Jet Reconstruction at STAR

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Outline

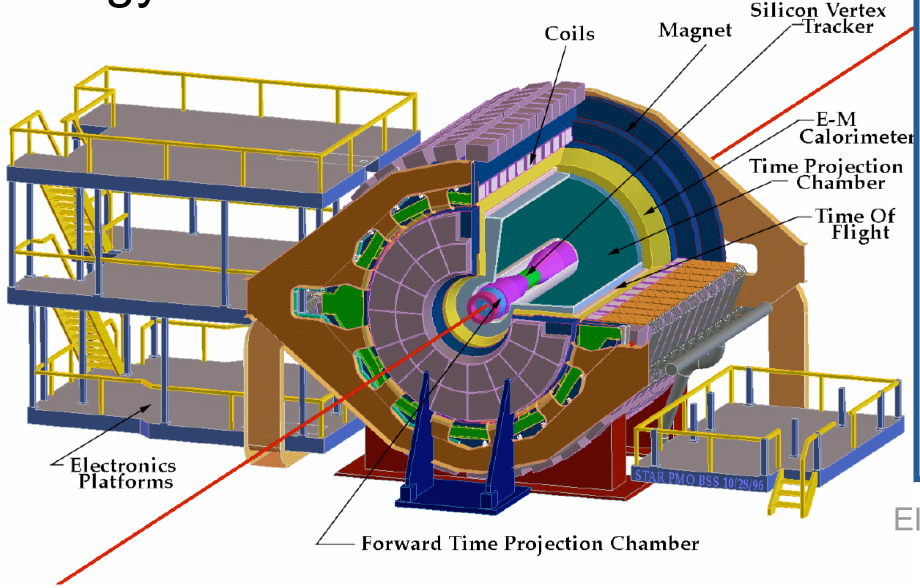
- Jet measurements in p+p: jets are “calibrated” pQCD probes
    - X-section
    - Jet energy profile and comparison to PYTHIA and NLO

- Jet measurements in d+Au: control experiment
    - Cold Nuclear Matter Effects

- Jet measurements in Au+Au: towards a consistent picture of jet quenching
    - Background characterization: the crucial issue
    - Jet R_{AA} , Jet-hadron correlations, di-jets, jet fragmentation

Jets at STAR

- TPC tracks for charged particles
- Barrel EMC for neutral energy
- $\Delta\varphi=2\pi$ of TPC and BEMC
- $-1\leq\eta\leq1$
- Unless stated otherwise, data are corrected for detector eff. and jet energy resolution



Data Sets:

p+p Run 2006
d+Au Run 2008
Au+Au Run 2007

Triggers:

- Min Bias (MB): Au+Au
- Jet-Patch (JP) in EMC
  $E_T > 8$ GeV in $\Delta\eta \times \Delta\phi = 1\times1$
- High Tower (HT) in EMC
  $E_T>5.4$ GeV in one tower
  $\Delta\eta \times \Delta\phi = 0.05\times0.05$

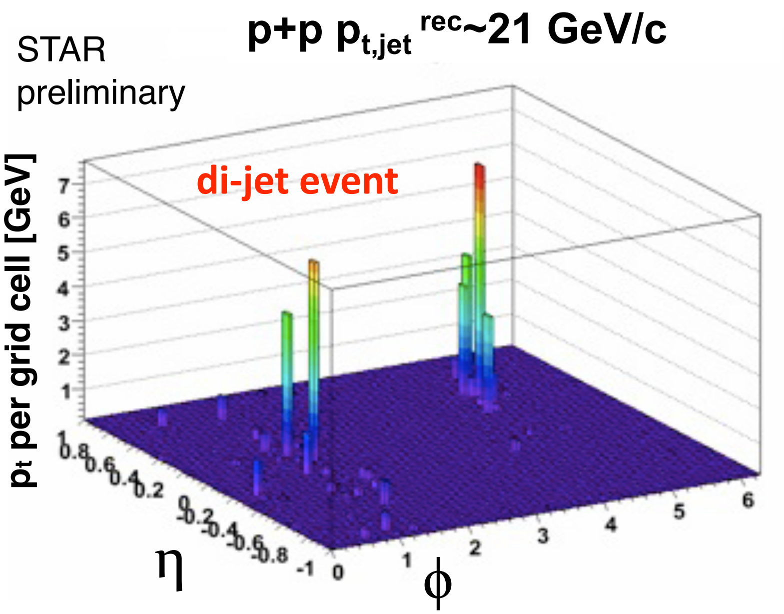
Jet Algorithms:

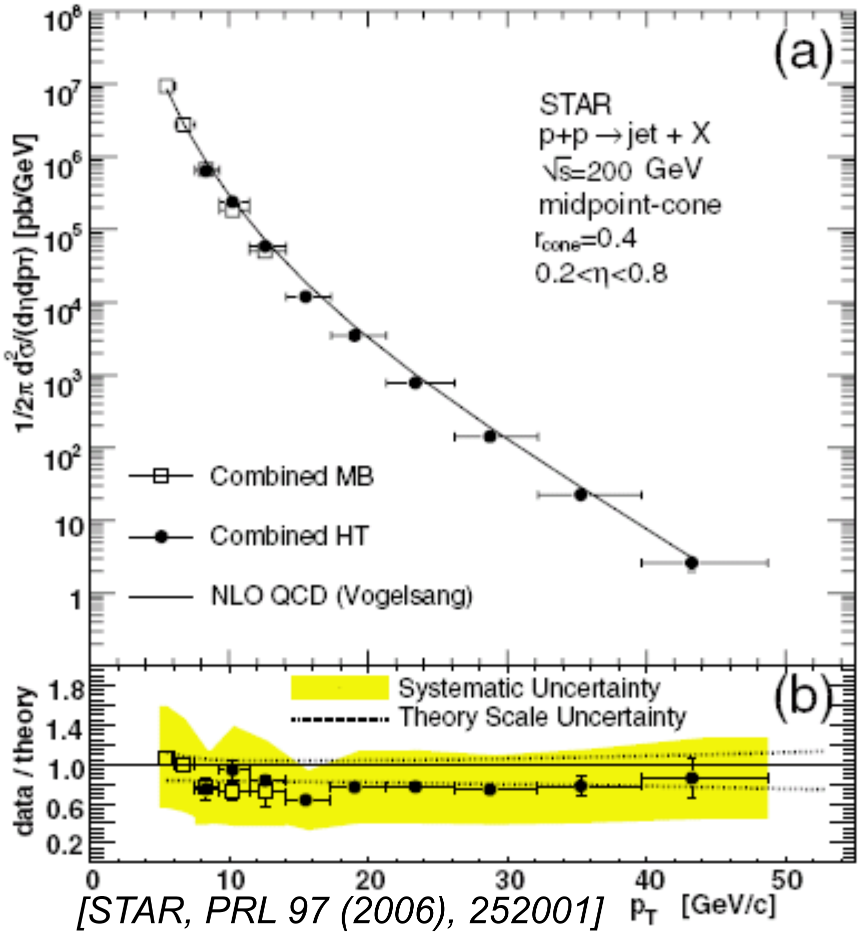
k_T, Anti-k_T
R= resolution parameter. R=0.2, 0.4, 0.7

Jets are “calibrated” probes

Jet cross section in p+p well described by pQCD

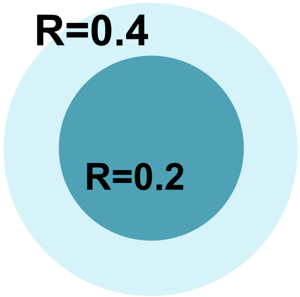
Jets in p+p are “calibrated” probes, good reference for Au+Au

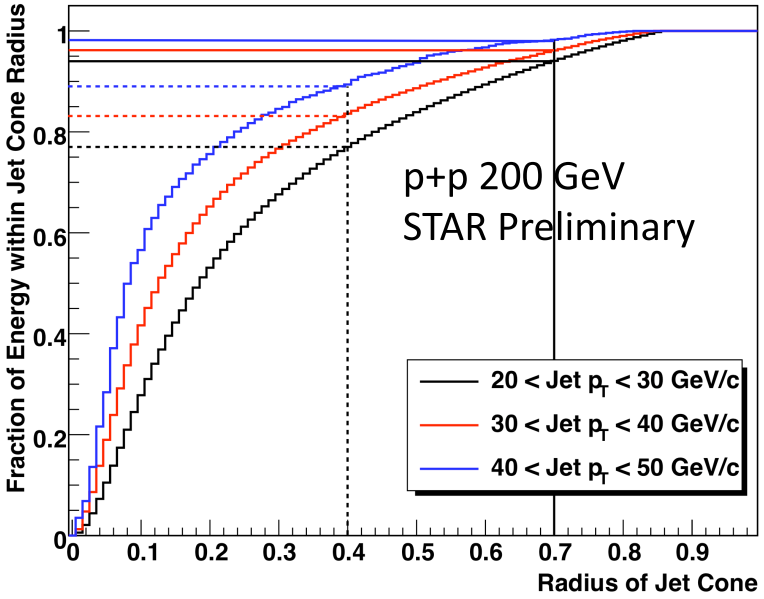




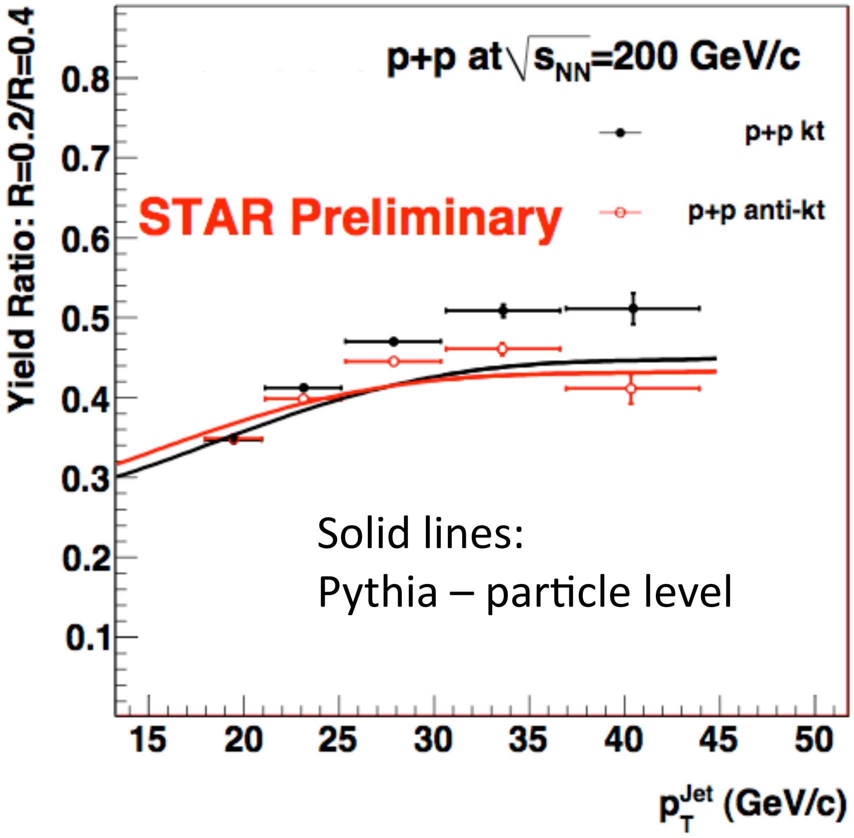
[STAR, PRL 97 (2006), 252001]

Jet energy profile in p+p





p+p 200 GeV
STAR Preliminary

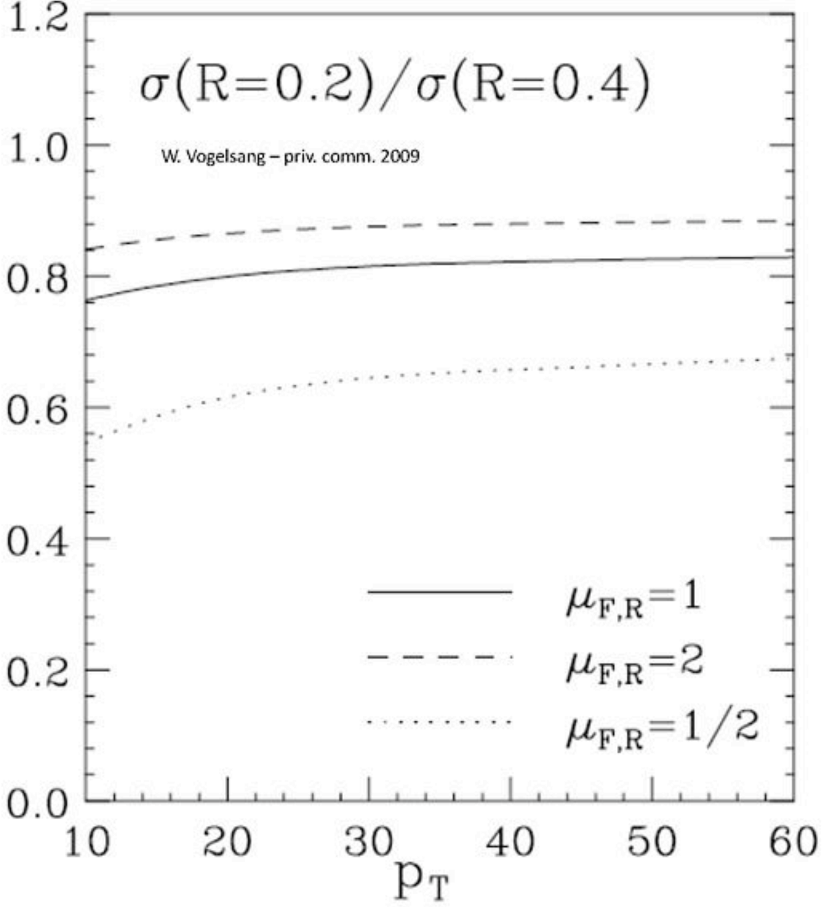


Solid lines:
Pythia – particle level

- jets more collimated with increasing p_T
- PYTHIA (fragmentation + hadronization) describes the data

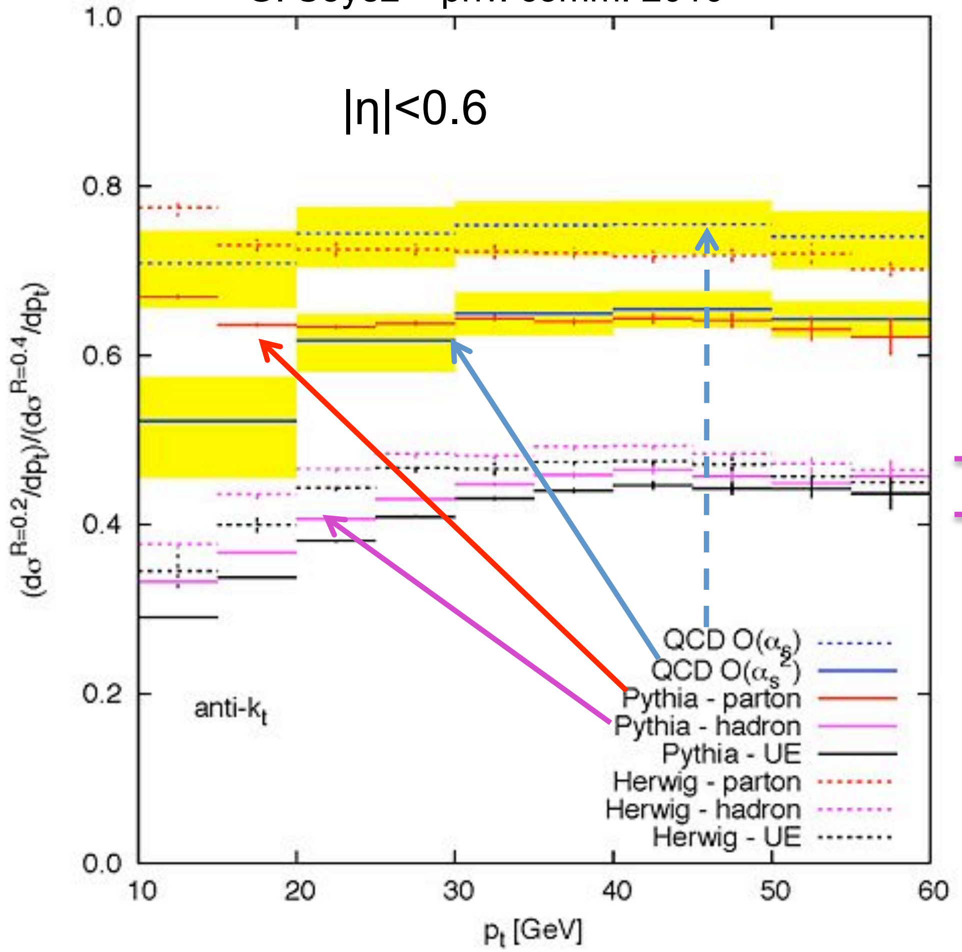
σ(R=0.2)/σ(R=0.4) : NLO

W. Vogelsang – priv. comm. 2009



σ(R=0.2)/σ(R=0.4) : NLO

G. Soyez – priv. comm. 2010



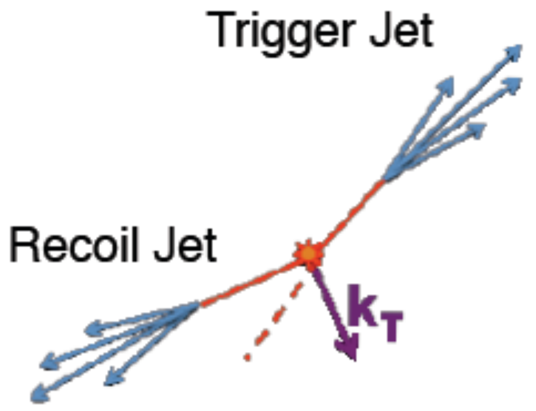
NLO ≈ PYTHIA parton level

— PYTHIA hadron level ≈

- - - HERWIG hadron level

Hadronization broadens the jet

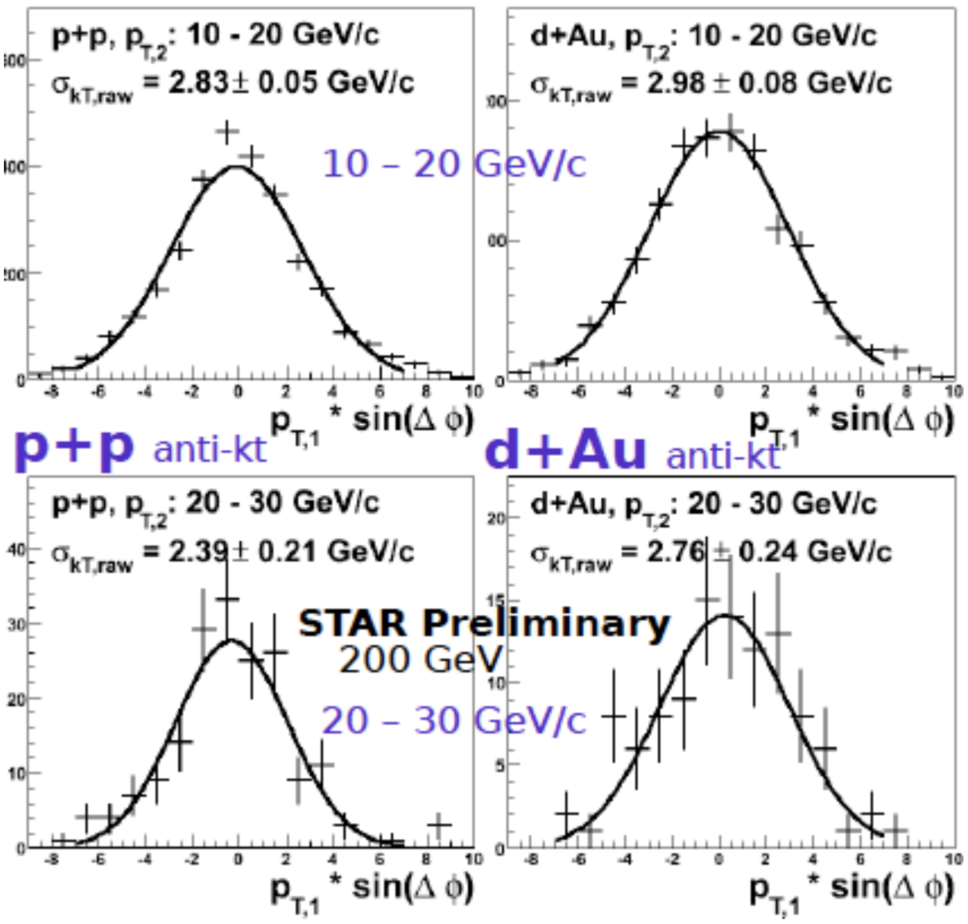
Jets in d+Au



$k_T = P_{T,1} * \sin(\Delta\phi)$

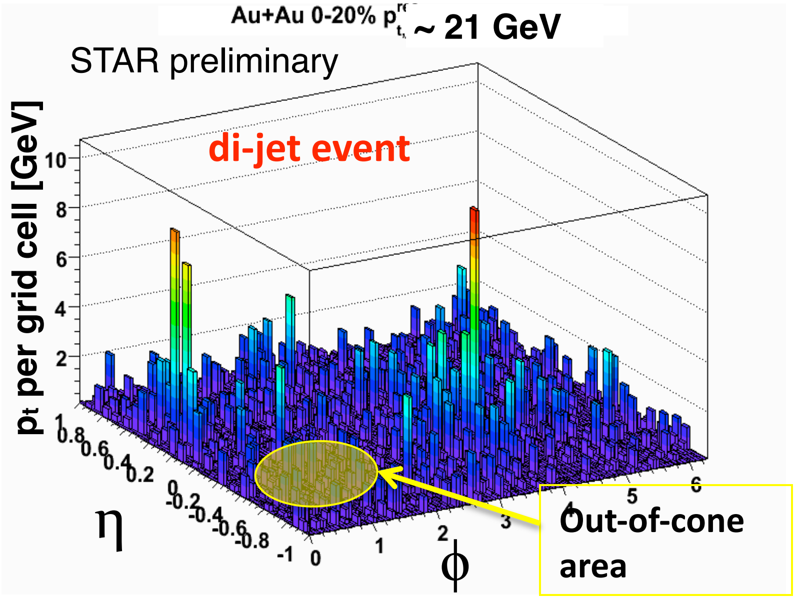
$\sigma_{kT,raw}$ (p+p) = 2.8 ± 0.1 GeV/c

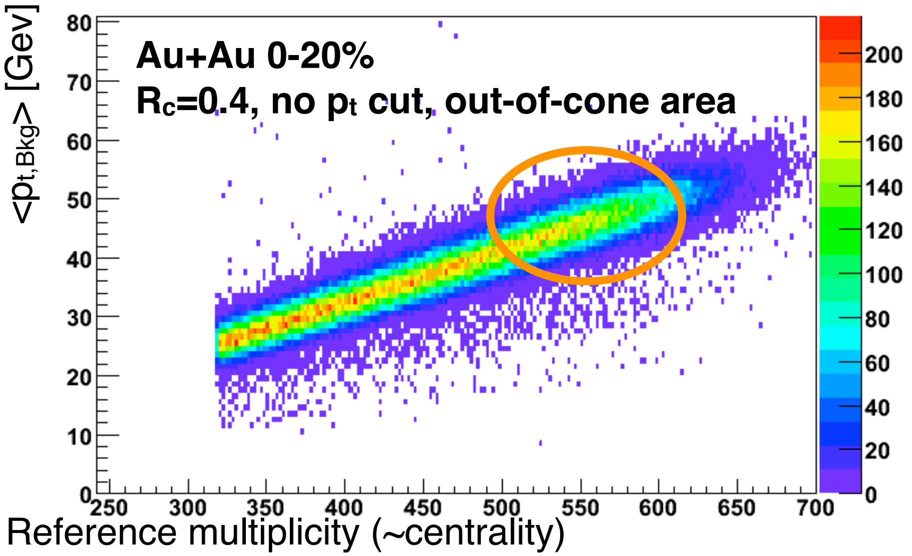
$\sigma_{kT,raw}$ (d+Au) = 3.0 ± 0.1 GeV/c



Cold Nuclear Matter effect on jet k_T broadening is small

Jet reconstruction in Au+Au





$$p_T^{\ Meas} \sim p_T^{\ Jet} + p_{T,Bkg}$$

- $p_{T,Bkg}$ fluctuates around $<p_{T,Bkg}> = \rho A$ = mean p_T in out-of-cone area

- Fake jets: = random association of uncorrelated soft particles (i.e. not due to hard scattering)

- Region-to-region background fluctuations described by *f*:

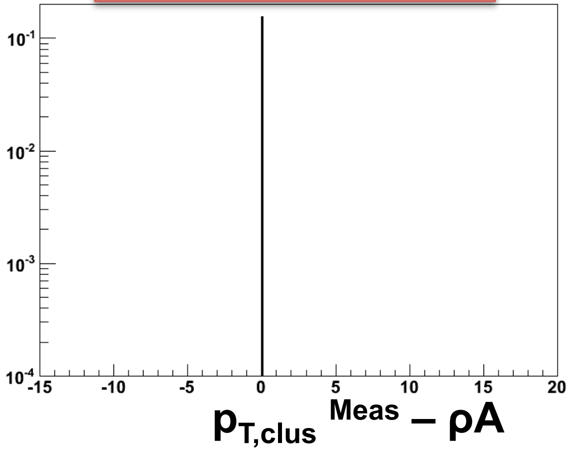
$$\frac{dN^{Meas}}{dp_T} = \frac{dN^{Jet}}{dp_T} \otimes f$$

Assessing background fluctuations

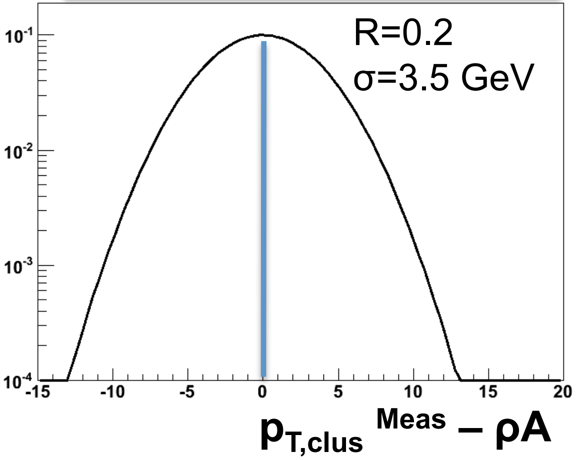
$$f\,(p_{T,clus}^{\,Meas} - \rho A)$$

$p_{T,clus}$ for only background jets

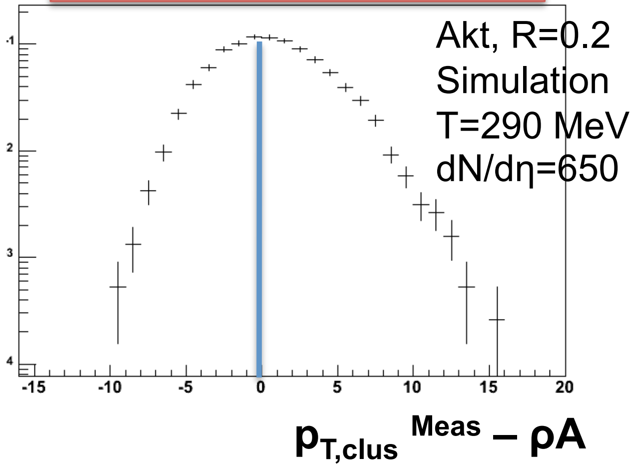
No fluctuations



Gaussian fluctuations



“Thermal” fluctuations

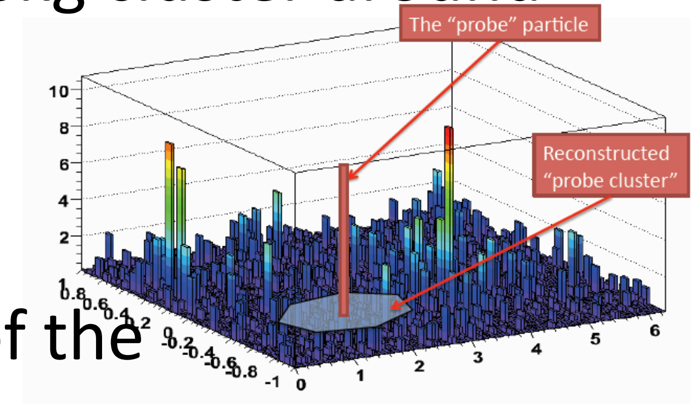


How to characterize the full shape of the bkg fluctuations?

Approaches to assess bkg fluctuations

1) Embed particles in Au+Au events, run the jet finder, extract the distribution of p_T of the bkg cluster around the probe particle.

   - » Study as a function of the probe p_T

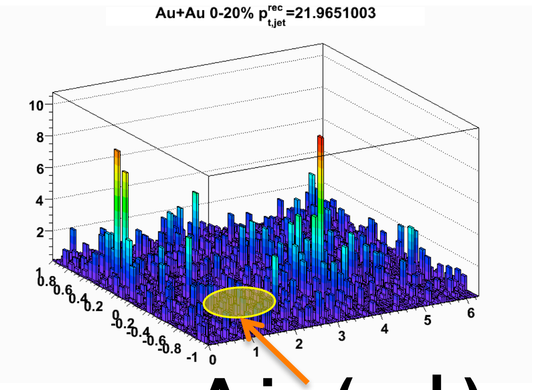


2) Derive a mathematical description of the fluctuations assuming statistical independent (thermal) particle emission. Assess the validity of this assumption on bkg jets in data

   - » Statistical bkg description: Lower estimate, no additional correlation

As an example, look in more detail at the second approach

Background fluctuations on Thermal model

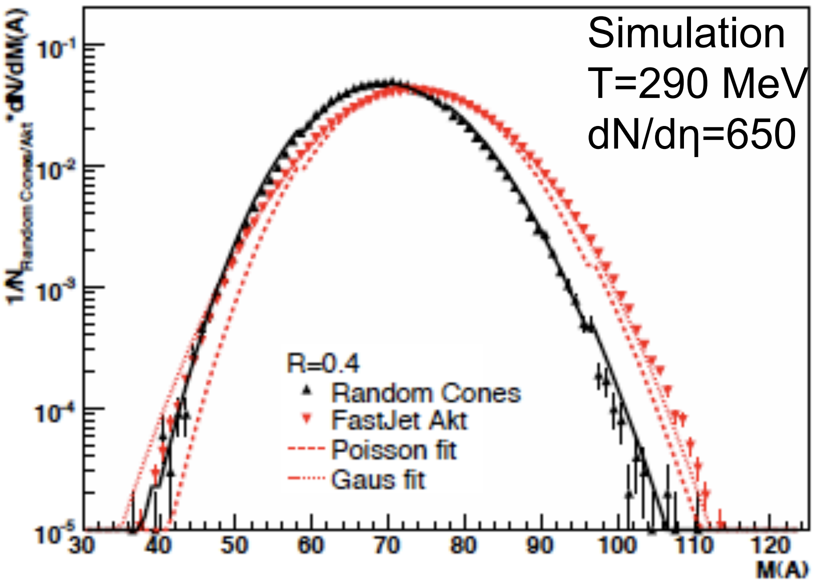


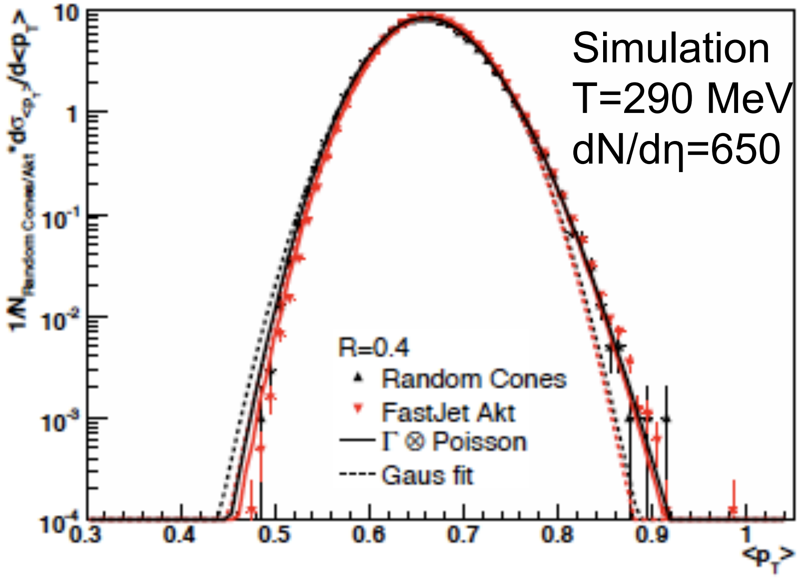
Background fluctuation distribution in a given area A in (η,ϕ):

$$F(p_T;A) = F_M(A)\otimes F_{<p_T>}(A)$$

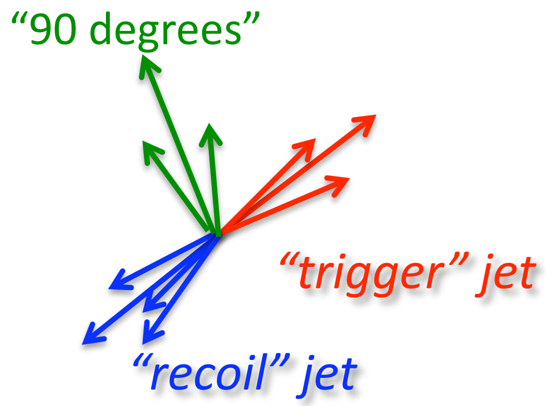
M.Tannenbaum PLB 498 2001

- M(A) = particle multiplicity in a given A → $F_M(A)$ **Poisson**
- $<p_T>$ = mean p_T in a given area → $F_{<p_T>}(A)$ **Gamma**



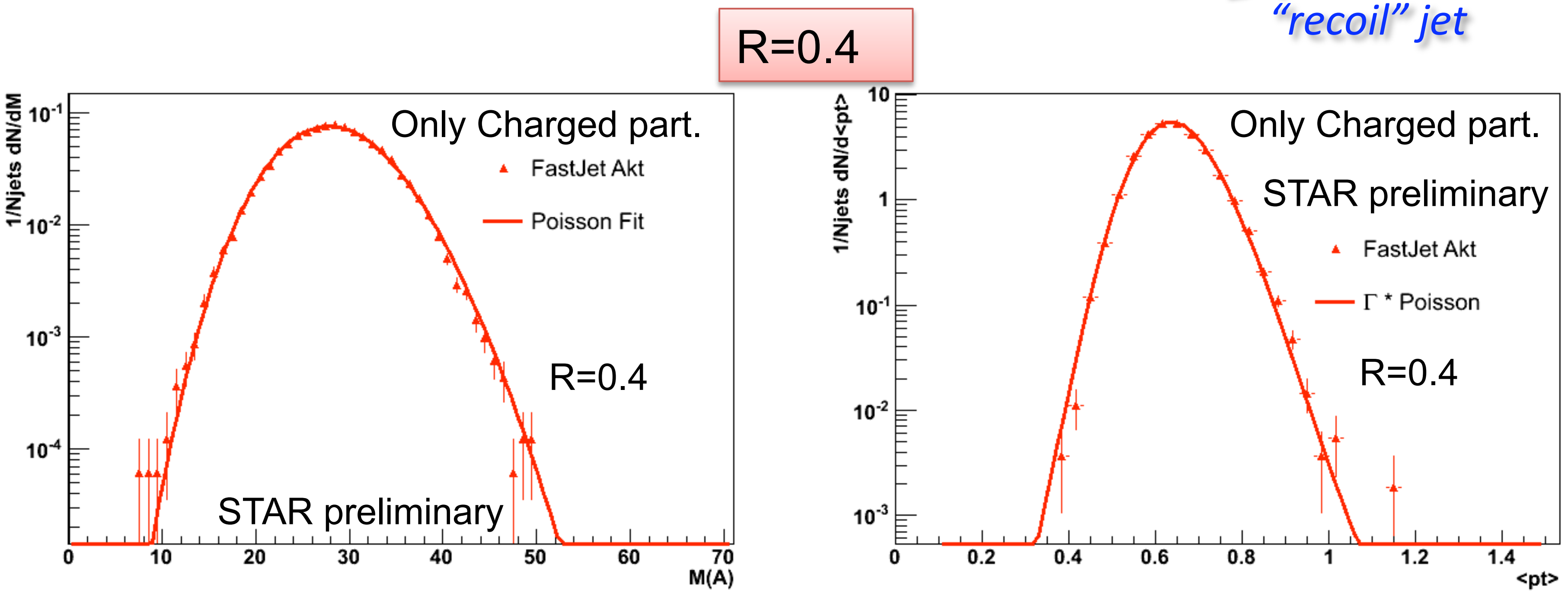


Background fluctuations on Au+Au data



HT 90° Anti-kt jets with $p_T^{Meas} - \rho A < 0$ (i.e. bkg jets)

Narrow area: 0.45<Akt area<0.55 ($\approx \pi R^2$)



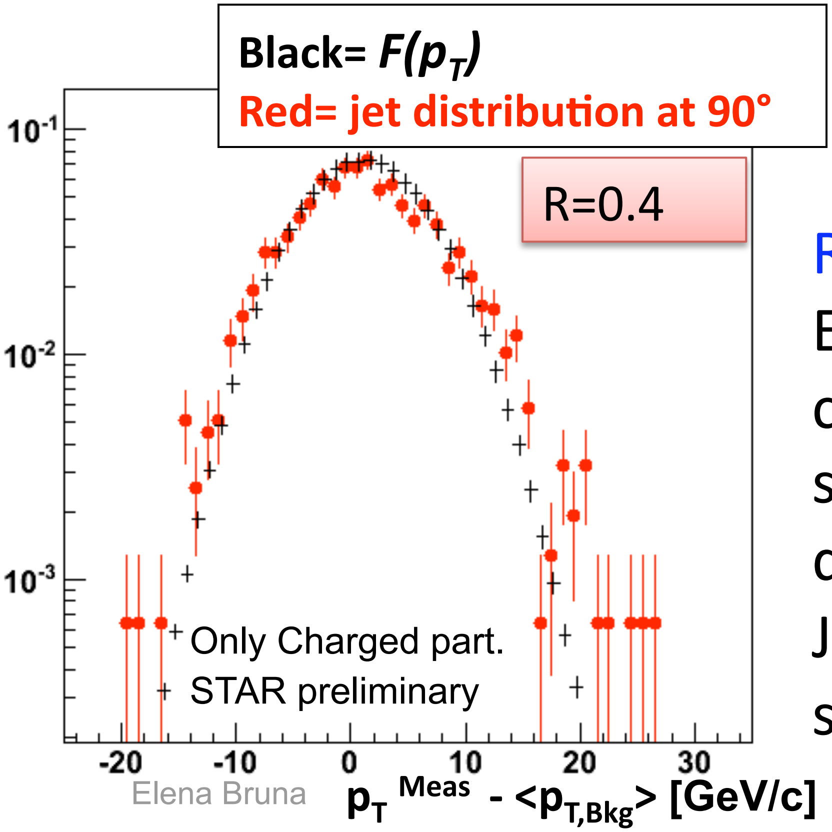
M(A) and $\langle p_T \rangle$ distribution well described by statistical functions

Fit parameters fixed from data

Extracting the Bkg fluctuations

- Extract $F_M(A)$ and $F_{<p_T>}(A)$ from M and $<p_T>$ distributions
- Fold them into $F(p_T;A) = F_M(A) \otimes F_{<p_T>}(A)$
- Extract pt(bkg jet) ≈ M × $<p_T>$
- Use *$F(p_T)$* to **unfold** bkg fluctuations from measured jet spectrum

Left hand side (bkg jets): Described by statistical function



Black= *$F(p_T)$*

Red= jet distribution at 90°

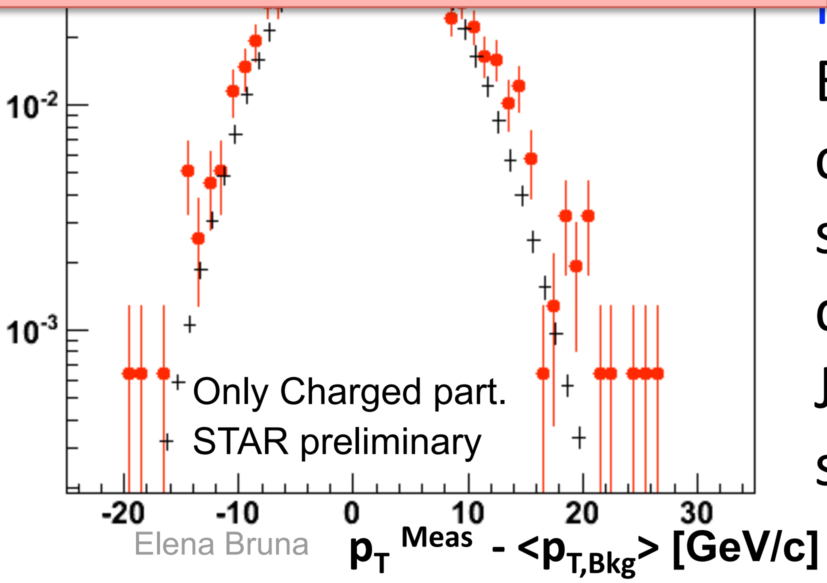
Right hand side: Excess of jets compared to statistical description. Jets from 2nd hard scattering?

Extracting the Bkg fluctuations

- Extract $F_M(A)$ and $F_{<p_T>}(A)$ from M and $<p_T>$ distributions
- Fold them into $F(p_T;A) = F_M(A) \otimes F_{<p_T>}(A)$
- Extract pt(bkg jet) ≈ M × $<p_T>$
- Use *F*(p_T) to **unfold** bkg fluctuations from measured jet spectrum

Looks promising, part of an overall effort towards a systematical evaluation of background fluctuations and their uncertainties

Left hand side (bkg jets): Described by statistical function

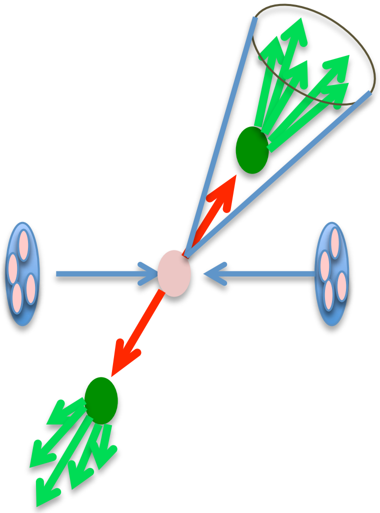


Right hand side: Excess of jets compared to statistical description. Jets from 2nd hard scattering?

Expected results

for unbiased jet reconstruction -

Jet energy fully recovered even in case of quenching
Jet is a hard process, scales as N_{bin}

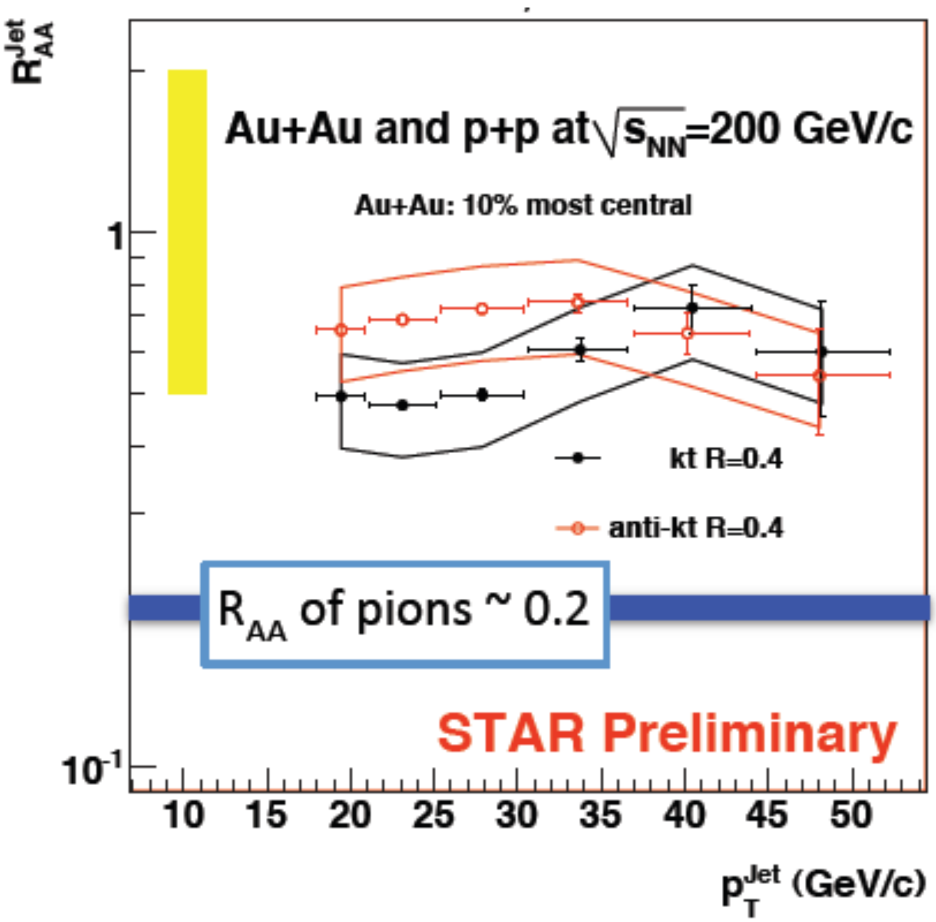


Inclusive spectra:
- $R_{AA}^{jet} = 1$

Di-jet analyses:
- Recoil spectra Au+Au same as p+p
- Modified fragmentation in case of dense medium

Wiedemann, Sapeta arXiv:0707.3494

Jet inclusive measurements: R_{AA}

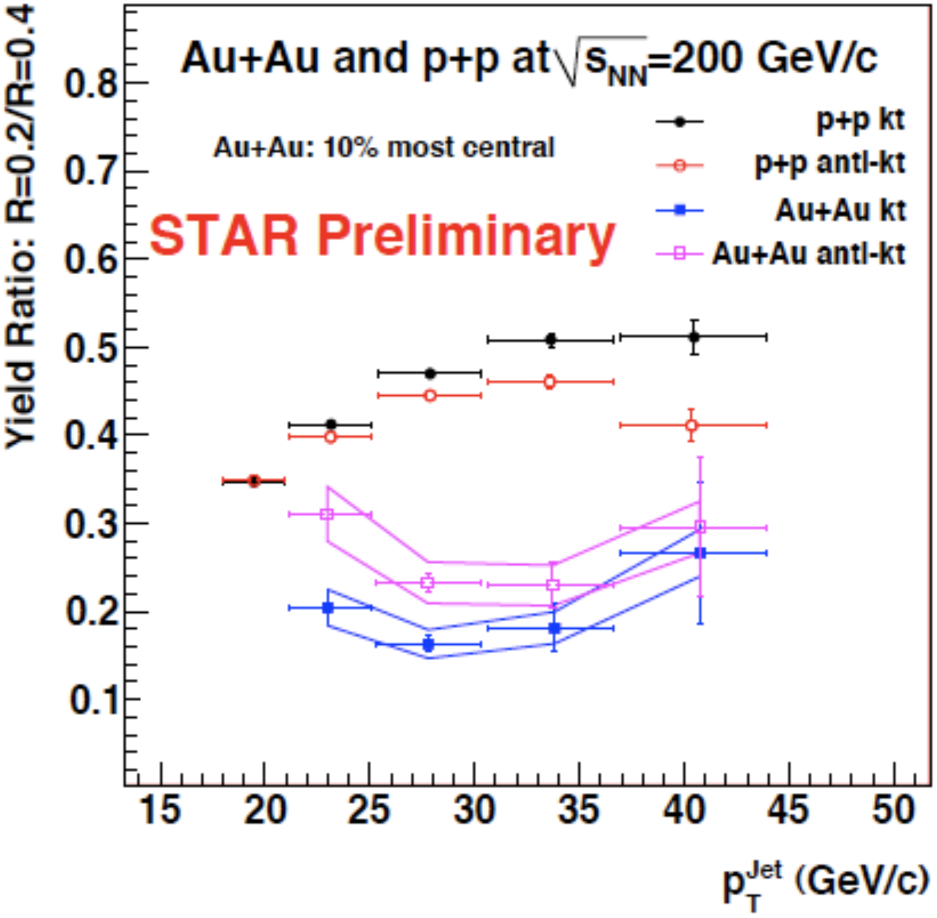


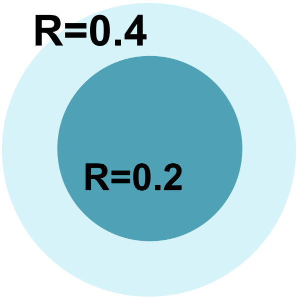
$R_{AA}^{jet}<1$

$R_{AA}^{jet} > R_{AA}$ for single hadron (R=0.4)

Full energy NOT recovered, jet broadened OR Absorption?

Broadening or absorption? Look at Jet energy profile: 0.2 vs 0.4





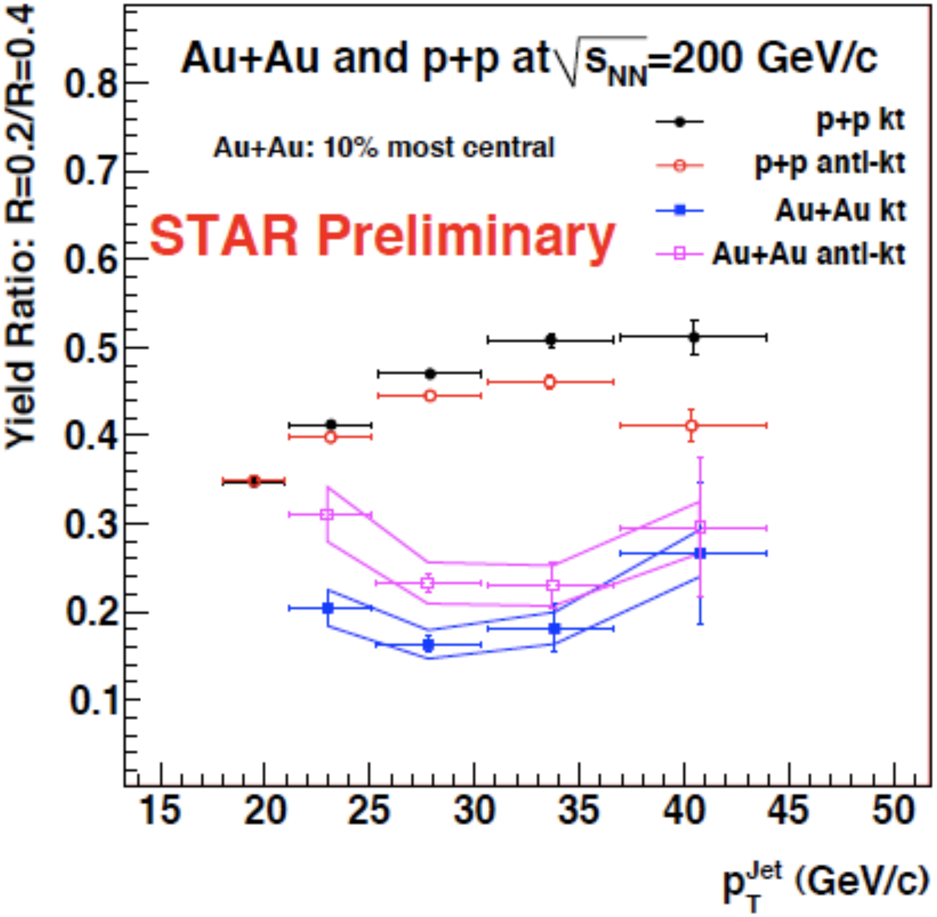
p+p:

- jets more collimated with increasing p_T
- PYTHIA describes the data

Au+Au:

- ratio lower than p+p

Jet Energy profile: 0.2 vs 0.4



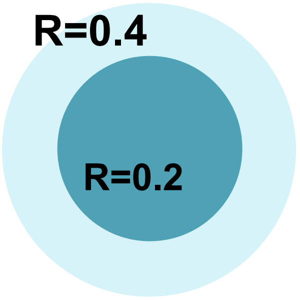
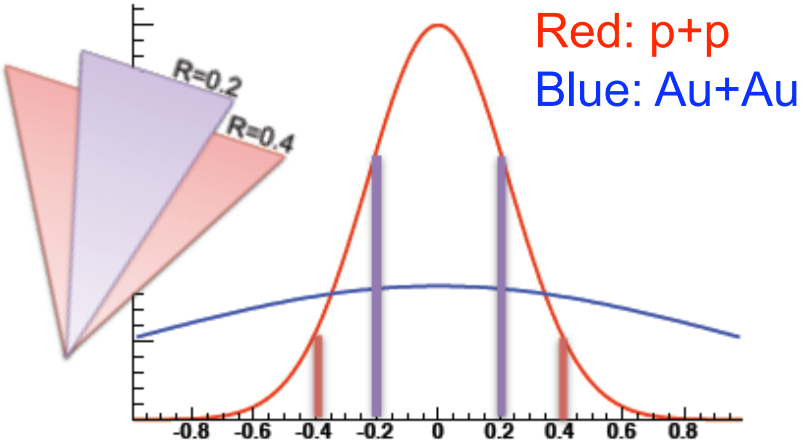


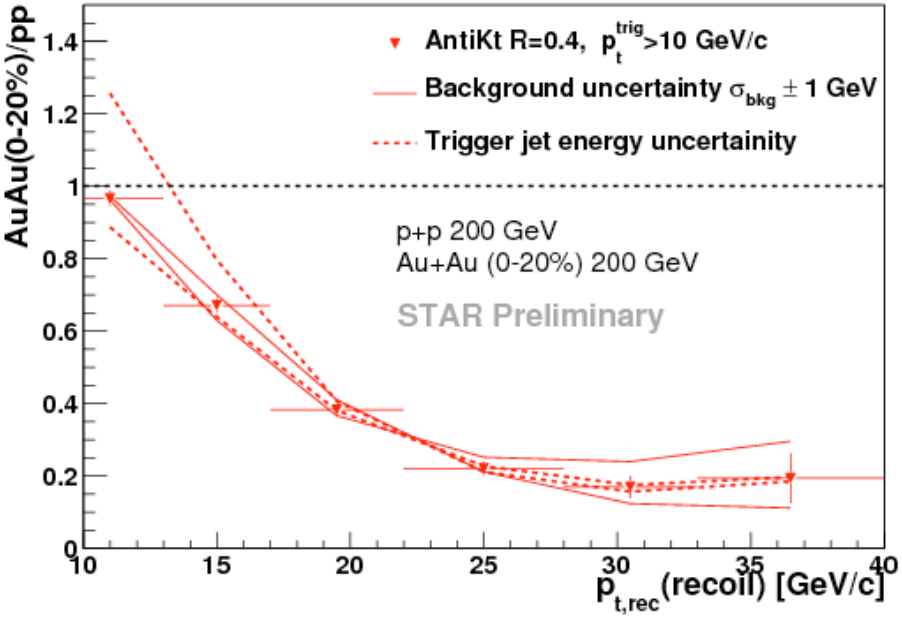
Illustration: Gaussian 1D profile



Red: p+p

Blue: Au+Au

di-jet measurements



Trigger jet: Anti-kt R=0.4, $p_{t,cut}$>2 GeV/c, $p_{t,rec}^{jet}$>10 GeV/c

$p_{T,cut}$ allows similar trigger jet population in p+p and Au+Au

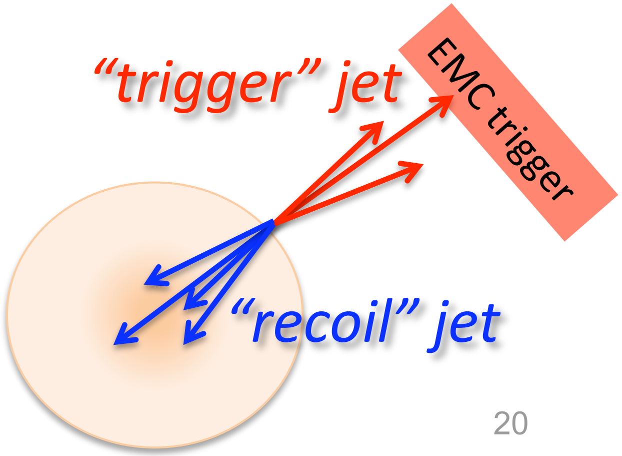
Recoil jets measured per trigger jet → coincidence rate

Significant suppression of recoil jets

Extreme path-length of recoil jets

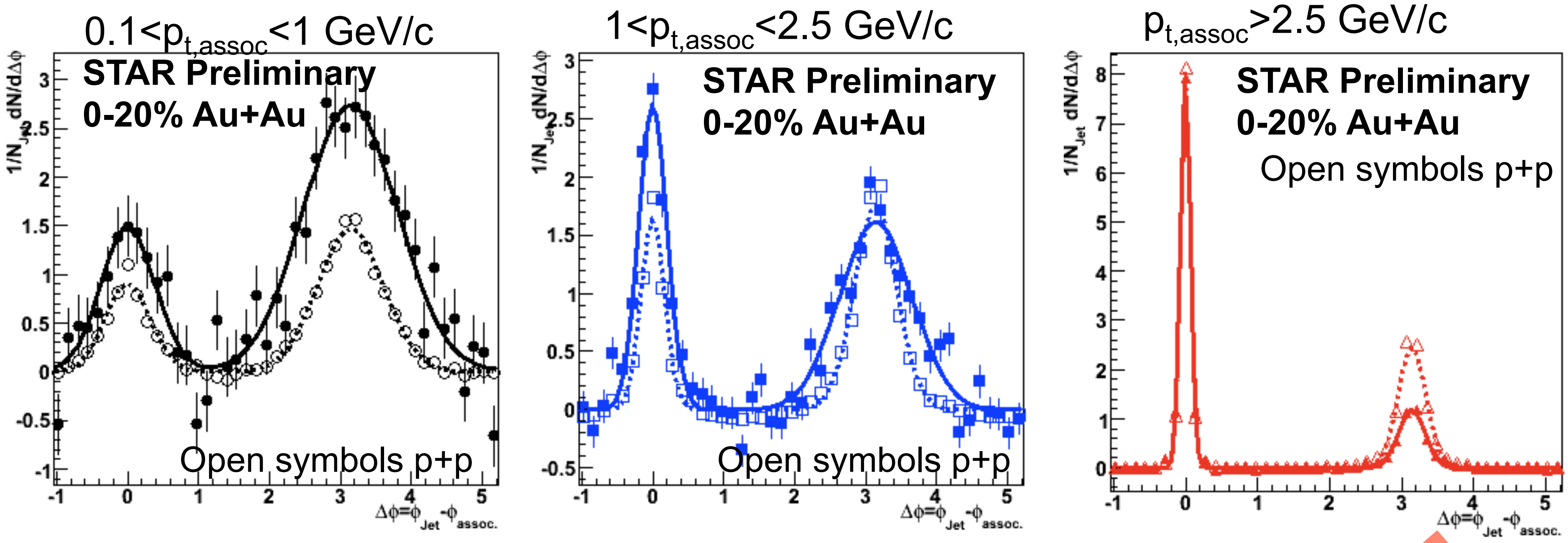
Indicates broadening:

- Energy shifts to larger cone radii (>0.4) or
- Some Jets "absorbed" in the limit



Jet-Hadron correlations

Trigger jet: Anti-kt R=0.4,
$p_{t,cut}$>2 GeV/c, $p_{t,rec}^{jet}$>20 GeV/c

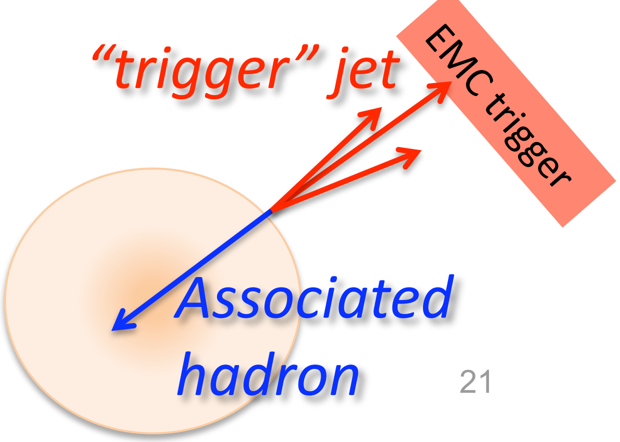


flat bkg subtraction by ZYAM - jet v2 under investigation

See A. Ohlson's poster on jet v2 studies

Significant broadening on the recoil side

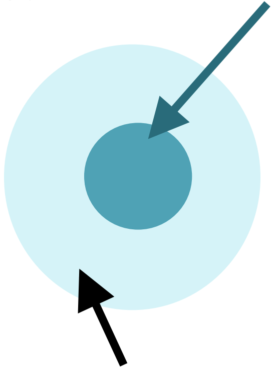
Observed modification of hadron p_T distribution in jets


"trigger" jet

EMC trigger

Associated hadron

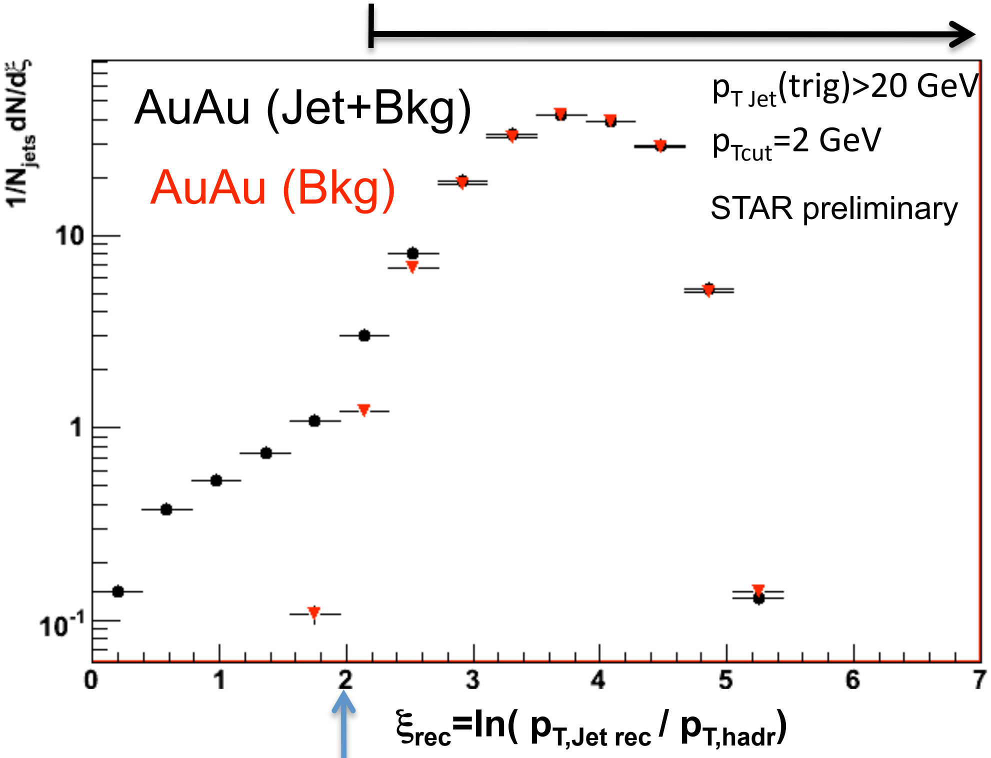
Jet fragmentation



Jet energy determined in R=0.4

Charged particle ξ: R=0.7

large uncertainties due to background
(further systematic evaluation needed)



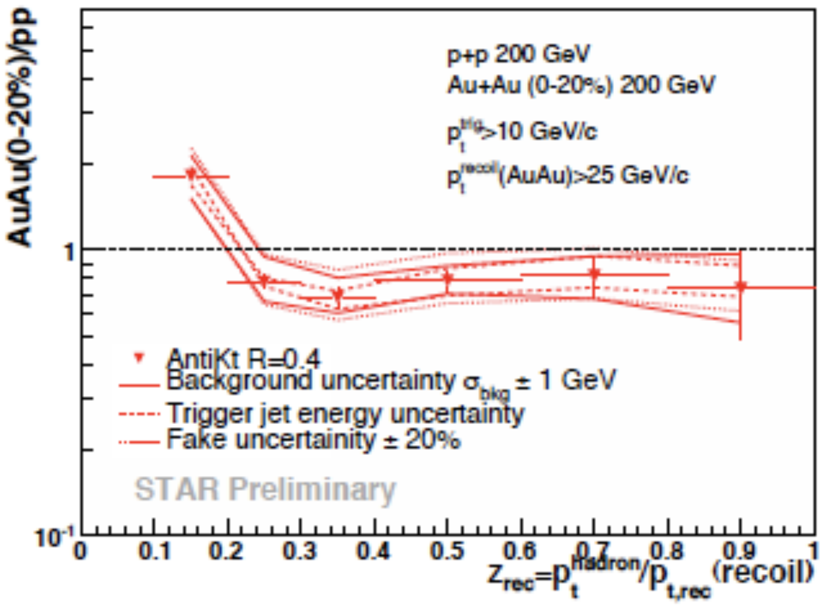
$p_{T,hadr}$ =2.7 GeV/c

AuAu: ξ(Jet)=ξ(Jet+Bkg)-ξ(bkg)

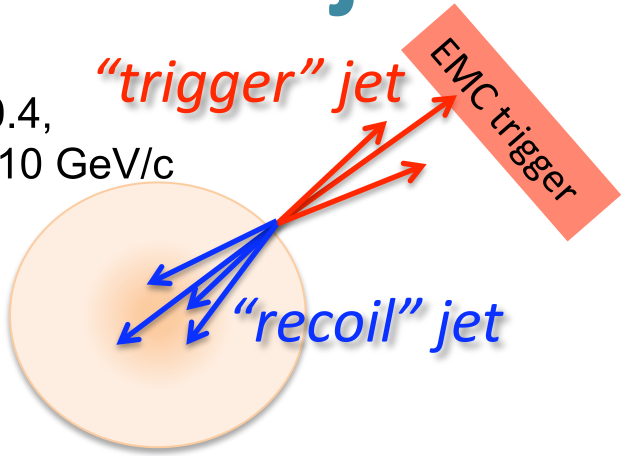
Bkg estimated from charged particle spectra out of jet cones

Bkg dominates at low p_T

di-jets: fragmentation of recoil jets



Trigger jet: Anti-kt R=0.4, $p_{t,cut}$>2 GeV/c, $p_{t,rec}^{jet}$>10 GeV/c



No apparent modification of z of recoil jets, would imply non-interacting jets, **but**:

If Jet broadening:

$p_{T,jet}^{AuAu}(R=0.4)=p_{T,jet}^{pp}(R=0.4) \rightarrow p_{T,parton}^{AuAu} > p_{T,parton}^{pp}$

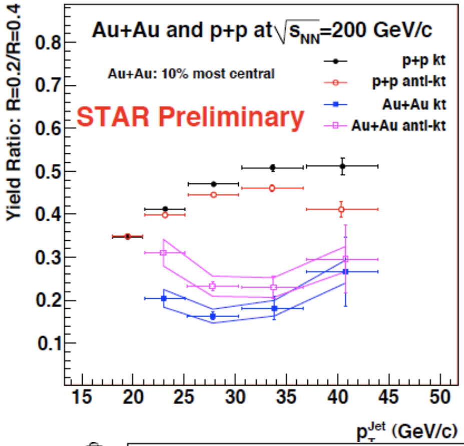
→z(Au) harder than z(pp) in absence of modification.

z(Au) ≈ z(pp) → in presence of jet broadening suggests that z(Au) is actually softened

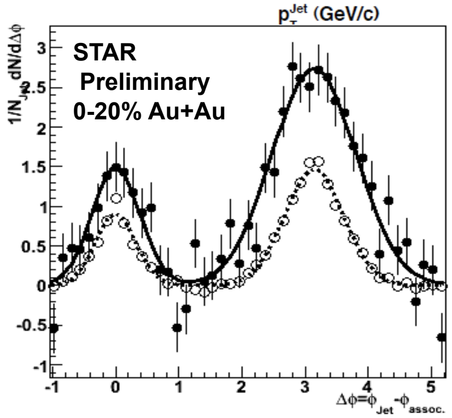
Crucial: better determine the jet energy

Summary

- Jet reference measurements in p+p and d+Au under control
- Background characterization:
  - ○ the most serious issue – current focus
- Inclusive jet results in Au+Au:
  - ○ Jet suppression at high-p_T (R_{AA}<1)
  - ○ Broadening of jet profile from R=0.2 to R=0.4

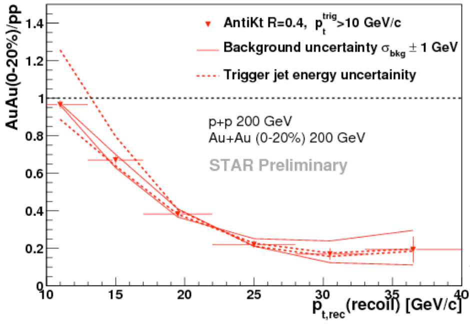


- Jet-Hadron correlation results:
  - ○ Broadening and softening of recoil side



- di-jet results in Au+Au:
  - ○ Recoil jets suppressed in Au+Au
  - ○ No significant modification of measured z

→Artifact of broadening!



Backup slides

Experimental setup for pp and AuAu

Trigger setup with the STAR e.m. calorimeter (EMC):

- Min Bias Trigger: Beam-Beam-Counter (BBC) coincidence
- High Tower Trigger (HT): MB + tower 0.05x0.05 ($\eta x \phi$) with E_t> 5.4 GeV
- Jet Patch Trigger (JP): MB + Jet-Patch (η x ϕ=1 x 1) above threshold (E_T>8 GeV)

Data Set analyzed:

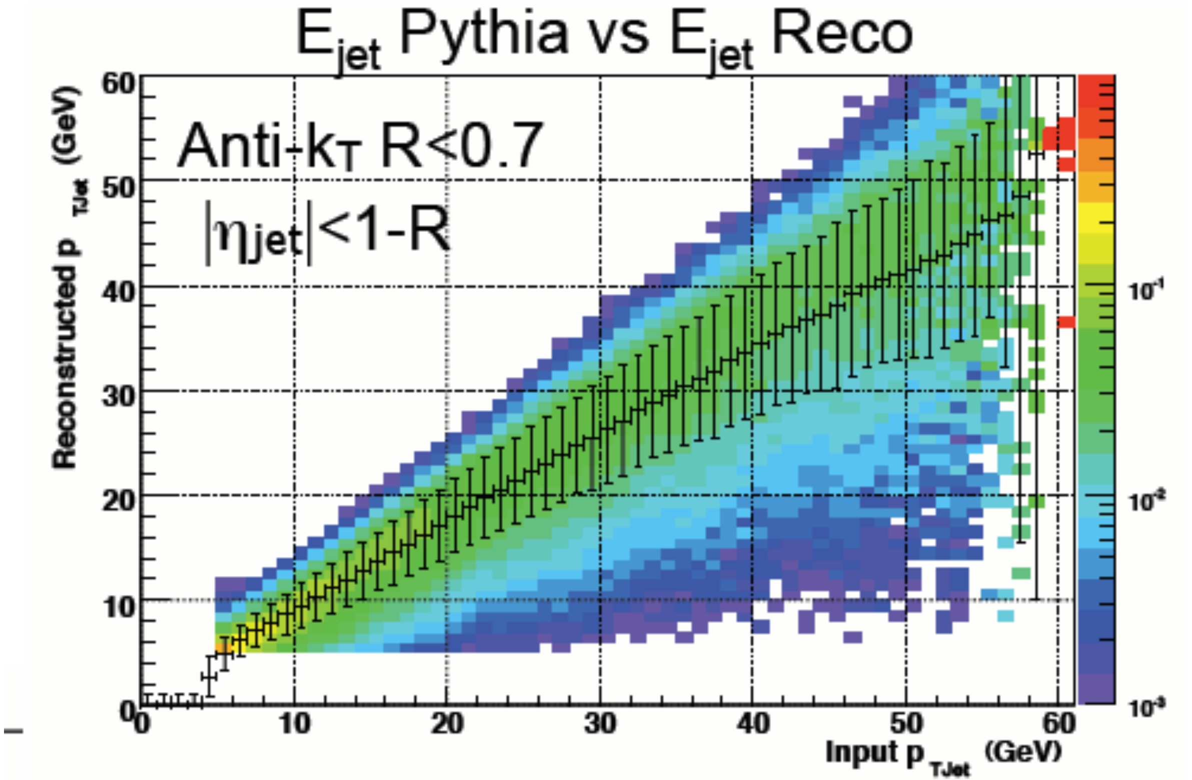
- pp (2006): HT trigger events, JP trigger events
- AuAu (2007): HT trigger events, 0-20% central; : MB trigger, 0-10%

Jet Finder Algorithm: Anti-kT (from FastJet package)

- R=0.4 , $|h_{jet}|<1-R$
- charged particle p_T (**TPC), 0.1<p_T<20 GeV/c**
- neutral tower E_t 0.05x0.05 ($\eta x \phi$) (**EMC**)
  - Hadronic correction
  - Electron correction for double counting

Jets in p+p @ STAR

Jet Energy Resolution – the jet energy scale



(1) Reconstructed Jet pT on average smaller than the Input (PYTHIA) jet pT

(2) The reconstructed jet pT is smeared

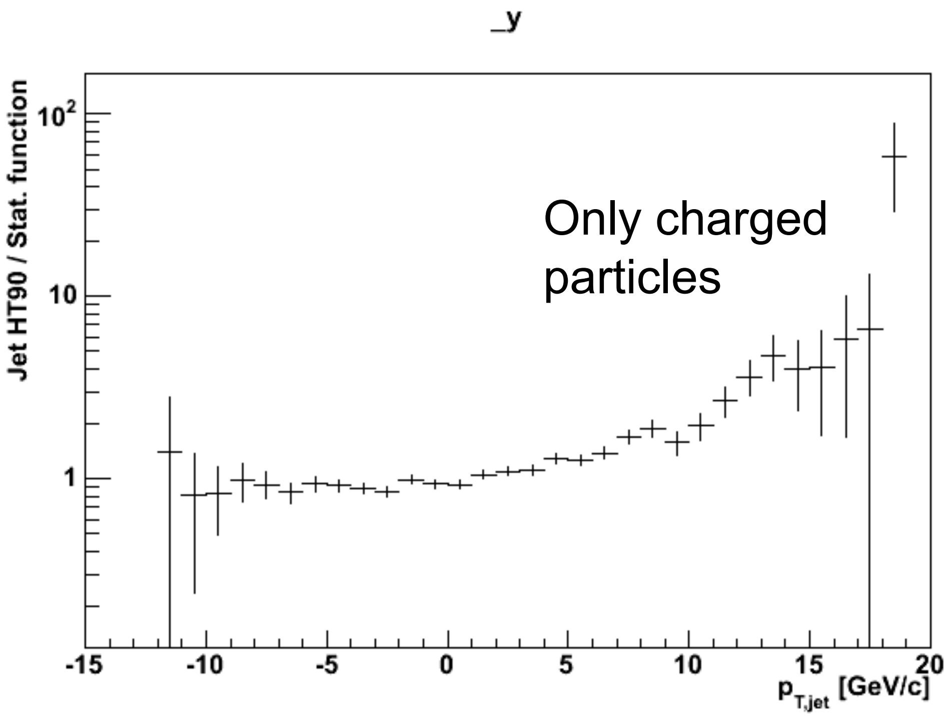
Need to know (1) and (2) to correct the measured jet pT back to the "true" jet pT

Background fluctuations

- Extract $F_M(A)$ and $F_{<p_T>}(A)$ from M and <pT> distributions
- Fold them into $F(p_T;A) = F_M(A) \otimes F_{<p_T>}(A)$

R=0.4

Left hand side: Described by statistical function

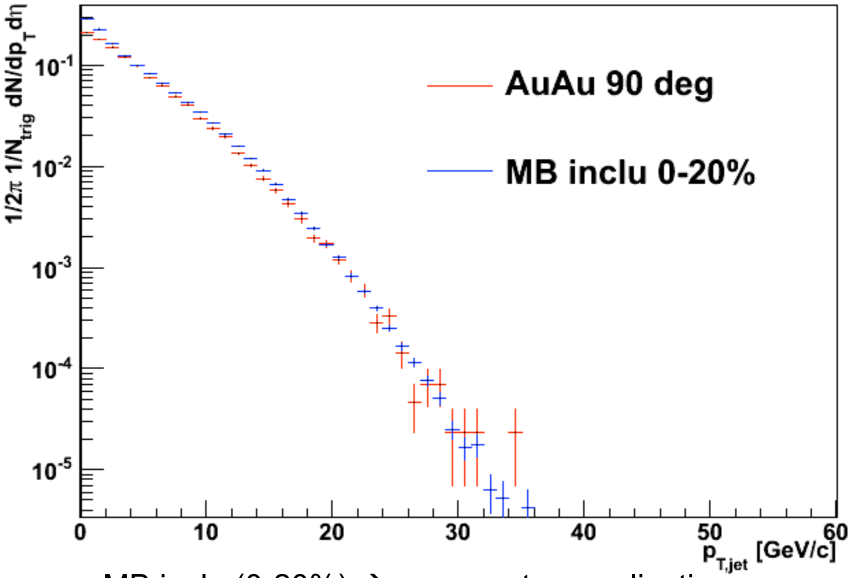


Right hand side: Excess of jets compared to statistical description. Jets from 2nd HS?

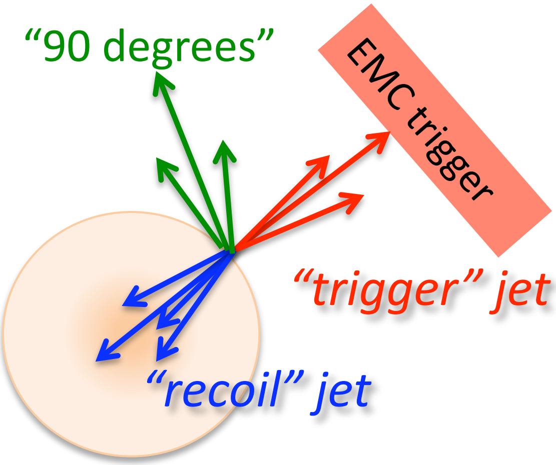
In qualitative agreement with Mateusz's fake rate estimate extracted from an independent analysis

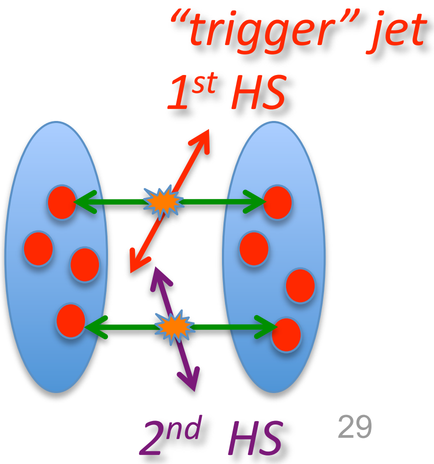
Background jets in HT Au+Au

Jet spectrum at 90° (di-jet analysis) = fake jets + 2nd hard scattering



MB inclu (0-20%) → per event normalization
HT 90° (0-20%) → per trigger jet normalization



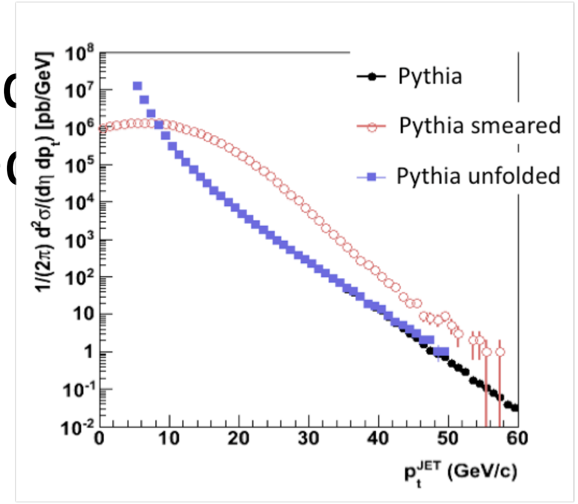


HT spectrum at 90° ≈ MB inclusive spectrum:

- not negligible 2nd HS contribution at 90°

Background correction

- Inclusive MB spectrum: bkg fluctuations anc fake jets (upward fluctuations) are correctec via statistical method (“unfolding”)



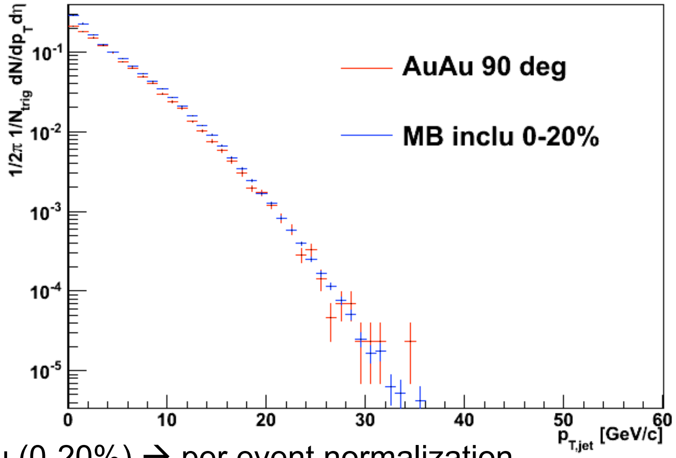
CAVEAT: the fluctuations under the “signal” jet have to be the same as under the “fake” jet

- HT recoil spectrum: (1) di-jets + (2) fake jets +

  (3) additional hard scattering

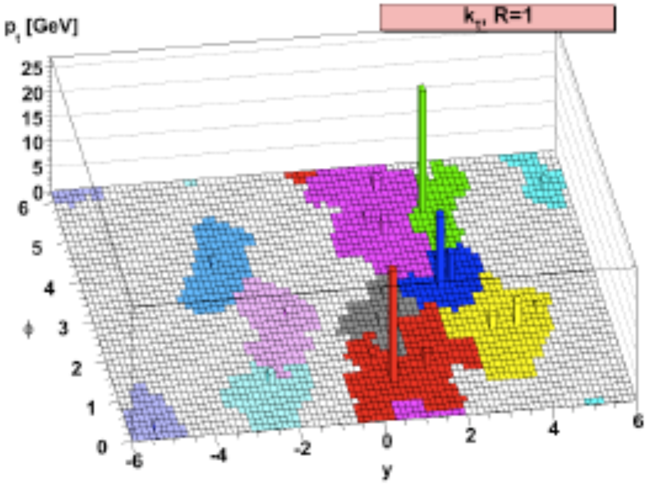
  → “Unfolding” accounts for fluctuations and fake jets.

  → Need to subtract the 90° spectrum (w.r.t. trigger jet) to remove the additional hard scattering spectrum

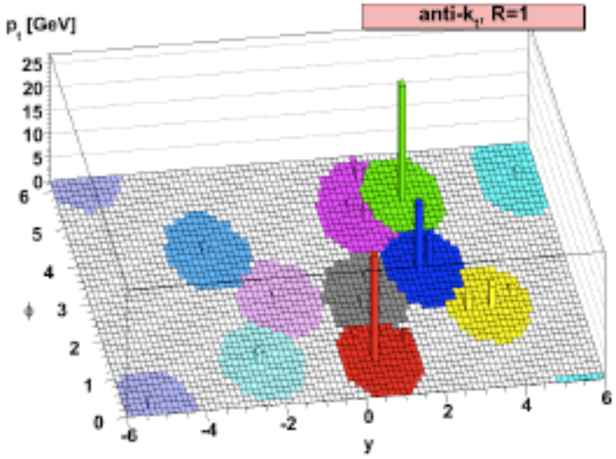


MB inclu (0-20%) → per event normalization
HT 90° (0-20%) → per trigger jet normalization

Recombination algorithms



FastJet M. Cacciari, G. Salam, G. Soyez 0802.1188



$$d_{ij} = \min(k_{Ti}^{\ p}, k_{Tj}^{\ p})(\Delta\phi_{ij}^{\ 2} + \Delta\eta_{ij}^{\ 2})/R^2$$

- Recombination algorithms:

Infrared safe

collinear safe

- Seedless - ALL particles are clustered into “jets”
- **k$_T$**: from pairs of low-p$_T$ particles. p=1
  - Not bound to a circular structure
- **Anti-k$_T$**: from pairs of high-p$_T$ particles. p=-1
  - Circular shape, radius ~R resolution parameter