Moving towards quantitative jet-quenching measurements in heavy-ion collisions

Applying lessons learned at RHIC to LHC

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Outline:

(Short) Introduction
- What do we want to measure?
- And how can one measure it?

Jet-quenching at RHIC
- Full-jet reconstruction at RHIC
- Towards fragmentation functions: Jet-Hadron correlations
- Discussion/Interpretation

Jet quenching at the LHC with ALICE
- Advantages / applying the lessons learned at RHIC

Summary and discussion

In a nutshell: The QGP at RHIC

At **RHIC** we see the

hottest

densest

matter

ever studied in the laboratory that

flows

as a (nearly) perfect fluid

with systematic patterns consistent with

quark degrees of freedom

and a viscosity to entropy density ratio

lower

than any other known fluid

and it is

opaque to colored objects

T=200-400 MeV ~ $3.5 \cdot 10^{12}$ K

ε=30-60 $\varepsilon_{\text{nuclear matter}}$

large "elliptic" flow

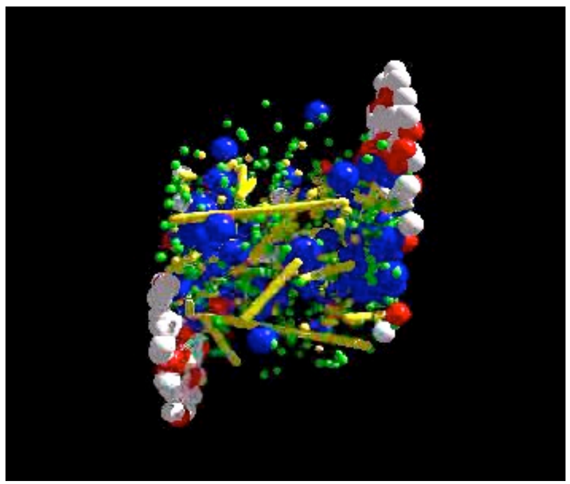
valence quark scaling

high-p_T suppression

All hint towards a ***strongly coupled*** *quark-qluon* system: **"s"QGP**

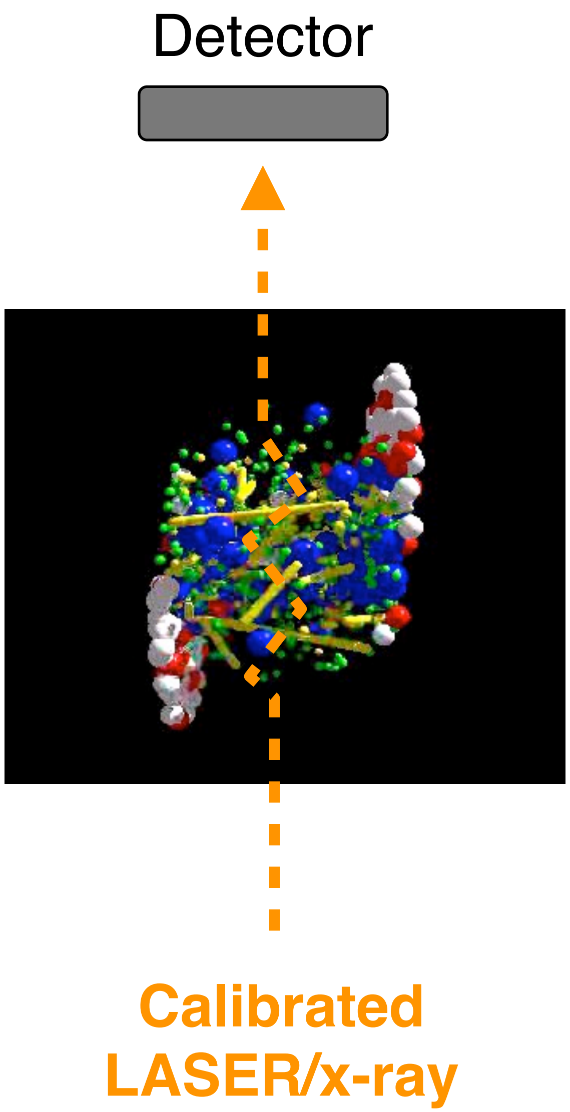
How can one study the QGP in more detail: “Tomography”

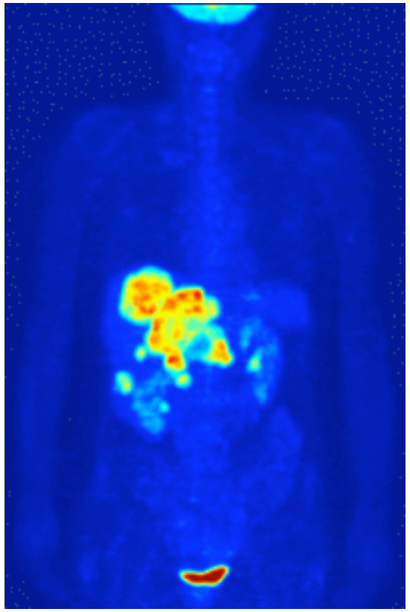
Detector



Calibrated LASER/x-ray

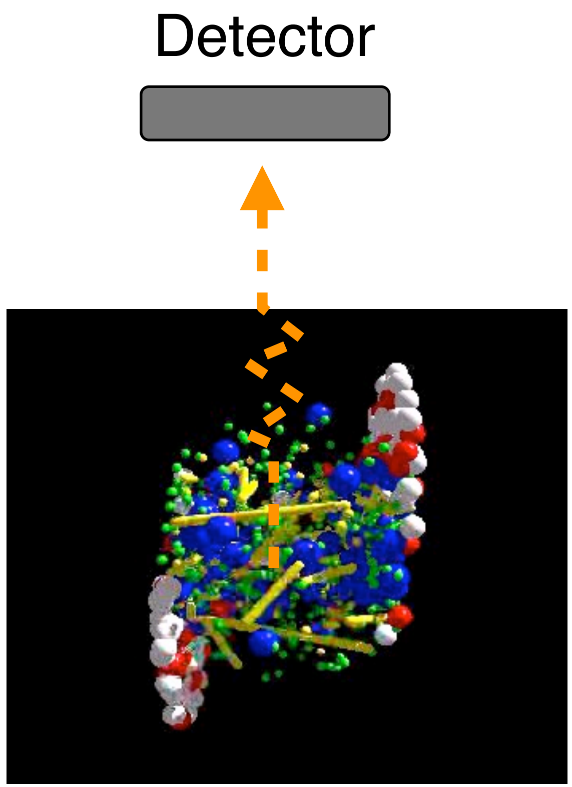
How can one study the QGP in more detail: “Tomography”



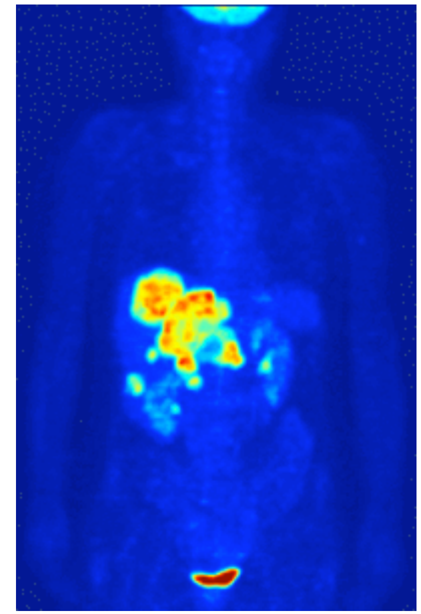


Human body

How can one study the QGP in more detail: “Tomography”



Self-generated “hard” probes



Human body

‘Hard’ processes/probes have a large scale in the calculation that makes perturbative QCD applicable:

- high momentum transfer, Q^2
- high mass, m
- high transverse momentum, p_T

N.B.: since $m \neq 0$ heavy quark production is ‘hard’ process even at low p_T

A variety of “hard” probes ...

Measurement difficulty

- **Hadron production**
- **Heavy flavours**
- **Jet production**
  - $e^+e^- \rightarrow$ jets
  - p(bar)+p $\rightarrow$ jets
- **Direct photon production**

Theory difficulty

Focus in this talk: Jet production

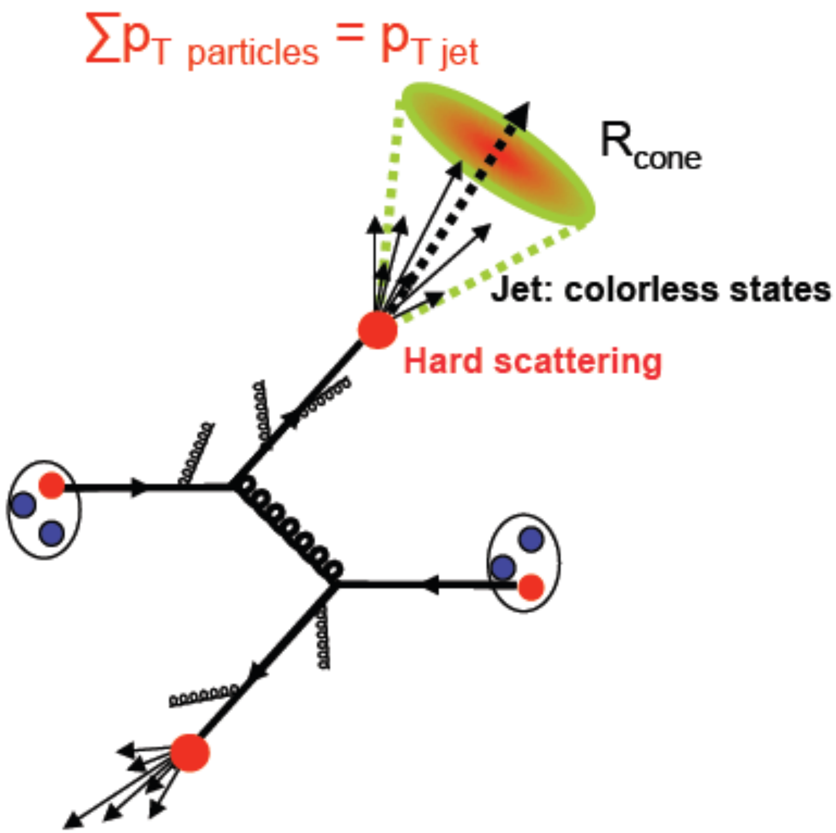
Why jets? Jets connect theory and experiment

pQCD factorization:

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

PDF **Partonic x-section** **Fragmentation function**

Jet spectrum



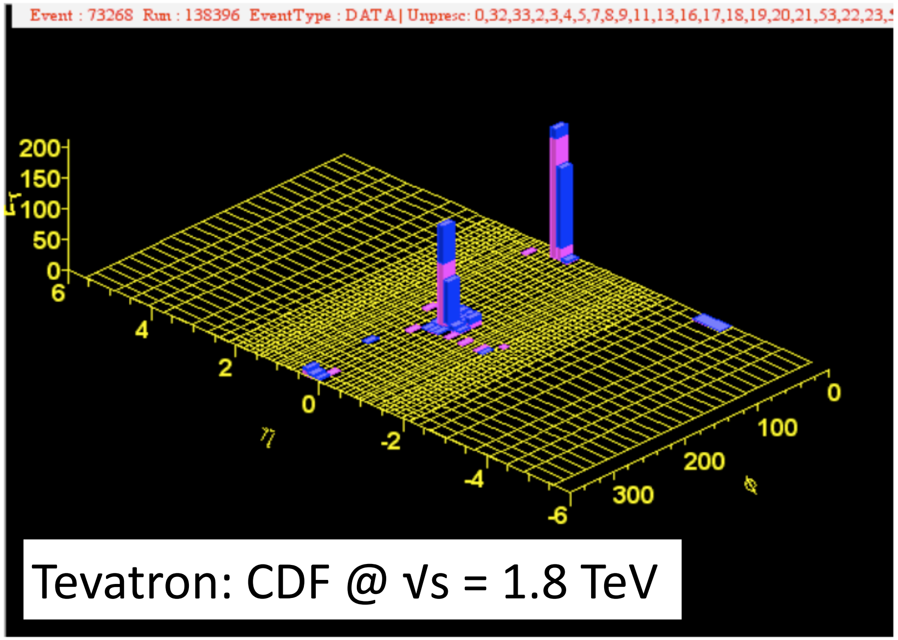
Jets are the experimental signatures of quarks and gluons. They reflect the kinematics and “topology” of partons:

- pQCD calculates partons
- experiments measure fragments of partons: hadrons

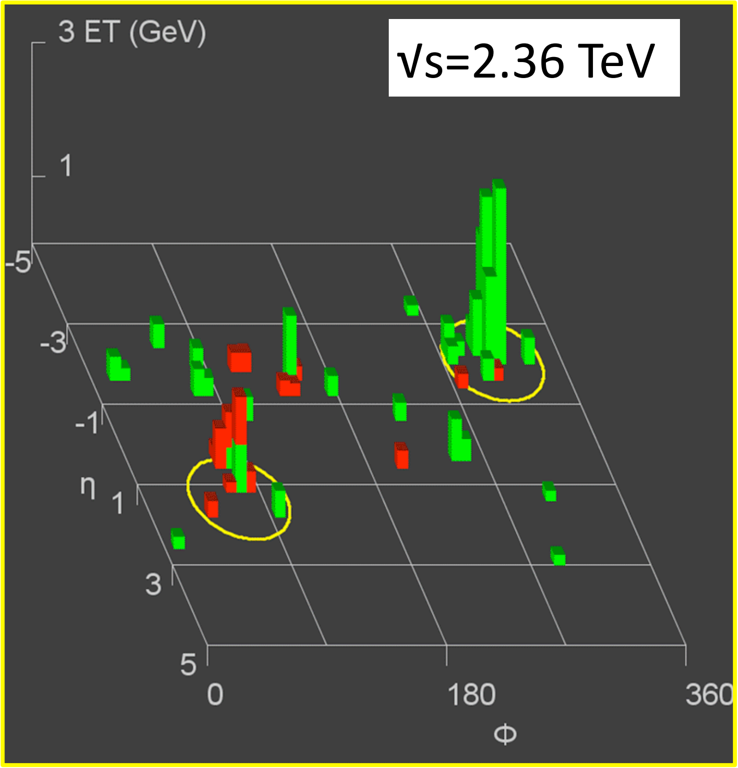
Goal: re-associate (measurable) hadrons to accurately reconstruct partonic kinematics

Tool: *Jet-finding algorithms:* Apply same algorithm to data and theoretical calculations

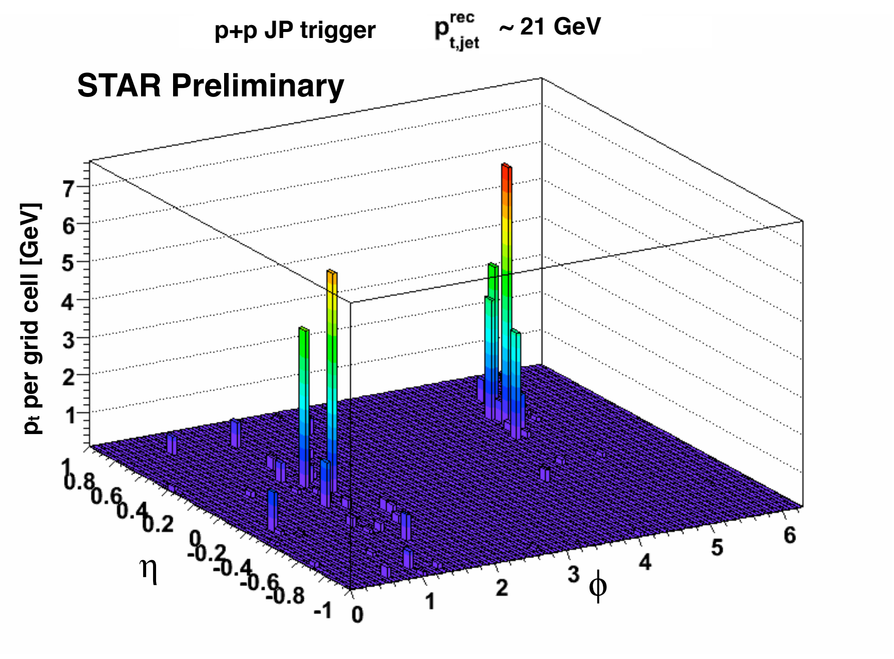
"Seeing" jets is "easy" ...



ATLAS Nov/Dec 2009



RHIC p+p @ √s = 200 GeV



at least in p+p collisions,
<u>but</u> how to define a jet ...

Jet definition ⇔ Jet algorithm

The construction of a jet is *unavoidably ambiguous*.
On at least two fronts:

- Which particles get put together into a common jet?
- How do you combine their momenta?

Jet definition ⇔ Jet algorithm

The construction of a jet is *unavoidably ambiguous*
On at

- Wh
- Hov

Jet Definition

$\{p_i\}$ jet algorithm $\longrightarrow$ $\{j_k\}$

particles
4-momenta,
calorimeter towers

jets

+ parameters (at least the cone radius/ resolution parameter R)

+ recombination scheme

Jet definition ⇔ Jet algorithm

Snowmass accord (1990)

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

And more ...

- Physical results independent of your choice of jet definition
- Jets should be invariant with respect to certain modifications of the event:
  - collinear splitting
  - infrared emission

This reduces the list of potential jet-finding algorithms to:

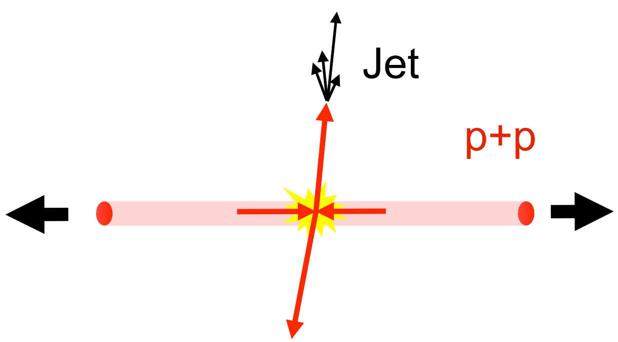
- k_T/Anti-k_T (recombination algorithms)
- SISCone (infrared, seedless cone algroithm)

all part of the FastJet package: *M. Cacciari, G.P. Salam, G. Soyez, JHEP 04, 005 (2008), 0802.1188*

Before we can utilize hard probes/jets (and their modifications/tomography) to probe the medium in heavy-ion collisions we first have to establish that:

1) <u>The probe is calibrated:</u>

Comparison of pQCD calculations with p+p measurements



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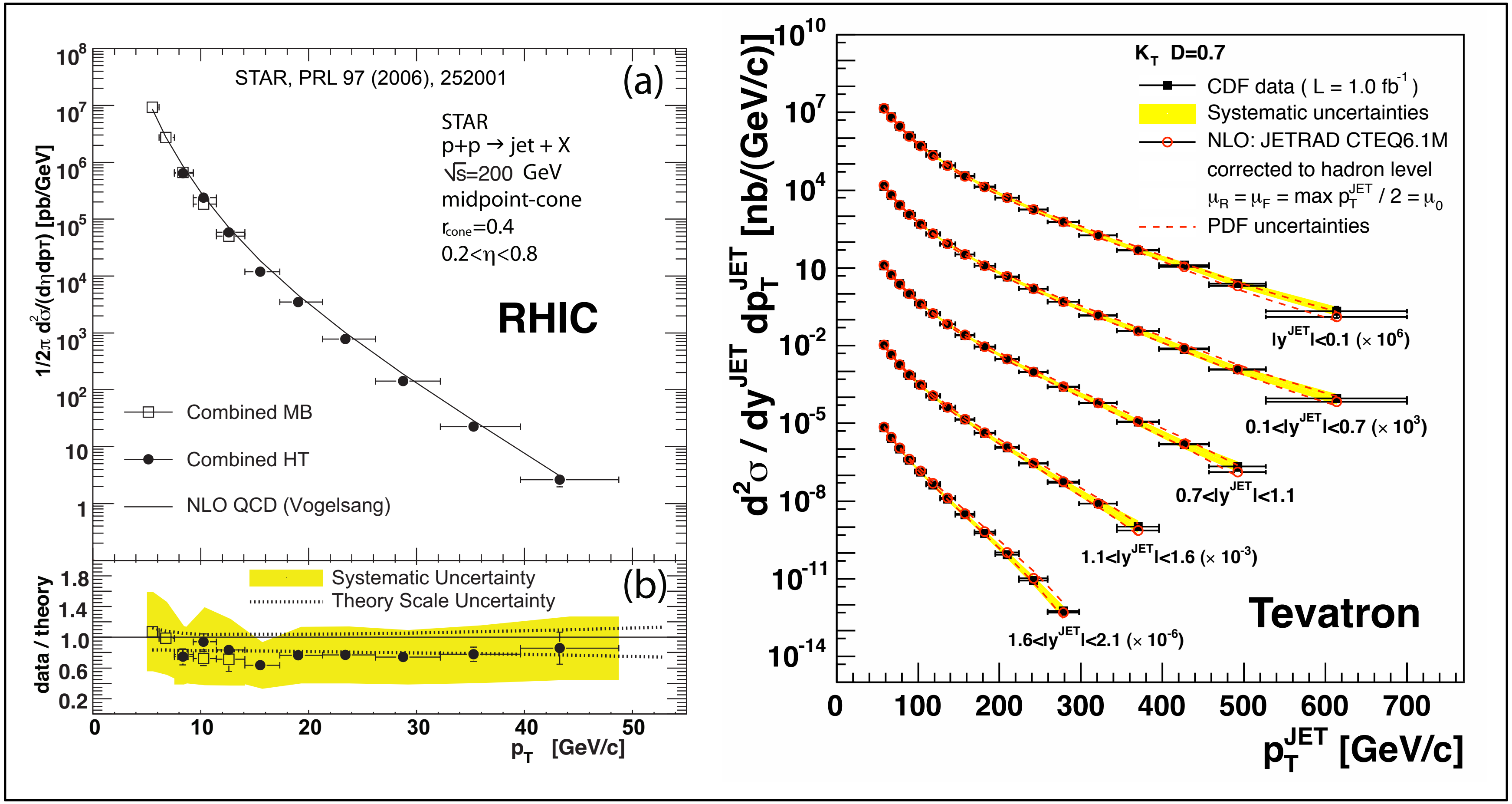

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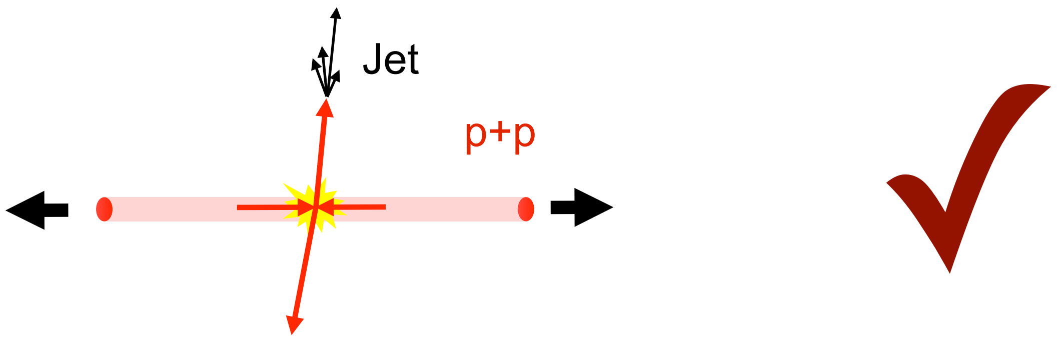
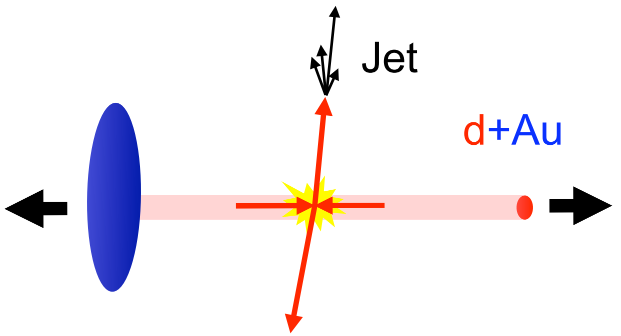


2) Control experiment:

Measure initial state/Cold Nuclear Matter (CNM) effects;
Probe the “cold medium” via d+Au collisions (compare to p+p)



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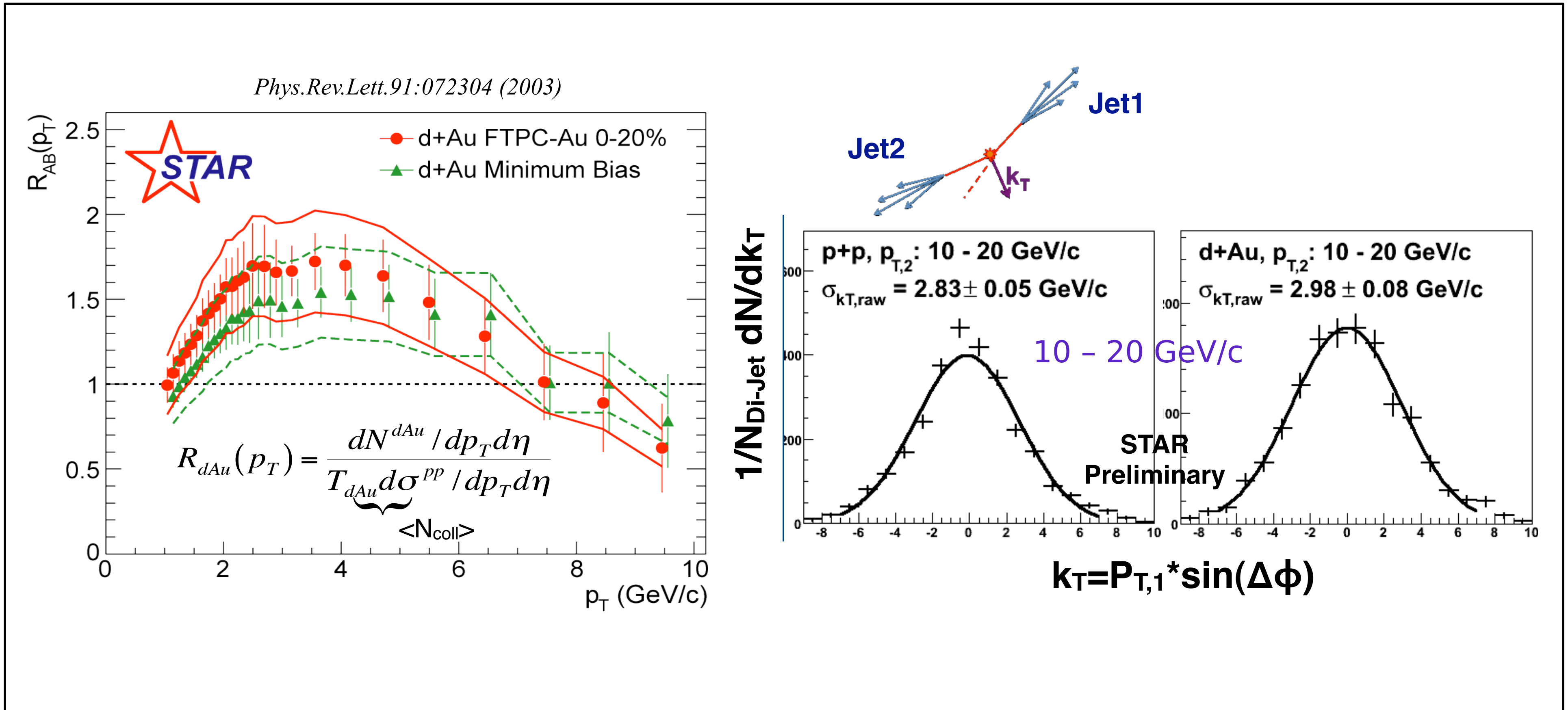

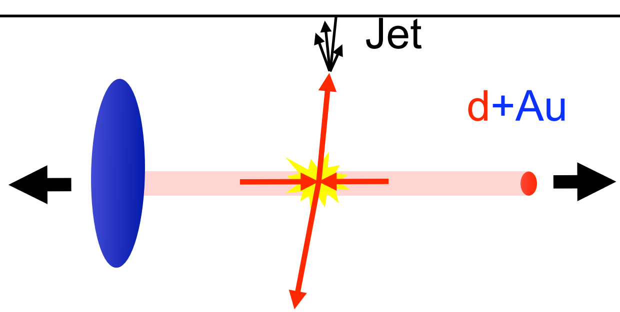

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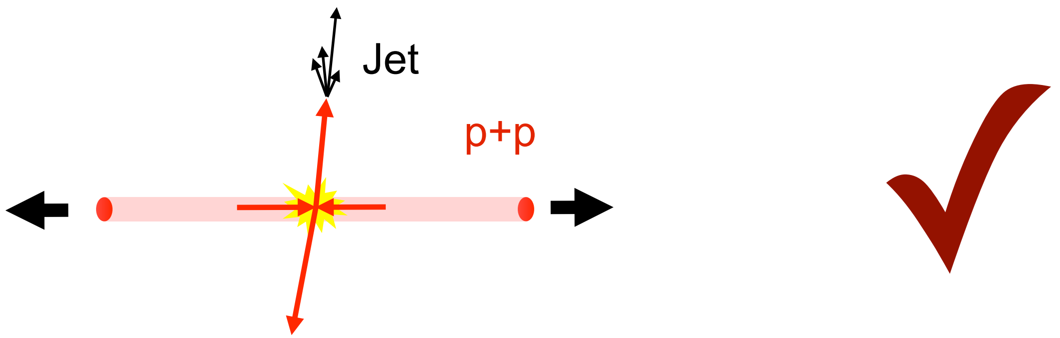

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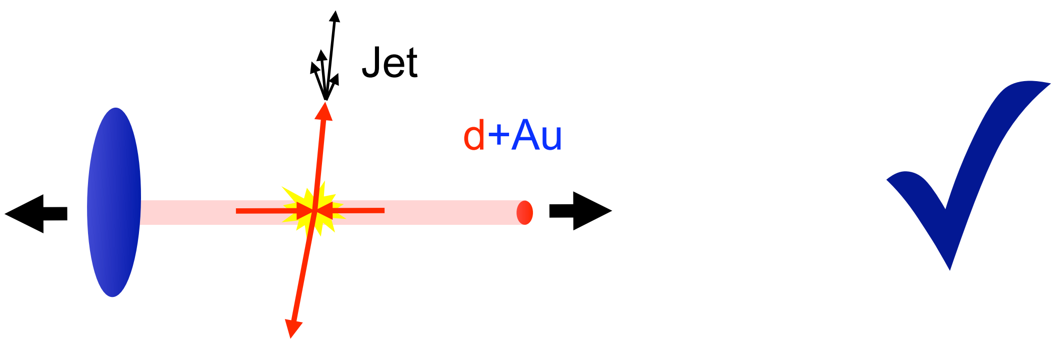
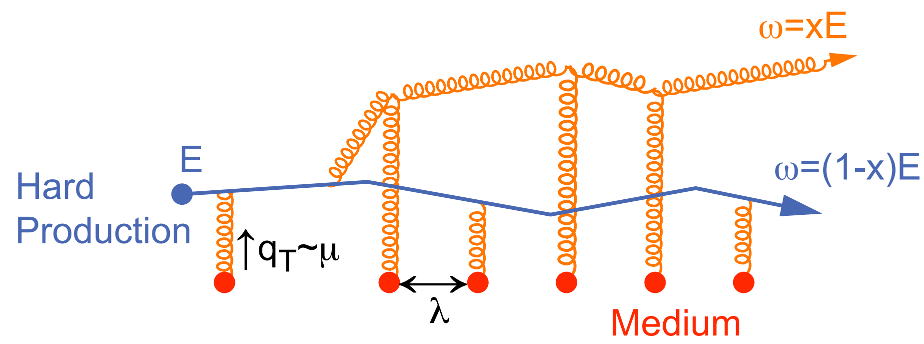


Jet-quenching theory from an experimentalists view

Gluon radiation

Multiple final-state gluon radiation off of the produced hard parton induced by the traversed dense colored medium



General form: Partonic spectrum E_{jet} ⊗ Nuclear geometry L ⊗ Energy loss $\Delta E(E_{jet})$ ⊗ Fragmentation $D(E_{jet}, \Delta E)$

- Mean parton energy loss $\propto$ medium properties:
  - $\Delta E \sim \rho_{gluon}$ (gluon density)
  - $\Delta E \sim \Delta L^2$ (medium length)

    $\Rightarrow \sim \Delta L$ with expansion

- Characterization of medium via transport coefficient $\hat{q}$ is mean p_T^2 transferred from the medium to a hard gluon per unit path length λ

A lot of theories/models on the market:

$\hat{q} \sim$ 2-10 GeV/fm

no quantitive agreement* (based on the available measurements) at RHIC so far!

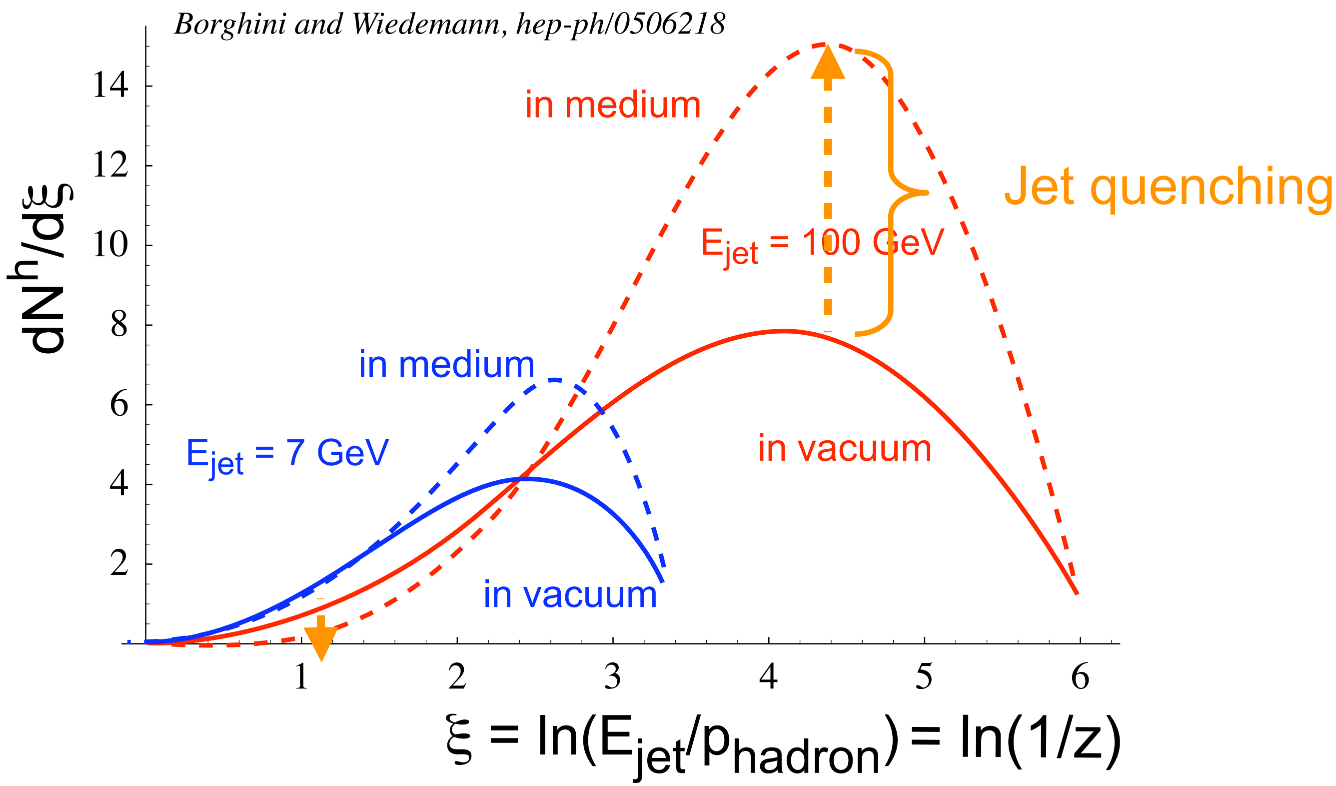
Naive summary:

To varying extent all theories (except AdS/CFT) predict a **softening** of the fragmentation and an overall **broadening** of the jet shape!

*Remark: The differences might be due to NLO corrections !? (Thesis and *Nucl.Phys.A820:115C-118C,2009*)

What we ideally want to measure ...

- MLLA: good description of vacuum fragmentation (basis of PYTHIA)
- Introduce medium effects at parton splitting *Borghini and Wiedemann, hep-ph/0506218*

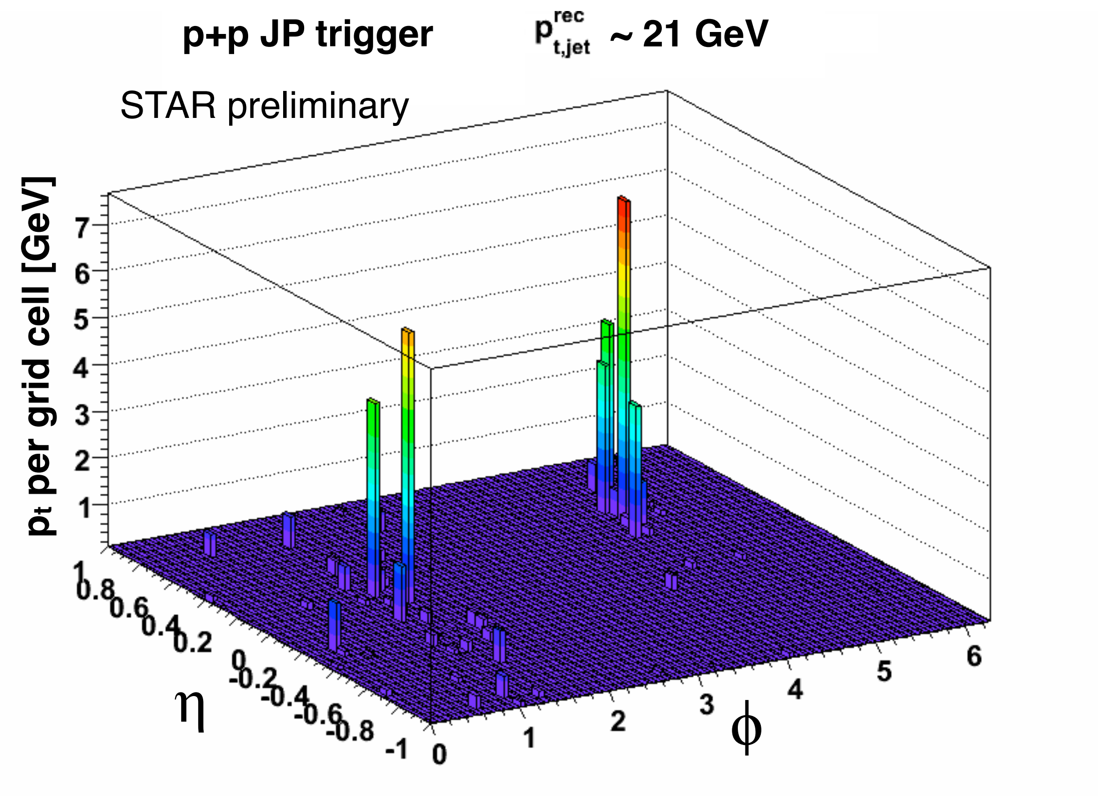


Modification of the fragmentation function/jet structure due to partonic energy loss in the medium, at a well defined partonic/jet energy, of an unbiased jet population

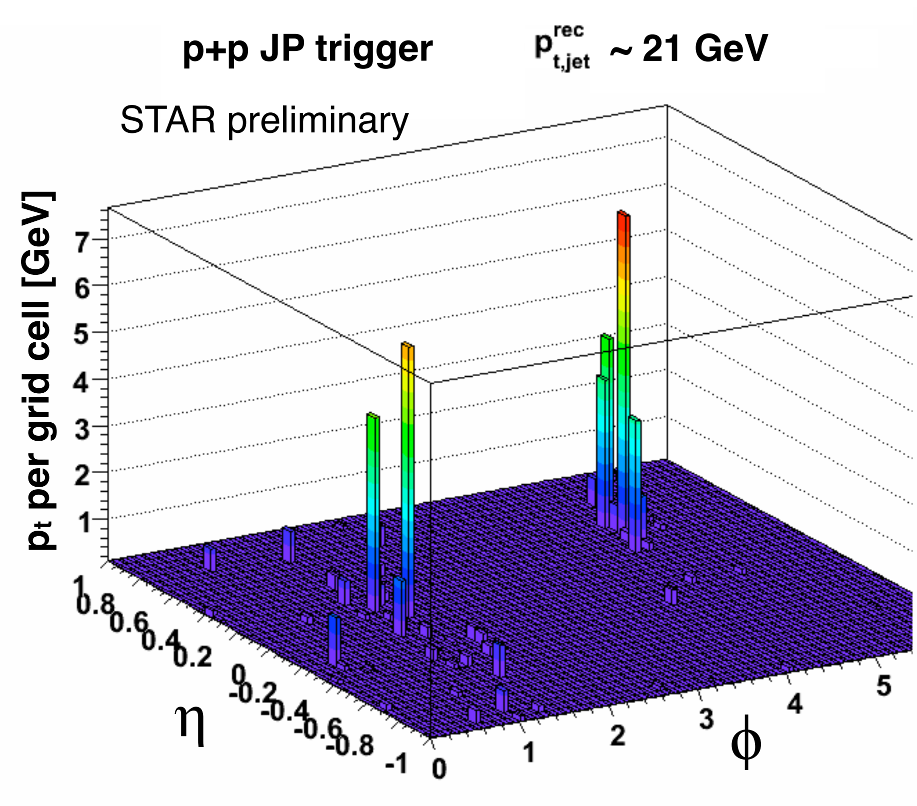
(no geometric/kinematical biases as in single or di-hadron measurements; single/di-hadron are indirect measurements of jet quenching)

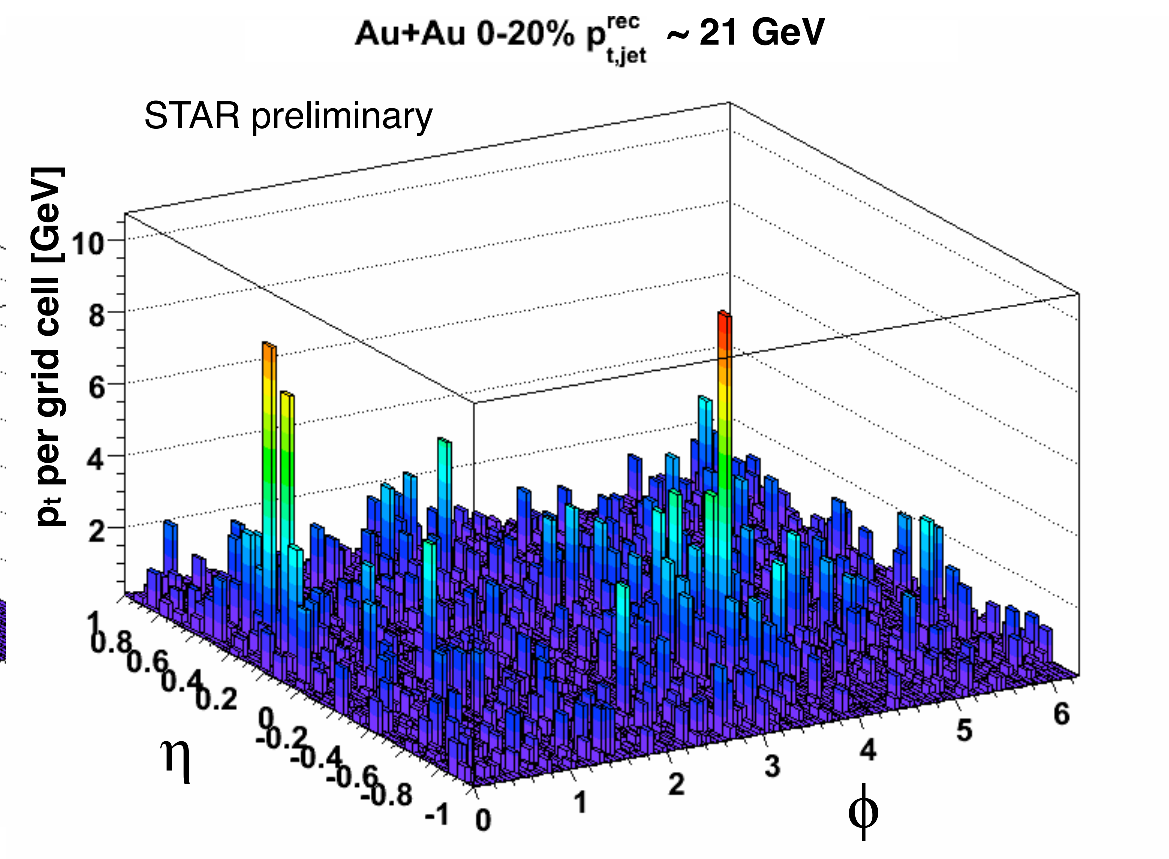

Full-jet reconstruction at RHIC ?
Sometimes one has to do
the first moves without
any further protection ...

Seeing jets in HI collisions ...



Seeing jets in HI collisions ...



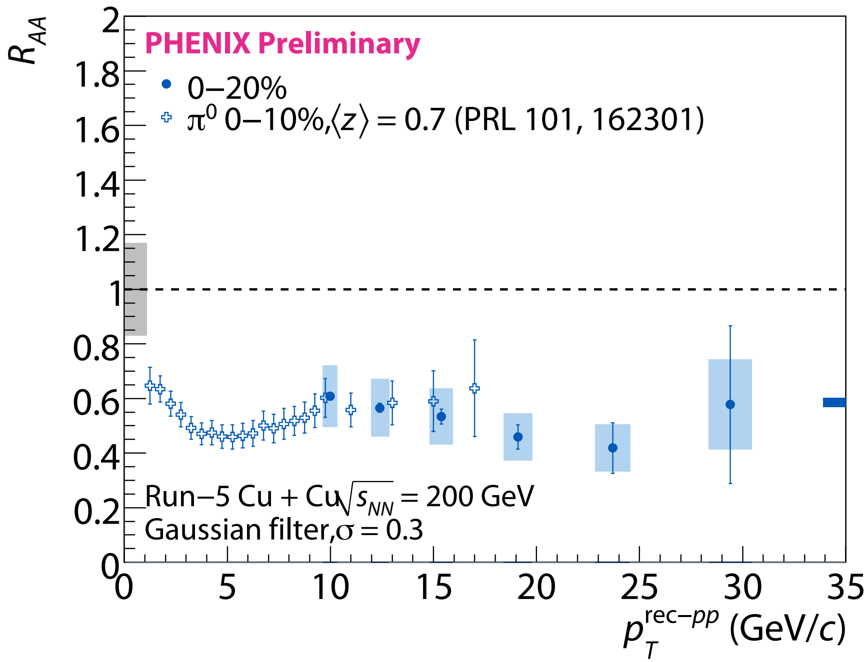


well, at least *some* are clearly visible!

But how to correct for the underlying heavy-ion background?

How to determine the jet energy scale?

Full jet reconstruction: (Hard) Lesson from RHIC

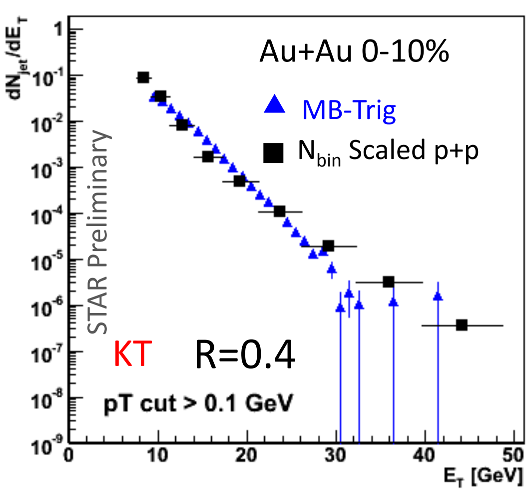


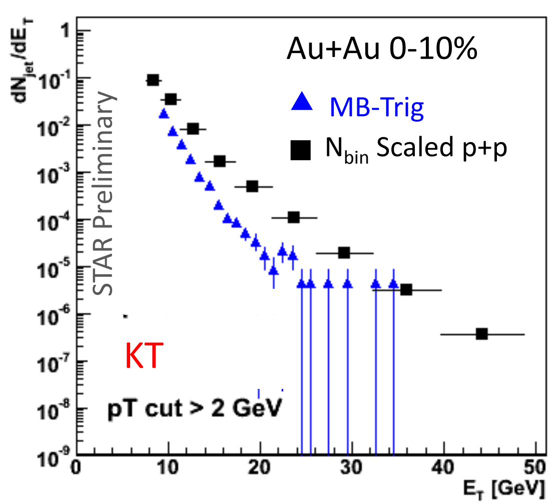
"A jet is what you ask for!"

Phenix for example:
jet-finder based on unmodified jet-shapes
⇒ veto against modified/quenched jets

p_T cut to minimize background
⇒ bias towards non-interacting jets

"Anti-quenching" biases are "everywhere"!





There are no shortcuts! We have to deal with the full complexity of the heavy-ion background!

BUT: The tools are available!

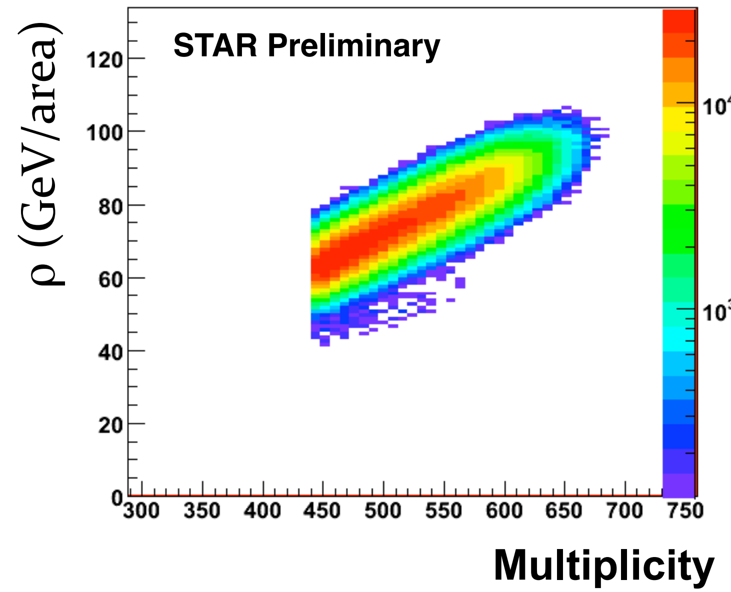
The challenge: Heavy-ion Background

A jet in HI collisions schematically:

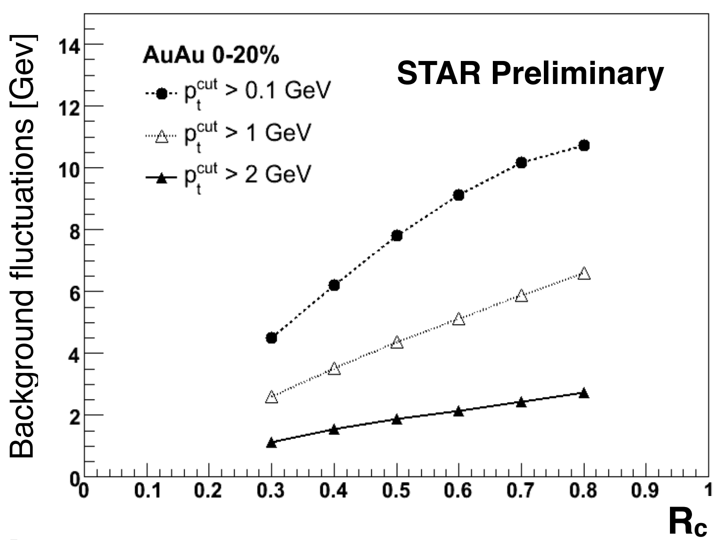
p_T (Jet Measured) ~ p_T (Jet) + ρ A ± F(A)

Three main components:

1. Overall background energy density per unit area ρ with A the jet area (determined by FastJet algorithm) ρ A ~ 45 GeV for R_C=0.4 (S/B ~0.5 for 20 GeV jet)



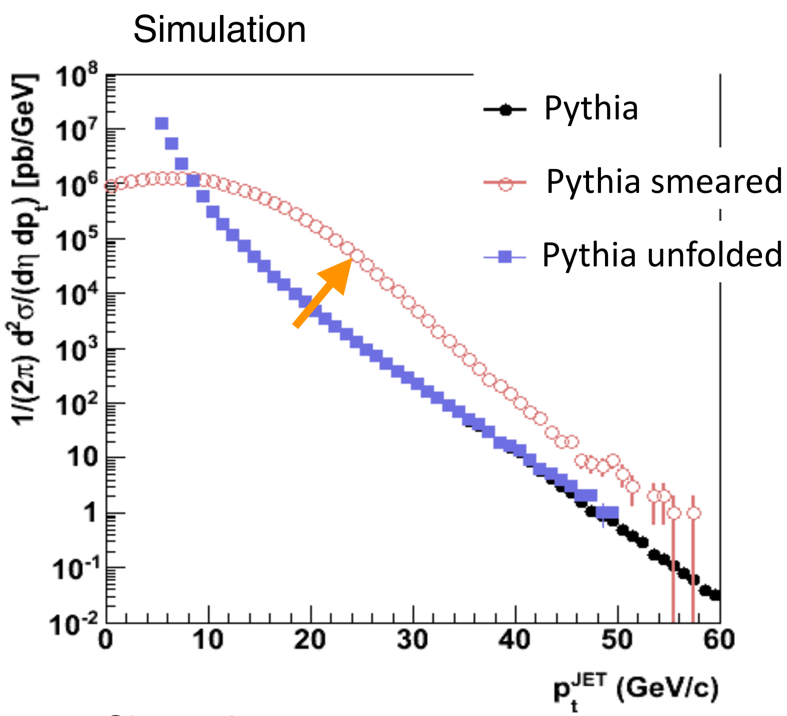
2. Background fluctuations: A priori unknown background fluctuation distribution F(A). In a gaussian approximation: ~ 6-7 GeV for R_C=0.4



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

Remark: 1. can be corrected for on an event-by-event basis, 2. (and 3.) only via a statistical method = *"unfolding"*

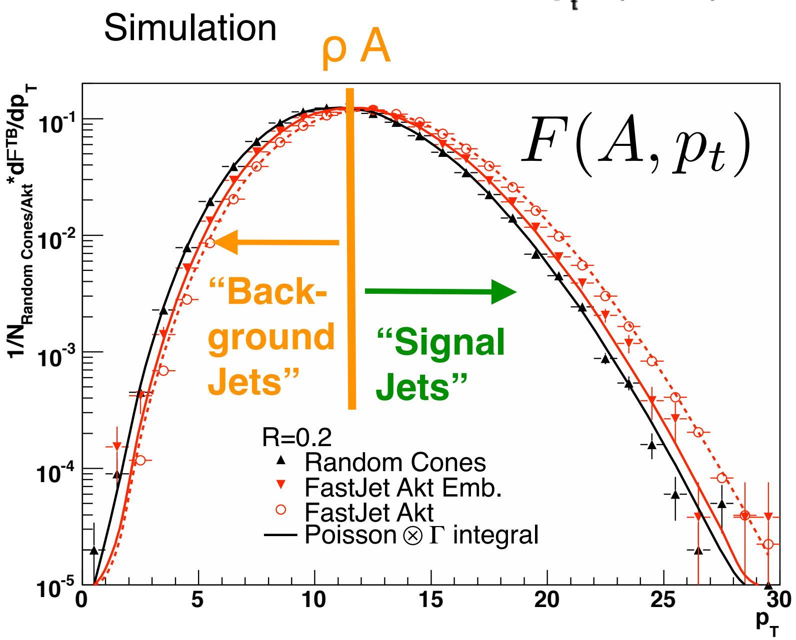
As an example: Focus on background fluctuations



Jet spectrum in Au+Au (schematically):

$$\frac{d\sigma_{AA}}{dp_t} = \frac{d\sigma_{pp}}{dp_t} \otimes F(A, p_t)$$

Effect of background fluctuations F(A,p_t)
⇒ substantial "feed-up" in the jet x-section



Conceptually F(A,p_t):

$$F(A, p_t) = Poisson((M(A)) \otimes \Gamma(M(A), \langle p_t \rangle)$$

F(A,p_t) can be measured in data:

- "background jets": p_t-ρ A < 0
- "spectrum" at 90deg. wrt to a di-jet

Non trivial issue, further studies actively being pursued, but we have all the tools!

Putting it all together: Spectrum Unfolding

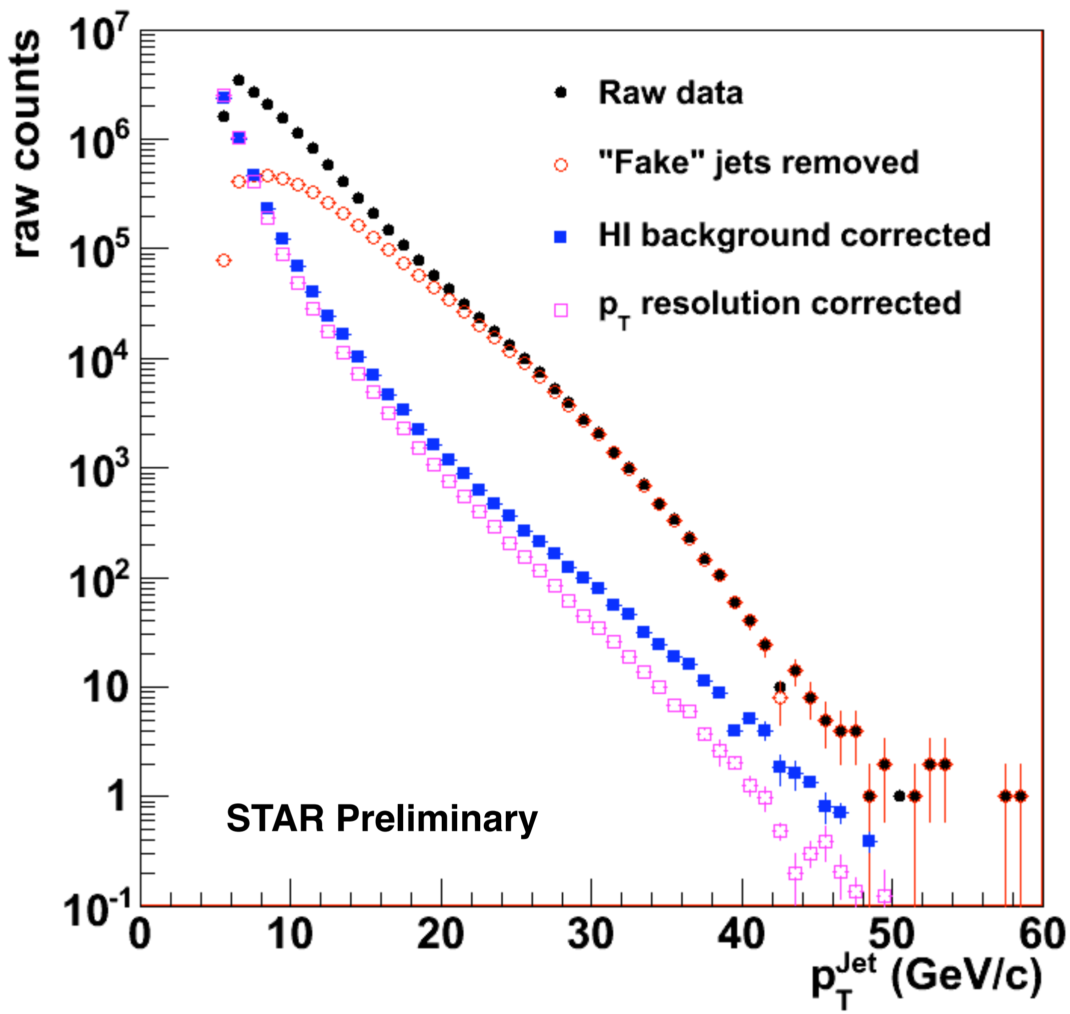
Corrections for smearing of jet p_T due to HI bkg. non uniformities:

1) raw spectrum

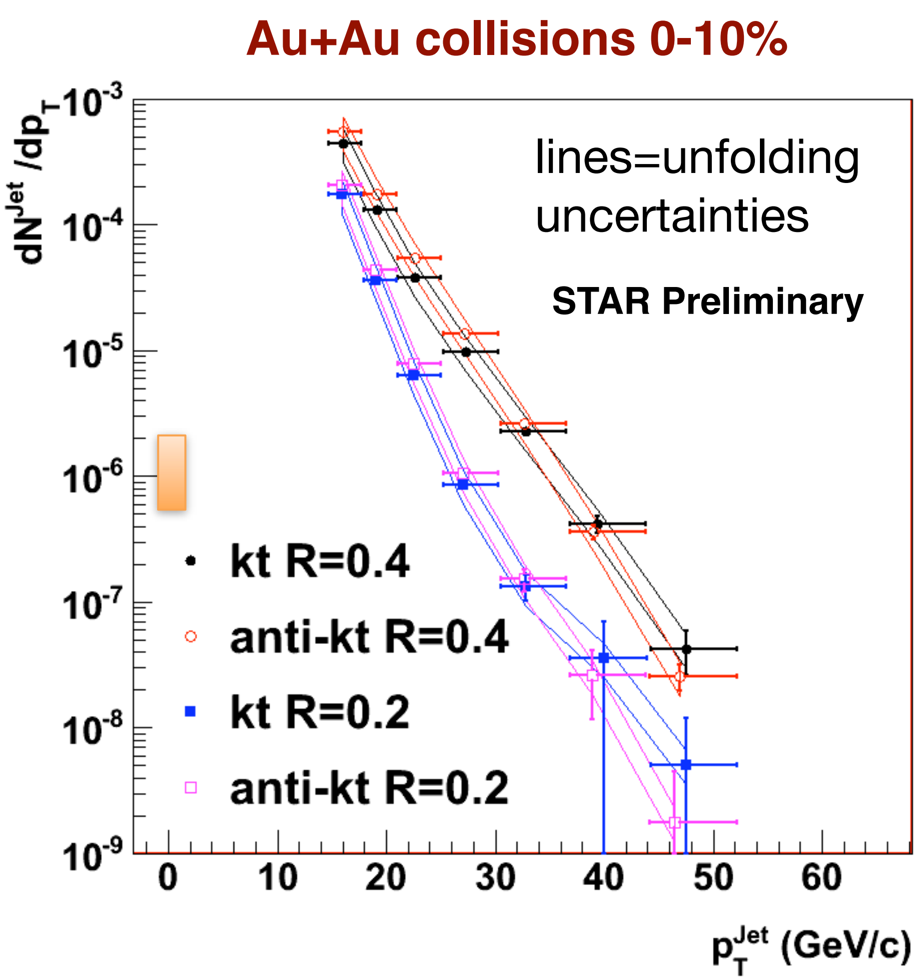
2) removal of “fake”-correlations

3) unfolding (bayesian) of HI bkg. fluctuations (“gaussian approximation”)

4) correction for jet energy resolution

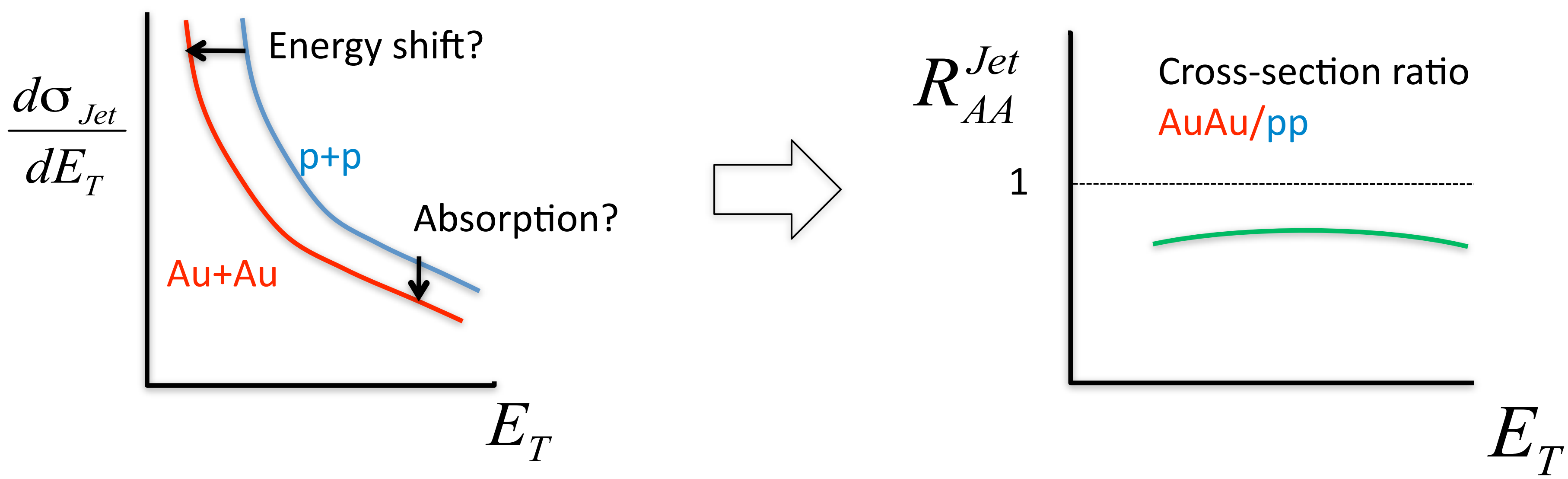


Inclusive jet x-section in heavy-ion collisions



- Inclusive Jet spectrum measured in central Au+Au collisions at RHIC
- Extended the kinematical reach to study jet quenching phenomena to jet energies > 40 GeV

What do we learn from the Au+Au jet spectrum ?

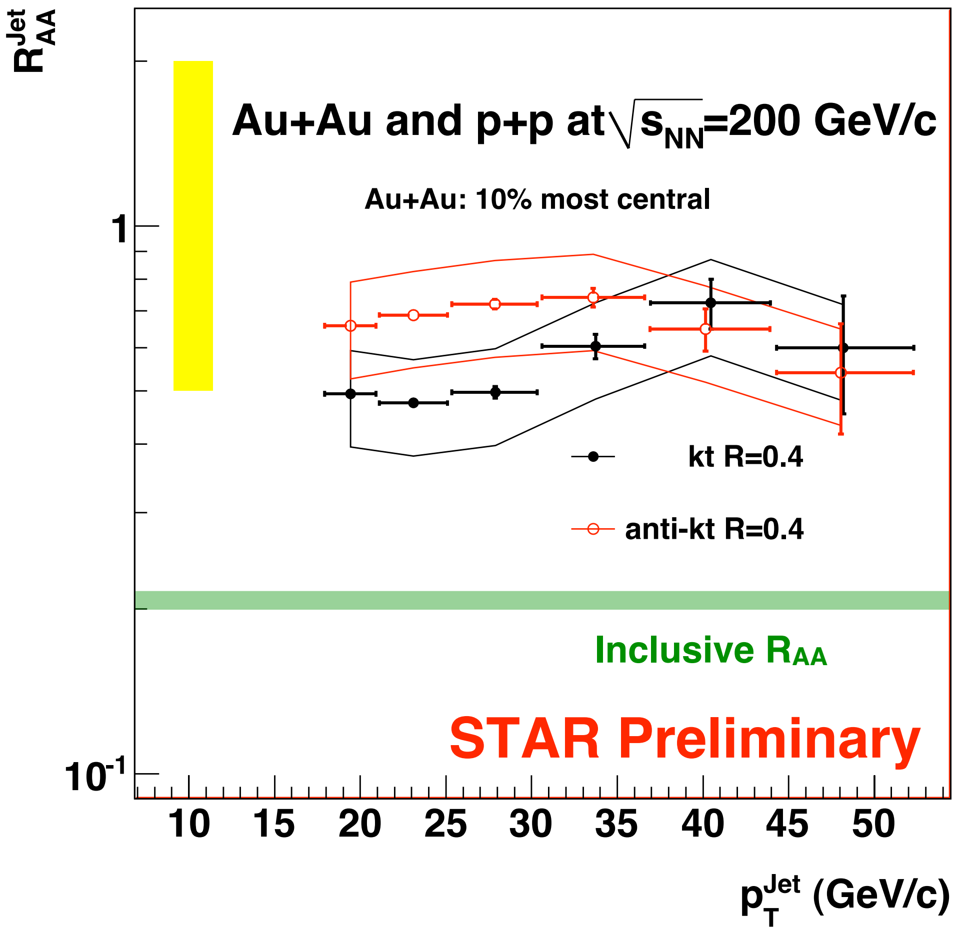


Momentum and energy is conserved even for quenched jets

If full jet reconstruction in heavy-ion collisions is unbiased

⇒ Inclusive jet spectrum scales with N_{coll} relative to p+p

Jet R_{AA} in central Au+Au collisions



- We see a substantial fraction of jets
  - in contrast to x5 suppression for light hadron R_{AA}
- k_T and Anti-k_T known to have different sensitivities to background

First look at the jet energy profile

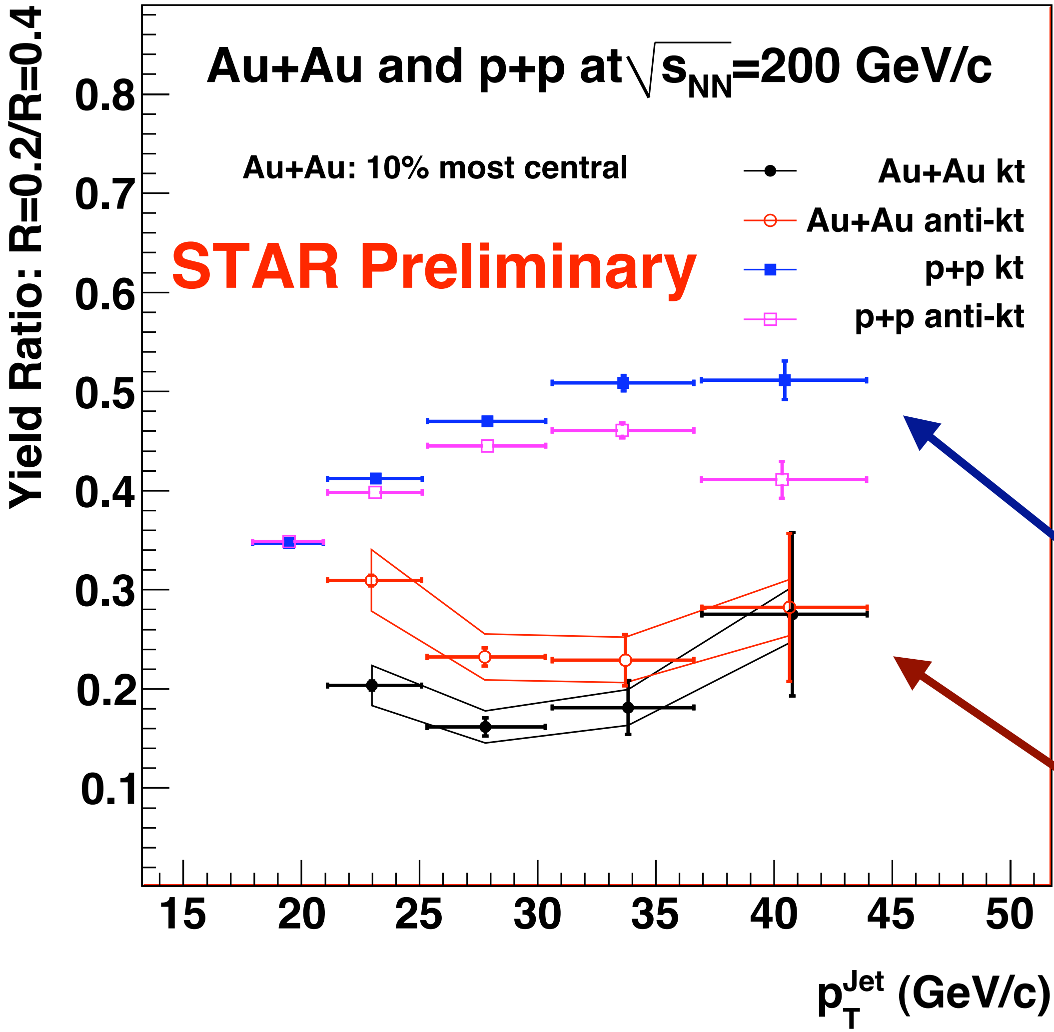
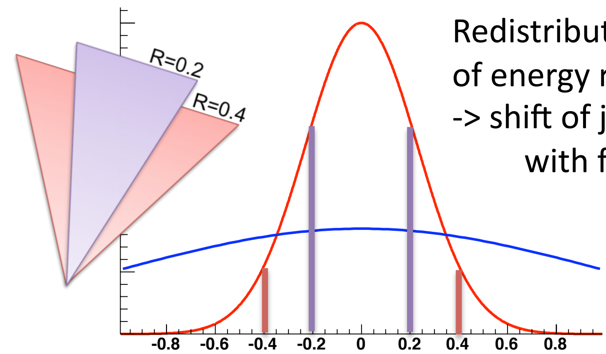


Illustration: Gaussian 1D profile



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

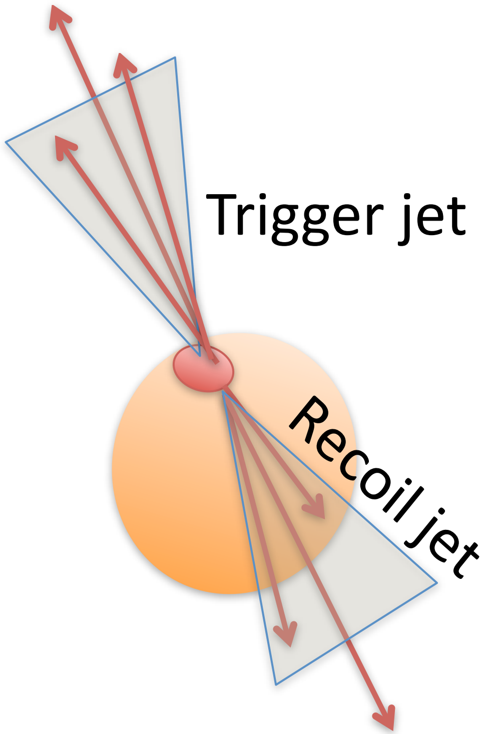
RED: p+p
BLUE: Au+Au

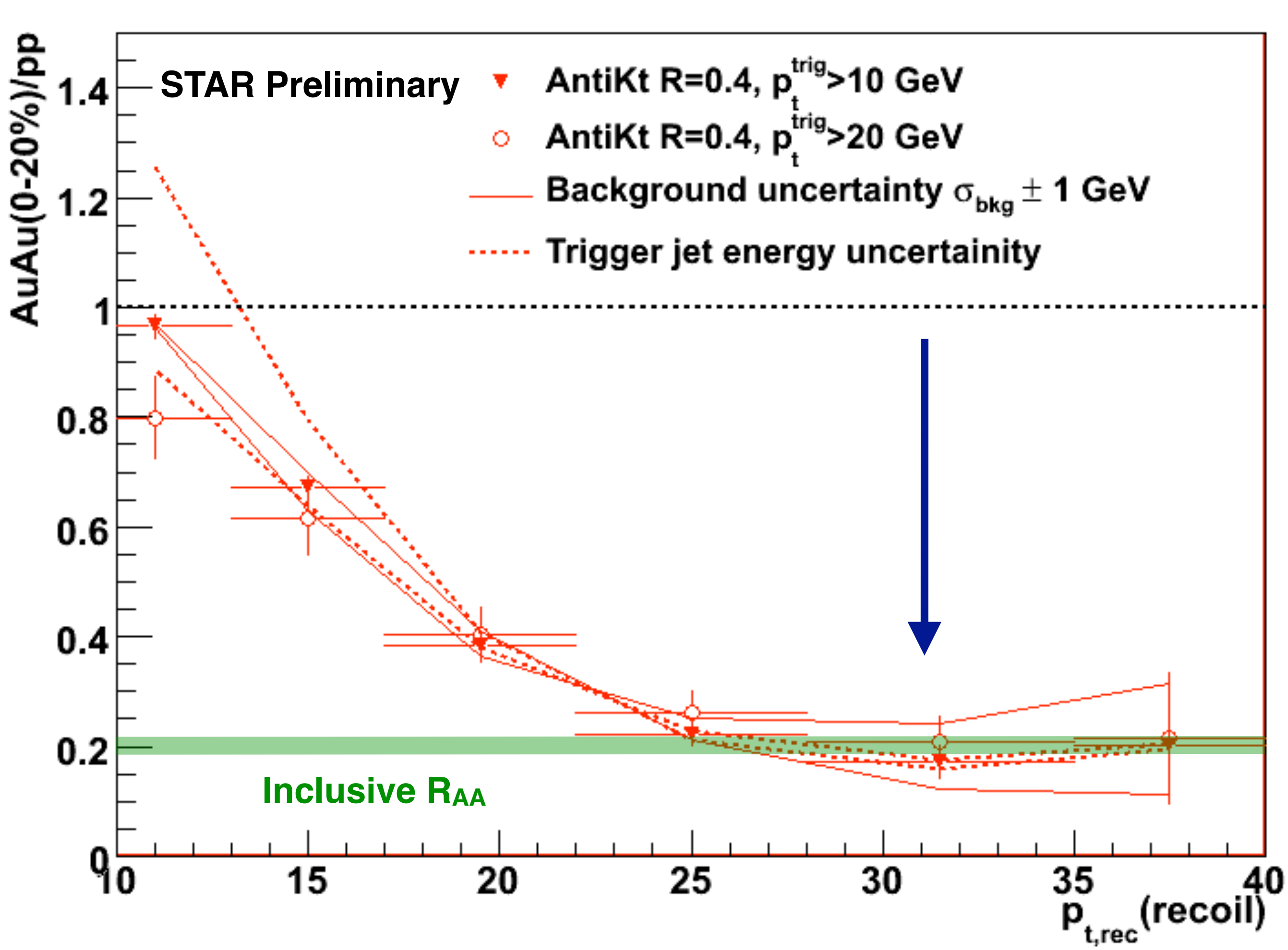
p+p: **"Narrowing" of the jet structure with increasing jet energy**

Au+Au: **"Deficit" of jet energy for jets reconstructed with R=0.2**

Strong evidence of broadening in the jet energy profile

Recoil jet spectrum R_{AA}



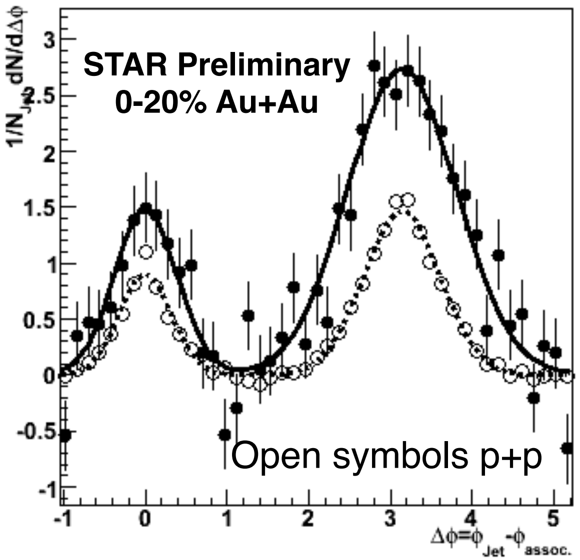


- Selecting *unmodified* trigger jet maximizes pathlength for the back-to-back jets: "extreme" selection of jet population
- Significant suppression in di-jet coincidence measurements

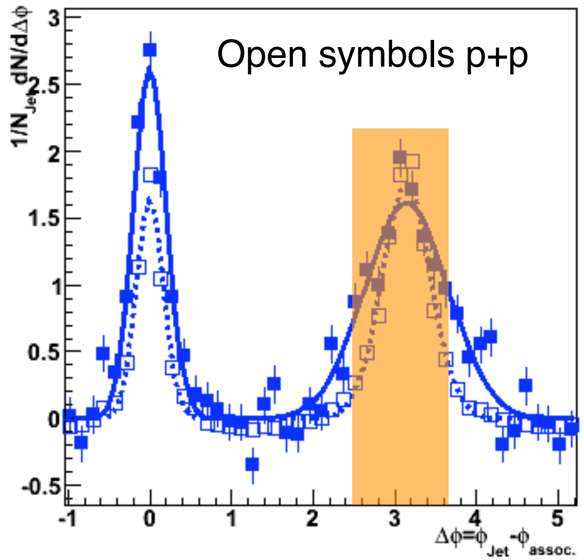
Towards fragmentation functions: Jet-Hadron correlations

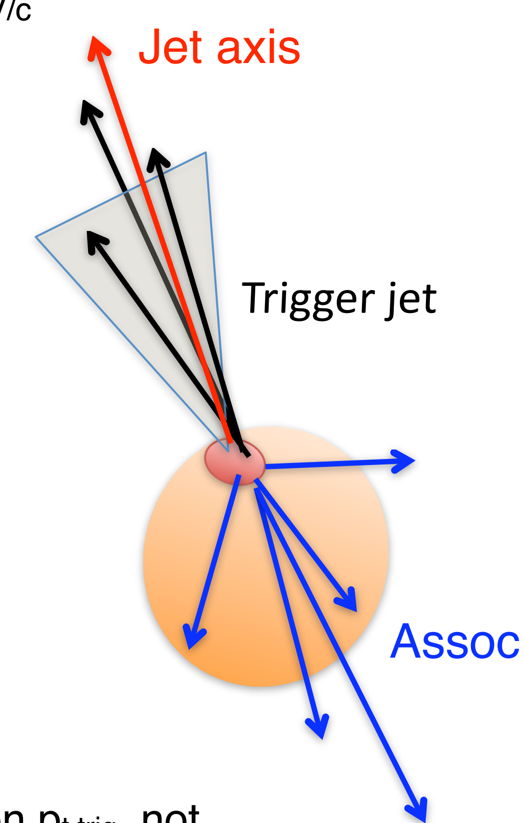
High Tower Trigger (HT): tower 0.05x0.05 ($\eta x \phi$) with E_t> 5.4 GeV, Anti-k_T, R=0.4, p_t^{cut}>2 GeV/c

$0.2<p_{t,assoc}<1.0$ GeV

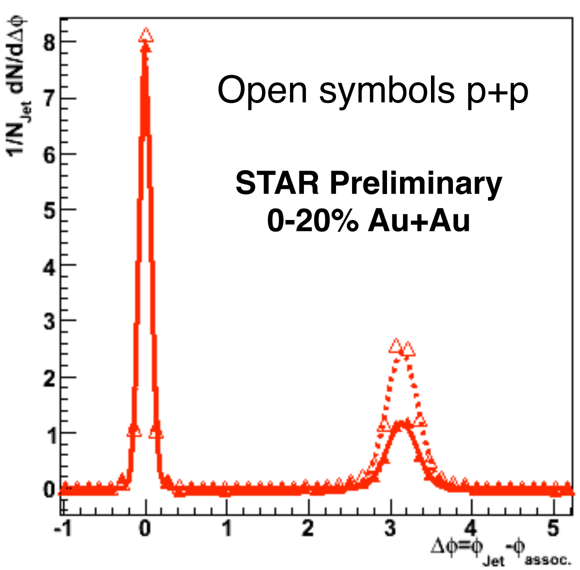


$1.0<p_{t,assoc}<2.5$ GeV





$p_{t,assoc}>2.5$ GeV



$\Delta\phi=\phi_{Jet}-\phi_{Assoc.}$

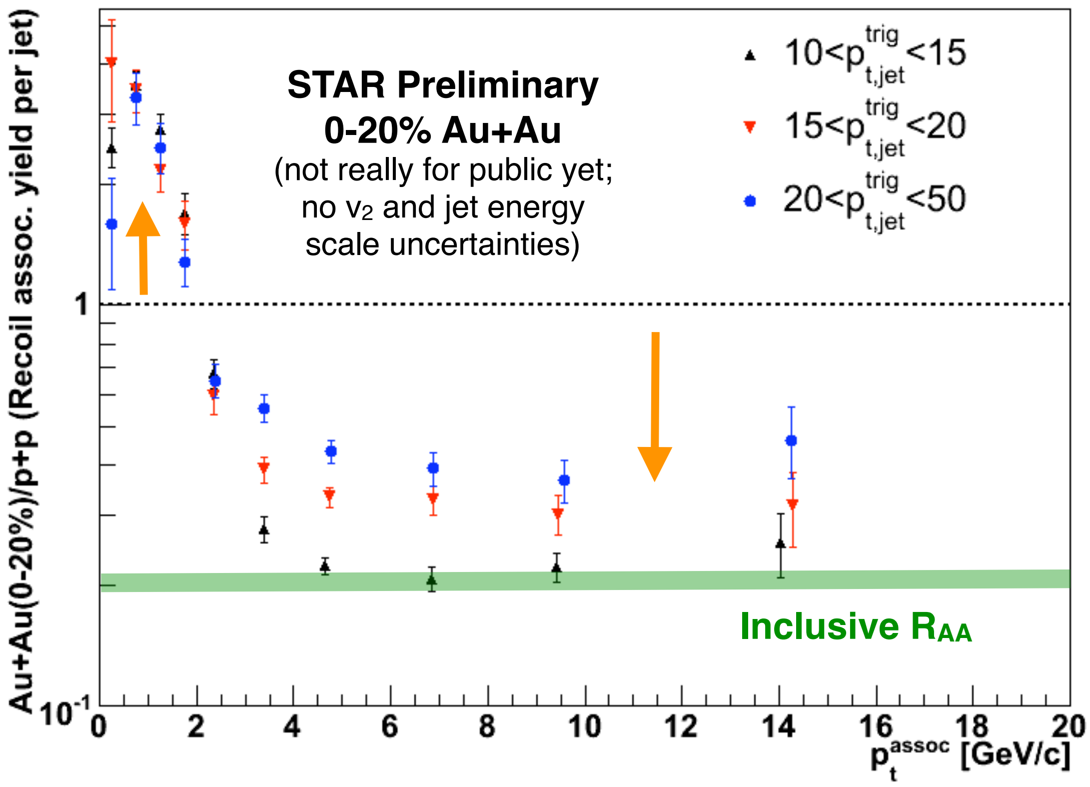
<u>In general:</u> $\phi_{Trig} \neq \phi_{Jet}$ and depending on $p_{t,trig}$, not necessary every trigger particle has to come from a jet! Jet-hadron correlations cleaner interpretation in terms of jet-quenching.

Extended kinematical reach!

Significant broadening and softening visible on the recoil side!

<u>Caveat:</u> "Jet v_2" contribution in background subtraction under investigation

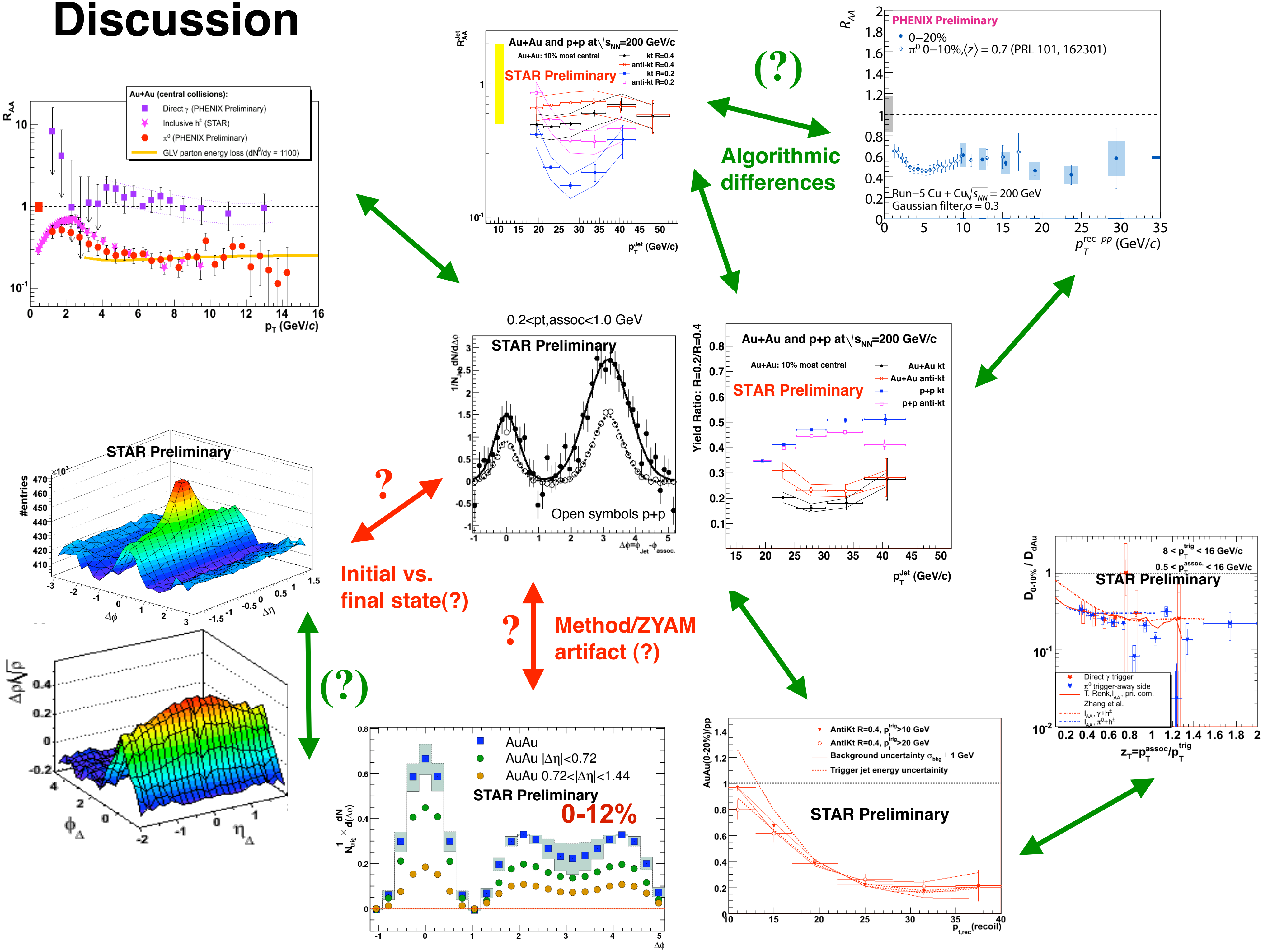
Almost there: “Modified Fragmentation Function”



<u>Note:</u> This is <u>not</u> z!
The jet energy dependence is <u>not</u> normalized out!

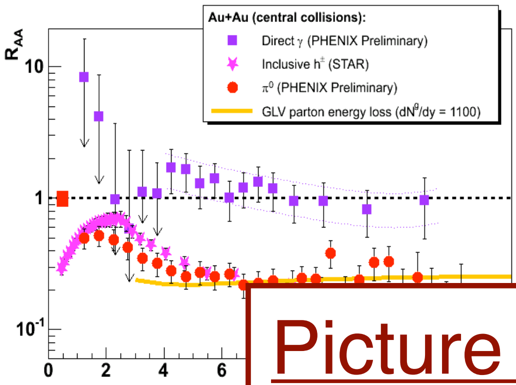
- **Enhancement at low-p_t and suppression at high-p_t of assoc. yield wrt p+p ≈ “modified fragmentation function”**
- **Out-of-Cone energy: Energy deposit outside the “cone” R used in jet-finding can be determined and is of the right order to describe the observed di-jet coincidence suppression/ FF measurements.**

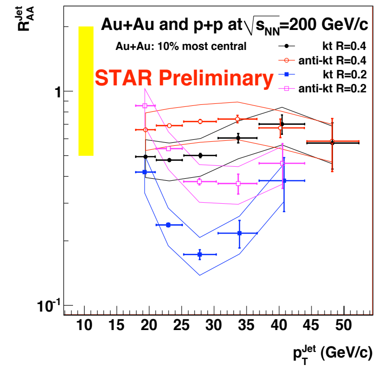
Discussion



Au+Au (central collisions):
Direct γ (PHENIX Preliminary)
Inclusive h± (STAR)
π0 (PHENIX Preliminary)
GLV parton energy loss (dN^g/dy = 1100)
R_AA
p_T (GeV/c)
Au+Au and p+p at √s_NN=200 GeV/c
Au+Au: 10% most central
STAR Preliminary
kt R=0.4
anti-kt R=0.4
kt R=0.2
anti-kt R=0.2
p_T^jet (GeV/c)
(?)
Algorithmic differences
PHENIX Preliminary
0–20%
π0 0–10%,⟨z⟩ = 0.7 (PRL 101, 162301)
Run-5 Cu + Cu √s_NN = 200 GeV
Gaussian filter,σ = 0.3
p_T^rec−pp (GeV/c)
0.2<pt,assoc<1.0 GeV
STAR Preliminary
Open symbols p+p
Δφ=φ_Jet-φ_assoc.
Au+Au and p+p at √s_NN=200 GeV/c
Au+Au: 10% most central
STAR Preliminary
Au+Au kt
Au+Au anti-kt
p+p kt
p+p anti-kt
Yield Ratio: R=0.2/R=0.4
p_T^Jet (GeV/c)
STAR Preliminary
#entries
Δφ
Δη
?
Initial vs. final state(?)
?
Method/ZYAM artifact (?)
(?)
8 < p_T^trig < 16 GeV/c
0.5 < p_T^assoc. < 16 GeV/c
STAR Preliminary
D_0-10% / D_dAu
Direct γ trigger
π0 trigger-away side
T. Renk, I_AA, pri. com.
Zhang et al.
z_T=p_T^assoc/p_T^trig
Δρ/√ρ
φ_Δ
η_Δ
AuAu
AuAu |Δη|<0.72
AuAu 0.72<|Δη|<1.44
STAR Preliminary
0-12%
Δφ
AntiKt R=0.4, p_t^trig>10 GeV
AntiKt R=0.4, p_t^trig>20 GeV
Background uncertainty σ_bkg ± 1 GeV
Trigger jet energy uncertainty
STAR Preliminary
AuAu(0-20%)/pp
p_t,rec(recoil)

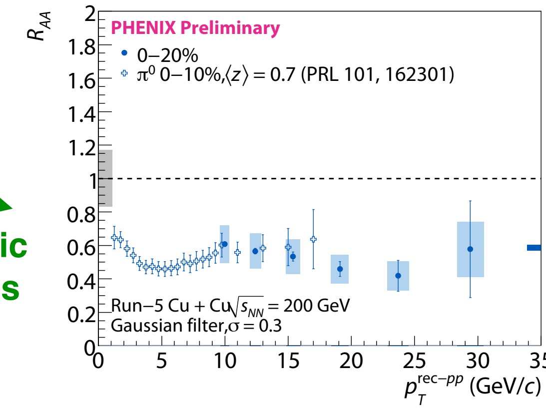
Discussion





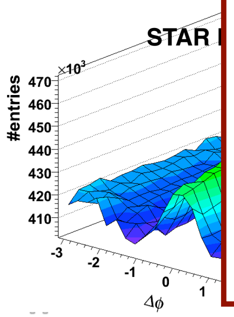
(?)

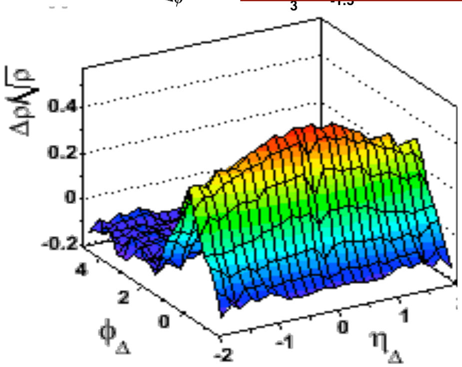
Algorithmic differences



Picture emerging:

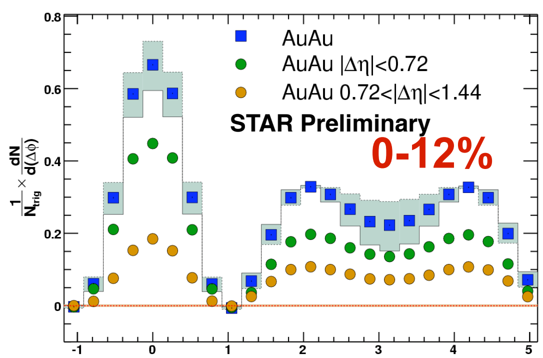
Current jet-quenching measurements at RHIC can be *qualitatively* explained by a significant *broadening* of the jet structure due to partonic energy loss (gluon radiation) in the medium (QGP).

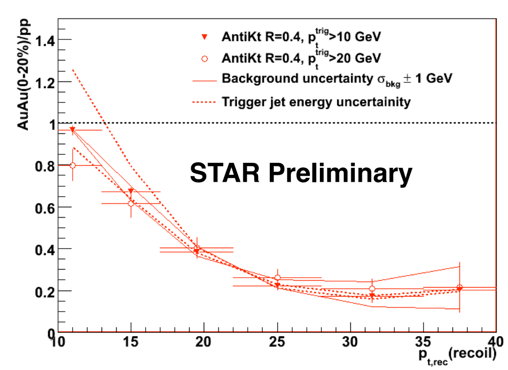


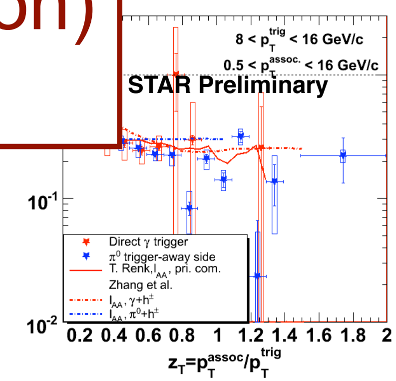


(?)

Method/ZYAM artifact (?)

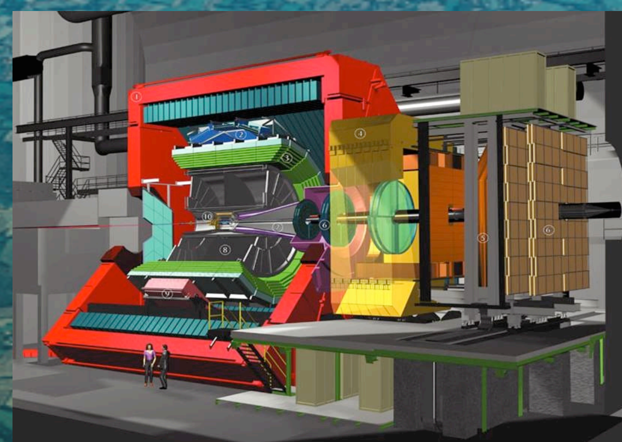






The next energy frontier:

ALICE @ LHC a “hard probes factory”!



From RHIC to LHC: The hard probes factory!

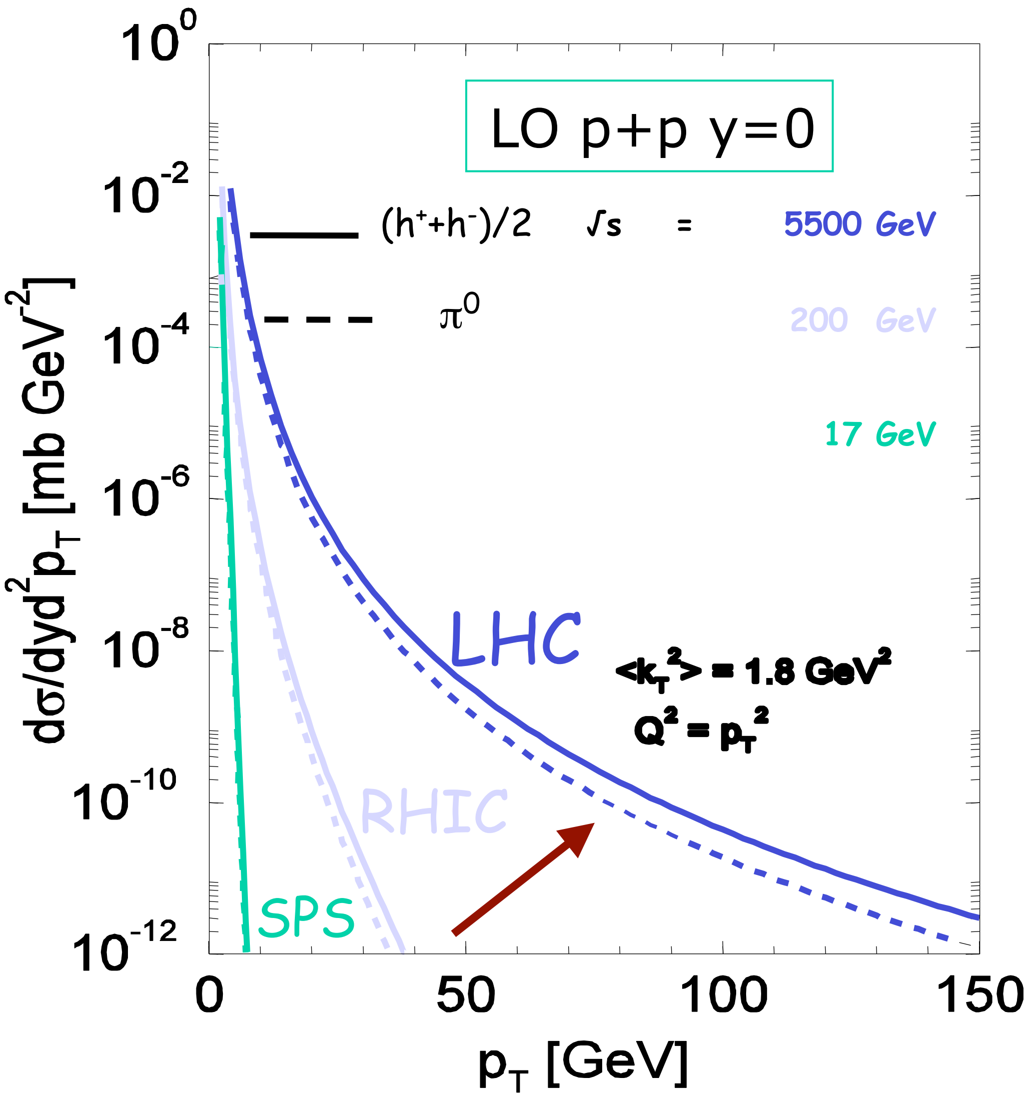
Heavy ions at the LHC:

• fireball hotter and denser, lifetime longer than at RHIC

• dynamics dominated by partonic degrees of freedom

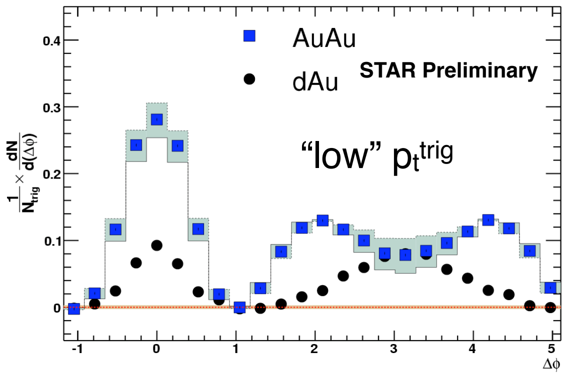
• **huge increase in yield of hard probes!**

(but needs triggering: EMCal for jet studies)

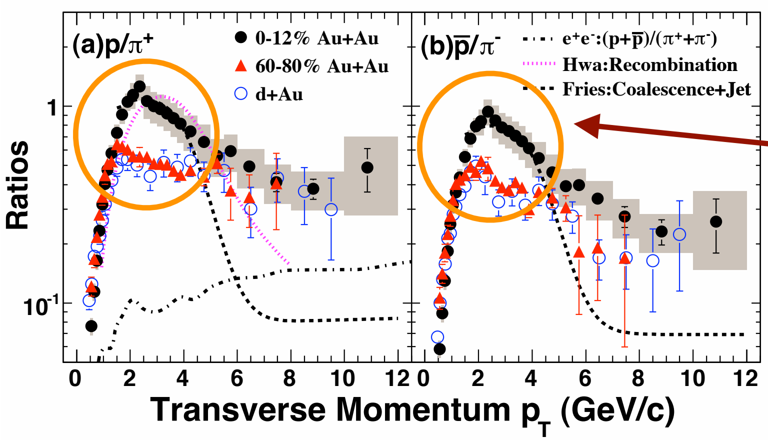


Remark/Caveat: Full EMCal acceptance not available for first Pb+Pb collisions;
⇒ Full-jet reconstruction not possible in ALICE ⇒ Di-hadron measurements first ...

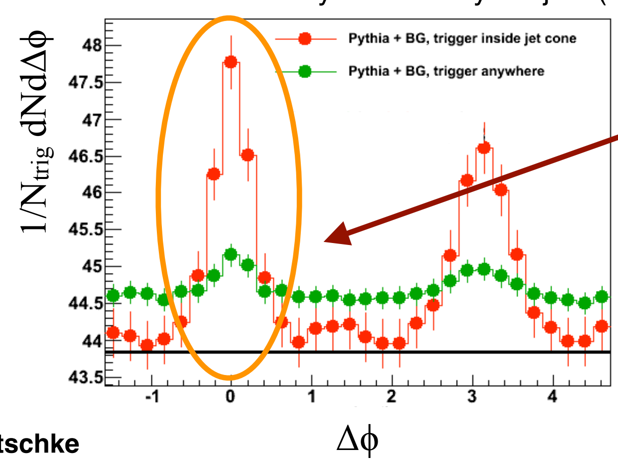
Di-hadron correlations: Lesson from RHIC



Phys. Rev. Lett. 97 (2006) 152301



Simulation: Thermal toy model + Pythia jets (no v_2)



High p_t^{trig}: geometric biases; limited sensitivity to partonic energy loss mechanisms

Lower p_t^{trig}: Possible Mach-Cones and near-side Ridge (Δη matters!)

BUT: Not every trigger part of a jet; recombination/coalescence!?
⇒ Interpretations in terms of "jet" physics complicated!

Also ambiguities in "jet" vs. background/hydrodynamical flow!

Example: Thermal toy model + Pythia jets (v_2=0):

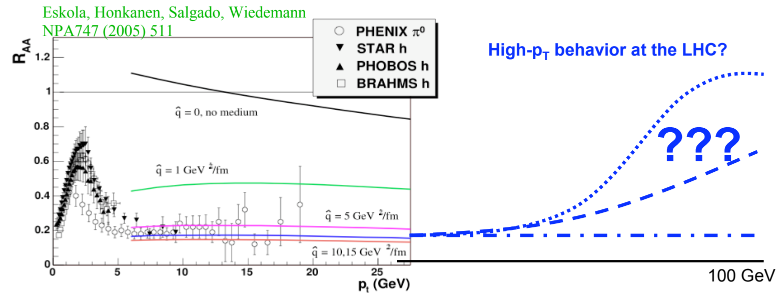
⇒ Dilution of "jet-like" associated yields !!!

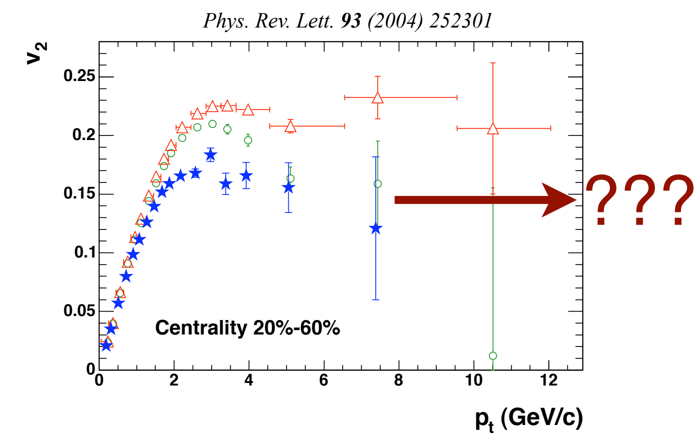
Can be studied in data via "di-hadron" correlations "in/out" of a fully reconstructed jet!

Larger effects, especially on shapes, by including v_2!

Day 1 Pb+Pb: Hadron/Di-hadron measurements in ALICE

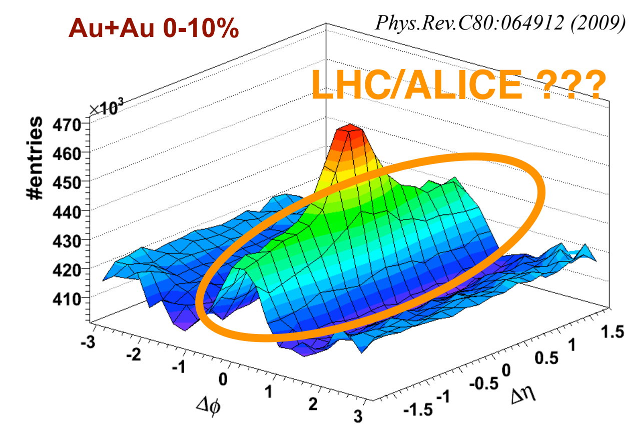
(I) R_{AA} at high-p_t





(II) **High-p_t di-hadron correlations:**

- high-p_t elliptic flow/v_2 measurements: "jet-flow"
- wrt to reaction plane: "pathlength dependence of jet quenching"



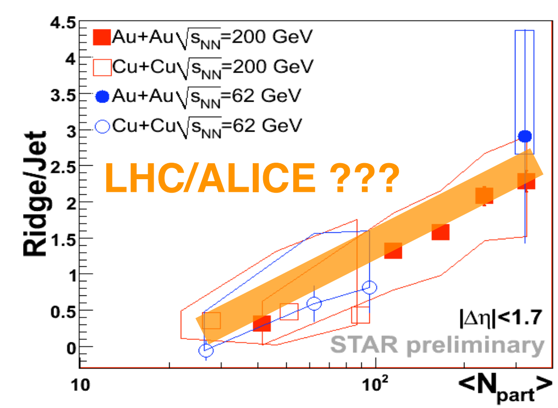
(III) **Ridge measurements:**

- high-p_t and wrt to reaction plane
- PID at high-p_t

Does the ridge/jet yield scale with collision energy !?

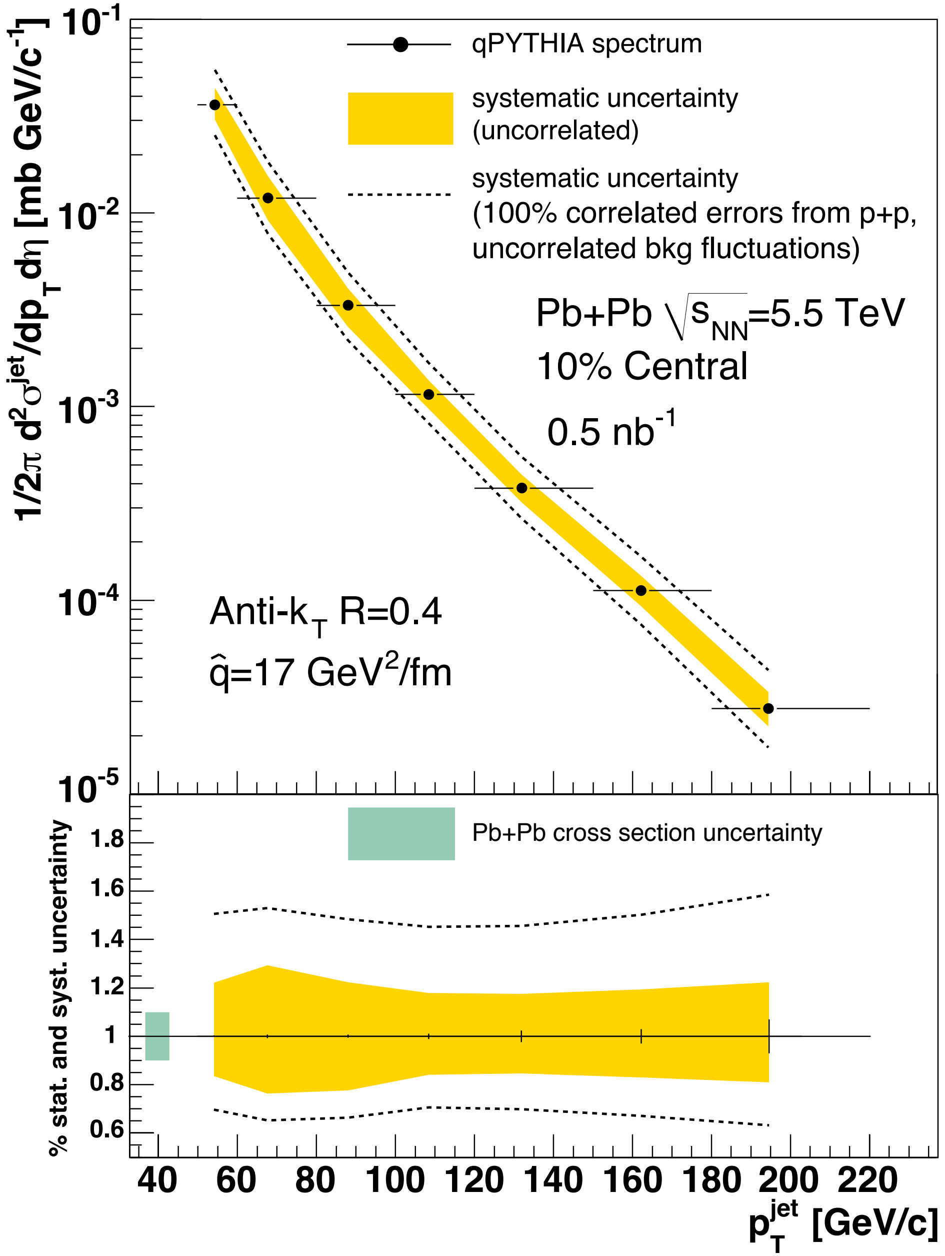
Ridge connected to pQCD jet properties?

Or initial state/medium?



Remark: Is there already a ridge in p+p at the LHC ?
A. Dumitru @ RBRC Workshop March 2010

Jet x-section measurement in ALICE



EMCal acceptance: |η|<0.7, Δφ=110°

EMCal needed for triggering and neutral jet energy component:

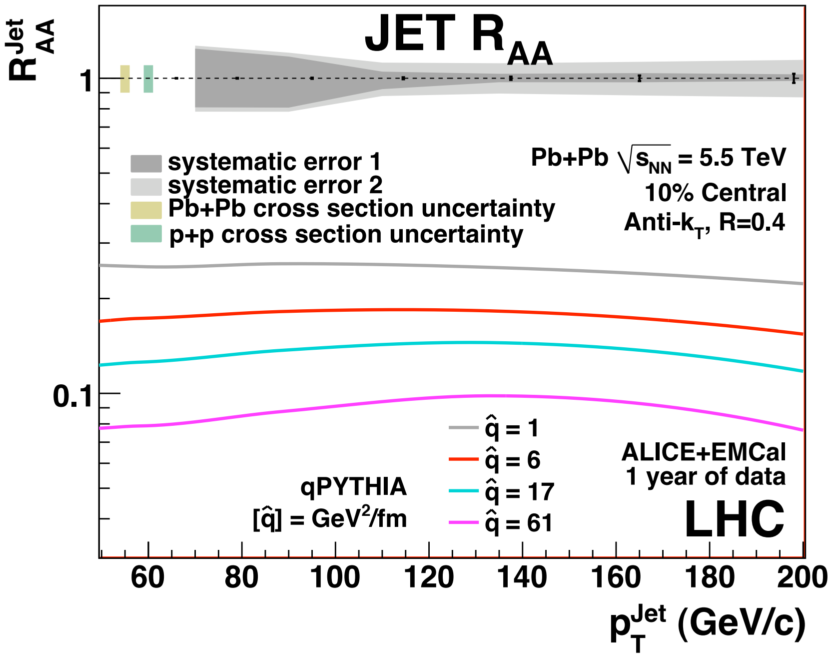
⇒ **Large kinematical reach in 1 year ALICE running**

⇒ **Precise measurement:**

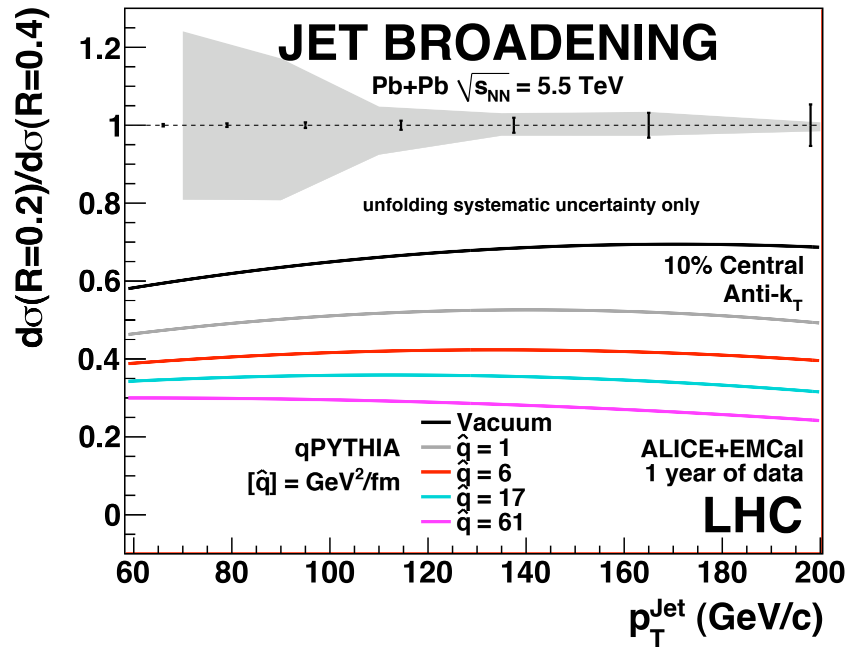
Effect of background fluctuations in jet spectrum suppressed due to harder underlying partonic spectrum!

Jet quenching measurements in ALICE

ALICE EMCal PPR (2009)



ALICE EMCal PPR (2009)

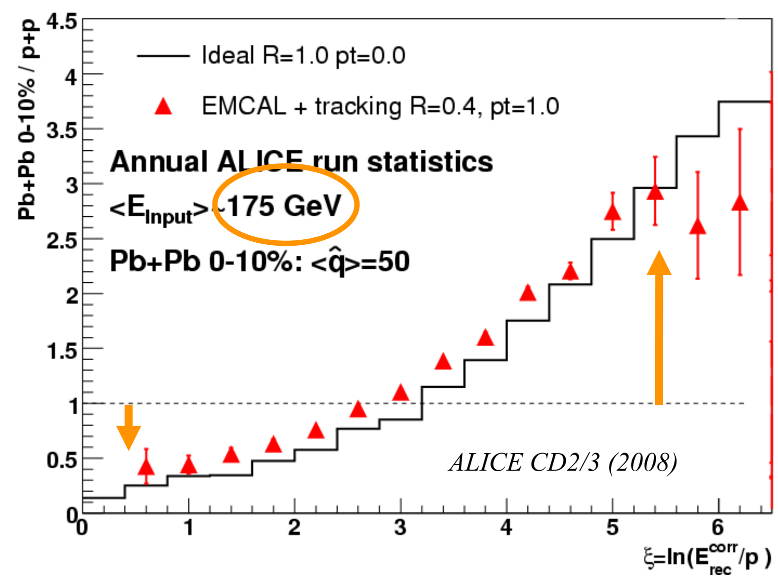


Large kinematic reach: p_T^{Jet}=50-200 GeV/c
⇔ study QCD evolution of jet quenching

Reduced systematic uncertainties due to heavy-ion background wrt to RHIC measurements

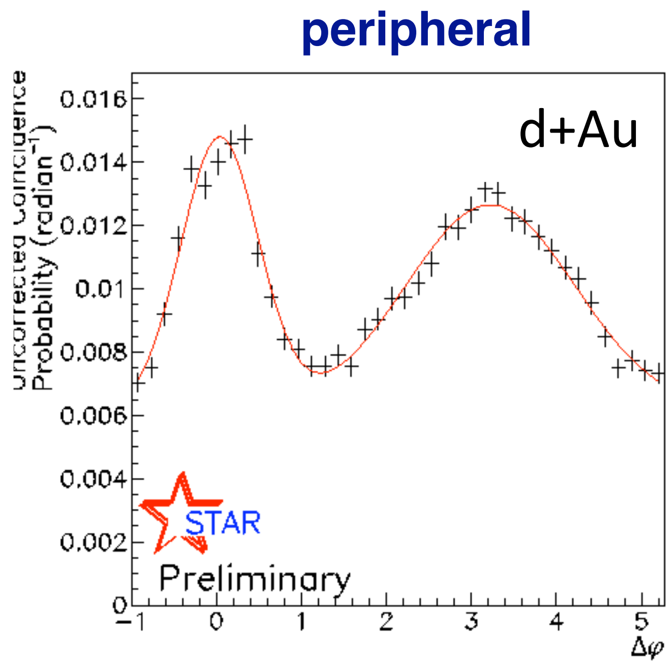
⇒ Precise jet quenching measurements will place <u>quantitative</u> constraints on partonic energy loss at LHC with ALICE!

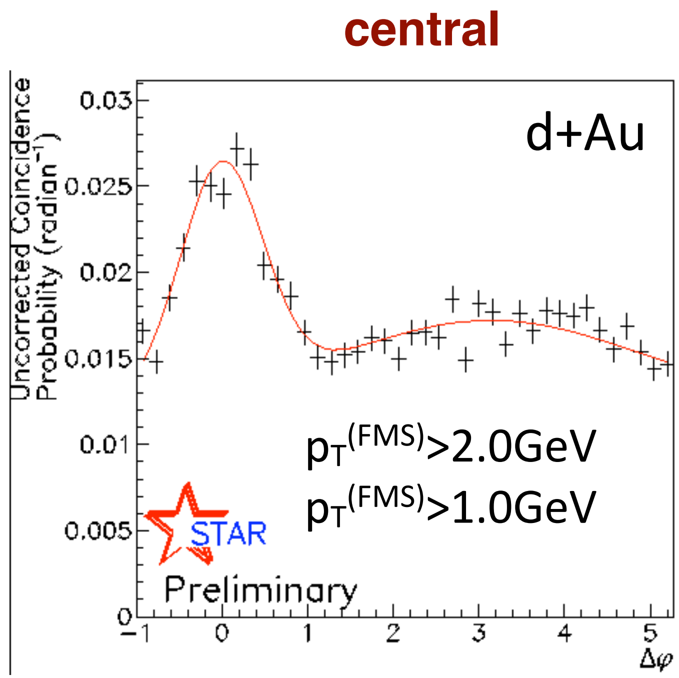
Simulated result APQ

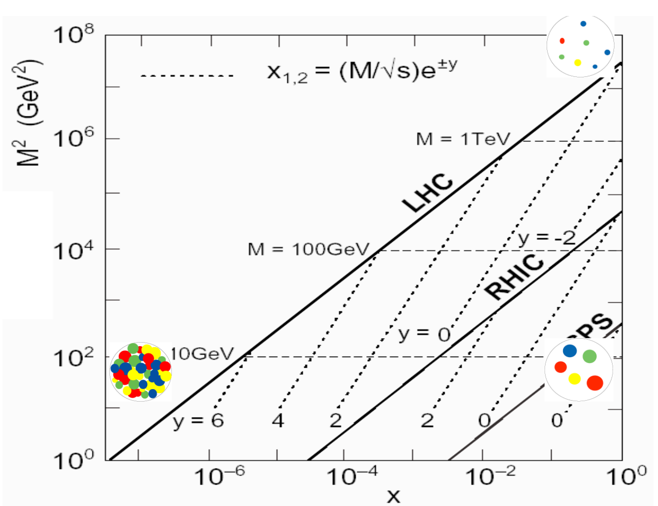


Remark: DCal upgrade funded; allows di-jet studies in ALICE!

Lesson from RHIC: Initial state effects at LHC ...







Forward rapidity d+Au measurements at RHIC (y~3) probe similar x-region as at mid-rapidity at LHC

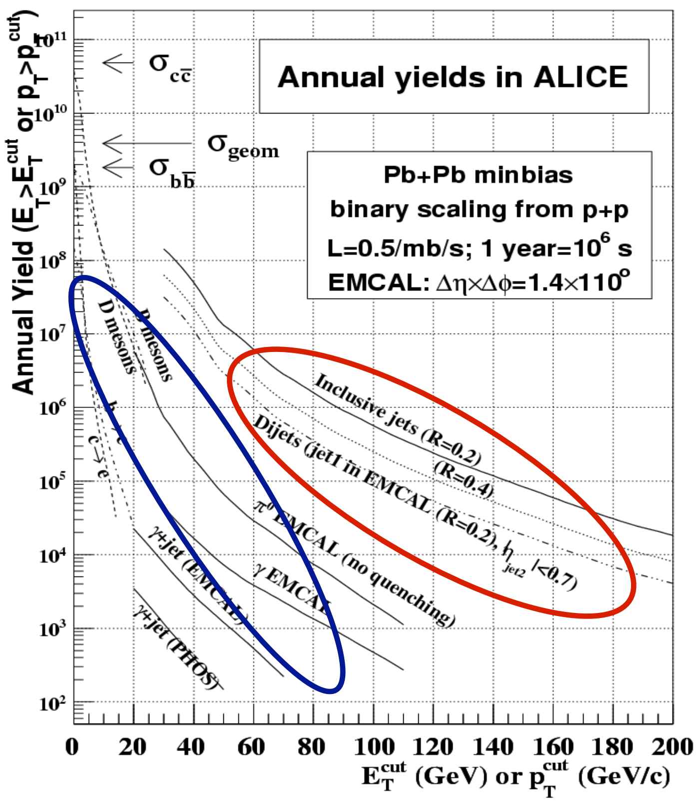
Recent forward correlation measurements at RHIC suggest suppression/de-correlation in central d+Au collisions. Onset of CGC !?

Control experiment p+Pb at LHC necessary to measure with high precision initial state effects to allow an unambiguous interpretation of jet-quenching measurements in Pb+Pb collisions!

Summary

Qualitative picture from RHIC:
Jet-quenching measurements can be "consistently" explained by jet-broadening/softening due to radiative energy loss in the medium!

Landscape of hard probes:



Large kinematical reach and precise (full) jet measurements in ALICE:

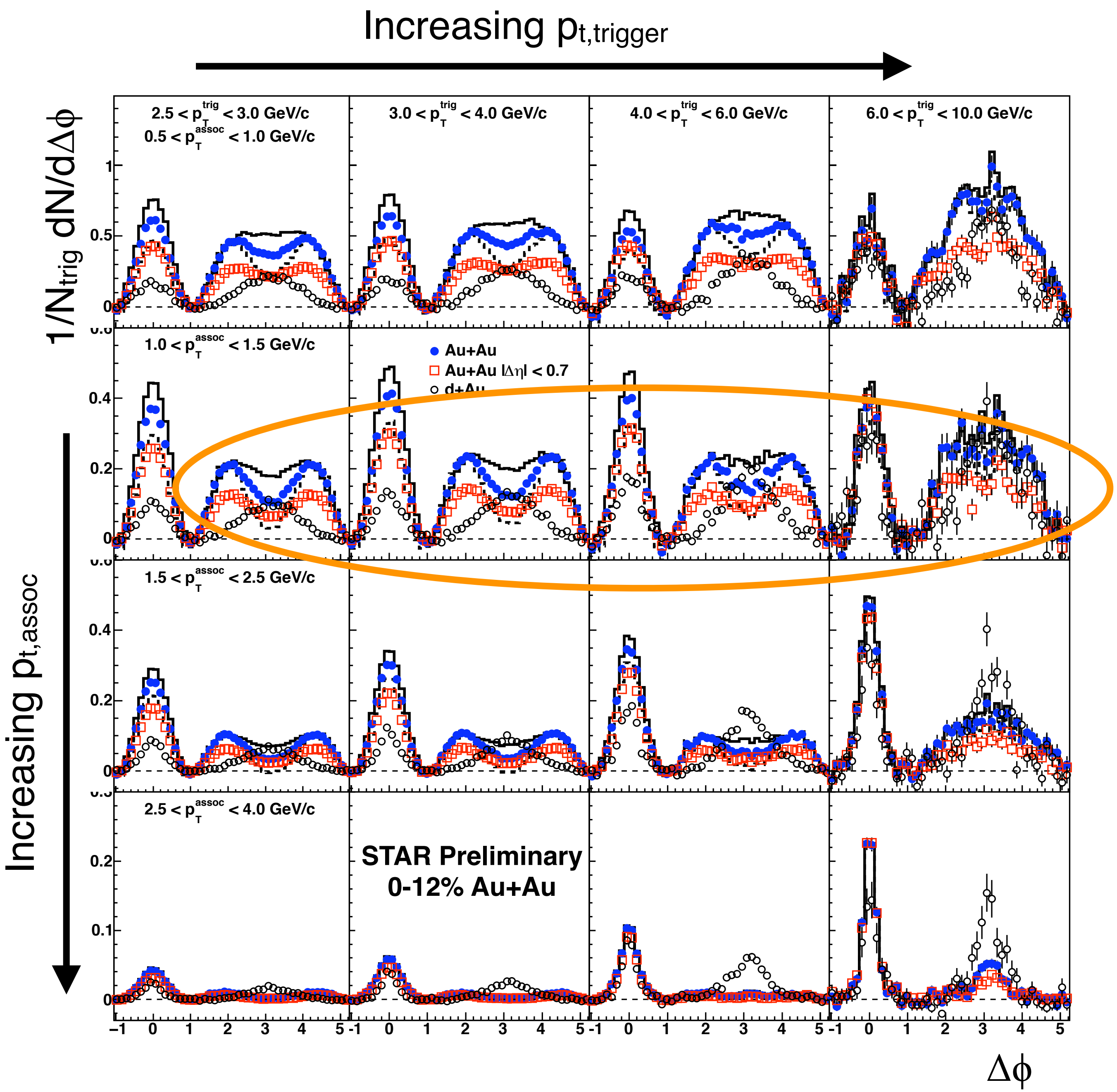
⇒ Quantitive constraints on underlying partonic energy loss mechanisms (for light quarks)!

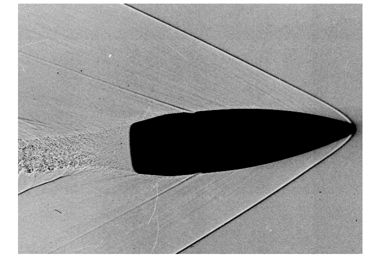
But this is just the start!
The landscape of hard probes is rich at the LHC!

Measure heavy quark energy loss (b-tagged jets), still open theoretical issue to describe heavy and light flavor energy loss in a consistent framework!

Backup

Surprise No. 2: Shock-Waves/Mach-Cones ...





Double-hump structure for lower $p_{T,trig}$ observed (similar observation in 3-particle correlations)

Is interpreted as conical emission/Mach-Cones of partons traveling faster then the speed of sound in the medium!

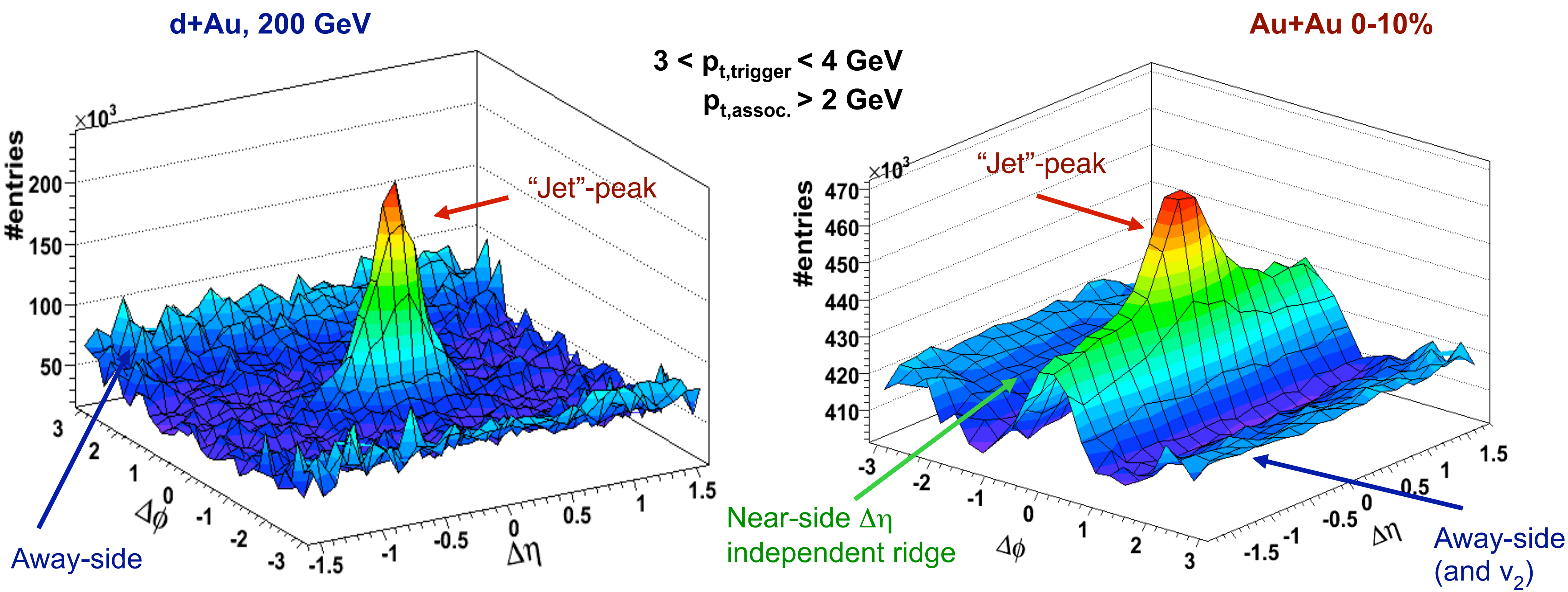
Why only visible in selected kinematic ranges? Punch-through jets? Ambiguities in our background subtraction? At lower $p_{T,trig}$ not every trigger particle has to come from a jet!?

Naive calculation of time averaged velocity of sound in medium:
Cone angle ~ 1.36 radians ⇒ $c_s = 0.2c$
(a bit too small)

Caveat: Large, elliptic flow modulated background has to be subtracted !

Surprise No. 3: Even on the near-side, the "Ridge"

Looking closer on the near-side: Including $\Delta\eta$ correlations ...



d+Au: "jet"-peak, symmetric in ϕ, η

Au+Au: Additional correlation strength at small $\Delta\phi$ and large $\Delta\eta$: **The "Ridge"**

What is the origin of the ridge ?

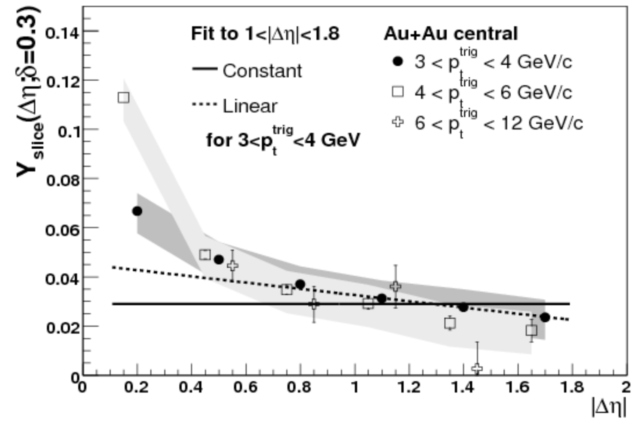
The ridge: A closer look ...

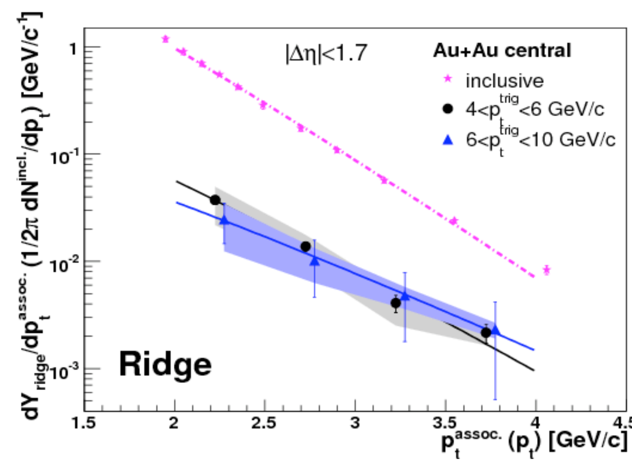
Ridge characteristics:

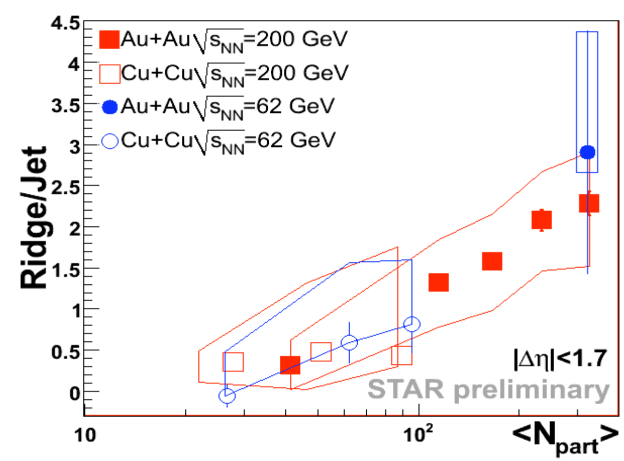
- approx. independent on $\Delta\eta$
- persists up to highest trigger p_t
  $\Rightarrow$ correlated to jet production
- spectrum ~ "bulk-like"
- energy roughly a few GeV
- Λ/K^0_S ratio in ridge ~ inclusive B/M ratio
- comparable in strength Au+Au and Cu+Cu at same N_{part}
- ridge yield/jet yield independent on collision energy

  change in jet yield can be explained by pQCD, but why does the ridge scale? Ridge properties correlated to jet/pQCD properties?

Are we seeing vacuum fragmentation after energy loss on the near-side in central Au+Au collisions with the lost energy deposited in the ridge ?

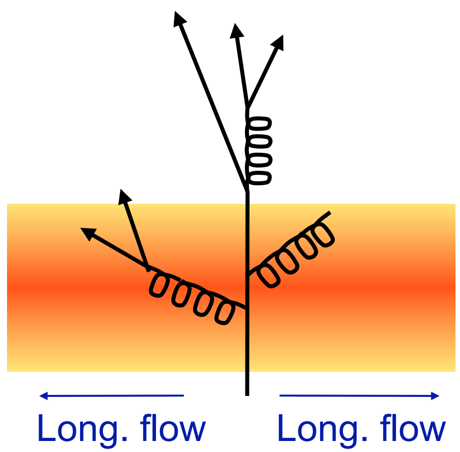






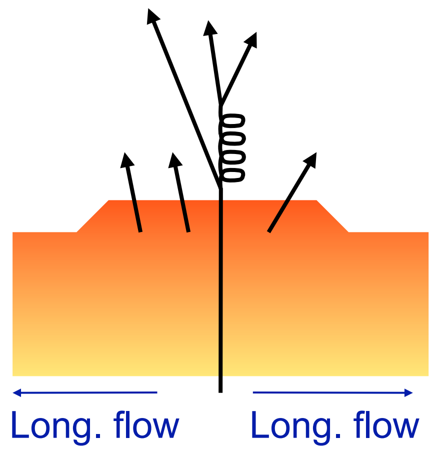
The ridge: A lot of “qualitative” models ...

Jet broadening



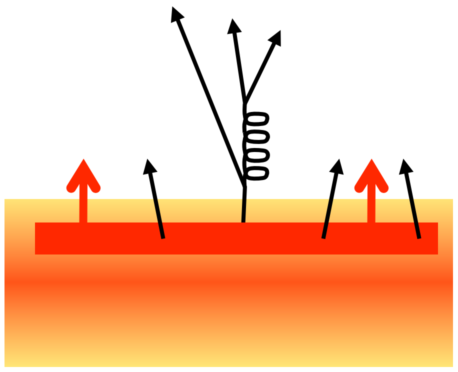
Soft gluons due to partonic energy loss couple to longitudinal flow

Medium response



Extra yield due to medium heating/drag or propagating parton

Trigger/Initial effect



Trigger selects existing structure in the medium (underlying event, color flux tubes)

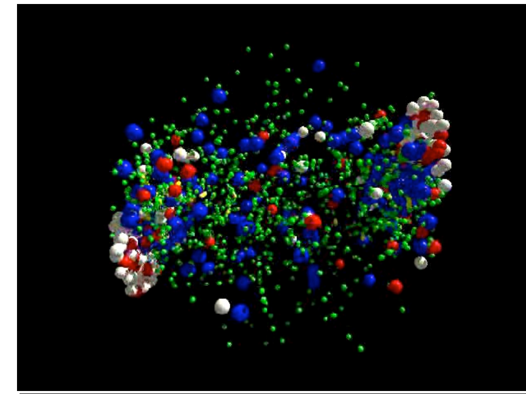
All models are currently in qualitative agreement with the measurements; but they predict different behavior concerning collision energy, ridge width and extend ...

Experimental tests ongoing ...

Where can we look for further details ?

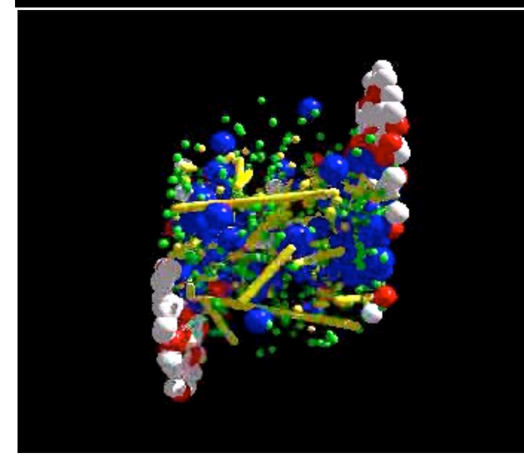
1. Final State

Yields of produced particles: Thermalization, Hadrochemistry



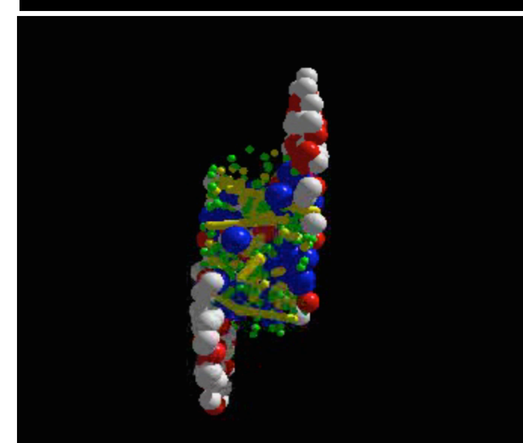
2. Probes of dense matter

"Tomography" with "hard probes"



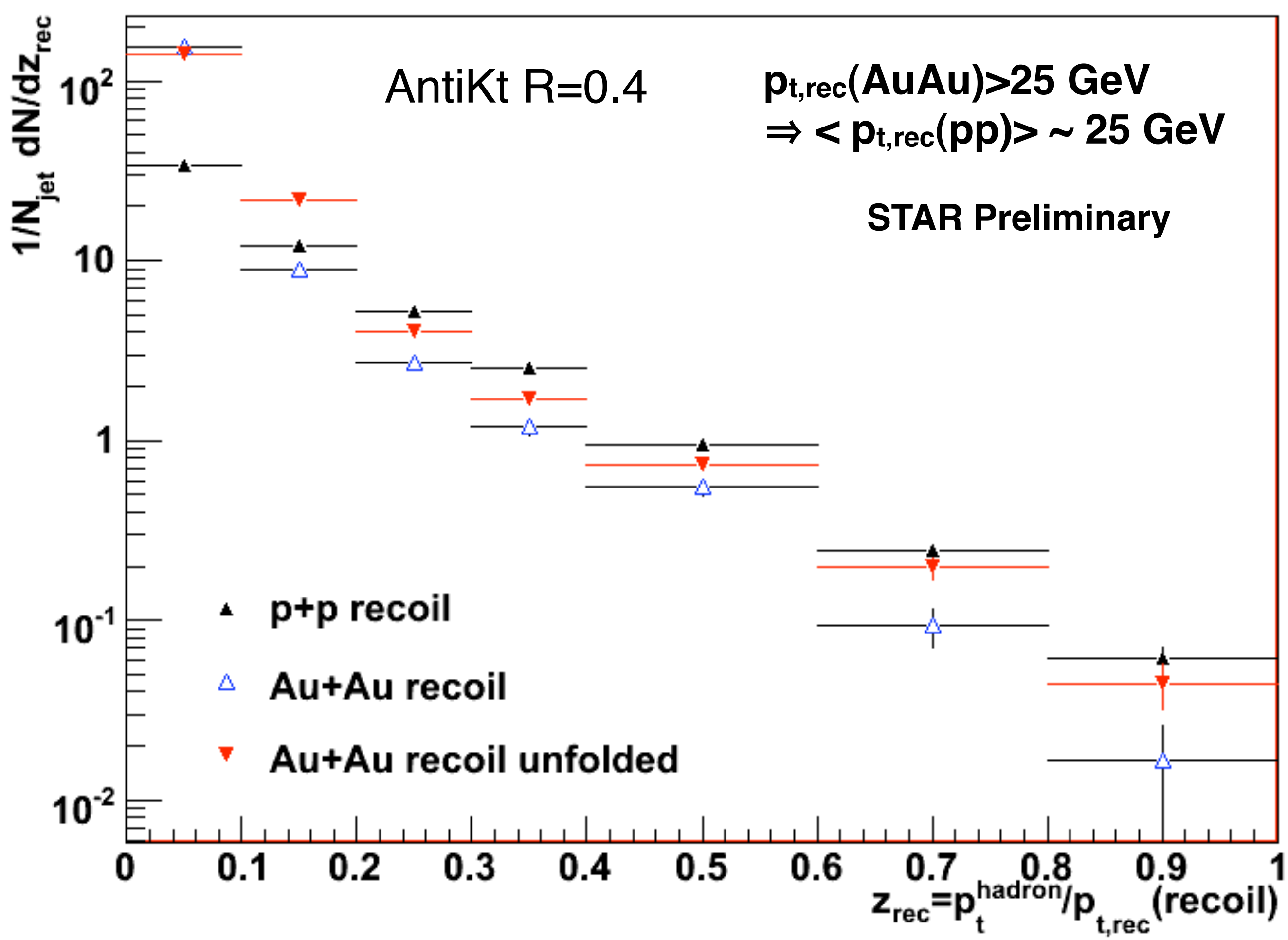
3. Early State

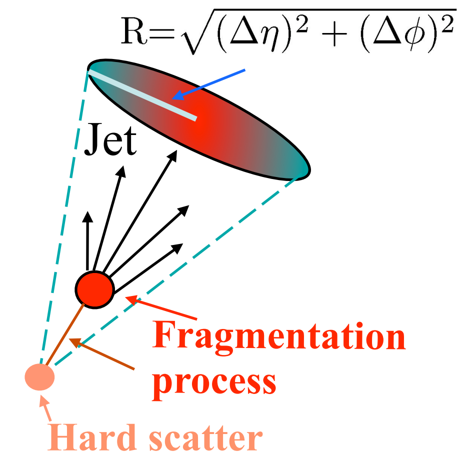
Hydrodynamic flow from initial spatial asymmetries



Recoil Fragmentation Function in Au+Au collisions

large uncertainties due to background
(further systematic evaluation needed)





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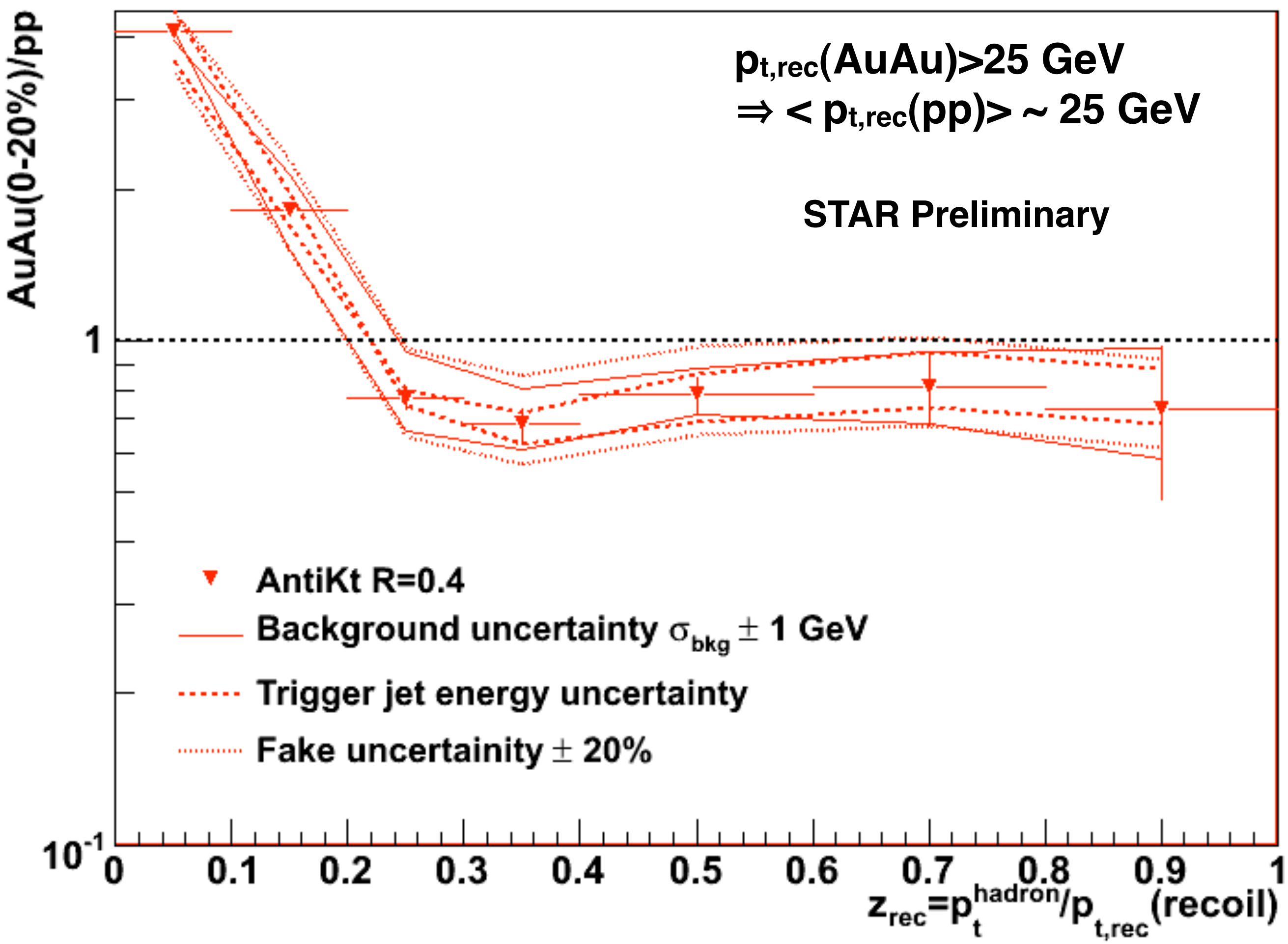

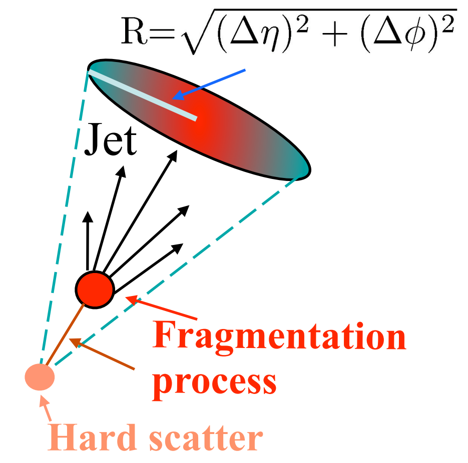

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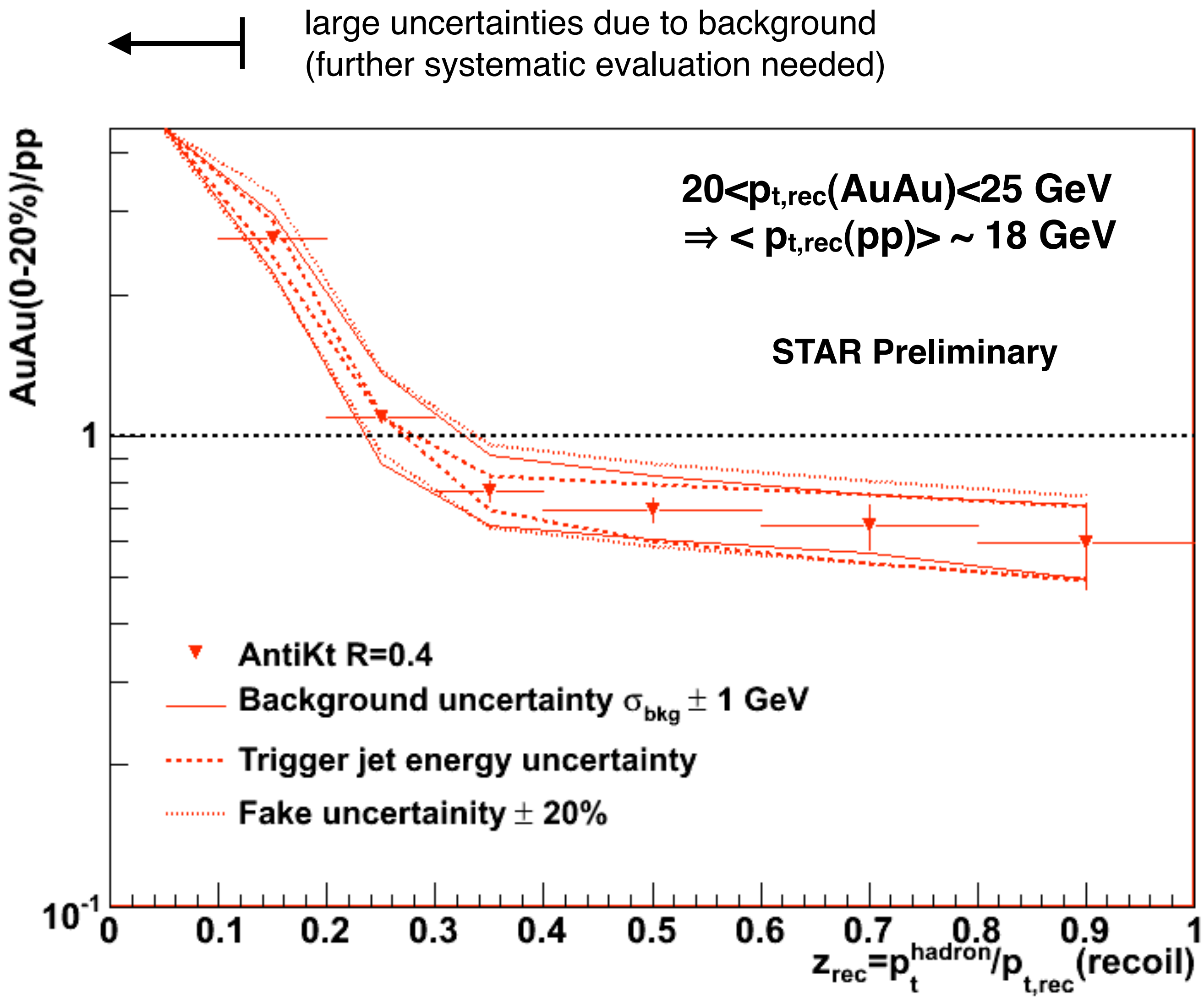
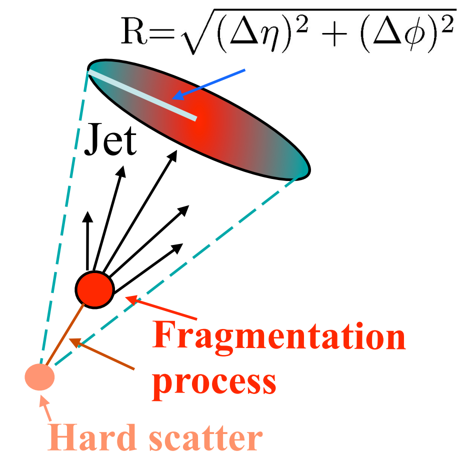
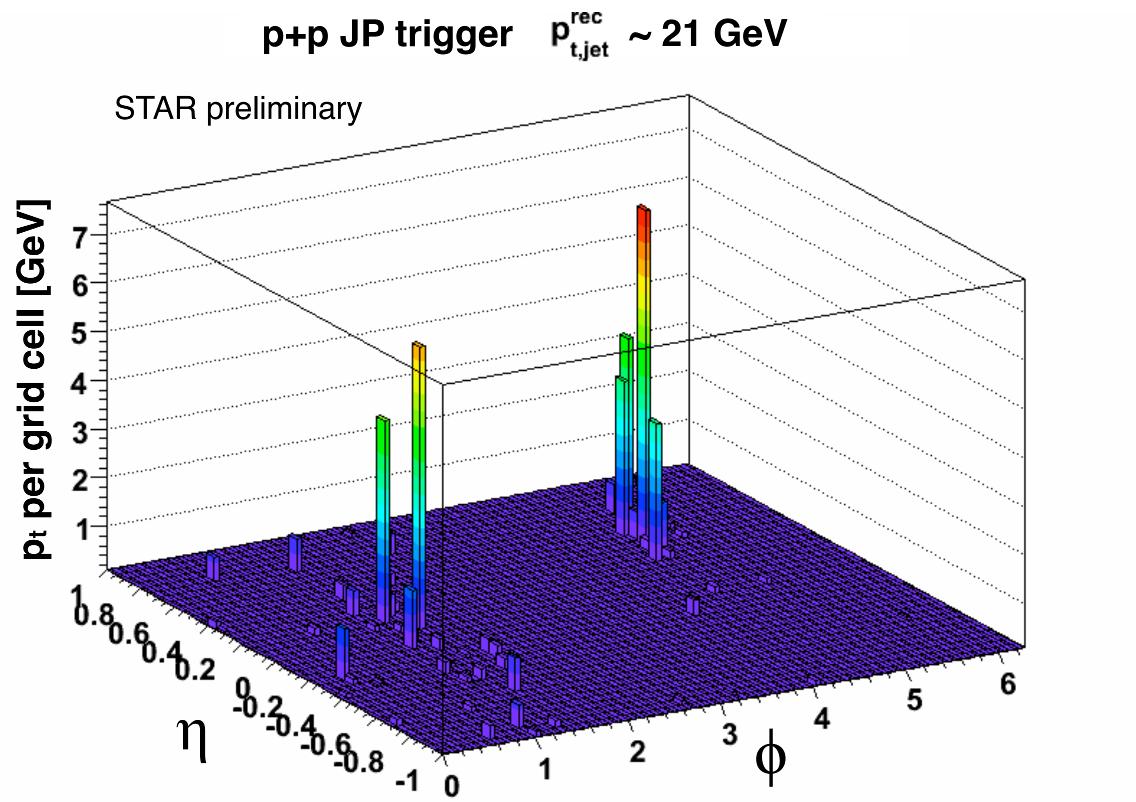




Indication of modification in the fragmentation function for lower jet p_t < $p_{t,rec}$(pp)> ~ 18 GeV

Experimental setup/data-sets



Jet-finding is performed on a "grid" using p_t/E_t from:

- charged particle p_t (TPC)
- neutral tower E_t 0.05x0.05 (ηxϕ) (EMC)

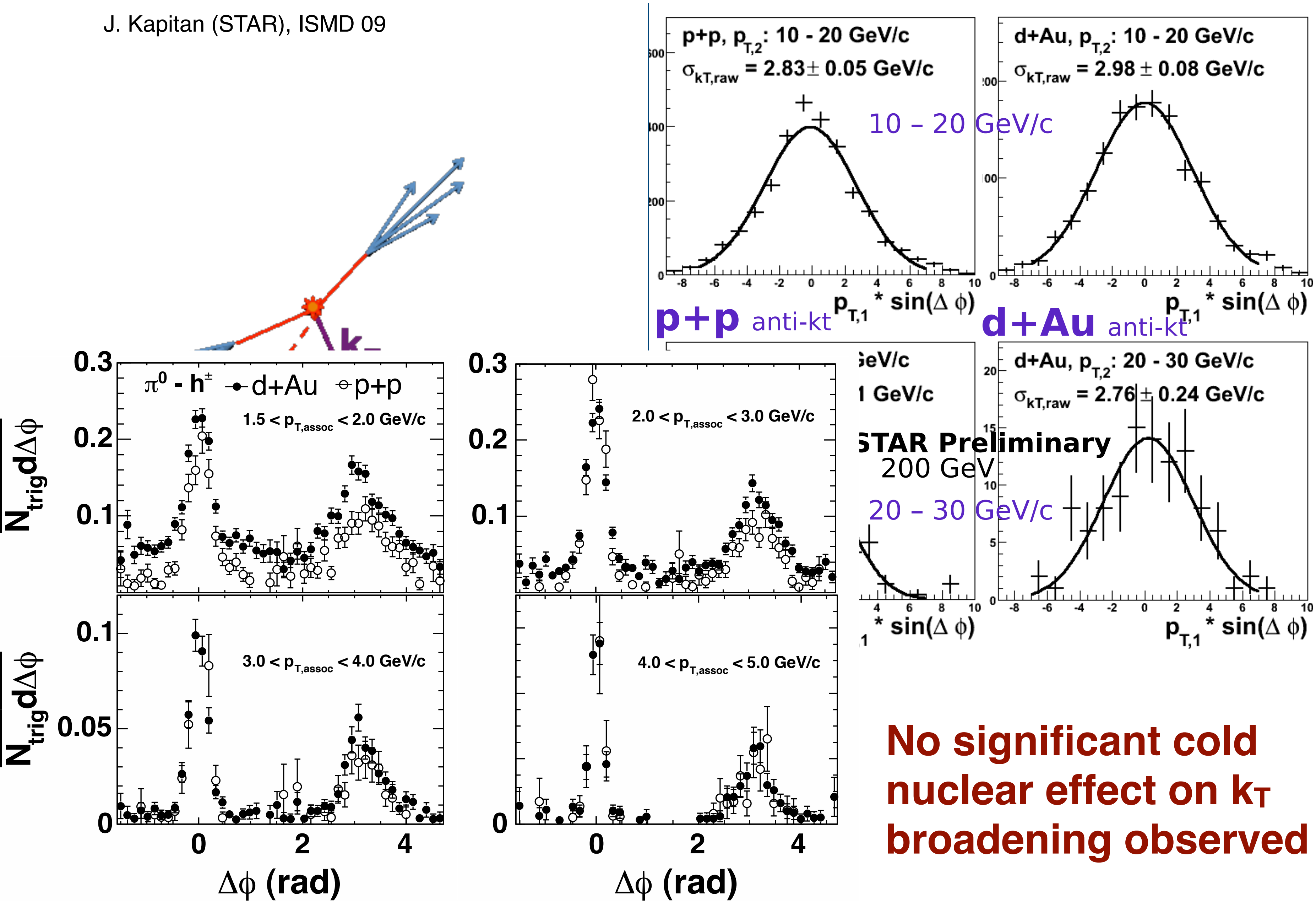
- corrected for hadronic energy.
- Electron correction applied.
- EMC provides fast trigger.

<u>Analyzed STAR data-sets:</u>

- *p+p (2006) High-Tower (HT) trigger (single tower E_t>5.4 GeV)*
- p+p (2006) Jet-Patch (JP) trigger (ηxϕ=1x1 with sum E_t>8 GeV)
- *Au+Au (2007) High-Tower (HT) trigger (E_t>5.4 GeV)*
- Au+Au (2007) Minimum-Bias (MB) trigger

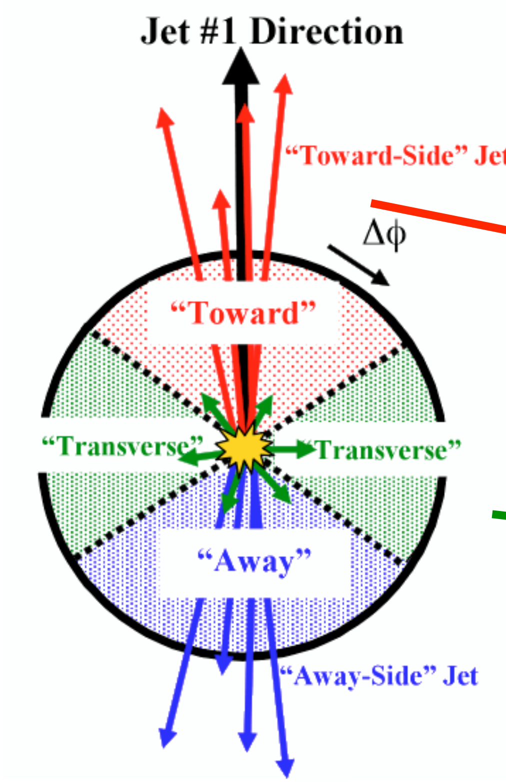
Cold nuclear matter effects: k_T broadening in d+Au

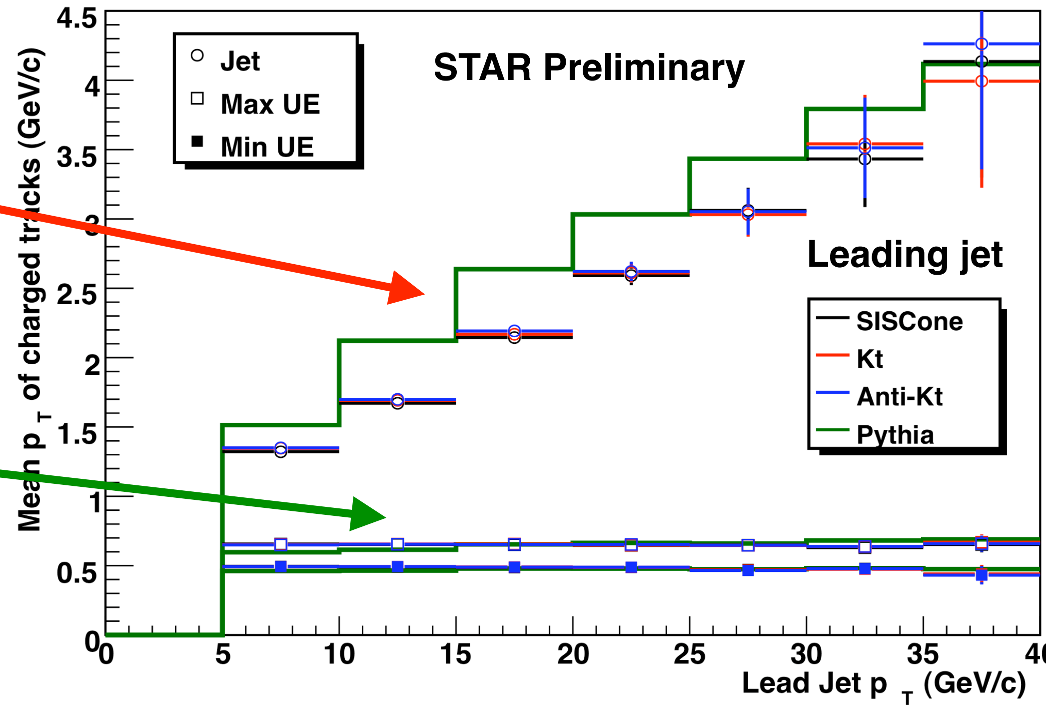
J. Kapitan (STAR), ISMD 09

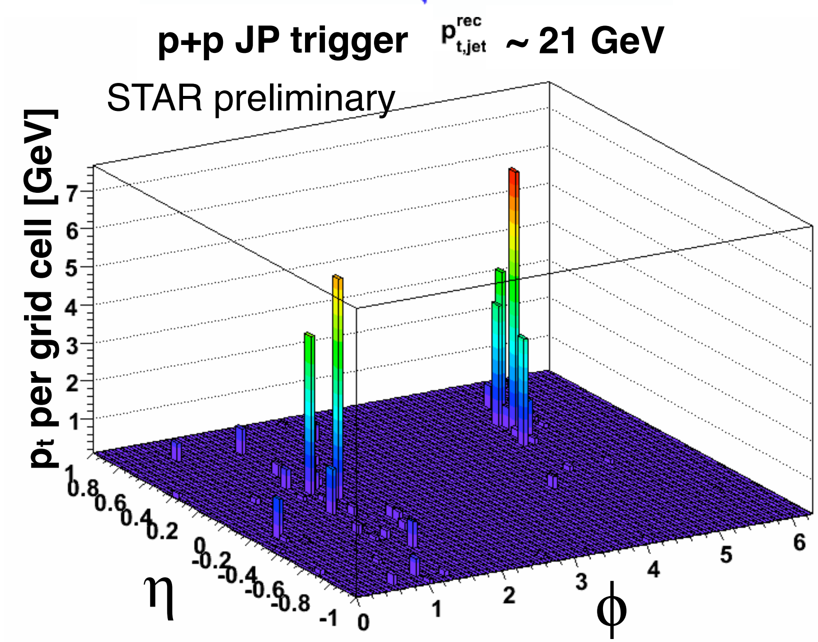


No significant cold nuclear effect on k_T broadening observed

The underlying event in p+p collisions

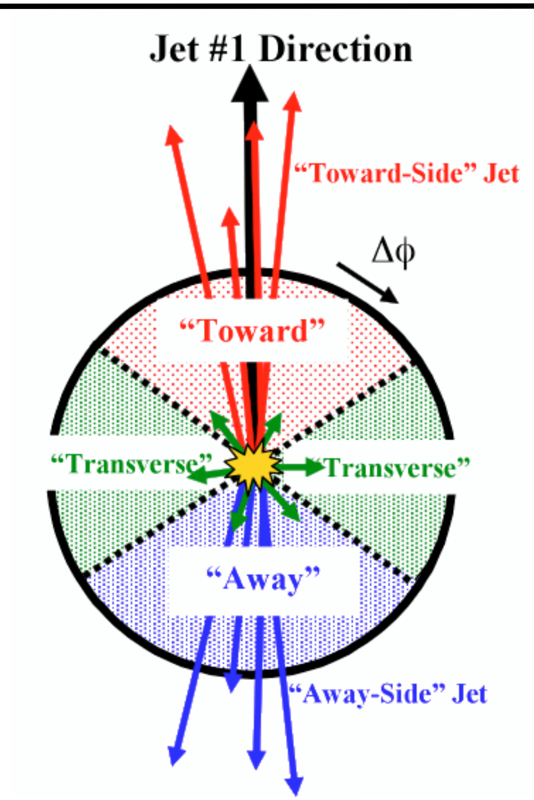


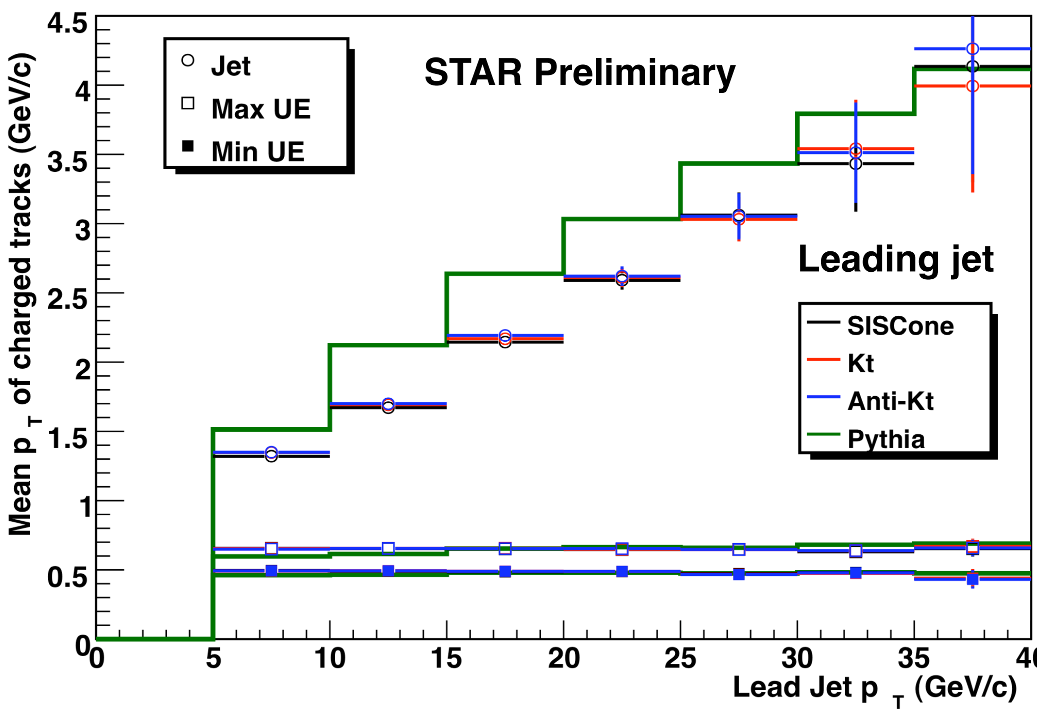


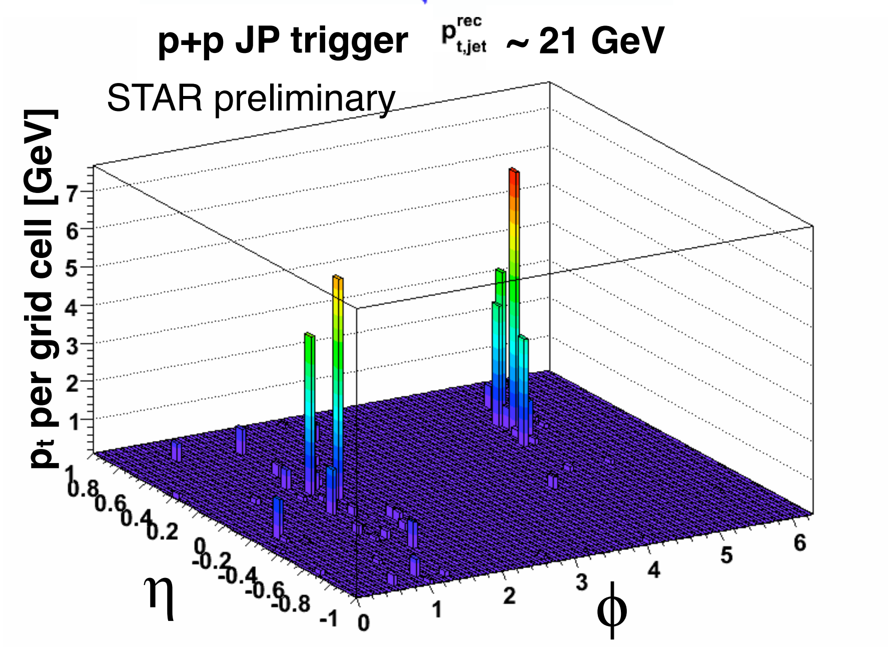


- Underlying event is decoupled from the hard scattering
- Small initial and final state radiation at large angles at RHIC energies

The underlying event in p+p collisions







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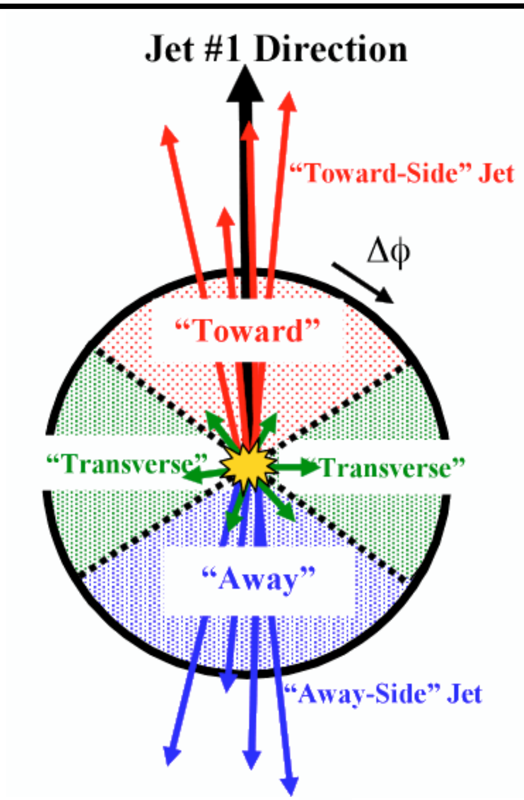
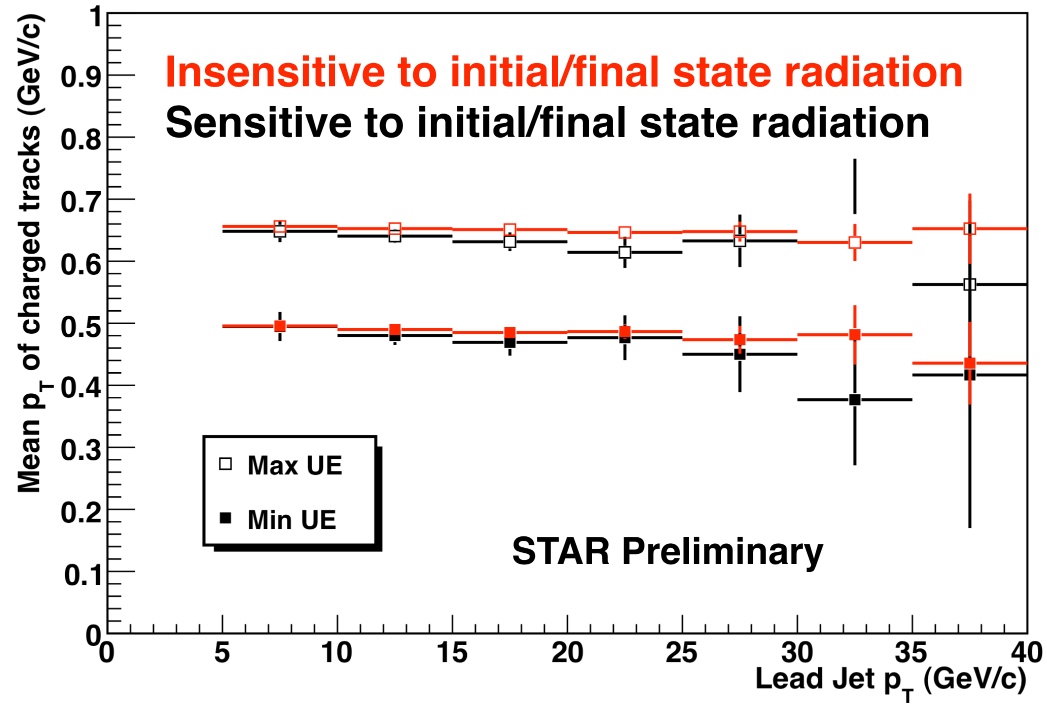
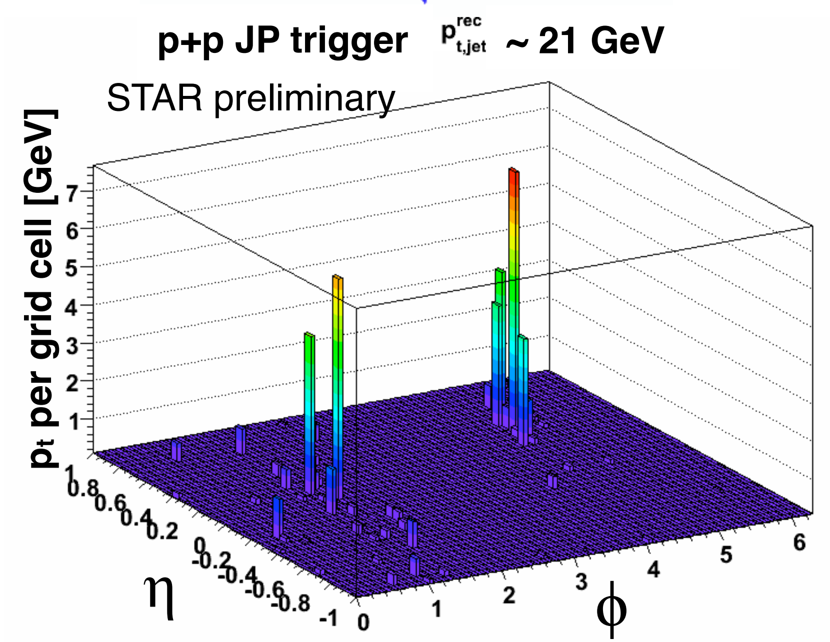
The underlying event in p+p collisions







- Underlying event is decoupled from the hard scattering
- Small initial and final state radiation at large angles at RHIC energies

Systematic corrections

Trigger corrections:

- p+p trigger bias correction

Particle level corrections:

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

Jet level corrections:

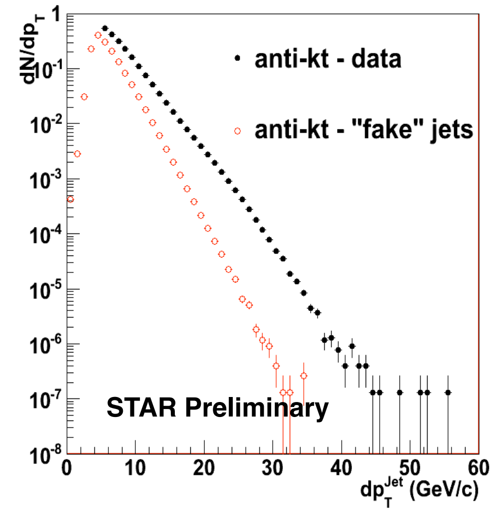
- Spectrum shift:
  - Unobserved energy
  - TPC tracking efficiency
- EMC calibration (dominant uncertainty in p+p)
- Jet pT resolution
- Underlying event (dominant uncertainty in Au+Au)

Full assessment of jet energy scale uncertainties

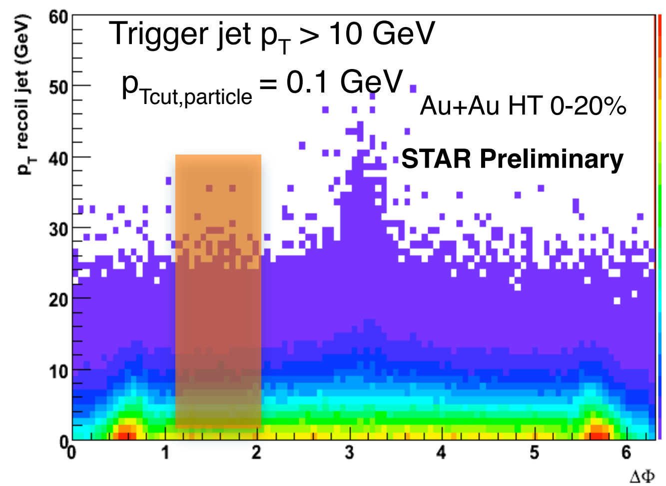
Data driven correction scheme !

“Fake-Jet” contribution

<u>“Fake” jets:</u> signal in excess of background model from random association of uncorrelated soft particles (i.e. not due to hard scattering)

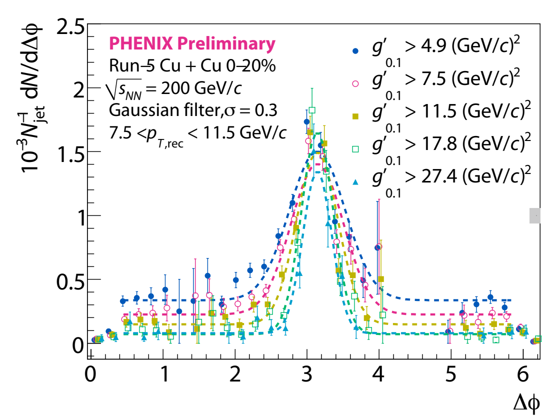


Inclusive jet spectrum:
Spectrum of “jets” after randomizing HI event in ϕ and removing leading jet particle



Di-Jet / Fragmentation function:
Background di-jet rate
= “Fake” + Additional Hard Scattering
Estimated using “jet” spectrum at 90 deg.

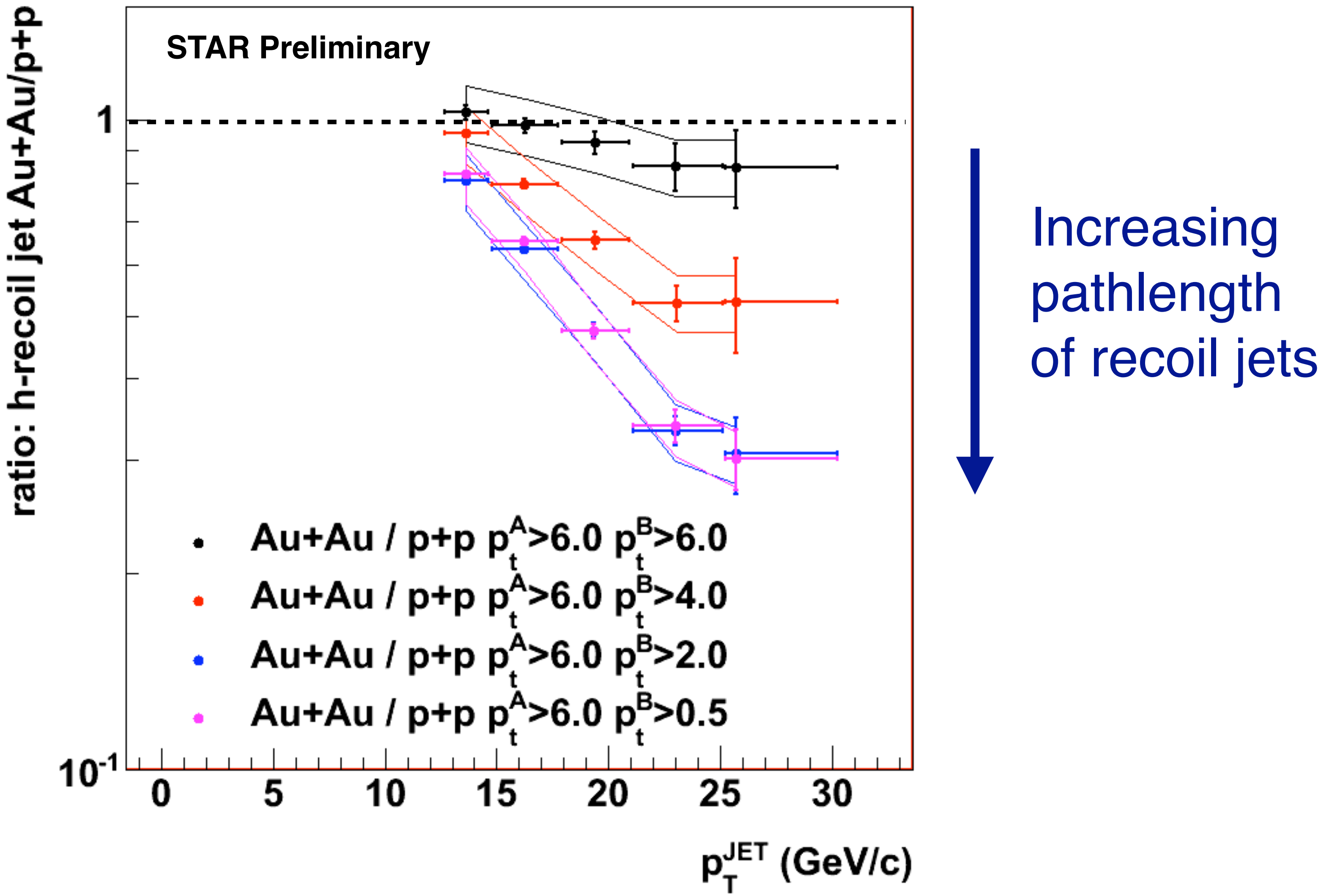
PHENIX:
Gaussian fake-jet rejection; use overall shape of jets for discrimination.



<u>Caveat:</u> If quenching distorts jet-shape substantially, danger of vetoing quenched jets!

Exploring pathlength dependence for recoil jets

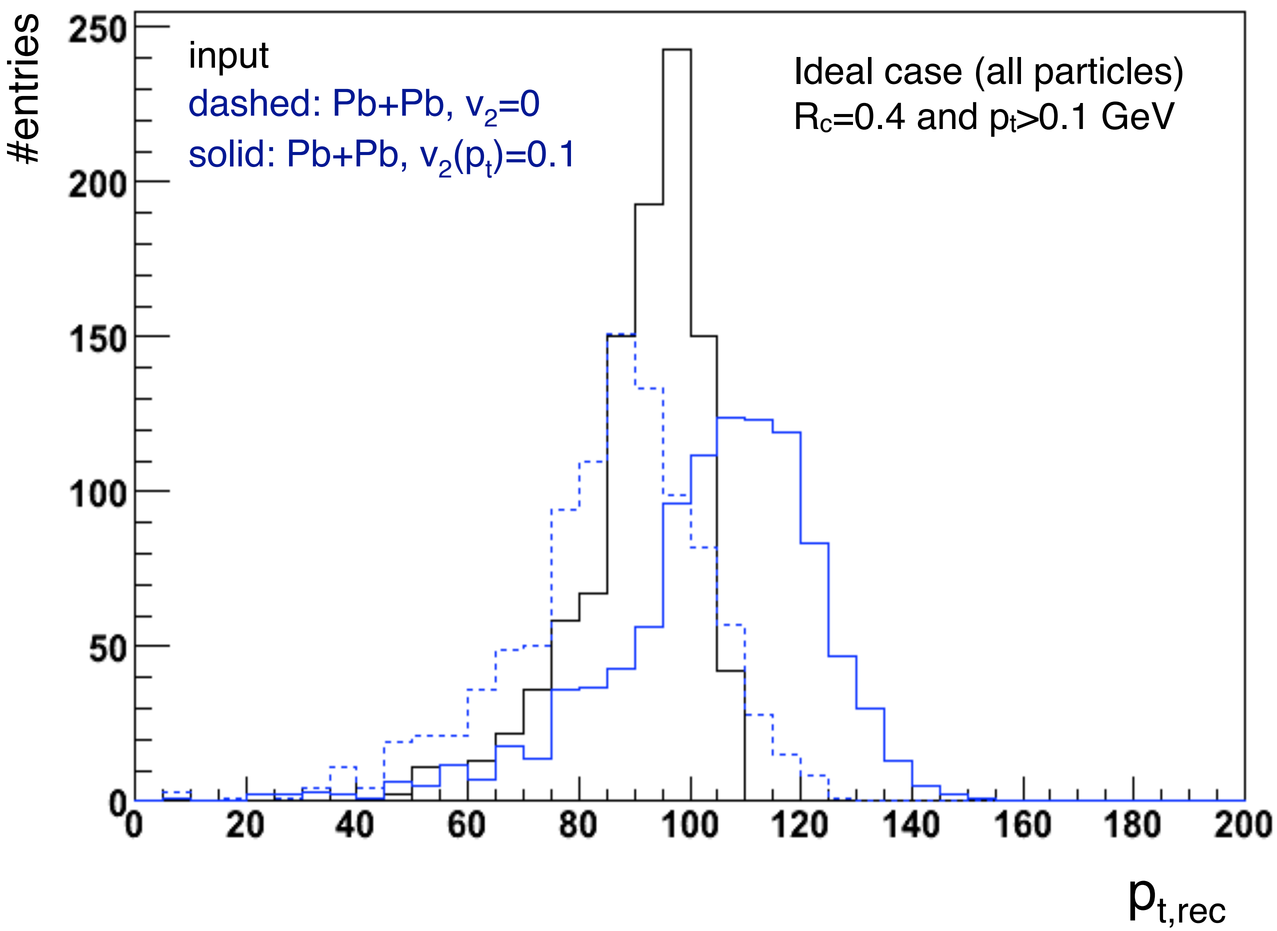
Trigger on high p_T π^0 and look at jet recoil spectrum

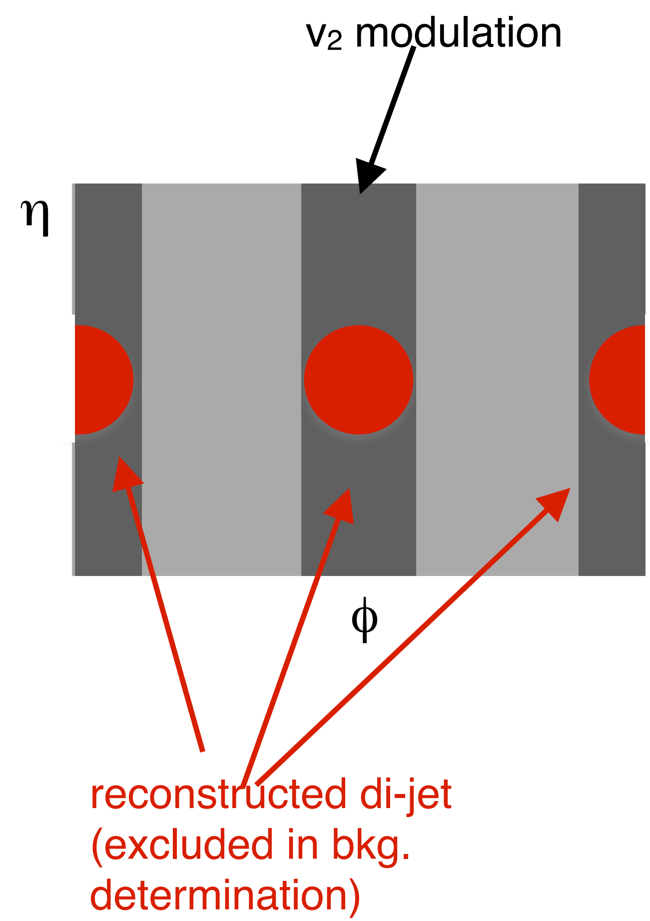


Significant suppression in hadron-jet coincidence measurements of the unbiased recoil jet spectrum

Effect of elliptic flow

Simple MC model of heavy-ion background: event-plane aligned with jet-axis (extreme case)

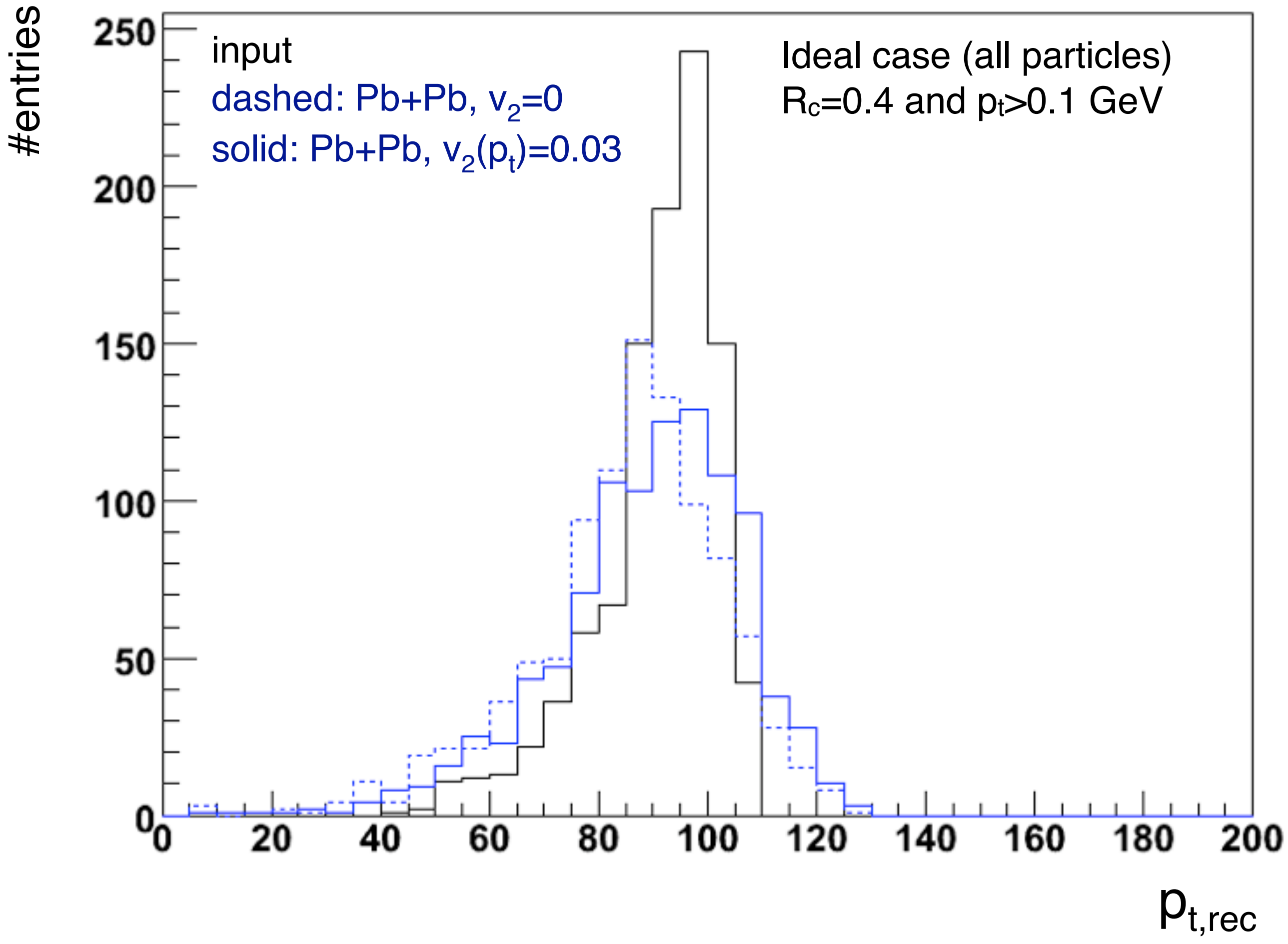




Elliptic flow can have a size-able effect in the background estimation !

Effect of elliptic flow cont.

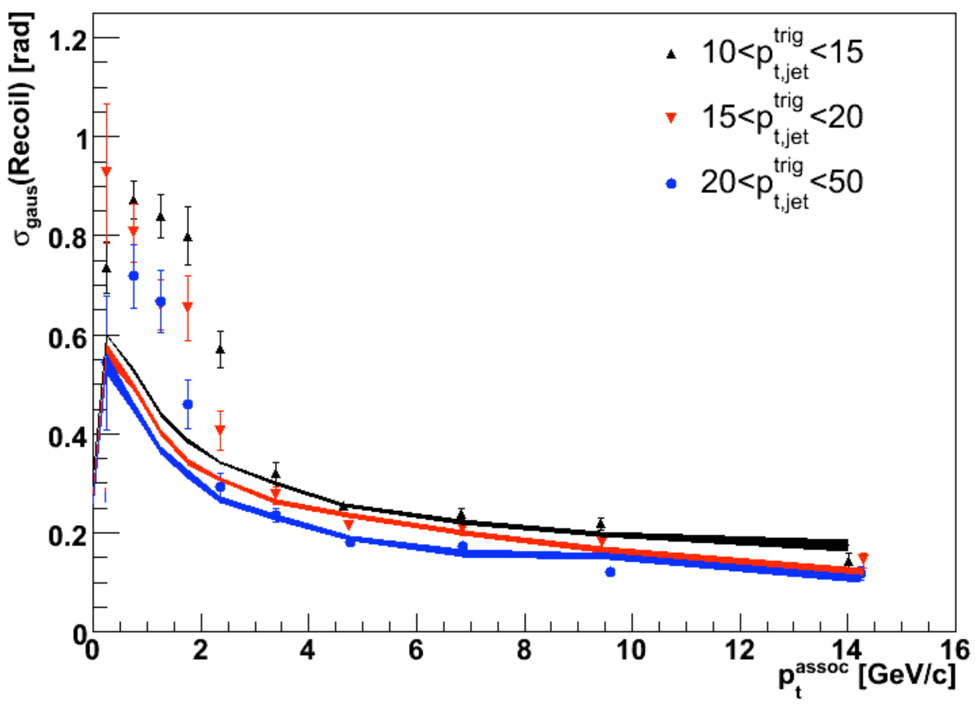
Simple MC model of heavy-ion background: $v_2(p_t)$=0.03 and event-plane angle randomly generated

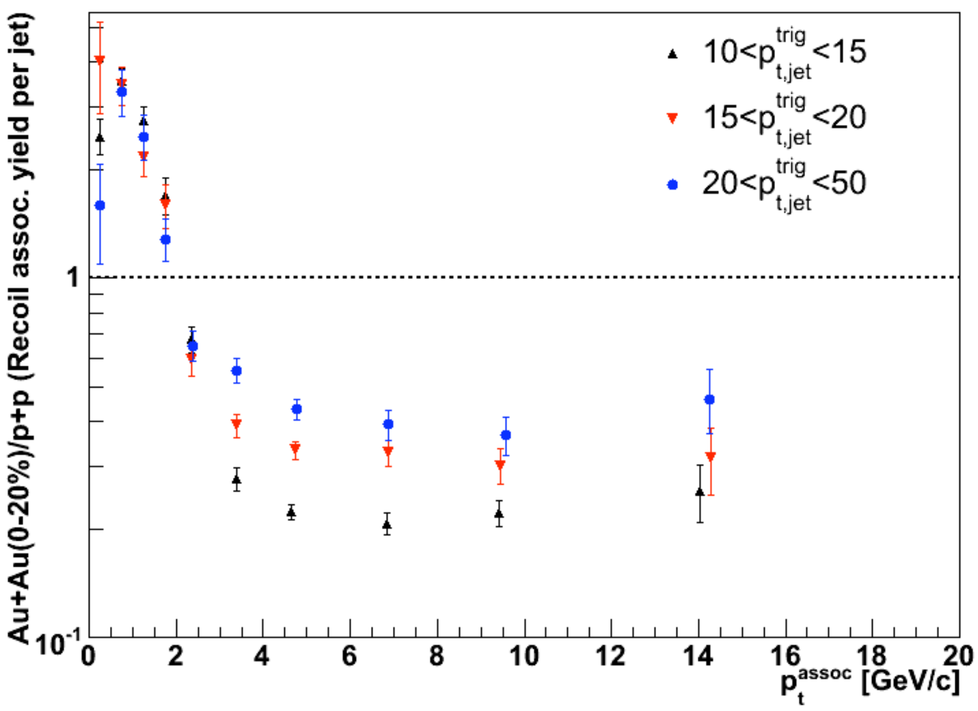


Elliptic flow in a more realistic scenario has a smaller but still visible effect.

Caveat: Different jet-energy response will affect the missing jet-energy correction with respect to p+p

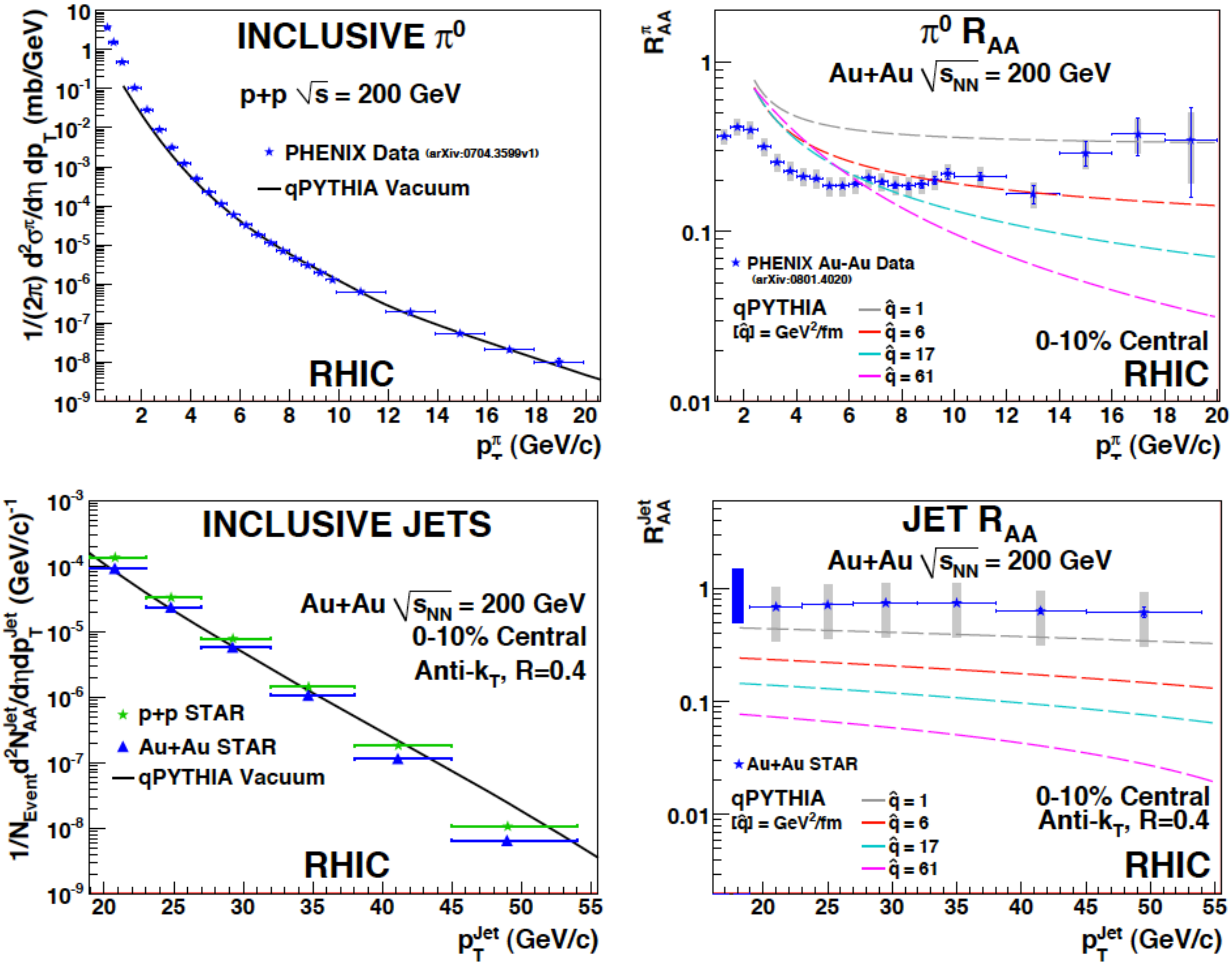
Jet broadening and “Modified FF”



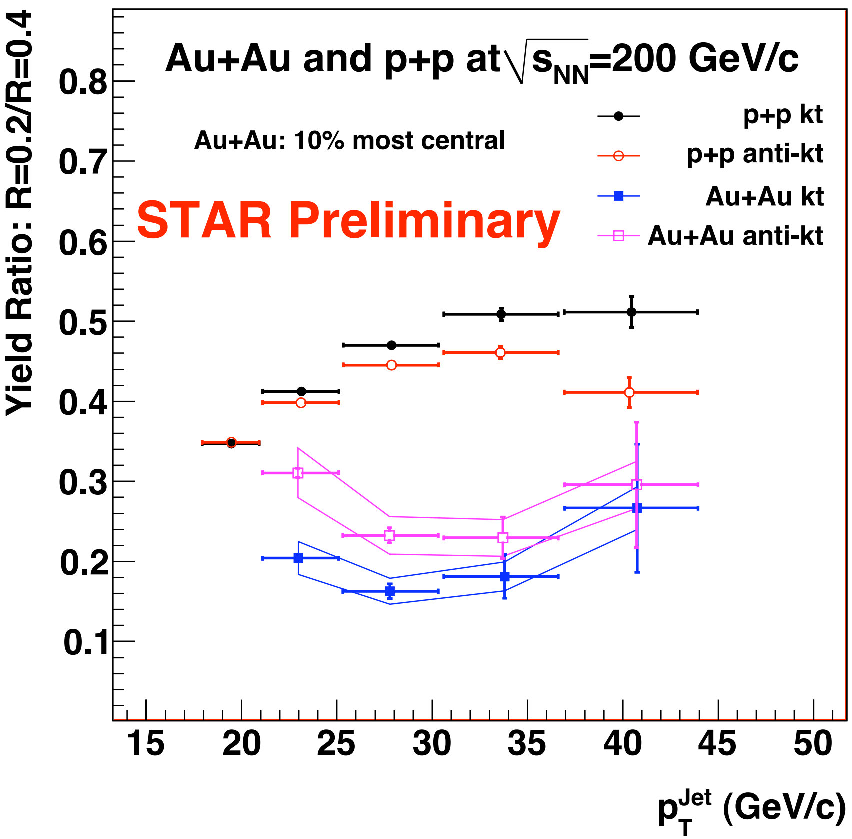


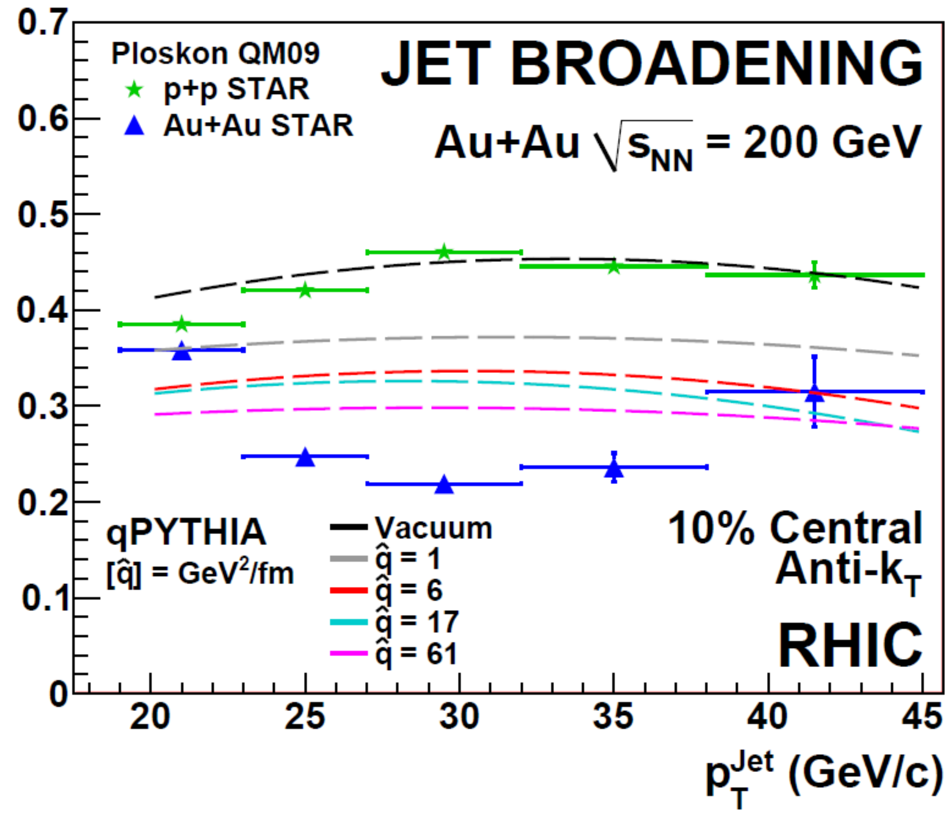
- Significant (gaussian) jet broadening for recoil jets wrt p+p
- Out-of-Cone energy can “account” for di-jet spectra suppression
- Enhancement for low-p_t and suppression at high-p_t assoc. yield wrt p+p ≈ “modified FF”

qPythia vs. RHIC data I



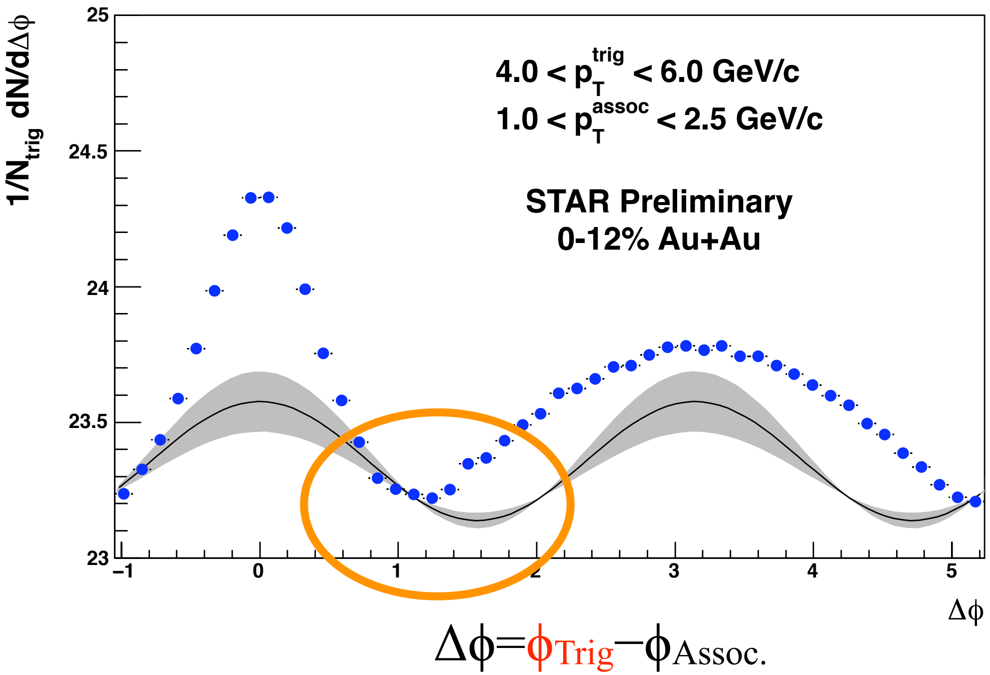
qPythia vs. RHIC data II



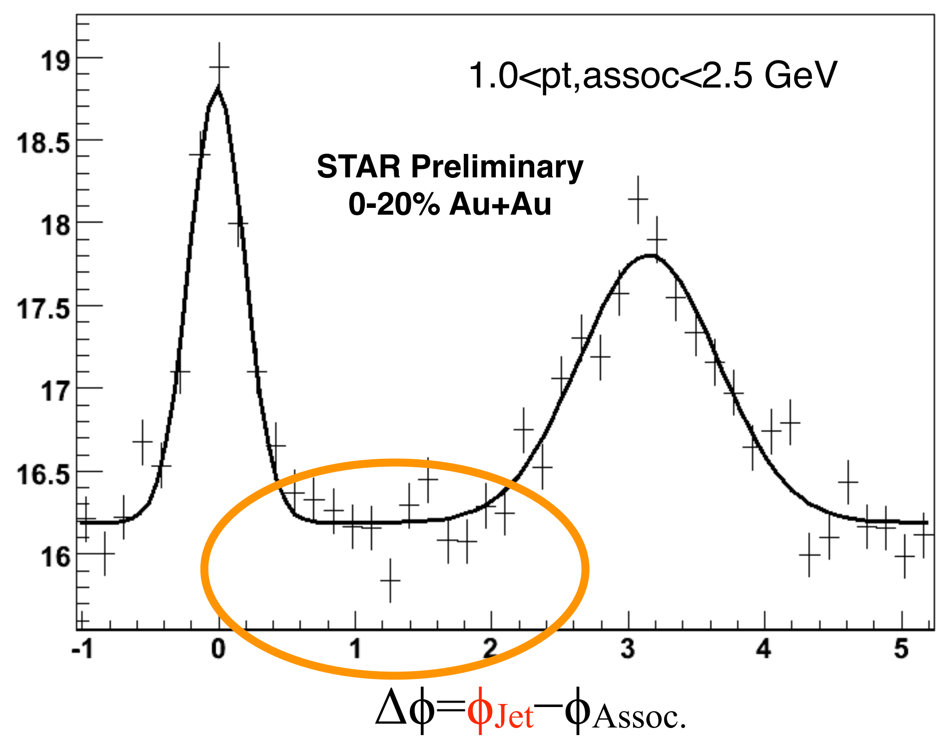


qPYTHIA predicts more suppression (smaller R_{AA}) and less broadening that observed

Unsubtracted Jet-hadron vs. di-hadron

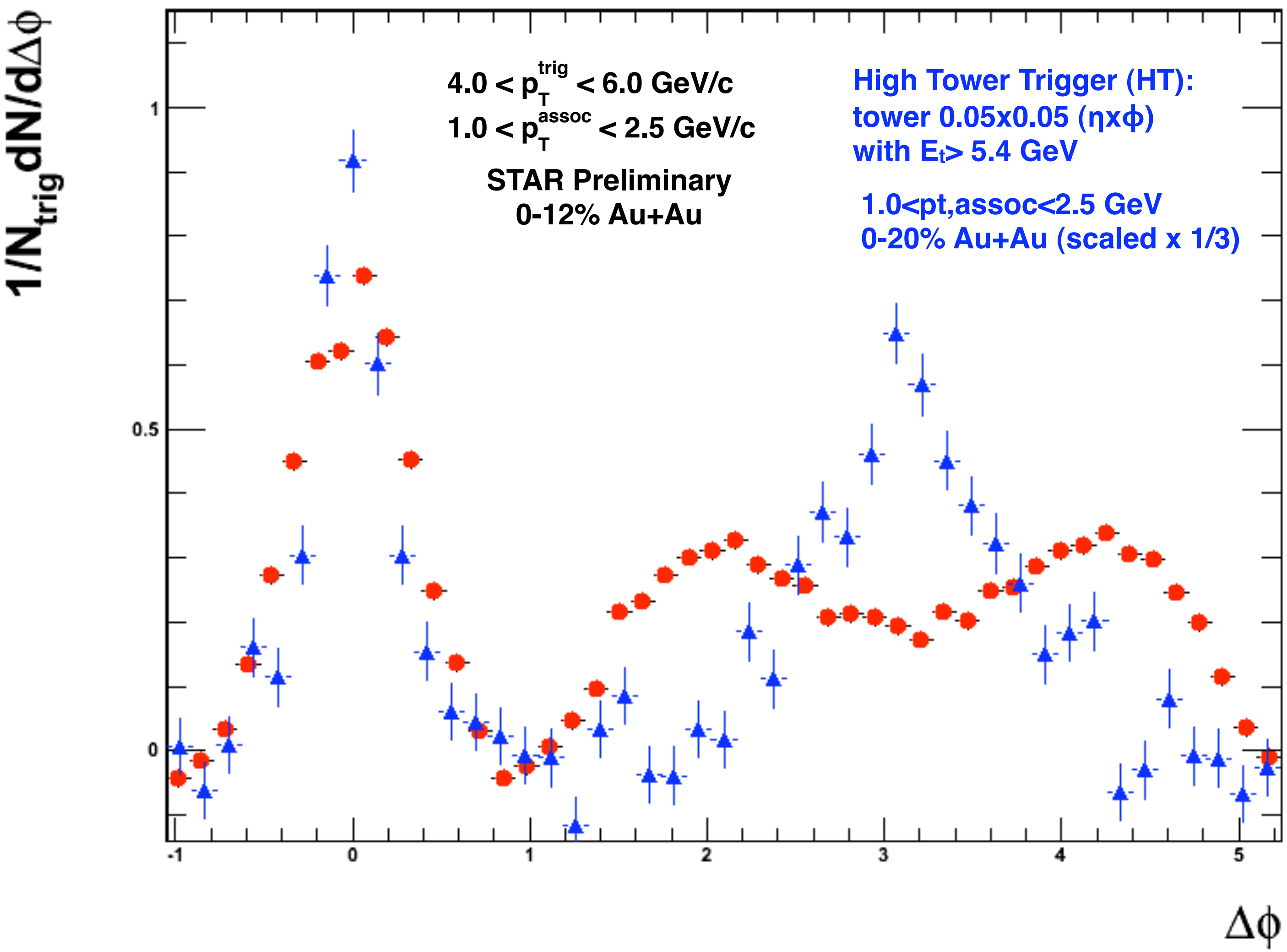


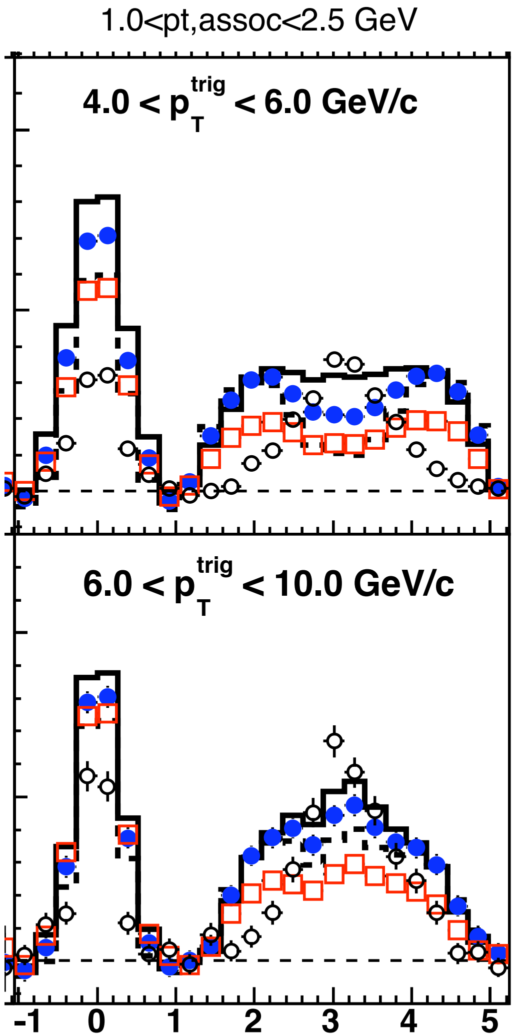
High Tower Trigger (HT): tower 0.05x0.05 (ηxφ) with Et> 5.4 GeV



- No apparent v2 modulation in Jet-hadron vs. di-hadron
- jet axis not correlated wrt to the event plane (?)
- v2 unsubtracted di-hadron correlation does not show mach-cone like structures, only after v2 subtraction (!?)

Away-side structure: di-hadron vs. jet-hadron





Jet-hadron away-side significantly narrower than di-hadron
=> can not be explained by punch-trough only/ no wings (!)

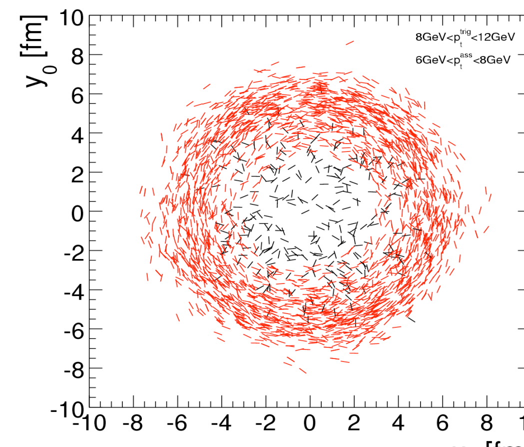
Surface and other bias effects

‘Surface bias’:
- Trigger, associated selection favours short path lengths

Surface bias is not the only possibility:
- Energy-loss fluctuations (at fixed path length) potentially large
- Fragmentation bias

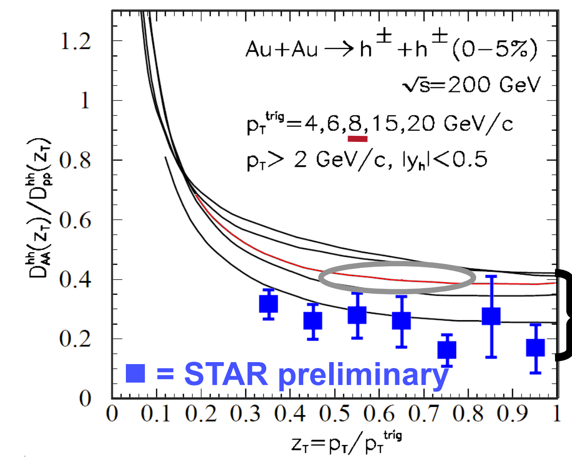
Wicks, Horowitz, Djordjevic, Gyulassy
nucl-th/0512076

PQM: Dainese, Loizides and Paic



Are we selecting pairs, events with small energy-loss?

X-N Wang, PLB 595, 165 (2004)



Alternative:
Shape of di-hadron fragmentation changes little if underlying partonic spectrum shape unmodified

This calculation underpredicts suppression

Note also: possible low-z enhancement from fragmentation of induced gluons. Outside measured range, awaits confirmation

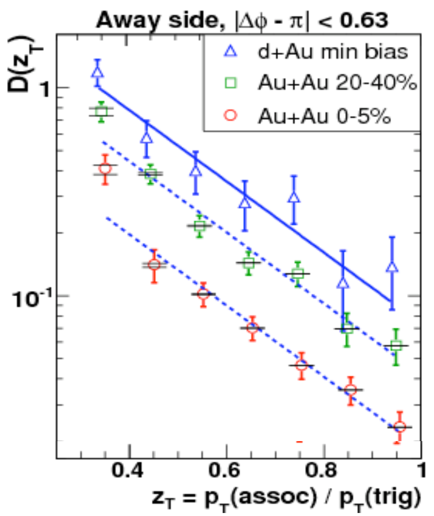
General form: Partonic spectrum E_{jet} ⊗ Nuclear geometry L ⊗ Energy loss $\Delta E(E_{jet})$ ⊗ Fragmentation $D(E_{jet}, \Delta E)$

Need full calculations, a la PQM

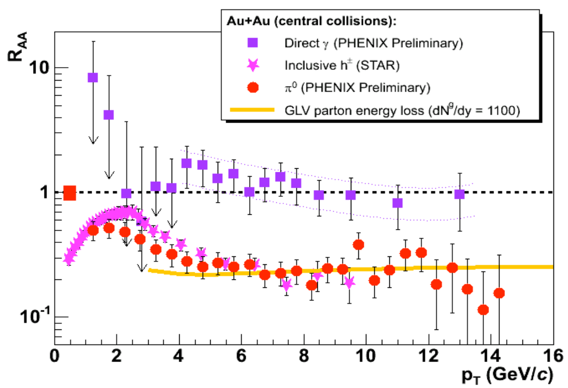
Different observables probe different parts of convolution

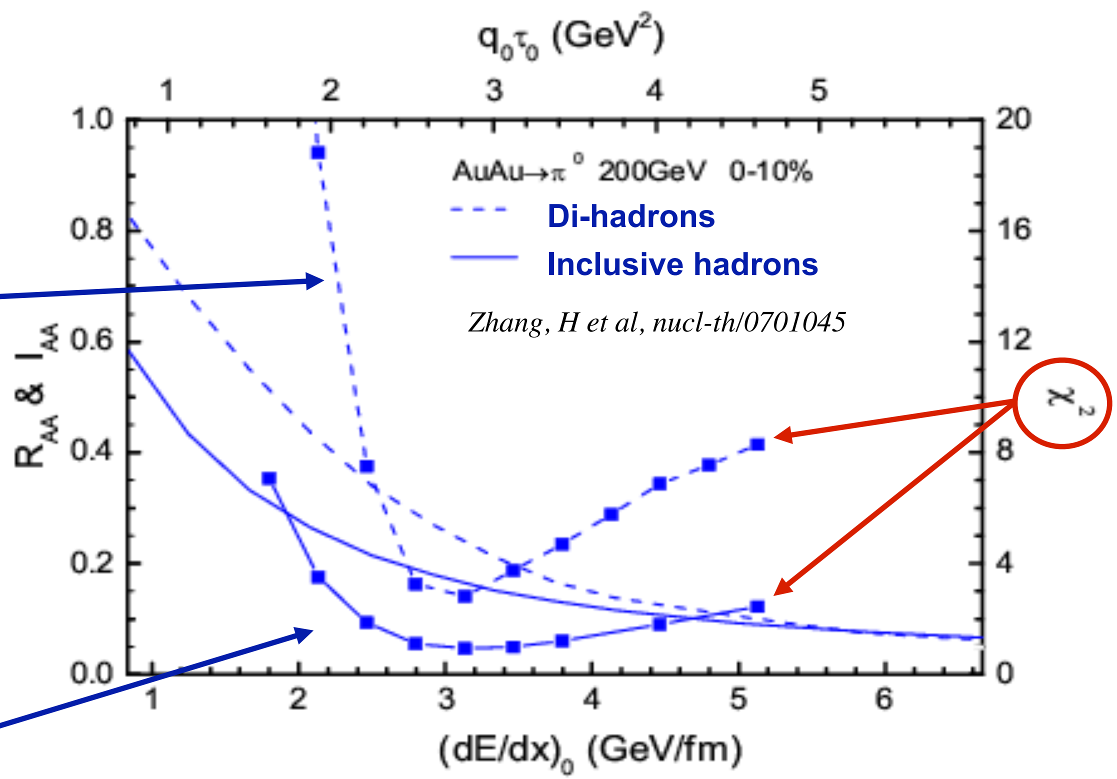
Extracting the transport coefficient "via suppression" @ RHIC

Di-hadron suppression



Inclusive hadron suppression





Di-hadrons provide stronger constraint on density

Extracted transport coefficient from singles and di-hadrons consistent

$$\hat{q} = 2.8 \pm 0.3 \text{ GeV}^2/\text{fm}$$

BUT: Different models extract different transport coefficient values …

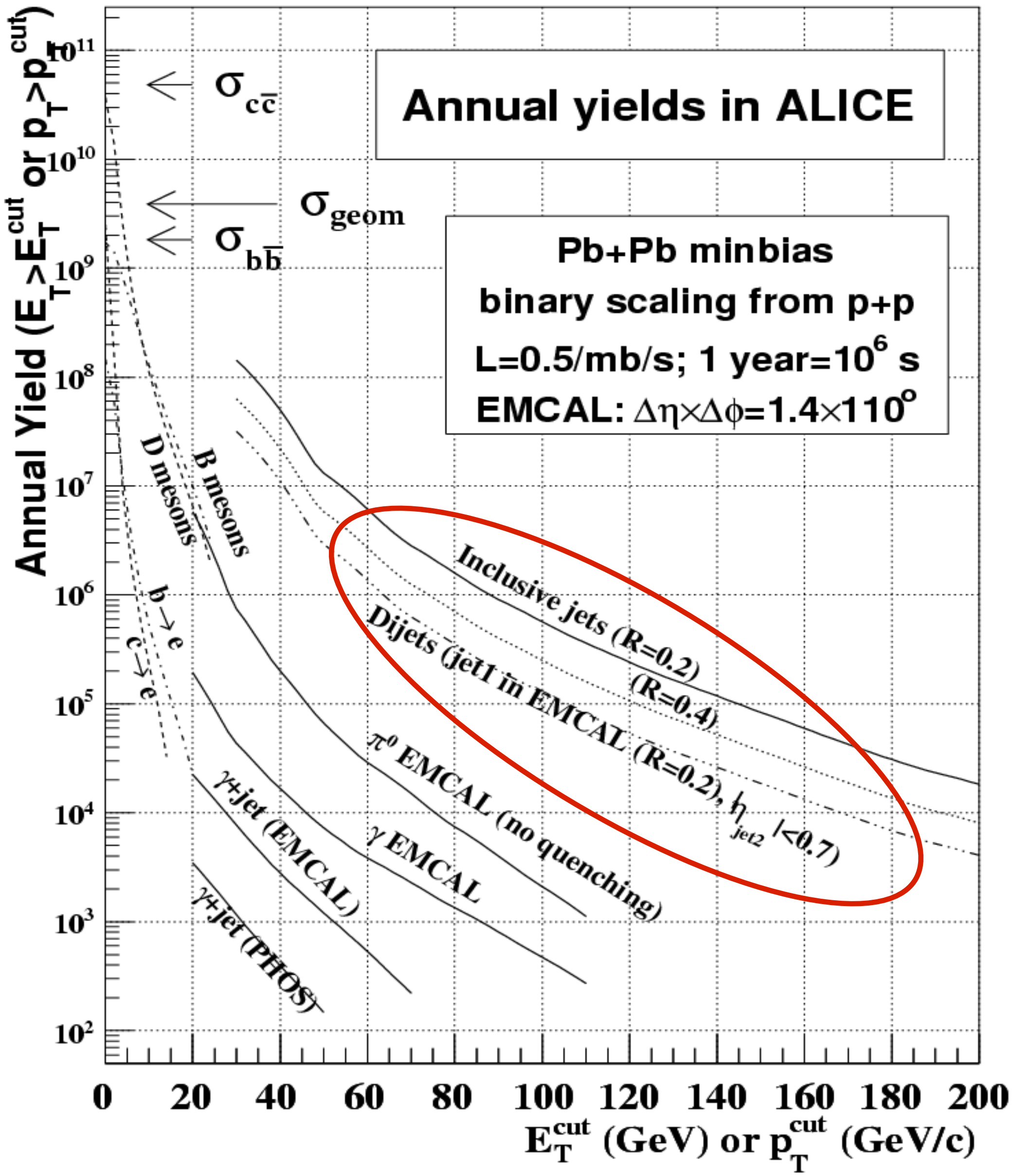
Misc.

Energy dependence of jet quenching: LHC

ALICE for example ...

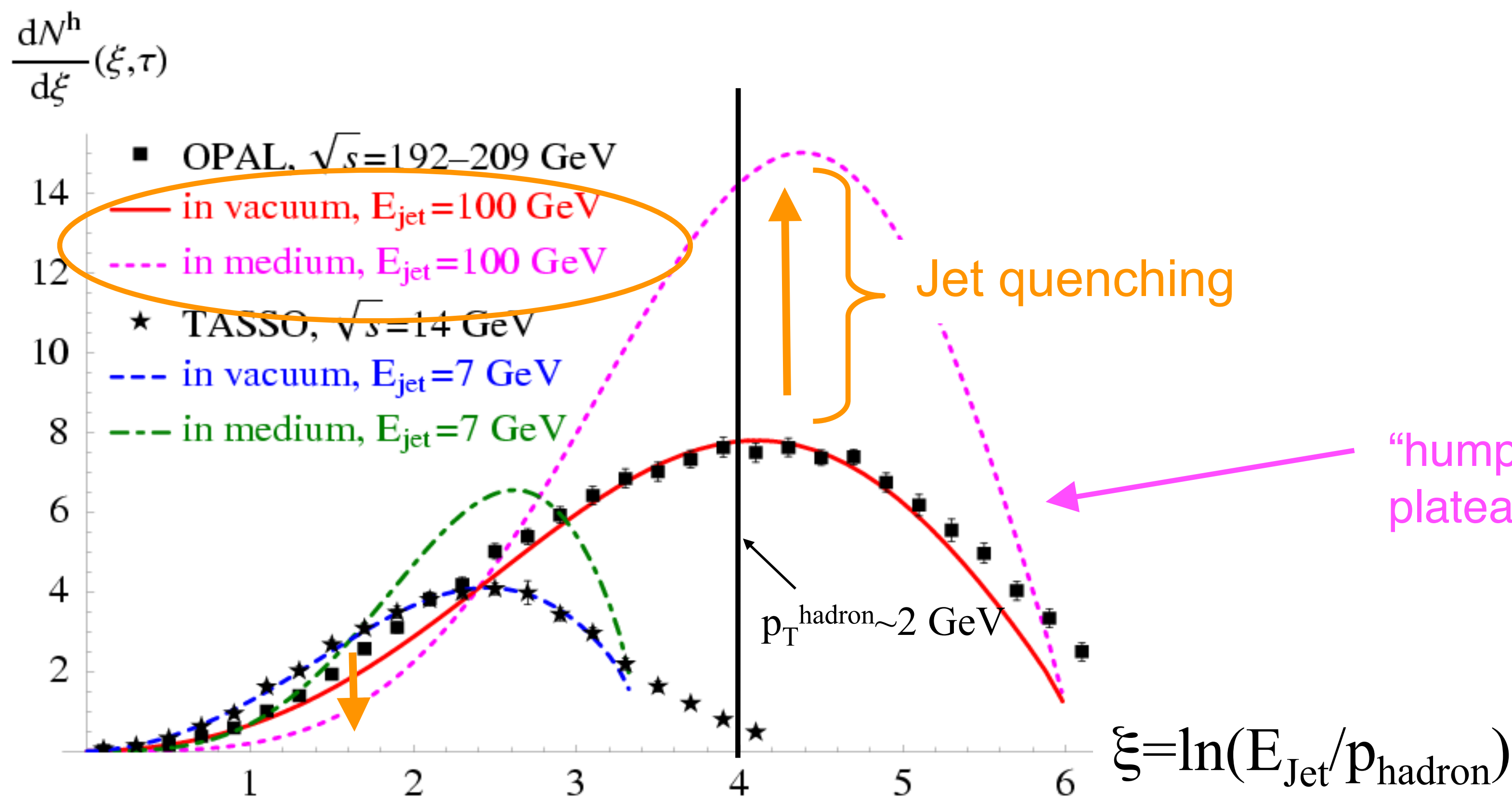
LHC enables measurements of a “logarithmically large” variation in jet energy

⇒ study QCD evolution of jet quenching



Benchmark observable: Modified Fragmentation Function

- MLLA: good description of vacuum fragmentation (basis of PYTHIA)
- Introduce medium effects at parton splitting *Borghini and Wiedemann, hep-ph/0506218*



Jet quenching ⇒ fragmentation should be strongly modified at p_T^{hadron}~1-5 GeV

Can we measure this at RHIC @ 200 GeV ?

Summary

• Jet reference measurements (p+p and d+Au) well understood

• Significantly larger fraction of the jet population measured via full-jet reconstruction wrt to single inclusive measurements (STAR, Au+Au), similar suppression in Cu+Cu (Phenix)

• Strong evidence of broadening in the jet energy profile

• Significant suppression of di-jet coincidence yields in central Au+Au collisions

• Only small modifications of the recoil-jet fragmentation function

• Jet-hadron correlations show a significant broadening and softening of the recoil jet ⇒ “modified” fragmentation function

Towards a complete study of jet-quenching

Di-hadrons are <u>indirect</u> measurements of jet quenching !

To study the full spectrum of jet quenching in an unbiased way we need new techniques

<u>Two approaches:</u>

1. **γ-jet:** clean, but limited kinematic reach due to x-section

2. Full jet reconstruction: large kinematic reach, but complex analysis

Hard = pQCD + Factorization + Universality

Hadron production cross-section in an AB collision where AB=pp,pA, AA is:

$$E\frac{d^3\sigma_h}{dp^3} \propto \sum_{a,b,c,d} \int dz_c dx_1 dx_2 \frac{s}{z_c^2} f_{i/A}(x_1,Q^2) f_{j/B}(x_2,Q^2)$$

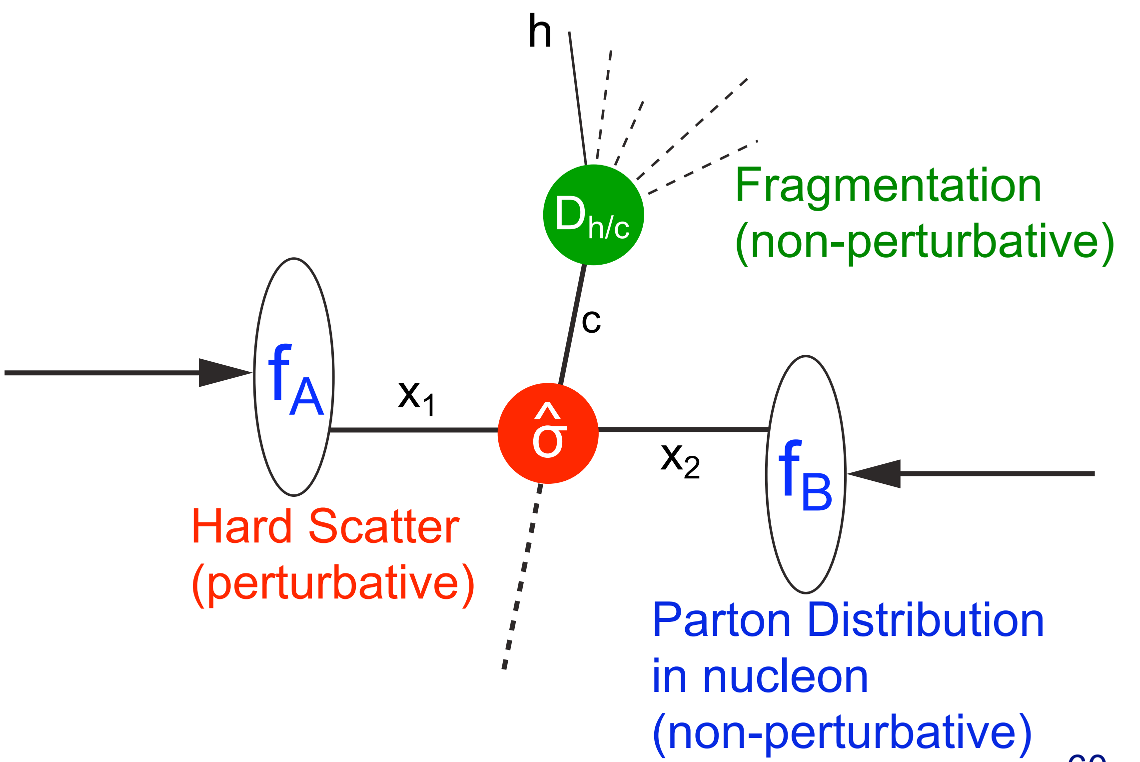
$$D_{h/c}(z_c,Q^2) \frac{d\hat{\sigma}^{(ab\to cd)}}{dt} \delta(s+u+t) + \mathcal{O}\left(\frac{\Lambda}{m}\right)^p$$

Collins, Soper, Sterman, Nucl. Phys. B263 (1986) 37

<u>Assumptions:</u>

Factorization assumed between the perturbative hard part and the universal, non-perturbative fragmentation (FF) and parton distribution functions (PDF)

Universal fragmentation and parton distribution functions (e.g. PDF from ep, FF from ee, use for pp)



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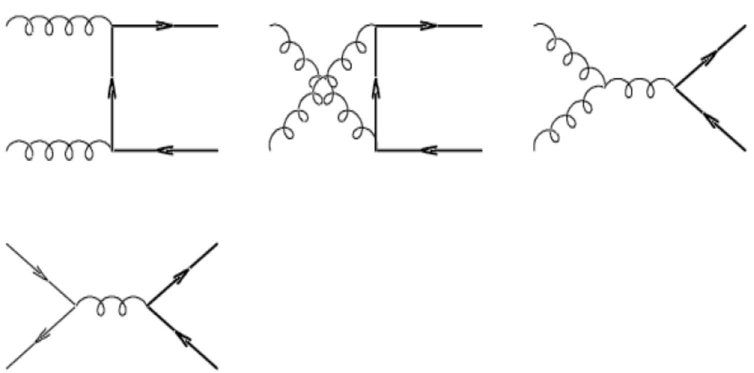
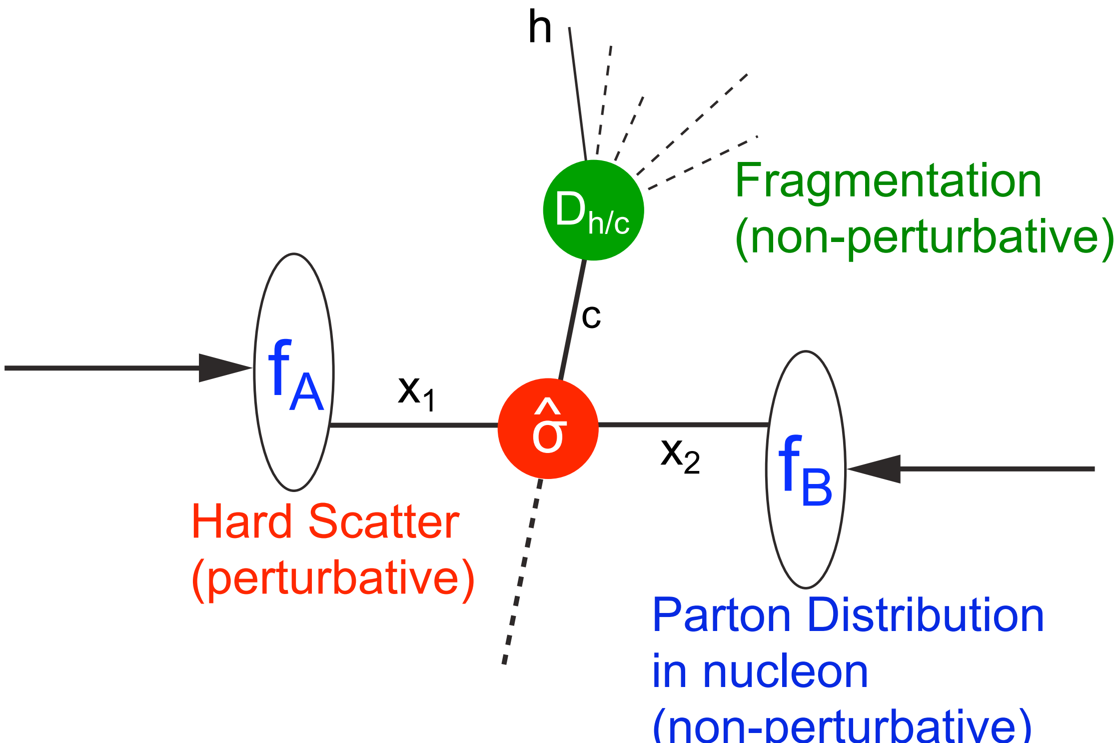
Perturbative QCD

dσ/dt = hard partonic cross section calculable in QCD in powers of α_s^{2+n}

- n=0: leadings order (LO)
- n=1: next-to-leading order (NLO)





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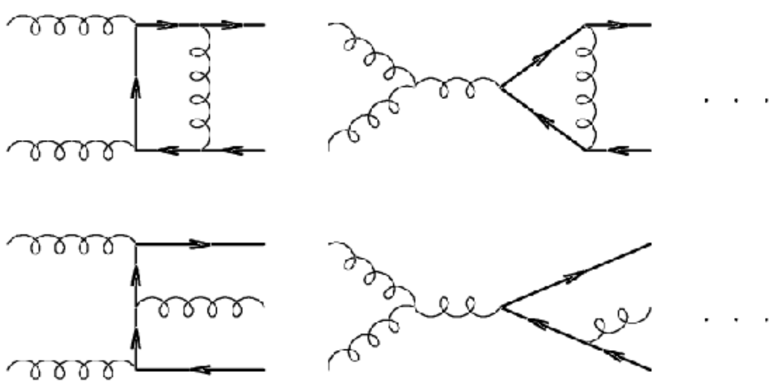
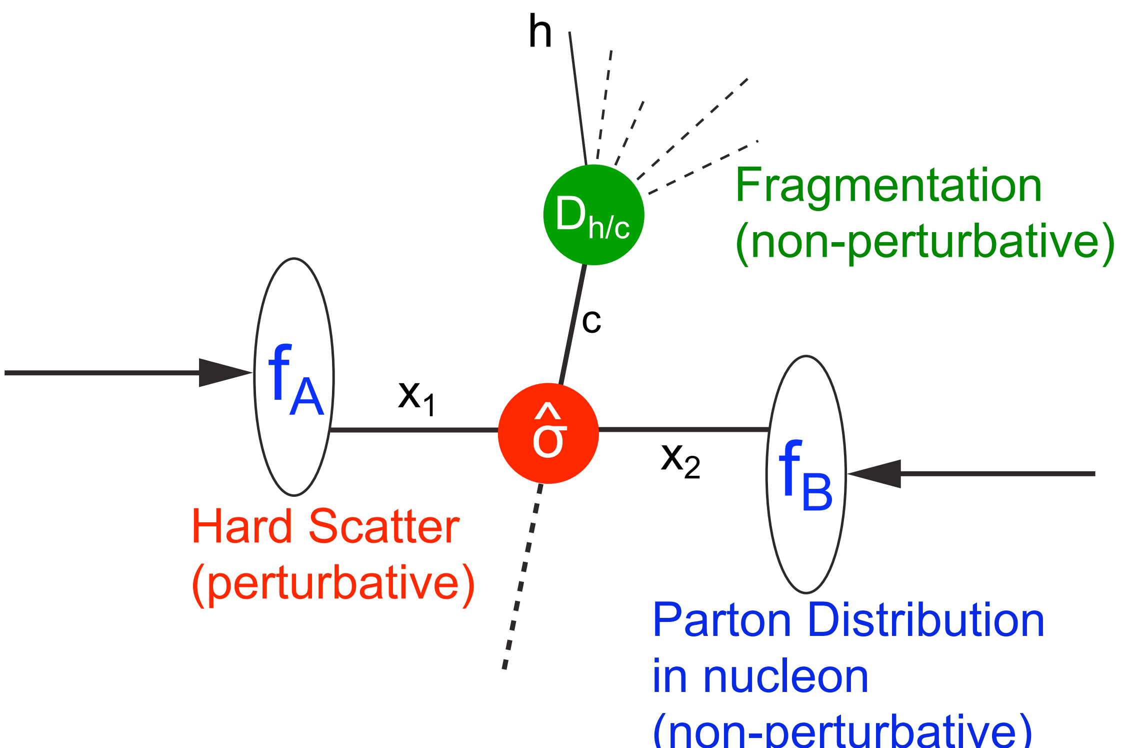




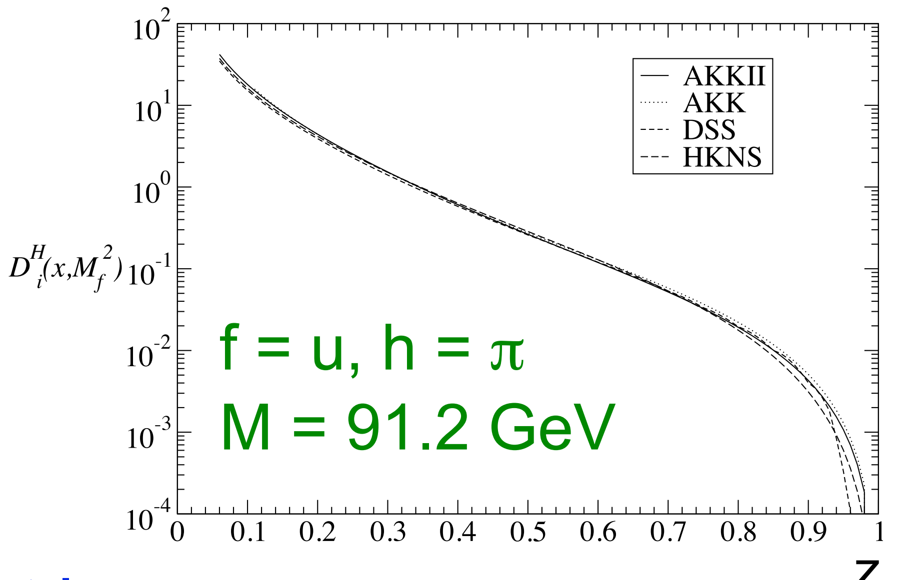
Examples: Fragmentation Functions

- Usual power ansatz for light quarks:

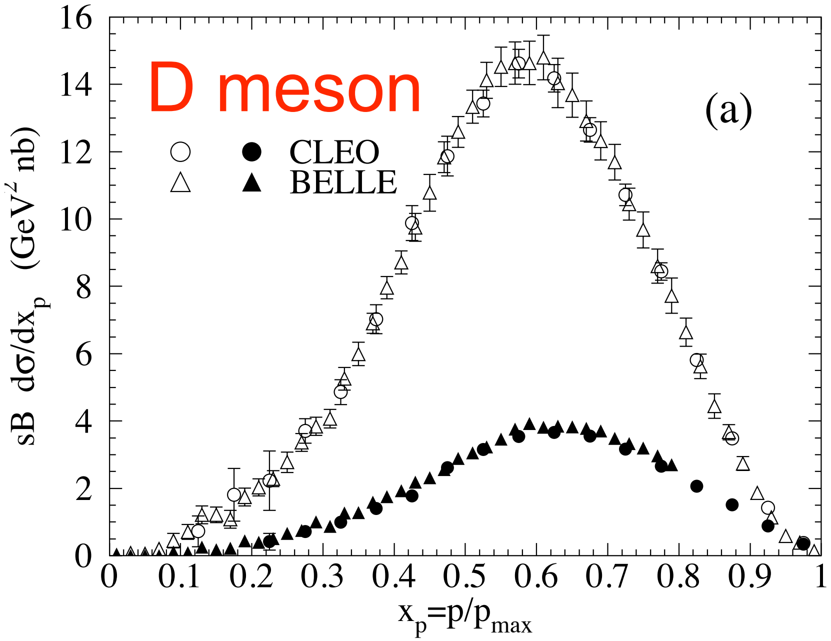
$$D_a^h(x, Q_0^2) = N x^\alpha (1-x)^\beta$$

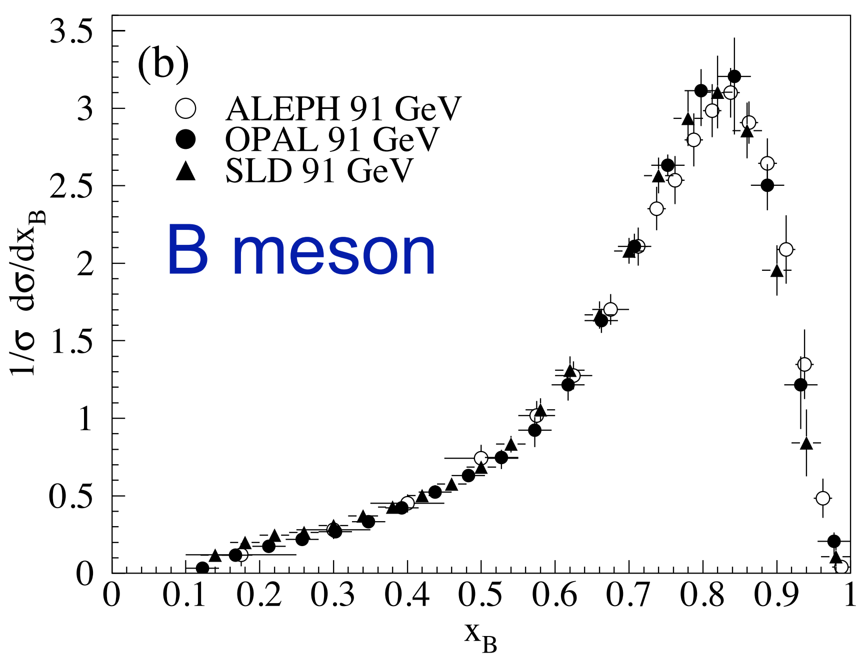
- Peterson:

$$D_a^h(x, Q_0^2) = N \frac{x(1-x)^2}{[(1-x)^2 + \epsilon x]^2}$$



Lingo: hard FF = frag. dominantly at large z
soft FF = peaks at low z



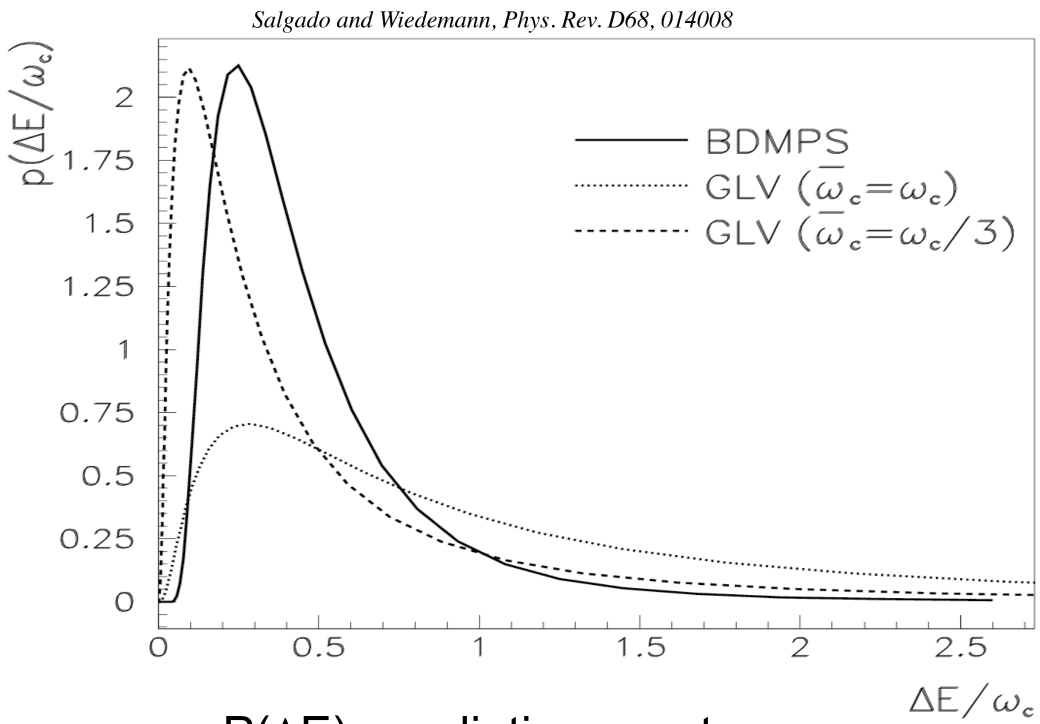


Measuring the radiation spectrum

Limited sensitivity of current measures to energy loss distribution P(ΔE)

Need to better constrain parton energy (in an unbiased way) to measure P(ΔE)

P(ΔE) tests theory !



P(ΔE) ≈ radiation spectrum

Two approaches:

1. Full jet reco.

2. **γ-jet**

If full jet reconstruction in heavy-ion collisions is unbiased

⇒ Inclusive jet spectrum scales with N_{binary} relative to p+p

Parton energy from γ-jet and jet reconstruction

Second-generation measurements at RHIC – first generation at LHC?

Qualitatively:

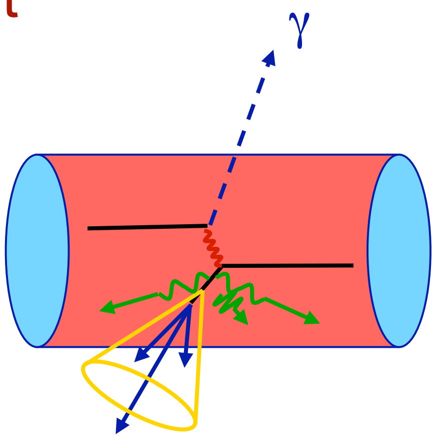
$$\left.\frac{dN}{dp_T}\right|_{hadr} = \left.\frac{dN}{dE}\right|_{jets} \otimes P(\Delta E) \otimes D(p_{T,hadr}/E_{jet})$$

known pQCDxPDF — extract — `known' from e^+e^-

Full deconvolution large uncertainties (+ not transparent)

Fix/measure E_{jet} to take one factor out

Two approaches:
– γ-jet
- Jet reconstruction

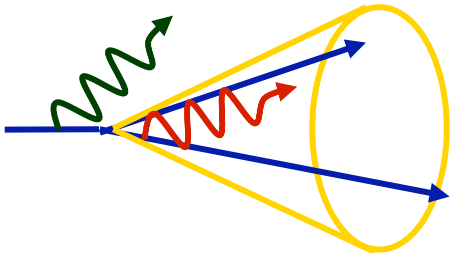


Relating jets and single hadrons

High-p_T hadrons from jet fragmentation

Qualitatively:

$$\left.\frac{dN}{dp_T}\right|_{hadr} = \left.\frac{dN}{dp_T}\right|_{jets} \otimes D(p_{T,hadr} / p_{T,jet})$$



Single hadrons are suppressed:

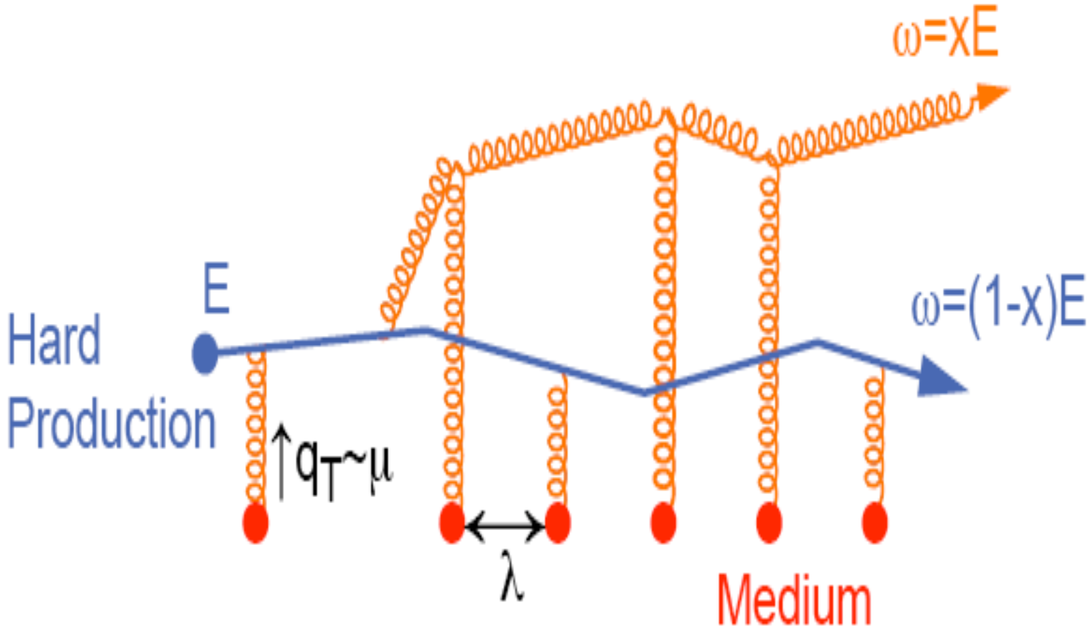
- Suppression of jet yield (out-of-cone radiation) $R_{AA}^{jets} < 1$
- Modification of fragment distribution (in-cone radiation)
  softening of fragmentation function and/or broadening of jet structure

Jet-medium interaction

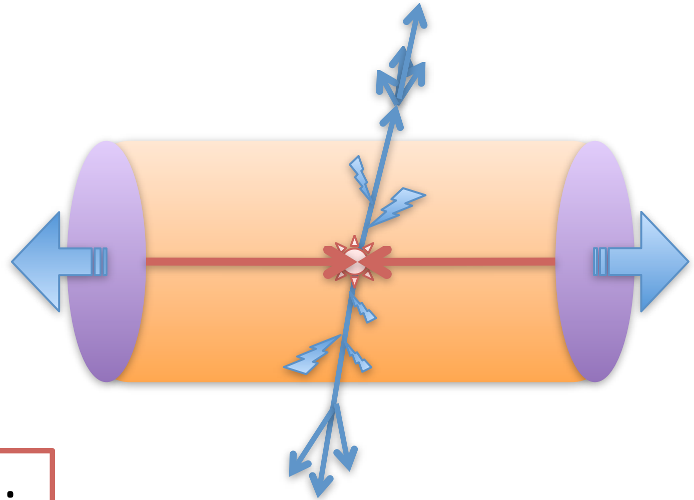
QED: Bremsstrahlung is dominant energy loss mechanism at high energy limit

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)



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

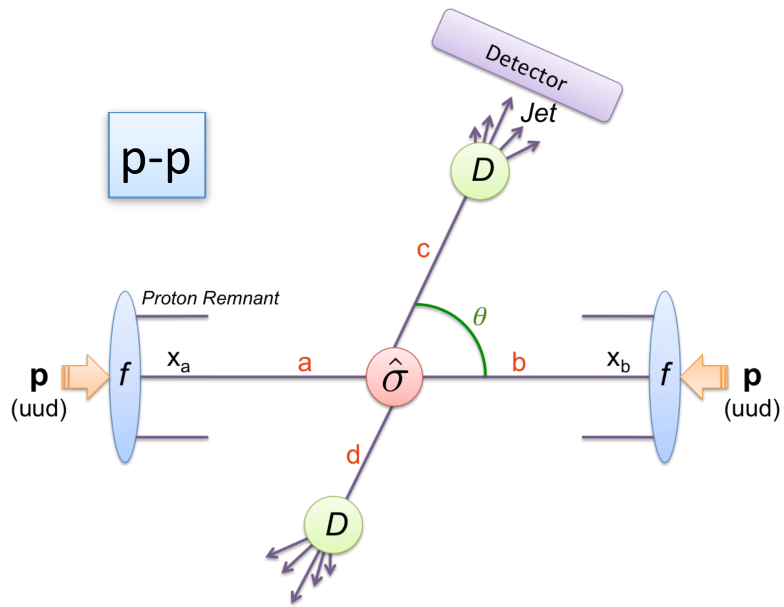


Partonic energy loss in QCD medium is proportional:

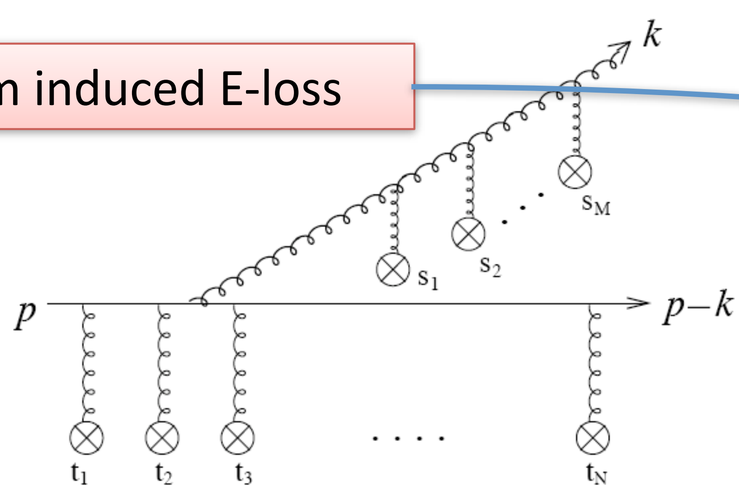
- to squared average path length (Note: QED ~ linear)
- to density of the medium

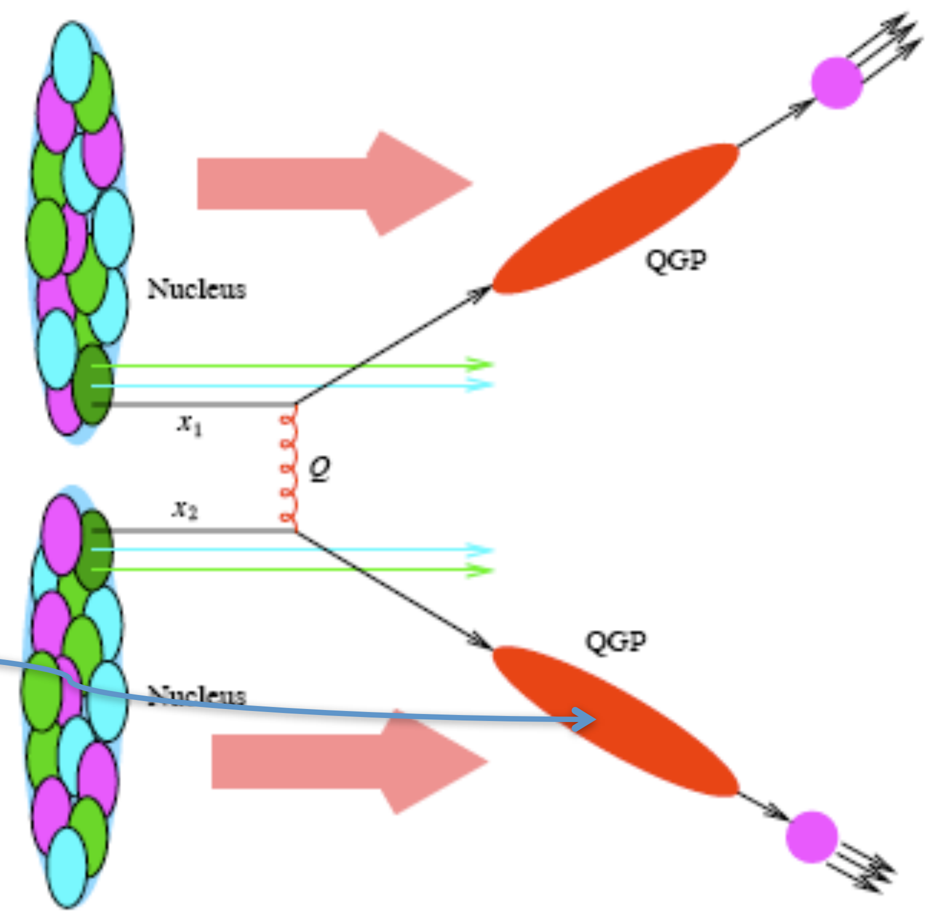
Factorization in HI collisions

p-p

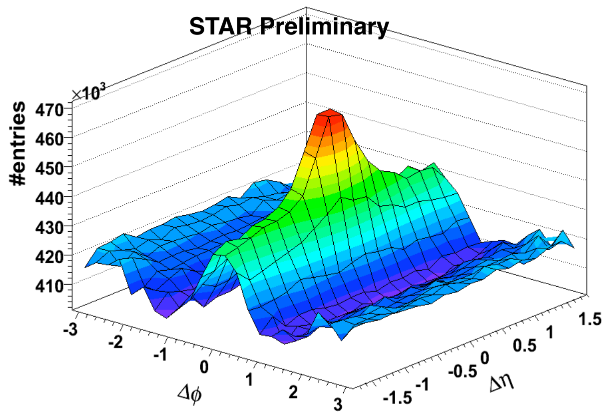


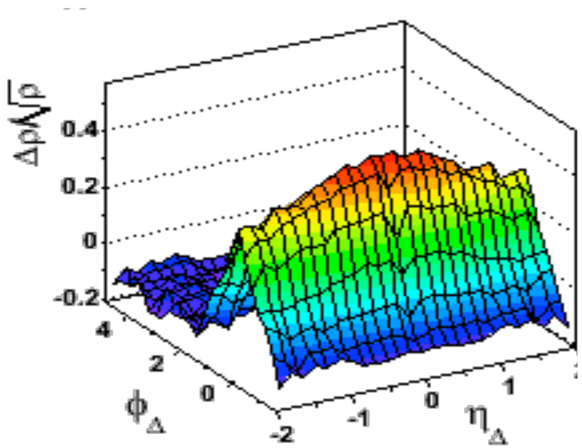
Medium induced E-loss





“Missing links”

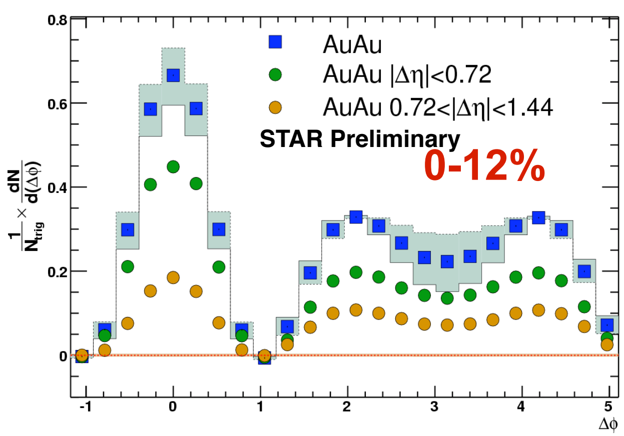


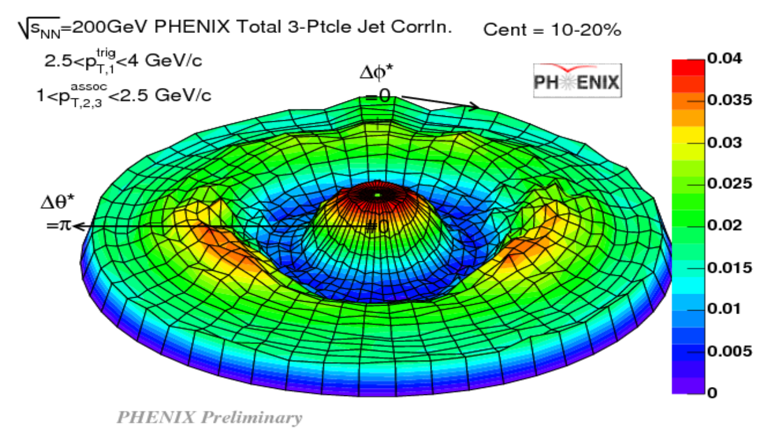


“Soft” to “Hard” ridge: Study “soft ridge” with varying p_T cut (already underway)

Is the ridge caused by jet-quenching ?

Study jet shapes in Δη (and Δφ), energy dependence (energy scan at RHIC)

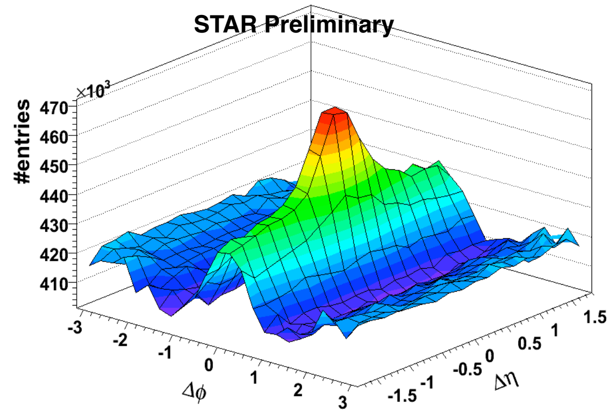


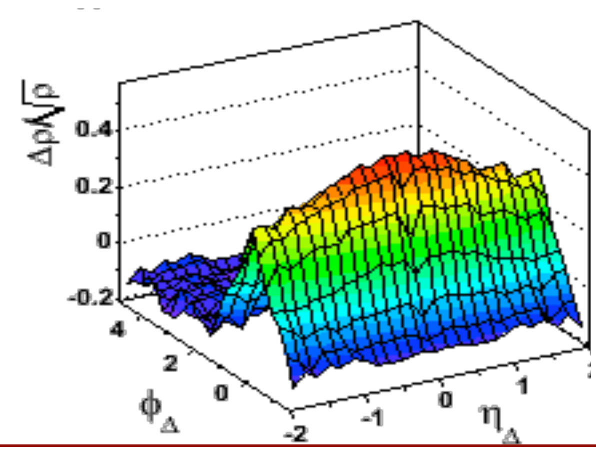


Is there really a Mach-Cone !?

Study di-hadron correlations (varying pT) in(out)-side a reconstructed jet

“Missing links”



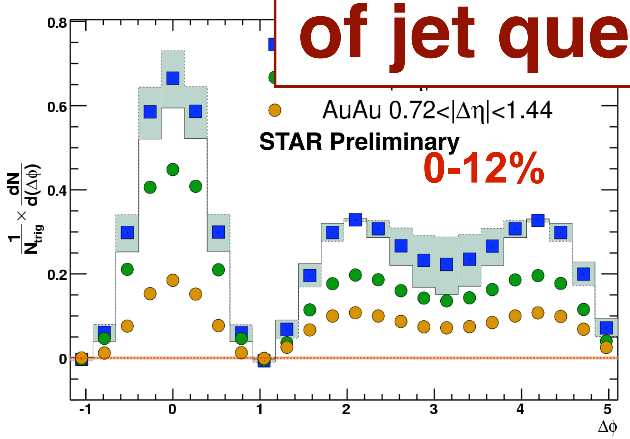


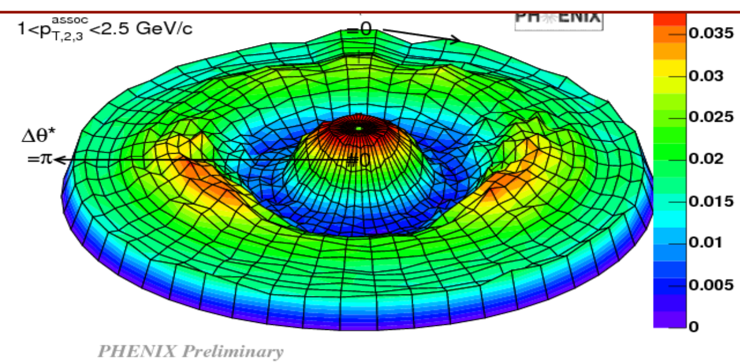
“Soft” to “H… …y underway)

Is the ridg…

Study jet s… …n at RHIC)

I think we have all the tools needed in order to come up with a coherent and consistent (quantitive) picture of jet quenching at RHIC.

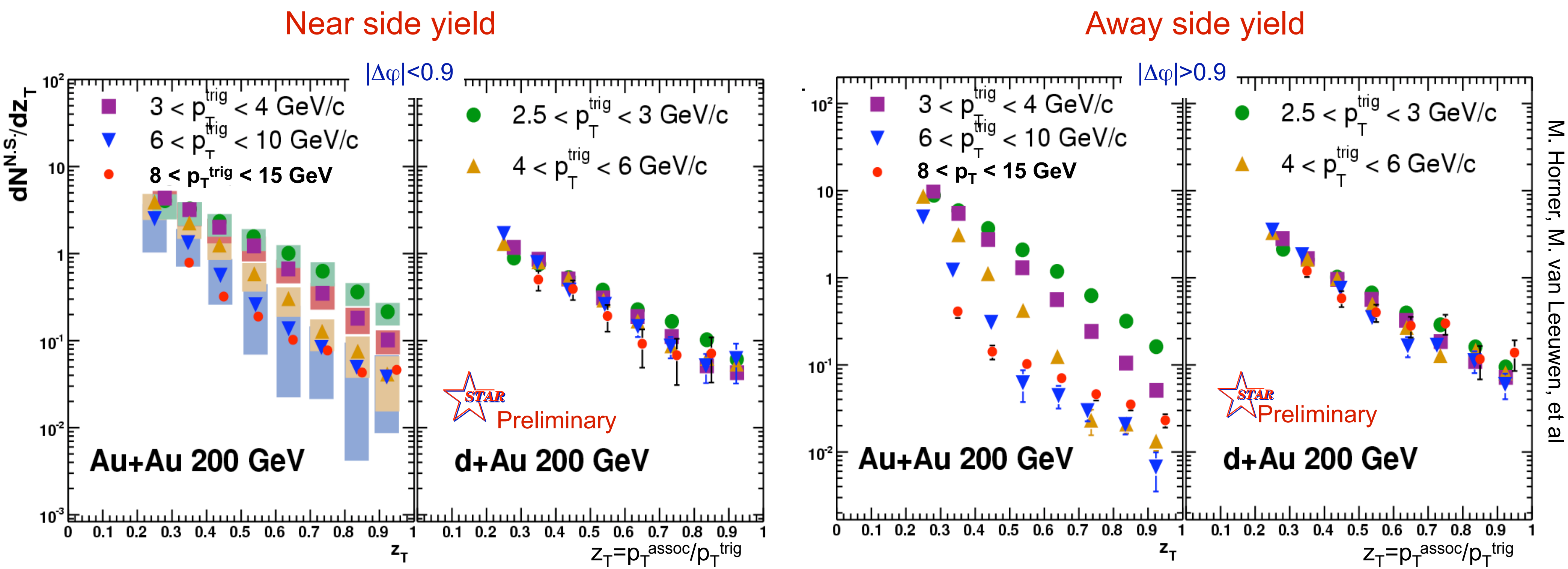




Is there really a Mach-Cone !?

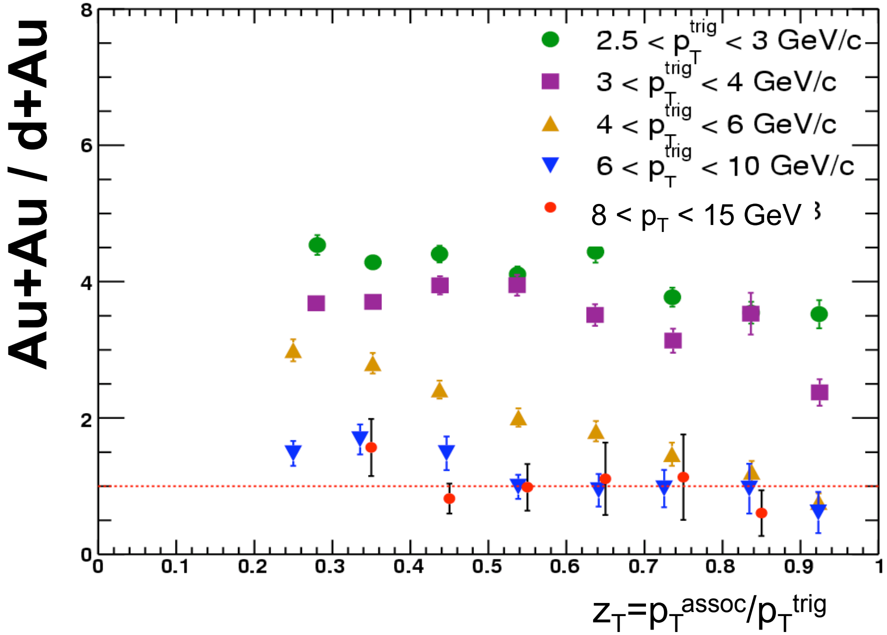
Study di-hadron correlations (varying pT) in(out)-side a reconstructed jet

Energy loss in action

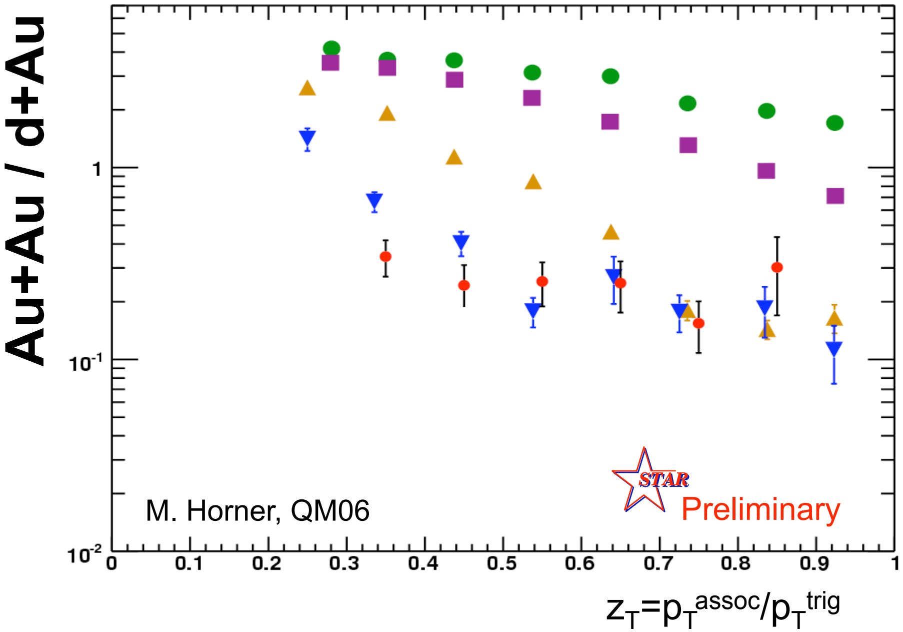


Energy loss in action

Near side yield ratio

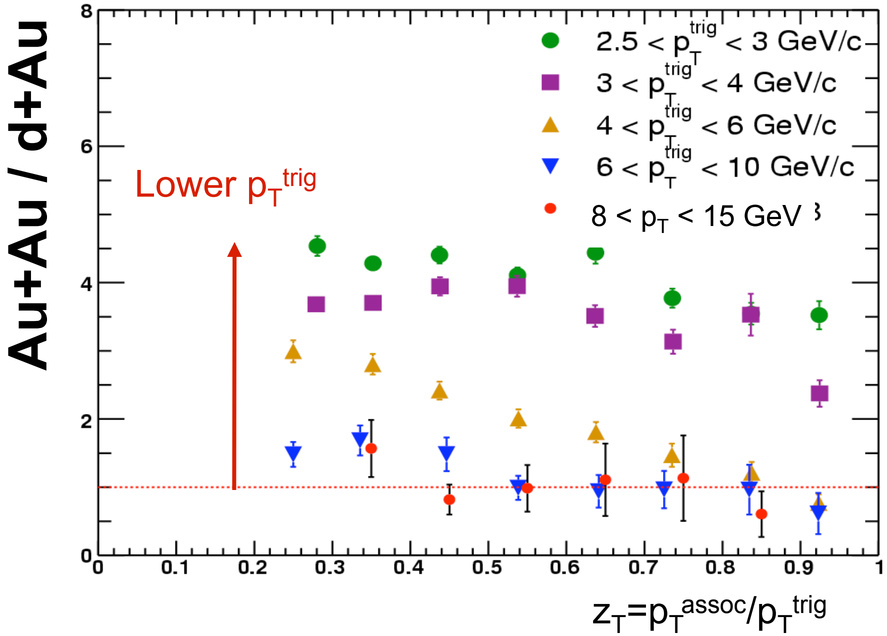


Away side yield ratio

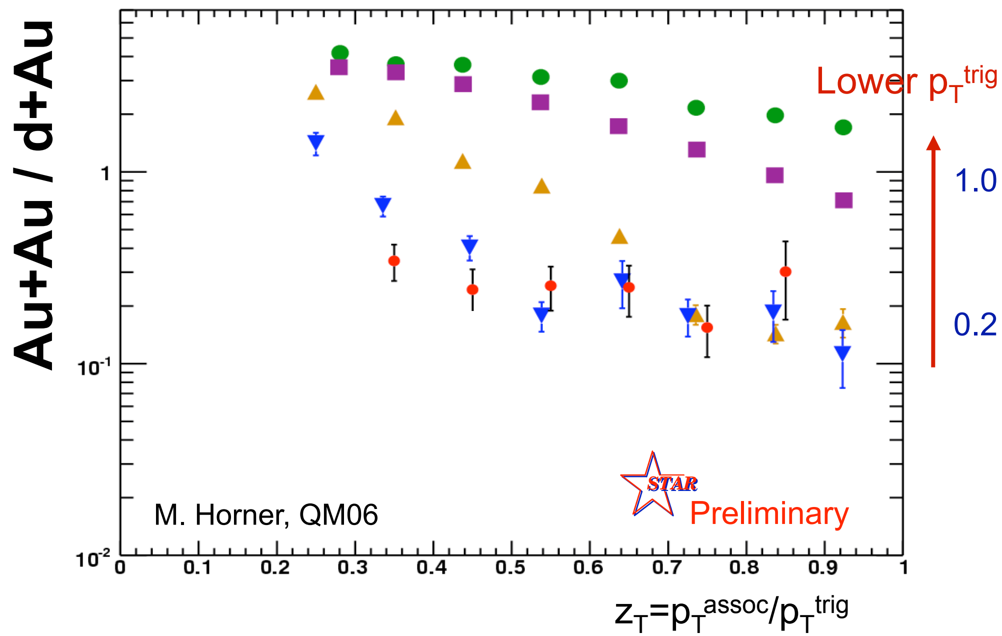


Energy loss in action

Near side yield ratio



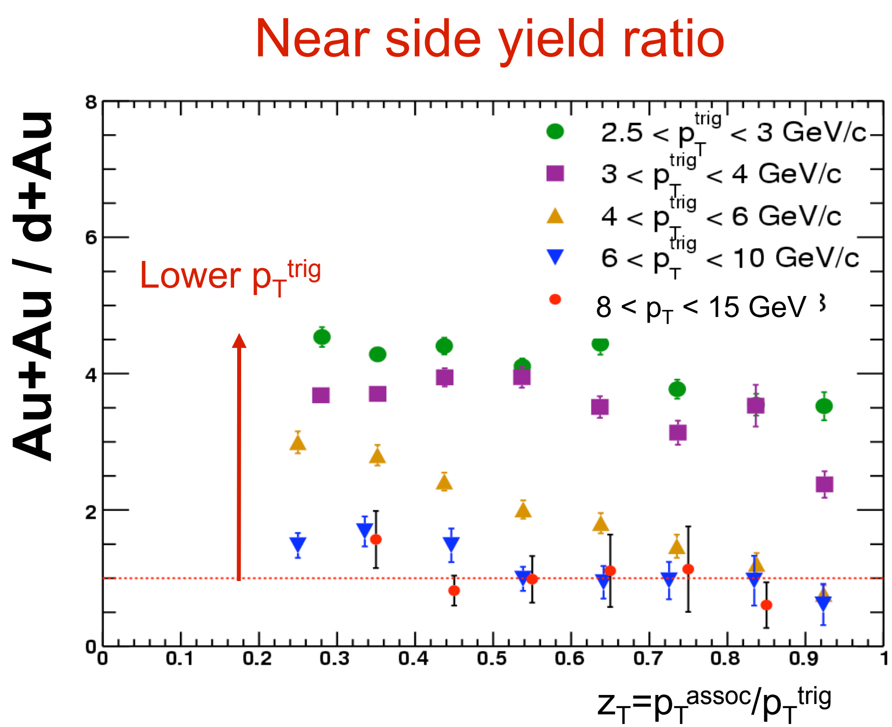
Away side yield ratio

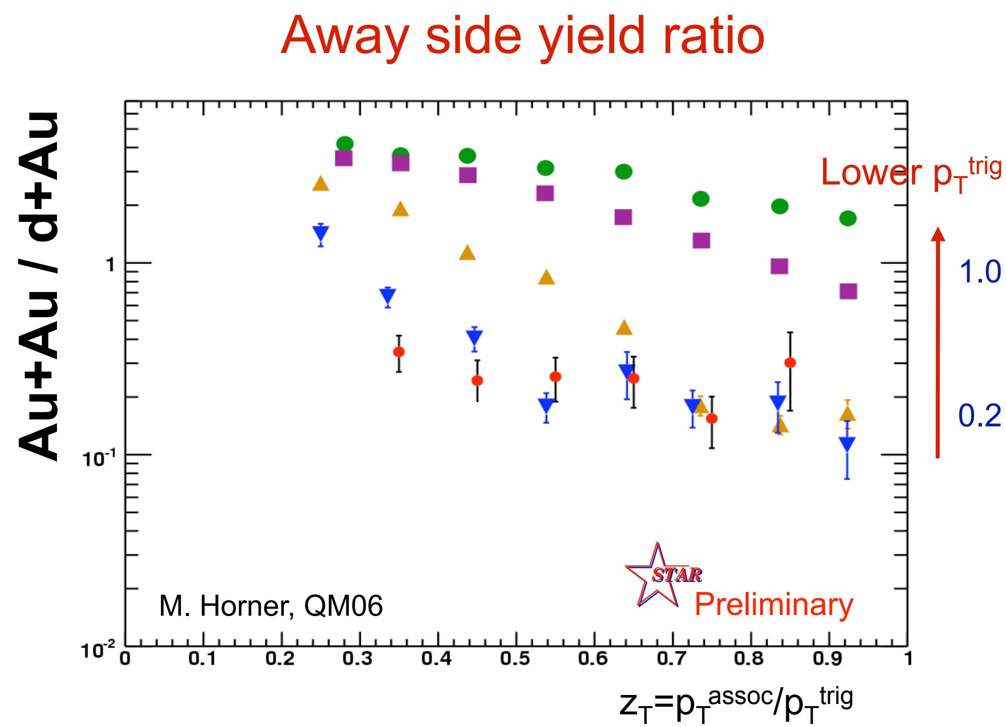


Near- and away-side show yield enhancement at low p_T

Away-side: gradual transition to suppression at higher p_T

Energy loss in action





Near- and away-side show yield enhancement at low p_T

Away-side: gradual transition to suppression at higher p_T

Possible interpretation:

di-jet → di-jet (lower Q^2) + gluon fragments

‘primordial process’

High-p_T fragments as in vacuum

Near side: ridge
Away-side: broadening

From long version ...

More specific: "Hard" = pQCD + factorization + universality

Hadron production cross-section in an AB collision where AB=pp,pA, AA is:

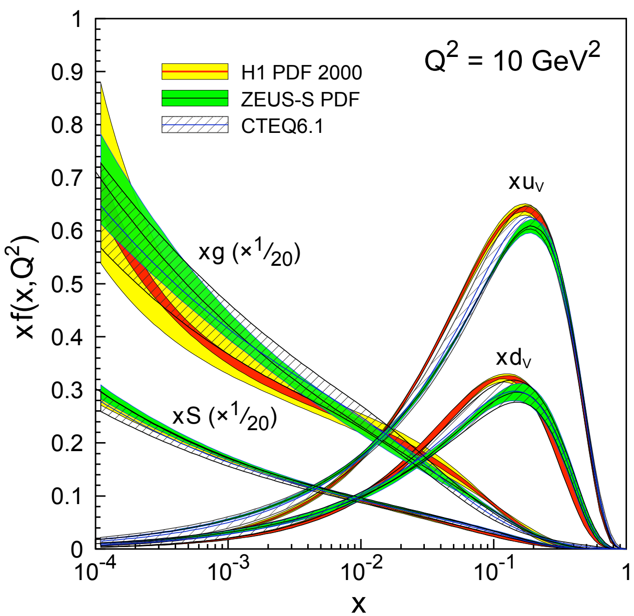
$$E\frac{d^3\sigma_h}{dp^3} \propto \sum_{a,b,c,d} \int dz_c dx_1 dx_2 \frac{s}{z_c^2} f_{i/A}(x_1,Q^2) f_{j/B}(x_2,Q^2)$$

$$D_{h/c}(z_c,Q^2) \frac{d\hat{\sigma}^{(ab\to cd)}}{dt} \delta(s+u+t) + \mathcal{O}\left(\frac{\Lambda}{m}\right)^p$$

Collins, Soper, Sterman, Nucl. Phys. B263 (1986) 37

Parton Distribution Functions

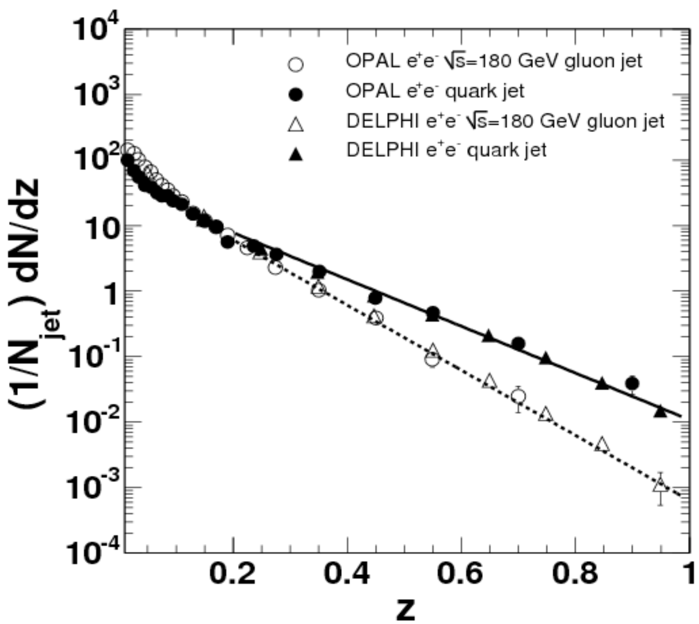
Flux of incoming partons (structure functions) from Deep Inelastic Scattering



Fragmentation Functions

D(z) in order to relate jets to observed hadrons

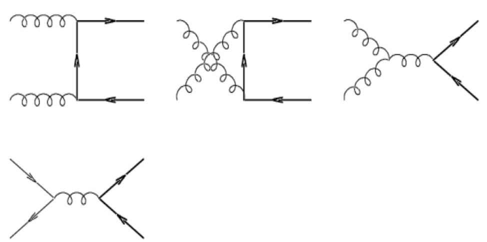
$z=E_{Hadron}/E_{Parton}$



Perturbative QCD (pQCD)

$d\sigma/dt$ = hard partonic cross section calculable in QCD in powers of α_s^{2+n}

- n=0: leading order (LO)
- n=1: next-to-leading order (NLO)



Outline

(Short) Introduction

- What do we want to measure?
- And how can one measure it?

Jet-quenching at RHIC

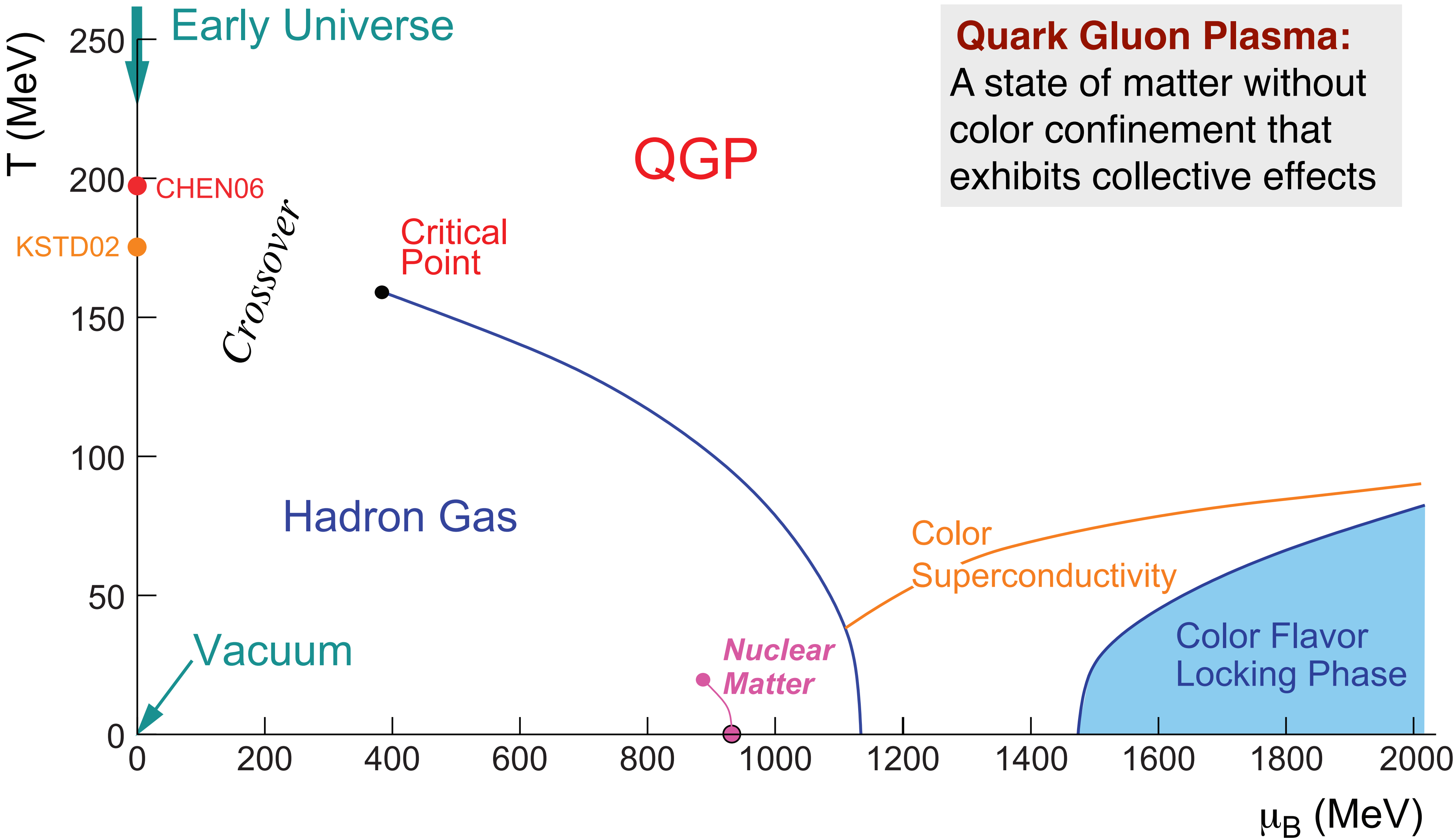
- Jet-quenching 101
- The rocky path towards full-jet reconstruction and *surprises* along that way ...
- Connecting the dots (?): Jet-Hadron correlations
- Discussion/Interpretation

Jet quenching at the LHC with ALICE

- Advantages / applying the lessons learned at RHIC

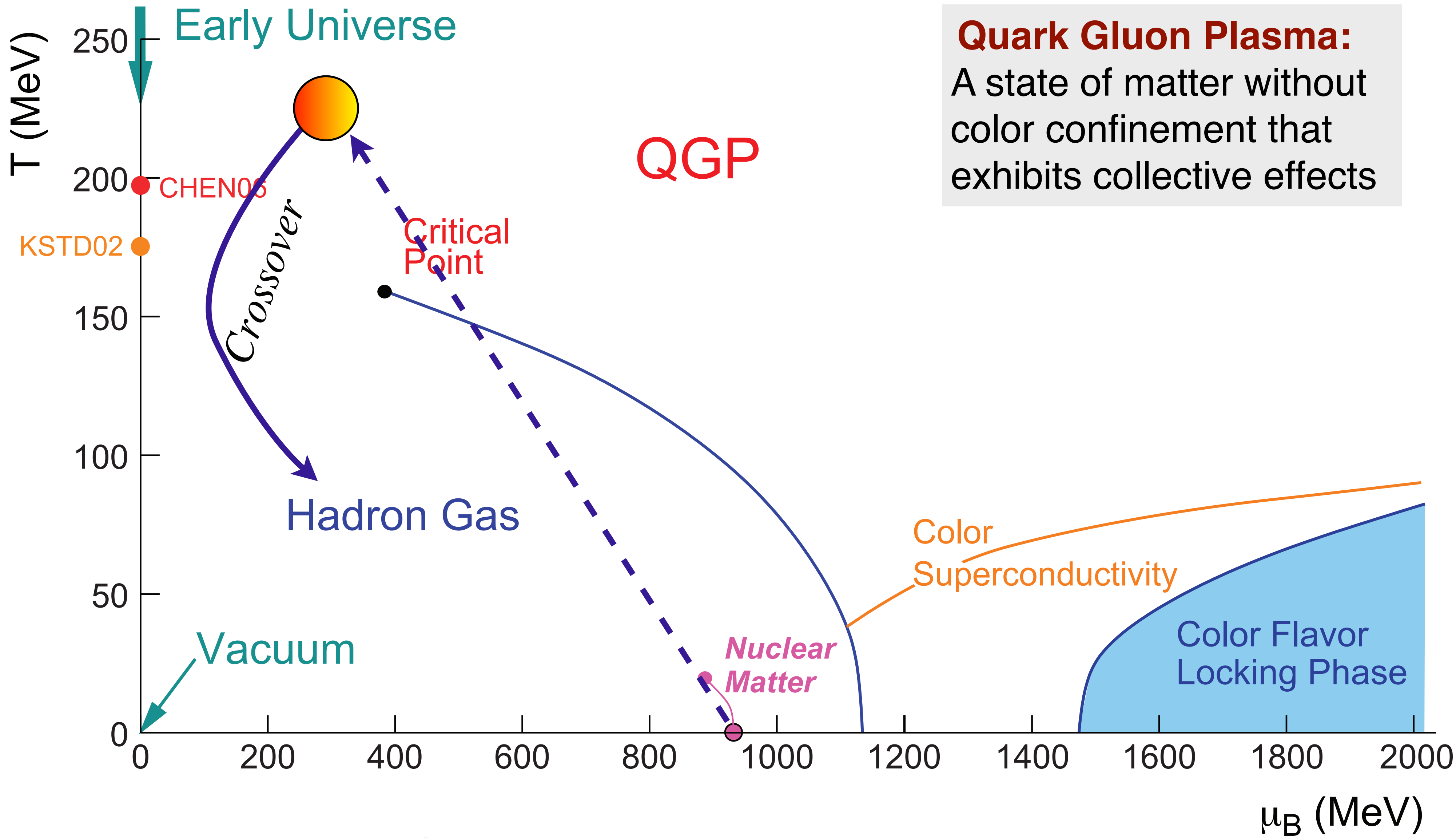
Summary and discussion

The Phases of QCD: Creating the Quark Gluon Plasma (QGP)



Quark Gluon Plasma:
A state of matter without color confinement that exhibits collective effects

The Phases of QCD: Creating the Quark Gluon Plasma (QGP)



Quark Gluon Plasma: A state of matter without color confinement that exhibits collective effects

Basic Idea: *Smash* heavy nuclei at highest possible energy ⇒ create conditions (*hot* and *dense*) sufficient to "melt" matter into a QGP (the state of all matter ~6 μs after the Big Bang)

Jet definition ⇔ Jet algorithm

The construction of a jet is *unavoidably ambiguous*.
On at least two fronts:

- which particles get put together into a common jet?
- How do you combine their momenta?

Jet definition ⇔ Jet algorithm

The construction of a jet is *unavoidably ambiguous*

On a

- wh
- He

Jet Definition

$\{p_i\}$ $\xrightarrow{\text{jet algorithm}}$ $\{j_k\}$

particles
4-momenta,
calorimeter towers

jets

+ parameters (at least the cone radius/resolution parameter R)

+ recombination scheme

Jet definition ⇔ Jet algorithm

The construction of a jet is *unavoidably ambiguous*.
On at least two fronts:

- which particles get put together into a common jet?
- How do you combine their momenta?

Modern Jet Finder Algorithms	
Sequential Recombination	**Cone**
• **bottom-up** • **successively undoes QCD branching**	• **top-down** • **centred around idea of an 'invariant', directed energy flow**
▸ **k_T algorithm** ▸ **anti-k_T algorithm** ▸ **Cambidge-Aachen algorithm**	▸ **CDF JetClu** ▸ **CDF MidPoint** ▸ **D0 (run II) Cone** ▸ **PxCone** ▸ **CMS Iterative Cone** ▸ ATLAS Cone ▸ PyCell/CellJet ▸ GetJet ▸ SISCone

Further conditions a jet algorithm has to fulfill ...

Snowmass Accord (1990):

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

Recent Additions (> 2000):

– Physical results independent of your choice of jet definition

– Jets should be invariant with respect to certain modifications of the event:

- collinear splitting
- infrared emission

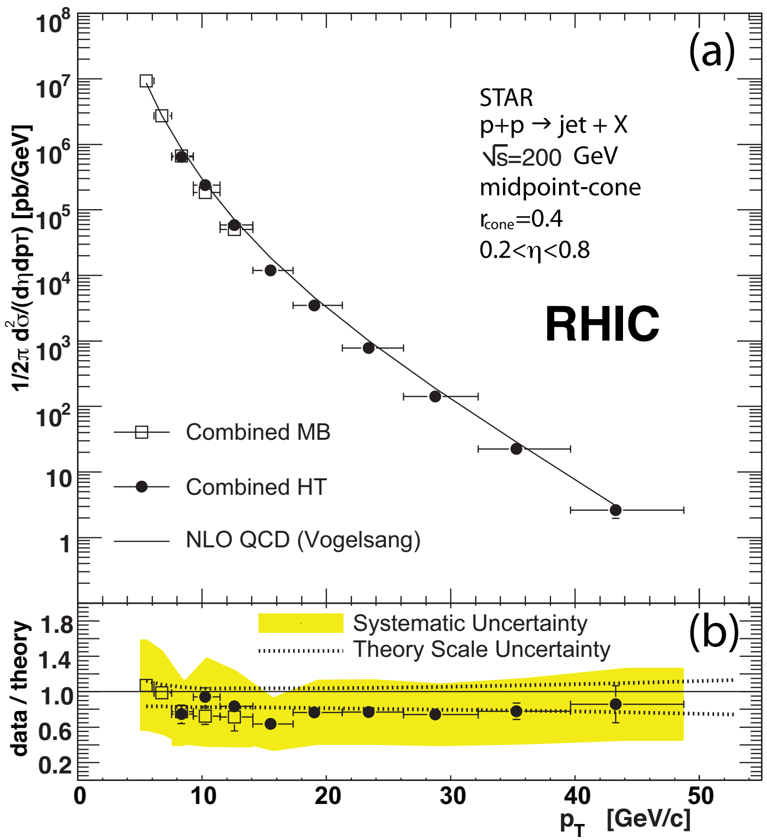
⇒ **Known as infrared and collinear safety**

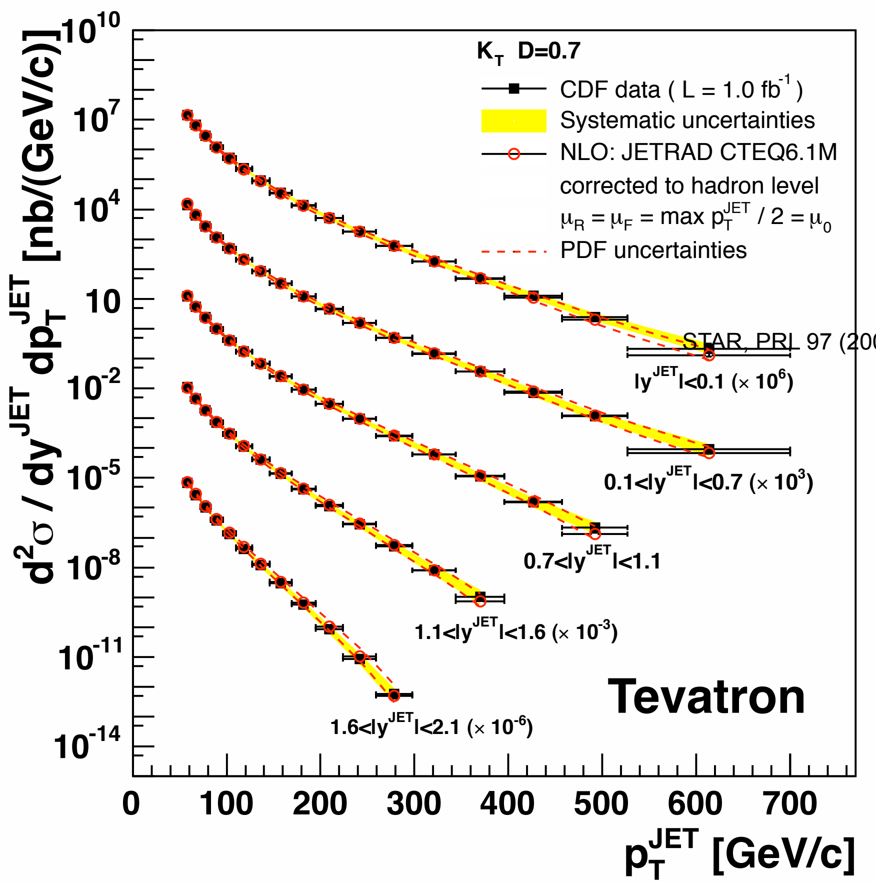
This reduces the list of potential jet-finding algorithms to:

- k_T/Anti-k_T (recombination algorithms)
- SISCone (infrared, seedless cone algroithm)

all part of the FastJet package: *M. Cacciari, G.P. Salam, G. Soyez, JHEP 04, 005 (2008), 0802.1188*

In short: The probe is calibrated !



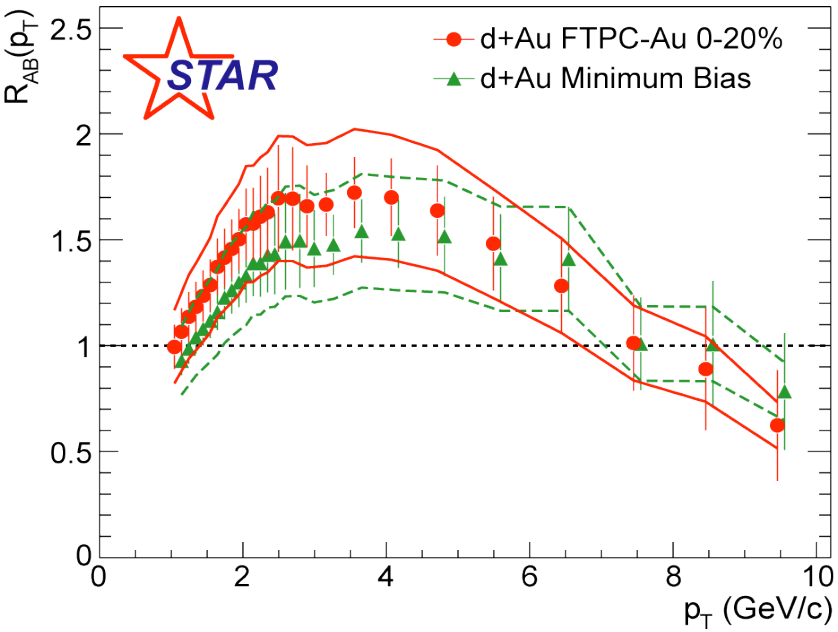


Jet x-section: data and theory/pQCD agree over many orders of magnitude ⇔ probe of underlying interaction

Many more measurements available which show the success of pQCD ...

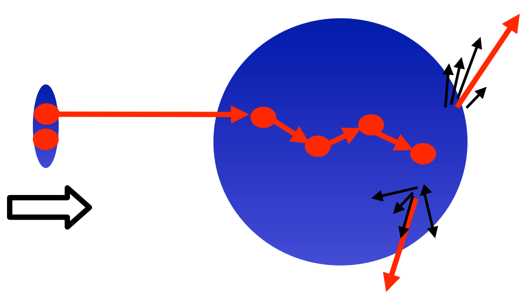
Initial state/CNM effects at mid-rapidity

Phys.Rev.Lett.91:072304 (2003)



$$R_{dAu}(p_T) = \frac{dN^{dAu}/dp_T d\eta}{\underbrace{T_{dAu}}_{\langle N_{coll} \rangle} d\sigma^{pp}/dp_T d\eta}$$

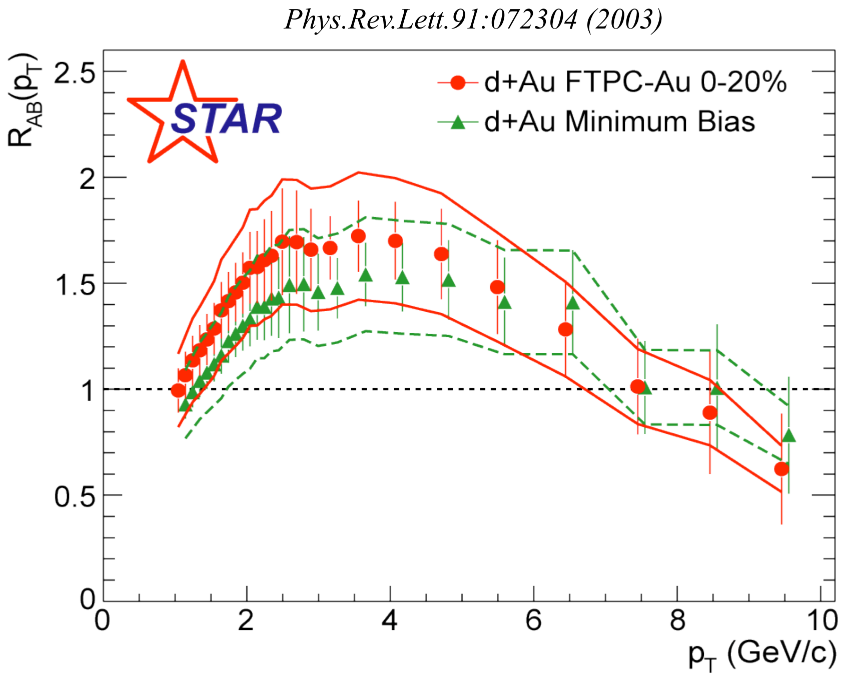
Final state CNM effect, $R_{dAu} > 1$

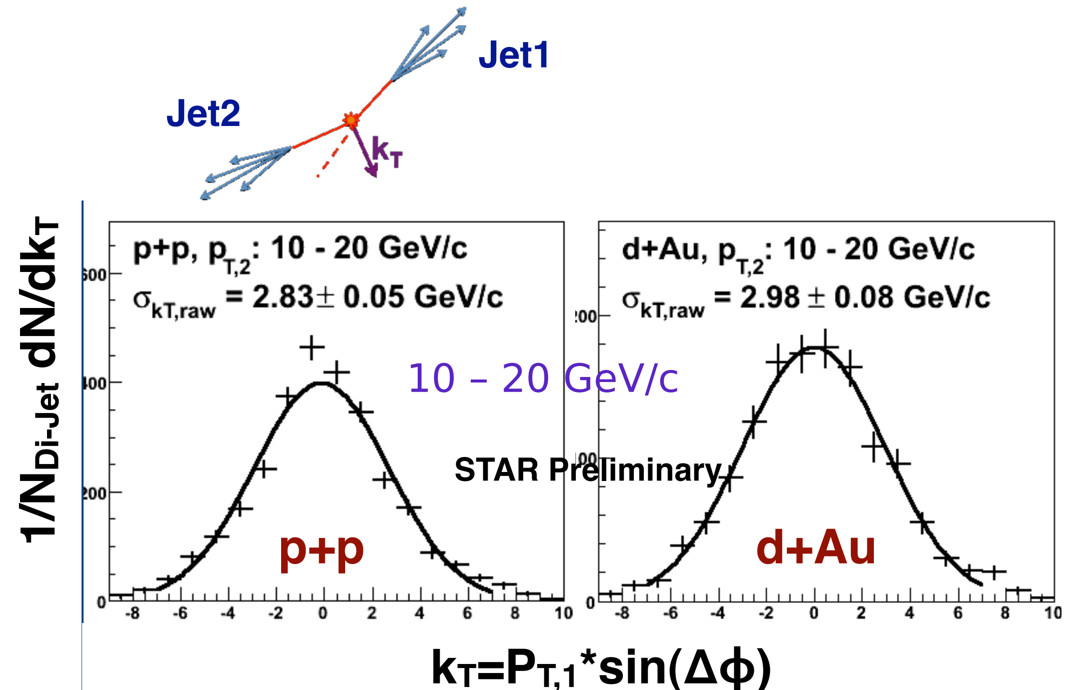


Initial state effect, $R_{dAu} < 1$

Nuclear modification factor R_{dAu}:
Small final state effect “Cronin enhancement” at intermediate p_T; At high-p_T collision scaling N_{coll}, as expected from pQCD processes.

Initial state/CNM effects at mid-rapidity





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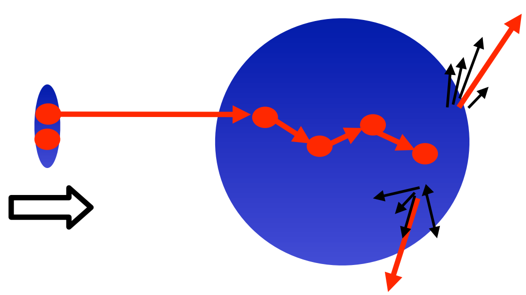

Initial state effect, $R_{dAu} < 1$

Nuclear modification factor R_{dAu}:
Small final state effect "Cronin enhancement" at intermediate p_T; At high-p_T collision scaling N_{coll}, as expected from pQCD processes.

No significant cold nuclear effect on k_T broadening in di-jets observed (also in jet-like yields)

⇒ **Initial state and CNM effects are small/ well known at mid-rapidity at RHIC!** ✓

Probing Dense Matter

Calibrated probe (high-p_T partons instead of X-rays)

Calibrated interaction (beam of known energy and direction, geometry)

Calibrated/measured initial state and CNM effects

Probing Dense Matter

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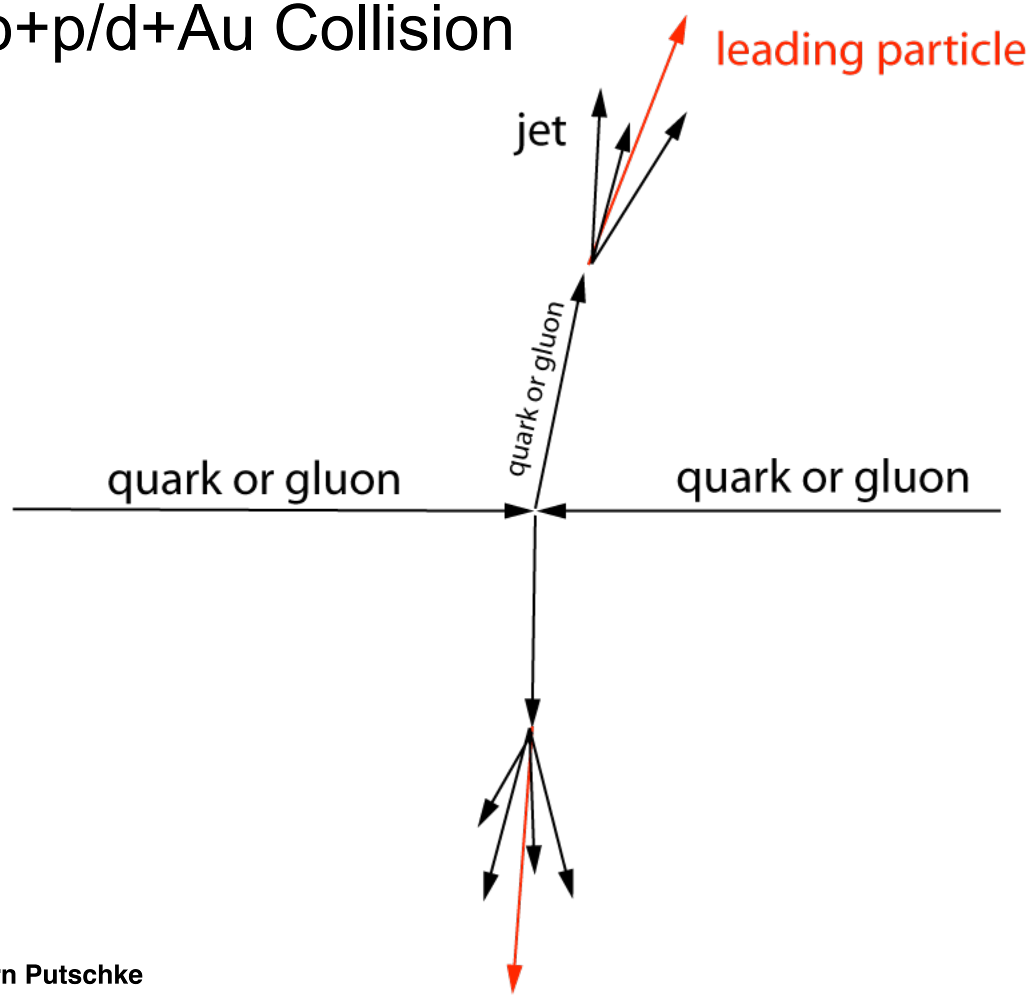
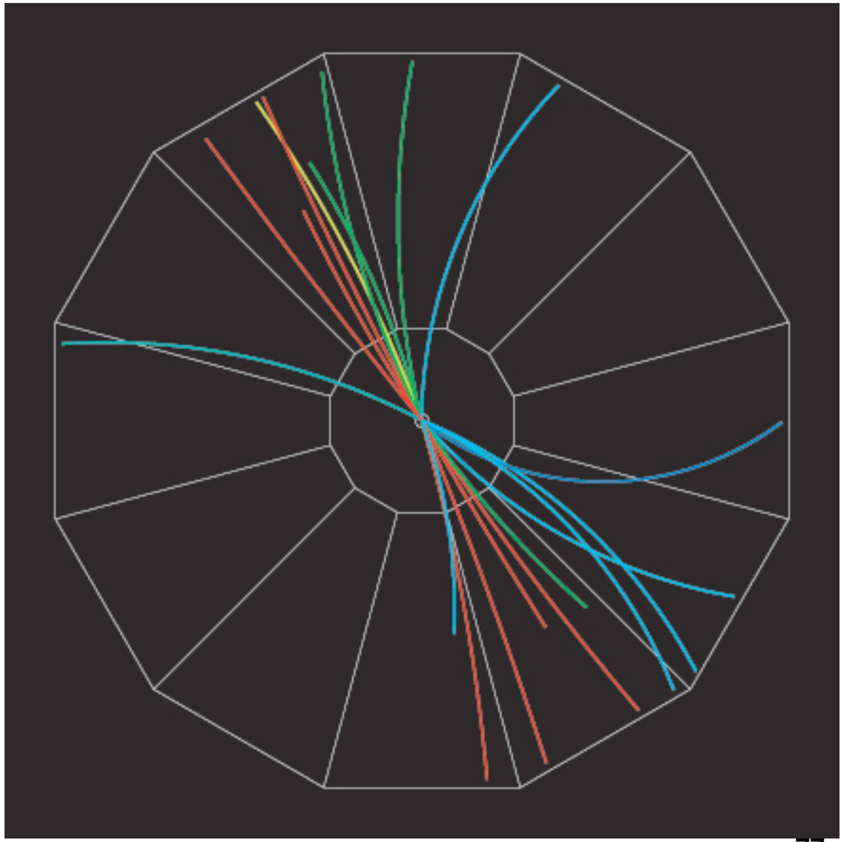
p+p/d+Au Collision



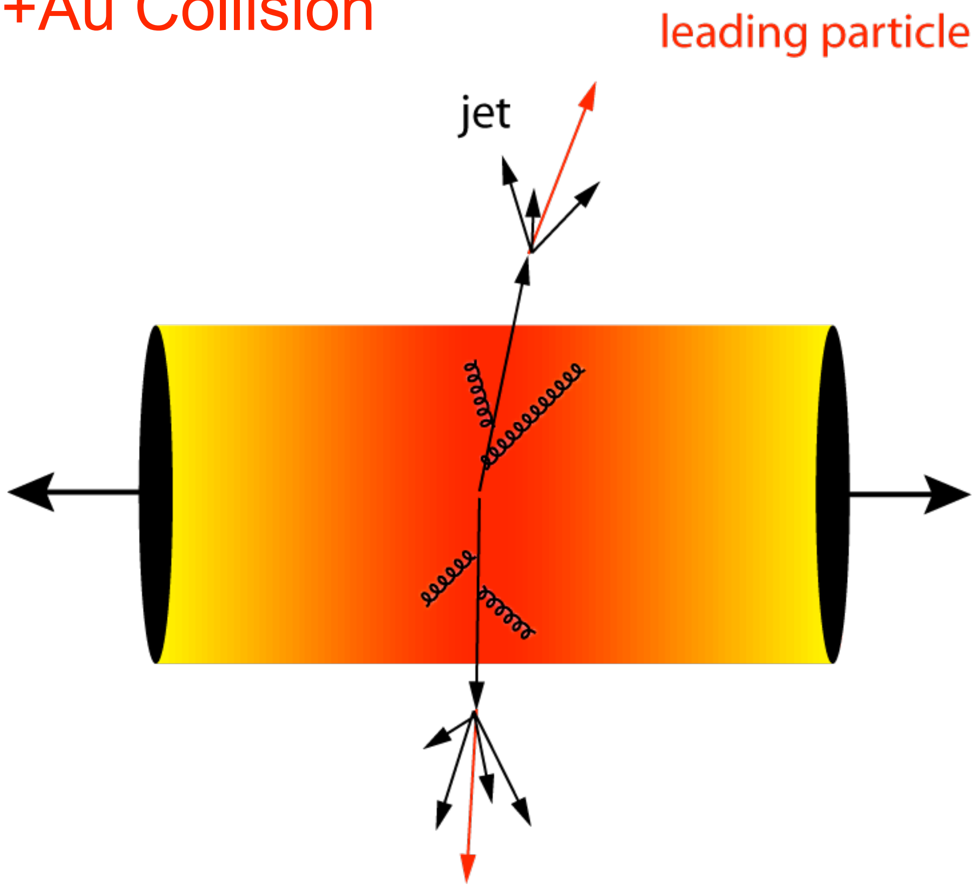


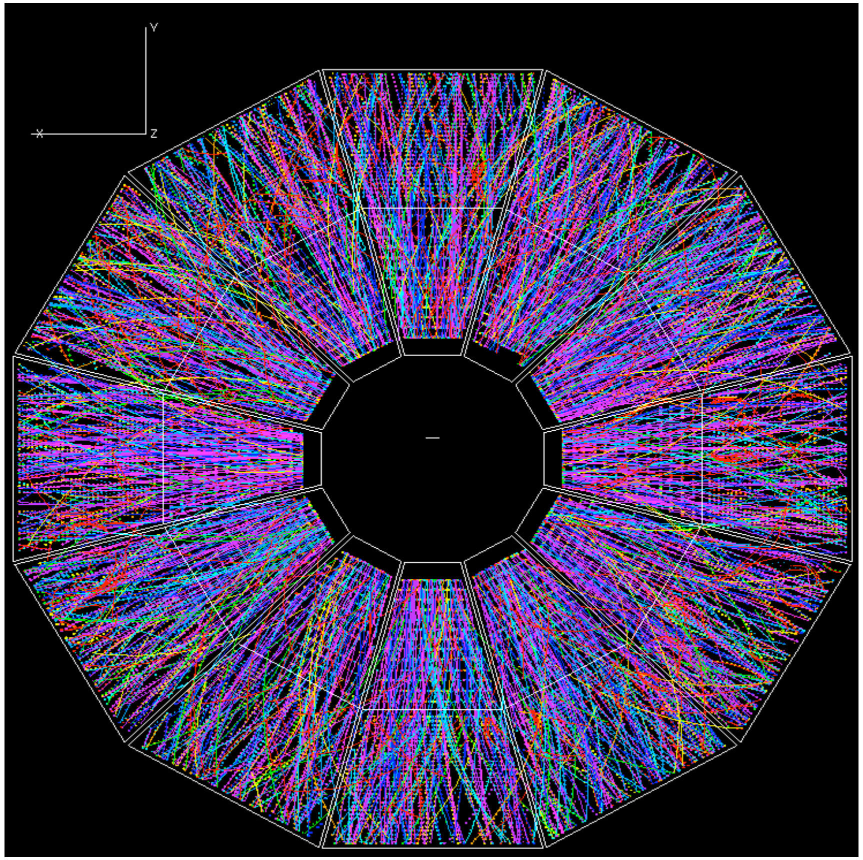
Probing Dense Matter

Calibrated probe (high-p_T partons instead of X-rays)
Calibrated interaction (beam of known energy and direction, geometry)
Calibrated/measured initial state and CNM effects

⇒ All modifications in the jet structure are due to interactions with the medium!

Au+Au Collision



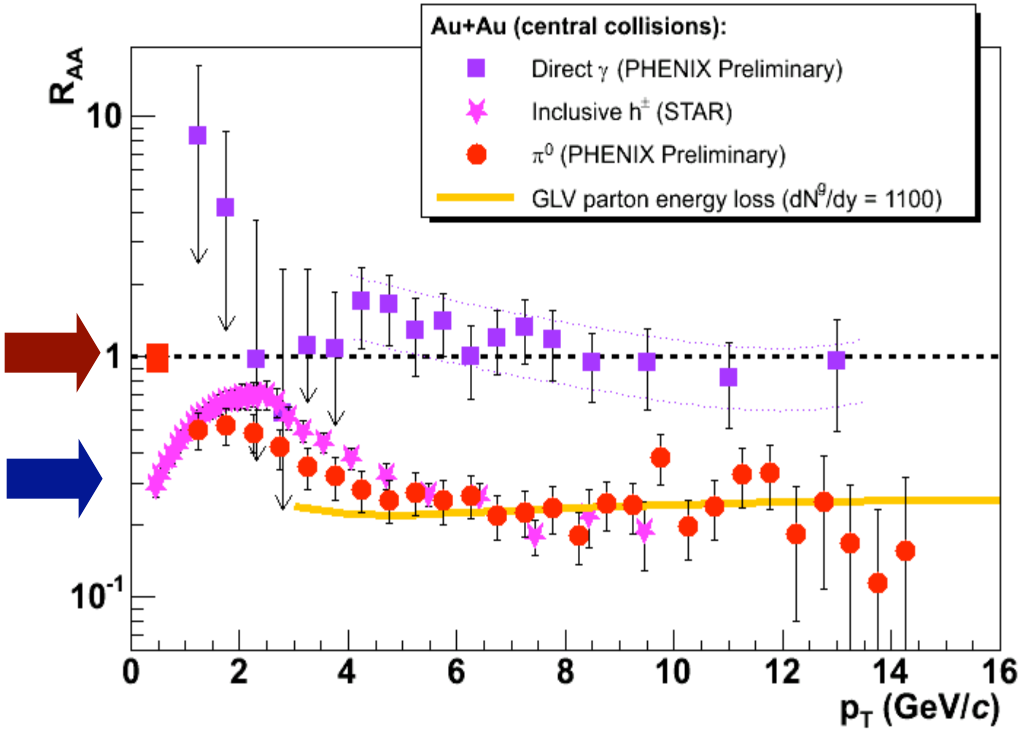


Jet-quenching 101: High-p_T hadron production

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

<u>Expectation for hard (pQCD) processes:</u>

R_{AA}=1 ⇔ N_{coll} scaling



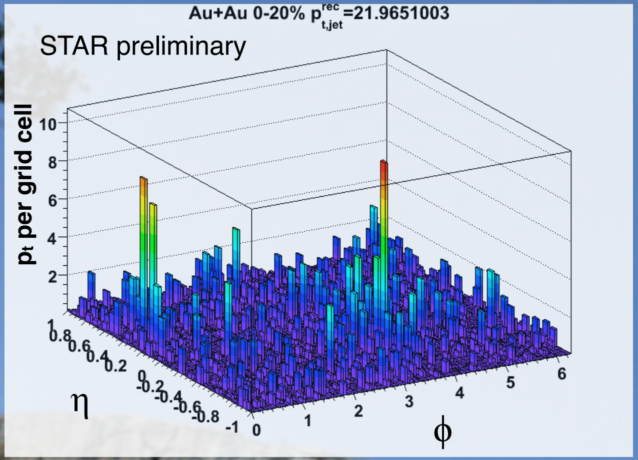
(I) Direct (colorless) photons are not suppressed - N_{coll} scaling works

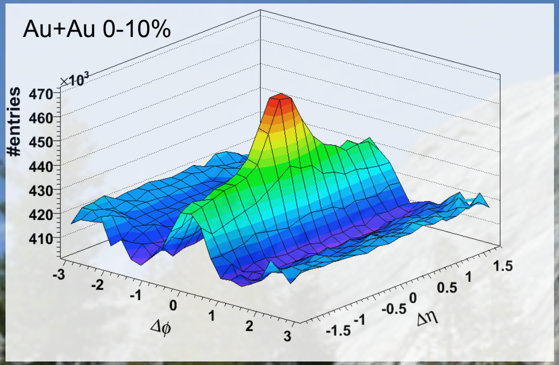
(II) Hadrons (colored) are suppressed in central heavy-ion collisions by a (huge) factor of 5

(III) Hadrons are not suppressed in peripheral collisions; less dense medium created

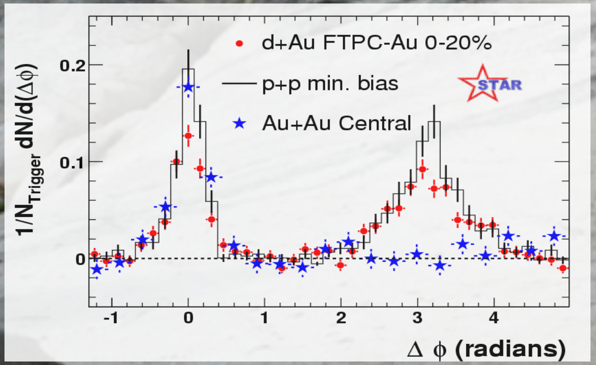
sQGP - strongly coupled - colored objects suffer *significant energy loss**

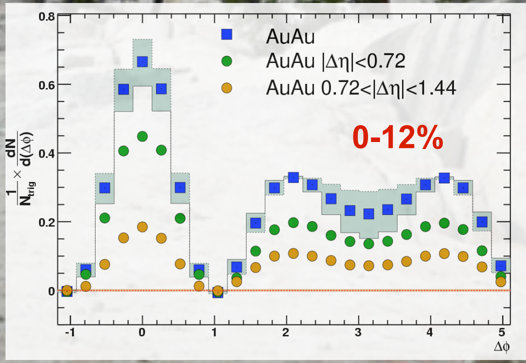
* <u>Side-remark:</u> Large suppression in ratio of yields on steeply falling spectra ≠ *"large"* energy loss!





Ridges!

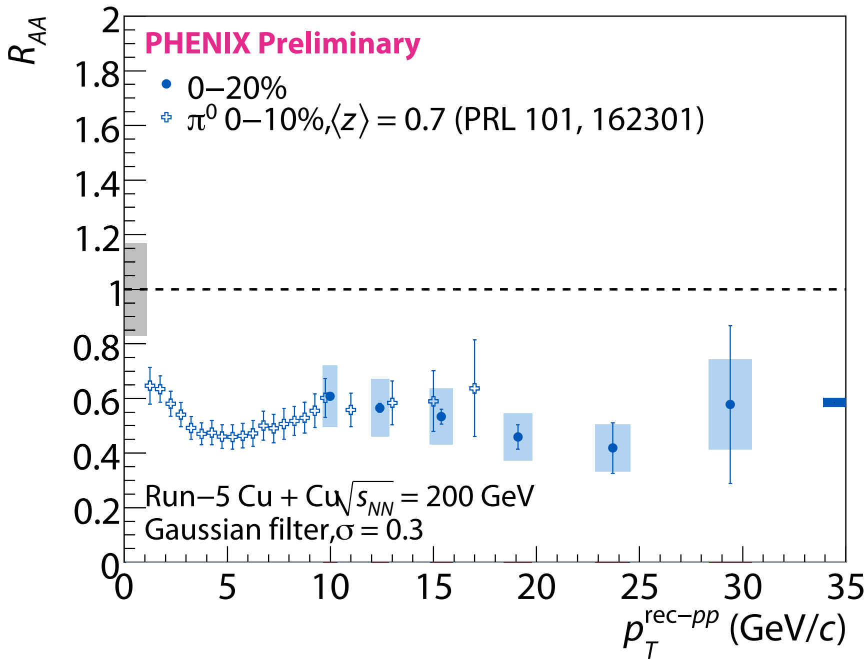




Mach Cones!?

The rocky path towards full-jet reconstruction and some surprises on the way ...

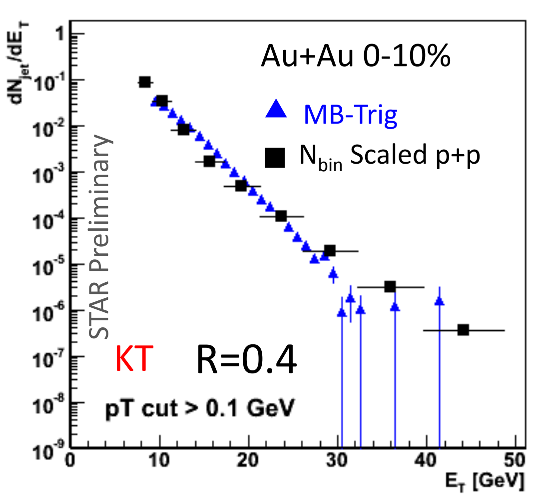
Full jet reconstruction: (Hard) Lesson from RHIC

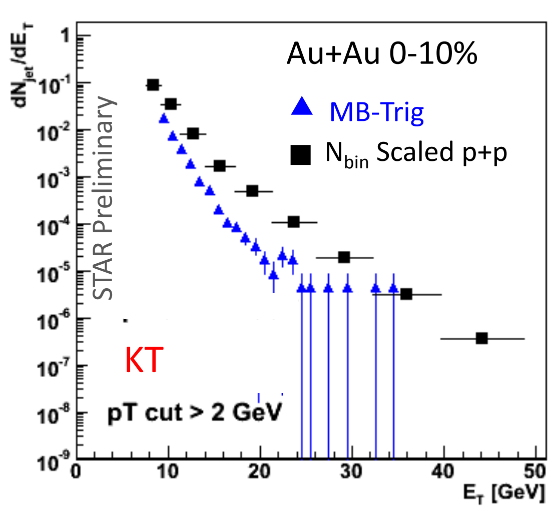


"A jet is what you ask for!"

Phenix for example:
Using a jet-finding algorithms based on unmodified jet-shapes vetos against the modified jets one want to study!

Using a p_T cut to minimize background contributions biases the jet population towards less/non-interacting jets!



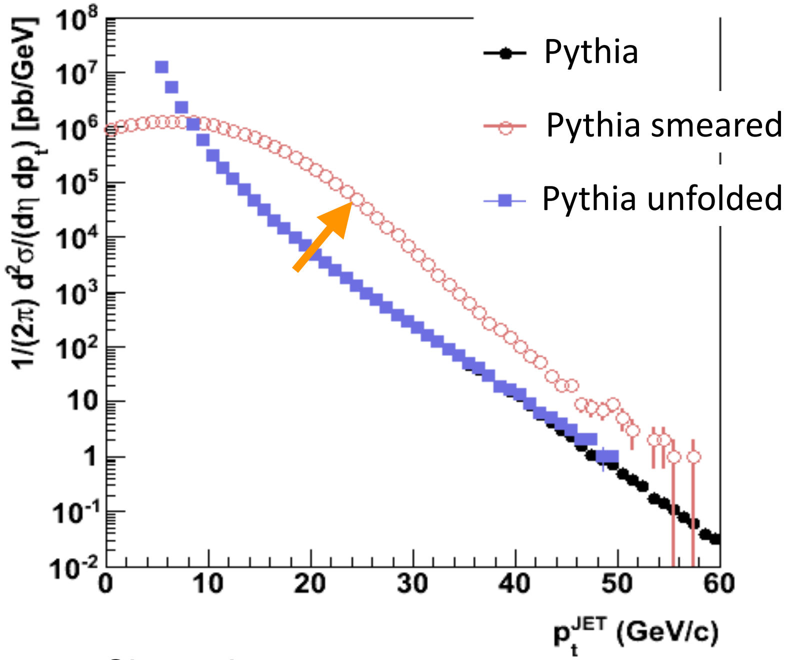


"Anti-quenching" biases are "everywhere"!

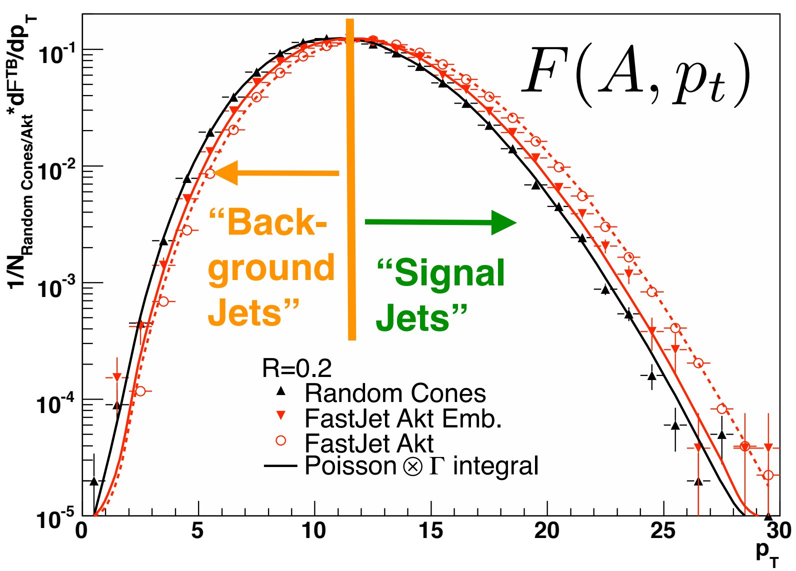
There are no shortcuts! We have to deal with the full heavy-ion background problematic!

BUT: The tools are available!

As an example: Focus on background fluctuations



Simulation



Jet spectrum in Au+Au (schematically):

$$\frac{d\sigma_{AA}}{dp_t} = \frac{d\sigma_{pp}}{dp_t} \otimes F(A, p_t)$$

The effect of background fluctuations (gaussian approximation) $F(A,p_t)$ in heavy-ion collisions is a **substantial "feed-up"** in the jet x-section, due to the steeply falling underlying partonic spectrum.

Conceptually $F(A,p_t)$ for statistically independent particle emission:

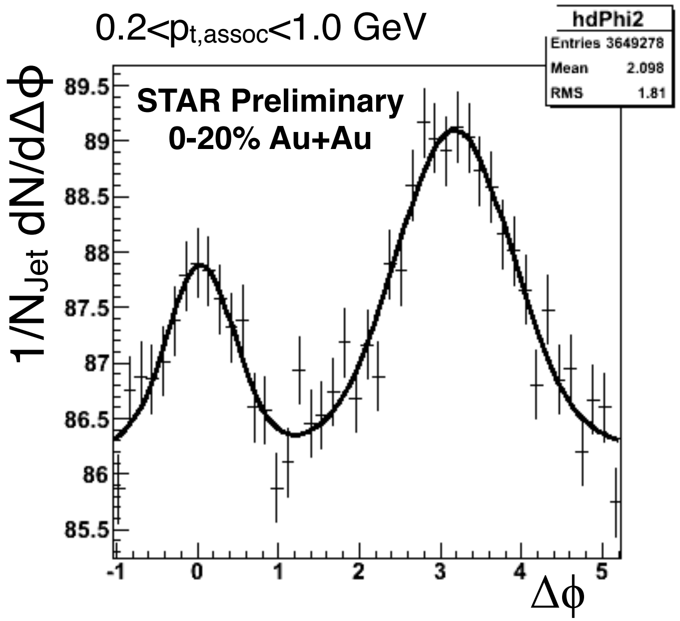
$$F(A, p_t) = Poisson((M(A)) \otimes \Gamma(M(A), \langle p_t \rangle)$$

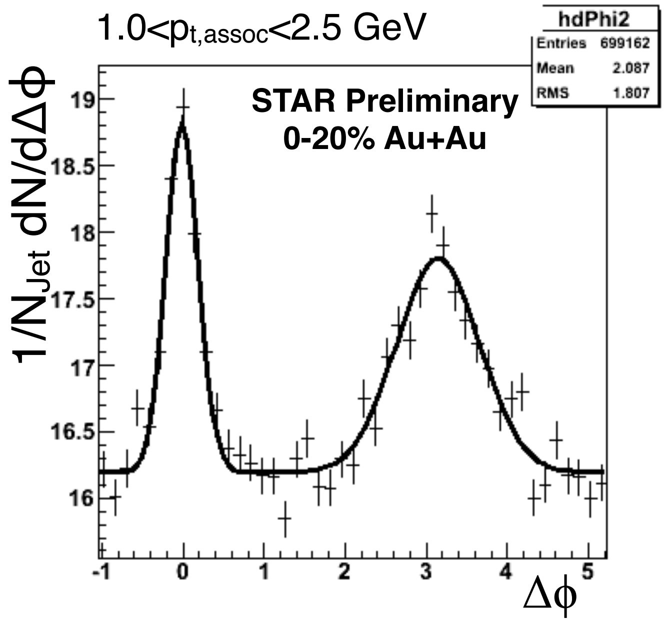
$F(A,p_t)$ can be measured in data using "background jets": p_t-ρ A < 0 and/or by utilizing the "spectrum" at 90deg. wrt to a di-jet (modulo corrections for 2nd hard scattering)

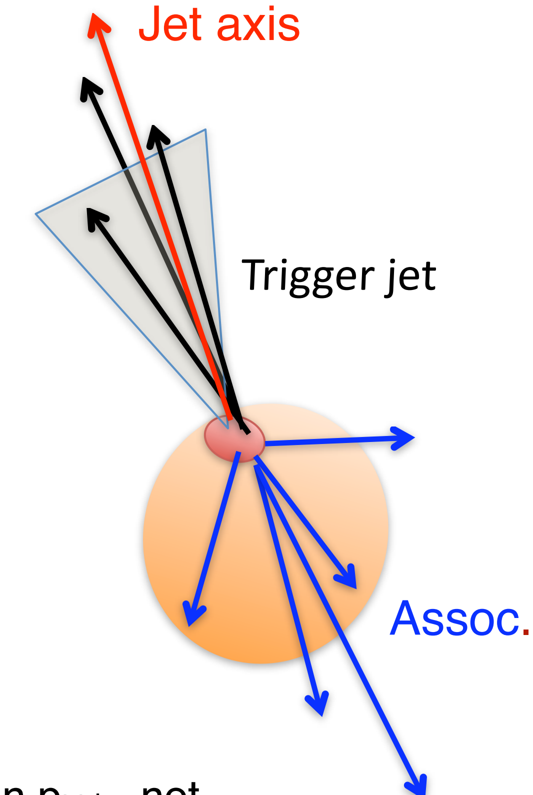
Non trivial issue, further studies actively being pursued, but we have all the tools!

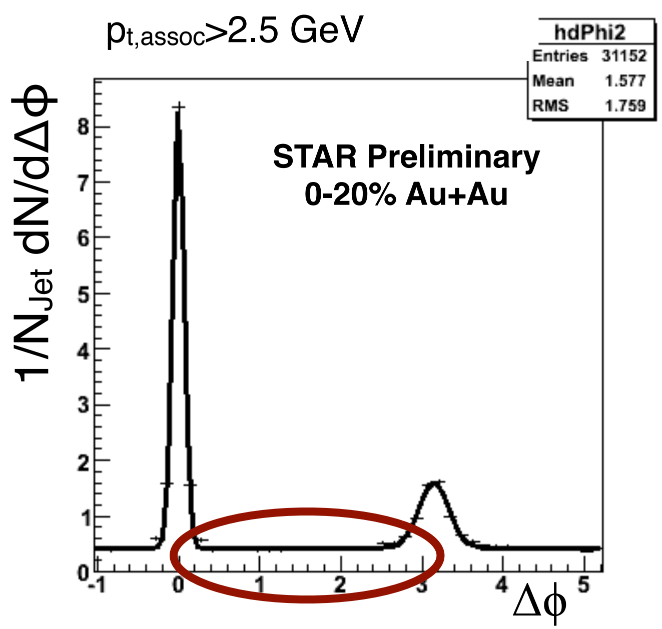
Connecting the dots ... Jet-Hadron correlations

High Tower Trigger (HT): tower 0.05x0.05 (ηxϕ) with E_t> 5.4 GeV









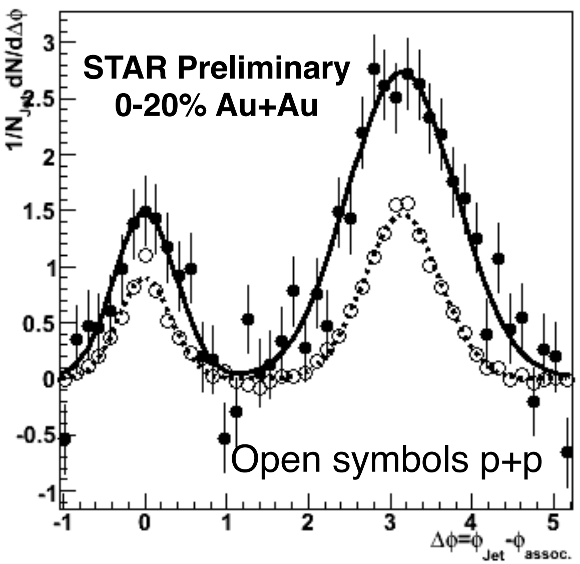
$\Delta\phi = \phi_{Jet} - \phi_{Assoc.}$

In general: $\phi_{Trig} \neq \phi_{Jet}$ and depending on $p_{t,trig}$, not necessary every trigger particle has to come from a jet! Jet-hadron correlations cleaner interpretable in terms of jet-quenching.

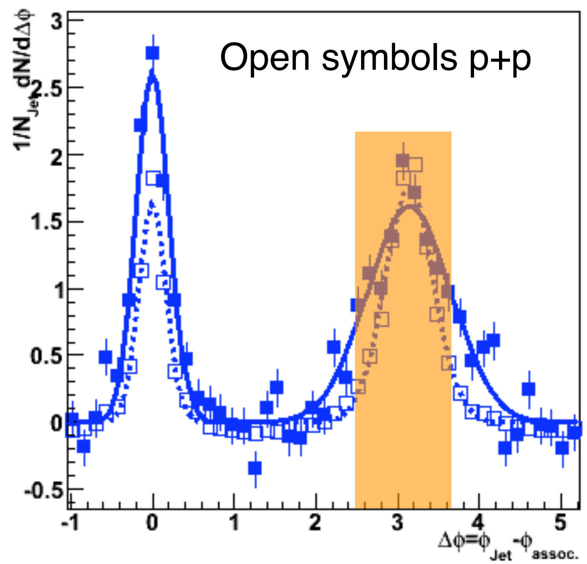
Connecting the dots ... Jet-Hadron correlations

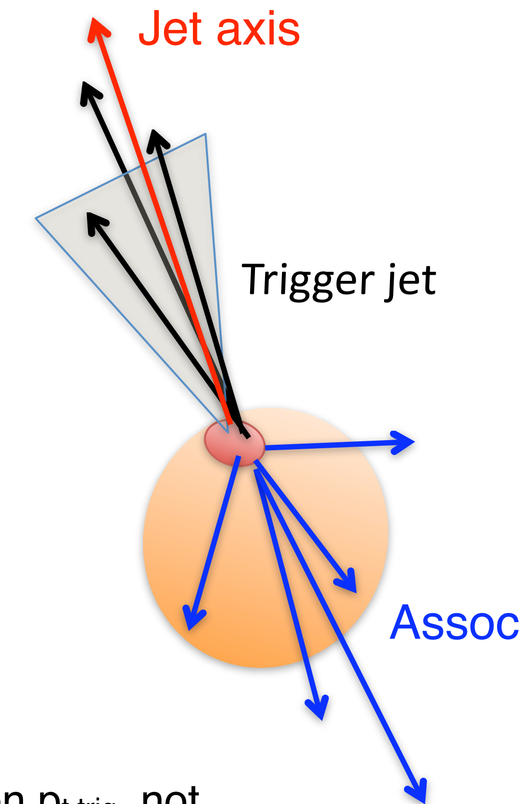
High Tower Trigger (HT): tower 0.05x0.05 (ηxϕ) with E_t> 5.4 GeV

$0.2<p_{t,assoc}<1.0$ GeV

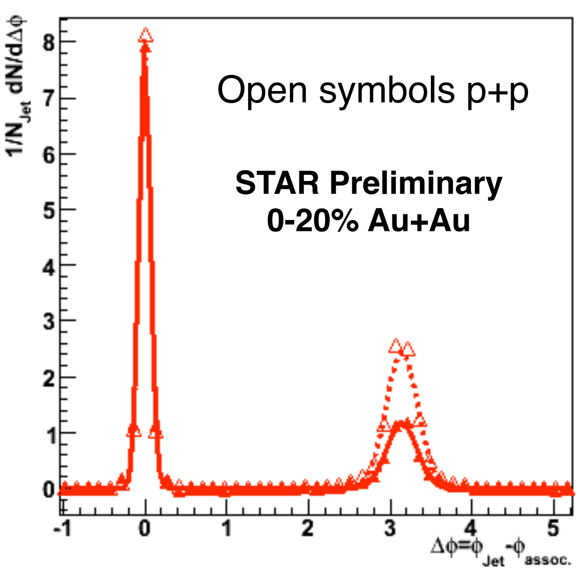


$1.0<p_{t,assoc}<2.5$ GeV





$p_{t,assoc}>2.5$ GeV



$\Delta\phi=\phi_{Jet}-\phi_{Assoc.}$

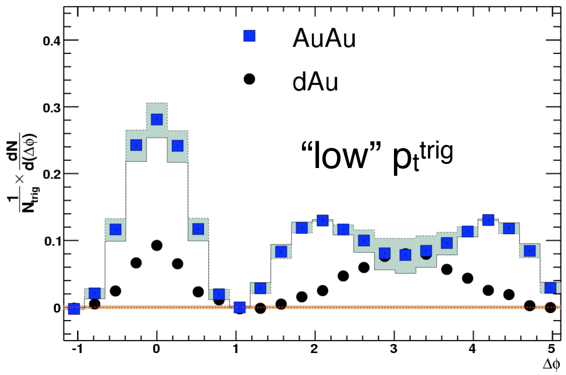
<u>In general:</u> $\phi_{Trig}\neq\phi_{Jet}$ and depending on $p_{t,trig}$, not necessary every trigger particle has to come from a jet! Jet-hadron correlations cleaner interpretable in terms of jet-quenching.

Extended kinematical reach!

Significant broadening and softening visible on the recoil side!

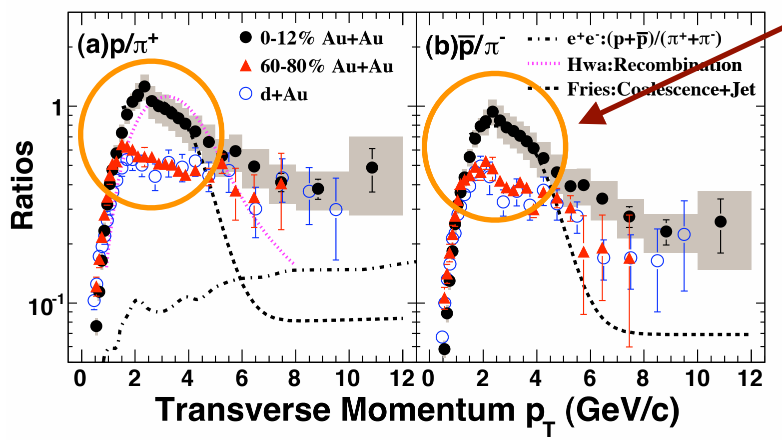
<u>Caveat:</u> "Jet v_2" contribution in background subtraction under investigation

Di-hadron correlations: Lesson from RHIC



High p_t^{trig}: geometric biases; limited sensitivity to partonic energy loss mechanisms

Lower p_t^{trig}: Possible Mach-Cones and near-side Ridge (Δη matters!)



BUT: Not every trigger part of a jet; recombination/coalescence!?
⇒ Interpretations in terms of "jet" physics complicated!

Also ambiguities in "jet" vs. background/hydrodynamical flow!

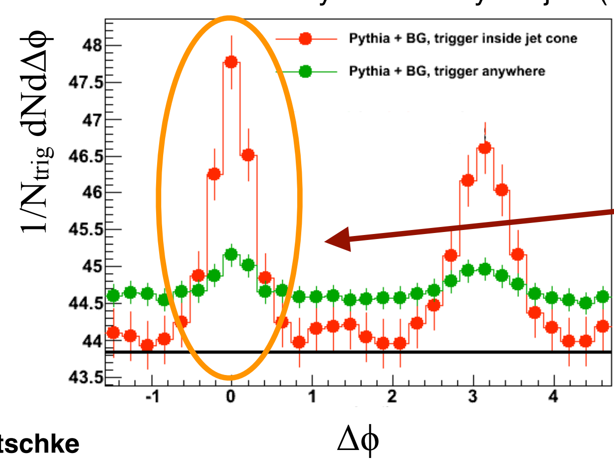
Example: Thermal toy model + Pythia jets (no v_2):

$$\frac{1}{N_{trig}}\frac{dN_{meas.}}{d\Delta\phi}(\Delta\phi) = \frac{1}{N_{trig}}(S(\Delta\phi) + b_{\Delta\phi})$$

$$N_{trig} = N_{trig}^{Jet} + N_{trig}^{Bkg.} = N_{trig}^{Jet}\cdot(1+f) \text{ ,with } f = \frac{N_{trig}^{Bkg.}}{N_{trig}^{Jet}}.$$

$$I_{AA}^{Sim} = \frac{Y^{Emb.}}{Y^{Py.}} = \frac{1}{1+f};$$

Simulation: Thermal toy model + Pythia jets (no v_2)



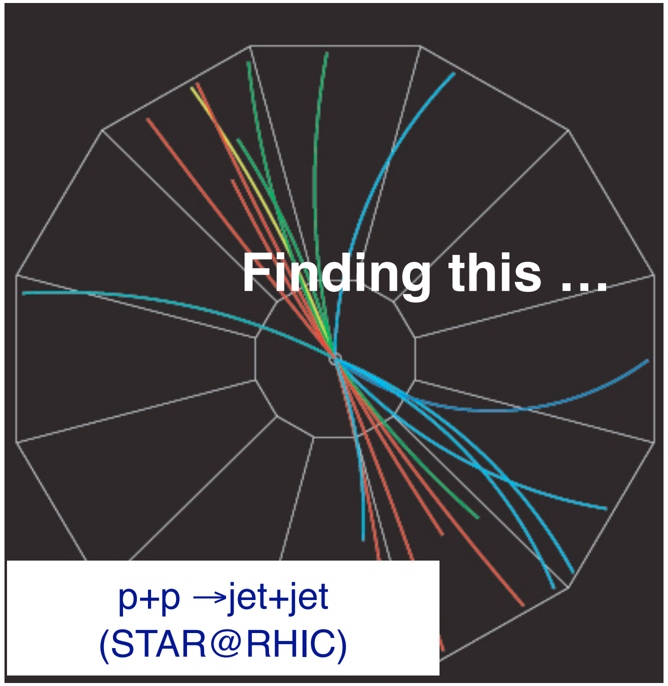
⇒ Dilution of "jet-like" associated yields !!!

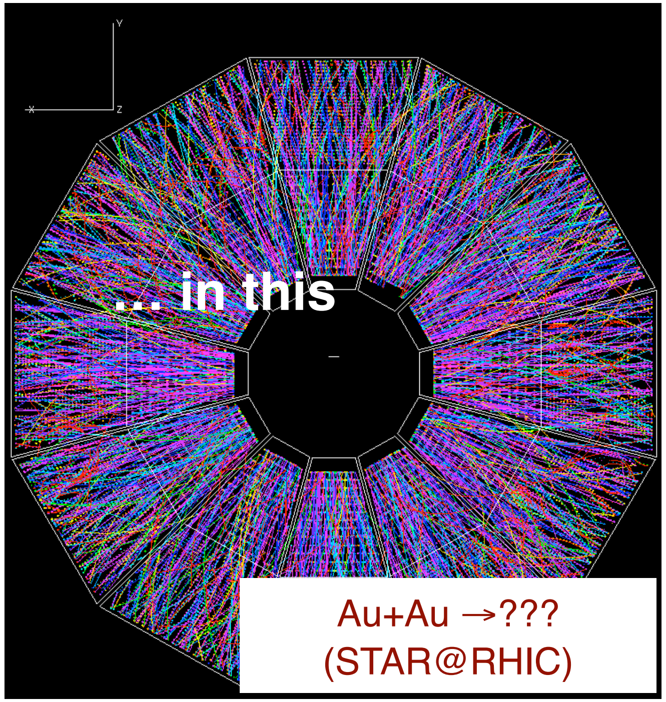
Can be studied in data via "di-hadron" correlations "in/out" of a fully reconstructed jet!

Larger effects, especially on shapes, by including v_2!


The rocky path towards full-jet reconstruction
and some surprises on the way ...

First: “Poor man’s” jet-finding ...





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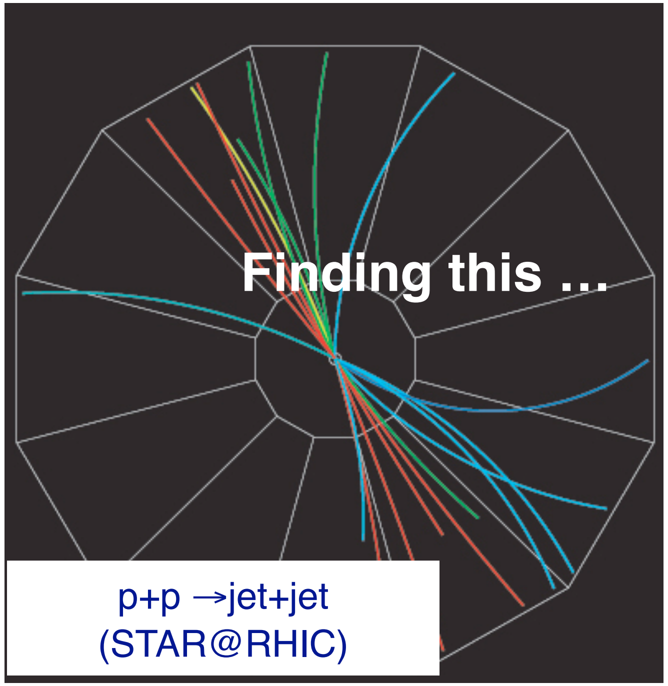
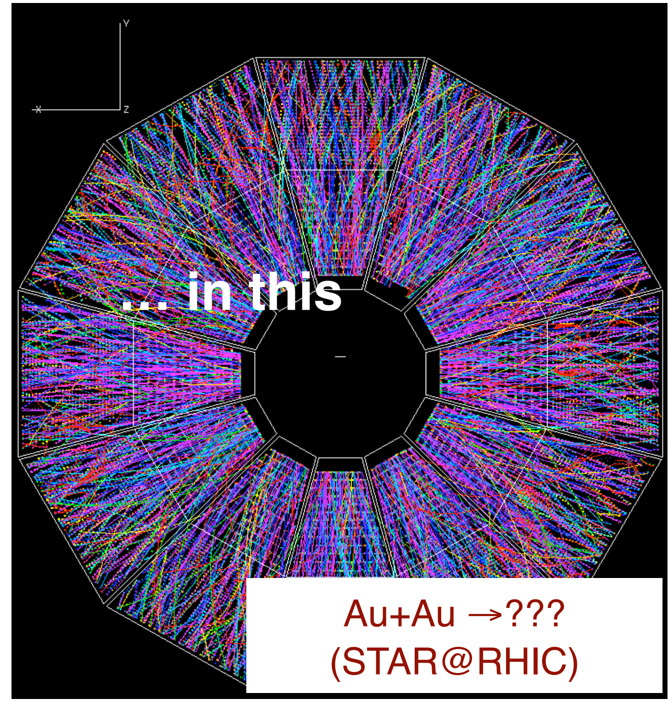
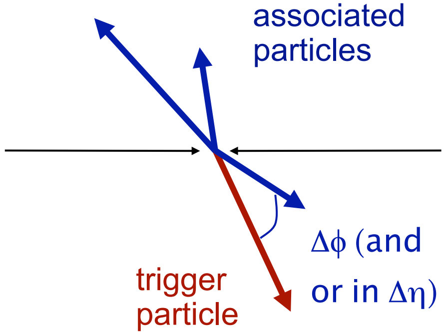


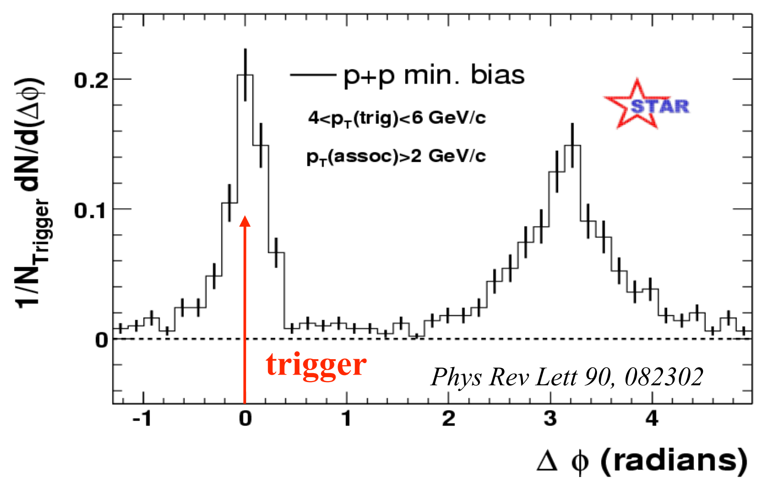


is not that easy ...

First have a look at a *jet-like* approximation:

Di-hadron correlations

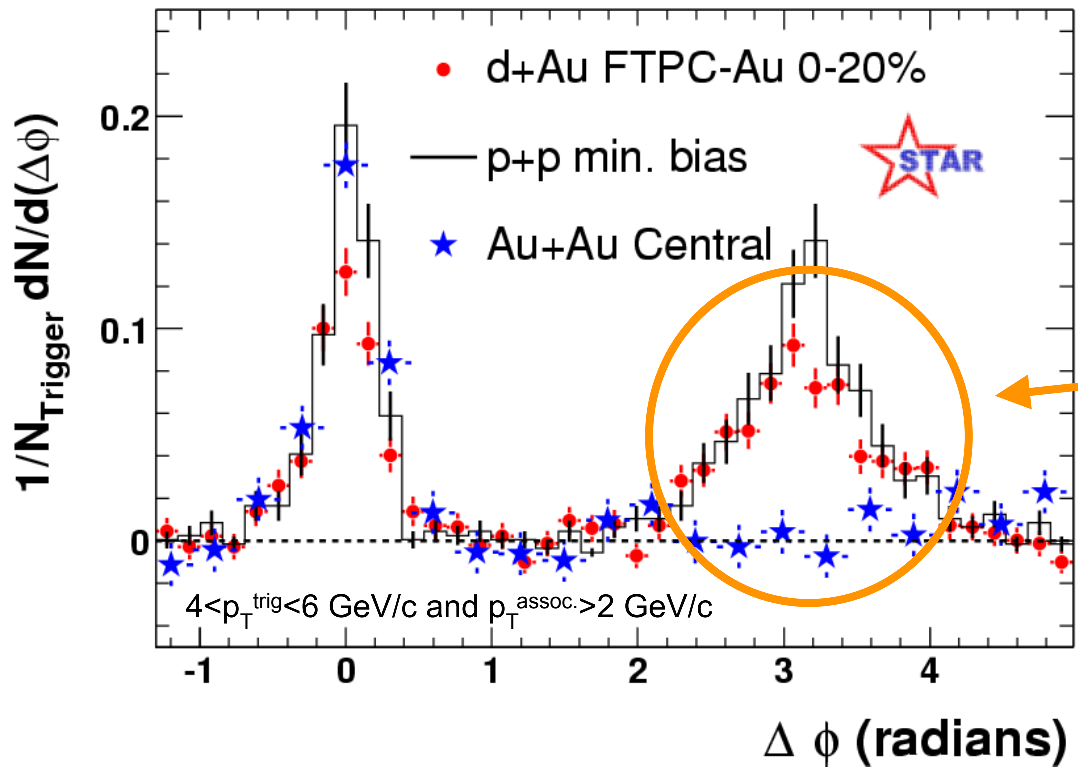


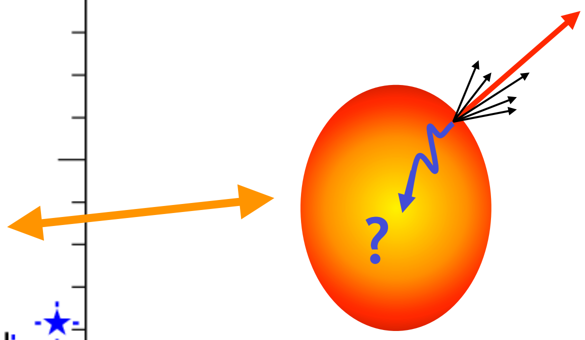


Di-hadron correlations in central Au+Au collisions

The measurement that started it all ...

Phys.Rev.Lett.91:072304 (2003)



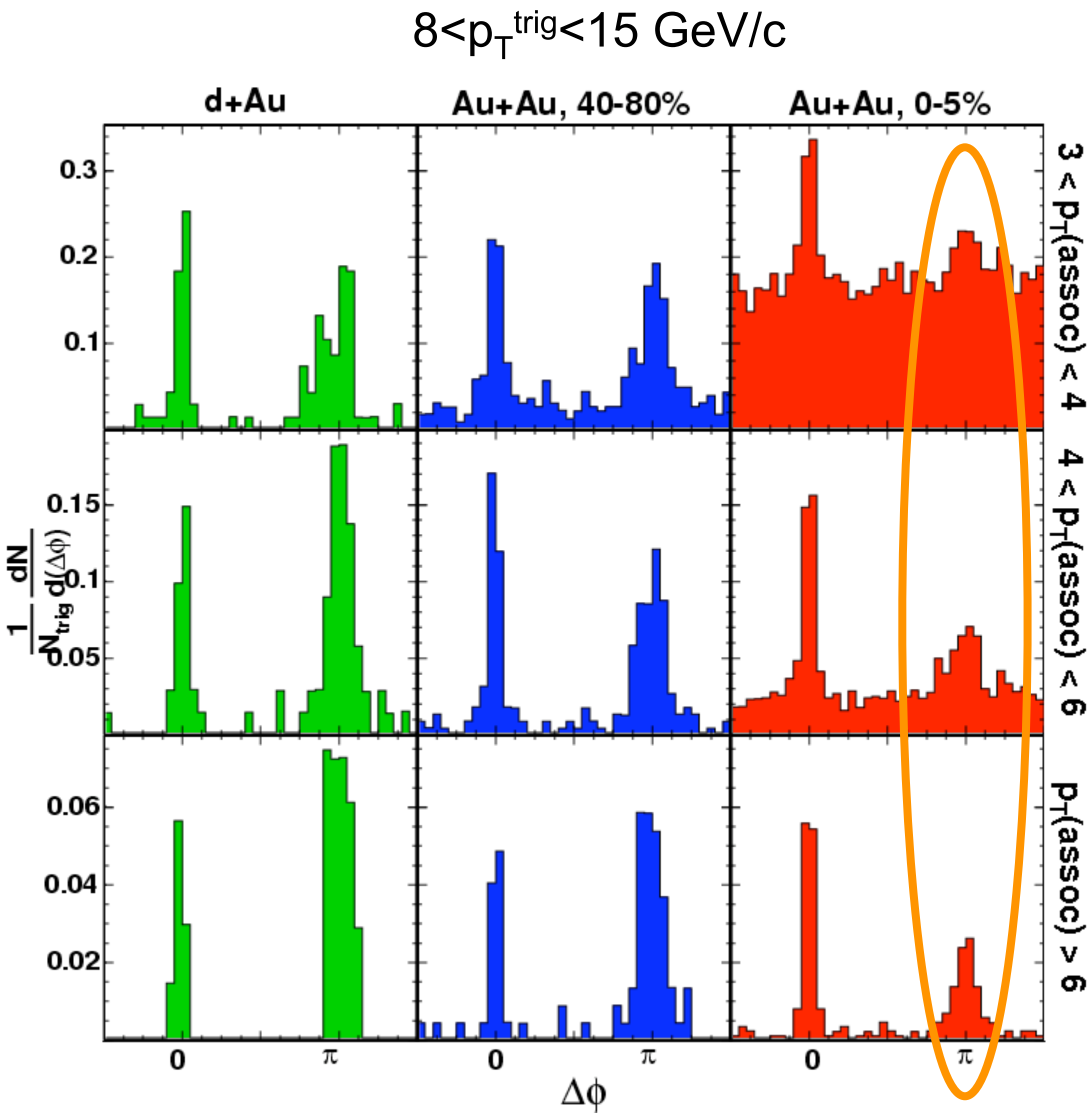


- **Au+Au back-to-back (recoil) jets are suppressed!**
- **d+Au similar to p+p (as discussed before)**
  ⇔ Jet-quenching is a final state effect!

<u>Caveat:</u> In Au+Au collisions large, elliptic flow modulated background has to be subtracted !

“One Surprise”: High-p_t ⇔ “Punch through jets”

STAR, Phys. Rev. Lett. 97 (2006) 162301



At high-p_T triggers:

Away-side yield is suppressed, but finite and measurable!

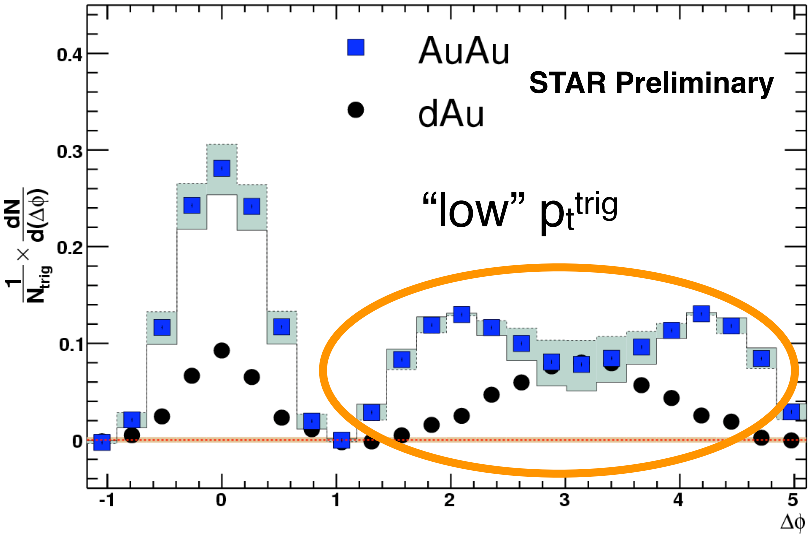
BUT:
Suppression without angular broadening or modification of (high z) “fragmentation”

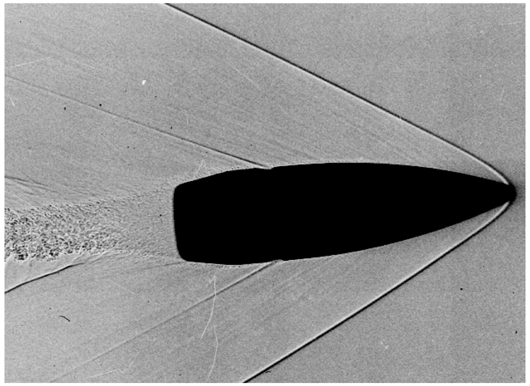
Surviving pairs seem to favor conditions with small energy loss!

Tangential (halo) emission, finite probability for no energy loss (energy loss fluctuations) or dilution due to the expanding system

(Dainese (PQM) et al, T. Renk et al)

More surprises from di-hadron correlations ...

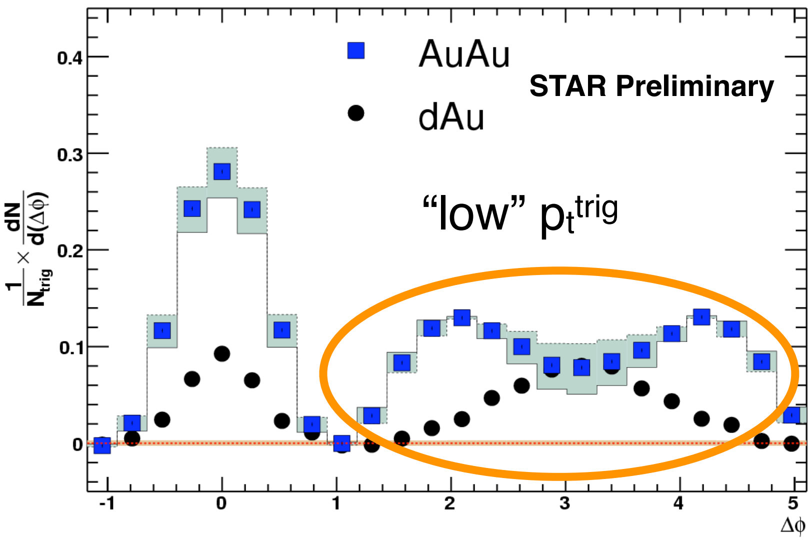


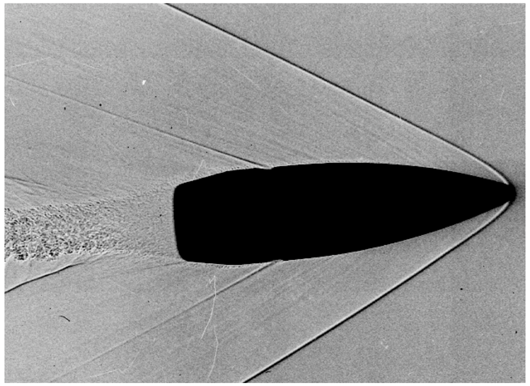


“Mach Cones” at RHIC!?

<u>Caveat:</u> Large, elliptic flow modulated background has to be subtracted !

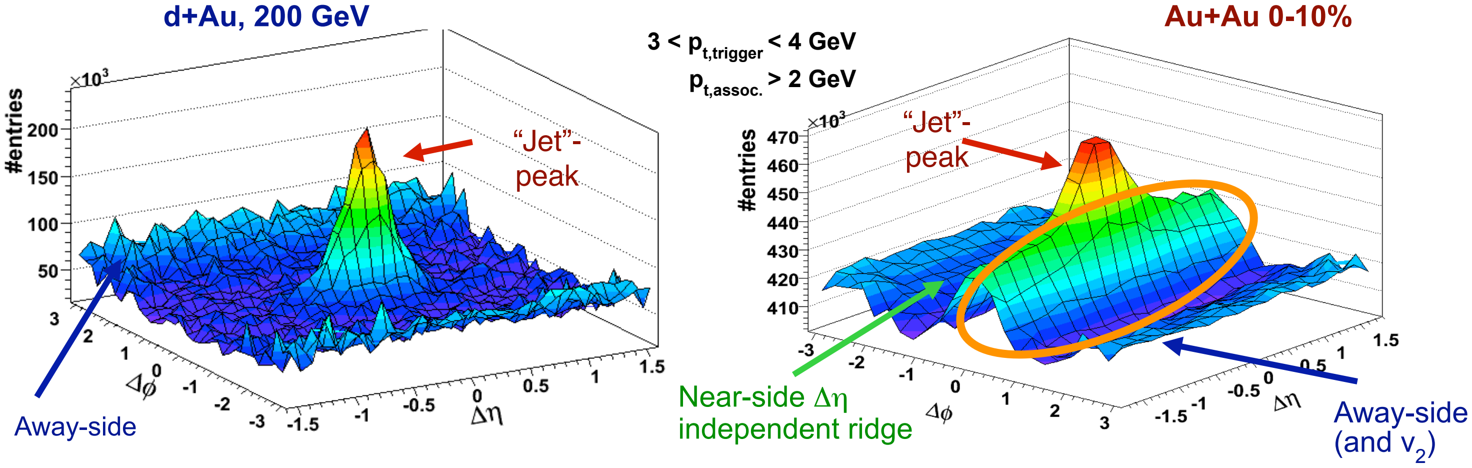
More surprises from di-hadron correlations ...





"Mach Cones" at RHIC!?

Phys.Rev.C80:064912 (2009)



What is the origin of the "Ridge" ?

Caused by jet-quenching or initial state (flux-tubes)/ medium+trigger bias?

d+Au: "jet"-peak, symmetric in ϕ, η

Au+Au: Additional correlation strength at small $\Delta\phi$ and large $\Delta\eta$: **The "Ridge"**

Caveat: Large, elliptic flow modulated background has to be subtracted !