Jets in heavy ion collisions at RHIC

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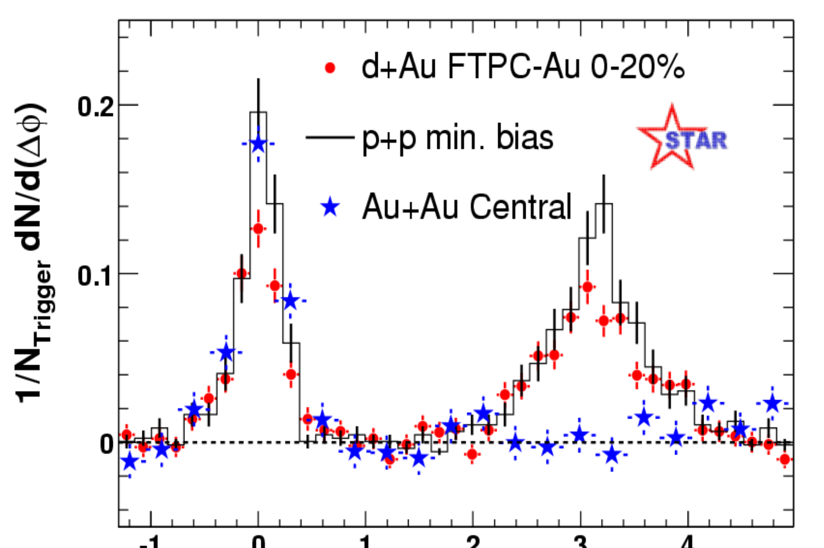
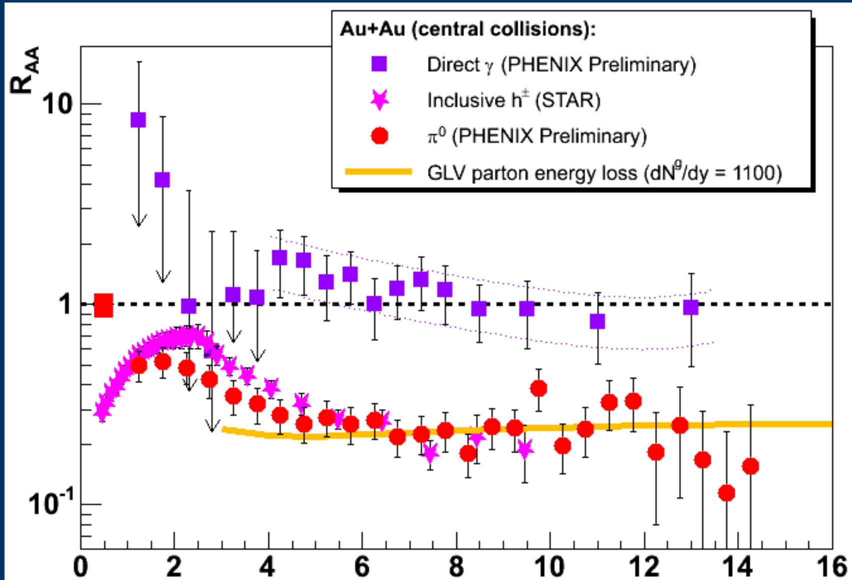
Jet quenching : indirect method



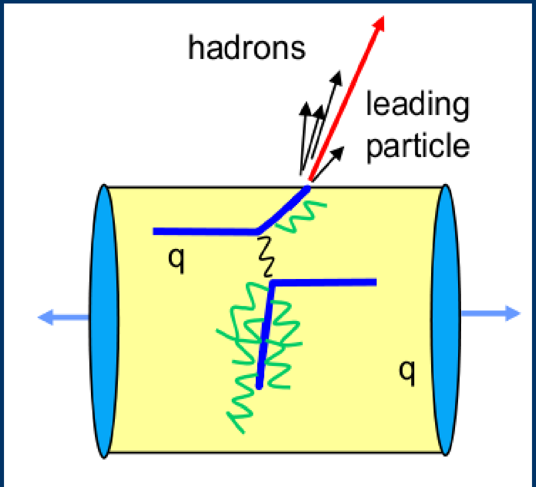
Phys. Rev. Lett. 91 (2003) 072304
Phys. Rev. Lett. 97 (2006) 162301

away side suppression of high-p_T hadrons



Phys. Rev. Lett 96 202301 (2006)

inclusive high-p_T hadron suppression (cf. direct γ)



$$R_{AA} = \frac{1}{\langle N_{bin} \rangle} \frac{d^2N^{AA} / dp_T\, d\eta}{d^2N^{pp} / dp_T\, d\eta}$$

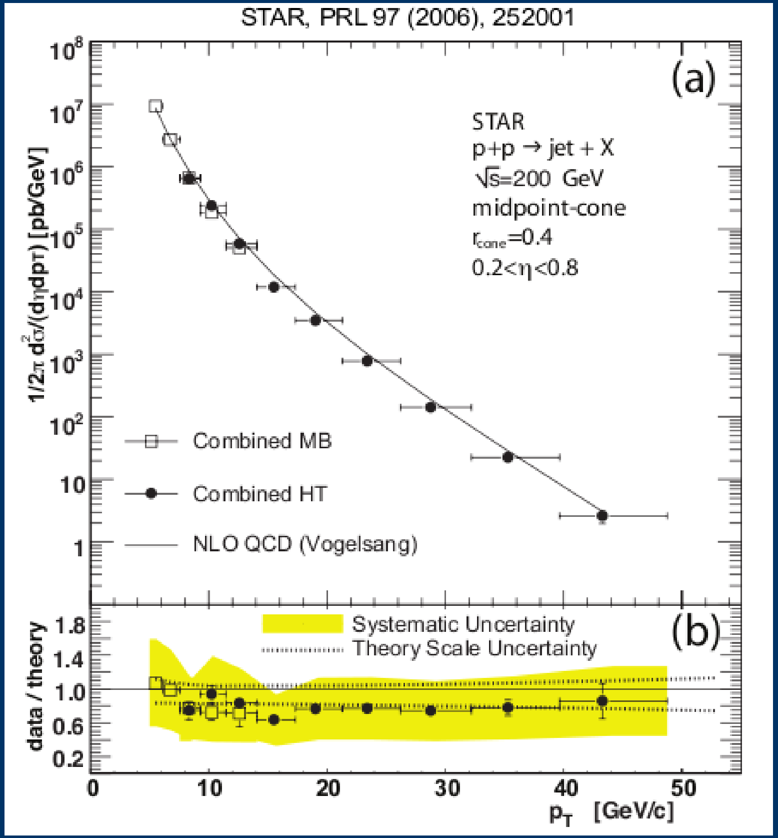
spectra & di-hadron correlations:

- indirect method to study jet quenching
- surface & fragmentation biases
- limited discrimination of medium parameters

Full jet reconstruction

<u>study the quenching directly with jets:</u>

- access the partonic kinematics
- well calibrated probe (pQCD)
- qualitatively new observables:
  - energy flow
  - fragmentation functions
- expecting R_{AA} = 1 for unbiased jet reconstruction (caveats: EMC effect at large x, possible jet broadening due to medium-induced radiation)



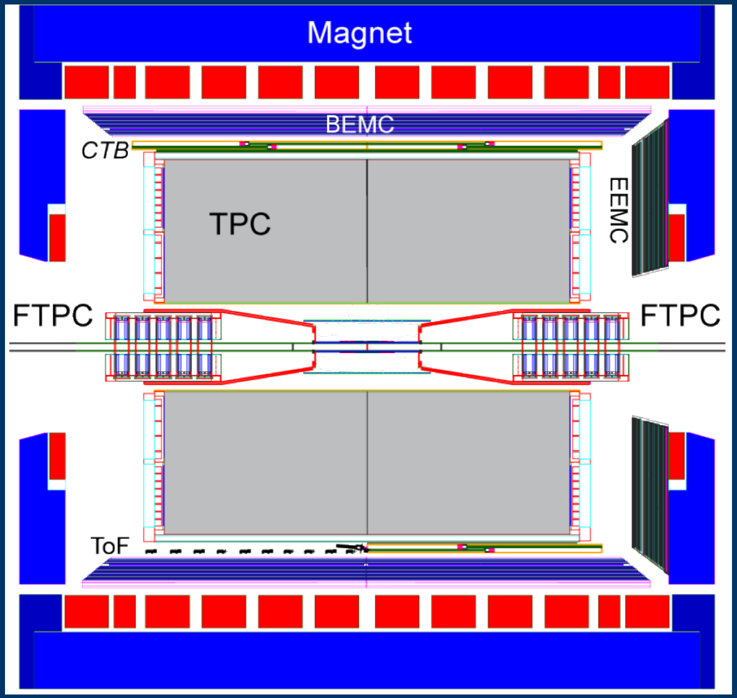
<u>Outline of the talk:</u>

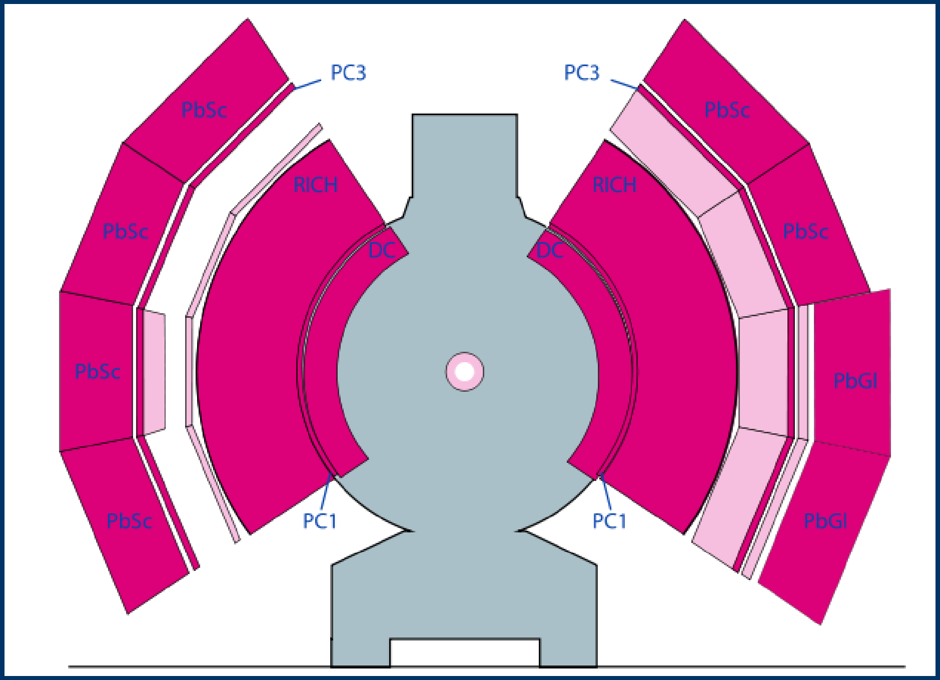
- RHIC experiments
- jet finding techniques for A+A collisions
- probing the initial state (d+Au vs p+p)
- probing the medium (Au+Au, Cu+Cu vs p+p): spectra, fragmentation functions, di-jets

Relativistic Heavy Ion Collider

BNL (Long Island, NY, USA)
p+p up to 500 GeV
A+A up to 200 GeV

STAR and PHENIX





|η| < 1 at mid-rapidity
full azimuthal coverage
TPC DAQ rate 50 Hz (till 2008)

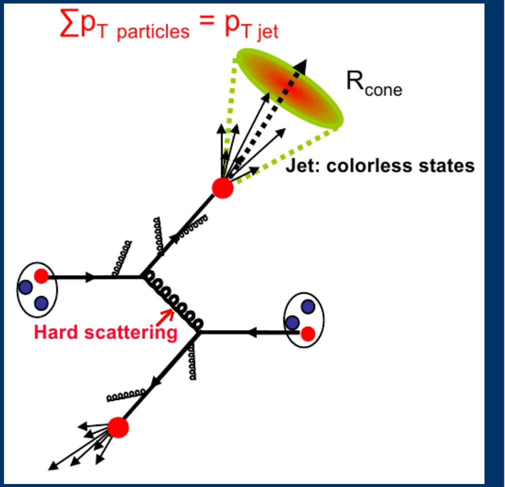
|η| < 0.35 at mid-rapidity
90° + 90° in azimuth
multi kHz DAQ rates (!)

jet reconstruction

charged energy (tracks) + neutral energy (elmg.calorimeter towers)
missing neutral energy: K^0_L, (anti) neutrons

data used: 2005-2008 p+p, d+Au, Cu+Cu, Au+Au $\sqrt{s_{NN}} = 200$ GeV

Jets in A+A collisions

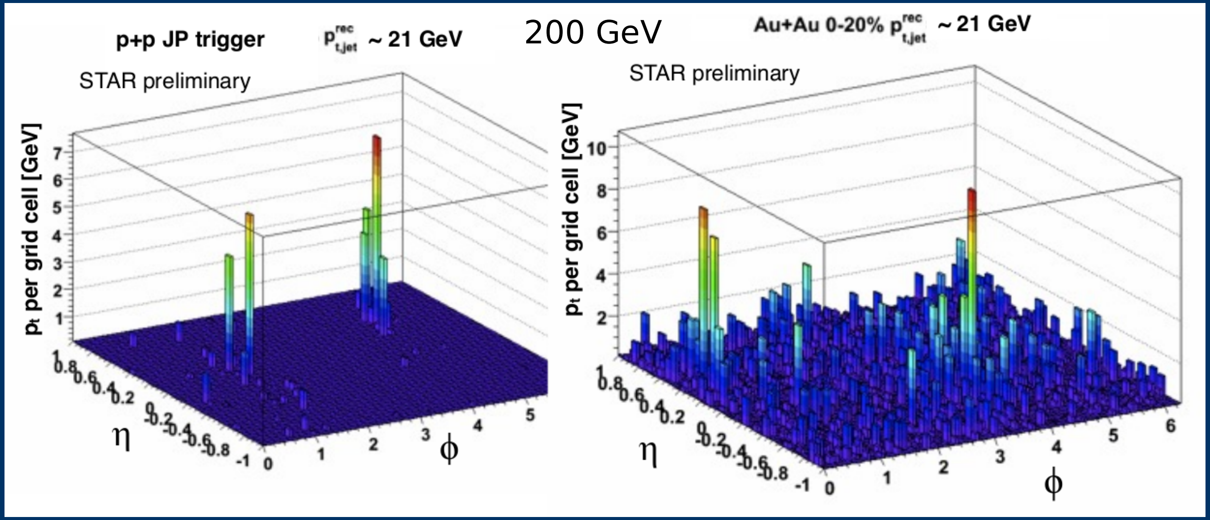


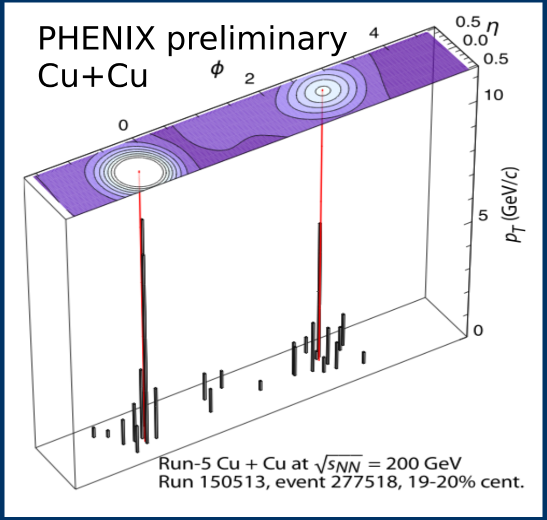
underlying event background in Au+Au central:
45 GeV in cone with R=0.4!

<u>general method:</u>

1. define jets (cone- and recombination- type algorithms)
2. subtract underlying event background
3. remove contribution from fake jets
4. correct (unfold) jet p_T smearing due to background fluctuations: to be able to compare to jets in p+p

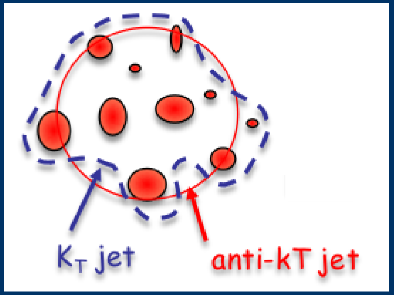
<u>despite the large background, we CAN see jets in A+A collisions:</u>





Jet finding techniques

jet reconstruction in p+p, d+Au, Au+Au collisions



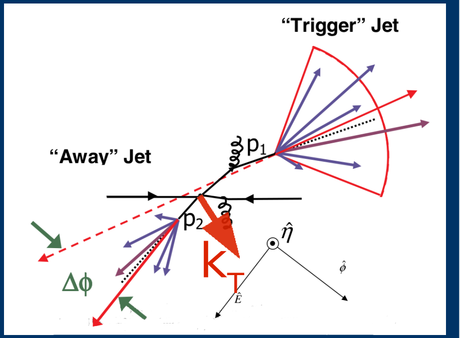
- kt and anti-kt recombination algorithms from FastJet
  Cacciari, Salam and Soyez, JHEP0804 (2008) 005, arXiv:0802.1188
- resolution parameter R: 0.2 to 0.5
- background subtraction: $p_{T,jet,observed} = p_{T,jet,true} + \rho * A$
  A: active jet area, ρ: median of p_T/A distribution
- statistical subtraction of fake jets (jet finder run at randomized event with jet-leading particles removed, or jet spectra in transverse region)
- unfolding of p_T smearing uses Gaussian widths from Pythia embedded into Au+Au

jet reconstruction in p+p, Cu+Cu collisions

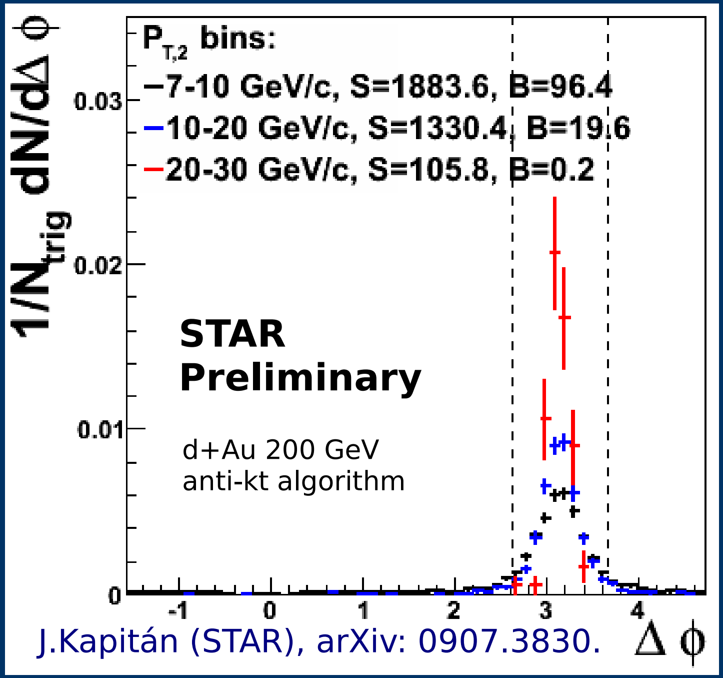
- Gaussian filter with σ=0.3 (Y.S.Lai, B.A.Cole, arXiv: 0806.1499)
  - core of the jet has higher weight: background suppression
  - ideal for limited-acceptance detector
- jet-by-jet fake rejection by Gaussian-filtered (σ=0.1) p_T^2 sum > cut:
  Y.S.Lai (PHENIX), arXiv: 0907.4725
  - shouldn't reject quenched jets (PYQUENCH simulation)
- unfolding based on p+p embedded into Cu+Cu

k_T effect: jets in d+Au

- run 8 RHIC data: p+p, d+Au 20% most central; R = 0.5
- select two highest energy jets in event: $p_{T,1} > p_{T,2}$
- use cut on $p_{T,2}$ to suppress background/fake jets
- di-jet ΔΦ broadening (k_T): intrinsic k_T + ISR,FSR (incl. CNM)



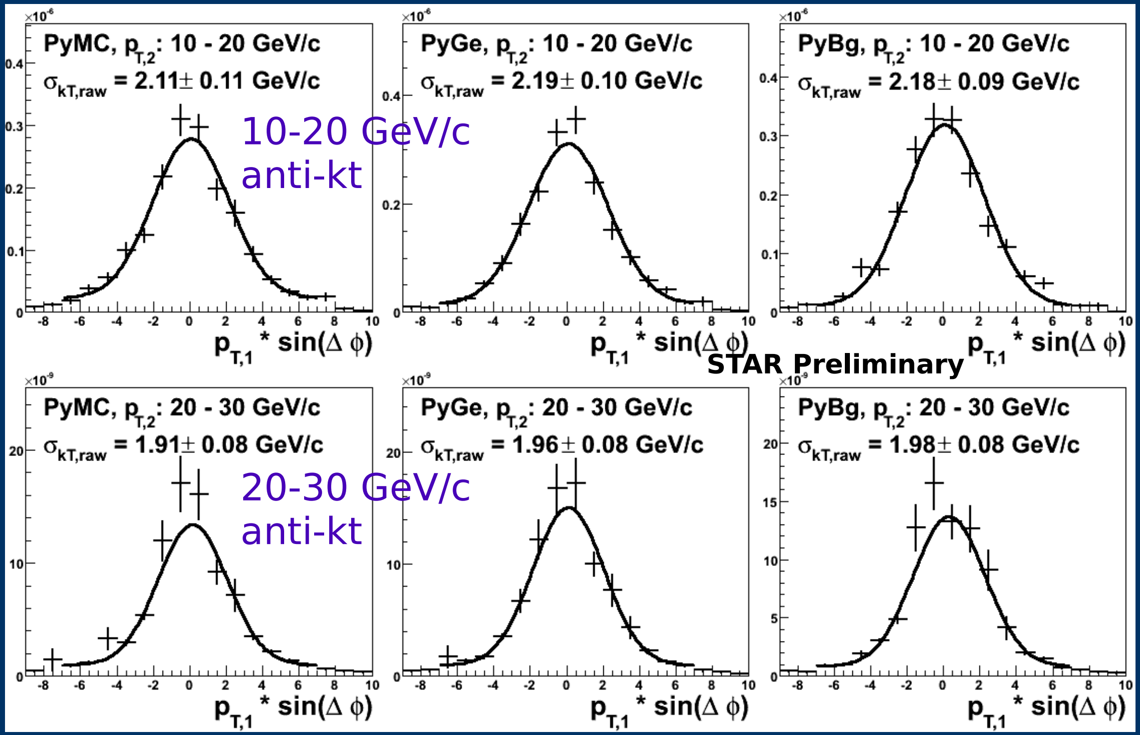
clear back-to-back di-jet peak in ΔΦ:



J.Kapitán (STAR), arXiv: 0907.3830.

$k_{T,raw} = p_{T,1} * \sin(\Delta\Phi)$, $|\sin(\Delta\Phi)| < 0.5$, Gaussian fit:

MC level: Pythia | detector level | dAu bg added

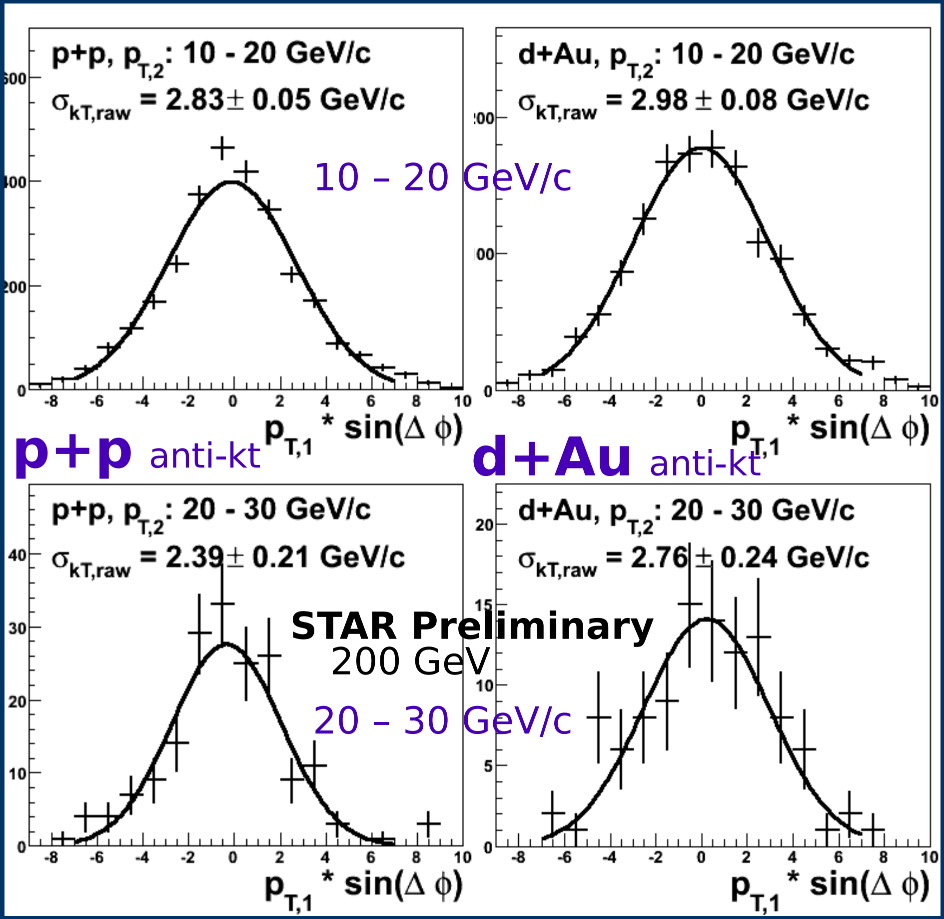


J.Kapitán (STAR), EPS HEP 2009.

...detector effects are small!

Do we see Cold Nuclear Matter effects?

- the same analysis technique in p+p and d+Au collisions
- average over 2 $p_{T,2}$ bins and 2 algorithms: kt, anti-kt



J. Kapitán (STAR), EPS HEP 2009.

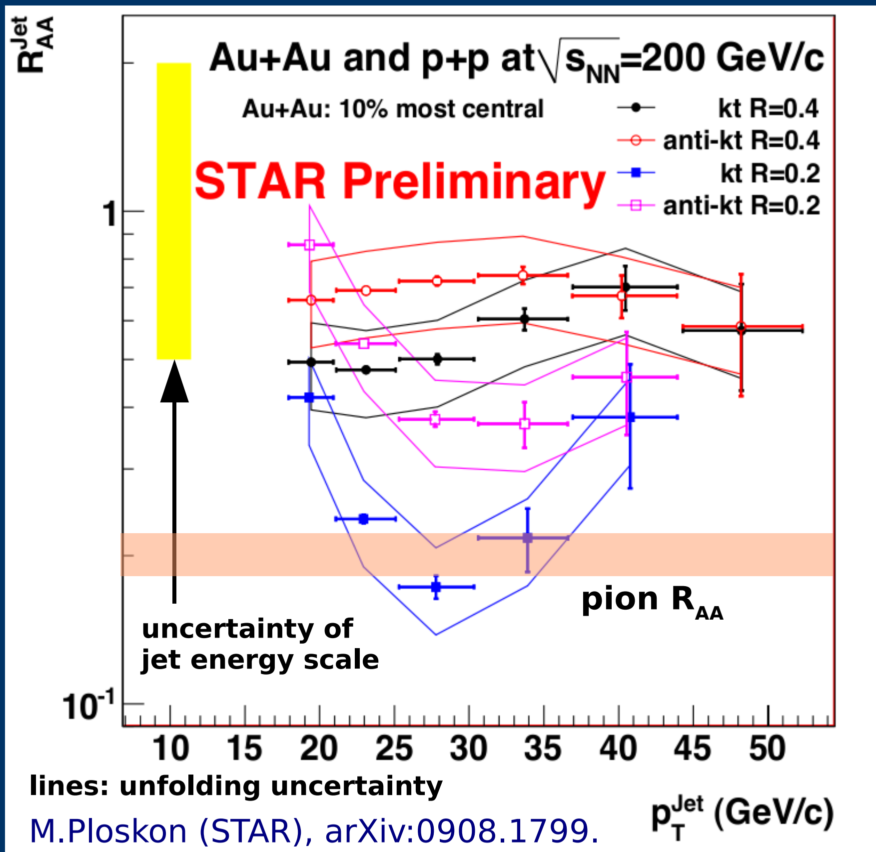
$\sigma_{kT,raw}$ (p+p) = 2.8 ± 0.1 GeV/c
$\sigma_{kT,raw}$ (d+Au) = 3.0 ± 0.1 GeV/c
?decrease at high p_T (quark jets?):
higher jet energies to be studied

<u>systematic uncertainties:</u>

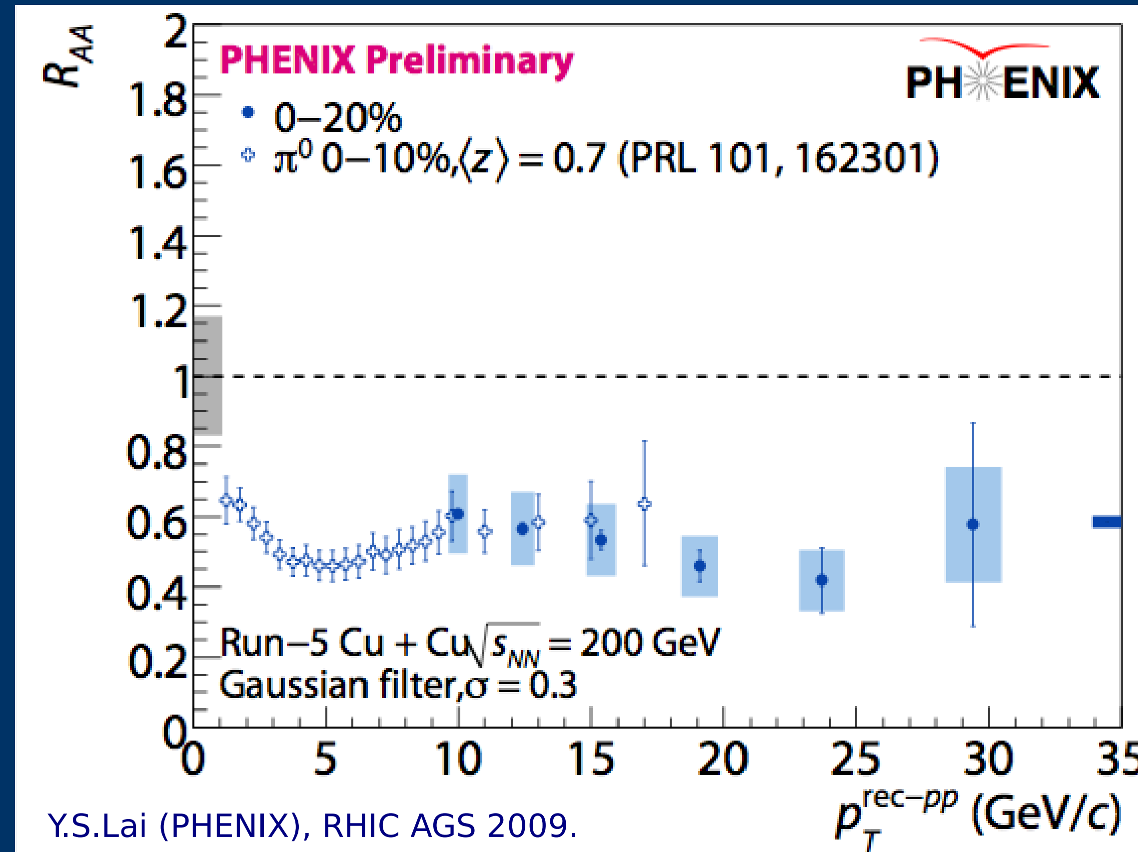
- neglecting detector effects, p_T-dependence
- BEMC calibration and TPC tracking at high luminosity: under study
- ➔ largely correlated between p+p and d+Au

<u>conclusion: no strong Cold Nuclear Matter effect on jet k_T broadening seen</u>

Medium modification of jet p_T spectra



M.Ploskon (STAR), arXiv:0908.1799.



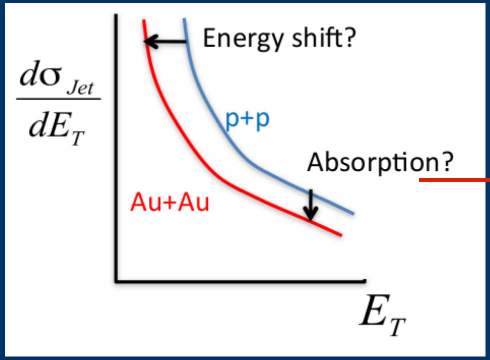
Y.S.Lai (PHENIX), RHIC AGS 2009.

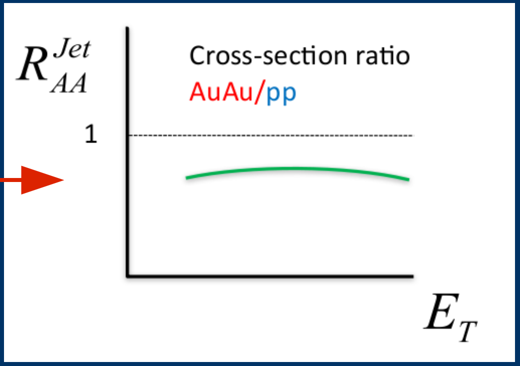
- different sensitivity of algorithms
- R=0.4: indication of energy recovery (cf. pion R_{AA})
- R=0.2 jets suppressed
- → is R=0.4 enough to achieve jet R_{AA} = 1?

- significant jet suppression
- → ?jet broadening -> energy shift
- → ?feature of fake jet rejection algorithm

Jet energy profile

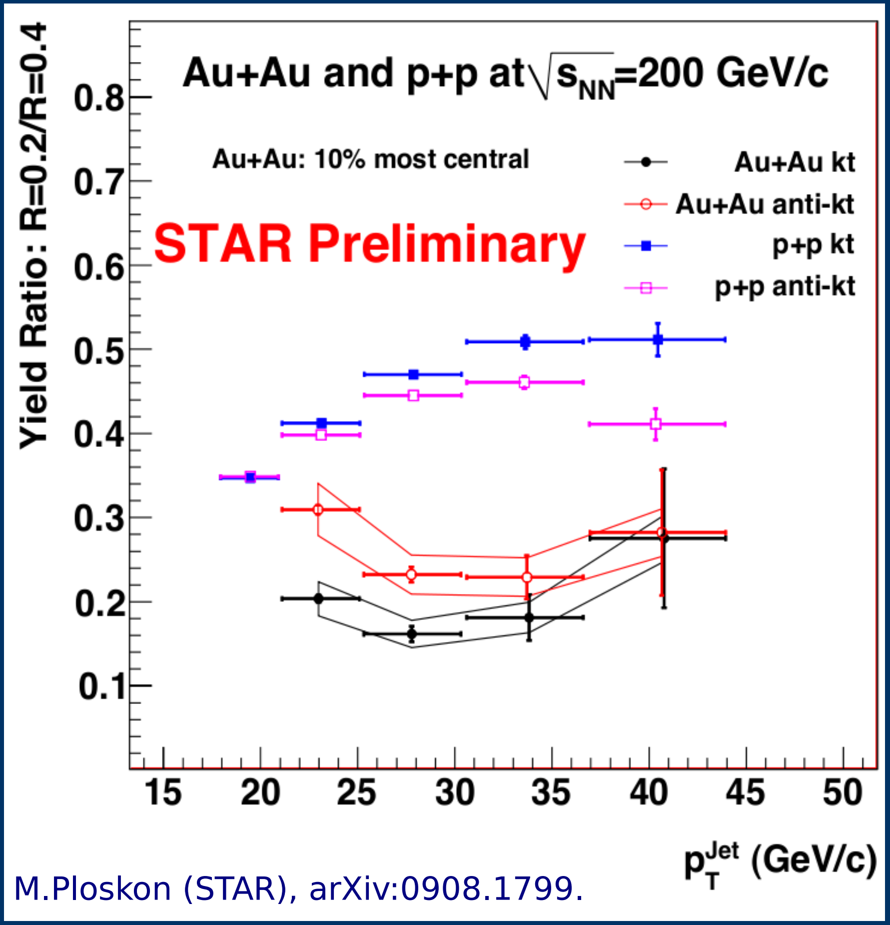
jet R_{AA} < 1: 2 options:





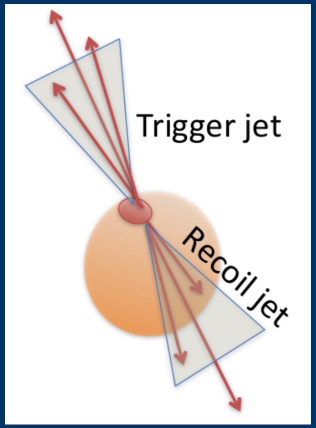
- modified jets are lost
- their energy shifted out of “jet cone” (large angle radiation)

R>0.4 not accessible due to large background, but can compare R=0.2 and R=0.4 jets

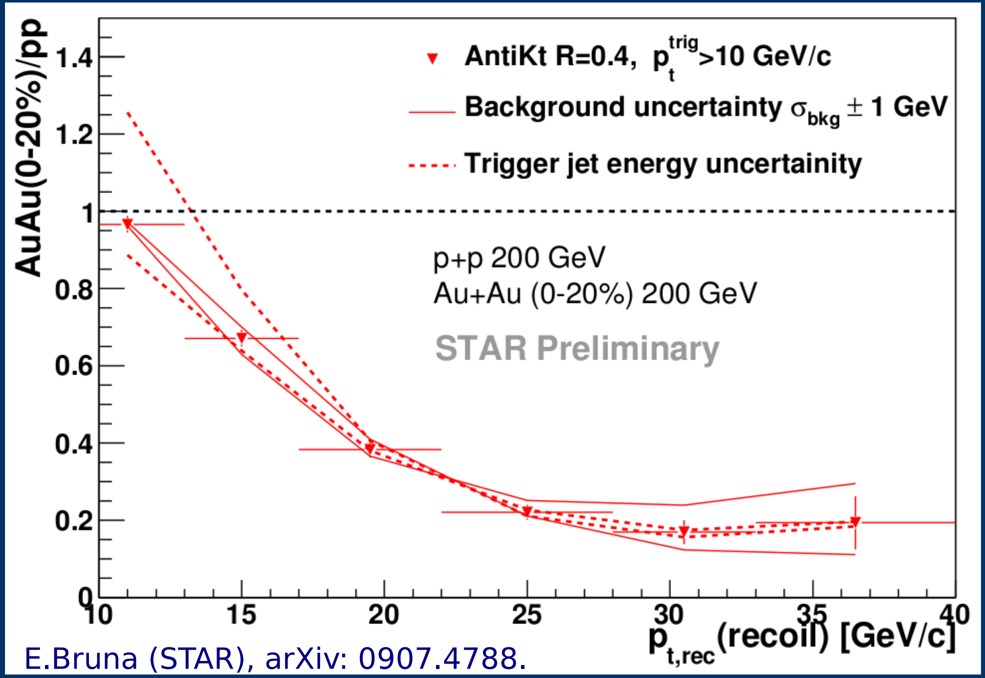


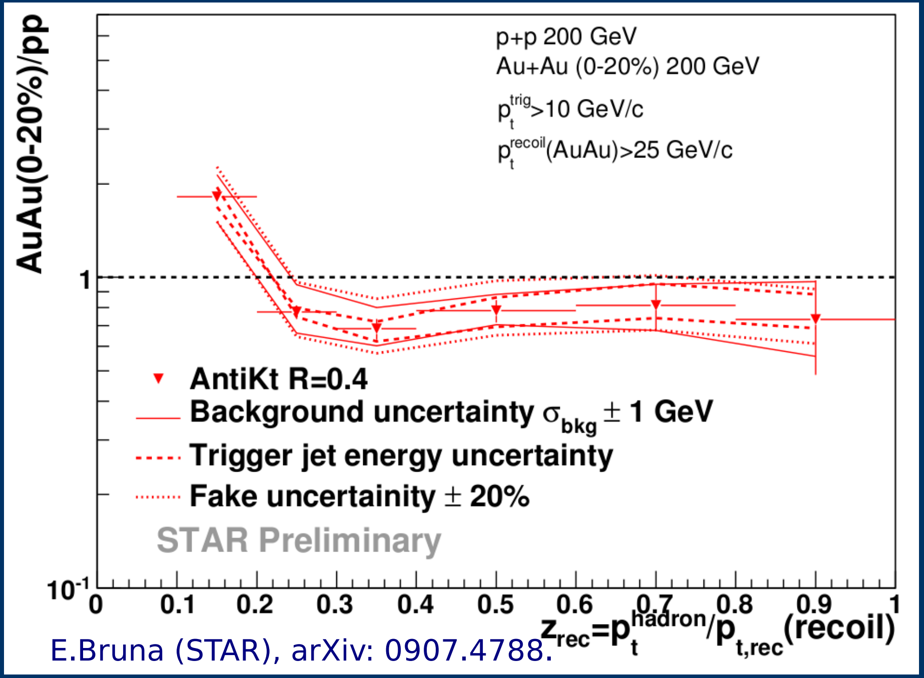
- p+p: “narrowing” of jet structure
- Au+Au: indication of jet broadening (deficit of energy in R=0.2)

Fragmentation functions



- trigger jet: leading hadron $E_T > 5.4$ GeV
- maximizing medium path-length of the recoil jet
- R=0.4 and recoil jet: measure of jet energy ($p_{t,rec}$)
- R=0.7 used for charged hadrons (p_t^{hadron}) and bg subtracted



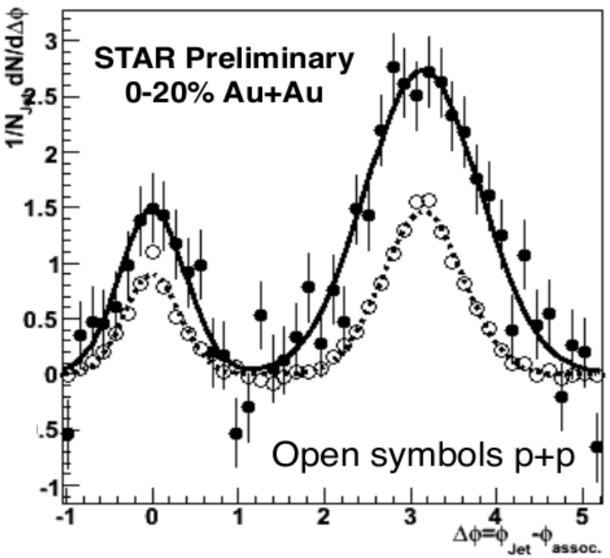


significant suppression of recoil jets:
?energy shift due to jet broadening
?are those that we see non-interacting (eg tangential emission?)

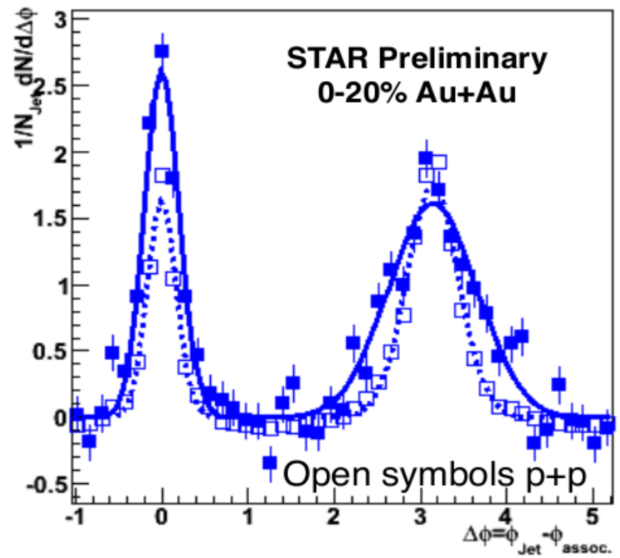
no significant modification of FF:
?dominated by non-interacting jets
?artificial hardening of Au+Au FF due to energy shift

Jet-hadron correlations 0-20% Au+Au vs. p+p

$0.2<p_{t,assoc}<1.0$ GeV



$1.0<p_{t,assoc}<2.5$ GeV

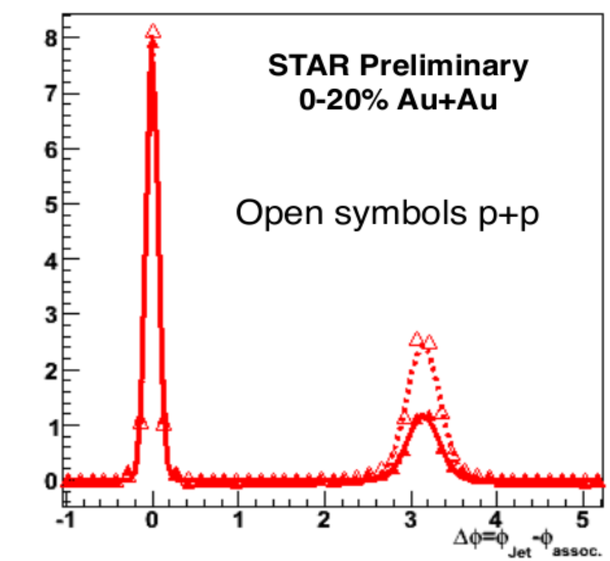


High Tower Trigger (HT): tower 0.05x0.05 (ηxϕ) with E_t> 5.4 GeV

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

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

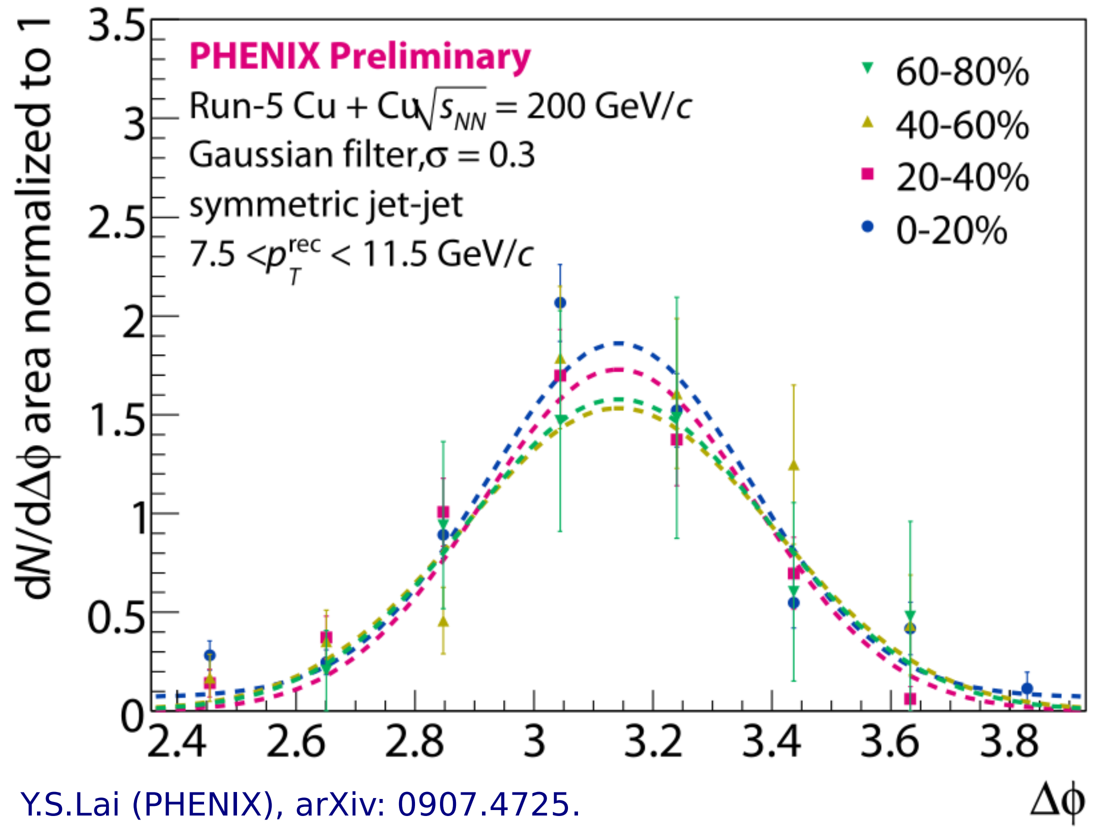
$p_{t,assoc}>2.5$ GeV



- **Significant broadening and softening visible on the recoil side**
- **"Modified fragmentation function"**
- **"Not" visible in di-jets, suggesting that current jet-finding approach is biased towards less interacting jets and/or underestimation of jet energy**
- **jet v_2 to be subtracted? (under study)**

J.Putschke (STAR), RHIC AGS 2009.

Di-jet azimuthal correlations



Y.S.Lai (PHENIX), arXiv: 0907.4725.

Gaussian widths of Δϕ distributions are consistent across different centralities:

not expected for quenched jets (k_T broadening)

algorithm feature? (preferential selection of unquenched jets?)

Conclusions

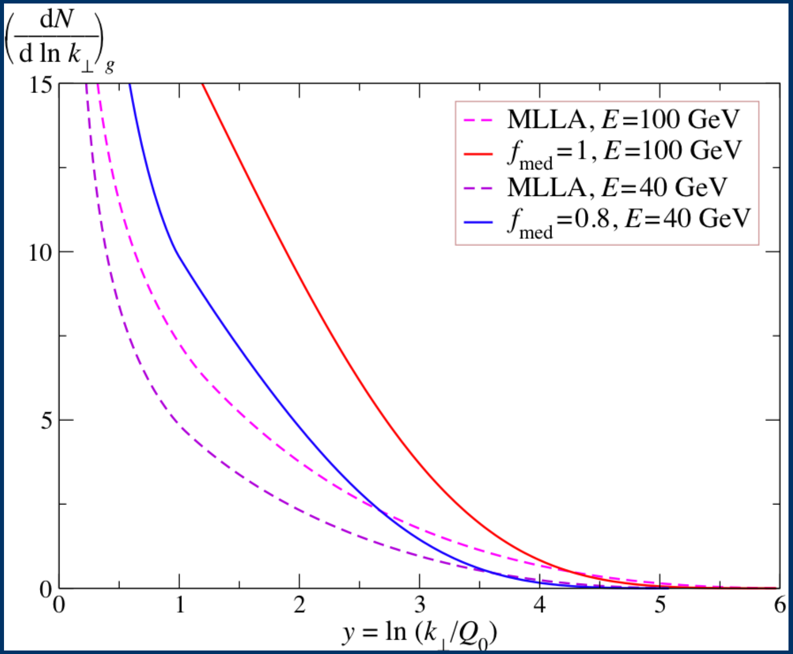
- Cold Nuclear Matter effects:
  - no strong evidence of k_T broadening in d+Au collisions
- Medium modification through jets in Cu+Cu collisions:
  - jets show suppression similar to π^0
  - no centrality dependence observed in di-jet $\Delta\phi$ width
  - ➔ algorithm preferentially selects unquenched jets?
  - ➔ observed effects could be due to jet broadening?
- Medium modification through jets in central Au+Au collisions:
  - significant suppression of R=0.2 jets observed
  - R=0.2/R=0.4 p_T spectra ratio qualitatively different from p+p
  - recoil jets: significant suppression & no strong FF modification
  - jet-hadron correlations: away side jet structure broadening
  - ➔ quenching leads to jet broadening!
- New rich set of observables to confront with theory!

Thank you!

Backup

Connection to theory

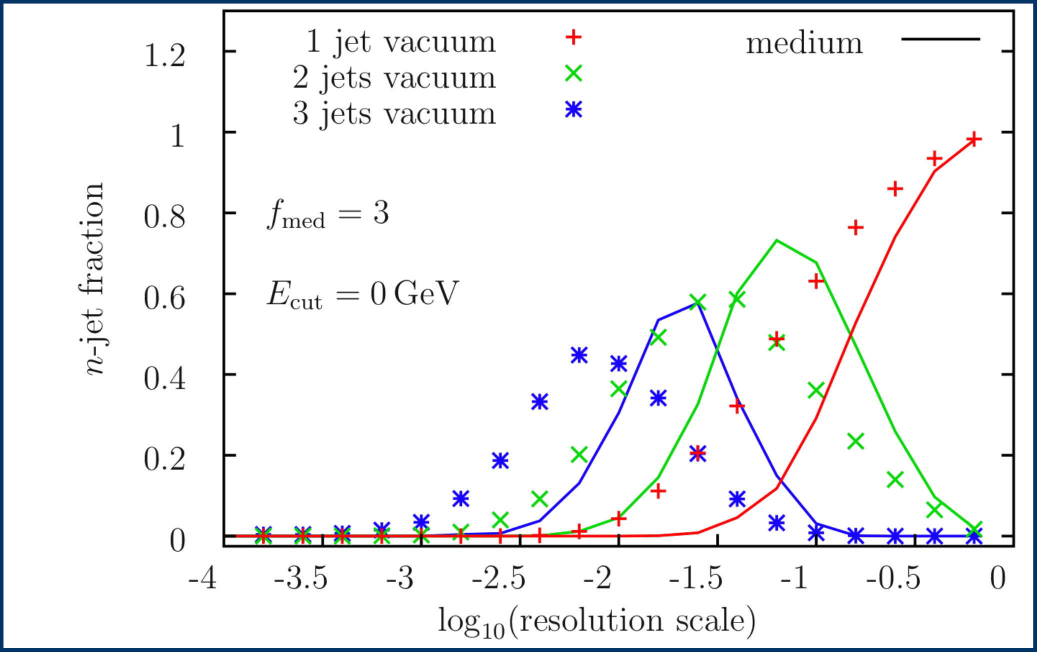
analytical calculations:



N. Borghini, arXiv: 0902.2951.

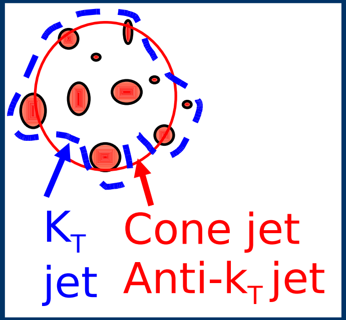
strong transverse broadening of parton shower w.r.t. jet axis!
may depend on p_T cuts?

IR safe observables – subjet distributions:



K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, U. A. Wiedemann arXiv:0804.3568.

medium induced radiation -> coarser jet structure



Theory: Jet quenching – Energy Loss

Elastic energy loss: Bjorken ’82
Bremsstrahlung: Gyulassy, Wang, Plumer ’92
jet quenching measures color charge density, plasma transport coefficients

But quantitative analysis of data requires model building
Current status: large discrepancies (factor~10) in extracted medium parameters (transport coefficients) → ongoing efforts to resolve this

YaJEM (Renk): medium increases virtuality of partons during evolution

PYQUEN (Lokhtin, Snigriev): PYTHIA afterburner reduces energy of final state partons and adds radiated gluons according to BDMPS expectations.

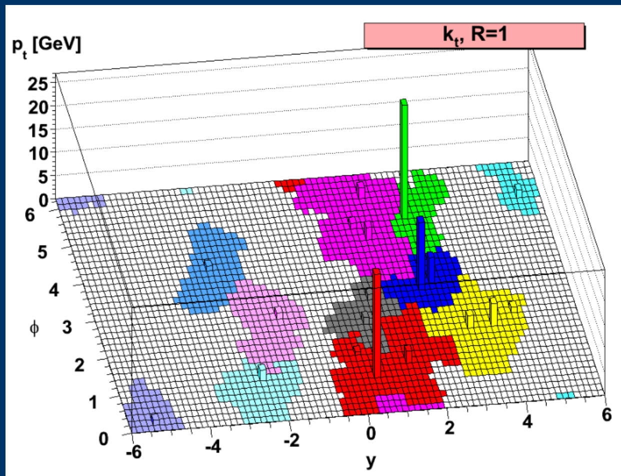
PQM (Dainese, Loizides, Paic): MC implementation of BDMPS quenching weights

HIJING (Gyulassy, Wang): jet and mini-jet production with induced splitting

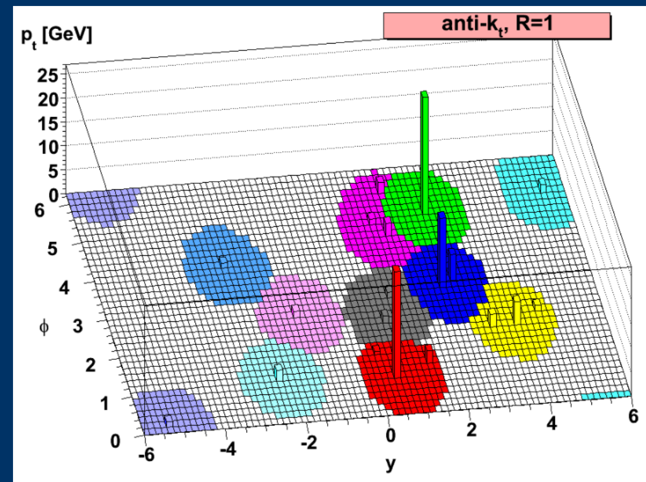
JEWEL (Zapp, Ingelman, Rathsman, Stachel, Wiedemann): parton shower with microscopic description of interactions with medium

q-PYTHIA (Armesto, Cunquiero, Salgado, Xiang): includes BDMPS-like radiation in modified splitting function

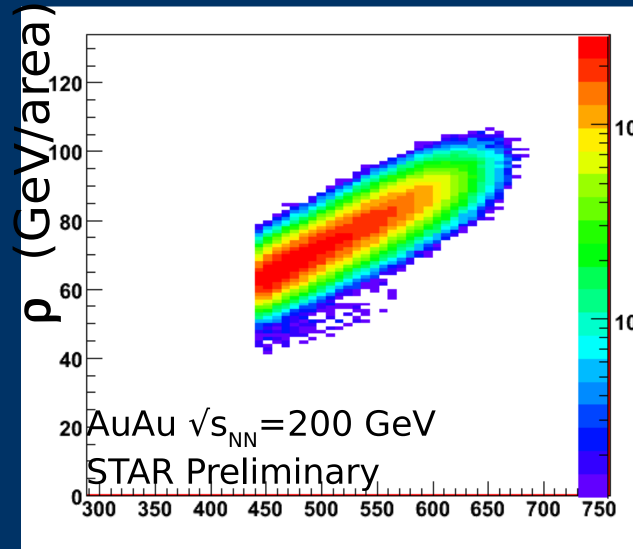
Jet finding



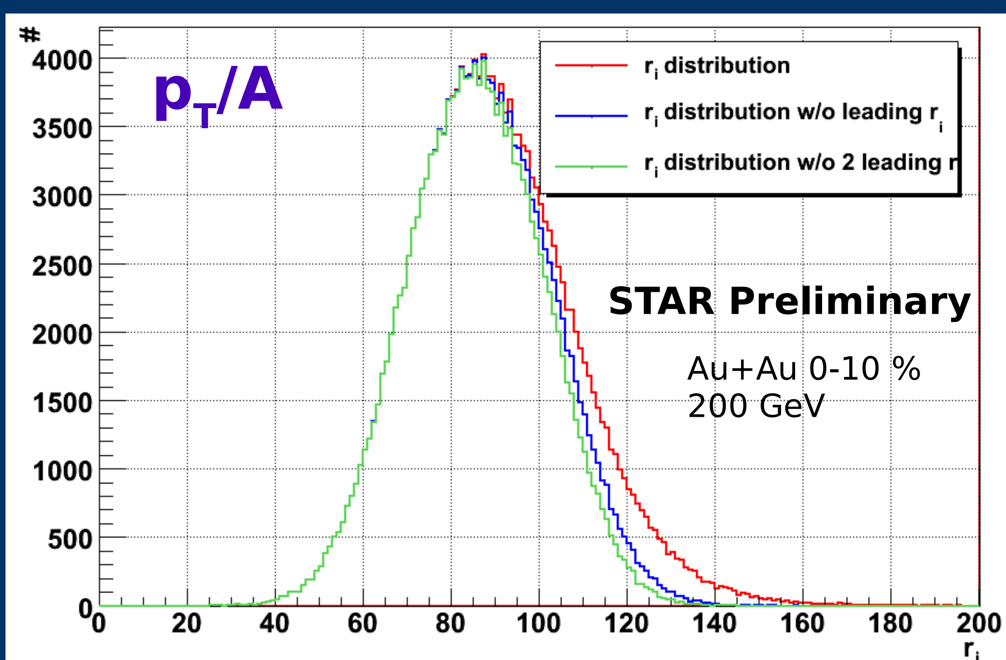
k_t, R=1
p_t [GeV]
y
ϕ



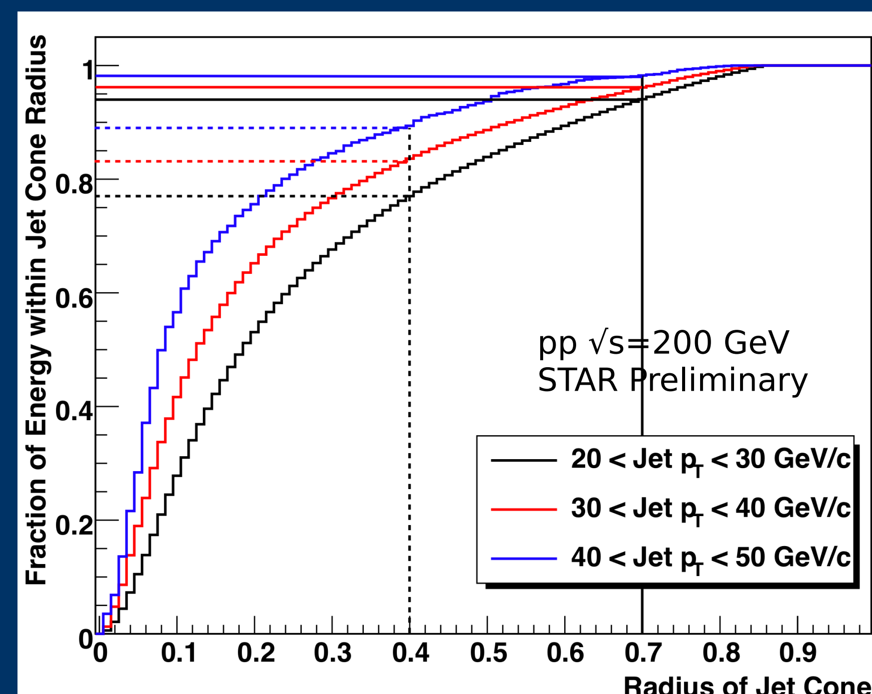
anti-k_t, R=1
p_t [GeV]
y
ϕ



ρ (GeV/area)
AuAu $\sqrt{s_{NN}}$=200 GeV
STAR Preliminary

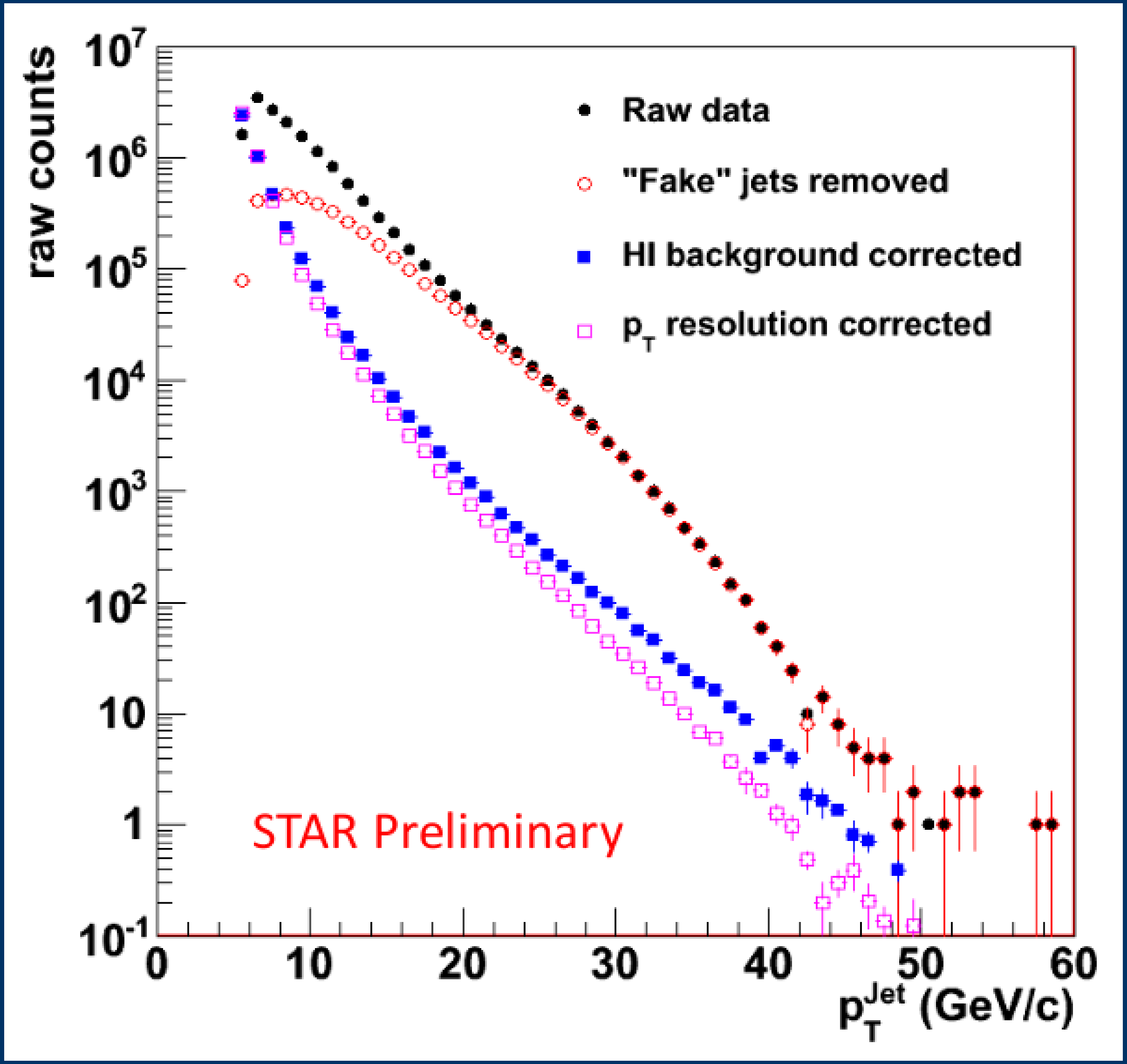


p_T/A
#
r_i distribution
r_i distribution w/o leading r_i
r_i distribution w/o 2 leading r_i
STAR Preliminary
Au+Au 0-10 %
200 GeV
r_i



Fraction of Energy within Jet Cone Radius
Radius of Jet Cone
pp $\sqrt{s}$=200 GeV
STAR Preliminary
20 < Jet p_T < 30 GeV/c
30 < Jet p_T < 40 GeV/c
40 < Jet p_T < 50 GeV/c

Jet spectra - unfolding



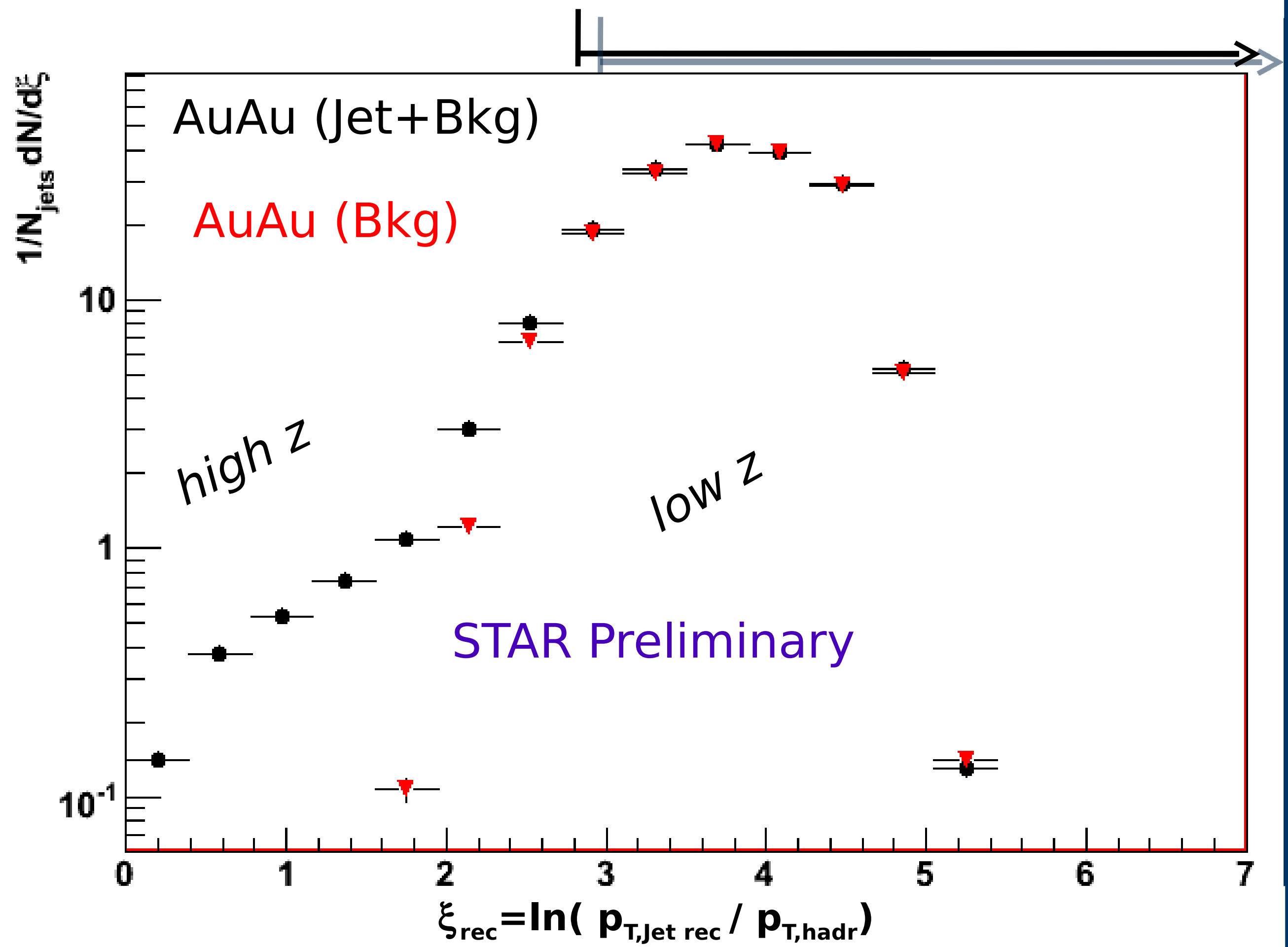
Gaussian widths – smearing/unfolding from Pythia embedding:

R=0.4: 6.8 GeV
R=0.2: 3.7 GeV

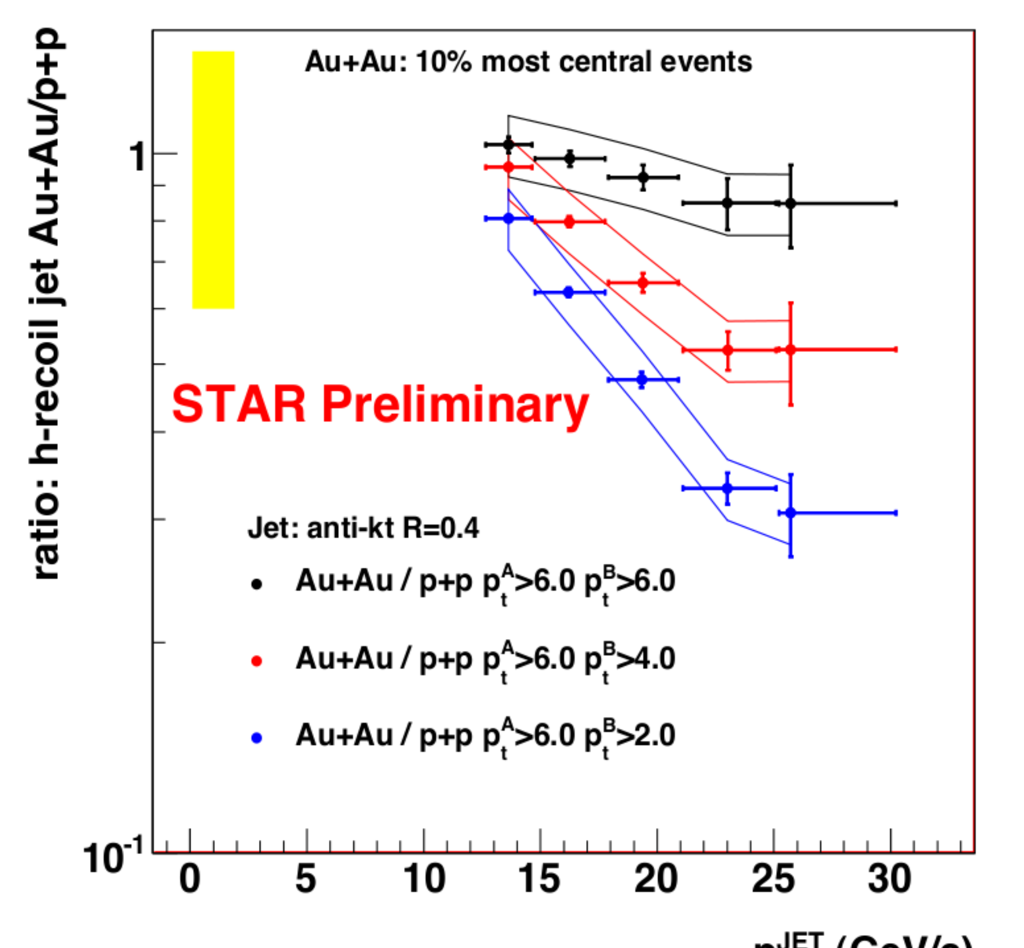
systematic uncertainty (bands): +-1 GeV

Fragmentation functions

large uncertainties due to background
(further systematic evaluation needed)



Hadron – jet correlations



M.Ploskon (STAR), arXiv:0908.1799.

high-p_T hadron - BEMC cluster:
p_t^A >6 GeV/c
recoil jet with leading particle:
p_t^B > 6, 4, 2 GeV/c
normalised per number of trigger di-hadrons

small suppression for p_t^A > 6 GeV/c:
this highly exclusive di-hadron trigger selects non-interacting jets!

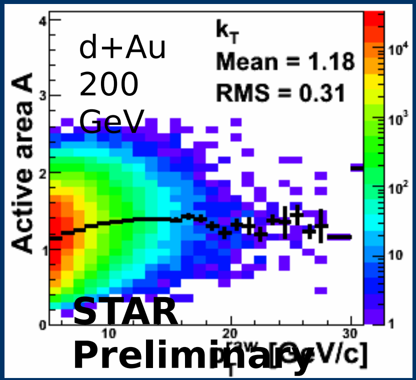
n.b.: trigger itself IS suppressed!

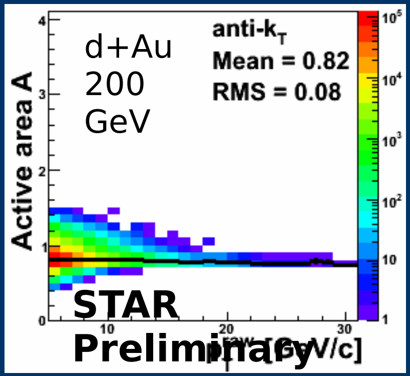
Jets in d+Au collisions

- run 8 RHIC d+Au data: 20% most central collisions
- compare to run 8 p+p data
- trigger: BEMC tower E_T>4.3 GeV (p+p, d+Au)

} similar systematics

- using p_T > 0.5 GeV/c, R = 0.5, fiducial jet acceptance |η| < 0.9-R

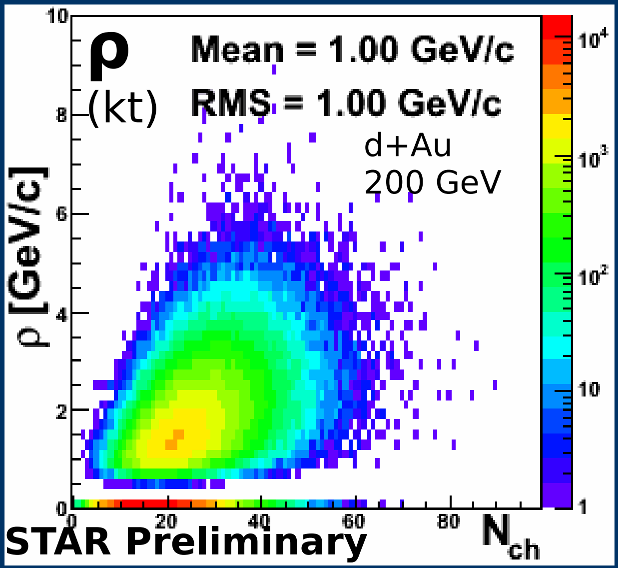


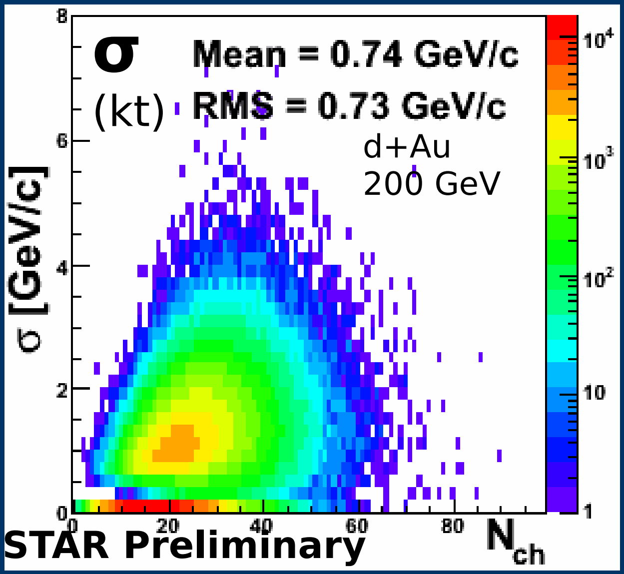


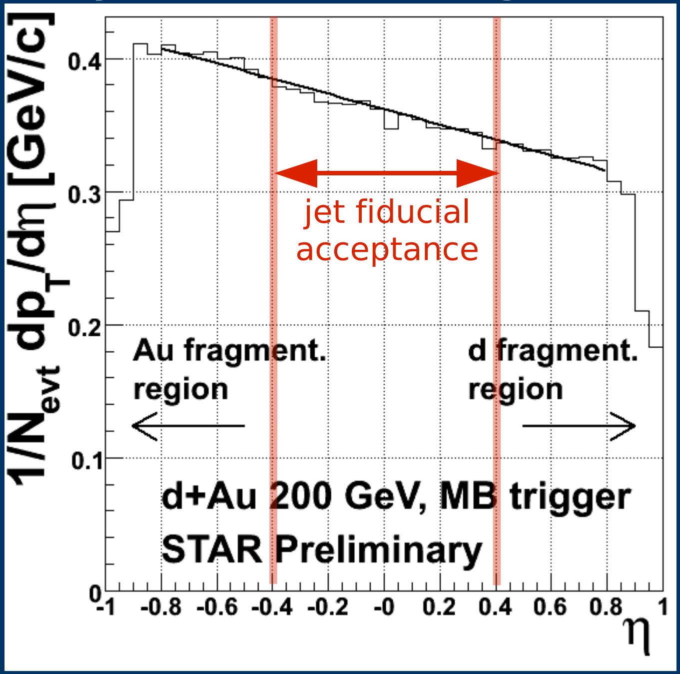
jet areas for kt and anti-kt algorithms

all here: J.Kapitán (STAR), EPS HEP 2009

d+Au: asymmetric system
- asymmetric background:







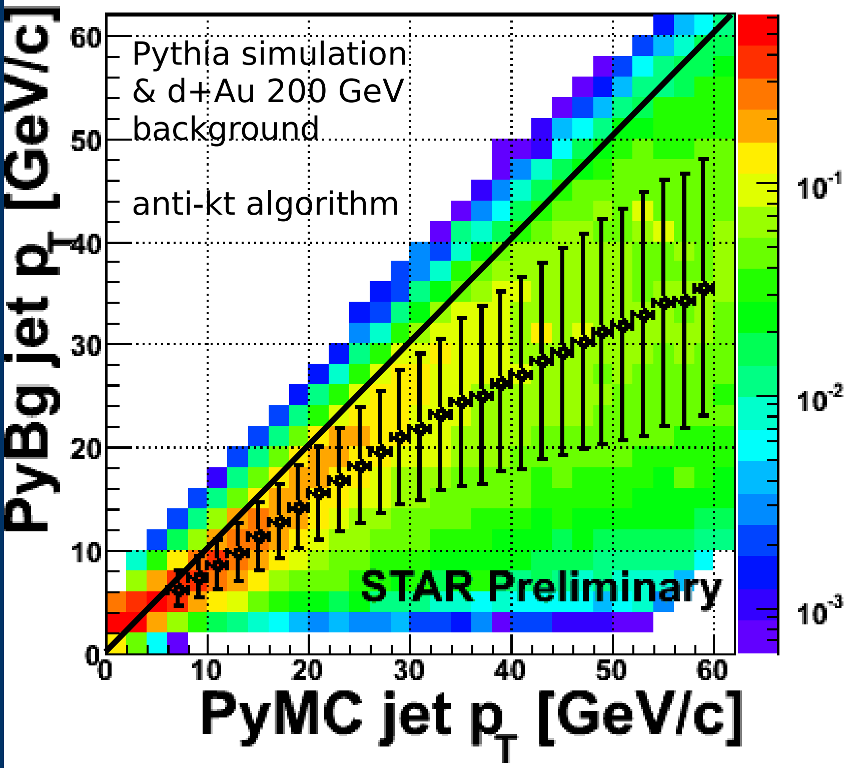
Pythia simulation for d+Au corrections

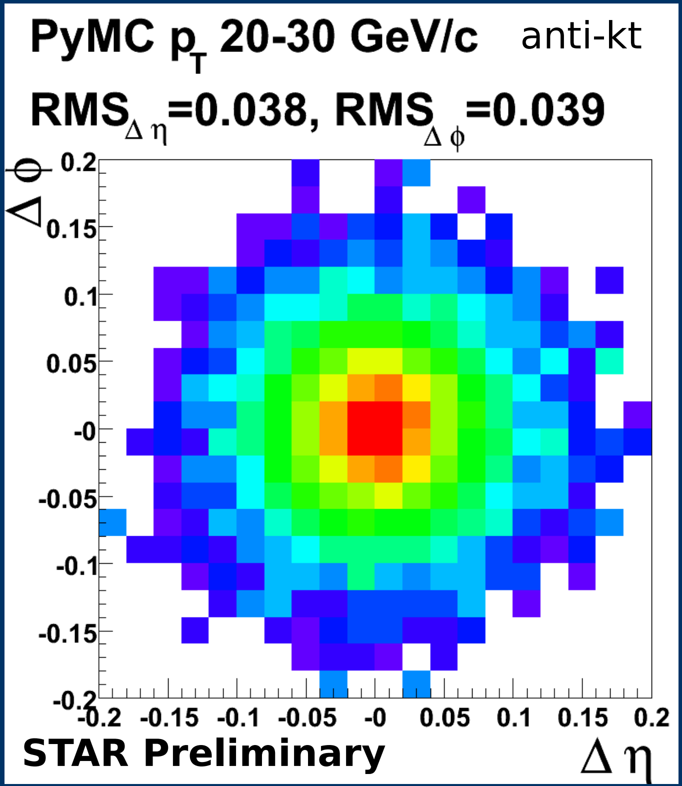
- Pythia 6.410, GEANT, STAR reconstruction software
- PyMC (particle level), PyGe (detector level), PyBg (detector level + bg)

jet p_T resolution:

roughly 20%

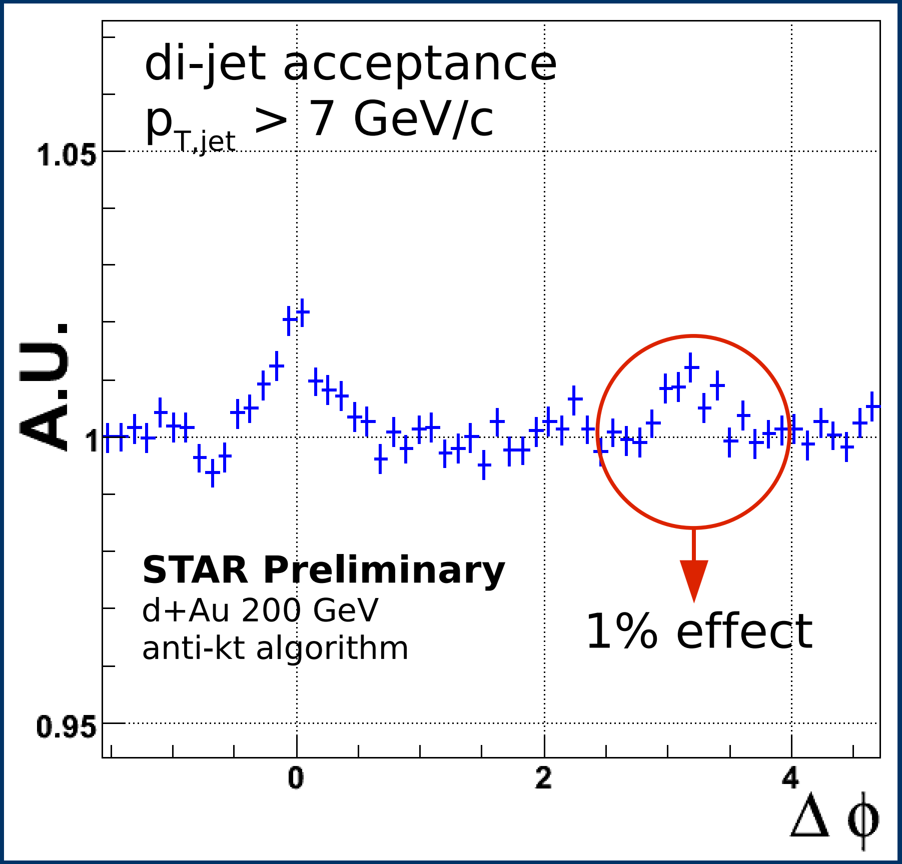
shift: unobserved neutral energy, tracking efficiency, dead towers





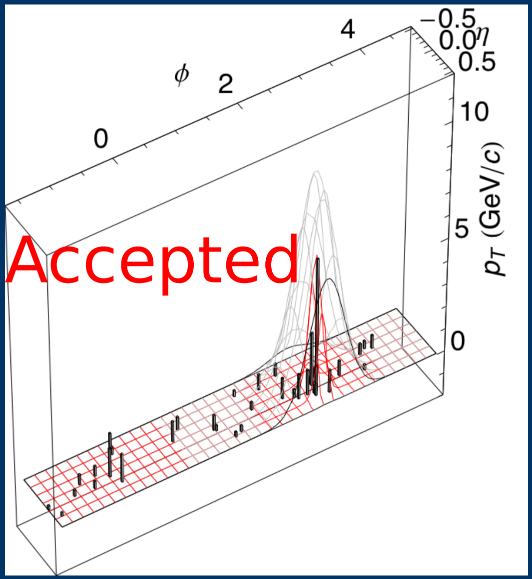
very good angular resolution

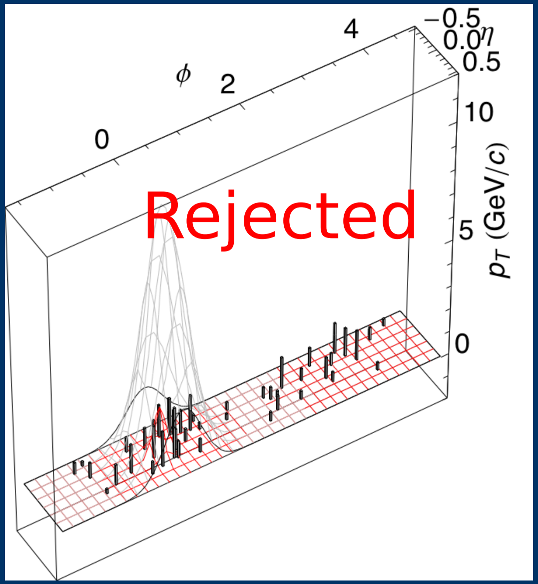
di-jet dphi acceptance...

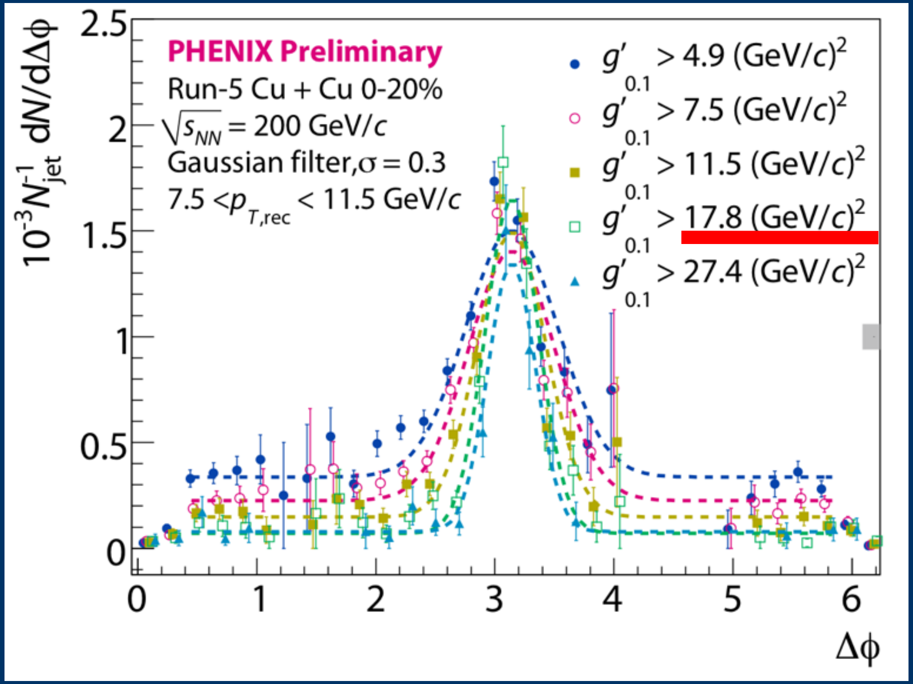


J.Kapitán (STAR), EPS HEP 2009.

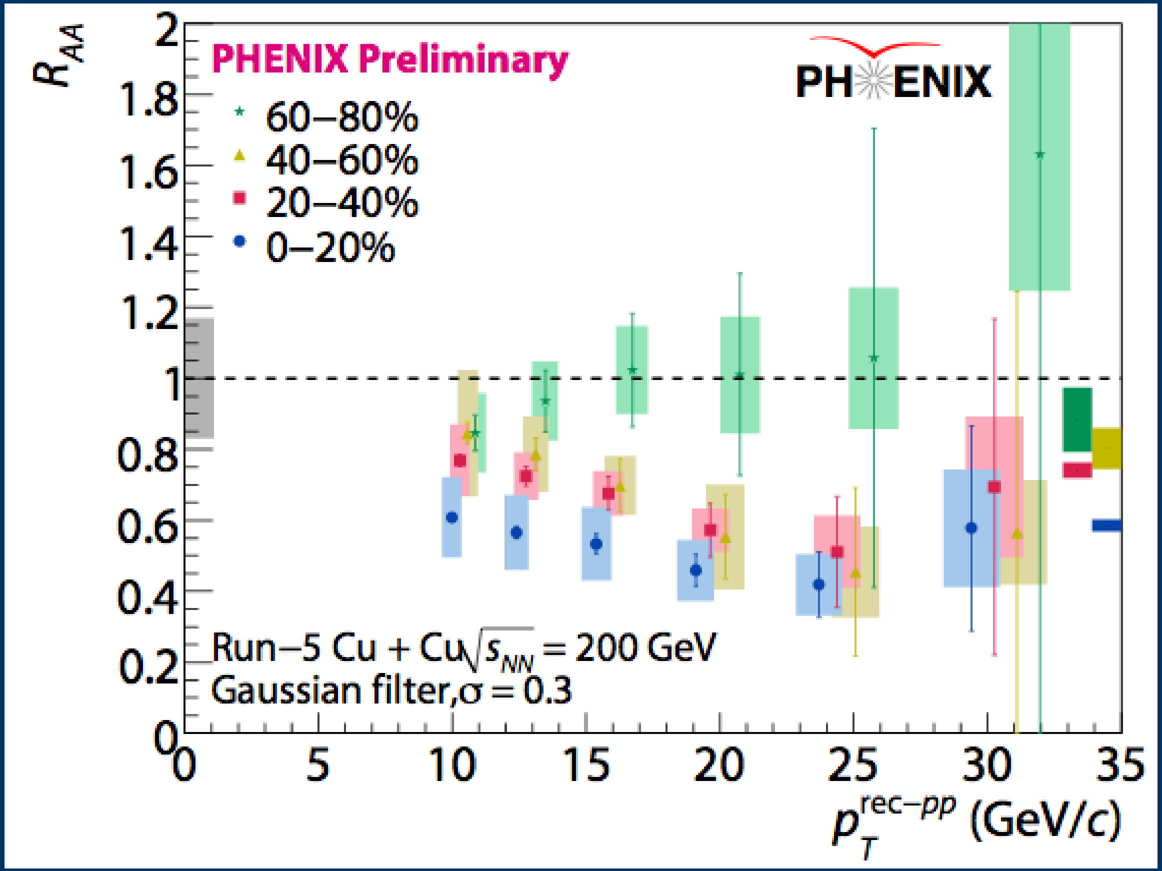
Fake jet rejection through filter







PHENIX centrality-depedent R_{AA}



Y.S.Lai (PHENIX), RHIC AGS 2009.