Direct Photons and Jet Conversions in Heavy Ion Collisions

Rainer Fries

Texas A&M University & RIKEN BNL

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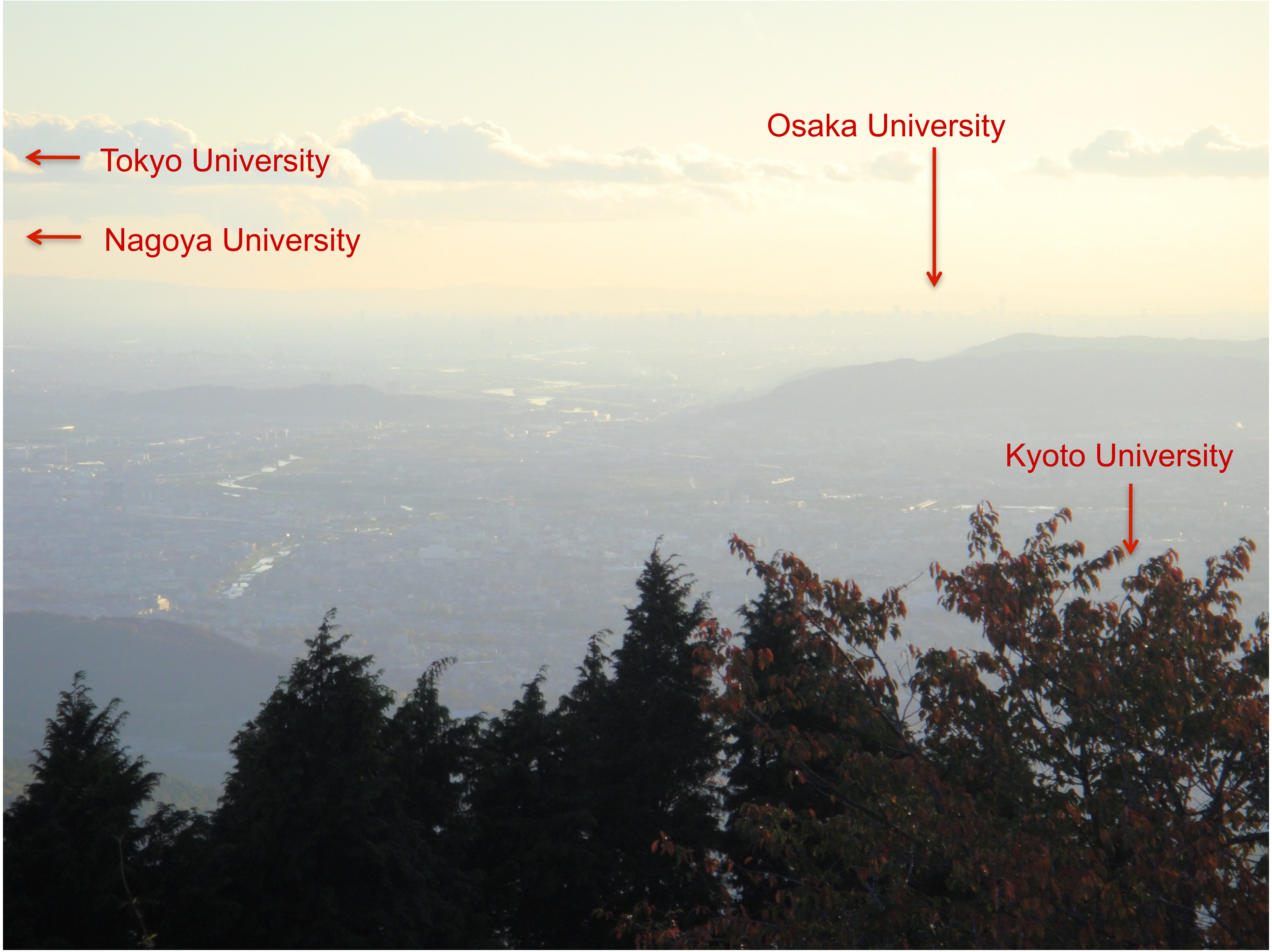
Thanks to my hosts at Nagoya University
and to JSPS for a wonderful and
productive stay in Japan!



Osaka University
Tokyo University
Nagoya University
Kyoto University

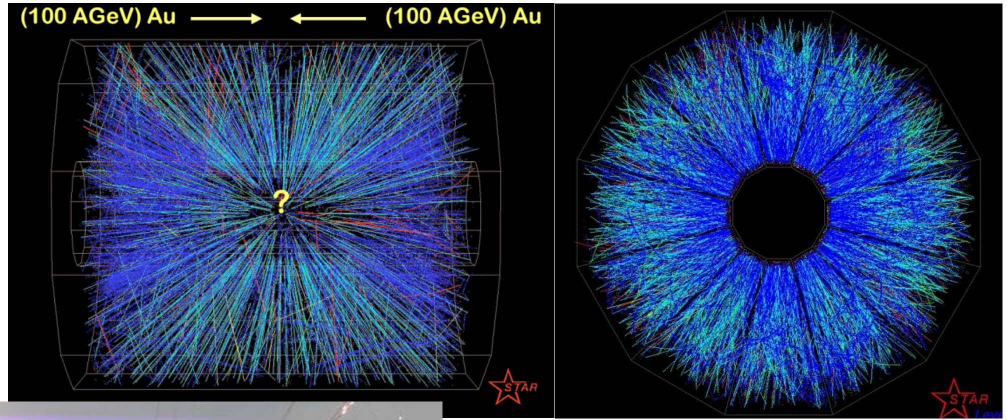
Overview

- Introduction : Electromagnetic probes
- Photon Sources
  - Initial hard photons
  - Thermal radiation
  - Jet-medium interactions
- Flavor Conversions
- Elliptic Flow
- Photon correlations

Introduction

How to Investigate 10^{12} K Matter?

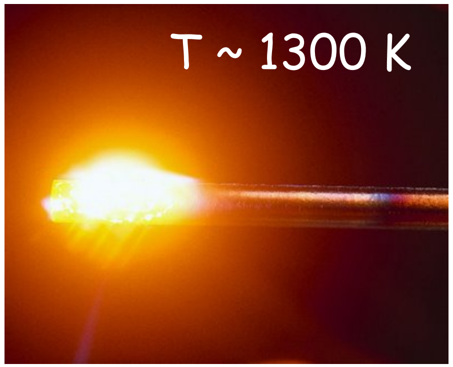
- Look at the Ashes
  - Soft bulk physics



- Look at projectiles
  - Hard probes

Some objects are violently ejected from an explosion.

- Look at radiation
  - Electromagnetic probes



Electromagnetic Probes

- Real and virtual photons are perfect probes for nuclear matter.
  - Quarks (and charged hadrons) couple to photons.

- Weak coupling $\alpha_{em} \ll \alpha_S$:
  - Photon mean free path ~ 100 fm in hot nuclear matter >> typical system size
  - photon probes usually interact only once with the system
  - least possible disruption of the system by the probe
  - but very low production rates

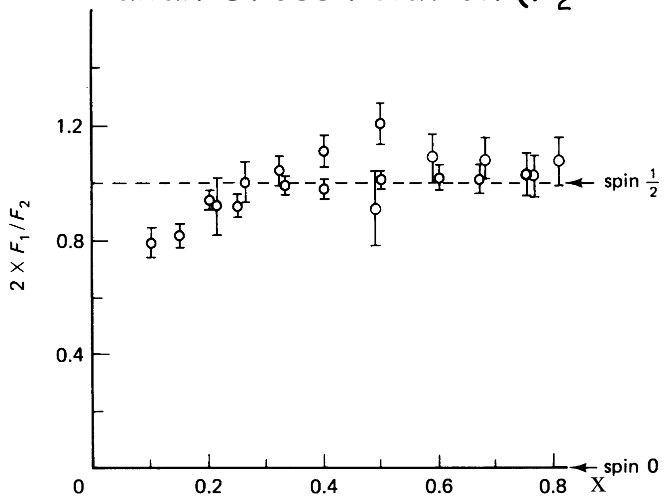
- What we can hope to measure is a current-current correlator.
  - Photons couple to $W^{\mu\nu} \sim \langle \text{system} | j^{\mu}_{\text{em}} j^{\nu}_{\text{em}} | \text{system} \rangle$

Learning From Success: DIS

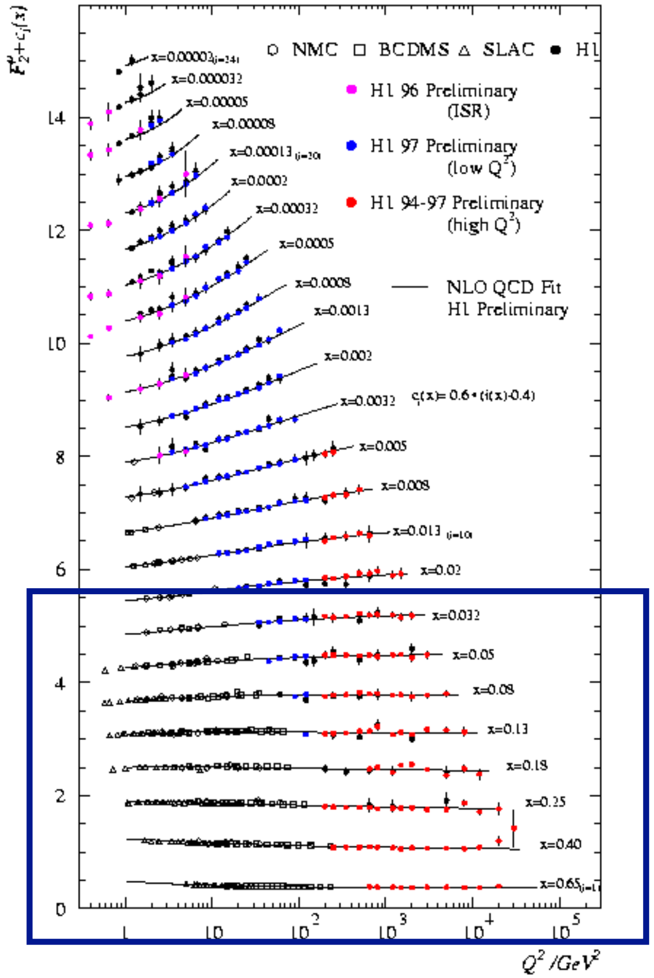
- Longitudinal structure of hadrons and nuclei can be revealed through deep inelastic scattering: $l + h \to l' + X$
  - Probe: virtual photon in the initial state

$$\frac{d\sigma}{dE' d\Omega} = \left(\frac{\alpha\hbar}{2E\sin^2(\theta/2)}\right)^2 \left[\frac{2F_1(x,Q^2)}{M}\sin^2(\theta/2) + \frac{2MxF_2(x,Q^2)}{Q^2}\cos^2(\theta/2)\right]$$

- Quarks exist!
  - Bjorken scaling ($\partial F_1/\partial Q^2 = 0 = \partial F_2/\partial Q^2$)
  - Callan-Gross relation ($F_2 = 2xF_1$)

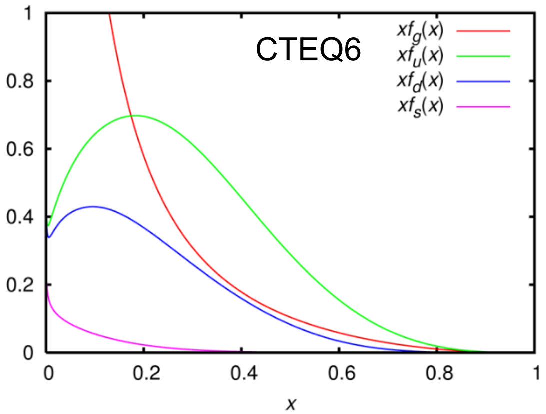


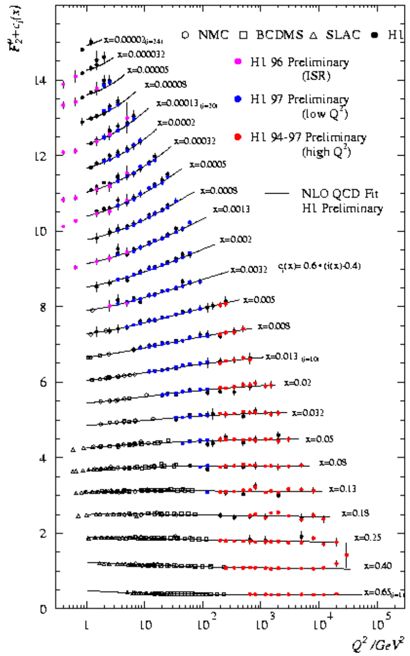
Hl Pub 2009



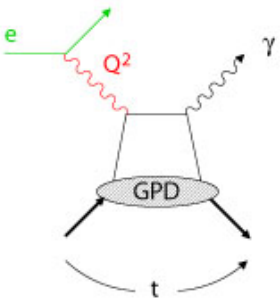
Learning From Success: DIS

- Rigorous procedure to extract parton distributions for protons and other hadrons.

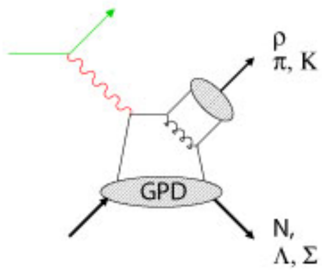




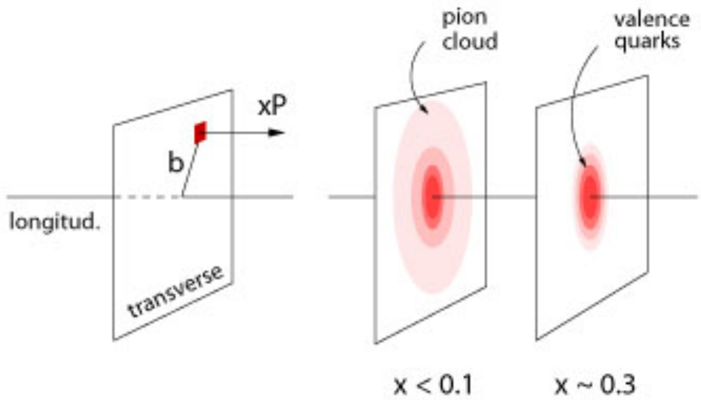
- Today: toward 3-d picture of hadrons
  - E.g. DVCS



Deeply virtual
Compton scattering



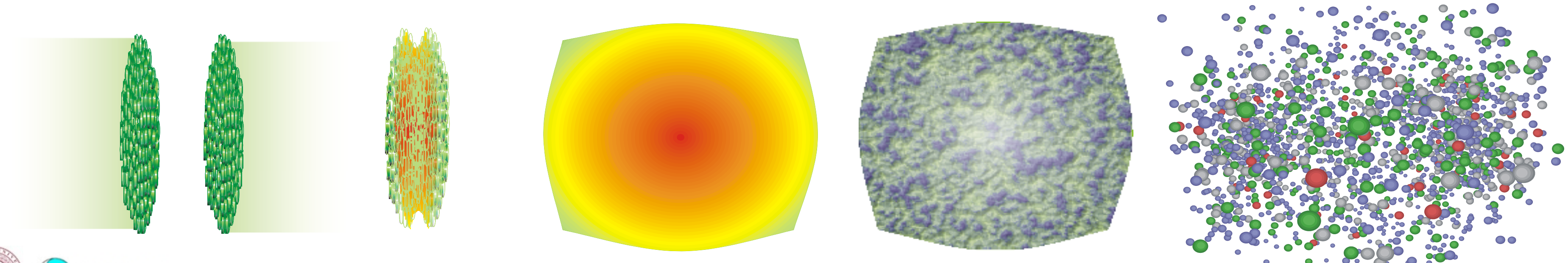
Deeply virtual
meson production



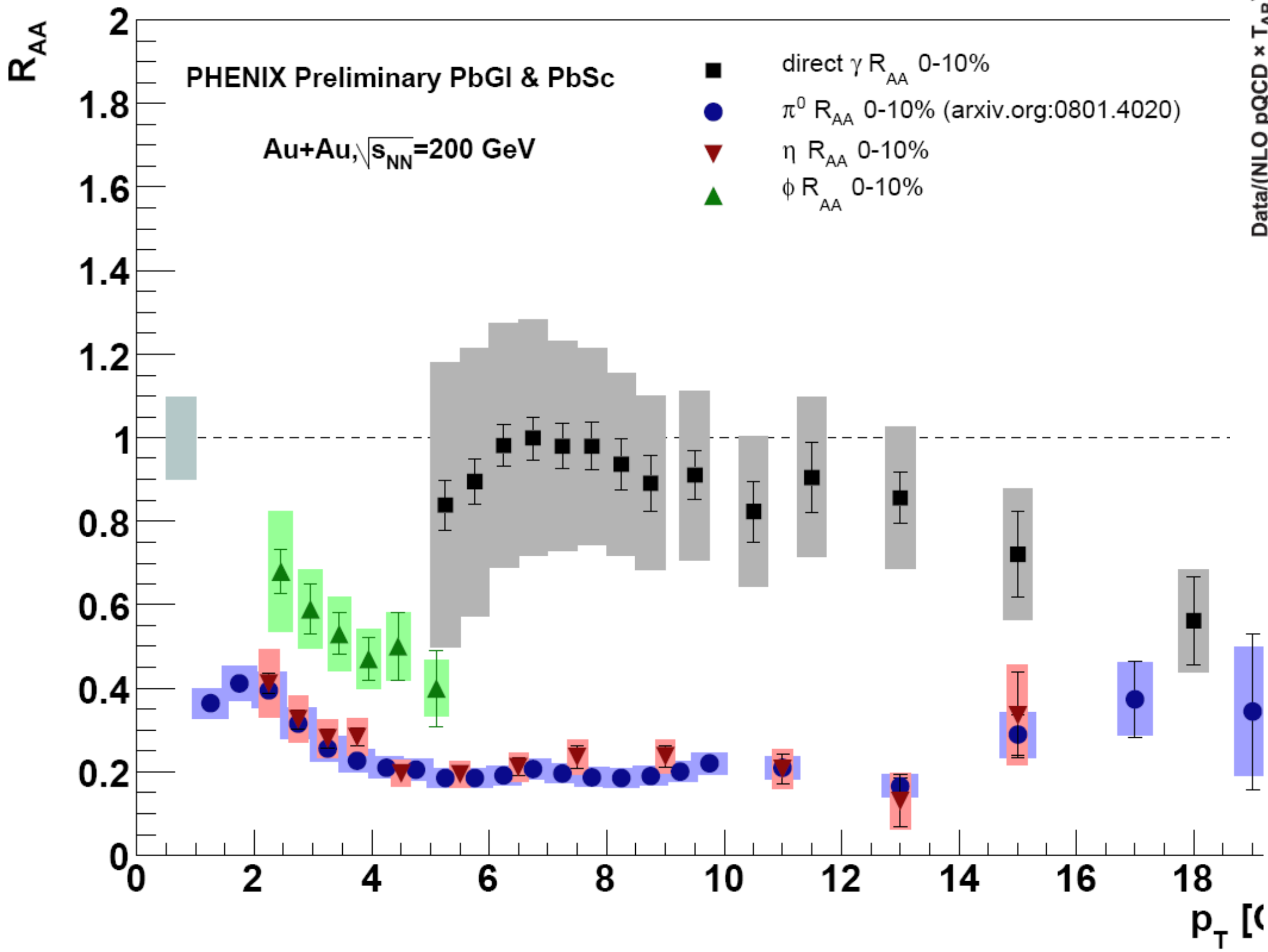
Nucleon tomography

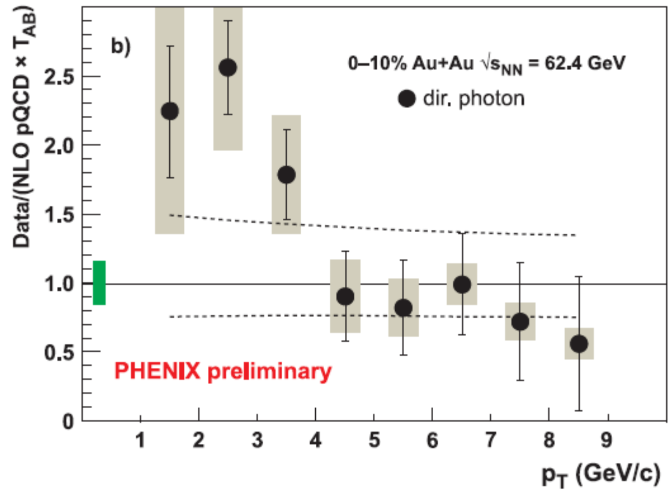
High Energy Nuclear Collisions

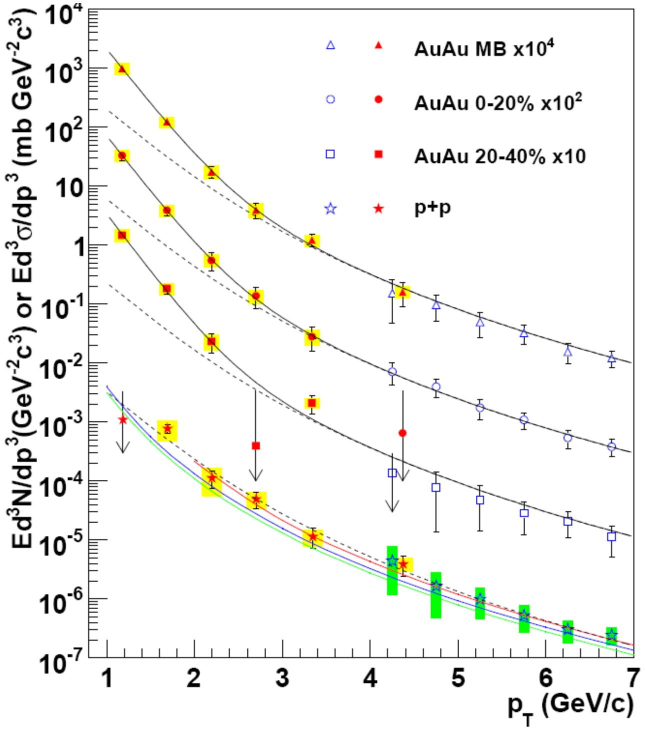
- Can we have a similarly successful program in Heavy Ion Physics?
  - E.g.: measure the distribution function of quarks in a QGP?
- In principle yes … but:
- Many sources: system is far from homogenous
  - Initial prompt photons, pre-equilibrium phase, QGP, jets, hadronic phase
- Moving target: system changes radically as a function of time
  - Photon signals are integrated over system history



Very Good Data Available

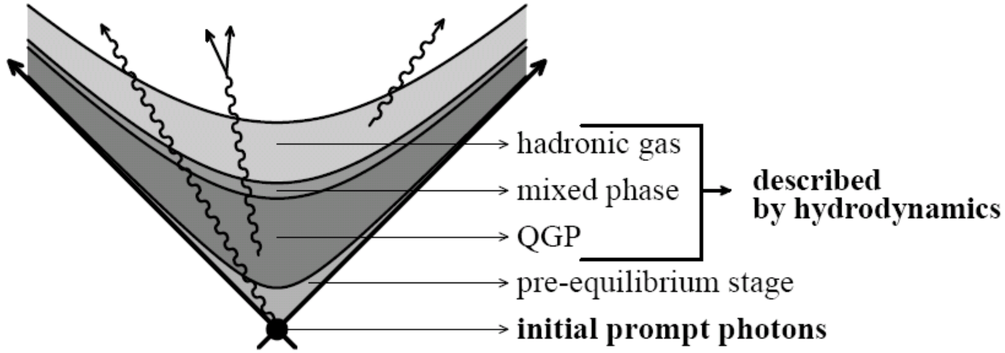






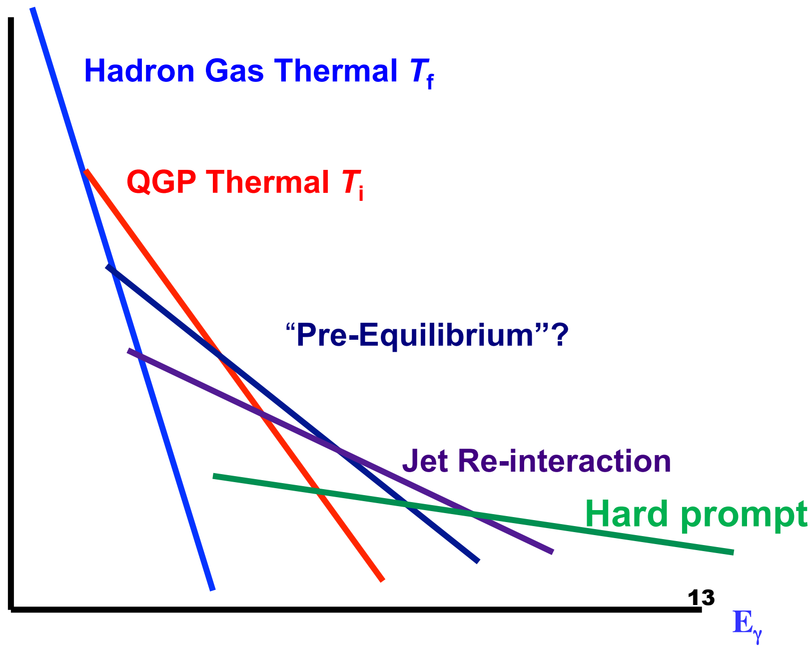
Photons in Nuclear Collisions

Classifying Photon Sources



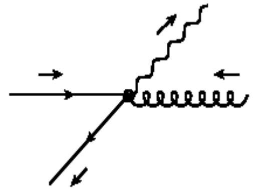
- Identify all important sources and develop a strategy to measure them individually.

- Transverse momentum spectra of single direct photons
  - Hierarchy in momentum
  - Reflects hierarchy in average momentum transfer (or temperature) in a cooling and diluting system)



- More sophisticated strategies:
  - Elliptic Flow
  - Correlations of photons with hadrons and jets

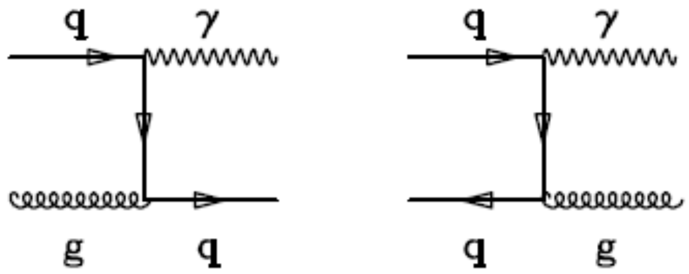
Initial Hard Photons



pQC

- Prompt photons from initial hard scattering of partons in the nuclei.

Parton processes at leading order:



Compton　　Annihilation

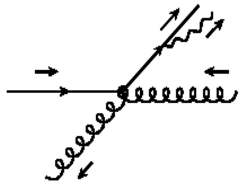
- Calculable in factorized QCD perturbation theory

$$d\sigma^{N+N\to\gamma} = \sum_{a,b} f_{a/N} \otimes d\sigma^{a+b\to\gamma} \otimes f_{b/N}$$

PDF　　Parton cross section　　PDF

- p+p collisions: important baseline to understand prompt photons in heavy ion collisions despite somewhat different initial state.

Fragmentation Photons



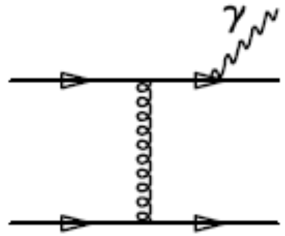
pQC

- Photons can also fragment off jets created in initial collisions (Bremsstrahlung)
  - Described by photon fragmentation function
  - Factorization:

$$d\sigma^{N+N\to\gamma} = \sum_{a,b,c} f_{a/N} \otimes d\sigma^{a+b\to c} \otimes f_{b/N} \otimes D_{c/\gamma}$$

PDF | Parton cross section | PDF | FF

Parton process:



- At NLO, prompt hard and fragmentation photons can be treated consistently.
- Possible problem in nuclear matter:
  - Final state suppression for fragmenting photons but not for prompt photons?
  - Induces uncertainty in direct photon baseline.

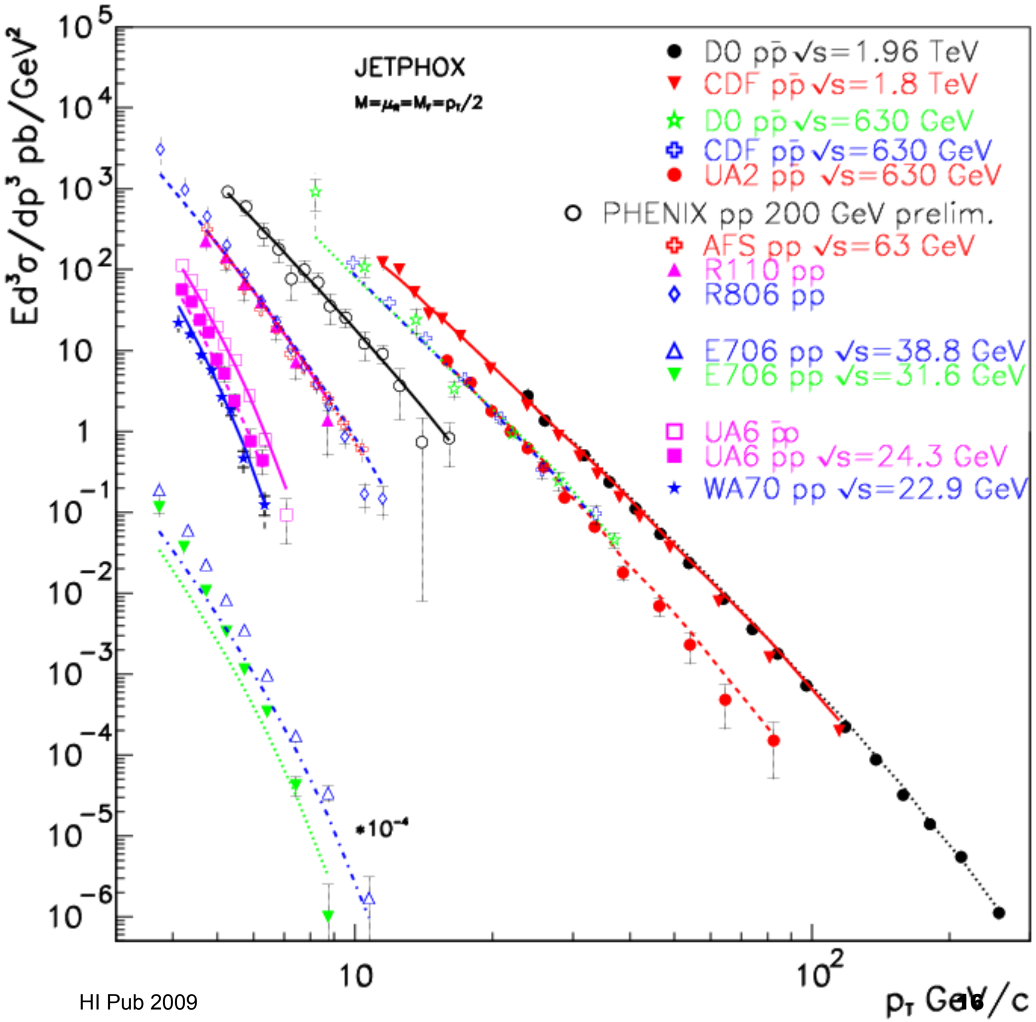
Initial Hard Photons

- Prompt photon data in p+p well described by NLO calculations.

- This seems like a safe baseline!

Photon world data @ hadron colliders

[Aurenche et al., PRD (2006)]



Initial Hard Photons: Nuclear Effects

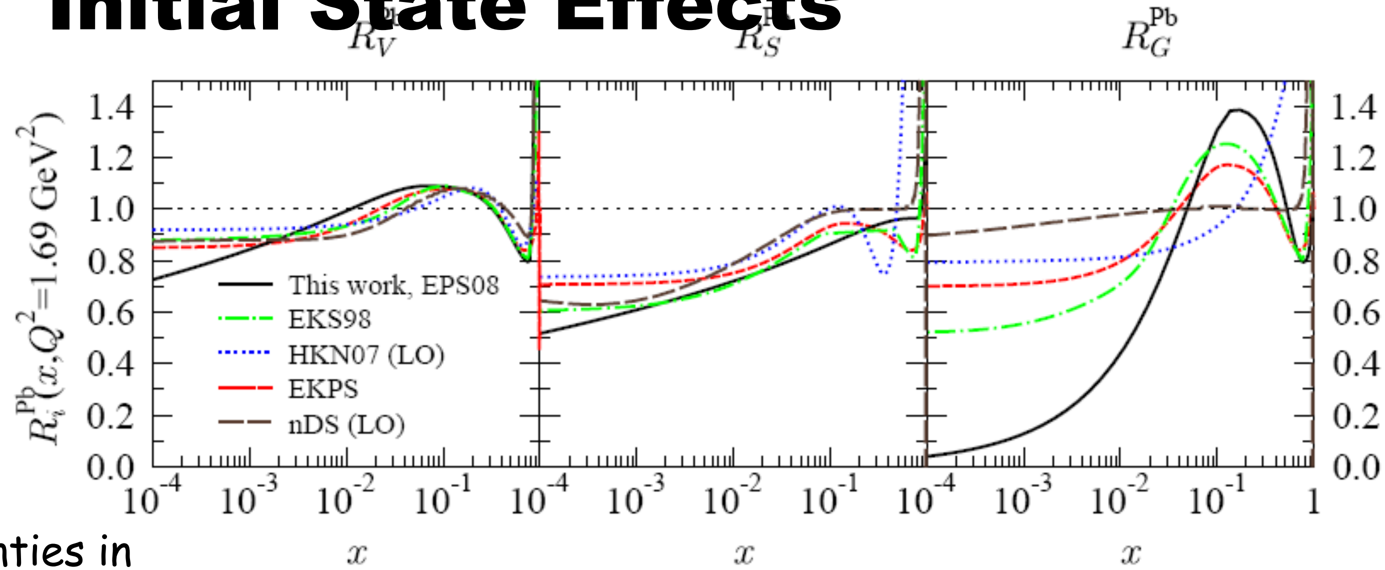
- Do we have control over initial state effects for prompt photons in nuclear collisions?
  - Isospin: correct blend of protons and neutrons in colliding nuclei is important ($\alpha_u = 4\alpha_d$!)
  - Shadowing and EMC effect: usually taken into account by modified parameterizations for nuclear PDFs (EKS …); source of some uncertainty!
  - Cronin effect: initial state scattering leading to broadening.

- Final state effects for fragmentation photons: most calculations assume final state parton is quenched until the photon is created.
  - Which often means full quenching until the parton leaves the fireball!

Initial State Effects

- Shadowing:

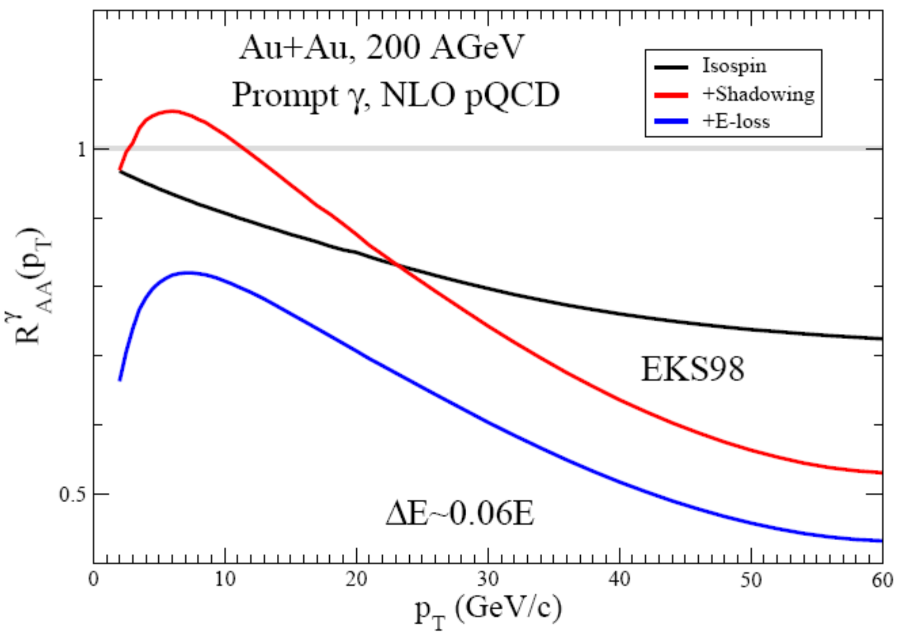
[Eskola et al., (1998, 2008)]



  - Large uncertainties in nuclear gluon distribution at small x!

- Estimated combined effect of isospin and shadowing on initial hard photons.

[Srivastava @ HP06]



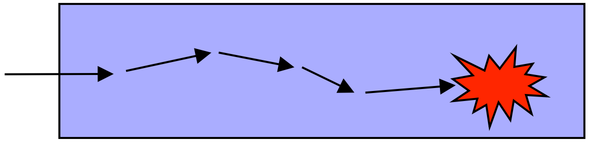
- Isolation cuts can in principle distinguish fragmentation photons.

Initial State Effects

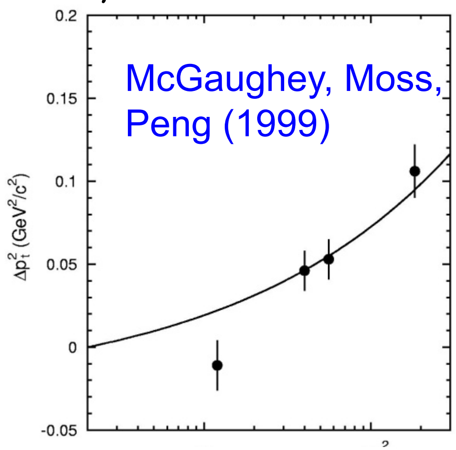
- Cronin et al. (1975): enhancement of hadron production at moderate P_T in proton-nucleus interactions.

$$d\sigma_{pA} = A^{\alpha} d\sigma_{pN}$$
$$\alpha > 1 \ (P_T > 2\,\mathrm{GeV}/c)$$

- Initial state multiple scattering leads to additional P_T



$$\langle \Delta P_T^2 \rangle \sim A^{1/3}$$



- Nicely explained for Drell-Yan as a higher twist effect

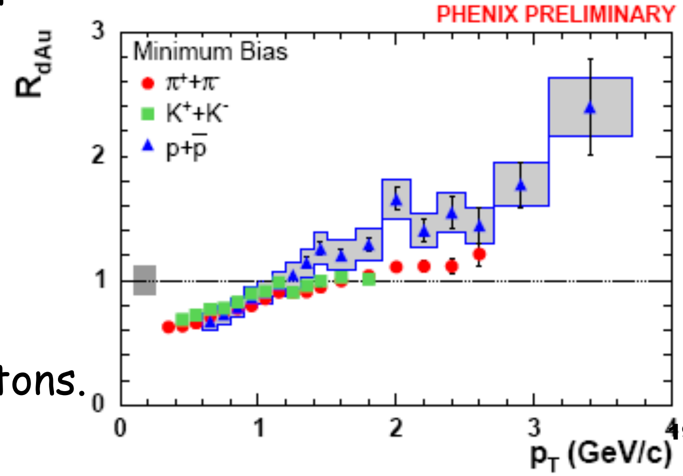
[RJF (2003)]

$$\langle P_T^{2n} \rangle \sim \frac{1}{n!} \left(\frac{4\pi\alpha_s}{N_c} A^{1/3} \langle FF \rangle \right)^n$$

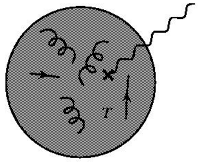
  - After resummation: diffusion equation for transverse momentum distribution.

    [Majumder, Müller (2006)]

- d+A at RHIC:
  - Effect might be small for photons.
  - Large (non-perturbative ?) effect for protons.



Thermal Photons



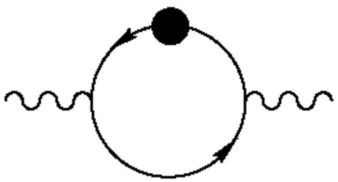
- Annihilation, Compton and bremsstrahlung processes also occur between thermalized partons in a QGP.
  - Emission Rate
    (β = 1/T, Π = polarization tensor)

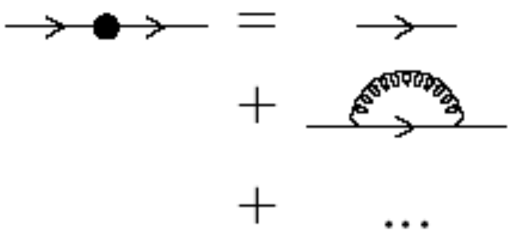
$$\omega \frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3}\,\mathrm{Im}\,\Pi^R_{\mu\nu}(k)\,\frac{1}{e^{\beta\omega}-1}$$

- Hope to measure the temperature *T* (or its time-average).

- Resummation program (+ hard thermal loop)

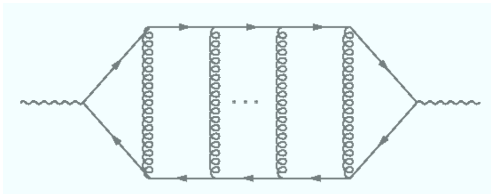
[Kapusta, Lichard & Seibert (1991)]
[Baier et al. (1996)]
[Aurenche et al. (1996, 1998)]



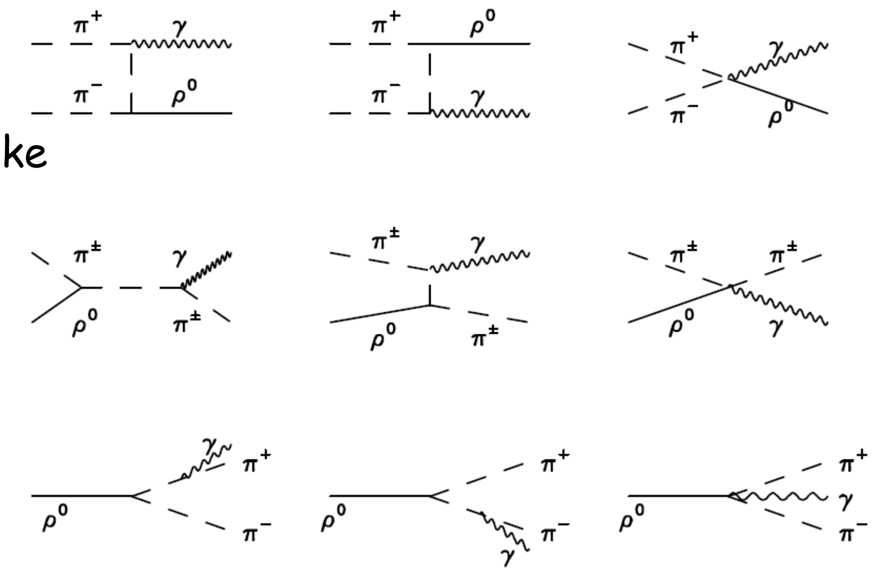


- AMY: complete leading order results

  [Arnold, Moore & Yaffe, JHEP (2001, 2002)]



More Thermal Photons



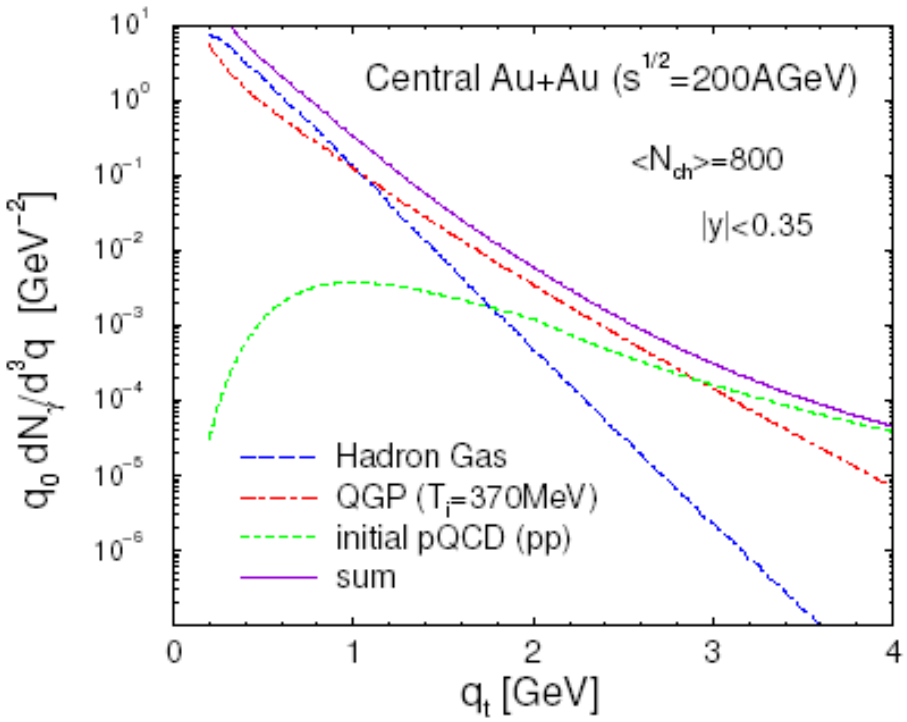
- A hot hadron gas shines as well.
  - Annihilation, creation and Compton-like processes with pions
  - Vector mesons, baryons …

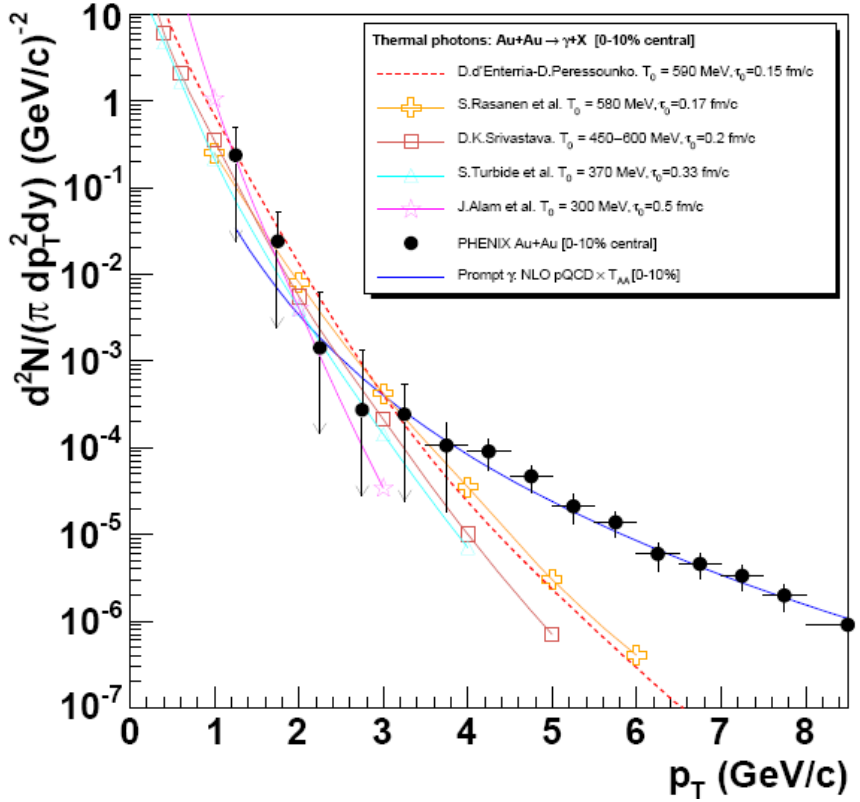
  [Kapusta, Lichard & Seibert (1991); …]

- From rates to spectra:
  - Need time evolution of the temperature over the system volume.
  - Plug rates into fireball evolution.
  - State of the art: hydrodynamics
- Challenge:
  - Need reliable rates to test fireball models and extract temperatures
  - But we would like to experimentally check rates first

Summary So Far

- Thermal + hard photons



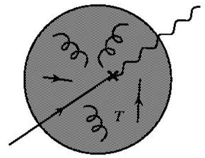


[Turbide, Rapp & Gale, PRC (2004)]

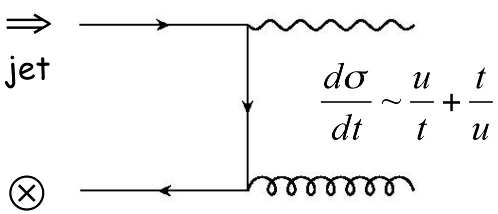
[d'Enterria & Peressounko (2006)]

- Sufficient to give a decent description of RHIC data.

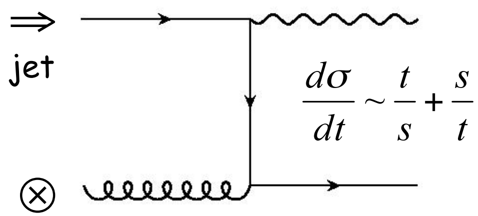
But Wait There's More!



- Final state interactions of jets can give us additional photons.
- Compton, annihilation and Bremsstrahlung processes can also occur between a fast parton in a jet a medium parton.



$$\vec{p}_\gamma \approx \vec{p}_{jet}$$
$$\vec{p}_\gamma \approx \vec{p}_{jet}$$



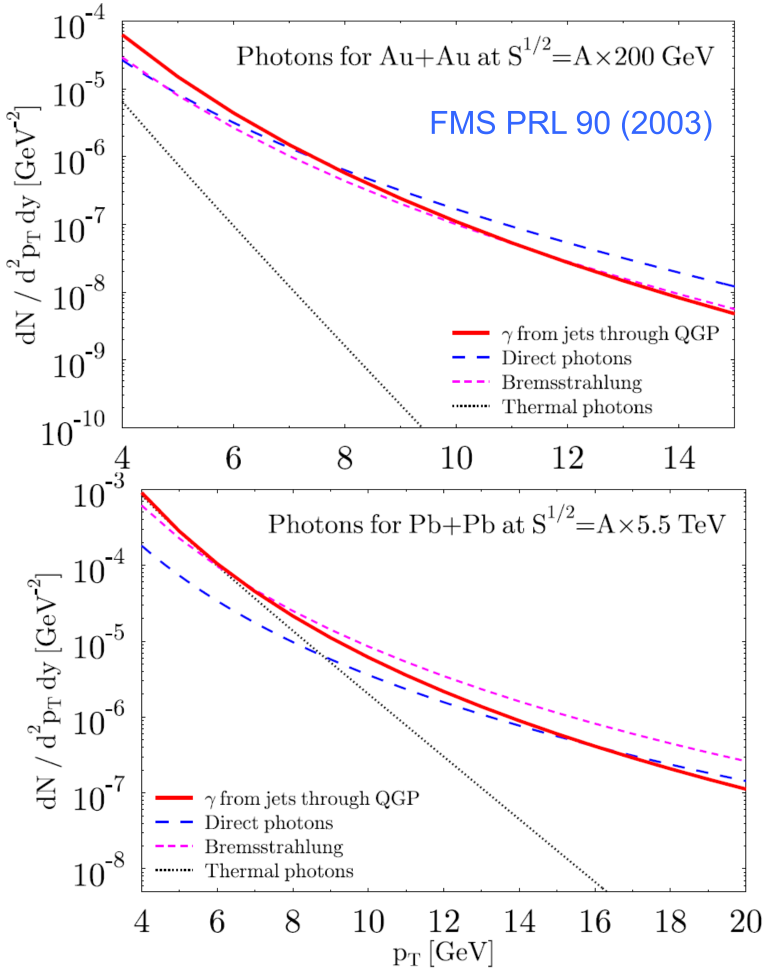
- Elastic cross sections peak forward and backward.
  - In ~ 50% of cases the photon ends up with half of the jet momentum or more.
- Yield from these jet-to-photon conversions:

$$E_\gamma \frac{dN_\gamma}{d^3 p_\gamma} = \frac{\alpha \alpha_s}{8\pi^2} \int d^4x \, \frac{2}{3} \left[f_q(p_\gamma) + f_q(p_\gamma) \right] T^2 \left(\ln \frac{4 E_\gamma T}{m^2} + C \right)$$

[RJF, Müller & Srivastava, PRL (2002)]
[Zakharov (2004)]

Jet-Medium Photons

- Interesting features:
  - Shape proportional to leading jet particle spectra (power law!)
  - Still strongly dependent on temperature.
  - An independent thermometer?
- How bright is this new source?
  - Our first quick check:



- Can be as important as initial hard photons at intermediate p_T!

Jet-Medium Photons

- The bigger picture:
  - Classify particles as either thermal or belonging to a (mini)jet: $f(p) = f_{th}(p) + f_{jet}(p)$
  - Photons from these particles in kinetic theory:

$$f_\gamma \sim f_{th} \otimes f_{th} + f_{jet} \otimes f_{th} + f_{jet} \otimes f_{jet}$$

thermal photons

conversion photons

Did we forget these? No, irrelevant at present collider energies

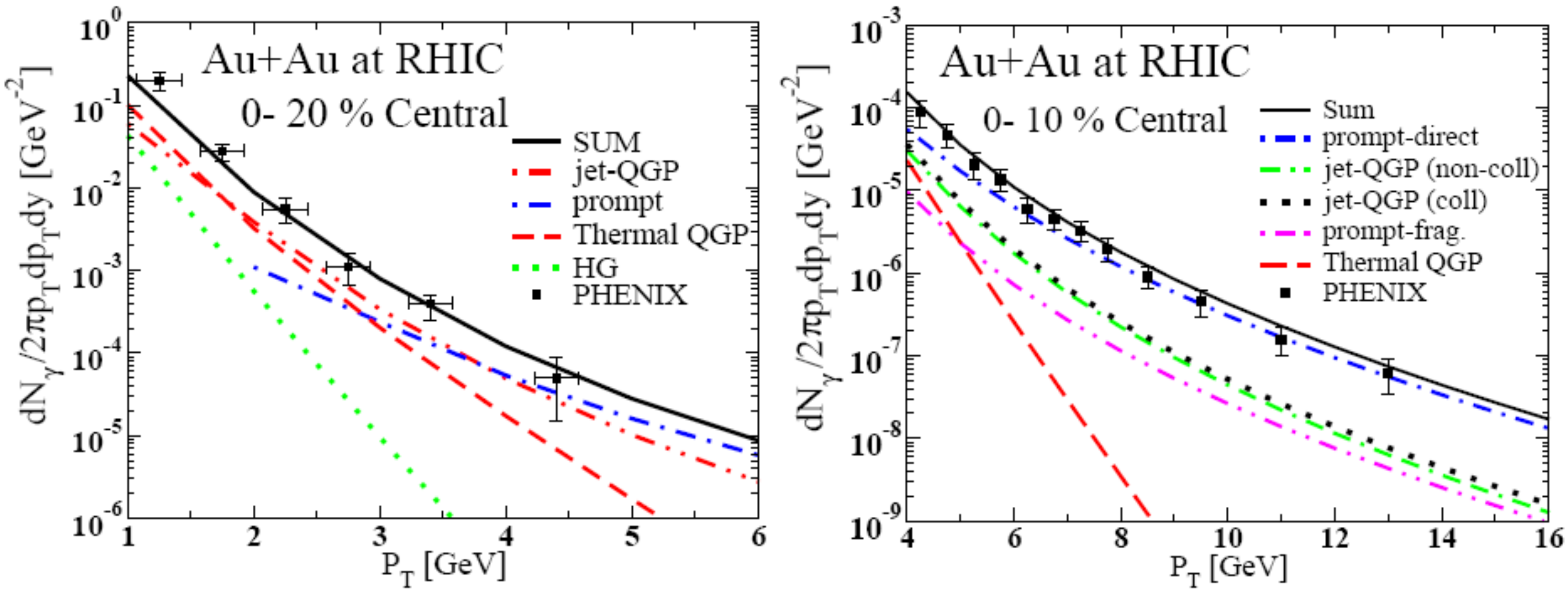
- Careful: jets will lose energy before conversion!
- Leads to additional uncertainties of photon observables
  - Additional constraints for jet quenching models?
- Most comprehensive scheme on the market: expanded AMY
  - Induced gluon + photon radiation
  - Rate equations for jets

$$\frac{dP_j(E,t)}{dt} = \sum_{ab} \int d\omega \left[P_a(E+\omega,t) \frac{d\Gamma_{a\to j}(E+\omega,\omega)}{d\omega dt} - P_j(E,t) \frac{d\Gamma_{j\to b}(E,\omega)}{d\omega dt} \right],$$

[Jeon & Moore]

Adding Jet-Medium Photons

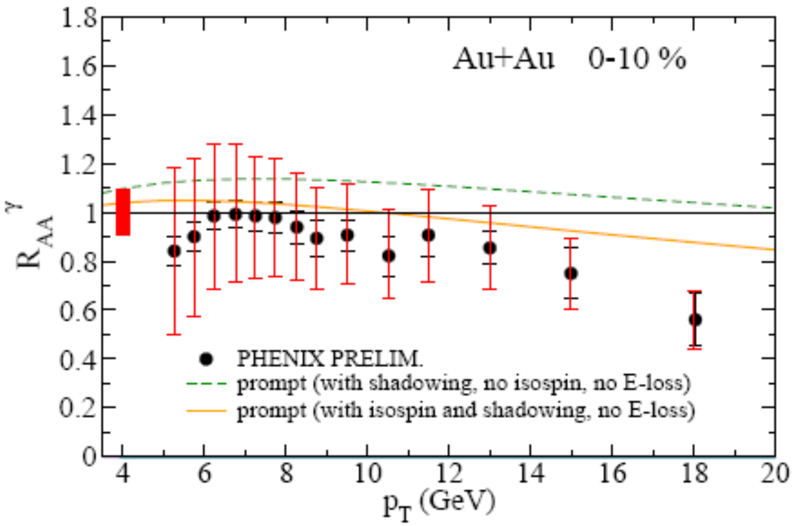
- Recent phenomenological analysis [Turbide, Gale, Frodermann & Heinz (2007)]
  - AMY + thermal hadron gas + elastic jet-medium conversions
  - Standard hydro fireball + initial state nuclear effects

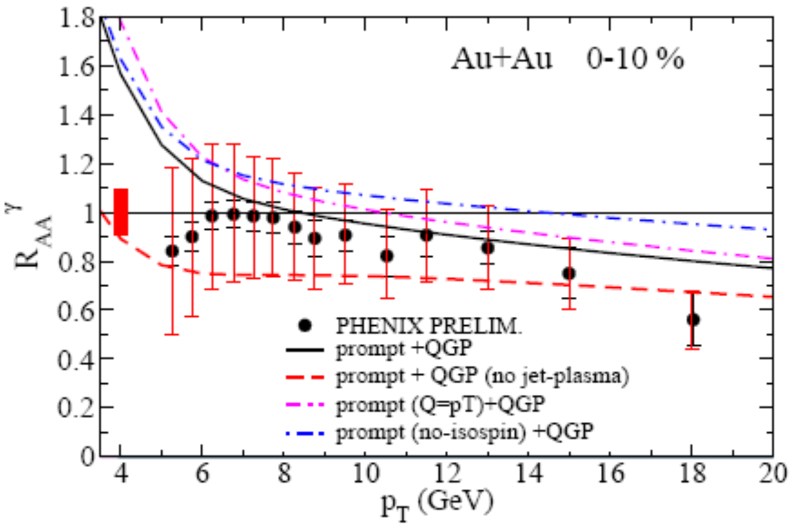


- But: little sensitivity to individual sources. How strong are conversion photons?

Adding Jet-Medium Photons

- More Sensitivity: Nuclear Modification R_{AA}





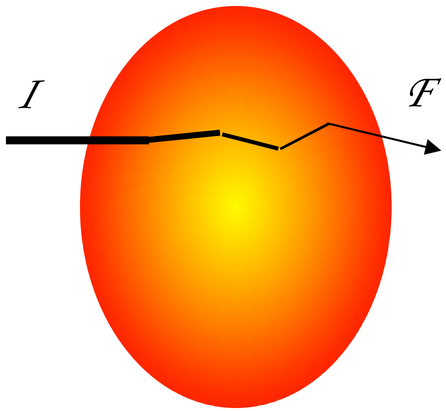
[Turbide, Gale, Frodermann & Heinz (2007)]

- Jet-medium photons roughly make up for the loss through jet quenching
  - Except for very large P_T.

“Flavor” Conversions

Hard Probes Revisited

- Simplest possible hard probe: measure opacity of the medium
  - Drag force on QCD jets or hadrons = jet quenching
  - Energy loss of the leading parton.
  - Related to broadening in transverse direction.
- Several models on the market.
  - Calculating energy loss through induced gluon radiation with different sets of assumptions.
  - AMY (full thermal QCD HTL calculation)
  - Medium modified higher twist (from DIS)
  - GLV, BDMPS in many varieties .

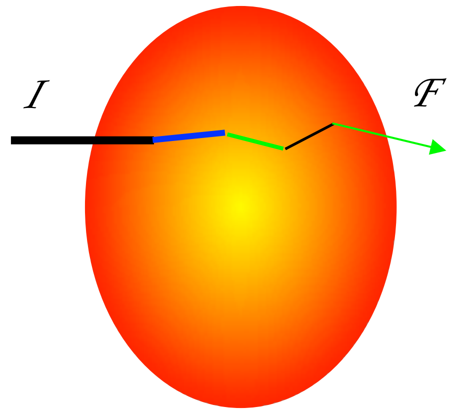


- Energy loss determined by the momentum transfer in collisions
  - Sensitive to transport coefficient $\hat{q} = \frac{\mu^2}{\lambda}$

    = momentum transfer squared per mean free path/collision.

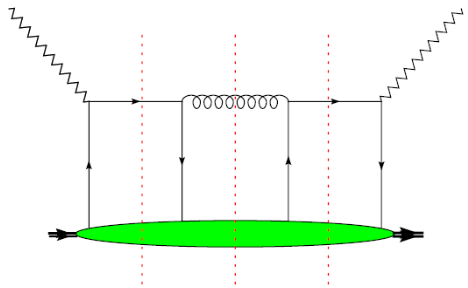
Hard Probes Revisited

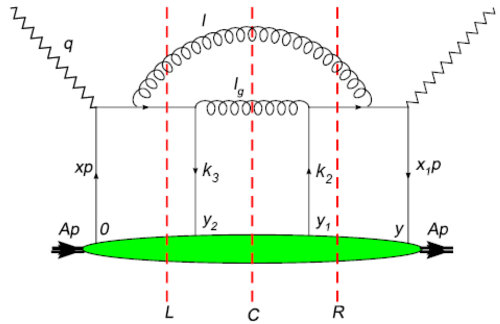
- How else can we use hard probes? Measure the flavor!
- Obviously: flavor of a parton can change when interacting with the medium.
- Here: very general definition of flavor:
  - Gluons g
  - Light quarks q = u,d
  - Strange quarks s
  - Heavy quarks Q = c,b
  - Real photons, virtual photons (dileptons)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



- Measure flavor conversions

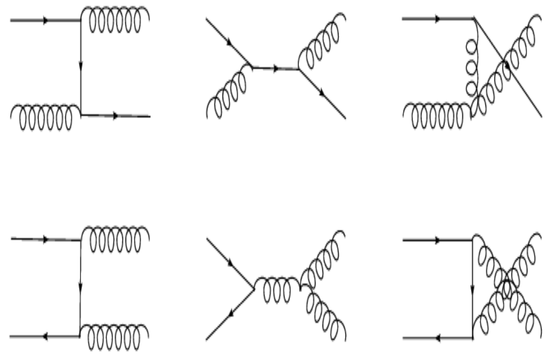
Example: Schäfer, Wang, Zhang; HT formalism





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 the 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.

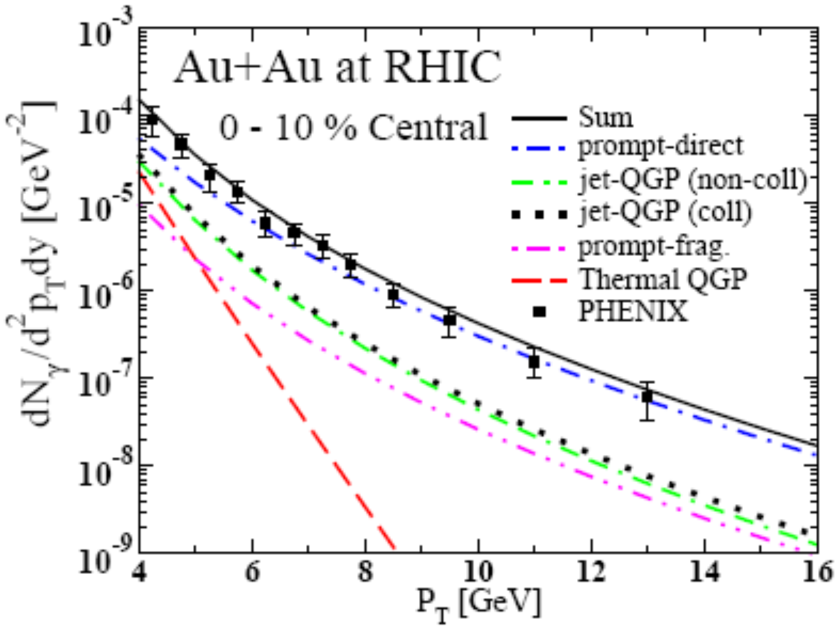
    [Sapeta, Wiedemann]
- Other mechanisms might also change hadron chemistry in jets:
  - E.g. changed multiplicities

Connection with Jet-Medium Photons

- Conversions into photons (and dileptons) corresponds to the jet-medium photon source discussed earlier.

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

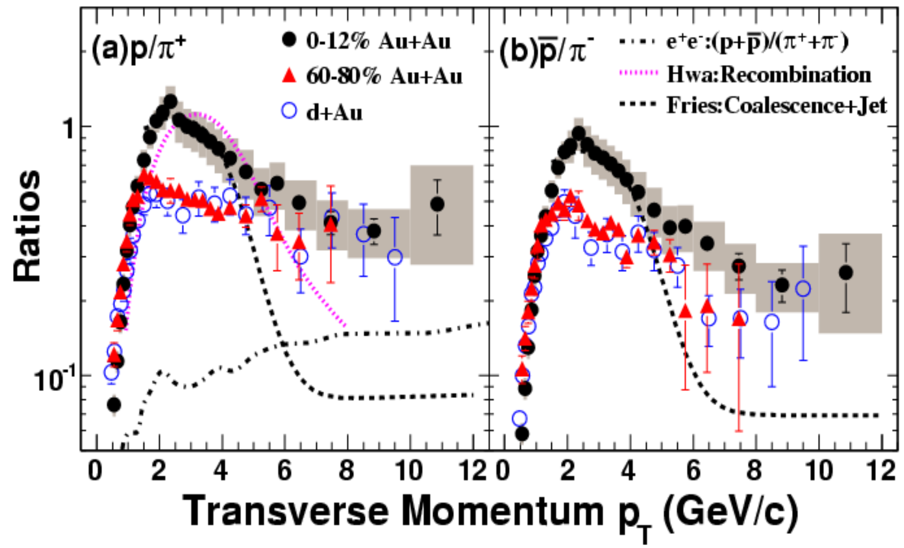
- Unambiguous proof of conversion processes?
  - No, experimental situation not resolved
  - Unlikely that single inclusive photon measurements at RHIC will deliver a clear answer

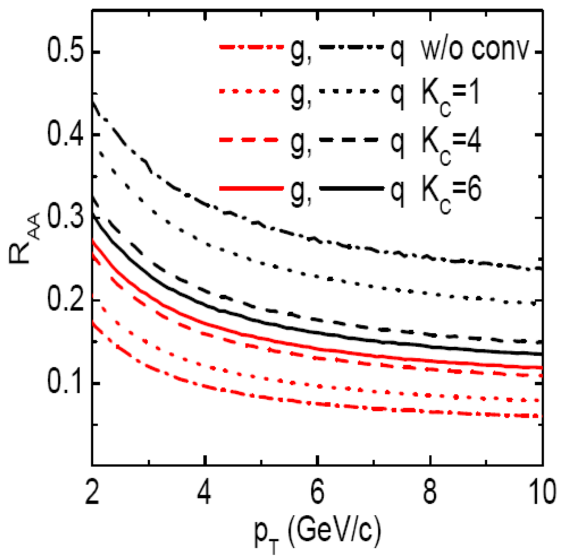


[Turbide, Gale, Frodermann, Heinz]

Another Application: 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 quarks: color factor 9/4
  - Not explicitly observed in data
  - Shouldn't be there in a system short mean free path!





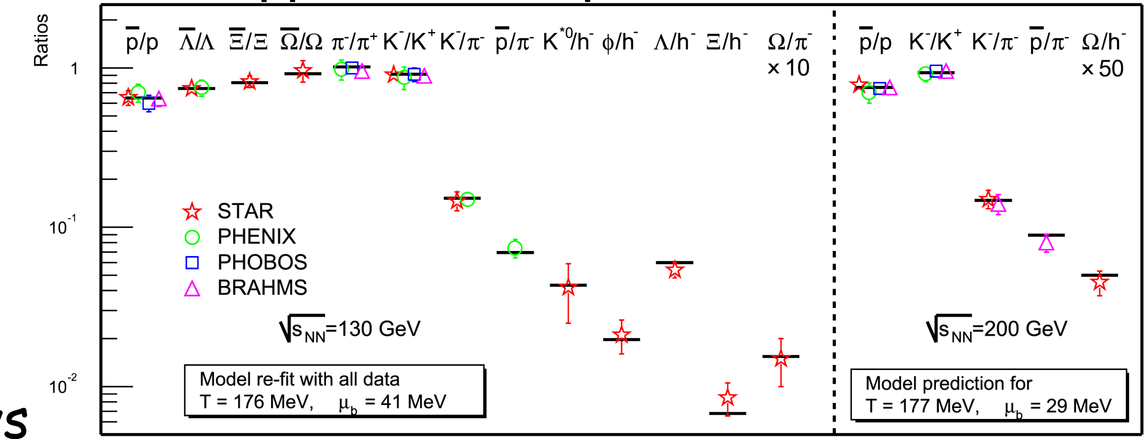
- Ko et al: elastic g ↔ q conversions
  - Lose 30% of quark jets at RHIC
  - enhance p/π ratio; need elastic cross sections × 4 to get p+p values
  - Dependence on fragmentation functions!

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.

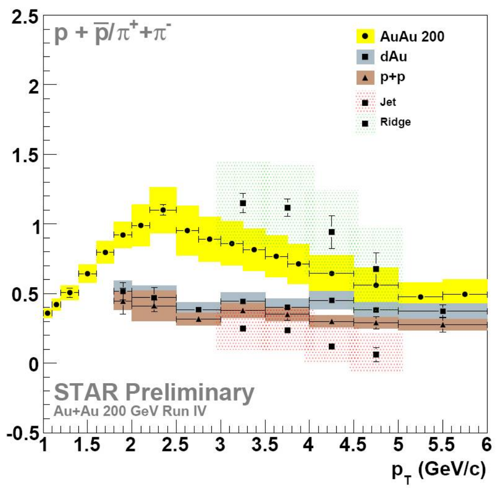
What Can Chemistry Tell Us?

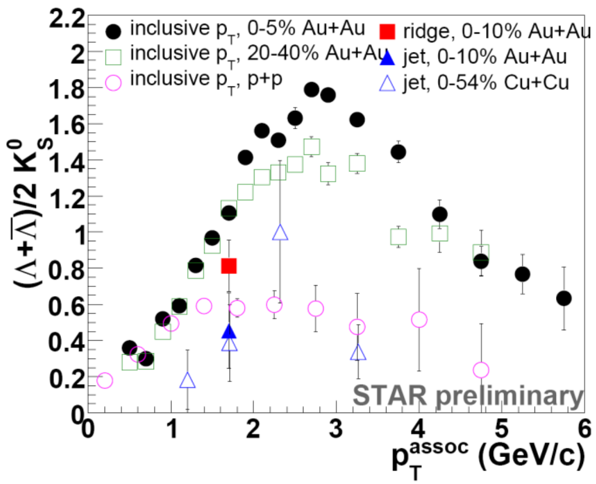
- Measure equilibrium or rate of approach to equilibrium.
- Low P_T:



Braun-Munzinger et al., PLB 518 (2001) 41 D. Magestro (updated July 22, 2002)

- Intermediate P_T: recombination, ridge vs



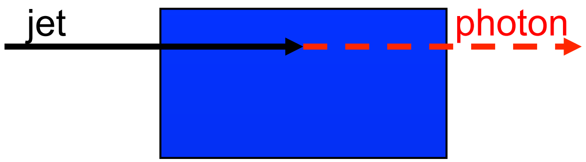


HI Pub 2009

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

Two Examples for Rare Probes

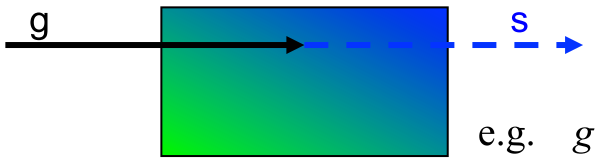
- Example 1: excess production of particles which are rare in the medium and rare in the probe sample



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

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

- Example 2: chemical equilibration of a rare probe particle



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

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

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

  - 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 → 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

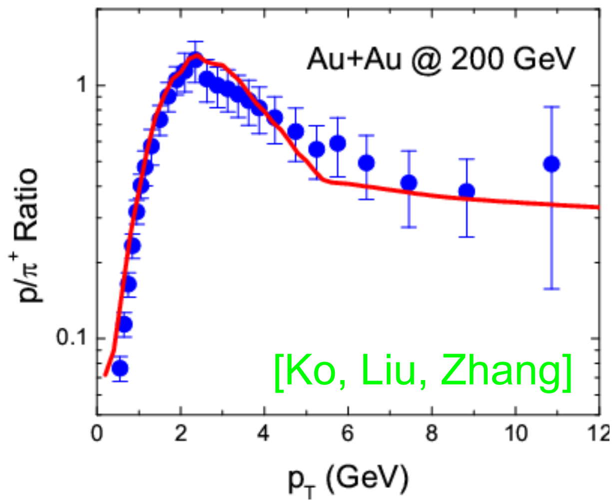
$$g+Q \leftrightarrow Q+g$$
$$g+g \leftrightarrow Q+\bar{Q}$$

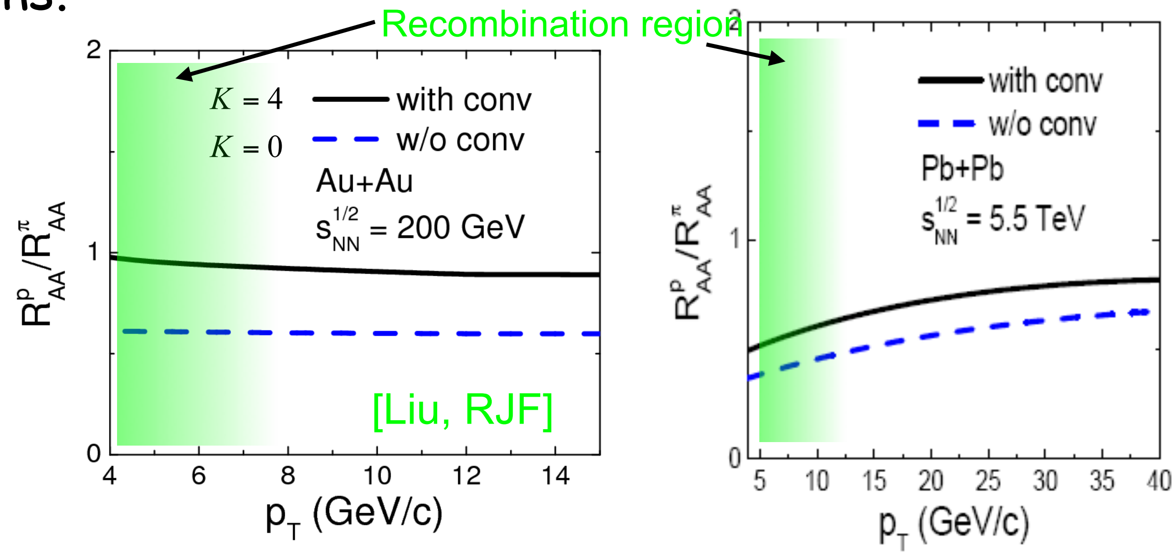
Heavy quarks production?

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

Results: Protons

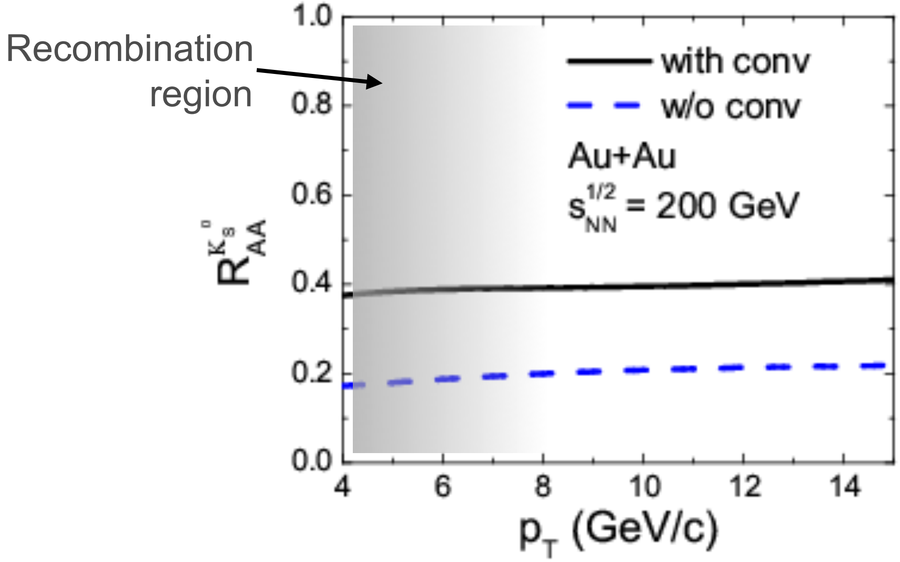
- Use the model by Ko, Liu and Zhang:
  - Rate equations plus energy loss.
  - Elastic channels; cross sections with *K*-factor
  - Longitudinally and transversely expanding fireball
    - RHIC: T_i = 350 MeV @ 0.6 fm/c
    - LHC: T_i = 700 MeV @ 0.2 fm/c
- Use double ratios $\gamma_{p/\pi^+} = \frac{(p/\pi^+)_{AA}}{(p/\pi^+)_{pp}} = \frac{R^p_{AA}}{R^{\pi^+}_{AA}}$ to cut uncertainties from fragmentation functions.



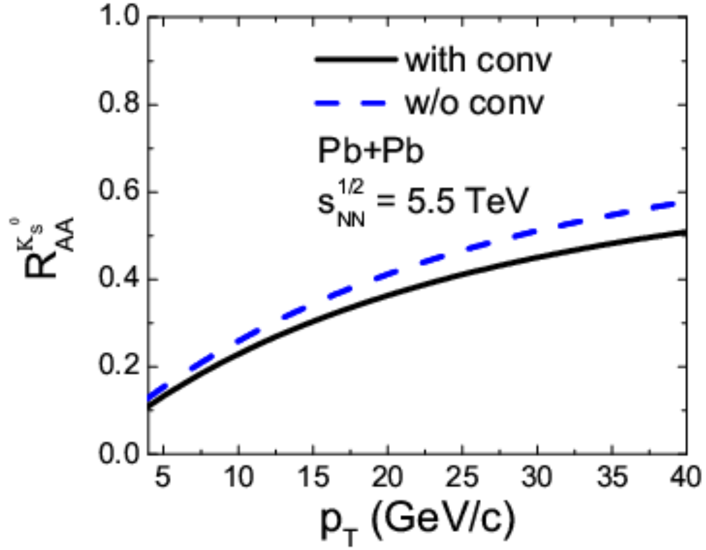


Results: Strangeness

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

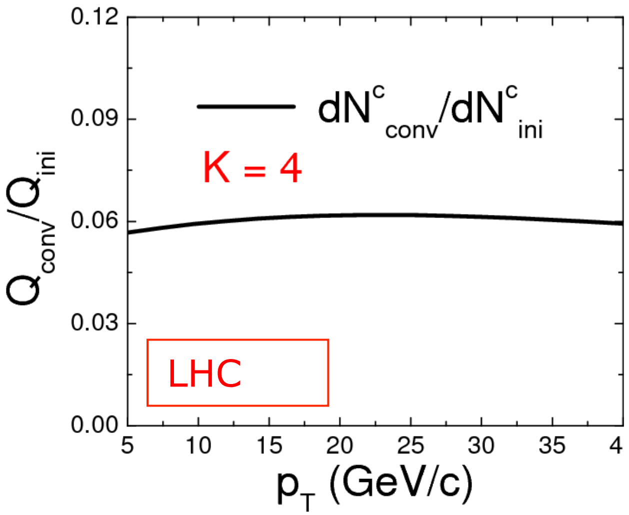


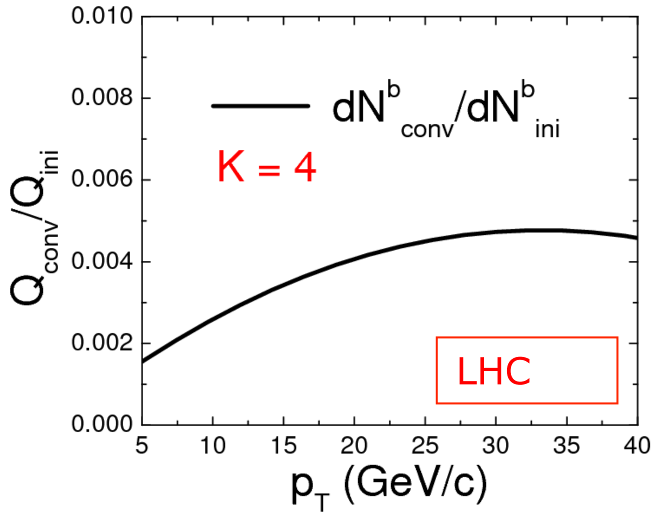
- No enhancement at LHC
  - Too much initial strangeness!
  - Maybe it works with charm at LHC?



Numerical Results: Heavy Quarks

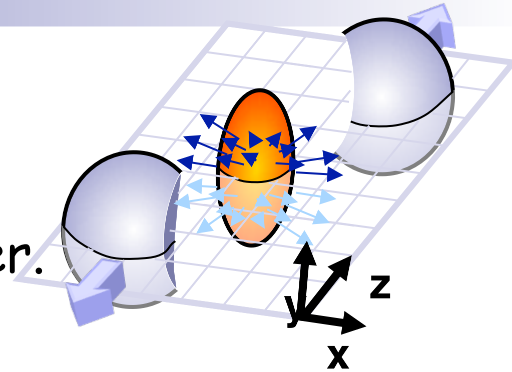
- Additional threshold effect
- At RHIC: additional heavy quark production marginal
- LHC: not at all like strangeness at RHIC; additional yield small
  - Reason: charm not chemically equilibrated at LHC
  - Results in small chemical gradient between jet and medium charm
  - Also: threshold effect





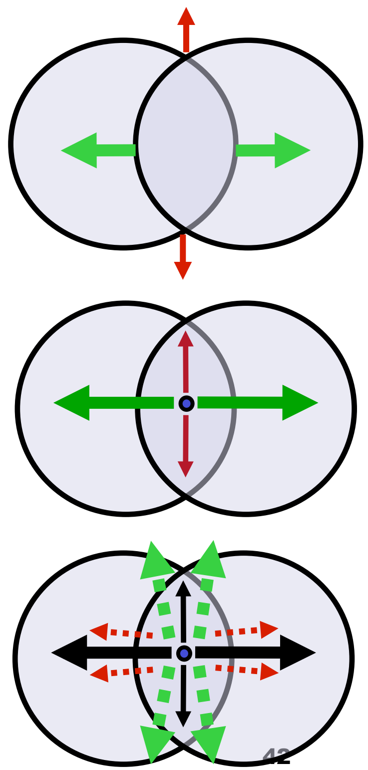
Elliptic Flow at High P_T

Elliptic Flow v_2



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

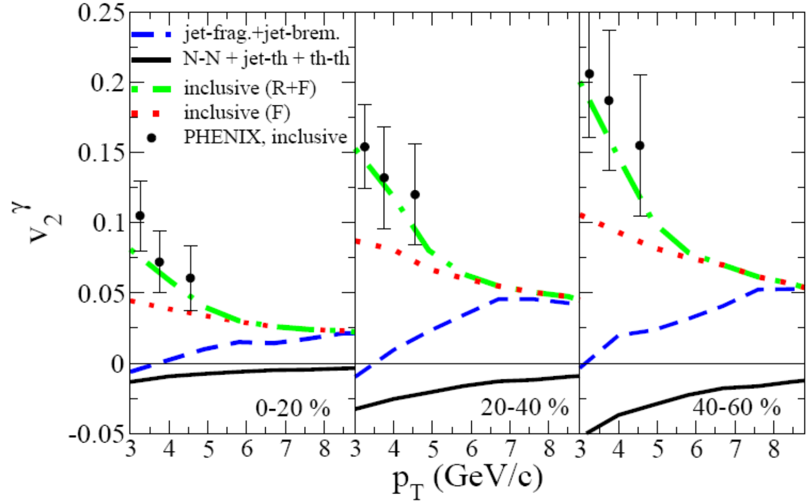
	Initial anisotropy	Final anisotropy	Elliptic flow v_2
Bulk	pressure gradient	collective flow	$v_2 > 0$
saturated hard probe	path length	quenching	$v_2 > 0$
rare hard P_T probe	path length	additional production	$v_2 < 0$



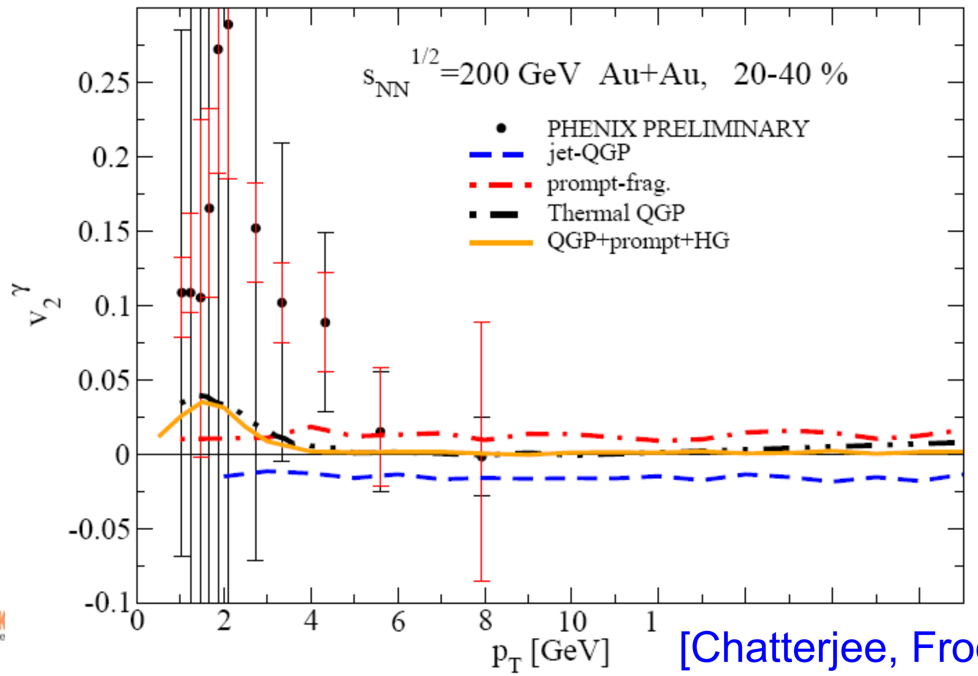
[Turbide, Gale & RJF, PRL 96 (2006)]

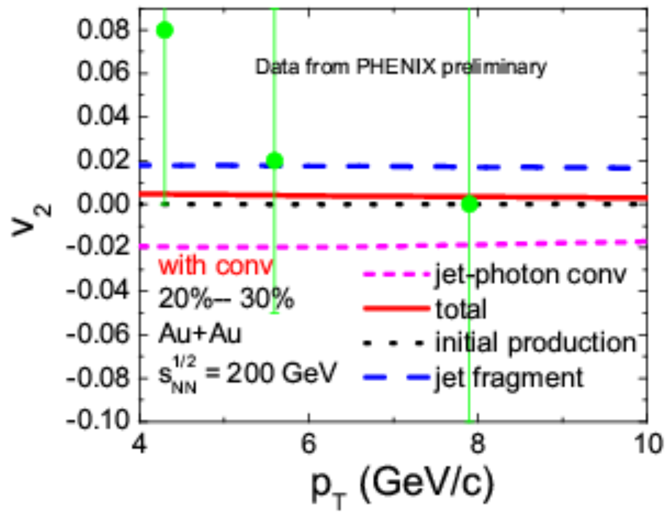
Photon Elliptic Flow

[Turbide, Gale, RJF]



- Have to add other photon sources with vanishing or positive v_2.
  - Almost perfect cancellation, $|v_2|$ small
- Status:
  - Large negative v_2 excluded by experiment
  - Large uncertainties from fireball model?



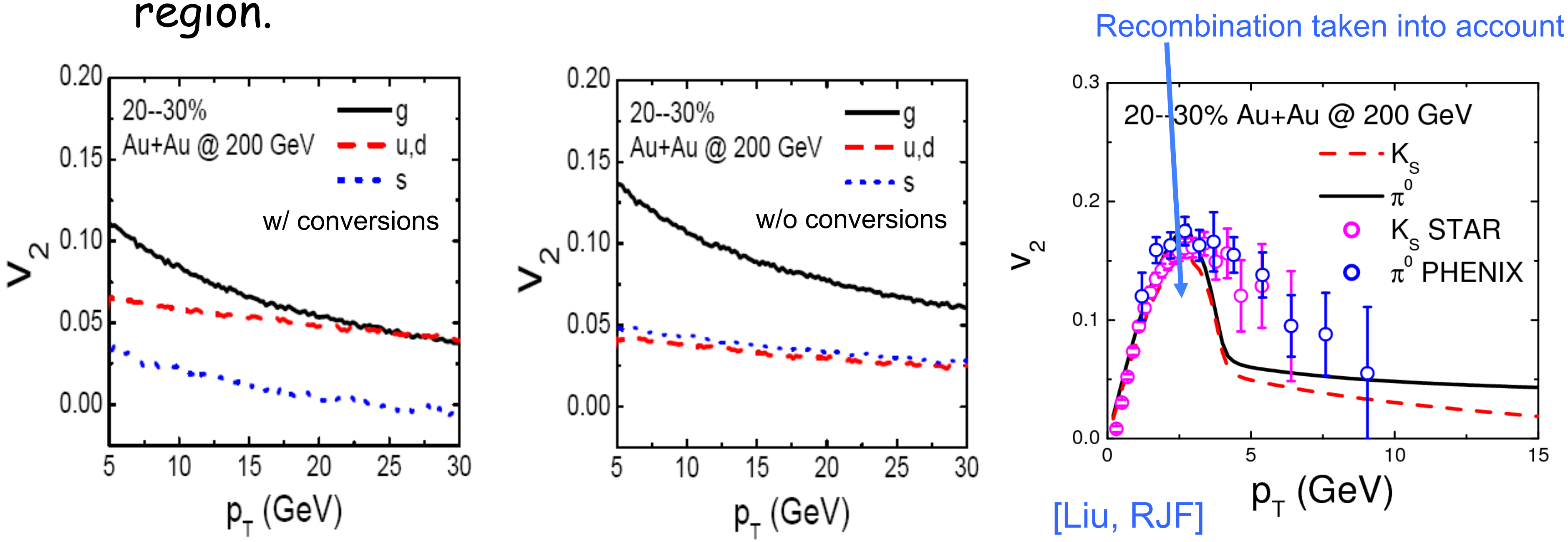


[Liu, RJF]

[Chatterjee, Frodermann, Heinz, Srivastava; …]

Strangeness Elliptic Flow

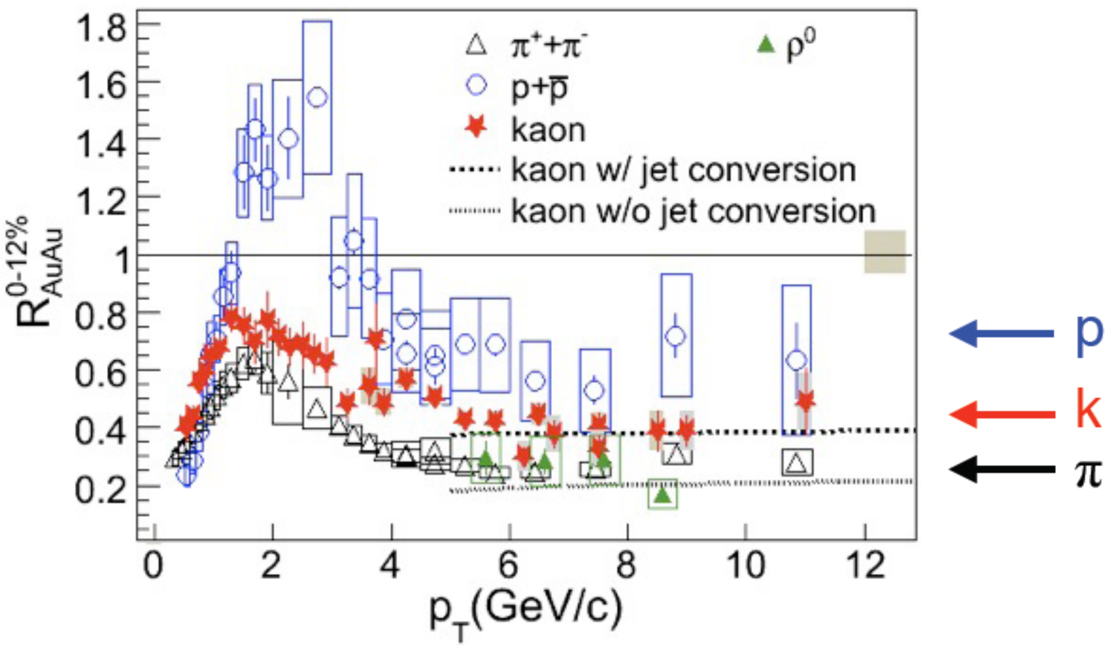
- Strangeness as non-equilibrated probe at RHIC: additional strange quarks have negative v_2.
- Expect suppression of kaon v_2 outside of the recombination region.



New Results from STAR

[Liu, RJF, PRC (2008)]

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

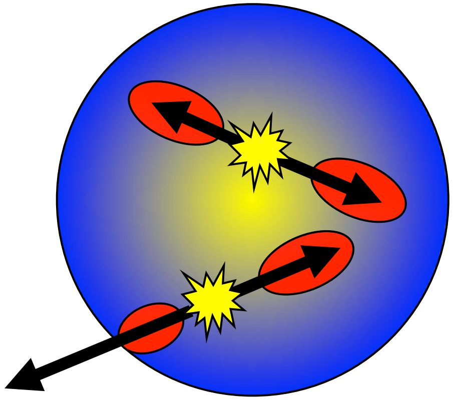


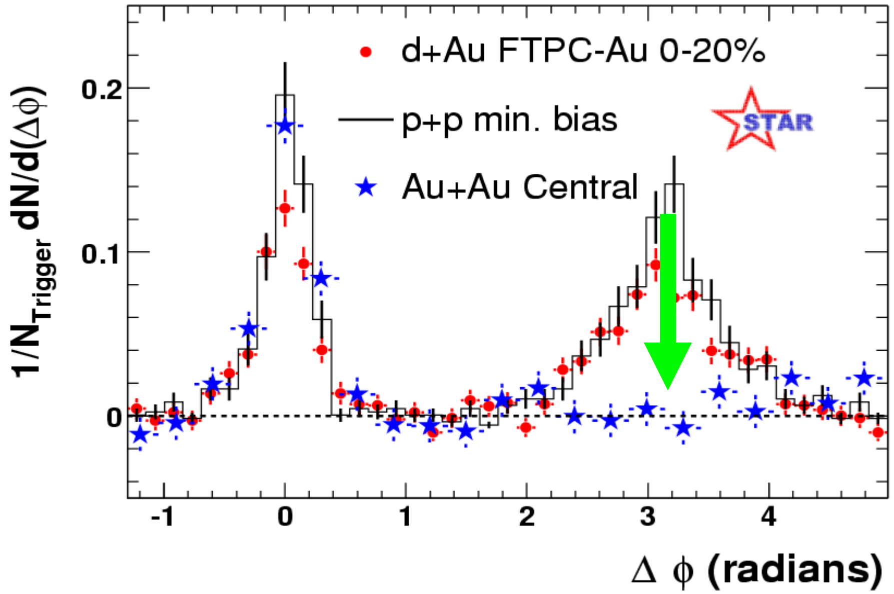
- Blast from the past: remember strangeness enhancement from the 1980s?

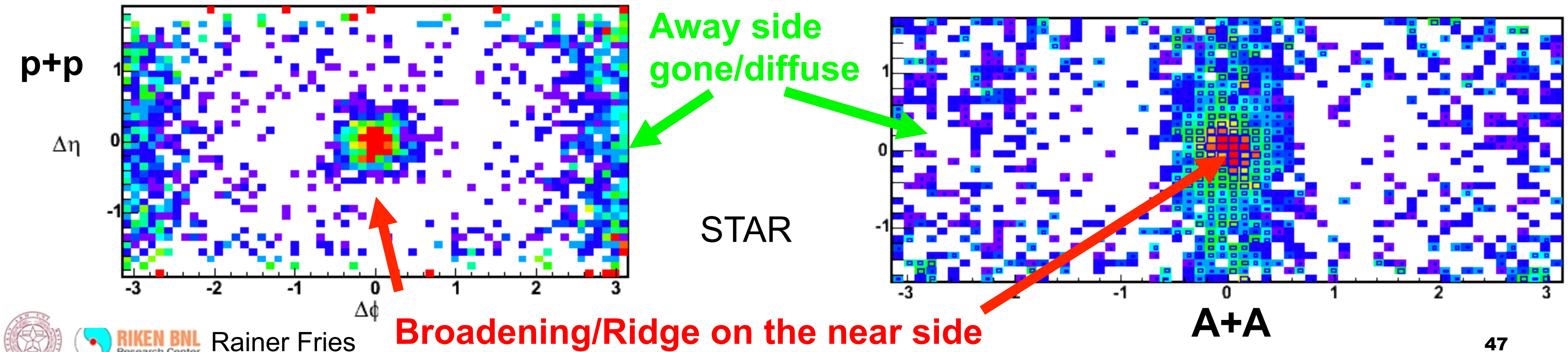
Correlations at High P_T

A New Playground: Correlations

- Hadron-hadron correlations
  - *Away-side jet extinct*
  - *Ridges and cones …*





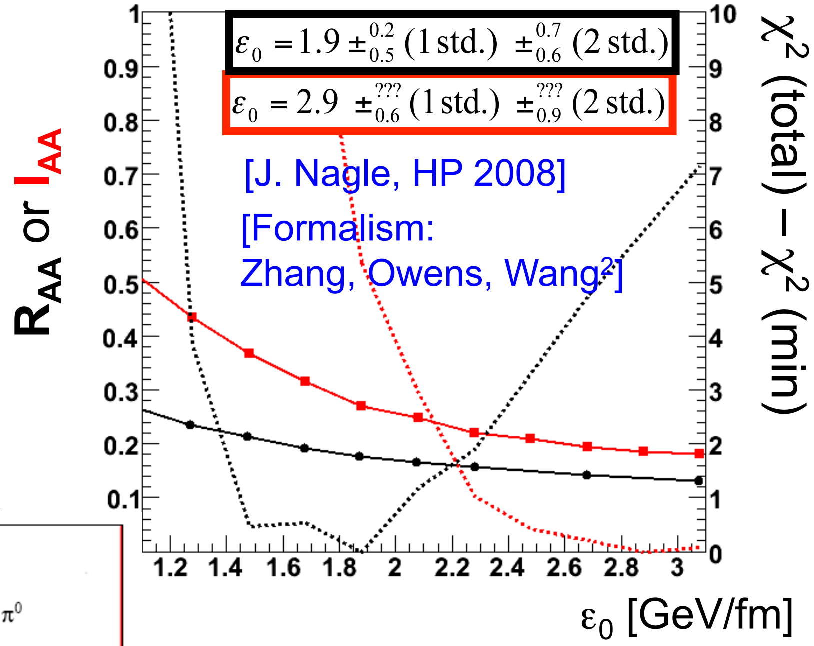


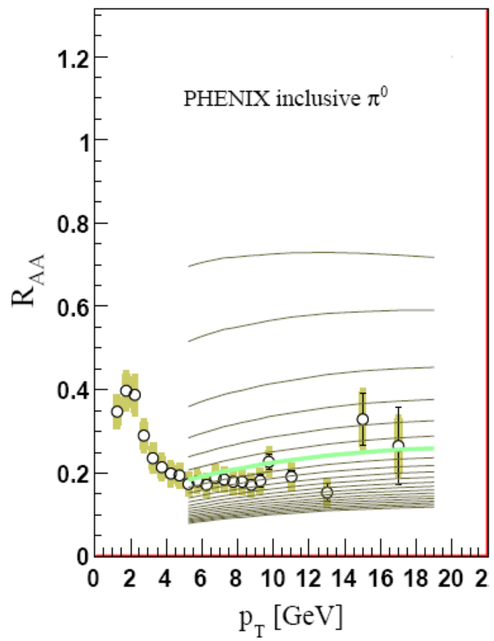
Importance for Precision Measurements

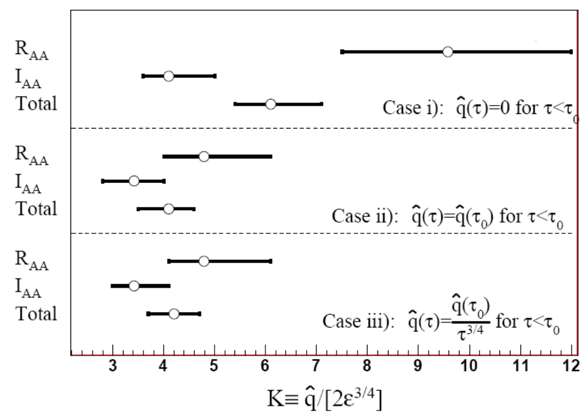
- Quantitative fits of $\hat{q}$ to data.
- Different energy loss models give results.

  $\hat{q} \approx 1 \ldots 14\ \mathrm{GeV}^2/\mathrm{fm}$

- Within a fixed model different observables give incompatible results.
- Details matter!
  - Calibration (shadowing, Cronin effect)
  - Treatment of the initial fireball
  - …





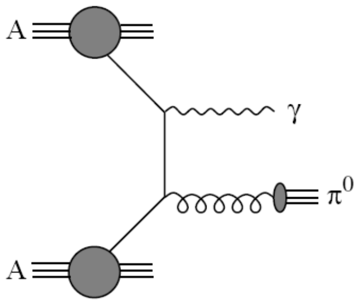


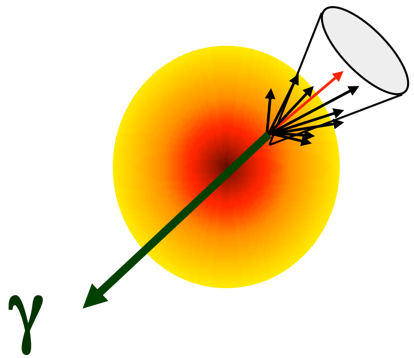
Armesto et al., arxiv:0907.0667

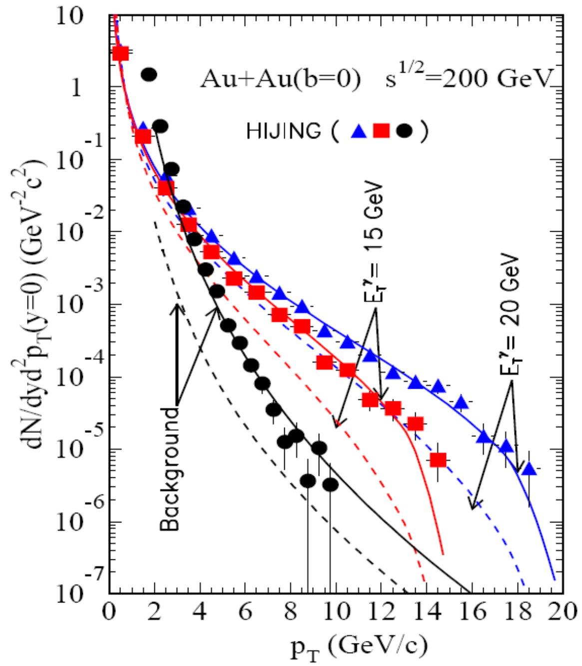
Correlations with Photons

- Photon-hadron and photon-jet correlations can provide a handle on the initial energy of a jet before quenching.

[Wang, Huang & Sarcevic (1996)]





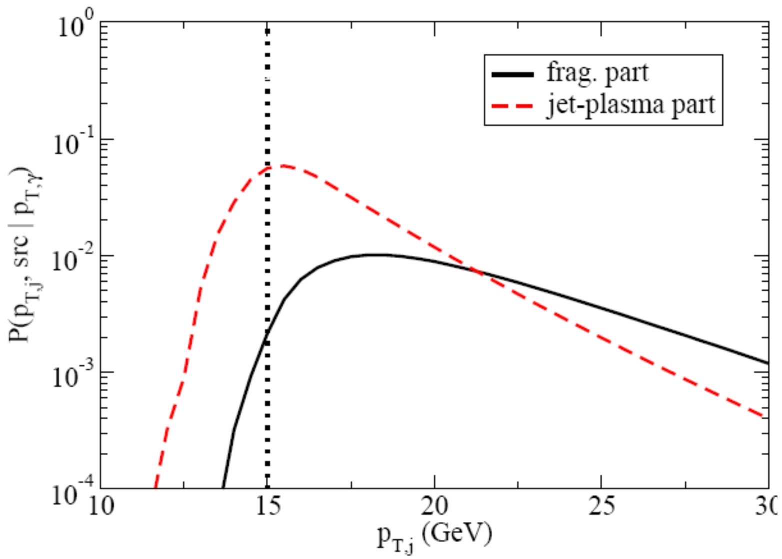


- "Gold Plated Measurement" for energy loss?

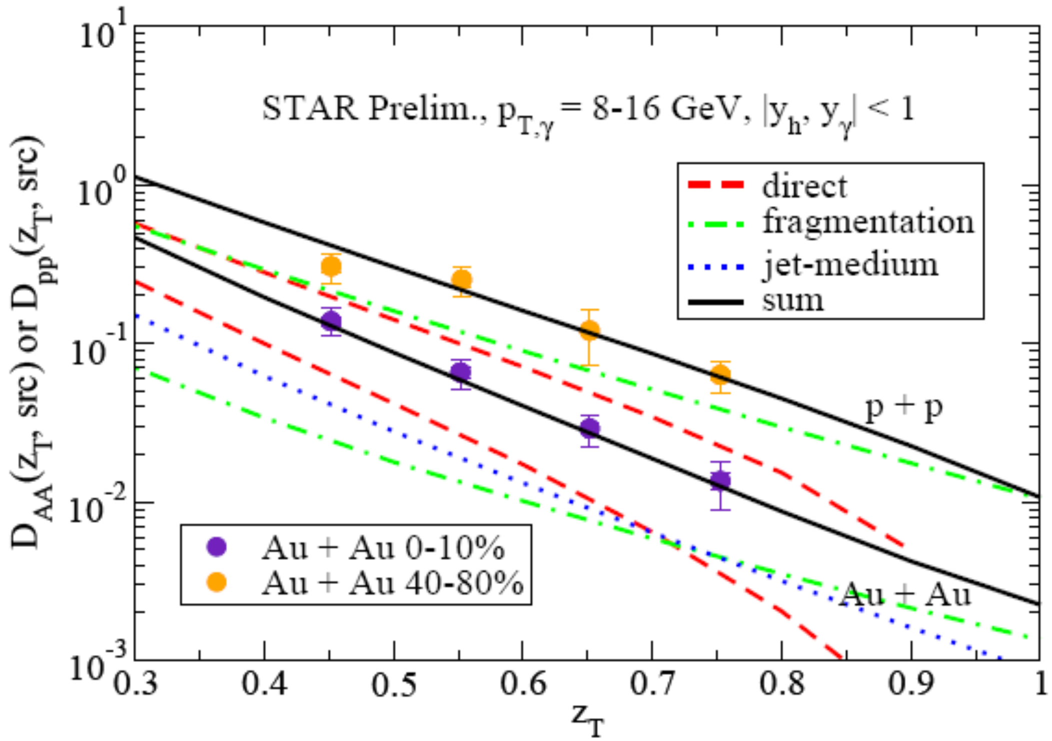
- Caution: this is again parton model thinking, not QCD. Additional photon sources + radiative corrections complicate the picture.

Correlations with Photons

- Dilution of kinematic correlation through different photon sources!



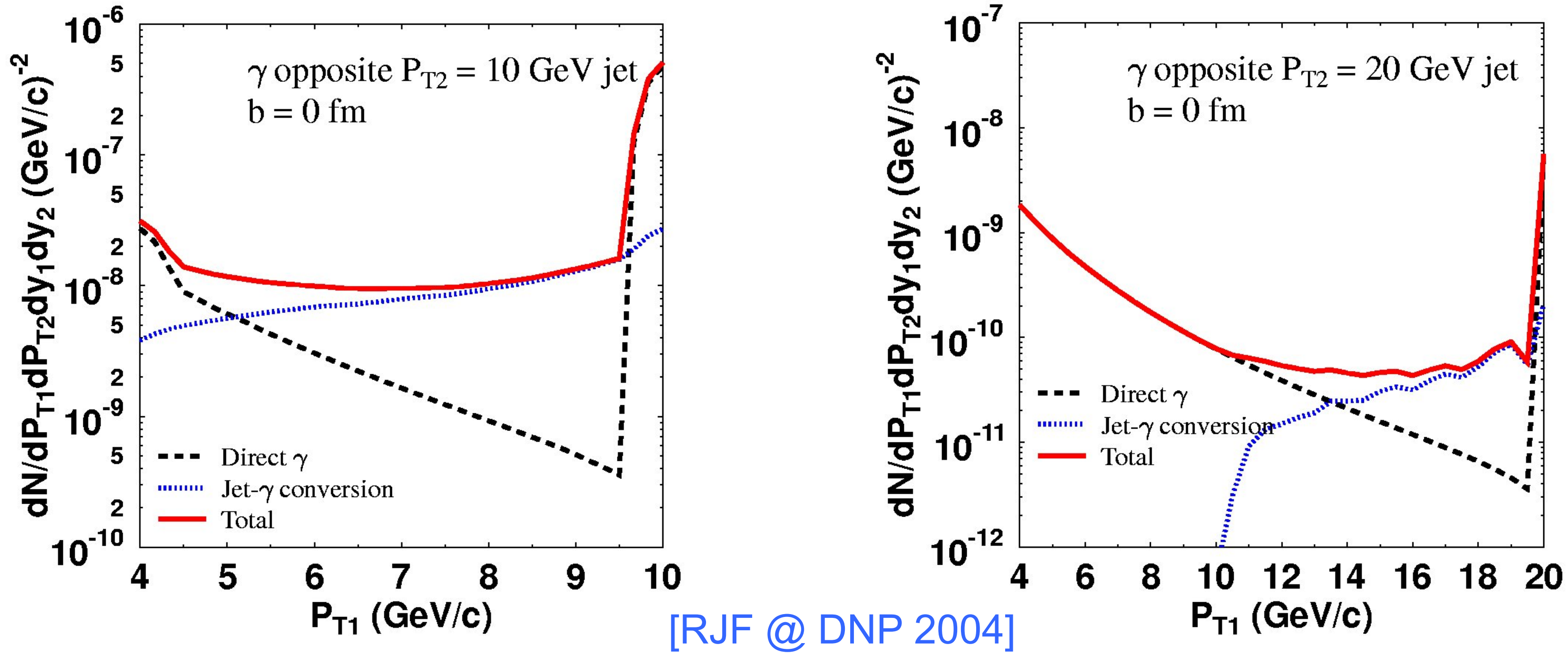
[Qin, Ruppert, Gale, Jeon, Moore,(2008); (2009)]



- Some NLO effects have been studied
  [Arleo et al. (2004)]

A New Twist on Correlations

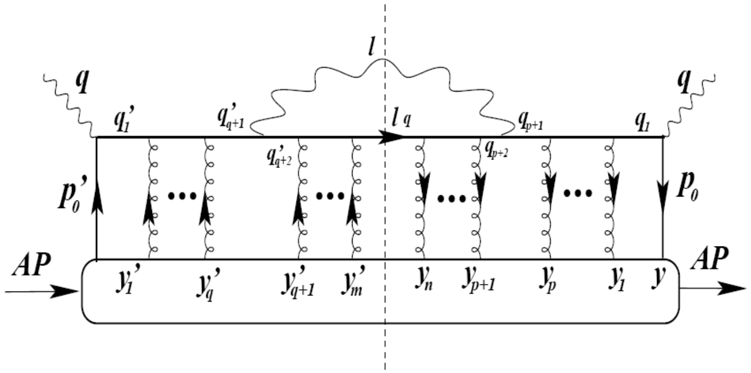
- Instead of using photons to measure jet modification: use jets to measure photon sources.
- To disentangle photon sources measure associated photon spectrum opposite to a jet of known energy E_T.
- Photons opposite 10 and 20 GeV jets:



[RJF @ DNP 2004]

Concluding Remarks

- For precision probes we need precision tools: need for consistent integration of NLO hard processes + fragmentation with final state interactions.
  - Need to address factorization issues.
- Back to the drawing board: study simple processes like DIS on nuclei.
  - E.g.



[Majumder, RJF & Müller, PRC (2008)]

  - Could make connections with transport description (e.g. diffusion equation for transverse momentum) $\nabla_L \phi = \frac{1}{4}\hat{q}\nabla^2_{q_T}\phi$
- Understanding photons and understanding energy loss are very closely related.

Summary

- Electromagnetic probes are still a very promising tool.
- Solid understanding of different sources needed.
- Precision in both theory and experiment!
- Conversions of high-P_T particles in quark gluon plasma: a new idea
- Strangeness enhancement at high P_T.
- v_2, correlations

- What I haven't talked about (with apologies):
  - Pre-equilibrium photons, dileptons, SPS, …

THANKS

- Thanks to my collaborators:
  - T. C. Awes, C. Gale, A. Majumder, B. Müller, D. K. Srivastava, S. Turbide

- Some slides borrowed from:
  - C. Gale, J. Kapusta, G. Y. Qin, D. K. Srivastava

Backup

New Simulation of Hard Probes

Plans for the Near Future

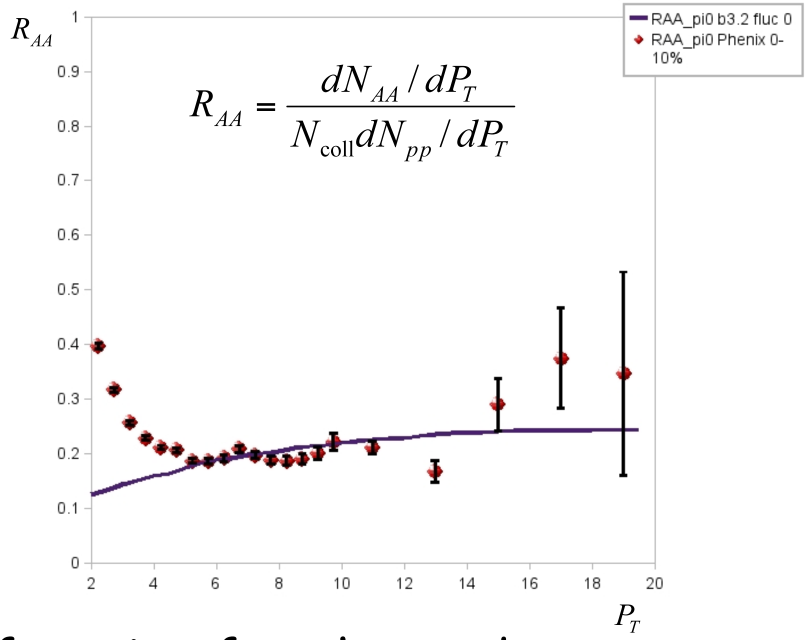
- We develop a standardized test bed to simulate *N* jets/hard particles in a fireball.
  - Part of a NSF project with R. Rodriguez, R.J. Fries, E. Ramirez
- Input:
  - initial phase space distributions
  - background (aka fireball)
  - specifics of dynamics (energy loss, fragmentation)
- What it should 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
  - Using vacuum fragmentation and GLV average energy loss

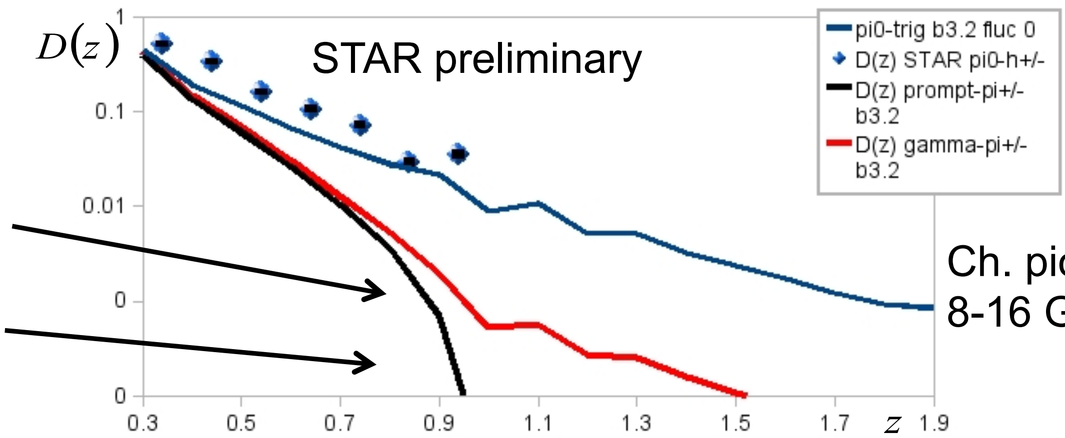
$$\Delta E = \frac{C_R \alpha_s}{4} \frac{\mu^2}{\lambda} L^2 \log E$$

- 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.

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



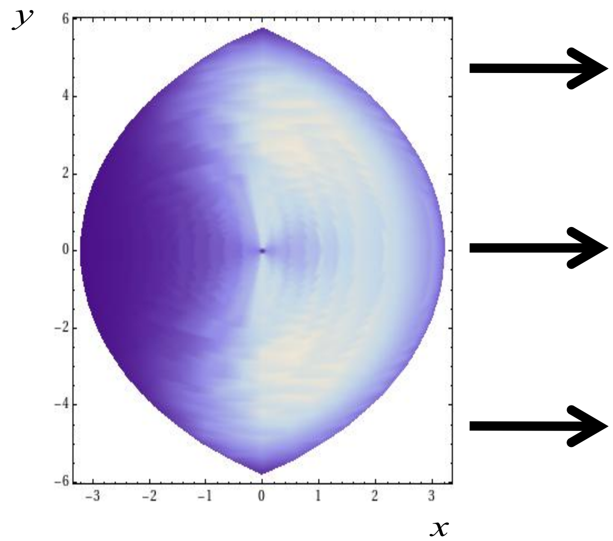
Direct photon trigger

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)