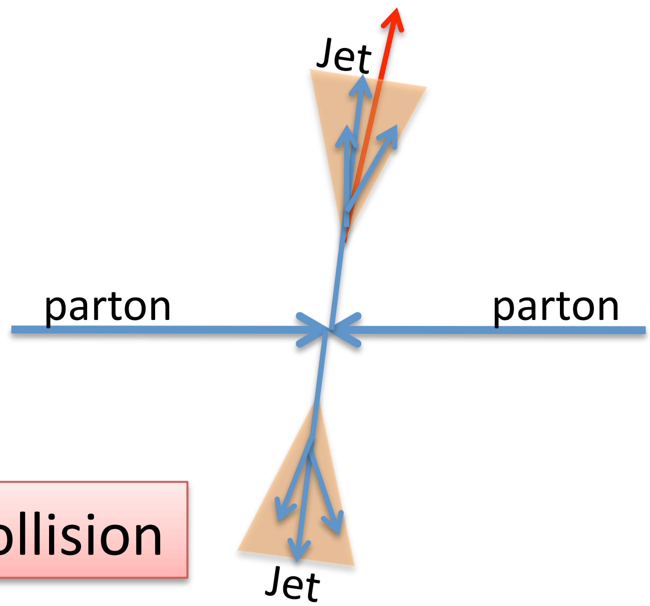
STAR
Jet quenching overview

Mateusz Ploskon

Outline

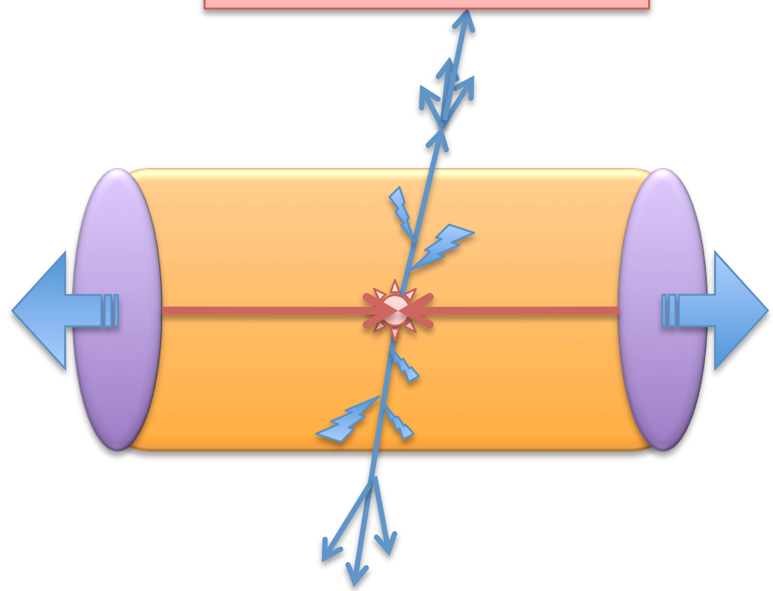
- Jet quenching and its measurements
- Full jet reconstruction in heavy-ion collisions?
- Recent measurements of jets at STAR/RHIC
- Outlook

Jets in p+p and Au+Au



p+p collision

Au+Au Collision



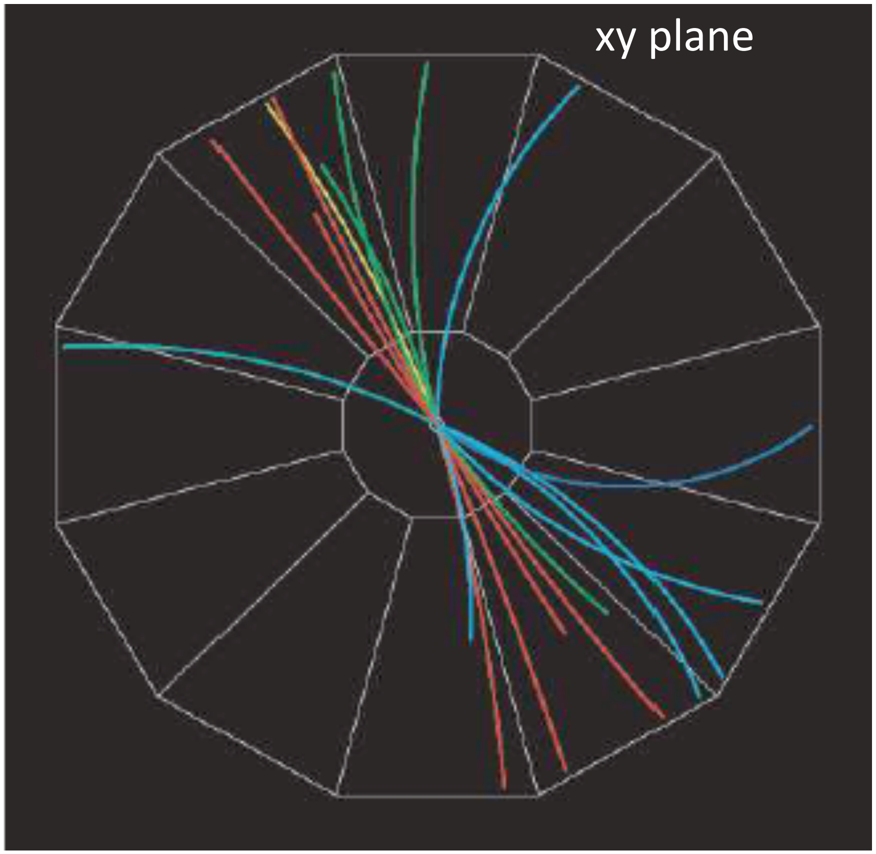
We use the jets to probe the medium!

Nice idea... but there is a price to pay...

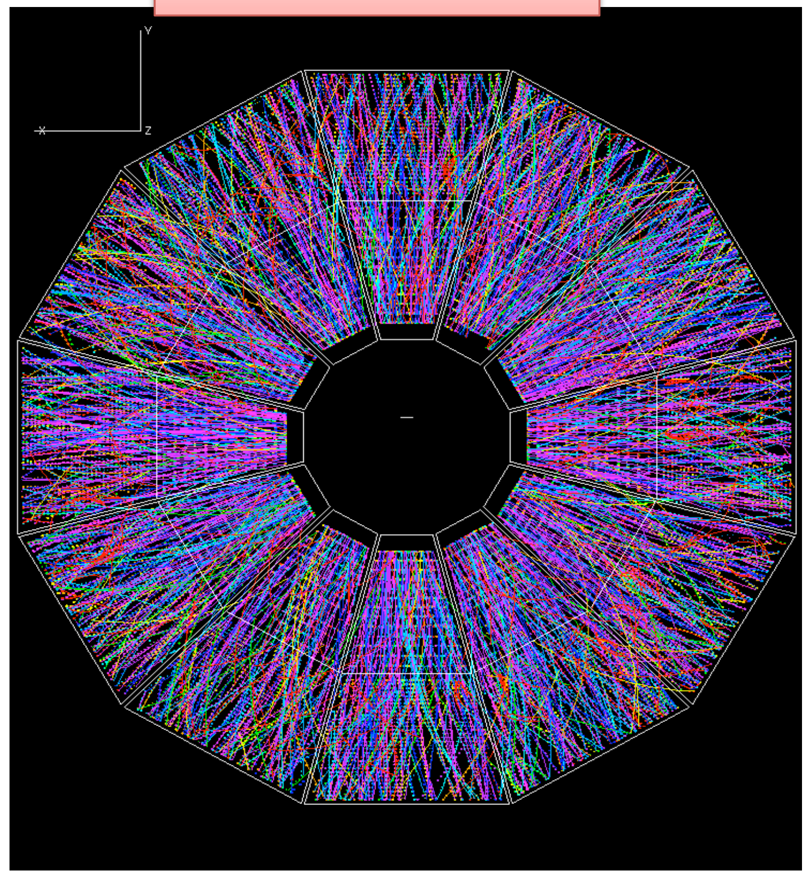
Finding jets?

STAR TPC Event Display

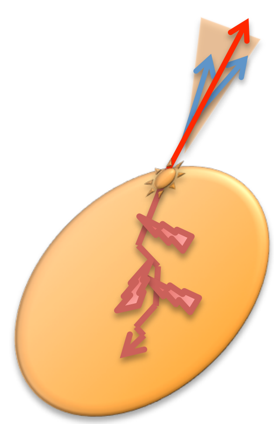
p+p Collision



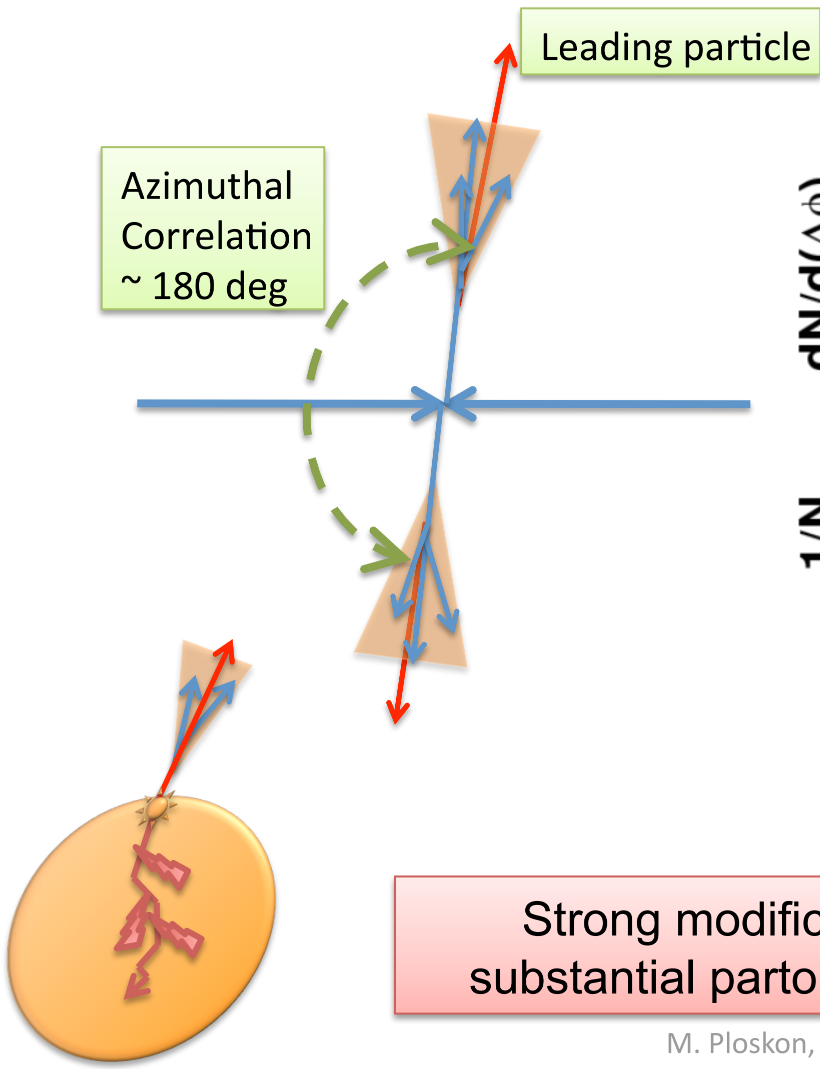
Au+Au Collision

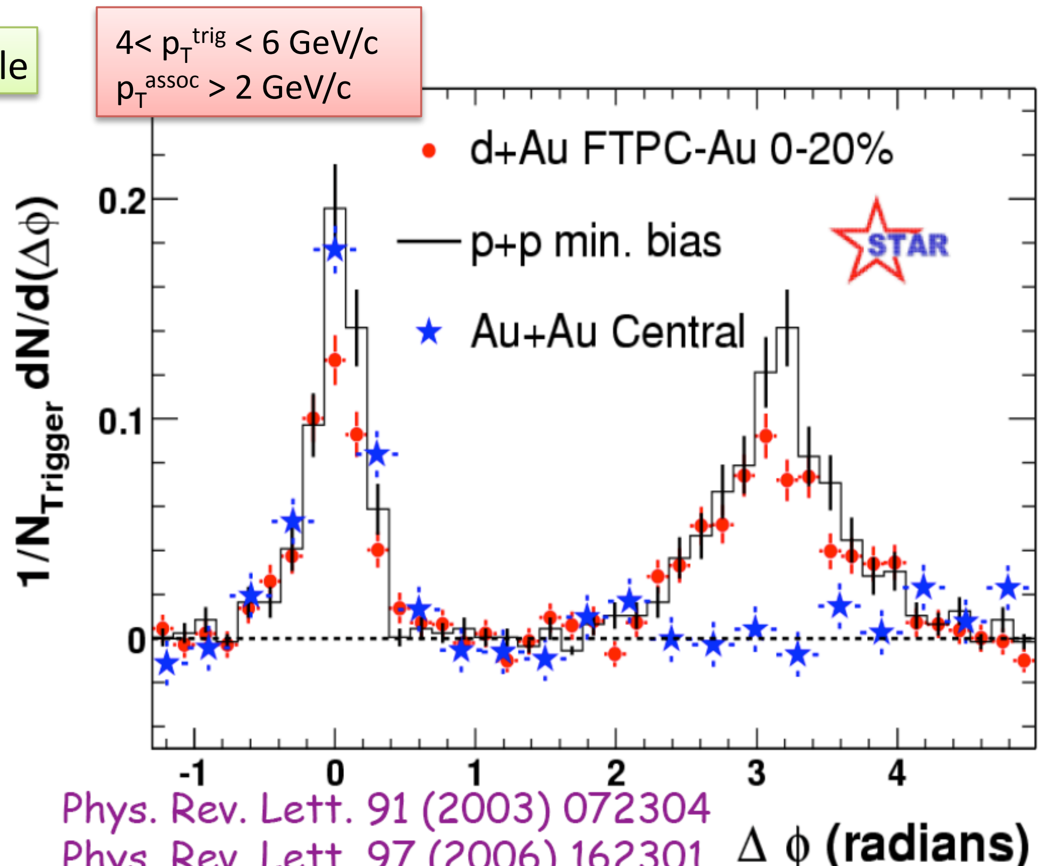


Jet quenching observations in heavy-ion collisions at RHIC



Jet quenching: recoil jet suppression via leading hadron azimuthal correlations



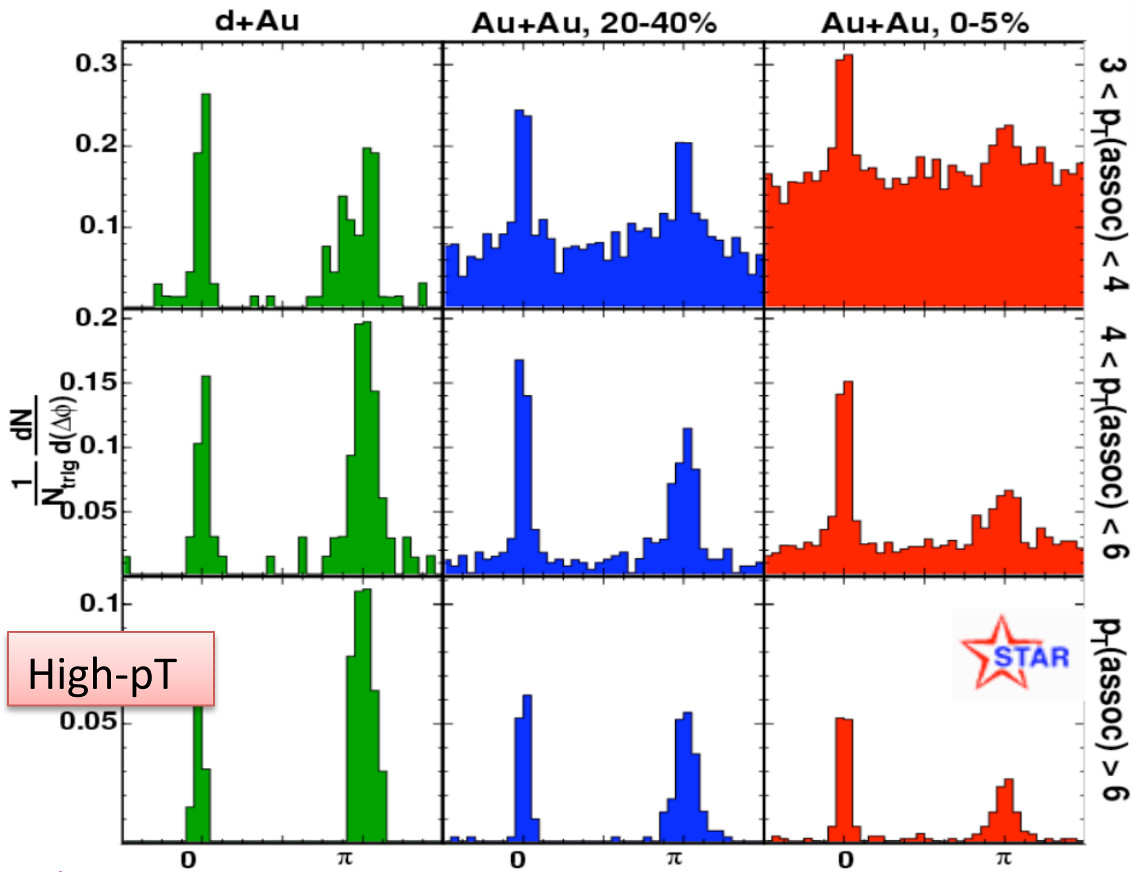


Phys. Rev. Lett. 91 (2003) 072304
Phys. Rev. Lett. 97 (2006) 162301

Strong modification of the recoil-jet indicates substantial partonic interaction within the medium

Di-hadron correlations with **high**-pt associated hadrons

Most central



High-pT

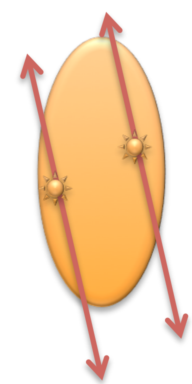
Phys.Rev.Lett.97:162301,2006

Reaperance of the away side peak at high-assoc.-pT:

- ○ similar suppression as in the inclusive spectra
- ○ unmodified shape

Differential measurement of jets **w/o interaction**

-> limitation of the LO probes



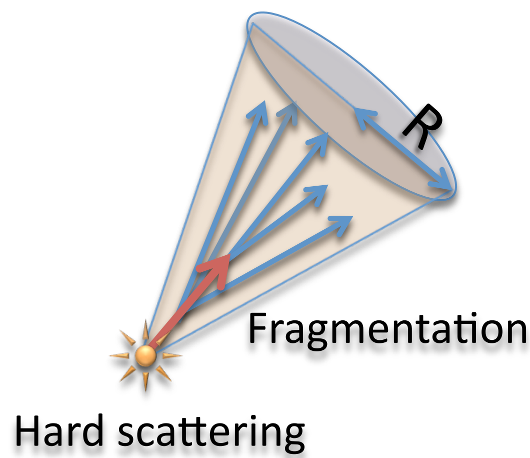
From hadronic to energy flow observables

- Single and di-hadron triggered observables:
  - Approximate jet (axis etc.)
  - **Single-hadron and di-hadron observables fold production spectra with probability of partonic energy loss**
    - Weak constrains on energy loss (upper and lower limits only)
    - Suffer from (geometrical?) bias towards non-interacting jets

Need for more differential measurements to probe ***partonic*** energy loss

Full jet reconstruction

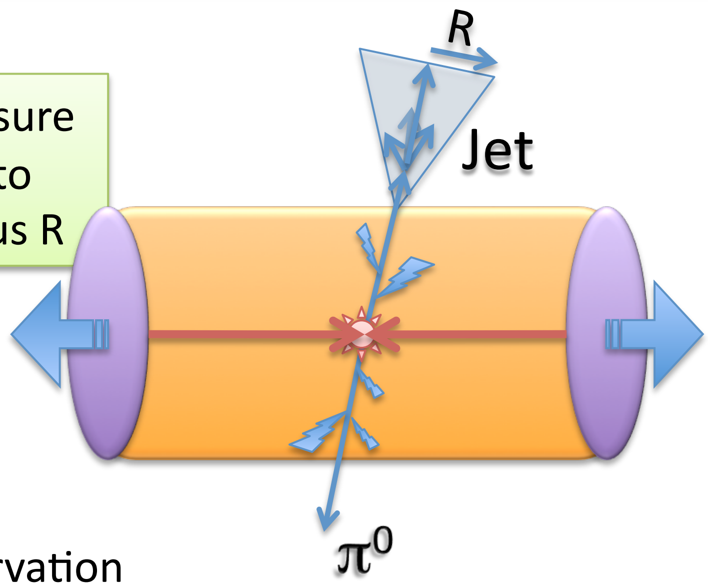
Full jet reconstruction

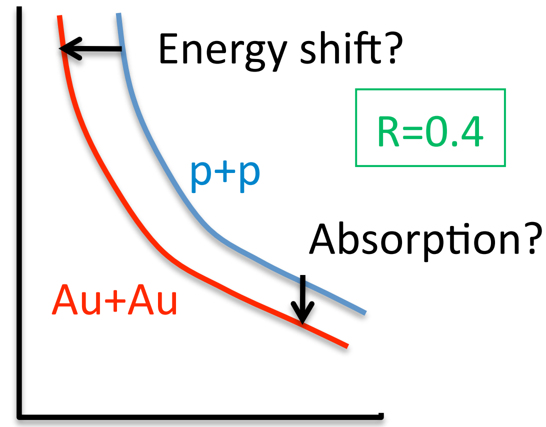


Motivation and Strategy

Physics of full jet reconstruction in heavy ion collisions

Example: Measure energy flow into "cone" of radius R

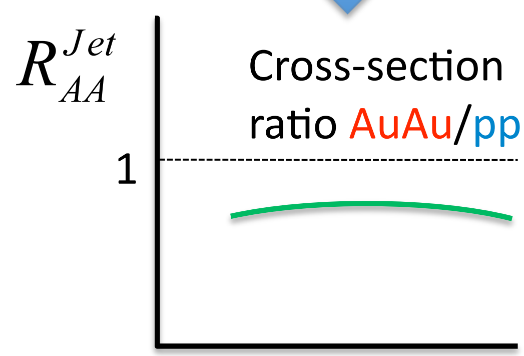




- Momentum conservation
- Jet reconstruction: recover the full jet energy

- Allow complete exploration of
  - Collision geometry
  - Fragmentation patterns

Strong constrains for quenching models



- Compare Au+Au and p+p jet spectra

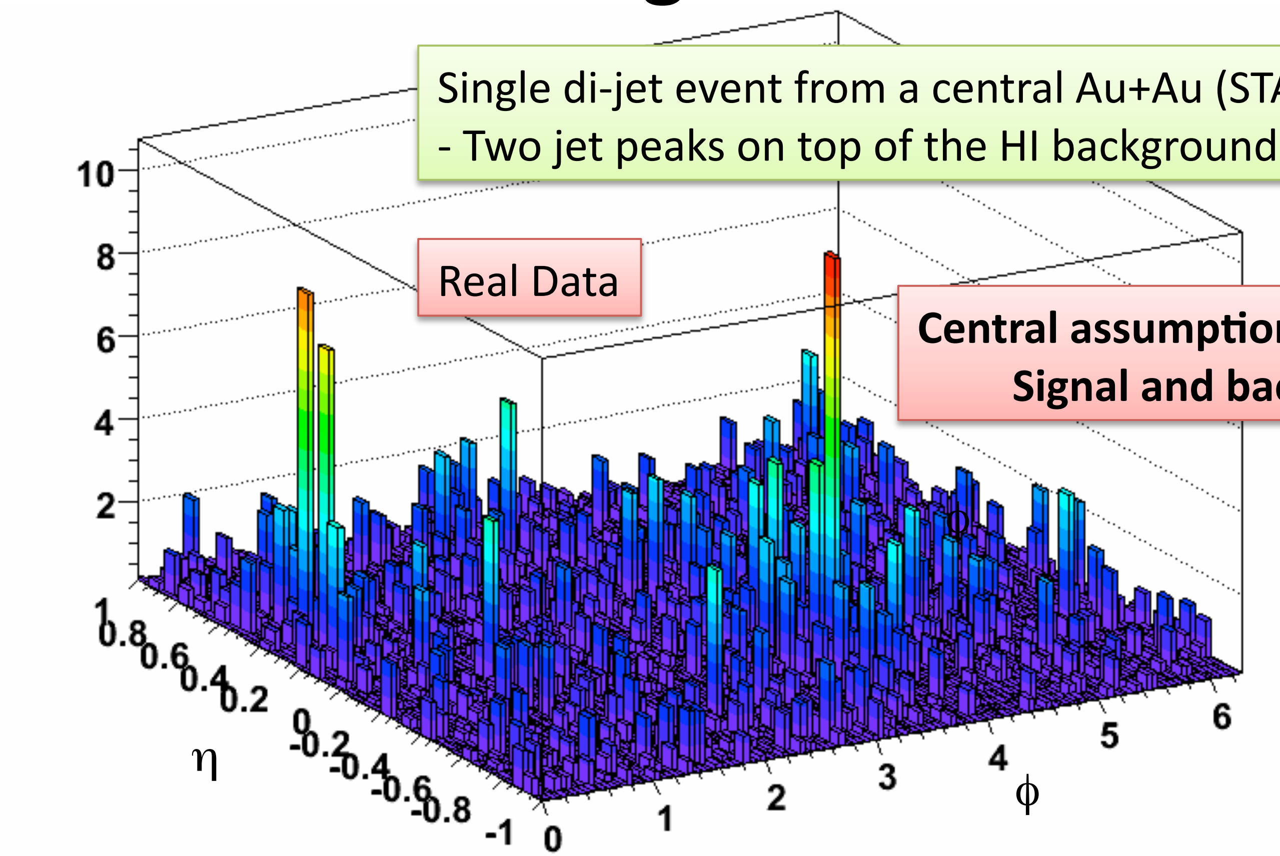
- Caveat: initial state nuclear effects

Heavy Ion collisions and background characterization

Single di-jet event from a central Au+Au (STAR):
- Two jet peaks on top of the HI background (underlying event)

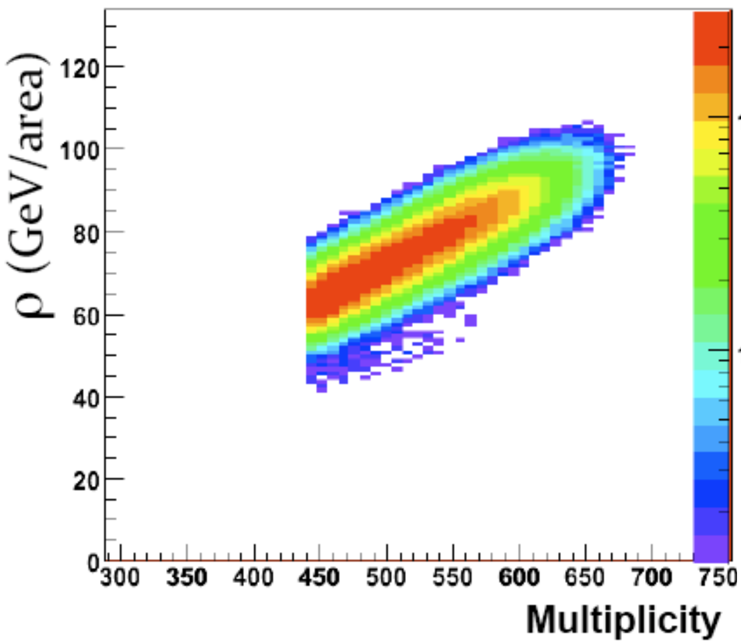
Real Data

Central assumption:
Signal and background can be factorized



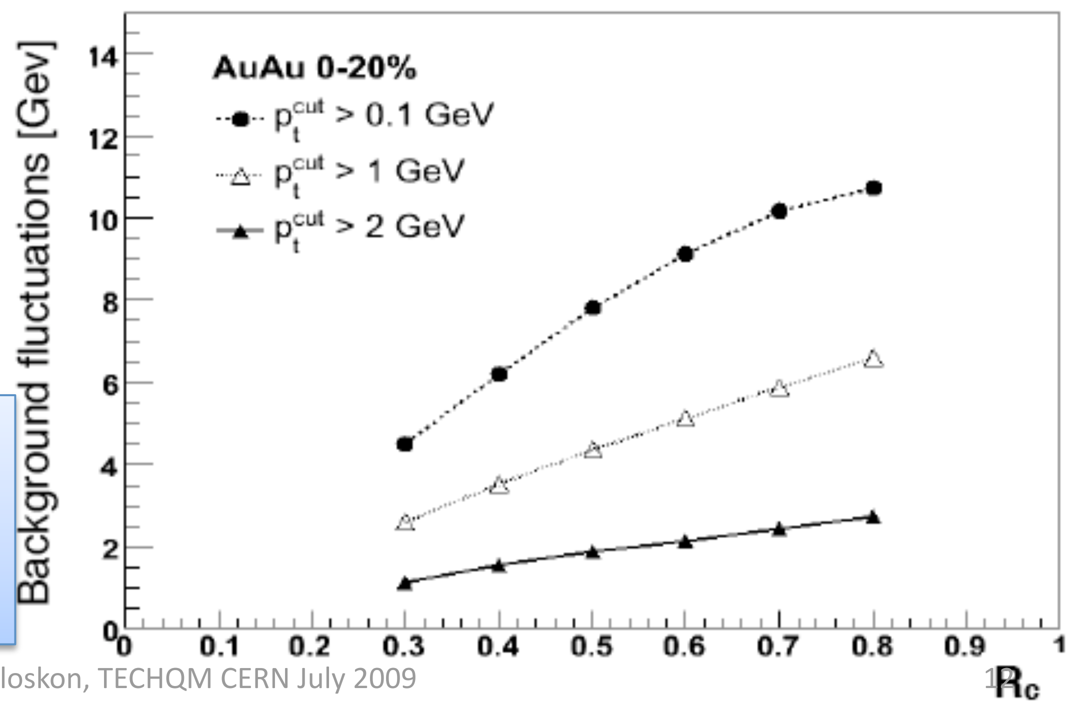
○ Main uncertainty: underlying event non-uniformities induce uncertainties on background estimation => jet energy resolution
○ Extra handle: utilize multiple jet algorithms and their different sensitivity to heavy-ion background.

Background



Background level in central Au+Au

Single parameter sufficient to characterize the BG(?)



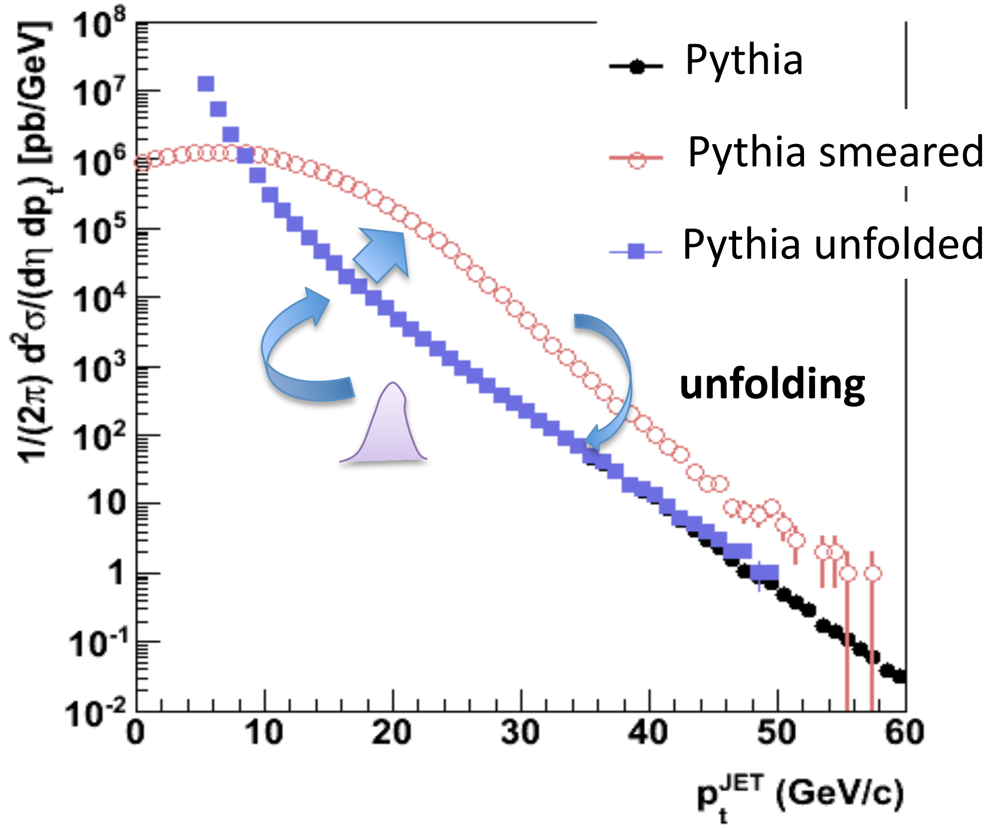
BG non-uniformities
-> BG level fluctuations
-> Not necessarily Gaussian

Spectrum unfolding

Background non-uniformity (fluctuations) and energy resolution introduce pT-smearing

Correct via "unfolding": inversion of full bin-migration matrix

Check numerical stability of procedure using jet spectrum shape from PYTHIA



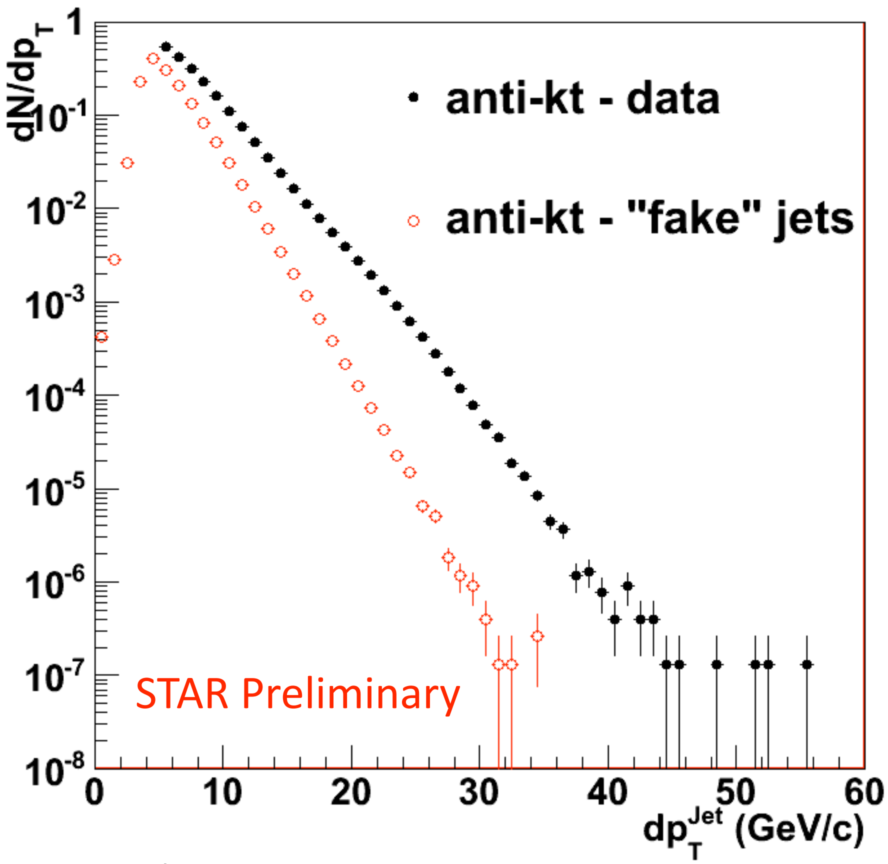
Procedure is numerically stable
Correction depends critically on background model
→ main systematic uncertainty for Au+Au

Fake jet contamination/STAR

"Fake" jets: signal in excess of background model from random association of uncorrelated soft particles (i.e. not due to hard scattering)

"Fake" jet rate estimation:

- Central Au+Au dataset (real data)
- Randomize azimuth of each charged particle and calorimeter tower
- Run jet finder
- Remove leading particle from each found jet
- Re-run jet finder

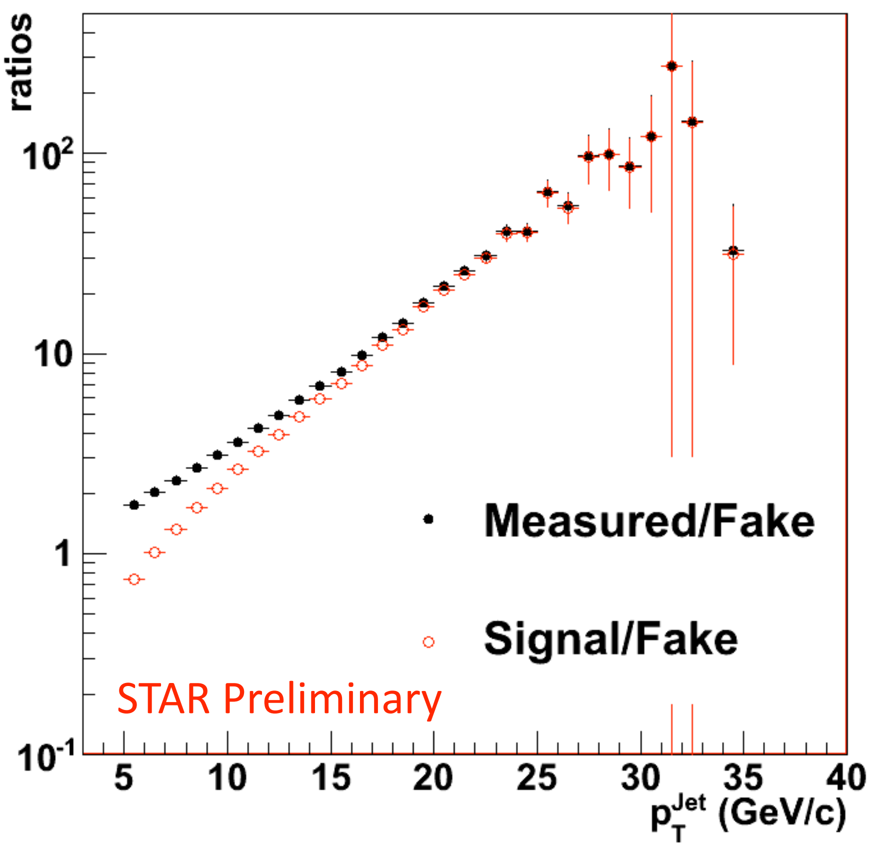


Fake jet contamination/STAR

"Fake" jets: signal in excess of background model from random association of uncorrelated soft particles (i.e. not due to hard scattering)

"Fake" jet rate estimation:

- Central Au+Au dataset (real data)
- Randomize azimuth of each charged particle and calorimeter tower
- Run jet finder
- Remove leading particle from each found jet
- Re-run jet finder



Systematic corrections

Trigger corrections:

- p+p trigger bias correction
- p+p Jet patch trigger efficiency

Particle level corrections:

- Detector effects: efficiency and pT resolution
- "Double* counting" of particle energies
  - * electrons: - double; hadrons: - showering corrections
  - All towers matched to primary tracks are removed from the analysis

Jet level corrections:

- Spectrum shift:
  - Unobserved energy
  - TPC tracking efficiency
- BEMC calibration (dominant uncertainty in p+p)
- Jet pT resolution
- Underlying event (dominant uncertainty in Au+Au)

Full assessment of jet energy scale uncertainties

Data driven correction scheme

- Weak model dependence: only for single-particle response, p+p trigger response
- No dependence on quenching models

Systematic corr

p+p trigger (coincidence) biases recorded jet population – jet Et dependent correction

Offline vertex cuts -> x-section calculation

Reaction trigger influencing jet spectra

Trigger corrections:

- p+p trigger bias correction
- p+p Jet patch trigger efficiency

Particle level corrections:

- Detector effects: efficiency and pT resolution
- "Double* counting" of particle energies
  - * electrons: - double; hadrons: - showering corrections
  - All towers matched to primary tracks are removed from the analysis

Jet level corrections:

- Spectrum shift:
  - Unobserved energy
  - TPC tracking efficiency
- BEMC calibration (dominant uncertainty in p+p)
- Jet pT resolution
- Underlying event (dominant uncertainty in Au+Au)

Full assessment of jet energy scale uncertainties

Data driven correction scheme

- Weak model dependence: only for single-particle response, p+p trigger response
- No dependence on quenching models

Systematic cor

Trigger corrections:

- p+p trigger bias correction
- p+p Jet patch trigger efficiency

Particle level corrections:

- Detector effects: efficiency and pT resolution
- "Double* counting" of particle energies
  - * electrons: - double; hadrons: - showering co
  - All towers matched to primary tracks are removed from the analysis

Jet level corrections:

- Spectrum shift:
  - Unobserved energy
  - TPC tracking efficiency
- BEMC calibration (dominant uncertainty in p+p)
- Jet pT resolution
- Underlying event (dominant uncertainty in Au+Au)

Jet patch trigger efficiency:
Patch 1x1 (in pseudo-rap. and azimuth) requesting ~7.5 GeV neutral energy (p+p only)

Large bias at low jet-pt (x2 at 20 GeV/c), but persists up to 30 GeV/c

Full assessment of jet energy scale uncertainties

Data driven correction scheme

- Weak model dependence: only for single-particle response, p+p trigger response
- No dependence on quenching models

Systematic corrections

Trigger corrections:

– p+p trigger bias correction
– p+p Jet patch trigger efficiency

Particle level corrections:

– Detector effects: efficiency and pT resolution
– "Double* counting" of particle energies
  • * electrons: … hadrons: - showering corrections
  • All towers … primary tracks are removed from

Jet level corrections:

  • Spectrum s

…y in p+p)

…y in Au+Au)

Full ass… s

Data dr…

- Weak model dependence: only for single-particle response, p+p trigger response
- No dependence on quenching models

-Relevant constant for EMCAL (response of calorimeter)

-Dead/hot tower corrections/ removal

-High-pt track quality/applicability

Calculate jet neutral energy fraction (NEF)
and apply pT corrections according to the fraction of carried jet energy by charge particles

- Different efficiencies in p+p and Au+Au

Systematic corrections

Trigger corrections:

- p+p trigger bias correction
- p+p Jet patch trigger efficiency

Particle level corrections:

- Detector effects: efficiency and pT resolution
- "Double* counting" of particle energies
  - * electrons: - double; hadrons: - showering correct
  - All towers matched to primary tracks are removed fro th

Jet level corrections:

- Spectrum shift:
  - Unobserved energy
  - TPC tracking efficiency
- BEMC calibration (dominant uncertainty in p+p)
- Jet pT resolution
- Underlying event (dominant uncertainty in Au+Au)

Several possibilities:
MIP, constant E-fraction,
complete removal of the
"matched energy"

Minimize the effect.

Full assessment of jet energy scale uncertainties

Data driven correction scheme

- Weak model dependence: only for single-particle response, p+p trigger response
- No dependence on quenching models

Systematic corrections

Trigger corrections:

- p+p trigger bias correction
- p+p Jet patch trigger efficiency

Particle level corrections:

- Detector effects: efficiency and pT resolution
- "Double* counting" of particle energies
  - * electrons: - double; hadrons: - showering correct
  - All towers matched to primary tracks are removed

Jet level corrections:

- Spectrum shift:
  - Unobserved energy
  - TPC tracking efficiency
- BEMC calibration (dominant unc tainty in p+p)
- Jet pT resolution
- Underlying event (dominant uncertainty in Au+Au)

Energy scale correction -> "Shift"

Estimate the unobserved jet energy and apply "average" correction

#neutron ~ #proton (?)

Full assessment of jet energy scale uncertainties

Data driven correction scheme

- Weak model dependence: only for single-particle response, p+p trigger response
- No dependence on quenching models

Systematic corrections

Trigger corrections:

- p+p trigger bias correction
- p+p Jet patch trigger efficiency

Particle level corrections:

- Detector effects: efficiency and pT resolution
- "Double* counting" of particle energies
  - * electrons: - double; hadrons: - showering corrections
  - All towers matched to primary tracks are removed fi

Jet level corrections:

- Spectrum shift:
  - Unobserved energy
  - TPC tracking efficiency
- BEMC calibration (dominant unc... in p+p)
- Jet pT resolution
- Underlying event (dominant uncertainty in Au+Au)

Energy scale correction -> "Shift"

TPC inefficiencies – averaged correction

Full assessment of jet energy scale uncertainties

Data driven correction scheme

- Weak model dependence: only for single-particle response, p+p trigger response
- No dependence on quenching models

Systematic corrections

Trigger corrections:

- p+p trigger bias correction
- p+p Jet patch trigger efficiency

Particle level corrections:

- Detector effects: efficiency and pT resolution
- "Double* counting" of particle energies
  - * electrons: - double; hadrons: - showering corrections
  - All towers matched to primary tracks are removed from the analysis

Jet level corrections:

- Spectrum shift:
  - Unobserved energy
  - TPC tracking efficiency
- BEMC calibration (dominant uncertainty in p
- Jet pT resolution
- Underlying event (dominant uncertainty in Au+Au)

5% uncertainty on calibration translates to large uncertainty on x-section!

Ongoing very active work to reduce it.

Full assessment of jet energy scale uncertainties

Data driven correction scheme

- Weak model dependence: only for single-particle response, p+p trigger response
- No dependence on quenching models

Systematic corrections

Trigger corrections:

- p+p trigger bias correction
- p+p Jet patch trigger efficiency

Particle level corrections:

- Detector effects: efficiency and pT resolution
- “Double* counting” of particle energies
  - * electrons: - double; hadrons: - showering corrections
  - All towers matched to primary tracks are removed from the analysis

Jet level corrections:

- Spectrum shift:
  - Unobserved energy
  - TPC tracking efficiency
- BEMC calibration (dominant unc
- Jet pT resolution
- Underlying event (dominant unc

Studies with di-jets in p+p (benchmarked with Pythia detector/particle jets)
- Correction by unfolding

Full assessment of jet energy scale uncertainties

Data driven correction scheme

- Weak model dependence: only for single-particle response, p+p trigger response
- No dependence on quenching models

Systematic corrections

Trigger corrections:
- p+p trigger bias correction
- p+p Jet patch trigger efficiency

Particle level corrections:
- Detector effects: efficiency and pT resolution
- "Double* counting" of particle energies
  - * electrons: - double; hadrons: - showering corrections
  - All towers matched to primary tracks are removed from the analysis

Jet level corrections:
- Spectrum shift:
  - Unobserved energy
  - TPC tracking efficiency
- BEMC calibration (dominant uncertainty in p+p)
- Jet pT resolution
- Underlying event (dominant uncertainty in Au+Au)

Background subtraction -> smearing – correction by unfolding

Full assessment of jet energy scale uncertainties

Data driven correction scheme
- Weak model dependence: only for single-particle response, p+p trigger response
- No dependence on quenching models

Systematic corrections

Trigger corrections:

- p+p trigger bias correction
- p+p Jet patch trigger efficiency

Particle level corrections:

- Detector effects: efficiency and pT resolution
- "Double* counting" of particle energies
  - * electrons: - double; hadrons: - showering corrections
  - All towers matched to primary tracks are removed from the analysis

Jet level corrections:

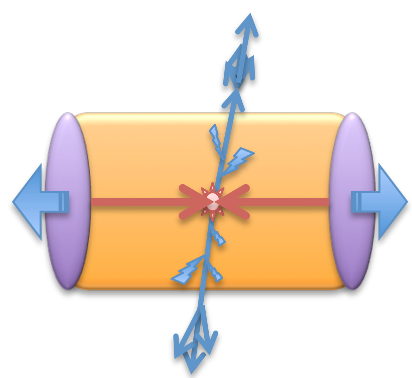
- Spectrum shift:
  - Unobserved energy
  - TPC tracking efficiency
- BEMC calibration (dominant uncertainty in p+p)
- Jet pT resolution
- Underlying event (dominant uncertainty in Au+Au)

Full assessment of jet energy scale uncertainties

Data driven correction scheme

- Weak model dependence: only for single-particle response, p+p trigger response
- No dependence on quenching models

What is a “jet” in HI collisions?



What is a jet?

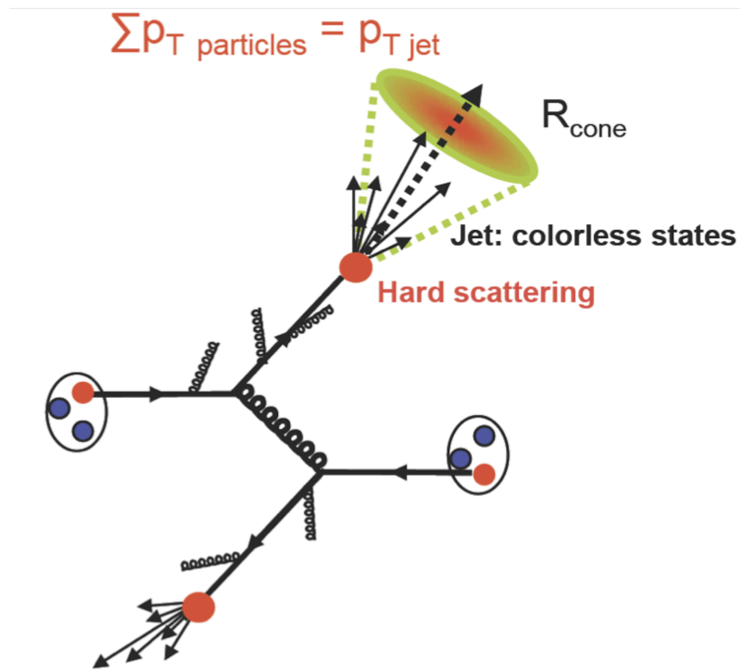
A spray of collimated showers/particles

- Hardly ever better defined...

- Direct indication of fragmenting parton
- **Good assumption**: approximate parton/jet energy by reconstructing energy of individual particles/ constituents
- Jets (unlike single hadrons) are objects which are “better” understood/calculable within pQCD

QCD collinear divergence

$$\mathrm{d}P \propto \alpha_s \frac{\mathrm{d}\theta}{\theta}$$

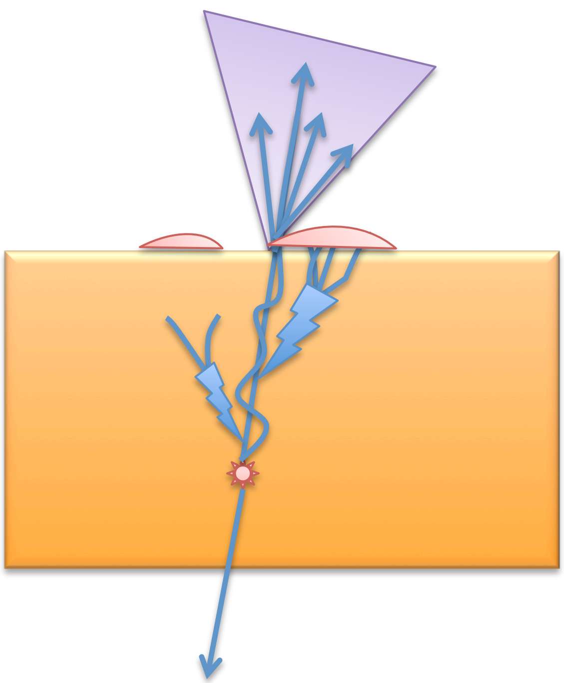


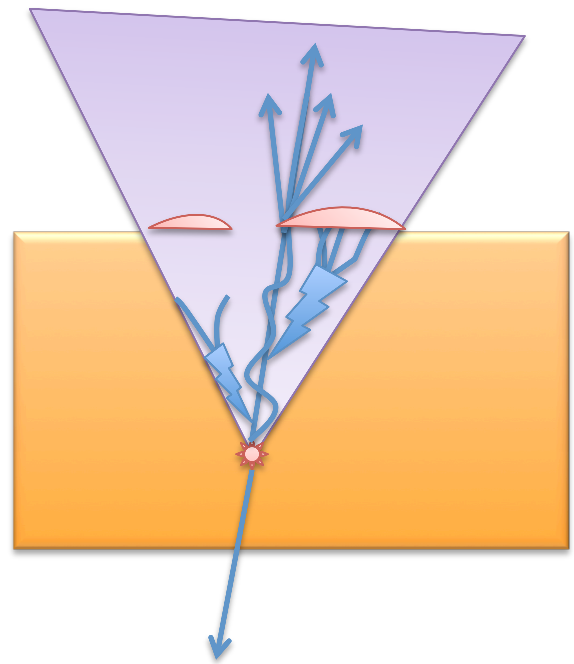
S.D Drell, D.J.Levy and T.M. Yan, Phys. Rev. **187**, 2159 (1969)
N. Cabibbo, G. Parisi and M. Testa, Lett. Nuovo Cimento **4**,35 (1970)
J.D. Bjorken and S.D. Brodsky, Phys. Rev. D 1, 1416 (1970)
Sterman and Weinberg, Phys. Rev. Lett. 39, 1436 (1977) ...

What is a jet in HI Collision?

Measure A: vacuum fragmentation

Measure B: vacuum fragmentation
+ medium induced radiation



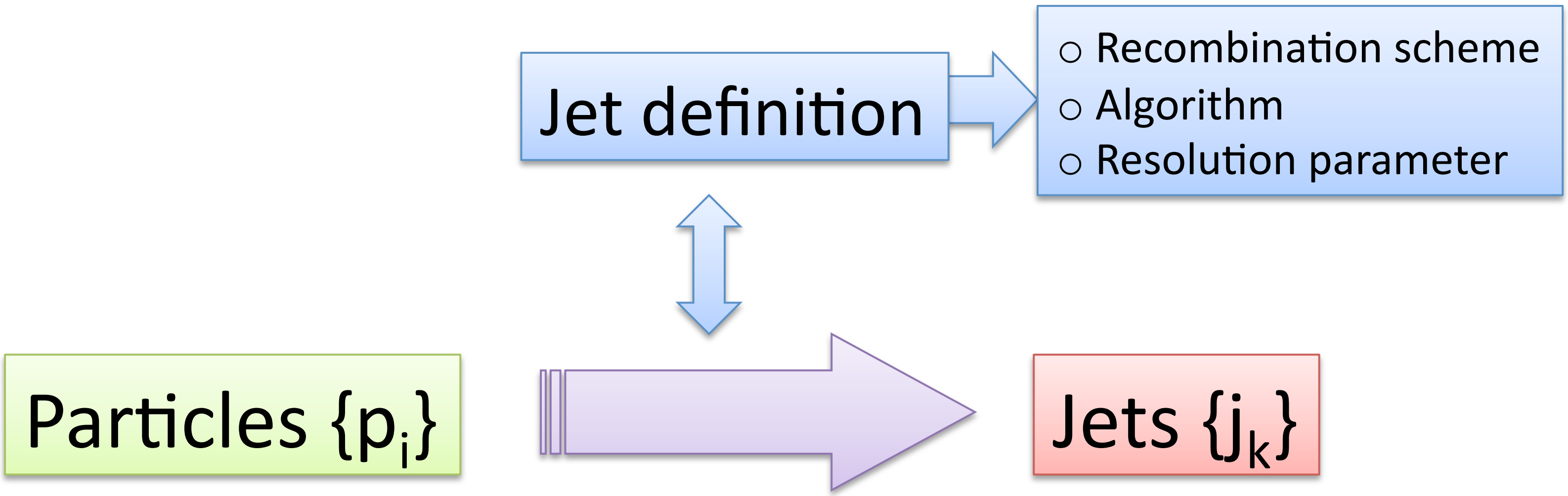


Unmodified fragmentation?
Loss of yield ⇔ energy deficit

Modified "fragmentation" pattern?
No loss of yield ⇔ full jet energy?

"Finding" jets

“Finding” jets

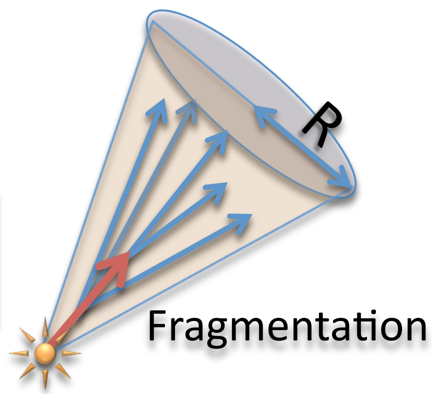


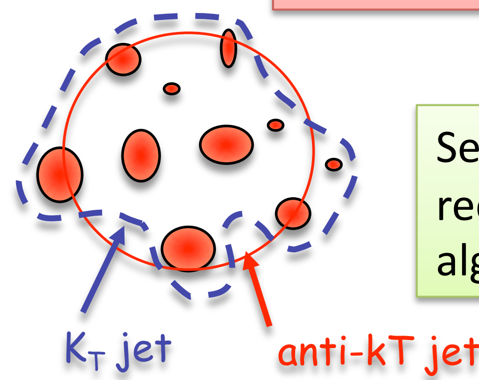
Jet algorithms

$$R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

Anti-k_t expected to be less susceptible to background effects in heavy ion collisions

Cone based algorithms

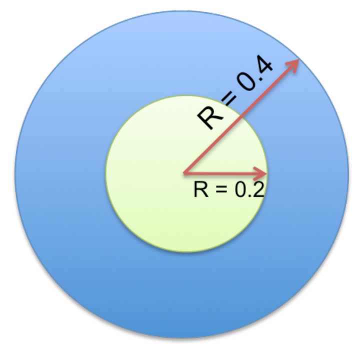




Sequential recombination algorithms

Algorithms: k_t and anti-k_t from FastJet*

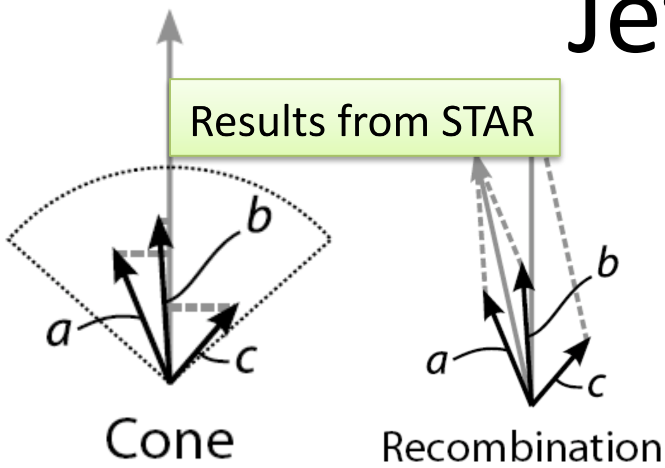
- Resolution parameter R = 0.4, 0.2
- Jet acceptance: $|\eta^{JET}| < 1.-R$
- Recombination scheme: E-scheme with massless particles



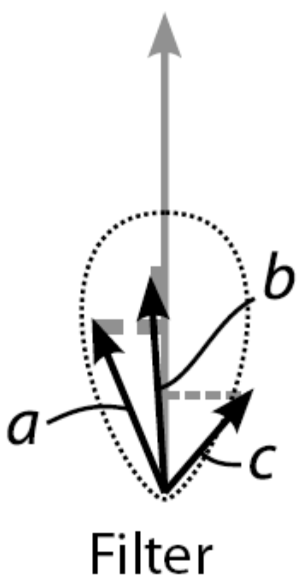
*Cacciari, Salam and Soyez, JHEP 0804 (2008) 005 [arXiv:0802.1188]

Jet algorithms

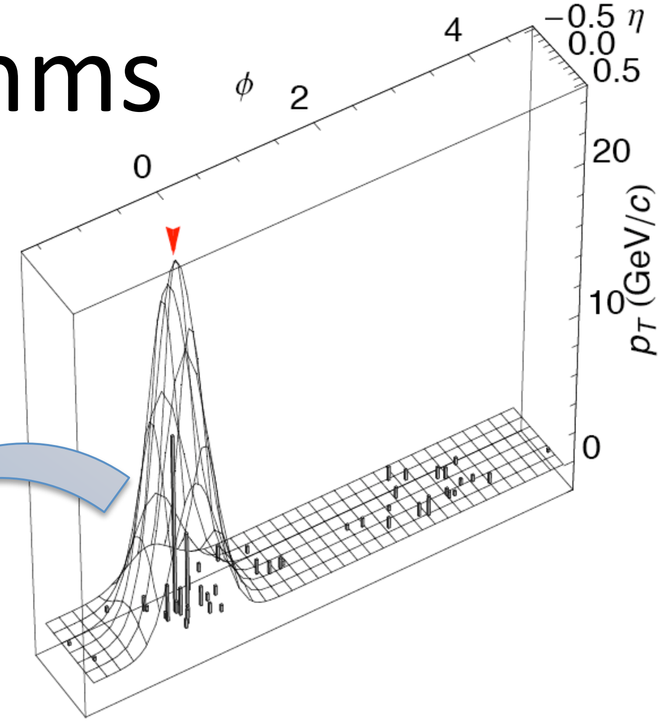
Results from STAR



Yui Shi Lai, arXiv:0806.1499, QM 2009



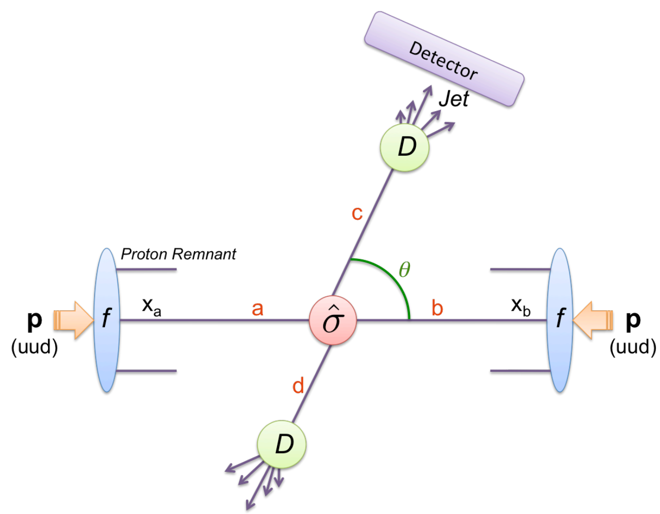
Results from PHENIX



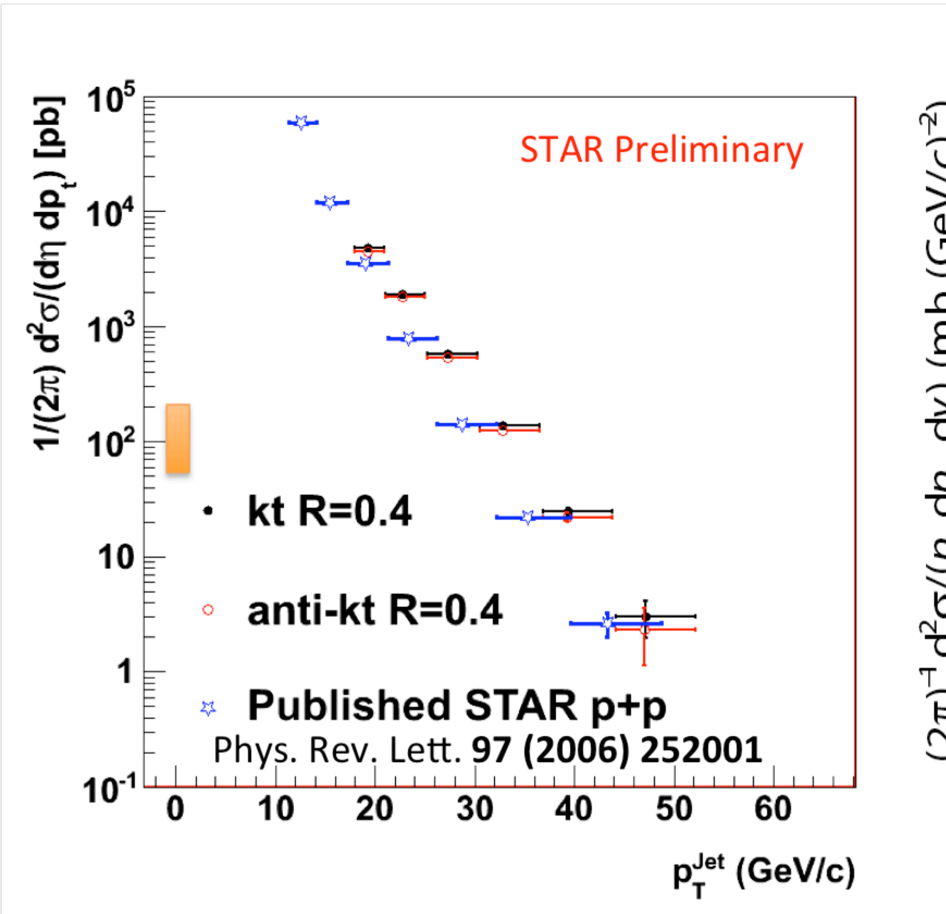
$$\iint_{\mathbb{R}\times S^1} d\eta' d\varphi' p_T(\eta', \varphi') \exp\left[-\frac{(\eta-\eta')^2+(\varphi-\varphi')^2}{2\sigma^2}\right] = \max!$$

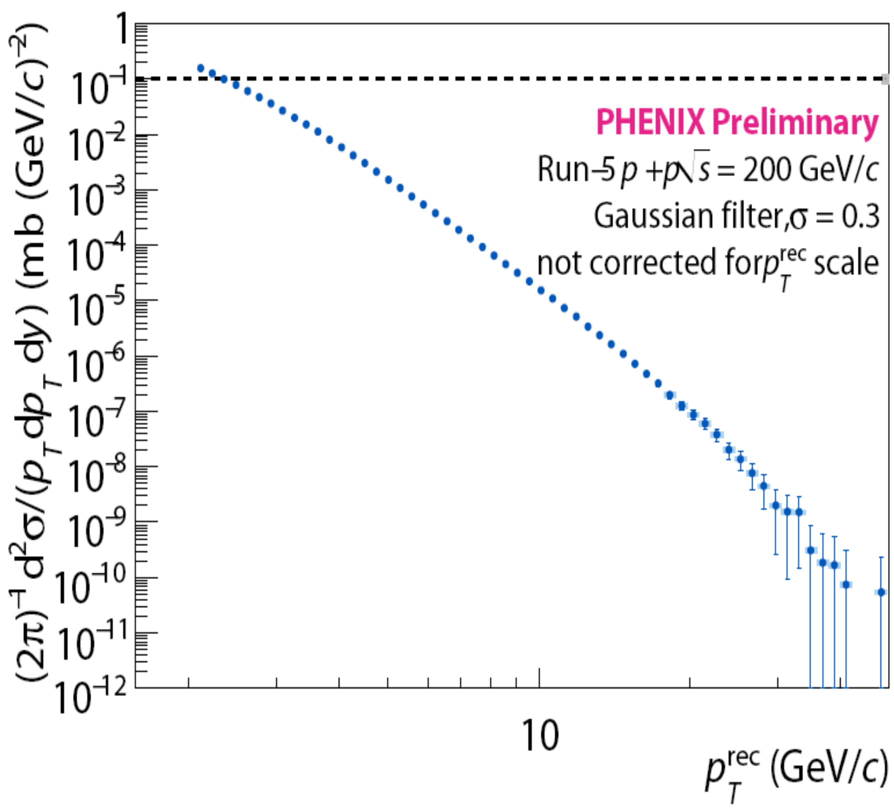
- Seedless, infrared and collinear safe
- Optimizes S/B (focus on the "core" of the jet)
- Robust against background

Jet measurements at RHIC

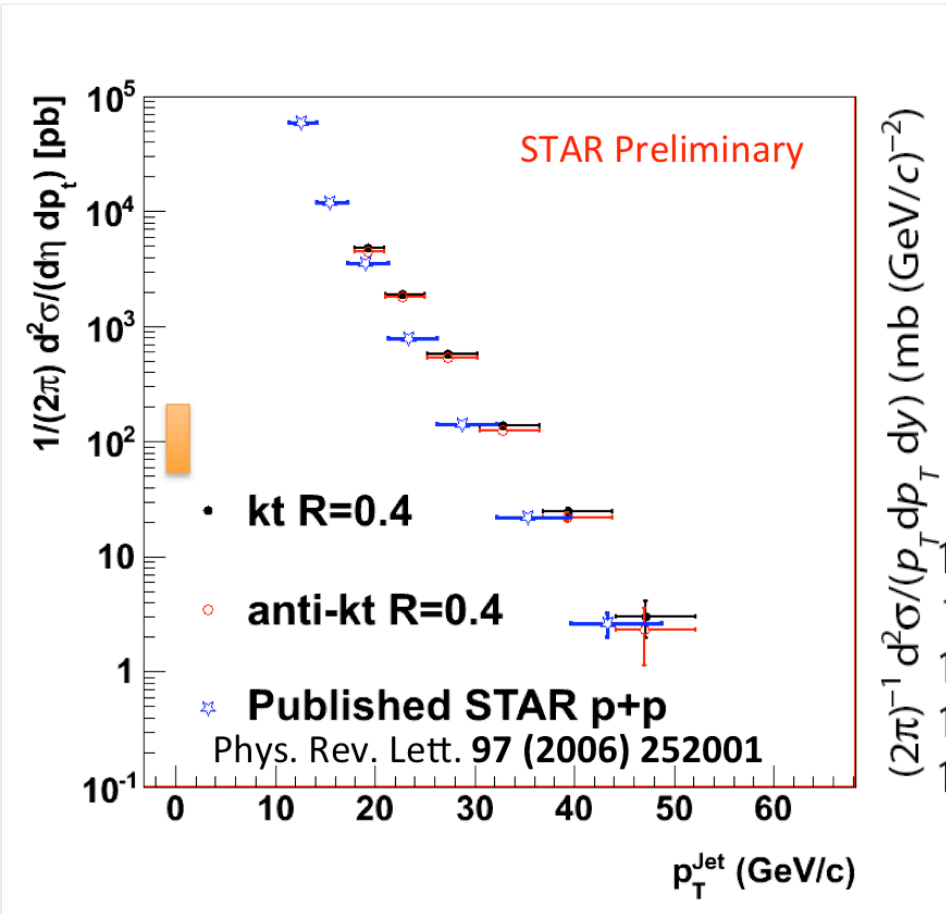


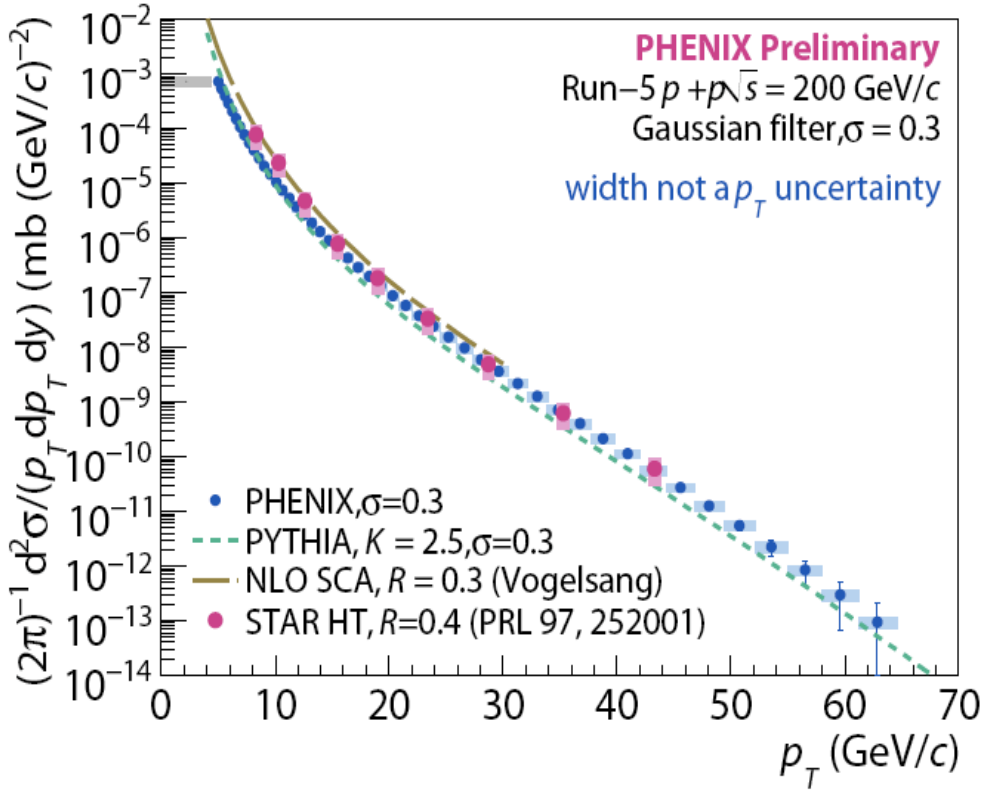
Inclusive jet cross-section in p+p at sqrt(s_{NN}) = 200 GeV – *new algorithms*





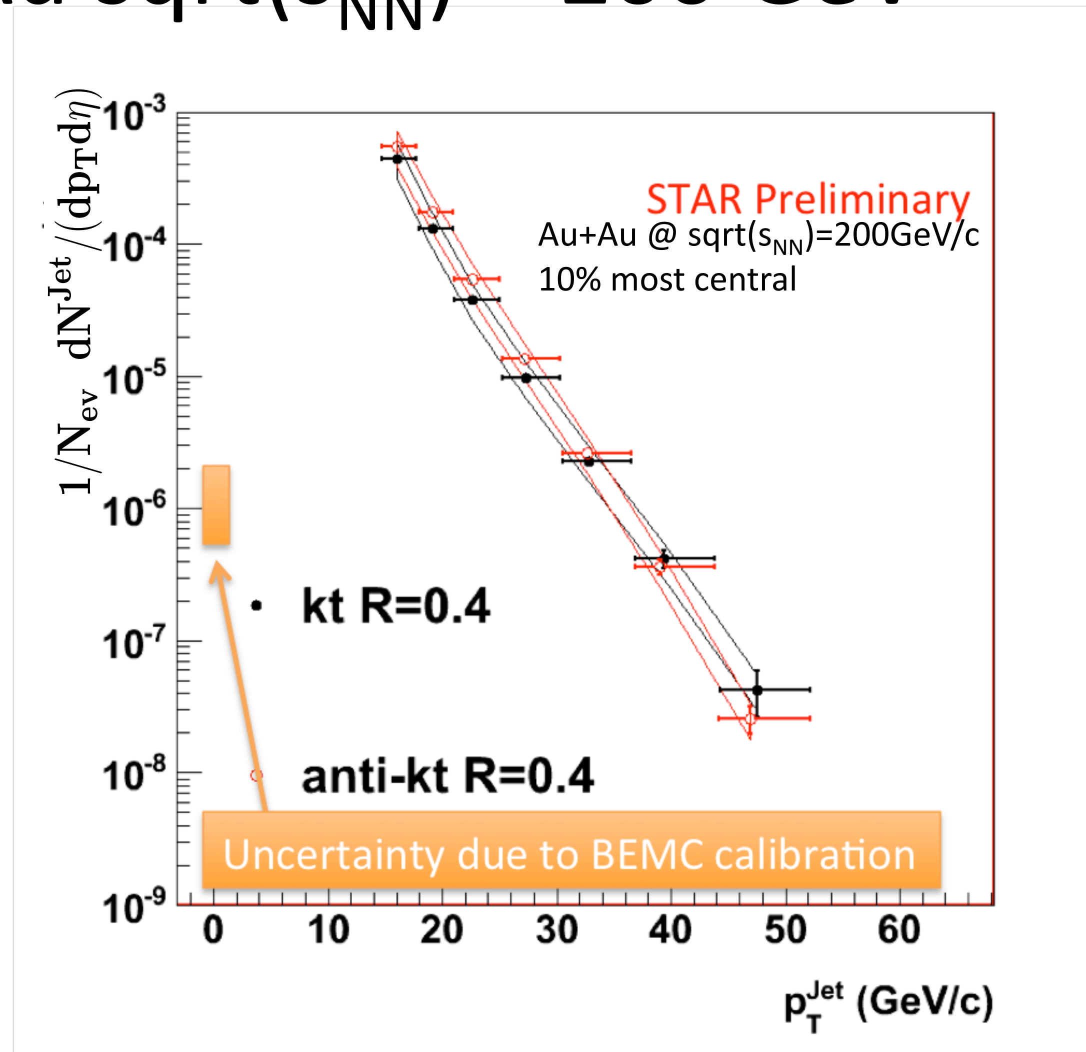
Inclusive jet cross-section in p+p at sqrt(s_{NN}) = 200 GeV – *new algorithms*



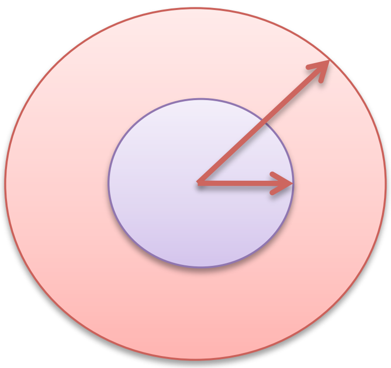


Jet yields in heavy-ion collisions: Central Au+Au sqrt(s_{NN}) = 200 GeV

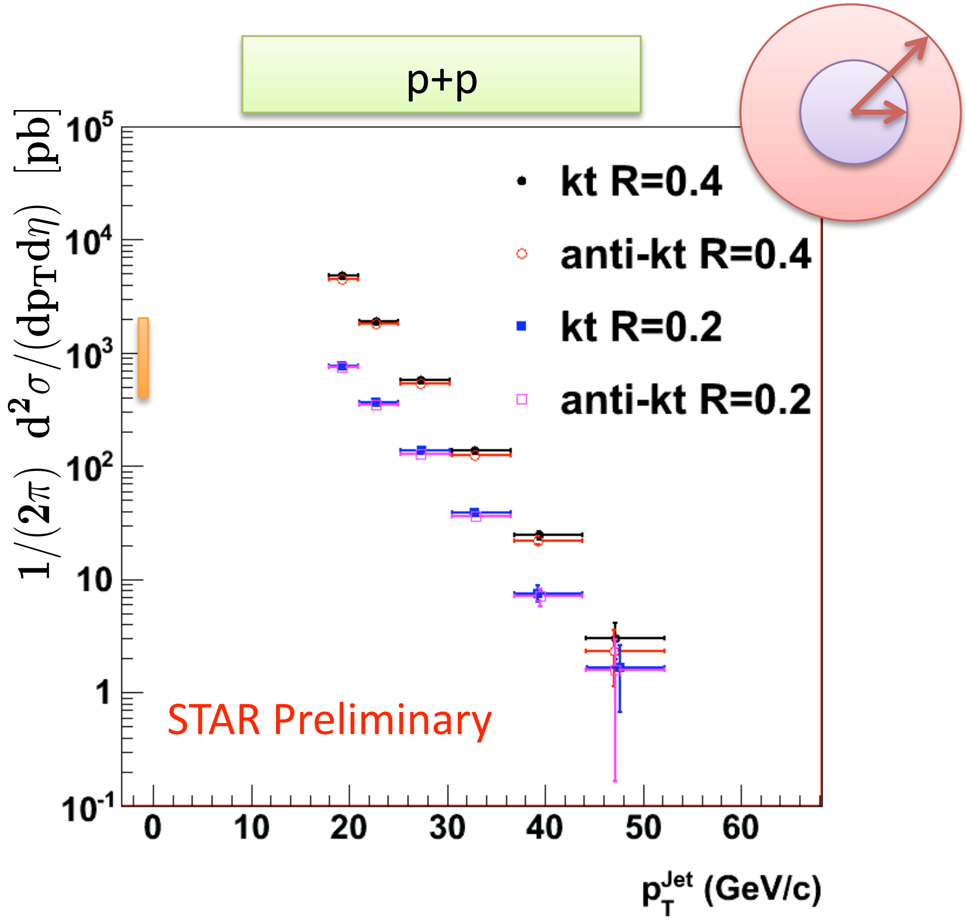
- Fully corrected jet spectrum
- Exactly the same algorithms and jet definitions used as compared to p+p
- Bands on data points represent estimation of systematic uncertainties due to background subtraction

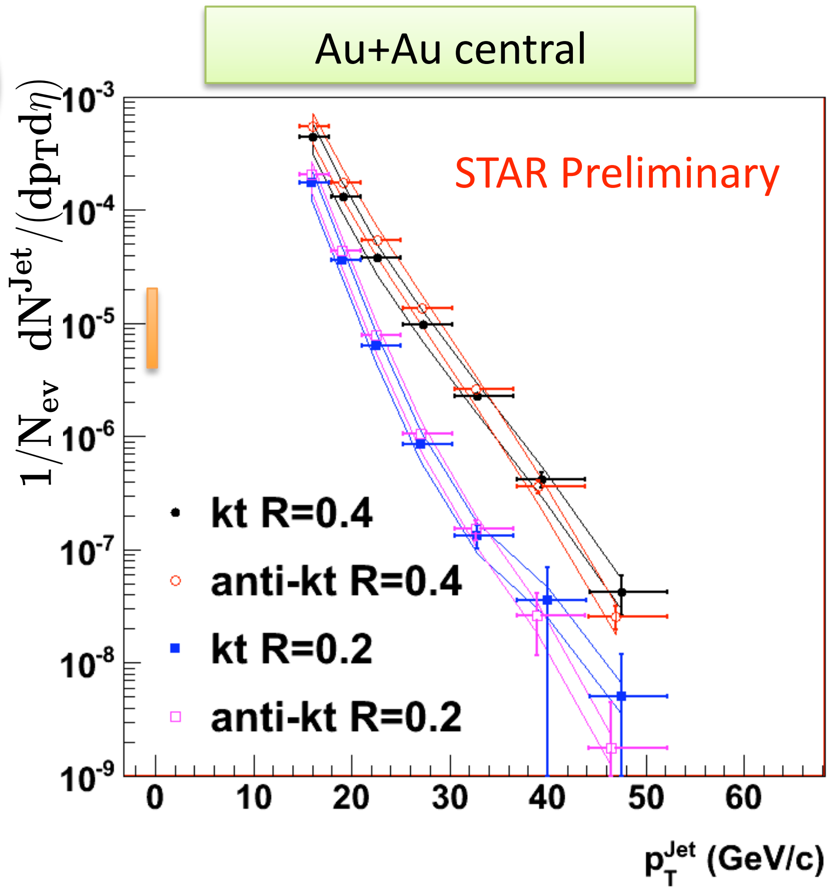


“R” systematics



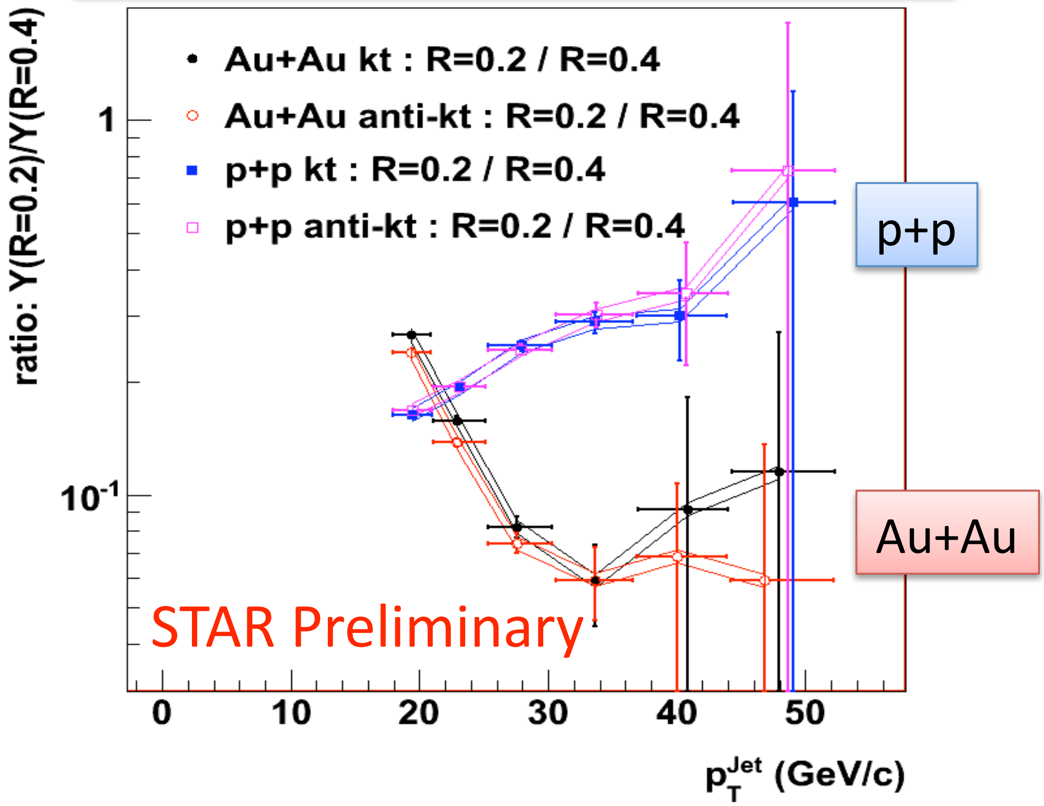
Inclusive jet spectrum: p+p and central Au+Au (R=0.4 and R=0.2)





Cross-section ratios in p+p and Au+ Au with R=0.2/R=0.4

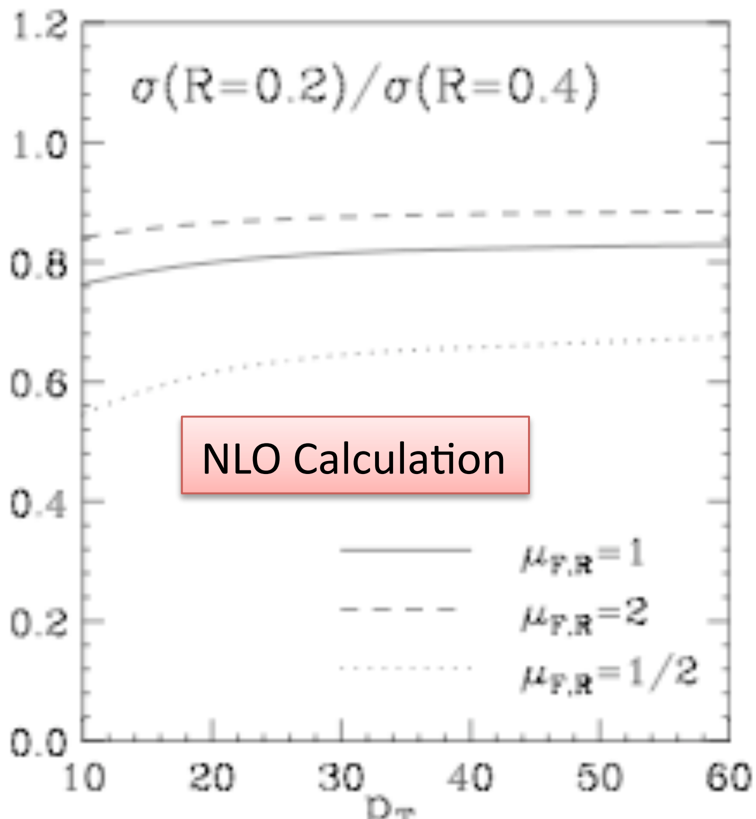
Many systematic effects cancel in **the ratio**



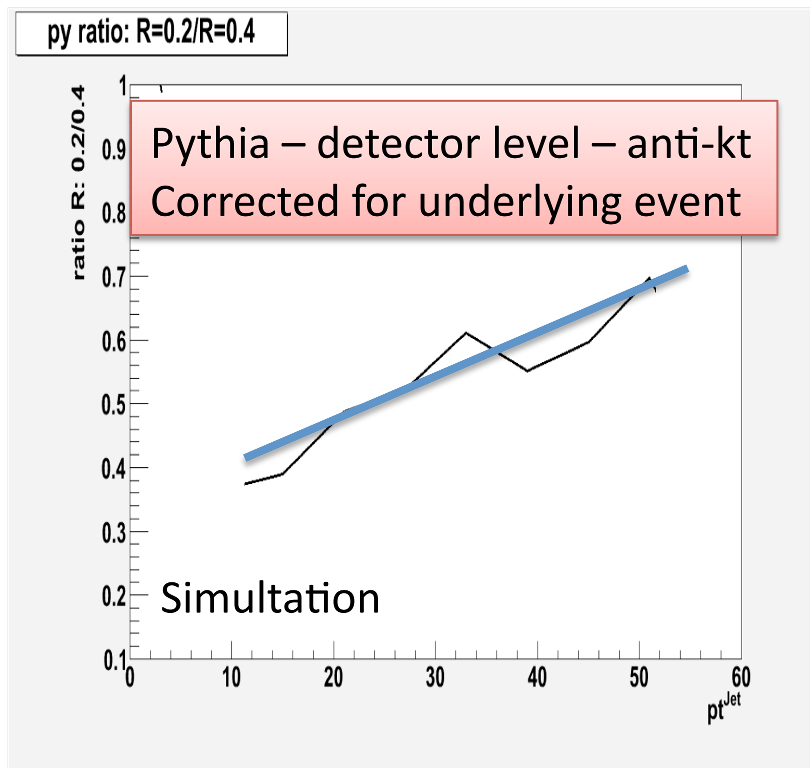
p+p: "Narrowing" of the jet structure with increasing jet energy

Au+Au: Strong broadening of the jet energy profile

Ratio R=0.2/R=0.4 in pp @ sqrt(s)=200 GeV/c

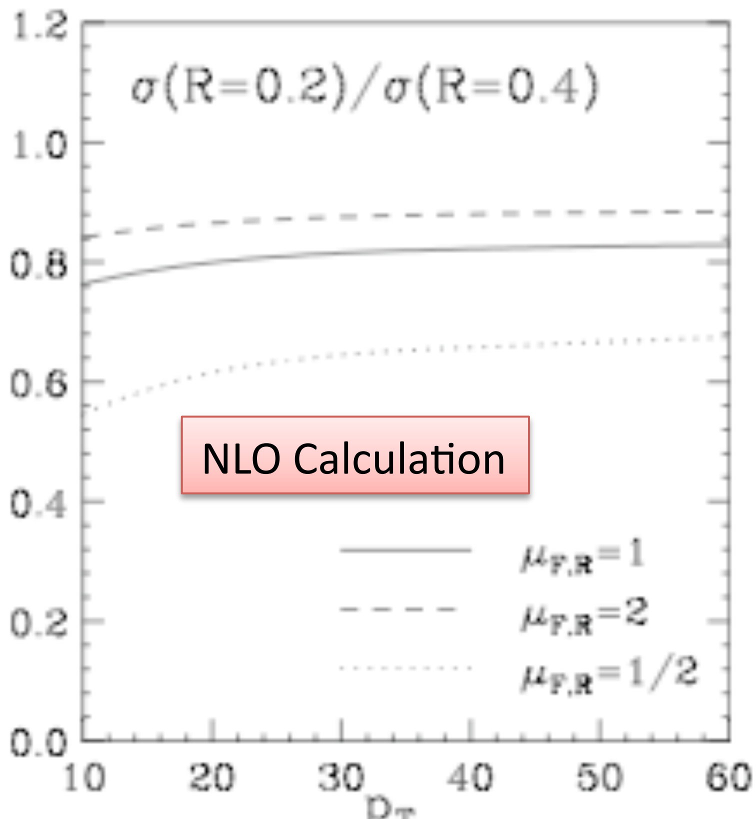


W. Vogelsang
D. De Florian ⇔ Ratio is FLAT!
Private comm.

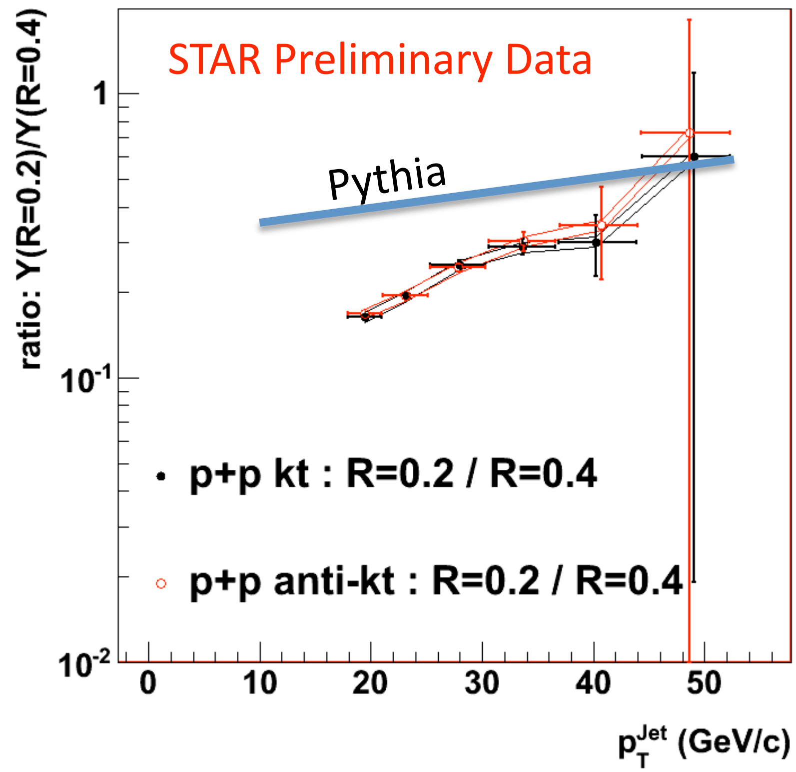


Ratio much smaller with strong tend

Ratio R=0.2/R=0.4
in pp @ sqrt(s)=200 GeV/c

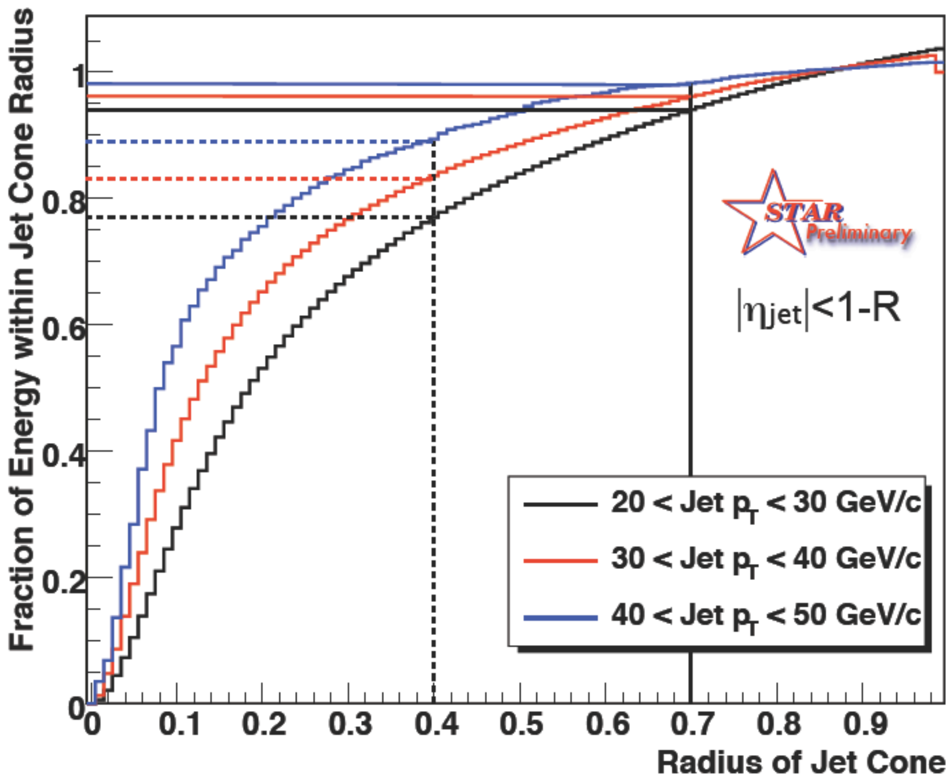


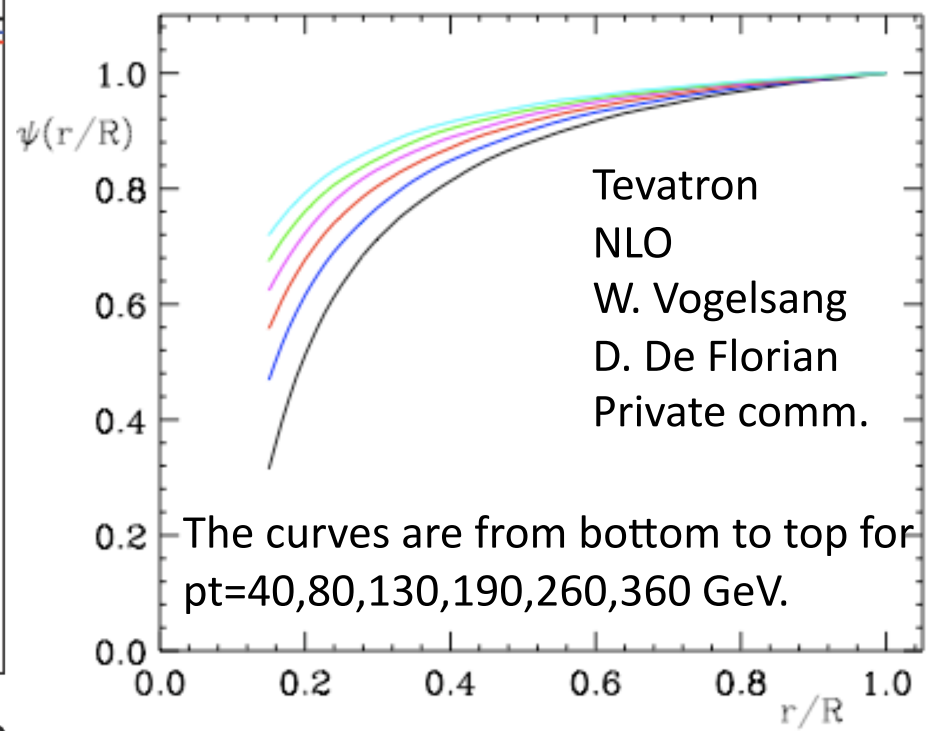
W. Vogelsang
D. De Florian ⇔ Ratio is FLAT!
Private comm.



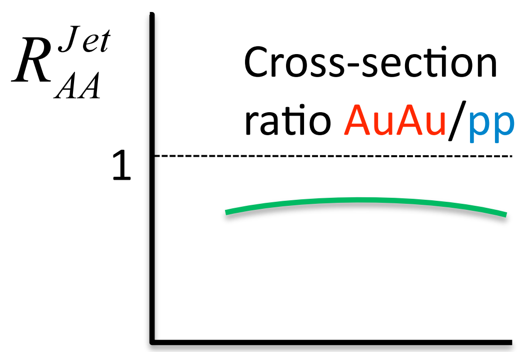
Ratio much smaller with strong tend

Jet shapes at RHIC and Tevatron

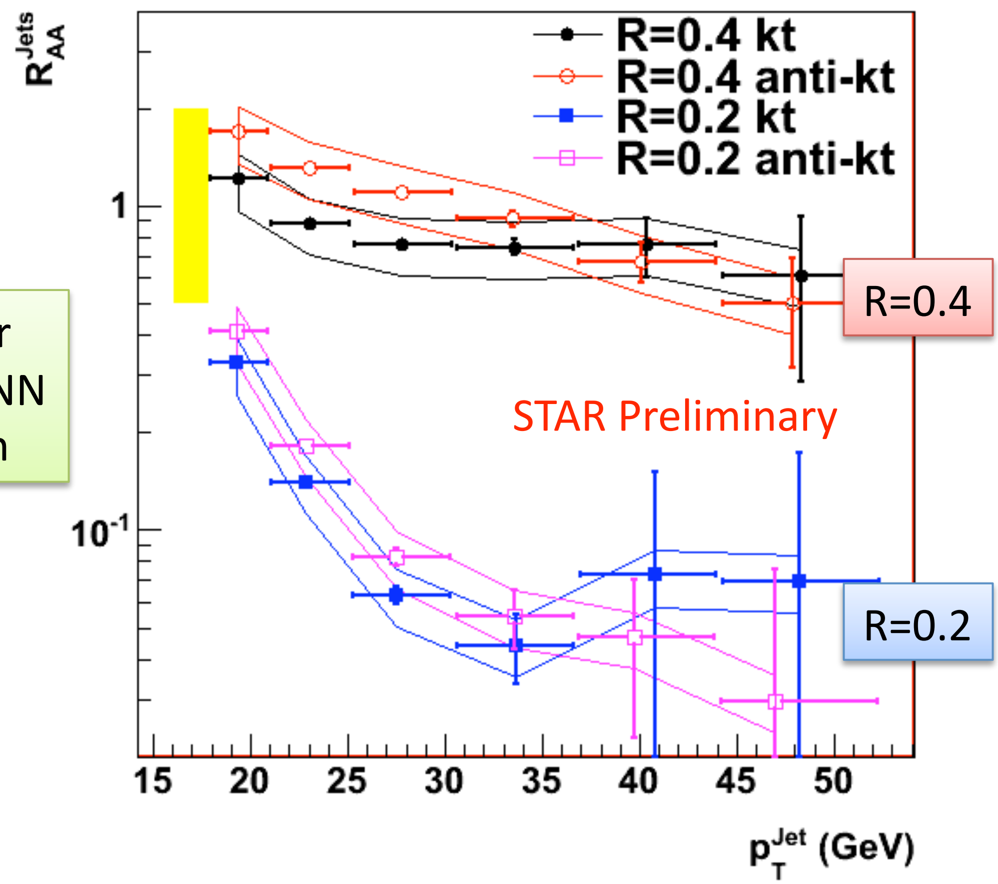




Jet R_{AA}



R_{AA} Jets and Energy flow in smaller “cone” radii

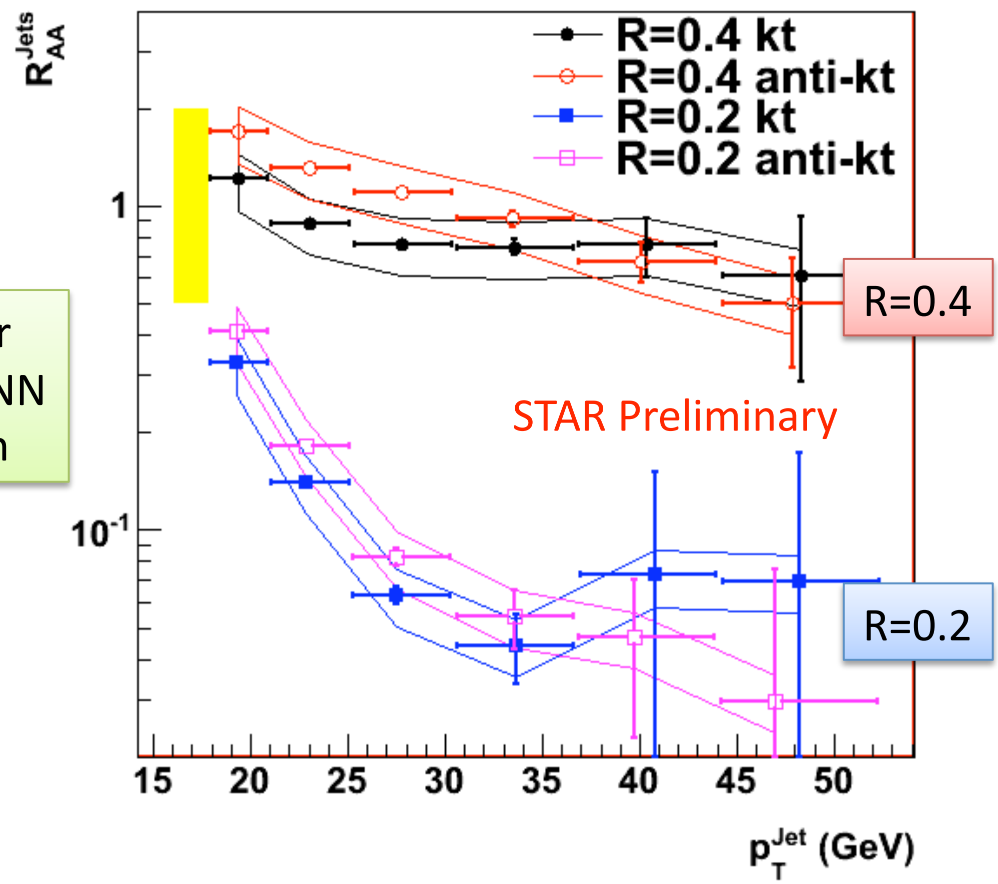


R_{AA}: yield per binary NN collision

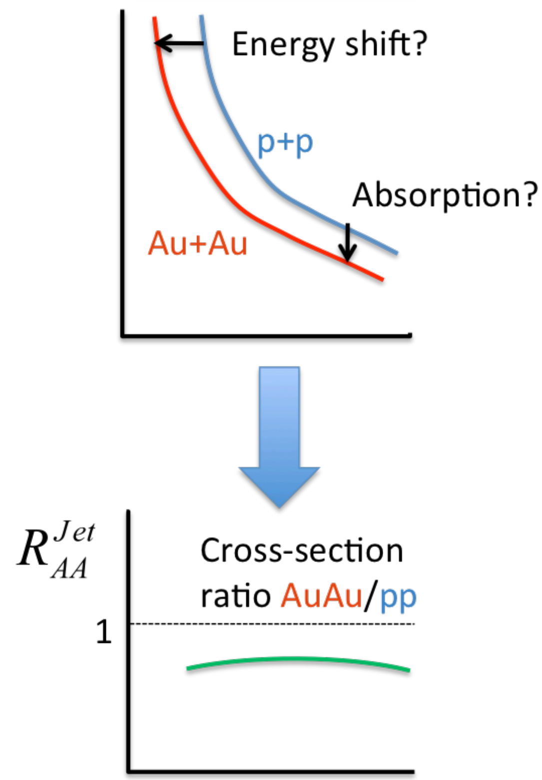
Significant drop of R_{AA} as a function of jet p_T for R=0.2 as compared to R=0.4
Jet energy not fully recovered in small “cones” – shift towards lower p_T

R_{AA} Jets and Energy flow in smaller "cone" radii

R_{AA}: yield per binary NN collision

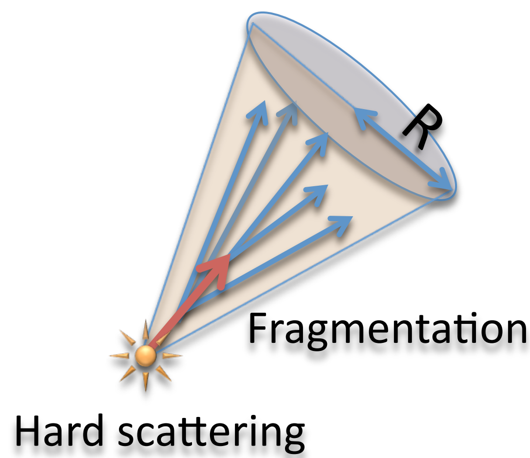


For a fixed R:



Significant drop of R_{AA} as a function of jet p_T for R=0.2 as compared to R=0.4
Jet energy not fully recovered in small "cones" – shift towards lower p_T

Jet fragmentation patterns

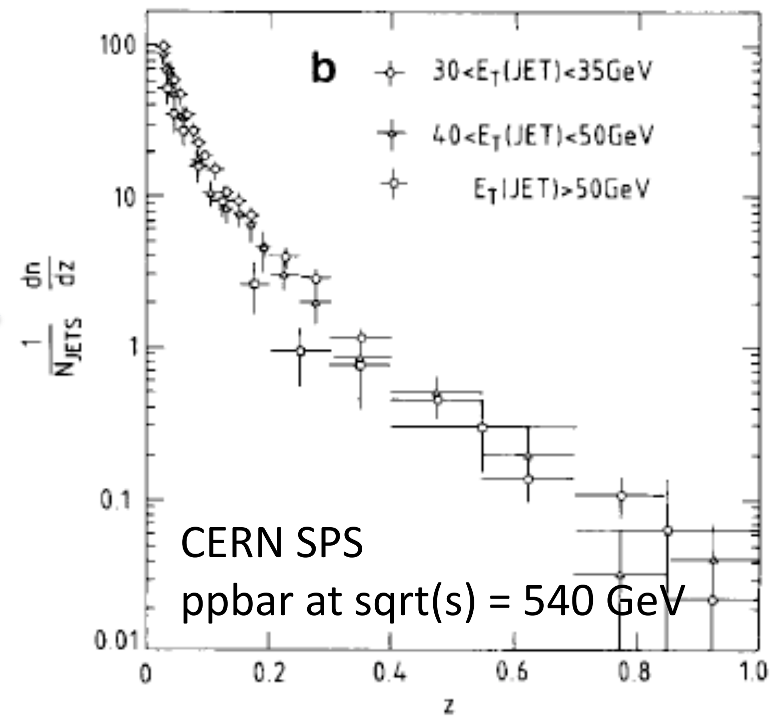


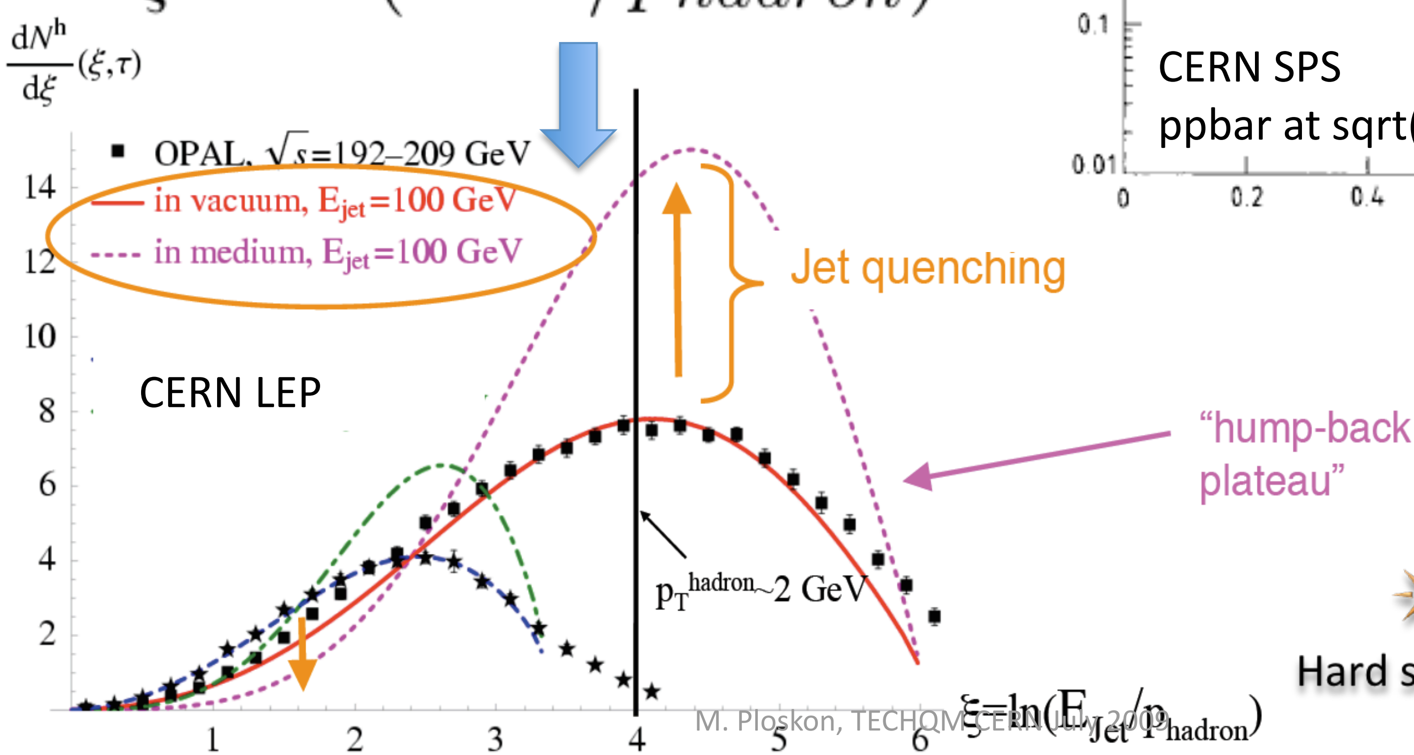
Fragmentation pattern - measurement

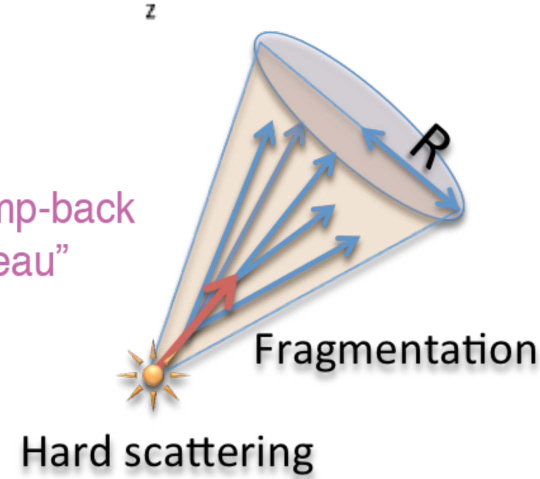
Fraction of jet energy carried by each constituent

$$z = p_{L|jet}^{hadron} / p^{Jet}$$

$$\xi = ln(E^{Jet} / p_{hadron})$$







Fragmentation Reference: p+p

JP trigger
$|\eta_{jet}|<1\text{-}R$

Data not corrected for particle level

Increasing Jet Energy

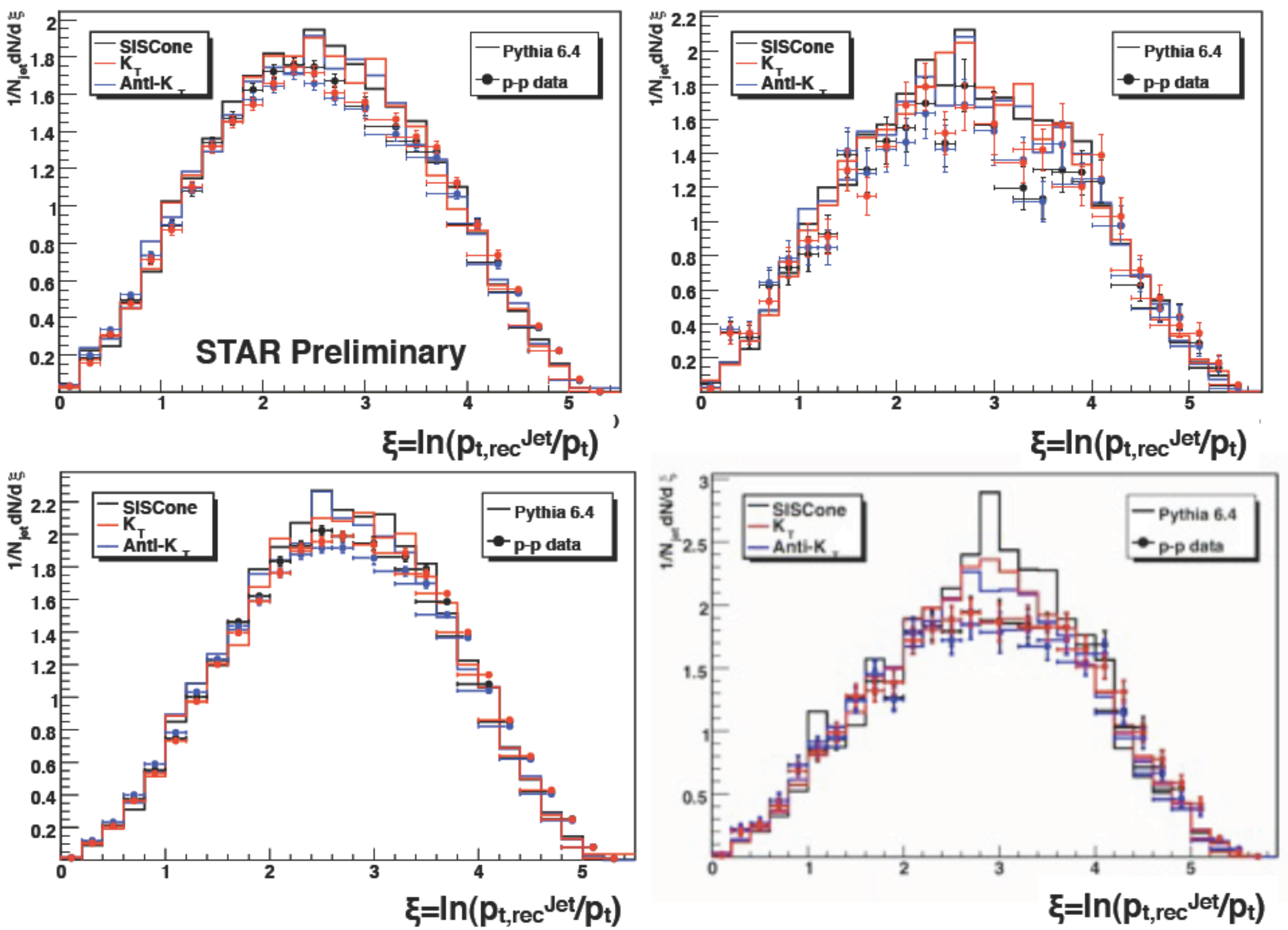
$20<E^{reco}<30$ GeV

$30<E^{reco}<40$ GeV

R<0.4

R<0.7

Increasing "Cone" R



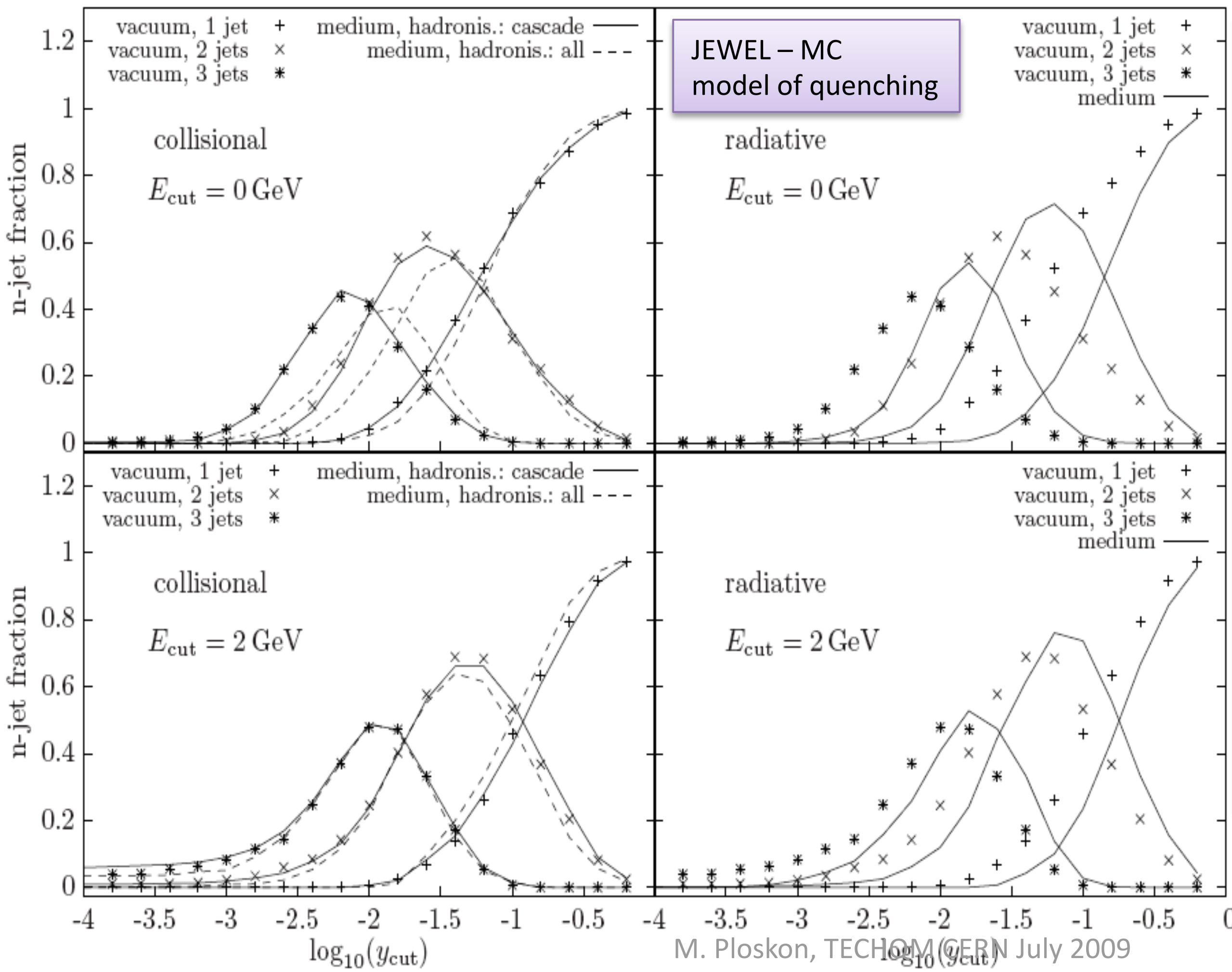
Good agreement between measurements at RHIC and PYTHIA

Further observables

- Jet shapes
- Intra-jet distributions
- 3-jet observables
- …

Subjets

Count sub-jets when $y_{ij} > y_{cut}$: $y_{ij} = 2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})/E_{\rm cm}^2$



Subjet distributions:

+ Insensitive to hadronization
+ Quenching signal with bg suppressing pt cut

- Suffer from energy irresolutions:

$$-log_{10}(f_{corr}^2)$$

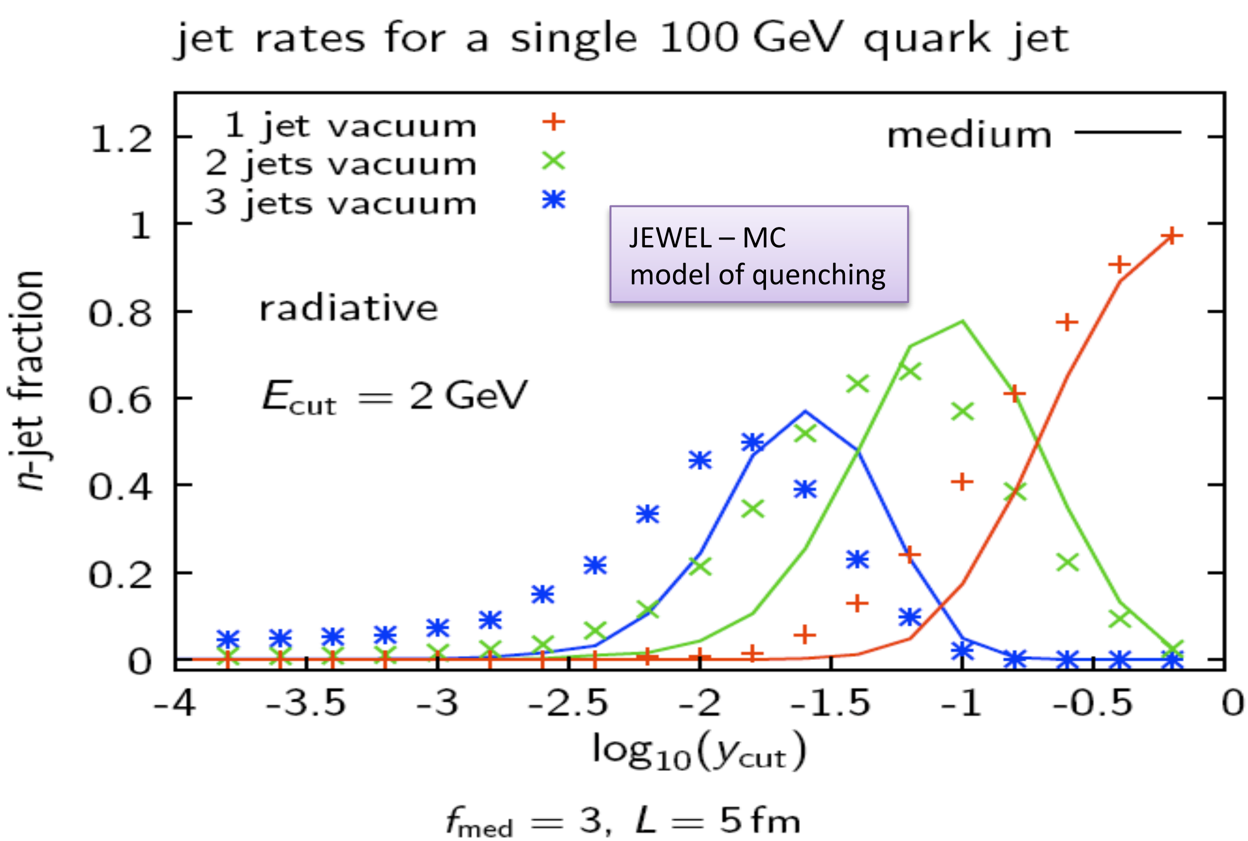
where

$$f_{corr} = E_{jet}^{true} / E_{jet}^{measured}$$

C. Zapp et al.
arXiv:0804.3568 [hep-ph]

Subjets

Count sub-jets when $y_{ij} > y_{cut}$: $y_{ij} = 2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})/E_{cm}^2$



JEWEL – MC model of quenching

Subjet distributions:

+ Insensitive to hadronization
+ Quenching signal with bg suppressing pt cut

- Suffer from energy irresolutions:

$$-log_{10}(f_{corr}^2)$$

where

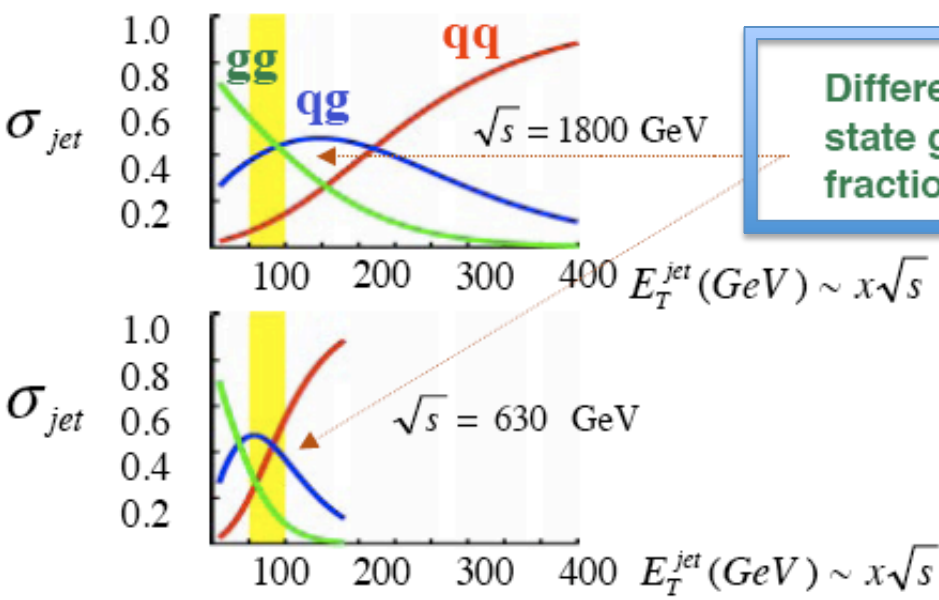
$$f_{corr} = E_{jet}^{true} / E_{jet}^{measured}$$

C. Zapp et al. arXiv:0804.3568 [hep-ph]

Subjets at Tevatron(D0)

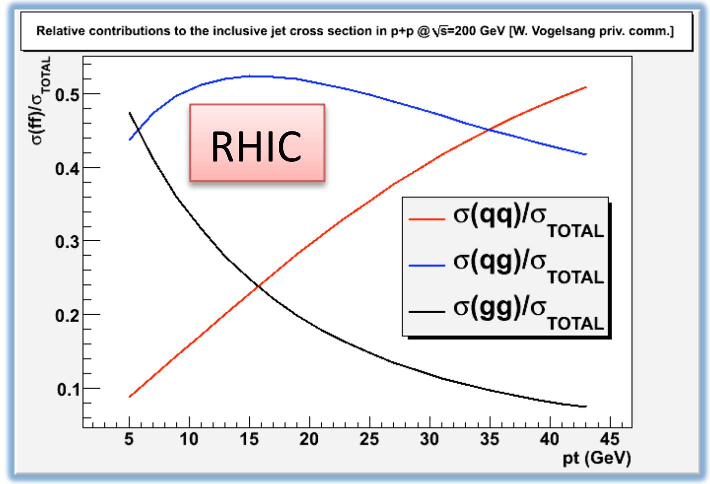
- Reclustering (re-run of a kt algor) on a jet -> recombination into n-subjets separated by y_{min} cut -> used for q-g jet discrimination

- Basic Idea:
  - Compare the subjet multiplicity of jets with same E_T and η at center of mass energies 630 and 1800 GeV



Different final state gluon fraction

Vogelsang: pp @ 200 GeV



RHIC will measure pp@500 GeV
LHC?

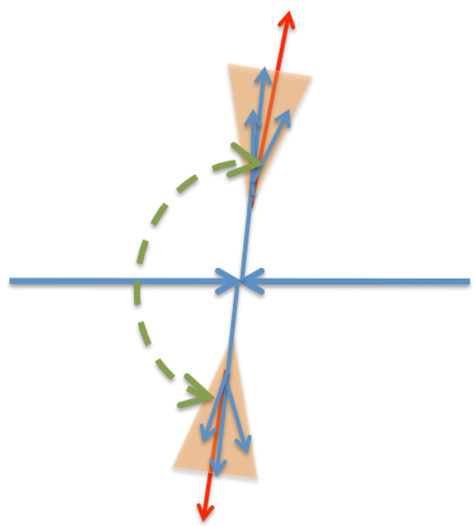
Summary

- HI collisions create dense, hot colored medium, opaque to energetic partons
- Hadronic observables provide limited constrains for understanding of the partonic energy loss -> need for full jet reconstruction:
- **Full jet reconstruction:**
  - **Qualitatively new tool for assessment of the jet quenching in terms of energy flow (rather than hadronic observables)**
  - Precision of the background estimation - crucial in AA
  - HI: Significant radiation “outside” R=0.4
  - Broadening of jet energy profile?
  - **“Detailed” studies of jet-medium interactions possible?**

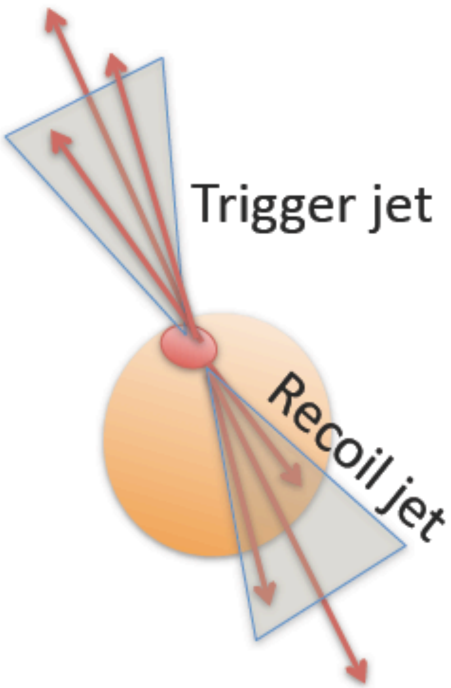
Outlook

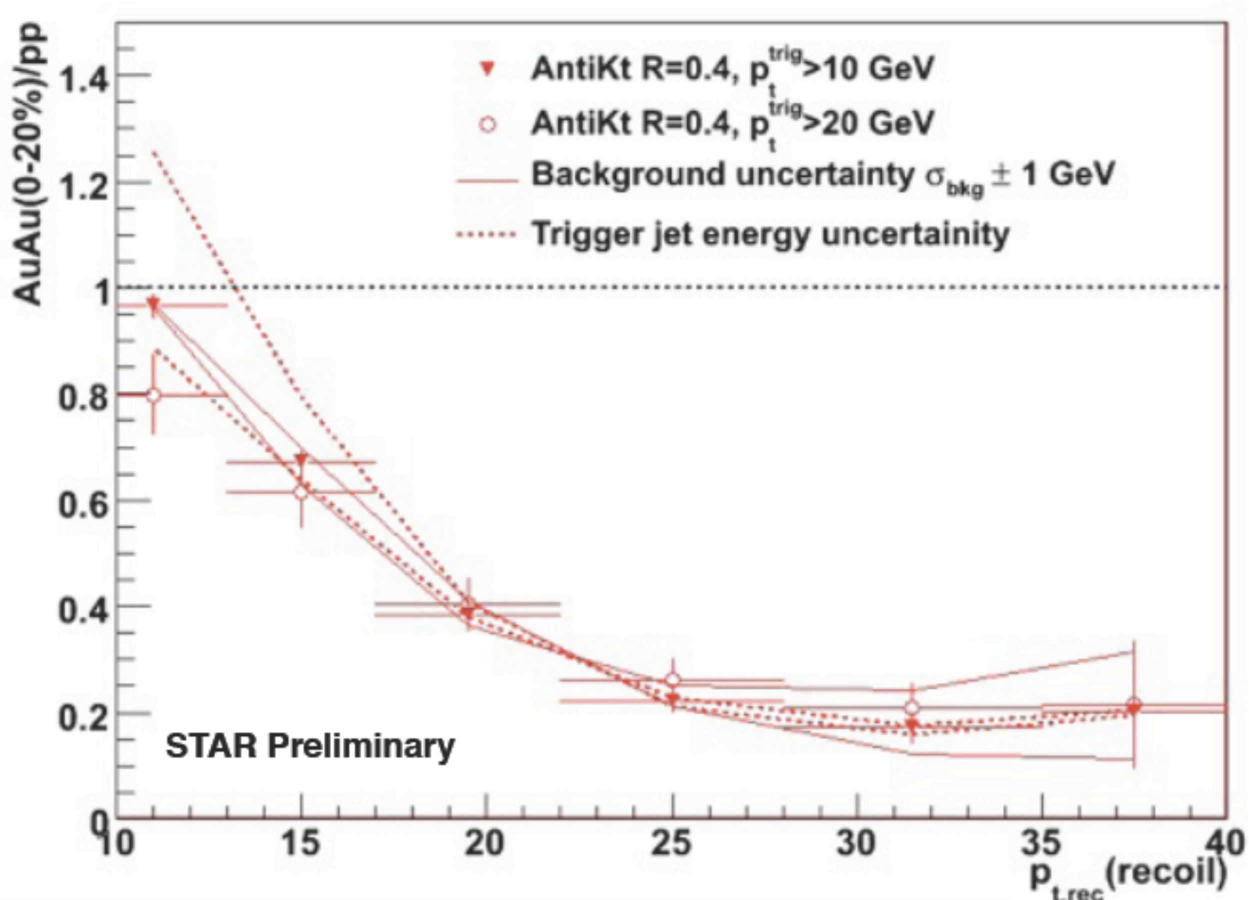
- Full jet reconstruction at LHC:
  - Algorithms developed for pileup removal at LHC applicable to HI collisions
  - New algorithms being defined and explored
  - Pioneering analyses at RHIC provide tools and analysis techniques directly applicable at LHC
  - Many data driven corrections already found and explored

Di-Jet measurements



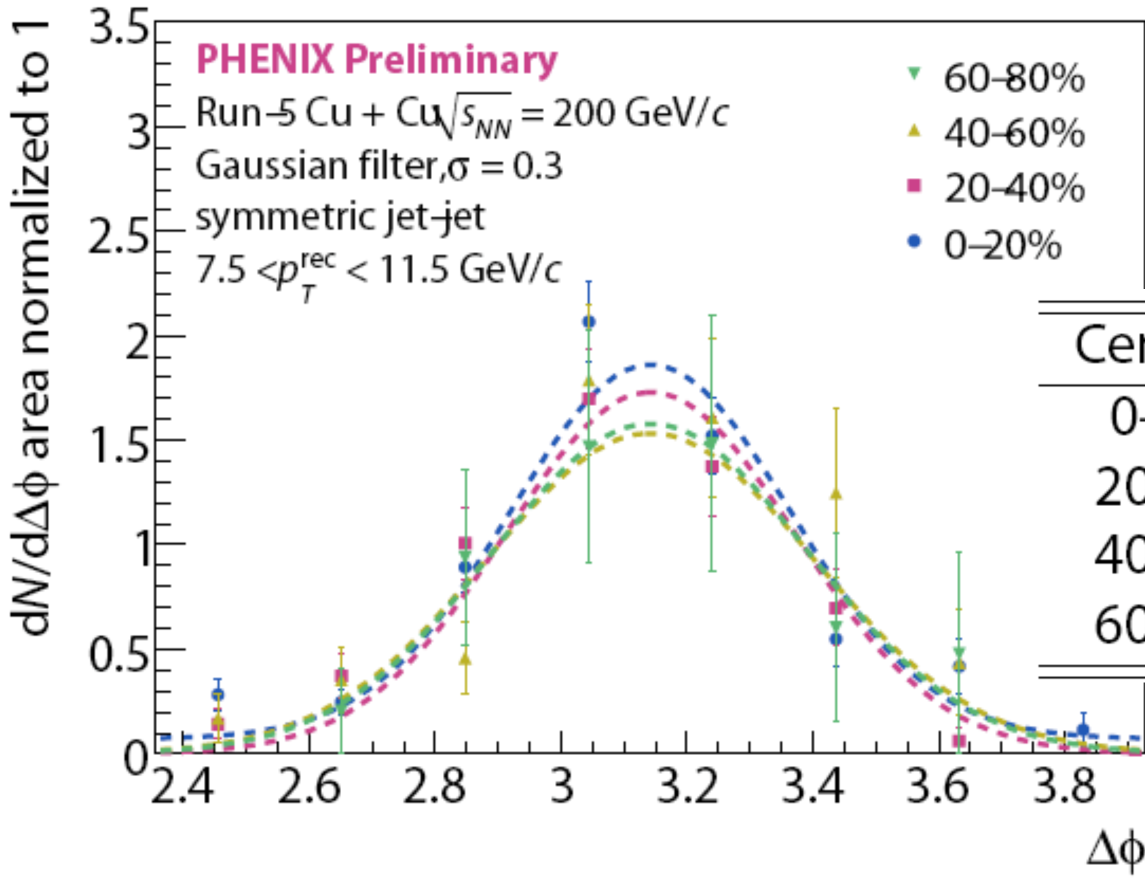
Di-jets in Au+Au





Trigger selection -> Biased population:
- Significant suppression of recoil jet spectrum
- Comparable to single particle R_{AA}

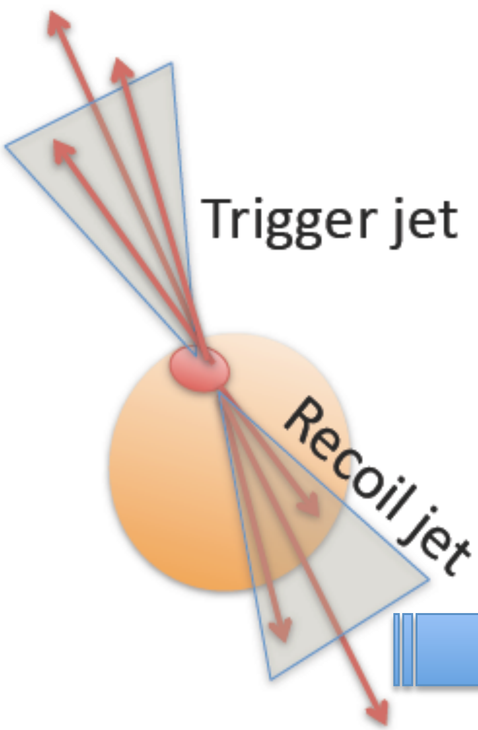
Di-jets in Cu+Cu

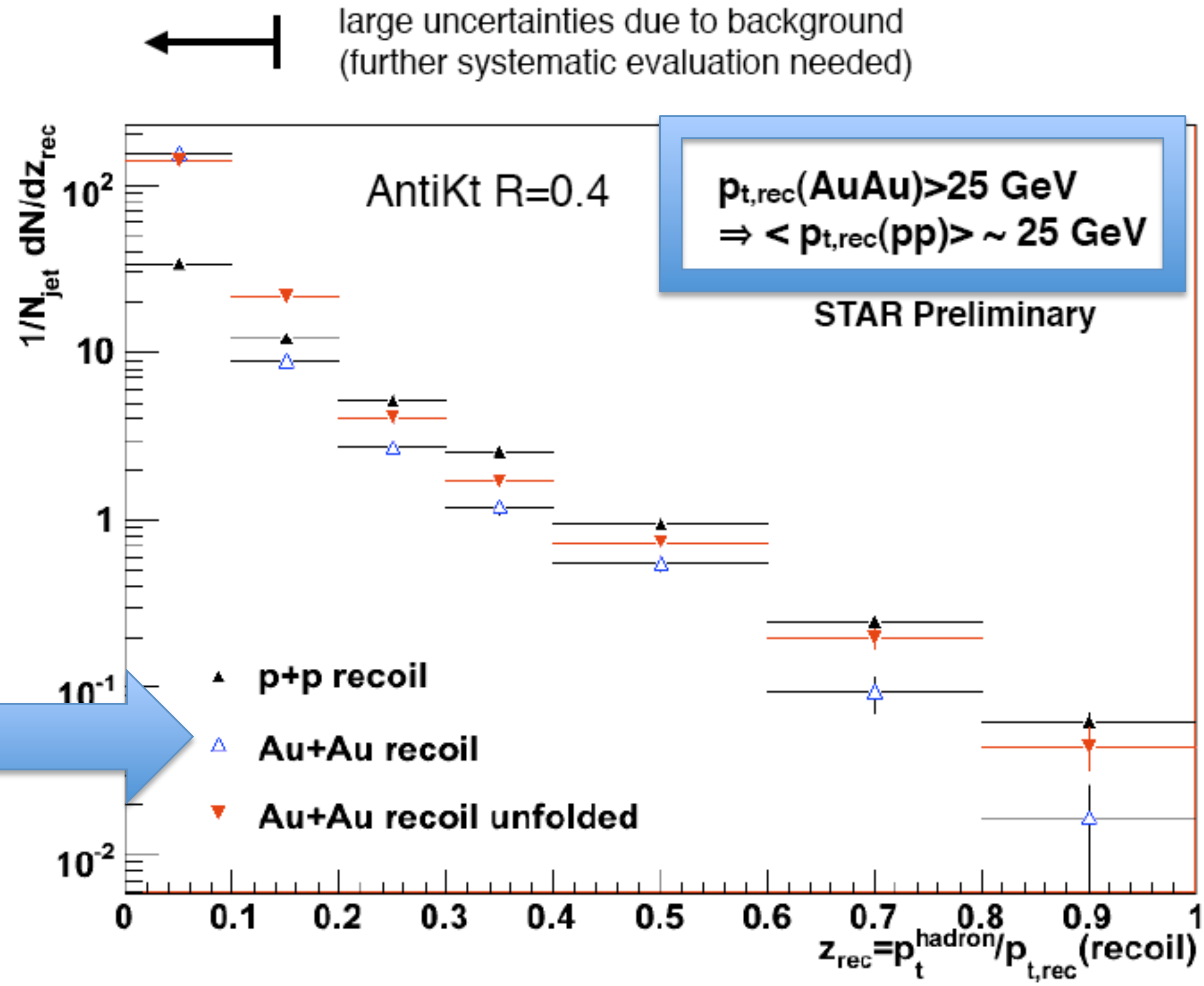


Centrality	$\Delta\varphi \approx \pi$ width σ
0–20%	0.223 ± 0.017
20–40%	0.231 ± 0.016
40–60%	0.260 ± 0.059
60–80%	0.253 ± 0.055

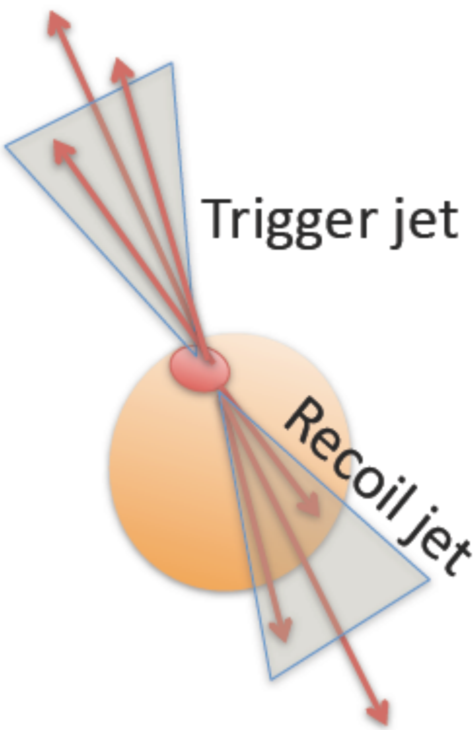
No centrality dependent broadening within uncertainties!

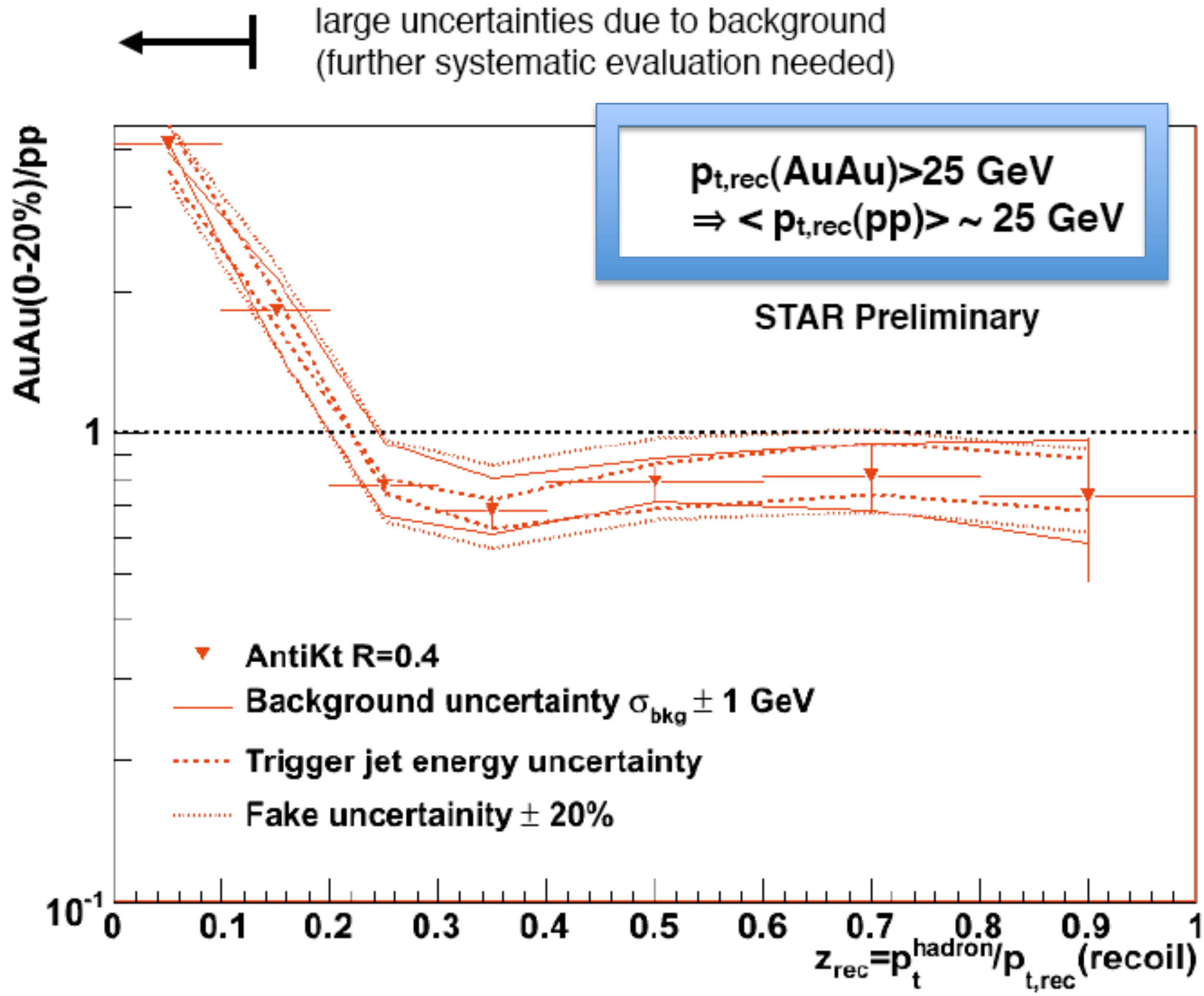
Jet fragmentation pattern in Au+Au



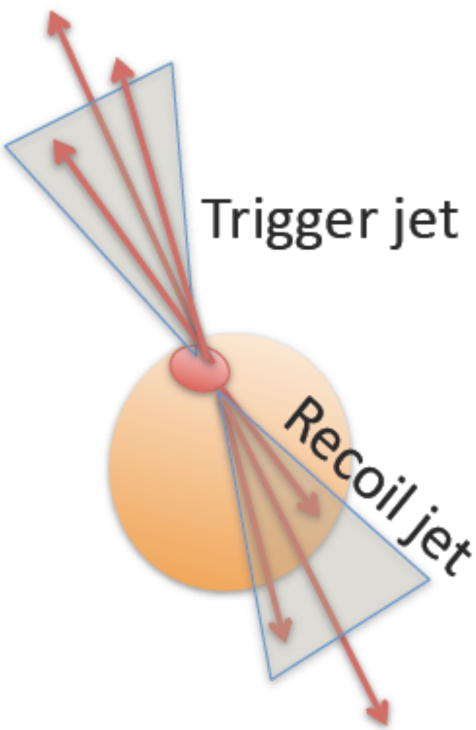


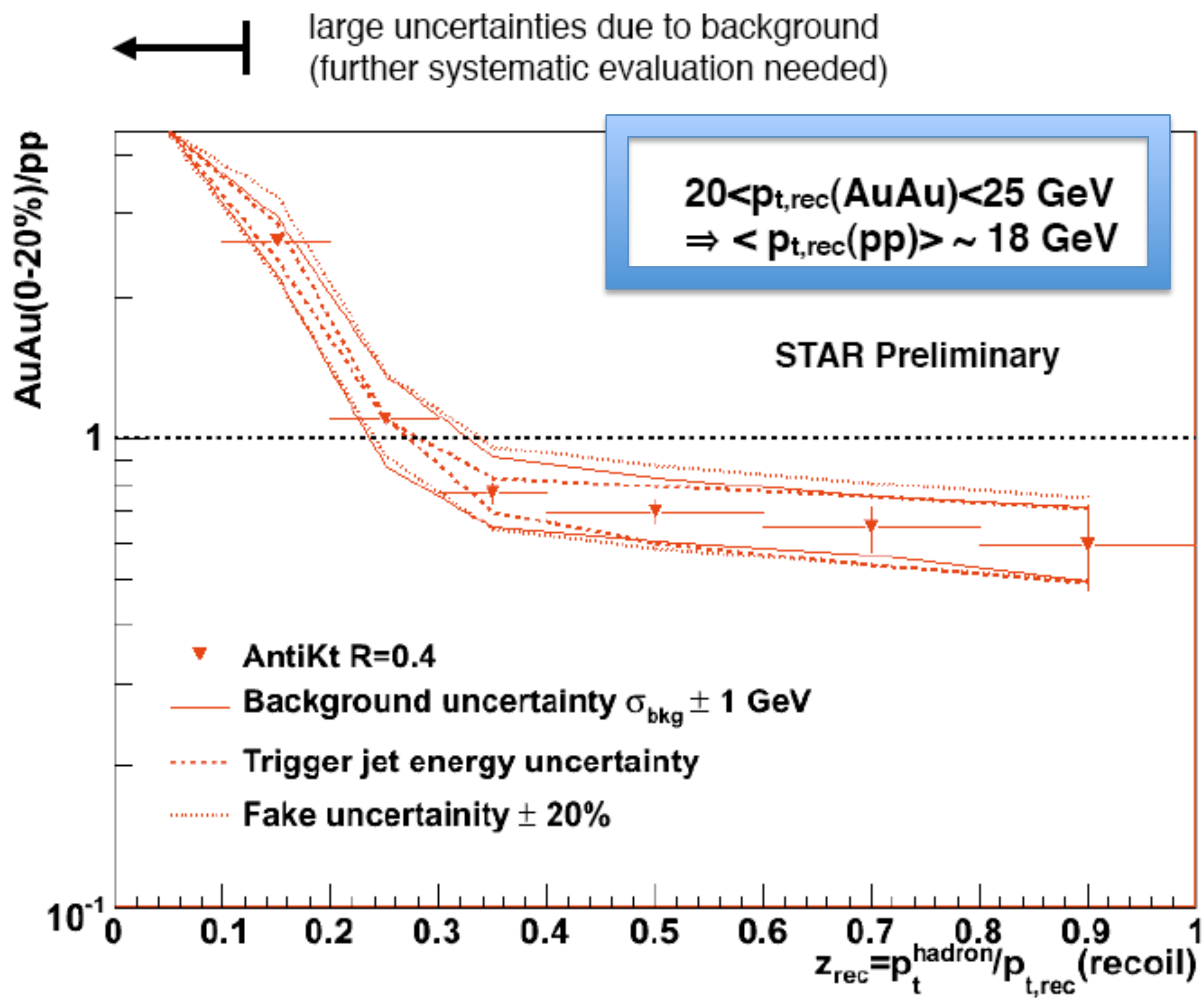
Fragmentation: ratio AuAu/pp



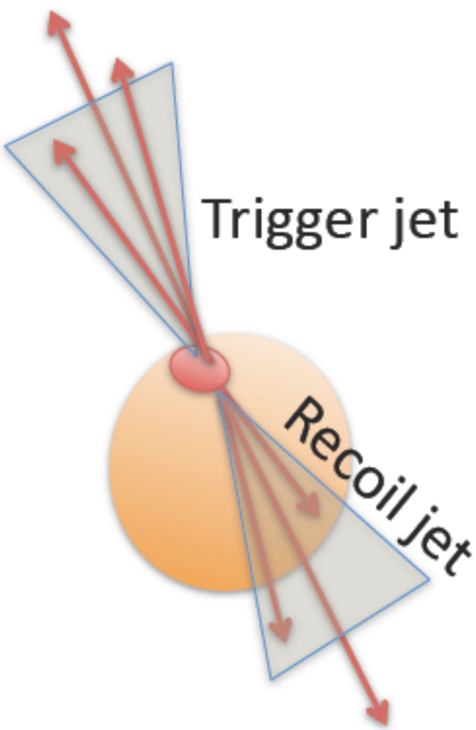


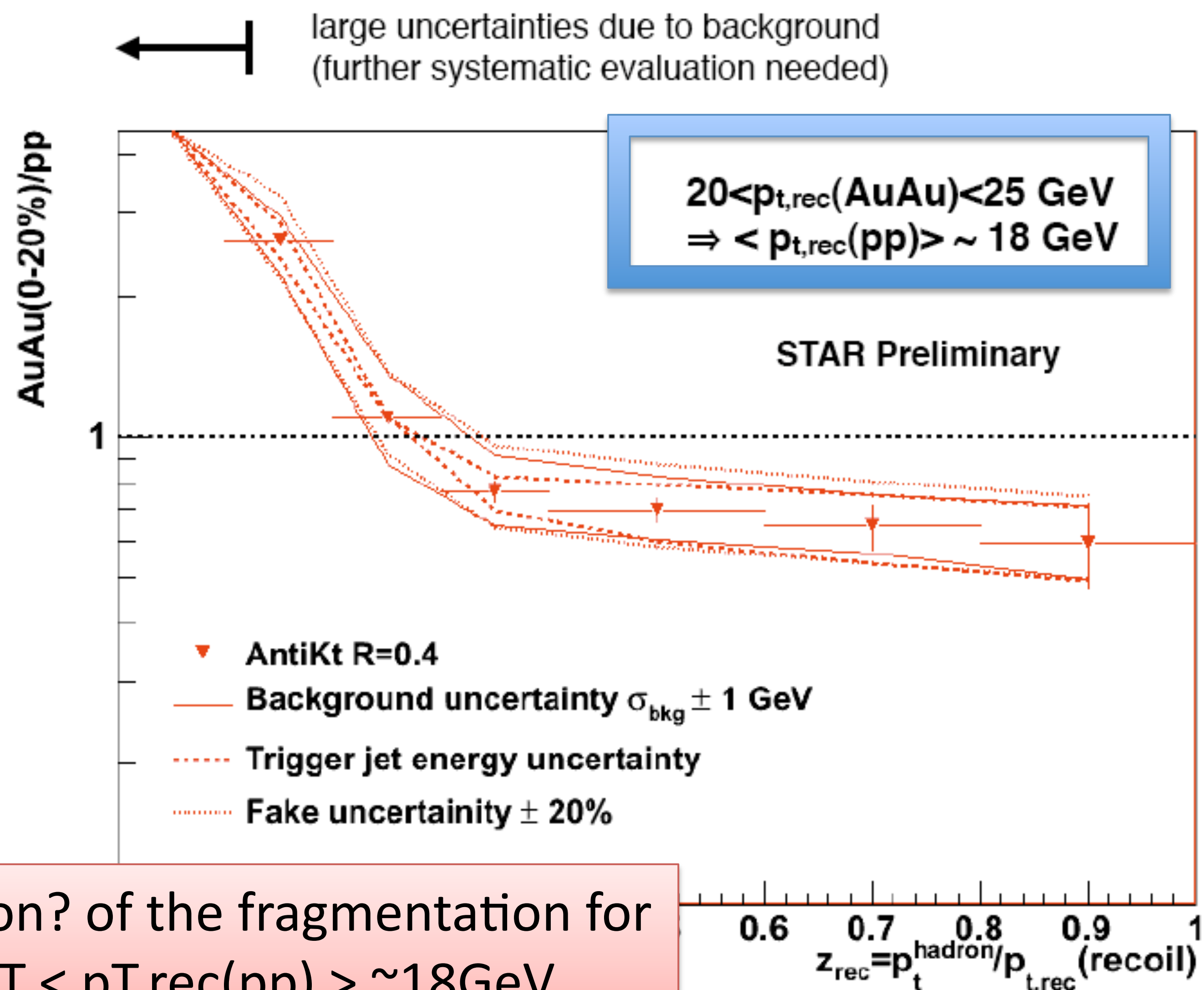
Fragmentation: ratio AuAu/pp





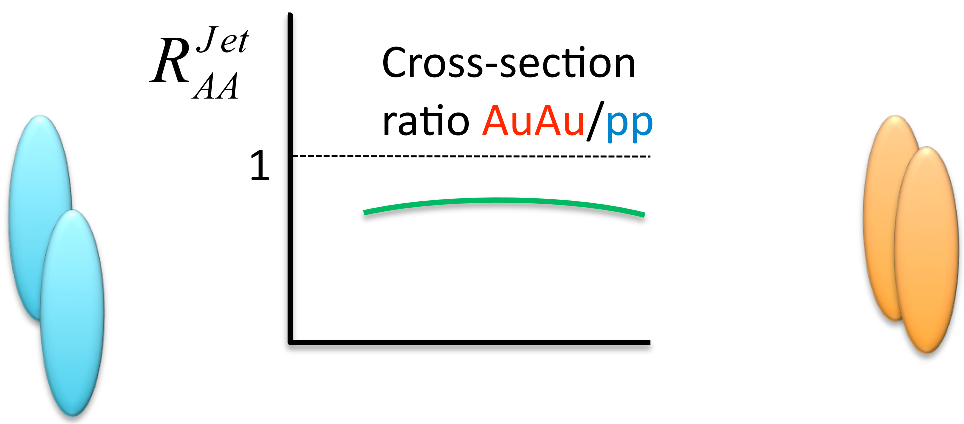
Fragmentation: ratio AuAu/pp



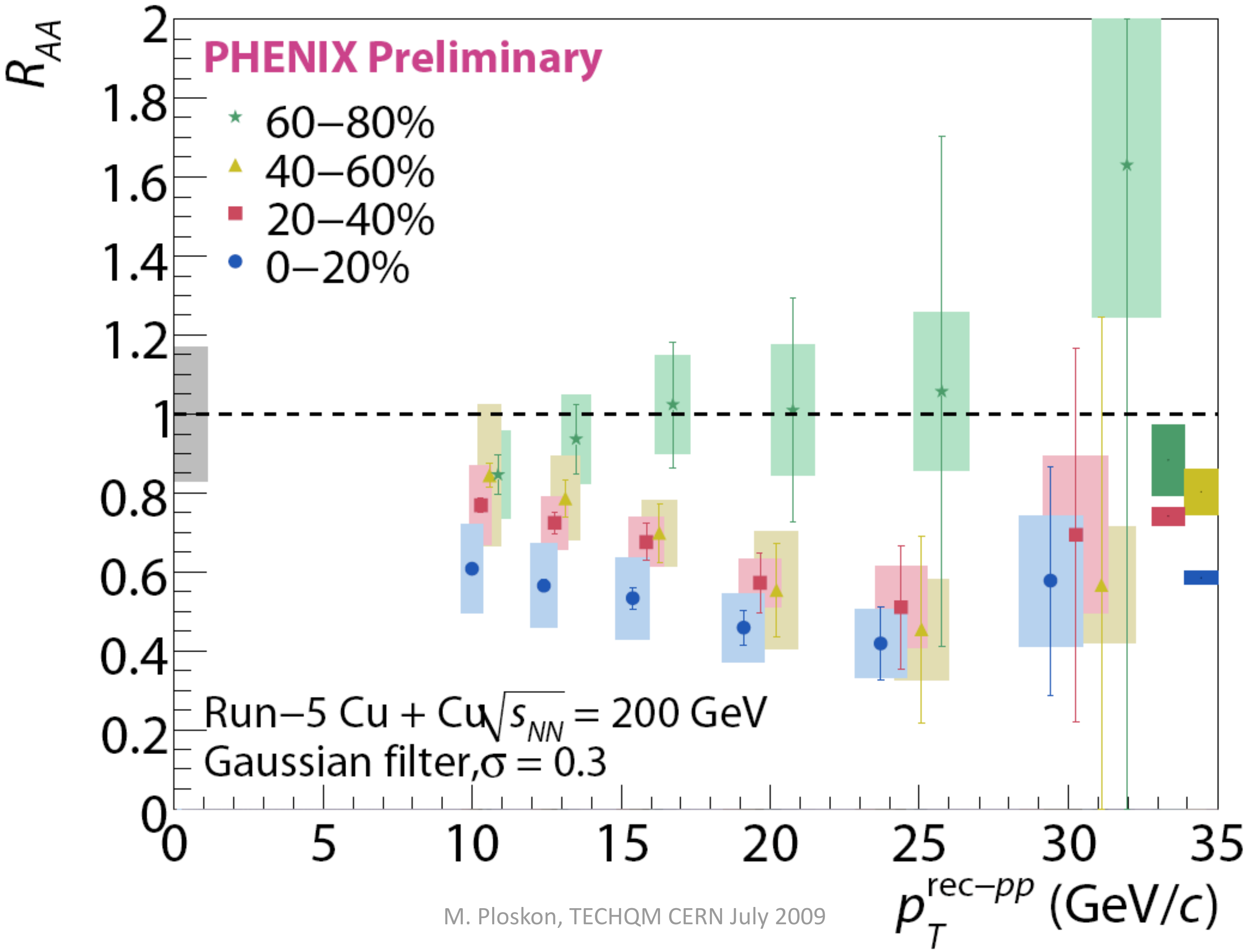


Modification? of the fragmentation for lower jet pT < pT,rec(pp) > ~18GeV

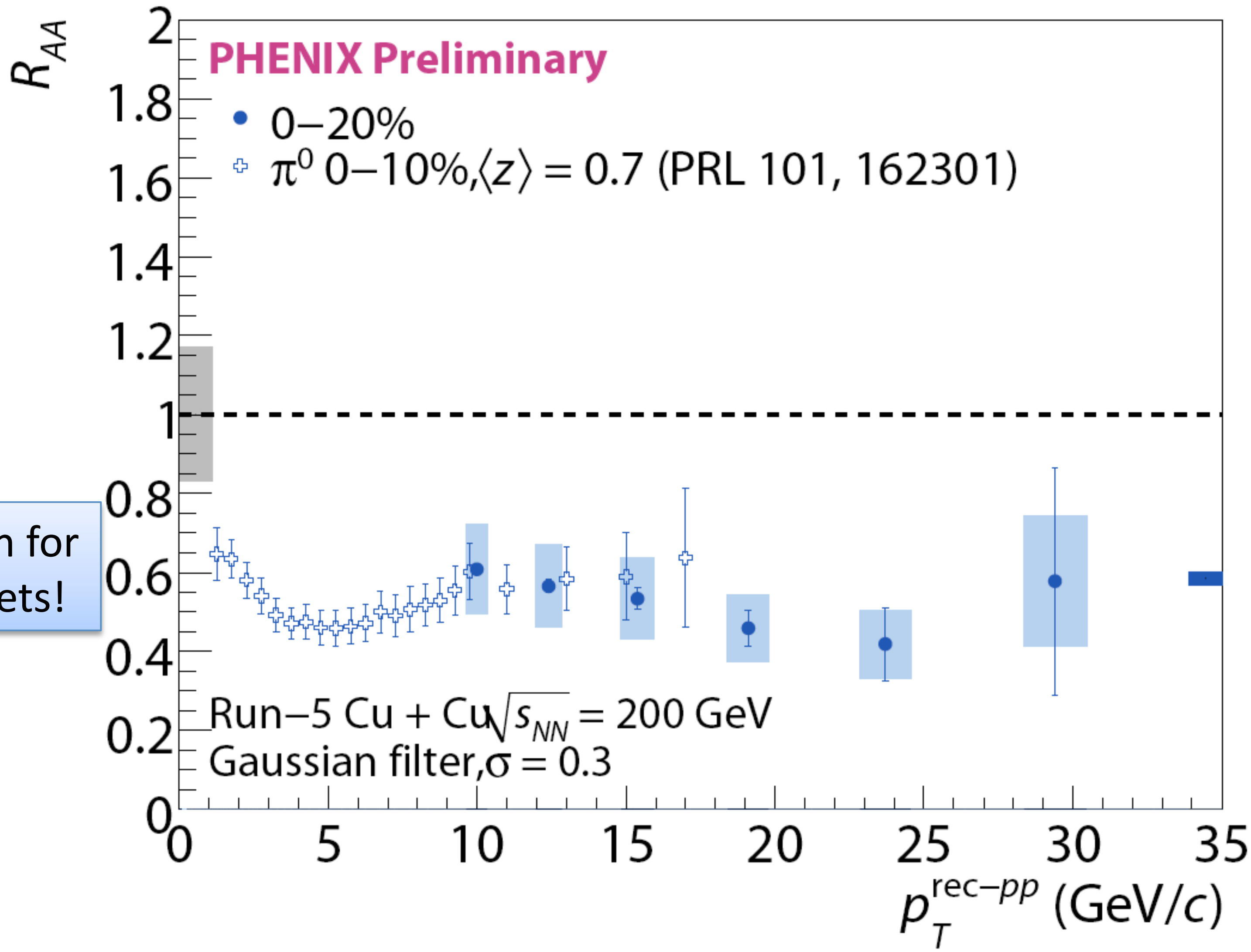
R_{AA} in Cu+Cu: Centrality systematics



Jet R_{AA} in Cu+Cu



Jet R_{AA} in Cu+Cu



"Similar" suppresion for Single particle and jets!