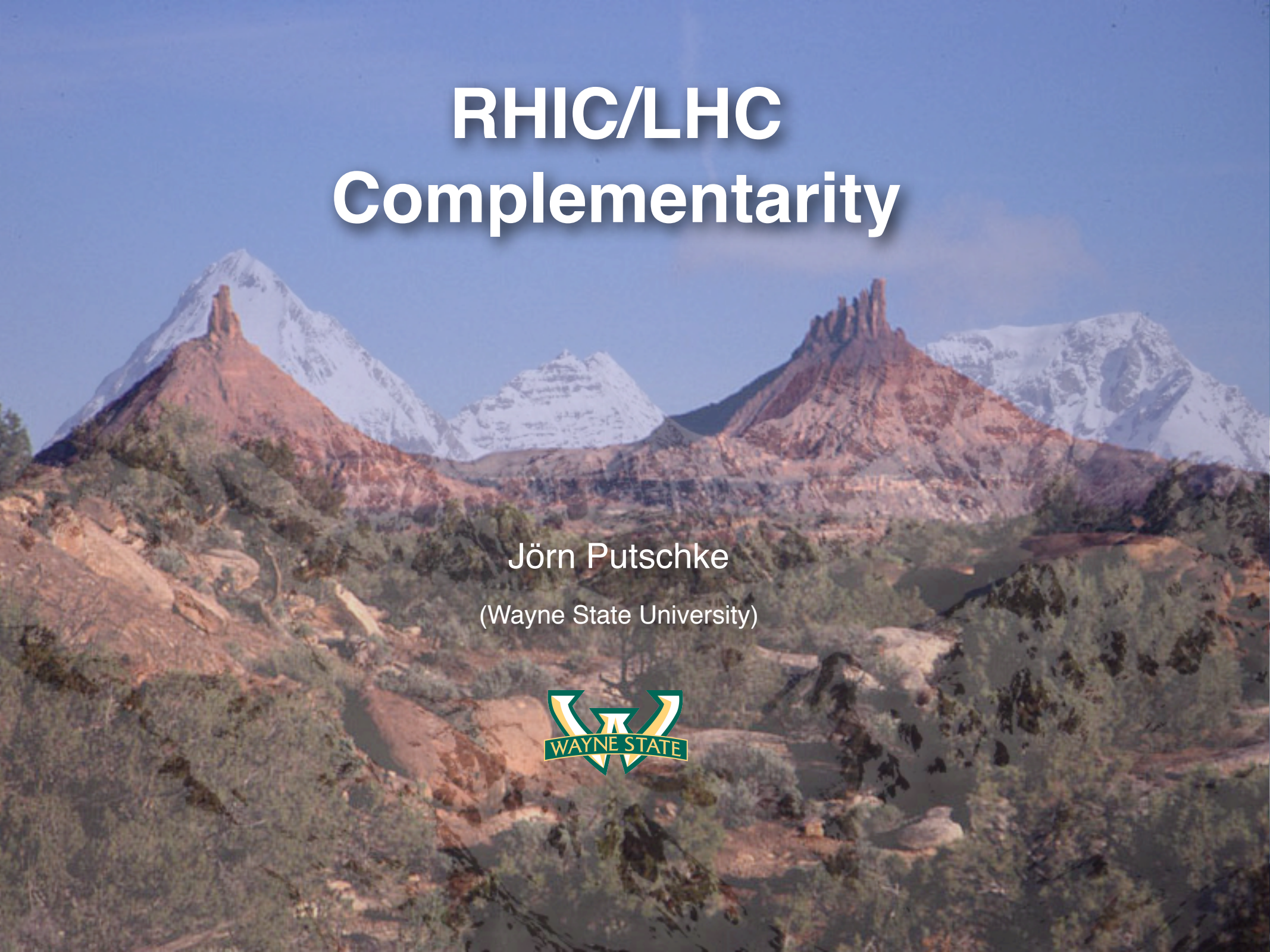
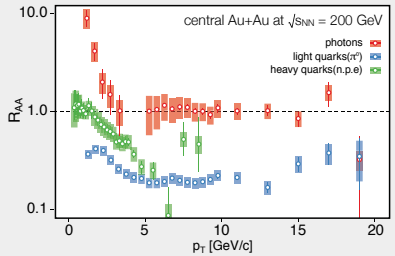


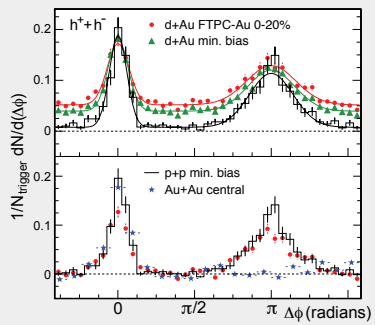
RHIC/LHC Complementarity

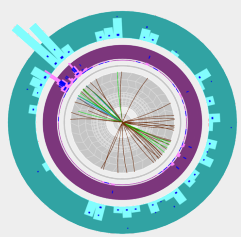
Jörn Putschke

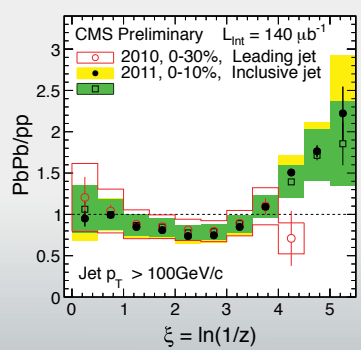
(Wayne State University)

Important experimental and theoretical developments









Full jet reconstruction measurements and comparison to theory over a wide range of collision and jet energies

Precision RHIC data are essential

2000
2002
2004
2006
2008
2010
2012
2014
2022

experimental techniques developed

×5 suppression in hadron R_{AA}

Away-side disappearance

d+Au "Null-Experiment": Jet-quenching unambiguously a final-state/QGP effect

Strong modification of an away-side jet: "Mach-Cone" ?

No direct photon suppression

Near-side modification: "The Ridge"

Feasibility measurements/studies of full jet reconstruction at RHIC

Ridge and Mach-Cone structure consistently explained by v_n (initial state fluctuations)

LHC data: Increase of charged hadron R_{AA} at high momentum; full jet measurements

Modification in jet fragmentation/ jet structures at the LHC (QM12) suggests radiative energy loss picture at high jet energies

RHIC BES-II and detector upgrades required to

- reduce $\hat{q}$ uncertainties
- determine $\hat{q}$(T) dependence
- characterize quasi particle nature over a wide range in jet energy
- constrain importance of collisional vs. radiative energy loss; QCD analog to QED energy loss

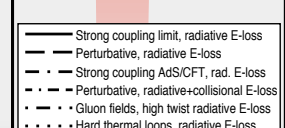
Increasing precision of key observable

1 10 100

Weak coupling regime

Strong coupling regime

Ten-fold reduction in the $\hat{q}_0$ uncertainty



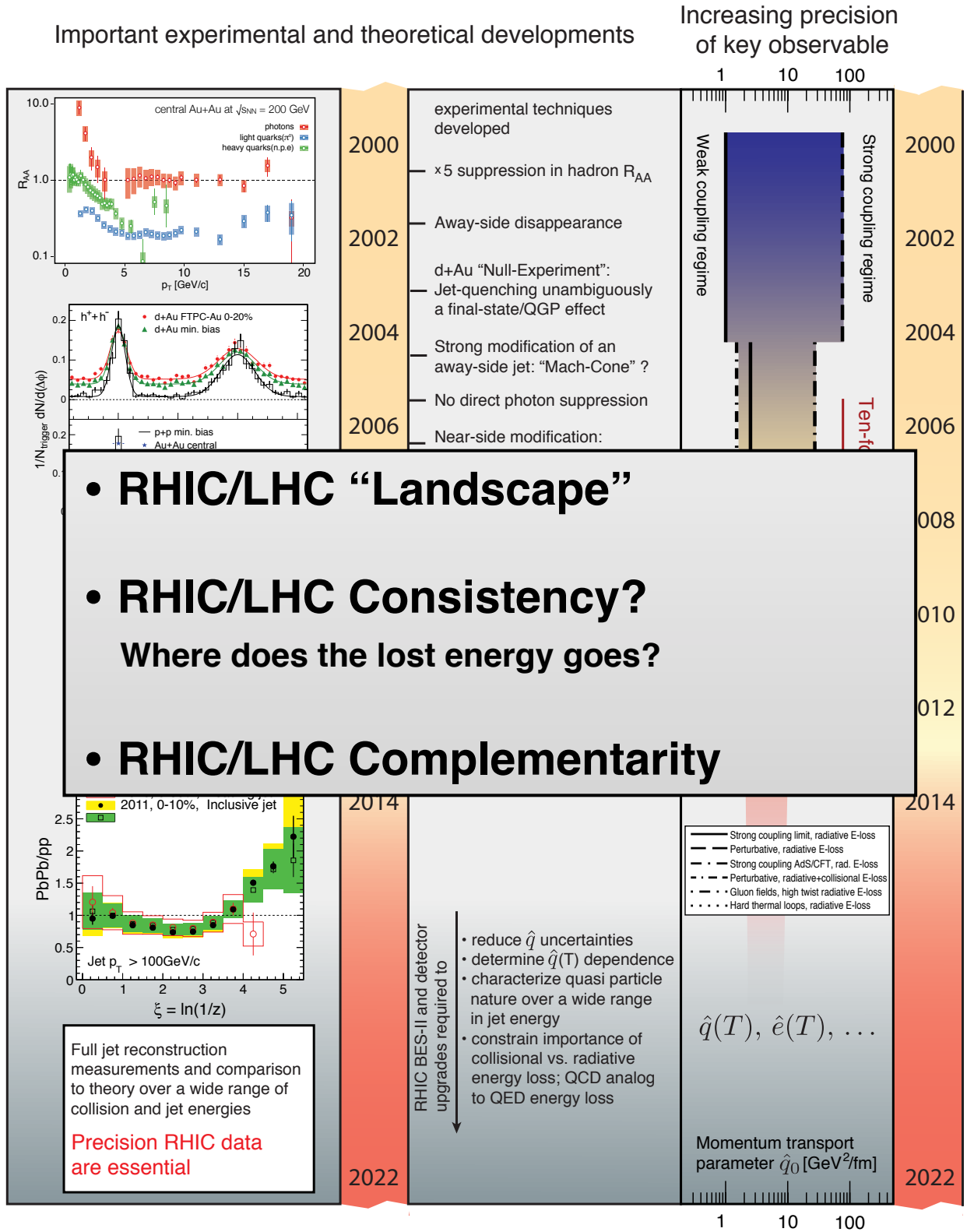
$\hat{q}(T),\ \hat{e}(T),\ \ldots$

Momentum transport parameter $\hat{q}_0$ [GeV^2/fm]

1 10 100

Used as a guideline ...

RHIC White Paper: "Hot and Dense QCD Matter"



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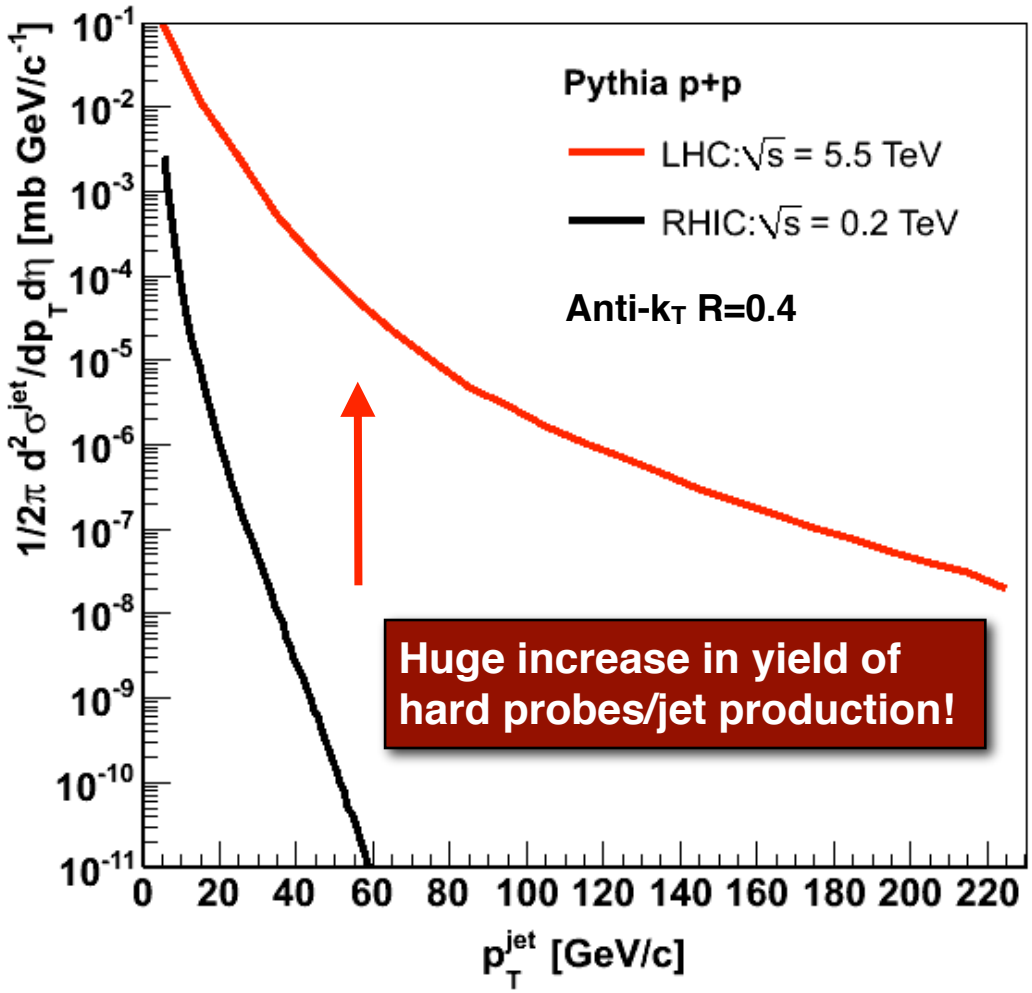
RHIC White Paper:
"Hot and Dense QCD Matter"

RHIC and LHC "Landscape"

The QGP at the LHC:

- fireball hotter (~20%) and denser (~x2) and longer lifetime wrt RHIC

- bulk dynamics, $v_n(p_T)$, similar at RHIC and LHC, mainly driven by initial state "geometry"



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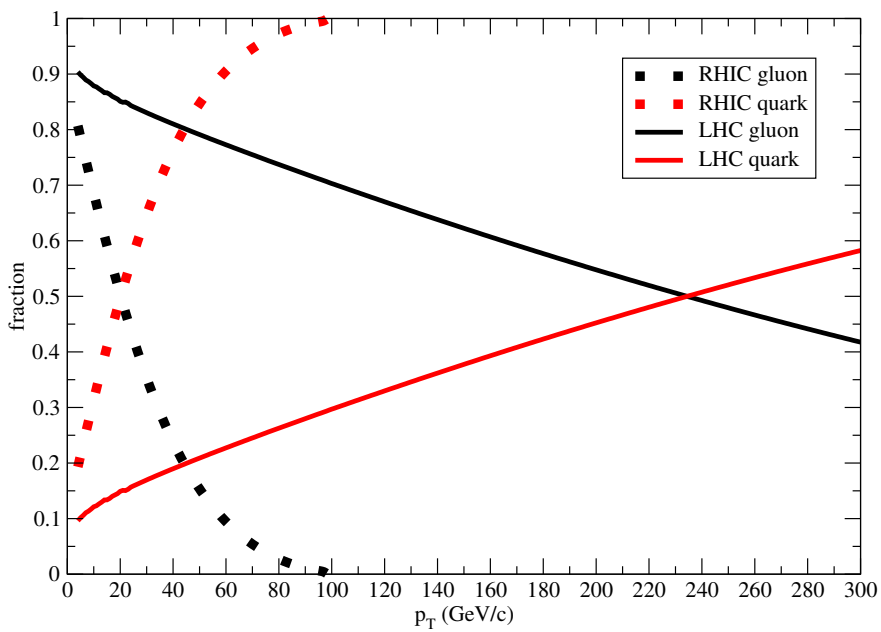
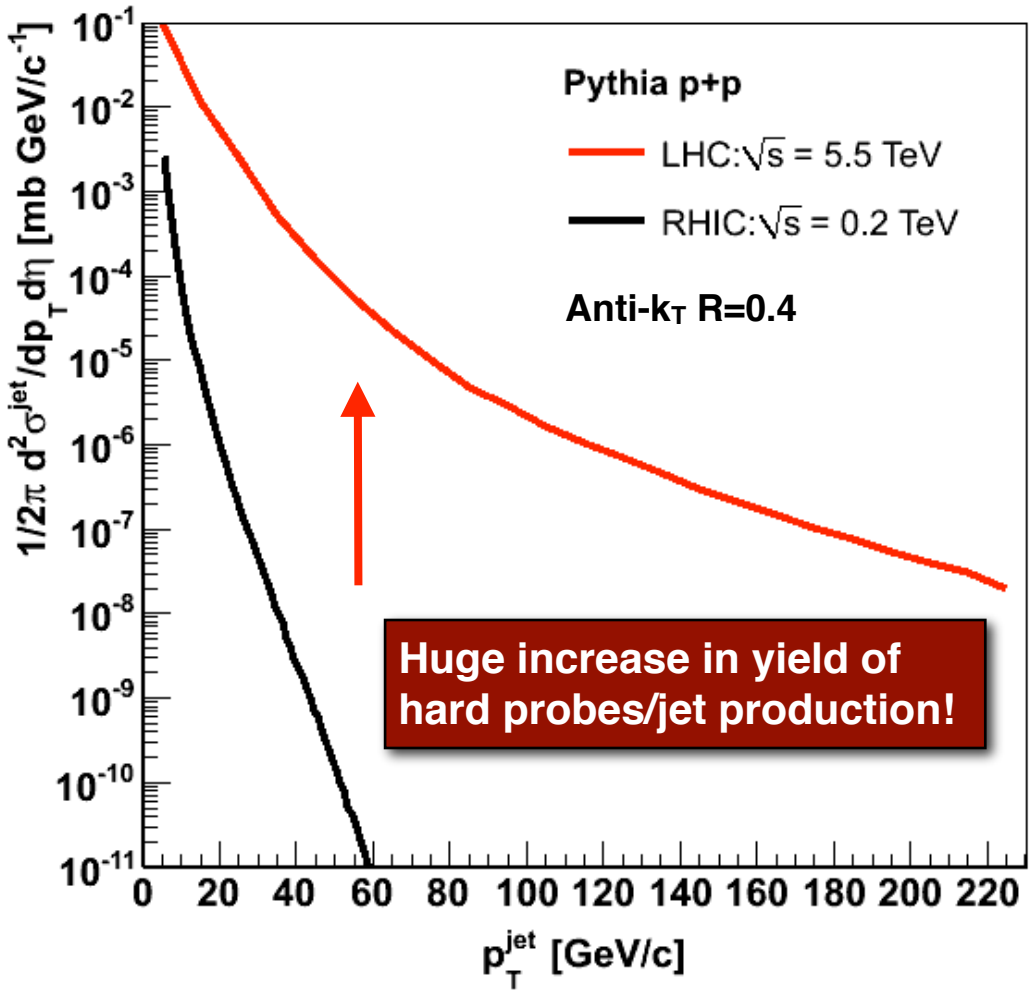
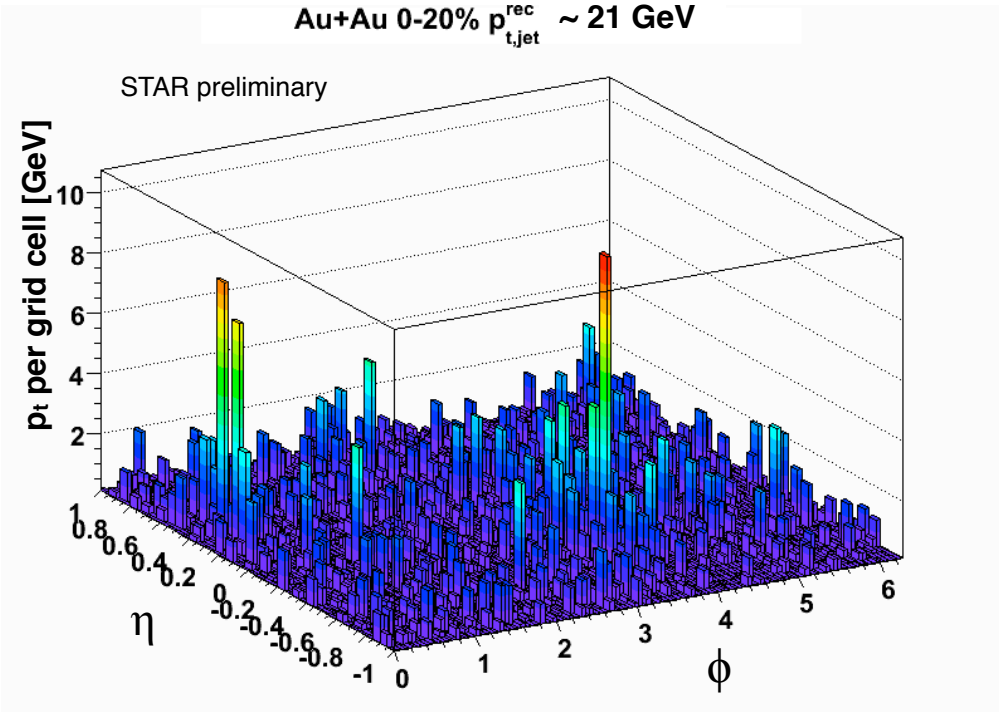
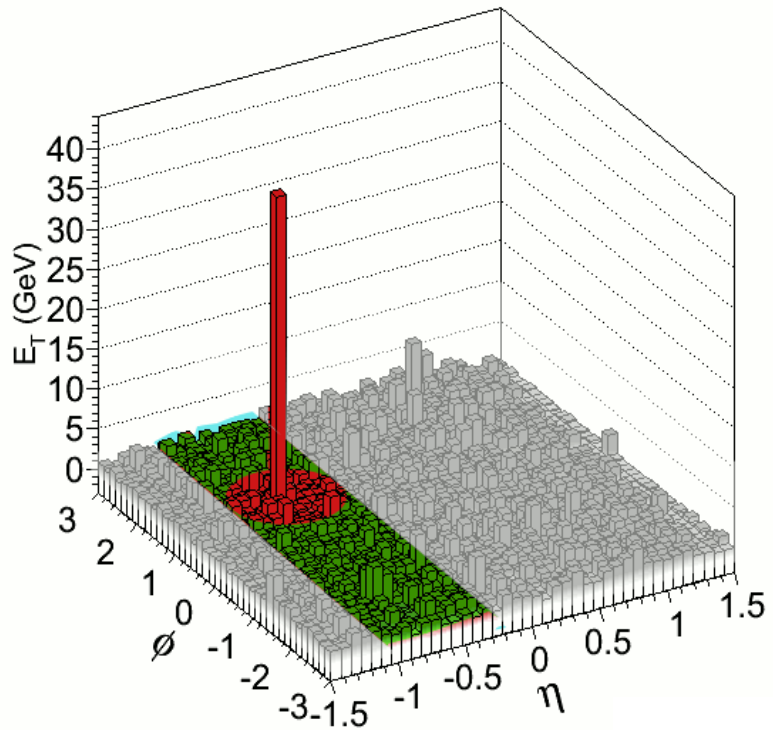




Mainly gluon jets (p_T<200 GeV) at the LHC. Quark jets at RHIC p_T>40 GeV.

The issue: Background in HI collisions





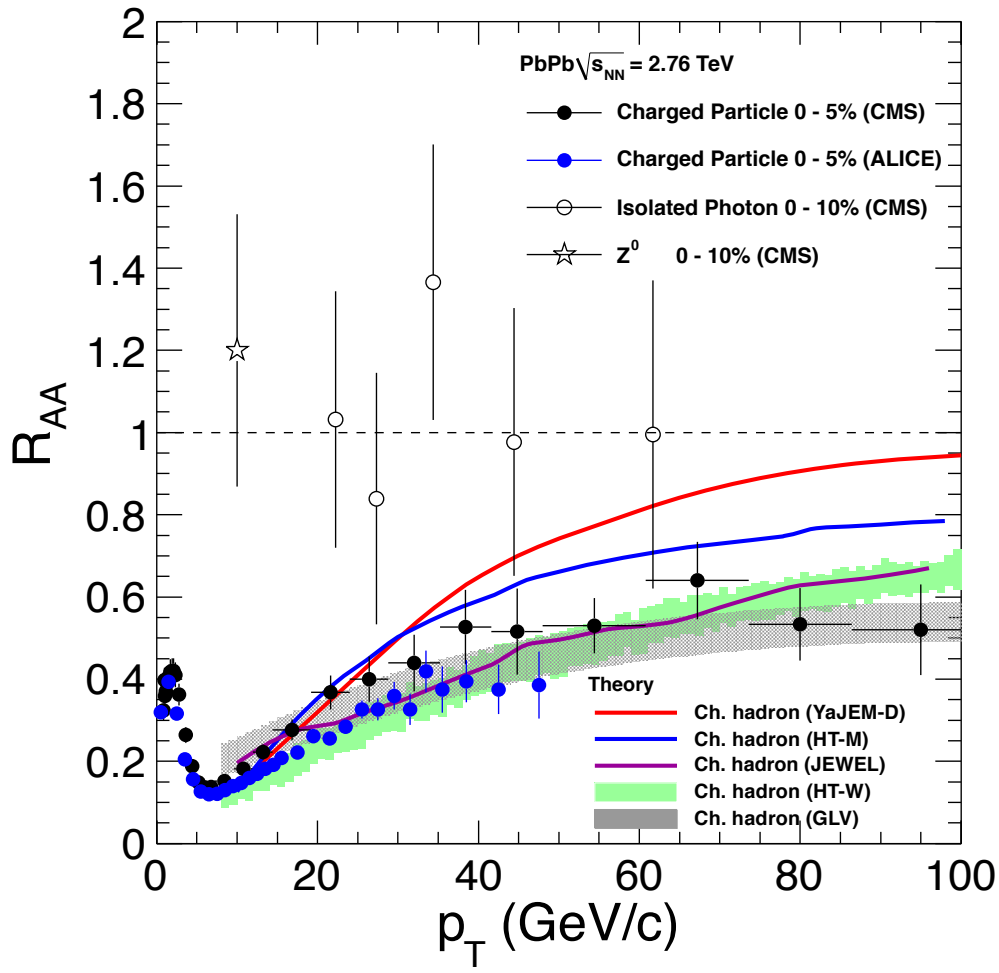
Full jet reconstruction in HI collisions is a challenge due to the underlying background

- Overall background pedestal
- Region-to-region background fluctuations and v_n contributions
- Multiple independent hard scattering in HI collisions

Different contributions depending on coincidence vs. inclusive measurements!

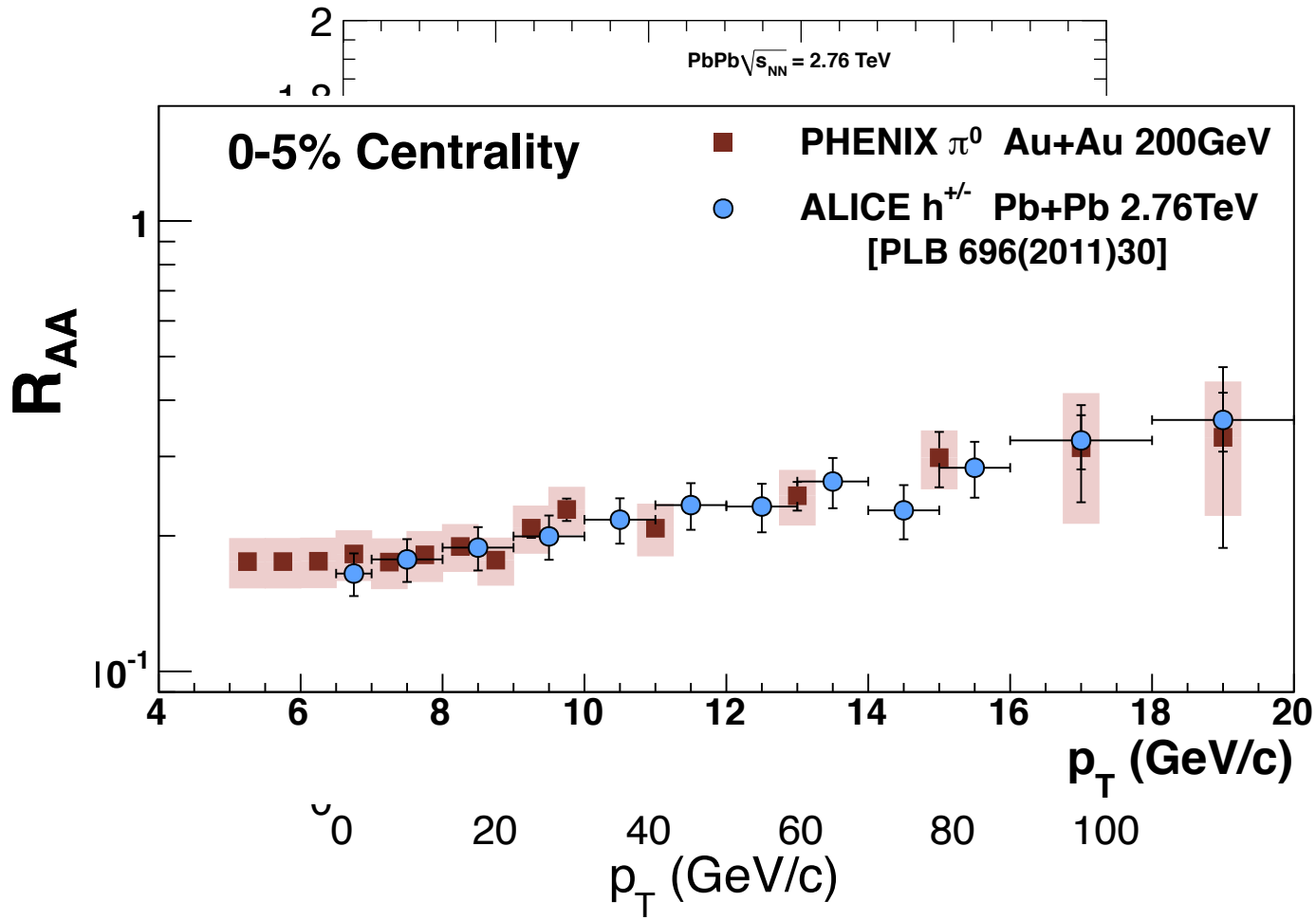
Remark: I will not talk about this in detail, a comprehensive summary concerning the different approaches currently used can be found in a talk by G. Roland: https://indico.cern.ch/getFile.py/access?contribId=3&sessionId=0&resId=0&materialId=slides&confId=198761

LHC and RHIC R_{AA}



R_{AA} rising as function of p_T; constant for p_T>50 GeV?

LHC and RHIC R_{AA}

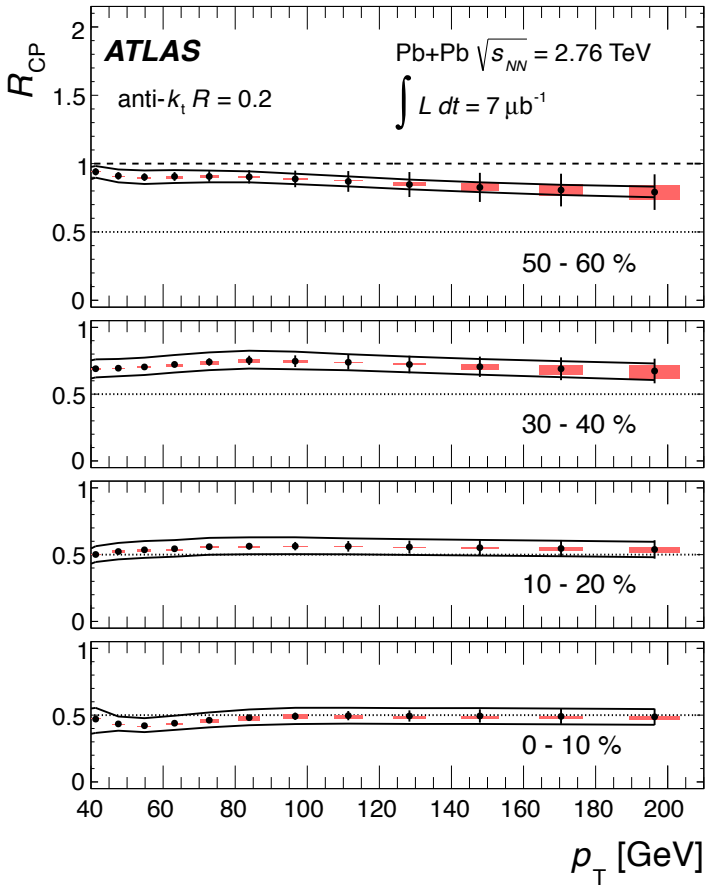


R_{AA} rising as function of p_T; constant for p_T>50 GeV?

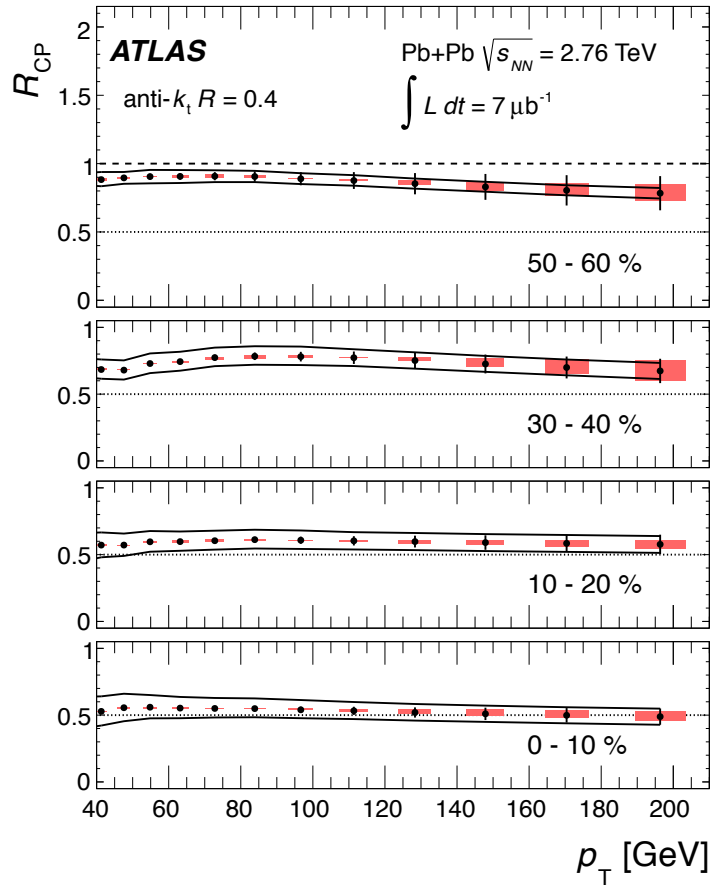
RHIC R_{AA} ~ LHC R_{AA} up to p_T~20 GeV

Jet R_{AA}/R_{CP} at the LHC

R=0.2



R=0.4



R_{CP}^{Jet}~ R_{AA} ~ 0.5 (>50 GeV)

No significant p_T and R dependence of R_{CP} for p_T>100 GeV

Jet R_{AA}/R_{CP} at the LHC

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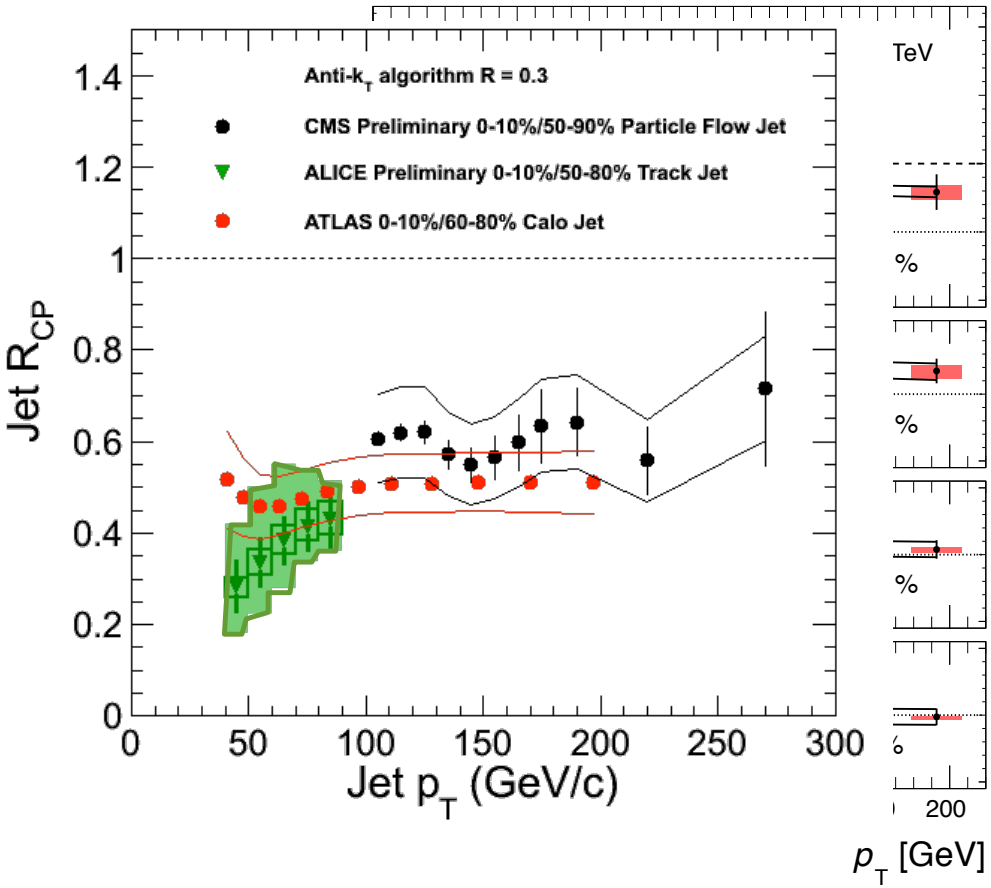
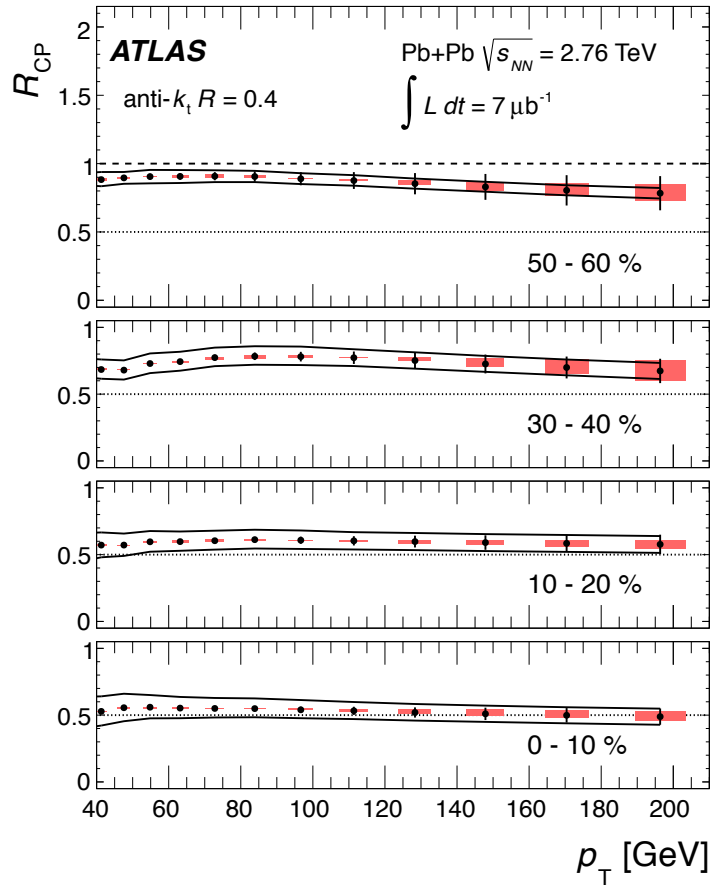


R=0.4



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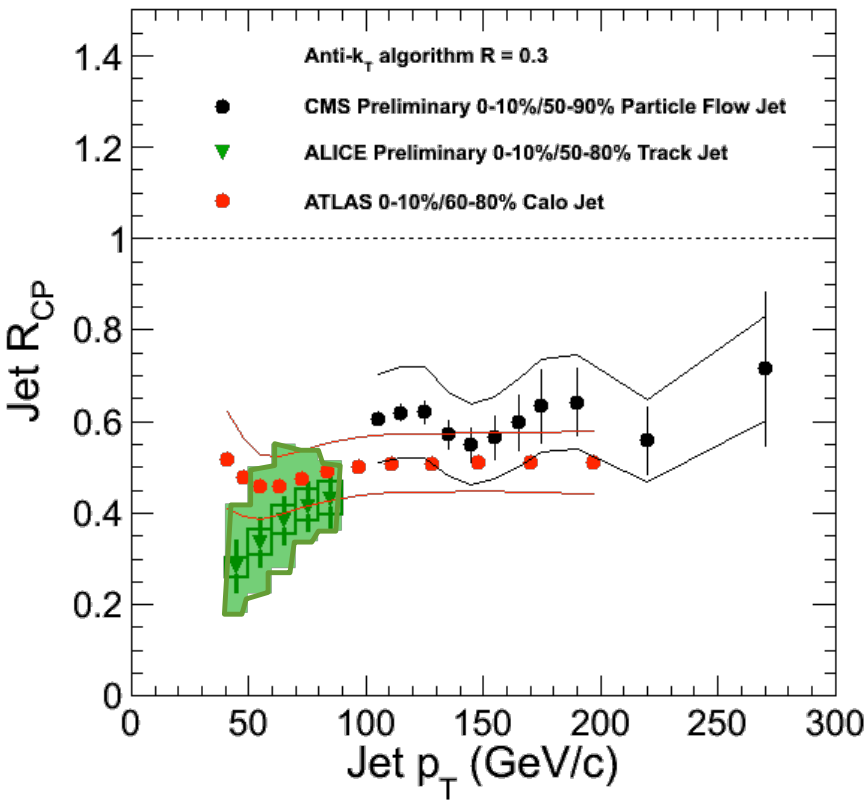
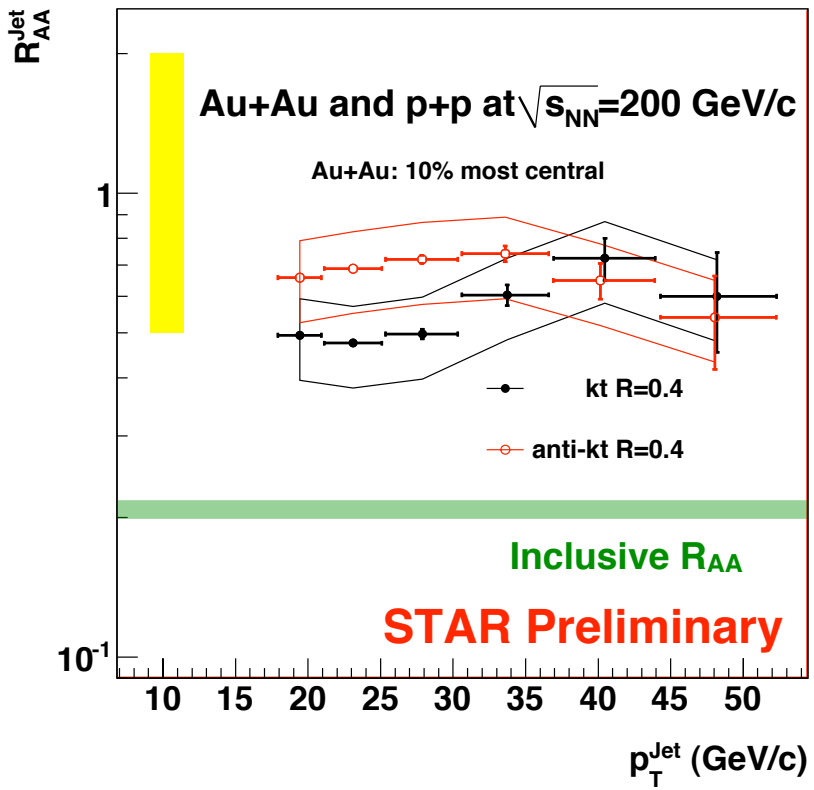
Jet R_{AA}/R_{CP} at the LHC





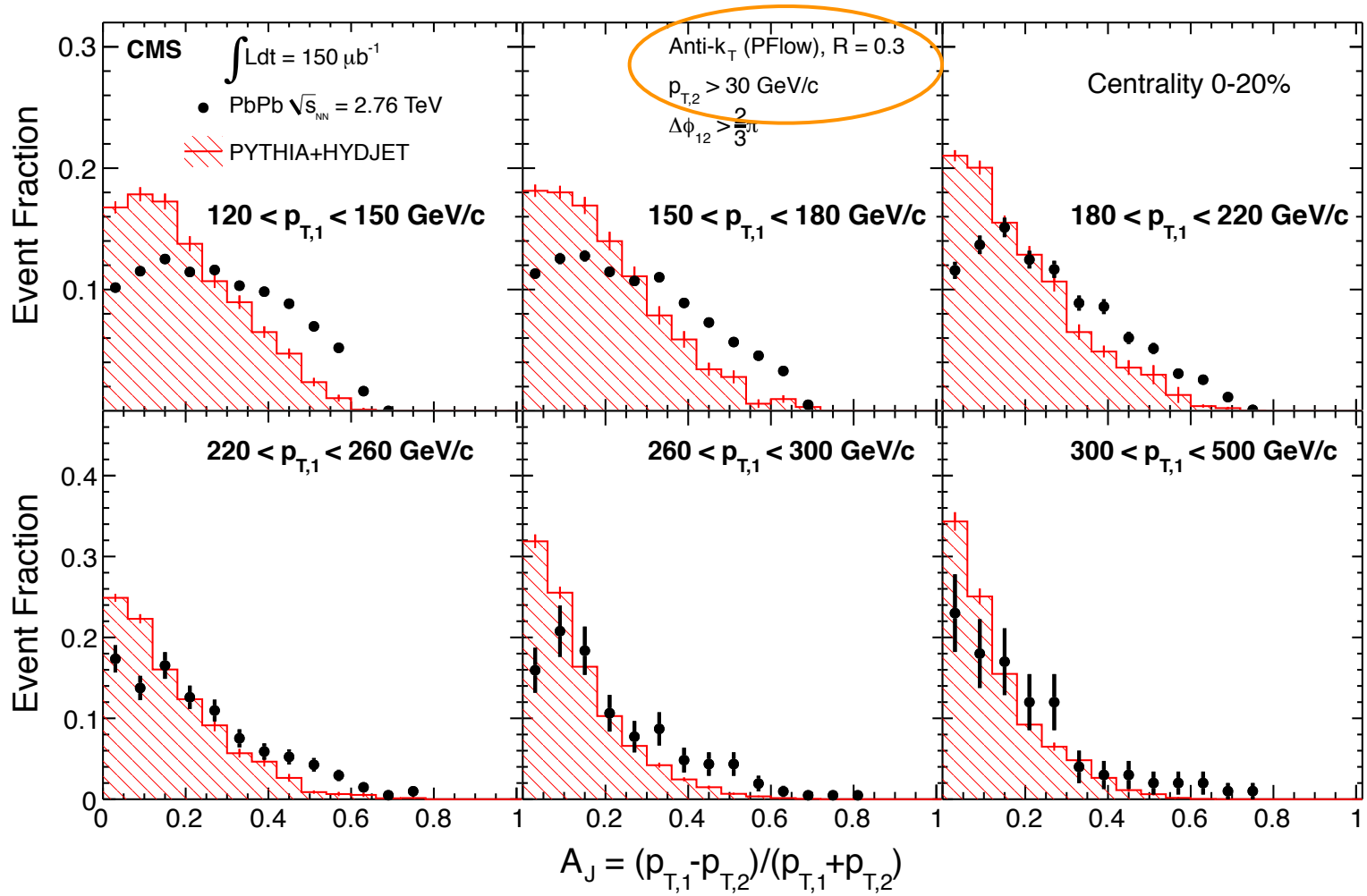
R_{CP}^{Jet}~ R_{AA} ~ 0.5 (>50 GeV)

No significant p_T and R dependence of R_{CP} for p_T>100 GeV

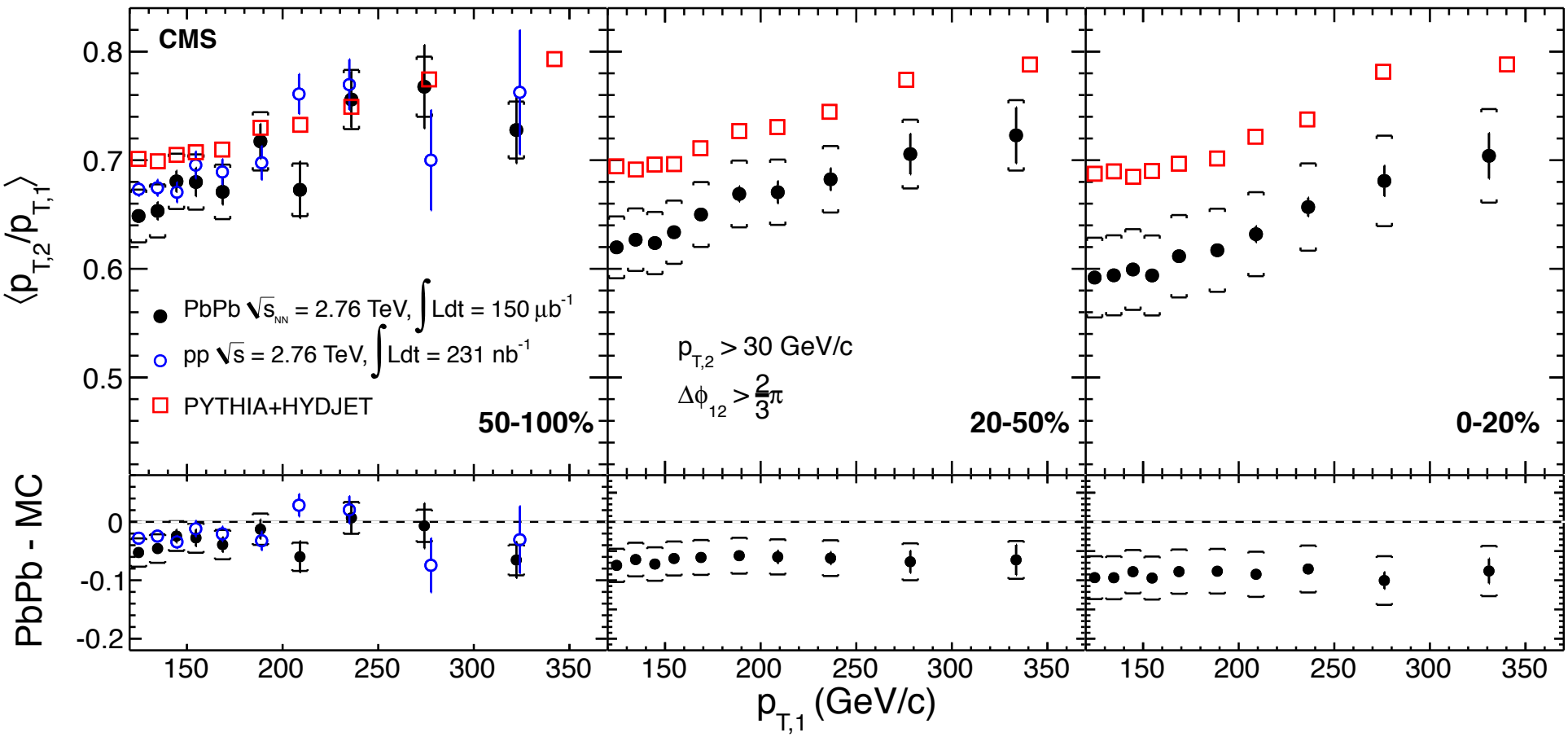
***RHIC:* Jet R_{AA} less suppressed than hadrons!**

Caveat: Large systematic uncertainties

Di-jet asymmetry/imbalance as function of leading jet p_T



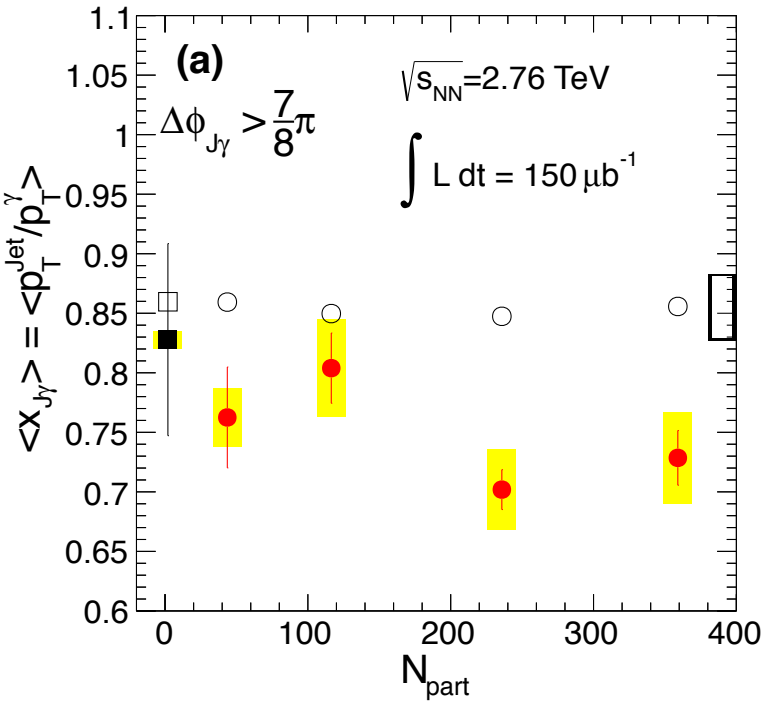
Di-jet asymmetry/imbalance as function of leading jet p_T

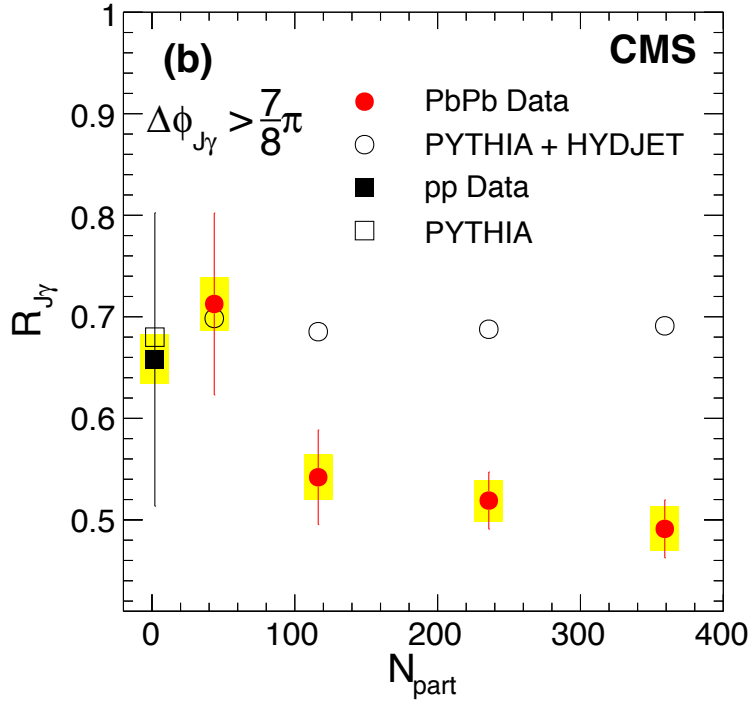


Di-Jet imbalance decreasing with increasing jet energy!

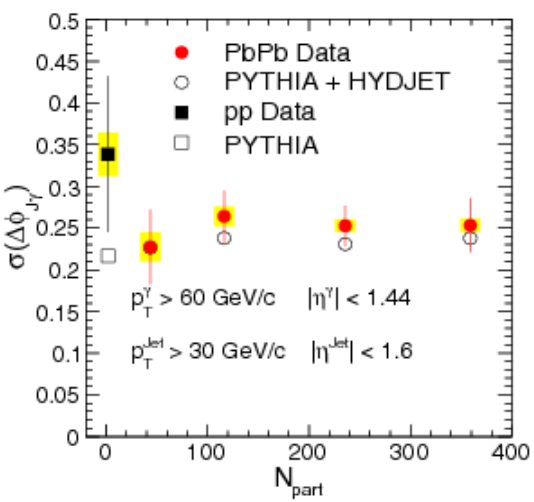
"Can be explained in terms of essentially known physics, i.e. the increased collimation of jets due to kinematics and a transition to a less gluon- dominated regime." : T.Renk, arXiv:1204.5572

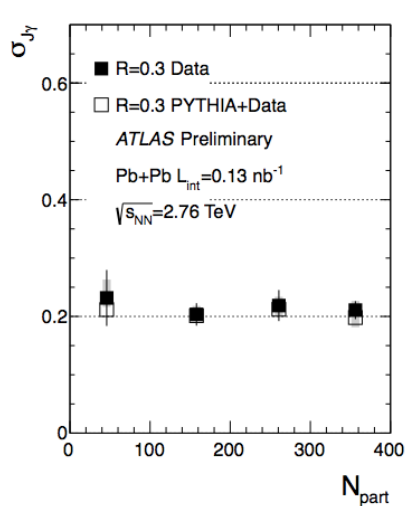
Direct Photon-Jet Measurements





p_T^{γ}>60 GeV
p_T^{Jet}>30 GeV





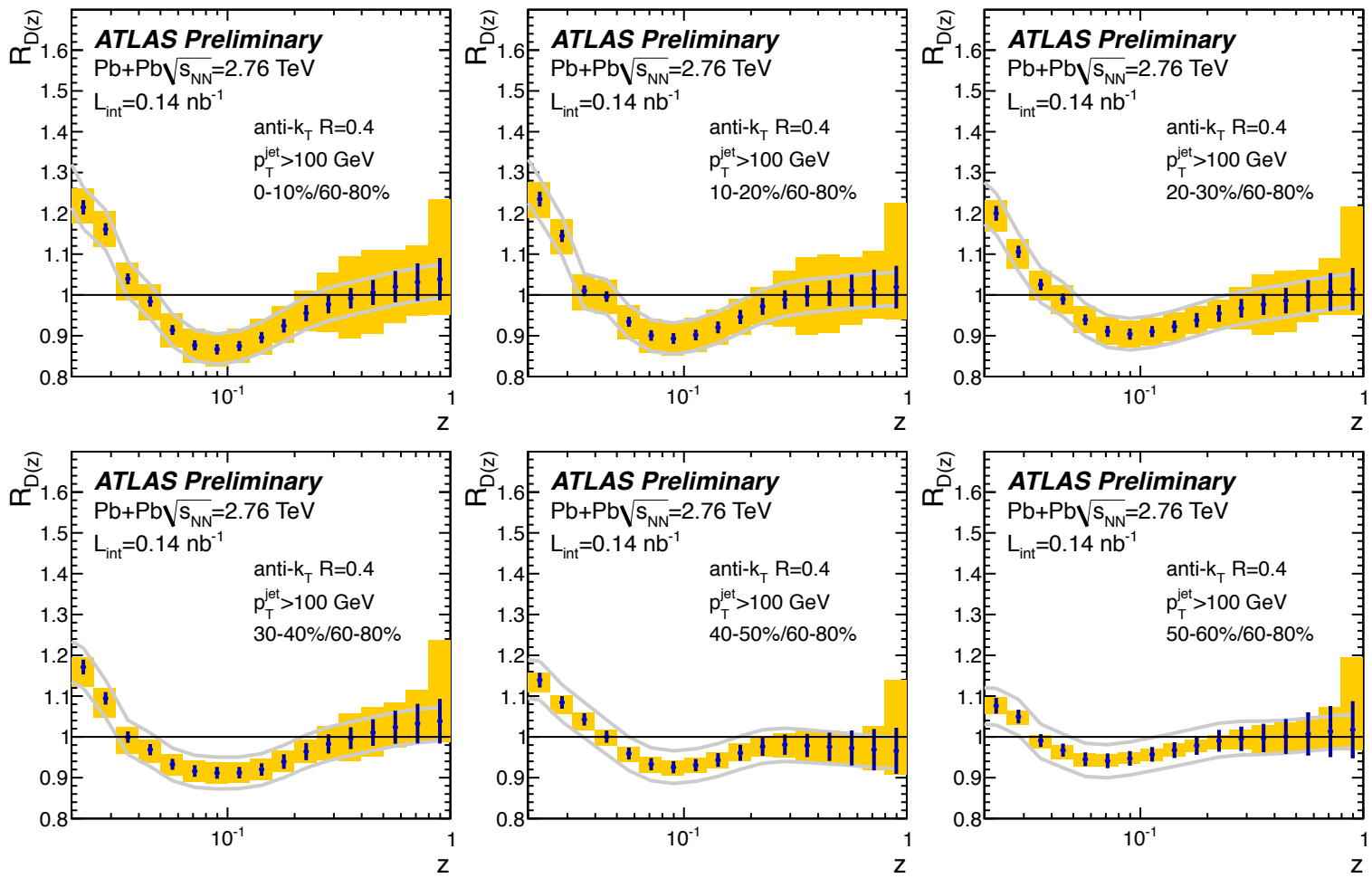
Large quenching effects seen in direct photon measurements

(Consistent with jets measurements? Quark vs. gluon energy loss?)

No angular de-correlation

(also seen in di-jets @RHIC)

Fragmentation Functions in Pb+Pb at the LHC



Enhancement at low z

Suppression at intermediate z

No suppression at high z

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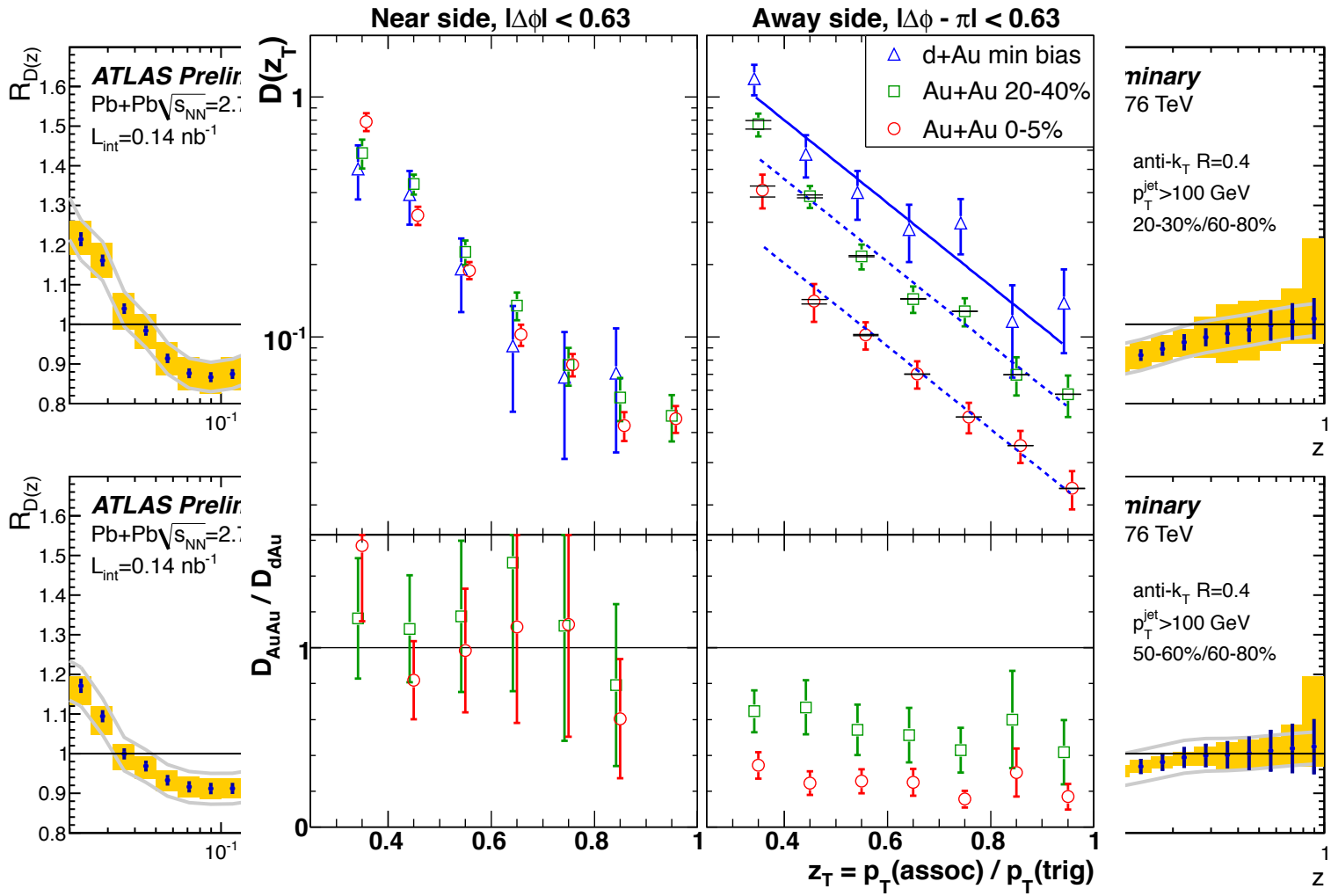


Enhancement at low z

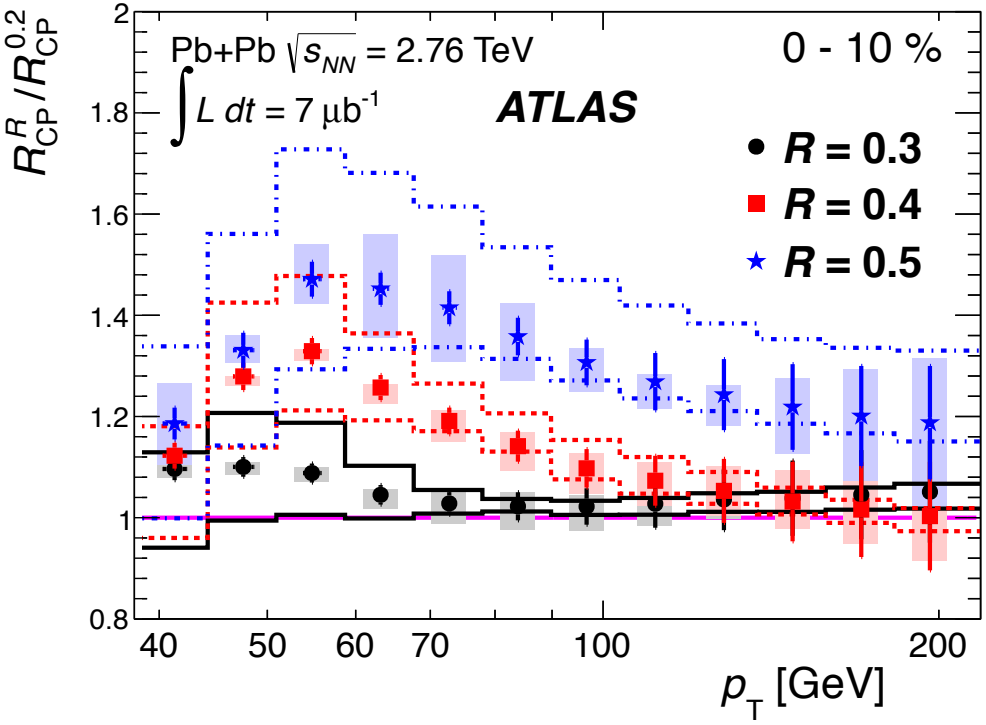
Suppression at intermediate z

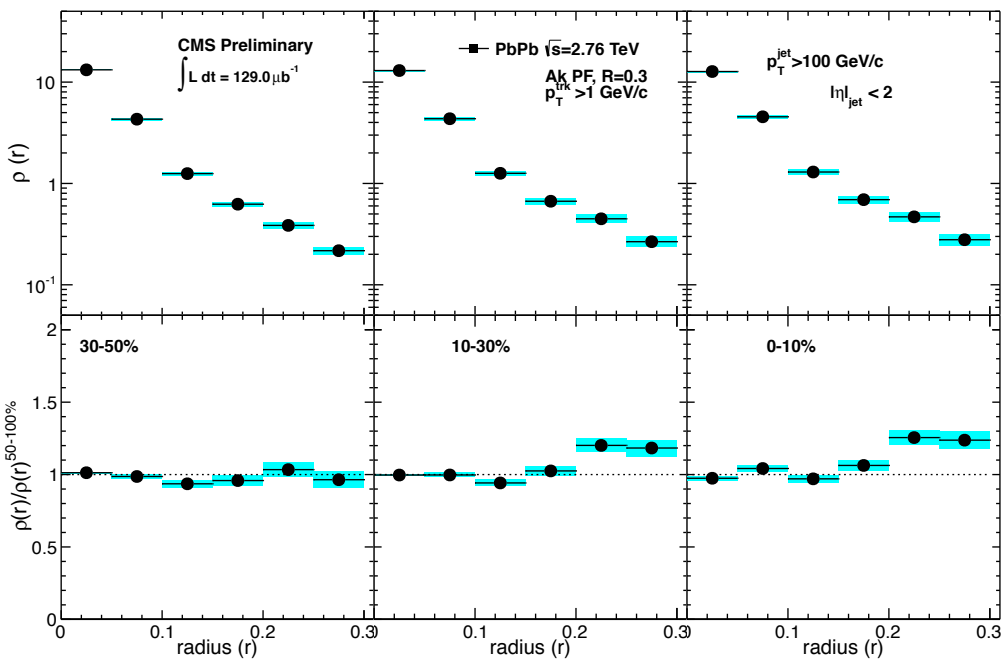
No suppression at high z

***RHIC:* Suppression at high di-hadron z_T**

Caveat: Not apple to apple comparison!

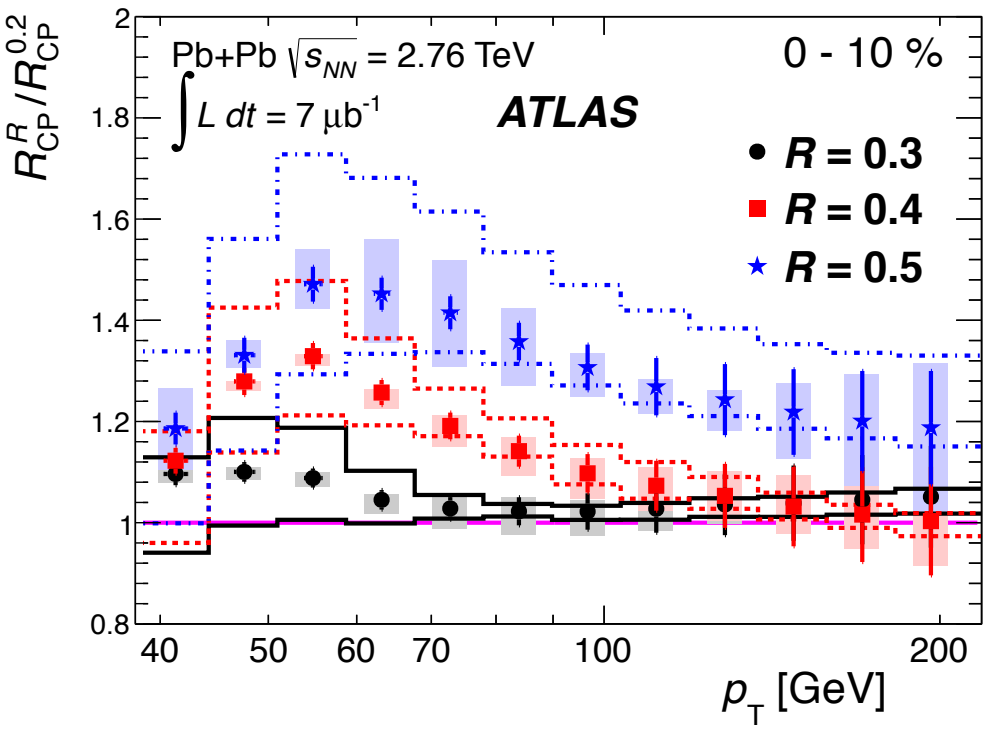
Jet Shape Observables

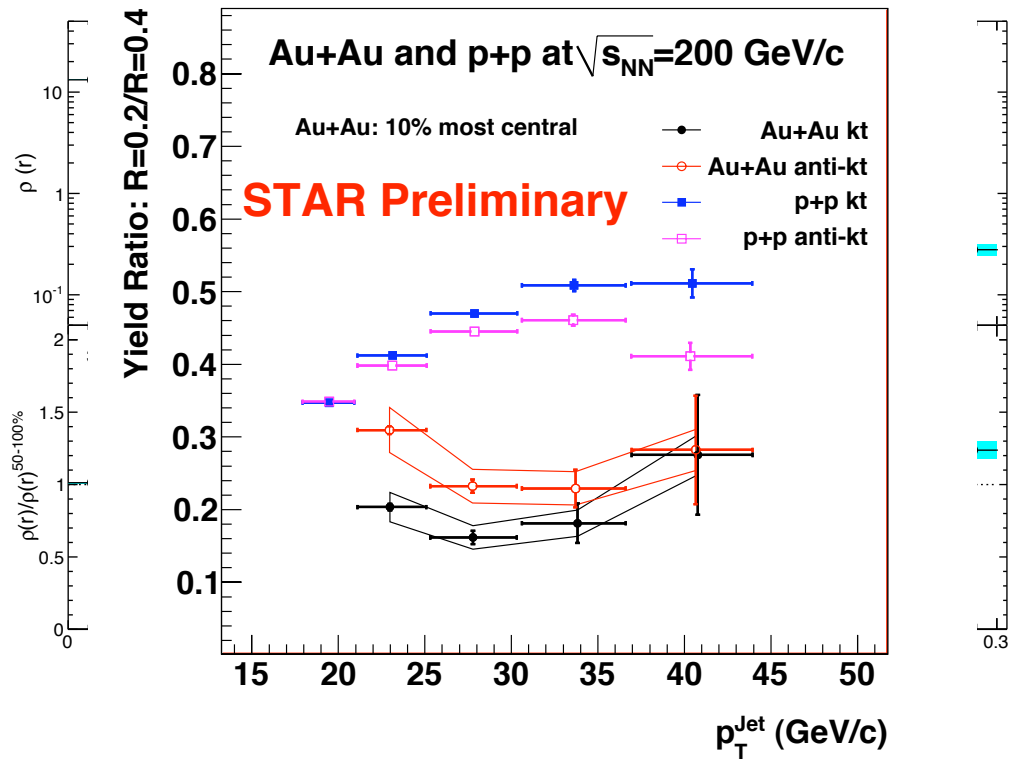




Jet broadening at the LHC:
Seen in differential jet shape and R dependence of jet R_{CP}
(especially at lower jet p_T)

Jet Shape Observables



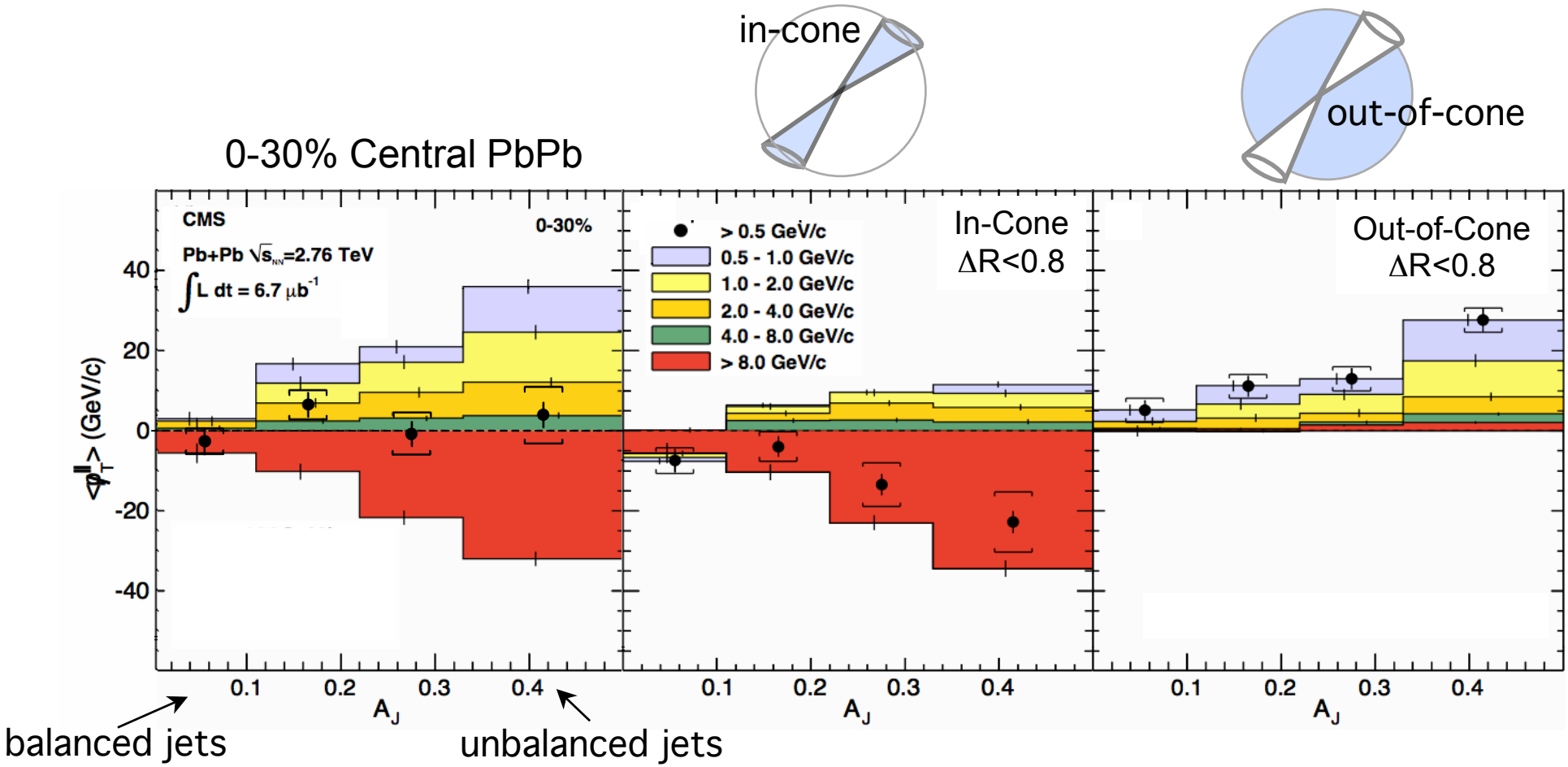


Jet broadening at the LHC:
Seen in differential jet shape and R dependence of jet R_{CP}
(especially at lower jet p_T)

***RHIC:* Stronger broadening observed**

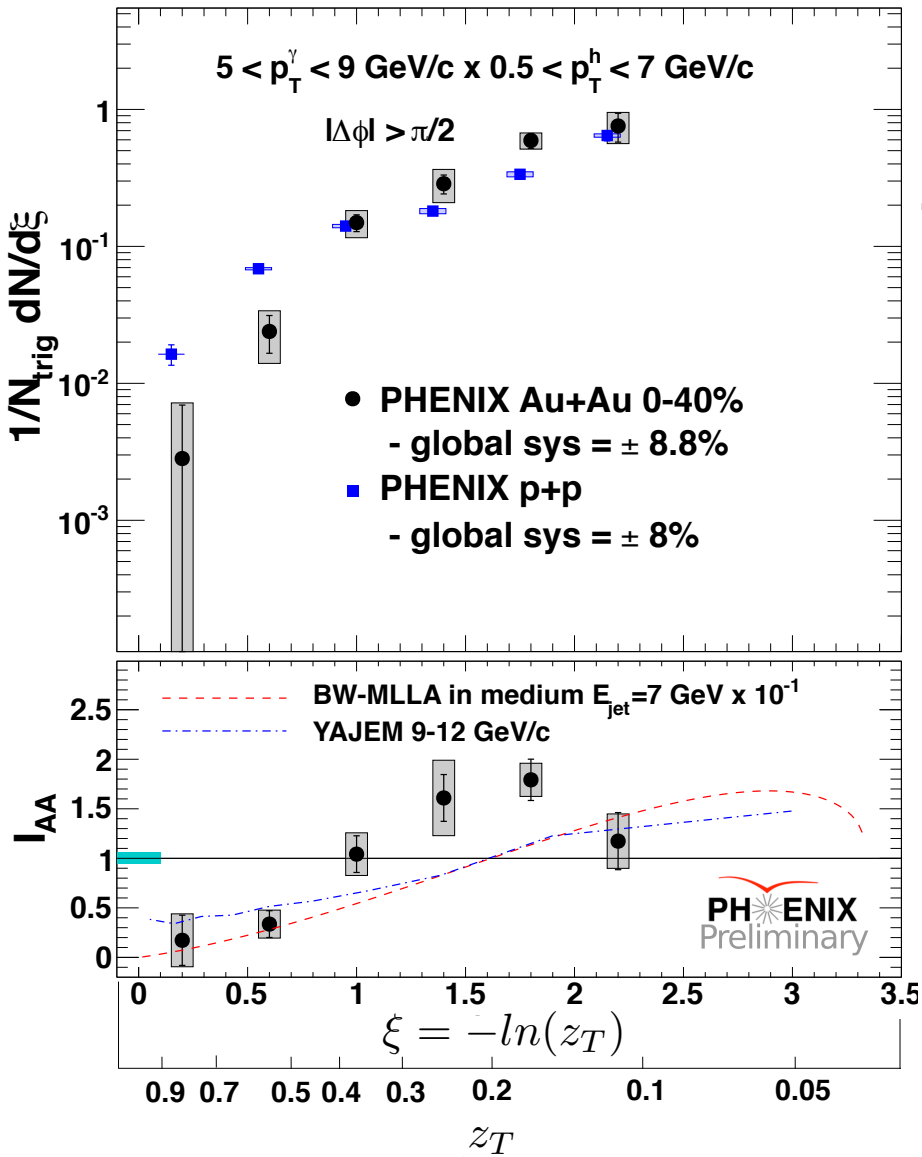
Reminder: These measurements look at the jet shape in a cone of R=0.2-0.5!

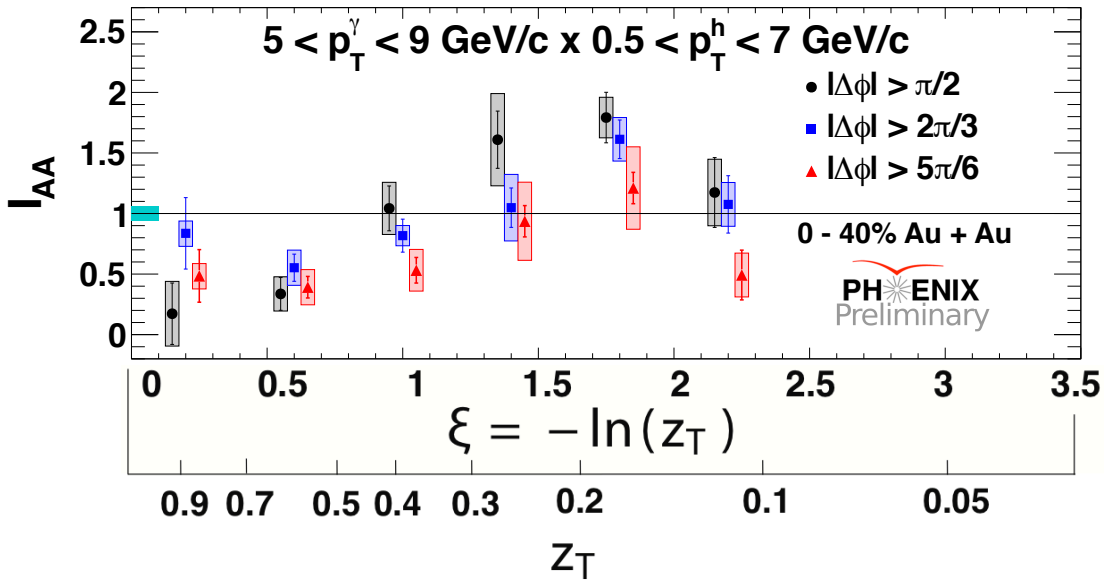
Where does the lost energy go? Missing p_T^{ll}



The momentum difference in the di-jet is balanced by low p_T particles at large angles relative to the away side jet axis

RHIC: Direct Photon - Hadron Correlations





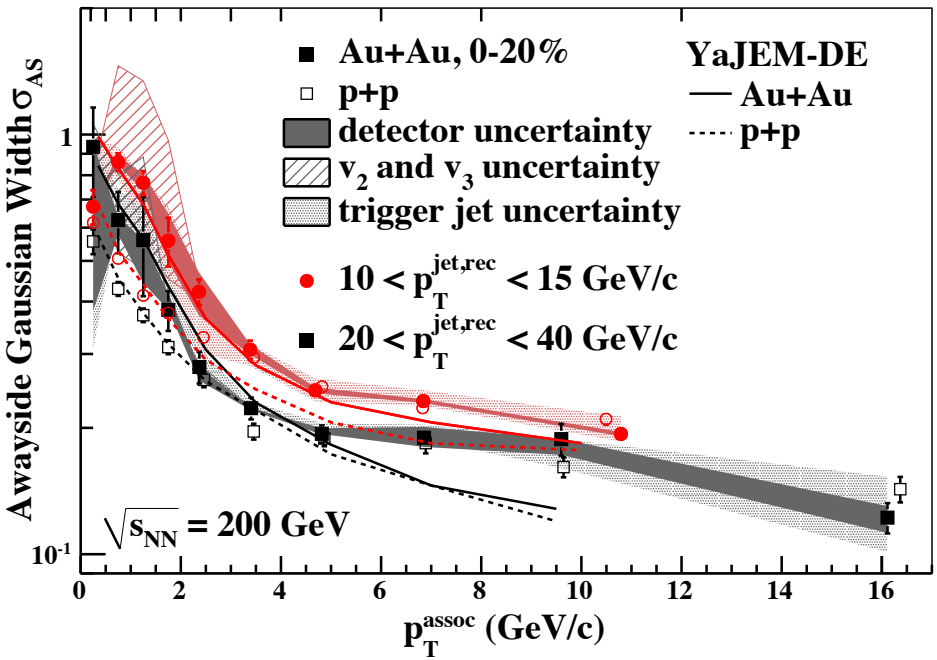
Enhancement at low z

Suppression at high z

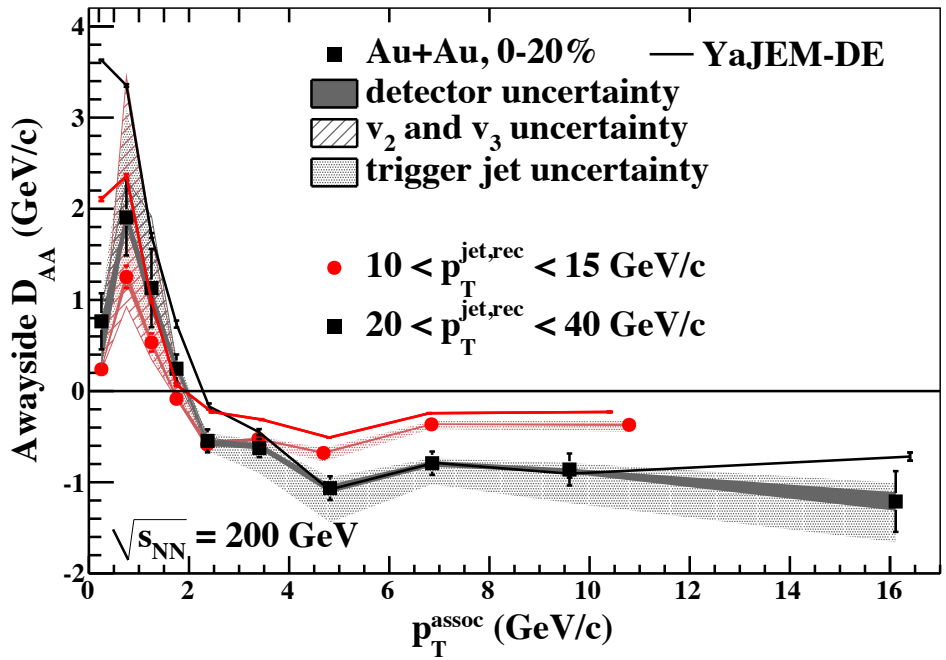
Broadening at low z

RHIC: Jet-Hadron Correlations

Trigger Jet: R=0.4, $p_{T,cut}$=2 GeV/c and EMCal Tower>6 GeV



Energy difference: AuAu-pp

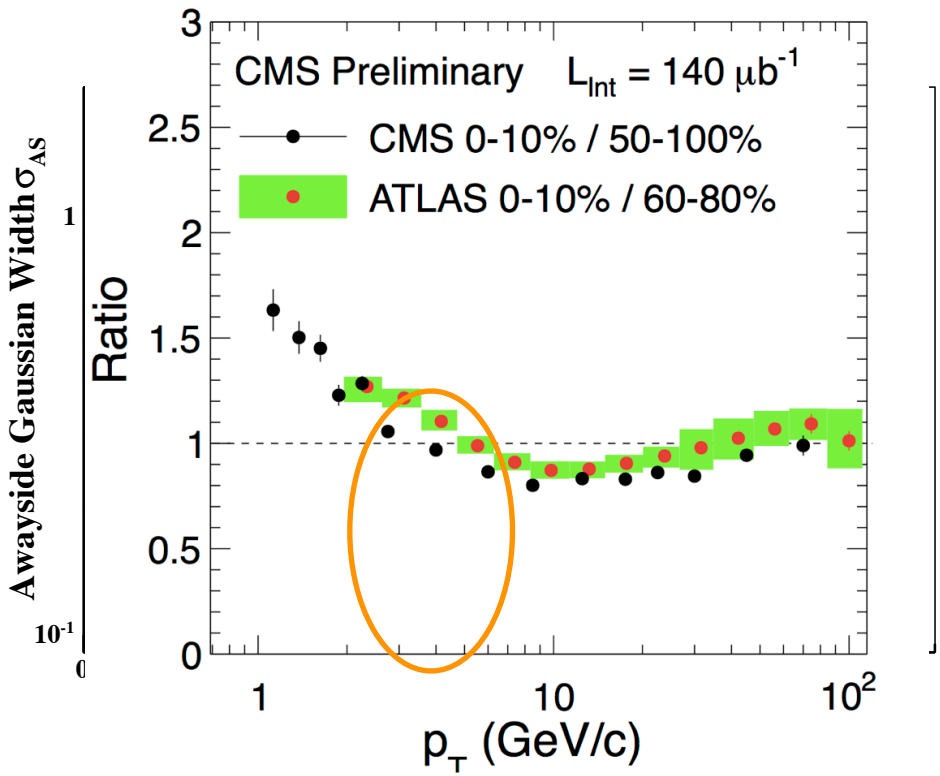


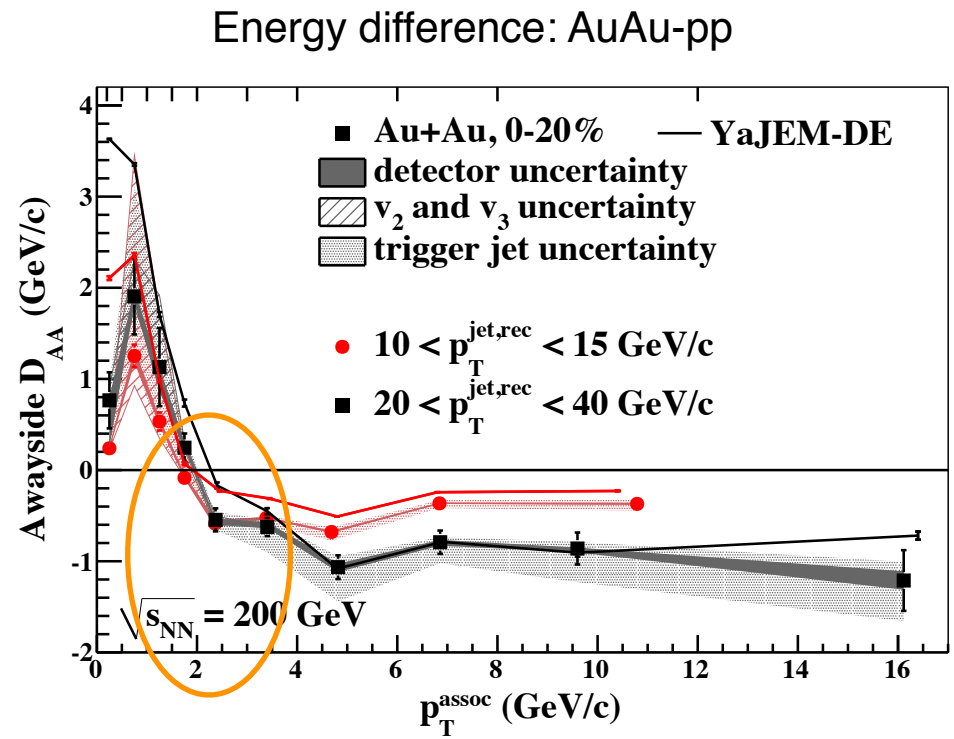
Hint of Jet Broadening at low p_T (large uncertainties due to potential jet v_2/v_3)

Quenched energy at high p_T balanced by low p_T enhancement
Consistent picture between γ^{direct}/jet-hadron correlations @ RHIC!

RHIC: Jet-Hadron Correlations

Trigger Jet: R=0.4, $p_{T,cut}$=2 GeV/c and EMCal Tower>6 GeV





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Quenched energy at high p_T balanced by low p_T enhancement
Consistent picture between γ^{direct}/jet-hadron correlations @ RHIC!

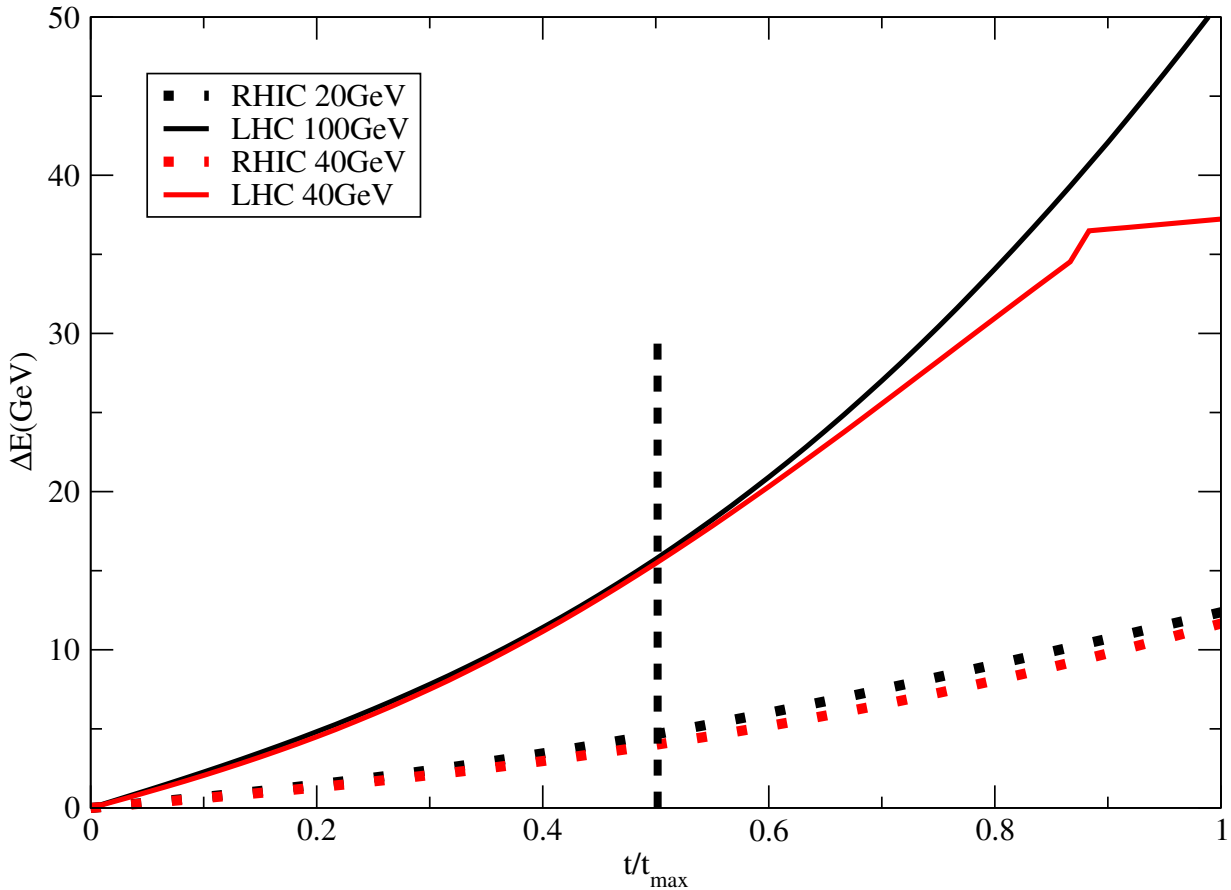
p_T scale of low p_T enhancement: ~2 GeV RHIC, 3-4 GeV LHC

Caveat: RHIC measurement: Statistical. Need per jet quantities (A_j, FF) to allow one-to-one comparison to LHC.

Consistency or a way too simplistic explanation?

We heard about this in more detail in A Majumder's talk today.

Integrated energy loss (in a brick)



t_{max}(LHC)=6fm
t_{max}(RHIC)=4fm

LHC larger energy loss at early times → diffusion in medium → larger angles

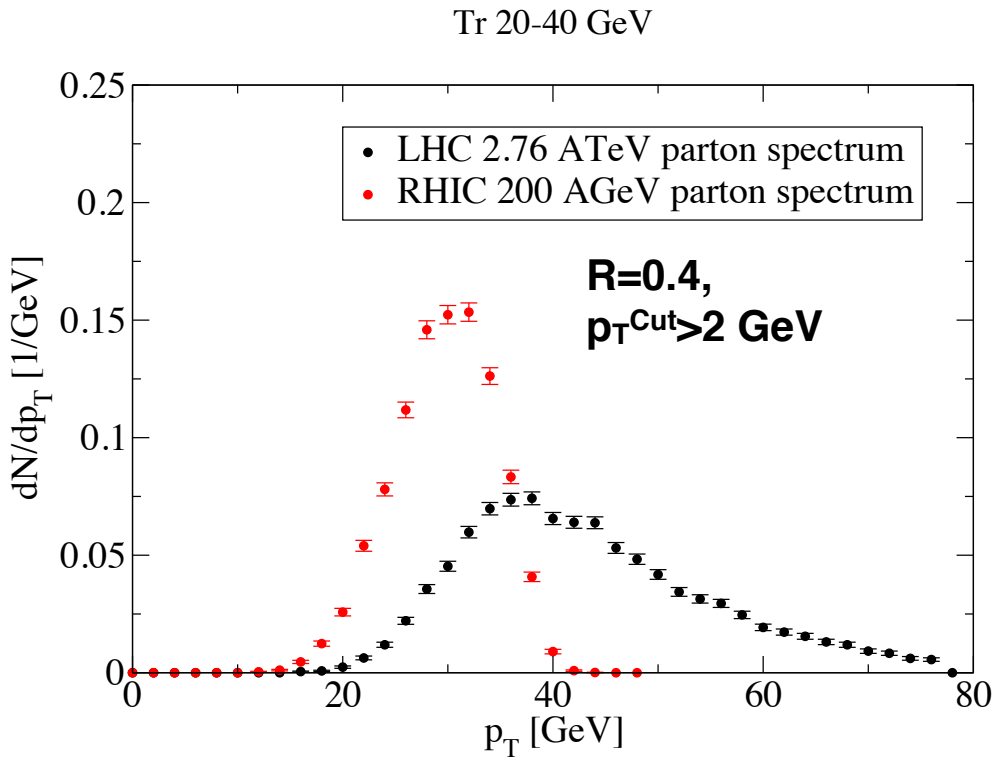
RHIC smaller energy loss at early times→ less diffusion in the medium → closer to jet axis → can qualitatively explain the differences RHIC/LHC (!?)

Easier to study details of soft gluon radiation at RHIC!?

Caveat: Realistic calculation needed? Can current MC models explain RHIC and LHC at the same time?

Biases are not always bad ...

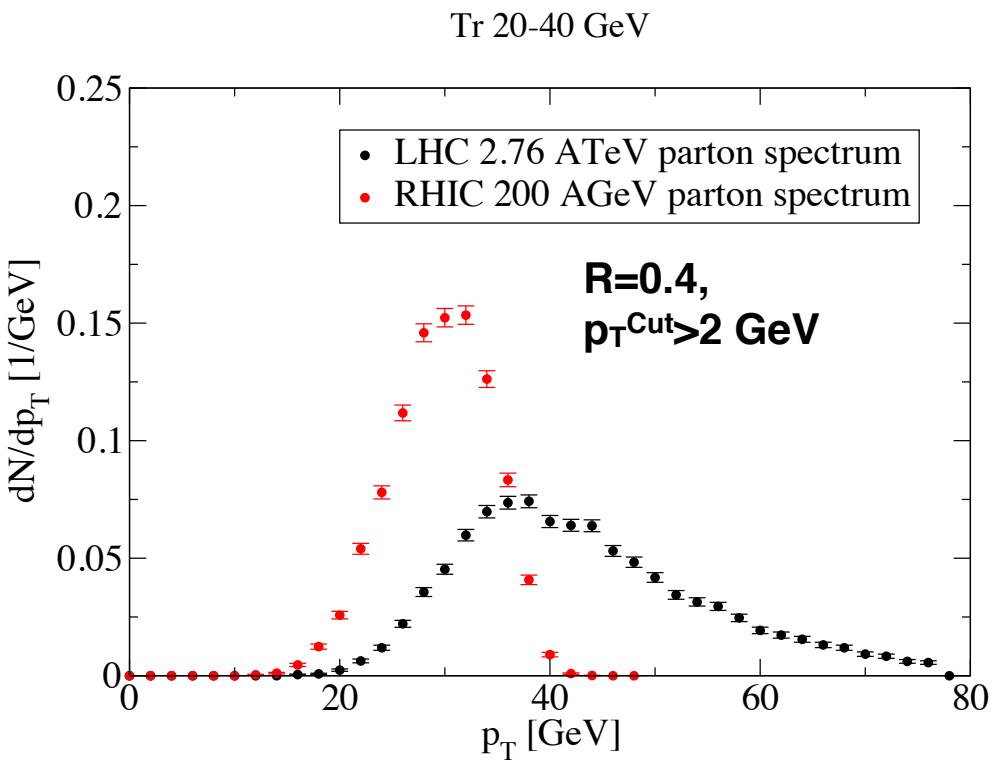
T. Renk, Phys.Rev. C87 (2013) 024905

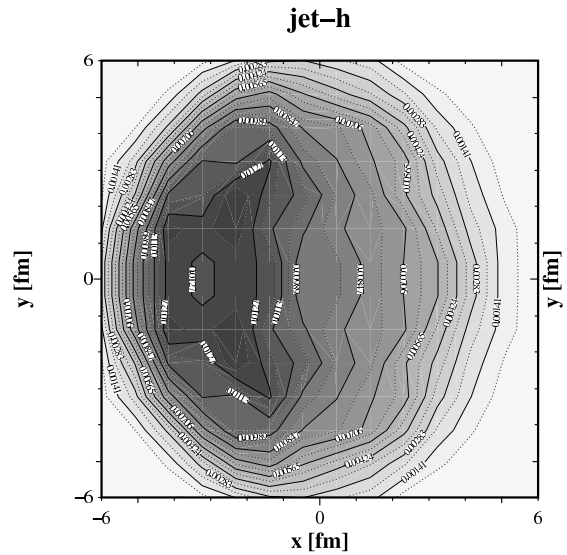


Due to the steeply falling spectrum at RHIC, even with imposing biases (p_T^{Cut}, ...), a good correlation to the initial parton energy is preserved

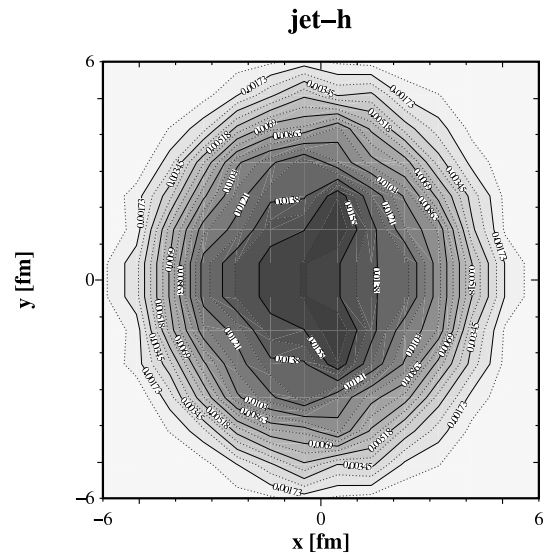
Biases are not always bad ...

T. Renk, Phys.Rev. C87 (2013) 024905





p_T^{Cut}>2 GeV



Ideal

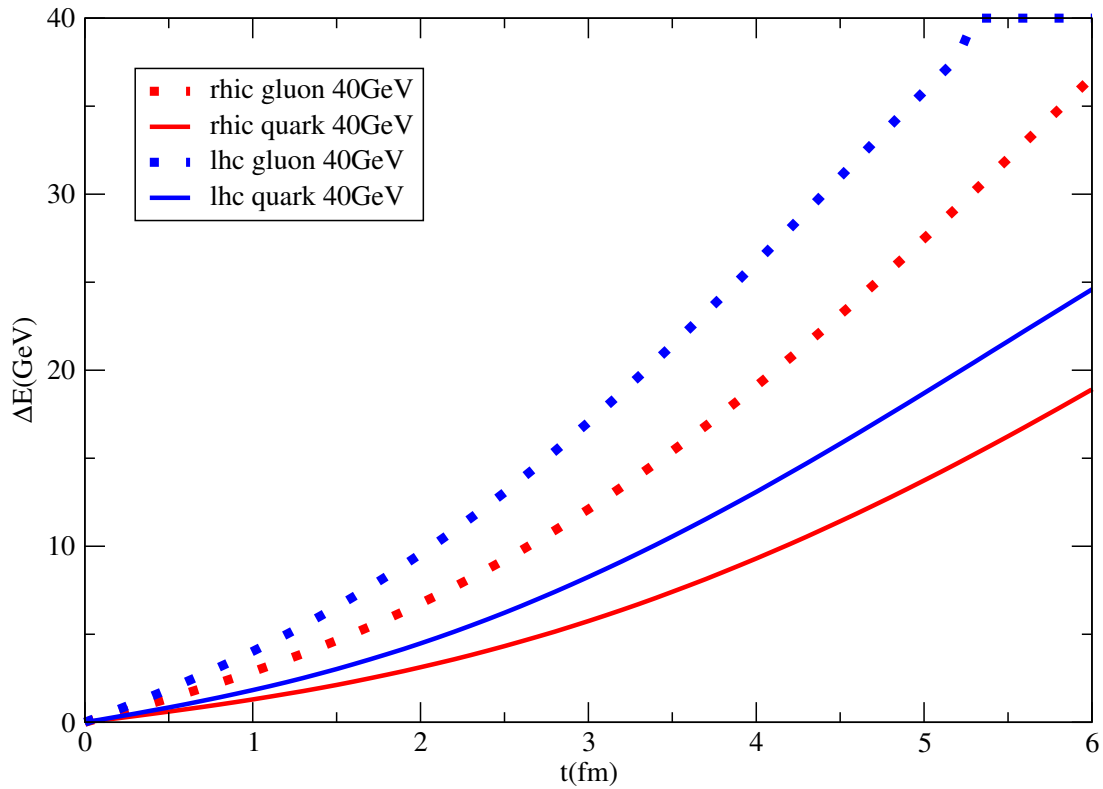
Due to the steeply falling spectrum at RHIC, even with imposing biases (p_T^{Cut}, ...), a good correlation to the initial parton energy is preserved

Biases (p_T^{Cut}, ...) can be used to change systematically the pathlength of the recoil jet

Biases (p_T^{Cut}, ...) can be further utilized to favor gluon recoil jets

Caveat: Can only compare to MC models!

“Direct” Comparison of RHIC and LHC energy loss

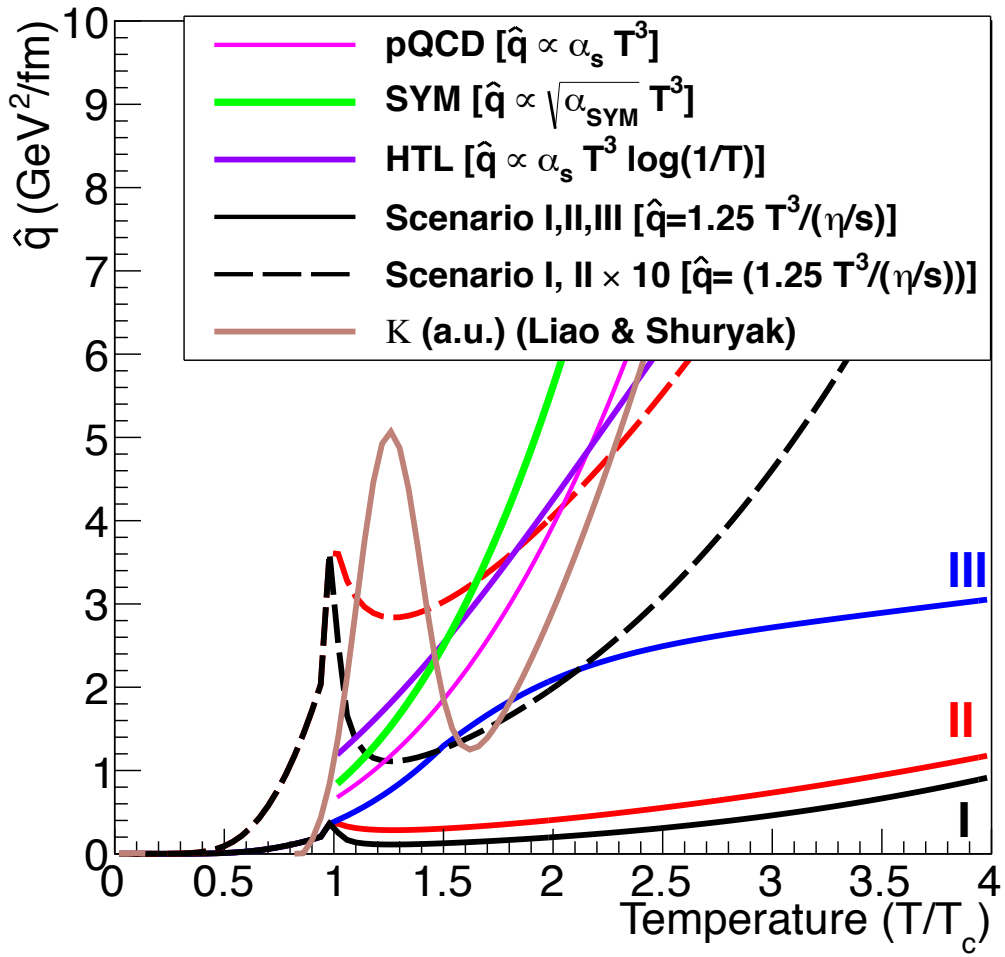


γ^{direct}-jet at the LHC (quark jet) compared to di-jets at RHIC (quark jets) @ 40-50 GeV

Caveat: To remove geometric biases one needs an unbiased jet measurement at RHIC!

Temperature dependence of energy loss

We had talks this morning discussing this in more detail!



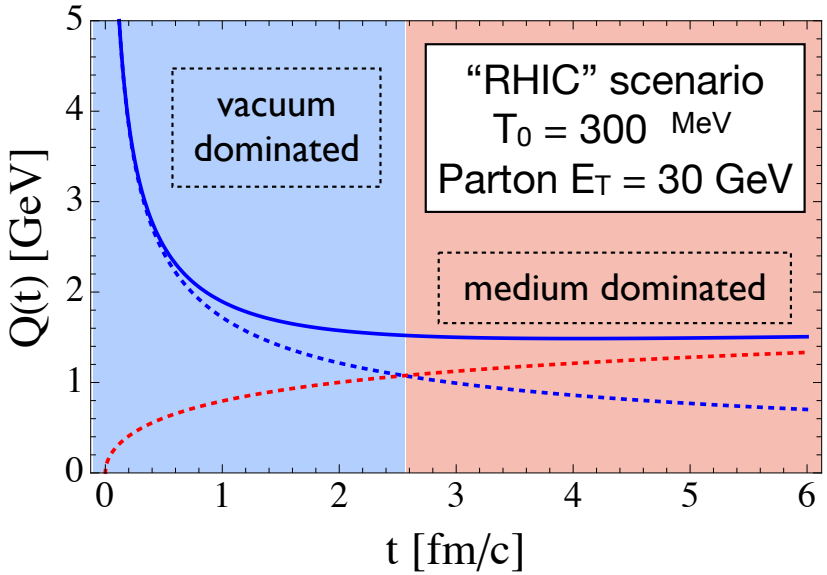
$$\eta / s = \text{const} \times T^3 / \hat{q}$$

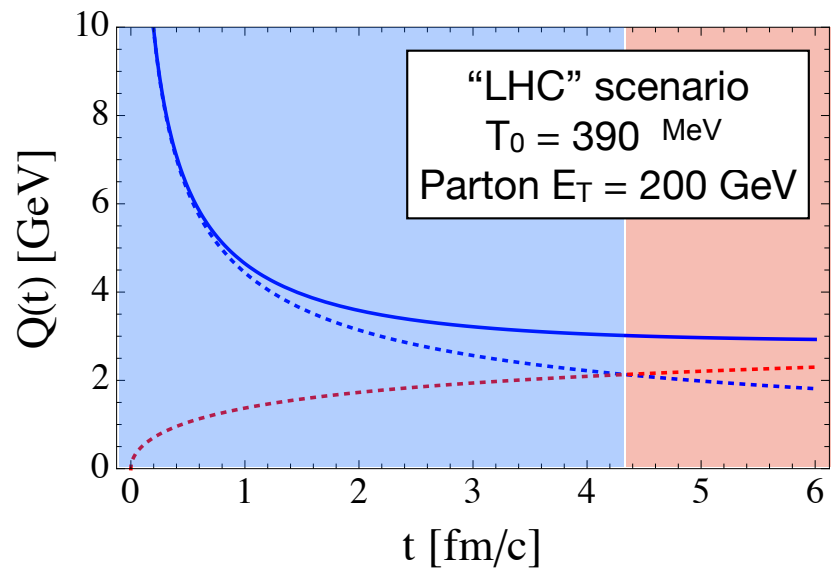
for weak coupling (PRL 99, 192301, 2007)

Differential measurements of transport properties of the QGP: Temperature dependence of q (ê, η/s, ..)

Sensitivity of q to 1-2 T_C requires RHIC measurements for different colliding systems and smaller √s (LHC larger initial T)

Testing the quasi-particle nature of the QGP





Jet Virtuality: Controls the Physics of Radiative Energy Loss

$$Q^2(L) \approx \max\left(\hat{q}\,L, \frac{E}{L}\right)$$

medium *vacuum*

RHIC: 20 GeV parton, L = 3 fm

$$\hat{q}\,L \approx 1.5\,\mathrm{GeV}^2 \quad \approx \quad \frac{E}{L} \approx 1.5\,\mathrm{GeV}^2$$

Virtuality of primary parton is medium influenced and small enough to "experience" the strongly coupled medium

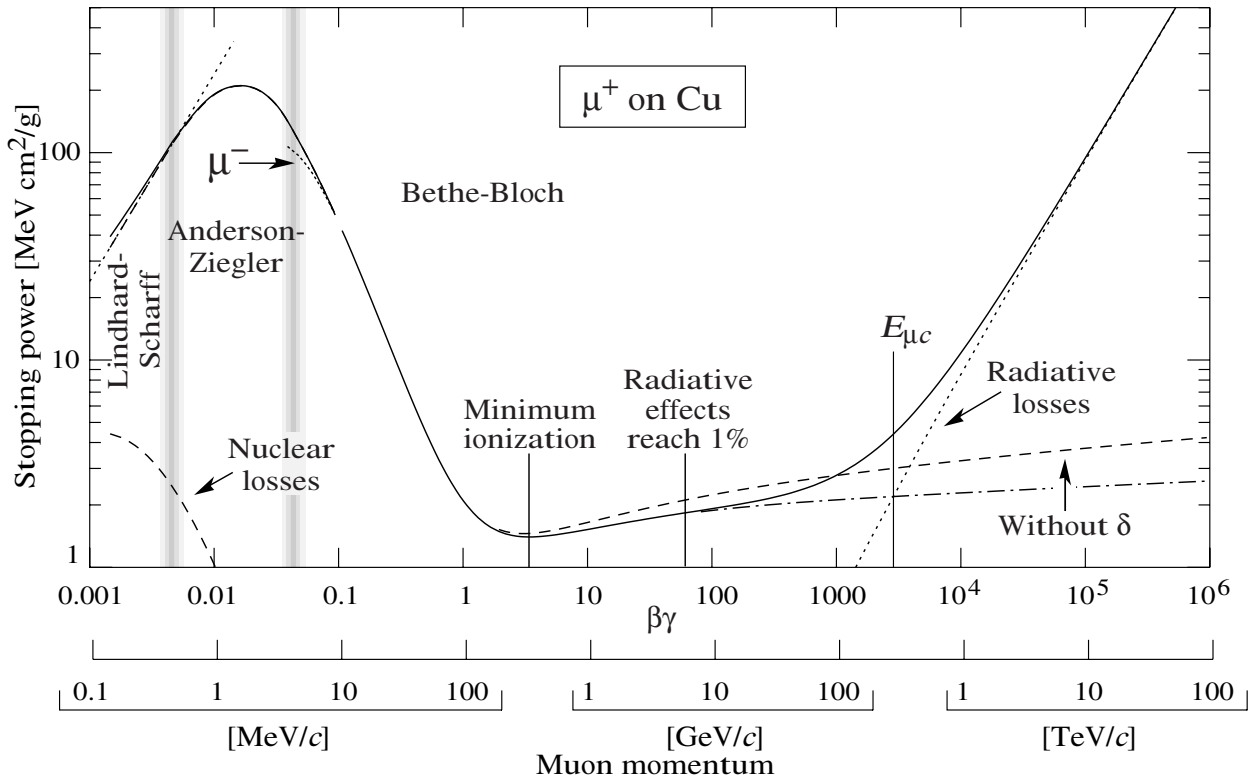
LHC: 200 GeV parton, L = 3 fm

$$\hat{q}\,L \approx 3.5\,\mathrm{GeV}^2 \quad < \quad \frac{E}{L} \approx 13\,\mathrm{GeV}^2$$

Virtuality of primary parton is vacuum dominated and only its gluon cloud "experiences" the strongly coupled medium

RHIC can explore the region between the weak and strong coupling limits!

"QCD Analog of Bethe-Bloch"

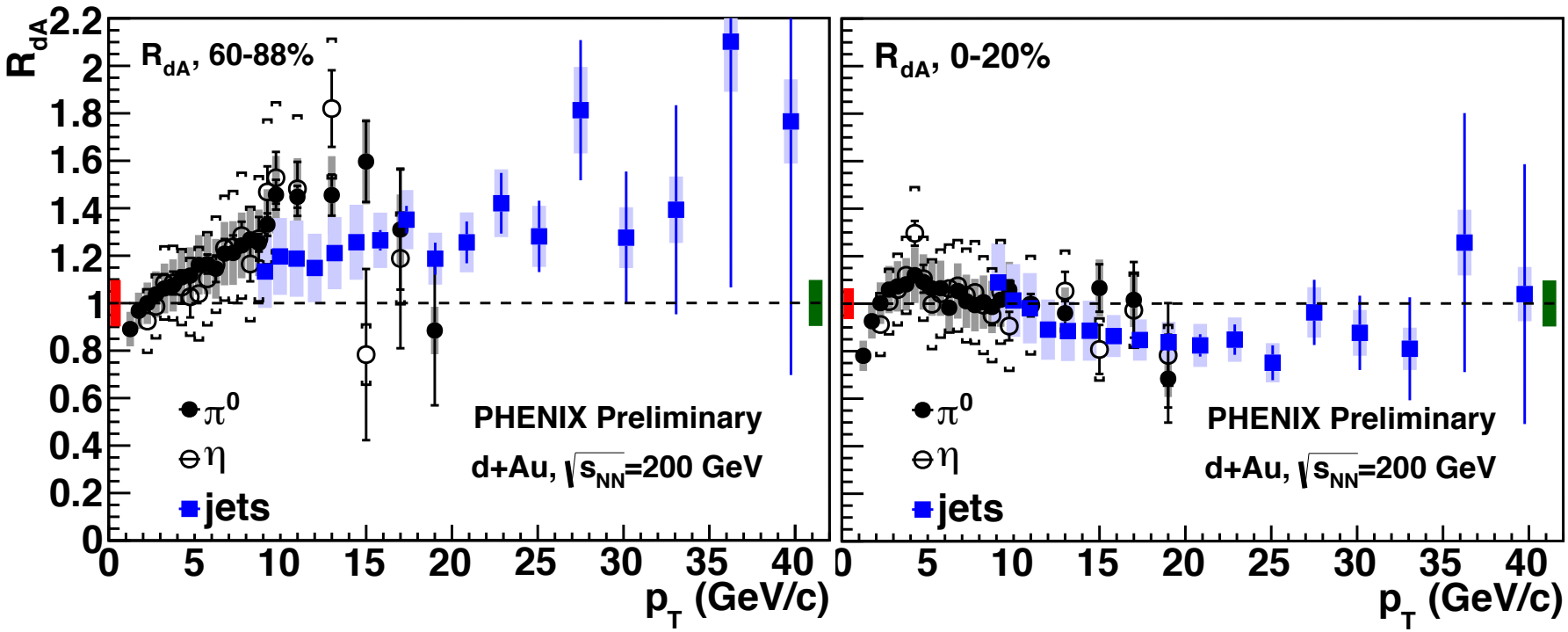


At the LHC/at large jet energies, jet modification dominated by radiative energy loss

At lower jet energies balance/interplay between radiative energy and collisional energy loss

RHIC and LHC combined will map out the stopping power –dE/dx of hot and dense QGP for colored patrons

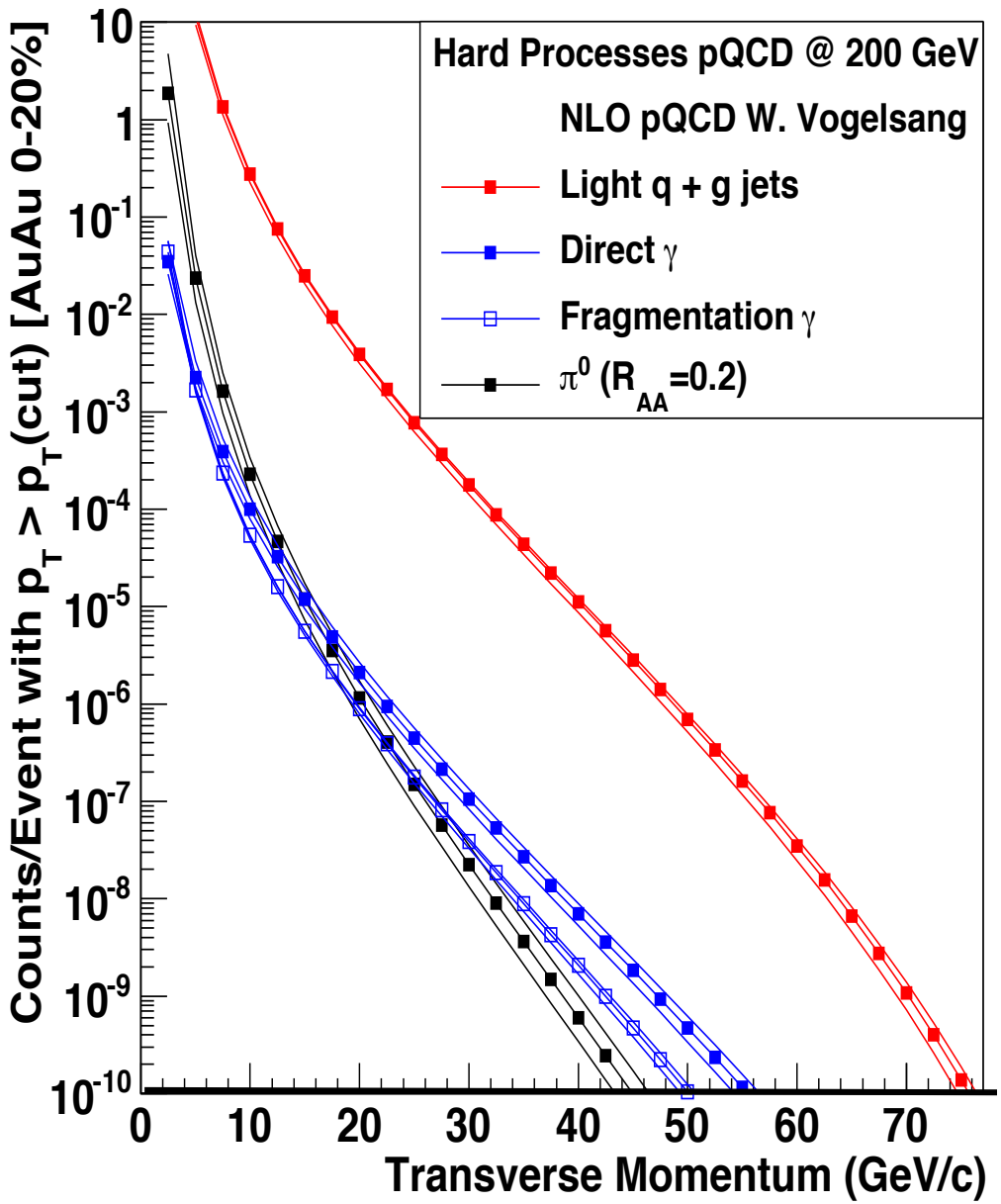
RHIC is always good for surprises: d+Au R_{AA}

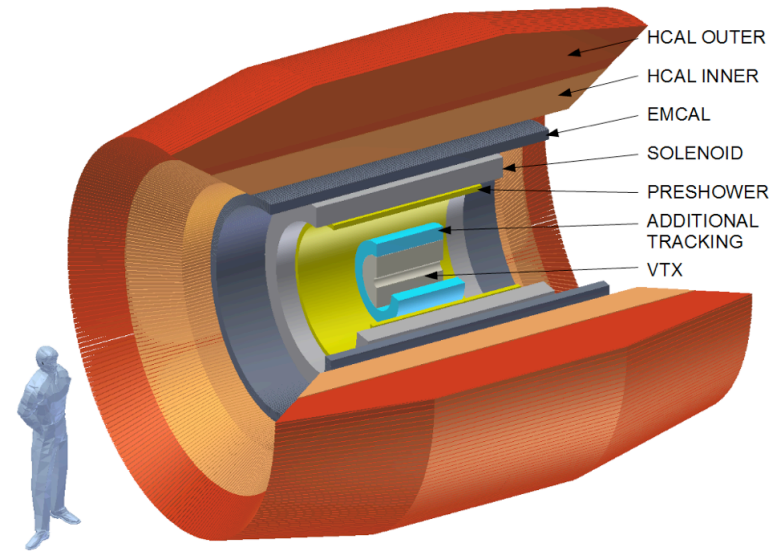


Enhancement of Jet R_{AA} in peripheral d+Au collision?

<u>Caveat:</u> We saw yesterday (G. David) that centrality determination in d+Au is not trivial ...

Future: Precision Jet Measurements @ RHIC / sPhenix





Full Calorimetry

Large kinematic reach
(can be used to reduce current biases)

Precision Jet measurements with the flexibility of RHIC concerning collision energy and system sizes

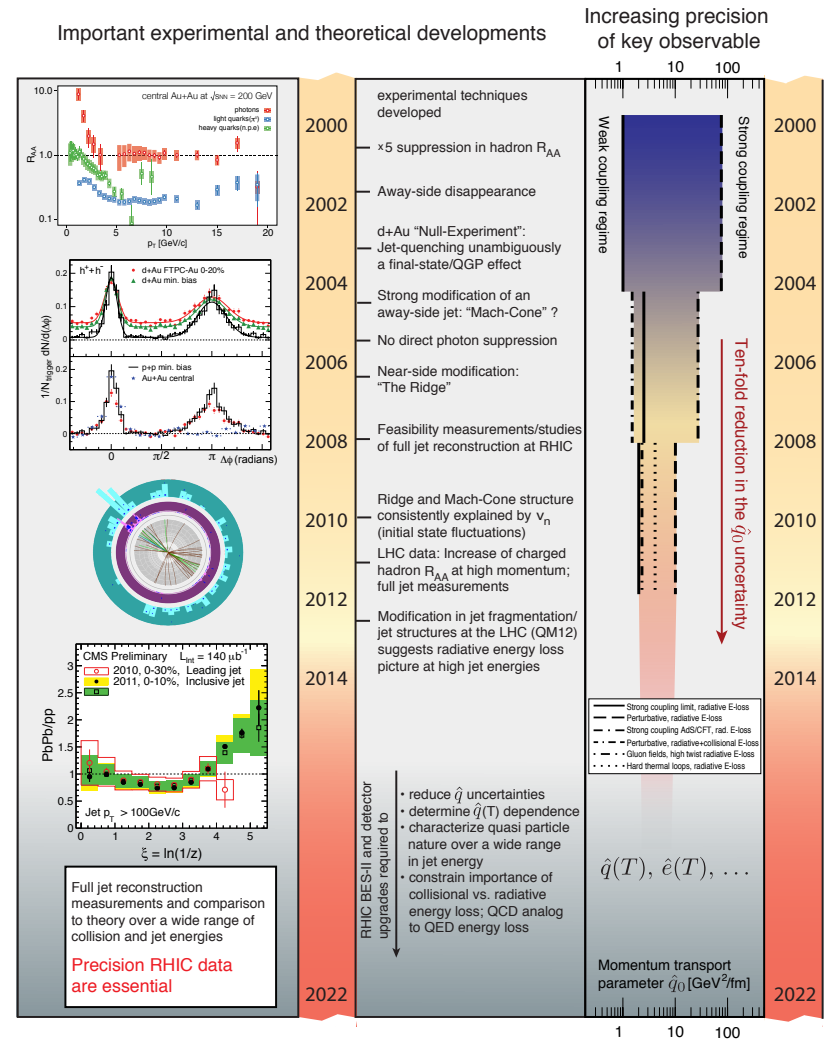
Can this be utilized to study pre-equilibrium effects?

Summary

Consistent (qualitative) jet quenching picture at RHIC emerging: suppression at high z, enhancement at low z. Jet broadening has to be quantified.

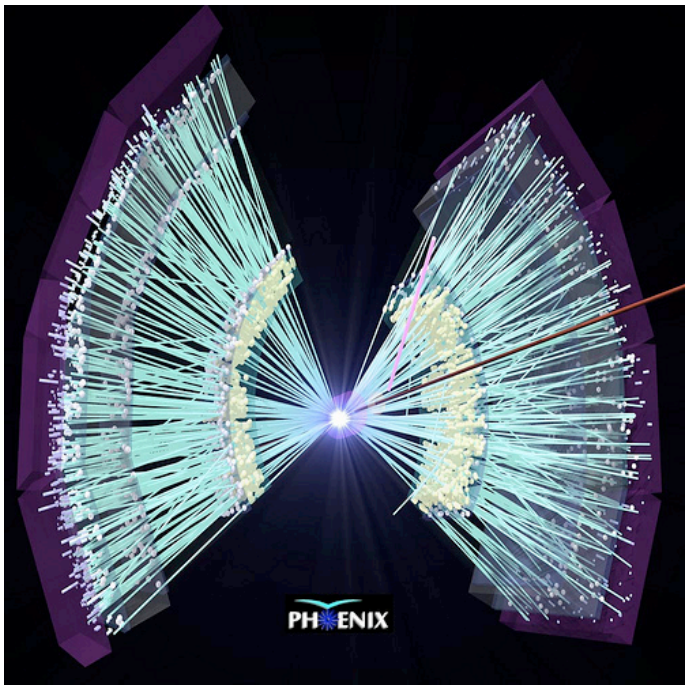
Can current LHC and RHIC quenching measurements be explained in a consistent picture?

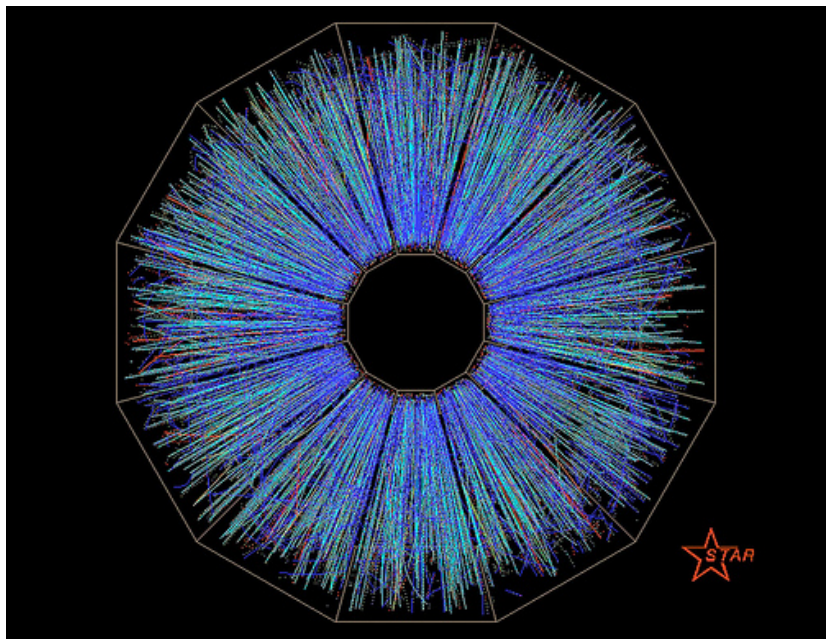
In many respects RHIC and LHC a complementary and an active jet program at RHIC is essential to further and quantify our understanding of partonic energy loss in the future!



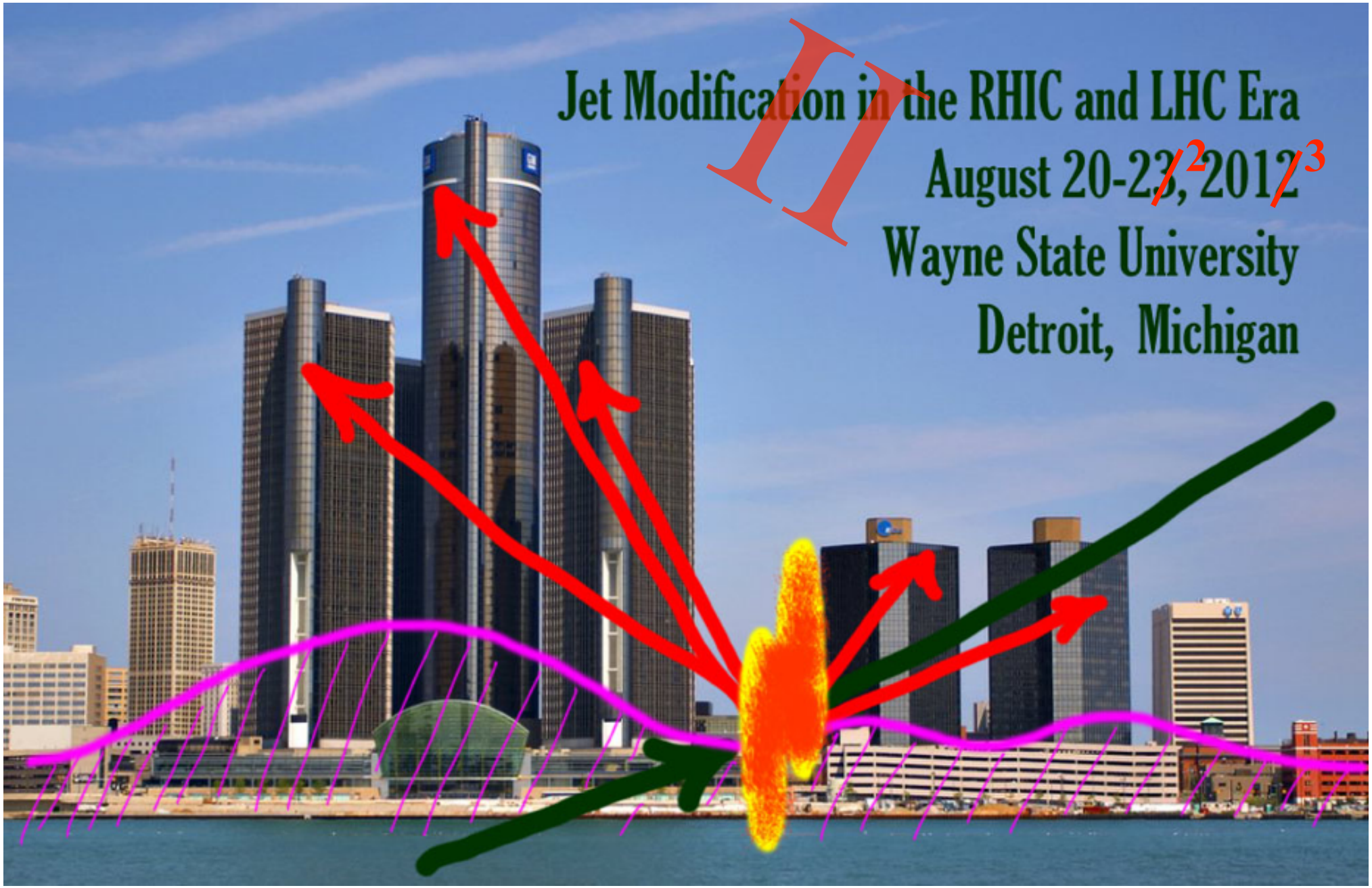
Near Future: RJE(T)T ?

RJE(T)T=RHIC **J**et **E**xperiments (& **T**heory) **T**askforce



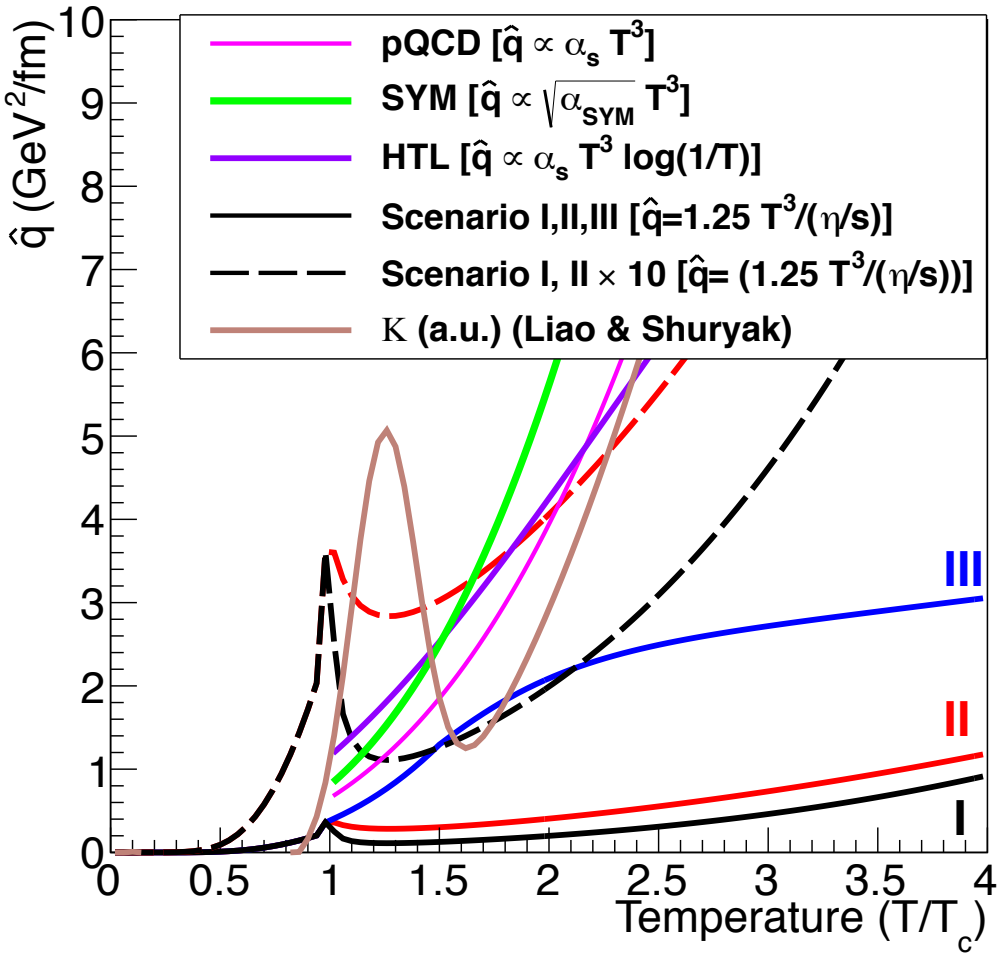


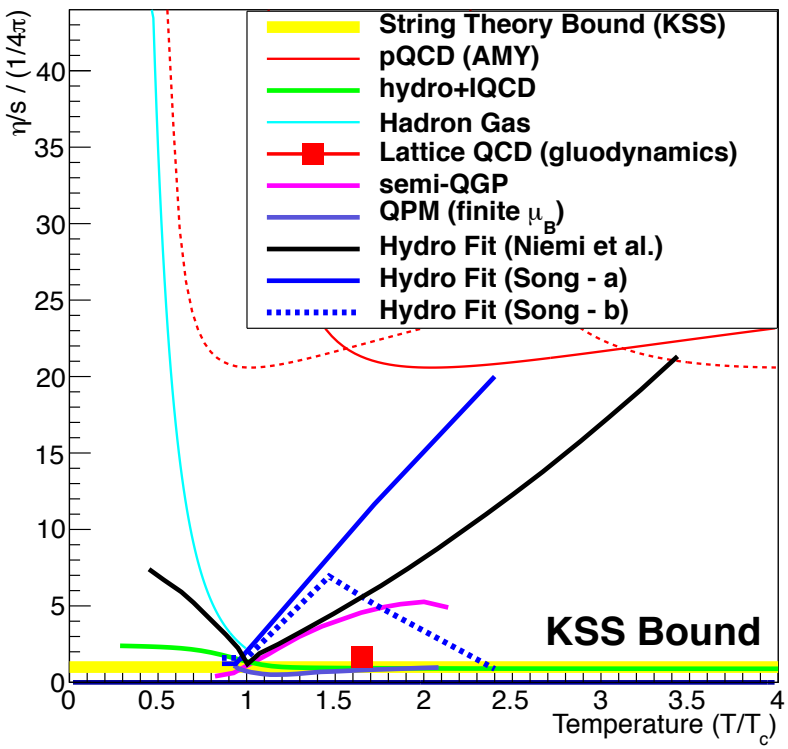
Can something like this be realized at RHIC?


Jet Modification in the RHIC and LHC Era
August 20-23, 2012
Wayne State University
Detroit, Michigan

Backup

Temperature dependence of energy loss





$\eta / s = \text{const} \times T^3 / \hat{q}$ for weak coupling (PRL 99, 192301, 2007)

η/s saturates in strong coupling, but energy loss increases w/o limit

Majumder, BM, W
that η/s and q̂ are
weak coupling in
[PRL 99, 192301

$\eta / s = \text{const} \times$

At strong couplin
at 1/4π, but q̂ incr
limit. Unambiguou
weak vs. strong c

Where does the lost energy go? Missing $p_T^{||}$

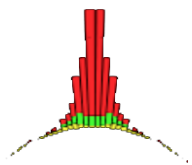
Taken from C. Roland (CMS), QM11

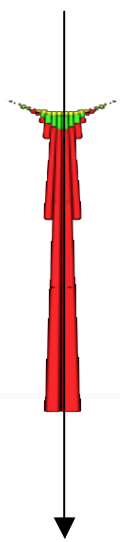
Missing $p_T^{||}$: $\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$ $|\eta| < 2.4$

Calculate projection of p_T on leading jet axis and average over selected tracks with

$p_T > 0.5$ GeV/c and

$|\eta| < 2.4$





Leading Jet defines direction

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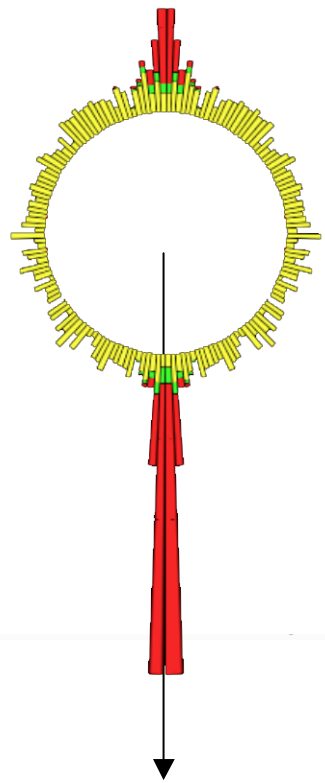

Sum all tracks in the event

Where does the lost energy go? Missing $p_T^{||}$

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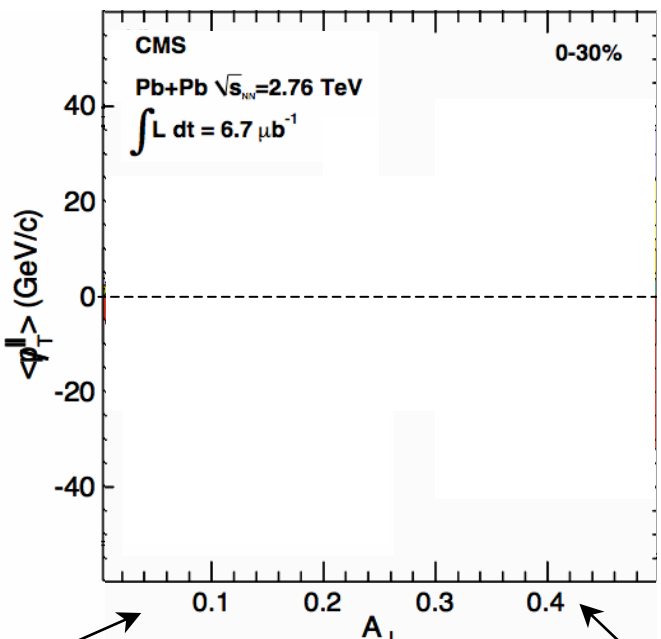
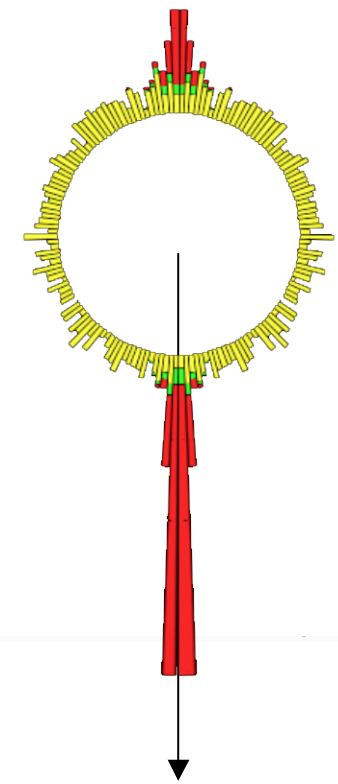
0-30% Central PbPb



excess away from leading jet

excess towards leading jet



alanced jets

unbalanced jets

Where does the lost energy go? Missing $p_T^{||}$

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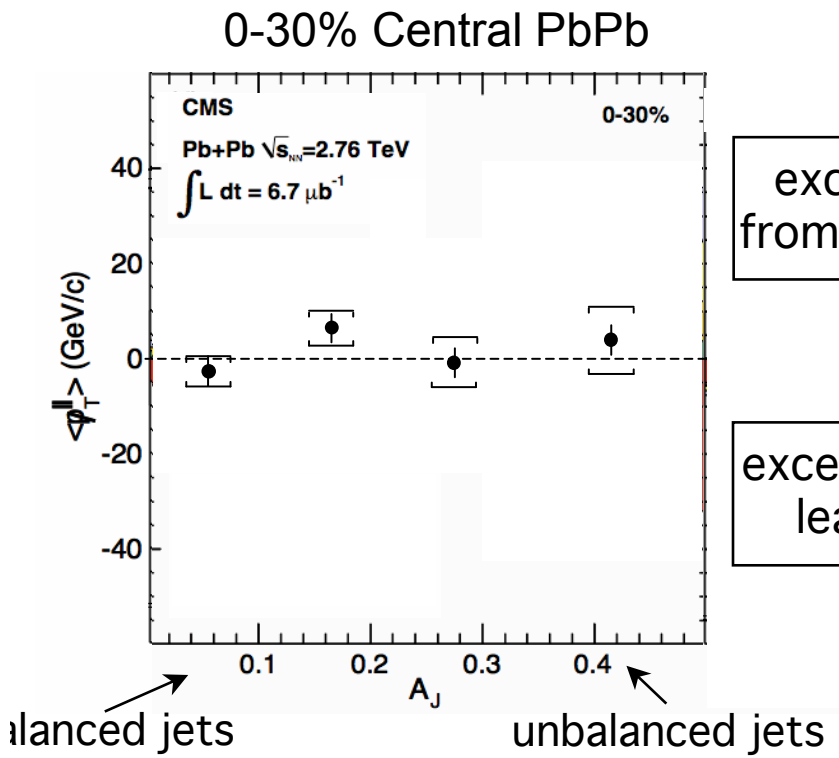
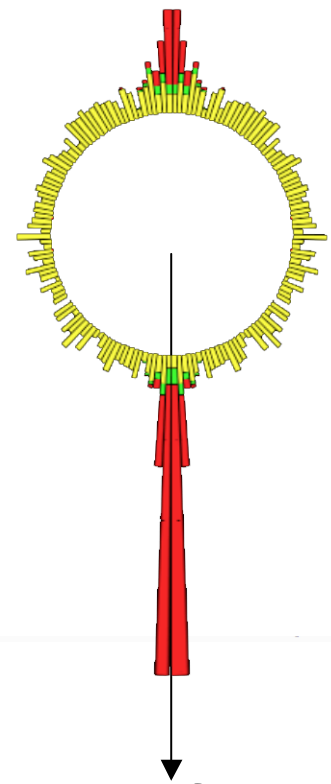


excess away from leading jet

excess towards leading jet

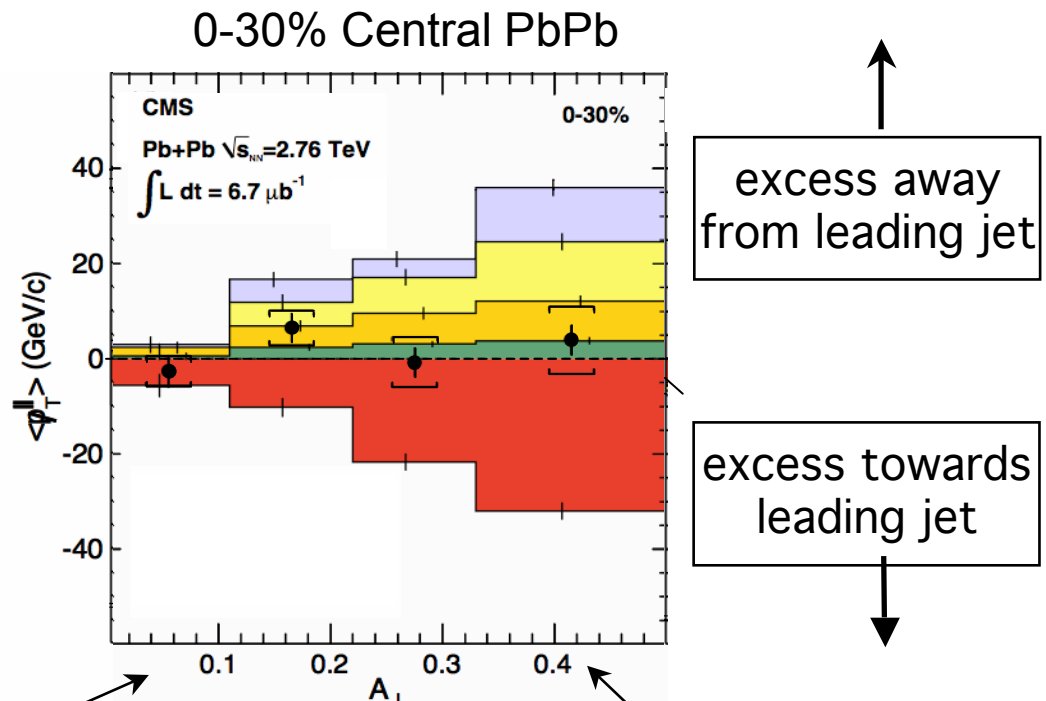


Integrating over the whole event final state the momentum balance is restored

Where does the lost energy go? Missing $p_T^{||}$

Taken from C. Roland (CMS), QM11

Missing $p_T^{||}$: $\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$ $|\eta| < 2.4$

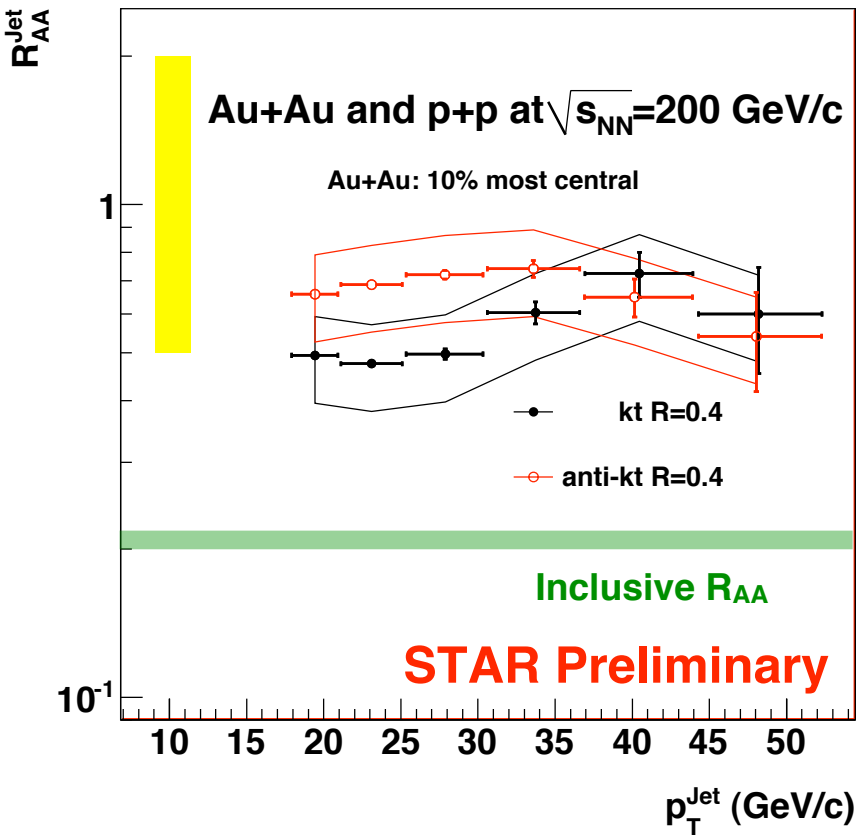


Calculate missing p_T in ranges of track p_T:

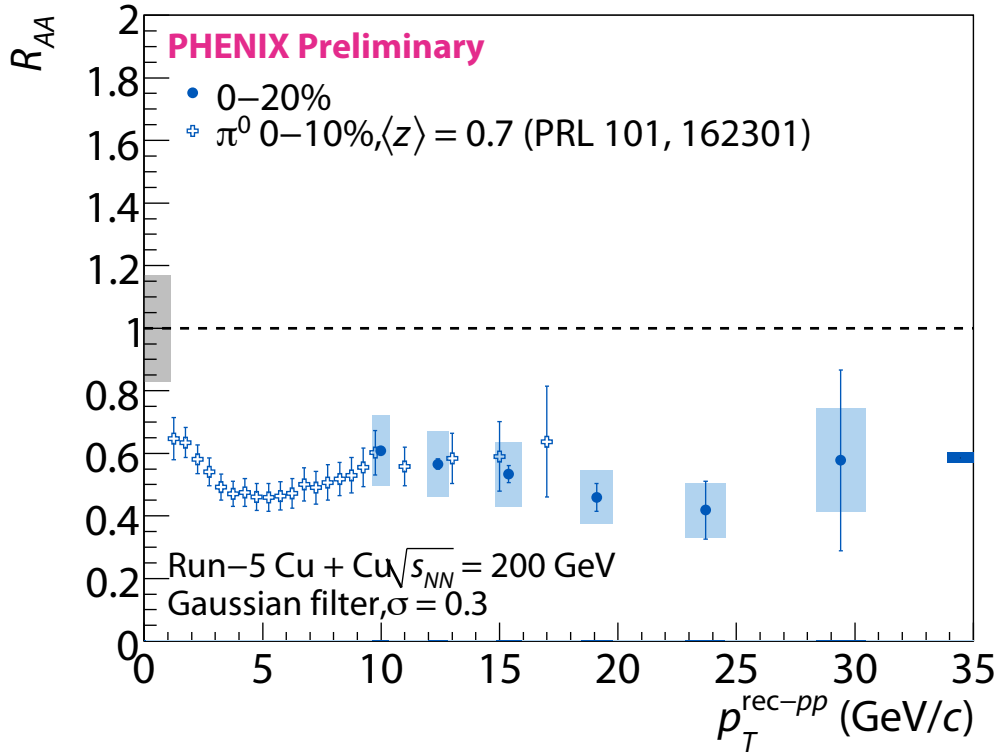
- > 0.5 GeV/c
- 0.5 - 1.0 GeV/c
- 1.0 - 2.0 GeV/c
- 2.0 - 4.0 GeV/c
- 4.0 - 8.0 GeV/c
- > 8.0 GeV/c

The momentum difference in the dijet is balanced by low p_T particles

Jet R_{AA} in central Au+Au and Cu+Cu



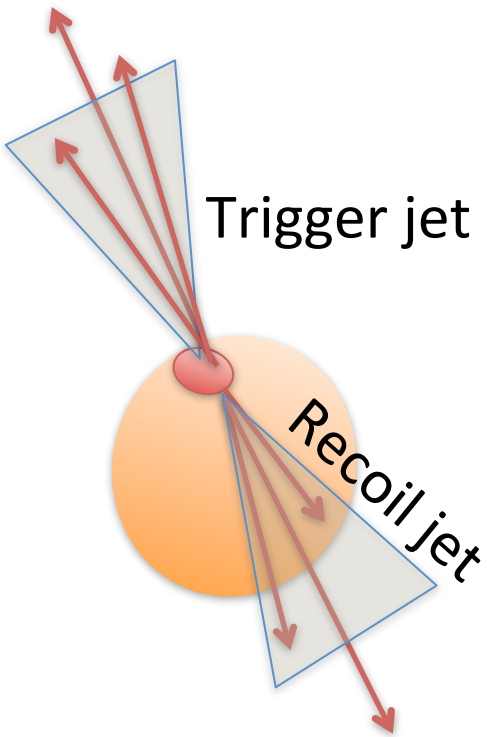
Y. Lai QM2009



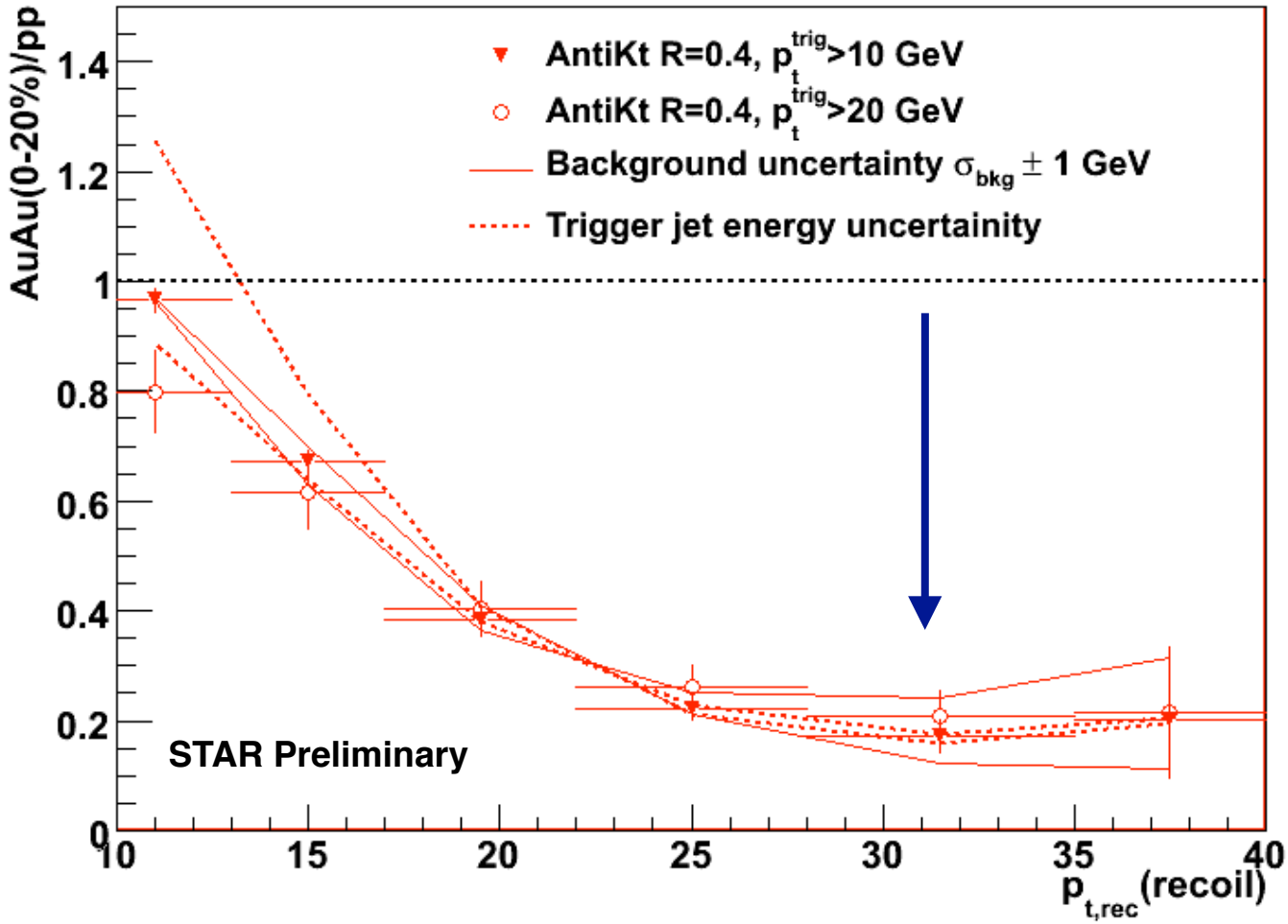
STAR sees a substantial fraction of jets in Au+Au
- in contrast to x5 suppression for light hadron R_{AA}

Strong suppression (similar to single particle)
in Cu+Cu measured by PHENIX

Recoil jet spectrum R_{AA}



E. Bruna QM2009



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