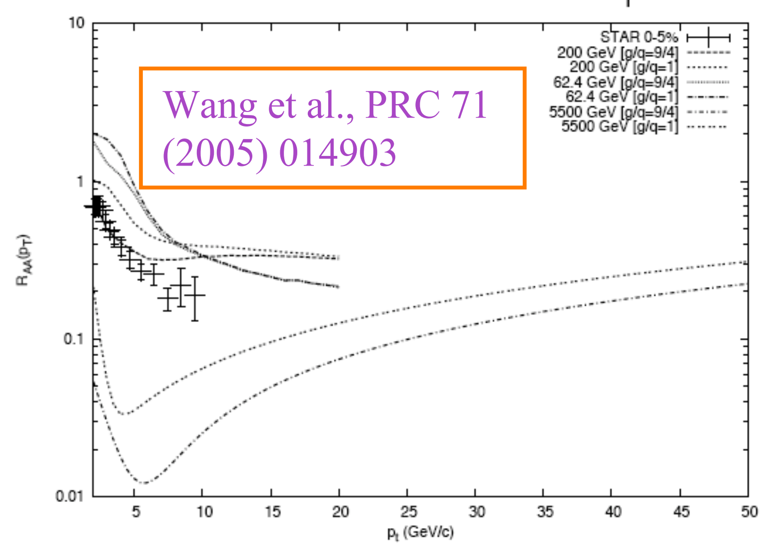
Experimental Results at RHIC - III



Complicated dependence
- initial jet spectra
- dN_g/dy
- color effect on parton E_{loss}



Observations at high p_T :
- In general R_{CP} at 62.4 higher than 200 GeV
- Values approach each other at highest p_T
- R_{AA} shape different beyond p_T= 4 GeV/c



Need for higher p_T measurements Au+Au collisions at RHIC

Given the errors in current measurements, may be not worth comparing to models

So why we do not observe the color charge effect

- Is it because of other mechanism of energy loss (e.g collisional) can smear the effect ?

- Is it because we have a gluon dominated initial conditions in heavy ion collisions at RHIC ?

- Is it because we still need to understand - how quarks and gluons interact with the medium formed. Is there a possibility of conversions between quark and gluon jets in the medium ?

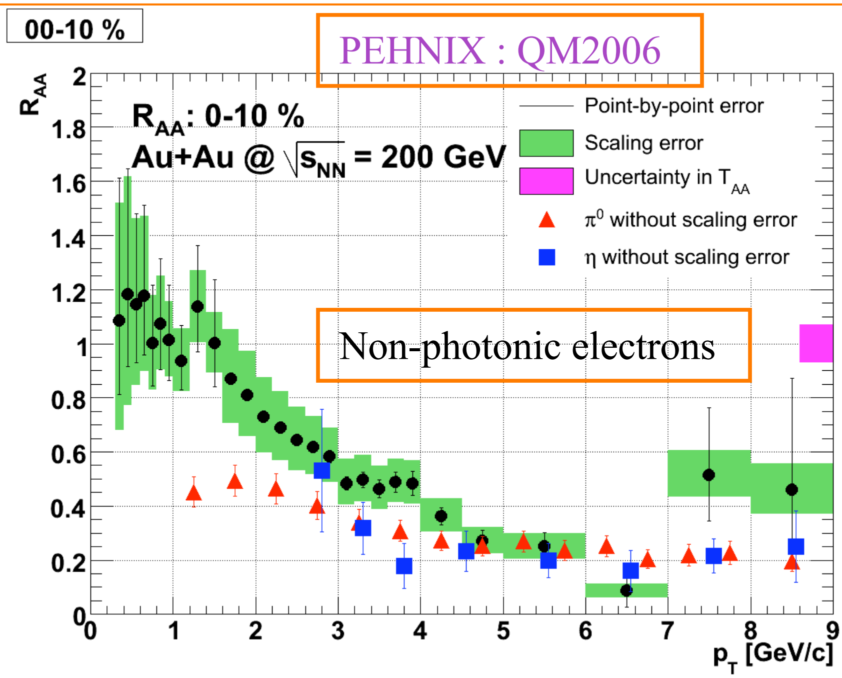
- Is it because in realistic calculations, to start with the differences are not very large ?

- Are color factors and α_S inter-dependent ?

Physics possibilities : different E_{loss} mechanism

Can collisional process of energy loss lead to non observation of the effect

PEHNIX : QM2006



Non-photonic electrons

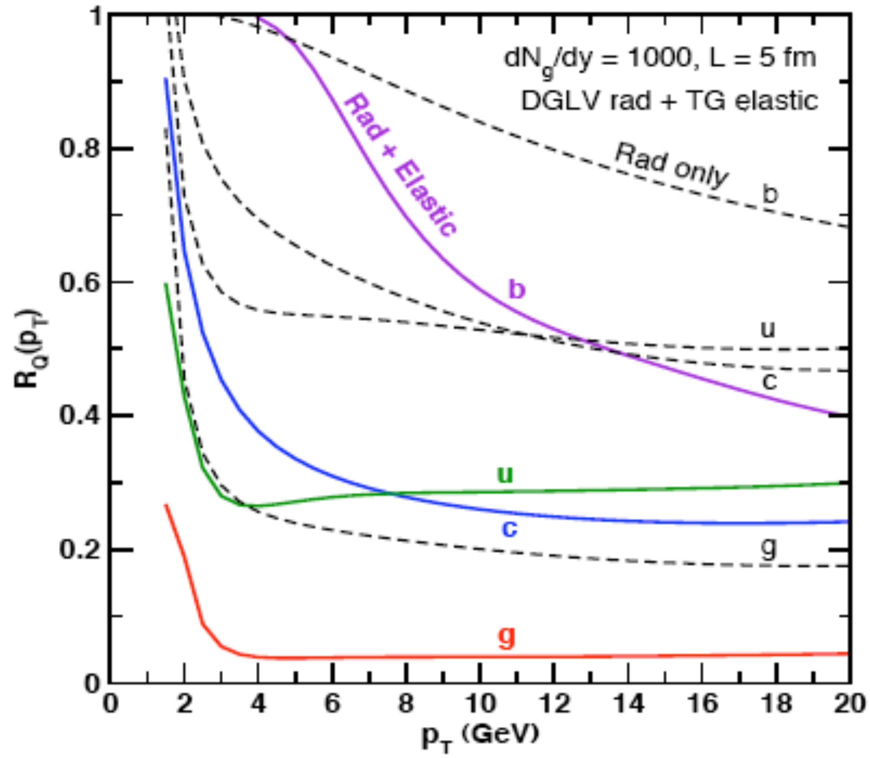


FIG. 5: Partonic nuclear modification, $R_Q^{II}(p_T)$ via Eq.(7), for g, u, c, b as a function of p_T for fixed L=5 fm path length and $dN_g/dy = 1000$. Dashed curves include only radiative energy loss, while solid curves include elastic energy loss as well.

$$\frac{dE^{el}}{dx} = C_R \pi \alpha_s^2 T^2 (1 + \frac{n_f}{6}) f(v) \log(B_c)$$

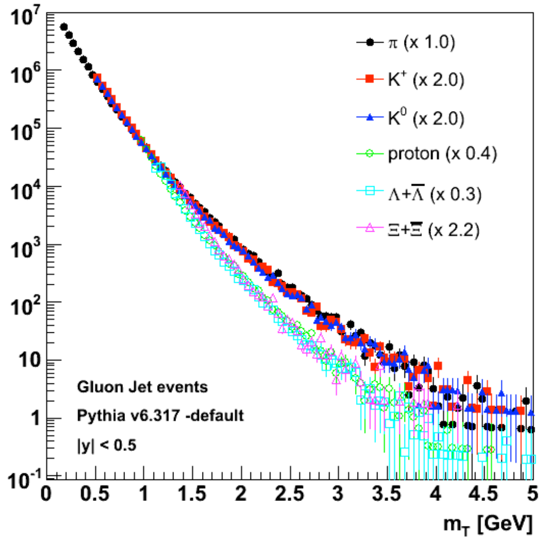
Theory : S. Wicks et al. - nucl-th/0512076

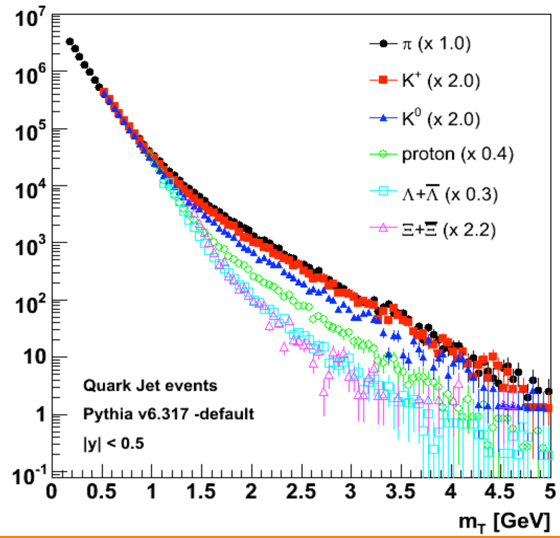
Collisional E_{loss} increases the difference from factor of 2 to 3
Really very puzzling why we do not see the effect

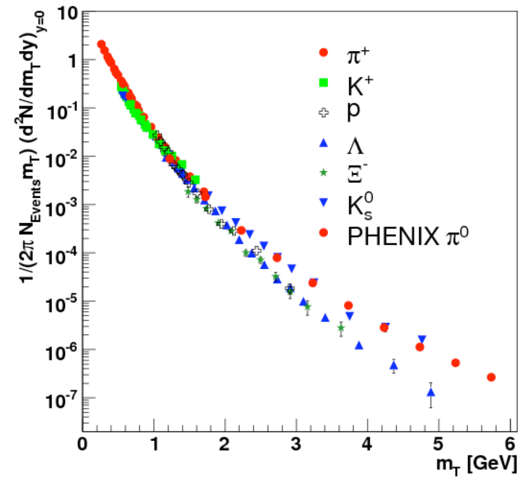
Physics possibilities : mostly gluons at initial stage

Is it all gluon jets in RHIC ?

STAR: nucl-ex/607033

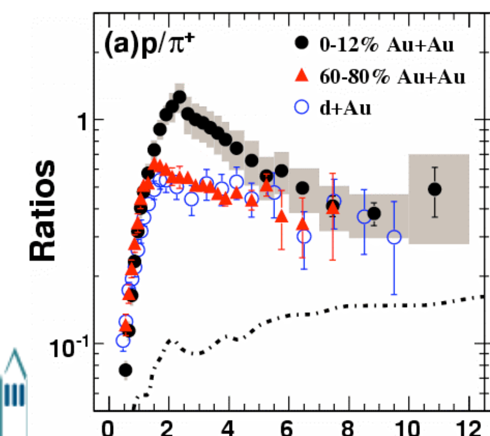






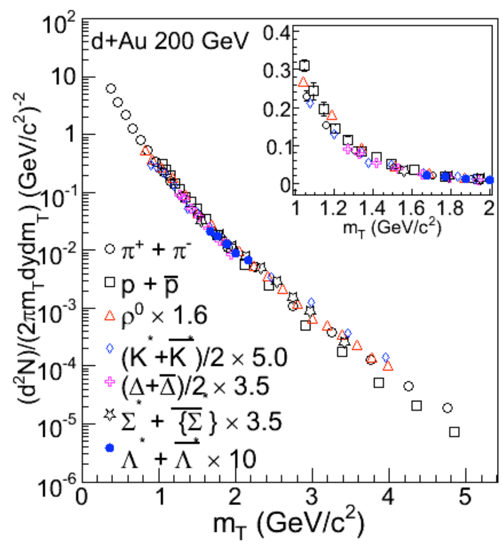
Generalized m_T scaling - gluon dominated initial state ?

Fragmentation of gluon, a baryon-meson splitting
Fragmentation from quark, a mass splitting



p/π ratio above quark jets from e^+e^- collisions

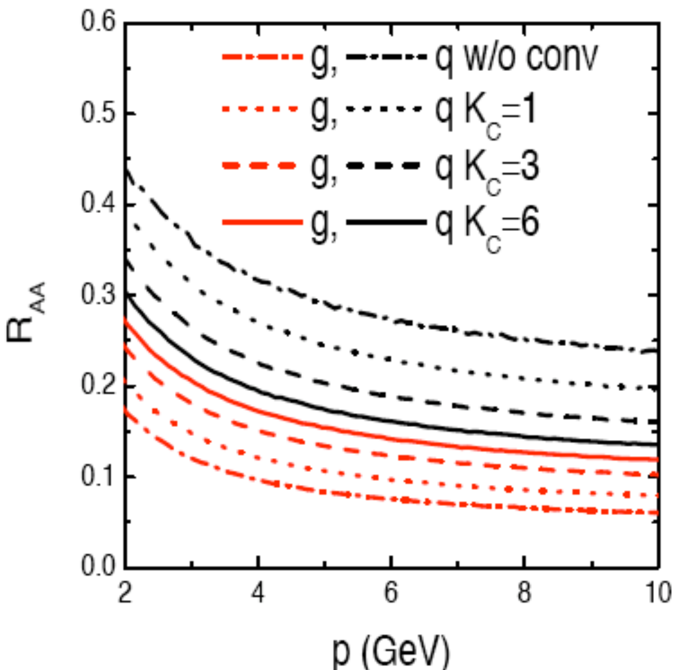
CGC: Nucl. Phys. A 705 (2002) 494



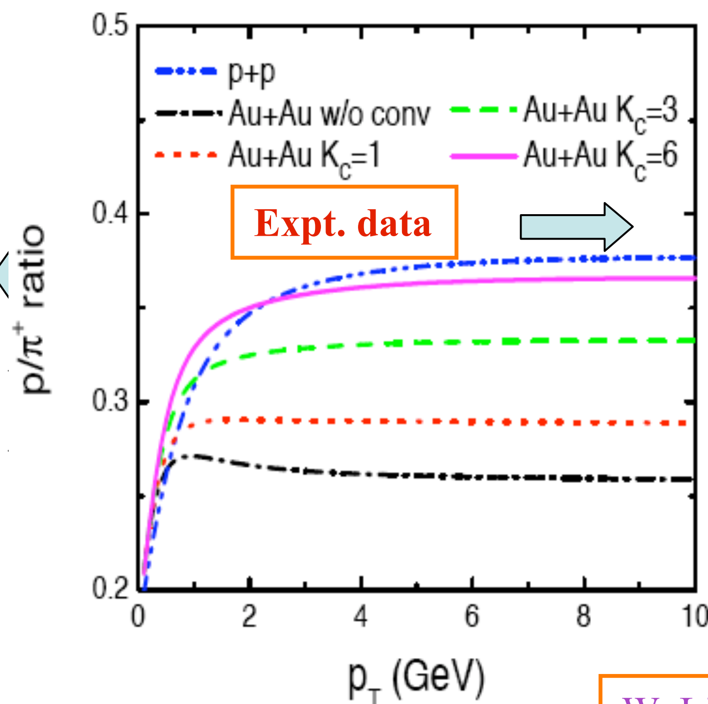
Physics possibilities : quark and gluon jet conversions

Mechanism to reduce the effect of color charge dependence of E_{loss} in QGP is to allow for conversions between q- and g- jets via both inelastic (qqbar -- gg) and elastic (gq(qbar) -- q(qbar)g) scatterings with thermal partons in the QGP

The conversion rate depends on collisional widths. For a chemically equilibrated QGP, the conversion rate for quark jet is larger than gluon jet. Increasing the final abundance of gluon jets and hence compensating for their larger E_{loss} in the QGP.



NMF for partons

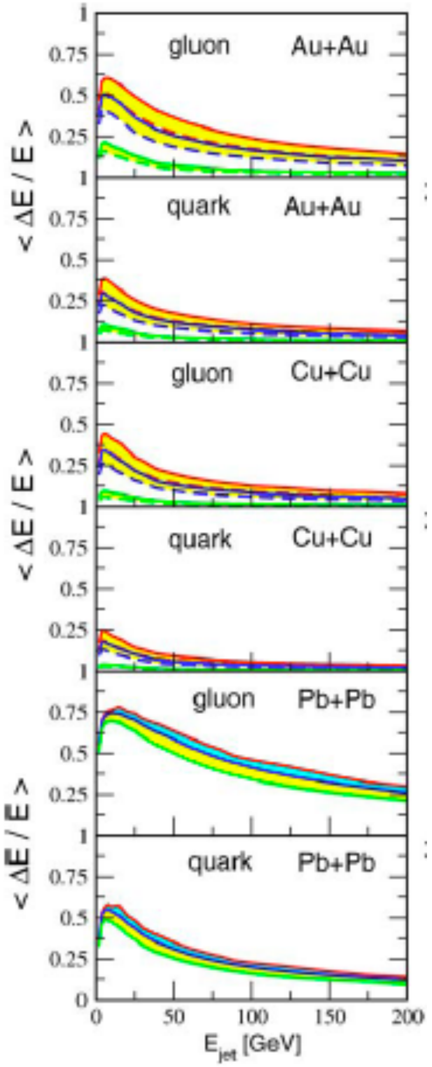


A pure gluon or quark matter - same result

AMPT has been successful at RHIC with large partonic sc. cross sections

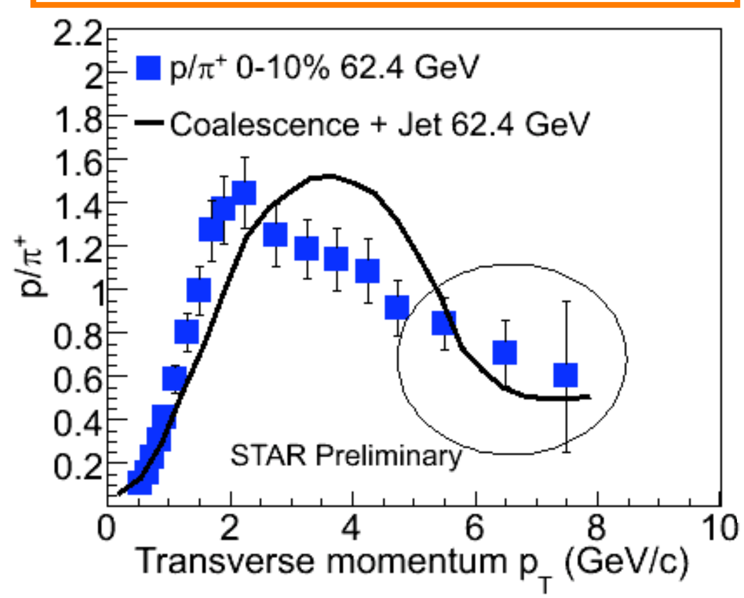
W. Liu et al., nucl-th/0607047

Physics possibilities : lower difference to start with

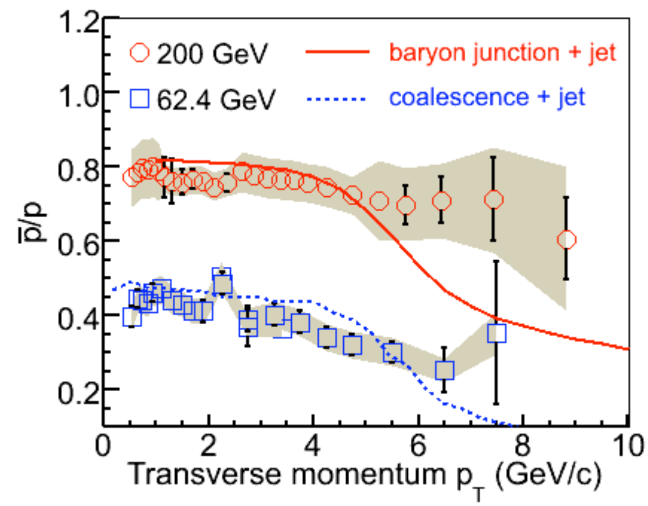


Calculations by I. Vitev (PLB 639 (2006) 38), suggests only in the limit E_{jet} tending to infinity, i.e ΔE/E tending to zero does the energy loss of quarks and gluons approach the naïve ratio $\Delta E^g/\Delta E^q \sim C_A/C_F \sim 9/4$. For large fractional energy loss this ratio is determined by the ΔE<<E constraint.

Indeed high p_T p/π ratio - data and theory are comparable

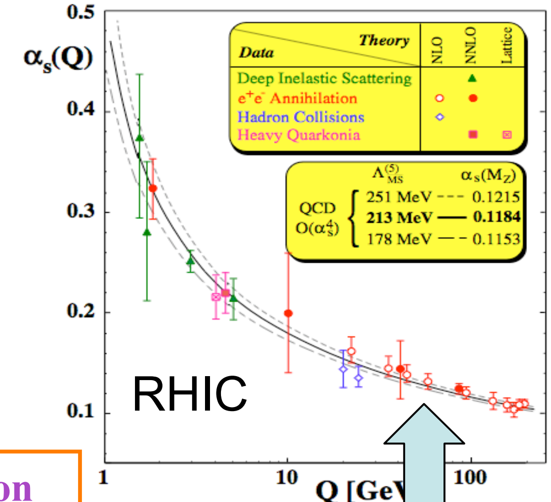


But …..



Physics possibilities : α_s and C interdependent

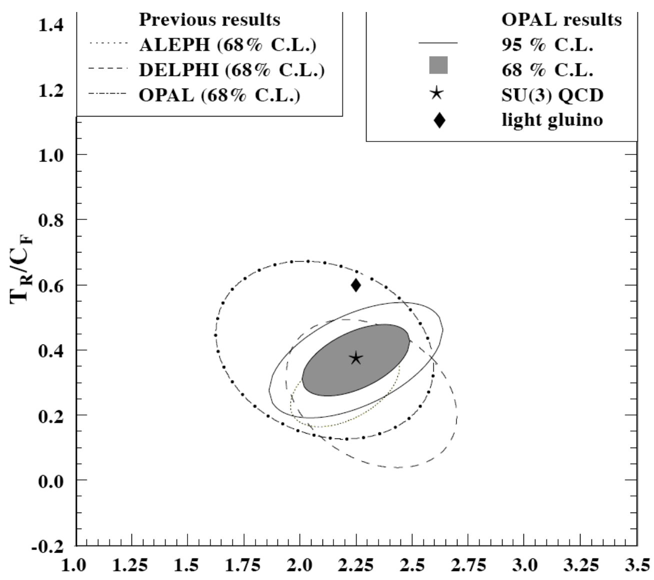
PRD 57 (1998) 5793 :
In the experimental analysis of color factor extraction from 4-jet events use of NLO predictions introduces an α_S dependence, that shifts the color factor ratios by $1 + 2\alpha_S$ in the direction of T_R/C_F



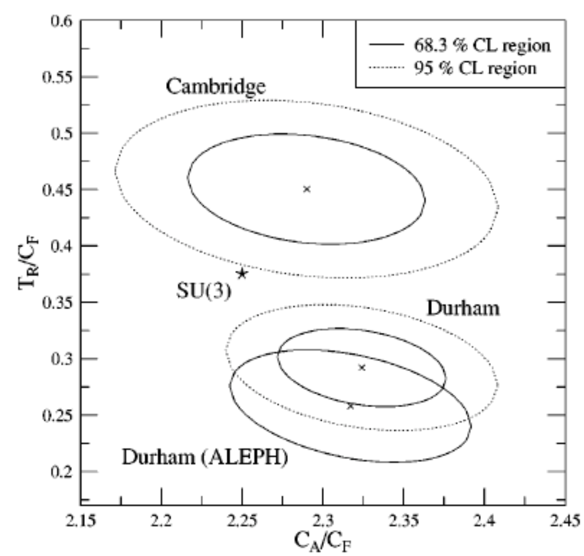
RHIC

Color Factor measurements

With LO calculation



With NLO calculation



Does this influence the conclusions ?

Outlook - Heavy flavor sector

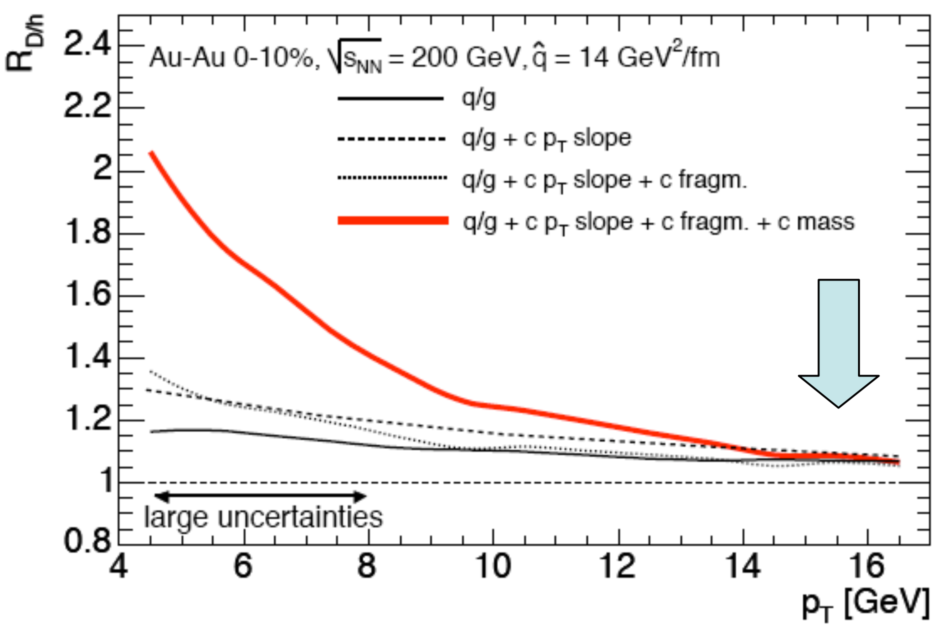
One possibility to look at color charge dependence is look at ratio of heavy to light NMF ratio.

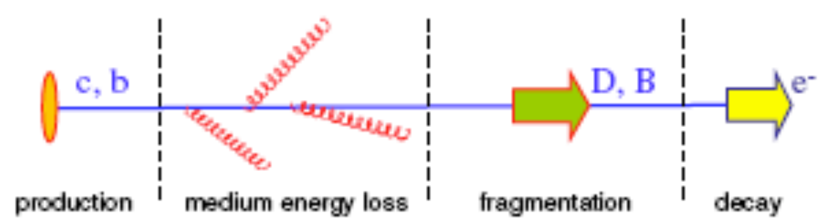
$$R_{D(B)/h}(p_t) = R_{AA}^{D(B)}(p_t) / R_{AA}^{h}(p_t)$$

Few aspects have to be disentangled to Get the color charge effect :

1. Mass effect - heavier the particle less is the Eloss. Solved by going to higher p_T
2. Partonic p_T spectra, heavy quarks have less steeper spectra. For same Eloss, steeper spectra, lower R_{AA}
3. Fragmentation of parton, heavy quarks have harder FF. For same parton E_{loss}, steeper FF, lower R_{AA}

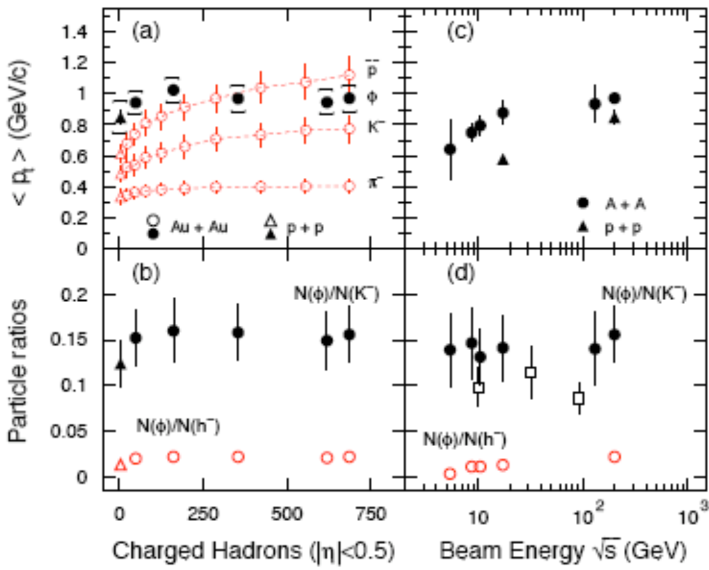
Theory : Armesto at al., PRD 71 (2005) 054027



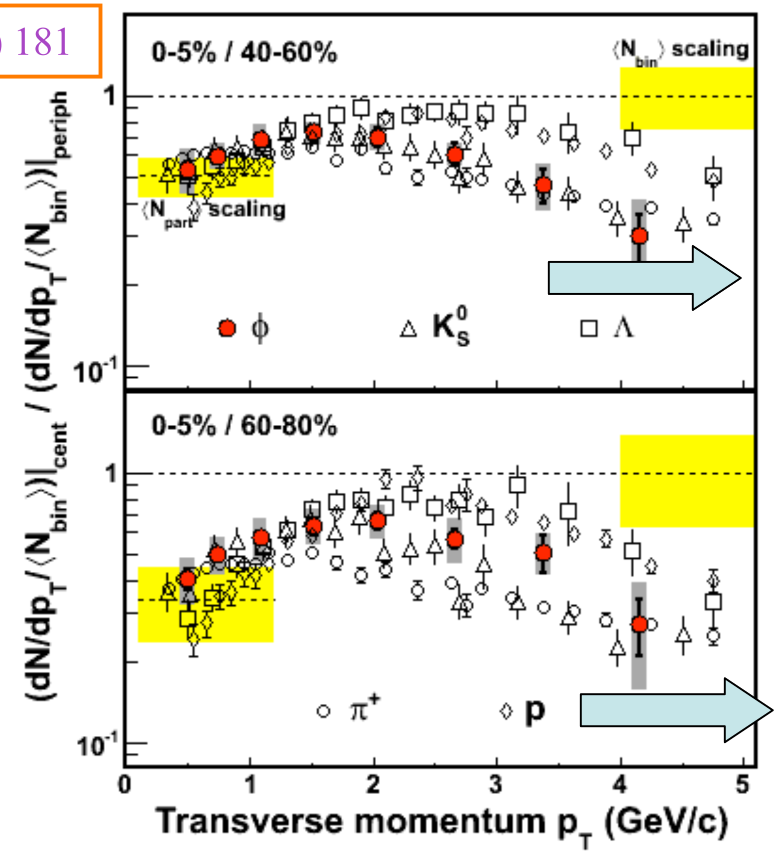


Outlook - Strangeness sector

Φ-meson can be used to study the color charge dependence.
At RHIC energies, Φ production is not dominantly from kaon coalescence,
So they may reflect s-quark energy loss.



STAR : PLB 612 (2005) 181



Similar to ratios of NMF heavy-to-light, the Φ-meson to light hadron (from gluon jets) NMF ratio can also be sensitive to color charge dependence of E_{loss} in heavy ion collisions

Summary

QCD with SU(3) as gauge group tells us, gluons are expected to loose more energy due to their strong coupling with the medium in heavy ion collisions compared to quarks. This effect is not washed out by collisional process of E_{loss}

Observations

1. Similar R_{CP} for protons and pions at high p_T
2. Λ and K^0_s R_{CP} approach each other at high p_T
3. Similar particle ratios (π,p,pbar) at high p_T for Au+Au and d+Au (p+p) collisions
4. Jet quenching not able to reproduce high p_T ratios
5. Energy dependence of NMF for pions is different at higher p_T
6. R(D/ h) and R(Φ/h) may provide a clear picture, or look at particle ratios in a jet

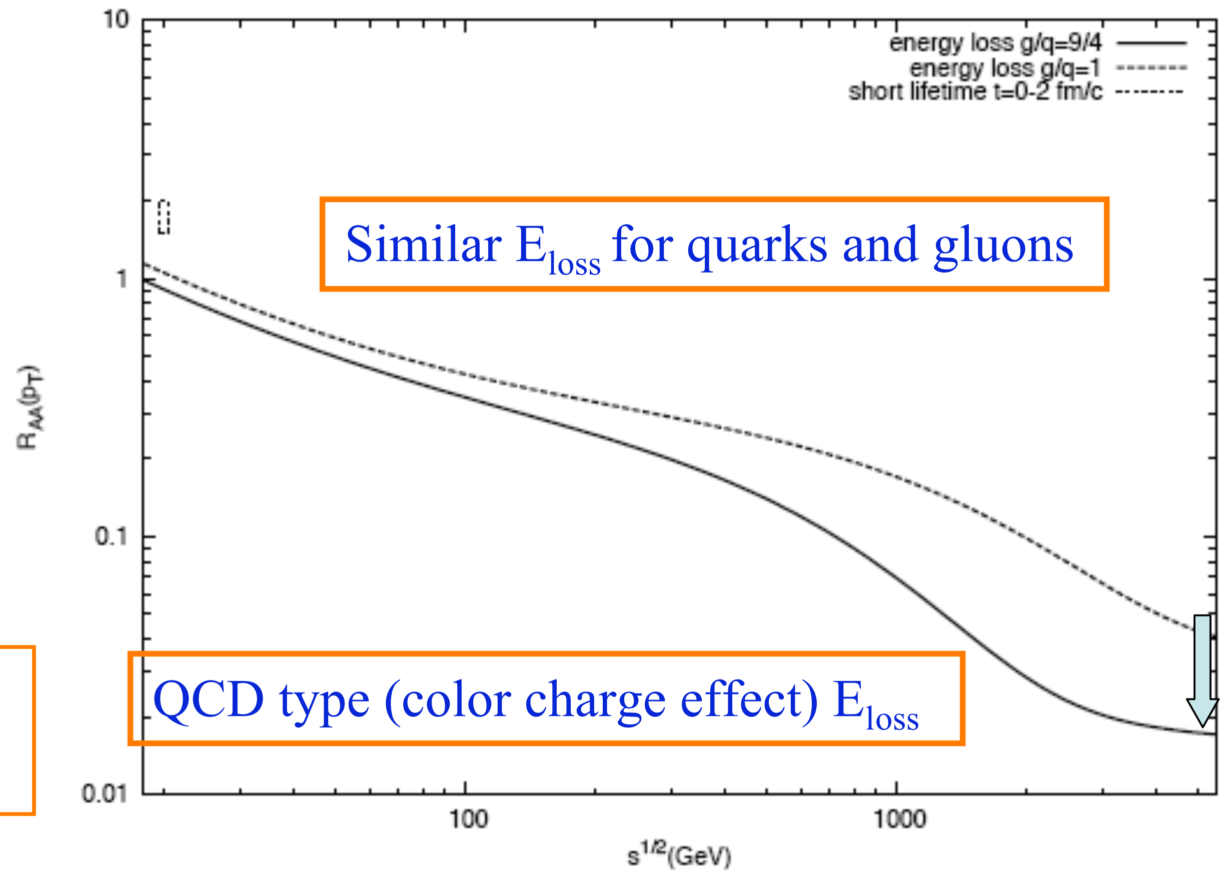
Conclusion and Possible interpretation

1. Similar E_{loss} for partons or gluon dominated matter at RHIC or need to understand quark and gluon jet interactions in medium
2. Need for higher p_T reach at RHIC. Higher statistics data needed
3. Energy dependence is complicated by initial jet spectra, gluon density. Models suggest differences larger at higher energies due to color effect
4. Color factor and α_S , $\Delta E/E$ dependence?
5. Use of better FF is needed in theory

Thanks

Outlook - Energy dependence of NMF RHIC &LHC

Probing quark dominated jet production at lower energy to gluon dominated jet production at higher energy

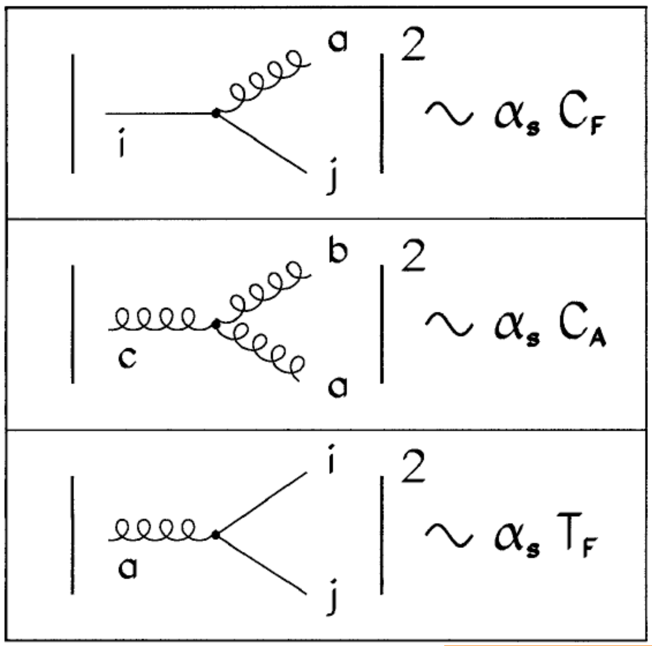


Theory :
Wang et al., PRC 58 (1998) 2321
Wang et al., PRC 71 (2005) 014903

Look for energy dependence of R_{AA} at a fixed high p_T (6 GeV/c). The big difference between similar E_{loss} for quarks and gluons and QCD type (color charge effect) E_{loss} only appears at higher energy as effect of initial gluon density and slope of initial jet spectra gets lesser

Physical picture - Color factors

- Color factors are related to fundamental couplings of the theory :
- C_F - determines coupling strength of a gluon to a quark,
- C_A - related to the gluon self coupling (fundamental property of QCD arising due to non-Abelian nature of the theory)
- T_F - strength of splitting of a gluon into a quark pair



$$= \sum_{\alpha} \left(T^{\alpha} T^{\alpha} \right)_{ij} = C_F \delta_{ij}$$

$$= \sum_{\alpha\beta} \left(f^{\beta\alpha\delta} f^{\gamma\alpha\delta} \right) = C_A \delta^{\beta\gamma}$$

- For $SU(N_c)$, the color factors are
  $C_A = N_c$,
  $C_F = (N_c^2-1)/2N_c$
  and $T_F = 1/2$

For SU(3) : $N_c = 3$
$C_A = 3$, $C_F = 4/3$

- i,j represent fermion field indices and a,b (α,β) gauge field indices
- T : Generators and f : Structure constants

Can we experimentally determine color factors ?