Collisions of Nuclei: New Ideas for Hard Probes

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Overview

- Introduction: heavy ion collisions and hard probes
- Hadron chemistry and flavor conversions

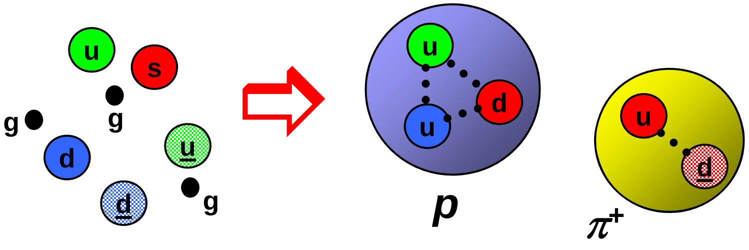
  [With W. Liu,
  Phys.Rev.C77:054902,2008
  Phys.Rev.C78:037902,2008]
- Tomography + development of a new test environment

  [In progress, with R. Rodriguez]
- Summary

Introduction

Matter in Extreme Conditions

- Evolution of the universe:
  - Microseconds after the Big Bang we start with a hot soup of matter
  - Quarks, gluons (and leptons)



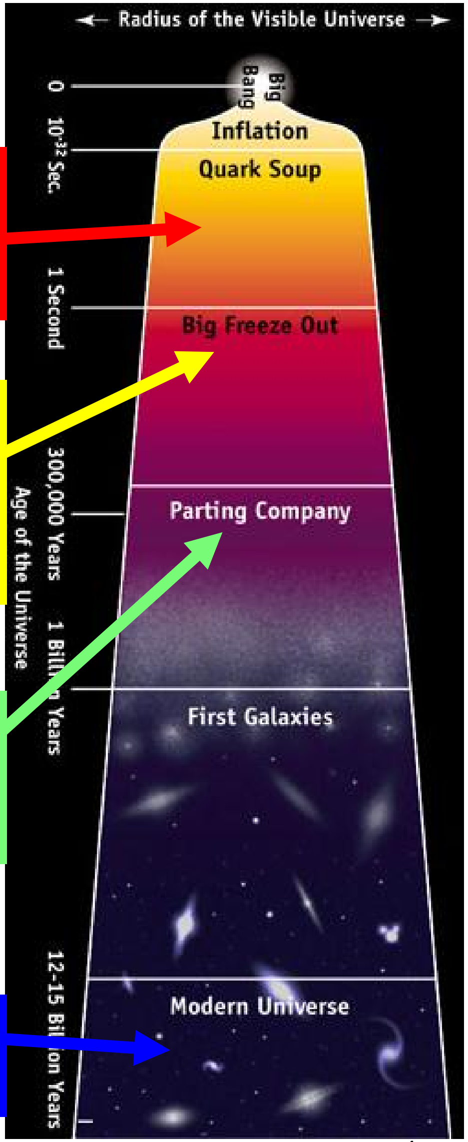
  - Phase transition to hadrons (and leptons)
  - Temperature $T \sim 10^{12}$ K

Hadrons melt: quark gluon plasma (QGP)

Too hot for nucleons to be bound inside nuclei

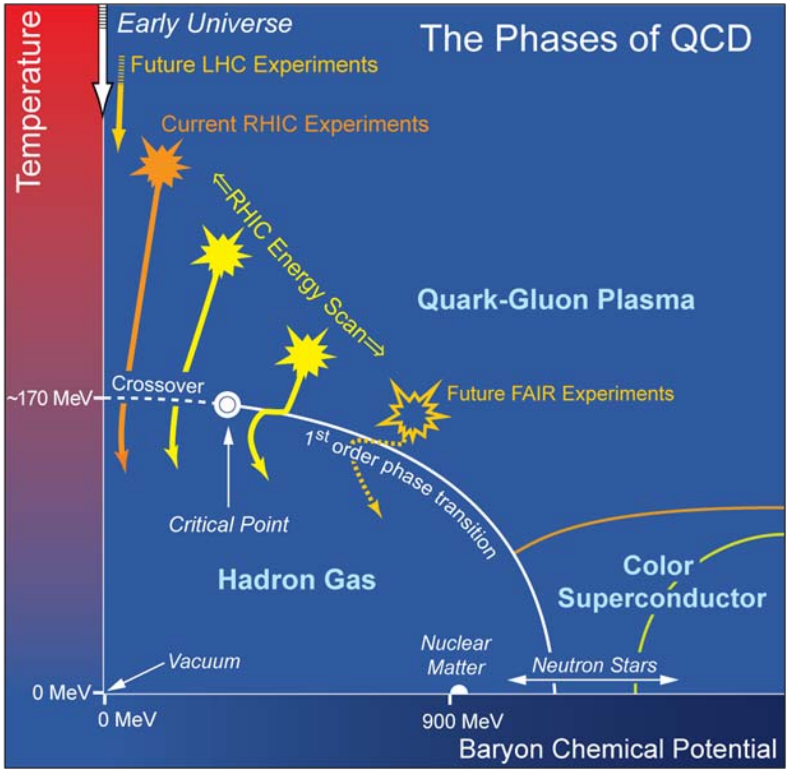
Molecules, atoms dissolve: EM plasma

Today's universe: 2.7 K

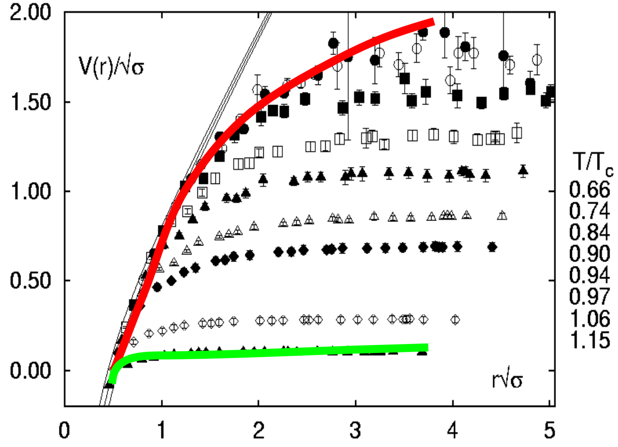


Quark Gluon Plasma

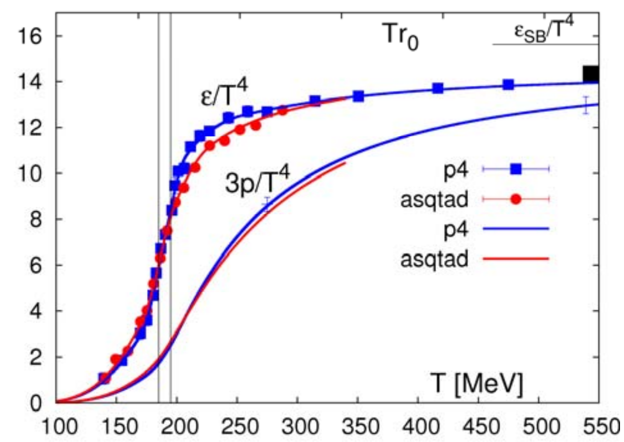
- Asymptotic freedom & lattice QCD predict deconfinement of quarks and gluons above a critical temperature T_c + restoration of chiral symmetry.



Static quark potential (Karsch et al.)



Energy density $\varepsilon(T)$, pressure $p(T)$

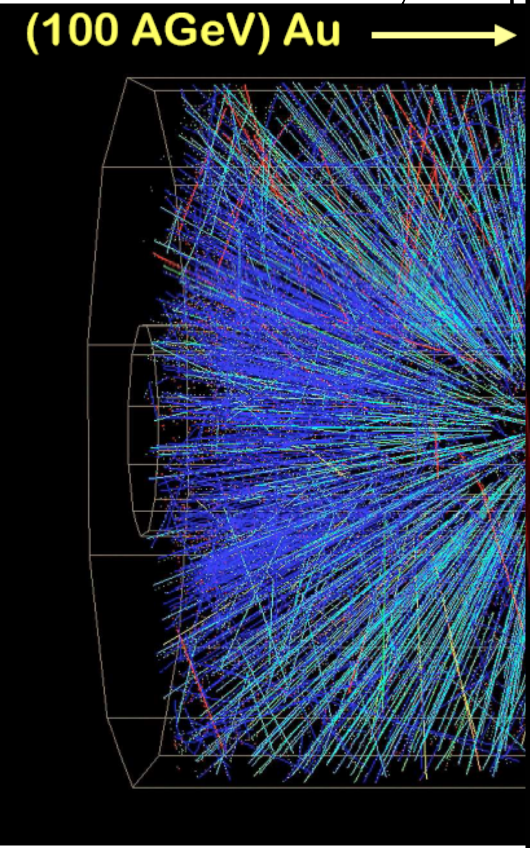


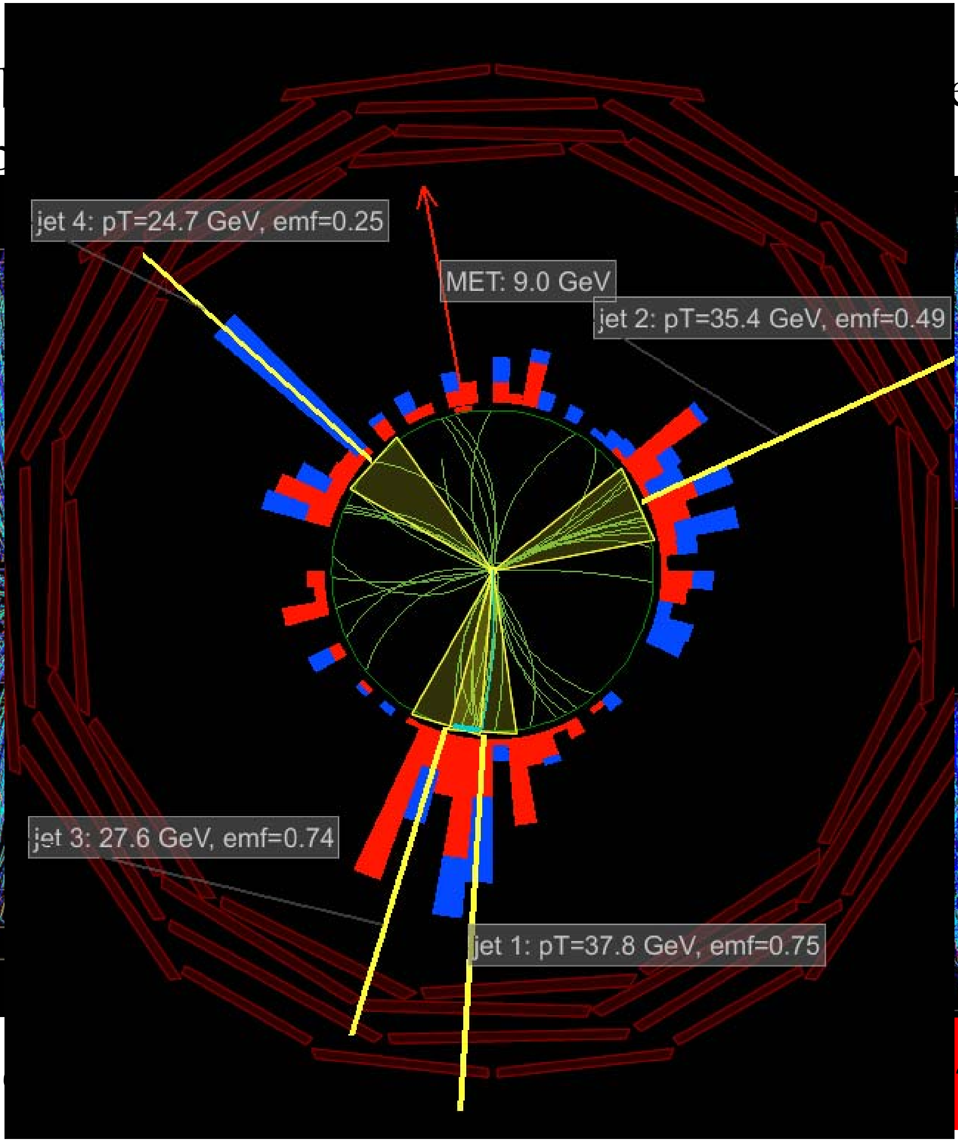
- Crossover at $\mu = 0$.

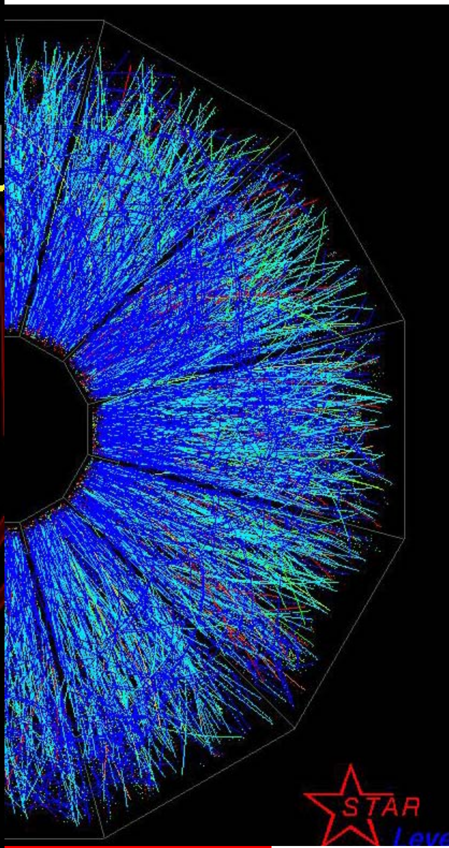
[Cheng et al, PRD 77 (08) 014511]

How to Produce 10^{12} K Matter?

- In nature: not o… …extreme energy cosmic rays imp…



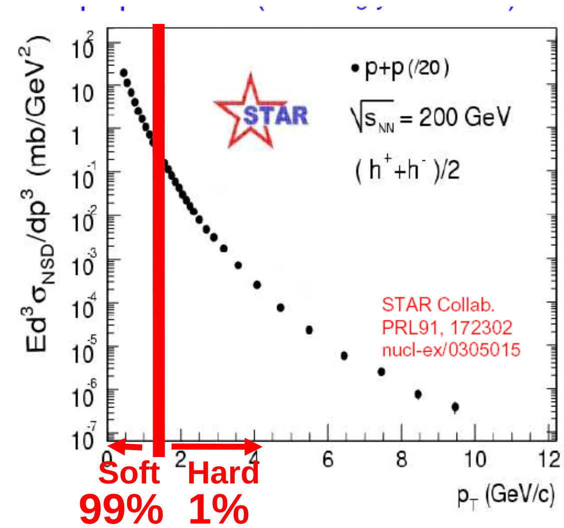


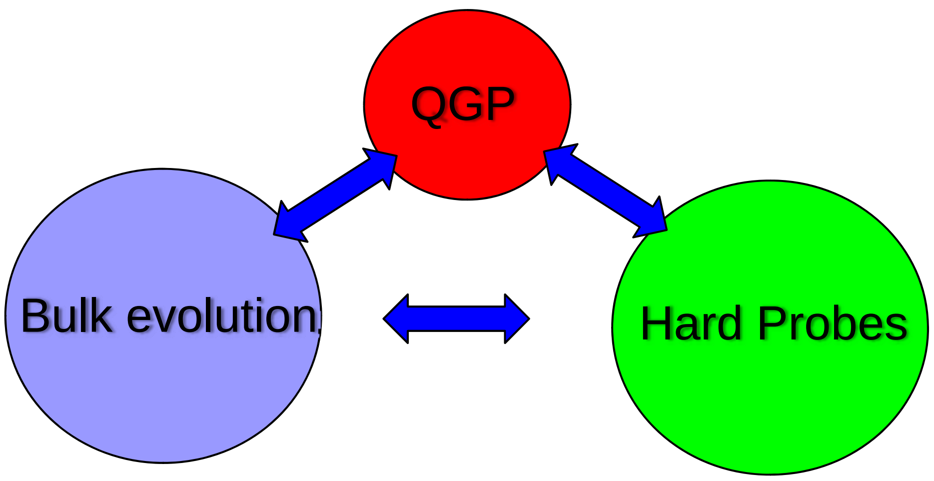


- In the lab: high … ??

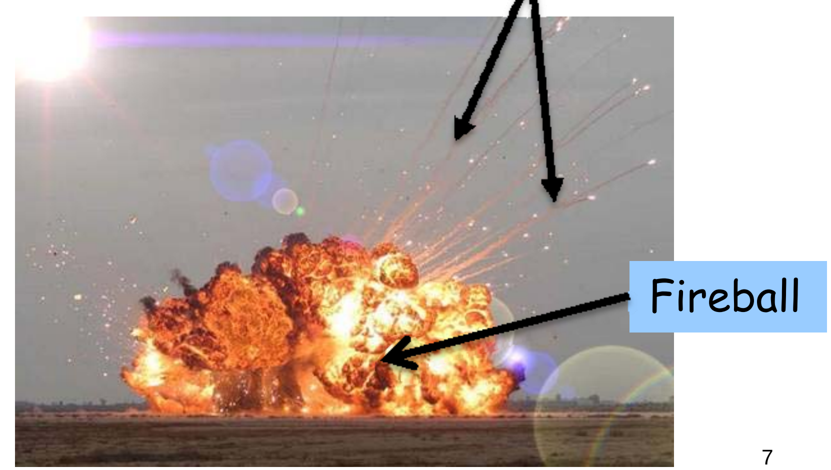
Sketch of a HE Nuclear Collision

- Where is the QGP?
- Hierarchy in Momentum Space:
- Soft particles (P_T < 1-2 GeV): Bulk fireball
  - Equilibration, thermalization → Quark Gluon Plasma
  - Non-perturbative dynamics
- Hard particles (P_T > 1 -2GeV): Rare probes
  - Hard probes of the bulk fireball (QGP)
  - Creation: perturbative, FSI: maybe perturbative.





Some particles accelerated much more: fast probes.



Sketch of a HE Nuclear Collision

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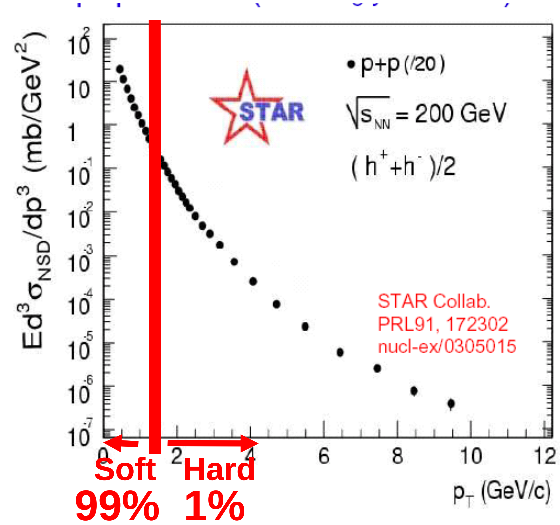
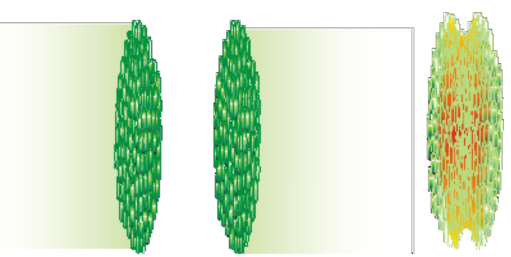
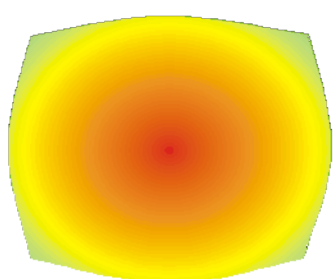
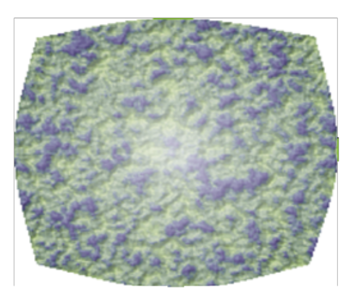


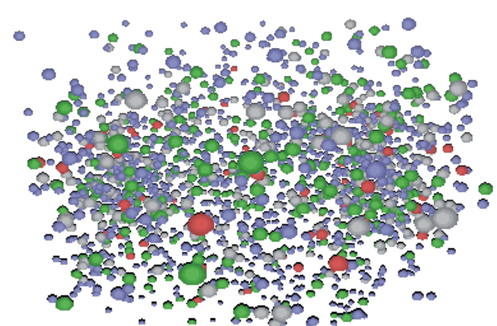
< 1fm/c ~ 10 fm/c Time

Initial stage Quark Gluon Plasma Hadronization Hadronic Phase





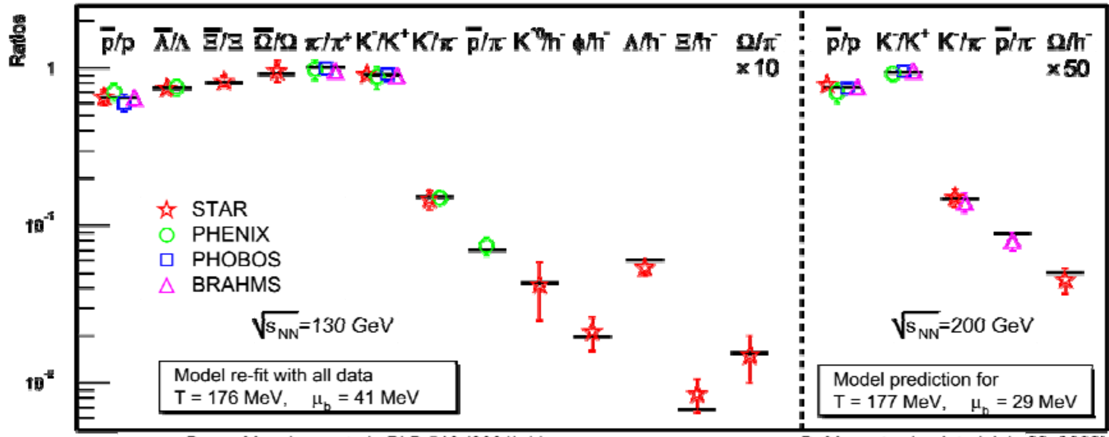




Bulk Fireball: Temperature and Pressure

- Hadron ratios: thermometer
  - Chemical freeze-out around 175 MeV
  - Low net baryon number

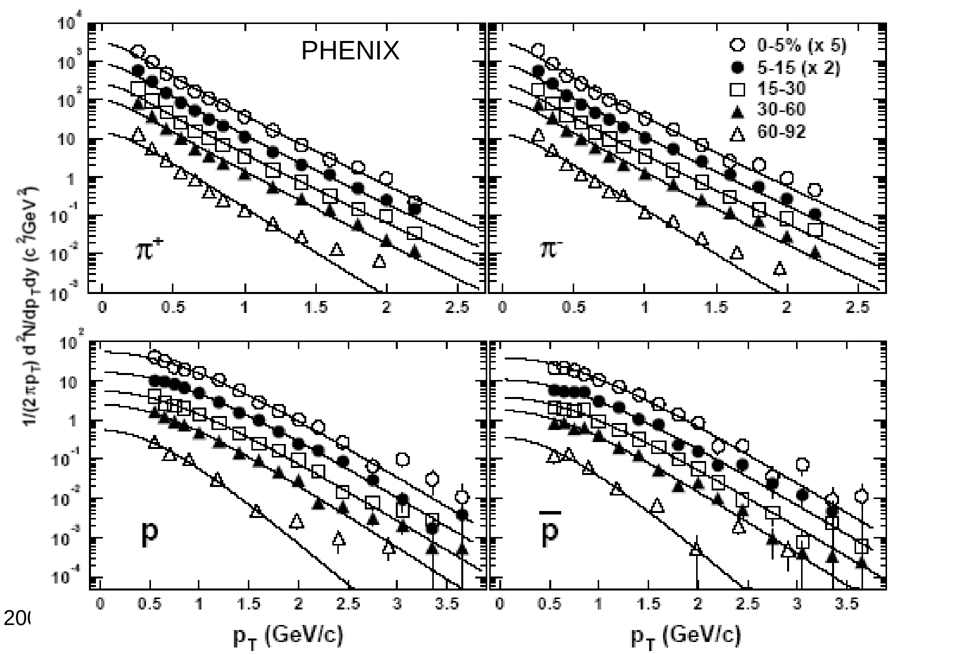
$$n_i(T,\mu) = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2\,dp}{e^{(E_i-\mu_i B_i-\mu_s S_i)/T} \pm 1}$$



Braun-Munzinger et al., PLB 518 (2001) 41

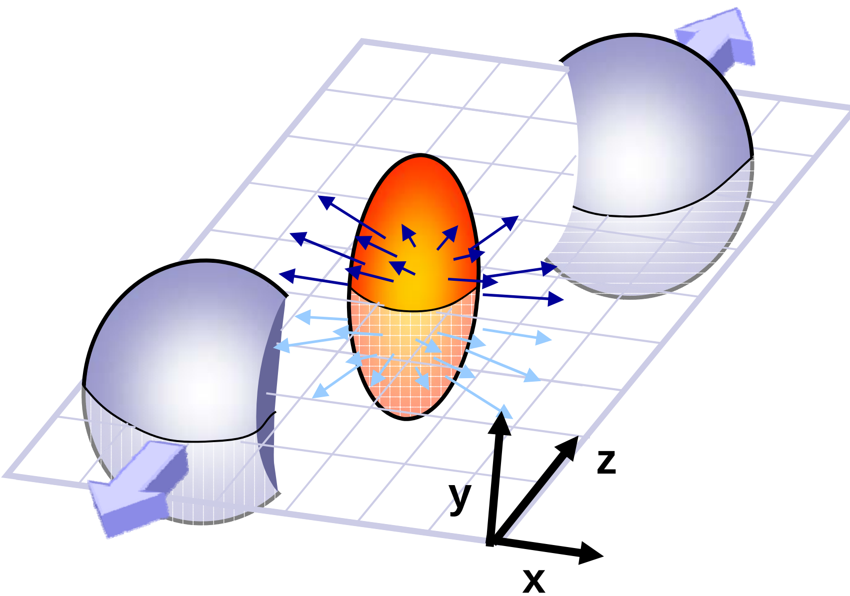
D. Magestro (updated July 22, 2002)

- Low-P_T spectra: explosion-like blastwave
  - Well described by hydrodynamic evolution.
  - Expansion velocity $\beta_L \sim 1$, $\beta_T \sim 0.5 - 0.7$



Bulk Fireball: v_2 Phenomenon

- Finite impact parameter $b > 0$:
  - Spatial anisotropy in the initial state
  - Momentum anisotropy in the final state

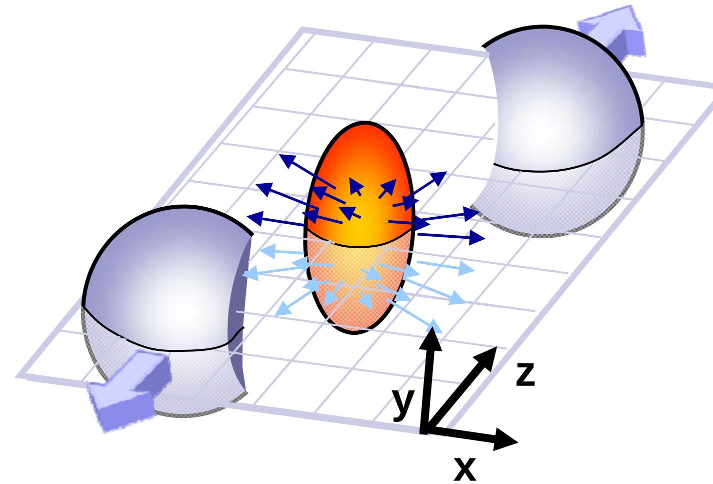


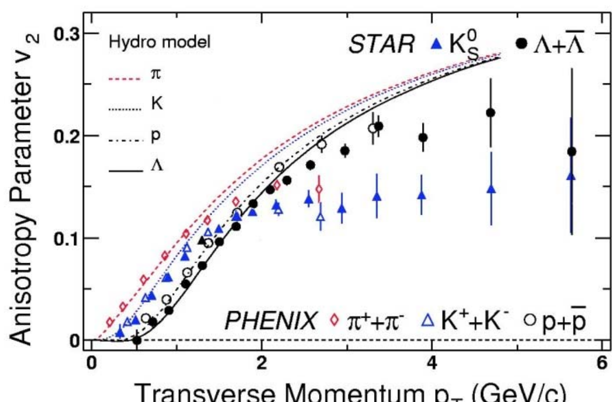
Bulk Fireball: v_2 Phenomenon

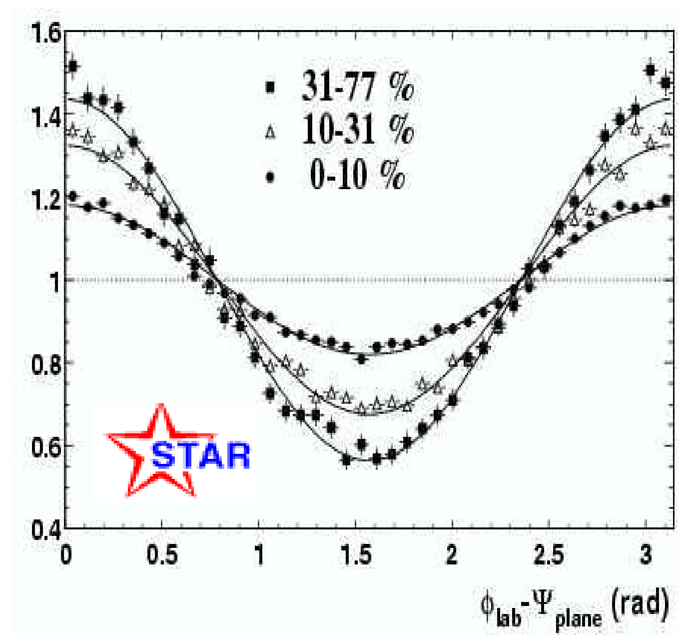
- Finite impact parameter $b > 0$:
  - Spatial anisotropy in the initial state
  - Momentum anisotropy in the final state
- Fourier analysis

$$\frac{dN}{P_T dP_T d\varphi} = \frac{dN}{2\pi P_T dP_T}\left[1+2\sum_n v_n(P_T)\cos(n\varphi)\right]$$

  - v_2 = second harmonic ("elliptic flow")
- Described very well by hydrodynamics

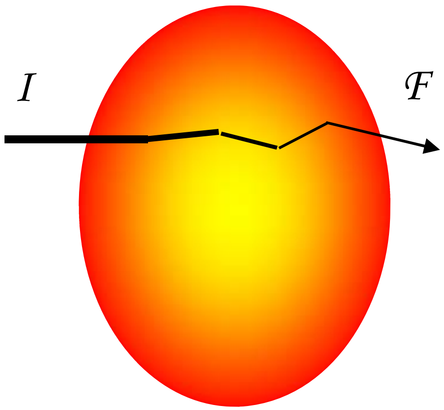






Hard Probes: Jet Quenching

- Simplest possible probe: measure opacity of the medium
  - Drag force on QCD jets or hadrons = jet quenching
  - Most models: energy loss of the leading parton.
  - Related to broadening in transverse direction.



- Energy loss determined by the momentum transfer in collisions
  - Sensitive to transport coefficient $\hat{q} = \frac{\mu^2}{\lambda}$

    = momentum transfer squared per mean free path/collision.
- Several calculations on the market using different sets of assumptions, e.g.

AMY

BDMPS
ASW

GLV
DGLV

Higher Twist

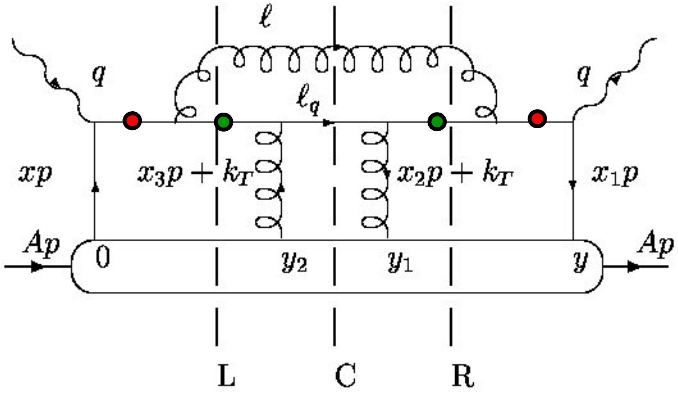
Perturbative plasma in the high temperature limit

Extrapolated from DIS off large nuclei (e+A $\rightarrow$ h+X)

Energy Loss

- Example: higher twist
  - Compute modification to evolution equations of fragmentation functions in DIS on large nuclei.

$$\tilde{D}_{q/h}(z_h,\mu^2) = D_{q/h}(z_h,\mu^2) + \int_0^{\mu^2} \frac{dl_T^2}{l_T^2} \frac{\alpha_s}{2\pi} \int_{z_h}^1 \frac{dz}{z}$$
$$\times \left[\Delta\gamma_{q\to qg}(z,x,l_T^2) D_{q/h}\left(\frac{z_h}{z}\right) + \Delta\gamma_{q\to gq}(z,x,l_T^2) D_{g/h}\left(\frac{z_h}{z}\right) \right]$$



$$\Delta\gamma_{q\to qg}(z,x,l_T^2) = \frac{2\pi\alpha_s C_A}{N_c l_T^2 f_{q/A}(x)} \left[\frac{1+z^2}{(1-z)_+} T_{qg}(x,x_L) + \delta(1-z)\Delta T_{qg}(x,l_T^2) \right]$$

$\frac{T_{qg}}{f_q} \sim$ number of gluon scattering partners $\sim \hat{q}L$

- Destructive interference between poles → LPM effect
- Expected shift in energy $\langle \Delta z \rangle = \int_0^{Q^2} \frac{dl_T^2}{l_T^2} \int_0^1 dz \frac{\alpha_s}{2\pi} z\Delta\gamma \sim \int \frac{dx_L}{x_L^2} R_A \sim \frac{R_A}{x_A} \sim A^{2/3}$
- Extrapolate to nuclear collisions.

[X. Guo, X.N. Wang, PRL 85,3591 (2000); NPA 696, 788 (2001)]

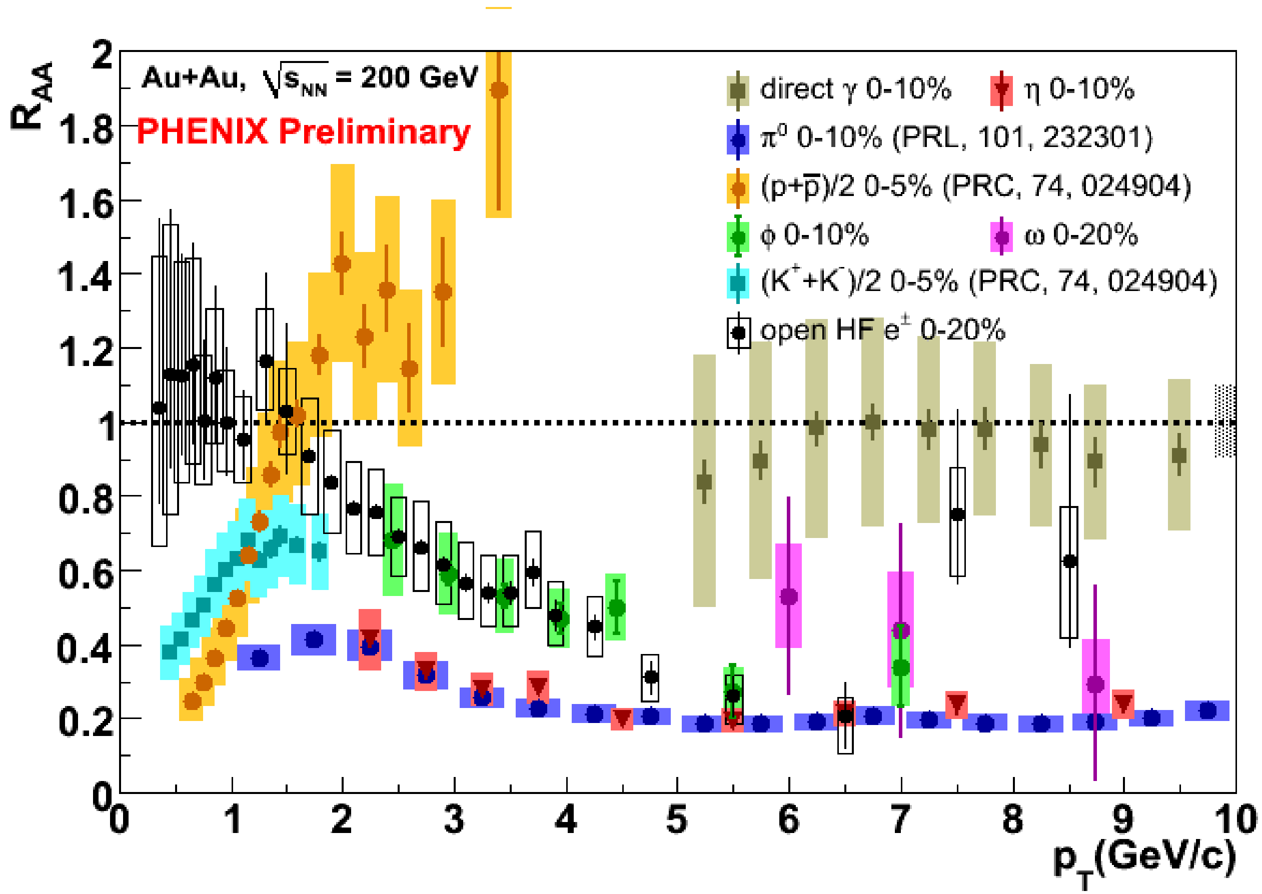
Jet Quenching: Results

- RHIC: dramatic suppression effect for single hadrons

$$R_{AA} = \frac{dN_{AA}/dP_T}{N_{coll} dN_{NN}/dP_T}$$

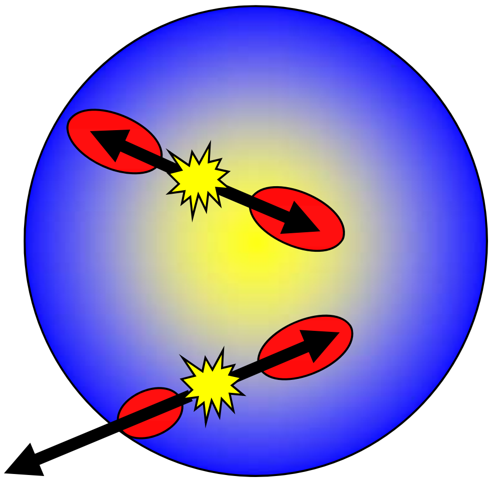
Nuclear modification factor

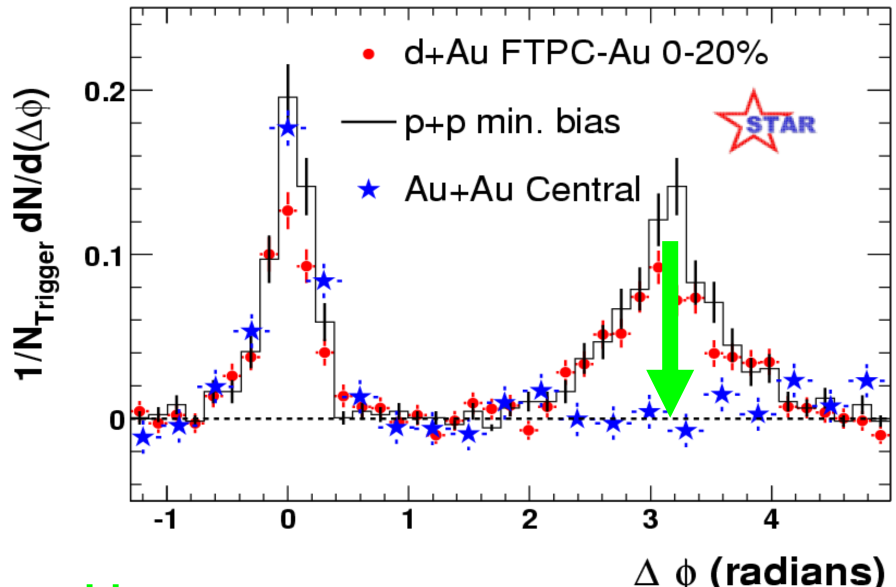
Factor 4 …5 suppression of the particle yield for P_T > 2 GeV



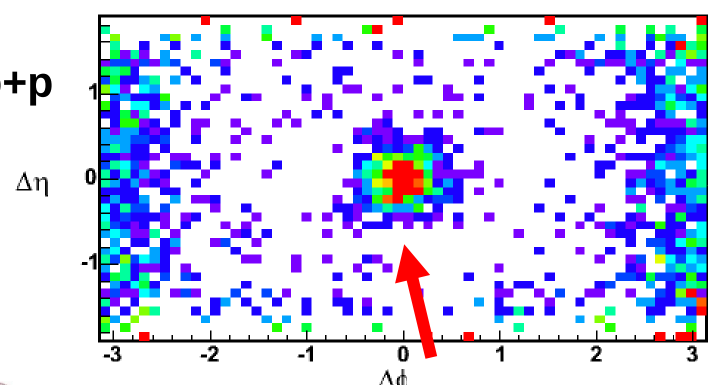
Jets: Correlations

- Away-side jets vanish
  - Trigger on a high P_T hadron and look for associated hadron as a function of relative azimuthal angle and rapidity



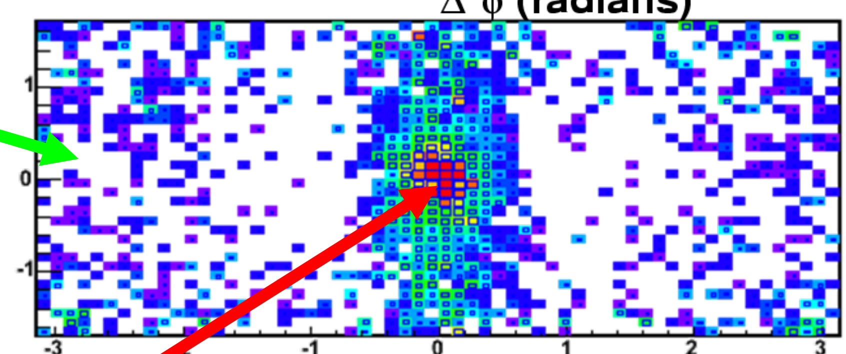


p+p



Away side gone/diffuse

STAR



A+A

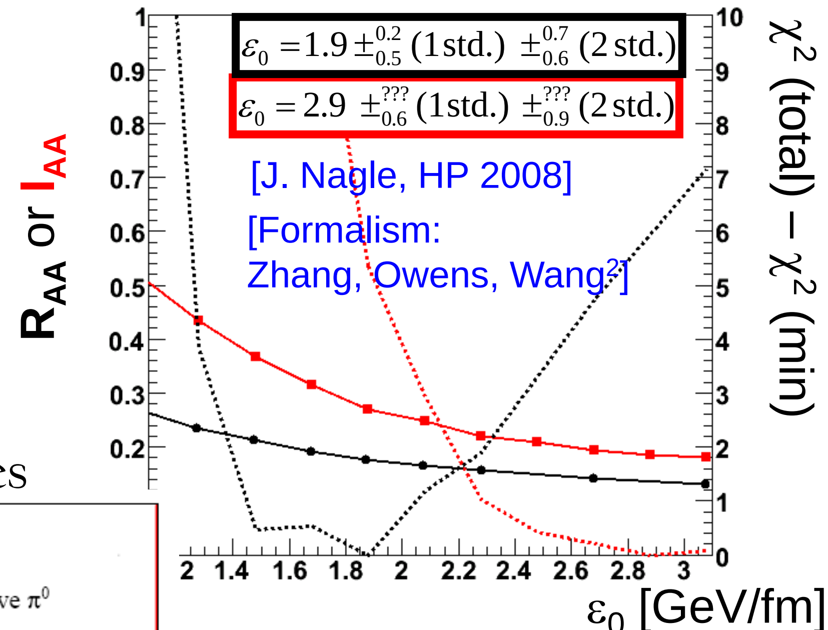
Broadening/Ridge on the near side

Towards Precision Measurements (?)

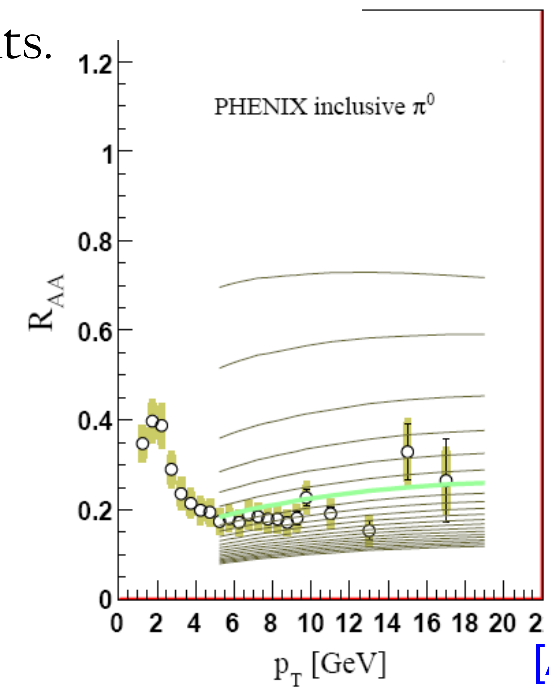
- Fits of $\hat{q}$ to data have begun.
- Different energy loss models give vastly different results.

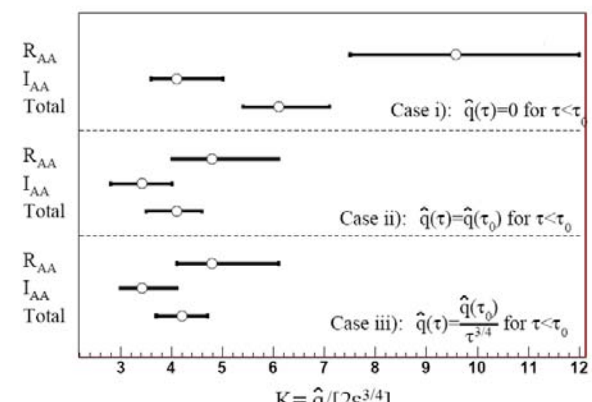
[S.A. Bass et al.]

$\hat{q}(\vec{r},\tau)$ scales as	ASW	HT	AMY
	$\hat{q}_0$	$\hat{q}_0$	$\hat{q}_0$
$T(\vec{r},\tau)$	10 $\mathrm{GeV}^2/\mathrm{fm}$	2.3 $\mathrm{GeV}^2/\mathrm{fm}$	4.1 $\mathrm{GeV}^2/\mathrm{fm}$



- Within a fixed model different observables give incompatible results.





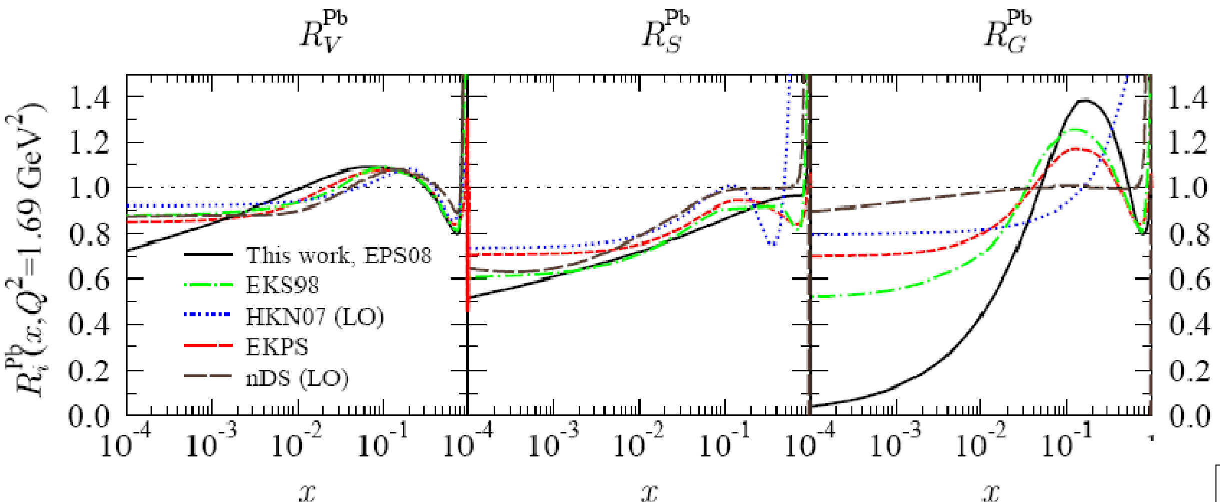
[Armesto et al., arxiv:0907.0667]

- Lots of details matter!
  - Calibration (shadowing, Cronin effect)
  - Treatment of the initial fireball
  - …

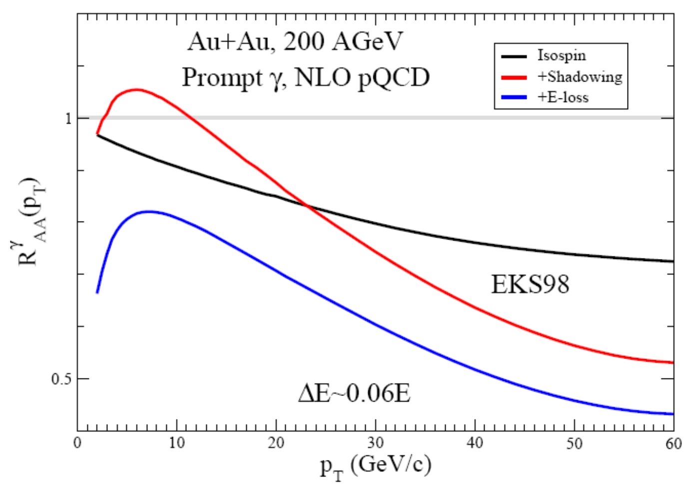
Details: Initial State Effects

- First hurdle: initial state nuclear effects
- Shadowing, anti-shadowing, EMC effect on nuclear parton distributions
  - Large uncertainties, in particular for gluons and at small x.

[Eskola et al., (1998, 2008)]



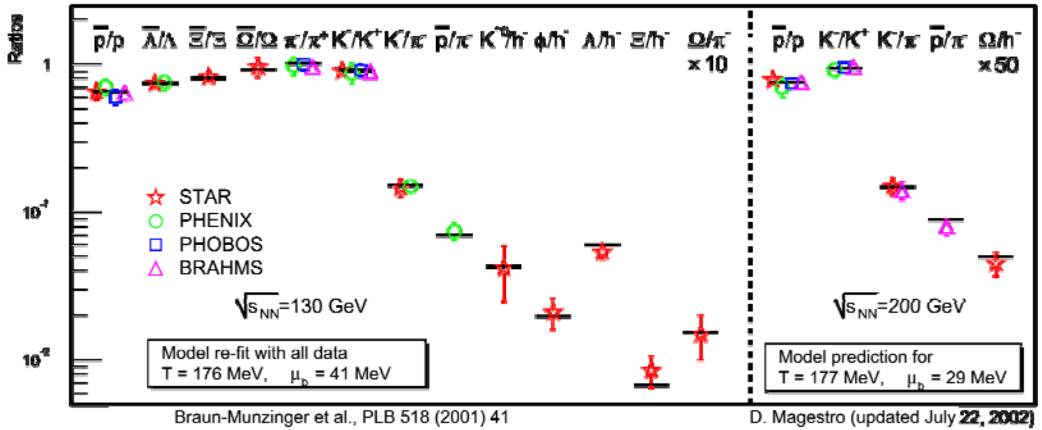
- Cronin effect
- We can use photon/dileptons production in A+A to check our understanding.
- Electron-Ion Collider!



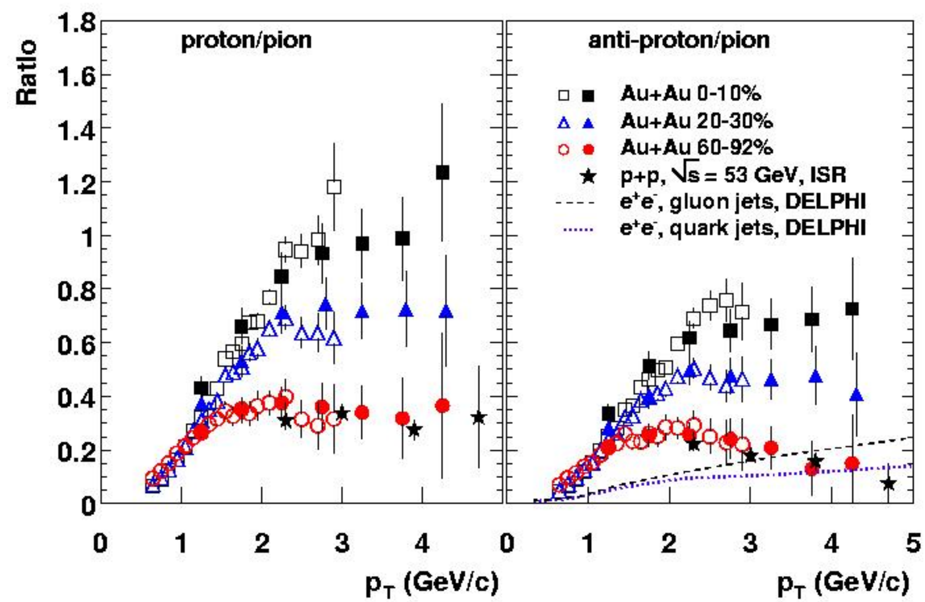
Chemistry of Hadrons at High P_T

Hadro-Chemistry at Low and Intermediate P_T

- Remember: hadron ratios given by statistical model.

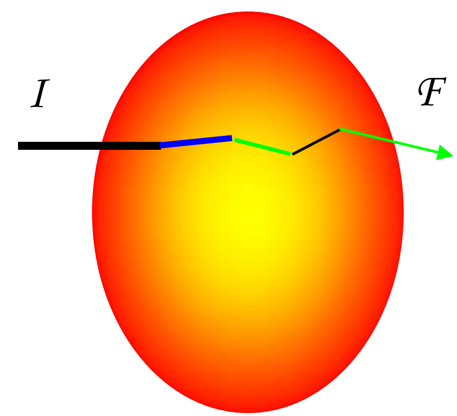


- Intermediate P_T: baryon/meson ratios and scaling laws led to quark recombination models.

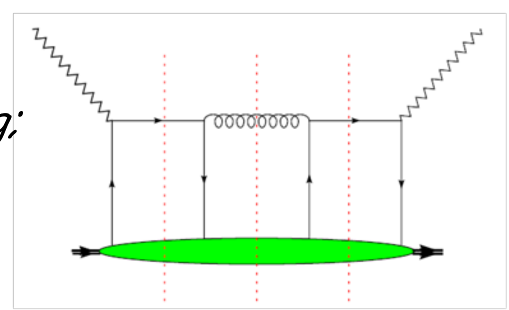


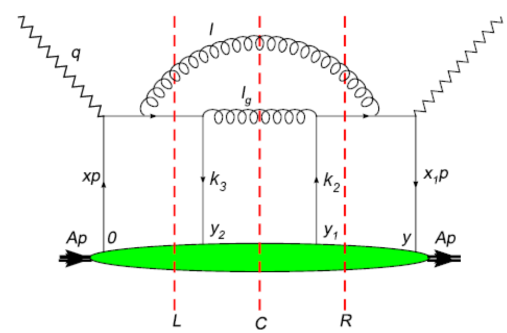
Hard Probes Revisited

- How else can we use hard probes? Measure the "flavor"!
- Obviously: flavor of a parton can change when interacting with the medium.
- Here: very general definition of flavor:
  - Gluons g
  - Light quarks q = u,d
  - Strange quarks s
  - Heavy quarks Q = c,b
  - Real photons, virtual photons (dileptons) γ
- Measure flavor conversions → jet chemistry



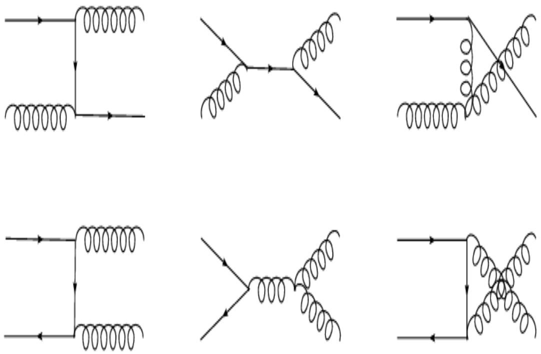
Example: Schäfer, Wang, Zhang; HT formalism





Jet Chemistry

- Flavor of a jet here = identity of the leading parton.
  - Flavor of a jet is NOT a conserved quantity in a medium.
  - Only well-defined locally!
- The picture here:
  - Parton propagation through the medium with elastic or inelastic collisions
  - After any collision: final state parton with highest momentum is the new leading parton ("the jet")



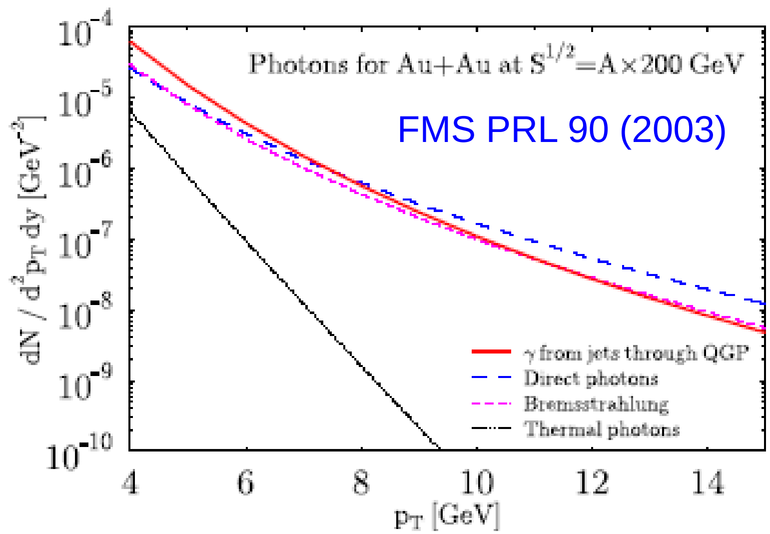
- Hadronization: parton chemistry → hadron chemistry
  - Hadronization washes out signals; need robust flavor signals on the parton side.
- Other mechanisms might also change hadron chemistry in jets:
  - E.g. changed multiplicities

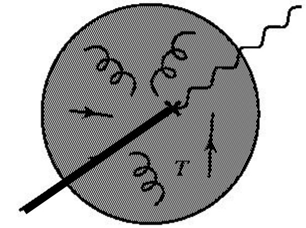
[Sapeta, Wiedemann]

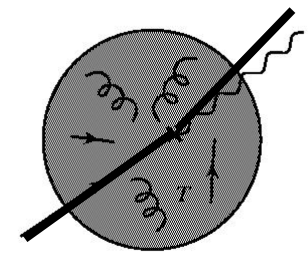
Applications: Photons

- Photon and dilepton conversions:

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

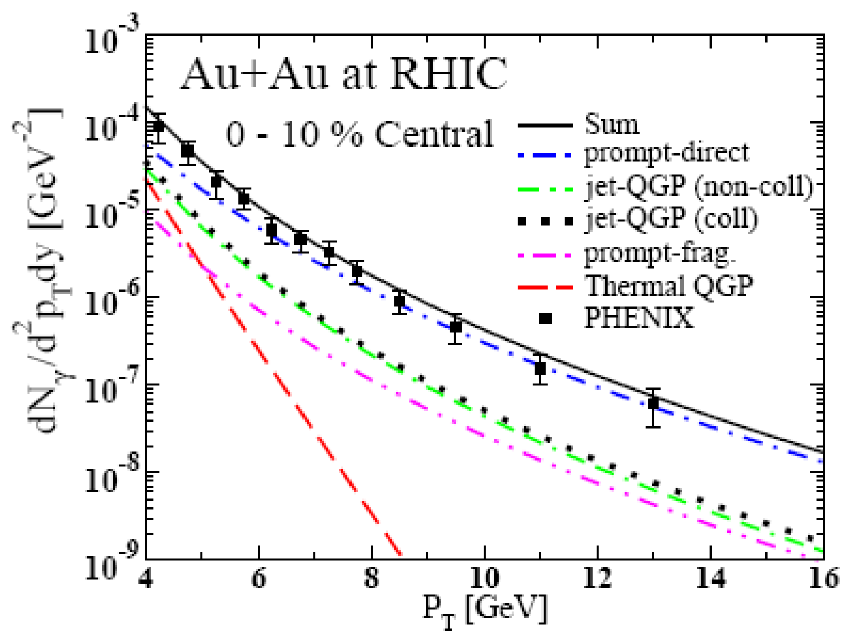






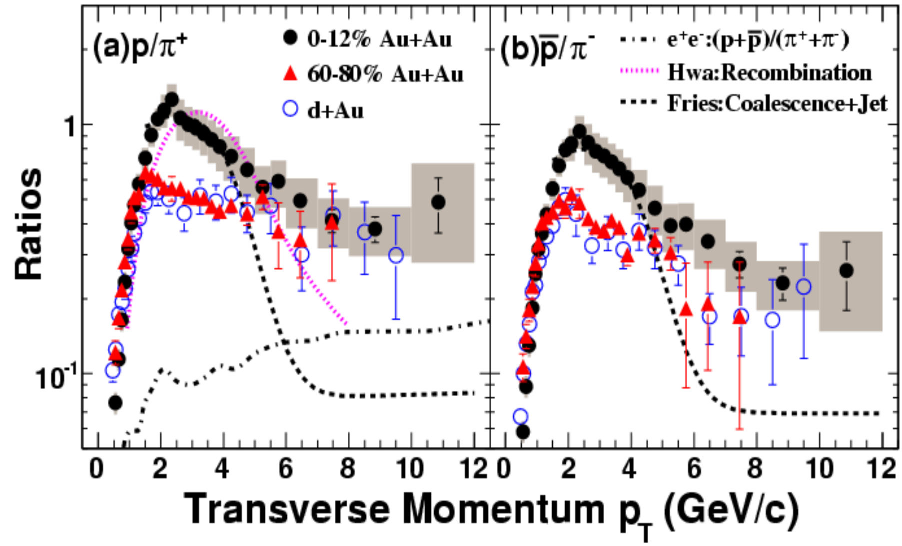
- First estimate:
  - Competitive photon sources for P_T ~ 4-6 GeV at RHIC energies, even more important at LHC.
- Experimental situation: not resolved
  - From a recent calculation:

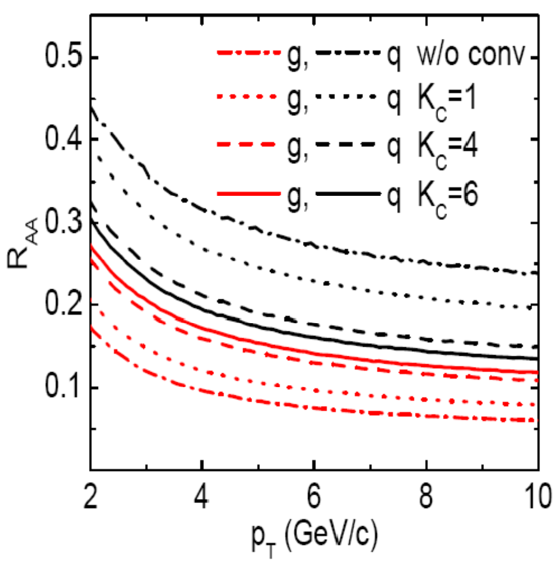
    [Turbide, Gale, Frodermann, Heinz]



Applications: Gluons and Protons

- Gluon ↔ (light) quark conversions [Ko, Liu, Zhang; Schäfer, Zhang, Wang; …]
- Available in some jet quenching schemes (HT, AMY, …)
- Relative quenching of gluons and factor 9/4
  - Not explicitly observed in data
  - Shouldn't be there in a system path!





- Ko et al: elastic g ↔ q conversions
  - Lose 30% of quark jets at RHIC
  - enhance p/π ratio; need elastic cross sections × 4 to get p+p values
  - Dependence on fragmentation functions!

Why Could It Be Exciting?

- For chemistry, momentum transfer is not important (unless there are threshold effects)

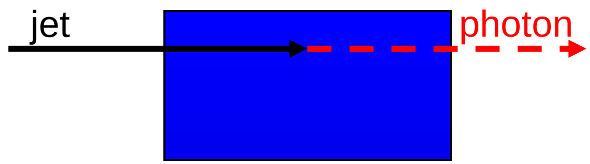
- Rather: flavor conversions are sensitive to the mean free paths λ of partons in the medium.

- Complementary information, could help settle interesting questions
  - Many interactions with small momentum transfer?
  - Few scatterings with large momentum transfer?

- But: measurements will be challenging
  - Need particle identification beyond 6-8 GeV/c at RHIC, outside of the recombination region.

Two Examples for Rare Probes

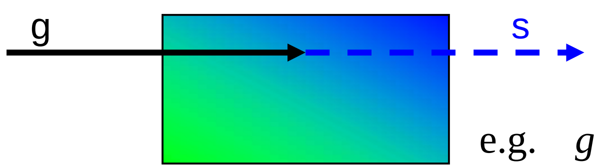
- Example 1: excess production of particles which are rare in the medium and rare in the probe sample



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

  - Example: photons
  - Need enough yield to outshine other sources of N^{rare}.

- Example 2: chemical equilibration of a rare probe particle



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

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

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

  - Example: strangeness at RHIC
  - Coupling of jets (not equilibrated) to the equilibrated medium should drive jets towards chemical equilibrium.

Conversion Rates

- Coupled rate equations for numbers of jet particles (flavors a, b, c, …) in a fireball simulation.

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

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

- Here: reaction rates from elastic $2 \to 2$ collisions

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

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 quarks production?

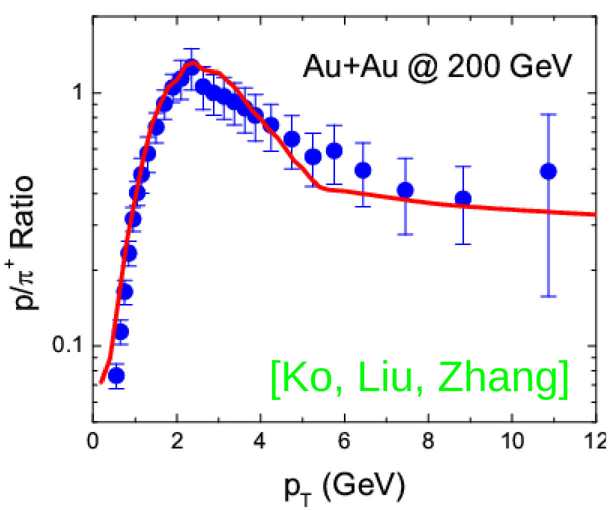
- Need to compare to $2 \to 3$ processes.
- Non-perturbative mechanisms?

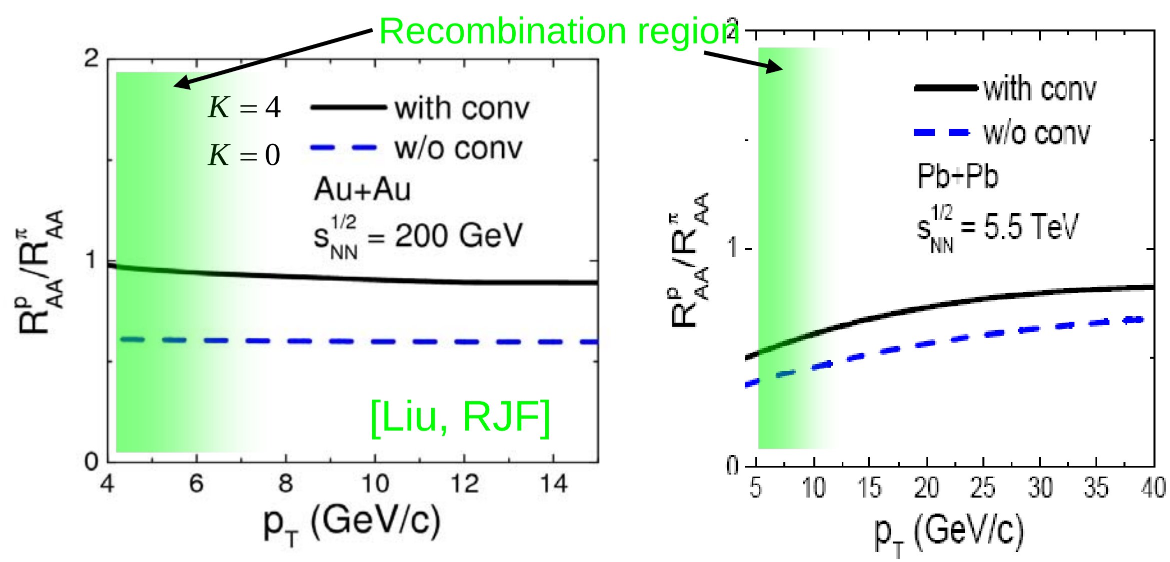
Results: Protons

- Use the model by Ko, Liu and Zhang:
  - Rate equations plus energy loss.
  - Elastic channels; cross sections with *K*-factor
  - Longitudinally and transversely expanding fireball
    - RHIC: T_i = 350 MeV @ 0.6 fm/c
    - LHC: T_i = 700 MeV @ 0.2 fm/c

- Use double ratios to cut uncertainties from fragmentation functions.

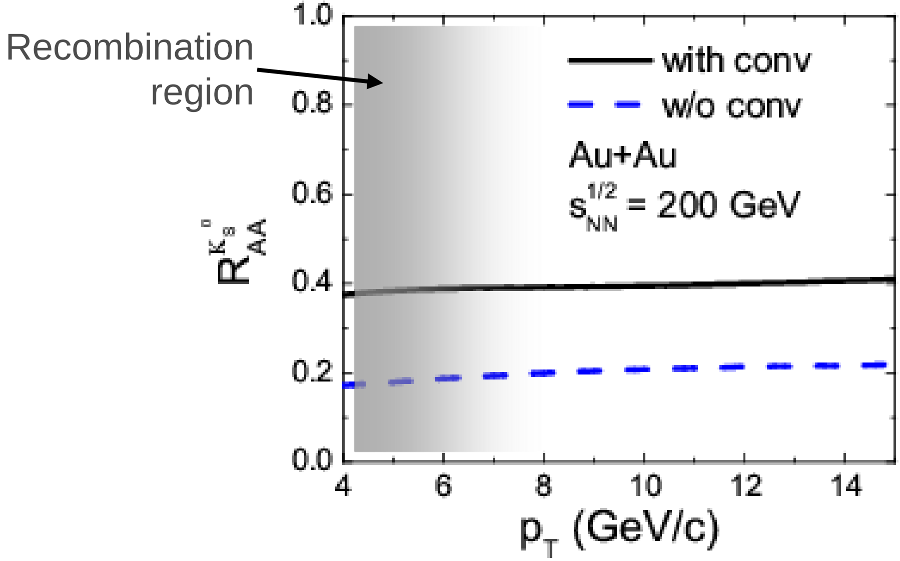
$$\gamma_{p/\pi^+} = \frac{(\mathrm{p}/\pi^+)_{AA}}{(\mathrm{p}/\pi^+)_{pp}} = \frac{R^p_{AA}}{R^{\pi^+}_{AA}}$$



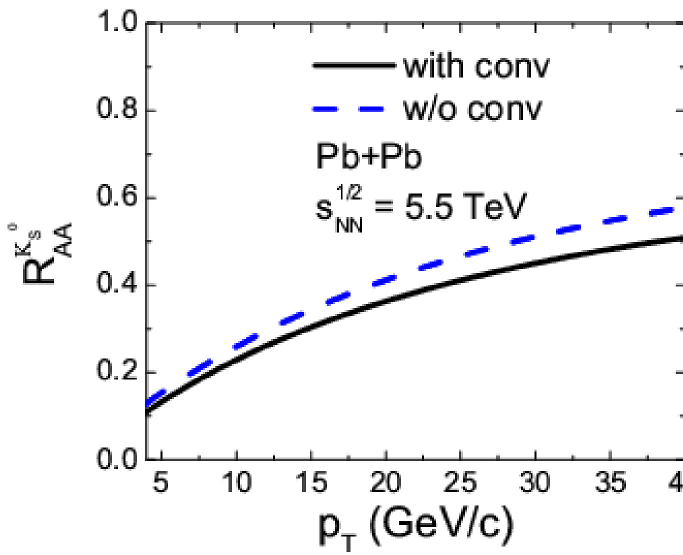


Results: Strangeness

- Kaons: see expected enhancement at RHIC
  - Measure above the recombination region!

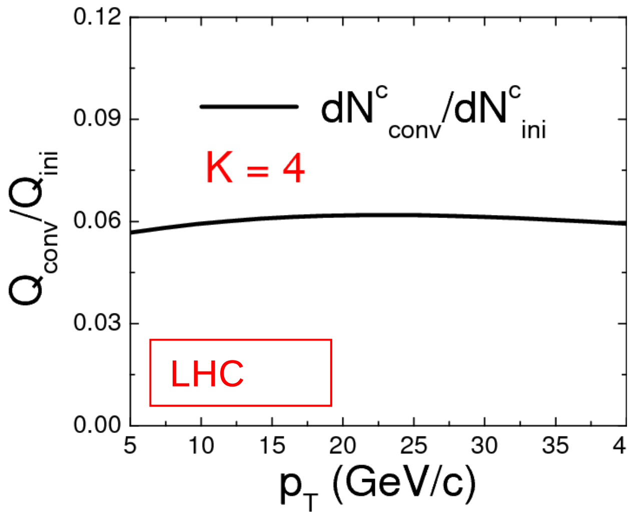


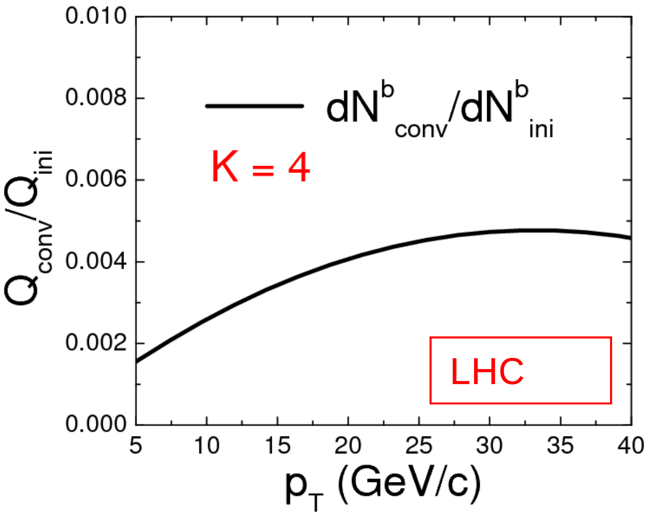
- No enhancement at LHC
  - Too much initial strangeness!
  - Maybe it works with charm at LHC?



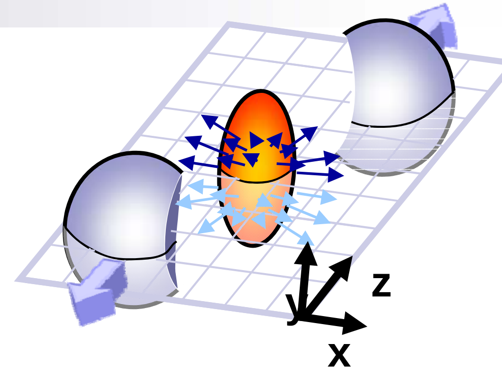
Numerical Results: Heavy Quarks

- Have to take into account threshold effect
- At RHIC: additional heavy quark production marginal
- LHC: not at all like strangeness at RHIC; additional yield small
  - Reason: charm not chemically equilibrated at LHC
  - Results in small chemical gradient between jet and medium charm
  - Also: threshold effect



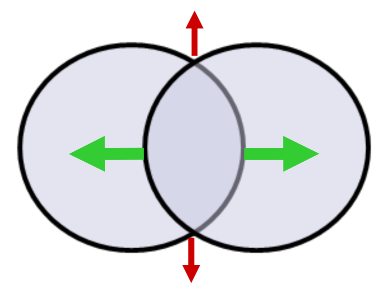


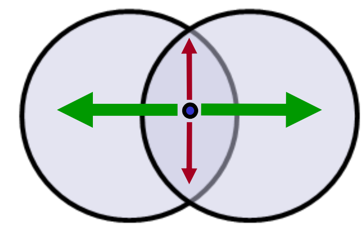
Elliptic Flow v_2

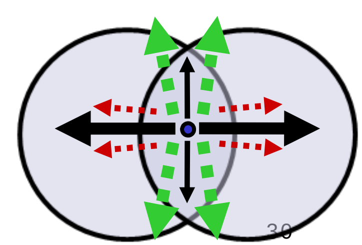


- Azimuthal anisotropy for finite impact parameter.
- Three different mechanisms:

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







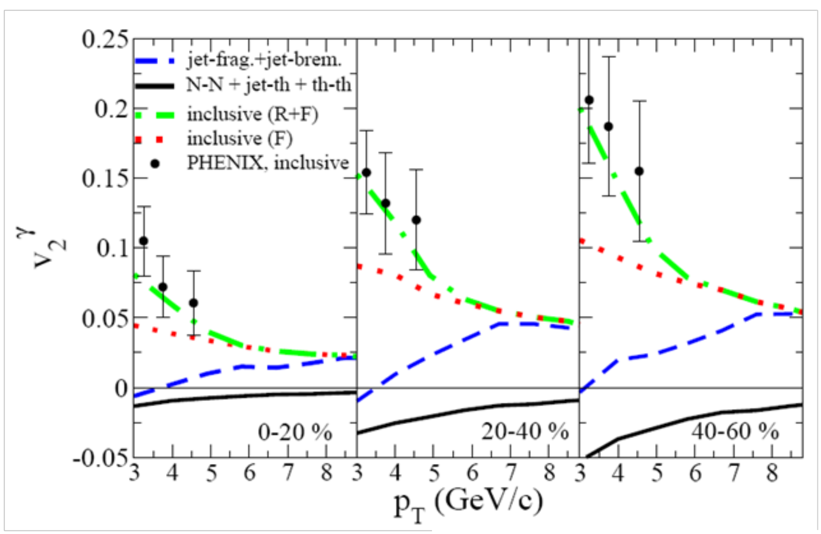
[Turbide, Gale & RJF, PRL 96 (2006)]

Photon Elliptic Flow

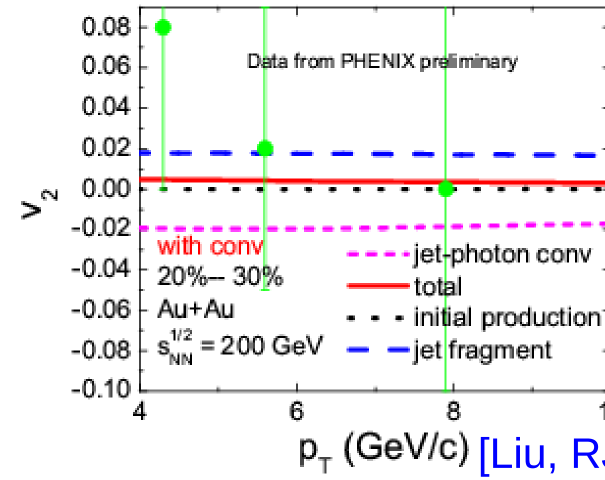
- Have to add other photon sources with vanishing or positive v_2.

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

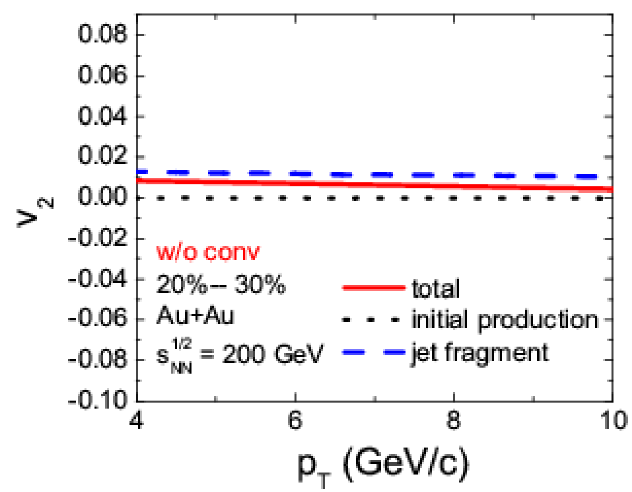
- Status:
  - Large negative v_2 excluded by experiment.
  - Large uncertainties from fireball model?



[Turbide, Gale, RJF]

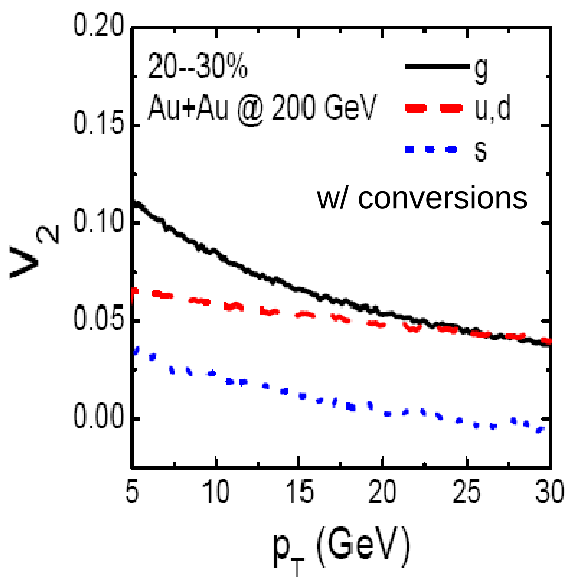


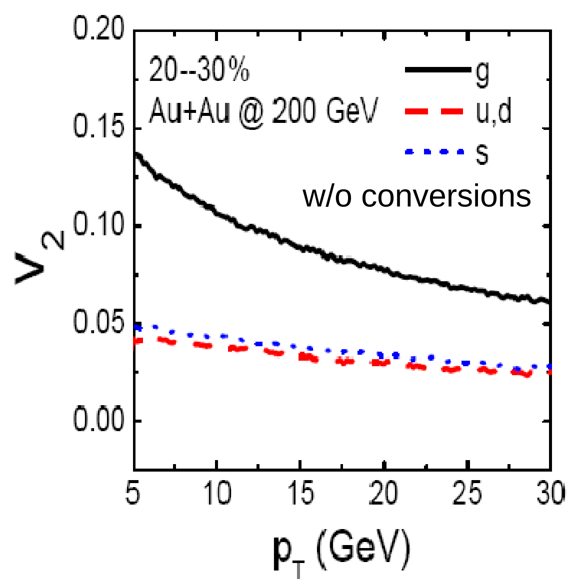
[Liu, RJF]



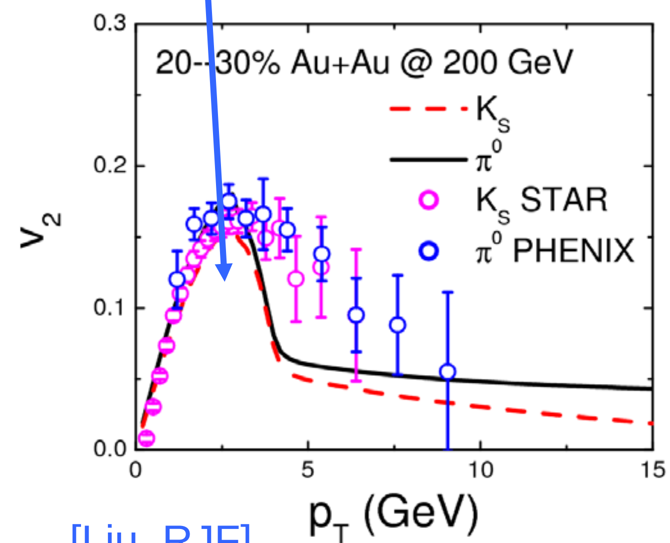
Strangeness Elliptic Flow

- Strangeness as non-equilibrated probe at RHIC: additional strange quarks have negative v_2.
- Expect suppression of kaon v_2 outside of the recombination region.





Recombination taken into account

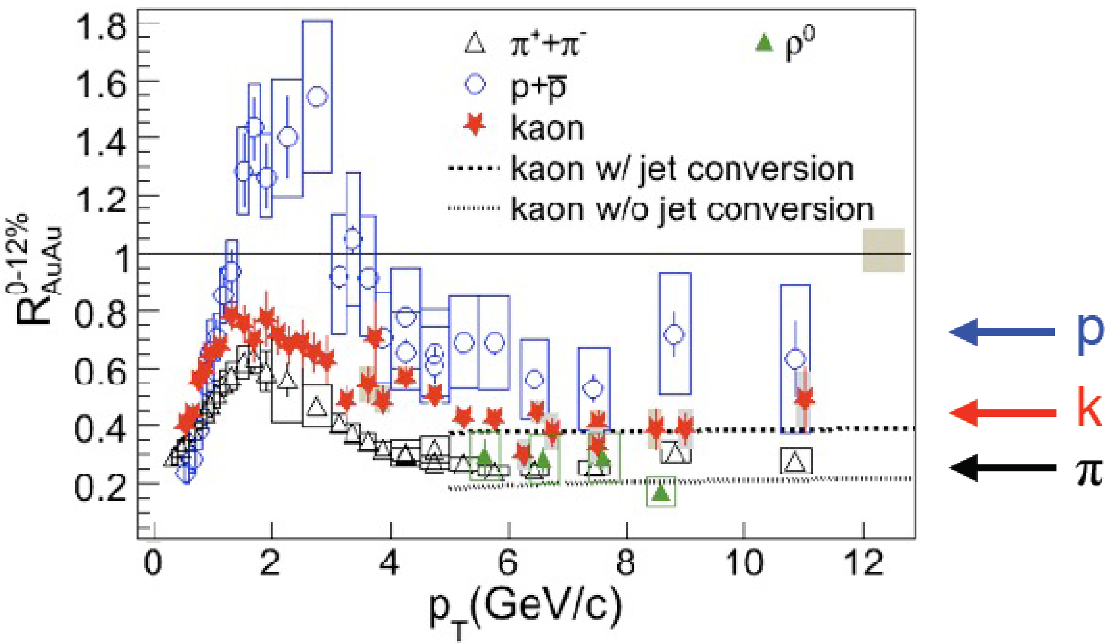


[Liu, RJF]

New Results from STAR

- STAR at QM 2009
  - Kaon enhancement seen between 6 and 10 GeV/c.
  - A first signal for conversions?
  - Caution: p enhancement too big.

[Liu, RJF, PRC (2008)]



- Blast from the past: remember strangeness enhancement from the 1980s?

New Simulation of Hard Probes

Plans for the Near Future

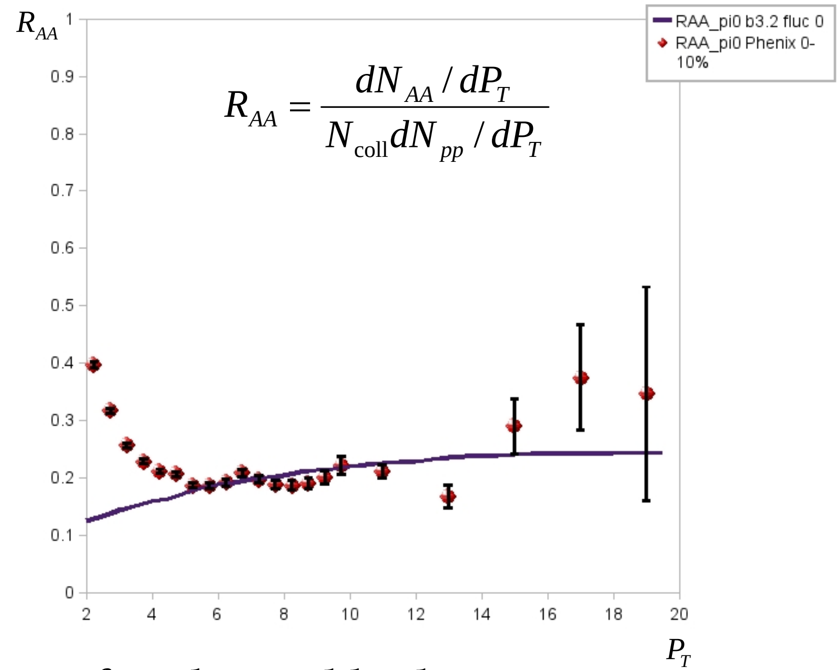
- We develop a standardized test bed to simulate *N* jets/hard particles in a fireball.
  - Part of a NSF project with R. Rodriguez, R.J. Fries, E. Ramirez
- Input:
  - initial phase space distributions
  - background (aka fireball)
  - specifics of dynamics (energy loss, fragmentation)
- What it should do:
  - Evolution of particle distributions;
  - (modified) fragmentation and hadronization
  - analysis of results in terms of experimentally relevant observables

Propagating Particles in a Medium (PPM)

- Some results from the testing process
  - Using vacuum fragmentation and GLV average energy loss

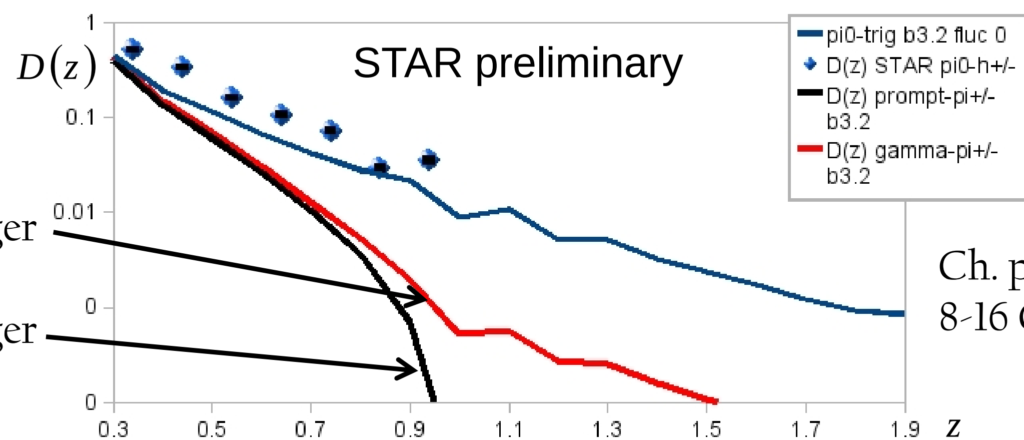
$$\Delta E = \frac{C_R \alpha_s}{4} \frac{\mu^2}{\lambda} L^2 \log E$$

- Neutral pion R_{AA} vs PHENIX data
  - Estimate $\hat{q} = \frac{\mu^2}{\lambda} \approx 2.5\,\mathrm{GeV}^2/\mathrm{fm}$



- Triggered away side fragmentation function for charged hadrons.

$$z = \frac{P_{T2}}{P_{T1}}$$



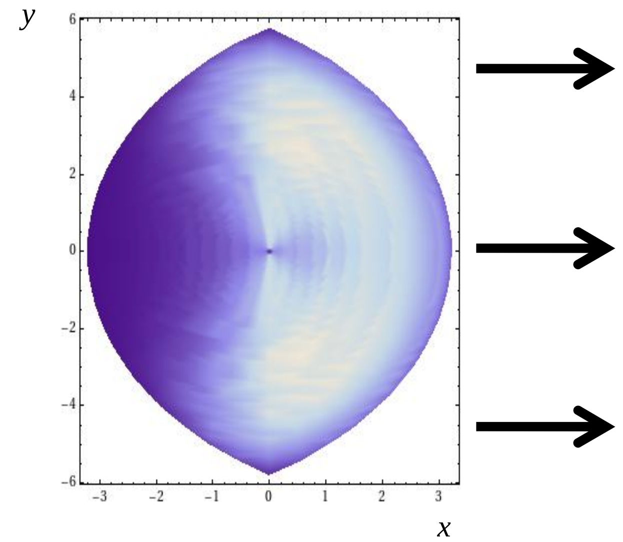
Direct photon trigger

Direct prompt photon trigger

Ch. pion with π^0 trigger
8-16 GeV trigger P_T

Propagating Particles in a Medium (PPM)

- Map functions
  - Example: emissivity for 8-10 GeV up-quarks going to the right, b=7.4 fm collision of Au ions.



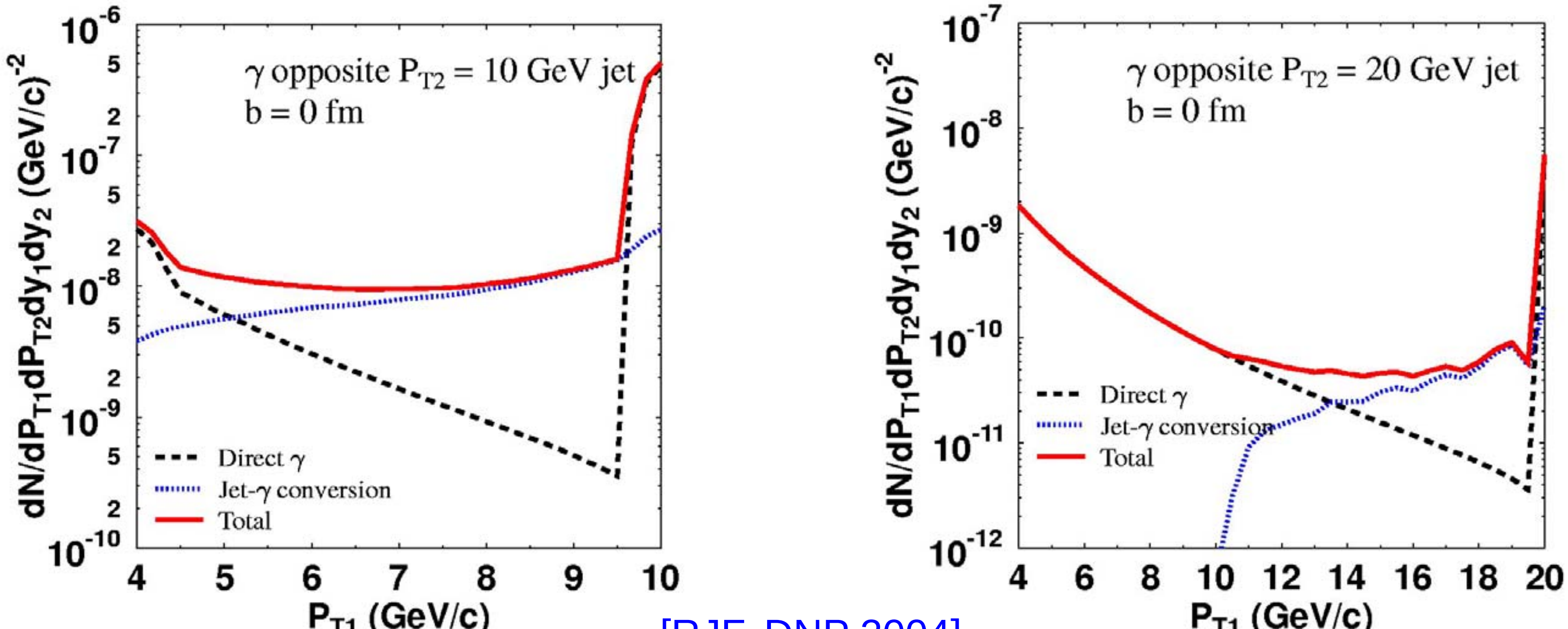
- Goals:
  - Build a flexible test bed for hard and electromagnetic probes.
  - Comprehensive, quantitative studies of observables.
  - photon/Z – jet/hadron correlations at NLO accuracy.

- Understanding photon/Z – jet/hadron correlations ↔ understanding electromagnetic sources and conversion processes.

- Eventually code can be made public and/or be made part of a larger effort (Techqm, JET)

Jet-Photon Correlations

- Additional photons are background for photon tagged jets.
- Turn this into an advantage: measure photon spectrum opposite to a jet of known energy to disentangle different sources.
- Photons opposite 10 and 20 GeV jets:



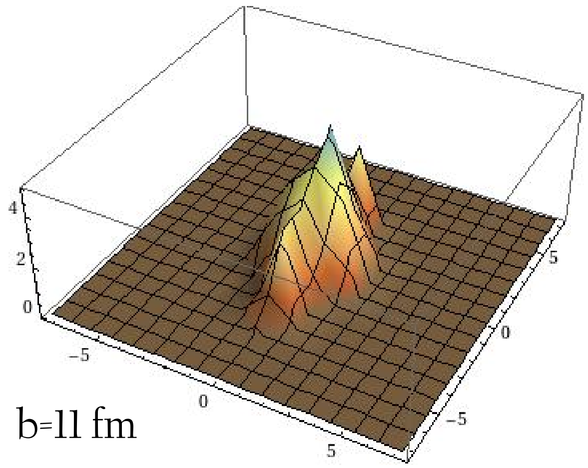
[RJF, DNP 2004]

First Results: Resolving Spatial Structures

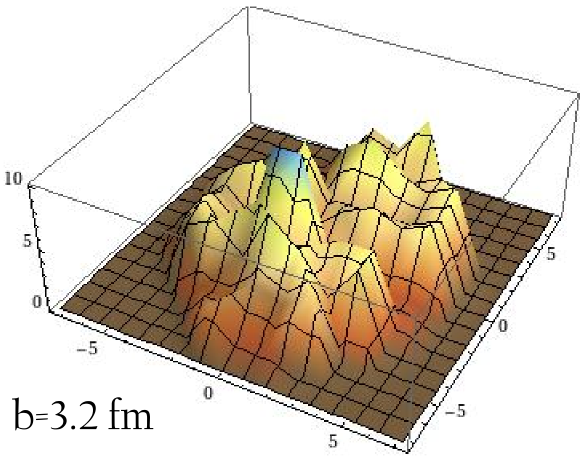
Probing the Spatial Structure

- What can hard probes tell us about the spatial structure of the fireball?
  - Or: can we do true tomography?
  - Seemingly hopeless: we sum over many events and only see an average fireball.

- What is the effect of an inhomogeneous fireball on hard probes?
  - Realistic initial conditions with fluctuations have been studied for hydrodynamics.
  - Applicability of hydro and elliptic flow seem to set some boundaries for times > 1 fm/c.
  - Hard probes from the surface layer and in peripheral collisions might be affected by fluctuations in the background.



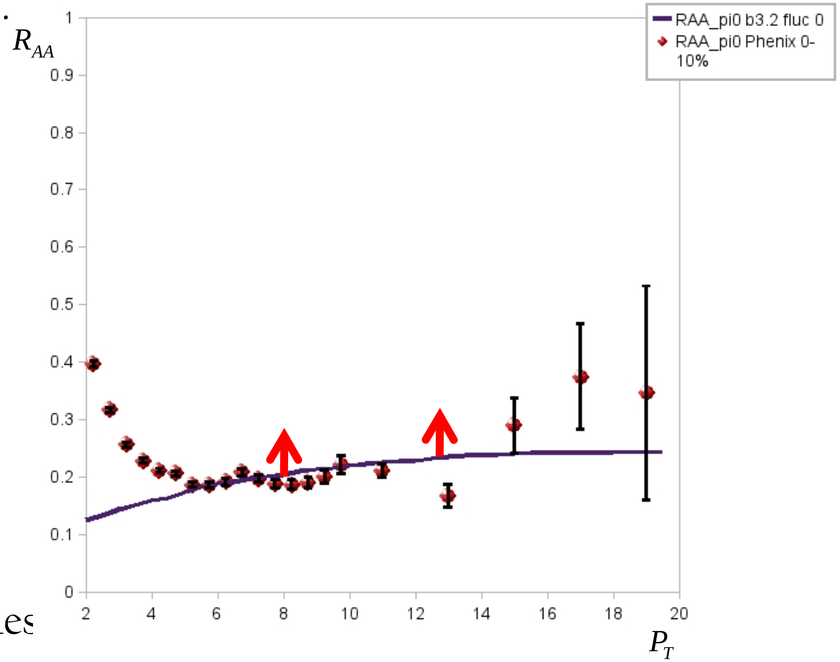
b=11 fm



b=3.2 fm

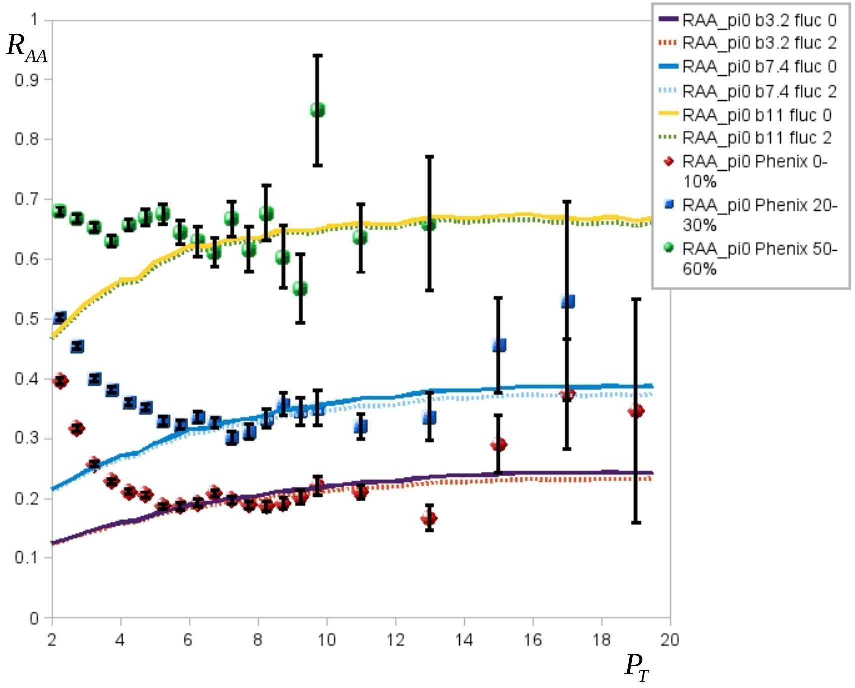
Probing the Spatial Structure

- Use events with fluctuating transverse profiles of the energy density.
  - Have tried simple transverse profiles with Gaussian fluctuations.
  - Here: initial state Glauber estimates of the number of participants (i.e. no energy flow build-up taken into account that would wash out inhomogeneities);
  - Assume $\hat{q} \propto \varepsilon^{3/4} \propto n_{\text{part}}^{3/4}$.
  - Will run some existing initial state simulations (e.g. GLISSANDO)
  - For every observable take average over events.
- Check single pion spectra:
  - As expected: fluctuations lead to slightly less suppression.
  - This can be absorbed in the definition of energy loss parameter,
  - Fit data well with $\hat{q} = 3.1\,\text{GeV/fm}^2$
  - Nothing won, effect no longer observable.
  - But the extracted strength of energy loss changes by 25%. Add to the list of uncertainties



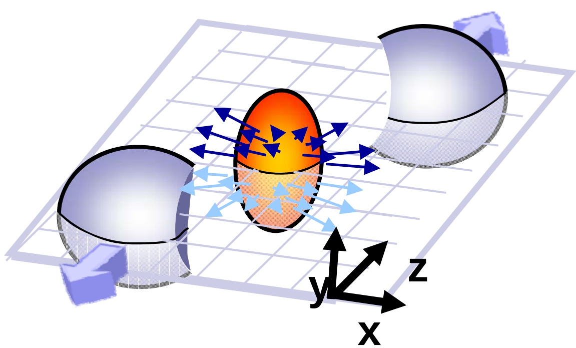
Probing the Spatial Structure

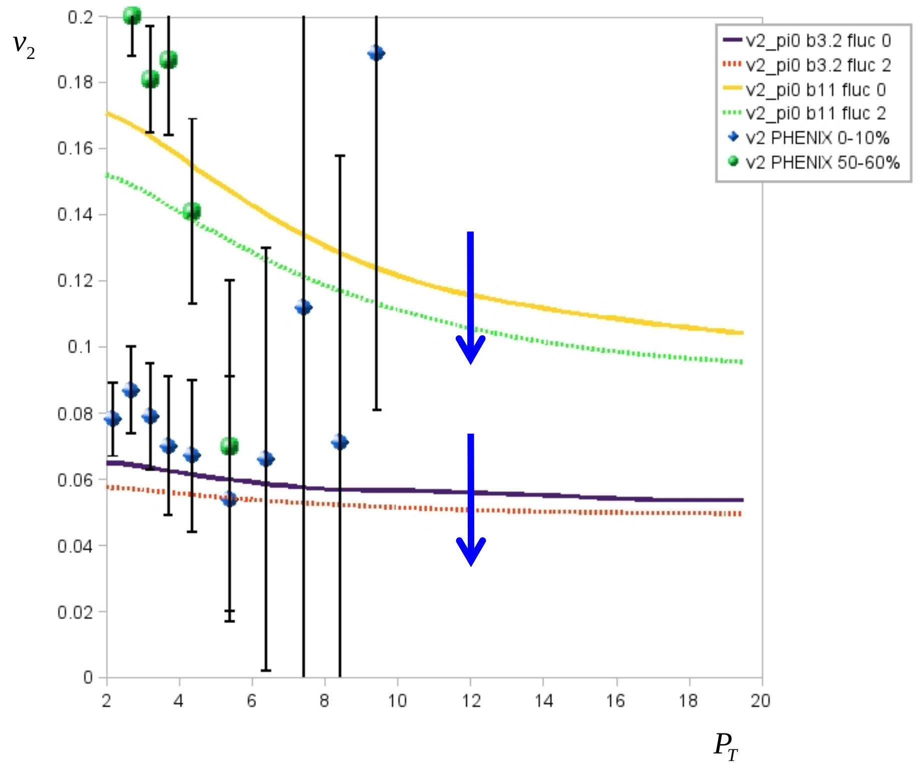
- Centrality dependence and P_T dependence:
- With inhomogeneities dependence stays the same after rescaling of $\hat{q}$.
  - Results fit PHENIX pion data.
- No signature.



Probing the Spatial Structure

- Elliptic Flow v_2:

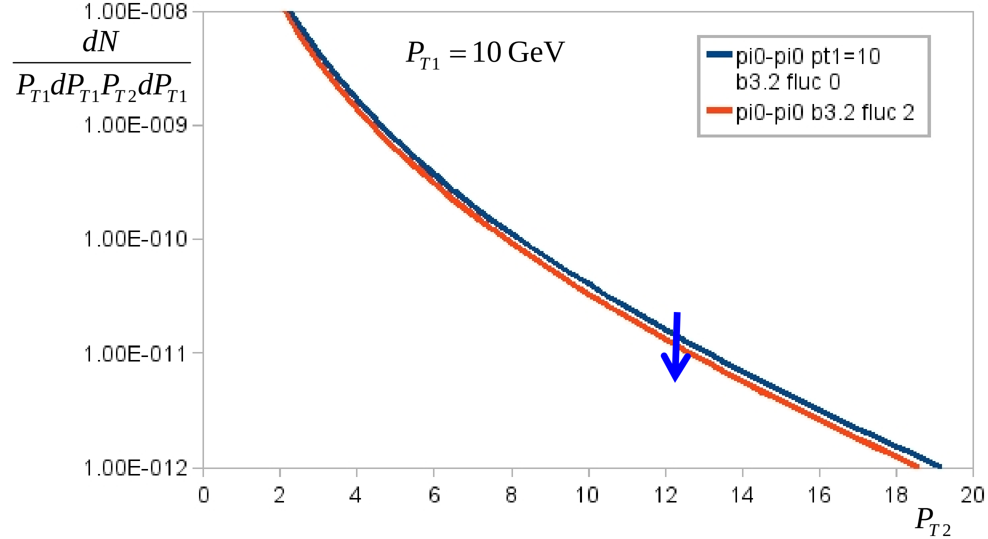


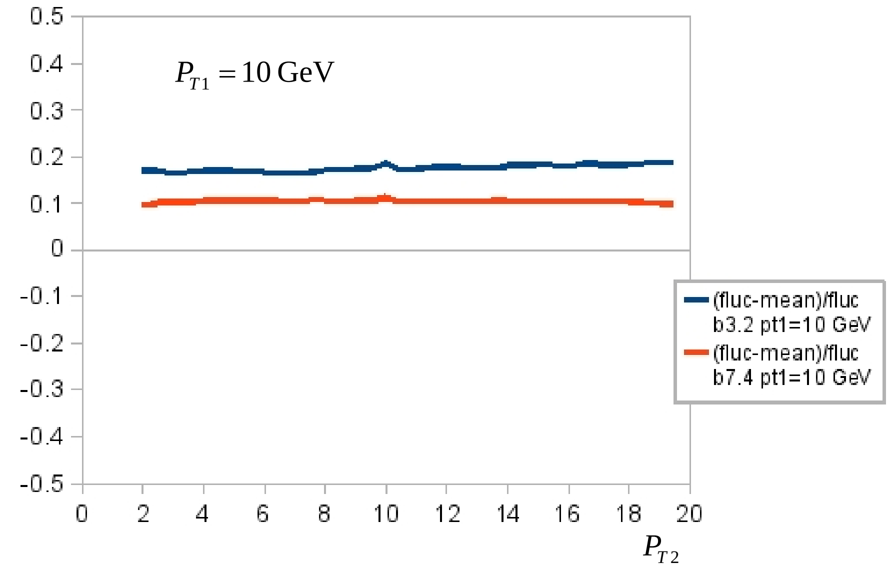


- 10-20% reduction in v_2 even after redefinition of $\hat{q}$.

Probing the Spatial Structure

- Dipion spectrum:
  - Visible deviation with inhomogeneities





- Relative deviation on linear scale:

- 10-20% reduction in correlation strength after redefinition of $\hat{q}$.

Summary & Outlook

- Hadro-chemistry for hard probes
  - Flavor changing processes are present in jet-medium interactions.
  - Jet chemistry contains information complementary to jet quenching measurements.
  - Predict strangeness enhancement at high P_T.

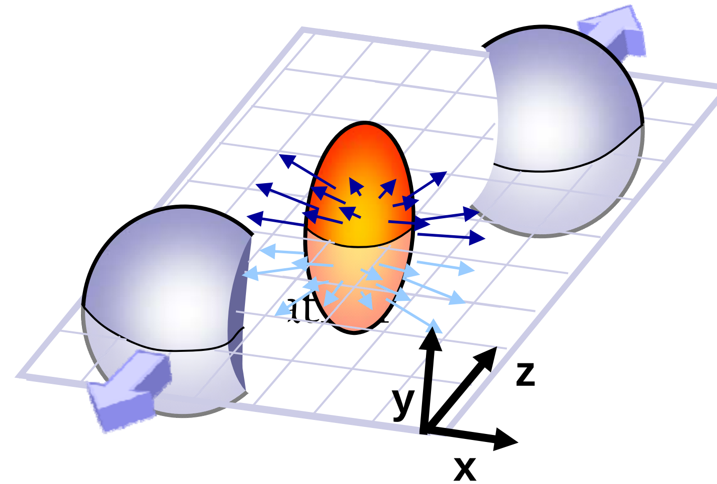
- Work progressing on a new framework for studies of hard and electromagnetic probes.

- Study of partons in inhomogeneous backgrounds:
  - Found 25% change in the extracted quenching strength to explain the data.
  - Even after adjusting the quenching strength, up to 20% secondary effect visible in elliptic flow and di-hadron correlations.

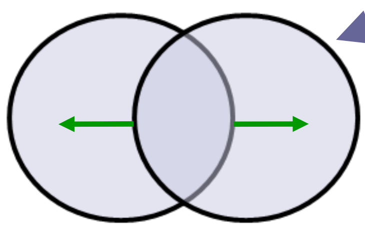
Backup

Pressure

- Finite impact parameter $b > 0$:
  - Spatial anisotropy in the initial state
  - Momentum anisotropy in the final state
- Space ↔ momentum space



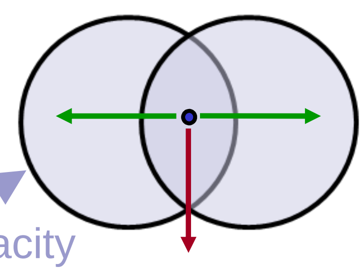
Bulk/soft particles



Test EOS of the system

$$Force = -\nabla P$$

Hard particles

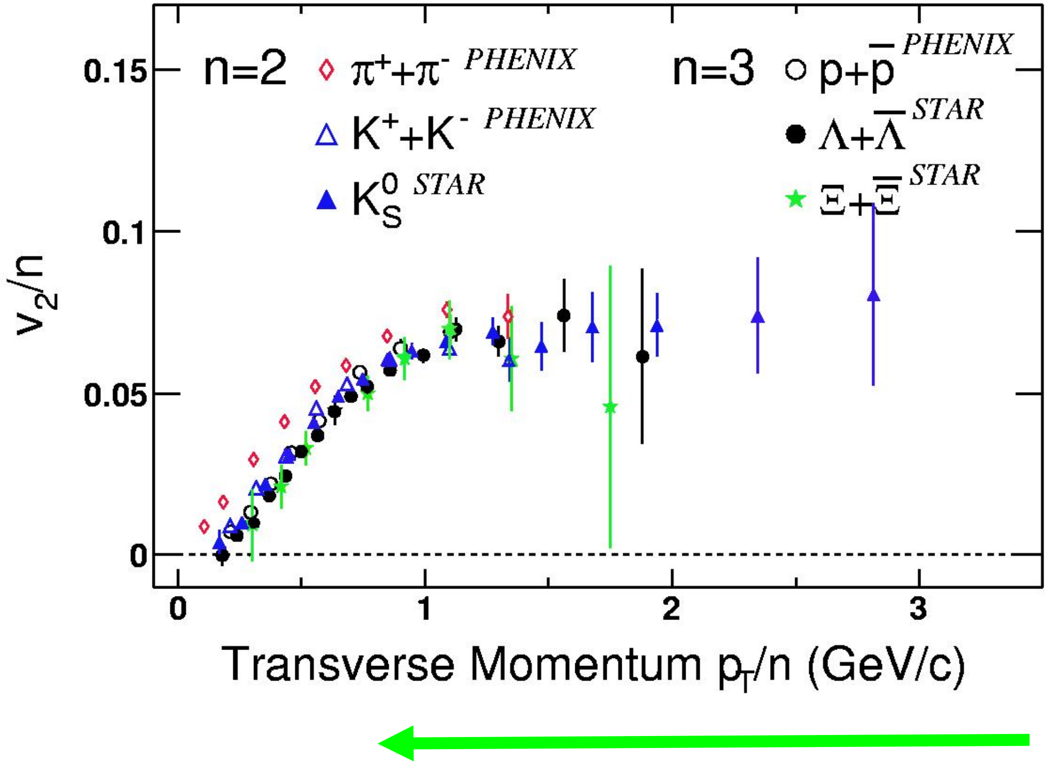


Test density/opacity of the medium

$$\Delta E \propto L$$

Two Great Discoveries

- v_2 scaling for mesons and baryons



Instantaneous Coalescence

- Simple realization of a recombination model
  - Recombine valence quarks of hadrons $q\bar{q} \rightarrow M$ $qqq \rightarrow B$
  - Dressed quarks, no gluons
- Instantaneous projection of quark states on hadron states:

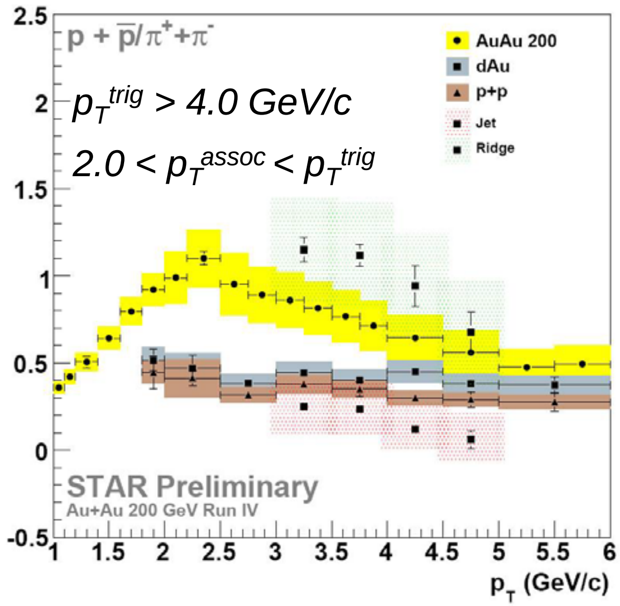
  [Fries, Muller, Nonaka, Bass]
  [Greco, Ko, Levai]
  [Hwa, Yang]

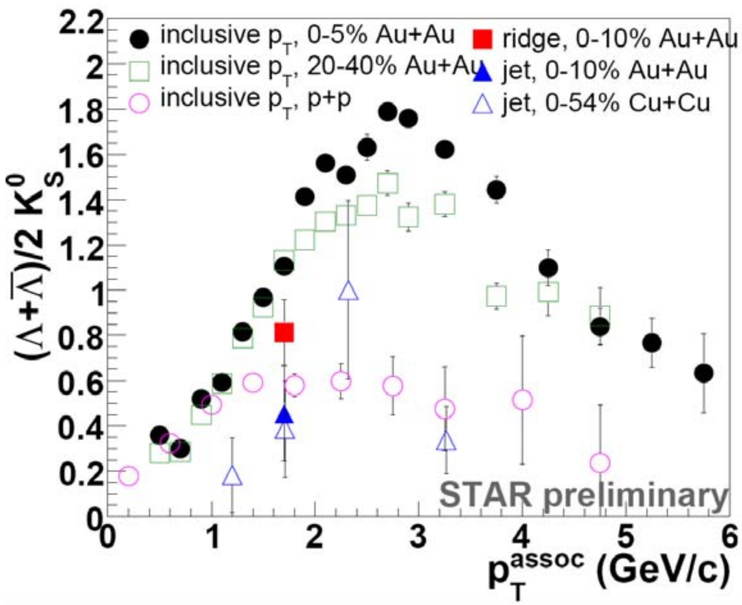
$$\frac{d^3 N_M}{d^3 P} = C_M \underbrace{\int_\Sigma}_{\text{Production hypersurface}} \underbrace{w_\alpha \otimes w_\beta}_{\text{Product of quark distributions}} \otimes \overbrace{\Phi_M}^{\text{Meson Wigner function}}$$

- Recombination itself does not make absolute predictions. If successful, it predicts the *difference* between hadron species $\rightarrow$ chemistry

Particle composition in "jet" and ridge

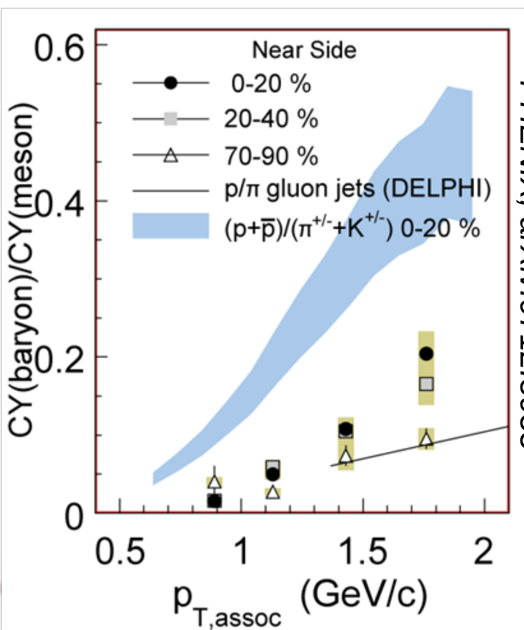
C. Suarez (STAR), poster, QM2008



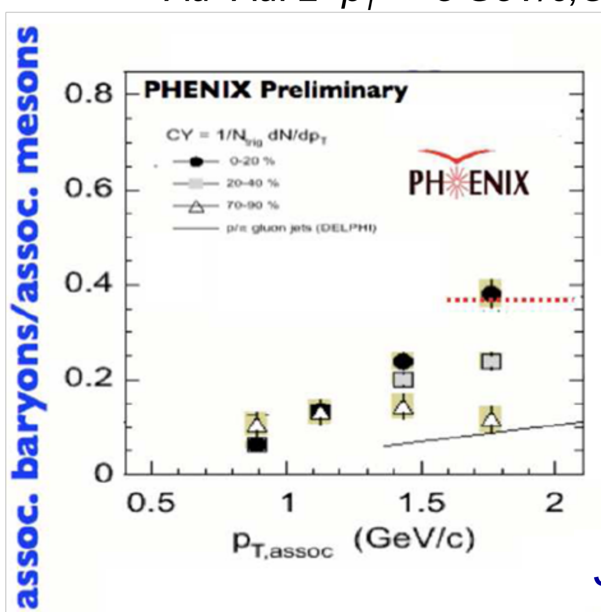


inclusive Au+Au: M. Lamont (STAR) SQM06
Cu+Cu: C. Nattrass (STAR), QM2008
Au+Au: J.B. (STAR), WWND07

Au+Au: $2<p_T^{trig}<3$ GeV/c, Cu+Cu: $3<p_T^{trig}<6$ GeV/c



PHENIX, arXiv:0712.3033

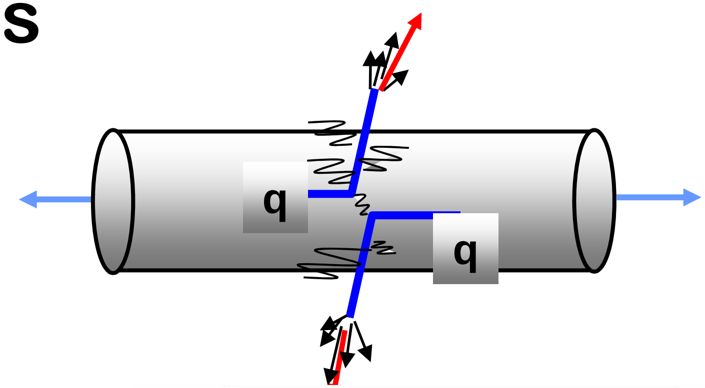


Baryon/meson ratios:
- "jet": smaller than inclusive and similar to p+p
- ridge: similar to inclusive

Jana Bielcikova, Hard Probes 2008

Hard Probes

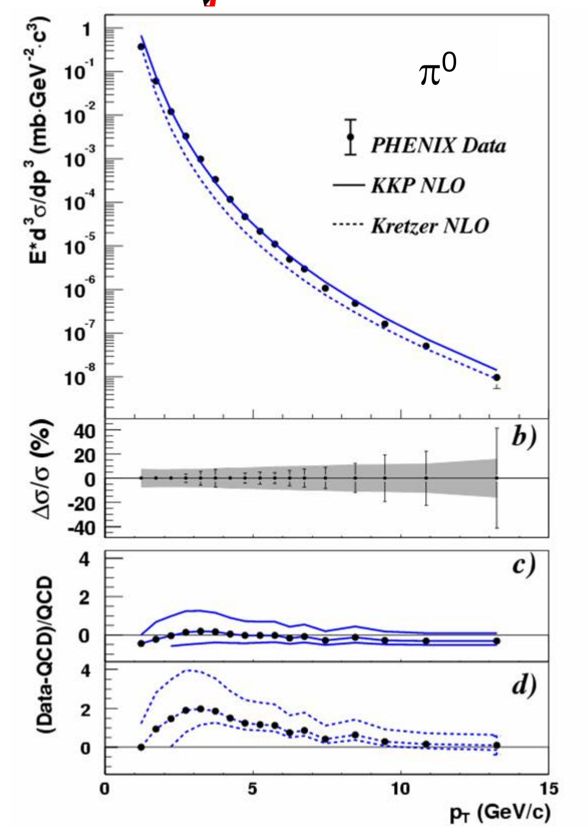
- Hard processes ⇨ QCD jets
- Our hope: this is a well-calibrated tool.
  - perturbative calculations available
  - p+p baseline experiment



- Description of initial hard process based on QCD factorization.

$$d\sigma^{A+B\to C+X} = \sum_{a,b,c} \underbrace{f_{a/A}}_{\text{PDF}} \otimes \underbrace{d\sigma^{a+b\to c+x}}_{\text{Parton cross section}} \otimes \underbrace{f_{b/B}}_{\text{PDF}} \otimes \underbrace{D_{C/c}}_{\text{FF}}$$

- p+p indeed well under control:



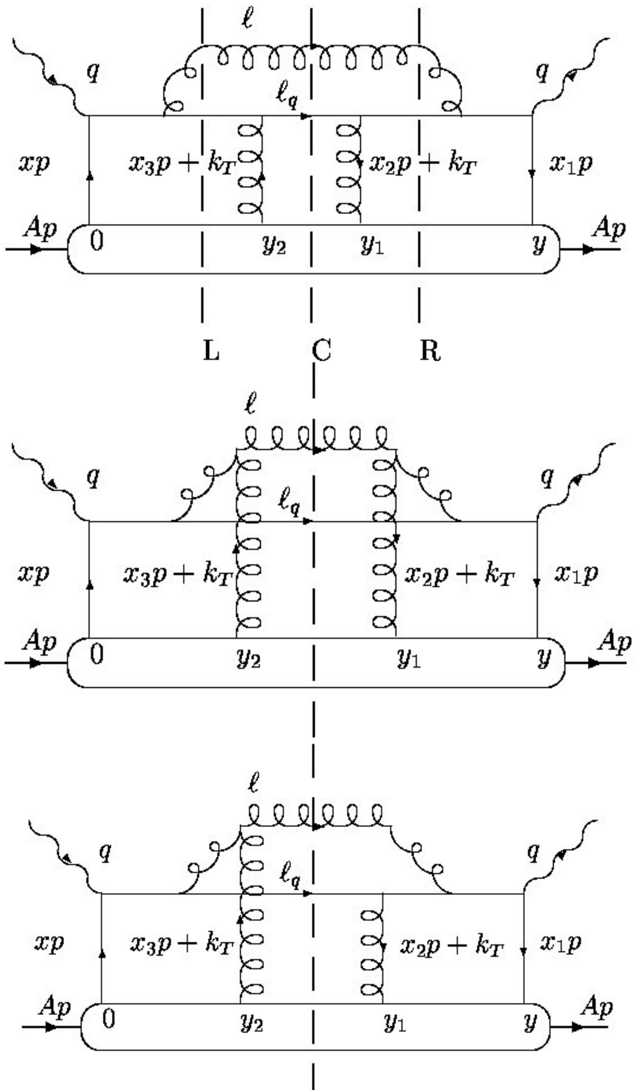
Higher Twist Fragmentation Functions

- Rescattering of the final state partons off the nucleus.
- Twist-4 = double scattering or interference between single and triple scattering
- Hadronic tensor W in lowest order in α_s

$$\frac{dW^{\mu\nu}}{dz_h} = \sum_q \int dx\, f_{q/A}\left(x,\mu^2\right) H^{\mu\nu}(x,p,q)\, \tilde{D}_{q/h}\left(z_h,\mu^2\right)$$

- Modified fragmentation function

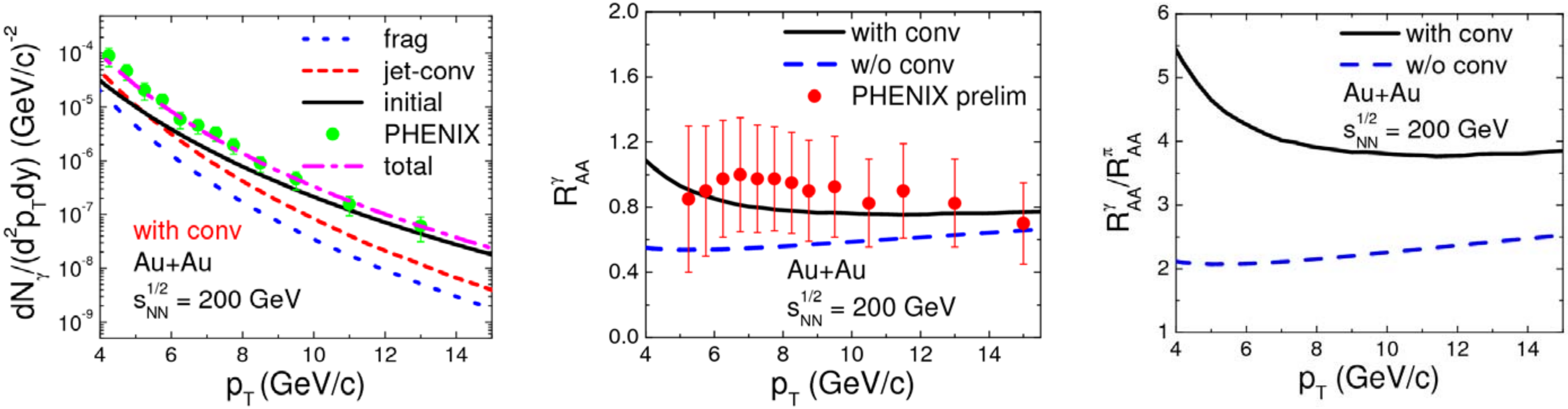
$$\tilde{D}_{q/h}\left(z_h,\mu^2\right) = D_{q/h}\left(z_h,\mu^2\right) + \int_0^{\mu^2} \frac{dl_T^2}{l_T^2} \frac{\alpha_s}{2\pi} \int_{z_h}^1 \frac{dz}{z}$$
$$\times \left[\Delta\gamma_{q\to qg}\left(z,x,l_T^2\right) D_{q/h}\left(\frac{z_h}{z}\right) + \Delta\gamma_{q\to gq}\left(z,x,l_T^2\right) D_{g/h}\left(\frac{z_h}{z}\right) \right]$$



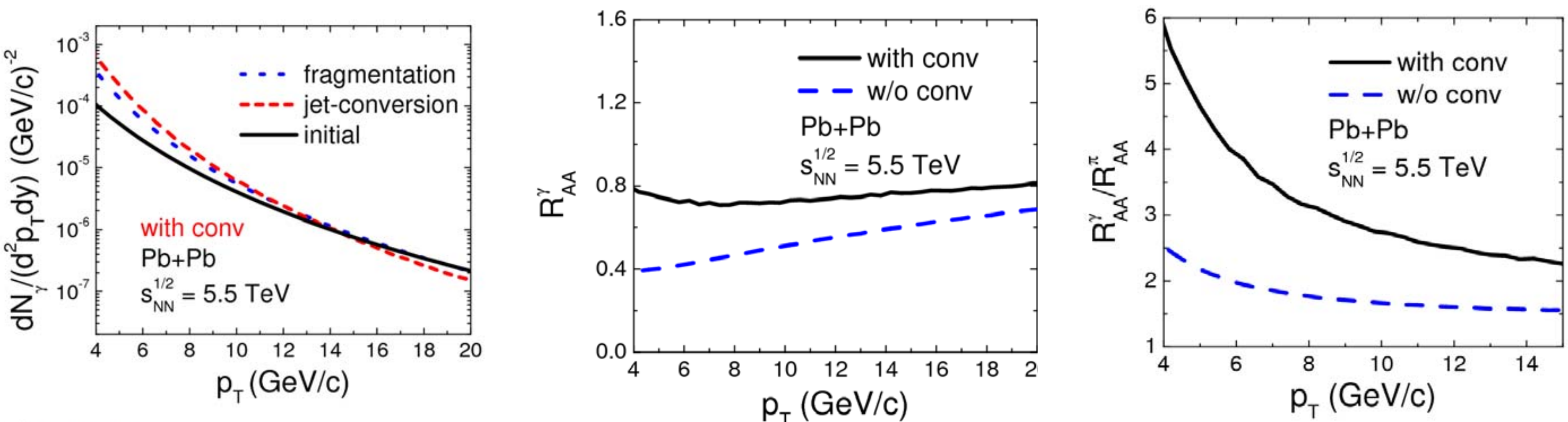
Numerical Results: Photons

[Liu, RJF]

- Real photons (RHIC):

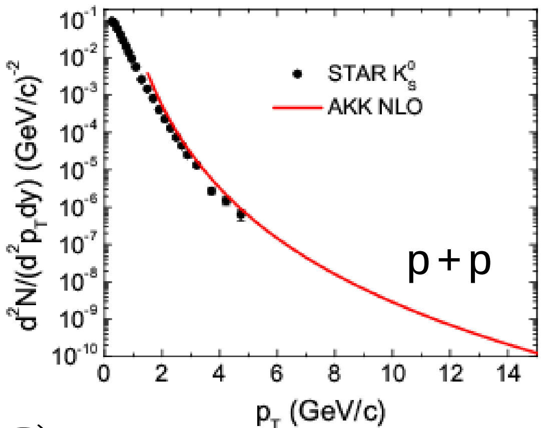


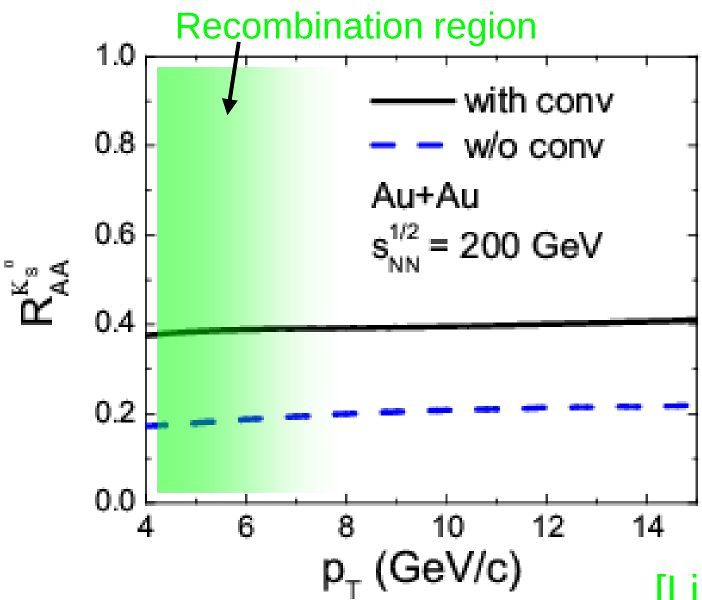
- Real photons (LHC):



Numerical Results: Strangeness

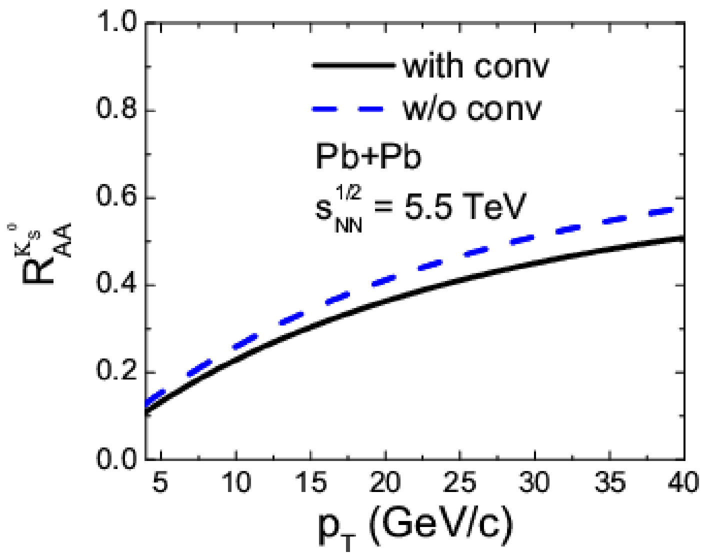
- Kaons (RHIC):
  - See expected enhancement
  - Outside the recombination region!





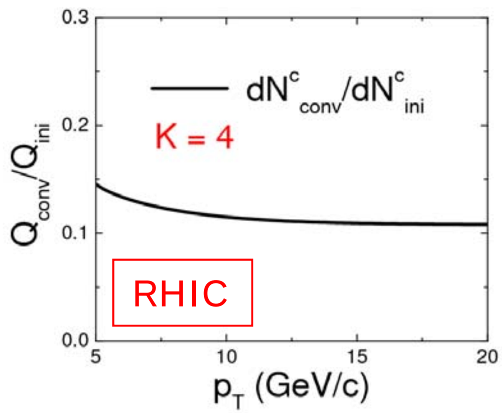
[Liu, RJF]

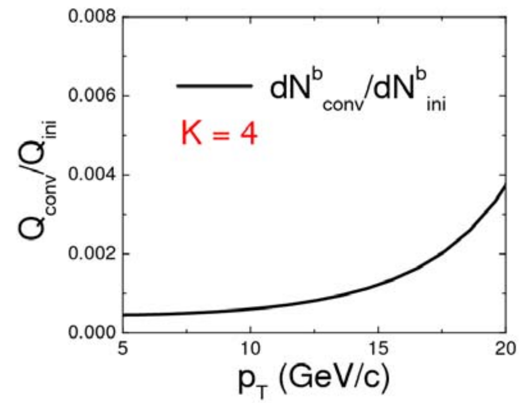
- Kaons (LHC):
  - No enhancement
  - Too much initial strangeness!
  - Maybe it works with charm?



Numerical Results: Heavy Quarks

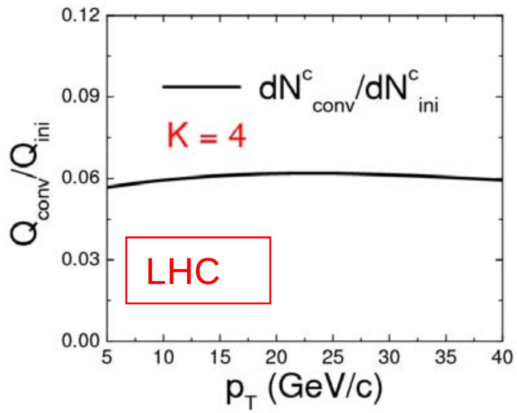
- Have to take into account threshold effect
- At RHIC: additional heavy quark production marginal

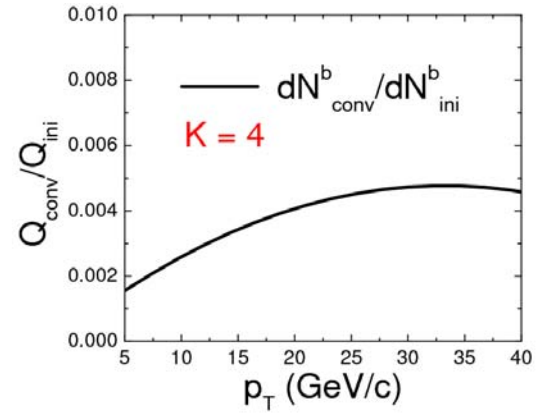




[Liu, RJF]

- LHC: not at all like strangeness at RHIC; additional yield small
  - Reason: small gradient between jet and medium charm
  - Threshold effect





Propagating Particles in a Medium (PPM)

- Developing flexible code to simulate N jets in a fireball.
  - Part of a NSF project; authors: R. Rodriguez, R.J. Fries, E. Ramirez
- Input:
  - initial phase space distribution
  - background (aka fireball)
  - specifics of dynamics (energy loss model, fragmentation)
- What it should do:
  - Evolution of particle distributions; (modified) fragmentation and hadronization; analysis of results in terms of experimentally relevant observables
- E.g. leading particle energy loss + fragmentation: