High-p_T & jet physics opportunities @ RHIC in the LHC era

and

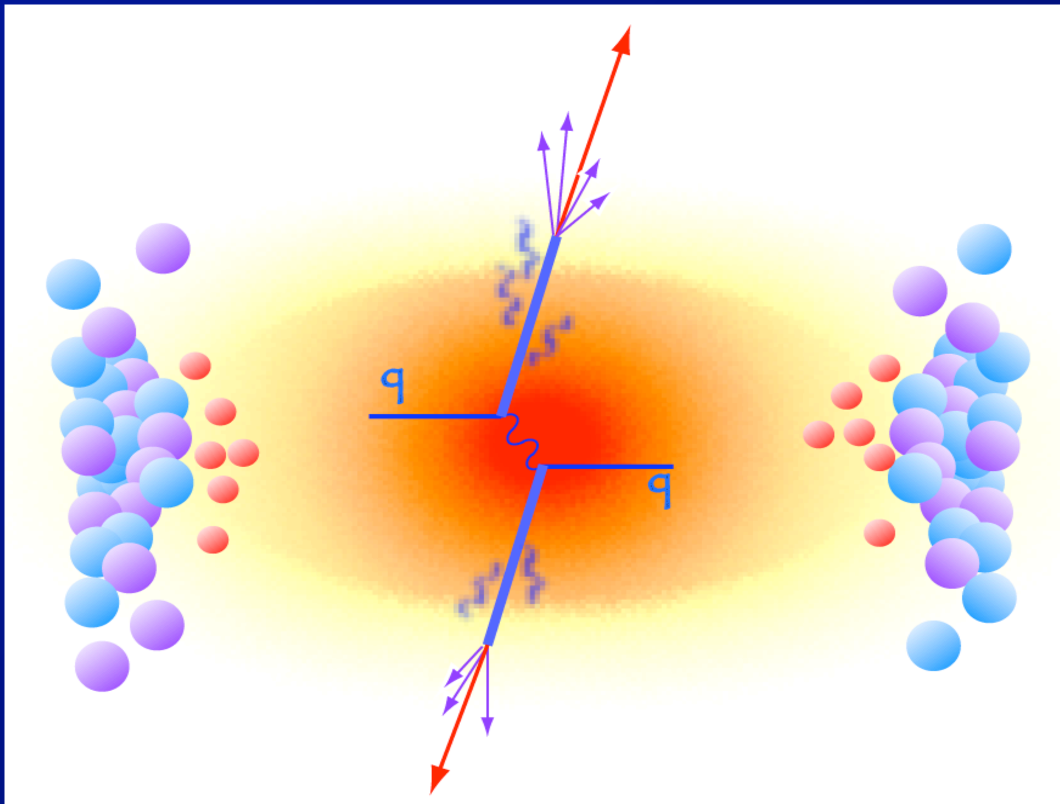
How sPHENIX proposes to exploit them

Brian. A Cole, Columbia University
ATLAS and (s)PHENIX

The big picture

Why jet quenching?

- We are probing the (s)QGP with a single or two correlated calibrated, colored particle(s).
  - ⇒ Directly measure the consequences of the interactions of the probes with the (s)QGP.



Our goals in studying jet quenching should be to answer the "big" questions

answering questions like "what is $\hat{q}$"? only a step along the path (in my opinion)

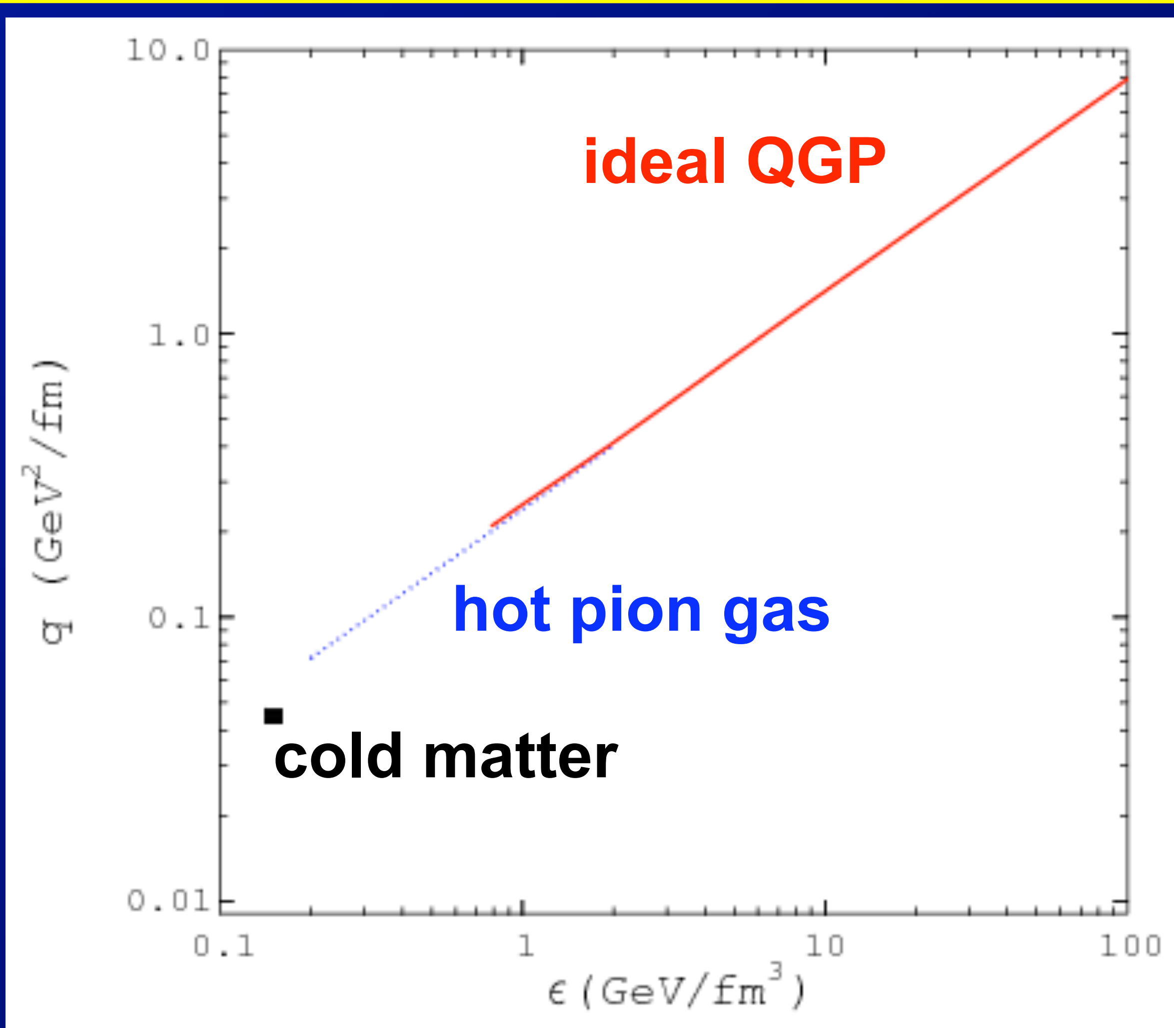
qhat evolution ca. 2002

Classic paper by R Baier:

"Jet Quenching"

hep-ph/0209038

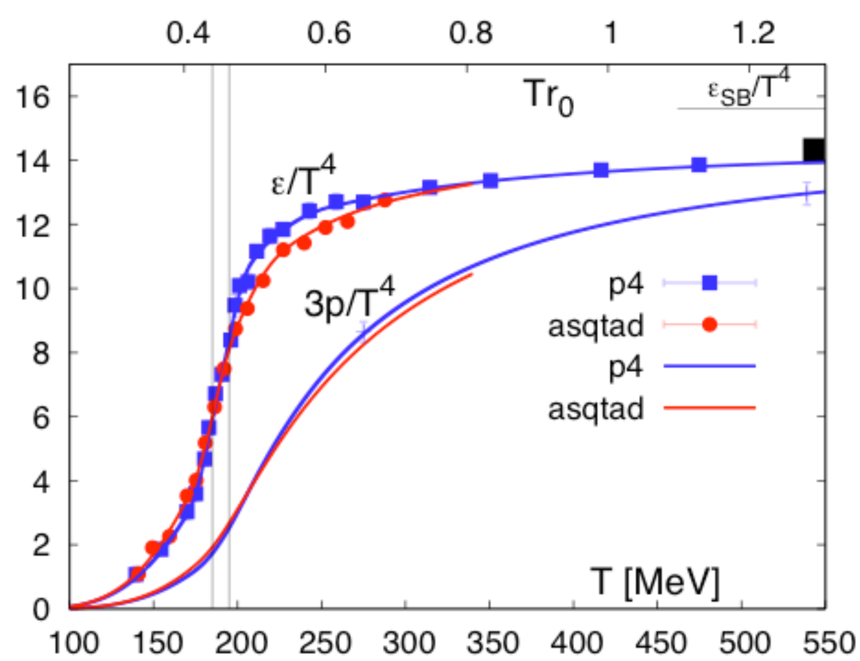
Nucl. Phys. A715 (2003) 209-218



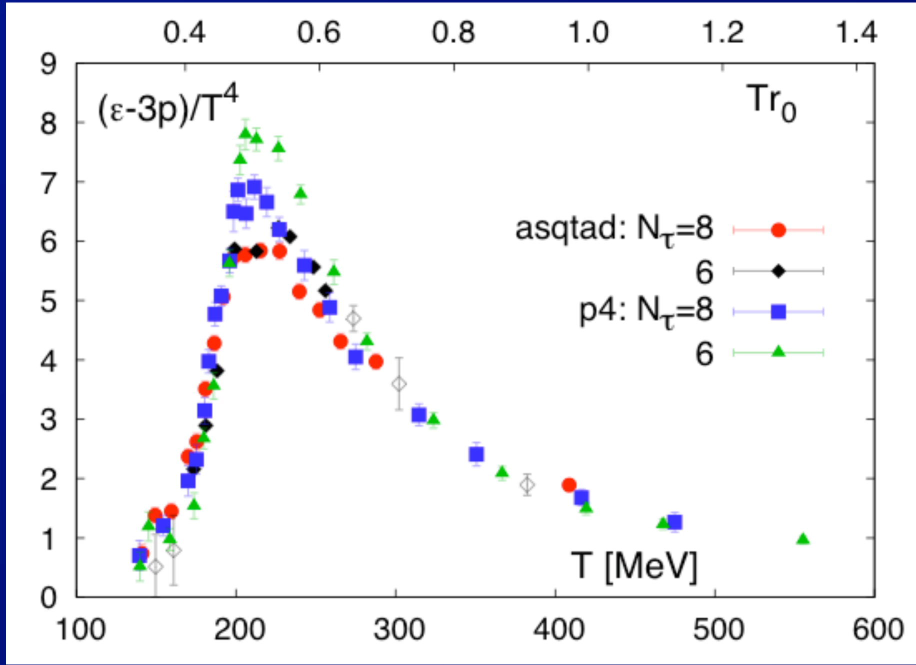
- Picture that many of us have had in our heads
  - But, we've learned something since 2002
    - ⇒The QGP near T_c is not ideal

QCD Thermodynamics on Lattice

Energy Density or pressure



Thermodynamic trace anomaly



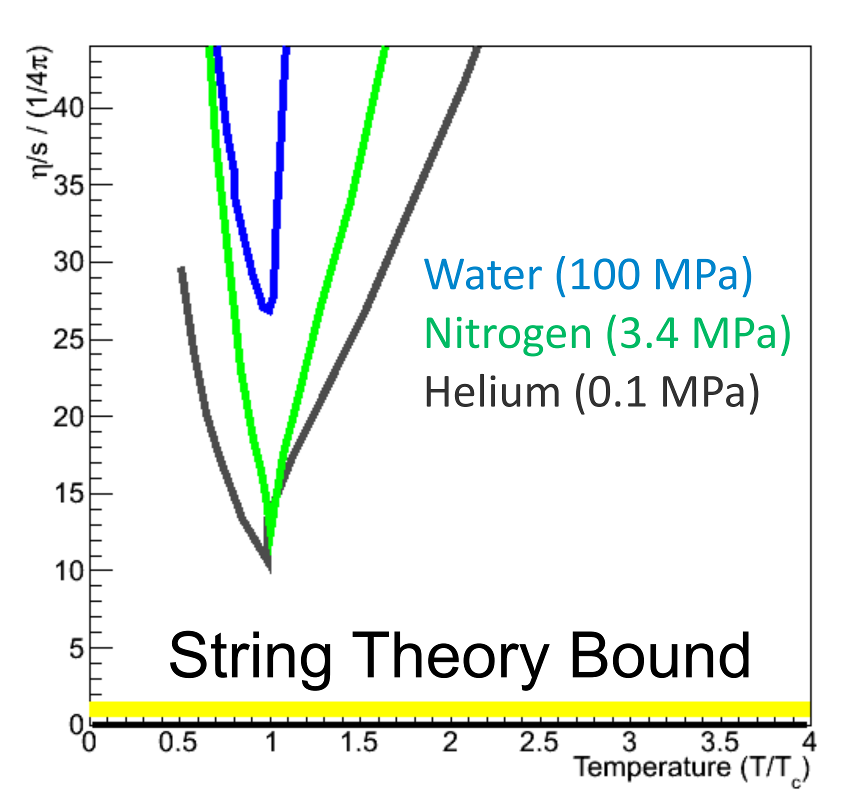
- Trace anomaly $(\varepsilon-3p)/T^4$ an interaction measure
  - Rapid change in QGP coupling strength between T_C and $2T_C$.

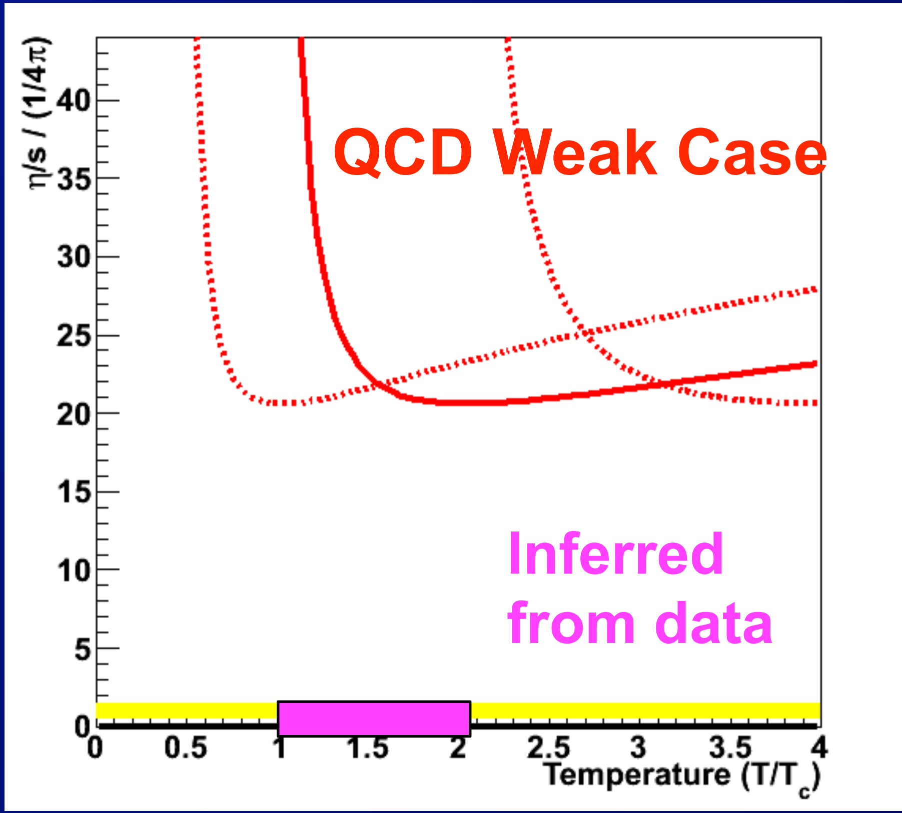
⇒Our goal should be to (e.g.) experimentally verify this change in QGP properties and understand its microscopic origin and implications.

QGP: η/s extremes

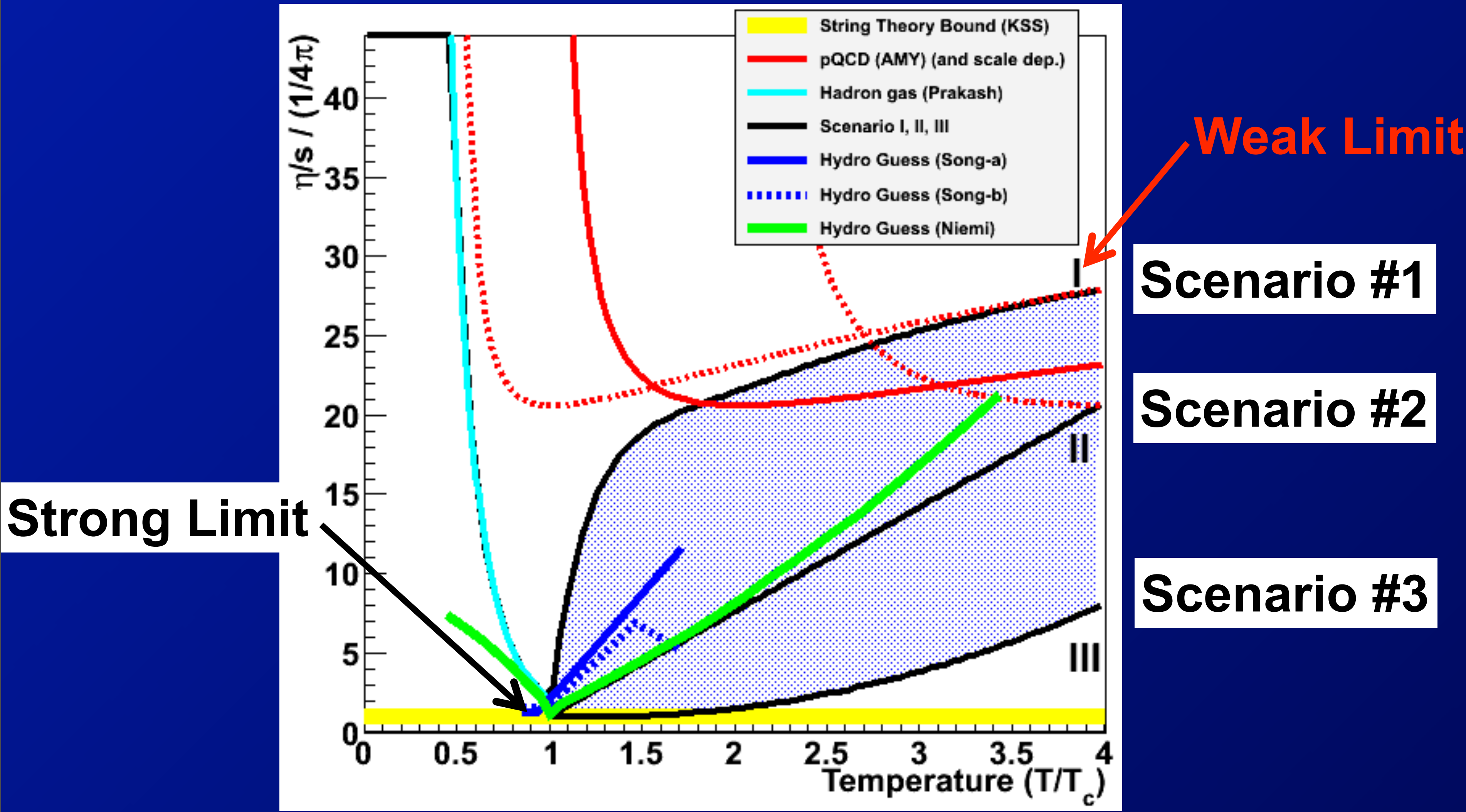
Csernai, Kapusta, and McLerran and KSS

Arnold, Moore, and Yaffe



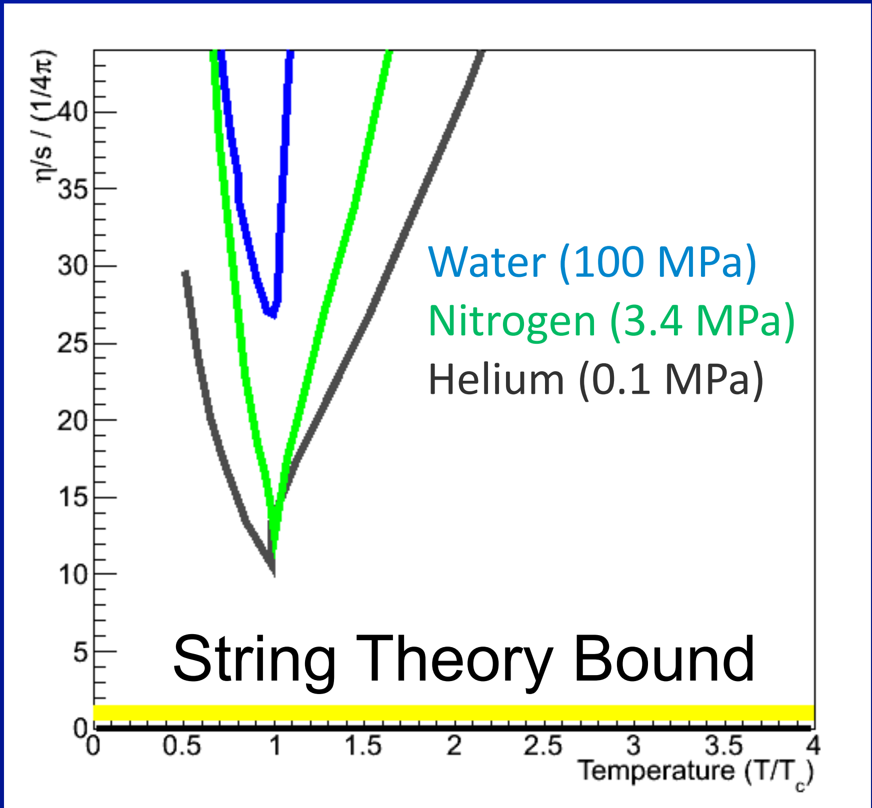


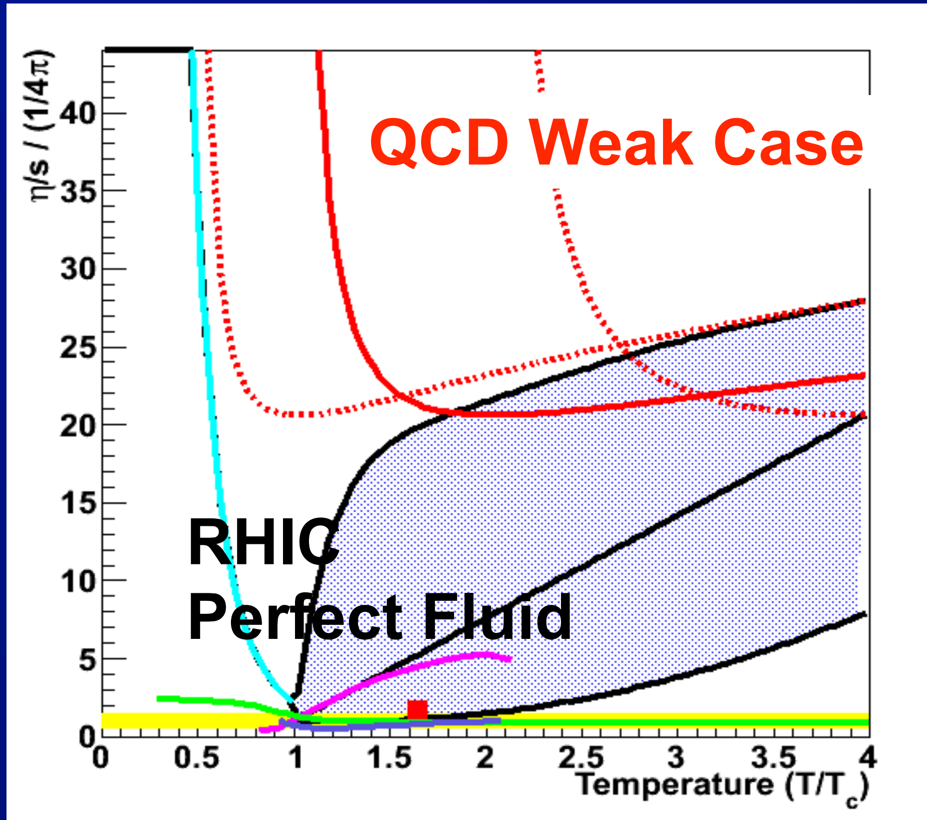
Strong - weak transition: how?



- Various constraints, calculations of η/s
  - Including 3 ad hoc scenarios

From strong to weak coupling





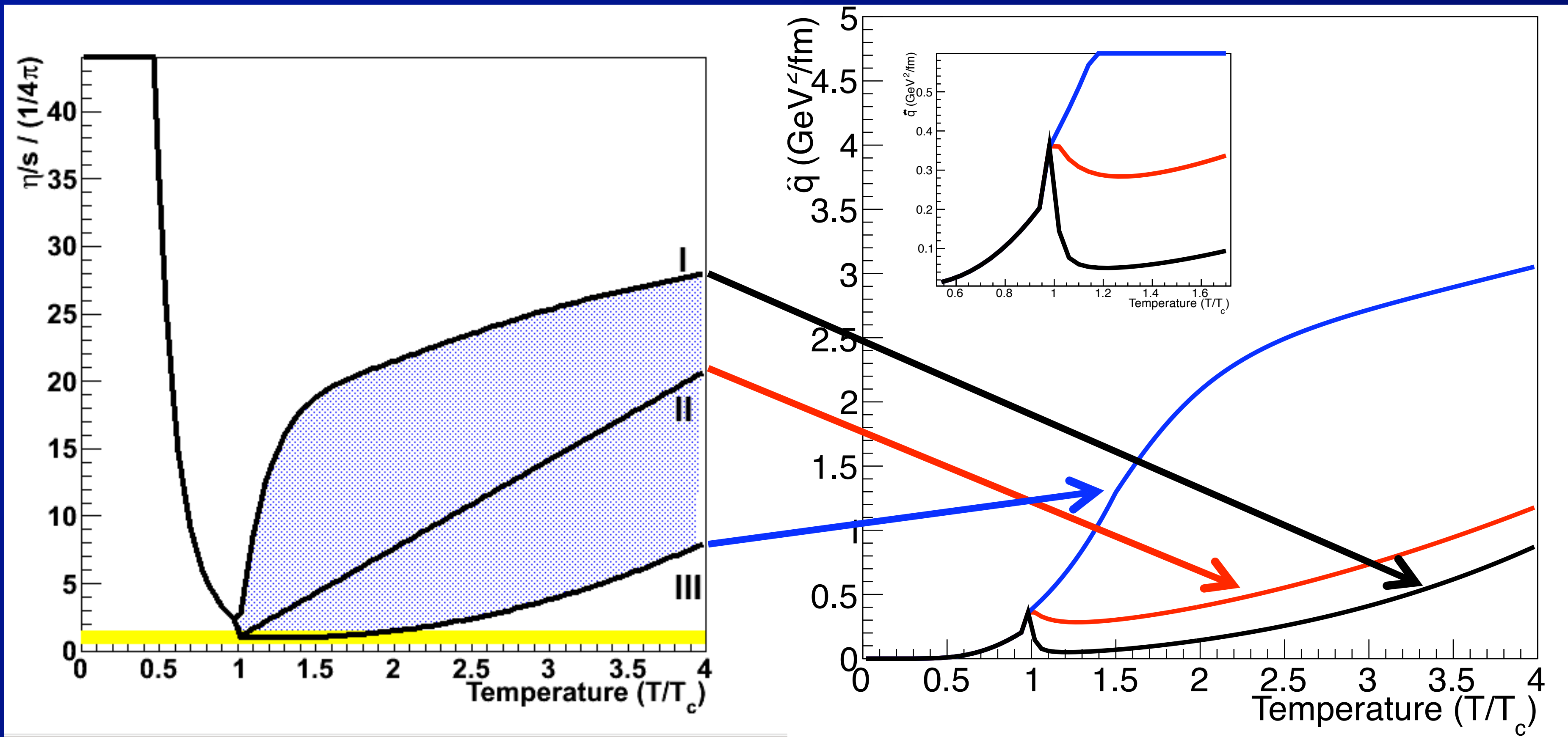
- How does the Quark-Gluon Plasma transition from Strong to Weak?
- How rapidly with increasing T?
- Is this transition associated with changes in quasi-particles, excitations, strong fields?

Studying strong coupling with jets

"Small Shear Viscosity Implies Strong Jet Quenching"

A. Majumder, B. Muller, X.N. Wang, PRL (2007).

$$\hat{q} = \frac{1.25T^3}{\eta / s}$$



- Implications for different scenarios for evolution from weak to strong coupling.

Change in quenching near T_c ?

PRL **102,** 202302 (2009) PHYSICAL REVIEW LETTERS week ending 22 MAY 2009

Angular Dependence of Jet Quenching Indicates Its Strong Enhancement near the QCD Phase Transition

Jinfeng Liao[1,2,*] and Edward Shuryak[1,†]
[1]*Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794, USA*
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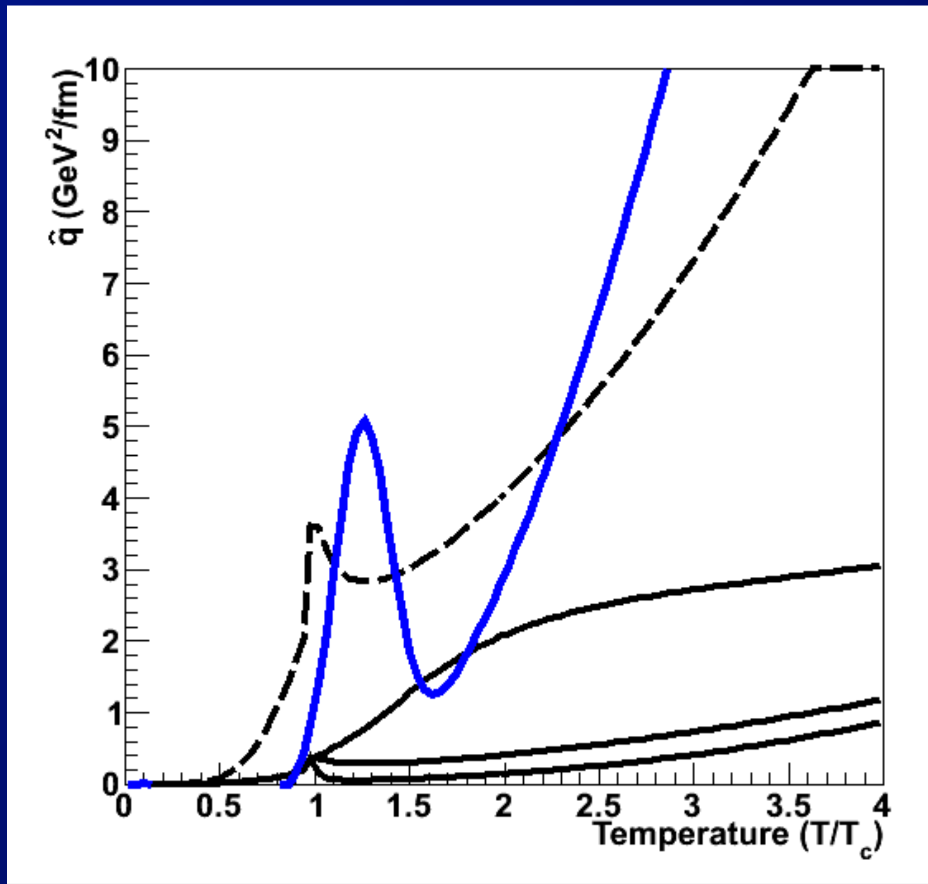
(Received 22 October 2008; revised manuscript received 19 February 2009; published 22 May 2009)

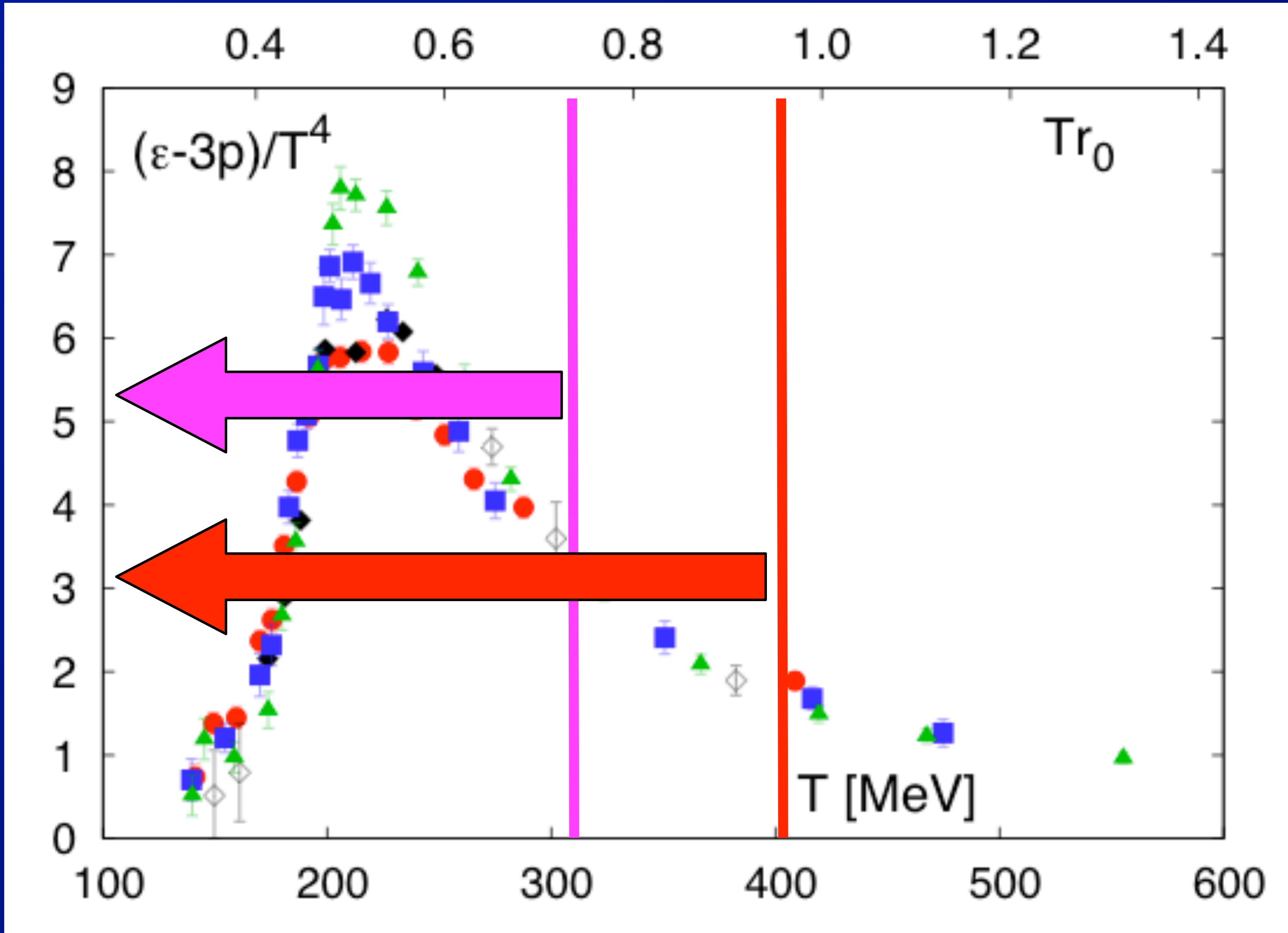
Near T_c region is a plasma of color magnetic monopoles

Constrained data fit implies strong enhancement of quenching near T_c

"[We find] the jet quenching is a few times stronger near T_c relative to the QGP at $T > T_c$."

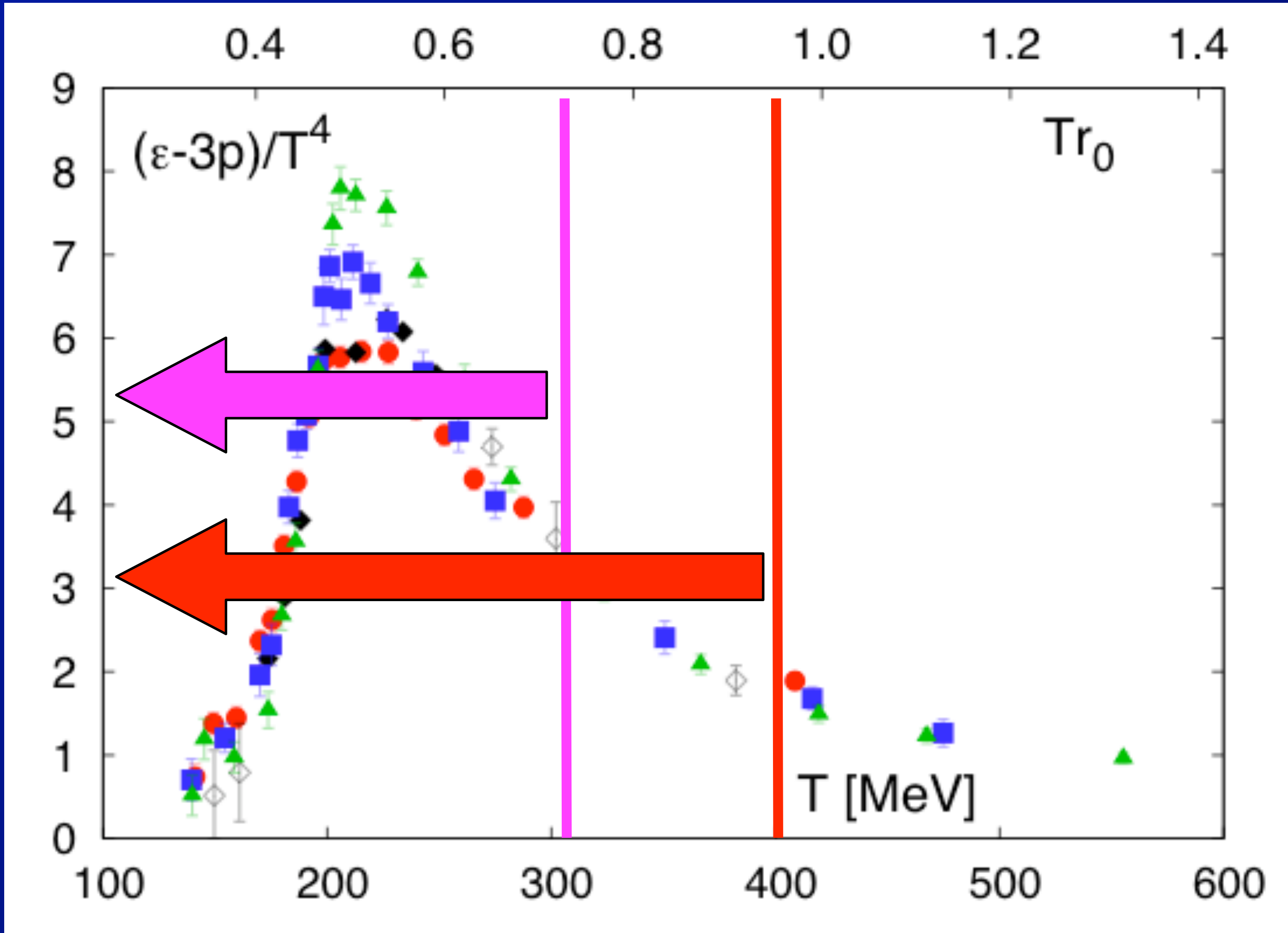


Probing time dependent QGP properties



- **All measurements that we perform integrate over the time history of heavy ion collision.**
  - ⇒No single value for T, η/s, $\hat{q}$, $\hat{e}$, ...

Probing time dependent QGP properties

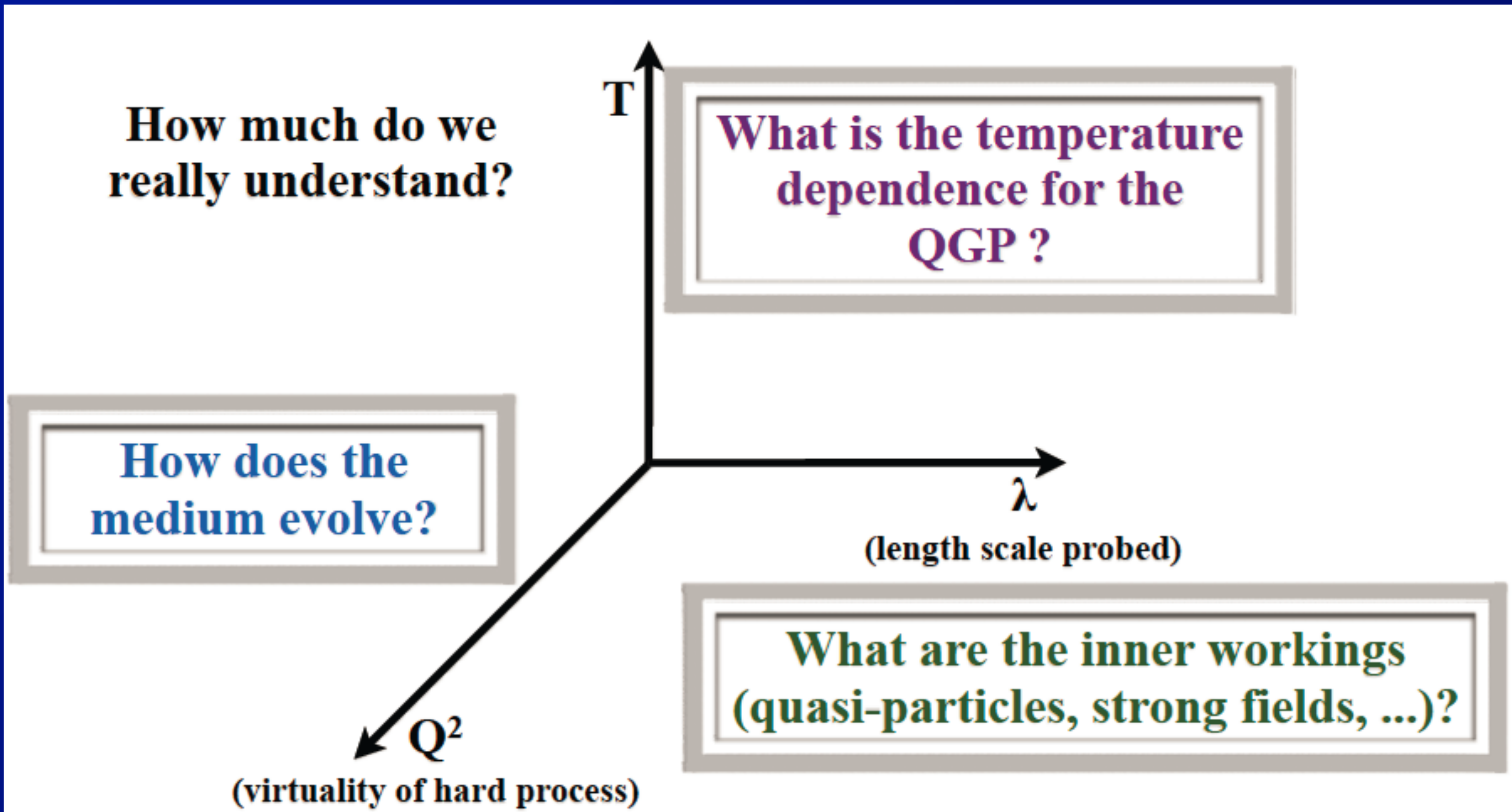


- How to unambiguously see changes near Tc ?
  - Use same probe, same geometry (R)
    - ⇒Run through time history starting @ different T_0.
    - ⇒NO OTHER WAY (prove me wrong!)

Exploring weak-strong transition

RHIC jet measurements are critical to exploring $\hat{q}$ & η/s evolution **along the temperature axis** (in concert with LHC measurements).

Also, pushing / probing the medium along other axes.



New studies of jet observables at RHIC energies

resulting from

Jets @ RHIC Workshop

March 3-4, 2012 at Duke University
lots of interest from theoretical community.

Follow up EVO meetings.

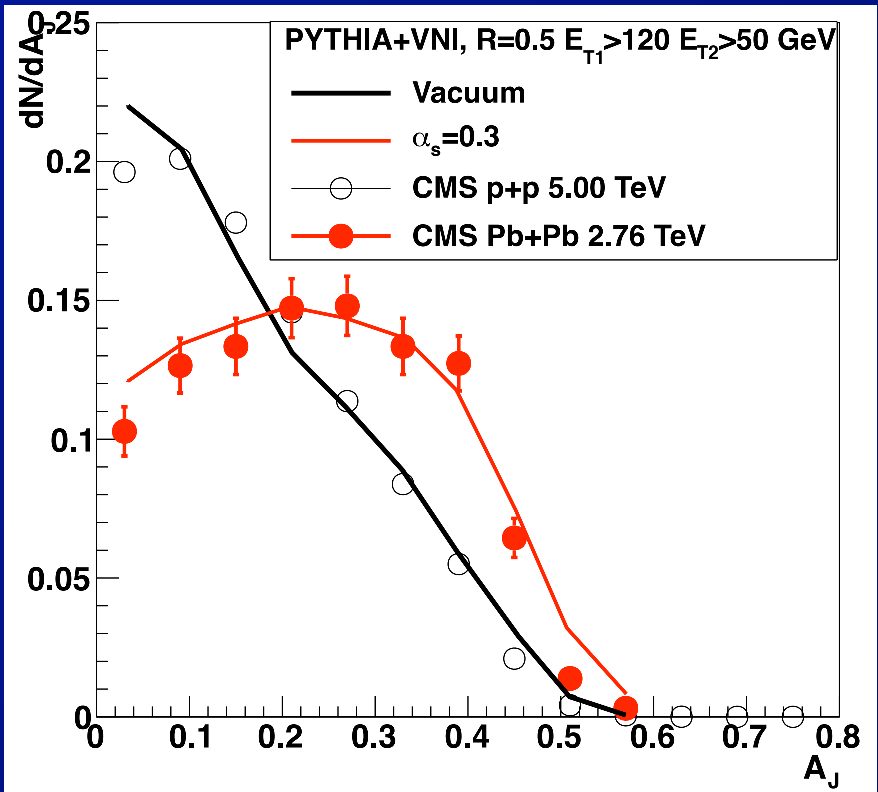
Input from Jet Collaboration (1)

Embedding parton showers into partonic medium.

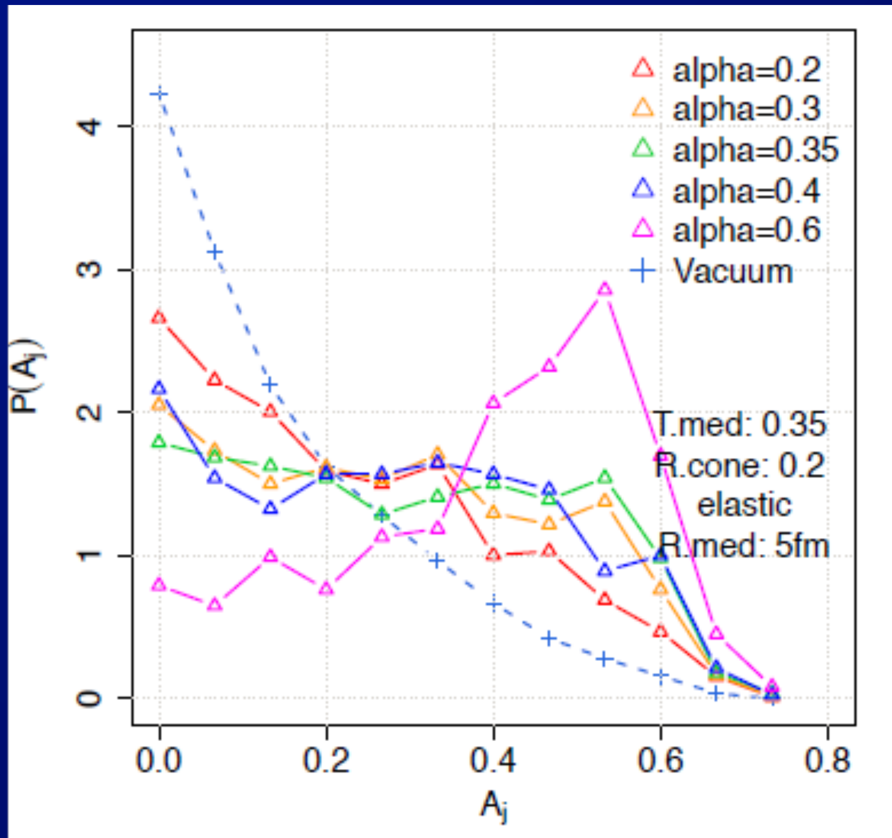
Full FastJet reconstruction of all modified partons.

Chris Coleman-Smith (Duke)

Good agreement with CMS Dijet $(E_1-E_2)/(E_1+E_2)$ for $\alpha_s = 0.3$



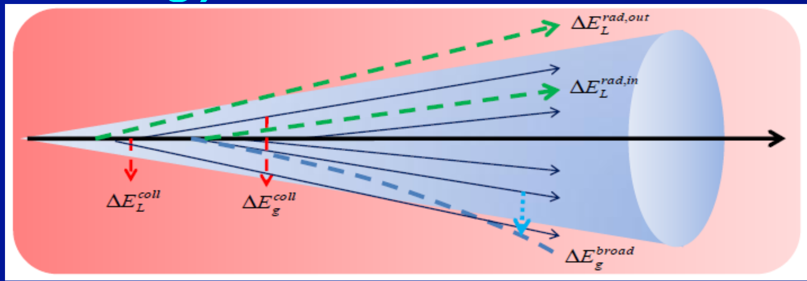
RHIC dijets very sensitive to effective coupling



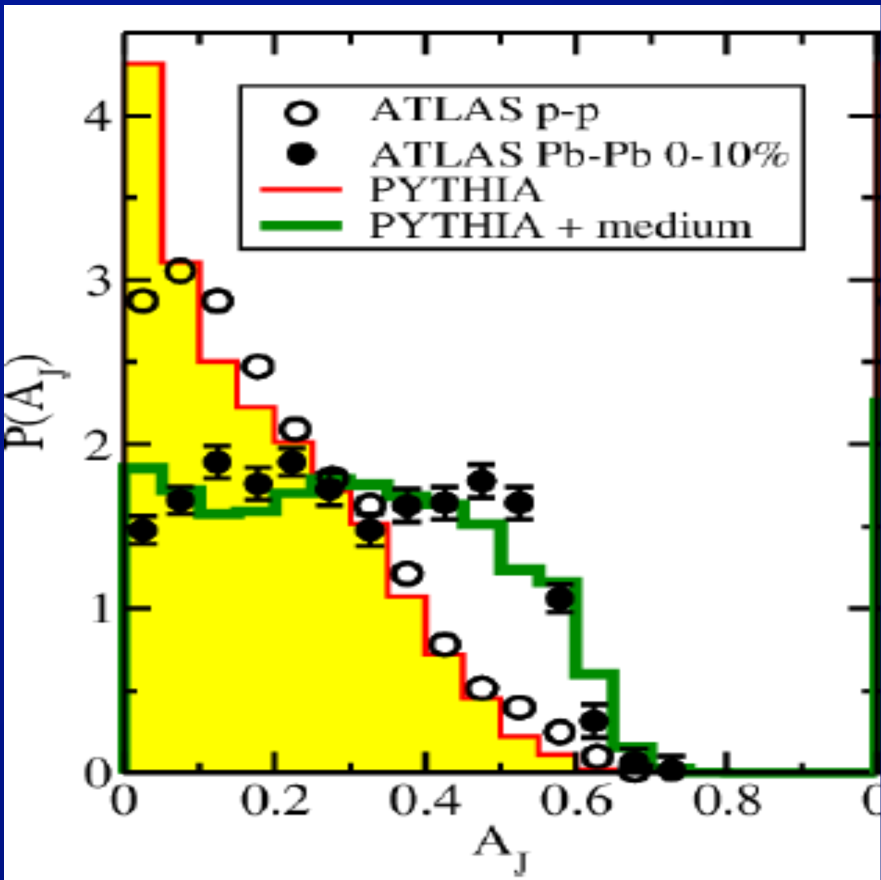
Input from Jet Collaboration (2)

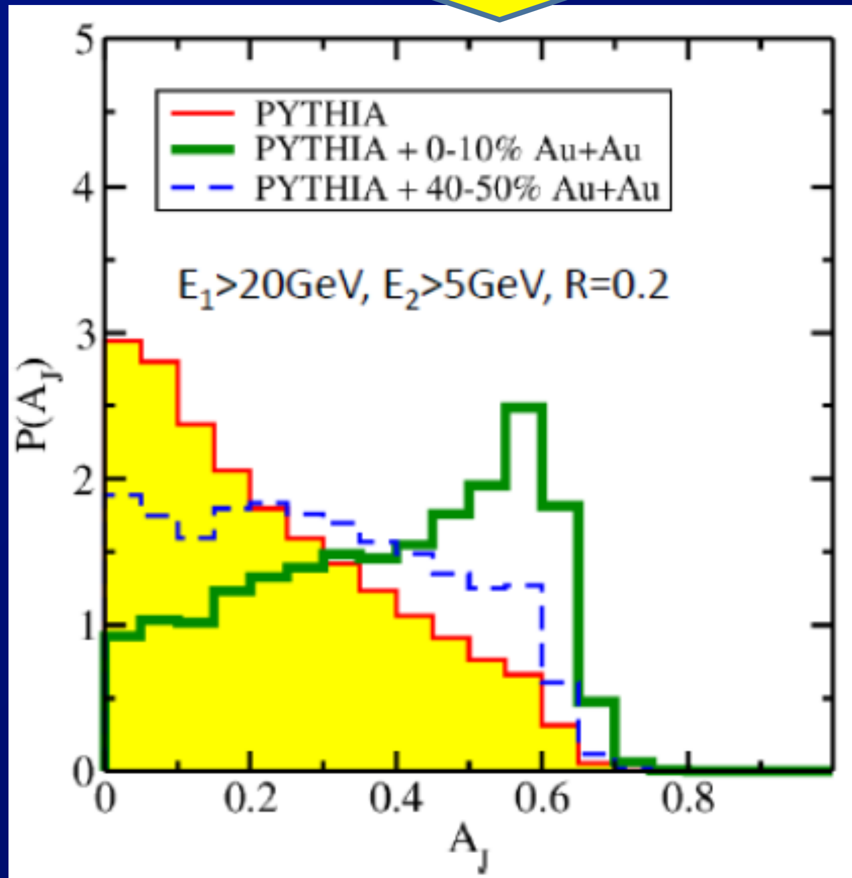
PRL 2011

Guangyou Qin, Berndt Muller

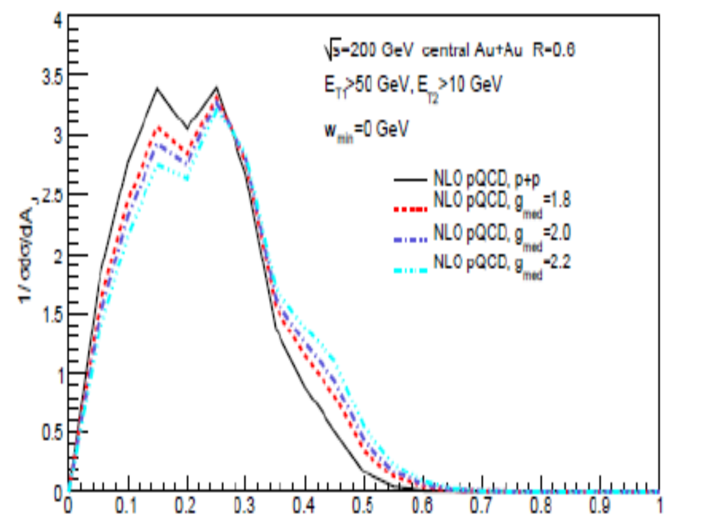


Larger modification
at RHIC
More of parton shower
equilibrated into medium.

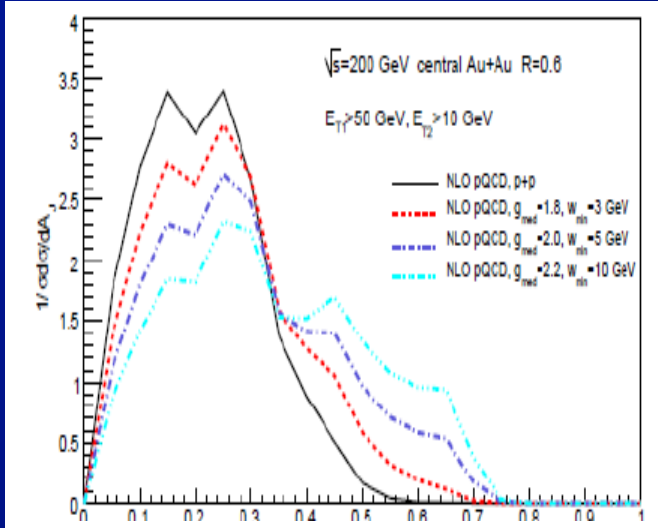




Input from Jet Collaboration (3)



Radiative E-loss only

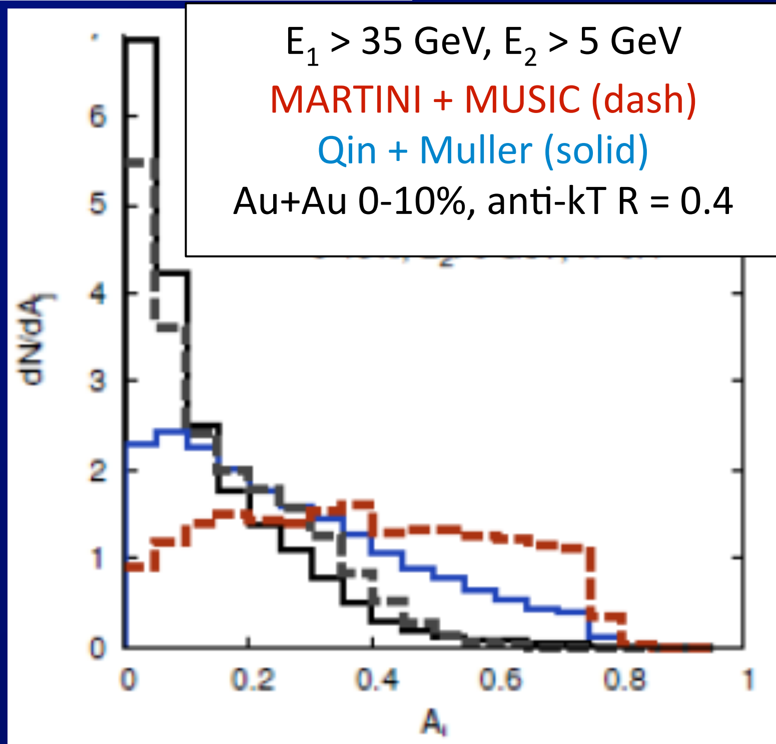


Radiative + Collisional E-loss

±10% changes in coupling strength

Ivan Vitev et al.

Bjorn Schenke, Clint Young et al.

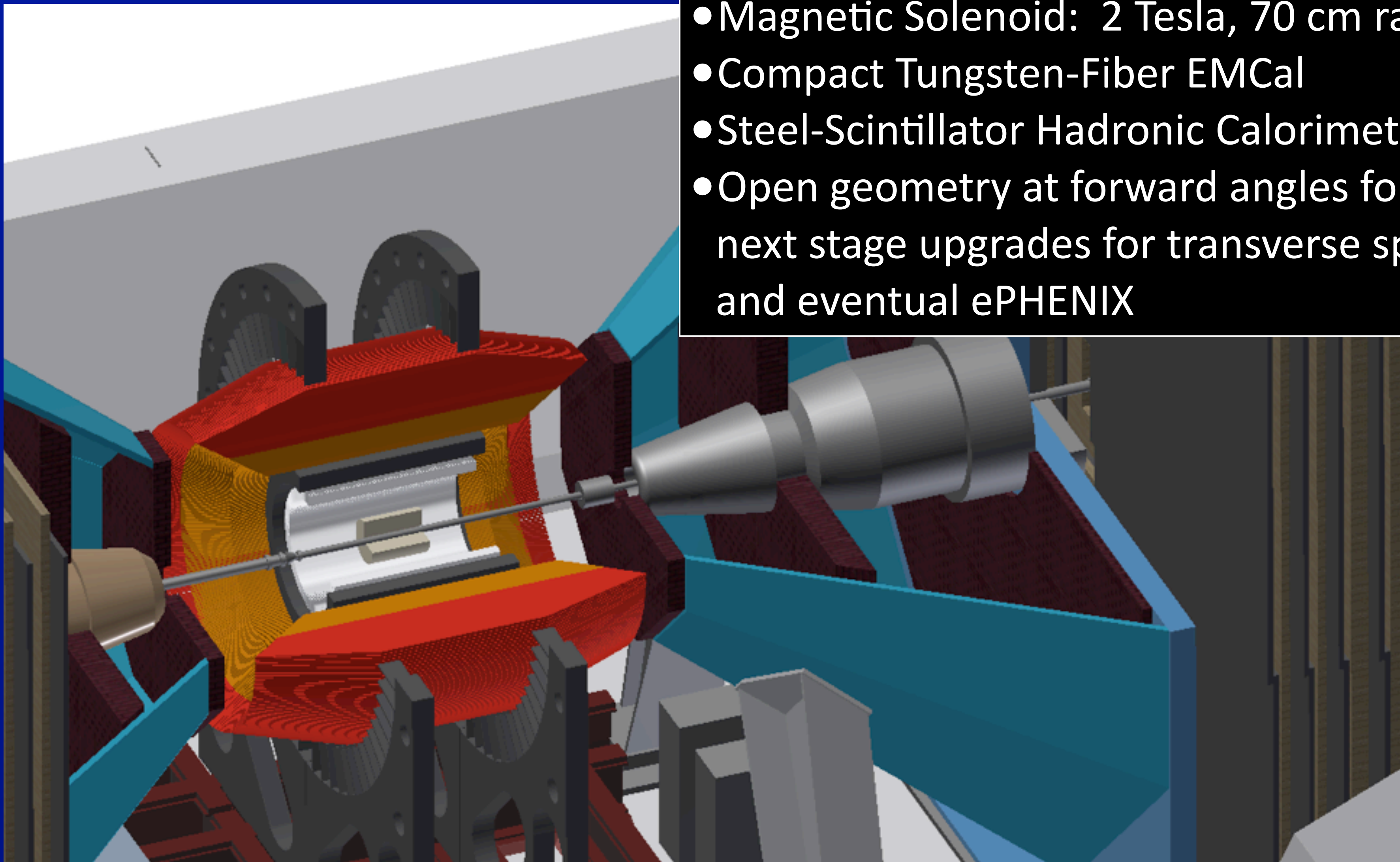


Large effects!
Different models matching LHC data disagree on RHIC predictions.

sPHENIX

Major change to the PHENIX detector. Removal of outer PHENIX central arms, keep VTX inner tracking.

- Magnetic Solenoid: 2 Tesla, 70 cm radius
- Compact Tungsten-Fiber EMCal
- Steel-Scintillator Hadronic Calorimeter
- Open geometry at forward angles for next stage upgrades for transverse spin and eventual ePHENIX



Big Questions: sPHENIX Proposal

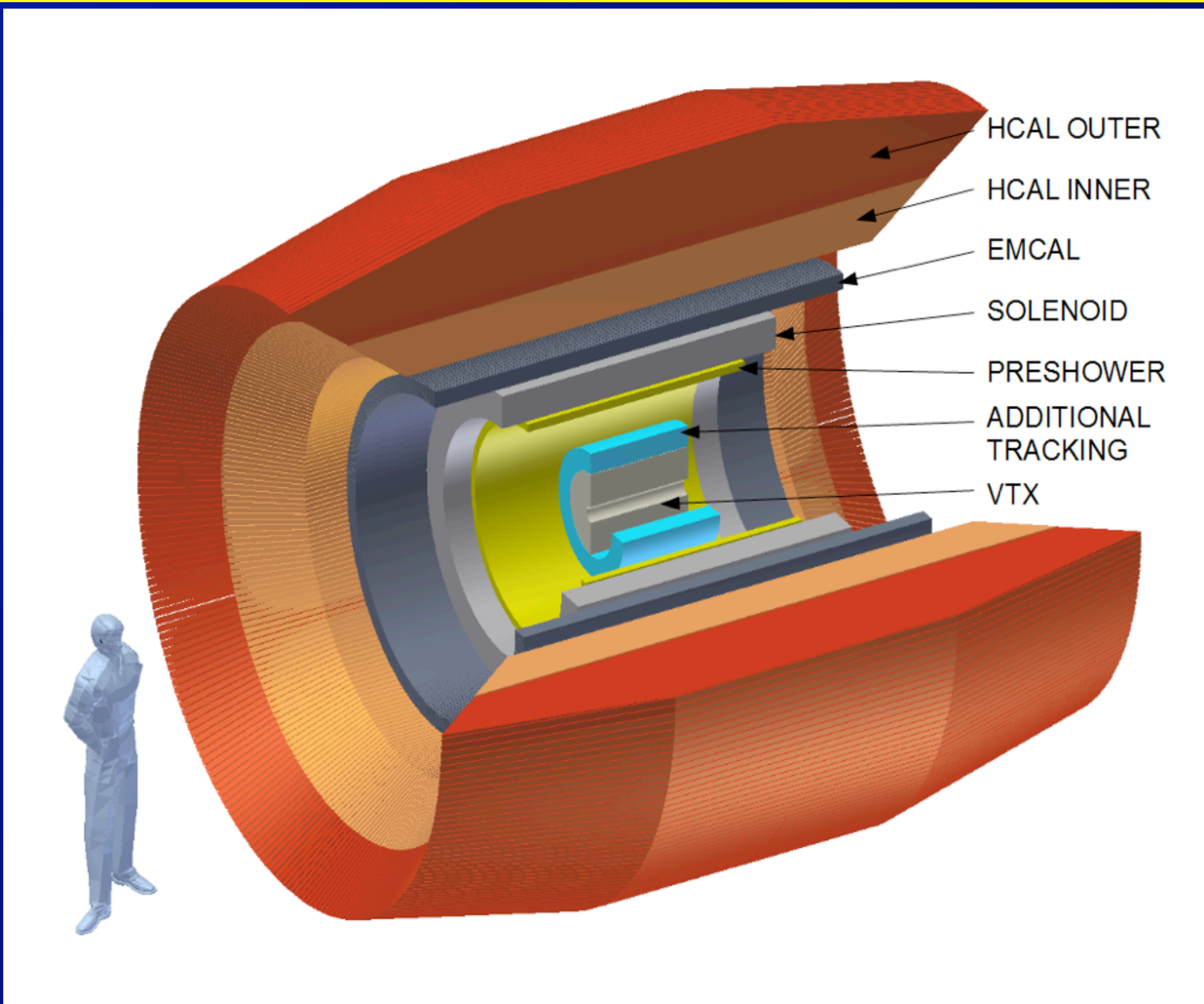
The Physics Case for sPHENIX

The past decade of results from RHIC and more recently from the LHC have resulted in a slew of new discoveries for nuclear physics. These results have also generated a number of very fundamental questions concerning the true nature of the strongly coupled "perfect fluid" quark-gluon plasma (QGP) and how such a strongly coupled medium arises from a system described by the QCD Lagrangian. Addressing this will require connecting the experimentally observable properties of the QGP with a deeper theoretical understanding of the interactions and dynamics within the QGP itself. We can turn this general drive for understanding into specific questions about the nature of the strongly coupled quark-gluon plasma:

- How does the strongly coupled quark-gluon plasma emerge from an asymptotically free theory of quarks and gluons?
- How rapidly does the quark-gluon plasma transition from the most strongly coupled system near the bound to the weakly coupled system of partons?
- What are the dynamical and underlying changes to the medium (for example quasi-particles and excitations) as one crosses this temperature expanse?

These are the fundamental questions that we will address with this sPHENIX upgrade (both in a first stage as funded through this proposal request and in possible future stages).

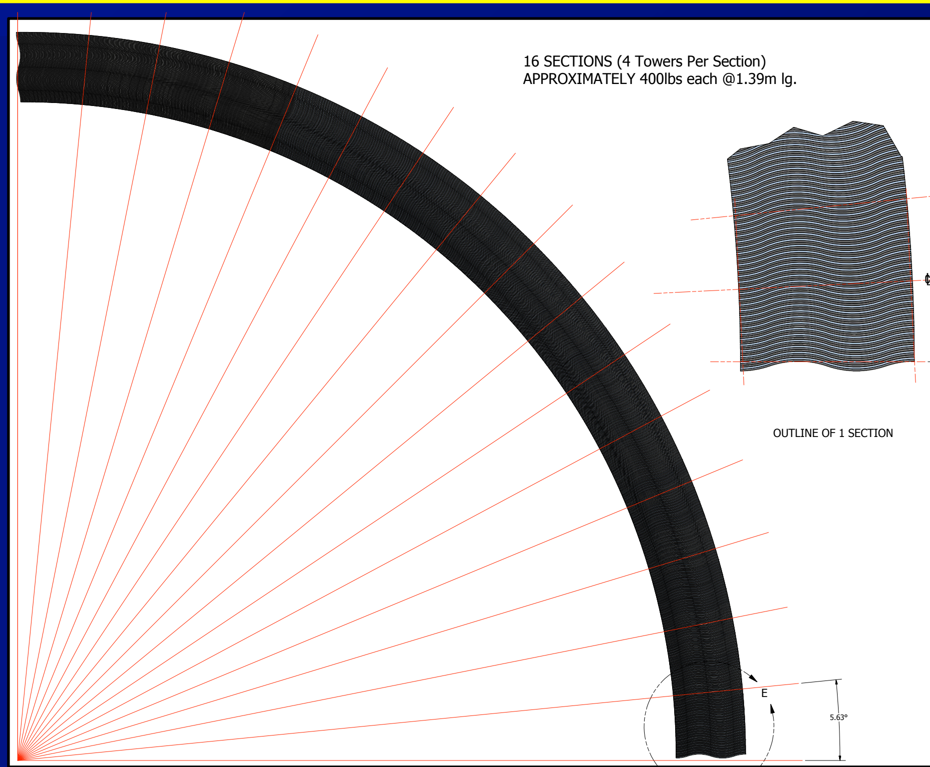
sPHENIX magnet, calorimeter, tracking

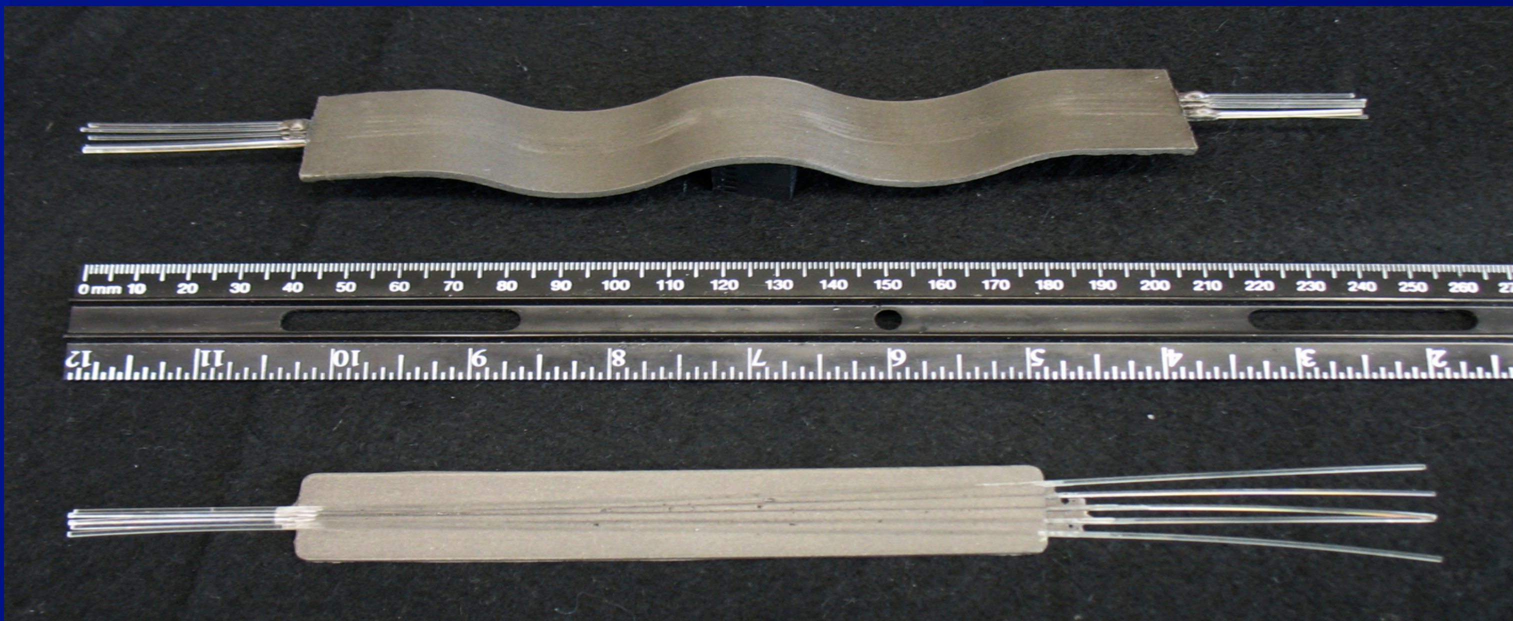


sPHENIX EM calorimeter

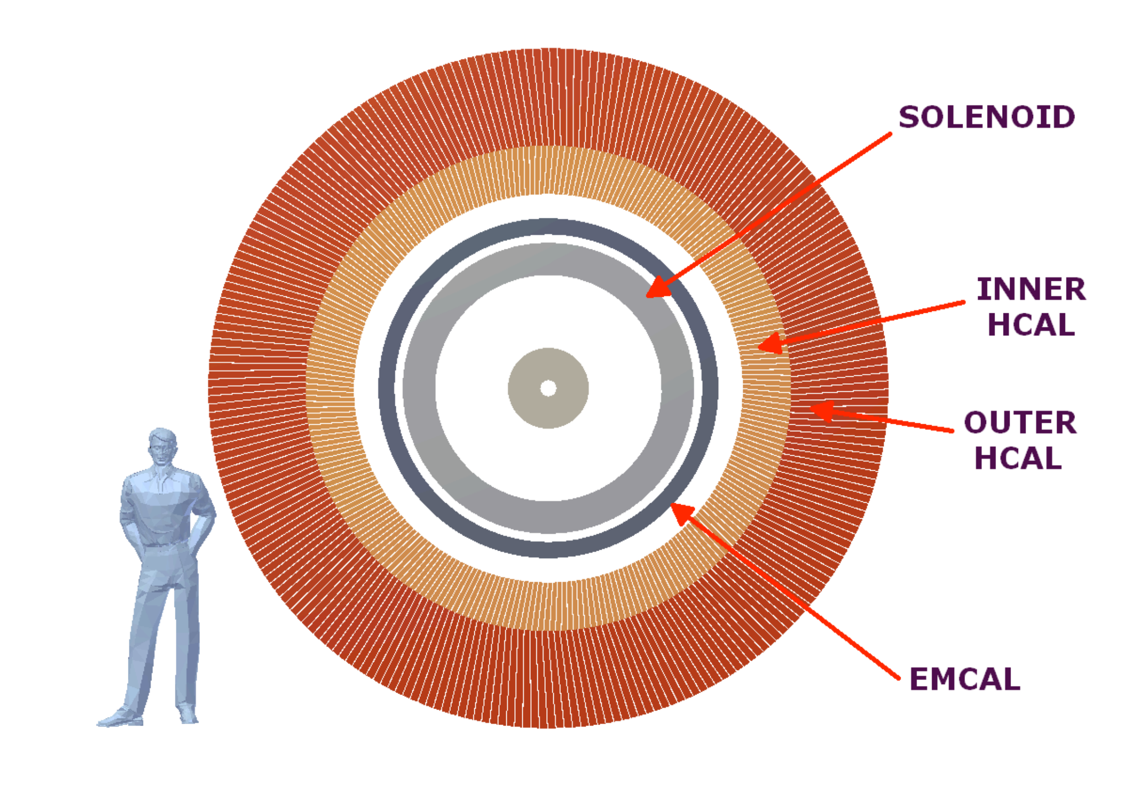
EMCal

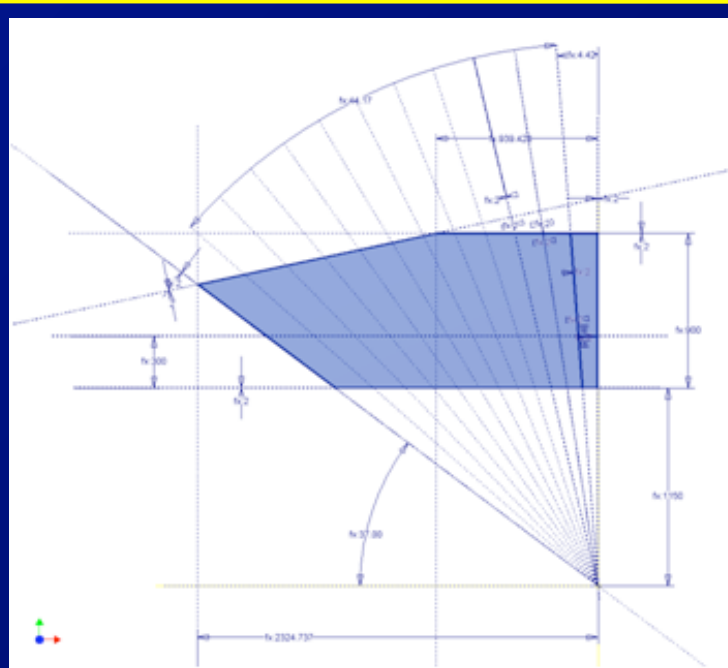
- Powdered tungsten accordion calorimeter
  - $\Delta\eta \times \Delta\varphi = 0.024 \times 0.024$
- SiPMT readout
- Resolution 15% / √E
- 17 cm thick

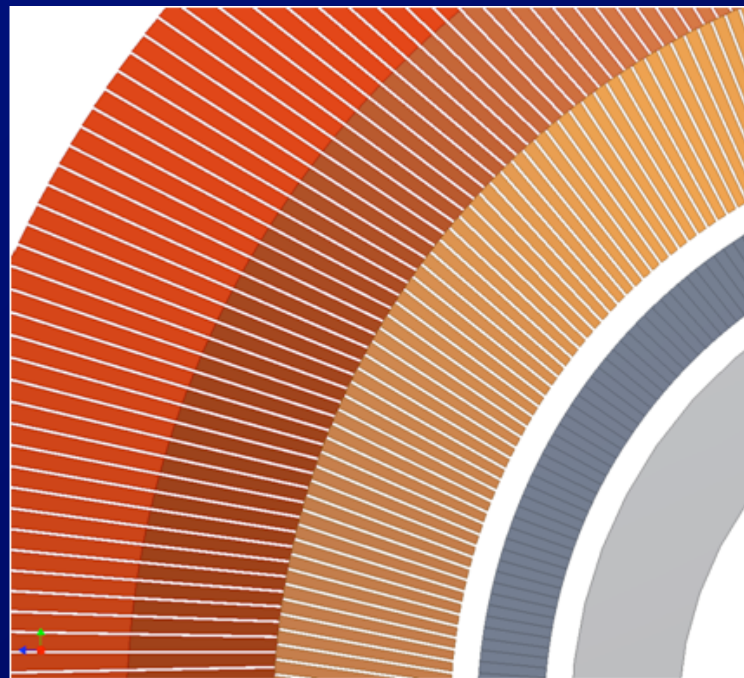




sPHENIX hadronic calorimeter

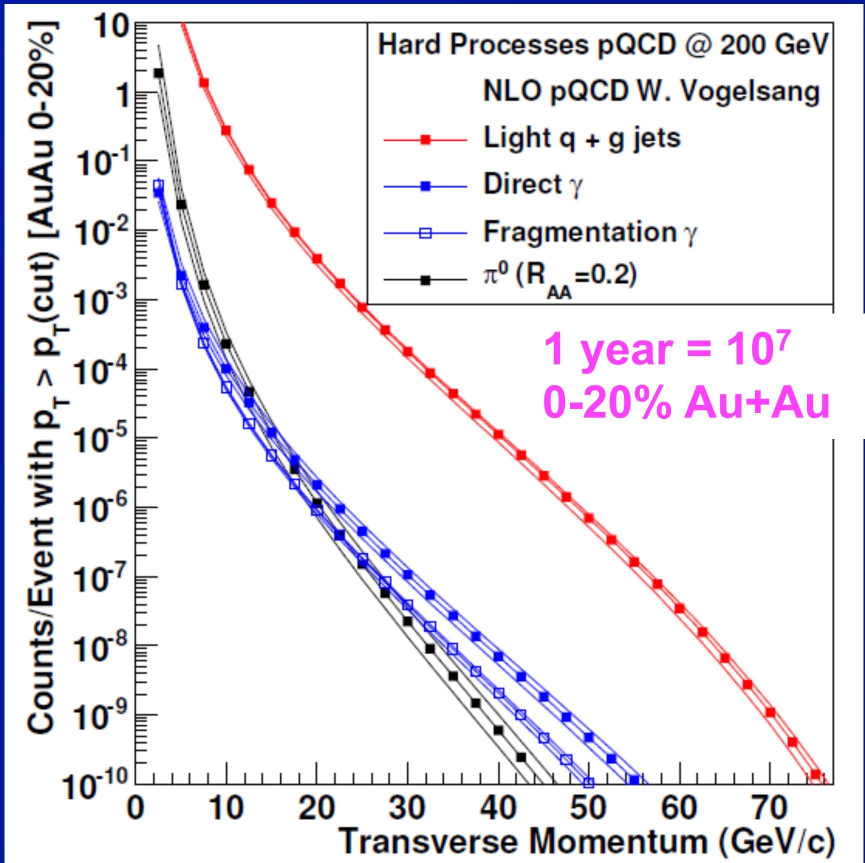






- Steel-scintillator HCal
  - $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$
  - 1m deep, $5\lambda_{int}$
- doubles as field return
- 2 radial layers

pQCD rates in 200 GeV Au+Au



	Au+Au (central 20%)	p+p	d+Au
>20GeV	10^7 jets 10^4 photons	10^6 jets 10^3 photons	10^7 jets 10^4 photons
>30GeV	10^6 jets 10^3 photons	10^5 jets 10^2 photons	10^6 jets 10^3 photons
>40GeV	10^5 jets	10^4 jets	10^5 jets
>50GeV	10^4 jets	10^3 jets	10^4 jets

Rates based on full stochastic cooling, but no additional accelerator upgrades.

Note, first ATLAS dijet paper based on ~ 1k pairs.

Huge rates allow differential measurements with geometry (v_2, v_3, A+B, U+U, …) & precise control measurements (d+Au & p+p).

Over 80% as dijets into |η|<1.0

Are jet measurements @ RHIC possible?

Jet - Underlying Event Separation Method for Heavy Ion Collisions at the Relativistic Heavy Ion Collider

J. A. Hanks[1], A. M. Sickles[2], B. A. Cole[3], A. Franz[2], M. P. McCumber[4], D. P. Morrison[2], J. L. Nagle[4], C. H. Pinkenburg[2], B. Sahlmueller[1], P. Steinberg[2], M. von Steinkirch[1], M. Stone[4]

[1] *Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, New York 11794-3400, USA*
[2] *Physics Department, Brookhaven National Laboratory, Upton, New York, 11973-5000*
[3] *Columbia University, New York, New York 10027 and Nevis Laboratories, Irvington, New York 10533, USA and*
[4] *University of Colorado, Boulder, Colorado 80309, USA*

(Dated: March 8, 2012)

arXiv:1203.1353

- Dedicated study with $|\eta| < 1$ ideal detector
  - Run > 1 billion HIJING events tagging HIJING jets by running FastJet on output of each fragmentation call
- Reconstruct jets @ particle level from hadrons, γ, e using background subtraction procedure adapted from ATLAS
  - Evaluate performance, particularly fake rate

    ⇒ Test the assertion that fake jets overwhelm real jet rate in central Au+Au @ RHIC

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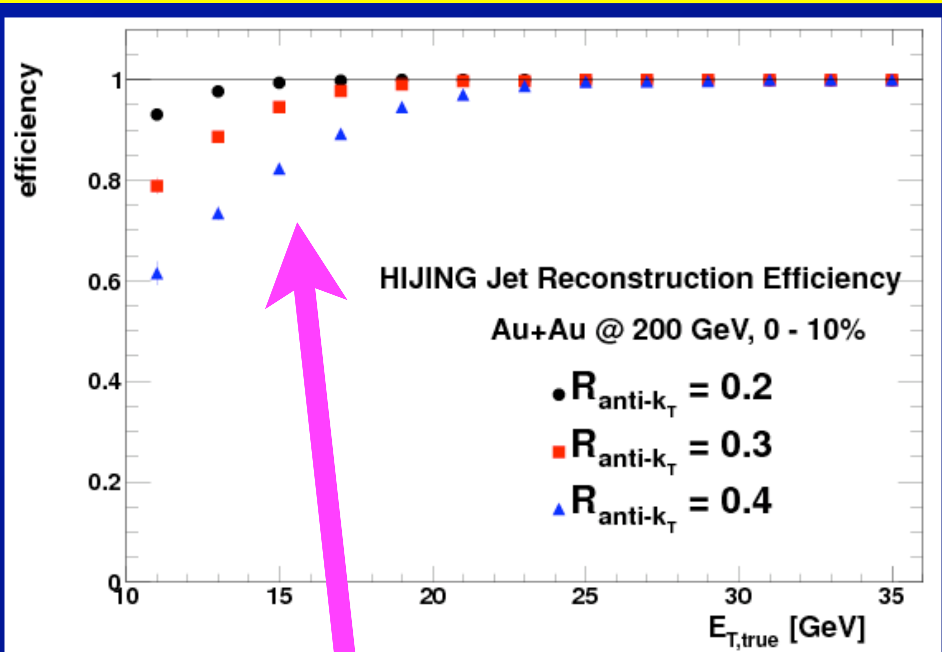
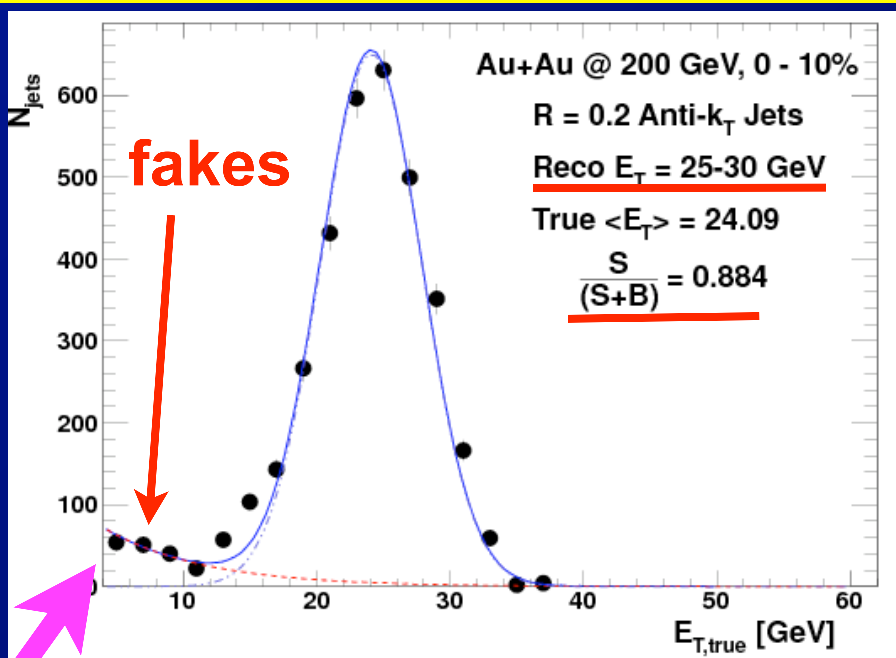
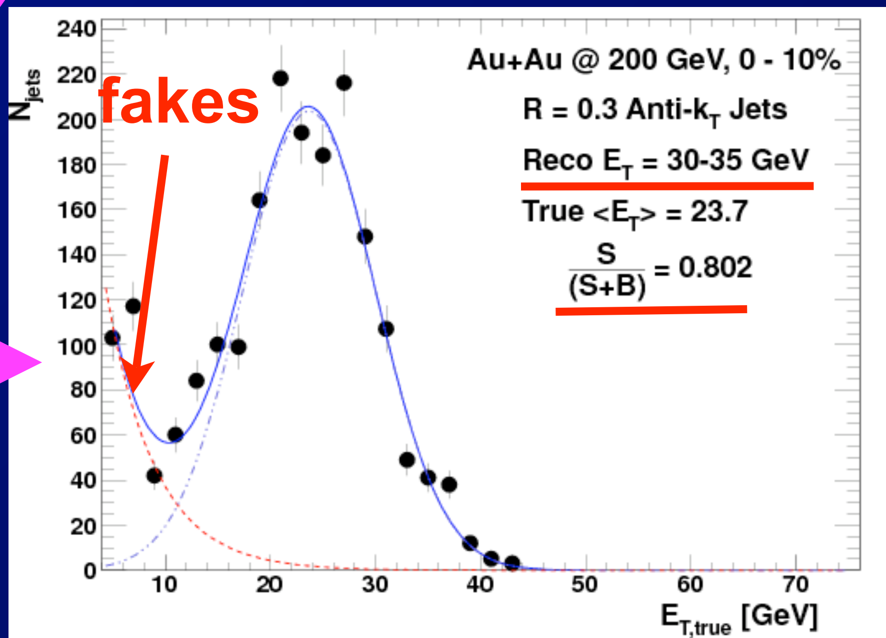
Are jet measurements @ RHIC possible?(2)



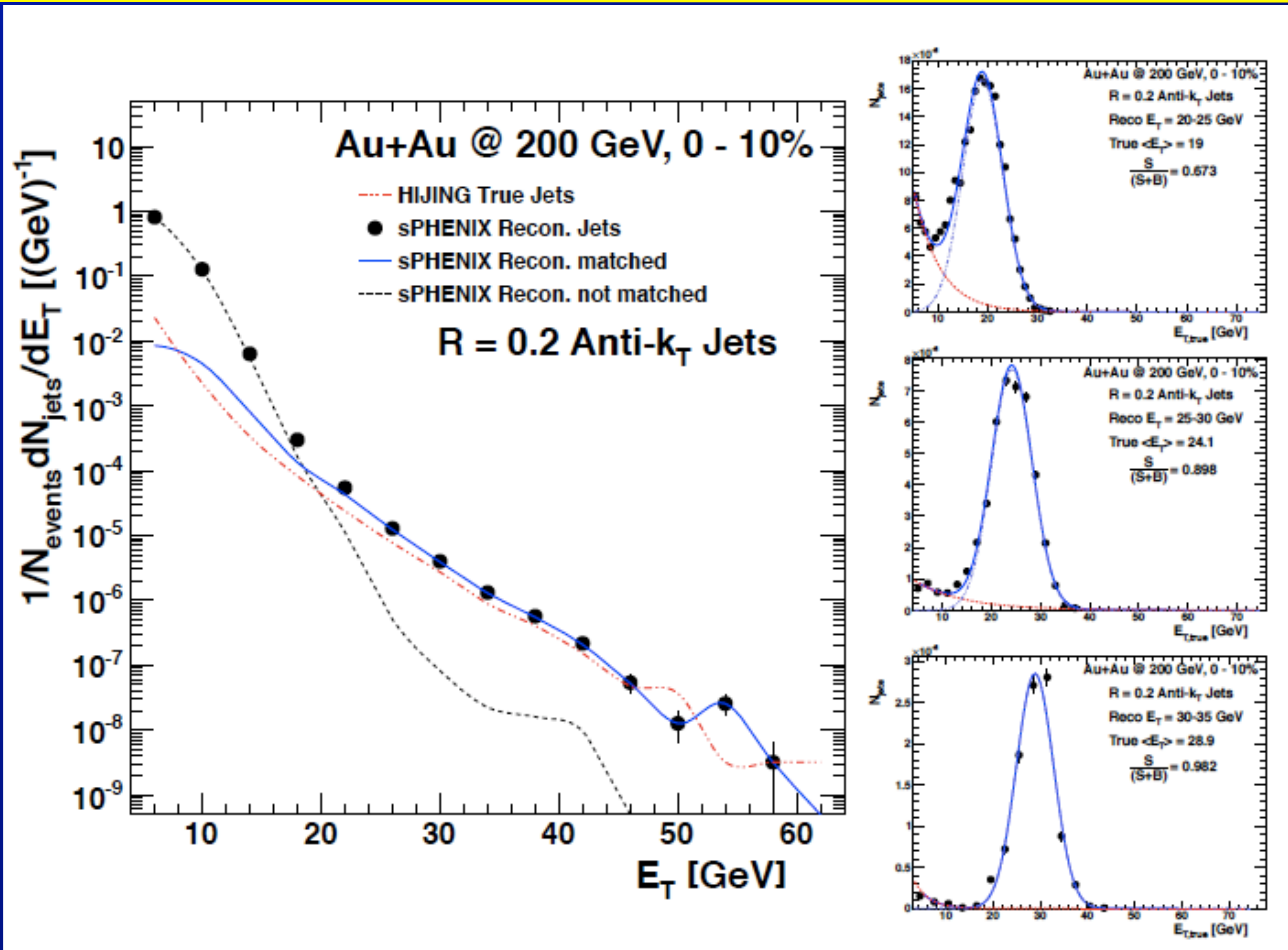




- reconstruction efficiency
  - ⇒Good
- truth E_T for R = 0.2 jets with $25 < E_T^{REC} < 30$
- truth E_T for R = 0.3 jets with $30 < E_T^{REC} < 35$
  - ⇒Dominated by real jets

- Answer: yes!

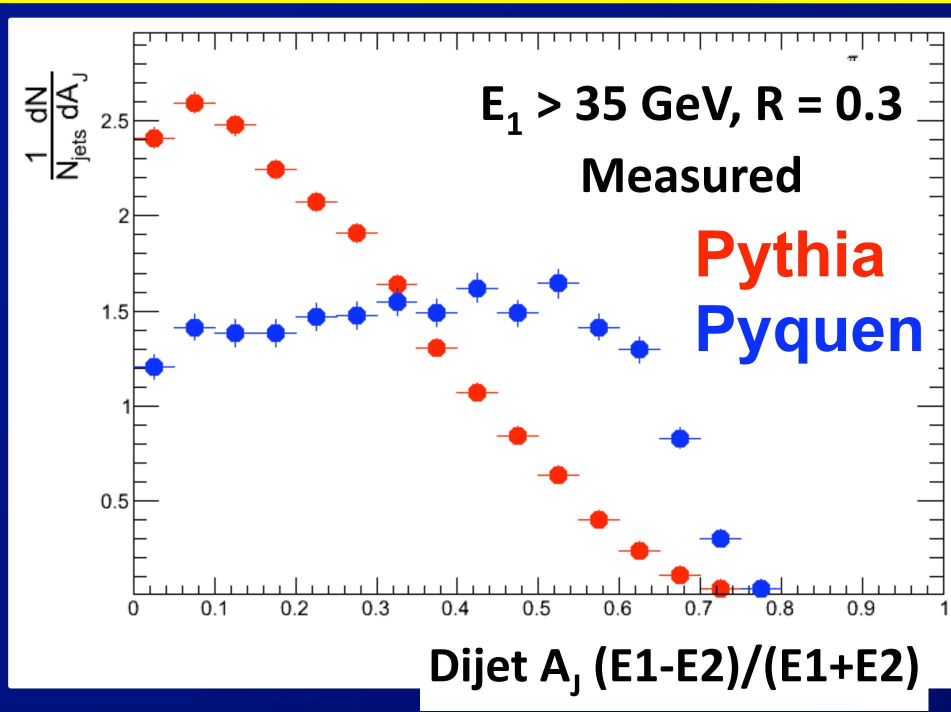
Are jet measurements @ RHIC possible?(3)

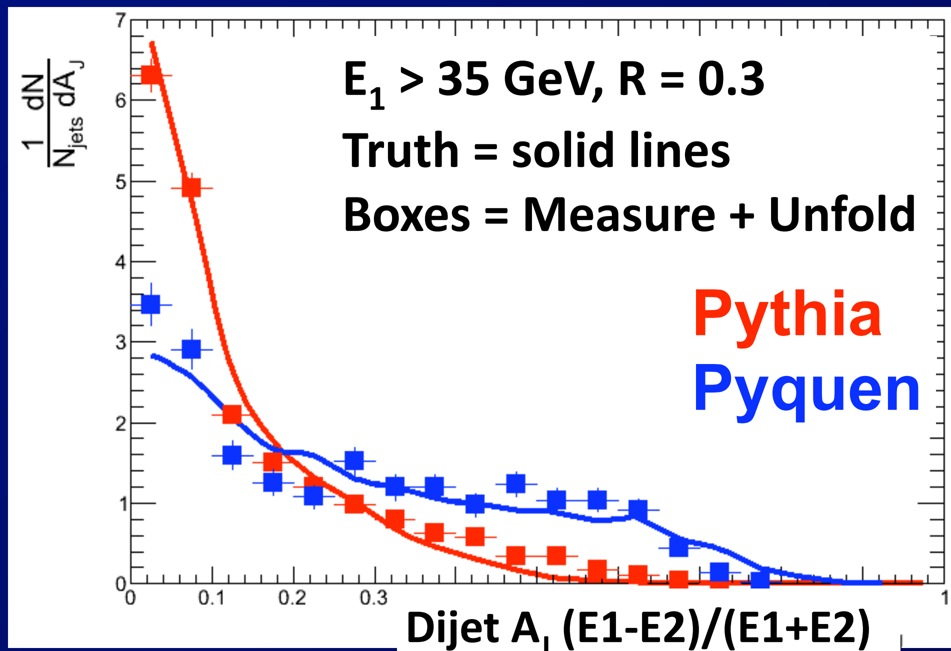


- Answer:YES

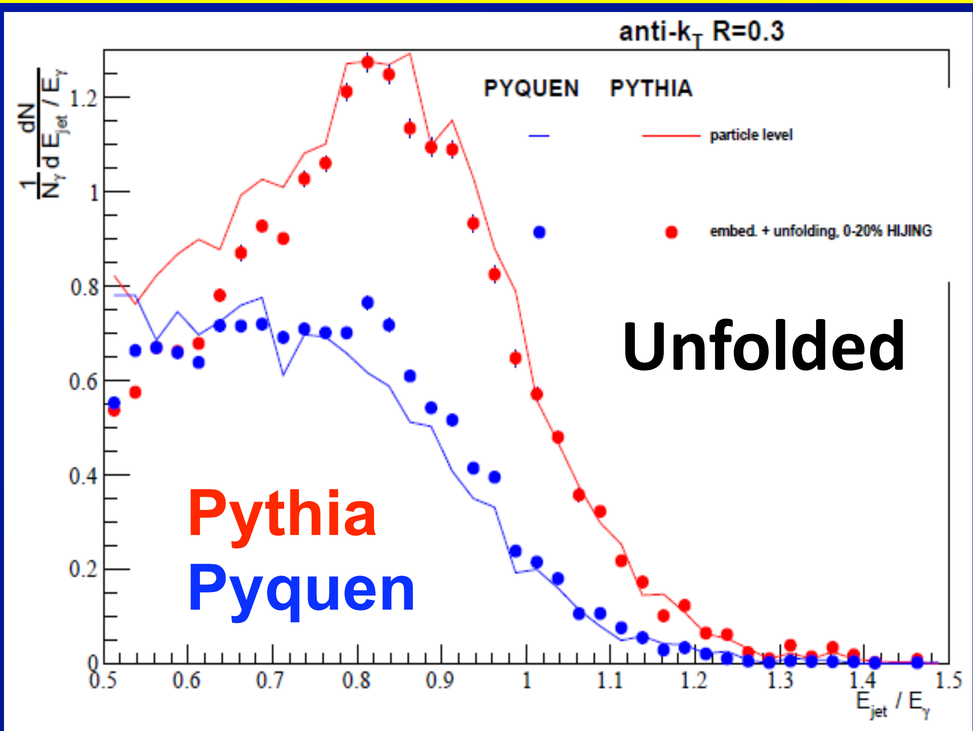
Dijet asymmetry in sPHENIX

- Compare PYQUEN and PYTHIA dijet A_j
- Simulation:
  - Full jets + HIJING background + detector resolution
- Analysis
  - FastJet + underlying event subtraction + leading jet unfolding
- Can clearly see the effects of quenching
  - Measured
  - Unfolded
    - ⇒ ~consistent w/ true





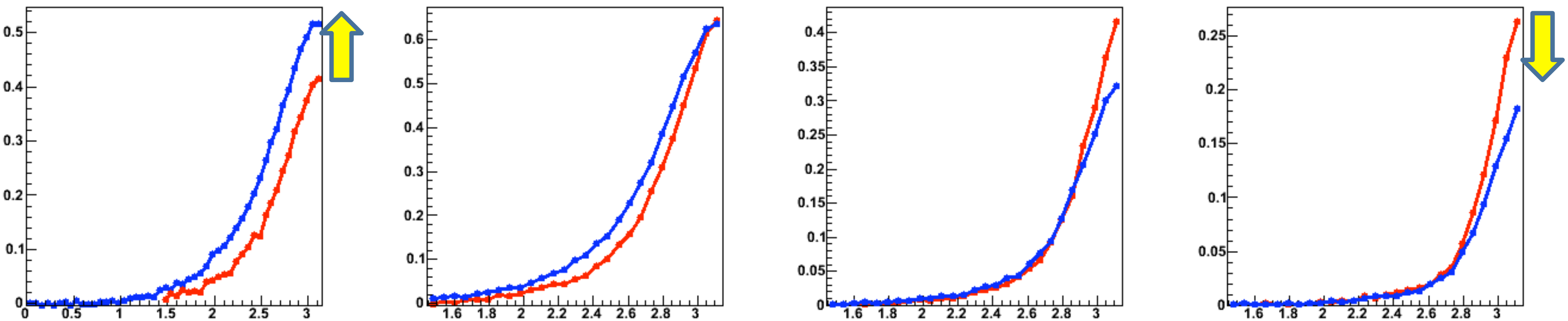
gamma - jet in sPHENIX



- PYTHIA and PYQUEN γ-jet, γ p_T > 15 GeV
  - ⇒ photons dominate
- Quenching big effect @ truth level
  - ⇒Observed in measured & unfolded x_{jet}

γ – hadron correlations

Track with VTX where the energy goes!

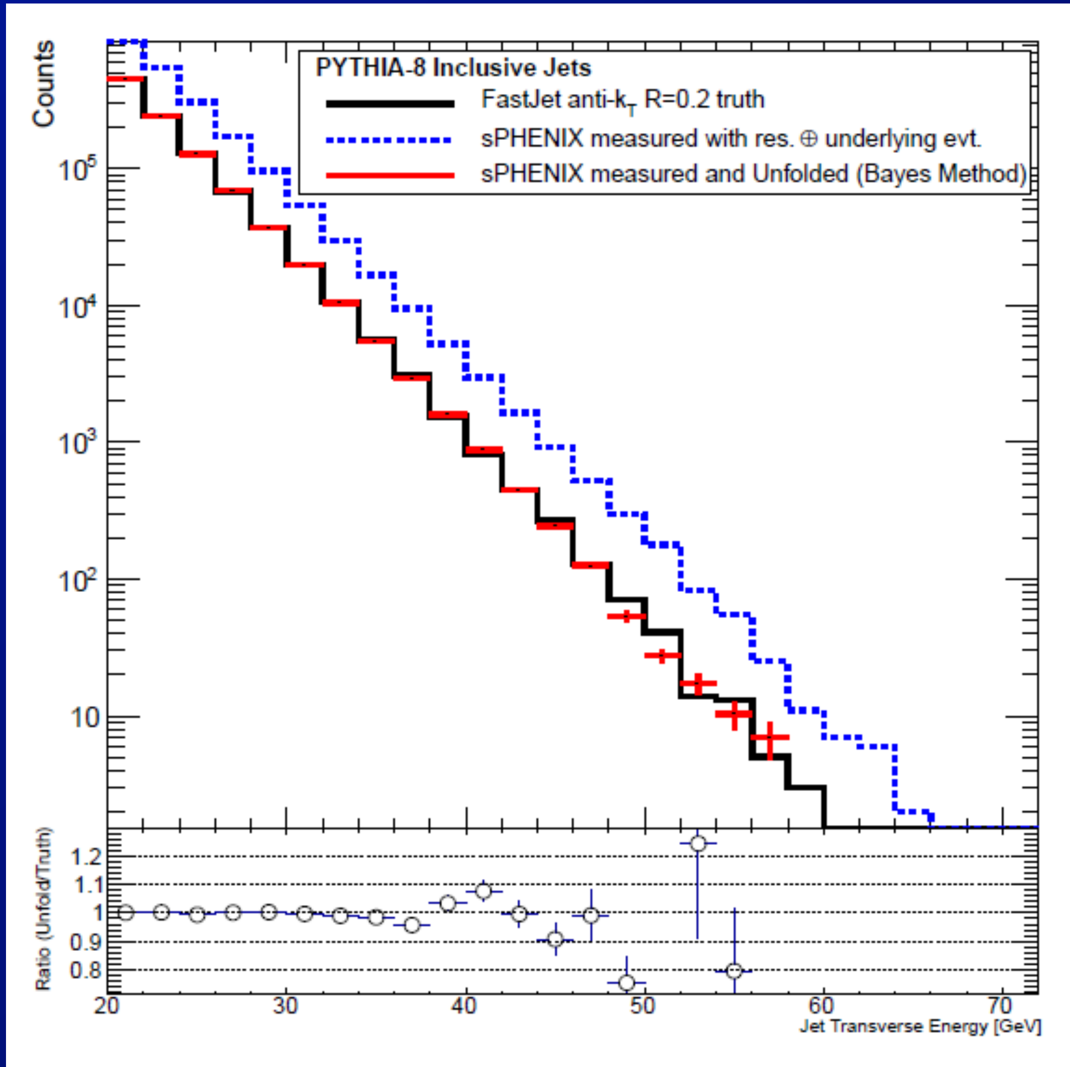


Jet spectrum measurement

In region above fake jet contributions, we can measure the inclusive jet spectra.

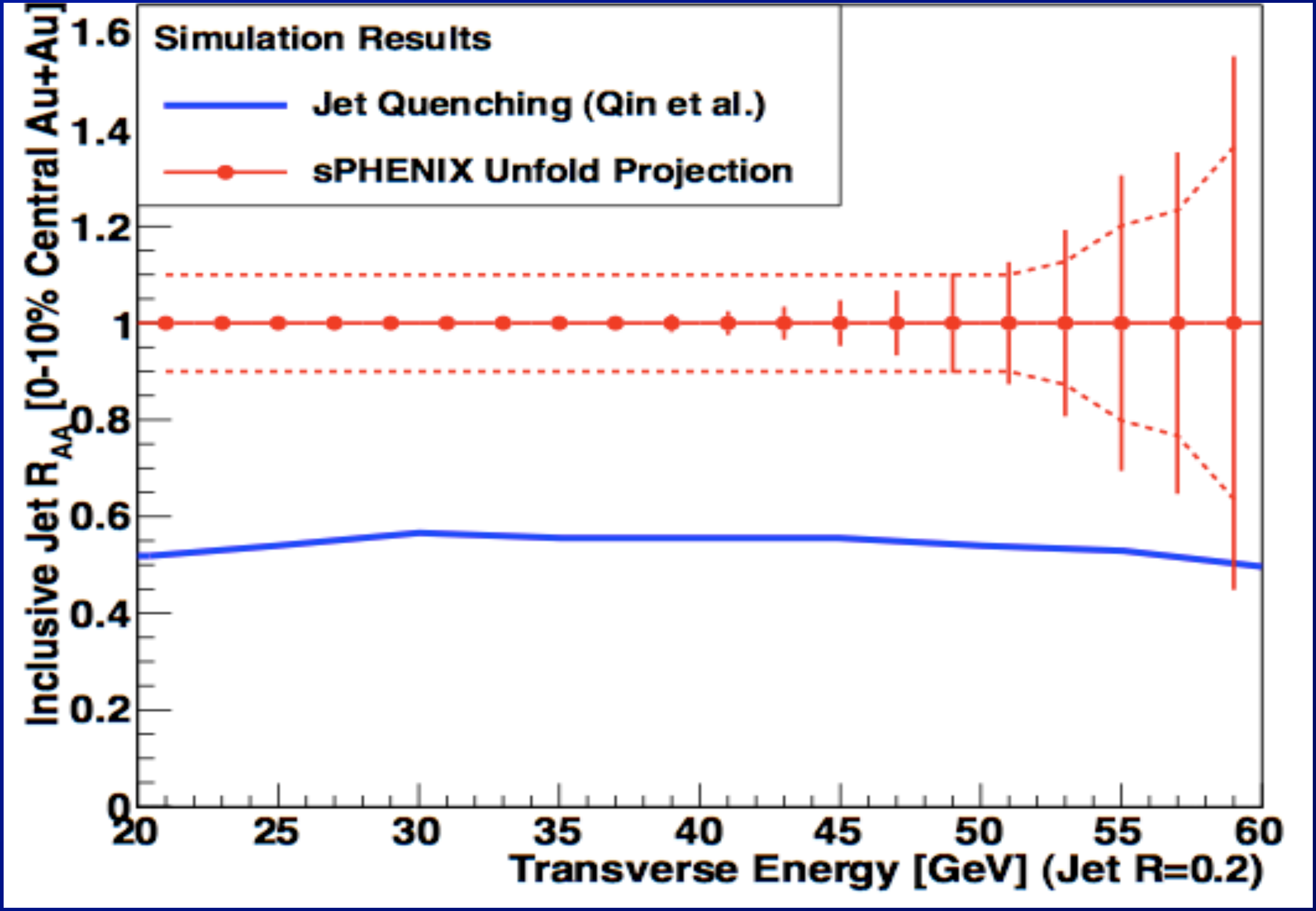
Example RooUnfold Iterative Bayes Method shows very good result.

Full GEANT-4 simulation with FastJet Reconstruction gives good resolution.



Jet R_{AA} measurable with high stats

Jet suppression: prediction

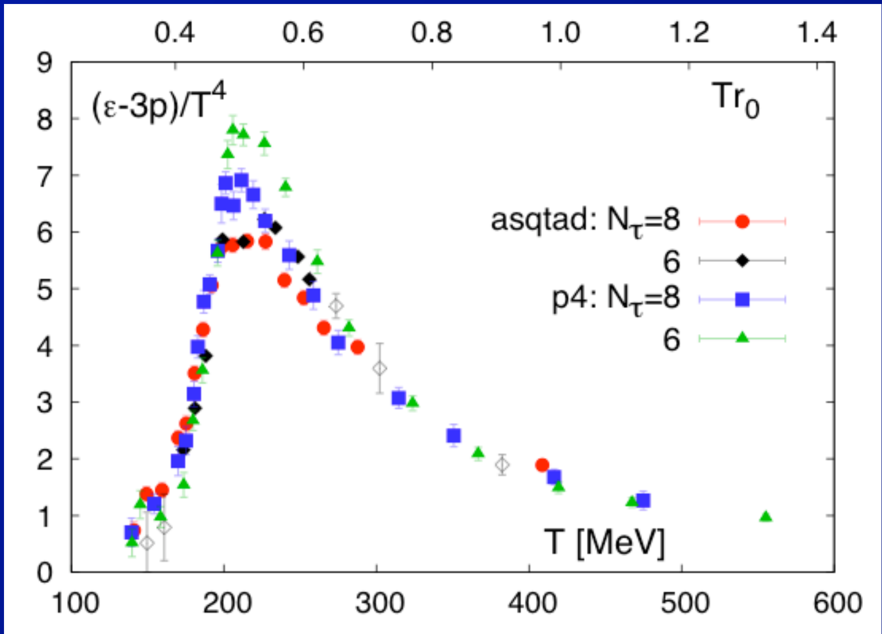


Guang-You Qin, private communication

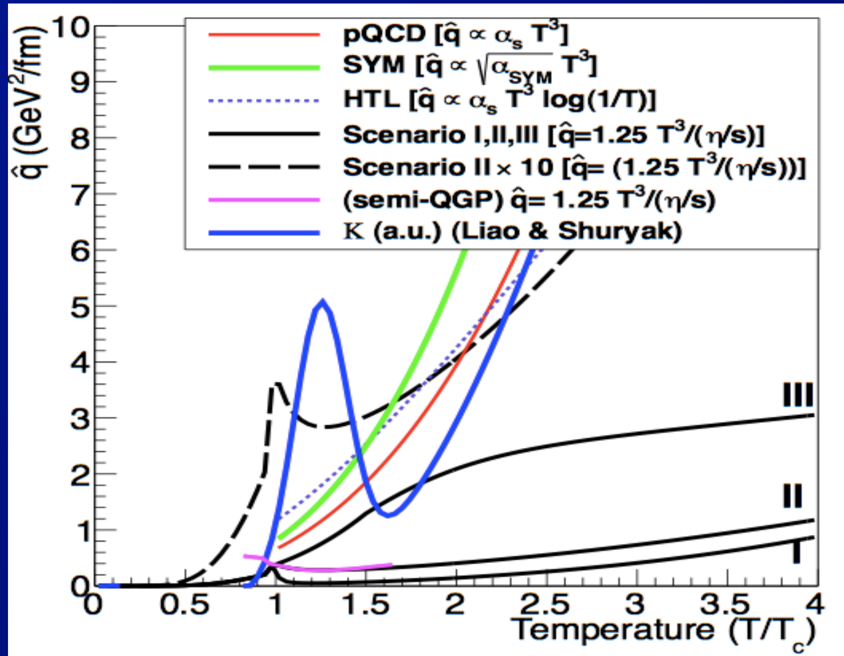
Summary

- Jet quenching @ RHIC remains a critical part of the heavy ion hard probes program.
  - ⇒Essential for disentangling QGP transport properties at $T \sim T_c$ and $T > \sim 2T_c$
- Jet results at the LHC provide strong motivation for similar measurements at RHIC
  - ⇒With luminosity improvements @ RHIC, plenty of rate for high-E_T jets, photons
- Initial theoretical studies show that jet, dijet, gamma-jet, … measurements @ RHIC are sensitive to quenching
  - ⇒Much more work to be done
- sPHENIX proposes integrated EM+hadronic calorimeter system to perform jet measurements

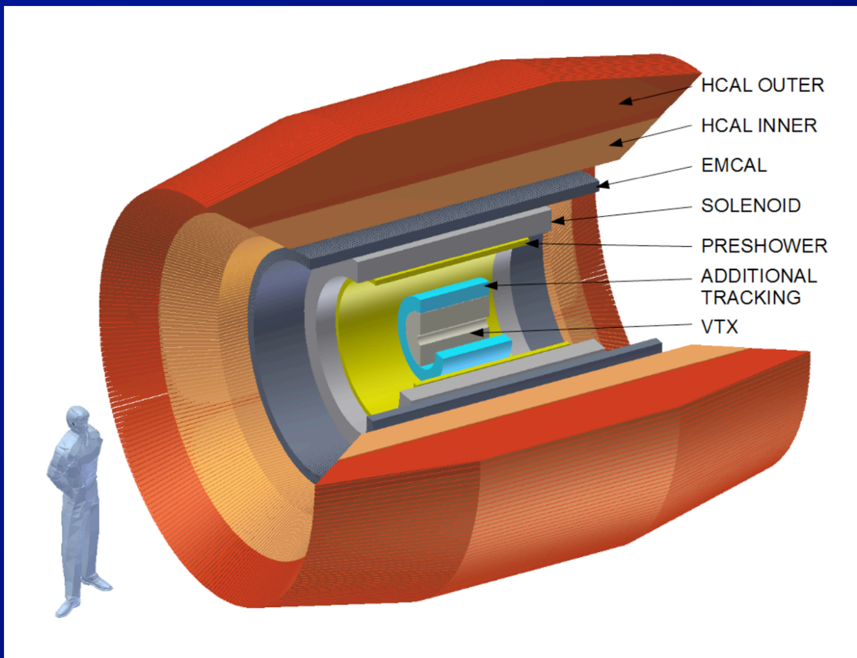
Summary (2)



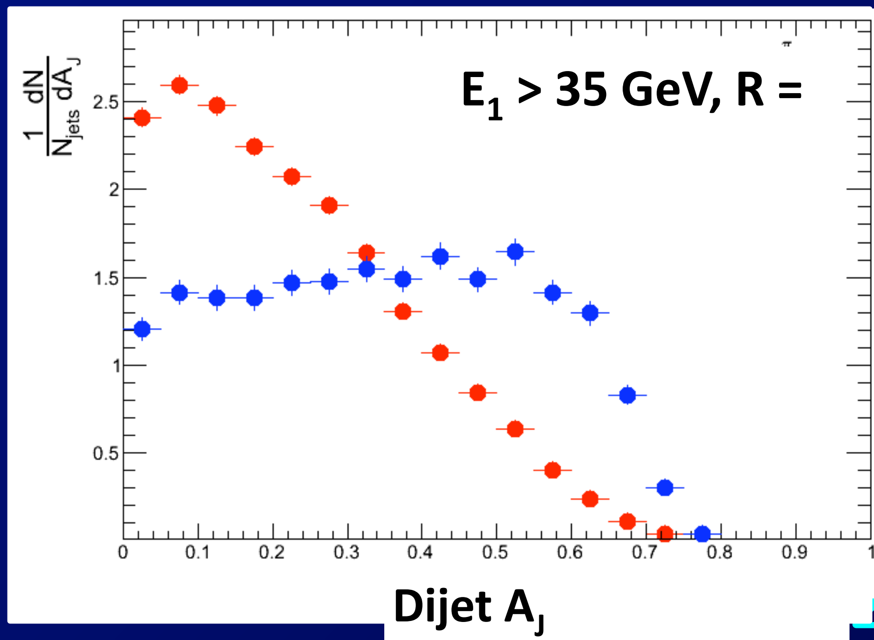
(ε-3p)/T^4
Tr0
asqtad: Nτ=8
6
p4: Nτ=8
6
T [MeV]



q̂ (GeV²/fm)
pQCD [q̂ ∝ αs T³]
SYM [q̂ ∝ √αSYM T³]
HTL [q̂ ∝ αs T³ log(1/T)]
Scenario I,II,III [q̂=1.25 T³/(η/s)]
Scenario II × 10 [q̂= (1.25 T³/(η/s))]
(semi-QGP) q̂= 1.25 T³/(η/s)
K (a.u.) (Liao & Shuryak)
III
II
I
Temperature (T/Tc)



HCAL OUTER
HCAL INNER
EMCAL
SOLENOID
PRESHOWER
ADDITIONAL TRACKING
VTX

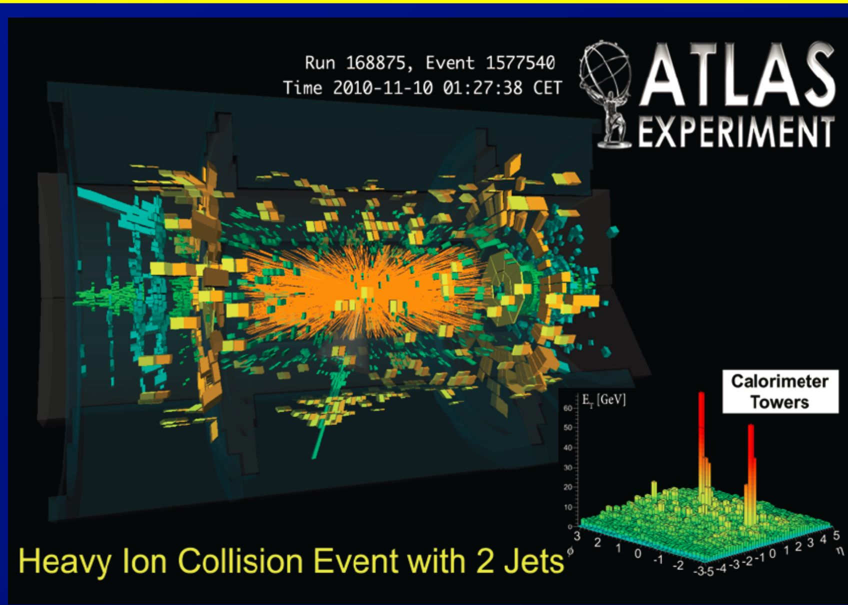


1/Njets dN/dAJ
E1 > 35 GeV, R =
Dijet AJ

Backup

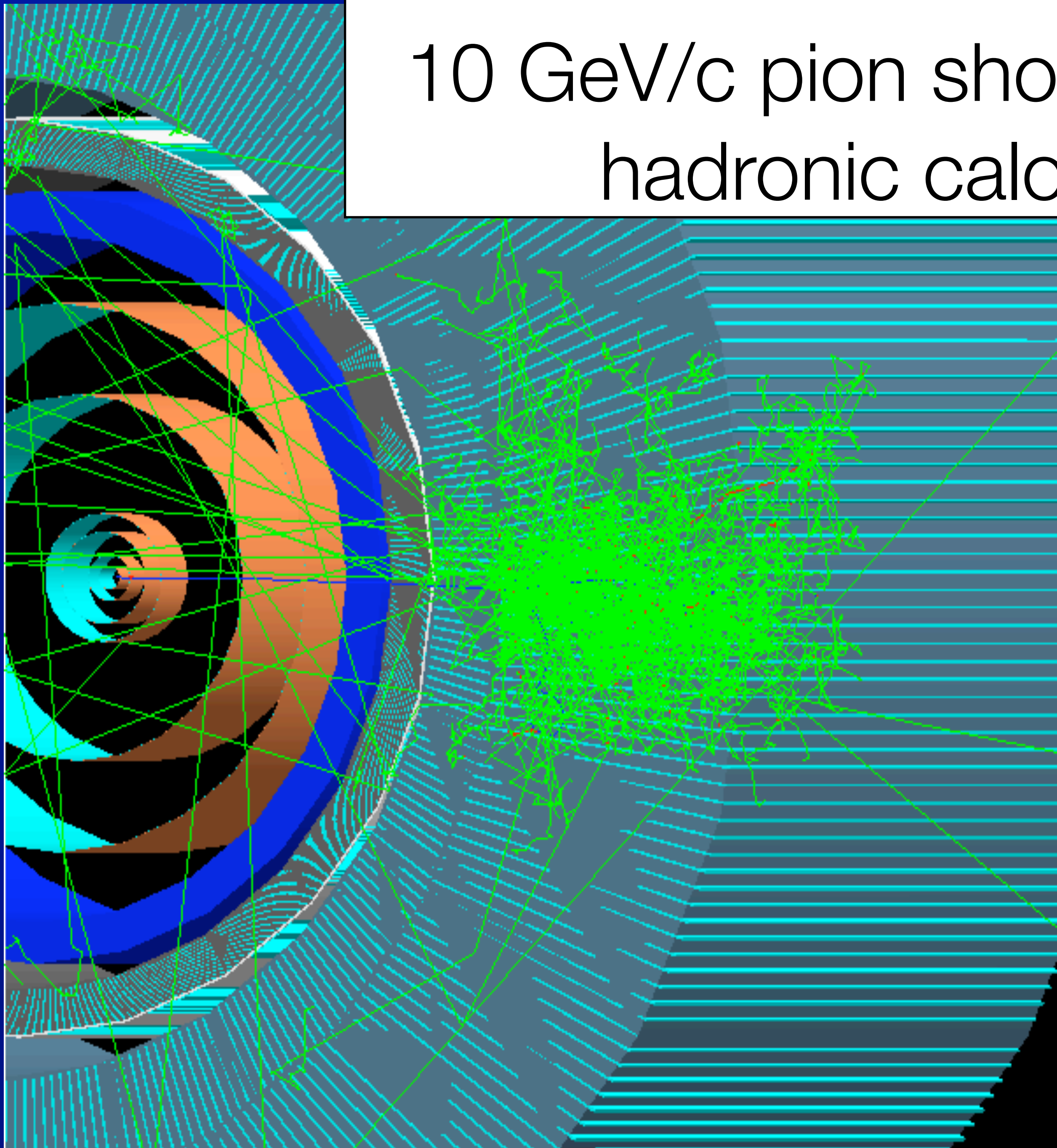
Why (hadronic) calorimetry?

- All heavy ion jet publications to date (i.e. ATLAS and CMS) from calorimeters.
  - No missing energy.
  - Tracking - calorimeter cross-checks
  - Separate measurement of jet and jet fragments.
  - Triggering
- sPHENIX calorimeter design goal:
  - EMCal + HCAL with continuous coverage (no gaps, spokes, holes) with large acceptance to see both jets and γ-jet and at very high rate.

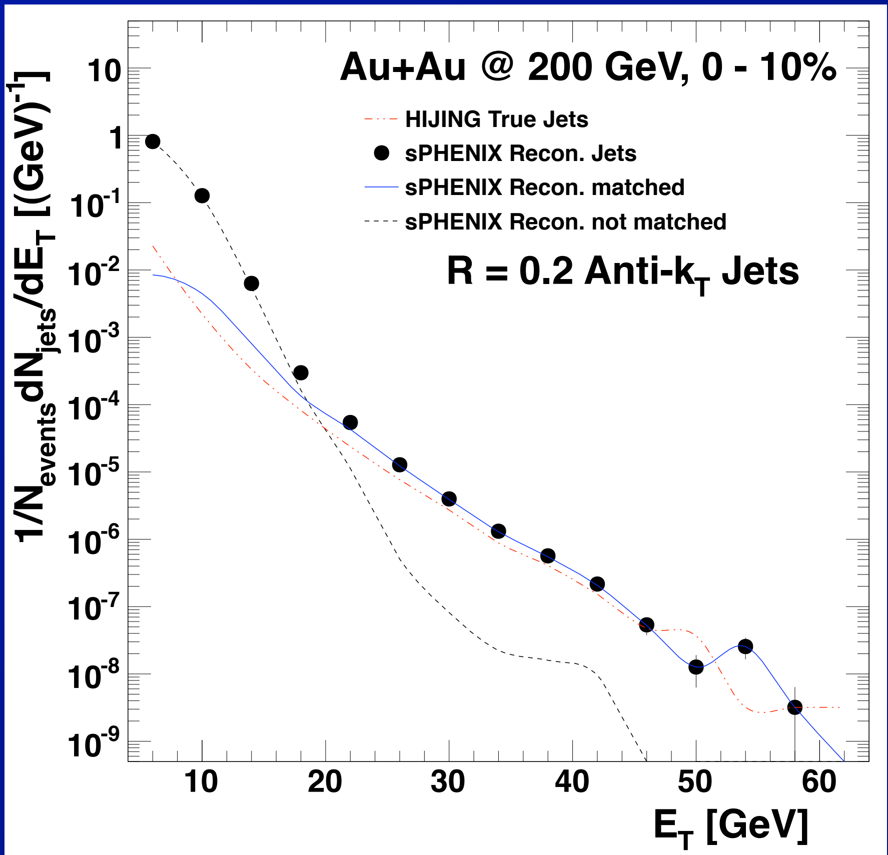


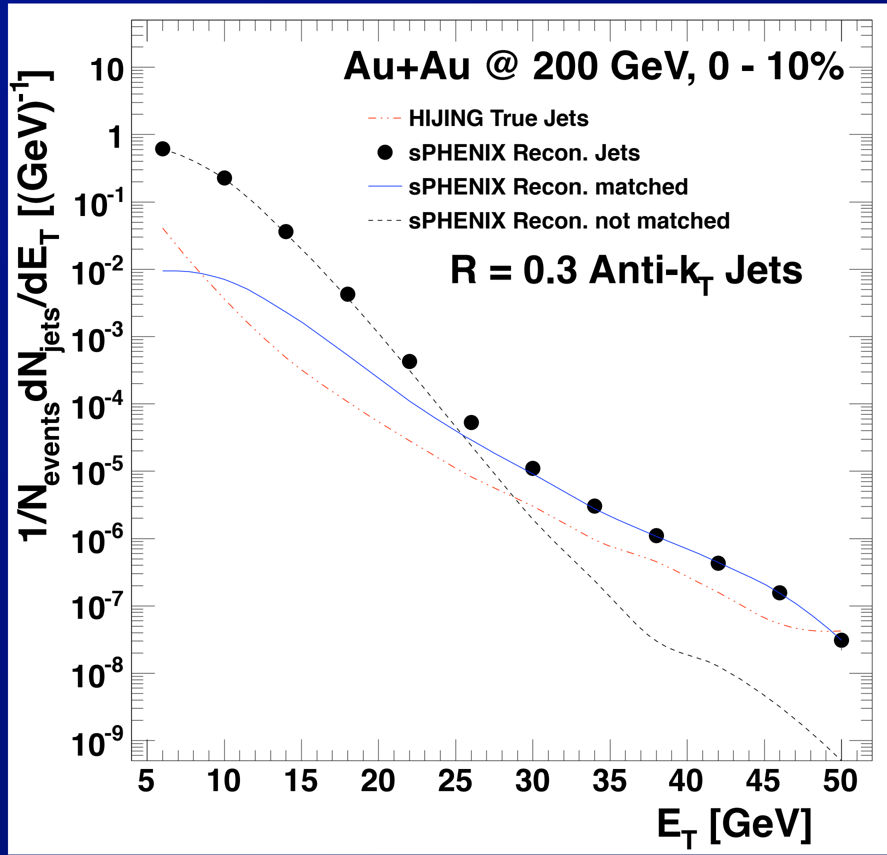
sPHENIX GEANT4

10 GeV/c pion showering in the hadronic calorimeter



sPHENIX: HIJING fake rates

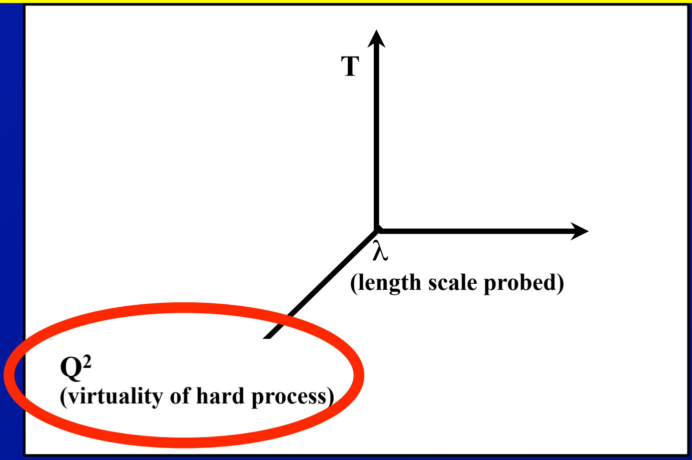




- HIJING fake rates for R = 0.2, 0.3 jets
  - S/B > 1 for E_T > 20 GeV (R = 0.2), 25 GeV (R = 0.3)
  - with no additional fake rejection

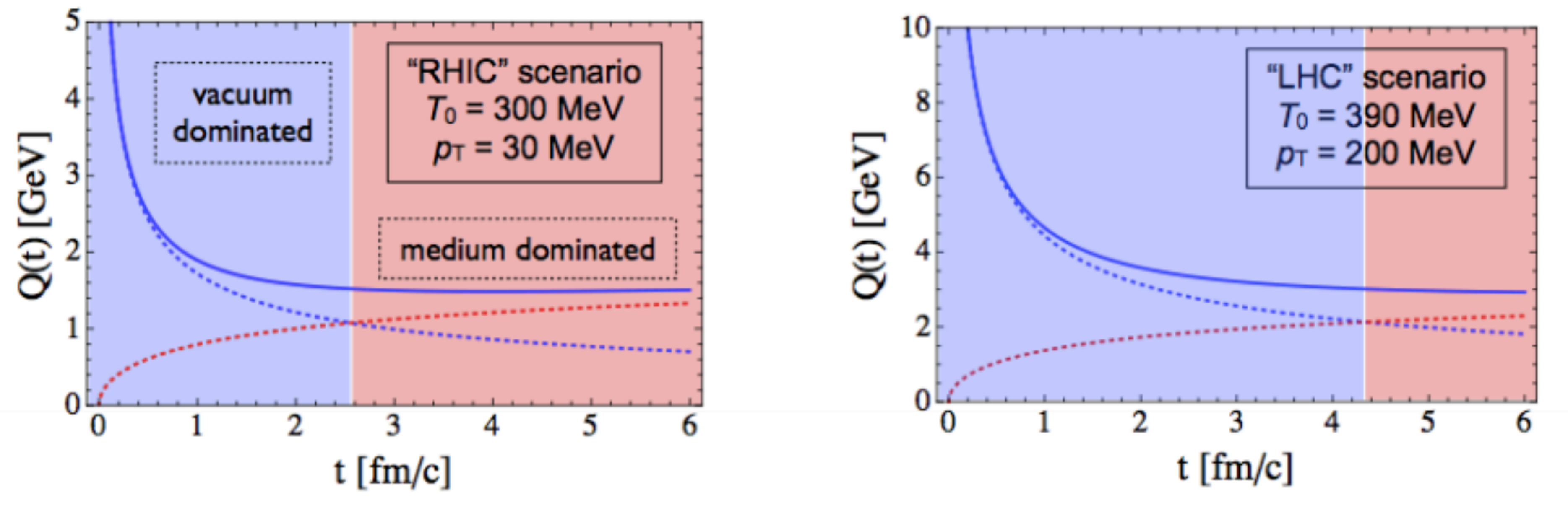
    ⇒in ATLAS > x10 reduction

Role of virtuality (Berndt's talk)



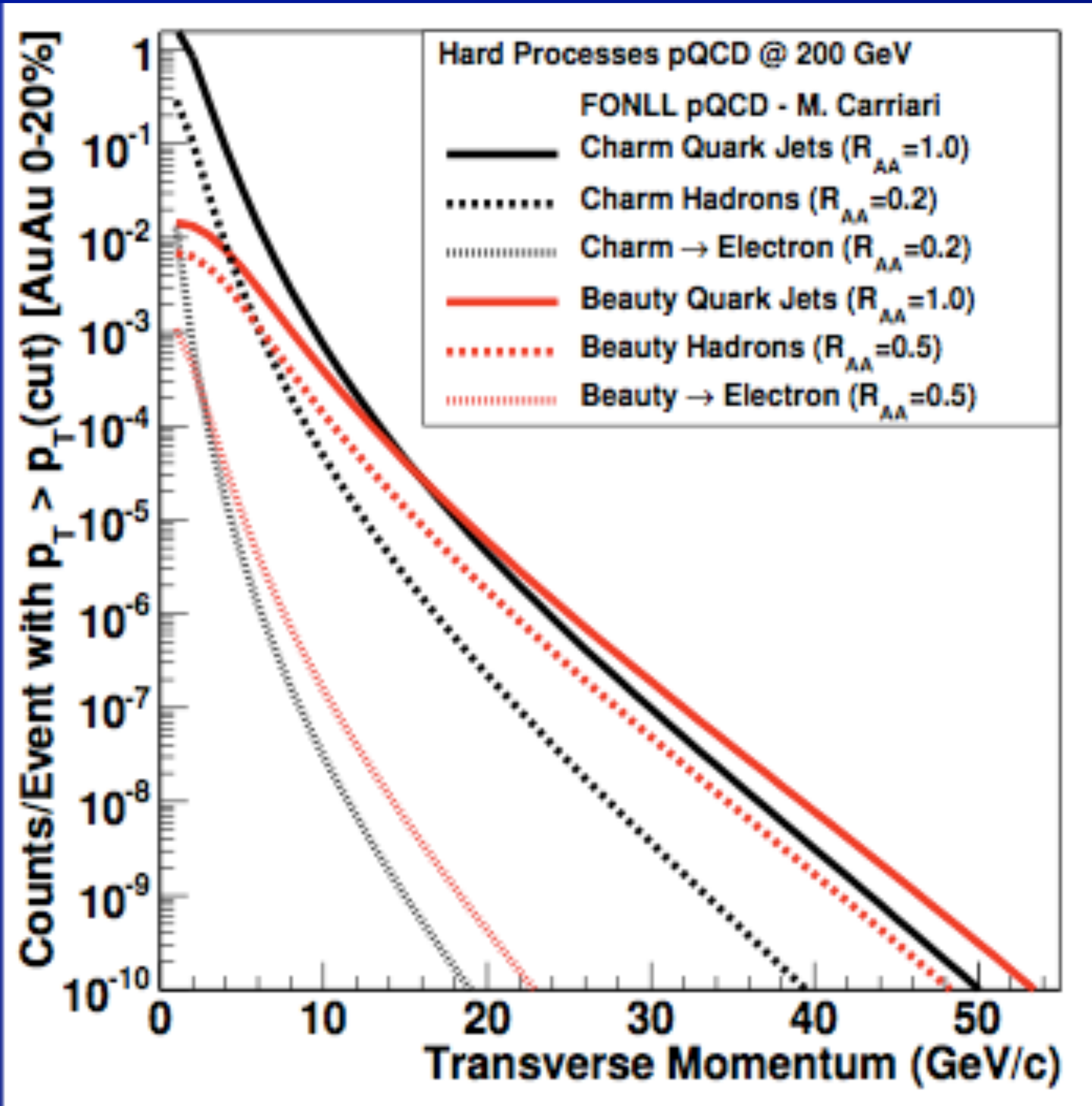
$$Q^2_{vac}(t) = \frac{E}{2t} \qquad Q^2_{med}(t) = \int \hat{q}(t)\,dt$$

$$Q^2(t) = Q^2_{vac}(t) + Q^2_{med}(t)$$



- Relative contributions of hard scattering and medium virtuality different @ RHIC, LHC.

heavy flavor (w/ additional tracking)



counts/year

10^9

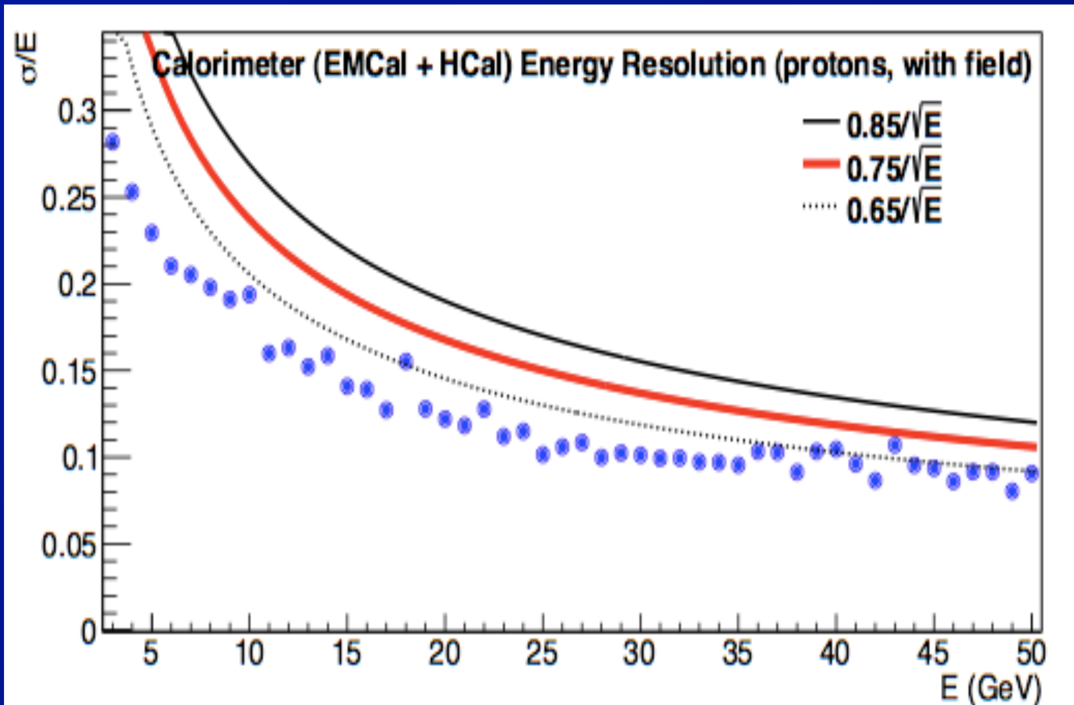
10^6

10^3

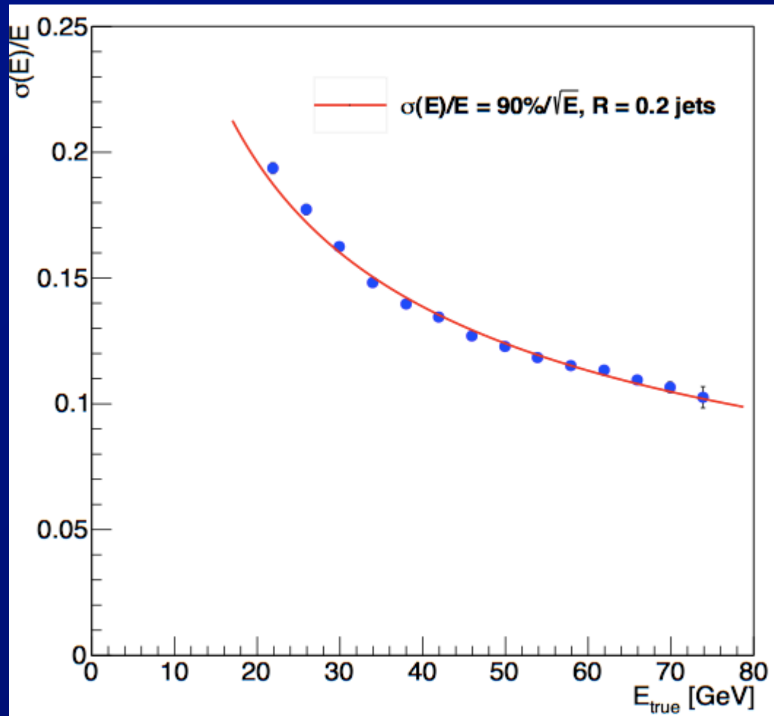
1

Calorimeter resolution

Single particle resolution in EMCal+HCal

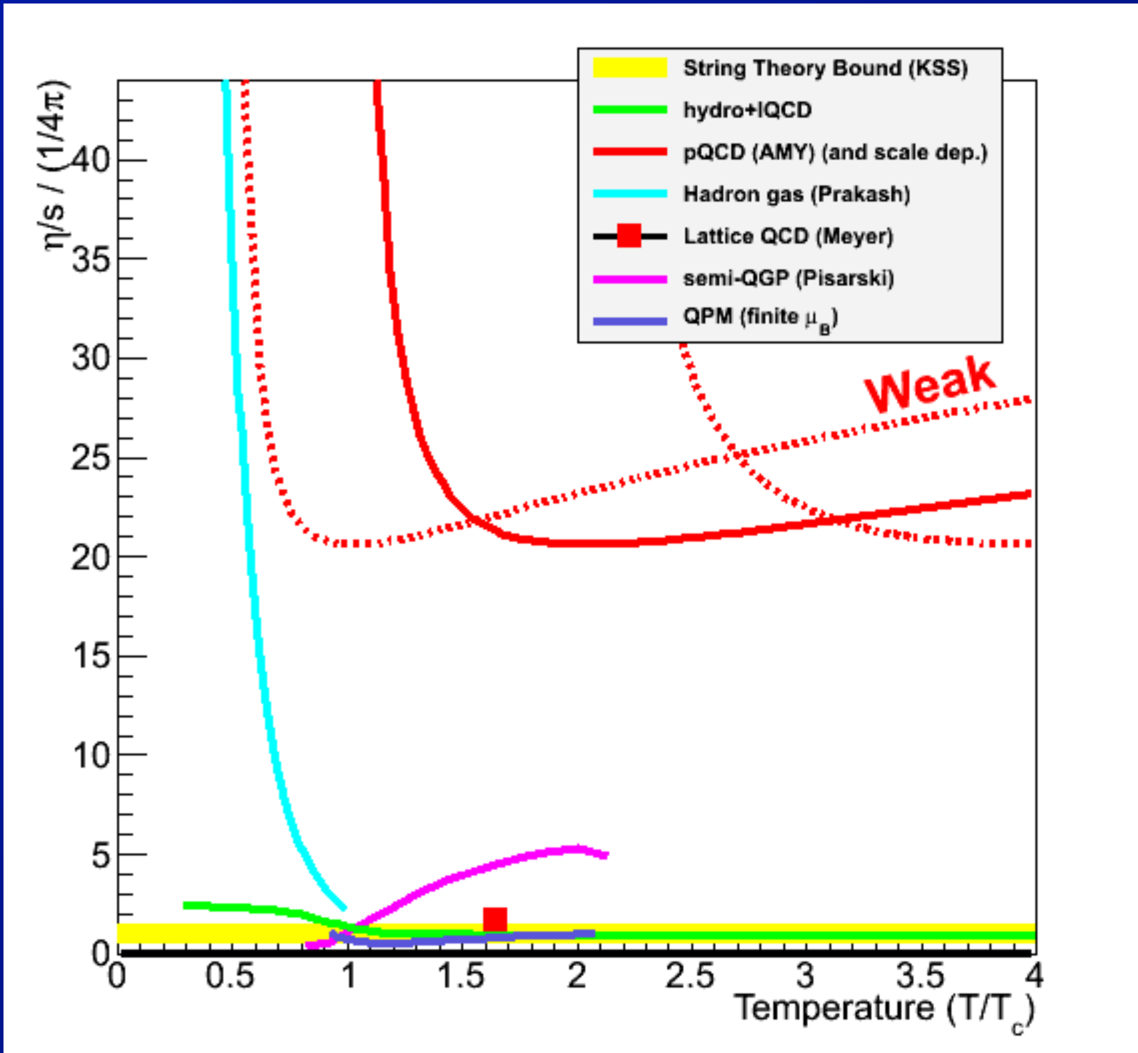


Jet energy resolution from full GEANT4 in *p+p*



- EM+HCal resolution better than 65% / √E
  - single particle (protons)
  - full GEANT4 simulation including field
- Jet resolution in p-p - 90% / √E
- Au+Au central UE δE ~ 5 GeV for R = 0.4 jet

Various studies of η/s



Hydro + lQCD calculation from Kovtun, Moore, and Romatschke http://arxiv.org/abs/arXiv:1104.1586

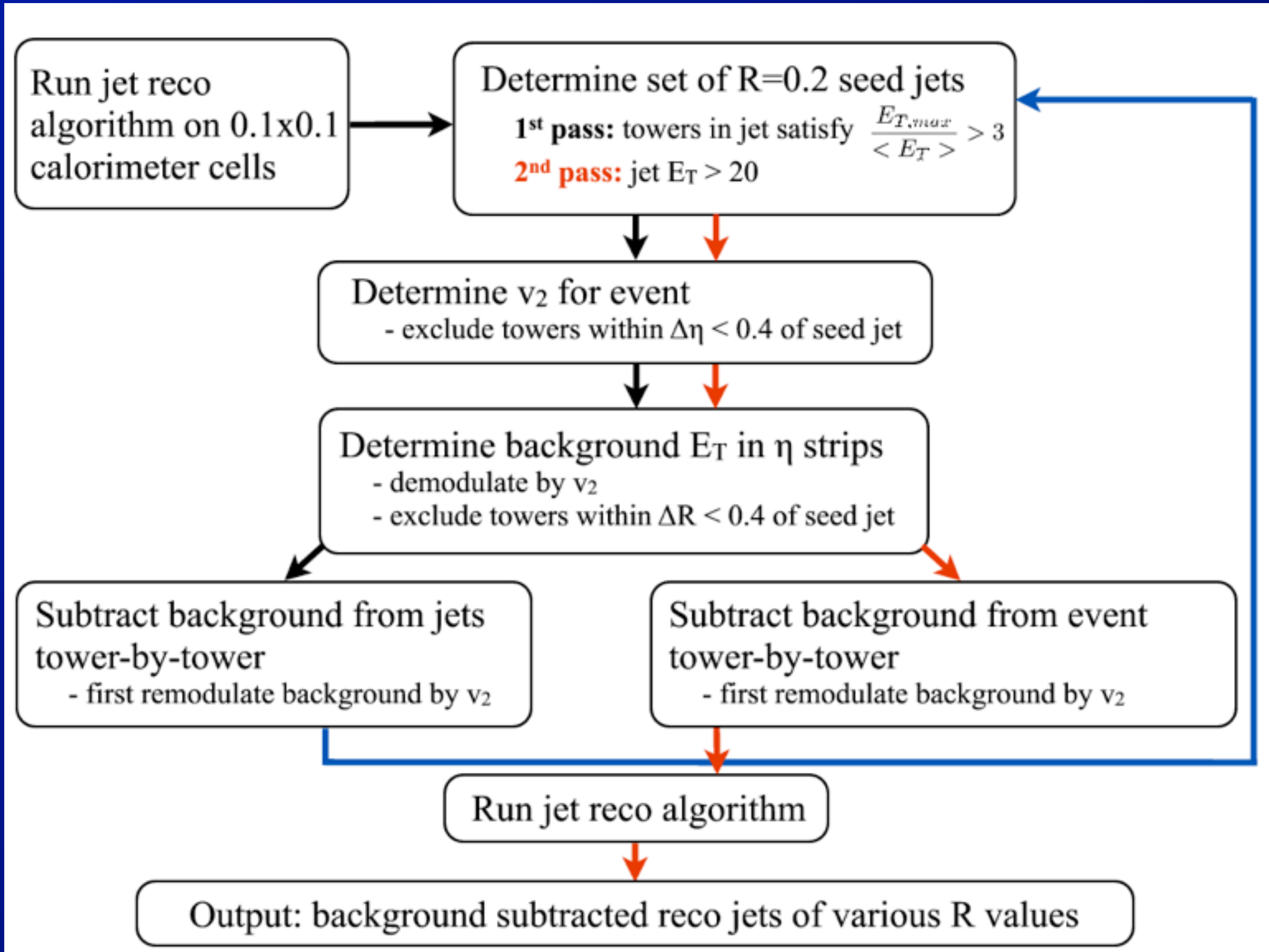
Hadron gas calculation from Prakash (almost 20 years ago) 1/T^4). http://www.sciencedirect.com/science/article/pii/037015739390092R

Lattice QCD result from Harvey Meyer (gluodynamics) http://arxiv.org/abs/0704.1801

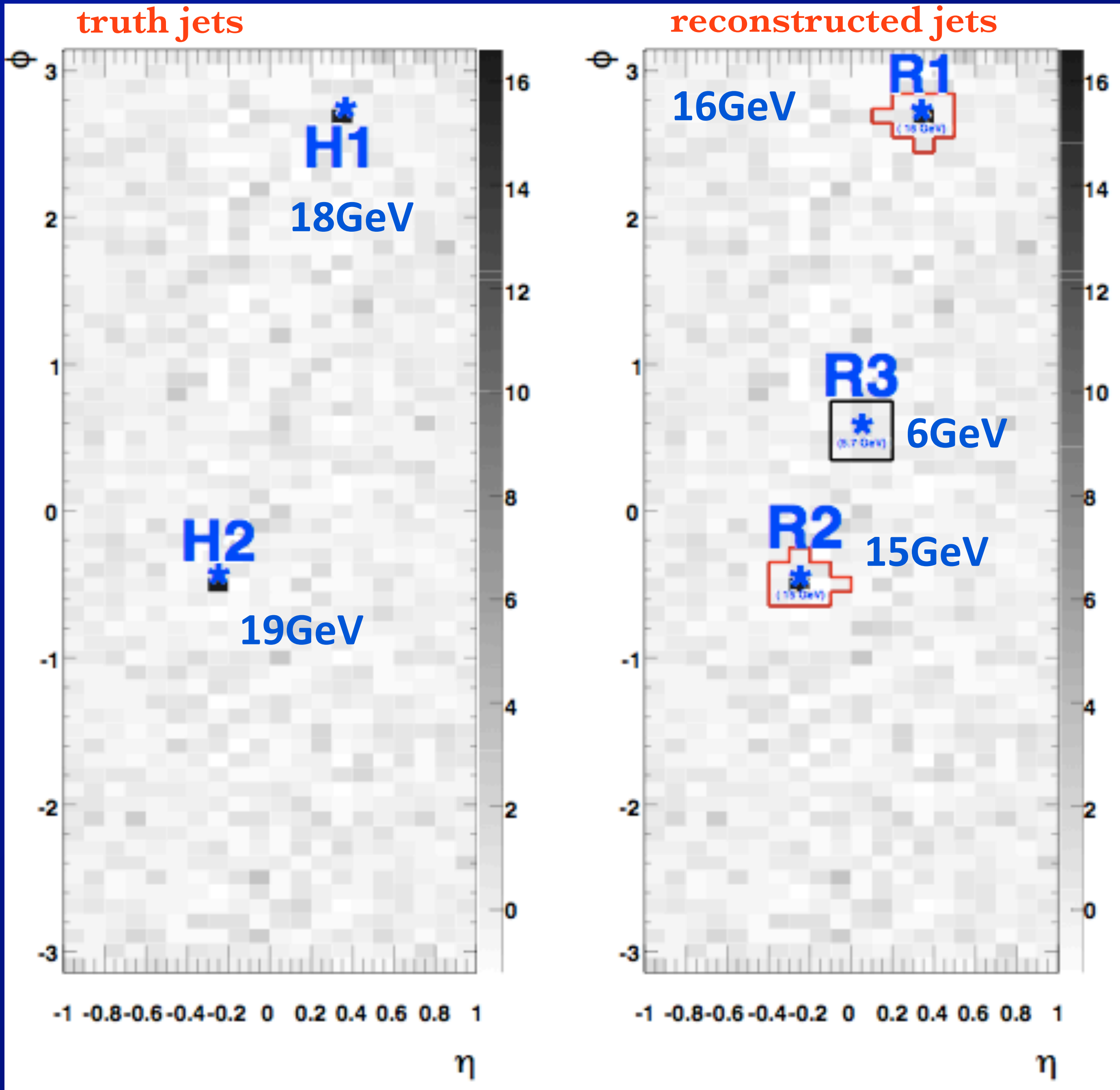
QPM, finite mu_B calculation from Shrivistava and Singh http://arxiv.org/abs/1201.0445

Semi-QGP calculation from Rob Pisarski with kappa = 8 http://arxiv.org/abs/arXiv:0912.0940

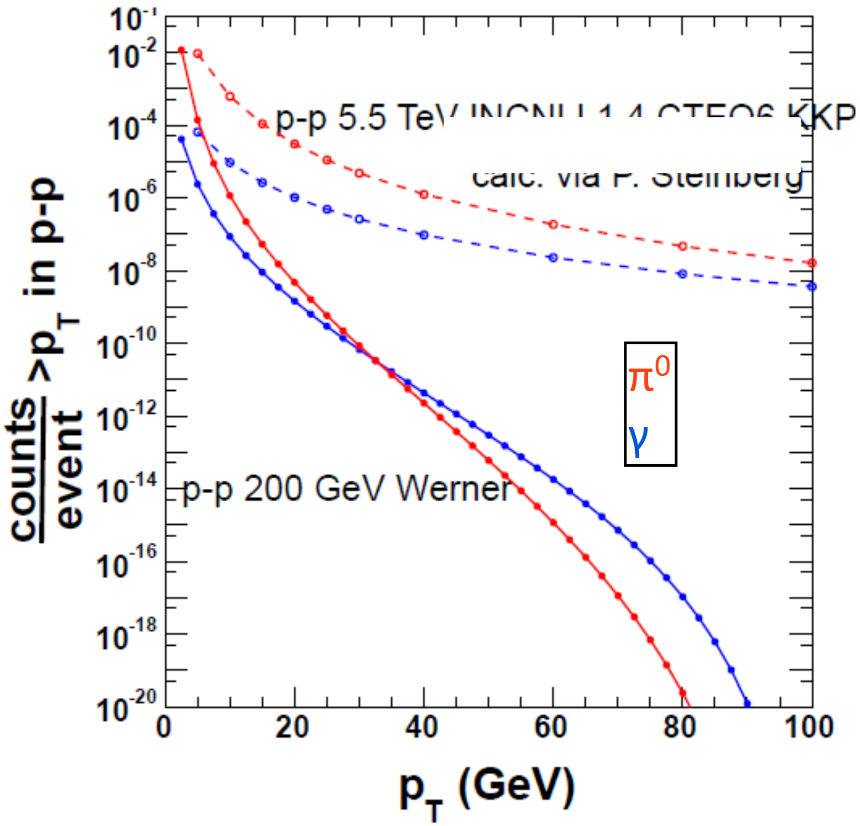
sPHENIX Jet Algorithm

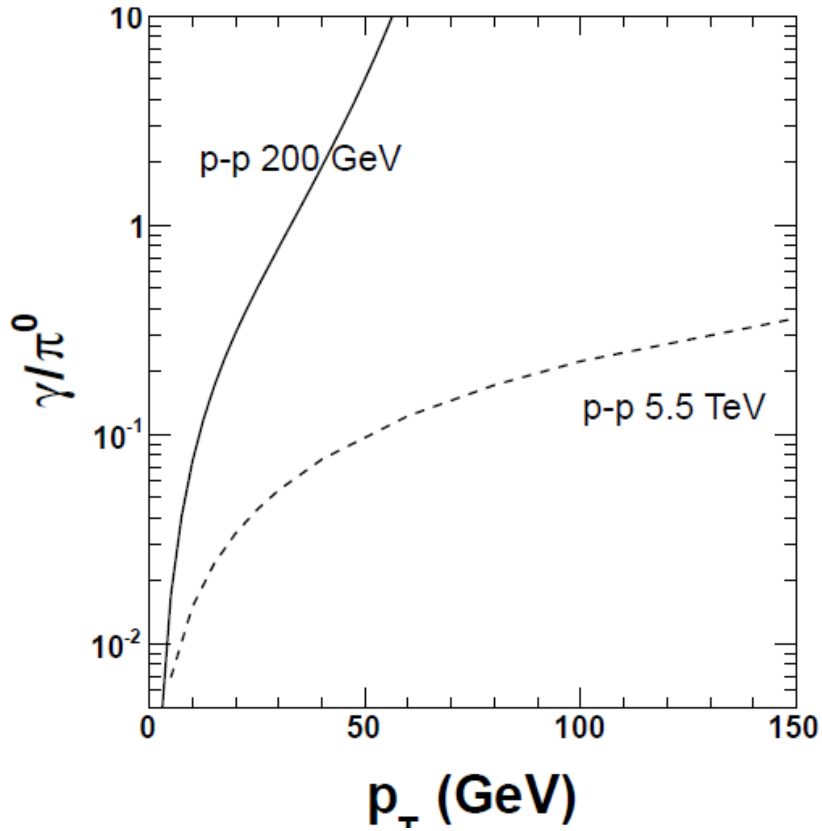


sPHENIX (ideal) event display



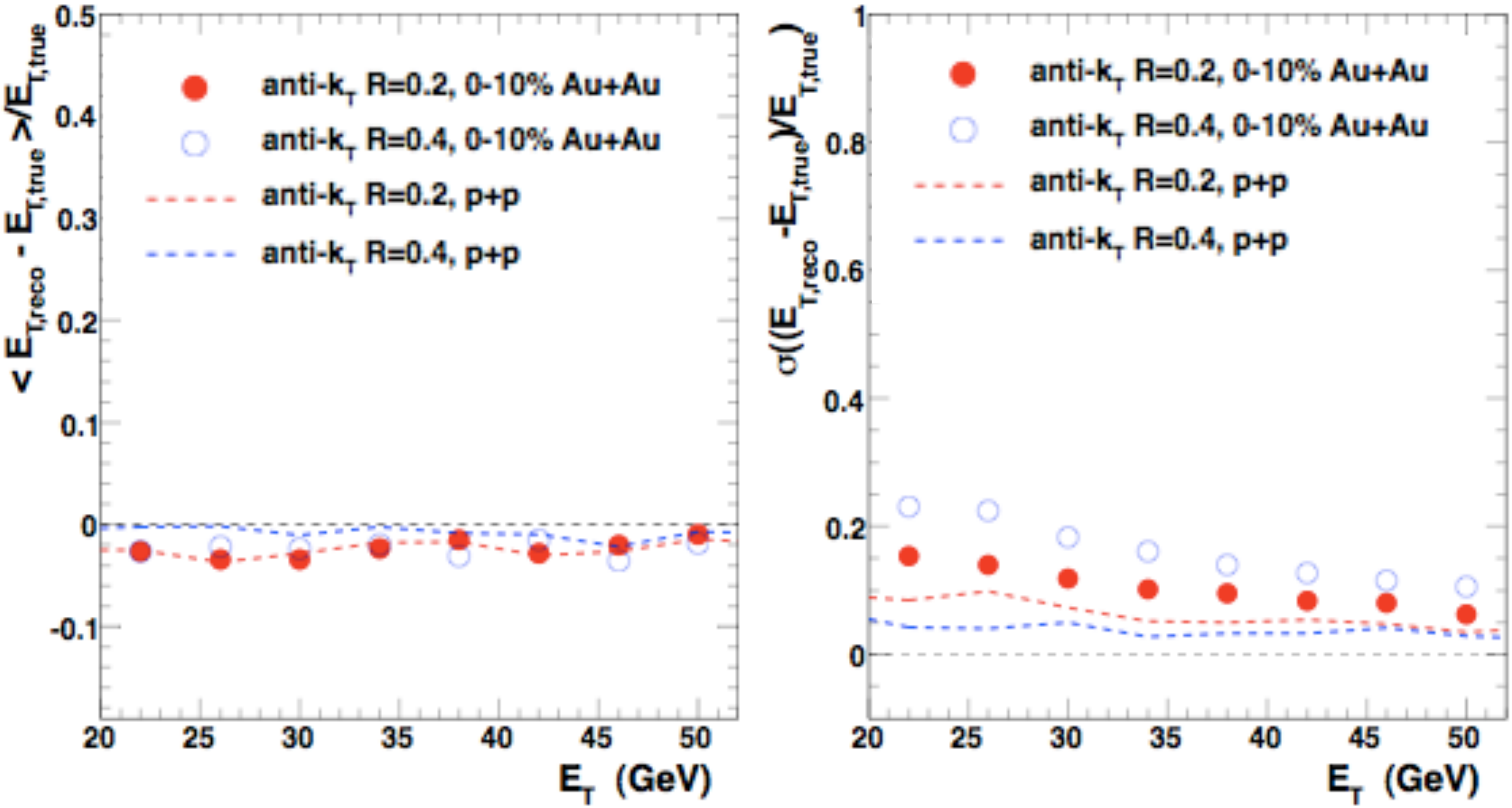
Direct Photons





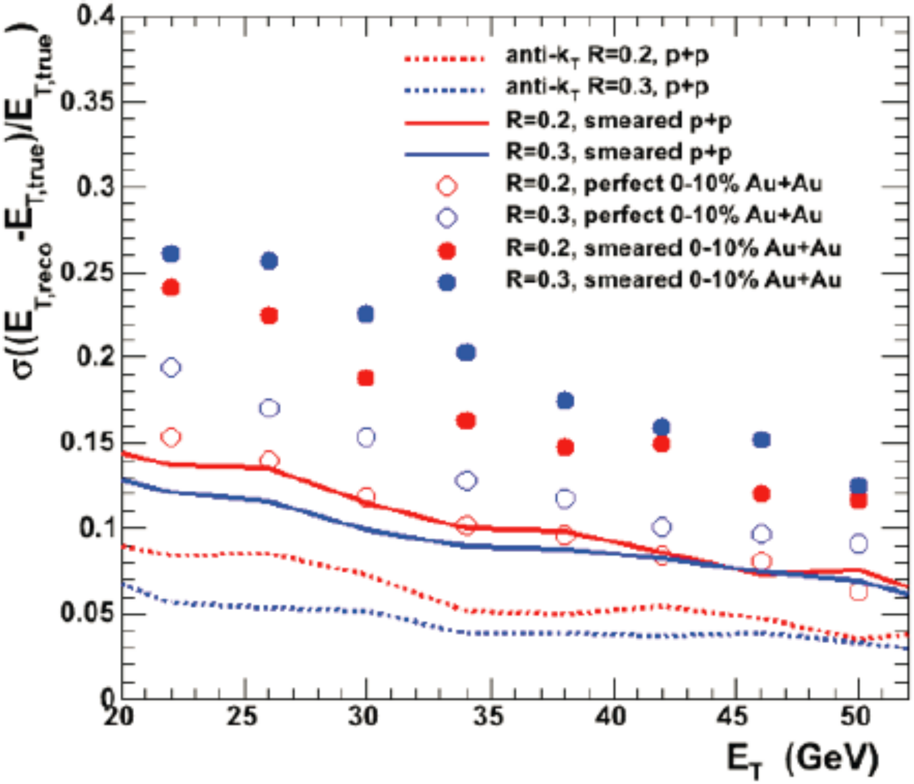
- γ/π^0 very large at RHIC
- good S/B >20GeV
- substantial rate even >30GeV
- RHIC a very good place for γ-jet correlations

Reconstruction performance

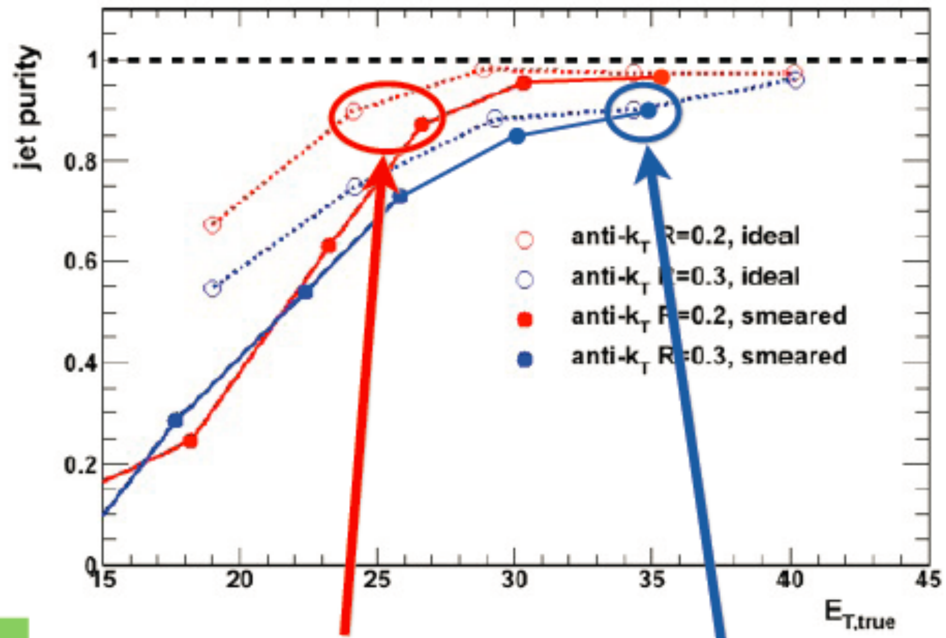


- good performance in heavy ion background
- resolution only from the underlying event, no detector resolution included

arXiv:1203.1353



Does this change the story of fake jets?

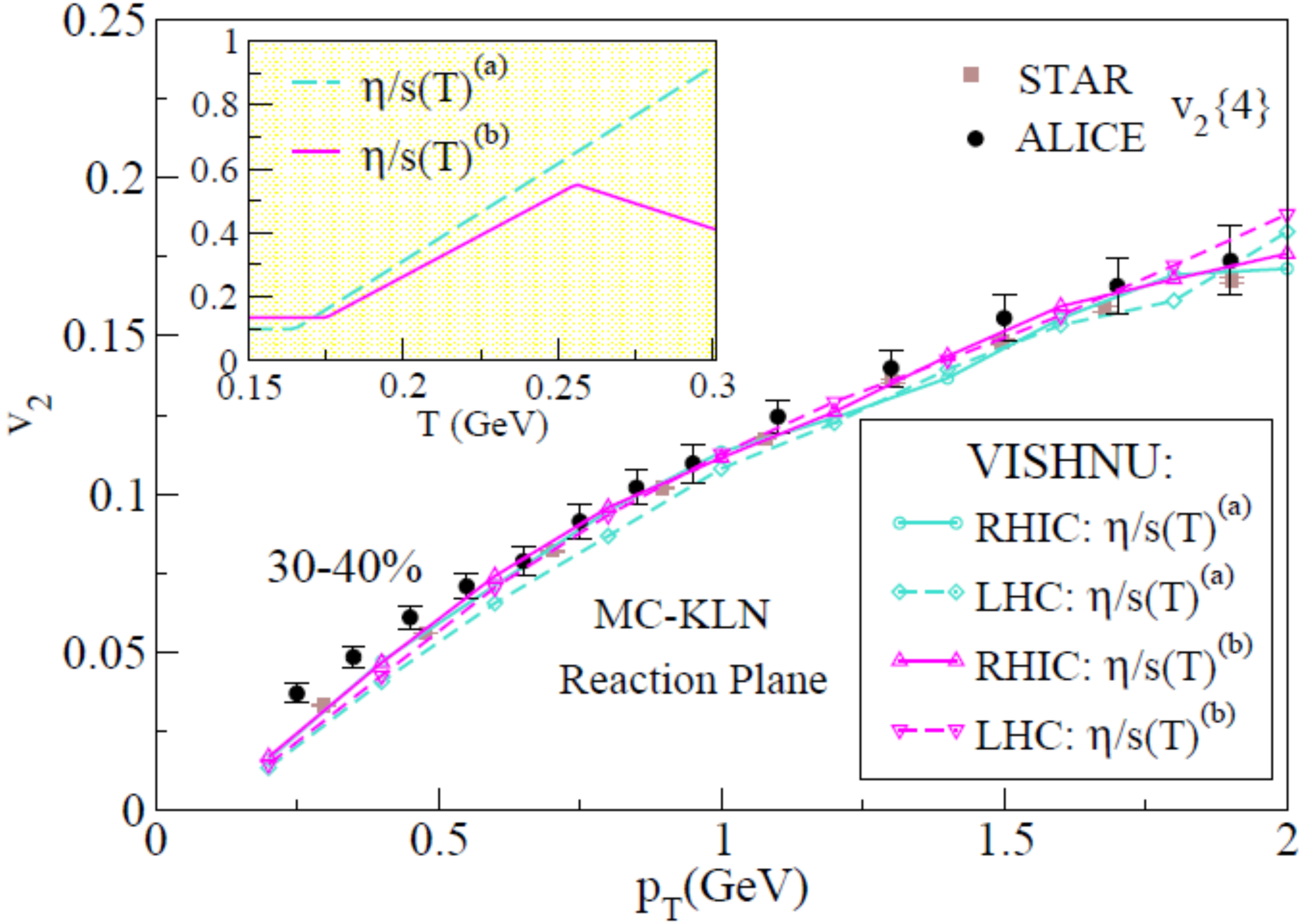


~25 GeV for R=0.2

~35 GeV for R=0.3

very conservative estimates for detector resolution added

Why hydrodynamics and bulk flow might not answer everything?



Song, Bass, Heinz, arXiv:1103.2380