Jet measurements in p-p and A-A collisions

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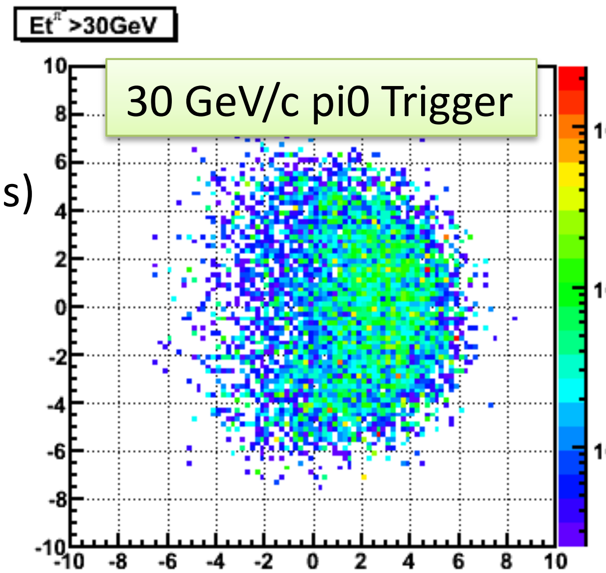
for the STAR Collaboration

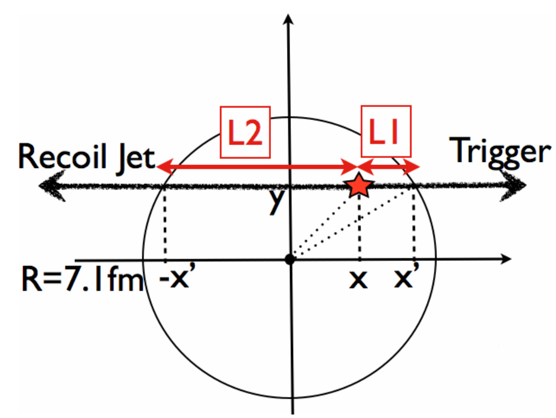
Outline

- Introduction – tools of heavy-ion collisions
- Inclusive jet cross-section and pQCD at RHIC in p-p collisions
- Jet quenching via single hadron observables
  - Success and limitations
- Full jet reconstruction in heavy-ion collisions
- Jet quenching using fully reconstructed jets in heavy-ion collisions
- Outlook

Quantitative analysis: tools of heavy-ion collisions

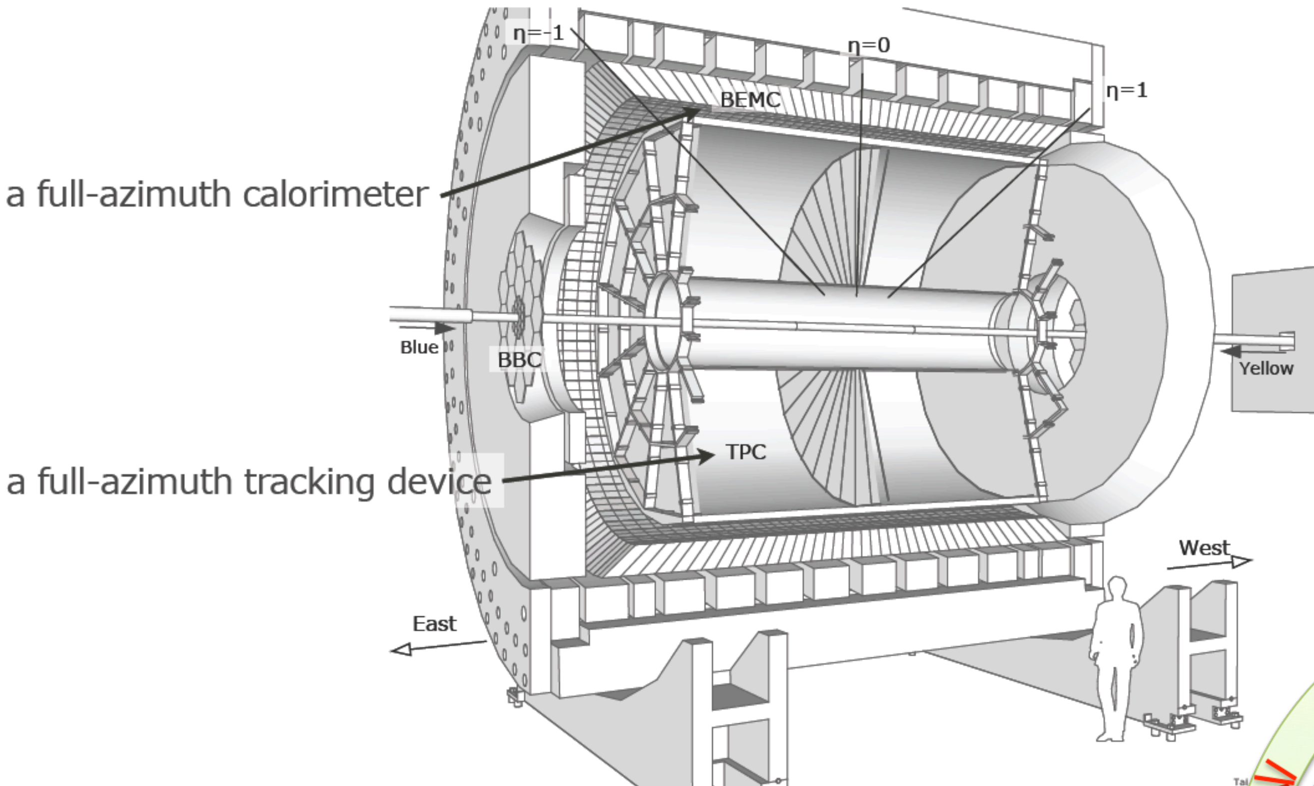


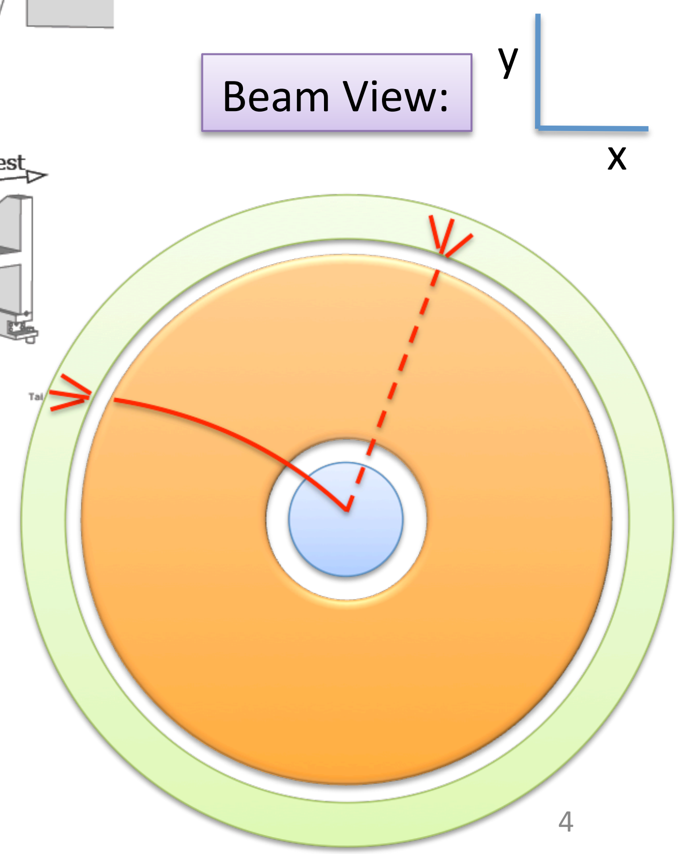
- Inclusive cross-sections
  - Scaling of x-section ("Glauber"; e.g. hard x-sec ~ Nbinary collisions)
- Correlation measurements
  - Observable "B" under a condition "A" (trigger)
- Control over geometry
  - Correlations with reaction plane
- Jet quenching
  - Geometric biases – use to the extreme
  - Color charged probes
  - Color neutral probes
- "Discovery by/through deviation"
  - use p-p and p-A collisions as references for A-A measured observables



- Interpretation -> Dependent upon modeling (!)

A jet detector. STAR:





Vertex detection

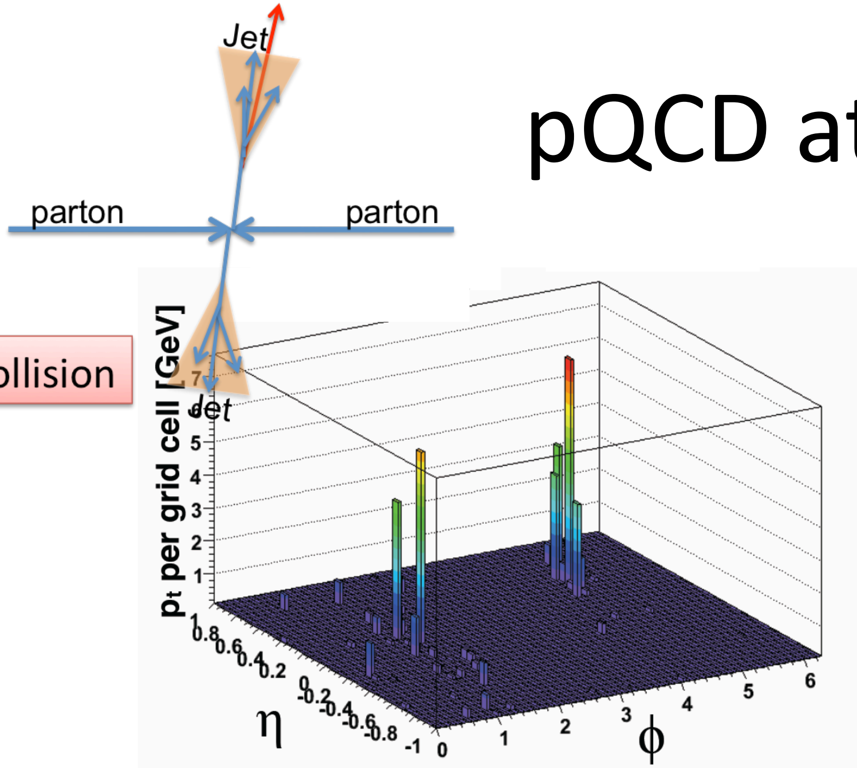
Charged track momentum determination

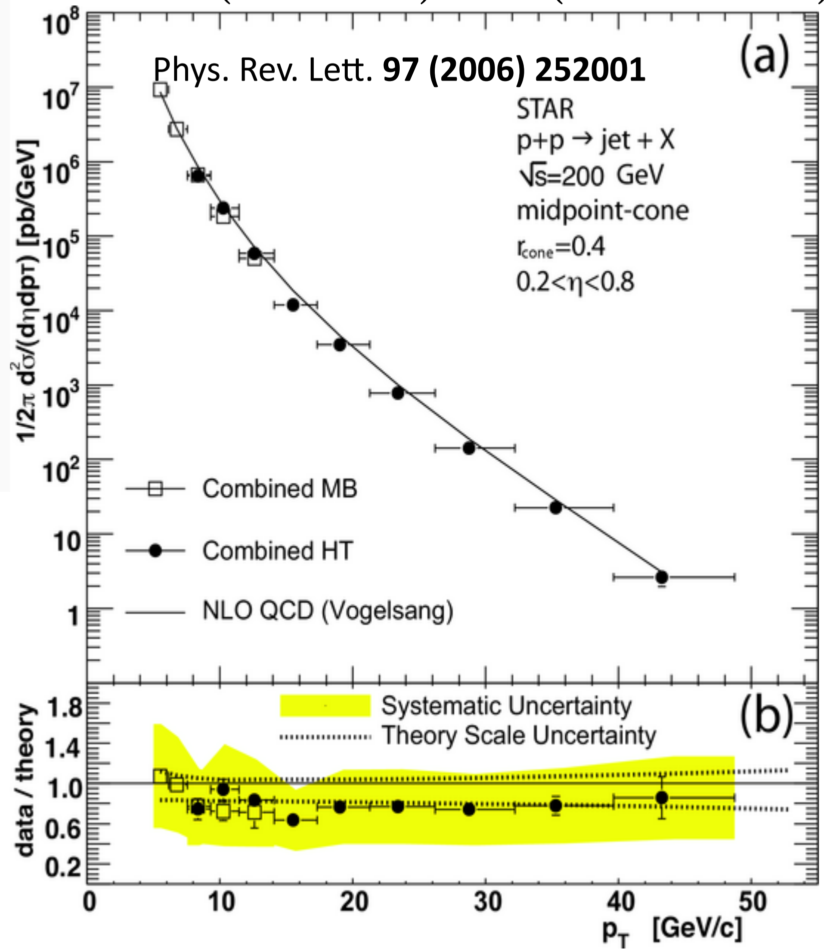
Electromagnetic calorimetry

pQCD at RHIC

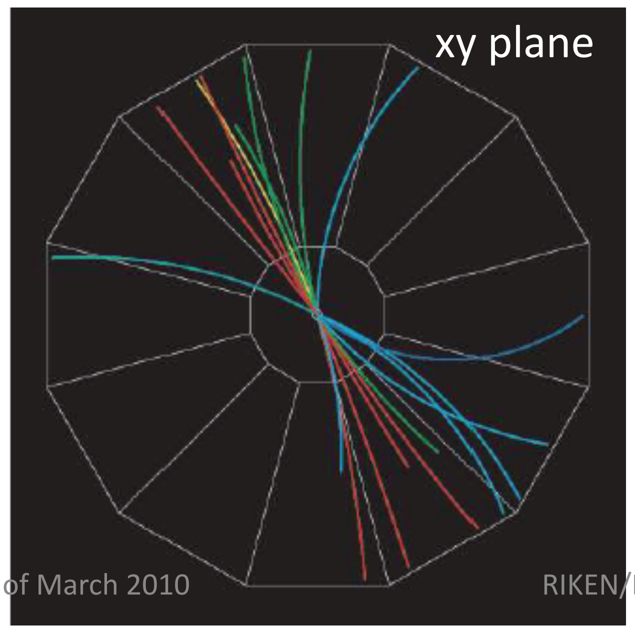
$$d\sigma \propto (PDF) \otimes (HARD)$$

p+p collision

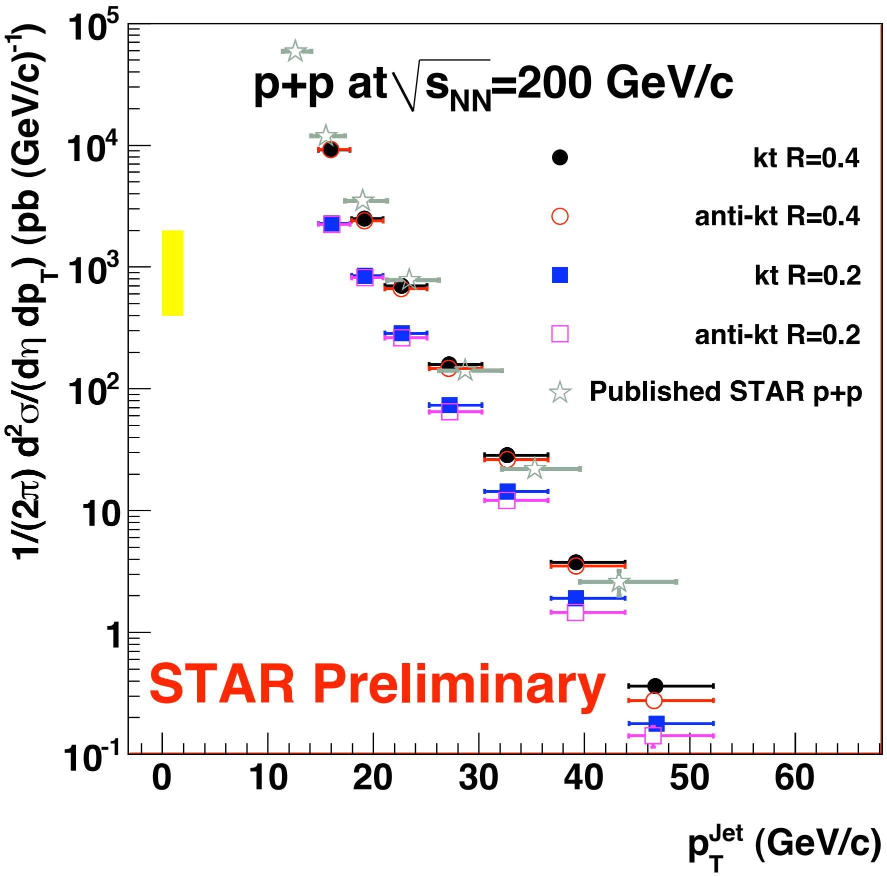


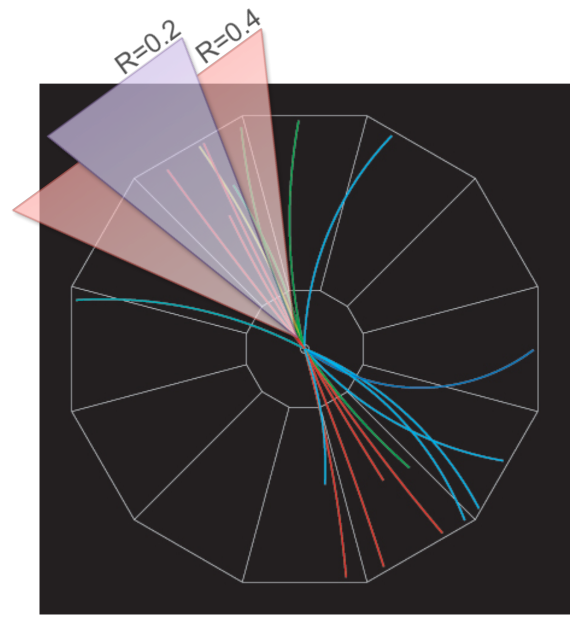


STAR TPC Event Display



Jet cross-sections in p+p at RHIC





Multiple algorithms at different resolution scales:

- Consistent results (within uncertainties)
- Outlook for AA: Systematic understanding of jet reconstruction

p+p: Cross-section ratio R=0.2/R=0.4

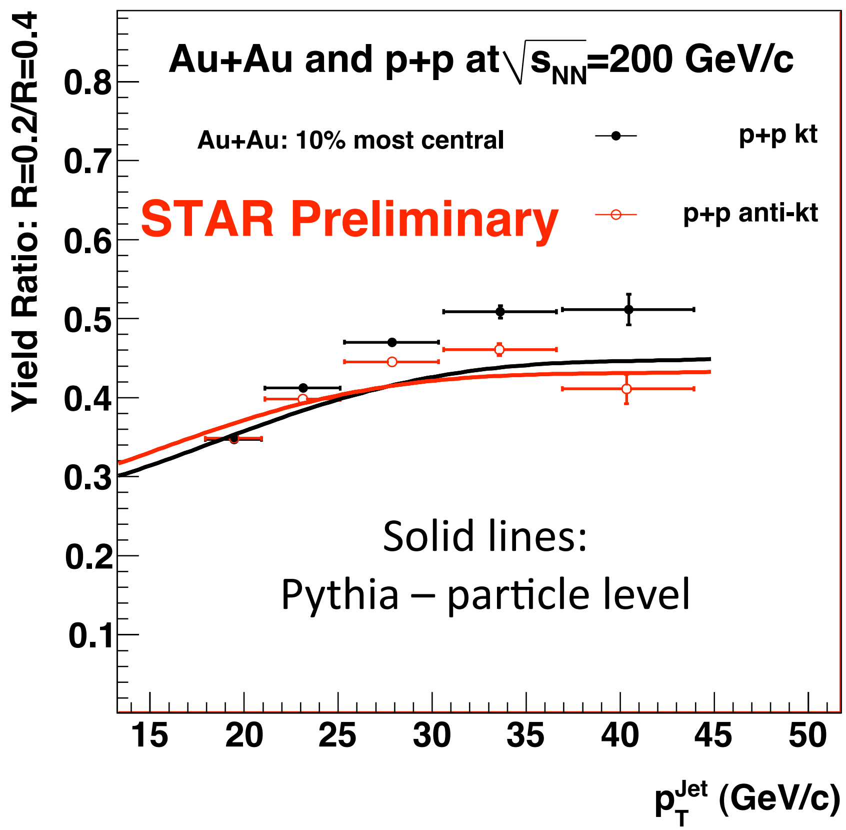
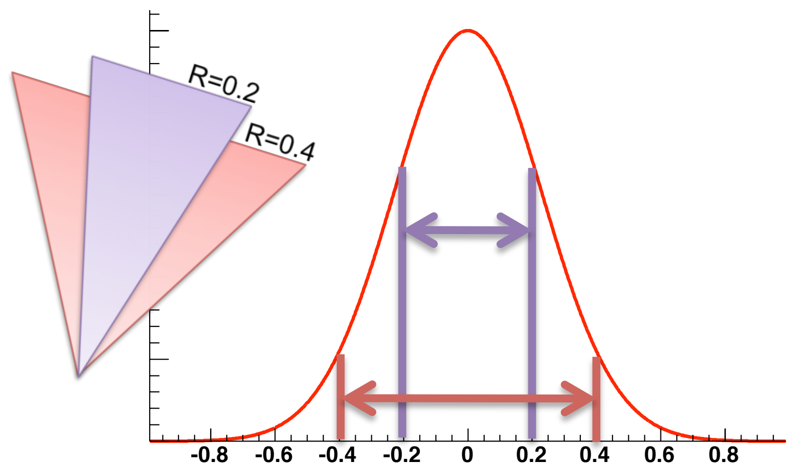
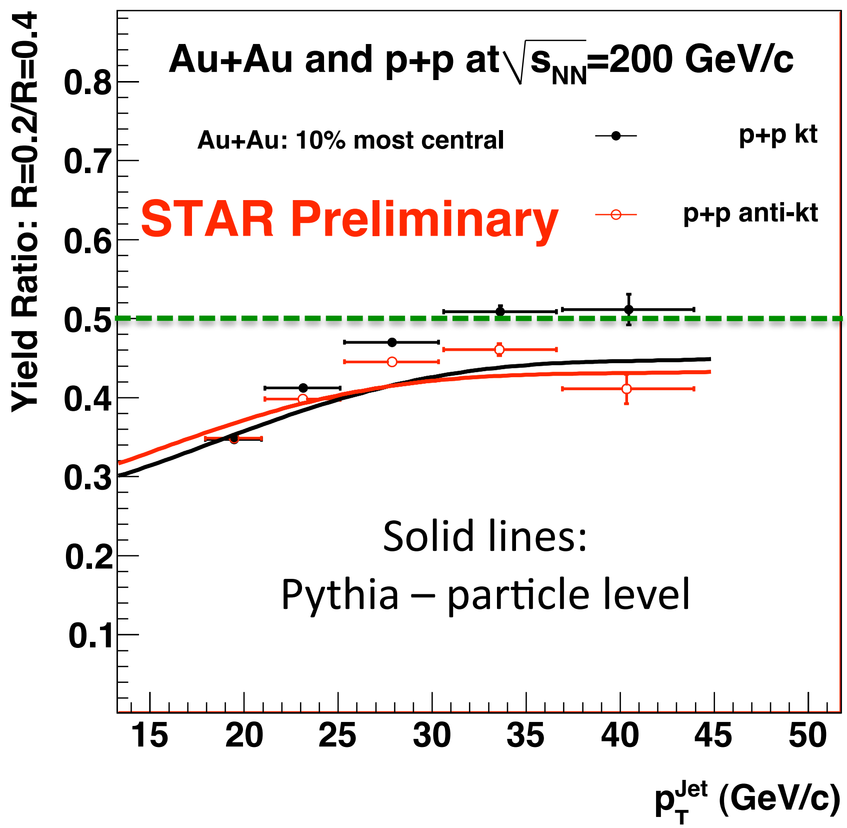


Illustration: Gaussian 1D profile

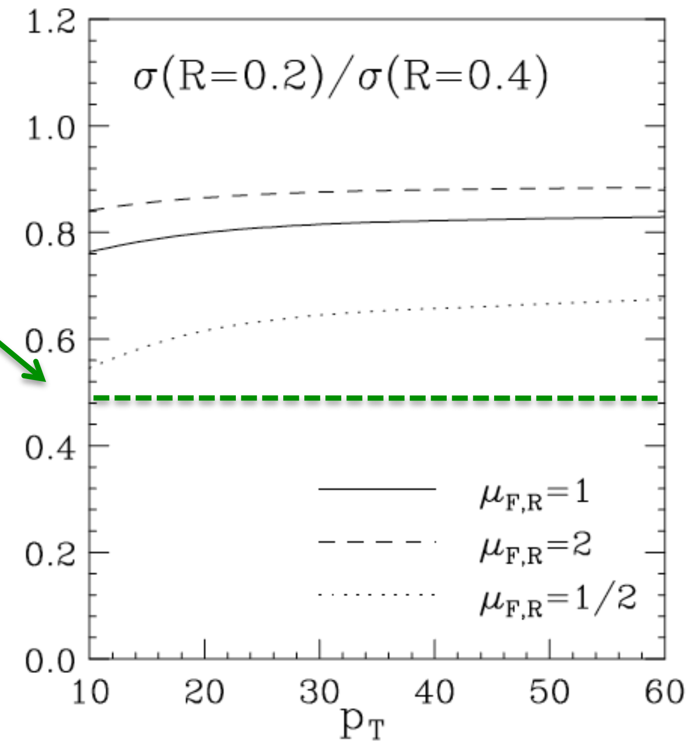


p+p: "Narrowing" of the jet structure with increasing jet energy

p+p: cross-section ratio R=0.2/R=0.4



NLO Calculation
W. Vogelsang – priv. comm. 2009



Narrowing of structure with increasing energy

NLO: narrower jet profile

➔fragmentation+hadronization effects?

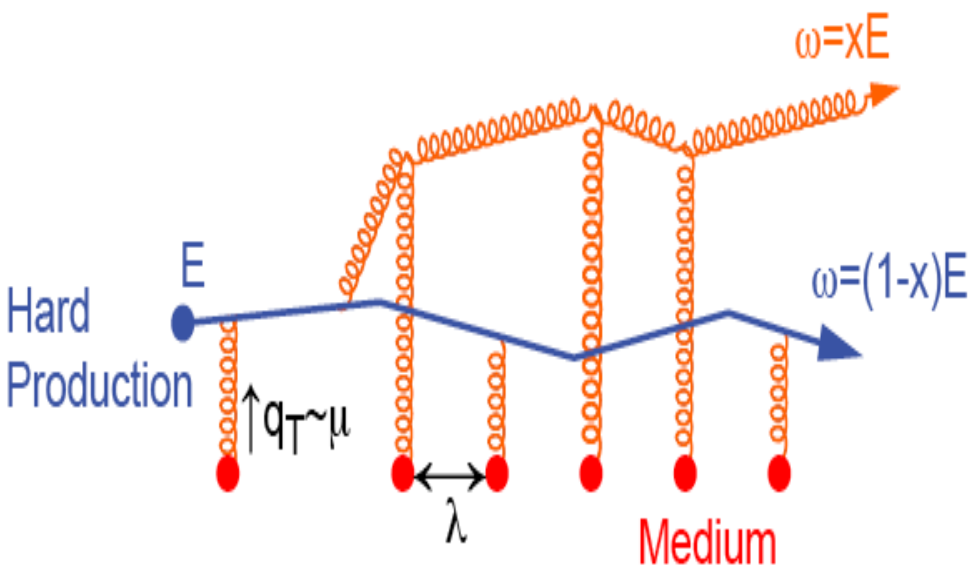
What happens in HI collisions?

Jet-medium interaction

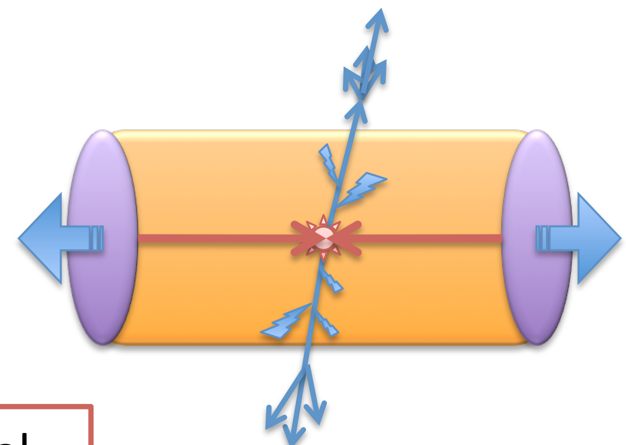
QED: Bremsstrahlung is dominant energy loss mechanism at high energy limit

QCD: High energy partons lose energy via gluon radiation (QCD bremsstrahlung)

Medium characterized by the transport coefficient qhat: squared momentum transfer per unit length (mean free path)



$$\hat{q} \sim \mu^2/\lambda$$



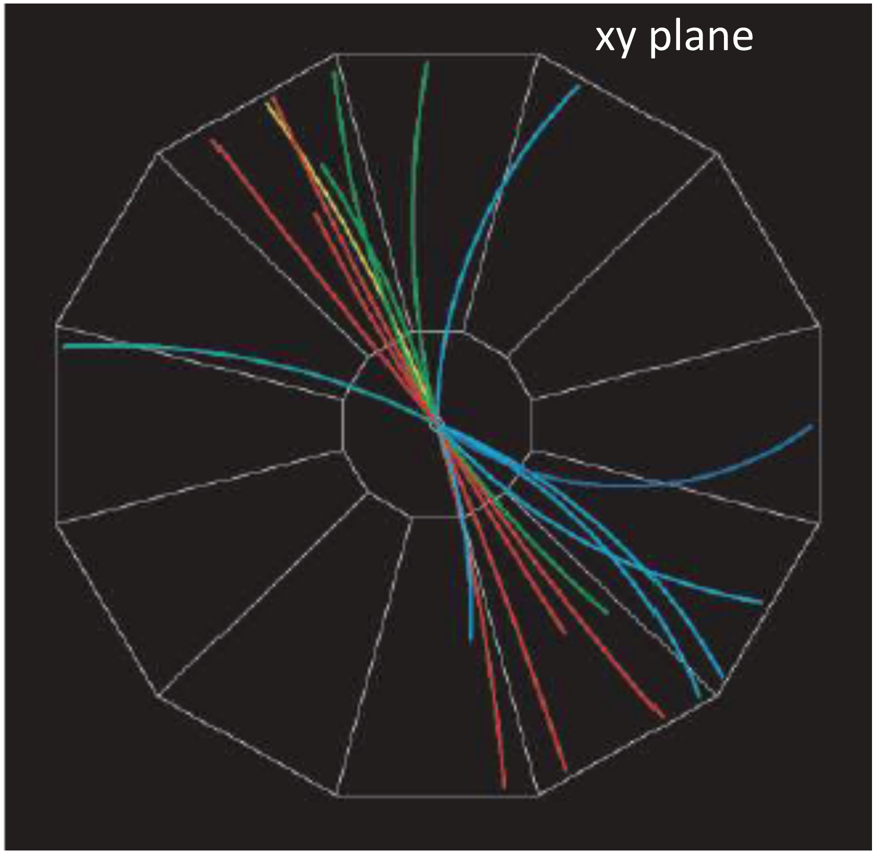
Partonic energy loss in QCD medium is proportional:
- to squared average path length (Note: QED ~ linear)
- to density of the medium

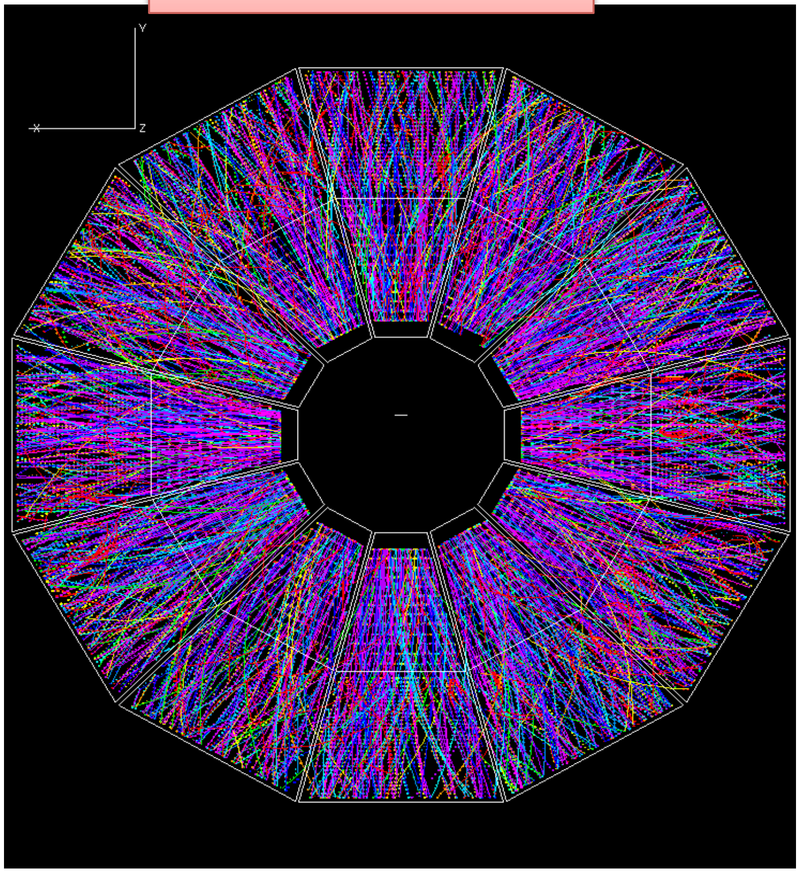
Jet finding in heavy-ion collisions

p+p Collision

Au+Au Collision

STAR TPC Event Display





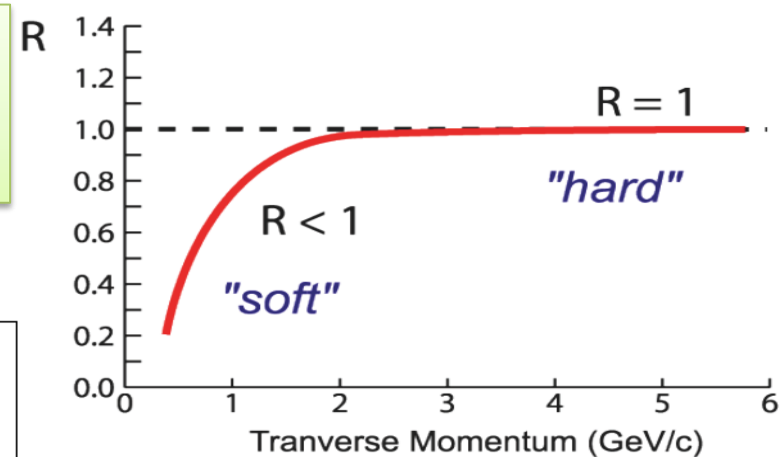
Difficult task -> approximation methods

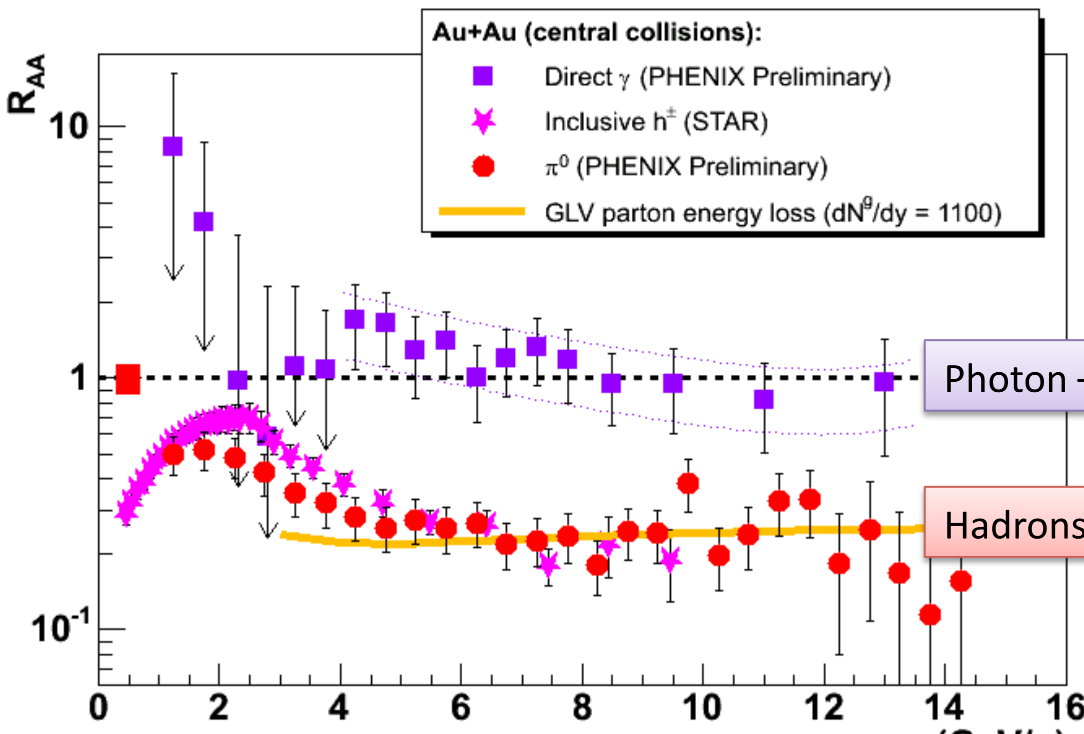
Jet quenching via hadron suppression

$$R_{AB} = \frac{d^2N/dp_t d\eta}{T_{AB} d^2\sigma^{pp}/dp_t d_\eta}$$

$$T_{AB} = < N_{bin} > / \sigma_{inel}^{pp}$$

No "effect":
R < 1 at small momenta
R = 1 at higher momenta where hard processes dominate

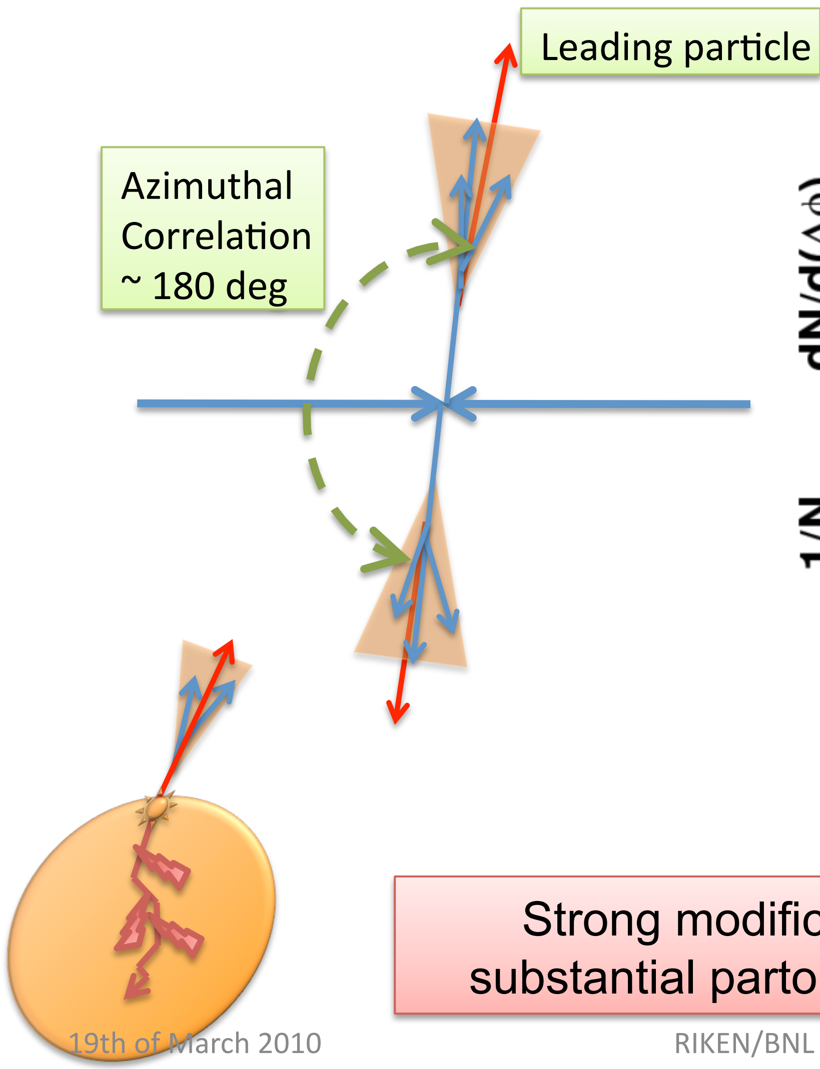


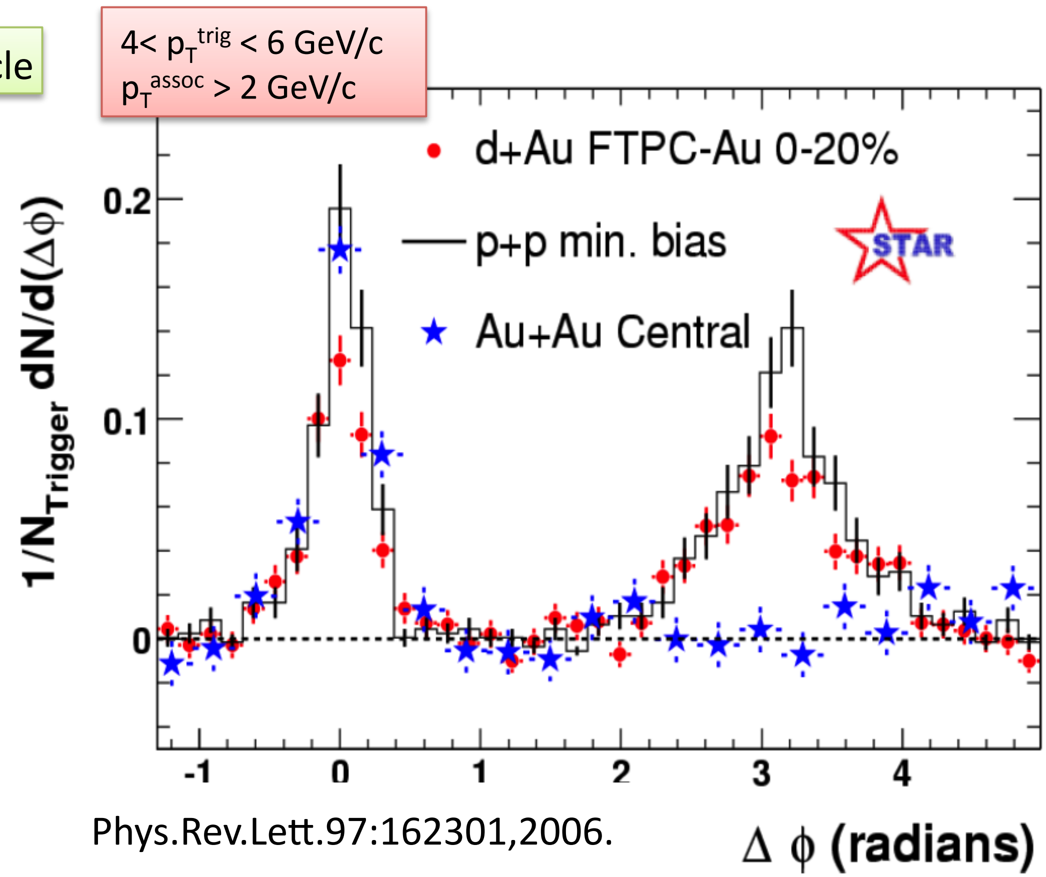


Photon – color neutral probe => No suppresion

Hadrons from color charged jets => Suppression

Jet quenching: recoil jet suppression via leading hadron azimuthal correlations



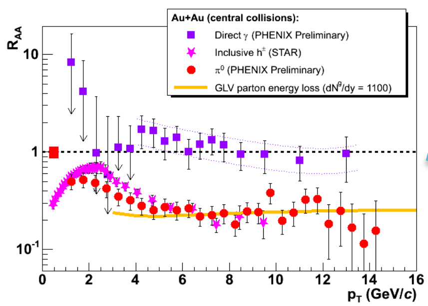


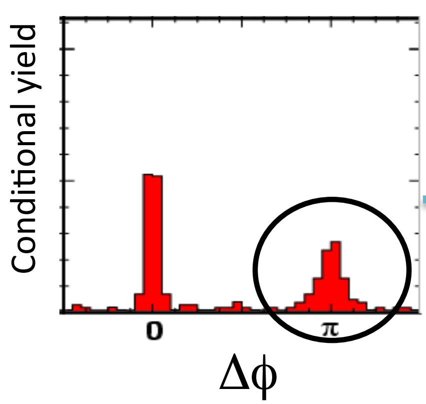
Phys.Rev.Lett.97:162301,2006.

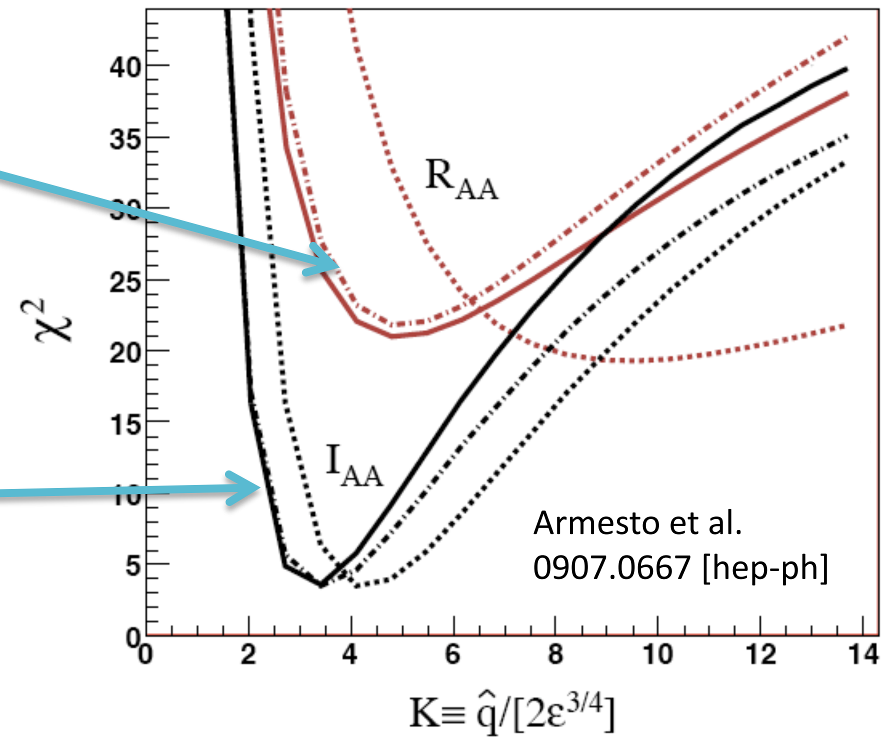
Strong modification of the recoil-jet indicates substantial partonic interaction within the medium

High p_T hadrons: quantitative analysis

Model calculation: ASW quenching weights, detailed geometry
Simultaneous fit to data.

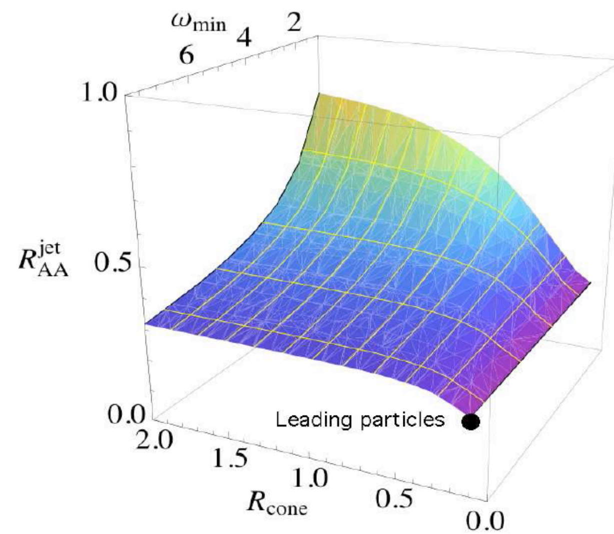






- Reasonably self-consistent fit of independent observables
- Main limitation is the accuracy of the theory
- So what is missing?

Complete Jet Reconstruction in Heavy Ion Collisions: why bother?



Jet quenching is a *partonic* proces

➔obscured by hadronization

High p_T hadron triggers bias towards non-interacting jets

➔suppresses the jet population that interacts the most

➔no access to dynamics of energy loss

Soft hadron correlations (p_T<few GeV/c) are difficult to interpret as QCD jets

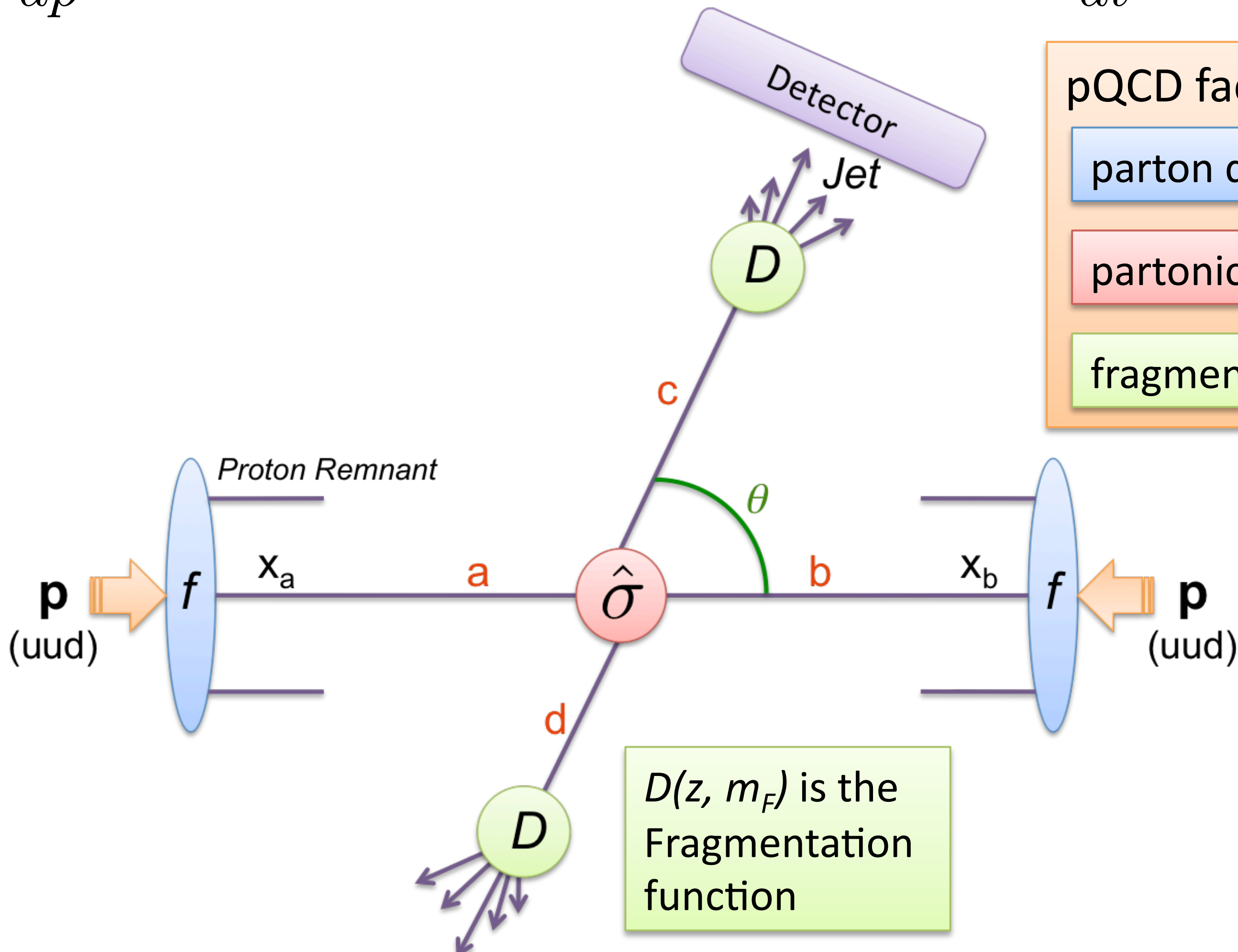
➔requires strong analysis and modeling assumptions

➔ no clear connection to theory

Goal of full jet reconstruction: integrate over hadronic degrees of freedom to measure medium-induced jet modifications at the *partonic* level ➔ much more detailed connection to theory

Hadronic collisions and pQCD. Factorization.

$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \frac{d\hat{\sigma}^{ab\to cd}}{dt} \otimes D_{h/c}(z_c, Q^2)$$



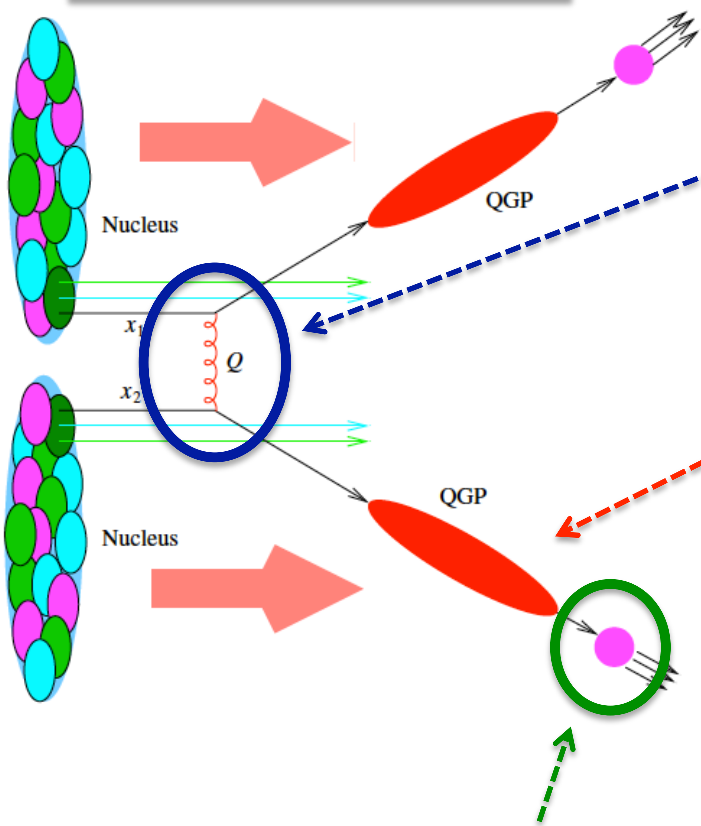
pQCD factorization:

- parton distribution fn $f_{a/A}$
- partonic cross section
- fragmentation fn $D_{h/c}$

D(z, m_F) is the Fragmentation function

Jets in heavy ion collisions: idealization

Factorized picture



production vertex: high Q^2

➔pQCD

Propagation in strongly coupled Quark Gluon Plasma

➔pQCD-based jet quenching

➔hydrodynamics

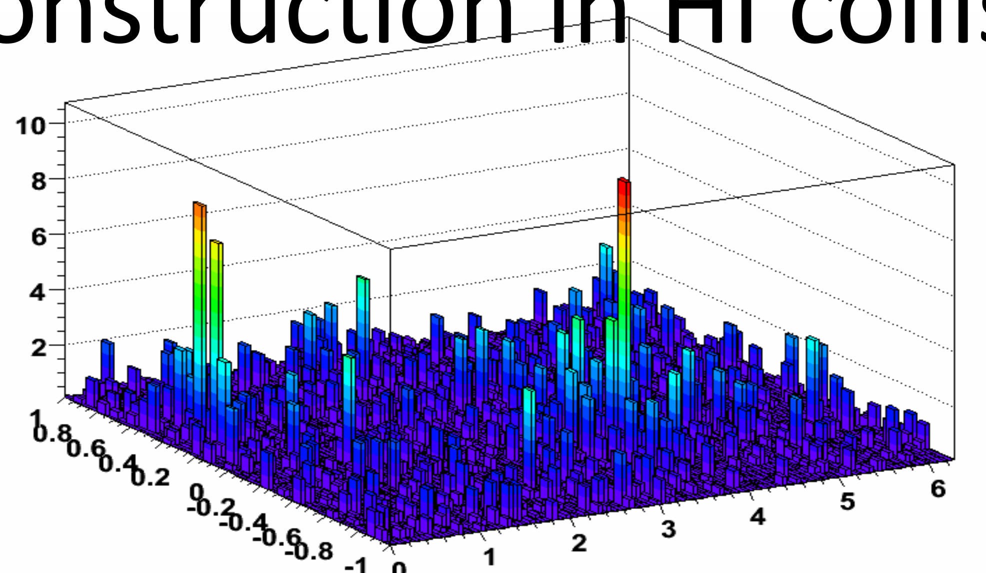
➔AdS/CFT

➔…

Vacuum fragmentation into hadrons

➔non-pert. QCD

Towards the full jet reconstruction in HI collisions

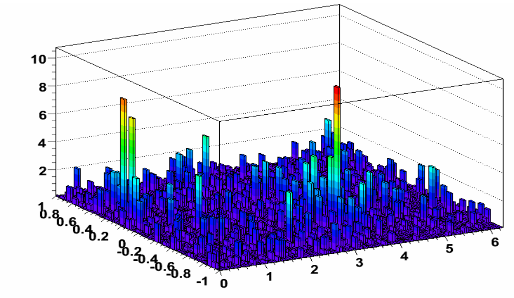


Data from Star: single event; central Au+Au @ 200 GeV

HI Jet Reconstruction: strategy

What we have learned over the past two years:
"anti-quenching" biases lurk everywhere!

1. Detector level trigger (high-pT single particle)
2. Seeded reconstruction algorithms
3. Track and tower p_T cuts to suppress background



No shortcuts: we have to face the full event background and its fluctuations head-on

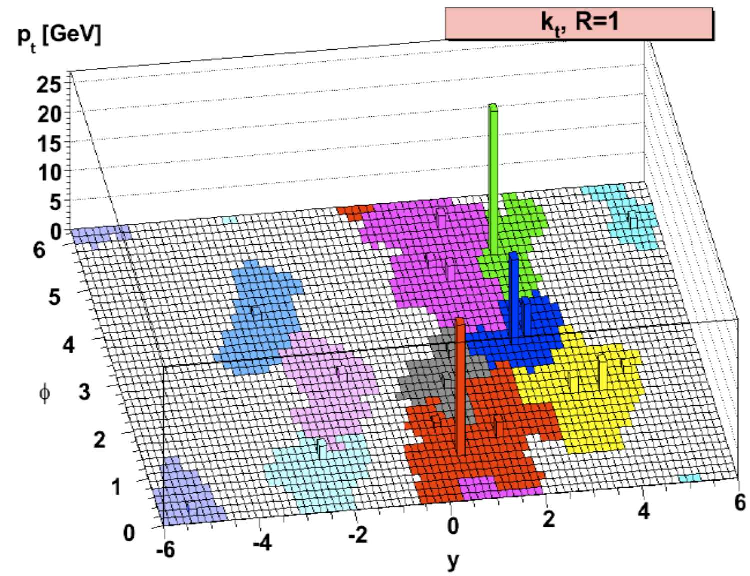
- complex interplay between event background and jet signal

Need multiple *independent* background correction schemes to assess systematics

- more is better than few, but must be independent
- no shortcuts: corrections depend on observable

Modern algorithms

- Collinear and infrared safe
- Improved performance
- Rigorous definition of jet area
- Different algorithms -> different response to the underlying event
  - Developed for uniform bg subtraction (pile-up) at LHC
  - ρ: median pT per unit area of the diffuse background in an event – measured using background *"jets"* as found by kT algorithm
  - δρ: uncertainty due to noise fluctuations – non-uniformity of the event background



$$p_T^{\mathrm{Meas}} = p_T^{\mathrm{Cand}} - \rho \times \mathrm{Area}$$

$$\frac{dN^{\mathrm{Meas}}}{dp_T} = \frac{dN^{\mathrm{True}}}{dp_T} \otimes f^{\mathrm{Resol}}(\delta\rho)$$

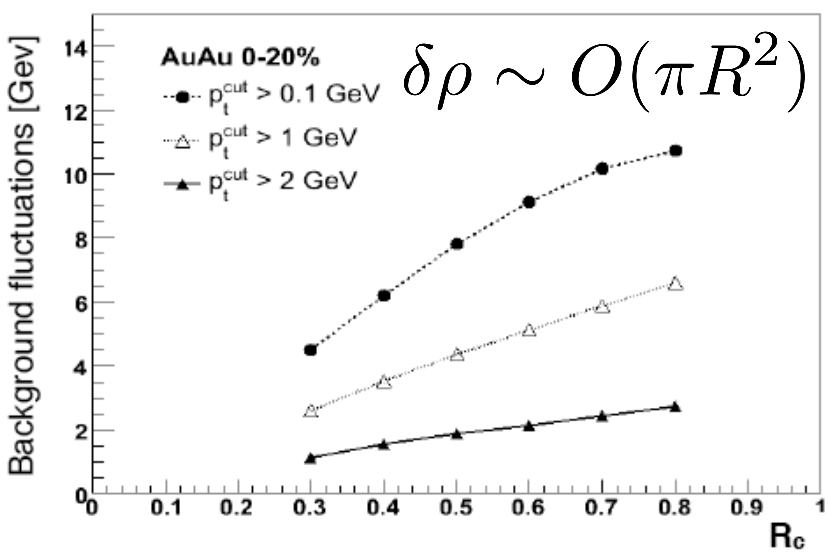
M. Cacciari, G. Salam, G. Soyez JHEP 0804:063,2008. e-Print: arXiv:0802.1189 [hep-ph]
M. Cacciari, G.Salam Phys.Lett.B659:119-126,2008. e-Print: arXiv:0707.1378 [hep-ph]

Jet pT irresolution due to HI background

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

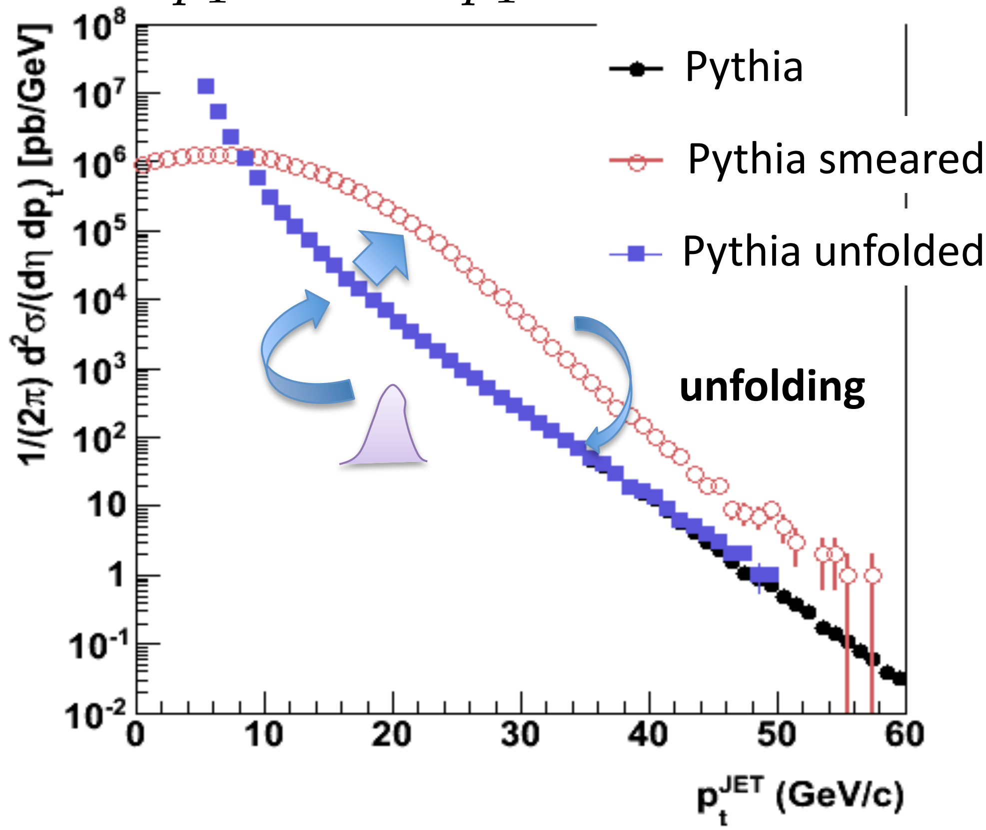
Correct via "unfolding": inversion of full bin-migration matrix

Check numerical stability of procedure using jet spectrum shape from PYTHIA



$$\delta\rho \sim O(\pi R^2)$$

$$\frac{dN^{\rm Meas}}{dp_T} = \frac{dN^{\rm True}}{dp_T} \otimes f^{\rm Resol}(\delta\rho)$$



Procedure must be numerically stable
Correction depends critically on background model → main systematic uncertainty for HI

HI Jet Reconstruction: observables

Primary observables (jets):

- Cross sections vs p+p
- Cross sections vs R: Energy redistribution (aka jet broadening)
- h+jet and jet+jet coincidences
- subjet distributions
- ....

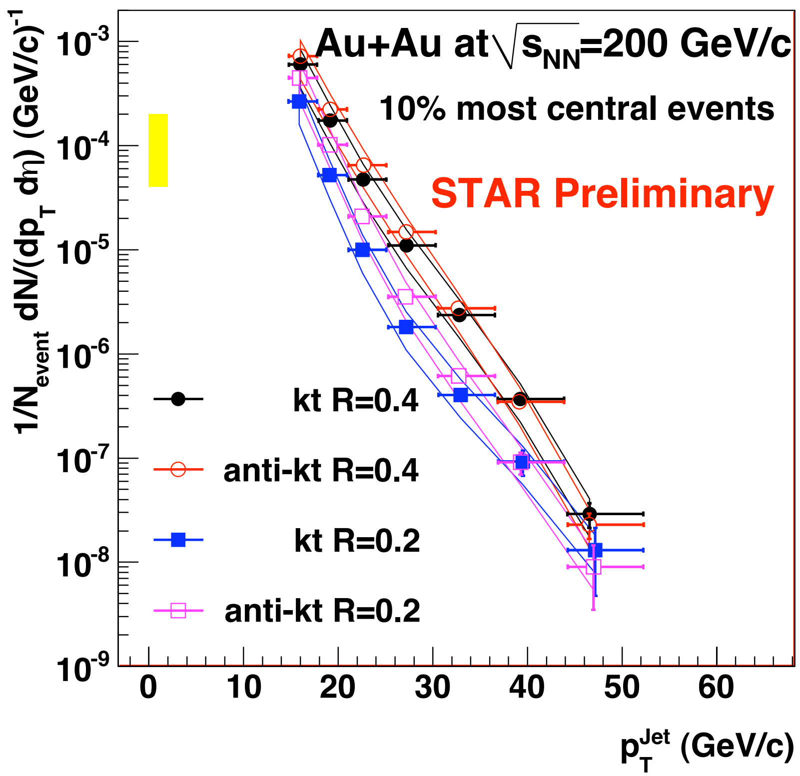
Note: in HI collisions we should very little rely on kinematics since E is smeared. Counting is more robust!

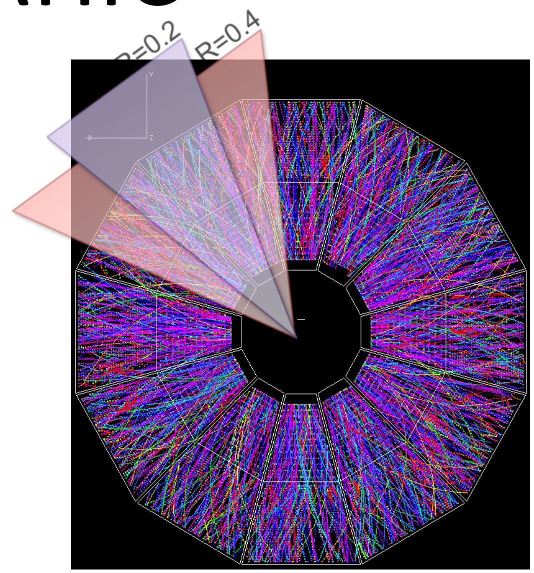
Secondary observables (hadrons):

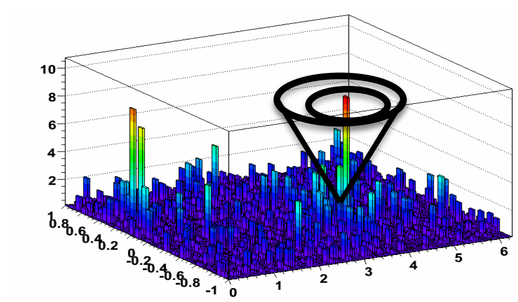
- longitudinal momentum distributions (which are not "fragmentation functions")
- Transverse momentum distributions (j_T)
- .....

E. Bruna [STAR] Nucl.Phys.A830:267c-270c,2009
H. Caines [STAR] Nucl.Phys.A830:263c-266c,2009; arXiv:0911.3211v1 [nucl-ex]
M.P. [STAR] Nucl.Phys.A830:255c-258c,2009
Y.-S. Lai [PHENIX] Nucl.Phys.A830:251c-254c,2009; arXiv:0911.3399v1 [nucl-ex]

Jet production cross-sections in HI Collisions at RHIC

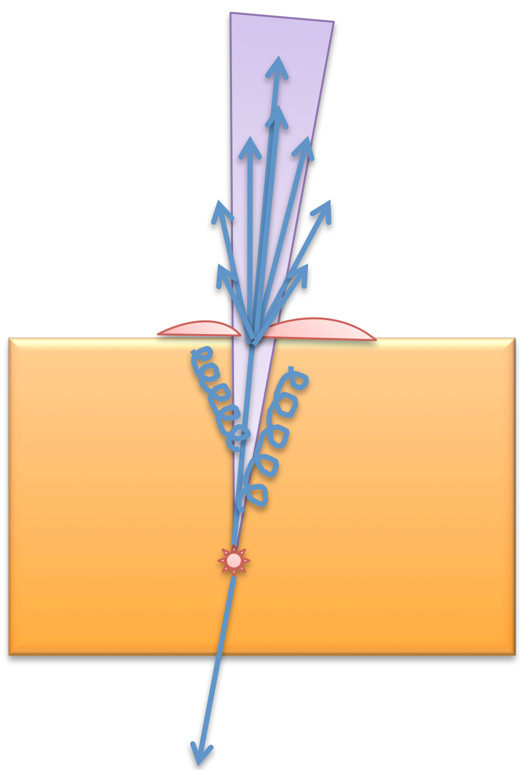






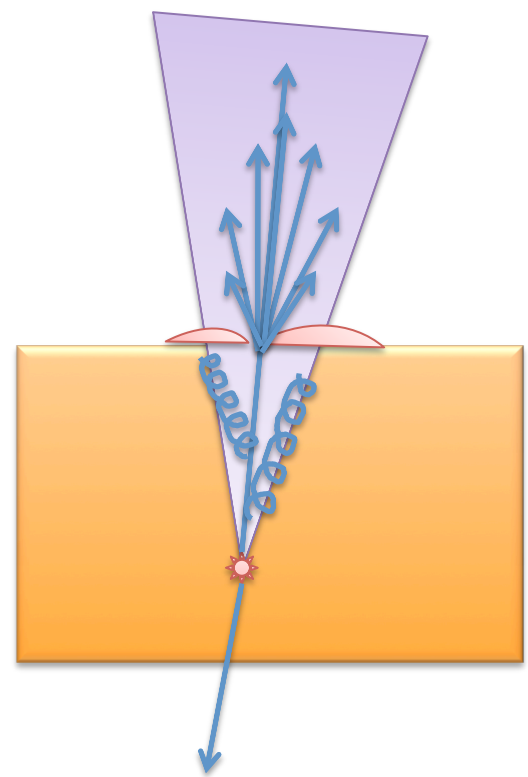
Why we compare different R?

Measure A: vacuum fragmentation



Jet core: vacuum fragmentation
Energy deficit ⇔ Loss of x-section for fixed E

Measure B: vacuum fragmentation
+ medium induced radiation



Modified "fragmentation" pattern?
Full jet energy? ⇔ Full x-section

Au+Au: cross-section ratio R=0.2/R=0.4

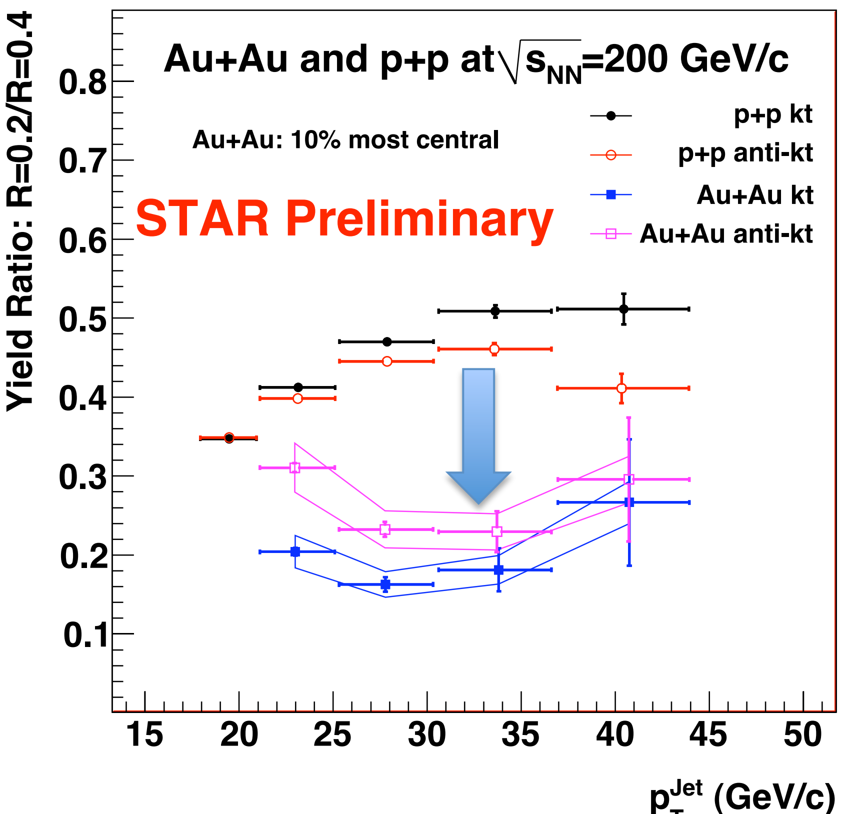
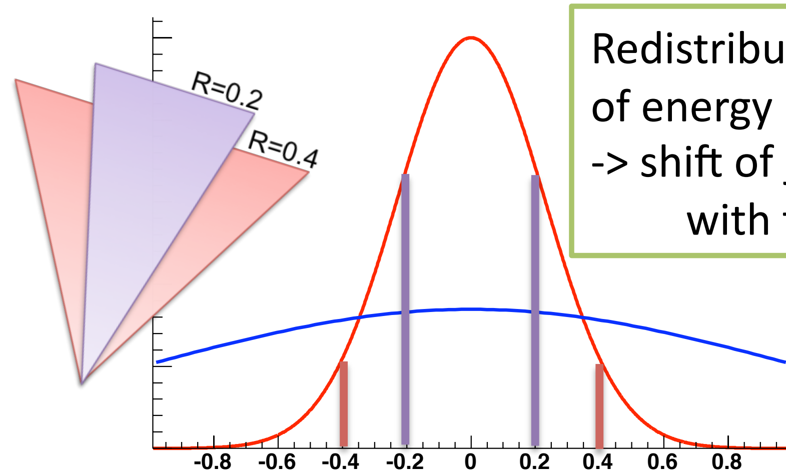


Illustration: Gaussian 1D profile



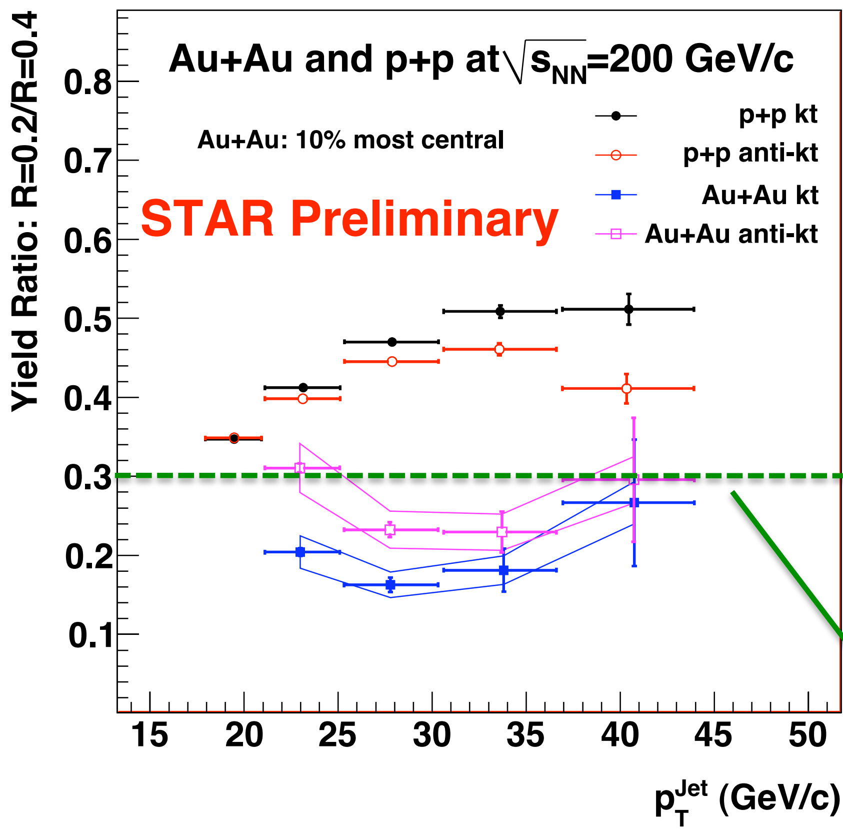
Redistribution of energy results in -> shift of jets p_T with fixed R

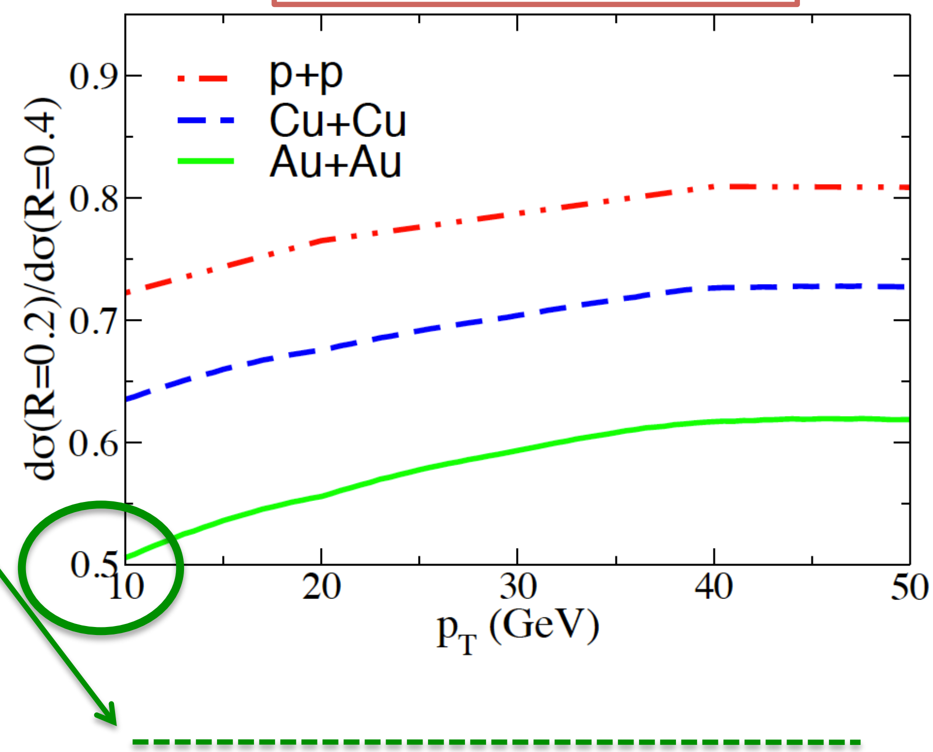
RED: p+p
BLUE: Au+Au

Marked suppression of ratio relative to p+p
- ➔ medium-induced jet broadening
- ➔ now observed with full jets, not hadron correlations

Au+Au: cross-section ratio R=0.2/R=0.4

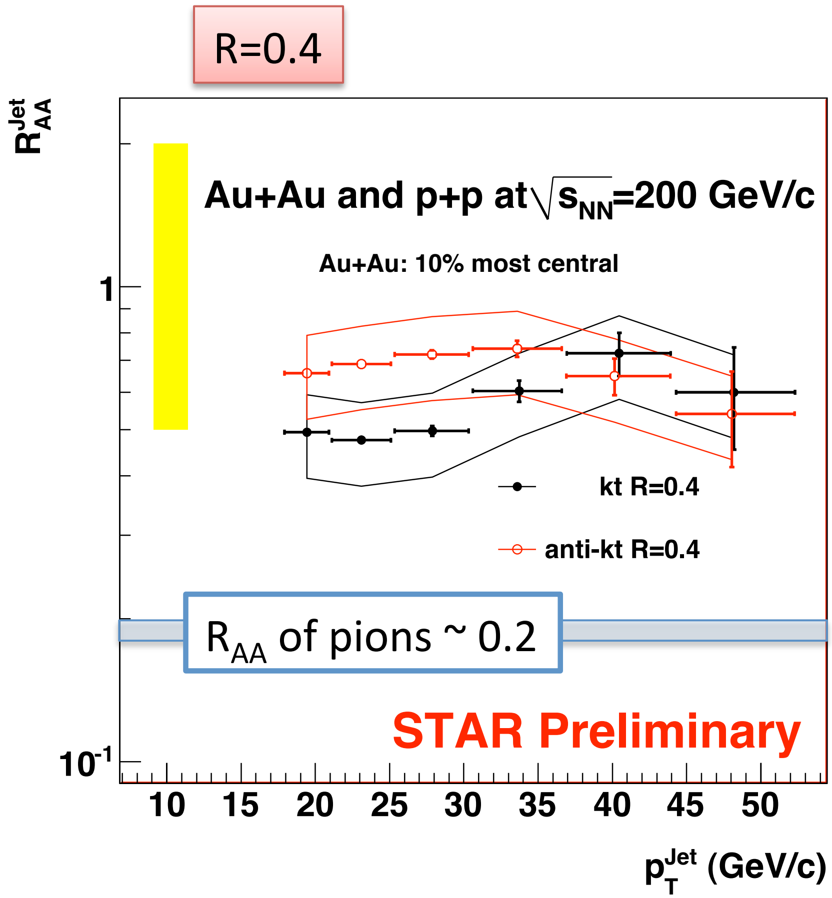
NLO Calculation
B.-W. Zhang and I. Vitev
priv. comm. 2009

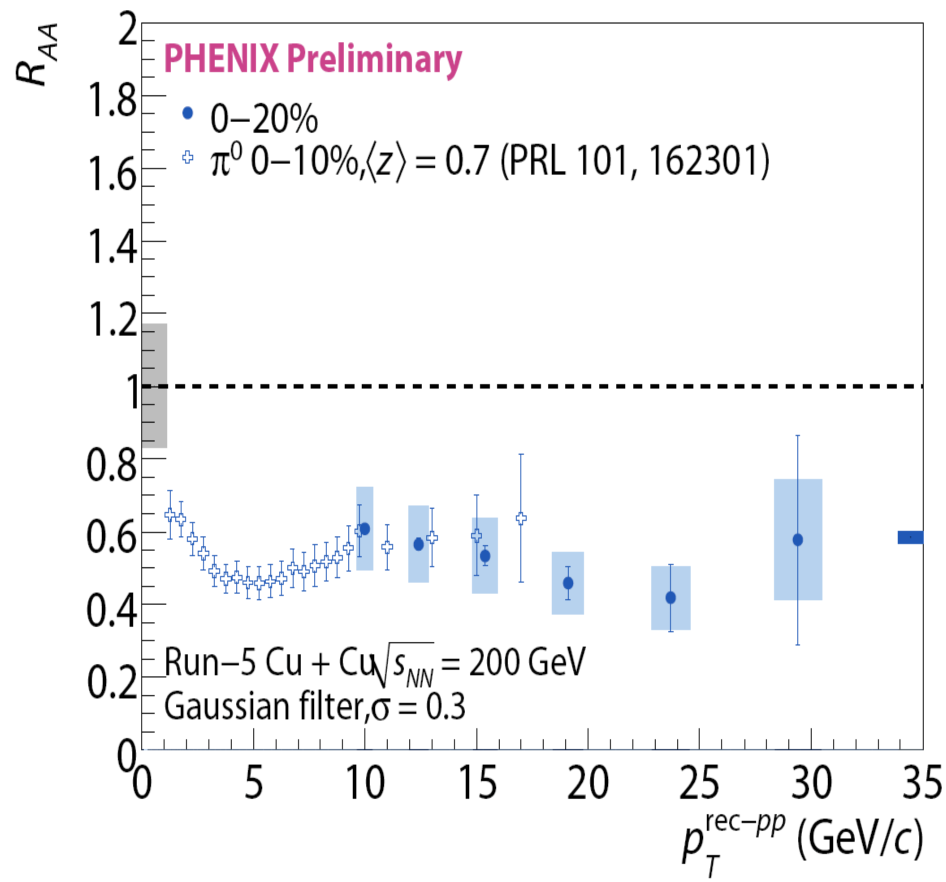




Stronger broadening seen in measurement than NLO calculation…
➔strong hadronization effects? (that would be unfortunate)

Jet R_{AA}





- $R_{AA} < 1$: full jet cross-section not recovered ➔jet broadening
- But systematically difficult measurement

Eur. Phys. J. C (2009) 63: 679–690
DOI 10.1140/epjc/s10052-009-1133-9

THE EUROPEAN PHYSICAL JOURNAL C

Special Article - Tools for Experiment and Theory

Q-PYTHIA: a medium-modified implementation of final state radiation

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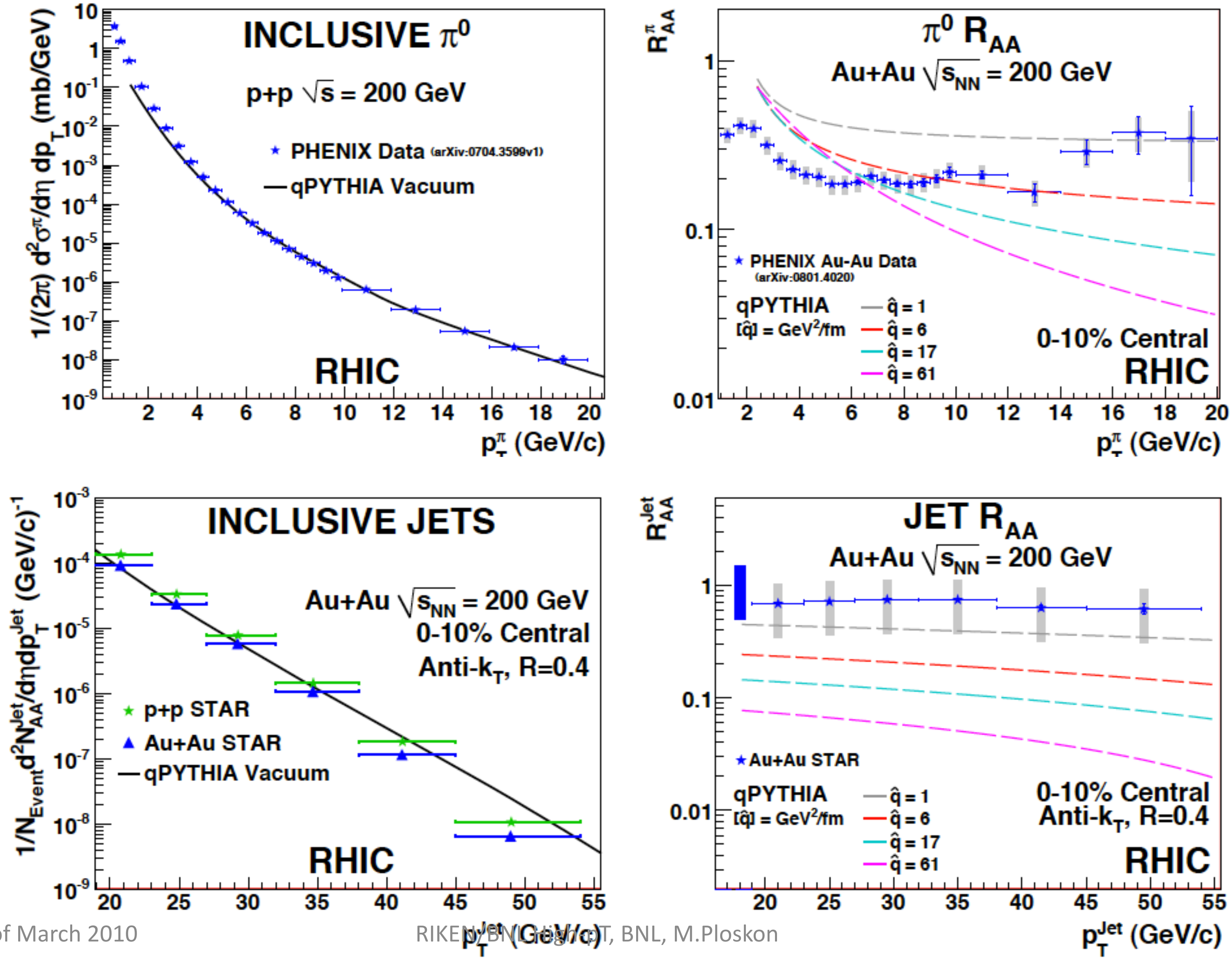
[2]Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, 00044 Frascati (Roma), Italy

qPYTHIA is the only publically released code at present…

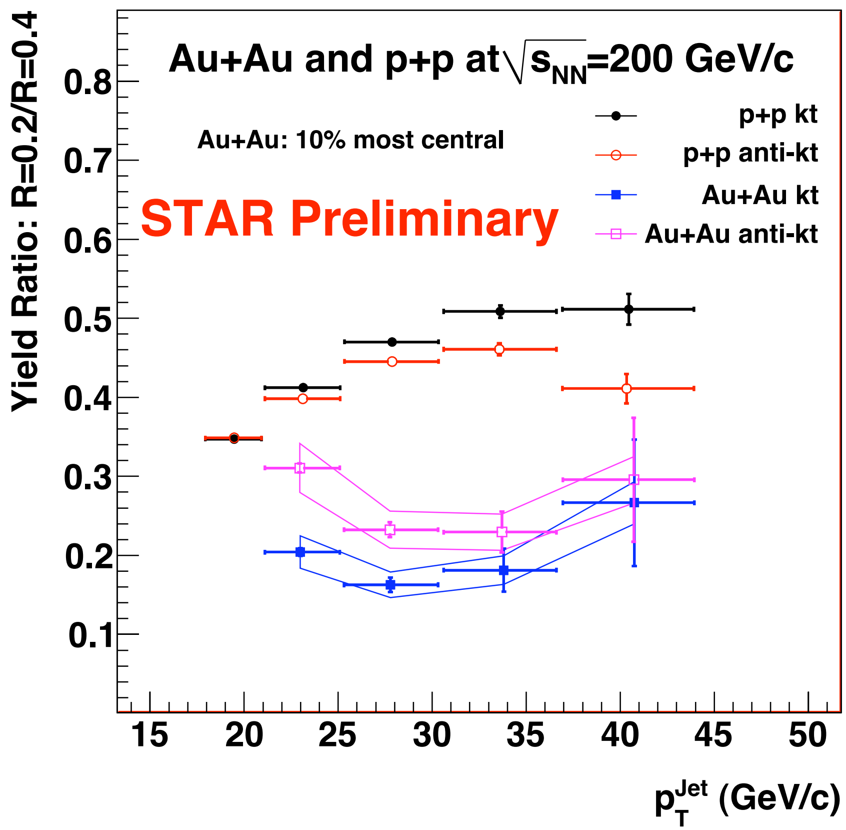
(Collision geometry: Glauber calculation (~PQM))

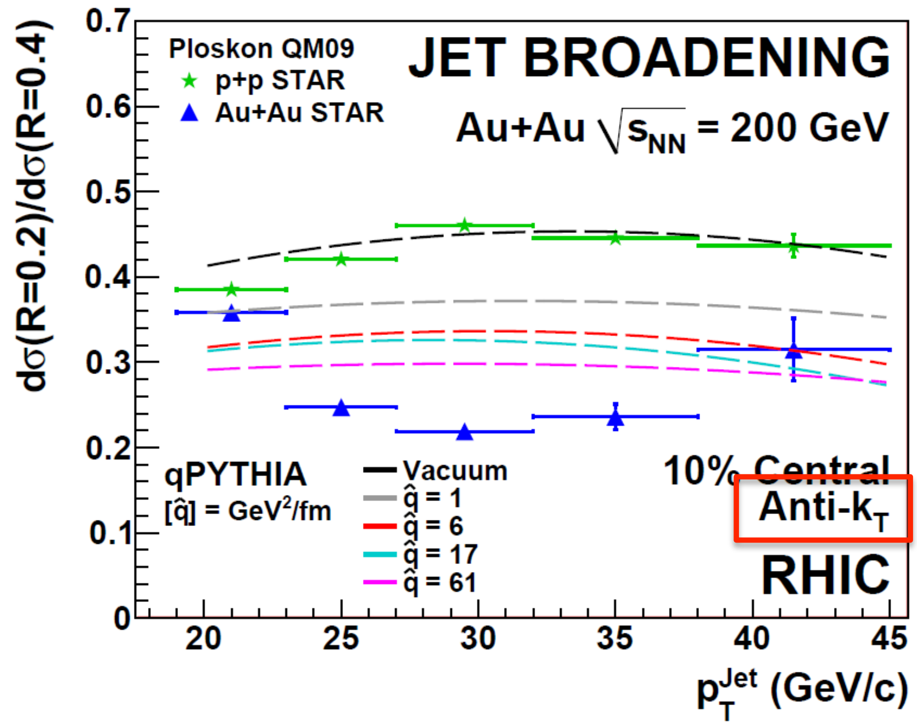
qPYTHIA vs RHIC data

B. Fenton-Olsen, LBNL



Au+Au: cross-section ratio R=0.2/R=0.4

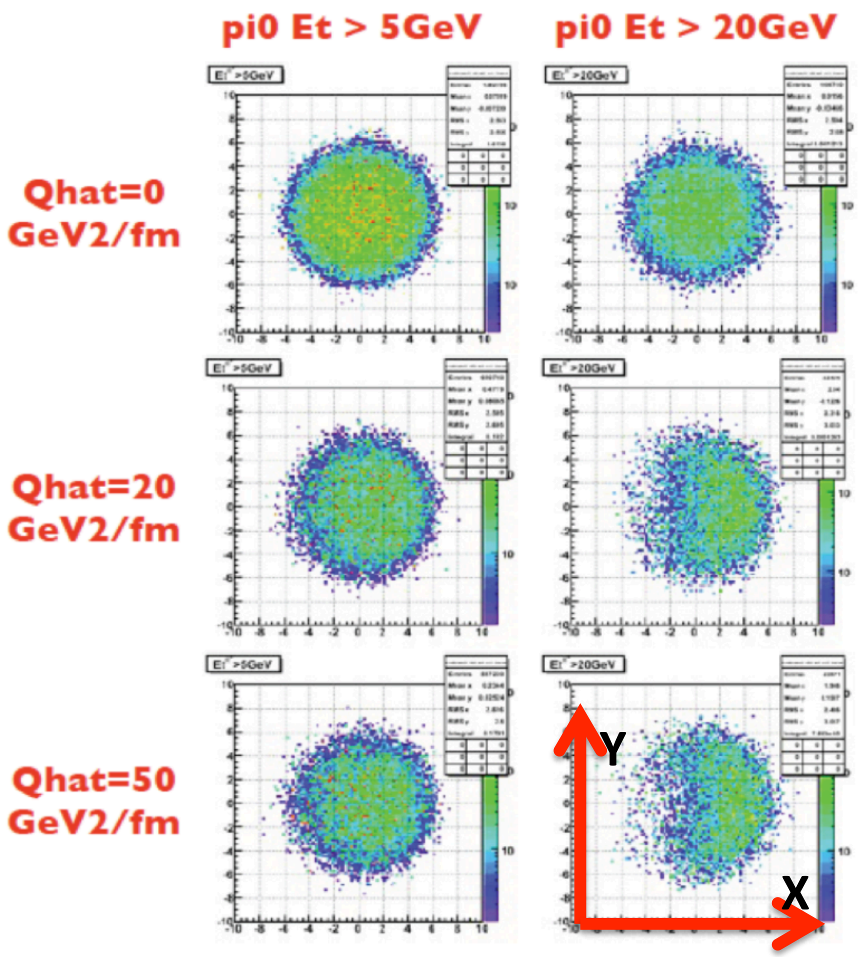


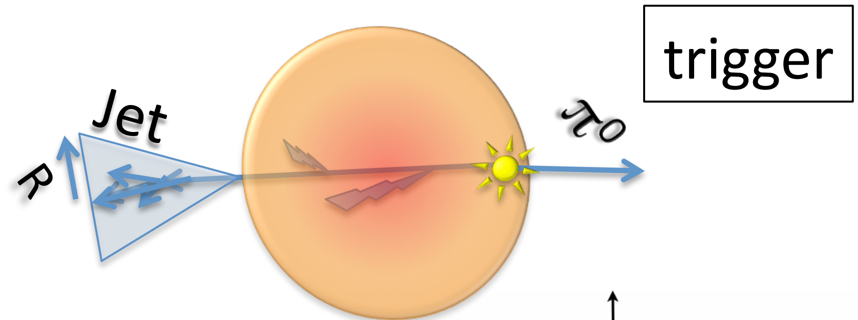


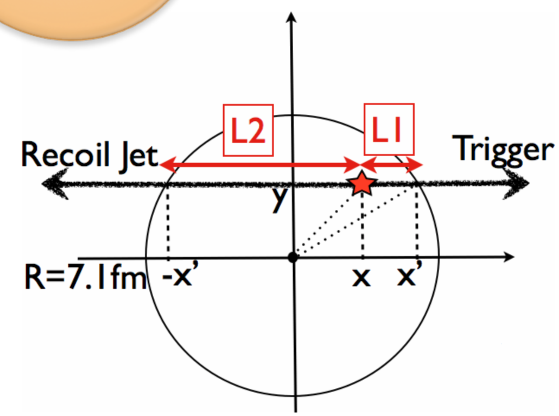
Stronger broadening seen in measurement than qPythia
- more suppression (smaller R_{AA}) and less broadening that observed

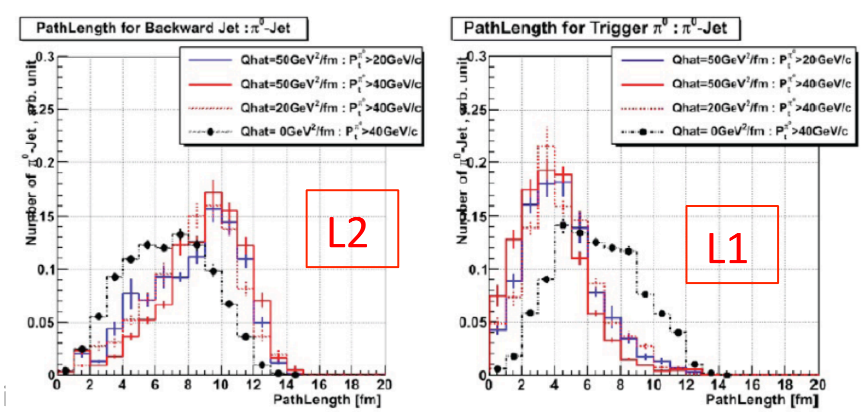
Next generation measurement: controlled variation of jet path length

Calculation: qPYTHIA



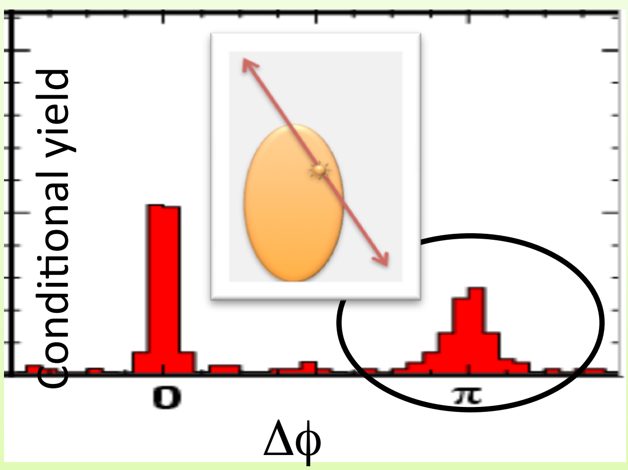


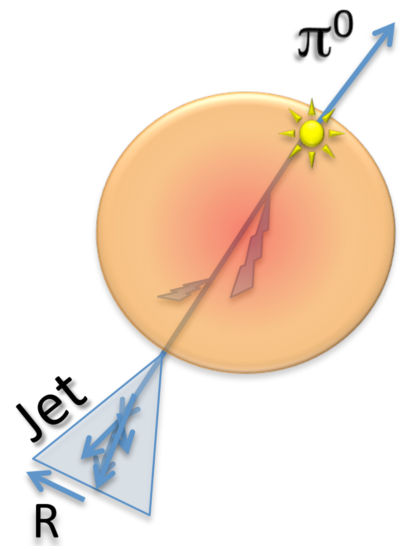


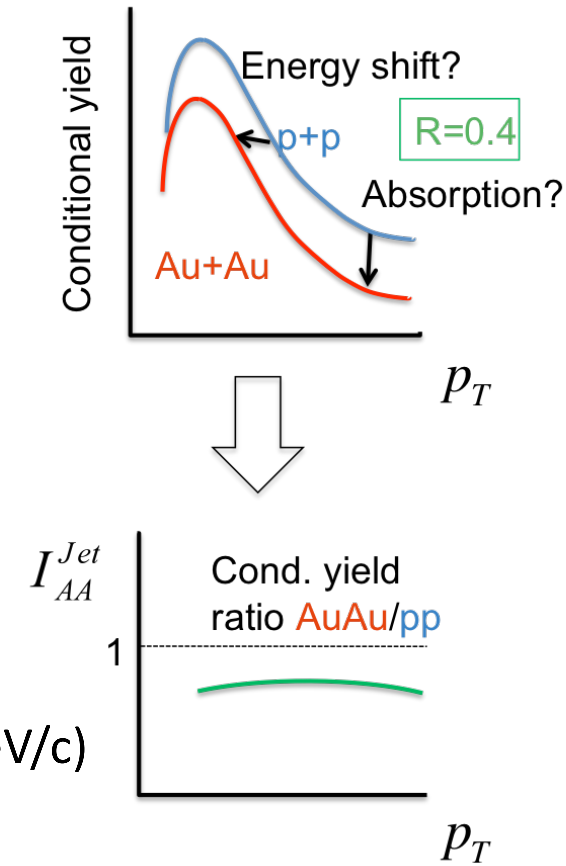


Hadron-jet coincidence

STAR high pT dihadrons: bias towards non-interacting jet population



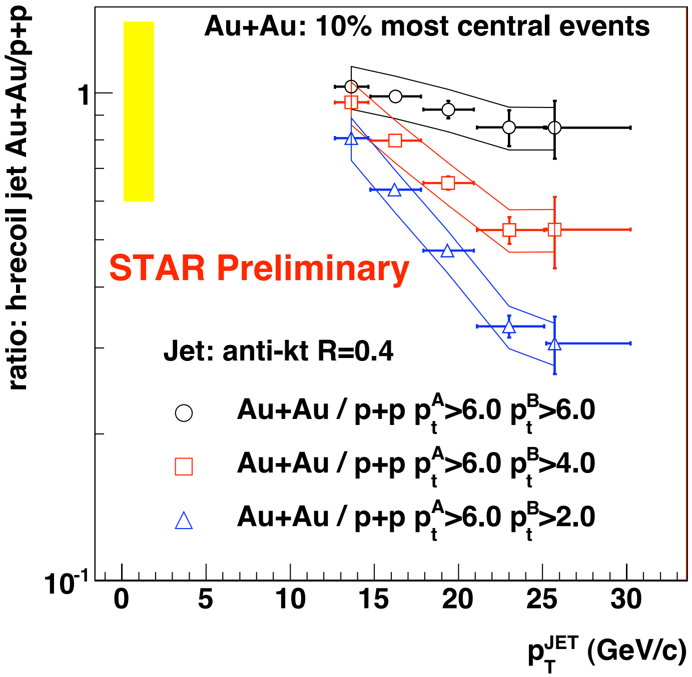


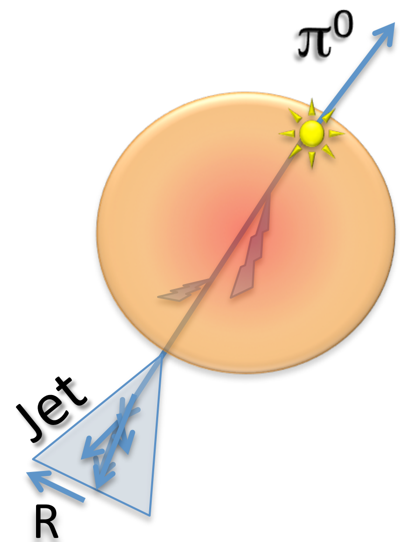


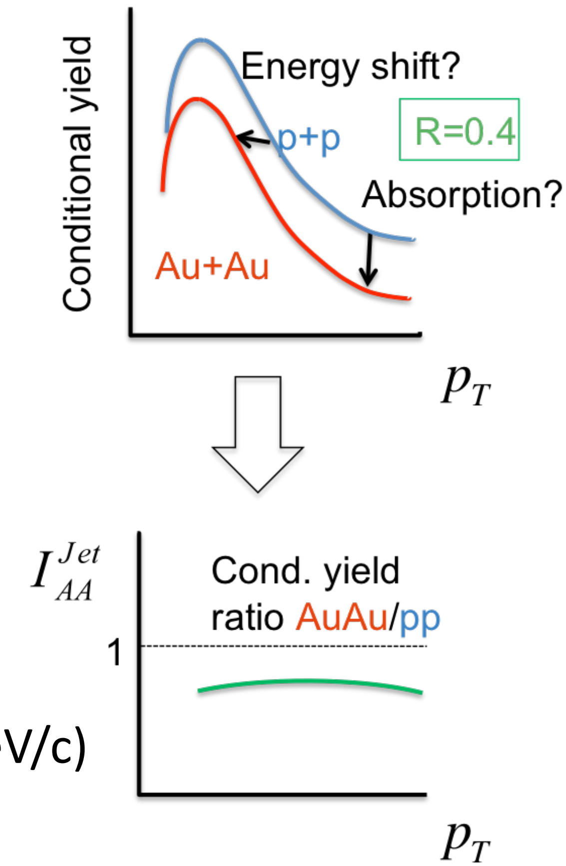
- Trigger on hard, leading π^0 (p_T>6 GeV/c)
    - 3x3 tower cluster in BEMC
- Construct spectrum of recoil jets
    - normalized per di-hadron trigger

This event selection will ***maximize*** the recoil path length distribution in matter

Hadron-jet coincidence







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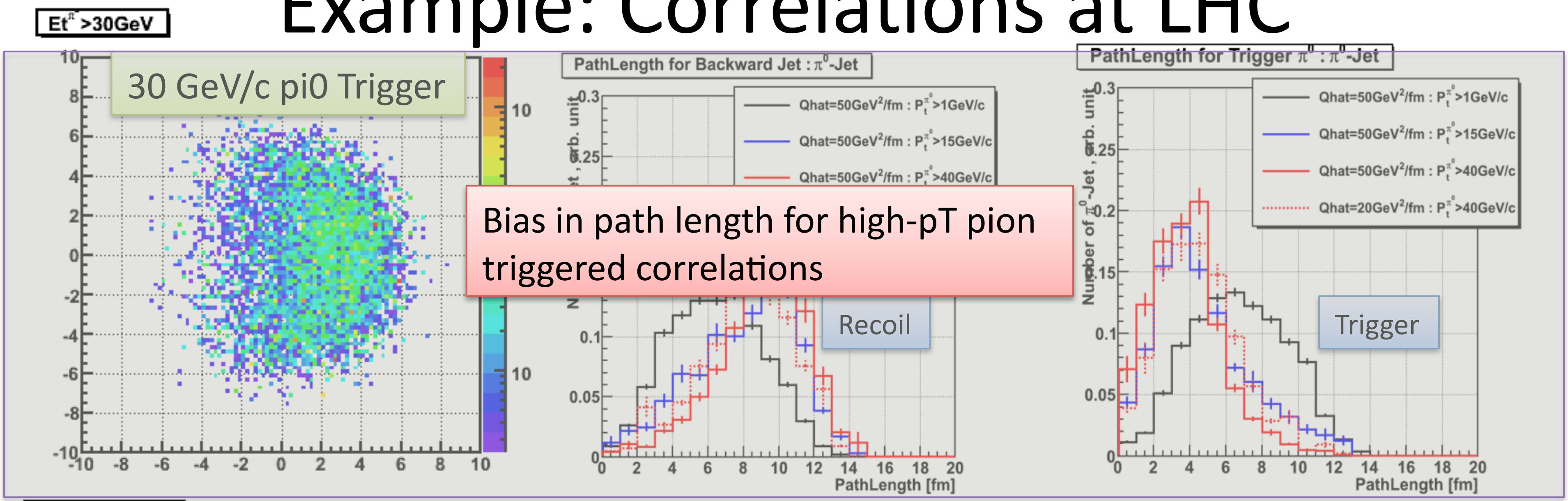
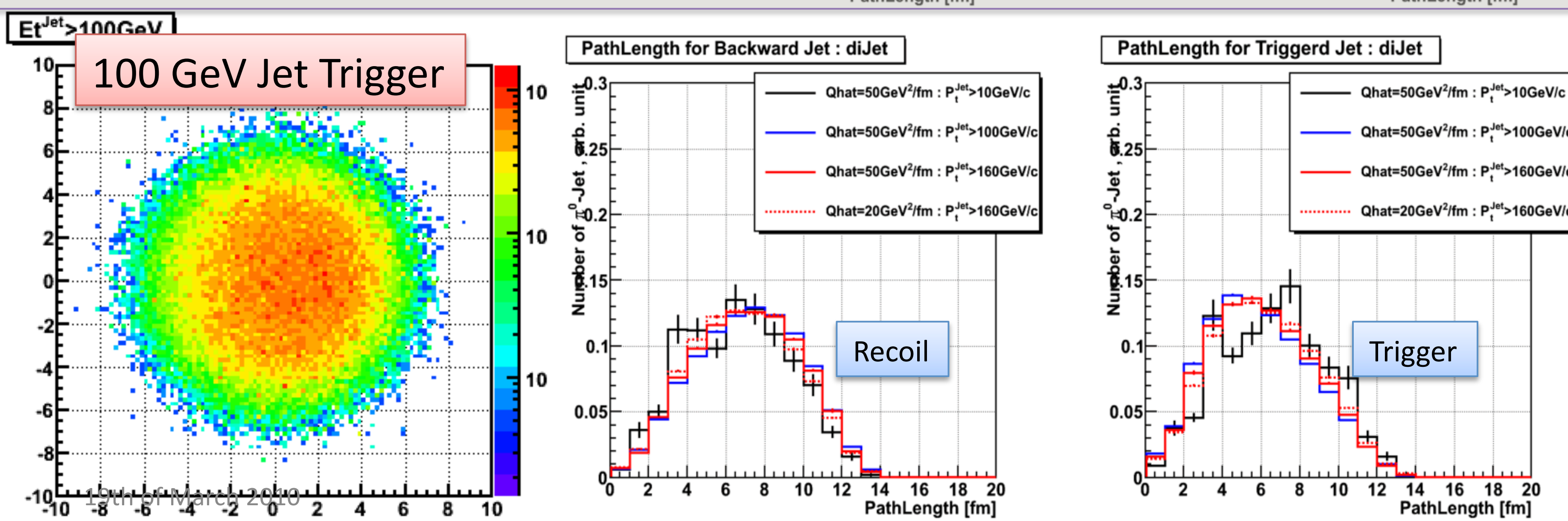
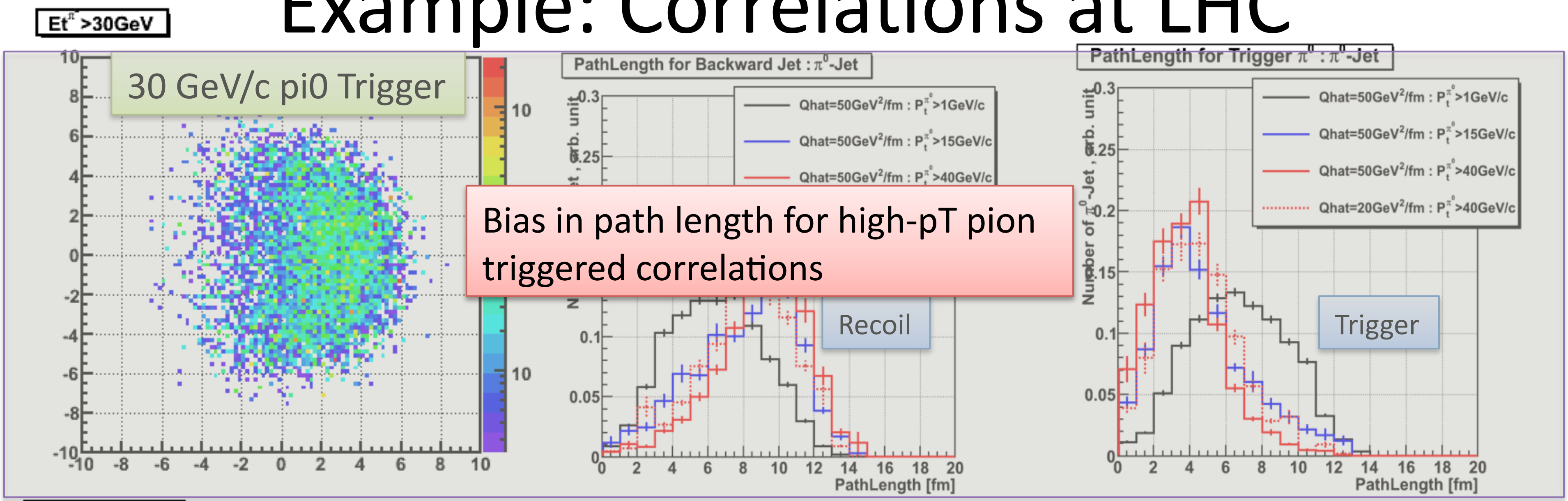
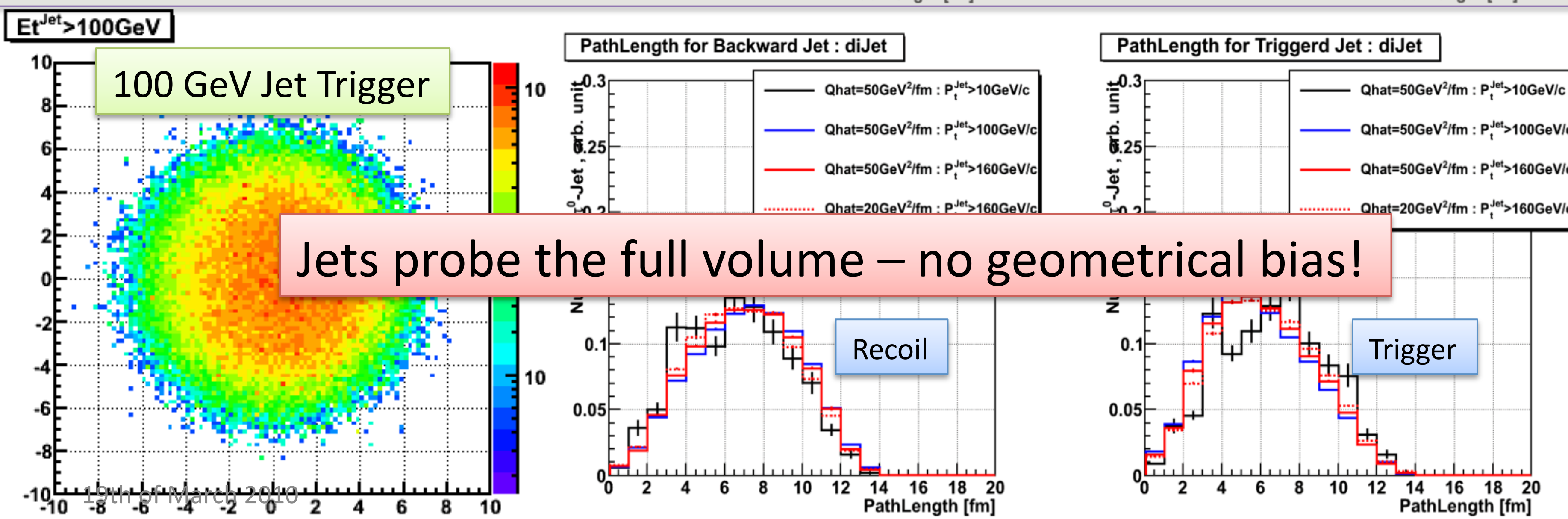
Model study: Geometrical bias. Example: Correlations at LHC



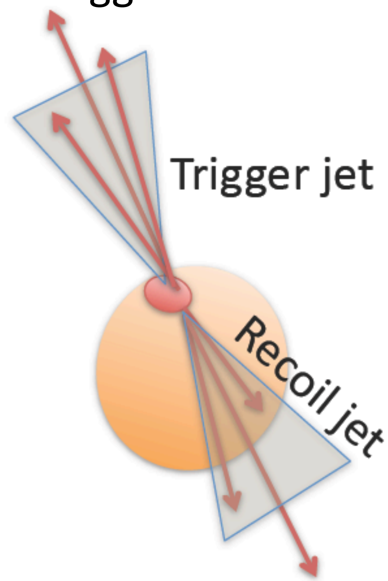


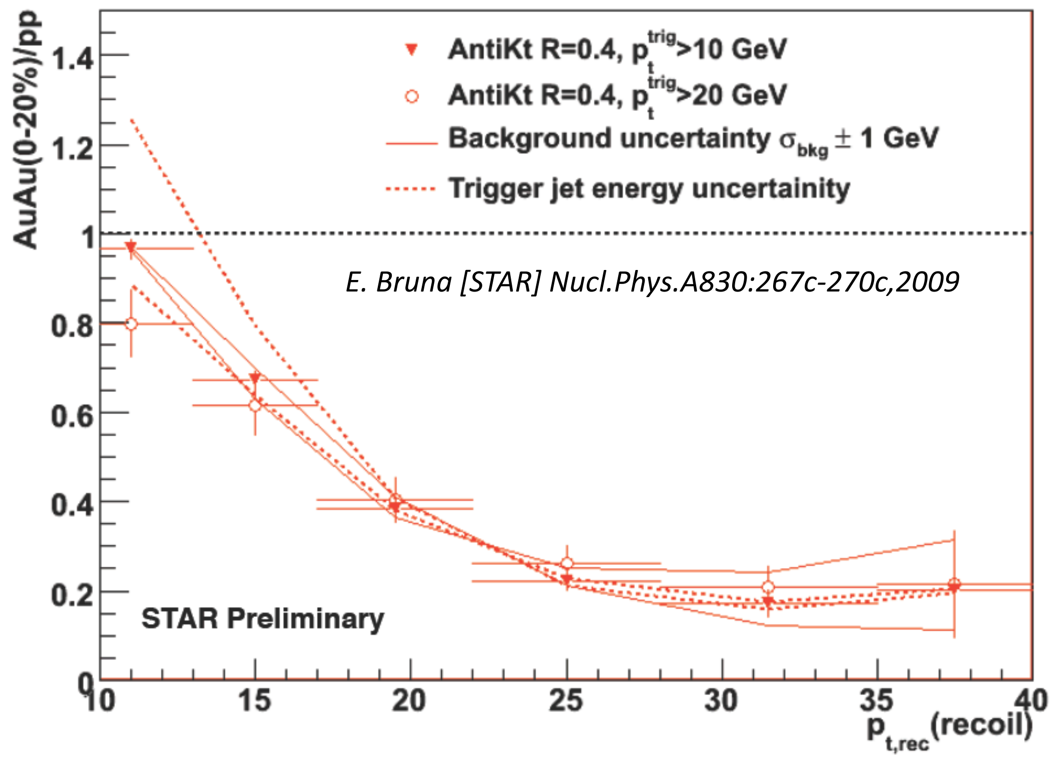
Model study: Geometrical bias.
Example: Correlations at LHC





Jet quenching via di-jet measurements at STAR





- Non-interacting/unmodified trigger jet maximizes path length for the back-to-back jets
- Significant suppression in di-jet coincidence measurements

Summary and Outlook

Complete jet reconstruction promises qualitatively new insight into jet interactions in matter

➔major focus of RHIC II and LHC HI programs
➔has stimulated significant new theory activity

First results from fully reconstructed jets from STAR/RHIC show significant broadening of the jet structure in HI collisions

But significant technical issues for systematically well-controlled measurements

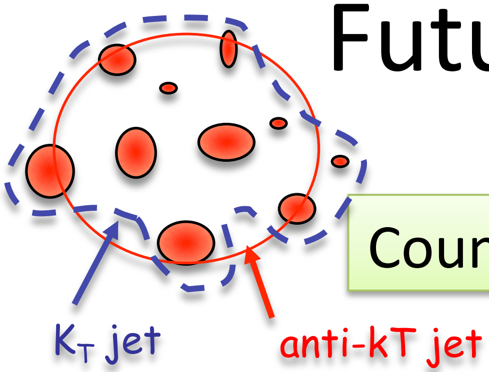
➔main issue: HI background characterization
➔high backgrounds expected also in high luminosity p+p at LHC

More on jets from STAR: E. Bruna [STAR] Nucl.Phys.A830:267c-270c,2009
H. Caines [STAR] Nucl.Phys.A830:263c-266c,2009; arXiv:0911.3211v1 [nucl-ex]

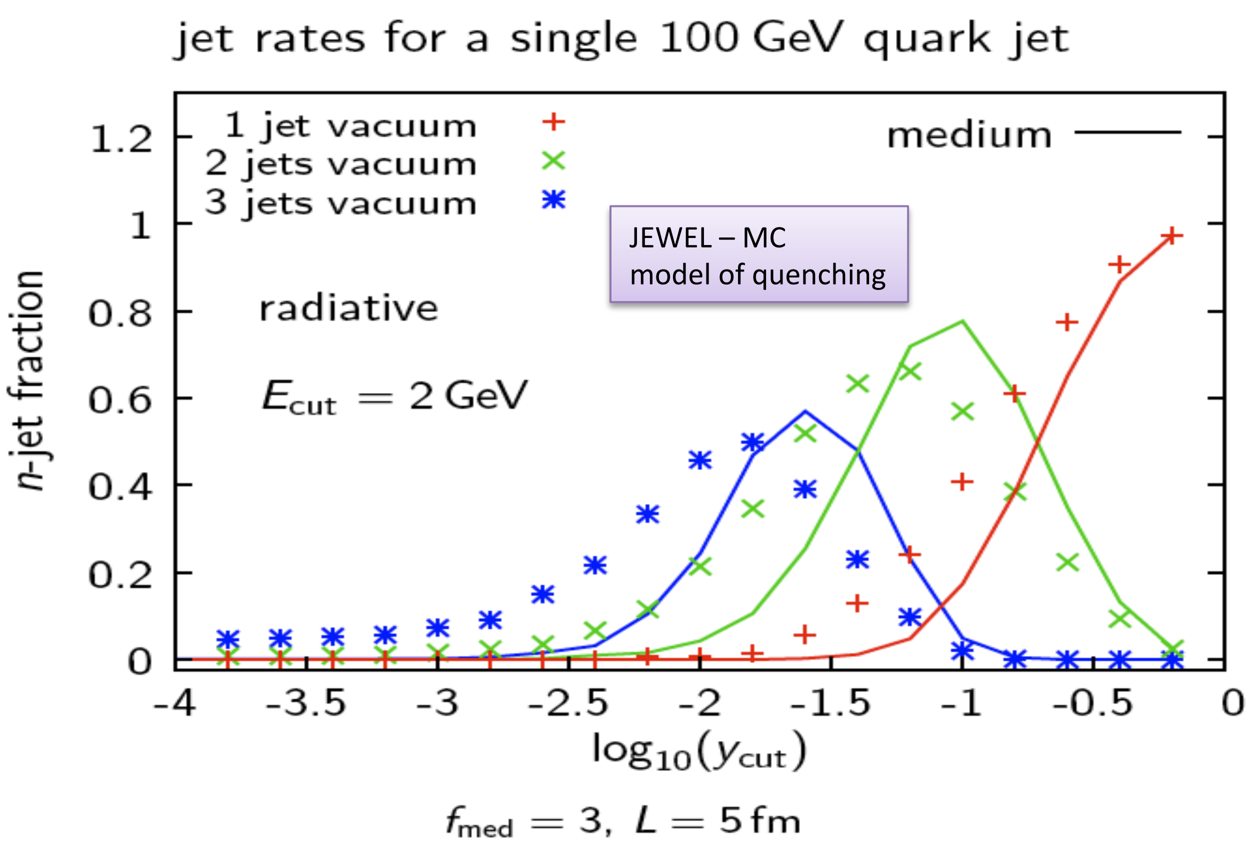
Future measurements

If time allows…

Future measurement: 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:

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

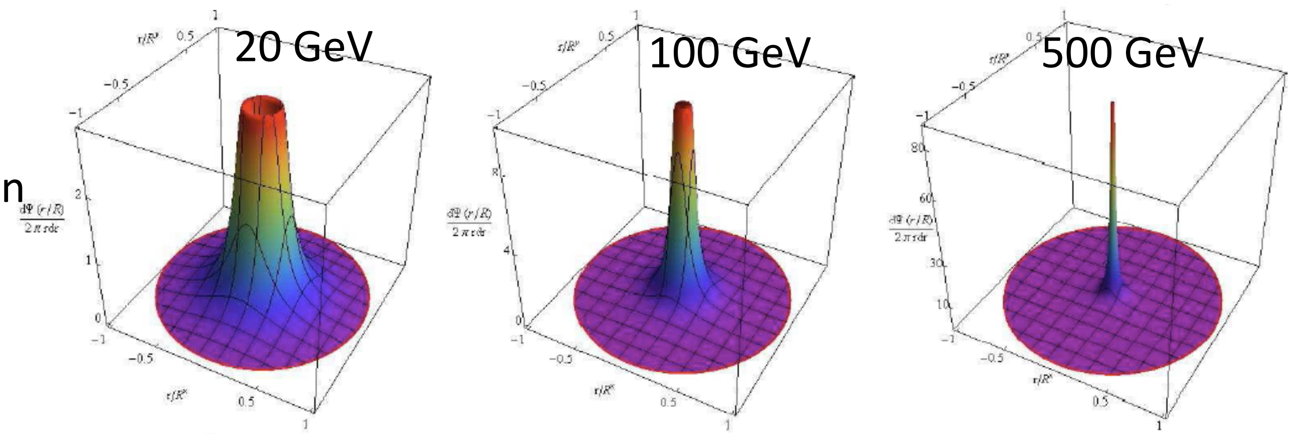
where

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

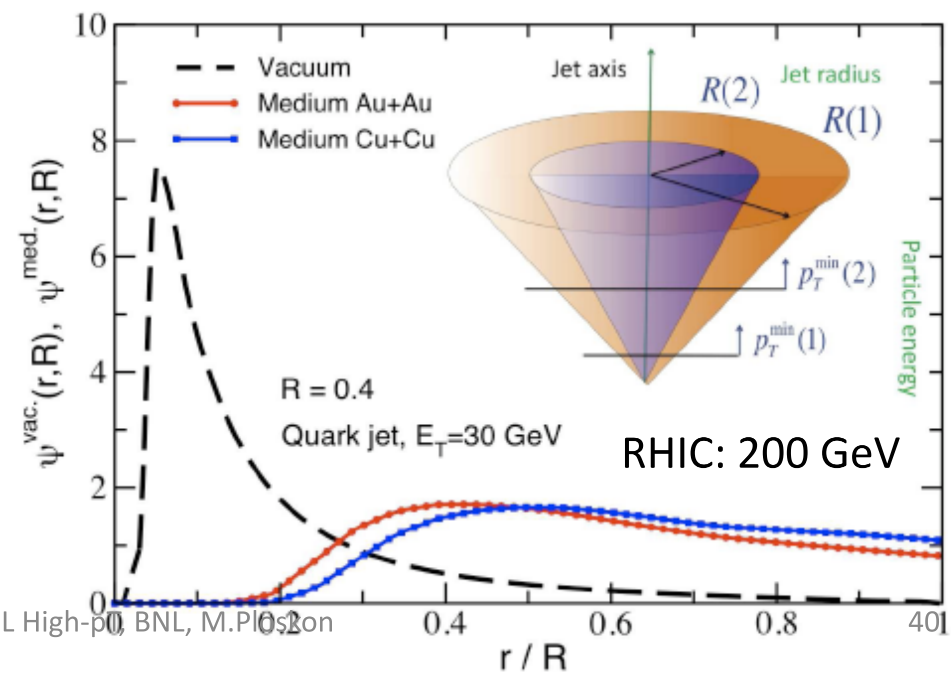
C. Zapp et al.
arXiv:0804.3568 [hep-ph]

Jet shapes

LHC/
Tevatron

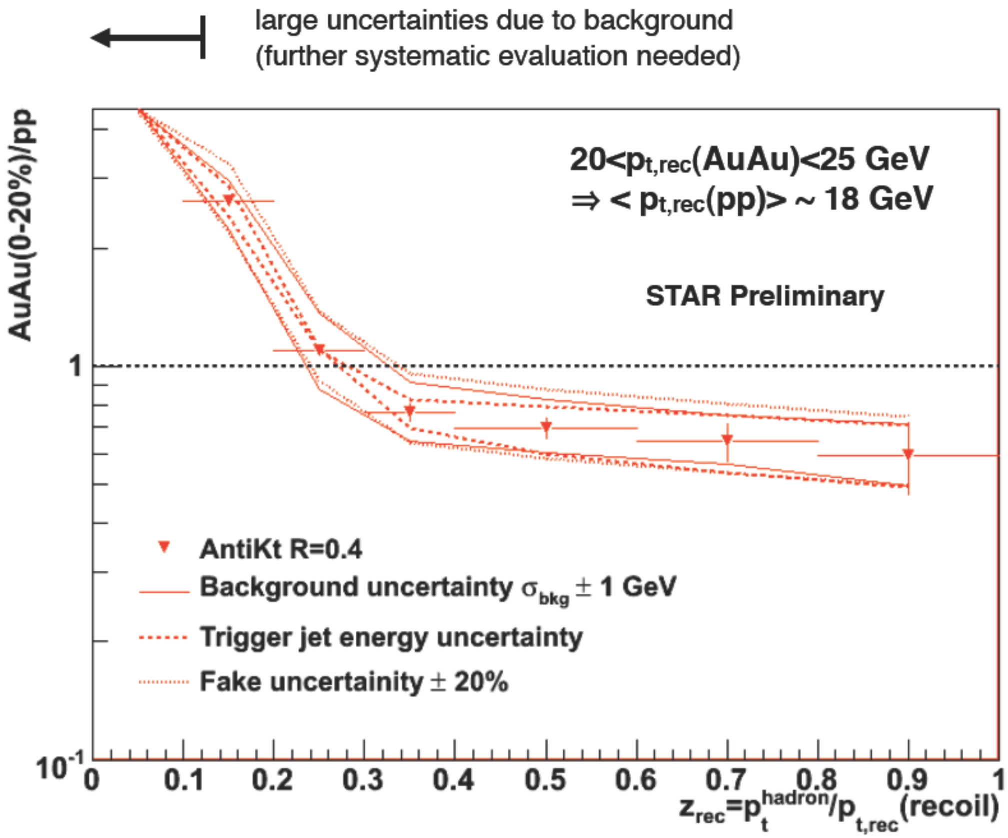


$$\psi(r,R) = \frac{d}{dr}\left\{\frac{\sum_i E_{T_i}\theta(r - R_{i,\mathrm{jet}})}{\sum_i E_{T_i}\theta(R - R_{i,\mathrm{jet}})}\right\}$$



[I. Vitev, B.-W. Zhang arXiv:0910.1090v1 [hep-ph]]

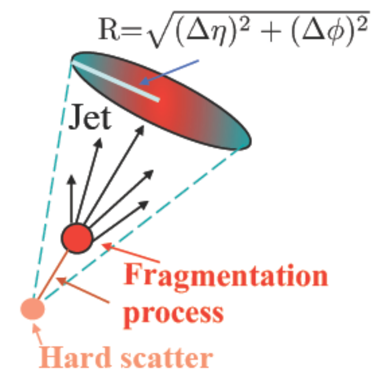
Jet quenching:
Modified jet fragmentation



E. Bruna [STAR] Nucl.Phys.A830:267c-270c,2009

Fragmentation pattern of jets which interact with the medium (AuAu) differs from same energy vacuum jets (pp)
-> ratio of zT: AuAu/pp

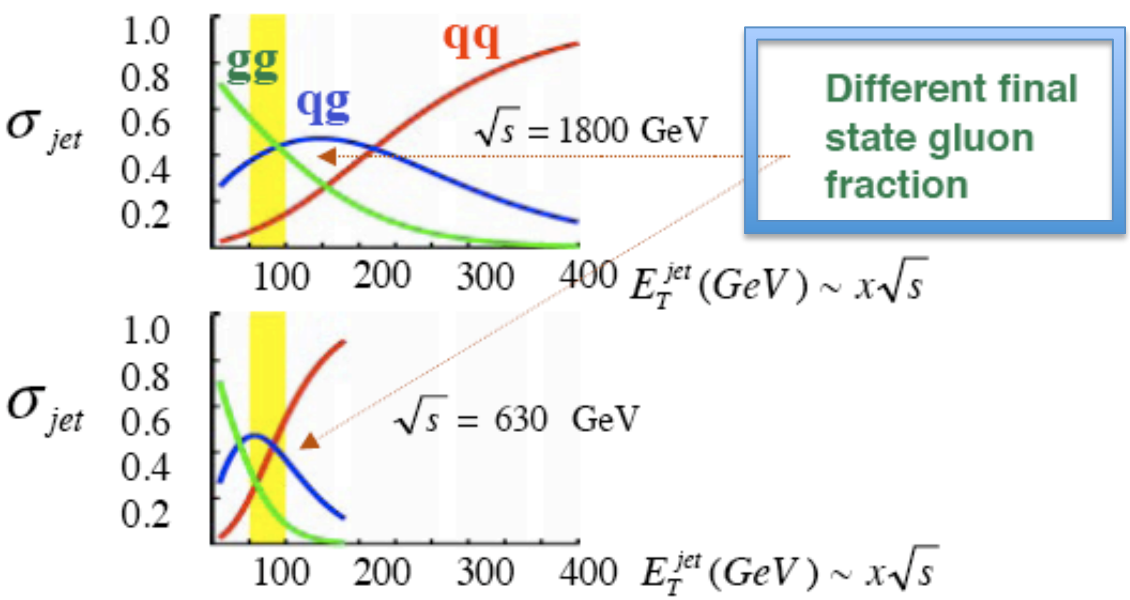
$$z_T = p_T^{hadron} / p_T^{jet}$$



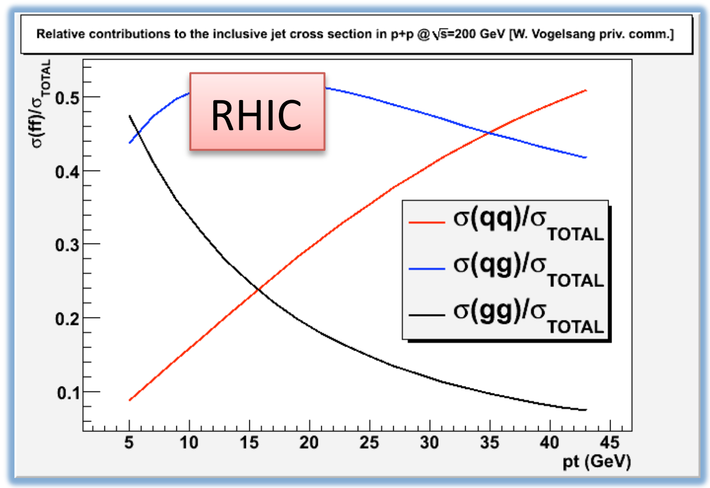
Possibility at RHIC – Sensitivity to final state gluon fraction in p-p
Example: Subjets at Tevatron(D0)

- 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



Vogelsang: pp @ 200 GeV



RHIC will measure pp@500 GeV
LHC?

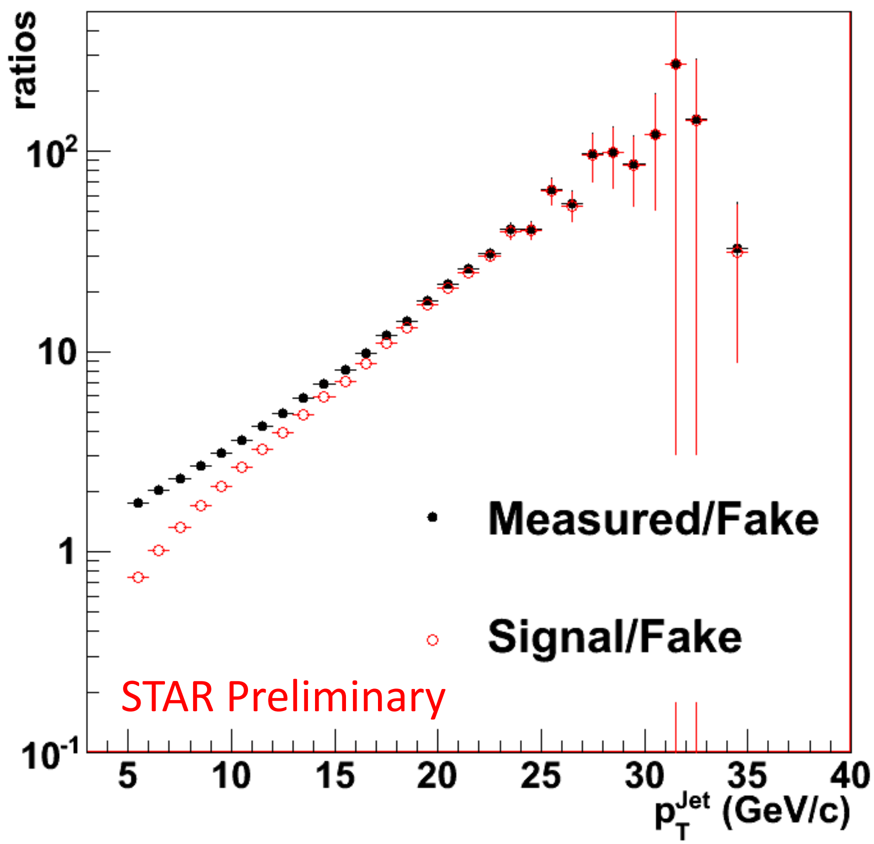
Additional considerations

Fake jet contamination/STAR

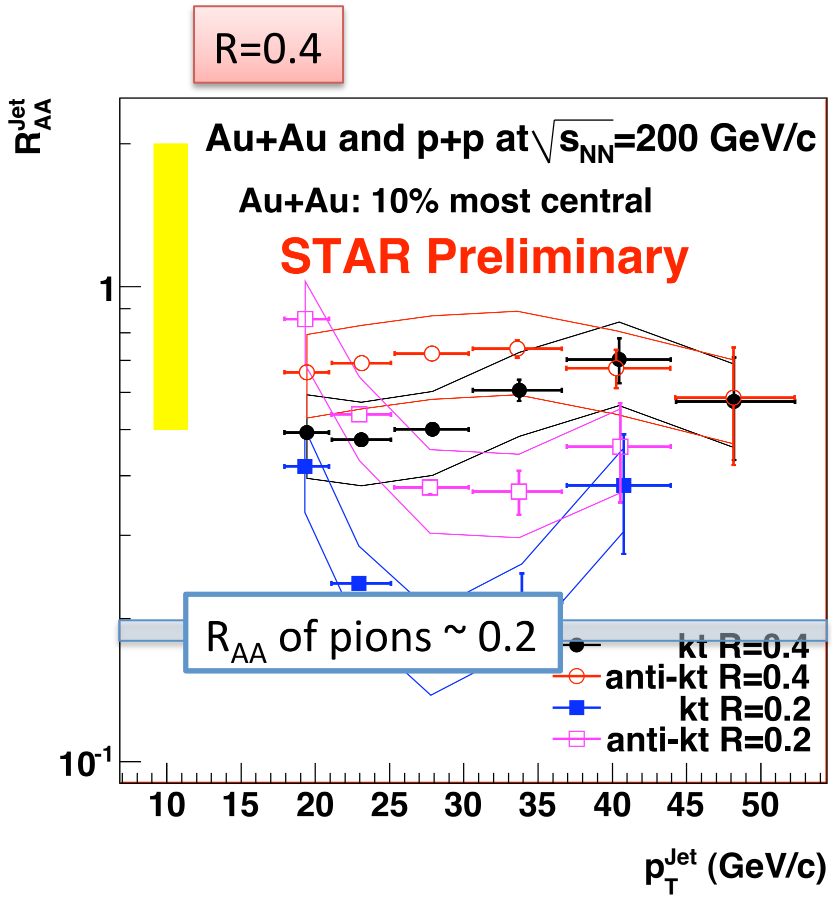
"Fake" jets: signal in excess of background model from random association of uncorrelated soft particles (i.e. not due to hard scattering)

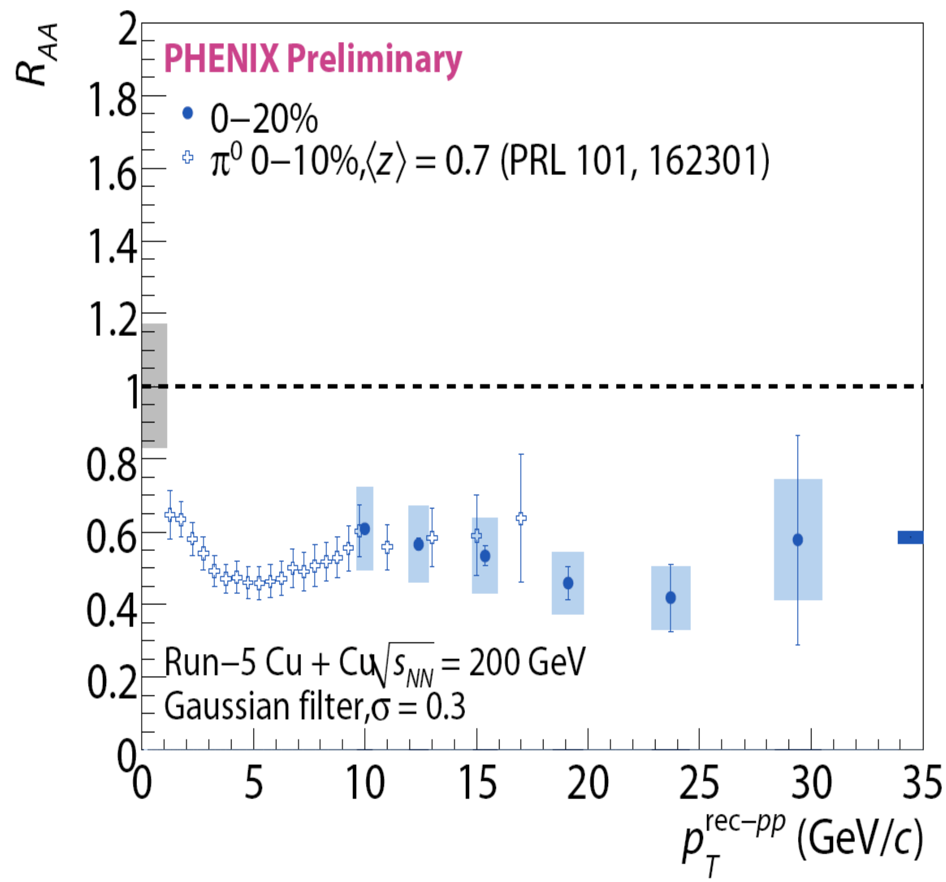
"Fake" jet rate estimation:

- 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



Jet R_{AA}





- $R_{AA} < 1$: full jet cross-section not recovered ➔jet broadening
- But systematically difficult measurement