Jets studies with STAR at RHIC
jet algorithms, jet shapes, jets in AA

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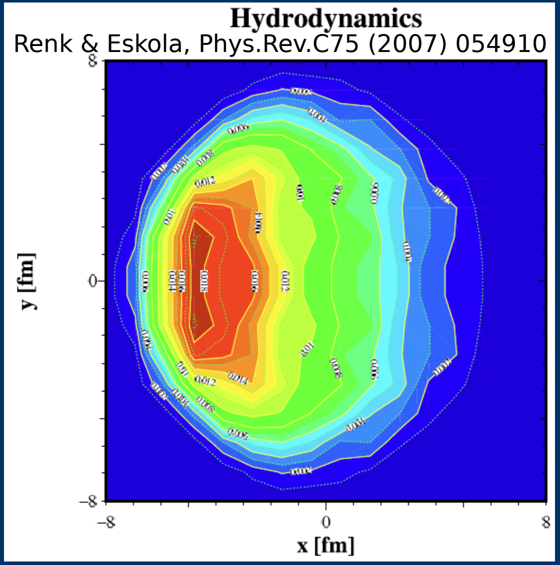
Full jet reconstruction

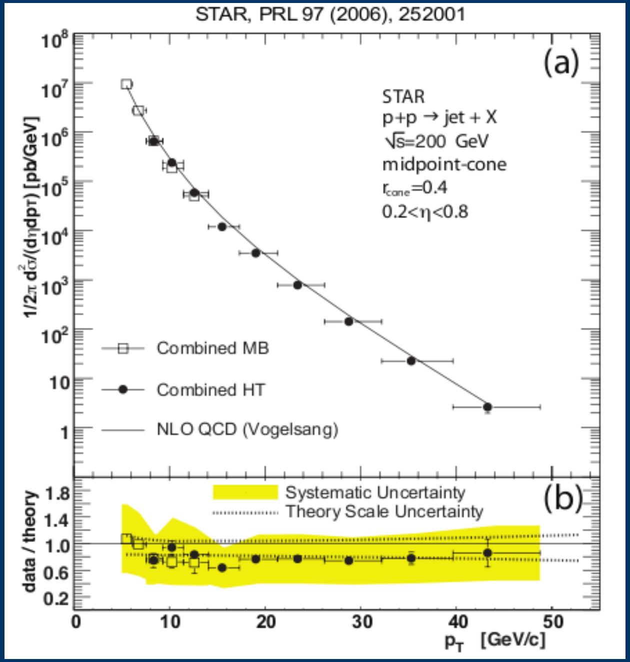
high-p_T hadron spectra and correlations:

- established jet quenching phenomena
- limited discrimination power due to:
  - fragmentation biases
  - bias towards least interacting jets (surface)



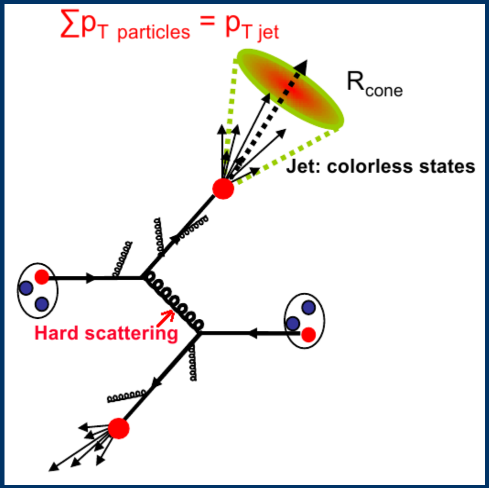
study the quenching directly with jets:

- access the partonic kinematics
- study energy flow, not individual hadrons
- well calibrated probe (pQCD)
- unbiased jet reconstruction: expecting R_{AA}=1 (caveats: nPDF, medium-induced jet broadening)

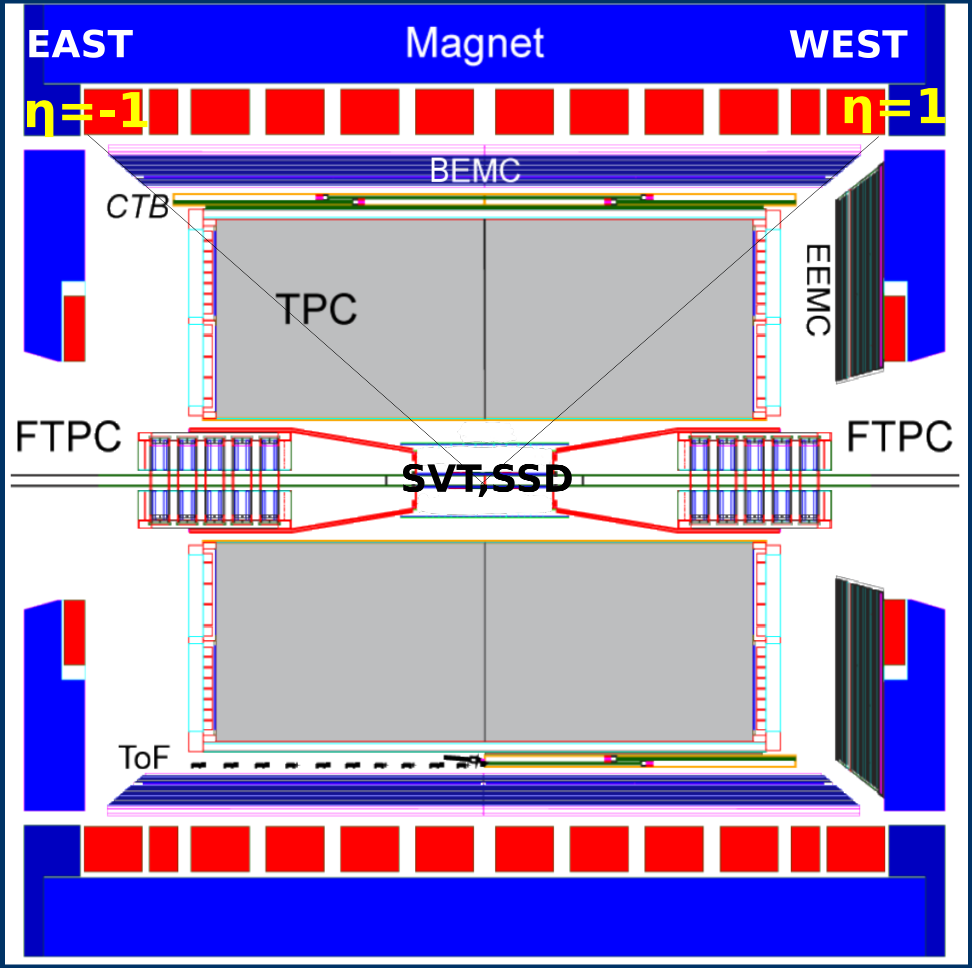


Outline

- jet reconstruction in STAR
- initial state: jet spectra in d+Au
- background fluctuations & jet spectra in Au+Au
- jet shapes
- di-jet and jet-hadron correlations



STAR experiment at RHIC



solenoidal magnetic field 0.5 T

detectors used (|η|<1, Φ: 2π):

- Time Projection Chamber: tracking
- Barrel EM Calorimeter (BEMC):
  - -neutral energy (towers 0.05x0.05)
  - -trigger

$p_{T,track/tower}$ > 0.2 GeV/c

"100% hadronic correction": subtract matched track p_T off tower E_T: avoid double-counting (MIP, electrons, hadronic showers)

centrality selection – charged multiplicity:
Au+Au: |η|<0.5, d+Au: -4<η<-2.5

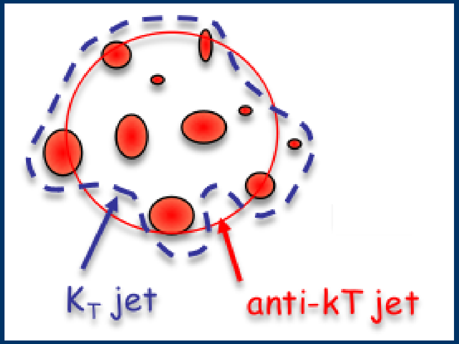
data used: 200 GeV p+p (2006), Au+Au (2007), d+Au (2007/2008)

Jet reconstruction

recombination algorithms - FastJet package

Cacciari, Salam and Soyez, JHEP0804 (2008) 005.

- k_T, anti-k_T: different sensitivity to background
- R: resolution parameter: 0.2 or 0.4
- recombination: E scheme with massless particles



analysis procedure:

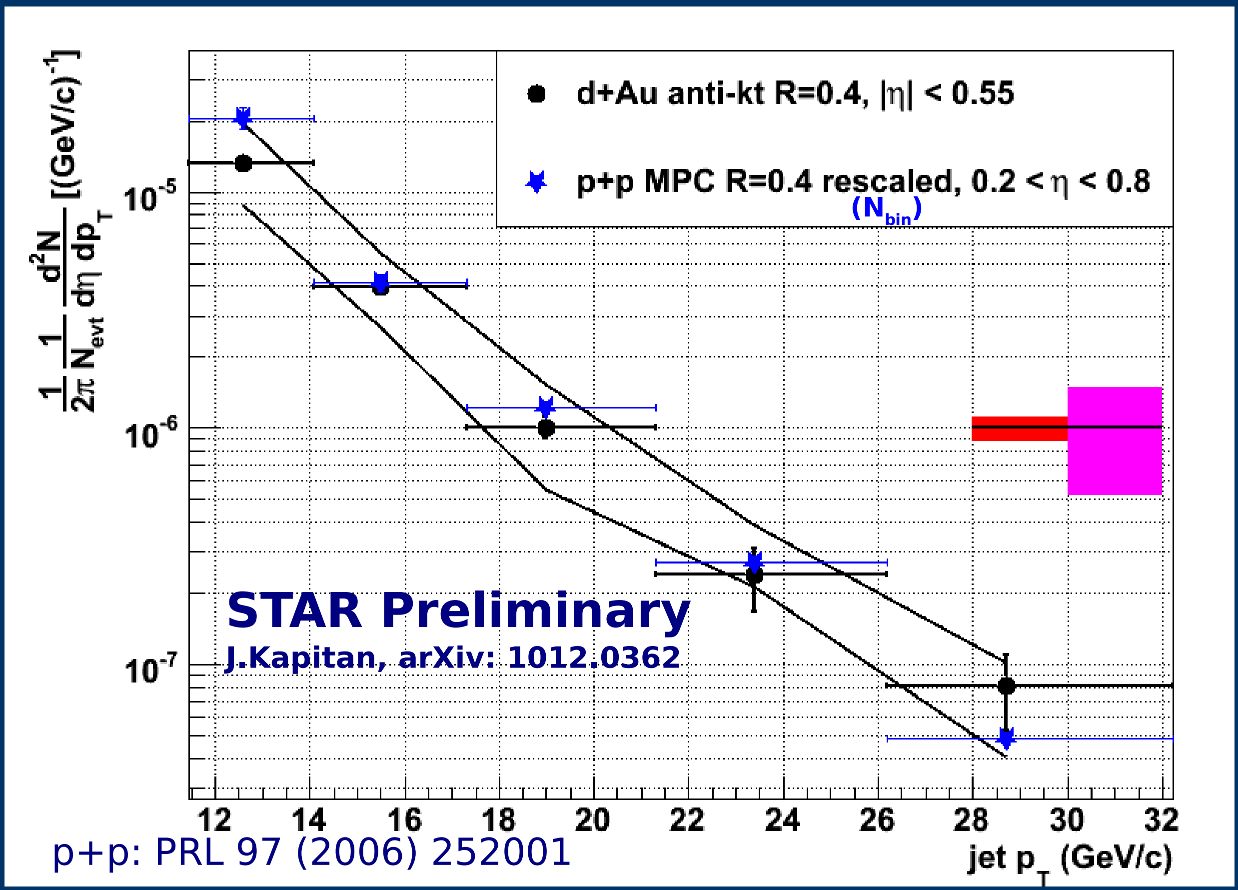
1. define jets (k_T, anti-k_T), active area A
2. estimate background density from k_T jets: ρ = median{p_T/A}
3. subtract the background: $p_{T,jet,true} = p_{T,jet,observed} - \rho * A$
4. correct for background fluctuations
5. correct for detector effects (jet p_T shift & resolution)

jet reconstruction uncertainties:

- Jet Energy Scale (BEMC calibration, TPC tracking efficiency): leading uncertainty in p+p, d+Au
- background fluctuations: leading uncertainty in Au+Au

Initial state: p+p & d+Au

- 10M 0-20% most central events, η-dependent background subtraction
- bg. fluctuations & detector effects corrected via Pythia jets embedding



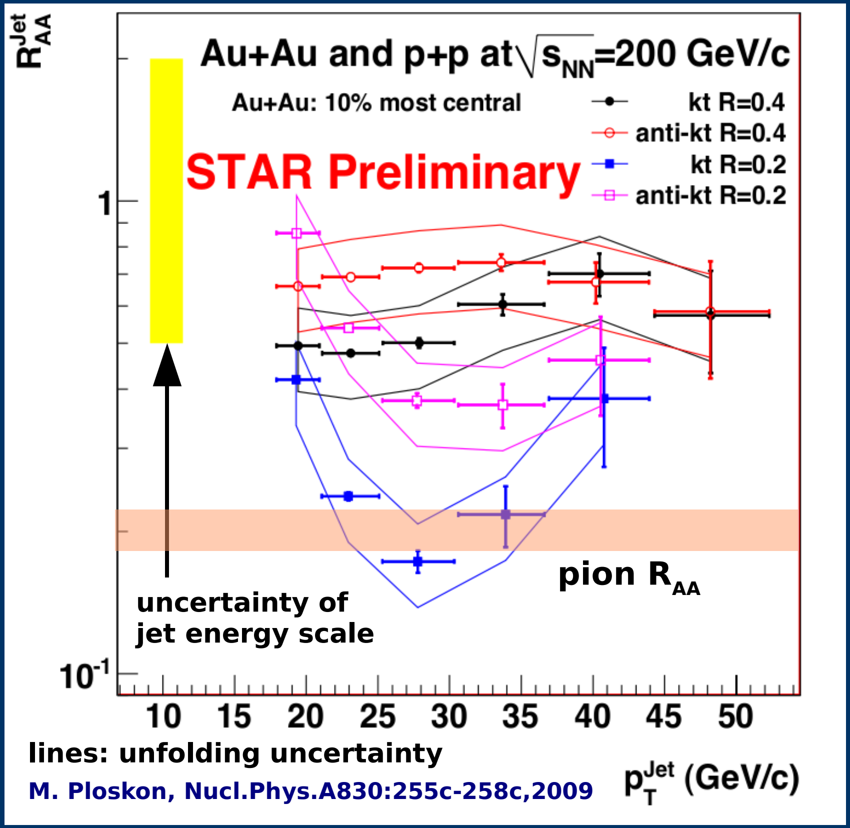
black error band: d+Au JES uncertainty (TPC: 10%, BEMC: 5%)
red box: $\langle N_{bin} \rangle$ 12% unc.
magenta box: p+p total systematic uncertainty (including jet energy scale)

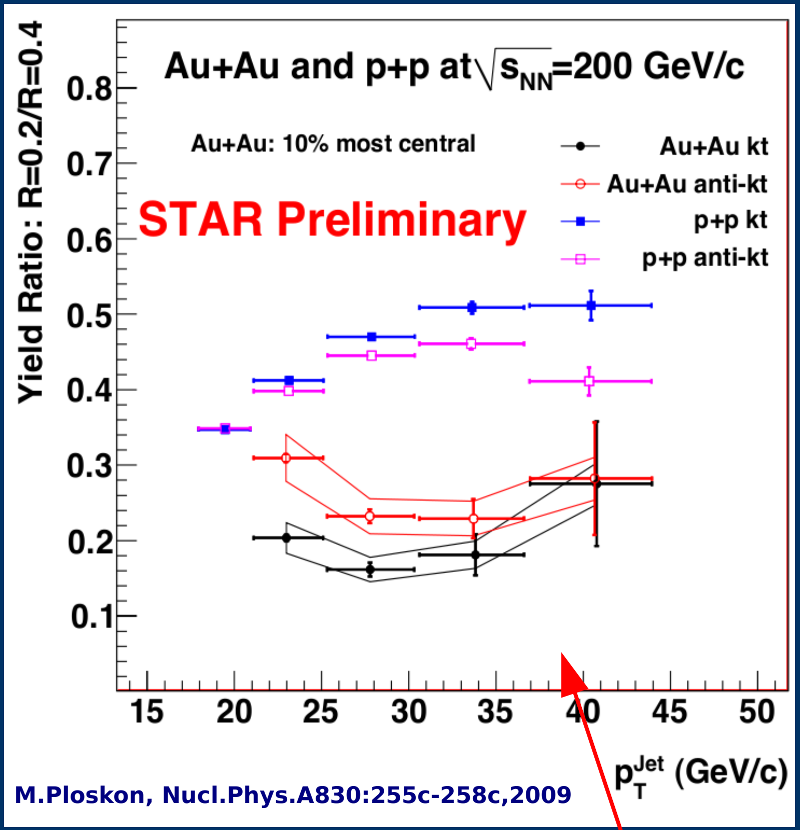
note
- different η range
- different jet algorithm

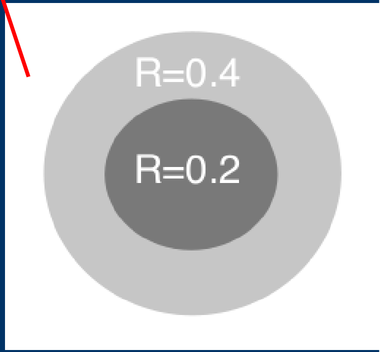
towards jet R_{dAu}:
- decrease syst.uncertainties
- extend to higher p_T

→no significant deviation from N_{bin} scaled p+p

Jet spectra: Au+Au vs. p+p







- **R=0.4 jet R_{AA} compatible with 1**
- **consistent with jet broadening from R=0.2 to R=0.4**

R>0.4 difficult to measure due to bg. fluctuations
→ di-jet and jet-hadron correlations (last part of the talk)

Background fluctuations

current results: Gaussian parametrization based on Pythia embedding

this presentation:

- is Gaussian model appropriate?
- we know there's jet quenching: how does fragmentation (and its modification) influence jet reconstruction in presence of background?
- assess background fluctuations with various fragmentation scenarios

embedding studies with real (central) Au+Au events:

1. determine background density with k_T algorithm: ρ = median{p_T/A}
2. embed a “jet” (various options) and run anti-k_T jet finder
3. find a cluster containing the embedded jet (> 50% of its energy)

quantify response to background via:

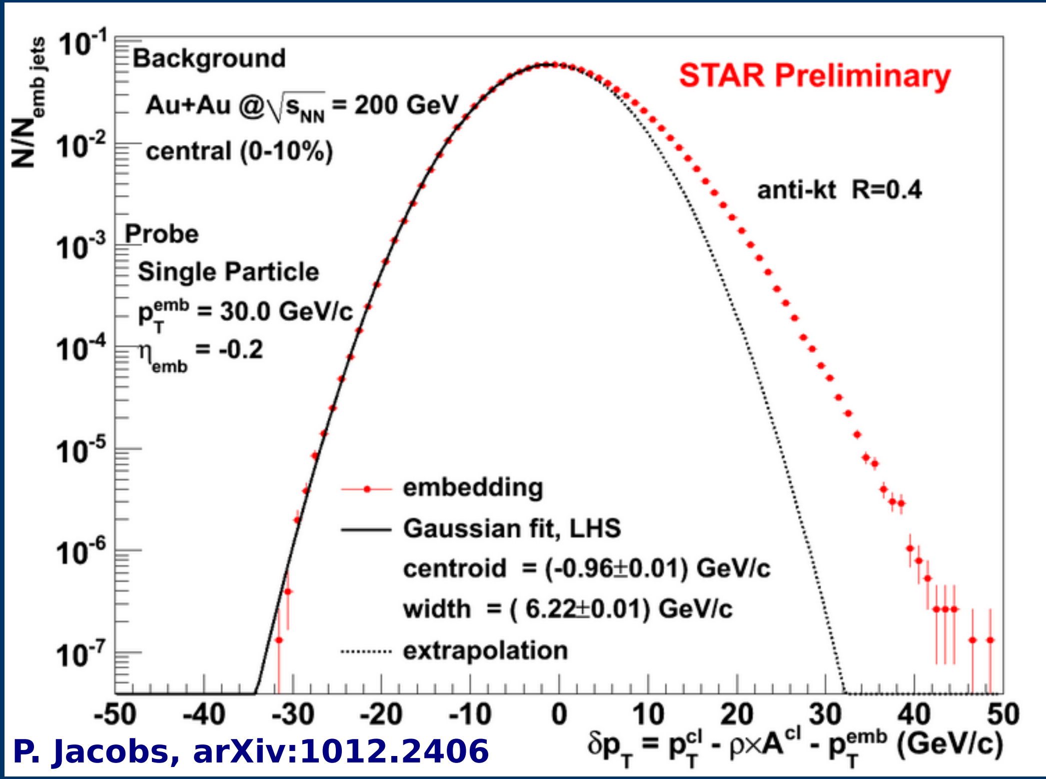
$$\delta p_T = p_T^{cluster} - \rho \cdot A^{cluster} - p_T^{emb}$$

identical to Δp_T in arXiv:1010.1759 (Cacciari, Rojo, Salam, Soyez)

Example of δp_T distribution

embedding single particle with p_T = 30 GeV/c, η = -0.2

same jet embedded into 8M events:



what does δp_T depend on?

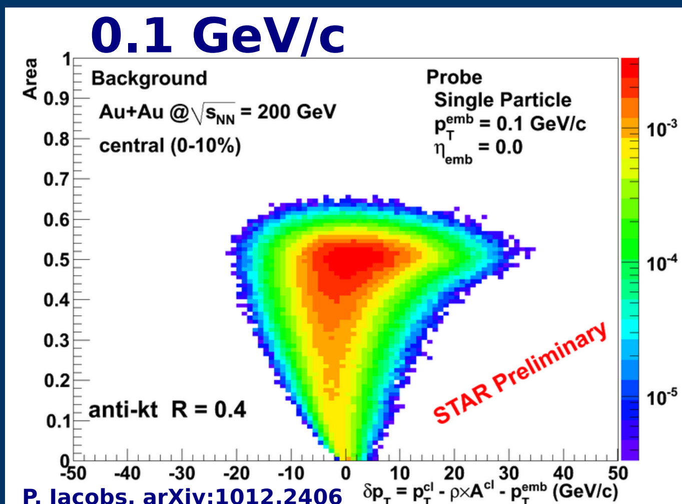
- jet area A
- jet p_T
- jet fragmentation pattern

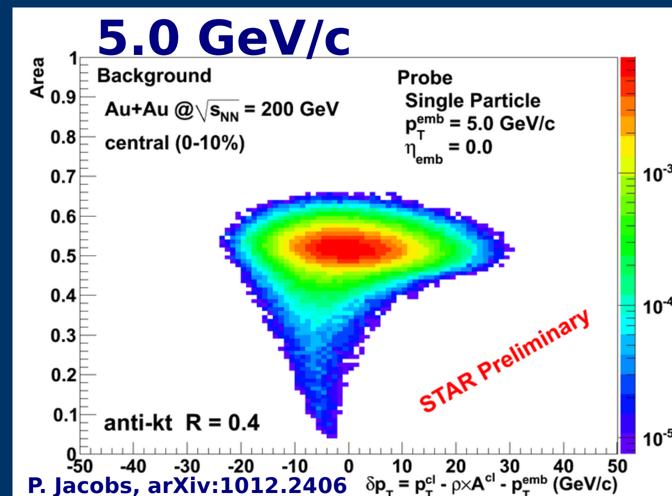
following studies:
for R=0.4 jets...

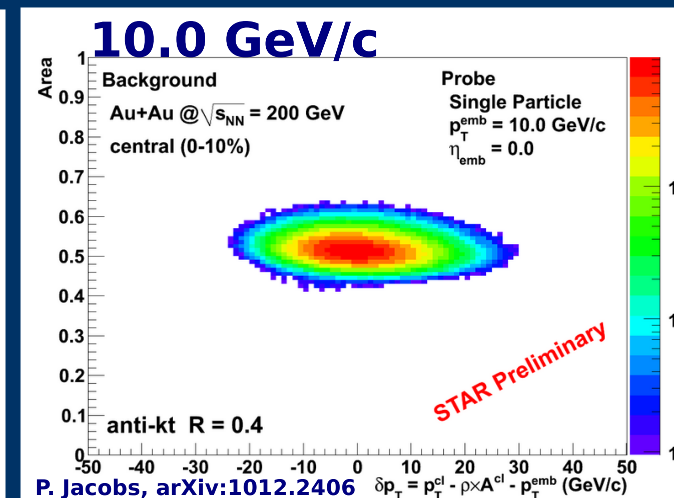
- response over 40 GeV and 5 orders of magnitude
- Gaussian fit to LHS good, non-Gaussian tail in RHS!

Dependence on jet area

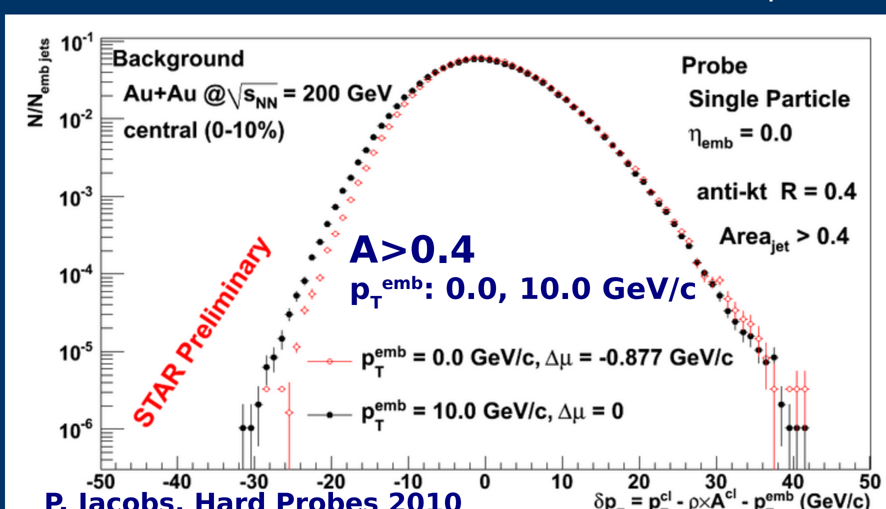
anti-k_T clustering: area distributions for various p_T^{emb}







area distribution for low p_T probes very broad -> constrain the area:

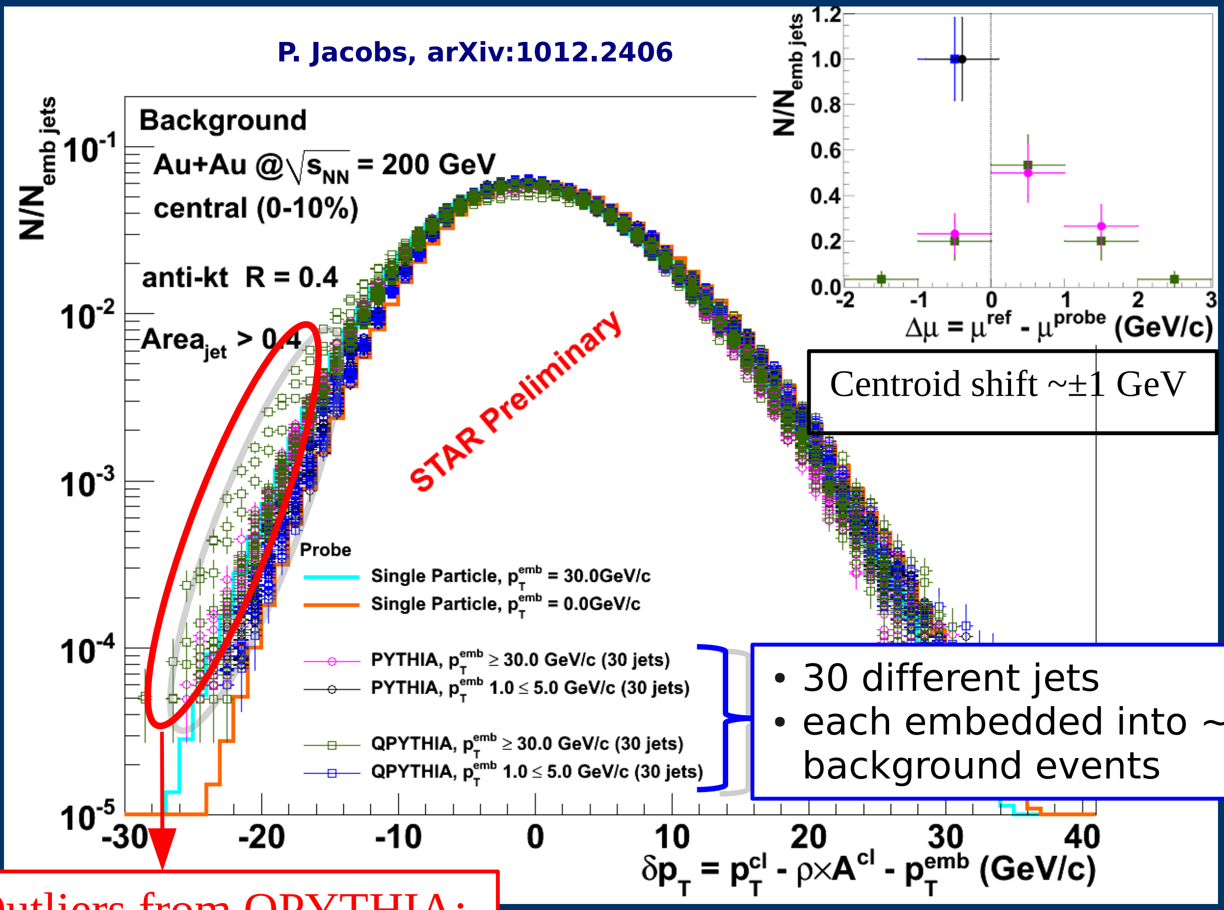


fixed area: δp_T varies little with p_T^{emb}

indication that specific jet structure is unimportant!

- verify this with Pythia, QPythia...

δp_T: sensitivity to fragmentation



Centroid shift ~±1 GeV

- 30 different jets
- each embedded into ~8M background events

Outliers from QPYTHIA:
•2 out of 30 jets
•physics or modeling?

negligible effect for final correction: it's for $\delta p_T < 0$

fluctuation distribution ~universal: independent of p_T^{emb}, fragmentation within factor 2 at 30 GeV/c

to do:

- fully characterize δp_T distribution
- implement in unfolding

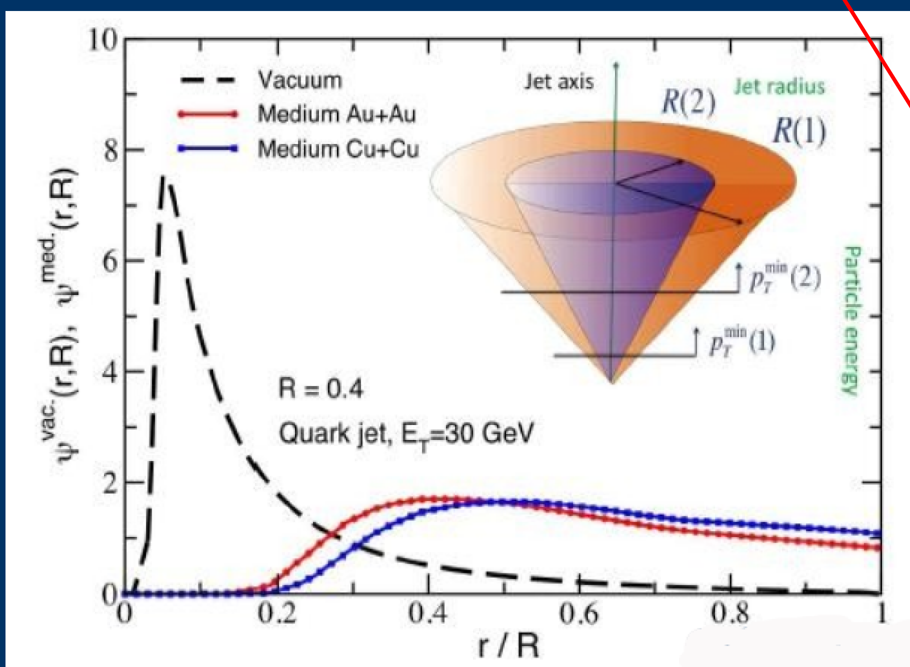
Irresolution due to background fluctuations ~independent of fragmentation pattern!

Jet shapes

- elementary particle collisions: jets getting narrower at high p_T
- modification of jet structure in HI collisions -> changes in jet shape!

differential jet shape:

$$\psi(r) = \frac{1}{N_{jets}} \int_{p_T^{\min}}^{p_T^{\max}} dp_{Tjet} \int_0^{p_T^{\max}} dp_T(r) \left(\frac{1}{p_{Tjet}} \frac{dp_T(r)}{dr} \right) \frac{d^2N}{dp_{Tjet}\, dp_T(r)}$$



I. Vitev, B. W. Zhang, Phys.Rev.Lett.104 (2010), 132001

ring at radius r, width dr
A: jet area

in the presence of background:

$$\frac{1}{P_{Tjet}^{\text{signal}}} \frac{dp_T^{\text{signal}}}{dr} = \frac{\overbrace{dp_T^{\text{cluster}} / dr - 2\pi\rho r}^{\text{Ring } P_T}}{\underbrace{p_{Tjet} - \rho A}_{\text{Jet } P_T}}$$

Jet shapes distortion: embedding

- Au+Au central events (0-10%)
- embed 30 GeV/c pion as a probe
- anti-k_T algorithm (R=0.6)
- analyze the cluster containing the probe
- area cut: $\pi^*R^2 < A < \pi^*R^2 + 0.05$
- only charged particles

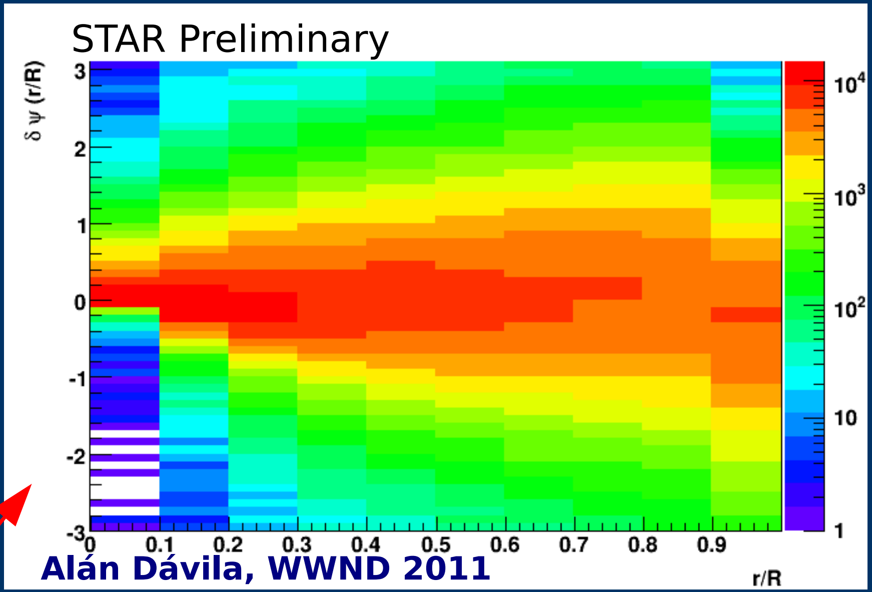
jet shape obtained from this cluster:
pure background

$$\delta(\psi) = \psi_{signal+Background} - \psi_{signal}$$

$$\psi_{signal} = 0$$

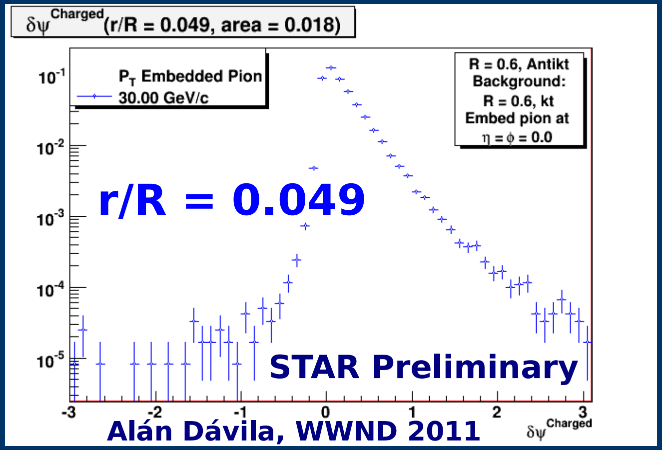
$$\delta(\psi) = \frac{dp_T^{cluster} / dr - 2\pi\rho r}{p_T^{cluster} - \rho A}$$

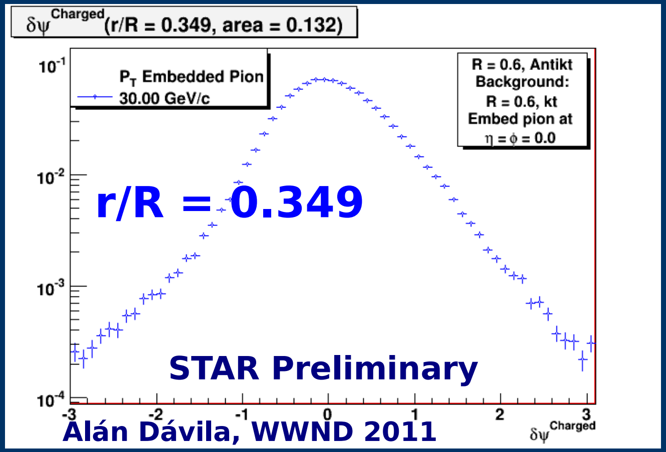
ρ: from k_T algorithm, R=0.6

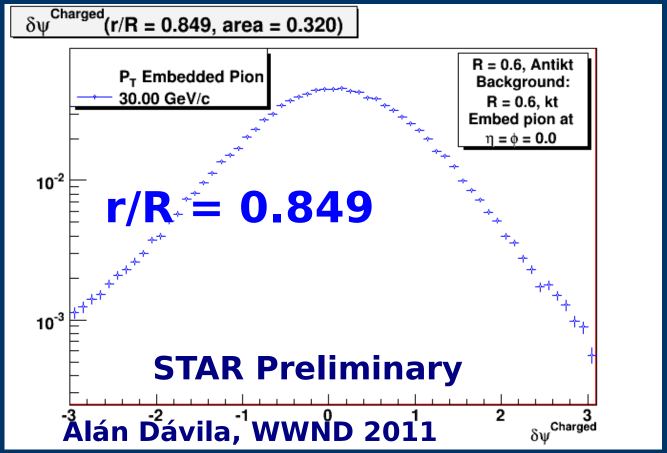


ring area increases with r/R
so does the fluctuation width...

Dependence on r/R





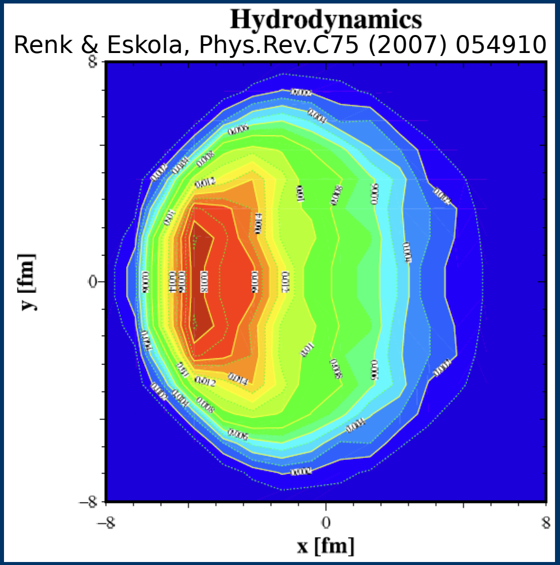


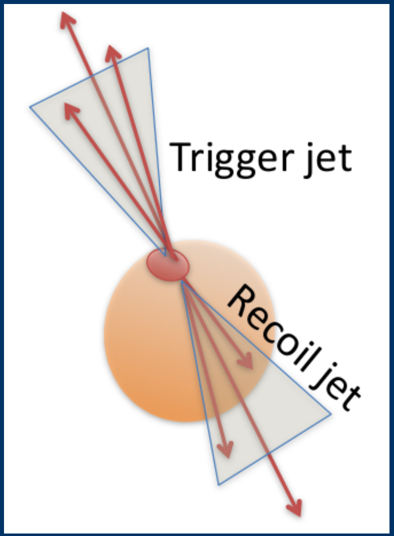
- dependence of fluctuations on r: expected from ring area dependence on r
- study in progress: variable r bins -> same area rings

Stay tuned:
➔ **checks of (in-)dependence on fragmentation**
➔ **unfolding of jet shapes from real data coming soon...**

Jet-triggered correlations

- use highly biased jet sample: jets containing BEMC tower with E_T>5.4 GeV
- strong surface bias
- idea: maximize recoil jet medium path length
- trigger jets reconstructed with $p_{T,cut}$=2 GeV/c to achieve similar jet energy scale in p+p, Au+Au
- trigger jet energy uncertainty: ± 2 GeV

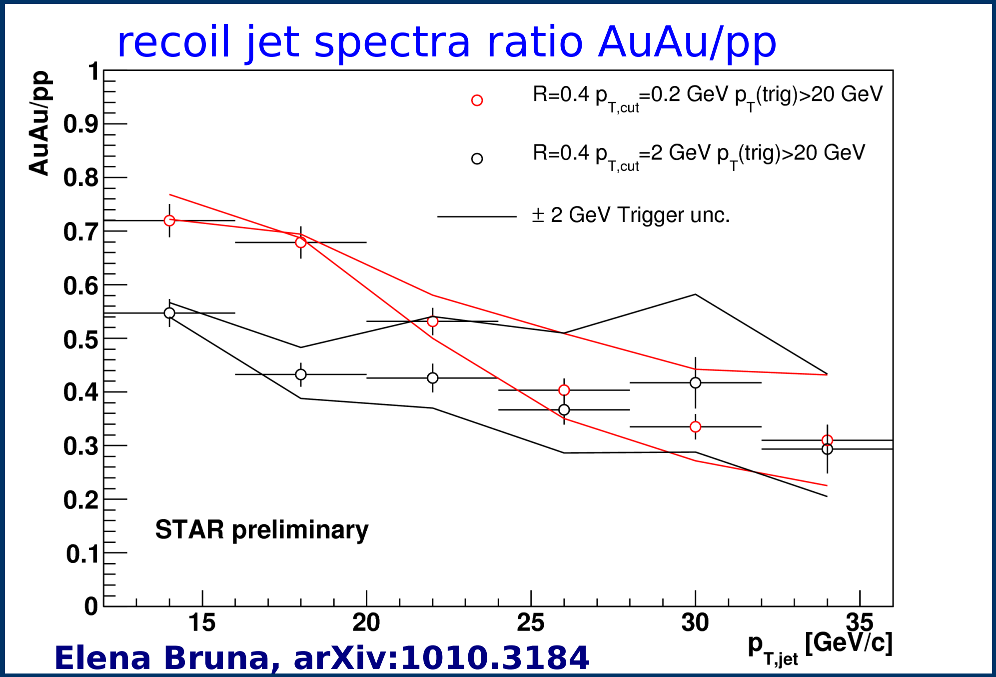




- **di-jet correlations (away side)**
- **jet-hadron correlations (near+away side)**

Di-jet correlations

- trigger jet: p_T>20 GeV/c
- look for away-side jet modification:
- construct ratio of AuAu/pp spectra of the recoil jets
- test for 2 different $p_{T,cut}$ values for recoil jets

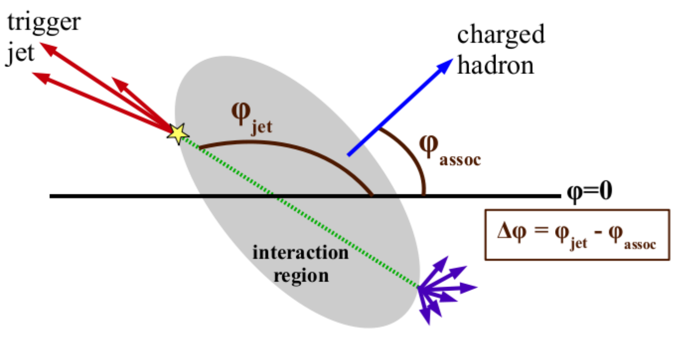


Gaussian unfolding of away-jets:
$p_{T,cut}$=0.2 GeV/c: σ = 6.5 GeV
$p_{T,cut}$=2 GeV/c: σ = 1.5 GeV

➔ **suggestive of energy profile broadening beyond R=0.4**

Jet-hadron correlations

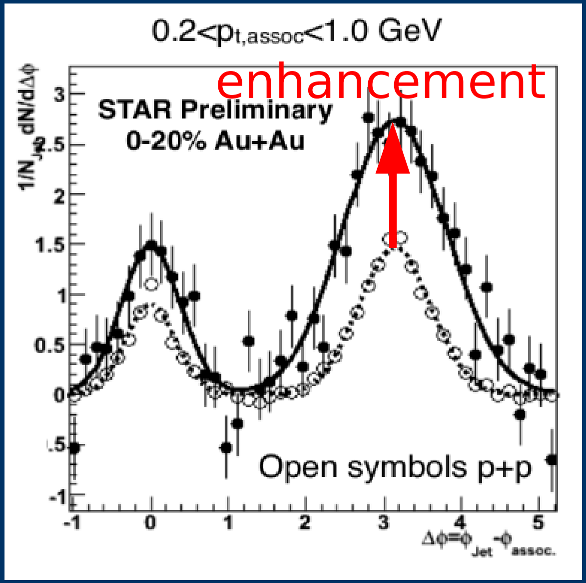
- azimuthal correlations of charged hadrons with respect to HT (trigger) jet axis
- increased kinematic reach compared to di-hadron correlations

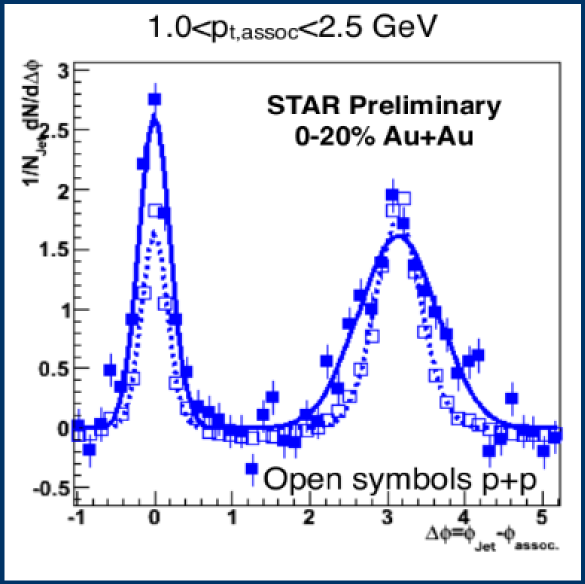


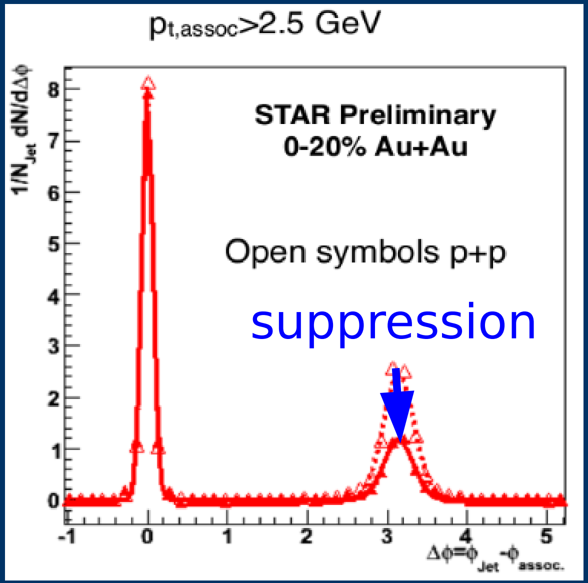
initial results – **flat background subtraction**, $p_{T,jet}$ > 20 GeV/c:

(J.Putschke, RHIC AGS Users Meeting 2009)

softening & broadening!







Background model: jet v_2, ZYAM

- ZYAM is known to overestimate background level in the presence of broad peaks (central collisions, low $p_{T,assoc}$)
- jet v_2 *a-priori* unknown (analysis in progress)

in the following, background estimated by fitting (ZYAM used for comparison):

$$2\ \text{Gaus} + B*(1+2*v_2^{assoc}*v_2^{jet}*\cos(2\Delta\varphi))$$

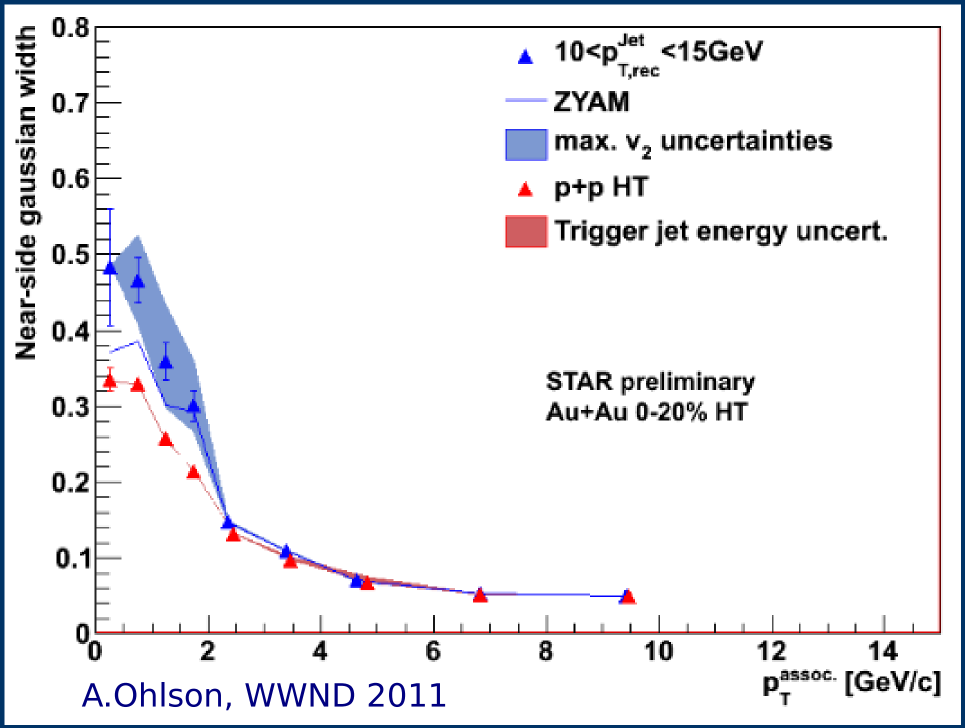
$(v_2\{2\}+v_2\{4\})/2$ $v_2\{2\}$ (p_T=6 GeV/c)

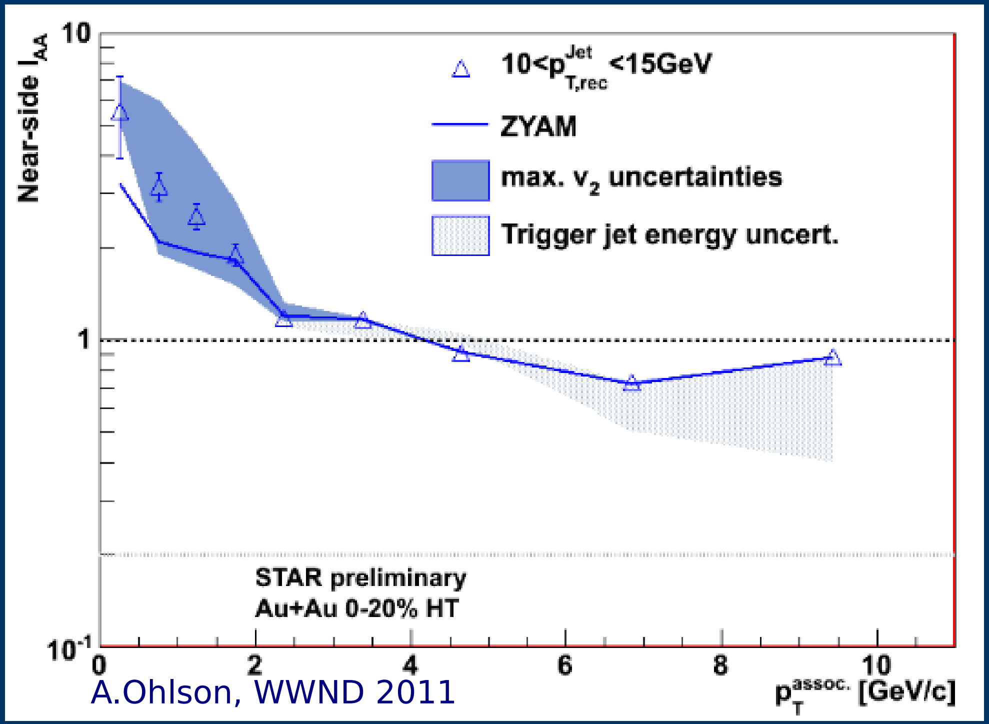
maximum v_2 uncertainties:

no v_2

nominal v_2 + 50% $v_2^{jet}*v_2^{assoc}\{2\}$

Nearside: Gaussian width, I_{AA}

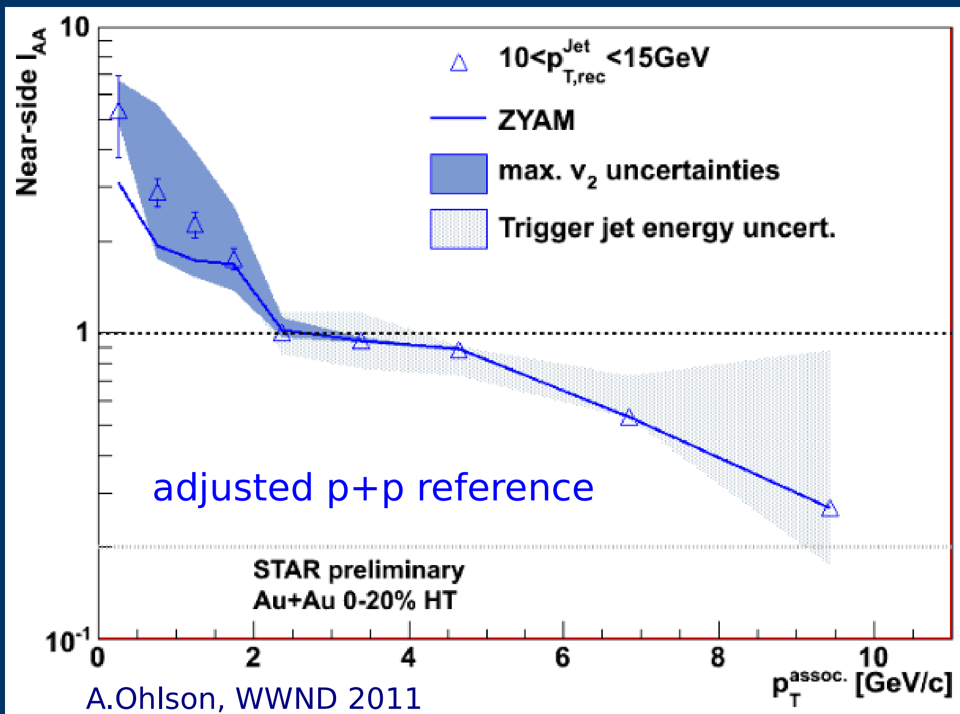


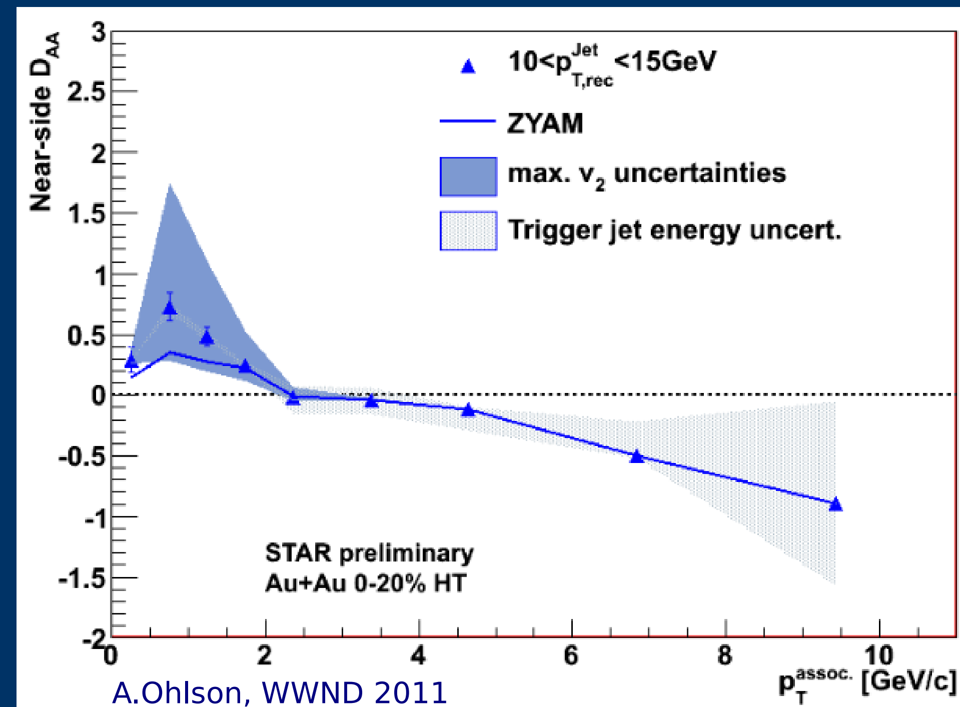


broadening & softening on the nearside:
- **unsubtracted background (ridge, v_3)?**
- **jet modification (energy loss)?**

let's assume there is energy loss on the nearside: from I_{AA} there is ~2GeV excess “charged” energy in Au+Au -> adjust the p+p reference: + 2GeV * 3/2

Nearside energy balance: D_{AA}





$$D_{AA}(p_T^{assoc}) = Y_{AA}(p_T^{assoc}) \cdot p_{T,AA}^{assoc} - Y_{pp}(p_T^{assoc}) \cdot p_{T,pp}^{assoc}$$

$$\Delta B = \int dp_T^{assoc} D_{AA}(p_T^{assoc})$$

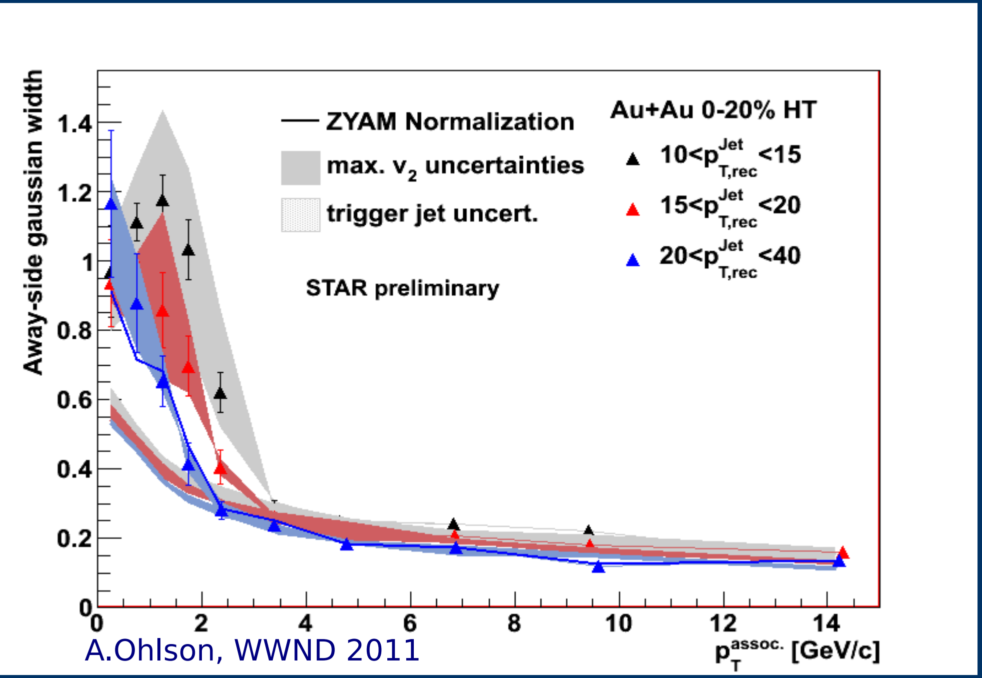
ΔB: is low-p_T enhancement compensated by suppression at high p_T?

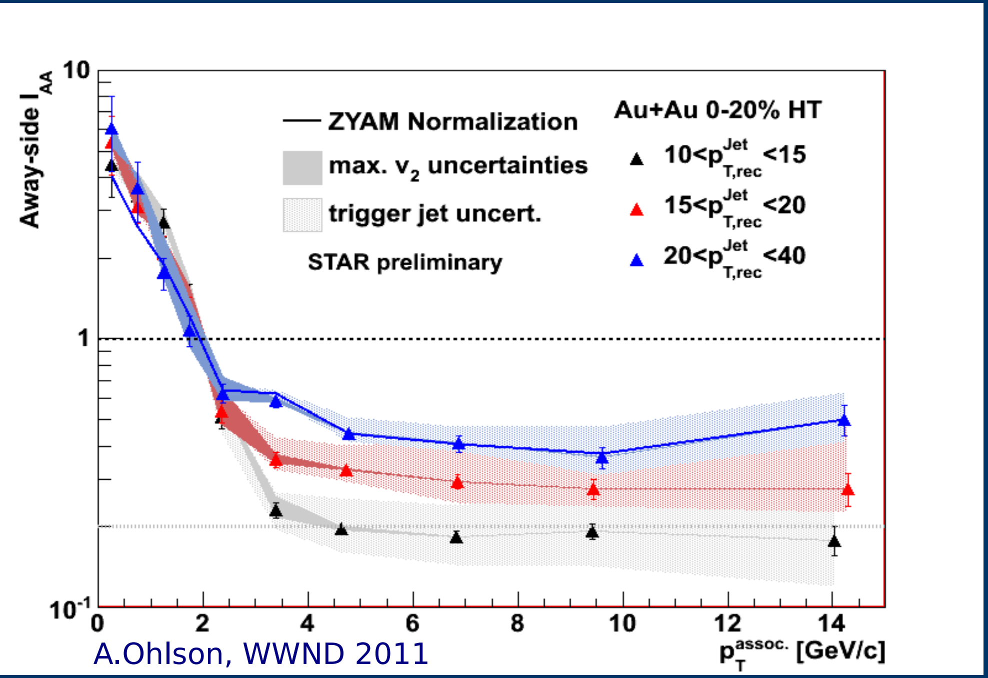
before p+p energy shift: ΔB ~ 1.6 GeV

after p+p energy shift: ΔB = 0.4 +- 0.2 (stat) GeV

indication of energy loss even for HT trigger jets

Awayside Gaussian width & I_{AA}

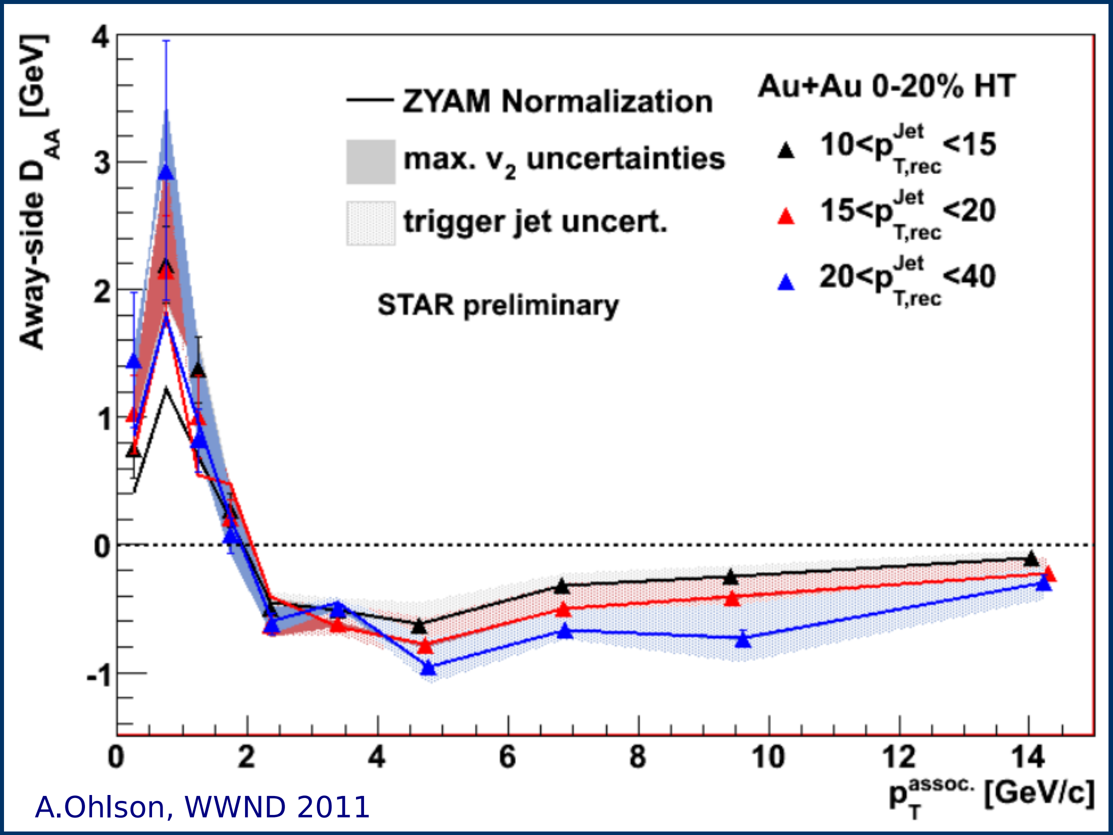




- **significant broadening and softening of awayside peak**
- **less modification of jets with higher p_T**

Awayside energy balance: D_{AA}

$$D_{AA}(p_T^{assoc}) = Y_{AA}(p_T^{assoc}) \cdot p_{T,AA}^{assoc} - Y_{pp}(p_T^{assoc}) \cdot p_{T,pp}^{assoc}$$



- significant compensation of low p_T enhancement and high p_T suppression: **jet quenching in action**

Conclusions

d+Au jet spectrum:

- no significant Cold Nuclear Matter effects observed

Au+Au jet spectrum:

- R = 0.4 jet R_{AA} compatible with 1
- consistent with jet broadening from R=0.2 to R=0.4

background fluctuations:

- **δp_T:**
  - non-Gaussian tails
  - largely independent of fragmentation pattern of the probe
- **jet shapes:**
  - studies in progress, stay tuned!

di-jet suppression suggestive of awayside broadening

jet-hadron correlations:

- softening, broadening and p_T redistribution observed
- HT trigger jet energy loss?

Thank you!

Backup

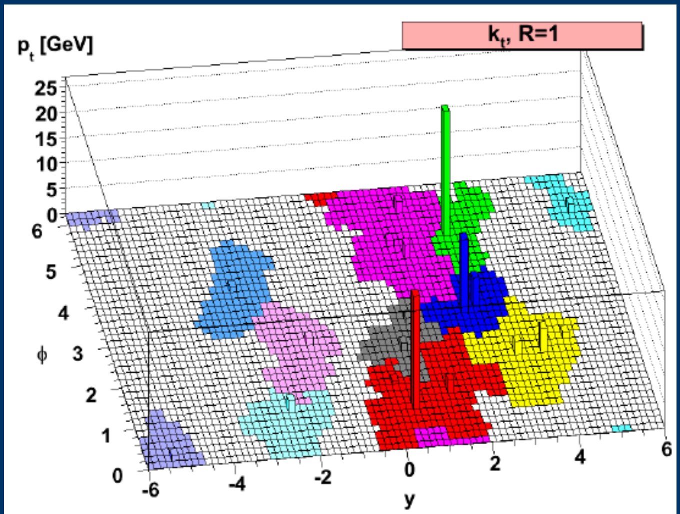
Algorithms details

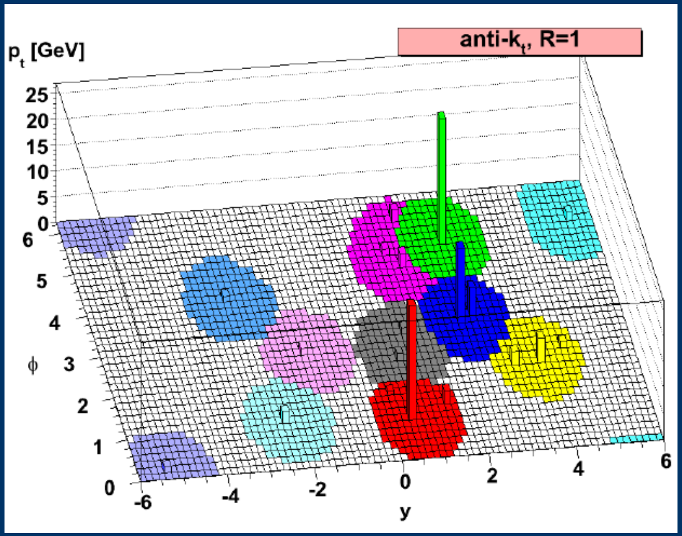
recombination algorithms - FastJet package

Cacciari, Salam and Soyez, JHEP0804 (2008) 005.

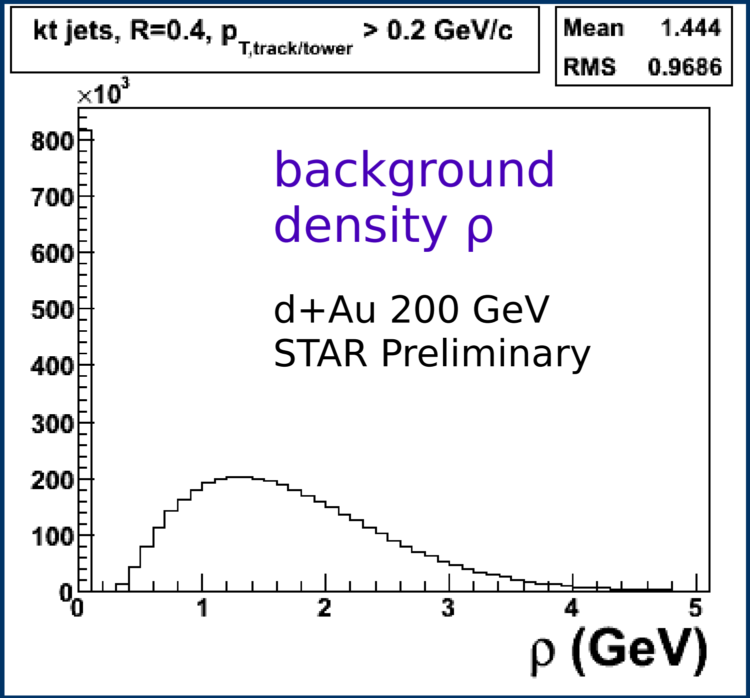
- $d_{ij} = \min(p_{Ti}^n, p_{Tj}^n)\,(\Delta\eta^2+\Delta\varphi^2)/R^2$, $d_i = p_{Ti}^n$
- $\min(d_i, d_{ij})$: d_i -> new jet, d_{ij} -> merge i,j

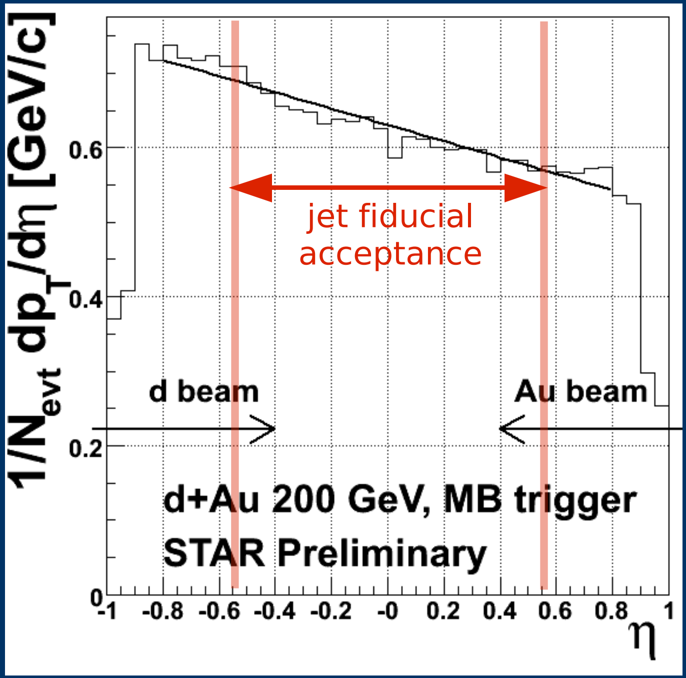
- n=2: kt, n=-2: anti-kt
- R: resolution parameter
- recombination: E scheme with massless particles

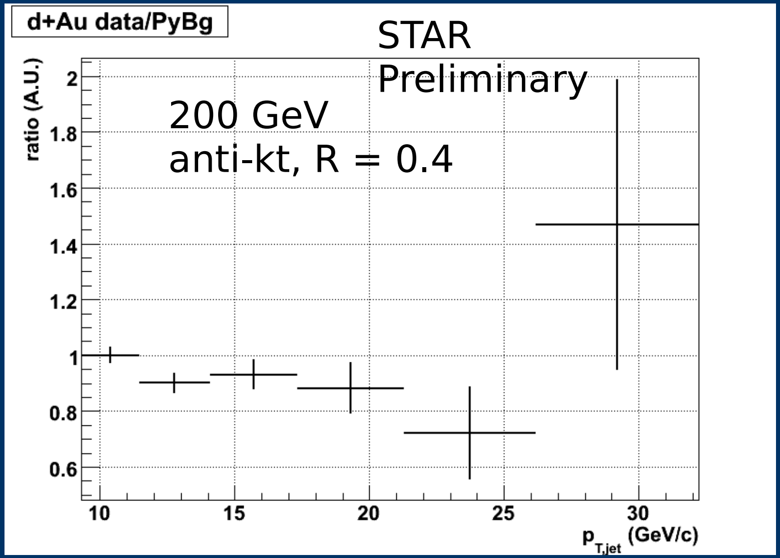




dAu details


kt jets, R=0.4, $p_{T,track/tower}$ > 0.2 GeV/c
Mean 1.444
RMS 0.9686
background density ρ
d+Au 200 GeV
STAR Preliminary
ρ (GeV)

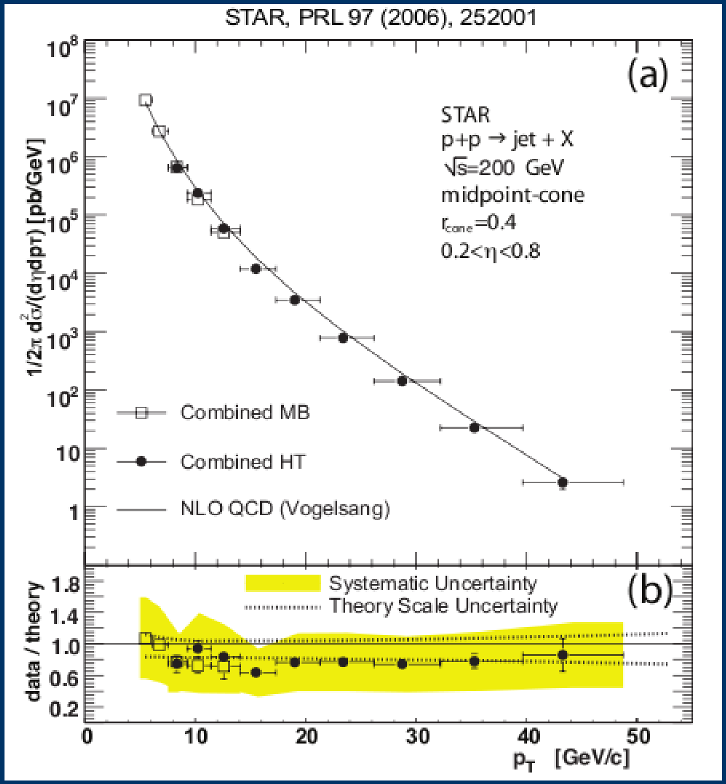

$1/N_{evt}\ dp_T/d\eta$ [GeV/c]
jet fiducial acceptance
d beam
Au beam
d+Au 200 GeV, MB trigger
STAR Preliminary
η


d+Au data/PyBg
STAR Preliminary
200 GeV
anti-kt, R = 0.4
ratio (A.U.)
$p_{T,jet}$ (GeV/c)

Jet cross section & relation to p+p

compare to STAR p+p jet cross section:

- Mid Point Cone algorithm
- R = 0.4



number of binary collision scaling:

if there are no nuclear effects, hard processes scale according to $<N_{bin}>$

for 20% most central run 8 d+Au collisions, $<N_{bin}> = 14.6 \pm 1.7$ from MC Glauber

d+Au: jet yield normalised per event rescaling p+p to this level:

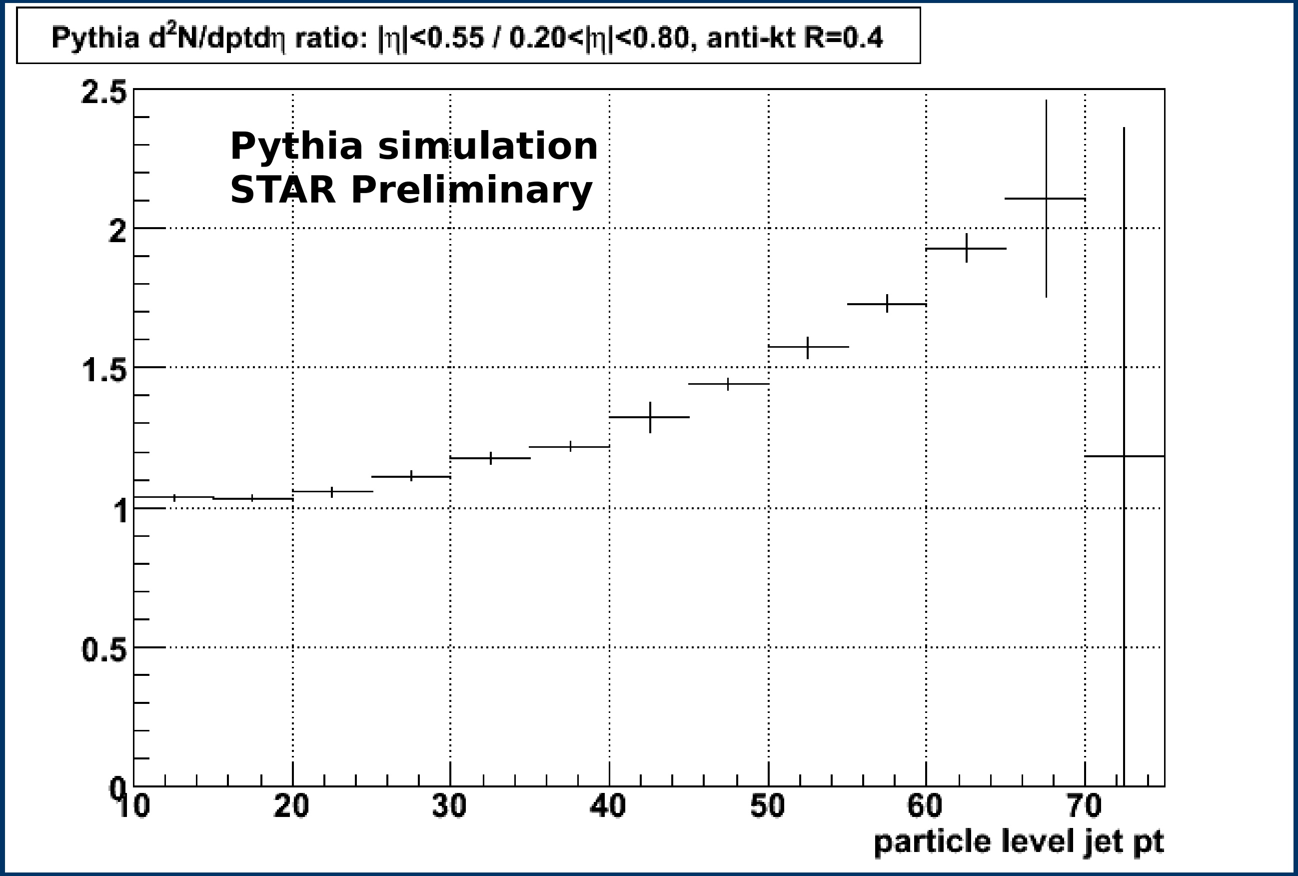
$$Y_{jet,p+p\ (d+Au\ level)} = \sigma_{jet,p+p} / \sigma_{inel,p+p} * <N_{bin}>$$

$\sigma_{inel,p+p}$ = 42 mb is p+p inelastic cross section

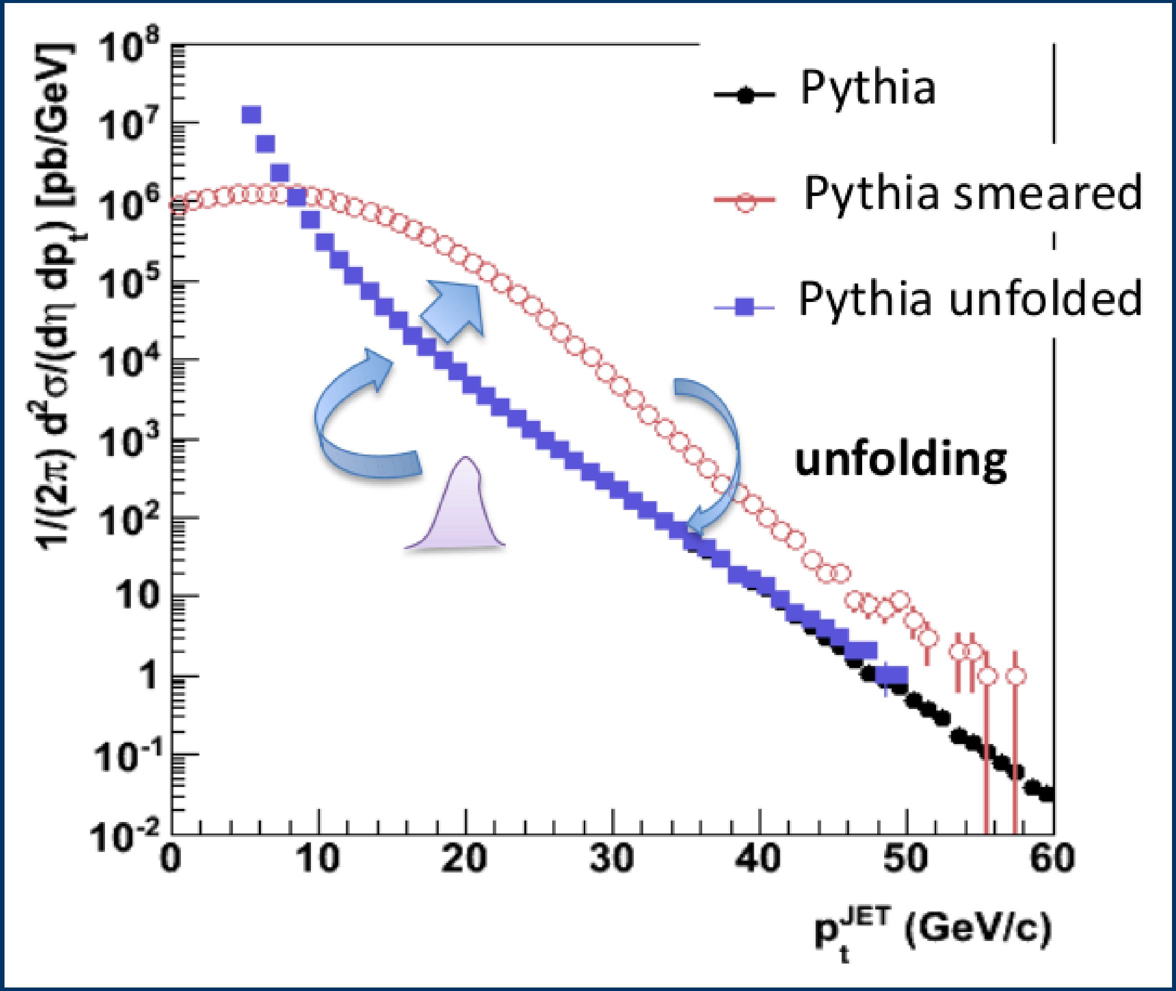
Pseudorapidity acceptance

jet dN/dη not flat: focusing towards η=0 for high jet p_T

$|\eta|<0.55$ vs $0.2<|\eta|<0.8$: 50% effect at 50 GeV/c, negligible below 20 GeV/c:



Jet spectra - unfolding

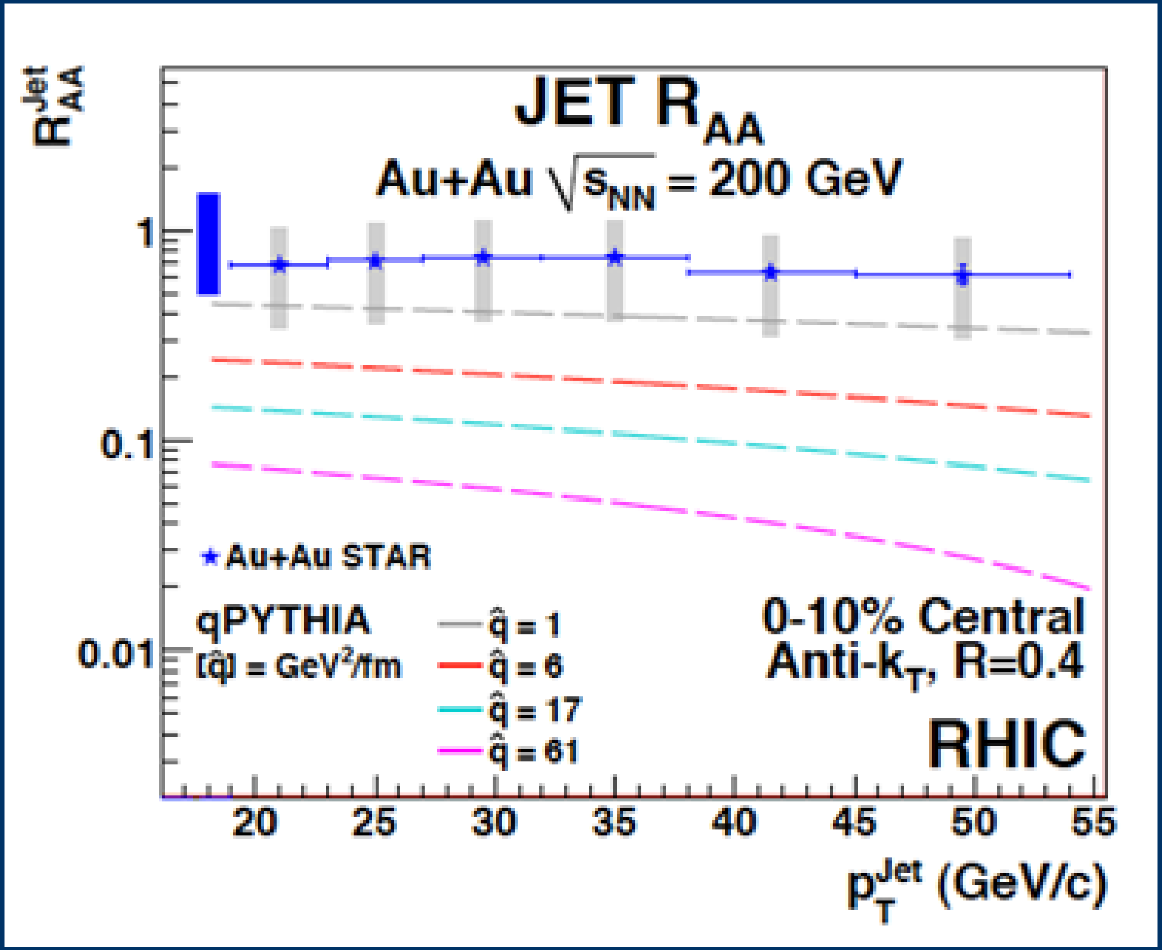


Gaussian widths – smearing/unfolding from Pythia embedding:

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

systematic uncertainty (bands): +-1 GeV

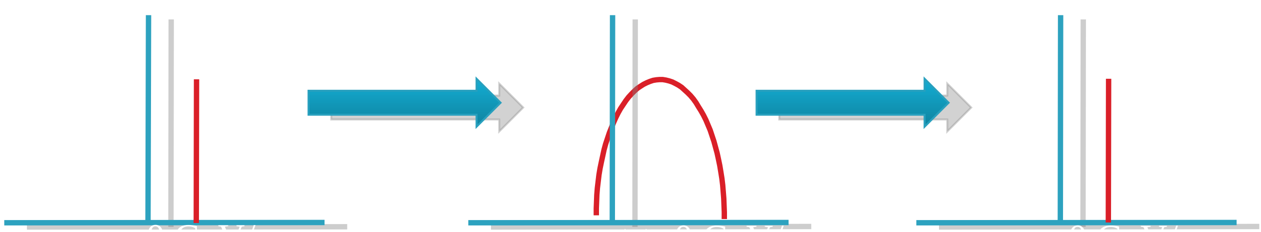
AuAu jets & theory



QPYTHIA...

False Jets

- Definition: Residual contribution of correlated background to the distribution of true jets after background subtraction
- Note 1: the pT irresolution caused by the background non-uniformities introduces false hard component to the reconstructed spectra (low pT objects are smeared and populate higher pT bins)
- Note 2: ideal unfolding procedure and complete knowledge of the background should revert the process -> retract the background objects from the pT spectrum leaving out only the true population of energy flow from hard scatterings
  - **Ideal de-convolution case: NO FALSE JETS**
- False jet yield is nothing but an estimate of how much of the residual background correlations are contaminating the reported jet yield -> precision of the unfolding matrix crucial(!)



Simple background model: uncorrelated particle emission

M. Tannenbaum
Phys. Lett. B498 (2001) 29

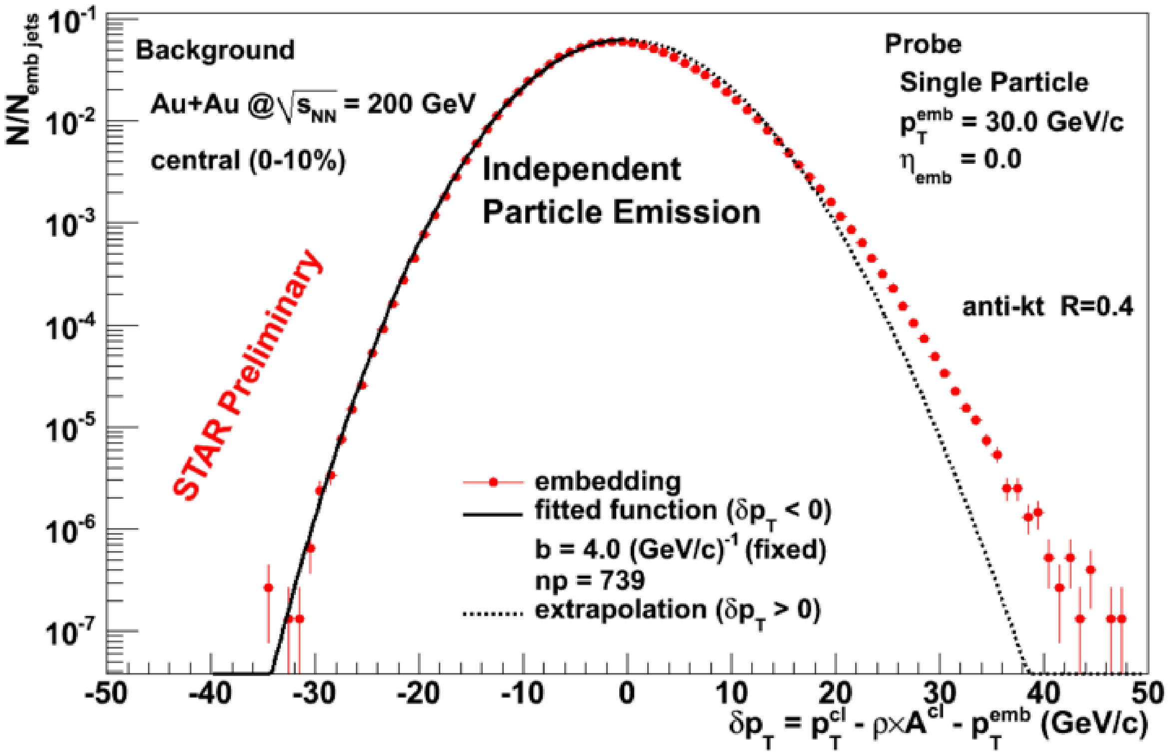
Inclusive single particle distribution:

$$\frac{d\sigma}{dp_T} = b^2 p_T^{p-1} e^{-bp_t}$$

E_T fluctuations in finite acceptance via *n*-fold convolution:

$$F_n(\delta p_T) = \frac{b}{\Gamma(np)} \cdot \left[b\left(\delta p_T + \frac{np}{b}\right)\right]^{np-1} \cdot e^{-b\left(\delta p_T + \frac{np}{b}\right)}$$

- No hard scattering
- No correlations
- Two parameters: *np*, *b*
  - $<p_T>$=2 GeV/*b*~500 MeV
  - *n*~740/2~370 “sources”



Simple uncorrelated-emission model can account for the bulk of background fluctuations (!)