Jet suppression in PHENIX

Dennis V. Perepelitsa
Columbia University
for the PHENIX Collaboration

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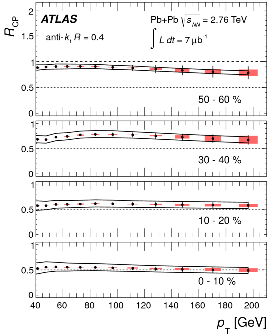
Outline

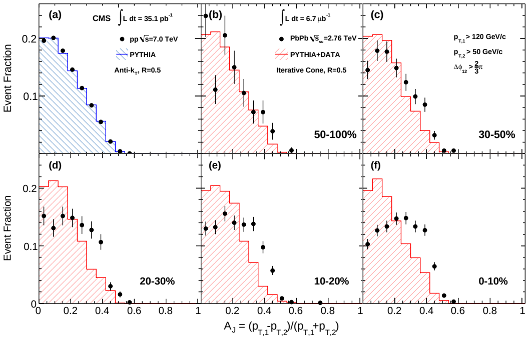
1. Benchmarking jet reconstruction
   - ⇒ Motivation
   - ⇒ Gaussian filter algorithm
   - ⇒ Jets in $p+p$ collisions

2. Exploring hot nuclear matter
   - ⇒ Suppressed jets in Cu+Cu collisions

3. Understanding CNM baselines
   - ⇒ **New results** from RHIC 2008
   - ⇒ Strong centrality dependence in d+Au collisions

Why jets . . . ?



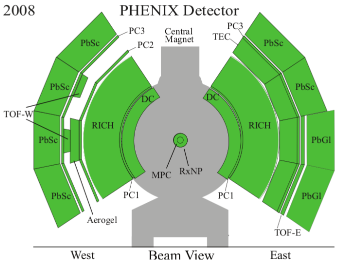


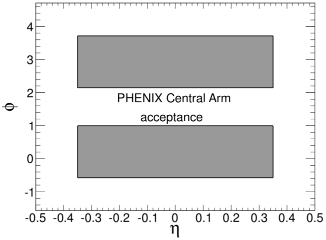
- Probing heavy ion collisions at RHIC and the LHC with reconstructed jets:
  - $\Rightarrow$ Reconstruct full fragmenting parton kinematics at LO.
  - $\Rightarrow$ Sensitive probe of suppression/quenching effects.

Why jets *at RHIC*?

- Complementary set of measurements from two high statistics colliders!
- Can measure jet modification at:
  - $\Rightarrow$ lower energies due to smaller underlying event
  - $\Rightarrow$ different x and Q^2 (different mixture of quark and gluon jets)
  - $\Rightarrow$ different temperature (lever arm for theory)
- Versatility of collision species at RHIC:
  - $\Rightarrow$ ability to vary system size, energy density, geometry
  - $\Rightarrow$ control against cold nuclear matter effects
  - $\Rightarrow$ Cu+Au, U+U from RHIC 2012 run

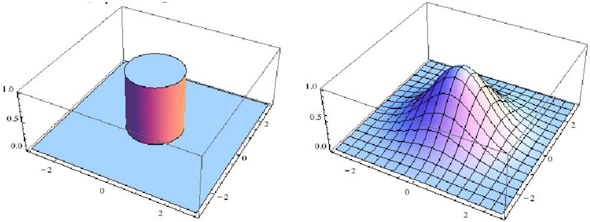
PHENIX detector





- Drift Chamber (DC), Pad Chambers (PC) and Ring Imaging Čerenkov Detector (RICH) measure charged hadrons and electrons
- Electromagnetic Calorimeter (EMCal) clusters photons, π^0's, (some) neutral hadrons
- EMCal/RICH Trigger (ERT) and high PHENIX DAQ rate allow complementary Minimum Bias and high-p_{T} triggered datasets
- Beam-beam counters (BBC) provide MinBias trigger, centrality

Gaussian filter algorithm



- Seedless, cone-like algorithm with a Gaussian angular weighting (`nucl-ex/0806.1499`)

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

- Developed for use in heavy ion collisions.

  $\Rightarrow$ Focuses on the energetic core of the jet, optimizing S/B

  $\Rightarrow$ Stabilizes the jet axis in the presence of background

- Most results **cross-checked with anti-k_{T}**

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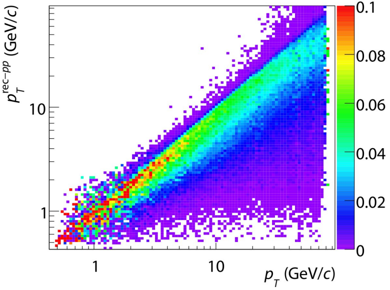
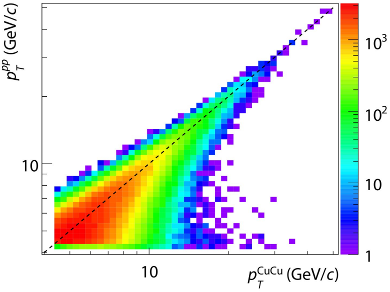
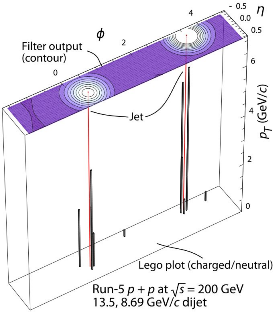
Understanding the energy scale

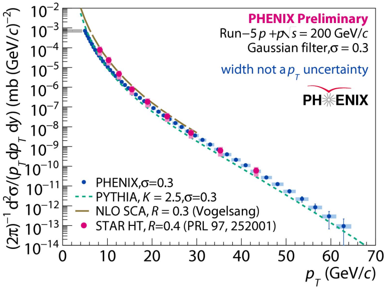




- 14×10^6 `PYTHIA` Tune A $2 \to 2$ QCD events, $\sqrt{Q^2} = 0.5$-64 GeV
  - $\Rightarrow$ Cross-checks with `HERWIG`, other `PYTHIA` tunes
  - $\Rightarrow$ PHENIX energy “resolution” driven by: tracking inefficiency, loss of n, K_L^0 neutral energy, edge of acceptance effects
- Embedding into real heavy ion background.
- Hadronization correction to NLO calculation **in progress**
  - $\Rightarrow$ will allow proper comparison to data

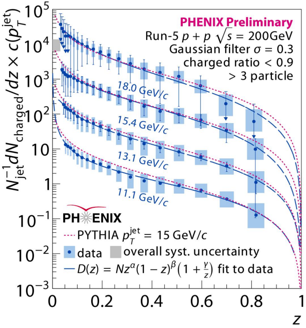
$p+p$: jet spectrum

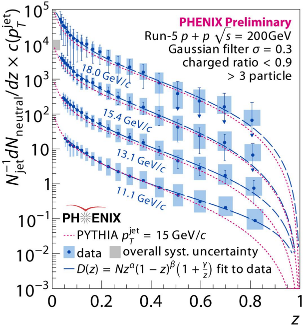




- $p+p$, $\sqrt{s} = 200$ GeV, RHIC 2005
- Demonstrates Gaussian filter reconstruction in PHENIX:
  - $\Rightarrow$ comparison with NLO pQCD across ten orders of magnitude
  - $\Rightarrow$ residual differences from jet definition
- Analysis being **finalized**, moving towards publication

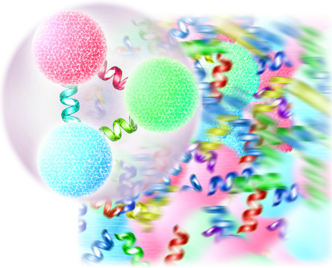
$p+p$: jet fragmentation





- Fragmentation function ($z = p_{||}^{\text{particle}}/p^{\text{jet}}$) measurement:
  - $\Rightarrow$ required development of n-dimensional generalization of SVD unfolding in `GURU`
  - $\Rightarrow$ another proof of principle for jet physics

On to heavy ion physics

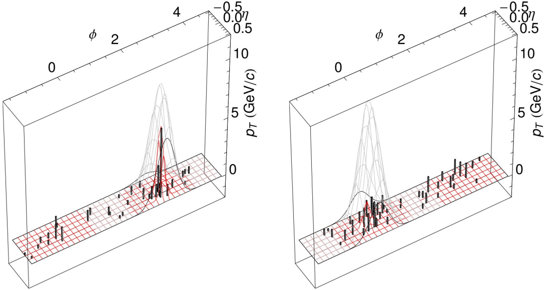


- Benchmarked the Gaussian filter in $p{+}p$ collisions
  - $\Rightarrow$ Cu+Cu collisions, $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, RHIC 2005
  - $\Rightarrow$ Measure jet suppression in heavy ions:

$$R_{\mathrm{AA}} = \frac{1}{N_{\mathrm{evt}}^{AA}} \frac{dN^{AA}}{dp_{\mathrm{T}}} / \langle T_{\mathrm{AB}} \rangle \frac{d\sigma^{p+p}}{dp_{\mathrm{T}}}$$

- Need a few more jet reconstruction techniques. . .

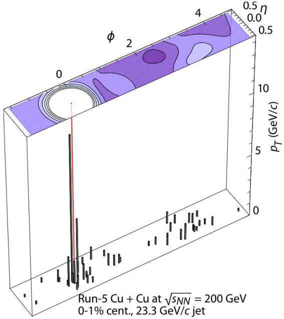
Rejecting fake jets

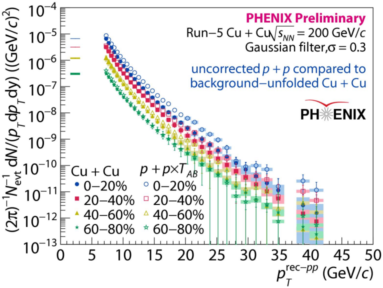


9.6 GeV/c jet passing fake rejection   Rejected 10.8 GeV/c background fluctuation

- Separate low-p_{T} jets from UE fluctuations on a **jet by jet basis**
  - $\Rightarrow$ trade reconstruction efficiency for sample purity
- Similar to "angularly-weighted" p_{T} cut
  - $\Rightarrow$ rewards jets with a tight core of energy, punishes diffuse jets
  - $\Rightarrow$ efficient saturation with reconstructed p_{T}
  - $\Rightarrow$ data-driven approaches set threshold

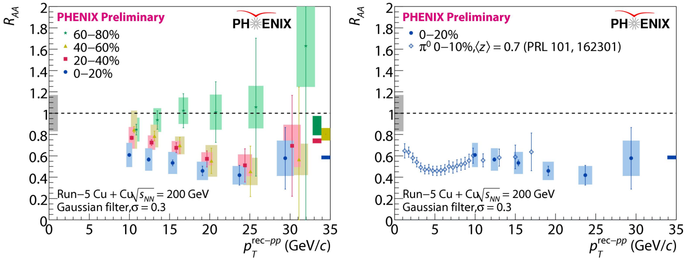
Cu+Cu: jet spectrum





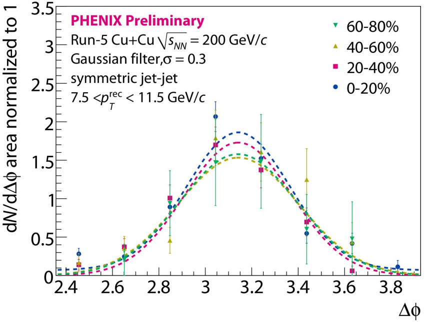
- p_{T}-feeding from underlying event
  - ⇒ subtraction of centrality- and z-vertex parameterized average background
- p_{T}-smearing from UE fluctuations
  - ⇒ evaluated through embedding $p+p$ jets into Cu+Cu minimum bias events
- results shown here unfolded to $p+p$-**equivalent detector scale**

Cu+Cu: jet suppression. . .



- Suppressed reconstructed jet R_{AA}
  - $\Rightarrow$ over a wide p_{T} range
  - $\Rightarrow$ increasing suppression in more central collisions
- Comparable to single hadron suppression at high-p_{T}
  - $\Rightarrow$ qualitatively similar to LHC single jet suppression results

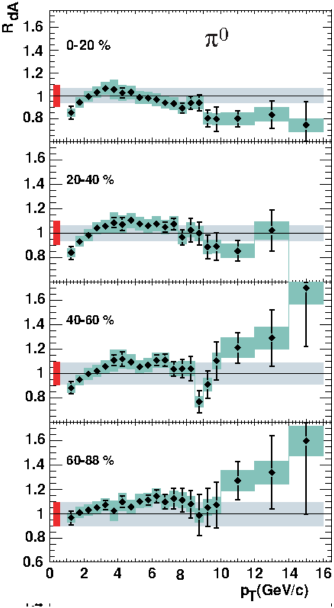
Cu+Cu: ... without de-correlation



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

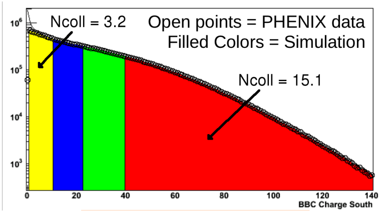
- Reconstructed di-jet $\Delta\phi$ distributions unmodified
  - $\Rightarrow$ no angular de-correlation in central collisions!
  - $\Rightarrow$ upper limits on cold/hot nuclear matter k_{T}-broadening
- Qualitatively similar to LHC dijet results

Cold nuclear matter effects in d+Au



- p/d+A collisions establish a baseline for A+A:
  - $\Rightarrow$ confirm that suppression in A+A is a final state effect
  - $\Rightarrow$ probe centrality dependence of nPDF's
  - $\Rightarrow$ test pQCD & factorization at high x
- PHENIX π^0 result from 2003 data:
  - $\Rightarrow$ weak centrality dependence
  - $\Rightarrow$ low statistics at high-p_{T}

d+Au centrality determination



cent.	$\langle N_{\mathrm{coll}} \rangle$	bias corr.
0-20%	15.1	-6%
20-40%	10.2	+0%
40-60%	6.6	+3%
60-88%	3.2	+3%

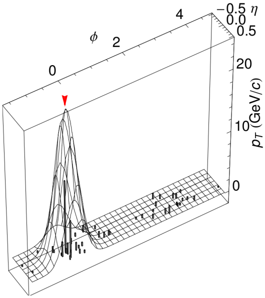
- Charge sum in Au-going BBC, $3.1 < \eta < 4.9$, used to classify centrality
- Glauber MC + negative binomial distribution description of signal

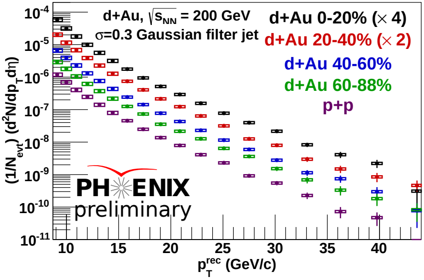
  $\Rightarrow$ see 88% of the inelastic d+Au cross section

- Small correlation between central arm particle production and BBC charge

  $\Rightarrow$ calibrated in p+p collisions
  $\Rightarrow$ additional correction to yield

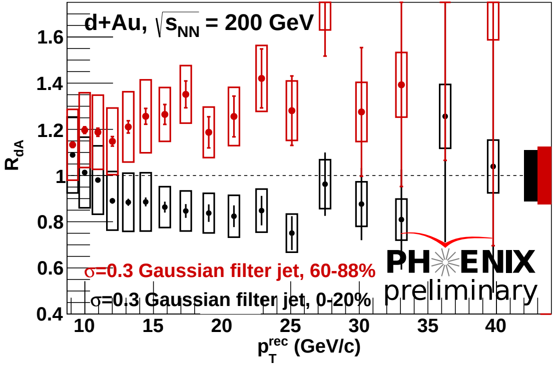
d+Au: jet spectrum





- p+p and d+Au, $\sqrt{s_{\rm NN}} = 200$ GeV, RHIC 2008
  - $\Rightarrow$ 30× increase from RHIC 2003 data
- Jets from 9 to 40 GeV/c at the p-p-**equivalent detector scale**
  - $\Rightarrow$ bin-by-bin unfolding of $p_{\rm T}$-feeding from mild d+Au UE
  - $\Rightarrow$ small residual fake rate ($< 5\%$) below < 12 GeV/c

d+Au: jet R_{dA}

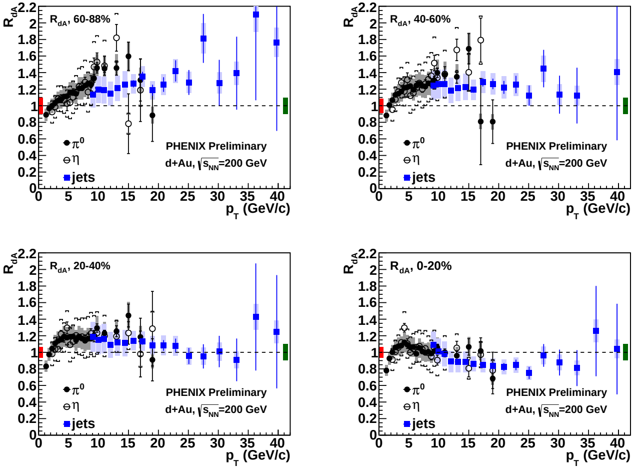


- $R_{\mathrm{dA}} = 1$ within errors at low-p_{T}
- Mild suppression in **central events** at high-p_{T}
- Moderate enhancement in **peripheral events** at high-p_{T}

$\Rightarrow$ unexpected result!

d+Au: confirmation from π^0s, ηs

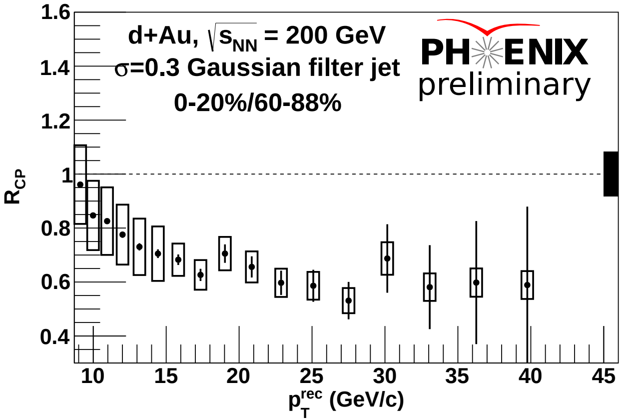
- Reconstructed from cluster pairs in π^0, η mass windows



- Consistent rise in peripheral R_{dA} in **jets** and **hadrons**
  - $\Rightarrow$ Different systematics, different p+p reference

d+Au: jet R_{CP}

- Another way to look at the central/peripheral difference:



- Significantly reduced systematics
- Cleaner measurement of relative centrality dependence

  $\Rightarrow$ evolves in p_{T} to $R_{\mathrm{CP}} = 0.6$ asymptote

d+Au: single hadron R_{CP} comparison

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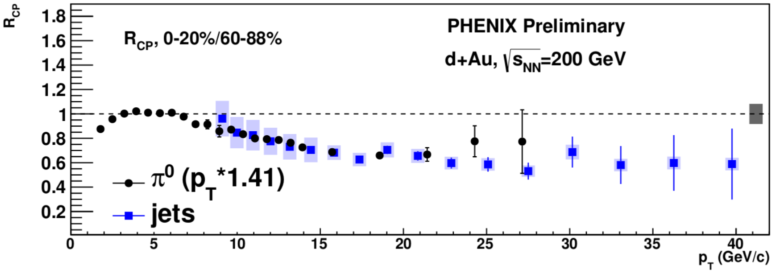
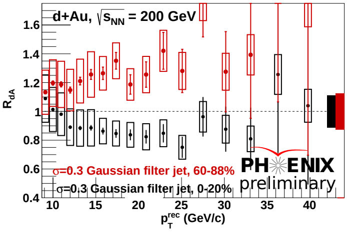
- Scale single hadron p_{T} by $1/\langle z\rangle$ using empirical $\langle z\rangle = 0.7$:

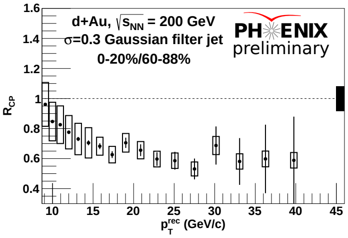


- Excellent agreement in shape between **jets** and **hadrons**

d+Au: what does it all mean?

- Small suppression in **central d+Au**
  - $\Rightarrow$ are nPDF effects, initial state E-loss enough?
- Moderate enhancement in **peripheral d+Au**
  - $\Rightarrow$ extreme centrality bias in high-p_T jet events?
  - $\Rightarrow$ not understood aspect of d+Au geometry?
  - $\Rightarrow$ something new?
- Strong centrality dependence at high-p_T
  - $\Rightarrow$ challenging to simultaneously explain both!
  - $\Rightarrow$ invites comparison to p+A at LHC (and RHIC)





Outlook

- Jet measurements at PHENIX delivering interesting physics:
  - ⇒ consistent algorithm across multiple collision systems
  - ⇒ benchmarked in p+p, exploring hot and cold nuclear matter
- Surprising, robust centrality dependence in d+Au:
  - ⇒ implications for centrality, p+A, CNM
- The future of PHENIX jet measurements: