Hard Photons as Probes of Medium Effects in Nuclear Collisions

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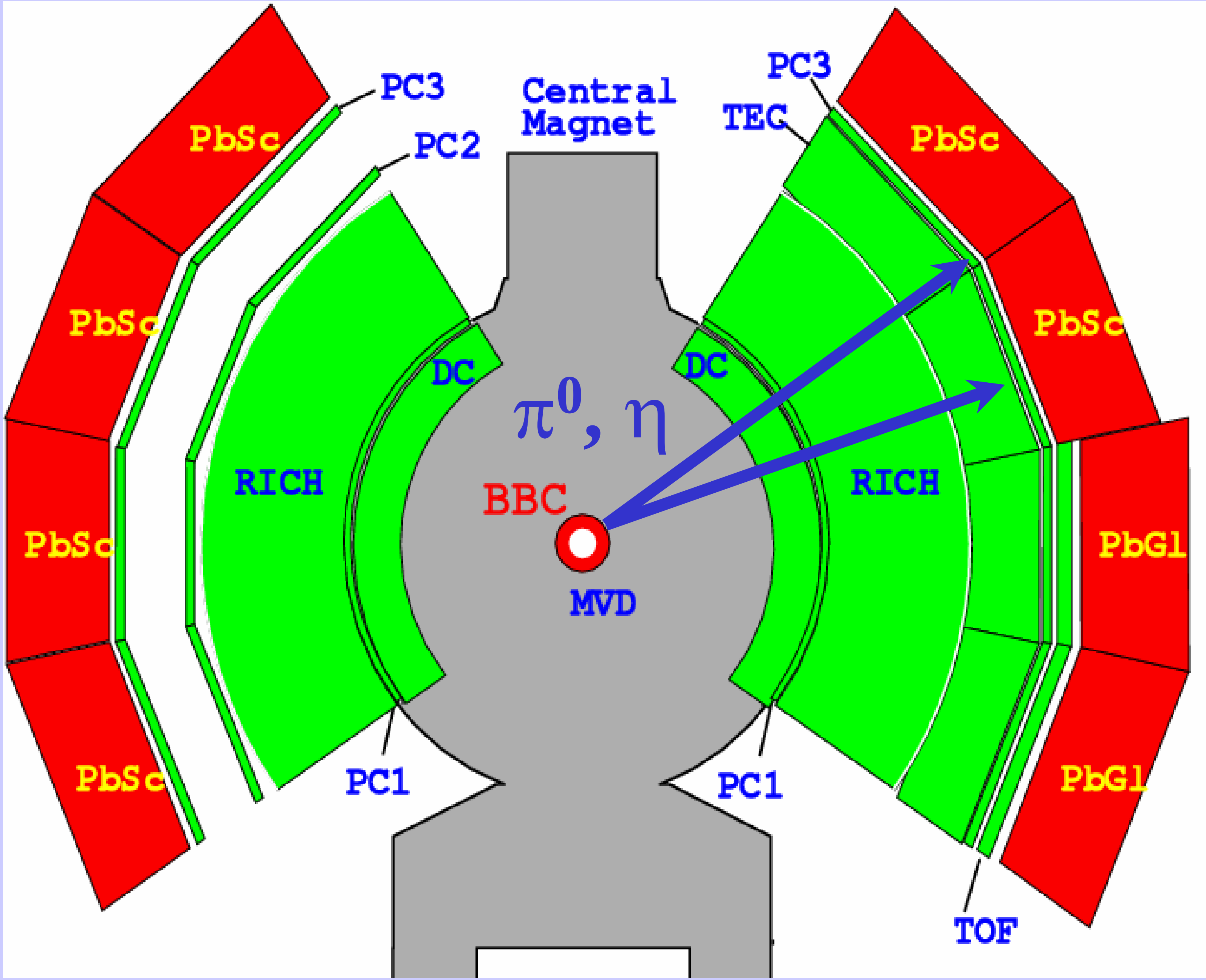
1. Introduction
2. Hard photons in pQCD
3. Hard photons: medium effects
4. How to probe medium effects?
5. Where we stand now
6. Summary

Photons: Broad Perspective

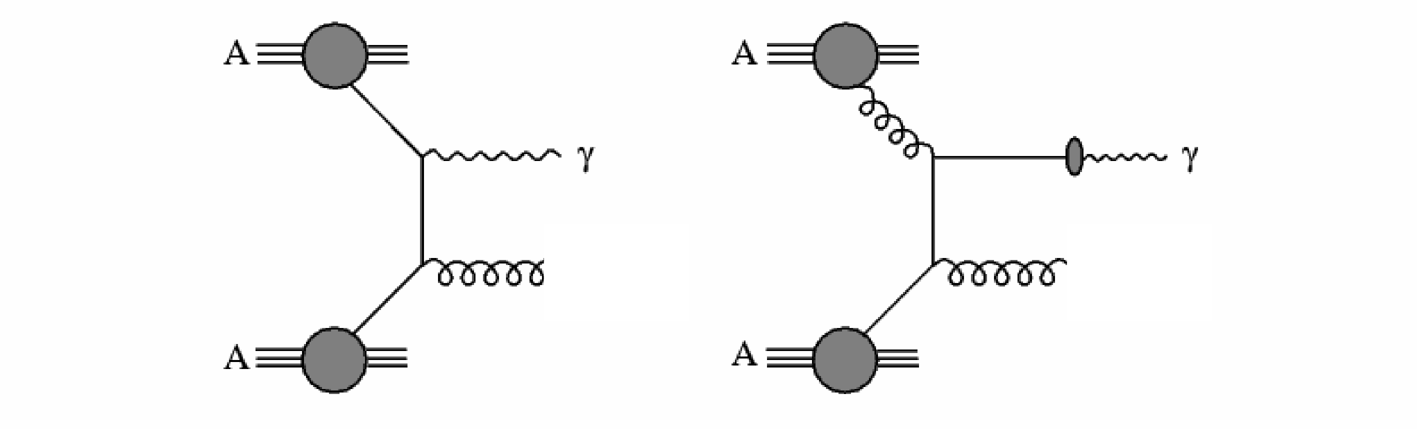
- **Many (most) of the talks in this meeting have discussed properties of the medium at low momentum scales**
  - Chiral symmetry, vector meson propagation in medium, spectral functions, …
- **Much of the interest in "direct" photon production has focused on "low" pT production**
  - Low $\equiv p_T < 2\text{-}3$ GeV/c
  - Goal: measure the temperature (history) of medium
- **But: physics of hard photons also extremely rich**
  - Photons as "calibrator" for jet quenching (γ-jet)
  - "Jet conversion" photons
  - Medium contributions to photon brehmstrahlung
  - "Partonic" Photons (probes of initial state)

PHENIX: Central ARMS



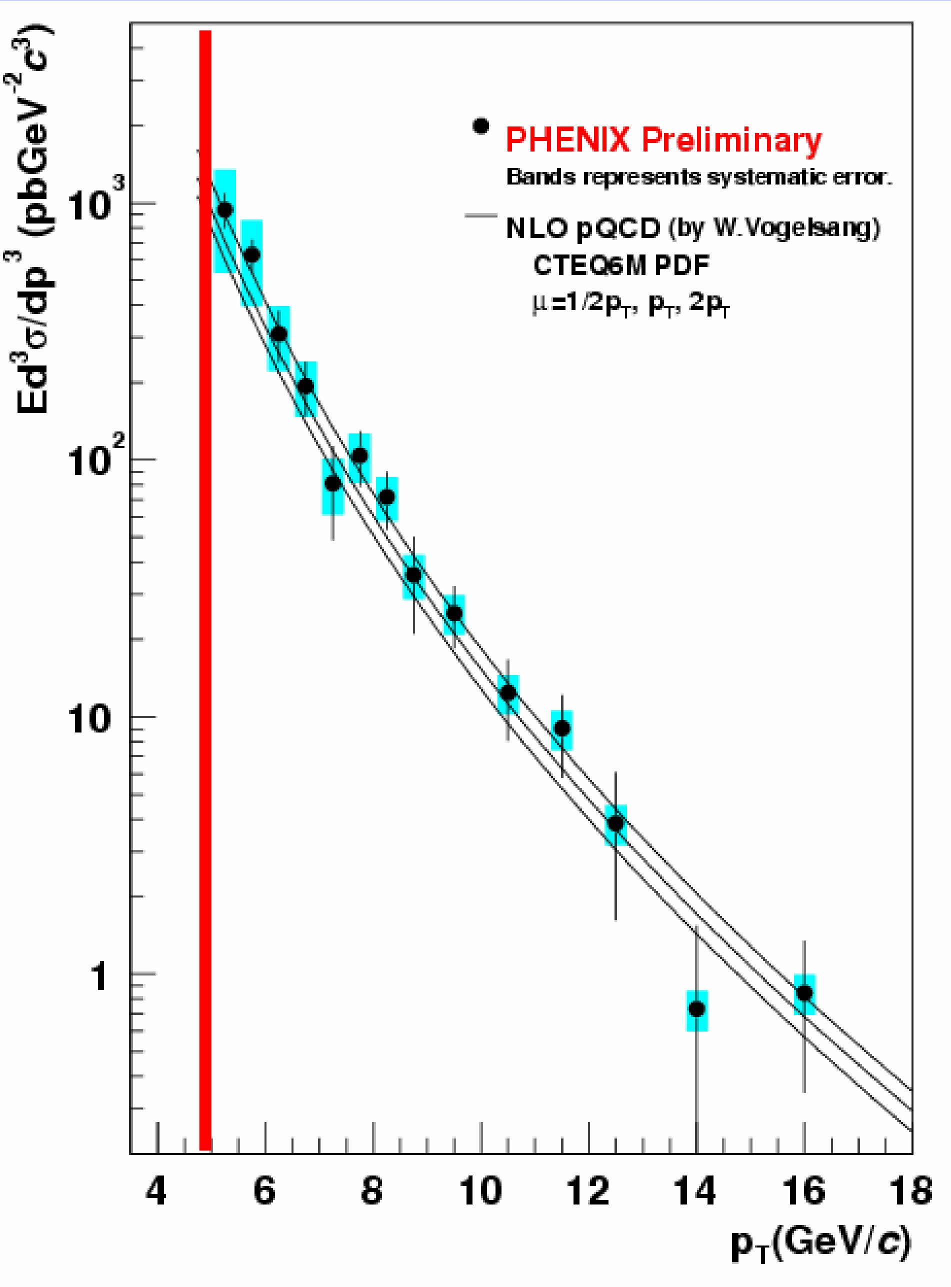
Hard Photon Production in pQCD

- @ LO in pQCD, photon production is simple.
- Two contributions:
  - "partonic" photons: direct from hard scattering
  - "Fragmentation" photons – from fragmentation of jet(s)



- But, @ NLO things are much more complicated
  - Distinction between partonic & fragmentation contributions becomes ambiguous.
  - In principle, "isolation" cuts possible – but matching those cuts with pQCD is difficult (virtual radiation).

Start by Measuring in p-p Collisions

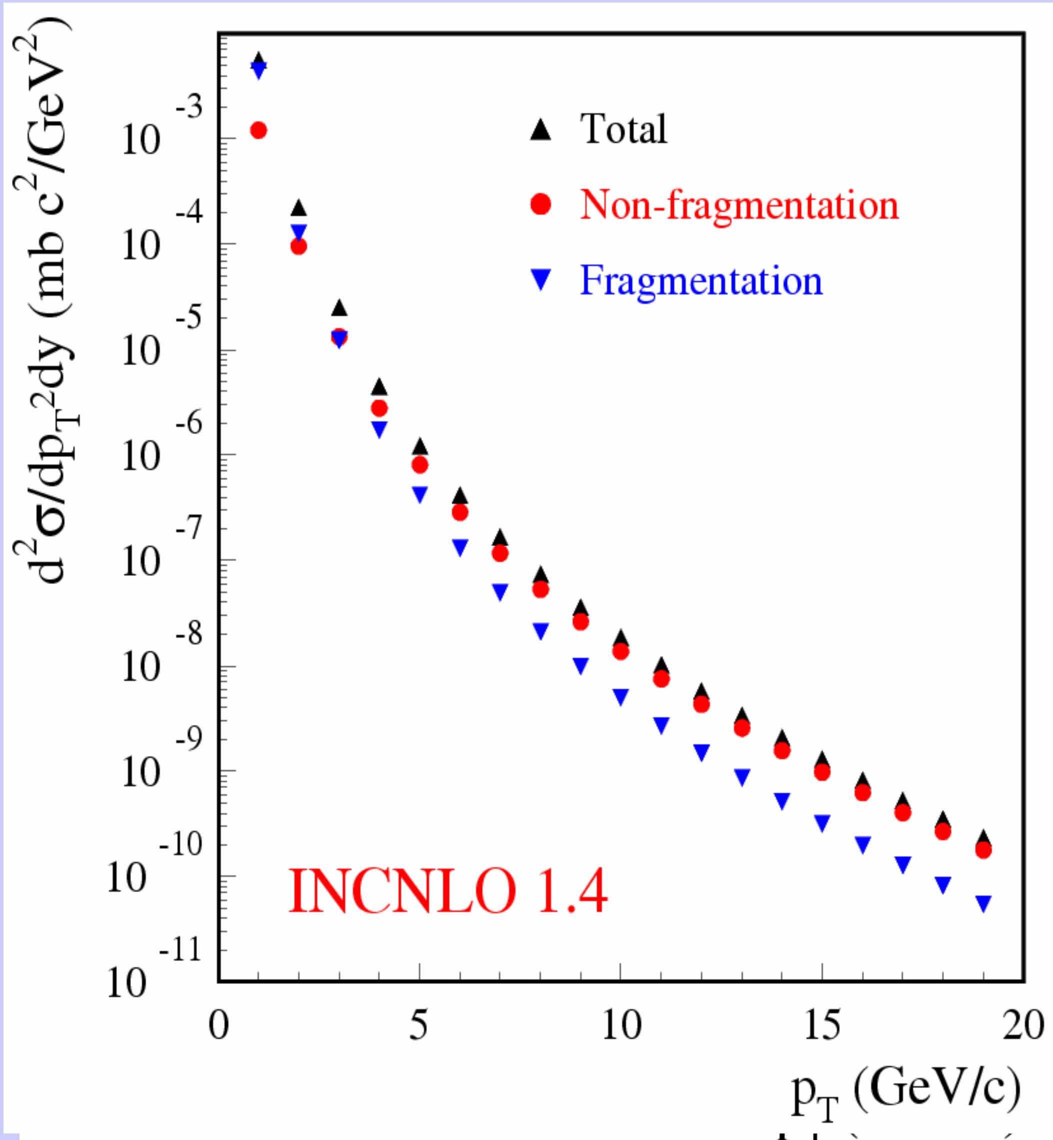


- PHENIX Preliminary Run-3 p-p prompt γ
- Background removed via combination of:
  - (Jet) isolation cuts
  - π^0 decay tag
  - Statistical subtraction
- Spectrum and yield well-described by NLO pQCD (w/ threshold & recoil resummation)
- ~ 15% scale uncertainty above 5 GeV/c

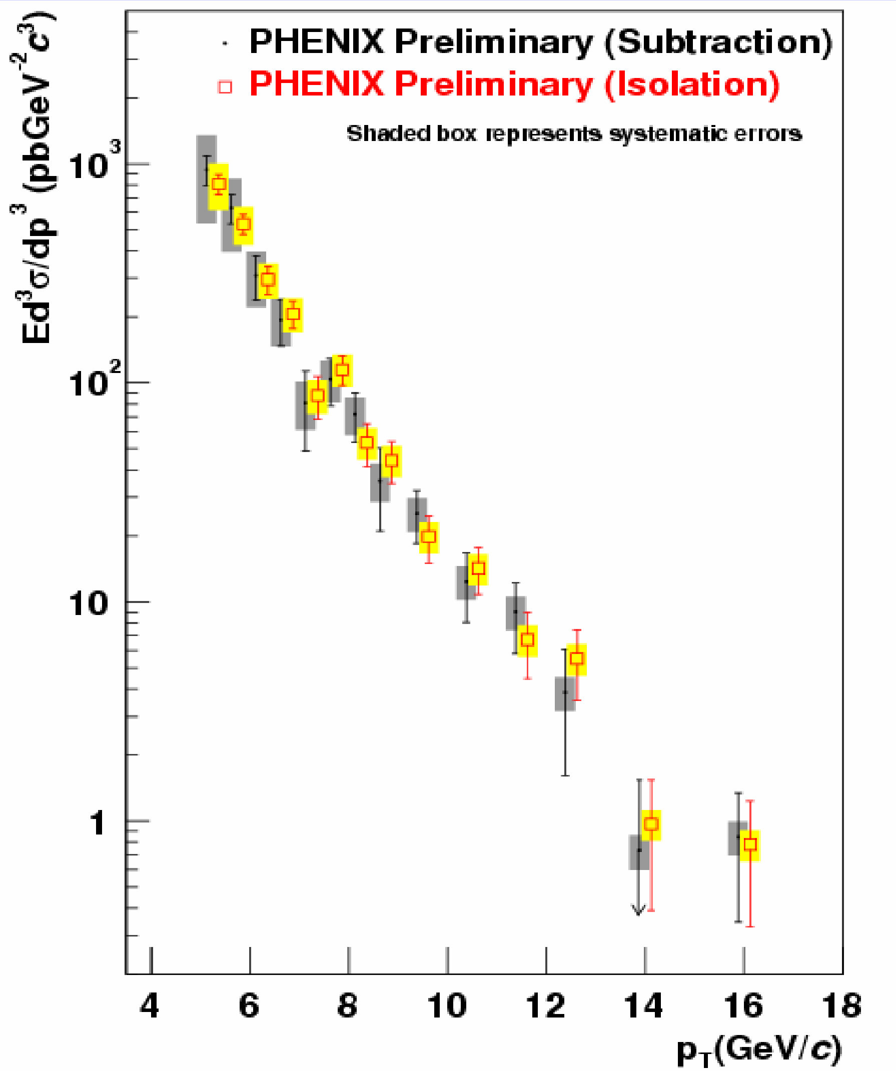
A different NLO pQCD Calculation

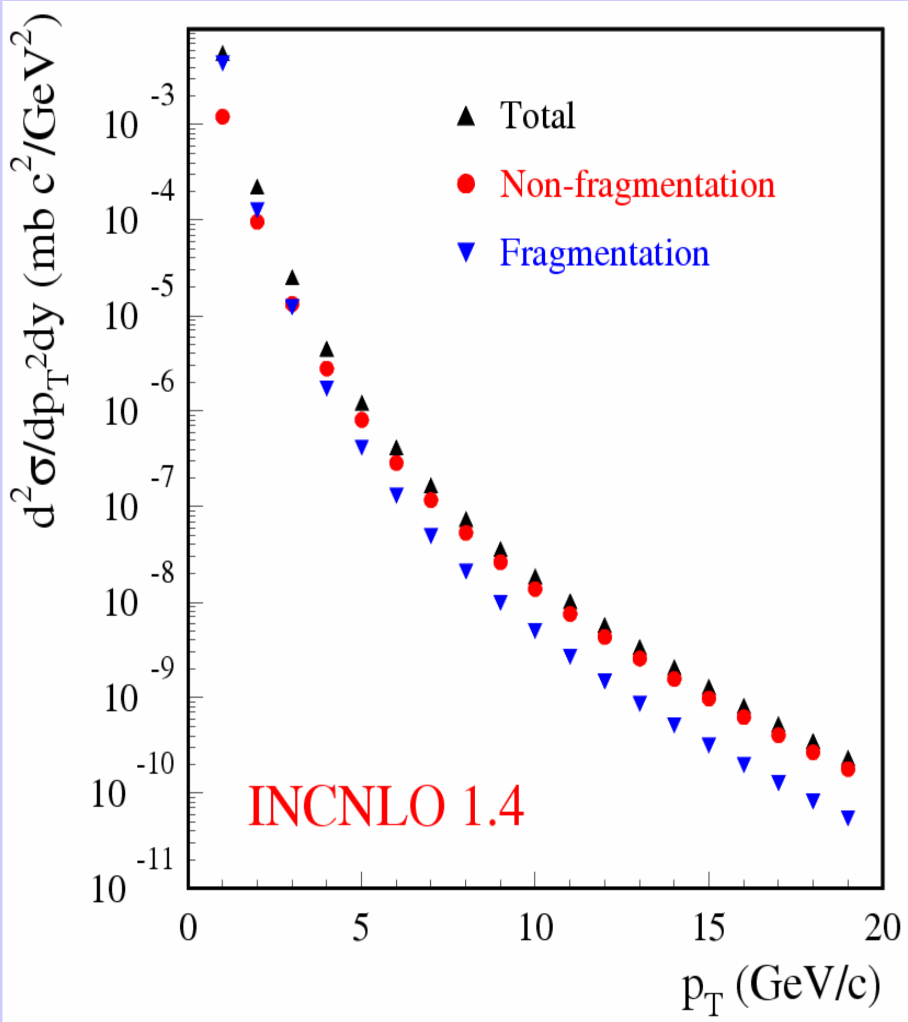
INCNLO (v1.4): J.Ph. Guillet, M. Werlen *et al*

- NLO pQCD calculation
- With calculated γ frag. function.
  - Compares well with HERA, CDF, D0 data
- Fragmentation ~ 25% at high p_T
- Large increase in fragmentation yield below 5 GeV.
  - Mostly from NLL contributions to γ FF
  - Right where we want to measure “thermal”



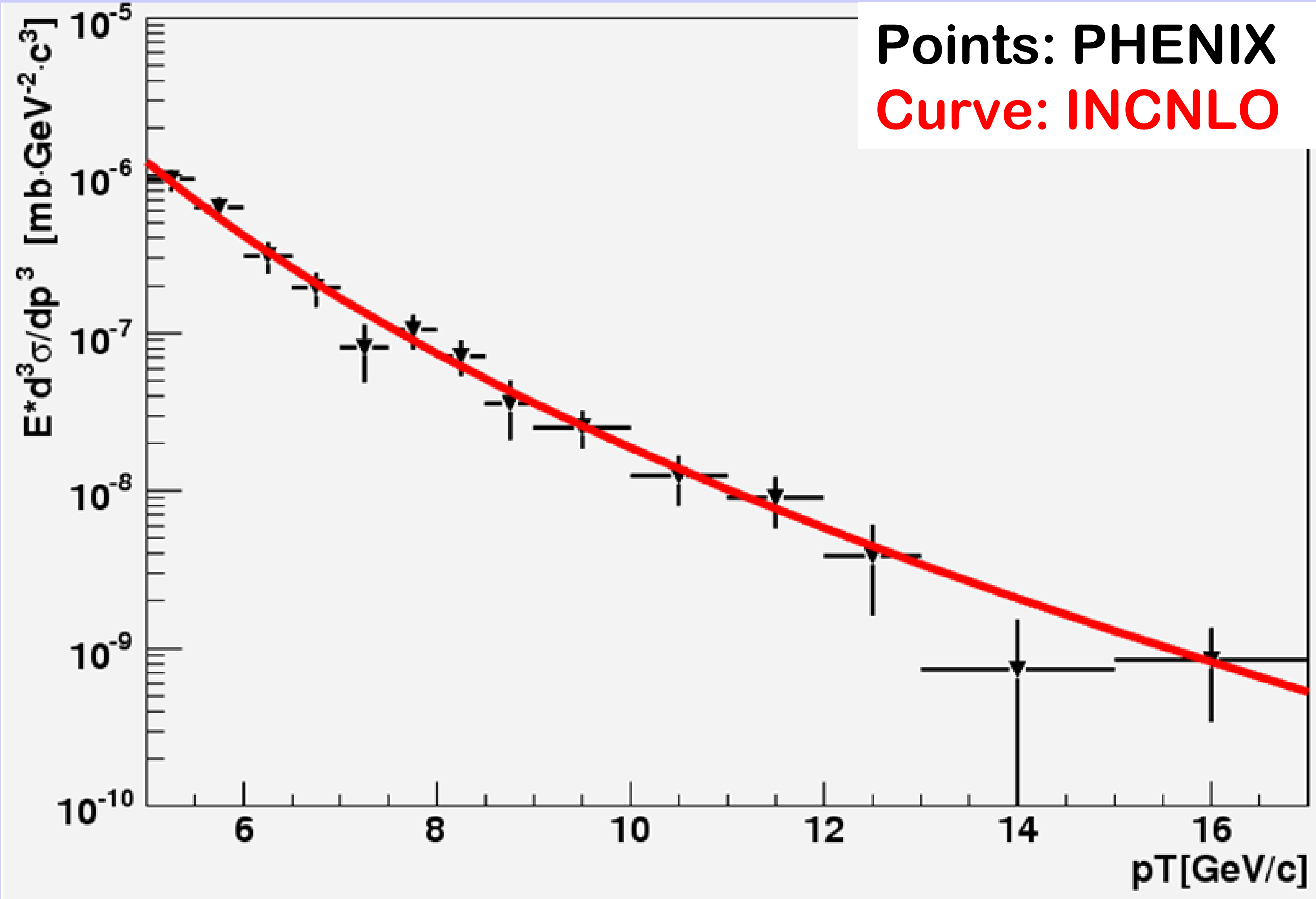
What about Frag. Contribution?





- p-p analyzed with and w/o an isolation cut.
  - By eye: not unreasonable.
  - data → less fragmentation, but too soon to conclude.

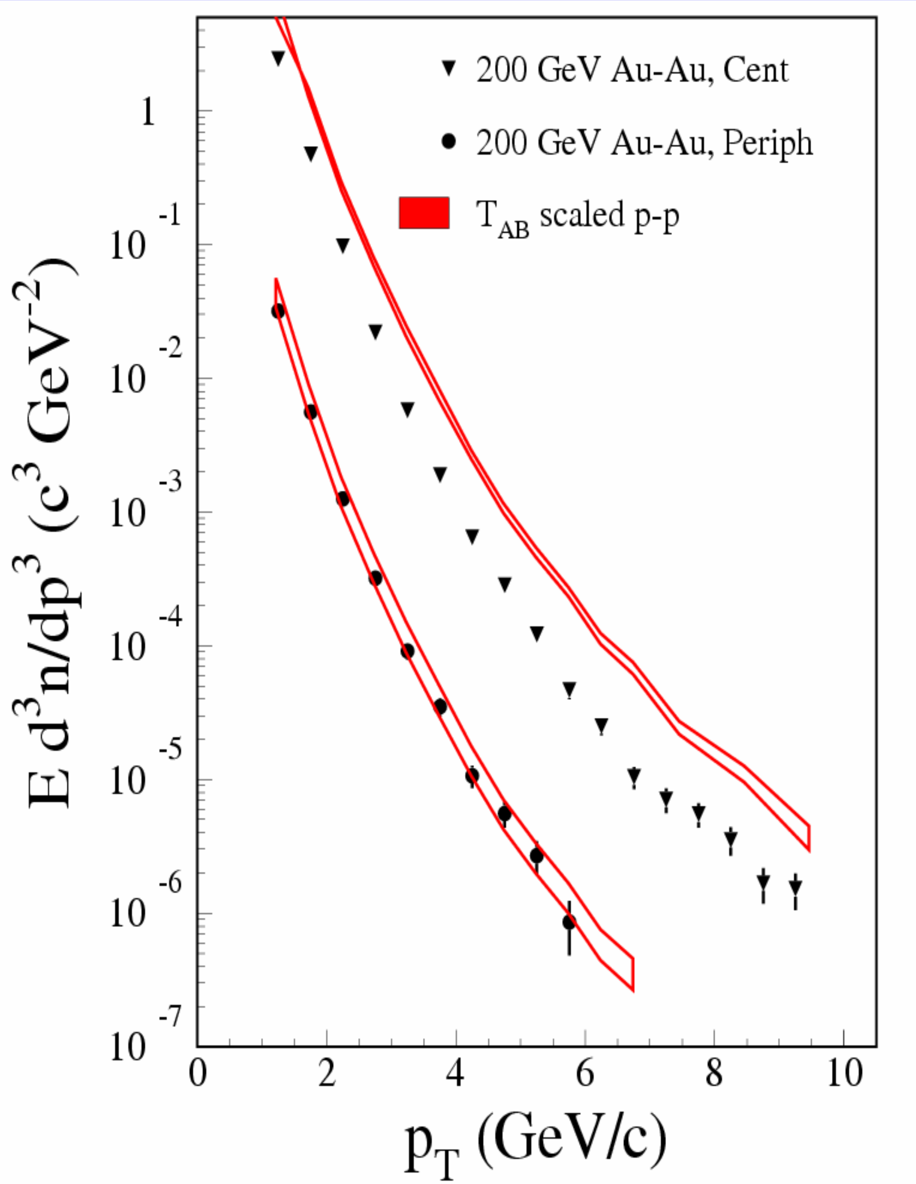
PHENIX Comparison to INCNLO

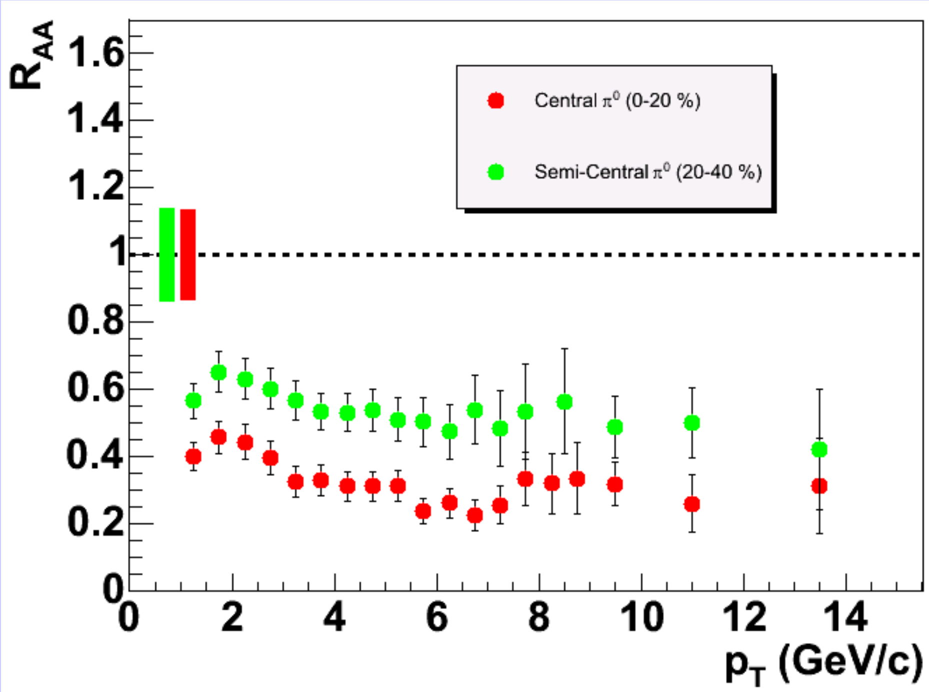


- No K factors, no fudge factors, absolute comp.
- Completely independent calculation.
  - Good control over pQCD prompt photon calculation @ RHIC.

Background: Jet Quenching @ RHIC

- Strong suppression of high-p_T hadron production

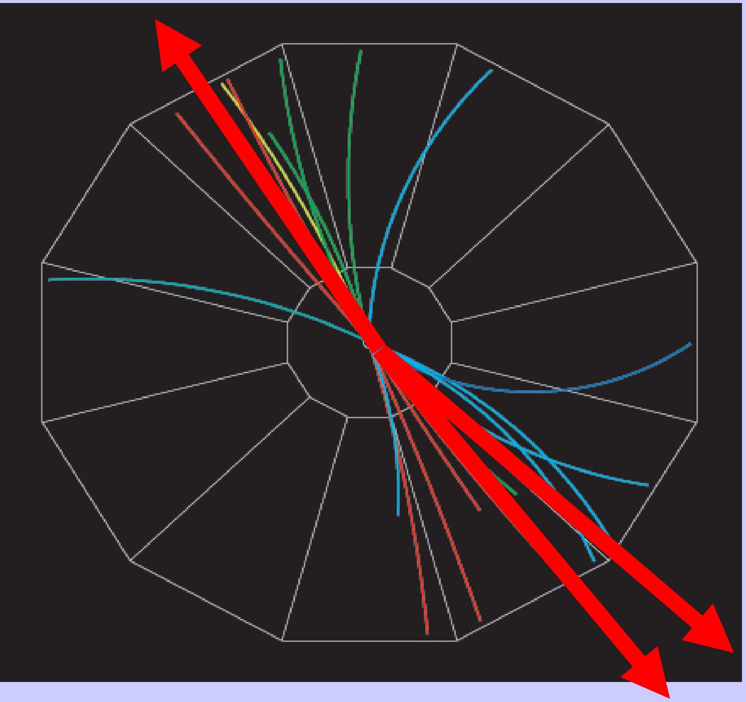




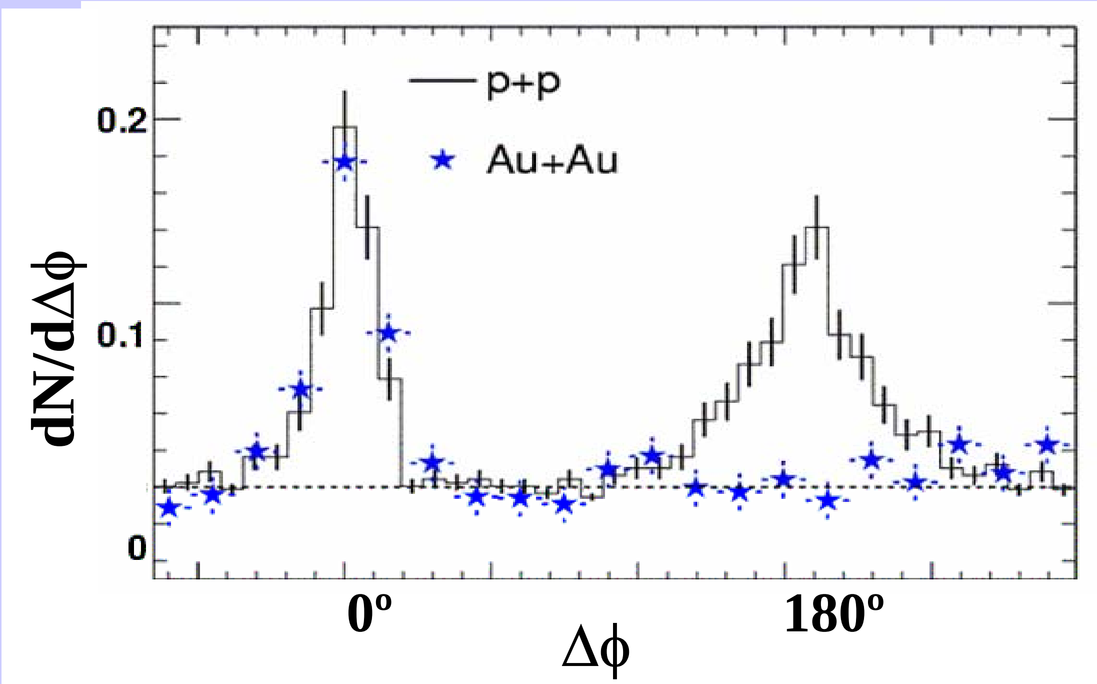
- $R_{AA} \equiv$ measured / expected
- Expected based on p-p
  - Scaled up by geometric T_{AB}
- Factor of 4-5 suppression in "central" Au-Au

Background: Jet Quenching @ RHIC (2)

STAR: p-p jet event

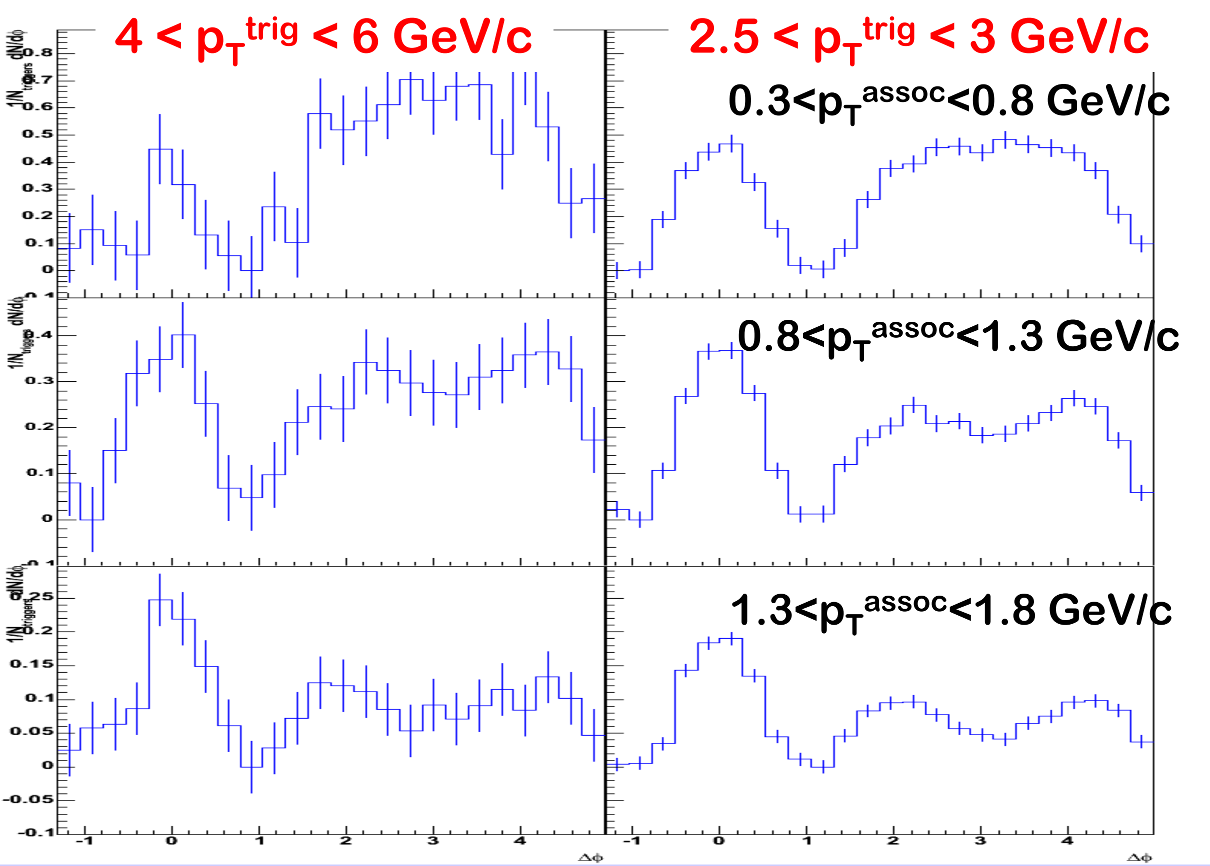


Analyze jets by measuring $\Delta\phi$ between high-p_T hadrons



- View of di-jet suppression >1 year ago
- Since then, much more data.
- With much “richer” interpretation
  - Combination of suppression & strong distortion

(di)jet Situation is Complicated

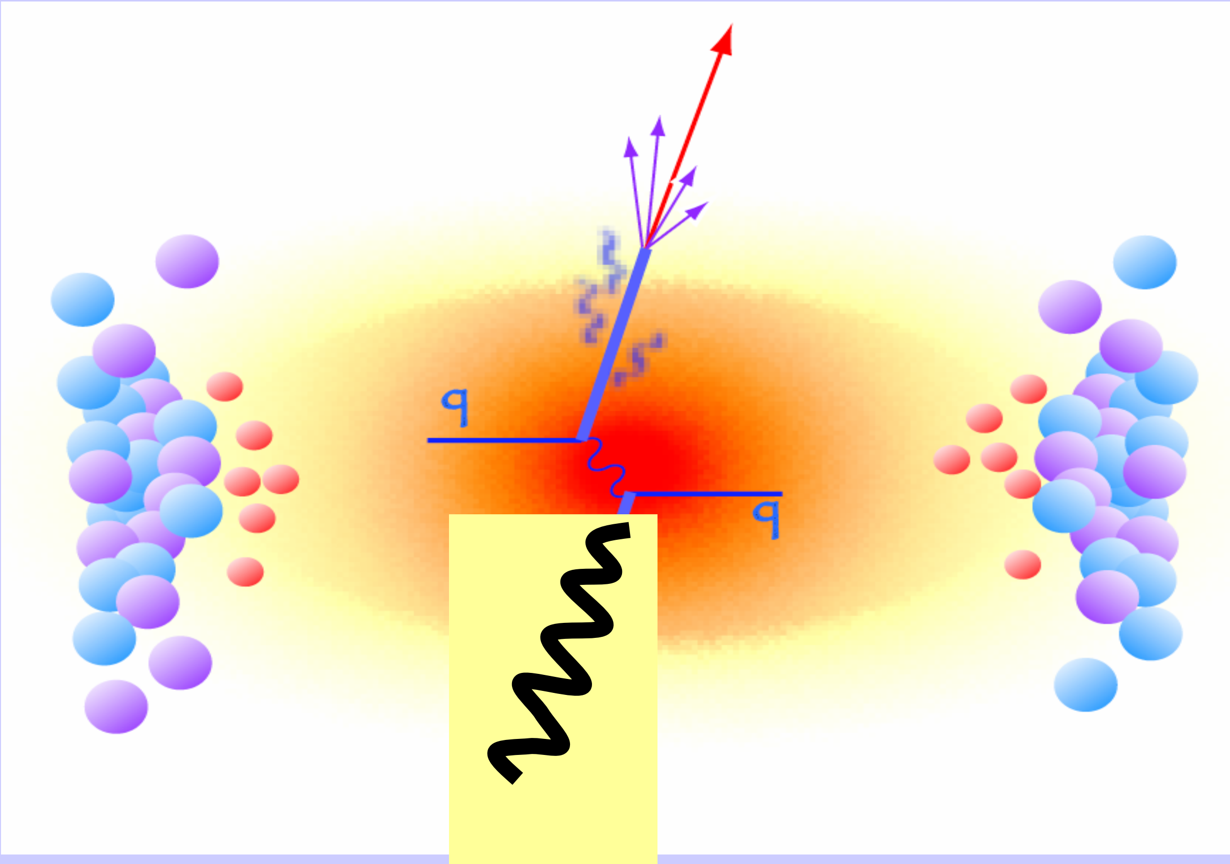


PHENIX Preliminary

STAR Preliminary

- **Recent preliminary result from PHENIX showing strong distortion of opposite-side jet.**
  - STAR sees similar but strongly p_T dependent.
- **Problem:**
  - gluon radiation strongly couples to the medium

Photon - Jet(Hadron) Measurements(?)



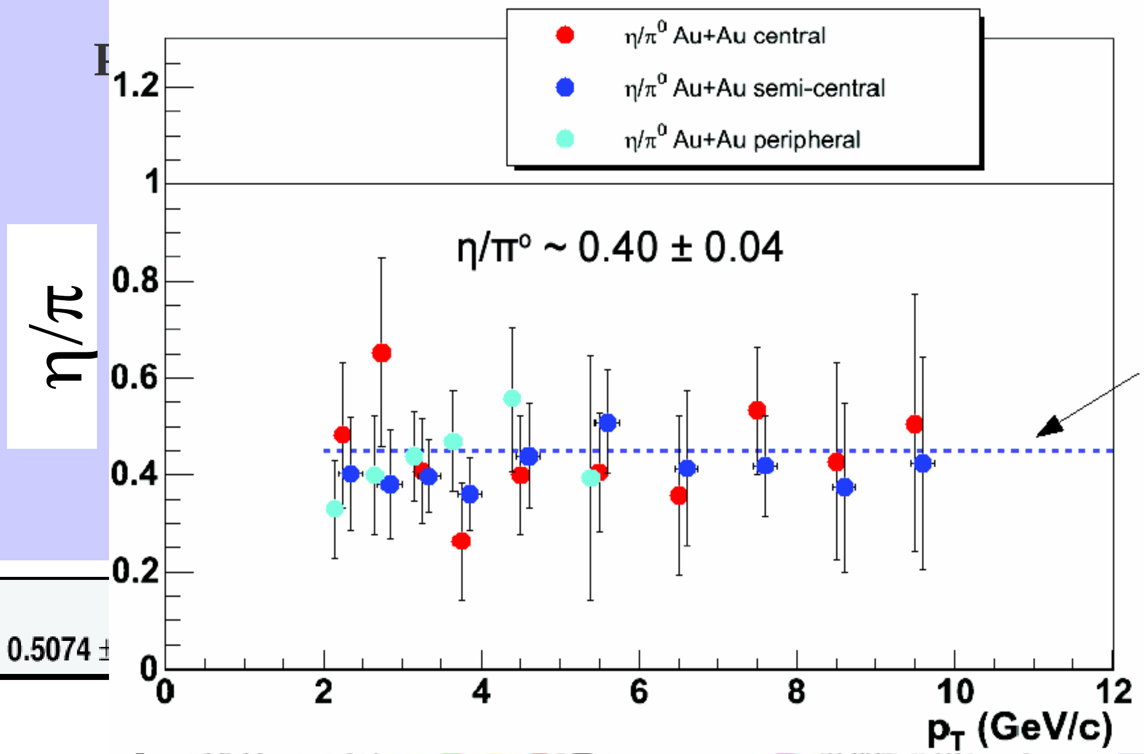
Old idea (Wang *et al*, Phys. Rev. Lett. 77:231-234, 1996)

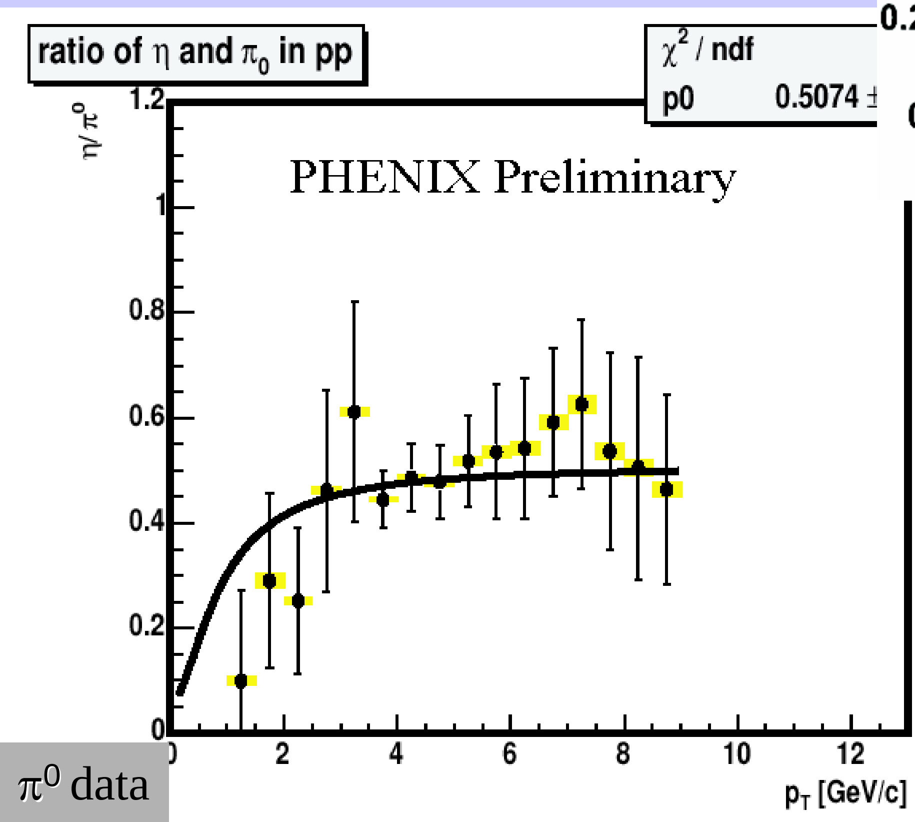
Use photon-jet pairs to study medium-induced energy loss under better controlled conditions

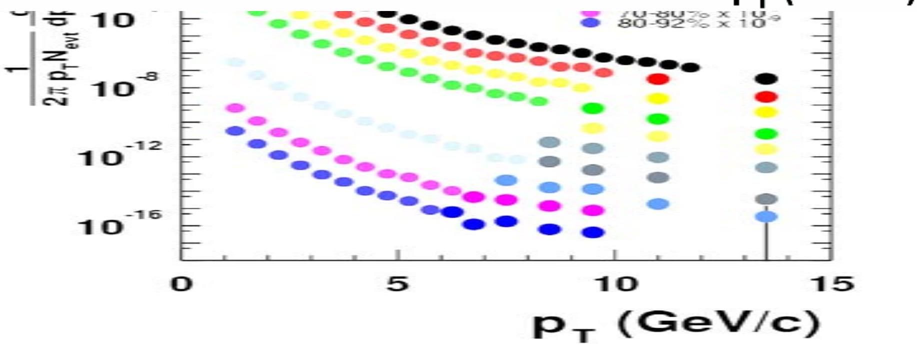
- Study of di-jet correlations affected by energy loss of both jets.
- Photon-jet "cleaner" because on parton escapes
  - "Direct" part of pQCD prompt photon
  - Photon-hadron more practical for now.

π^0's and η's

- π^0 and η spectra measured in Au+Au
- World average:
  - η/π^0 = 0.45+/-0.1

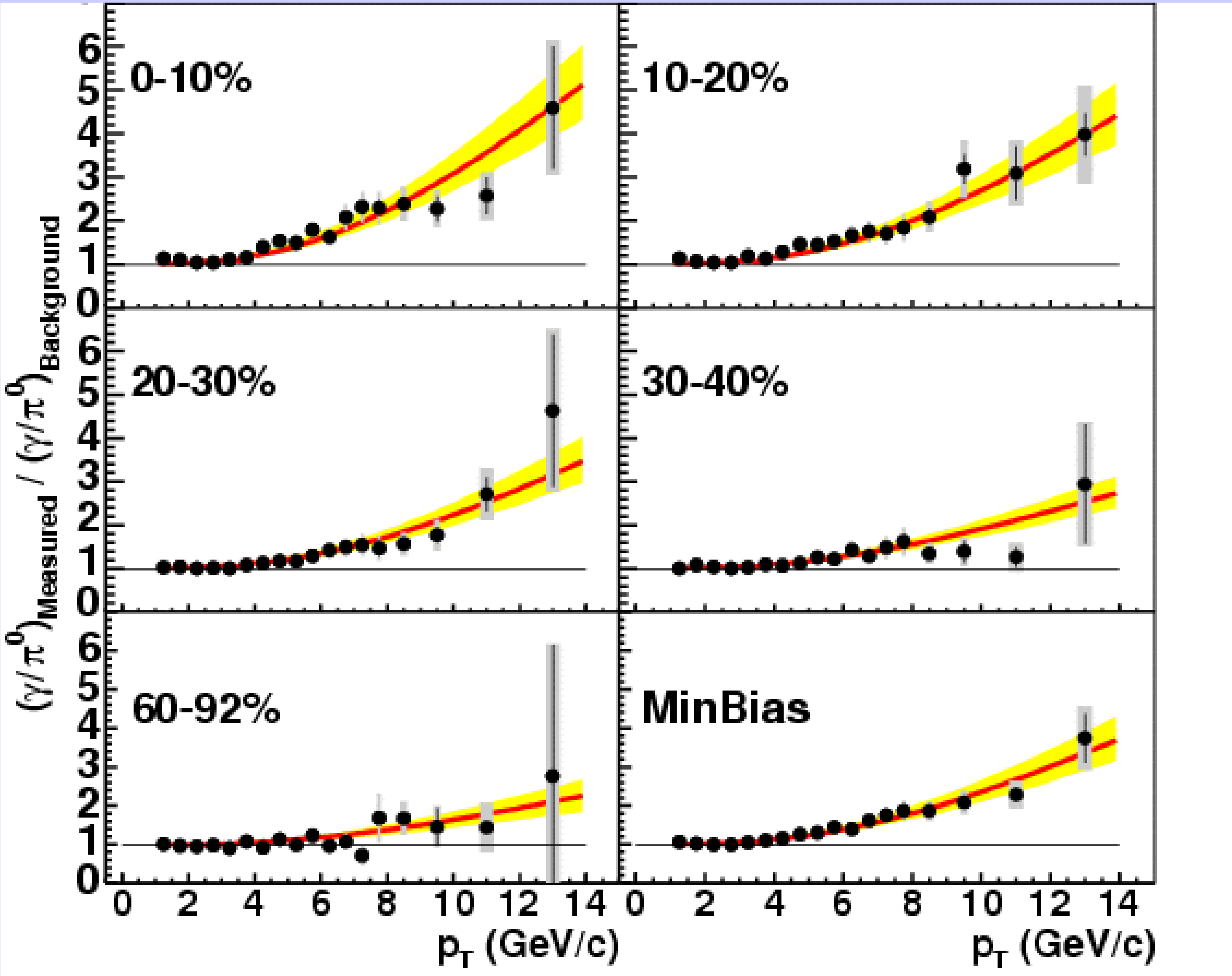






95% of prompt photon background directly measured

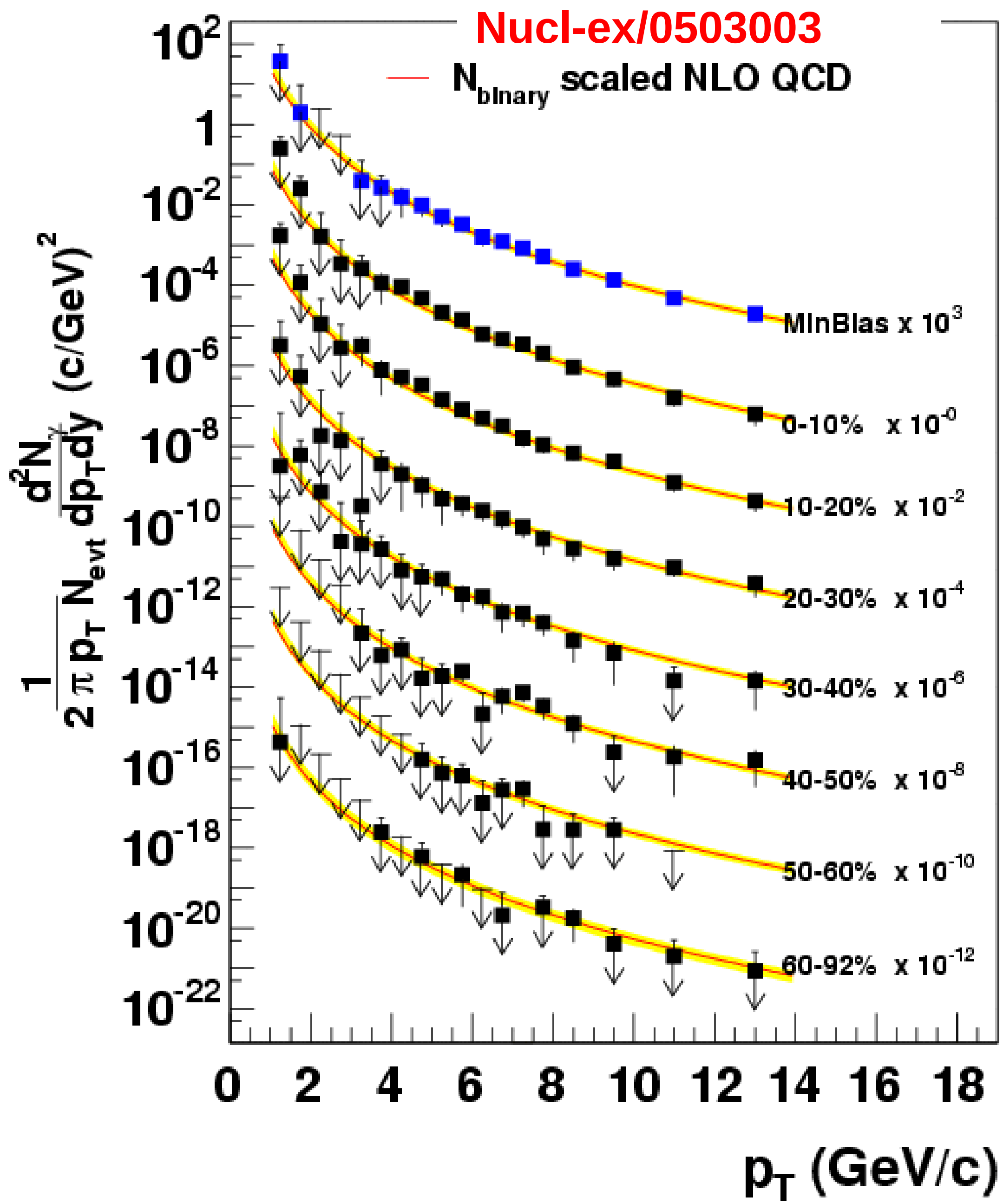
PHENIX Au+Au Prompt Photon



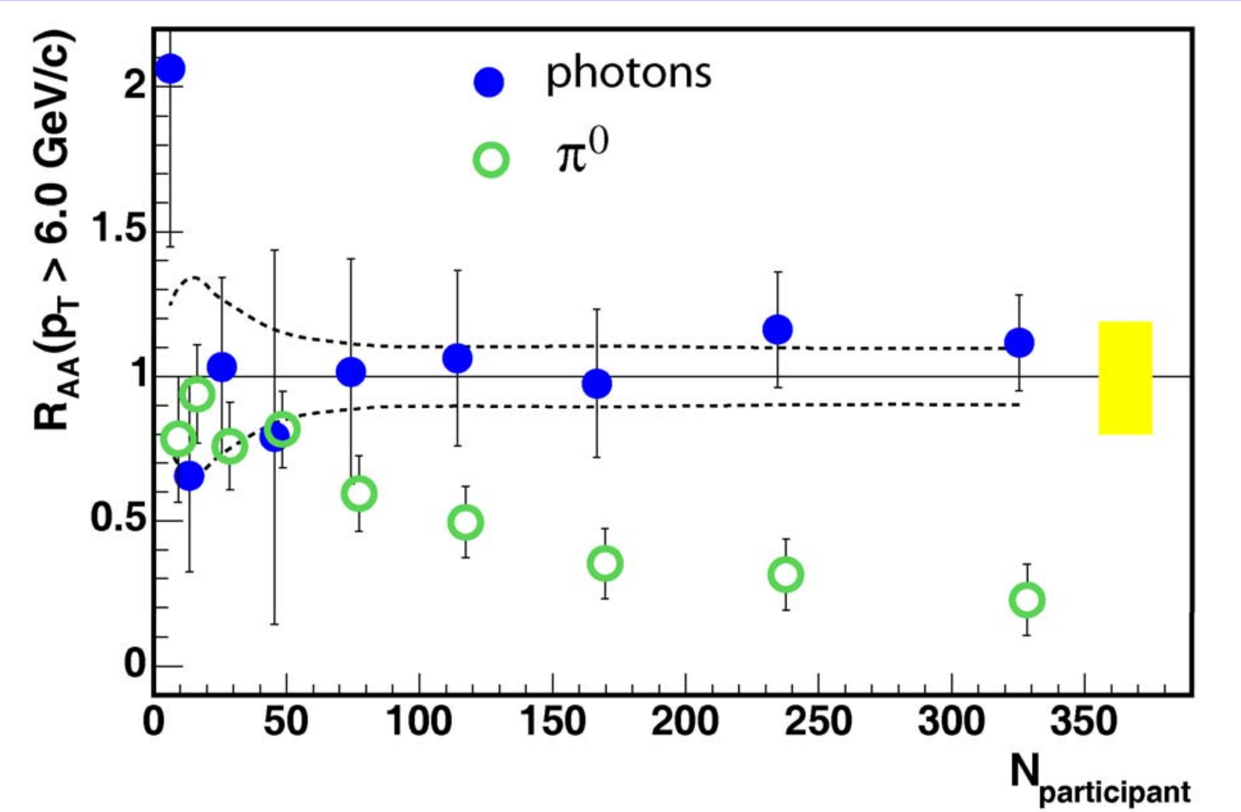
- Ratios of total photon to decay photon yields
- Observe large prompt (non-decay) yield, p_T >4

PHENIX Au+Au Prompt Photon Spectra

- Points: data for different centrality bins, scaled by factors of 10
- Curves: pQCD scaled by "thickness"



Current PHENIX Prompt γ Measurement



Observe: this is for pT > 6 GeV/c

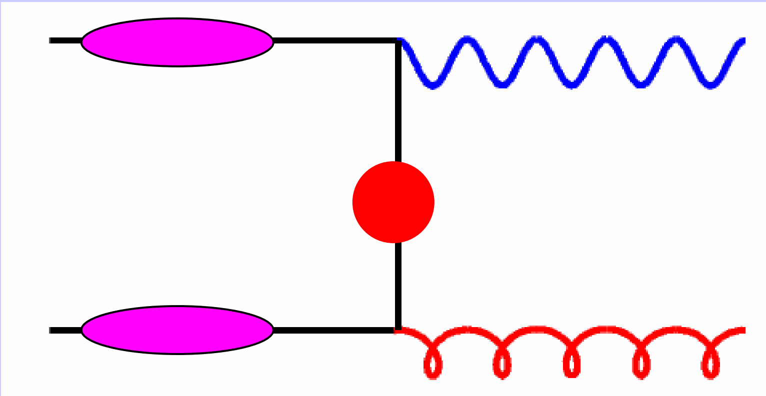
- "R_{AA}" excludes strong suppression of hard scattering rate.
- But, remember the denominator is pQCD …
  - pQCD matches low-statistics p-p measurement
  - Still room for ~30-40% effects

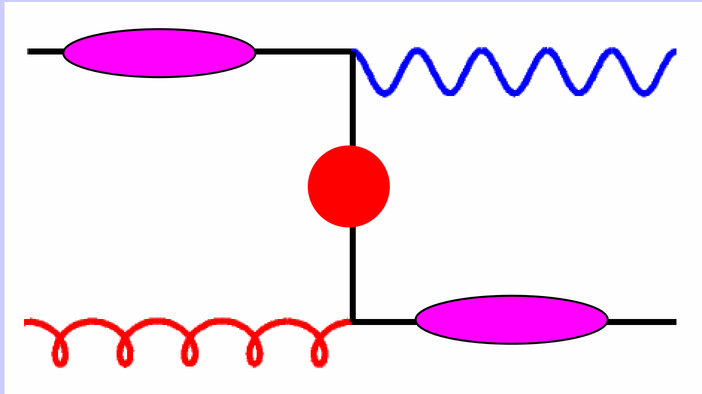
Photon - Jet Measurements: Status

- PHENIX has clear, statistically significant pQCD prompt photon measurement in Au+Au (Run 2).
  - ~ 10x statistics in Run 4.
- High-pT suppression reduces decay bkgd.
- In principle, possible to remove part of remaining background:
  - Direct tagging of π^0 decays
  - "Jet" isolation cuts – require that photon not in jet
- But these cuts are problematic in central Au-Au
  - Frequently satisfied by background.
- What about non-central?
  - For now, I am pessimistic: background drops slowly
- Will need to do statistical bkgd subtraction
  - Stay tuned.

Jet Conversion Photons

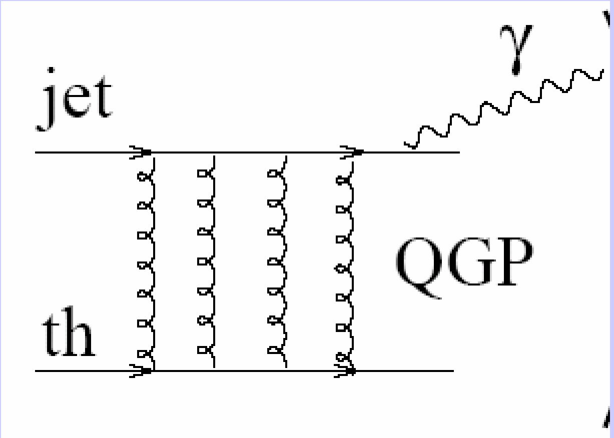
- There is a new source of “hard” photons in QGP
  - High p_T quarks/gluons convert into photons in medium

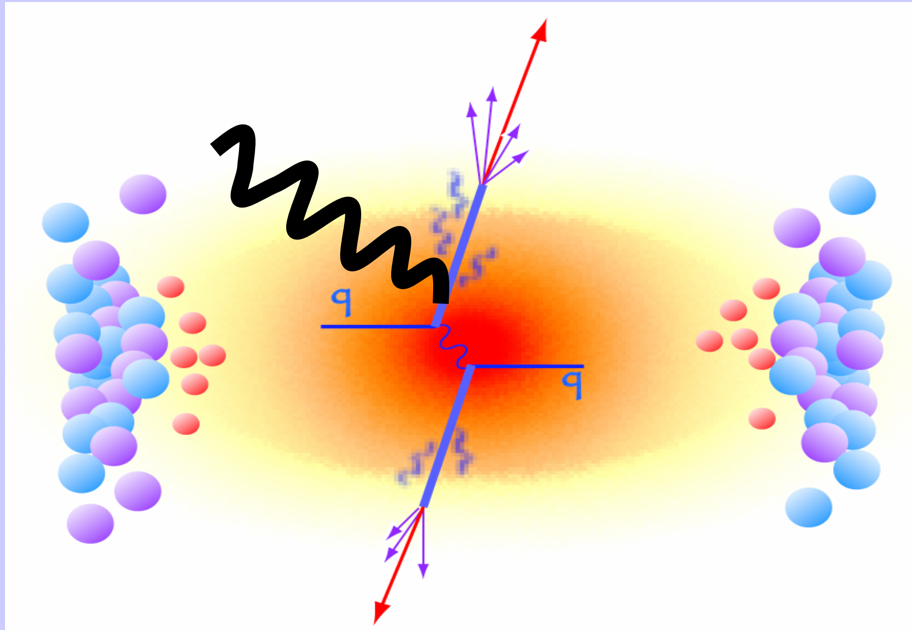




- This extra contribution must be present
  - @ large enough *t*, incident jet sees unscreened partons
- What about at low-*t* ?
  - In principle, pole in the t channel produces “large” $\hat{\sigma}$
- But medium screens @ low-t & regulates pole.
  - Jet-conversion γ rate sensitive to screening mass.
  - And potentially also to quark/gluon thermal masses.

Jet Quenching: Photon Bremstrahlung

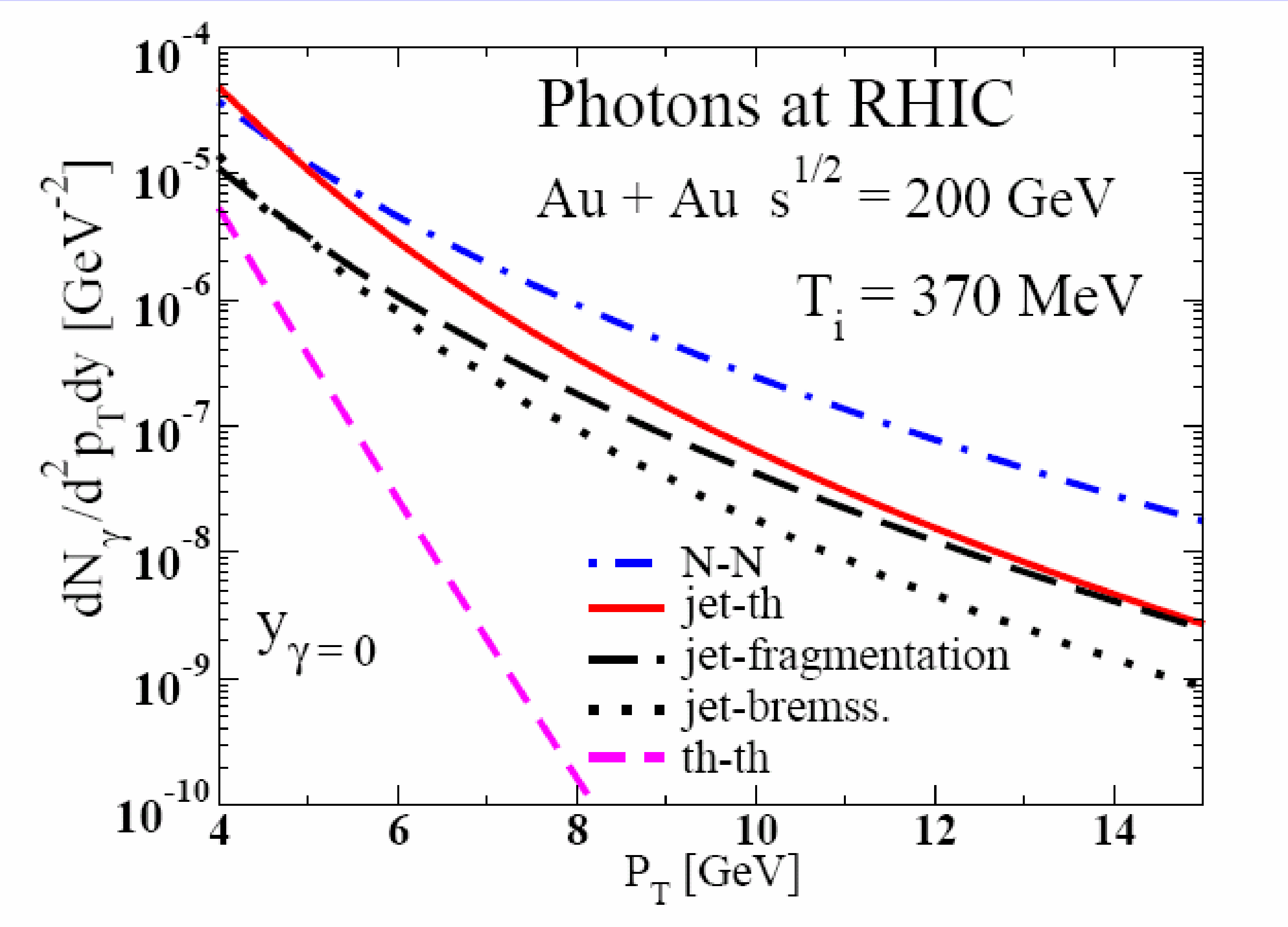




- For light quarks (and gluons??), in-medium energy loss dominated by radiation.
  - Interference between vacuum & induced radiation.
  - For large parton p_T (> ~10 GeV/c) coherence crucial.
- Unfortunately, we can't measure the gluons.
- But we could measure photon bremstrahlung!

⇒Direct measurement of medium properties.

Put it all together …



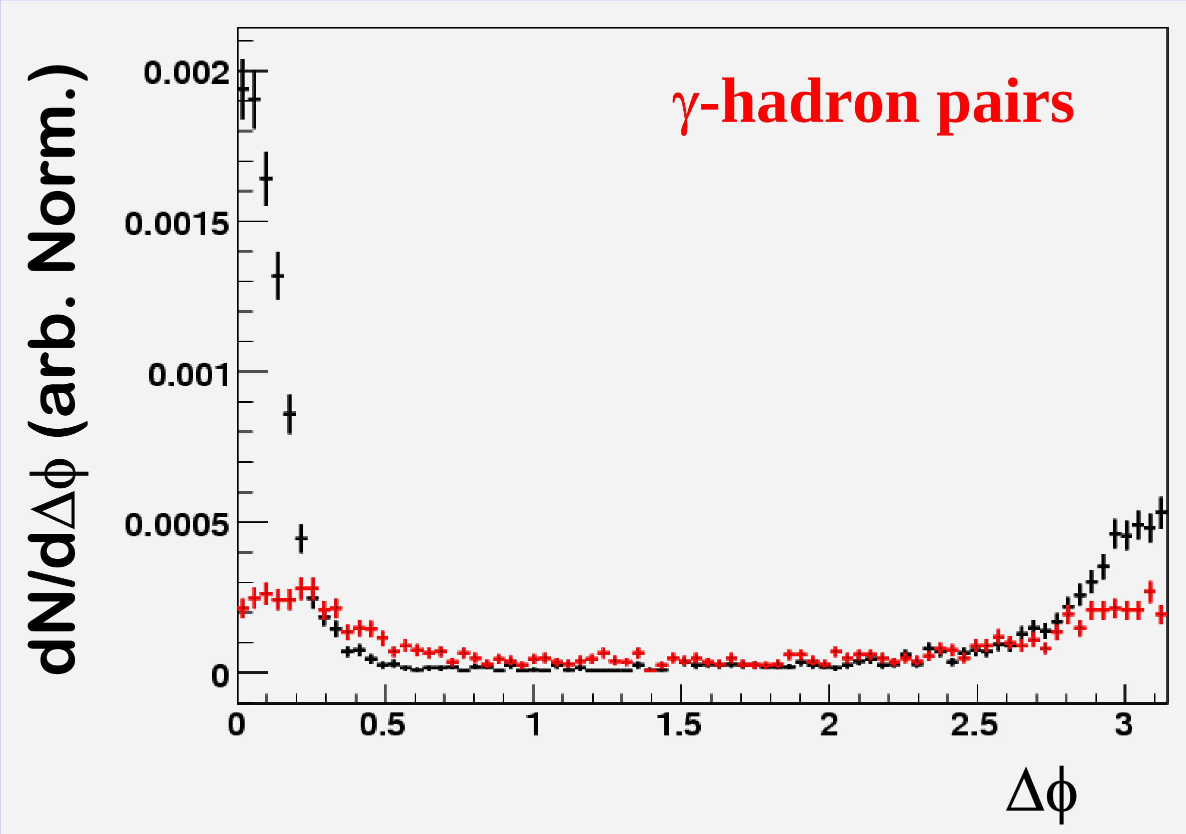
Shamelessly stolen from Simon's talk.

- Extremely rich mixture of physics contributing to the photon spectrum in ~ 4-10 GeV/c range.
- How to unravel all of the different pieces?

How to Measure Frag. & Brem. ? (2)

- But, we can measure prompt photons produced in associate with hadrons of given p_T.
  - e.g. for hadron p_T > 3 GeV, with k_T<1 GeV
  - confusion from IS radiation, jet intermingling, inter-jet radiation strongly reduced

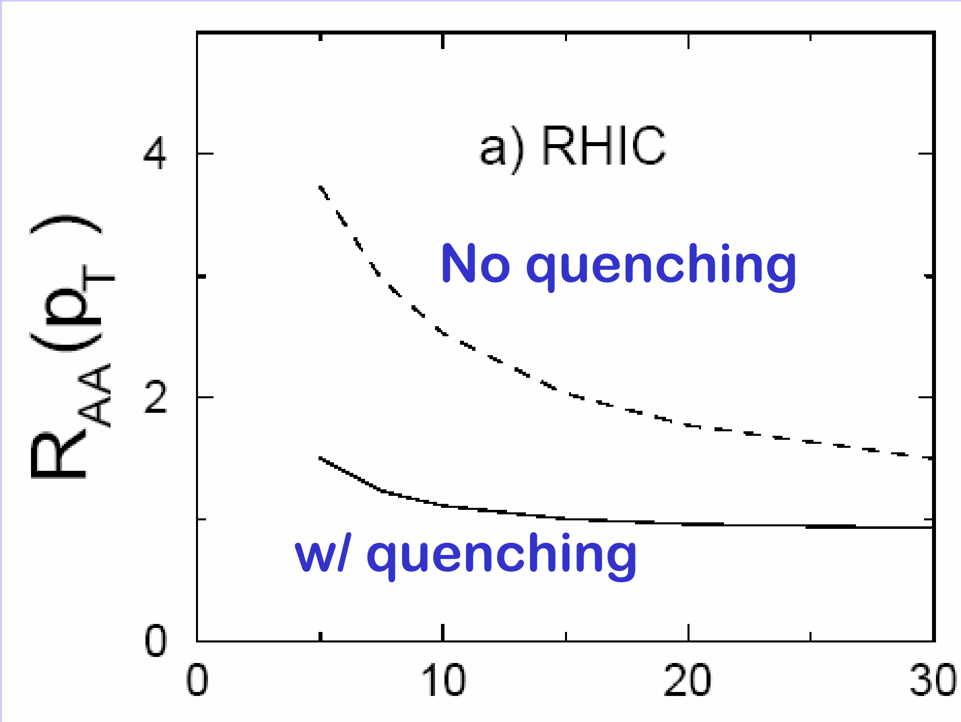
- Need statistical subtraction of decay photons.
  - π^0 "tagging" will help significantly.
  - In p-p can obtain ~ 60% π^0 rejection.
- Pythia study:
  - $E\gamma$ > 4 GeV
  - pT hadron > 3 GeV/c.



Bremsstrahlung in Heavy Ion Collisions

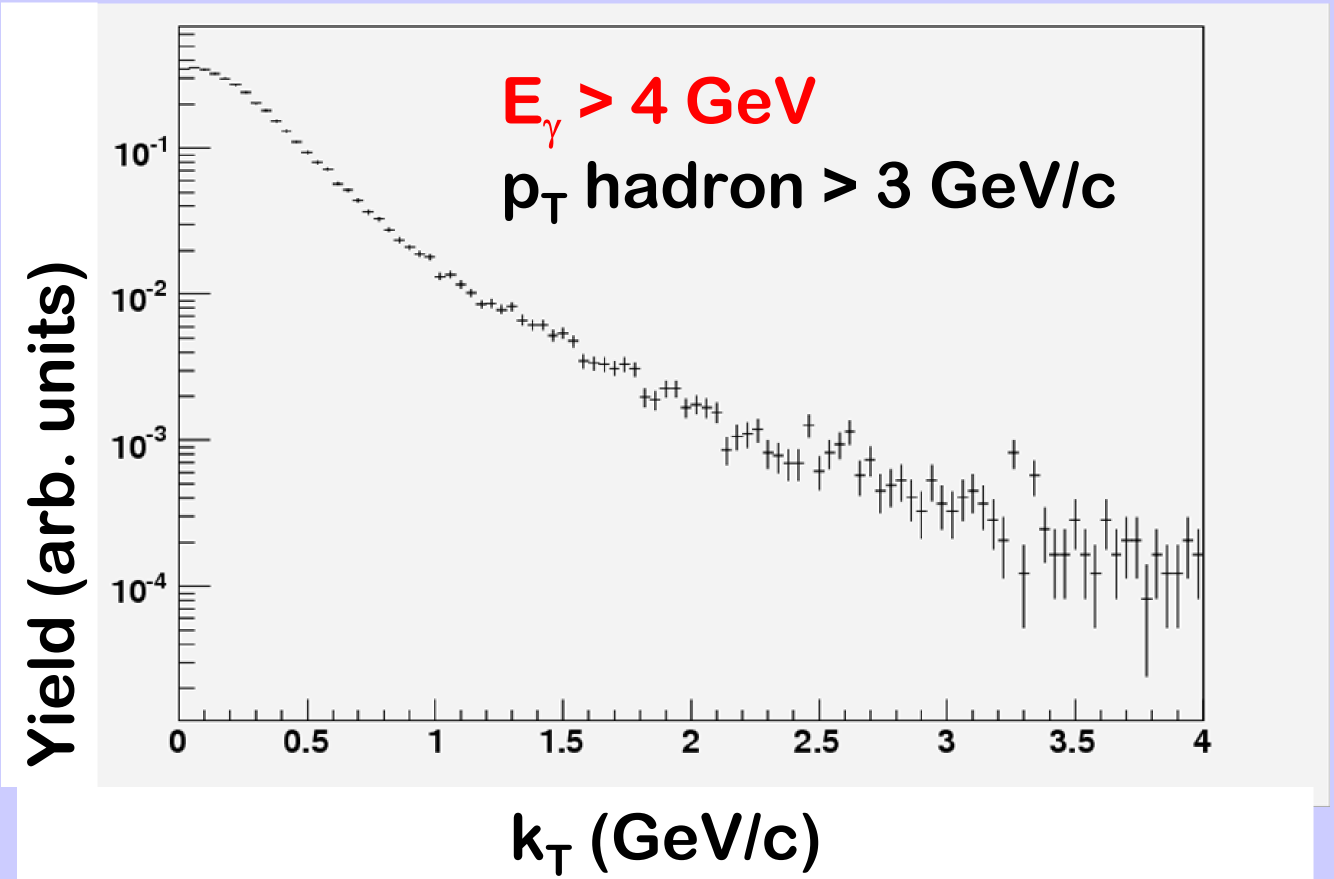
- Bremsstrahlung contribution only!
- Potential increase in bremsstrahlung yield in medium.
- More important:
  - Energy & k_T spectrum will directly reflect medium properties.

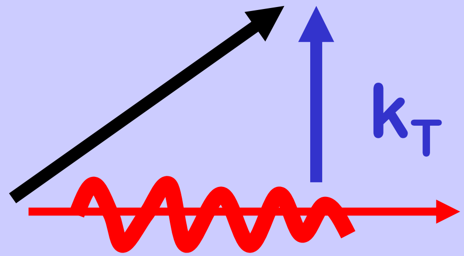
Zakharov (hep-ph/0405101)



- In my opinion: "Holy Grail" of energy-loss physics
  - Can "see" the radiation itself.
  - Photon bremsstrahlung calculation is much less model dependent than the gluon radiation calculations.
  - Will not be easy to measure but it's worth trying …

Bremsstrahlung: k_T distribution





Pythia photon-hadron k_T dist.

- Pythia (p-p) k_T distribution reflects
  - Non-perturbative jet fragmentation scale (j_T)
  - "Hard" tail due to accumulated radiation effects
- Medium bremsstrahlung should have completely different k_T scale (> 1 GeV !?)

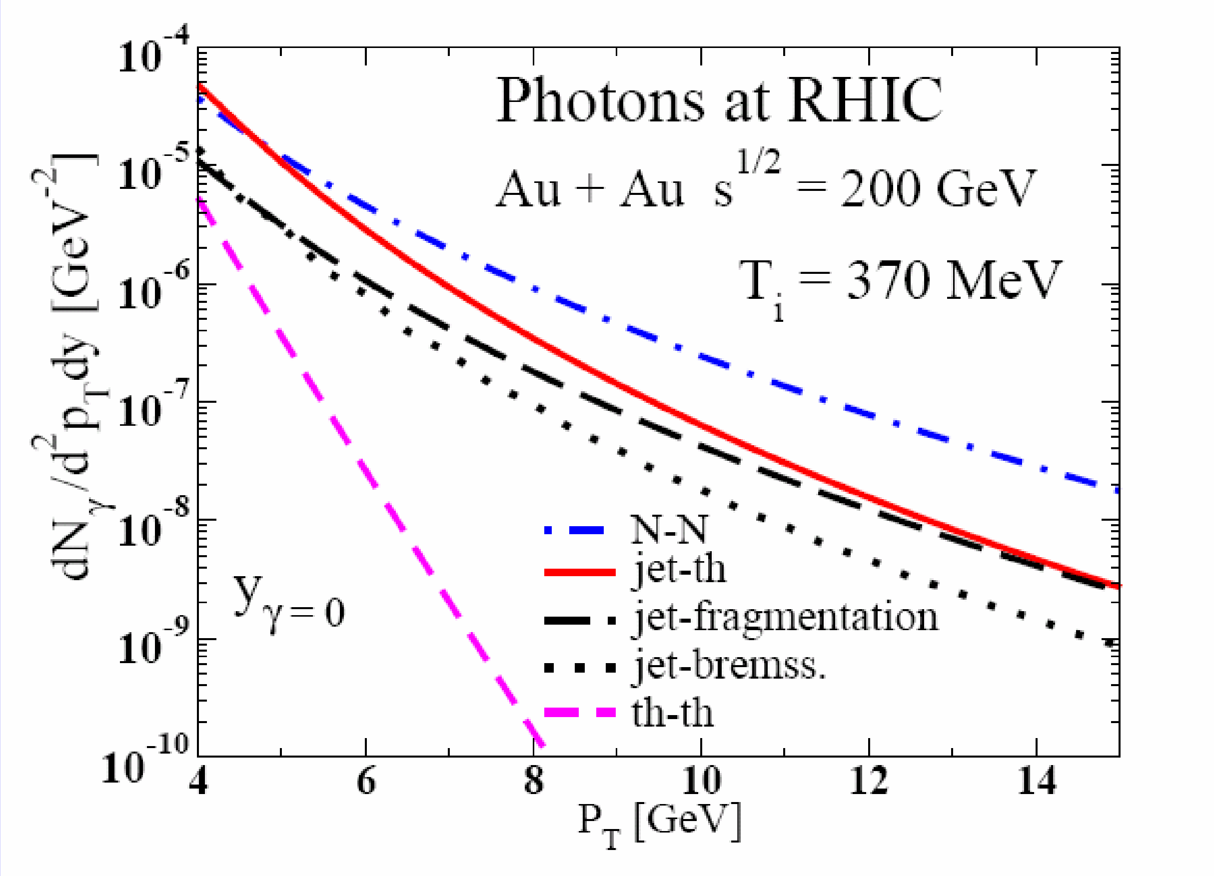
Bremsstrahlung Measurements

- Real opportunity for qualitatively new insight on the physics of in-medium parton scattering.
- Let's be clear – this measurements won't be easy.
  - In worst case, need to dig out bremsstrahlung out from under x10 larger decay signal.
    - ⇒Jet quenching no longer helps when you require the photon to be in a jet !!
  - But, if the bremsstrahlung is enhanced, angular distribution is broadened, then life is better.
- Observation by Axel: "trigger bias effect"
  - Will be an issue.
  - But potentially controllable by using opposite-side "jet"/high-p_T hadron requirement.
  - Guidance from complete in-medium interaction calculation like AMY would be a big help.

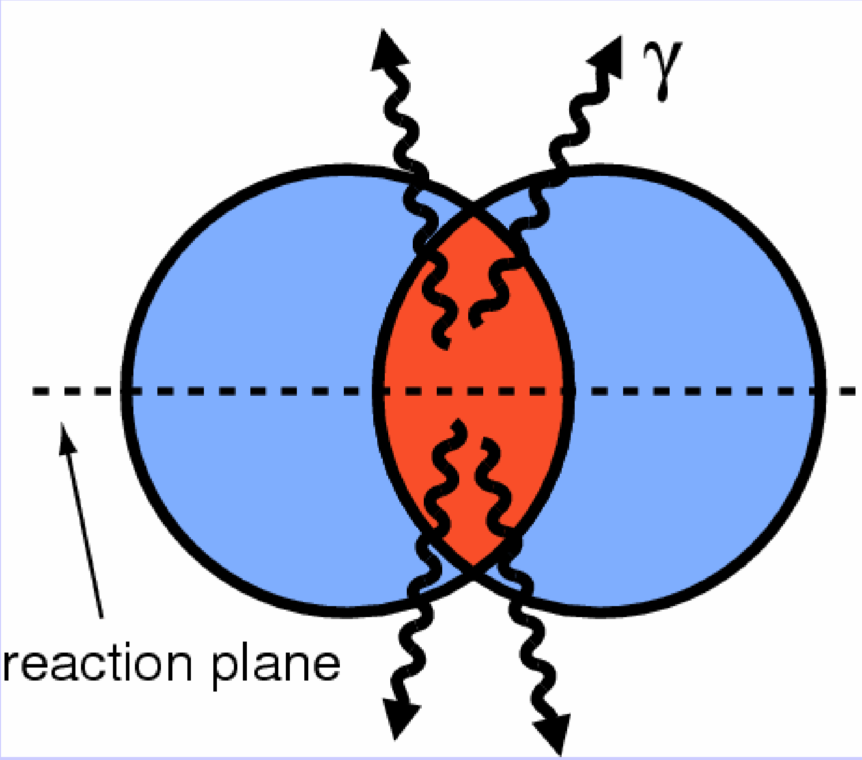
How to Measure Jet Conversion γ ?

- Brute force:
  - Measure p-p accurately enough to provide a baseline with ~ 10% accuracy.
  - Measure the Au-Au, Cu-Cu yield vs p_T well enough to see >30% effects.

- Might work if the jet-conversion yield is as large as has been predicted.
- But, Cronin ???
- Bremsstrahlung? (measure it – but enough of total yield ??)



One Hope: Reaction Plane Dependence



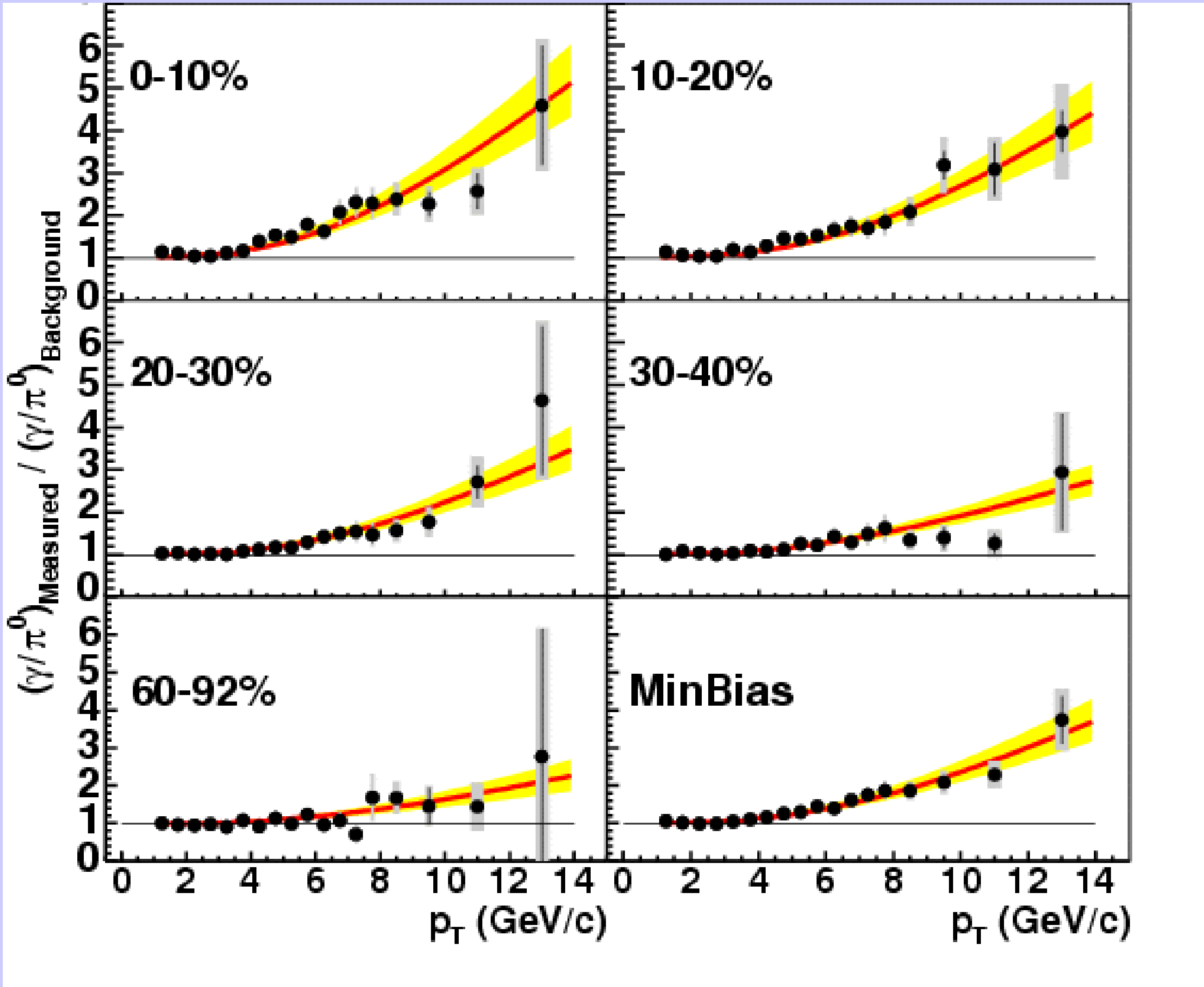
•Jet conversion will produce more photons out-of-plane than in-plane

→ Negative v_2 for these "jet quenching" photons

- **Both Bremsstrahlung and jet-conversion photons could contribute to prompt photon v_2.**
  - **Observation of prompt photon $v_2 \Rightarrow$ one or both mechanisms are present (high priority!)**
  - **If we observe prompt photon v_2, then we need to unravel the contributions.**

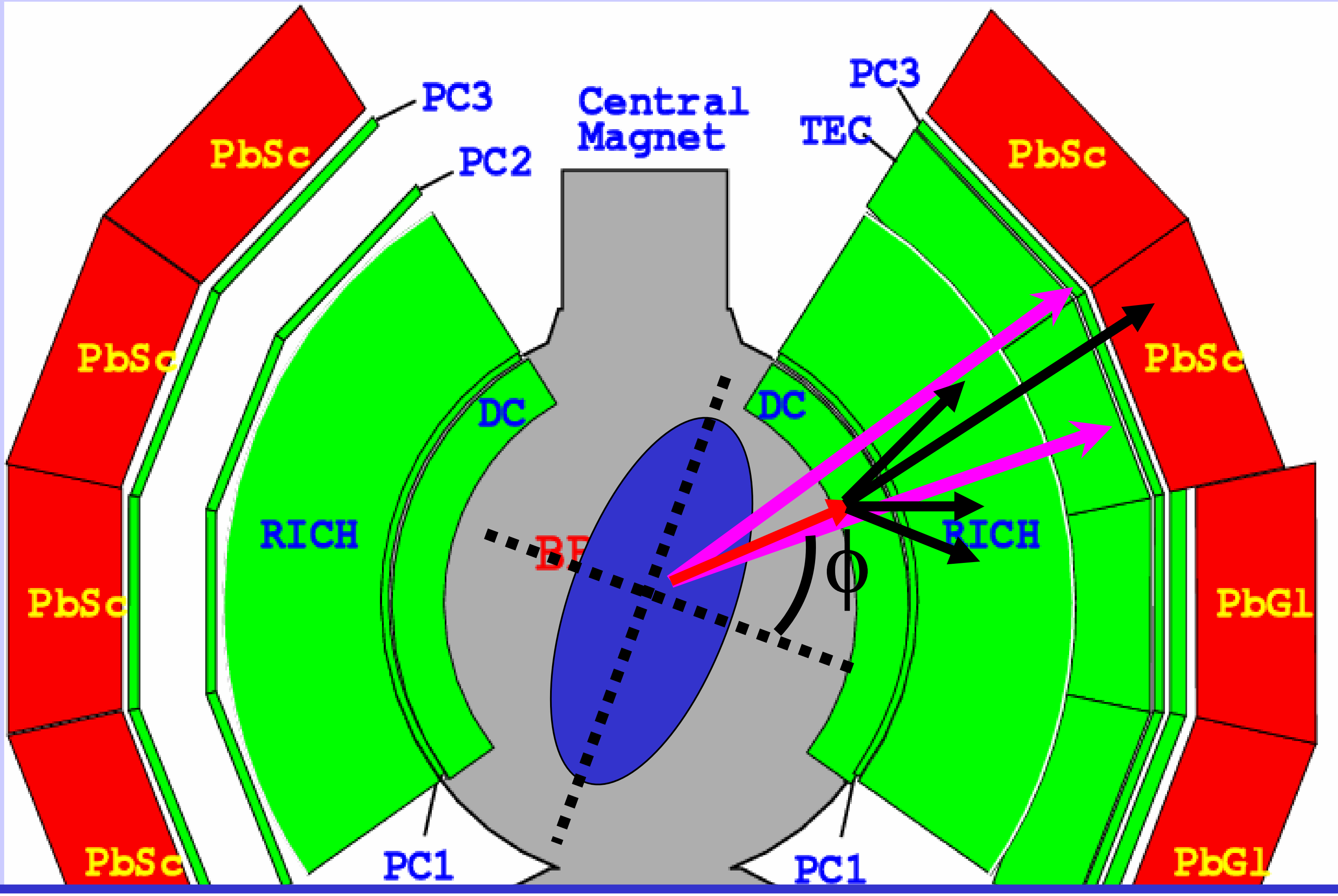
Prompt Photon v_2 – How ?

- **Do vs $\Delta\phi$**



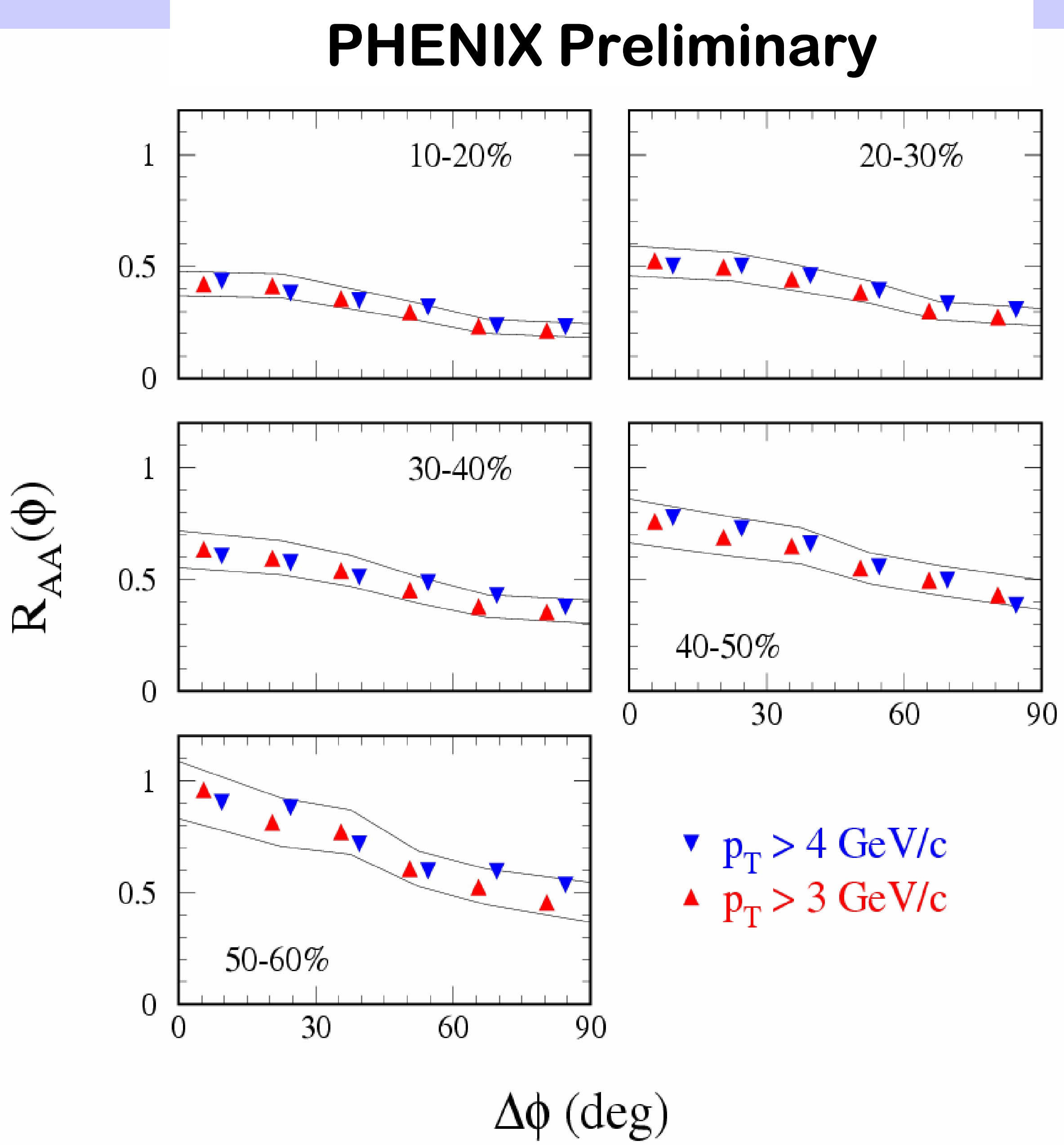
- **More specifically, measure inclusive photon, π^0, η yield vs $\Delta\phi$, extract prompt yield vs $\Delta\phi$.**

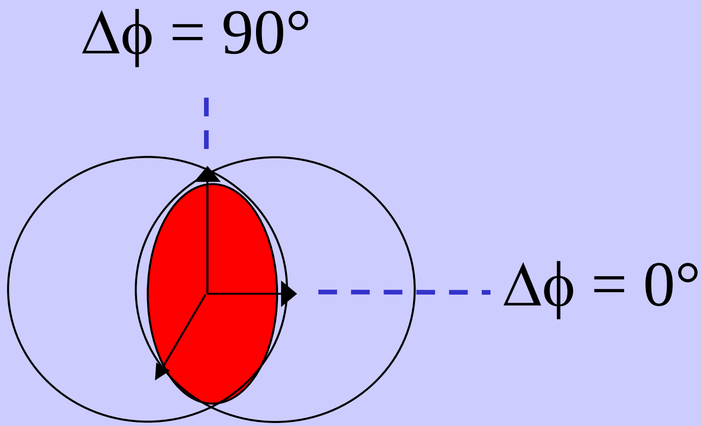
The First Step on the Path: π^0 ($\Delta\phi$)



- **Find reaction plane with PHENIX Beam-Beam counter**
- **Measure π^0 yield vs angle relative to reaction plane, $\Delta\phi$**
- **Correct for measured reaction plane resolution.**

π^0 Suppression vs $\Delta\phi$

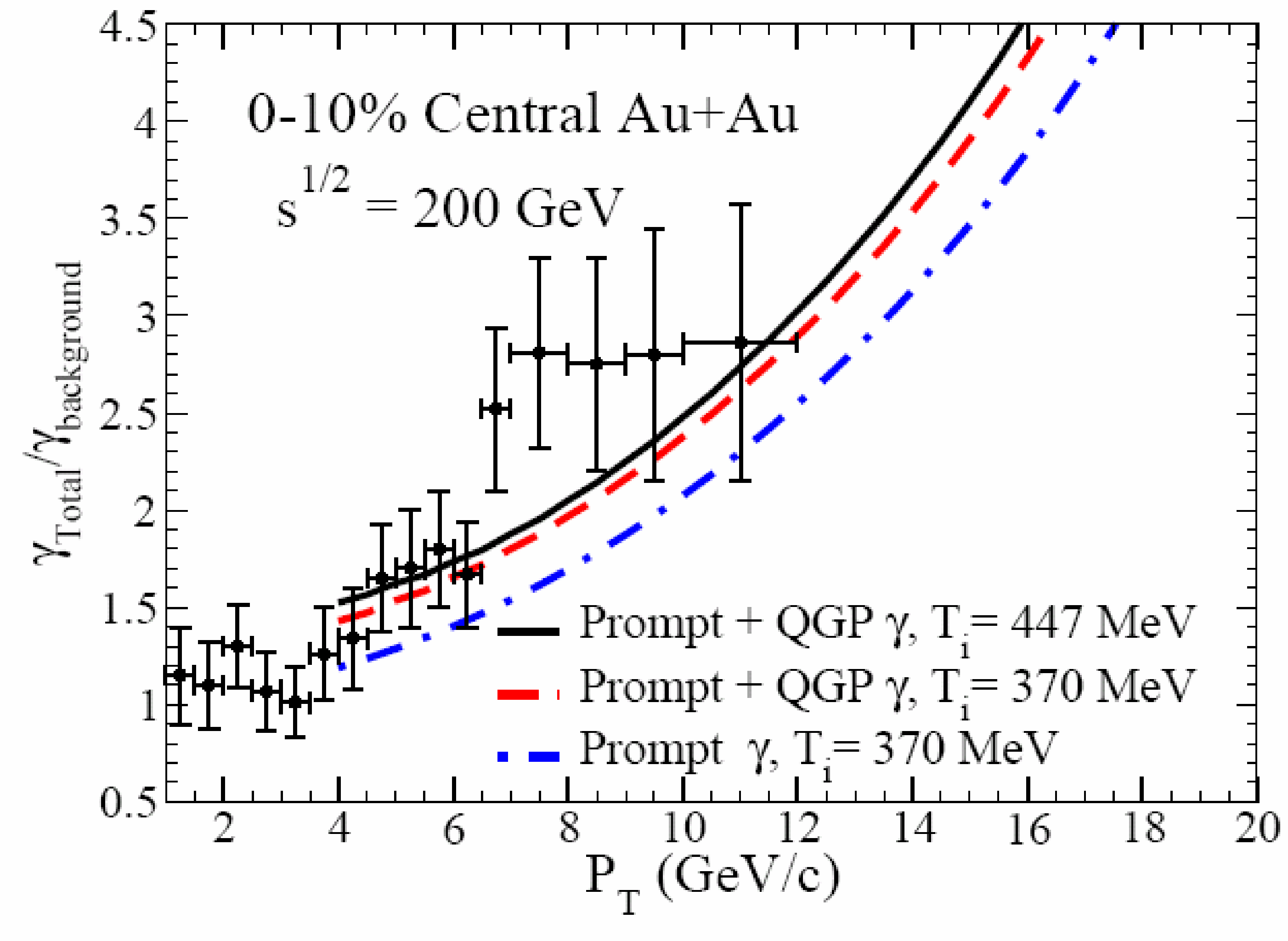




Observe:

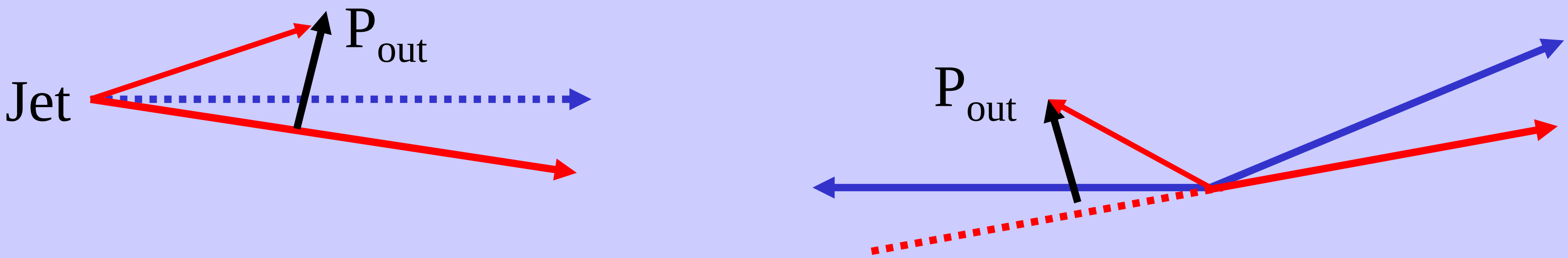
- Less suppression in "short" direction.
- More suppression in "long" direction.
- Big variation in peripheral events.
- p_T dependence ?

From S. Turbide *et al*

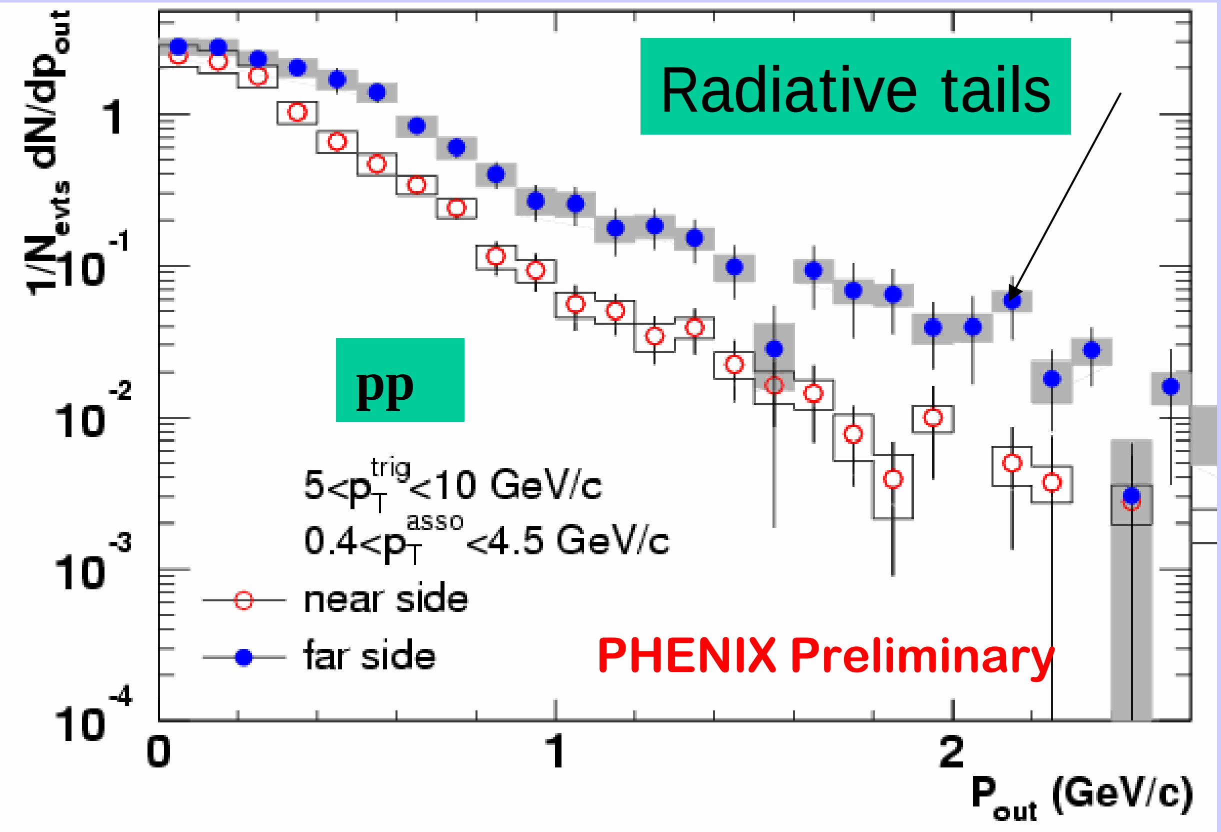


- **Inclusion of extra QGP contributions improves agreement with data ??**
- **Too soon for conclusion – but real motivation!**

Studying Jet Properties @ RHIC



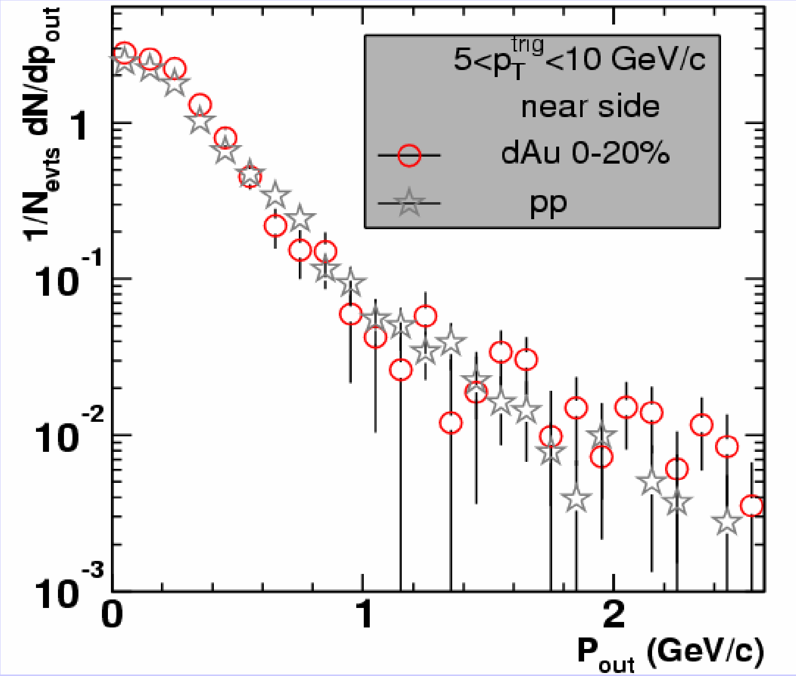
PHENIX, From J. Jia, DNP'04 Talk

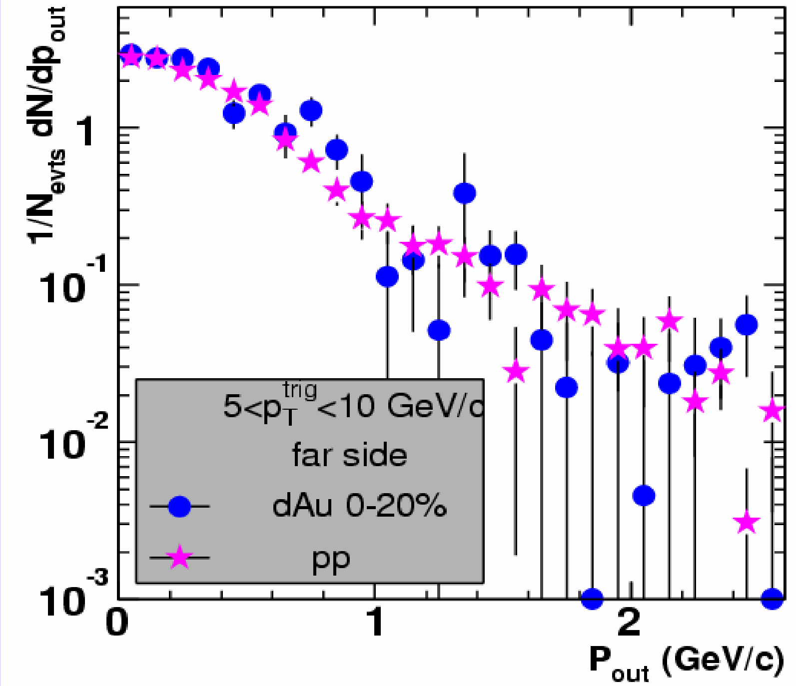


- Use hadron pairs to study jet properties
- p_{out} dist. has both non-pert. (Gaussian) + hard (power) contributions.

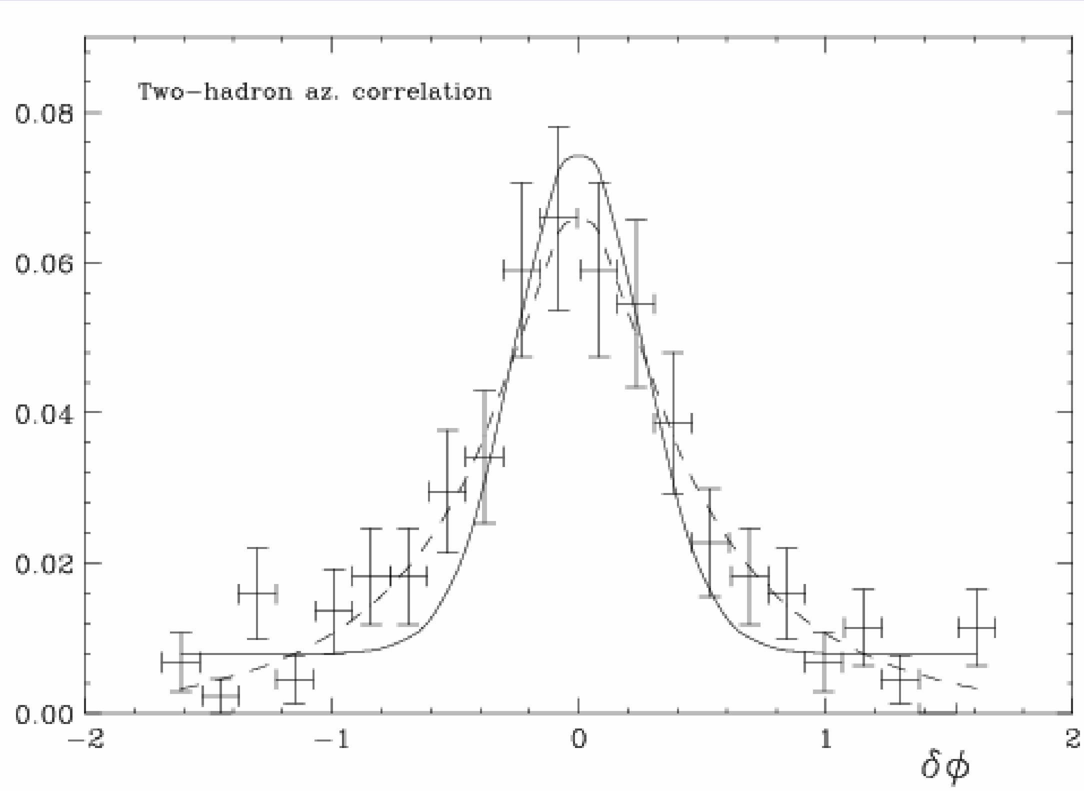
Jet Properties in d-Au

- Compare p_{out} dist's in p-p and d-Au.
- Evidence for effects of re-scattering, modified radiation, ... ?
  - Not so far!
  - But this is just the beginning!
- Such measurements w/ one jet @ $\eta > 2$ would be very interesting!!
  - But not possible yet





Radiative Effects on (di)Jets



Analysis of STAR di-hadron Δϕ distribution by Boer & Vogelsang,

Phys. Rev. D69 094025, 2004

- **Large radiative component to di-jet acoplanarity**
  - Also see Vitev, Qiu : Phys.Lett.B570:161-170,2003.
- **Radiative effects are so large that we may have to re-think p-p and d-Au analysis**
  - Cannot subtract off "constant background"

Summary

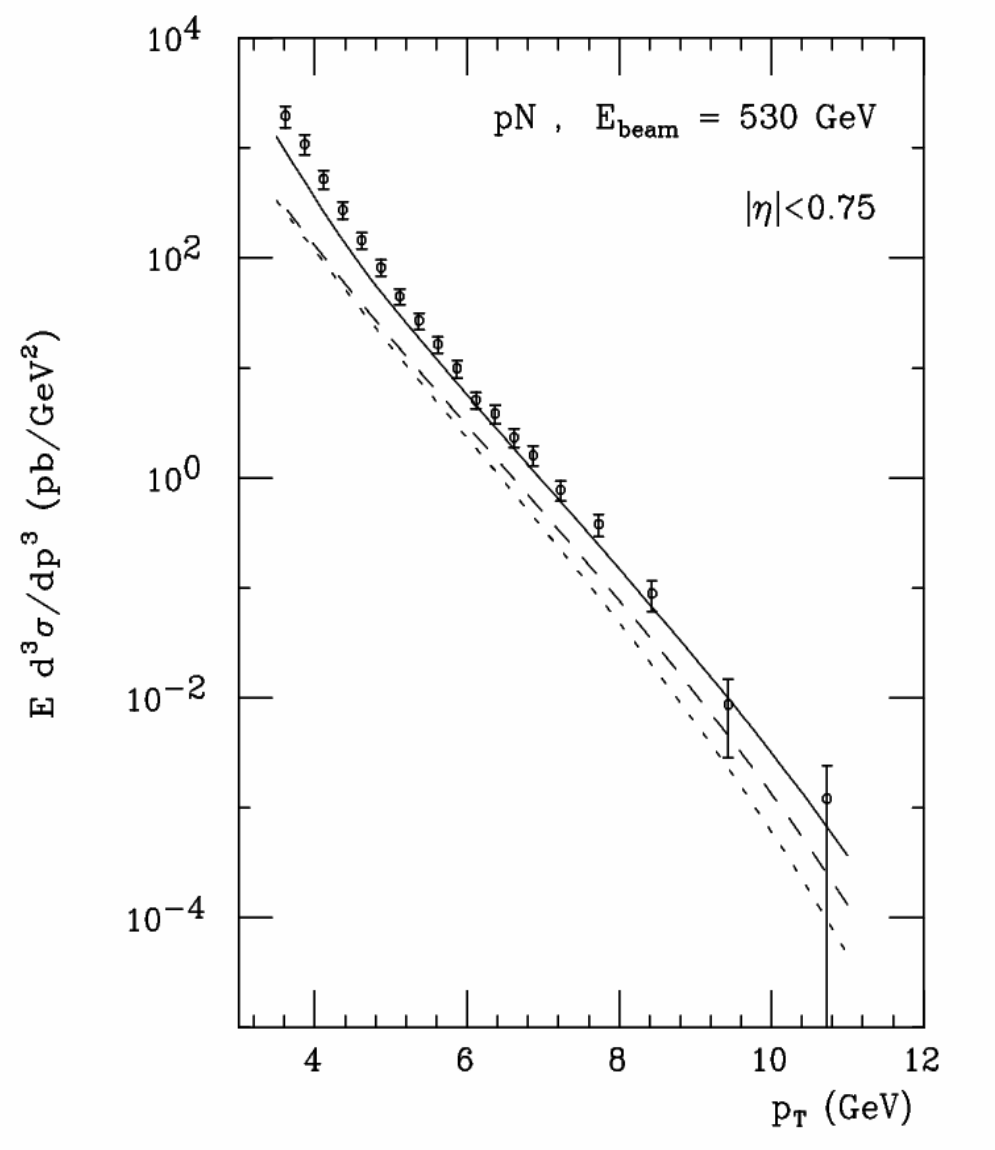
- There is surprisingly rich physics in the hard photon sector.
- So much so, that understanding it & unraveling the contributions will take some time.
- Another example of the importance of penetrating probes
  - Bremsstrahlung photons should provide cleaner insight on parton energy loss physics.
  - Jet-conversion photons are the extreme case of radiation from parton interactions in medium.
- I personally have real hope for the medium generated bremsstrahlung measurement
  - but it will take time.

Summary (2)

- We are still in the infancy of pQCD physics program RHIC.
  - Only a few relevant measurements in p-p
  - And some (e.g. prompt photons) subject to non-trivial ambiguities.
  - Many opportunities to study effects like those discussed by Werner.
- Huge final-state effects in Au-Au
  - ⇒So big that understanding the observed effects may be difficult (e.g. di-jet)
- I have high hopes for Cu-Cu data
  - See effects “turn on”
- Need more differential “jet” probes.

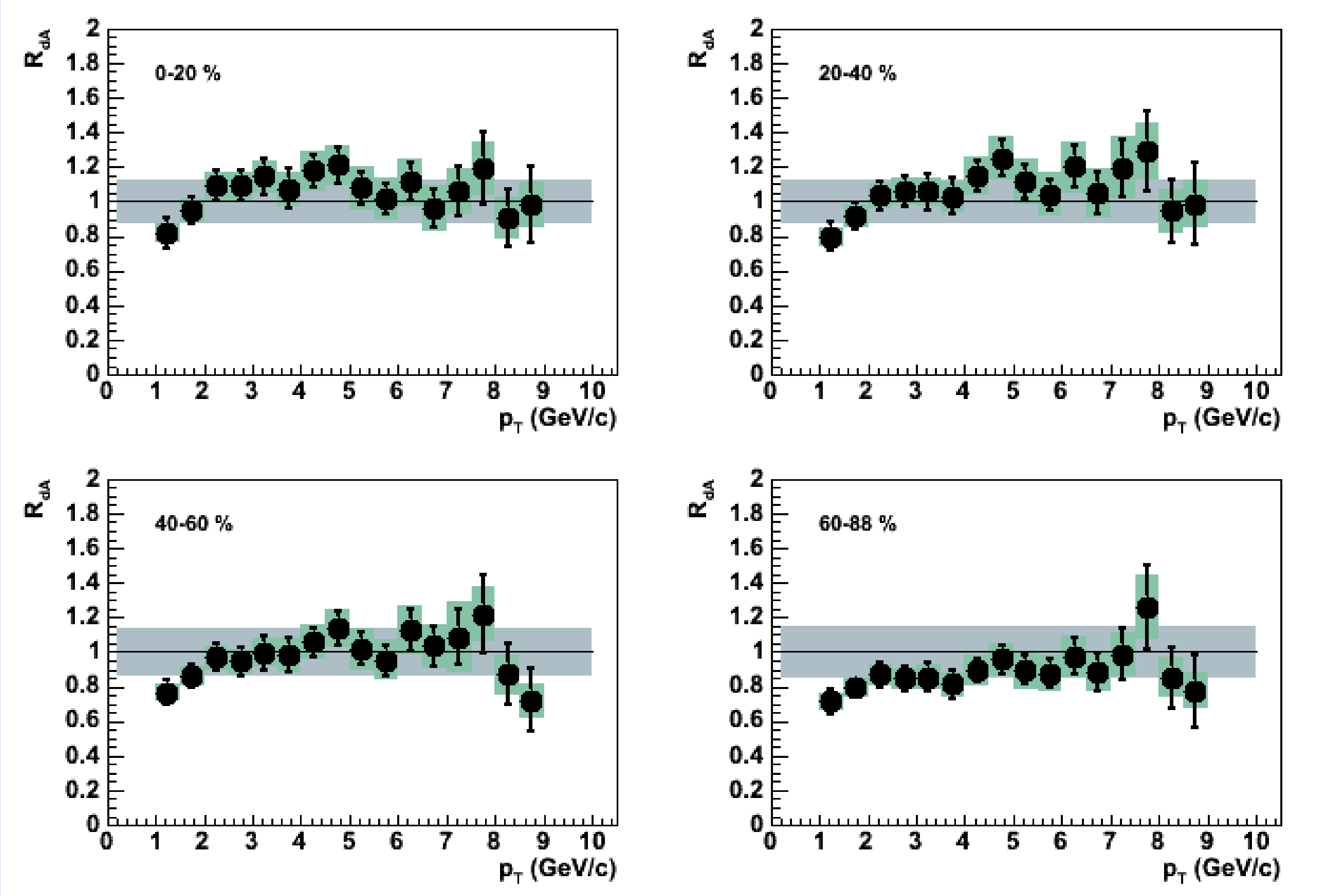
p-p Prompt γ Production (Fixed target)

Laenen, Sterman, Vogelsang, Phys.Rev.Lett.84:4296 (2000)



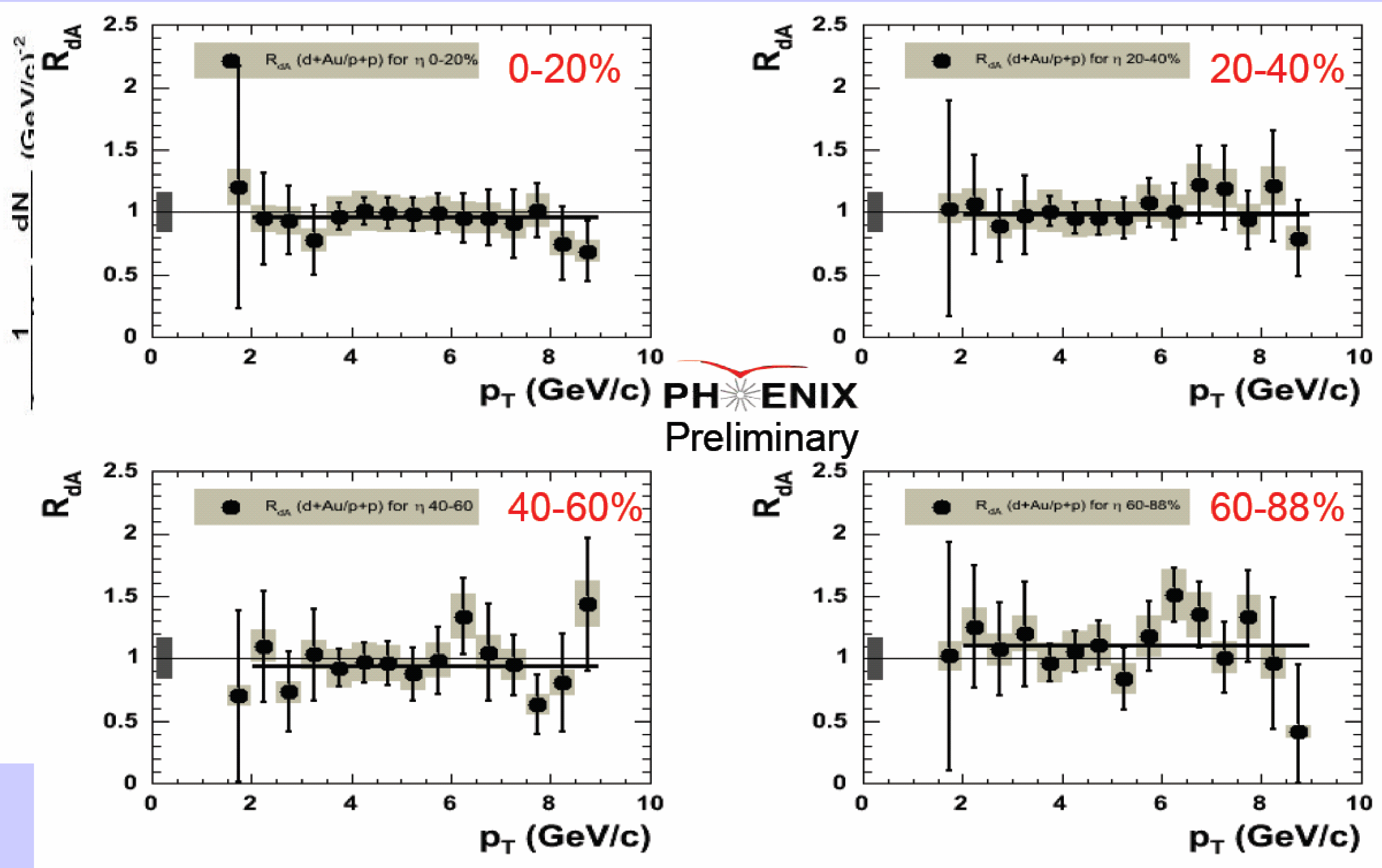
- NLO pQCD also needs corrections to match fixed-target data.
- E706 claims that intrinsic $k_T \sim 1$ GeV is needed to match pQCD to data.
- With incorporation of soft gluon recoil and threshold resummation, much better description of the data.

PHENIX d-Au π^0 vs Centrality



- Small Cronin effect (not expected to be large)
- It is now known that preliminary data suffer from small trigger bias (central will go ↓ peripheral ↑).

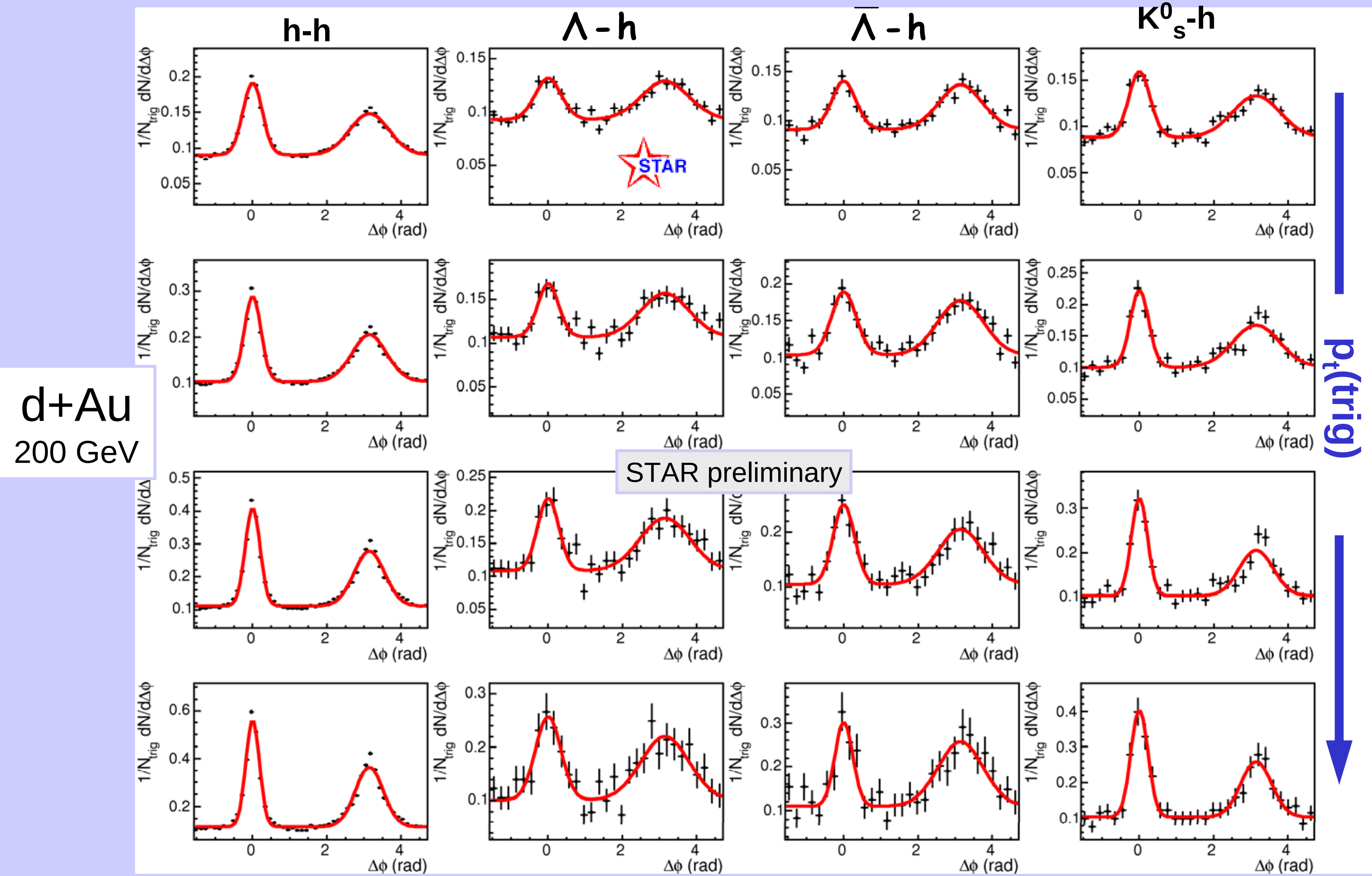
PHENIX d-Au η Production



- PHENIX sees small Cronin effect
  - Approx. consistent within errors with STAR K_s result
  - Enhancement seen in charged (baryons) all the more striking!

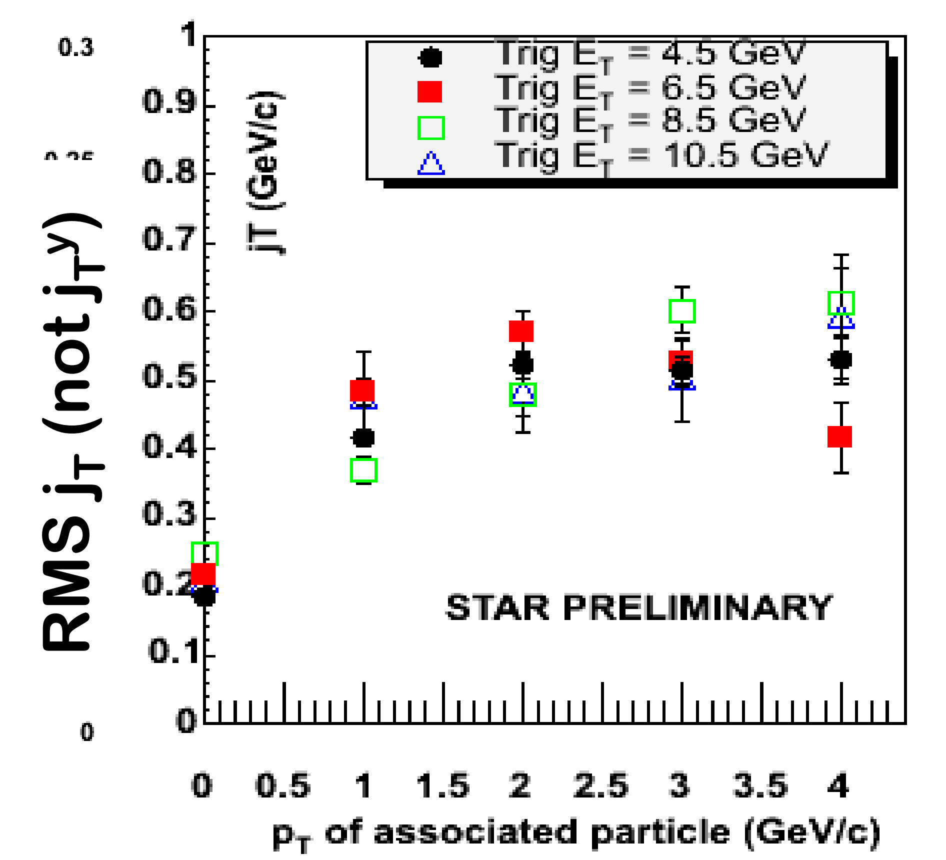
(di)jet h-h Correlations in d-Au / p-p

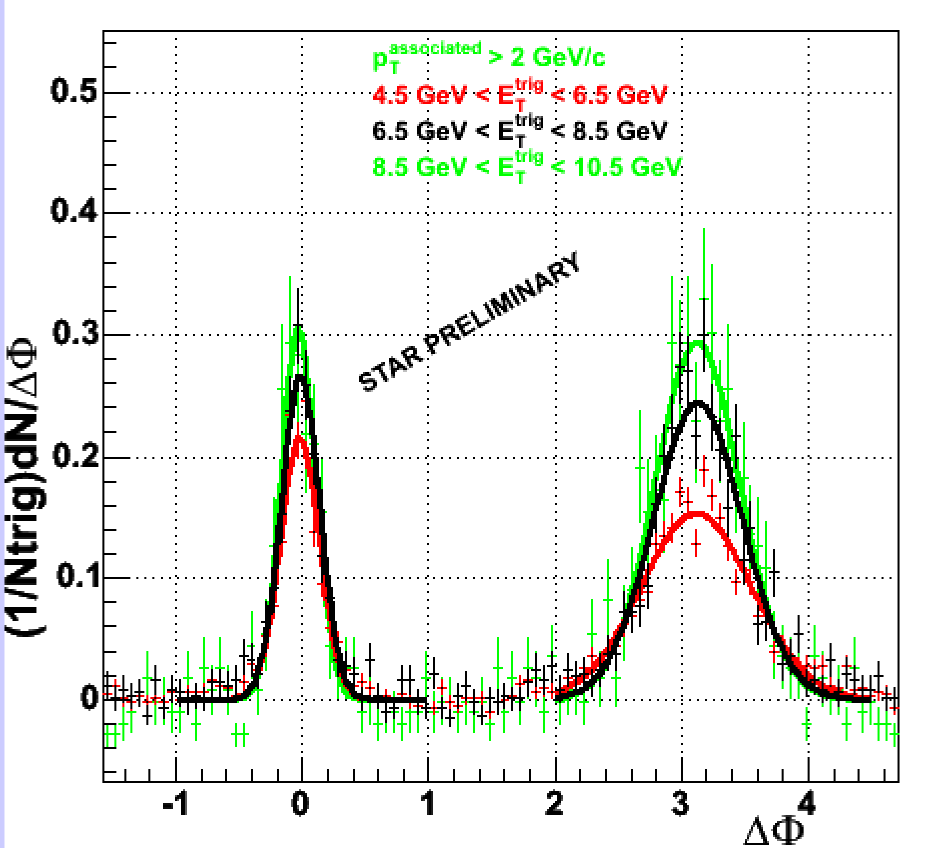
From Dan Magestro, Hard Probes 2004 talk



- STAR version of "shock and awe" (and I mean it!)

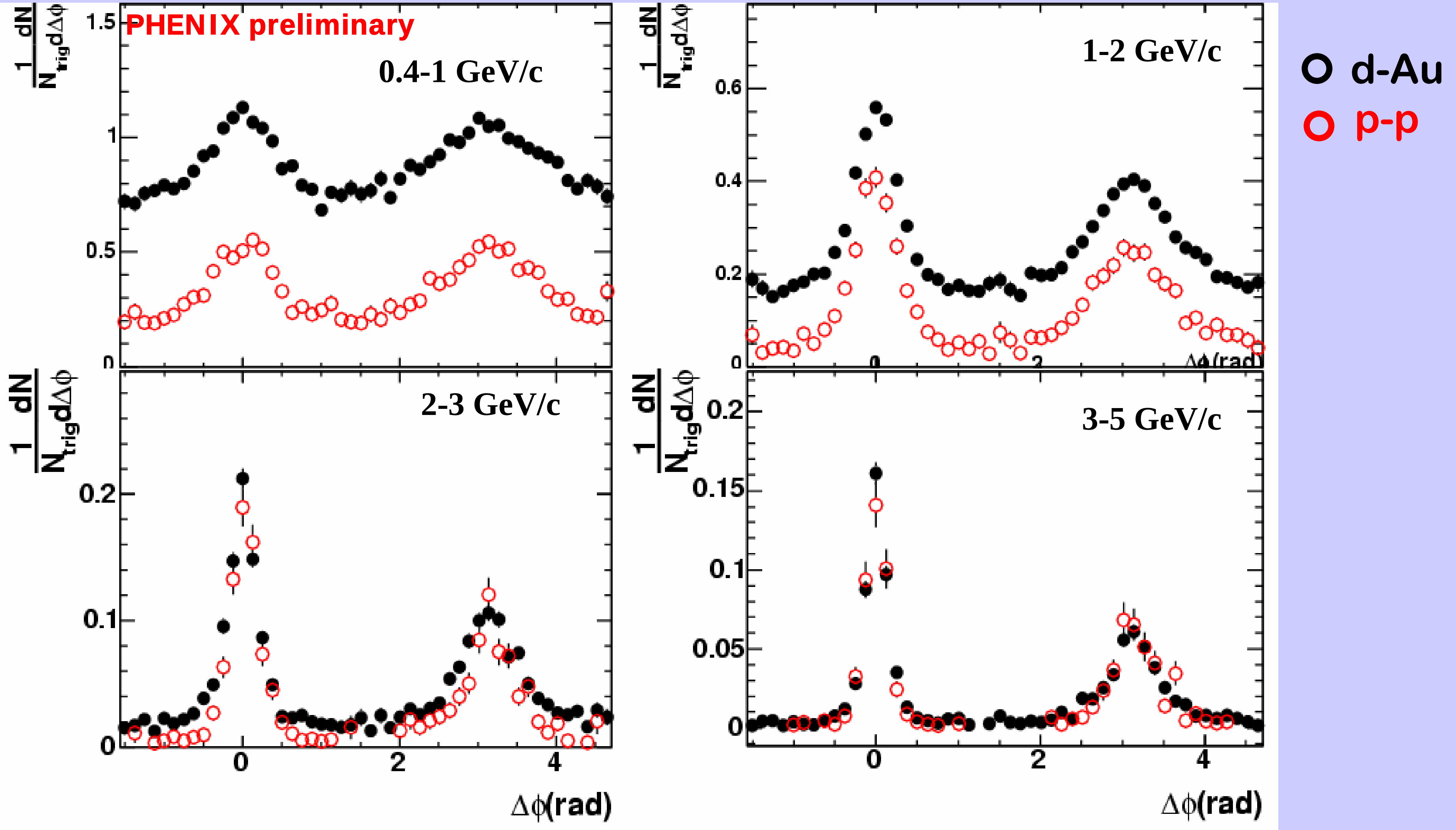
STAR d-Au γ-h Δφ Correlations





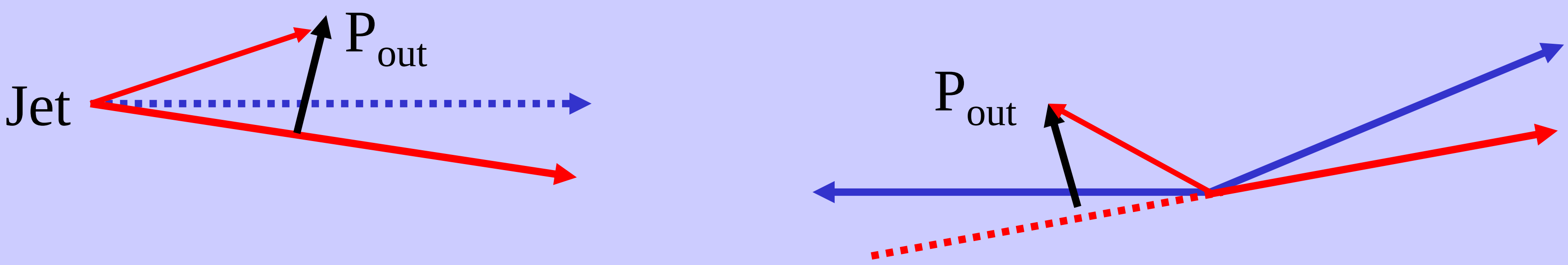
- Photons dominantly from π^0 decay
  - Reflect π^0 direction
- Assume Gaussian distribution for hadron j_T
- Study how j_T depends on p_T of hadrons
  - Away from phase space boundaries j_T constant.

PHENIX d-Au/p-p, $\pi^{\pm}$ - h, $\Delta\phi$ Correlations

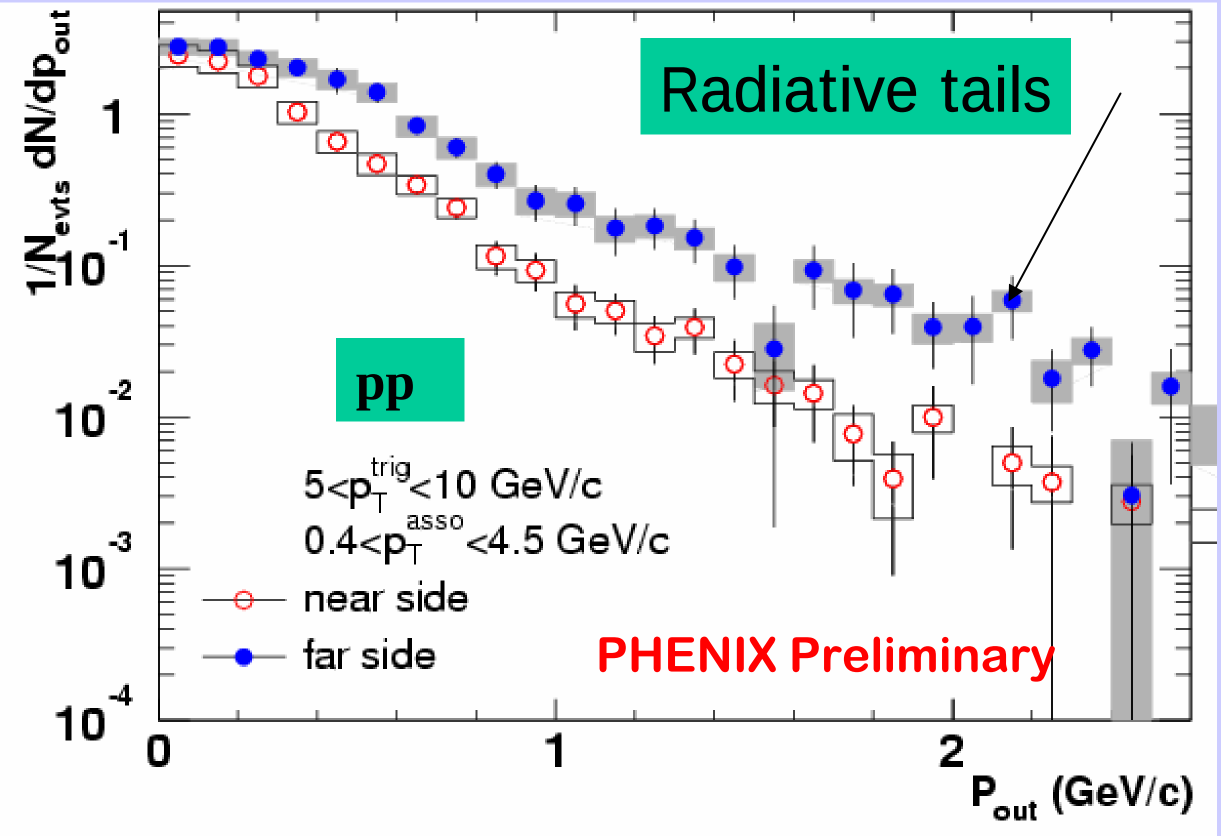


- "Trigger" pion p_T > 5 GeV/c
- Four different associated hadron p_T bins
- Clearly see role of constant j_T, contribution from k_T

Alternative Method for Studying (di)jets

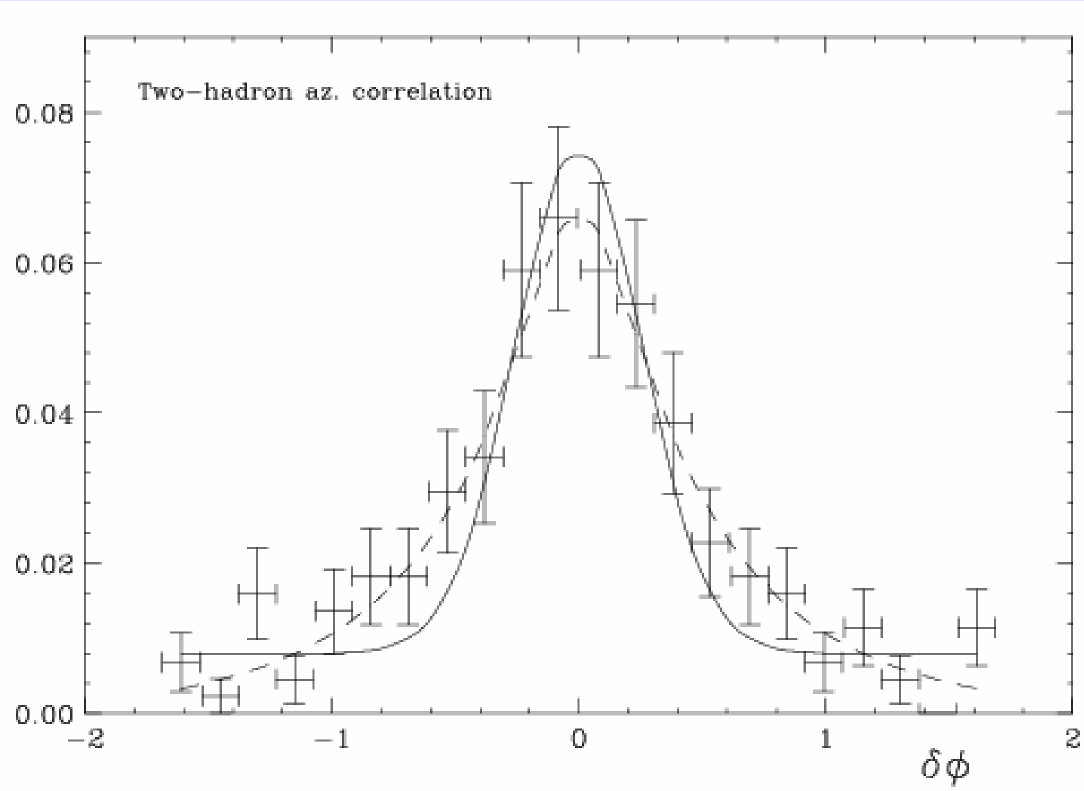


PHENIX, From J. Jia, DNP'04 Talk



- By measuring pout pair-by-pair, more directly see the shape of the j_T/k_T dist's.
- See non-Gaussian tails – expected due to hard radiation.

Explicit Treatment of Radiation

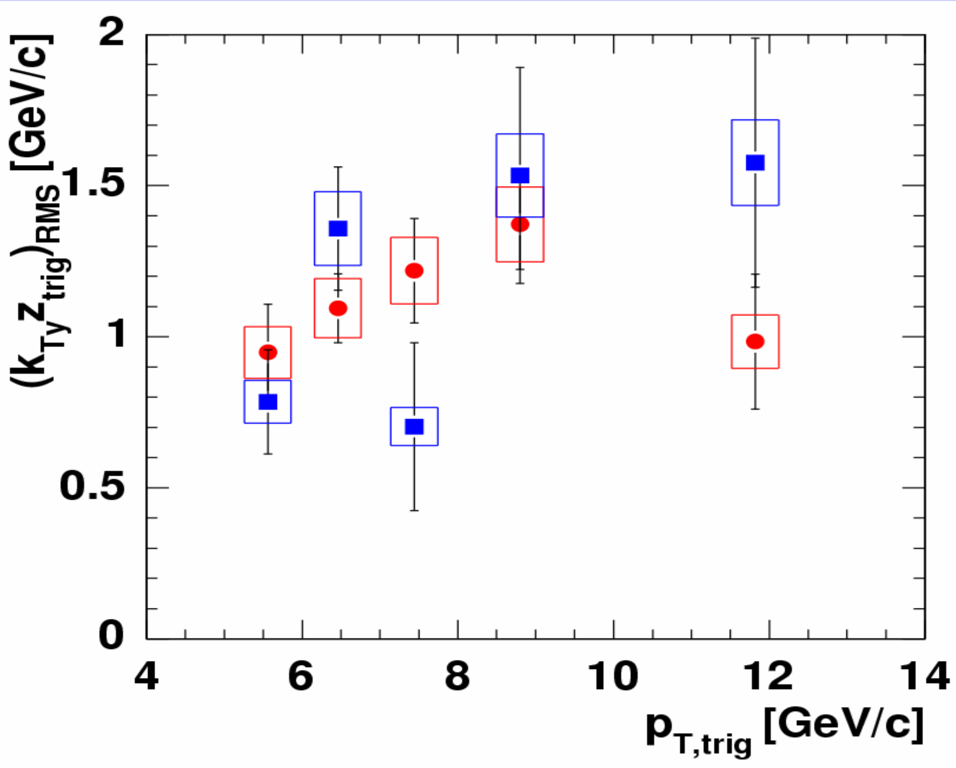


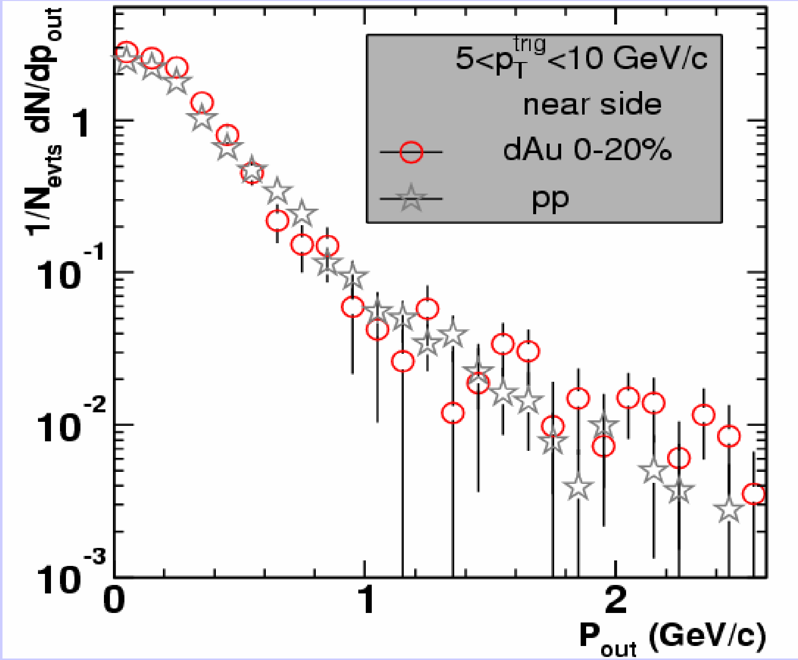
Analysis of STAR di-hadron Δϕ distribution by Boer & Vogelsang,

Phys. Rev. D69 094025, 2004

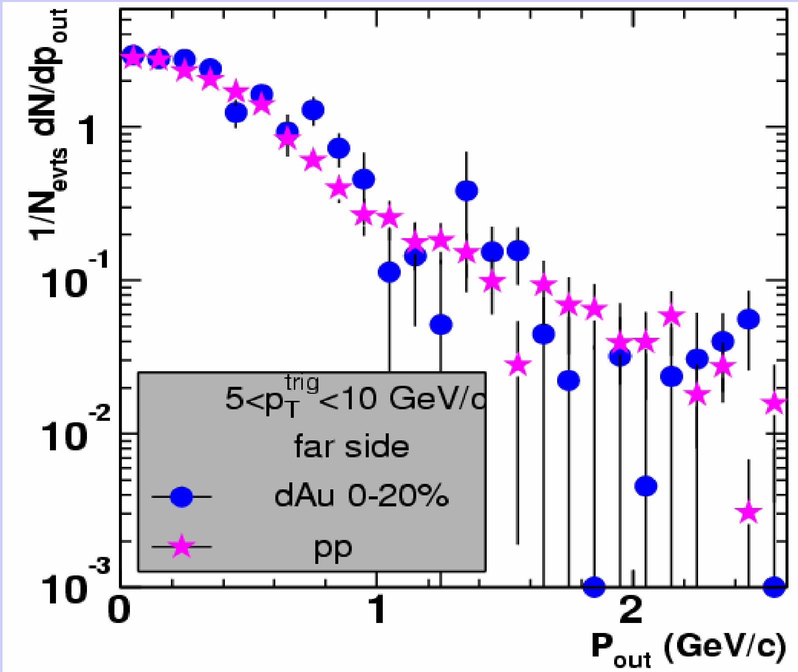
- **Conclude: large radiative component to di-jet k_T**
  - **Also see Vitev, Qiu : Phys.Lett.B570:161-170,2003.**
- **Without accounting for radiation initial parton intrinsic k_T ~ 2 GeV/c (RMS).**
- **After accounting for radiation ~ 1 GeV/c**

di-jet broadening in d-Au?





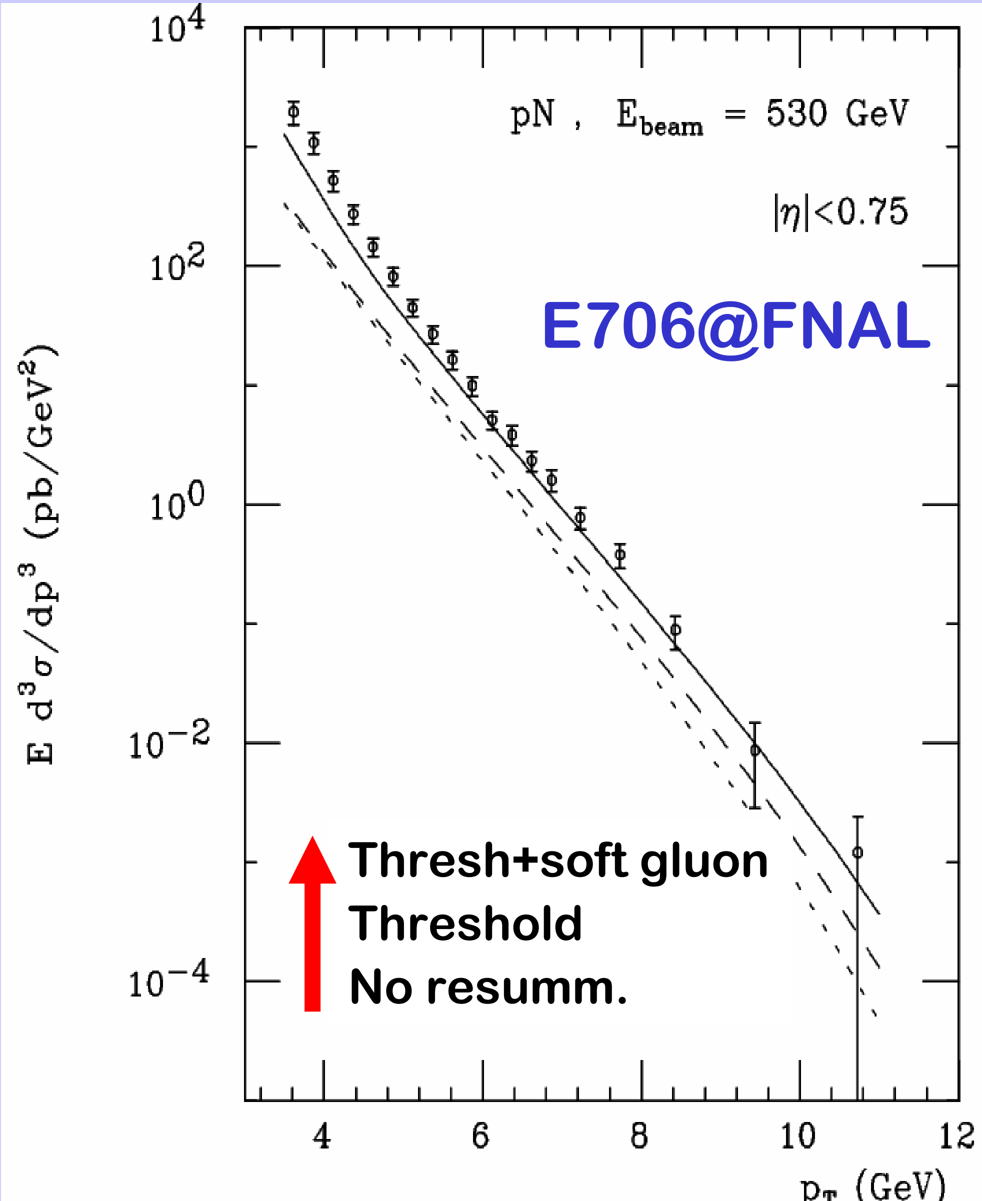
- No apparent indication of increased k_T.
- But these data are not yet sensitive enough.
- New publication from PHENIX with more results soon ...



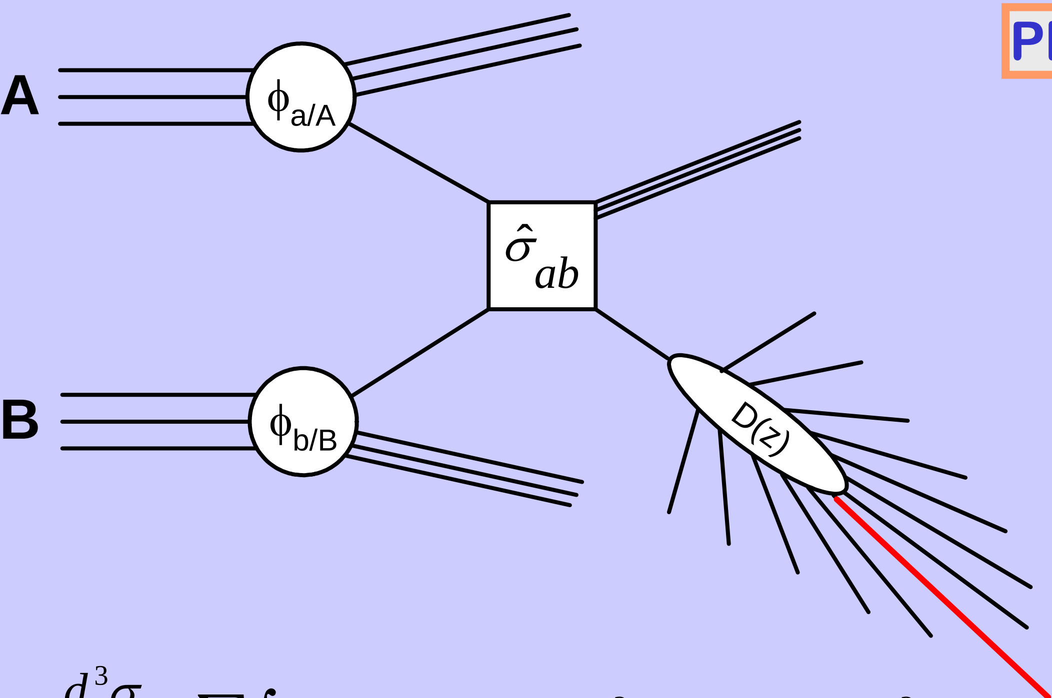
Initial-state Effects on Photons

- E706, FNAL fixed-target experiment, claims that parton "intrinsic" k_T , with RMS k_T > 1 GeV/c needed to explain their data.
- But Sterman& Volgelsang re-summation largely "explains" low-p_T "excess"
- Soft gluon resummation is the largest contribution.
  - Recoil against initial-state radiation.
- Photons very sensitive to initial-state effects
  - No fragmentation dilution

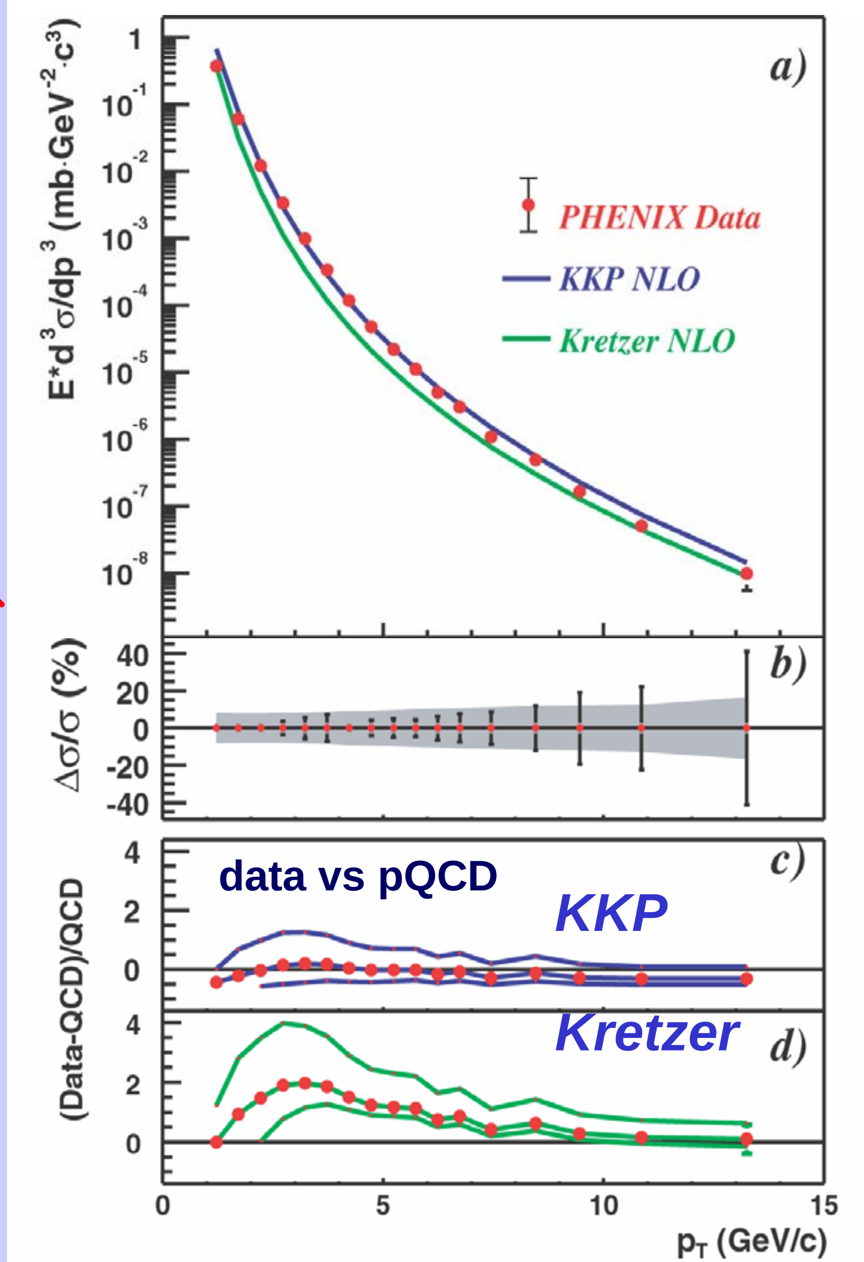
Laenen, Sterman, Vogelsang, Phys.Rev.Lett.84:4296 (2000)



Single High-pt Hadron Production



Phys. Rev. Lett. 91, 241803 (2003)



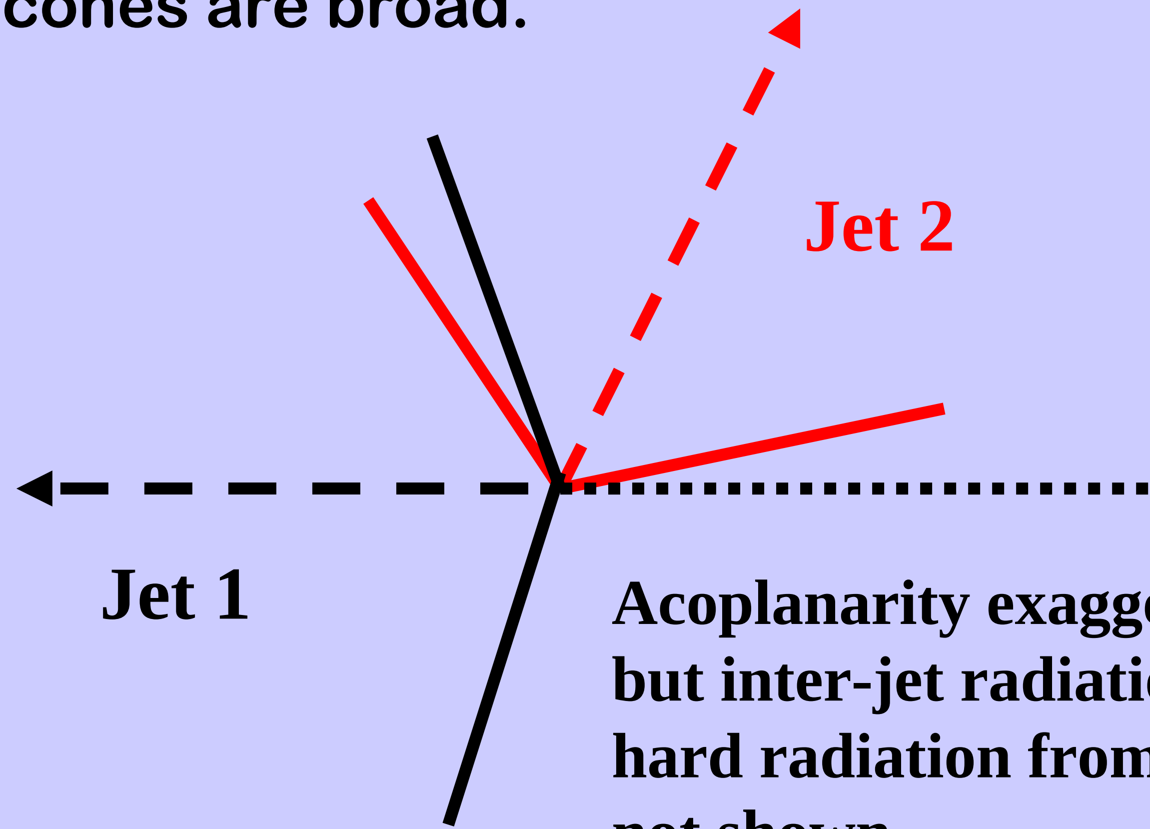
$$E\frac{d^3\sigma}{dp^3} = \sum_{abc}\int dx_a dx_b\, \phi_{a/A}(x_a, Q^2, \mu)\,\phi_{b/B}(x_a, Q^2, \mu)$$

$$\times \frac{D_{\pi^0/c}(z, Q^2, \mu)}{z\pi}\frac{d\hat{\sigma}}{dt}$$

- NLO calculation agrees well with PHENIX π^0 spectrum (!?)
  - BUT, FF dependence ?
  - Lore: KKP better for gluons
  - Calc. Includes resummation!

How to Measure Frag. & Brem. ?

- Remember: separation of prompt γ spectrum into direct, fragmentation contributions is “arbitrary”.
- This may be particularly an issue @ RHIC:
  - photon/jet p_T scales are < x10 p_T scale of IS radiation.
  - And jet cones are broad.



Acoplanarity exaggerated – but inter-jet radiation, hard radiation from one jet not shown.