Hadro Chemistry with High-P_T Particles in Nuclear Collisions

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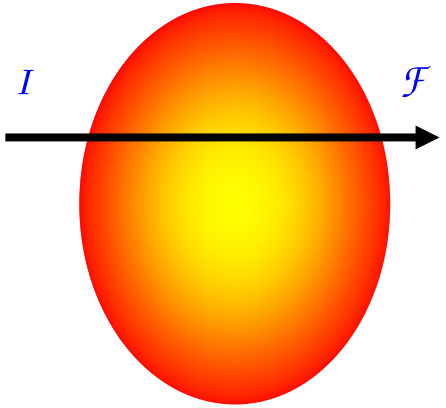
Overview

- From flavor conversions to jet chemistry
- Results for protons, photons, strangeness, charm
- Elliptic Flow

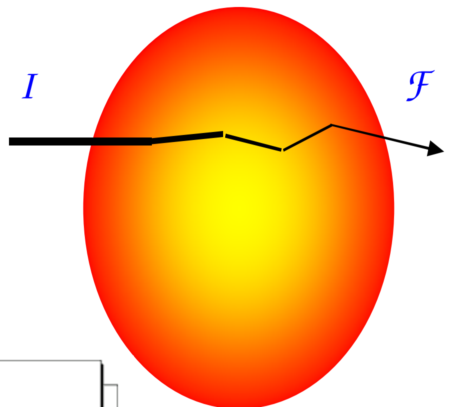
Jets and Hard Probes

- How do we know what's in a black box? Send in a probe!
  - Compute/measure the initial state I, measure the final state F
  - Compare to expectations.
  - Observables ↔ transport coefficients of the medium
- QGP in nuclear collisions: too short-lived to interact with a third particle beam.
- Use penetrating probes that are naturally occurring in the very same high energy collision: QCD jets!

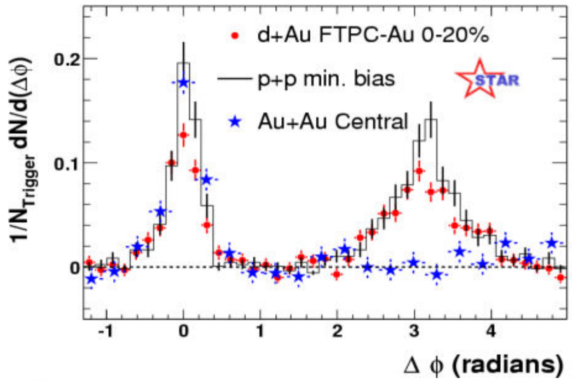


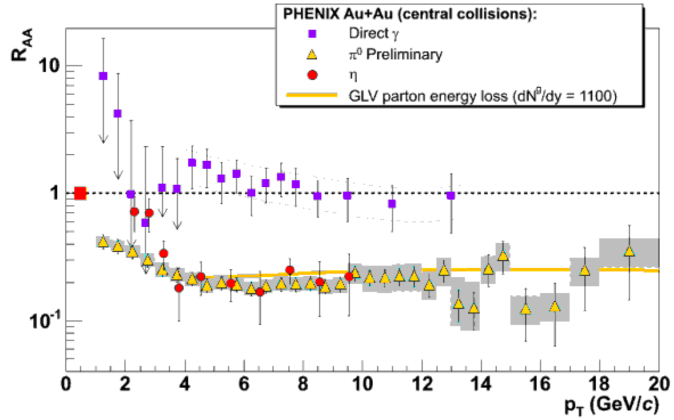
Jet Quenching

- Accessible so far: drag and diffusion in the medium
  - Drag force on fast partons (energy loss) via collisions or radiation
  - Transverse broadening and other transverse dynamics.
  - Energy loss $\leftrightarrow$ momentum transfer in collisions, transport coefficient $\hat{q} = \frac{\mu^2}{\lambda}$
- Observables for "jet quenching":
  - Suppression of single particle spectra.
  - Away-side jets and other two-particle correlations
  - Jet yields, …



- Current status at RHIC:
  - See talks by J. Jia, S. Salur, Y. Lai.

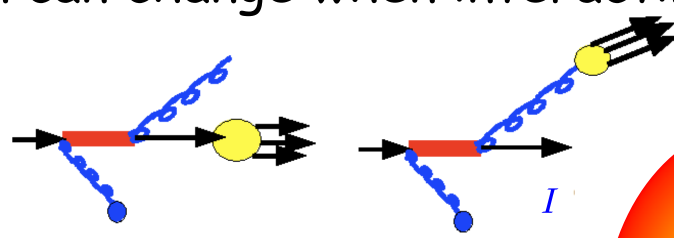


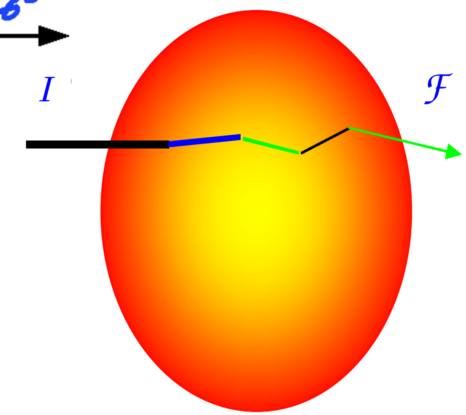


New Degrees of Freedom: Flavor

- What else can we observe related to hard probes?
- Measure changes in chemical composition of jets.

- Identity (flavor) of a parton can change when interacting with the medium.
  - Pair production and radiation
  - Exchange of particles



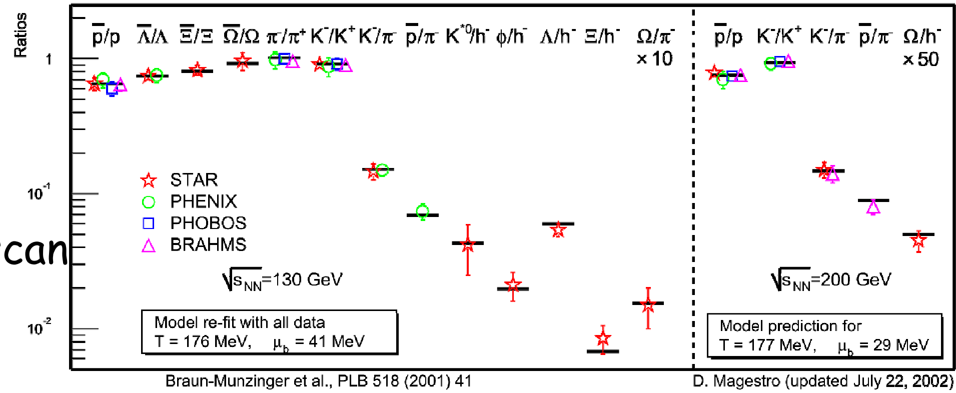


- "Flavor" here defined by the leading jet parton.
  - We use a generous definition of flavor: gluons g; light (q) and strange quarks (s), heavy quarks (Q), real and virtual photons (γ).

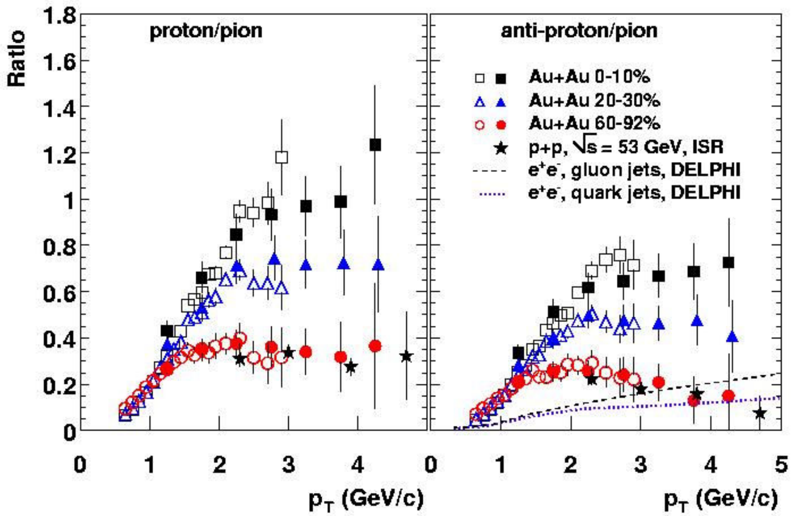
- Hadronization: parton chemistry $\rightarrow$ hadron chemistry at high p_T
  - Hadronization washes out signals in parton chemistry; need robust flavor signals on the parton side.

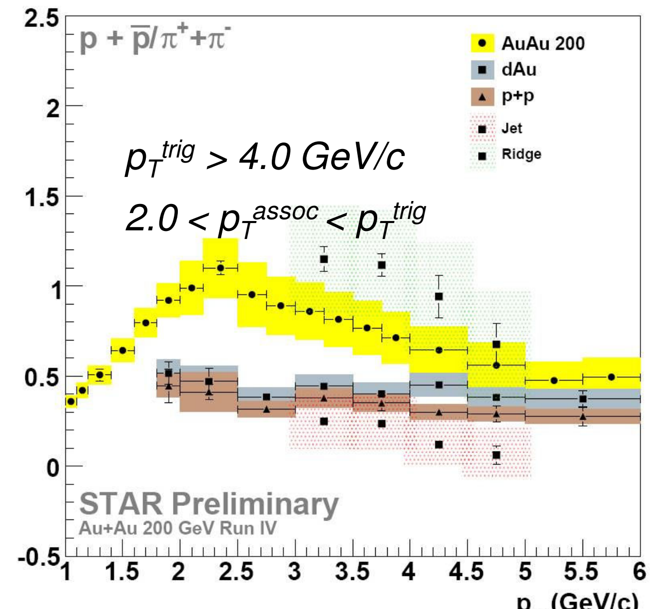
Hadro-Chemistry

- Low P_T: bulk matter
  - Chemical equilibration
  - Search for phase transition in $\sqrt{s}$ scan



- Intermediate P_T:
  - baryon vs meson ratios ⇒ recombination models.



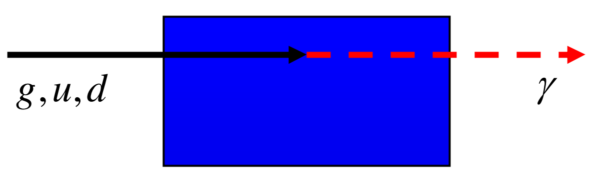


- A good measure of equilibration
  - e.g. energy from jets transferred to the medium.

What can we learn from jet chemistry?

- Flavor conversions are …
  - … not very sensitive to the momentum transfer with the medium.
  - … sensitive to the mean free path λ.
- A chance to get our hands on a quantity complementary to $\hat{q} = \frac{\mu^2}{\lambda}$.
- Example: rare "flavor" (not contained in the medium), which can be produced off the medium
  - E.g. photons through Compton scattering and annihilation of jets in the medium.

$$q + \bar{q} \to \gamma + g$$
$$q + g \to \gamma + q$$

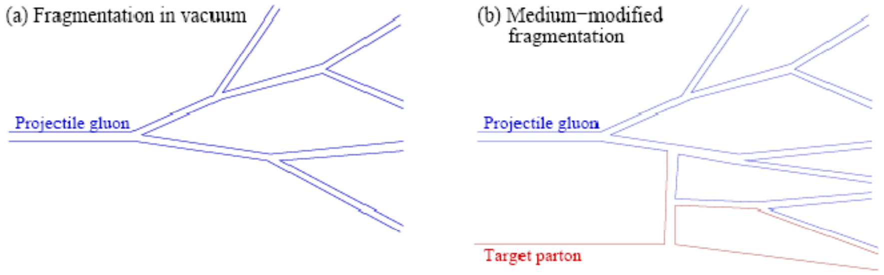


$$\frac{dN^{\text{rare}}}{dt} = \frac{1}{\lambda} N^{\text{jet}} \quad \Rightarrow \quad \frac{N^{\text{rare, excess}}}{N^{\text{jet}}} = \frac{L}{\lambda}$$

  - In this idealized situation: direct access to λ.

From Jets to Hadrons

- The picture here:
  - Parton propagation through the medium with elastic or inelastic interactions.
  - After any collision: final state parton with the highest momentum is the new leading parton ("the jet")
  - ⇒ Study changing chemistry in ensemble of jets coupling to the medium.
  - Vacuum hadronization: parton chemistry → hadron chemistry
- Caveat: hadronization itself might be changed.
  - Gives rise to a complementary mechanism: changing chemistry inside a single jet cone due to increased multiplicities
  - Both mechanisms should be considered for a full picture.



[e.g. Sapeta and Wiedemann, EPJ C55 (2008), …]

Quark-Gluon Conversions

- Possible pair annihilation/creation and Compton like processes lead to quark ↔ gluon conversions

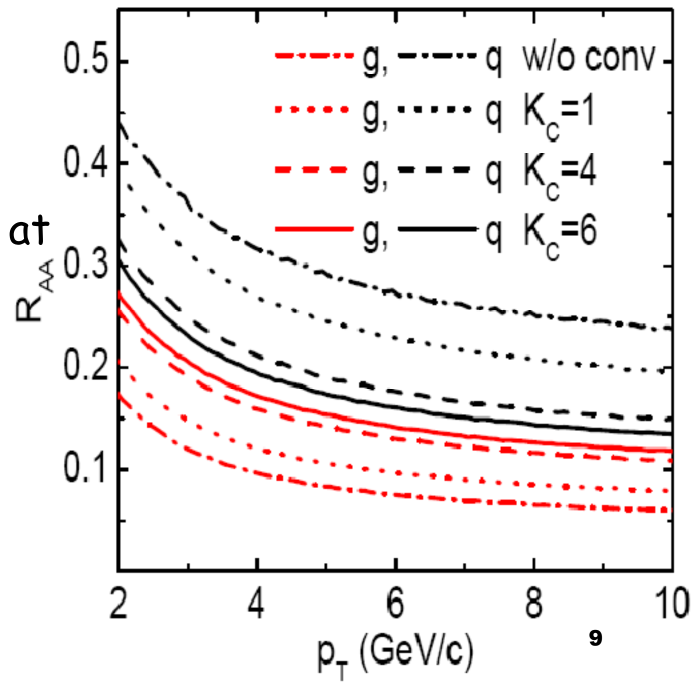
  [Ko, Liu, Zhang]
  [Liu, RJF]

$$q+\bar{q} \leftrightarrow g+g$$

$$q+g \leftrightarrow g+q$$

- Motivation: search for relative quenching factor 9/4
  - Will be washed out if λ ~ system size or smaller
- Elastic g ↔ q conversions:
  - Find effective conversion of quark to gluon jets at RHIC energies (30% of quark jets lost).
  - Find K factor > 1 needed to get rid of the difference in quark-gluon suppression.
  - How does it translate into hadrons?

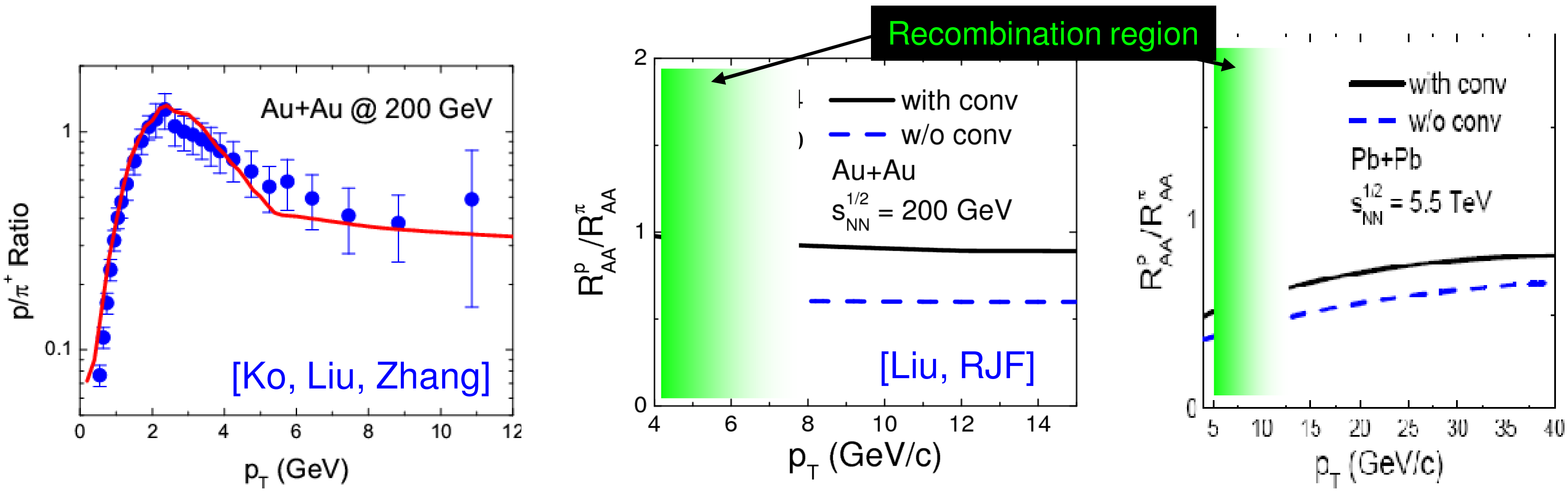
[Ko, Liu, Zhang]



Quark-Gluon Conversions: Estimates

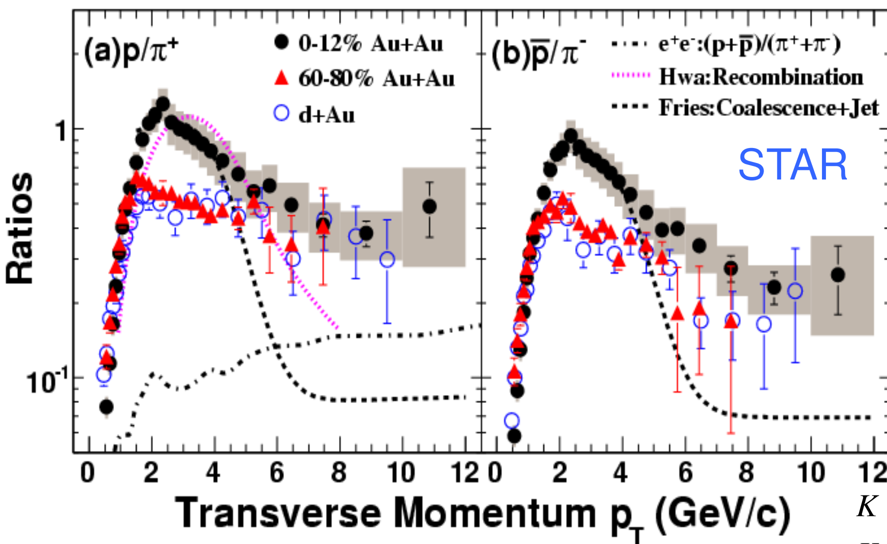
- Potential signature: differences in quark vs gluon fragmentation into pions and protons.
  - Should result in more suppression of protons vs pions.
  - Expect uncertainties from fragmentation functions.
- Decrease dependence on fragmentation functions by using double ratios

$$\gamma_{p/\pi^+} = \frac{(p/\pi^+)_{AA}}{(p/\pi^+)_{pp}} = \frac{R_{AA}^{p}}{R_{AA}^{\pi^+}}$$



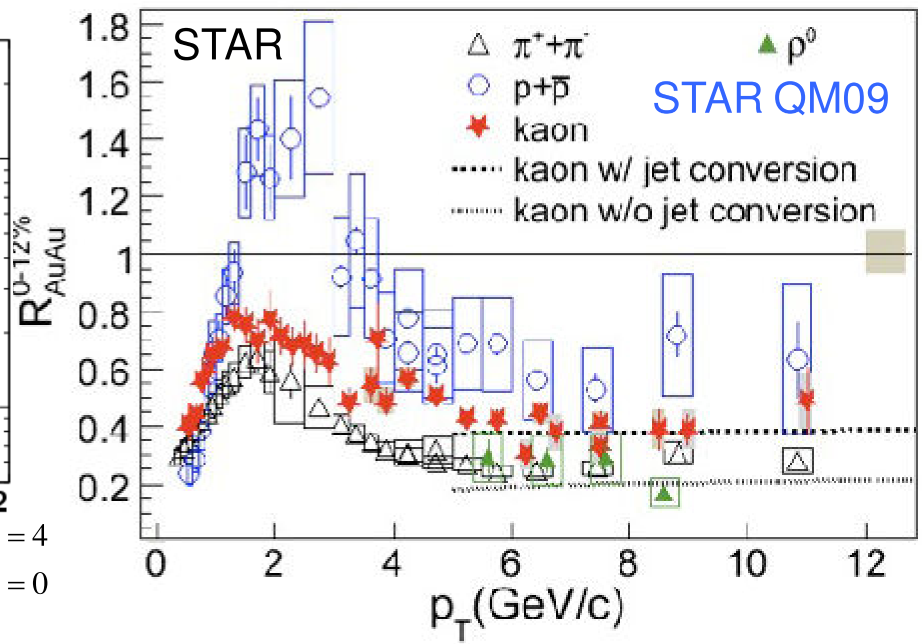
Quark Gluon Conversions: Data

- Most recent PHENIX and STAR data:



$K = 4$

$K = 0$



- R_{AA} surprise: Proton > Pion
  - Could mean additional source of protons even at 10 GeV/c.
  - Recombination?

Rare "Flavors"

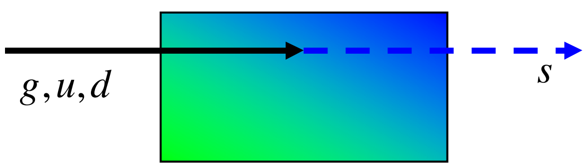
- Rare probes: not chemically equilibrated in the jet spectrum.
- Obvious example: photons and dileptons
  - Need enough yield from conversions to outshine other sources of N^{rare}.

- Another class: flavor chemically equilibrated <u>in the medium</u> but not in the jet sample

- True for strangeness at RHIC:

$$w_{jet} = \left(\frac{s}{u+d}\right)_{jet} \approx 5\% \qquad \text{@ 10 GeV for RHIC}$$

$$w_{ce} = \left(\frac{s}{u+d}\right)_{medium} \approx 50\%$$

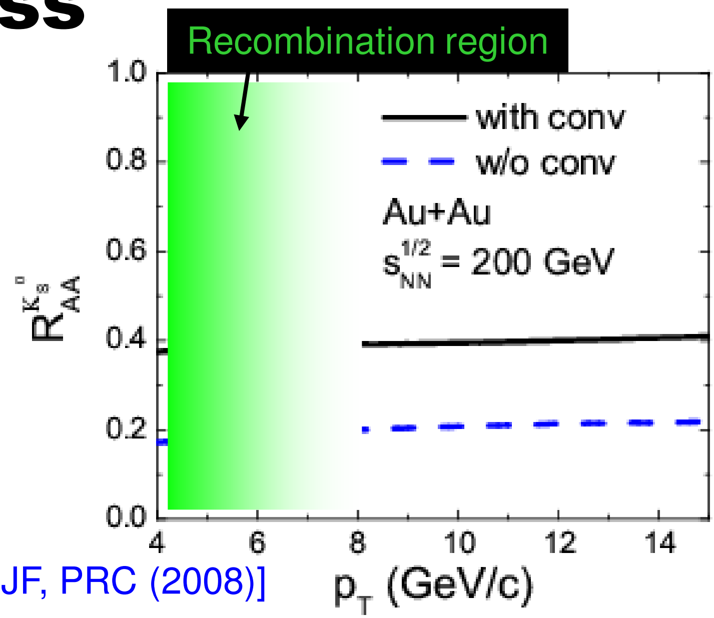


e.g. $g + s \rightarrow s + g$

- Coupling of (not equilibrated) jets to the equilibrated medium should drive jets towards chemical equilibrium.

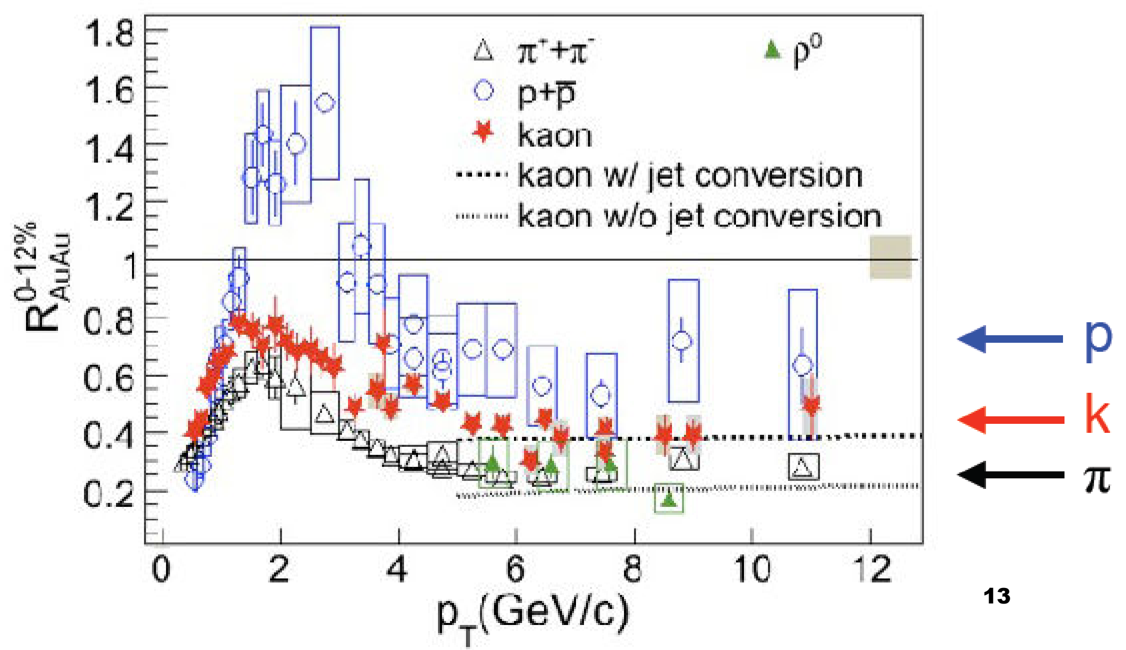
Strangeness

- Expect s-jet enhancement at RHIC
- Translates into kaon enhancement:
  - Caution: would like to avoid recombination effects.
  - Check above 6-8 GeV/c.



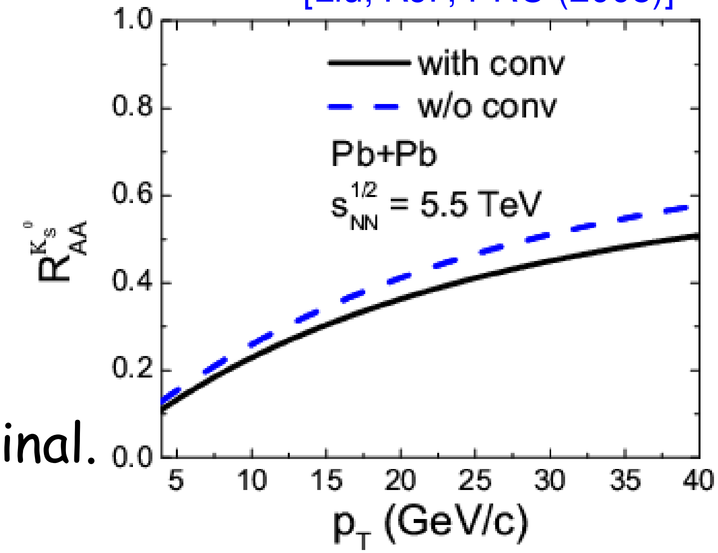
[Liu, RJF, PRC (2008)]

- New STAR result:
  - Kaon enhancement seen between 6 and 10 GeV/c.
  - A first unambiguous signal for conversions?



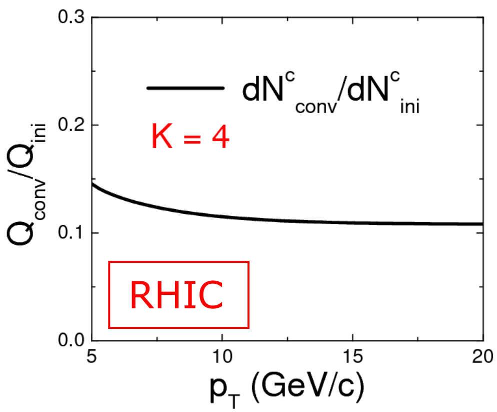
LHC, Heavy Quarks

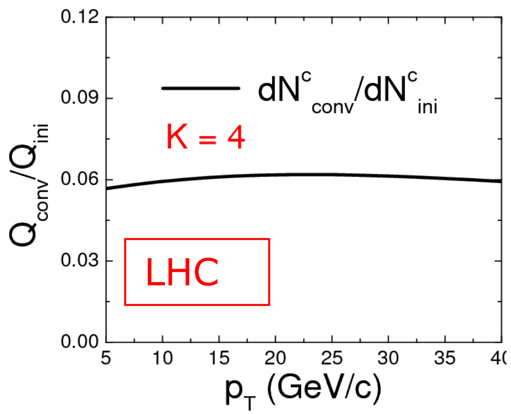
[Liu, RJF, PRC (2008)]

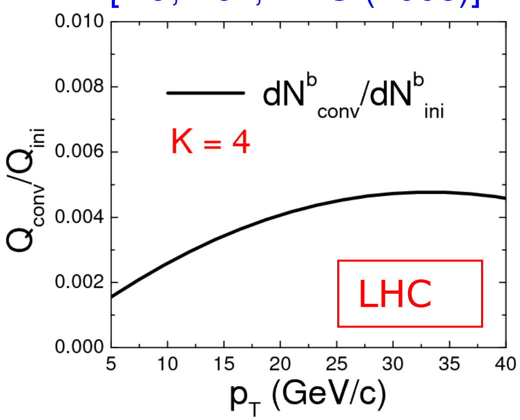


- Kaons at LHC: find no enhancement
  - Reason: strangeness in initial jet sample almost equilibrated.
  - Maybe it works with charm?
- RHIC: conversion to heavy quarks marginal.
- LHC: charm does not act like strangeness at RHIC, conversion yields are small.
  - Reason: small gradient between jet and medium charm.

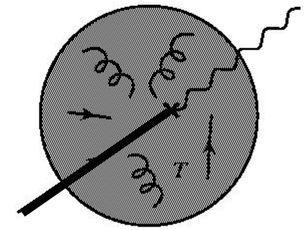
[Liu, RJF, PRC (2008)]

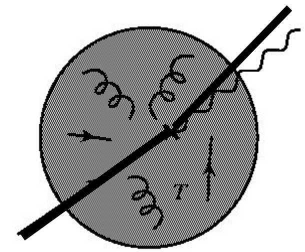






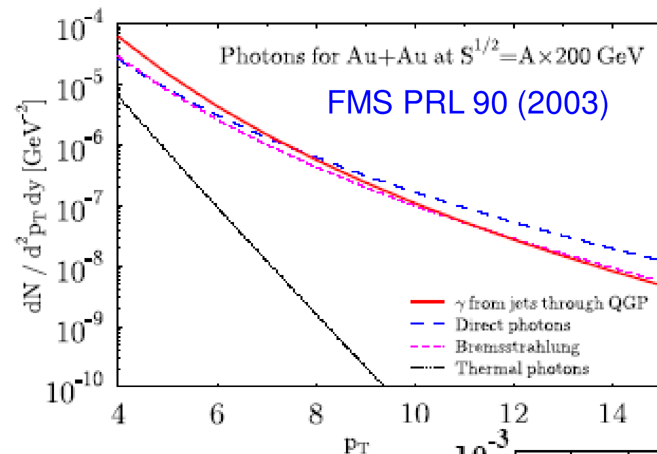
Photons and Dileptons





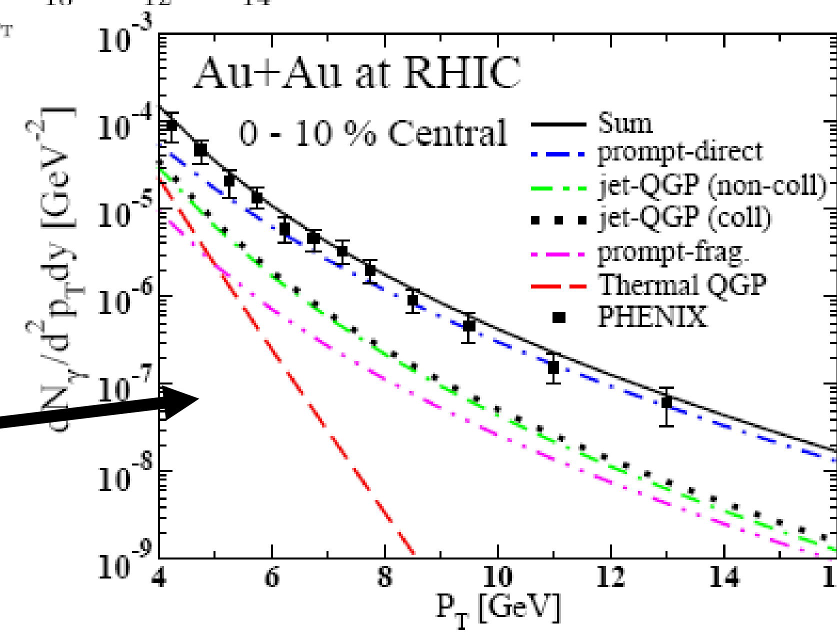
- Photon and dilepton conversions from jets
  - See talks by C. Gale, G. David

    [RJF, Müller, Srivastava; Srivastava, Gale, RJF; Zakharov;.....; Zhang, Vitev]

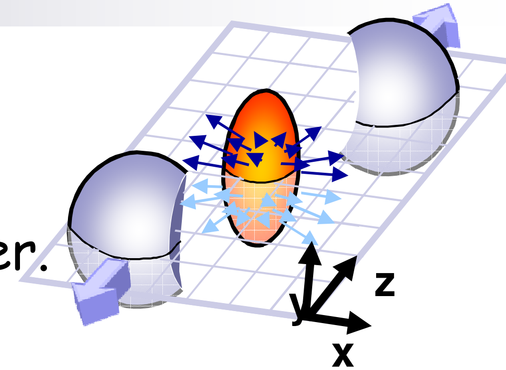


- First estimate:
  - Competitive photon sources for P_T~ 4-6 GeV at RHIC energies, even more important at LHC.
- Experimental situation:
  - Not resolved
- State of the art calculation

  [Turbide, Gale, Frodermann, Heinz]

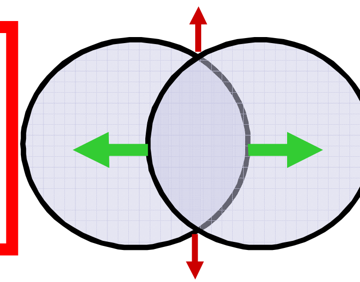


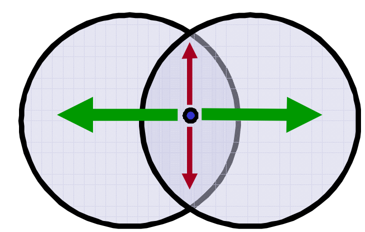
Elliptic Flow v_2

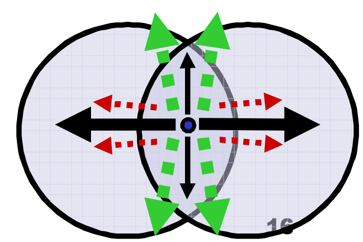


- Azimuthal anisotropy for finite impact parameter.
- Three different mechanisms:

	Initial anisotropy	Final anisotropy	Elliptic flow v_2
Bulk	pressure gradient	collective flow	$v_2 > 0$
saturated high-P_T probe	path length	quenching	$v_2 > 0$
rare high-P_T probe	path length	additional production	$v_2 < 0$







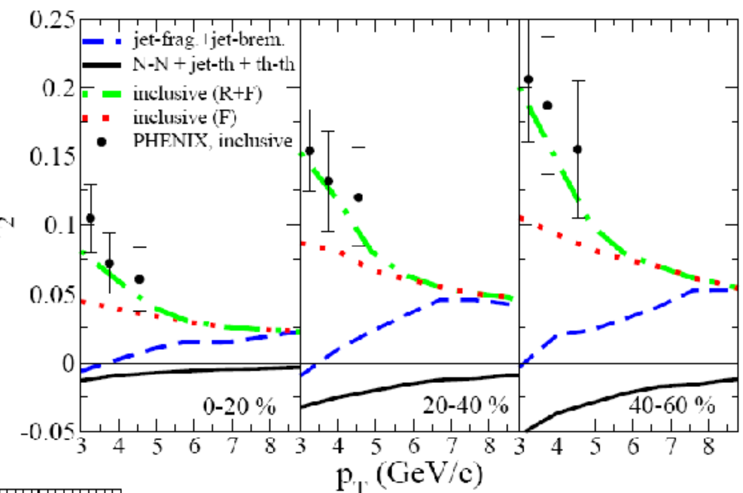
[Turbide, Gale & RJF, PRL 96 (2006)]

Photon Elliptic Flow

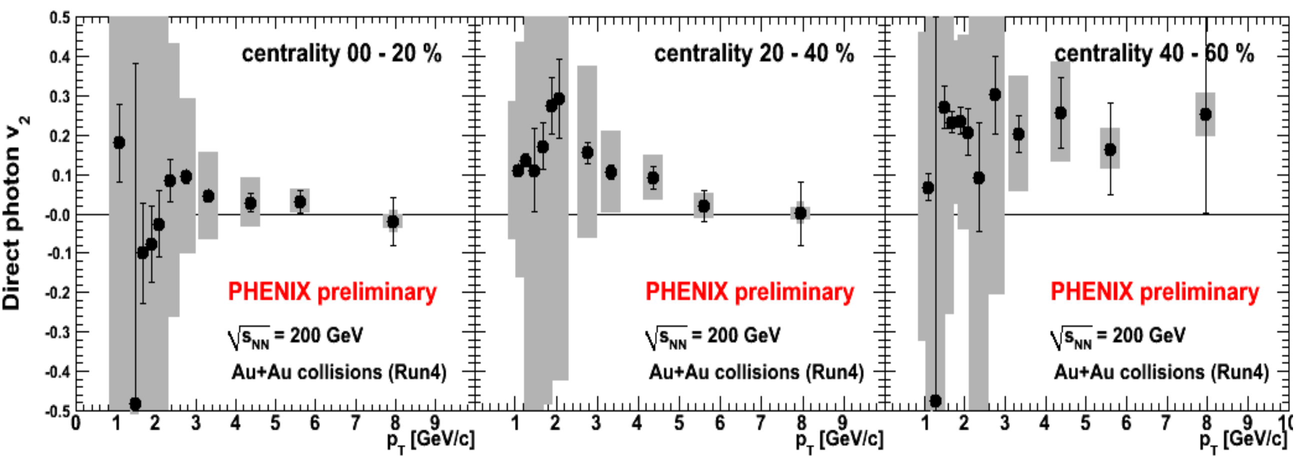
- Have to add other photon sources with vanishing or positive v_2.

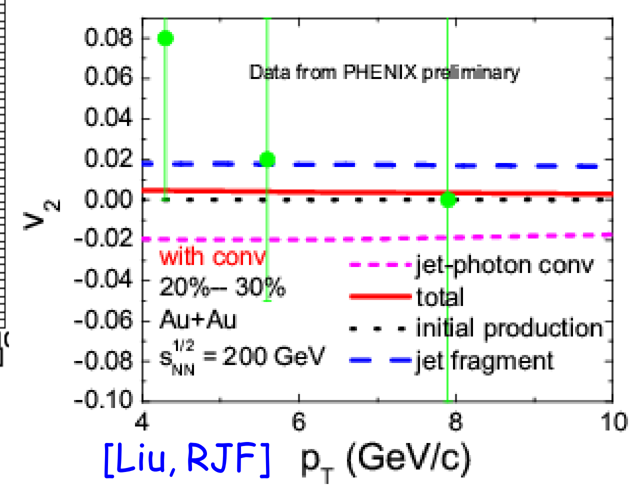
[Turbide, Gale, RJF;
Chatterjee, Frodermann, Heinz, Srivastava; …]

- Status:
  - Large negative v_2 excluded by PHENIX for $P_T > 3$ GeV/c.
  - Sensitivity to fireball evolution.



[Turbide, Gale, RJF]

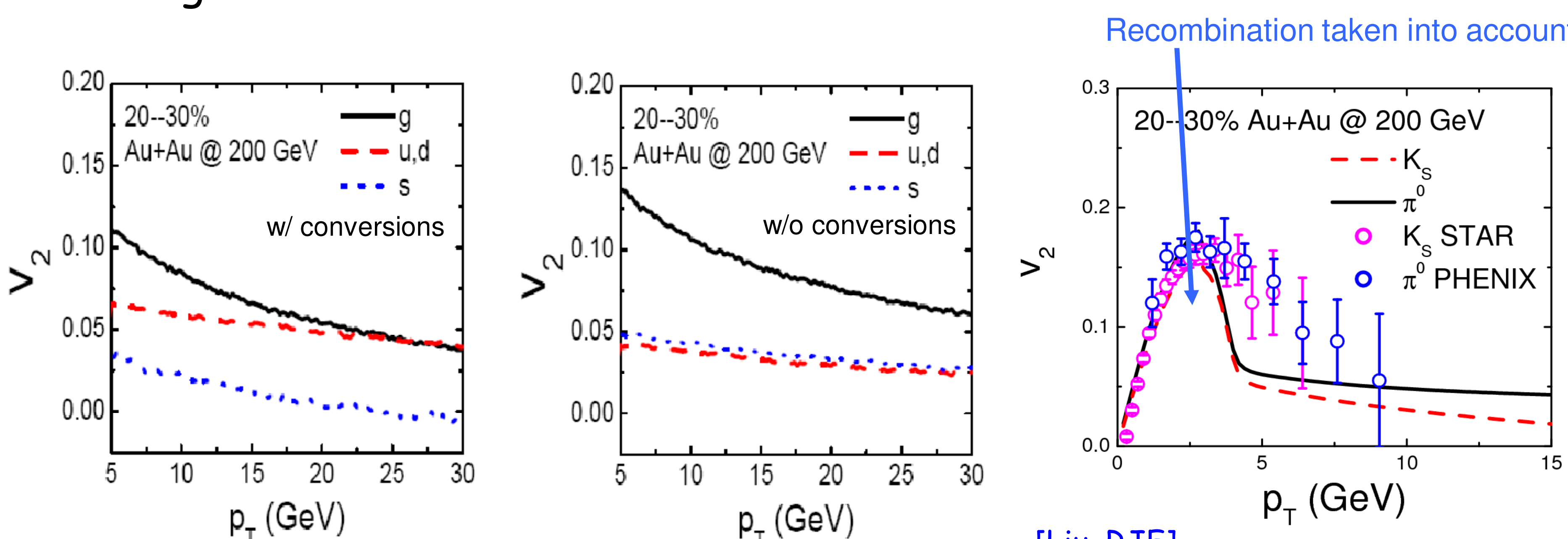




[Liu, RJF]

Strangeness Elliptic Flow

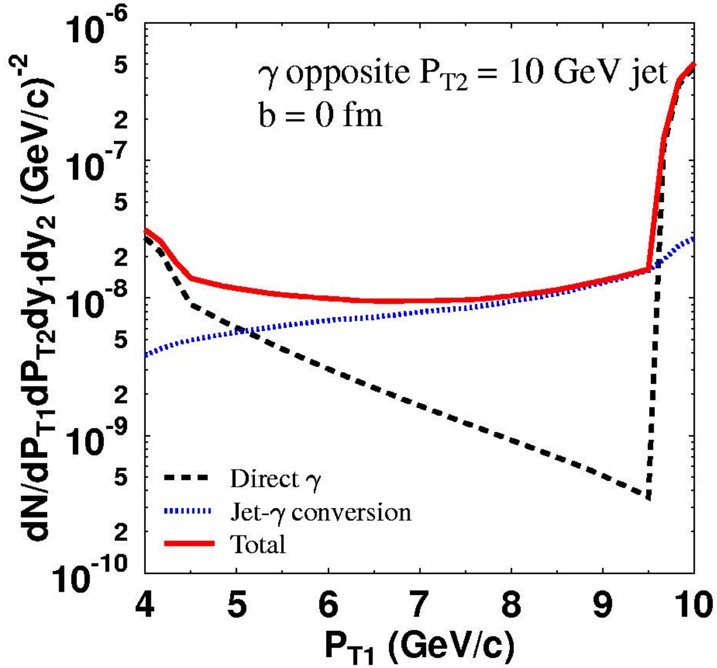
- Elliptic flow argument also holds for rare probes that are driven toward chemical equilibration while traversing the medium.
- Expect suppression of kaon v_2 outside of the recombination region.

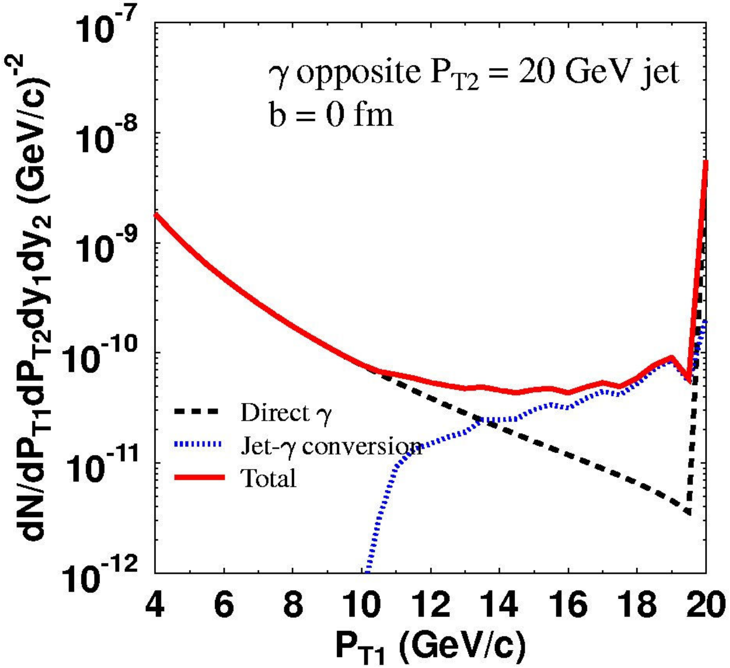


[Liu, RJF]

Last Comment on Photons

- Instead of using photons to measure jet modification: use jets to disentangle photon sources.
- Photons opposite 10 and 20 GeV jets.





[RJF]

- See also recent work by the McGill group. [Qin et al. (2008)]

RIKEN BNL Research Center

Summary

- Flavor changing processes are present in jet-medium interactions.
- Jet chemistry contains information complementary to jet quenching measurements. Mean free path measurements?
- Potential signatures:
  - Quark-gluon conversions: compatible with absence of increased proton suppression as seen by STAR.
  - Conversion photons and dileptons: good agreement with data, but alternative explanations not ruled out
  - Enhanced strangeness at RHIC: first direct indication for conversion?
  - Photon, dilepton and kaon v_2: awaiting final verdict
  - Future: photon-hadron or photon-jet correlations
- Better calculations:
  - Event generators

Backup

Conversion Rates

- Coupled rate equations for particle numbers (flavors a, b, c, …)

$$\frac{dN^a}{dt} = -\sum_b \Gamma^{a\to b}(p_T, T) N^a + \sum_c \Gamma^{c\to a}(p_T, T) N^c$$

- Reaction rates

$$\Gamma_C = \frac{1}{2E_1}\int \frac{g_2 d^3p_2}{(2\pi)^3 2E_2}\frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4} f(p_2)[1\pm f(p_4)]\overline{|M_{12\to 34}|^2}(2\pi)^4\delta^{(4)}(p_1+p_2-p_3-p_4)$$

- Here: elastic channels

$$q+\bar{q} \leftrightarrow g+g$$
$$q+g \leftrightarrow g+q$$

Quark / gluon conversions

$$q+\bar{q} \to \gamma+g$$
$$q+g \to \gamma+q$$

Photons and dileptons;
inverse reaction negligible

$$g+Q \leftrightarrow Q+g$$
$$g+g \leftrightarrow Q+\bar{Q}$$

Heavy quark creation/acceleration