Characterization of energy loss by direct jet reconstruction in $p + p$ and Cu + Cu at PHENIX

Yue Shi Lai, for the PHENIX Collaboration

Columbia University and Nevis Laboratories

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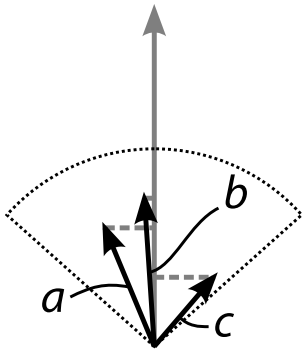
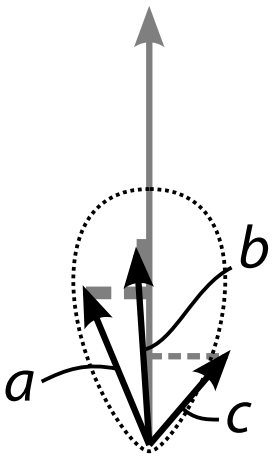
Gaussian filter



Cone

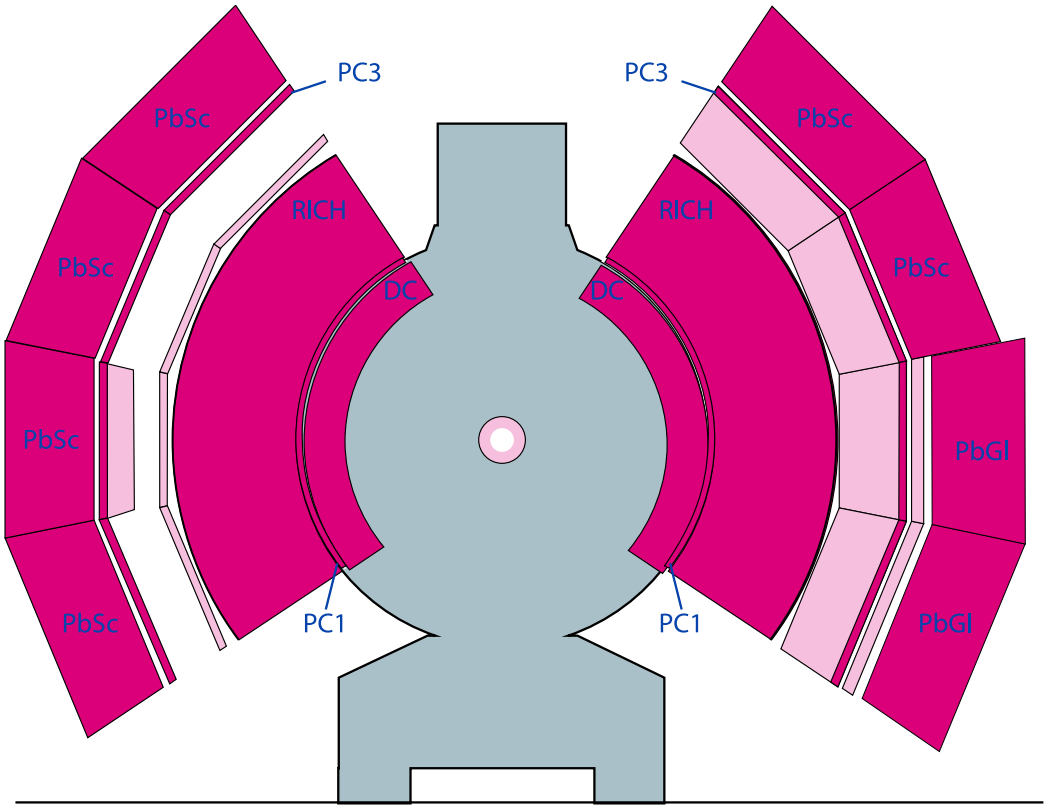
$$\iint_{\mathbb{R}\times S^1} d\eta' d\varphi' p_T(\eta', \varphi') \exp\left[-\frac{(\eta-\eta')^2+(\varphi-\varphi')^2}{2\sigma^2}\right] = \text{max!}$$



Filter

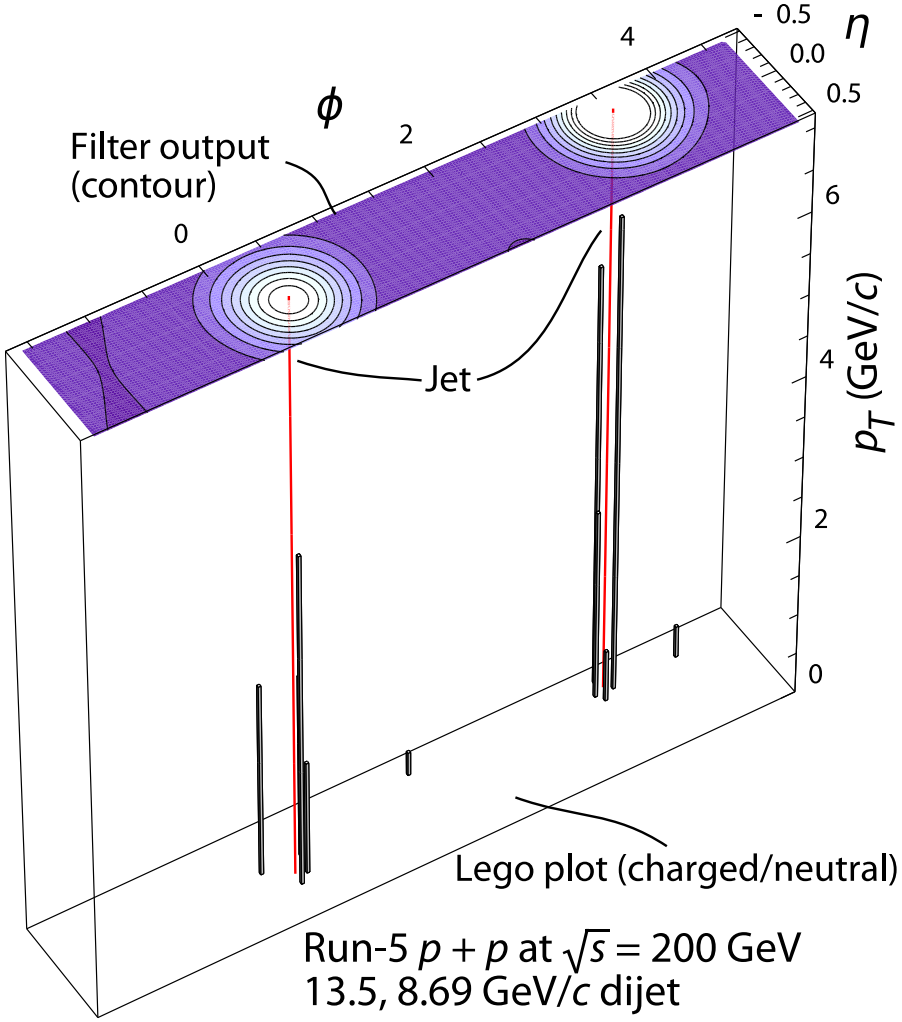
- Seedless
- Cone-like, but without infrared and collinear unsafety from hard angular cut-off
- Shape of the filter:
  - Optimizes the signal-to-background by focusing on the core of the jet
  - Stabilizes the jet axis in the presence of background
- Naturally handles isolated particles vs. collective background

Jet reconstruction in PHENIX Run-5

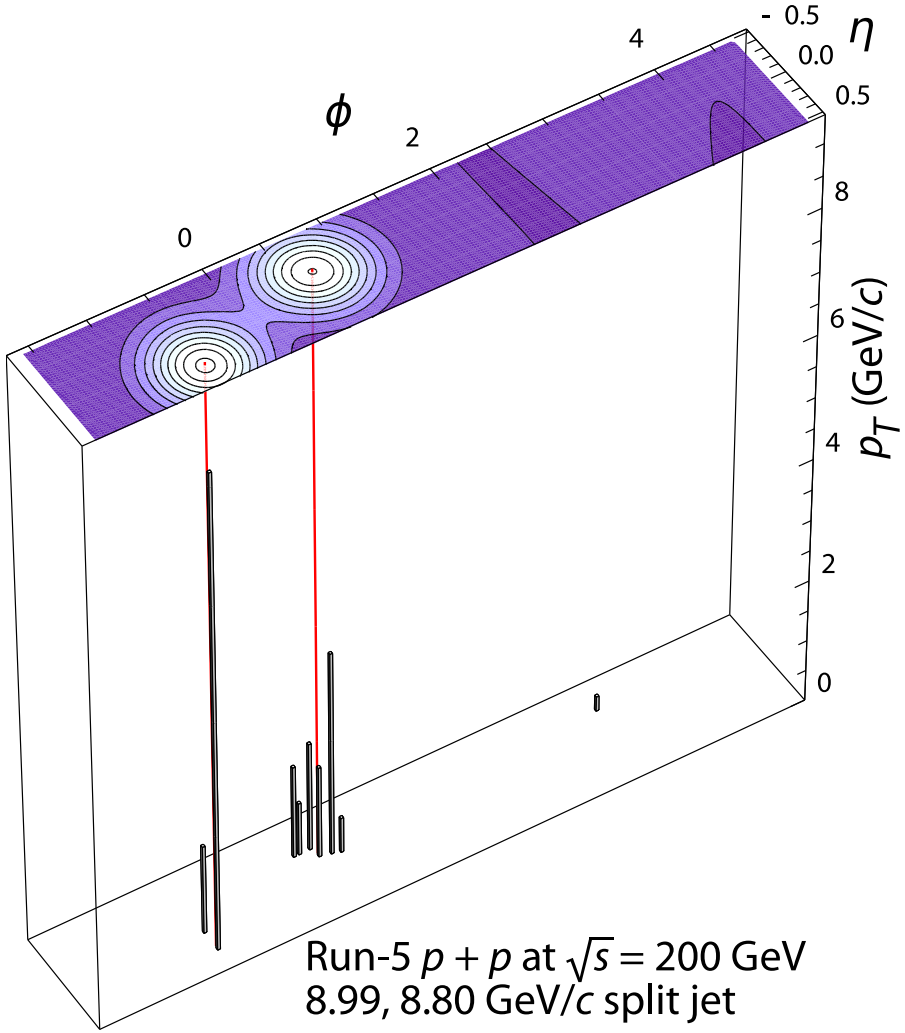


- Data set: PHENIX Run-5 $p + p$ at $\sqrt{s} = 200$ GeV, Cu + Cu at $\sqrt{s_{NN}} = 200$ GeV
  - Tracking detectors: Drift Chamber (DC), Pad Chambers (PC) 1/3, RICH
  - Calorimeters: Lead-Scintillator (PbSc), Lead-Glass (PbGl)
- Gaussian kernel with $\sigma = 0.3$

Event display, $p + p$

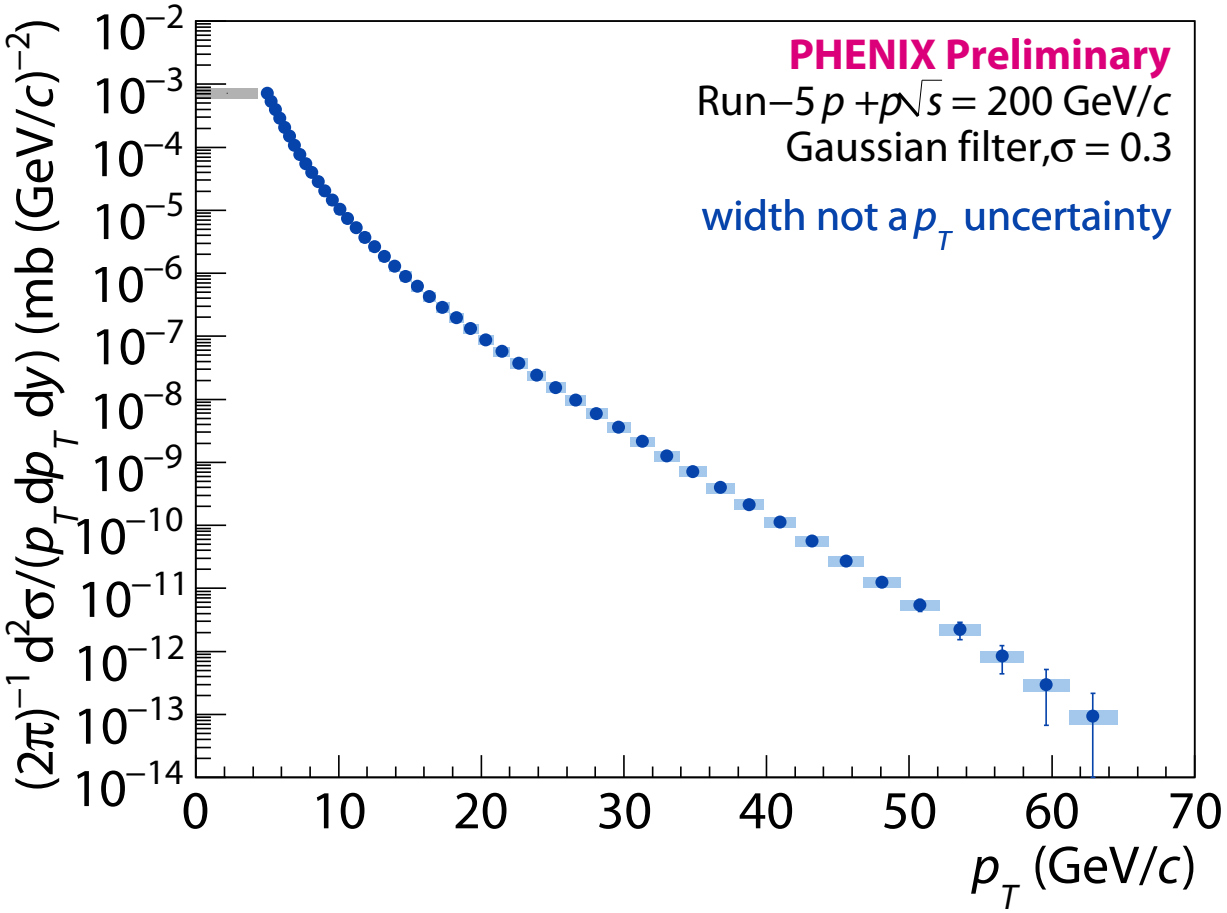


Run-5 $p + p$ at $\sqrt{s} = 200$ GeV
13.5, 8.69 GeV/c dijet



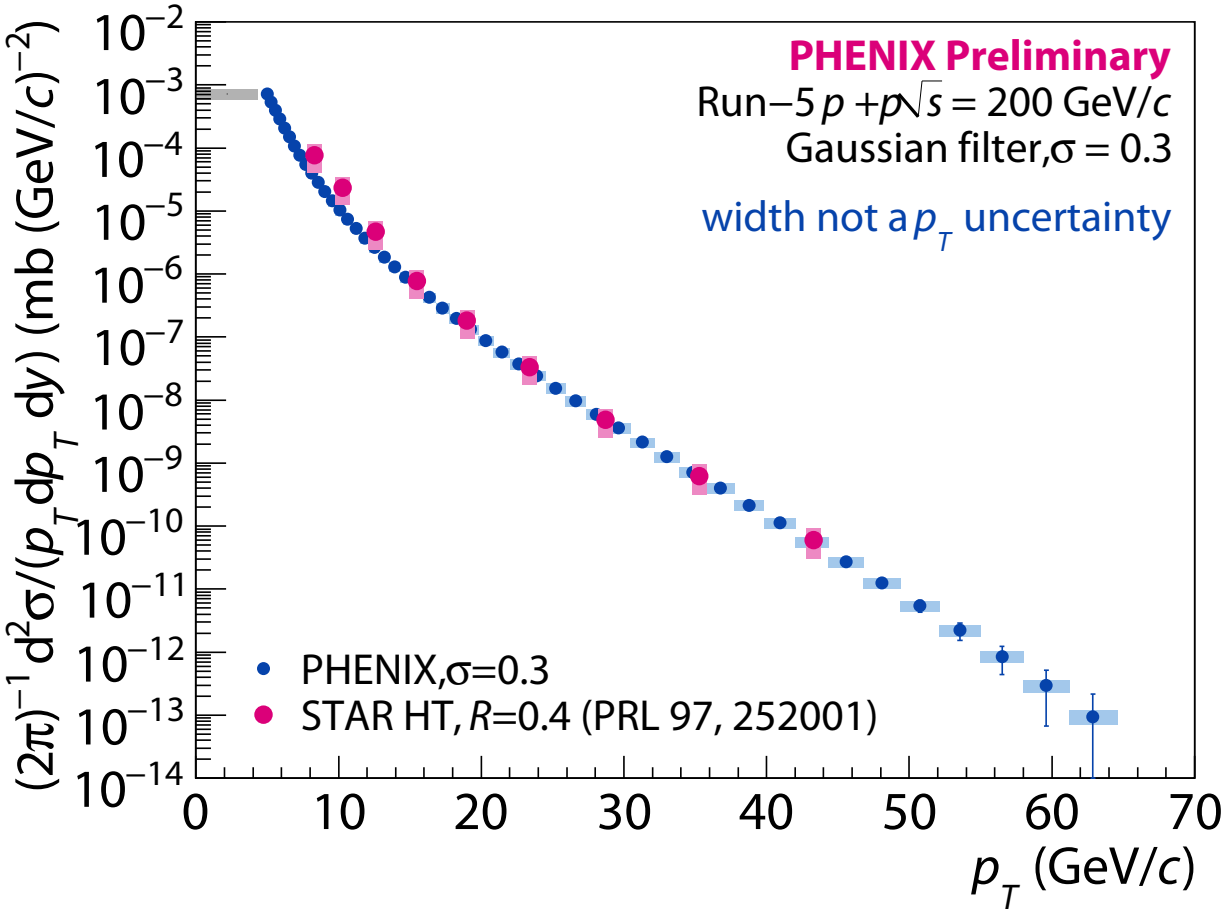
Run-5 $p + p$ at $\sqrt{s} = 200$ GeV
8.99, 8.80 GeV/c split jet

Run-5 $p + p$ spectrum



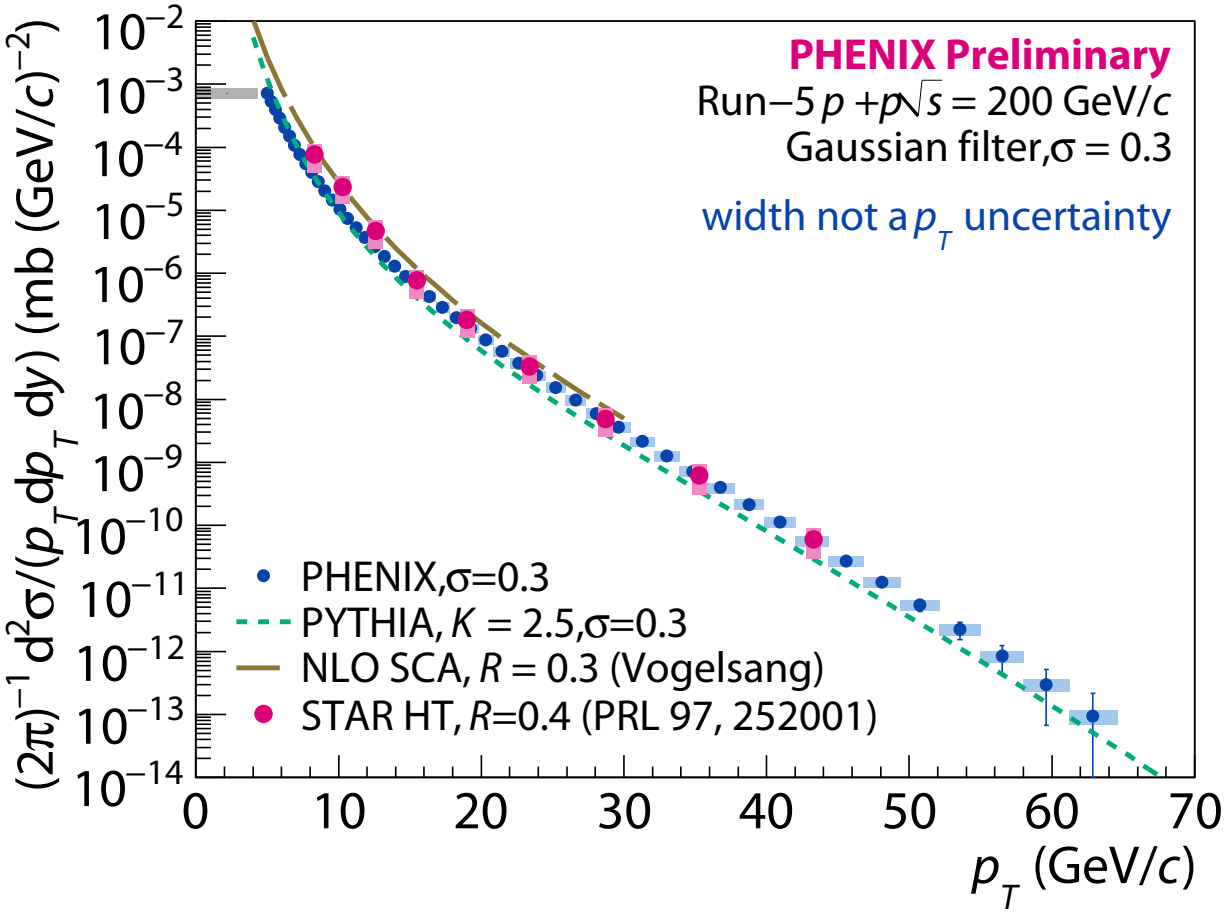
- $\int \mathscr{L} = 2.2\,\mathrm{pb}^{-1}$
- Regularized SVD unfolding (GURU, Höcker & Kartvelishvili, NIM A 372, 469)

Run-5 $p + p$ spectrum



- Cross section consistent with STAR HT, but $x_{\max} \approx 0.6$
- $\sigma = 0.3$ not the same as $R = 0.4$ midpoint cone, but apparently close

Run-5 $p + p$ spectrum



- PYTHIA leading order K and NLO SCA also apples to oranges
- NLO calculation for larger p_T range and using filter is needed

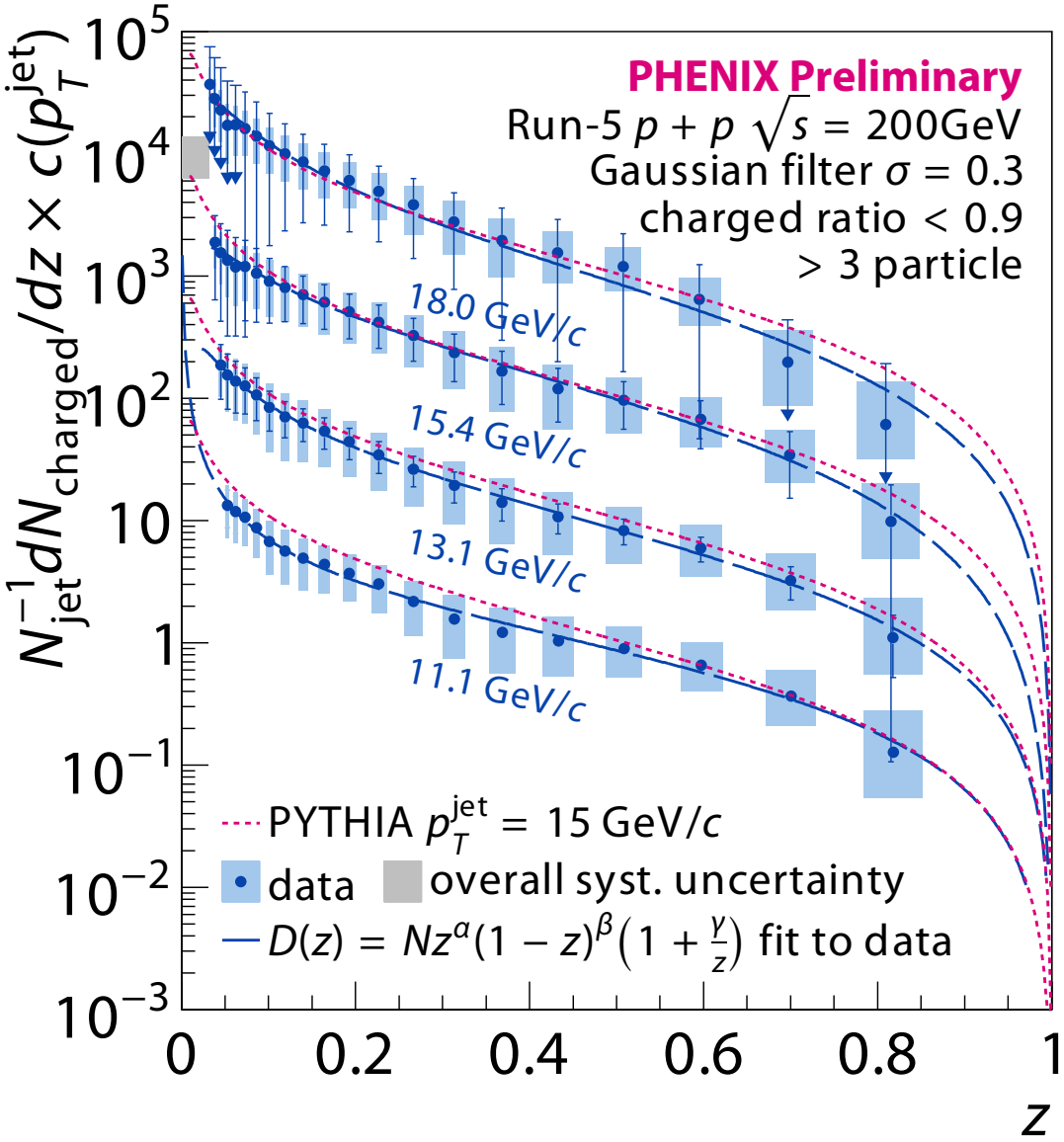
Notes about fragmentation functions

- $z = p_{\parallel}^{\text{particle}} / p^{\text{jet}}$
  - $\Rightarrow$ p^{jet} must be the true jet energy to perform "apple-to-apple" division
  - $\Rightarrow$ Otherwise z is shifted
- 2D unfolding needed to simultaneously unfold $(p_{\parallel}^{\text{particle}}, p^{\text{jet}})$
  - $\Rightarrow$ We developed a n-D generalization to GURU
  - $\Rightarrow$ First time 2D regularized SVD unfolding is applied in HEP

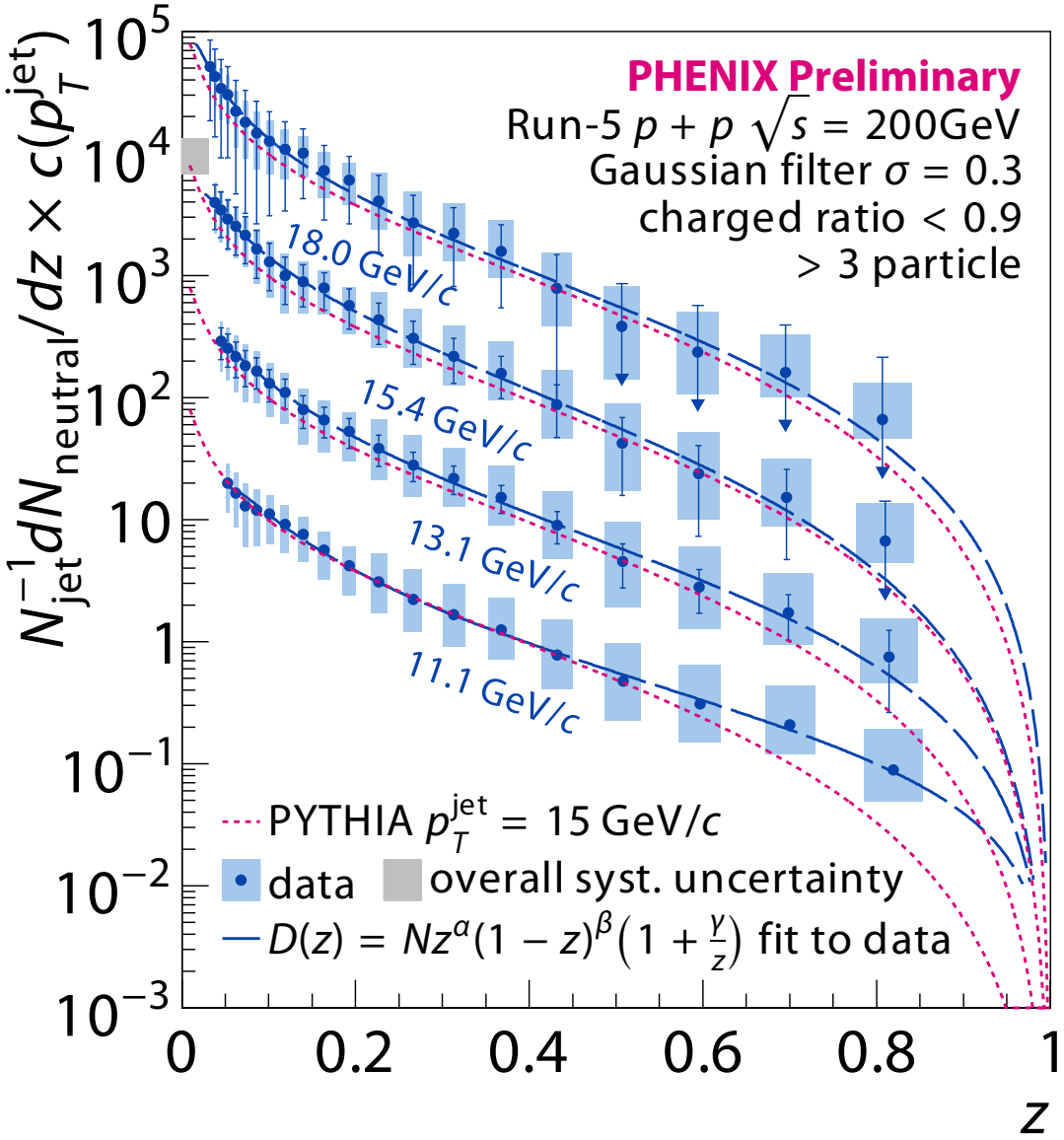
- Data shown uses Run-5 $p + p$ minimum bias (triggered data is in the works)
- Direct comparison to (perfect detector) PYTHIA at $p_T^{\text{jet}} = 15\,\text{GeV}/c$
- Particle species:
  - Non-ID charged tracks (rejecting $e^{\pm}$)
  - Neutral clusters (electromagnetic)
- Single particle resolution not yet unfolded (very small effect)

Run-5 $p + p$ fragmentation function

- **Charged particles (with $e^{\pm}$ rejection)**
- $z = p_{\parallel}^{\text{particle}} / p^{\text{jet}}$
- $c(\cdot) = 10^{i}, i = 0, 1, \ldots$
- Jet cut bias uncorrected, but fully quoted in the systematic uncertainty
- $z_{\max} \approx 0.81$

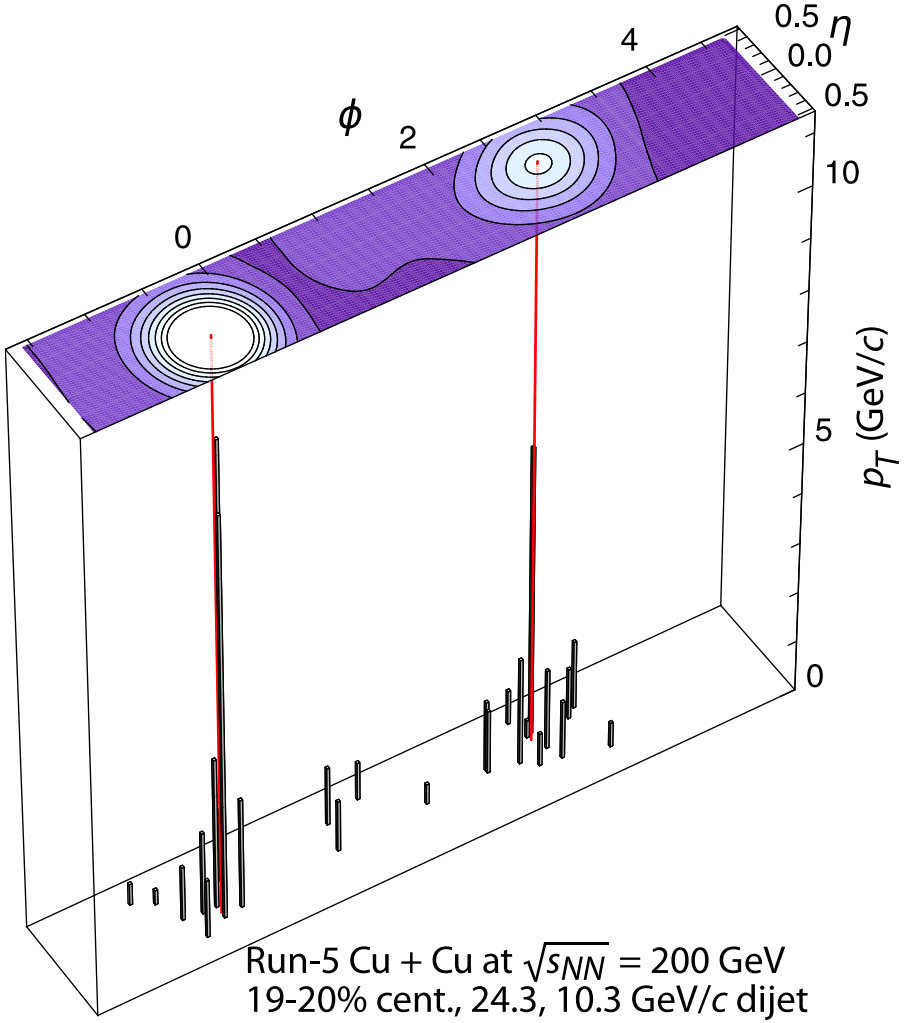


Run-5 $p + p$ fragmentation function

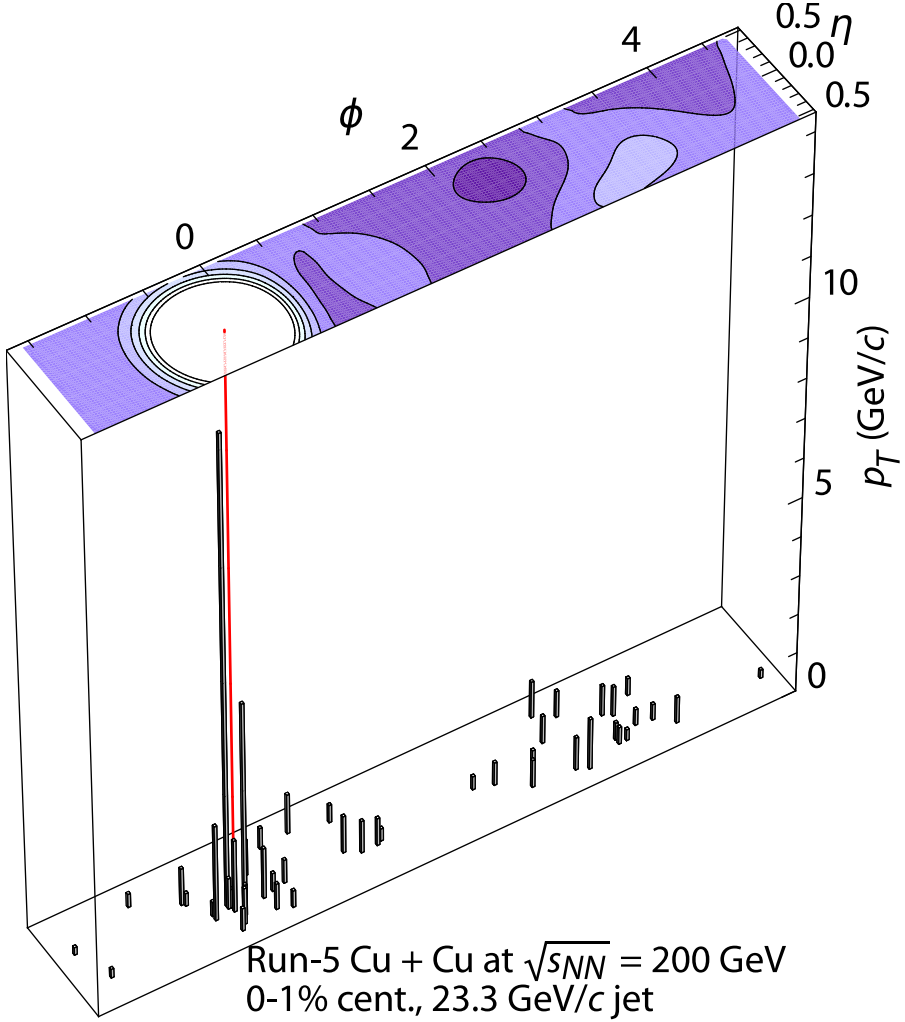


- **Neutral particles (electromagnetic)**
- $z = p_{\parallel}^{particle}/p^{jet}$
- $c(\cdot) = 10^i, i = 0, 1, \ldots$
- Jet cut bias uncorrected, but fully quoted in the systematic uncertainty
- $z_{max} \approx 0.81$

Event display, Cu + Cu



Run-5 Cu + Cu at $\sqrt{s_{NN}}$ = 200 GeV
19-20% cent., 24.3, 10.3 GeV/c dijet



Run-5 Cu + Cu at $\sqrt{s_{NN}}$ = 200 GeV
0-1% cent., 23.3 GeV/c jet

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,

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

  - $\Rightarrow$ 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

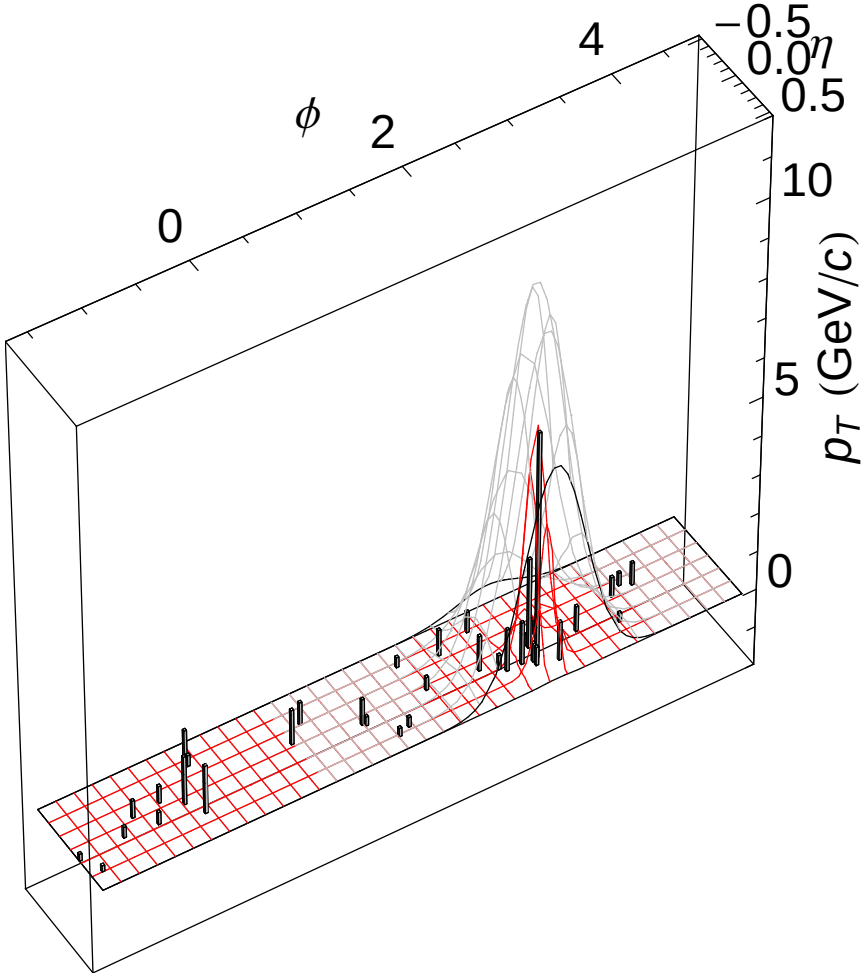
Gaussian fake rejection

- 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:

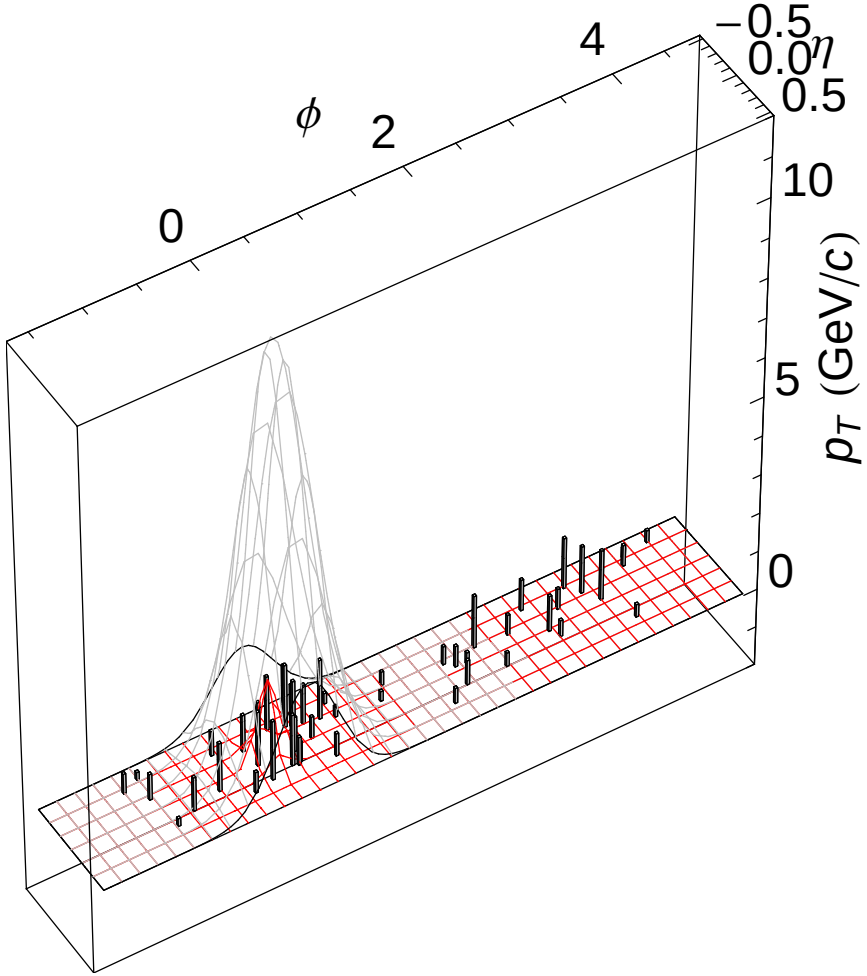
$$g_{\sigma_{\text{dis}}}(\eta, \varphi) = \sum_{i \in \text{fragment}} p_{T,i}^2 \exp\left[-\frac{(\eta_i - \eta)^2 + (\varphi_i - \varphi)^2}{2\sigma_{\text{dis}}^2}\right],$$

  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



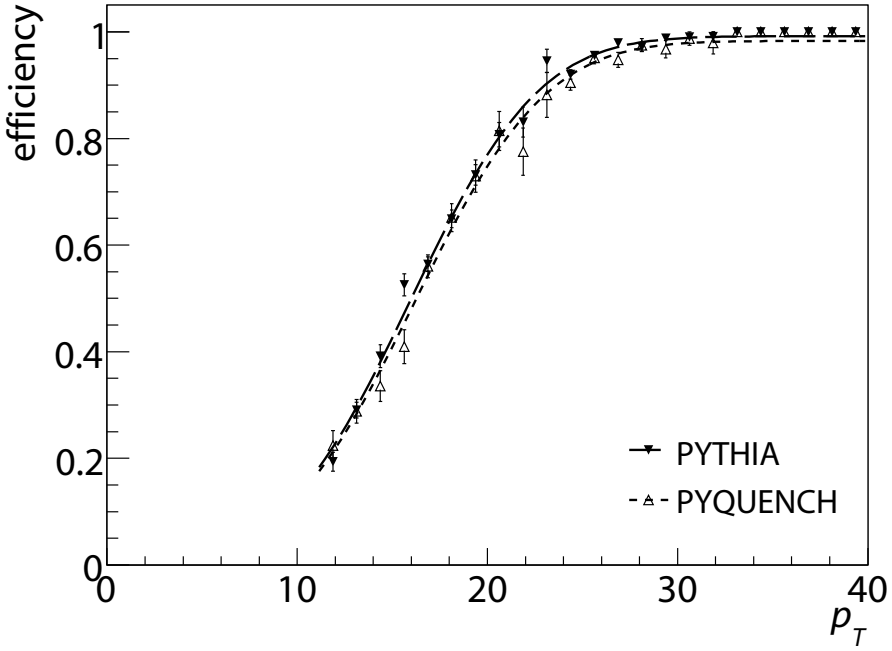
9.6 GeV/c jet passing fake rejection



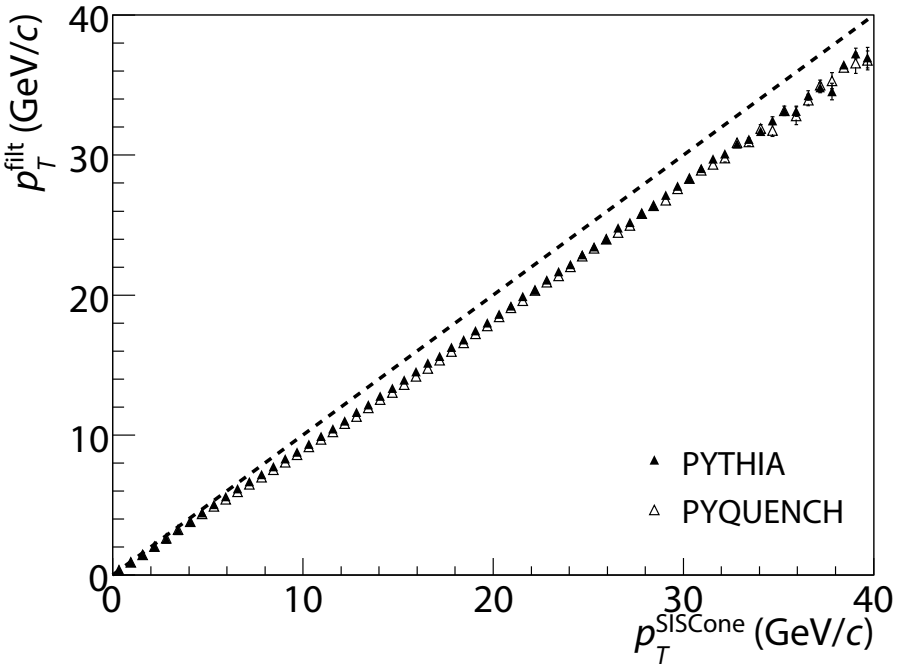
Rejected 10.8 GeV/c background fluctuation

Fake rejection in PYQUENCH

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



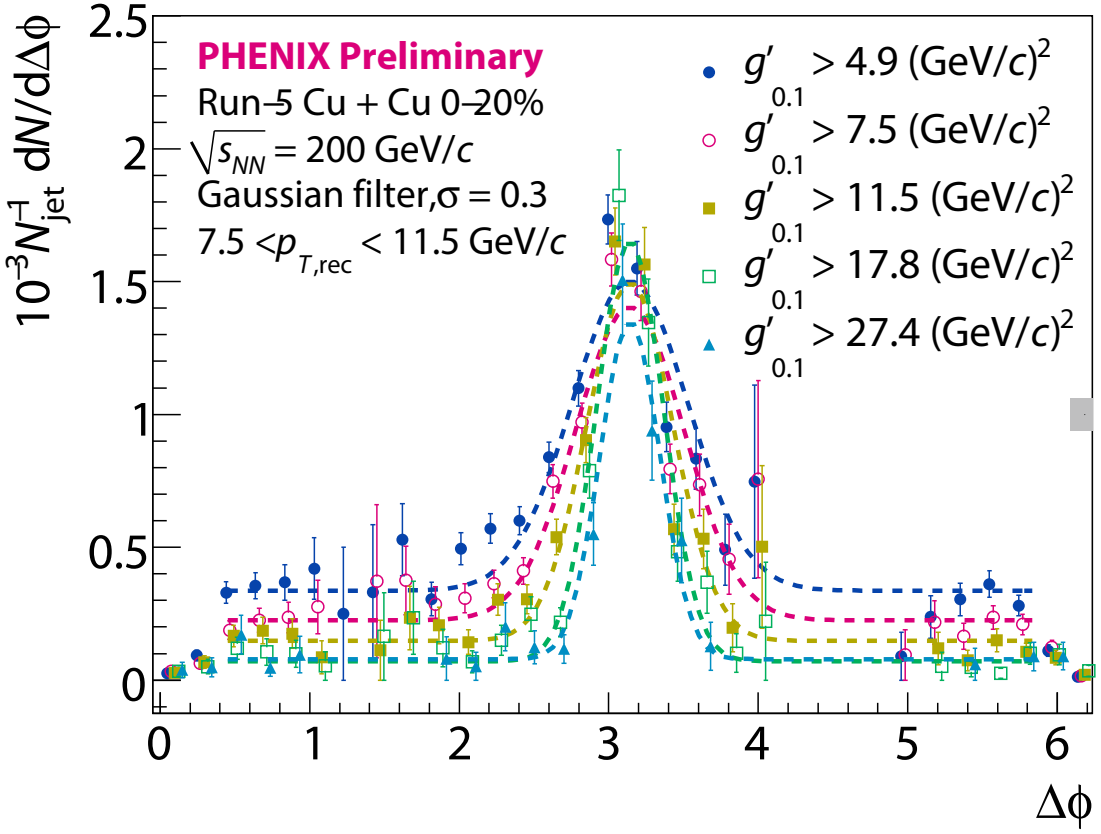
Efficiency turn-on after applying fake rejection



Energy scale $\sigma = 0.3$ Gaussian filter against $R = 0.4$ SISCone

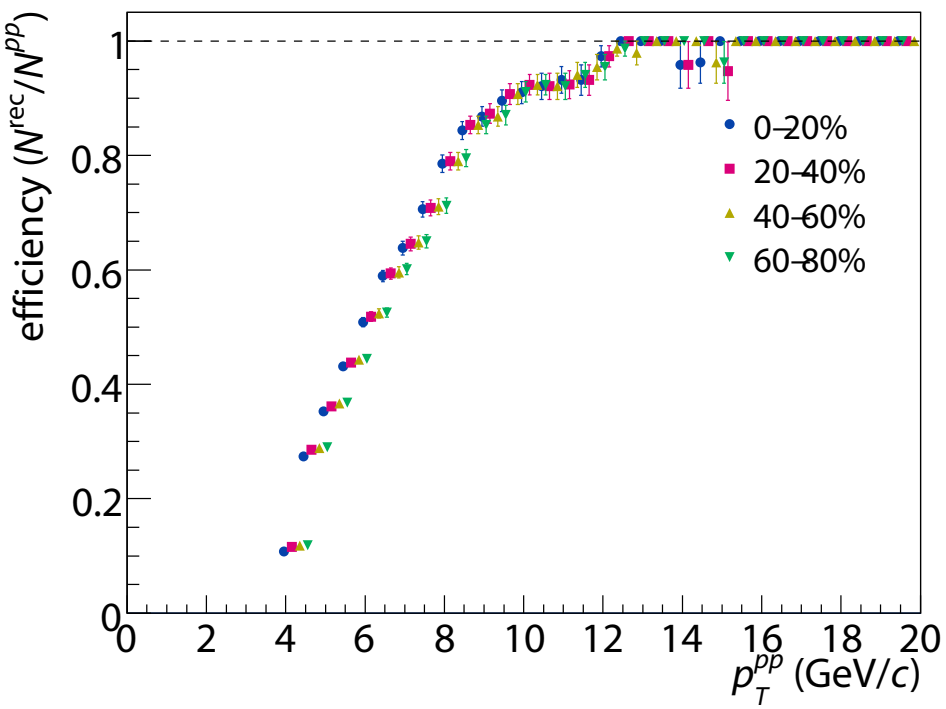
- Difference quenched vs. $p + p$ jets negligible (vs. our current systematics)
- Also observed by the ATLAS Collaboration (Grau *et al.*, arXiv:0810.1219, 2008)

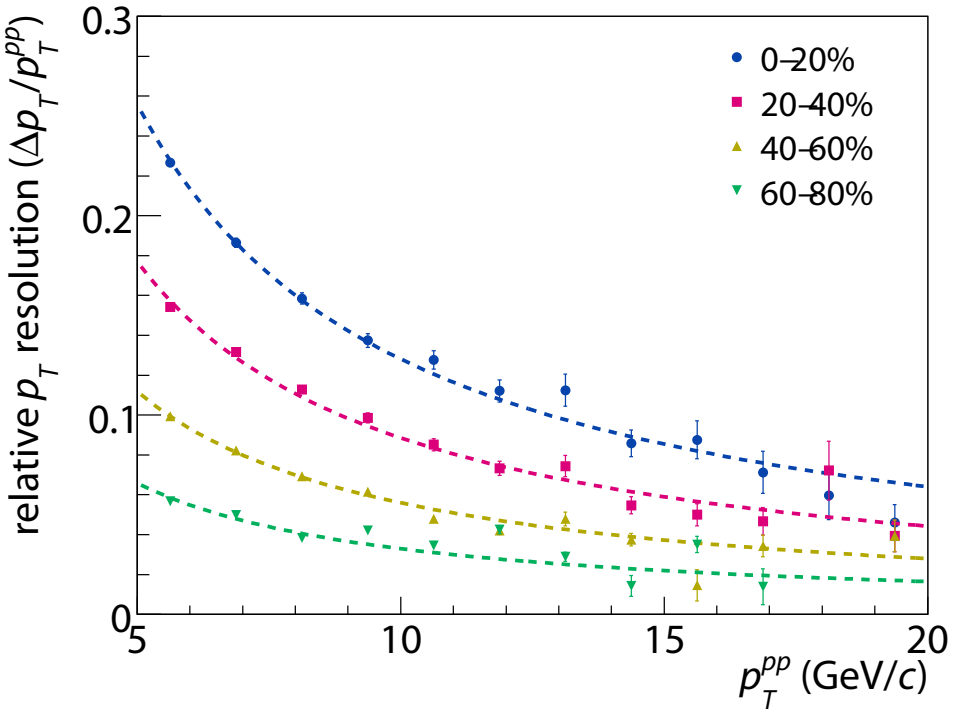
Fake rejection in Cu + Cu



- Pedestal $\approx 0.3 \times 10^{-3}$ translates into $\frac{1}{2\pi}\frac{1}{N_{evt}}\frac{dN}{p_T dp_T dy} \approx 10^{-5}(\mathrm{GeV}/c)^{-2}$, 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

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

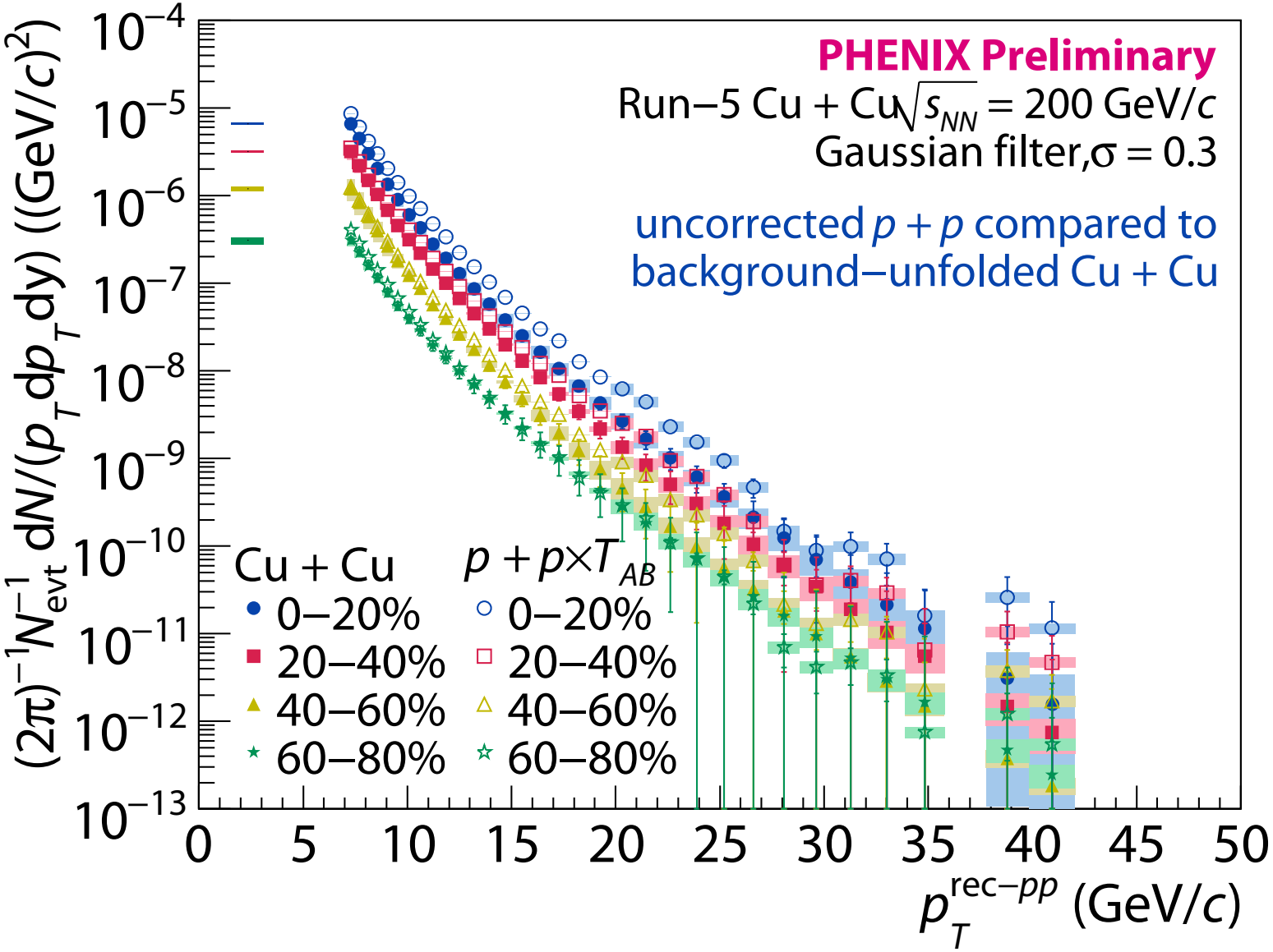




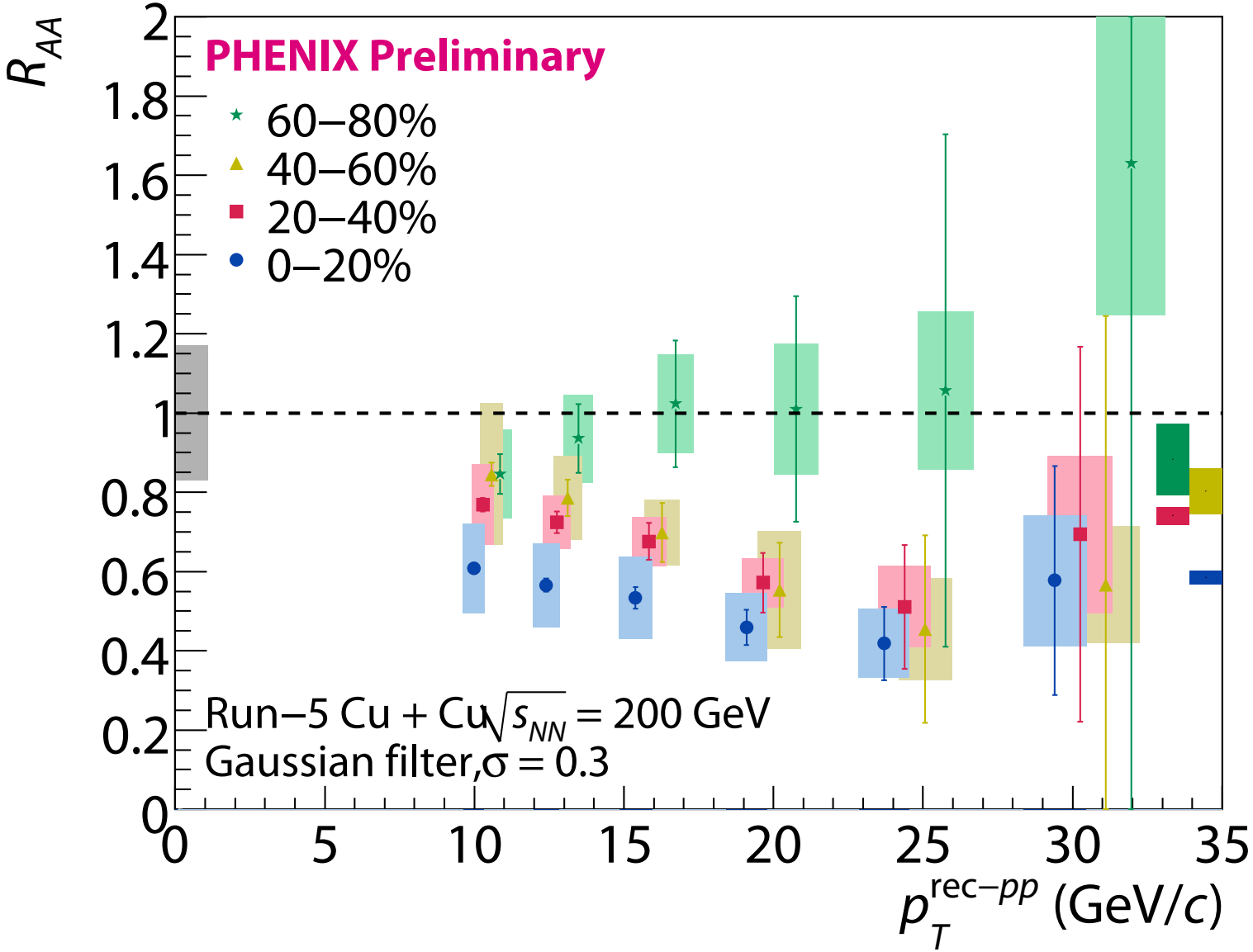
Several desirable properties for heavy ion jet reconstruction:

- Fast saturation to unitary efficiency
- **Negligible centrality dependence of jet reconstruction efficiency**
  - Efficiency includes the fake rejection

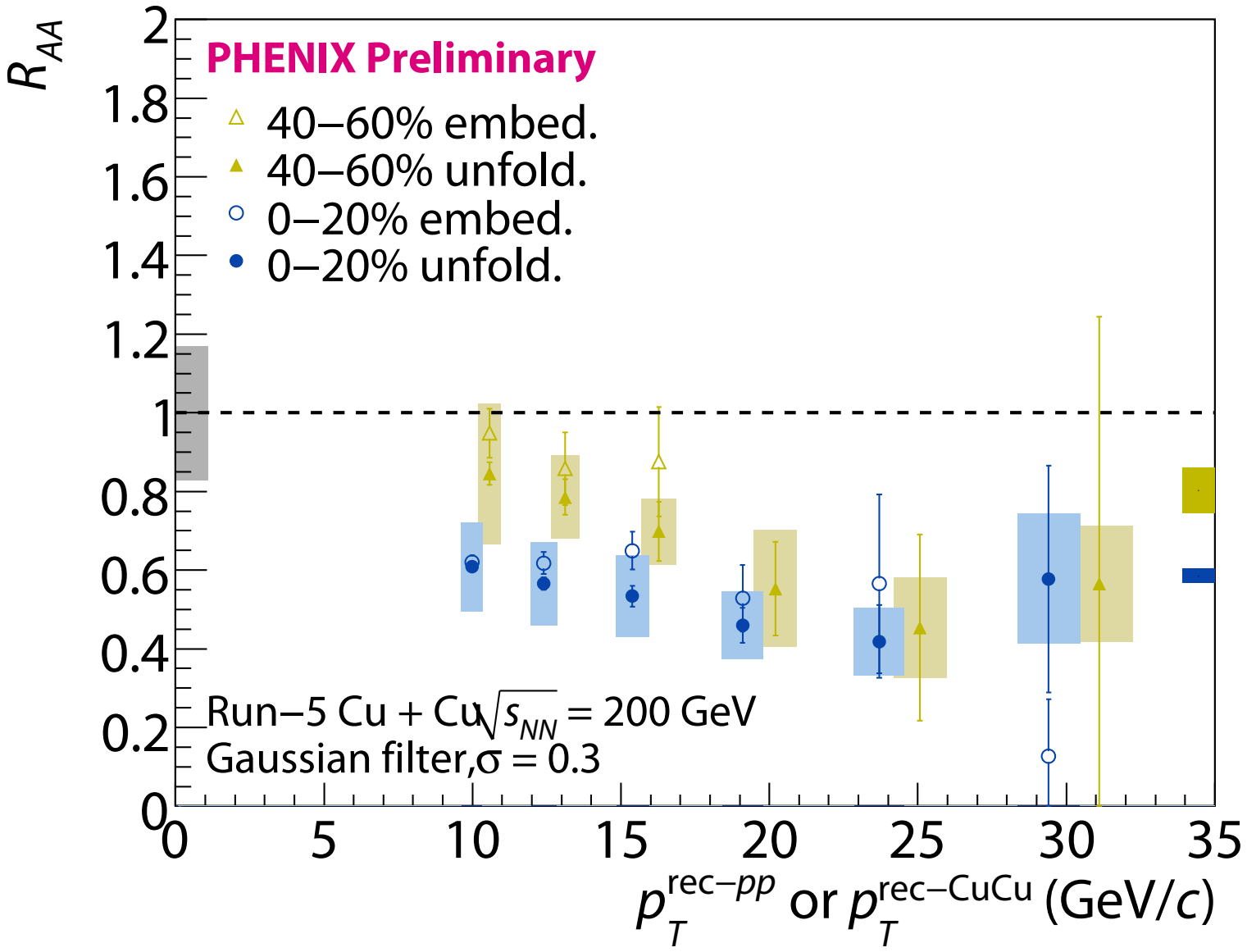
Run-5 Cu + Cu spectra with fake rejection



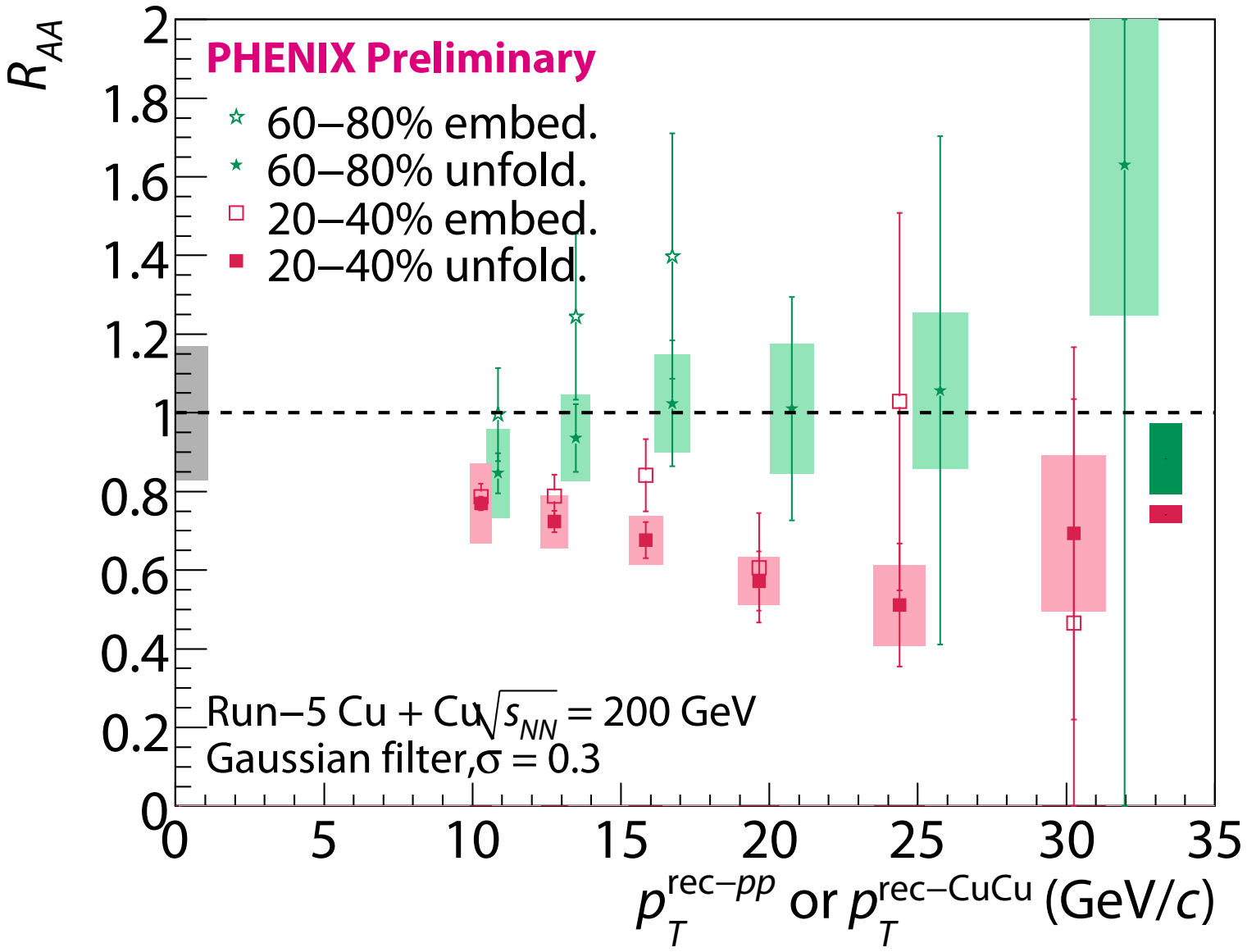
Run-5 Cu + Cu R_{AA}



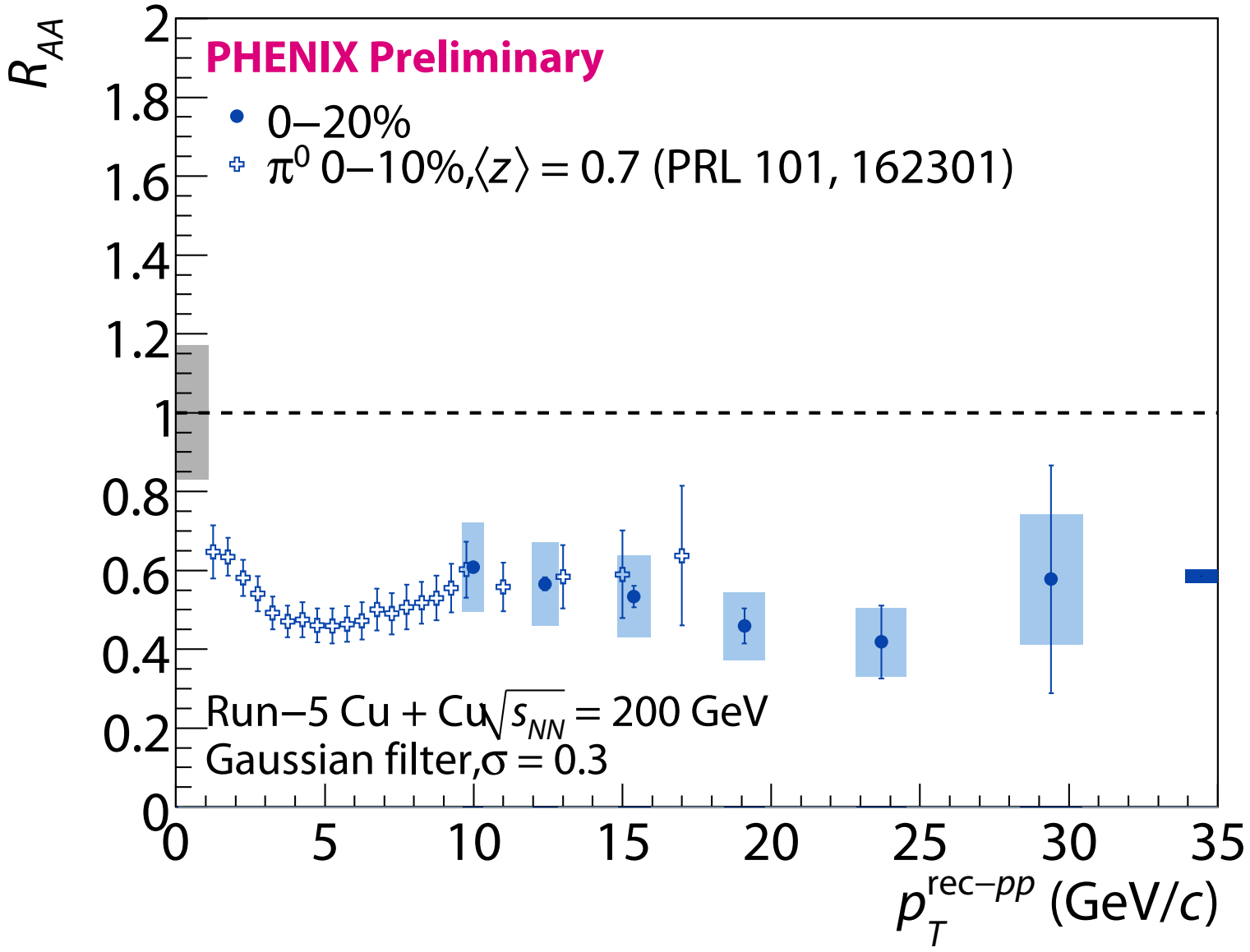
Run-5 Cu + Cu R_{AA} compared to embedding



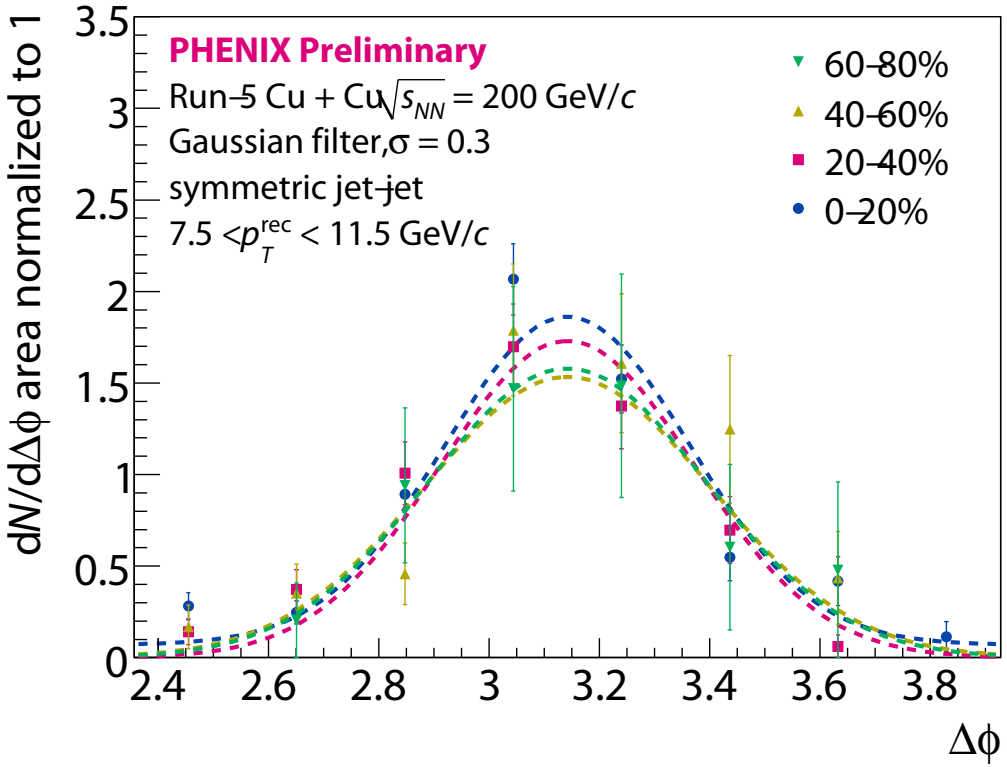
Run-5 Cu + Cu R_{AA} compared to embedding



Run-5 Cu + Cu R_{AA} compared to π^0



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 I

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

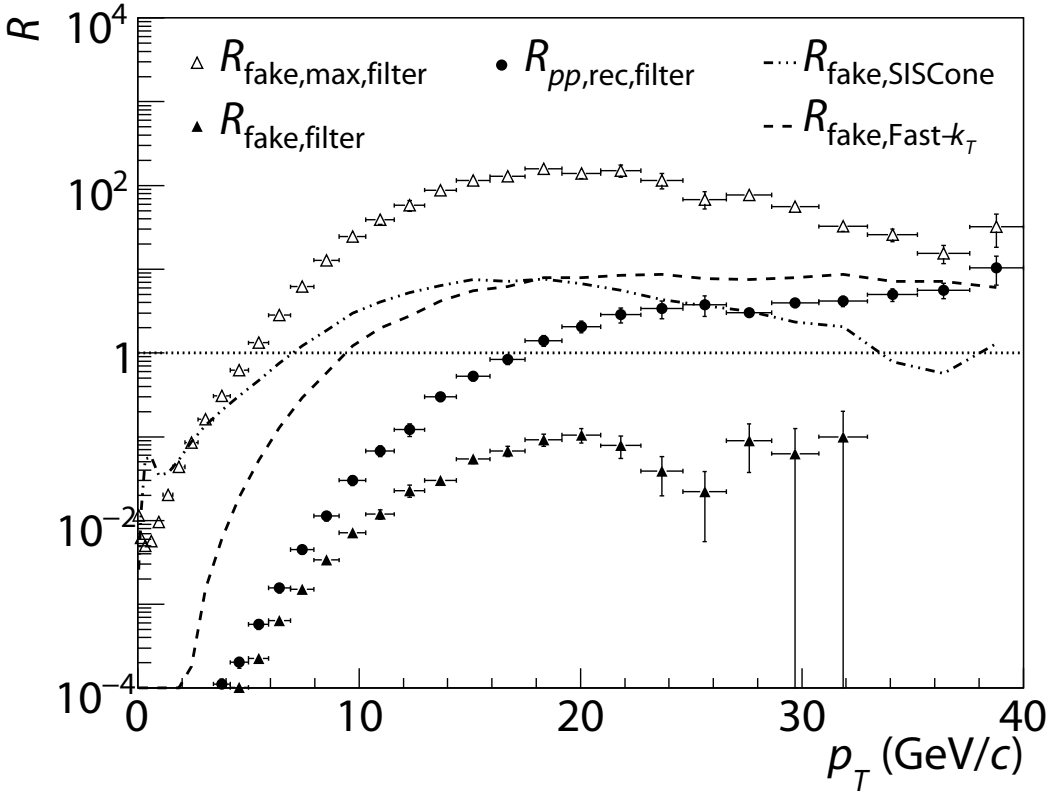
Summary & outlook II

- 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 the first measurement of $p + p$ spectrum at RHIC upto $x \approx 0.6$
- Obtained the first measurement of $p + p$ jet fragmentation function at RHIC, inclusive and upto $z \approx 0.8$
- Obtained the first measurement of the dijet angular correlation in Cu + Cu collisions
- Obtained the first measurement of the jet R_{AA} in Cu + Cu collisions
- ... and still the only all-centrality heavy-ion jet measurement
- Cu + Cu a stepping stone in understanding heavy ion jet reconstruction
  - $\Rightarrow$ We are intrigued by the current Cu + Cu results, and aim at understanding its physics implication before moving on to Au + Au
  - $\Rightarrow$ Measurement of jet modification variables, e.g. fragmentation functions, j_T distributions, are in the works

Part I

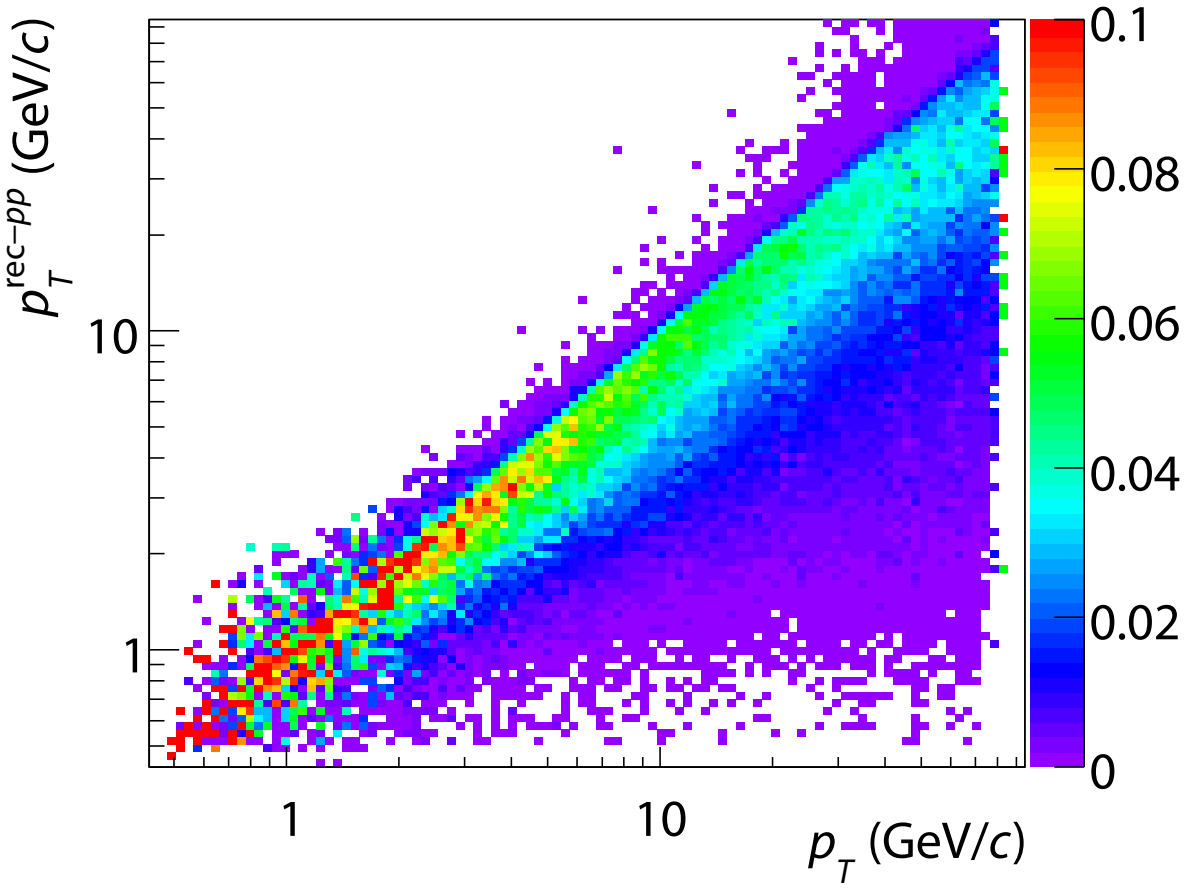
Backup

Fake rejection in HIJING central Au + Au



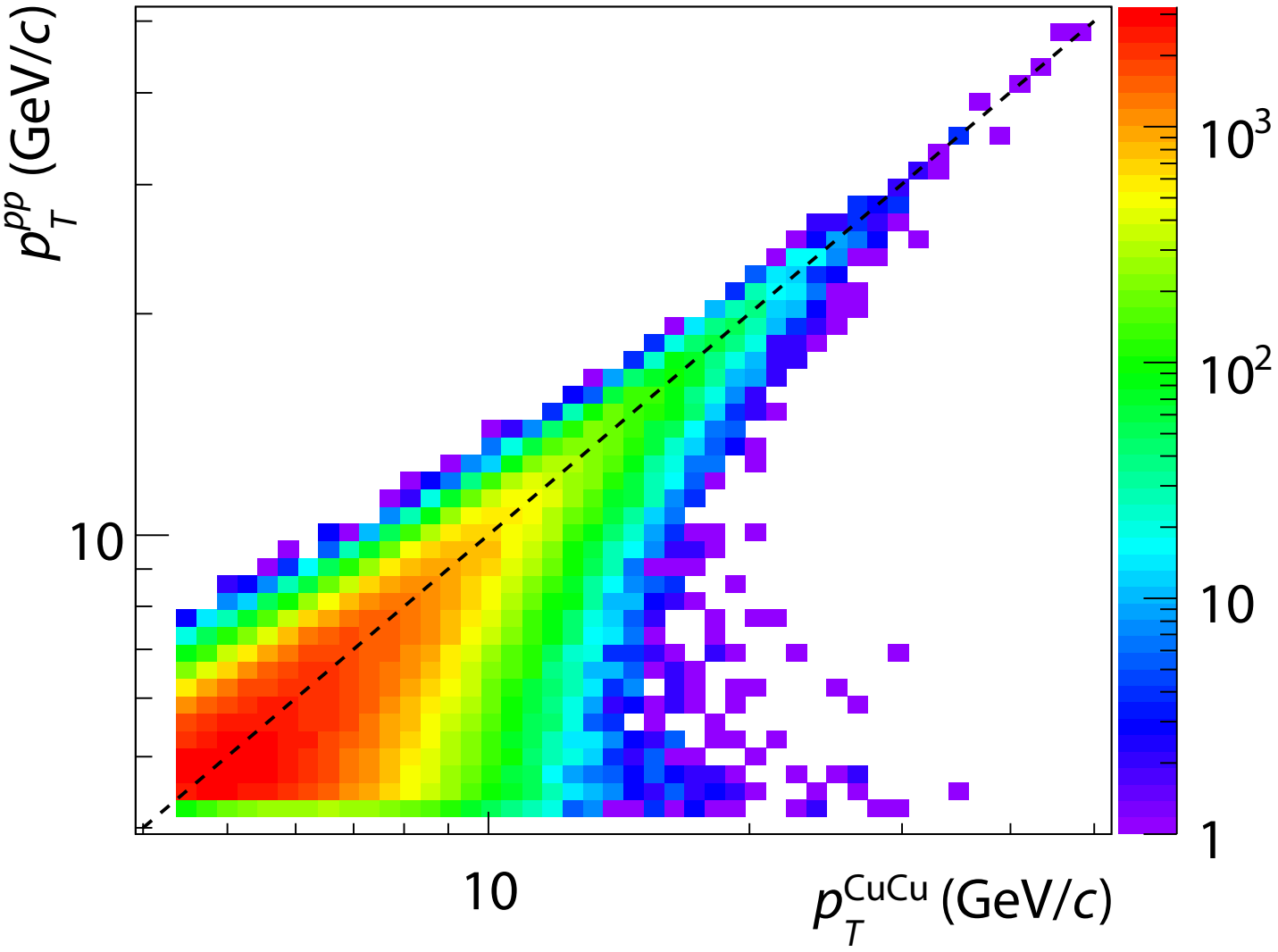
- Filter with Gaussian fake rejection compared to
  - $k_\perp$ with $1/\sqrt{A}$ (Cacciari & Salam, Phys. Lett. B 659, 119, 2008)
  - SISCone with Σj_T (Grau *et al.*, ATLAS Collab., arXiv:0810.1219, 2008)
- Filter can efficiently fake reject even in worst-case assumption for Au + Au at RHIC energy

PHENIX jet energy scale

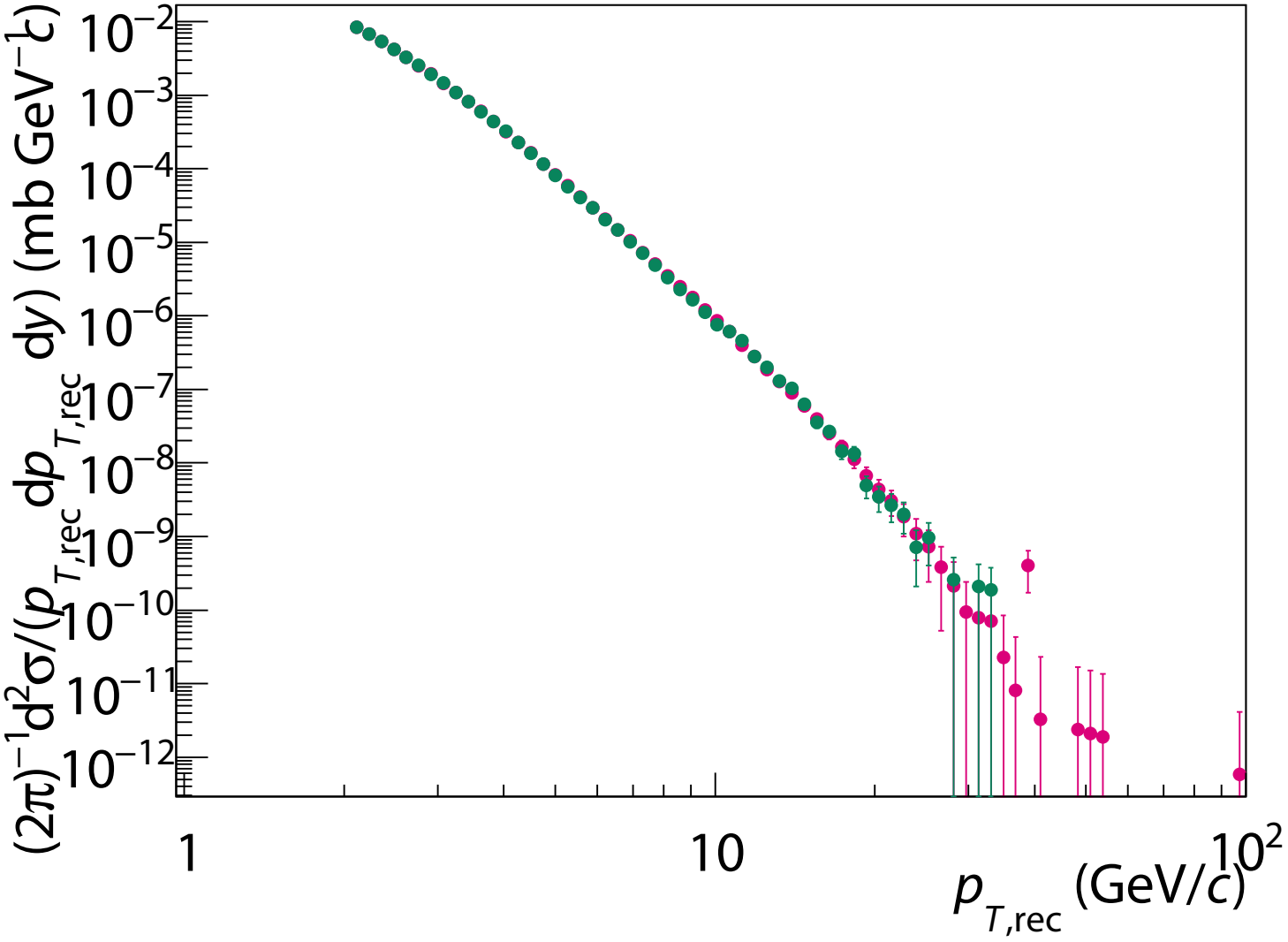


- PYTHIA + GEANT simulation with $\sim$ 16 million events
- $p_T^{rec-pp} < p_T$ region dominated by n, K_L^0 energy loss

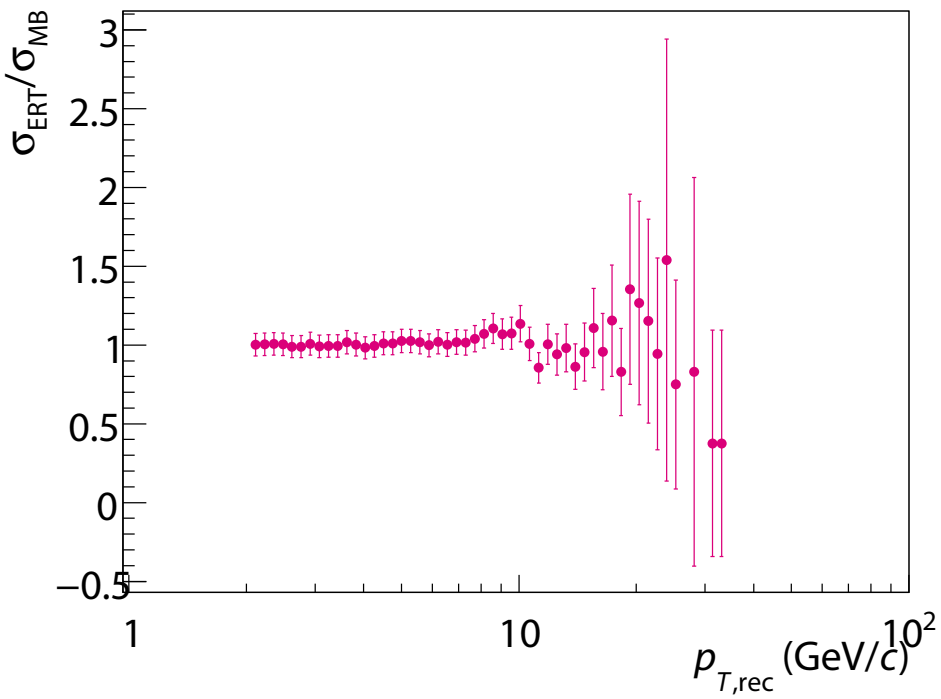
$p + p$ to Cu + Cu transfer matrix, 0–20% centrality

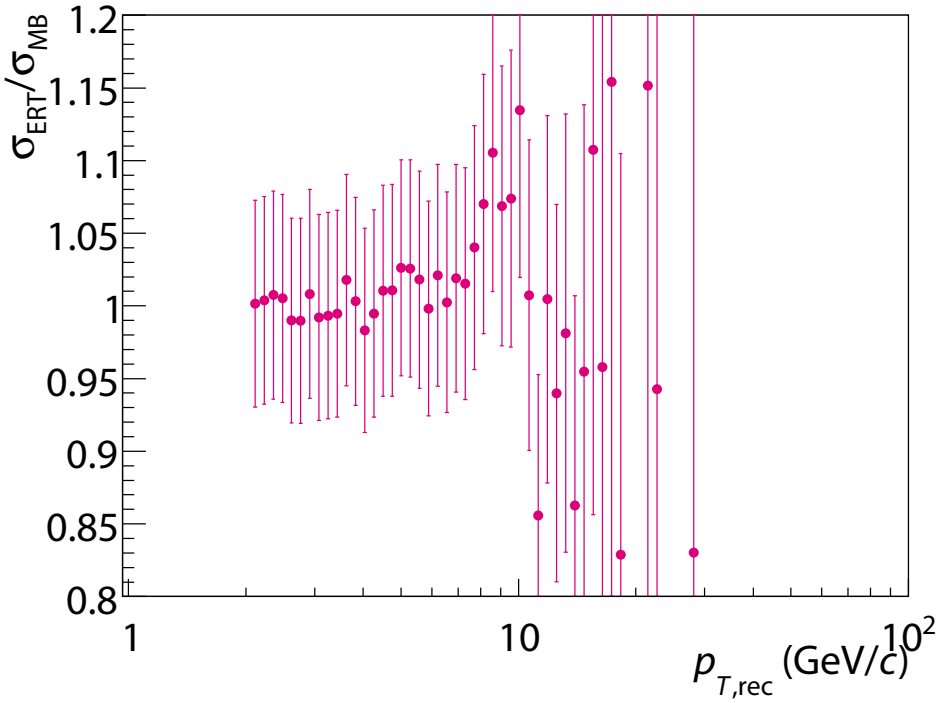


PHENIX ERT vs. minimum bias trigger

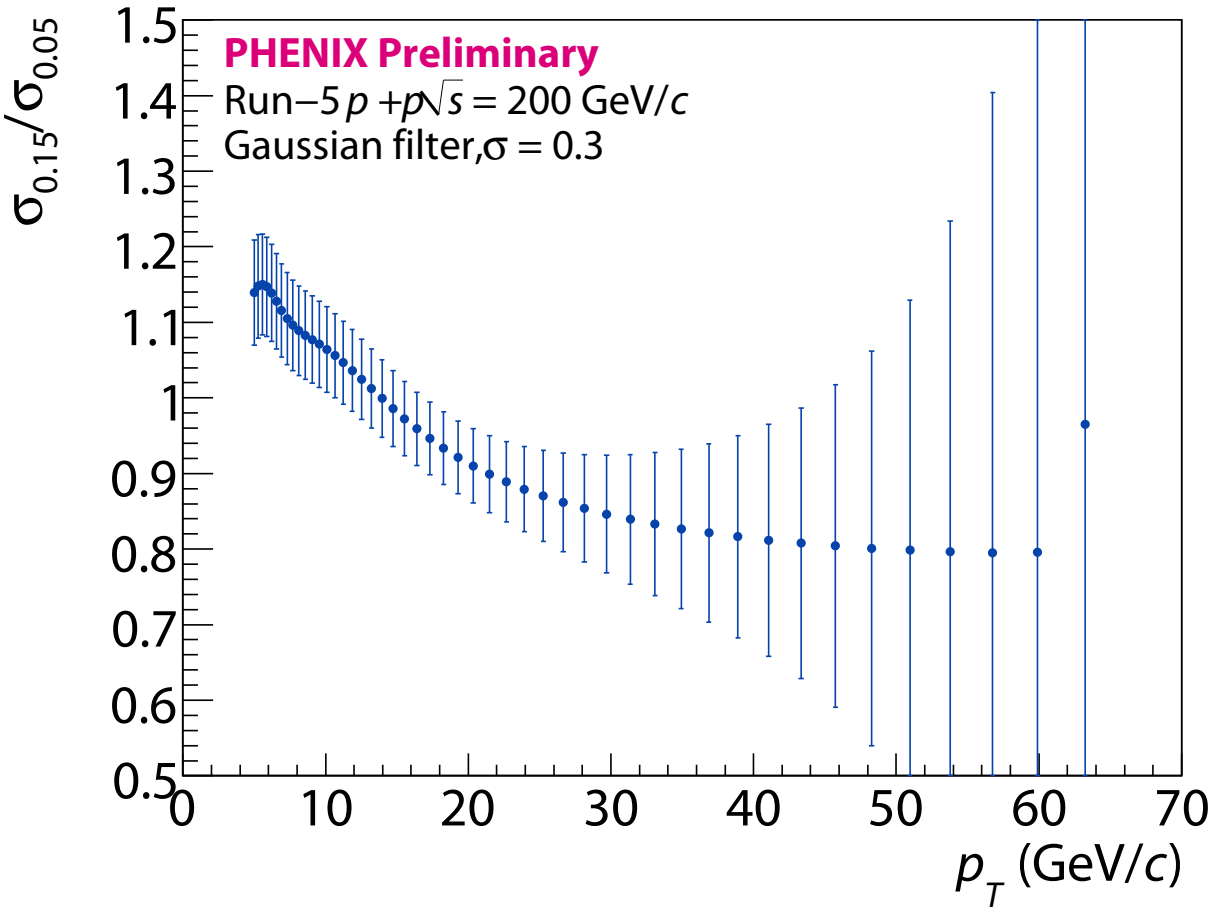


PHENIX ERT vs. minimum bias trigger

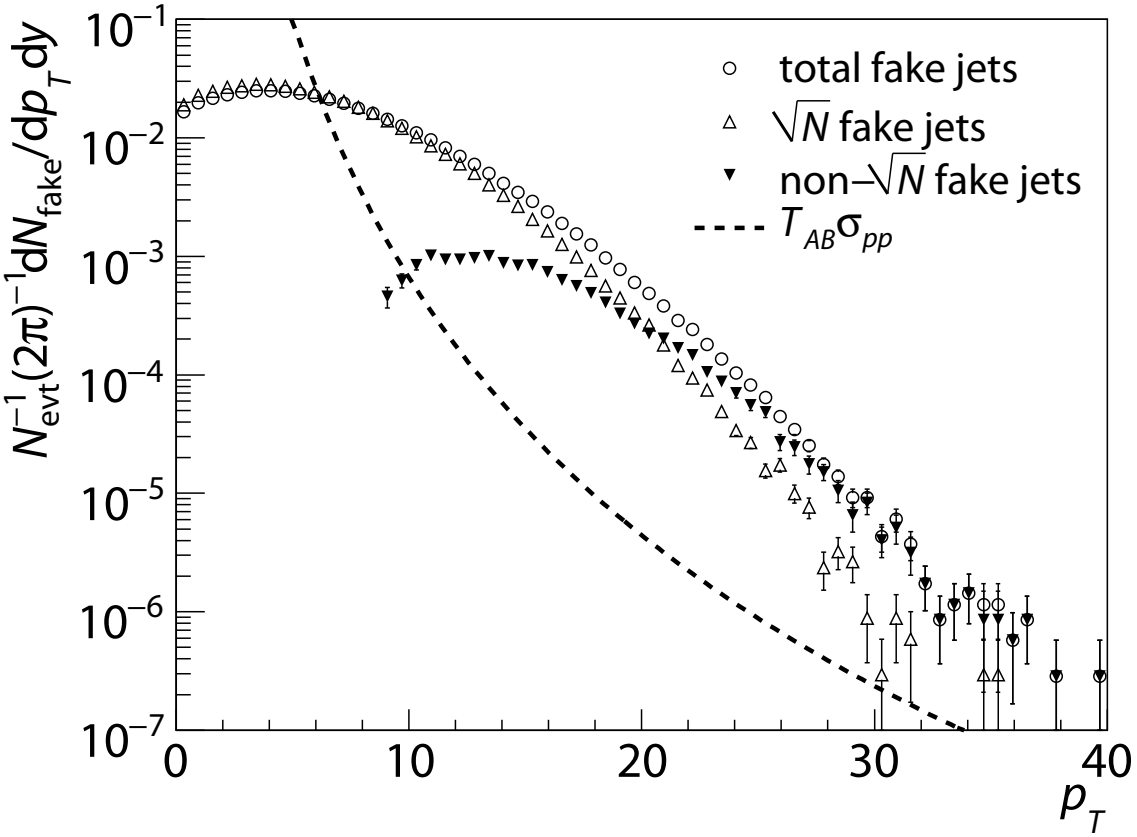




Effect of the PHENIX detector edge



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**

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

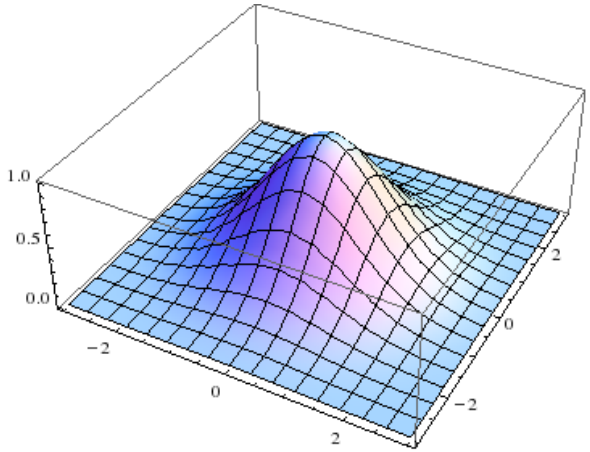
Flat (1D) integration:

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

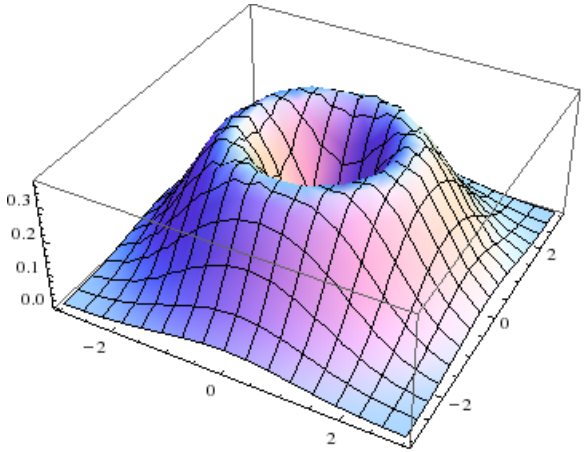
- $p_T^1 \ll p_T^0$ demonstrates that Gaussian filter is not losing significant amount of energy
- p_T^1 is closely related to the jet width, possible interesting physics

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

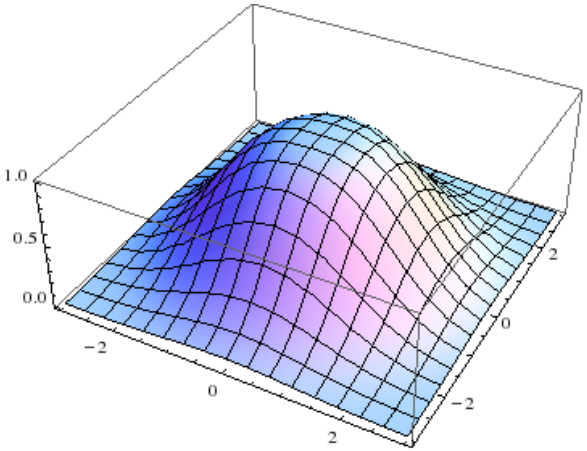
In pictures:



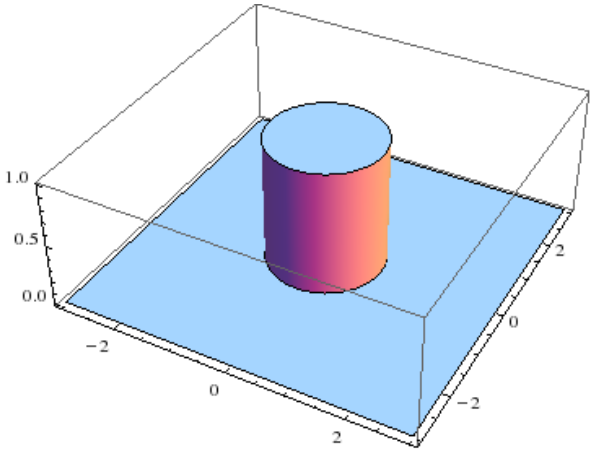
p_T^0 weight



p_T^1 weight

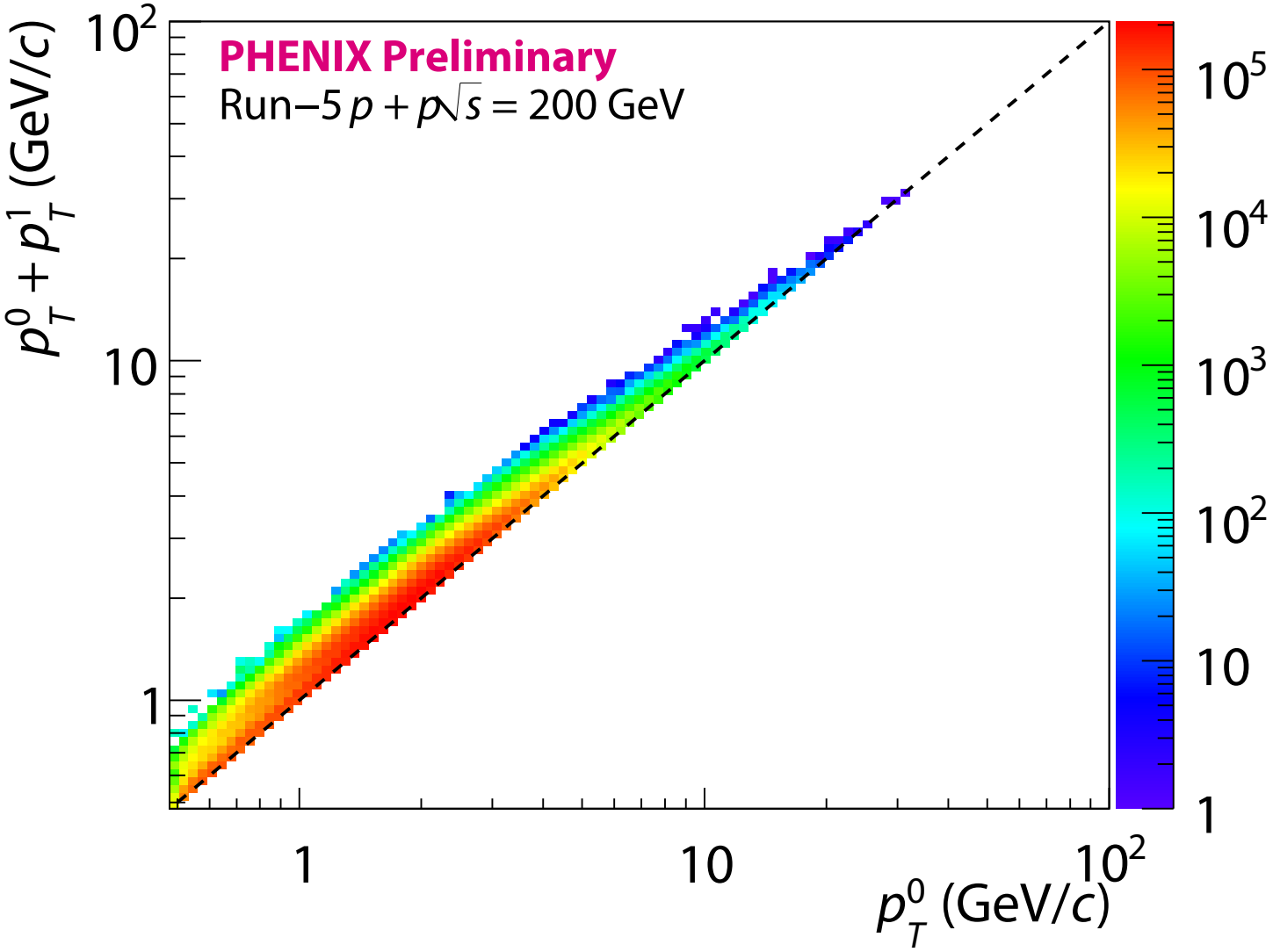


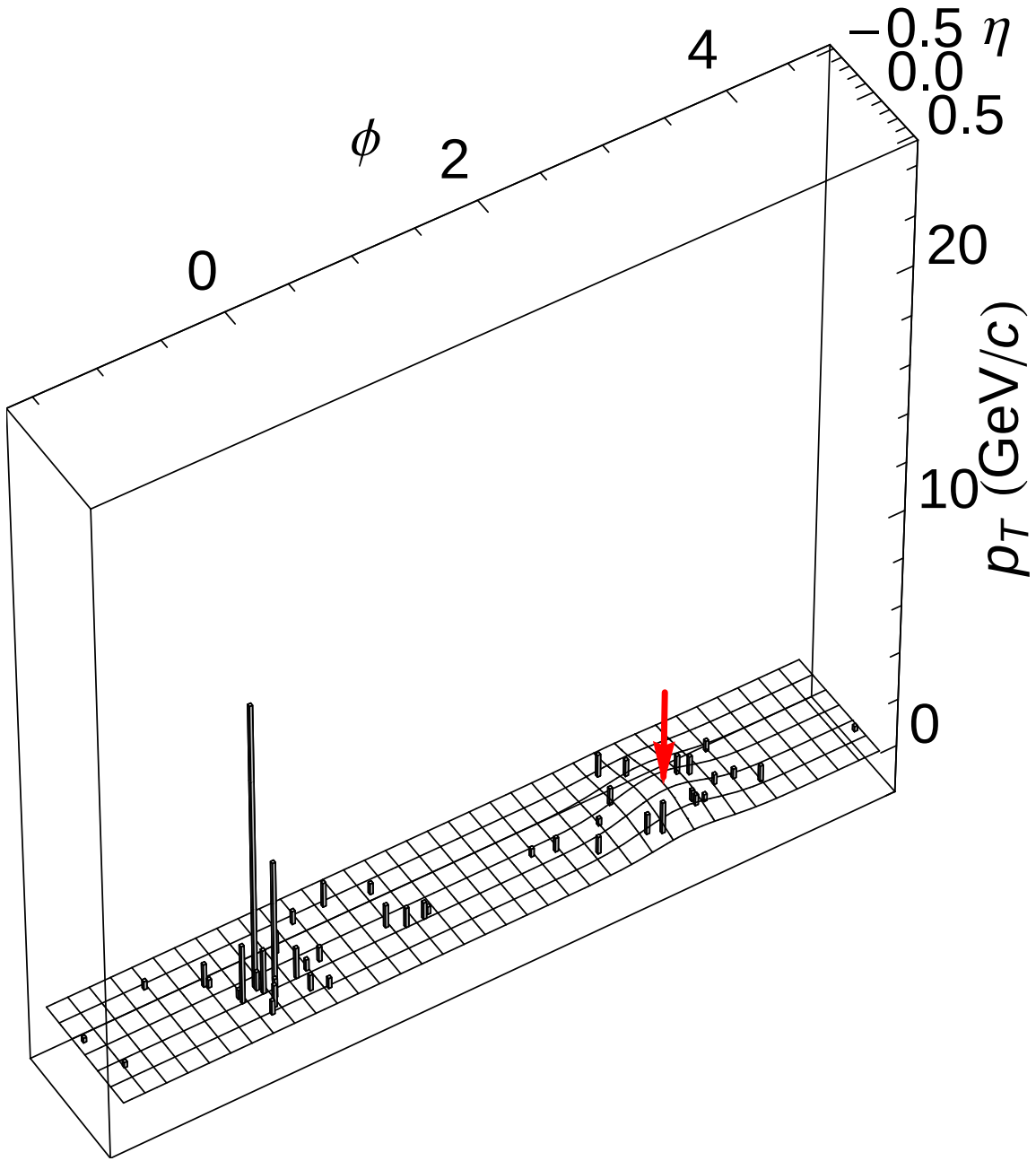
$p_T^0 + p_T^1$ weight



cone

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




ϕ
0
2
4
η
−0.5
0.0
0.5
p_T (GeV/c)
0
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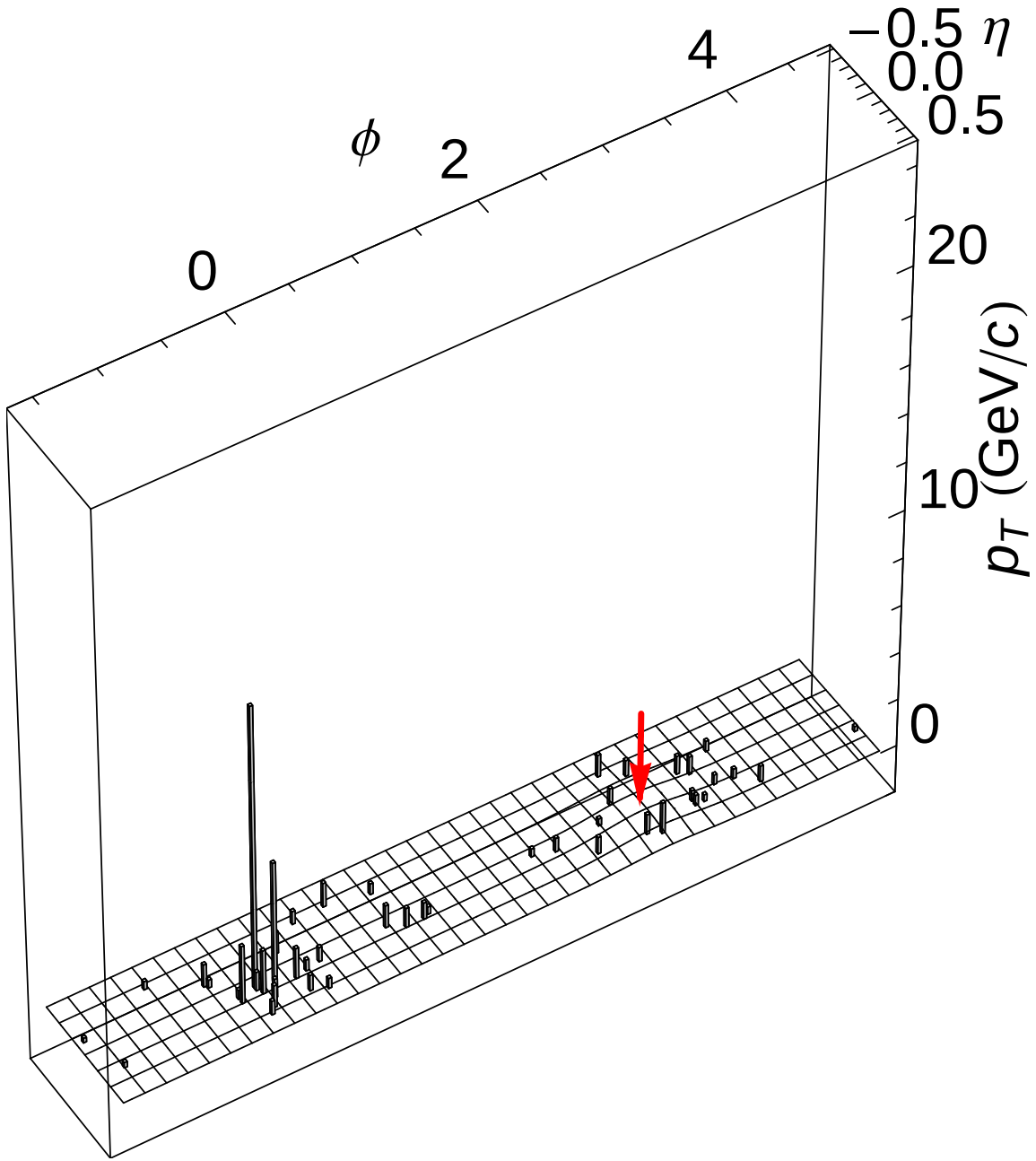
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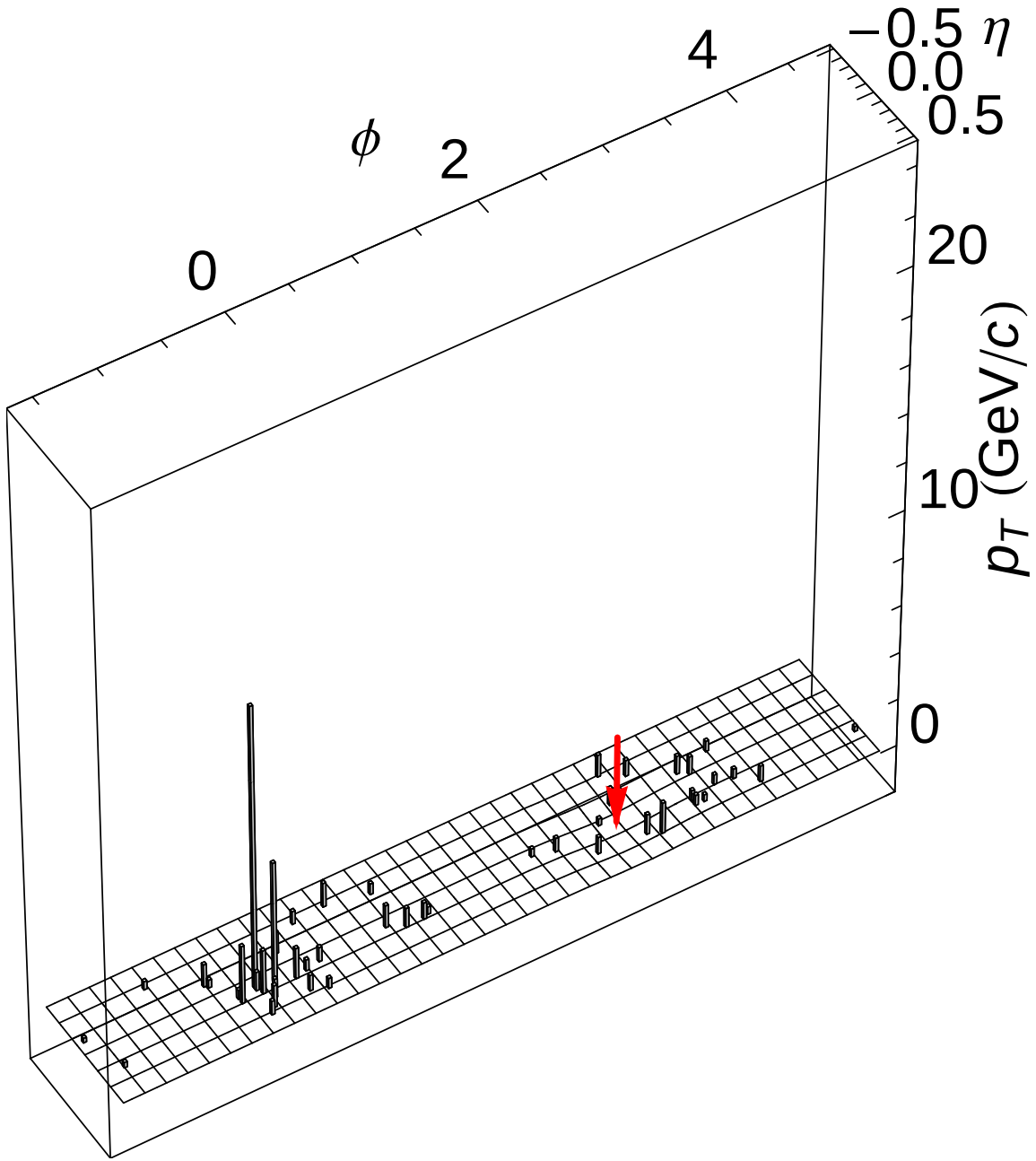
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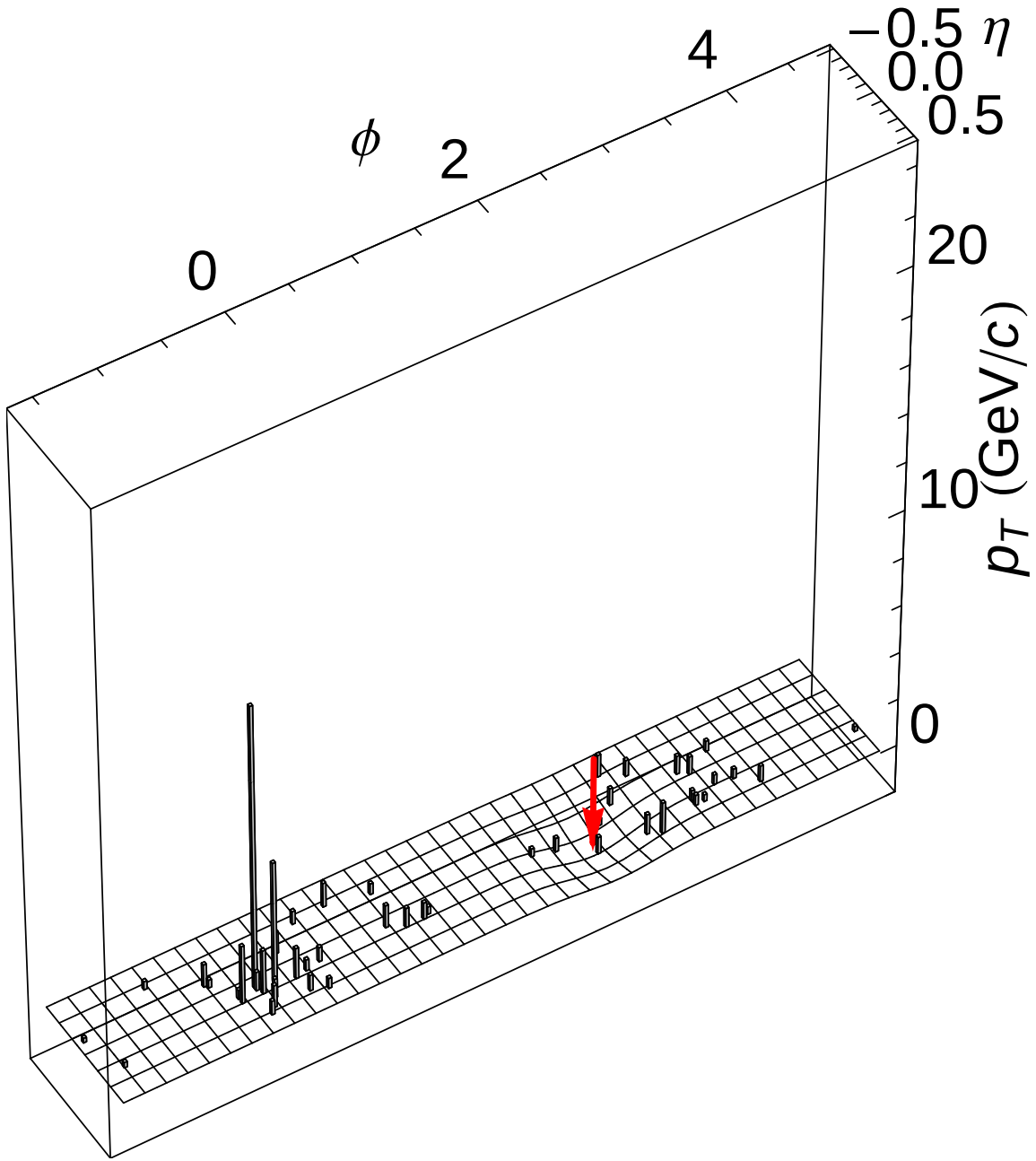
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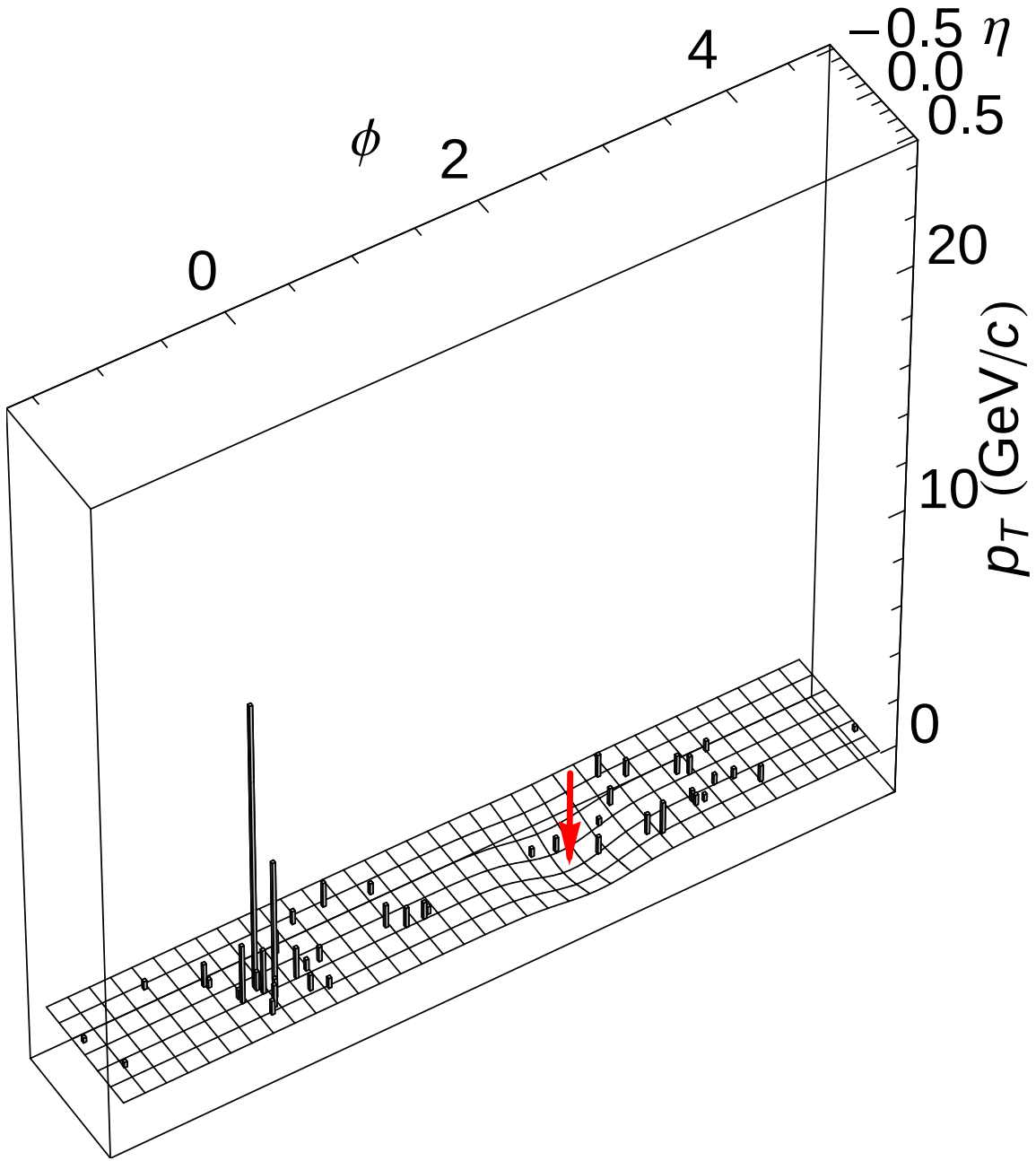
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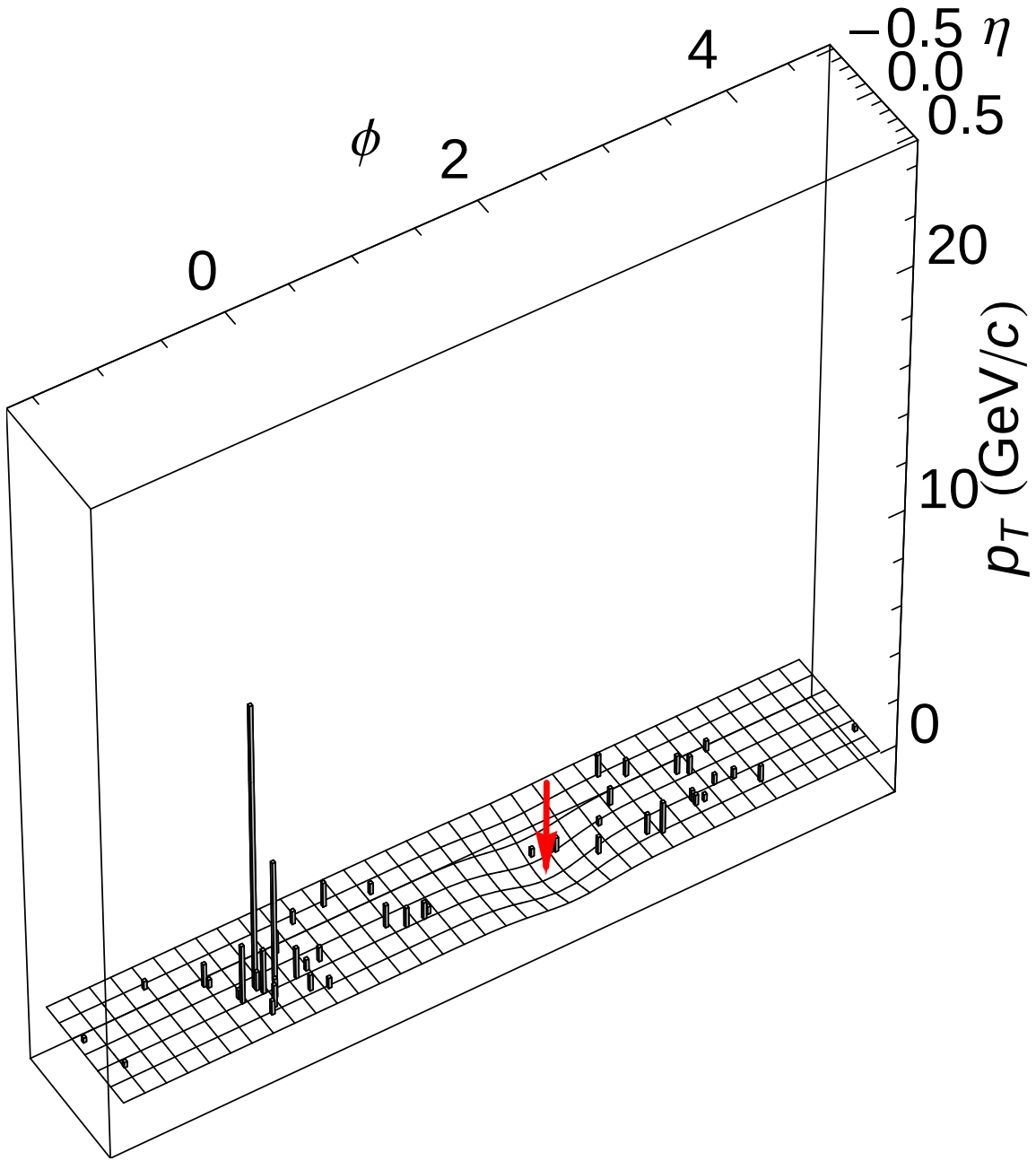
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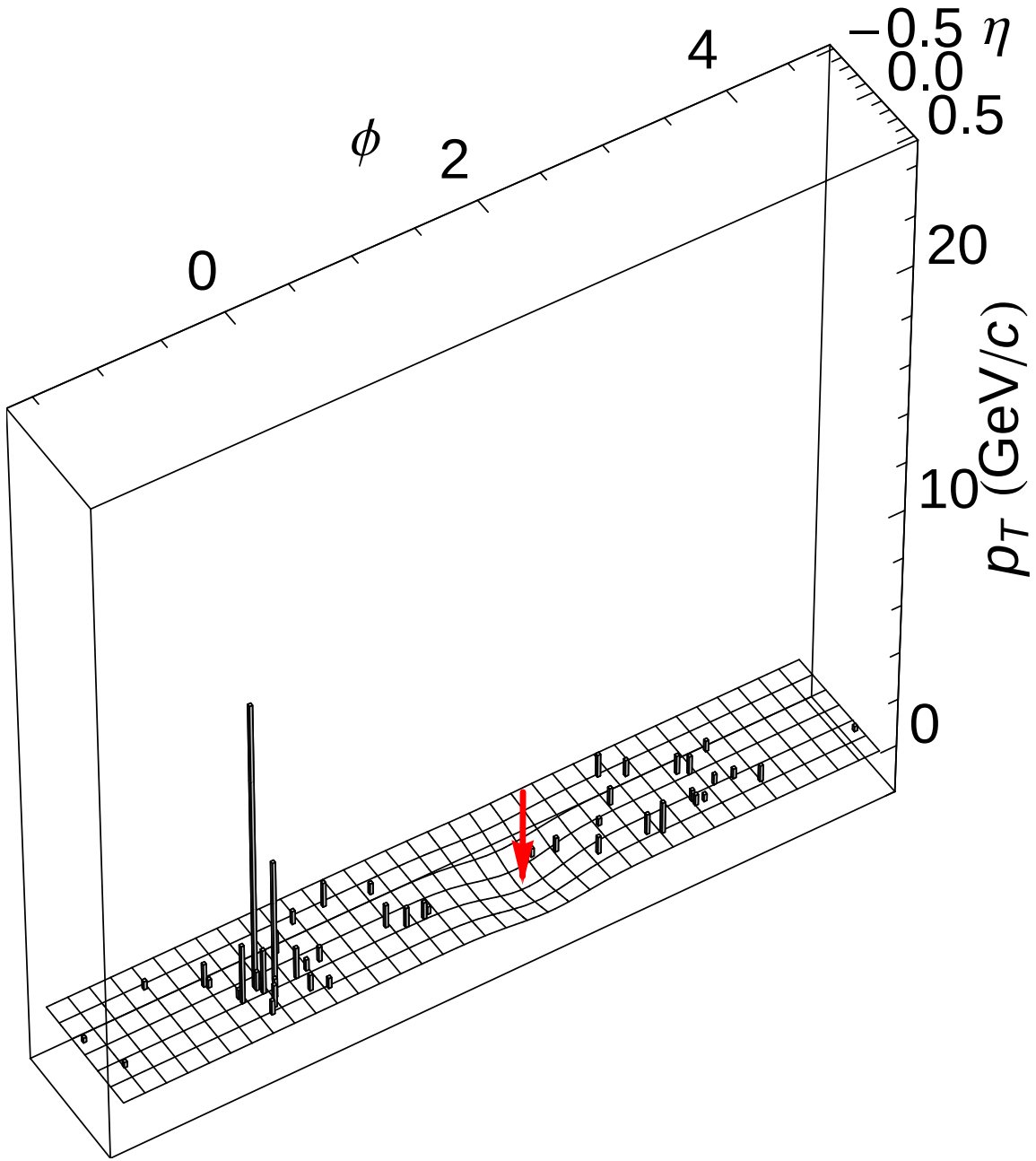
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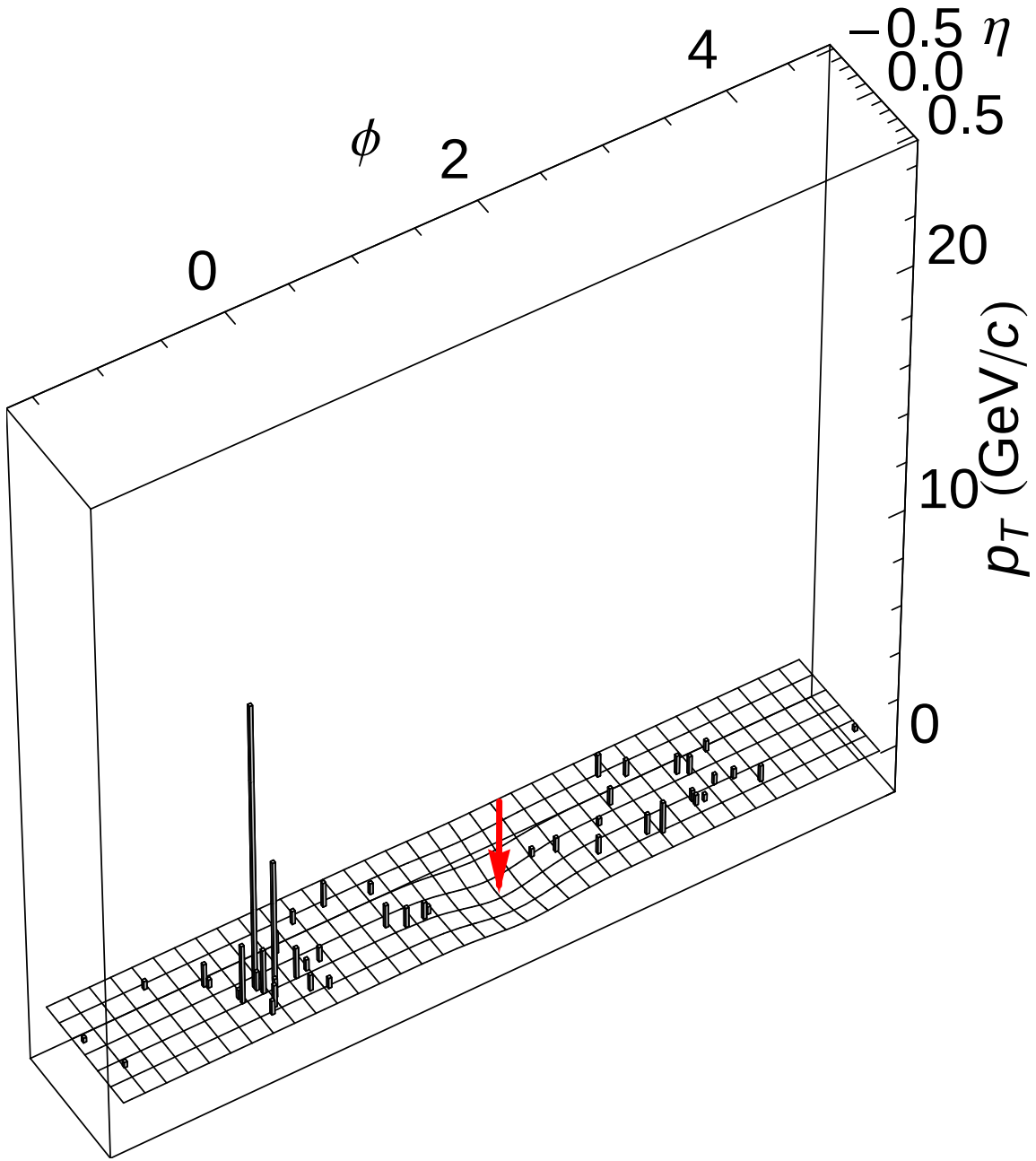
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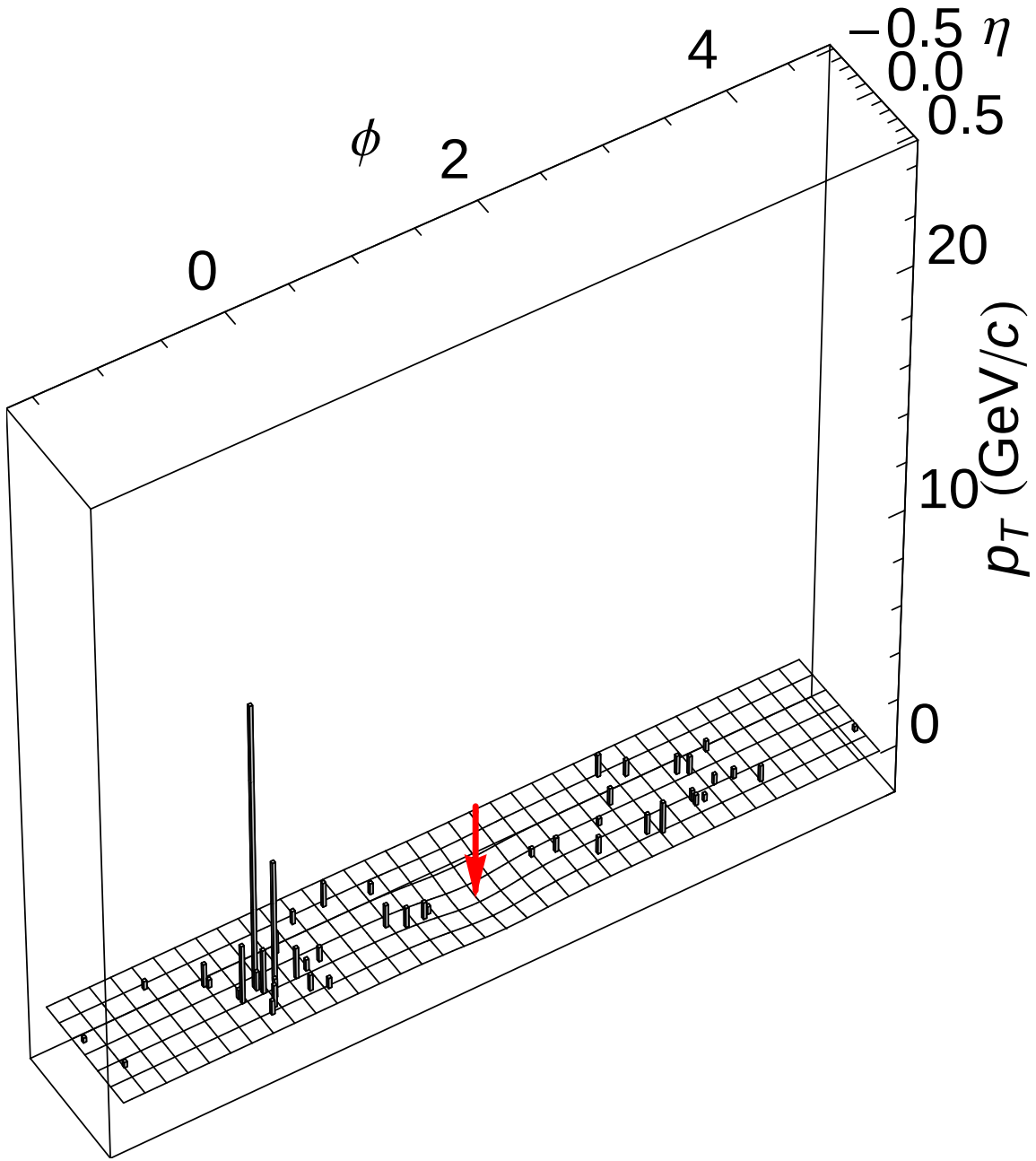
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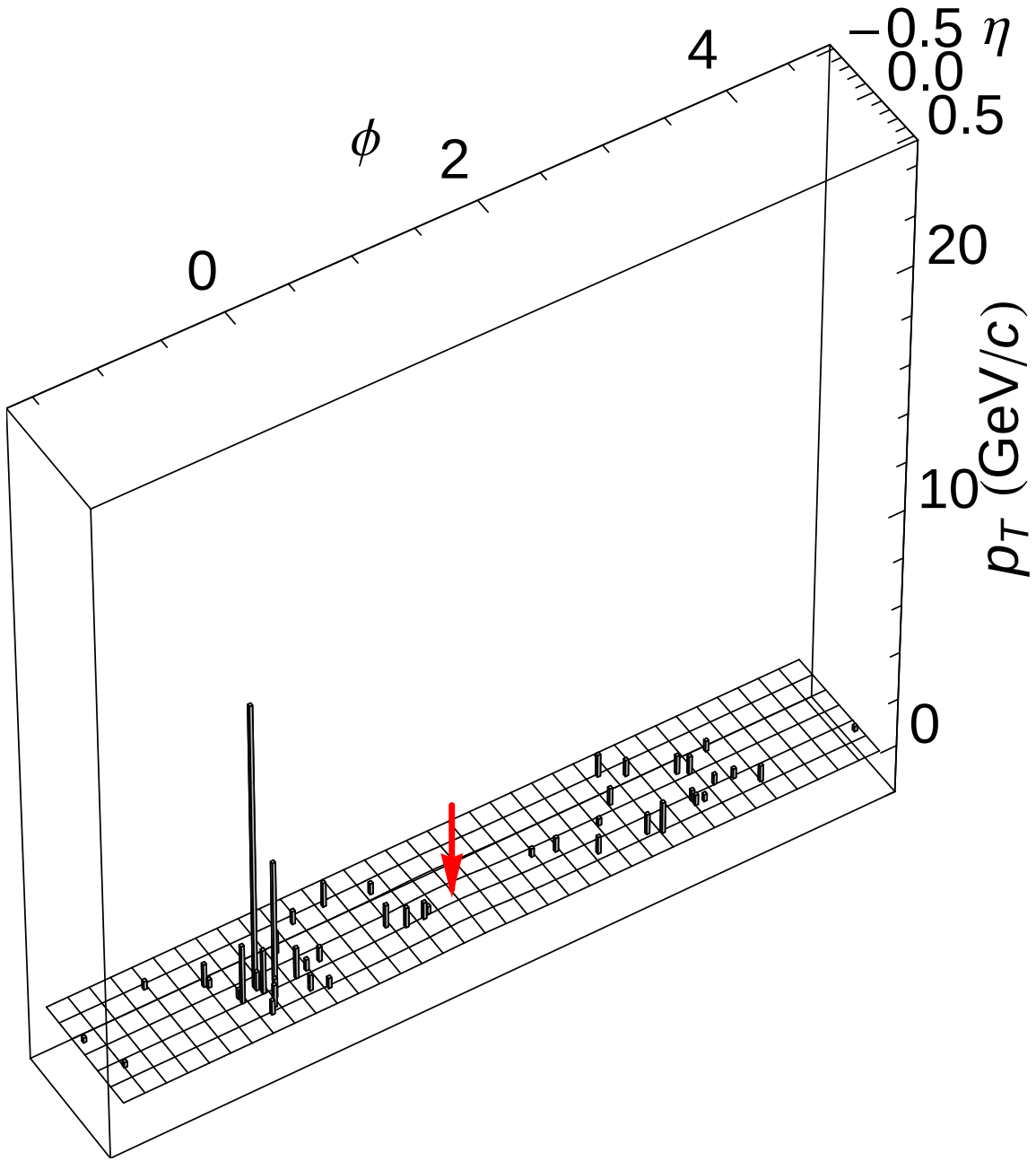
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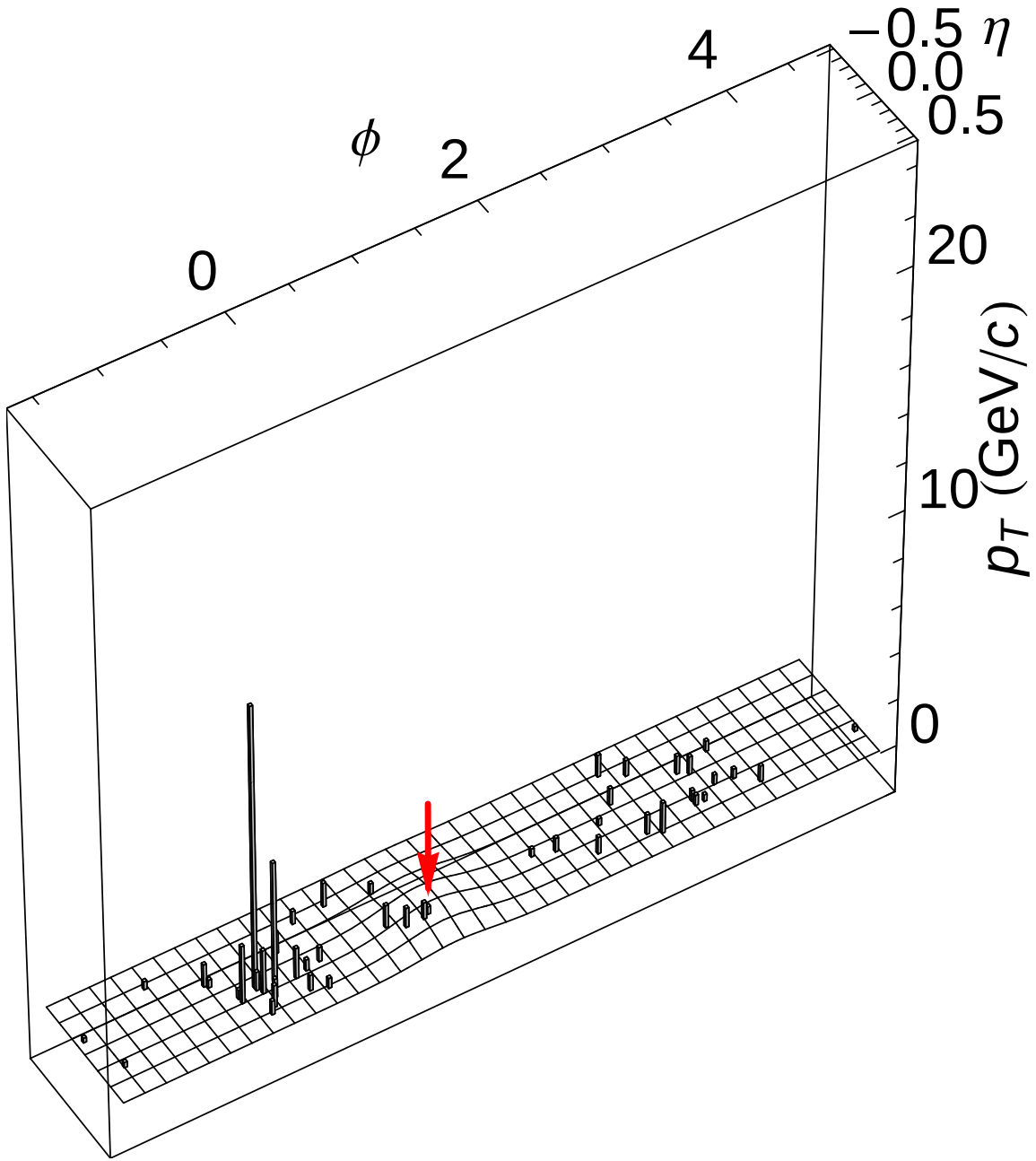
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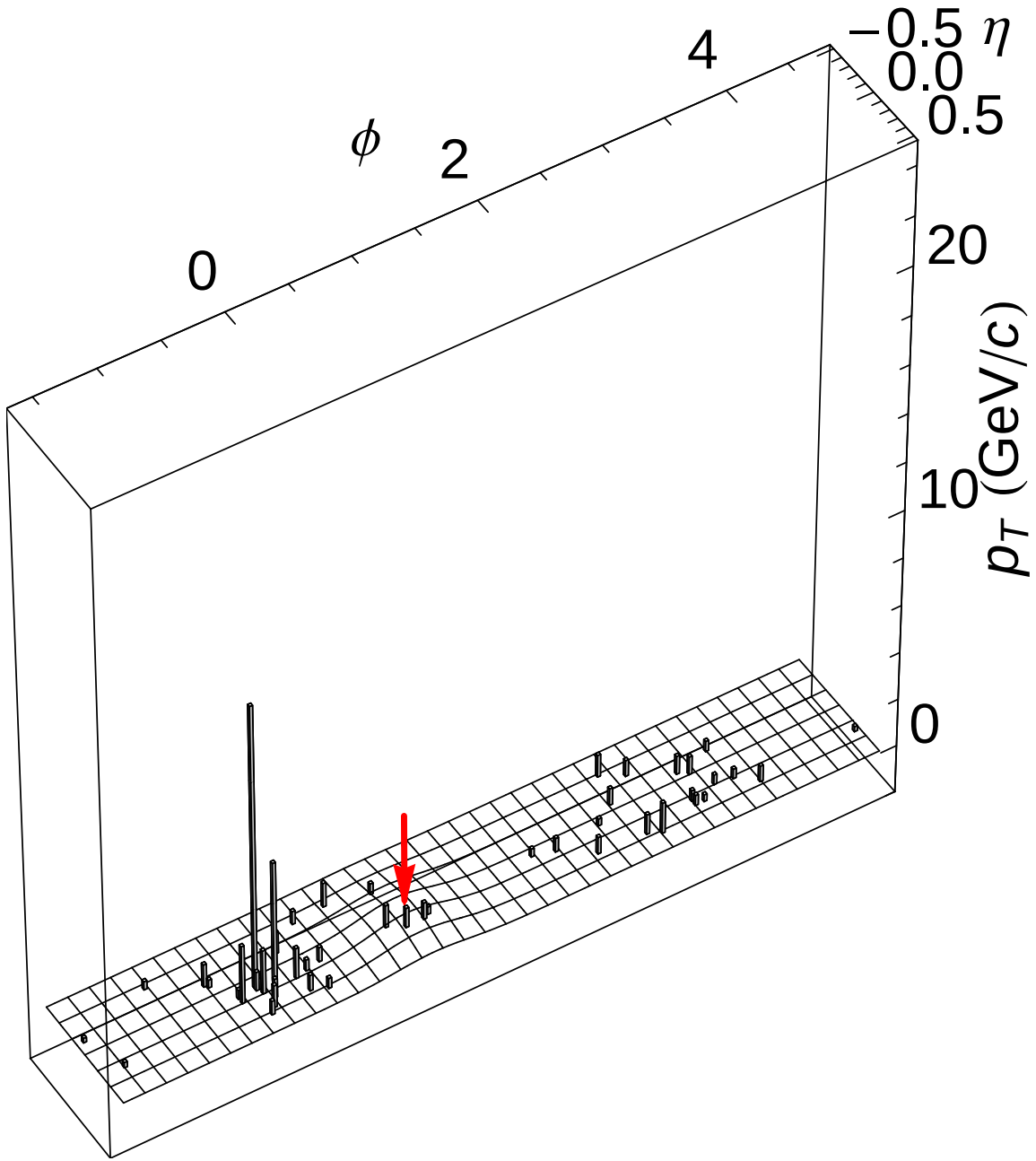
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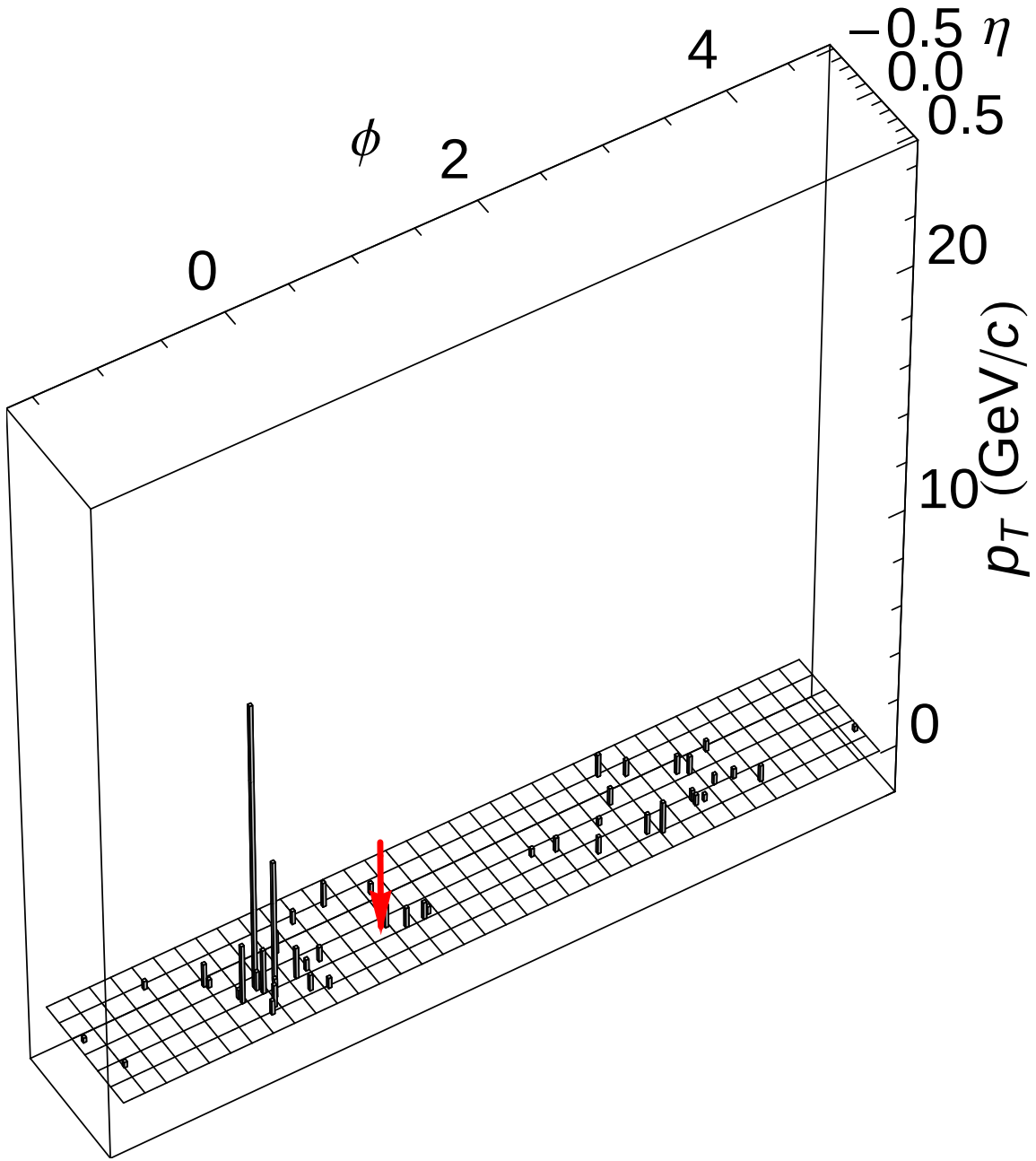
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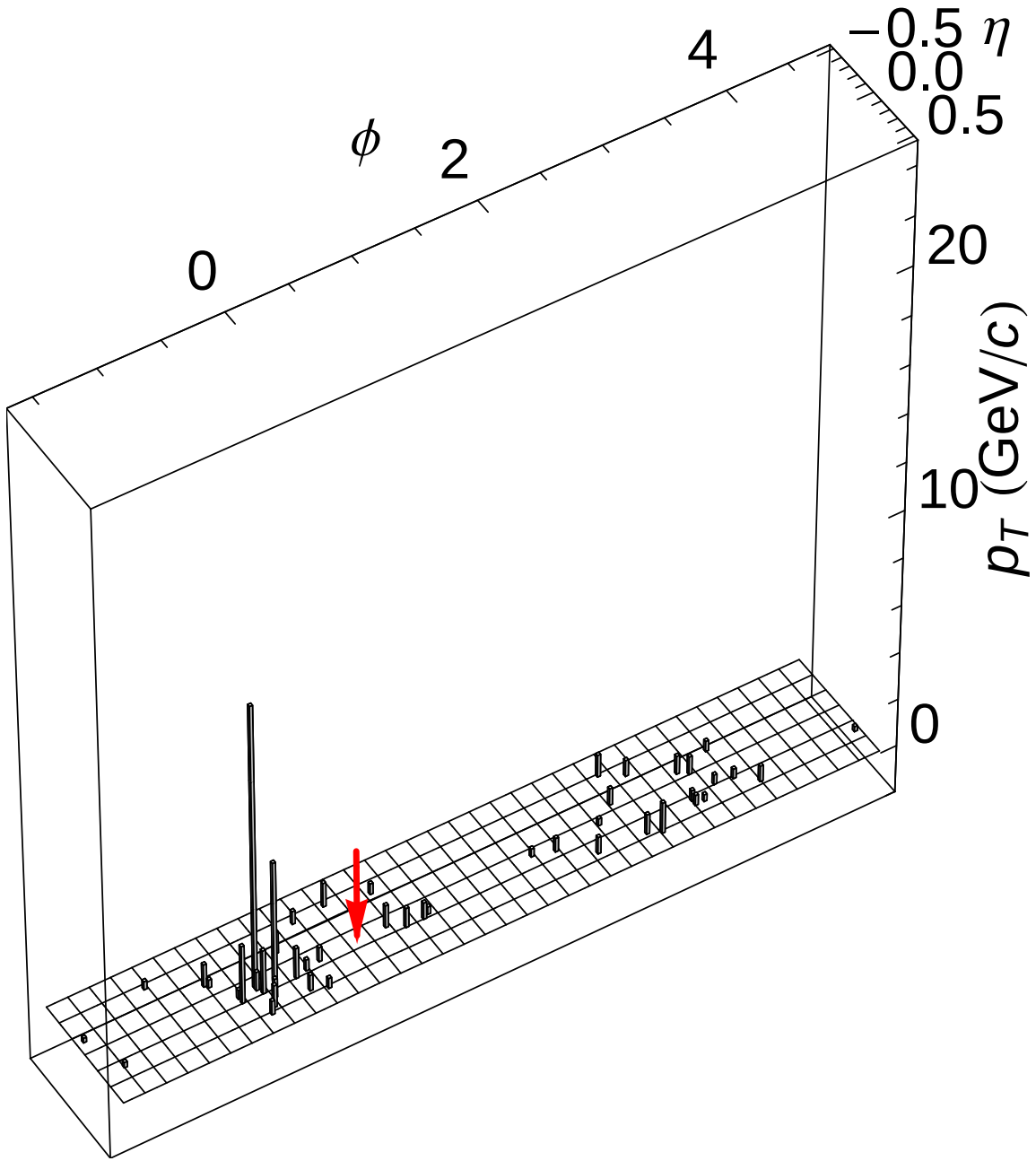
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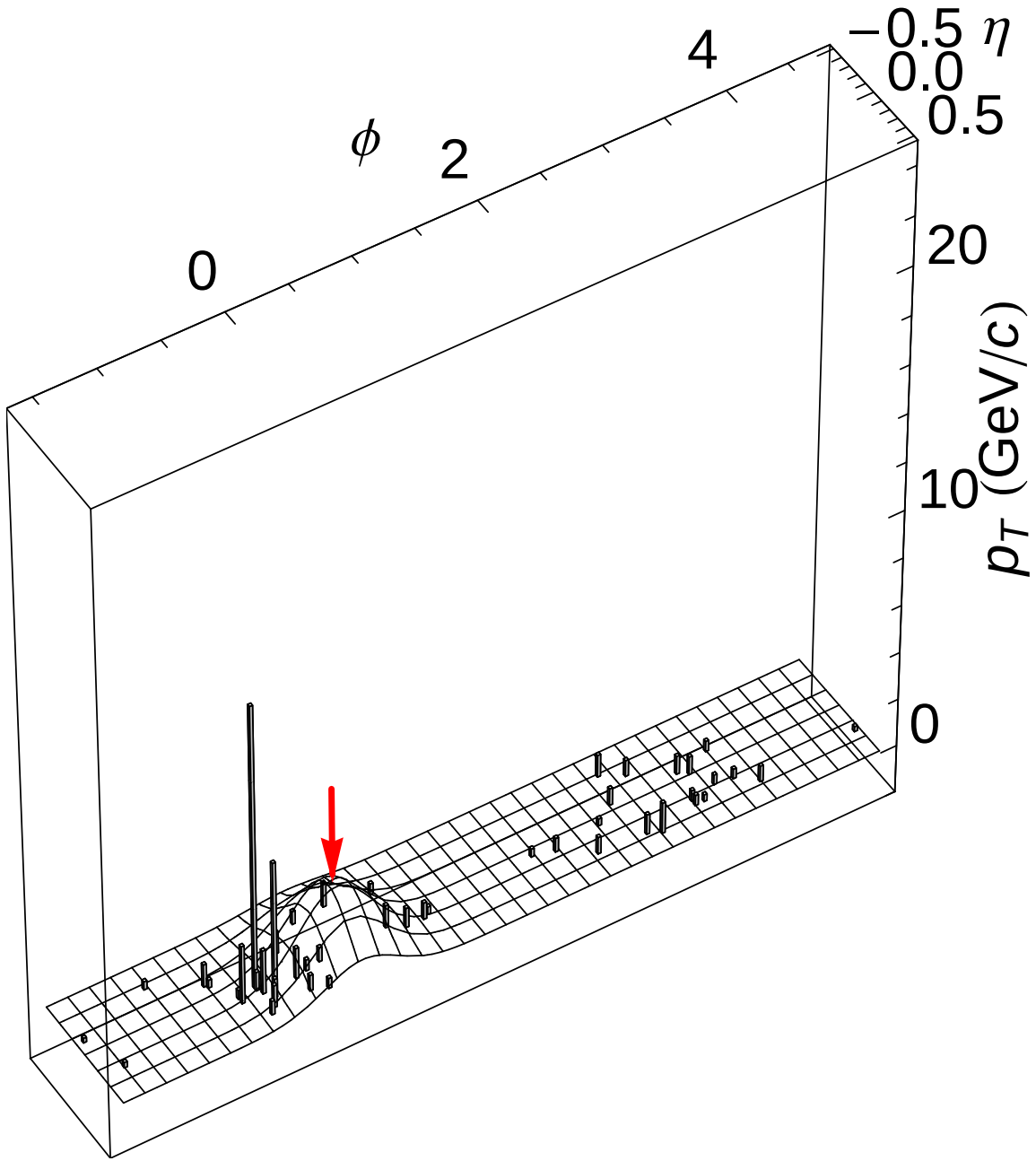
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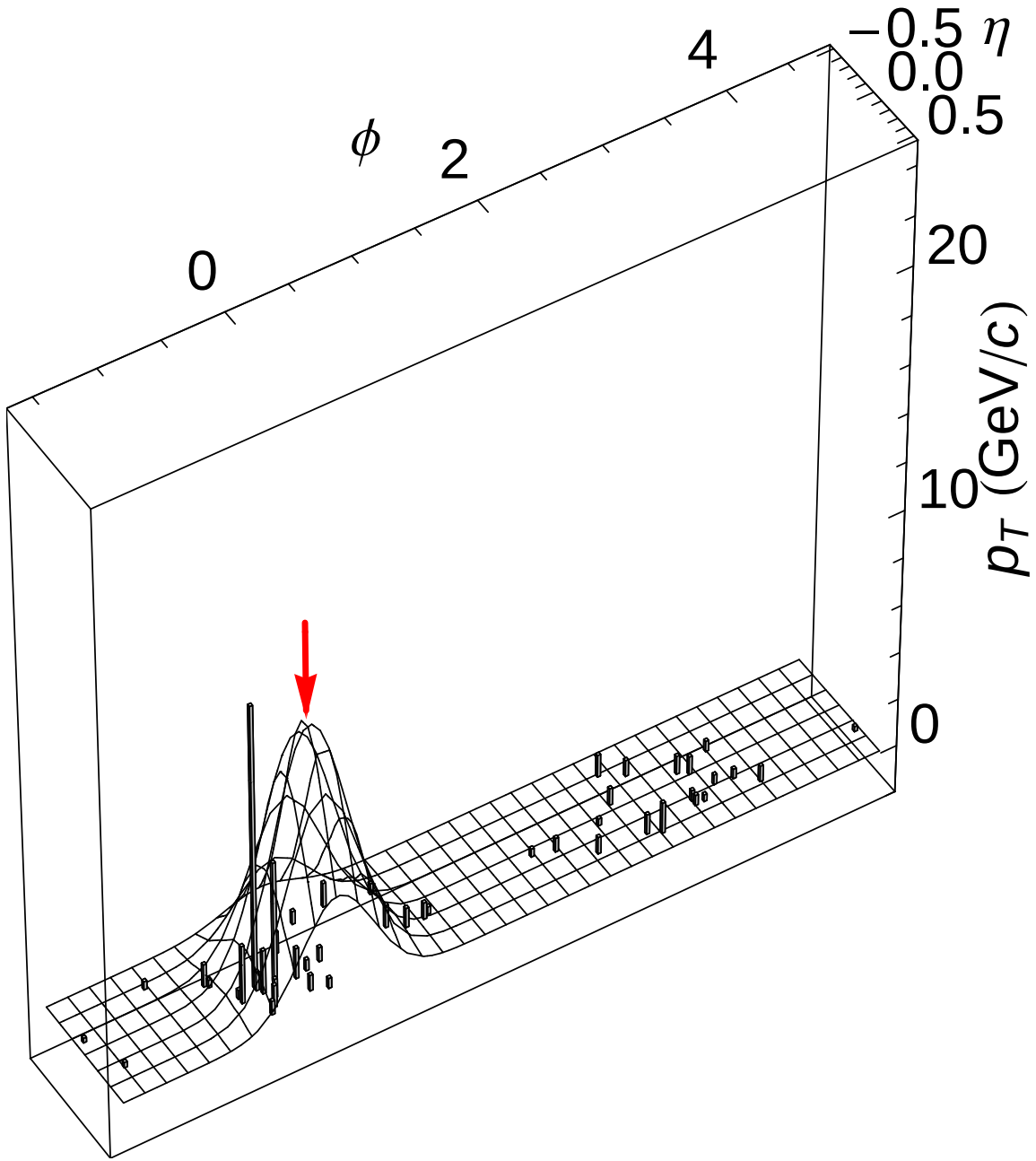
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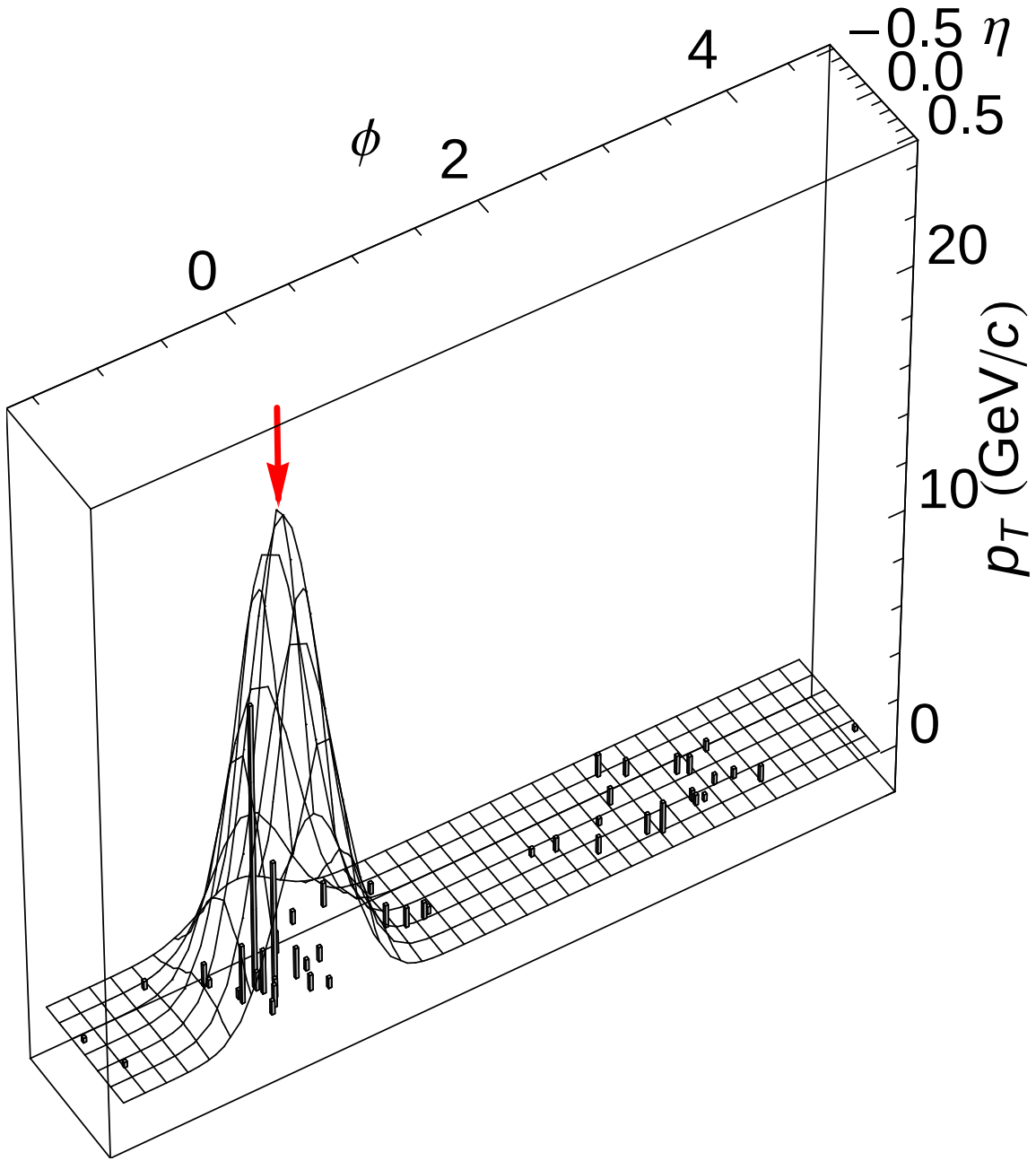
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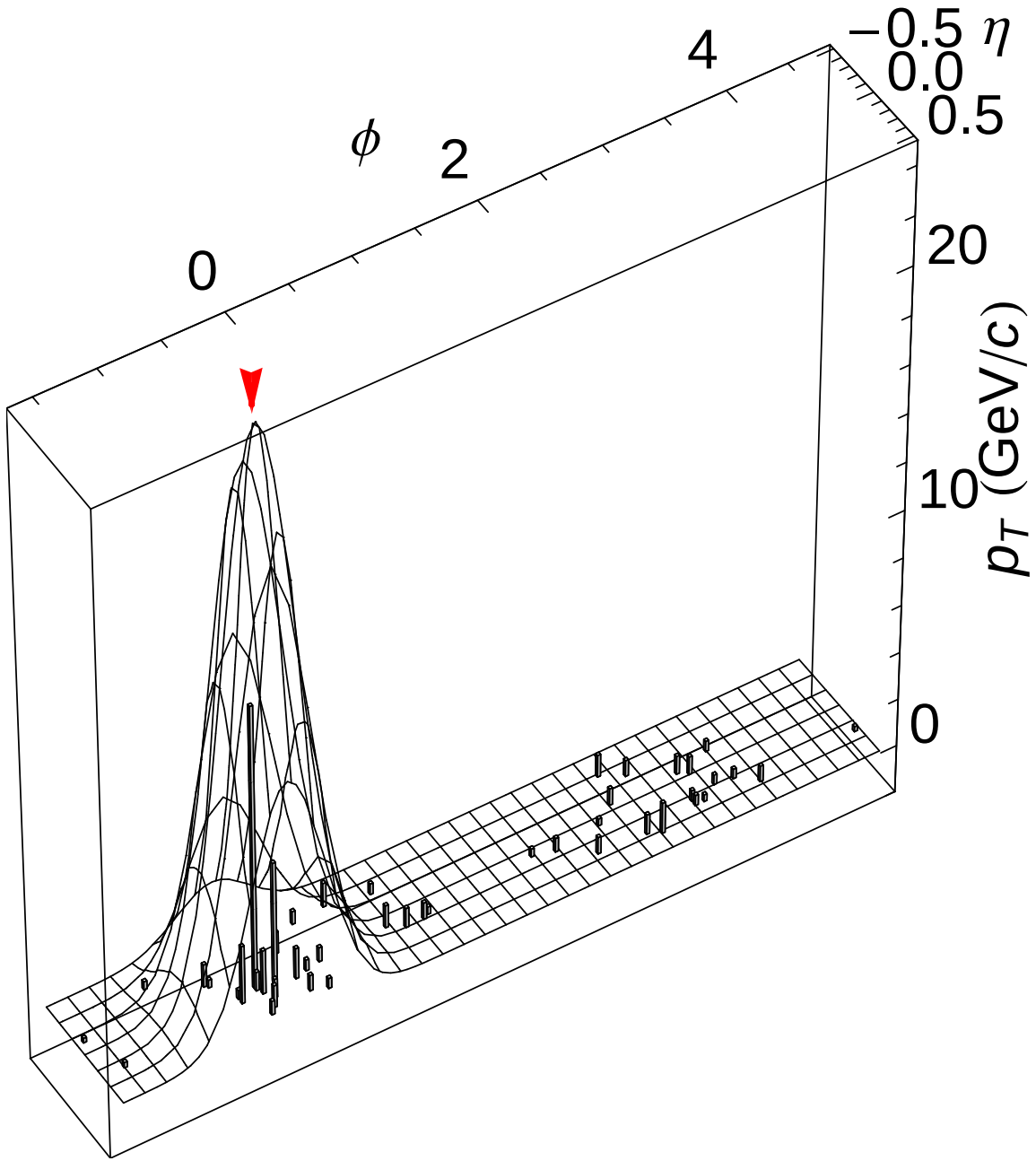
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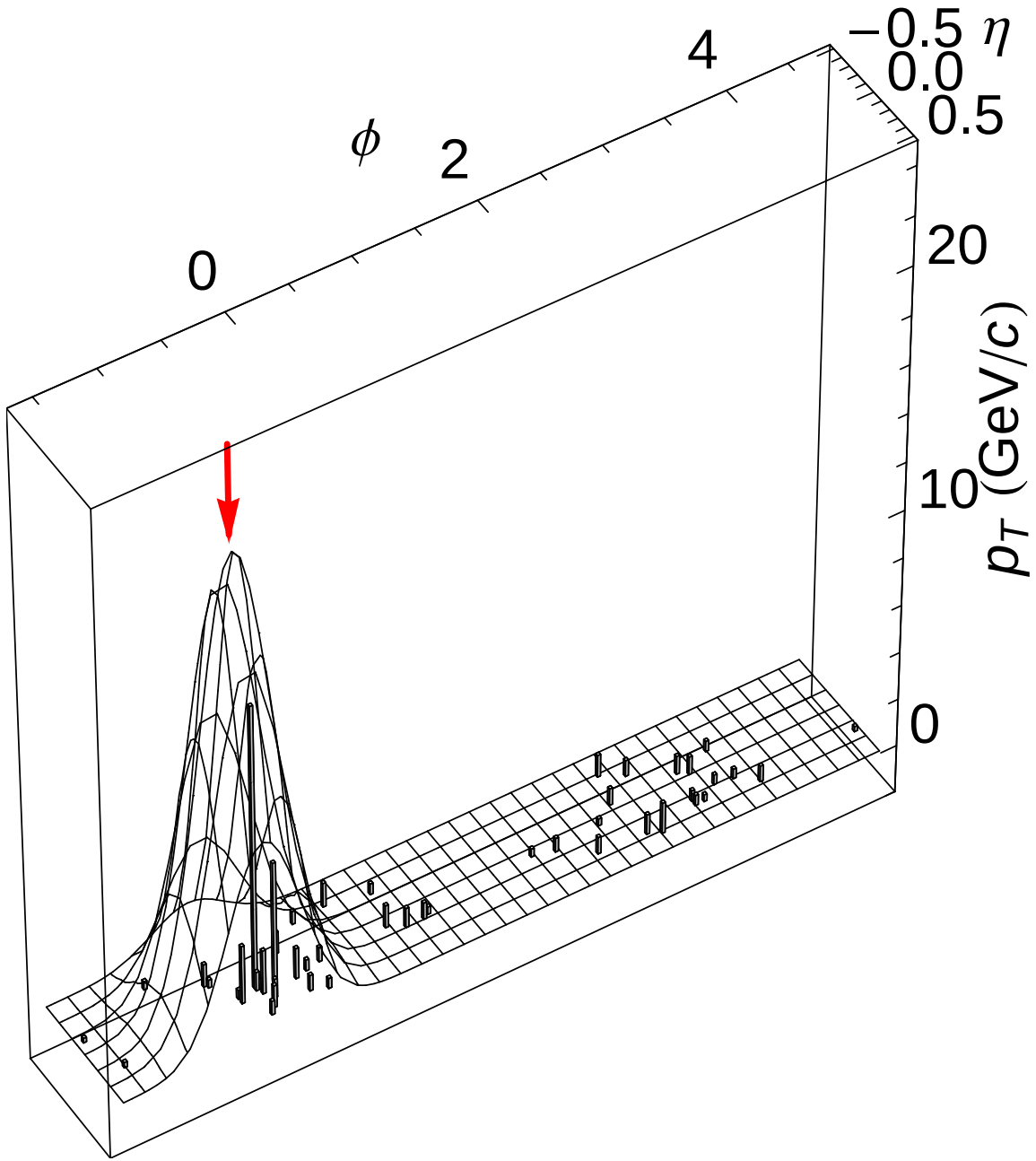
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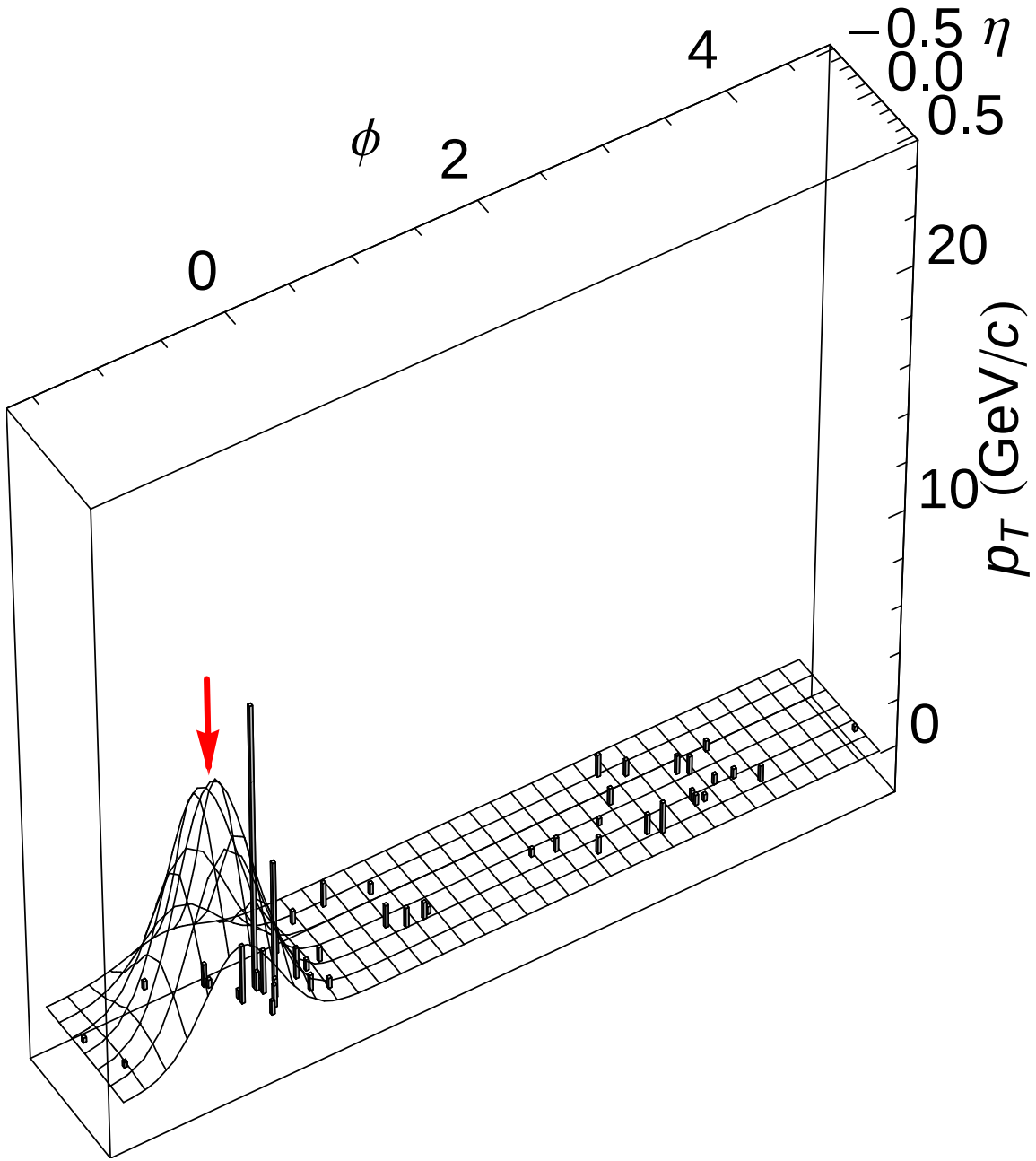
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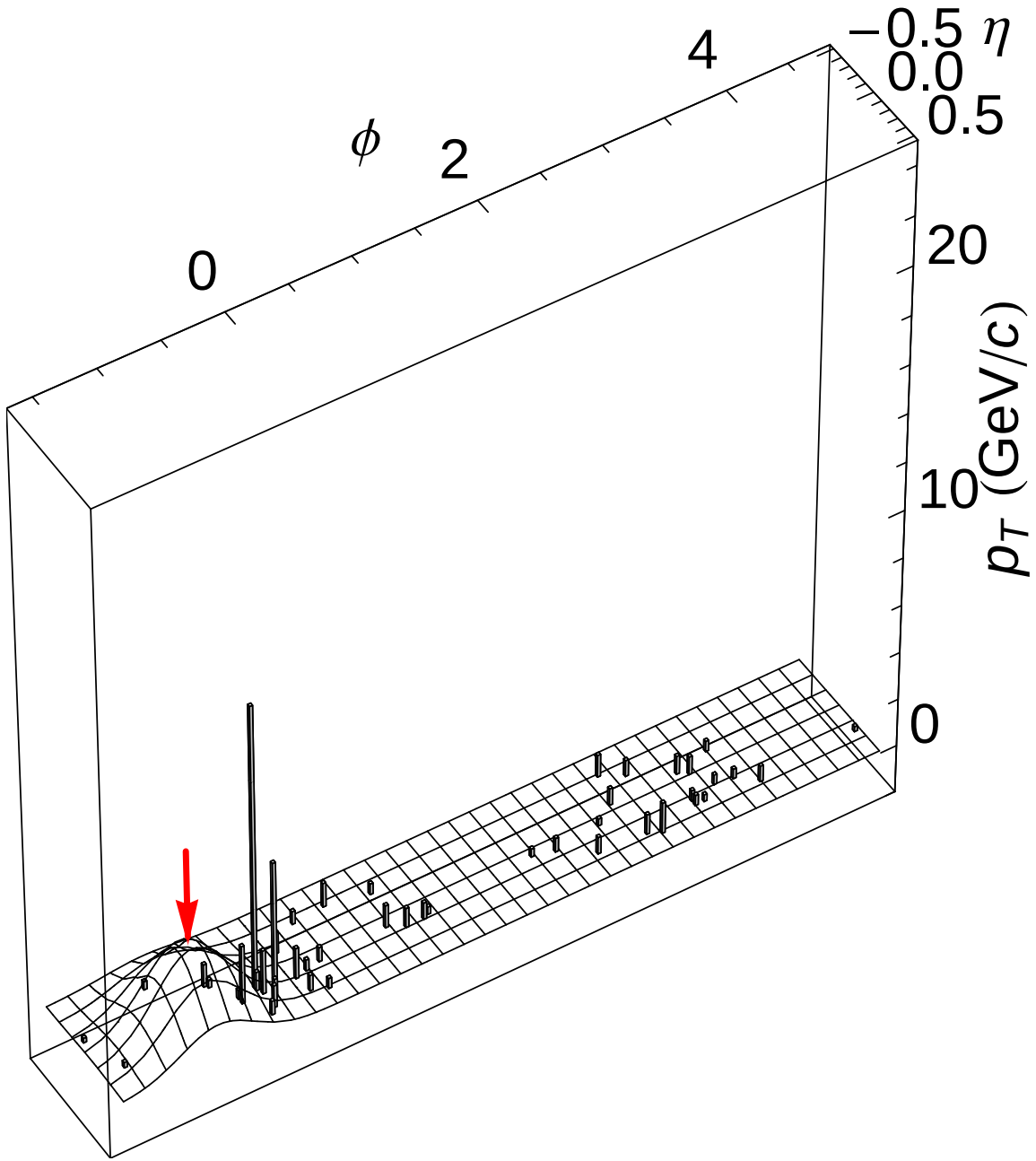
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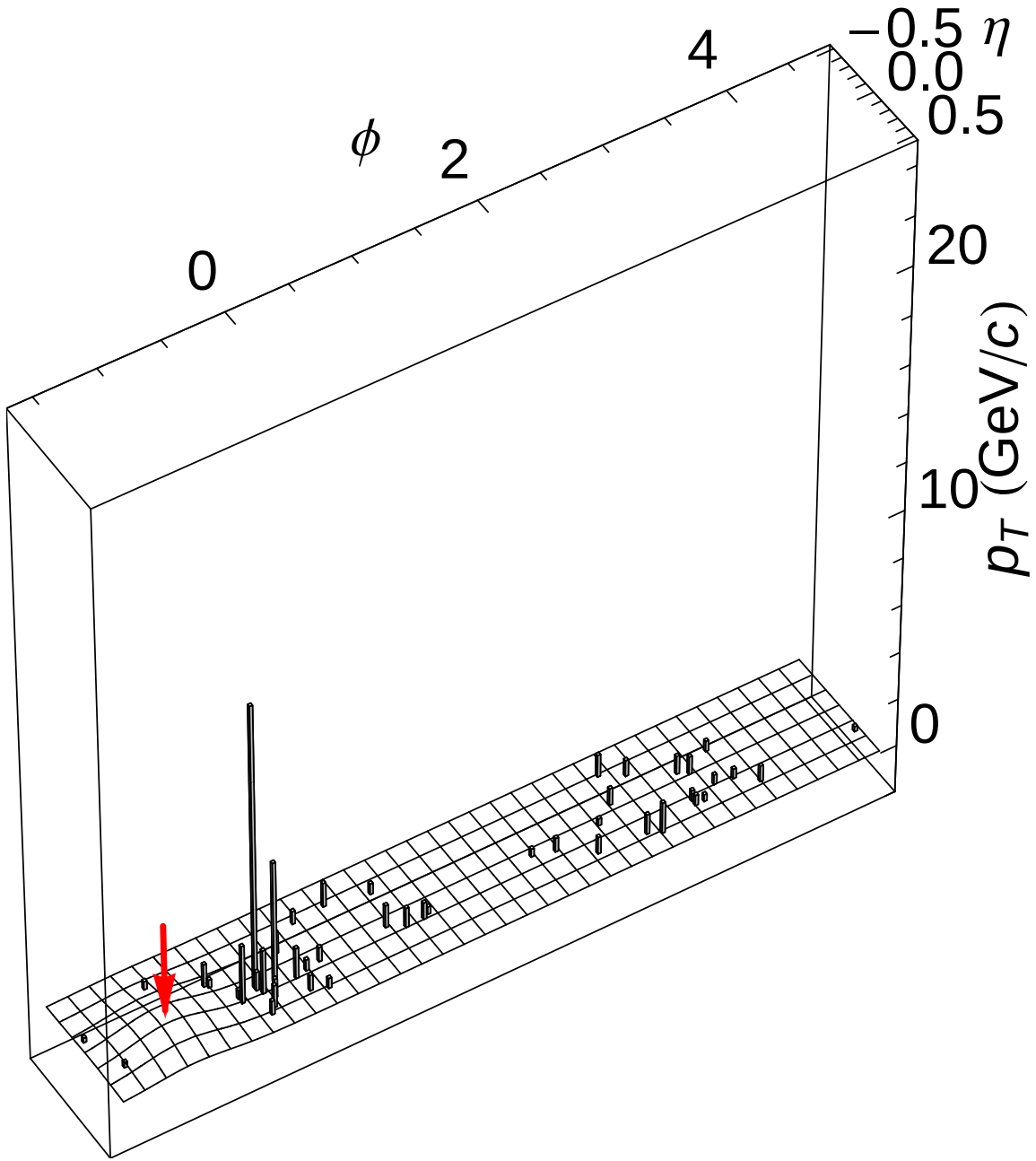
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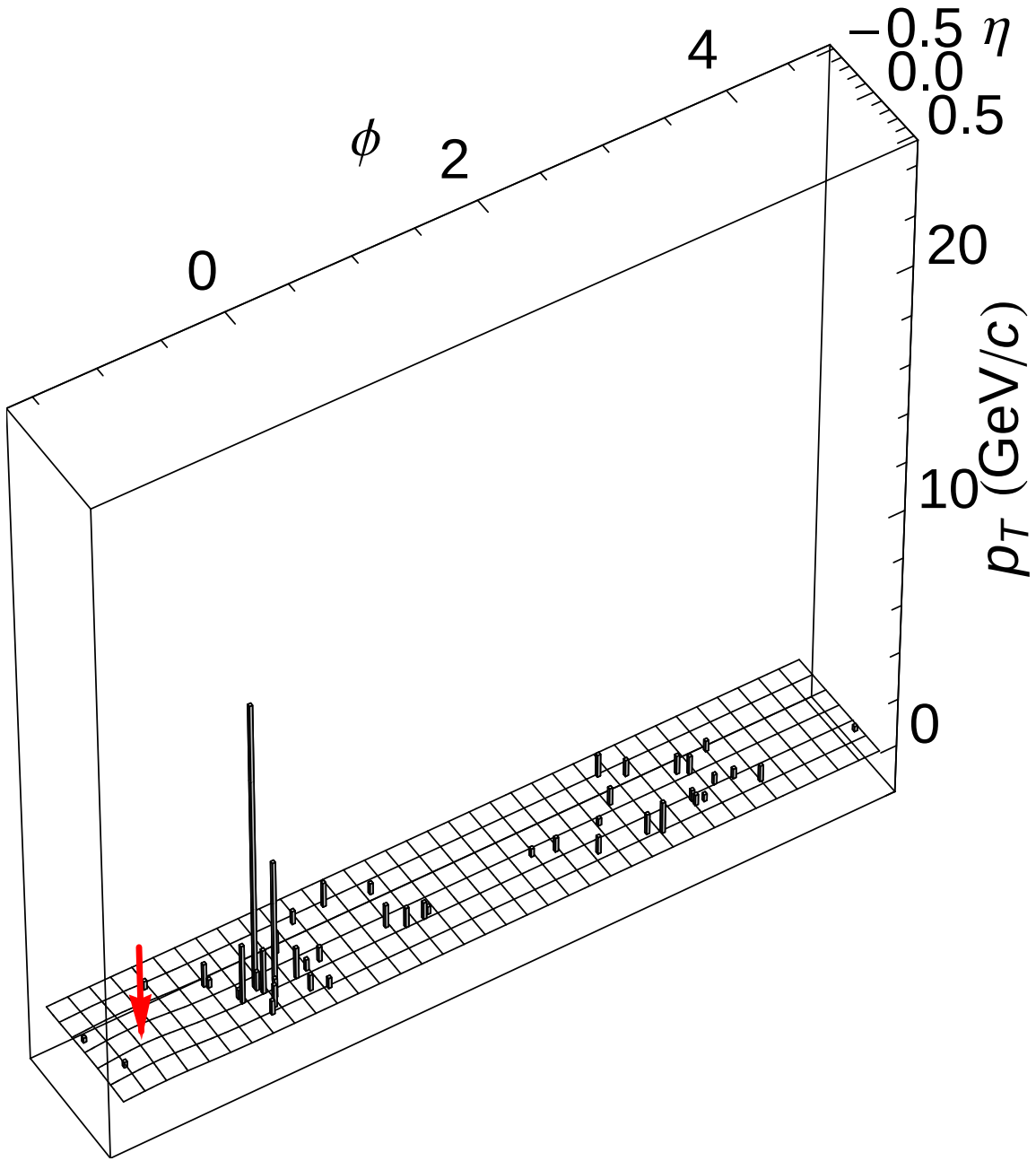
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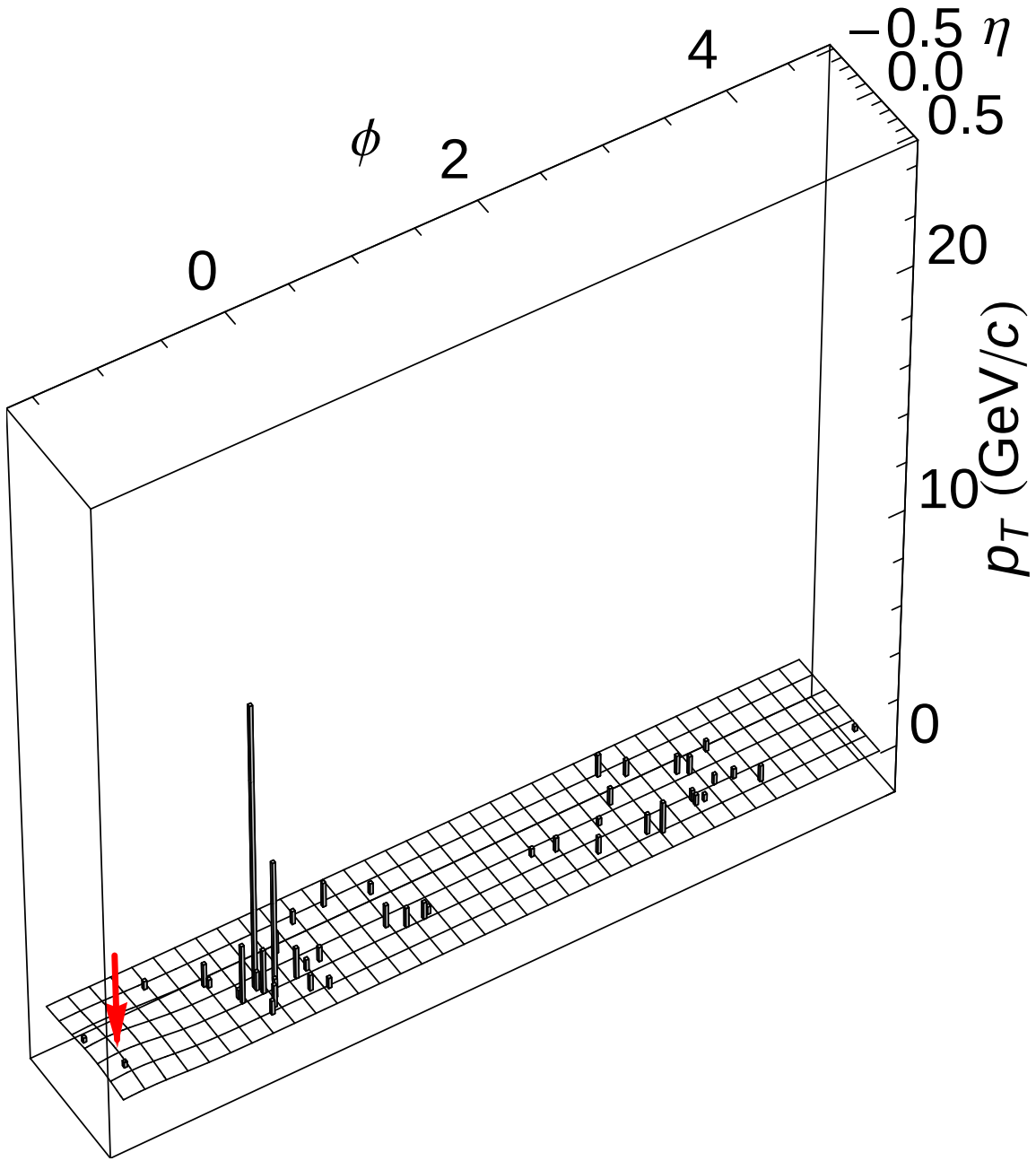
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