Direct jet reconstruction in $p + p$ and Cu + Cu at PHENIX

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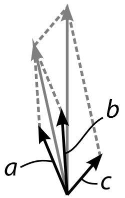
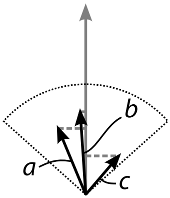
Columbia University and Nevis Laboratories

APS DPF Meeting 2009, Heavy Ions III

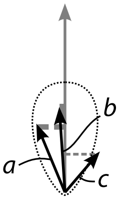
Jet reconstruction algorithms



Recombination



Cone

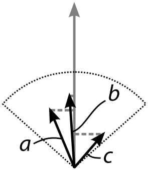


Filter

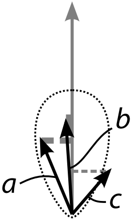
- $k_\perp$: Catani, Dokshitzer, Webber, Phys. Lett. B **285**, 291 (1992); Ellis & Soper, Phys. Rev. D **48**, 3160 (1993)
- Cambridge-Aachen, anti-$k_\perp$

- Angular sampling
  - Cone: Huth *et al.*, 1990 Summer Study on High Energy Physics, 134
  - Filter: Study for $p + p$ collisions: arXiv:0806.1499; heavy ion properties & performance: in preparation

Gaussian filter



Cone

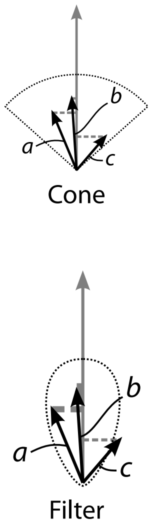


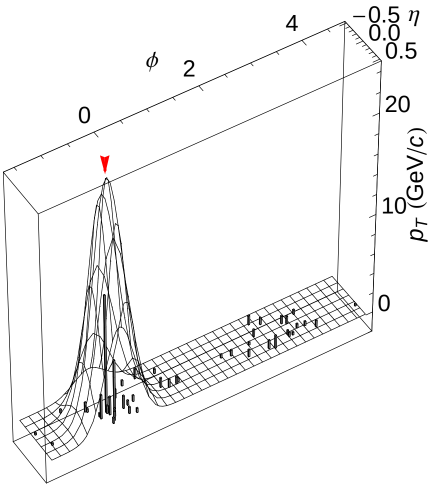
Filter

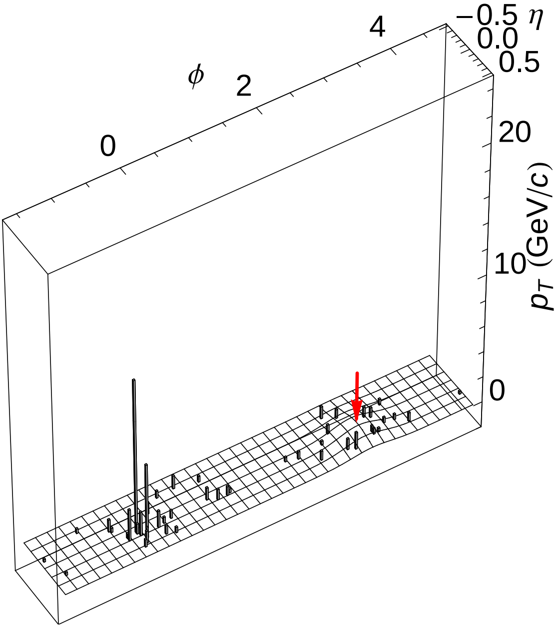
$$\iint_{\mathbb{R}\times S^1} d\eta' d\varphi' p_T(\eta', \varphi') \exp\left[-\frac{(\eta-\eta')^2 + (\varphi-\varphi')^2}{2\sigma^2}\right] = \text{max!}$$

- Seedless
- Cone-like, but without infrared and collinear unsafety from hard angular cut-off
- 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
- Naturally handles isolated particles vs. collective background

Gaussian filter






−0.5 η
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p_T (GeV/c)
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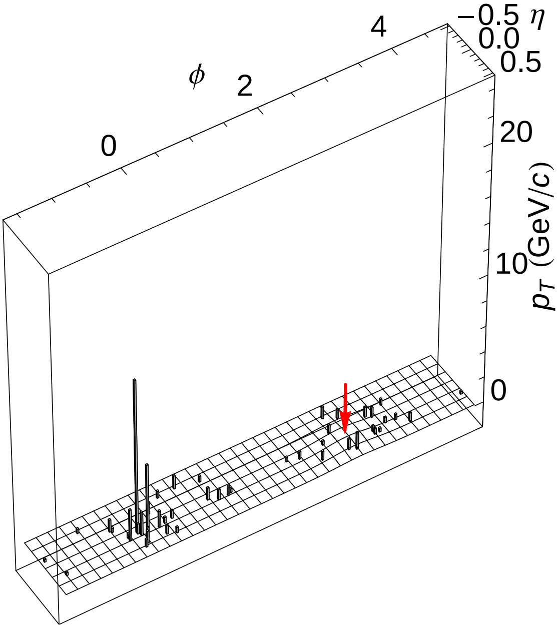

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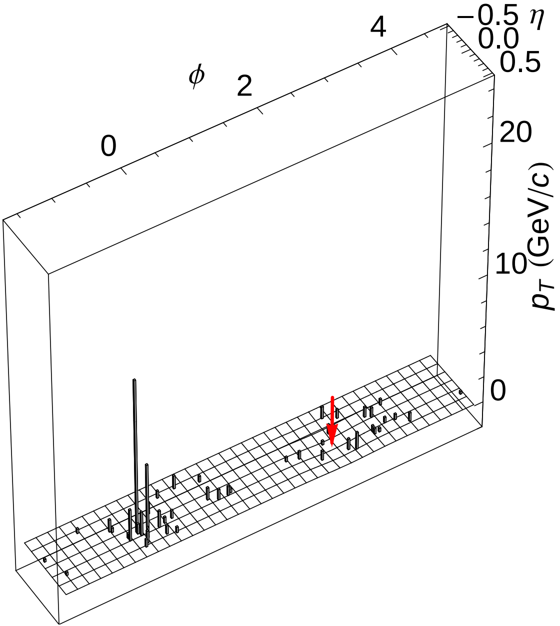
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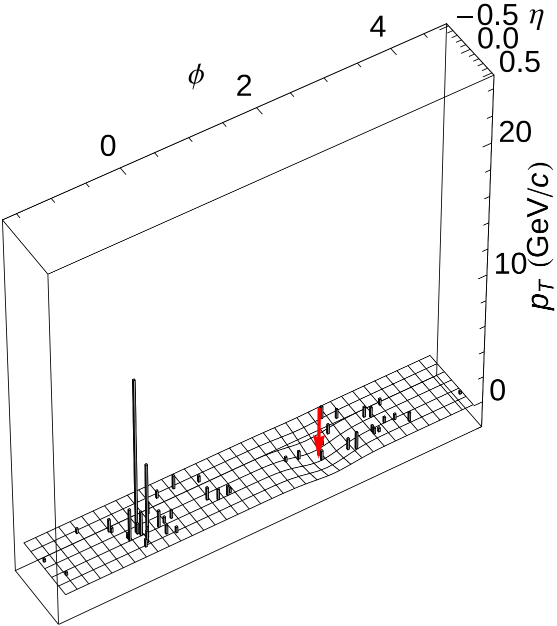

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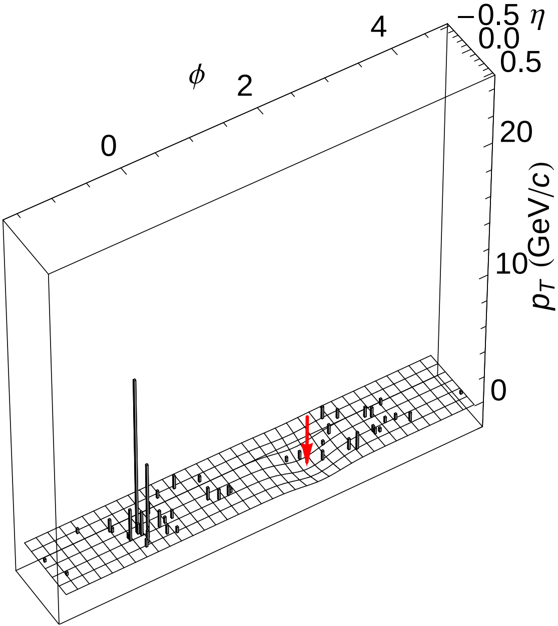
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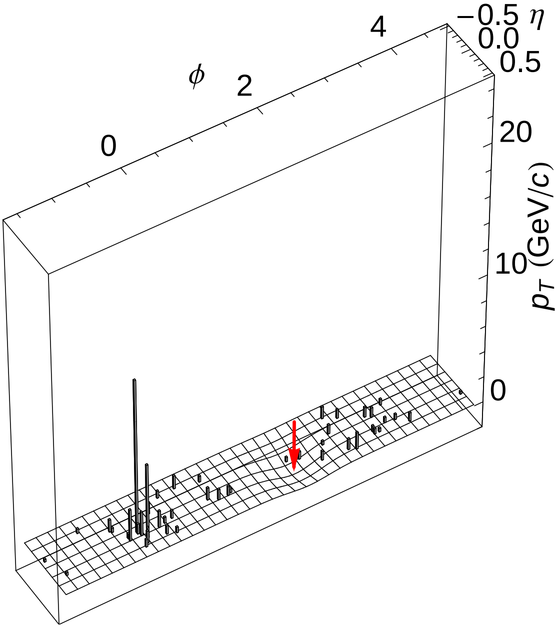

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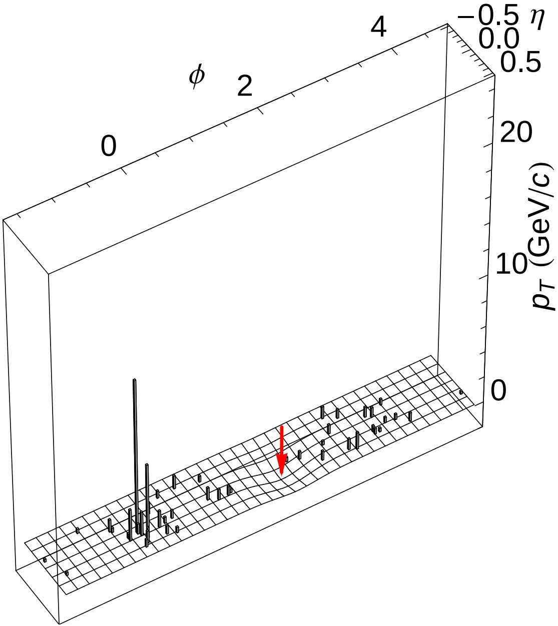

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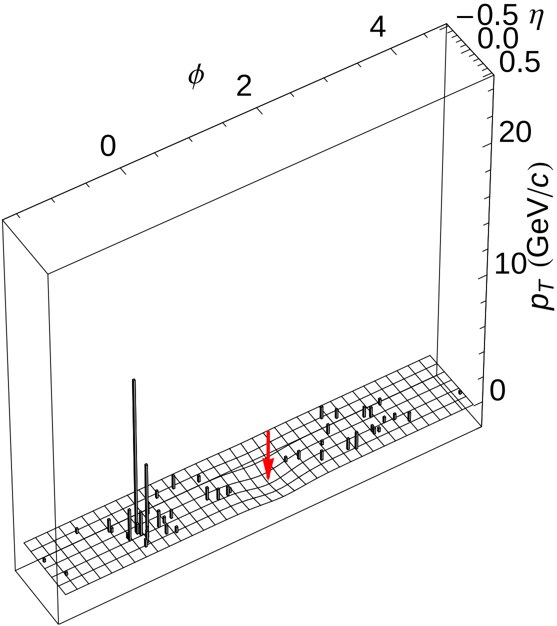

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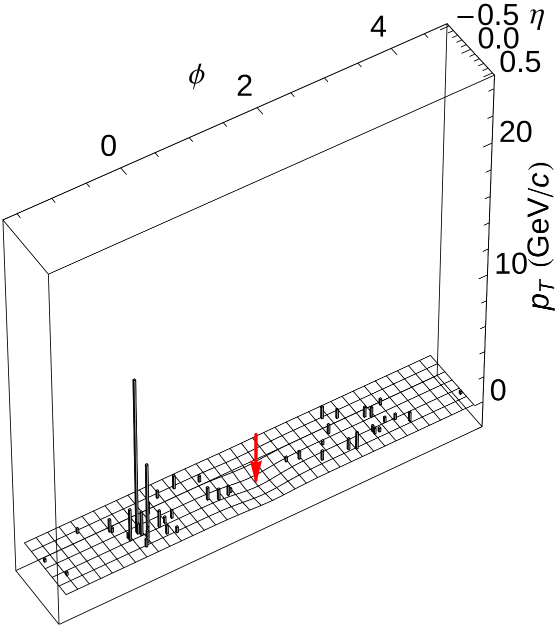

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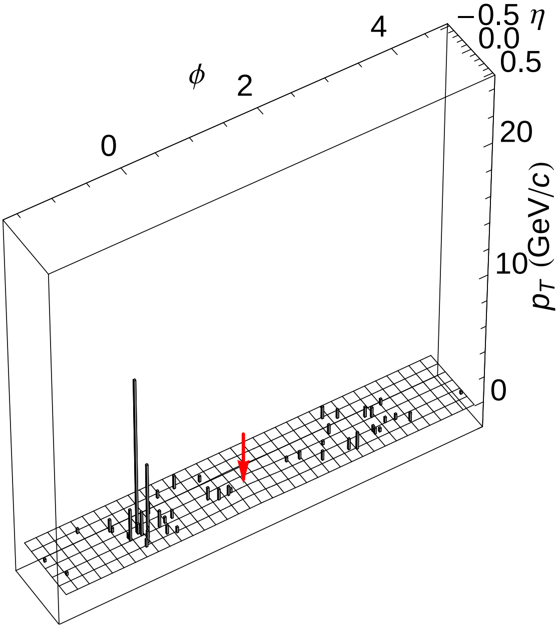

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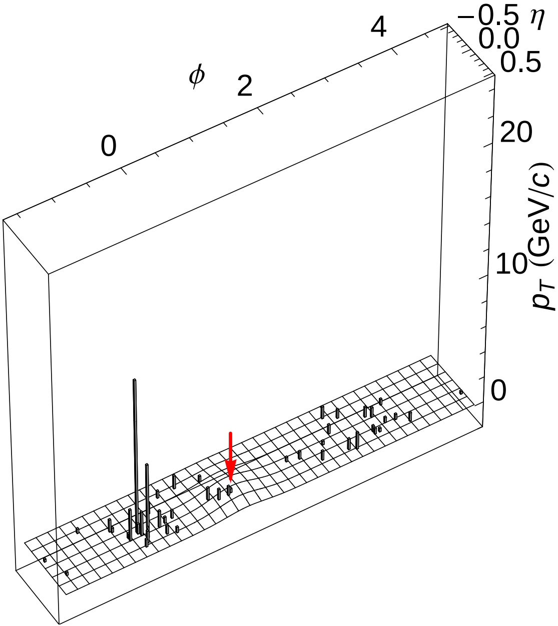

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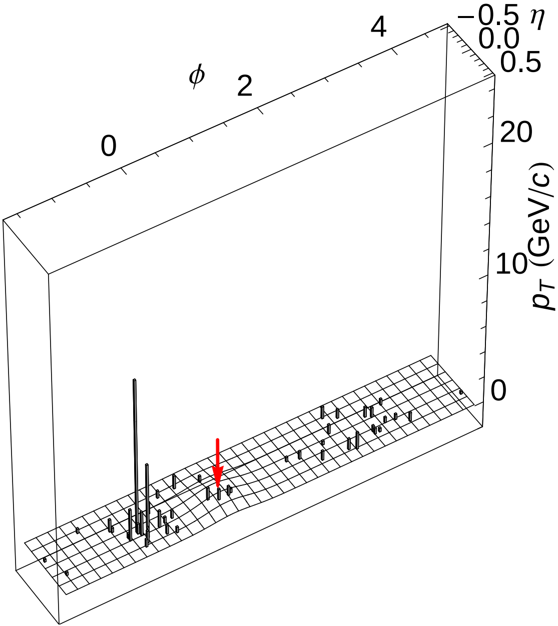
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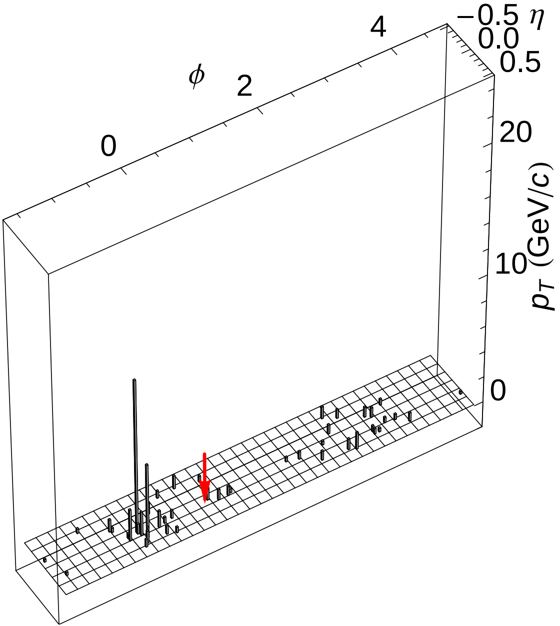

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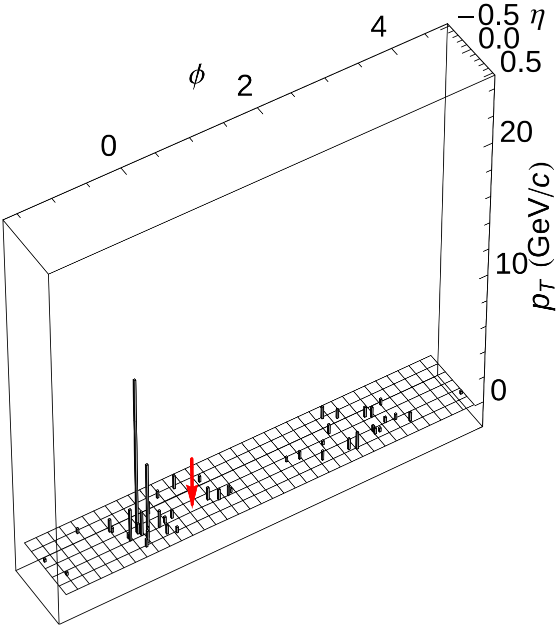

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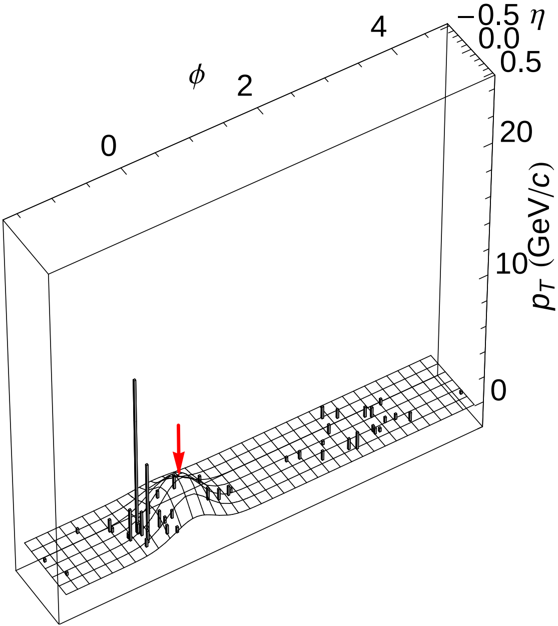
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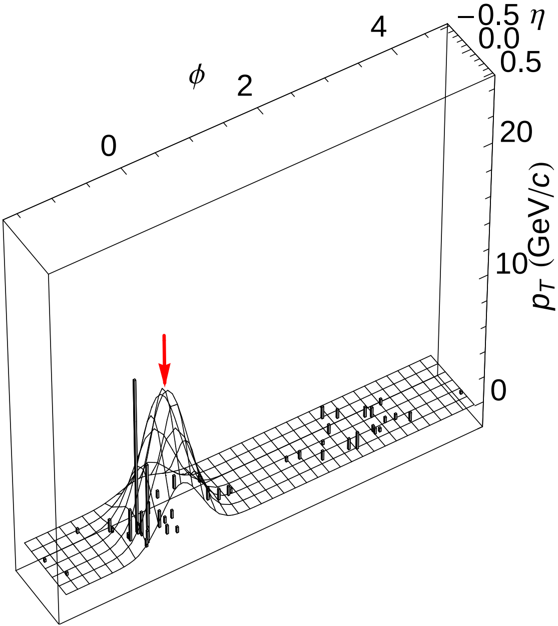

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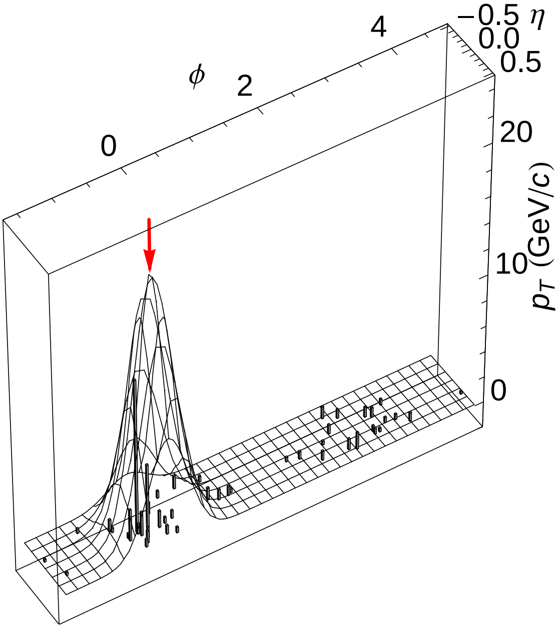

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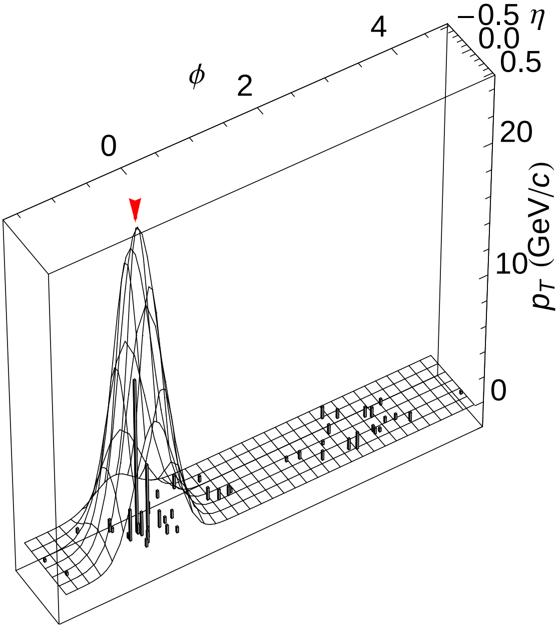

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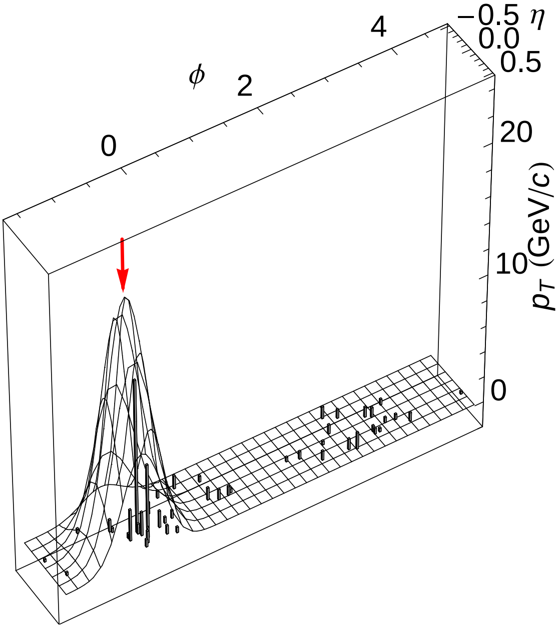

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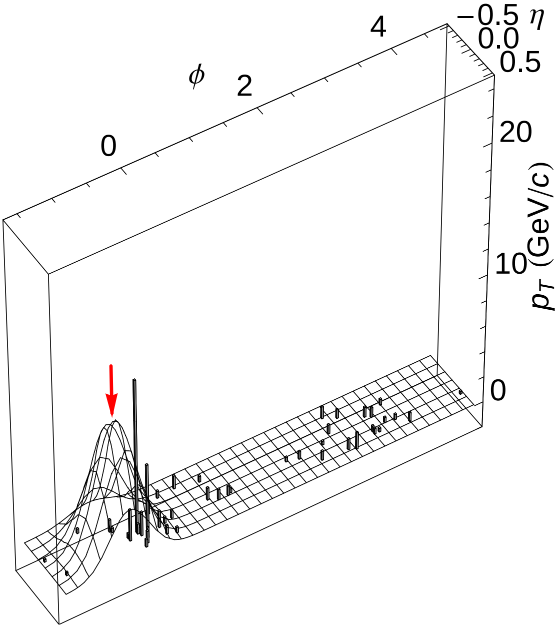

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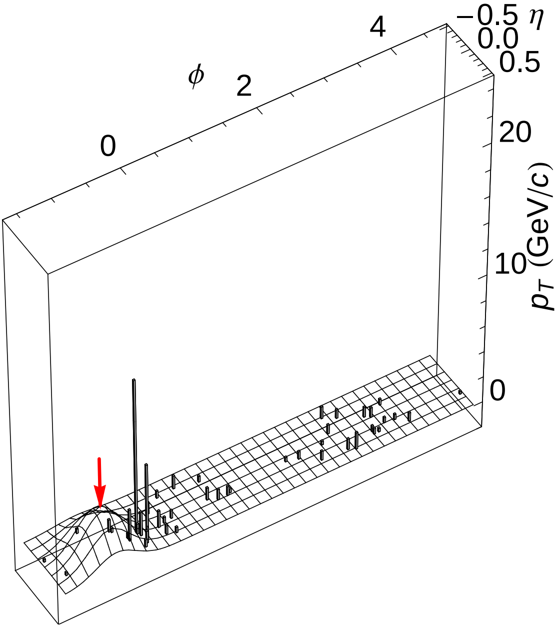

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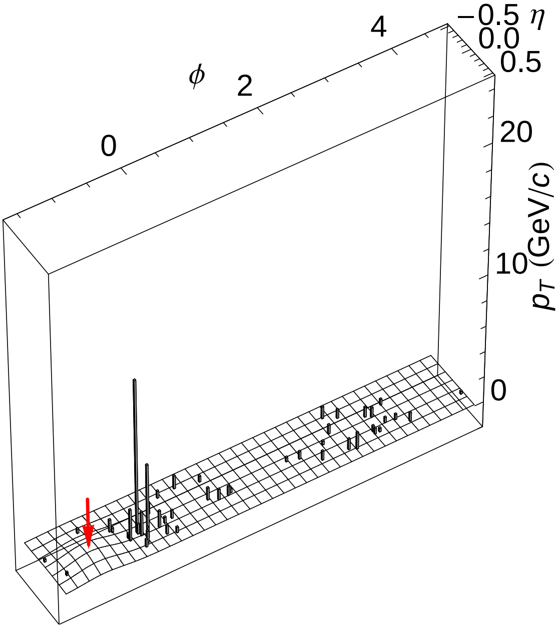

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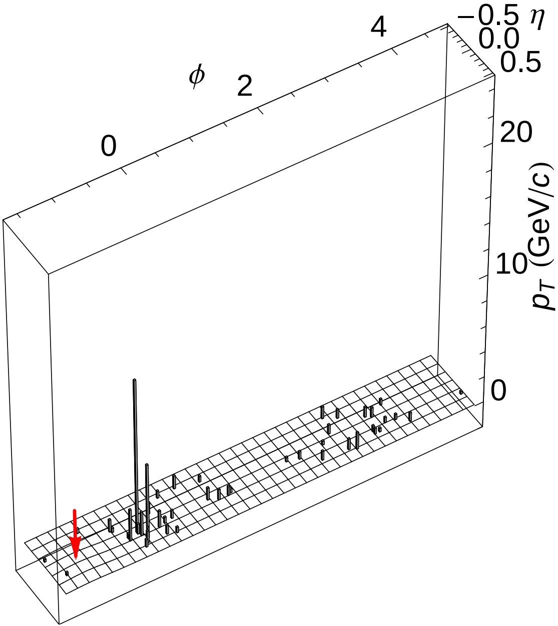

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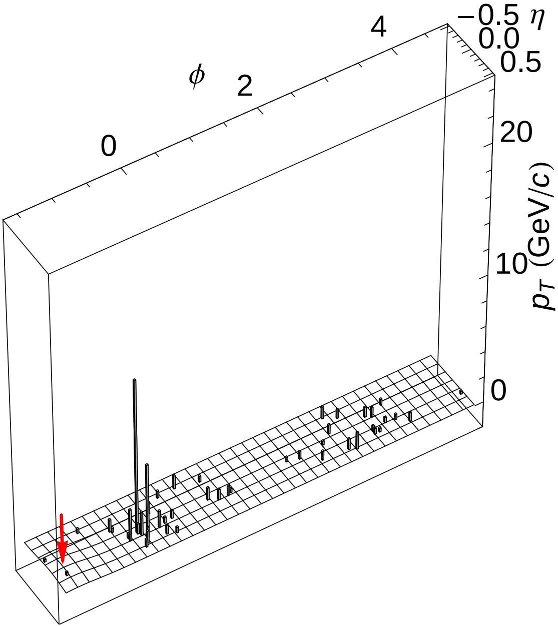

−0.5 η
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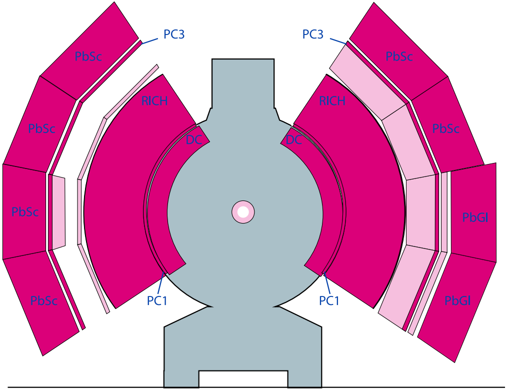
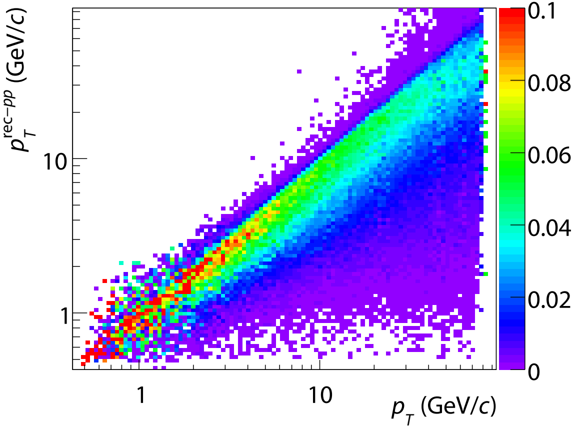
p_T (GeV/c)

Jet reconstruction in PHENIX Run-5



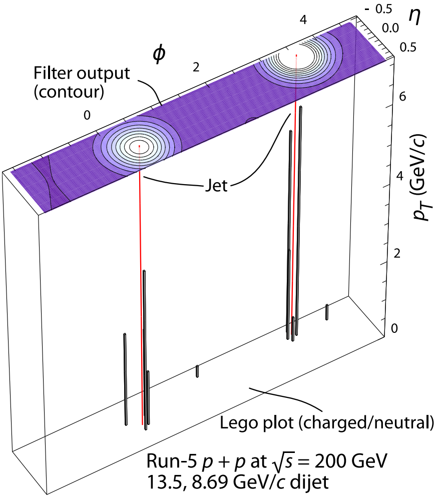
- Data set: PHENIX Run-5 $p + p$ at $\sqrt{s} = 200$ GeV, Cu + Cu at $\sqrt{s_{NN}} = 200$ GeV
  - Tracking detectors: Drift Chamber (DC), Pad Chambers (PC) 1/3, RICH
  - Calorimeters: Lead-Scintillator (PbSc), Lead-Glass (PbGl)
- Gaussian kernel with $\sigma = 0.3$

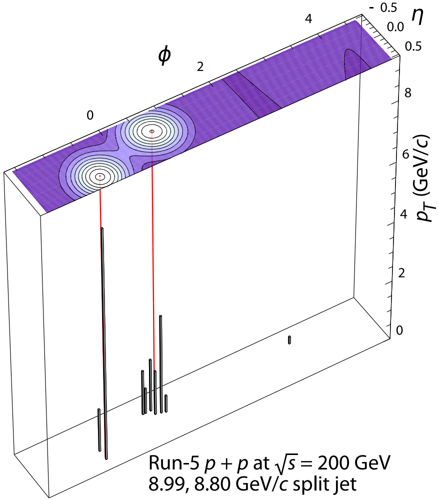
PHENIX jet energy scale



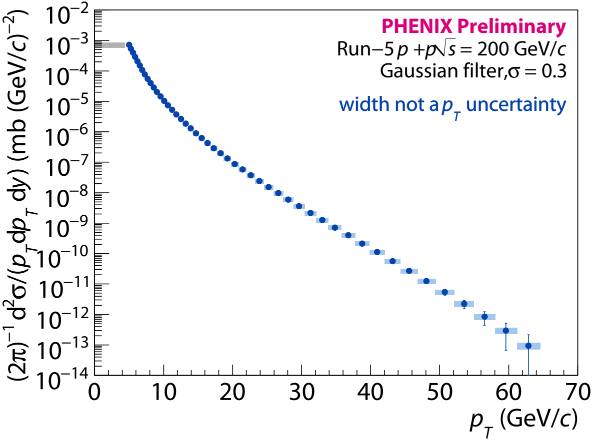
- PYTHIA + GEANT simulation with $\sim$ 16 million events
- $p_T^{rec-pp} < p_T$ region dominated by n, K_L^0 energy loss

Event display, $p + p$



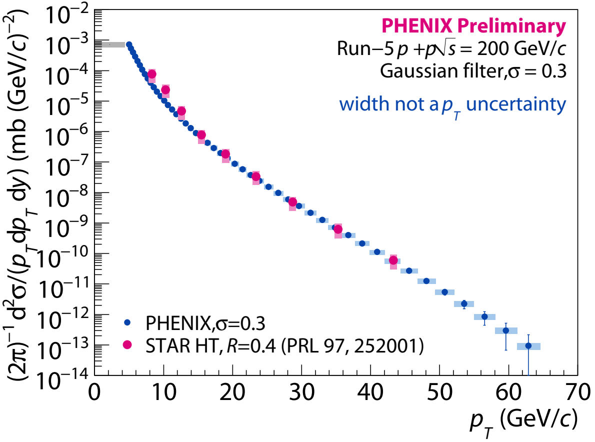


Run-5 $p + p$ spectrum



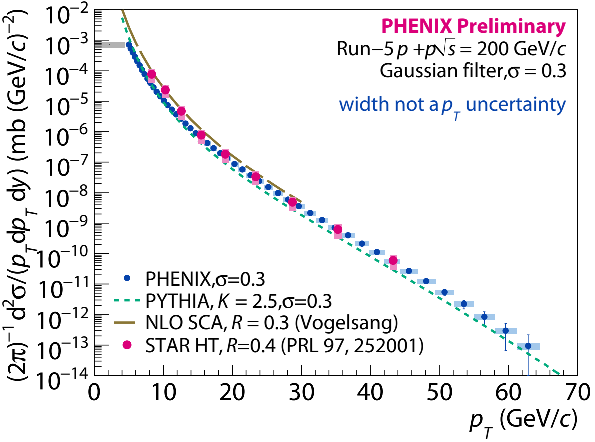
- Rate sufficient to measure 10 orders of magnitude

Run-5 $p + p$ spectrum



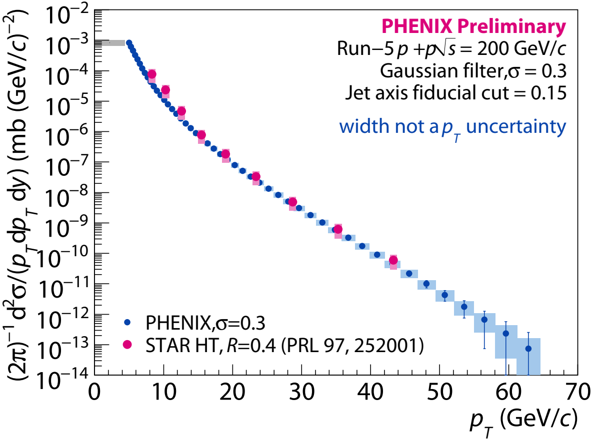
- Cross section consistent with STAR HT, but $\approx$ 20 GeV/c further p_T reach

Run-5 $p + p$ spectrum



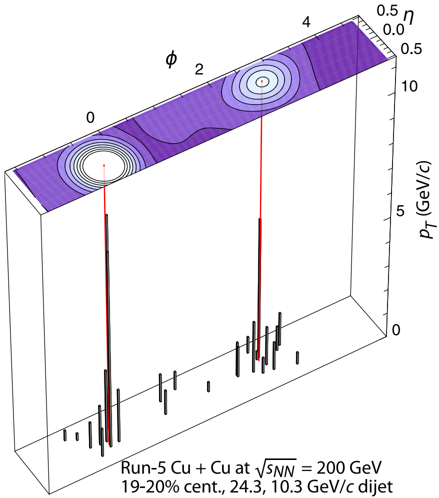
- NLO calculation for larger p_T range and using filter is needed

Effect of the PHENIX detector edge



- Cross section remains consistent when lookin only at jets 0.15 in $\Delta\eta$, $\Delta\varphi$ from the detector edge
- Residual systematic effect $\approx$ 15%, $\ll$ systematics due to energy scale

Event display, Cu + Cu



Jet reconstruction in RHIC heavy ion: fake jets

- Large $dN/d\eta$, small jet σ_{pp} (vs. LHC):

  $\Rightarrow$ Cu + Cu central jet yield at 10 GeV/c,

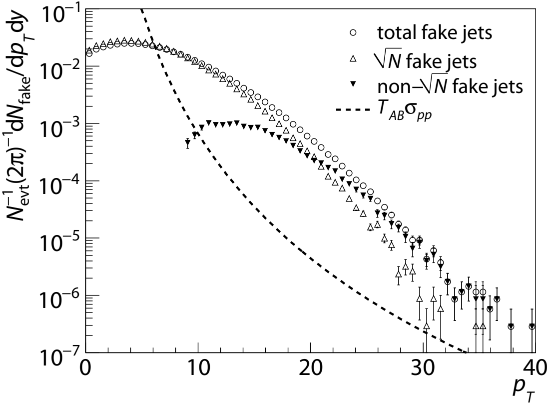
$$\frac{1}{2\pi}\frac{1}{N_{\mathrm{evt}}}\frac{dN}{p_T dp_T dy} \approx 10^{-6}(\mathrm{GeV}/c)^{-2}:$$

  $\Rightarrow$ Several approach are proposed/may be suitable for jet reconstruction:

  1. Reconstruct only very high p_T jets
  2. Apply a large p_T cut on fragments
  3. Statistically subtract the background
  4. Direct rejection of fake jets

- Approach (4) is preferred by PHENIX:
  - Low and controllable biases
  - Residual systematic errors easier to estimate/correct

QCD background: $\sqrt{N}$?



- $\sqrt{s_{NN}} = 200$ GeV Au + Au HIJING
- Most of the high p_T portion not $\sqrt{N}$ fluctuation, yield well above $T_{AB}\sigma_{pp}$
- HIJING background may be overly pessimistic, but demonstrates:
  - $\Rightarrow$ **$\sqrt{N}$ a highly dangerous assumption**

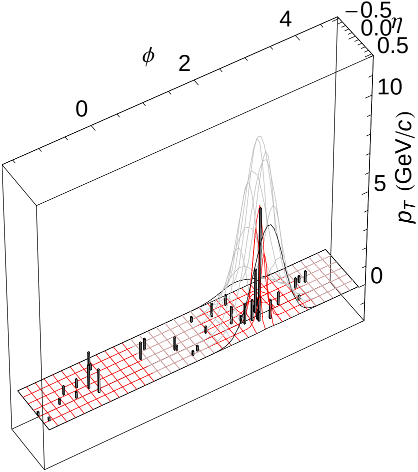
Gaussian fake rejection

- Cut on the overall shape of the jet
- Inspired by the principle of Gaussian filter
- Strategy:
  1. Sum p_T^2 inside a Gaussian kernel to obtain a discriminant:

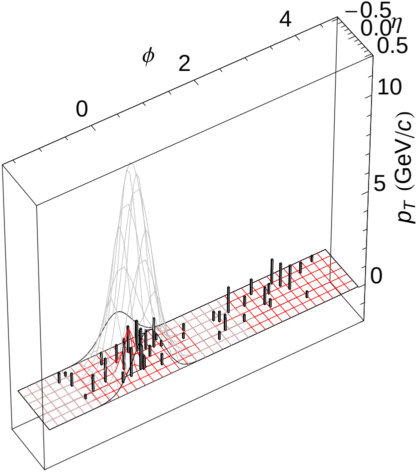
$$g_{\sigma_{\text{dis}}}(\eta, \varphi) = \sum_{i \in \text{fragment}} p_{T,i}^2 \exp\left[-\frac{(\eta_i - \eta)^2 + (\varphi_i - \varphi)^2}{2\sigma_{\text{dis}}^2} \right],$$

  2. Gaussian kernel $\sigma_{\text{dis}} \approx 0.1$
  3. (Technical detail: allow adaption for jets with very close maxima, obtain an updated $g'_{\sigma_{\text{dis}}}$)
- Cut on $g'_{0.1} =$ weighted p_T^2-sum
- In central Au + Au HIJING simulation proves to be more effective than $\sigma/\sqrt{\langle A \rangle}$ (Cacciari & Salam, Phys. Lett. B **659**, 119, 2008) and Σj_T (Grau *et al.*, arXiv:0810.1219, 2008)

Principle of fake rejection

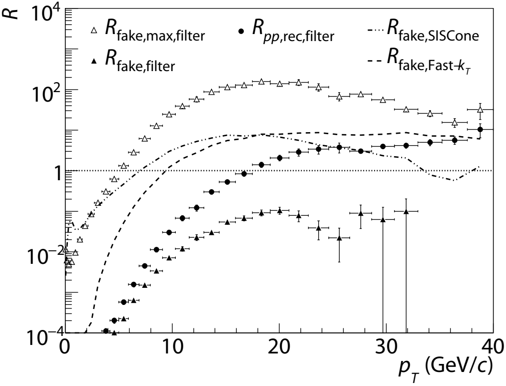


9.6 GeV/c jet passing fake rejection



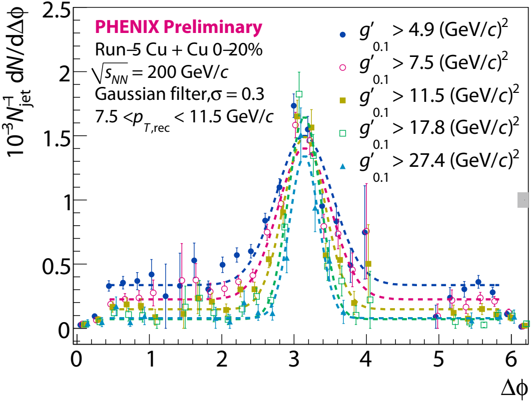
Rejected 10.8 GeV/c background fluctuation

Fake rejection in HIJING central Au + Au



- Filter with Gaussian fake rejection compared to
  - $k_\perp$ with $1/\sqrt{A}$ (Cacciari & Salam, Phys. Lett. B 659, 119, 2008)
  - SISCone with Σj_T (Grau *et al.*, arXiv:0810.1219, 2008)
- Filter can efficiently fake reject even in worst-case assumption for Au + Au at RHIC energy

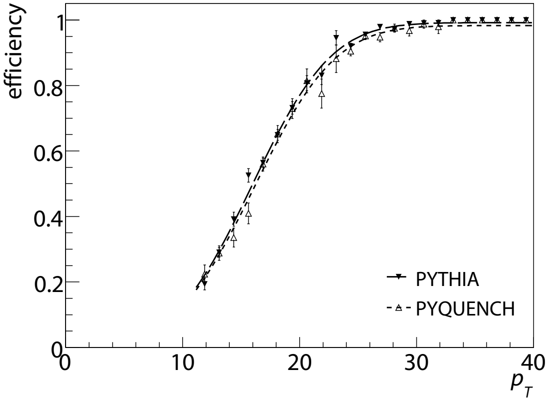
Fake rejection in Cu + Cu



- Pedestal $\approx 0.3 \times 10^{-3}$ translates into $\frac{1}{2\pi} \frac{1}{N_{\mathrm{evt}}} \frac{dN}{p_T dp_T dy} \approx 10^{-5} (\mathrm{GeV}/c)^{-2}$, substantial contamination for 7.5 GeV/c
- 17.8 $(\mathrm{GeV}/c)^2$ used as standard fake rejection cut level:
  $\Rightarrow$ $<$ 10% contamination at 7.5 GeV/c

Fake rejection in PYQUENCH

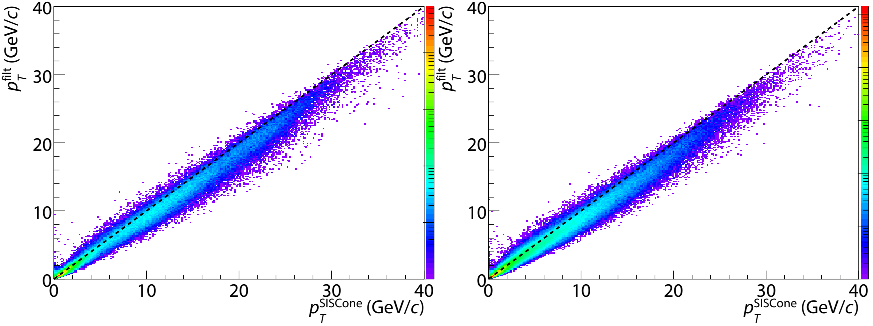
- Fake rejection at $g'_{0.1} > 54\,(\mathrm{GeV}/c)^2$ for central Au + Au:



- Impact of PYQUENCH is negligible, efficiency dominated by QCD fragmentation
- Also observed by the ATLAS collaboration (Grau *et al.*, arXiv:0810.1219, 2008)

Energy scale in PYQUENCH

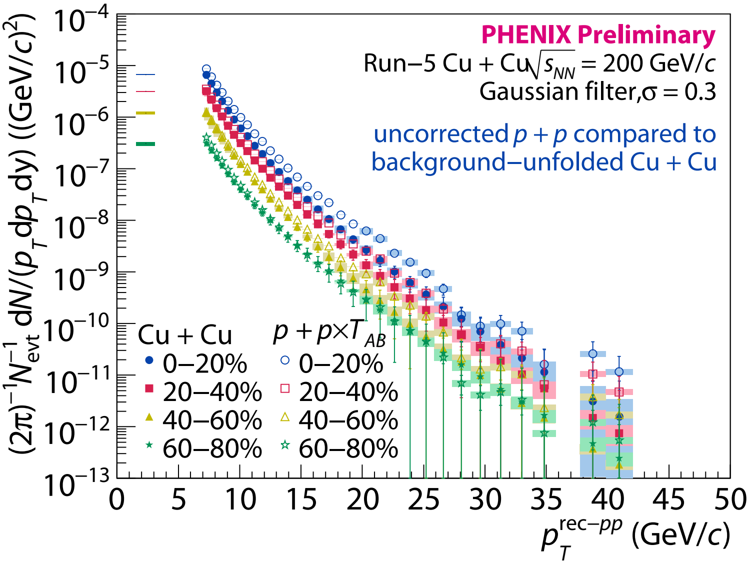
- Is the $\sigma = 0.3$ Gaussian filter losing significant out of cone energy for a typical quenched jet – than traditional algorithms?
- Compare $\sigma = 0.3$ Gaussian filter against $R = 0.4$ SISCone:



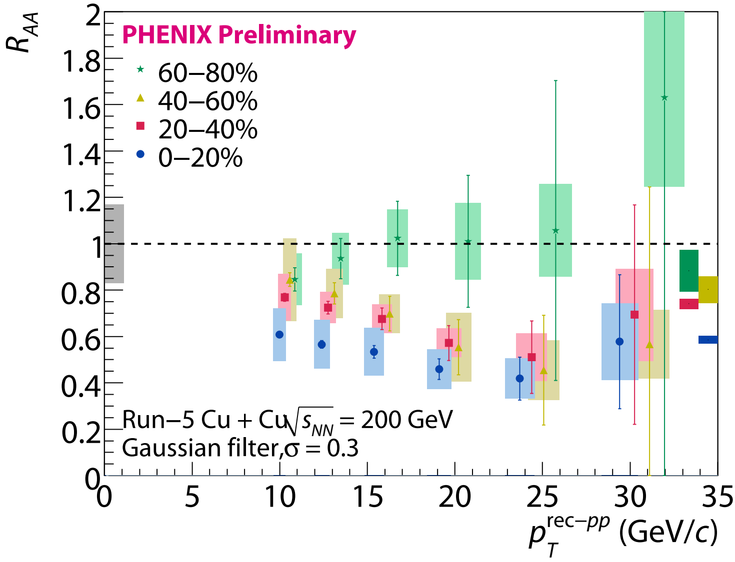
PYTHIA PYQUENCH

- The difference is very subtle, $\approx 5\%$ at 15 GeV/c

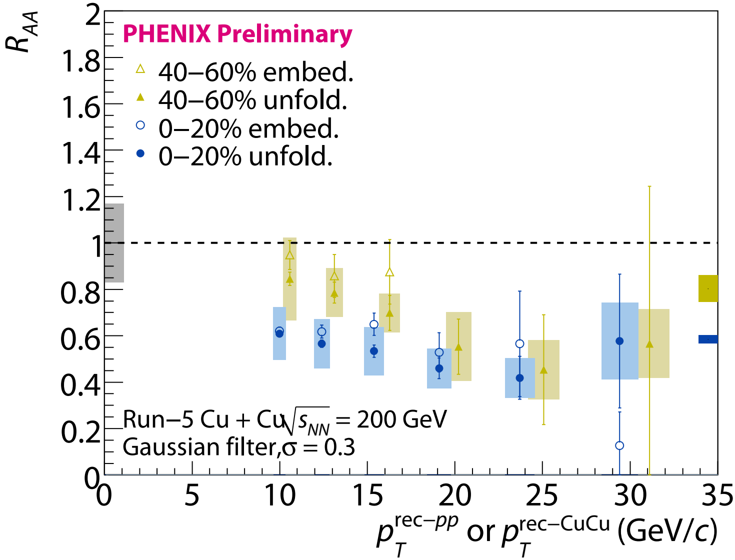
Run-5 Cu + Cu spectra with fake rejection



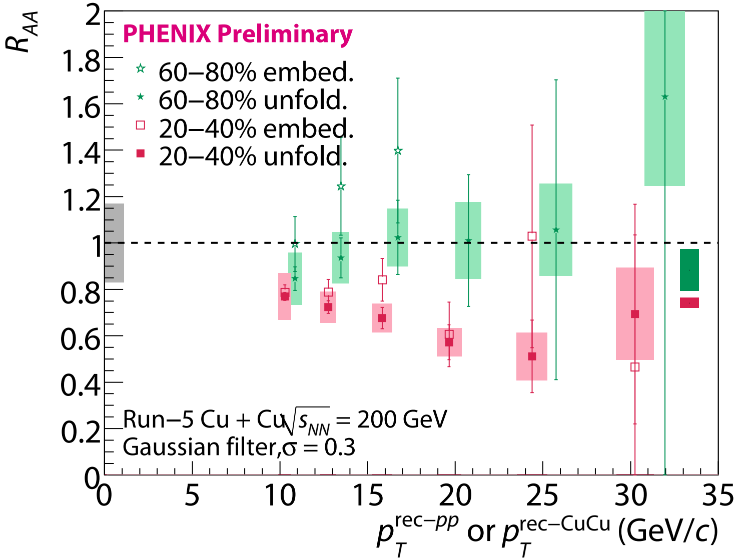
Run-5 Cu + Cu R_{AA}



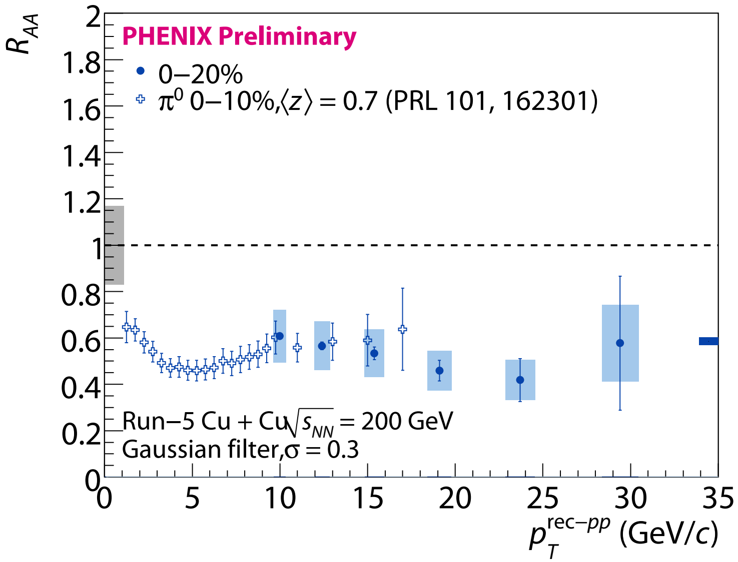
Run-5 Cu + Cu R_{AA} compared to embedding



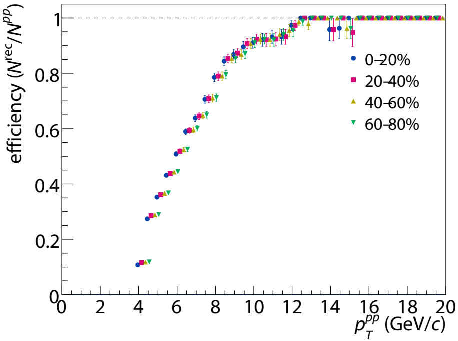
Run-5 Cu + Cu R_{AA} compared to embedding

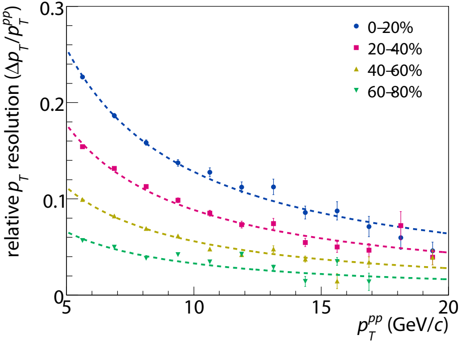


Run-5 Cu + Cu R_{AA} compared to π^0



$p + p$ embedding in Cu + Cu: performance

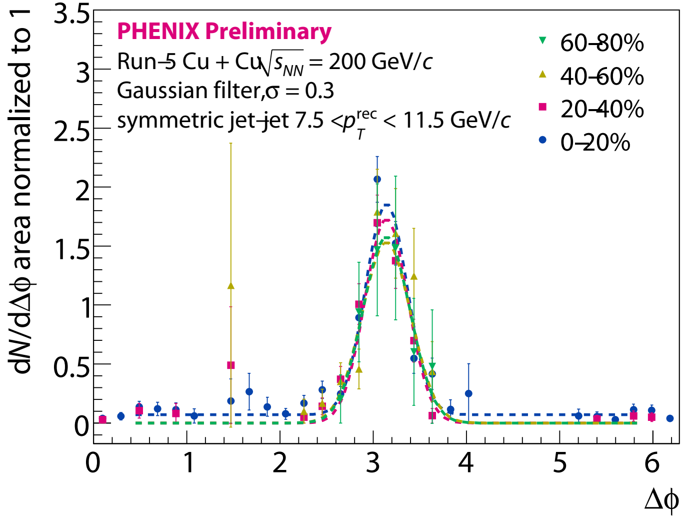




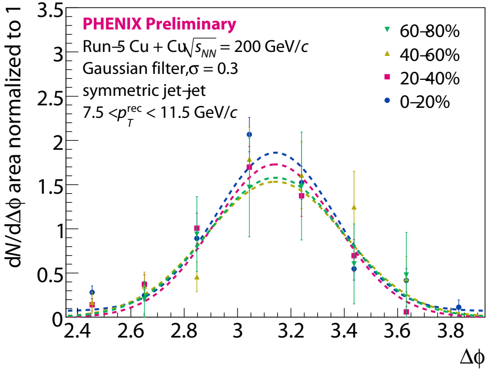
Several desirable properties for heavy ion jet reconstruction:

- Fast saturation to unitary efficiency
- **Negligible centrality dependence of jet reconstruction efficiency**
  - Efficiency includes the fake rejection
- The energy resolution follows $1/p_T$

Cu + Cu jet–jet azimuthal correlation



Cu + Cu jet–jet azimuthal correlation



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

Summary & outlook

- Fake jets must be removed even in Cu + Cu at $\sqrt{s_{NN}} = 200$ GeV
- Gaussian filter with the Gaussian fake rejection ($\sigma_{\mathrm{dis}} = 0.1$) a highly effective algorithm for jet reconstruction at RHIC energy
- High-rate, accurate calorimeter makes PHENIX suitable for jet physics

- PHENIX is studying the medium using a uniquely suitable jet reconstruction algorithm with wide p_T range coverage, high efficiency, and low fake rate
- Obtained first measurement of $p + p$ spectrum at RHIC upto 60 GeV/c, across 10 orders of magnitude
- Obtained first measurement of the dijet angular correlation in Cu + Cu collisions
- Obtained first measurement of the jet R_{AA} in Cu + Cu collisions
- Cu + Cu a stepping stone in understanding heavy ion jet reconstruction
  - ⇒ We are intrigued by the current Cu + Cu results, and aim at understanding its physics implication before moving on to Au + Au
  - We are on the verge of other measurements of jet modification
    - ⇒ fragmentation function
    - ⇒ j_T distribution

Part I

Backup

Zeroth + first order sum p_T (Run-5 $p + p$ ERT)

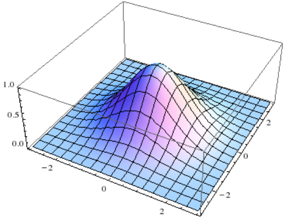
Flat (1D) integration:

$$\int dx\, p_T(x) = \int dx\, e^{x^2/(2\sigma)} e^{-x^2/(2\sigma)} p_T(x)$$
$$= \underbrace{\int dx\, e^{x^2/(2\sigma)} p_T(x)}_{p_T^0} + \underbrace{\frac{1}{2\sigma} \int dx\, x^2 e^{x^2/(2\sigma)} p_T(x)}_{p_T^1} + \ldots$$

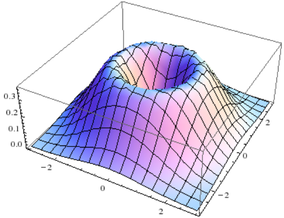
- $p_T^1 \lll p_T^0$ demonstrates that Gaussian filter is not losing significant amount of energy
- p_T^1 is closely related to the jet width, possible interesting physics

Zeroth + first order sum p_T (Run-5 $p + p$ ERT)

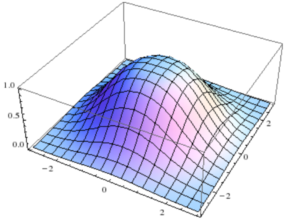
In pictures:



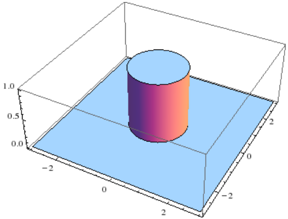
p_T^0 weight



p_T^1 weight

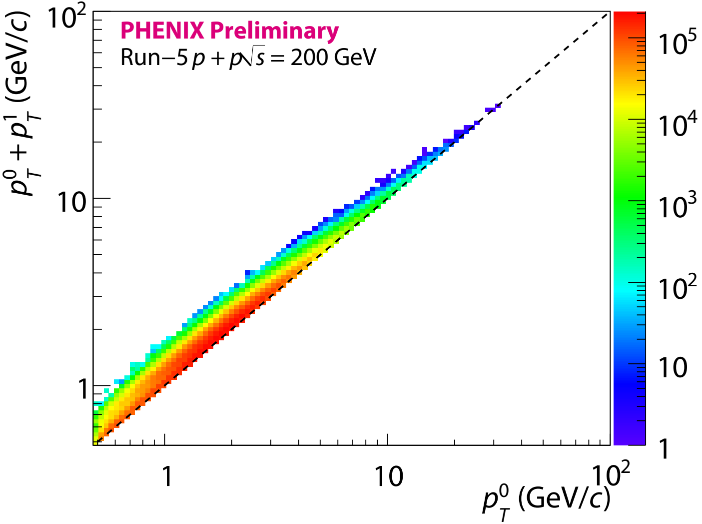


$p_T^0 + p_T^1$ weight

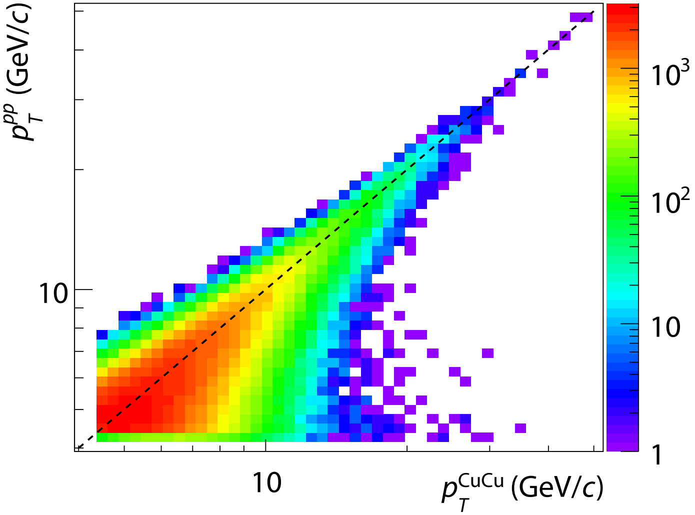


cone

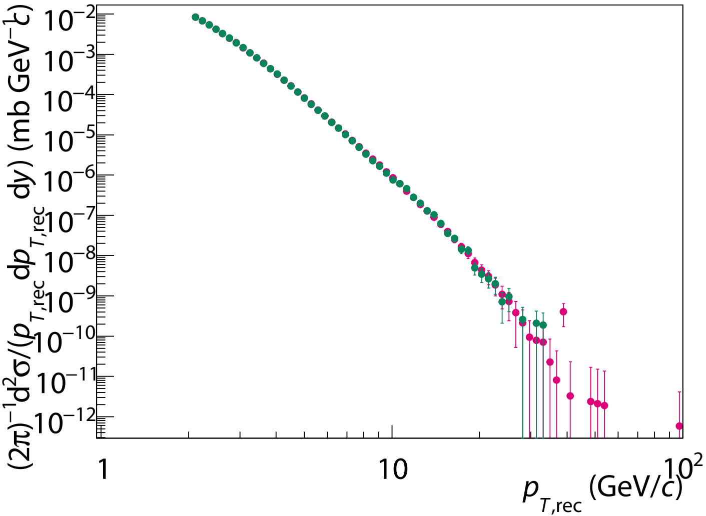
Zeroth + first order sum p_T (Run-5 $p+p$ ERT)



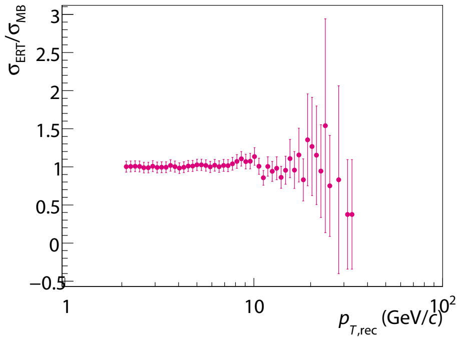
$p + p$ to Cu + Cu transfer matrix, 0–20% centrality

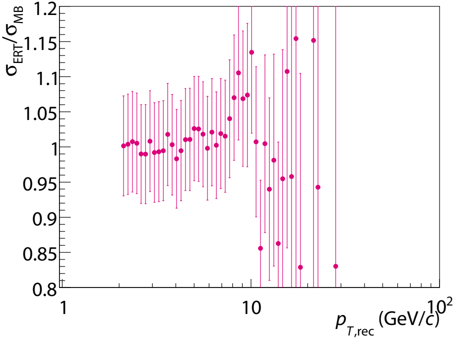


PHENIX ERT vs. minimum bias trigger

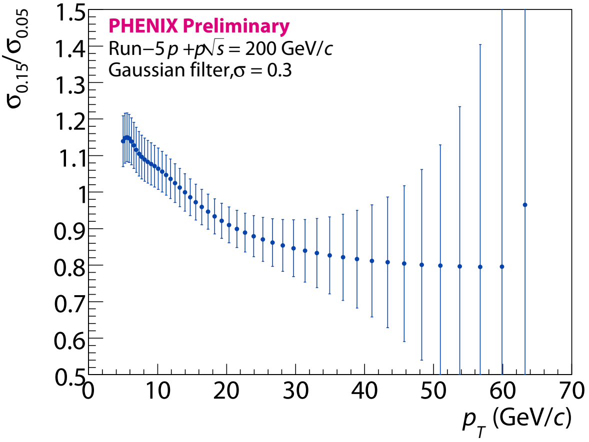


PHENIX ERT vs. minimum bias trigger





Effect of the PHENIX detector edge



Energy scale in PYQUENCH