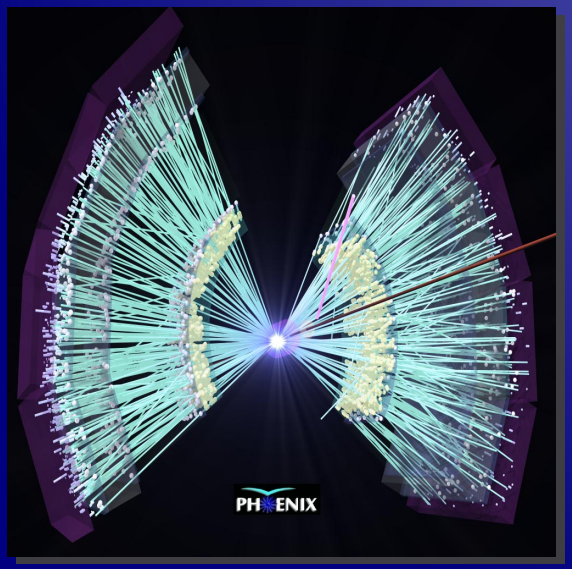
Stony Brook University | The State University of New York

High p_T photons and jets with (s)PHENIX



Ali Hanks

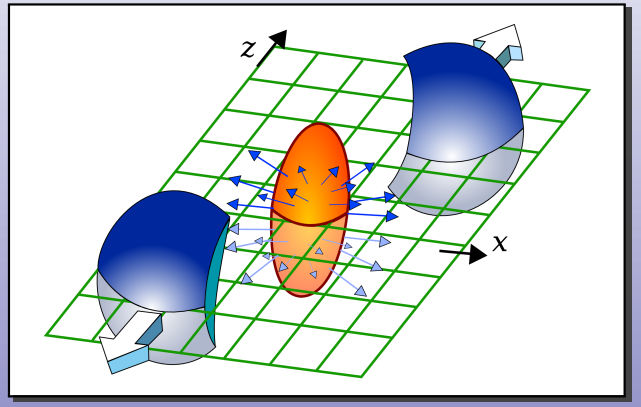
Hard Probes 2013

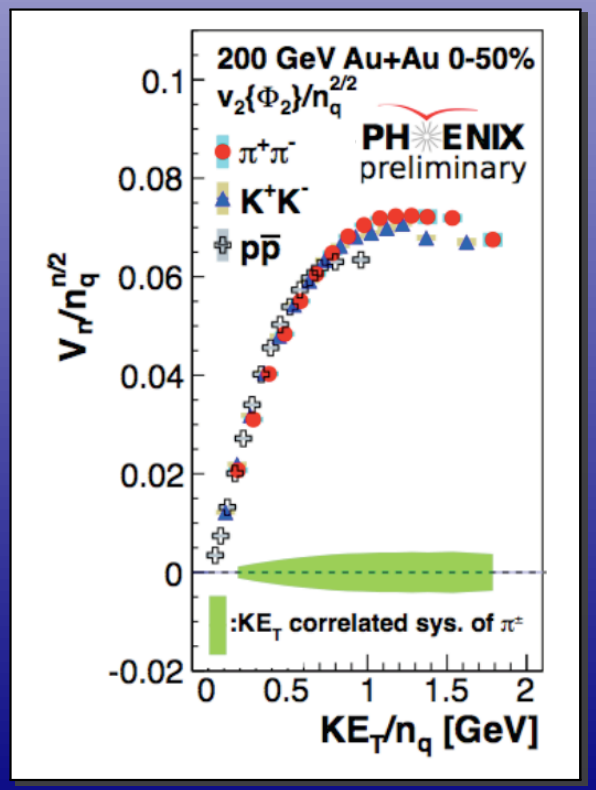
Cape Town, South Africa

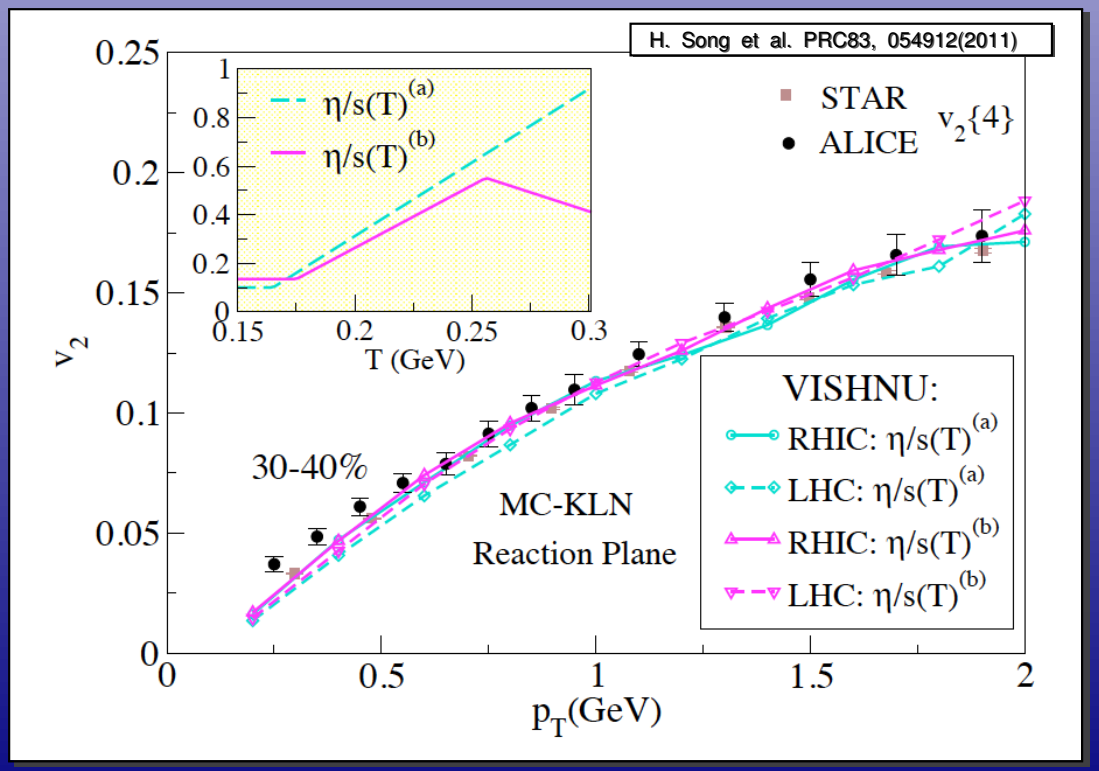
November 6th, 2013

– What can bulk properties teach us? –

- Hydrodynamics describes data well
  - → near-perfect fluid produced!
  - How can we learn more?

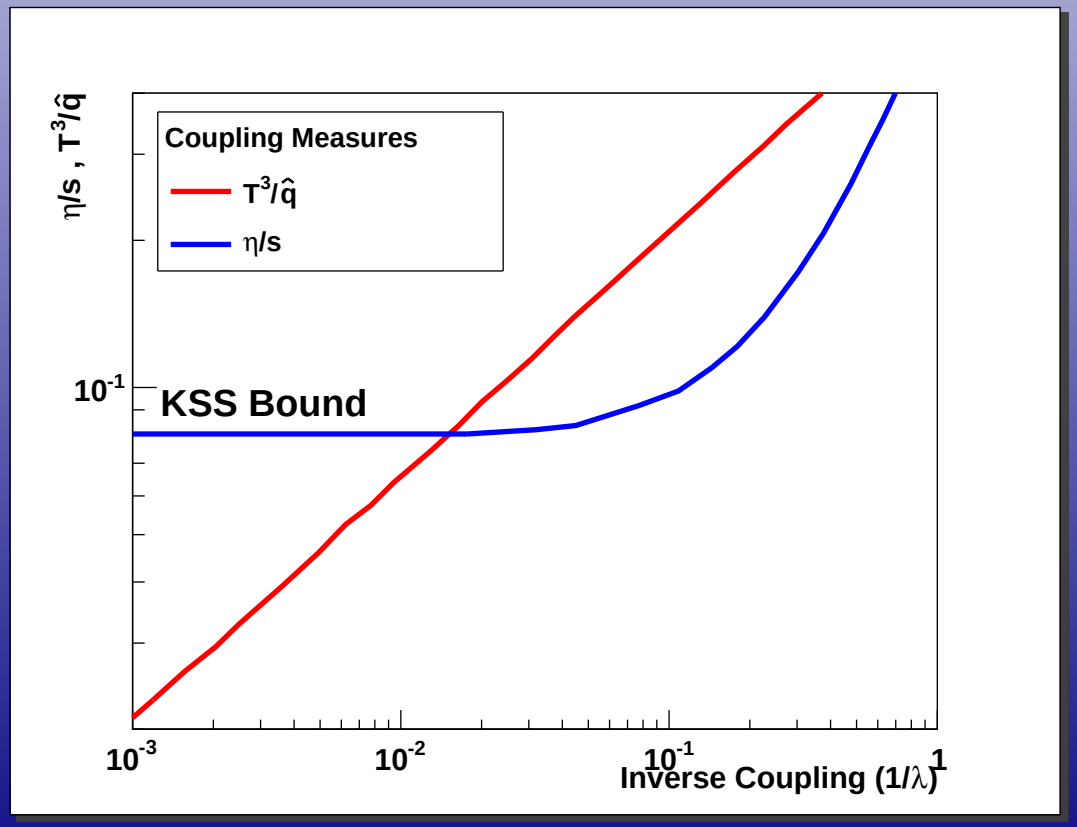


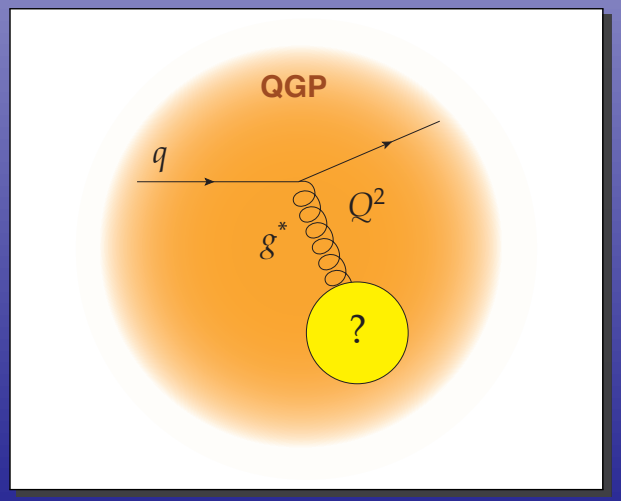




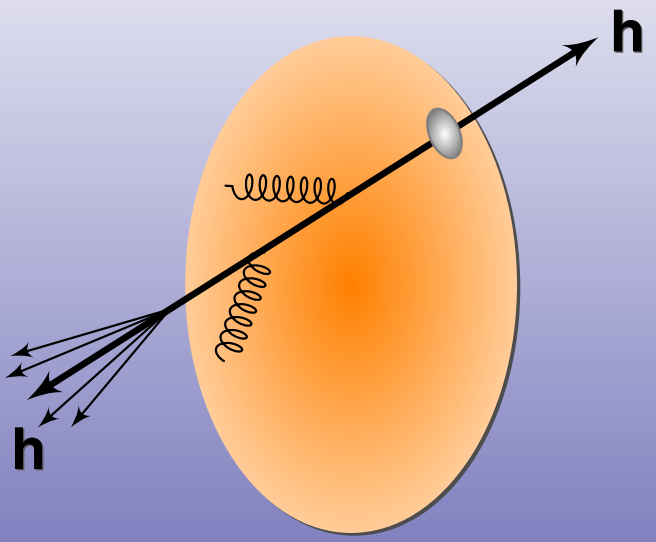
– Learning more with hard probes –

- Greater sensitivity to coupling strength
- Unique insight into structure of medium
  - → Studied using jet-quenching observables



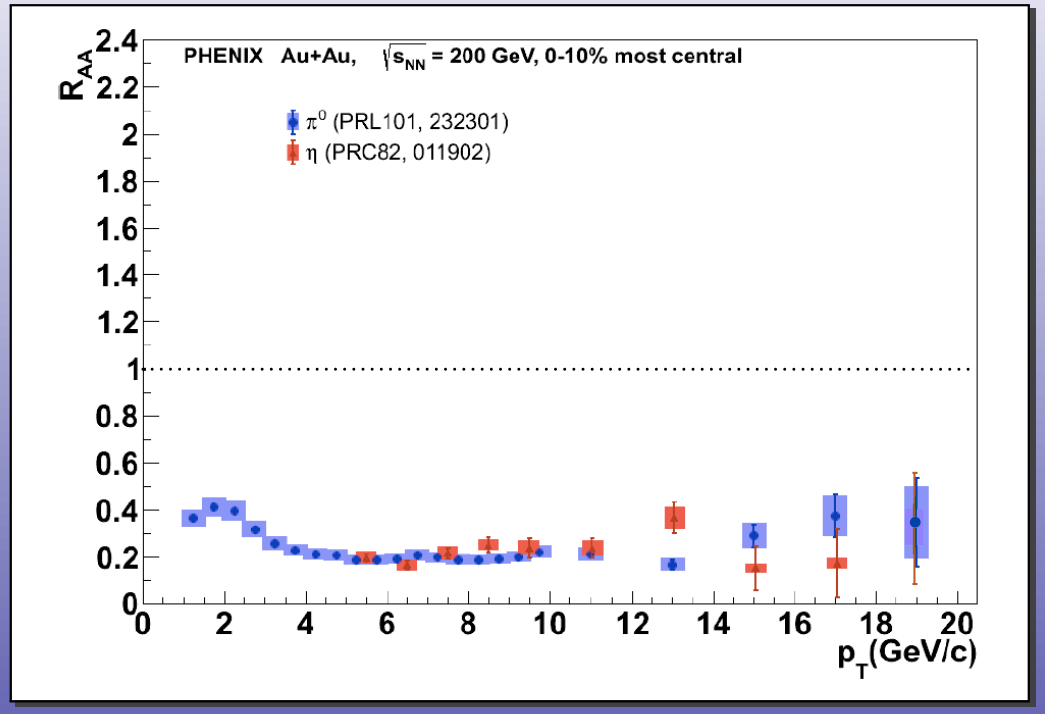


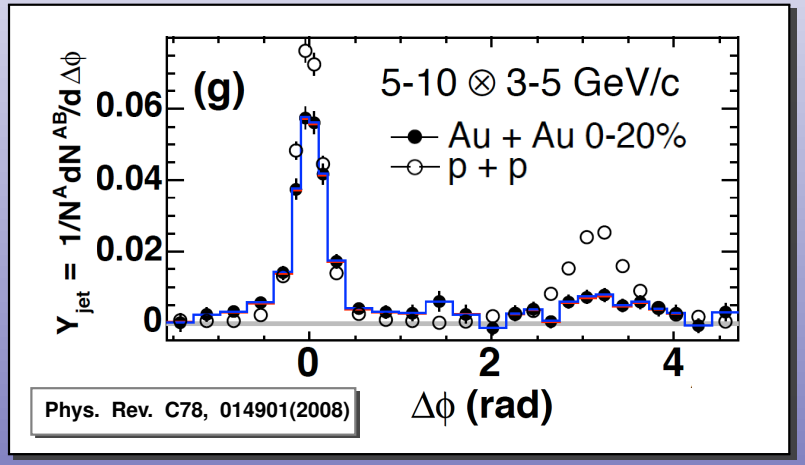
– Studying energy loss (with hadrons) –



- **Single hadrons and h-h correlations:**
  - straightforward experimentally
- most surface bias
- poor constraint on modified parton p_T

– The basic picture of energy loss –



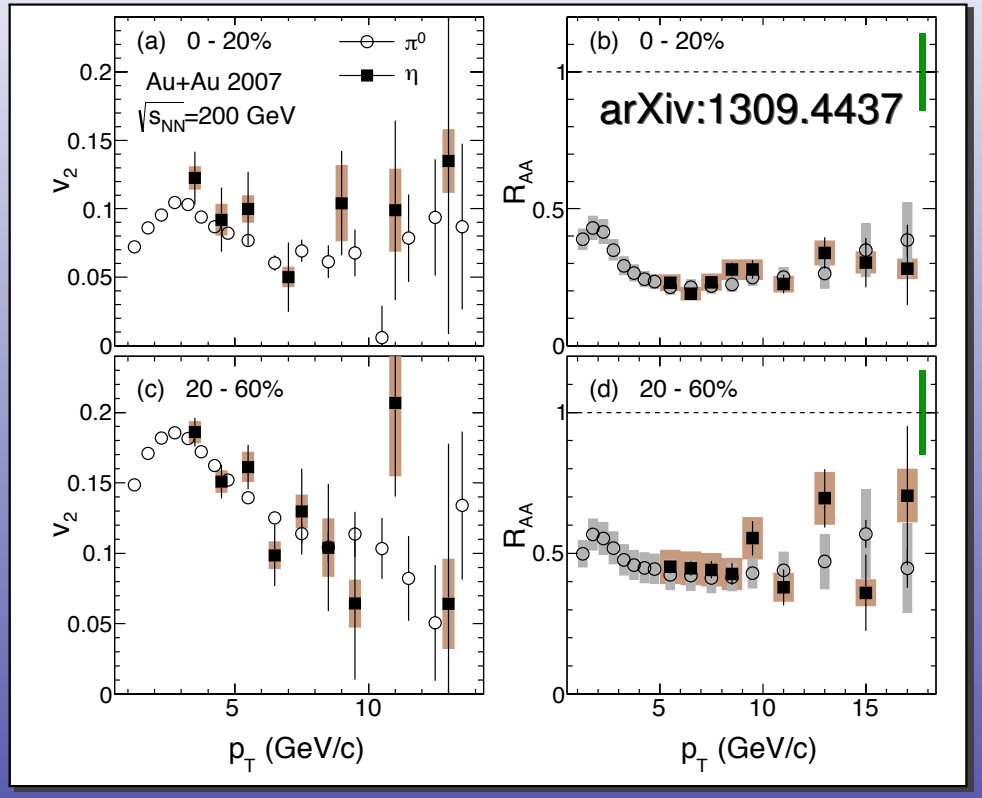


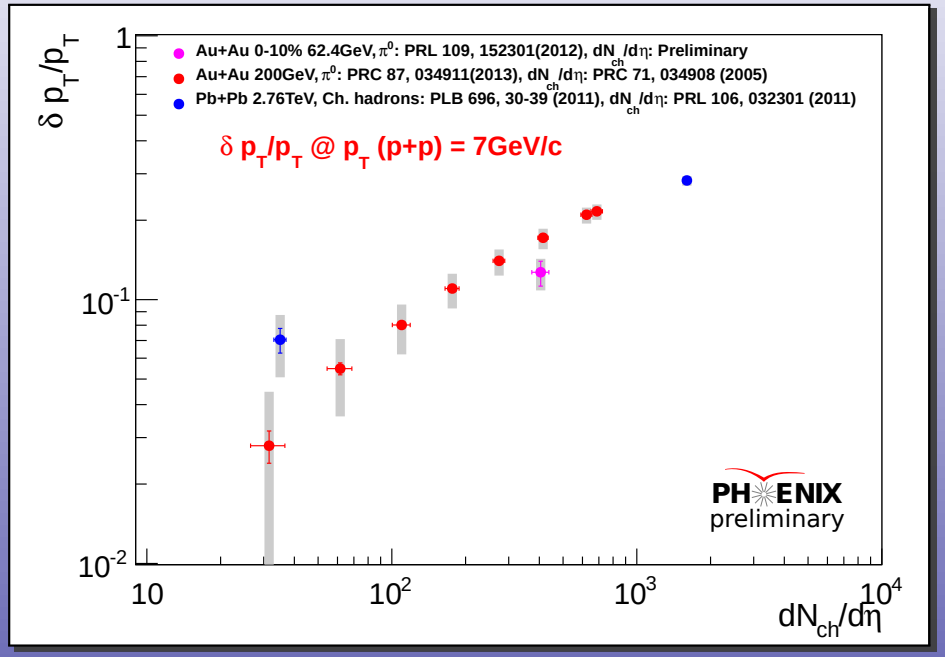
Key signatures of partonic energy loss

- Single particle (hadron) production suppressed at high-p_T
- Di-hadron correlations show suppression of away-side

leave details of energy loss mechanism poorly constrained

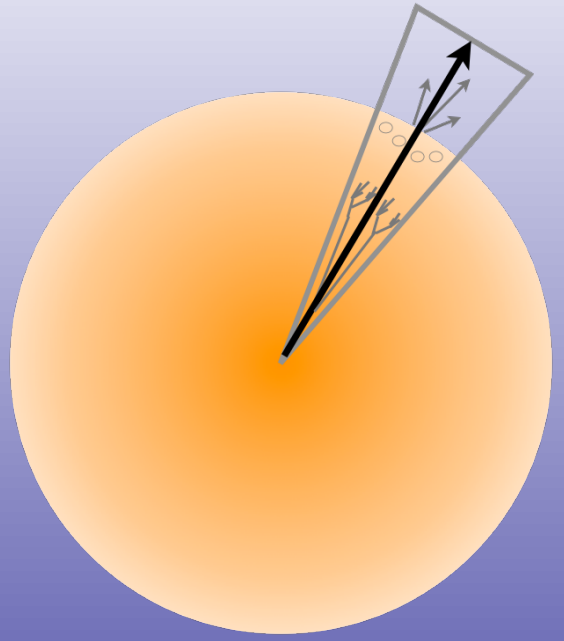
– Lessons from single particles –



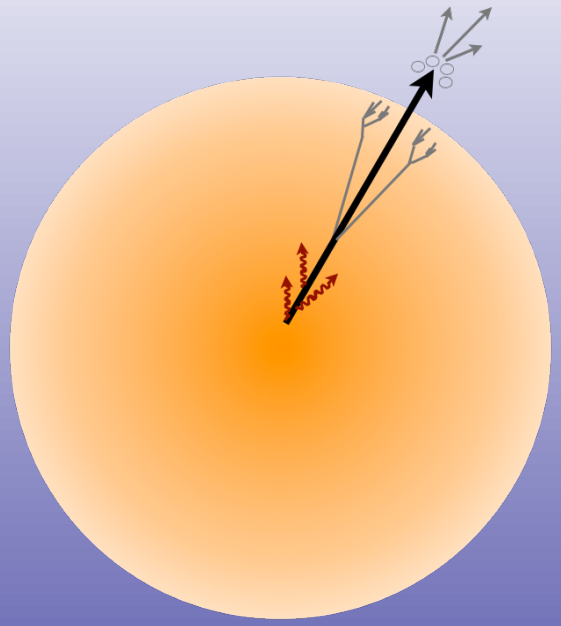


- High p_T v_2 provides additional constraint
  - sensitive to path length dependence?
  - independent of particle type
- suppression sensitive to energy density
  - see talk by T. Sakaguchi, Mon. @ 17:30

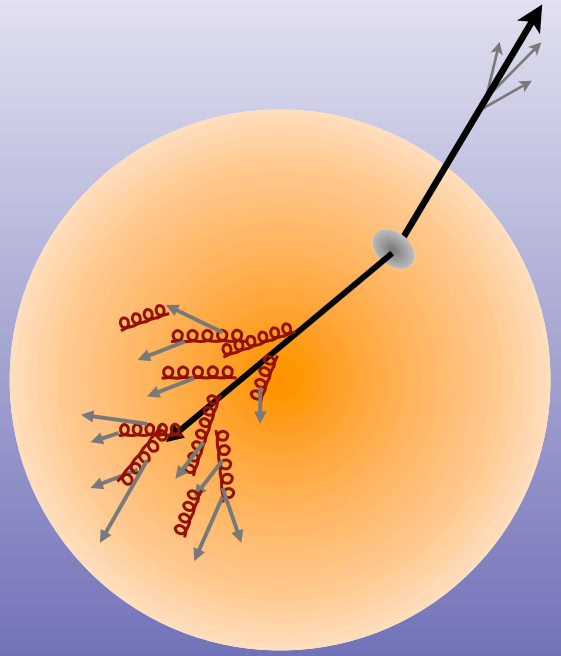
– Where does the energy go? –



extra gluons at small angles, i.e. within jet cone



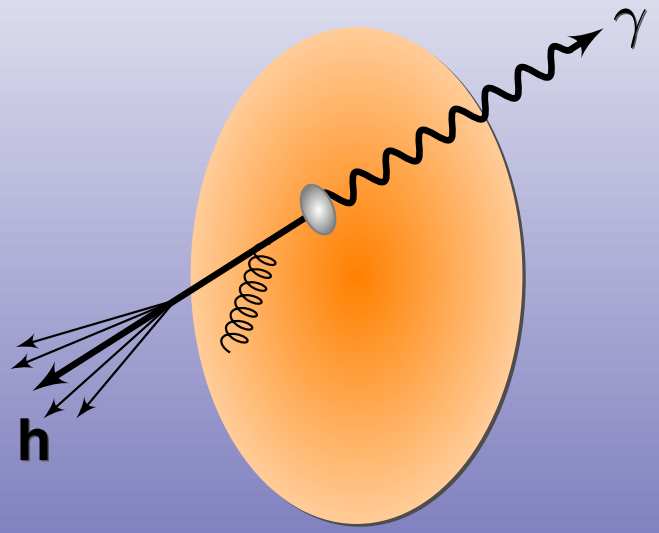
correlated with leading parton but significantly modify jet shape



radiated gluons thermalize in medium with no residual correlation

How does the answer depend on conditions of the collision and measurement (energy density, surface bias)

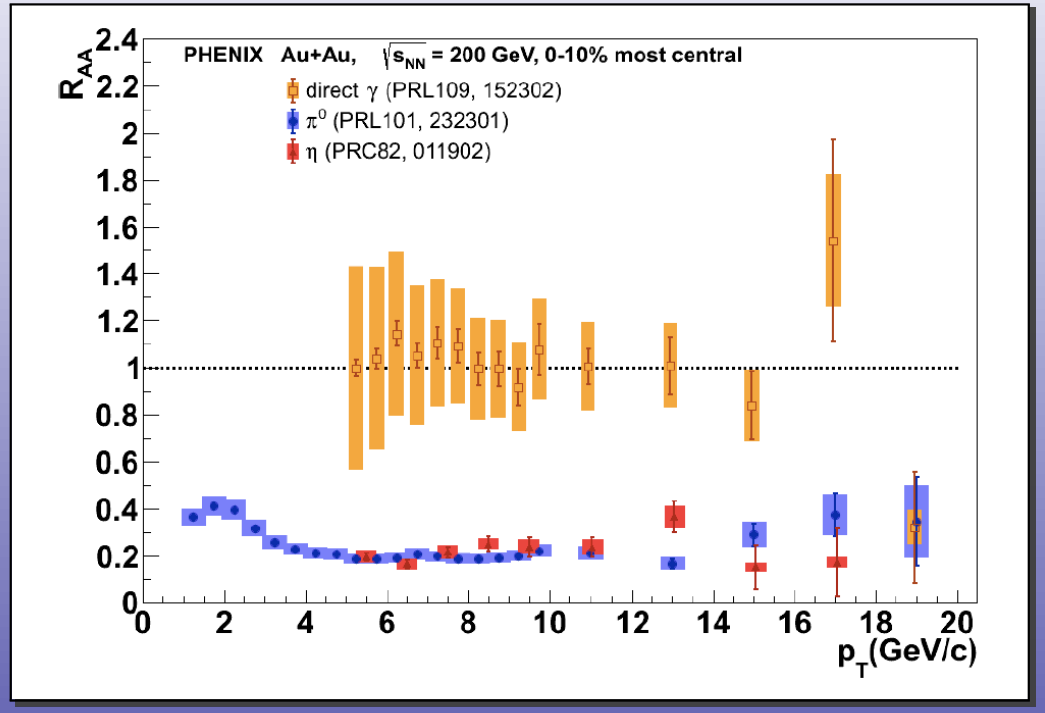
– Studying energy loss (with photons) –

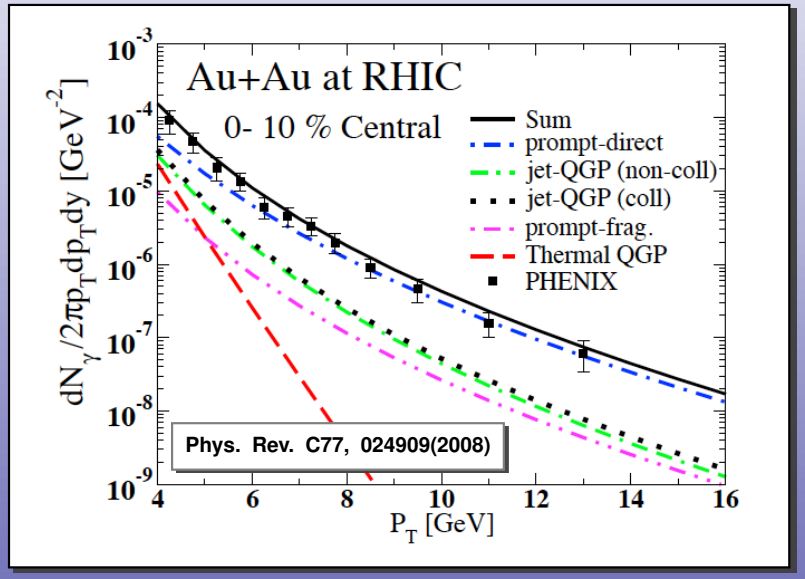


- **Direct photons and γ-h (γ-jet):**
  - low signal rate
  - large background
- no surface bias
- closest measure of initial parton p_T

dominated by quark jet

– What high p_T direct photons can teach us –

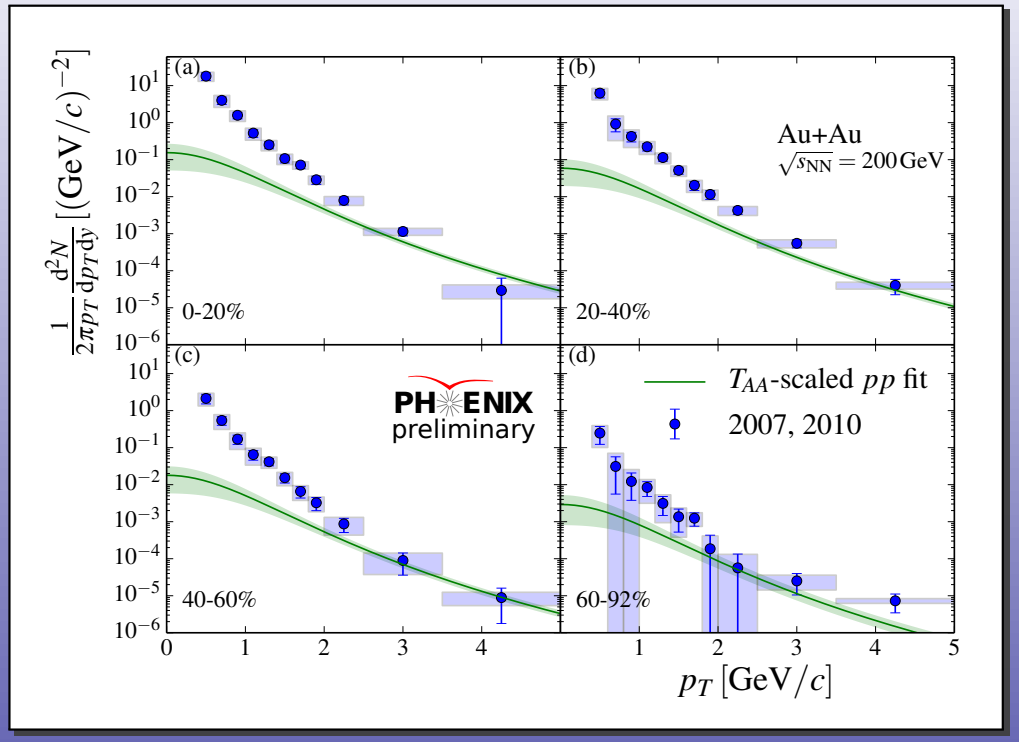


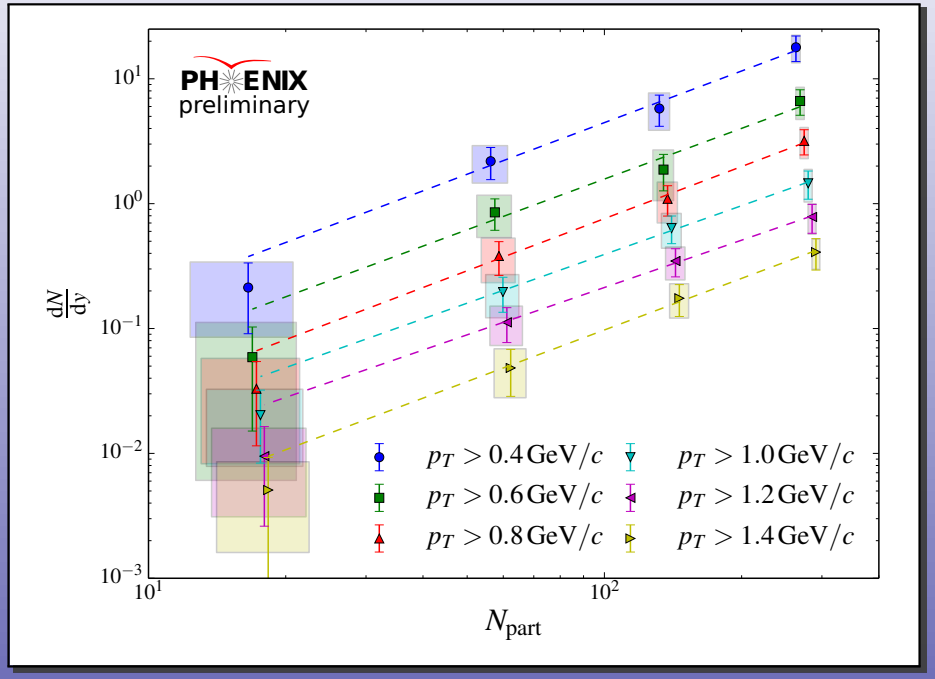


- **Calibrated probe:** largely insensitive to medium post-production
  - once produced photons will not interact strongly with the medium
  - at high-p_T yield is dominated by hard processes
- LO photons are produced back-to-back with parton

  $\Longrightarrow$ calibrated measure of initial parton energy

– What direct photons can teach us –





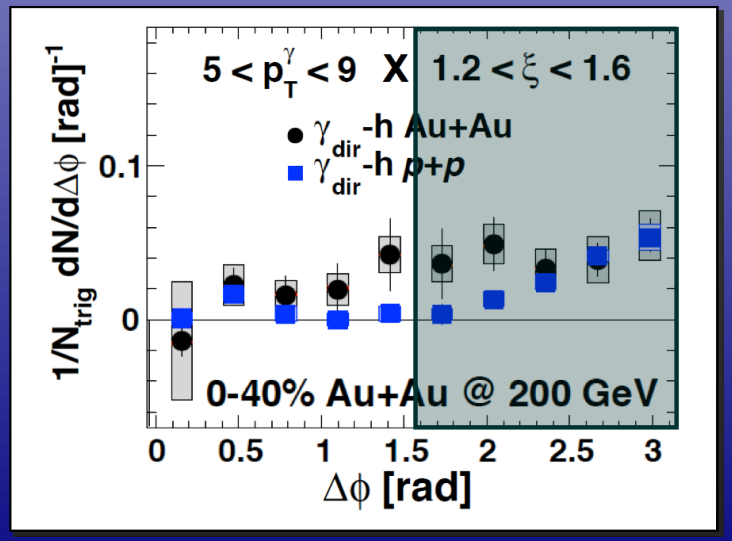
- **Calibrated probe:** largely insensitive to medium post-production
  - at low p_T yield **is not** p+p-like
  - yield grows like $N_{part}^{1.5}$
- Yield + large v_2 presents challenge for theorists

  see talk by B. Bannier, Tues. @ 13:30

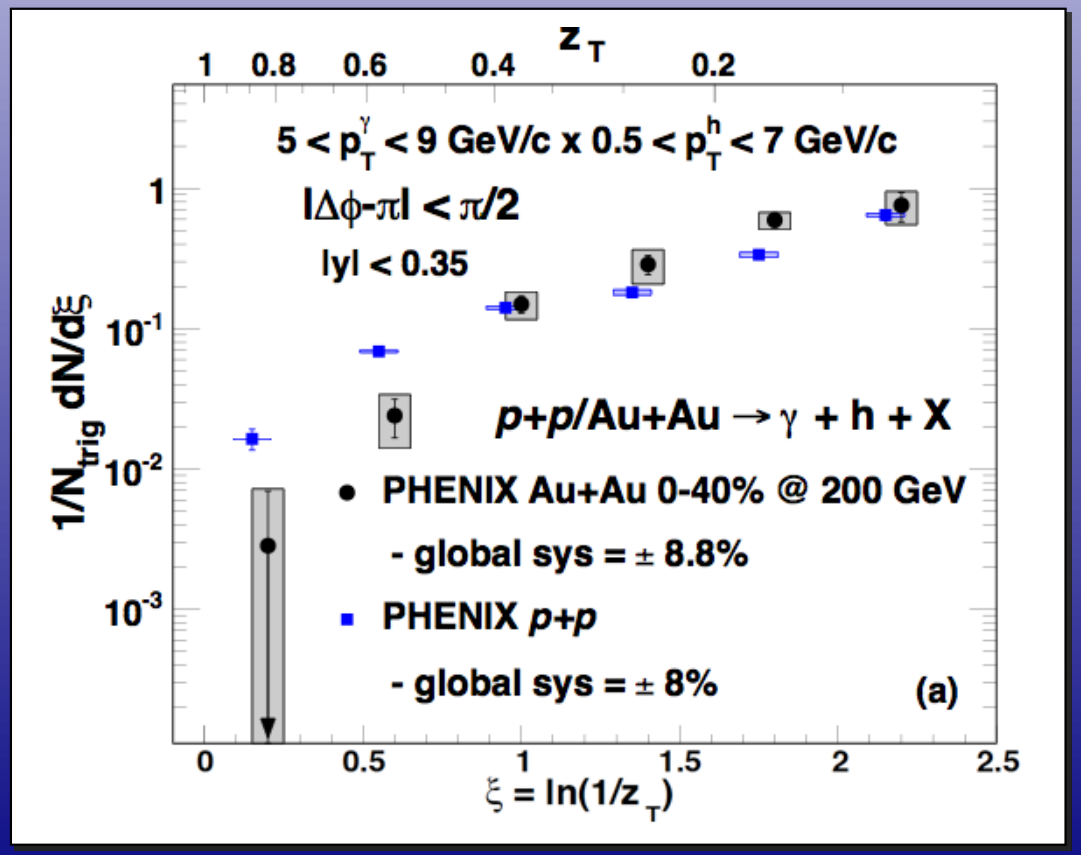
– The fragmentation function –

$$p_T^\gamma \approx p_T^{jet} \quad z_T = \frac{p_T^h}{p_T^\gamma} \quad \Longrightarrow \quad D_q(z_T) = \frac{1}{N_{evt}} \frac{dN(z_T)}{dz_T}$$

- measure away-side yield to get effective fragmentation function
- for low $z_T \rightarrow \xi = \ln(1/z_T)$

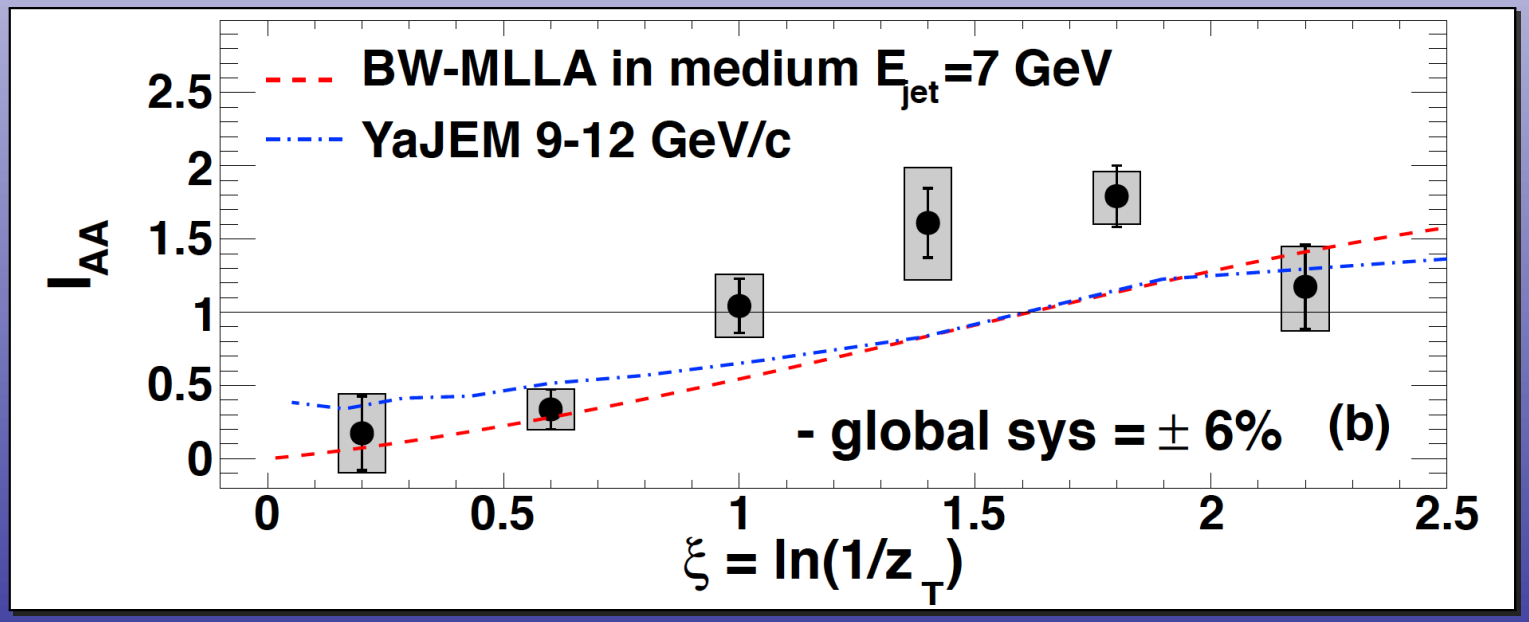


PRL 111, 32301 (2013)



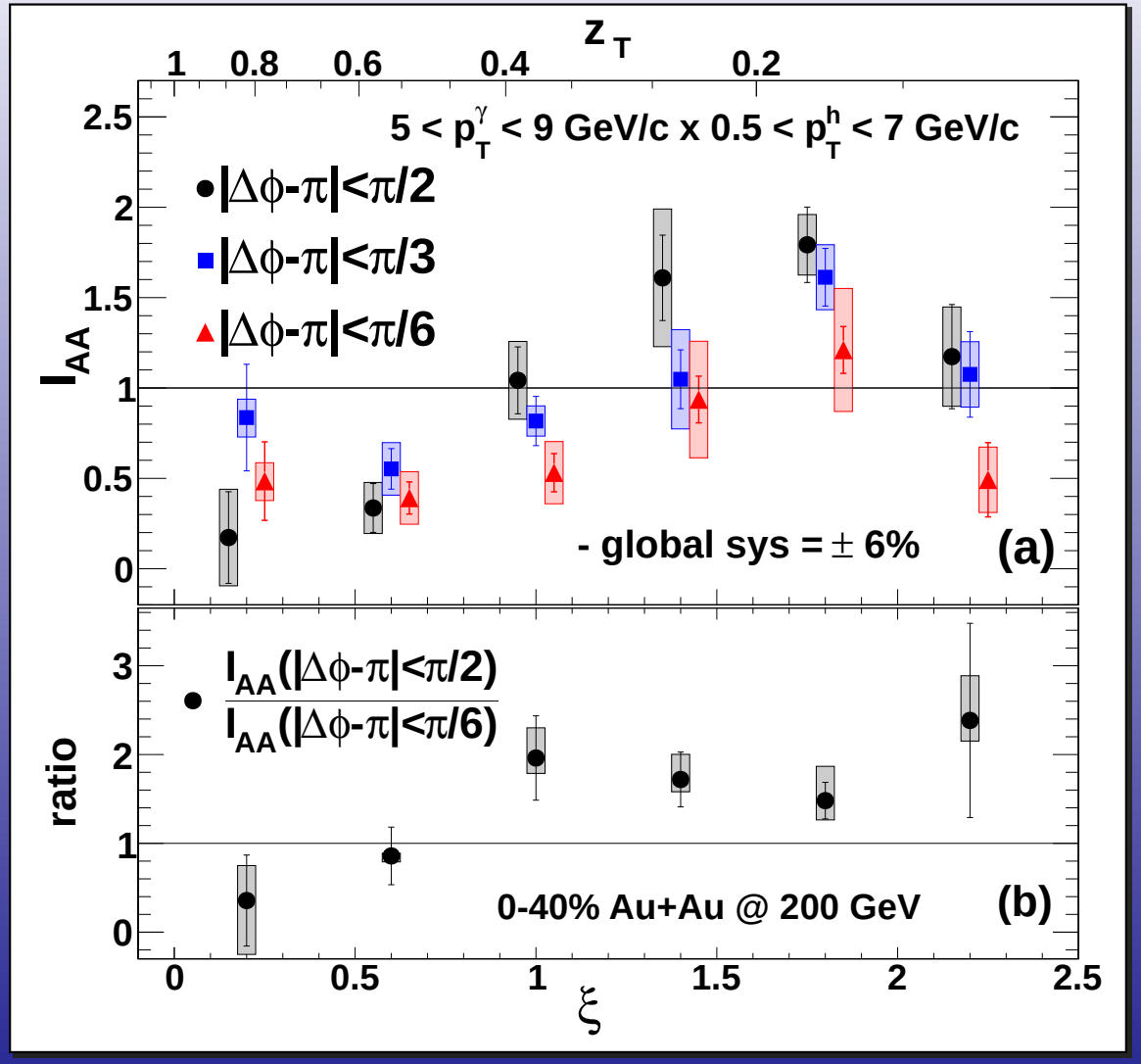
– The modified fragmentation function –

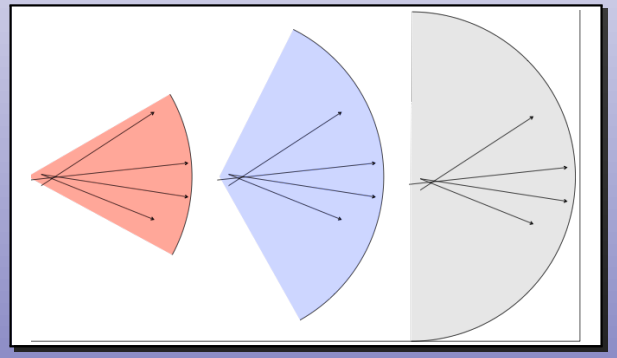
$$I_{AA} = \frac{Y_{AA}}{Y_{pp}} \sim \frac{D_{AA}(z_T)}{D_{pp}(z_T)}$$



- See modification to effective fragmentation function
- Inconsistent with $I_{AA} = 1$ for $\xi > 0.8$
- suppression for $\xi > 0.8$ consistent with previous results

– Is the away-side broadened? –

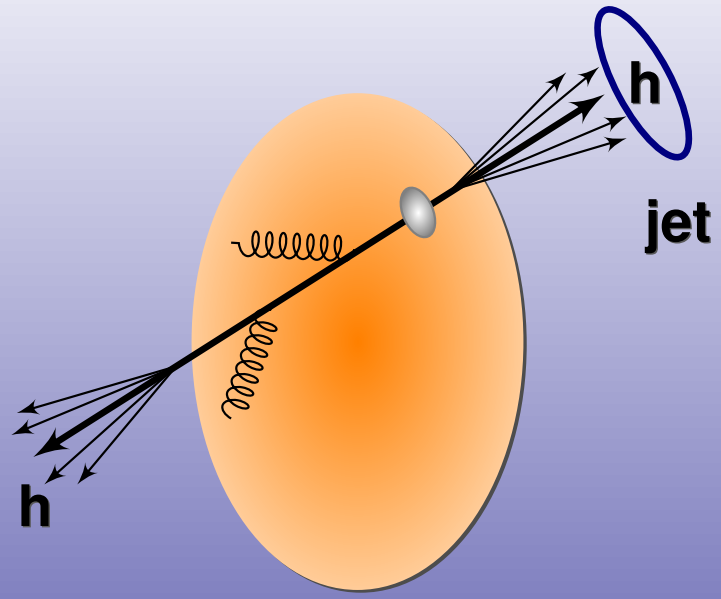




Significant variation in I_{AA} when integration range is varied

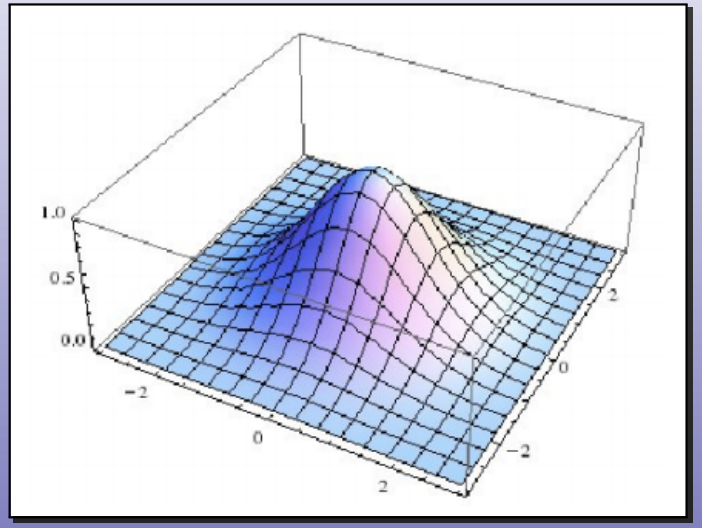
Enhancement at low z_T predominantely at large $\Delta\phi$

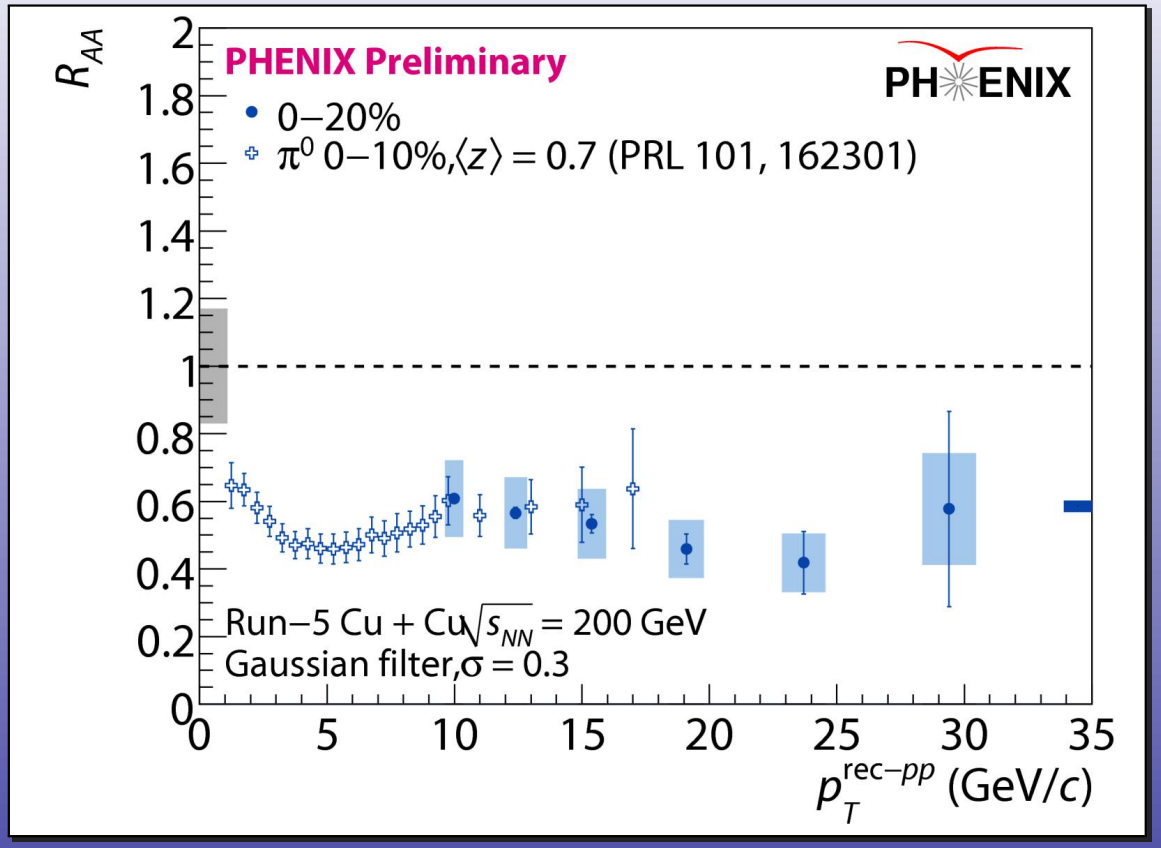
– Studying energy loss (with jets) –



- **reconstructed jets and jet FF (jet-h):**
  - HI background presents challenge
- some surface bias
- closest measure of modified parton p_T

– Jets in PHENIX –

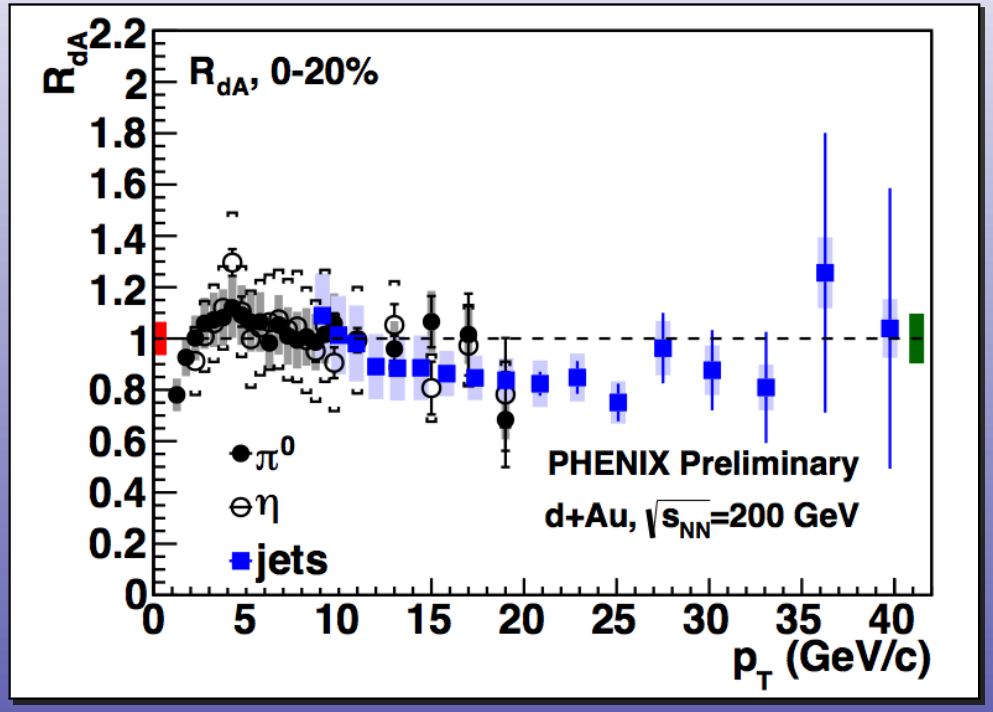


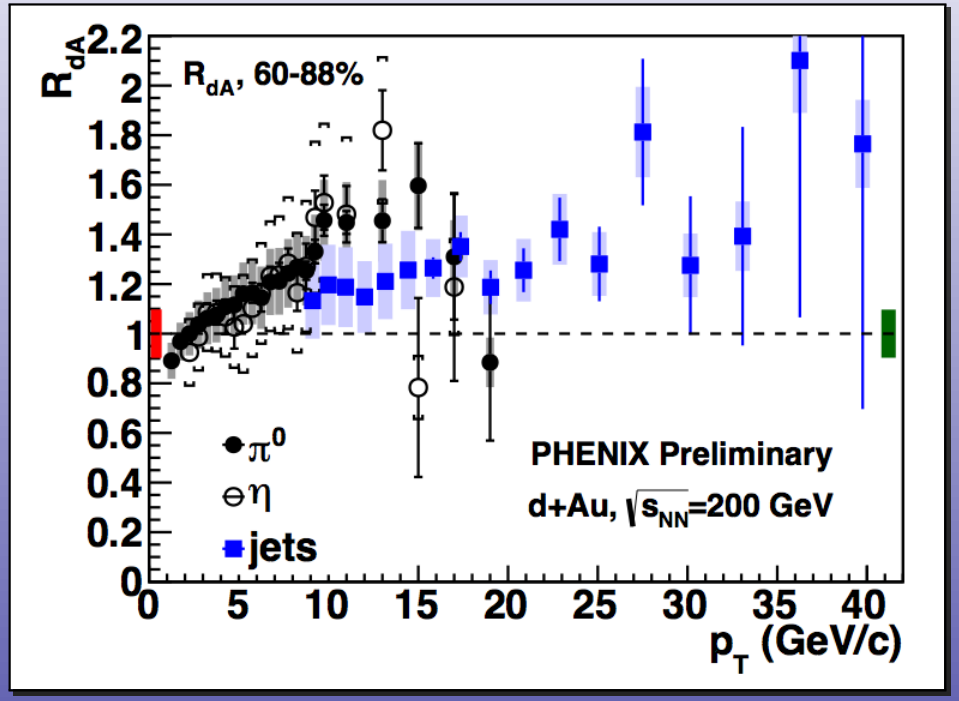


- Full jet vs leading fragment shows similar suppression
  - → splitting within jet cone not the dominant effect
  - – need larger jet sizes to learn more

$$p_T^{jet} \equiv \max\left\{\iint d\eta' d\phi' p_T(\eta', \phi') e^{-(\Delta\eta^2+\Delta\phi^2)/2\sigma^2}\right\}$$

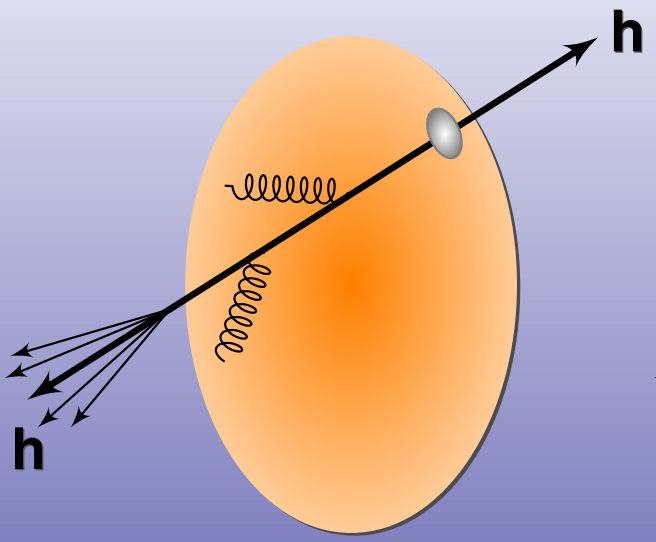
– Jets in PHENIX –

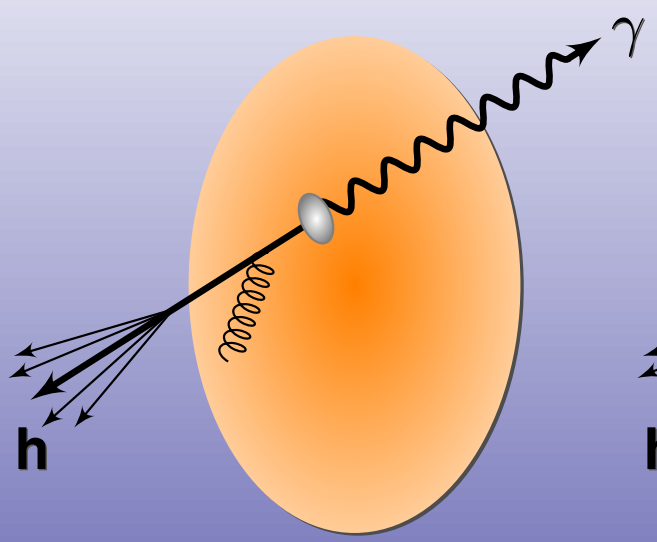


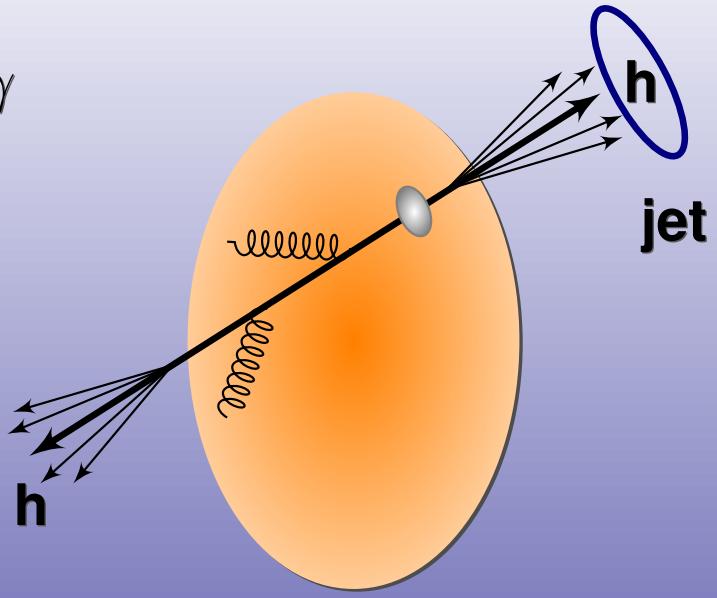


- Full jet vs leading fragment shows similar suppression
  - → splitting within jet cone not the dominant effect
  - – need larger jet sizes to learn more
- In d+Au have independent measure of CNM effects
  - – carefull analysis of biases ongoing

– Studying energy loss with hard probes –







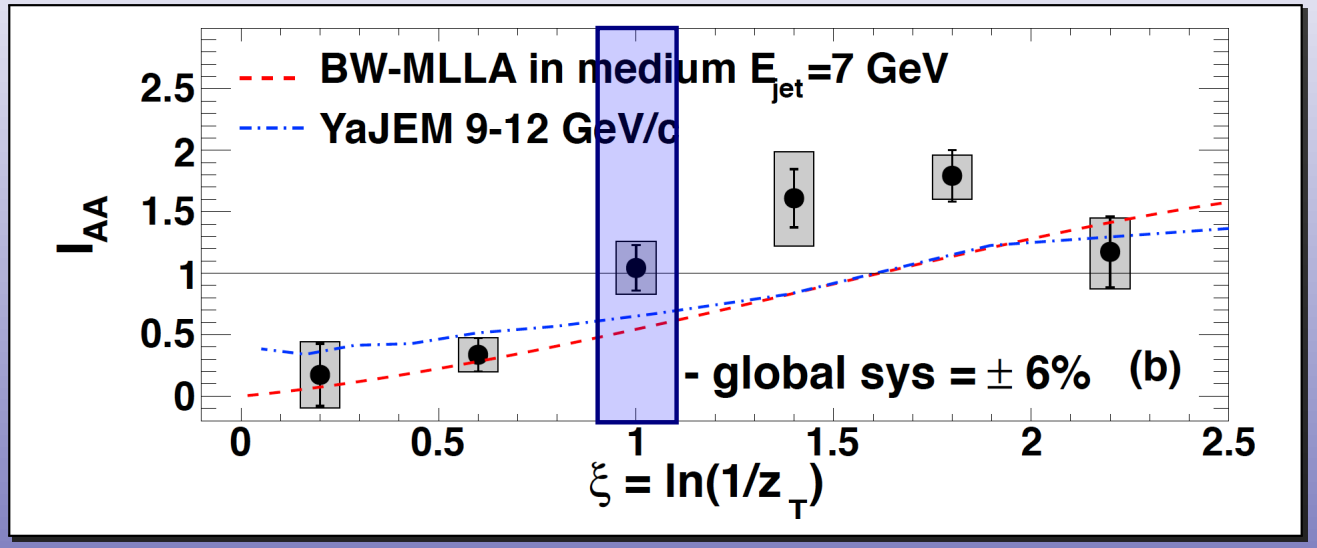
- **Single hadrons and h-h correlations:**
  - straight forward experimentally
- most surface bias
- poor constraint on modified parton p_T

- **Direct photons and γ-h (γ-jet):**
  - low signal rate
  - large background
- no surface bias
- closest measure of initial parton p_T

- **reconstructed jets and jet FF (jet-h):**
  - HI background presents challenge
- some surface bias
- closest measure of modified parton p_T

complementary measurements with different sensitivities

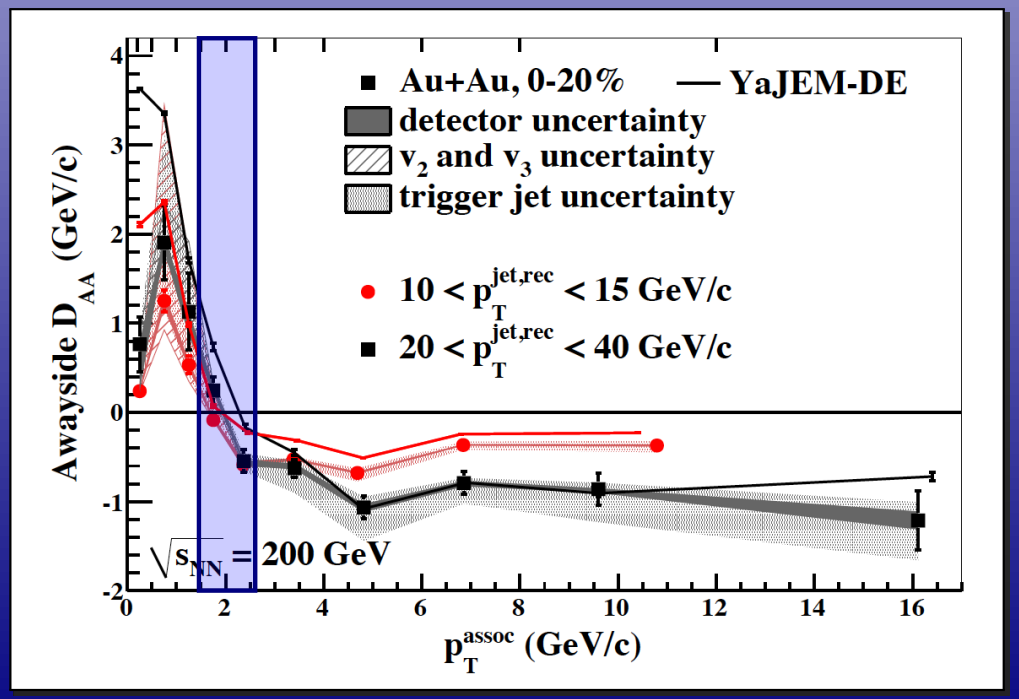
– Variations on the theme of I_{AA} –



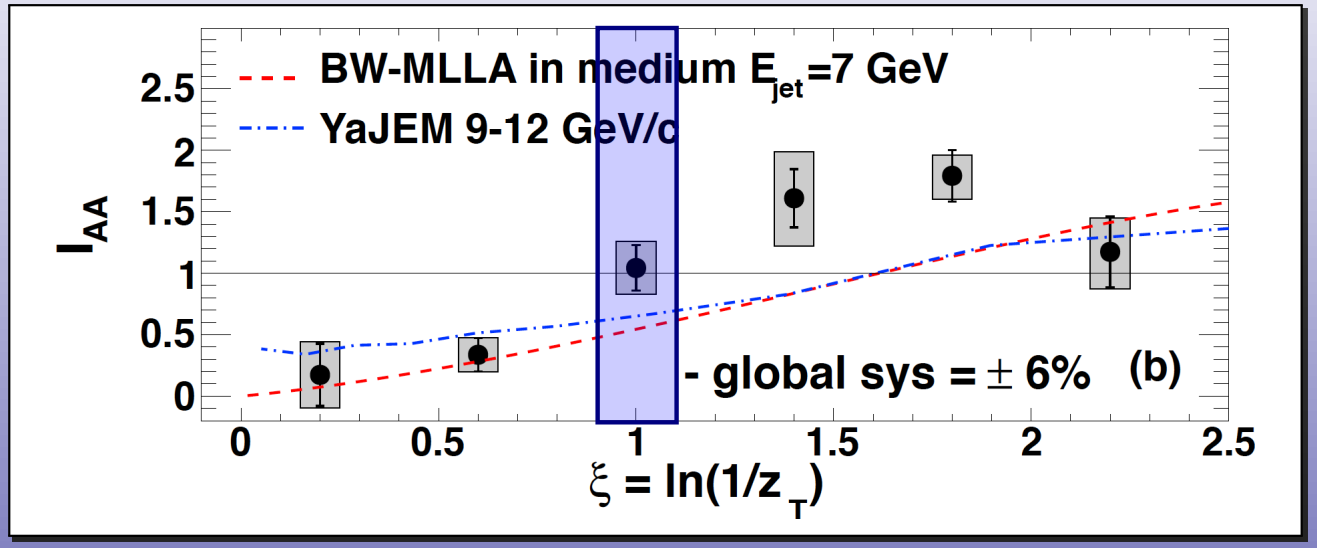
$$D_{AA} \equiv Y_{AA} * \langle p_T^a \rangle_{AA} - Y_{pp} * \langle p_T^a \rangle_{pp}$$

Transition from suppression to enhancement

- $\sim$ 2 GeV/c p_T^{assoc} for range of p_T^{trig}



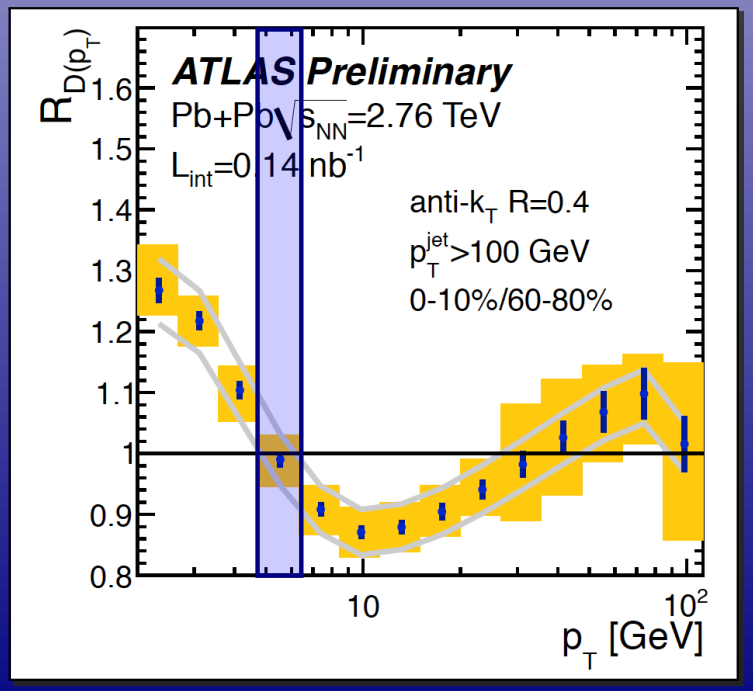
– Variations on the theme of I_{AA} –



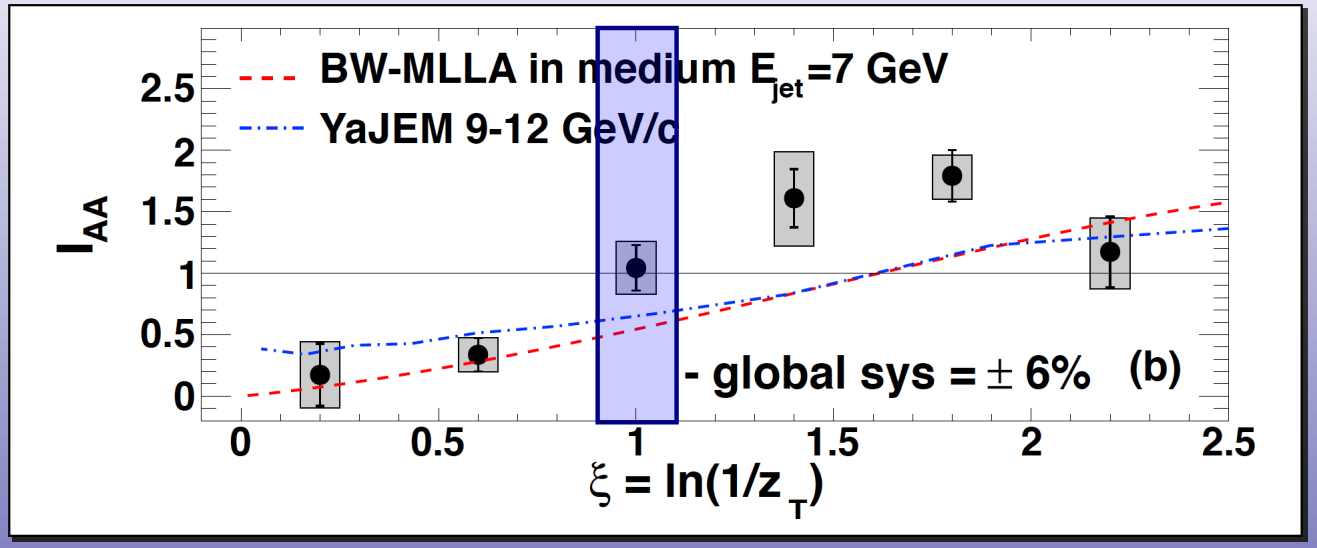
Transition from suppression to enhancement

- $\sim$ 2 GeV/c p_T^{assoc} at RHIC
- $\sim$ 3-5 GeV/c p_T^{assoc} at LHC

What determines the constituent p_T at which enhancement appears?



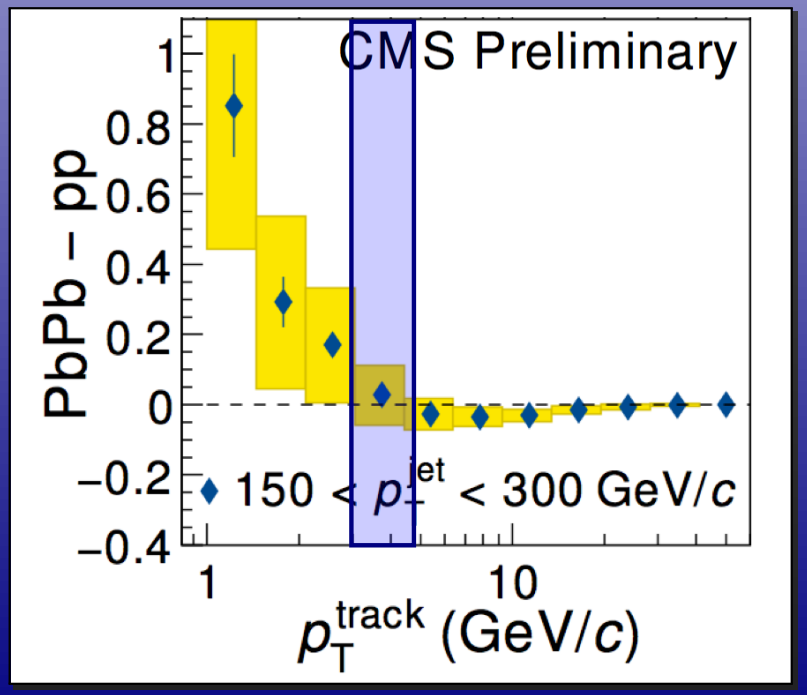
– Variations on the theme of I_{AA} –



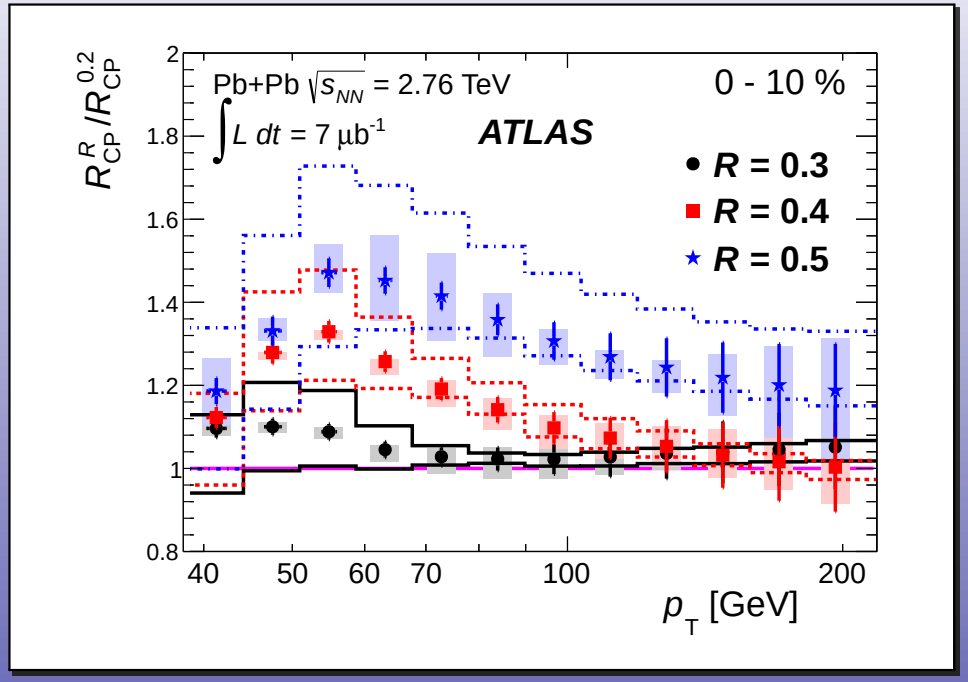
Transition from suppression to enhancement

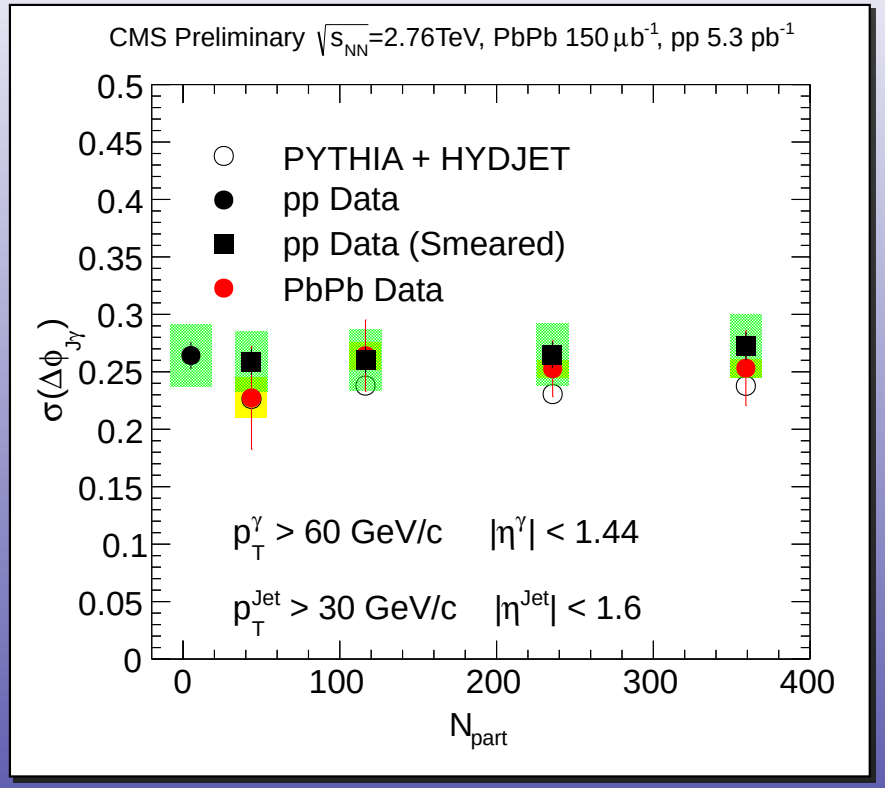
- $\sim$ 2 GeV/c p_T^{assoc} at RHIC
- $\sim$ 3-5 GeV/c p_T^{assoc} at LHC

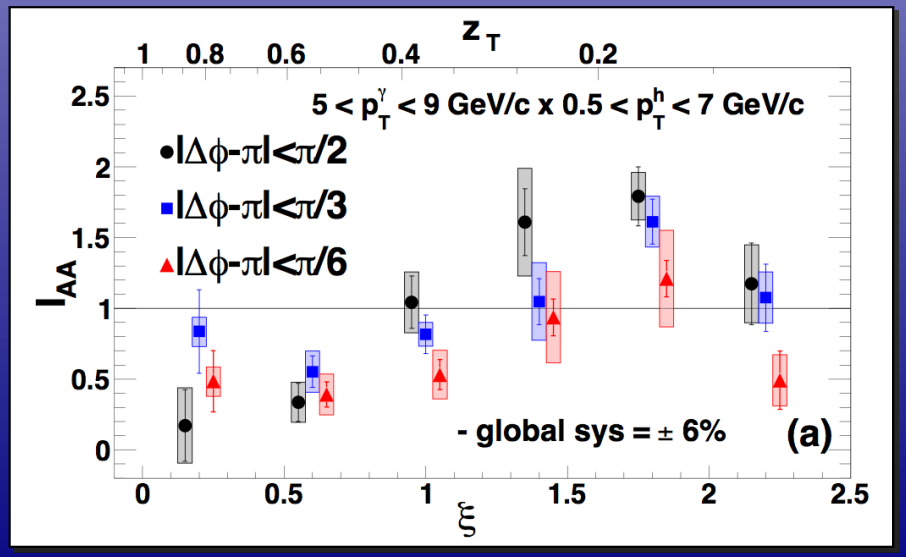
What determines the constituent p_T at which enhancement appears?



– What does away-side broadening imply? –

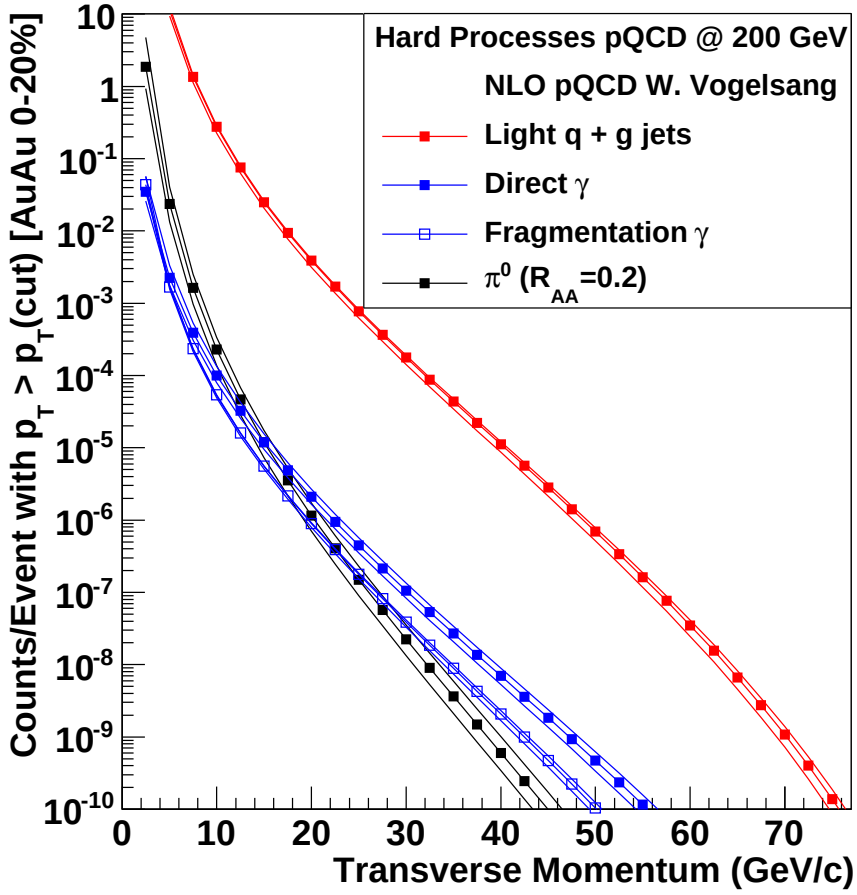


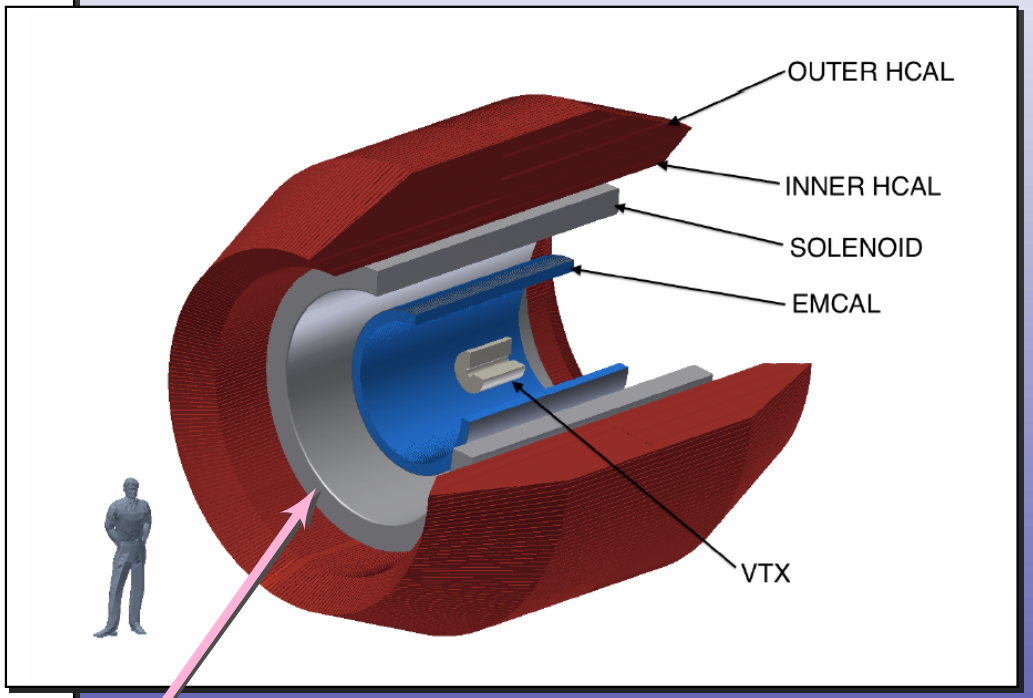




- γ-h $\Delta\phi$ variation results from either
  - variation in γ-quark p_T balance
  - broadening of away-side jet
- broadening of jet seen at LHC
  - inclusive jet measurements
  - different jet p_T and energies

– Going further with jets –





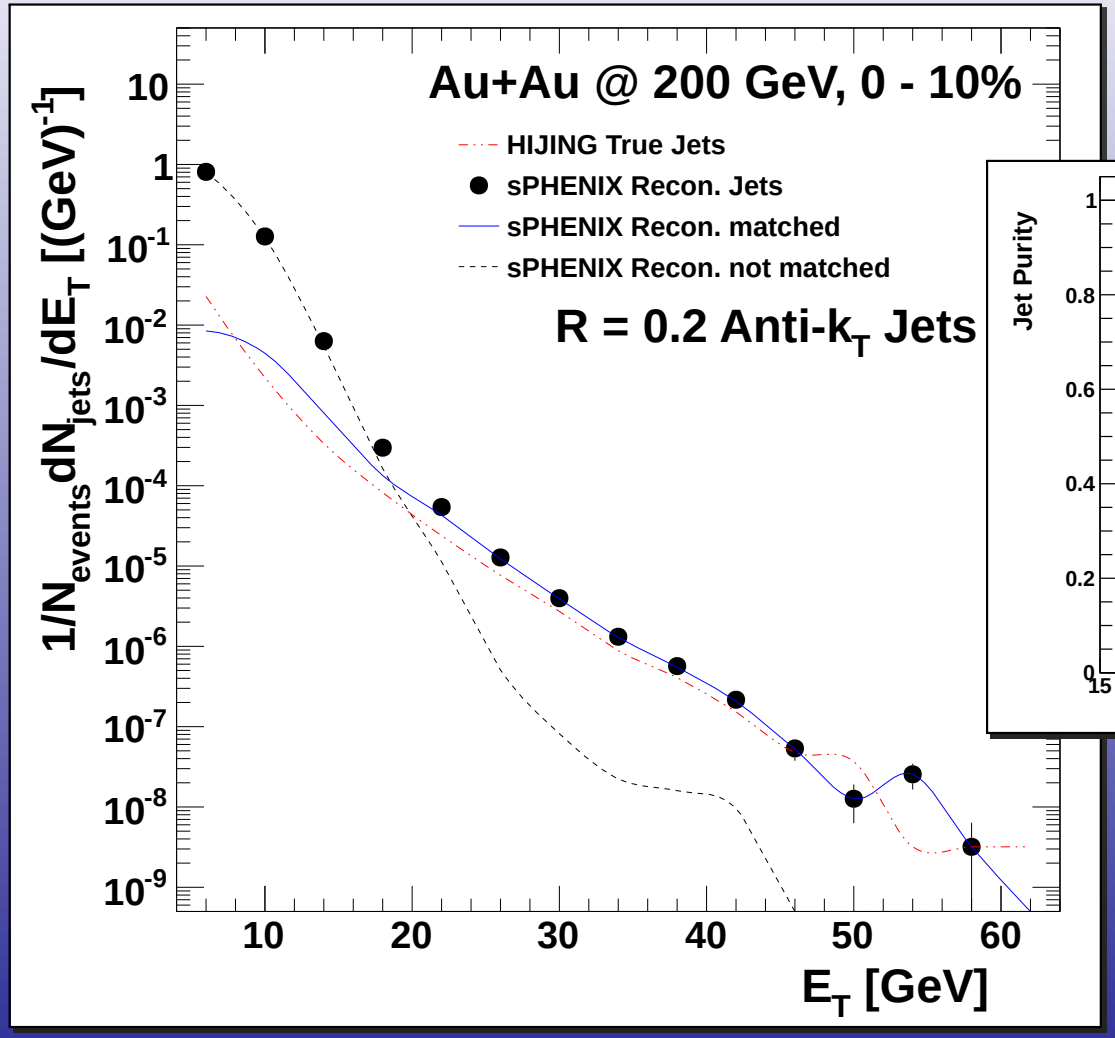
Now using BaBar magnet!

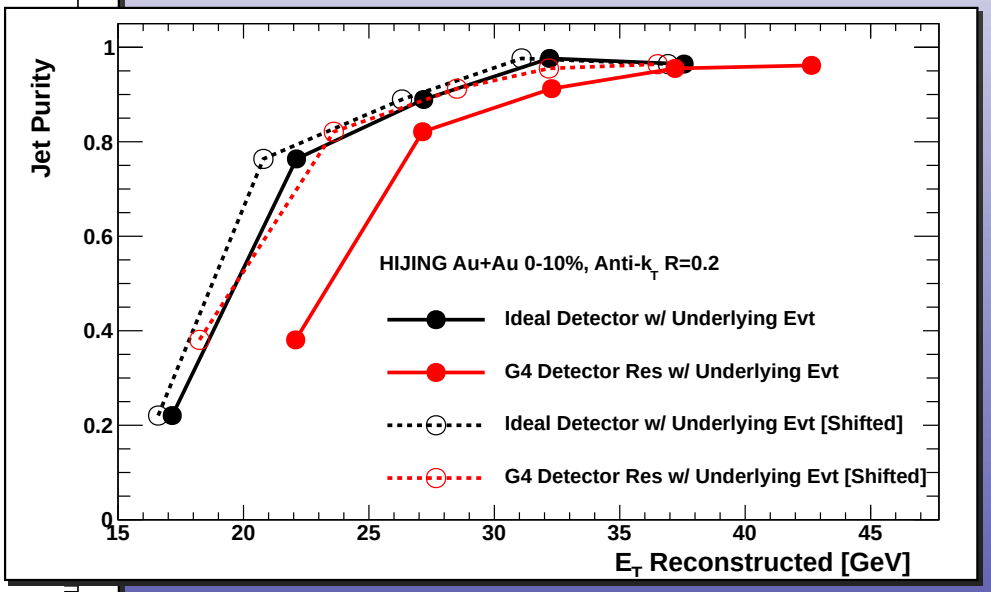
- Large rates and fast readout
  - → 10^6 jets above 30 GeV
  - → 10^3 photons above 30 GeV

Range of geometries/species/energies accessible

http://www.phenix.bnl.gov/phenix/WWW/publish/dave/PHENIX/sPHENIX_MIE_09272013.pdf

– Going further with jets –

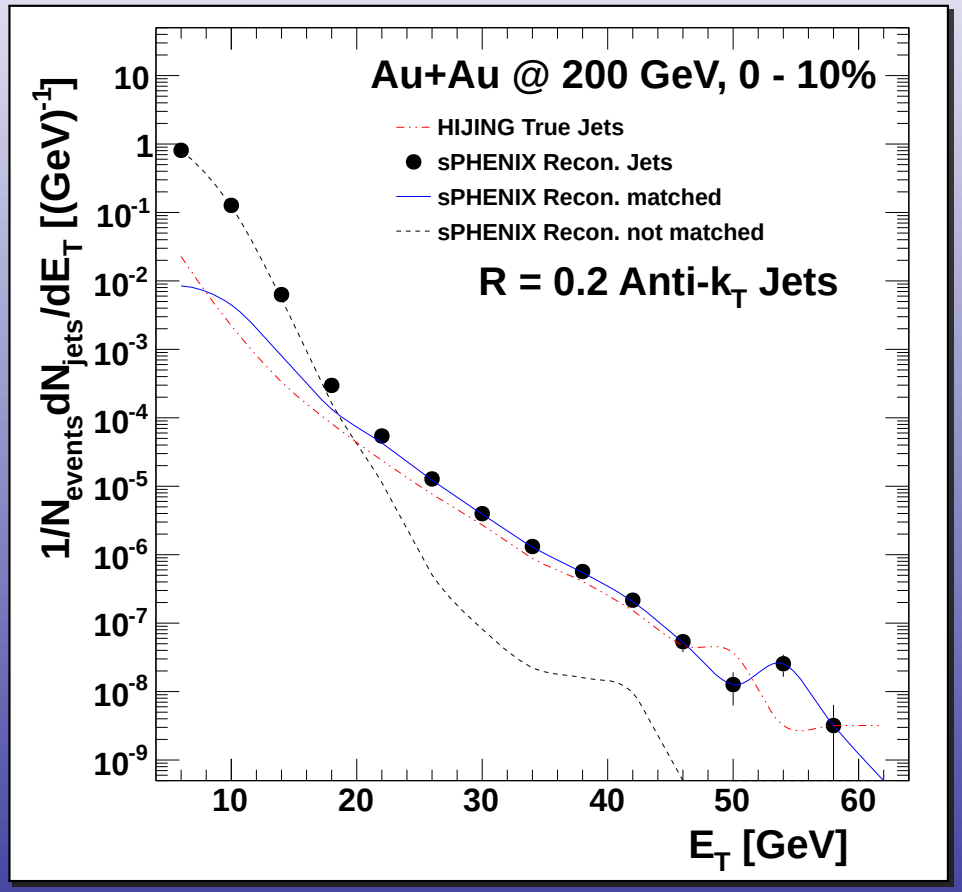


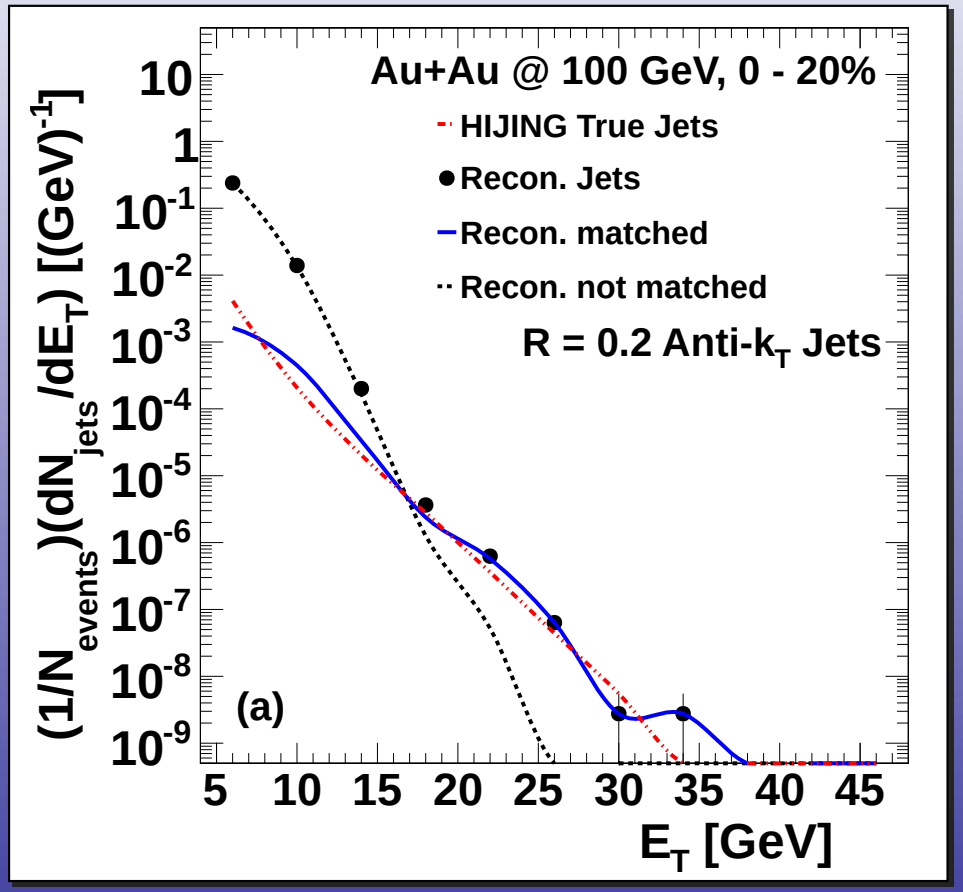


Clean signal above 30 GeV including detector effects

No fake jet rejection applied

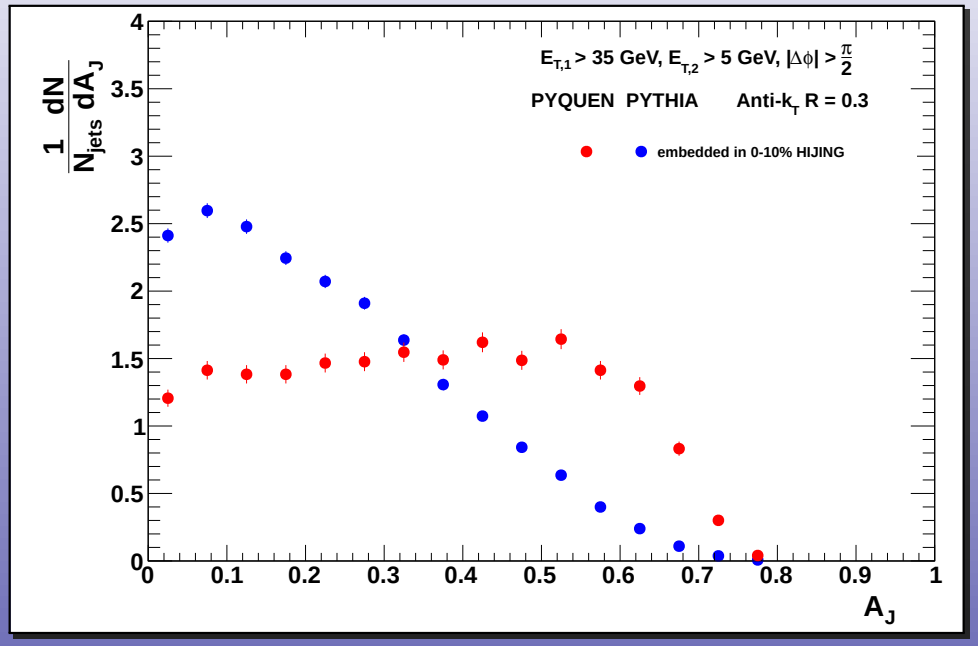
– Going further with jets –

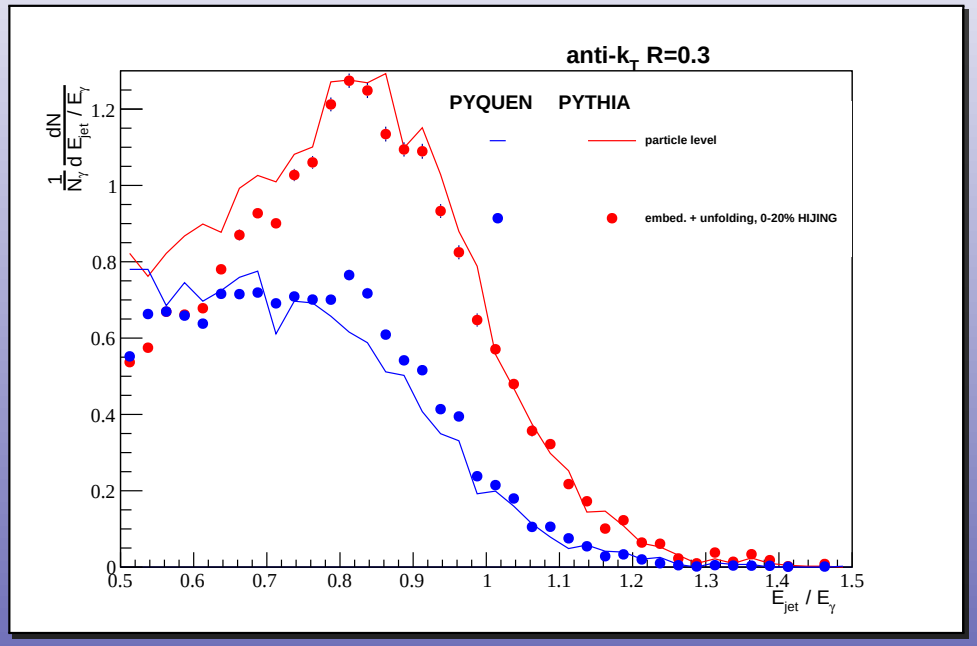




Jets out to ~ 35 GeV down to $\sqrt{s} = 100$ GeV

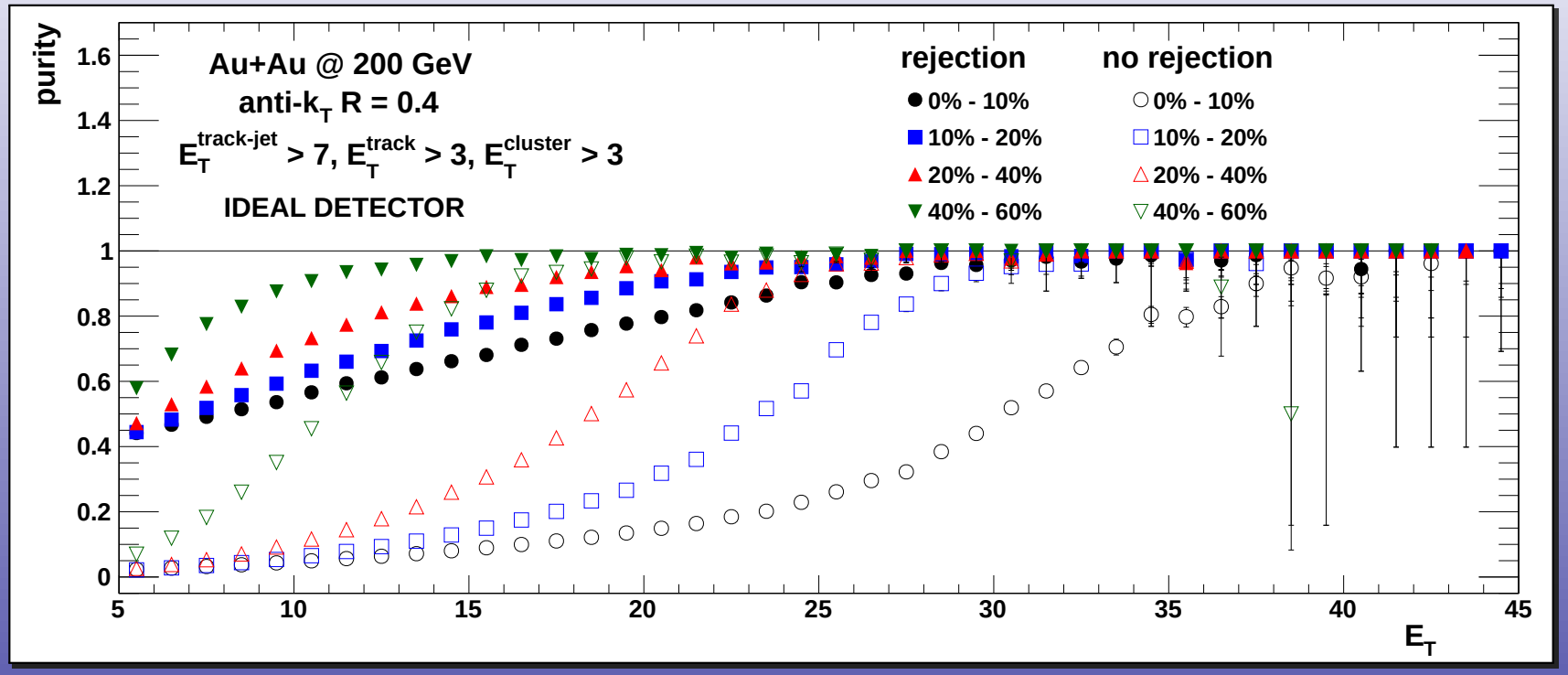
– Beyond inclusive jets –





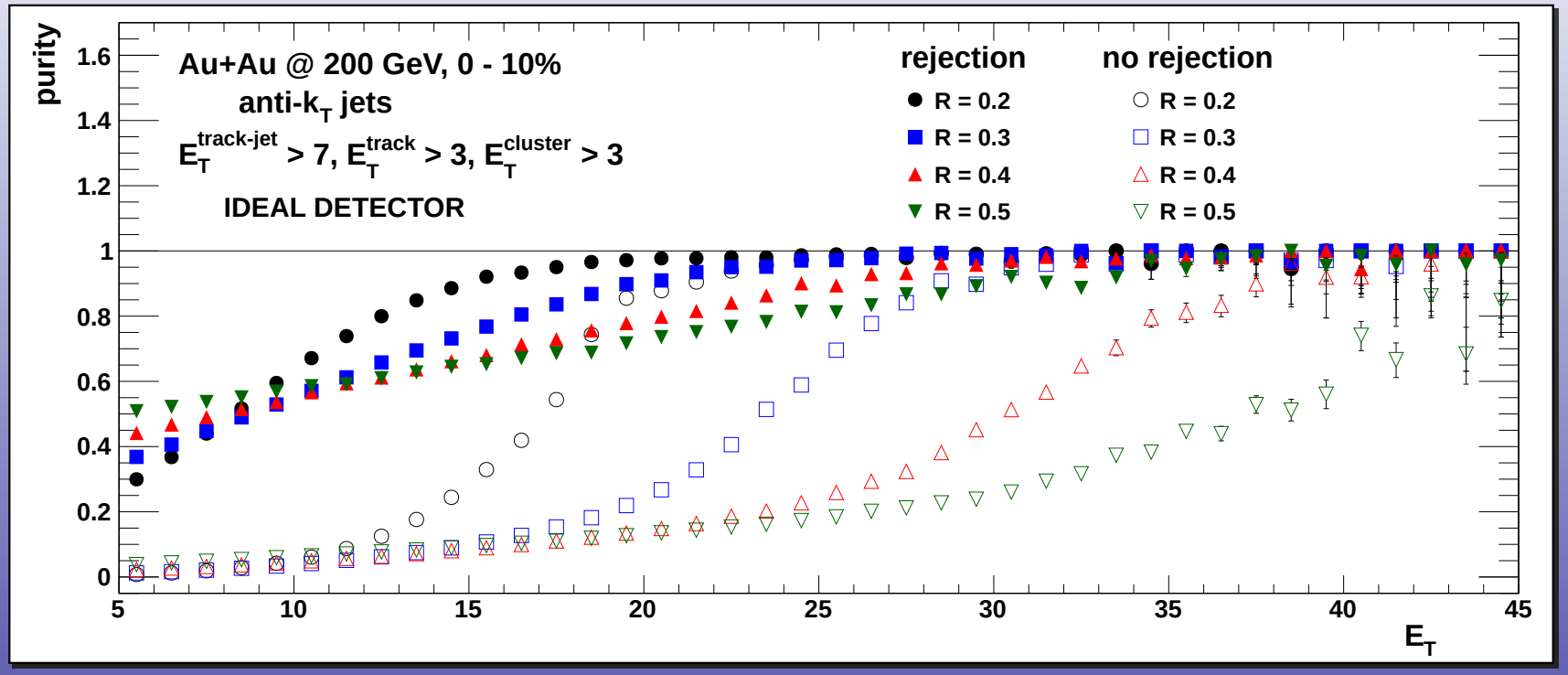
- Di-jet and γ-jet measurements sensitive to medium effects
  - good precision with one year of running
  - high E_T jet/photon trigger reduces effect of background fluctuations

– The power of fake jet rejection –



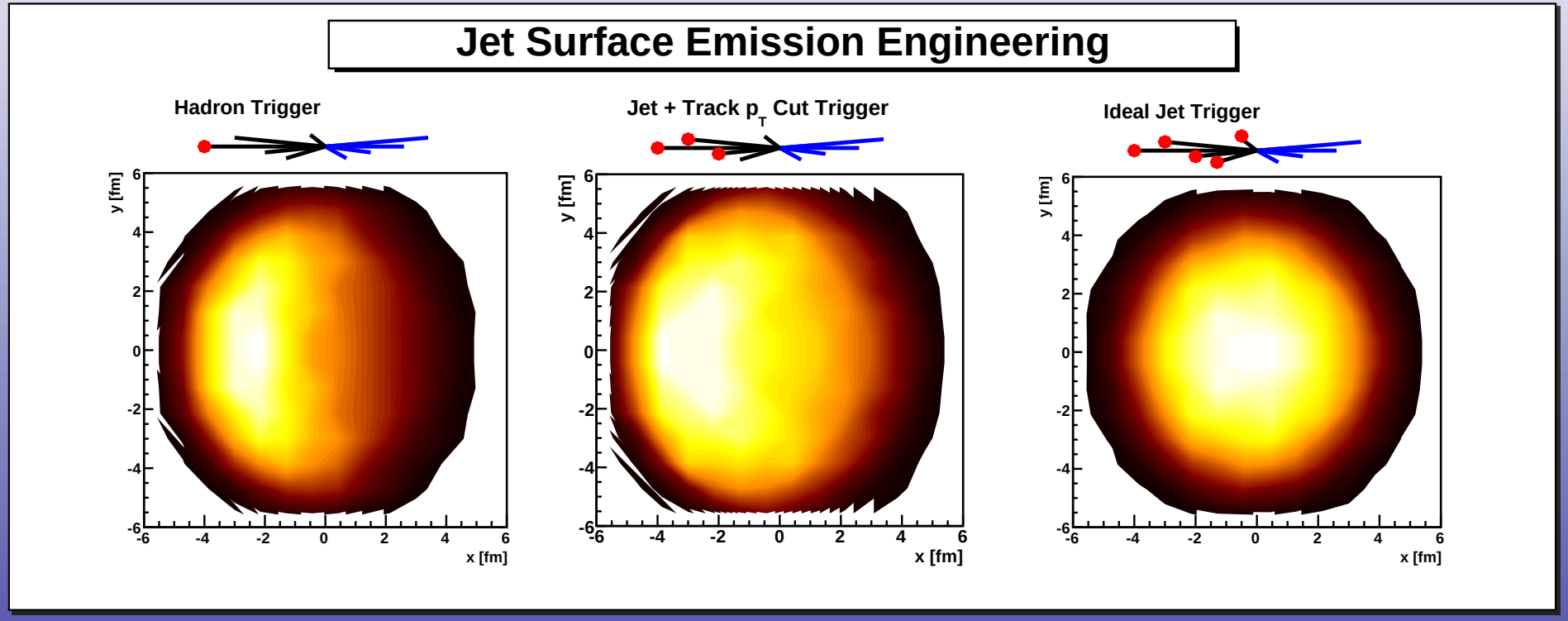
- Optimize choice of cuts on track-jets/clusters
  - trade off between rejection and efficiency
- Extends measurements to lower E_T and larger R

– The power of fake jet rejection –



- Optimize choice of cuts on track-jets/clusters
  - trade off between rejection and efficiency
- Extends measurements to lower E_T and larger R

– Engineering Surface Bias –

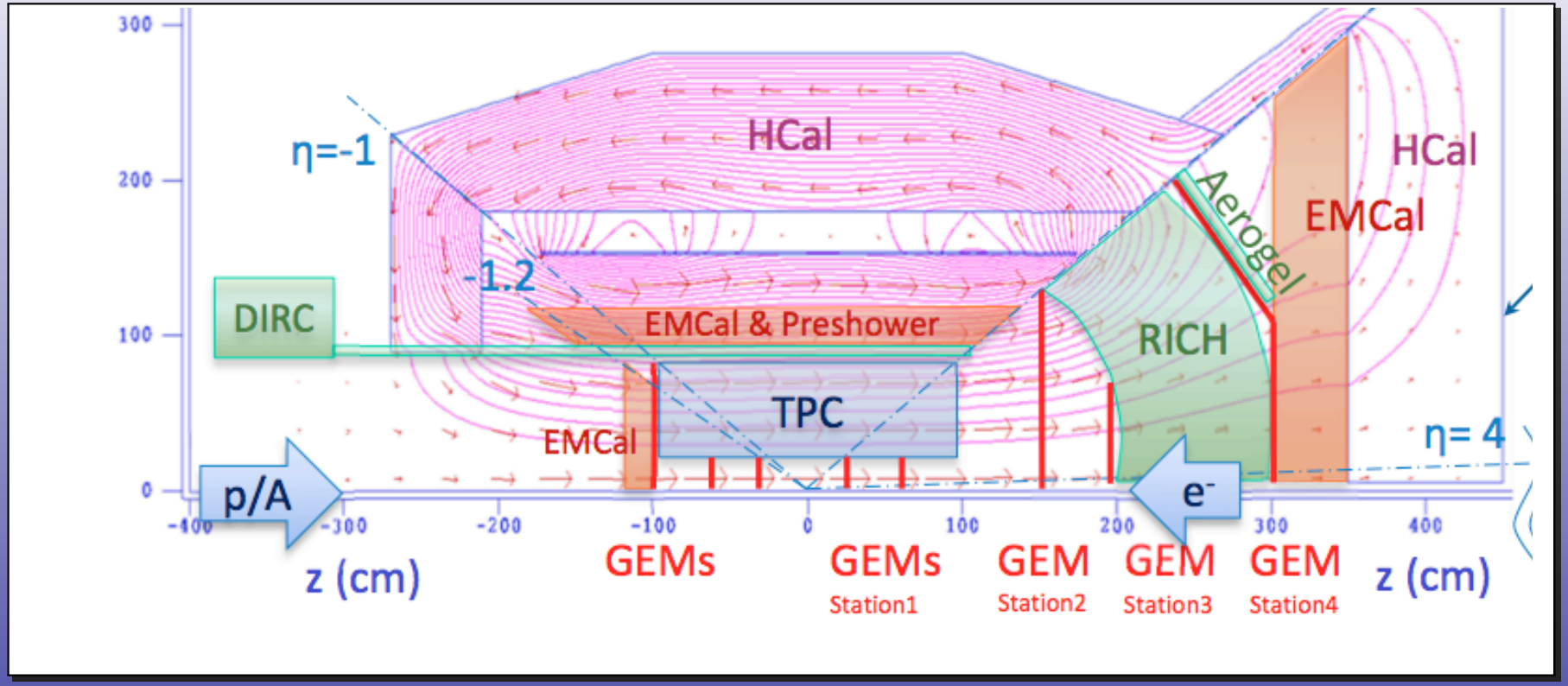


- Track/cluster requirement hardens the jet
  - can be used as experimental handle on surface bias
  - powerful tool for understanding medium properties

– Summary –

- A lot to learn from γ-h results
  - clear modification to fragmentation function
  - comparision with jet measurements informative
- Range of jet measurements will help to clarify picture of energy loss
- sPHENIX upgrade well suited to take full advantage of jets at RHIC and **pave the way for future upgrades**

– The far future with ePHENIX –



- sPHENIX → fsPHENIX → ePHENIX
  - Uses sPHENIX barrel calorimetery
  - Add hadron/electron endcaps
  - Add GEM tracking, TPC, DIRC

http://www.phenix.bnl.gov/phenix/WWW/publish/dave/PHENIX/ePHENIX_LOI_09272013.pdf

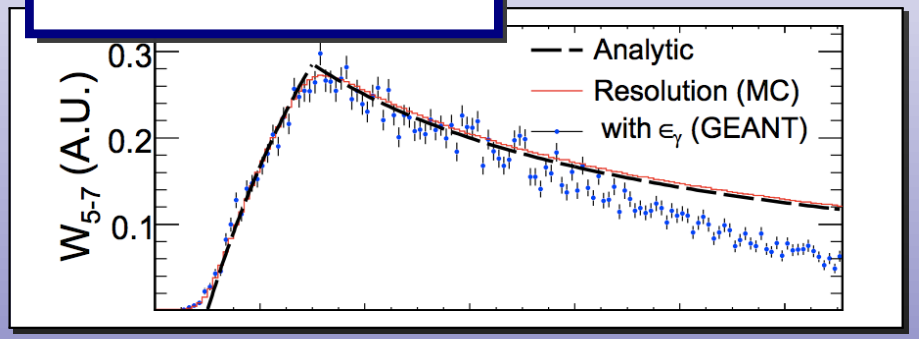
BACKUPS

– Extracting the γ_{dir}-h signal –

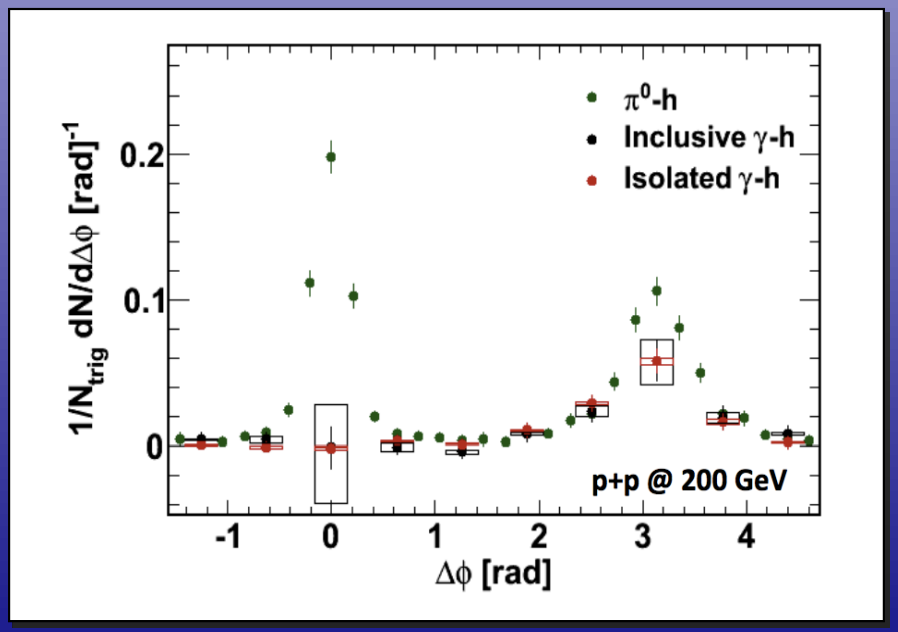
$$Y_{direct} = \frac{R_\gamma Y_{inc} - Y_{decay}}{R_\gamma - 1}$$

$$R_\gamma = \frac{N_{inc}}{N_{decay}}$$

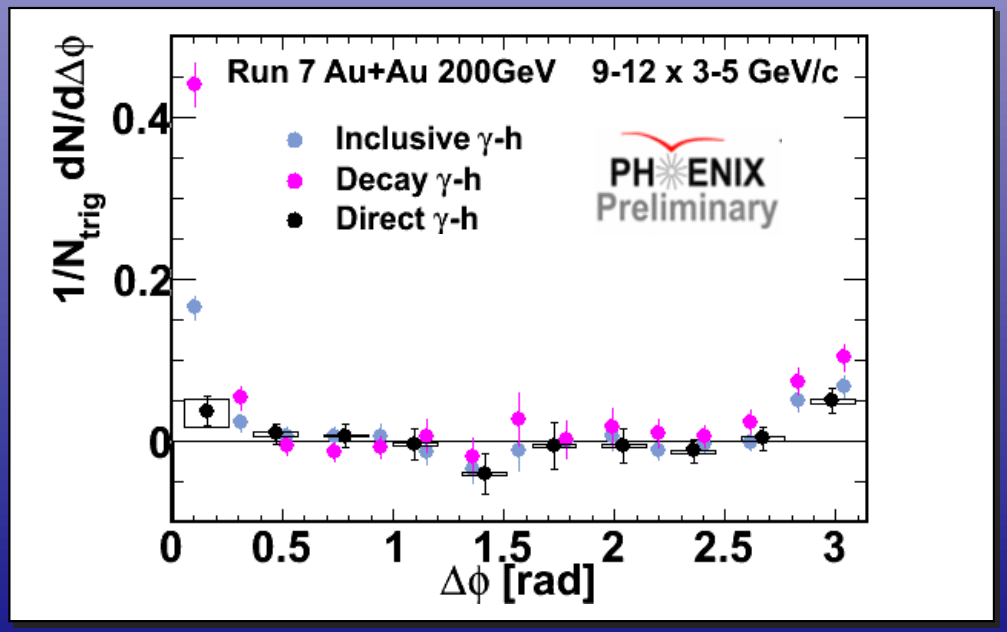
$$Y_{\pi^0} \rightarrow Y_{decay}$$



p+p



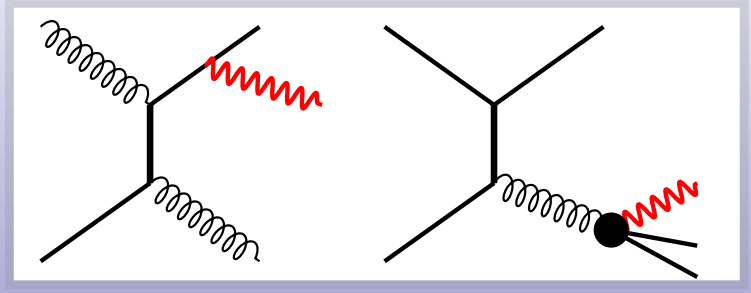
Au+Au



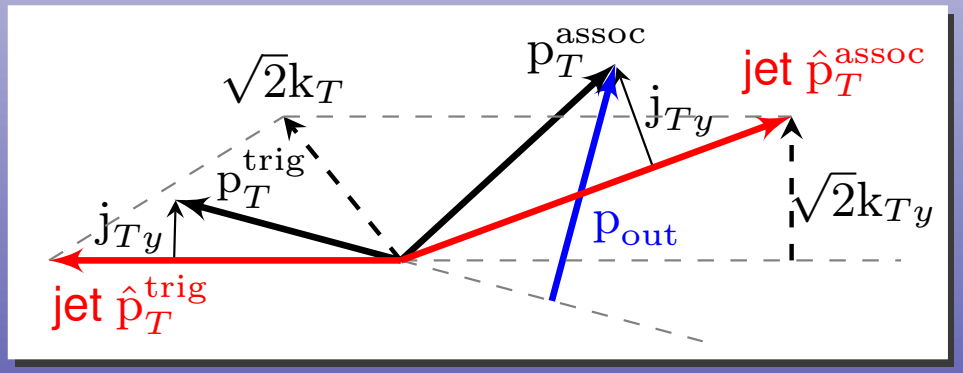
isolation cut improves systematic uncertainties (p+p only)

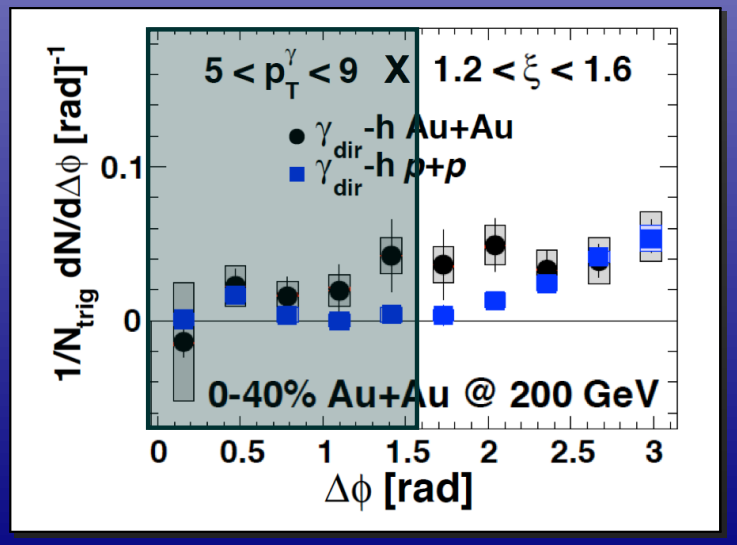
– NLO effects –

$$p_T^{\gamma} \approx p_T^{jet}?$$



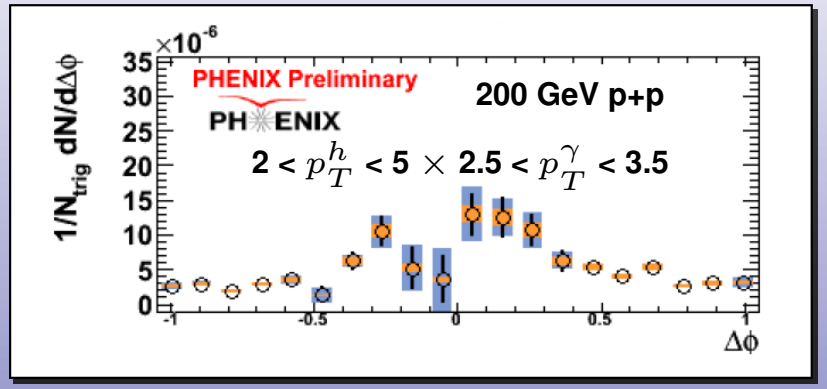
- Why is p_T balance only approximate?
  - Holds only at LO (Compton QCD)
- Higher order effects that can lead to imbalance
  - NLO perturbative processes
  - non-perturbative fragmentation
  - initial k_T effects
- How significant are such beyond-leading-order effects?



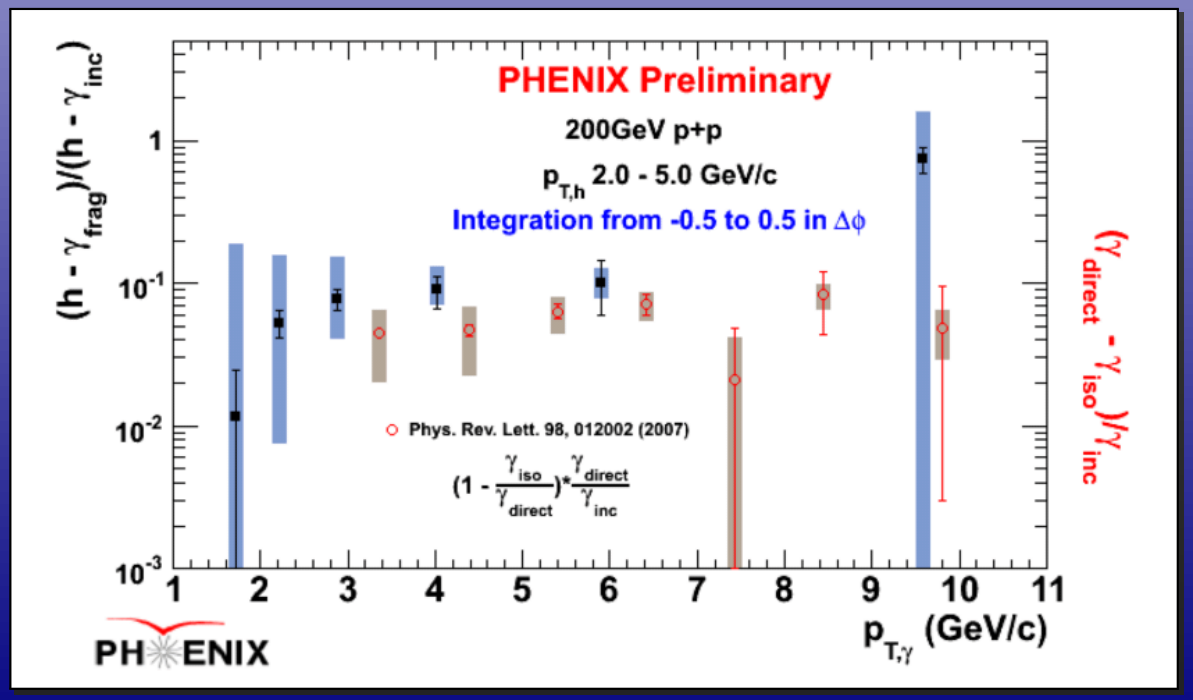


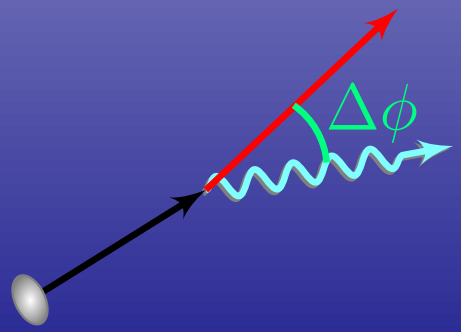
– The near side –

$$p_T^{\gamma} \approx p_T^{jet}?$$



- Measuring fragmentation photons
  - use hadron-photon correlations
  - integration of near-side shows significant yield of NLO photons
- Comparable to unconditional yield using isolation cuts

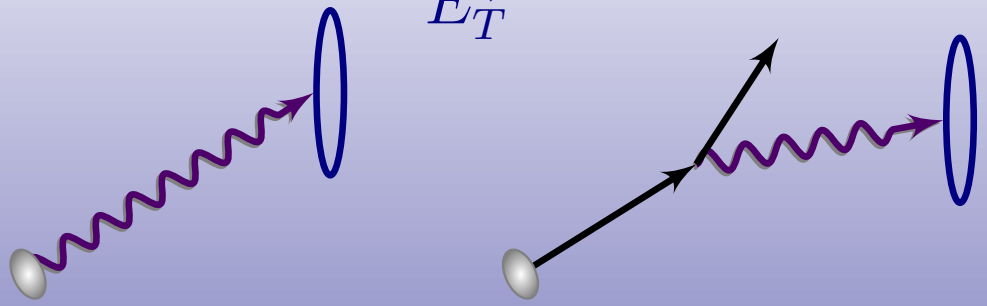




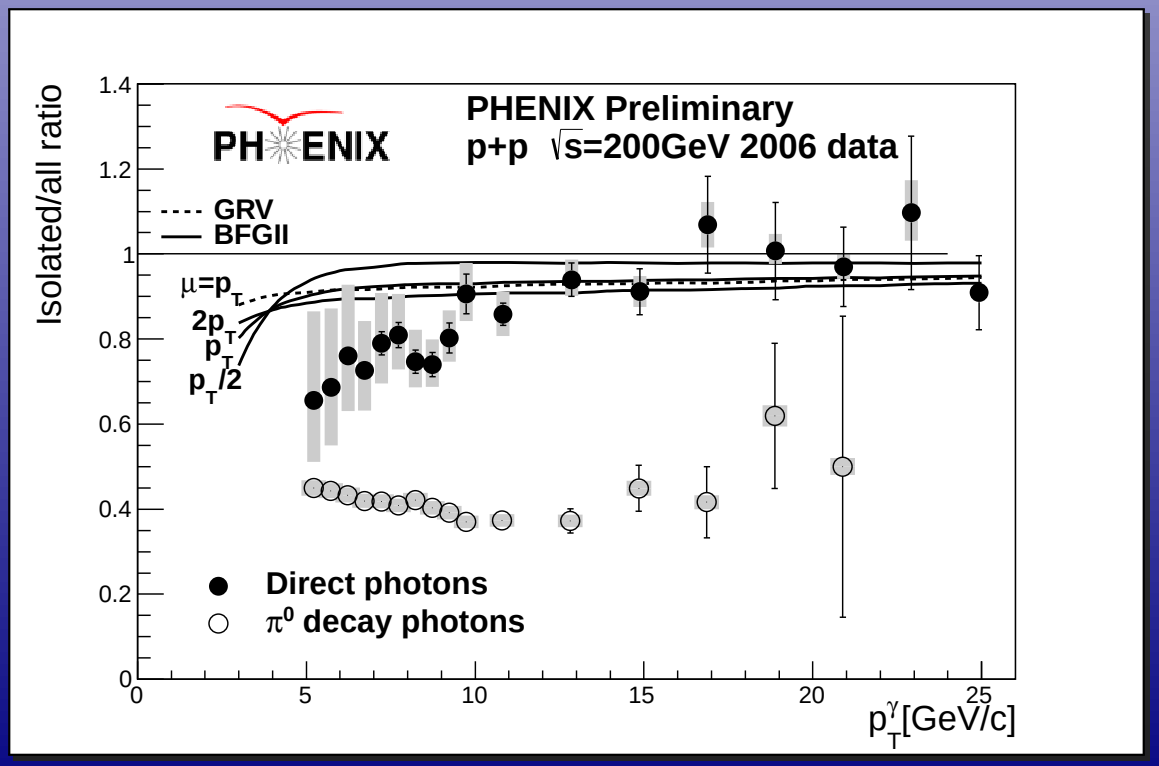
– The near side –

$$p_T^{\gamma} \approx p_T^{jet}?$$

$$\frac{\sum_{\Delta R<0.5} E_T}{E_T^{\gamma}} < 10\%$$



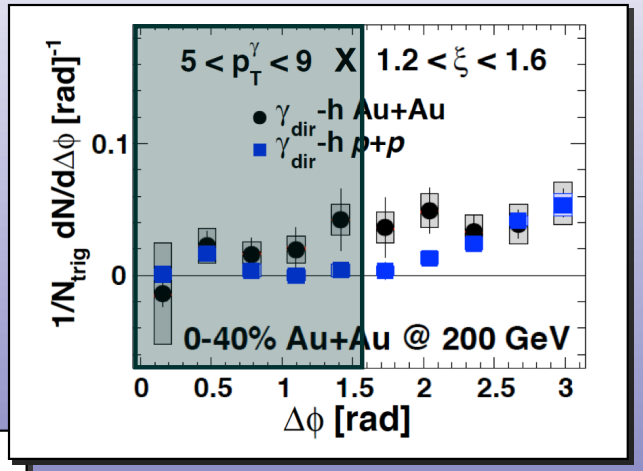
- Can use isolation cuts to reduce yield of non-prompt photons

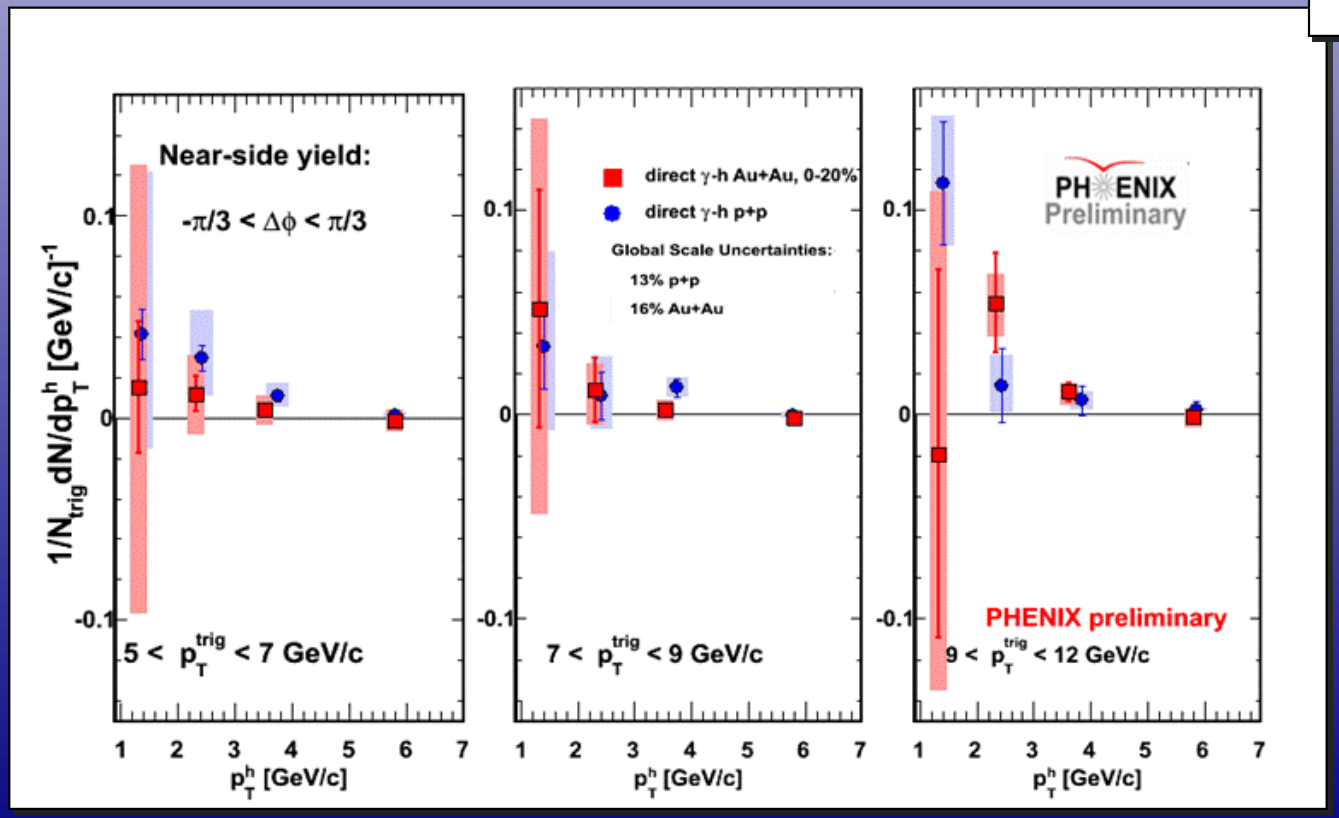


– The near side in Au+Au –

$$p_T^{\gamma} \approx p_T^{jet}?$$

- Isolation cut difficult in Au+Au
  - near-side yield consistent with zero
  - no significant variation from p+p to Au+Au



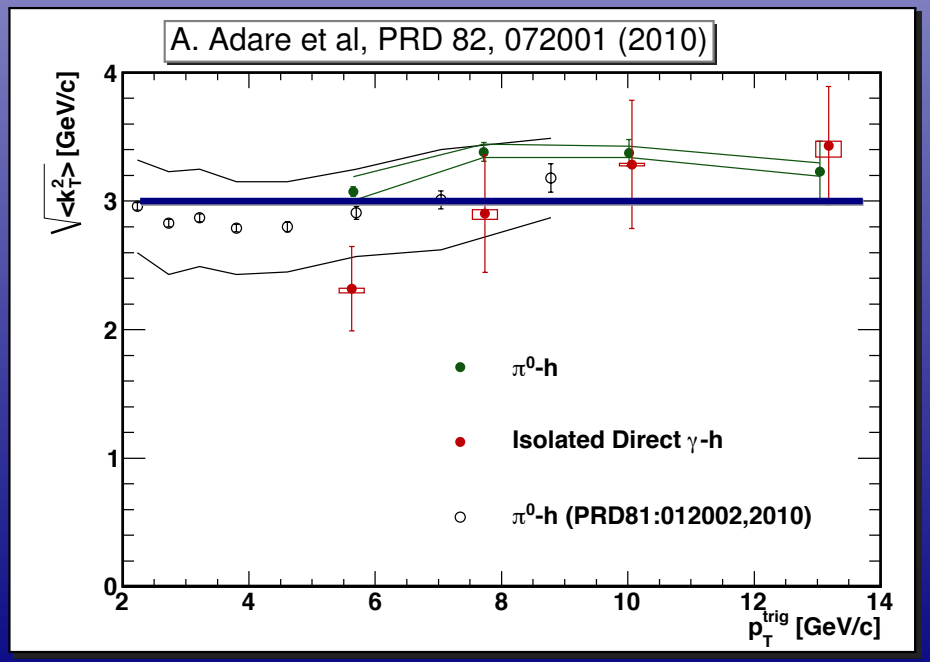


– System dependence of k_T –

- Measured k_T from γ-h consistent with other jet measurments
- No significant variation in k_T observed between p+p and d+Au

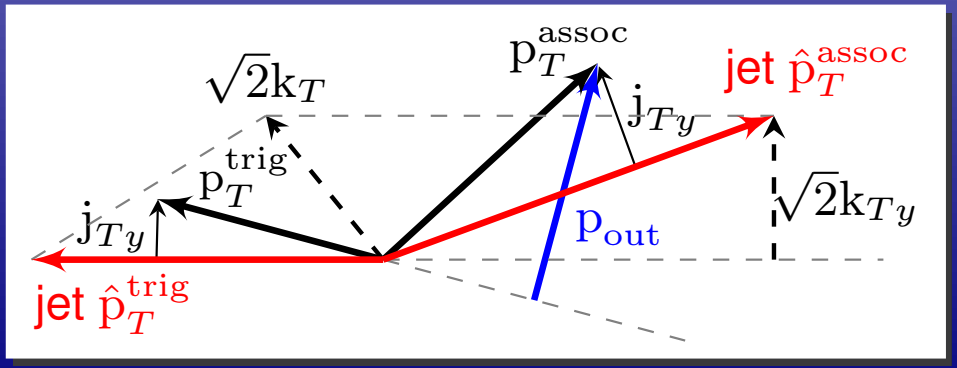
  Adler et al, Phys.Rev.C73, 054903 (2006)

$\Longrightarrow$ no effective modification in fragmentation function from p+p to Au+Au



$$|p_{\rm out}| = |p_T^{\rm assoc}|\sin\Delta\phi$$

$$|p_{\rm out}|^2 = x_E^2[2\langle k_{Ty}\rangle^2 + \langle j_{Ty}\rangle] + \langle j_{Ty}\rangle$$

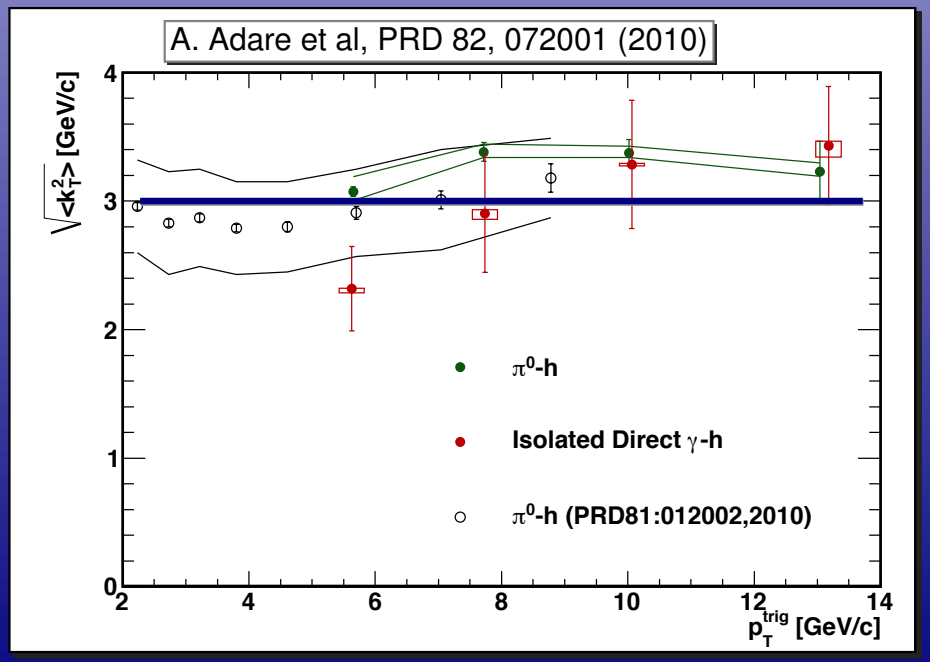


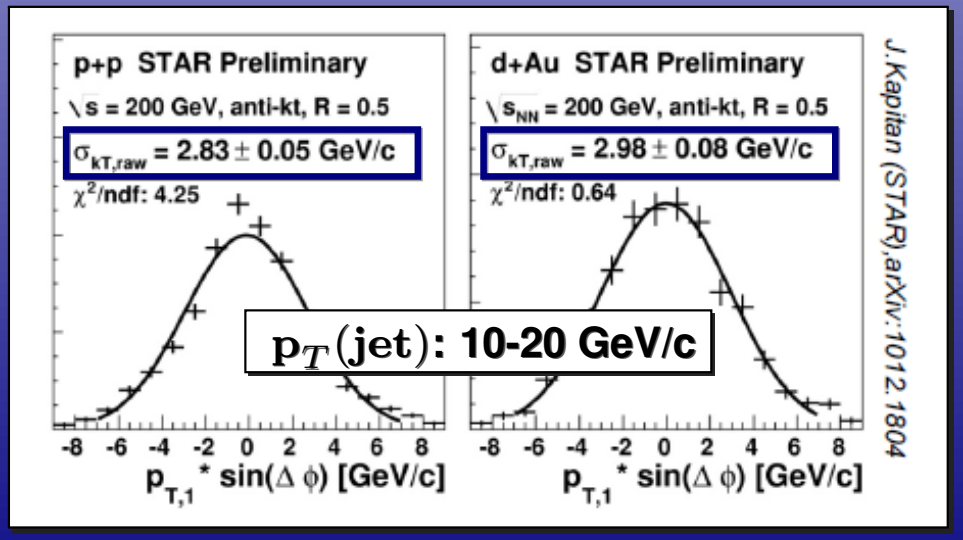
– System dependence of k_T –

- Measured k_T from γ-h consistent with other jet measurments
- No significant variation in k_T observed between p+p and d+Au

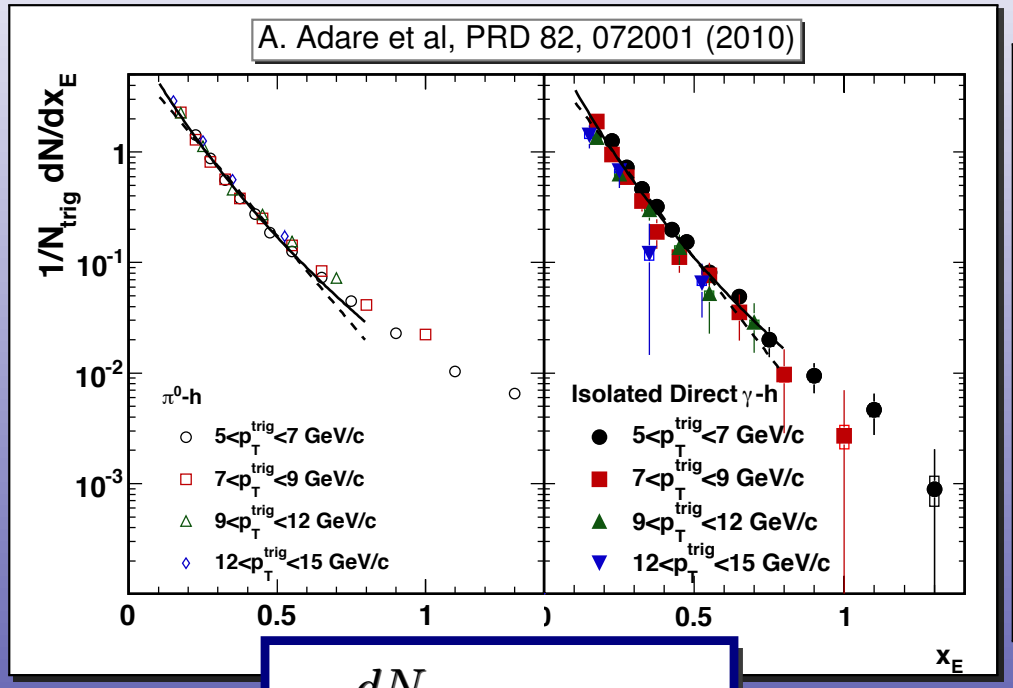
  Adler et al, Phys.Rev.C73, 054903 (2006)

$\Longrightarrow$ no effective modification in fragmentation function from p+p to Au+Au

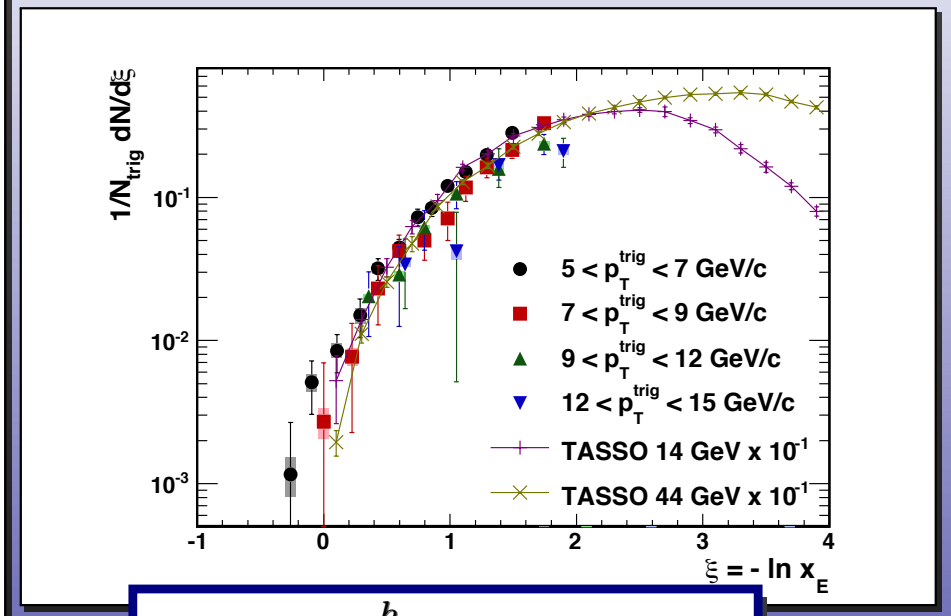




– Establishing the $p+p$ baseline –



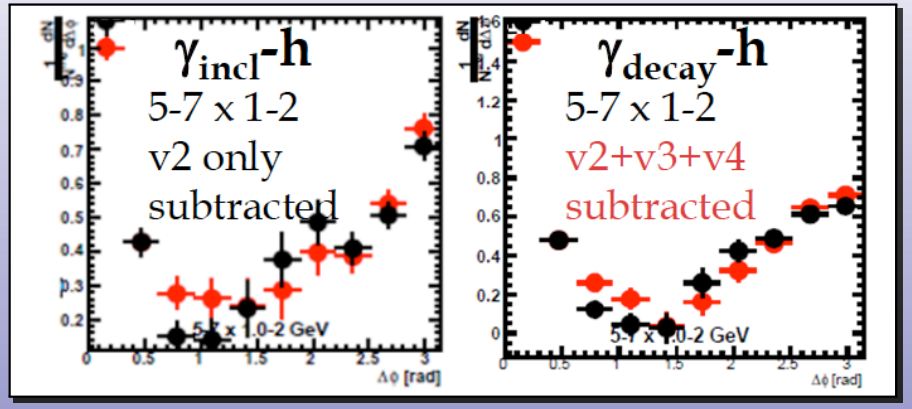
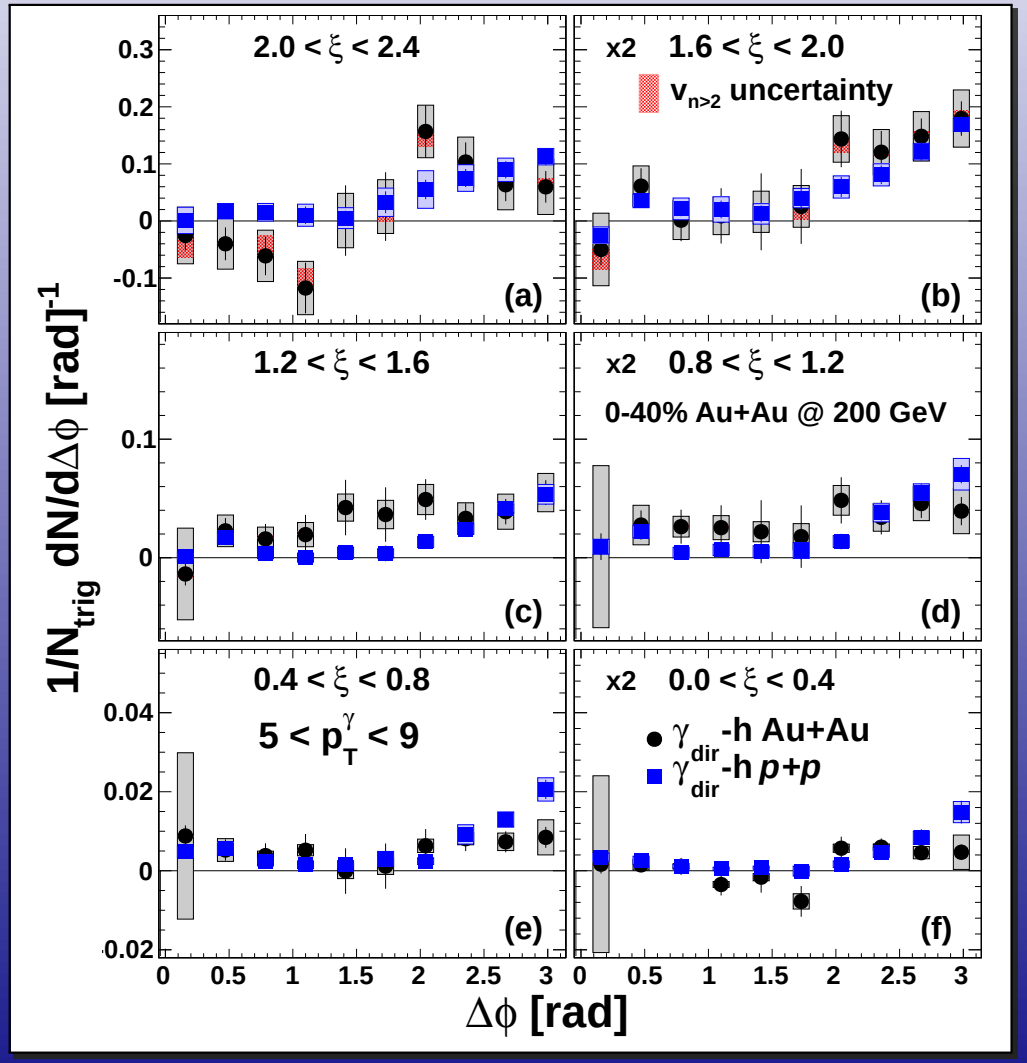
$$\frac{dN}{dx_E} = Ne^{-bx_E}$$



$$x_E = -\frac{p_T^h}{p_T^\gamma}\cos(\Delta\phi) \sim z_T$$

- approximate universal scaling
- b $= 8.2 \pm 0.3 \longrightarrow$ consistent with quark fragmentation
- good agreement with TASO measurements (e^+e^-)

– Could this be flow? –



- No high p_T γ $v_{3,4}$ measurement
- Conservative estimate from π^0
  - assume γ_{dir} $v_n = 0.5 v_n^{\pi^0}$
- Uncertainties in $\Delta\phi$ shown separately
- Additional source of uncertainty in I_{AA}