*The City of Detroit (from Canada Shore)*, 1872, by A. C. Warren

# Near- and Medium-Term Future of $E_{loss}$ Measurements at RHIC


**Justin Frantz**

**Ohio University**


**2nd Annual Wayne State Jet Workshop**

# Plans at RHIC

From RHIC ALD Berndt Muller talk in June:

| Years | Beam Species and Energies | Science Goals | New Systems Commissioned |
|---|---|---|---|
| 2013 | • 510 GeV pol p+p | • Sea quark and gluon polarization | • upgraded pol'd source<br>• STAR HFT test |
| 2014 | • 200 GeV Au+Au<br>• 15 GeV Au+Au | • Heavy flavor flow, energy loss, thermalization, etc.<br>• Quarkonium studies<br>• QCD critical point search | • Electron lenses<br>• 56 MHz SRF<br>• full STAR HFT<br>• STAR MTD |
| 2015-2016 | • p+p at 200 GeV<br>• p+Au, d+Au, $^3$He+Au at 200 GeV<br>• High statistics Au+Au | • Extract η/s(T) + constrain initial quantum fluctuations<br>• More heavy flavor studies<br>• Sphaleron tests | • PHENIX MPC-EX<br>• Coherent electron cooling test |
| 2017 | • No Run | | • Electron cooling upgrade |
| 2018-2019 | • 5-20 GeV Au+Au (BES-2) | Search for QCD critical point and deconfinement onset | • STAR ITPC upgrade |
| 2020 | • No Run | | • sPHENIX installation |
| 2021-2022 | • Long 200 GeV Au+Au w/ upgraded detectors<br>• p+p/d+Au at 200 GeV | • Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism<br>• Color screening for different QQ states | • sPHENIX |
| 2023-24 | • No Runs | | Transition to eRHIC |

- This talk will focus on the next decade of Heavy Ion (A+A) $E_{loss}$ physics - special focus on sPHENIX
- Won't talk ~much about Initial State and Forward Physics

# RHIC in Next 10 years

- Exploit RHIC's **Flexibility** to study different systems, small and large
- **Geometry:** Exotics CuCu, CuAu, UU, dAu, tAu, $He^3Au$
- (**Cool stuff:** $p^{\uparrow}$ + A !)
- **Energy:** (2 Roles)
  - For $E_{loss}$
    factor of 20-40 lower sqrt(s) → 0.1 TeV ?
    - Heavy Flavor
    - Jets → sPHENIX
  - Another factor of 20 lower (with fixed target statistics!)
    e.g. The BES : Phase Transition Physics

# Complementarity of RHIC/LHC

We have seen demonstrated in many ways why RHIC remains crucial in understanding sQGP physics (list a few big ones)

- $v_n$
  - Idea put forth for RHIC data (n = 3?)
  - Confirmed and Widely Expanded by LHC (n >= 6…)
  - Hydro models extract small $\eta/s$ , quantitatively from RHIC and LHC establishing universality of perfect fluid
- Jets: Enhancement at Low z in Fragmentation Function
  - Discovered at RHIC first (at first in spite of LHC null effects)
  - Confirmed and made precise by measurement at LHC
  - Uniformly defined measurement key tool in constraining $E_{loss}$ models
- Hydro-like signals in small systems?
  - Flow-like signals discovered in small systems at LHC
  - Looks like they exist at RHIC: constraining CGC contributions? Subnucleonic glauber?
  - PID behavior at LHC also hydro-like
- Heavy Flavor?

# Near Term RHIC Outlook

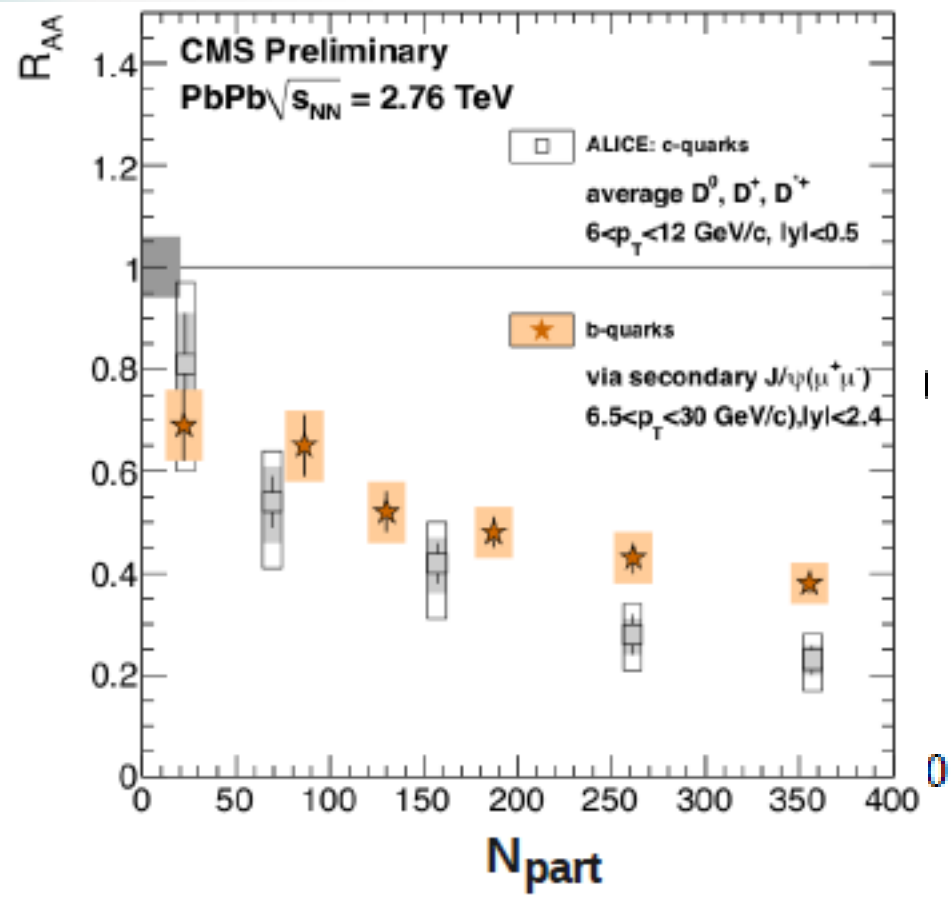
Heavy Flavor

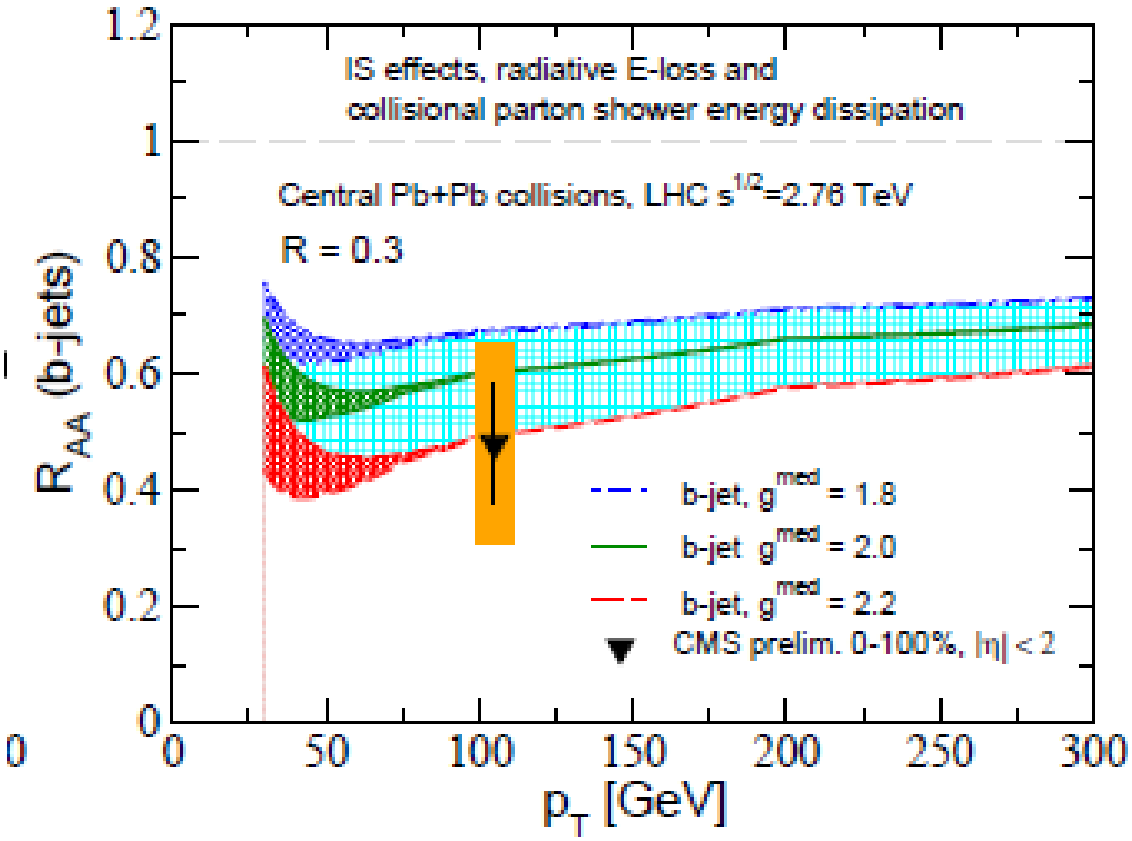
Small system stuff

Jets/Jet Reco

# Near-Term HF At RHIC

- The near future at RHIC has a decidedly Heavy flavor! Especially 2014: 2 STAR/2 PHENIX HF upgrades
- Perfect timing: LHC b-quark suppression

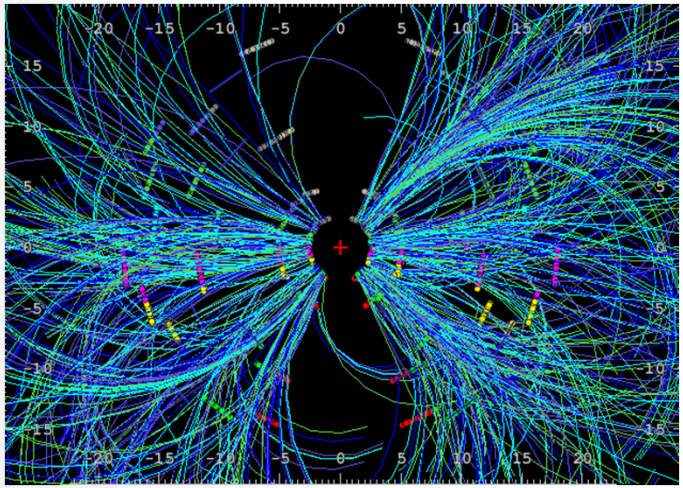


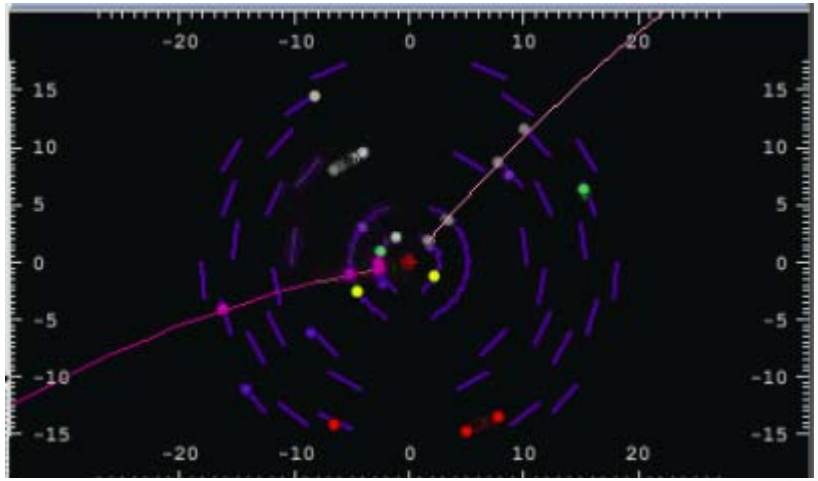
# PHENIX Silicon Vertexing

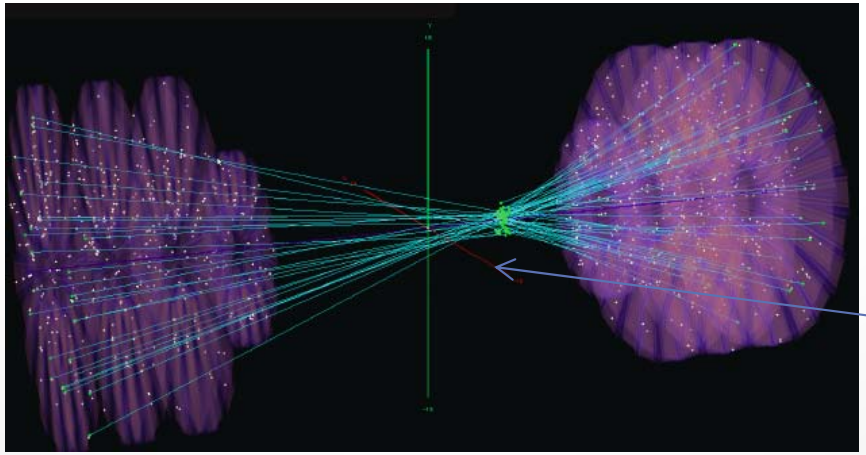
- VTX dataset in Au+Au 2011 and 2012 p+p
- FVTX Commisioning 2012 , Data taking 2013
- $R_{AA}$ $v_2$ of $c$, $b$ separately

Data: Au+Au@200 GeV, 2011



2012 p+p @ 200 dataset!



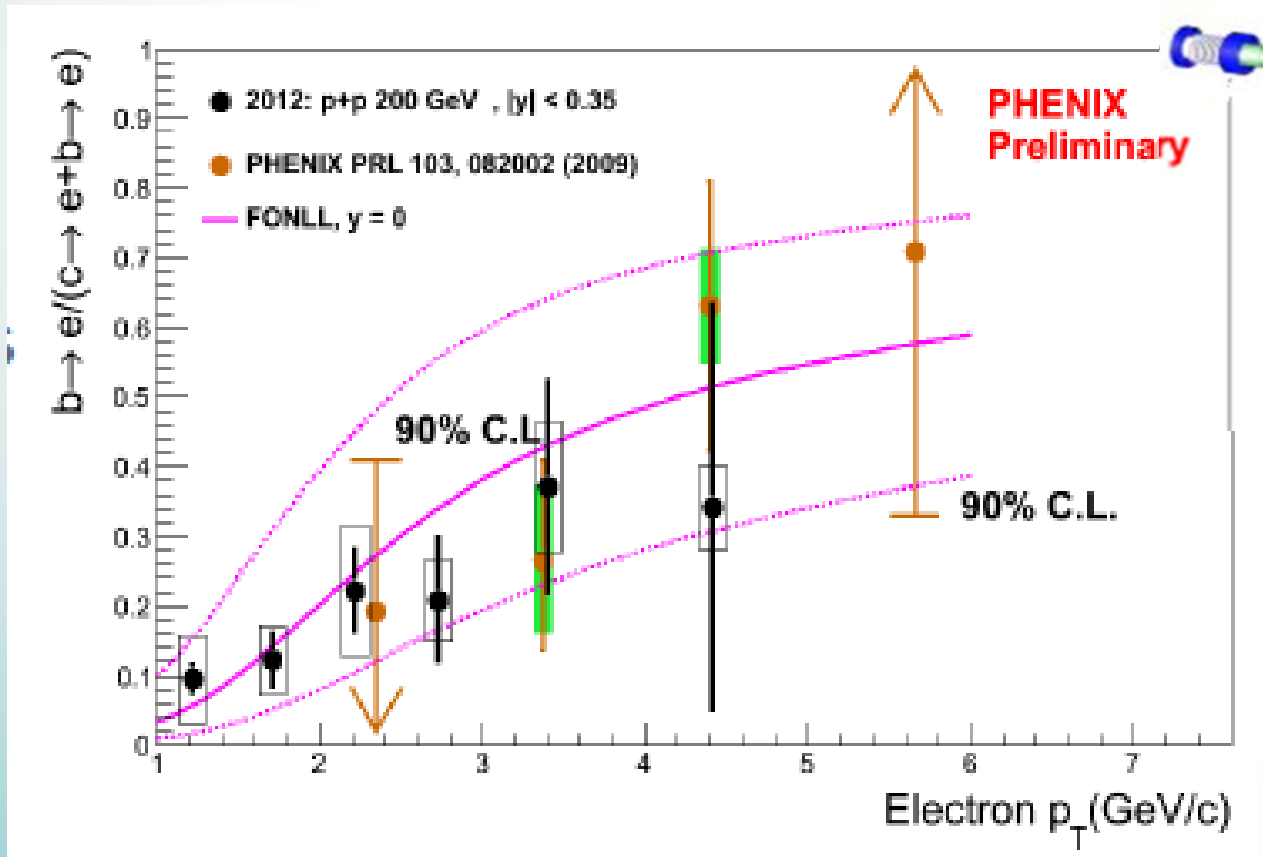


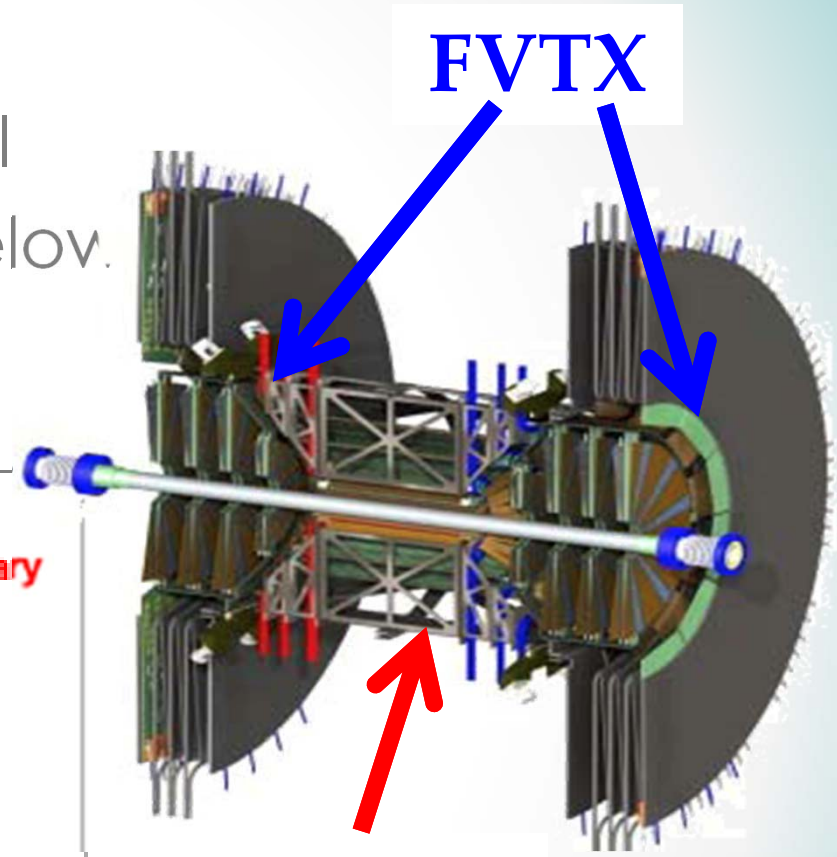
Detector commissioning /p+p reference went well

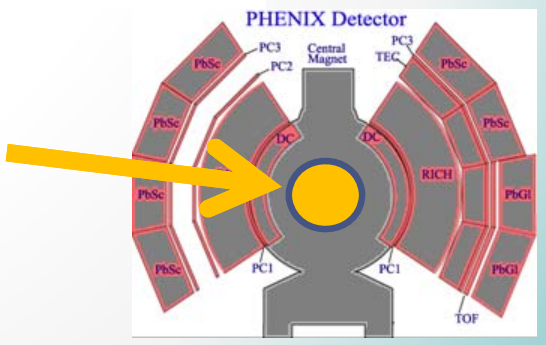
FVTX

# PHENIX VTX Upgrade

- c→ / b→ e separation
- Run11 Commissioning successful
- Run 12 p+p preliminary results below

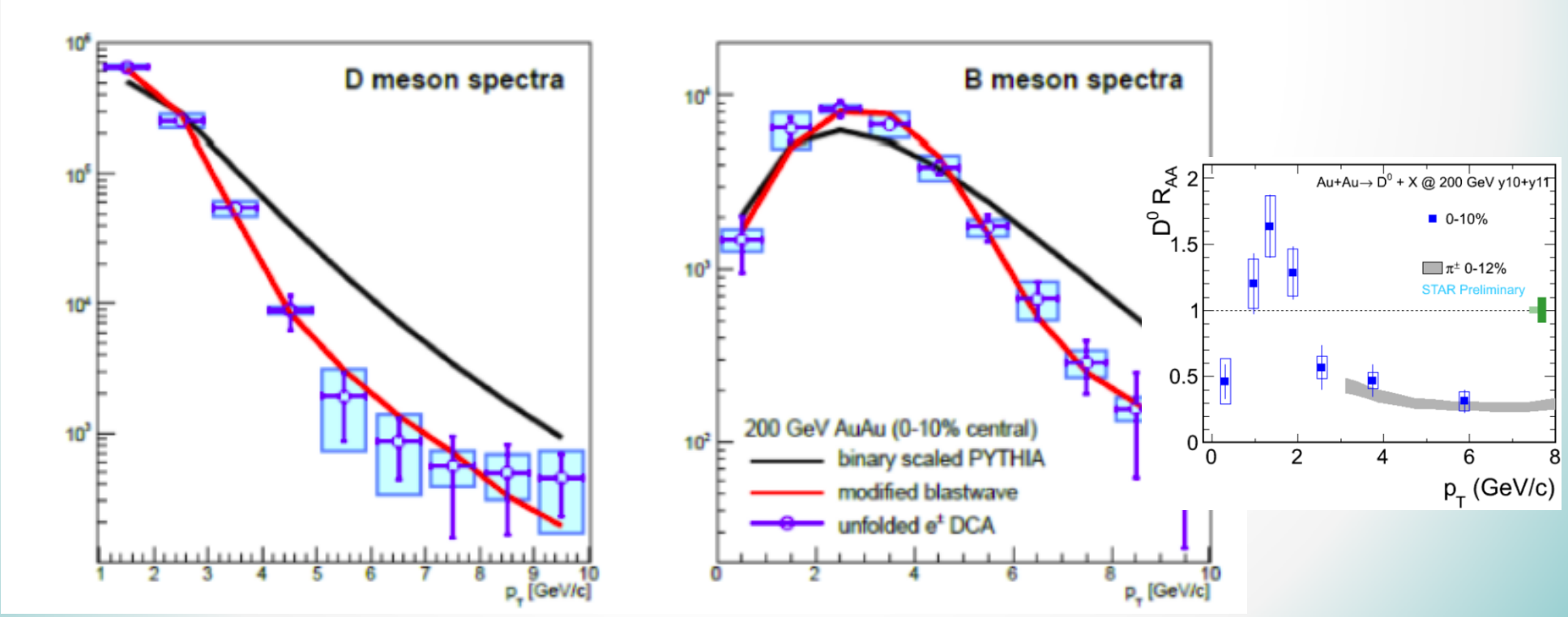


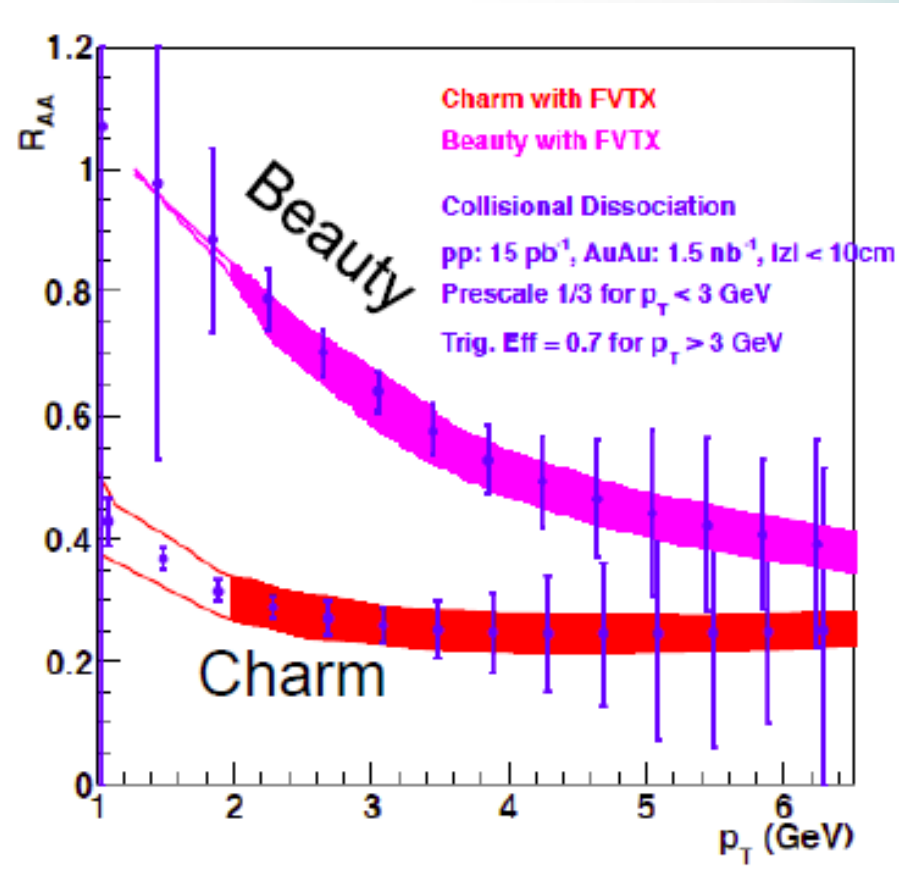
# PHENIX VTX

- Run 11/12 data indicated repairs necessary, much of detector offline for 2013 run
- QM12 A+A results did not include full b/c parent spectra unfolding systematics
  - Re-analysis underway QM 12 analysis to be updated
- **Run14: Full Repairs completed, ready!** functionality updated, unfolding techniques ready for first A+A production run! Projections with full unfolding systematics below:



# PHENIX FVTX

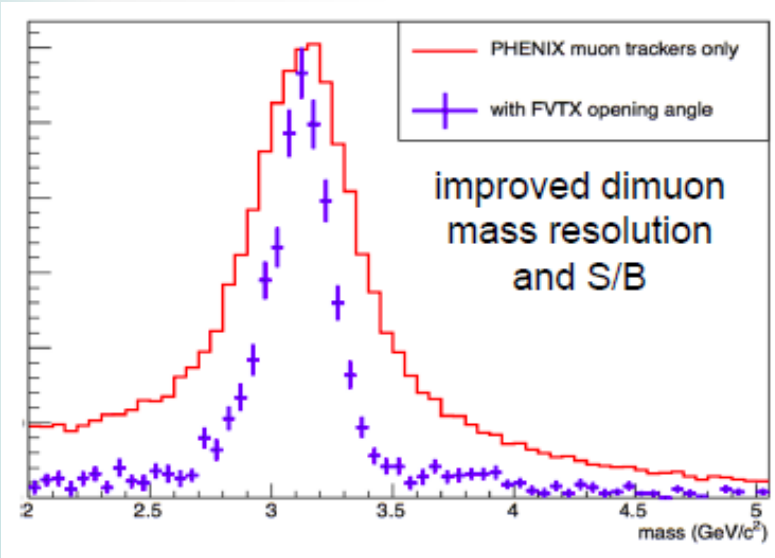
- FVTX provides *c/b* separation for forward/bkwd Muon arms
- HF Single and Di-muons / Drell-Yan
- FVTX commissioning run in Run-12 > 96% live active area
- Displaced vertex results for open heavy flavor from Run-12 Cu+Au expected soon



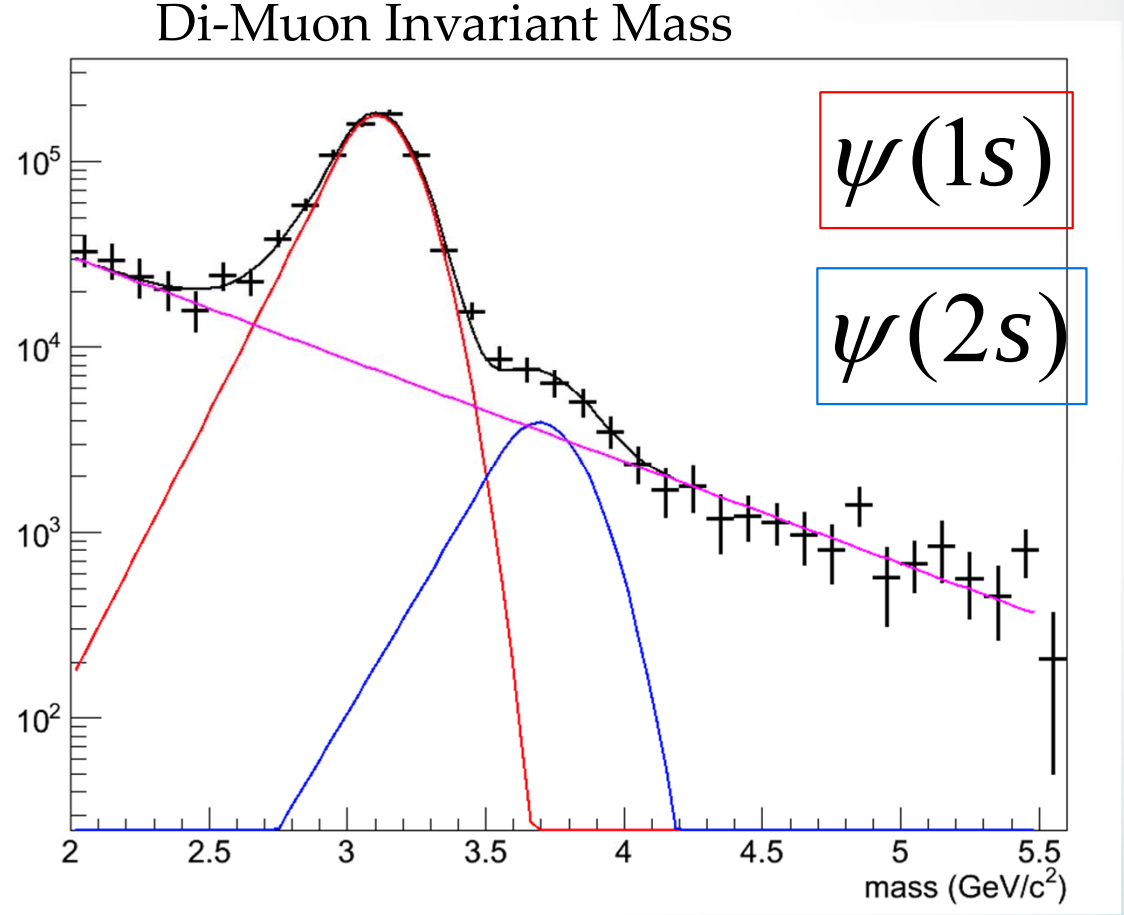
# FVTX Di-muons Run-13

- Dimuons matched to FVTX
  - use FVTX opening angle
  - require tight matching between FVTX/MuTr tracks

Di-Muon Invariant Mass




Di-Muon Invariant Mass

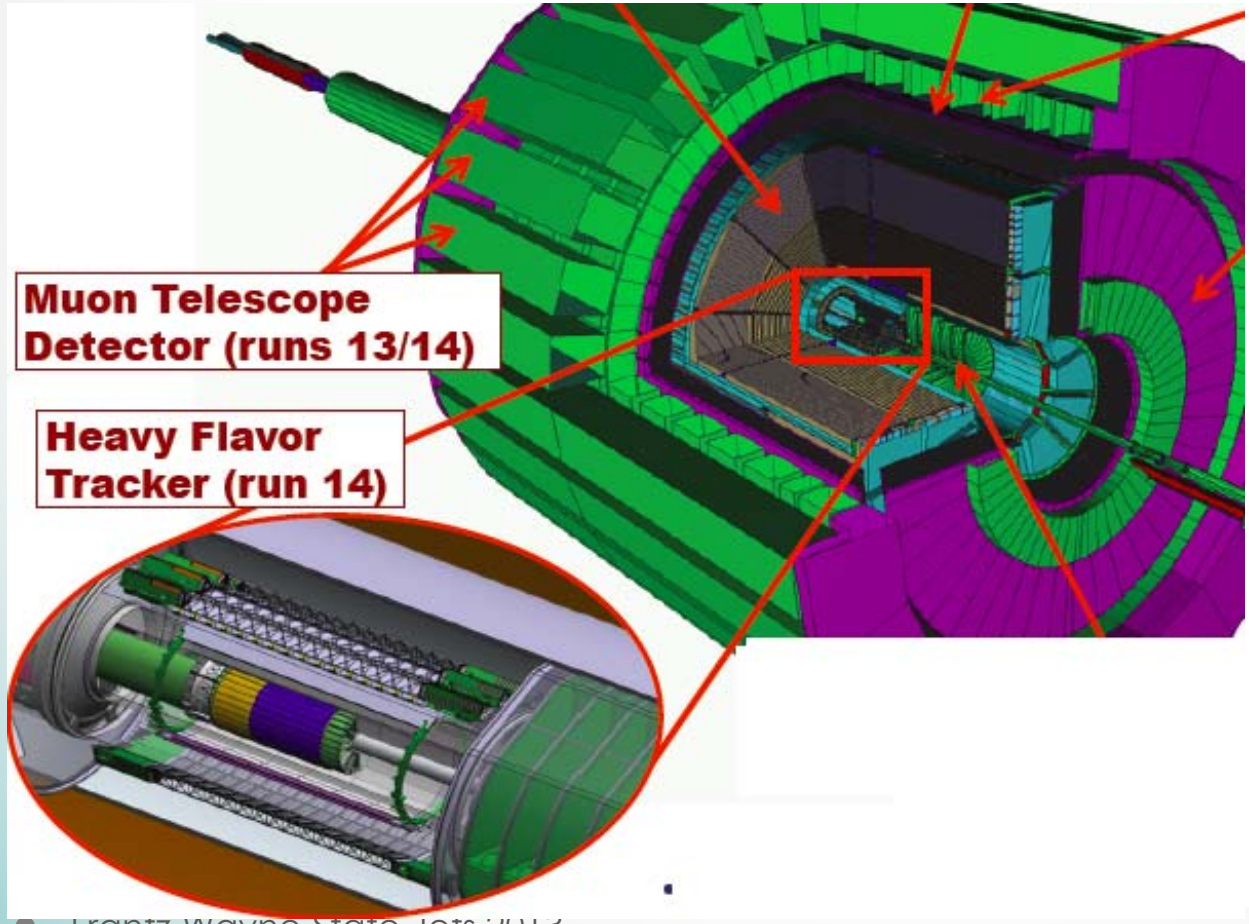


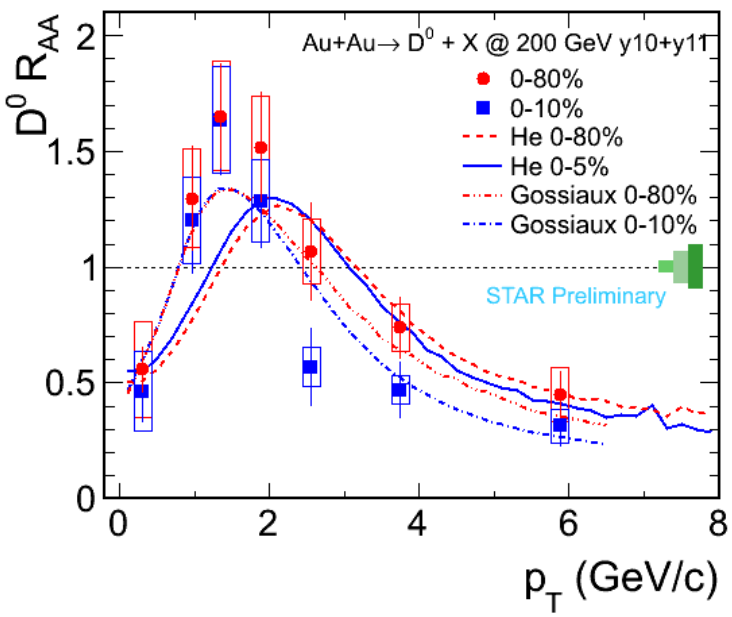

FVTX working great!

Awaiting external improvements (global alignments, multi-collision vertex finding, VTX repairs) to realize ultimate performance

# STAR HF Upgrades

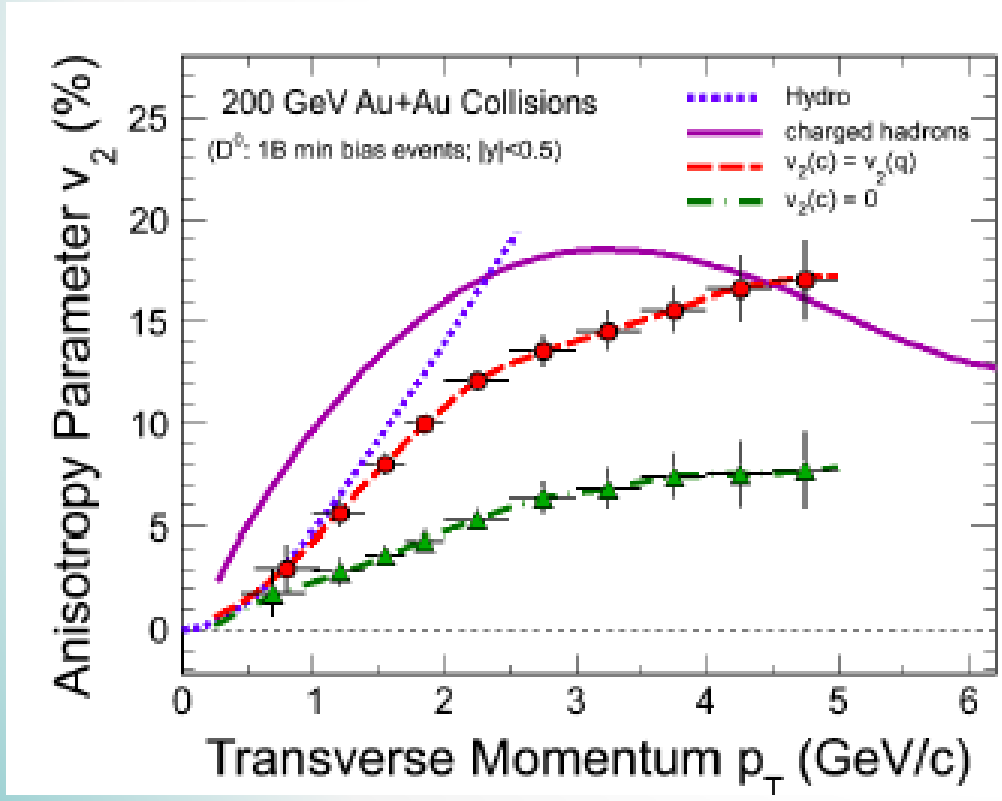
- MTD and HFT Upgrades are two large acceptance central rapidity PID detectors complementing the STAR barrel
- Add c/b quark separation complementing current nice e.g. D meson, D→e / expanding w/ μ capabilities

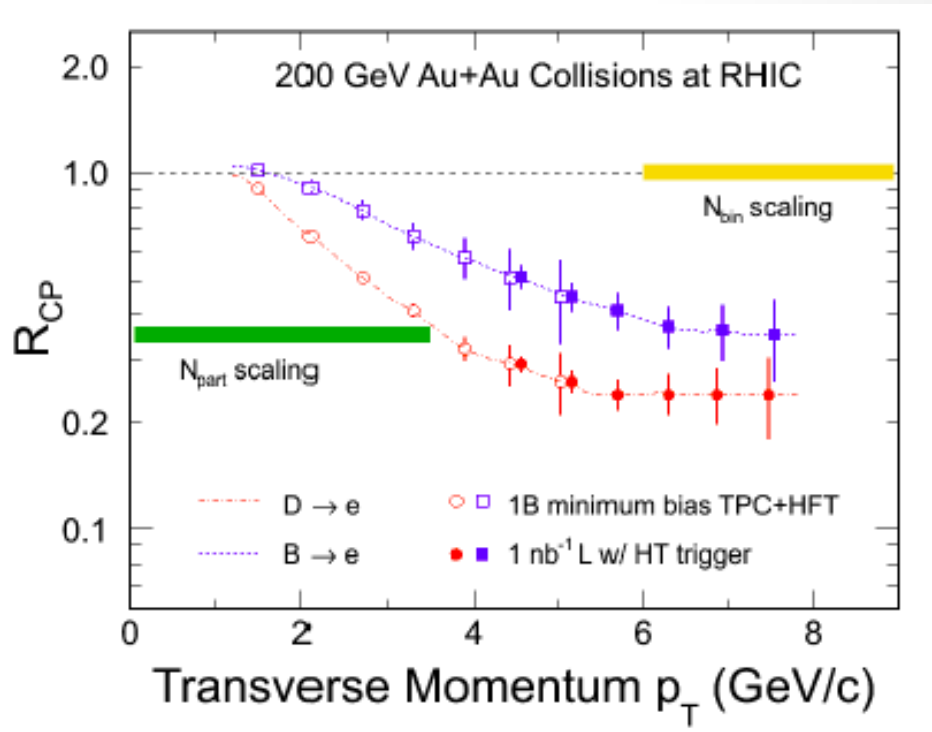


# STAR Heavy Flavor Tracker

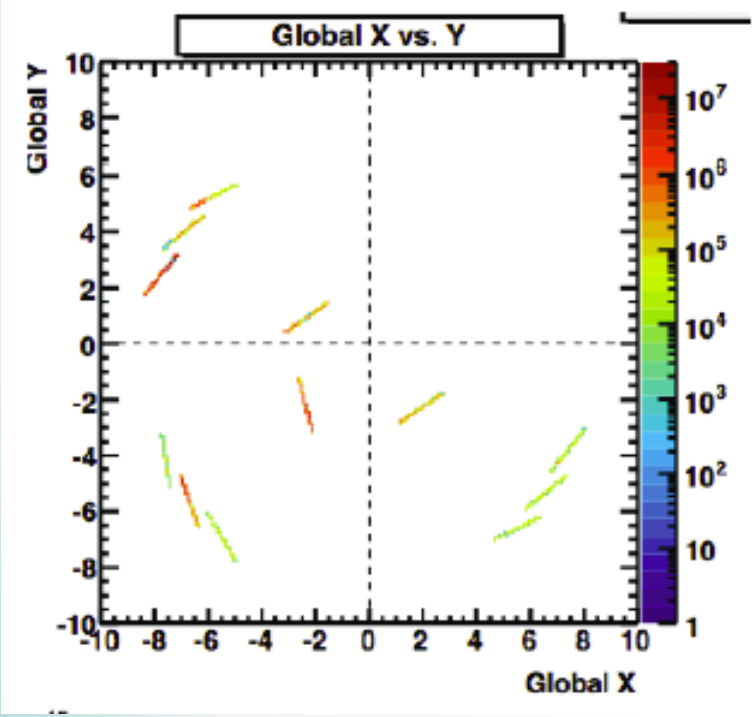
- Matches TPC acceptance
- 3 types of layers, SSD, IST, PXL innermost
- Precise Charm v2, c/b Rcp, RAA, J/Psi from B, Charm Baryons (test recombination for HF)

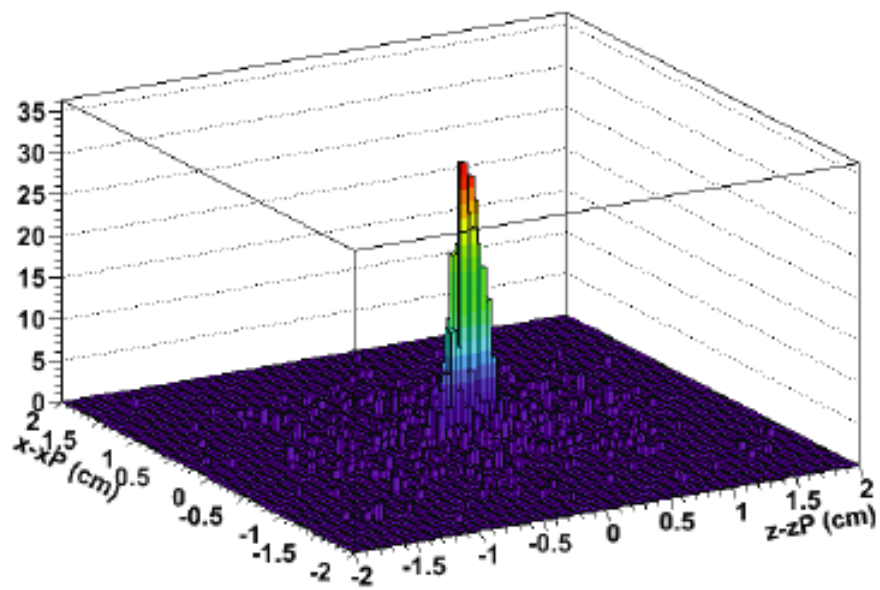


# STAR Heavy Flavor Tracker

- Engineering Partial Installation for PXL during Run13
- Full commissioning  and physics for long AuAu run

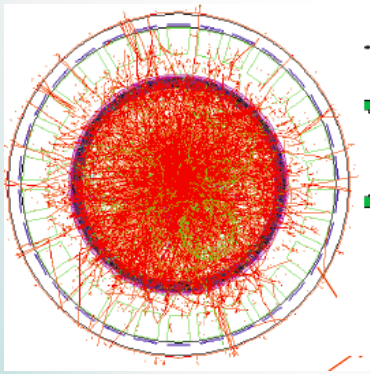


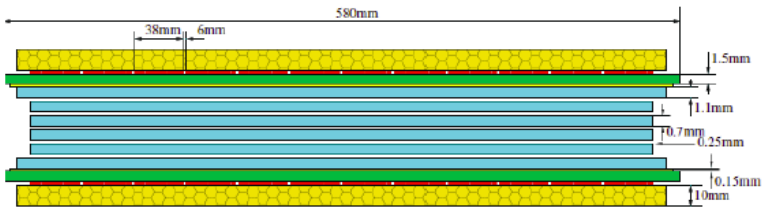




- 2D correlation between measured pxl hit and TPC track projection on a sensor

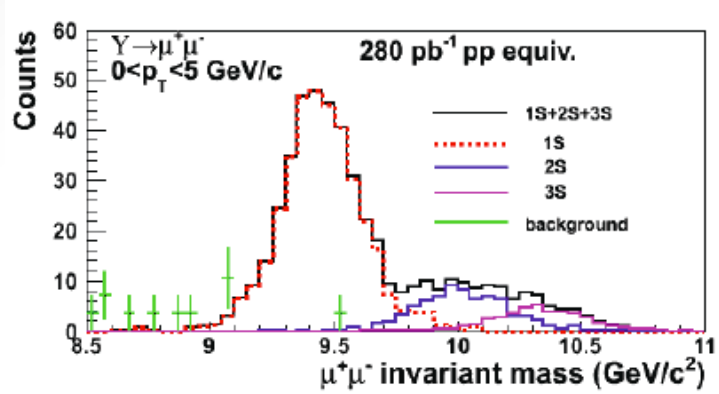
# STAR Muon Telescope Detector

- Multi-gap Resistive Plate Chamber (MRPC) technology
- Onia states resolution, e-μ correlations (for di-lepton contributions), muonic atoms?



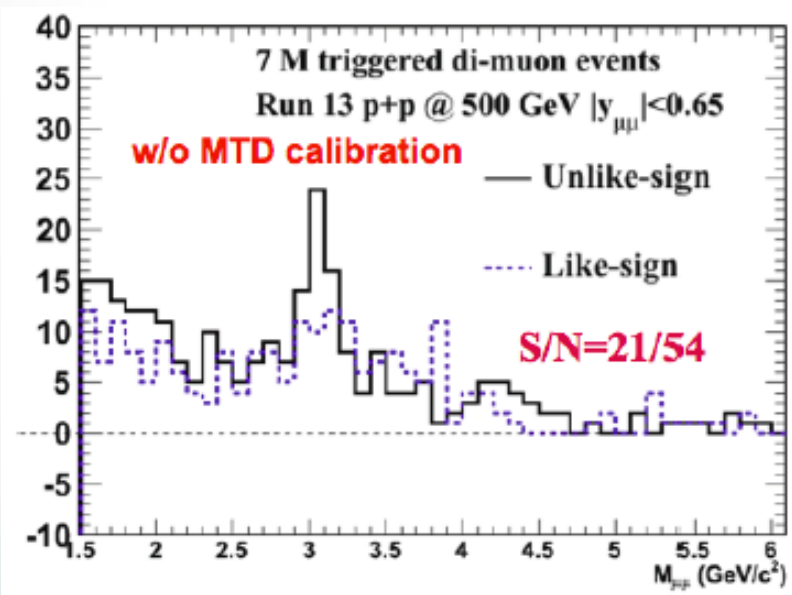


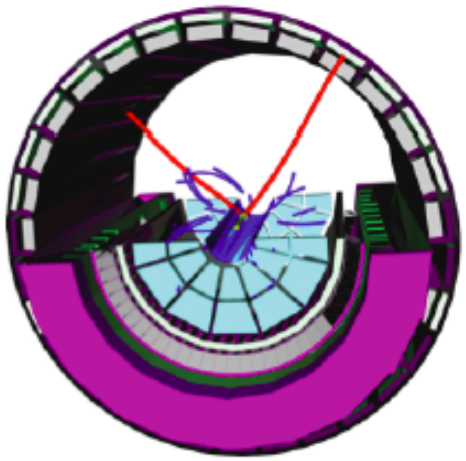
# STAR MTD




simulation with MTD

- 63% installed in Run13 Working well! Ahead of schedule→ Ready for Run14 Au+Au



One di-muon trigger event

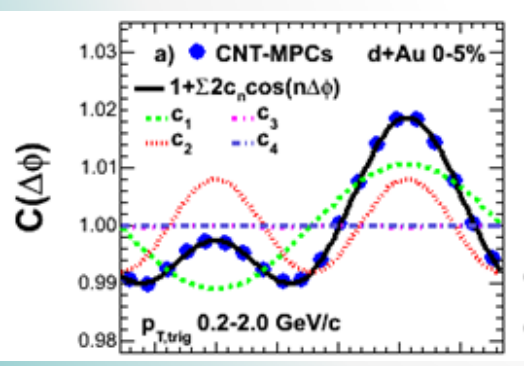
# Small System Flow

- STAR/PHENIX BUP small systems Run15-16

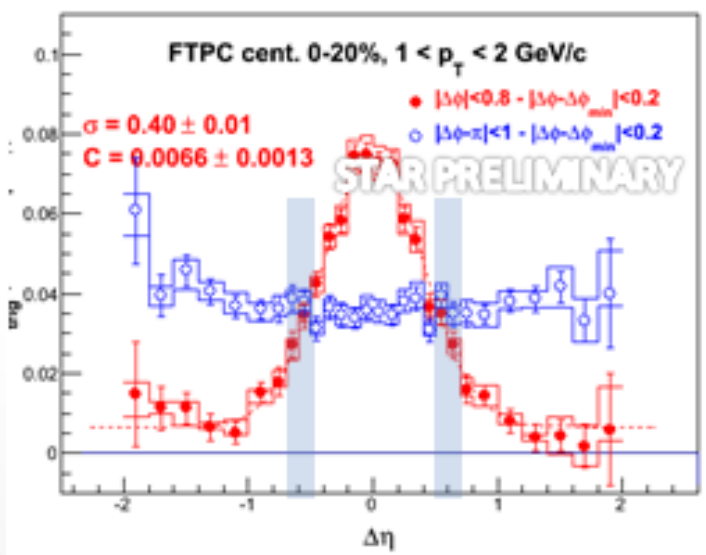
| | | | |
|---|---|---|---|
| 2014 | • 200 GeV Au+Au<br>• 15 GeV Au+Au | • Heavy flavor flow, energy loss, thermalization, etc.<br>• Quarkonium studies<br>• QCD critical point search | • Electron lenses<br>• 56 MHz SRF<br>• full STAR HFT<br>• STAR MTD |
| 2015-2016 | • p+p at 200 GeV<br>• p+Au, d+Au, $^3$He+Au at 200 GeV<br>• High statistics Au+Au | • Extract η/s(T) + constrain initial quantum fluctuations<br>• More heavy flavor studies<br>• Sphaleron tests | • PHENIX MPC-EX<br>• Coherent electron cooling test |

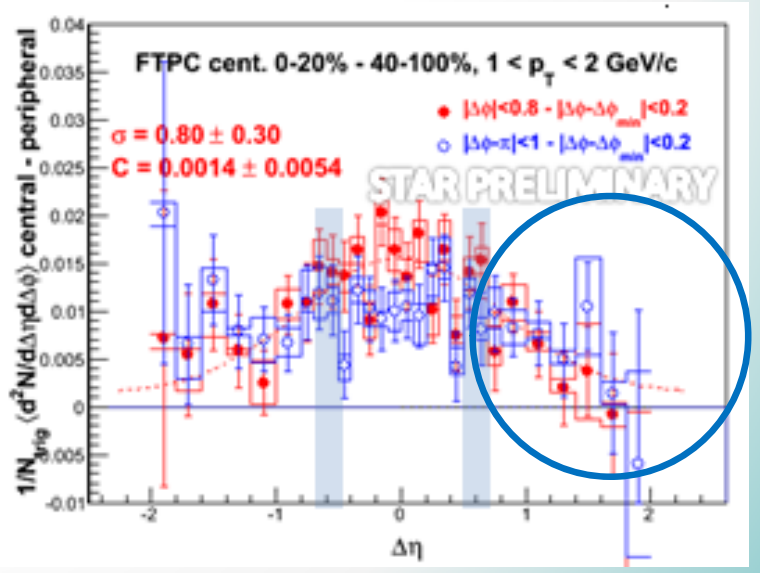
# d+Au Flow: STAR vs. PHENIX

- After digesting Fuqiang's last week presentation Helen mentioned:
- With increased $\Delta\eta$, STAR sees (weak?) **very long range ridge**: agreement with PHENIX Central-Backward
- Although broader than normal jet, contribution measured by PHENIX at mid-rapidity may be larger than the very long range component




PHENIX Prelim



# Near Term Jet Results

• • •

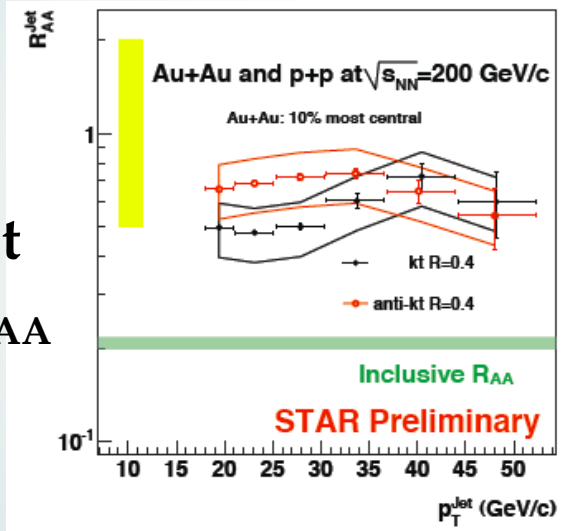
Jet Reco of Light Jets

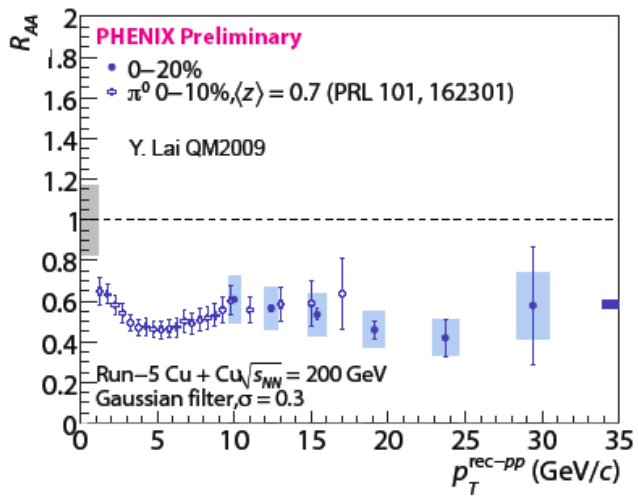
Gamma-Hadron

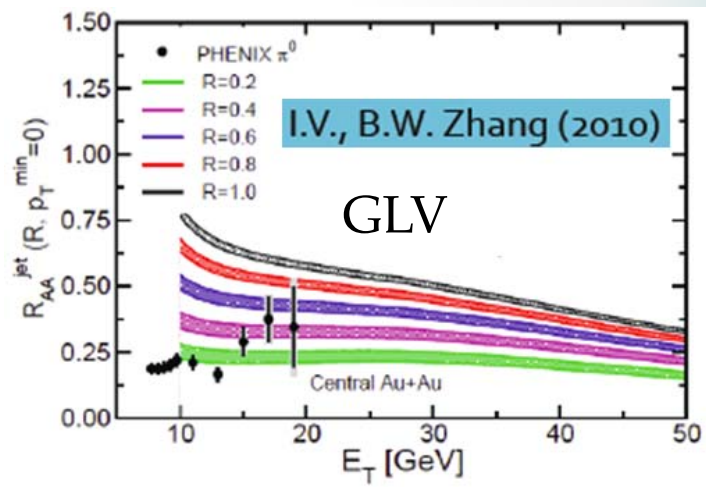
# Jet Reco @ RHIC

- So far warm ups: preliminary results only in A+A
- First STAR Preliminary Results 2009
- PHENIX Cu+Cu ~'09 Jet RAA Results:

Jet $R_{AA}$



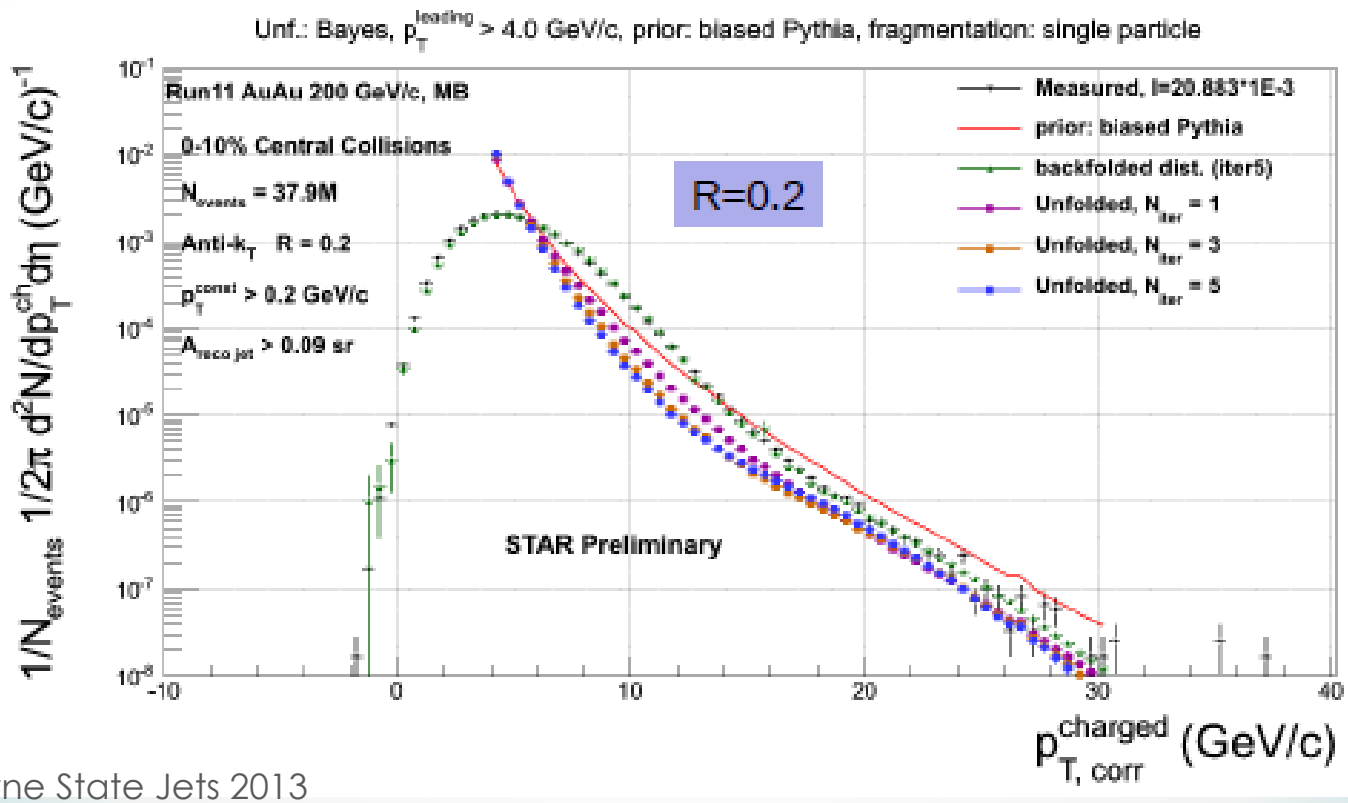




- Need Updated Experimental RHIC Jet Reco RAA result (STAR and PHENIX)!
- PHENIX: sPHENIX work → A+A expertise increasing
  - Cu+Au: Jet Reco Analysis Underway: First Asymmetric System

# New STAR Jet Reco Coming Soon

- Full Bkg Subtraction/Unfolding Technique Completely Updated (Shared ALICE/STAR method)
- Seems to be working well
- STAR Run 11 Au+Au Large Jet Dataset
- Abstract Submitted for Nov. Hard Probes



# A Different Complementarity

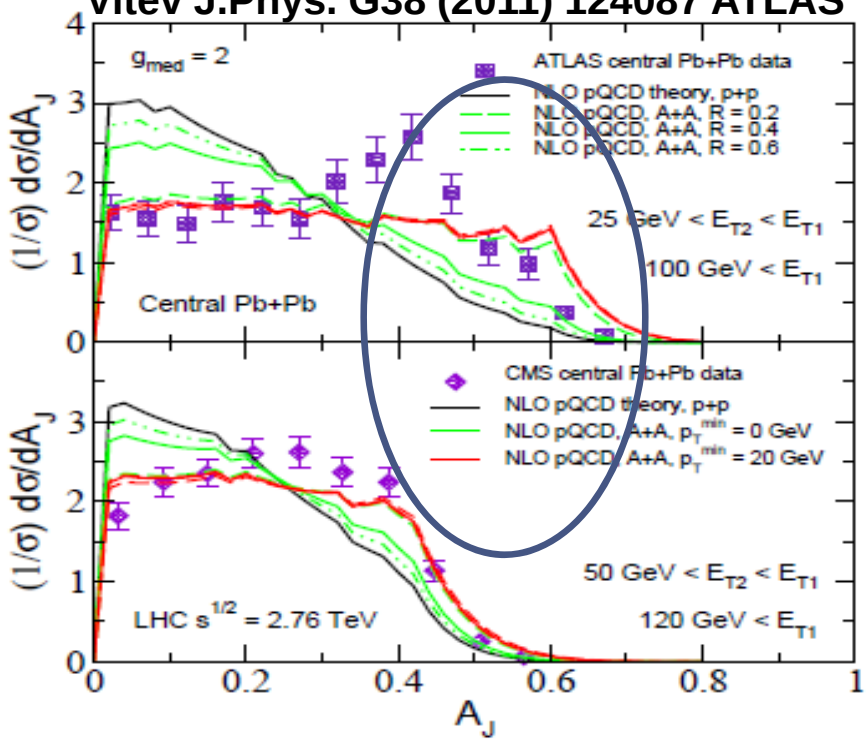
- Both 2-p correlations AND Jet Reco need to be explored!
- **My Opinion:** (Seems to be theme of this meeting too)
- **Jet Reconstruction is crucial** for final understandings of Jet Quenching → Modifications to Showering Process
  - sPHENIX!
- In the short term : **DANGER** : Don't let jet quenching studies (RHIC/LHC) become too Jet Reco- biased!
- We first need to learn what quenched jets look like!
  - May need completely new jet finding techniques to study quenched jets
- Complementarity: Jet Finding + Angular Correlation (Jet-h and $\gamma$-h) Measurements
  - We can study when modification is mostly NOT there with jet finding: e.g. Energy Asymm
  - Don't ignore modification just because it not seen w/ jet finding observables

# Example: "Jet" Finding + Correlations

- **Event by Event CHOOSE Jets with quenching $A_J/x_{\gamma J}$**
- The Ultimate Tool? Identify perturbative quenching regions, vary the quenching fraction?
- Look for shape of quenched jets in regions of di-jet asymmetry Direct γ-jet/di-jet different systematics
  - Di-jet $A_J$ Gamma-jet $x_{j\gamma}$ cut
- Need to do it with and without quench jet reco axis!

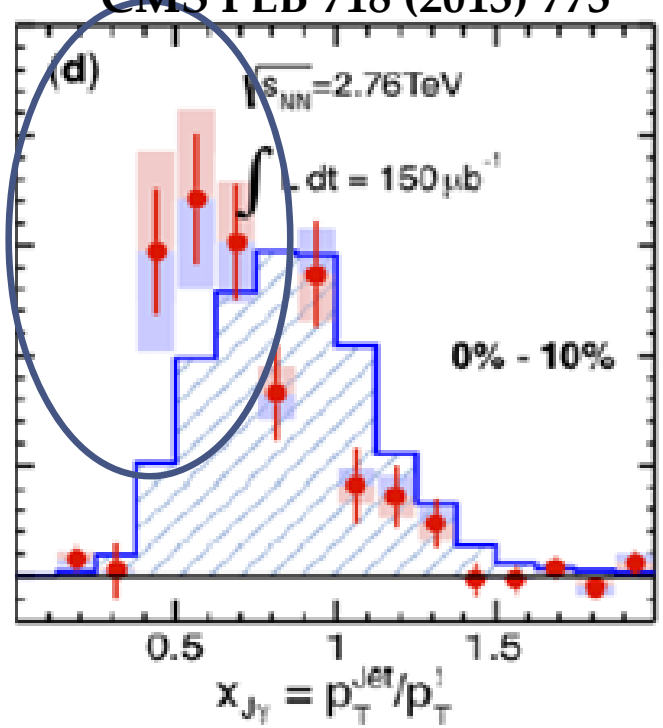
Di-jet Asymmetry Distribution

**Vitev J.Phys. G38 (2011) 124087 ATLAS**




γ-jet Asymmetry Distribution

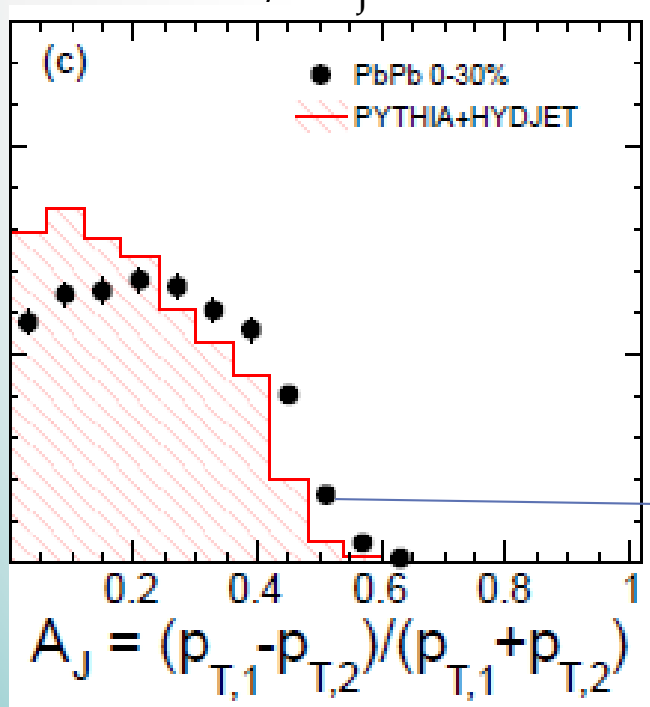
**CMS PLB 718 (2013) 773**



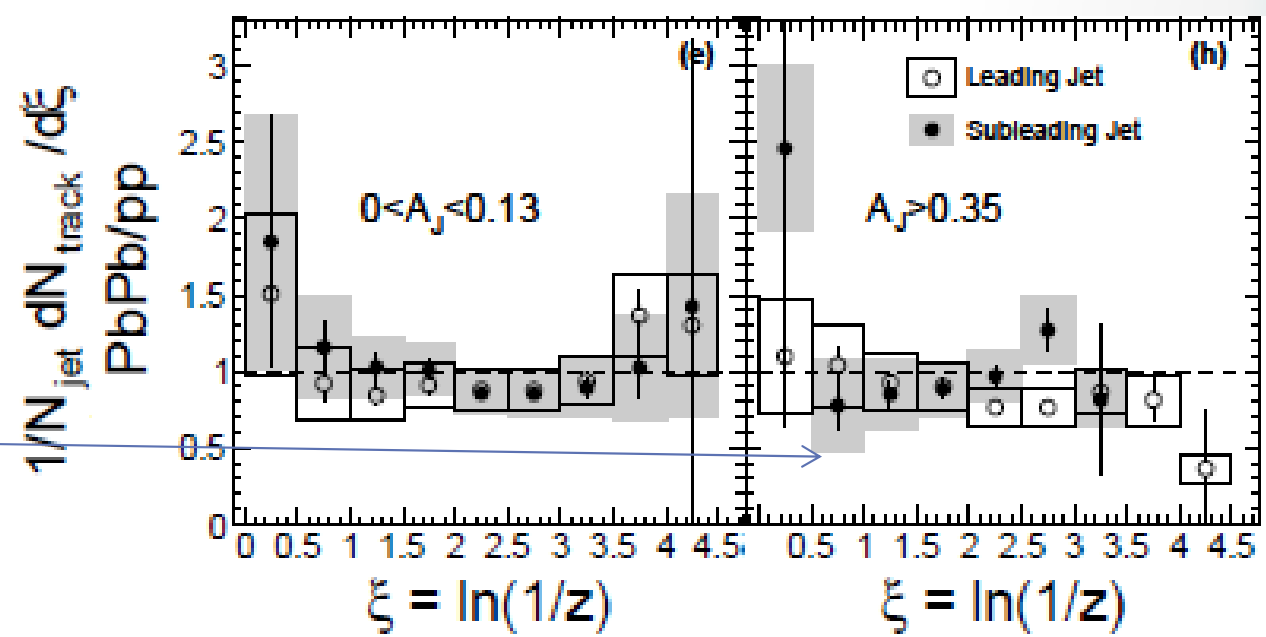
# "Jet" Finding + Correlations

- This has been tried at LHC
- LHC FF Modification Correlates with Large $A_J$? No?
- Bias of found jets
  - → **Look outside jet cone!**
  - → **Look below jet finding cutoff**
- Technical Difficulties due to UE event subtraction: Don't use awayside jet energy

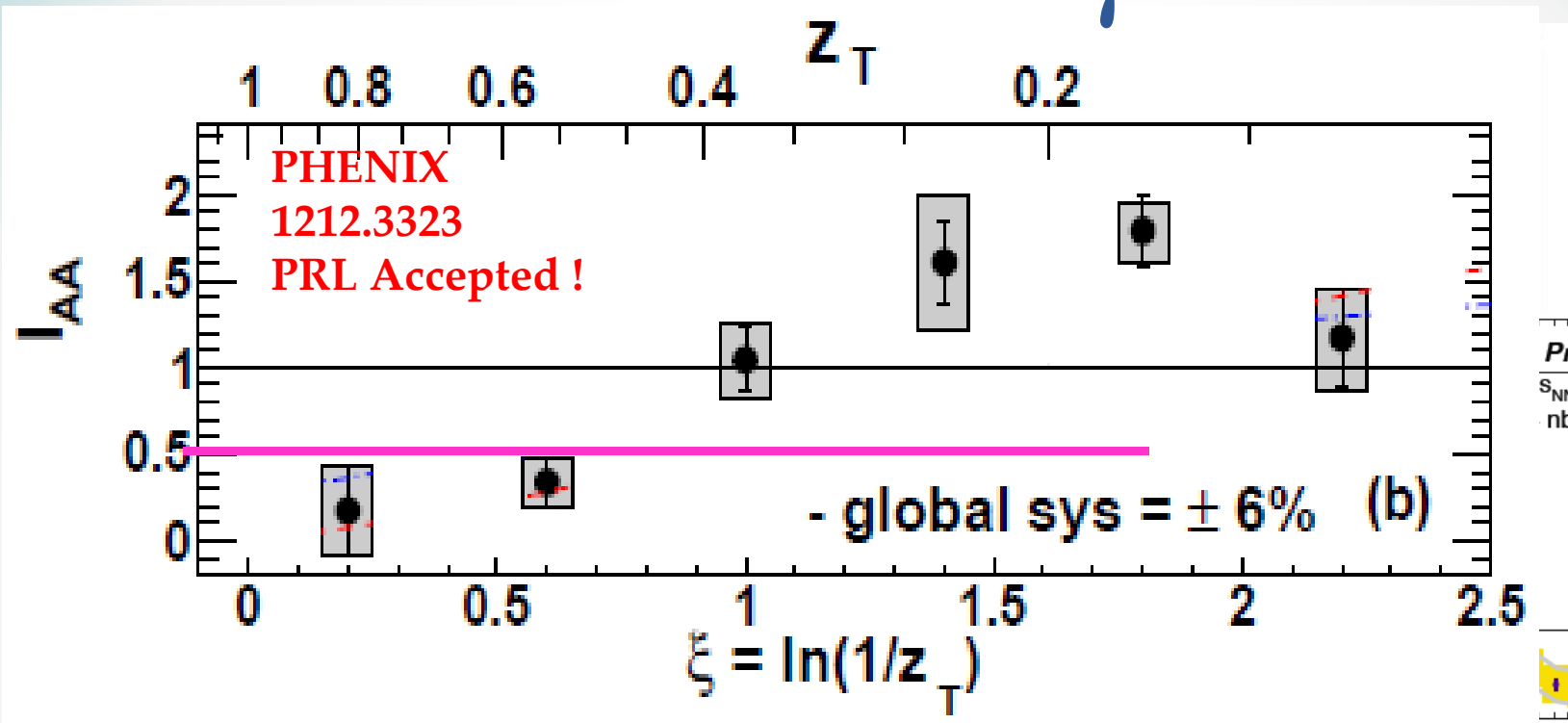
$dN/dA_J$

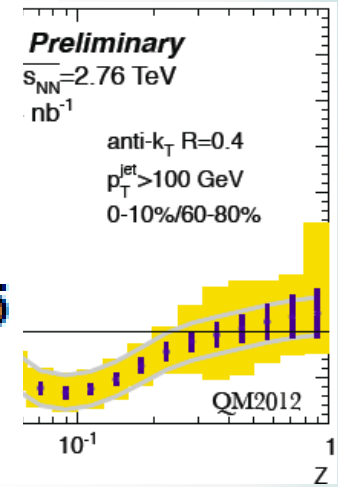



Ratio FF Pb+Pb / p+p = 1 → No mod?

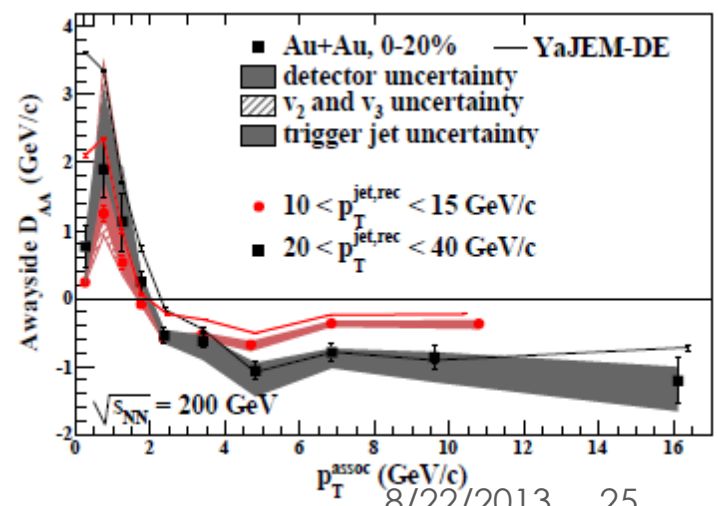


# PHENIX Direct γ-Hadron



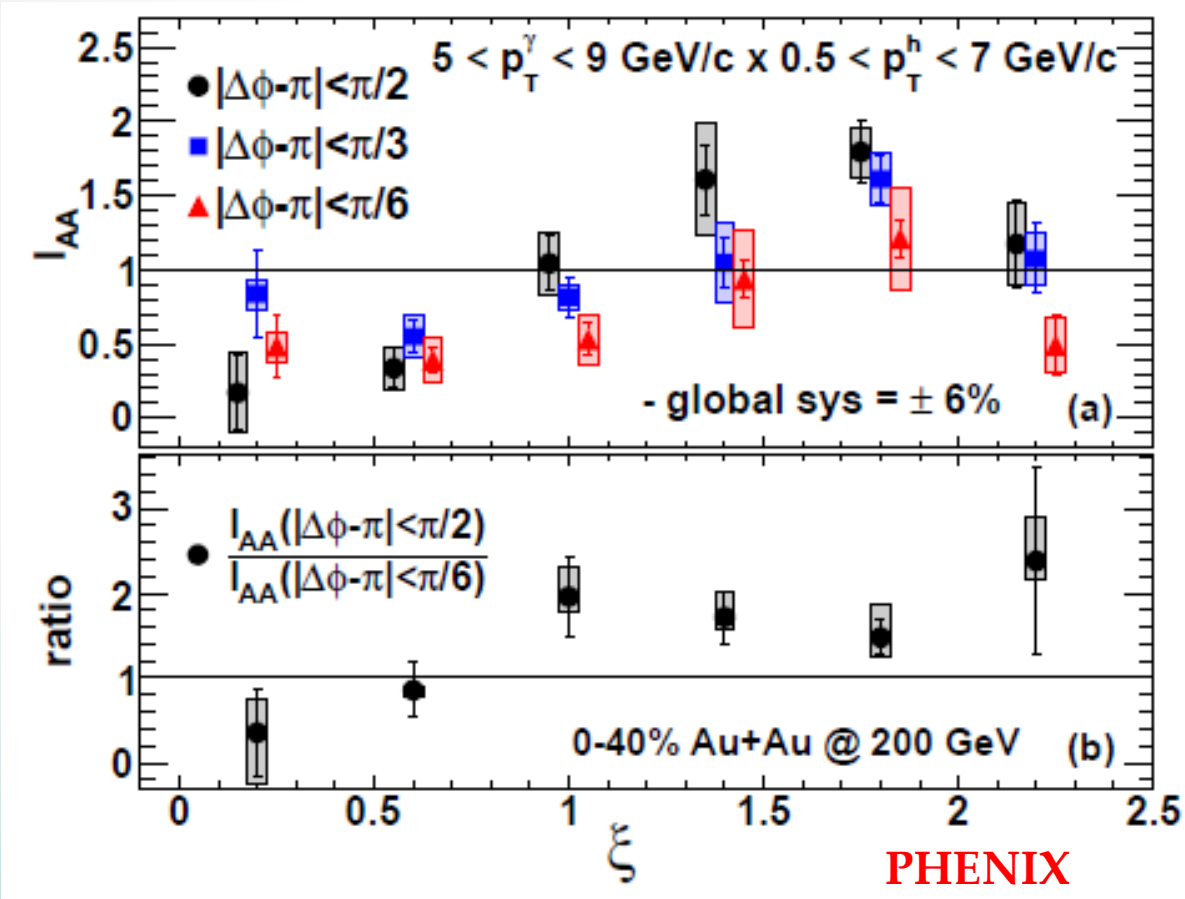

STAR 1302.6184



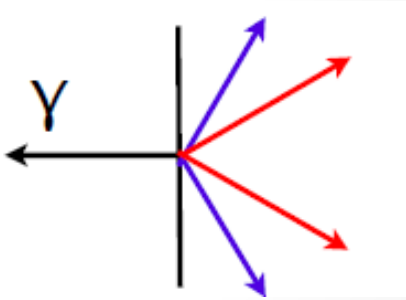

- Photon Hadron FragFn Modification!
- Low z Enhancement
- Very Similar to LHC Jet-reco
  - **LHC FF=1 ~= Jet RAA**
- ~Consistent with STAR Jet-hadron
  - RHIC-RHIC Consistency!
- These analyses are important!
- **Reco jets != All Jet Suppression (?)**

# There's more information

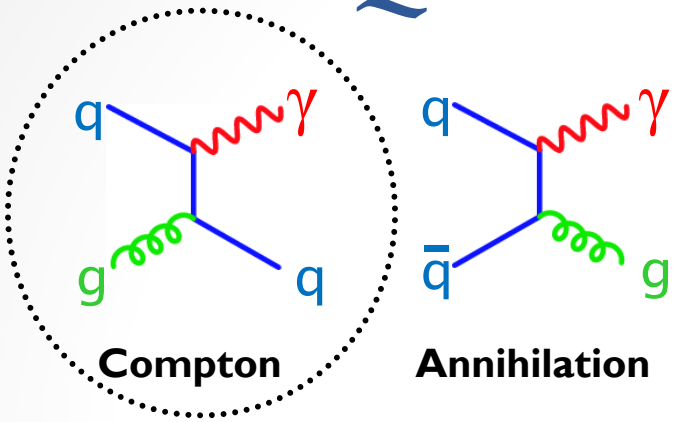
- Modified FF isn't the whole story (don't stop there!)
- Correlations: angular shape



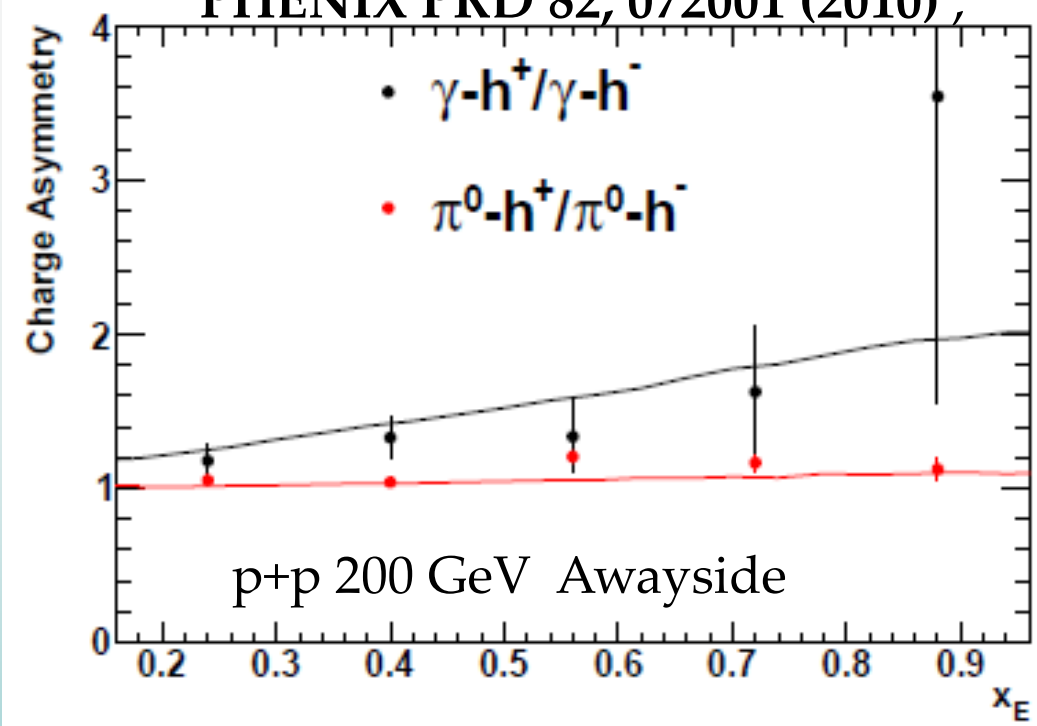

PHENIX
1212.3323
PRL Accepted



# Example 2: Correlations + "Jet"(γ) Quark Tagging




PHENIX PRD 82, 072001 (2010) ,



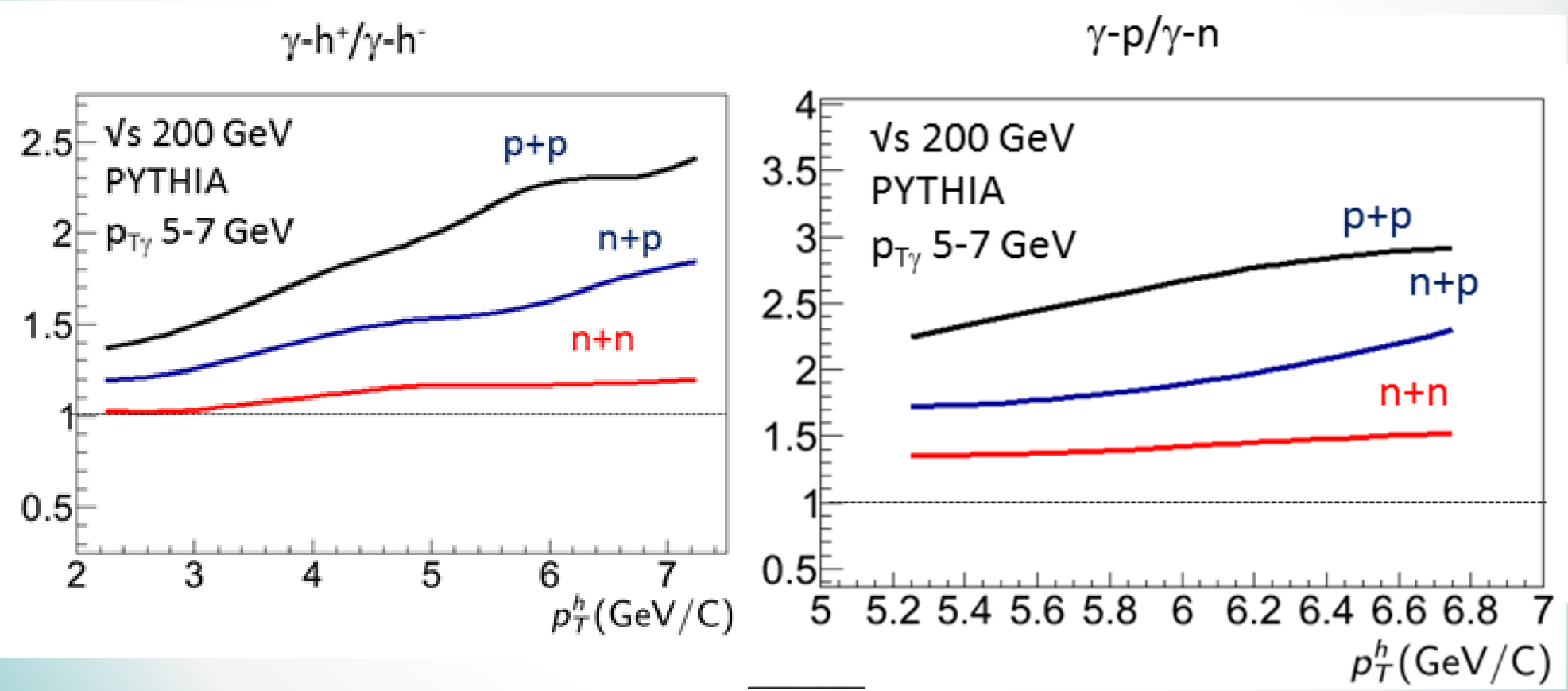

- In γ-h Compton scattering means **quark jet tag**
- Charge asymmetry of cross section and valence *u vs d* quark should be reflect in final state charged hadrons

**SEEN IN p+p 2-p @ PHENIX**
**Allow q vs g Eloss study in AuAu**

**MENTIONNED IN STAR BUP!**

# Charge Asymmetry

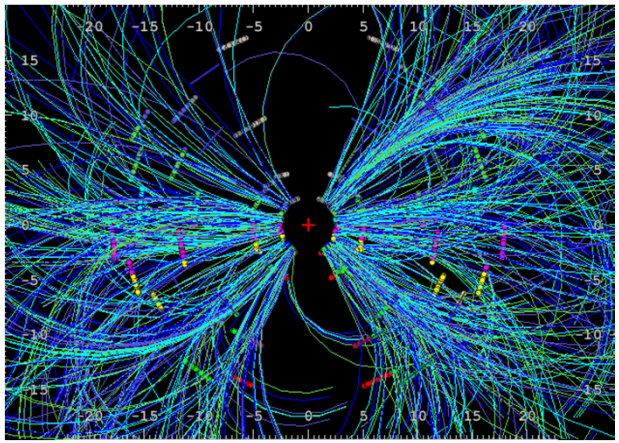
- Applying Iso Cut allows selection of Compton-- u, d quark counting should govern expected scale of asymmetry
  - o : $d\sigma \sim Z_q^2$ u:d → 8:1 p+p, A+A, d+Au : 4.7-6.2
- Assoc p vs n similar - independent




- How do these go together (d+A → p+A)?

# Near-term PHENIX jet/ γ-jet

- Run 11/14 VTX installed : 10 x stats (track acceptance) for γ-jet associated hadron acceptance
- And ~2-3 x Integrated Lumi Run 7/10 Current Result

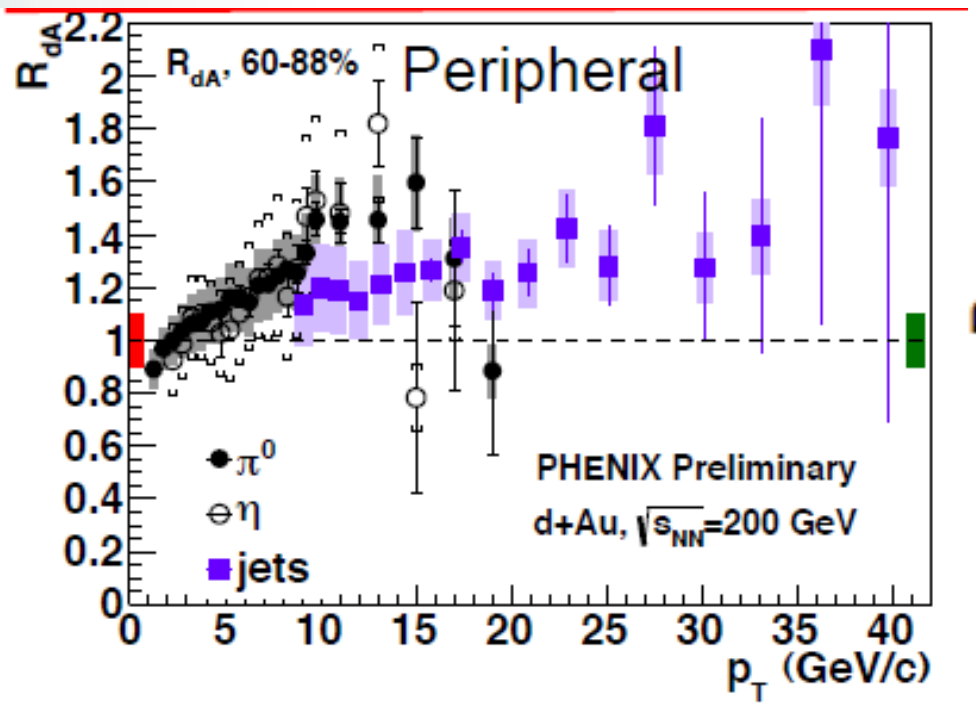


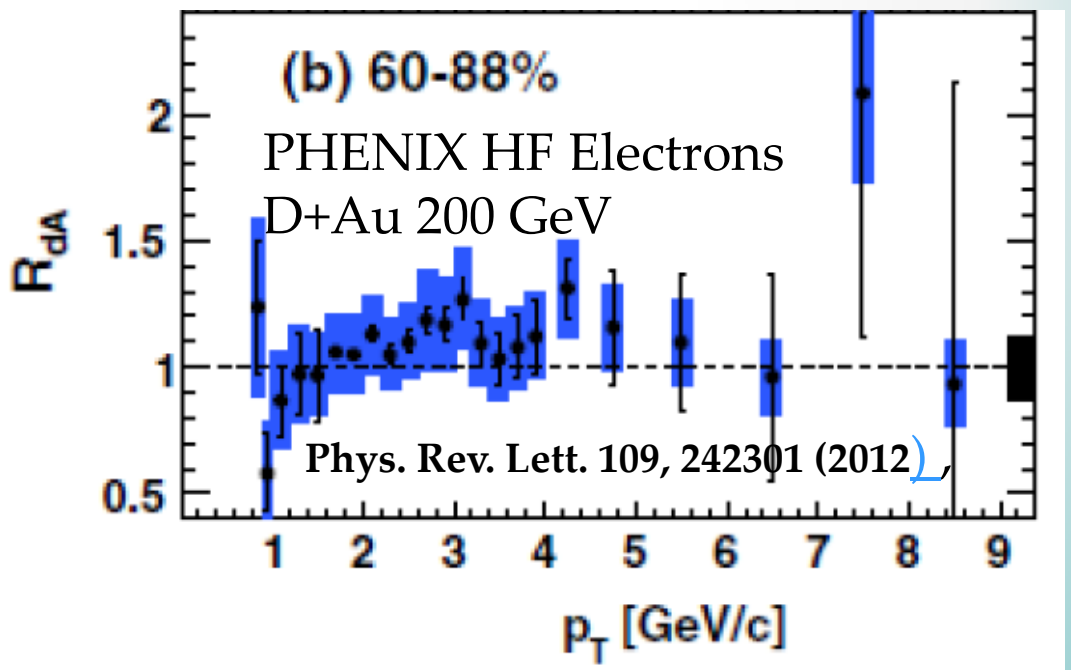
VTX

- Isolation cut in Au+Au analysis well underway
  - Should improve precision in peripheral collisions→ towards centrality dependence of enhancement
- Cu+Au Jet Reconstruction analysis underway
- **STAR interest for γ-jet again for Run11**

# D+Au Jet Reco

- Status: Helen described situation well yesterday
- Enhancement at pretty high $p_T$ (HF e comparison?)
- Some possibility of cross talk between Jet reco and Pi0 (2-ana's weren't blinded, EM calibration, etc…)

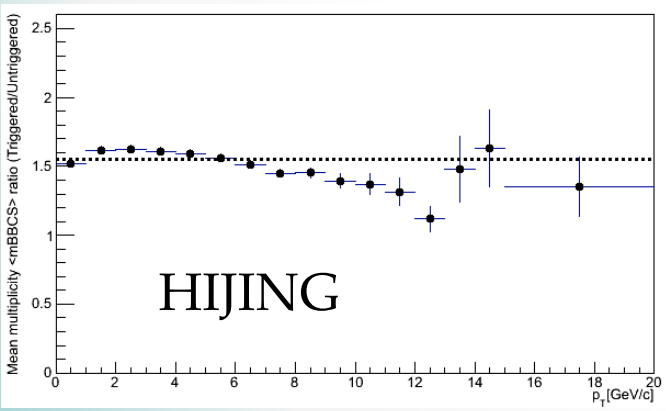


# Recent Re-check of Auto Correlations

- Recent Recheck of Bias Factors in HIJING study
- $C_{bias}$ → (partly) increased BBC mult w/ Jet Trigger: (Underlying Event, Rapidity Shifts etc. ) → Shifts <Ncoll> for triggered centrality samples
- HIJING: Small effect for RHIC consistent with previous published $C_{bias}$ factors ! (bigger for LHC ?)

Ratio BBC multiplicity with particle $p_T > x$ / Untriggered BBC multiplicity




Good matching to real p+p

TABLE I: Total number of participants $N_{\rm part}$, number of collisions $N_{\rm coll}$, nuclear overlap function $T_{AB}$, see Eq. 10, average number of collisions per participant nucleon from deuteron $\nu$, and the BBC bin correction factor for different centrality classes.

| Cent. bin | $\langle N_{\rm part}\rangle$ | $\langle N_{\rm coll}\rangle$ | $\langle T_{AB}\rangle$, mb$^{-1}$ | $\nu$ | $C_{\rm BBC}$ |
|---|---|---|---|---|---|
| A | 15.0±1.0 | 15.4±1.0 | 0.37±0.02 | 7.5±0.5 | 0.95±0.03 |
| B | 10.4±0.4 | 10.6±0.7 | 0.25±0.02 | 5.6±0.4 | 0.99±0.01 |
| C | 7.0±0.6 | 7.0±0.6 | 0.17±0.01 | 4.0±0.3 | 1.03±0.01 |
| D | 3.2±0.3 | 3.1±0.3 | 0.07±0.01 | 2.2±0.2 | 1.04±0.03 |
| tag A | 10.6±0.7 | 9.6±0.7 | 0.23±0.02 | 9.6±0.7 | 0.93±0.03 |
| tag B | 8.0±0.6 | 7.0±0.6 | 0.17±0.02 | 7.0±0.6 | 0.95±0.02 |
| tag C | 5.6±0.3 | 4.6 ±0.3 | 0.11±0.01 | 4.6±0.3 | 0.95±0.02 |
| tag D | 3.1±0.2 | 2.1±0.2 | 0.05±0.01 | 2.1±0.2 | 0.97±0.04 |

PHENIX Run3 dAu Phys. Rev. C77, 014905

# Mid-term Outlook

The ~5 yrs after the new few

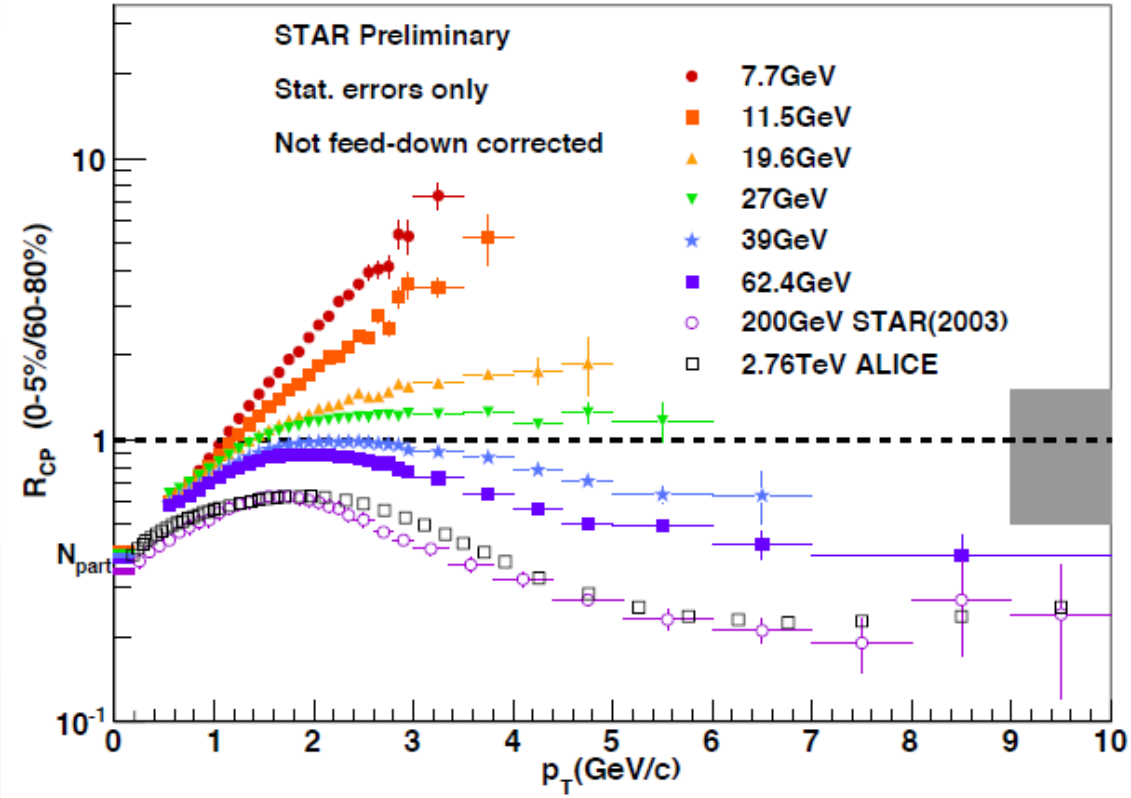
# Beyond the next few years

- Tension between sPHENIX /Jet vs BES goals?
  - There is ample time for both

| Years | Beam Species and Energies | Science Goals | New Systems Commissioned |
|---|---|---|---|
| 2013 | • 510 GeV pol p+p | • Sea quark and gluon polarization | • upgraded pol'd source<br>• STAR HFT test |
| 2014 | • 200 GeV Au+Au<br>• 15 GeV Au+Au | • Heavy flavor flow, energy loss, thermalization, etc.<br>• Quarkonium studies<br>• QCD critical point search | • Electron lenses<br>• 56 MHz SRF<br>• full STAR HFT<br>• STAR MTD |
| 2015-2016 | • p+p at 200 GeV<br>• p+Au, d+Au, $^3$He+Au at 200 GeV<br>• High statistics Au+Au | • Extract η/s(T) + constrain initial quantum fluctuations<br>• More heavy flavor studies<br>• Sphaleron tests | • PHENIX MPC-EX<br>• Coherent electron cooling test |
| 2017 | • No Run | | • Electron cooling upgrade |
| 2018-2019 | • 5-20 GeV Au+Au (BES-2) | Search for QCD critical point and deconfinement onset | • STAR ITPC upgrade |
| 2020 | • No Run | | • sPHENIX installation |
| 2021-2022 | • Long 200 GeV Au+Au w/ upgraded detectors<br>• p+p/d+Au at 200 GeV | • Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism<br>• Color screening for different QQ states | • sPHENIX |
| 2023-24 | • No Runs | | Transition to eRHIC |

# Hard Physics during BES-2 ?

- There could be some interesting things to learn e.g. about the onset of initial state effects

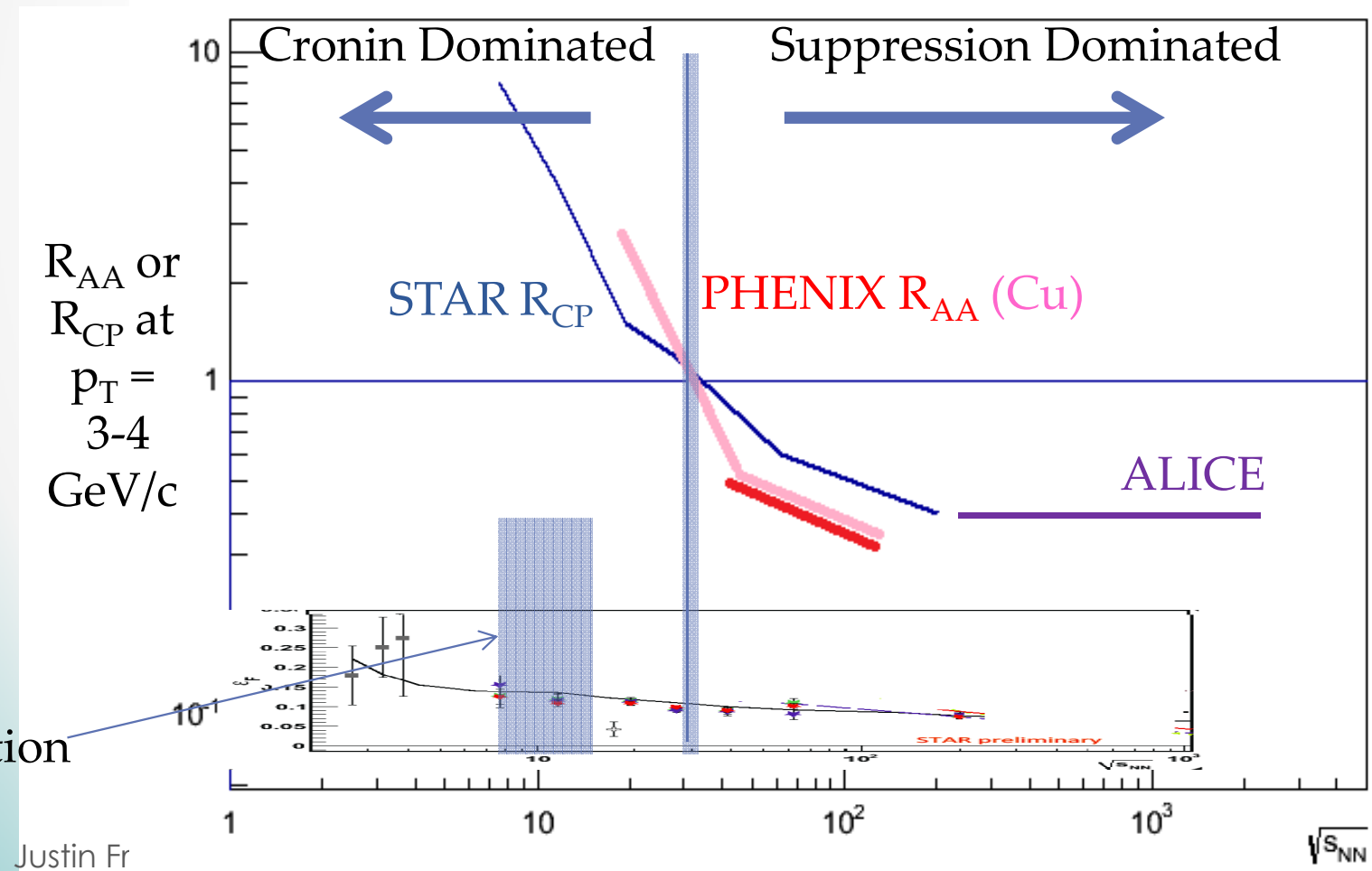



H.Caines : Tues Talk

# Initial vs Final State Scan

- Significant critical mass of theorists interested in CNM developing? April Workshop very successful!
- RHIC should continue to lead this effort!
- Short term "Scan" ?: Get p+p and p+A ~one point above and below ~ 30 GeV ?
- Longer term sPHENIX can contribute with full Jet studies → a key observable?

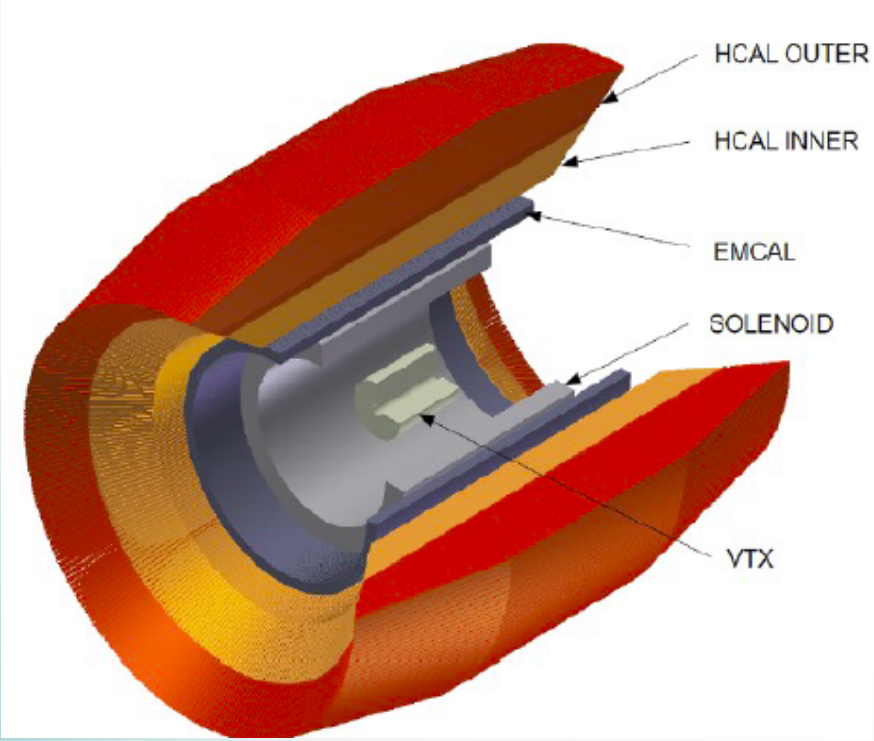
think color tranparency effects




Phase transition

# sPHENIX

- Upgrade optimized around jet/di-jet/photon measurements
- **Compact**, High rate, large uniform acceptance over $|\eta| < 1$
- Submitted by BNL to DOE for MIE CD-0 review last Feb
  - Review will start soon…



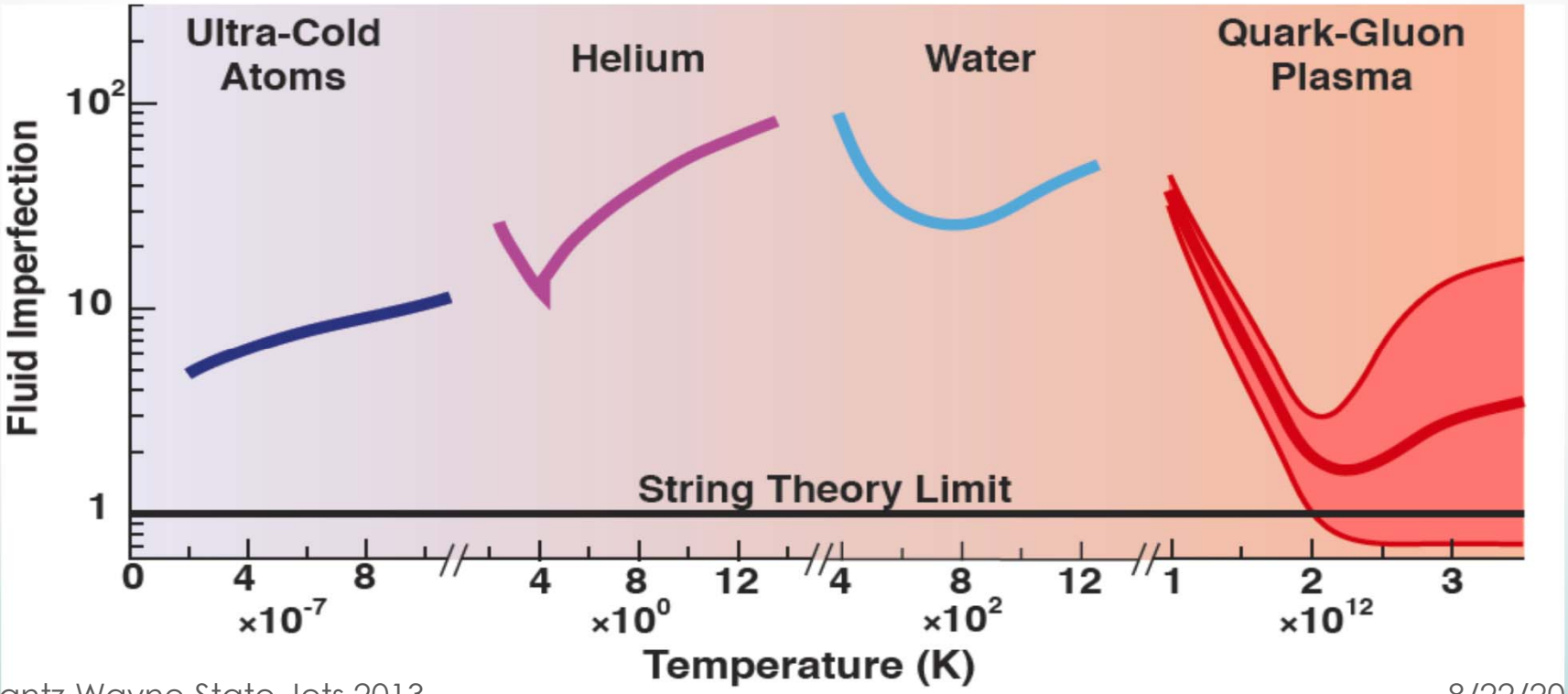

Fe-Scint Hcal Unique Design

Prototyping underway (Previous Design Beam Tested Dec 12 )

W-Sc EMCal – Accordion Design

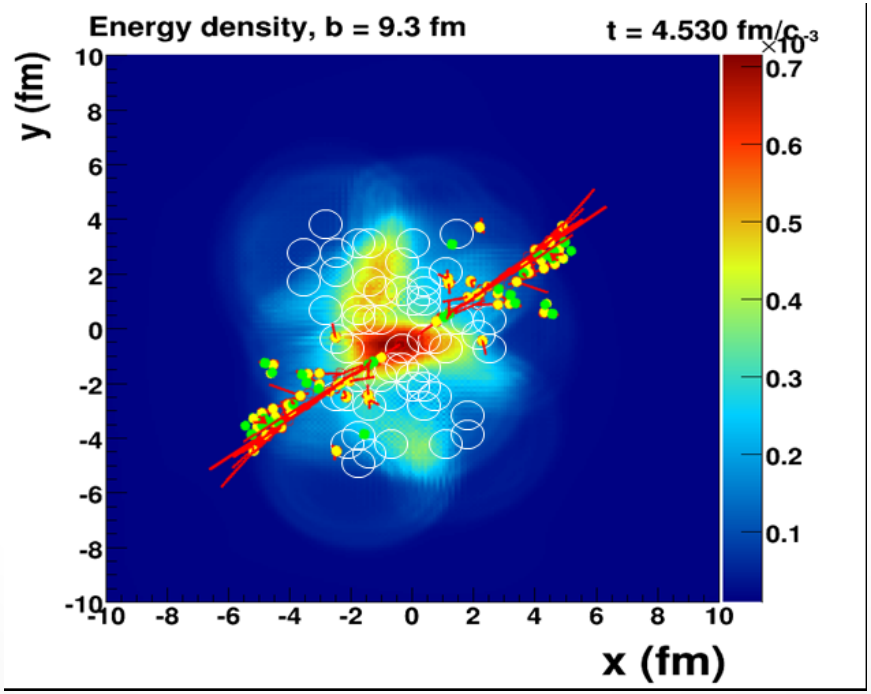
# sPHENIX Motivation

- The goal of sPHENIX is determine the basic nature of the perfect fluid, the strongly coupled QGP, via jet "x-rays"
  - its unique coupling and effective constituents (or lack thereof)
  - its formation vs. temperature/time
- Jets and their $E_{loss}$ are the most obvious and natural ***external*** probe for doing this

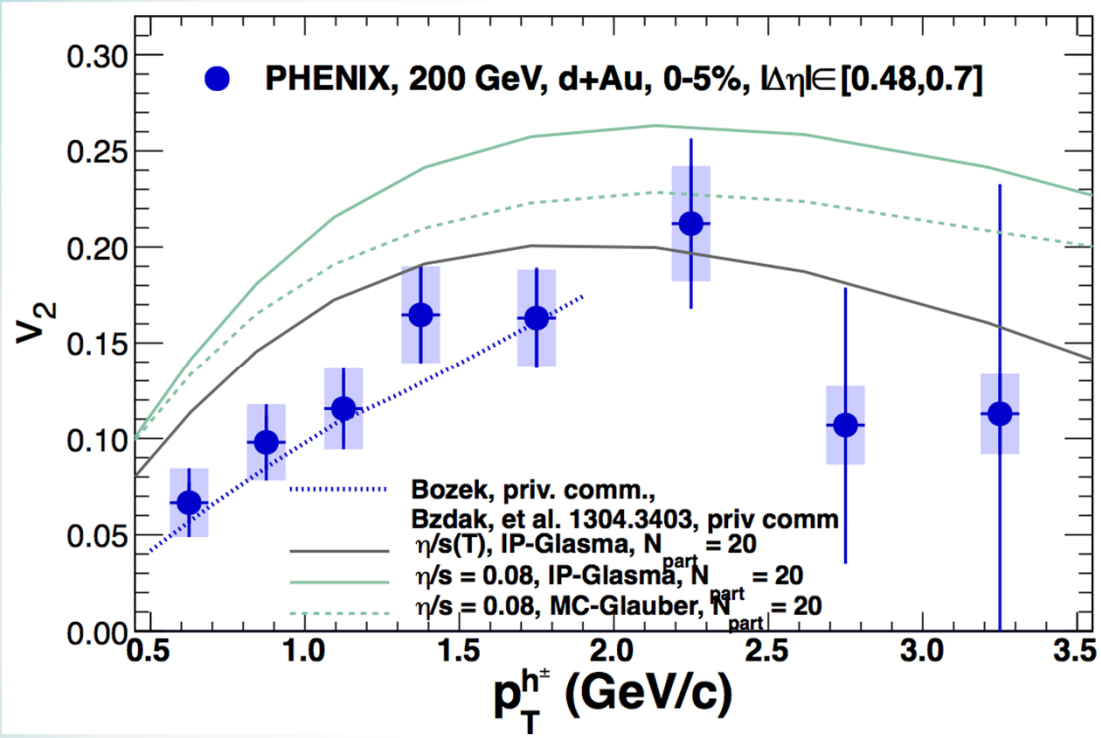


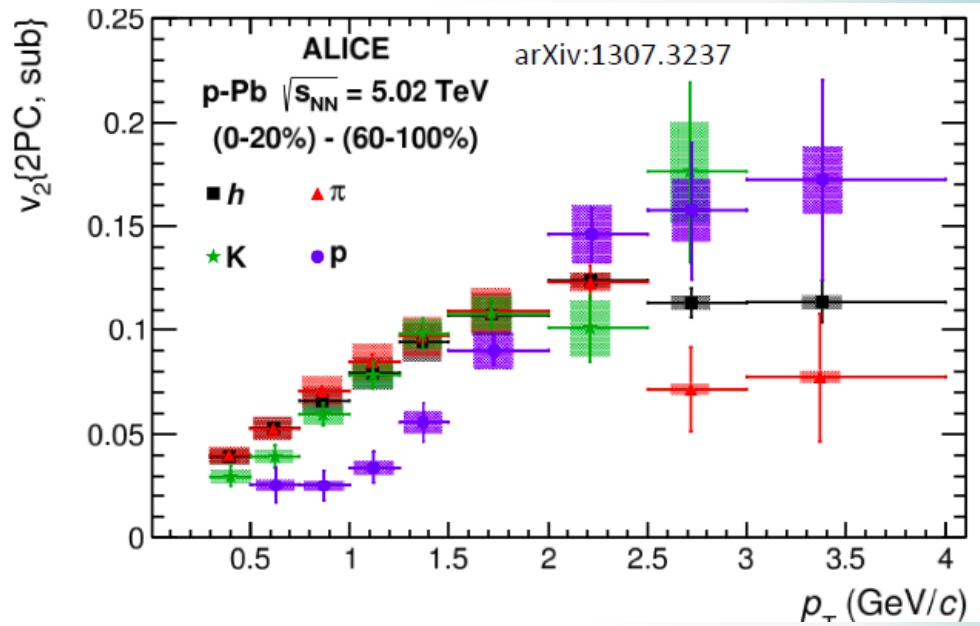
# sPHENIX Motivation

- Another restatement of the above (mine):
- The novel sQGP coupling that results in such *fast* anisotropization/thermalization needs externally probed
  - (by something other than viscosity)
- Jets/hard scattering ***must*** be sensitive to the nature of this coupling!



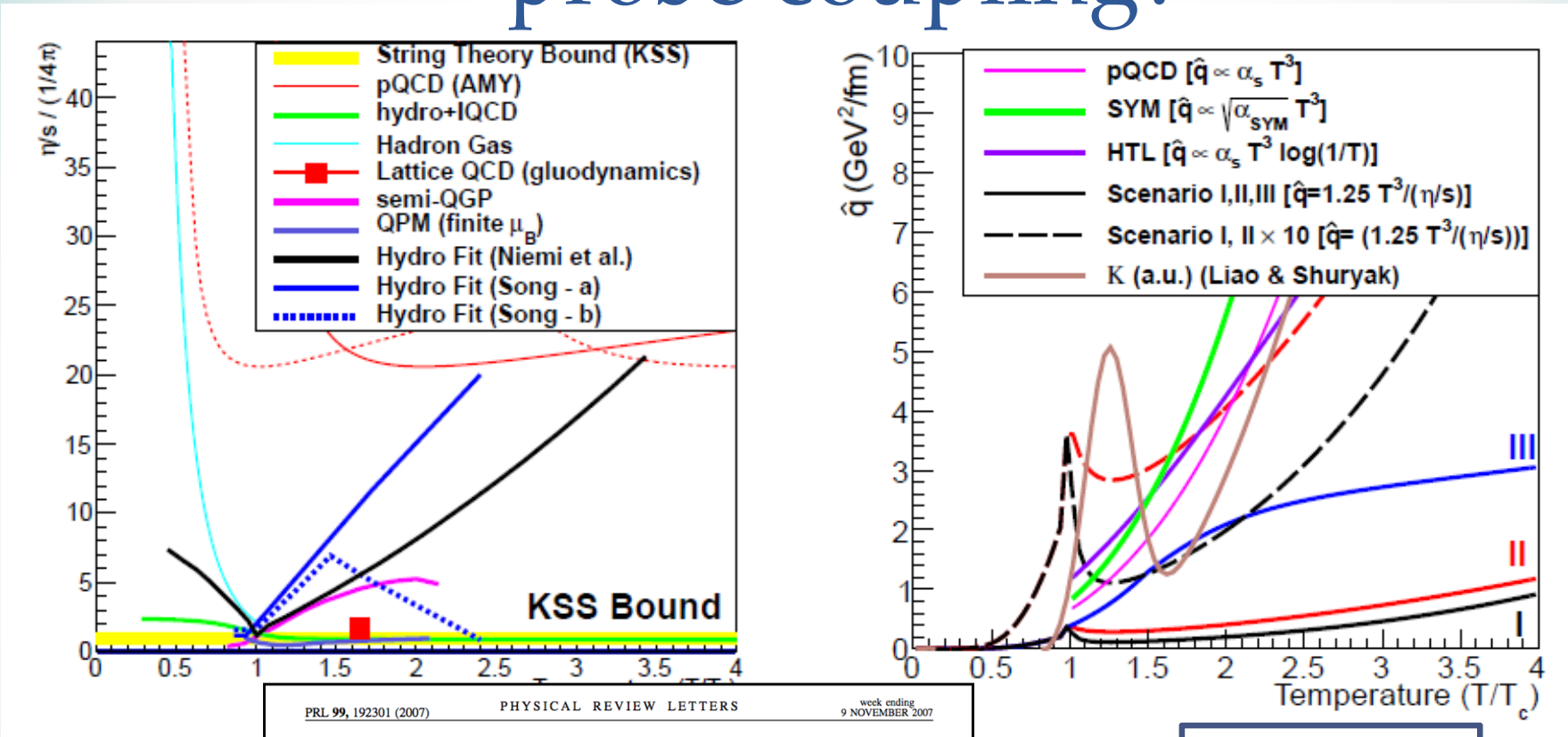
# Can even d+Au/p+Pb produce a perfect fluid?

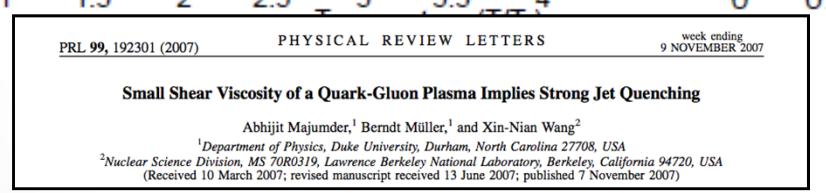



These developments in the past year underscore the need for measurements to address <u>why</u> and <u>how</u> perfect fluidity arises

# At what scale does bulk coupling relate to probe coupling?





PRL 99, 192301 (2007) PHYSICAL REVIEW LETTERS week ending 9 NOVEMBER 2007

**Small Shear Viscosity of a Quark-Gluon Plasma Implies Strong Jet Quenching**

Abhijit Majumder,[1] Berndt Müller,[1] and Xin-Nian Wang[2]

[1]*Department of Physics, Duke University, Durham, North Carolina 27708, USA*

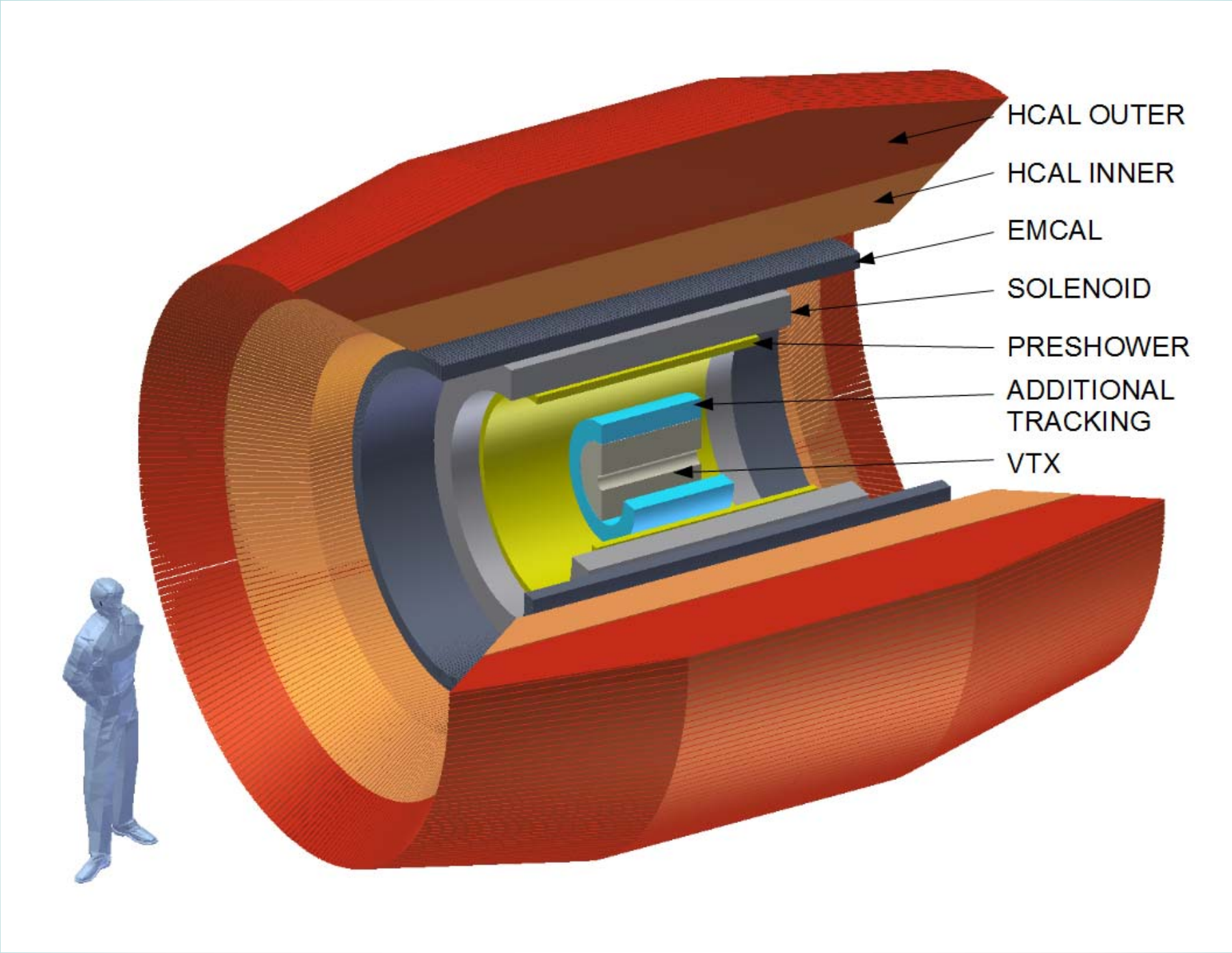
[2]*Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

(Received 10 March 2007; revised manuscript received 13 June 2007; published 7 November 2007)

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

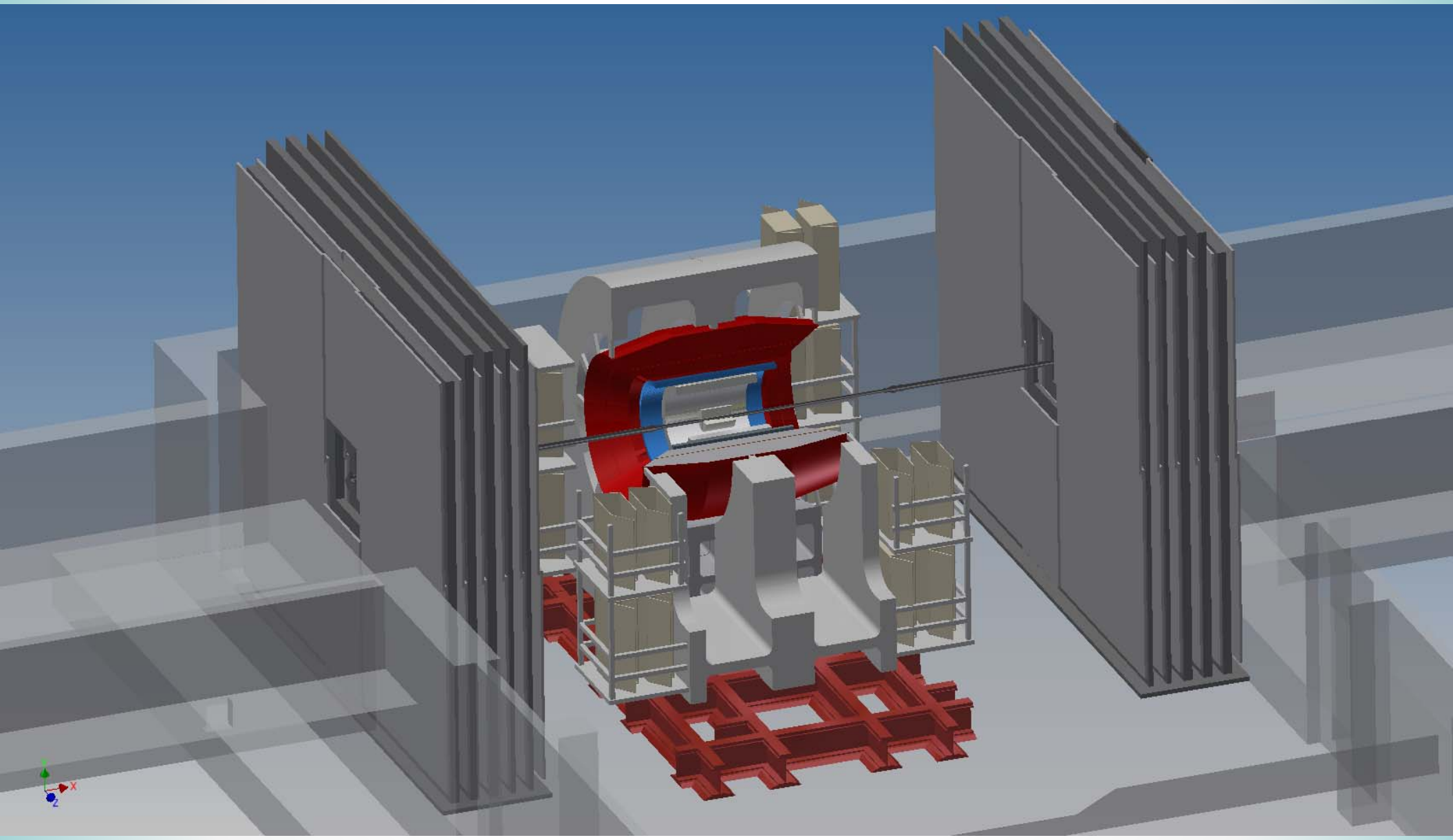
-Although qhat (ehat) might not be the only way to quantify $E_{loss}$ and realize goals of sPHENIX, it is one example of a framework for doing so

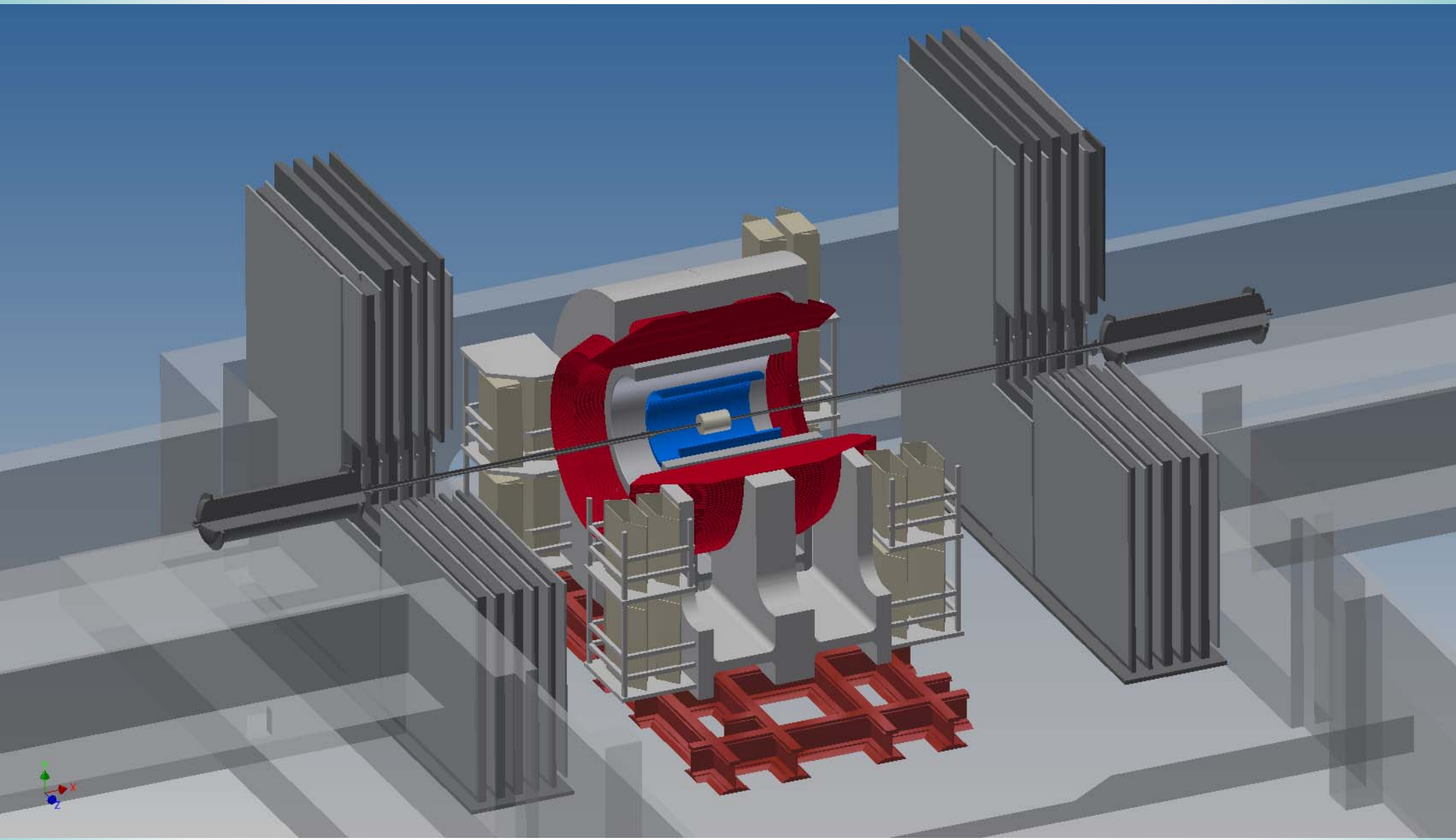
-How best to demonstrate its robustness (going into strong coupling?) and impedance match for theory community?


HCAL OUTER
HCAL INNER
EMCAL
SOLENOID
PRESHOWER
ADDITIONAL TRACKING
VTX

# BaBar solenoid

- A major positive update to the MIE considerations :
- BaBar Magnet from SLAC recently made available!
- Major parameters:
  - 1.5 T solenoid
  - Inner radius: 140 cm  (x 2 compared to MIE)
  - Outer radius: 173 cm
  - Length: 385 cm





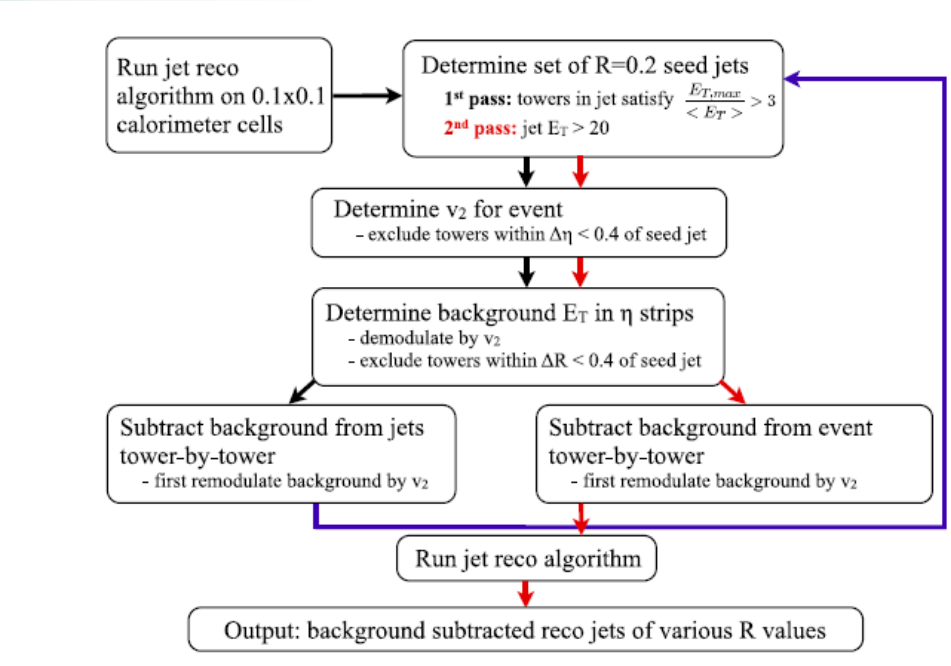
# Impacts

- The sPHENIX cost estimate in the MIE proposal was
  - $29.1M of new equipment (including $7.9M for the magnet)
  - $6.3M of redirected labor
- We are still evaluating the costs with the BaBar solenoid; the detector is larger, costs increase
  - Increase in radius of HCal 112 cm to 173 cm
- the possibility of improved performance (EMCAL resolution, for example)
- removing a very risky $7.9M cost is a huge win

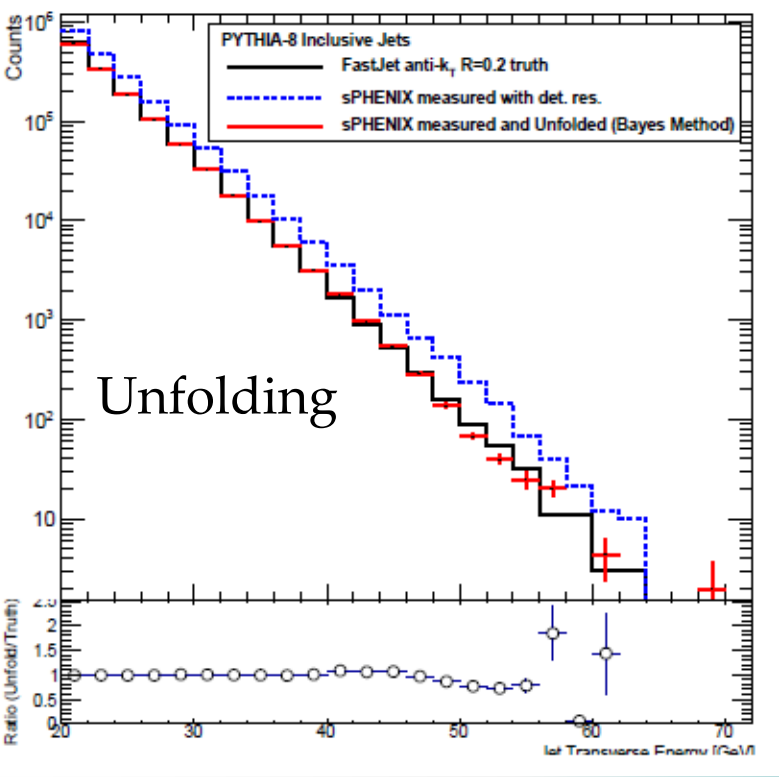
- Should only positively impact schedule

# sPHENIX MIE Proposal

- CD-0 DOE MIE Proposal: 60/120 pages: Generic RHIC Jet Physics Discussion!
  - (A good read! link to mie pdf)
- The crucial physics offered by an LHC-like detector at RHIC using LHC-like Jet Reconstruction Methods




Bkg Subtraction



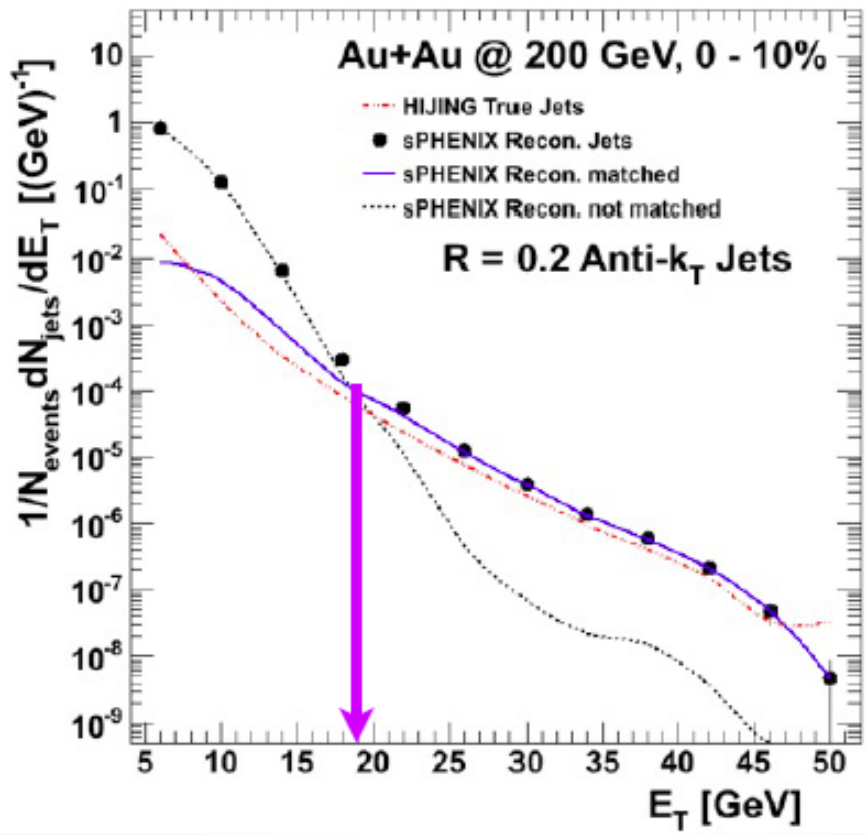
# Possible "in Principle"?

(No published results so far…)

- Too many Fake Jets? **NOPE!**

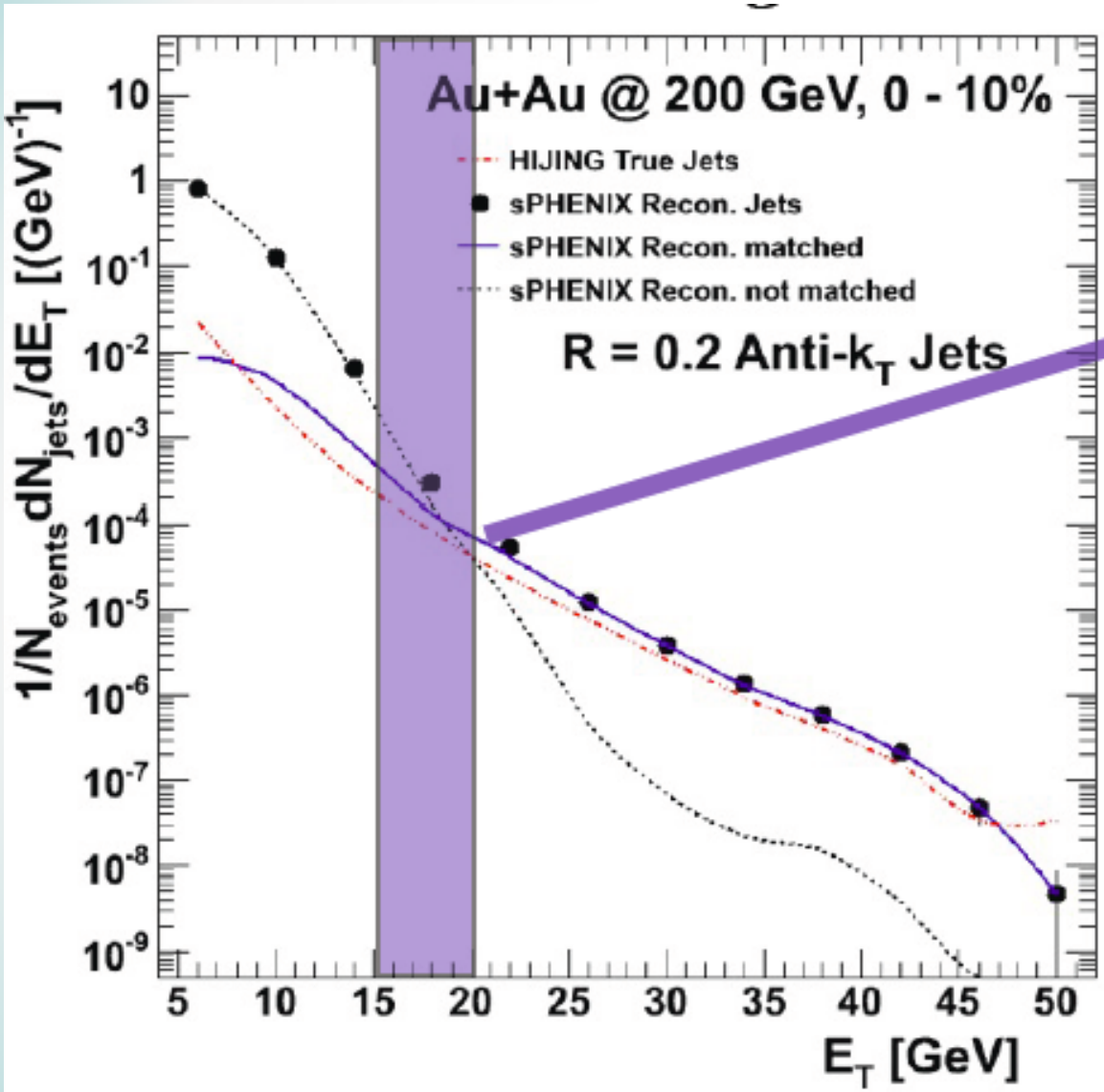
matched jets:
within ΔR< 0.25 of a HIJING truth jet (>5GeV)

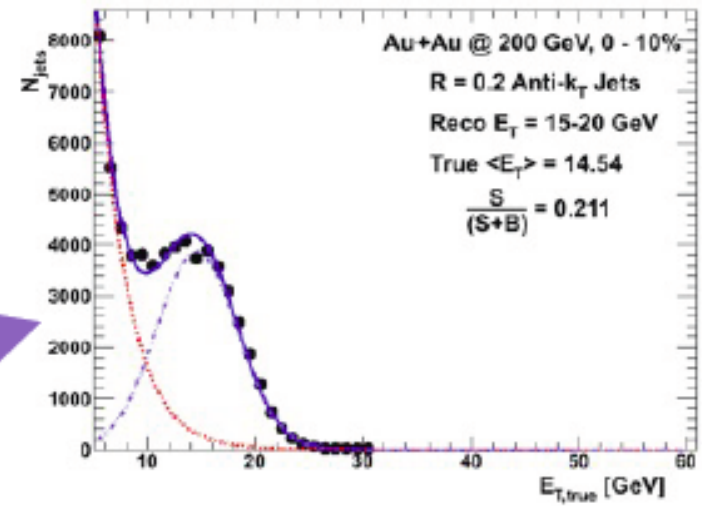
not matched jets:
no nearby HIJING jets
"fakes"




-vs LHC:
Lower underlying event wins over steeper production spectra for E > 18 GeV

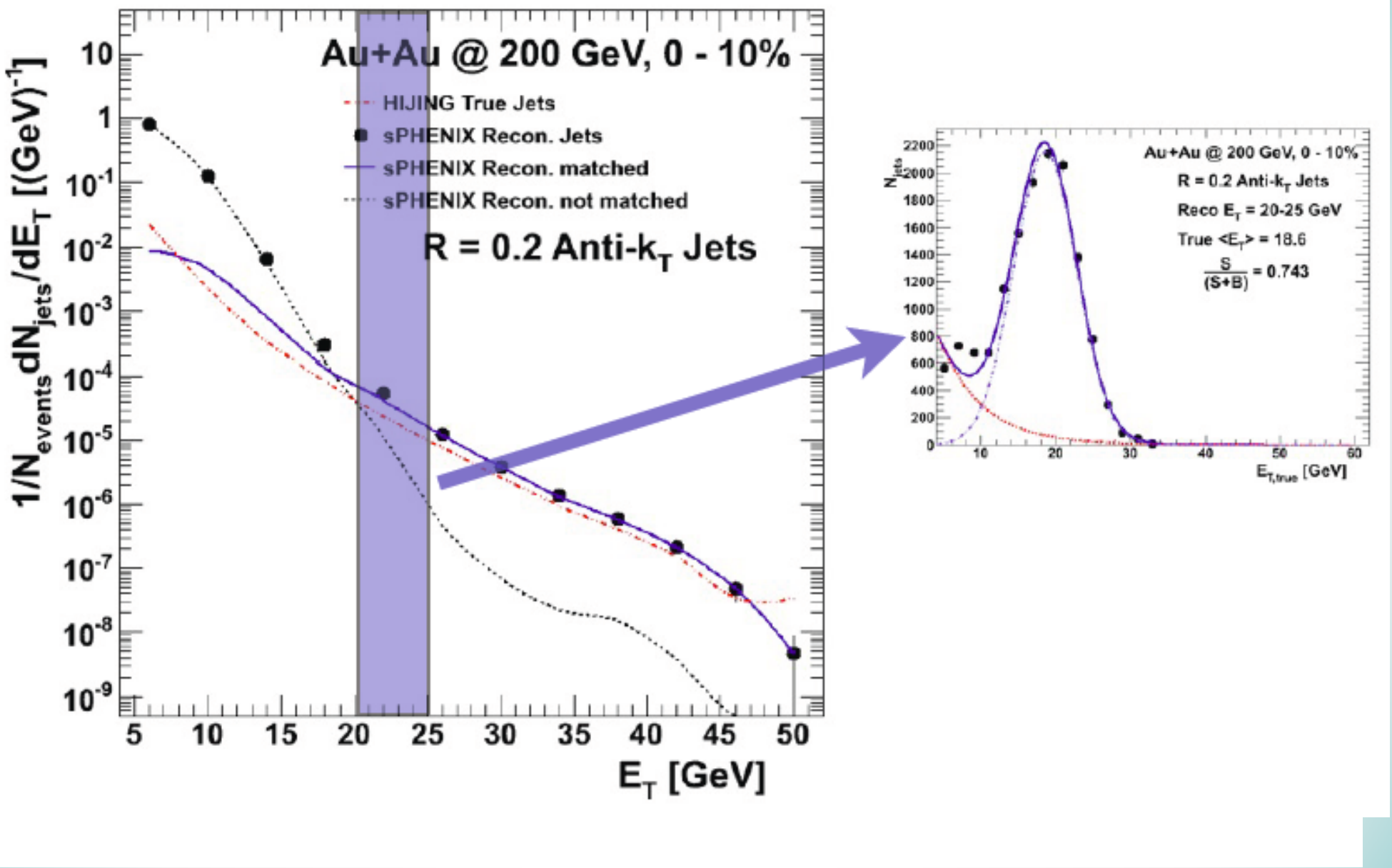
# Fake vs Real Jets



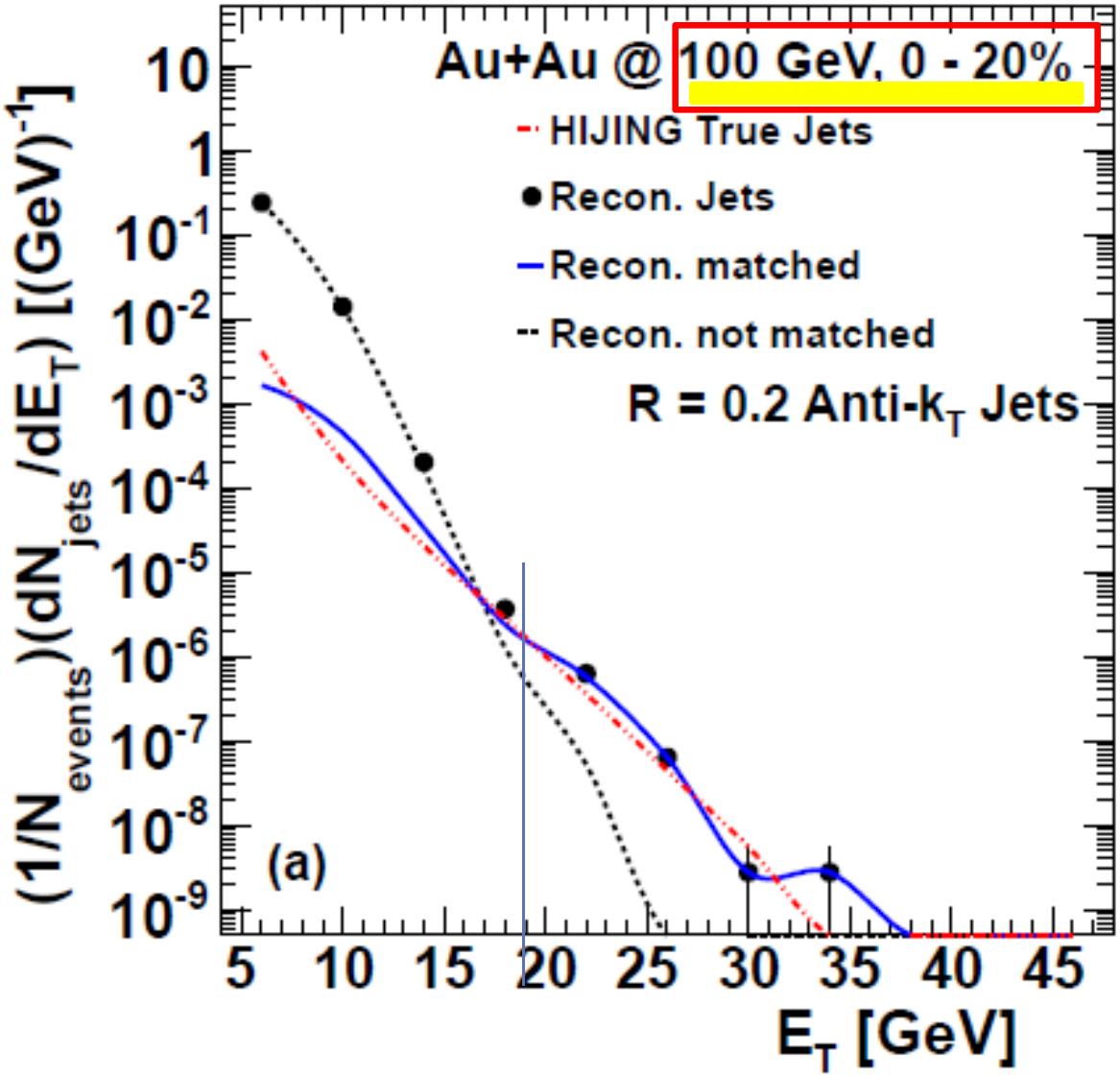




No FAKE Rejection applied yet either!
(Studies Underway:
e.g. track jet/cal jet matching cuts)

# Fake vs Real Jets



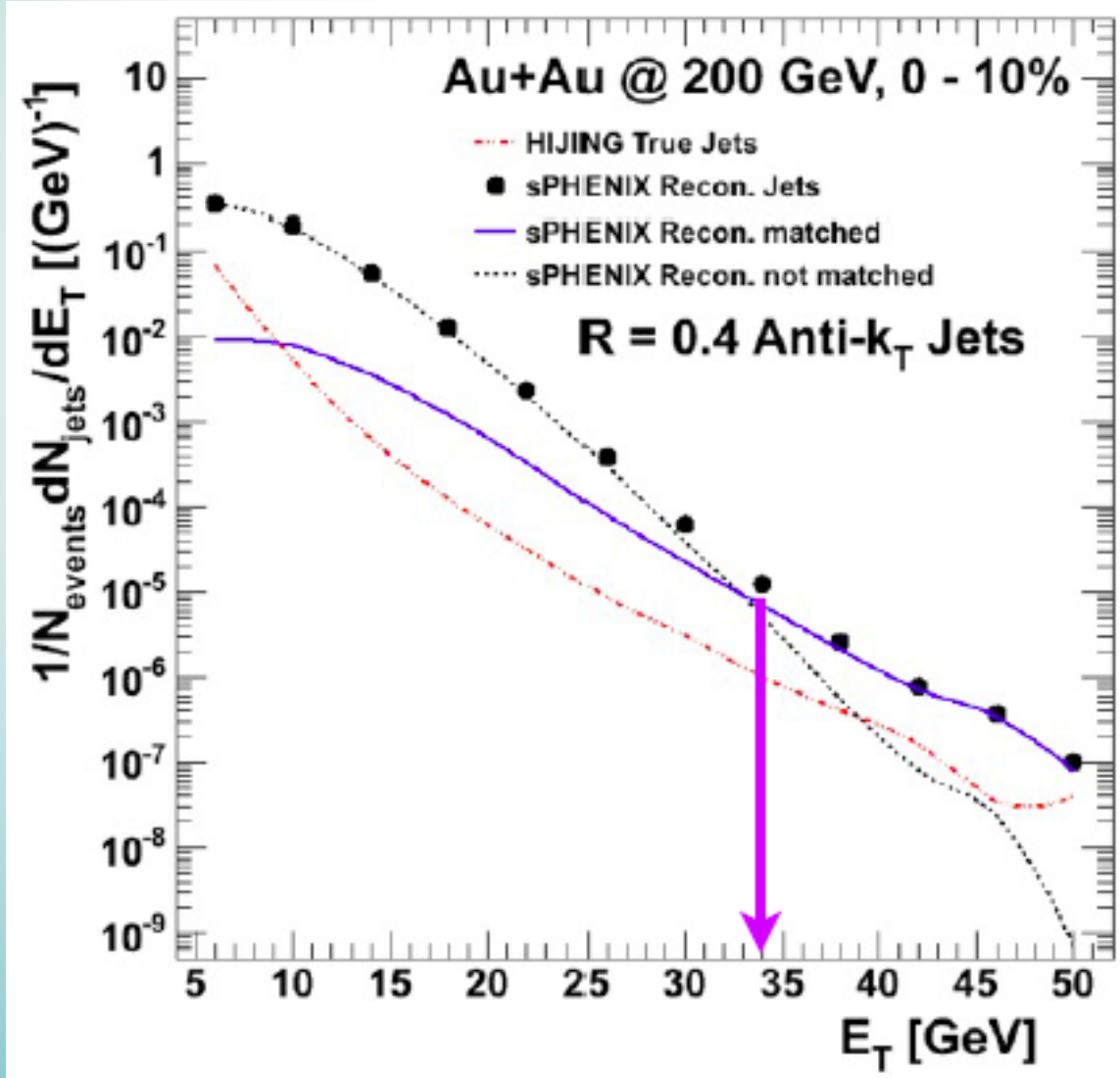
# sPHENIX @ √s 100 GeV?

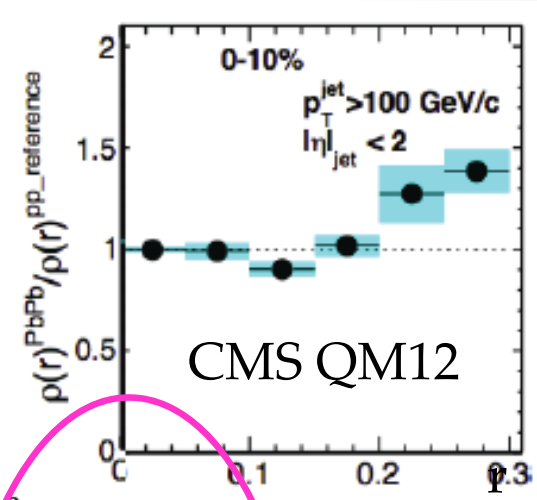


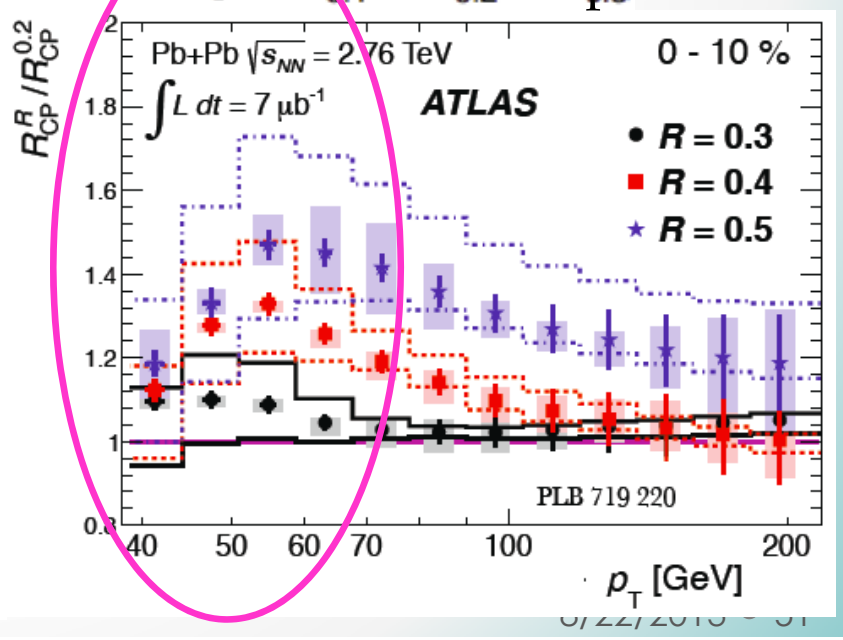

- fake-jet dominance subsides at ~same E
- Lower UE wins again!
- Stats > 20 GeV ~1/50 compared to 200
- Still $10^5$-$10^6$ Jets > 20
- **Even Lower E limited by stats not fake jets?**
- How would this addt'l factor of 2 in √s leverage for theory ?

# Larger Cone Sizes?

- Yes: baseline for 0.4: $E_{min\ from\ bkg}$ = 35 –> fake rejection should lower this
- LHC: Interesting at these cones, sPHENIX energies

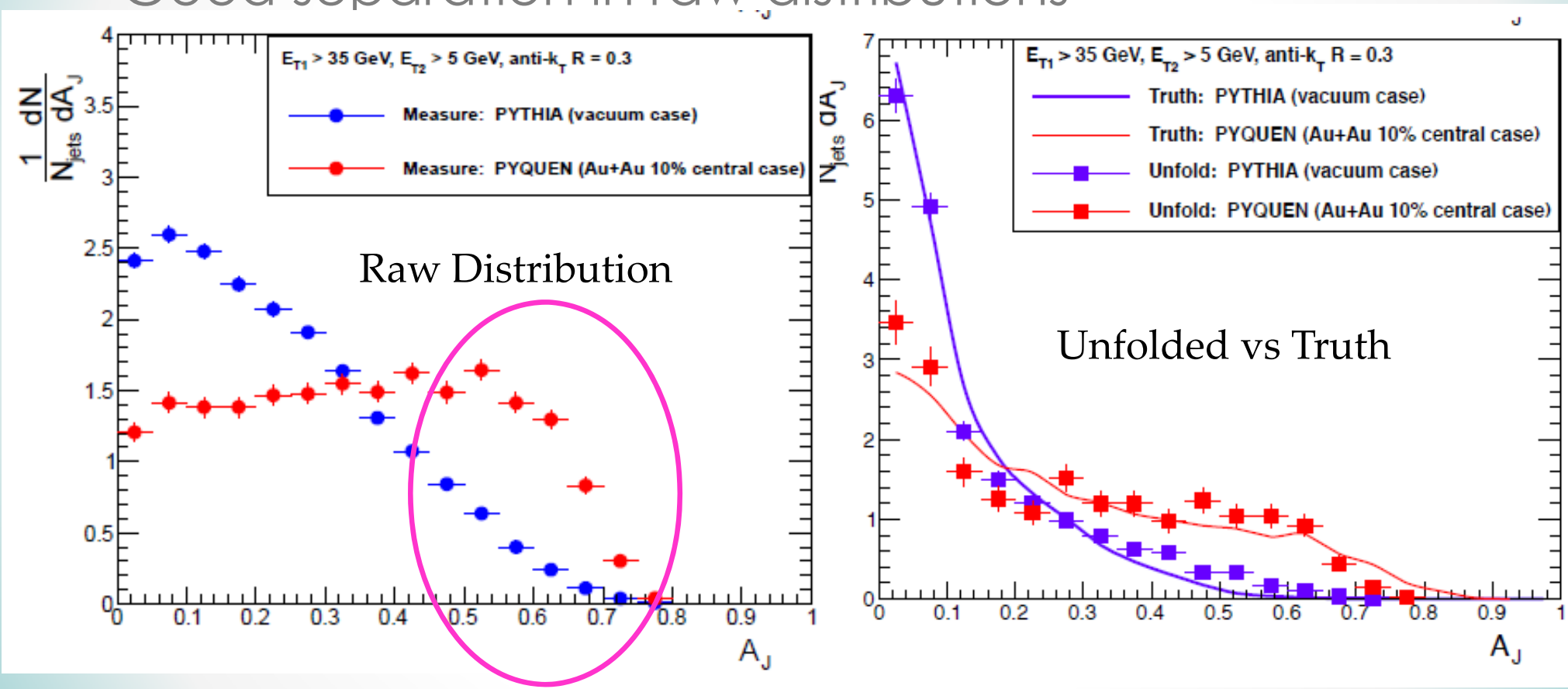


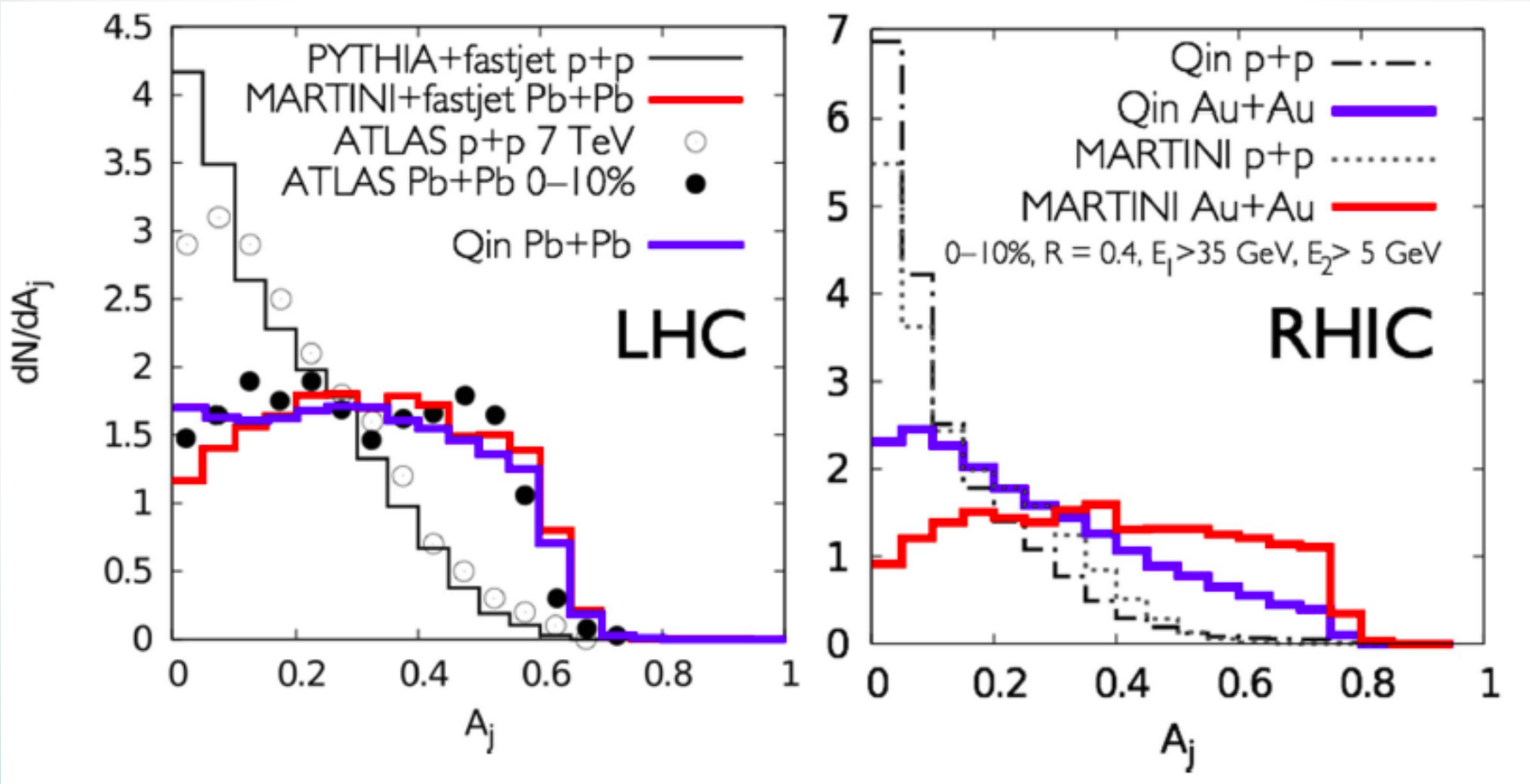
# Event By Event Opportunities

- Dijet $A_J$ : 0-10 % HIJING Embedding—Unfolding procedure works well
- Good separation in raw distributions



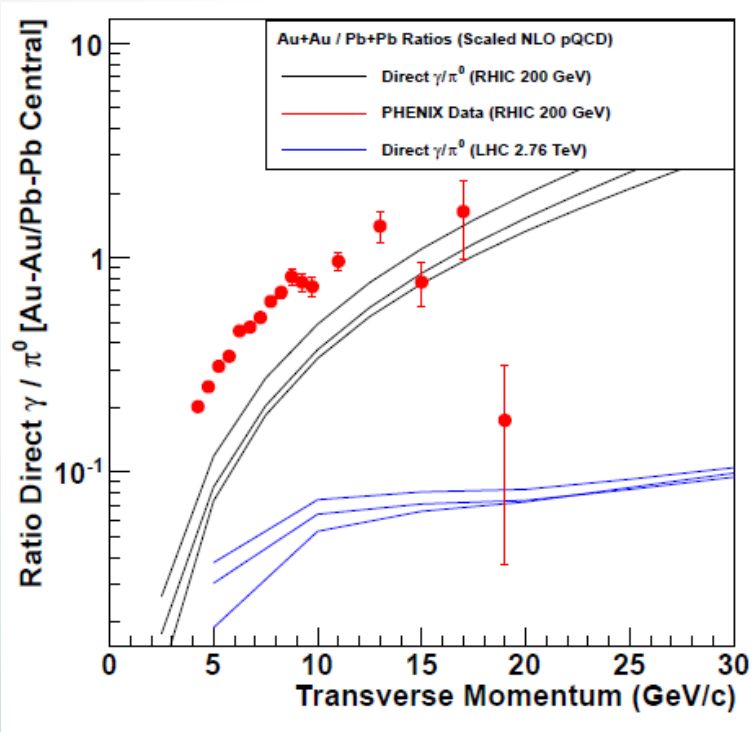
# RHIC: Key Discrimination

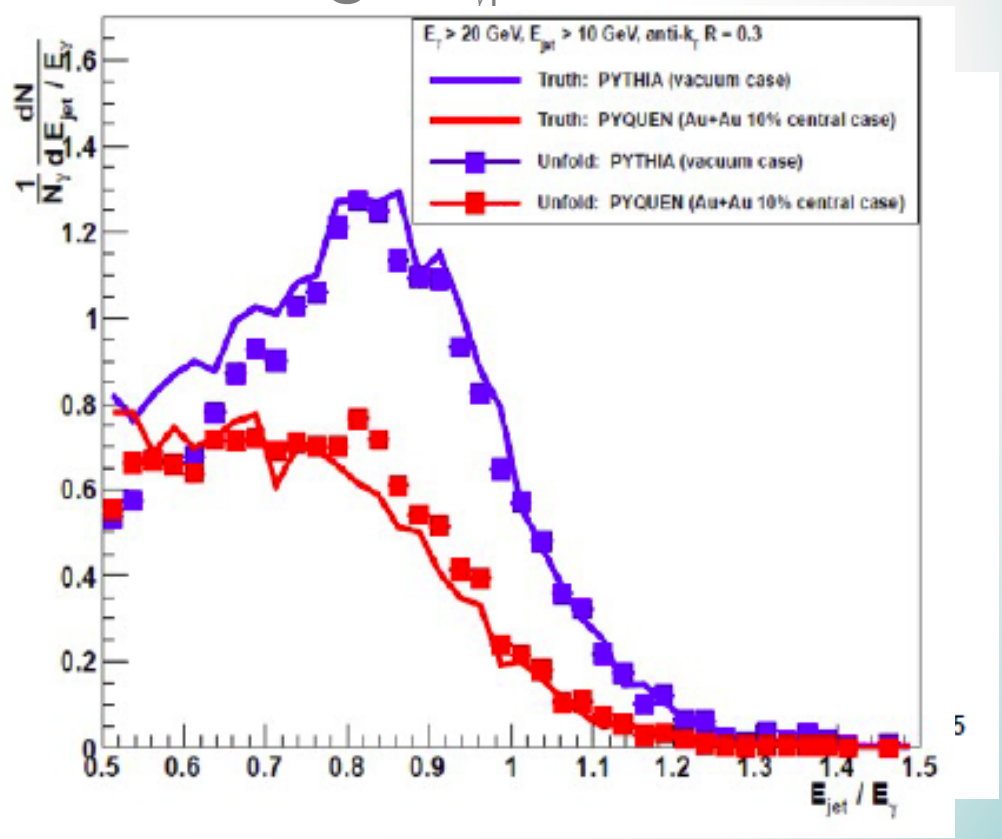
- Between models



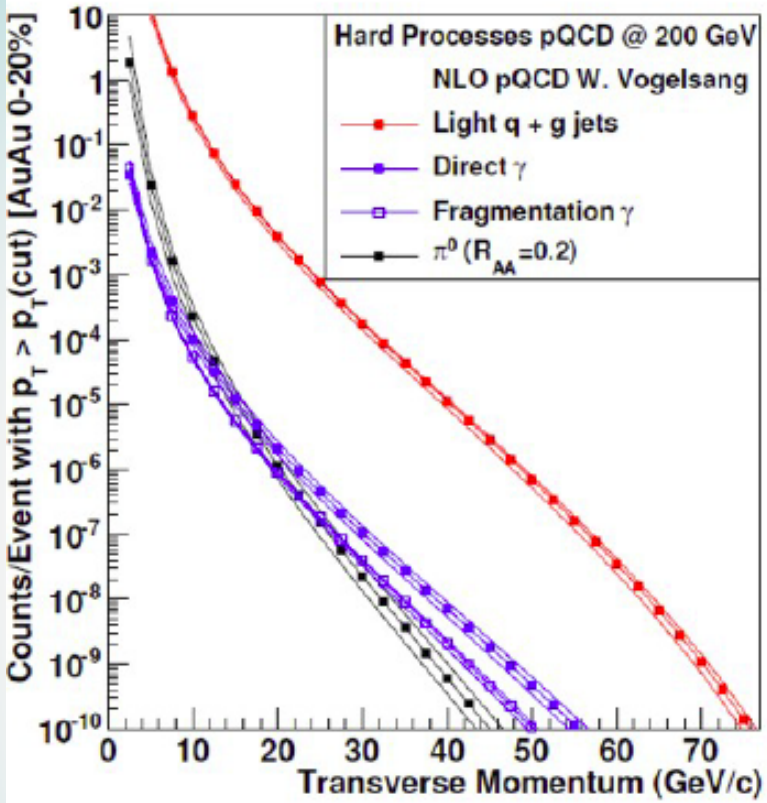
# γ-Jet in SPHENIX

- Access high stats…
- Clear Modification signal, comparable to current LHC Results
- Separation in raw distributions at large $x_{\gamma j}$



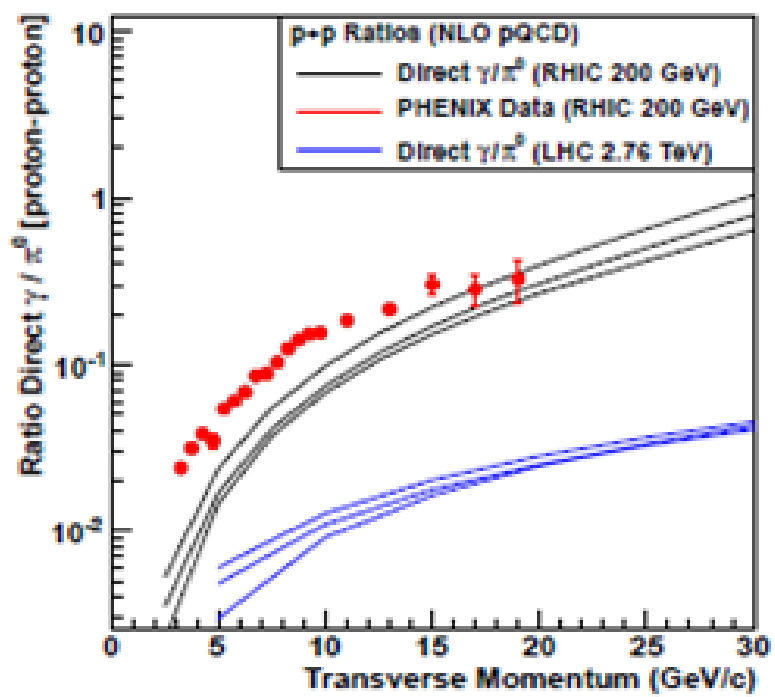



# sPHENIX: u & d-jet "tagger"



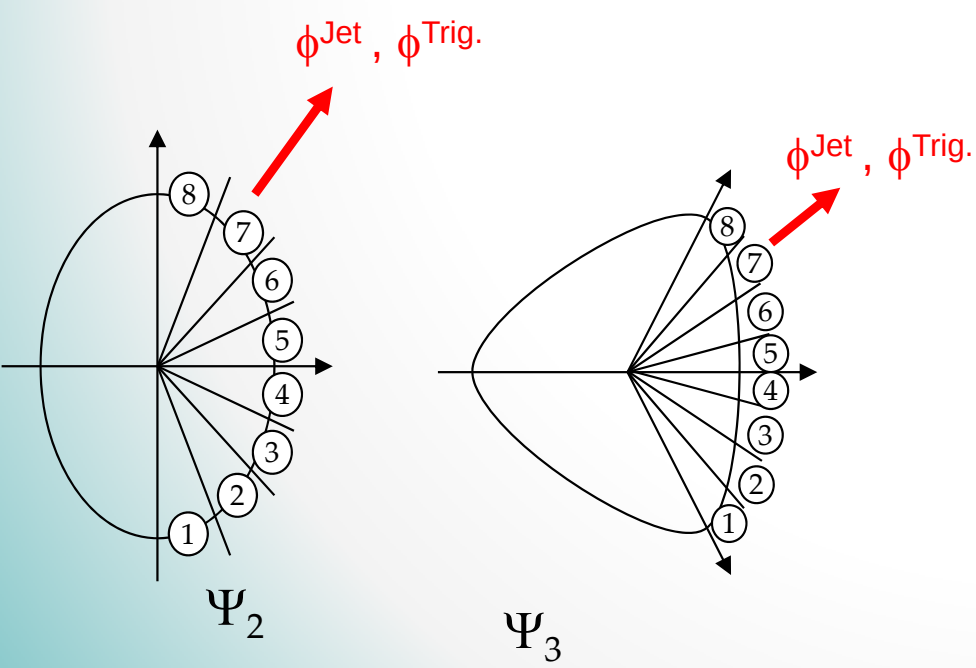

rates based on full stochastic cooling, but no additional accelerator upgrades

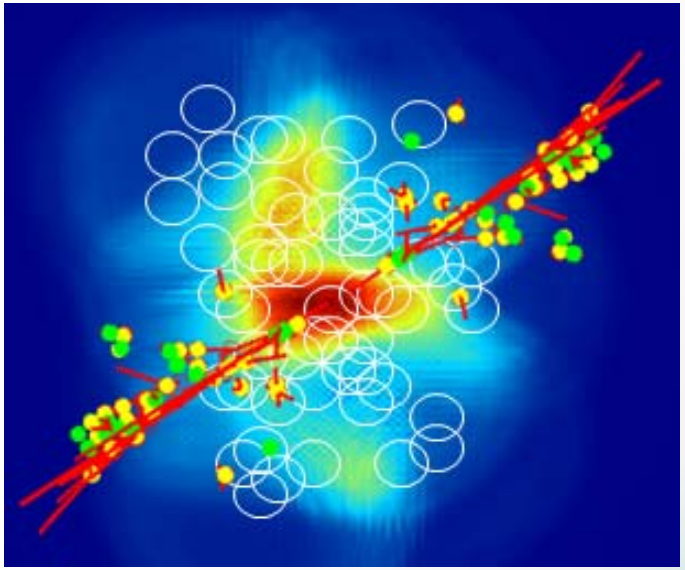
| | Au+Au (central 20%) | p+p | d+Au |
|---|---|---|---|
| >20GeV | $10^7$ jets<br>$10^4$ photons | $10^6$ jets<br>$10^3$ photons | $10^7$ jets<br>$10^4$ photons |
| >30GeV | $10^6$ jets<br>$10^3$ photons | $10^5$ jets<br>$10^2$ photons | $10^6$ jets<br>$10^3$ photons |
| >40GeV | $10^5$ jets | $10^4$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



# $\Psi_n$ Dependence of $E_{loss}$

- One of the key questions addressed by the sPHENIX proposal is the length scale of the jet medium interaction
  - Presumably can tells us about the nature (size) of the medium constituents
- Correlations w/ volume geometry (e.g. pathlength) have already been important
- Higher order moments could play an even more important role (event by event)



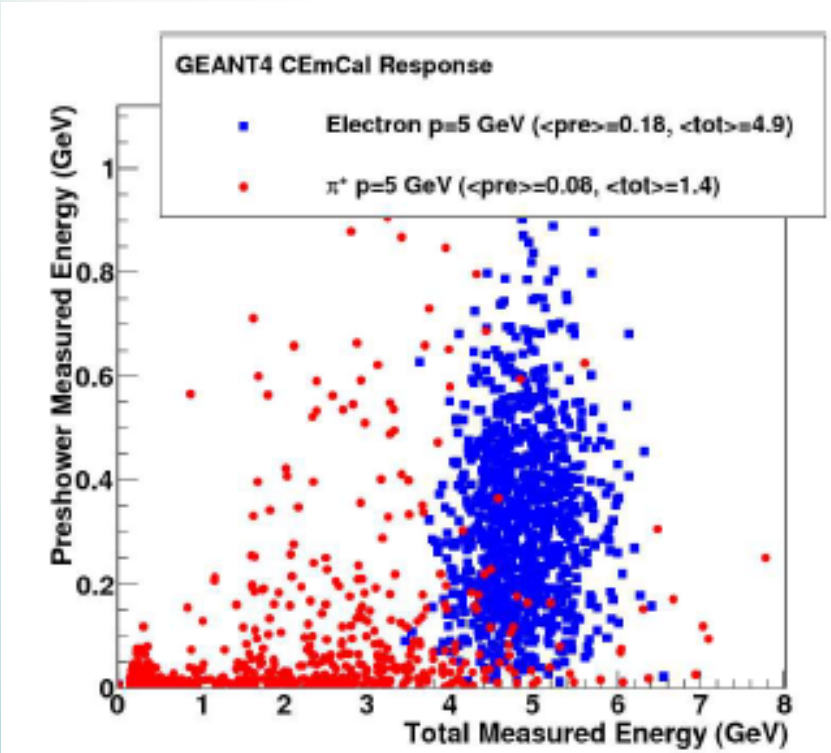



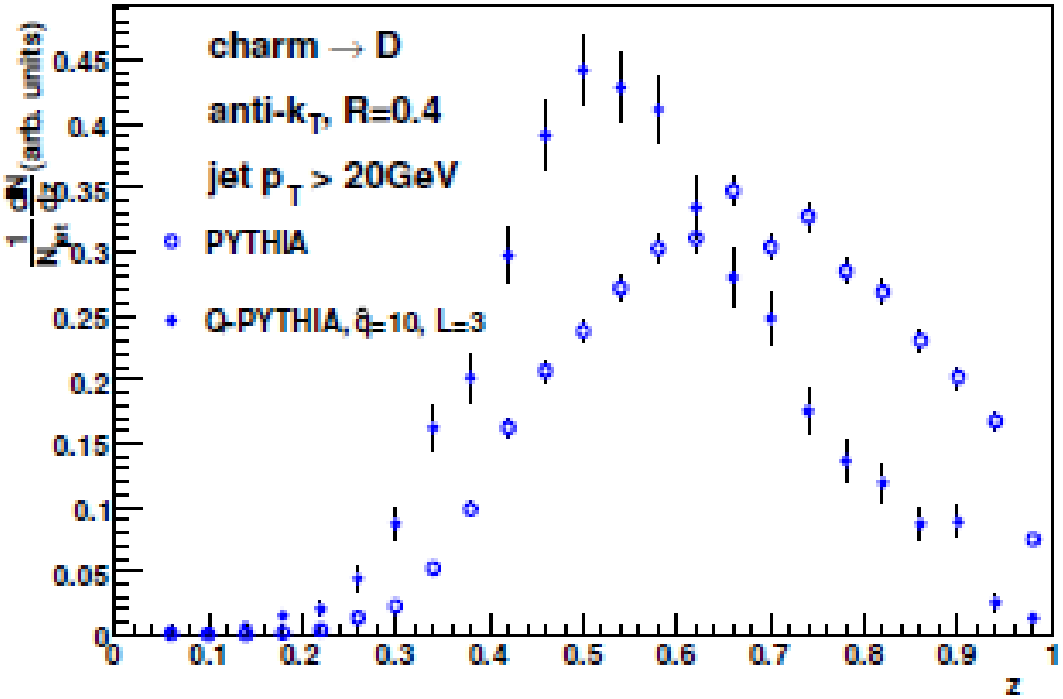
# sPHENIX $v_n$ ?

- Jet vn: statistics in the right region? Looking into
- Supposition that bulk $v_n$ will be pretty much done by sPHENIX
- However, some fronts (high n >= 5 and high $p_T$ n > 2! @ RHIC) are converging slowly.
- **Can sPHENIX make any contributions?**

# sPHENIX Heavy Flavor

- Electron ID with additional tracking/pre-shower (modest addition to base MIE, hopeful for Day 1)
- b-tagging from displaced vertices may be possible with base sPHENIX?– currently being investigated



# Other Plans/Upgrades

- Many other upgrades : hopefully these were discussed a bit by Stefan Bathe in his talk on dAu
- These are focused on understanding initial state/cold nuclear effects obviously very important to understanding $E_{loss}$ at RHIC

**PHENIX:**

- PHENIX MPC-EX 2015 Forward Tracking/PreShower for MPC
  - Direct g/p separation for eta 3.1-3.8: contraining spin pdf's, npdf's
- fsPHENIX : Forward sPHENIX (Strong Interest Coming on Shell) ideally as close timewise to sPHENIX as possible
- ePHENIX : farther future suite of upgrades for eRHIC

**STAR:**

-Forward Gem Tracker

-VFGT

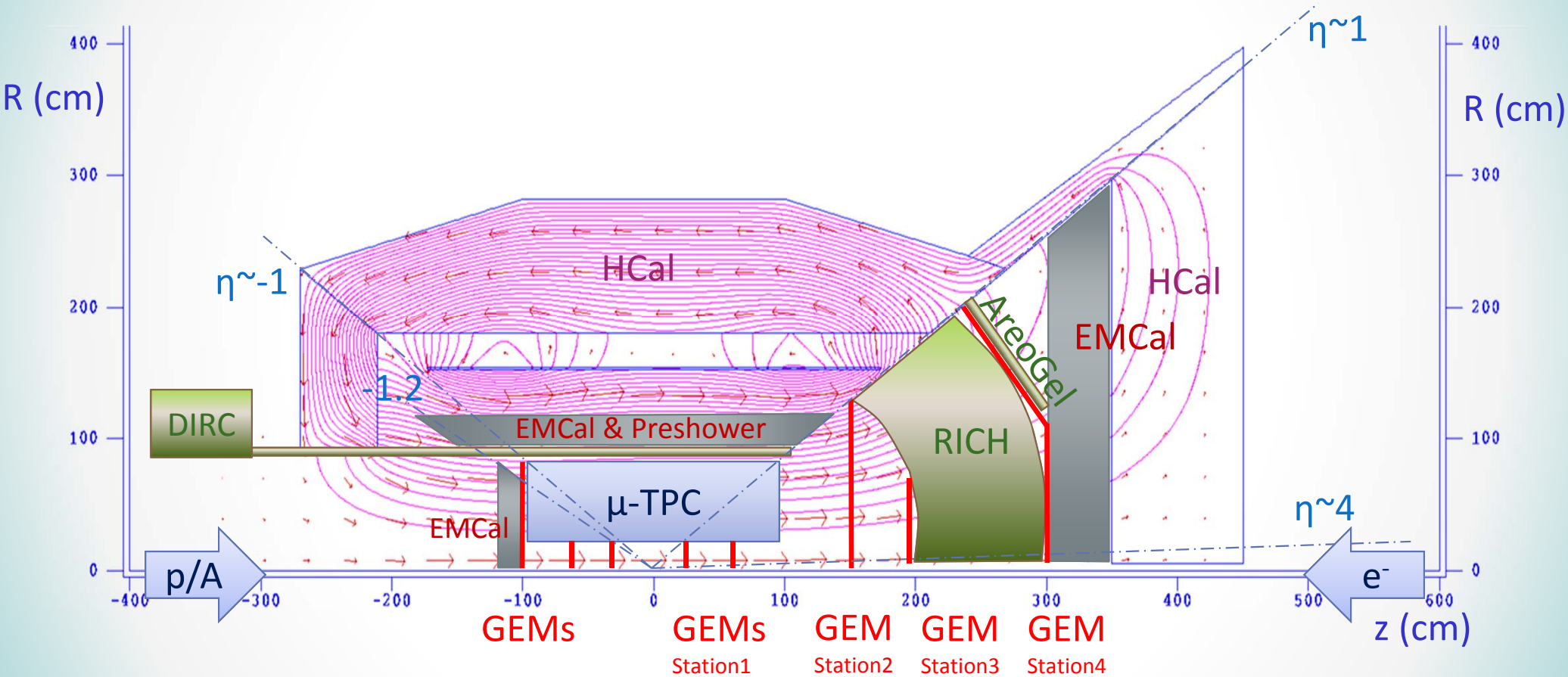
- TOF

-eSTAR

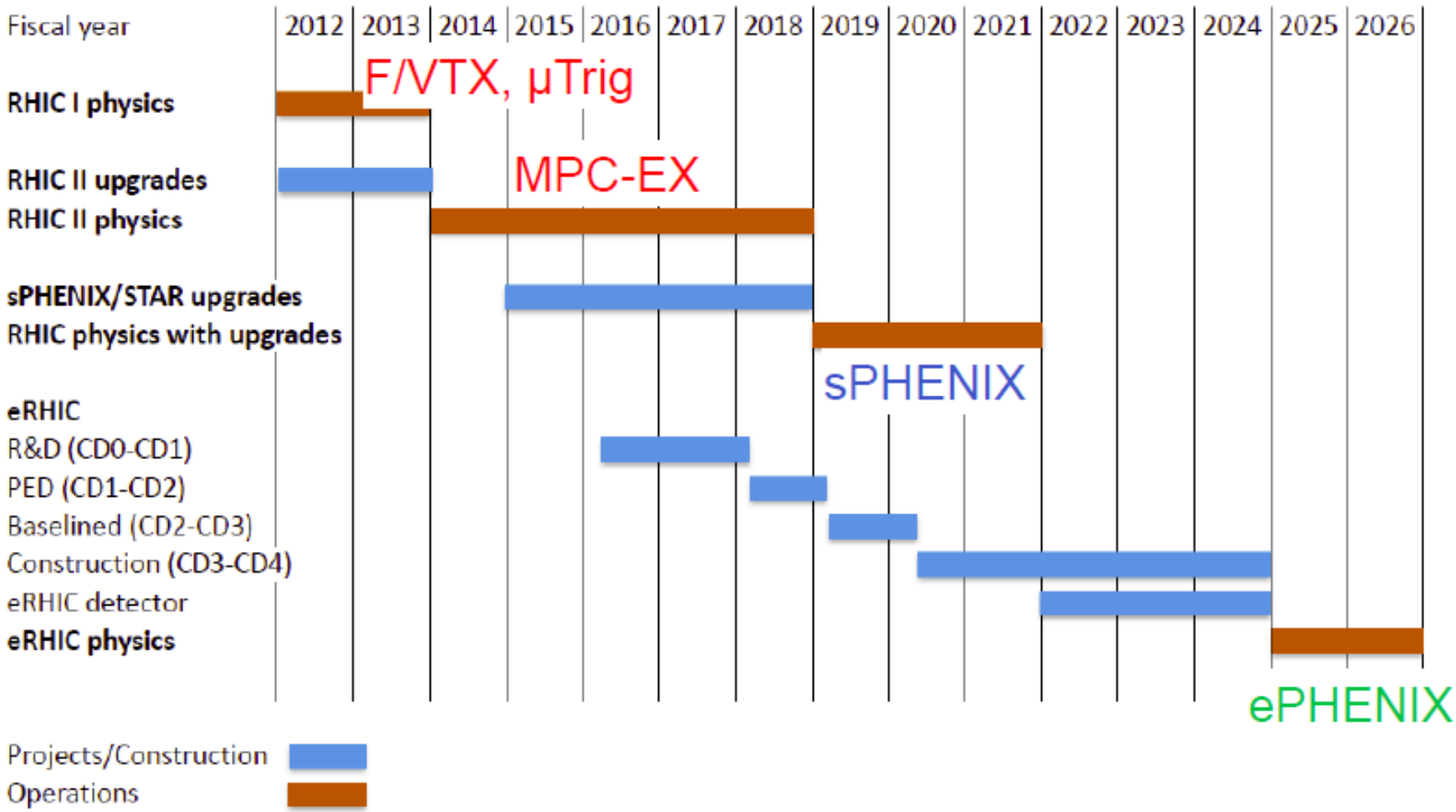
# Conclusions

- Jet Quenching Studies at RHIC are and should exploit RHIC's Flexibility
- Coming Soon: RHIC c/b Heavy Flavor! (Upgrades)
- Jet Reco , Spectra, Jet/ $\gamma$/ h Correlations
  - Both STAR and PHENIX have nice comprehensive spectral data that can be a nice starting point for finally understanding Cronin Effect
    - With sufficient theoretical interest!
  - RHIC spans the key energy range to do this uniquely!
  - Di-hadrons at intermediate $p_T$ are focused on understanding medium/jet medium systematics, not so much quenching itself
  - Could this be largely resolved within a few years?

  - Direct $\gamma$-hadron and Jet-h and ARE important to quenching considerations NOW and shouldn't be disregarded because of bias in field towards pure jet reconstruction
- sPHENIX!
  - A powerful new detector to understand robust physics of jet quenching across 2 orders of magnitude in $\sqrt{s}$ at RHIC and the LHC

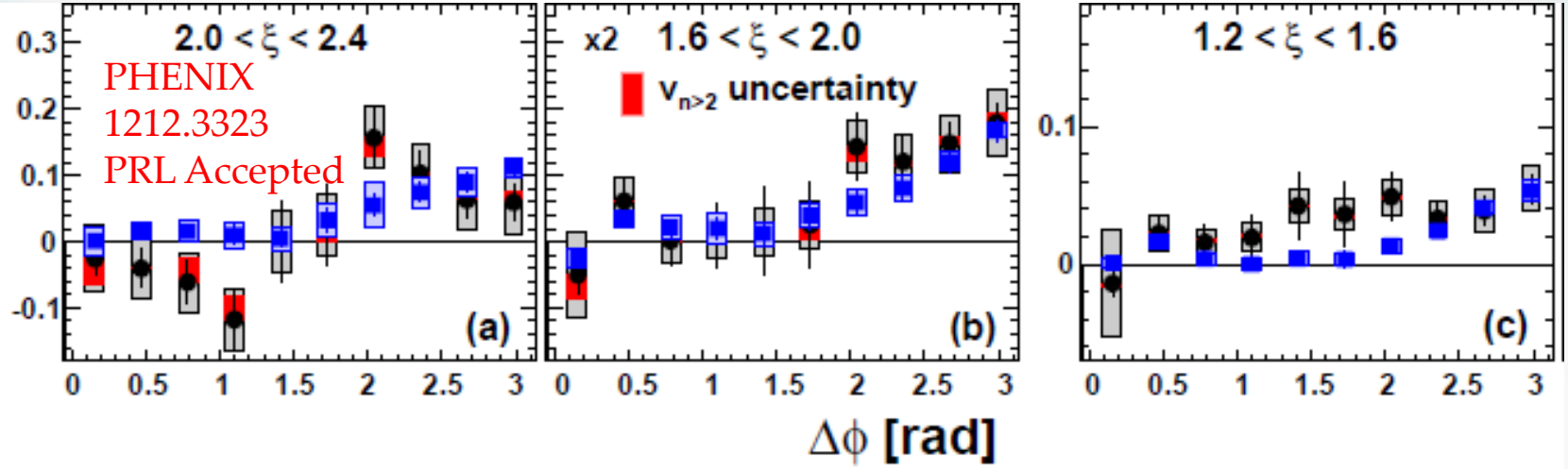

R (cm)
R (cm)
z (cm)
η~1
η~-1
η~4
-1.2
HCal
HCal
EMCal
AreoGel
RICH
DIRC
EMCal & Preshower
μ-TPC
EMCal
p/A
e-
GEMs
GEMs
Station1
GEM
Station2
GEM
Station3
GEM
Station4

# upgrades and physics on many timescales

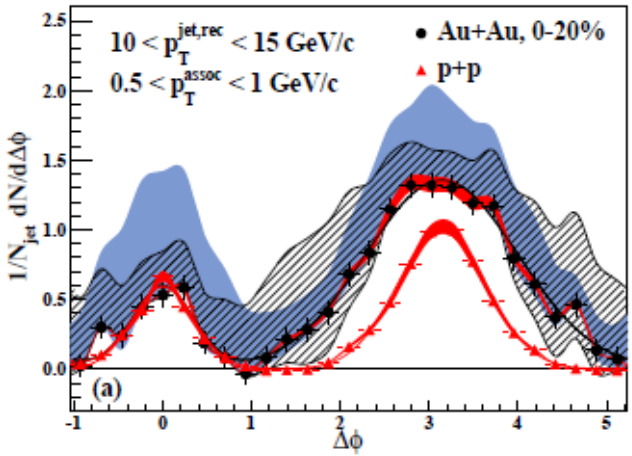


# Angular distributions

γ-h




Jet –h




STAR 1302.6184

So much broadening too "weird"?

-There's a lot of interesting stuff at R > 0.8!