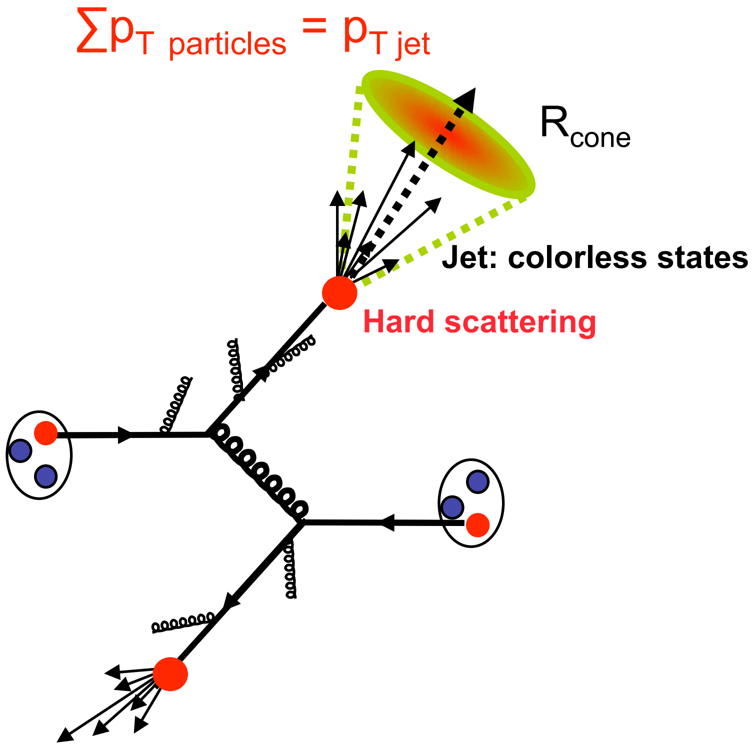
A Short Review on Jet Identification

SEViL SALUR for the STAR Collaboration
LAWRENCE BERKELEY NATIONAL LABORATORY

What Are Jets ?



JETS: Colored partons from the hard scatter
- via soft quark and gluon radiation
- hadronization process to form a “spray” of colorless hadrons

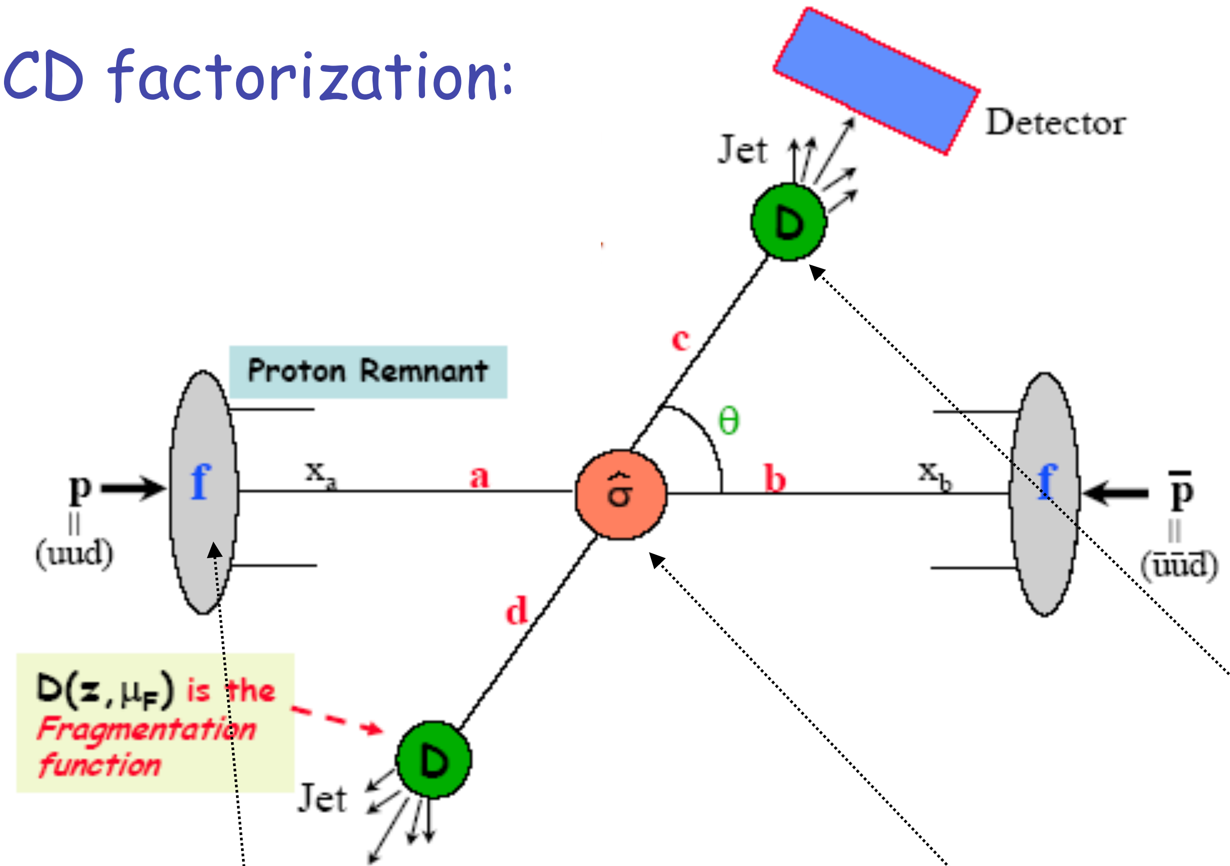
Early production from parton-parton scatterings

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 are the **experimental** signatures of quarks and gluons.
They are expected to reflect kinematics and topology of partons.

Jets as described by p-QCD

p-QCD factorization:



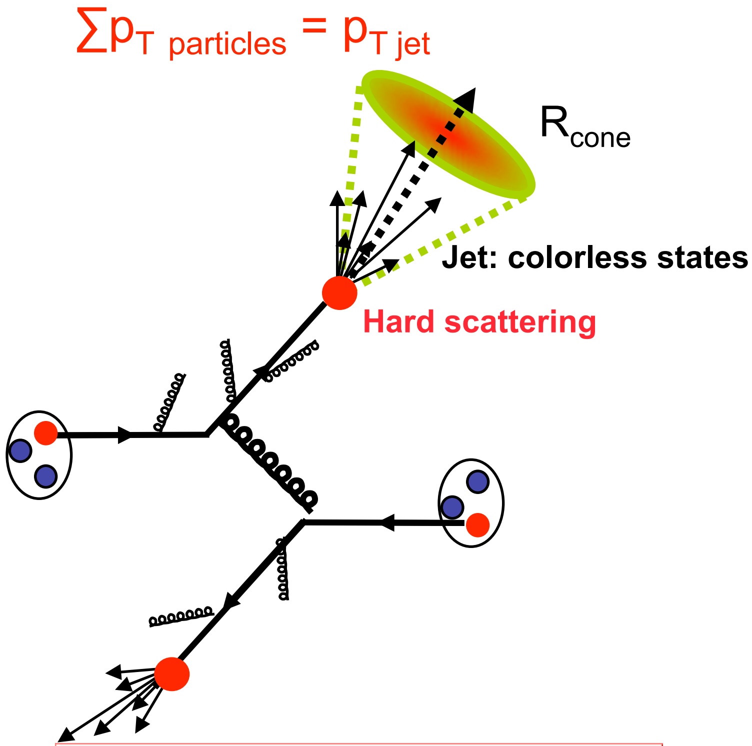
$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/A}(x_b, Q^2) \otimes \frac{d\hat{\sigma}^{ab\to cd}}{dt} \otimes D_{h/c}(z_c, Q^2)$$

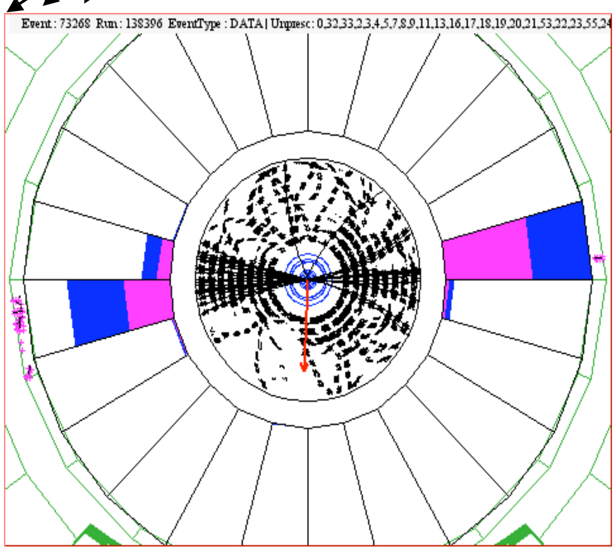
Parton distribution functions

Partonic cross -section

Fragmentation function

Jet reconstruction: connect theory and experiment



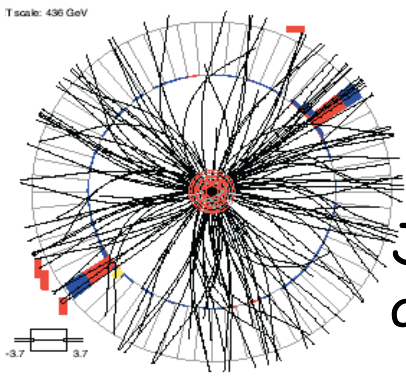


Goal: re-associate hadrons to accurately reconstruct the partonic kinematics

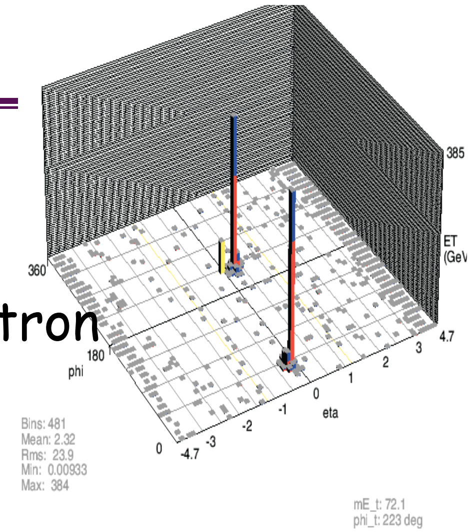
- pQCD theory calculates partons
- experiment measures fragments of partons: hadrons and calorimeter towers (clusters of hadrons)

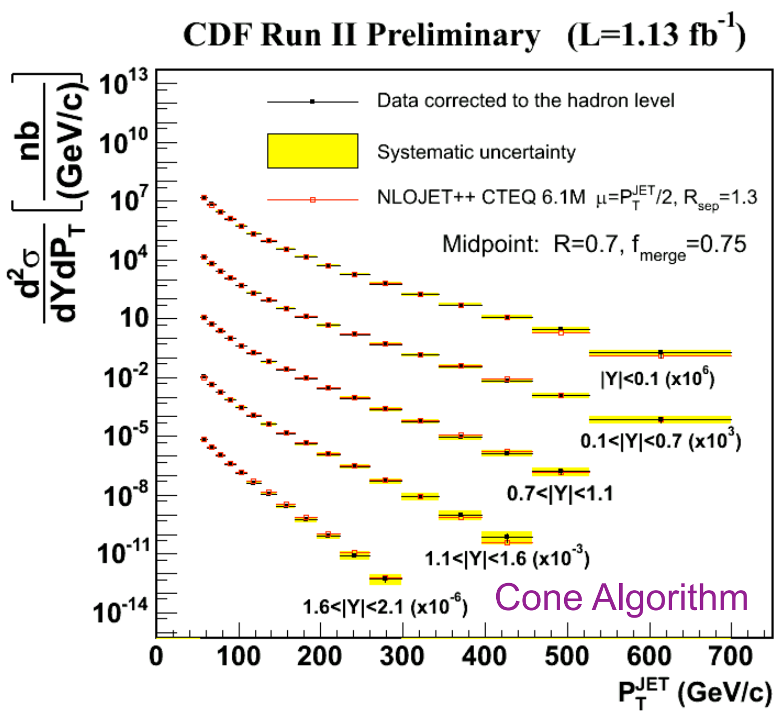
Apply "same" jet clustering algorithm to data and theoretical calculations

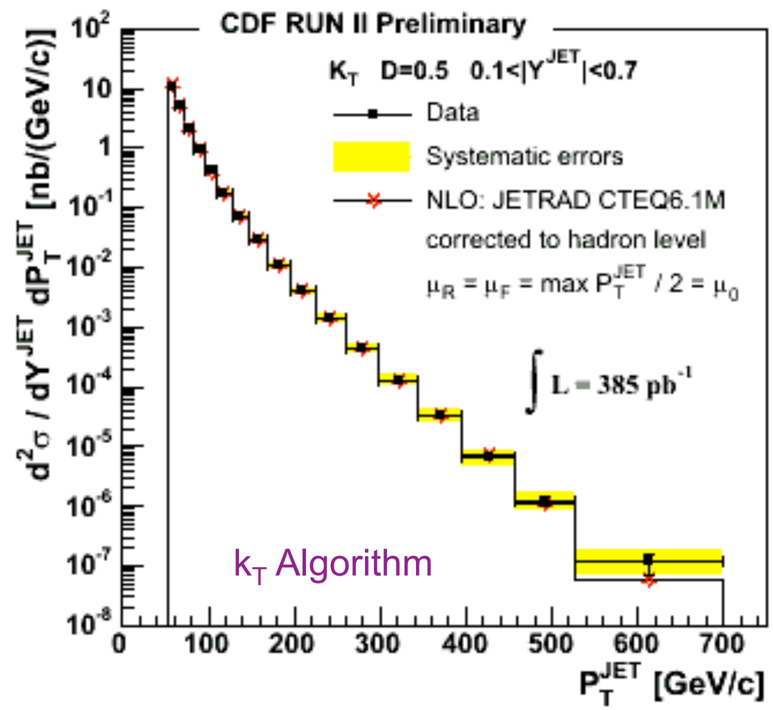
Jets in p+p at Fermi Lab



Jets are identified with various algorithms and are consistent with each other in Tevatron







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

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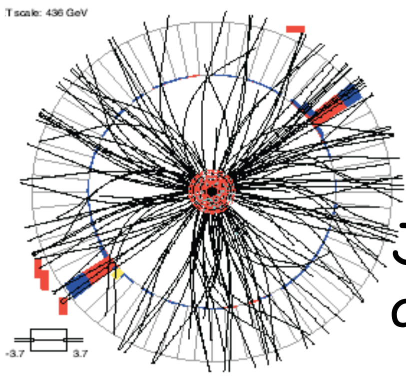

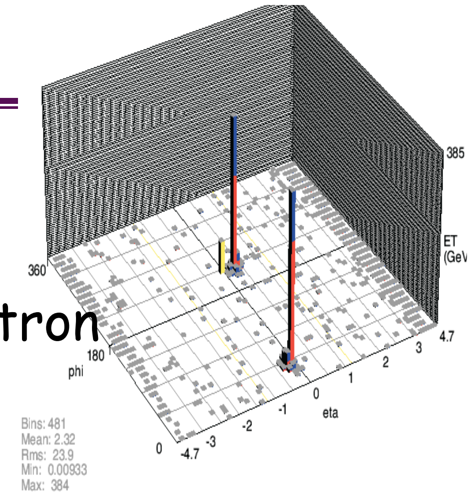

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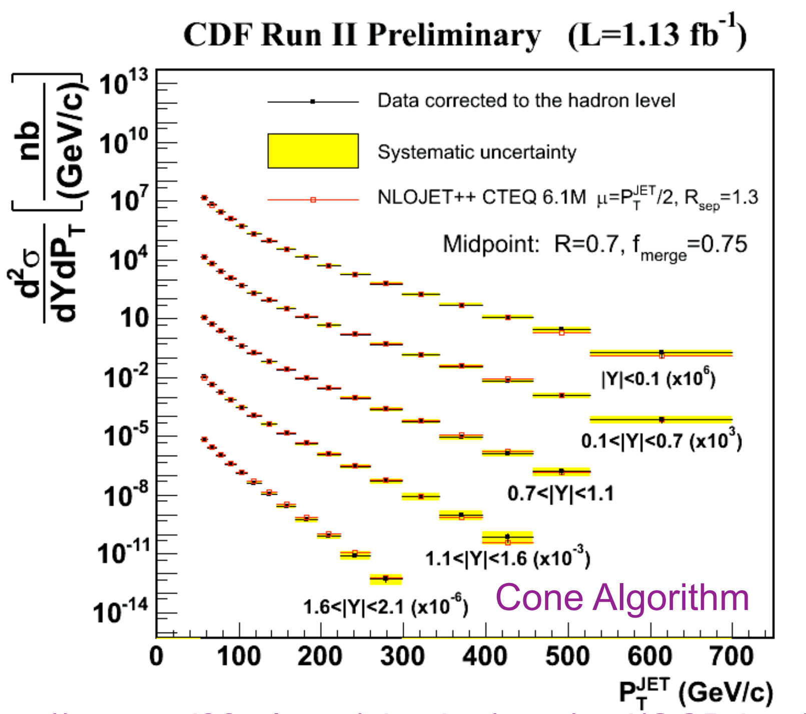
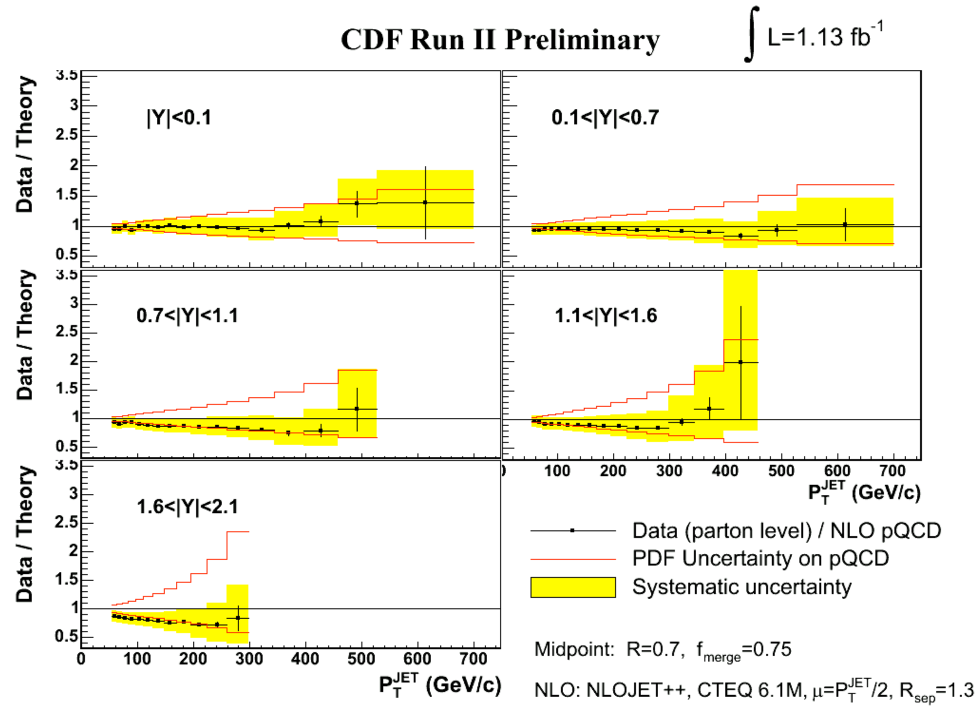
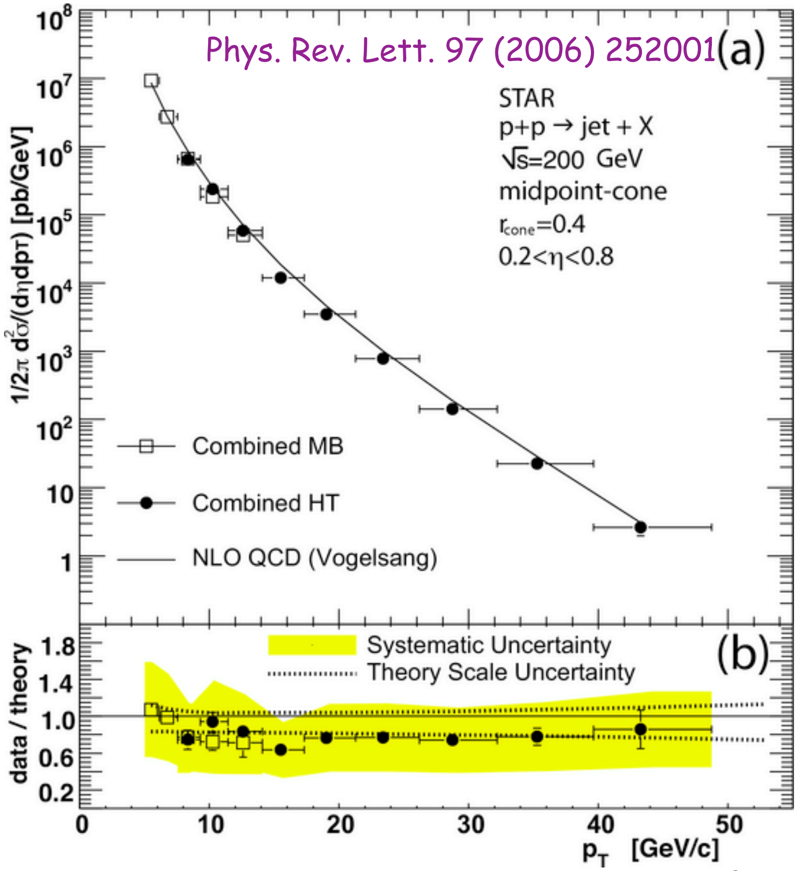




http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

Inclusive jet cross section for 20 orders of magnitude consistent with the NLO QCD prediction CTEQ 6.1.

Jets in p+p at RHIC



Experimental uncertainty ~50%

See Elena Bruna's Upcoming Talk

Inclusive mid-rapidity jet production in polarized proton collisions at √s=200 GeV.

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

Agrees also well with NLO p-QCD

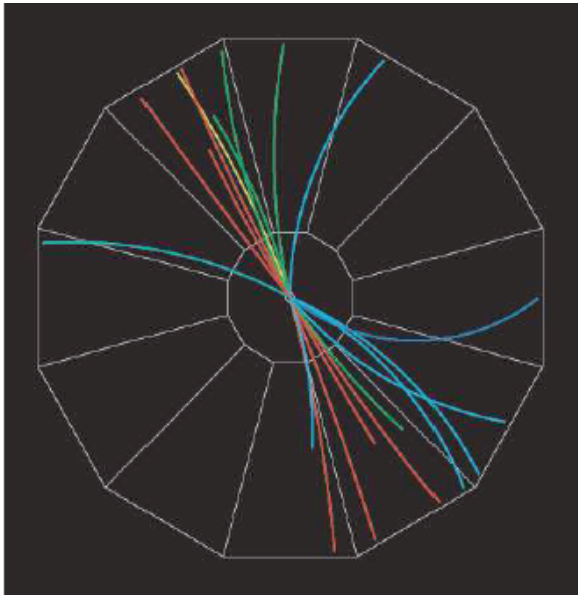
Use this result as a reference for Au+Au:

$$\frac{dN^{jet}_{Au+Au}}{dE_T} = T_{AA}\frac{\sigma^{jet}_{p+p}}{dE_T}$$

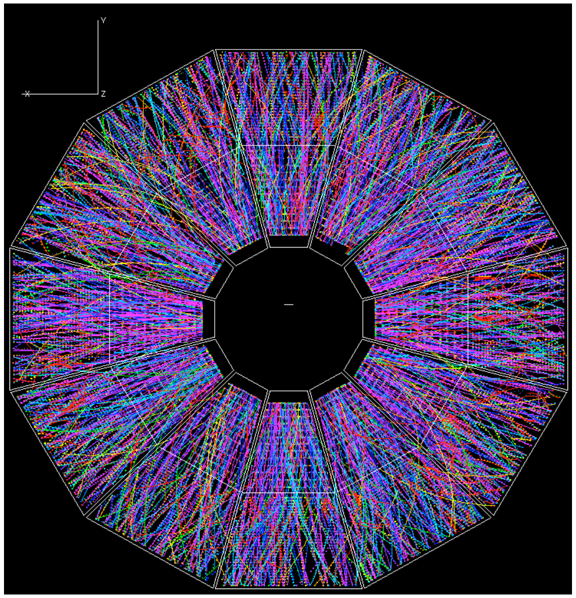
If jet reconstruction in Au+Au is unbiased, N_{binary} scaling relative to p+p will be observed.

Jets at RHIC & LHC:

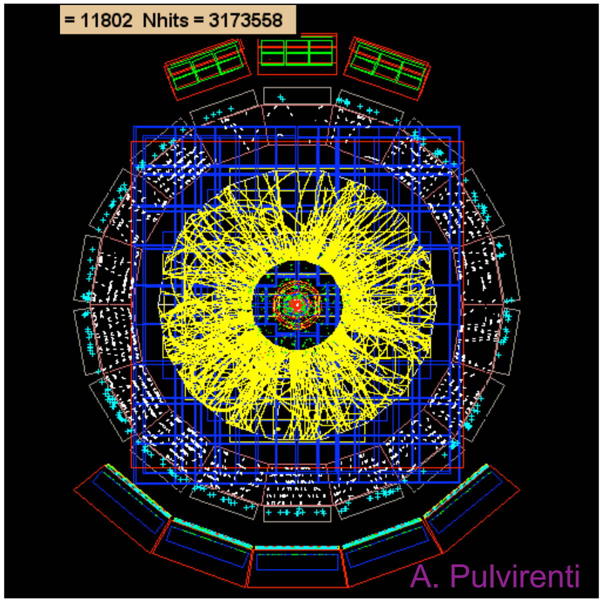
p+p @ $\sqrt{s}$ = 200 GeV



Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV



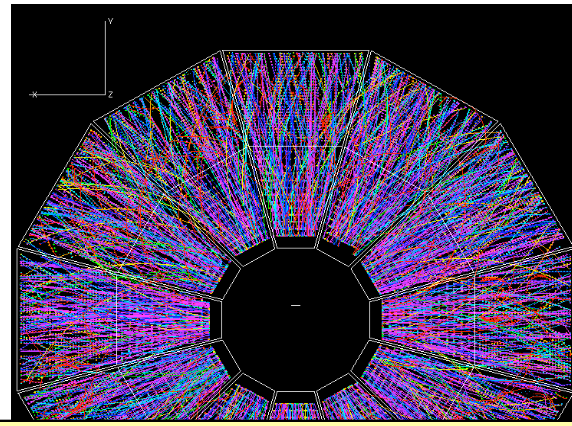
Pb+Pb @ $\sqrt{s_{NN}}$ = 5.5 TeV

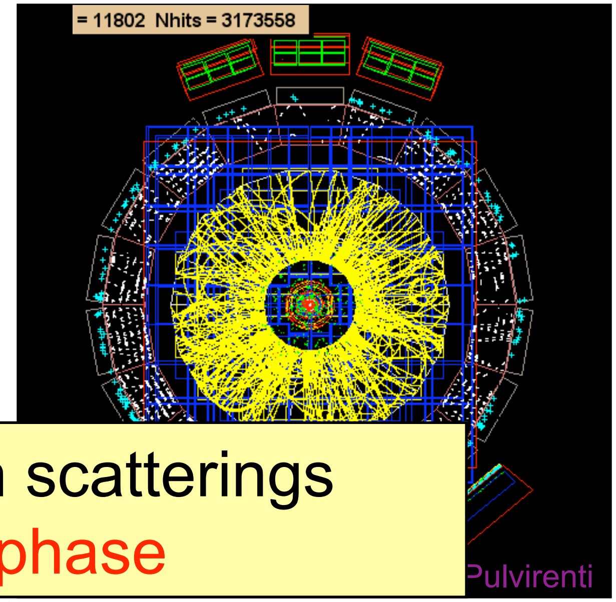


New opportunities & experimental challenges

Jets at RHIC & LHC:

p+p @ $\sqrt{s}$ = 200 GeV   Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV   Pb+Pb @ $\sqrt{s_{NN}}$ = 5.5 TeV

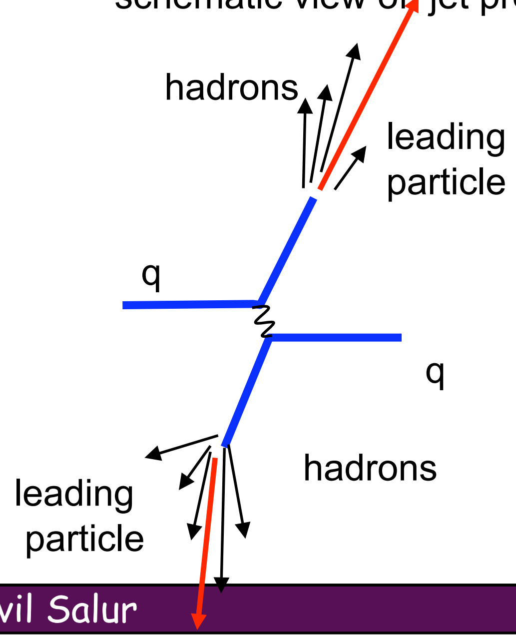




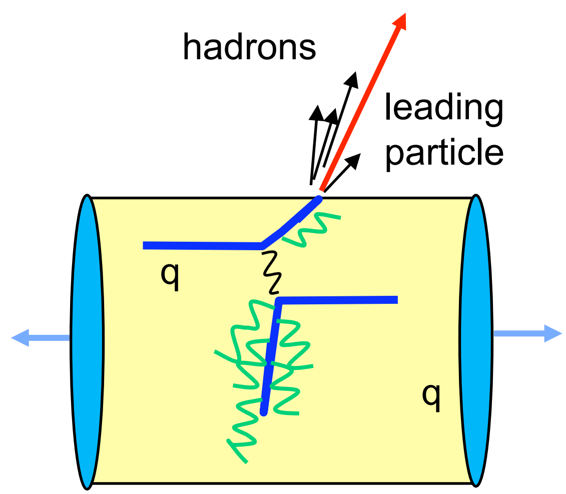
Early production from parton-parton scatterings

Direct probes of partonic phase

schematic view of jet production



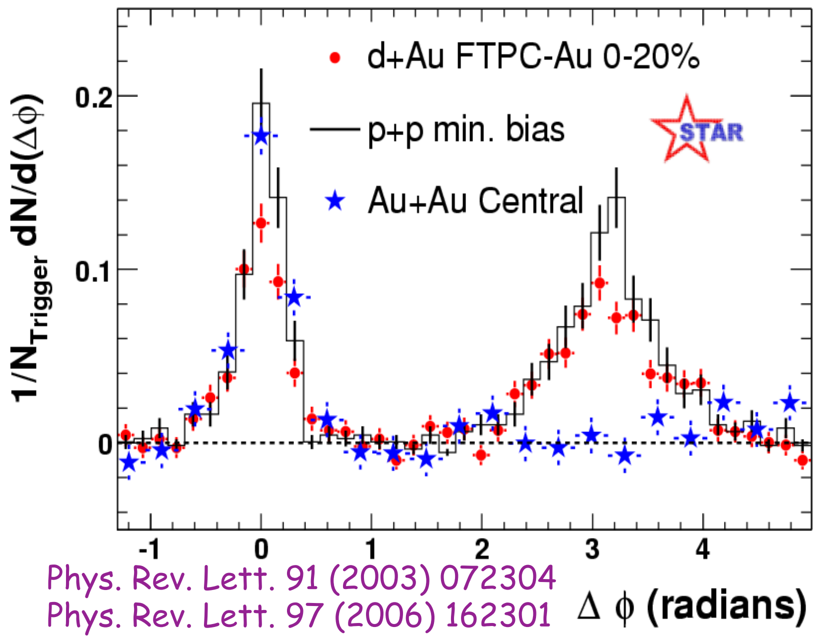
jet production in quark matter



Multiple interaction inside the collision region

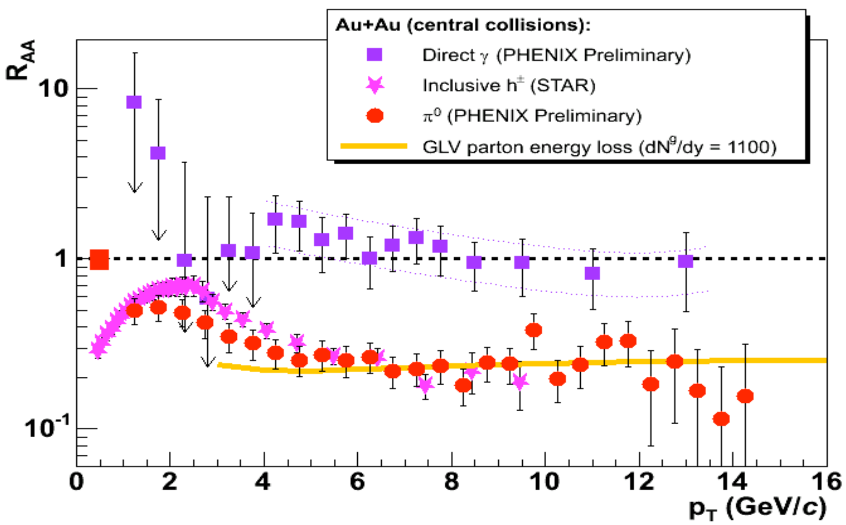
Lose energy through medium induced gluon radiation

RHIC Famous Results

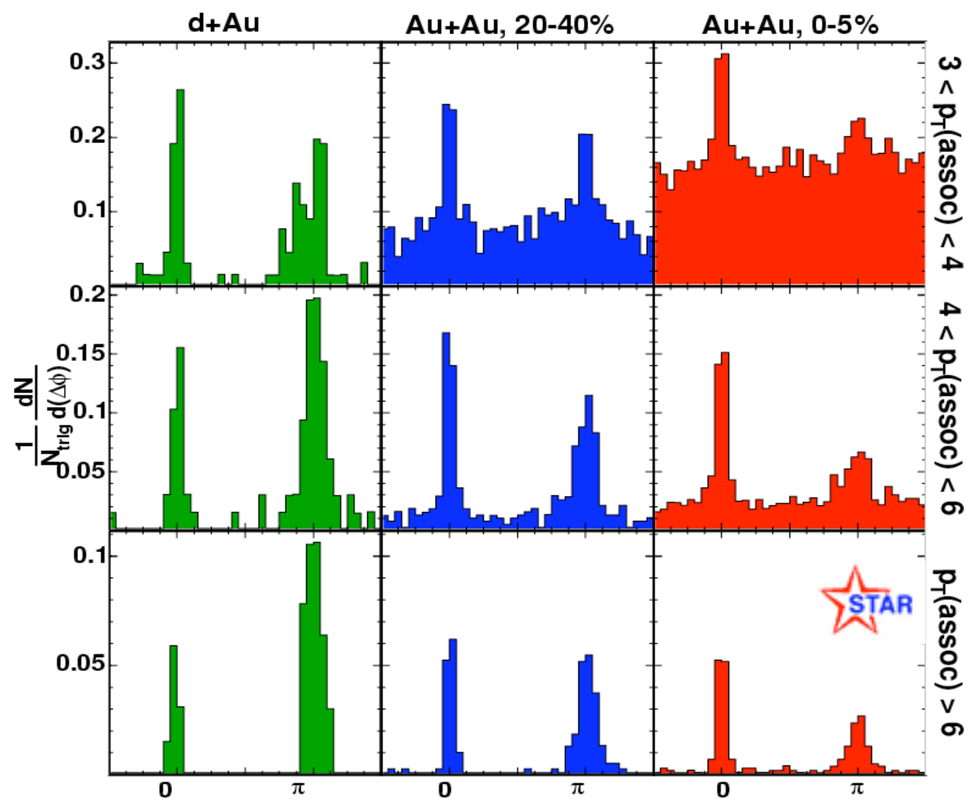


Phys. Rev. Lett. 91 (2003) 072304
Phys. Rev. Lett. 97 (2006) 162301

"Colorful" measurements of High p_T hadron suppression at RHIC observed via di-hadron corelations and R_{AA} and described by pQCD+partonic energy loss.

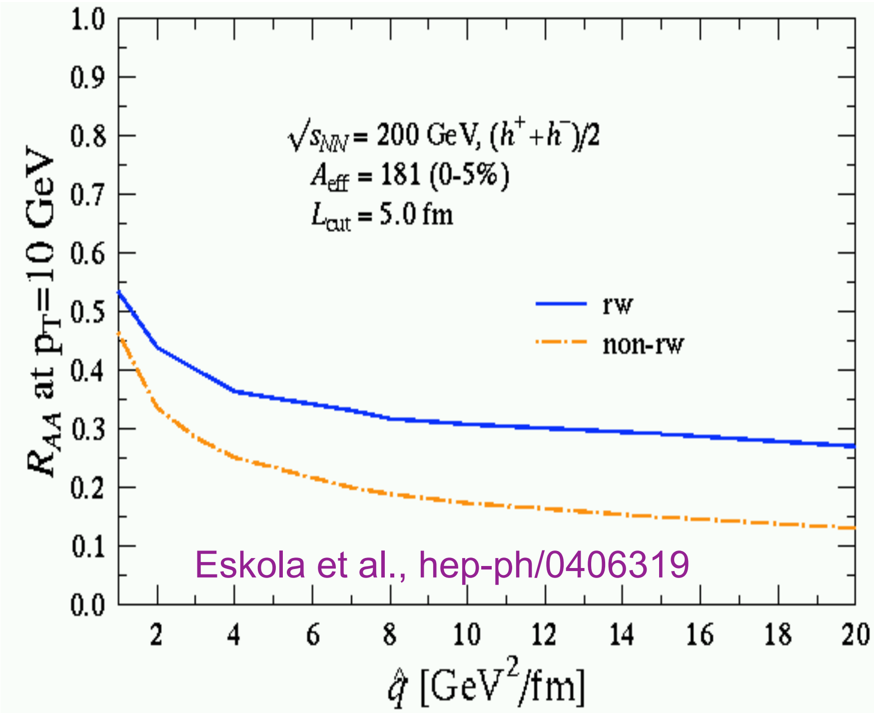


Phys. Rev. Lett 96 202301 (2006)

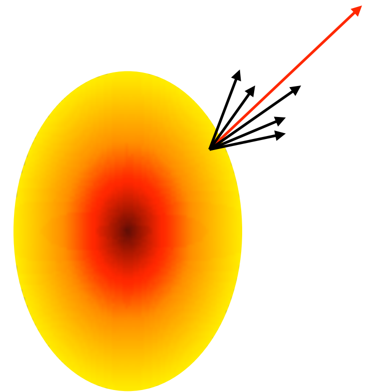


Phys.Rev.Lett.97:162301,2006 Δφ

Sensitivity



R_{AA}~0.2-0.3 for broad range of $\hat{q}$



Surface emission bias limits sensitivity to $\hat{q}$

R_{AA} measurements are consistent with pQCD based energy loss calculations.

A lower bound to the initial color charge density.

Full Jet Reconstruction in Heavy-Ion Collisions

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

- much reduced geometric biases, full exploration of quenching.

- qualitatively new observables: jet shape, fragmentation function, energy flow,...

Goal is Unbiased Jet Reconstruction:

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

Event Selection and Terminology

Au+Au STAR: 0-10% Central Au+Au $\sqrt{s_{NN}}$=200 GeV selected via charged multiplicity from Year 7 Run.

MB-Trig: Minimum Bias Trigger

HT-Trig: Satisfied Minimum Bias and additional condition that EMC cluster >7.5 GeV

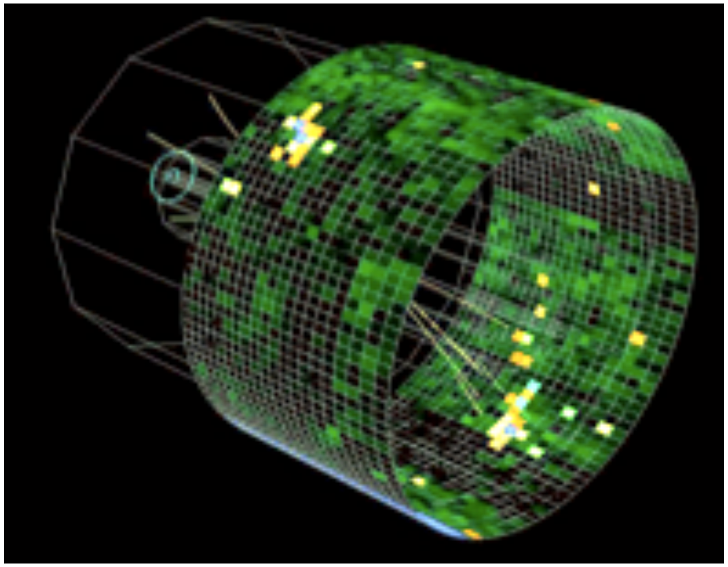
p+p STAR: p+p at $\sqrt{s}$ =200 GeV (Phys. Rev. Lett. 97 (2006) 252001)

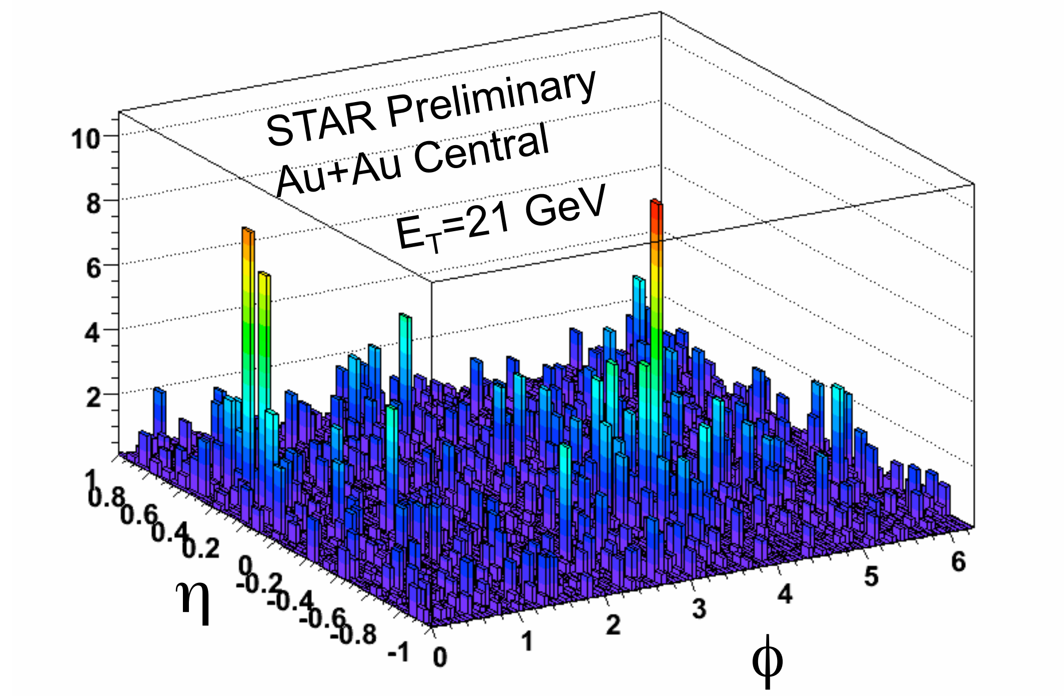
PyTrue: Pythia 8.107 p+p at $\sqrt{s}$ =200 GeV, all particles except neutrinos.

PyDet: Pythia p+p at $\sqrt{s}$ =200 GeV at detector level.

PyEmbed: PyDet, embedded into real Au+Au 0-10% events.

Jet Measurements

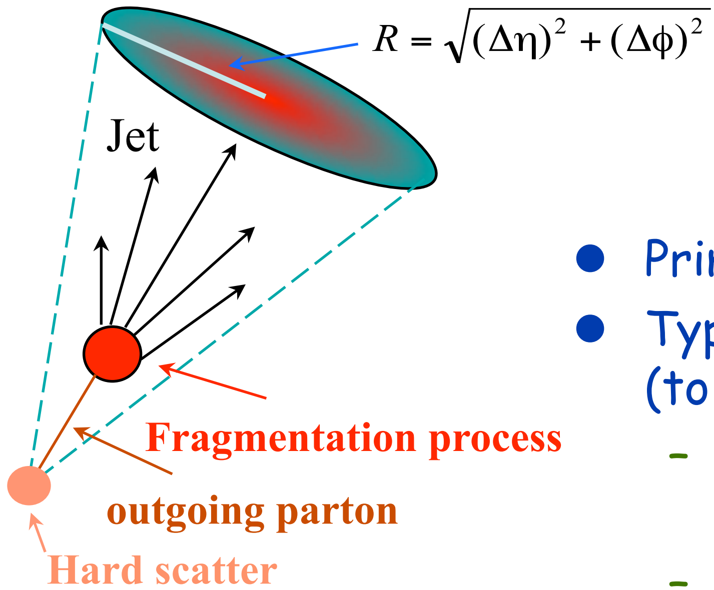




Jets are reconstructed via STAR EMC and TPC.
Correction applied for the hadronic energy in the EMC.

Jet Selection: Take only the highest energy jet per event.

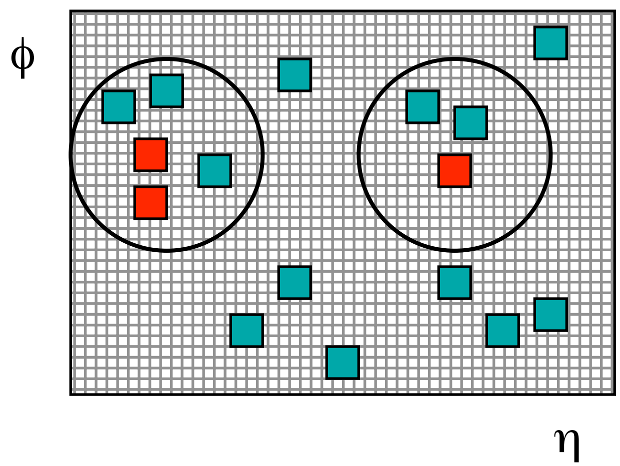
The Cone Jet Algorithm



Combine with closeness in space (angles)

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

- Primary algorithm at hadron colliders
- Typically, "seeds" are used with a minimum energy (to save computing time)
  - In η-ϕ space combine seed towers with their neighbors within a cone of radius R.
  - Various other steps: iteration, merging, splitting
- ☹ Infrared and Collinear Safety is not a guarantee
  - sensitive to "soft" radiation
  - Splitting might change jets



Sequential Recombination:

Cluster objects close in relative p_T

3. KT
4. Cambridge/ Aachen
5. Anti-KT

1. For each pair of clusters, i and j, define:

$$d_{ij} = \min(p_{T,i}^2, p_{T,j}^2)\frac{\Delta R_{ij}^2}{D^2}$$

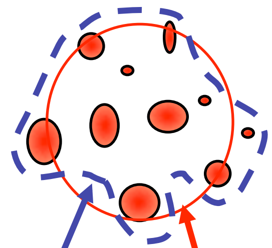
where $\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\varphi_i - \varphi_j)^2$. For each cluster define: $d_i = p_{T,i}^2$

2. Find the minimum, d_{min}, of all d_i and d_{ij}

3. If d_{min} is a d_{ij} then the clusters are merged by a 4-vector recombination scheme, into a new cluster *k*.

4. If d_{min} is a d_i then the cluster is "not mergable" and it is dropped from the cluster list and added to the jet list

5. Repeat 1-5 until all clusters have become jets



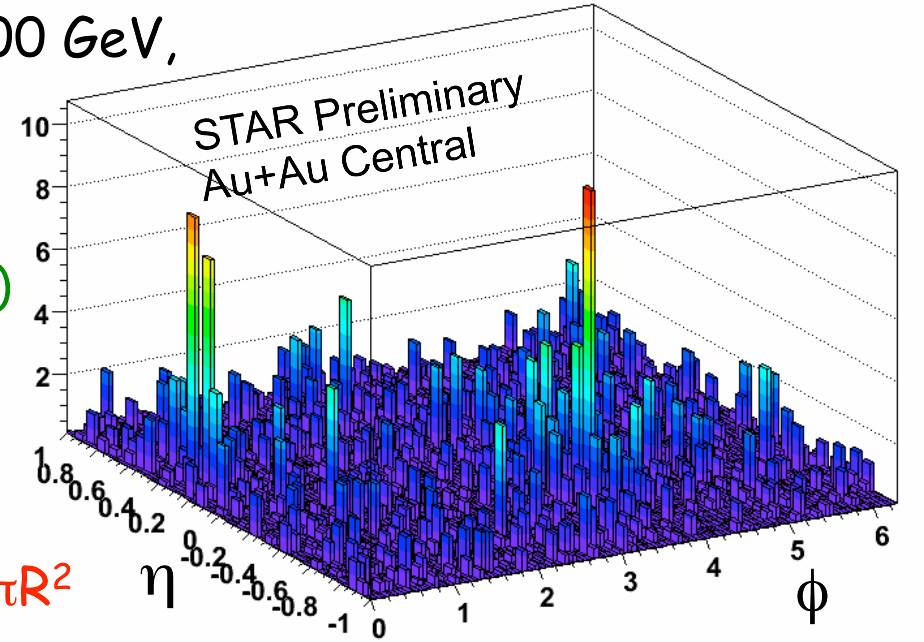
☺ Infrared and Collinear Safety is a guarantee

M. Cacciari, G. Salam, G. Soyez 0802.1188 [hep-ph]
FastJet - http://www.lpthe.jussieu.fr/~salam/fastjet

Correction for Heavy-Ion Background

0-10% Most Central Au+Au at $\sqrt{s_{NN}}$= 200 GeV,

- R=0.4, Bkg Energy ~ 40 GeV



- Unmodified (p+p) jets: ~80% of energy within R~0.3 for 50 GeV jet (CDF/D0 Jets)

- Background Estimates:

Assess backgrounds event by event.

Cone: Look at $\langle p_T \rangle$ out-of jet cones $A=\pi R^2$

Sequential Recombination:

Underlying event (UE) & pile-up are distributed uniformly in y and ϕ

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

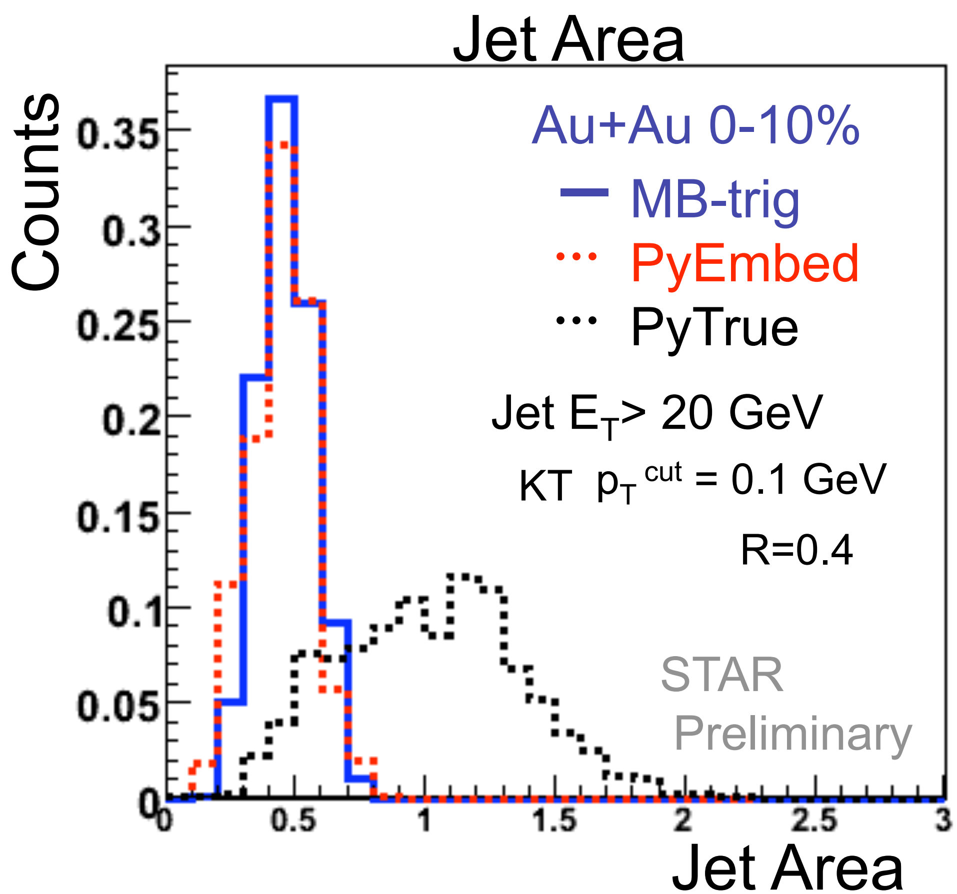
ρ = Diffuse noise, σ=noise fluctuations

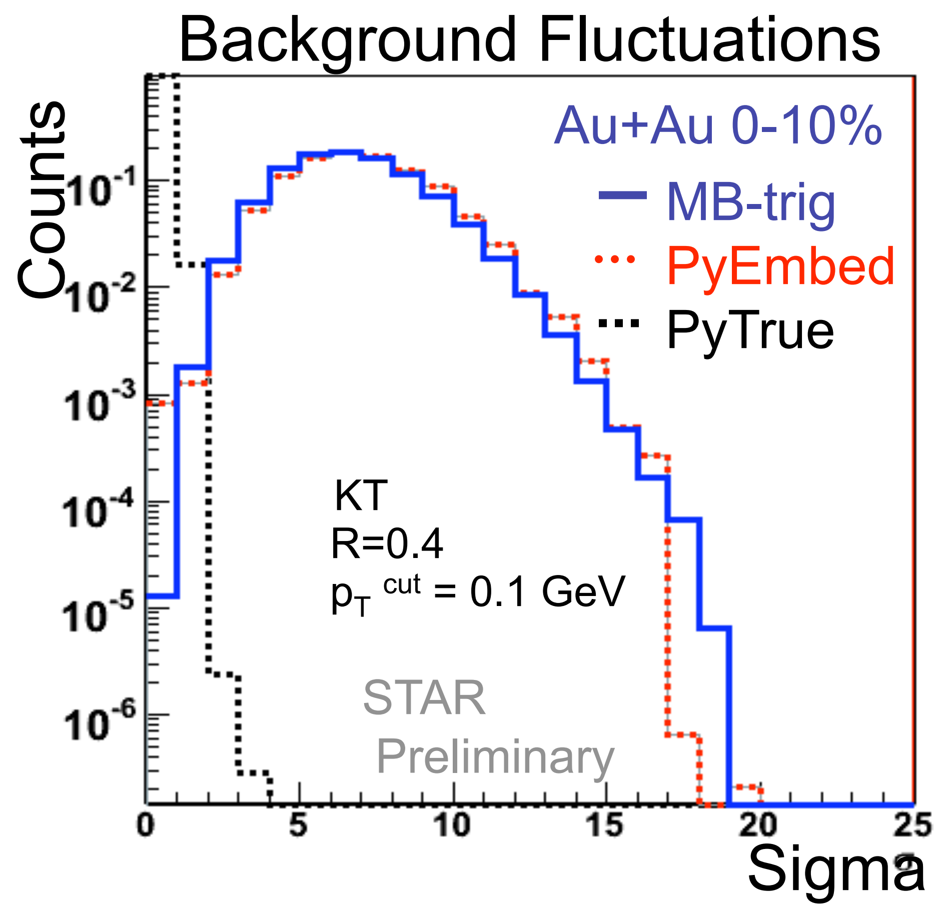
Area Definition: Estimate the active area of each jet by filling event with many very soft particles then count how many are clustered into given jet

Reduction of background fluctuations: p_T cuts, limit R.

Event Characteristics: Jet Area & Fluctuations

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



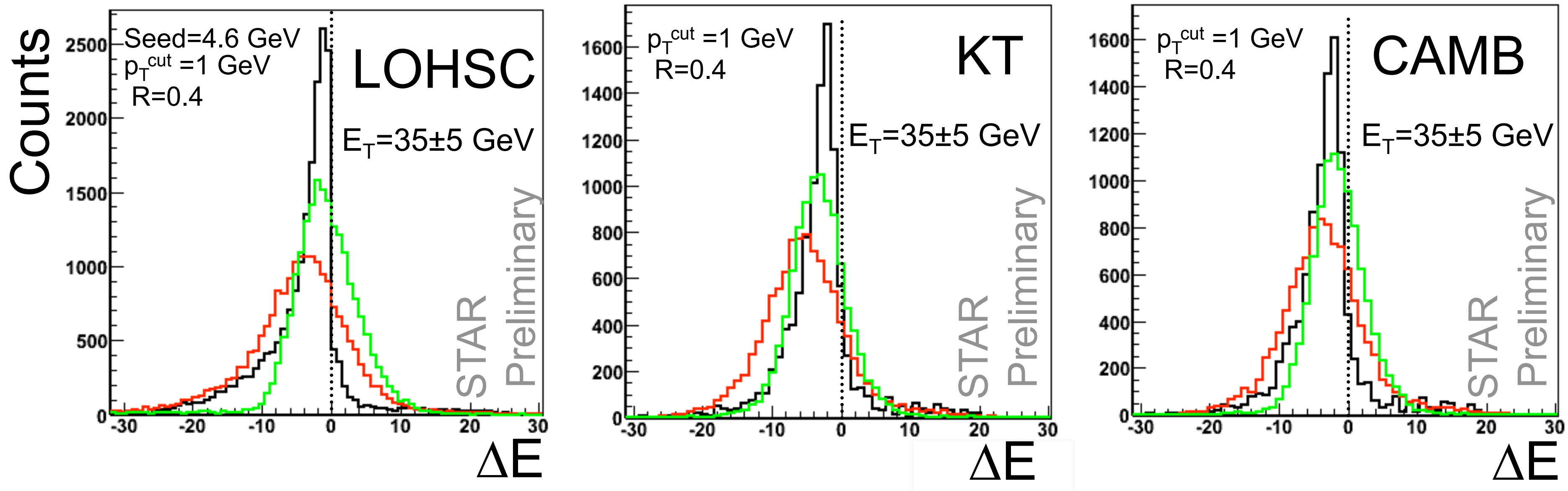


Heavy-ion: Reduction in Jet Area & Increase in fluctuations

Pythia Jets embedded in real Au+Au background events have the same area and fluctuations with that of Jets in real Au+Au data.

Energy Resolution

Event by event comparison of PyTrue vs PyDet vs PyEmbed.



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

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

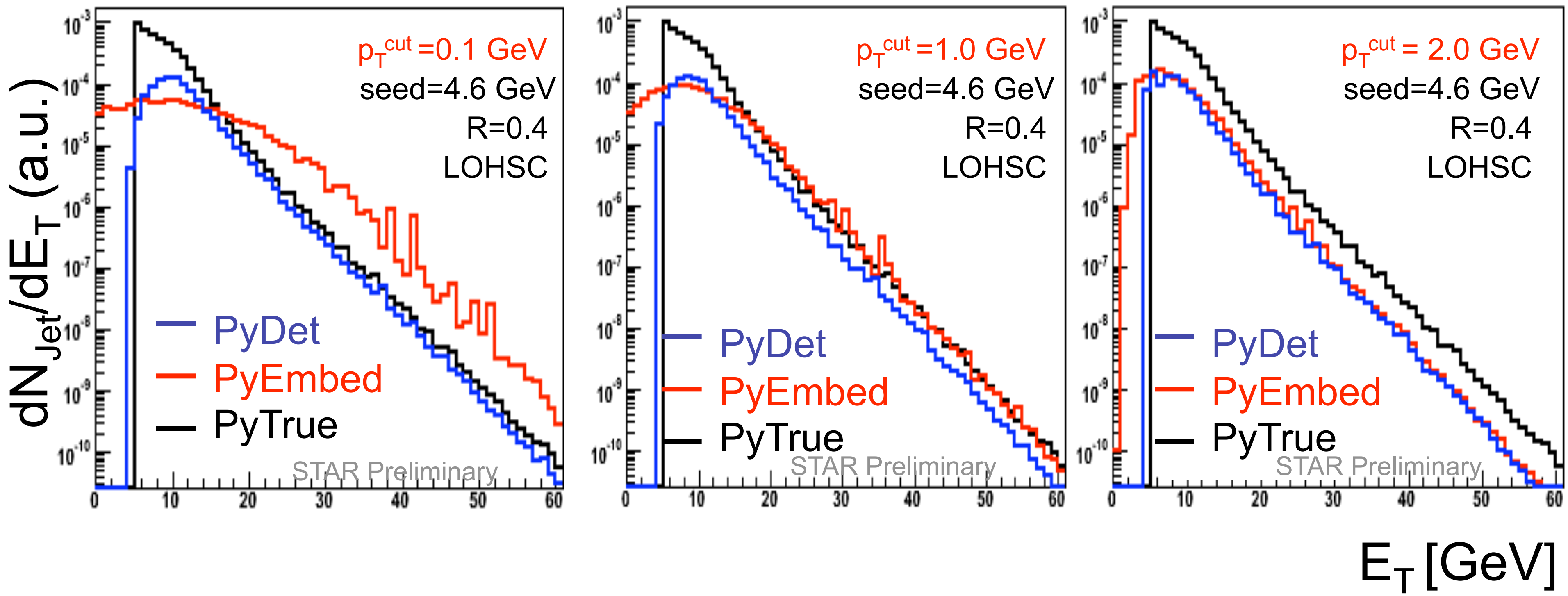
$\Delta E = E^{PyEmbed} - E^{PyTrue}$

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



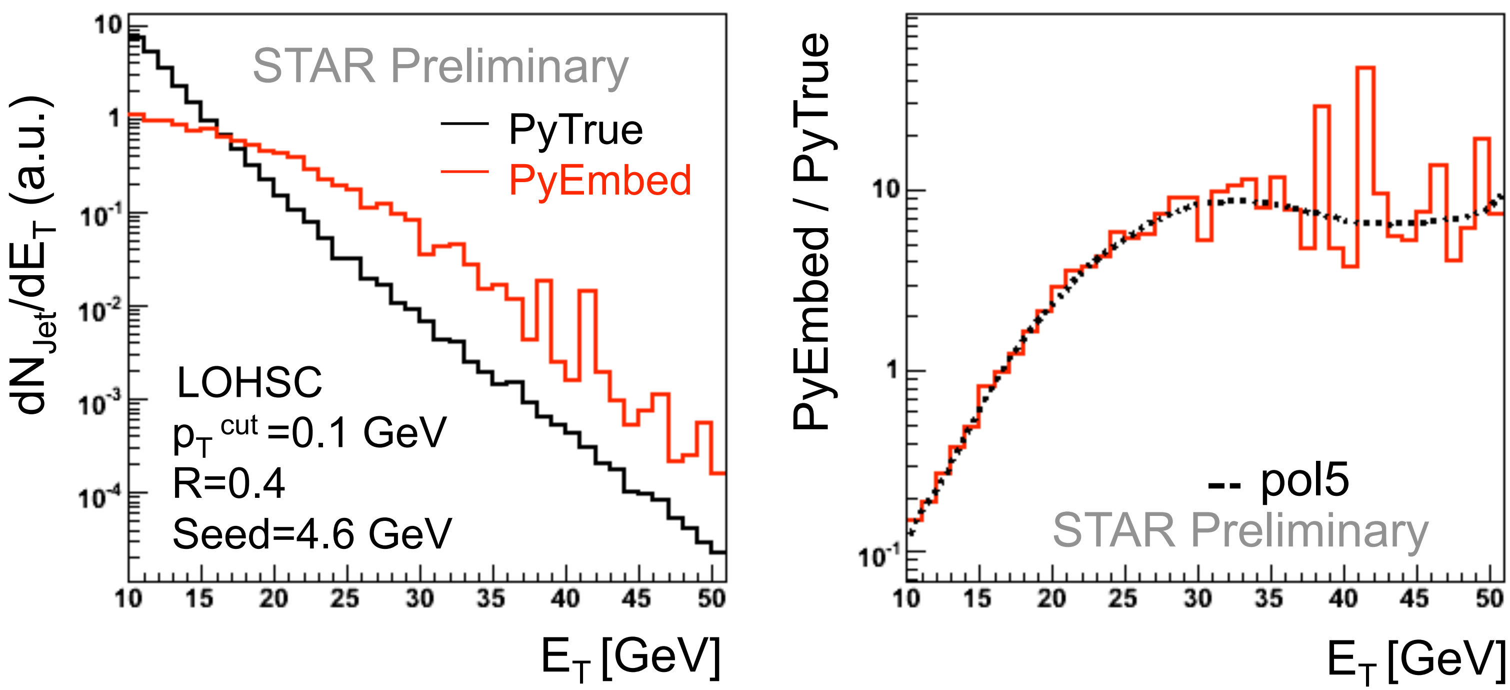
-Increase p_T threshold: Reduce the effect of background fluctuations (jet reconstruction in 0-10% Au+Au is similar in p+p)

- The p_T cut is expected to produce biases.

Similar effects also observed for KT & Cambridge/Aachen

Resolution and Efficiency & Acceptance Corrections

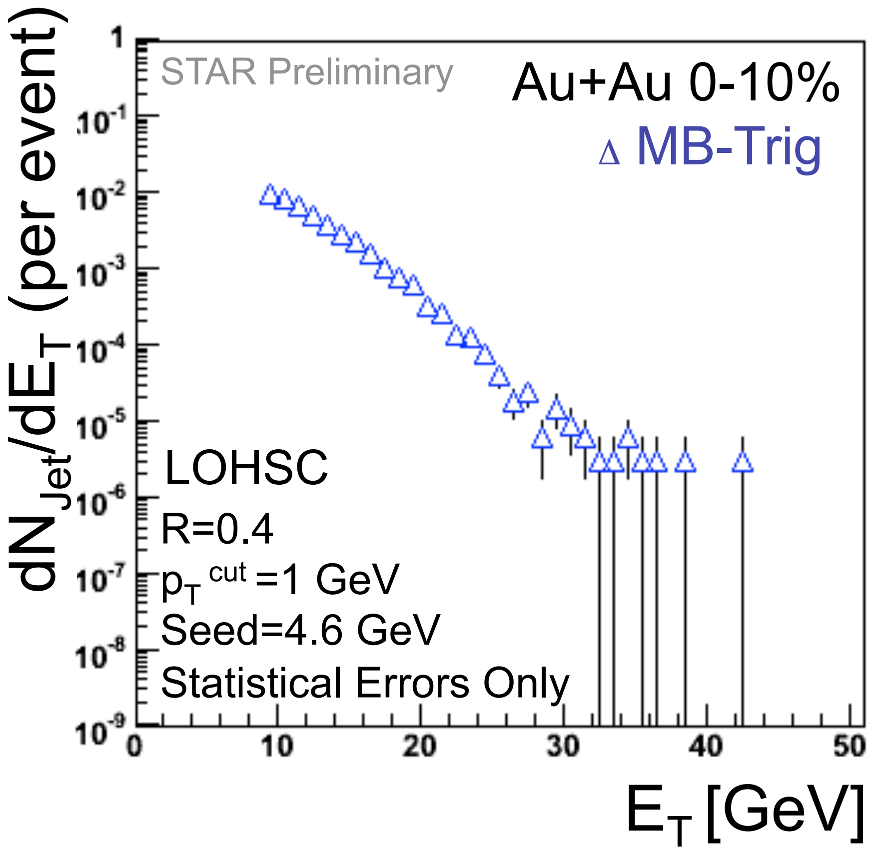
Resolution effect corrected assuming **Pythia Fragmentation**.
Embed Pythia Jets in 0-10% Central Events with MBtrig.



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.

Reconstructed Jet Spectra & Corrections:



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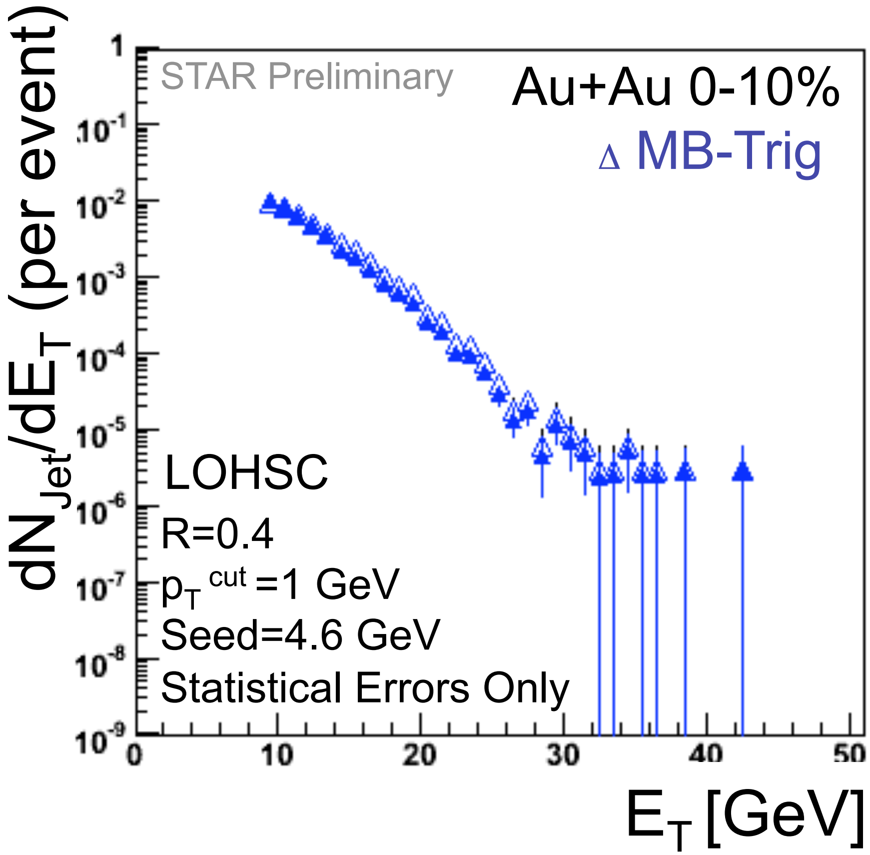

Resolution effect corrected assuming **Pythia Fragmentation**.

p_T^{cut}=1 GeV small correction for resolution, efficiency & acceptance.

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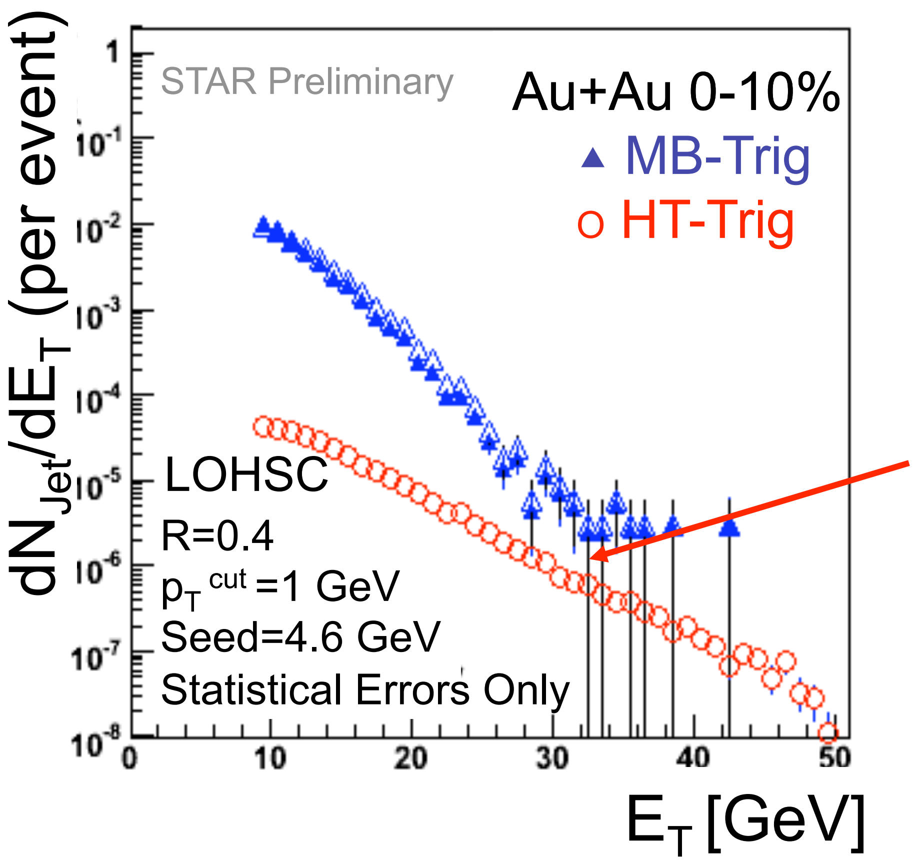

Resolution effect corrected assuming **Pythia Fragmentation**.

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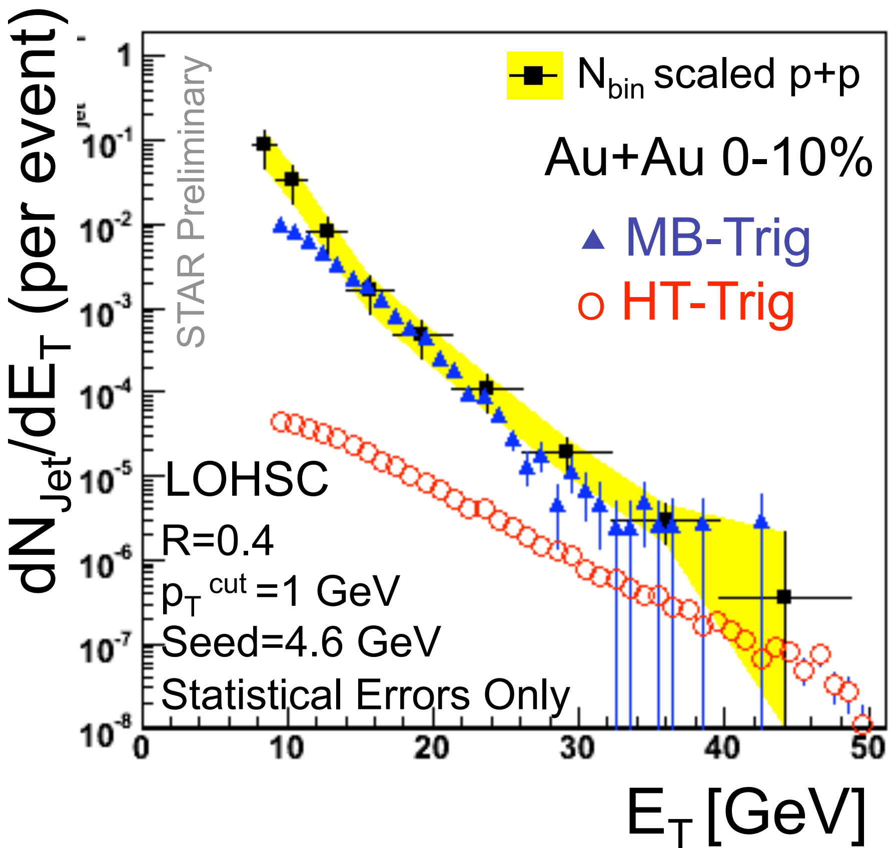
Large trigger bias persists at least to 30 GeV.

Further statistics of MB is needed to assess the bias in HT Trigger. (~20 more MB is recorded)

Reconstructed Jet Spectra & Corrections:



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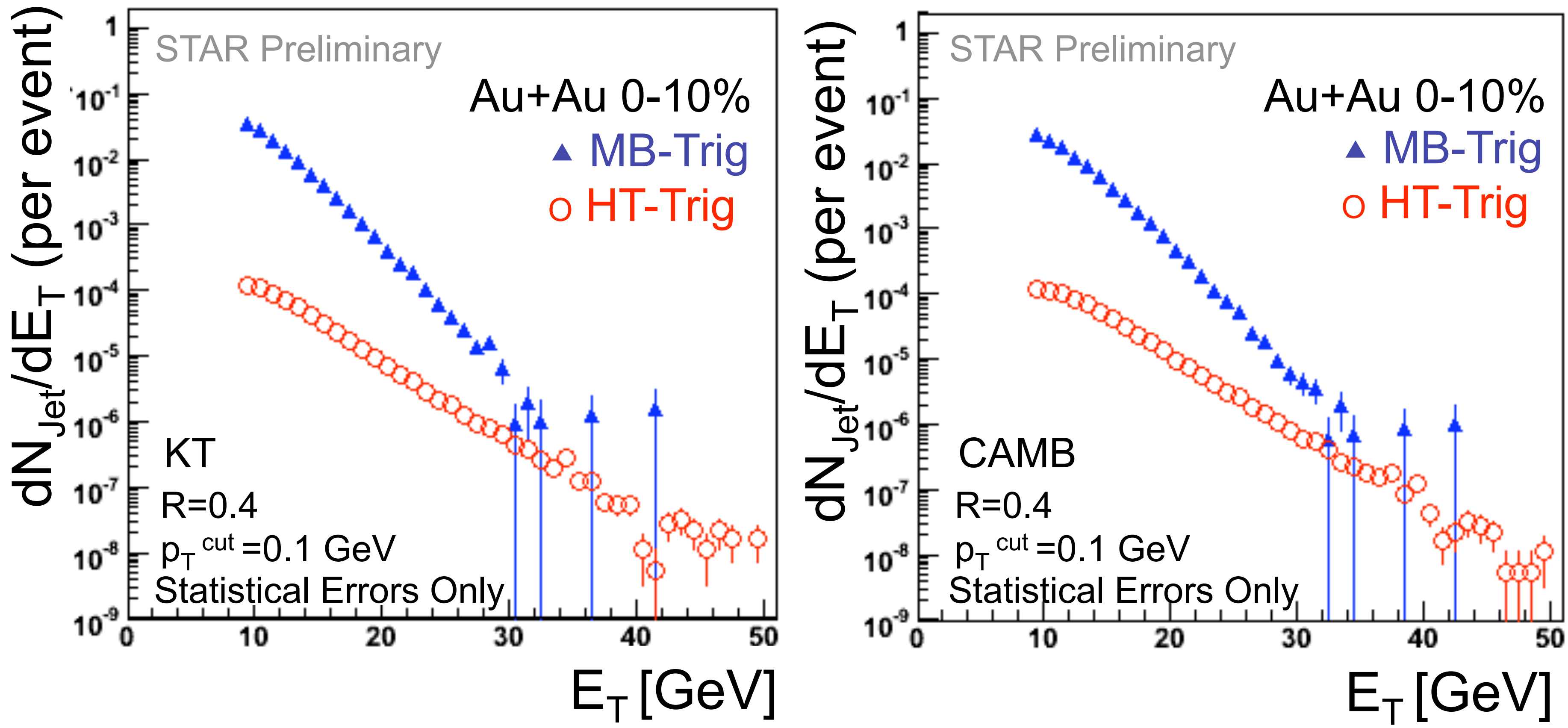
Resolution effect corrected assuming **Pythia Fragmentation**.

Relative normalization systematic uncertainty: ~50%

Good agreement with N_{bin} Scaled p+p.

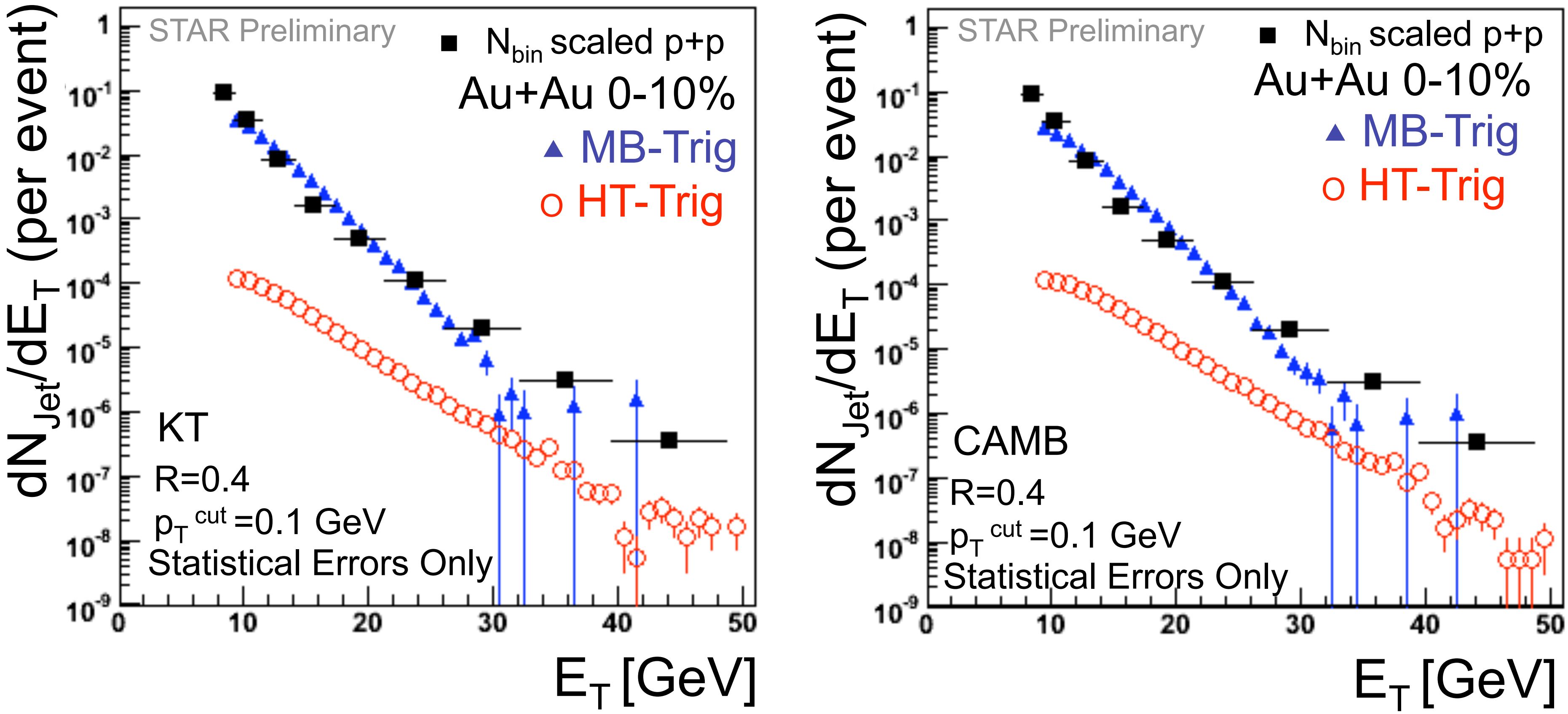
What does this mean? Lets look at other algorithms.

Jets with Sequential Recombination Algorithm



KT & CAMB biases are different wrt. LOHSC due to:
-- background subtraction algorithm
-- no seed
-- low p_T cut

Jets with Sequential Recombination Algorithm



KT & CAMB biases are different wrt. LOHSC due to:

-- background subtraction algorithm

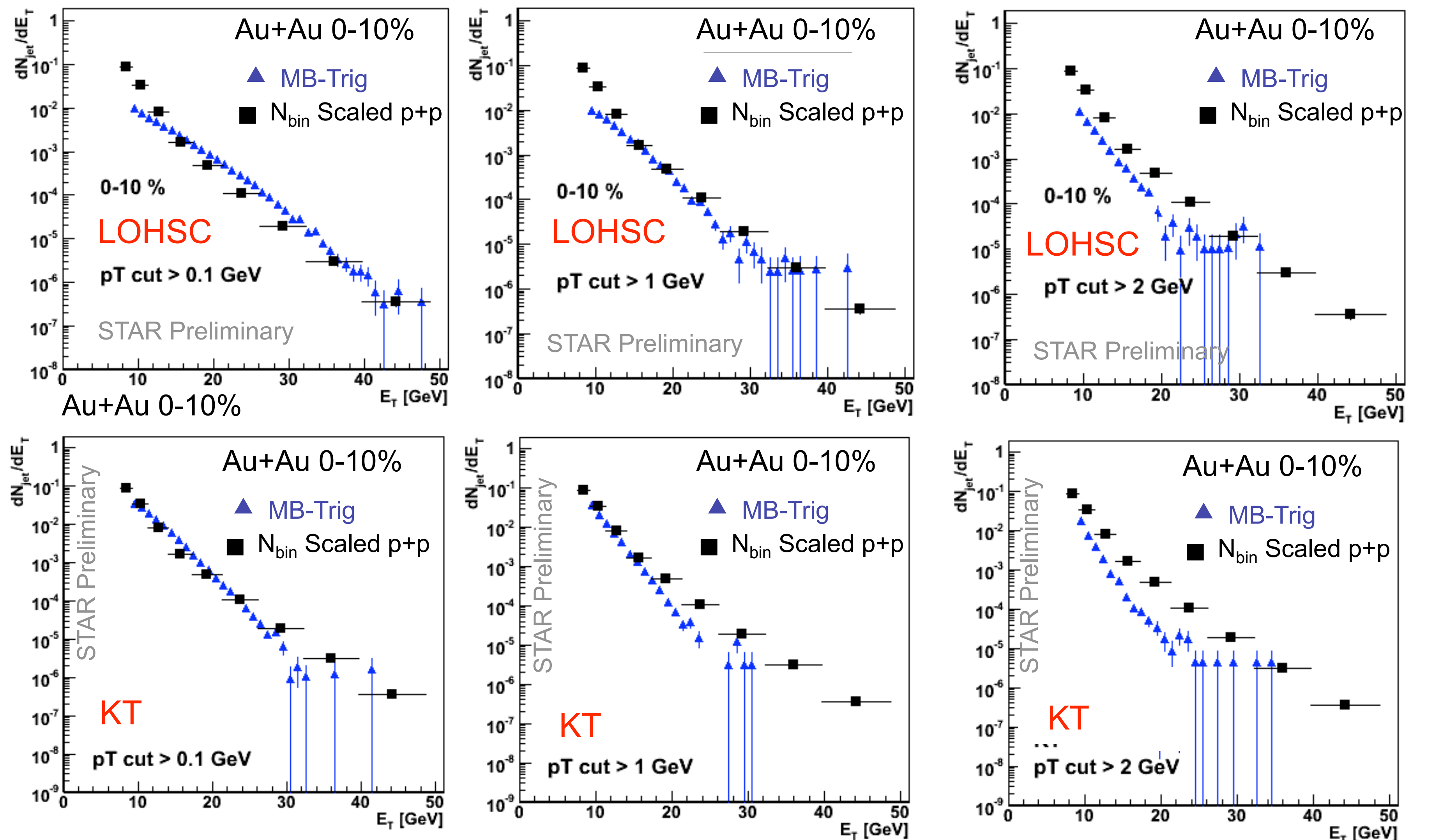
-- no seed

-- low pt cut

Systematic Uncertainity on Normalization: 50%

Good agreement with N_{bin} scaled p+p for unbiased algorithms.

Effect of Variation of p_T Cuts on spectra:



Imprecise subtraction of underlying event?
Do we introduce a bias with p_T-cuts?

P_T Cut

How sensitive are we to fragmentation model in corrections (PYTHIA) ?

Conclusions

- It is possible to reconstruct jets in 0-10% central heavy ion collisions at RHIC collisions. (Current reach is 50 GeV)

- Heavy ion background subtraction is possible, systematics studied via utilizing various algorithms.

- **N_{bin} scaling (50% Syst Uncert.) observed for least-biased cuts → Unbiased Jet Reconstruction ?**

- All the corrections are based on Pythia Fragmentation. Require systematic checks with quenching models.

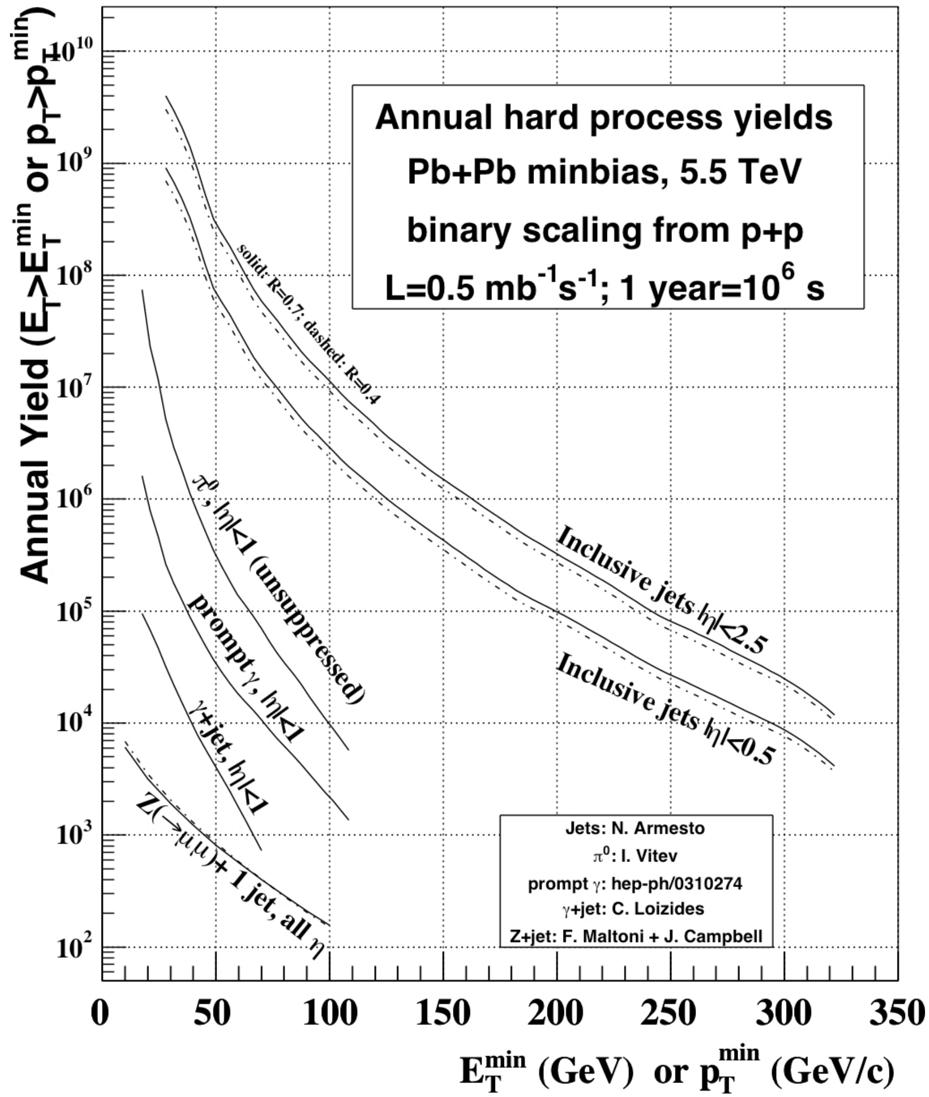
- Biases due to online triggers… Will be addressed with full Min-Bias data set (on tape).

Jets at LHC

LHC = Jet Factory

- Copious production of jets at sufficiently high energies to get above the HI background.

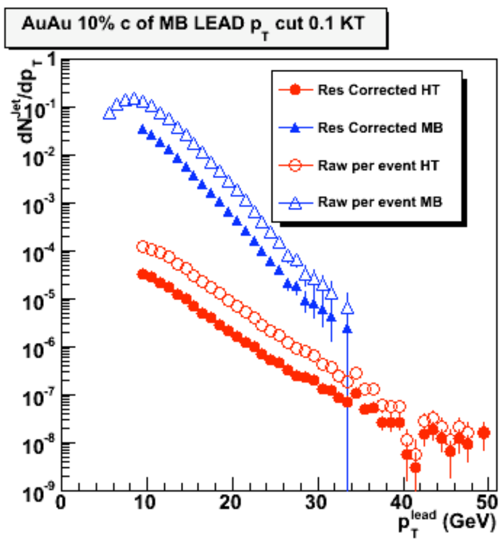
- Lever arm to measure the energy dependence of the medium induced energy loss.

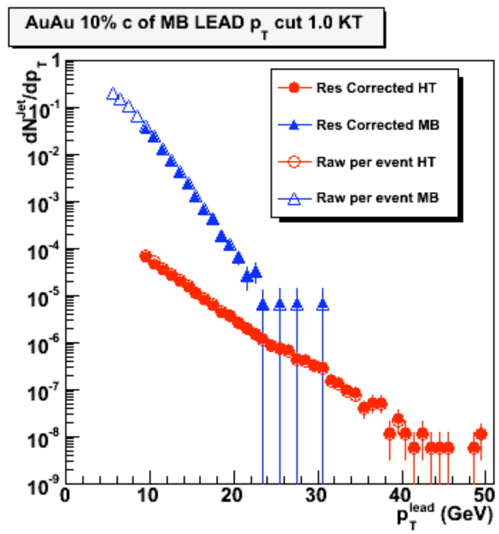


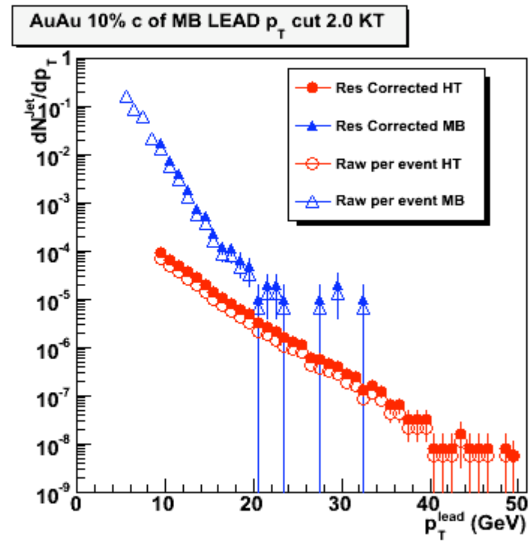
P.M. Jacobs, M. van Leeuwen
Nucl.Phys. A774 (2006) 237-246

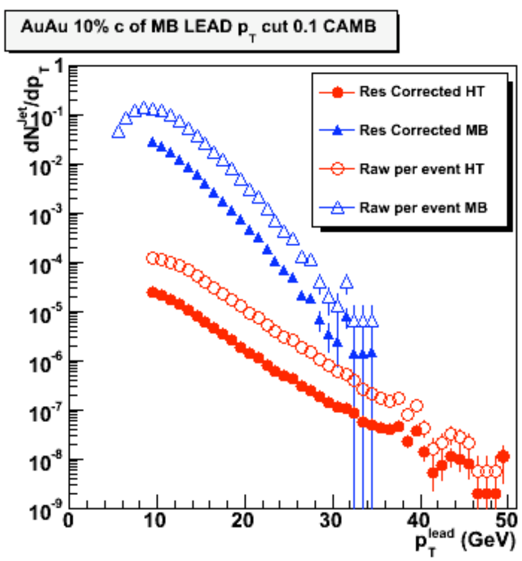
Extras

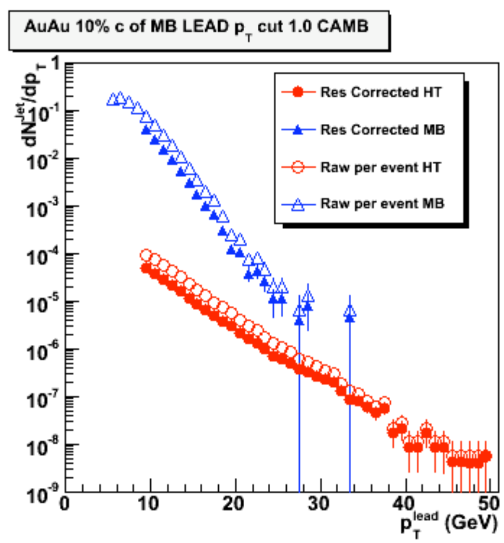
KT and Cambridge

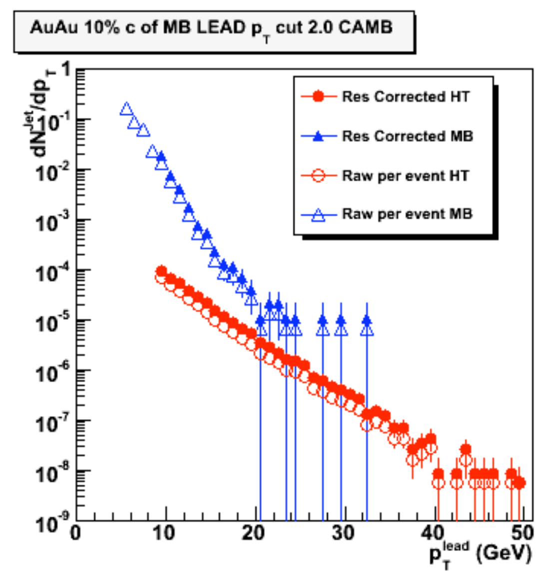




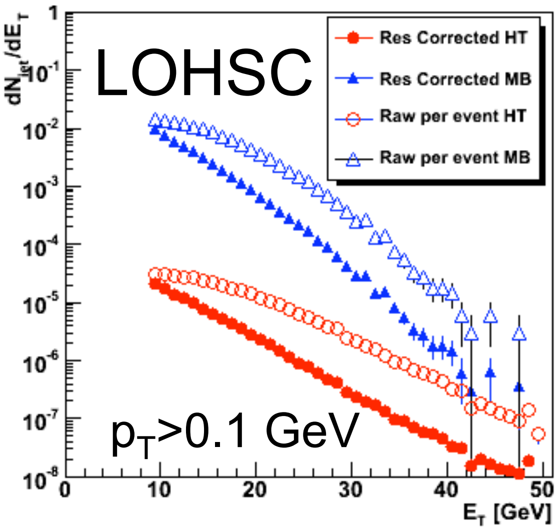


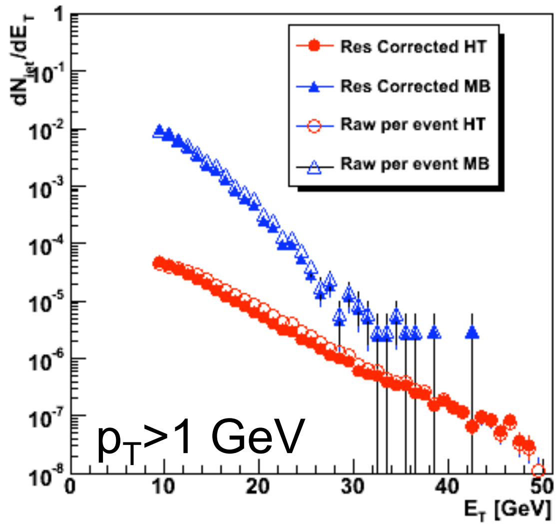


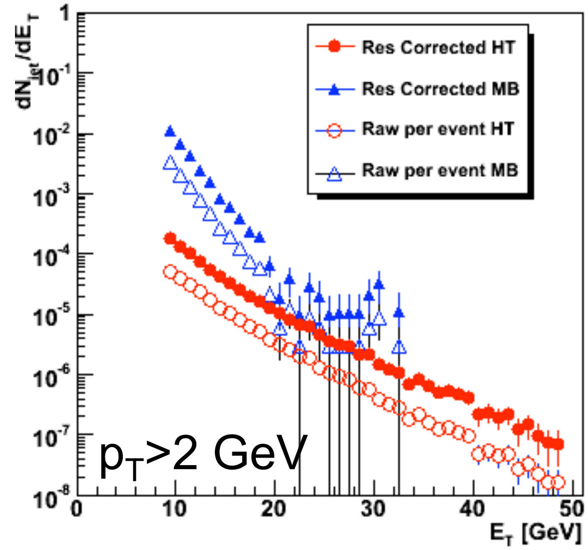




Correction factors:







Jet Algorithms - Requirements

Theoretical:

- Infrared & Collinear safety
  - Insensitive to “soft” radiation
  - Splitting shouldn’t change jets
- Define equally at hadron & parton level
  - Calculation & experiment comparable
- Low sensitivity to hadronization
- Underlying Event & Pile Up
- Applicable at detector level

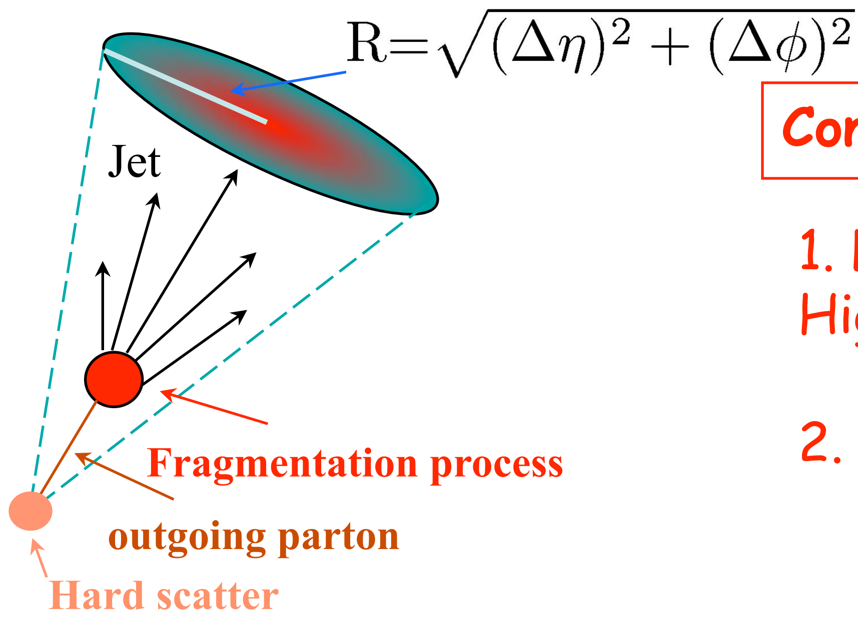
Experimental:

- Detector independence: Combination of detectors (EMCAL + TPC)
- Minimization of resolution effects
- Stability with Luminosity
- Computational efficiency
- Maximal reconstruction efficiency

Gerald C. Blazey et al. FERMILAB-CONF-00-092-E, hep-ex/0005012

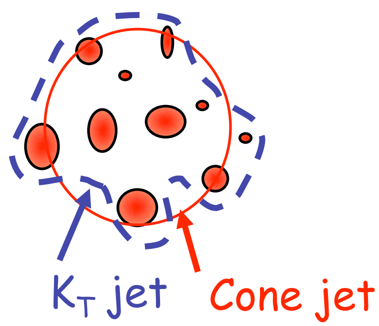
Quark and gluon jets (identified to partons) can be compared to detector jets, if jet algorithms respect collinear and infrared safety
(Sterman&Weinberg, Phys. Rev. Lett. 39, 1436 (1977))

Jet Reconstruction Algorithms:



Cone Algorithm

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

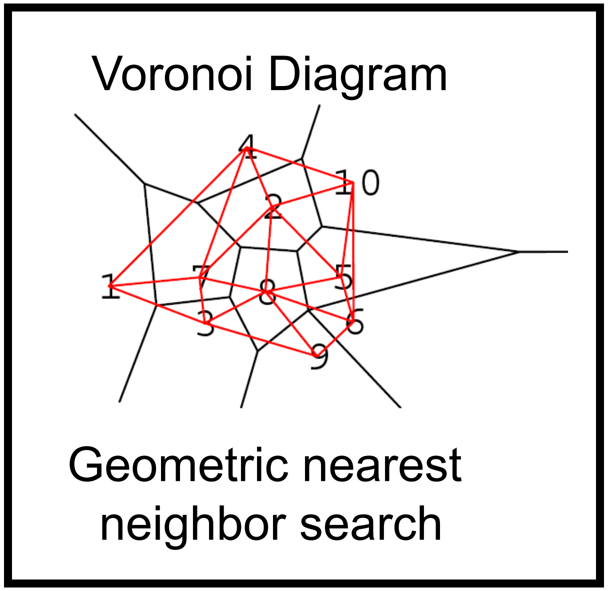


Sequential recombination

3. KT
4. Cambridge/ Aachen

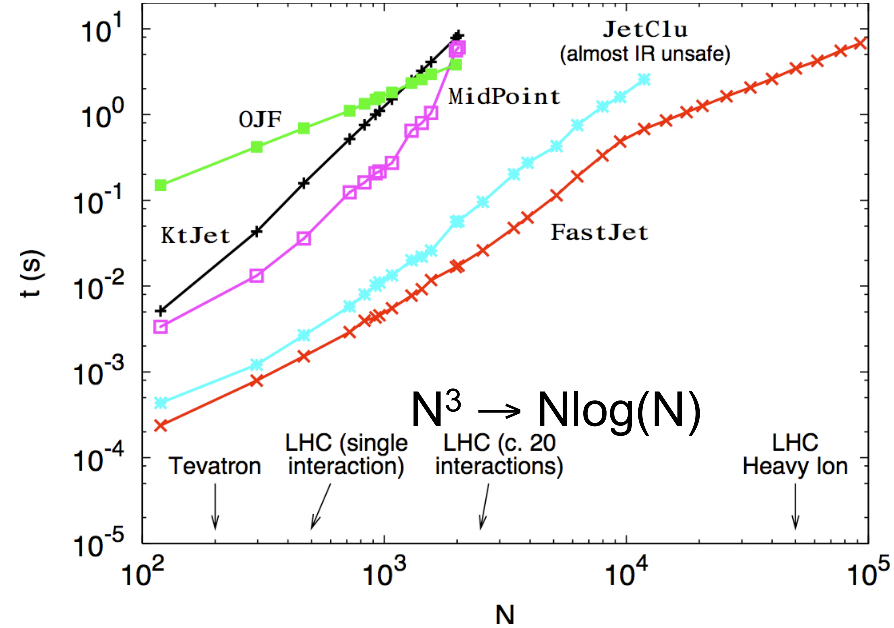
Explore systematics: Use both Clustering & Cone algorithms.

k_T Algorithms are not so slow after all



Computational Geometry Algorithms Library

- Divide the plane into cells (one per vertex),
- N points can be constructed with O (N ln N)



M. Cacciari, G. Salam hep-ph/0512210

Orders of magnitude faster
Large N region is feasible.

Geometrical and minimum-finding of the kt jet-finder require O (N ln N)

Summary

- It is essential to reconstruct jets at LHC & RHIC in heavy ion collisions.
- Tools: EMCAL, TPC etc … utilize clustering & cone algorithms
- Multiple jet algorithms provide systematic study. Depending on the algorithm: study infrared and collinear safety. Large heavy ion UE, fluctuations … has to be under control. Not an easy task.

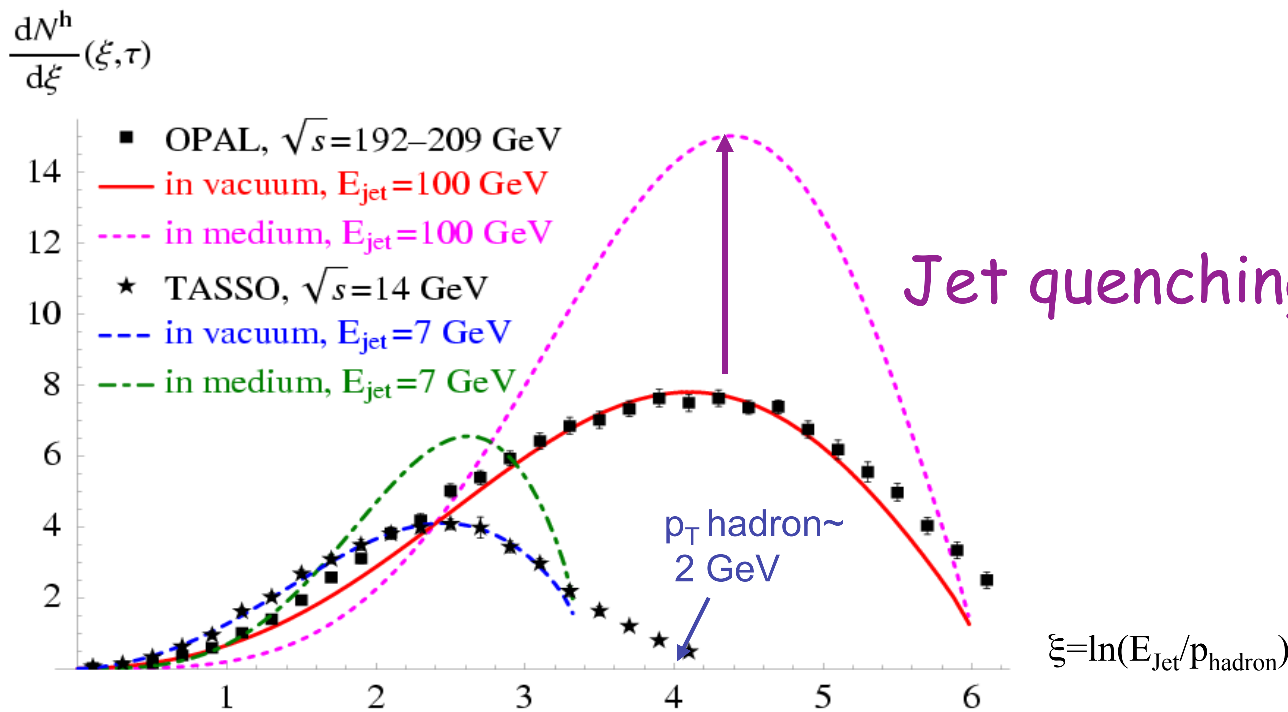
At the LHC: Sufficiently high cross-sections of high momentum jets but larger backgrounds.

- High rates providing sufficient energy lever-arm to map out the energy dependence of jet quenching.
- Large effects: Jet structure changes due to energy loss and the additional radiated gluons.

At RHIC: Smaller backgrounds but also smaller cross-sections of high momentum jets , lower energy lever-arm.

Modified Fragmentation Function

Modified **L**eading **L**ogarithmic **A**pproximation:
- good description of vacuum fragmentation (basis of PYTHIA)
- introduce medium effects at parton splitting



Borghini and Wiedemann, hep-ph/0506218

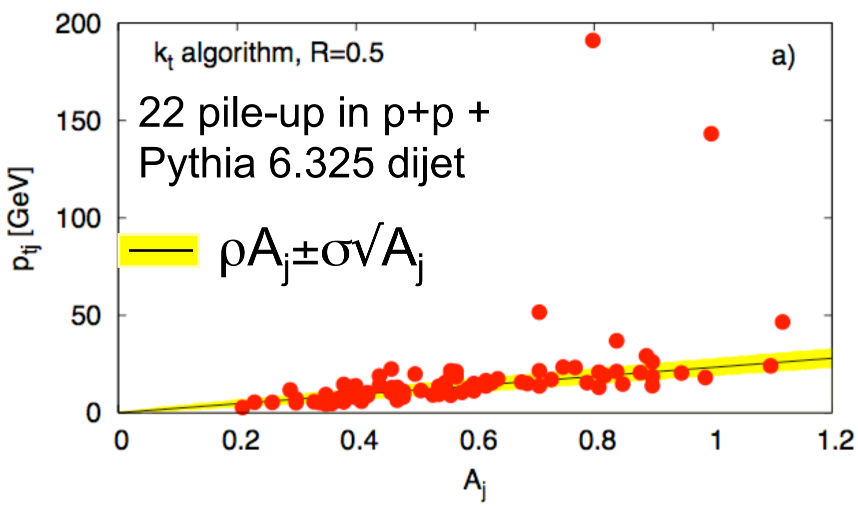
Jet quenching: Low p_T enhancement

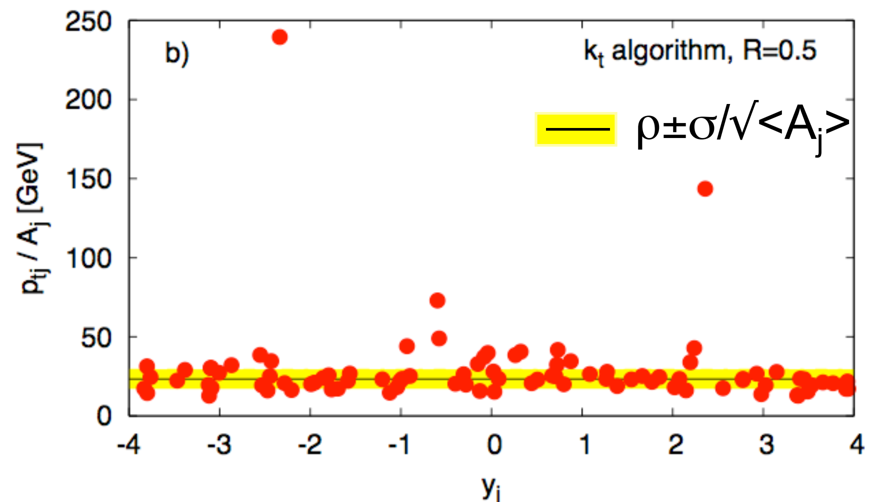
Fragmentation is strongly modified at p_T^{hadron}~1-5 GeV

Background in sequential clustering (K_T)

Underlying event (UE) & pile-up are distributed uniformly in y and ϕ

p_T(Jet Measured) ~ p_T(Parton) + <p_T(UE)> X A(Jet)





ρ = Diffuse noise (p_T added)

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

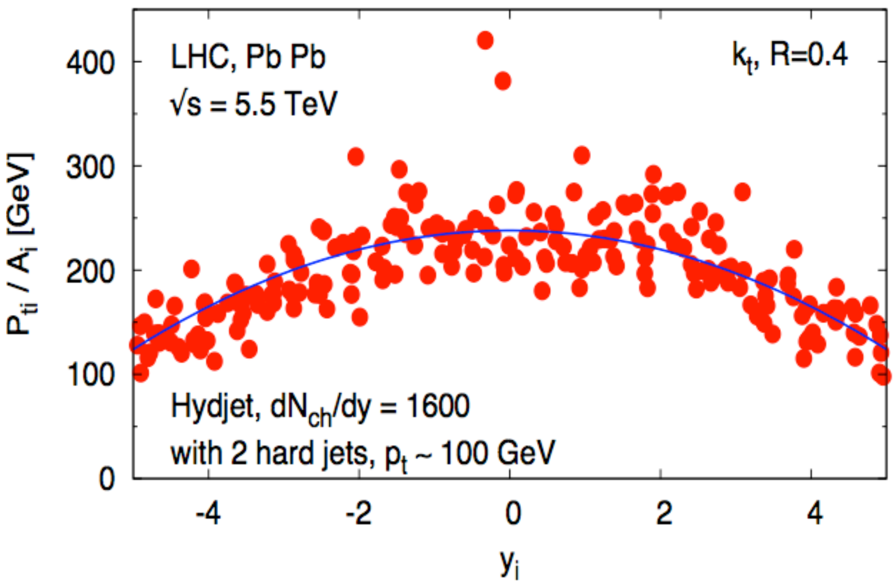
M. Cacciari, G. Salam, G. Soyez 0802.1188 [hep-ph]

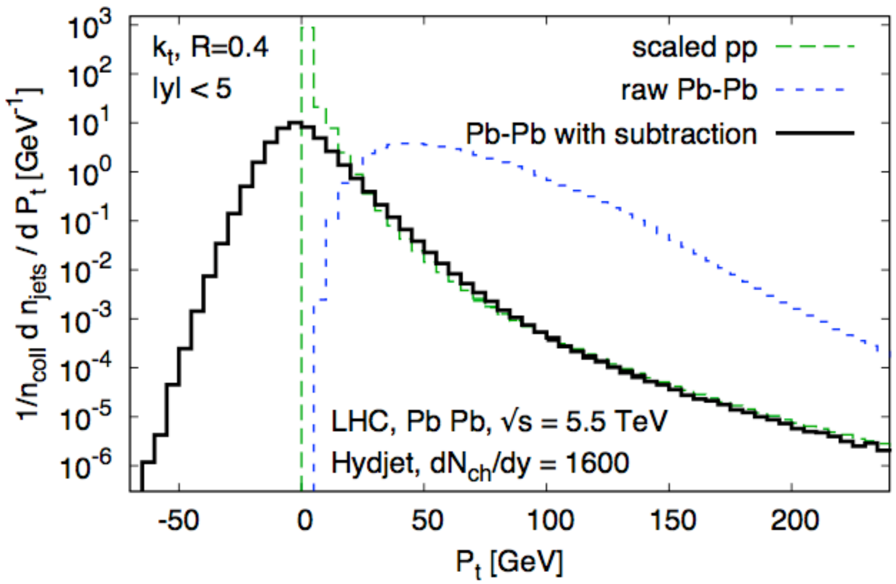
Area Definition: Estimate the active area of each jet by filling event with many very soft particles then count how many are clustered into given jet

Study of P_T/A_j determine the noise density ρ on an event-by-event basis

Heavy-Ion Background Subtraction in sequential clustering (K_T)

Use the same approach for HI
Study the p_T/A_j and remove the contribution $\propto A_j$





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

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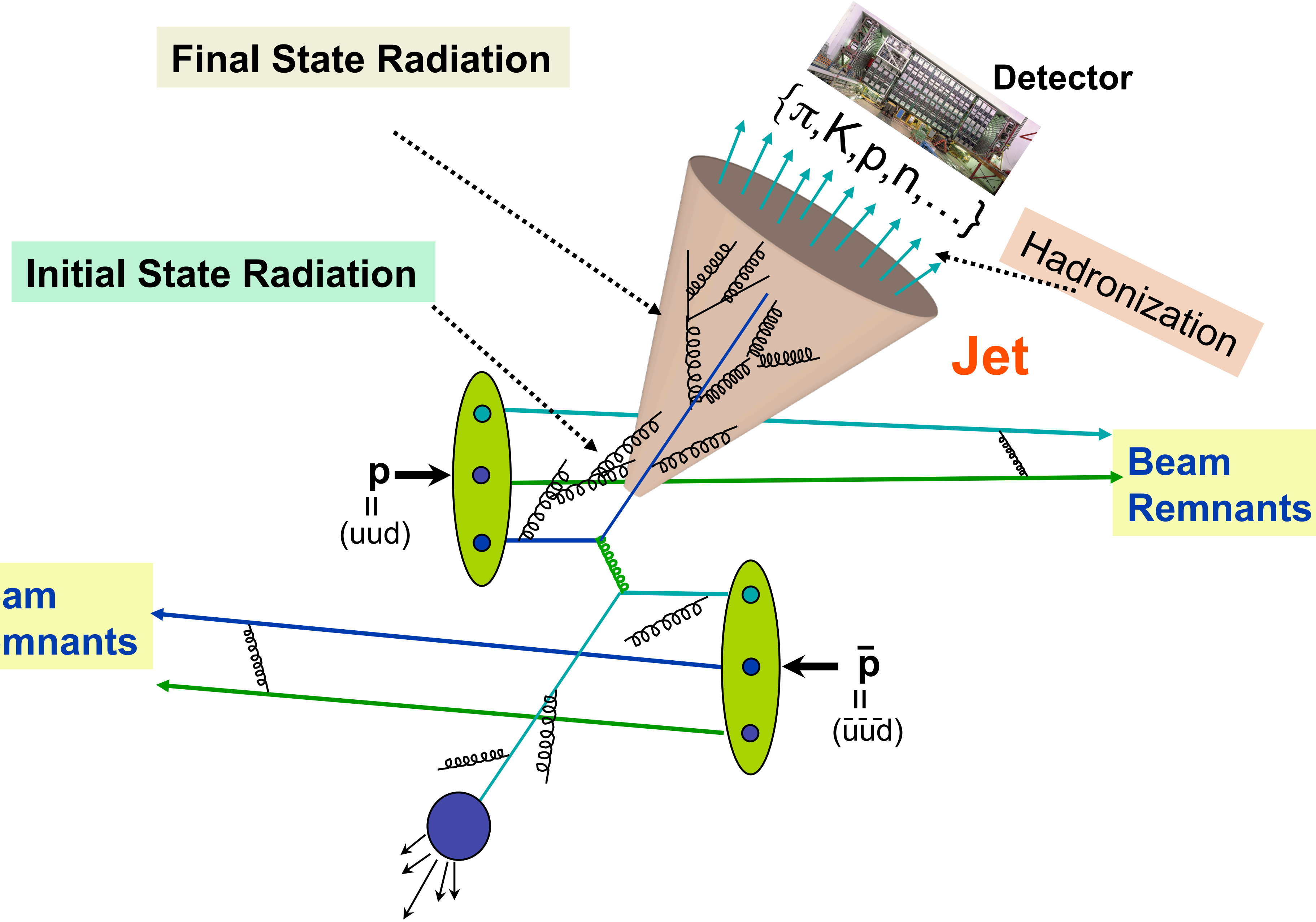
The scaled pp cross-section is recovered after the subtraction

Jets as seen by a theorist



Jets as seen by an experimentalist