Direct photon and high-pT π^0 Correlations at RHIC and LHC

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Motivation

pQCD jet quenching :

- ❑ **Similar suppression pa ttern** of high-p_T electrons from semi-leptonic ***D* and *B* mesons decays**; PRL 91, 172302 (2003)
- ❑ **No broadening of the associated correlation peak** (nucl-ex/051000) in contrast to "standard picture" e.g. Phys. Lett. **B630**, 78 (2005)
- ❑ **Induced gluon radiation should violate the x_T scaling**, not seen in π^0 seen in $h^{\pm}$.   E.g. *Brodsky, Pirner and Raufeisen*, hep-ph/0510315.
- ❑ Why **NLO pQCD** work **without k_T** ?

Detailed understanding of "unmodified" parton properties in p+p is crucial

p+p data @ RHIC and LHC

- Fragmentation function D(z)
- Jet shape

$\langle j_T \rangle$ jet fragmentation transverse momentum

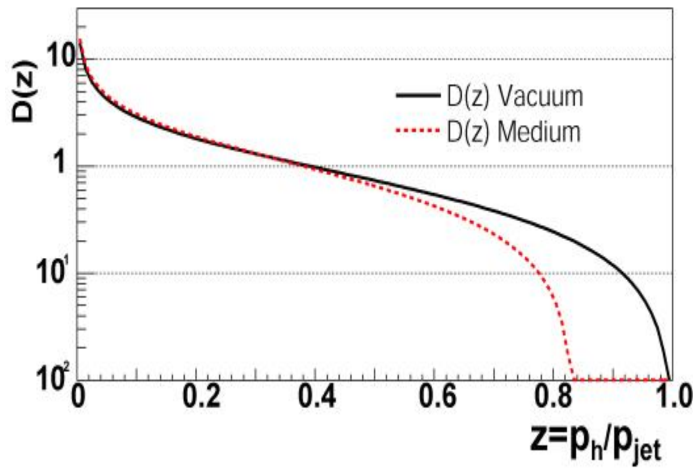
$\langle k_T \rangle$ parton transverse momentum

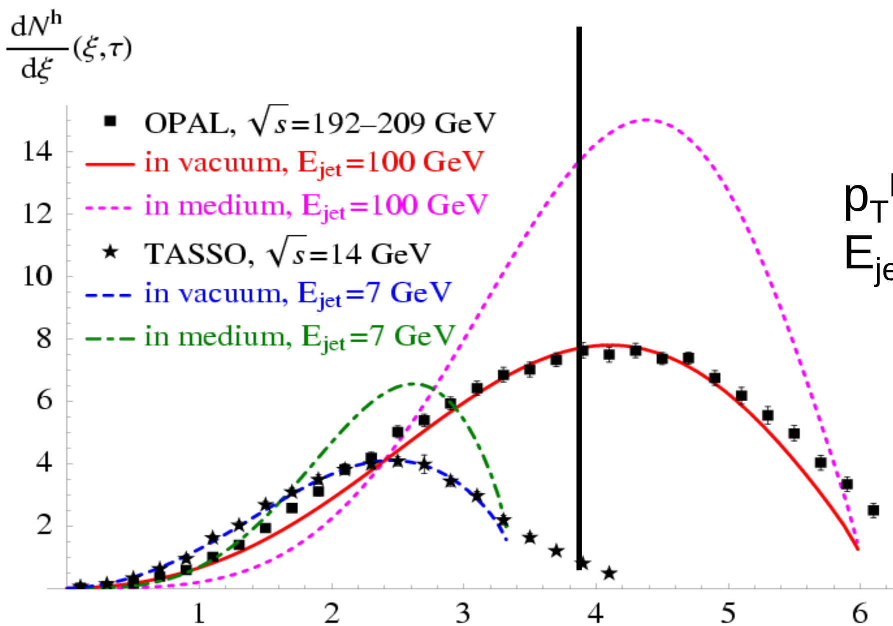
pQCD quenching - modification of D(z)

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

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

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





Borghini and Wiedemann, hep-ph/0506218

p_T^{hadron}~2 GeV for

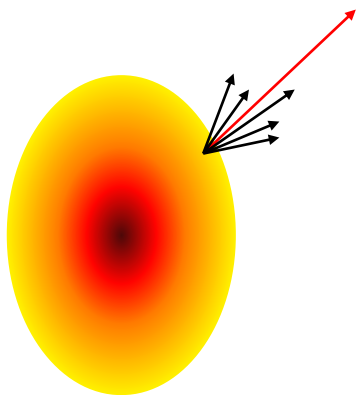
E_{jet}=100 GeV

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

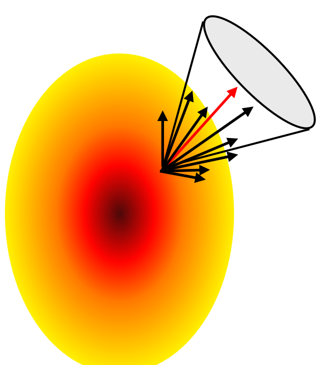
Fragmentation strongly modified at p_T^{hadron}~1-5 GeV even for the highest energy jets

Width of Away-Side Peaks - where is broadening ?

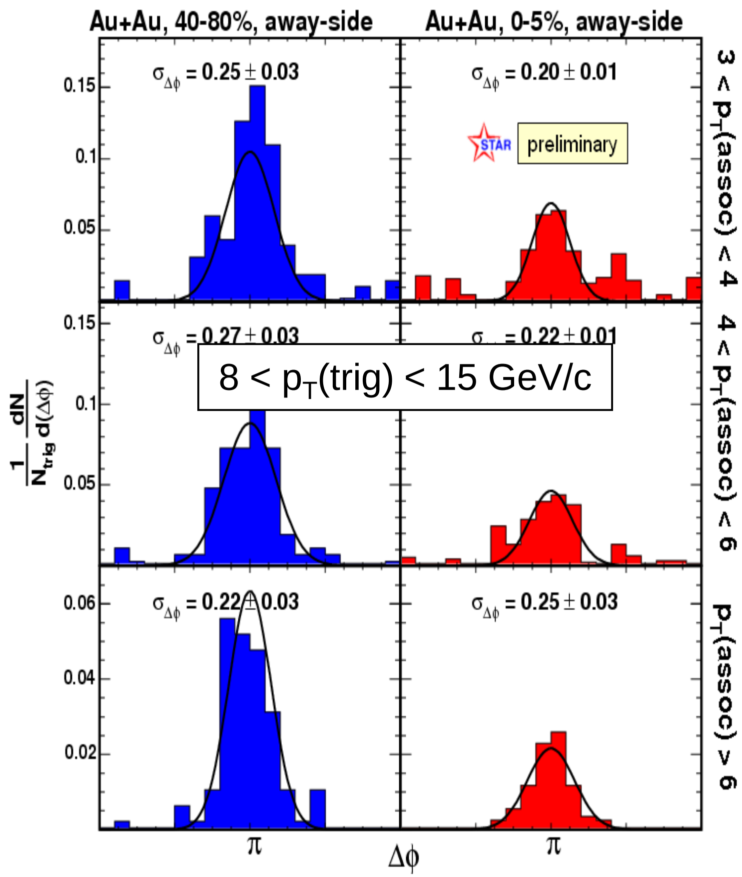
Leading Particle



Reconstructed Jet

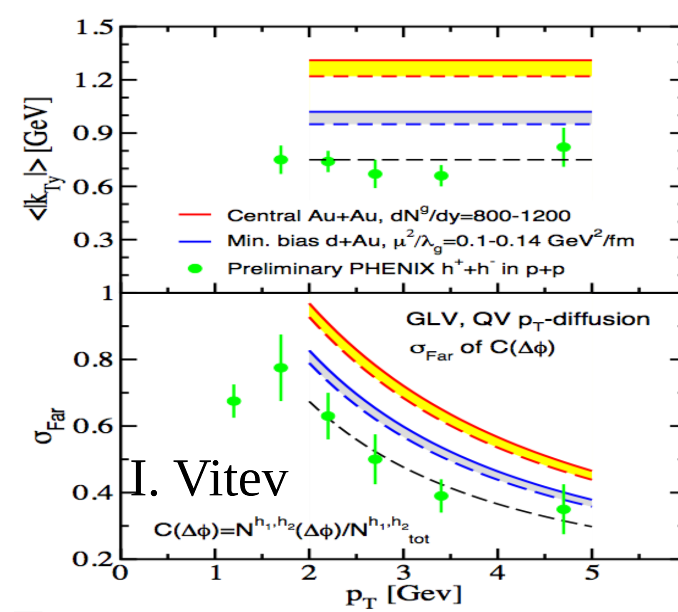


STAR nucl-ex/0604018



- **away-side widths similar for central and peripheral**
  - d+Au 0.24+-0.07 rad
  - Au+Au 20-40% 0.20+-0.02 rad
  - Au+Au 0-5% 0.22+-0.02 rad
- **Where is the jet broadening at RHIC? How about LHC?**

nucl-th/0308028



k_T physics

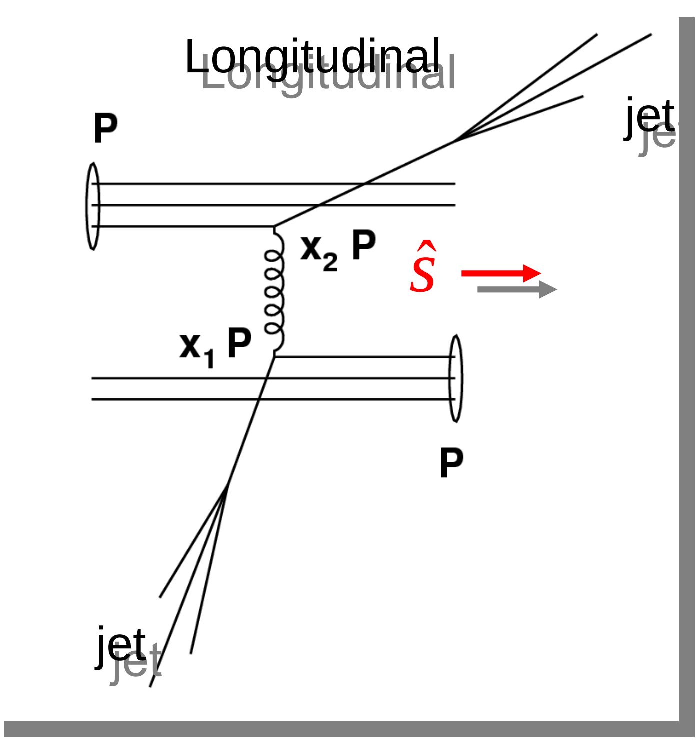
Reference to heavy ion:

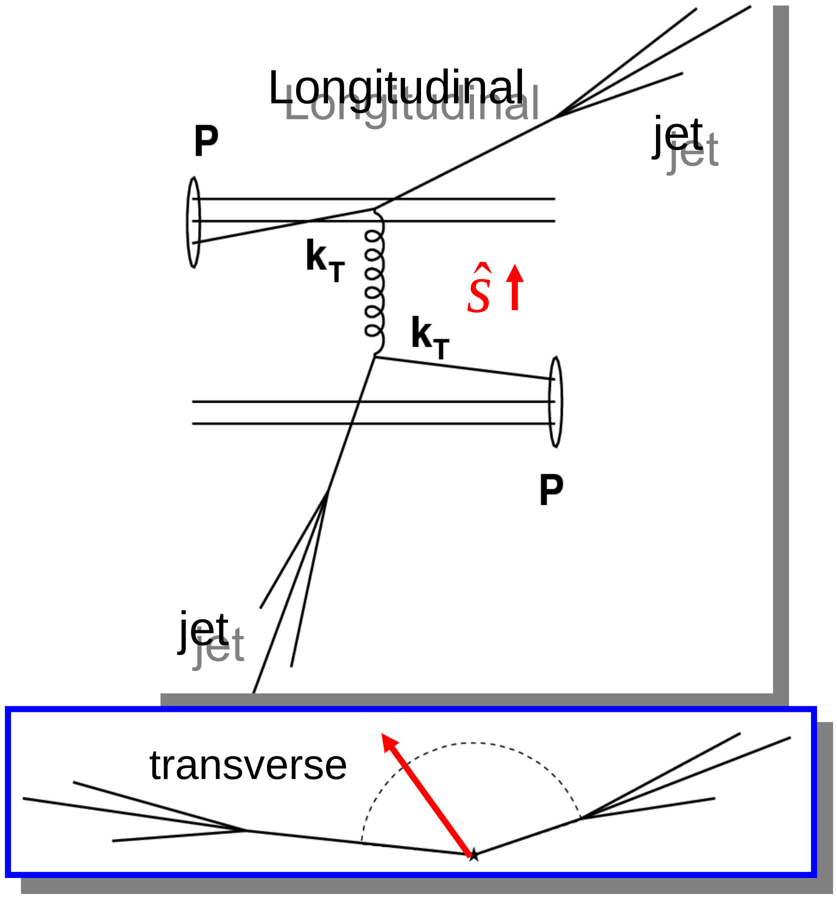
- Broadening in the “punch through” - high-pT ?
- Broadening in the “Mach cone” - low-pT ?

Understanding of (p)QCD phenomena

- $\sqrt{\langle k^2_T \rangle}$ evolution with $\sqrt{s}$.
- Resummation techniques *Vogelsang,Sterman,Keusza Nucl Phys A721,591(2003).*
- NLO physics - p_{out} distribution.

Hard scattering – k_T





- acoplanar in $P_L \times P_T$ space
- acoplanar in $P_X \times P_Y$ space

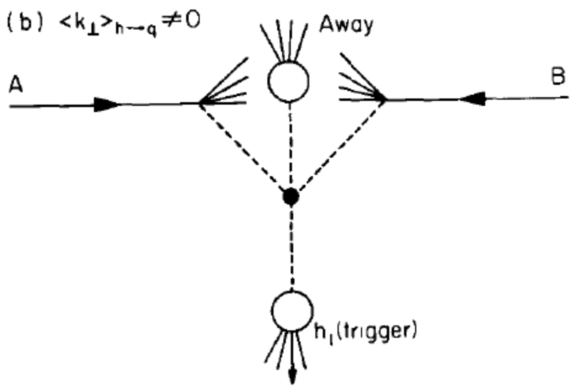
k_T measures the accoplanarity of the two back-to-back jets in transverse plane

Origin of k_T

Feynman, Field, Fox and Tannenbaum (see *Phys. Lett. 97B (1980) 163*)

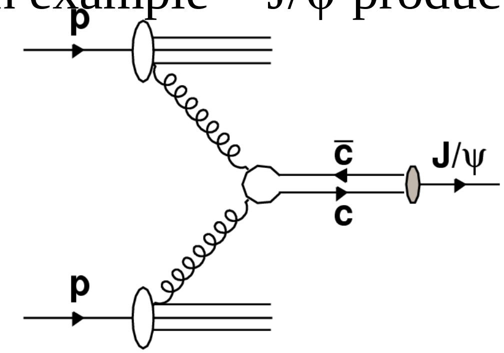
Intrinsic k_T "fermi motion"

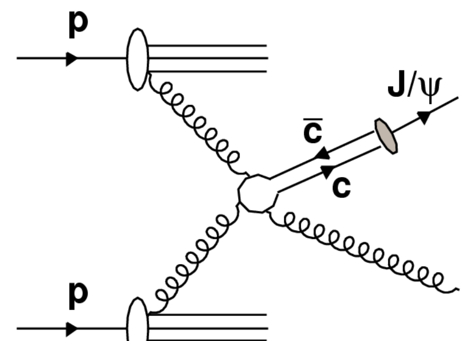
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.



Soft QCD NLO radiation.

As an example - J/ψ production.





Power law tail @
large value of $p_{T,pair}$

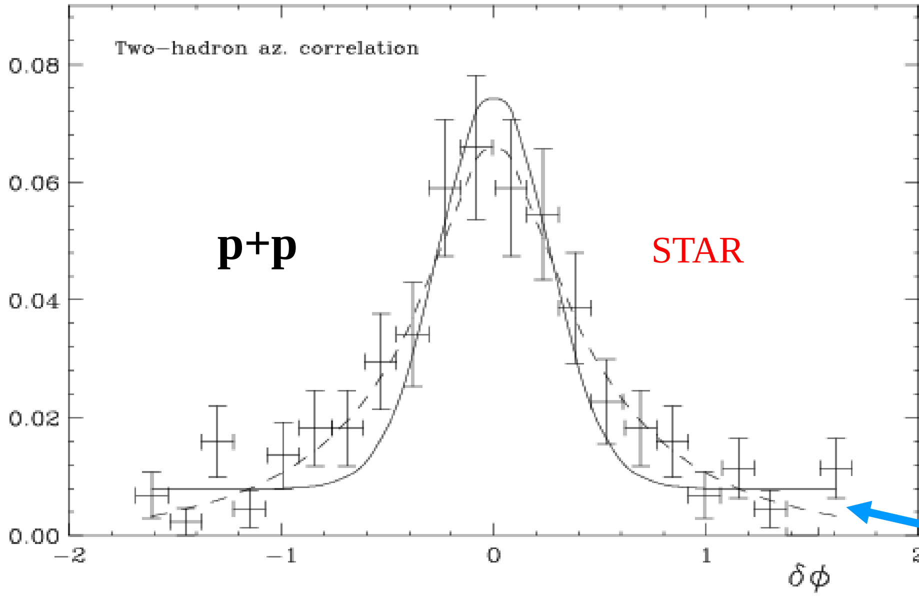
$\langle p_T \rangle_{J/\psi} = 1.8 \pm 0.23 \pm 0.16$ GeV/c

Phys. Rev. Lett. 92, 051802, (2004).

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

Gussian @ $p_{T,pair} \to 0$
Leading-Log resummation
Vogelsang, Sterman, Keusza
Nucl Phys A721,591(2003)

Soft Gaussian + hard power law

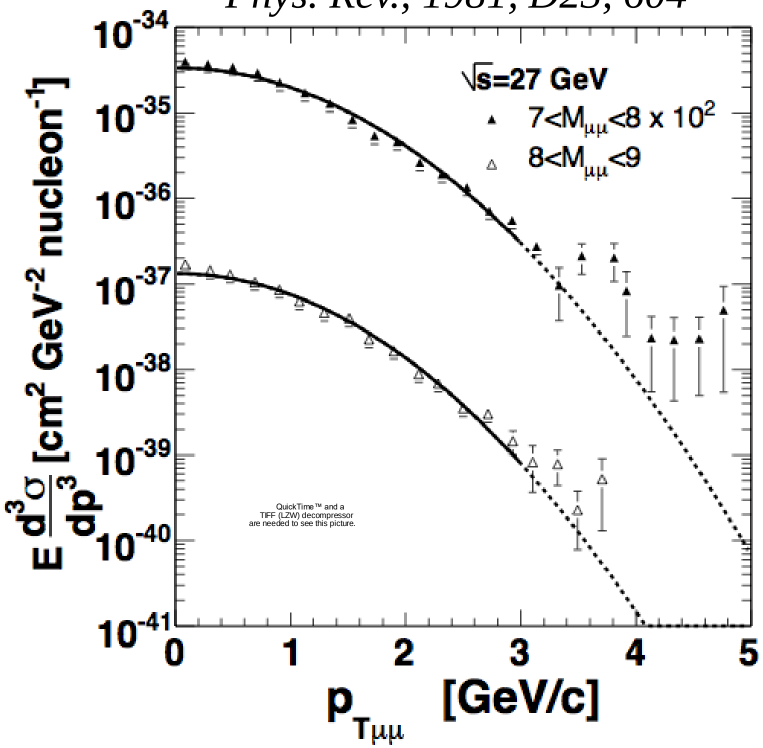


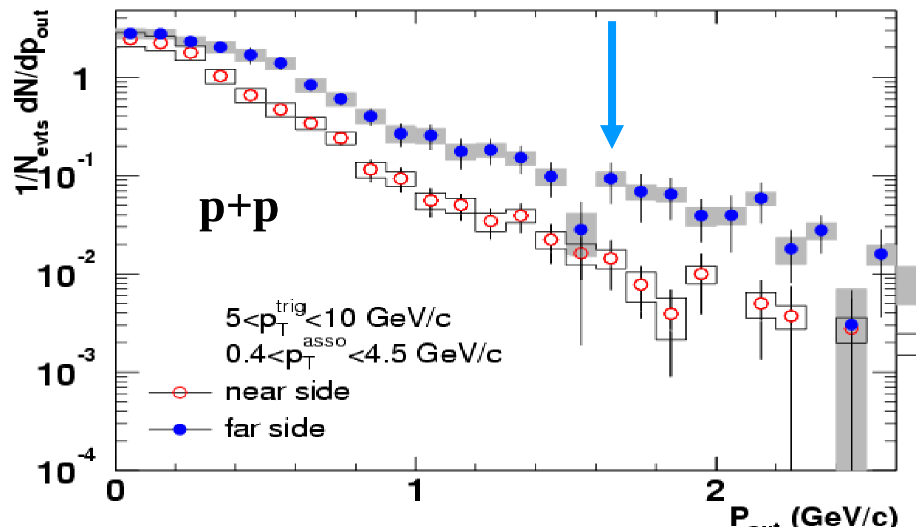
D. Boer and W. Vogelsang,
Phys. Rev. D69 (2004) 094025

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

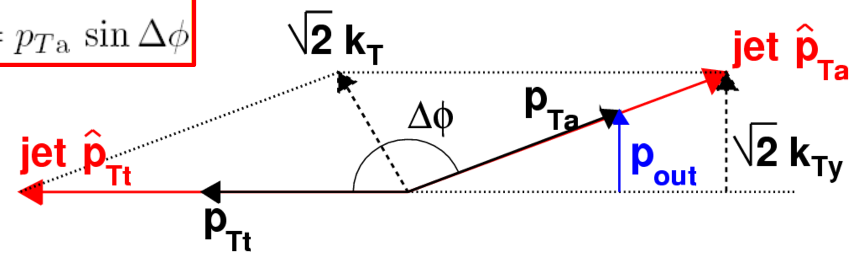
radiative tails

Phys. Rev., 1981, D23, 604

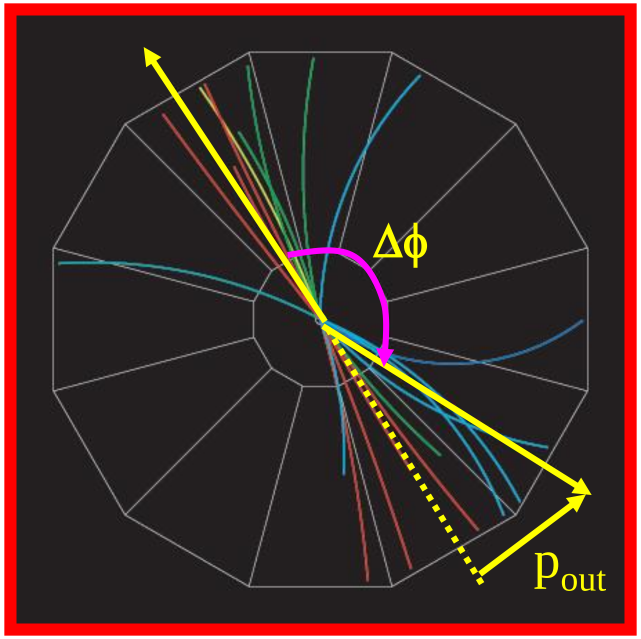




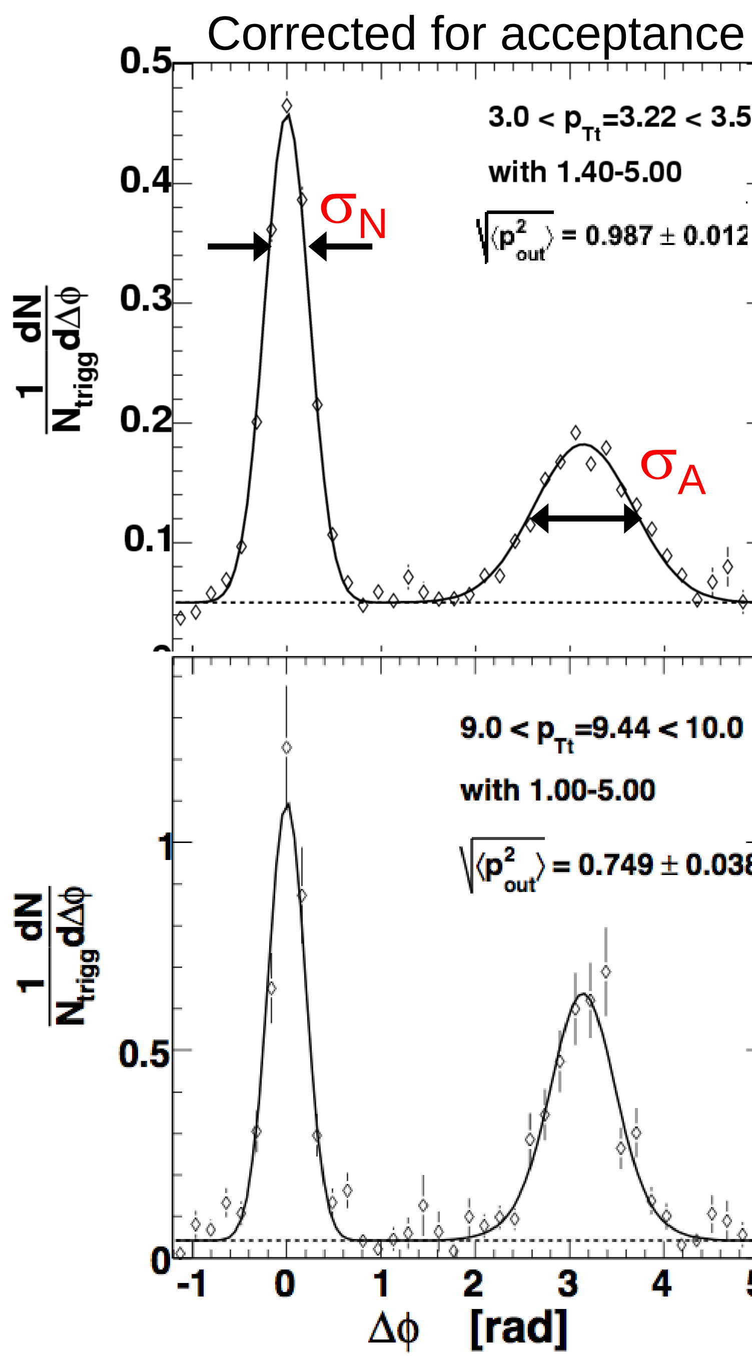
$$p_{\rm out} = p_{Ta}\ \sin \Delta\phi$$



π^0 - $h^\pm$ correlation functions p+p $\sqrt{s}$=200 GeV



p + p → jet + jet



$\sigma_N \propto \langle j_T \rangle$ jet fragmentation transverse mom.

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

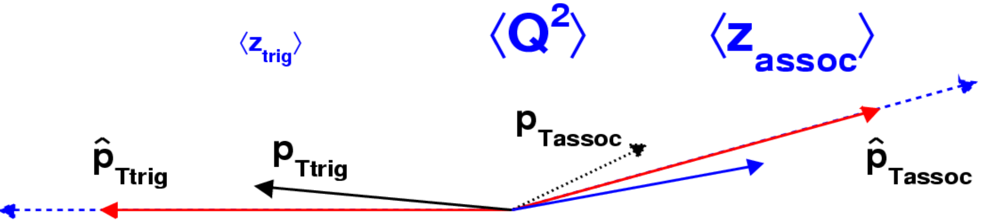
$Y_A \propto$ folding of D(z) and final state PDF.

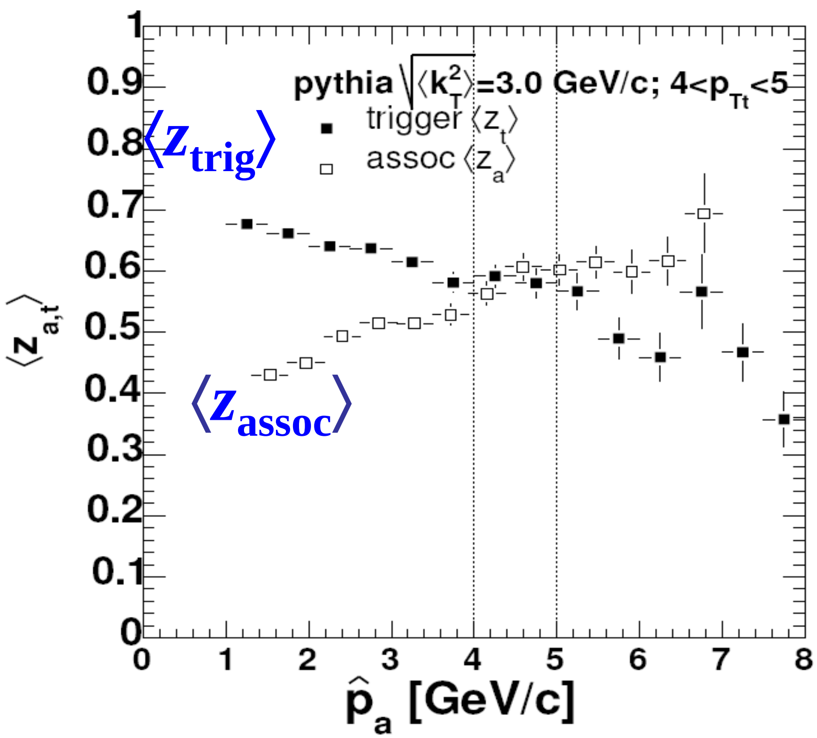
Trigger bias

There are ALWAYS two types of trigger biases when correlating $p_{Ttrigger} \neq p_{Tassoc}$

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

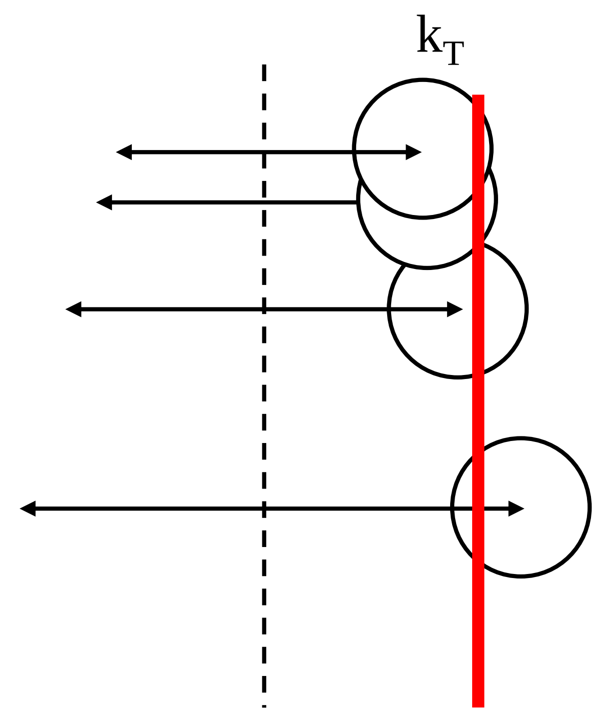
hat-x_h bias





Selecting events with $p_{Tt} > p_{Ta}$ forces k_T vector toward trigger jet:

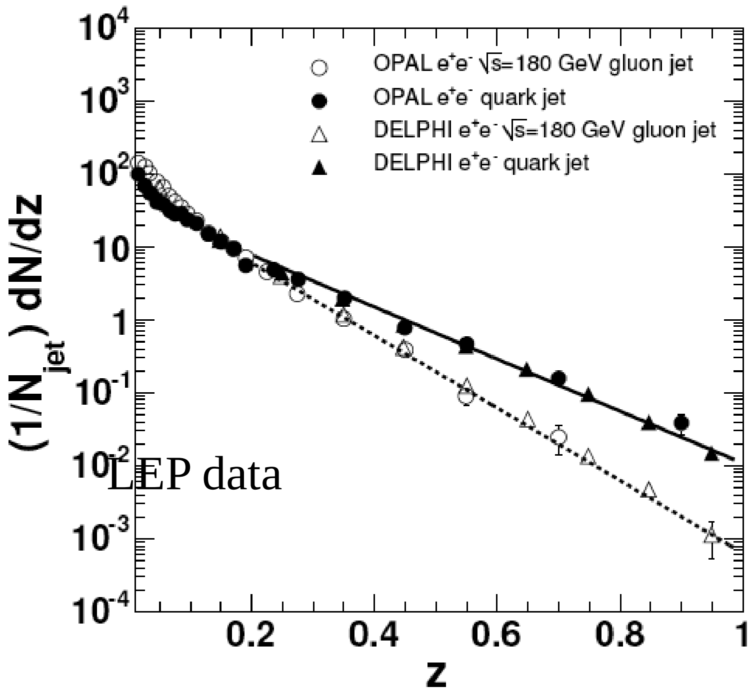
$$\langle \hat{p}_{Ttrigg} \rangle > \langle \hat{p}_{Tassoc} \rangle$$

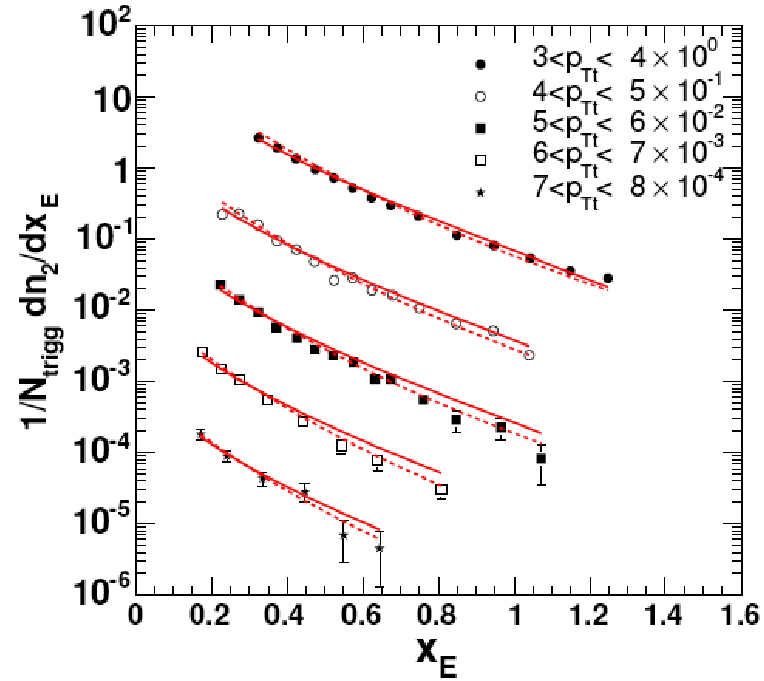


Trigger associated spectra are insensitive to $D(z)$

$$x_{\rm E} = -\frac{\vec{p}_{T{\rm t}} \cdot \vec{p}_{T{\rm a}}}{p_{T{\rm t}}^2} = -\frac{p_{T{\rm a}} \cos\Delta\phi}{p_{T{\rm t}}} \simeq \frac{z_{\rm a}\,\hat{p}_{T{\rm a}}}{z_{\rm t}\,\hat{p}_{T{\rm t}}}$$

x_E ≈? two particle equivalent of the fragmentation variable z.





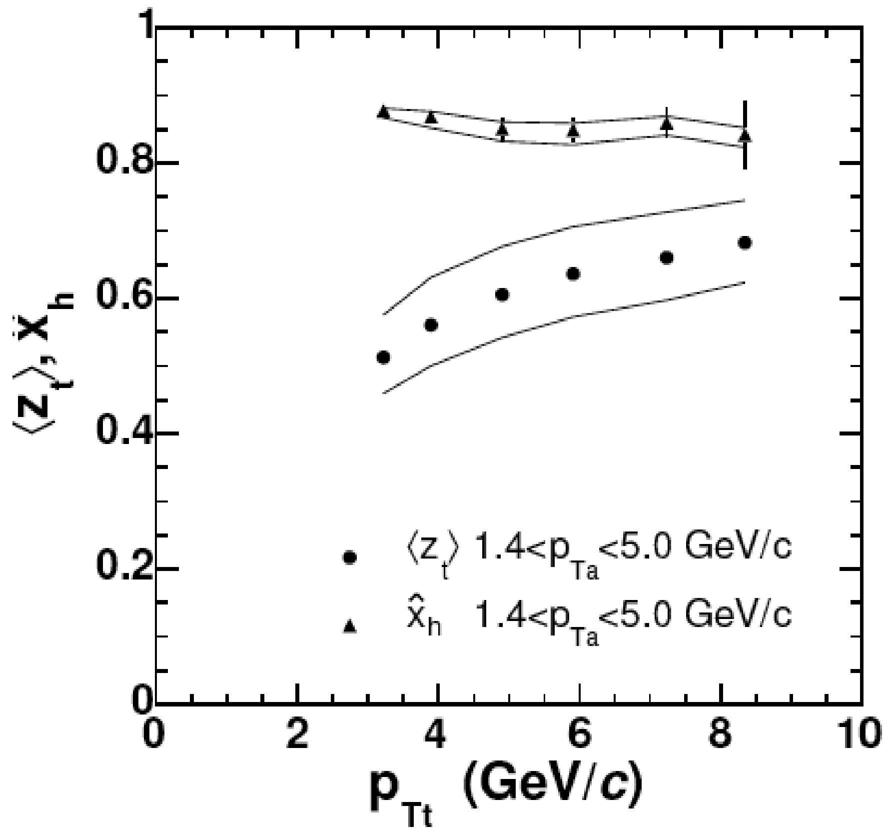
M.J. Tannenbaum Approximation - Incomplete Gamma function when assumed power law for final state PDF and exp for D(z)

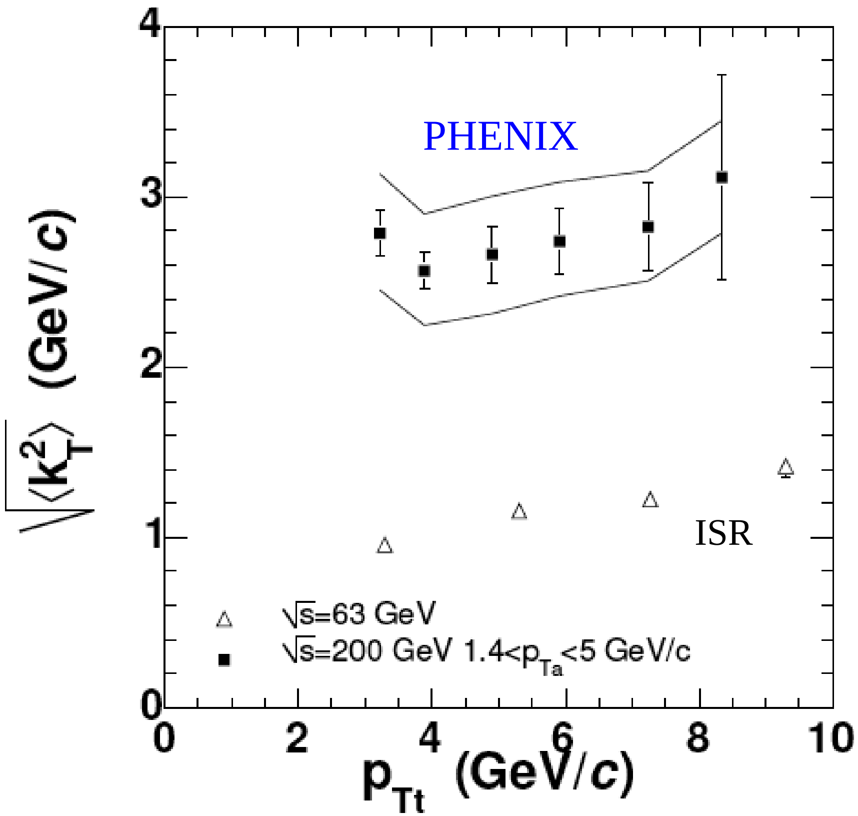
$$\frac{d\sigma_\pi}{dp_{T{\rm t}}} = \frac{1}{p_{T_{\rm t}}^{n-1}} \int_{x_{T_{\rm t}}}^{1} dz_{\rm t}\, z_{\rm t}^{n-2} \exp -b z_{\rm t}$$

$$\approx \langle m \rangle \, (n-1) \frac{1}{\hat{x}_{\rm h}} \frac{1}{(1+\frac{x_E}{\hat{x}_{\rm h}})^n}$$

$\sqrt{\langle k^2_T \rangle}$, $\langle z_t \rangle$ in p+p @ 200 GeV

We gave up an effort to extract fragmentation function from di-hadron data, direct photon analysis under way. For D(z) the LEP date were used.





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

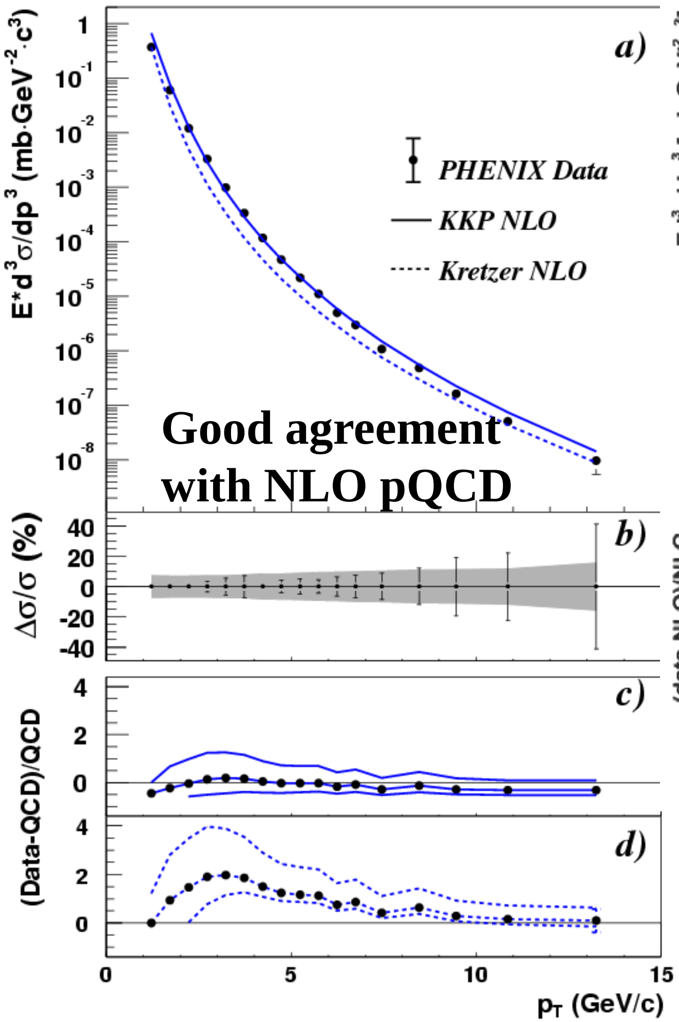
Iterative solution for each p_T bin by varying $\sqrt{\langle k^2_T \rangle}$

Systematic errors comes from unknown ratio gluon/quark jet => D(z) slope.

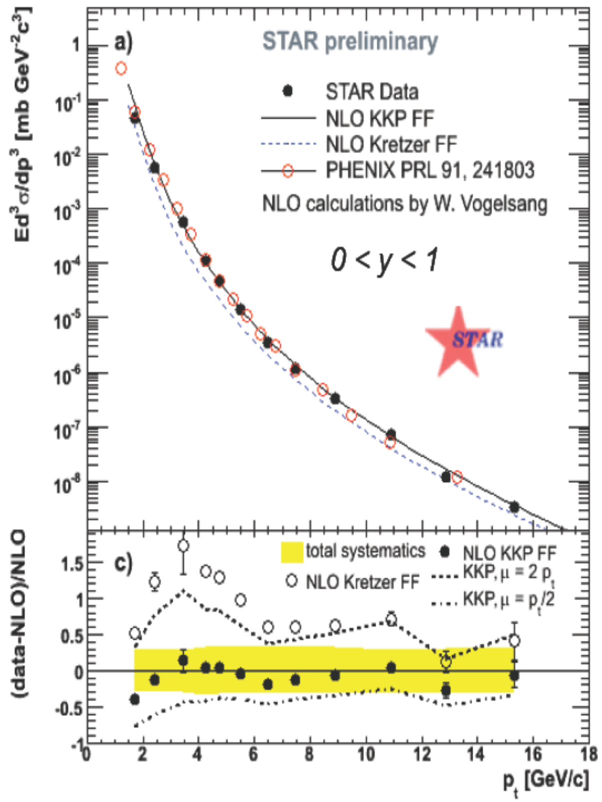
NLO at work at RHIC.

Phys.Rev.Lett.91:241803,2003

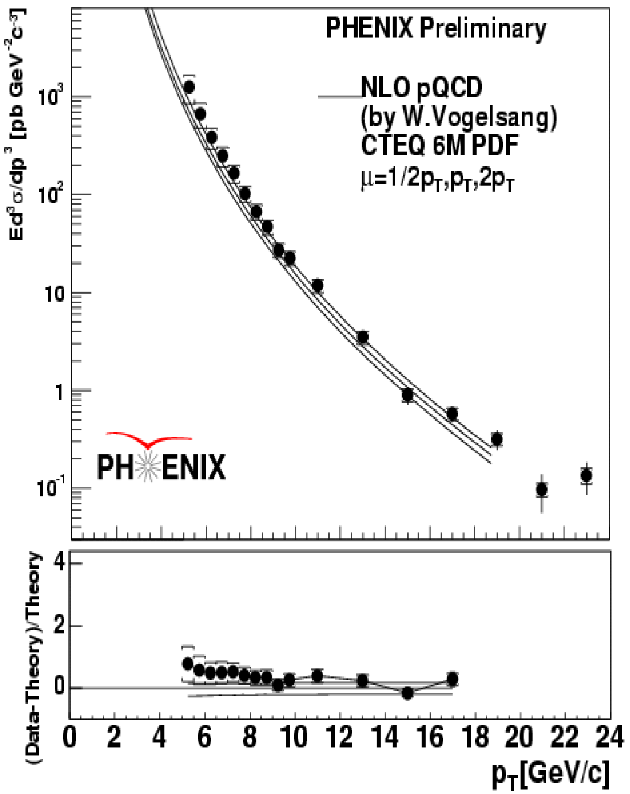
$p+p \rightarrow \pi^0+X$



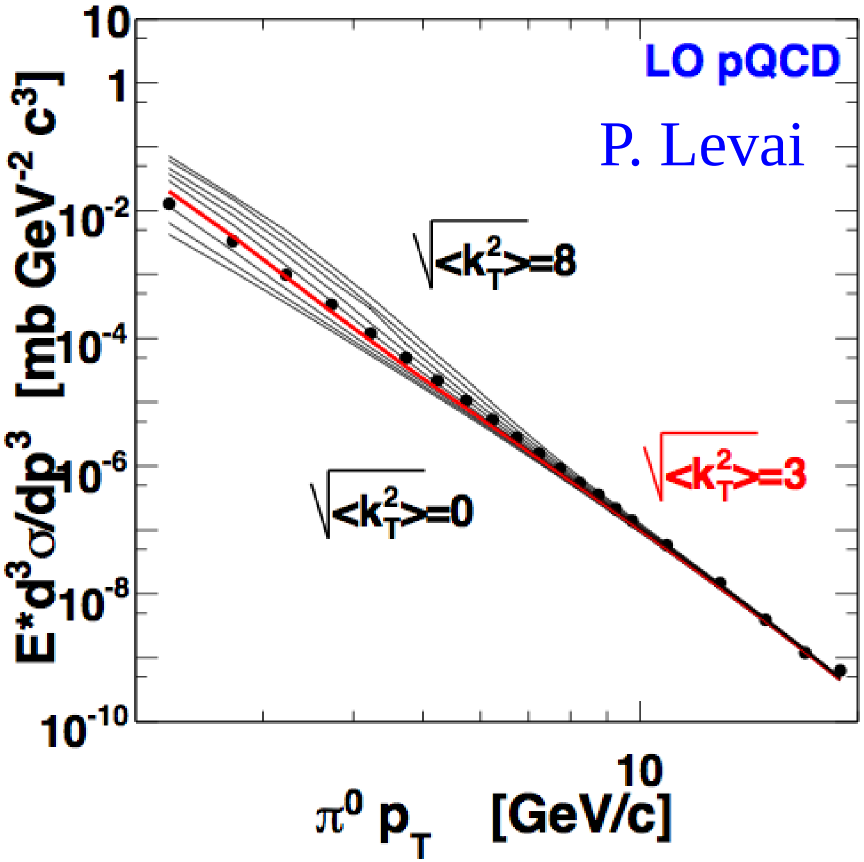
$p+p \rightarrow \pi^0+X$

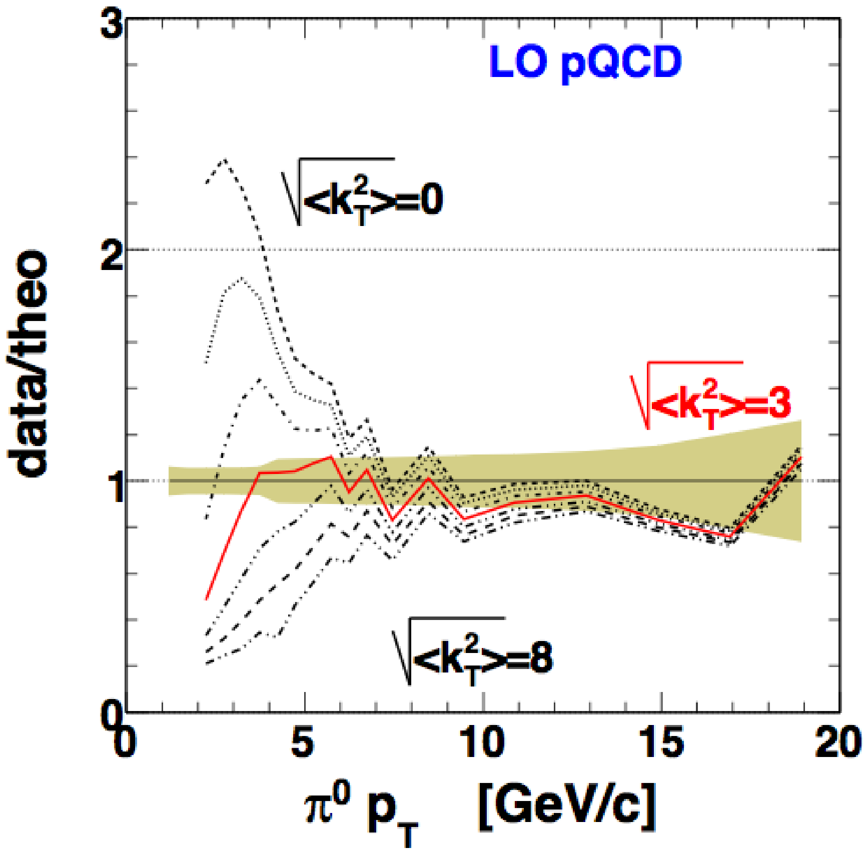


$p+p \rightarrow \gamma_{direct}+X$



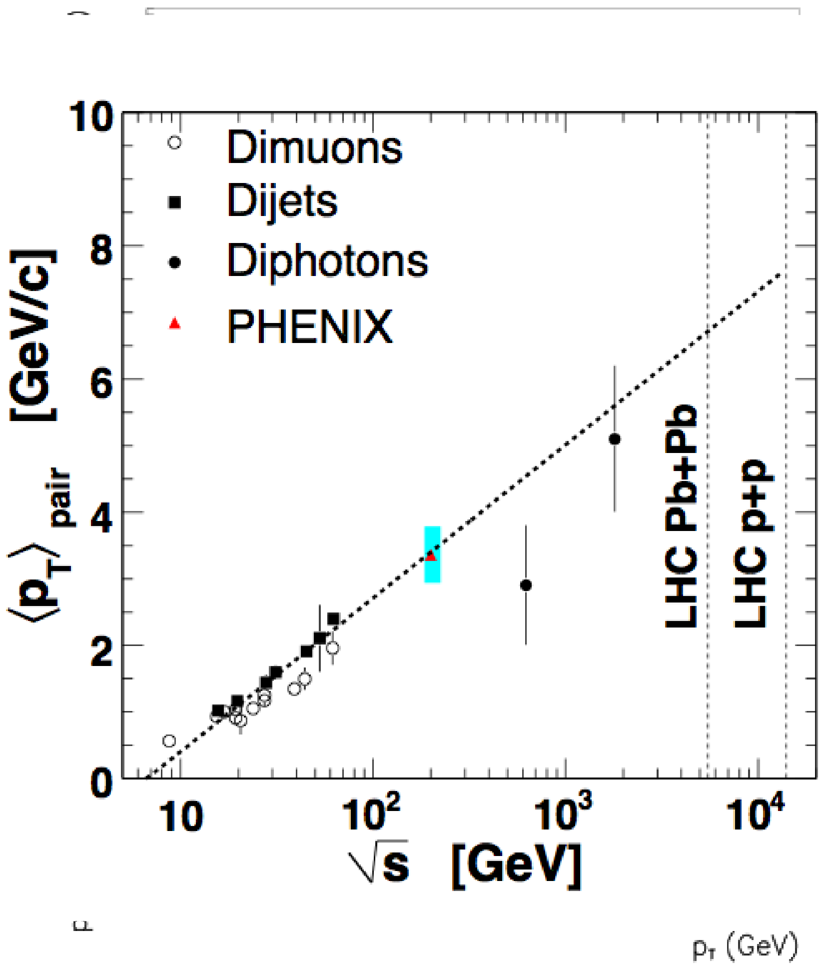
LO pQCD and inclusive yield

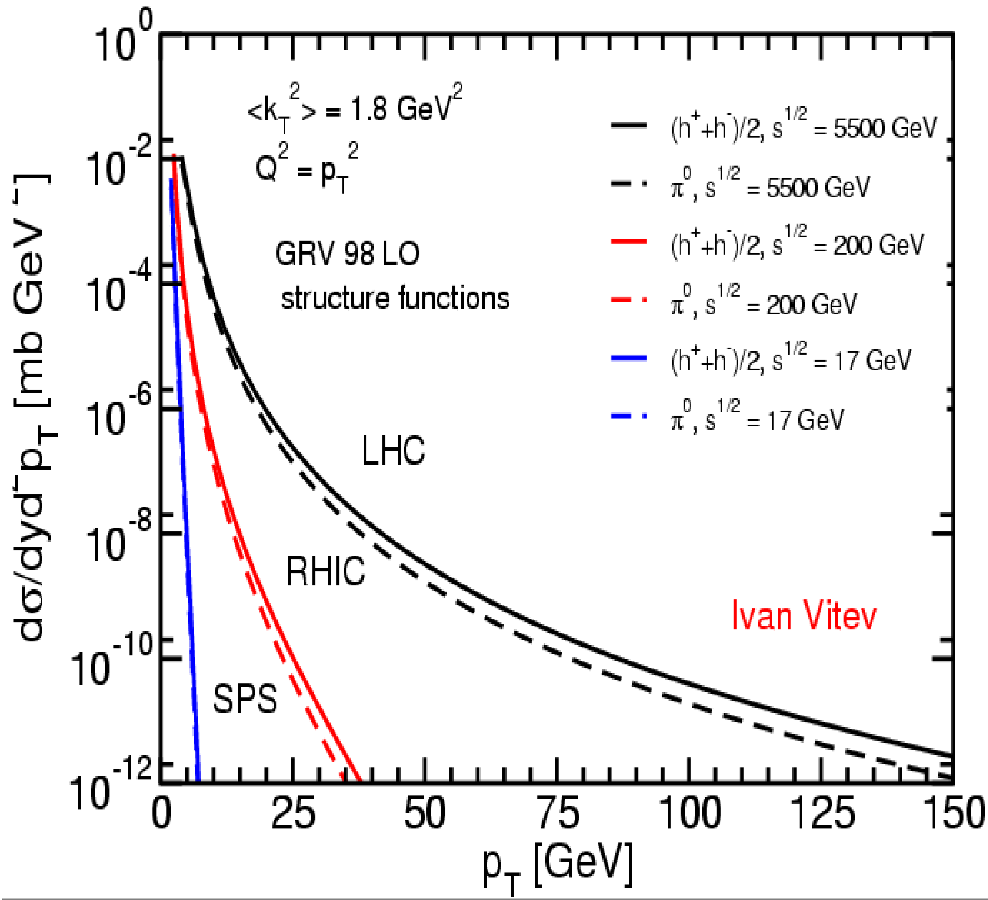




LO gets the data only when Gaussian smearing of order of $\sqrt{\langle k_T^2 \rangle} \approx 3$ GeV/c used.

High p_T: ref. for HI, detailed NLO tests

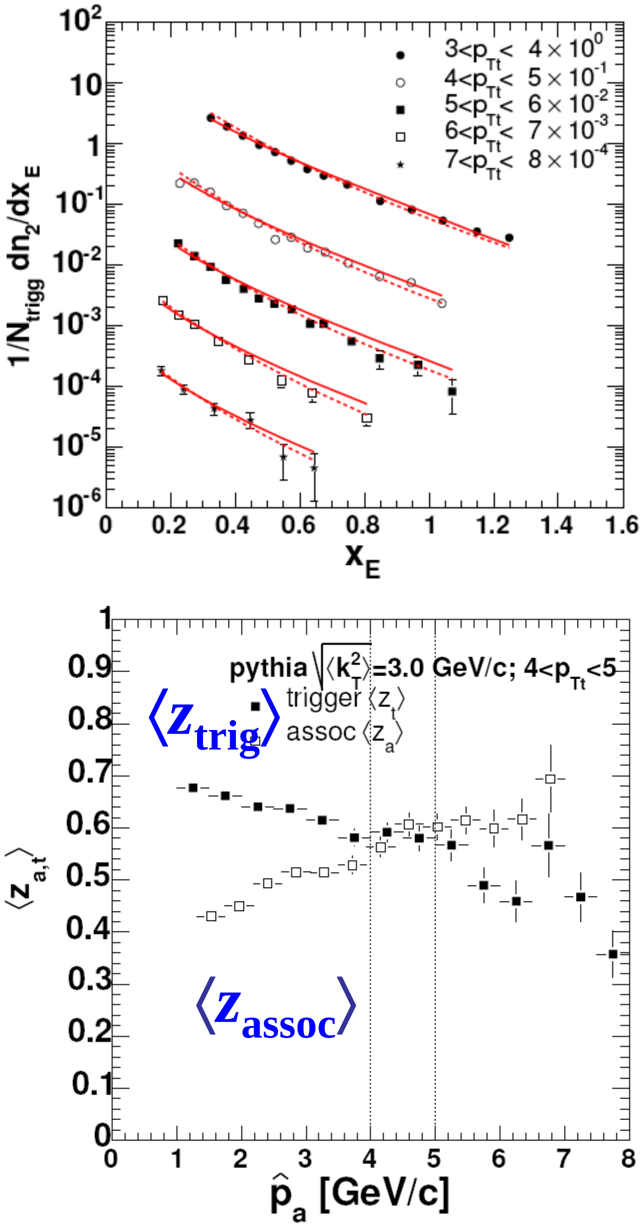




PHENIX measured $\langle p_T \rangle_{pair}$=3.36±0.09±0.43GeV/c

extrapolation to LHC $\sqrt{\langle k^2_T \rangle}$=**6.1 GeV/c**

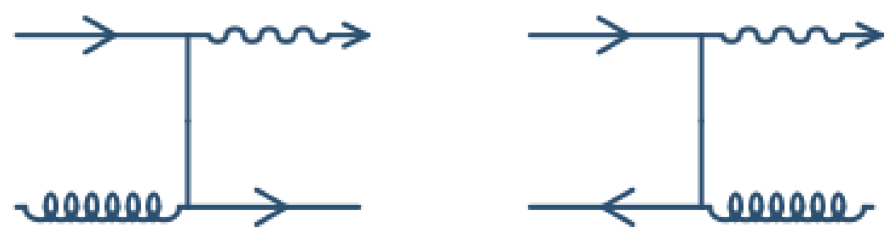
Trigger γ associated spectra are sensitive to *D(z)*



Di-hadron correlations

$$\frac{d^2\sigma}{dp_{Tt}dx_E} = \frac{dp_{Ta}}{dx_E} \otimes \frac{d^2\sigma}{dp_{Tt}dp_{Ta}} \approx \frac{1}{\hat{x}_h} \int_{xTt}^{\hat{x}.pTt/pTa} D(z_t) D(\frac{z_t p_{Ta}}{\hat{x}_h p_{Tt}}) \Sigma^{'}(\frac{p_{Tt}}{z_t}) dz_t$$

Direct photon correlations $D(z_t) \rightarrow \delta(z_t)$



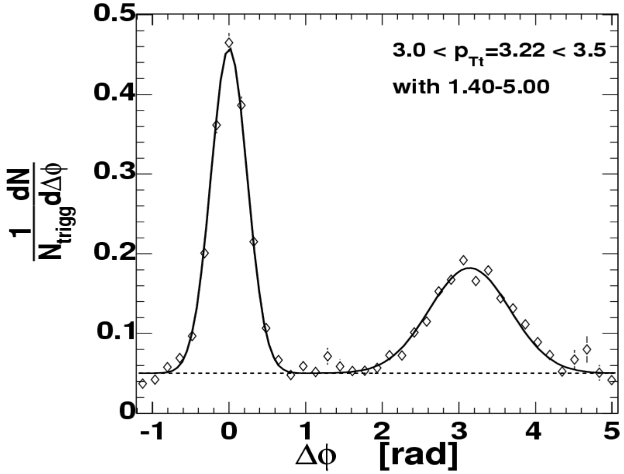
$$\frac{d^2\sigma}{dp_{Tt}dx_E} = \frac{dp_{Ta}}{dx_E} \otimes \frac{d^2\sigma}{dp_{Tt}dp_{Ta}} \approx \frac{1}{\hat{p}_{Ta}} \Sigma^{'}\left(\frac{p_{Ta}}{\hat{p}_{Ta}}\right) D\left(\frac{p_{Ta}}{\hat{p}_{Ta}}\right)$$

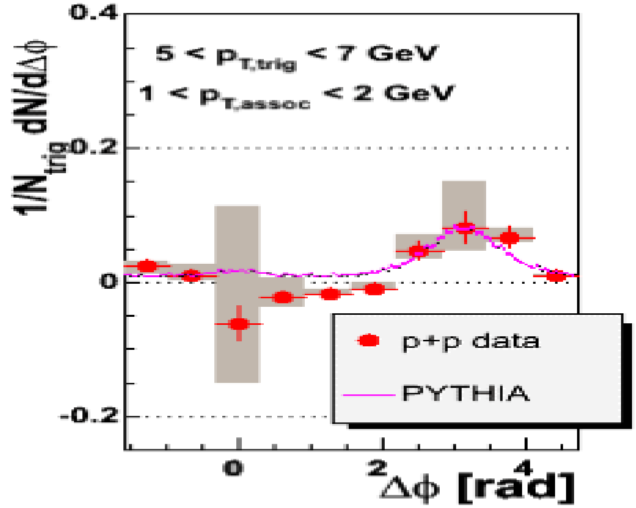
No trigger bias - associated spectra reflect the actual Fragmentation Function

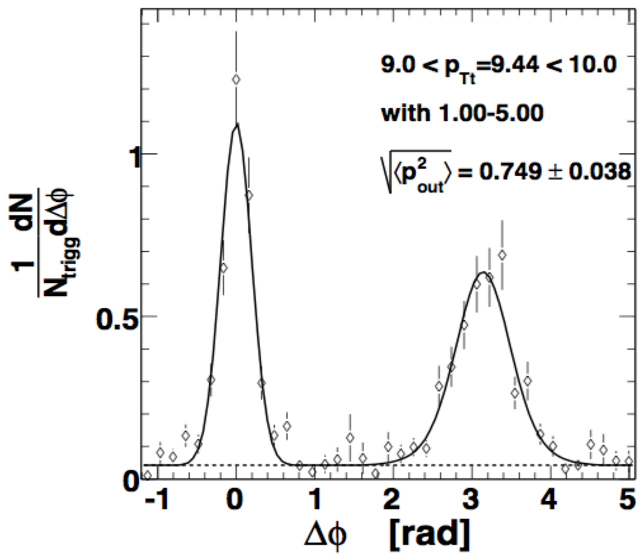
π^0-h vs Direct γ-h correlation functions

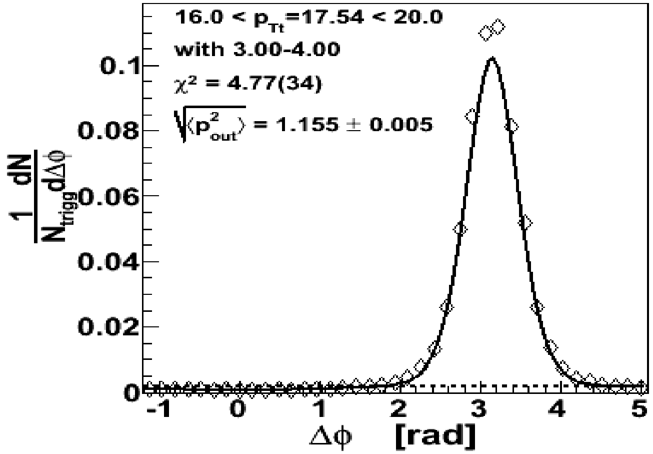
π0-h (Data)

Direct γ-h(PYTHIA)

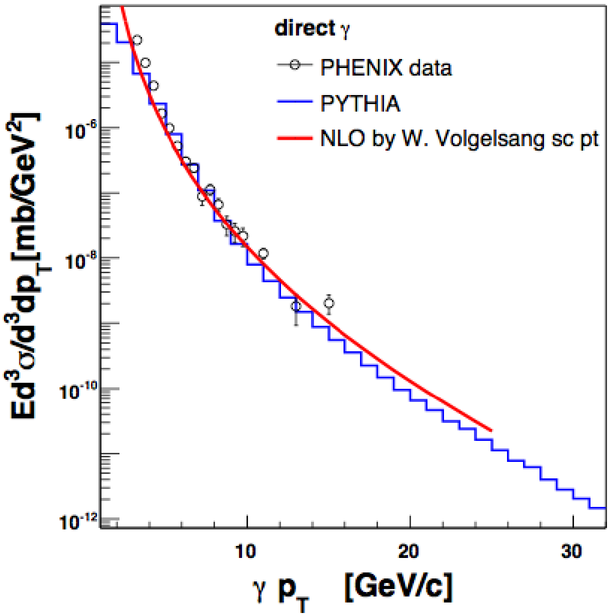


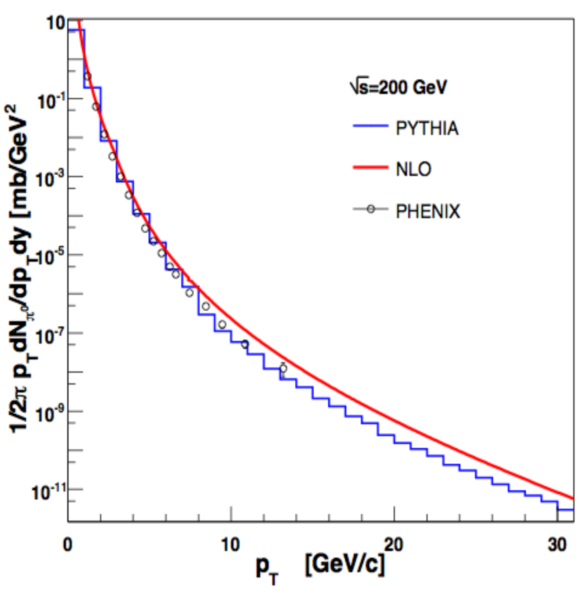




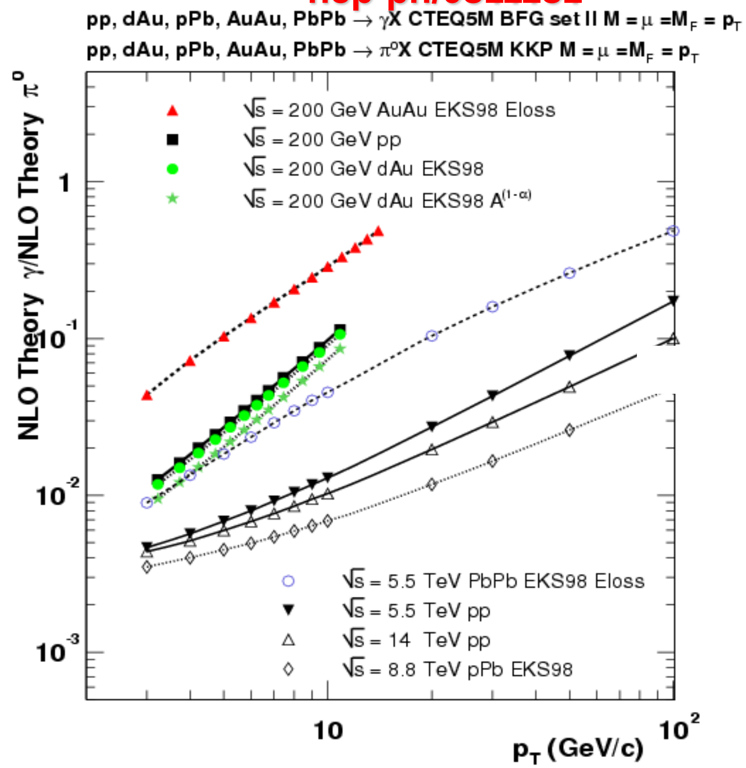


Direct photon measurement





hep-ph/0311131



Very Challenging measurement: $\gamma/\pi^0 < 0.1$ in accessible kinematic region

How to construct direct γ-h yield

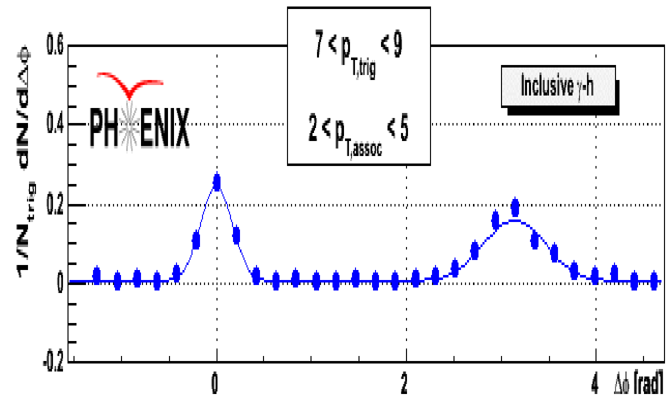
i. Construct inclusive γ-h yield

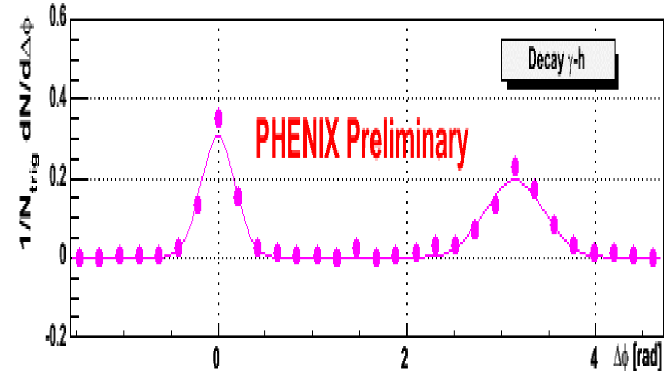
ii. Construct decay γ-h yield via:

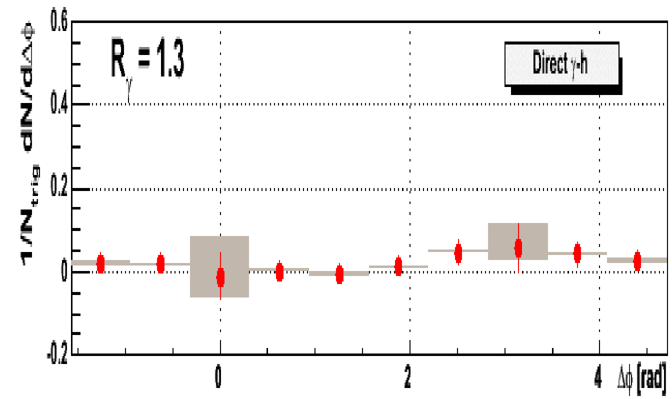
- ❖ **Pair by pair weighted summation method**
  - convolutes all π^0-h pair contributions from higher p_T
  - Weight reflects the probability from kinematics for a π^0 at given p_T to decay into a photon in a given p_T range

iii. Subtraction via:

$$Y_{dir-h} = \frac{1}{1-1/R}\left(Y_{inc-h} - \frac{1}{R}Y_{dec-h}\right)$$



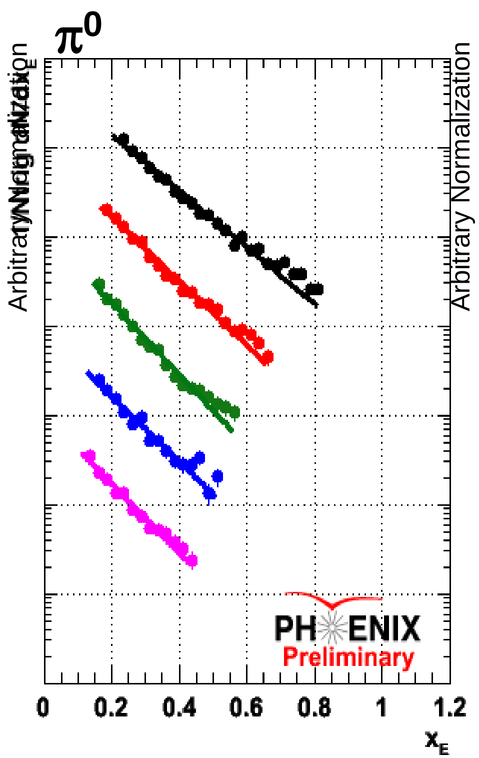


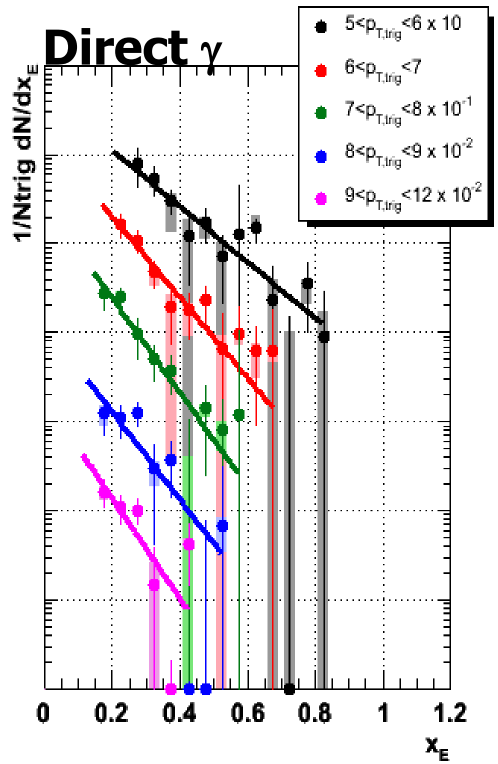


PHENIX √s=200 GeV π^0 and dir-γ assoc. distributions

APS Spring Meeting, April 15, 2007

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



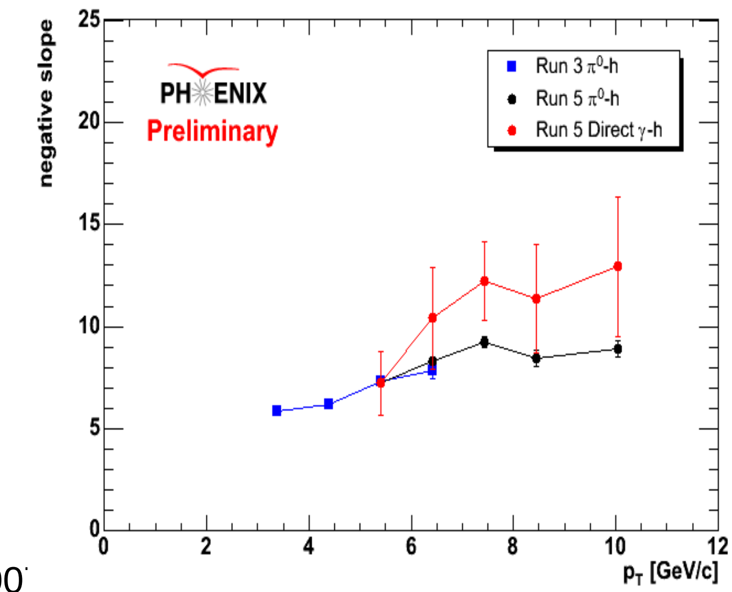


Run 5 p+p @ 200 GeV

Statistical Subtraction Method

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

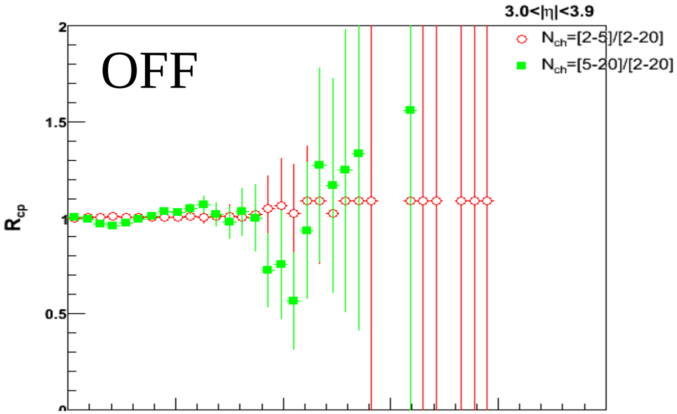
If $dN/dx_E \propto dN/dz$ then the local slope should be $p_{T\gamma}$ independent.

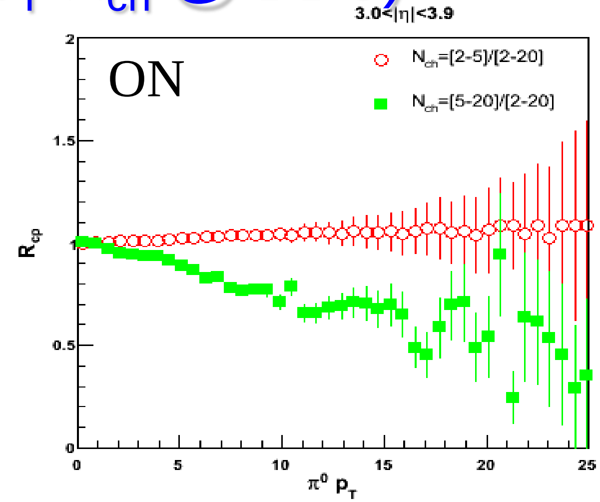


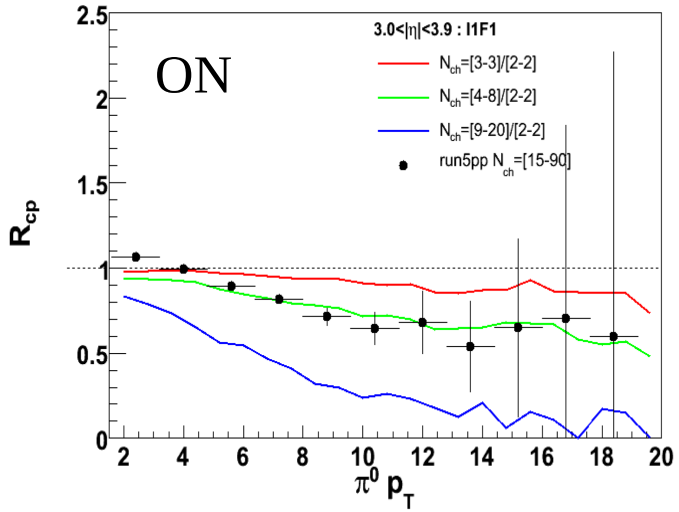
Initial/Final State Radiation (ex)

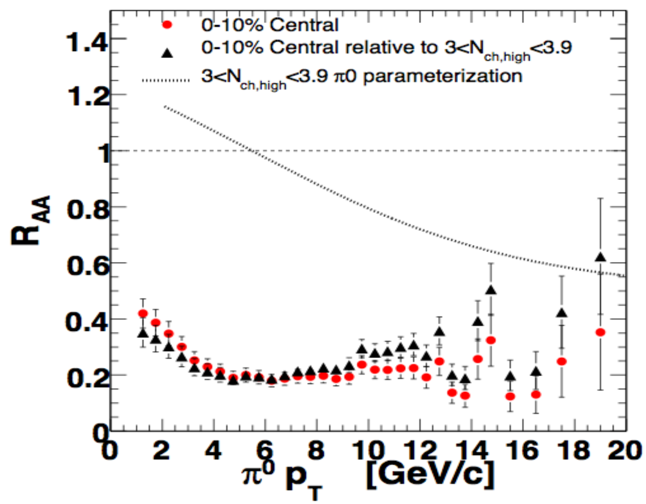
(High-p_T π^0) x (low-p_T N_{ch} @ BBC)

PYTHIA







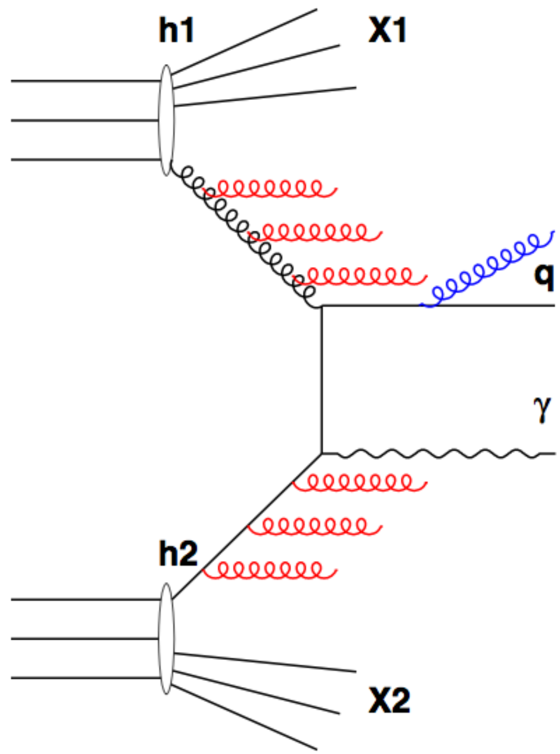


A Caution should be taken into for "Jet-Quenching model"

Soft + hard QCD radiation k_T phenomenology

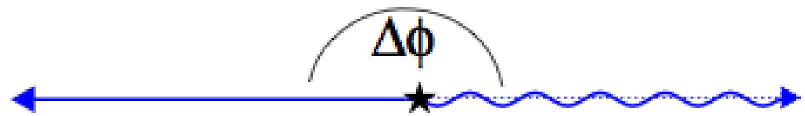
Compton photo-production

$$q + g \to \text{quark}(\hat{q}_T) + \text{photon}(p_{T\gamma})$$



Back-to-back balanced

$$\frac{d\sigma}{d\Delta\varphi} = \delta(\varphi - \pi) \qquad \left.\frac{d\sigma}{d\hat{q}_T}\right|_{p_{T\gamma}} = \delta(\hat{q}_T - p_{T\gamma})$$

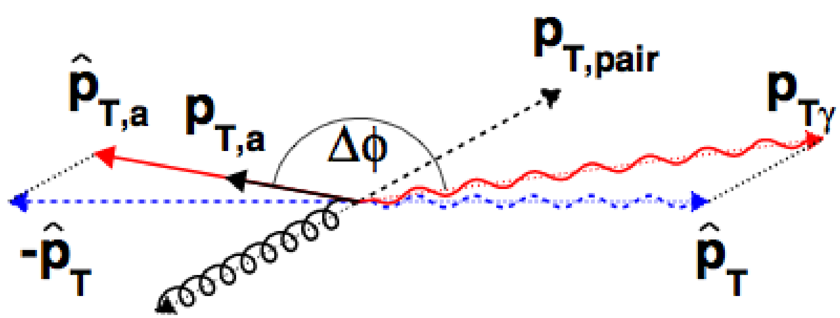


Soft QCD radiation

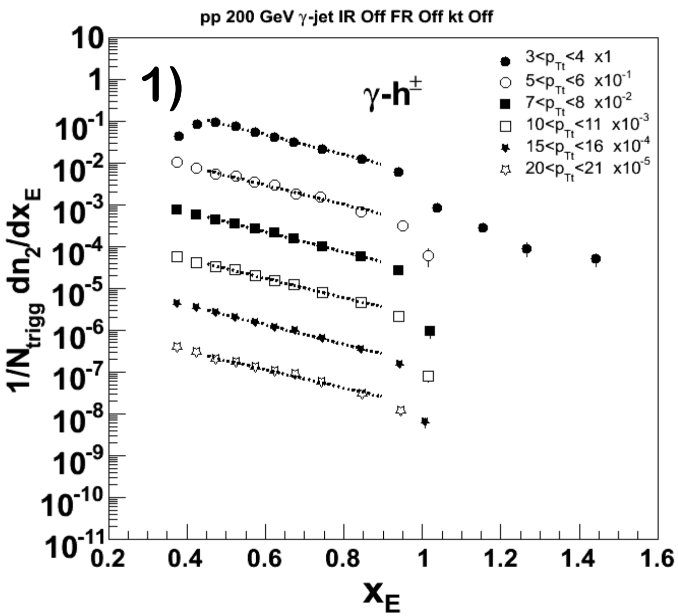
$$\frac{d\sigma}{d\Delta\varphi} \propto Gauss(\Delta\varphi) \qquad \left.\frac{d\sigma}{d\hat{q}_T}\right|_{p_{T\gamma}} \propto Gauss(p_{T\gamma})$$

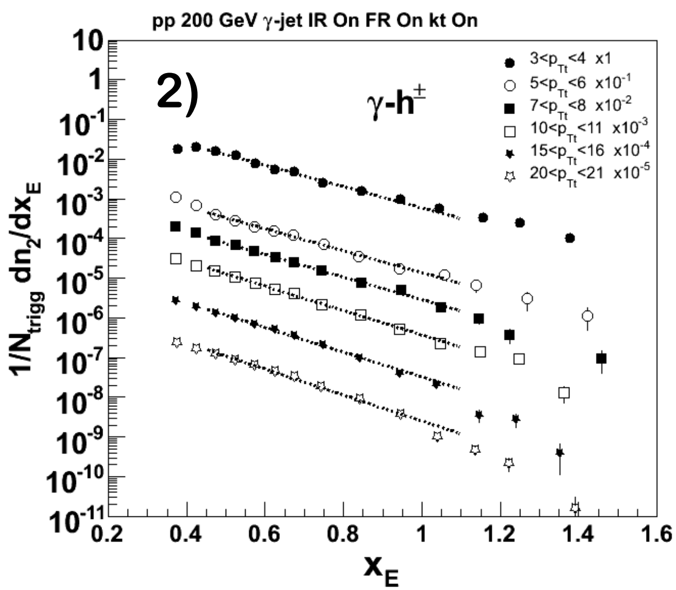
Hard NLO radiation not in PYTHIA

$$\frac{d\sigma}{d\Delta\varphi} \propto \frac{1}{\Delta\varphi^{-n}} \qquad \left.\frac{d\sigma}{d\hat{q}_T}\right|_{p_{T\gamma}} \propto \frac{1}{p_{T\gamma}^{\;-n}}$$



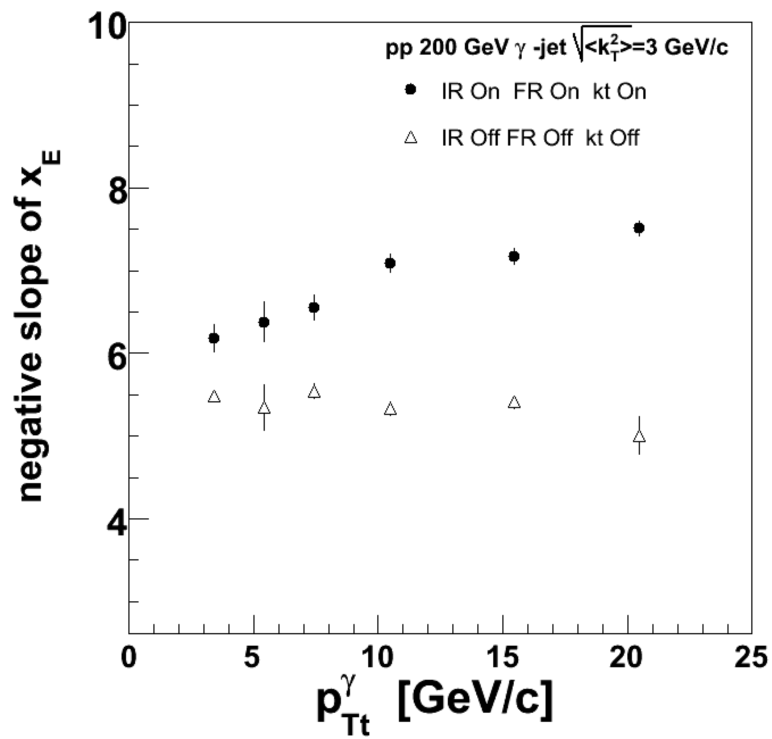
PYTHIA γ-h simulations





1) Initial State Radiation/Final State Radiation OFF, $\sqrt{\langle k_T \rangle^2}=0$ GeV/c

x_E slope is constant

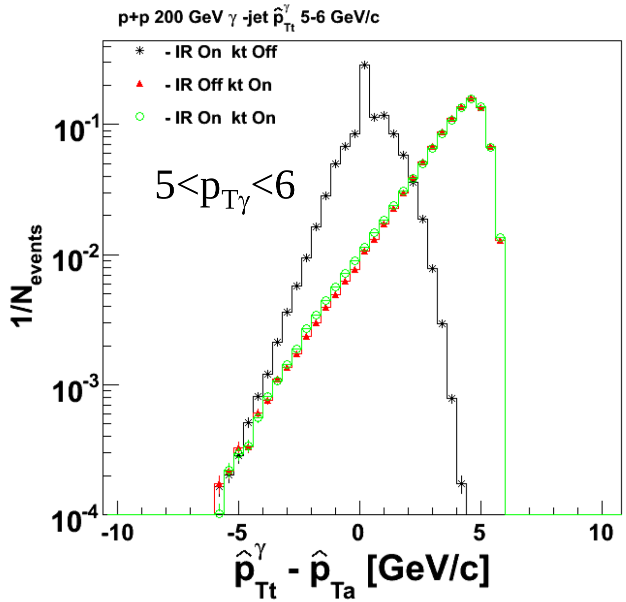


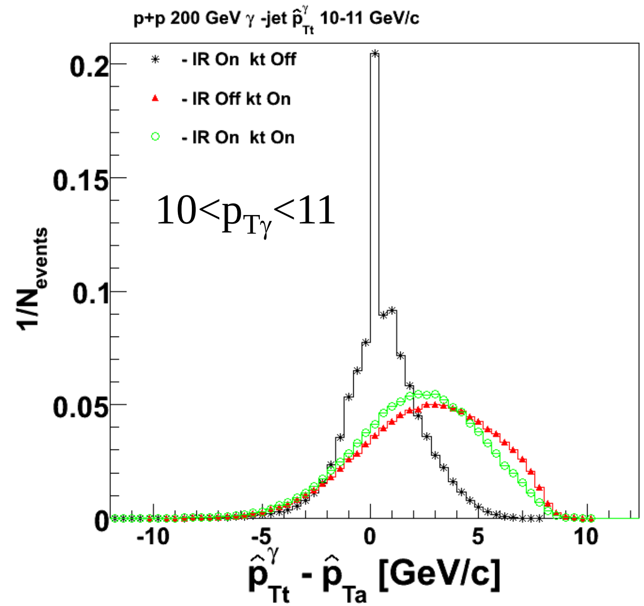
2) IR/FR ON, $\sqrt{\langle k_T \rangle^2}= 3$ GeV/c

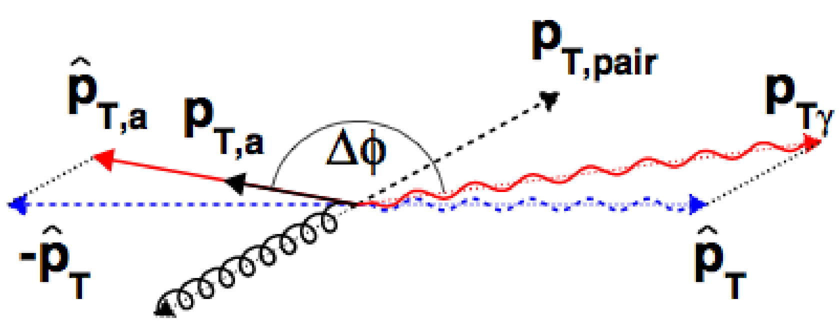
x_E slope is raising!

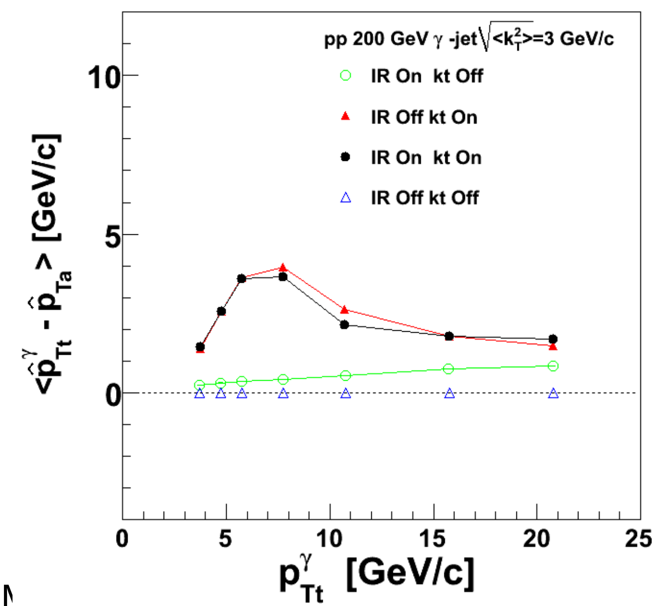
Also PYTHIA shows the same trend, though, not as large as in the data, not so trivial even with Direct photons

PYTHIA γ-h simulation - mom. imbalance

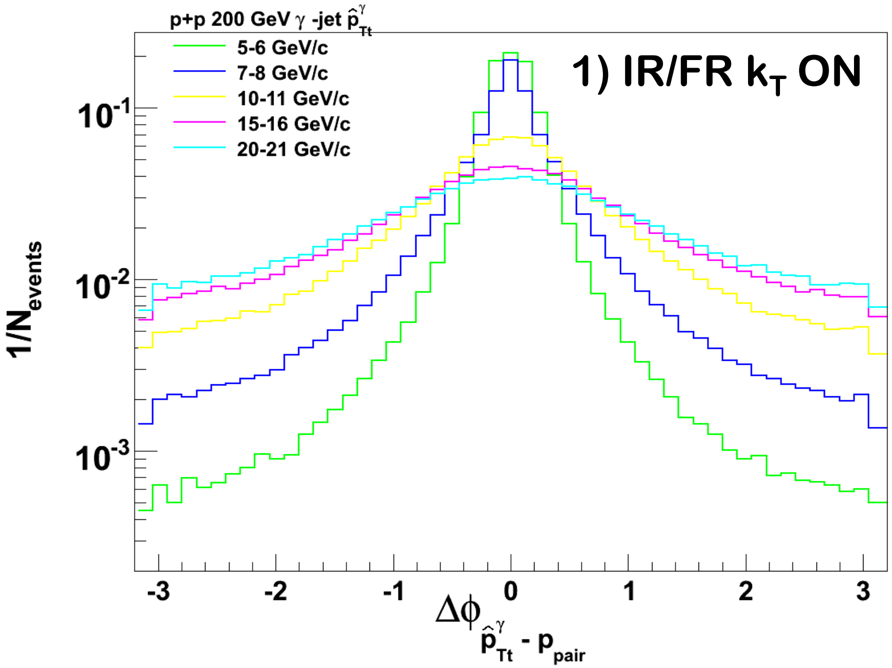


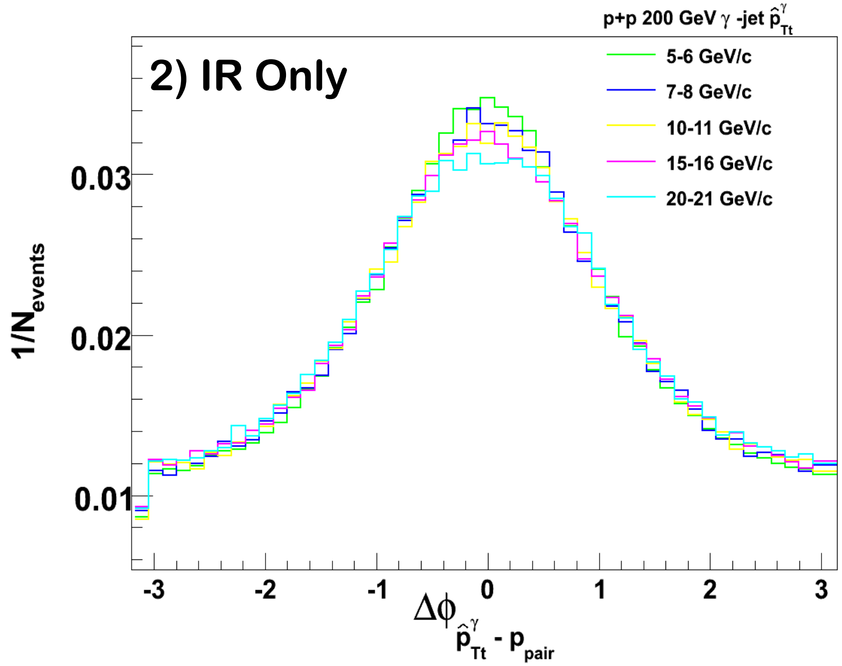


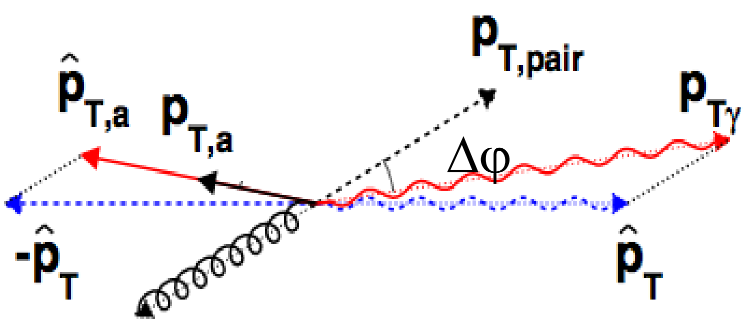




PYTHIA γ-h simulation $p_{T,pair}$ - γ correlation





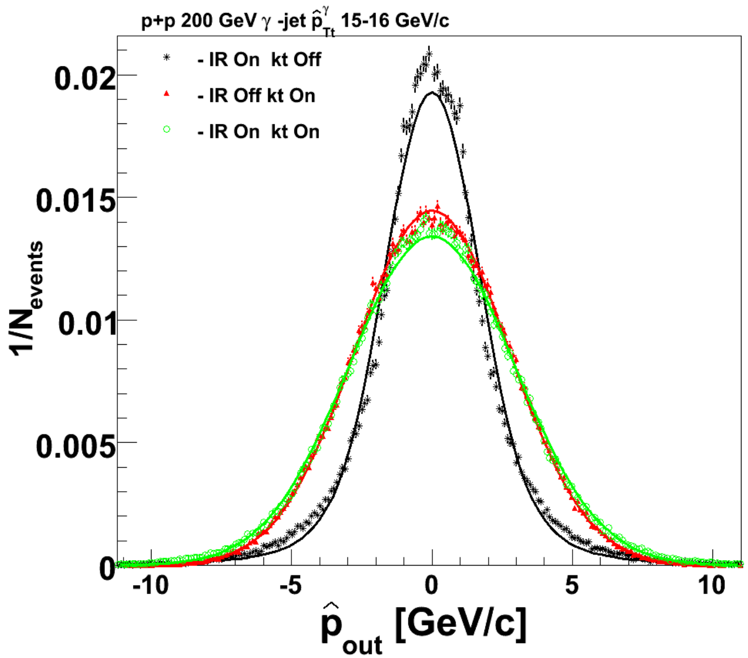


1) $p_{T,pair}$ correlated with trigger photon.
(IR/FR ,k_T : “ON”)

2) Not in the case of “Initial State Radiation”.

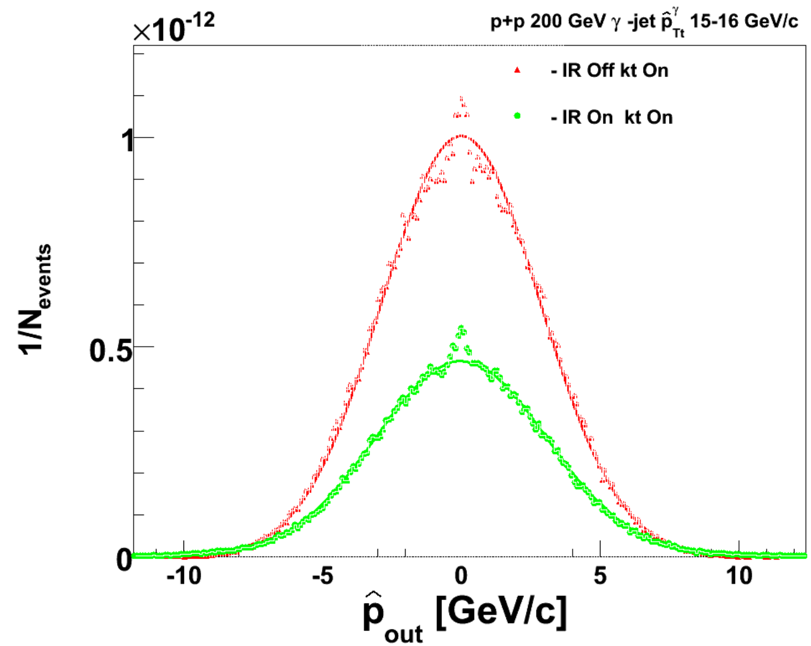
- ❑ It is due to the collinearity of initial quark with photon

Before and After the Correction



Without trigger correction

config	sigma	error
IR Off kt On	2.57	0.003
IR On kt On	2.25	0.038

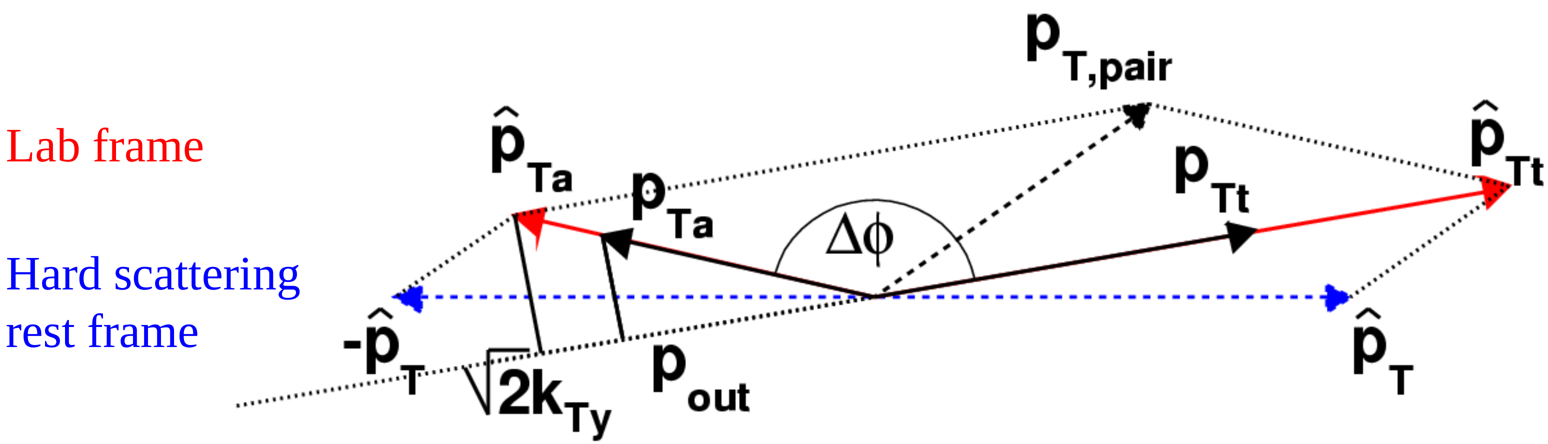


With trigger correction

config	sigma	error
IR Off kt On	2.84	0.258
IR On kt On	3.08	0.335

Analytic approach
much simpler solution than what we found in PRD

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



In the similar way as we did in *Phys. Rev. D*, **2006**, *D74, 072002*, we found a conditional probability for detecting photon p_{Tt} and assoc p_{Ta} given parton momentum p_T in CMS of hard scattering as:

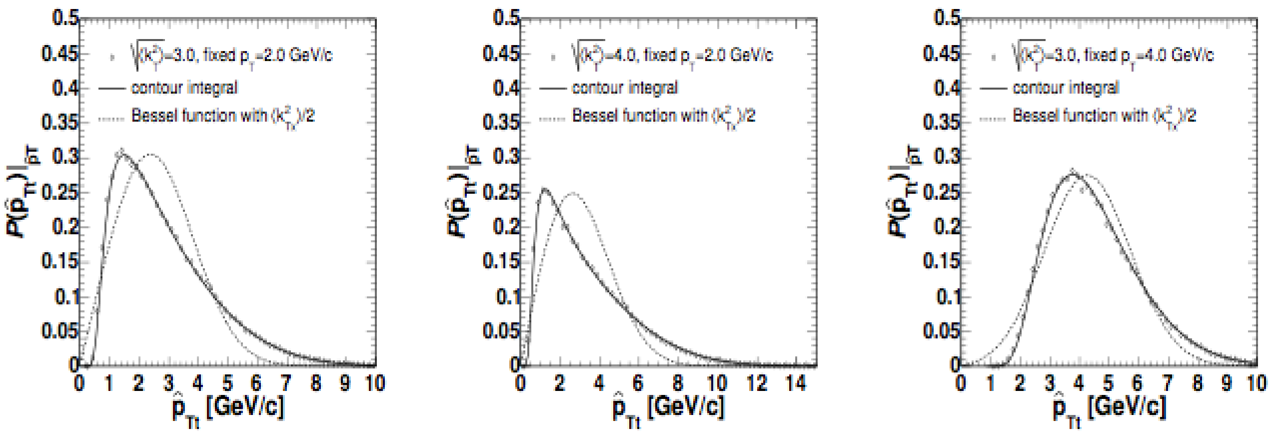
$$\mathcal{P}(\hat{p}_{T\mathrm{a}}\&\hat{p}_{T\mathrm{t}})\Big|_{\hat{p}_T} = \frac{\hat{p}_{T\mathrm{t}} + \hat{p}_{T\mathrm{a}}}{\pi\sigma^2\sqrt{\hat{p}_{T\mathrm{a}}\hat{p}_{T\mathrm{t}} - \hat{p}_T^2}} \exp\left(-\frac{(\hat{p}_{T\mathrm{t}} + \hat{p}_{T\mathrm{a}})^2 - 4\hat{p}_T^2}{2\sigma^2}\right)$$

More details will come soon

Momentum imbalance

Phys. Rev. D, **2006**, *D74, 072002*

$$\mathcal{P}(\hat{p}_{Tt})\Big|_{\hat{p}_T} = \left(\frac{\hat{p}_T^2 + 1.8}{\hat{p}_{Tt}} + \frac{\hat{p}_{Tt}}{2.4}\right)\frac{1}{\langle k_T^2\rangle}\left[\int_{0+\epsilon}^{\pi/2} \exp\left(-\frac{(k_{Tt}+k_{Ta+})^2}{2\langle k_T^2\rangle}\right)d\phi + \int_{\pi/2}^{\pi-\epsilon} \exp\left(-\frac{(k_{Tt}+k_{Ta-})^2}{2\langle k_T^2\rangle}\right)d\phi\right]d\hat{p}_{Tt} \quad (23)$$



NEW formulae ! : same results but much simpler

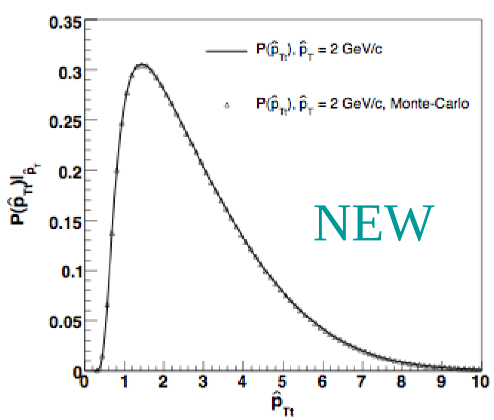
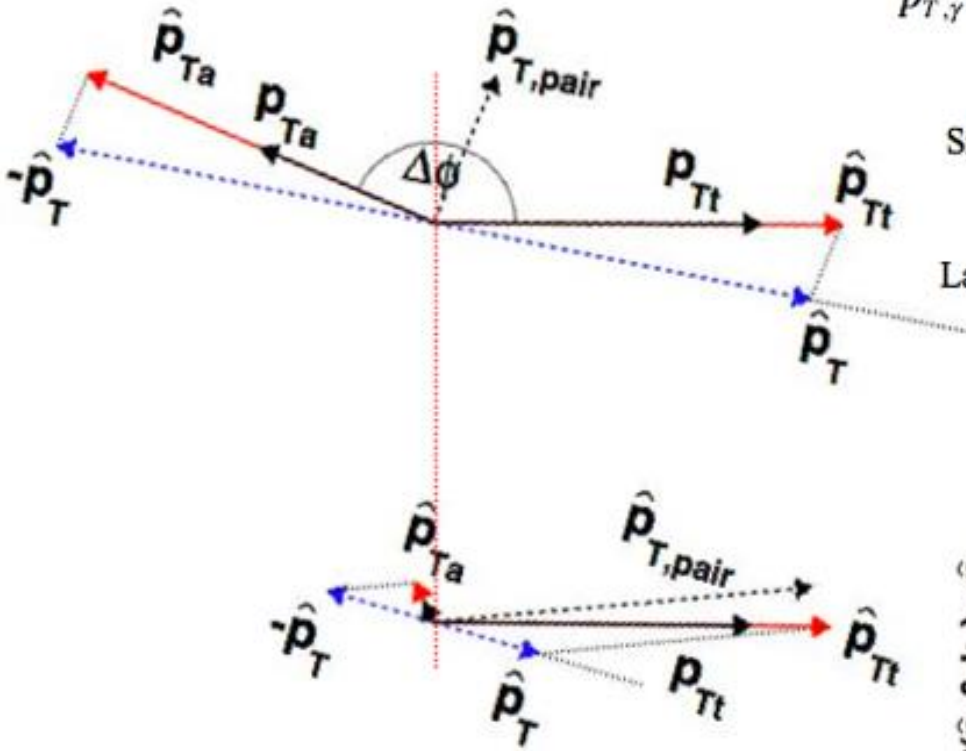


Figure 4: $\mathcal{P}(\hat{p}_{Tt})\Big|_{\hat{p}_T}$, with $\hat{p}_T = 2.0$ GeV/c

$$\mathcal{P}(\hat{p}_{Ta}\&\hat{p}_{Tt})\Big|_{\hat{p}_T} = \frac{\hat{p}_{Tt}+\hat{p}_{Ta}}{\pi\sigma^2\sqrt{\hat{p}_{Ta}\hat{p}_{Tt}-\hat{p}_T^2}}\exp\left(-\frac{(\hat{p}_{Tt}+\hat{p}_{Ta})^2-4\hat{p}_T^2}{2\sigma^2}\right)$$

10 GeV/c γ-h pairs still not fully in pQCD regime?

courtesy of J. Rak



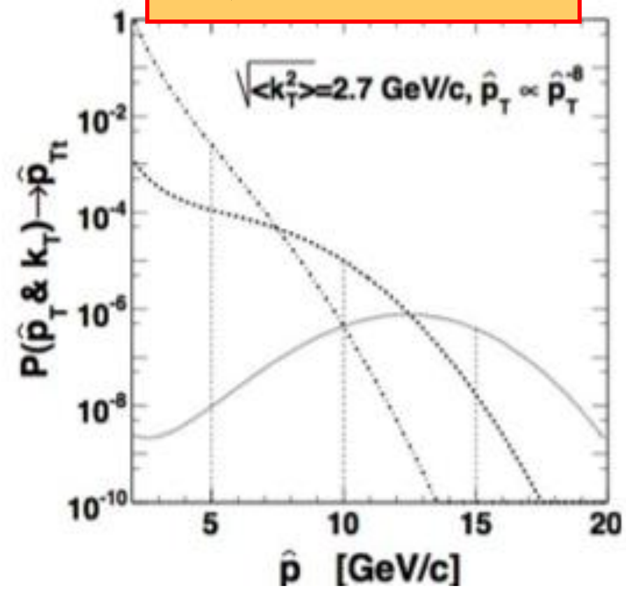
$$p_{T,\gamma} \propto \text{Gauss}\left(\sqrt{\langle k_T^2\rangle}\right) \otimes \frac{1}{\hat{p}_T^8}$$

Small k_T (Gauss) and large p_T power law

less probable than

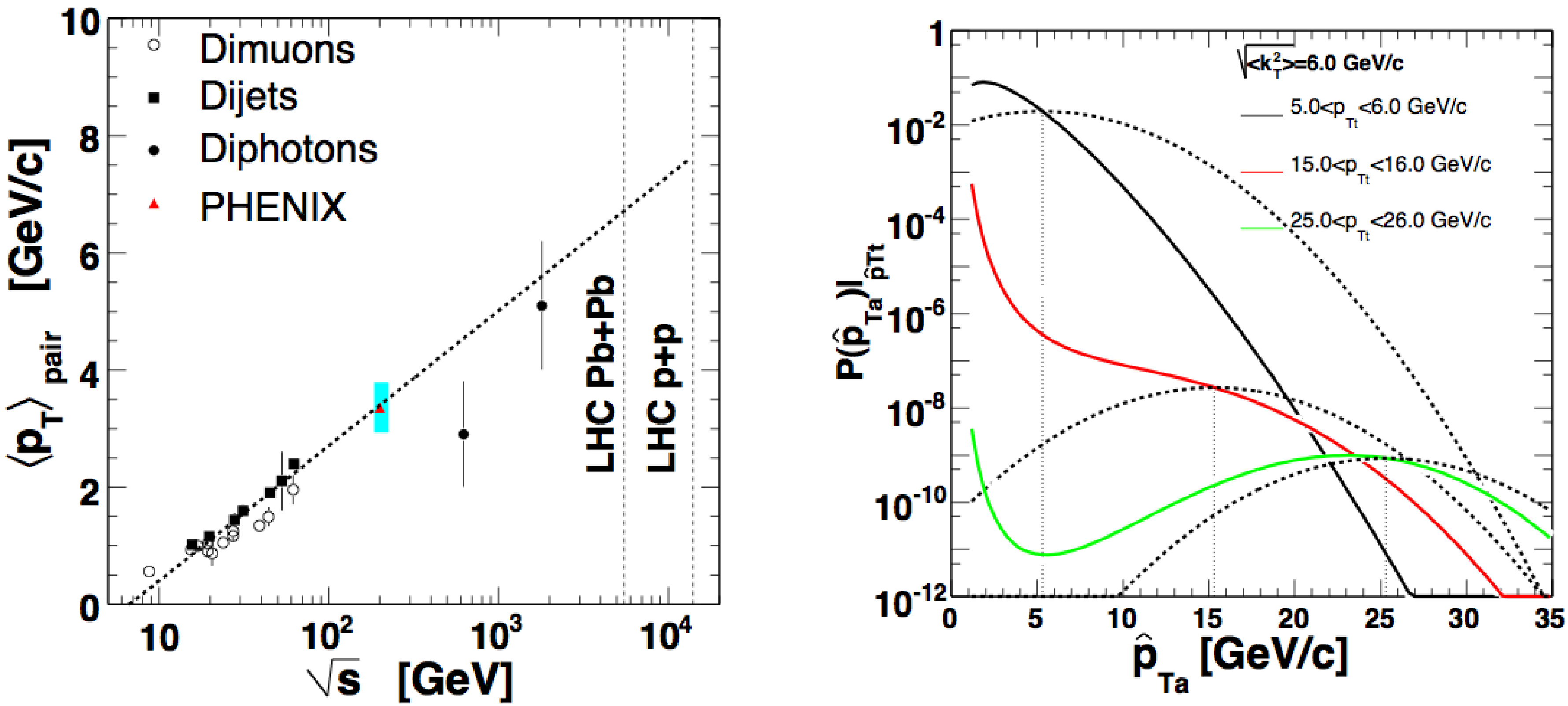
Large k_T (Gauss) and small p_T power law

√s = 200 GeV



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

What about LHC ?

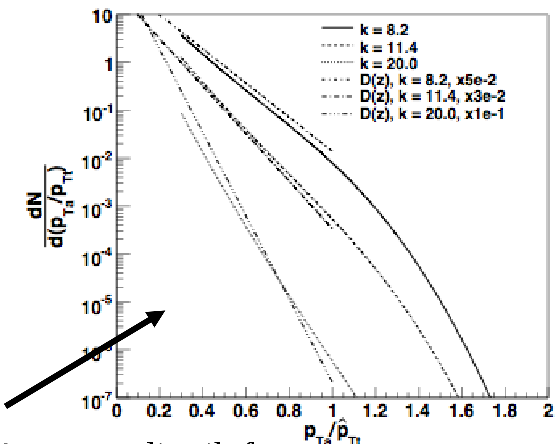


PHENIX measured $\langle p_T \rangle_{pair}$=3.36±0.09±0.43GeV/c

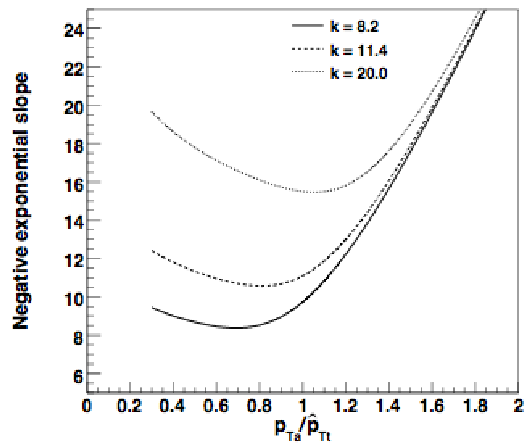
extrapolation to LHC $\sqrt{\langle k^2_T \rangle}$=**6.1 GeV/c**

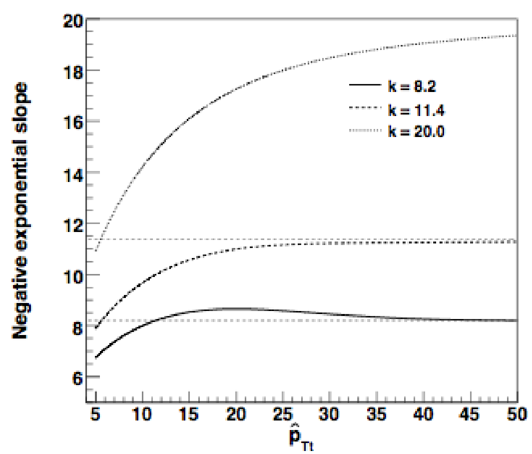
Folding with a Fragmentation function

$$\mathcal{P}(\hat{p}_{Ta})\Big|_{\hat{p}_{Tt}} = \frac{\int_{-\Delta\theta_{max}}^{\Delta\theta_{max}} f(\hat{p}_T)(\hat{p}_{Tt}+\hat{p}_{Ta})\exp\left(-\frac{(\hat{p}_{Tt}+\hat{p}_{Ta})^2-4\hat{p}_{Tt}\hat{p}_{Ta}\cos^2(\frac{1}{2}\Delta\theta)}{2\sigma^2}\right)d\Delta\theta}{\int_{\hat{p}_{Ta,\min}}^{\infty}\int_{-\Delta\theta_{max}}^{\Delta\theta_{max}} f(\hat{p}_T)(\hat{p}_{Tt}+\hat{p}_{Ta})\exp\left(-\frac{(\hat{p}_{Tt}+\hat{p}_{Ta})^2-4\hat{p}_{Tt}\hat{p}_{Ta}\cos^2(\frac{1}{2}\Delta\theta)}{2\sigma^2}\right)d\Delta\theta\, d\hat{p}_{Ta}}, \quad (26)$$



Assoc x_E distrib for various slopes of $D(z) \propto \exp(-k*z)$



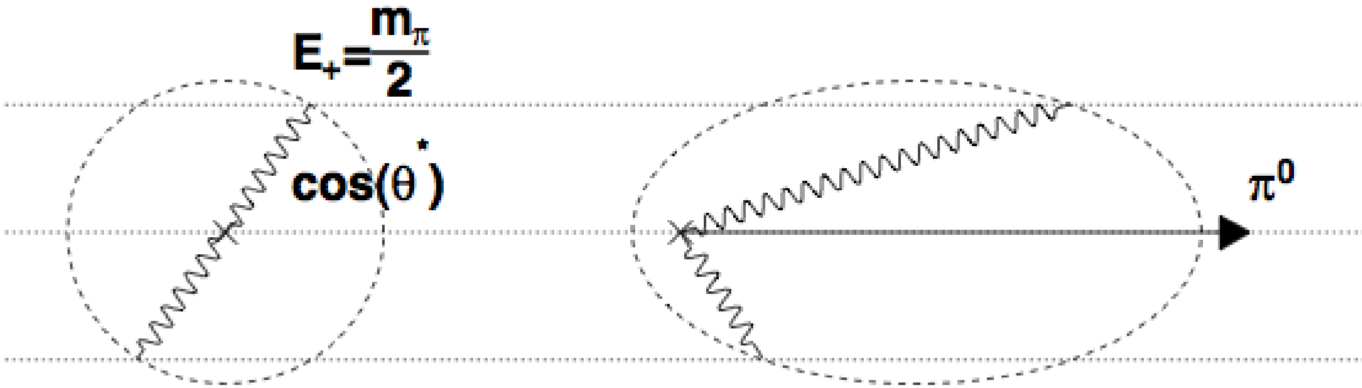


- ❑ Deviation from dashed lines (the true slopes of D(z)) at low p_T due to the k_T bias.
- ❑ Unlike the di-hadron correlation it asymptotically converges to the correct value.
- ❑ **Knowing that we could unfold the k_T or correct for the bias.**

All you need to know , π^0 kinematics

$\pi^0 \rightarrow 2\gamma$ decay kinematics

E_π = 250 MeV



($\theta^* = 0$ and $\alpha \approx 1$) one photon takes almost all π^0 momentum and the other photon travels backwards with negative momentum component $p_\gamma < m_0/2$.

Trans. From π^0 rest frame RF to LAB

$$E^{LAB}_{\pm,||} = \gamma(E^{RF} \pm \beta E^{RF}_{||}) = \gamma\frac{m_\pi}{2}(1 \pm \beta\cos\theta^*)$$

$$E^{LAB}_{\perp} = E^{RF}_{\perp} = \frac{m_\pi}{2}\sin\theta^*$$

$$p^{LAB}_{\pm,||} = \gamma(\beta E^{RF} \pm p^{RF}_{||}) = \gamma\frac{m_\pi}{2}(\beta \pm \cos\theta^*)$$

$$p^{LAB}_{\perp} = E^{RF}_{\perp} = \frac{m_\pi}{2}\sin\theta^*$$

Useful definition - asymmetry parameter:

$$\alpha = \left|\frac{E_+ - E_-}{E_+ + E_-}\right| \qquad \alpha = \beta\cos\theta^*$$

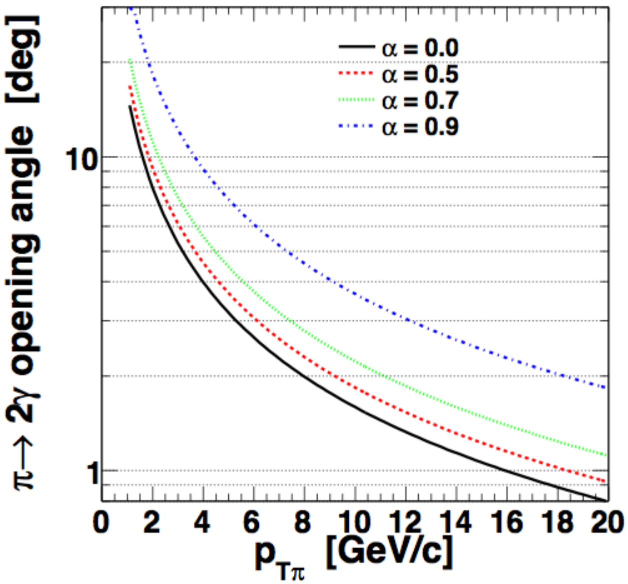
Decay photon opening angle

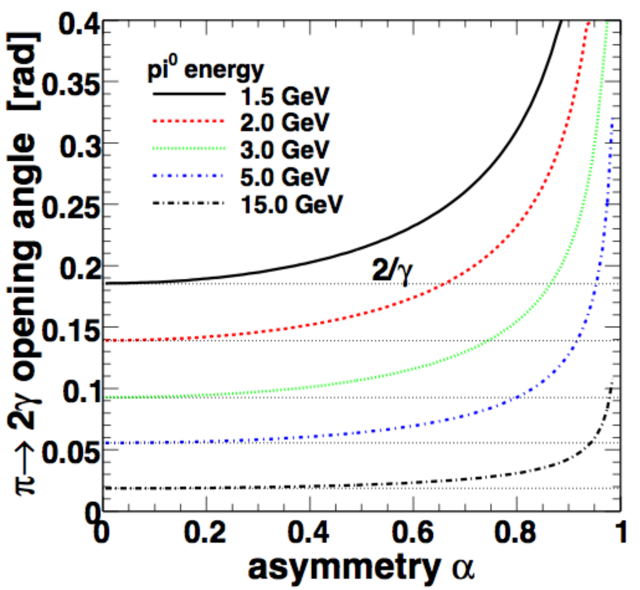
Inv. mass of the two dec γ $m_\pi^2 = (G_+ + G_-)^2 = 2E_+E_- - 2E_+E_- \cos\theta_L$

$$\cos\theta_L = \frac{\gamma^2(1-\alpha^2)-2}{\gamma^2(1-\alpha^2)} = \frac{\gamma^2(\beta^2-\alpha^2)-1}{\gamma^2(1-\alpha^2)} = \frac{E_\pi^2(1-\alpha^2)-2m_\pi^2}{E_\pi^2(1-\alpha^2)}$$

When $\alpha \to 0$ and do the Taylor expansion of $\cos^{-1}(1-2/\gamma^2)$ you find

$$\vartheta_L \approx \frac{2}{\gamma}$$

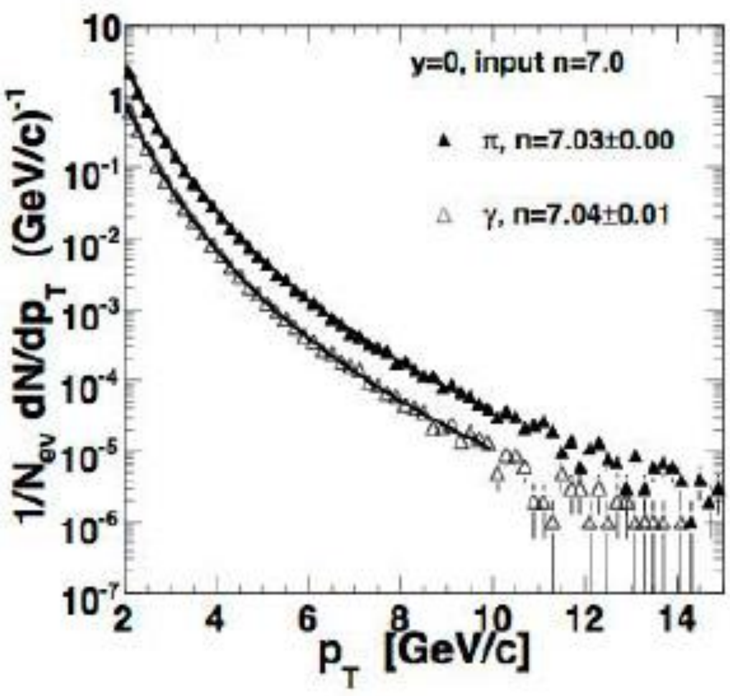


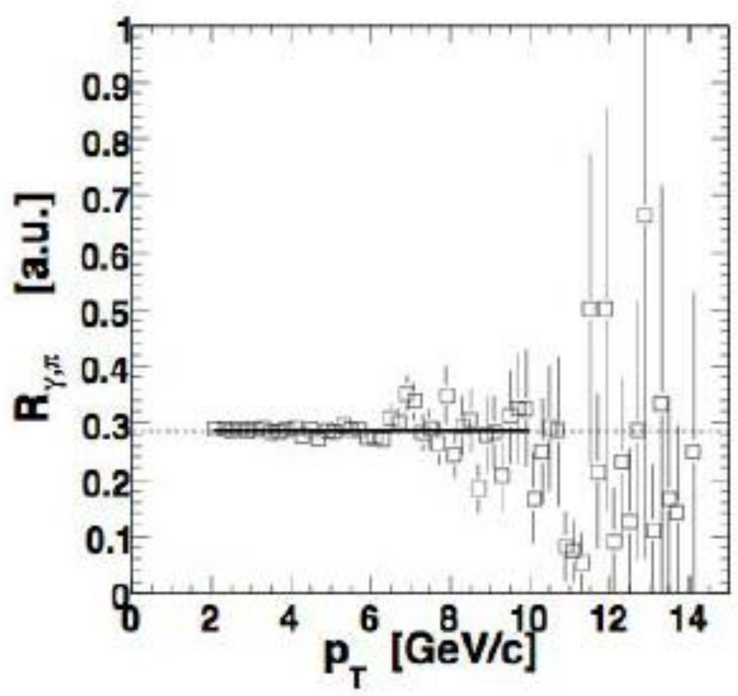


Energy Distribution of Decay photons @ y=0

$$\left.\frac{dN_\gamma}{dE_\gamma}\right|_{y=0} = \frac{dN_\gamma}{d\theta^*}\frac{d\theta^*}{dE_\gamma} = \frac{2}{p_{T\pi}}$$

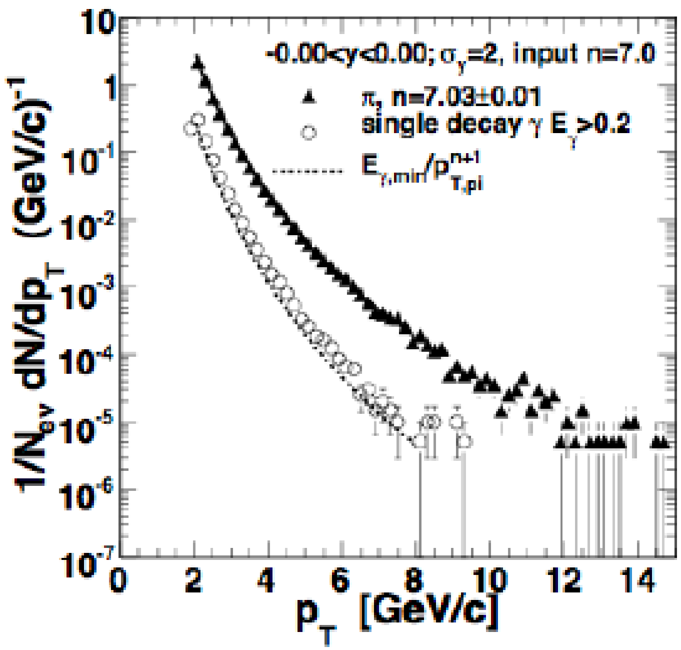
$$R_{\gamma,\pi^0} = \frac{dN_\gamma/dE_\gamma}{dN_{\pi^0}/dp_{\pi^0}} = \frac{2}{n}$$

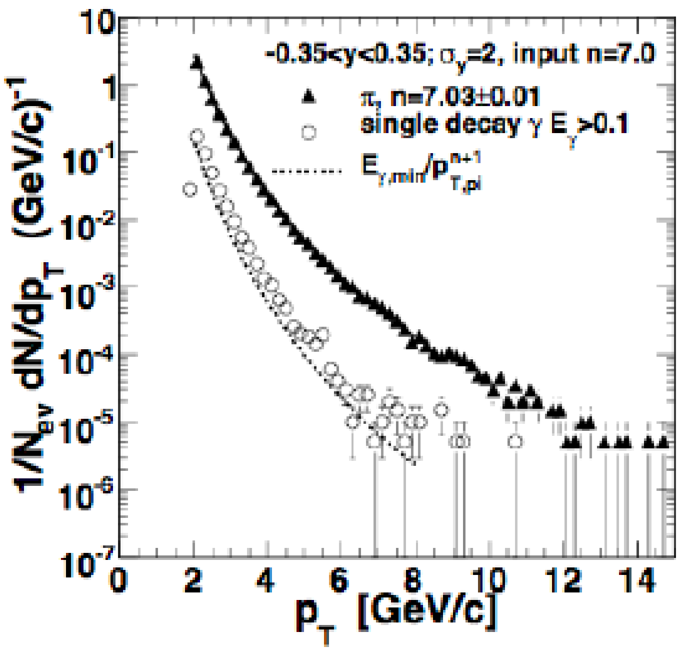




"Fake" Rate of Direct photons

Since $\left.\frac{dN_\gamma}{dE_\gamma}\right|_{y=0} = \frac{dN_\gamma}{d\theta^*}\frac{d\theta^*}{dE_\gamma} = \frac{2}{p_{T\pi}}$ thus $R_{\mathrm{fake}} = \frac{E_{\mathrm{min}}}{p_{T\pi}}$ and $\frac{dN}{dE_{\mathrm{fake}}} = \frac{E_{\mathrm{min}}}{p_{T\pi}^{n+1}}$



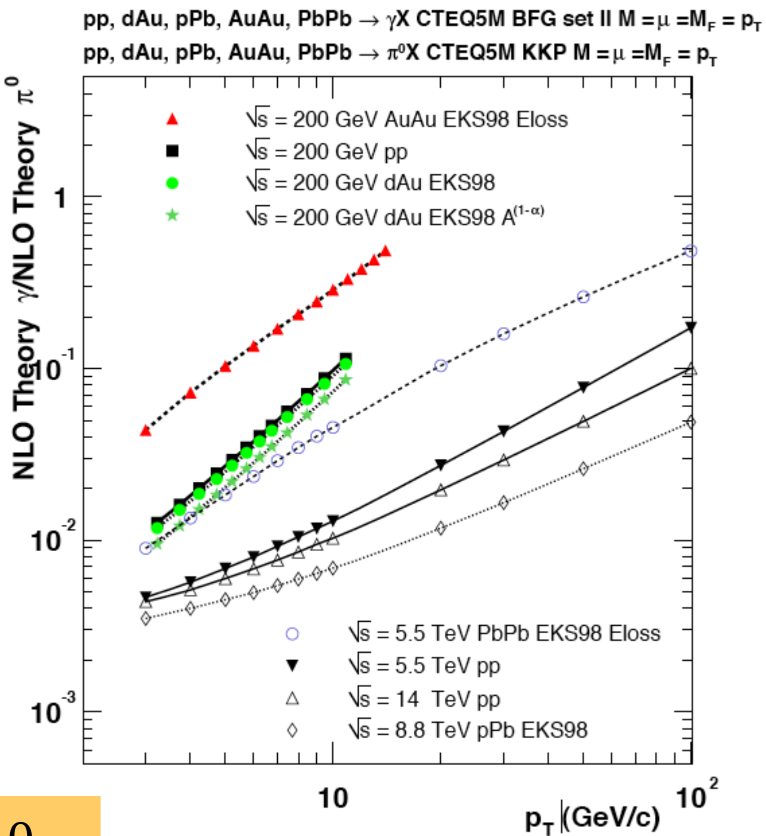


EMCal energy cut : another source of "direct" photons

$$\frac{dE_\gamma}{d\theta^*} = \mp\frac{1}{2}E_\pi\beta\sin\theta^*$$

$$\frac{dN_\gamma}{dE_\gamma} = \frac{dN_\gamma}{d\theta^*}\frac{d\theta^*}{dE_\gamma} = \frac{2}{p_{T\pi}}$$

Decay photons energy and asymmetry distributions are in the ideal situation (no detector response) flat.



"Direct" photons from π^0 $E_{cut}/E_\pi \approx 2\%$ @ $E_\pi = 10$ GeV, however, γ/π ratio is also of that order

Conclusion and perspectives

- High pT π^0 suppression at RHIC itself poorly informs us on how exactly the produced medium affects the propagation and the hadronization of high-energy quarks and gluons.
  - Detailed understanding of "unmodified" parton properties in p+p is important
- π^0 - h correlation is not sensitive on the determination of fragmentation
  - Trigger bias
  - PHENIX measured $\langle p_T \rangle_{pair}$=3.36±0.09±0.43GeV/c
  - Extrapolation to LHC $\sqrt{\langle k_T^2 \rangle}$=6.1 GeV/c
- Need γ-h correlation
  - but we found there are still biases ☹
- But Trigger bias due to the k_T in both h-h and γ-h
  - seems to be under control. ☺☺☺☺☺☺☺☺☺
  - We developed the analytical tools to correct the spectra and resolve the fragmentation function.
- Experimental aspects of direct-γ isolation were discussed
  - Isolation cut - contribution from π^0
  - Subtraction method under development
- Data are being looked at with more strict isolation cuts and subtraction method with combined PHENIX run5+run6 data sets.
- ALICE PHOS full chain analysis with recent updated responses on-going from PYTHIA standalone mode.