Jets in STAR

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High-p_T Probes of High-Density QCD at the LHC

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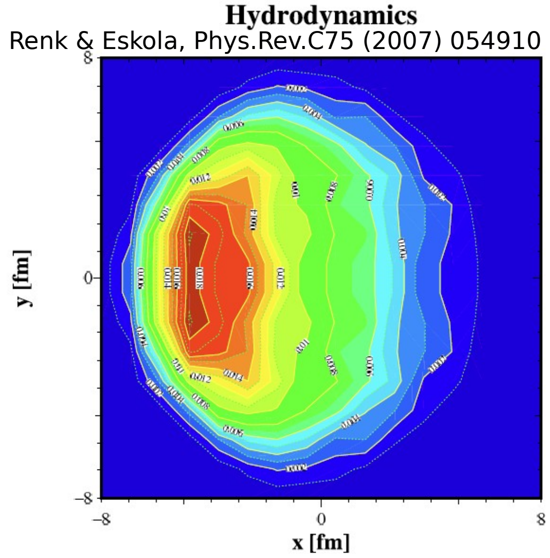
Full jet reconstruction

high-p_T hadron spectra and correlations:

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

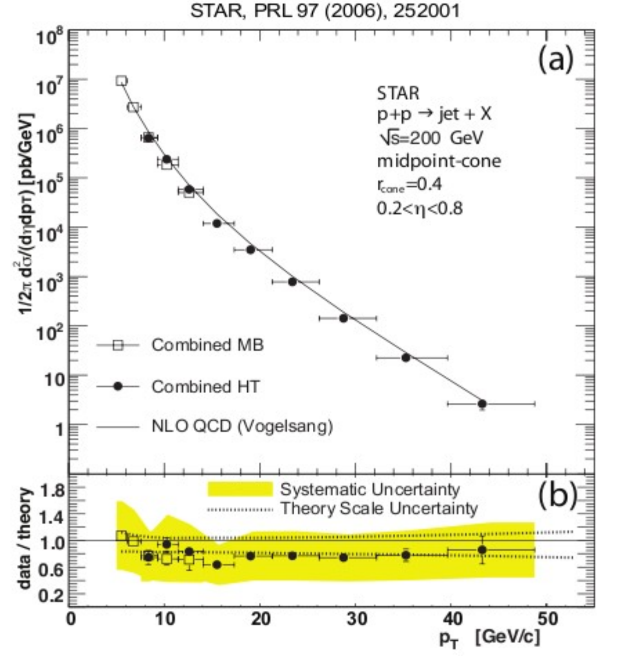


Hydrodynamics

Renk & Eskola, Phys.Rev.C75 (2007) 054910

study the quenching directly with jets:

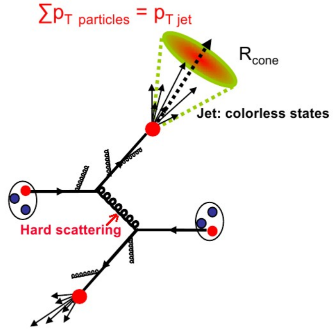
- access the partonic kinematics
- study energy flow, not individual hadrons
- well calibrated probe (pQCD)
- unbiased jet reconstruction: expecting R_{AA}=1 (caveats: nPDF, medium-induced jet broadening)



STAR, PRL 97 (2006), 252001

Outline

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



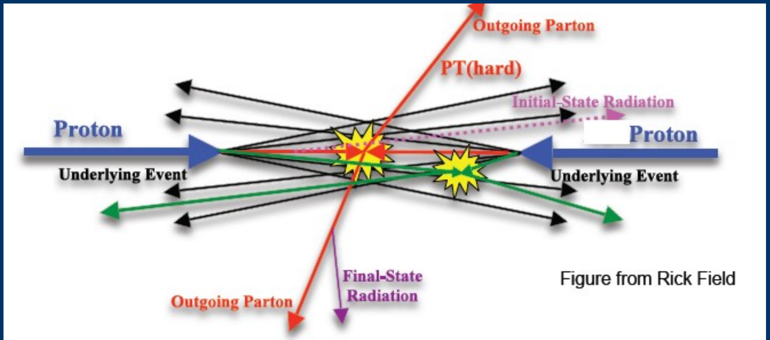
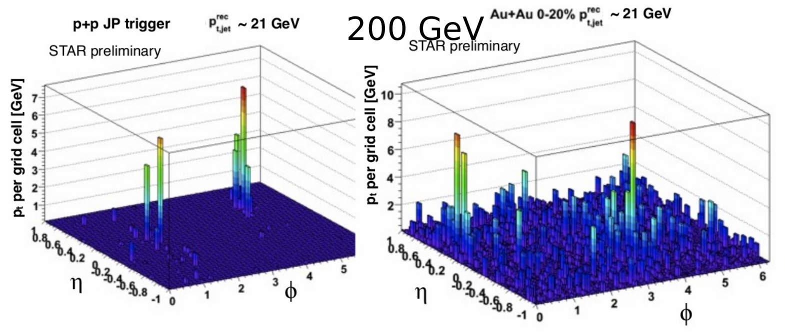
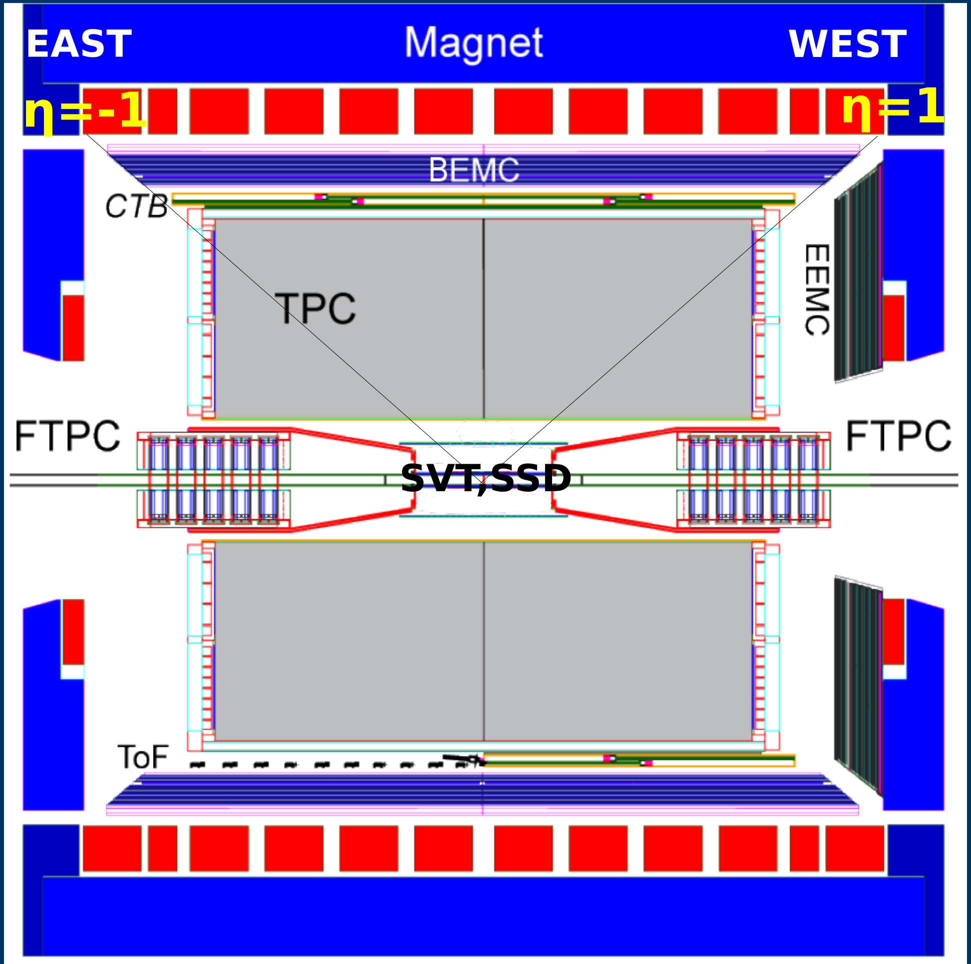


Figure from Rick Field



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

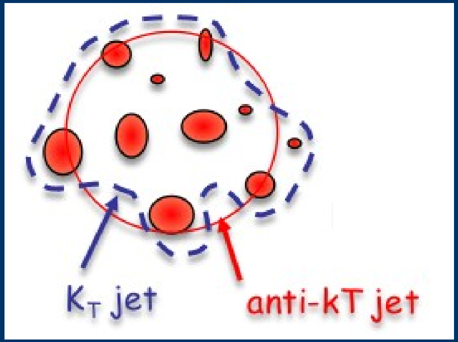
$p_{T,\mathrm{track/tower}} > 0.2$ GeV/c

“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:

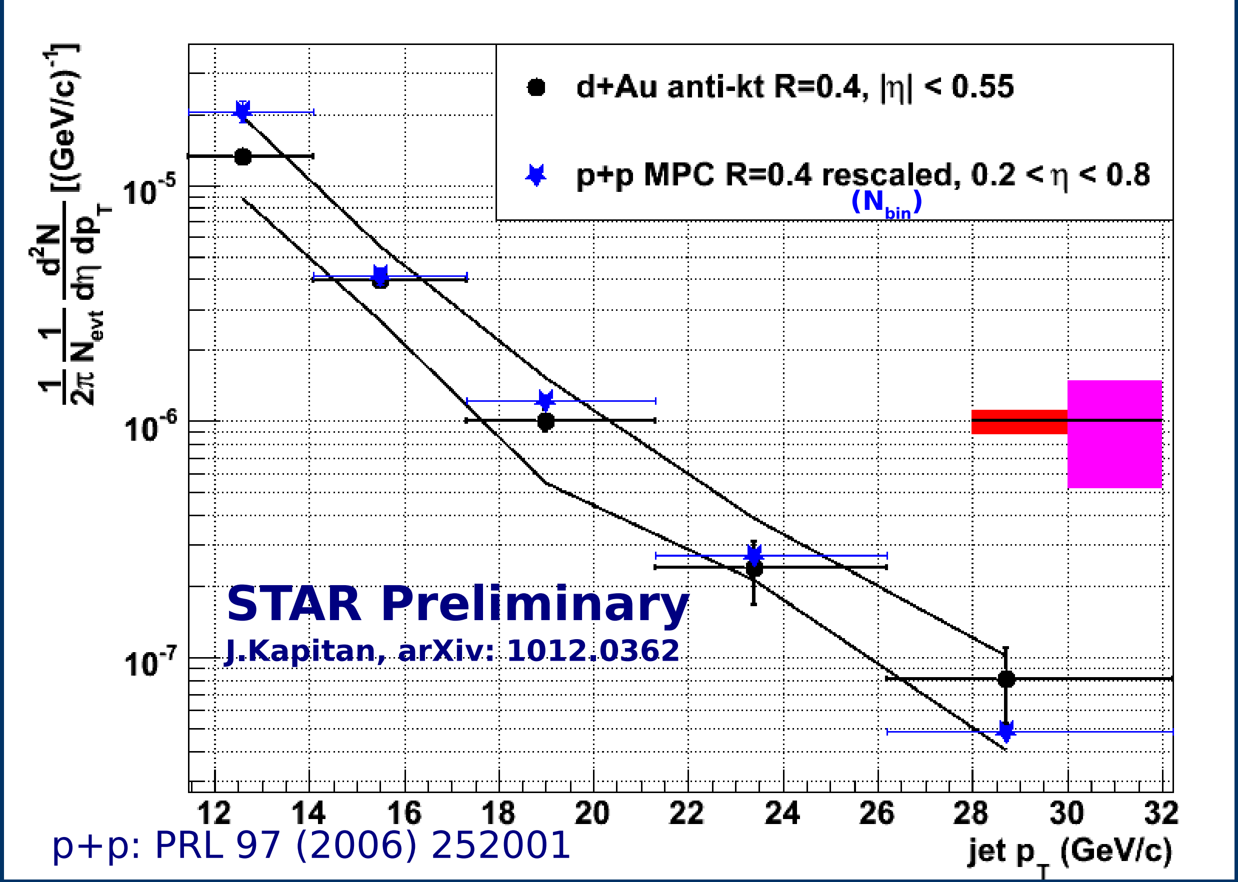
1. define jets (k_T, anti-k_T), active area A
2. estimate background density from k_T jets: $\rho = \text{median}\{p_T/A\}$
3. subtract the background: $p_{T,\text{jet,true}} = p_{T,\text{jet,observed}} - \rho * A$
4. correct for background fluctuations
5. correct for detector effects (jet p_T shift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



p+p: PRL 97 (2006) 252001

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

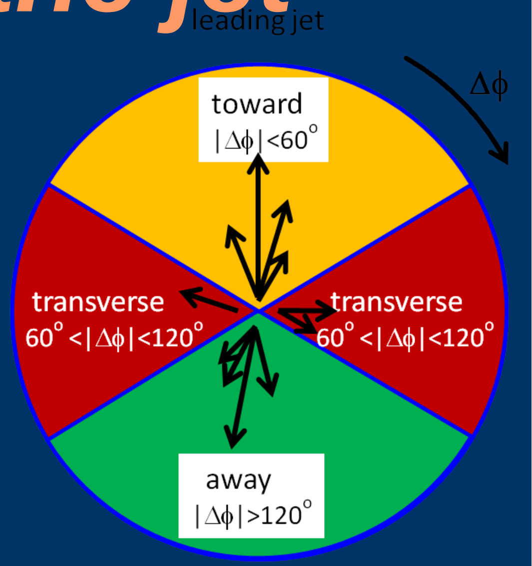
- different η range
- different jet algorithm

towards jet R_{dAu}:

- decrease syst.uncertainties
- extend to higher p_T

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

Underlying event – all but the jet



UE in p+p:

Multiple Partonic Interactions
Initial & Final State Radiation (ISR, FSR)
Beam-beam remnants

access to UE: transverse region with respect to a leading jet / di-jet

transverse region is split to two parts:

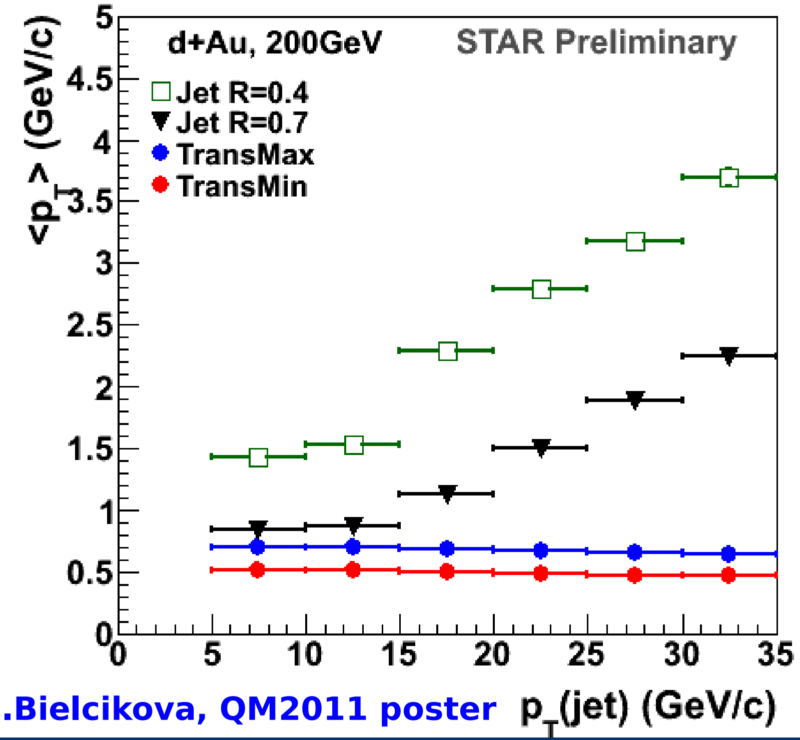
- TransMax: transverse region with highest $\sum p_T$, $\sum N_{track}$
  enhanced probability of containing hard ISR/FSR component
- TransMin transverse region with least $\sum p_T$, $\sum N_{track}$
  sensitive to beam-beam remnants and multiple parton interactions

Two types of analysis:

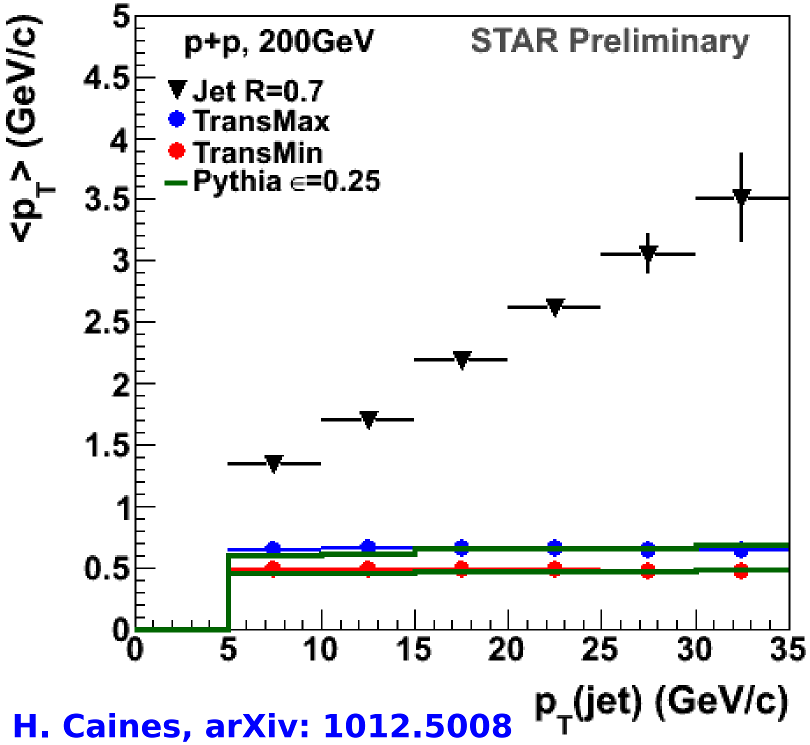
- leading jet in the acceptance
- di-jet: $|\Delta\phi|>150^{\circ}$, $p_T^{away}/p_T^{leading}>0.7$ (suppression of ISR, FSR)

- **compare TransMax from leading jet and di-jet samples: information about large angle ISR/FSR**
- **modification of UE by Cold Nuclear Matter in d+Au?**

Jet and UE: mean p_T



J.Bielcikova, QM2011 poster



H. Caines, arXiv: 1012.5008

UE $<p_T>$:

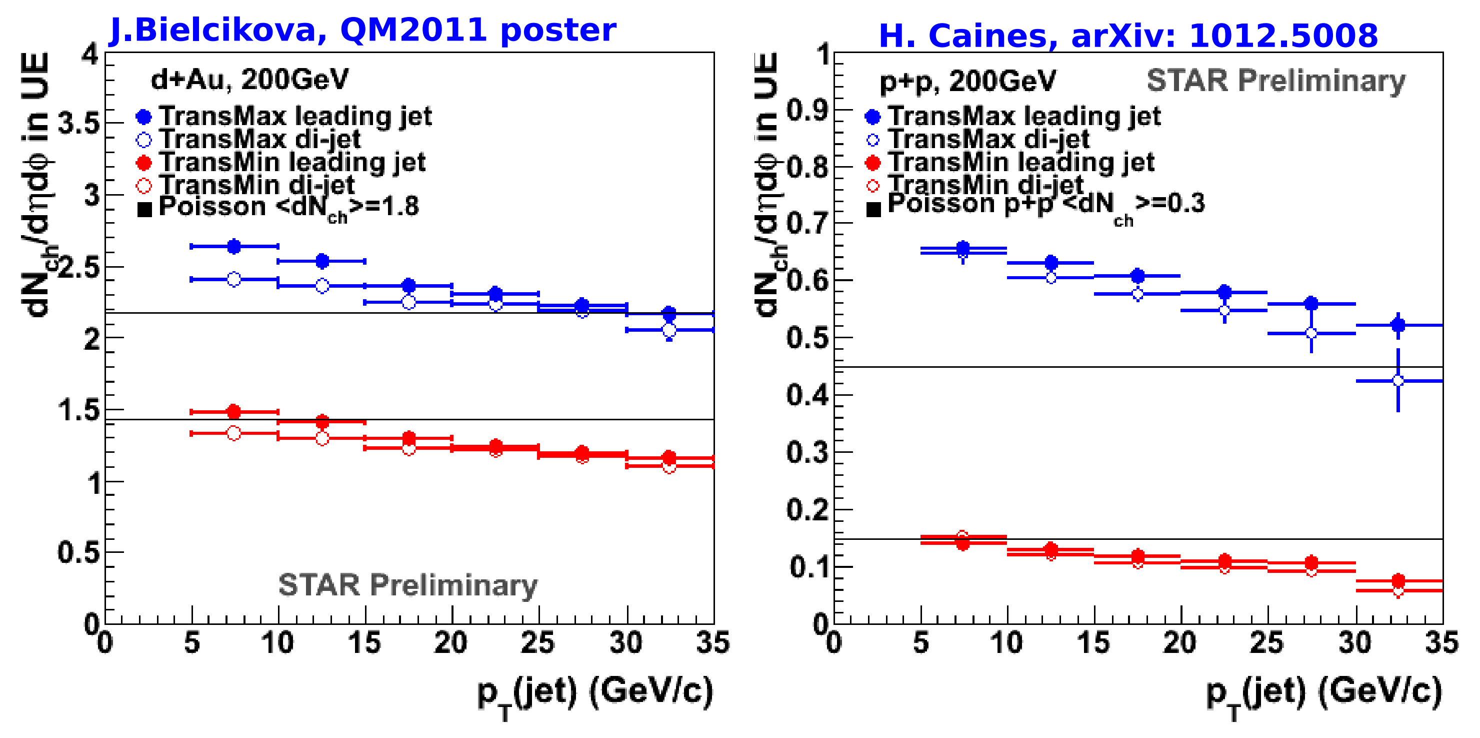
- largely independent of jet p_T
- only slightly higher in d+Au than in p+p collisions.

Jet:

- $<p_T>$ rise with jet p_T
- d+Au: UE influences significantly the properties of jets and needs to be corrected

p+p, d+Au data at detector level; d+Au: 0-20% highest multiplicity

UE: $\langle N_{ch} \rangle$ and ISR/FSR


J.Bielcikova, QM2011 poster

H. Caines, arXiv: 1012.5008

No large difference between leading jet and di-jet analysis!

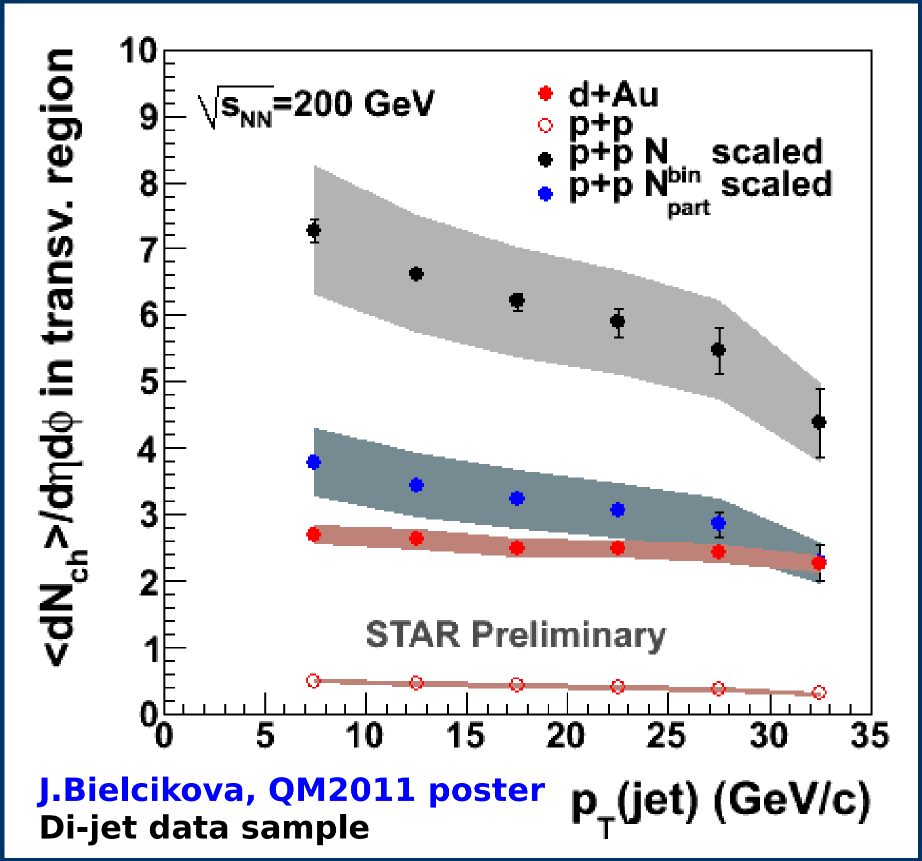
c.f.: at √s=1.96 TeV, UE $\langle N_{ch} \rangle$ in leading jet sample ~50% higher than in di-jet sample

in p+p and d+Au collisions at RHIC energies, there's no significant ISR/FSR at large angles

difference between TransMax and TransMin mostly described by Poisson sampling

UE $\langle N_{ch} \rangle$ significantly higher in d+Au compared to p+p

UE: Scaling between p+p and d+Au



J.Bielcikova, QM2011 poster
Di-jet data sample

d+Au 0-20%:
$<N_{bin}>$ = 14.6 ±1.7 (syst.)
$<N_{part}>$ = 15.2 ± 1.8 (syst.)
p+p collisions: N_{bin} =1, N_{part} =2

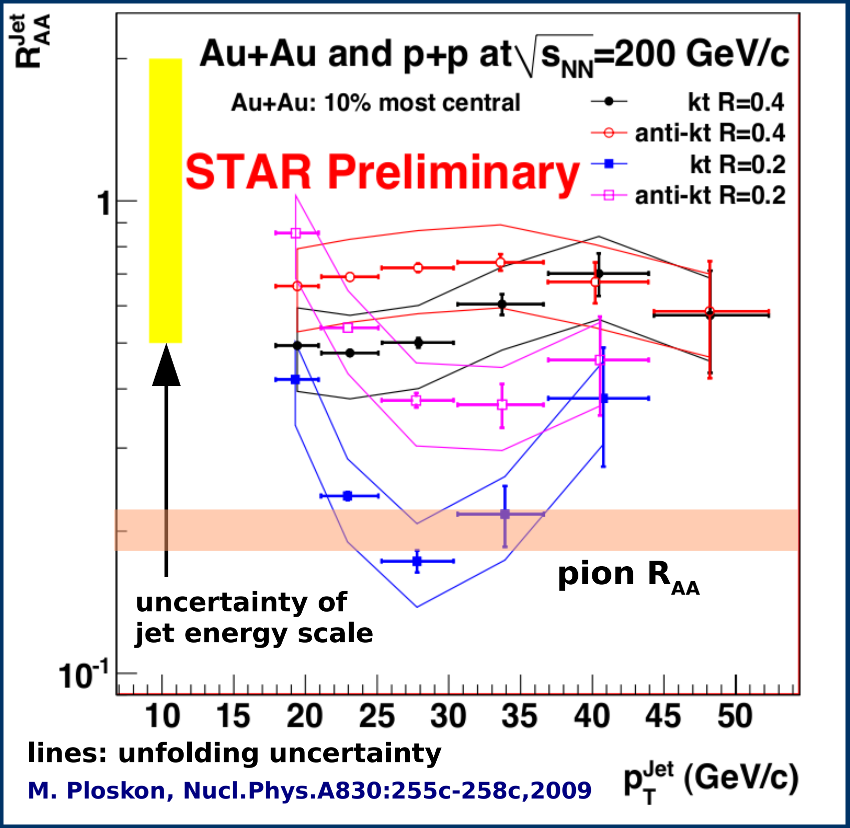
Data corrected for reconstruction efficiency in TPC at $<p_T>$ of UE.

Systematic errors:

- reconstruction efficiency: 5% in p+p and d+Au
- scaled p+p: Glauber calculation uncertainty

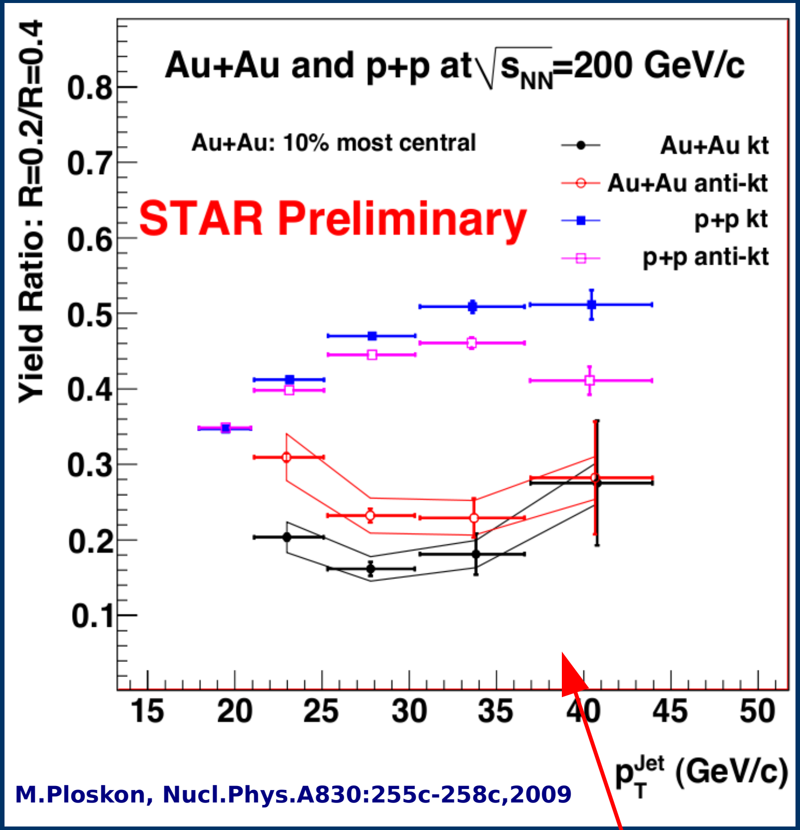
Charged particle density in UE in d+Au collisions scales approximately with $<N_{part}>$

Jet spectra: Au+Au vs. p+p



lines: unfolding uncertainty

M. Ploskon, Nucl.Phys.A830:255c-258c,2009



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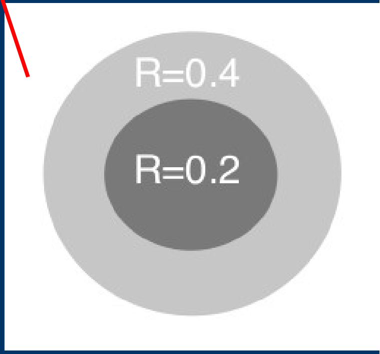


- R_{AA} of R=0.4 jets close to 1
- consistent with jet broadening from R=0.2 to R=0.4

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:

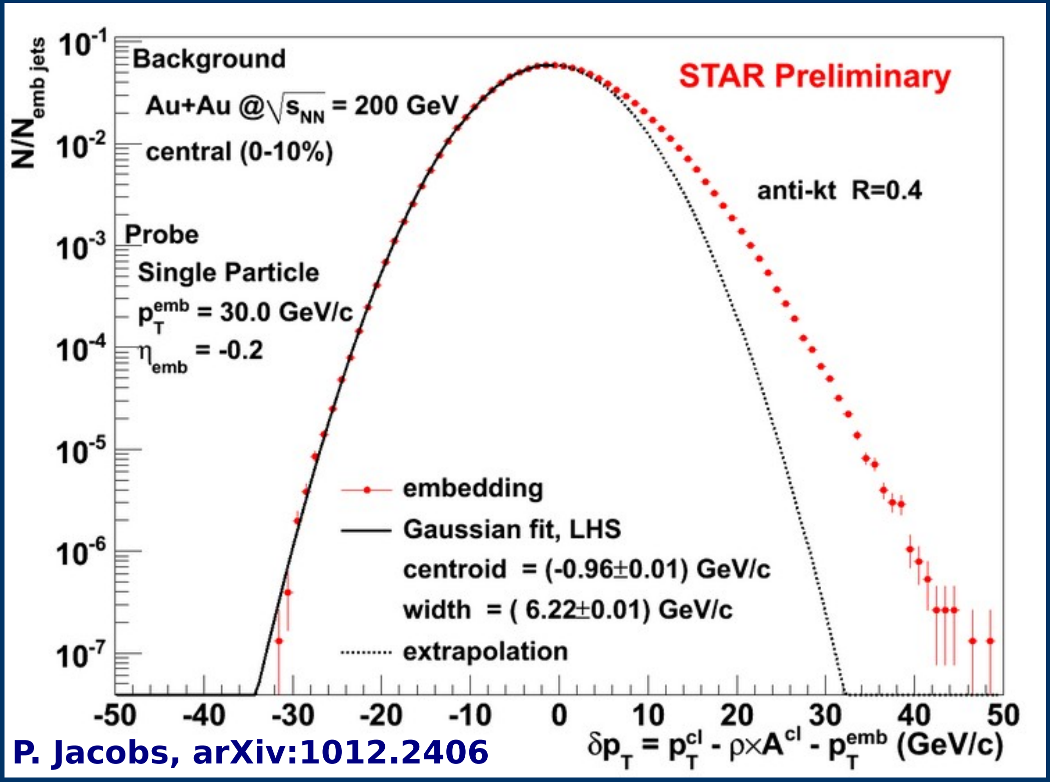
$$\delta p_T = p_T^{cluster} - \rho \cdot A^{cluster} - p_T^{emb}$$

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, $\eta = -0.2$

same jet embedded into 8M events:



P. Jacobs, arXiv:1012.2406

what does δp_T depend on?

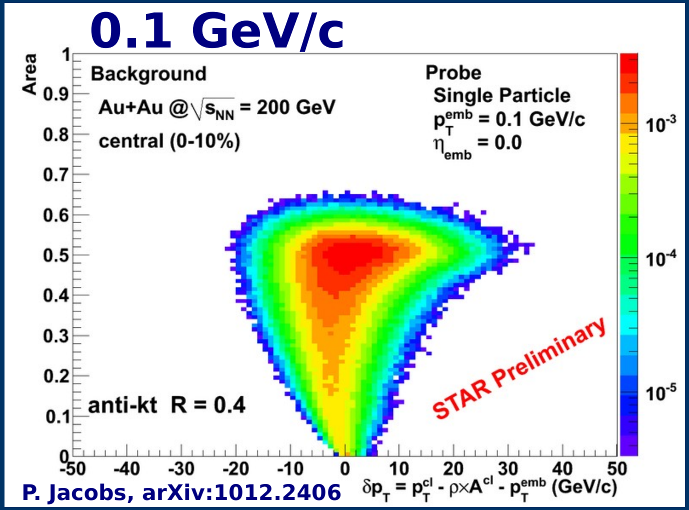
- jet area A
- jet p_T
- jet fragmentation pattern

following studies:
for R=0.4 jets...

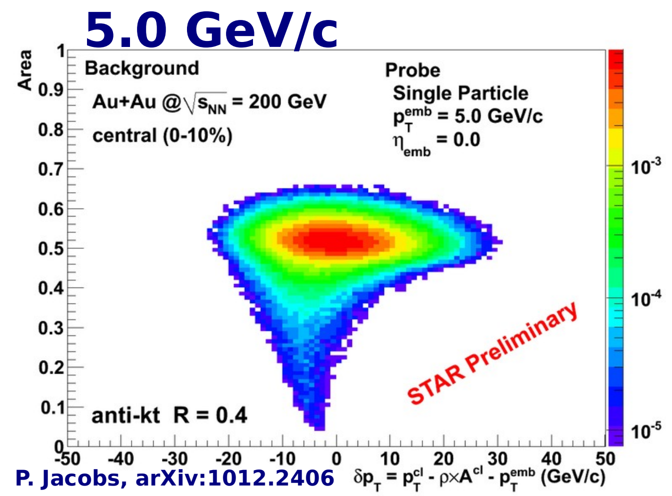
- response over 40 GeV and 5 orders of magnitude
- Gaussian fit to LHS good, non-Gaussian tail in RHS!

Dependence on jet area

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



P. Jacobs, arXiv:1012.2406



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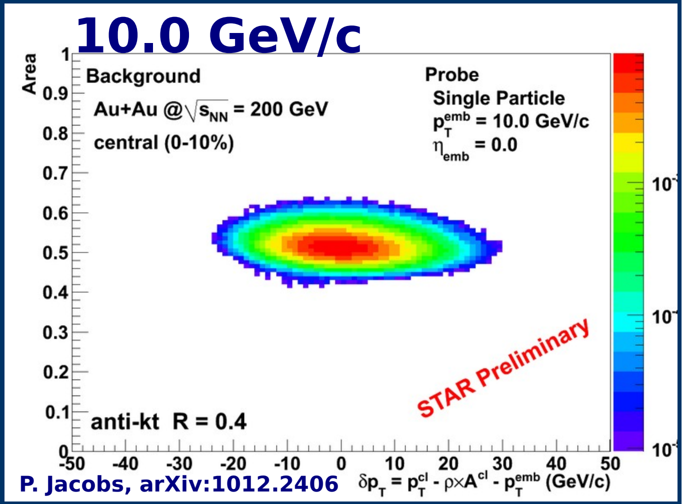
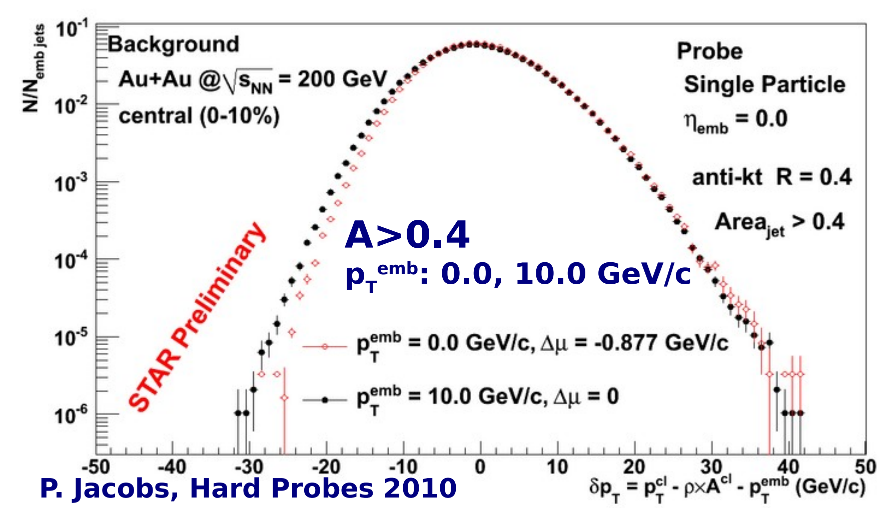


P. Jacobs, arXiv:1012.2406

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



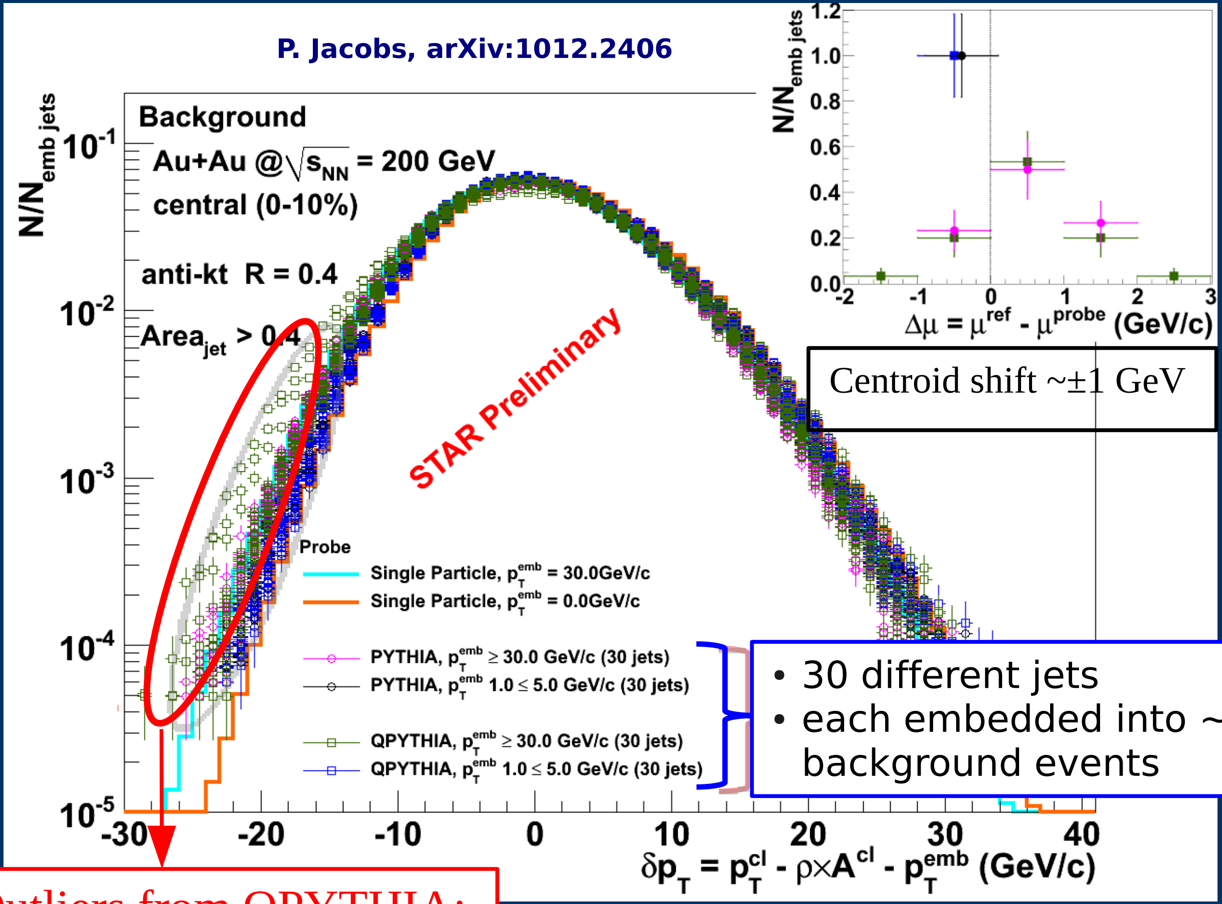
P. Jacobs, Hard Probes 2010

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

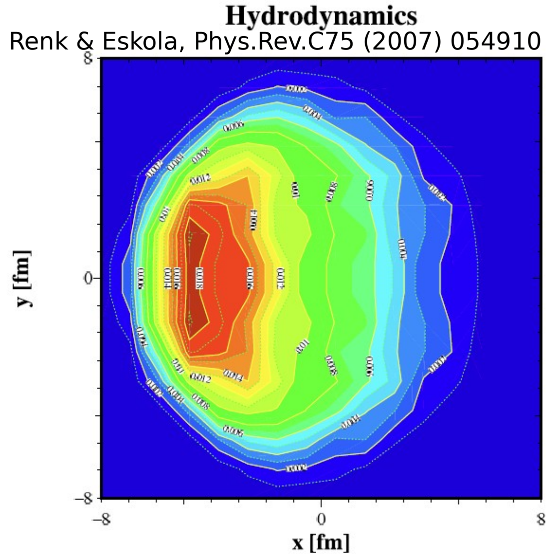
Smearing due to background fluctuations ~independent of fragmentation pattern!

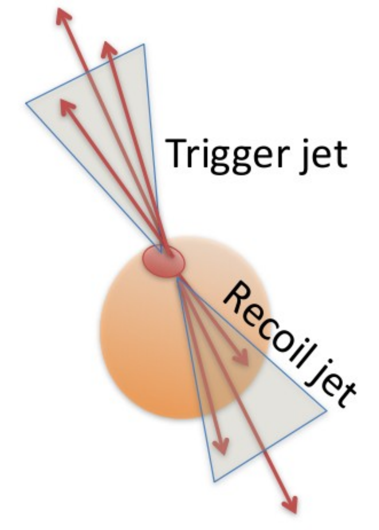
Jet-triggered correlations

- use highly biased jet sample: jets containing BEMC tower with E_T>5.4 GeV: “trigger jets”
- 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

→ **di-jet correlations**

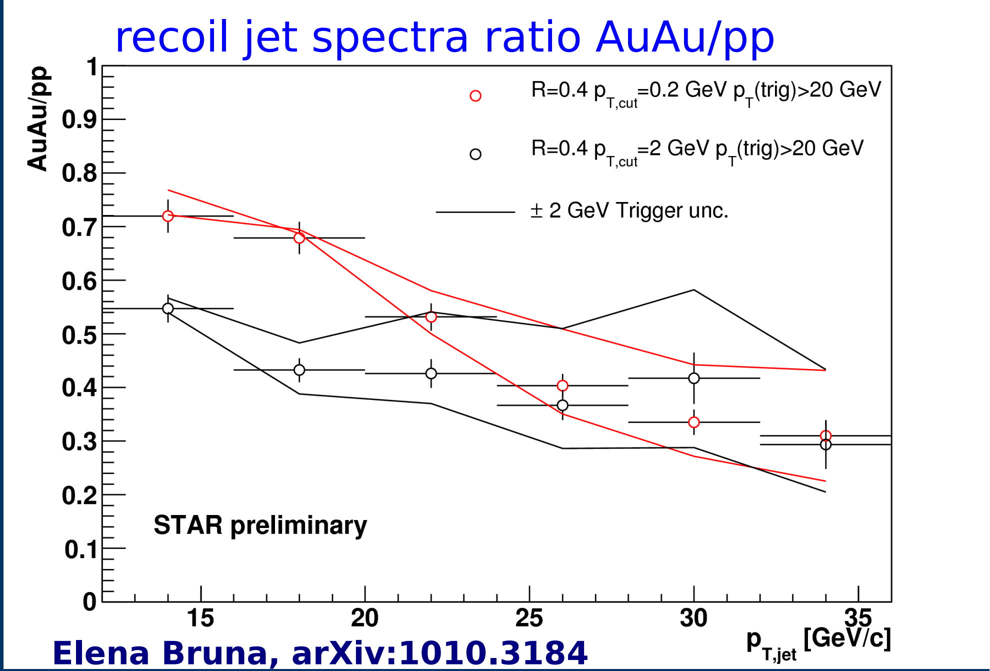
→ **jet-hadron correlations**


Hydrodynamics
Renk & Eskola, Phys.Rev.C75 (2007) 054910



Di-jet correlations

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



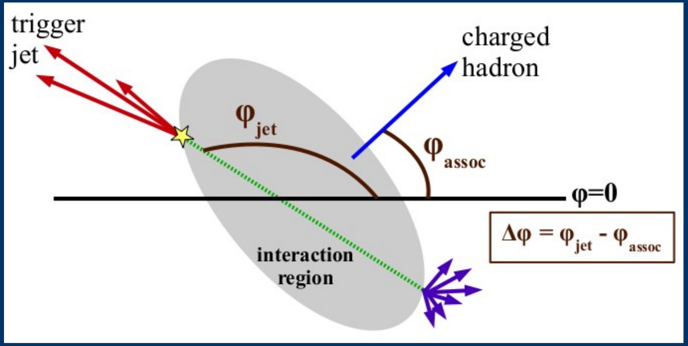
Elena Bruna, arXiv:1010.3184

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

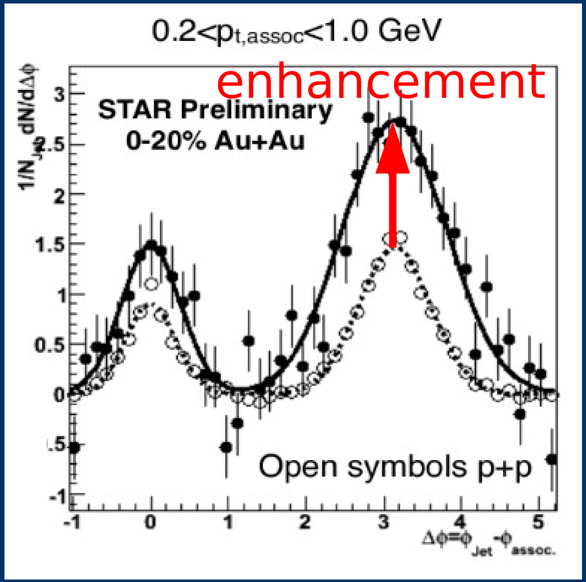
- azimuthal correlations of charged hadrons with respect to trigger jet axis
- increased kinematic reach compared to di-hadron correlations

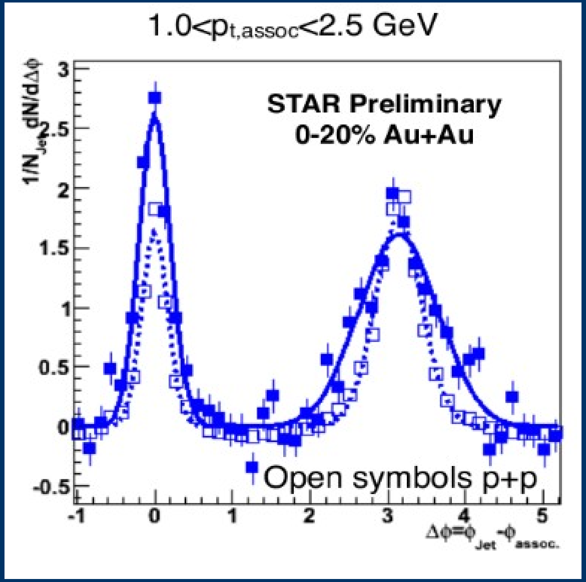


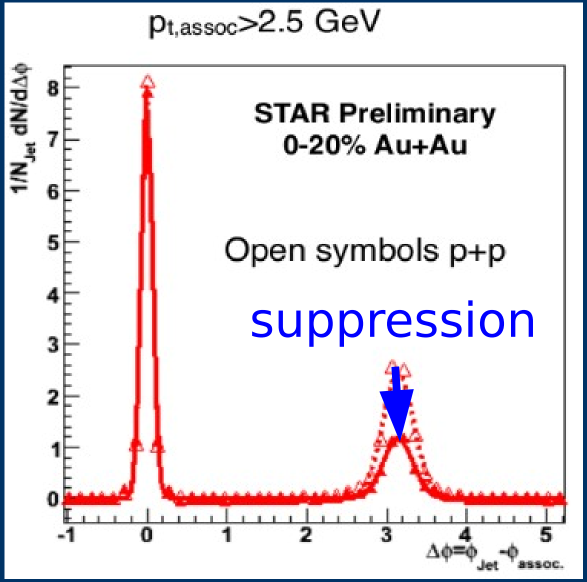
initial results – **flat background subtraction**, $p_{T,jet} > 20$ GeV/c:

(J.Putschke, RHIC AGS Users Meeting 2009)

softening & broadening!







ΔΦ background model

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

in the following, background estimated by fitting:

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

$(v_2\{2\}+v_2\{4\})/2$

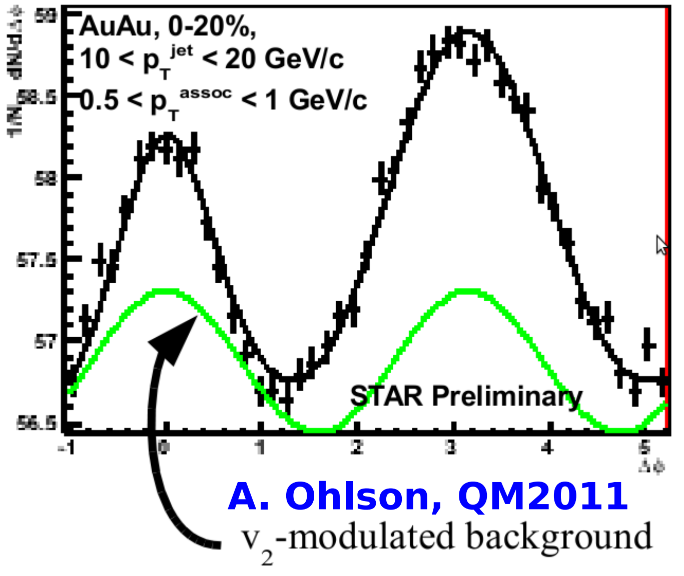
$v_2\{2\}$ (p_T=6 GeV/c)

Max. v_2 uncertainties:

no v_2

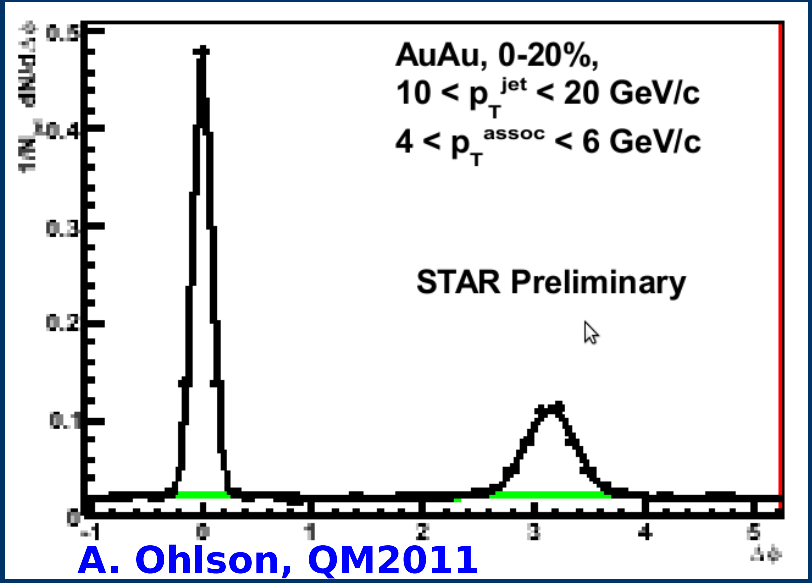
nominal v_2 +

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



A. Ohlson, QM2011

v_2-modulated background



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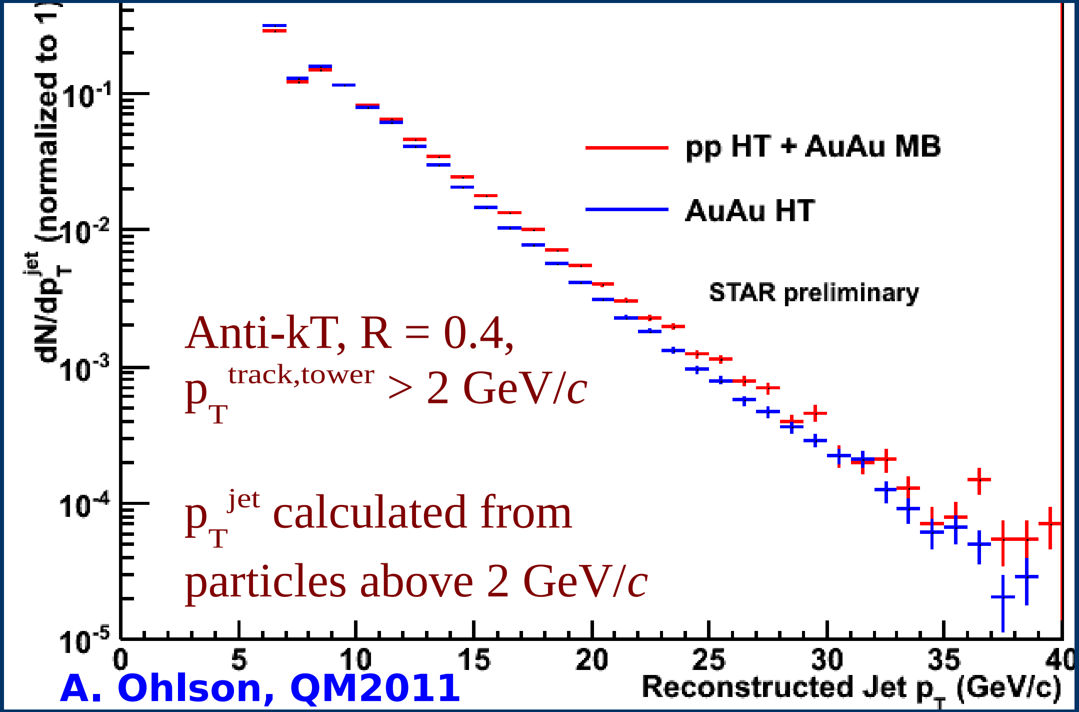
Comparing trigger jets

Comparison of J-H correlations in p+p, Au+Au → are trigger jets are similar?

Expected differences are corrected (p+p adjusted):
- detector effects (different tracking efficiencies)
- background fluctuations (embedding into minimum bias events used)



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Shapes of trigger jet spectra don't quite match...

Comparing trigger jets

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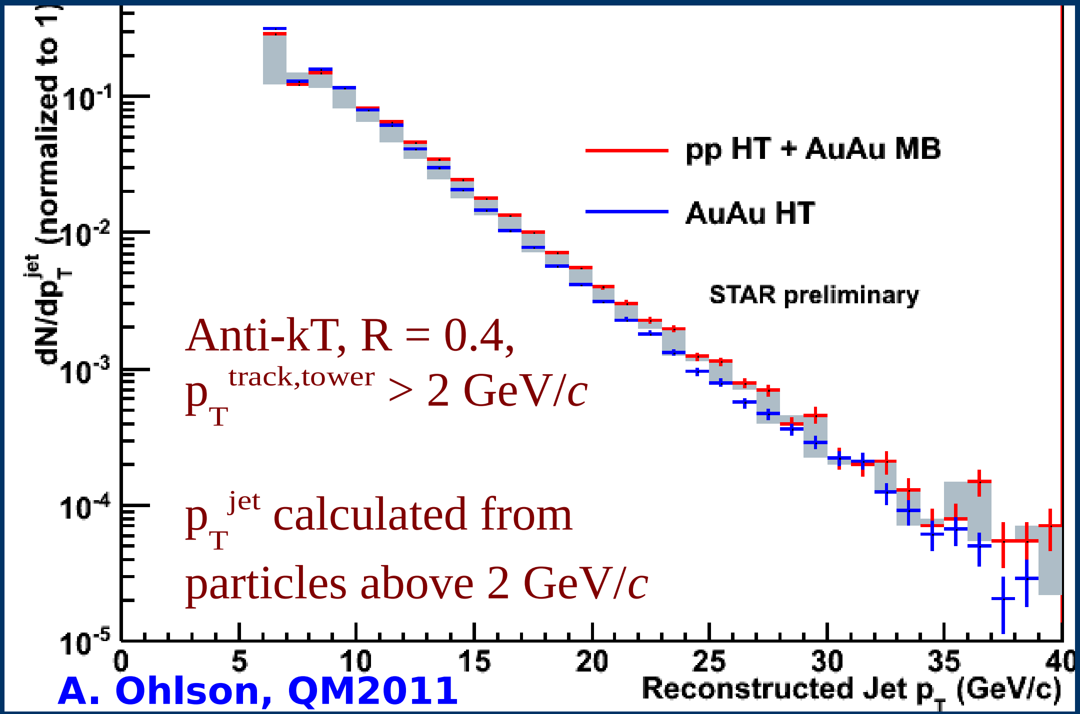
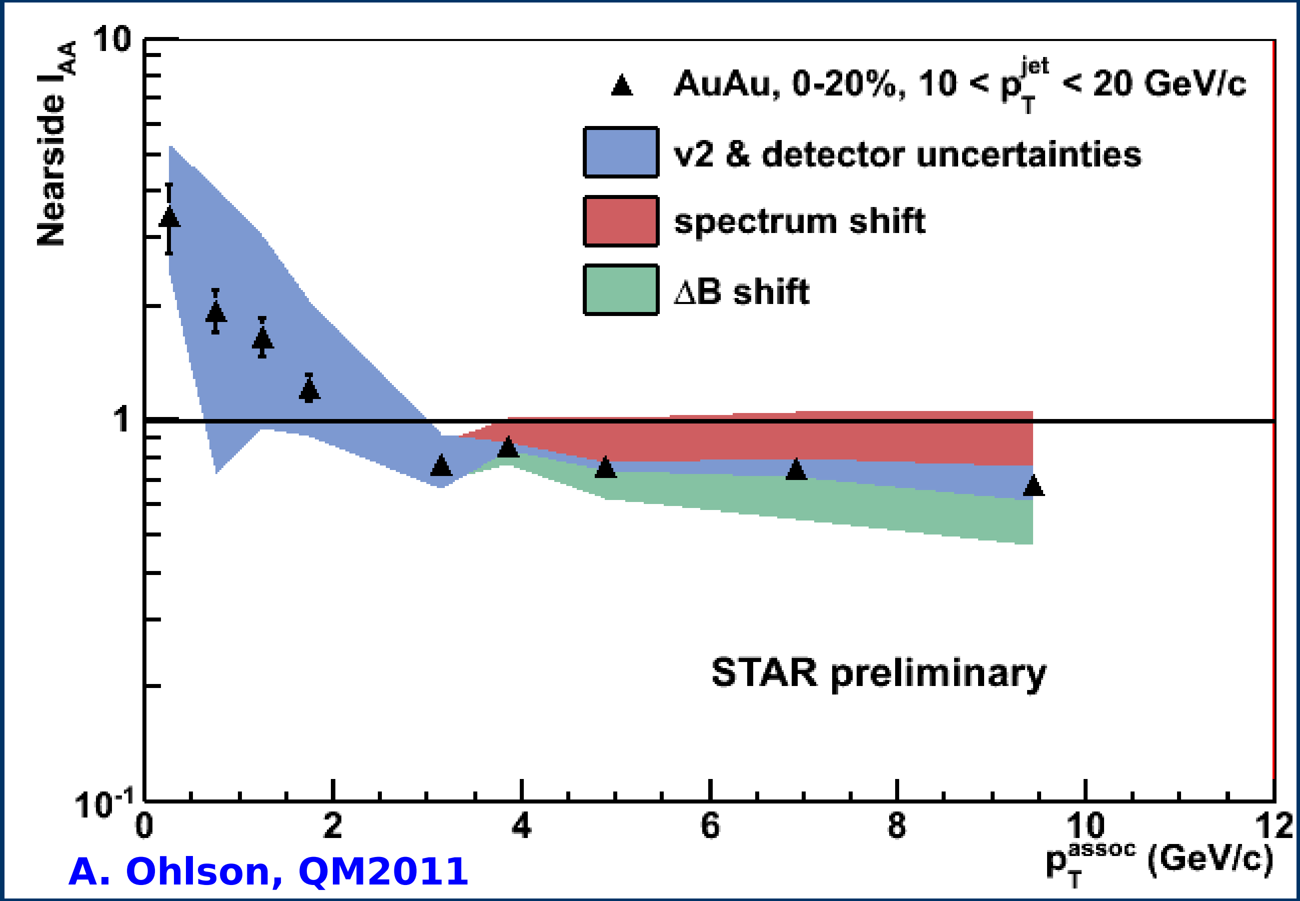


A. Ohlson, QM2011

Shapes of trigger jet spectra don't quite match...

include $\Delta E = -1$ GeV/c energy shift included in systematic uncertainties to account for possible trigger jet energy mismatch.

Nearside I_{AA}



$I_{AA} = Y_{A+A}/Y_{p+p}$

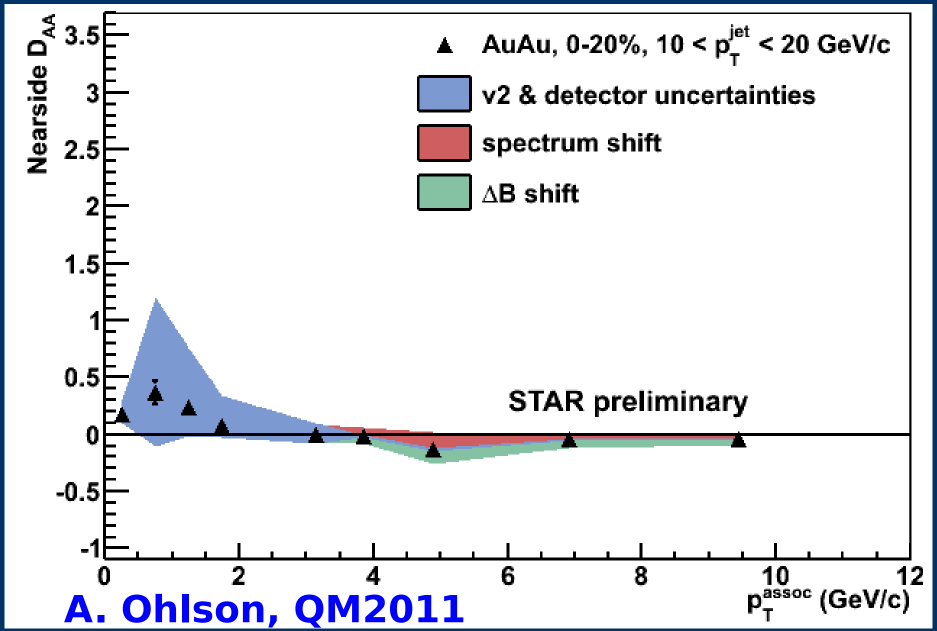
Y: per-trigger yield

- high-p_T suppression observed in the nearside I_{AA} → consistent with apparent ΔE (-1 GeV spectrum shift)
- possible low-p_T enhancement

Nearside energy balance: D_{AA}

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

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



A. Ohlson, QM2011

p_T^{jet} (GeV/c)	NS ΔB (GeV/c)
10-15	$0.6^{+1.9+0.5}_{-1.1-0.5}$
15-20	$1.7^{+1.9+0.6}_{-1.0-1.7}$
20-40	$1.9^{+2.1+0.4}_{-1.1-1.1}$

v_2+det.unc.

unc.due to shifts

ΔB small → good matching of trigger jet energies

For 10 < p_T^{jet} < 20 GeV/c: $\Delta B = 0.6^{+1.9+0.5}_{-1.0-0.5}$ (syst.) GeV/c

Include trigger jet energy shift (+ΔB*3/2) in systematic uncertainties to achieve ΔB ~ 0

Maximum trigger jet energy uncertainties

Shift to match trigger jet spectrum with embedding → corresponds to scenario in which Au+Au trigger jets are p+p-like (even for jet constituents below p_T=2 GeV/c)

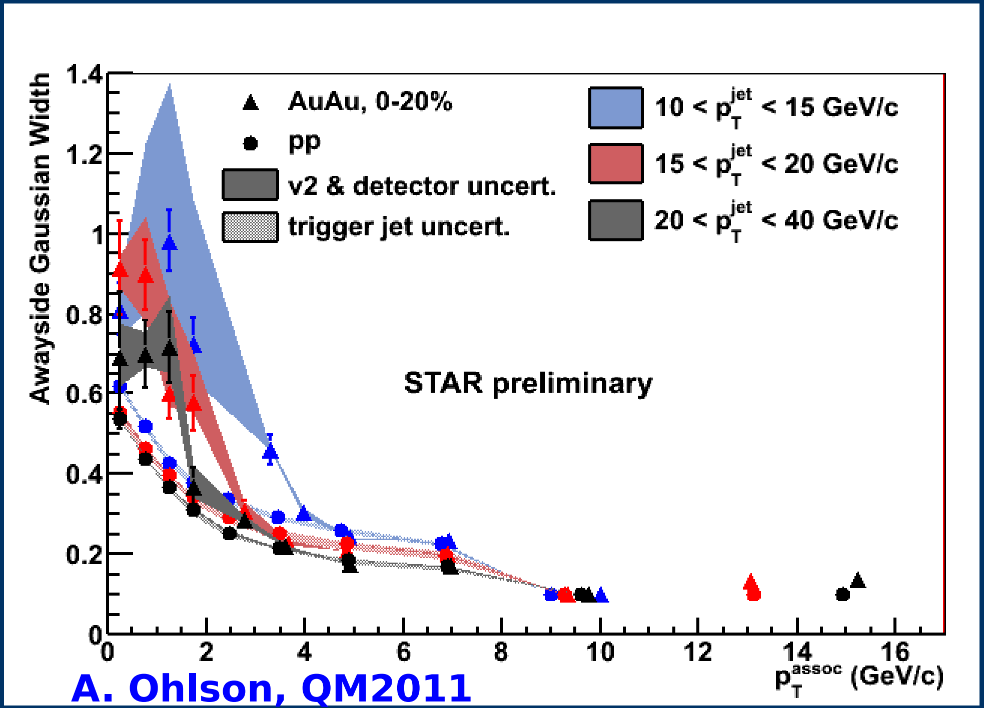
“low p_T^{assoc} enhancement is bulk”

Shift to get ΔB = 0 → energy mismatch is due to jet modification

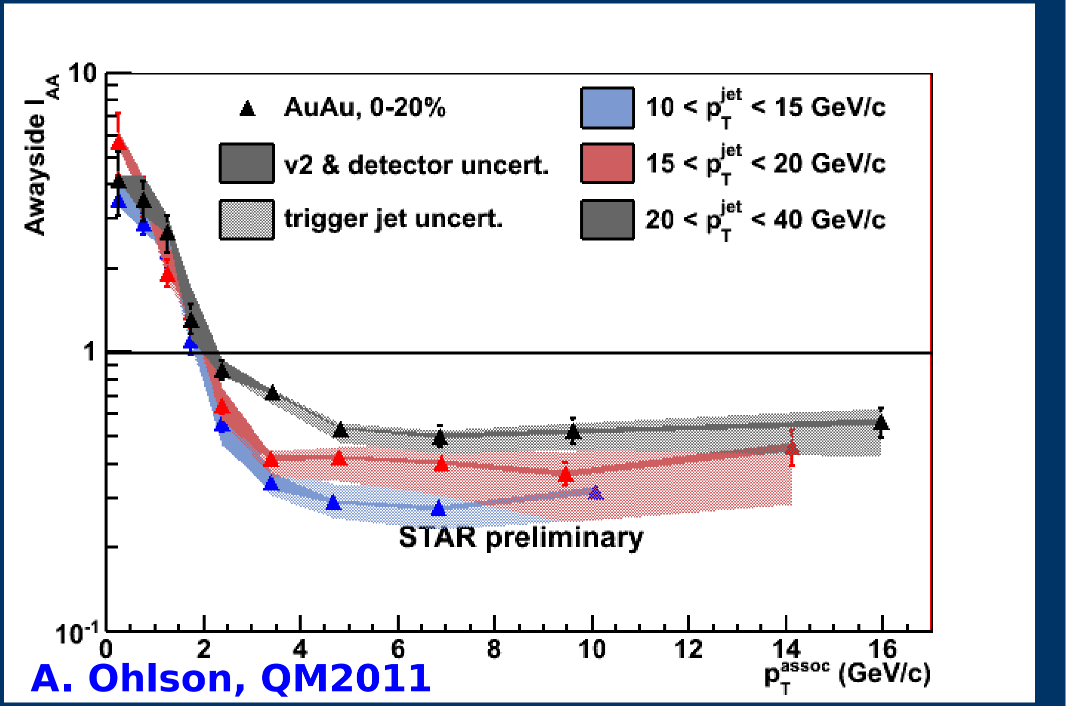
“low p_T^{assoc} enhancement is jet”

**With these two extreme cases covered,
we can now move to the awayside!**

Awayside Gaussian width & I_{AA}



A. Ohlson, QM2011



A. Ohlson, QM2011

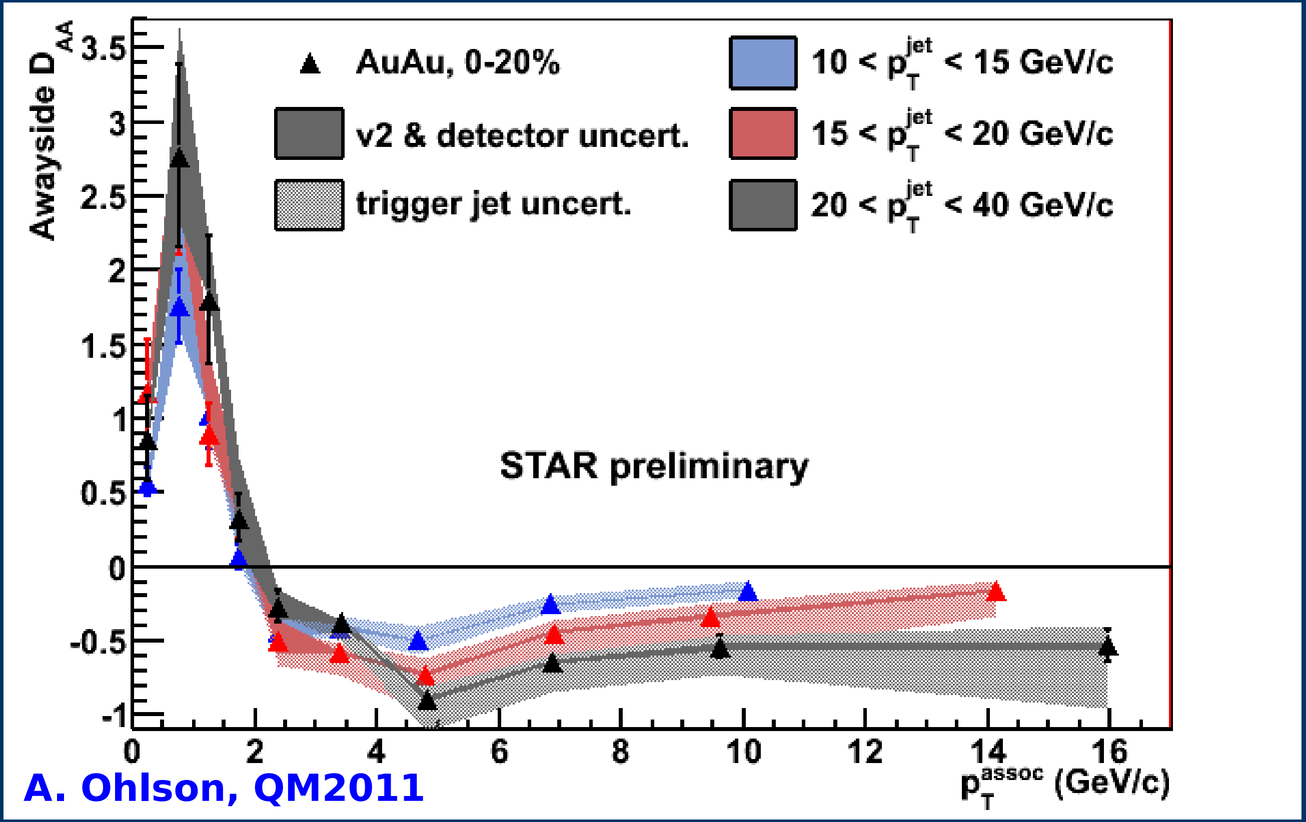
n.b.: this is not z!

- **significant enhancement at low p_T^{assoc} and suppression at high p_T^{assoc} on the awayside**
- **significant broadening of awayside jets in Au+Au compared to p+p**

Awayside energy balance: D_{AA}

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

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



A. Ohlson, QM2011

p_T^{jet} (GeV/c)	AS ΔB (GeV/c)
10-15	$1.7^{+1.5+0.5}_{-0.3-0.5}$
15-20	$2.4^{+1.7+0.5}_{-0.5-1.4}$
20-40	$2.5^{+2.0+0.4}_{-0.8-1.3}$

- **significant part of energy “lost” at high p_T shows up at lower p_T and at larger distance from the jet axis**
- **jet quenching in action**

Conclusions

d+Au jet spectrum:

- no significant Cold Nuclear Matter effects observed

UE in p+p and d+Au:

- $<p_T>$ in UE only slightly higher in d+Au compared to p+p
- no significant ISR/FSR at large angles
- $<N_{ch}>$ in UE scales approximately with $<N_{part}>$ from p+p to d+Au

Au+Au jet spectrum:

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

background fluctuations - δp_T:

  - largely independent of fragmentation pattern of the probe

di-jet suppression suggestive of awayside broadening

jet-hadron correlations:

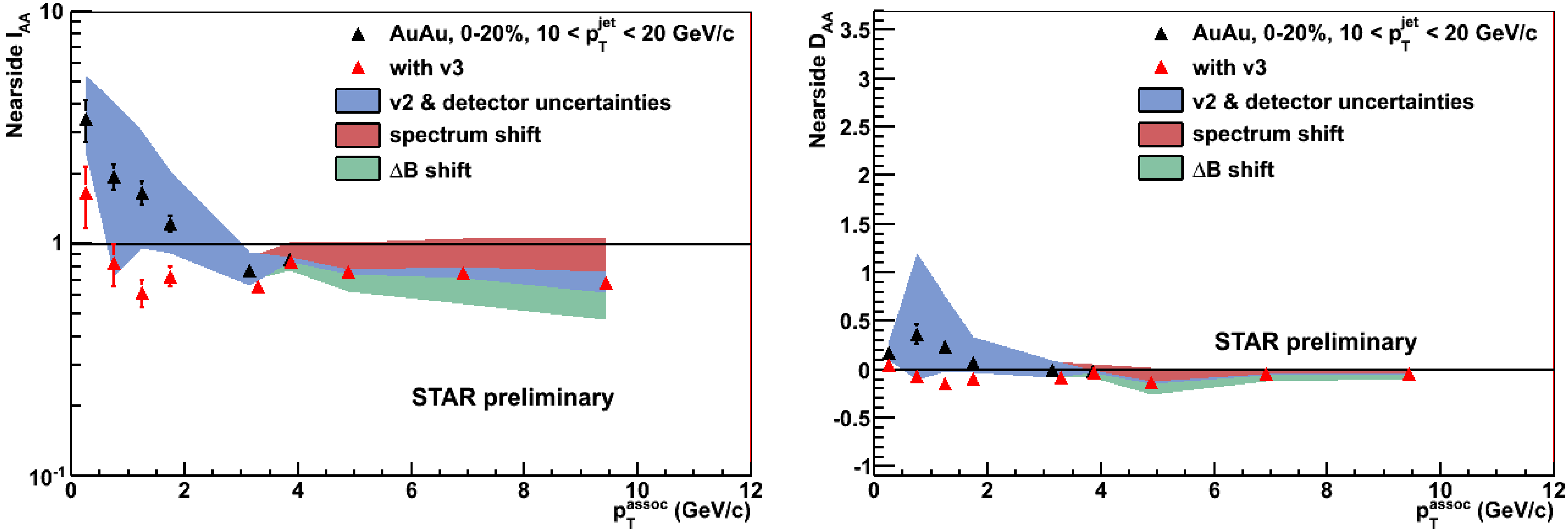
- softening, broadening and p_T redistribution observed
- measured jet modification disfavors black-and-white e-loss picture

Thank you!

ÉCOLE
POLYTECHNIQUE

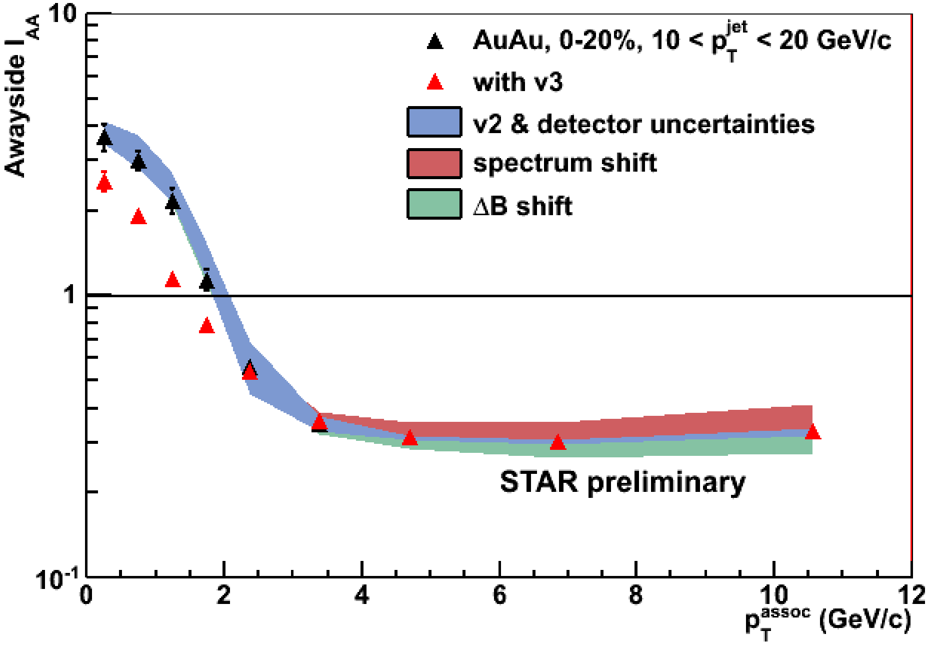
Backup

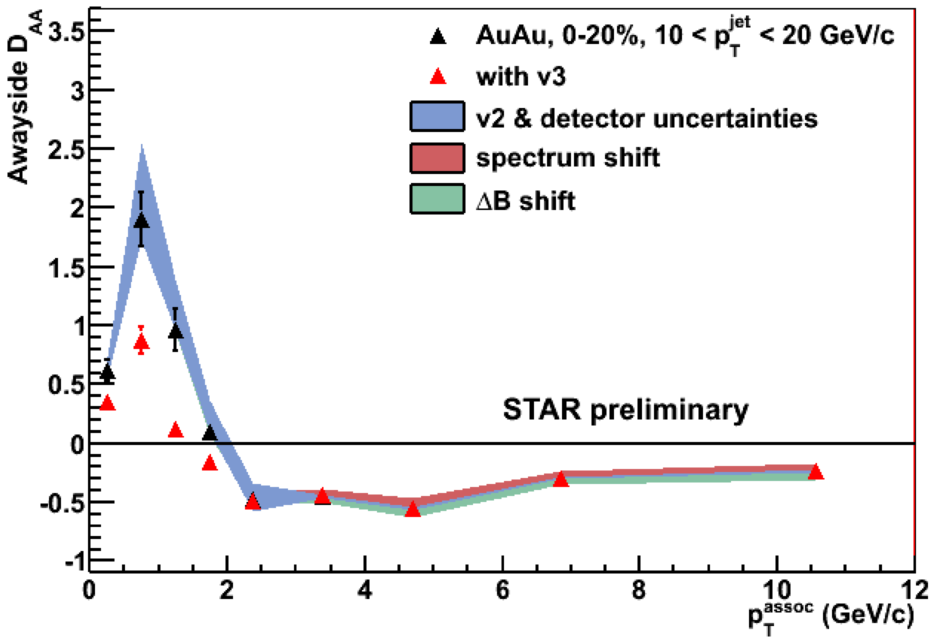
The Effect of v_3 on the Nearside



- Do jets to have a non-zero v_3? If yes, must include a cos(3Δφ) in background subtraction.
- Maximum v_3^{jet} assumption: $v_3^{jet} = v_3(p_T = 5$ GeV/*c*)
- Under this assumption, HT trigger jets in AuAu become quite pp-like.
- For 10 < p_T^{jet} < 20 GeV/*c*: NS ΔB ~ -0.6 GeV/*c* (errors not calculated)
- Note: Error bars on v_3 points (red triangles) are statistical only.

The Effect of v_3 on the Awayside





- For $10 < p_T^{jet} < 20$ GeV/*c*: AS ΔB ~ -0.8 GeV/*c* (errors not calculated)
- Even with extreme v_3^{jet} assumption, the qualitative conclusions about quenching on the awayside hold: low-p_T enhancement, high-p_T suppression, p_T redistribution

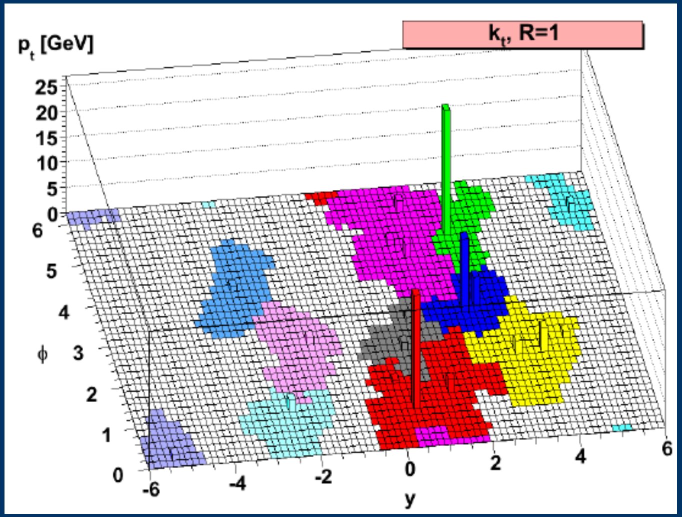
Algorithms details

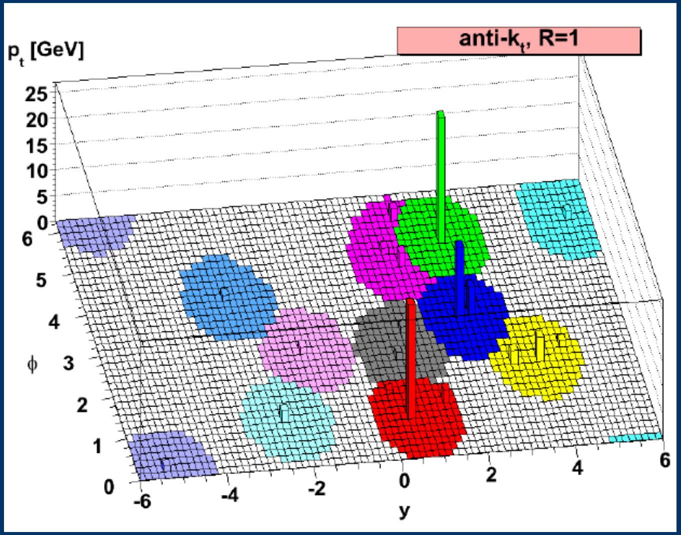
recombination algorithms - FastJet package

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

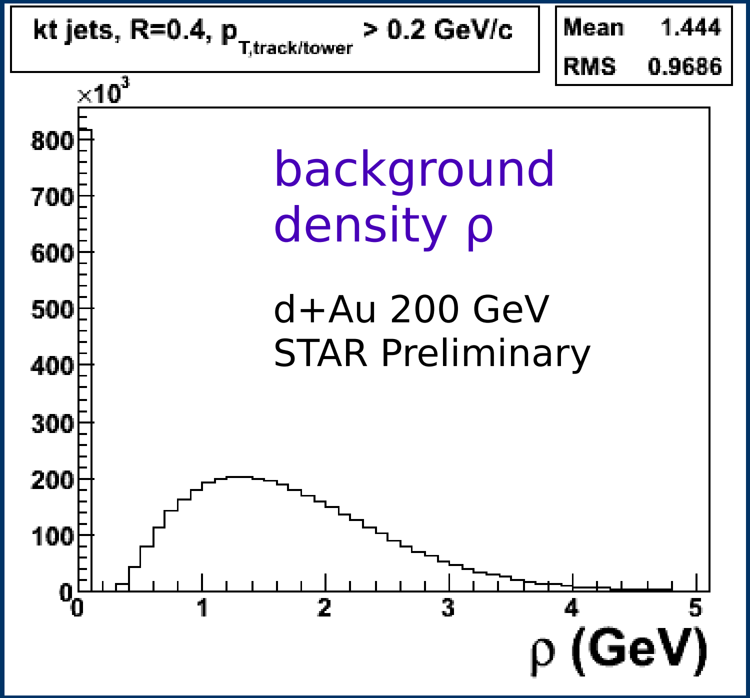
- $d_{ij} = \min(p_{Ti}^{n}, p_{Tj}^{n}) (\Delta\eta^2 + \Delta\varphi^2)/R^2$, $d_i = p_{Ti}^{n}$
- $\min(d_i, d_{ij})$: d_i -> new jet, d_{ij} -> merge i,j

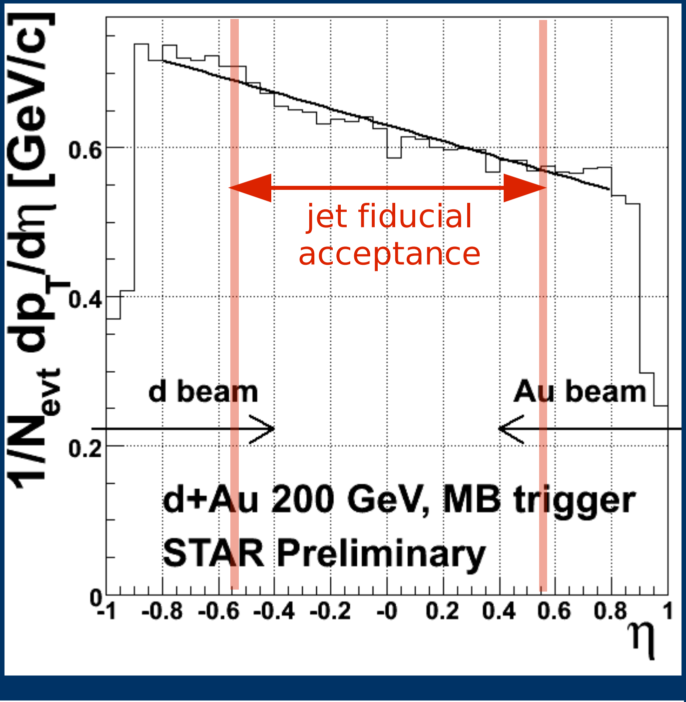
- n=2: kt, n=-2: anti-kt
- R: resolution parameter
- recombination: E scheme with massless particles

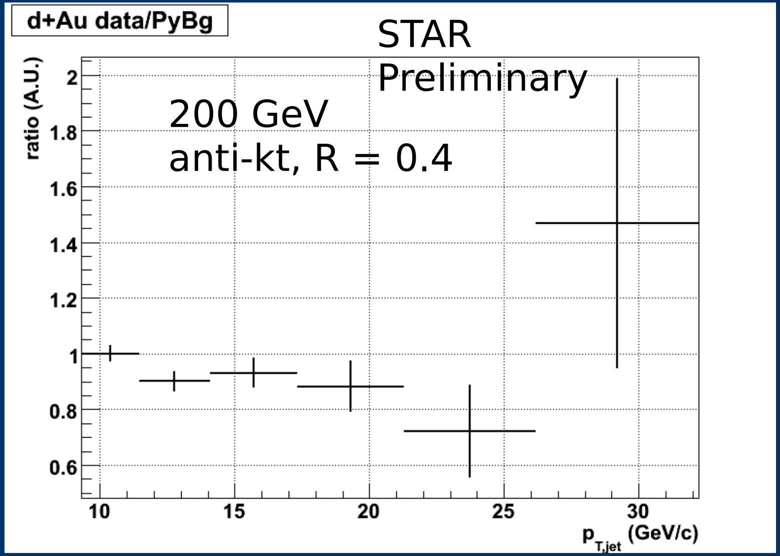




dAu details


kt jets, R=0.4, $p_{T,track/tower}$ > 0.2 GeV/c
Mean 1.444
RMS 0.9686
×10³
0
100
200
300
400
500
600
700
800
0
1
2
3
4
5
ρ (GeV)
background density ρ
d+Au 200 GeV
STAR Preliminary

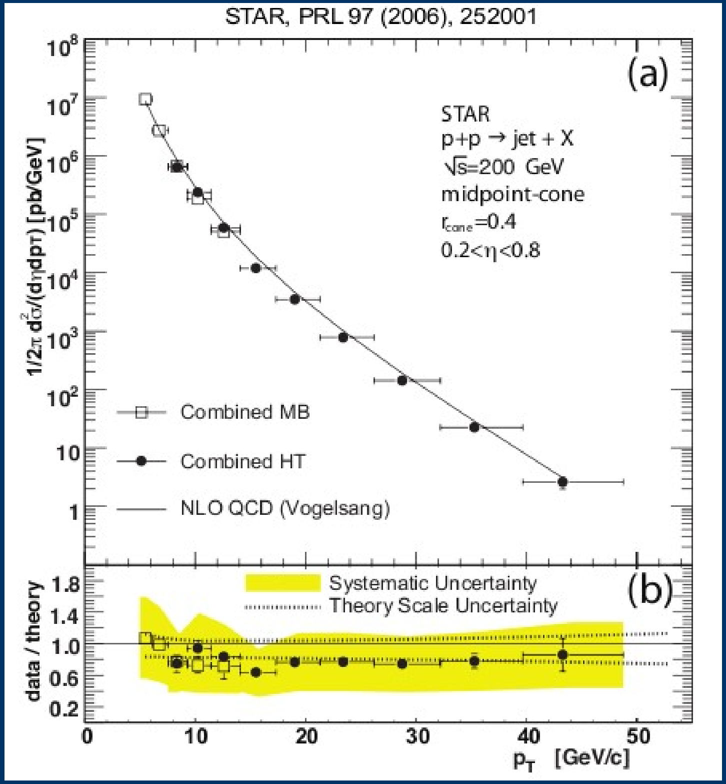

$1/N_{evt}\ dp_T/d\eta$ [GeV/c]
0
0.2
0.4
0.6
-1
-0.8
-0.6
-0.4
-0.2
-0
0.2
0.4
0.6
0.8
1
η
jet fiducial acceptance
d beam
Au beam
d+Au 200 GeV, MB trigger
STAR Preliminary


d+Au data/PyBg
STAR Preliminary
200 GeV
anti-kt, R = 0.4
ratio (A.U.)
0.6
0.8
1
1.2
1.4
1.6
1.8
2
10
15
20
25
30
$p_{T,jet}$ (GeV/c)

Jet cross section & relation to p+p

compare to STAR p+p jet cross section:

- Mid Point Cone algorithm
- R = 0.4



STAR, PRL 97 (2006), 252001

number of binary collision scaling:

if there are no nuclear effects, hard processes scale according to $\langle N_{bin} \rangle$

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

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

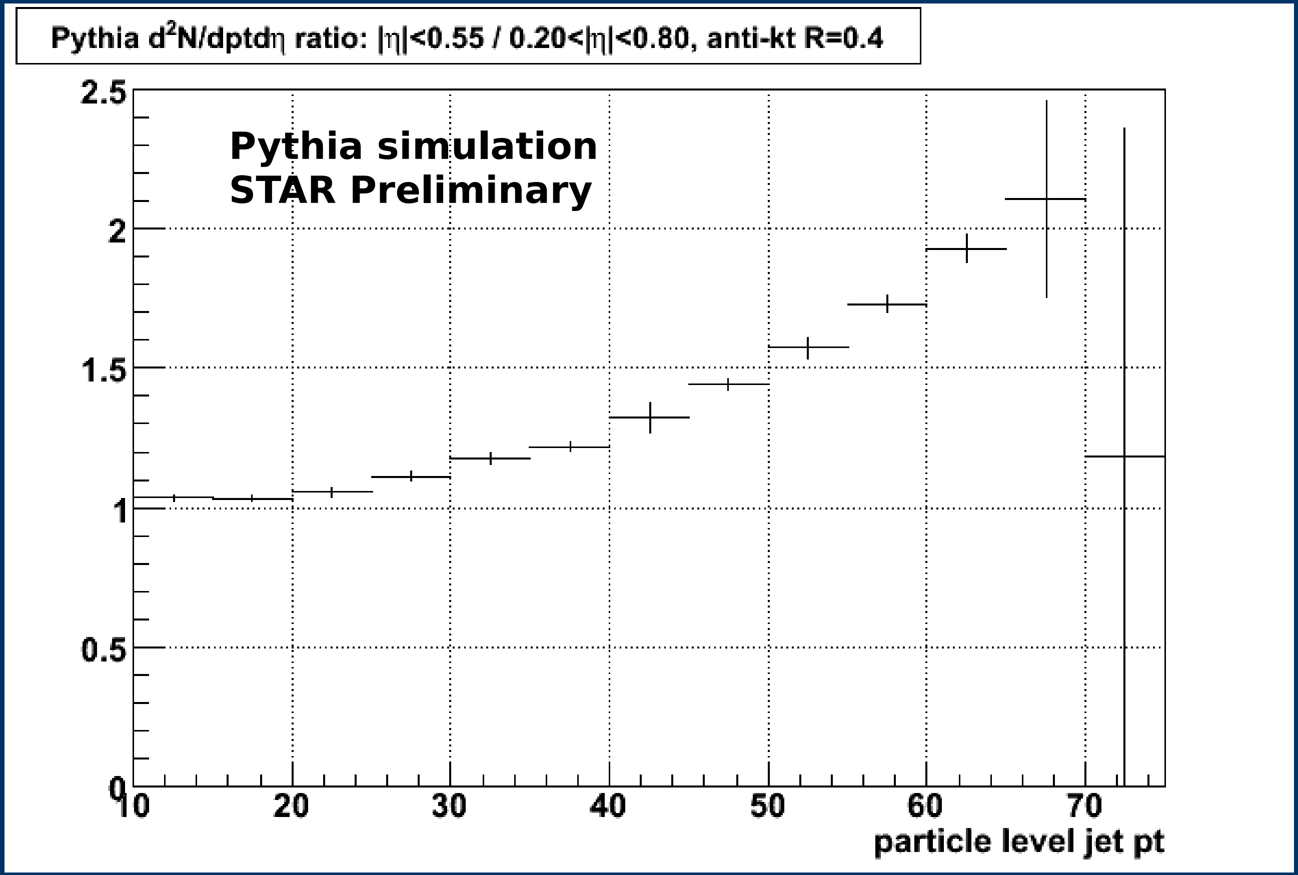
$Y_{jet,p+p\ (d+Au\ level)} = \sigma_{jet,p+p} / \sigma_{inel,p+p} * \langle N_{bin} \rangle$

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

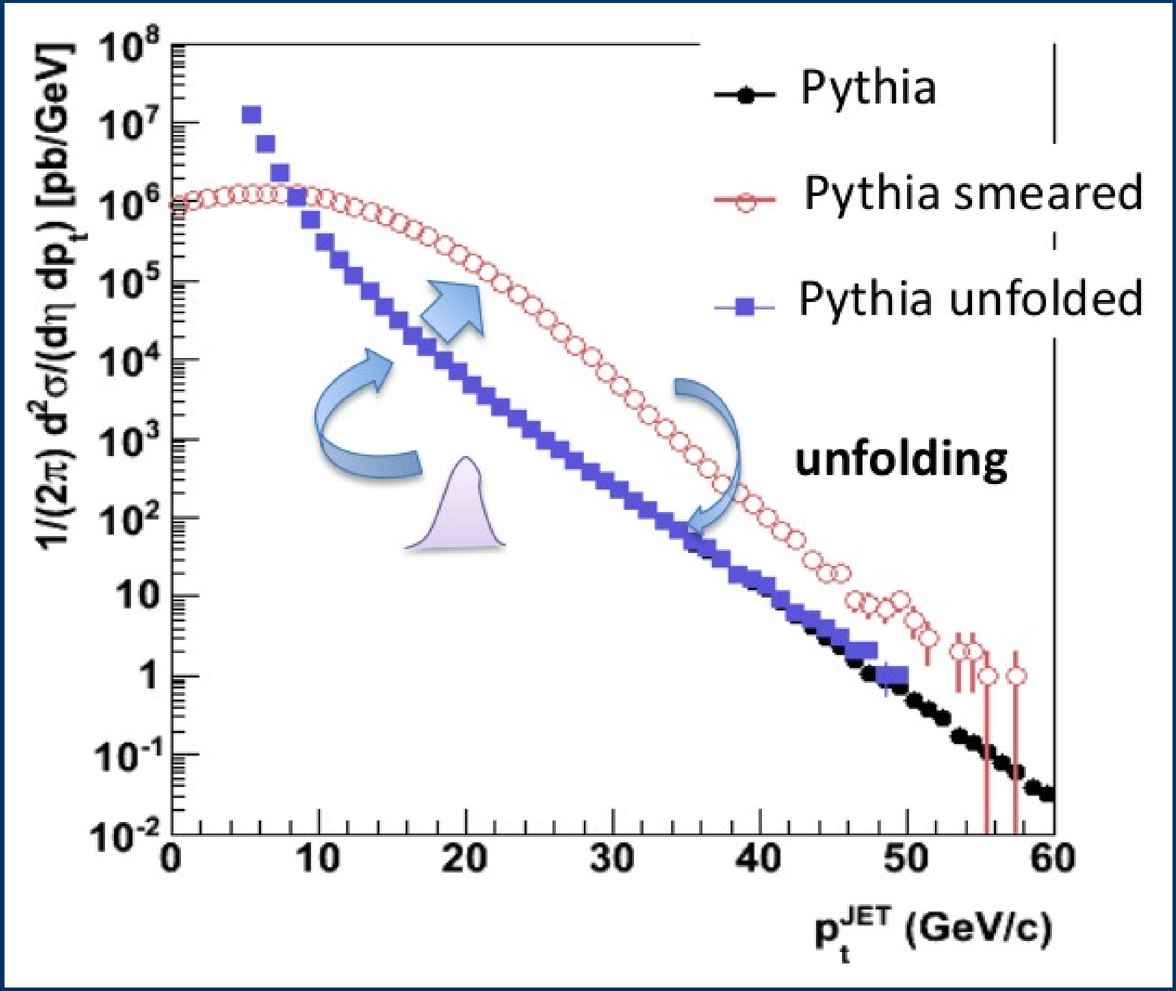
Pseudorapidity acceptance

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

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



Jet spectra - unfolding



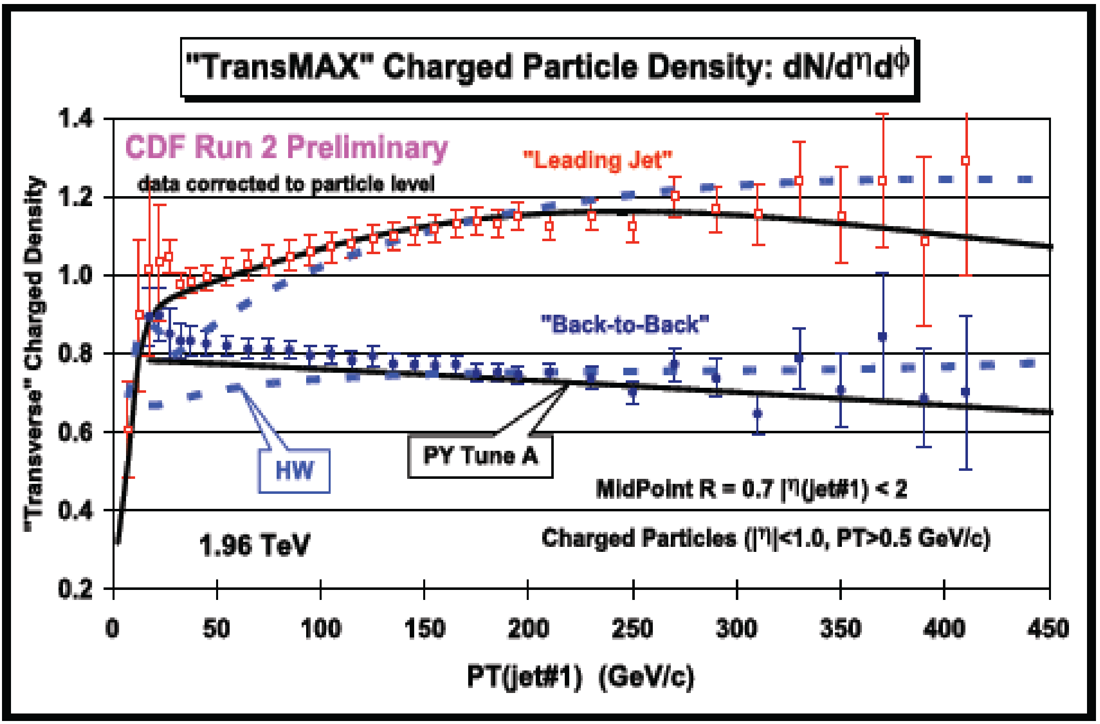
Gaussian widths – smearing/unfolding from Pythia embedding:

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

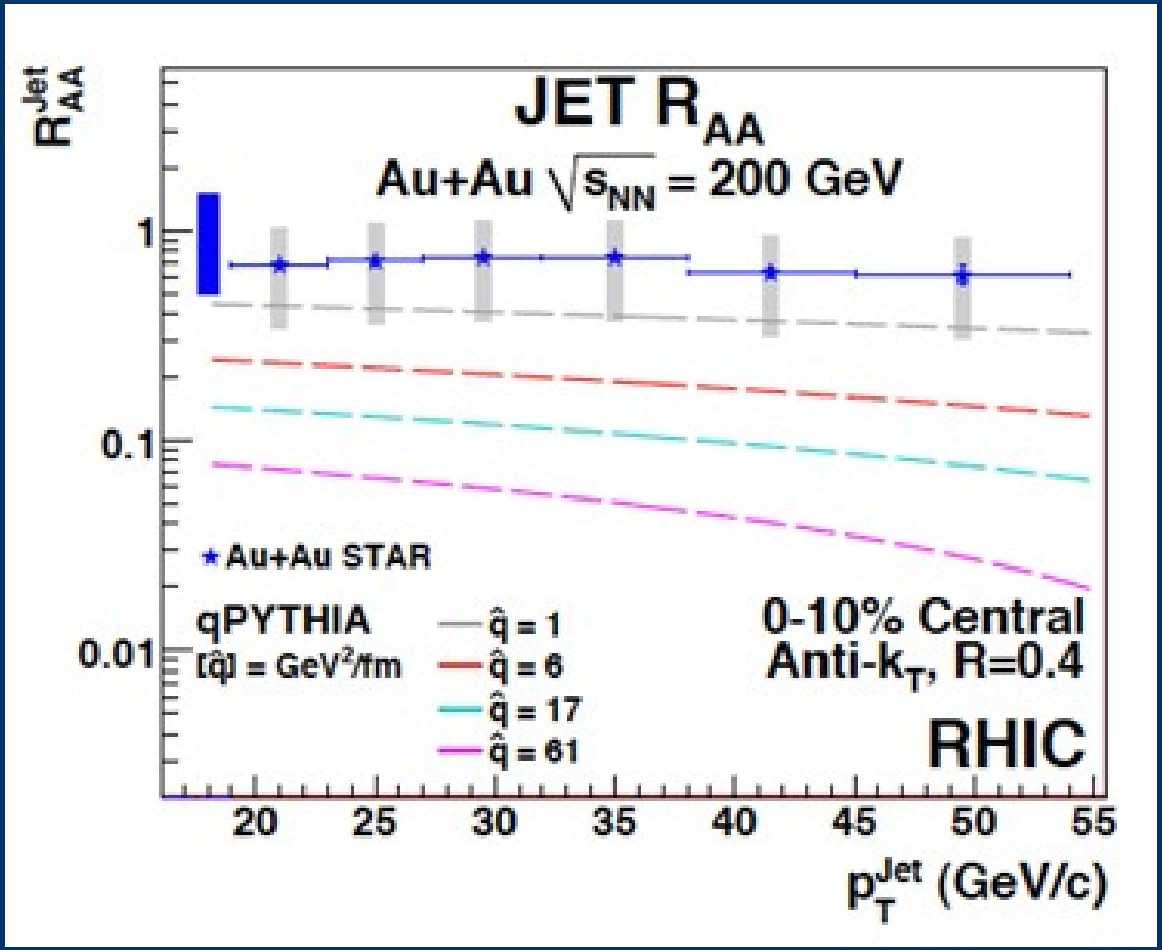
systematic uncertainty (bands): +-1 GeV

UE at Tevatron

R. Field et al. (CDF), hep-ph/0510198



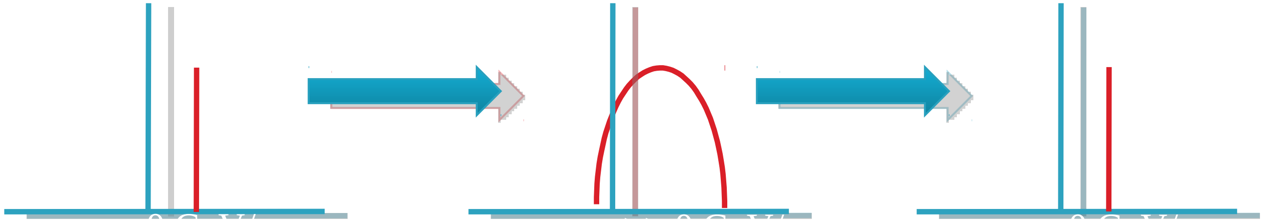
AuAu jets & theory



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:

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

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

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

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

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