Full Jet Reconstruction in Heavy Ion Collisions: Prospects and Perils

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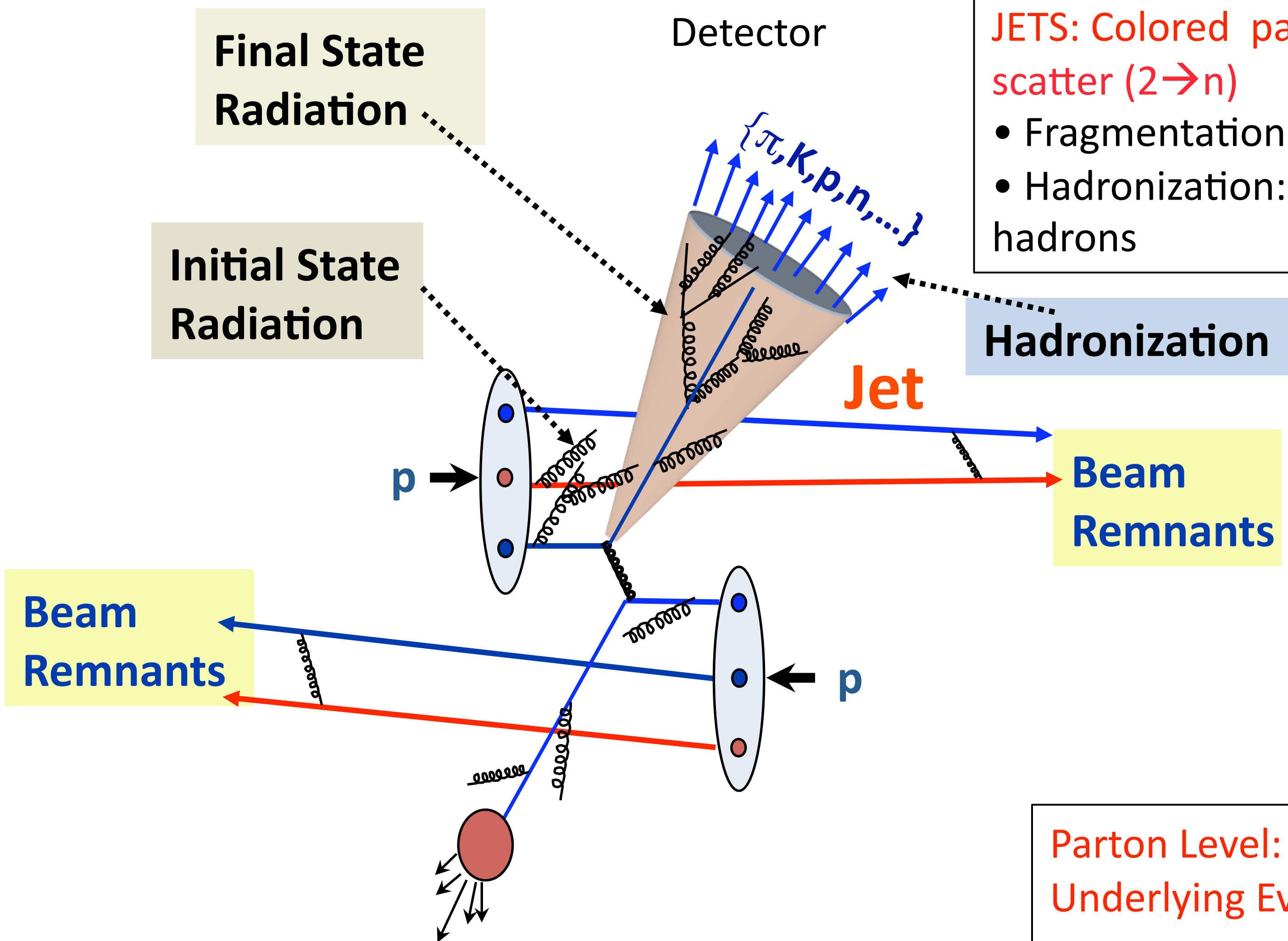
BERKELEY LAB

Why Pursue 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

Jets: a theorist's view



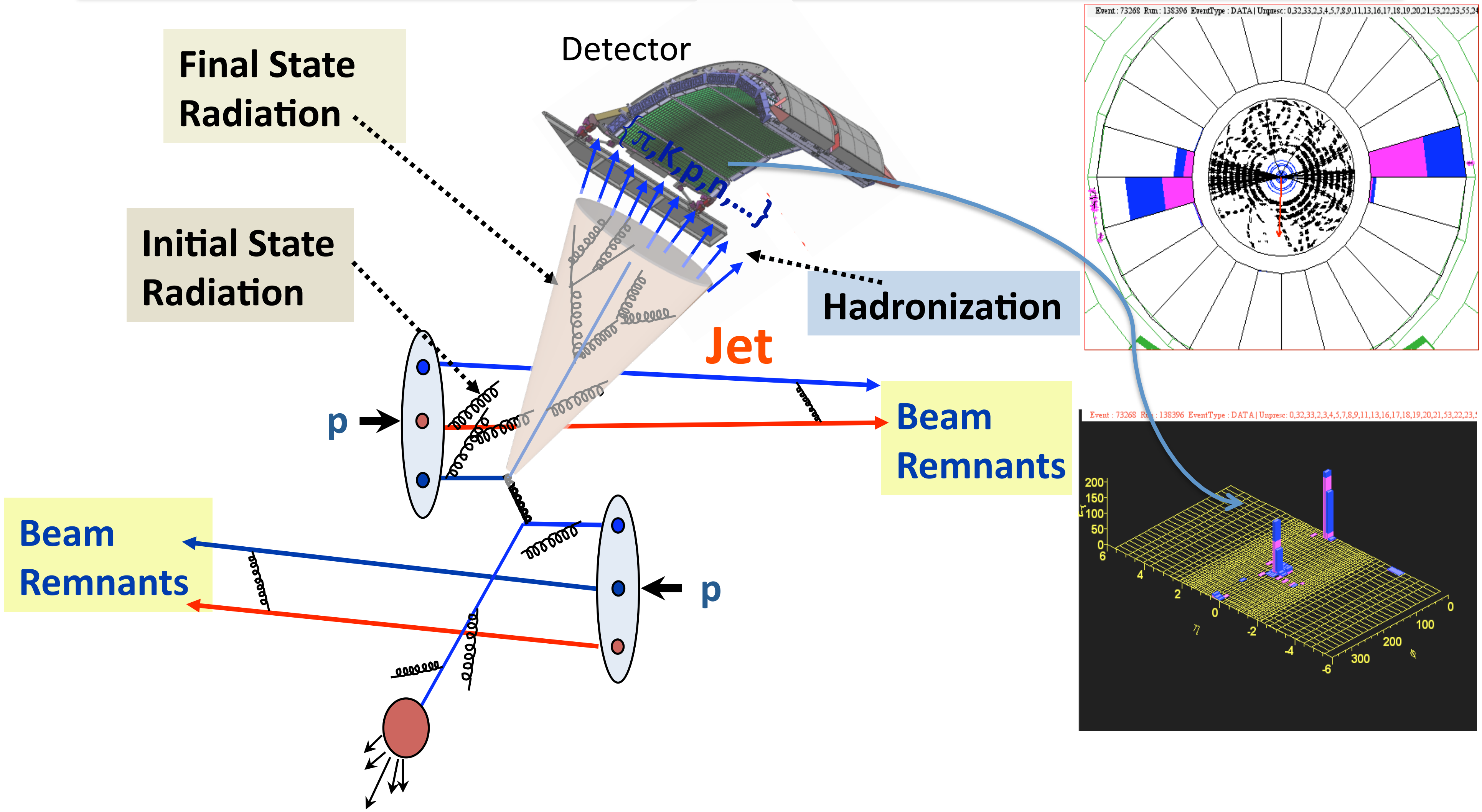
JETS: Colored partons from the hard scatter (2→n)

- Fragmentation via gluon radiation
- Hadronization: "spray" of colorless hadrons

Parton Level: Calculable with pQCD
Underlying Event: Beam remnants
→ Soft Background

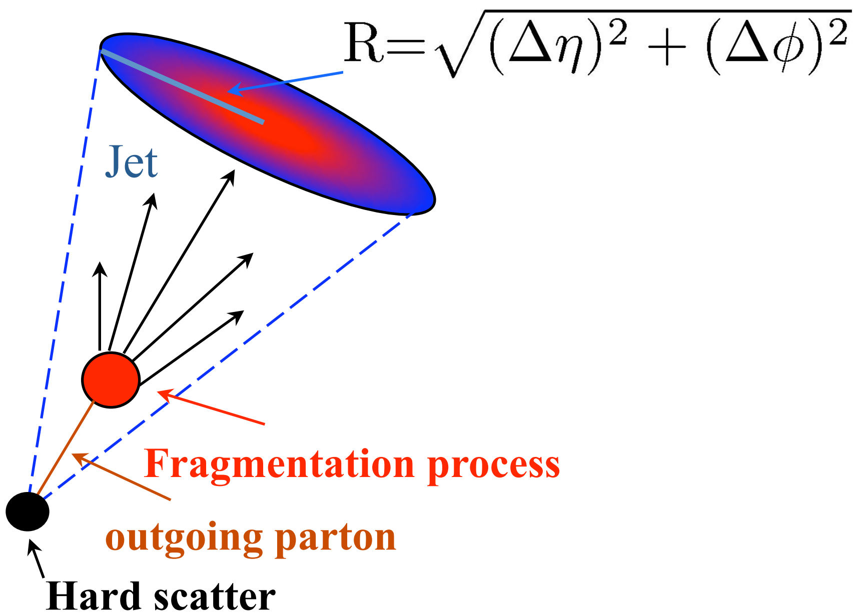
S.D Drell, D.J.Levy and T.M. Yan, Phys. Rev. **187**, 2159 (1969)
N. Cabibbo, G. Parisi and M. Testa, Lett. Nuovo Cimento **4**,35 (1970)
J.D. Bjorken and S.D. Brodsky, Phys. Rev. D 1, 1416 (1970)
Sterman and Weinberg, Phys. Rev. Lett. 39, 1436 (1977)
… and many more

Jets: an experimentalist's view



JETS: Collection of 4-vectors of calorimeter energy clusters and charged track momentum

Jet Reconstruction Algorithms:



Goal: re-associate hadrons to accurately reconstruct the partonic kinematics.

Cone Algorithm:

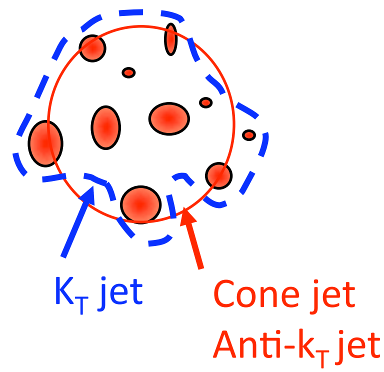
1. Mid Point Cone: Merging & Splitting
2. SIS CONE
3. Leading Order High Seed Cone (LOHSC)

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



Prospects: 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**

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

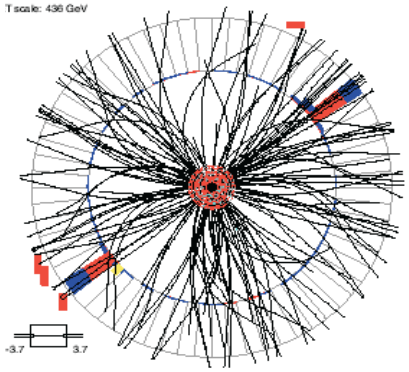
A= Jet Area ρ = Diffuse noise, σ=noise fluctuations

A, ρ, σ are all measurable quantities!

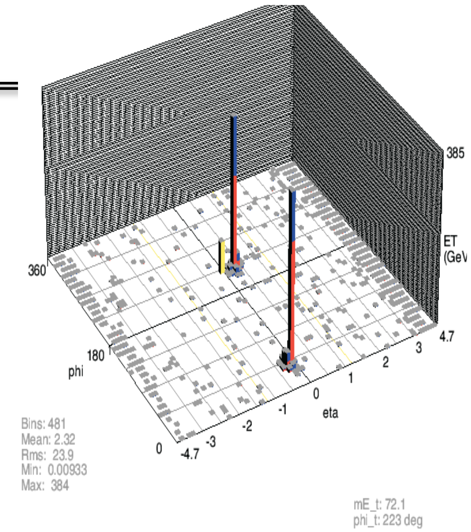
M. Cacciari, G. Salam 0707.1378 [hep-ph]

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

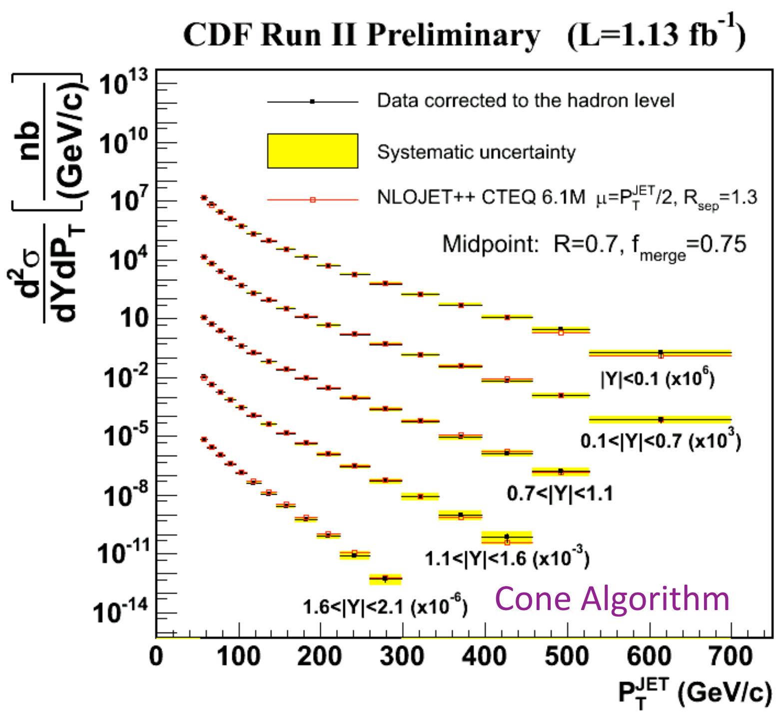
FastJet – http://www.lpthe.jussieu.fr/~salam/fastjet



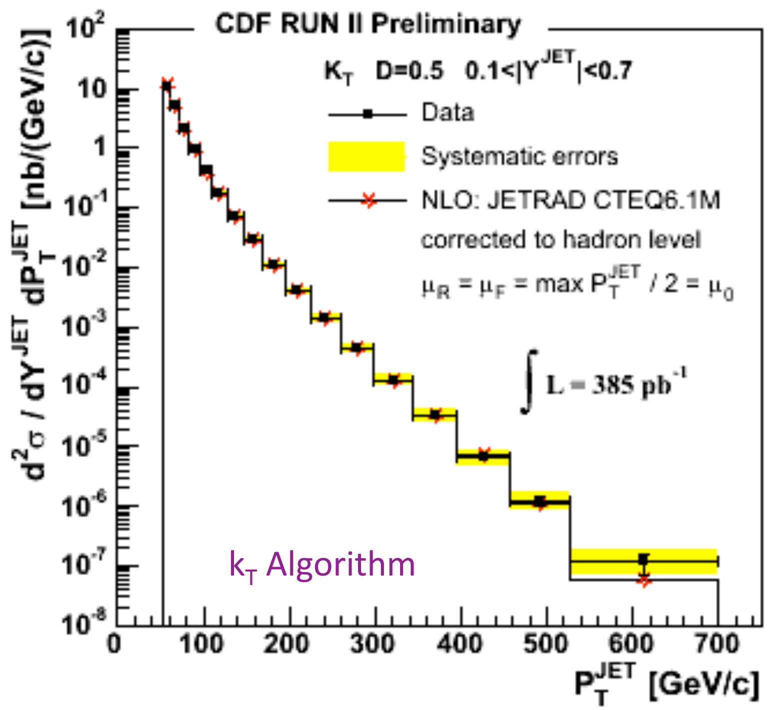
Jets in p+p at the Tevatron



Cone and k_T jet spectra are consistent



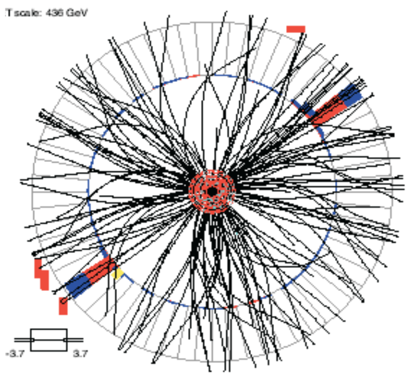
Cone Algorithm



k_T Algorithm

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

Jets in p+p at the Tevatron



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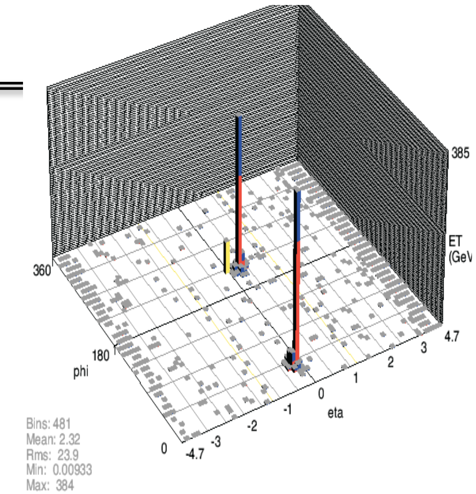
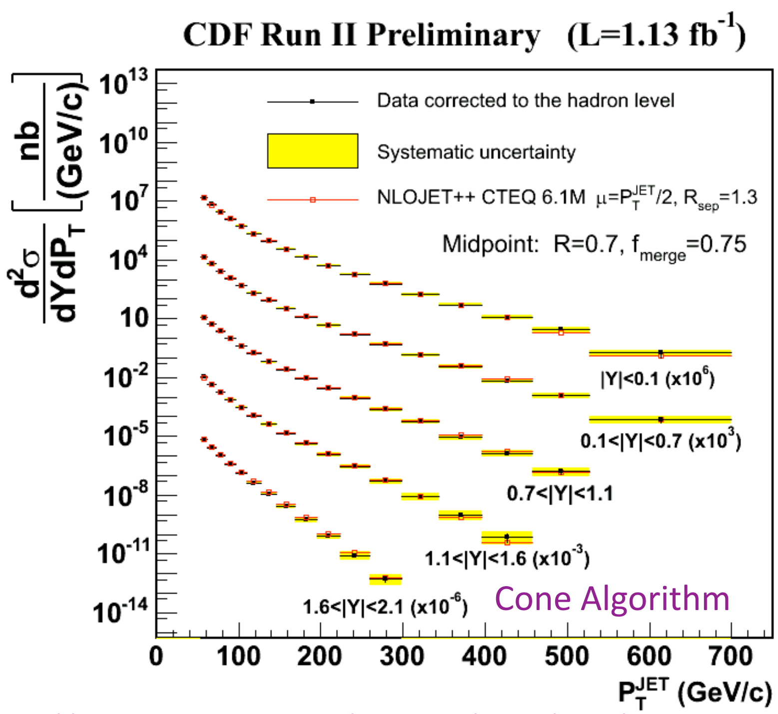
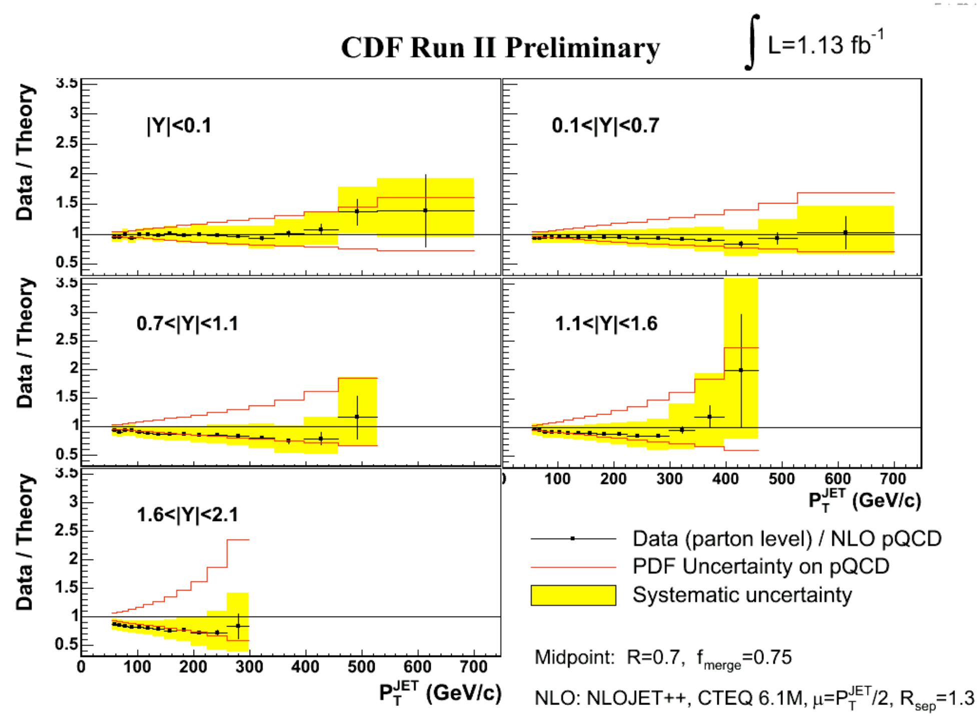


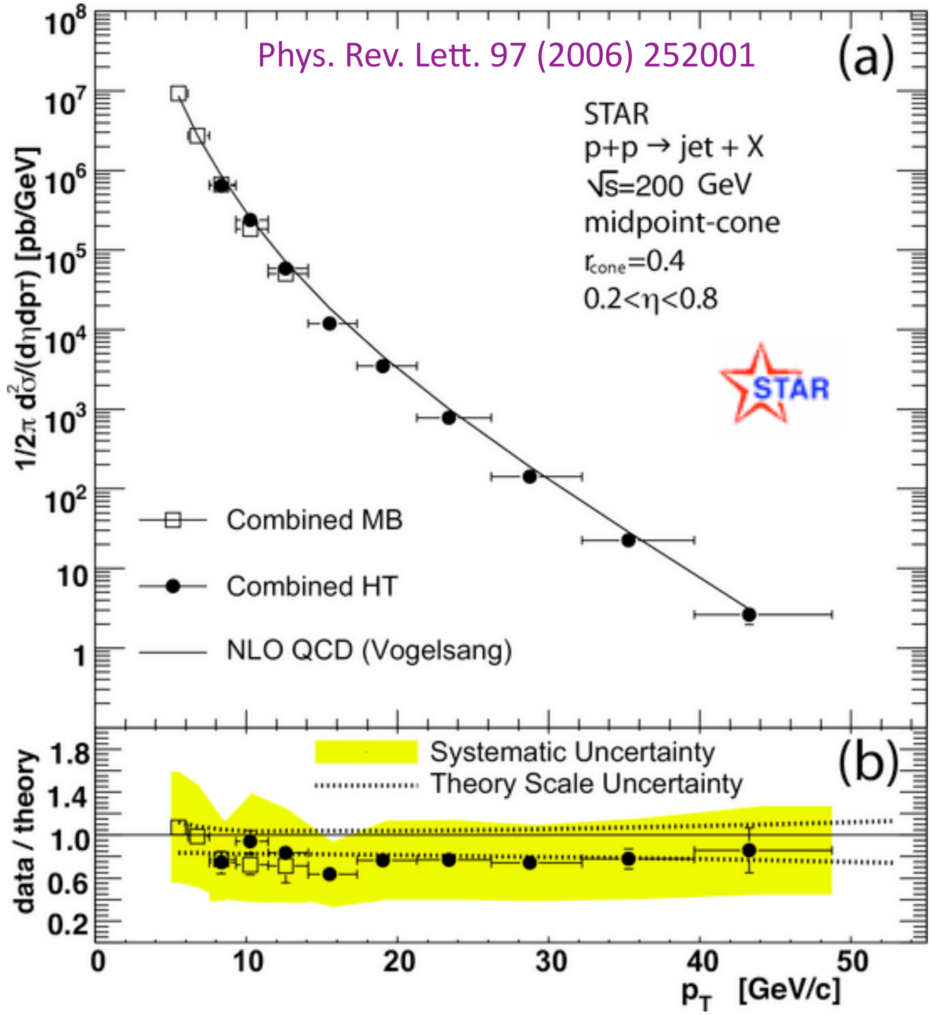




http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

Inclusive jet cross section over many orders of magnitude consistent with the NLO QCD

Jets in p+p at RHIC



Reconstructed by a mid-point jet cone algorithm with R = 0.4

STAR jet reconstruction:

- neutral energy from Barrel EMC
- charged hadrons from TPC

Experimental uncertainty ~50%

Agrees with NLO p-QCD

Perils: Heavy Ion Background

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

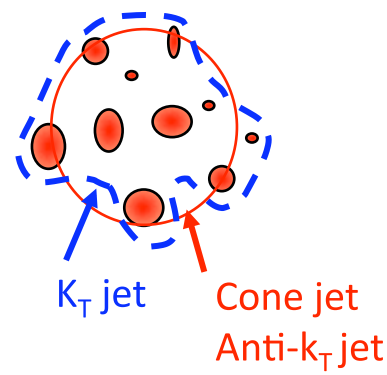
A= Jet Area ρ = Diffuse noise, σ=noise fluctuations

Fundamental Assumption: Two separable components: signal and background.

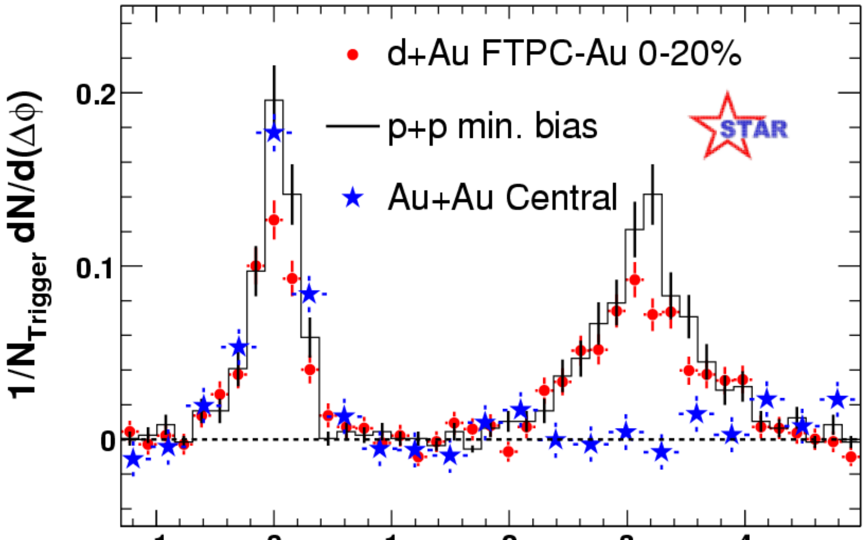
How might it be violated?

1. 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.

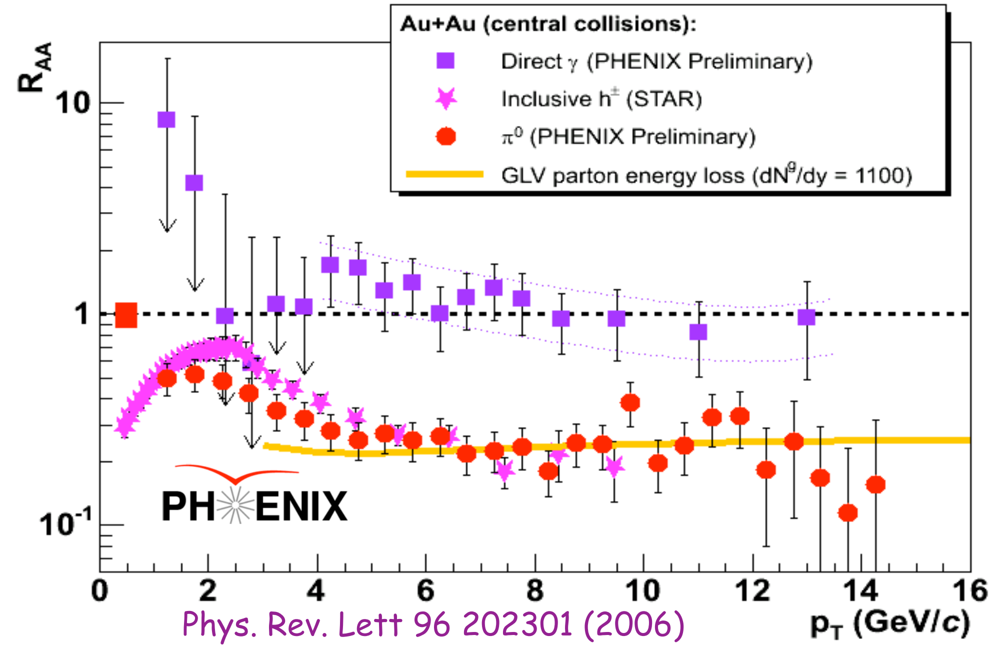
2. Different Algorithms respond differently to background. (k_T and Anti-k_T)



Towards Jets in A+A at RHIC



Phys. Rev. Lett. 91 (2003) 072304 $\Delta\ \phi$ (radians)



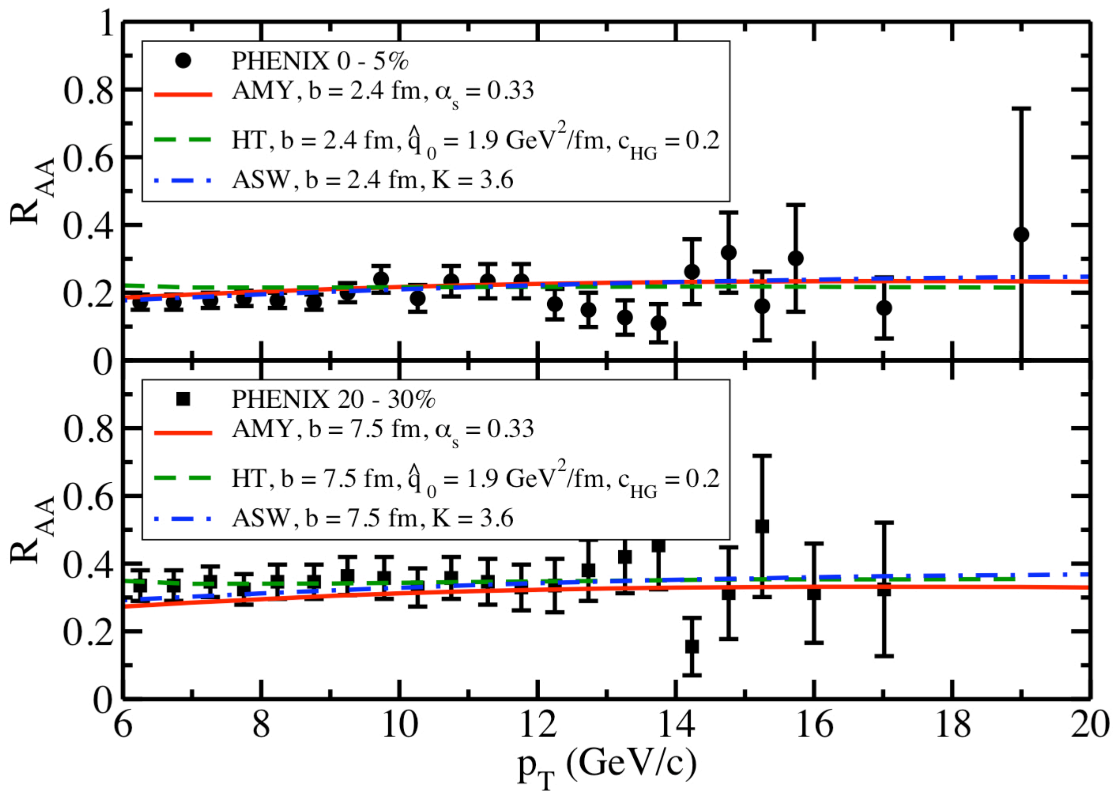
Phys. Rev. Lett 96 202301 (2006)

High p_T hadron suppression described by pQCD+partonic energy loss

Medium seems to be transparent to photons → colored medium.

Conclusive evidence for large partonic energy loss in dense matter (final state effect)

Jet quenching via inclusive hadrons: Quantitative Understanding?



Theory: Modifications of jets in a 3-D hydrodynamic medium

All calculations have same initial structure, final vacuum fragmentation, nuclear geometry.

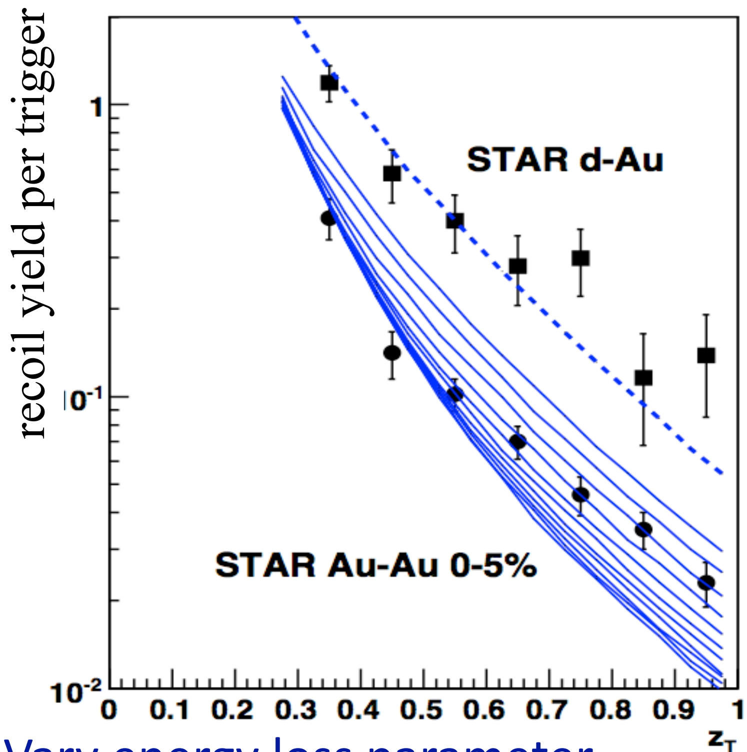
S. A. Bass, C. Gale, A. Majumder , C. Nonaka, G. Qin, T. Renk, J. Ruppert 0808.0908 [nucl-th]

Parameters can be adjusted to describe data well: $\hat{q}$ varies between 4-18 GeV/c^2

Good fit of theory to data but limited discrimination of underlying physics.

https://wiki.bnl.gov/TECHQM

Di-Hadrons : Quantitative Understanding?



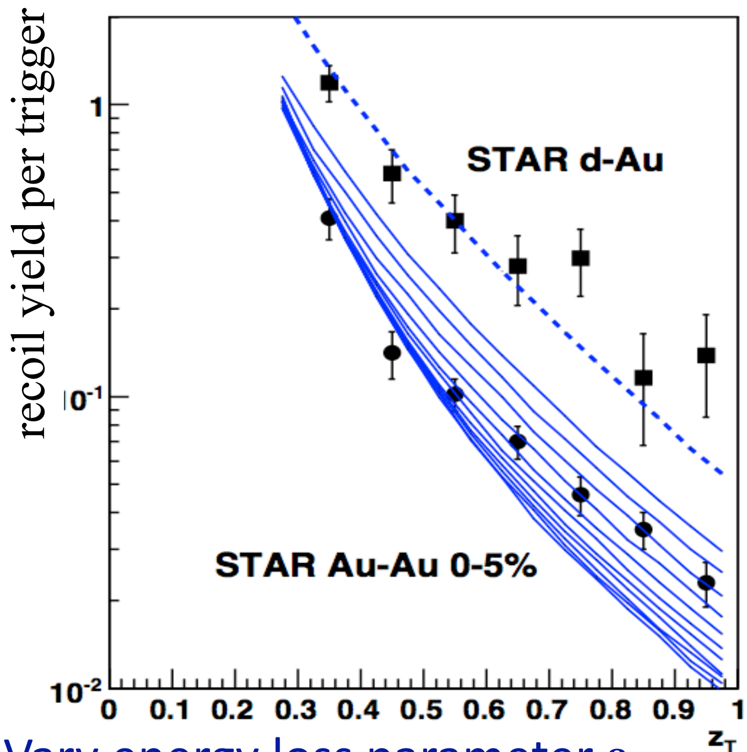
Vary energy loss parameter

H. Zhang, J. F. Owens, E. Wang, X.N. Wang Phys. Rev. Lett. 98, 212301 (2007)
J.L. Nagle arXiv:0805.0299 [nucl-ex]
J. Adams, et al Phys Rev. Lett. 97, 162301 (2006)

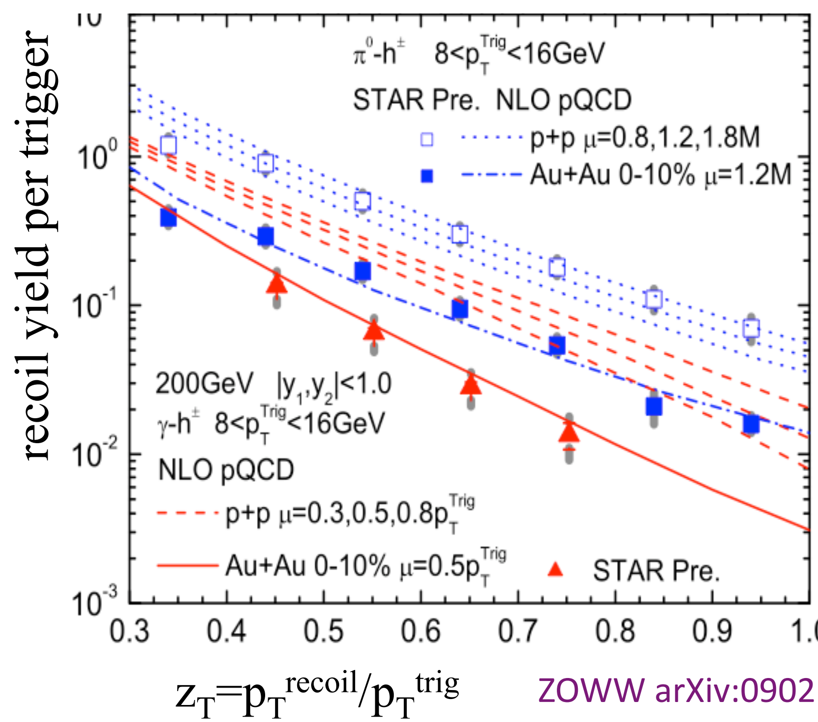
$z_T = p_T^{recoil}/p_T^{trig}$

Di-hadron suppression not yet well-described by NLO theory

Di-Hadrons : Quantitative Understanding?



Vary energy loss parameter ε_0



ZOWW arXiv:0902.4000

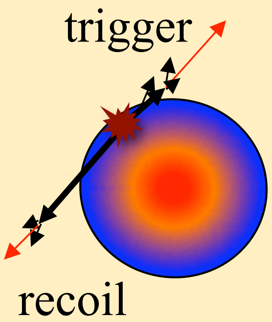
H. Zhang, J. F. Owens, E. Wang, X.N. Wang Phys. Rev. Lett. 98, 212301 (2007)

J.L. Nagle arXiv:0805.0299 [nucl-ex]

J. Adams, et al Phys Rev. Lett. 97, 162301 (2006)

New developments are in progress! ☺

Full Jet Reconstruction in Heavy Ion Collisions



Multi-hadronic Observables:

- Geometric Biases: dominated by jets that have not interacted!
- Limited kinematic reach.
- Jet energy not constrained.

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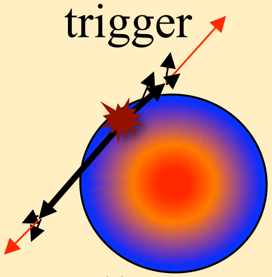

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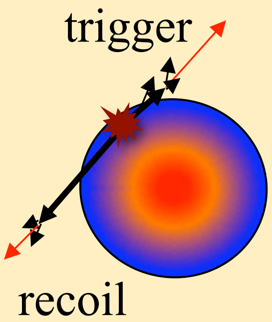

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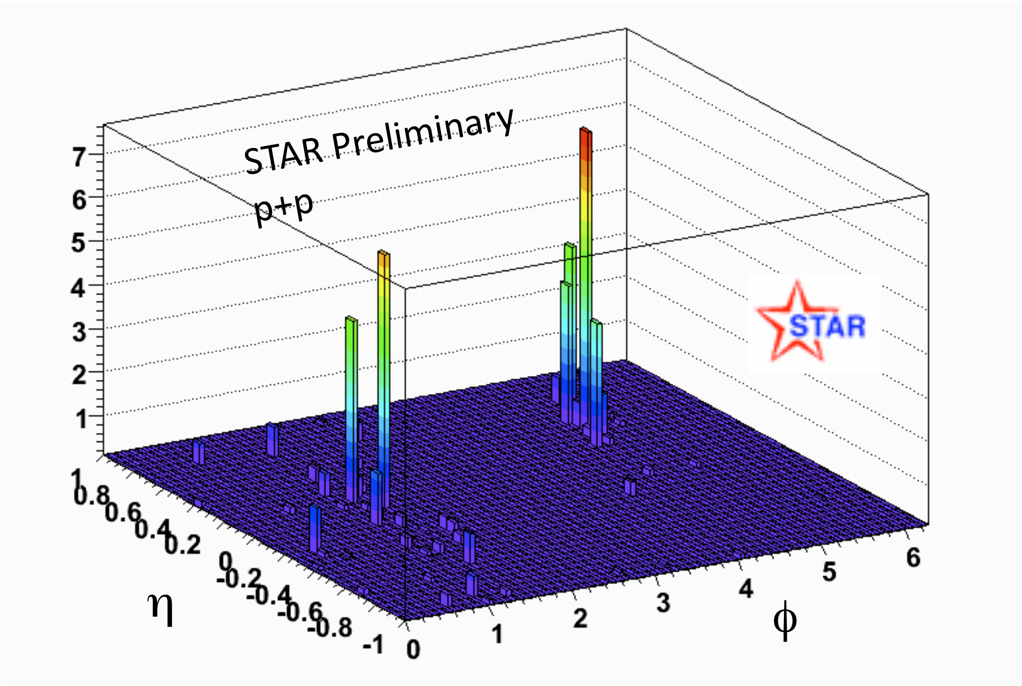
Goal is Unbiased Jet Reconstruction:

Reconstruct partonic kinematics independent of fragmentation details - quenched or unquenched.

Can we see jets at RHIC?



QM 2009 J. Putschke for the STAR Collaboration

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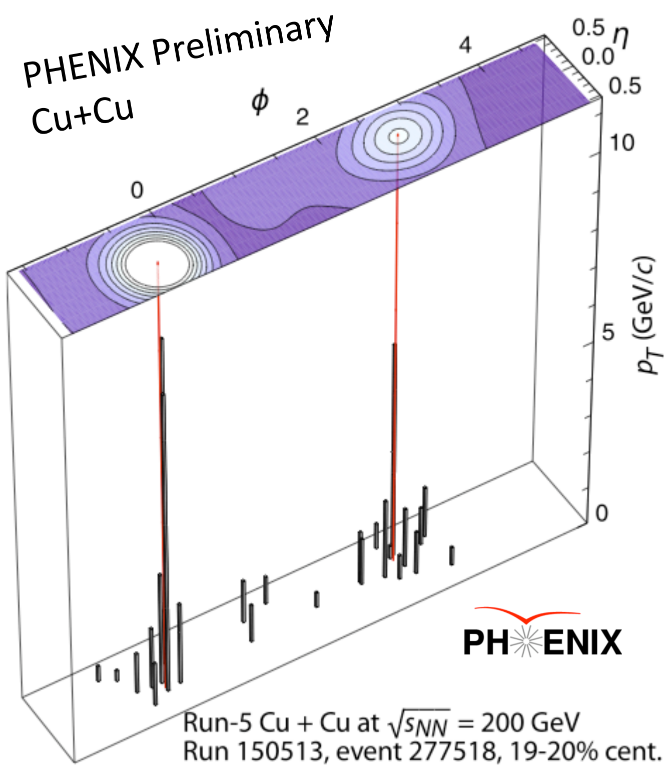
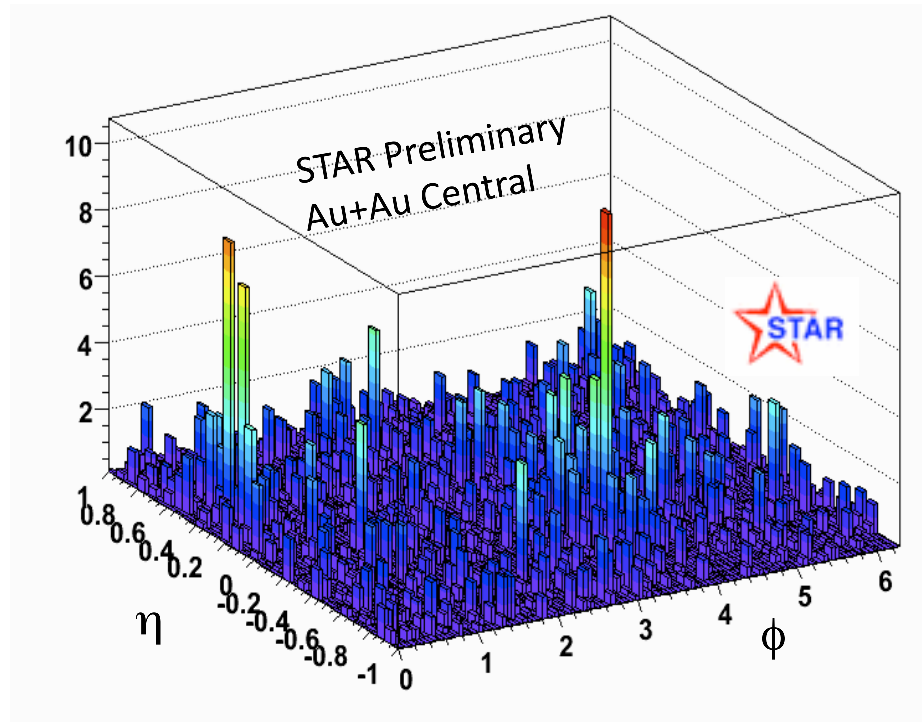
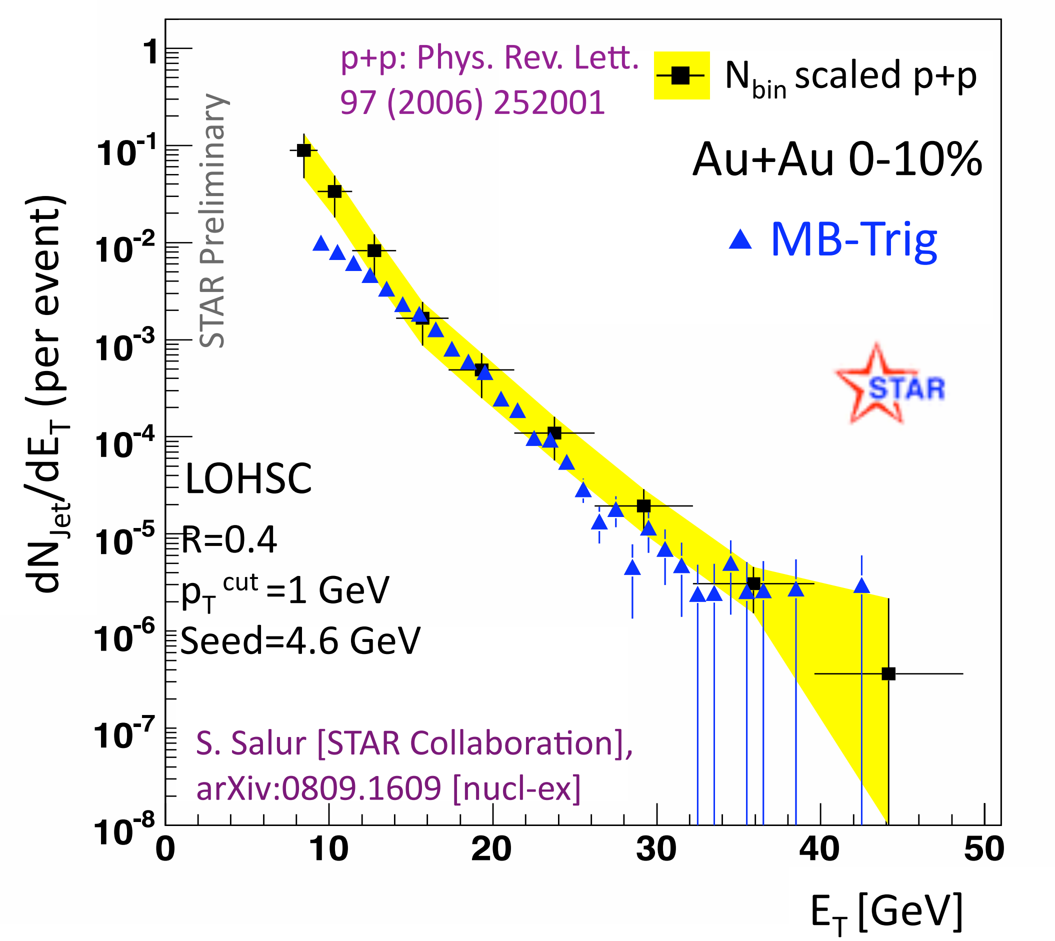




Next Talk: Yue Shi Lai

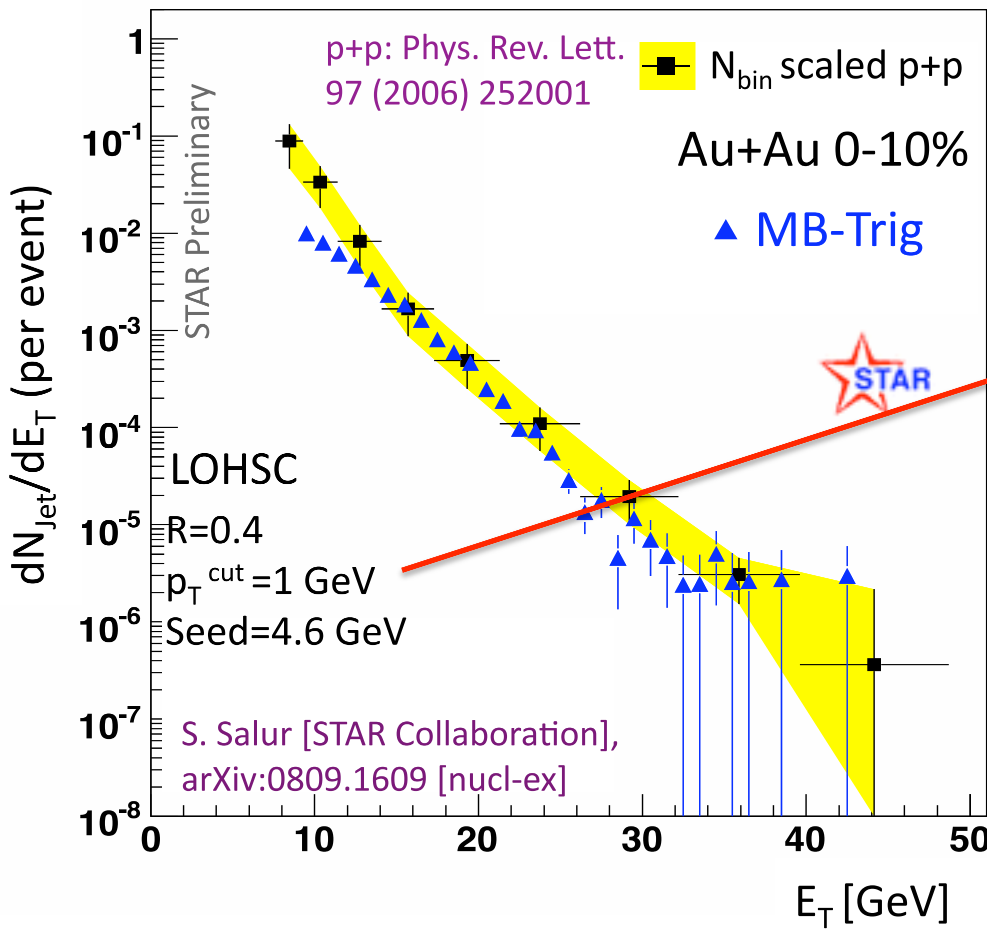
Reconstructed Jet Spectra & Corrections:



MB-Trig: Minimum Bias Trigger

Agreement with N_{bin} Scaled p+p (~50%).

Reconstructed Jet Spectra & Corrections:



MB-Trig: Minimum Bias Trigger

Suppression of backgrounds in heavy ions:

Limit jet resolution parameter R

Cut on track/calorimeter p_T

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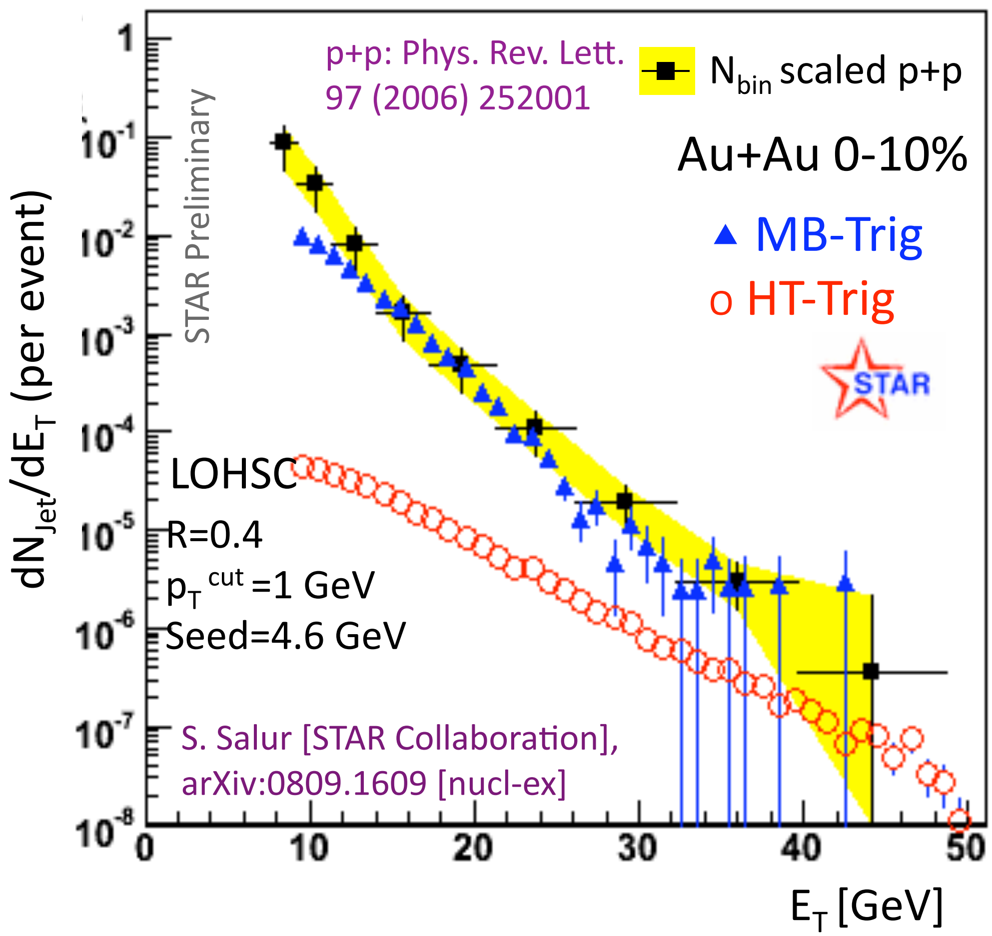
Reconstructed Jet Spectra & Corrections:



MB-Trig: Minimum Bias Trigger

Suppression of backgrounds in heavy ions:
Limit jet resolution parameter R
Cut on track/calorimeter p_T

HT-Trig: Satisfied Minimum Bias and requires a pion/photon with p_T>7.5 GeV

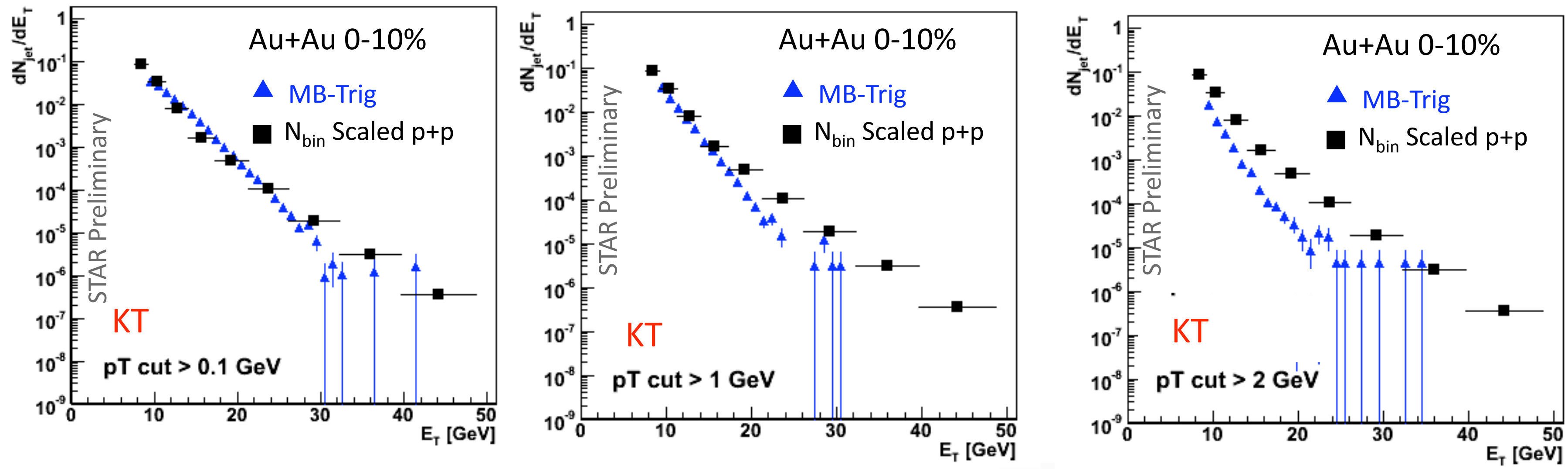
Large HT-trigger bias persists at least to 30 GeV. Similar to leading particle bias.

MB-Trigger: Agreement with N_{bin} Scaled p+p (~50%).
HT-Trigger: Bias towards hard fragmentation:
Bad for quenching Studies!

What about other algorithms?

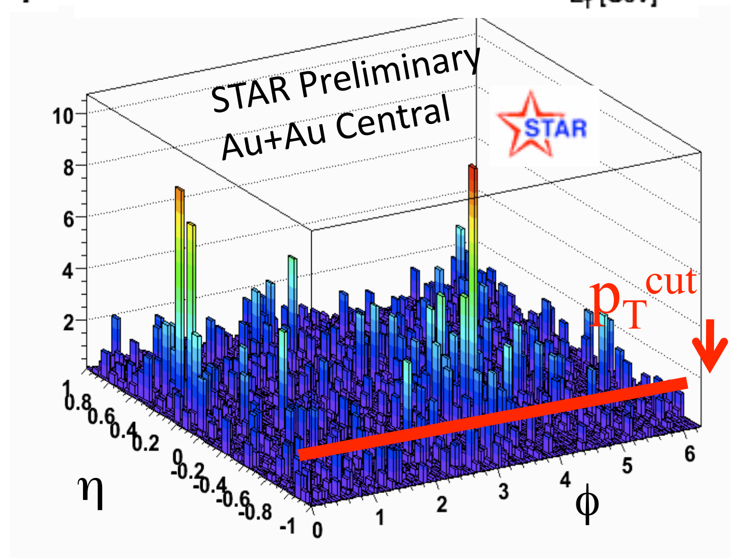
P_T ^{Cut} Dependence Bias

P_T Cut



p+p: Phys. Rev. Lett. 97 (2006) 252001

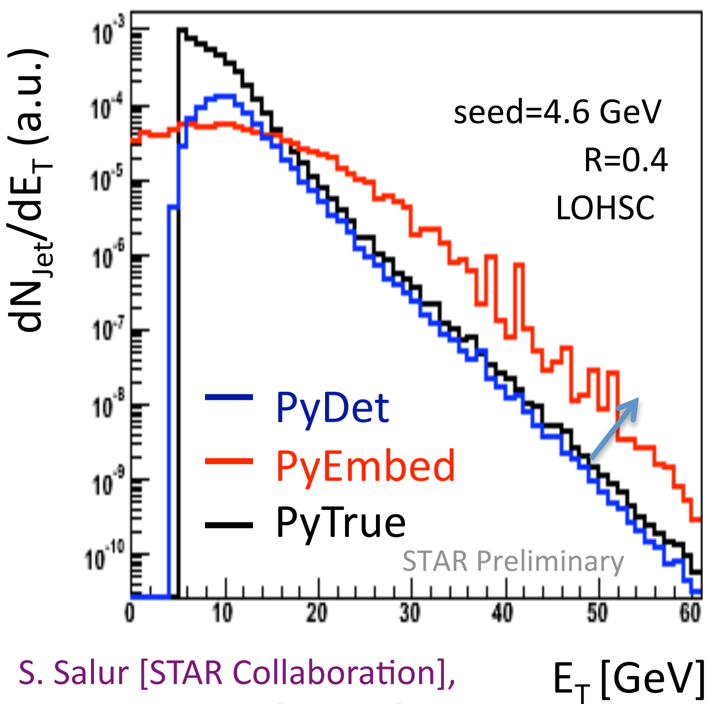
S. Salur [STAR Collaboration], arXiv:0810.0500 [nucl-ex]



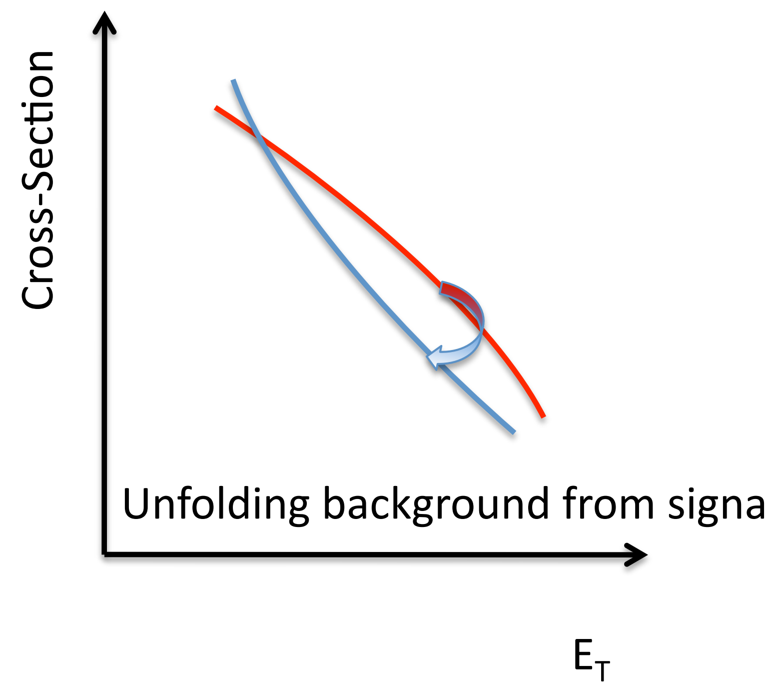
Imprecise subtraction of underlying event?
Do we introduce a bias with p_T-cuts?
Sensitivity to fragmentation model?

Un-Biased Jet Measurements

1) Minimize the kinematic cuts, e.g P_T^{Cut}
2) Data driven corrections :
   a. Experimental characterization of background fluctuations.
   b. Detailed unfolding of fluctuations. → Correcting for smearing

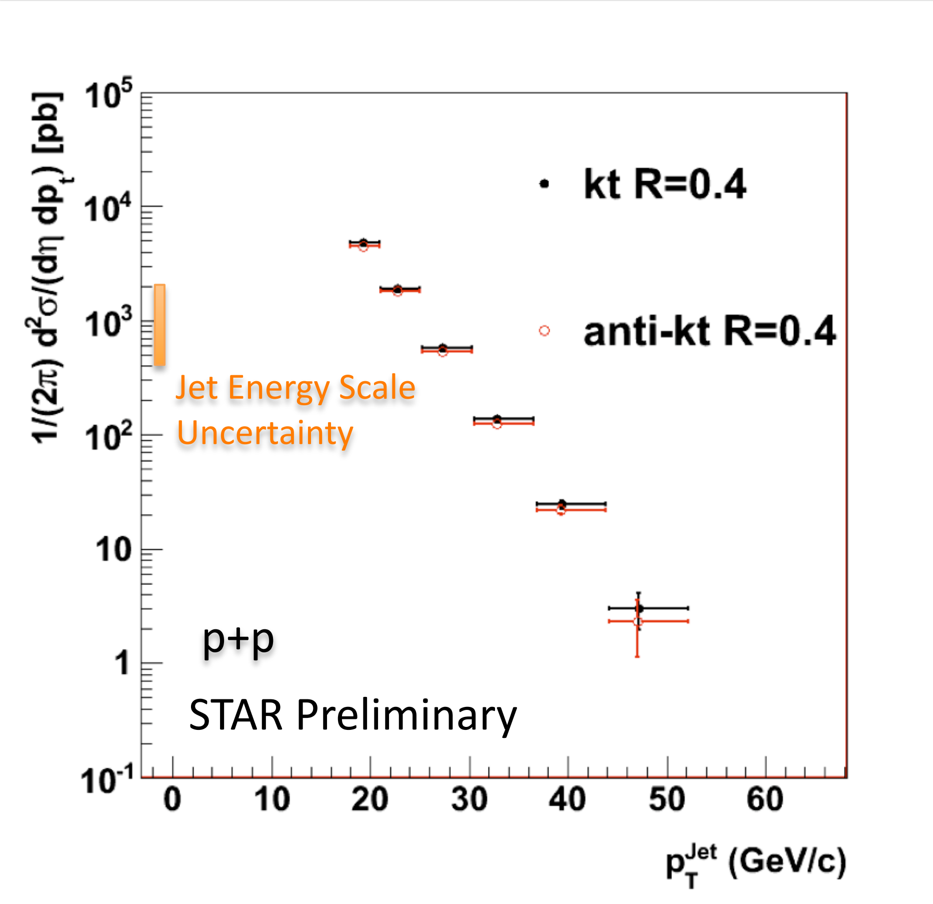


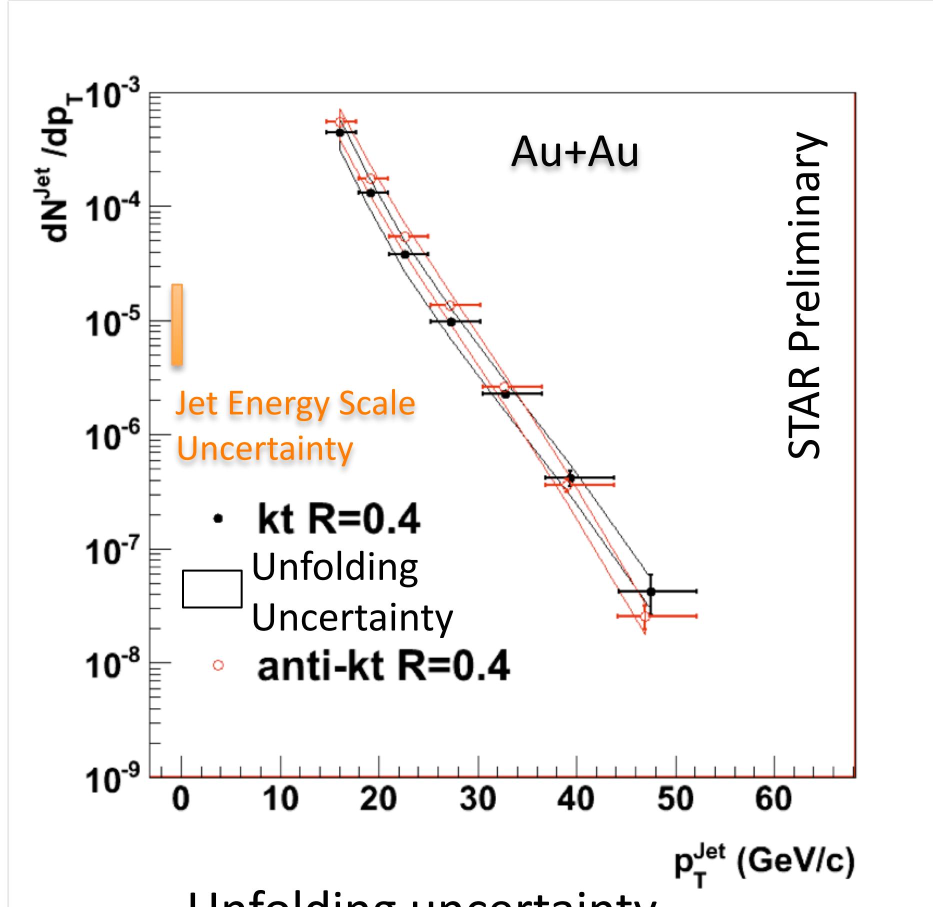
S. Salur [STAR Collaboration], arXiv:0809.1609 [nucl-ex]



Correct via “unfolding” for the “min-bias” jet reconstruction.

Inclusive jet spectrum:





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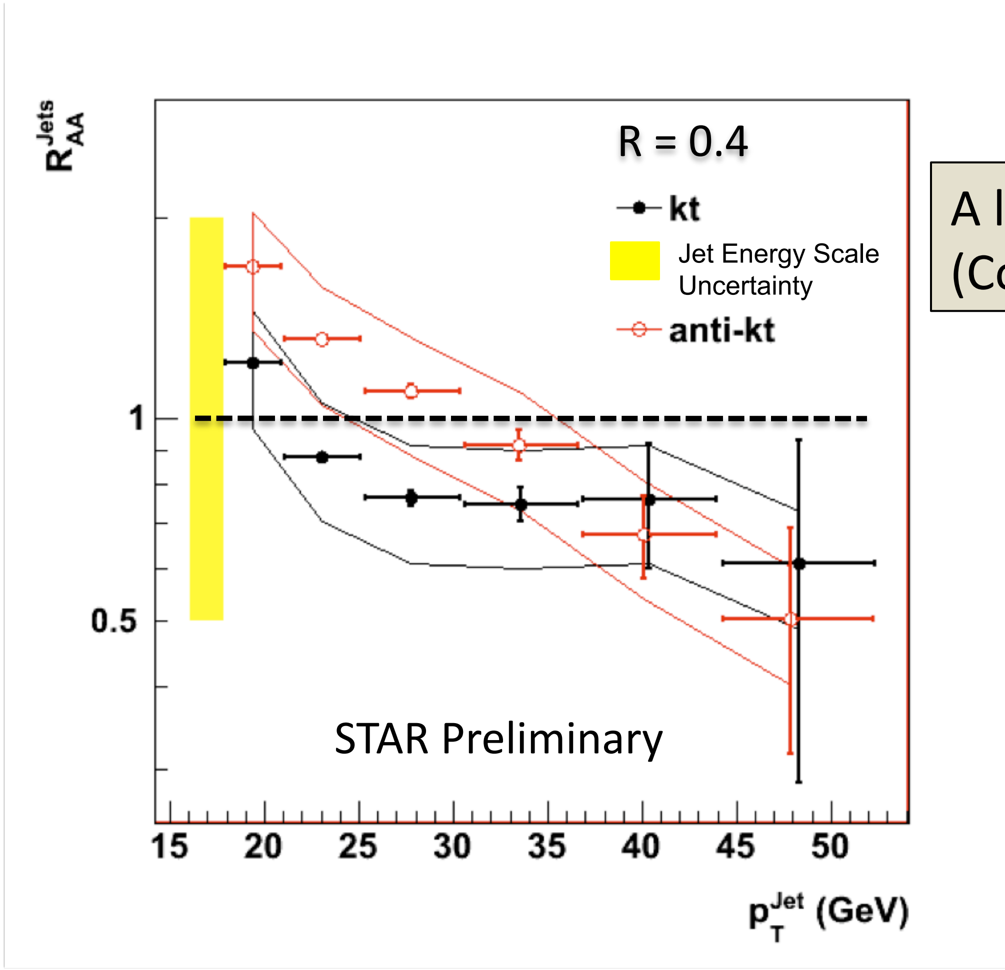
Unfolding uncertainty corresponds to a factor of 2 in jet cross-section.

Anti-k_T and k_T jet spectra are consistent.

R_{AA} of Jets



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

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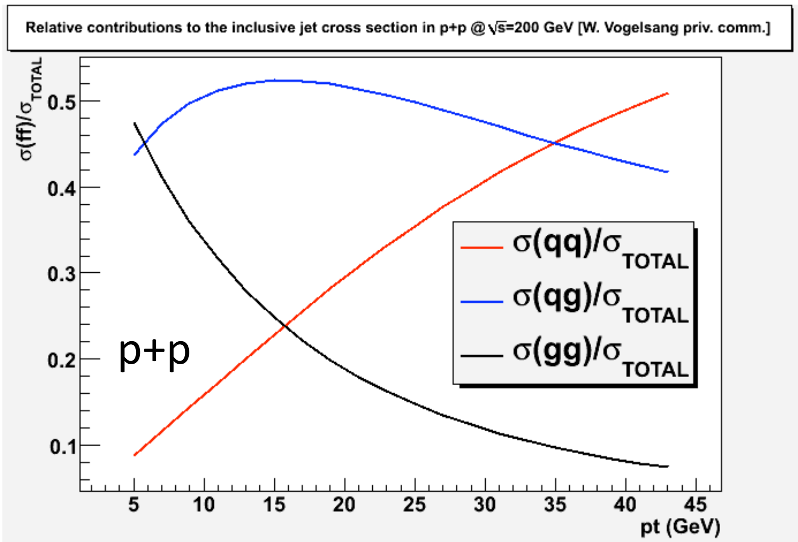
What happens at high p_T?

Relative contribution of sub-processes to inclusive jet production



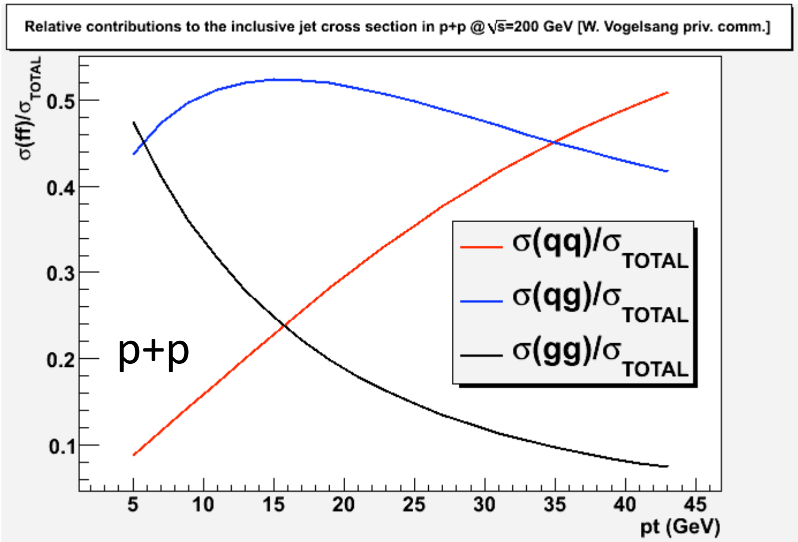
W. Vogelsang Private Communication

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



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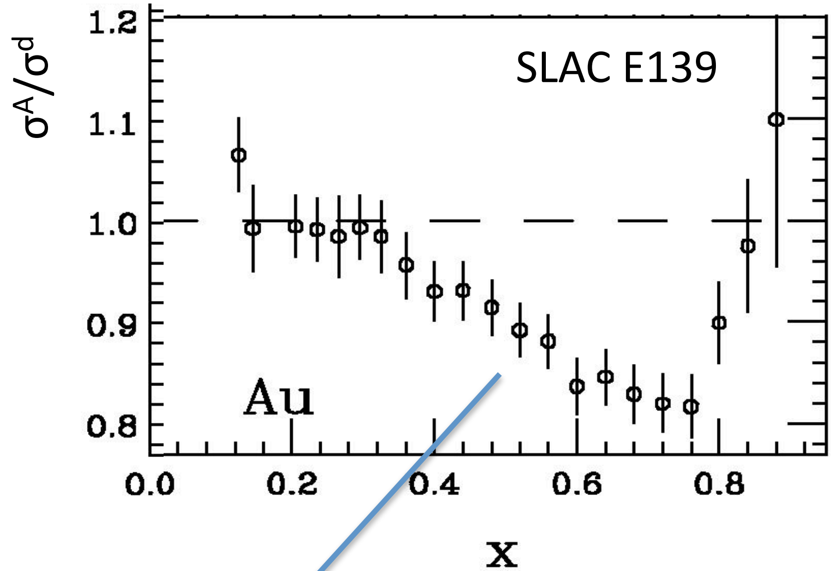


The EMC Effect: Deviation between structure Functions of Au and deuterium.

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 x effects?

Quantitative analysis of data requires model building…

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

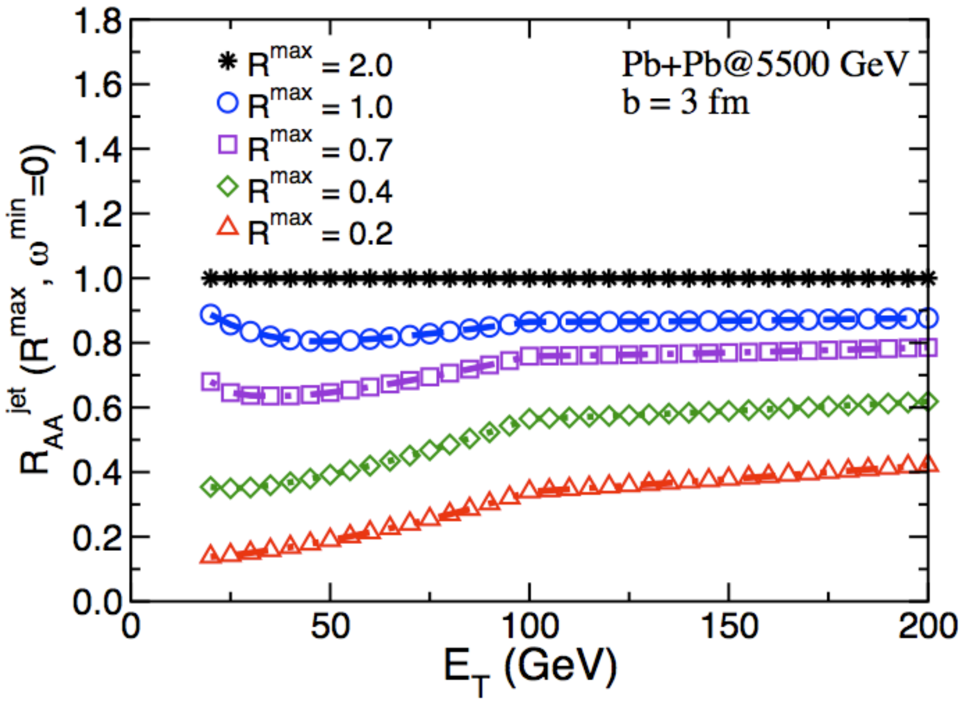
Q-Pythia:
N. Armesto, L. Cunqueiro and C. A. Salgado arXiv:0809.4433[hep-ph]
MC implementation in Pythia of medium-induced gluon radiation through an additive term in the vacuum splitting functions.

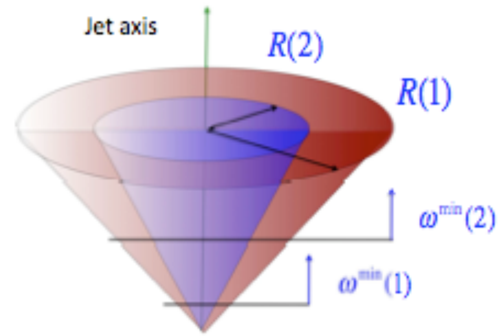
YaJEM:
T. Renk arXiv:0808.1803

Analytic Calculations:
Nicolas Borghini arXiv: 0902.2951
Ivan Vitev et al JHEP 0811:093 (2008), arXiv:0810.2807

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

R_{AA} of Jets at LHC

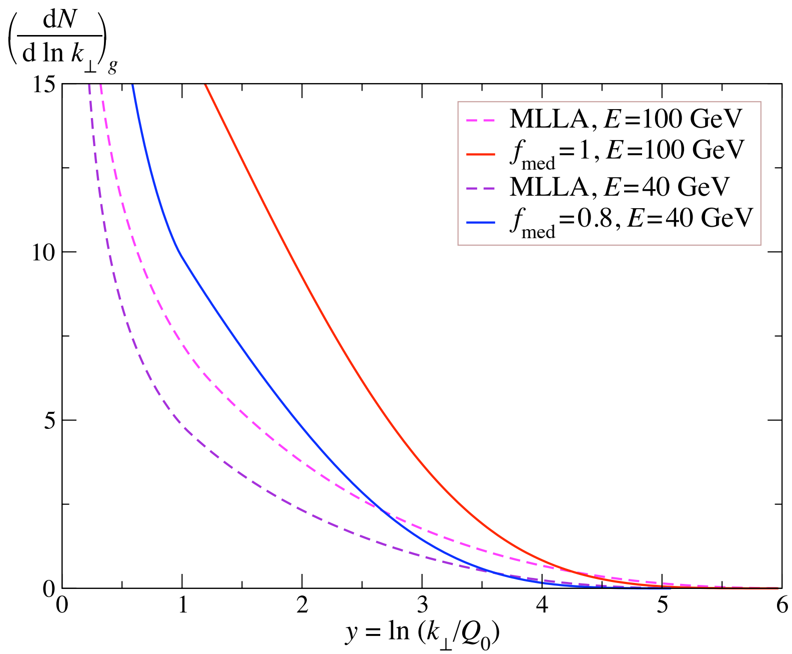




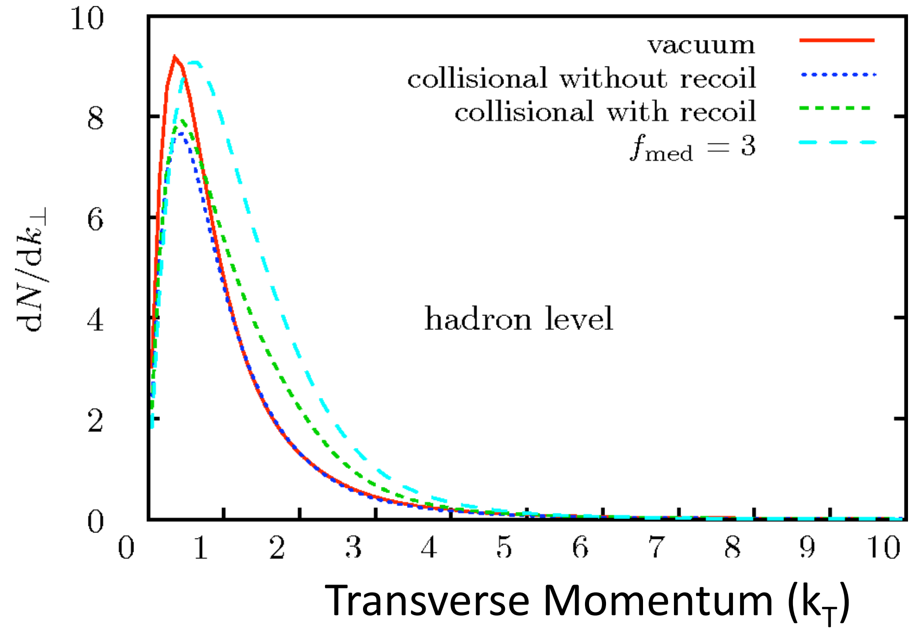
I. Vitev et al JHEP 0811:093 (2008), arXiv:0810.2807

Vary Resolution Parameter → Implication of broadening of jets

Analytic Calculations vs New Monte Carlos



Nicolas Borghini arXiv: 0902.2951



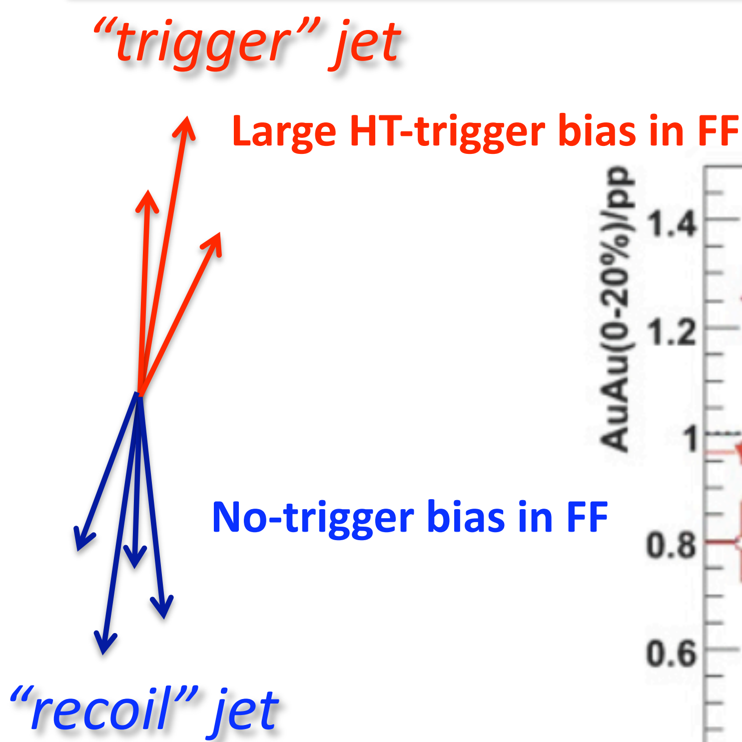
K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, U. A. Wiedemann arXiv:0805.4759

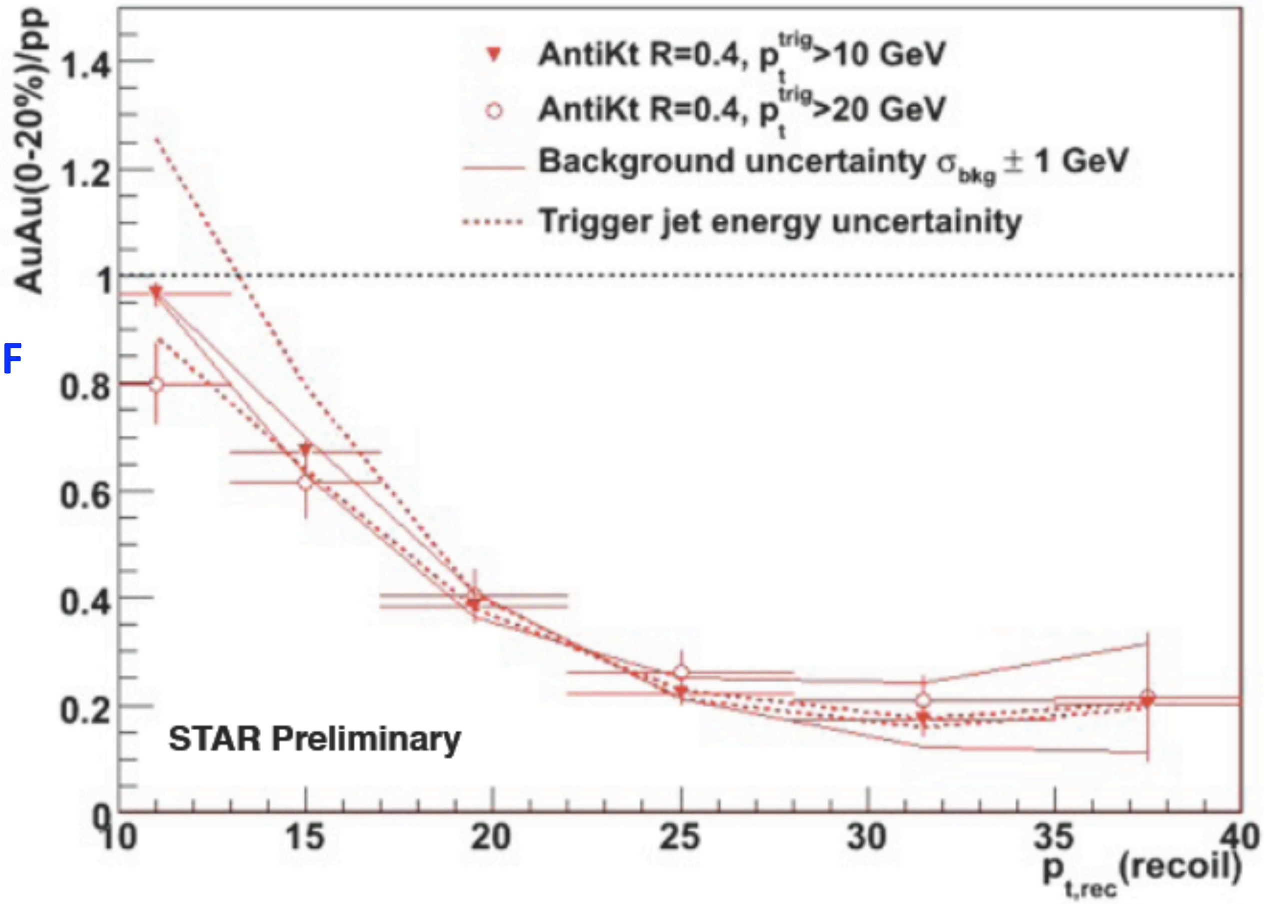
Strong broadening of shower in transverse momentum with respect to jet axis.
Angular distribution becomes wider!

No strong broadening of shower when P_T^{cut} >2 GeV is selected.
(limitations of broadening observable)

We need to confront the calculations with data!

Di-jets





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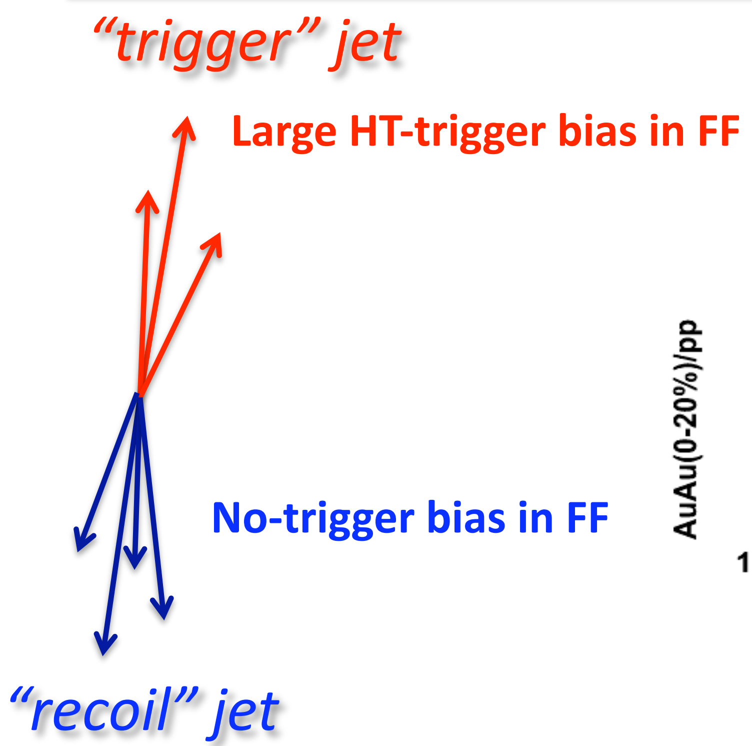
Trigger selection -> Biased population:
- Significant suppression of recoil jet spectrum
- Comparable to single particle R_{AA}

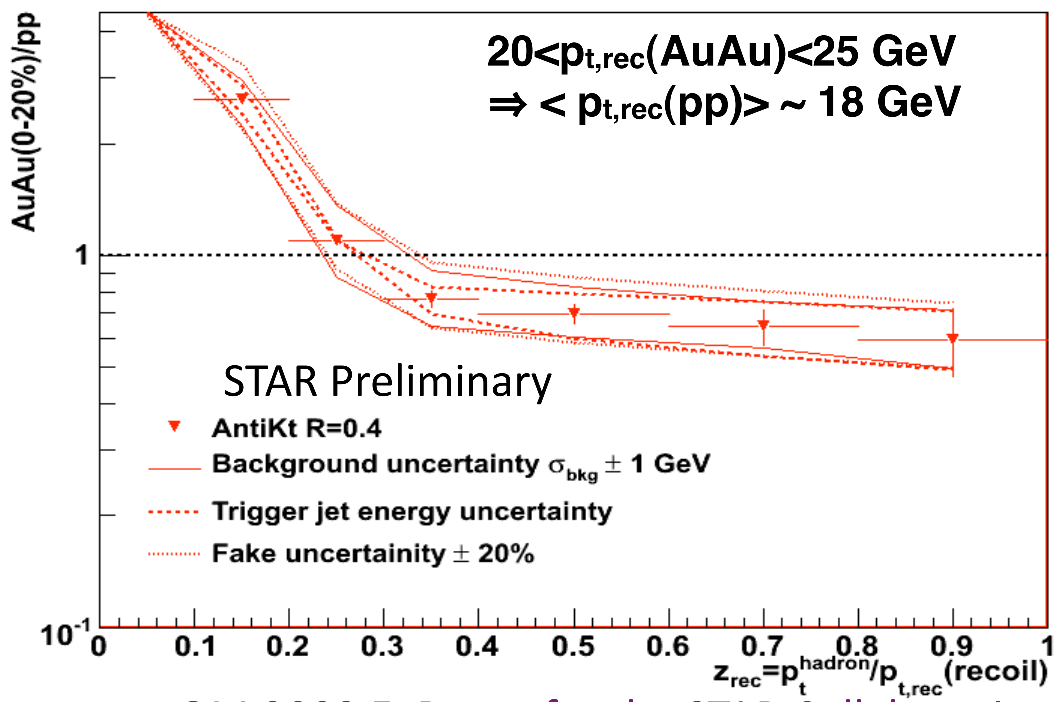
Fragmentation Functions from di-jets



p_T(trigger) > 10 GeV & P_T^{cut}=2 GeV

20<p_T(recoil jet) < 25 GeV & P_T^{cut}=0.1 GeV

large uncertainties due to background
(further systematic evaluation needed)

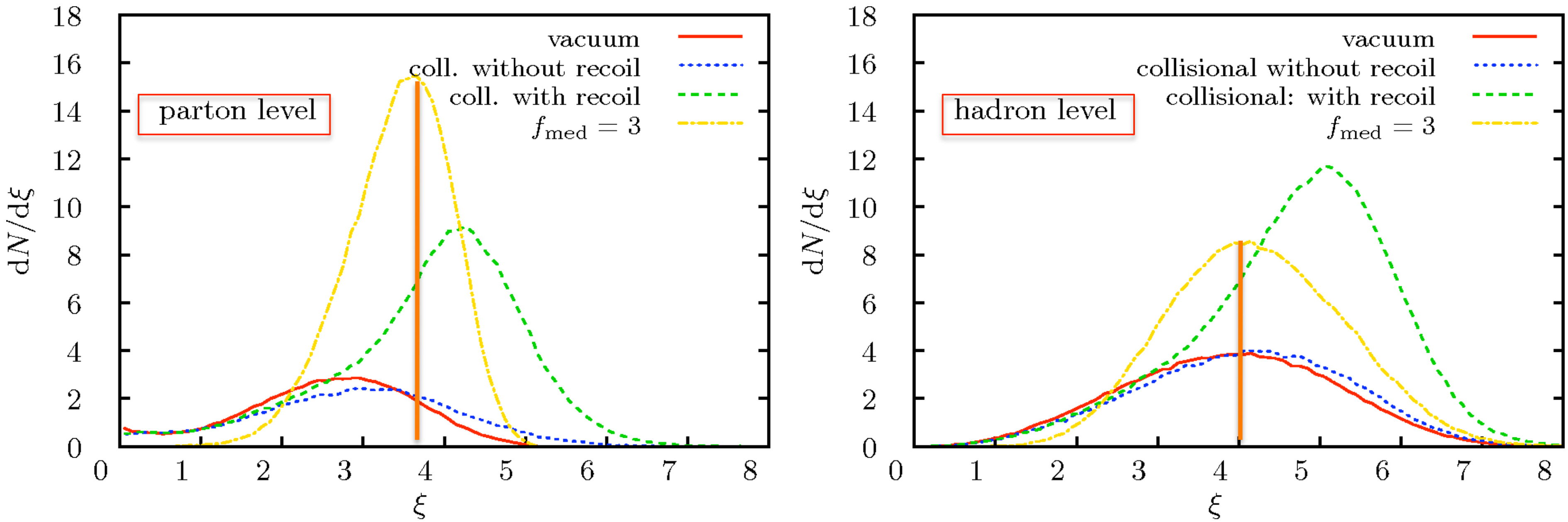


QM 2009 E. Bruna for the STAR Collaboration

Apparent modification in the z of Au+Au with respect to p+p.

But a biased population of jets.

Parton vs Hadron



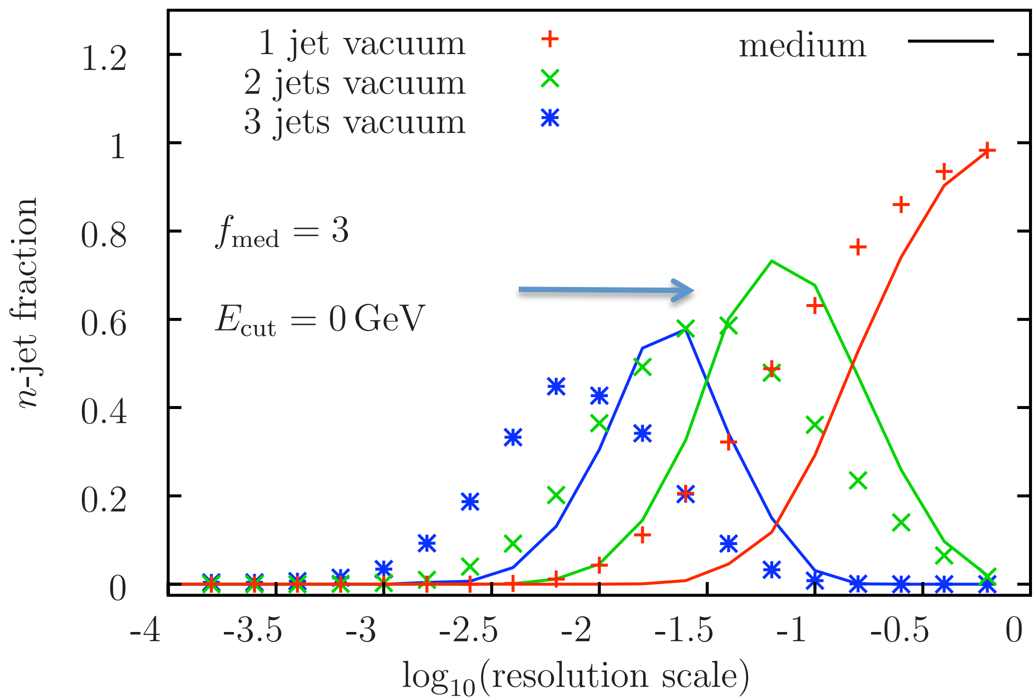
K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, U. A. Wiedemann arXiv:0804.3568

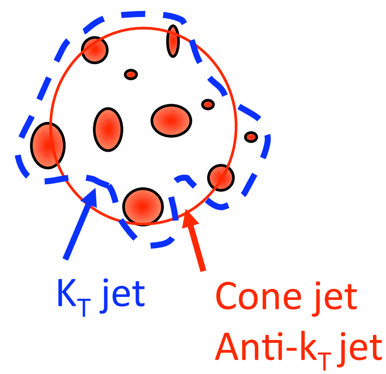
Clear increase in multiplicity due to radiative energy loss
Collisional energy loss when recoils are counted toward the jet

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





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

Medium Induced Radiation → More Coarser Jet Structure

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

Conclusions: Why Pursue Full Jet Reconstruction?

Full jet reconstruction gives access to the full spectrum of fragmentation topologies:

- 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, γ-jets
- Qualitatively new observables: energy flow, jet substructure, fragmentation function

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– First full jet reconstruction at RHIC (0-10% central heavy ion collisions - reach is up to 50 GeV).

– ~N_{bin} scaling (50% Syst Uncert.) observed for the least biased case, R=0.4 and p_T^{cut}=0.1 GeV

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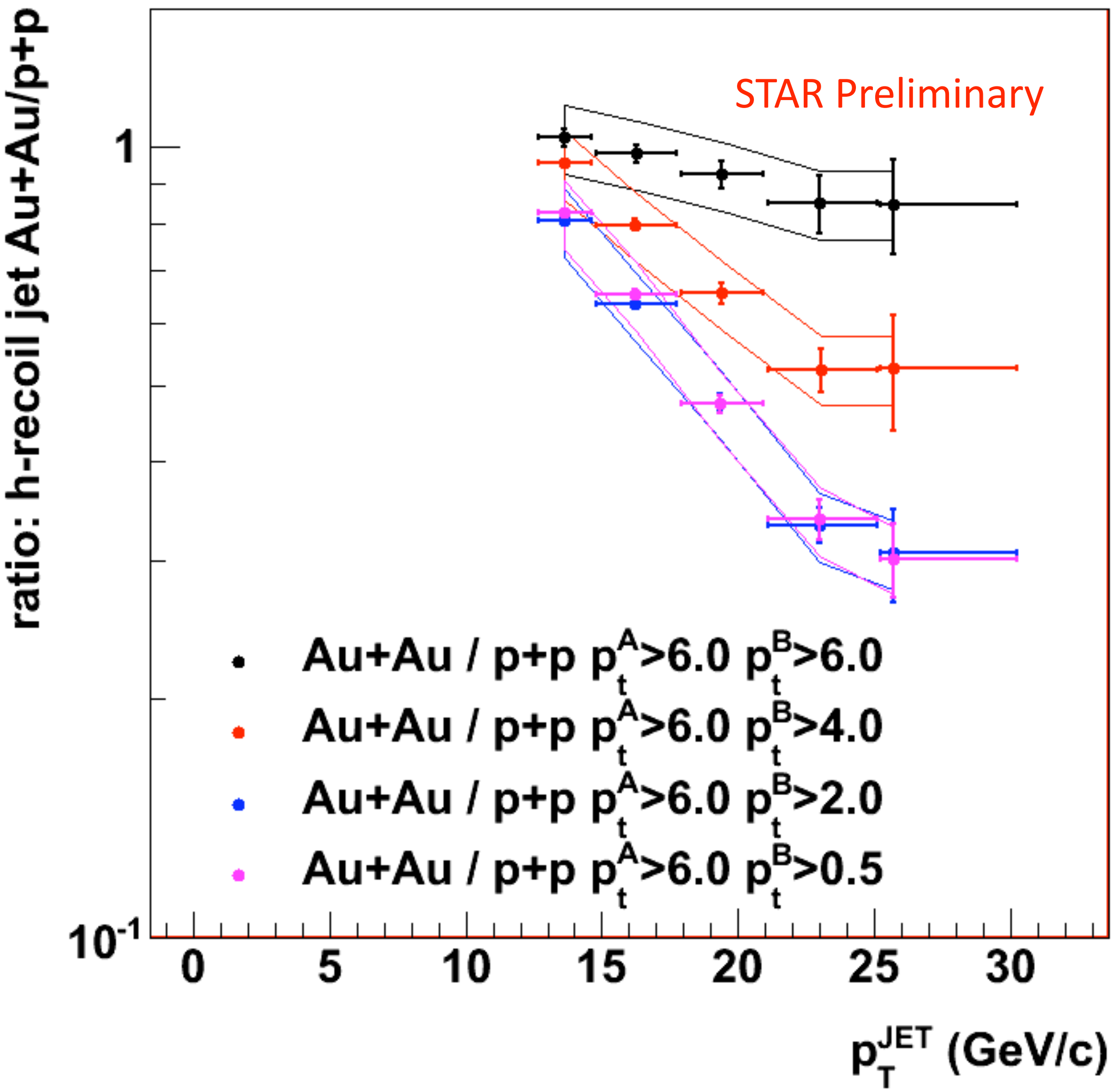
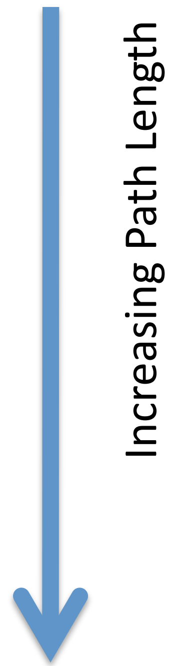
"When you have completed 95 percent of your journey, you are only halfway there."
Japanese Proverb

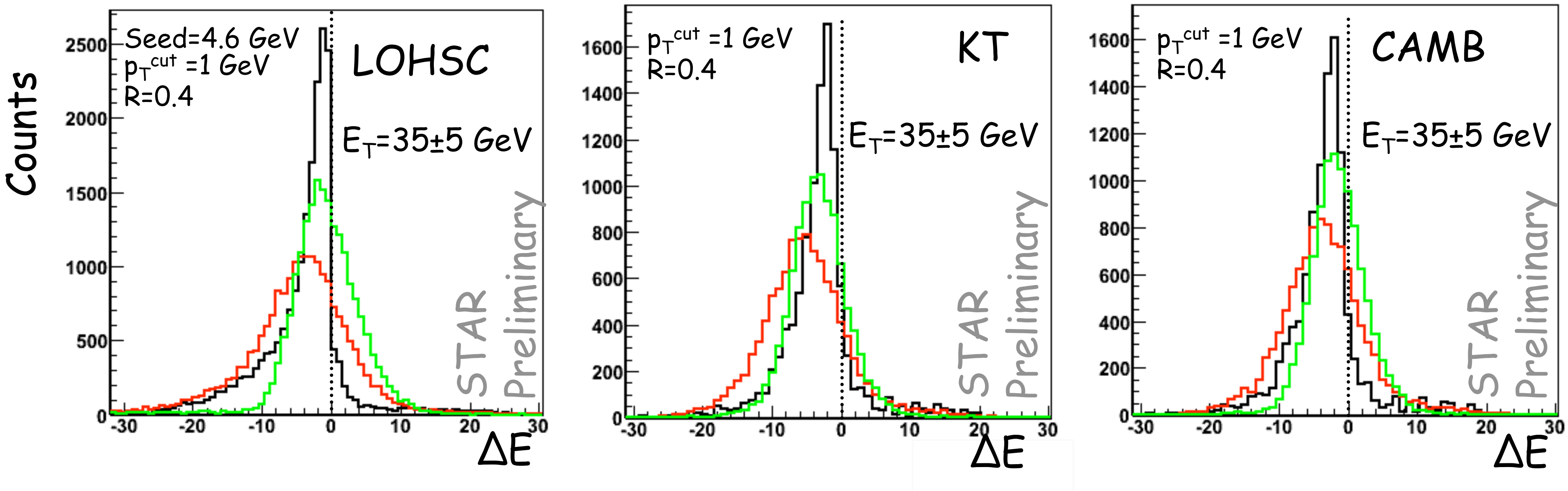
H – recoil jet coincidences





Energy Resolution

Event by event comparison of PyTrue vs PyDet vs PyEmbed.



$\Delta E = E^{PyDet} - E^{PyTrue}$

$\Delta E = E^{PyEmbed} - E^{PyDet}$

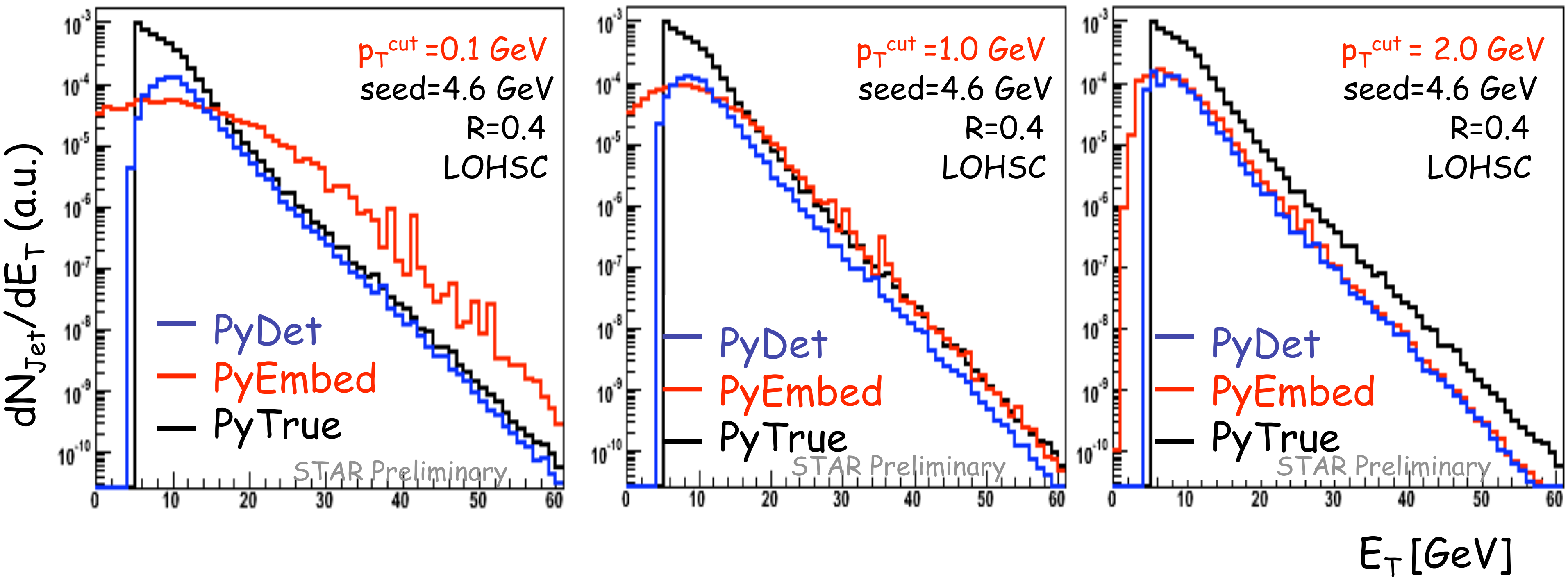
$\Delta E = E^{PyEmbed} - E^{PyTrue}$

Shift of median due to un-measured particles (n, K^0_L) and the p_T cut.

Smearing due to background subtraction in Au+Au.

Tail at positive ΔE causes a kick in the spectrum.

Effect of Resolution on Spectrum



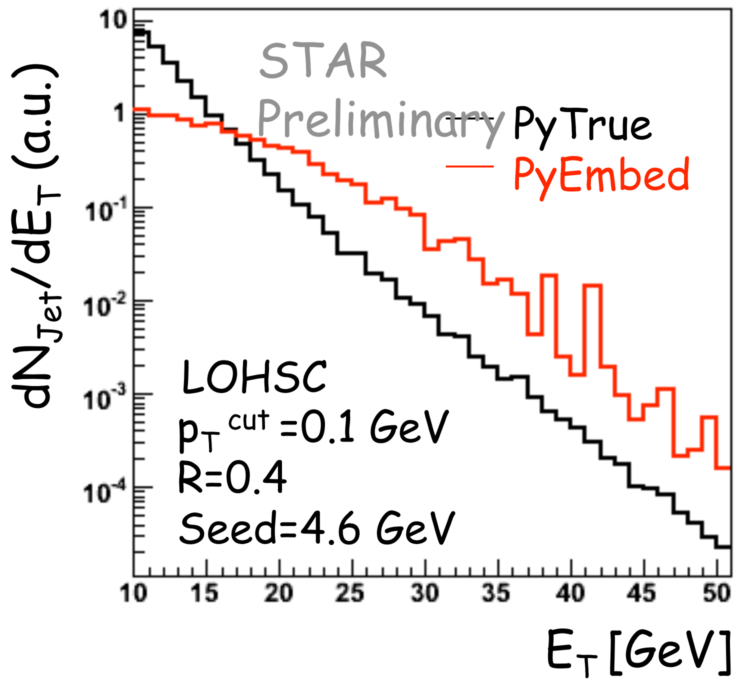
-Increase p_T threshold: Reduce the effect of background fluctuations (jet reconstruction in 0-10% Au+Au is similar in p+p)

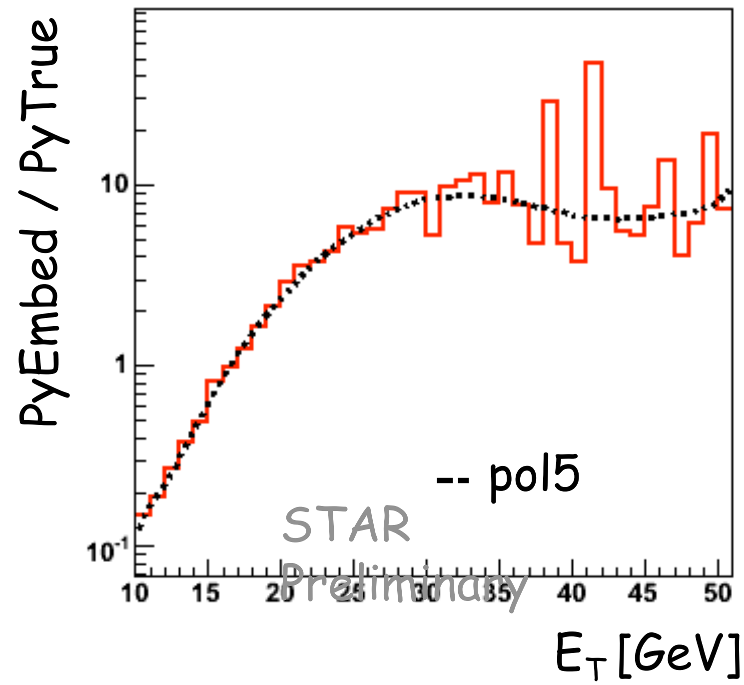
- The p_T cut is expected to produce biases.

Similar effects also observed for KT & Cambridge/Aachen

Resolution and Efficiency & Acceptance Corrections

Resolution effect corrected assuming **Pythia Fragmentation**.
Embed Pythia Jets in 0-10% Central Events with MBtrig.





E_T-dependent correction factors			
P_T^{cut}	**LOHSC**	**KT**	**CAMB**
0.1 GeV	0.2-10	1-4	2-6
1 GeV	0.2-1	0.7-1	1-2
2 GeV	0.2-0.3	0.5-1	0.5-1

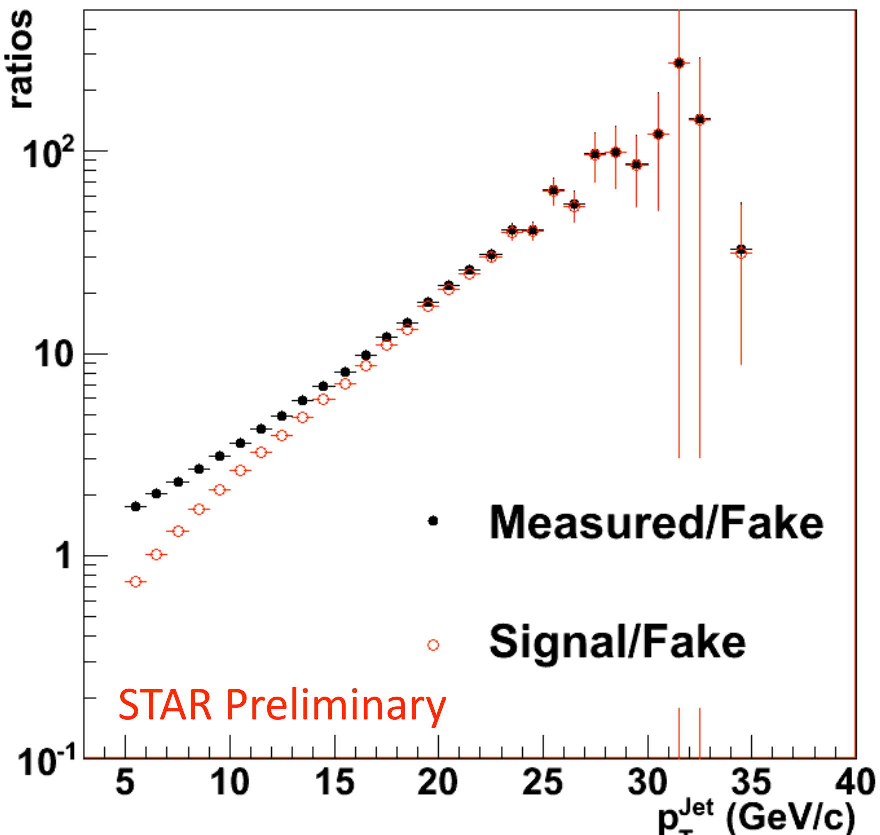
Use the fit functions from the ratio of PyEmbed to PyTrue to correct for energy resolution, efficiency & acceptance.

Fake jet contamination

"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

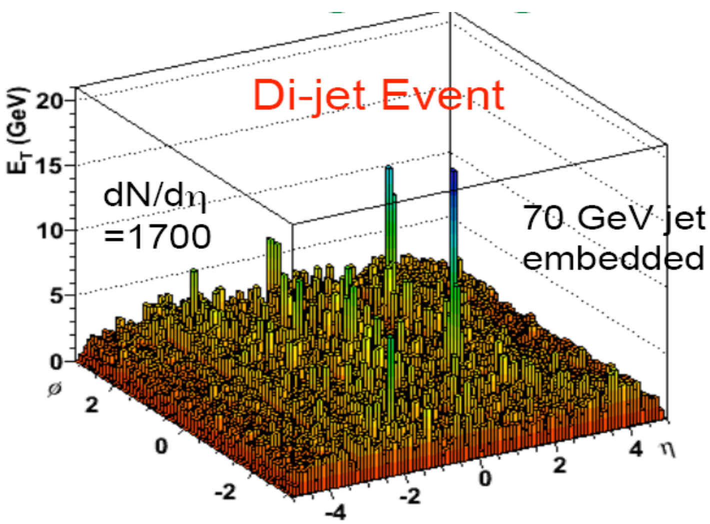


Another way to do it: Jet quenching at the LHC

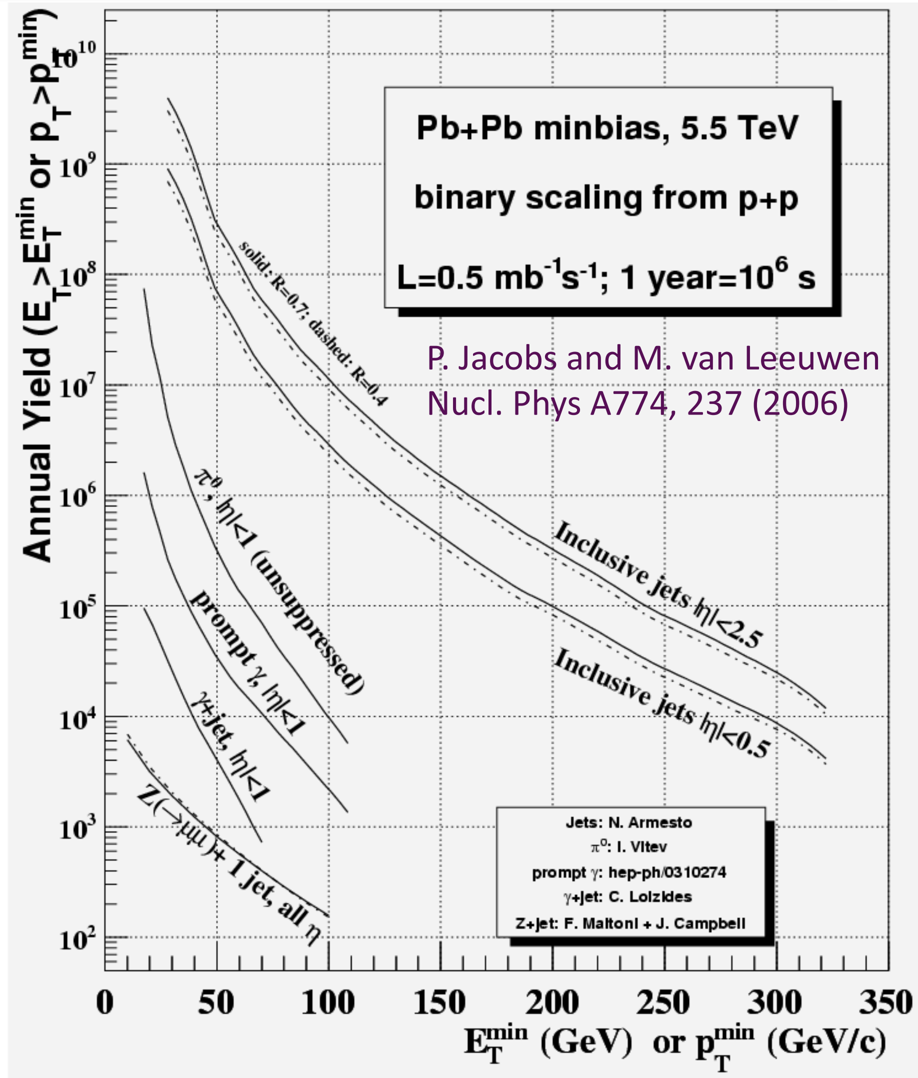
Pb+Pb at 5.5 TeV:

enormous jet energy range

⇒ qualitatively new probes



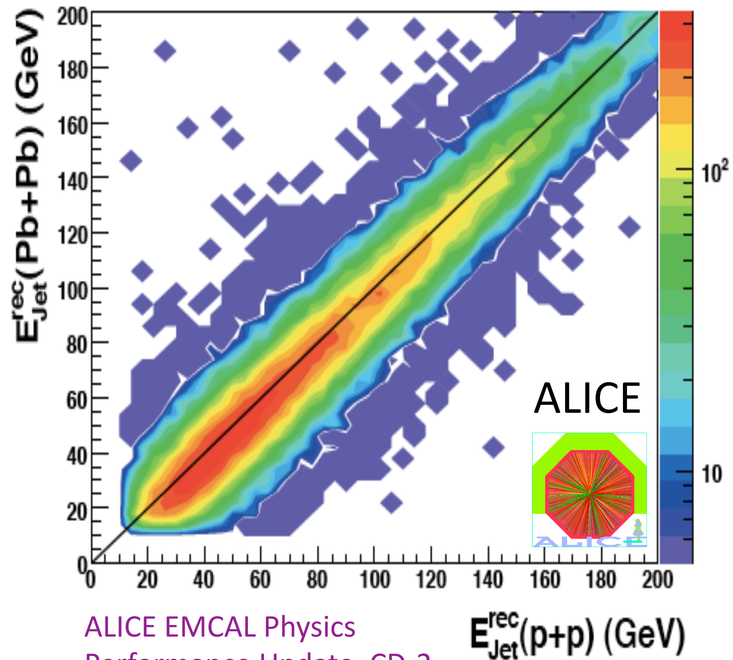
N. Grau for ATLAS



P. Jacobs and M. van Leeuwen
Nucl. Phys A774, 237 (2006)

Copious production of hard probes :
Jets, charm & bottom…

High p_T Jets well above the background at LHC



ALICE EMCAL Physics
Performance Update, CD-2

LHC

• Pb+Pb background seems to be under control for the reconstructed jet-energy.

• Detector Upgrades:
2 super modules are installed for ALICE
Full azimuthal calorimetric coverage for ATLAS & CMS

γ+jet (Z+jet) cleaner means to determine FF