Jet and Direct Photon 2-p Physics at RHIC and beyond

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WWND
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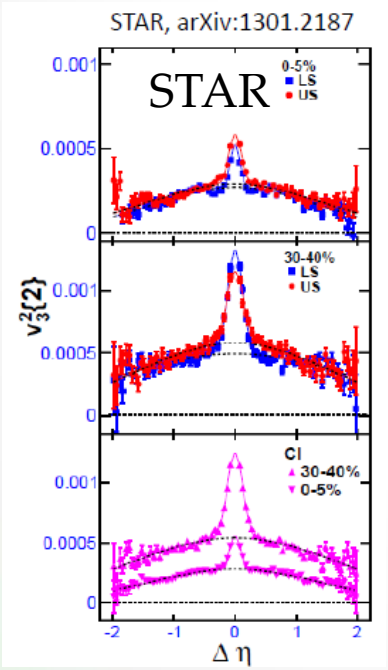
Outline

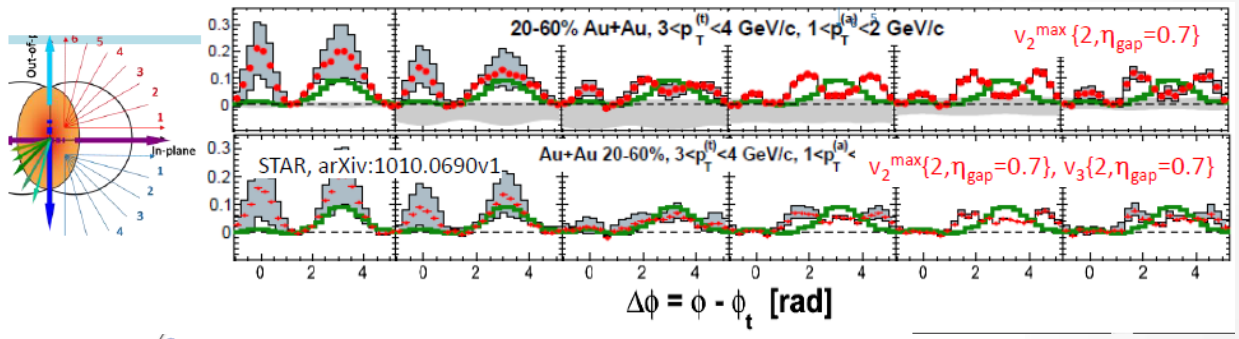
- 2-p physics **for jets** / "mini" jet studies in Au+Au
- Includes Jet-hadron, Photon-hadron, **but also di-Hadron** at RHIC
  - di-Hadron "mini" jets are limited in the systematics of the flow subtraction
  - New Ideas/ Progress Report

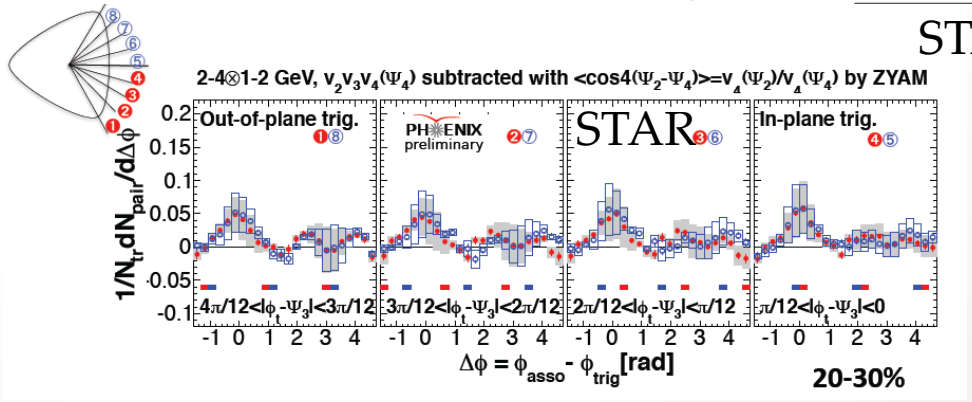
- In d+Au (y+X in the future) at RHIC:
  - 2-particle correlations a good observables
  - There di-Hadron

Di-hadrons for jets?

- RHIC continues to explore di-hadron correlations at medium p_T but currently there is still too many unknowns with the flow correlations to be sure we are isolating the jet or jet medium.

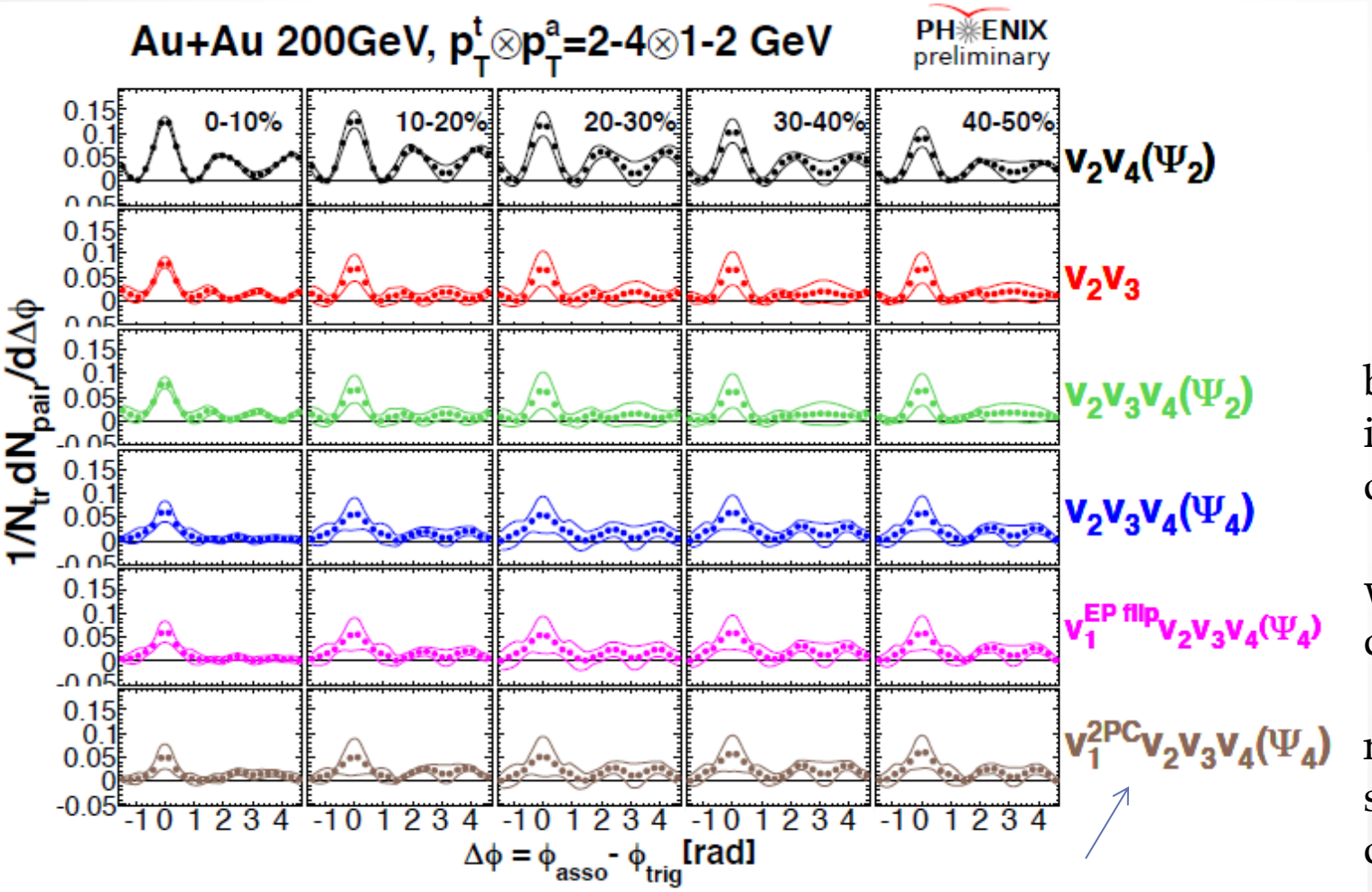






Case in point

- Takahito Todoroki Thesis: Watch for at RHIC/AGS Users meeting : Finalized results ~same as QM'12



bkg flow mode increasingly complicated

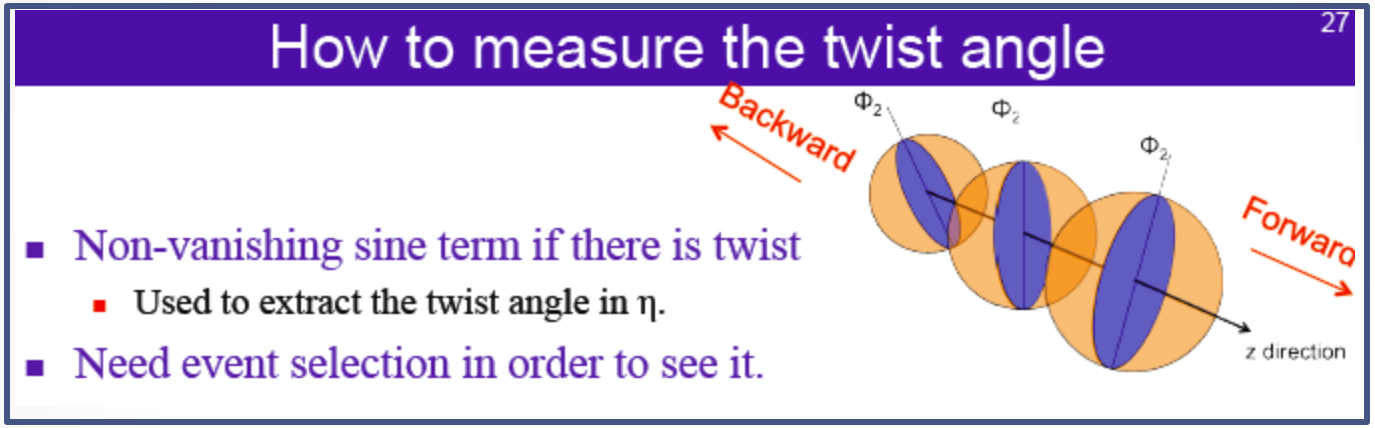
when are we done?

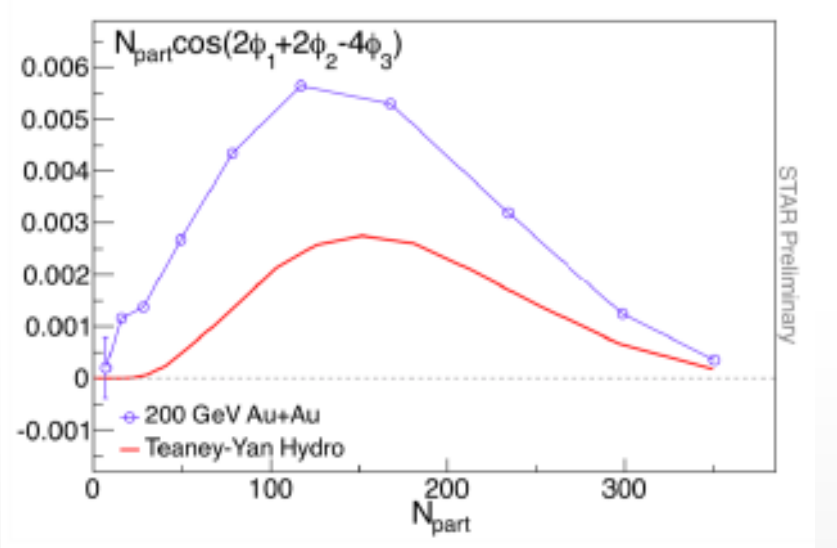
non-trivial shapes all choices

includes Ψ2 -4 correlation

More needs settled

- P. Sorensen & J. Jia's WWND talks highlighted this:
  - Reaction Plane correlations and e.g. rapidity fluctuations





J.Jia

What can be done for now

- A couple current ideas :
- Need to continually keep trying to model the various correlations and effects we see AND subtract them.
- 1) use large rapidity gap shape to subtract.
  - Is this free from longitudinal RP fluctuation effects like "Twist"?

- 2) explore L/R asymmetry → e.g. path length difference

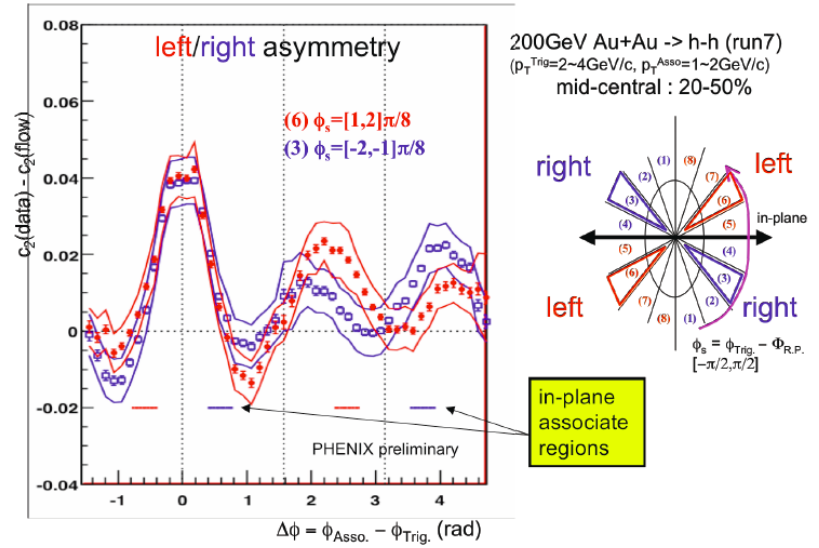
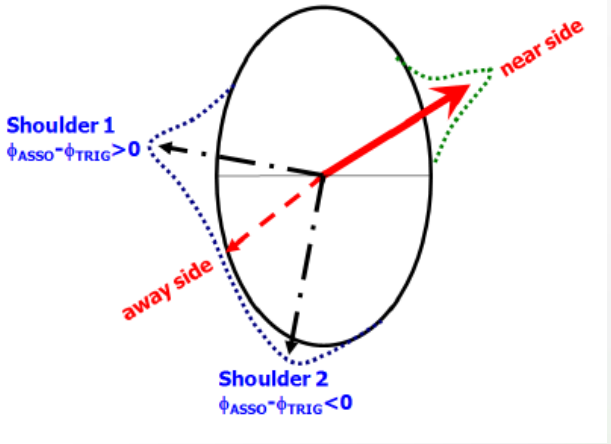


Figure P2 : comparison between trigger window (3) and (6).



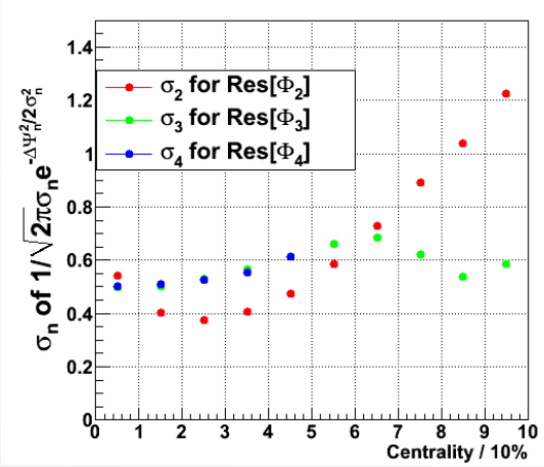
Back to subtraction ana

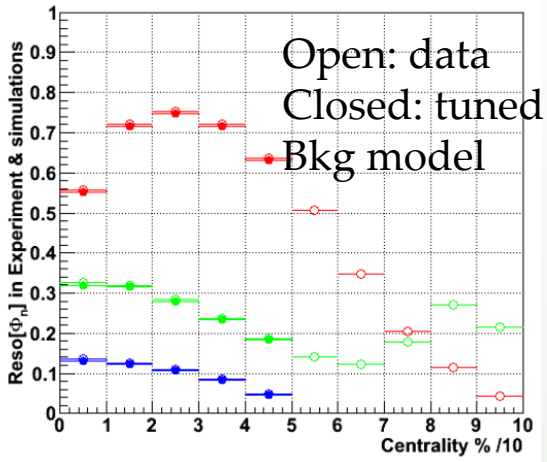
$$JPR(\Delta\phi) \equiv C(\Delta\phi) - \xi(1 + 2\langle v_2^{\gamma}\rangle\langle v_2^{h}\rangle \cos 2\Delta\phi) + v_3\ldots$$

- Current background model should cover dominant background contributions → "standard" inclusive and reaction plane dependent 2-p correlations
- Including not only higher order vn (&v_1), but also Ψ_2-Ψ_4 evt plane correlations

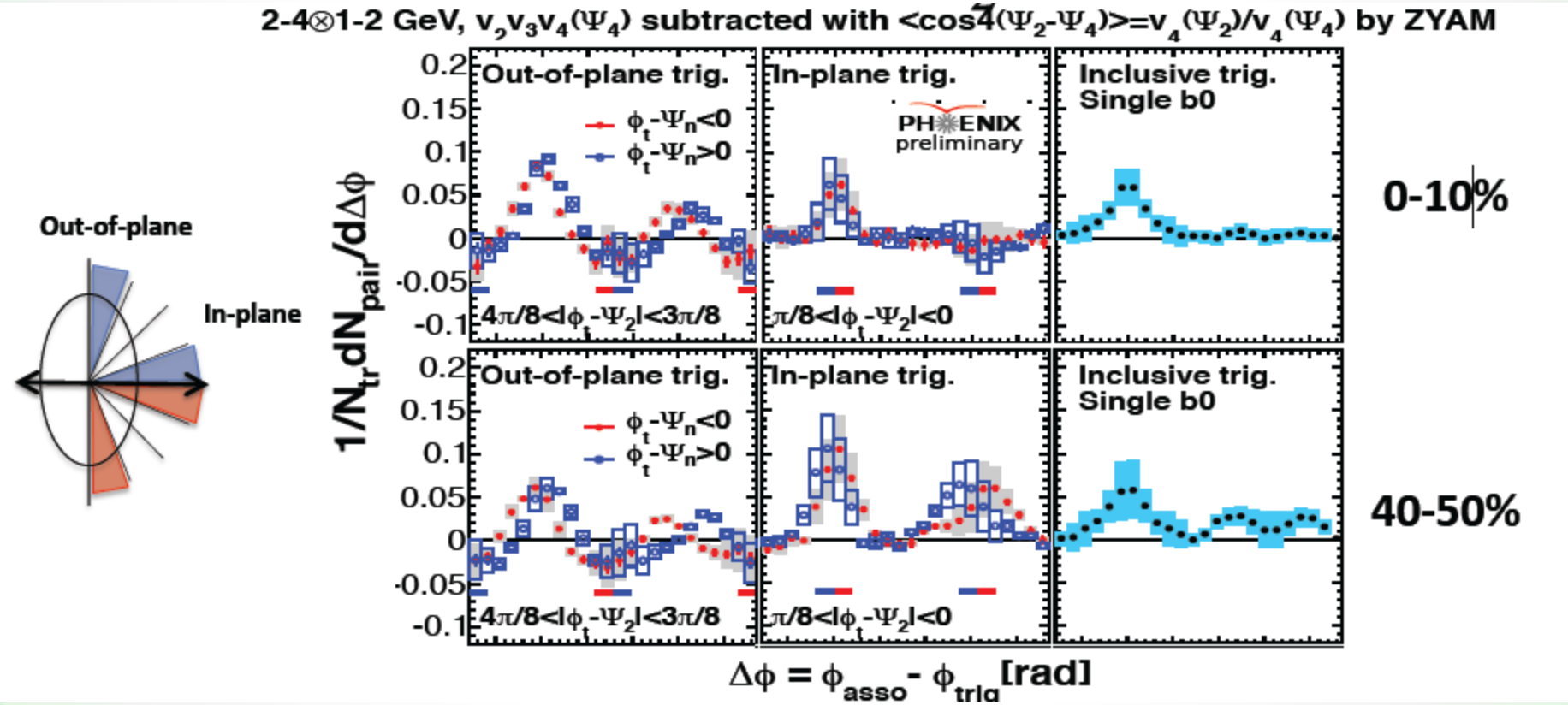
$$\langle \cos 4(\Phi_4 - \Phi_2)\rangle = \int d\Delta\Phi_{42} \cos 4(\Delta\Phi_{42})\rho(\Delta\Phi_{42}) = \int d\Delta\Phi_{42} \frac{\cos 4(\Phi_4 - \Phi_2)}{\sqrt{2\pi}\sigma_{42}} \exp\left(-\frac{\Delta\Phi_{42}^2}{2\sigma_{42}^2}\right)$$

- These are also the most important contributors for making the subtraction measurements Ψ_2/Ψ_3 reaction plane dependent





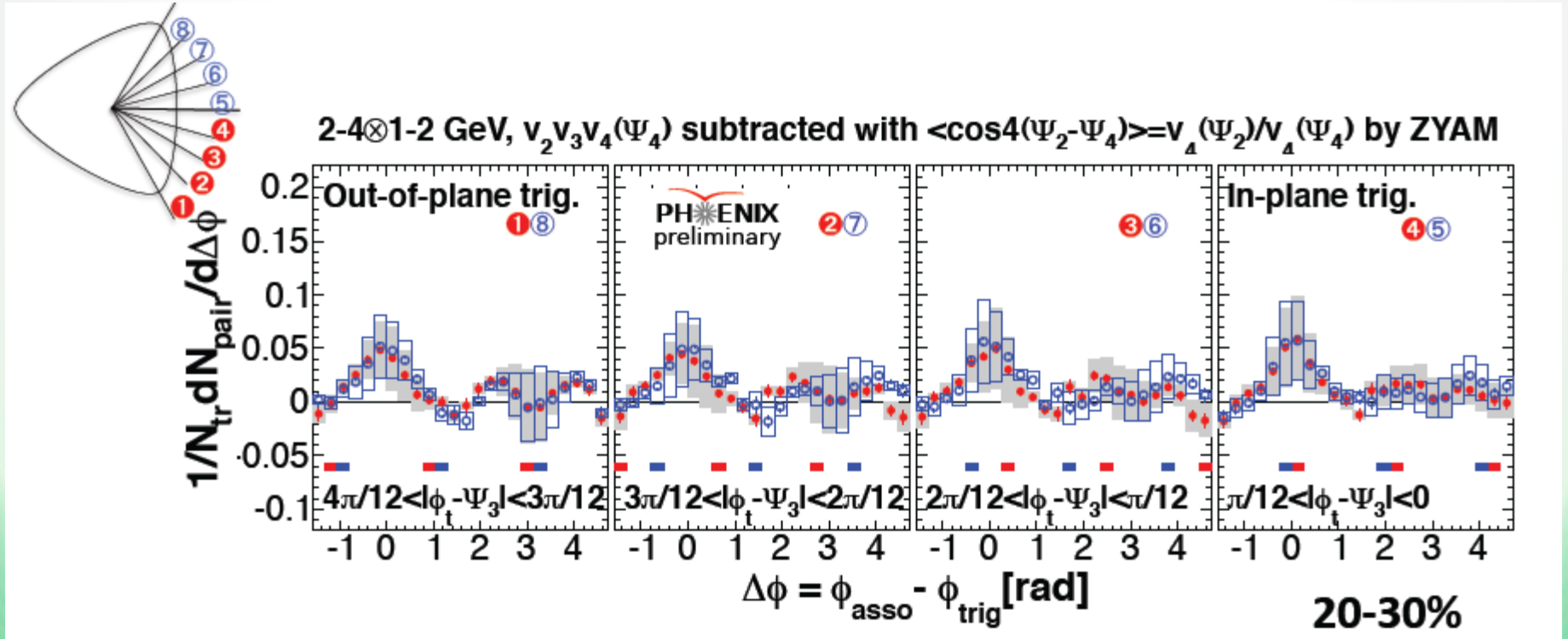
Psi 2 dependent corr's

- Improved in Thesis result,
- Some dependence seen… esp L/R asymmetry
- 

- Evidence of interplay jet and background
  - Just 'subtraction" issue?

Psi_3 Dependence of Corr's

- Not large dependence, but updated result is unfolded for RxP resolution and sees L/R asym
- Implications for higher order n E_{loss} eventually?



2-p/Correlations vs Jet Reco Complimentarity

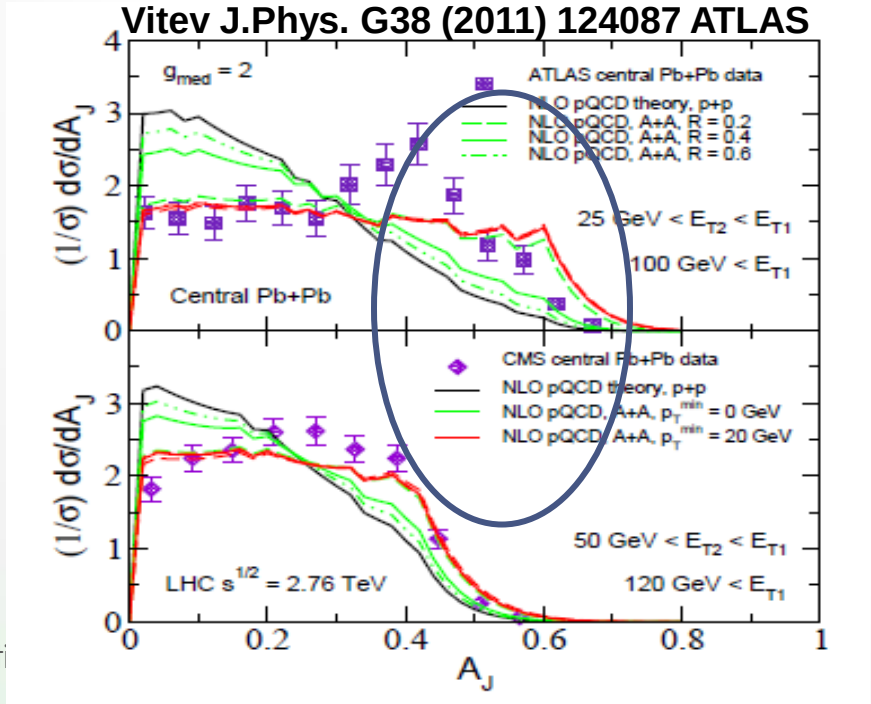
- **Both Jet Reco and Correlations: (Jet-h and γ-h 2-p) Correlations should be used** to uncover shower modifications
- Jet Reconstruction is crucial for final understandings of Jet Quenching → Modifications to Showering Process
  - sPHENIX!
- In the short term : jet quenching studies (RHIC/LHC) shouldn't 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
- Complimentarity: Jet Finding + Angular Correlation (Jet-h and γ-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
- **Hoping to see e.g. LHC γ-h correlations at QM?**

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 reco axis!

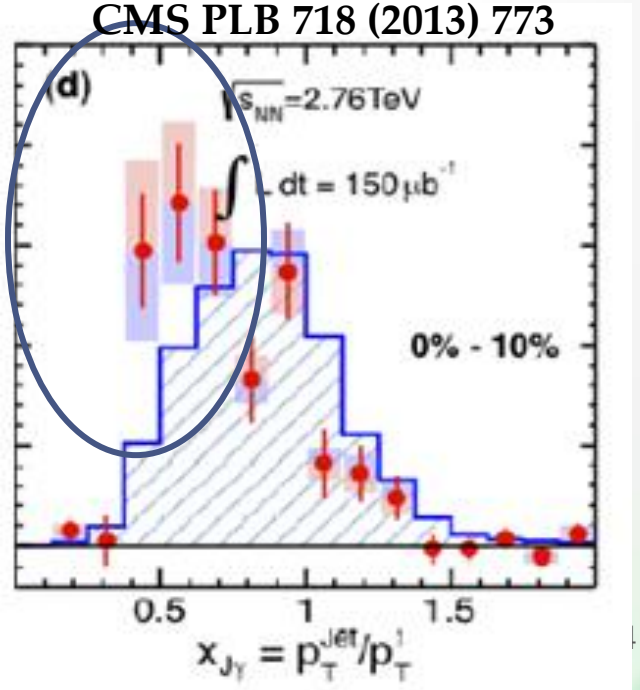
Di-jet Asymmetry Distribution

Vitev J.Phys. G38 (2011) 124087 ATLAS



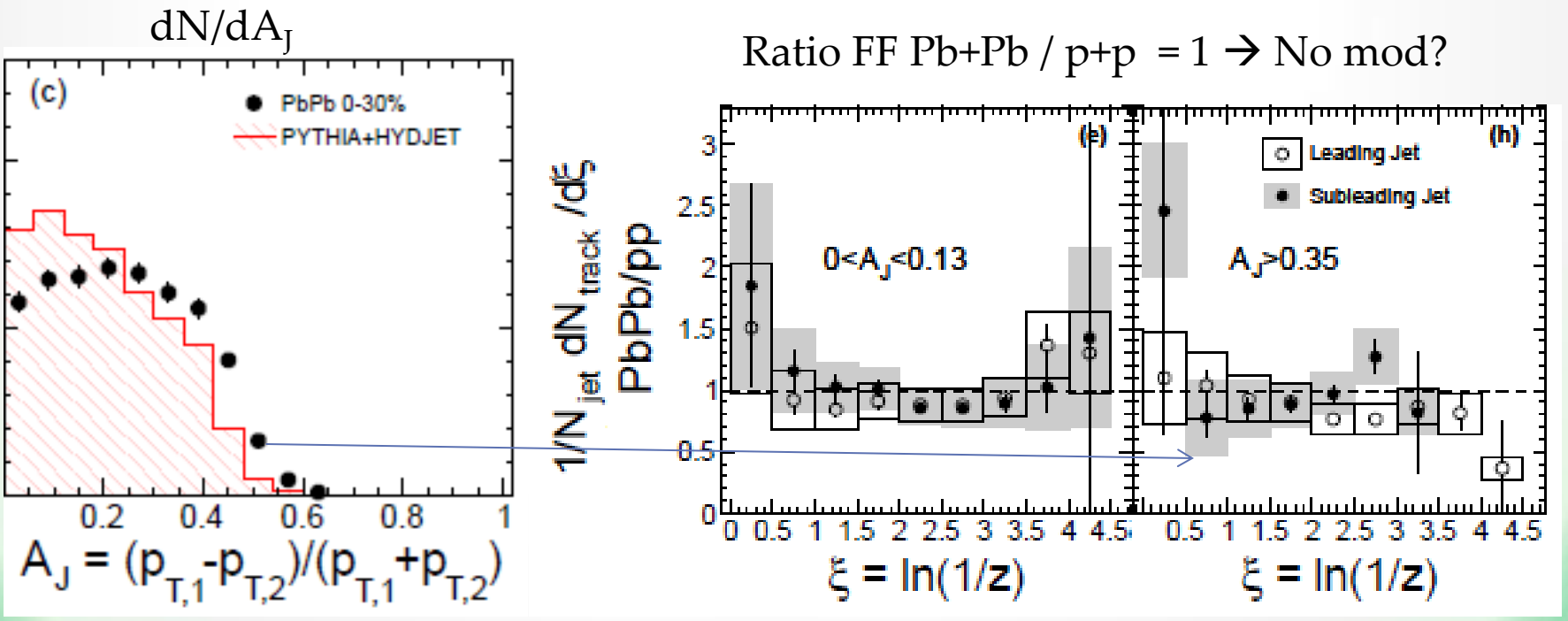
γ-jet Asymmetry Distribution

CMS PLB 718 (2013) 773

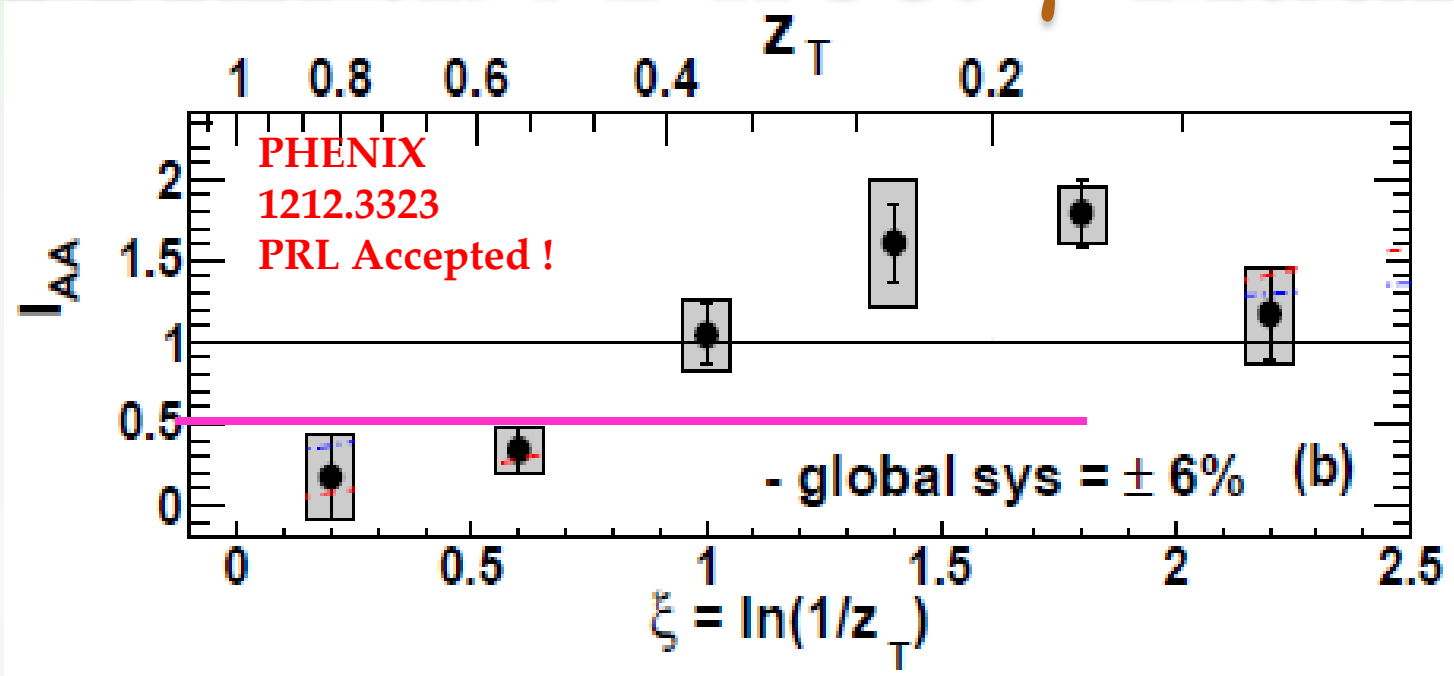


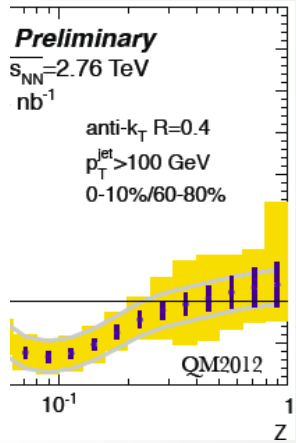
"Jet" Finding + Correlations

- Previous measurements didn't show this…
- LHC FF Modification Correlates with Large A_J? No?
- Bias of found jets
  - → **Look outside jet cone!**
  - → **Look below jet finding cutoff**



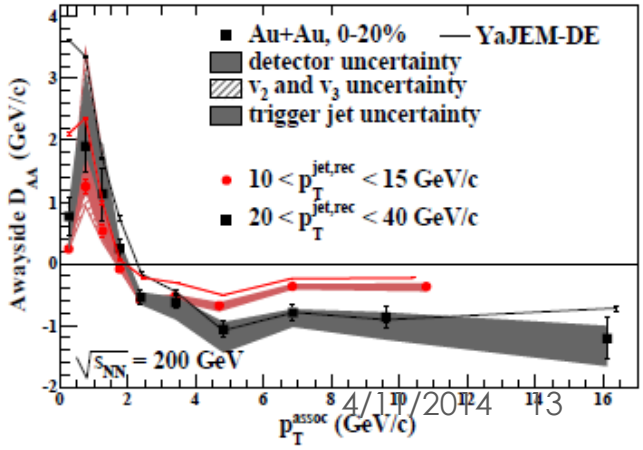
PHENIX Direct γ-Hadron





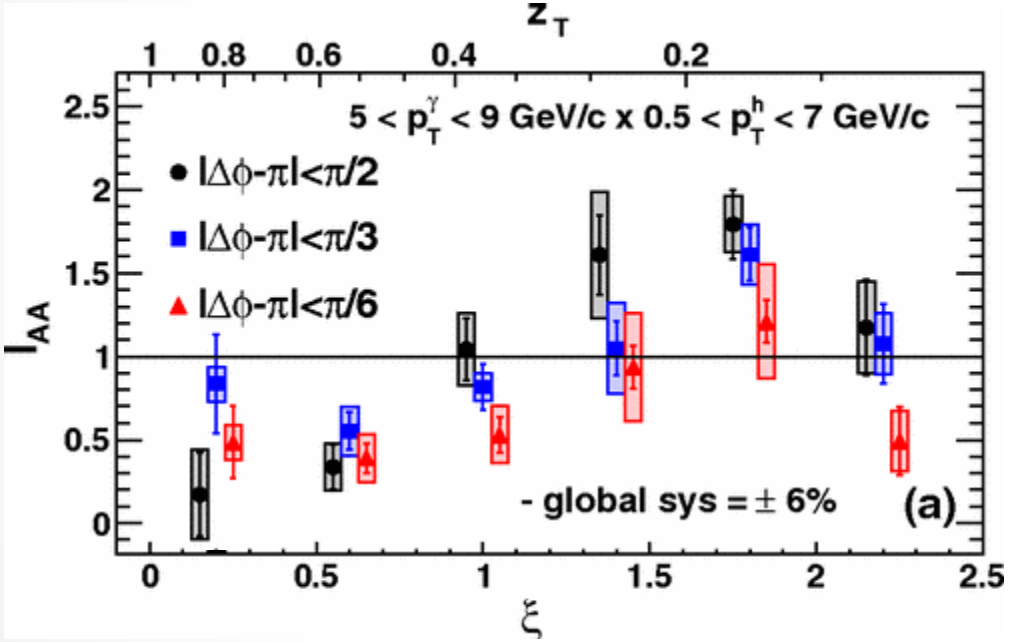
- Photon Hadron FragFn Modification!
- Low z Enhancement
- Very Similar to LHC Jet-reco
  - **LHC FF=1 ~= Jet RAA**
- ~Consistent with STAR Jet-hadron
  - RHIC-RHIC Consistency!
- These analyses are important!
- **Reco jets != All Jet Suppression (?)**

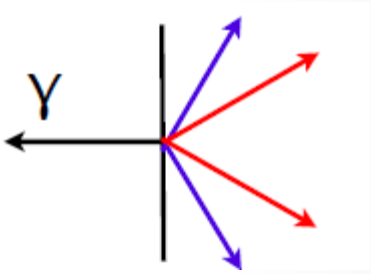
STAR 1302.6184



There's more information

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

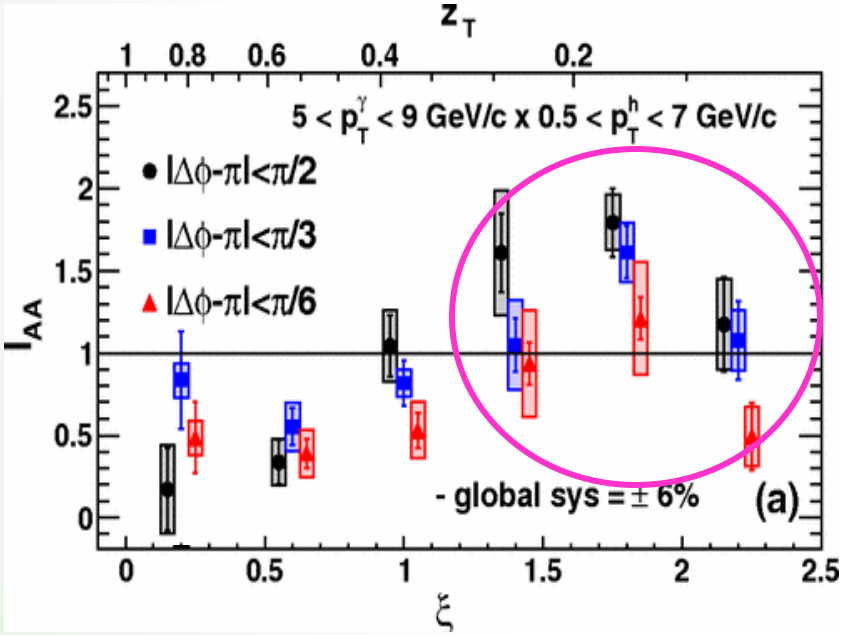


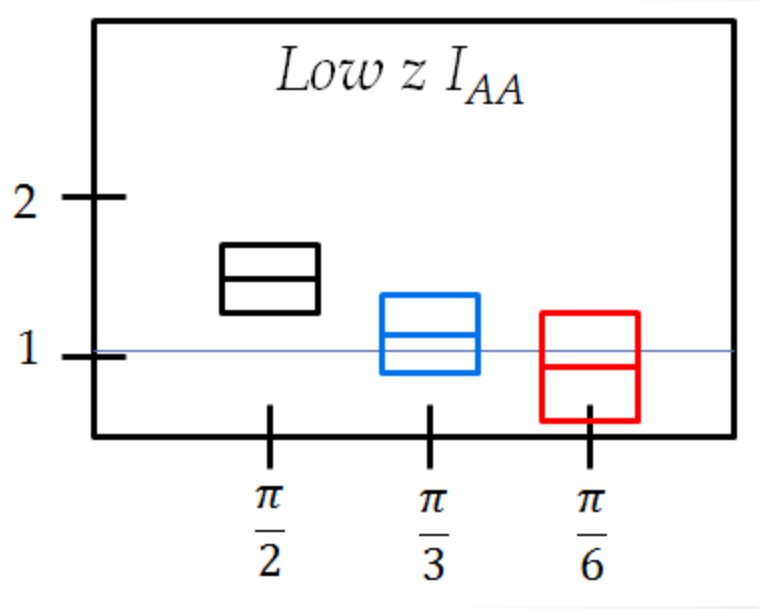


PHENIX
1212.3323
PRL 111, 32301 (2013)

No Significant Enhancement in Small Cones?

- Judging enhancement only by IAA > 1 is misleading
- Must look at size of I_{AA} relative to suppressed jet level.

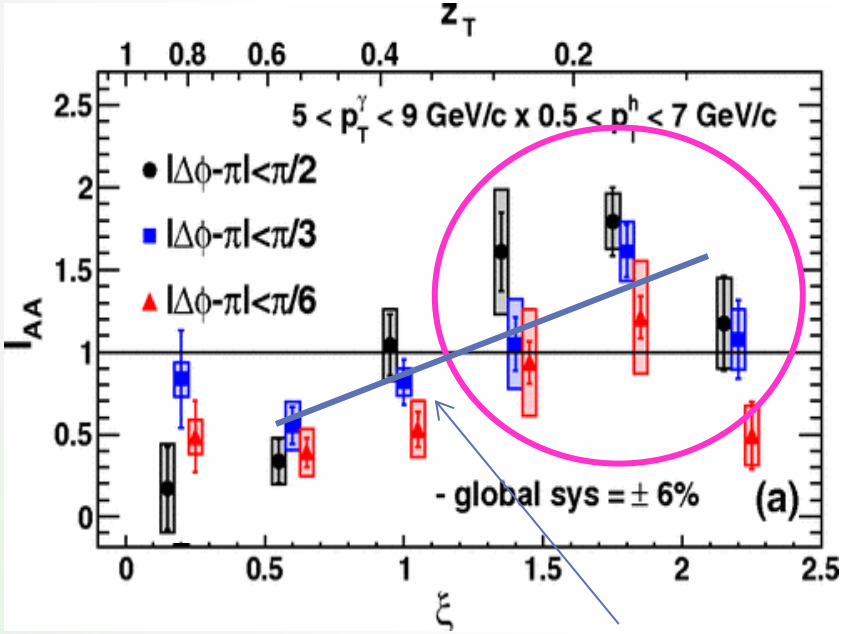


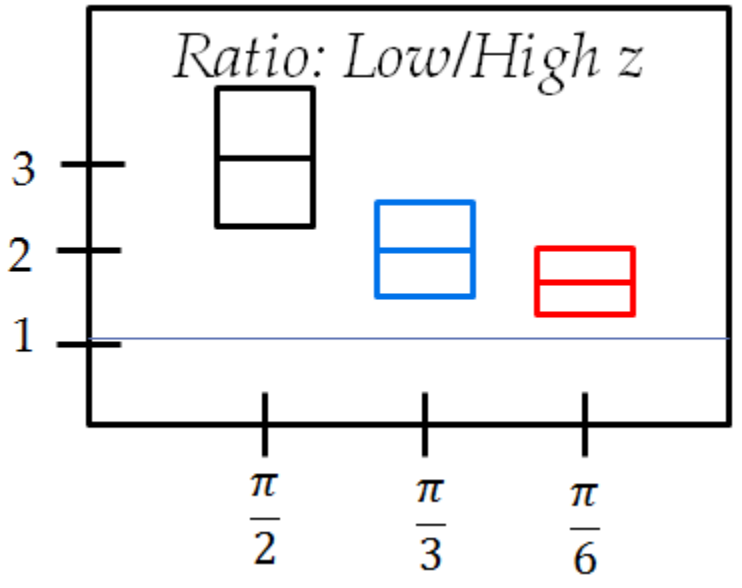


Integration Region (~Cone size)

No Significant Enhancement in Small Cones?

- Judging enhancement only by IAA > 1 is misleading
- Must look at size of I_{AA} relative to suppressed jet level—enhancement→ "energy recovery" in all bins".



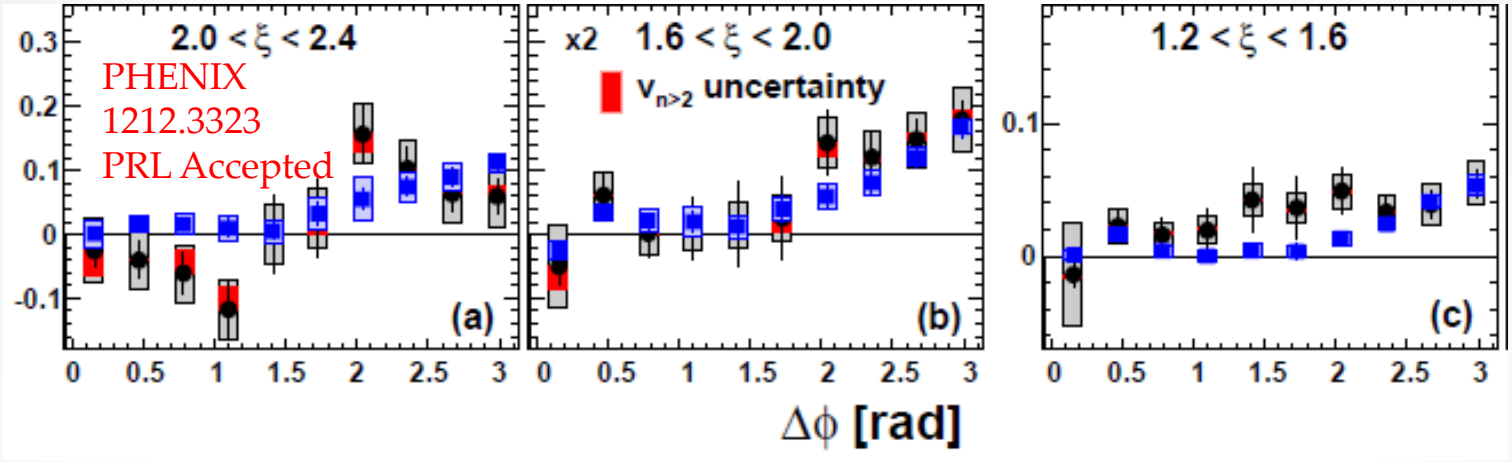


Integration Region (~Cone size)

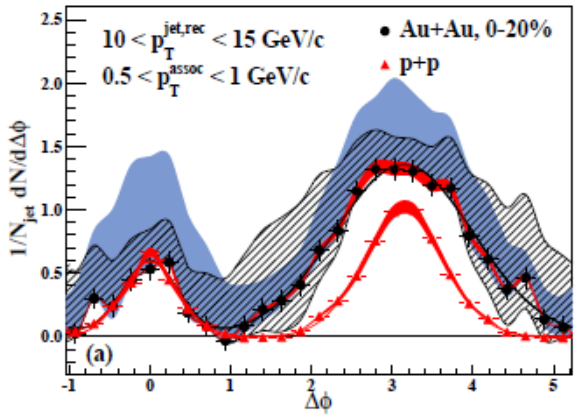
Non-flat shape → significant slope for line fit

Angular distributions

γ-h



Jet –h

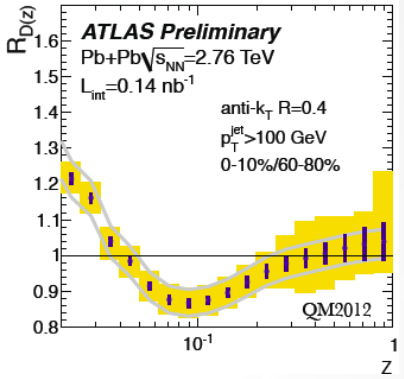


STAR 1302.6184

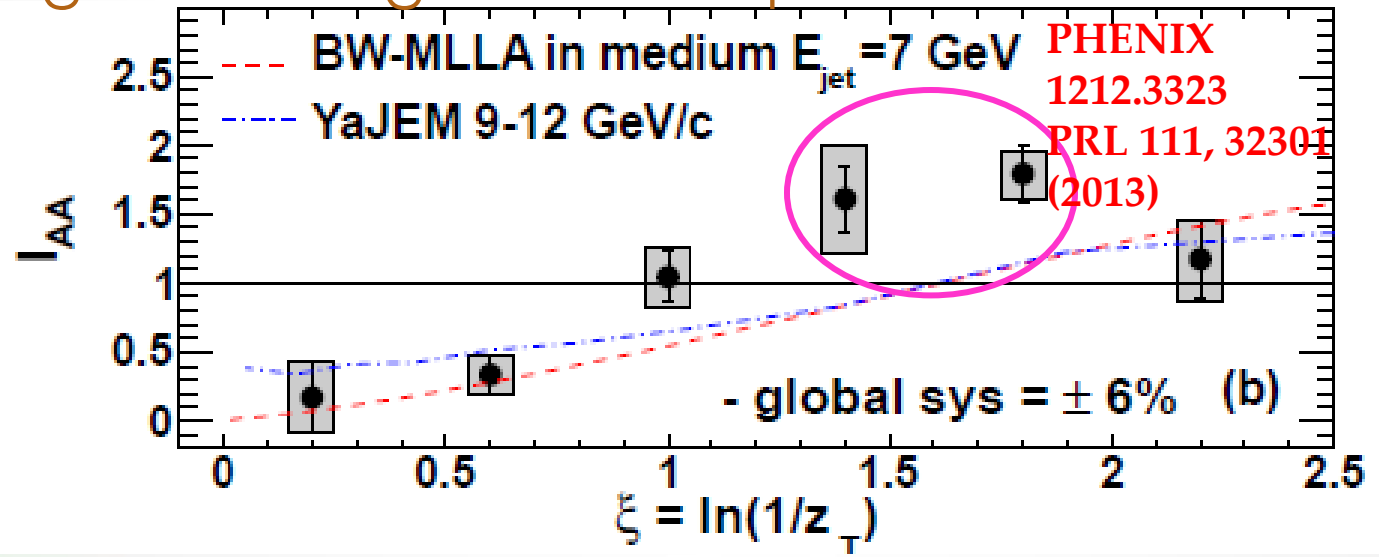
Qualitative Agreement in STAR Jet-h correlations

Also Keep in Mind

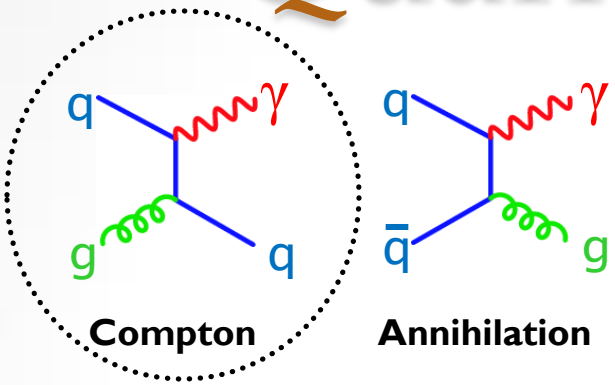
- Results dominated by $\langle p_T \rangle \sim 6$ GeV Jets with an RMS O(2GeV) due to k_T
  - < 2 X Lower Than STAR Jet-*h*
  - << than LHC Results



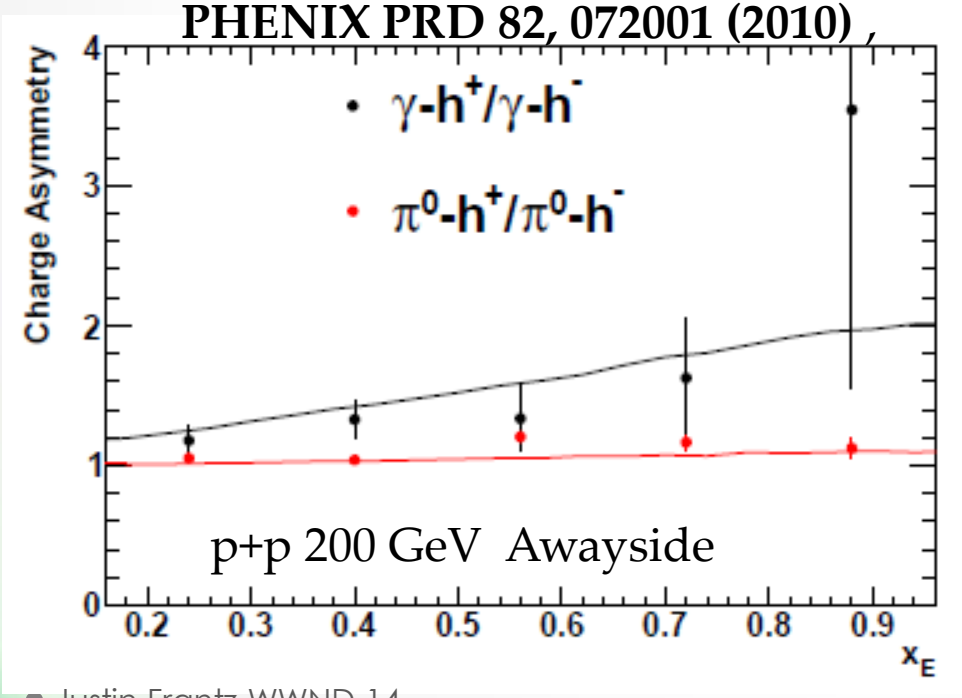
- No Isolation Cut applied: other photons sources: e.g. more fragmentation photons



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



PHENIX PRD 82, 072001 (2010) ,

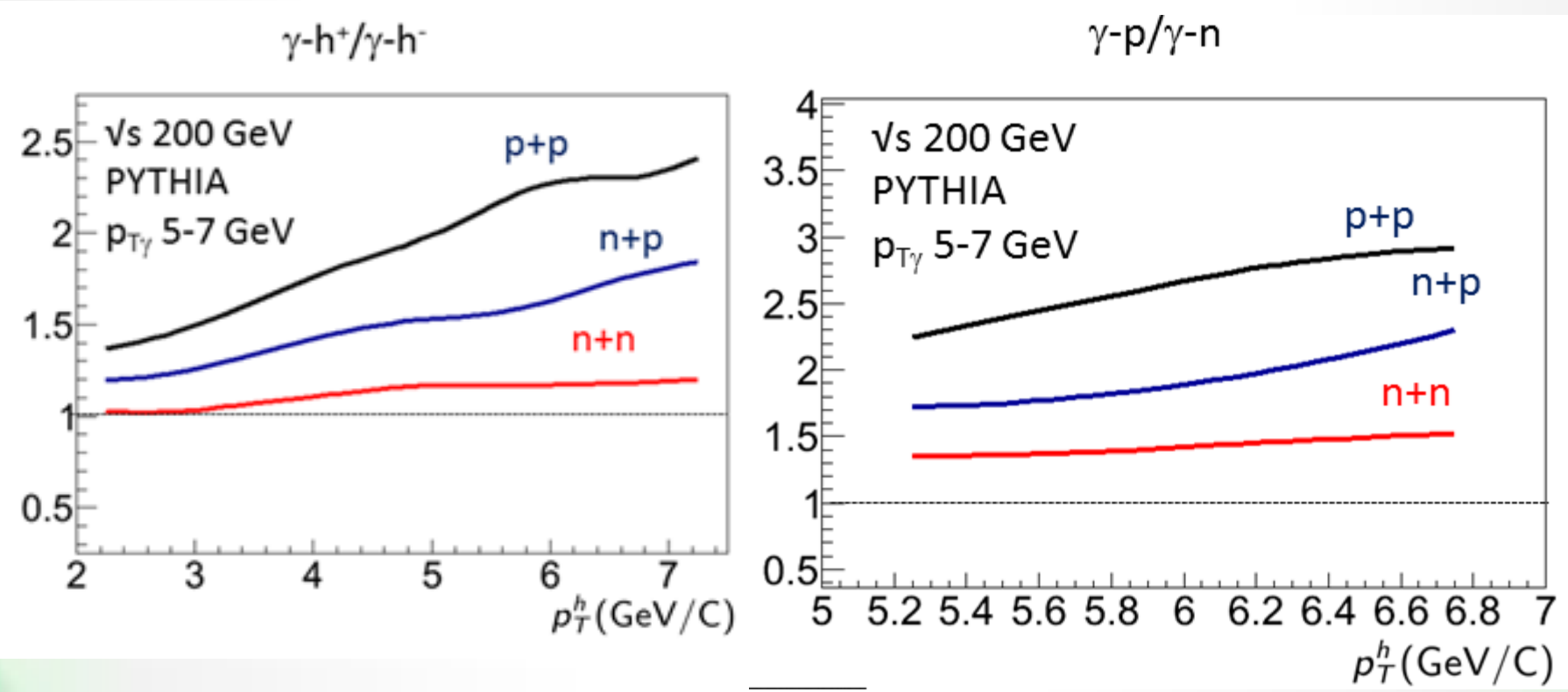


- In γ-h Compton scattering means **quark jet tag**
- Charge asymmetry of cross section and valence *u vs d* quark should be reflect in final state charged hadrons:
- **Start asking what's the composition of the enhancment!**

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

Charge Asymmetry

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



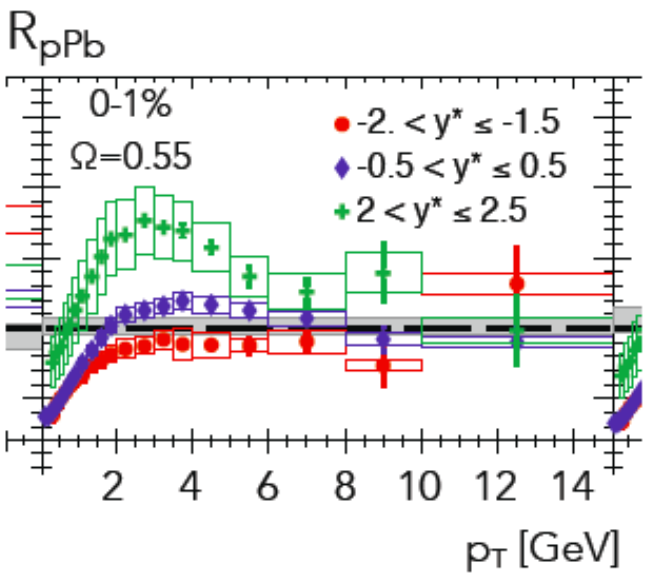
- How do these go together (d+A → p+A)?

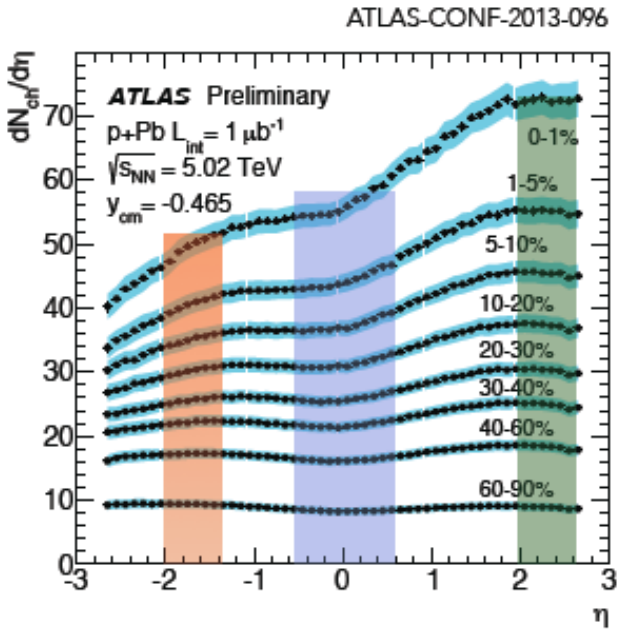
p+Pb/d+Au

- Baseline: "Cold" Nuclear Effects? Hot Medium?

P. Steinberg Hard Probes '13

Connection to multiplicity?

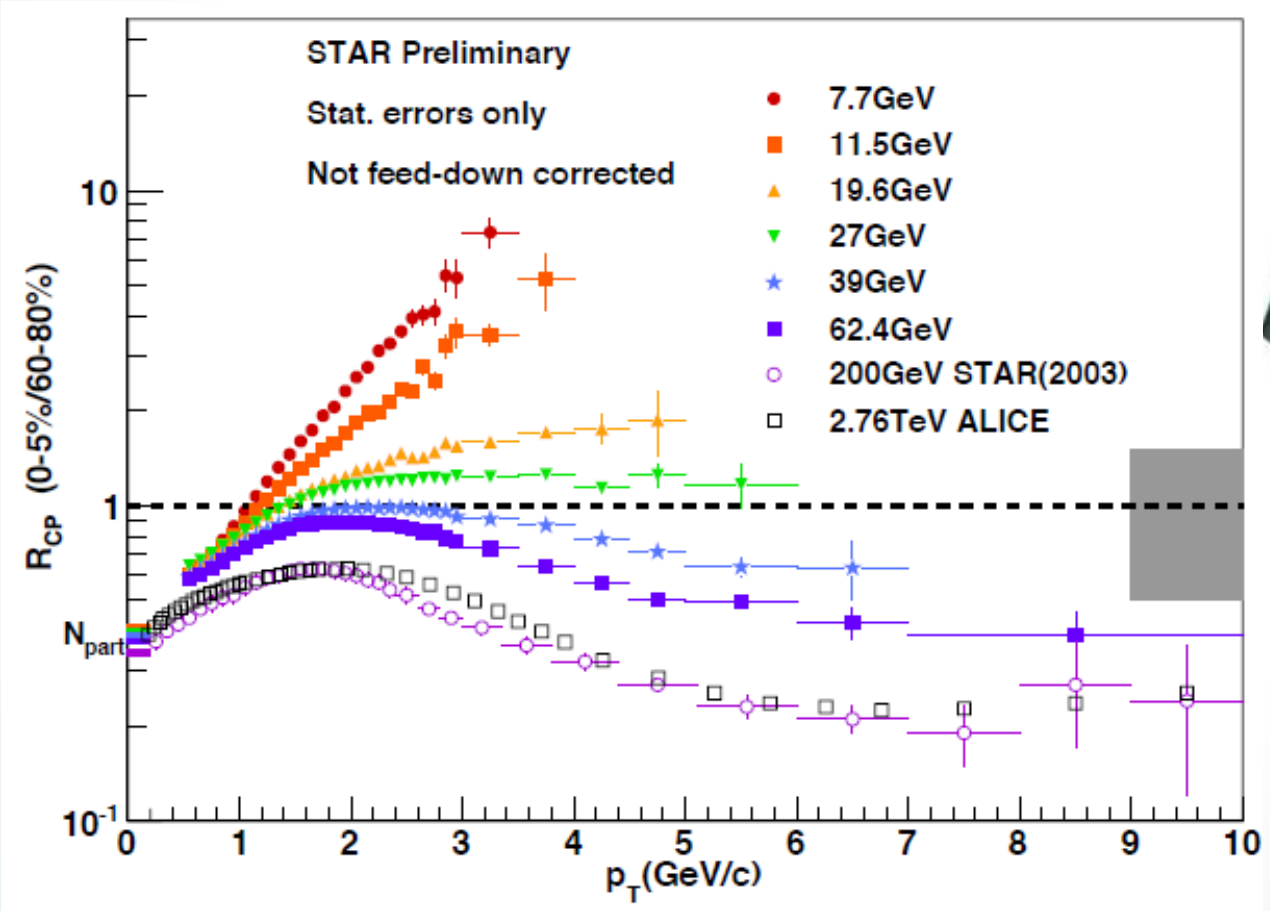




Observe correlation between multiplicity and magnitude of "Cronin" peak relative to constant region

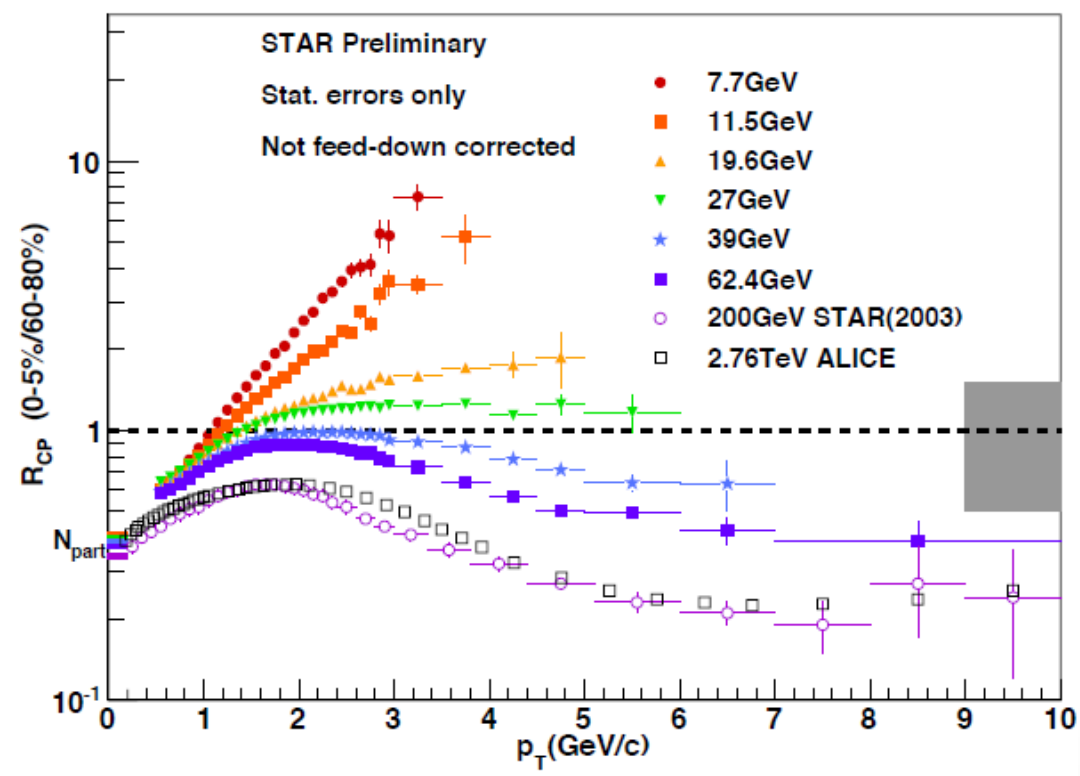
New Results Exploiting RHIC's Flexibility in s

- Another T-shirt Plot?



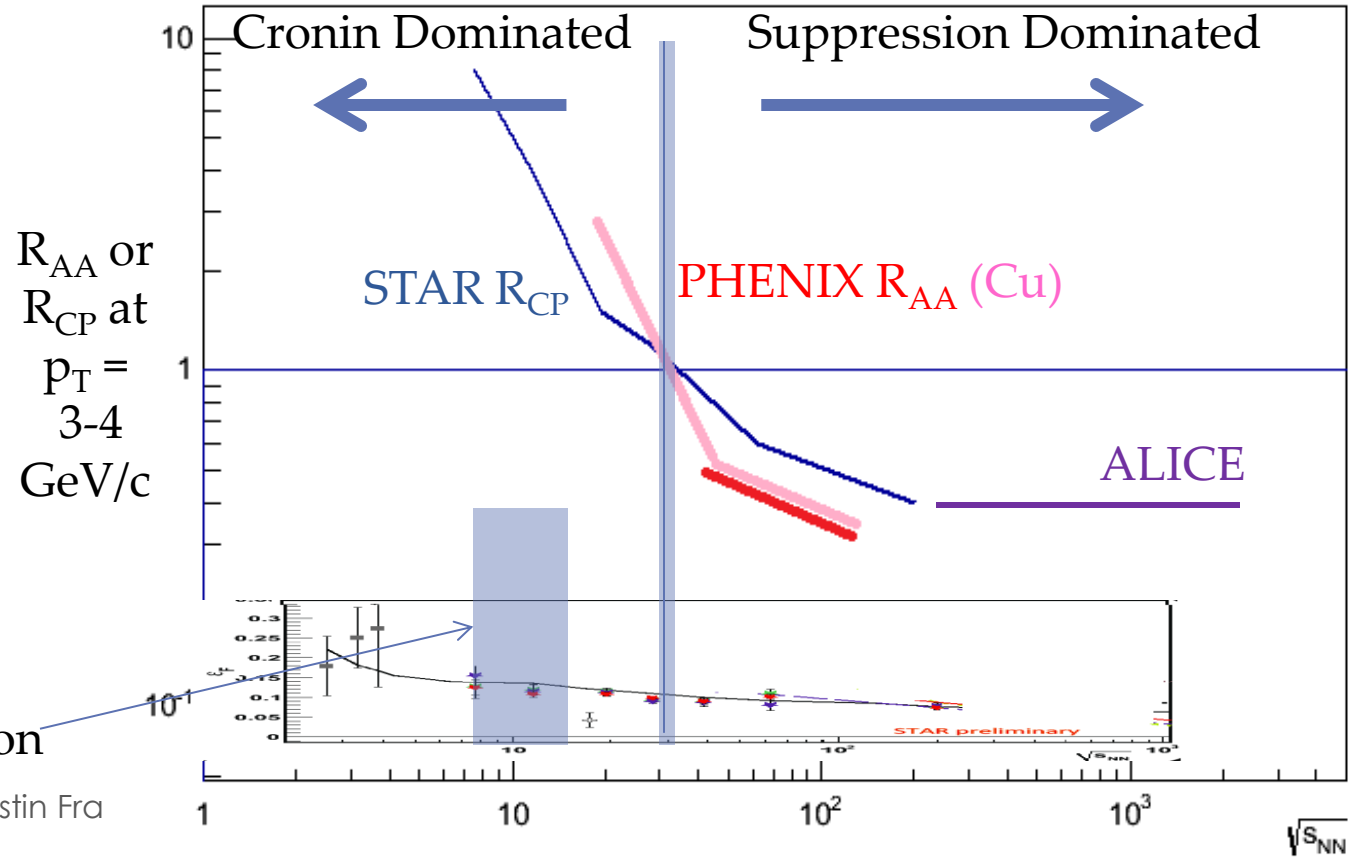
Understanding Cronin?

- Presumably there is still quenching below ~30 GeV
- Cronin Effect blows up at low $\sqrt{s}$ → (k_T ($\sqrt{s}$))
- What would a collective explanation for Cronin say about this data



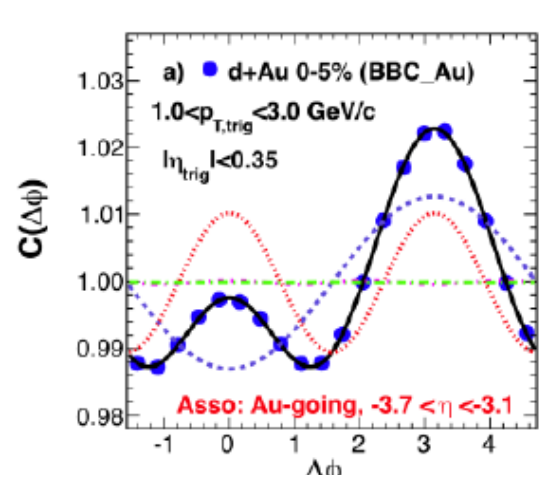
High p_T pp/pA Energy "Scan"?

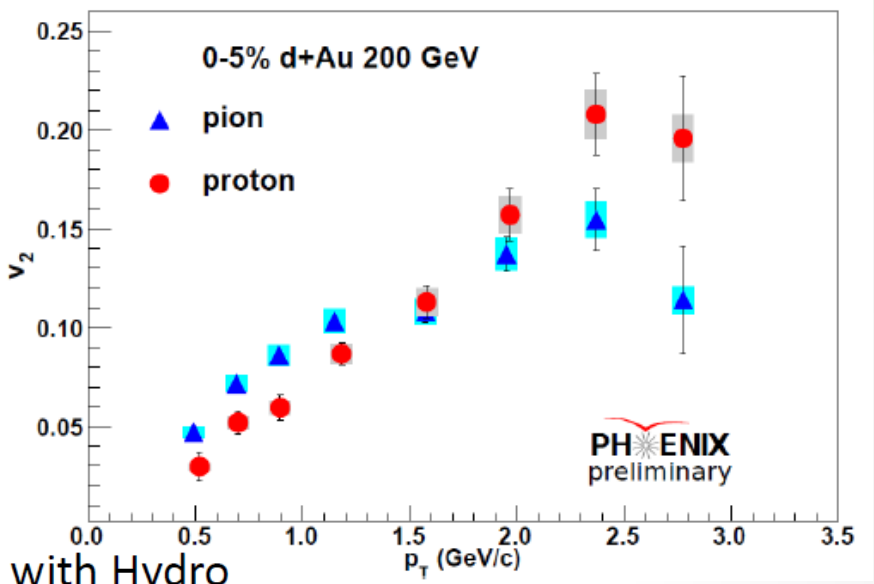
- Short term "Scan" ?: Get p+p and p+A ~one point above and below ~ 30 GeV ?
- Longer term sPHENIX can contribute with full Jet studies → a key observable?



Collective Effects in dAu

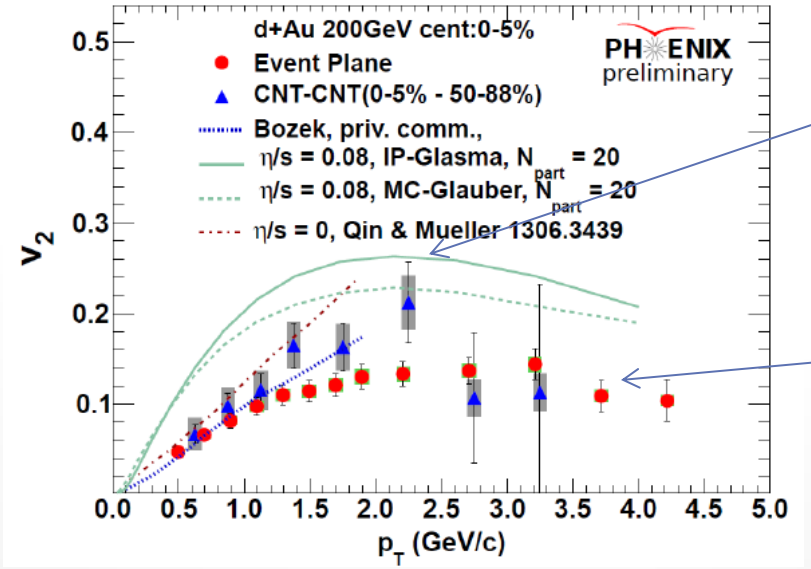
- **The latest:** long range ridge and mass ordering also seen at RHIC/PHENIX





Comparing with Hydro

v_2 factor of ~1.5-2 smaller in long range

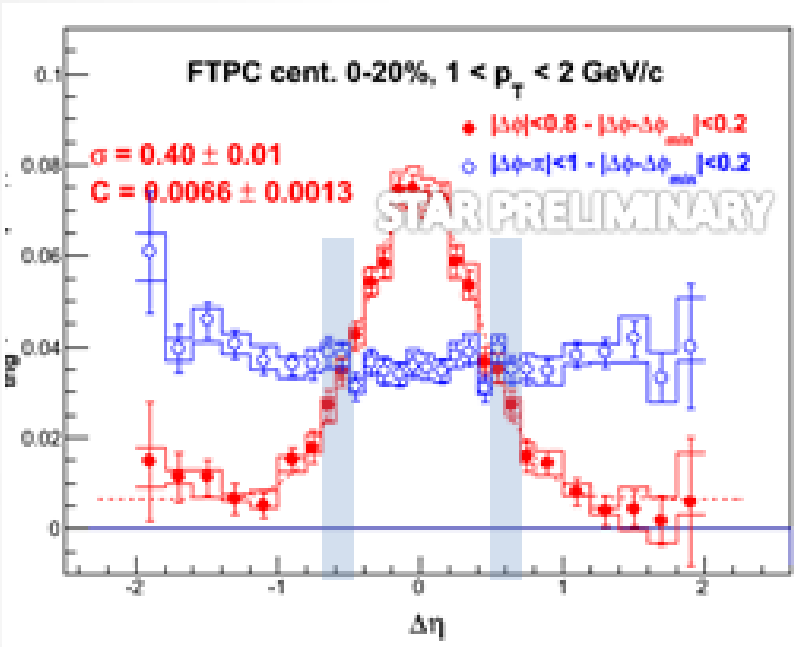


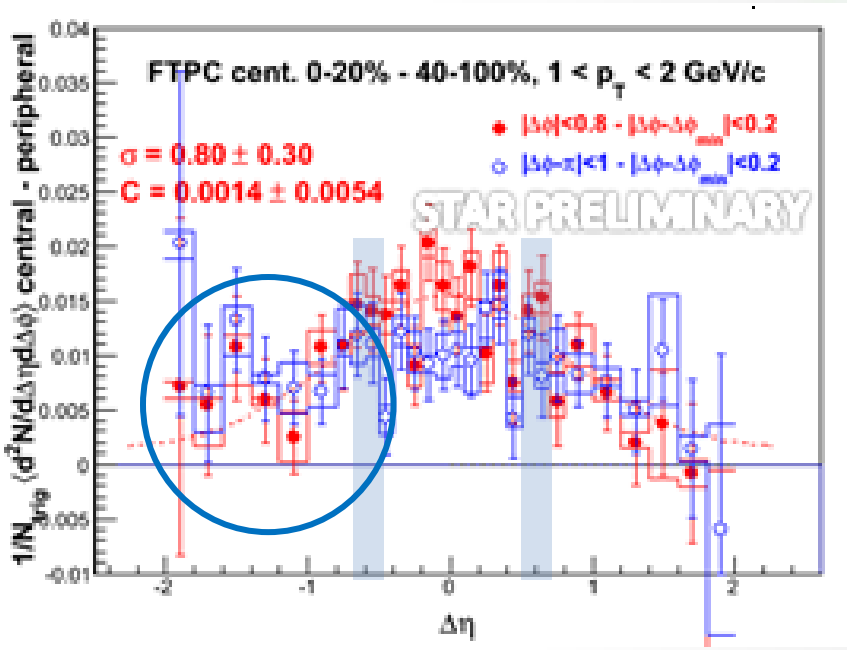
Last year's Central-Central

New Fwd-Central

Collective Effects in dAu

- STAR Disagreement?





STAR results quite consistent w/ PHENIX decrease of v_2 :/ridge
2 interesting possiblilities implied:

Collective effects bigger at different absolute eta (STAR result has some averaging.
-Somehow related to the jet, since it looks like a broadened jet

How about E_{loss} in d+Au?

- Rewind Circa ~2005

PHENIX Phys. Rev. C 73, 054903 (2006) ,

Jet Structure from Dihadron Correlations in d+Au collisions at $\sqrt{s_{NN}}$=200 GeV

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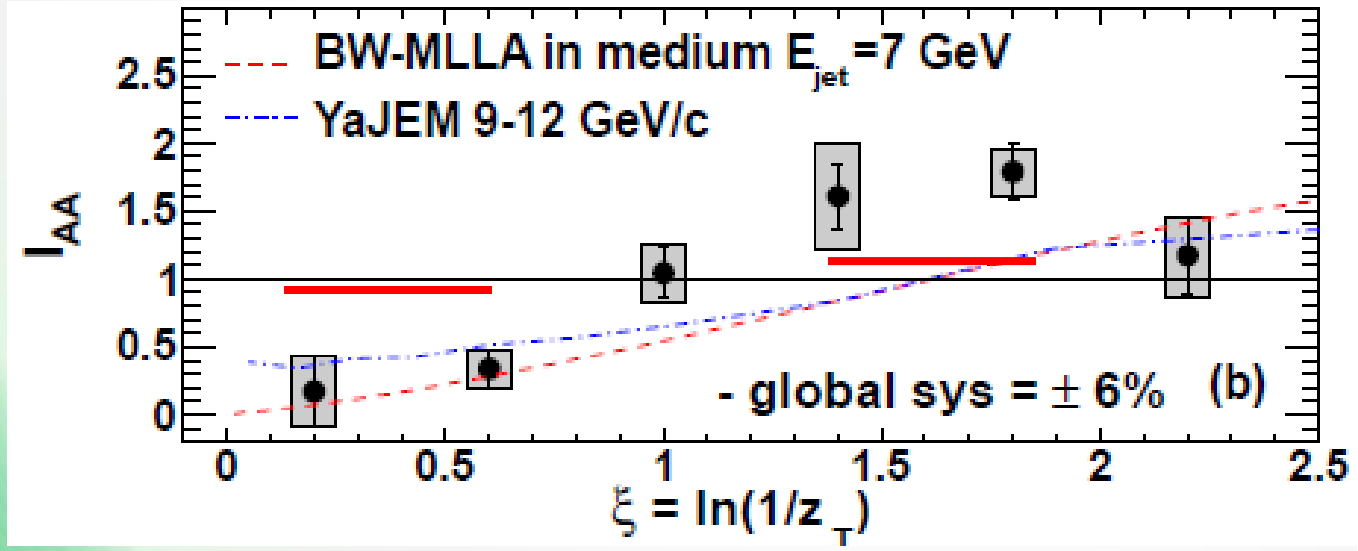
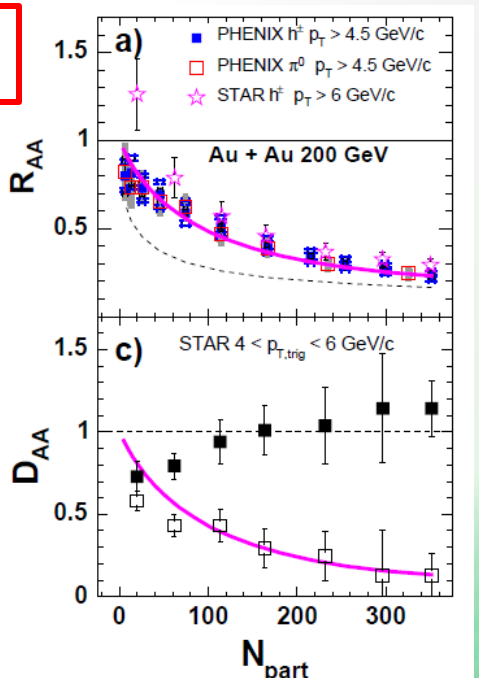
How small should E_{loss} in pA be?

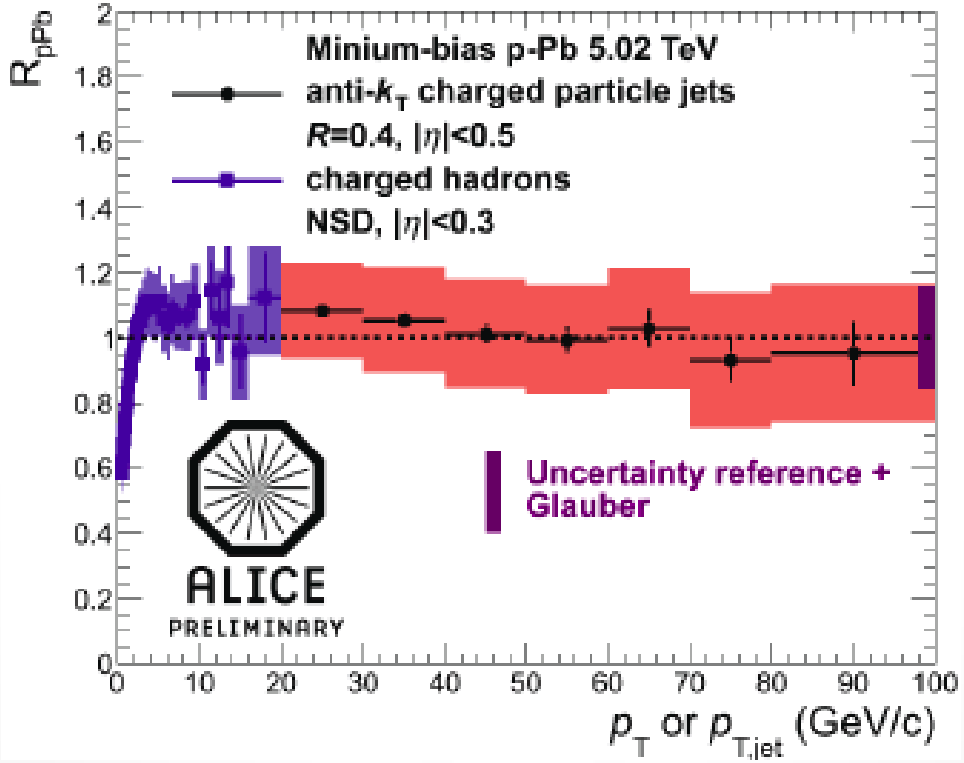
- Very small:
- Simple best-case (upper bound) emprical estimate: assume ***suppression and enhancement*** scale with ~ L $N_{part}^{1/3}$
- Suppression= 1- $N_{part}^{1/3}/350^{1/3}$ * R_{AA} (high pt jet) = 0.4
- Enhancement: 1+ $N_{part}^{1/3}/350^{1/3}$ * $D_{\gamma-h}^{excess}$ (low z) = 0.5
- In Central d+Au: **Supp = 0.9 Enh = 1.1**





Precision Limits to these small effects: singles

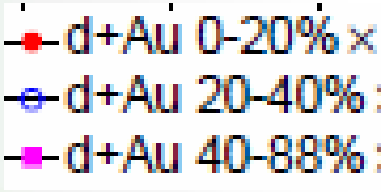
- Single particle RpA / RdA suffer from Ncoll systematics

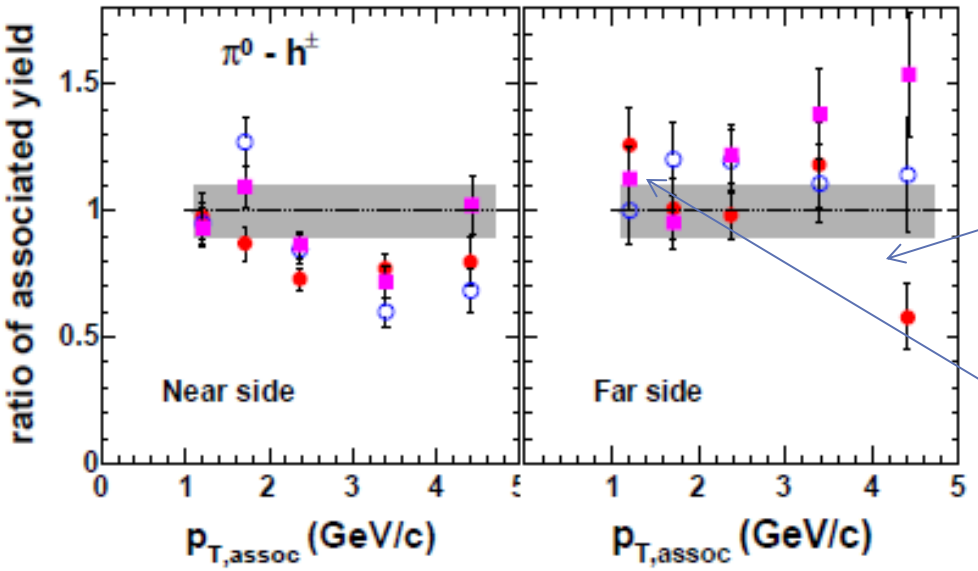


Precision Limitations to these small effects 2-p

- Direct Photon Statistics/Systematics Limit for d+Au
- Di-Hadron have better statistics/systematic control: 5-10 GeV/c trigger → Lowest Jet Energies looked at: (much lower than LHC`

$I_{AA} \equiv I_{dAu}$





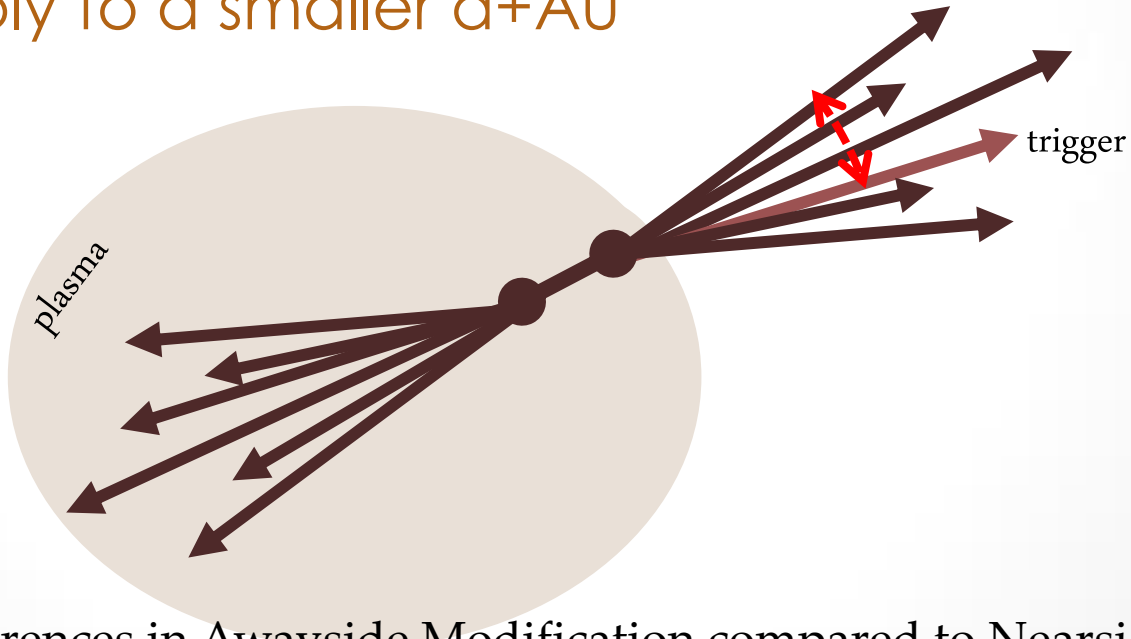
suppression?

enhancement?

- But efficiencies limit:
- Need to find observable
- A plus: collective effects smaller in dAu

A Nice Observable for Exploring E_{loss} ?small systems?

- Assume well-known surface bias picture for Au+Au should apply to a smaller d+Au

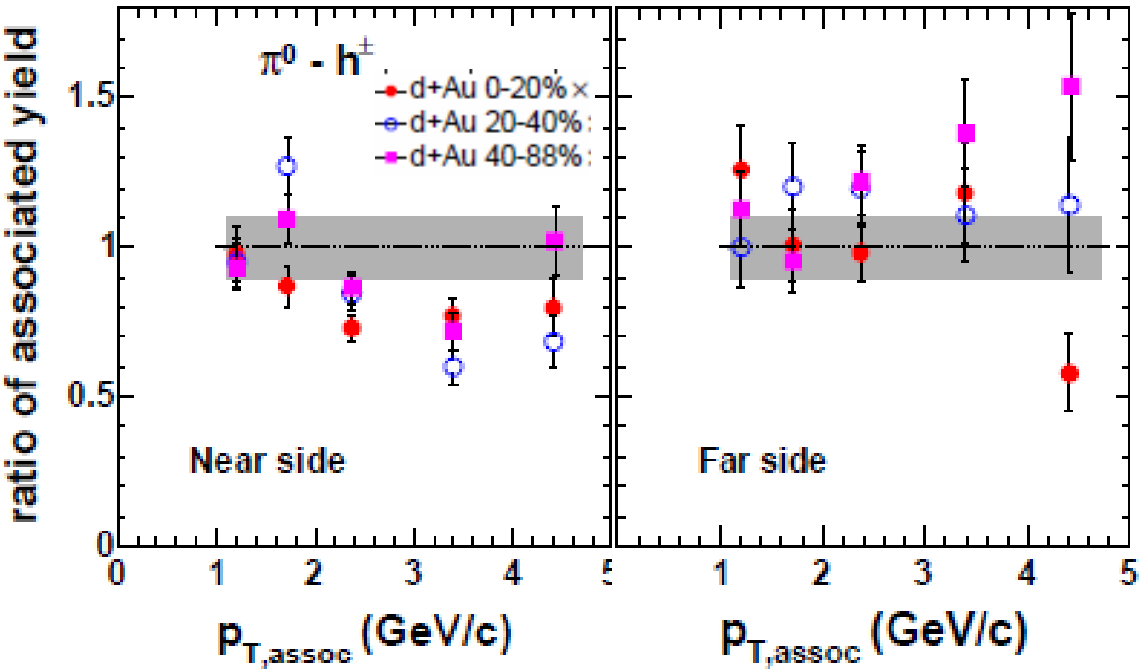


Look for Differences in Awayside Modification compared to Nearside
Some class of initial state nPDF effects won't show up to first order?
CGC?

Awayside/Nearside Ratio RI_{AN}

- Taking the ratio of nearside to awayside cancels efficiency systematics

I_{dAu}



$$RI_{NA} = \frac{AS_{dAu}/NS_{dAu}}{AS_{p+p} / NS_{p+p}} = \frac{I_{dAu\ Away}}{I_{dAu\ Near}}$$

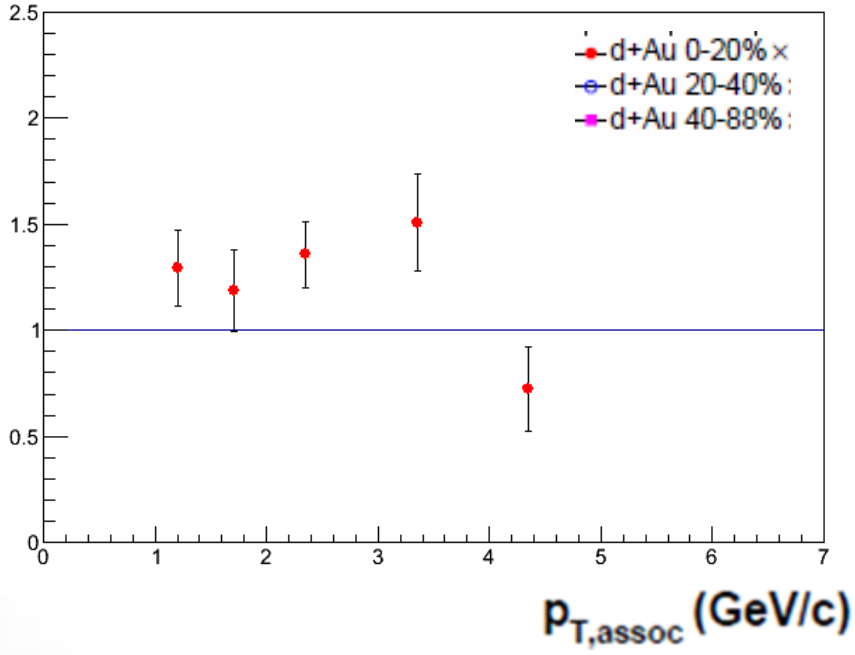
- Choosing Full pi/2 range cancels v_{2k} contributions!
- Only left with v_{odd}: v_3 small in d+Au

Awayside/Nearside Ratio

- Taking the ratio of nearside to awayside cancels efficiency systematics

Slope of fit line like for direct photon-h FF fit.

PHENIX PRL Data **C 73, 054903**



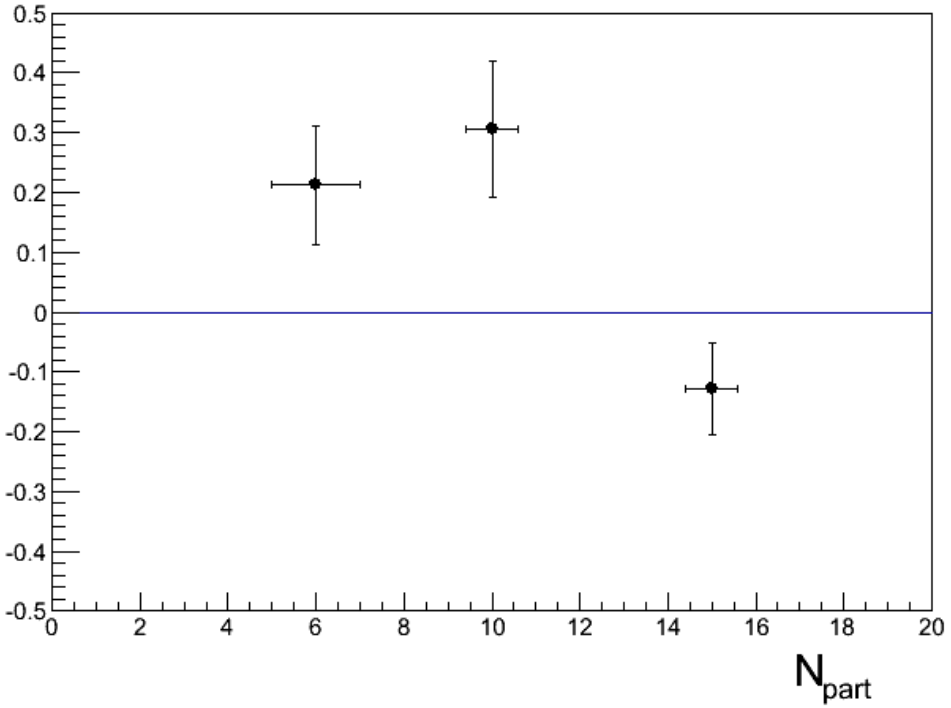
$$\frac{AS_{dAu} / NS_{dAu}}{AS_{p+p} / NS_{p+p}} = \frac{I_{dAu\ Away}}{I_{dAu\ Near}}$$

- Choosing Full pi/2 range cancels v_{2n} contributions!
- Only left with vodd: v_3 small in d+Au

RI_{AN} Slope Centrality Dependence

- Slope Change in most central?

Slope of RI_{AN}



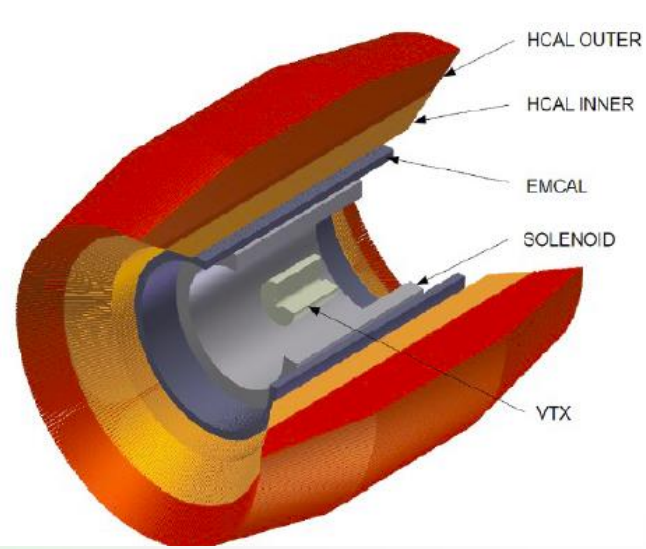
- Limited only by statistics?: this is Run3! (Stay tuned for Run8!)

Conclusions

- 2-p particle correlations results still ongoing and needed to fill out the whole picture of jet modification
- In A+A (now p+A?) it's a challenging time to isolate jet contributions.
- But by choosing clever techniques we should be able to contribute to the overall picture.

sPHENIX

- Upgrade optimized around jet/di-jet/photon/HF measurements
- **Compact**, High rate, large **uniform** acceptance over $|\eta| < 1$
- Submitted by BNL to DOE for MIE CD-0 review in ~Feb
- Opportunity for detector building experience:
- Prototyping is already underway! Join us!



Inner Radius 70 cm
B = 2 T

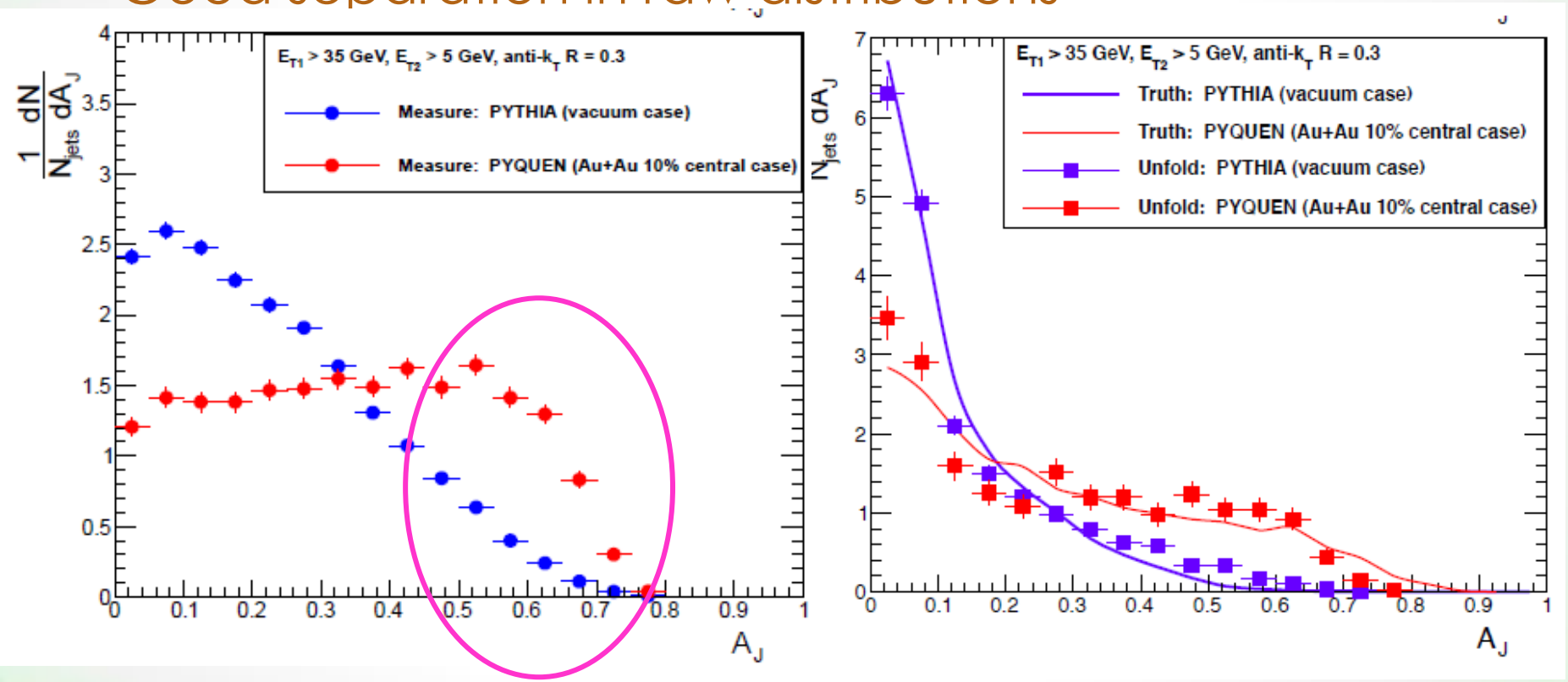
Fe-Scint Hcal Unique Design

Prototyping underway
(Previous Design Beam Tested Dec 2012) OHIO UNIVERSITY

W-Sc EMCal – Accordion Design

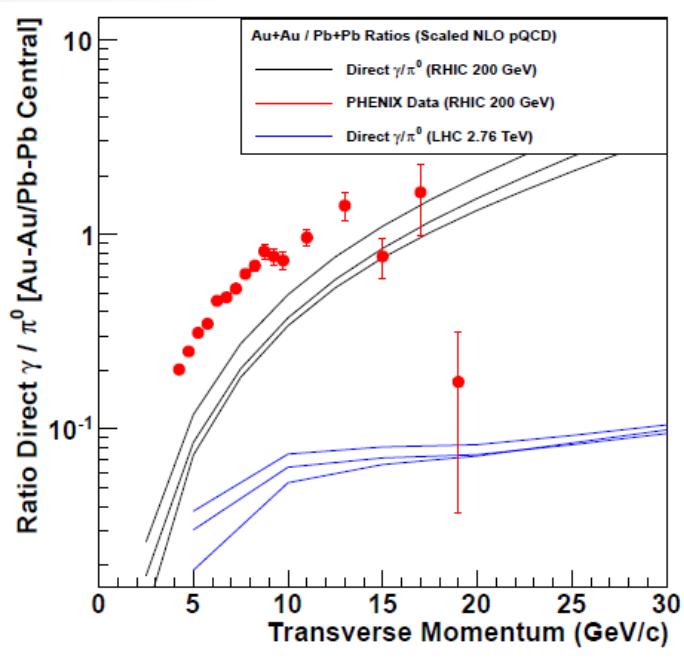
Event By Event Opportunities

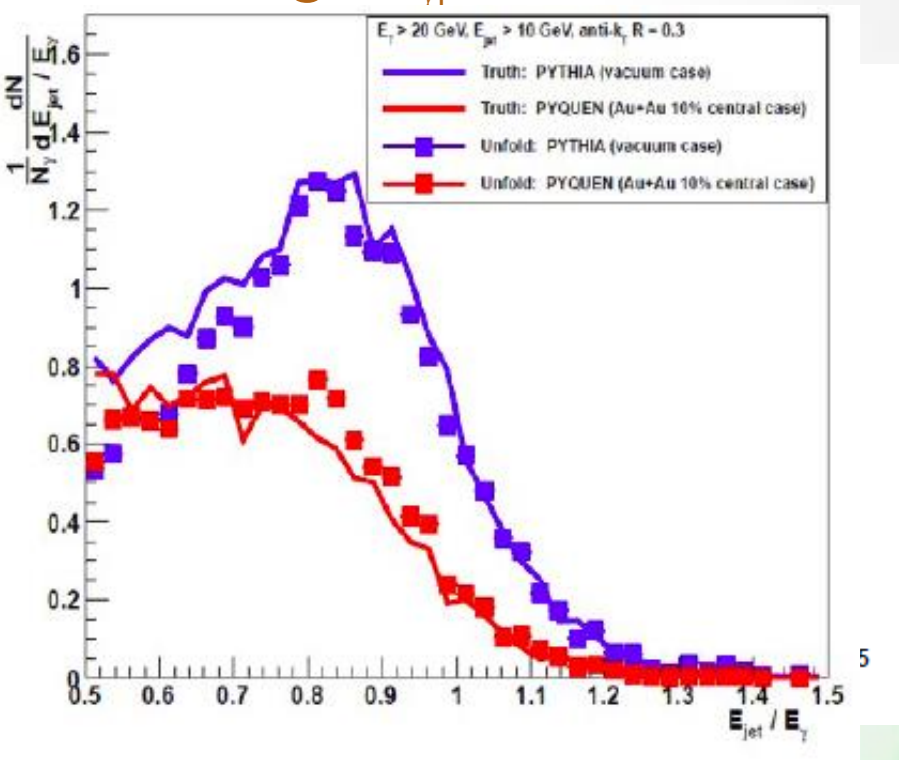
- Dijet A_J : 0-10 % HIJING Embedding—Unfolding procedure works well
- Good separation in raw distributions



γ-Jet in SPHENIX

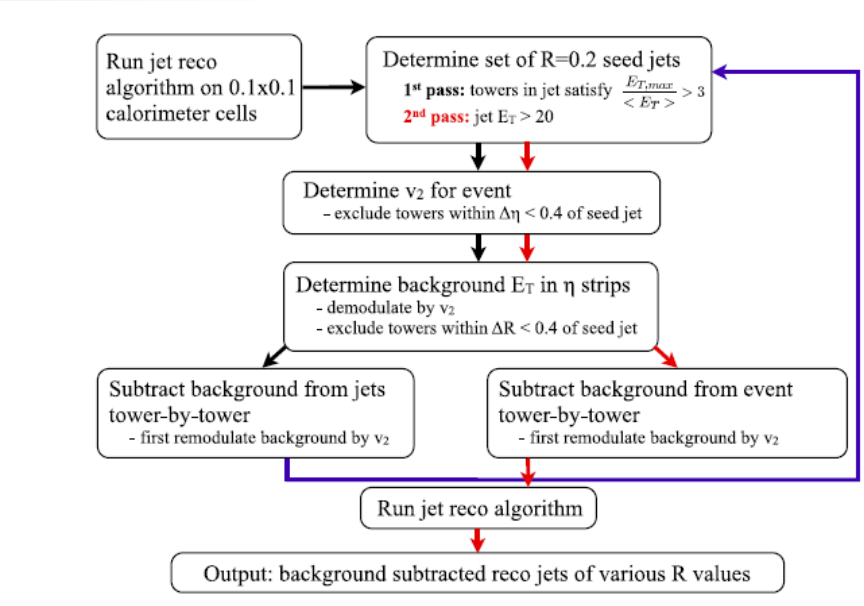
- Access high stats…
- Clear Modification signal, comparable to current LHC Results
- Separation in raw distributions at large $x_{\gamma i}$



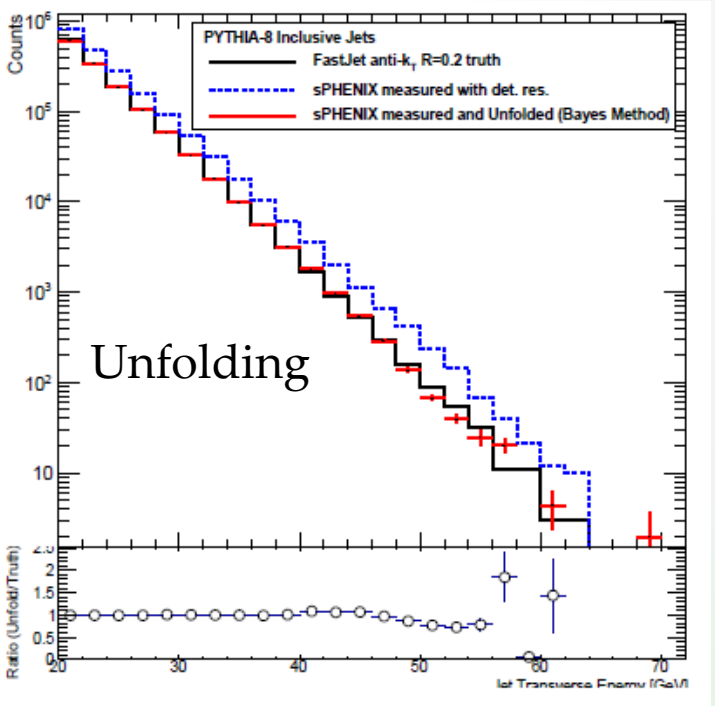


sPHENIX MIE Proposal

- CD-0 DOE MIE Proposal: 60/120 pages: Generic RHIC 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

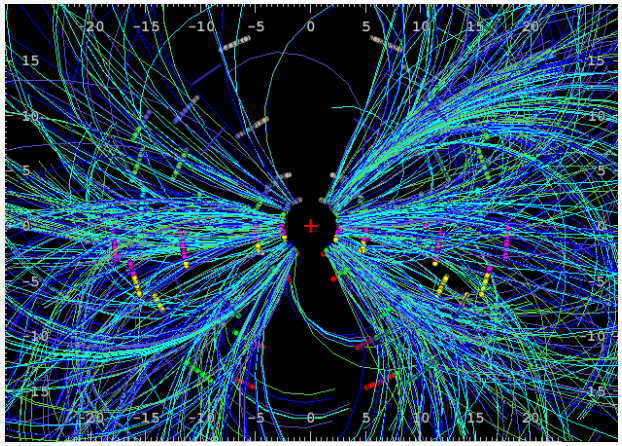


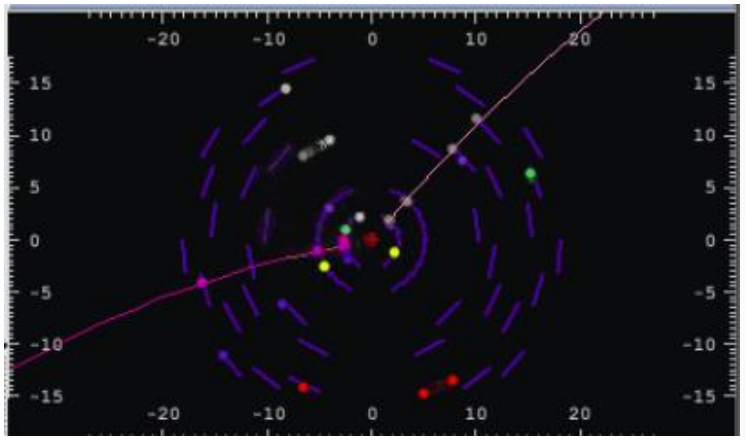
PHENIX Silicon Vertexing

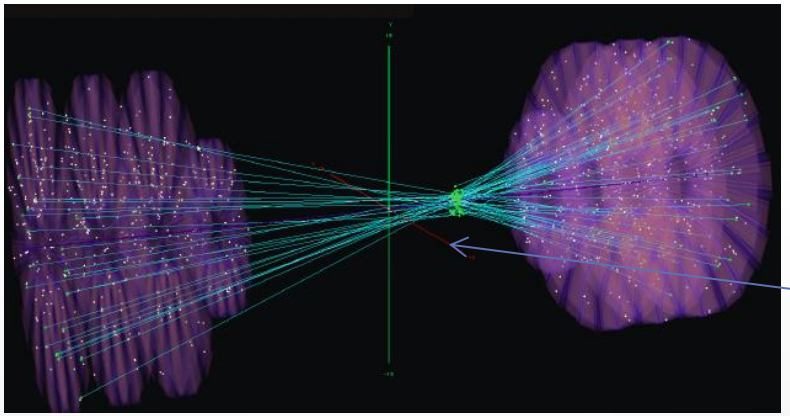
- VTX dataset in Au+Au 2011 and 2012 p+p
- FVTX Commisioning 2012 , Data taking 2013
- R_{AA} v_2 of *c*, *b* separately

Data: Au+Au@200 GeV, 2011

2012 p+p @ 200 dataset!





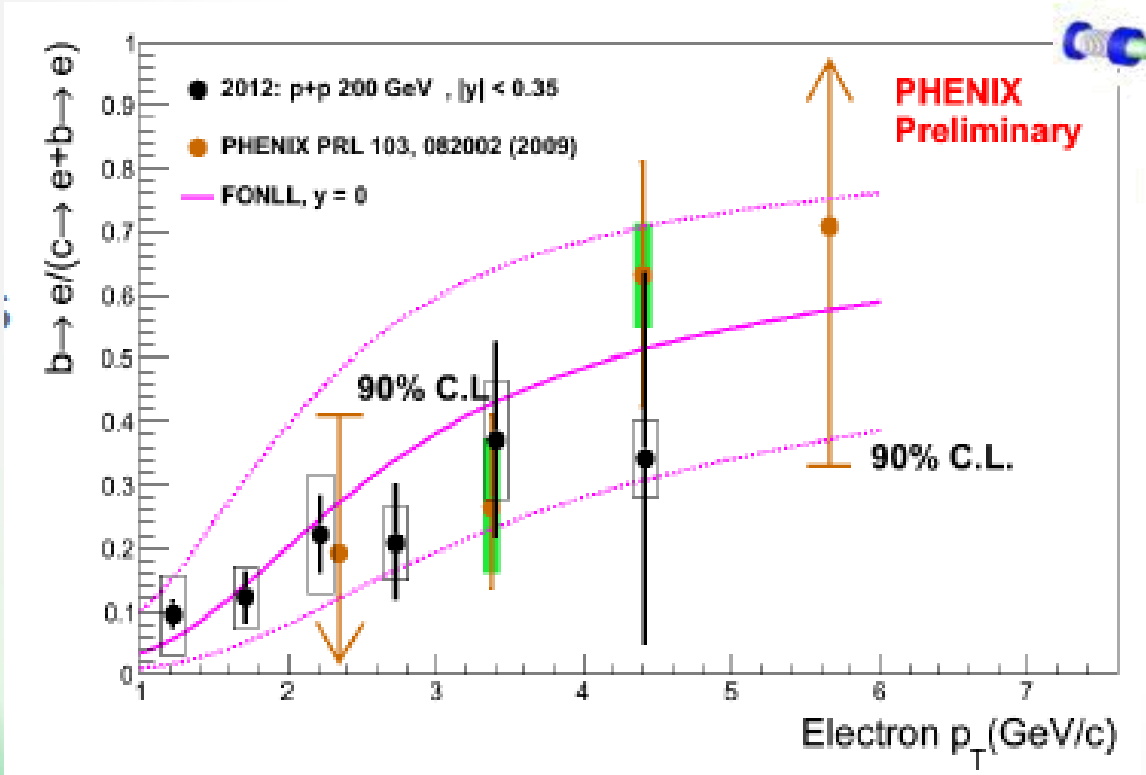


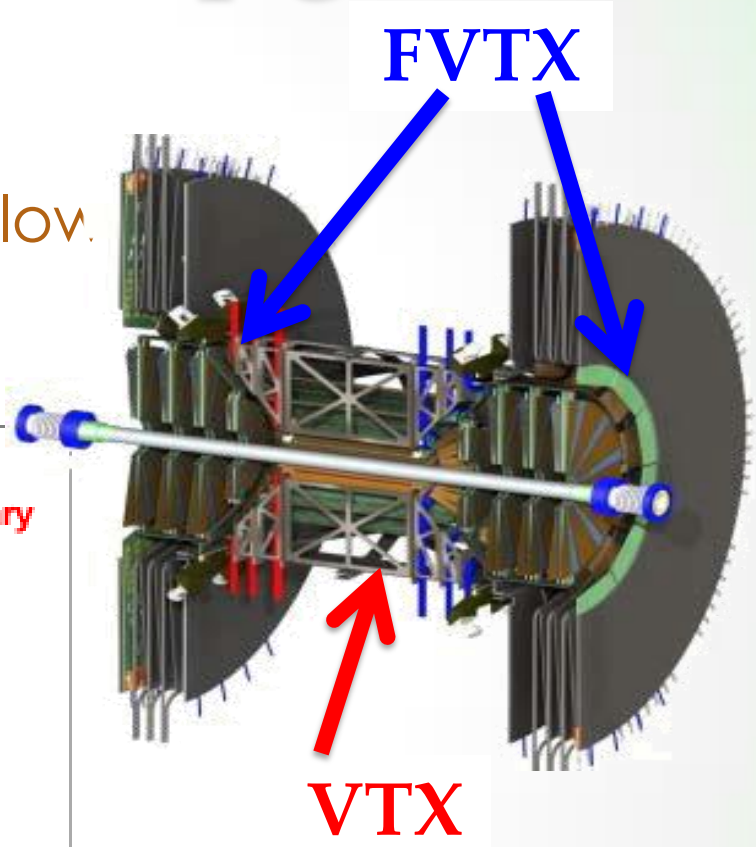
Detector commissioning /p+p reference went well

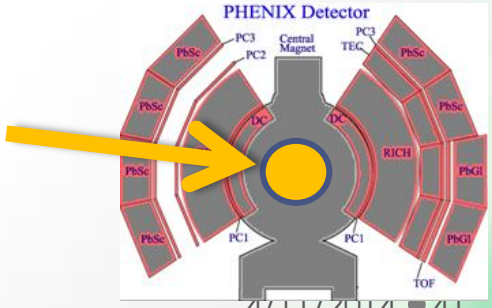
FVTX

PHENIX VTX Upgrade

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

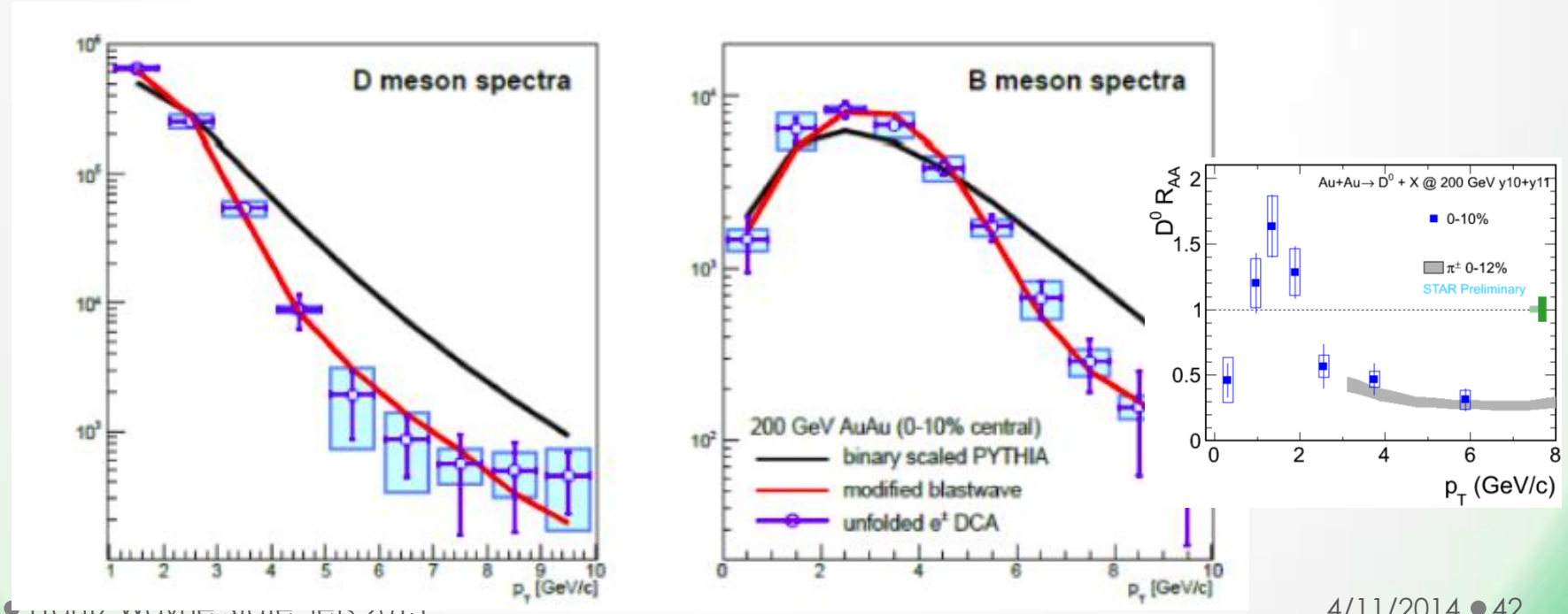






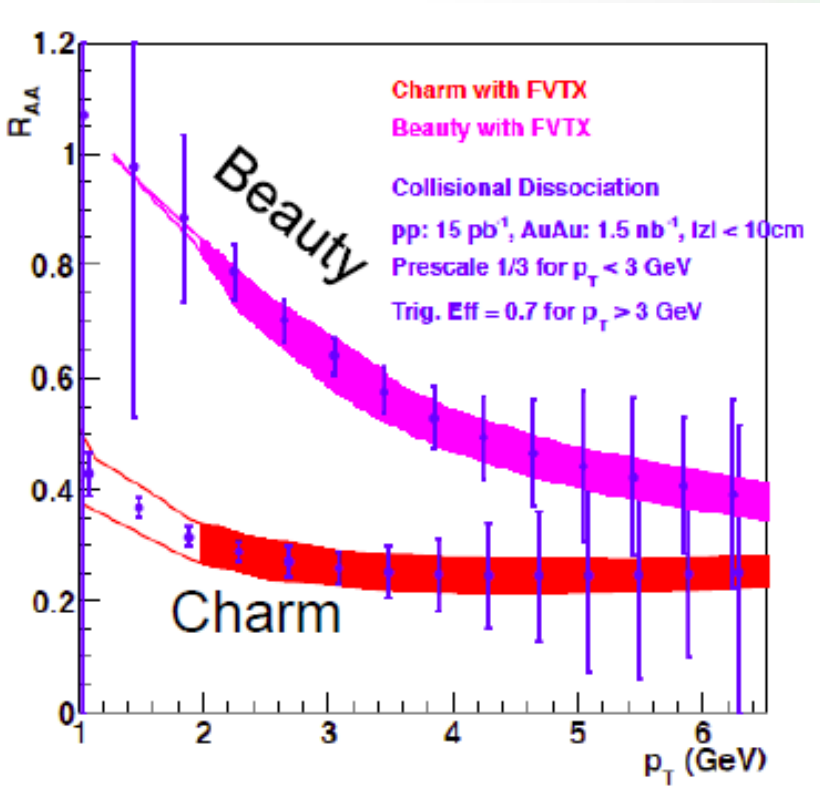
PHENIX VTX

- 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

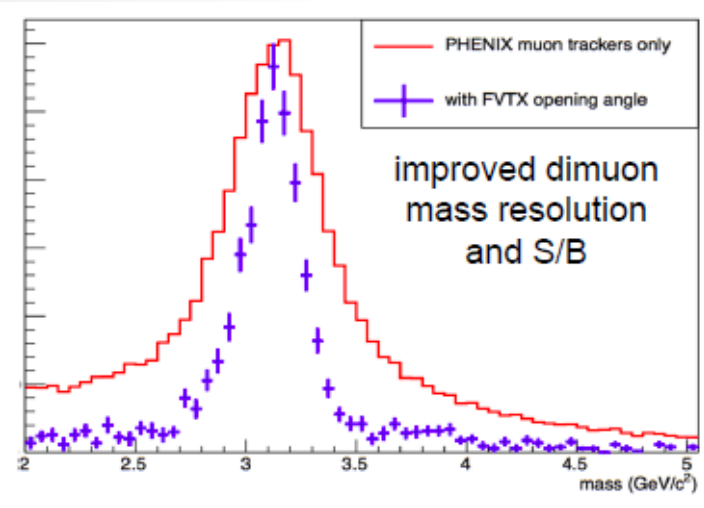
- FVTX provides *c*/*b* separation for forward/bkwd Muon arms
- HF Single and Di-muons / Drell-Yan
- FVTX commissioning run in Run-12 > 96% live active area
- Displaced vertex results for open heavy flavor from Run-12 Cu+Au expected soon



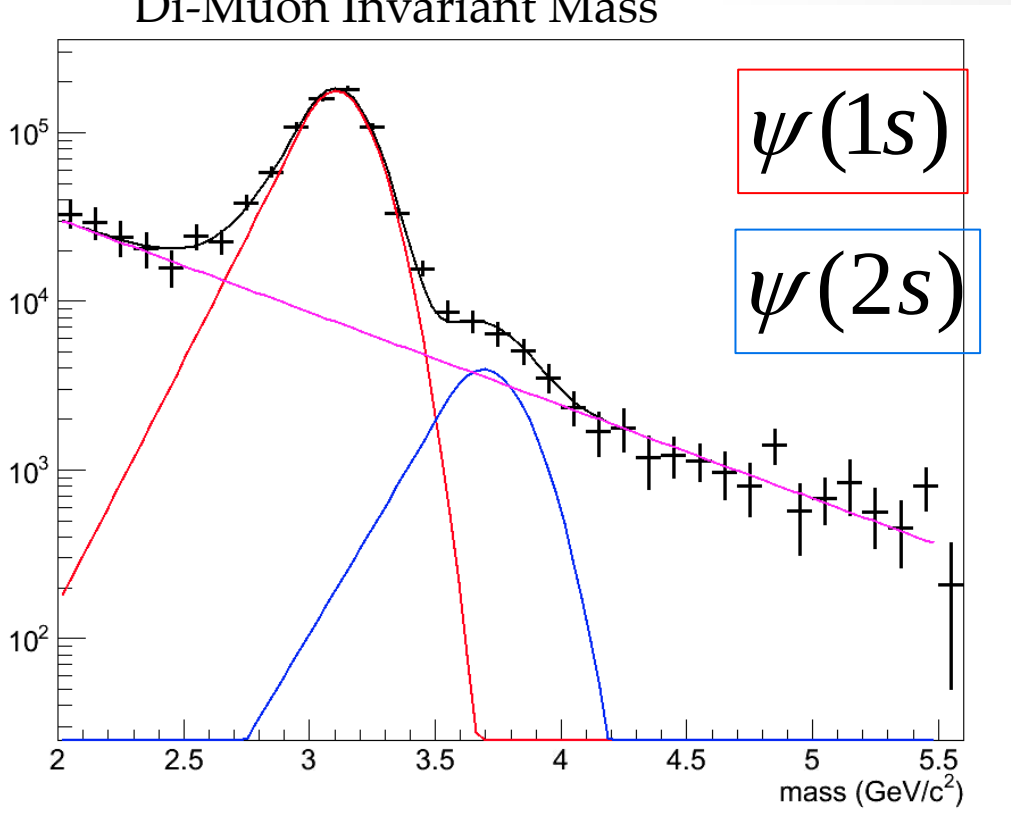
FVTX Di-muons Run-13

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

Di-Muon Invariant Mass



Di-Muon Invariant Mass

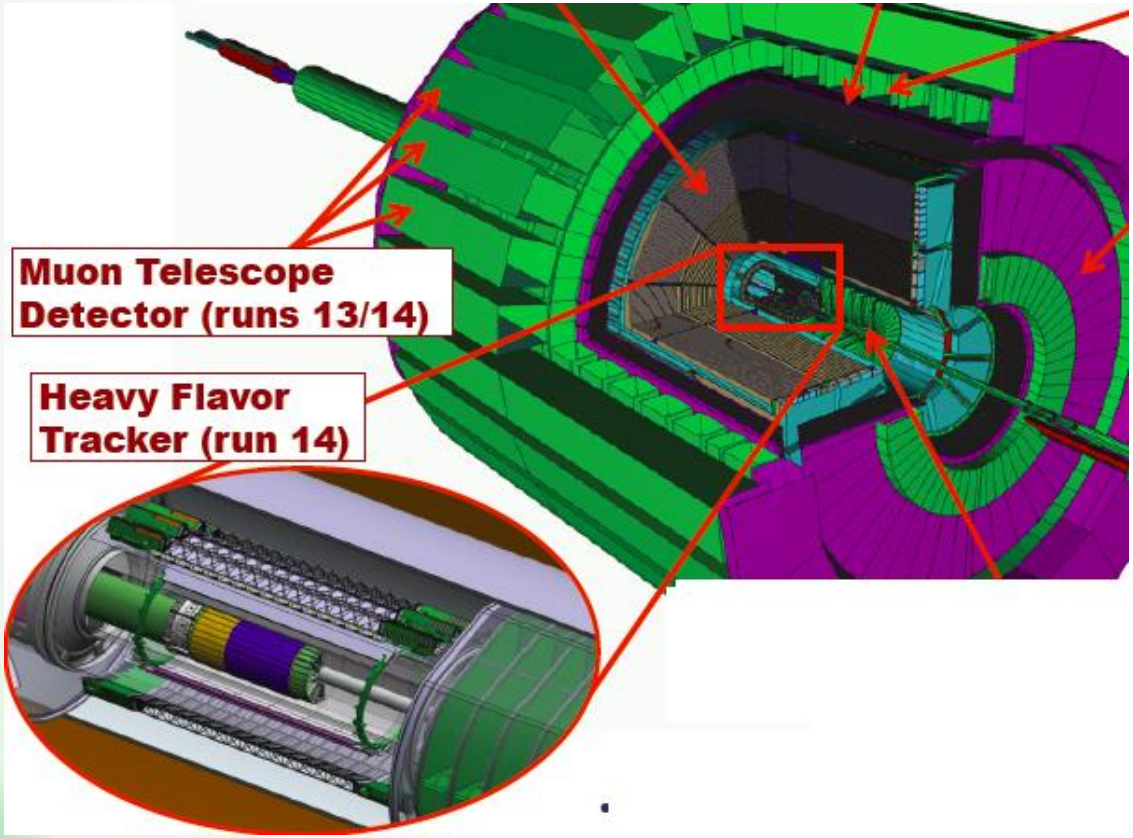


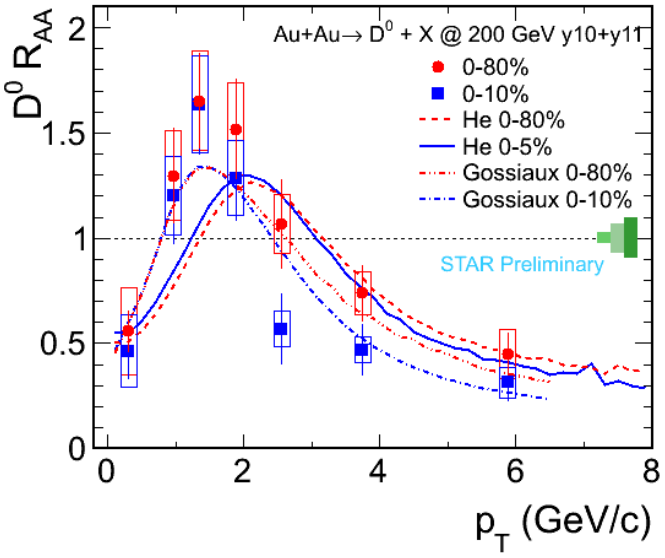
FVTX working great!

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

STAR HF Upgrades

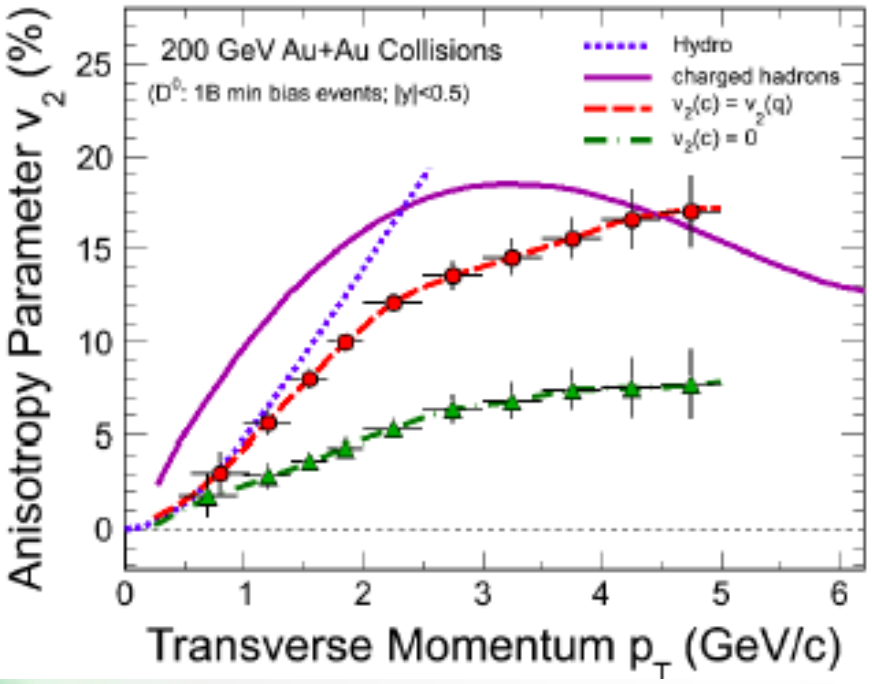
- MTD and HFT Upgrades are two large acceptance central rapidity PID detectors complementing the STAR barrel
- Add c/b quark separation complementing current nice e.g. D meson, D→e / expanding w/ μ capabilities

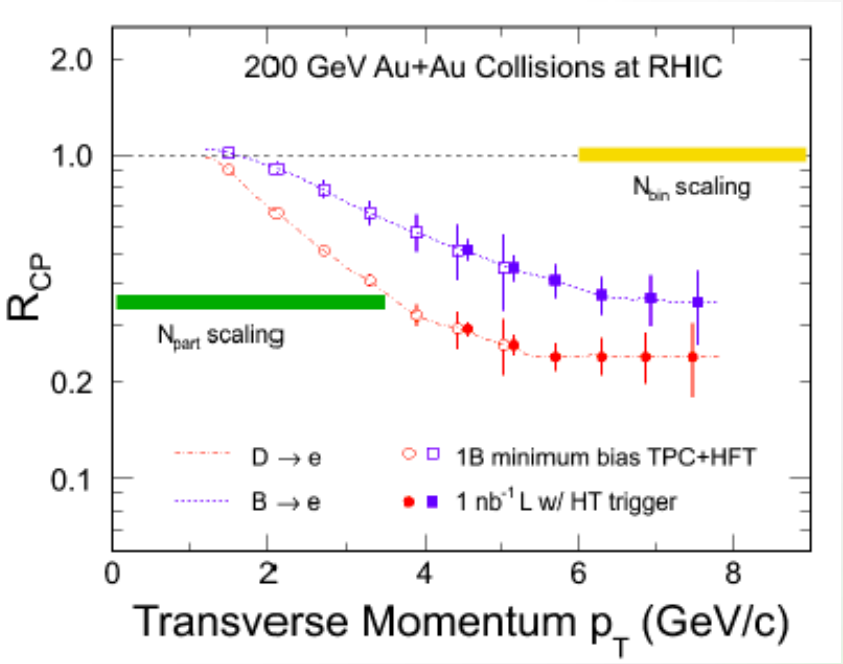




STAR Heavy Flavor Tracker

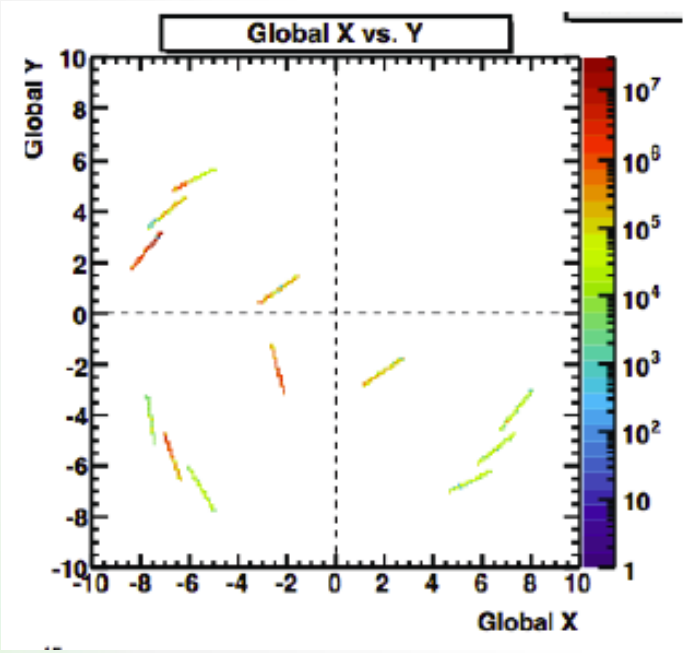
- Matches TPC acceptance
- 3 types of layers, SSD, IST, PXL innermost
- Precise Charm v2, c/b Rcp, RAA, J/Psi from B, Charm Baryons (test recombination for HF)

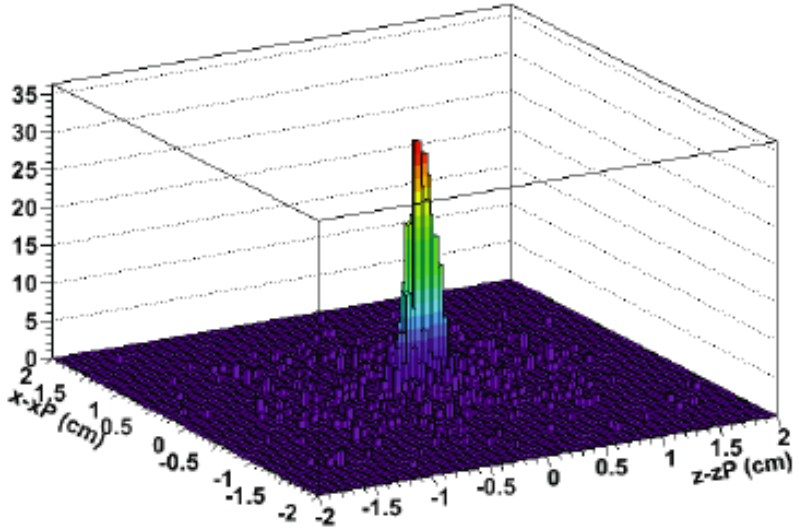




STAR Heavy Flavor Tracker

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

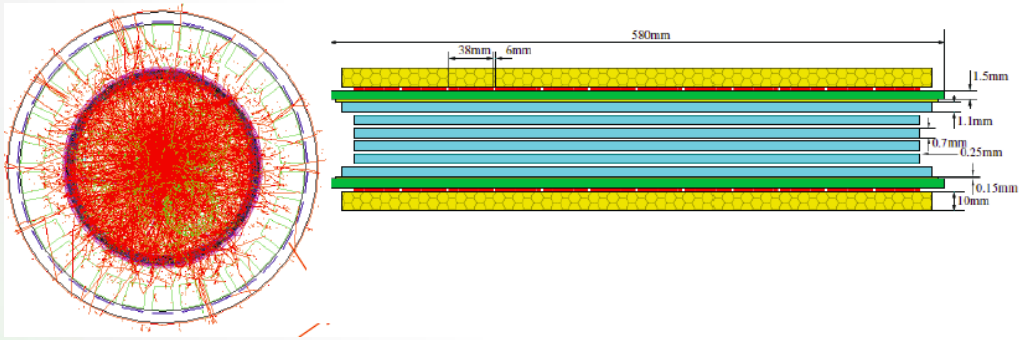




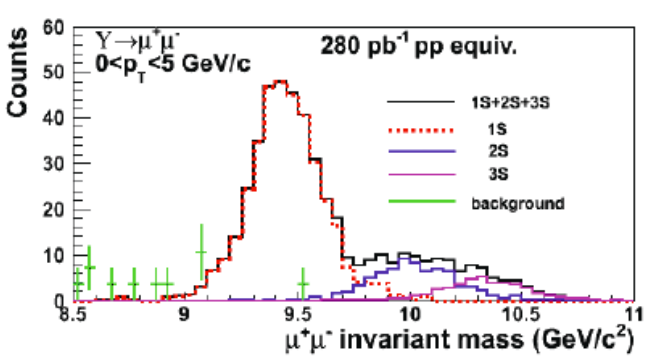
- 2D correlation between measured pxl hit and TPC track projection on a sensor

STAR Muon Telescope Detector

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

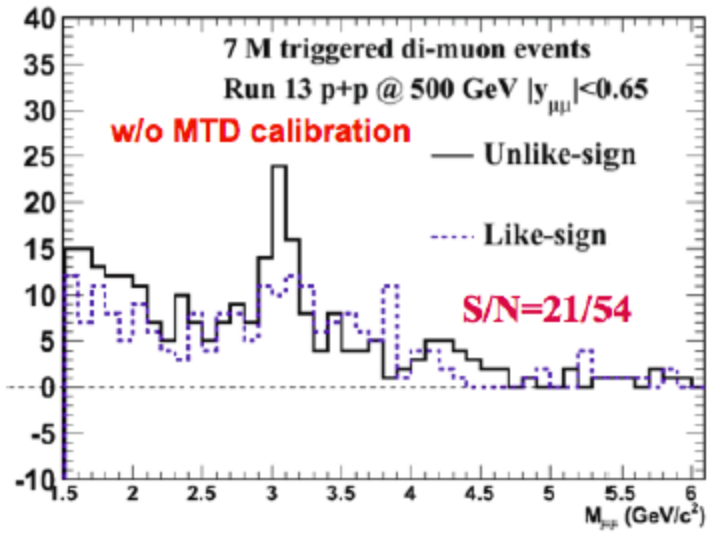


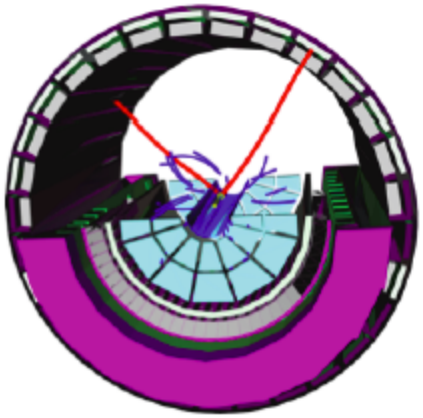
STAR MTD



simulation with MTD

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

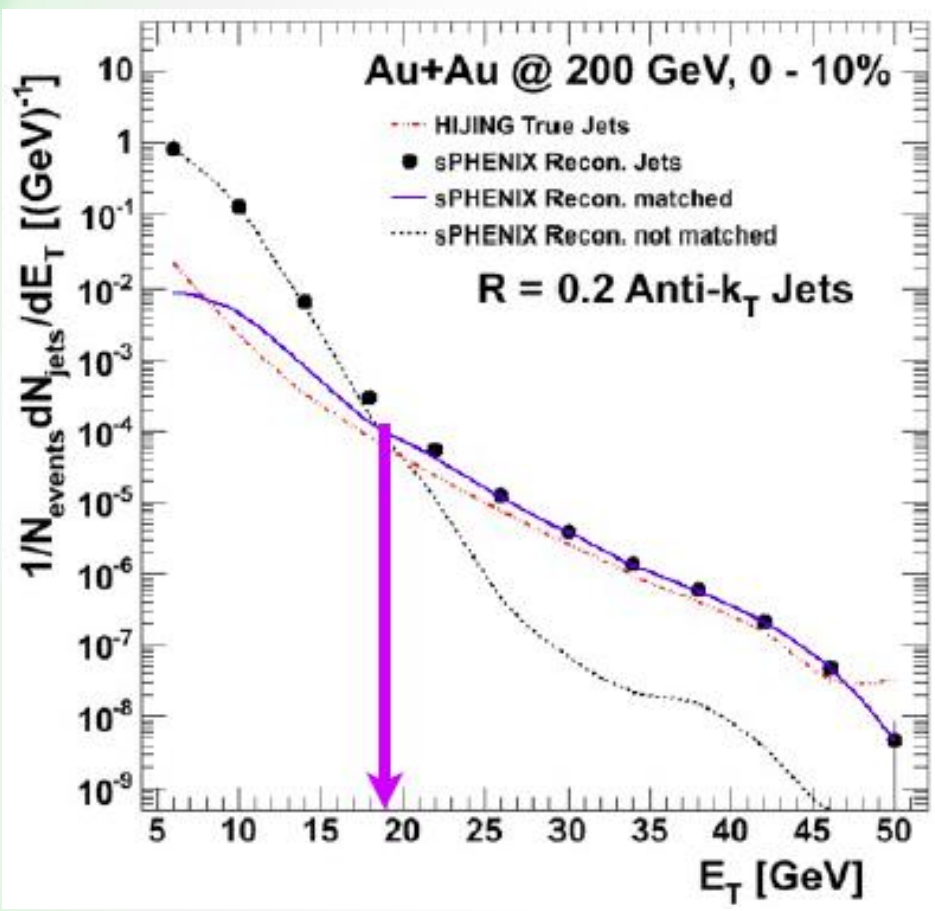


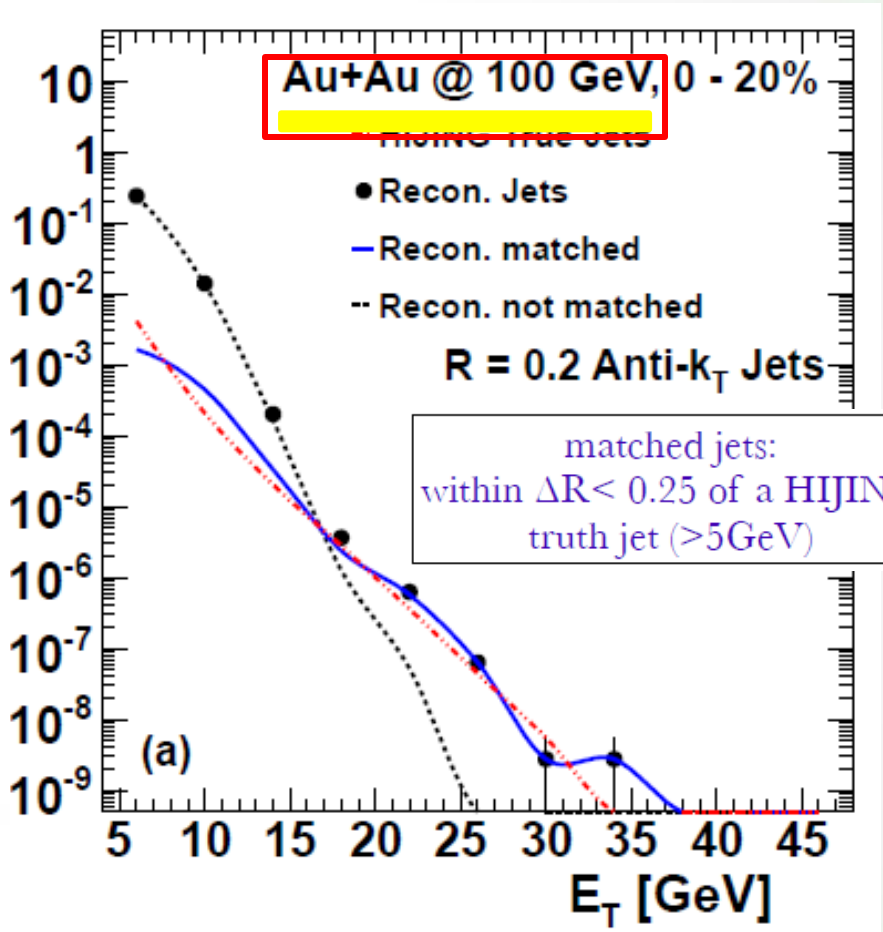


One di-muon trigger event

Possible "in Principle"?

- Too many Fake Jets? **NOPE!** Even at √s = 100 GeV





- -vs LHC: Lower underlying event wins over steeper production spectra for E > ~18 GeV
- **Lower E limited by stats not fake jets? (& stats good down to 100!)**

Larger Cone Sizes?

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