Jet properties in p+p and heavy ion collisions.

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PHENIX

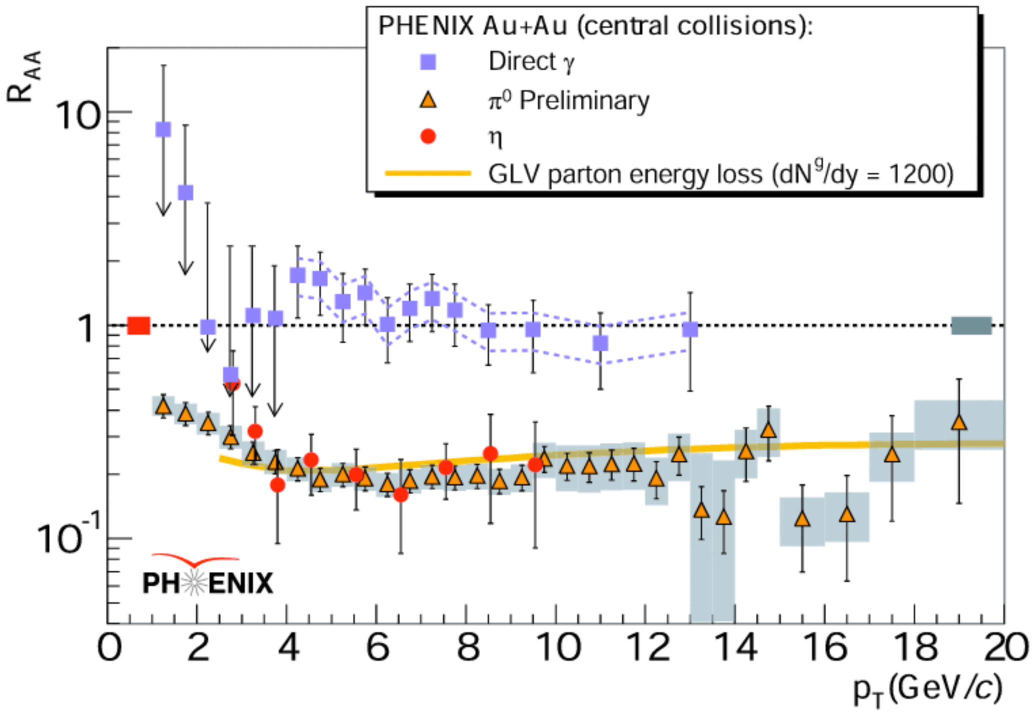
Single inclusive vs two particle correlations

Inclusive distributions - R_{AA} - limited sensitivity to details of parton interaction with QGP

- Energy loss, surface bias - different models *similarity*
- π vs p R_{AA} quark vs gluon R_{AA} *similarity*
- π vs direct gamma R_{AA} *similarity*
- Light vs heavy quark R_{AA} (non-photonic electron) *similarity*

Two particle correlations - more detailed view into a nature of parton interactions with QCD medium. Access to parton intrinsic momentum k_T -> *soft pQCD radiation*, jet shape parameters j_T -> *induced radiation*, fragmentation function -> *energy loss*.

- Di-hadron correlations and conditional yields
- Direct photons-hadron correlations in $p+p$ @ $\sqrt{s}$=200 GeV



$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

Measured for:

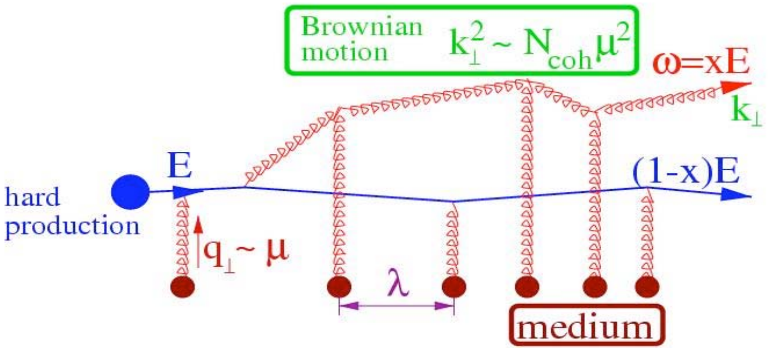
variety of species

$\pi^{0,}$ $\pi^{\pm}$, η, γ_{dir}, p, K_S, ϕ, ω, J/ψ, Ω…

and CMS energies

√s=17, 22.4, 62.4, 130, 200 GeV/c

Jet quenching - one of the most celebrated results. Light mesons suppressed by factor of 5, direct-γ unsuppressed => FS nature of observed suppression. Data successfully described by pQCD models.



Transp. Coef. Scatt. power of QCD med:

Density of scattering centers

Range of color force

$$\hat{q} = \rho \int q^2 dq^2 \frac{d\sigma}{dq^2} \equiv \rho\sigma\left\langle k_T^2 \right\rangle = \frac{\mu^2}{\lambda_f}$$

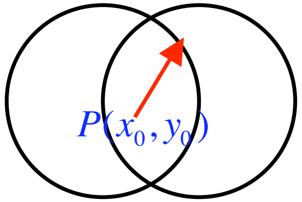
R_{AA} sensitivity to P(ΔE,E)?

T. Renk, k. Eskola *et al.*

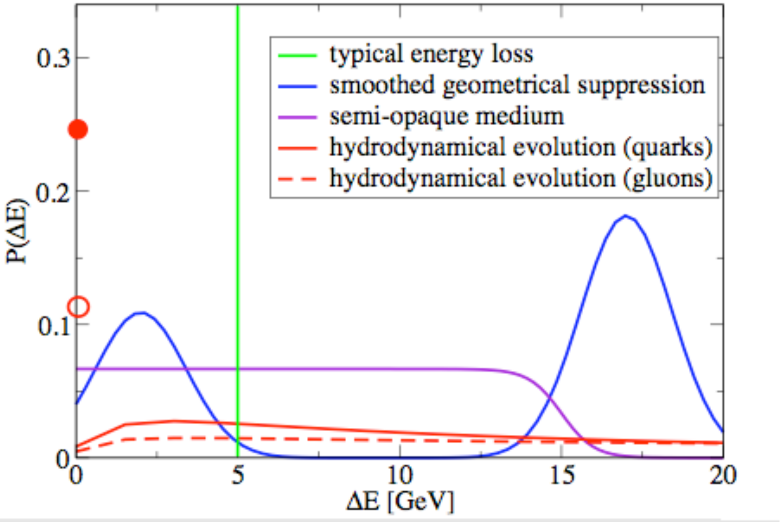
R_{AA} uniquely determined by $p_{had} = p_{part} \otimes \langle P(\Delta E, E) \rangle \otimes D^{vac}_{f\to\pi}(z, \mu_F^2)$

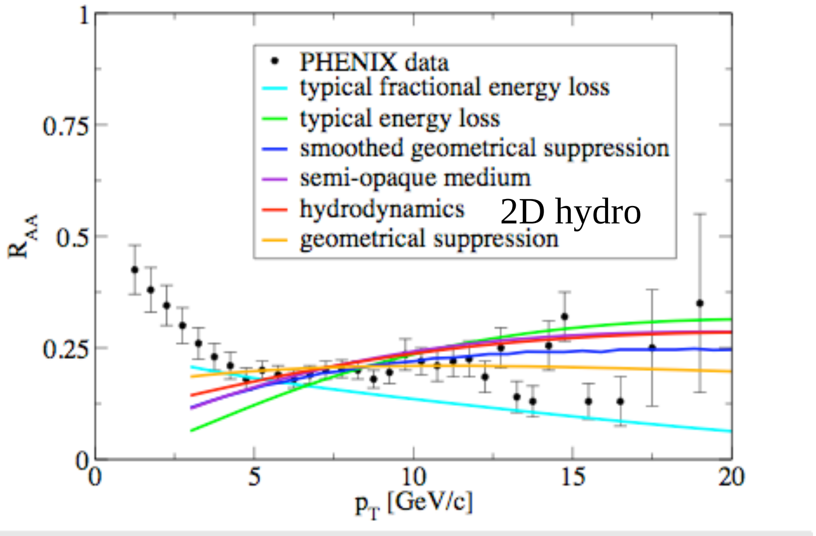
The E-loss probability can be defined:

$$\langle P(\Delta E, E) \rangle_{TAA} = \frac{1}{2\pi} \int_0^{2\pi} d\varphi \int_{-\infty}^{\infty} dx_0 \int_{-\infty}^{\infty} dy_0 P(x_0, y_0) P(\Delta E, E)_{path}$$



Where hard vertices $P(x_0, y_0) = \frac{[T_A(r_0)]^2}{T_{AA}(0)}$ and $T_A(\vec{r}) = \int dz \rho_A(\vec{r}, z)$



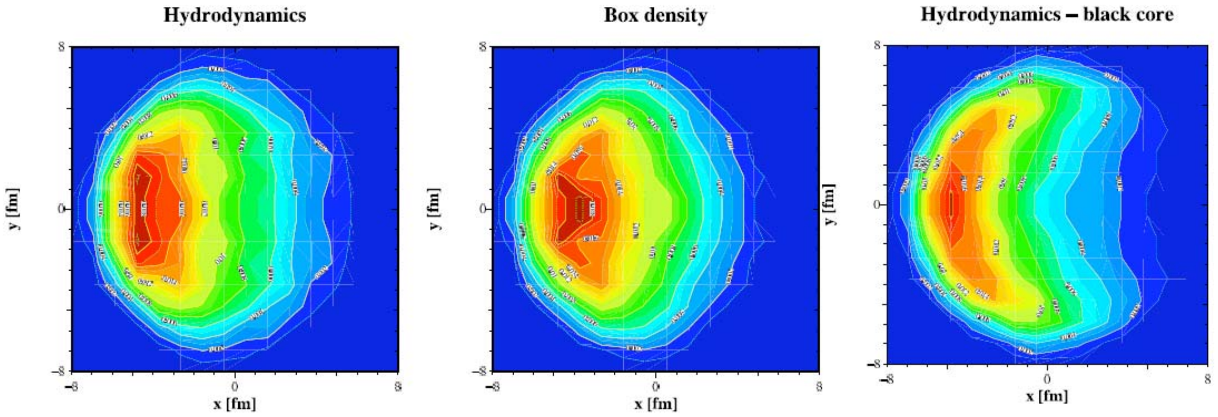


R_{AA} sensitivity - surface bias

Medium tomography:
T. Renk, K. Eskola
hep-ph/0610059

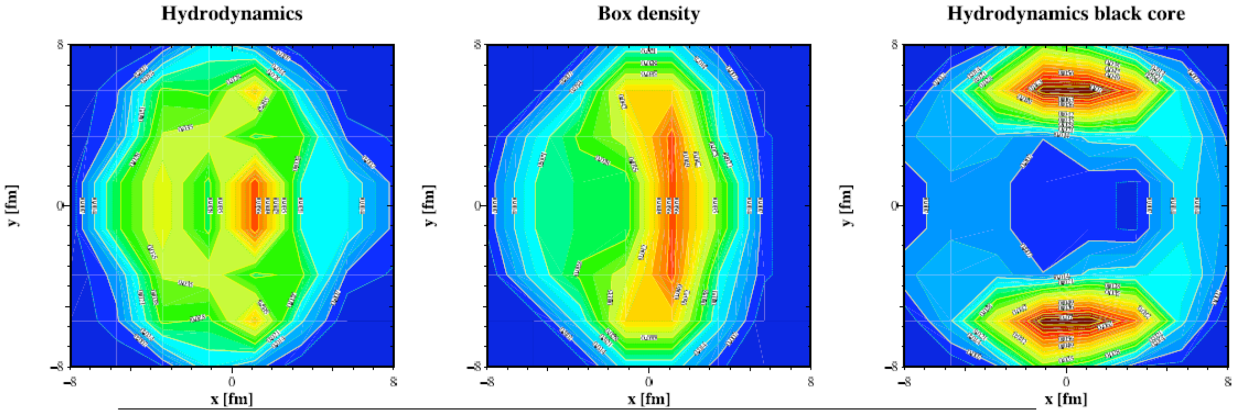
$P(x_0, y_0)\big|_{\text{single detected}}$

Singles: $8 < p_T < 15$ (near side $\equiv -x$)



$P(x_0, y_0)\big|_{\text{dihadron detected}}$

Dihadron: $(8 < p_T < 15) \otimes (4 < p_T < 6)$ GeV/c



What do we learn about the mechanism of *quark* and *gluon* interaction with QGP? MJT comment:
"Theory is interesting only if it doesn't agree with data."

non-photonic e± $R_{AA}^{c-quark} \approx R_{AA}^{u,d}$

Heavy quarks are expected to loose less energy than light quarks, but @ 6 GeV/c:

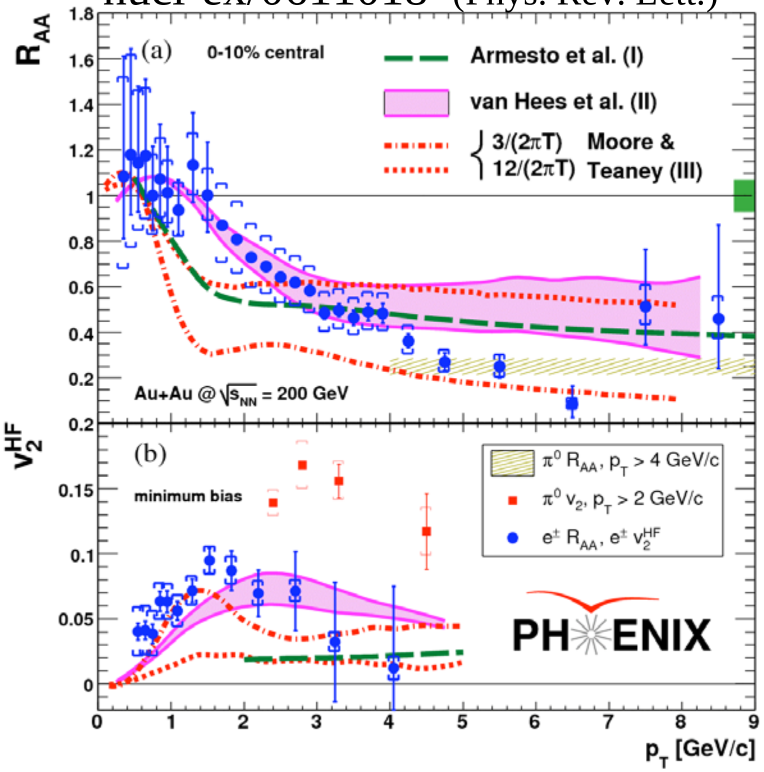
charm quarks (e±)

equally suppressed as

light quarks (π^0)

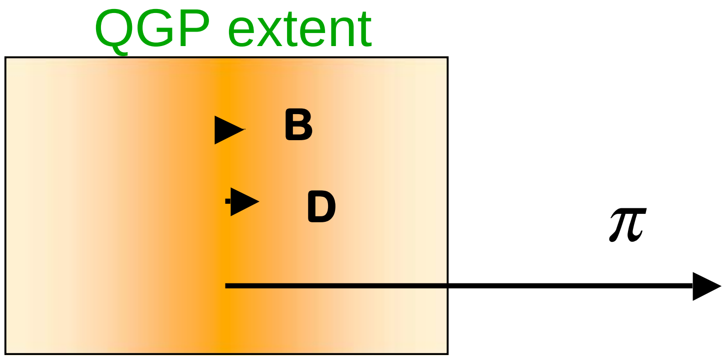
Radiative energy loss only fails to reproduce non-photonic e± R_{AA} and/or v_2

nucl-ex/0611018 (Phys. Rev. Lett.)



Possible interpretation:

I. Vitev (A.Adil, I.V., hep-ph/0611109)



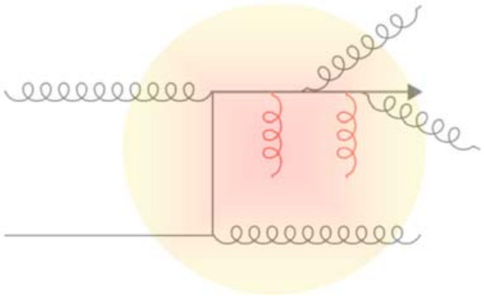
$\tau_{form}(p_T = 10\ GeV)$	π	D	B
	25 fm	**1.6 fm**	**0.4 fm**

- Fragmentation and dissociation of hadrons from heavy quarks inside the QGP

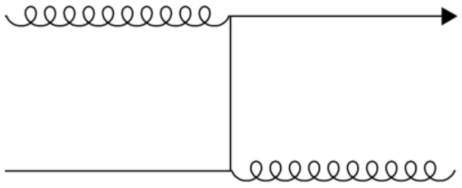
Elastic vs Radiative energy loss

Partonic Energy Loss

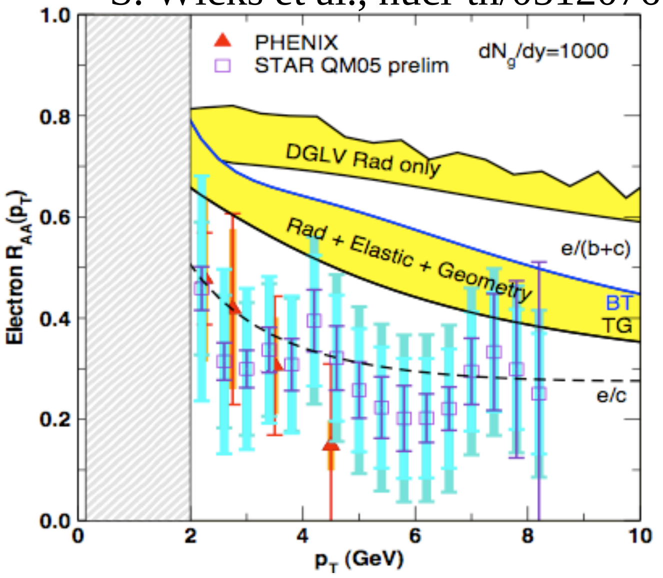
Radiative 2→N processes. Final state QCD radiation as in vacuum (p+p coll) - enhanced by QCD medium.



Elastic 2→2 LO processes



S. Wicks et al., nucl-th/0512076



8 LO subprocesses

$qq' \to qq'$ $\quad \frac{4}{9}\frac{s^2+u^2}{t^2}$

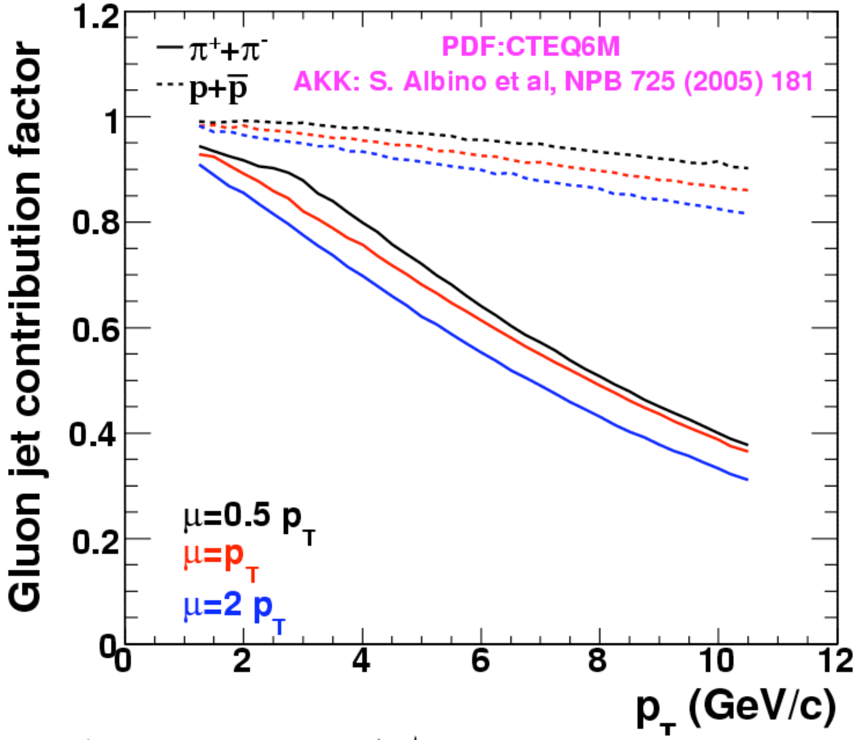
$qq \to qq$ $\quad \frac{4}{9}\left[\frac{s^2+u^2}{t^2}+\frac{s^2+t^2}{u^2}\right]$

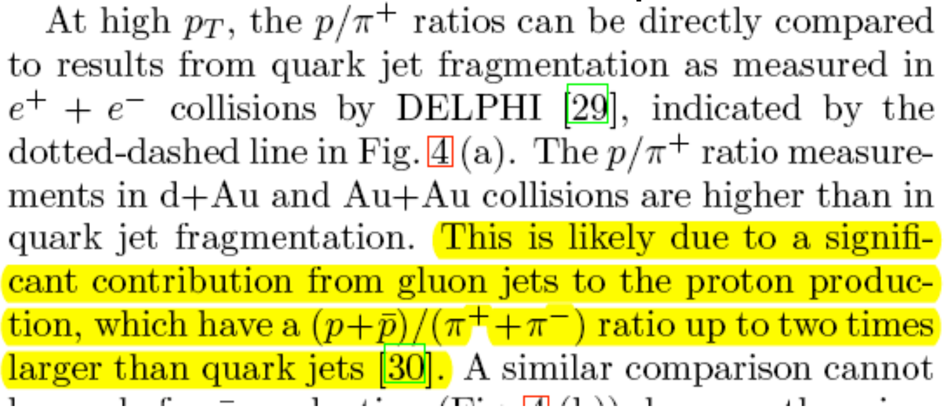
$q\bar{q} \to q\bar{q}'$ $\quad \frac{4}{9}\frac{t^2+u^2}{s^2}$

......

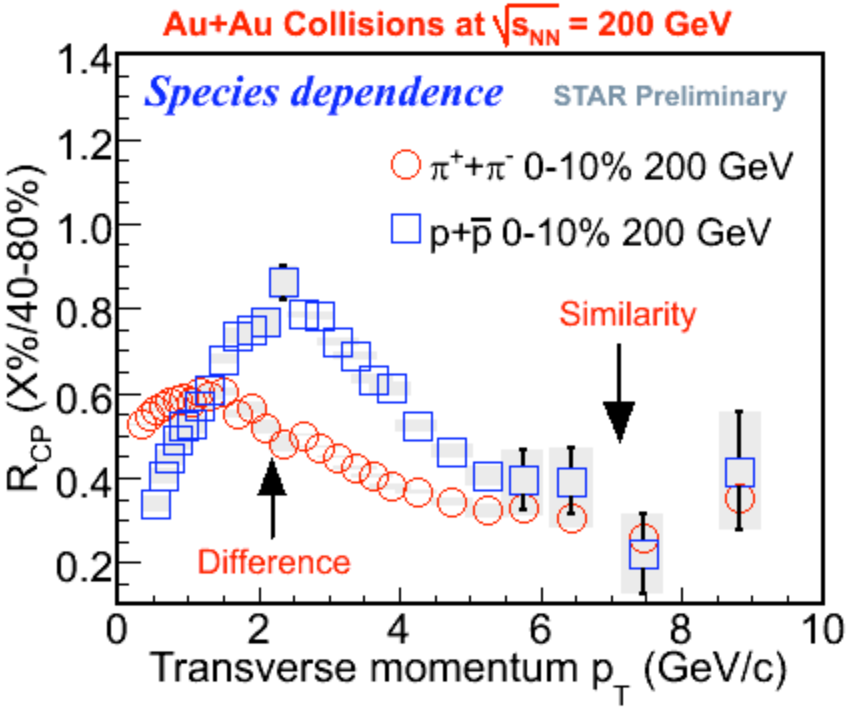
Elastic ΔE models predict stronger broadening of away-side correlation peak - *not seen in the data*. Also various models differ significantly in radiative/elastic fraction.

pions versus protons $R_{AA}^{quark} \approx R_{AA}^{gluon}$





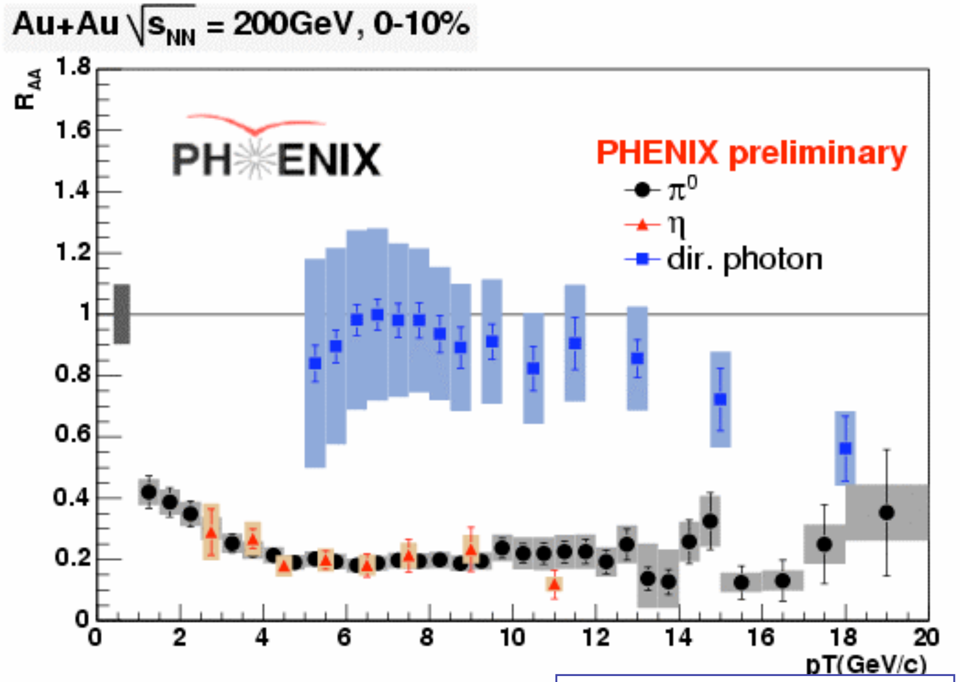
At high p_T, the p/π^+ ratios can be directly compared to results from quark jet fragmentation as measured in $e^+ + e^-$ collisions by DELPHI [29], indicated by the dotted-dashed line in Fig. 4 (a). The p/π^+ ratio measurements in d+Au and Au+Au collisions are higher than in quark jet fragmentation. This is likely due to a significant contribution from gluon jets to the proton production, which have a $(p+\bar{p})/(\pi^+ + \pi^-)$ ratio up to two times larger than quark jets [30]. A similar comparison cannot



STAR : PRL 97, 152301 (2006)

Question raised by STAR at QM06: shouldn't be p and π supp. differently due to C_A / C_F ?

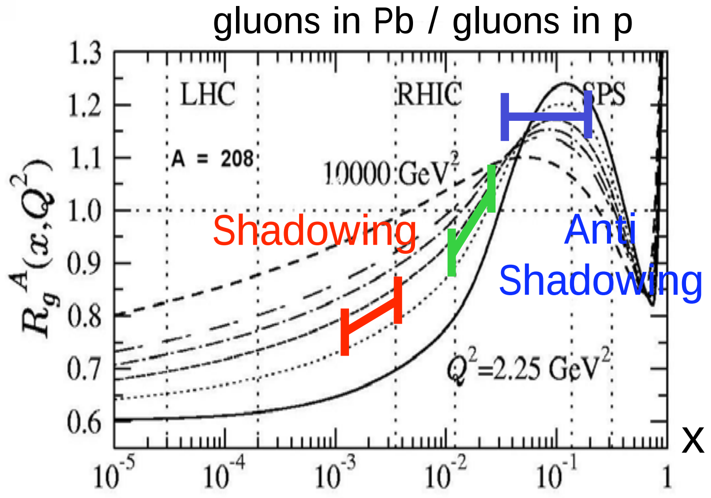
High-p_T photons $R_{AA}^{q,g} \approx R_{AA}^{gamma}$

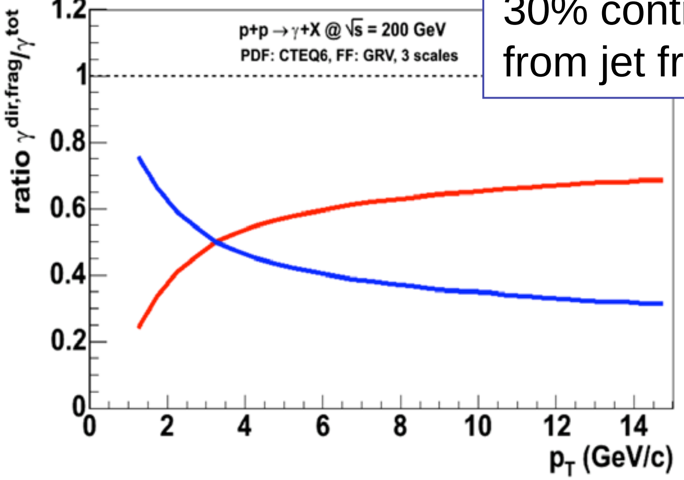


Thoroughly discussed today by Gabor. At high-p_T direct-γ almost as suppressed as π^0.

Is it shadowing?

Eskola et al. NPA**696** (2001) 729





30% contribution from jet frag.

Is the the quark→γ jet suppression?

(Taadaki Isobe, QM06)

Some of the open questions

Inclusive nuclear suppression factor R_{AA} is not quite sensitive to the particular dE/dx mechanism - is it due to the *surface bias*?

Light and *heavy quarks* suppression looks similar: $R_{AA}^{c-quark} \approx R_{AA}^{u,d}$

Quarks and *gluons* suppression looks similar: $R_{AA}^{quark} \approx R_{AA}^{gluon}$

Direct photon suppression at *high p_T* looks similar: $R_{AA}^{q,g} \approx R_{AA}^{gamma}$

It is evident that the detailed understanding of unmodified parton properties

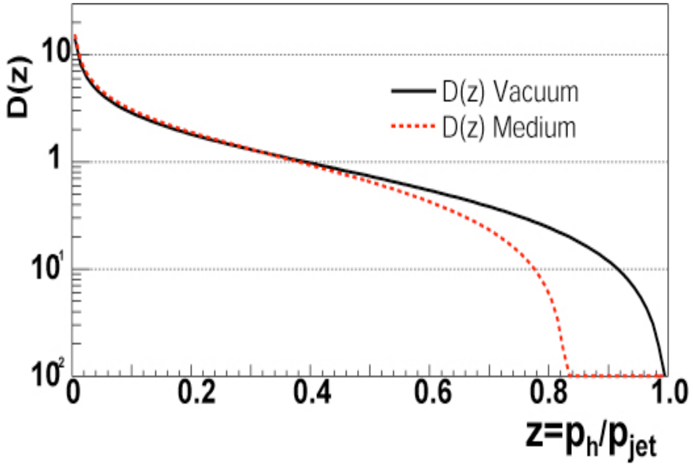
CRUTIAL

pQCD quenching - modification of D(z)

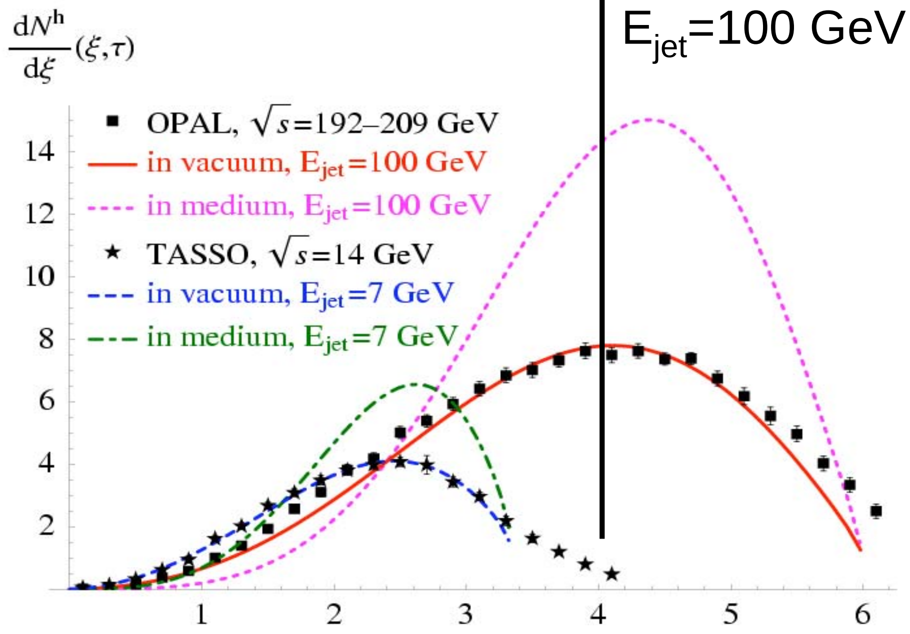
$$D(z) \equiv dN/dz; \quad z = p(fragment)/p(jet)$$

$$\tilde{D}(z) \approx \frac{1}{1-1/\Delta E} D\left(\frac{z}{1-\Delta E/E}\right)$$

Wang, X.N., Nucl. Phys. A, 702 (1) 2002



p_T^{hadron}~2 GeV for E_{jet}=100 GeV



Borghini and Wiedemann, hep-ph/0506218

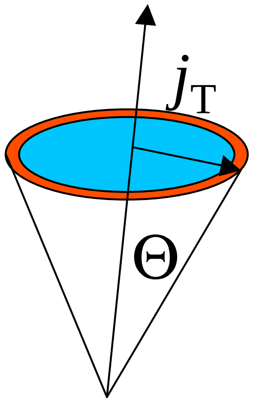
- MLLA: parton splitting+coherence ⇒ angle-ordered parton cascade. Theoretically controlled, experimentally verified approach

- Medium effects introduced at parton splitting

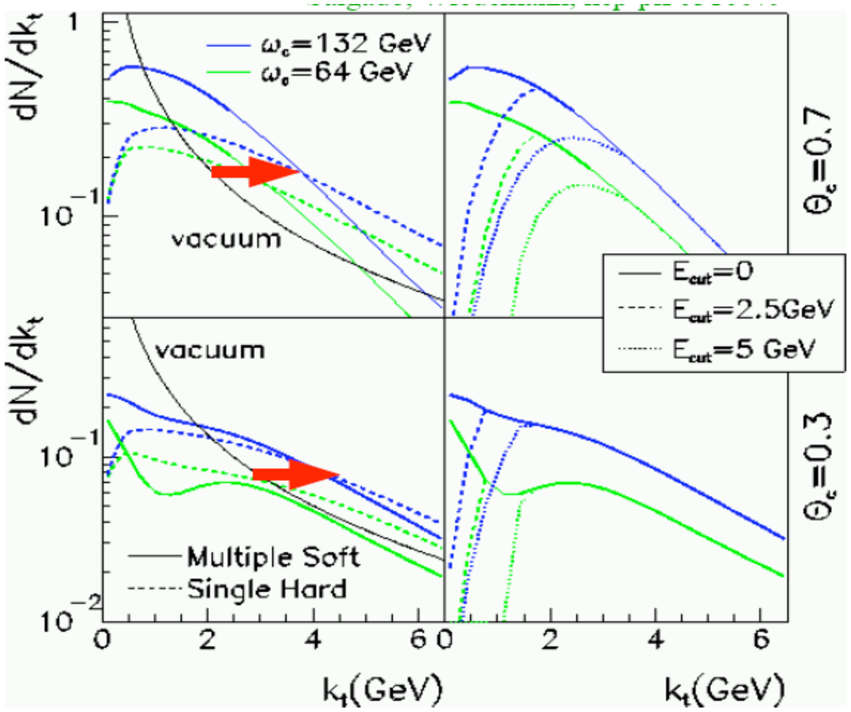
$\xi = \ln(E_{Jet}/p_{hadron})$

Transverse Heating at LHC : j_T - Broadening

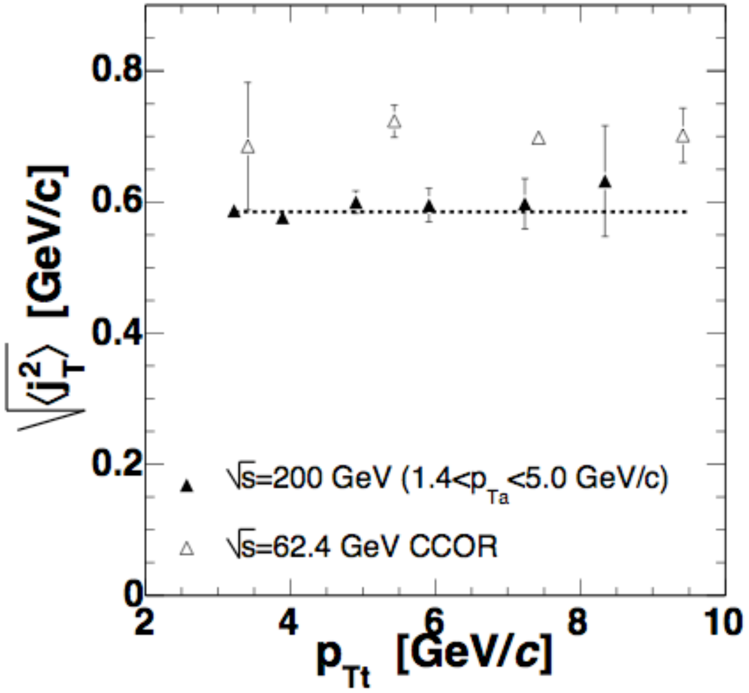
- Unmodified jets $\sqrt{\langle j_T^2 \rangle} = 600$ MeV ~ const(R).
- Transverse heating - $\sqrt{\langle j_T^2 \rangle}$ broandening



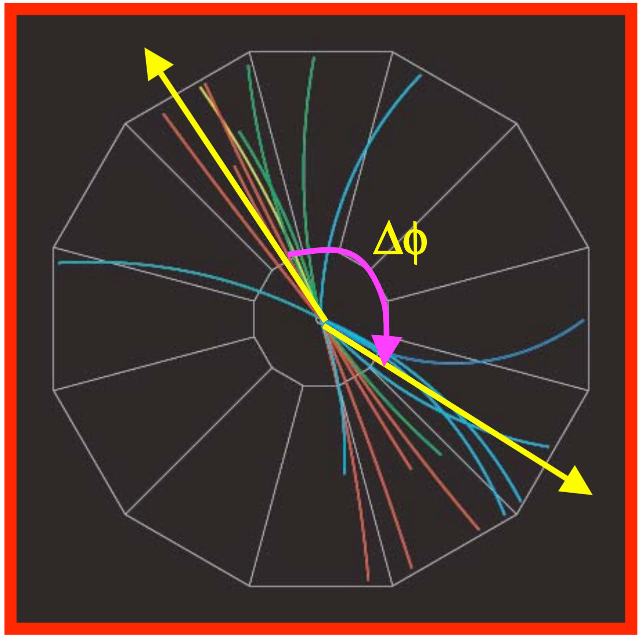
Salgado, Wiedemann, hep-ph/0310079



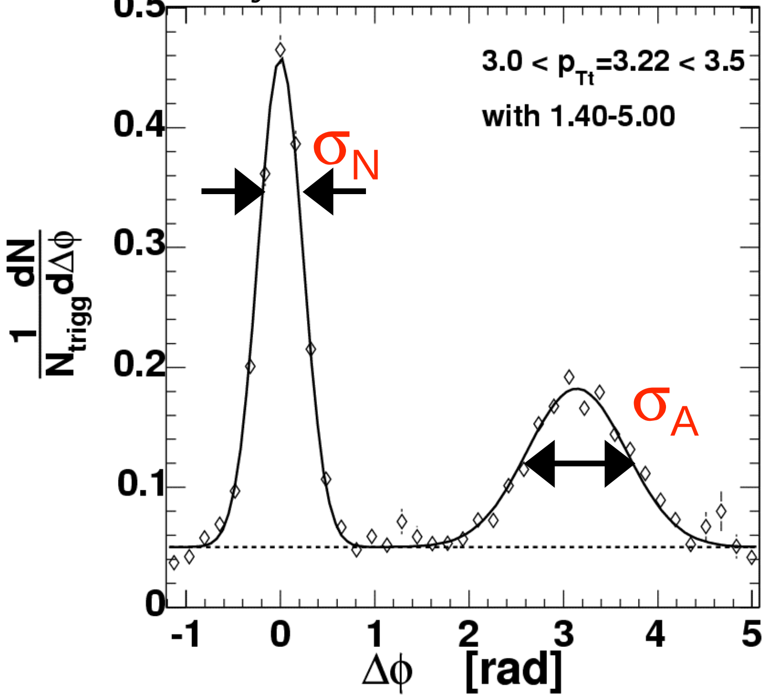
Phys.Rev.D74:072002,2006



Azimuthal correlation function in *p+p* @ √s=200 GeV



p + p → jet + jet


Phys.Rev.D74:072002,2006

$$\frac{1}{N_{\rm trigg}}\frac{dN}{d\Delta\phi} = \frac{R_{\Delta\eta}}{N_{\rm trigg}\,\epsilon(p_T)}\frac{dN_{\rm uncorr}(\Delta\phi)/d\Delta\phi}{dN_{\rm mix}(\Delta\phi)/d\Delta\phi}$$

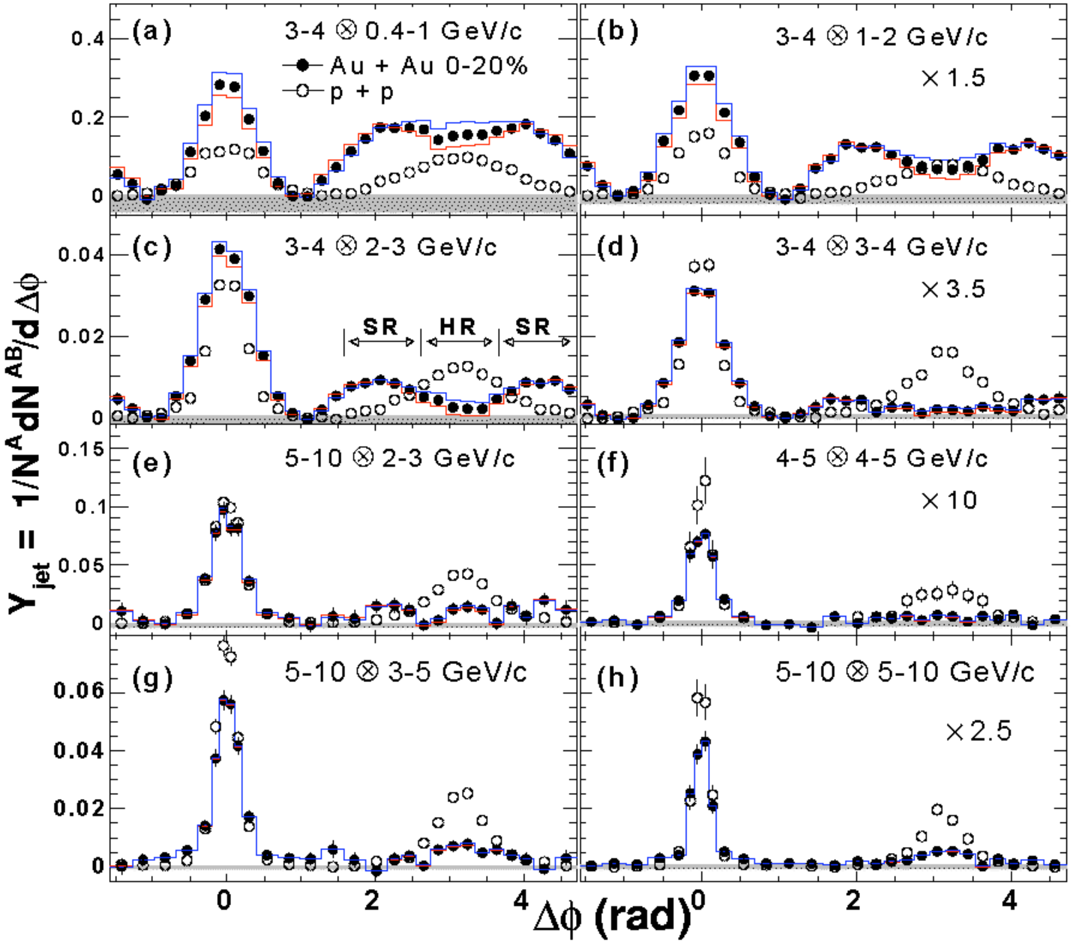
$\sigma_N \propto \langle j_T \rangle$ jet fragmentation transverse momentum

$\sigma_F \propto \langle k_T \rangle$ parton transverse momentum

$Y_A \propto$ folding of D(z) and final state parton dist.

Jet shape evolution with trigger and assoc. p_T

Au+Au / p+p √s = 200 GeV



Per-trigger yield vs. $\Delta\phi$ for various trigger and partner p_T ($p^A_T \otimes p^B_T$), arranged by increasing pair momentum ($p^A_T + p^B_T$)

arXiv:0705.3238 [nucl-ex]

- Flat region:

  celebrated b2b disappearance

- Punch through region (HR):

  reappearance at high-p_T

- Shoulder region (SR):

  Medium induced "Mach cone"

- Low p_T:

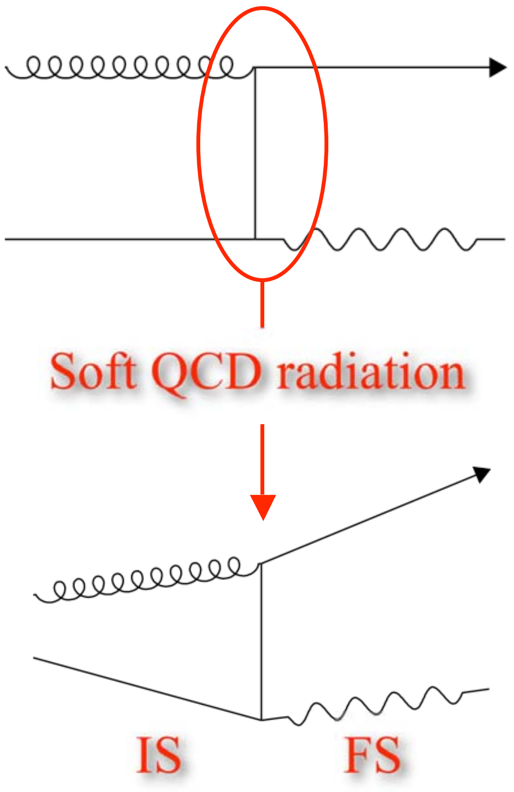
  Enhancement in SR & suppression in HS

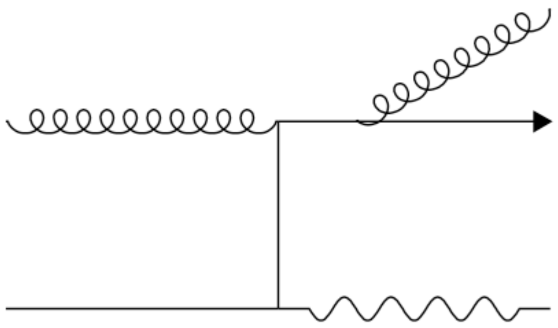
- High p_T:

  Reappearance of away-side jet not due to merging of side peaks

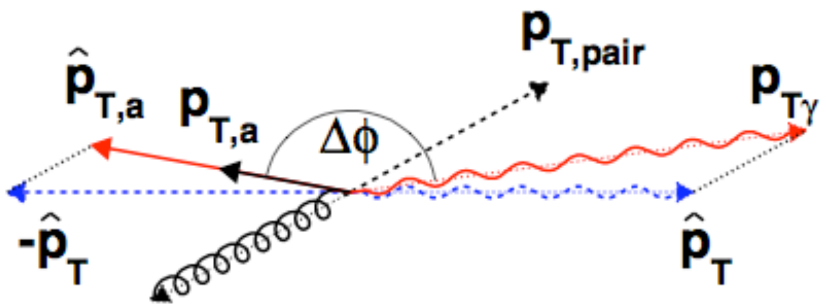
Jet shape analysis - accoplanarity - k_T

LO Compton q+g->q+gamma





Hard QCD radiation NLO

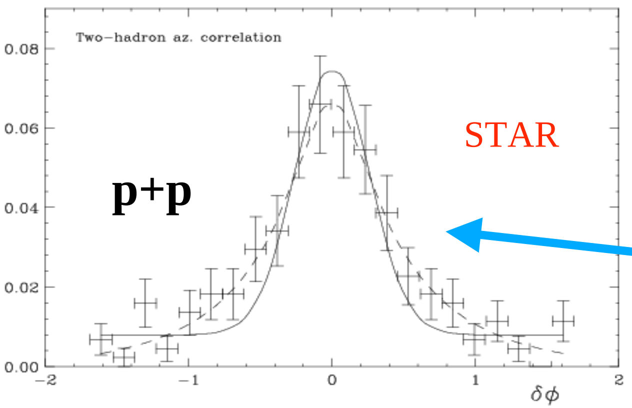


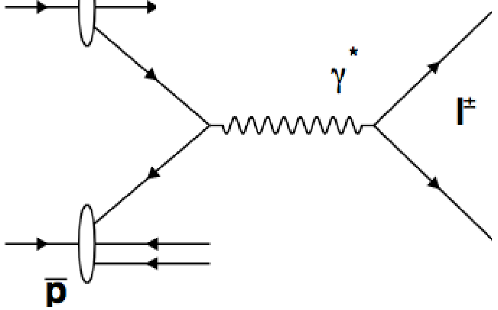
$$\boxed{\left\langle k_T^2 \right\rangle = \frac{\left\langle p_{T,pair}^2 \right\rangle}{2} = \left\langle k_T^2 \right\rangle_{\text{intrinsic}} + \left\langle k_T^2 \right\rangle_{\text{NLO}} + \left\langle k_T^2 \right\rangle_{\text{soft}}}$$

Soft Gaussian + hard power law

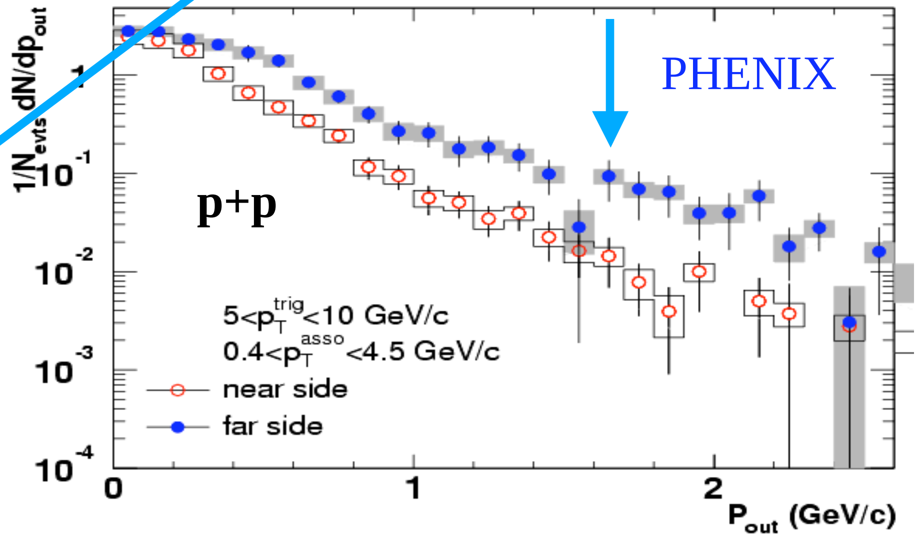
D. Boer and W. Vogelsang,
Phys. Rev. D69 (2004) 094025

J. Qiu and I. Vitev,
Phys. Lett. B570 (2003) 161

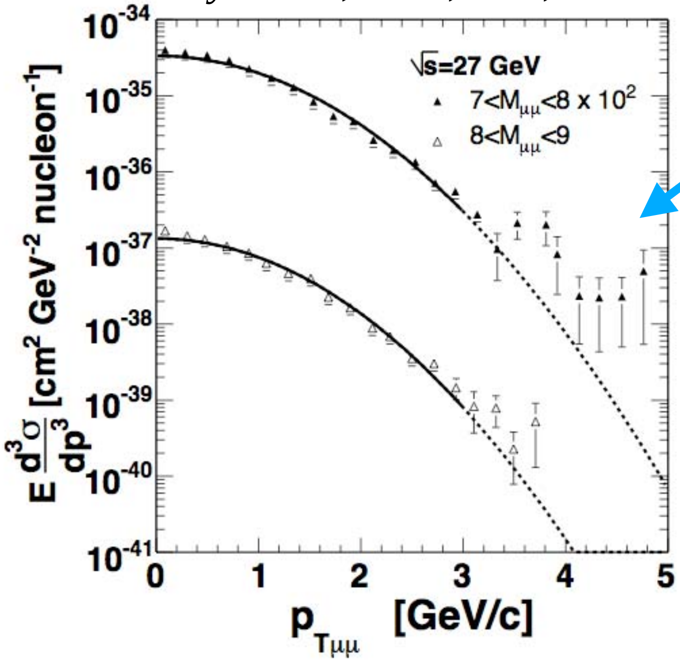


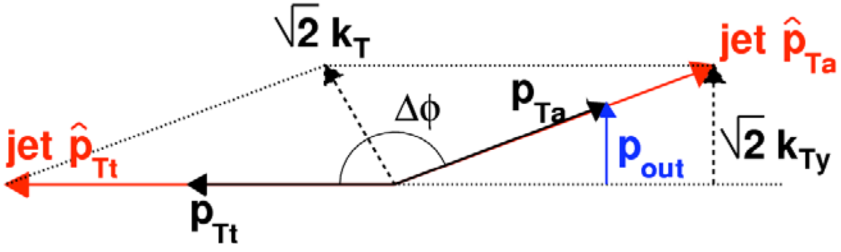


radiative tails



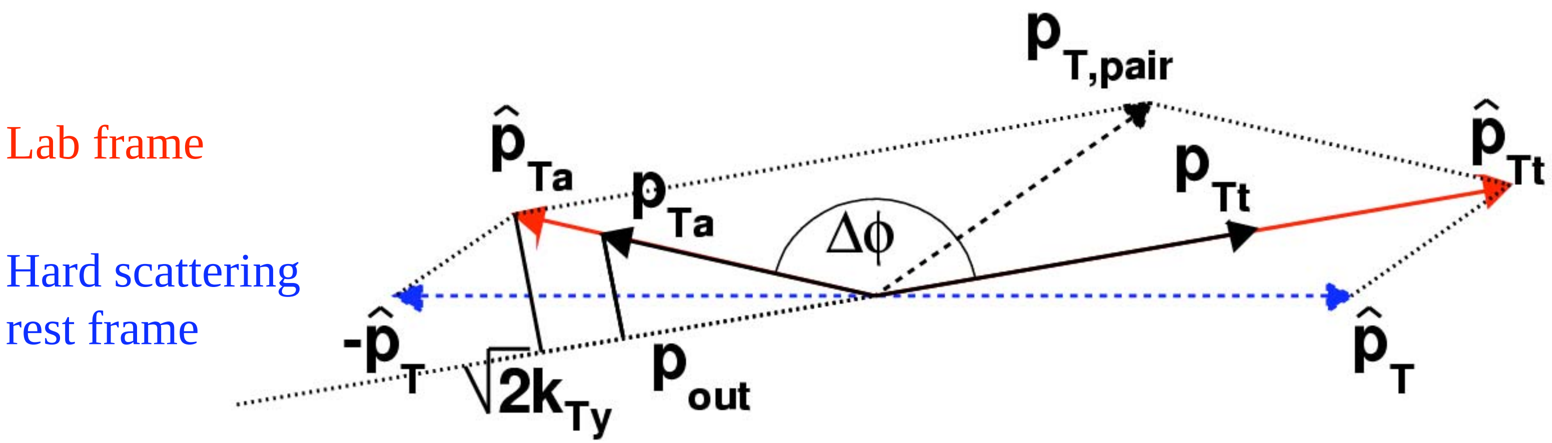
Phys. Rev., 1981, D23, 604





Correl. fcn width - k_T and acoplanarity

$p_{T,pair}$ Lorentz boost preserves $M_{inv}^2 = 4\hat{p}_T^2 = 2\hat{p}_{Tt}\hat{p}_{Ta} - 2\vec{\hat{p}}_{Tt}\vec{\hat{p}}_{Ta}$



$$\langle|p_{out}|\rangle = \sqrt{2}\langle|k_{Ty}|\rangle \frac{p_{Ta}}{\langle\hat{p}_{Ta}\rangle} \quad \Rightarrow \quad \sqrt{\langle p_{out}^2\rangle} = \langle z_t\rangle \sqrt{\langle k_T^2\rangle}\,\frac{x_h}{\hat{x}_h}$$

Jet momenta imbalance due to k_T smearing $\hat{x}_h = \frac{\langle\hat{p}_{Ta}\rangle}{\langle\hat{p}_{Tt}\rangle}$ $x_h = \frac{p_{Ta}}{p_{Tt}}$

partonic $\boxed{\hat{x}_h^{-1}\langle z_t\rangle\sqrt{\langle k_T^2\rangle} = x_h^{-1}\sqrt{\langle p_{out}^2\rangle - \langle j_{Ty}^2\rangle(1+x_h^2)}}$ hadronic

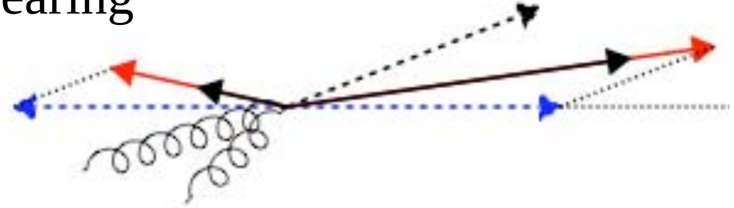
From an analysis of **associated yield**

Assoc. yield - "Averaged" pQCD approach

Assumptions (*Phys.Rev.D74:072002,2006 for details*) :

1. Invariant mass of mass-less partons in hard-scattering CMS and in LAB is the same -> non-Gaussian k_T-smearing

$$M_{inv}^2 = 4\hat{p}_T^2 = 2\hat{p}_{Tt}\hat{p}_{Ta} - 2\vec{\hat{p}}_{Tt}\vec{\hat{p}}_{Ta}$$



2. Effective FS parton distribution: $\Sigma_Q(\hat{p}_T) \propto \hat{p}_T^{-n}$
3. Effective Fragmentation function: $D(z) = z^{\alpha}\cdot(1-z)^{\beta}\cdot(1+z)^{\gamma}$

α,β,γ to be extracted from fit to gamma-h or LEP

One can then evaluate:

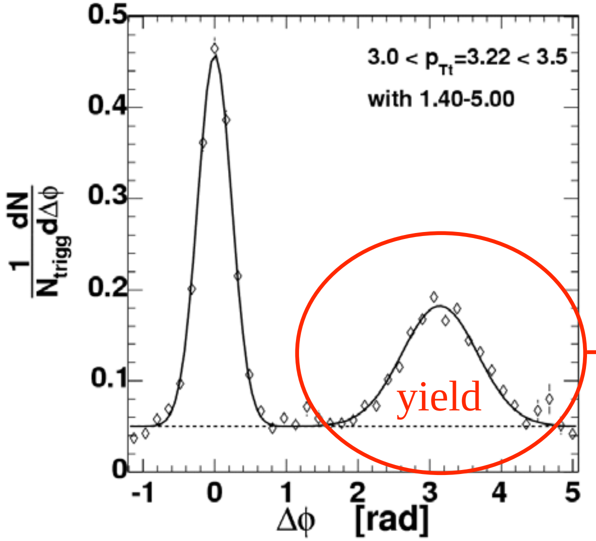
1. Inclusive π^0 cross section

$$\frac{1}{p_T}\frac{d\sigma_\pi}{dp_T} = \int_{x_T}^{1}\frac{dz}{z^2}\cdot D(z)\cdot\Sigma'_Q\left(\frac{p_T}{z}\right)$$

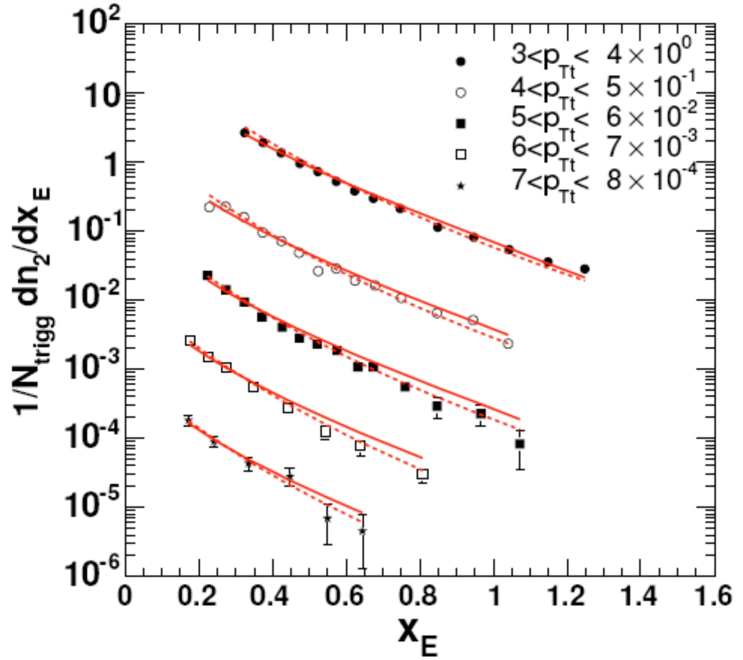
2. Trigger π^0 associated dist.

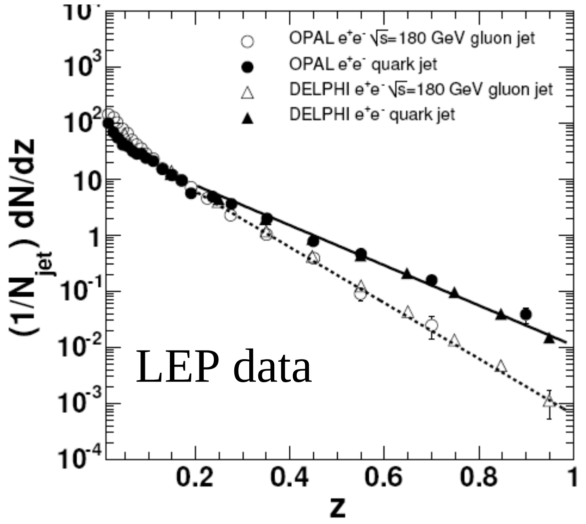
$$\frac{d^2\sigma_\pi}{dp_{Tt}dp_{Ta}} = \frac{1}{p_{Tt}}\int_{x_{Tt}}^{1}\frac{dz_t}{z_t}\cdot D(z_t)\cdot D\left(\frac{p_{Ta}}{p_{Tt}}z_t\right)\cdot\Sigma'_Q\left(\frac{p_{Tt}}{z_t}\right)$$

Trigger associated spectra are insensitive to $D(z)$



$$x_E = \left|\frac{\vec{p}_{Ta}\cdot\vec{p}_{Tt}}{\vec{p}_{Tt}^{\,2}}\right| = -\frac{p_{Ta}}{p_{Tt}}\cos\Delta\phi \approx -\frac{p_{Ta}}{p_{Tt}}$$



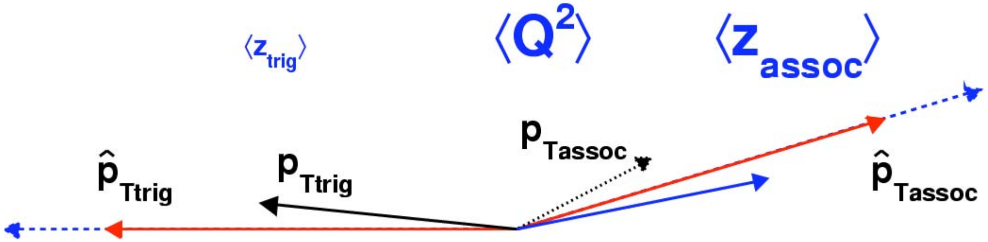


MJT Approximation - Incomplete Gamma function when assumed power law for final state PDF and exp for D(z)

$$\frac{d\sigma_\pi}{dp_{Tt}} = \frac{1}{p_{Tt}^{n-1}}\int_{xTt}^{1} dz_t z_t^{n-2} e^{-b.z_t} \approx \langle m\rangle (n-1)\frac{1}{\hat{x}_h}\left(1+\frac{x_E}{\hat{x}_h}\right)^{-n}$$

Unavoidable *z*-bias in di-hadron correlations

z-bias; steeply falling/rising D(z) & PDF(1/z)

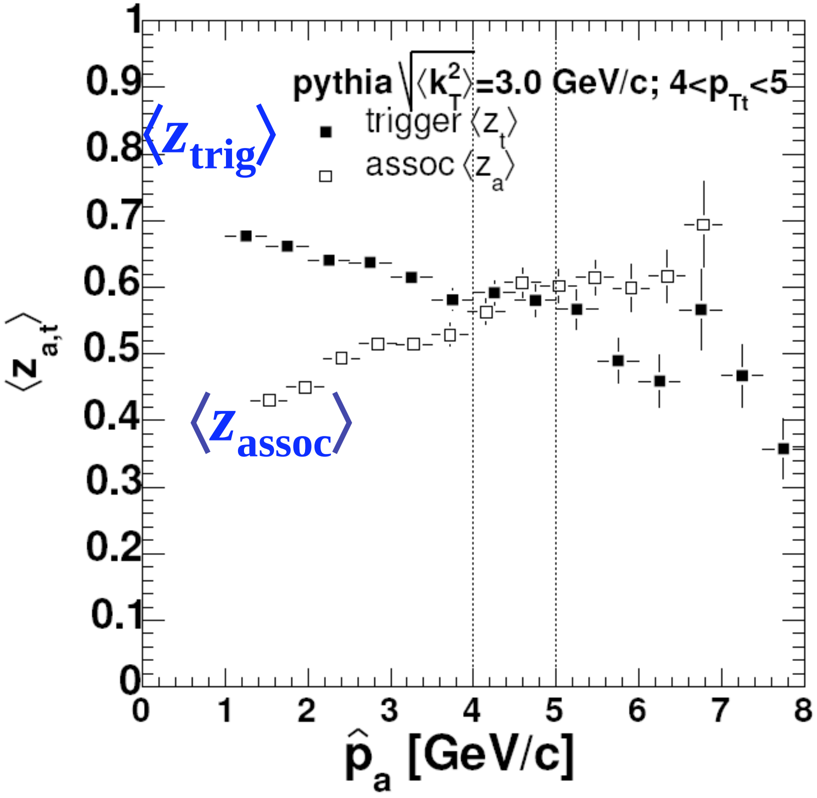


Fixed trigger particle momentum

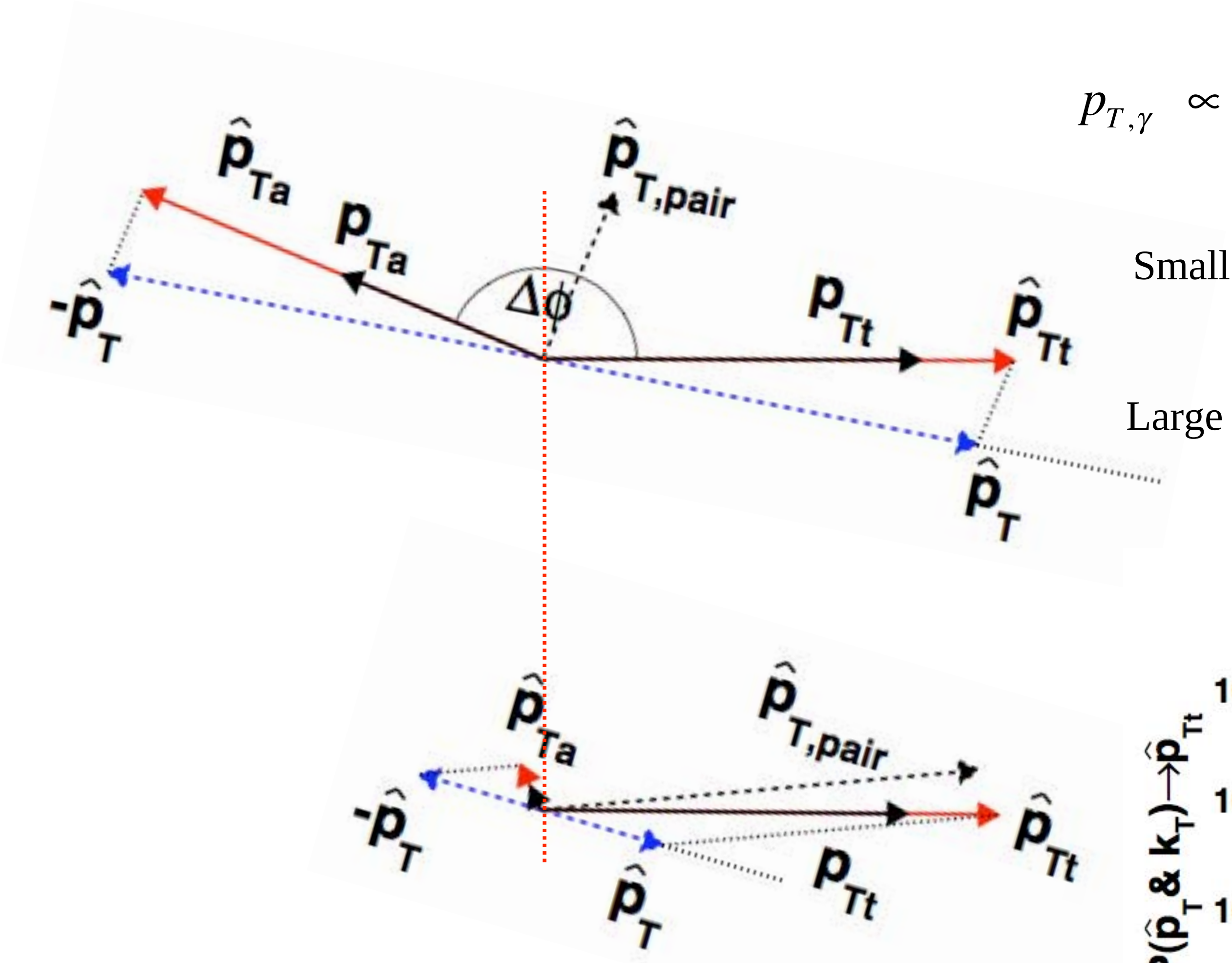
does not fix

the jet energy!

Varying p_{Tassoc} with $p_{Ttrigger}$ kept fixed leads to variation of both trigger and associated jet energies.



k_T bias

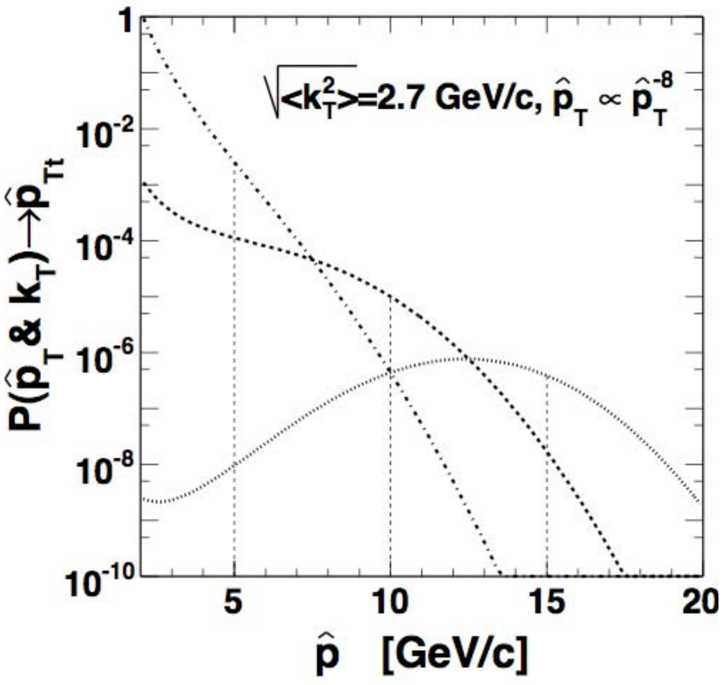


$$p_{T,\gamma} \propto \text{Gauss}\left(\sqrt{\langle k_T^2 \rangle}\right) \otimes \frac{1}{\hat{p}_T^8}$$

Small k_T (Gauss) and large p_T power law

less probable than

Large k_T (Gauss) and small p_T power law

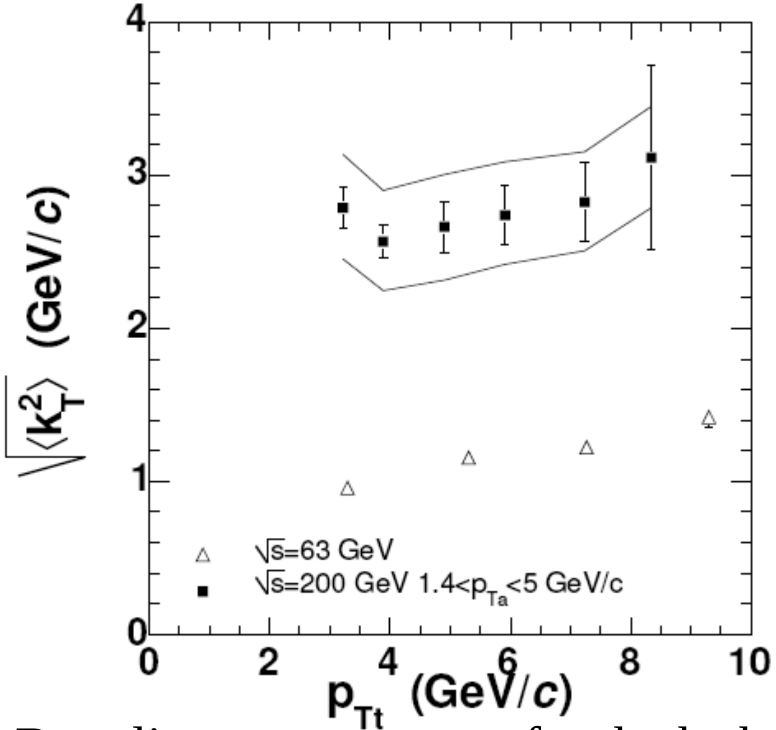


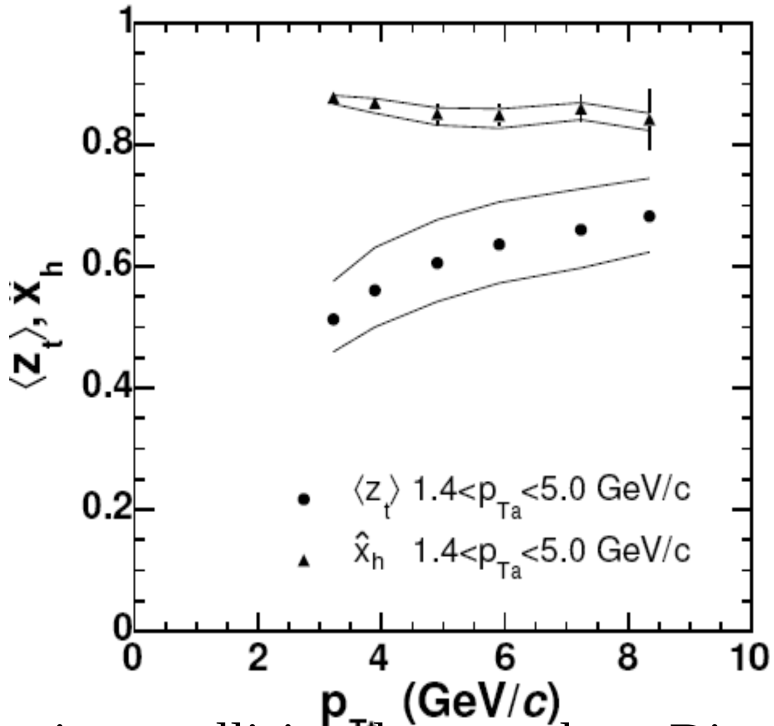
Even at relatively high photon momentum (10 GeV/c) γ-h pairs still not fully in power law pQCD regime.

$\sqrt{\langle k^2_T \rangle}$ and $\langle z_t \rangle$ in p+p @ 200 GeV from π^0-h CF

Phys.Rev.D74:072002,2006

For D(z) the LEP date were used. Main contribution to the systematic errors comes from unknown ratio gluon/quark jet => D(z) slope.



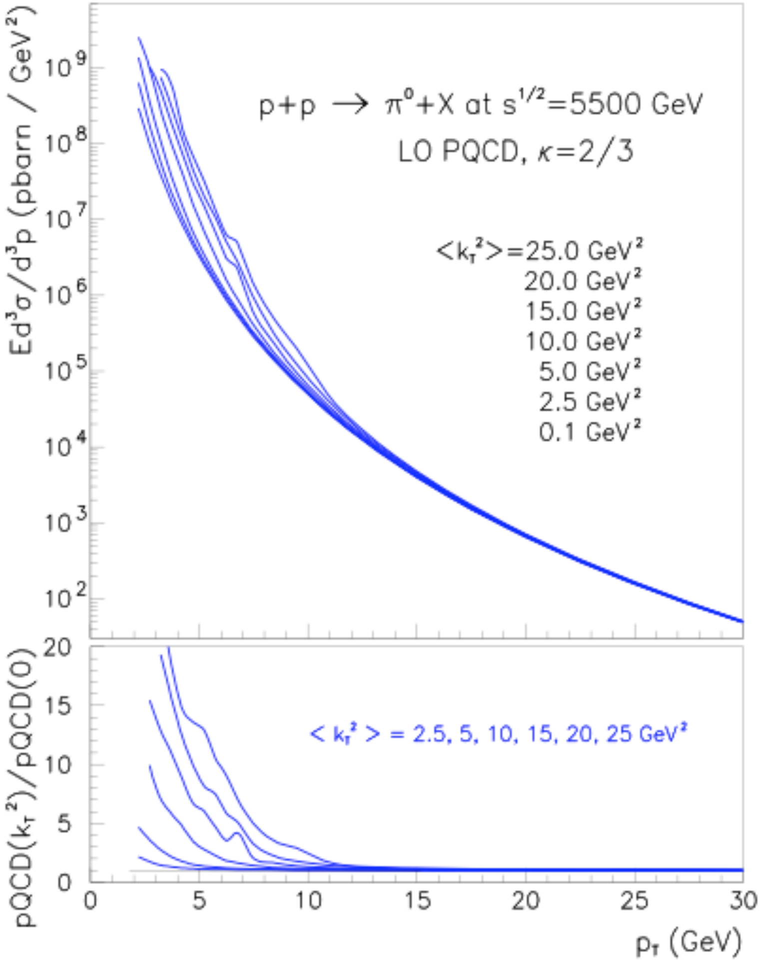


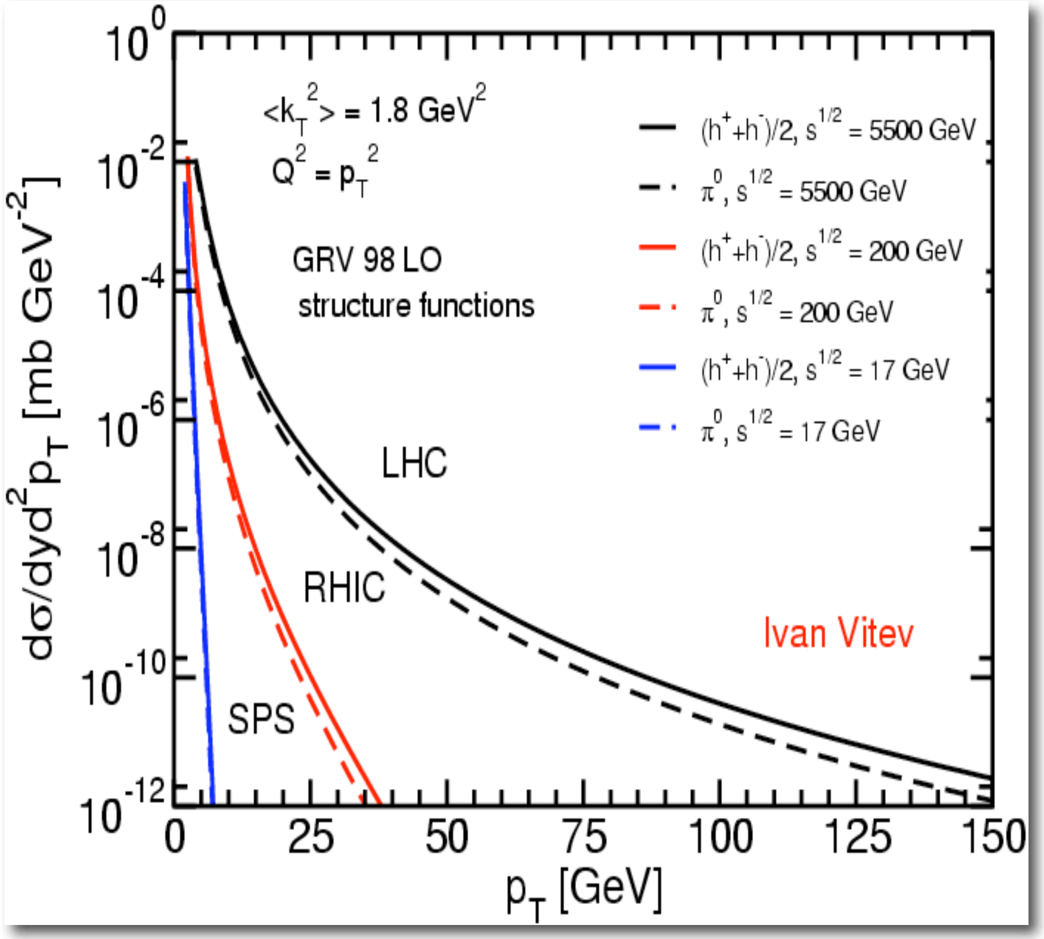
Base line measurement for the k_T broadening - collisional energy loss. Direct width comparison is biased.

Still, we would like to extract FF from our own data -> direct photon-h correl.

High p_T: ref. for HI, resummation, detailed NLO tests

G.G. Barnaföldi, P.Levai

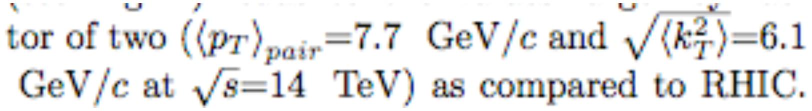




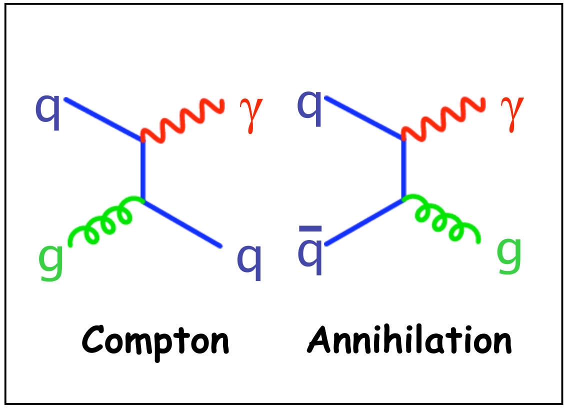
Ivan Vitev

PHENIX measured $\langle p_T\rangle_{pair}$=3.36±0.09±0.43GeV/c

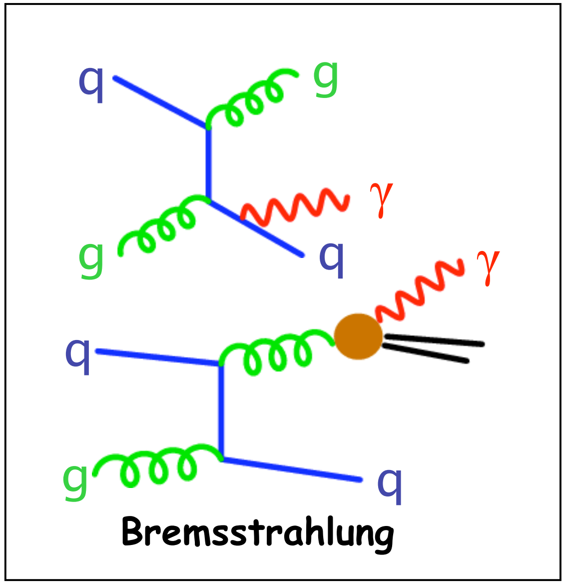
extrapolation to LHC $\langle k_T^2\rangle\approx$36 GeV²/c²


tor of two ($\langle p_T\rangle_{pair}$=7.7 GeV/$c$ and $\sqrt{\langle k_T^2\rangle}$=6.1 GeV/$c$ at $\sqrt{s}$=14 TeV) as compared to RHIC.

Avoidable in Direct Photons Correlations



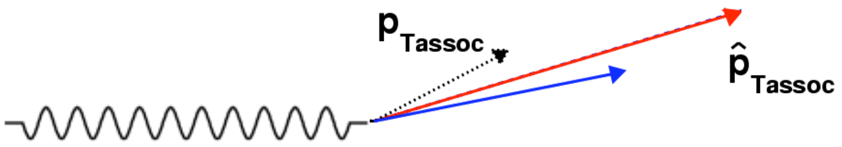
Direct Photon Processes



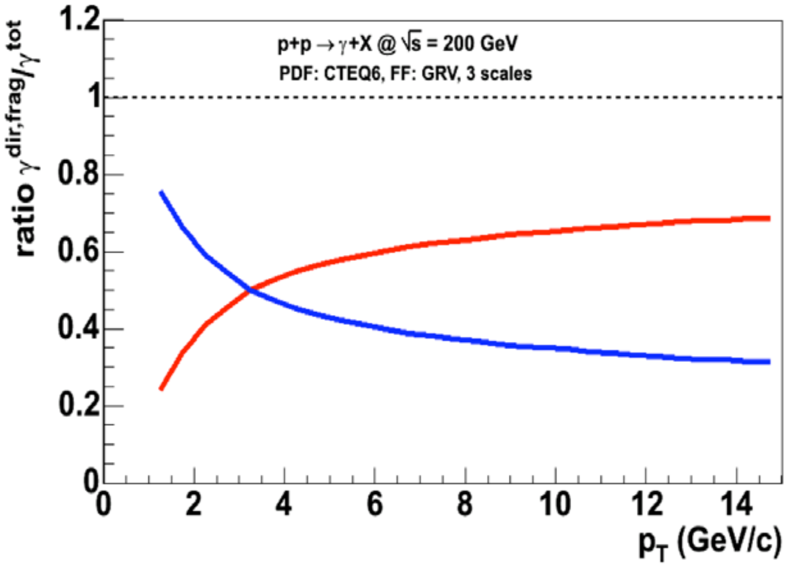
These two diagrams fix the jet energy scale

Up to the k_T effect !

$z_{trig} = 1 \pm k_T / \hat{p}_T$ $\langle Q^2 \rangle \approx const$ $\mathrm{dN/dz_{assoc}} \propto D(z)$



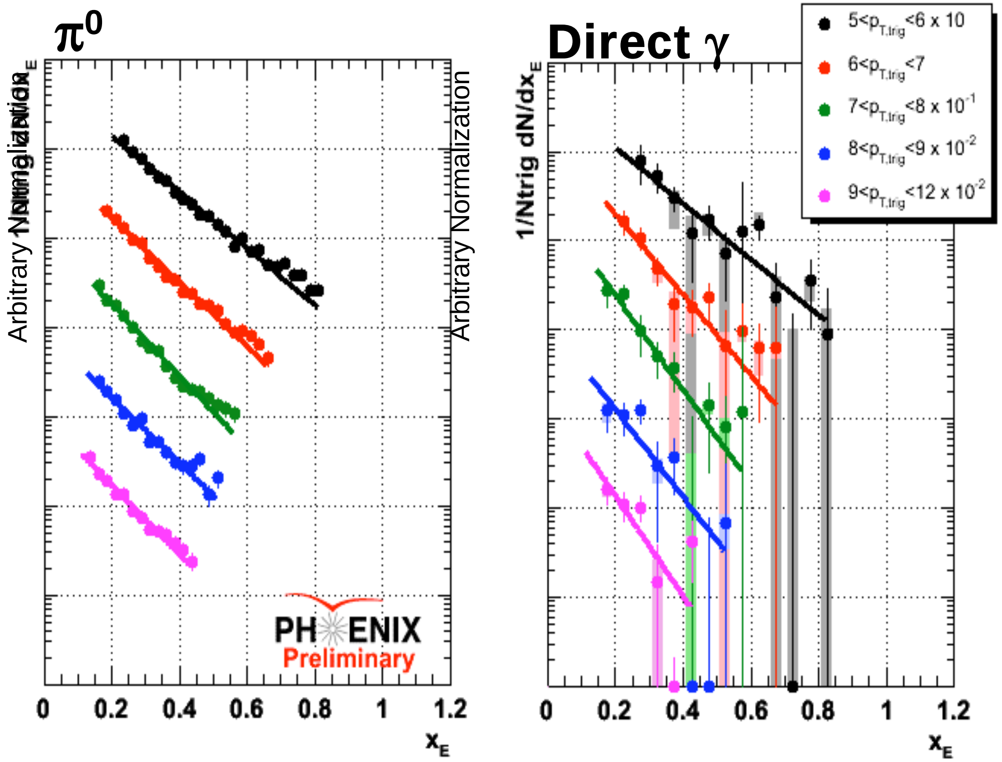
Fragmentation photons measured using isolation cut analysis



PHENIX $\sqrt{s}$=200 GeV π^0 and dir-γ assoc. distributions

Matthew Nguyen
APS Spring Meeting, April 15, 2007

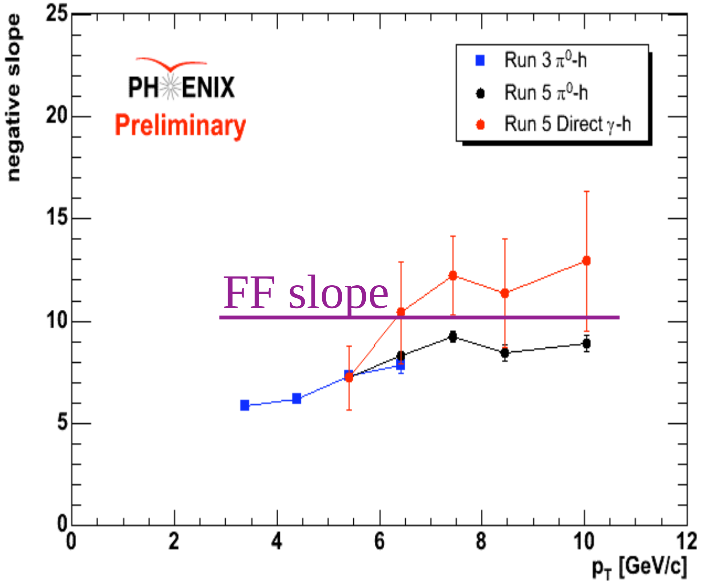
$$x_E = \left| \frac{\vec{p}_{Ta} \cdot \vec{p}_{Tt}}{\vec{p}_{Tt}^{\,2}} \right| = -\frac{p_{Ta}}{p_{Tt}} \cos\Delta\phi \approx -\frac{p_{Ta}}{p_{Tt}}$$



Run 5 p+p @ 200 GeV
Statistical Subtraction Method

Exponential slopes still vary with trigger γ $p_{T\gamma}$.

If $dN/dx_E \propto dN/dz$ then the local slope should be $p_{T\gamma}$ independent.



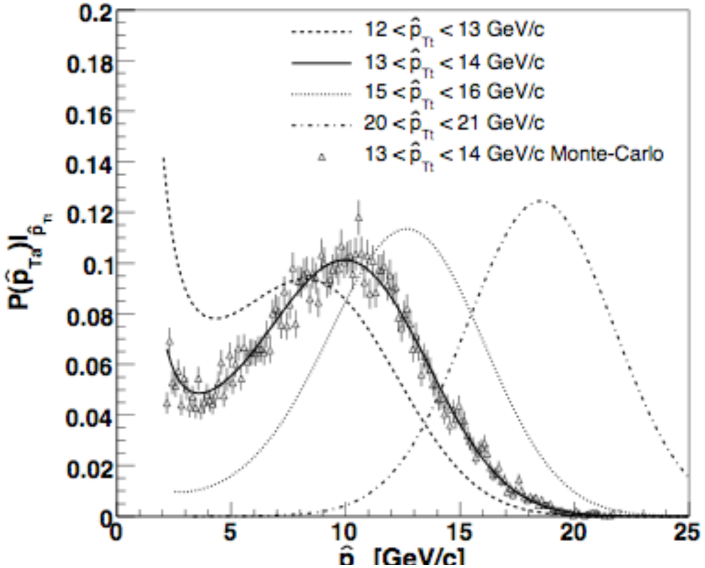
Photon associated yields - “averaged” pQCD

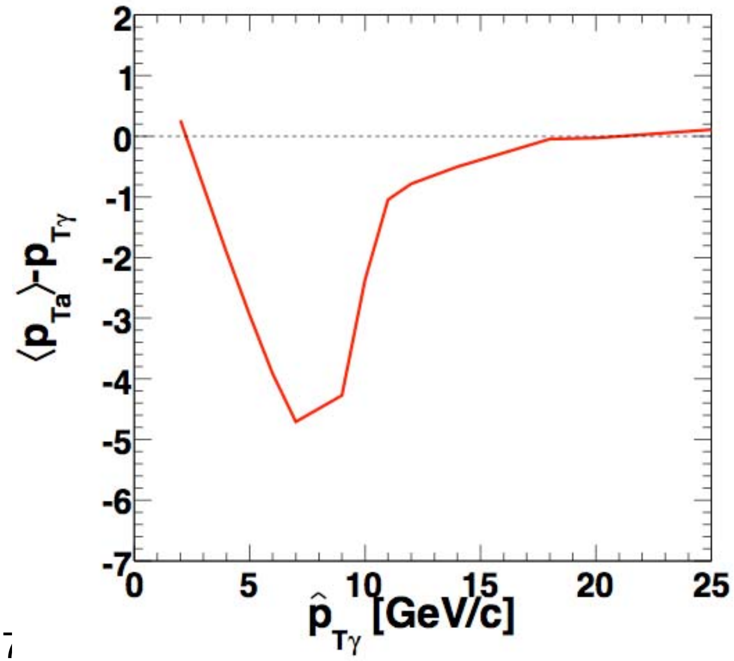
$$P(\hat{p}_{Tt}\ \&\ \hat{p}_{Ta})\Big|_{\hat{p}_T}\ \frac{\hat{p}_{Tt}+\hat{p}_{Ta}}{\sqrt{\hat{p}_{Tt}\hat{p}_{Ta}-\hat{p}_T^2}}\exp\left(\frac{(\hat{p}_{Tt}+\hat{p}_{Ta})^2-4\hat{p}_T^2}{2\sqrt{\langle k_{Tx}^2\rangle}}\right)$$

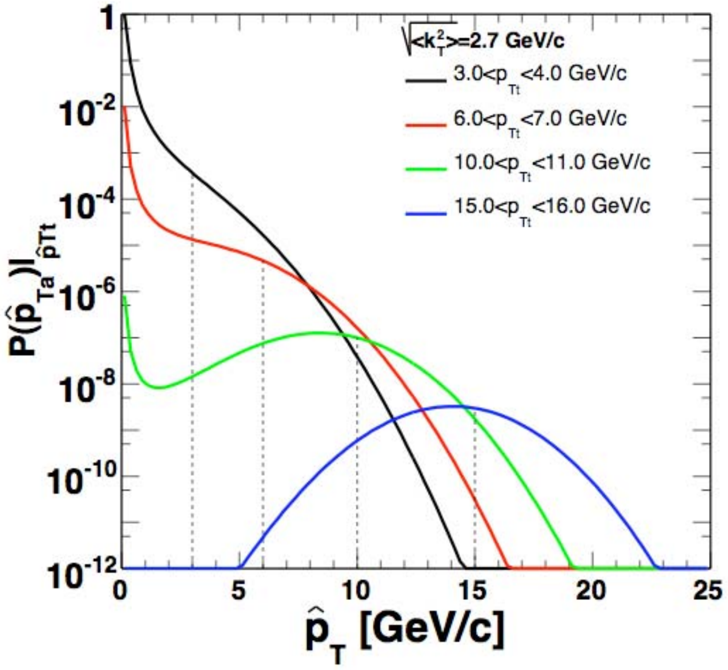
$\hat{p}_{Tt}$ = gamma mom.

$$\left.\frac{dN}{dp_{Ta}}\right|_{pTt} = D(z_t)\otimes\Sigma_Q^{'}\left(\frac{p_{Tt}}{z_t}\right)\otimes\int d\hat{p}_{Tt}\,P(\hat{p}_{Tt}\ \&\ \hat{p}_{Ta})\Big|_{\hat{p}_T}$$

k_T bias still important, sensitivity to the D(z) shape as expected, the slope is also changing as in the data - parton imbalance.







Summary

Inclusive and two-particle correlation measurement in the high-p_T sector at RHIC opened a new window into a QGP physics. Inclusive measurements have limited discrimination power -> complementary multiparticle correlations are important. However, two-particle correlations are not bias-free either:

di-hadron correlations:

- k_T and initial/final state QCD radiation, resummation vs NLO
- j_T near-side jet shape modifications
- z-bias washes out the sensitivity of the associated x_E yield to the Fragmentation Function.

direct photon-hadron correlations

- Fragmentation function can be extracted from the associated x_E yield. However
- k_T-bias still present - pushes the minimum photon-trigger p_T above 10 GeV/c at RHIC.

Direct γ-h Correlations in PHENIX p+p $\sqrt{s}$=200 GeV

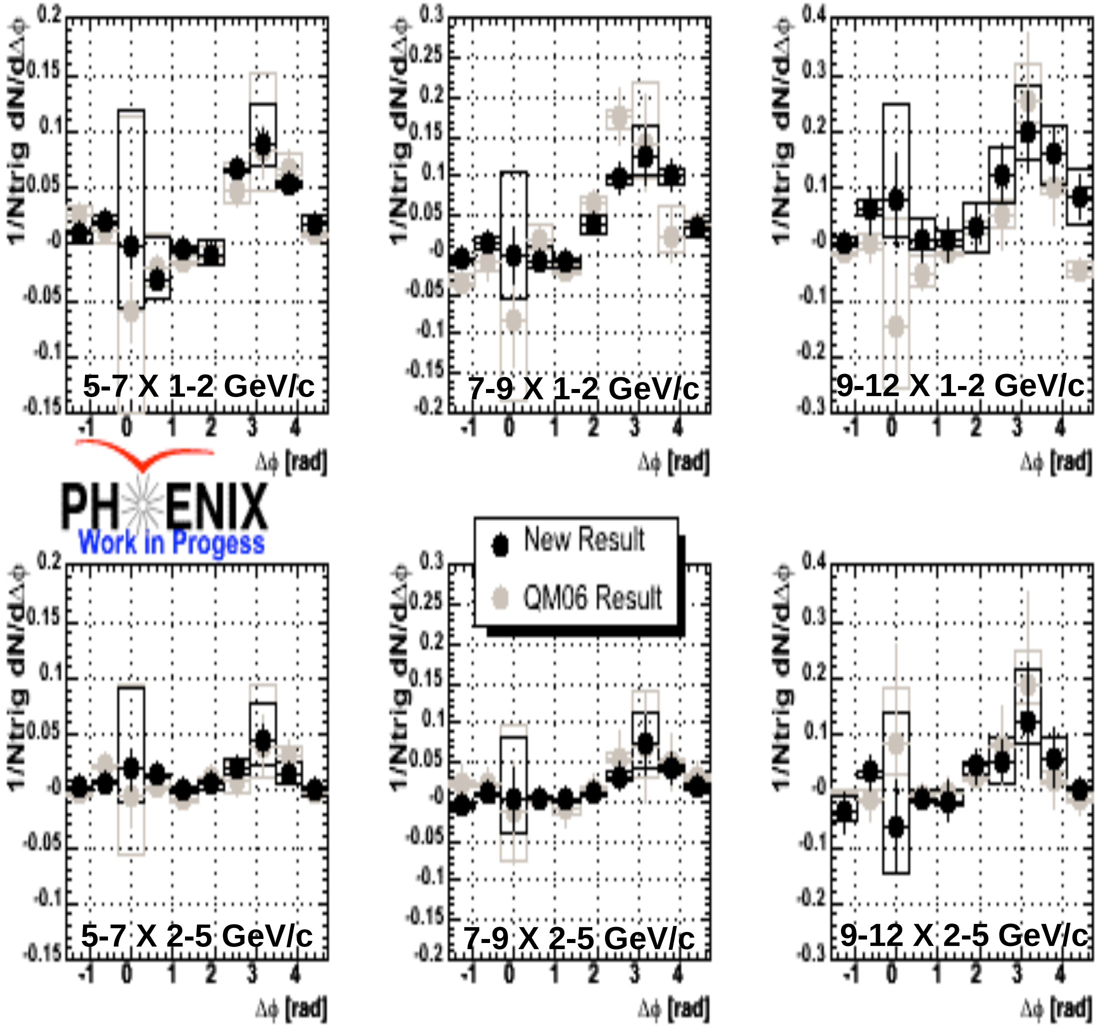
Statistical Subtraction method:

$$\gamma_{\mathrm{direct}} = \gamma_{\mathrm{all}} - \gamma_{\mathrm{decay}}$$

Matthew Nguyen
APS Spring Meeting, April 15, 2007

- Signature small near-side correlation signal apparent
- Yield sensitive to η contribution at the near-side
- Still room for some fragmentation contribution

Run 5 p+p @ 200 GeV



Summary

Inclusive and two-particle correlation measurement in the high-p_T sector at RHIC opened a new window into a QGP physics. LHC will be an ideal laboratory - larger xsection and center-of-mass energy available for hard-probes production.

As a next goal after "day one" physics: di-hadron and direct photon-h correlations - base line measurement for nuclear modification study:

- k_T and initial/final state QCD radiation, resummation vs NLO
- j_T near-side jet shape modifications (Carlos talk)
- fragmentation function - can be measured using jets - not from the first data. Despite our expectation FF is not accessible in di-hadron correlations. FF can be extracted from direct photons correlation only at relatively high trigger-photon momenta.

We are at the beginning of hard-probes exploration in heavy ion environment - LHC will be fun!