Jet Reconstruction - Understanding the backgrounds and biases is key

Helen Caines - Yale University

RHIC Paradigms
Austin, Tx
April 14-17 2010

Outline

- p-p
  - Underlying event
  - Initial and final state effects
  - Fragmentation
- d-Au
  - Cold nuclear matter effects
- Au-Au
  - Understanding the background
  - Probing jet modifications

Jet definitions ⇔ Jet algorithms

The construction of a jet is unavoidably ambiguous

- Which particles get put together into a common jet?
- How do you combine their momenta?

Jet Algorithm

$\{p_i\} \rightarrow \{j_k\}$

individual 4-mtm jets

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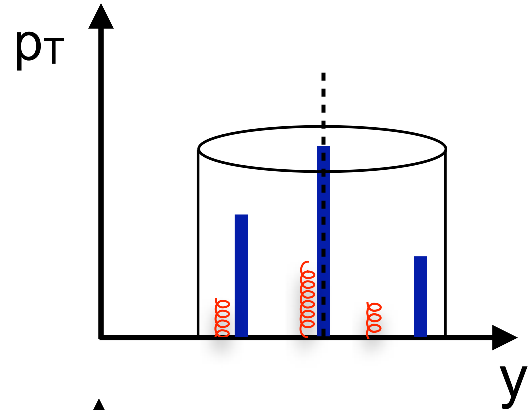


- Jet algorithms:

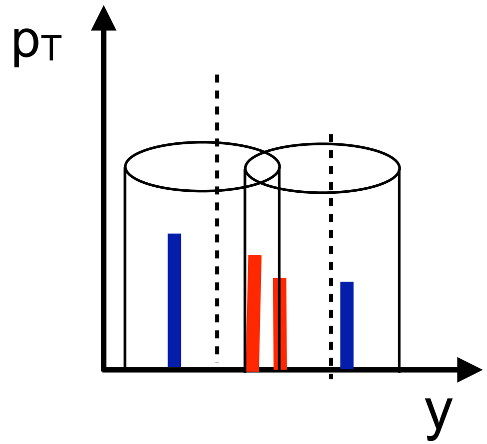
  radius parameter

  infra-red safe

  - jet unaffected by soft gluon emission

  collinear safe

  - jet unaffected by parton splitting



Jet finders used at RHIC

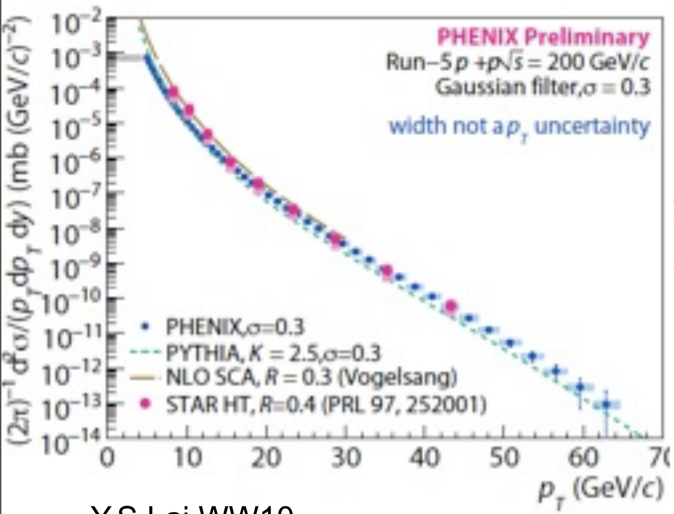
STAR

- k_T and anti-k_T recombination algorithms from FastJet
  Cacciari, Salam and Soyez, JHEP0804 (2008) 005, arXiv:0802.1188
- resolution parameter R: 0.2 - 0.7
- background subtraction:
  $p_{T,meas}$ (Jet) ~ $p_{T,true}$ (Jet) + ρ A $\pm \sigma \sqrt{A}$
  A: active jet area, ρ: median of p_T/A distribution

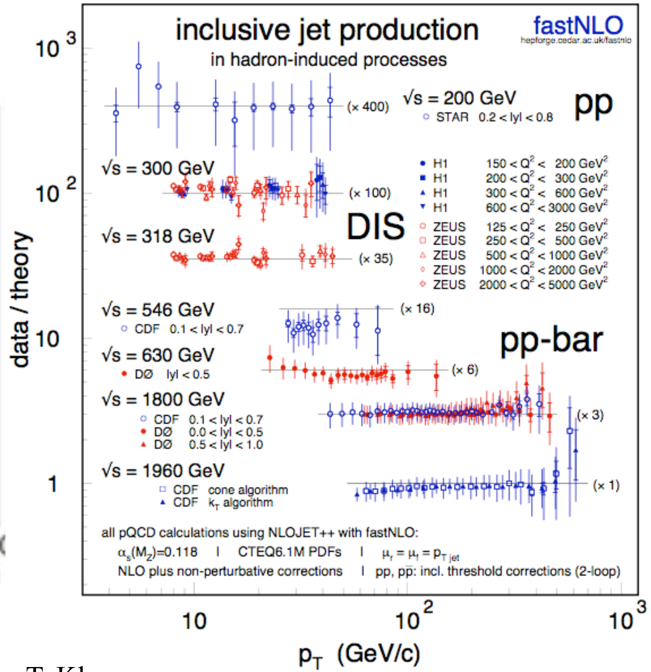
PHENIX

- Gaussian filter with σ=0.3 (Y.S.Lai, B.A.Cole, arXiv: 0806.1499)
  core of jet has higher weight: optimized to suppress background
  ideal for limited-acceptance detector
  seedles
  ‘cone like’ but not infrared or collinear safe
- Jet-by-jet fake rejection by Gaussian-filtered (σ=0.1) p_T^2 sum > cut
  Y.S.Lai (PHENIX), arXiv: 0907.4725
  shouldn't reject quenched jets (PYQUENCH simulation)

Jets in p-p at RHIC



Y.S.Lai WW10



T. Kluge,
K.Rabbertz, M.Wobish

- Jet cross-section in p+p is well described by NLO pQCD calculations over 7 orders of magnitude.
- Excellent description when included in world data

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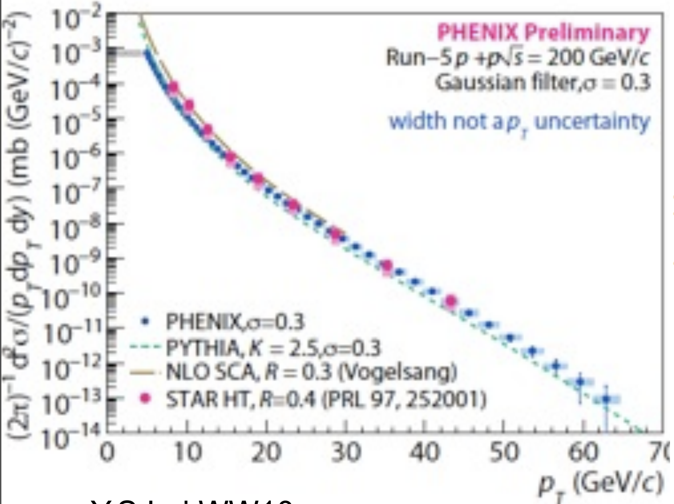

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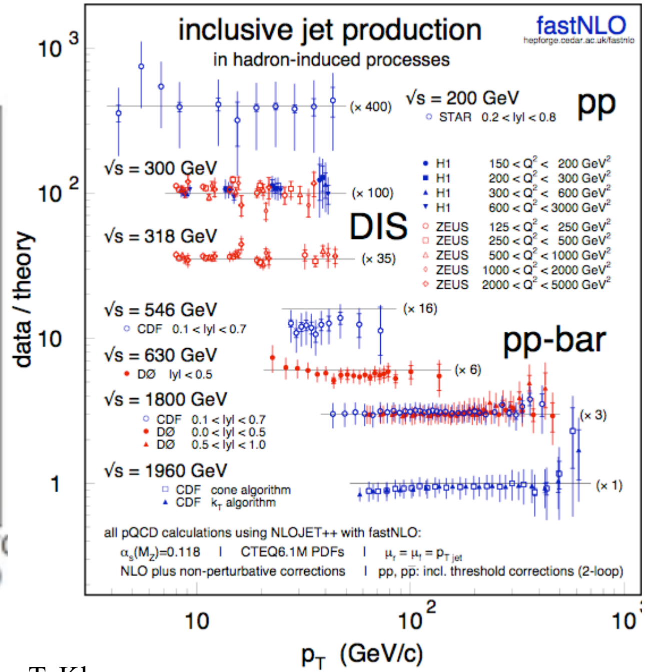

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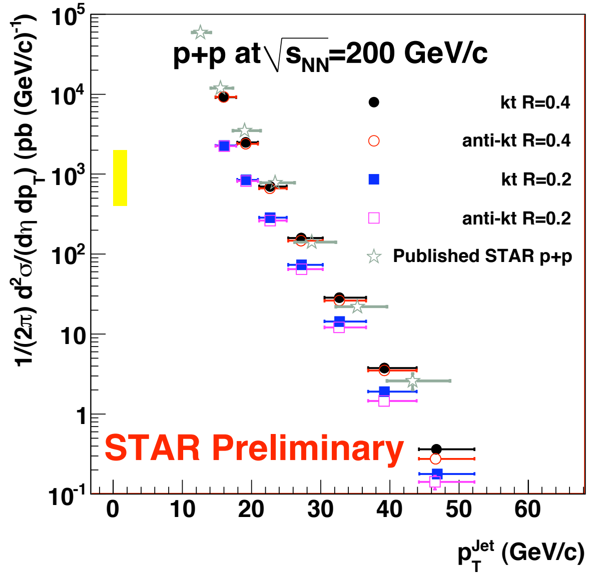

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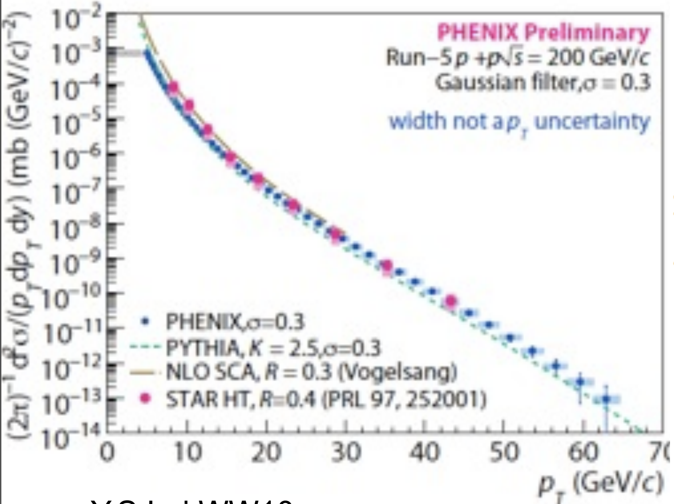

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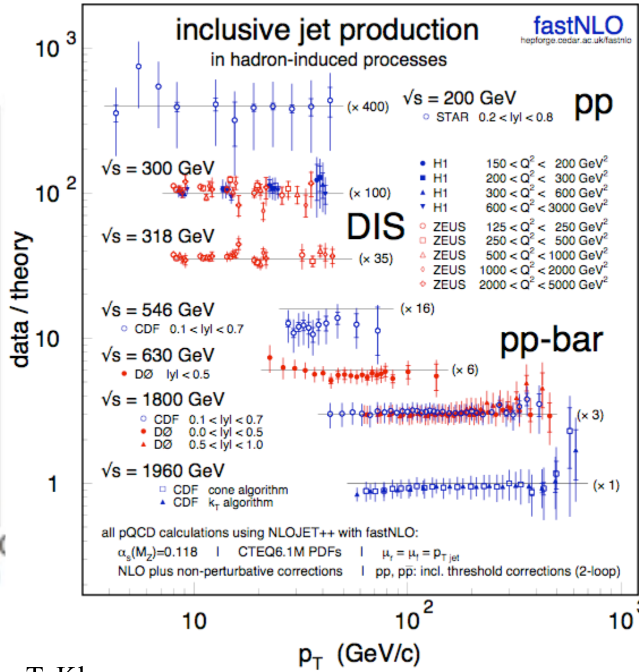

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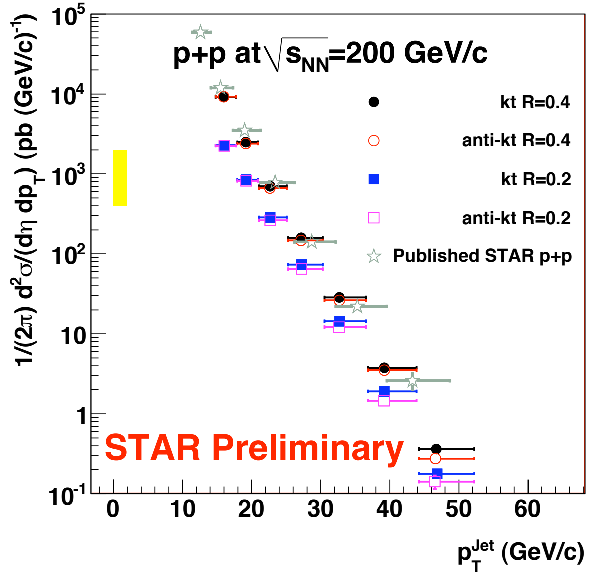

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Seem to have a well calibrated probe

Measuring the underlying event

leading : Most basic jet cut, one jet in our acceptance

back-to-back : Sub-set of leading jet collection.
Require $|\Delta\phi| > 150$, $p_{TAway}/p_{TLead} > 0.7$
Suppresses hard initial and final state radiation.

TransMin : Sensitive to beam-beam remnants and soft multiple parton interactions. - region 90^0 to jet with least Σp_T

TransMax : Enhanced probability of containing hard initial and/or final state radiation component. - region 90^0 to jet with least Σp_T

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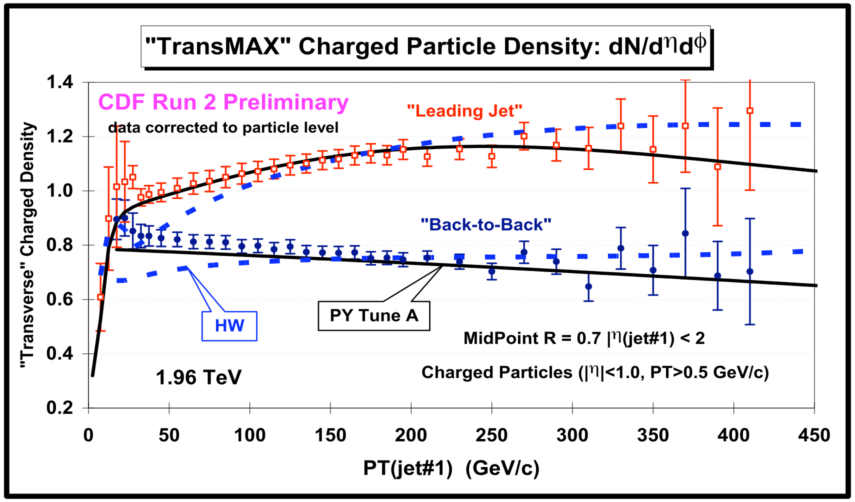
Compare TransMin and TransMax data from leading and back-to-back jet samples →

Information about large angle initial/final state radiation.

TransMin vs TransMax regions of UE



CDF √s=1.96 TeV

- leading TransMax > back-to-back TransMax

Significant initial/final state radiation at large angles.

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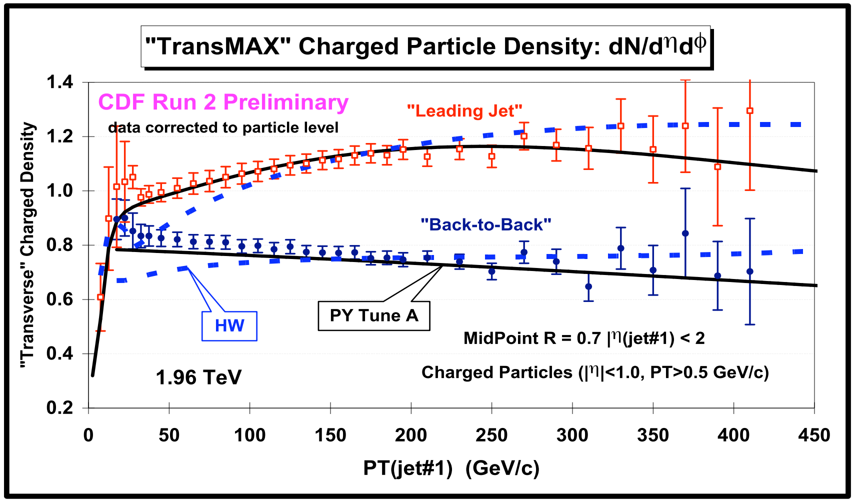

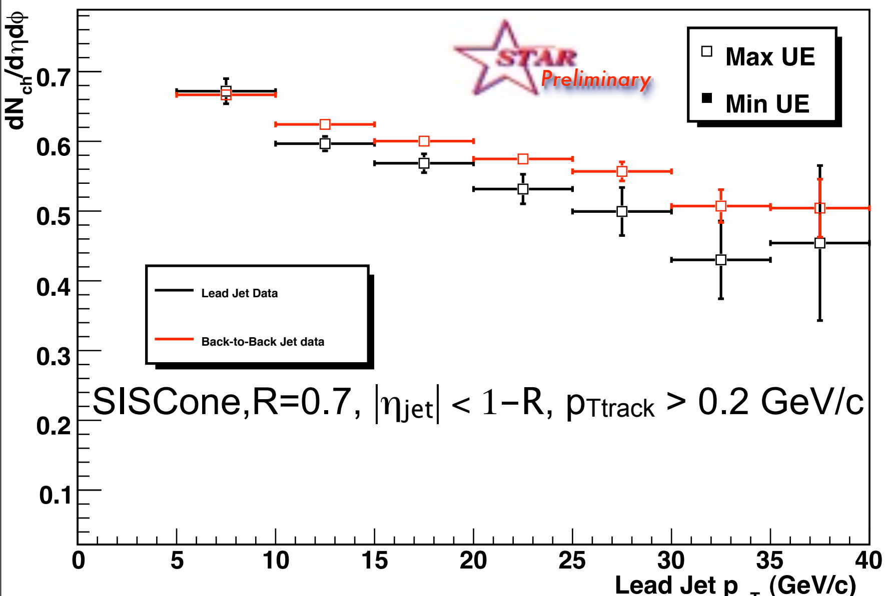

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STAR √s=200 GeV

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Small initial/final state radiation at large angles.

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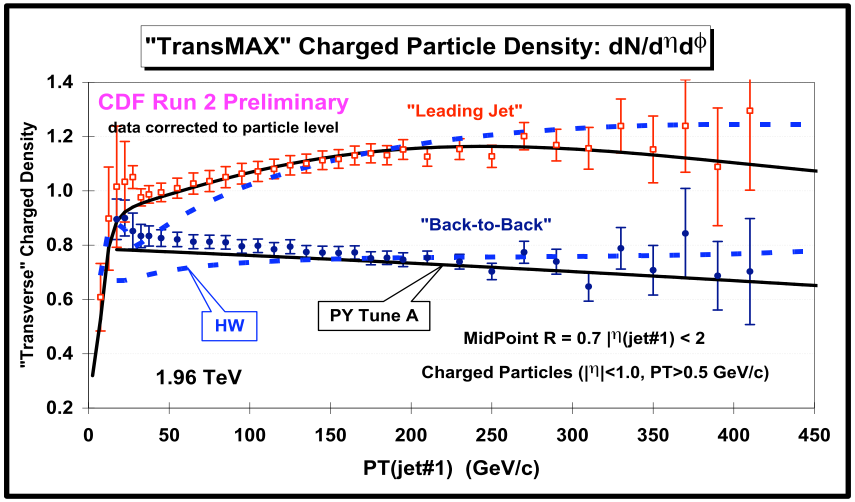

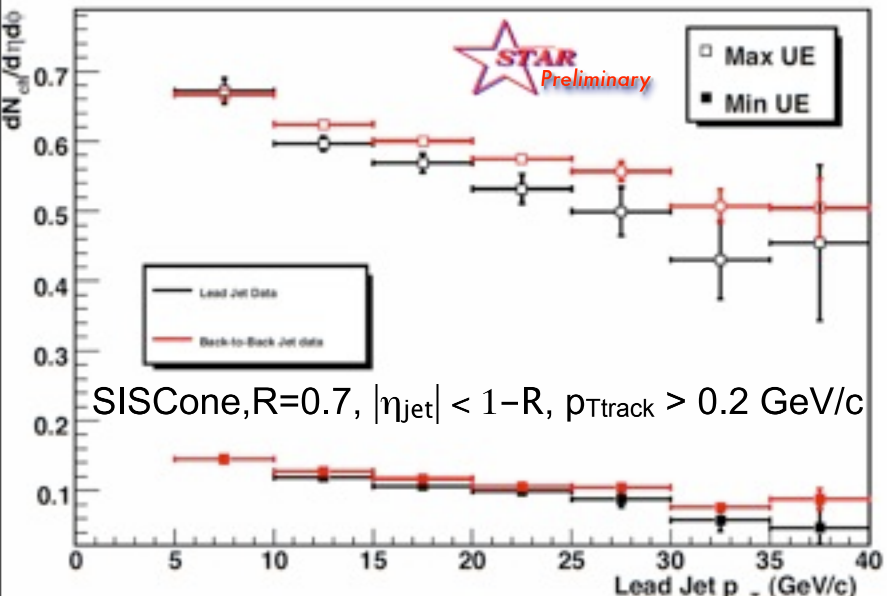

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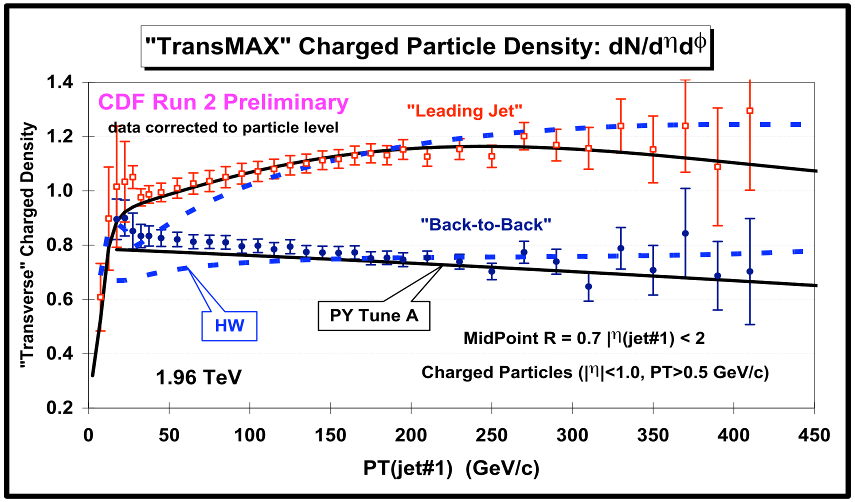
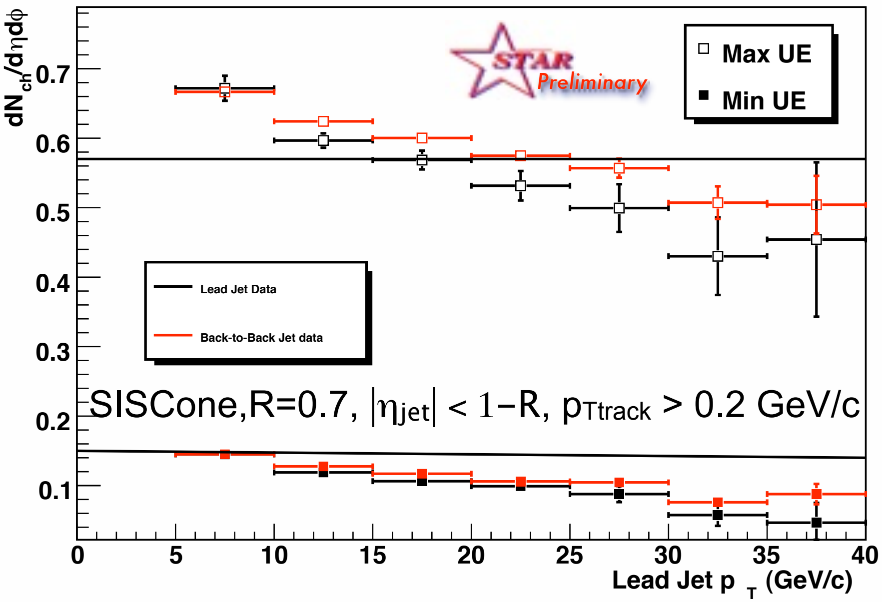


Data not corrected to particle level.



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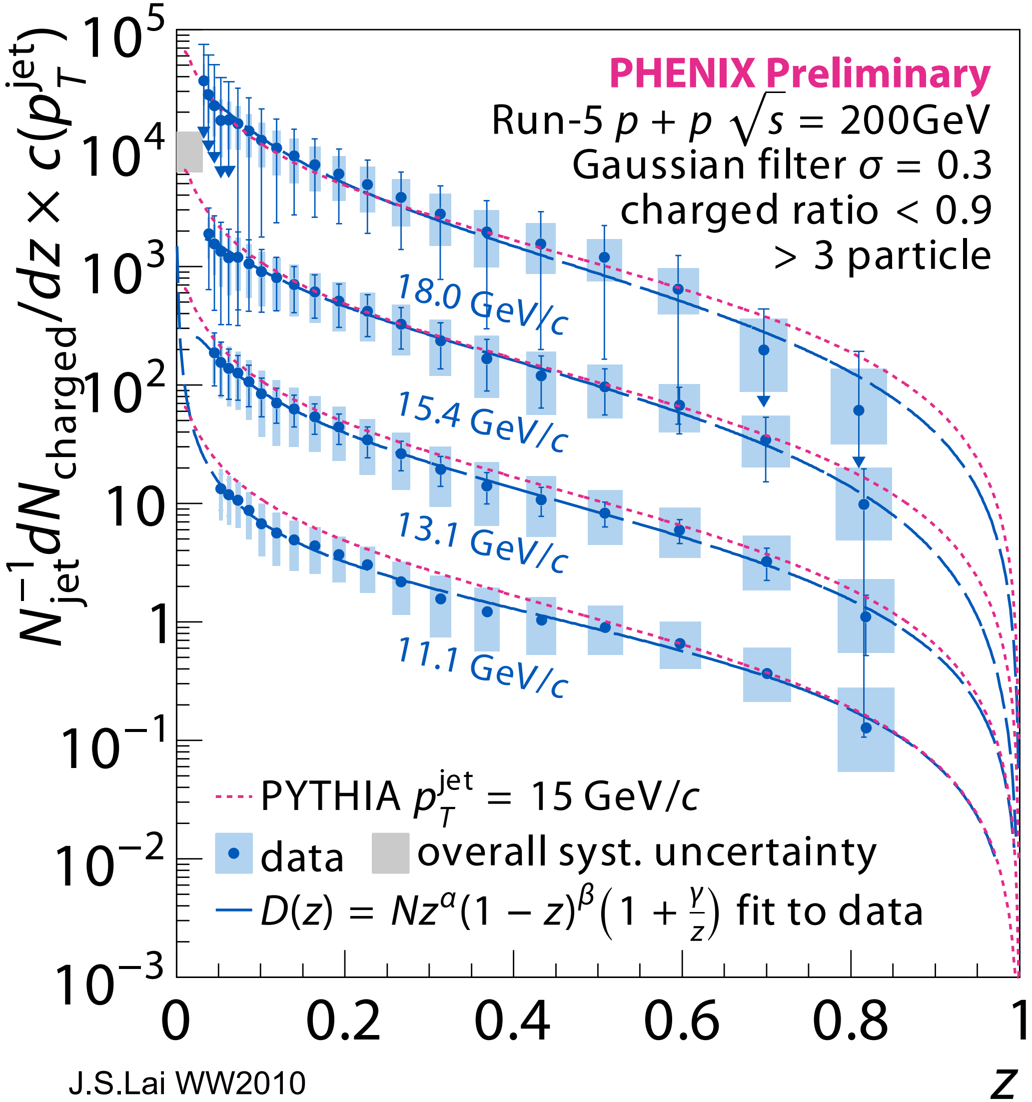
Poisson distribution with average $dN_{ch}/d\eta d\phi$ = 0.36

- UE barely there in p-p

Fragmentation functions for charged hadrons



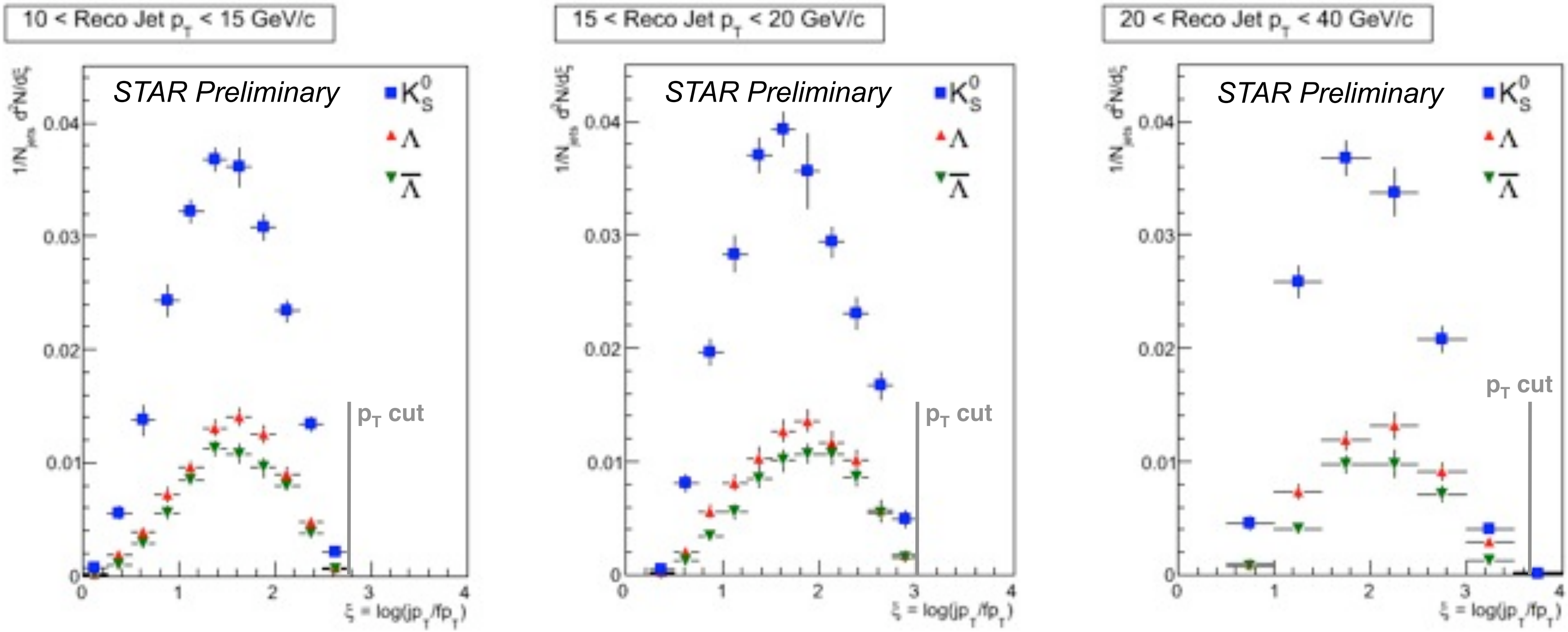
- Z_{max} ~ 0.81
- Electrons are rejected
- FF scaled by successive factors of 10

Reasonable agreement between data and PYTHIA

- Similar good agreement has been shown by STAR using R=0.4 and 0.7

NLO corrections small or accounted for in PYTHIA

Strange hadron FF



A. Timmins SQM2009

- Data presented at detector level
- Errors estimated from averaging results from k_T, anti-k_T and SISCone
- V0 $p_T > 1$ GeV/c - artificial cut in distribution

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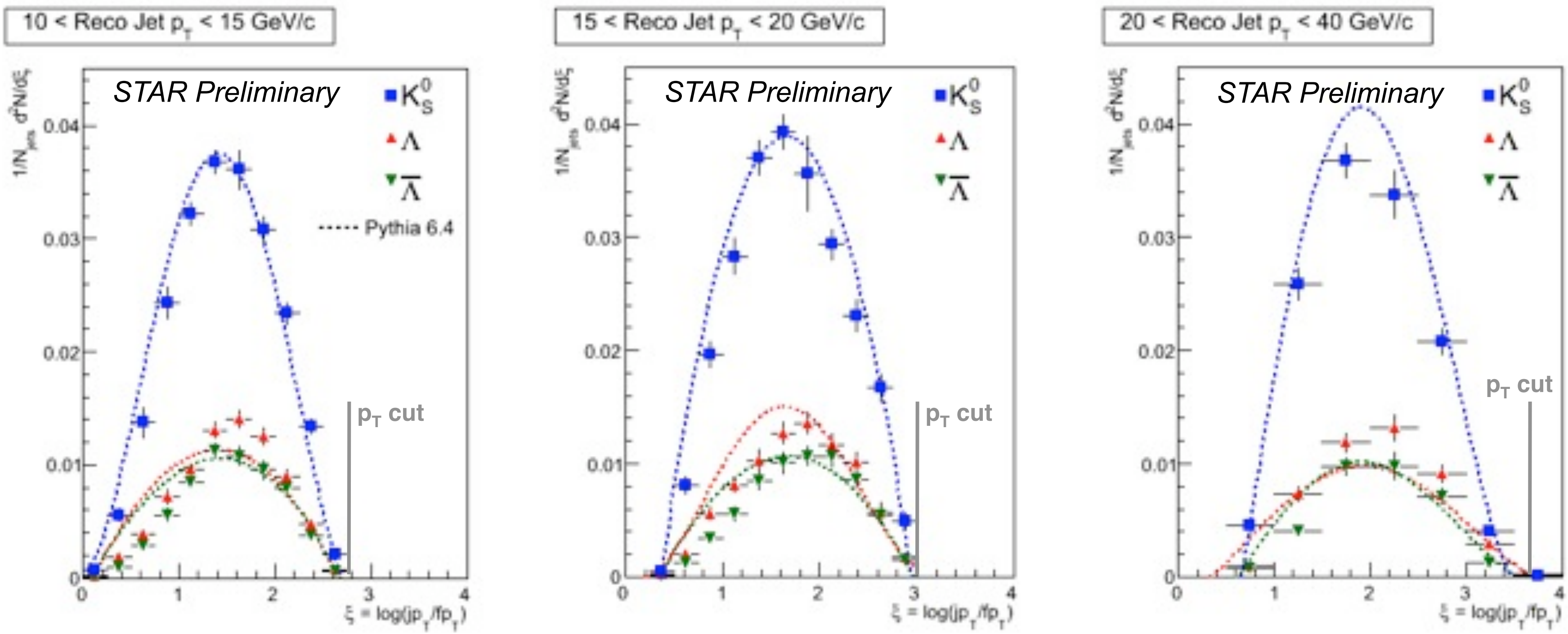

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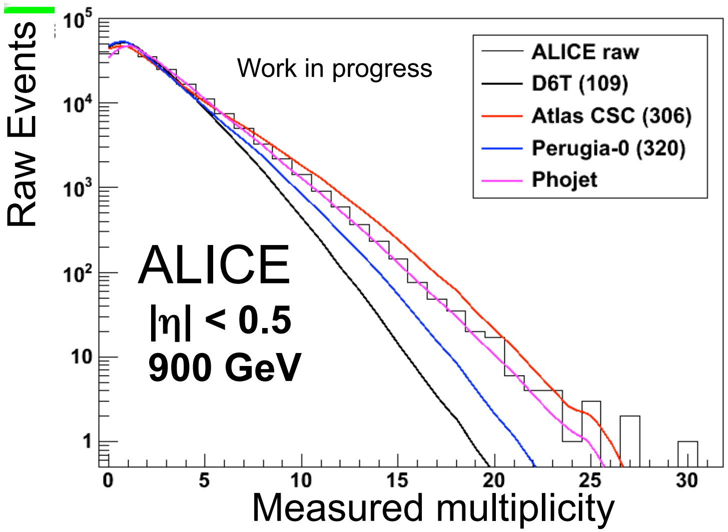
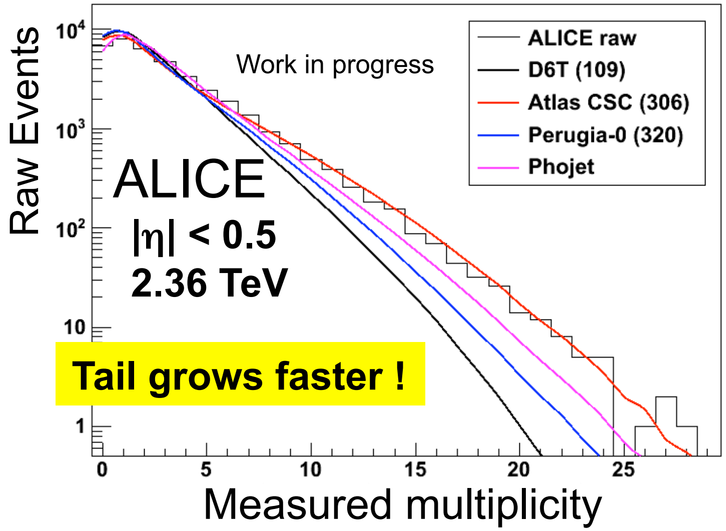
- V0 p_T > 1 GeV/c - artificial cut in distribution
- PYTHIA = PYTHIA+GEANT

Description of K^0_s seems better than for Λ
- also true for min-bias p_T distributions

p-p production still not very well understood

J.Schukraft (John H. 60th symposium)





Increase .9 to 2.3 TeV (%)	NSD
ALICE preliminary*	24.0 ± 0.5 ± ? %
CMS	28.4 ± 1.4 ± 2.6 %
Pythia D6T (109)	18.7 %
Pythia ATLAS CSC (306)	18.3 %
Pythia Perugia-0 (320)	18.5 %
Phojet	14.5 %
QGSM	19 %

- The measured multiplicity grows much faster than models predict
- "Tracklet" analysis
- PYTHIA - Perugia-0 matches RHIC data
  ATLAS CSC - too little UE
  D6T -

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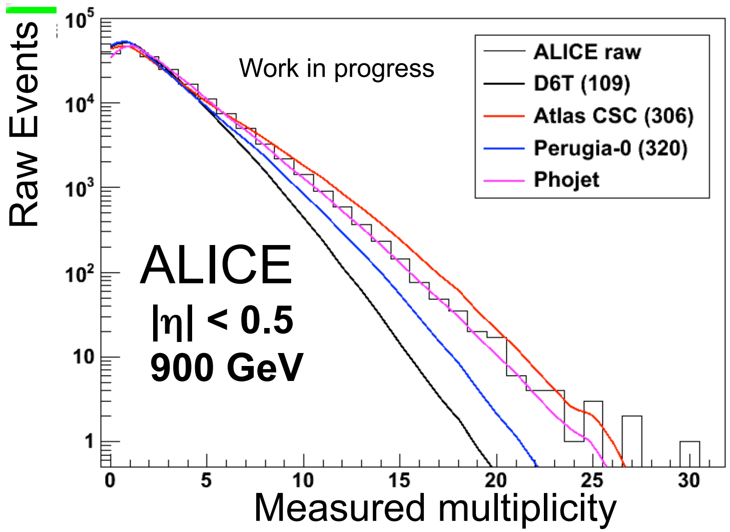

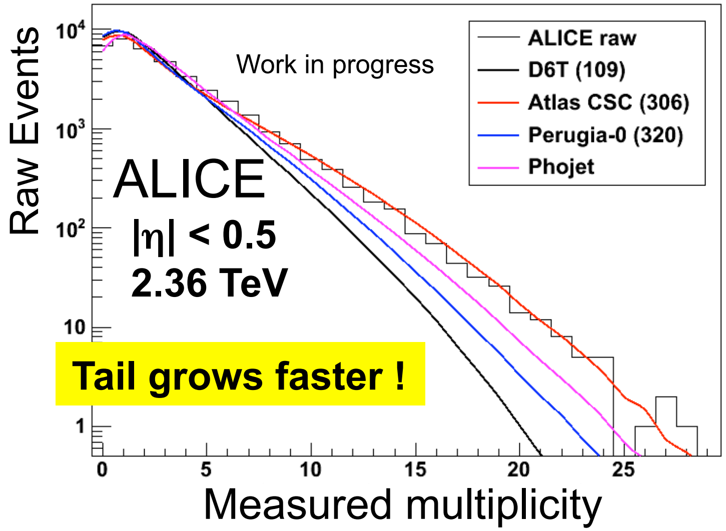

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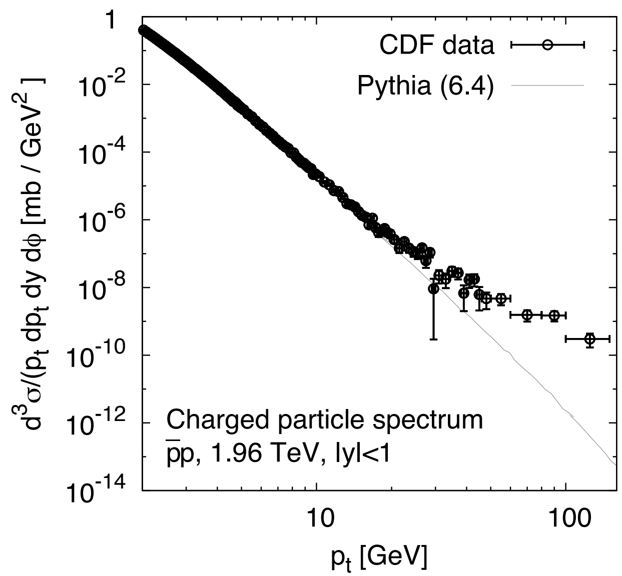
Increased jet or UE production?

Need to be alert to inconsistencies

CDF Phys. Rev. D 9 (2009)



- At ~80 GeV/c data 3 orders magnitude above PYTHIA

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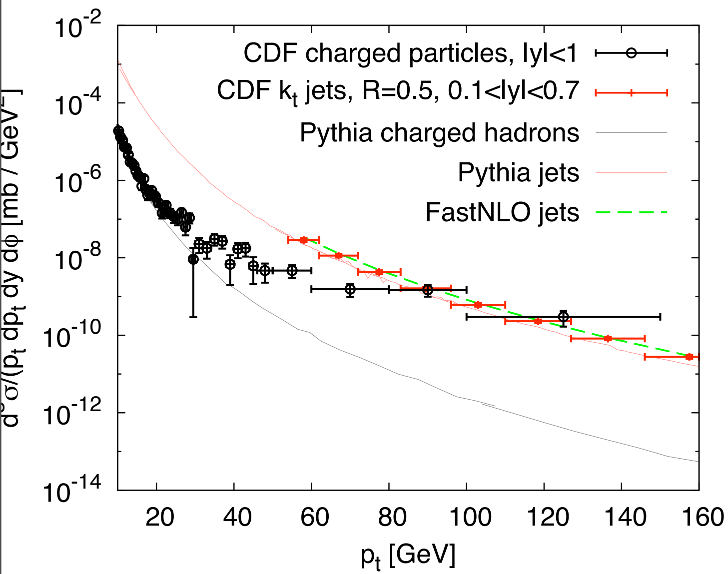
CDF Phys. Rev. D 9 (2009) , Cacciari et al. arXiv:1003.3433



- At ~80 GeV/c data 3 orders magnitude above PYTHIA
- Jet cross-section well described

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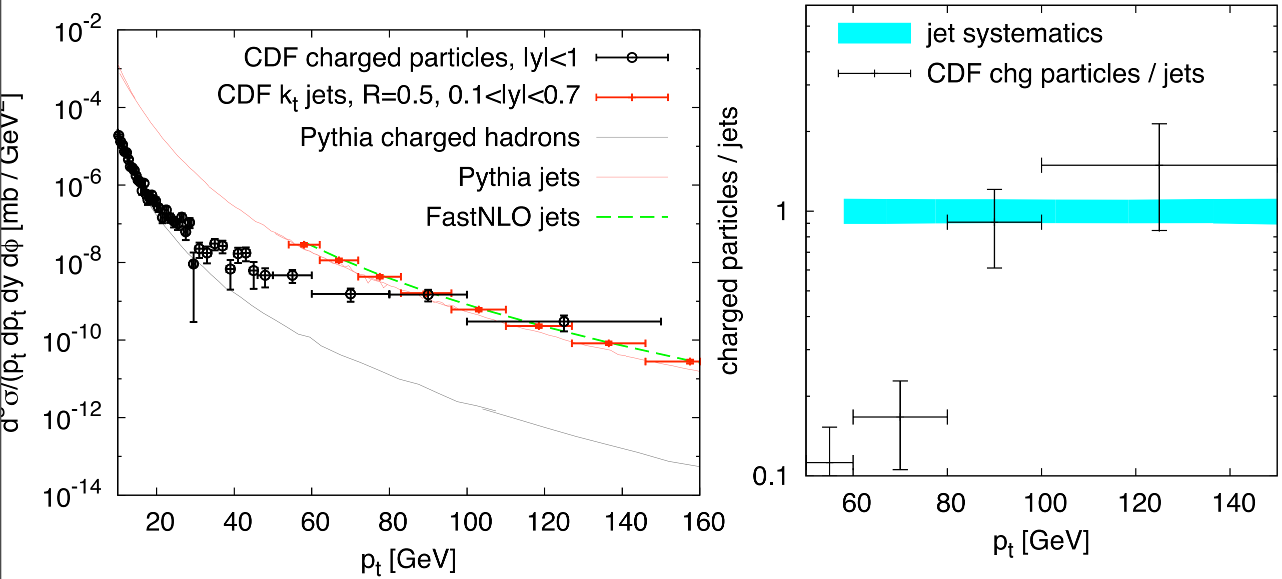

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- Partons appear to violate factorization of fragmentation
  collinear splitting turns off, single particles produced!

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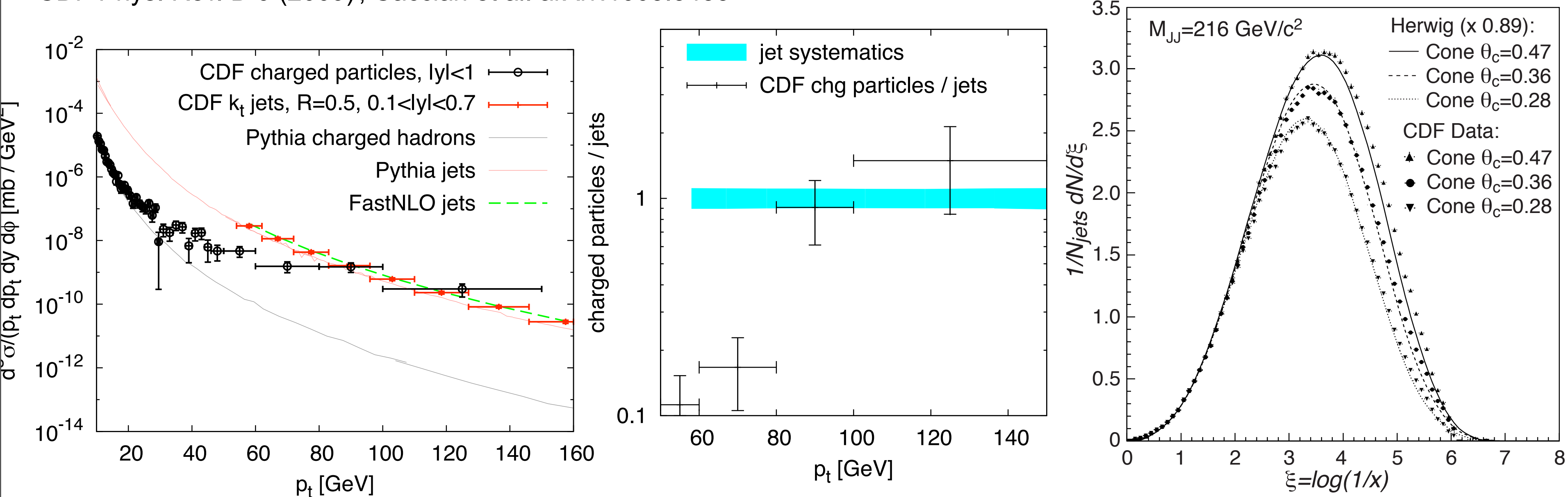

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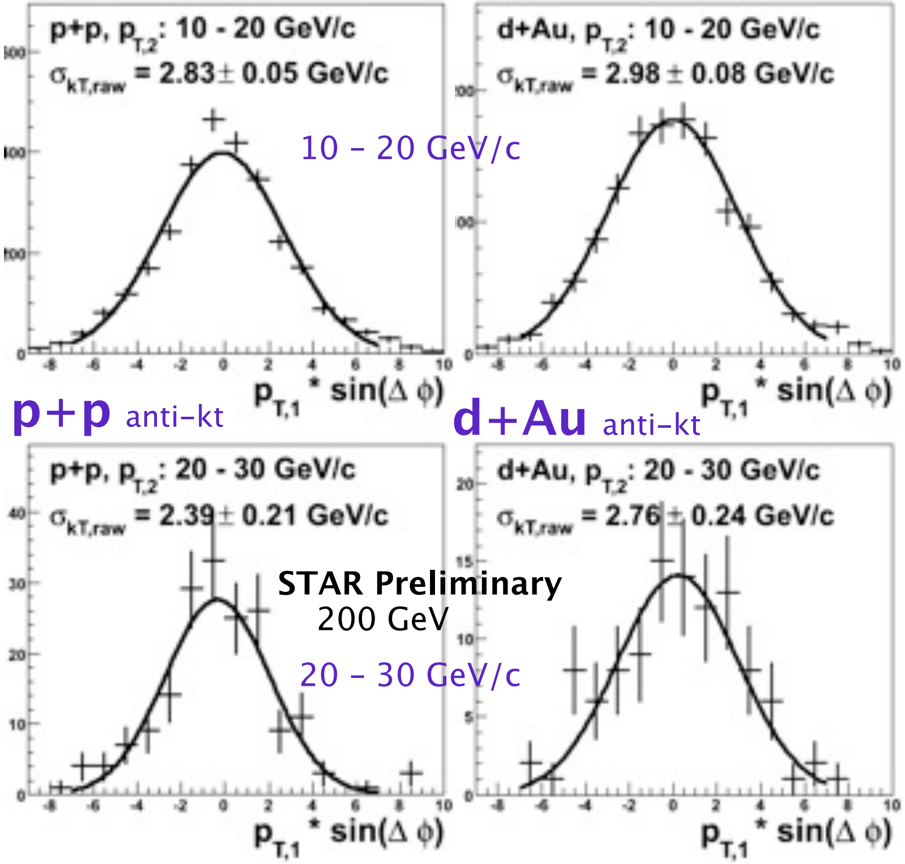
- Jet cross-section well described   Cross-sections are equal!
- Partons appear to violate factorization of fragmentation
  collinear splitting turns off, single particles produced!
- Seems in contradiction to di-jet FF measurement

Either Nobel Prize winning or wrong! to be checked by LHC

CNM are small at RHIC

d-Au - Additional smearing due to parton interaction with CNM

$k_{T,d\text{-}au} > k_{T,p\text{-}p}$



J. Kapitán, EPS HEP 2009

$k_T = p_T(\text{Jet}) \sin(\Delta\Phi)$

$\sigma_{kT,raw}$ (p+p) = 2.8 ± 0.1 GeV/c

$\sigma_{kT,raw}$ (d+Au) = 3.0 ± 0.1 GeV/c

$k_{T,\text{di-hadron}}$(p-p) = 2.68 +/- 0.07(stat) +/- 0.34(sys) GeV/c

(PHENIX S.S. Adler et al. Phys. Rev. D 74, 072002 (2006))

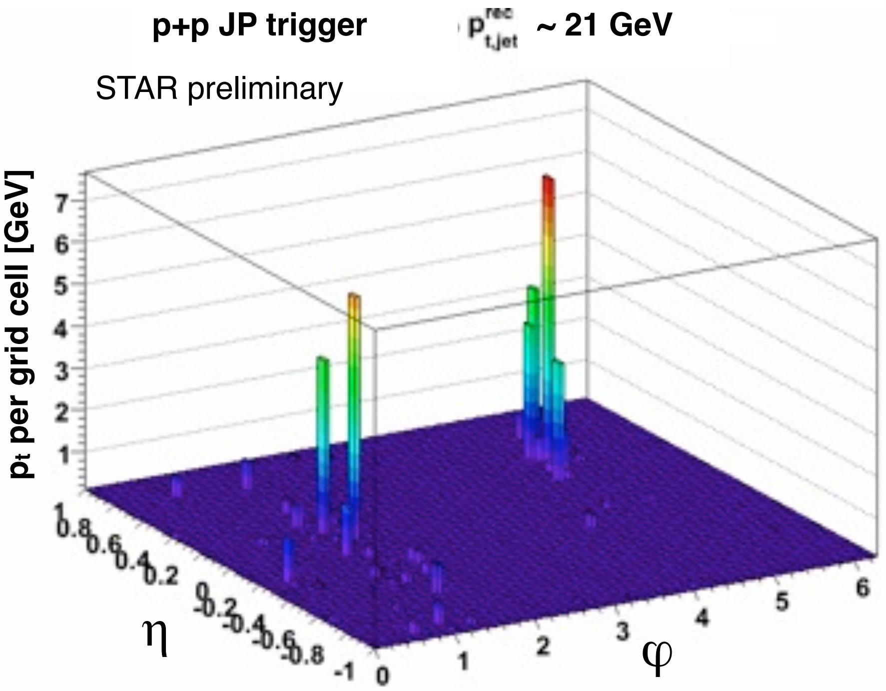
systematic uncertainties under study:

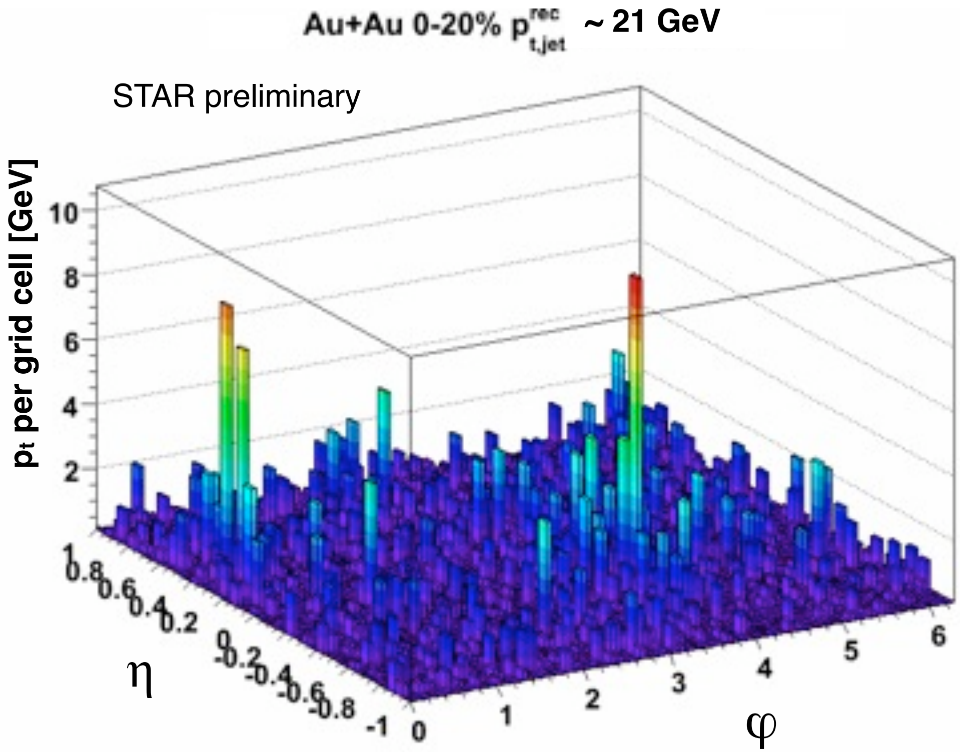
- neglected detector effects p_T-dependence
- BEMC calibration and TPC tracking at high luminosity

largely correlated between p-p and d-Au

There are some CNM effects - Cronin enhancement seen in d-Au spectra

A-A - now things get really complicated





- One can at least see some jets if you plot summed p_T

Now have to deal with the background

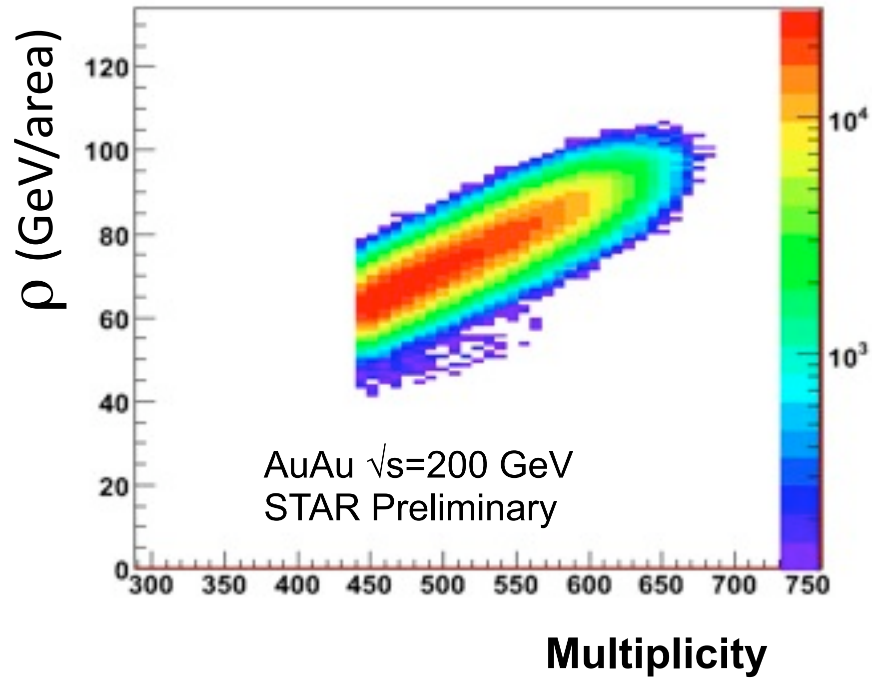
Au-Au - the underlying event

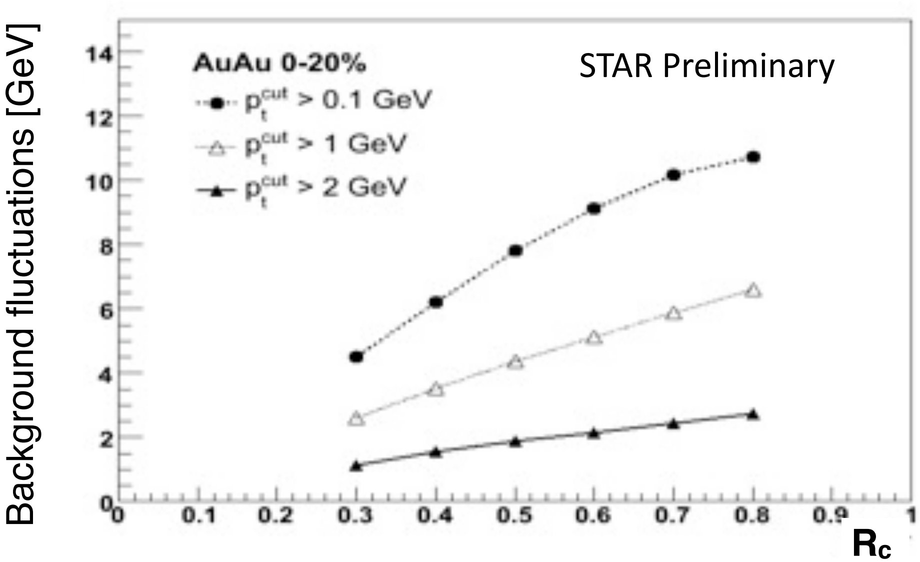
p_T (Jet Measured) ~ p_T (Jet) + ρ A $\pm$ σ(A)

Background E (from Fastjet algo.)

ρ A ~ 45 GeV, R_C=0.4

Substantial region-to-region fluctuations σ(A)
Gaussian approx:~ 6-7 GeV (R_C=0.4)





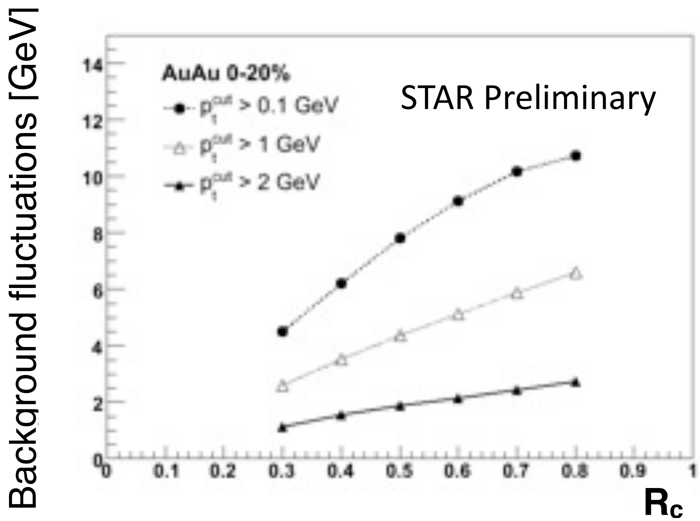
- Average background energy can be corrected on an event-by-event basis
- Fluctuations only corrected for statistically via unfolding

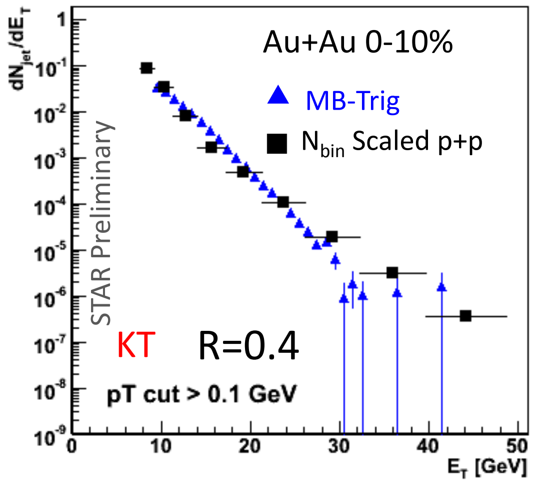
What about fake jets?

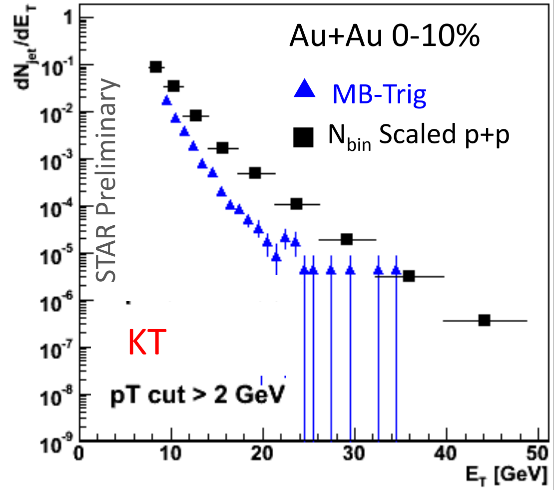
There are no short cuts

Anti-quenching biases are hiding everywhere!

- triggering on high p_T particles ⇒ bias towards non-interacting jets







S.Salur HP2008

- p_T cut reduces background ⇒ bias towards non-interacting jets
- Assumptions about jet shape in finding ⇒ bias towards non-interacting jets

Lesson learned: There are NO short cuts
Essentially every cut applied introduces measurement bias

Have to fully understand background to make progress

Closer look at the fluctuations

Schematically Au-Au jet spectrum: $$\frac{d\sigma_{AA}}{dp_T} = \frac{d\sigma_{pp}}{dp_T} \otimes F(A, p_T)$$

$F(A,p_T)$ - investigation in data via jets with p_T-$\rho A < 0$ - assume symmetric distribution (i.e. Gaussian a la FastJet)

$$F(A, p_T) = Poisson(M(A)) \otimes \Gamma(M(A), \langle p_T \rangle$$

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If background is independently distributed particles:

number fluct ~ Poisson distribution

$\langle p_T \rangle$ fluct for fixed M~ Gamma function

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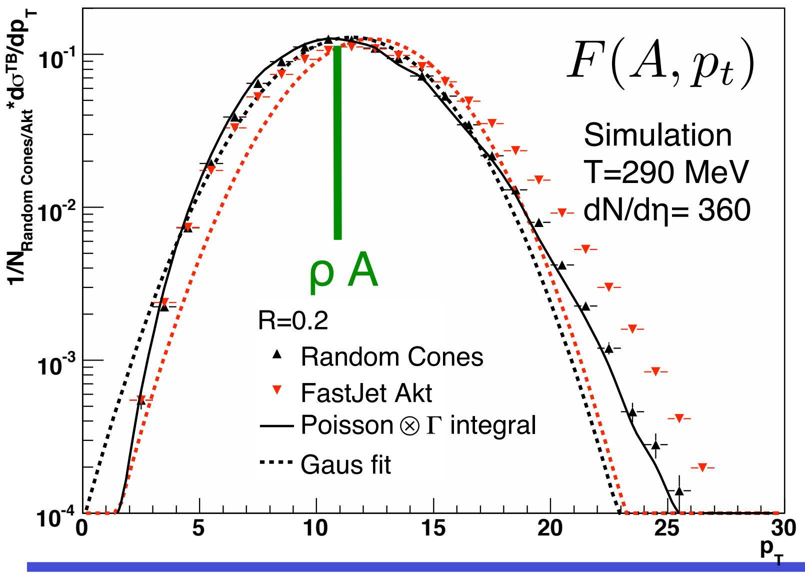
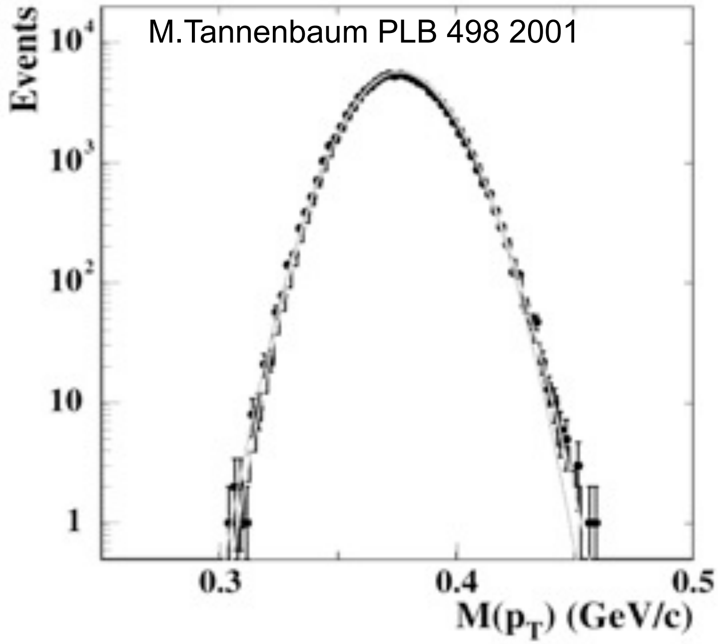
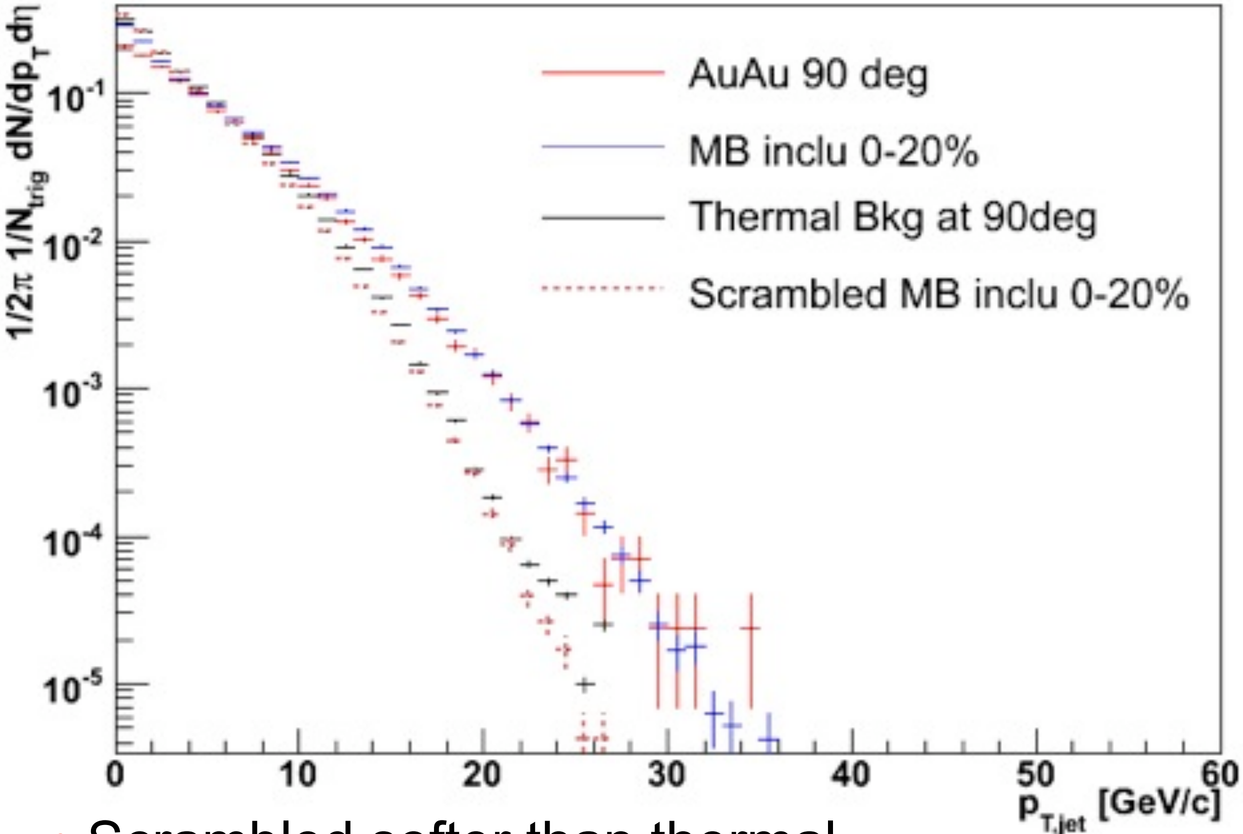




$F(A,p_T)$ - No longer symmetric AND clustering algorithm affects results - not random

Non-trivial issue, further studies actively being pursued, but we have all the tools!

Thermal simulation compared to scrambling event



- Thermal spectrum is an approximation
  - different fit ranges give different T
- Need a 2nd approach to compare to
- Try scrambling real events - break all physical correlations

- Scrambled softer than thermal
  - naively expect harder as jet particles still there
  - need to implement tracking efficiency in thermal toy
- Per trigger jet normalized 90^0 spectrum ~ Per event Min-bias spectrum

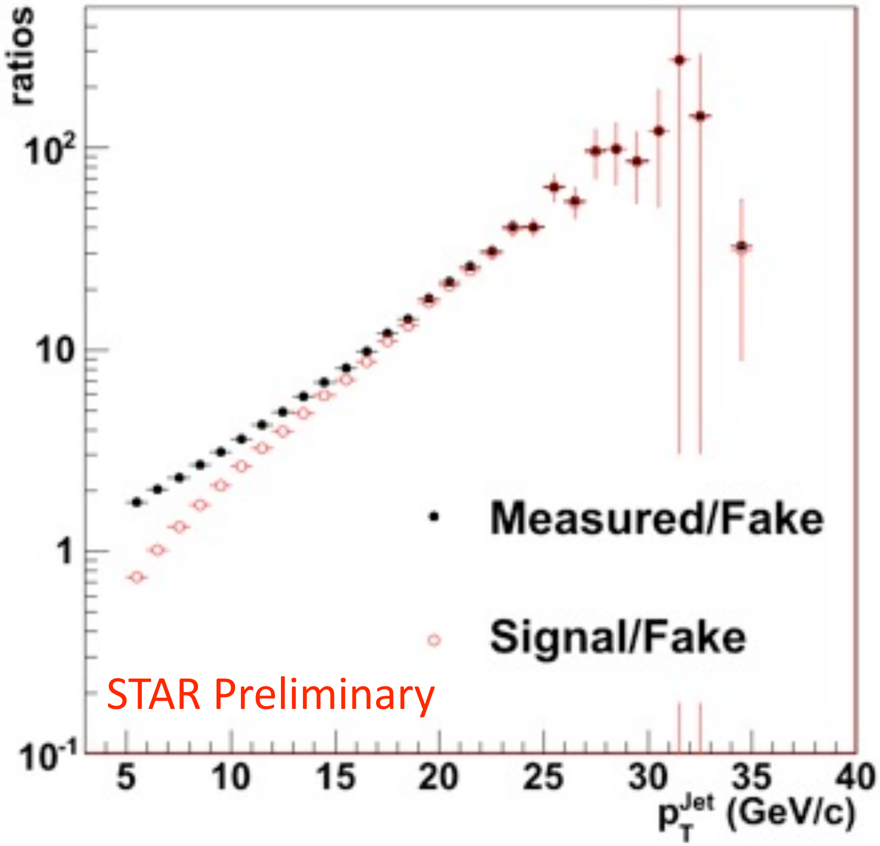
Significant rate for two (or more) hard scatterings in Au-Au event

Fake jet rate in a Au-Au event

Definition: “Fake” jet - signal in excess of background model from random association of uncorrelated soft particles (i.e. not due to hard scattering)

Estimating the “Fake” jet rate:

- Use the real data - Au+Au dataset
- Run jet finder
- (Remove leading particle from each found jet if p_T>X GeV/c)
- Randomize azimuth of each charged particle and calorimeter tower
- Re-run jet finder



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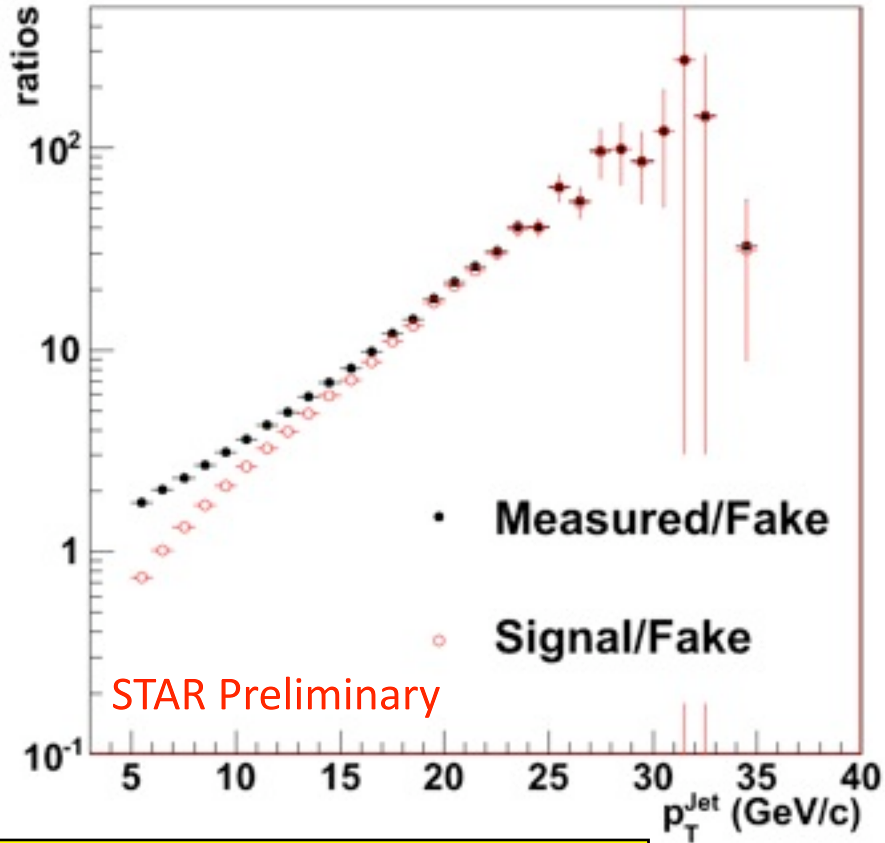
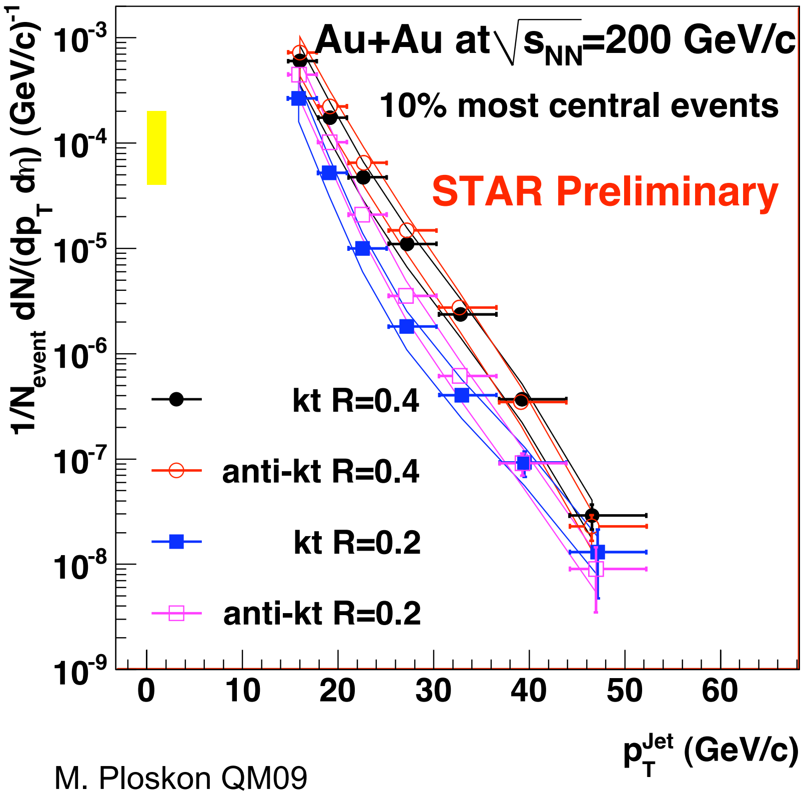


Note: PHENIX have direct rejection of fakes via algorithm

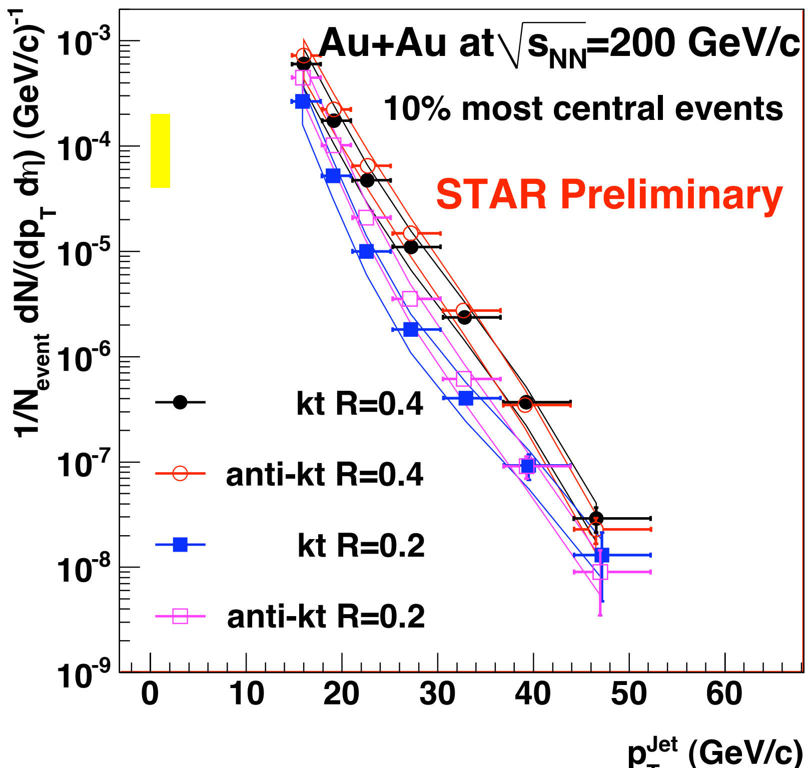
A-A Jet spectrum



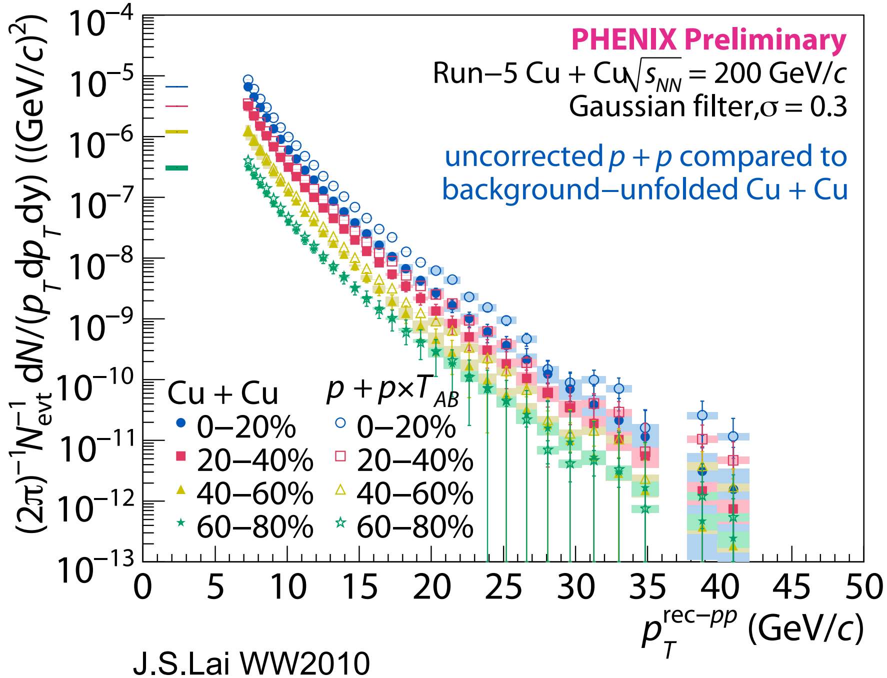
M. Ploskon QM09

First measurement of jet cross-section in heavy-ion experiments

A-A Jet spectrum



M. Ploskon QM09



J.S.Lai WW2010

First measurement of jet cross-section in heavy-ion experiments

PHENIX also able to make very impressive measurements

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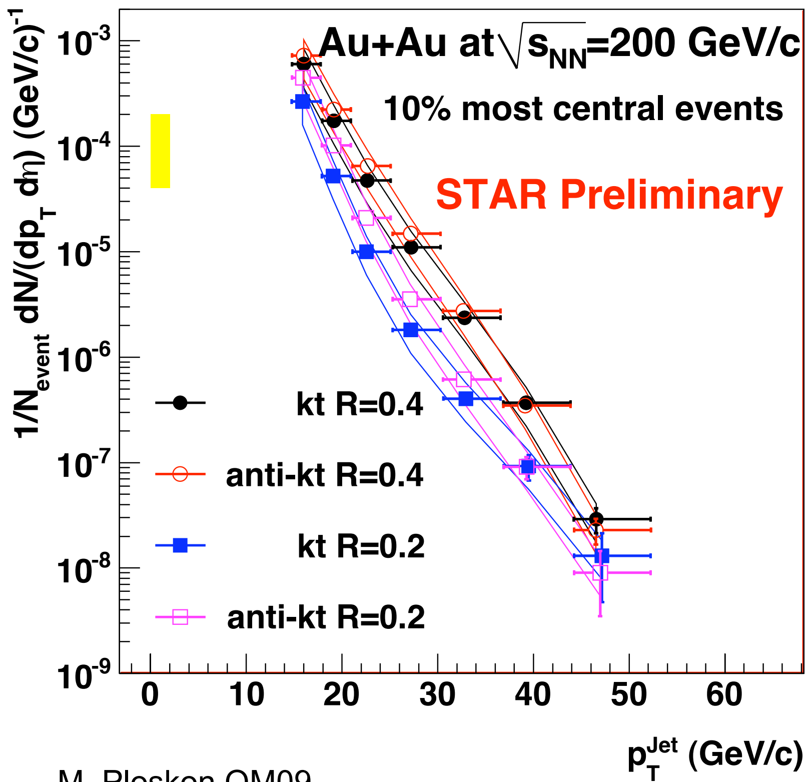

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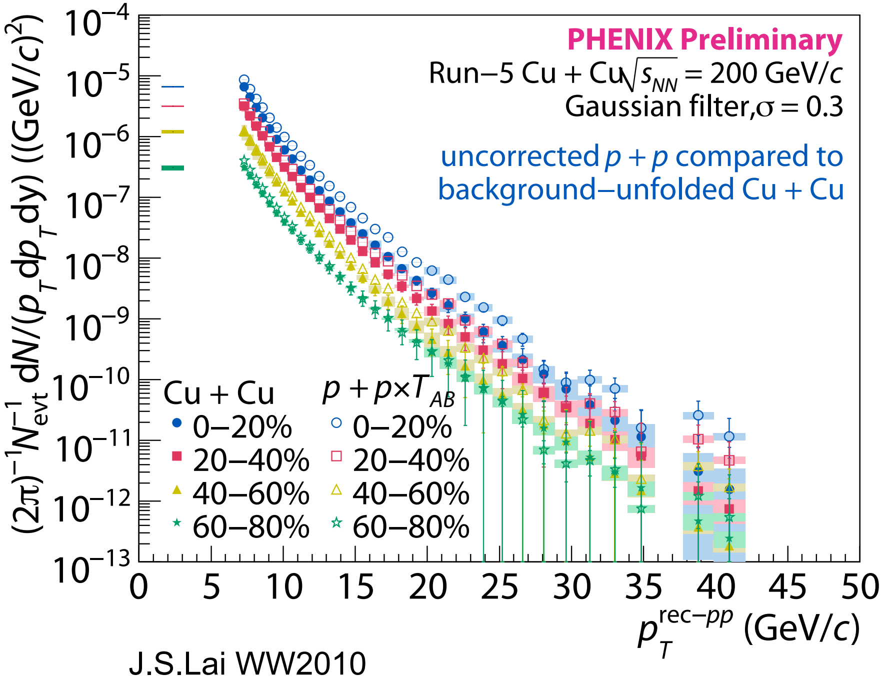

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First measurement of jet cross-section in heavy-ion experiments

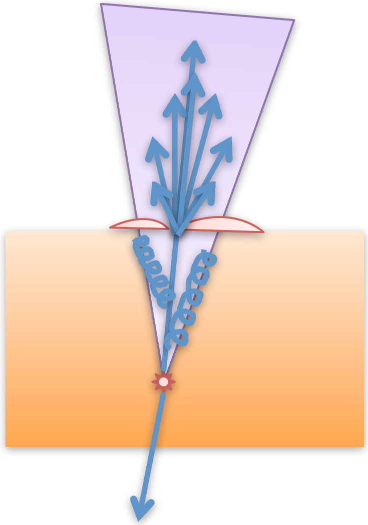
PHENIX also able to make very impressive measurements

Compare to p-p and/or look at fragmentation to learn something

R_{AA} expectations

If we have succeeded in fully capturing all jet energy

Jet R_{AA} = 1
Fragmentation function modified



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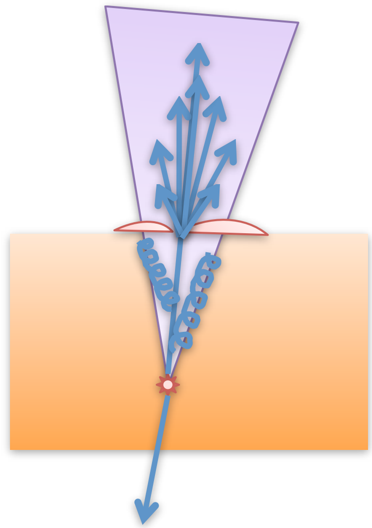

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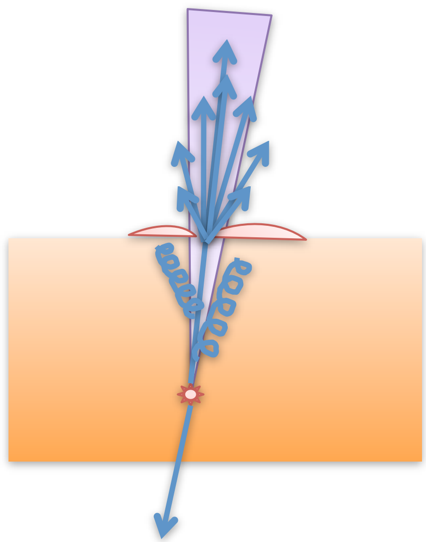
However, we run with fixed (and small) R and may miss some particles/energy flow



Jet R_{AA} < 1
Fragmentation function potentially unmodified

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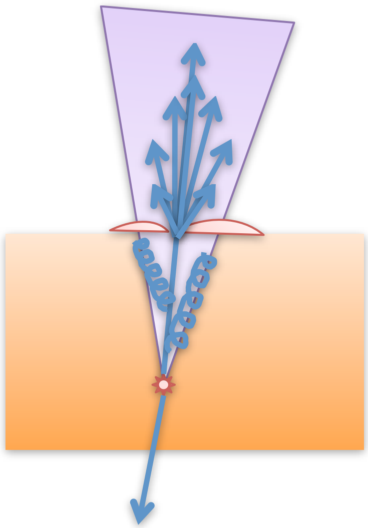

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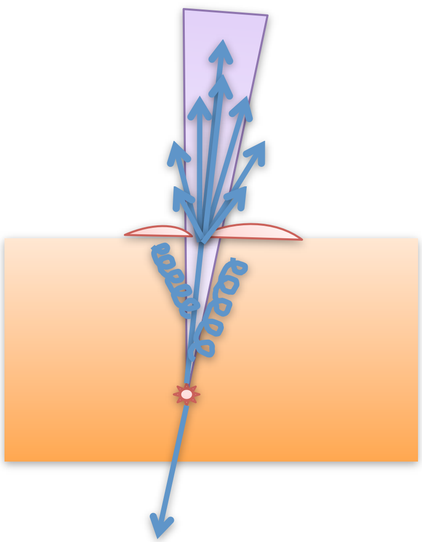
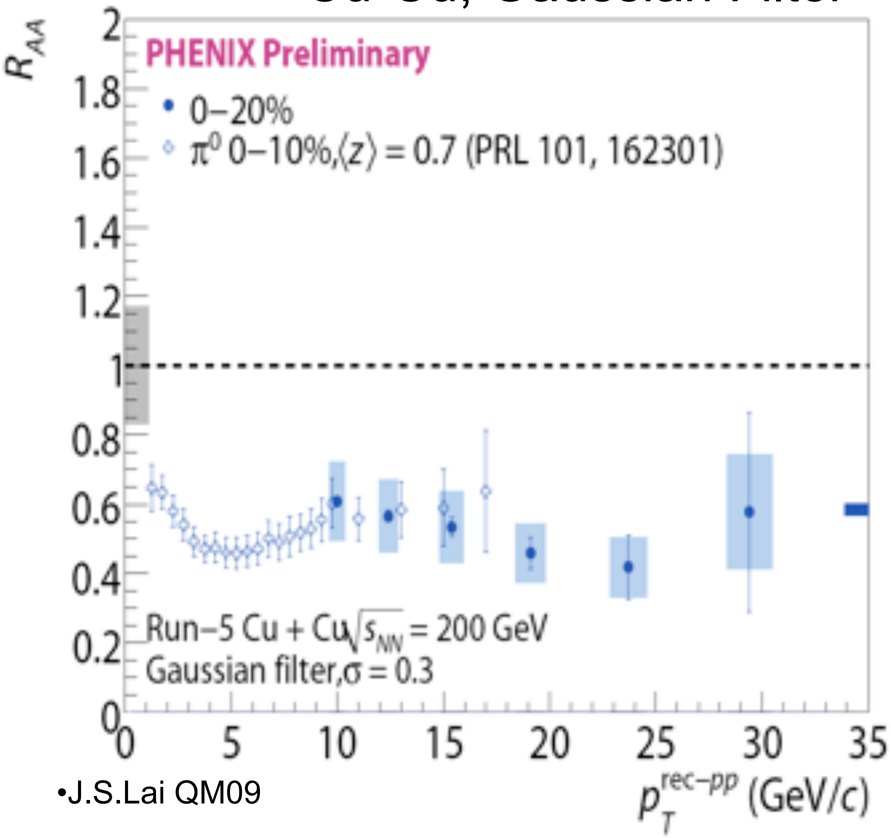


Essential to run and compare with different radii

Jet R_{AA}

Cu-Cu, Gaussian Filter

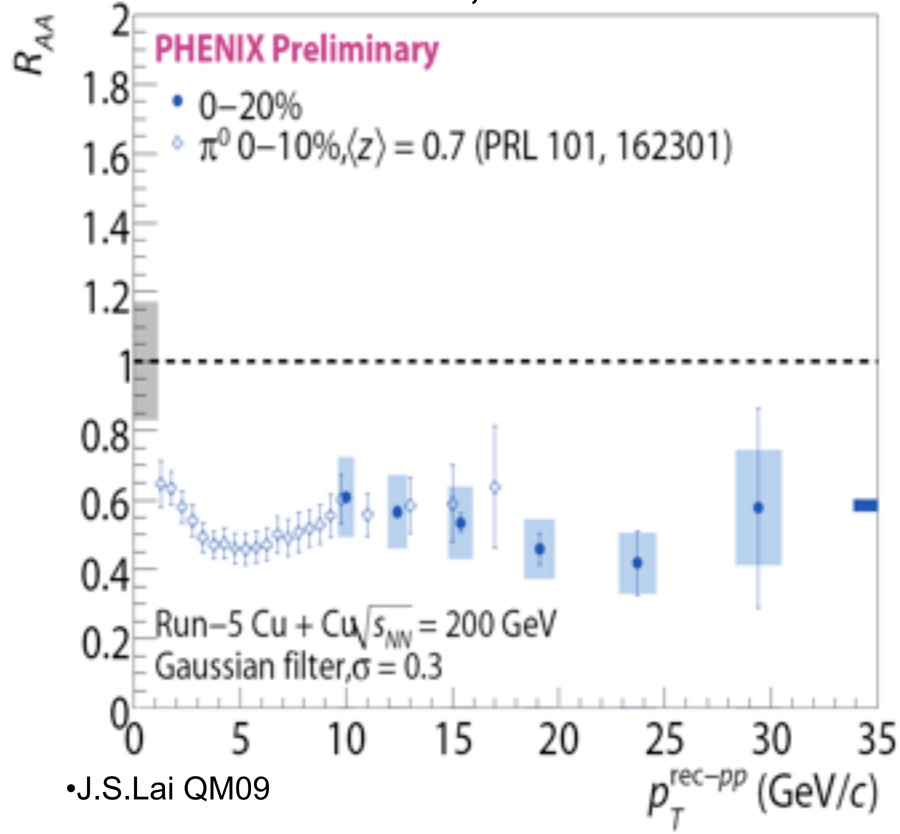


•J.S.Lai QM09

- Jet R_{AA} = single hadron R_{AA} - (Gauss filt)

Jet R_{AA}

Cu-Cu, Gaussian Filter



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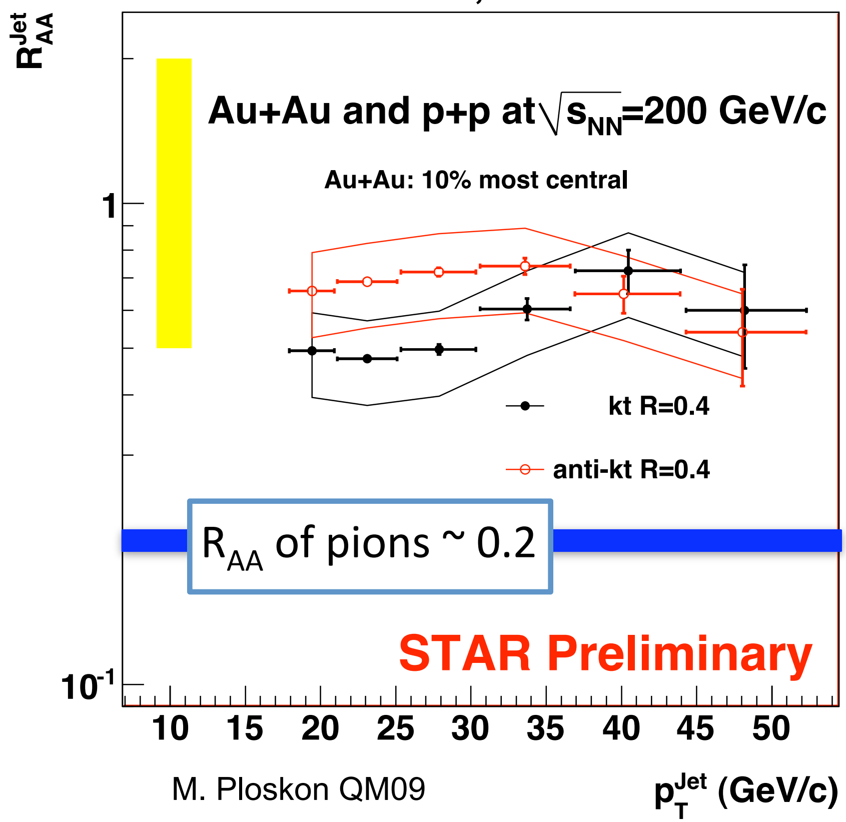
Au-Au, R=0.4



M. Ploskon QM09

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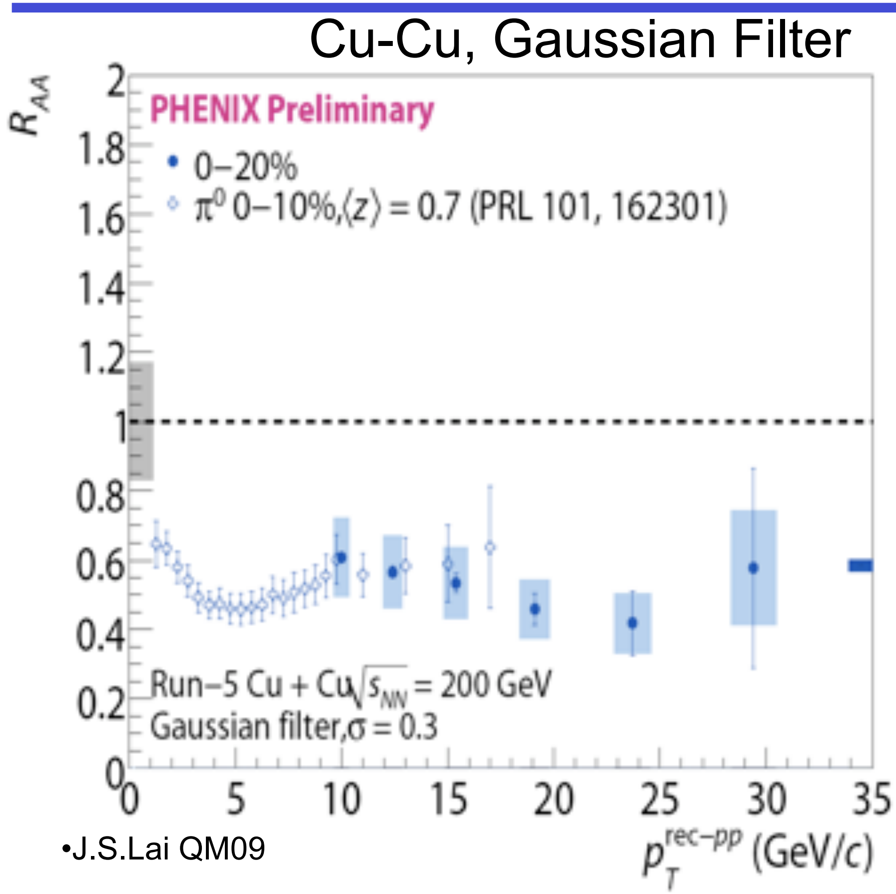
Algorithms fail to recover full jet cross-section

Jet R_{AA}



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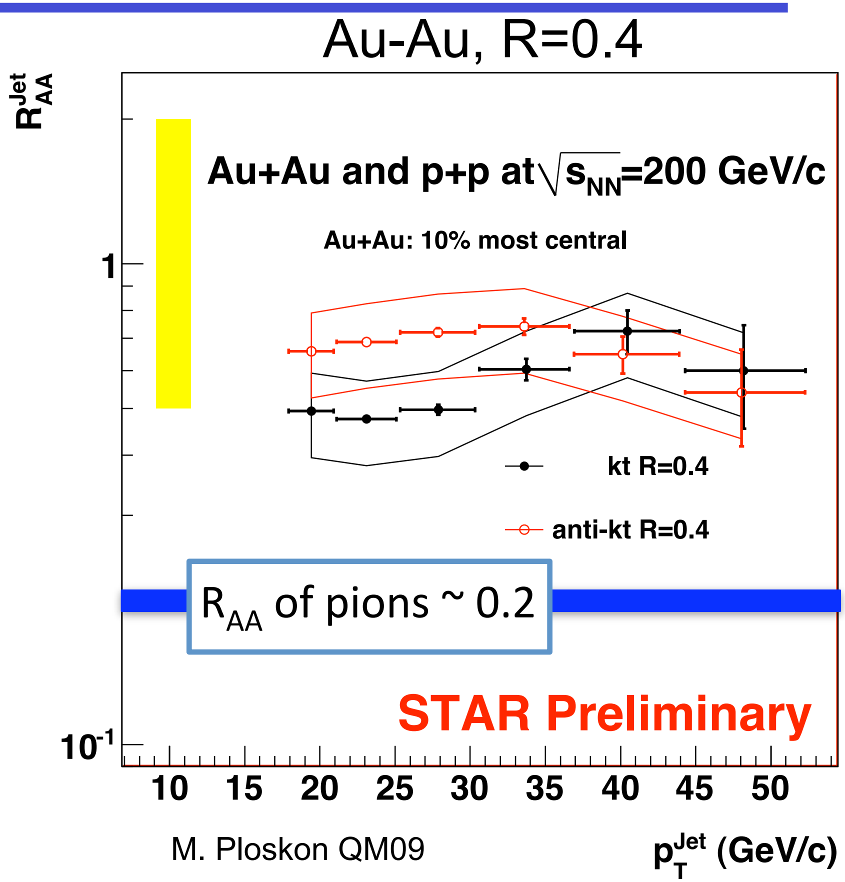

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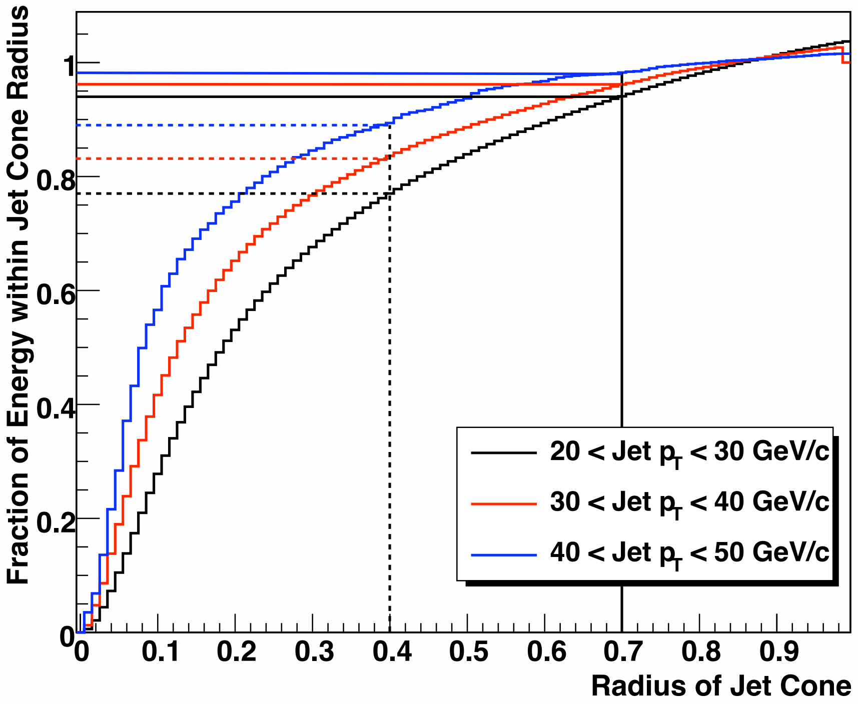
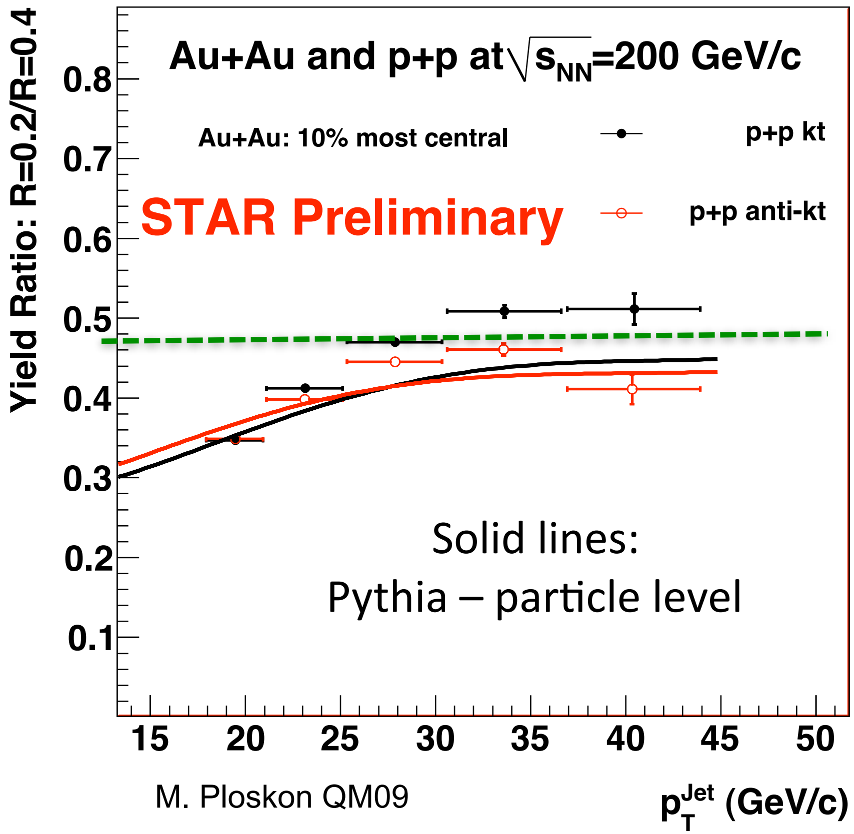
Broadening of distribution of jet fragments compared to p-p

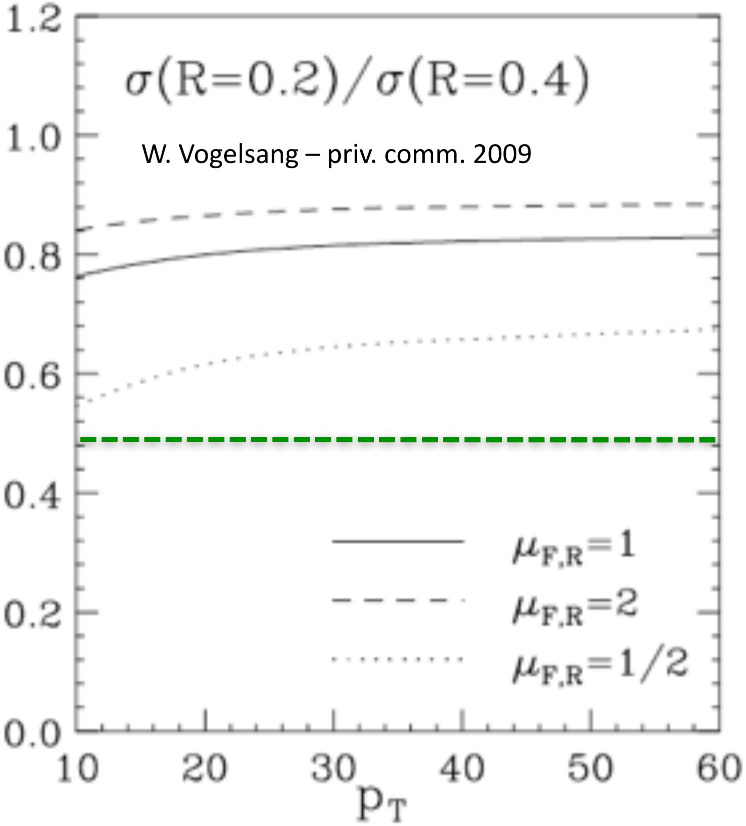
R=0.2 compared to R=0.4 - p-p

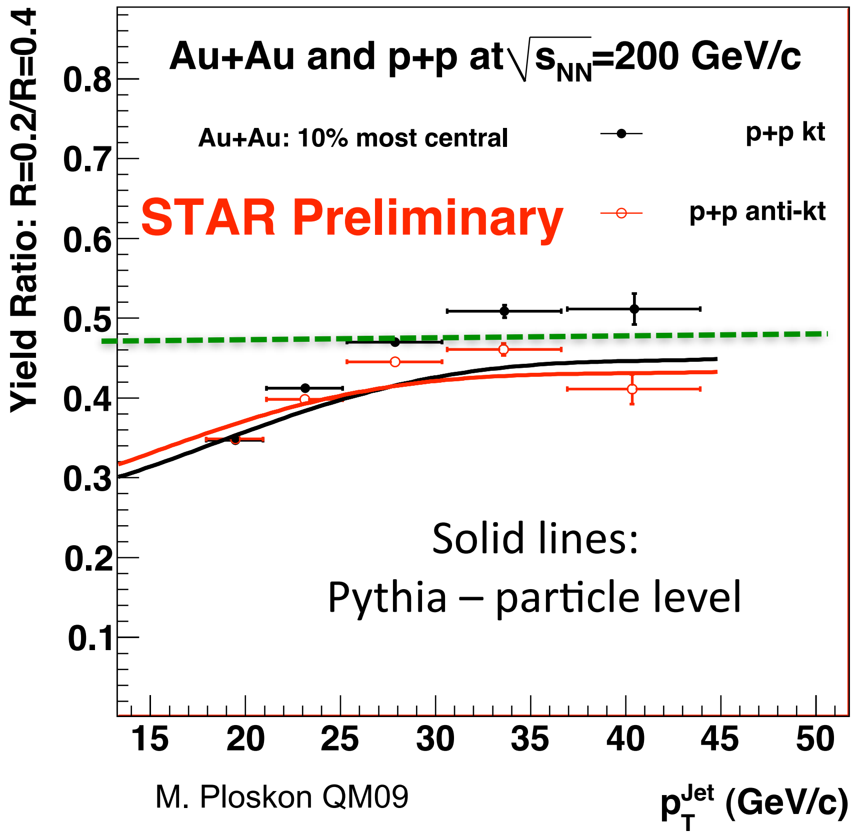




- Jets become focussed as p_T increases - R=0.2/R=0.4 increases with jet p_T
- PYTHIA (including fragmentation+hadronization) describes the data

R=0.2 compared to R=0.4 - p-p

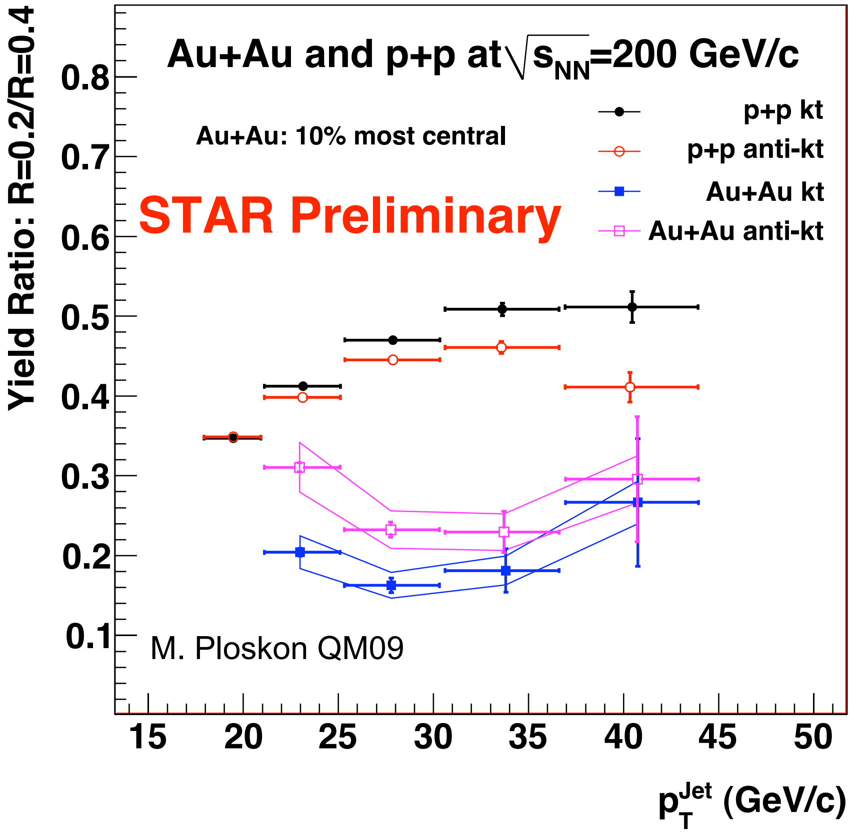




- Jets become focussed as p_T increases - R=0.2/R=0.4 increases with jet p_T
- PYTHIA (including fragmentation+hadronization) describes the data

NLO fails - Suggests fragmentation and/or hadronization broaden jet

R=0.2 compared to R=0.4 - Au-Au



- Au-Au ratio significantly lower than in p-p

R=0.2 compared to R=0.4 - Au-Au

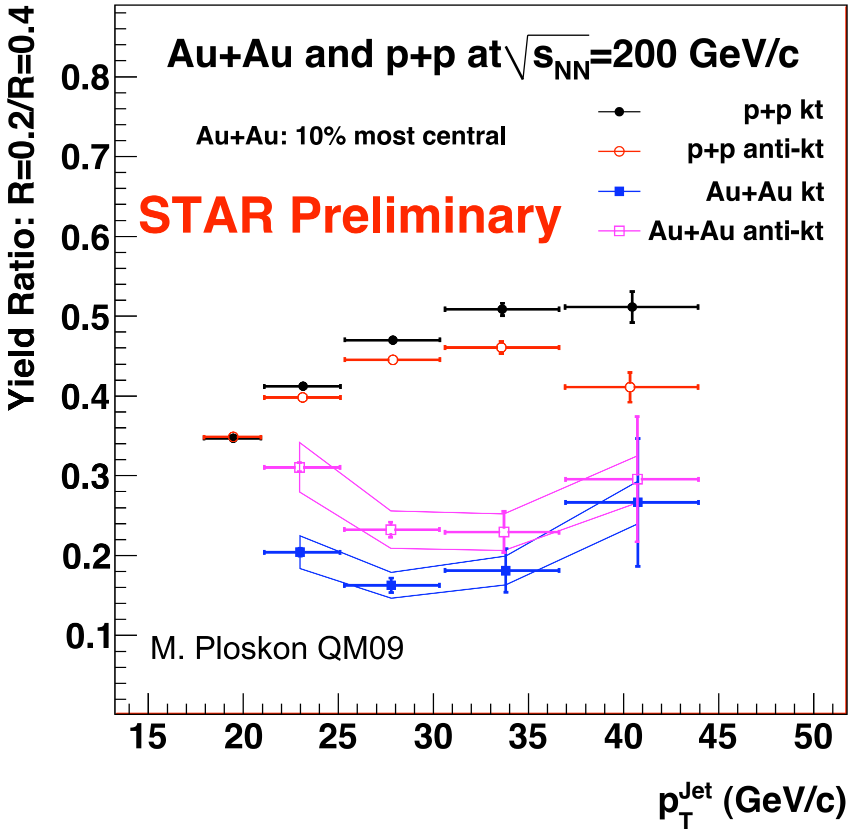
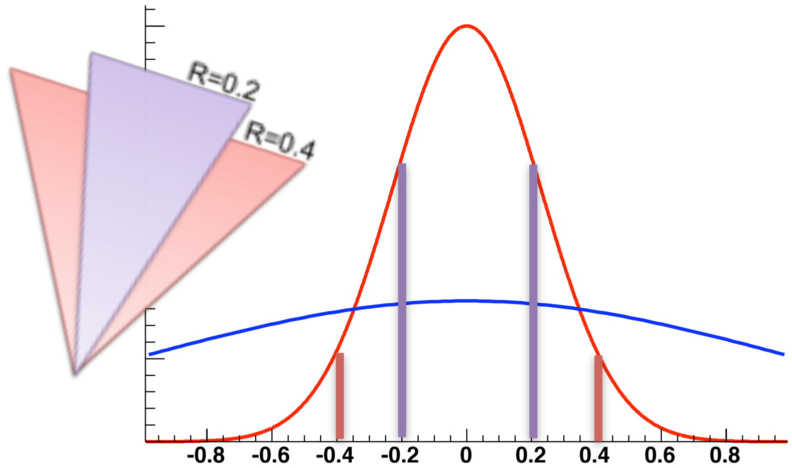


Illustration: Gaussian 1D profile

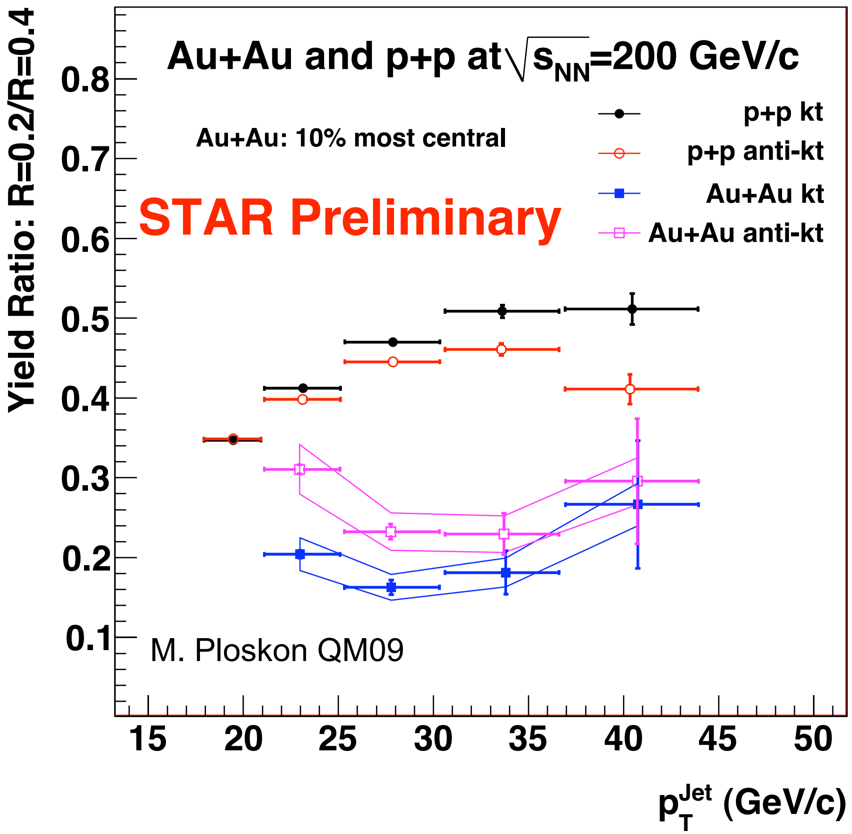


Red: p-p

Blue: Au-Au

- Au-Au ratio significantly lower than in p-p
- Broadening of jet reduces energy contained in fixed R compared to p-p

R=0.2 compared to R=0.4 - Au-Au



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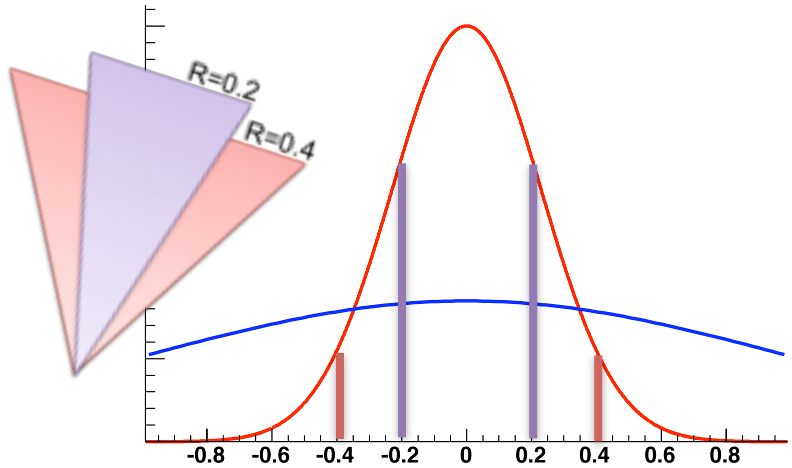

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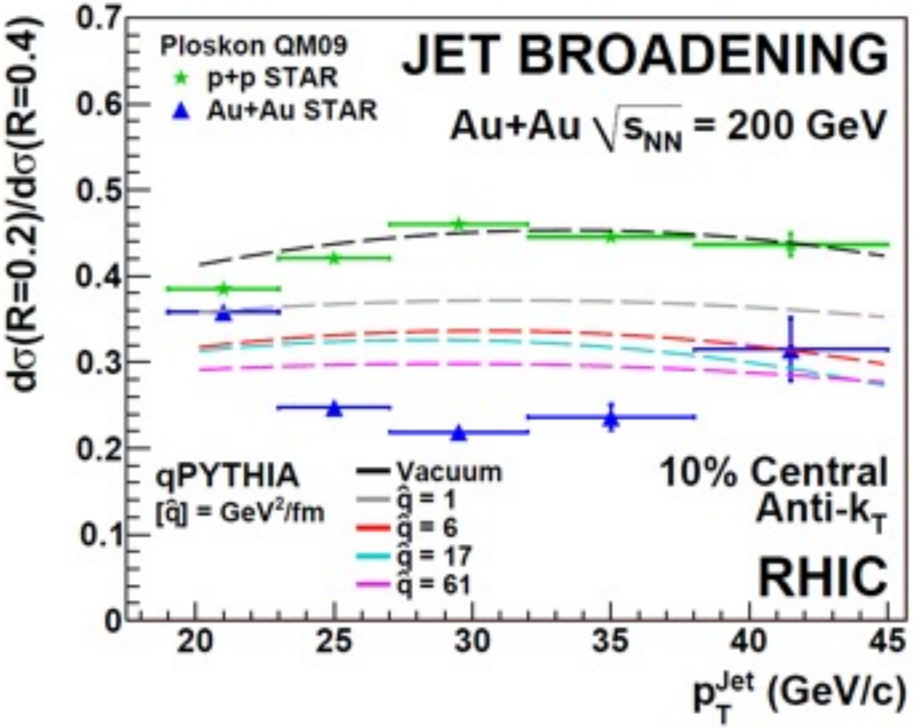
- Au-Au ratio significantly lower than in p-p
- Broadening of jet reduces energy contained in fixed R compared to p-p

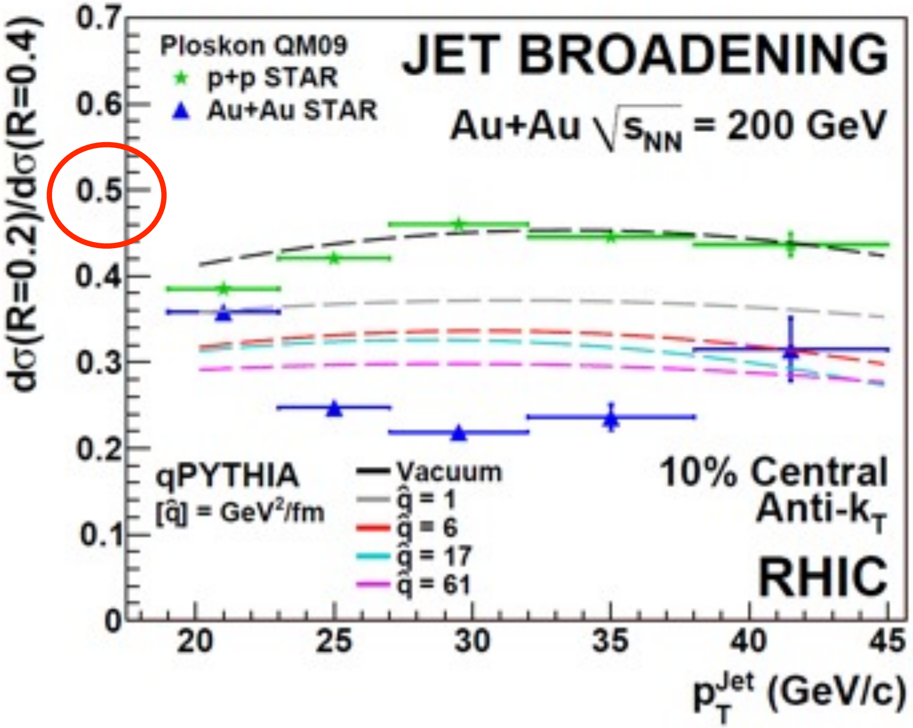
Significant broadening of Au-Au jets even within R=0.2→ 0.4
- related to away-side broadening in di-hadrons?

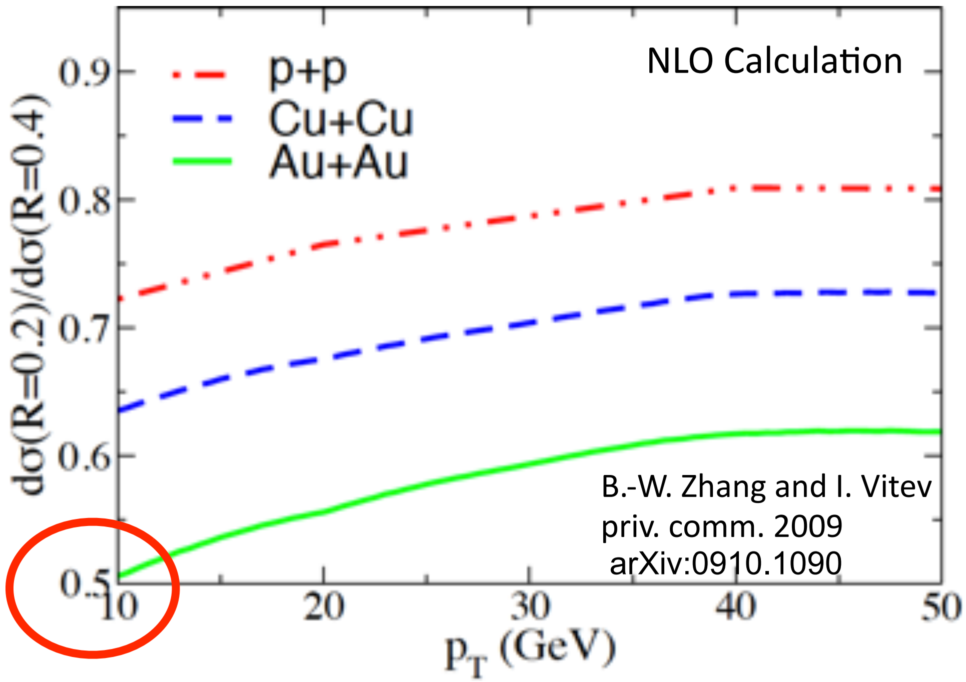
Comparison to theory



- NLO - less broadening than seen in data
  N.B. in p-p ratio = 0.6-0.8

Comparison to theory

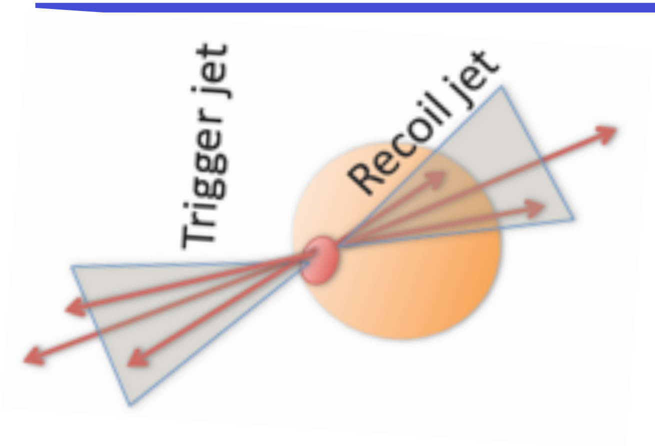




- qPYTHIA - less broadening than seen in data
- NLO - less broadening than seen in data
  N.B. in p-p ratio = 0.6-0.8

Is broadening mostly hadronization effect?

Di-jet suppression

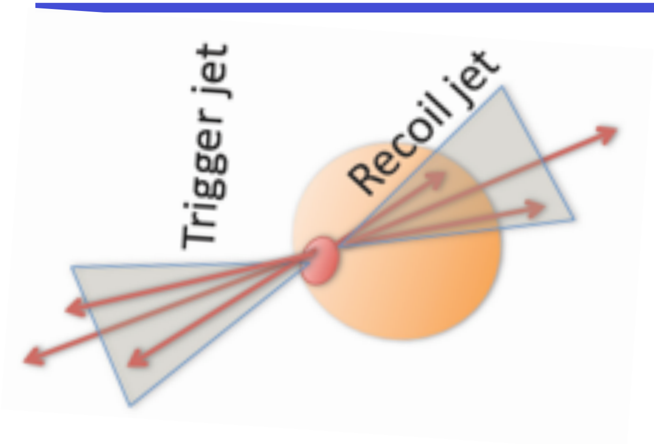


High tower trigger - single particle with high p_T

maximize medium traversed by recoil jet

Compare yield of di-jets in p-p to that Au-Au

Di-jet suppression



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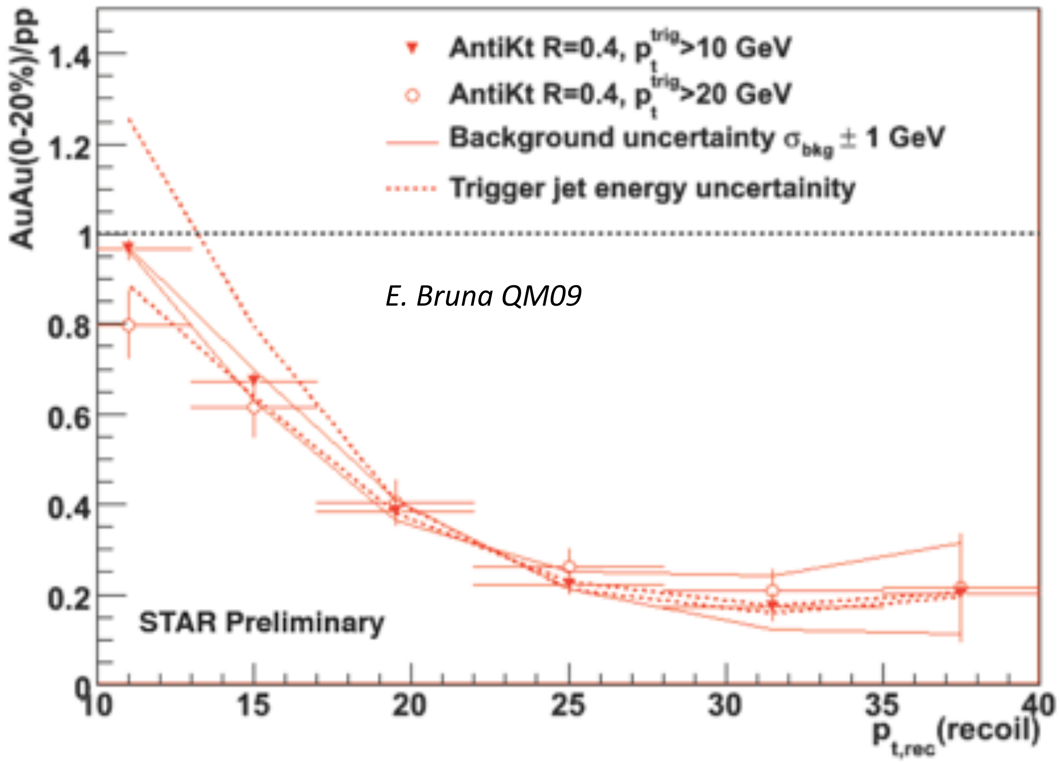
Again indicates broadening



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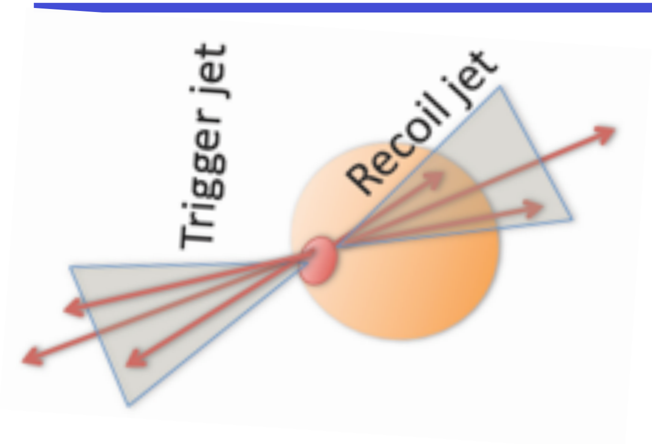

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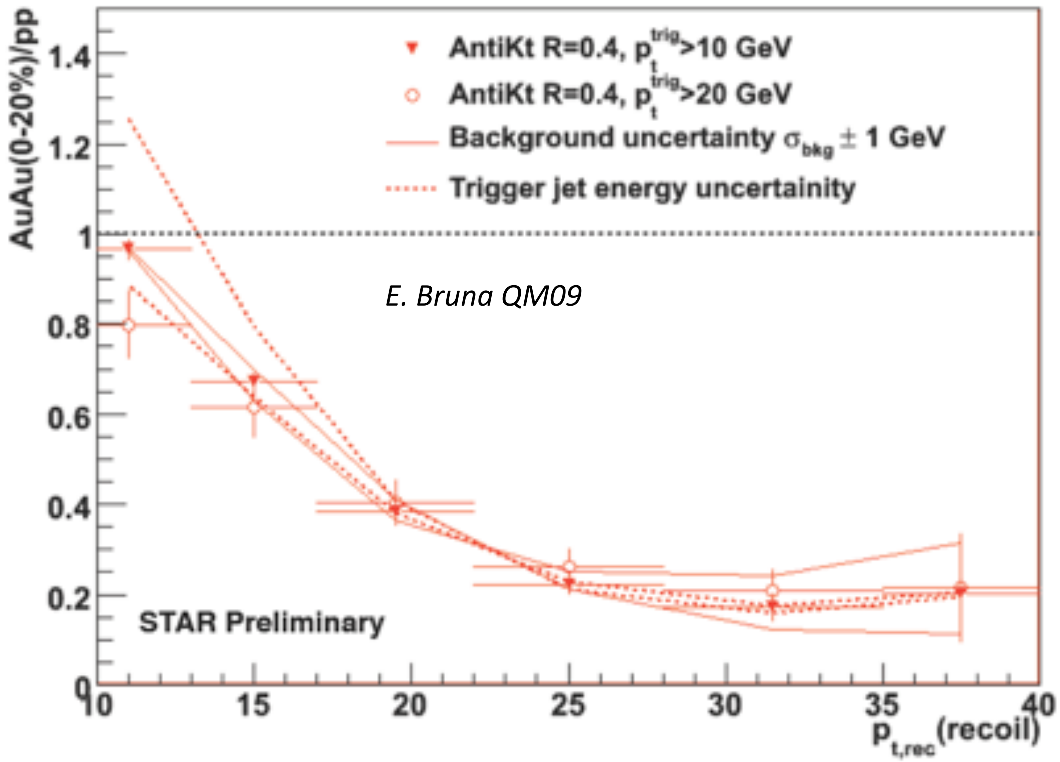
Again indicates broadening

Large path length results in larger suppression/ broadening



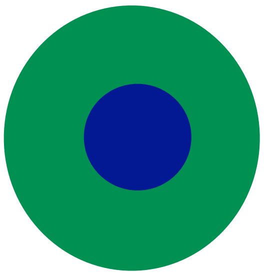
Looking at the broadening - FF

Au-Au:

FF(Jet)=FF(Jet+Bkg)-FF(bkg)

Bkg estimated from charged particle spectra out of jets, rescaling to the area with R=0.7

To make jet definition cleaner try finding jet with R=0.4



For FF consider charged particles within R=0.7

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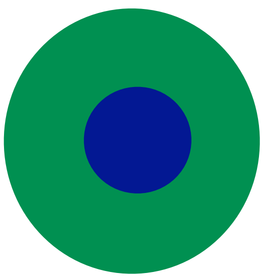
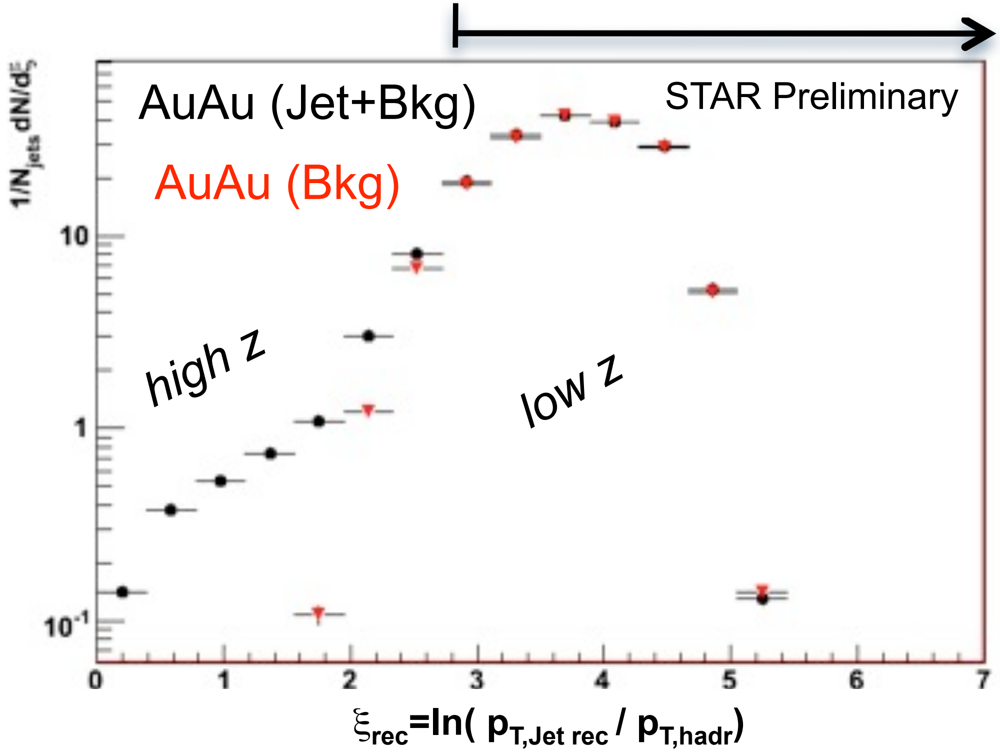


For FF consider charged particles within R=0.7

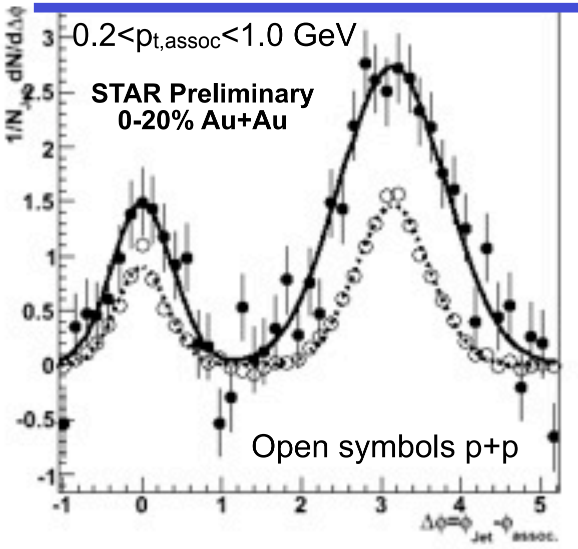
large uncertainties due to background
(further systematic evaluation needed)

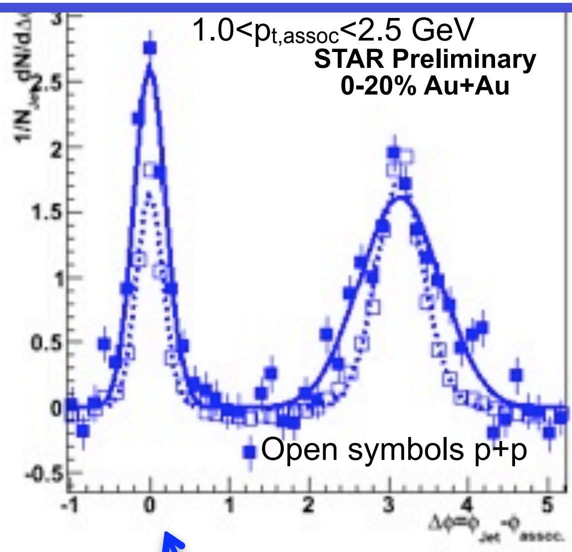


$p_{T\ Jet\ rec}$(trigger)>20 GeV & $p_{Tcut,particle}$=2 GeV

Background dominates at low p_T - where action is expected

Jet-hadron correlations



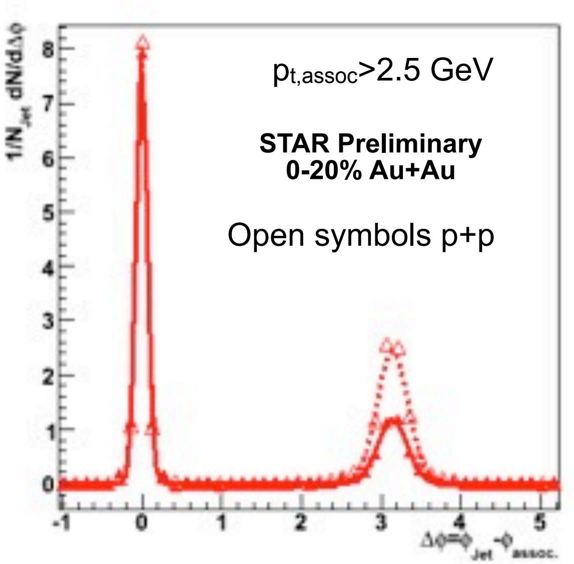


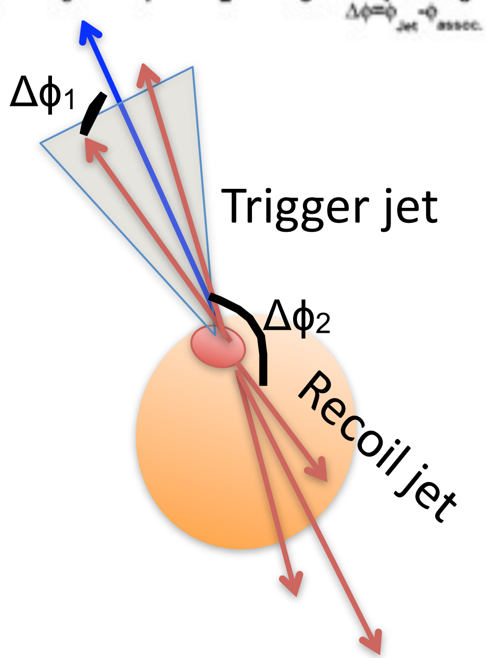
High Tower Trigger (HT):
tower 0.05x0.05 (ηxϕ)
with E_t> 5.4 GeV

$\Delta\phi=\phi_{Jet} - \phi_{Assoc.}$

ϕ_{Jet} = jet-axis found by Anti-k_T, R=0.4, $p_{t,cut}$>2 GeV and $pt_{,rec}$(jet)>20 GeV

J.Putschke RHIC/AGS 2009





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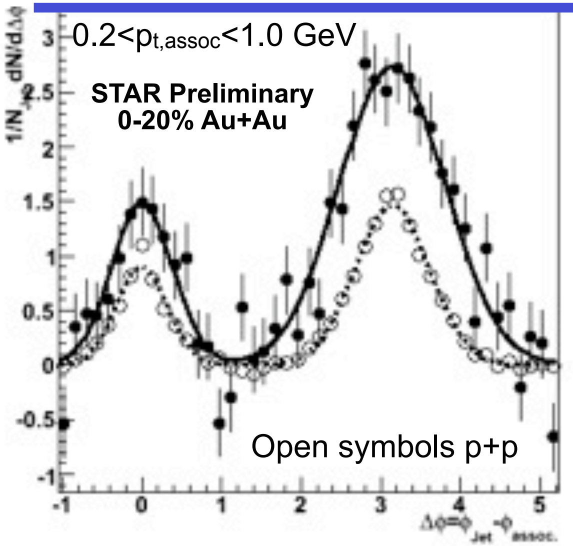

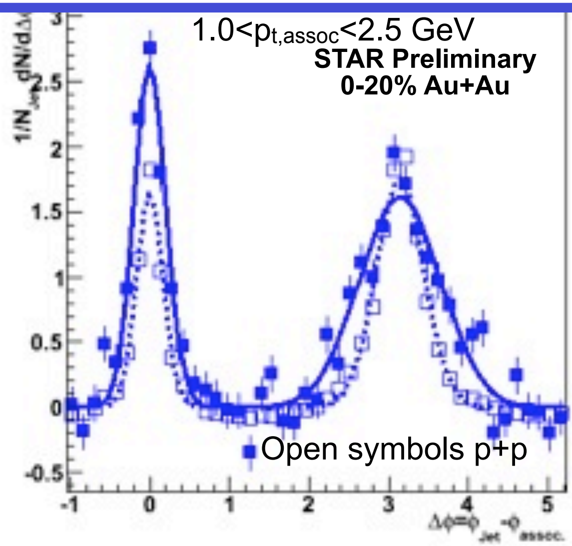

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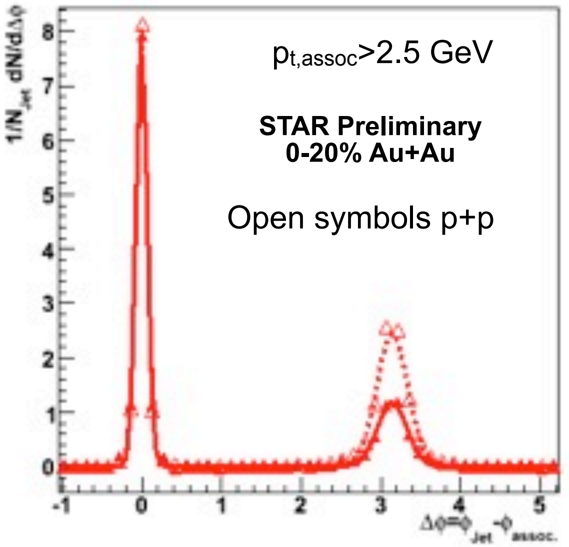
J.Putschke RHIC/AGS 2009



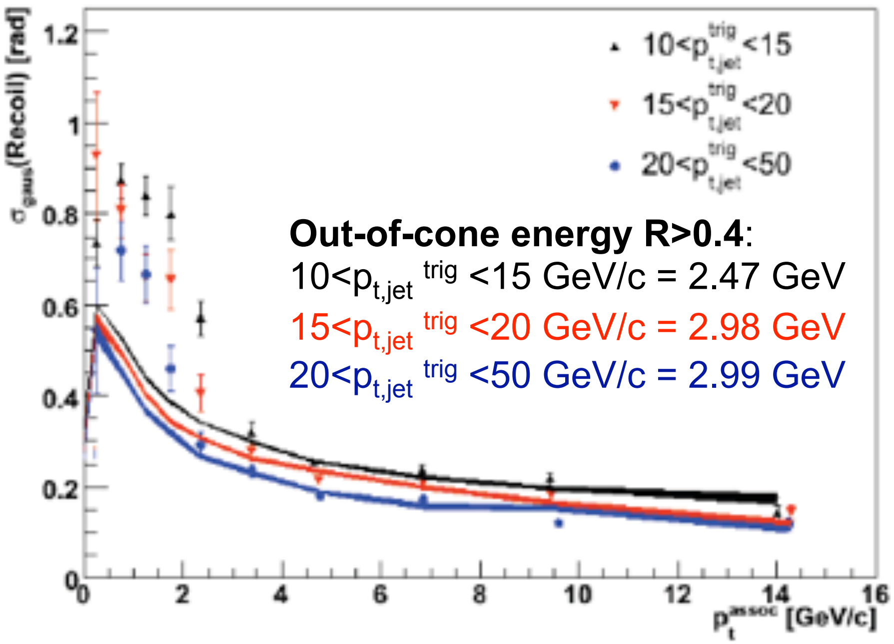
Broadening of recoil-side

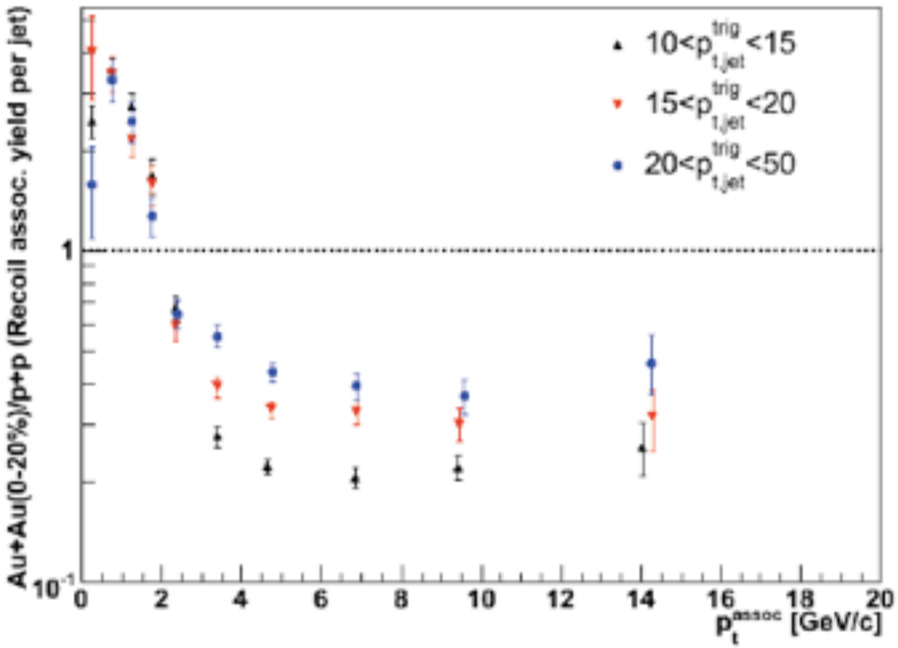
Softening of recoil-side

Caveat: "Jet v_2" effects still under investigation

First direct measurement of Modified Fragmentation due to presence of sQGP

Modification of recoil jet



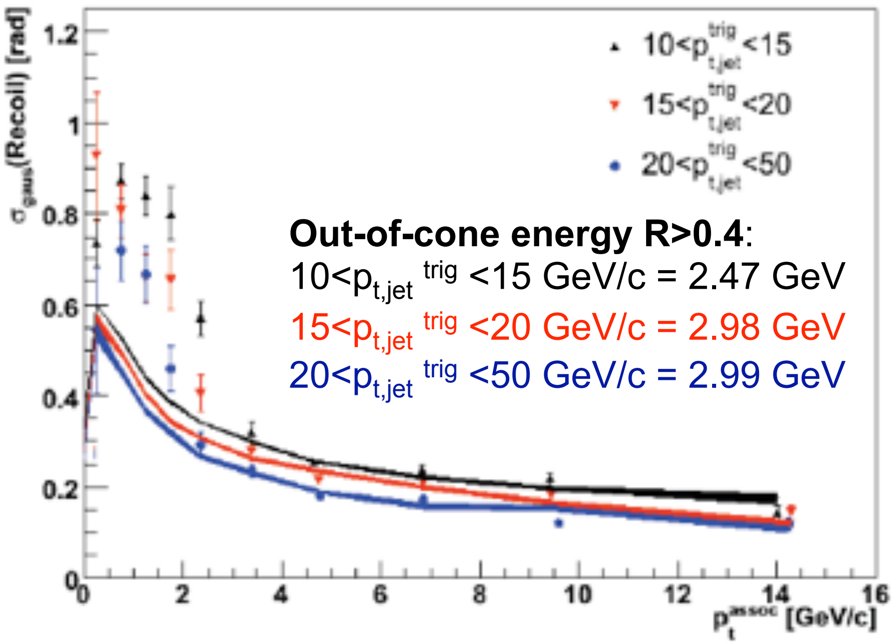


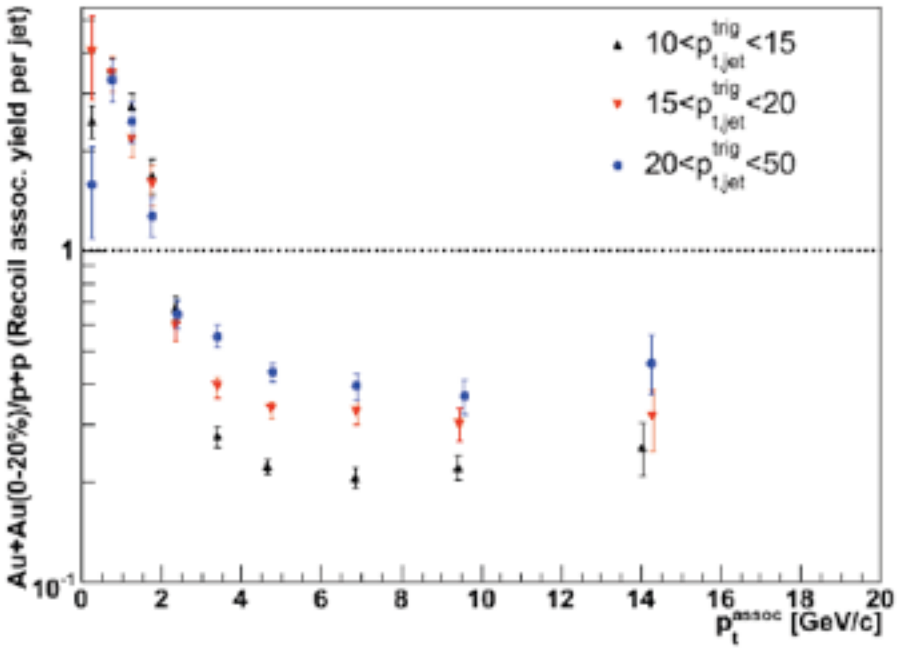
low p_T^{assoc} : azimuthal width: Au-Au > p-p

high p_T^{assoc} : azimuthal width: Au-Au ~ p-p

Broadening of soft fragments

Modification of recoil jet





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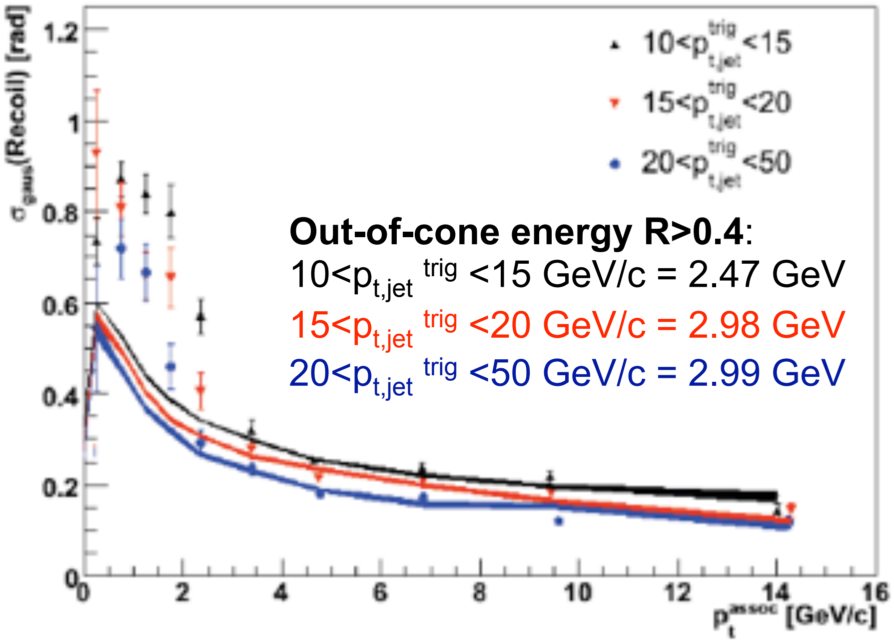
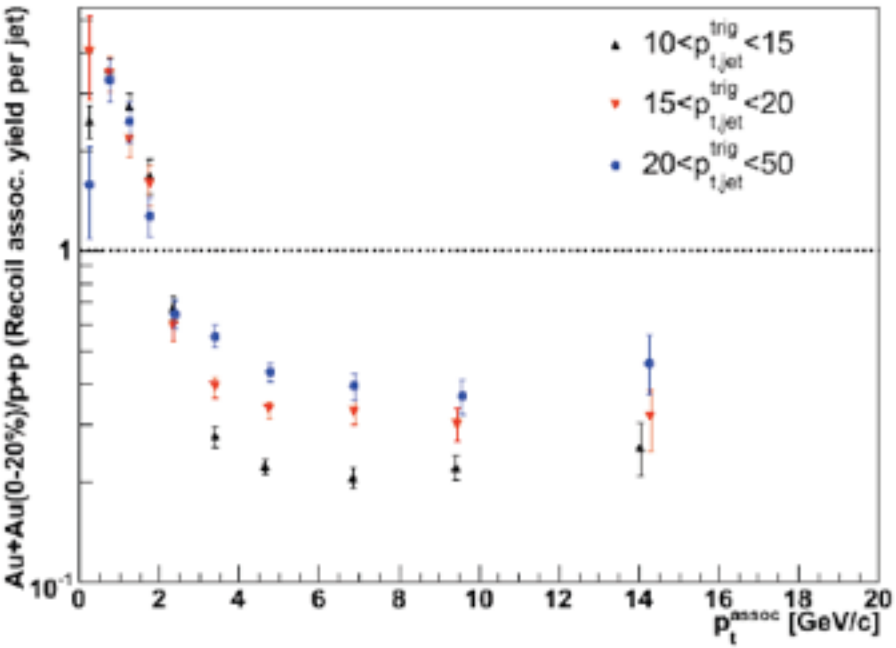
Quenching from hard to soft fragments

Modification of recoil jet





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Quenching from hard to soft fragments

Energy outside R=0.4 ~accounts for di-jet suppression

Summary

- p-p jet reference measurements are well understood - we have a calibrated probe
- Cold nuclear matter effects on jets are small (d-Au compared to p-p)
- Once parton escapes medium fragments as in vacuum
- Jets reconstructed in A-A assuming vacuum frag. show same suppression as for single hadrons (Gaussian filter studies)
- Strong evidence of broadening and softening of the jet energy profile (R=0.2/R=0.4, jet-hadron)
- Background subtraction the most serious issue - current focus

Results can be explained as due to significant partonic energy loss in the sQGP before fragmentation - numerous details left to be understood