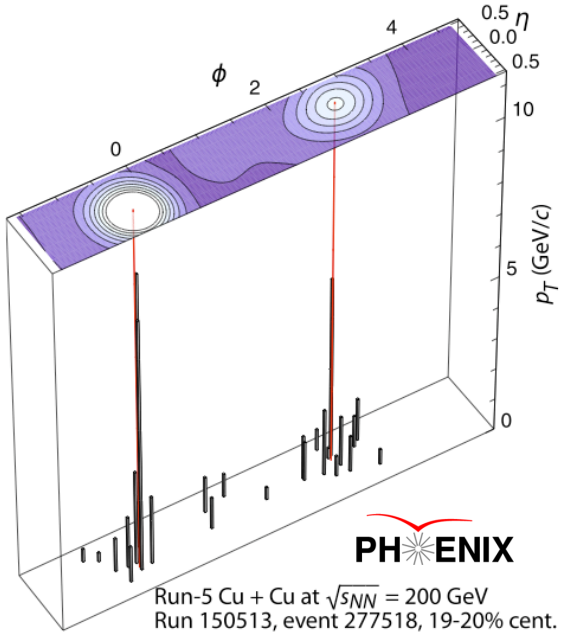
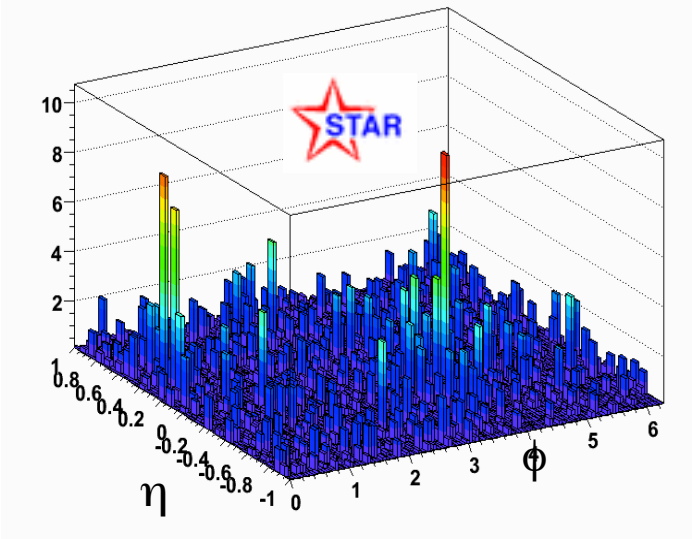




Jets at RHIC

Sevil Salur

UC Davis & Rutgers U.

Why we should study jets in heavy ion collisions?

Full Jet Reconstruction: Enables study of jet quenching at the partonic level.

- Uniquely large kinematic reach
- In A+A much reduced geometric biases, full exploration of quenching.
- Multiple channels for consistency checks: Inclusive, di-jets, h-jets, gamma-jets
- Qualitatively new observables: energy flow, jet substructure, fragmentation function

Goal is Unbiased Jet Reconstruction:

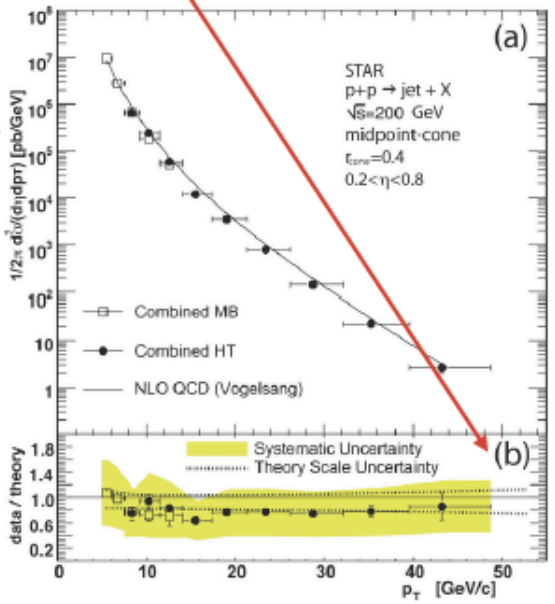
Reconstruct partonic kinematics independent of fragmentation details - quenched or unquenched and study the QGP dynamics.

But are we succeeding?

Outlook

Year	Collision System $\sqrt{s_{NN}}$=200 GeV	Threshold	Integrated Luminosity	p+p equivalent
2003	p+p	2.5 GeV	200 nb^{-1}	0.2 pb^{-1}
		4.5 GeV	170 nb^{-1}	0.17 pb^{-1}
2004	p+p	2.2 GeV	133 nb^{-1}	0.133 pb^{-1}
		4.6 GeV	150 nb^{-1}	0.150 pb^{-1}
2005	Cu+Cu	2.4 GeV	3.6 μb^{-1}	0.014 pb^{-1}
		3.75 GeV	860 μb^{-1}	3.4 pb^{-1}
2007	Au+Au (L2-gamma)	5.5 GeV	506 μb^{-1}	19.6 pb^{-1}

0.65 pb^{-1} reach of 50 GeV



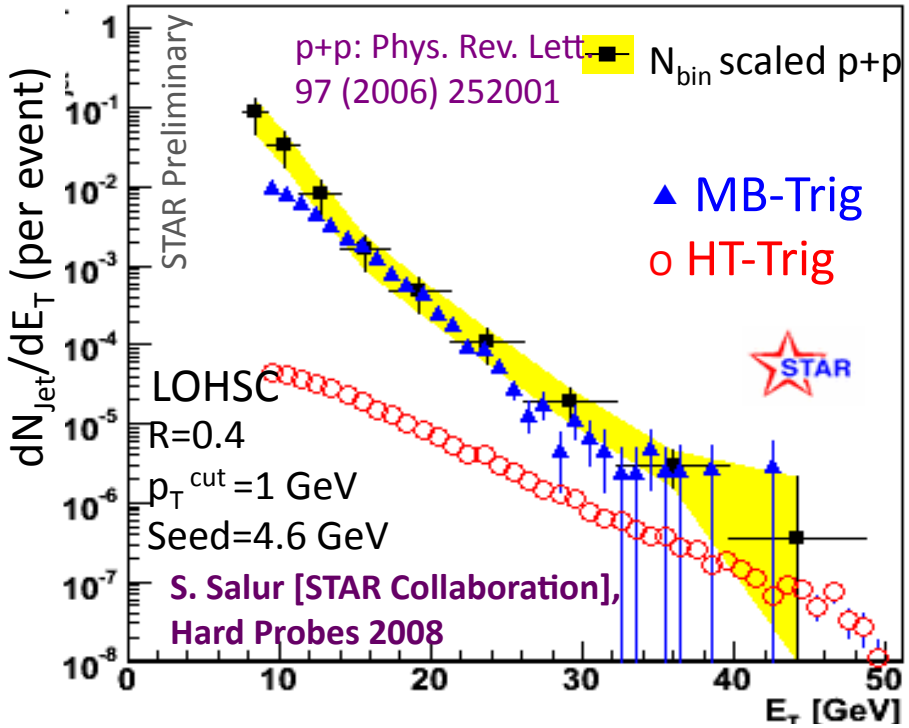
Private Communication J. Dunlop

Jets at RHIC are already in the disk and we already started to sorting them out.

Energy resolution depends on (PDFs, Fragmentation Functions & hard scattering cross sections) But what about quenching - theoretical input is essential.

More to come soon…

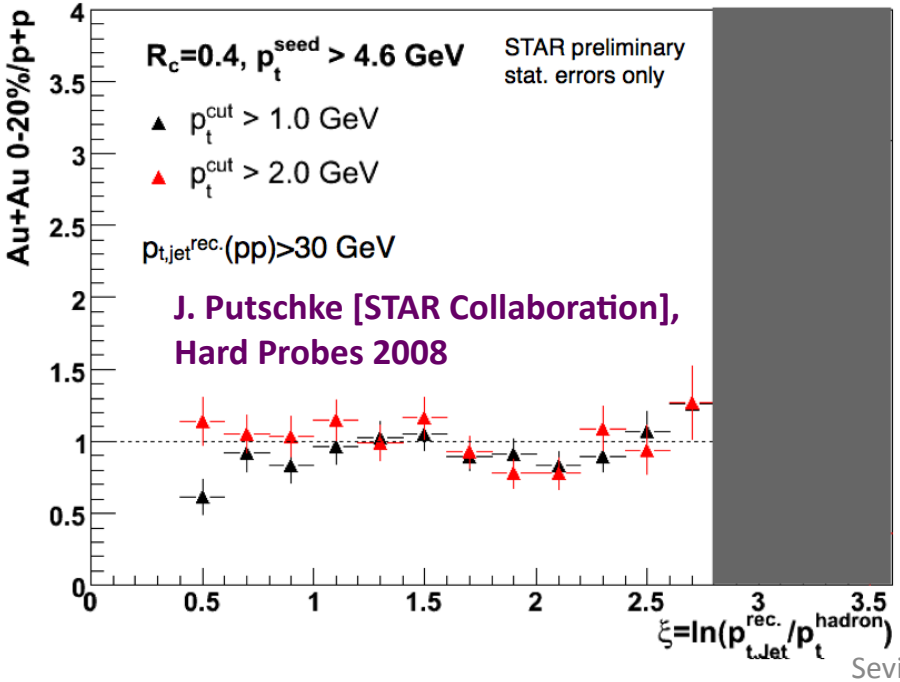
Hard Probes 2008



Agreement with N_{bin} scaled p+p

Resolution effect corrected assuming **Pythia Fragmentation**.

Trigger Biases due to event recording



Ratio of A+A to pp in FF~1.

Tower energy threshold bias→
No modification in FF…

Conclusions

Jet quenching in hot QCD matter is now well-established:

- Conclusive measurements in multiple channels.
- Partial theoretical understanding – progress being made

New theory developments and increased luminosities now enable complete jet measurements in heavy ion collisions at RHIC.

- First full jet reconstruction at RHIC (0-10% central heavy ion collisions - current reach is up to 50 GeV)
- Trigger biases and corrections based on Pythia, require further systematic checks with quenching models.

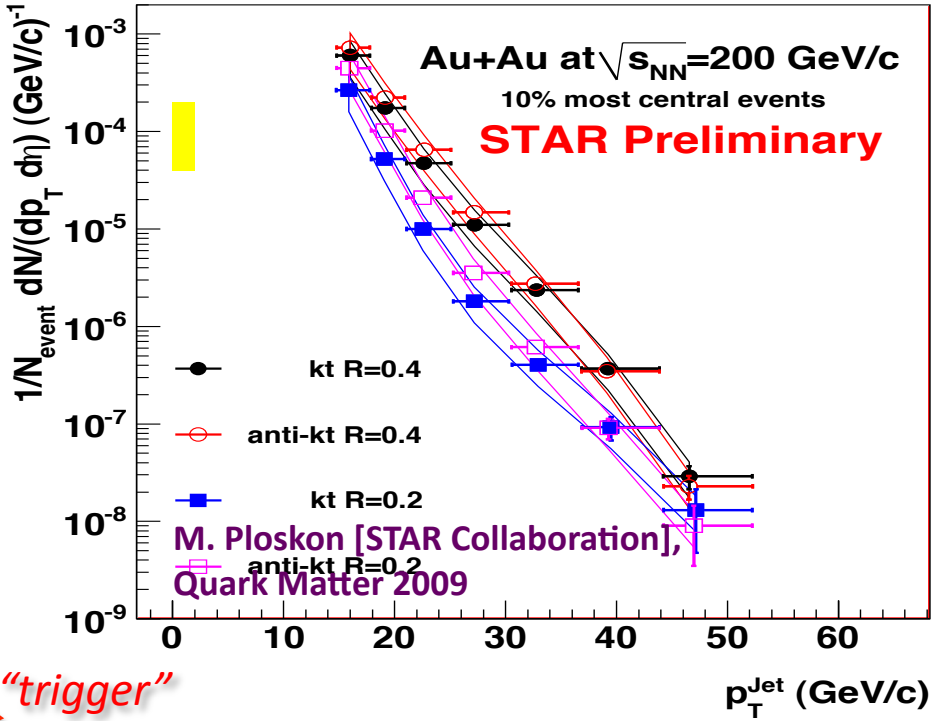
New observables with clear predictions in QCD theory:

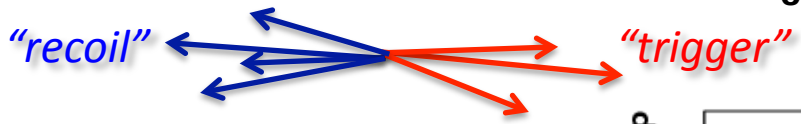
- fragmentation functions
- subjet distributions
- etc …

More to come soon !

Correct via **unfolding**:

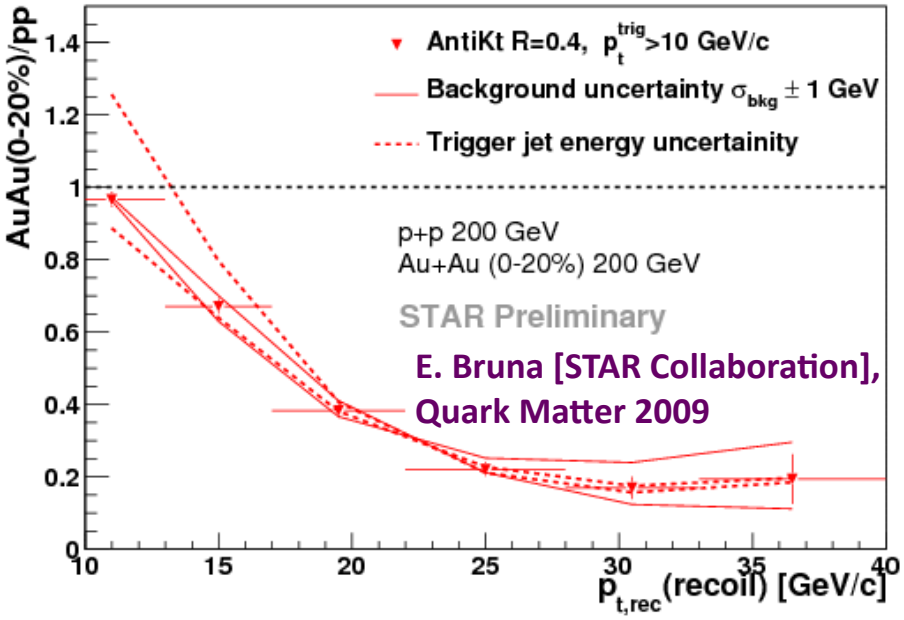
Exactly the same algorithms and jet definitions used as in p+p collisions

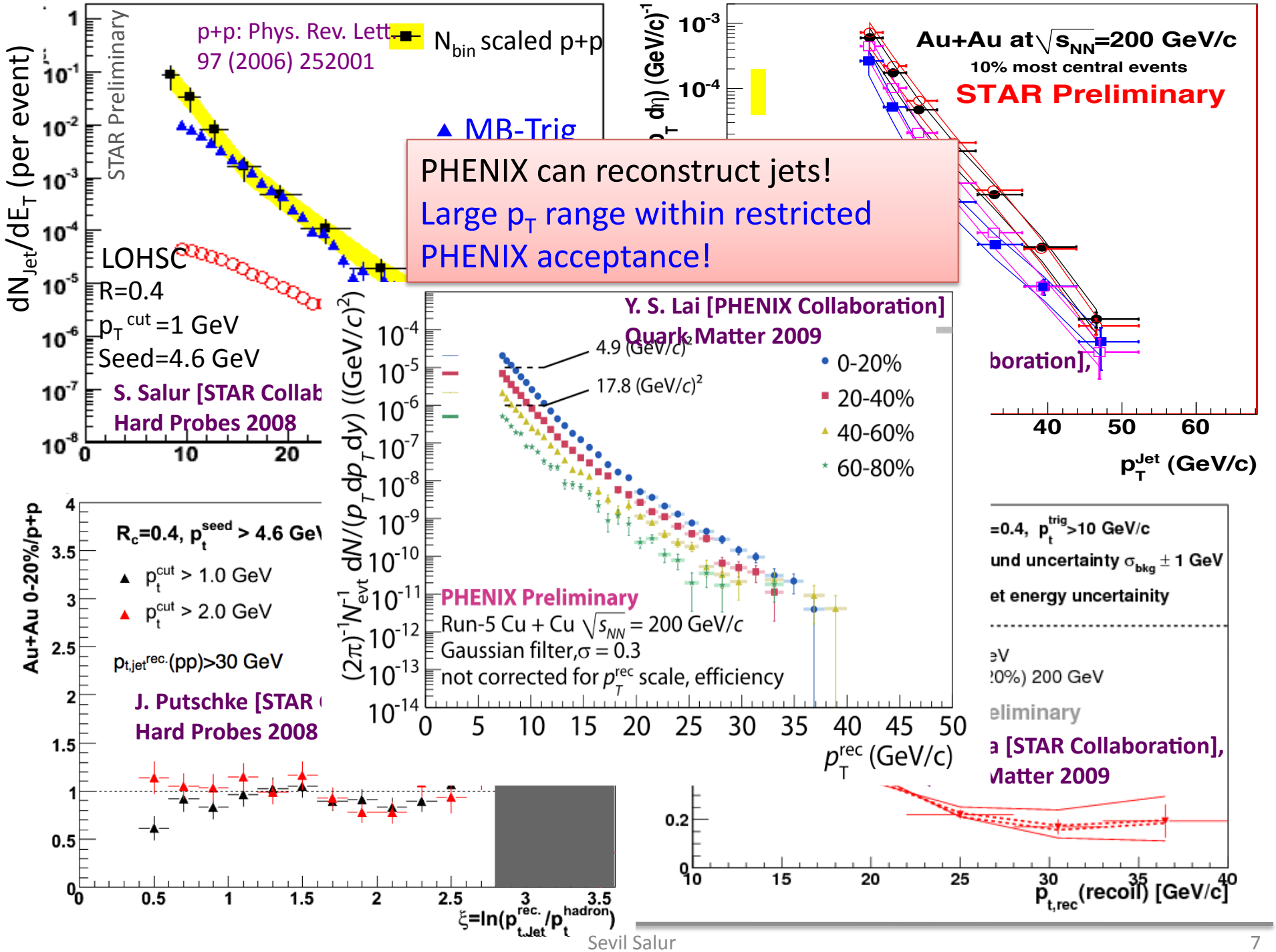


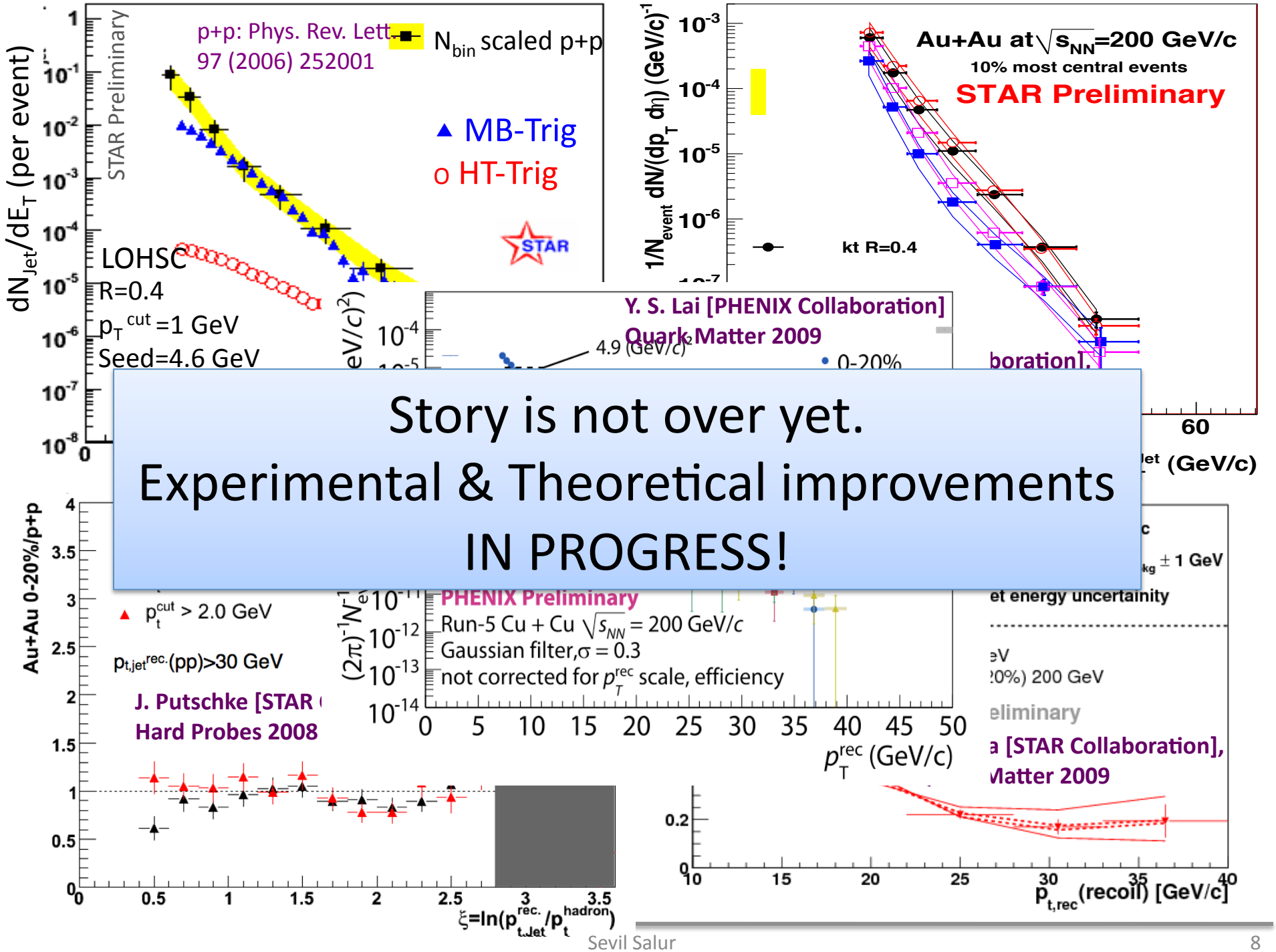


Remove the trigger bias:

Apparent suppression of the recoil jet of Au+Au with respect to p+p.




p+p: Phys. Rev. Lett. 97 (2006) 252001
N_bin scaled p+p
MB-Trig
STAR Preliminary
dN_Jet/dE_T (per event)
LOHSC
R=0.4
p_T^cut =1 GeV
Seed=4.6 GeV
S. Salur [STAR Collab
Hard Probes 2008
PHENIX can reconstruct jets!
Large p_T range within restricted PHENIX acceptance!
Au+Au at √s_NN=200 GeV/c
10% most central events
STAR Preliminary
p_T^Jet (GeV/c)
Y. S. Lai [PHENIX Collaboration]
Quark Matter 2009
4.9 (GeV/c)²
17.8 (GeV/c)²
0-20%
20-40%
40-60%
60-80%
PHENIX Preliminary
Run-5 Cu + Cu √s_NN = 200 GeV/c
Gaussian filter,σ = 0.3
not corrected for p_T^rec scale, efficiency
p_T^rec (GeV/c)
Au+Au 0-20%/p+p
R_c=0.4, p_t^seed > 4.6 GeV
p_t^cut > 1.0 GeV
p_t^cut > 2.0 GeV
p_t,jet^rec.(pp)>30 GeV
J. Putschke [STAR
Hard Probes 2008
ξ=ln(p_t,Jet^rec./p_t^hadron)
=0.4, p_t^trig>10 GeV/c
und uncertainty σ_bkg ± 1 GeV
et energy uncertainty
eV
20%) 200 GeV
eliminary
a [STAR Collaboration],
Matter 2009
p_t,rec(recoil) [GeV/c]


p+p: Phys. Rev. Lett. 97 (2006) 252001
N_bin scaled p+p
▲ MB-Trig
o HT-Trig
STAR Preliminary
LOHSC
R=0.4
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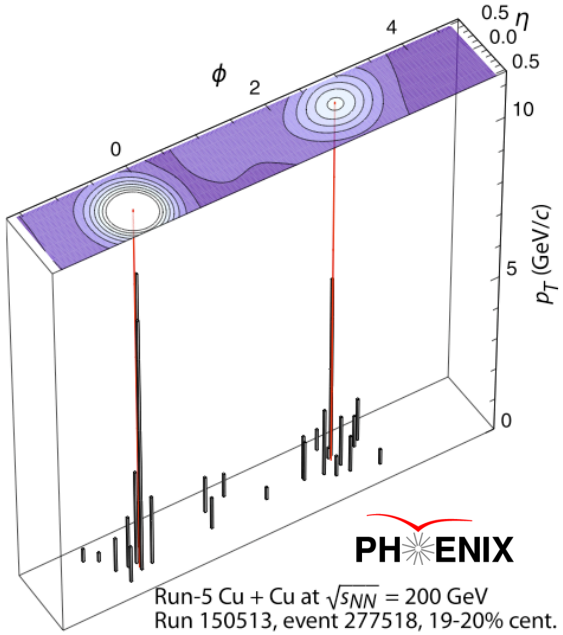
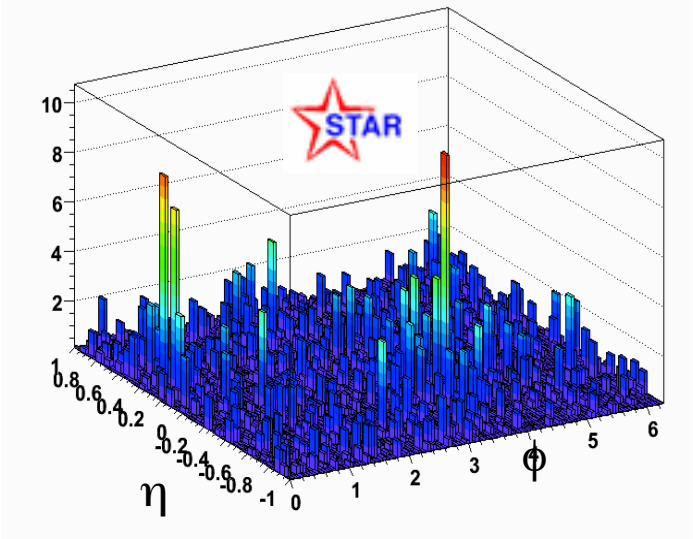
dN_Jet/dE_T (per event)
Au+Au at √s_NN=200 GeV/c
10% most central events
STAR Preliminary
kt R=0.4
1/N_event dN/(dp_T dη) (GeV/c)^-1
Y. S. Lai [PHENIX Collaboration]
Quark Matter 2009
4.9 (GeV/c)
0-20%
Story is not over yet.
Experimental & Theoretical improvements
IN PROGRESS!
Au+Au 0-20%/p+p
p_t^cut > 2.0 GeV
p_t,jet^rec.(pp)>30 GeV
J. Putschke [STAR
Hard Probes 2008
PHENIX Preliminary
Run-5 Cu + Cu √s_NN = 200 GeV/c
Gaussian filter,σ = 0.3
not corrected for p_T^rec scale, efficiency
p_T^rec (GeV/c)
± 1 GeV
et energy uncertainity
eliminary
a [STAR Collaboration],
Matter 2009
ξ=ln(p_t,jet^rec./p_t^hadron)
p_t,rec(recoil) [GeV/c]





Reconstructed Jets at RHIC:

What to do next?

Sevil Salur

UC Davis & Rutgers U.

Experimental Challenges

1) Data taking - Trigger-bias

- Biased fragmentation functions

2) Particle and jet level corrections

Calorimeter calibration

- ~5% uncertainty on calibration
  translates to a larger uncertainty.

Double counting of particle energies:

- electrons: Include energy only once!
- hadrons: showering corrections
  such as MIP, constant E-fraction

High momentum tracking

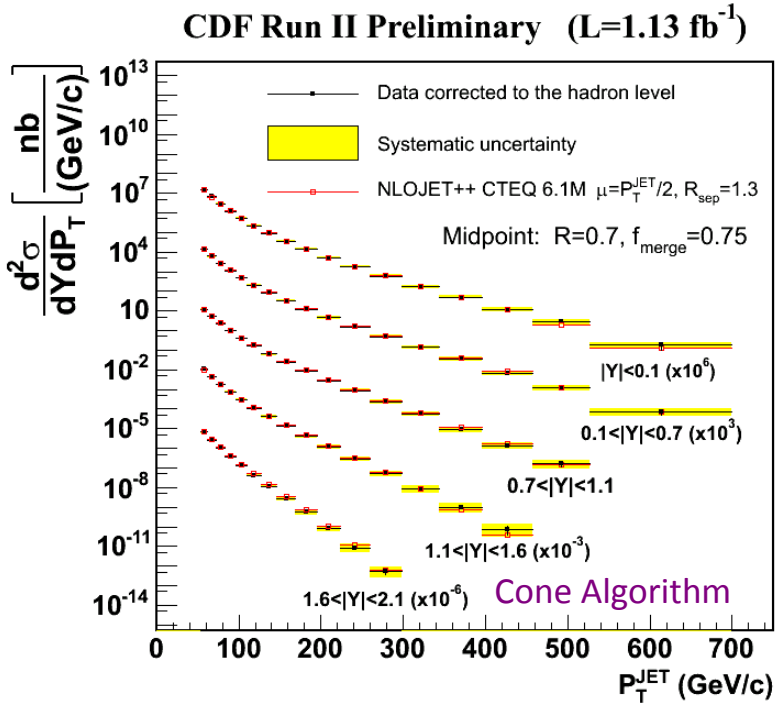
- Do not include cosmics

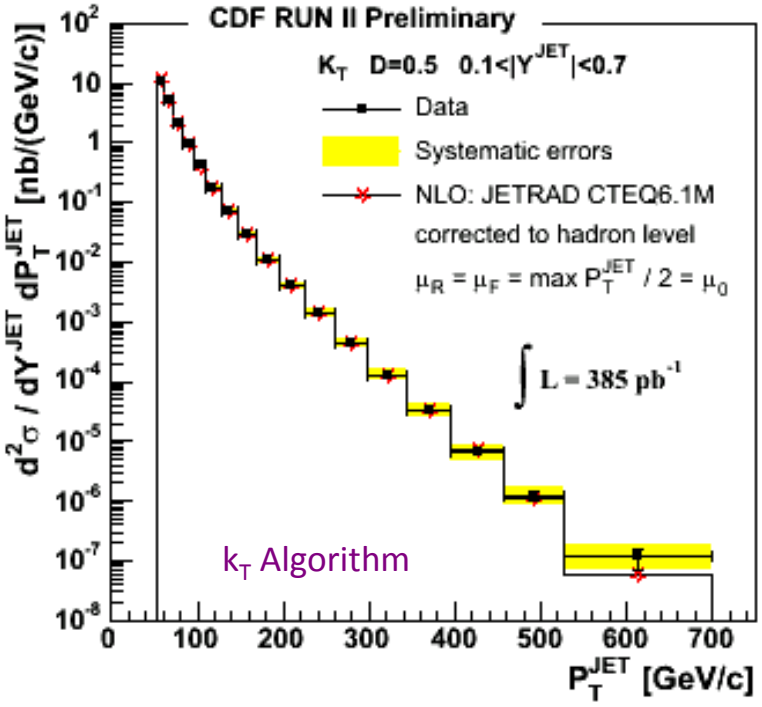
Unobserved energy

- Energy shift (protons for neutrons)

Jet P_T resolution

Jet Reconstruction is not a new phenomena…

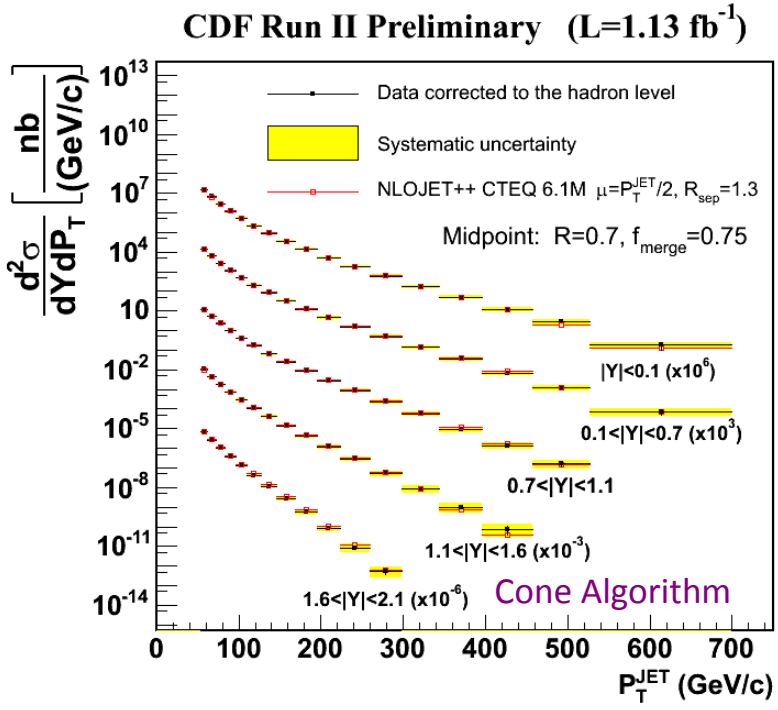


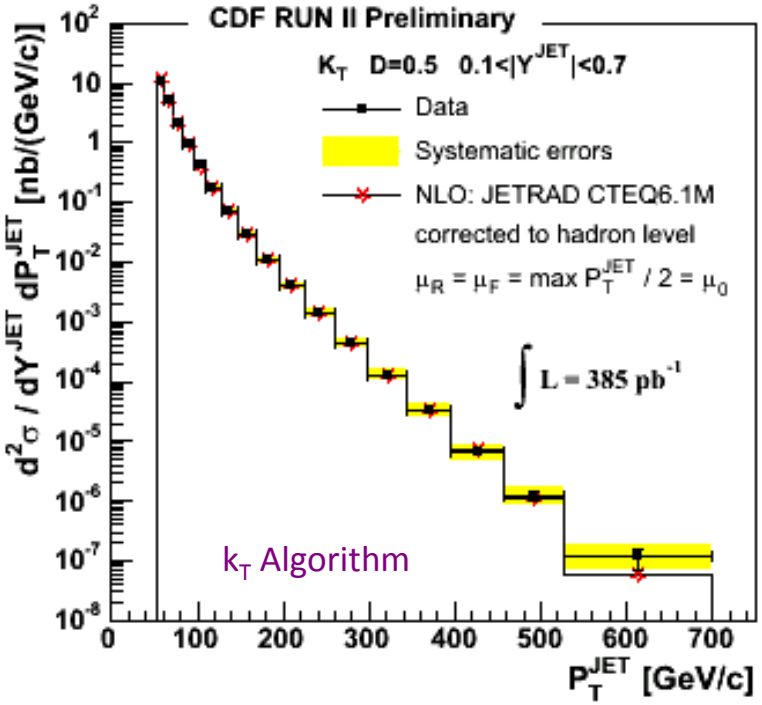


http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

Guidance from earlier measurements …

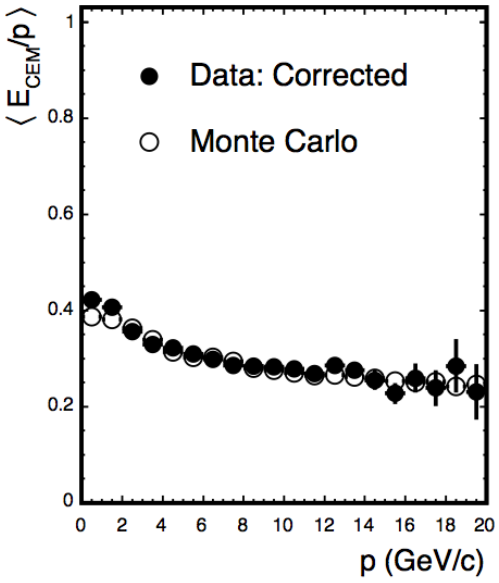
Jet Reconstruction is not a new phenomena…





http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

Fractional energy loss vs momentum MC comparisons…



A. Bhatti et. al. Nucl.Instrum.Meth.A566:375-412 (2006)

Experimental Challenges

1) Data taking - Trigger-bias

- Biased fragmentation functions

2) Jet Level and Particle Corrections

High momentum tracking

- Including cosmics

Calorimeter calibration

- ~5% uncertainty on calibration translates to large uncertainty in cross-sections.

Double counting of particle energies:

- electrons: Include energy only once!
- hadrons: showering corrections such as MIP, constant E-fraction

Unobserved energy:

- Energy shift (protons for neutrons)

Jet P_T resolution

3) Heavy–Ion Background

Fundamental Assumption: Two separable components: signal and background.

How might it be violated?

Biases in background estimation due to presence of a jet.

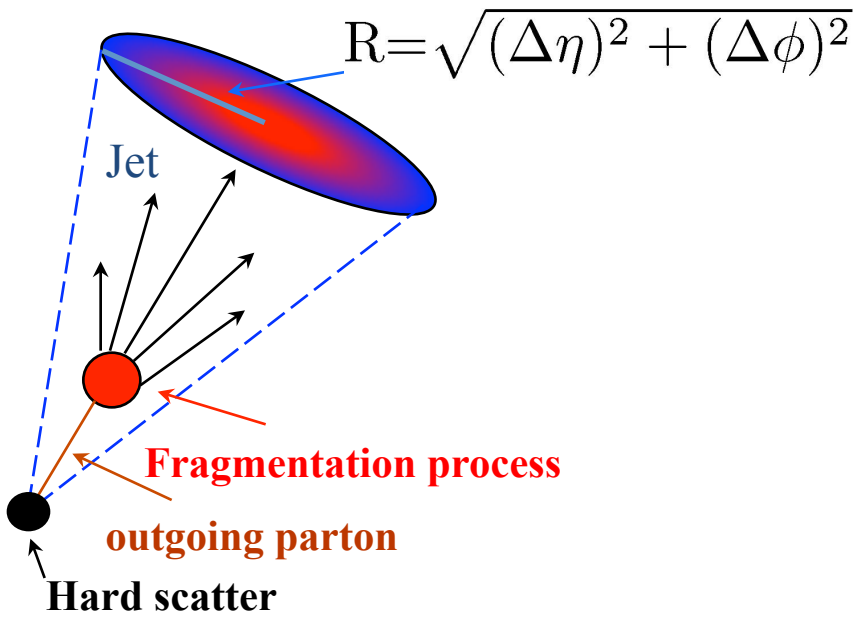
a) Initial state radiation (Expected to be small compared to jet energy).

b) Final state "out-of-cone" radiation.

Some others like Fake Jets…

Various Jet Reconstruction Algorithms

Different Algorithms respond differently to background!



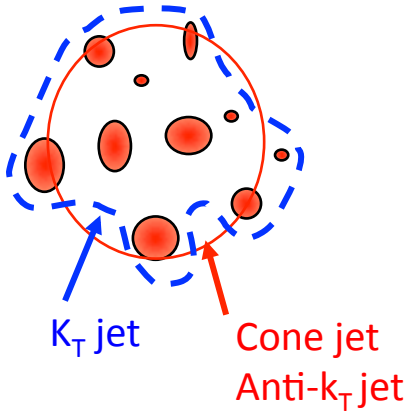
Cone Algorithm:

1. Mid Point Cone: Merging & Splitting
2. SIS CONE
   - Insensitive to "soft" radiation
   - Splitting doesn't change jets
3. Leading Order High Seed Cone (LOHSC)

Sequential recombination:
Cluster pairs of objects close in relative p_T

4. K_T (starting point: low p_T particles)
5. Anti-K_T (starting point: high p_T particles)

6. Gaussian filtering. Y. Lai, B. Cole arXiv:0806.1499



The FastJet Algorithms

Suite of modern Collinear and infrared safe jet algorithms
- sequential recombination: k_T, Cambridge/Aachen, anti-k_T
- cone: SISCone (Seedless Infrared-safe Cone)

Motivated by high precision jets in high luminosity p+p at LHC (pileup)
- but directly applicable to heavy ion collisions

Two important algorithmic advances:

1. Large improvements to processing time vs. event multiplicity
2. **Rigorous definition of jet area for subtraction of diffuse event background**

Assume: Signal and background can be separated

$$p_T(\text{Jet Measured}) \sim p_T(\text{Parton}) + \rho \times A(\text{Jet}) \pm \sigma\sqrt{A(\text{Jet})}$$

A= Jet Area ρ = Diffuse noise, σ=noise fluctuations

A, ρ, σ are all measurable quantities!

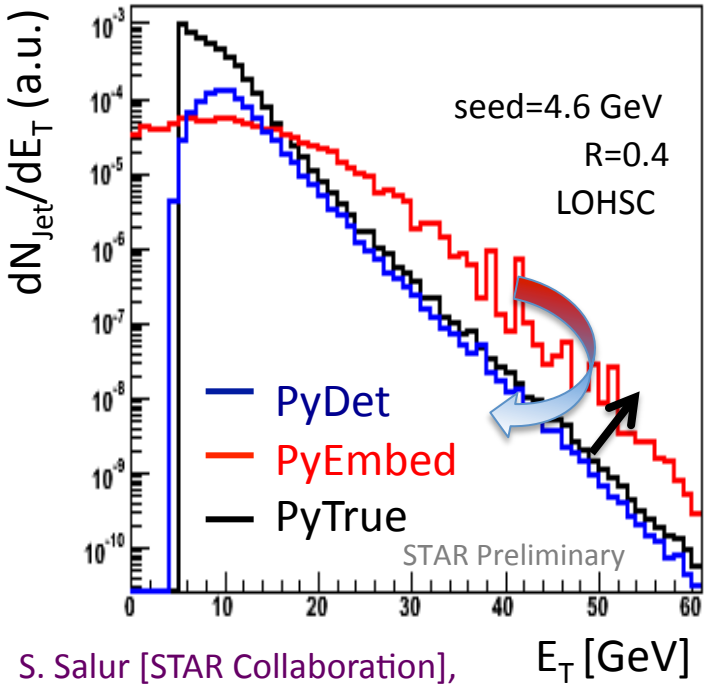
M. Cacciari, G. Salam 0707.1378 [hep-ph]

M. Cacciari, G. Salam, G. Soyez 0802.1188 [hep-ph]

FastJet – http://www.lpthe.jussieu.fr/~salam/fastjet

Jet Measurements

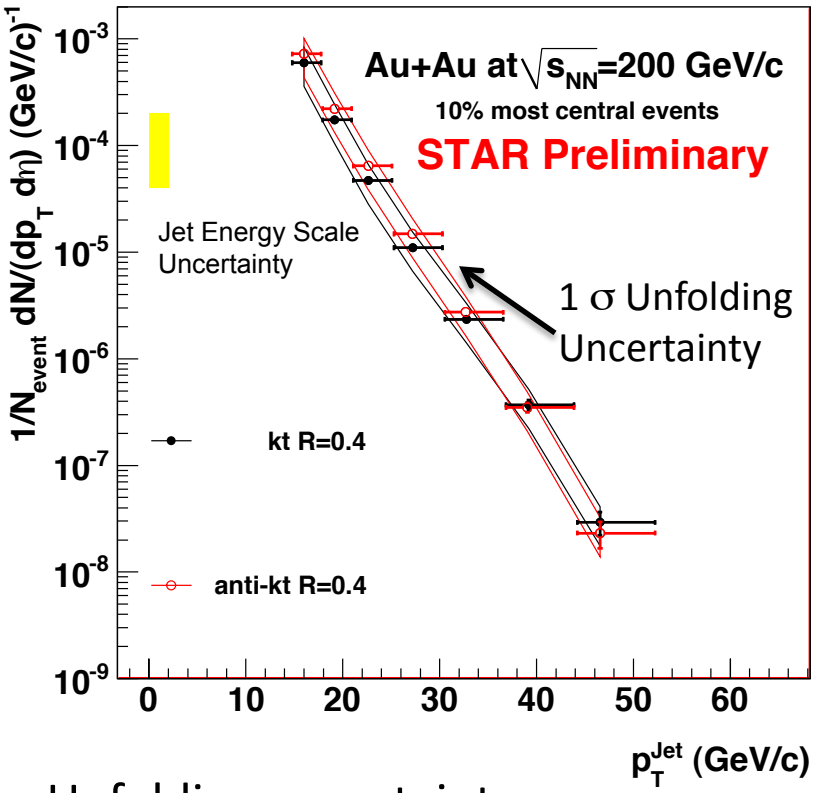
1) Minimize the kinematic cuts.
2) Data driven corrections :
   a. Experimental characterization of background fluctuations.
   b. Detailed unfolding of fluctuations & energy resolution. → Correcting for p_T smearing



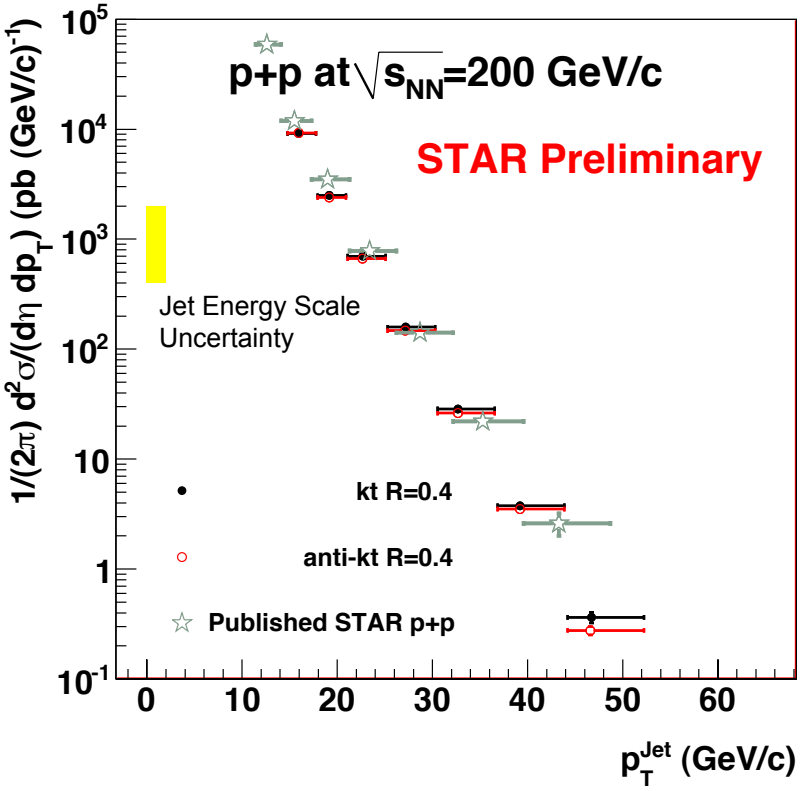
S. Salur [STAR Collaboration], arXiv:0809.1609 [nucl-ex]

Correction **depends highly on the background model.**

Jet Measurements



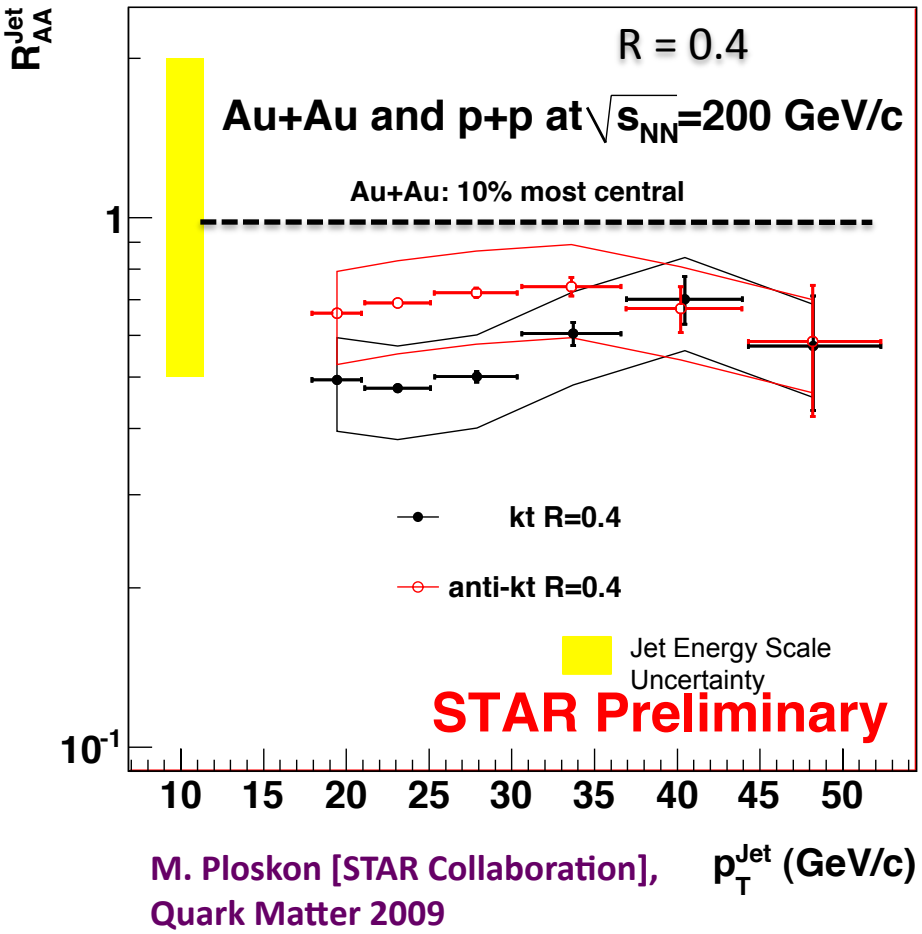
Unfolding uncertainty corresponds to a factor of 2 in jet cross-section.



M. Ploskon [STAR Collaboration], Quark Matter 2009

Anti-k_T and k_T jet spectra are consistent.

R_{AA} of Jets



M. Ploskon [STAR Collaboration], Quark Matter 2009

A large fraction of jets are reconstructed!
(Compare pion R^{π}_{AA} = 0.2)

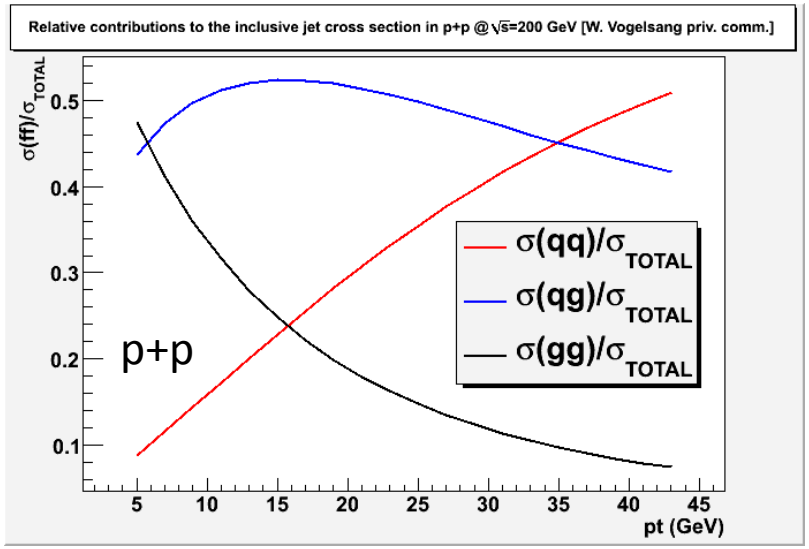
R_{AA} < 1 : unable to recover complete jet energy - jet broadening

R_{AA} = 1 : recover complete jet energy

We need to constrain the approximation of the Jet Energy Scale Uncertainty…

What happens at high p_T?

Relative contribution of sub-processes to inclusive jet production



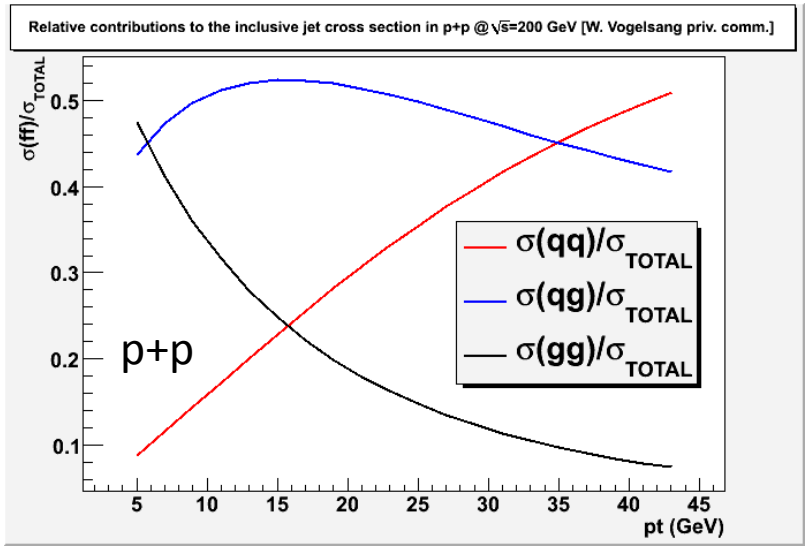
W. Vogelsang Private Communication

Relative contributions of quark and gluon vary.

What about quenching dependence on parton species?

What happens at high p_T?

Relative contribution of sub-processes to inclusive jet production



W. Vogelsang Private Communication

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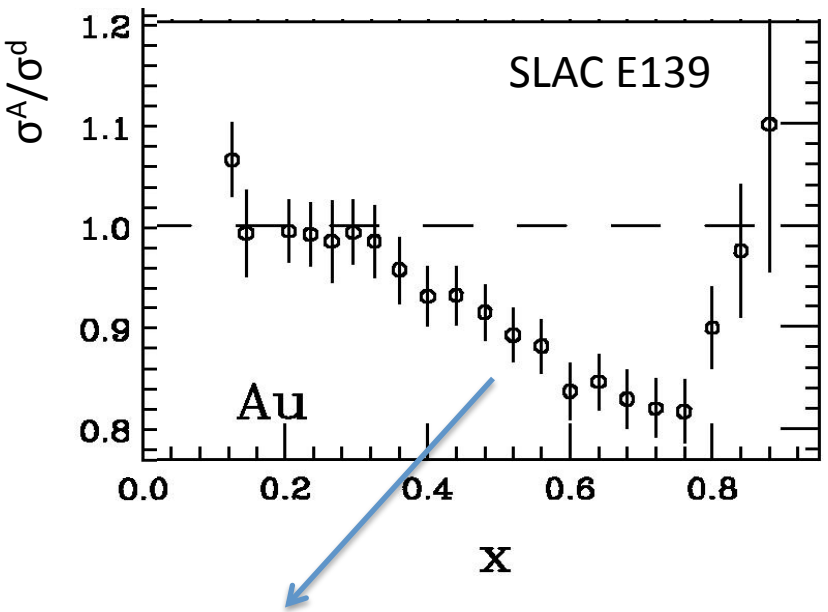


The EMC Effect: Deviation between structure Functions of Au and deuterium.

Initial state effects at large x ~15%

J. Gomez et al., SLAC–PUB–5813 June 7, 2001
D.F. Geesaman et al., Ann. Rev. Nucl. Part. Sci. 45, 337 (1995)
B. A. Cole. et al, arXiv:hep-ph/0702101

What about other high effects?

Theoretical Challenges: Rigorous calculations of full jet variables?

Model building of in-medium modifications…

JEWEL (Jet Evolution with Energy Loss):

K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, U. A. Wiedemann arXiv:0805.4759
Parton shower with microscopic description of interactions with medium – random process of scattering is used to modify the formation time of the radiated gluon.

Q-Pythia:

N. Armesto, L. Cunqueiro and C. A. Salgado arXiv:0809.4433[hep-ph]
MC implementation in Pythia of medium-induced gluon radiation through an additive term in the vacuum splitting functions.

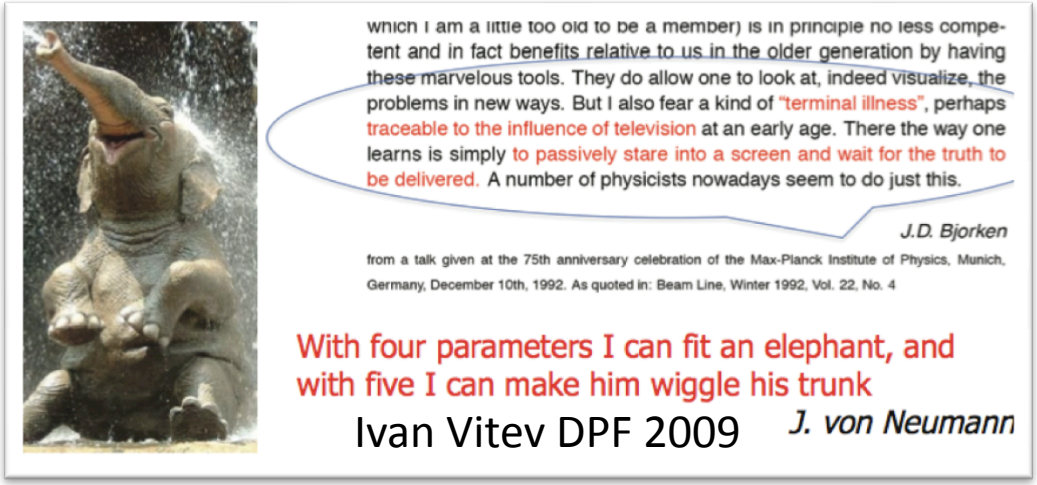
YaJEM:

T. Renk arXiv:0808.1803

Analytic Calculations:

Nicolas Borghini arXiv: 0902.2951

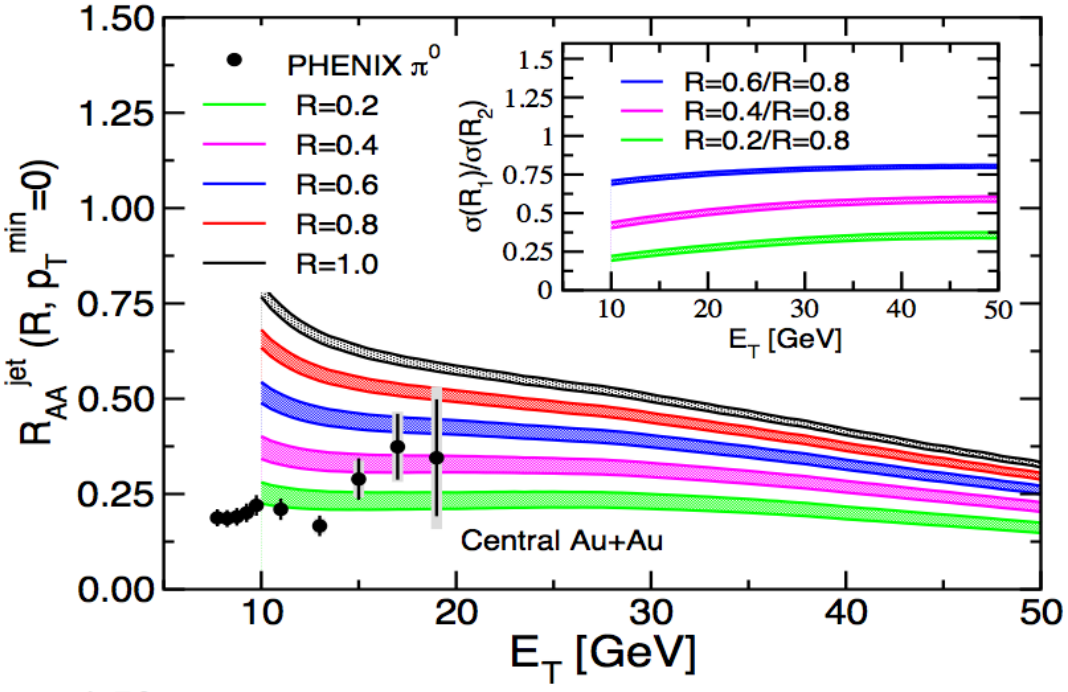
Ivan Vitev et al JHEP 0811:093 (2008), arXiv:0810.2807

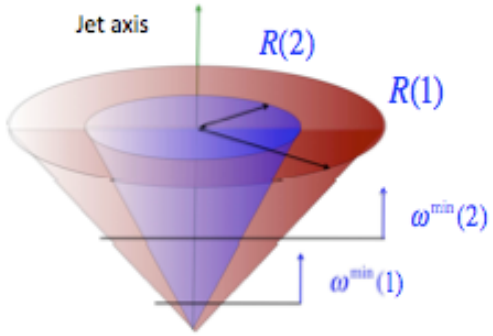


Many more….
Martini (S. Jeon), PYQUEN (Lokhtin, Snigriev), PQM (Dainese, Loizides, Paic), HIJING (Gyulassy, Wang)…

R_{AA} of Jets at RHIC

NLO Calculation:



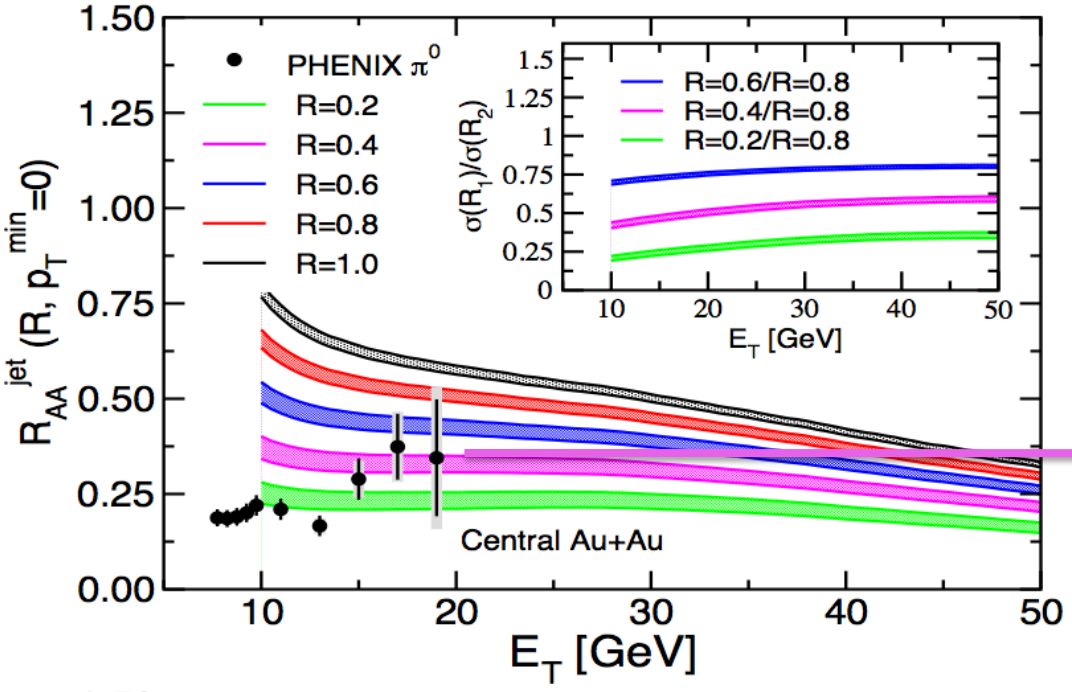


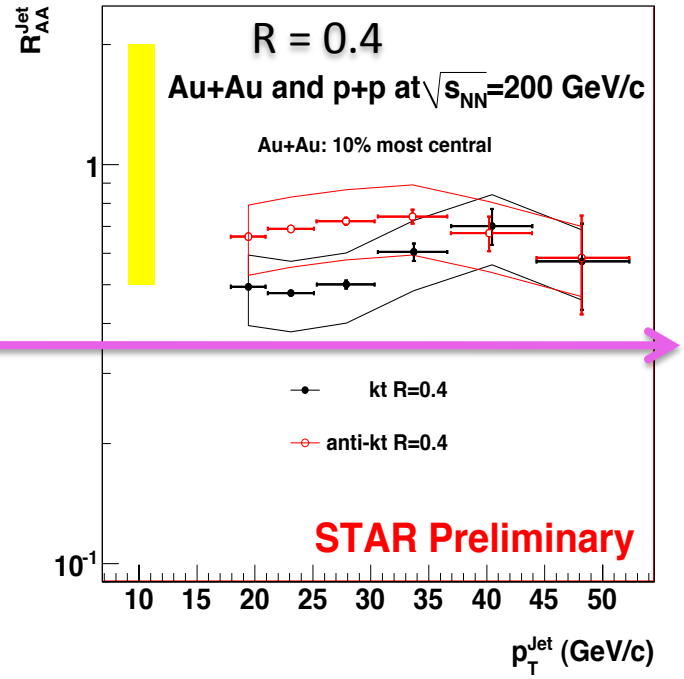
I. Vitev et al. arXiv:0910.1090v1 [hep-ph]

Vary Resolution Parameter → Implication of broadening of jets

R_{AA} of Jets at RHIC

NLO Calculation:





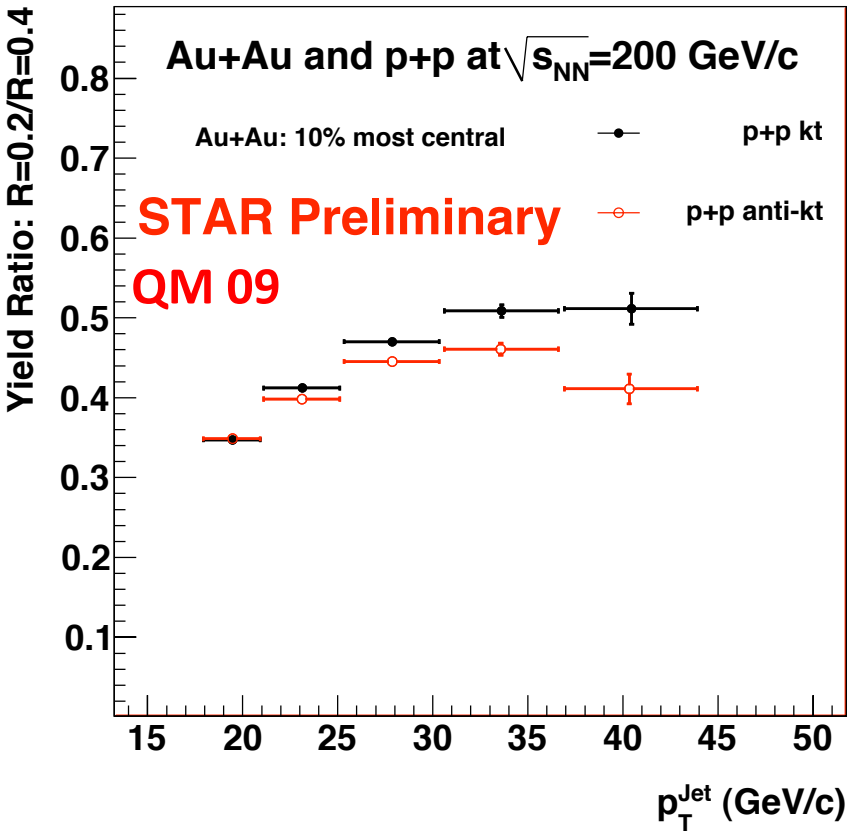
I. Vitev et al. arXiv:0910.1090v1 [hep-ph]

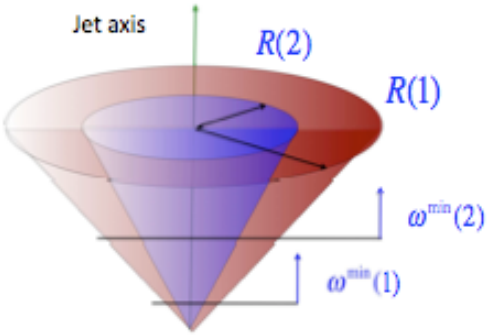
Vary Resolution Parameter → Implication of broadening of jets

But before can do this: **constrain systematic uncertainties & jet energy resolution**

Vary Resolution Parameter: R=0.2/R=0.4

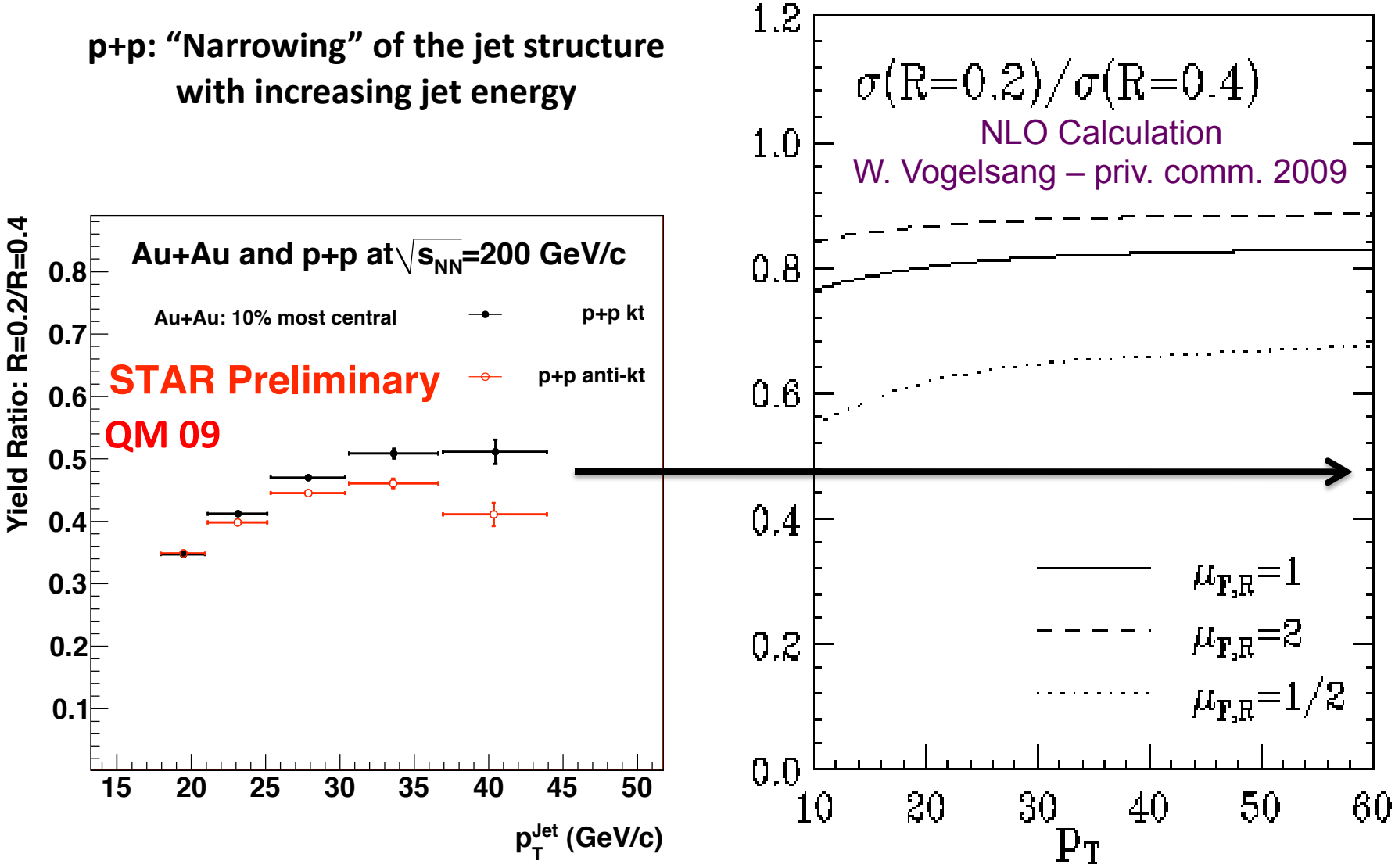
p+p: "Narrowing" of the jet structure with increasing jet energy





Vary Resolution Parameter: R=0.2/R=0.4

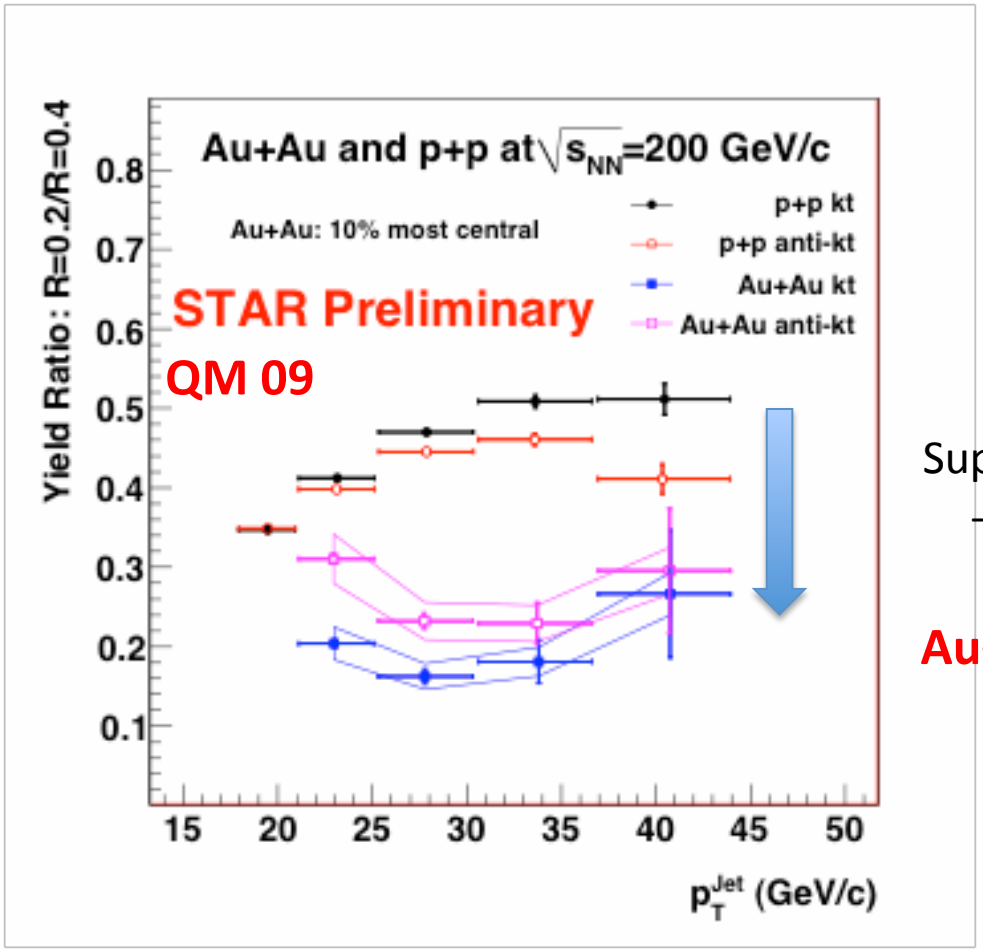
p+p: "Narrowing" of the jet structure with increasing jet energy



Broader jet profile further investigation is required

Vary Resolution Parameter: R=0.2/R=0.4

p+p: “Narrowing” of the jet structure
with increasing jet energy

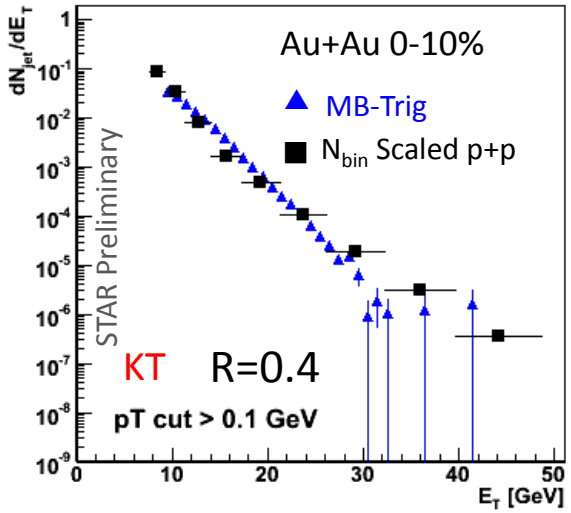


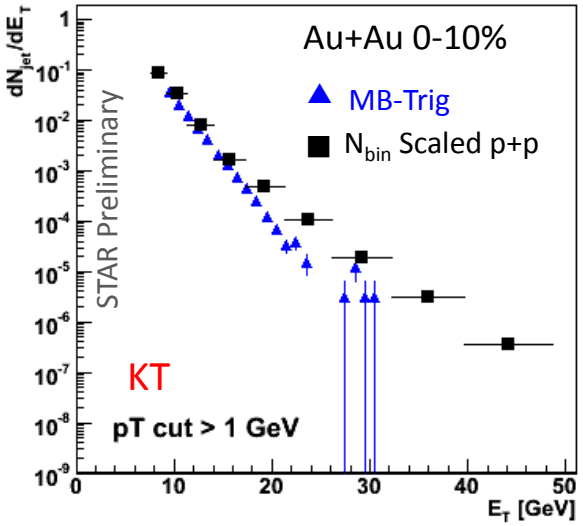
Suppression in Au+Au collisions
-> loss of jet yield for R=0.2

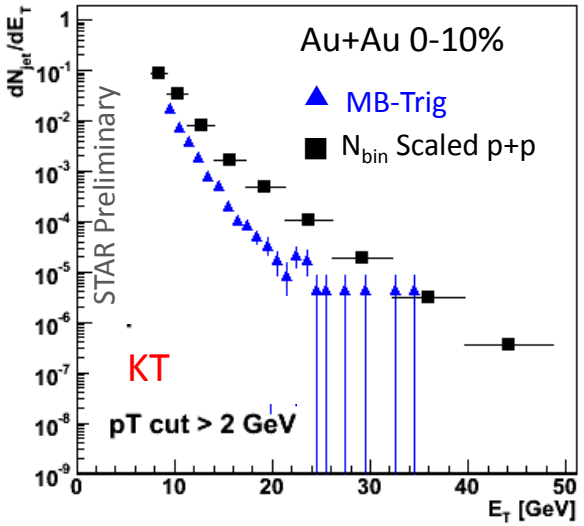
Au+Au: Broadening of the jet energy profile

Vary P_T ^{Cut} : Bias or Physics?

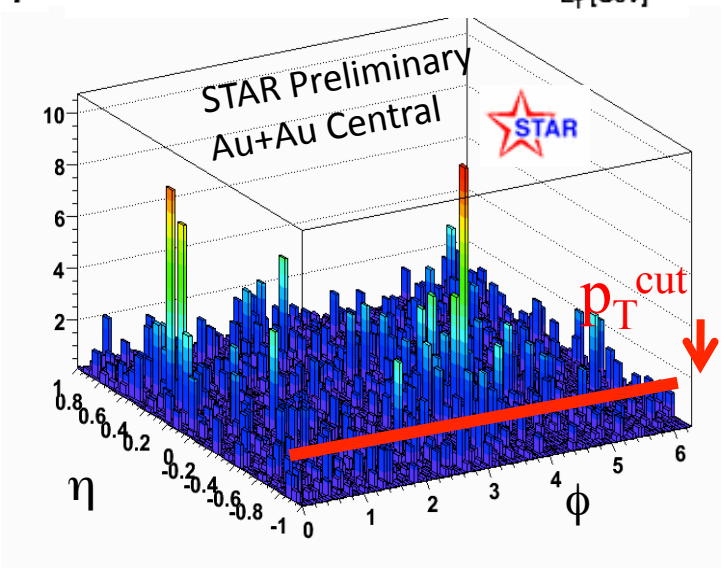
P_T Cut







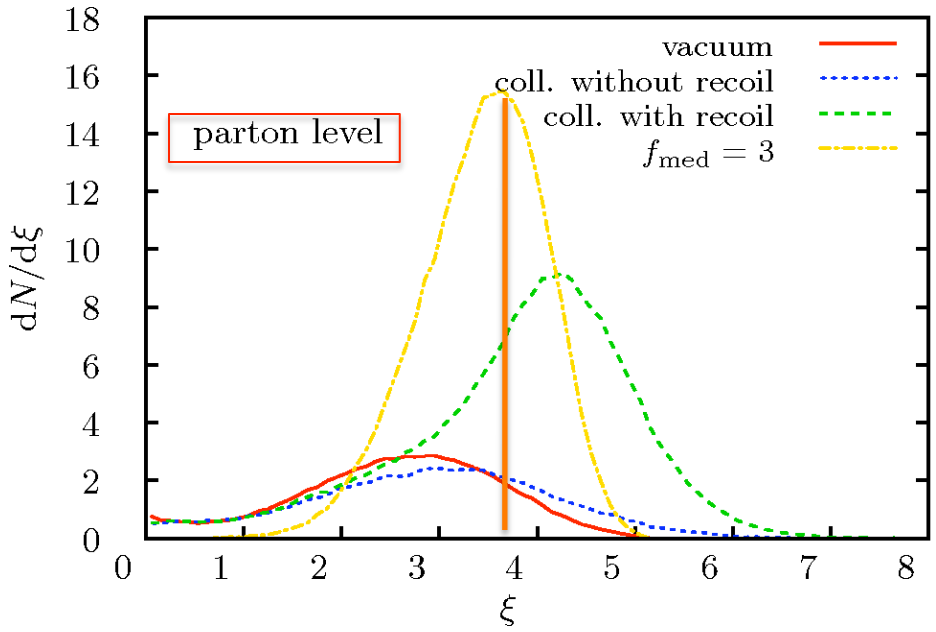
S. Salur [STAR Collaboration], arXiv:0810.0500 [nucl-ex]

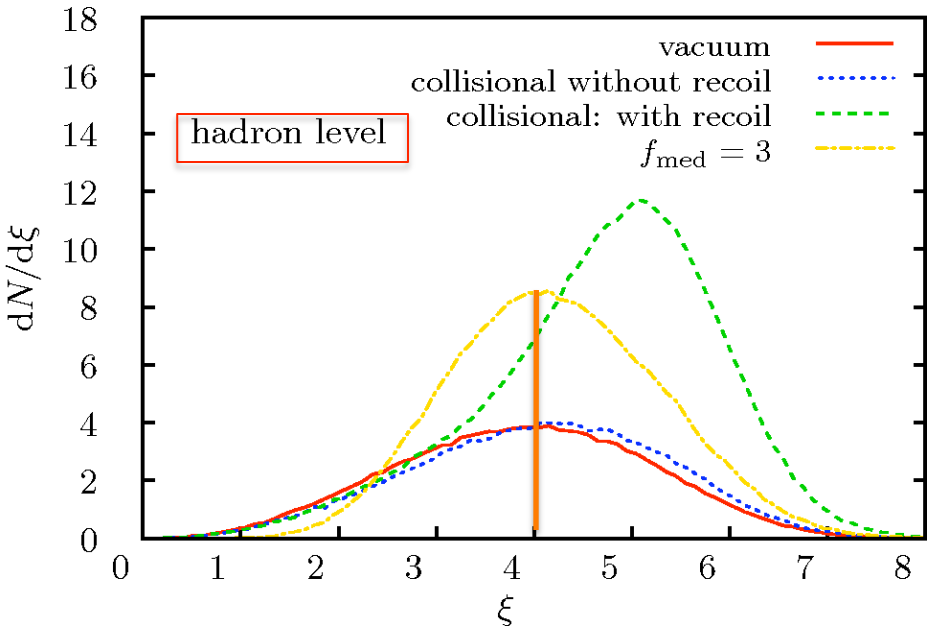


A good test for quenched Monte Carlo's and heavy ion background.

Highly sensitive to fragmentation …

Fragmentation functions: Parton vs Hadron





K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, U. A. Wiedemann arXiv:0804.3568

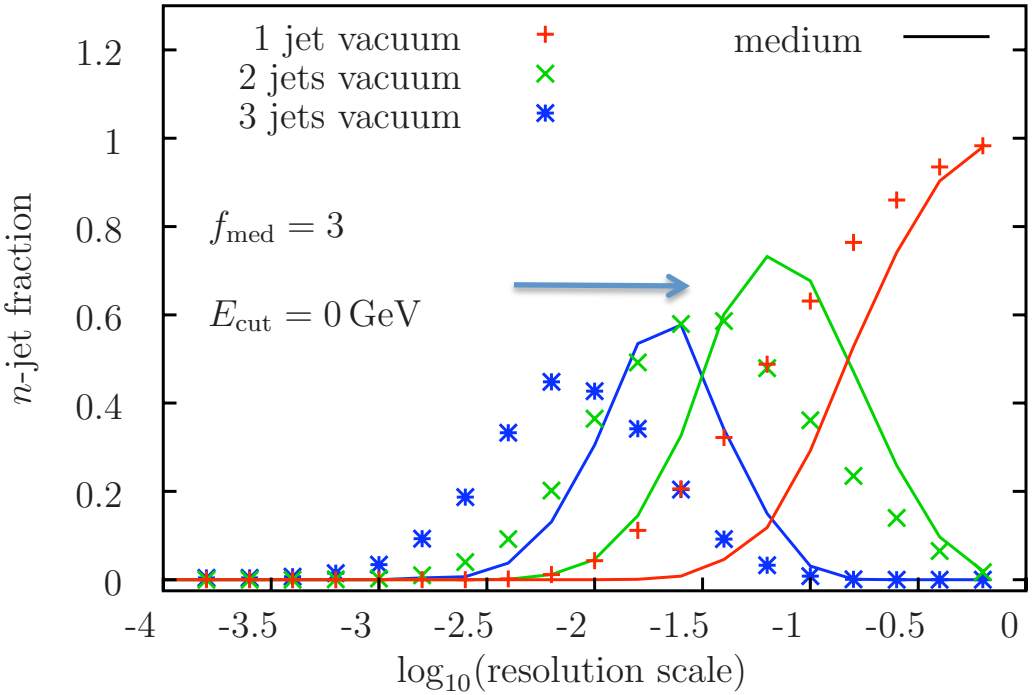
Clear increase in multiplicity due to radiative energy loss

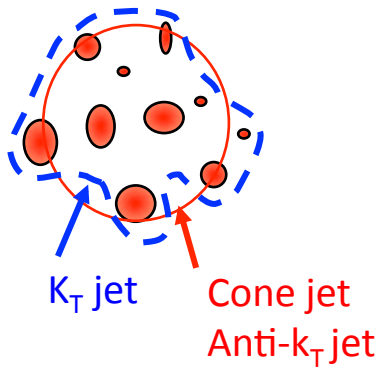
See talks of
Elena Bruna
Ant Timmins
Yue Shi Lai

Significant uncertainties due to the sensitivity to hadronisation:
Look for new observables unaffected by the hadronisation.

QCD JET Observables

In vacuum (LEP) data well understood in pQCD





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Medium Induced Radiation → More Coarser Jet Structure

We need to confront with data….

p_T cut infrared safe insensitive observables! : number of subjets, thurst …

- Full jet reconstruction at RHIC is possible. A new tool to study partonic energy loss…
- First studies indicate significant broadening of the jet energy profile due to quenching

LONG ROAD AHEAD….

- Experimental & Theoretical challenges
- Consistency Checks Multiple channels: Inclusive, di-jets, h-jets, γ-jets
- New observables: energy flow, jet substructure…

•Full jet reconstruction at RHIC is possible. A new tool to study partonic energy loss…

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LONG ROAD AHEAD….

- Experimental & Theoretical challenges
- Consistency Checks Multiple channels: Inclusive, di-jets, h-jets, γ-jets
- New observables: energy flow, jet substructure…

… MORE TO COME SOON!