Jets in PHENIX

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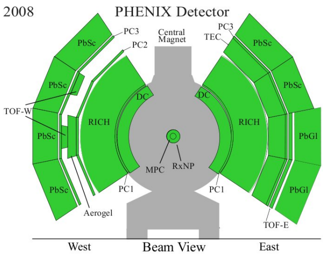
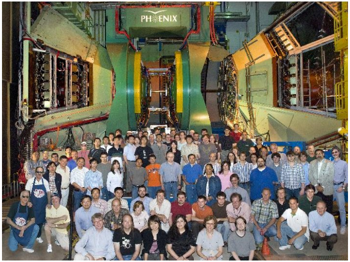
Why Jets at PHENIX?

- Can measure jet modification at:
  - different collision energies and system sizes.
  - lower energies due to softer underlying event.
  - different x and Q^2 (different mixture of quark and gluon jets).
- Cold nuclear matter effects are important!
  - Need p+A (d+Au at RHIC) baselines *ASAP*.
  - No p+Pb LHC run until $\gtrsim$ 2012?

$\Rightarrow$ Insight into energy loss mechanisms.

The PHENIX detector





- Run 5 p+p and Cu+Cu @ $\sqrt{s_{NN}} = 200$ GeV.
- Run 8 p+p and d+Au @ $\sqrt{s_{NN}} = 200$ GeV.
- (Run 11 with the VTX: took p+p @ $\sqrt{s} = 500$ GeV and taking Au+Au @ $\sqrt{s_{NN}} = 20$) GeV now!)

The PHENIX detector

- Advantages:
  - High DAQ rate (> 7kHz under good conditions) means we can take a large Minimum Bias sample and still trigger.
  - Good electromagnetic calorimetry ($\sigma_E \sim 3\%/\sqrt{E}$).
- Disadvantages:
  - $|\eta| < .35$. Weak acceptance for (low p_{T}) dijets.
  - Lack of hadronic calorimetry (miss neutral hadronic energy in jet E_T).
  - Tracking efficiency falls at high p_{T} from conversions and ghosts.

Basic Cuts

- Perform reconstruction at the particle level *first*.
- Goal: balance acceptance (needed for jet reconstruction) vs. quality considerations.
  - PHENIX Drift Chamber, Pad Chambers: select good charged hadrons and electrons.
  - PHENIX Electromagnetic Calorimeter: select good photons.
  - To avoid double-counting, DC acts as a veto on clusters.
- Use EMC clusters and DC tracks as (massless) inputs to reconstruction. Require $p_T, E_T > 400$ MeV/c, respectively.

Jet Reconstruction

- "A jet is not a physical quantity; it is a legal contract between theorists and experimentalists"

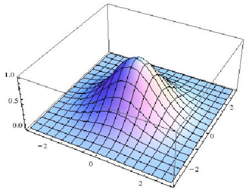
  – M. Tannenbaum

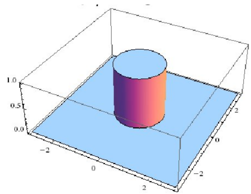
  - An algorithm is a stupid thing that takes in four-vectors and spits out different four-vectors.
  - *Have to understand the output and context of reconstruction algorithms.*
  - Want observables (R_{AA}, di-jet $\Delta\phi$, quenching) to be insensitive to choice of algorithm.

Reconstruction Algorithms

- **Is it a good algorithm?**
  - Is the algorithm stable against the addition of small particles at odd angles (infrared safe) or splitting (collinear safe)?
- **Is it useful in my detector?**
  - Does the algorithm behave well around holes in the acceptance?
  - Is it sensitive to the underlying event?
  - Does the algorithm reconstruct background fluctuations at jets?
- **Does it encode meaningful physics?**
  - Does the algorithm recover most of the fragmenting parton's energy?
  - Does the algorithm reconstruct the fragmenting parton's *direction*?

Gaussian Filter



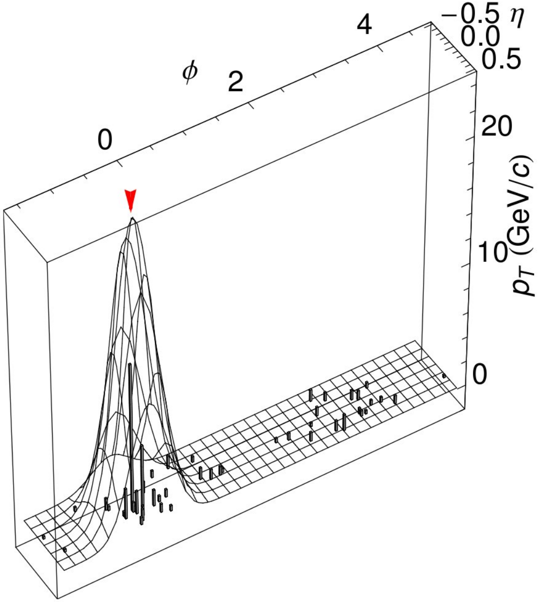


- Seedless, infrared and collinear safe algorithm with angular weighting (`nucl-ex/0806.1499`)

$$p_{\mathrm{T}}^{\mathrm{jet}} \equiv \max\left\{ \int\int d\eta' d\phi' p_{\mathrm{T}}\left(\eta',\phi'\right) e^{-(\Delta\eta^2+\Delta\phi^2)/2\sigma^2} \right\}$$

- Shape of the filter:
  - Optimizes the signal-to-background by focusing on the core of the jet
  - Stabilizes the jet axis in the presence of background
- *Additive*: good against collective background, holes in acceptance.

Gaussian Filter example



Reconstruction Challenges in a Heavy Ion Environment

- Jet reconstruction algorithms are originally a HEP idea.
- The fluctuating, large combinatorial background in heavy ion collisions adds unique challenges.
- New techniques are needed. Here are the some of the ones we use at PHENIX.

Presence of the Underlying Event

How does the underlying event influence jet reconstruction?
(And which effects can we correct?)

- Jittering of the jet axis p^μ (important for di-jet measurements).
  - Low-p_T effect.
- Split-jet
  - Low-p_T and large cone size effect.
- p_T feeding (important for yields, suppression, etc.):
  - Event-averaged background subtraction
    - (PHENIX Cu+Cu: `hep-ph/0802.1188`, but not appropriate for d+Au).
  - Unfolding from embedding (PHENIX d+Au).
  - Background subtraction on event-by-event basis:
    - LHC Pb-Pb iterative subtraction, *O. Kodolova et al., EPJC (2007) 117*,
    - Cacciari/Salam $A\rho \pm \sigma\sqrt{A} - L$ method, `hep-ph/0707.1378`, `hep-ph/0802.1188`.

Fake Jet Identification and Rejection

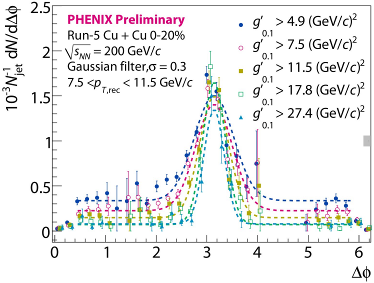
- Fluctuations of the underlying event ⇒ can be reconstructed as low-p_{T} "jet" by your algorithm!
- Solutions:
  - Pick a p_{T} cutoff where the fake rate is negligible (e.g. ATLAS does this at 100 GeV for R=0.4 anti-k$_T$ jets).
    - Different ways to do this: compare to p+p, look at dijets, etc.
  - Subtract off fake jet yield (*very* difficult to do properly).
  - Look at each jet and cut out the ones that look "fake" (e.g. don't have energy distributed in a way that looks like a fragmenting parton). Discriminants:
    - $(E_T)_{max}/(E_T)_{avg}$ in jet (e.g. ATLAS calorimeter jets)
    - Σj_T (nucl-ex/0810.1219)
    - Cacciari/Salam (Cacciari & Salam, Phys. Lett. B 659, 119, 2008)
  - In PHENIX: $g_{\sigma_{dis}}$ (nucl-ex/0907.4725)

$g_{\sigma_{dis}}$ discriminant method

- Reject jets that don't have a Gaussian distribution of energy around the core.

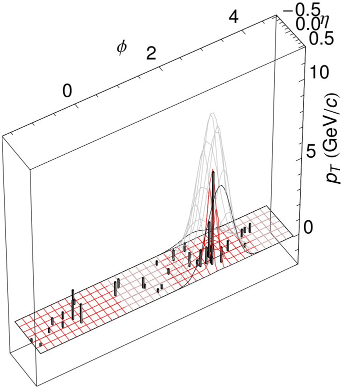
$$g_{\sigma_{\rm dis}}(\eta,\phi) \equiv \sum_{i\in\text{fragment}} (p_T)_i^2 \exp\left(-(\Delta\eta^2 + \Delta\phi^2)/2\sigma_{\rm dis}^2\right)$$

- Choose $\sigma_{dis} < \sigma_{rec}$.

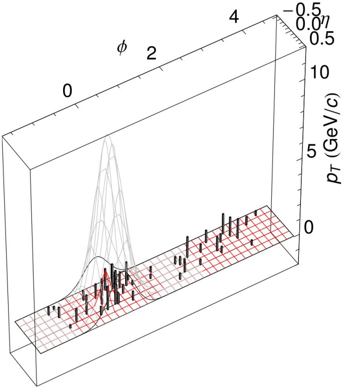


- Data-driven approach to determine where to cut.
- Cut efficiency saturates quickly with $p_{\rm T}$.

$g_{\sigma_{dis}}$ method example

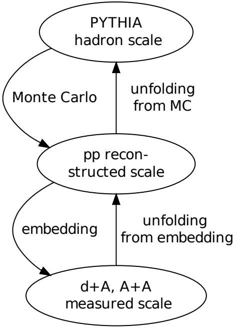


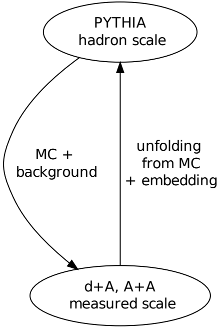
9.6 GeV/c jet passing fake rejection



Rejected 10.8 GeV/c background fluctuation

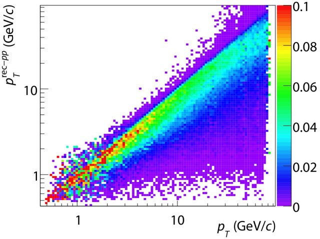
Energy Scales in Reconstruction



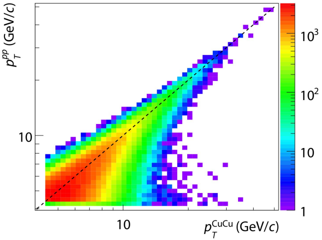


- We talk about jet reconstruction at a given *energy scale*.
- Would like to make a "detector free" measurement and correct for all detector effects.

Jet p_{T} transfer matrices



truth → pp transfer matrix $T_{\mathrm{truth}}^{\mathrm{pp-rec}}$ (MC)



pp → 0-20% Cu+Cu transfer matrix $T_{\mathrm{pp-rec}}^{\mathrm{CuCu-rec}}$ (embedding)

- Smearing of a power law spectrum:
  - small fluctuations from low to high p_{T} get exponentially magnified
  - in PHENIX, dominated by missing n, K_L^0 energy
- Can perform a bin-by-bin ("0th order unfolding") by just looking at the spectra before and after.
  - Dangerous: assumes you know the shape of your input spectrum (but most analyses do it this way)

Jet spectrum unfolding

- Need to invert the spectrum smearing:

$$\frac{dN}{dp_T^{\mathrm{rec}}} = \int dp_T^{\mathrm{truth}} \frac{dN}{dp_T^{\mathrm{truth}}} T_{\mathrm{truth}}^{\mathrm{rec}}$$

- For near-diagonal matrices (e.g. ${p_{\mathrm{T}}}^{\mathrm{dAu}} \rightarrow {p_{\mathrm{T}}}^{\mathrm{pp-rec}}$ unfolding), can use a Neumann series:

$$(I_{n\times n} - T)^{-1} = \sum_{n=0}^{+\infty} T^n$$

- Best (and hardest solution) is to use singular value decomposition (SVD) methods with some regularization (`hep-ph/9509307`)
  - implemented in the `GURU` software package

Triggering, Tracking, Acceptance, etc.

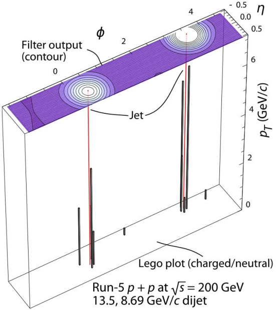
. . . many other issues!

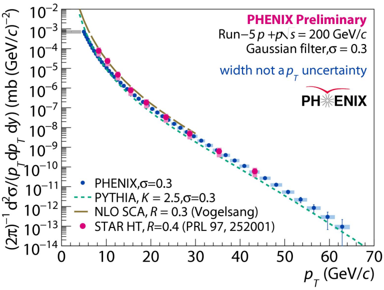
- PHENIX Electromagnetic/RICH trigger (ERT):
  - Fires on electromagnetic showers with $\gtrsim$ 1.6-2 GeV.
  - Use event trigger bits in large minimum bias sample to construct a (centrality-dependent) efficiency.
- Fake high-p_{T} tracks from drift chamber conversions:
  - Require 3+ constituents in jet.
  - Cut out highly charged jets and those dominated by a single high-p_{T} track.
- Fiducial effects:
  - Require jets to be within $\Delta\eta, \Delta\phi < 0.05$ within the edge of acceptance.
  - Evaluate detector edge effects on reconstruction.

Overview of PHENIX Jet Results

- p+p @ 200 GeV (PHENIX Run 5):
  - Jet yields, fragmentation function $D(z)$ for charged and neutrals
  - Demonstrate Gaussian filter reconstruction capability.
- d+Au @ 200 GeV (PHENIX Run 8):
  - Jet yields, R_{CP}, di-jet $\Delta\phi$ and p_{out}distributions
  - Measure/constrain cold nuclear matter effects on suppression and k_{T} broadening
- Cu+Cu @ 200 GeV (PHENIX Run 5):
  - Jet yields, R_{AA}, di-jet $\Delta\phi$ distributions
  - Measure high-p_{T} parton suppression in hot nuclear matter

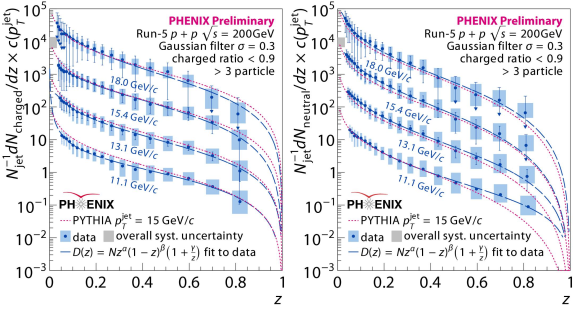
PHENIX p+p: yields





- Unfolded back to the ideal hadron stage p_T^{truth}.
- PHENIX can perform reconstruction out past $p_{\mathrm{T}} \sim 60$ GeV/c.
- Residual difference from theory could be related to jet definitions.

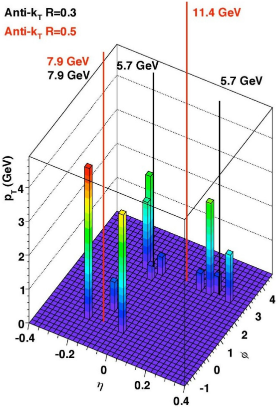
PHENIX p+p: fragmentation function

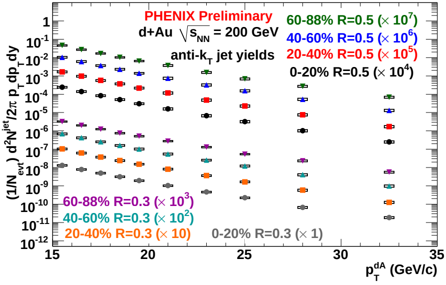


- $z = p_{||}^{\mathrm{particle}} / p^{\mathrm{jet}}$ (Data offset by powers of 10)
- n-Dimensional generalization to GURU used to unfold

$$\left(p_{||}^{\mathrm{particle,rec}}, p_{\mathrm{T}}^{\mathrm{jet,rec}}\right) \rightarrow \left(p_{||}^{\mathrm{particle,truth}}, p_{\mathrm{T}}^{\mathrm{jet,truth}}\right)$$

PHENIX d+Au: jet yields





- Cold nuclear matter effects are an important baseline in understanding QGP energy loss / jet quenching.
- Testing the usability of the anti-k$_\mathrm{T}$ algorithm (hep-ph/0802.1189) at PHENIX. Two cone sizes:
  - control for jet area.
  - control for effect of underlying event.

PHENIX d+Au: 2007 π^0 results

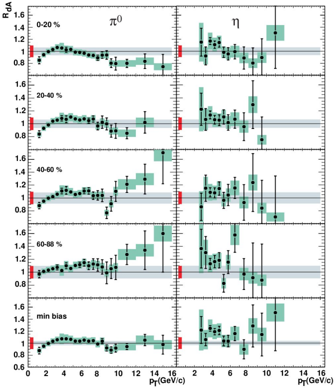
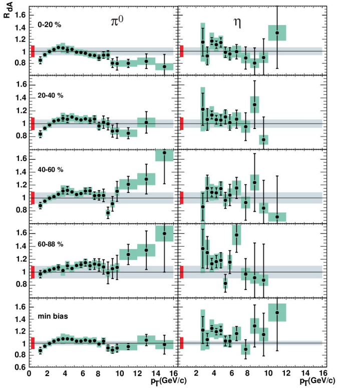


FIG. 2: Nuclear modification factor R_{dA} for π^0 and η in different centrality selections and min. bias data. The bands around the data points show systematic errors which can vary with p_{T} . The shaded bands around unity indicate the $\langle T_{AB}\rangle$ uncertainty and the small bands on the left side of the data points indicate the normalization uncertainty due to the $p+p$ reference.

PRL 98 172302 2007

PHENIX d+Au: 2007 π^0 results



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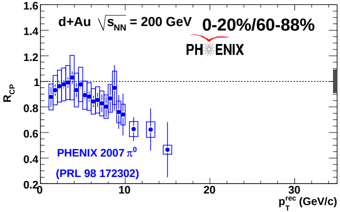
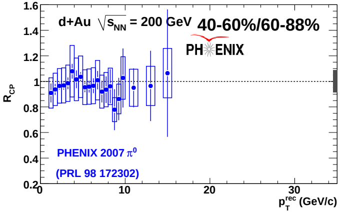
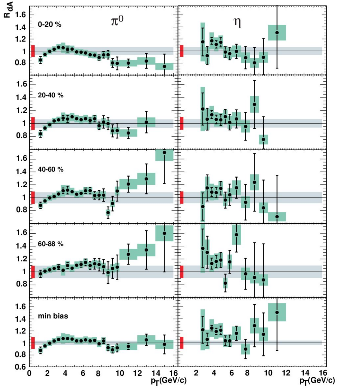




PHENIX d+Au: jet R_{CP}



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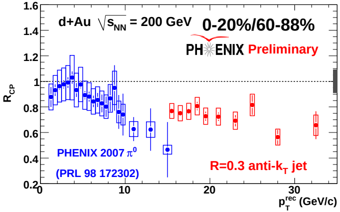
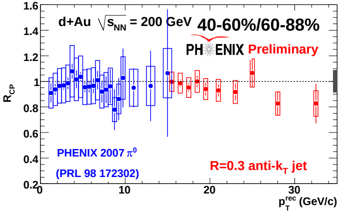
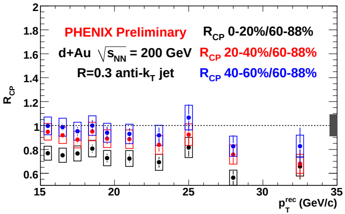
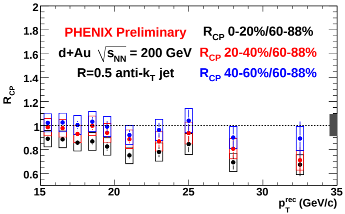




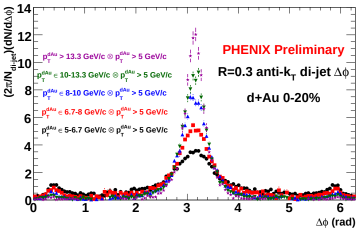
PHENIX d+Au: jet R_{CP}

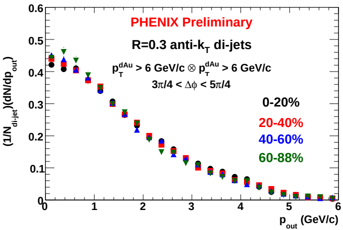




- At the pp reconstructed scale.
- Caveat: these are R_{CP}, not R_{dAu}.
- Evidence of cold nuclear matter effect:
  - centrality-dependent nPDF modification (EMC region)?
  - E-loss?
- Need R_{dAu} and lower p_{T} reach (and higher p_{T} π^0's) to tell the whole story . . . stay tuned.

PHENIX d+Au: di-jet p_{out}



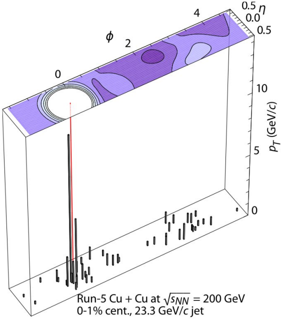


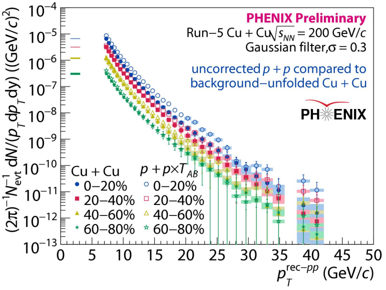
- Search for broadening by examining

$$p_{\text{out}} \left(= \langle k_T \rangle\right) \equiv (p_{\text{T}})_{\text{low}} \cdot \sin \Delta\phi$$

- With kinematic and away-side cuts to remove combinatorial contribution, little room for centrality-dependent broadening.
- $\Rightarrow$ Investigate possible j_{T} broadening in constituents?

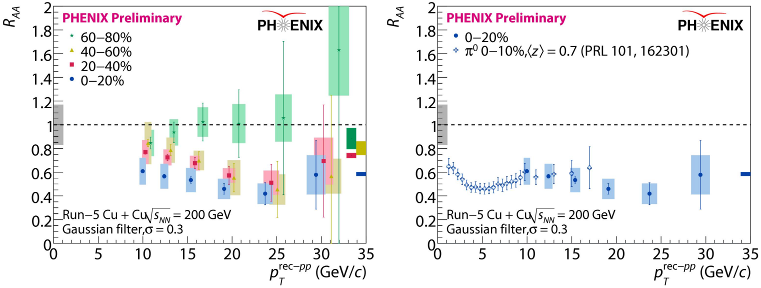
PHENIX Cu+Cu: yields





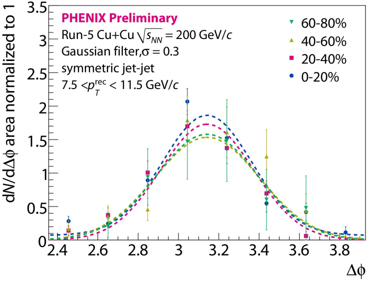
- Direct jet reconstruction in heavy ion collisions at RHIC.
- Plotted at the *pp reconstructed* scale.
- Not unfolded back to $p_{\mathrm{T}}^{\mathrm{truth}}$ . . . yet.

PHENIX Cu+Cu: R_{AA}



- At the pp reconstructed scale.
- Centrality-dependent suppression over a wide p_{T} range.
- Extends and agrees with previous single leading hadron measurement (π^0).
- $\Rightarrow$ Out of cone radiation or otherwise modified jet.

PHENIX Cu+Cu: di-jet $\Delta\phi$



Centrality	$\Delta\varphi \approx \pi$ width σ
0–20%	0.223 ± 0.017
20–40%	0.231 ± 0.016
40–60%	0.260 ± 0.059
60–80%	0.253 ± 0.055

- No centrality-dependent broadening observed within sensitivity.

Outlook

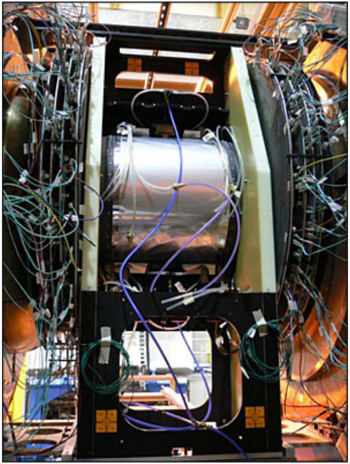
Developing jet reconstruction techniques and making PHENIX measurements!

- Gaussian filter gives reliable p+p results (and can recover the fragmentation function).
- Measuring di-jet broadening and high-p_{T} suppression in cold nuclear matter . . .
  - . . . and in hot nuclear matter!

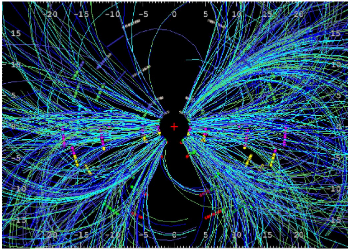
. . . but there is much more to do.

Stay tuned!

Silicon Vertex Detector



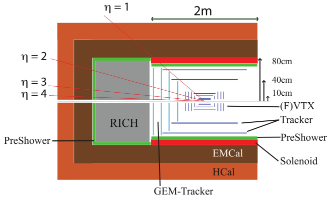
Successfully commissioned in 2011 p+p.

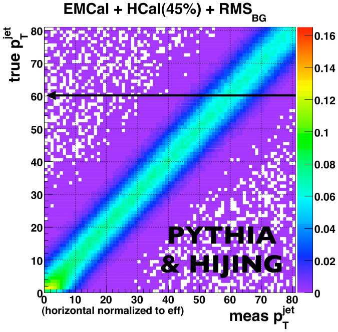


Taking data in Au+Au *right now*!

- Secondary vertex identification can tag heavy flavor jets.
- Improved tracking to reject background.
- Jet reconstruction with standalone tracking.

Potential Future Upgrades: sPHENIX





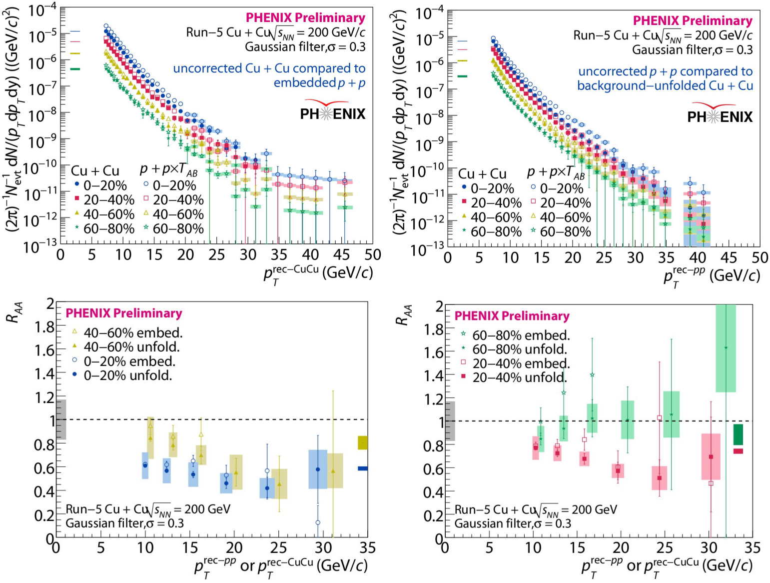
- Maintain and capitalize on PHENIX high rate capability (record lots of heavy ion data without rare triggers).
- Large, uniform acceptance. Hadronic calorimetry at mid-rapidity (first at RHIC).
- Resolution and efficiency out to $p_T \geq 60$ GeV/c.

Many thanks to. . .

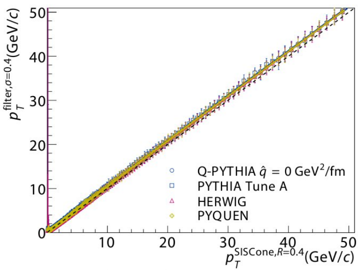
- Brian Cole, Nathan Grau, Yue Shi Lai
- PHENIX Collaboration
- HPHD2011 organizers

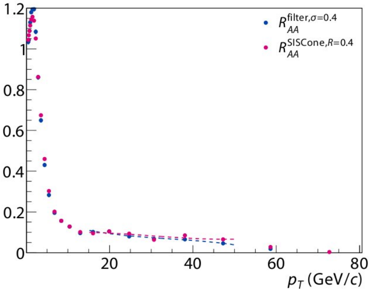
BACKUP

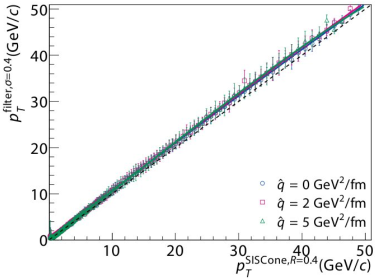
PHENIX Cu+Cu: yields at two energy scales

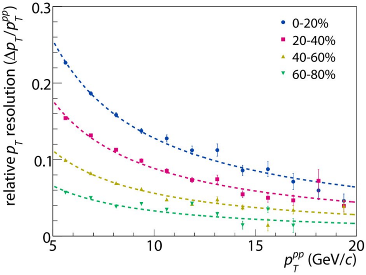


Misc. Gaussian filter backup slides

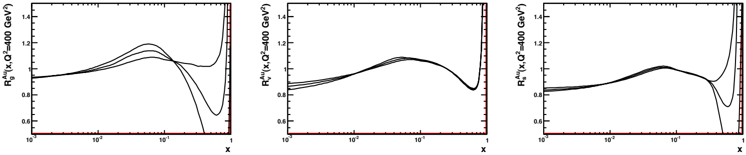








EPS09 nPDFs for high-x d+Au cold nuclear matter effects



- $Q^2 \sim 400\ \text{GeV}^2$, $x \sim .2 - .4$.

Comparison with STAR d+Au

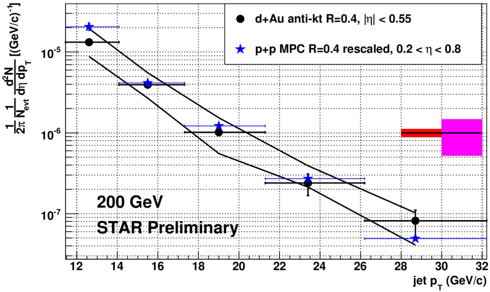


Figure 5. Jet $p_{\rm T}$ spectrum from d+Au collisions compared to scaled p+p spectrum [7]. Red box indicates uncertainty of $\langle N_{\rm bin}\rangle$, black lines indicate JES uncertainty in d+Au and the magenta box shows the total systematic uncertainty of p+p measurement (including JES uncertainty).

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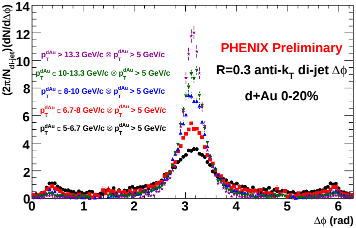
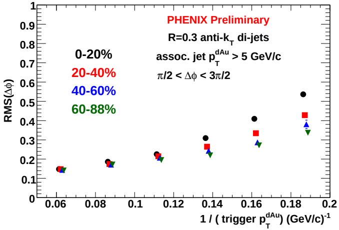
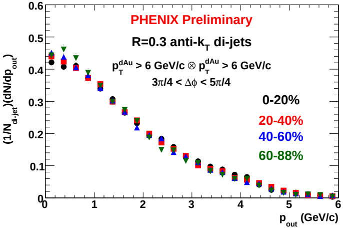
PHENIX $\Delta\phi$ RMS, STAR $p_{\rm out} = k_{\rm T}$ comparison







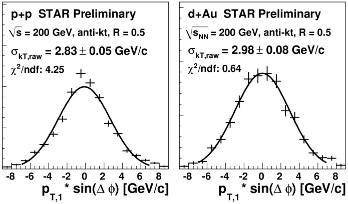


Figure 3. Distributions of $k_{\rm T,raw}$ for p+p, d+Au ($10 < p_{\rm T,2} < 20$ GeV/c).