Direct Jet Measurements in p-p and Cu+Cu Collisions by the PHENIX Experimenent

~~RHIC-AGS Users Meeting~~

~~June 5, 2009~~

~~Brian A. Cole~~

~~for the PHENIX Collaboration~~

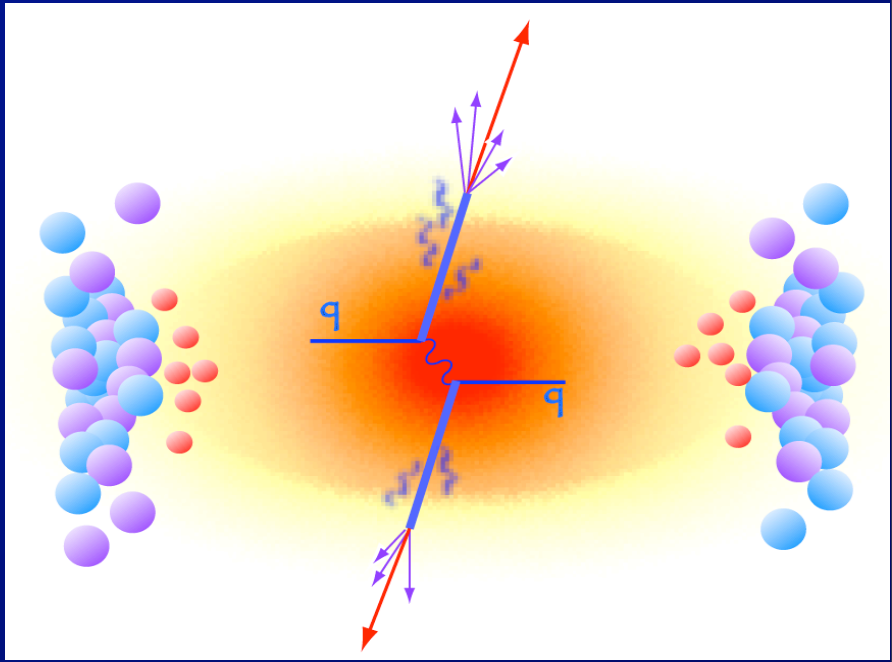
Not an officially sanctioned PHENIX talk

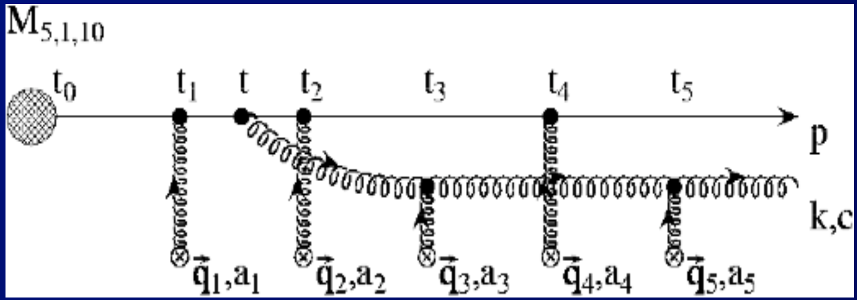
Jet Probes of the Quark Gluon Plasma

- **High-p_T quarks and gluons are valuable probe of QGP**
  - Can be separated from final-state "mess".
  - Directly interact with the medium.

    ⇒ Probe color-charge density in medium
  - Medium response probes QGP properties
  - Production rate (almost) calculable

    ⇒ "Calibrate-able"

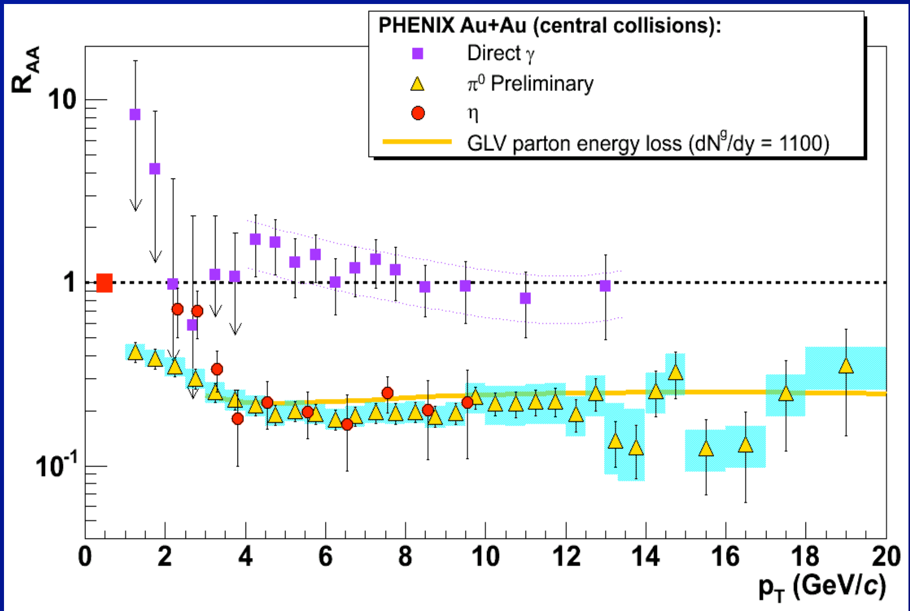




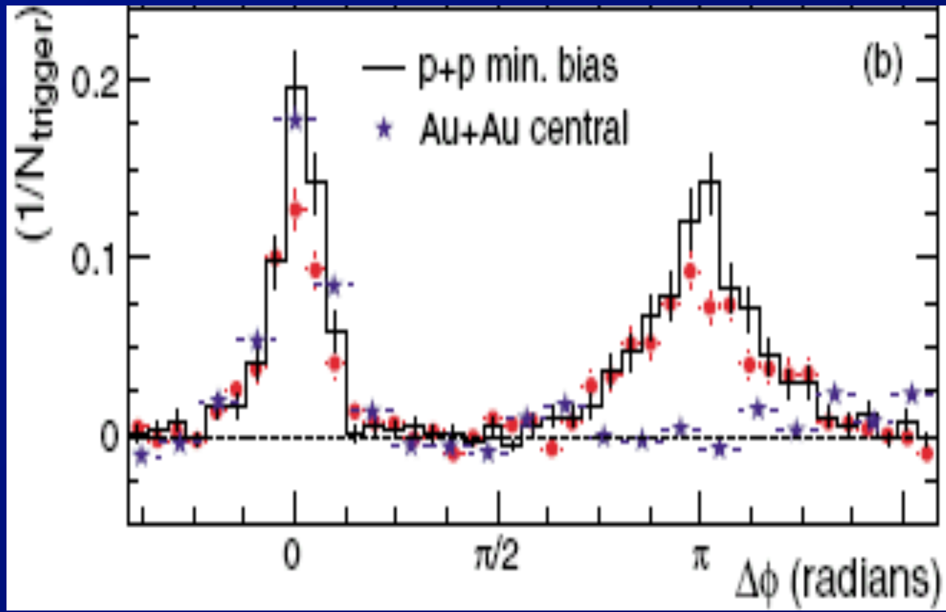
(GLV) Diagram for medium induced gluon radiation

"Jet" Quenching at RHIC

Single hadron but not γ suppression



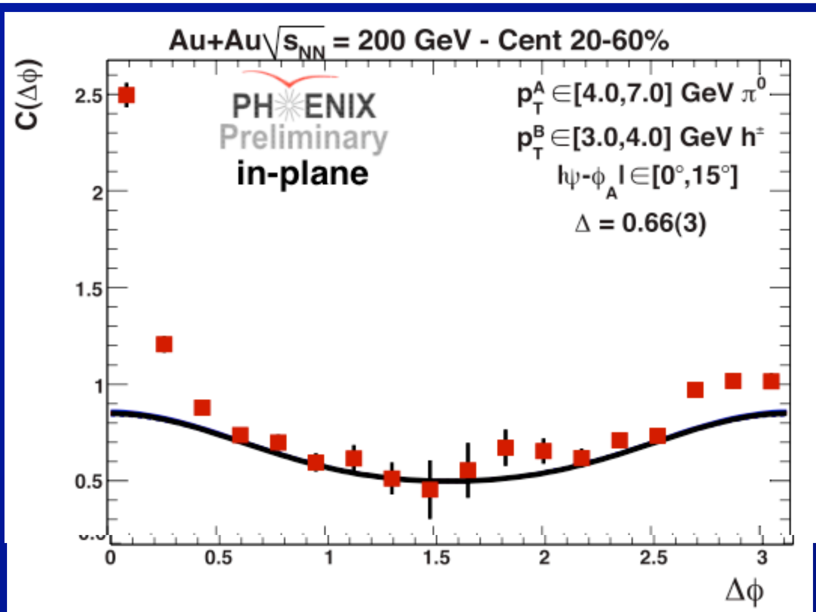
di-jet disappearance via di-hadron Δϕ correlations

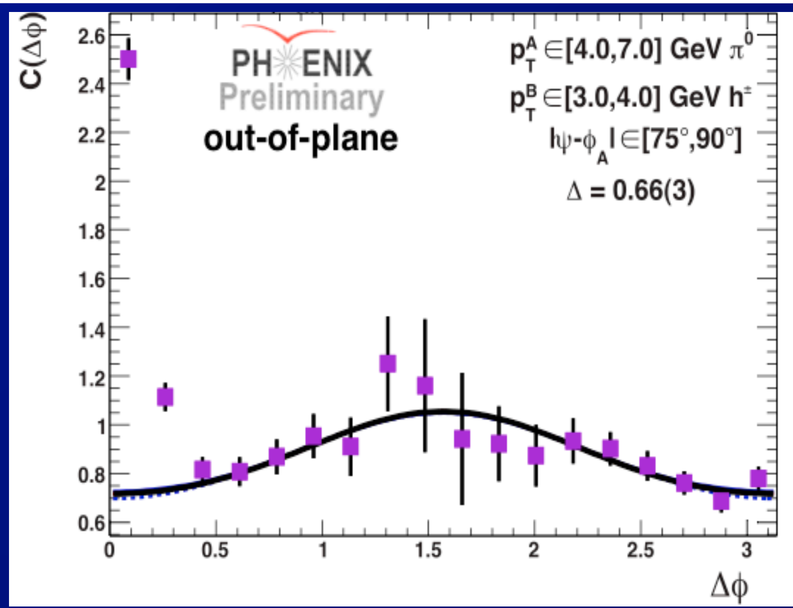


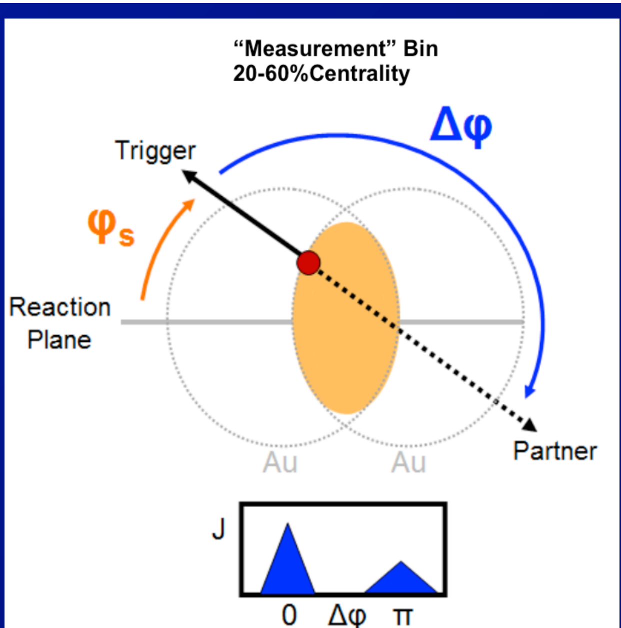
- RHIC results have clearly established "jet quenching" as an experimental fact
  - By using single, di, tri-hadrons
  - But, where are the jets?

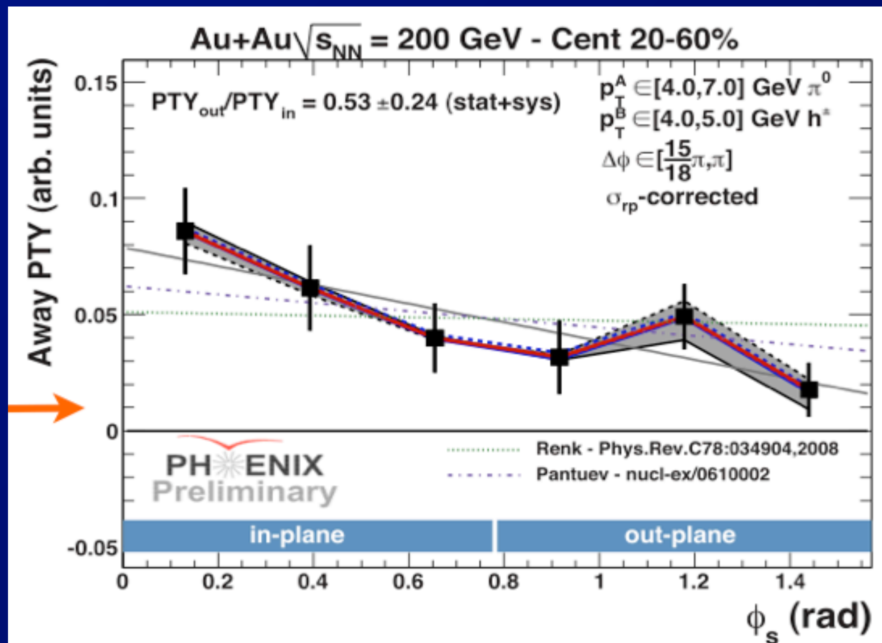
    ⇒Until recently: too hard in soft background

PHENIX: Di-jet Suppression, Updated







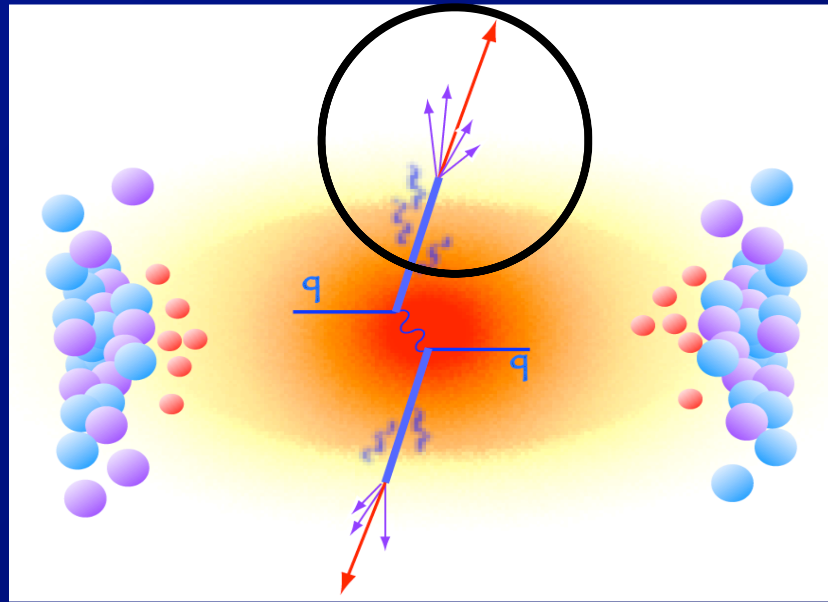


- Detailed test of di-jet differential quenching.

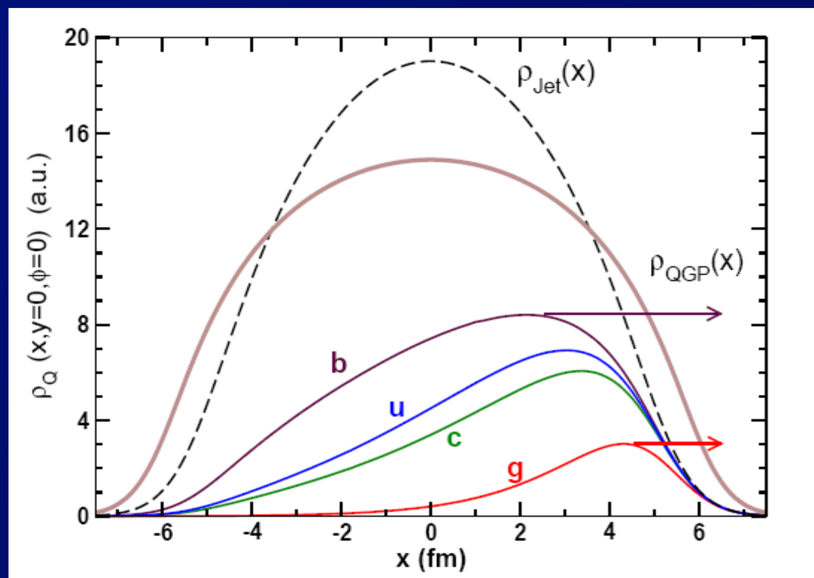
Problem with relying on hadrons

- **Energy loss bias**
  - Hadrons biased to jets that lose the least energy
    - ⇒ geometry
    - ⇒ radiation fluctuations
- **Averaging**
  - Hadron measurements average over jet energies
    - ⇒ Indirect measurement of jet quenching
- **Rates**
  - Suffer from steep fragmentation function

⇒ USE FULL JETS!



Wicks et al (GLV + collisional)

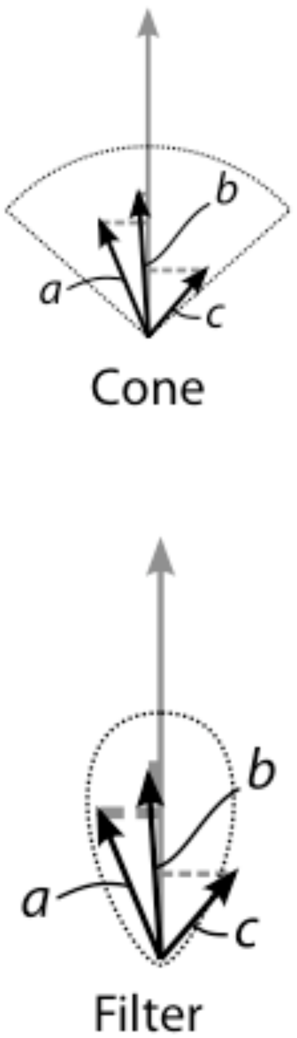


PHENIX: A+A Optimized Jet Reconstruction

- ~ 3 years ago PHENIX started investigating approaches to full jet reconstruction in A+A
- Considerations:
  - Flat angular weight of cone algorithms
    - ⇒Non-optimal signal/background
    - ⇒Small cones susceptible to bkgd fluctuations
  - Limited angular coverage of PHENIX
    - ⇒Control of edge effects
  - Initial studies of k_T algorithm
    - ⇒Jet shape sensitive to background
- Which led us to a new approach:
  - Cone-like algorithm but with angular weight
    - ⇒Implementation naturally seedless, (analytically) collinear , infrared safe.

PHENIX: Gaussian Filter

Shamelessly borrowed from Y. Lai, QM2009 talk



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

- 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

Y. Lai, BAC, arXiv:0806.1499

Gaussian Filtering: Demonstration

$$E_T^{filt}(\eta_0, \phi_0) = \int\int d\phi d\eta \, \frac{d^2 E_T}{d\eta d\phi} \, e^{-\left((\eta-\eta_0)^2+(\phi-\phi_0)\right)/2\sigma^2}$$

- Example event
  - 200 GeV p-p
- Lego plot of E_T $\Delta\eta\Delta\varphi = 0.1 \times 0.1$
  - Charged + EM
- Plot E_T^{filt} vs ϕ_0 at $\eta = 0$.
  - Clearly visible maximum

    $\Rightarrow$ Jet

Gaussian Filtering: Demonstration

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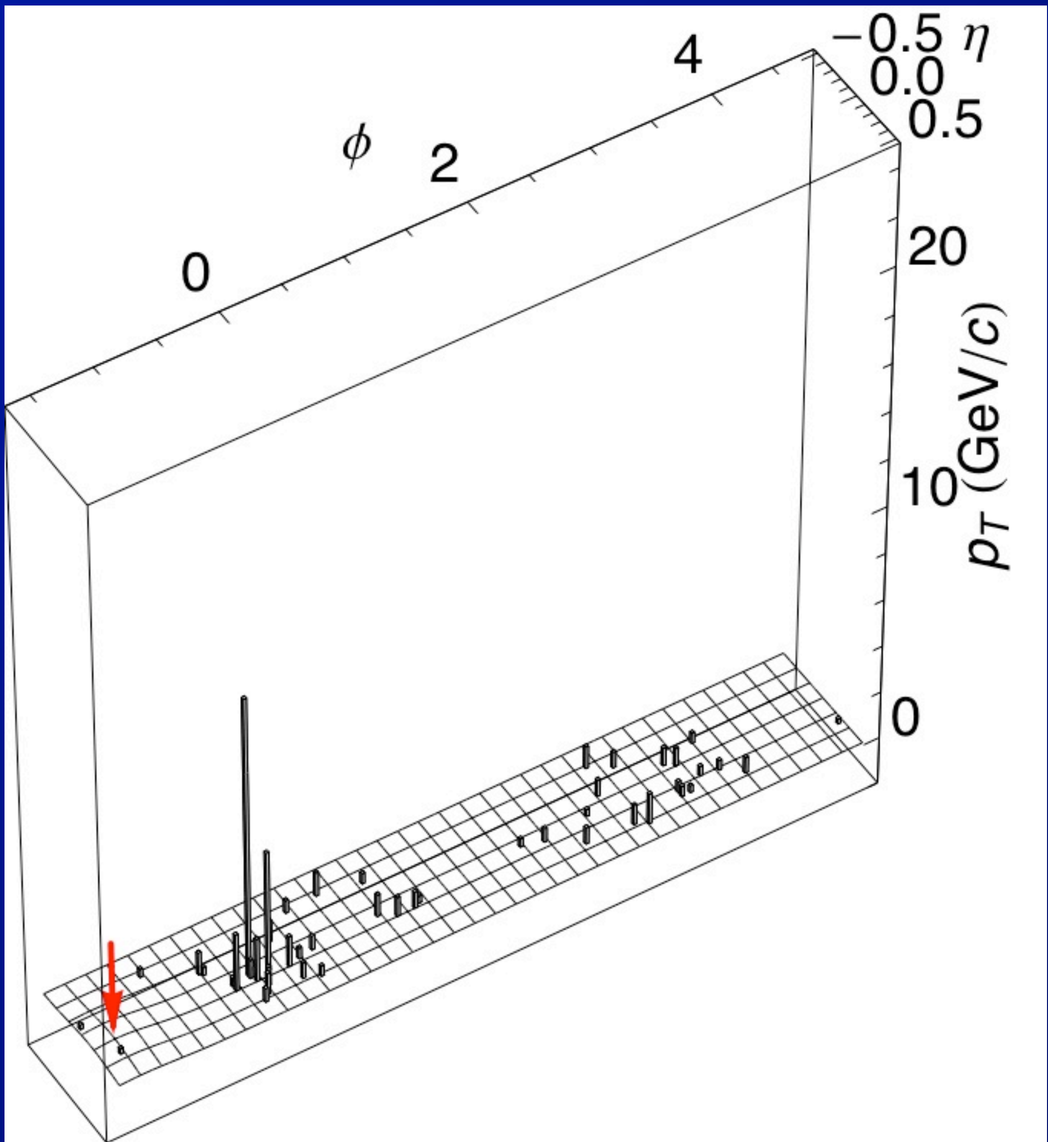

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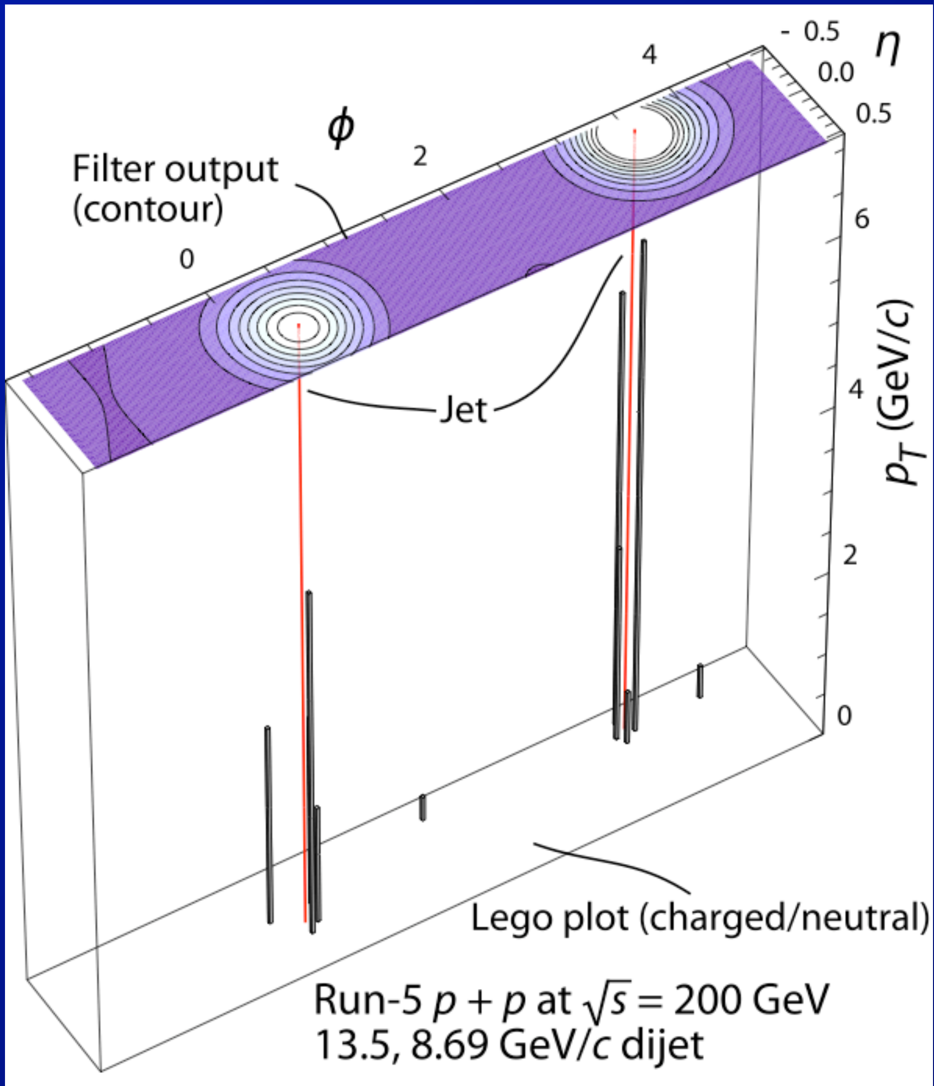
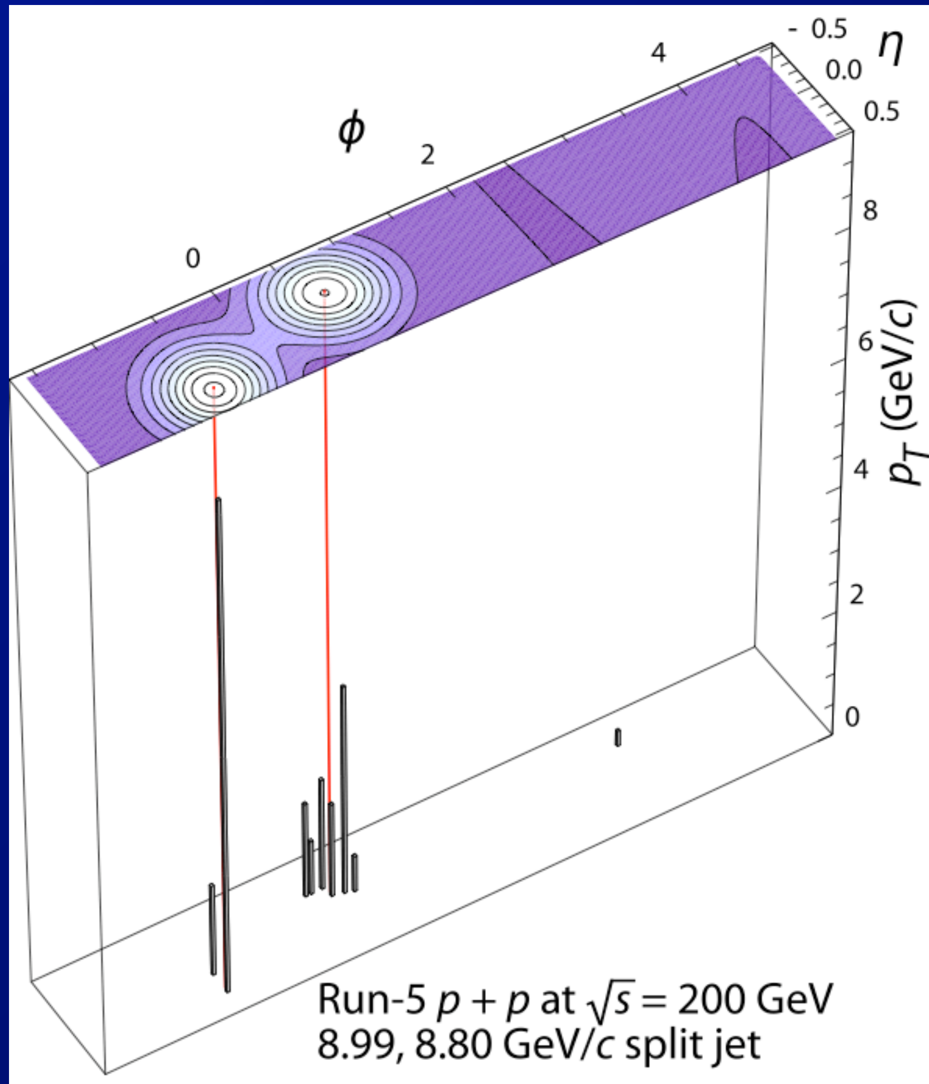
  - –Clearly visible maximum

    ⇒Jet

PHENIX: p-p Jet Reconstruction

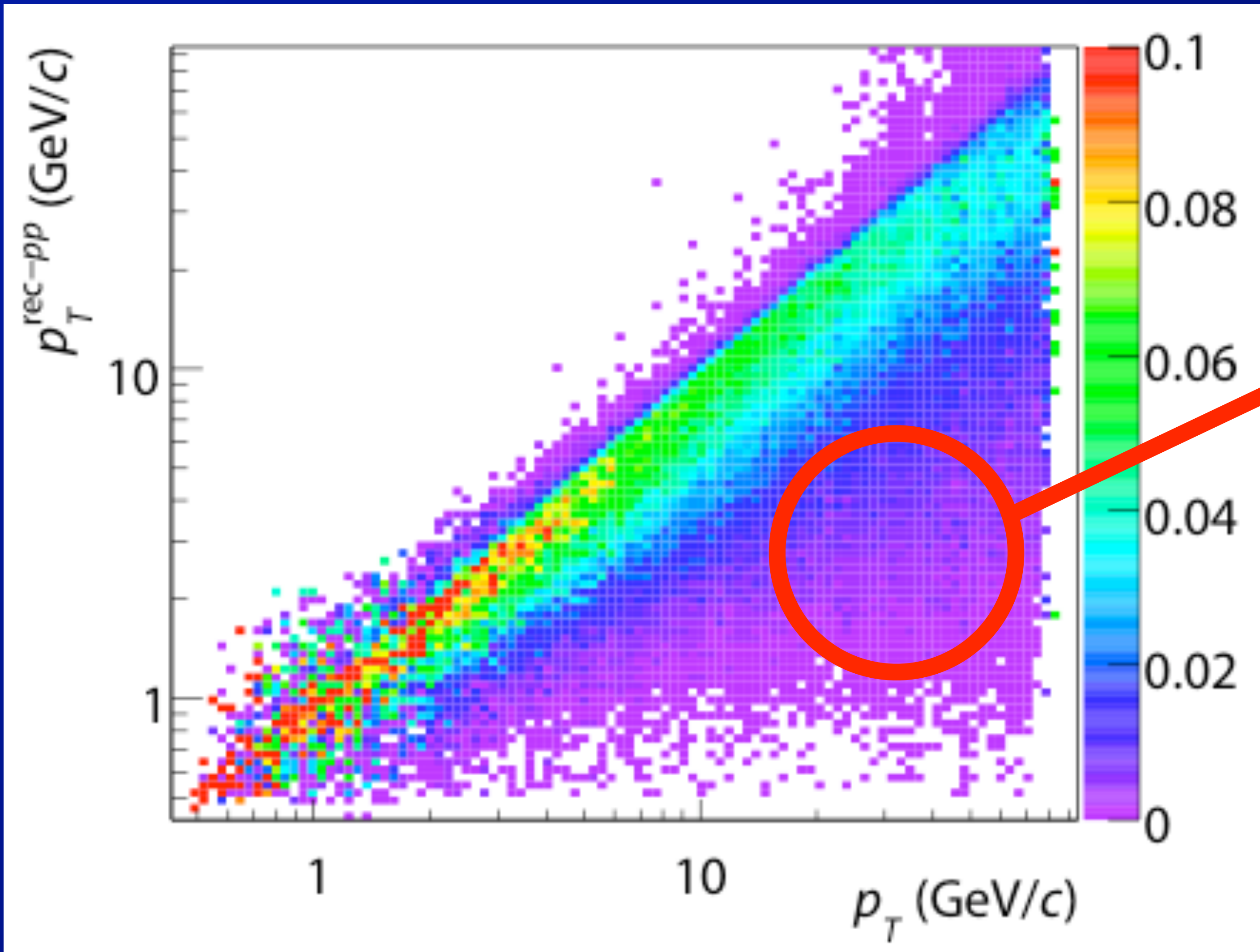




Di-jet event

Split jet (NLO/parton shower) event

PHENIX p-p: Detector Response

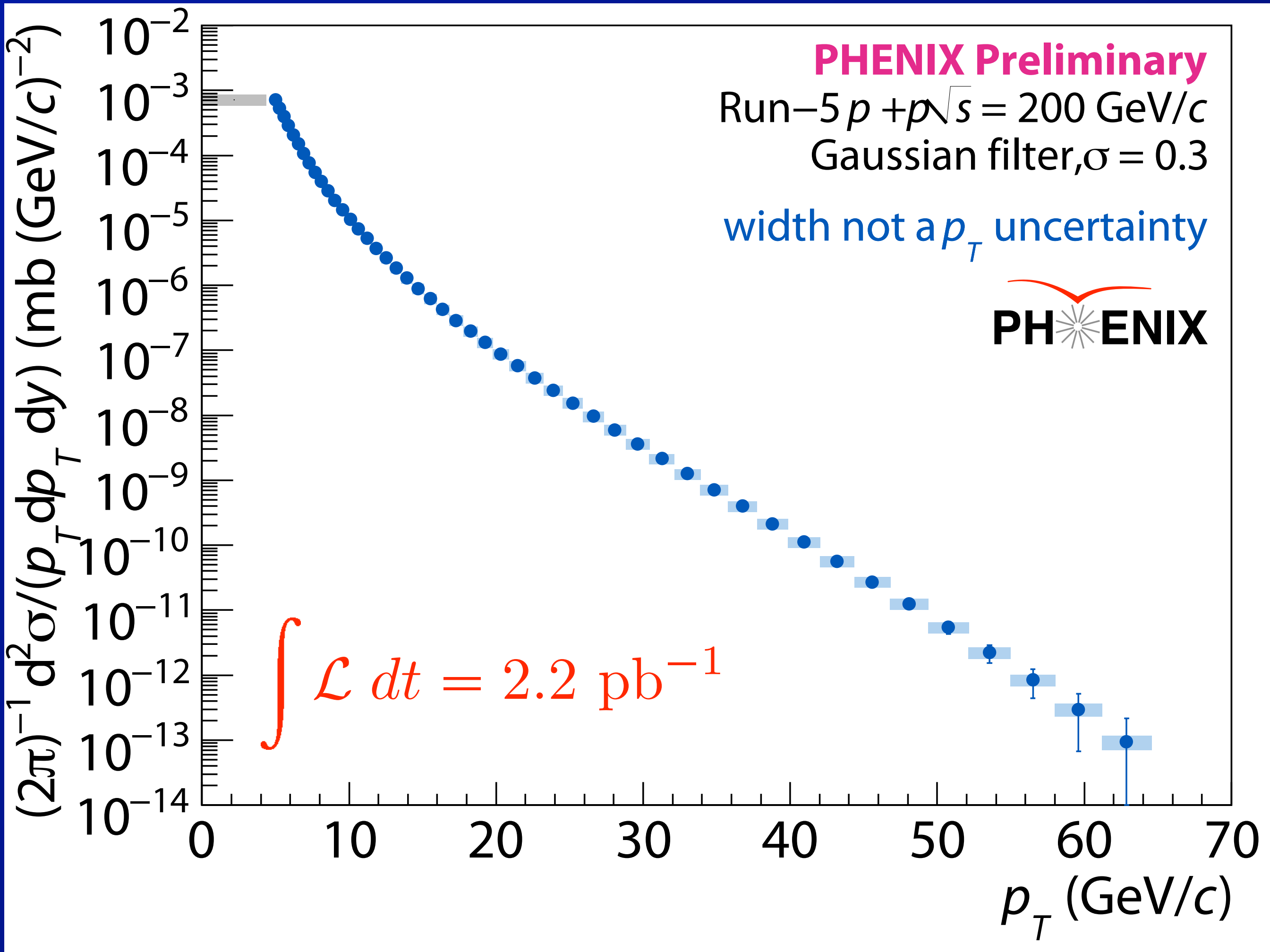


Losses primarily from K_L, neutron

But also edges and "holes"

- From 16 Million Pythia+GEANT simulated events
  - Complete transfer matrix used for unfolding spectrum

PHENIX Corrected p-p spectrum

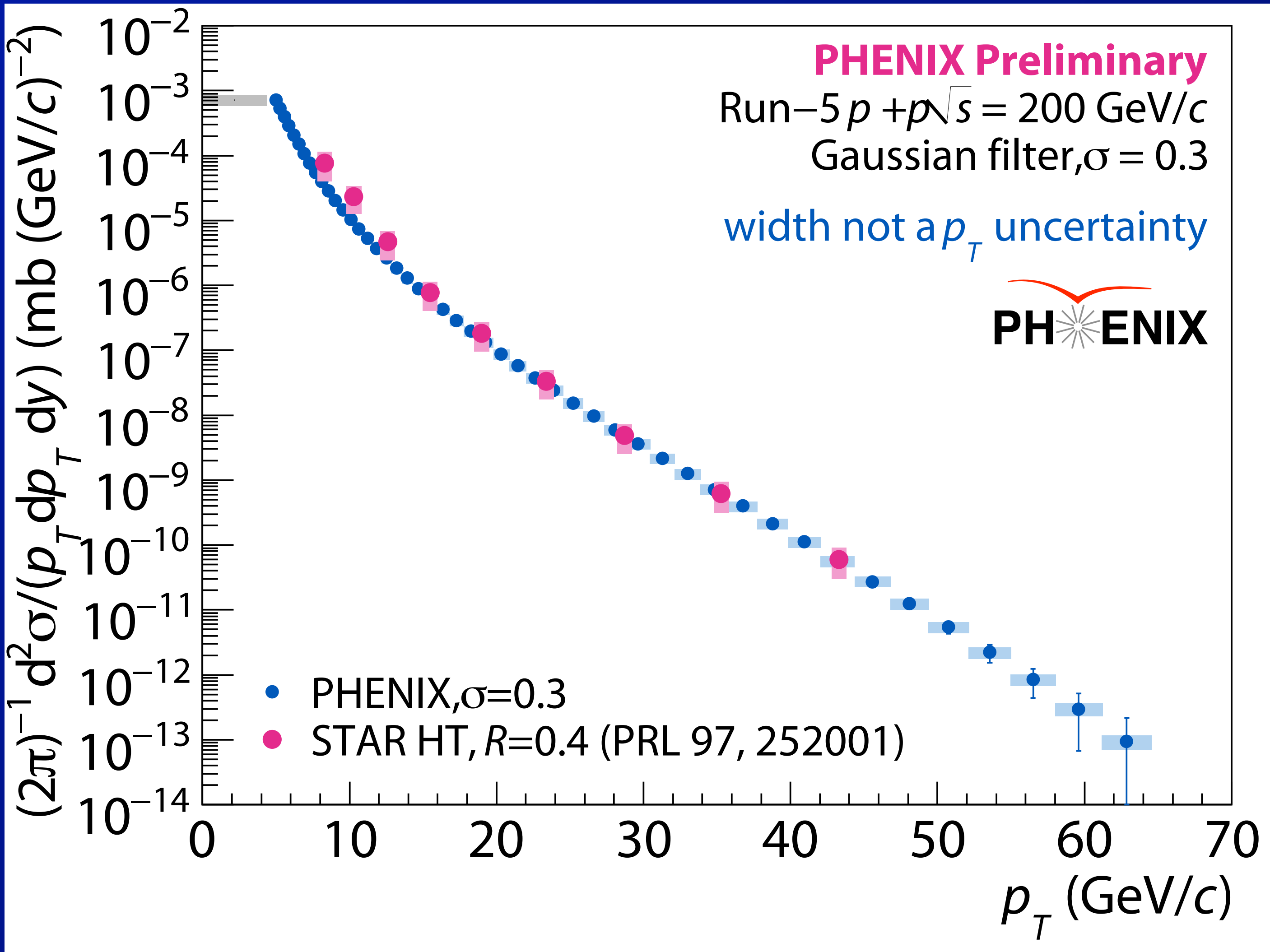


Grey band: systematic normalization uncertainty

Blue boxes: systematic errors due unfolding, "acceptance"

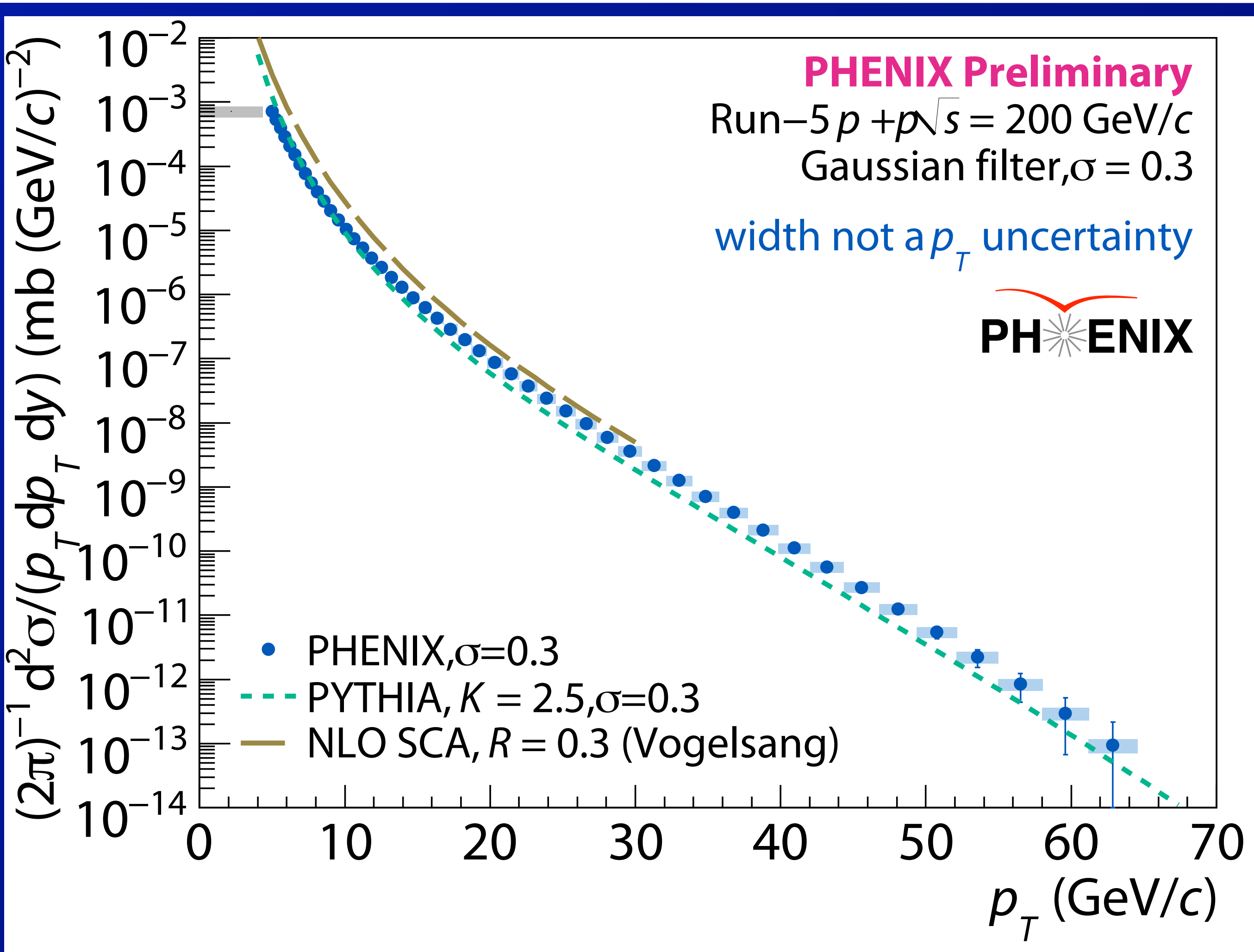
- **Spectrum unfolded for detector response**
  - **With Guru Singular Value Decomposition code (NIM A372:469-481,1996)**
    - **⇒ Also Used by (e.g.) D0**

PHENIX, STAR Spectrum Comparison



- **Beware: "apples to oranges" comparison**
  - ⇒**Different jet algorithms ⇒ different cross-section**
  - ⇒**But, narrow jets @ high p_T ⇒ (how?) small difference**

PHENIX p-p spectrum, pQCD comparison

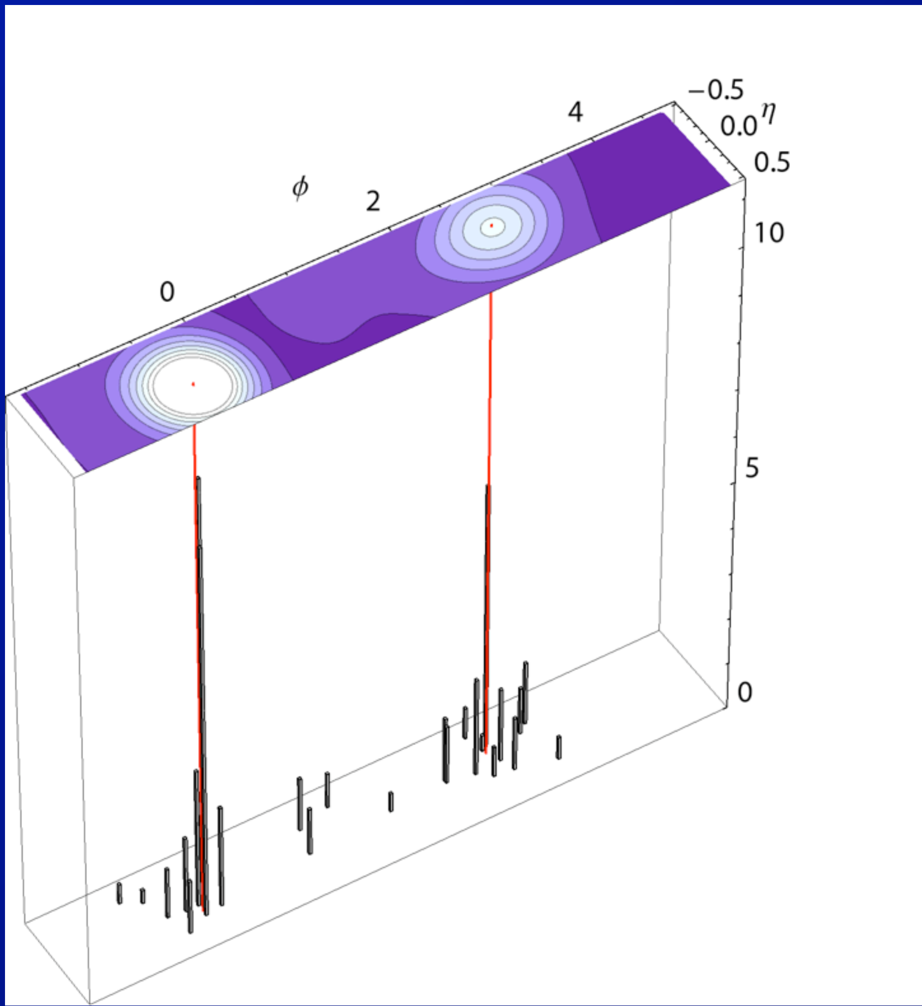


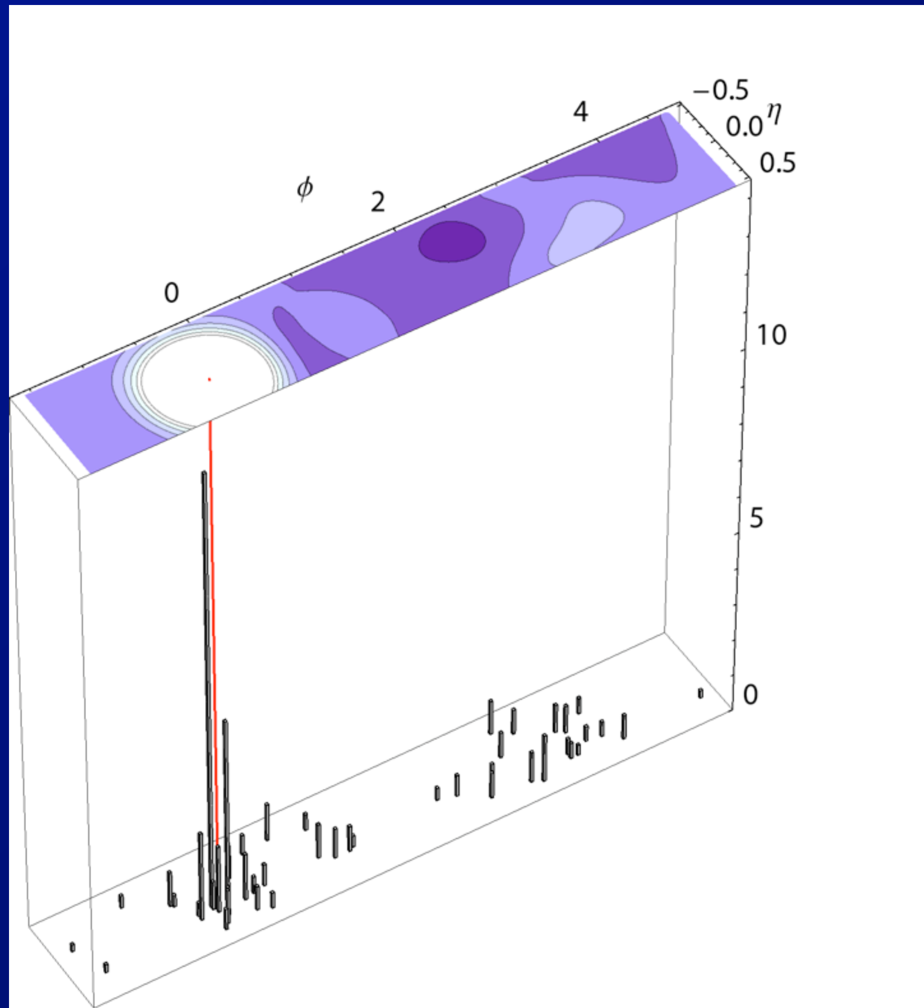
– Pythia LO K value only a guess

– Vogelsang SCA (Small cone approx.) apples-and-oranges comparison

⇒Need real NLO pQCD calculation for filter

Cu+Cu Event Display



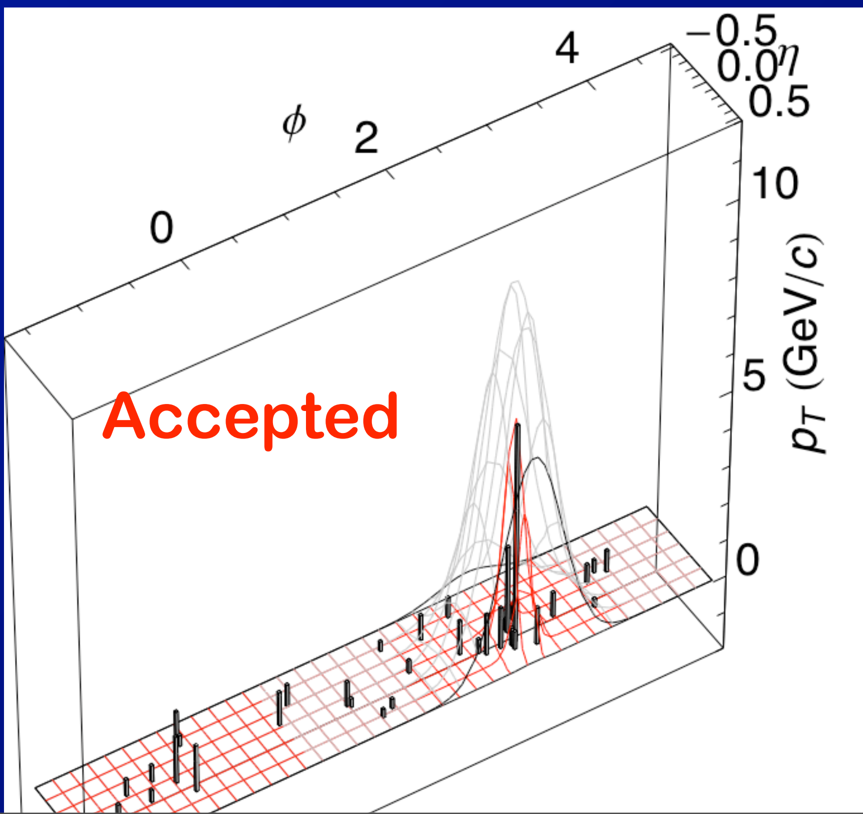


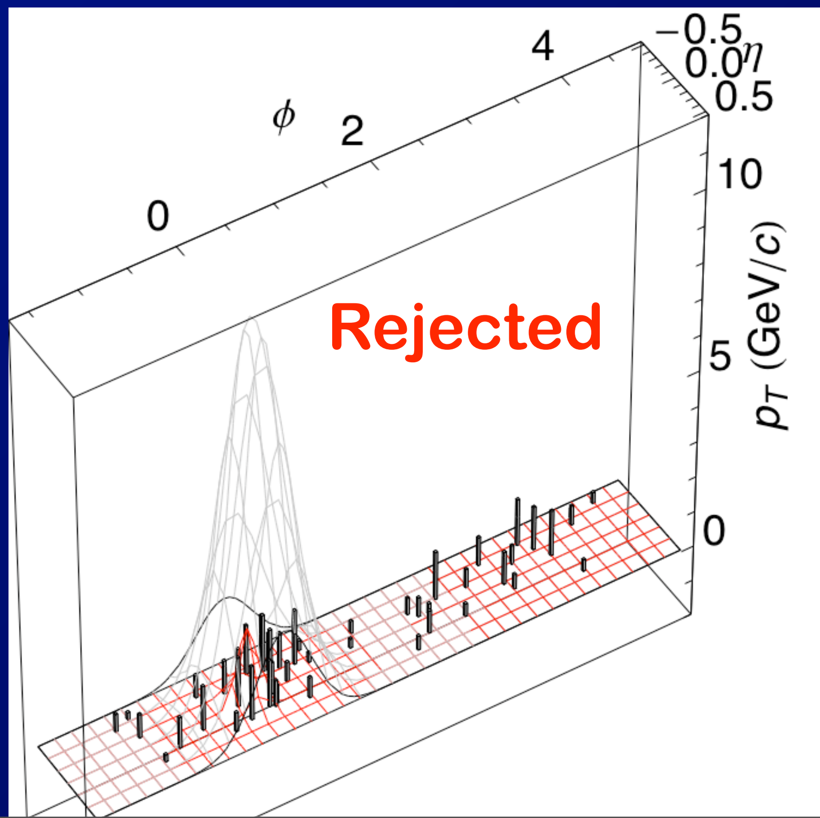
- Event display of two Cu+Cu events
  - Di-jet event
  - Single-jet event, other outside acceptance (?)

PHENIX: Fake Jet Rejection

- **Fake jets potentially serious problem**
  - Especially with correlated background fluctuations
- **Reject background with jet "shape" cut**
  - $$g_{\sigma_{\mathrm{dis}}}(\eta,\varphi) = \sum_{i \in \mathrm{fragment}} p_{T,i}^2 \exp\left[-\frac{(\eta_i-\eta)^2+(\varphi_i-\varphi)^2}{2\sigma_{\mathrm{dis}}^2}\right],$$

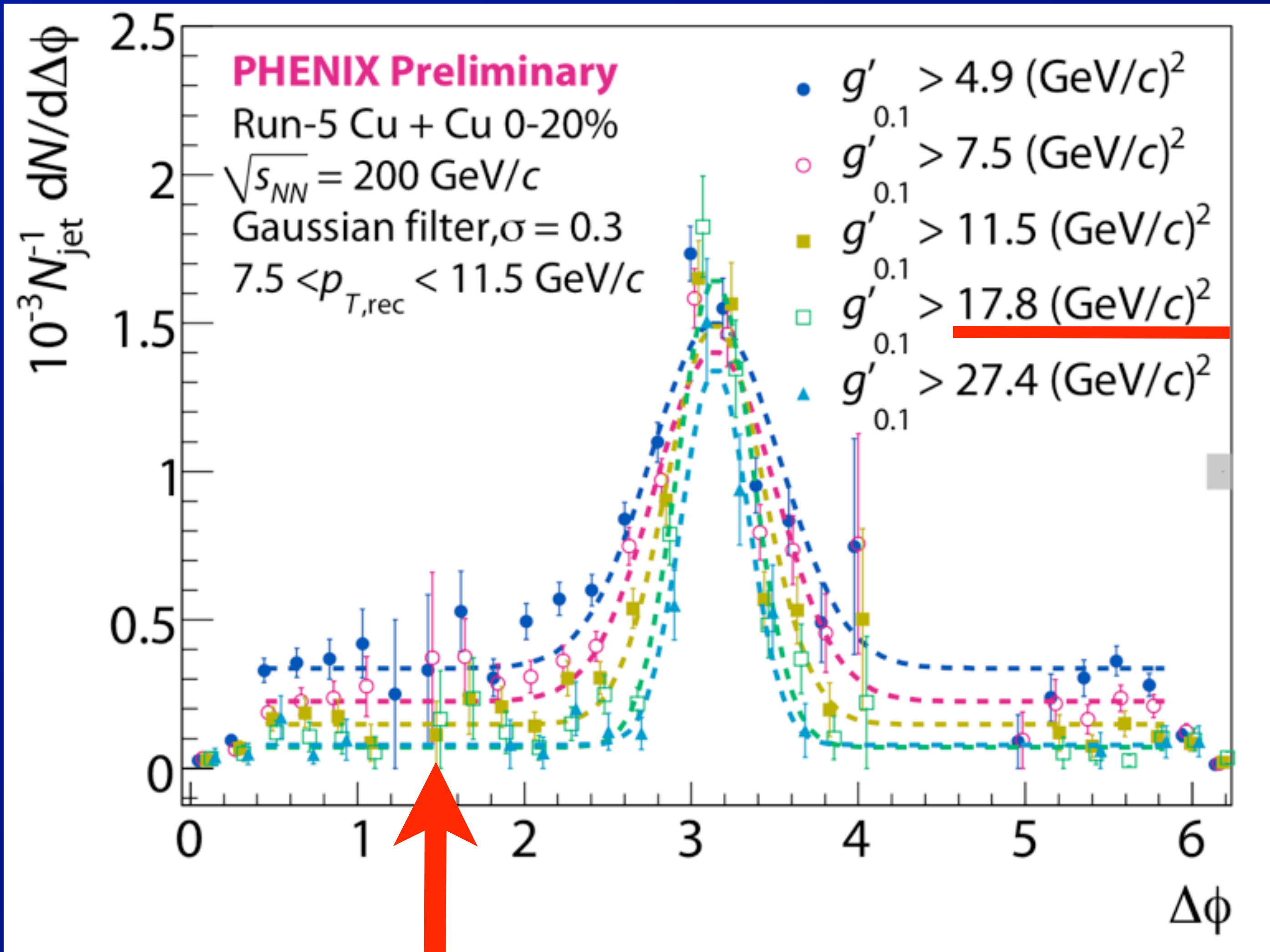
$\sigma_{dis} = 0.1$





PHENIX: Fake Rejection (2)

Cu+Cu di-jet Δϕ distribution prior to fake rejection



Increasing rejection

Increasing rejection

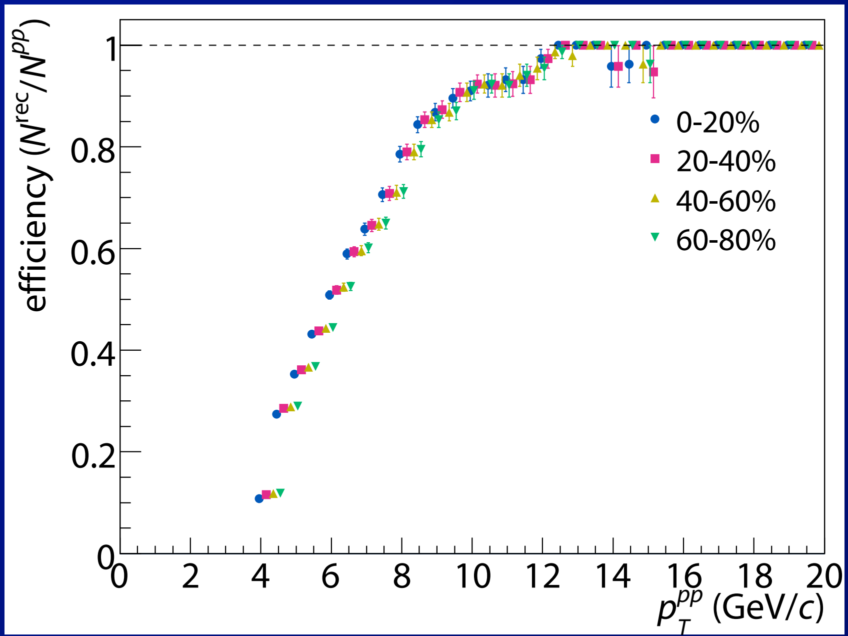
~ Entirely combinatoric pairs due to fake jets

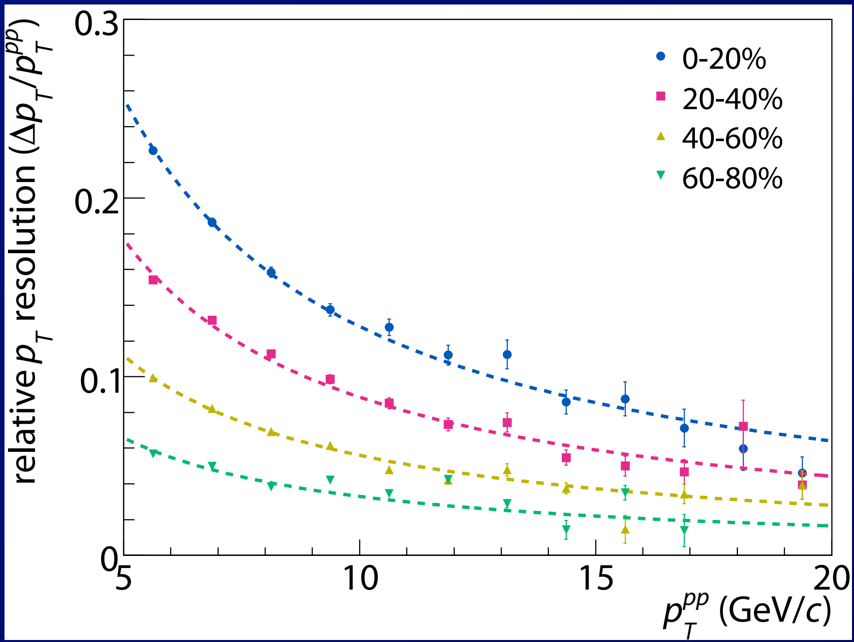
PHENIX Cu-Cu Performance

- Event-averaged background folded w/ filter subtracted during jet finding process

$$E_T^{filt}(\eta_0,\phi_0) = \int\int d\phi d\eta \, \frac{d^2E_T}{d\eta d\phi} \, e^{-((\eta-\eta_0)^2+(\phi-\phi_0))/2\sigma^2} - B(\eta_0,\phi_0,N_{part})$$

- Cu+Cu performance (including fake rejection) by embedding p-p events into Cu+Cu events

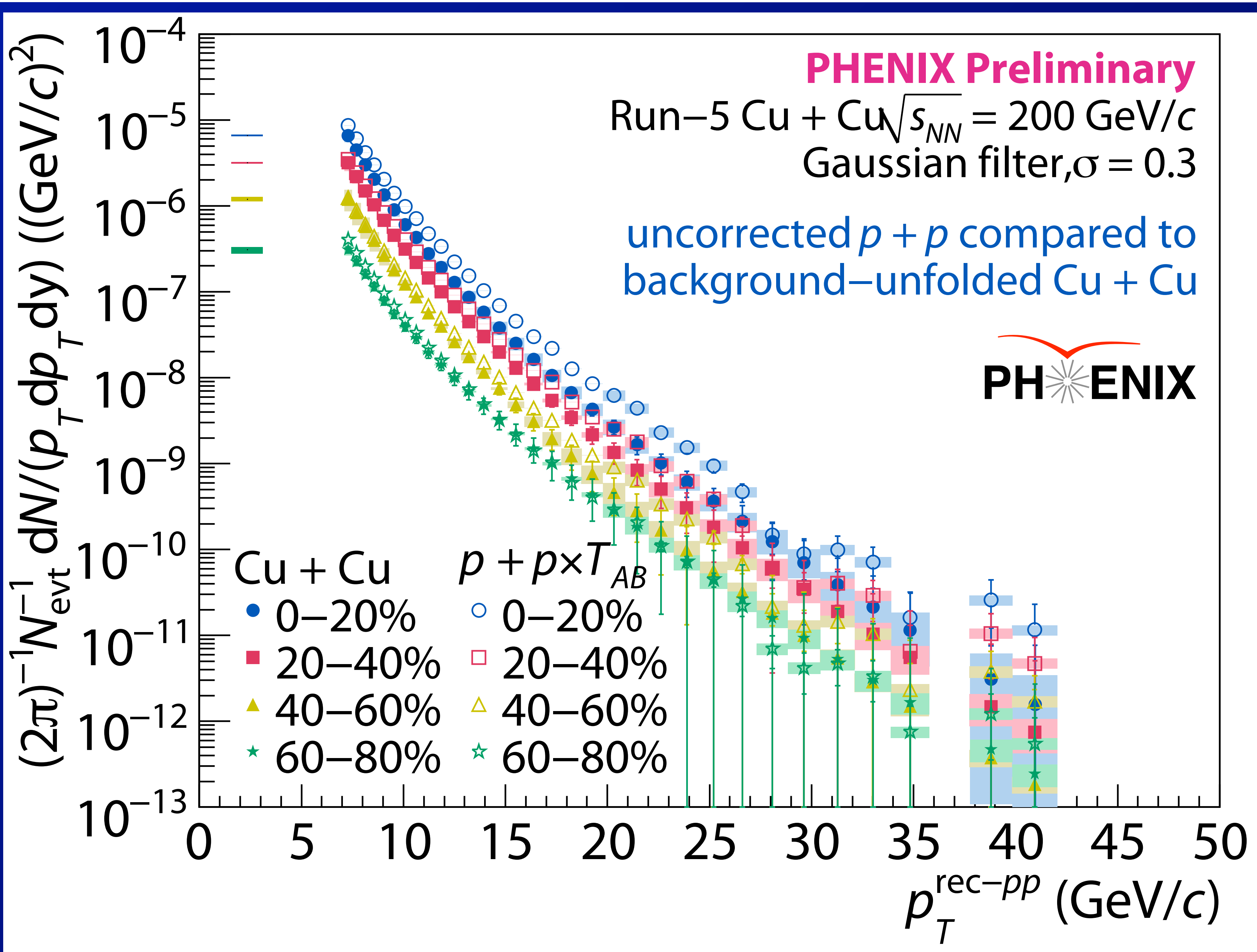




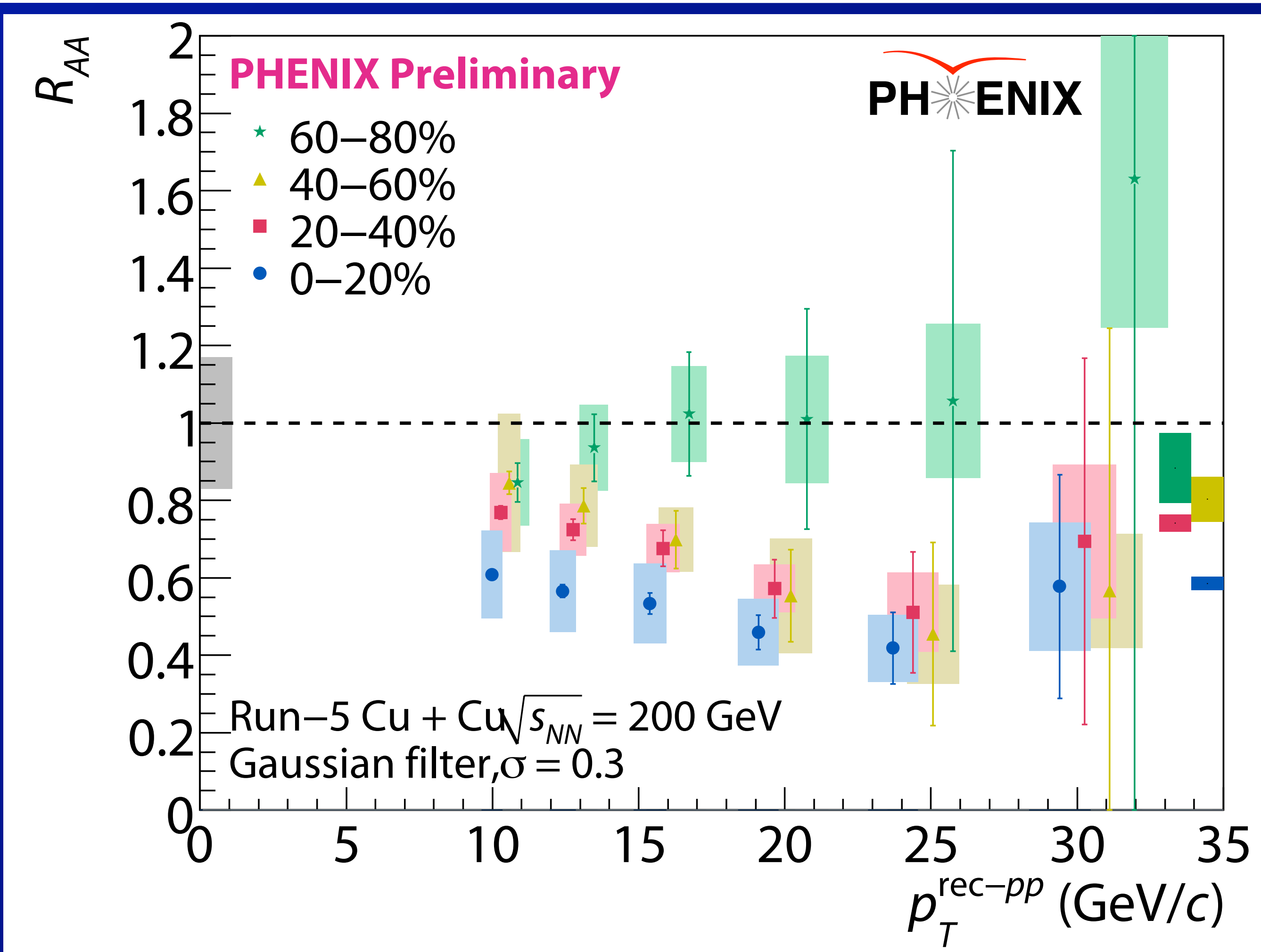
PHENIX: Cu-Cu ⇔ p-p Comparison

- Evaluate Cu-Cu, p-p comparison (and R_{AA}) using two different methods:
  - Method #1
    - ⇒Unfold Cu-Cu data for background smearing
    - ⇒Correct for inefficiencies
    - ⇒Compare to p-p data at p-p reconstructed energy scale
  - Method #2
    - ⇒DO NOT unfold Cu+Cu for background.
    - ⇒Evaluate "smeared" p-p spectrum from embedding analysis w/ correct normalization.
    - ⇒Compare Cu-Cu to smeared p-p
  - Valuable test of systematics in unfolding

Unfolded Cu-Cu Spectra

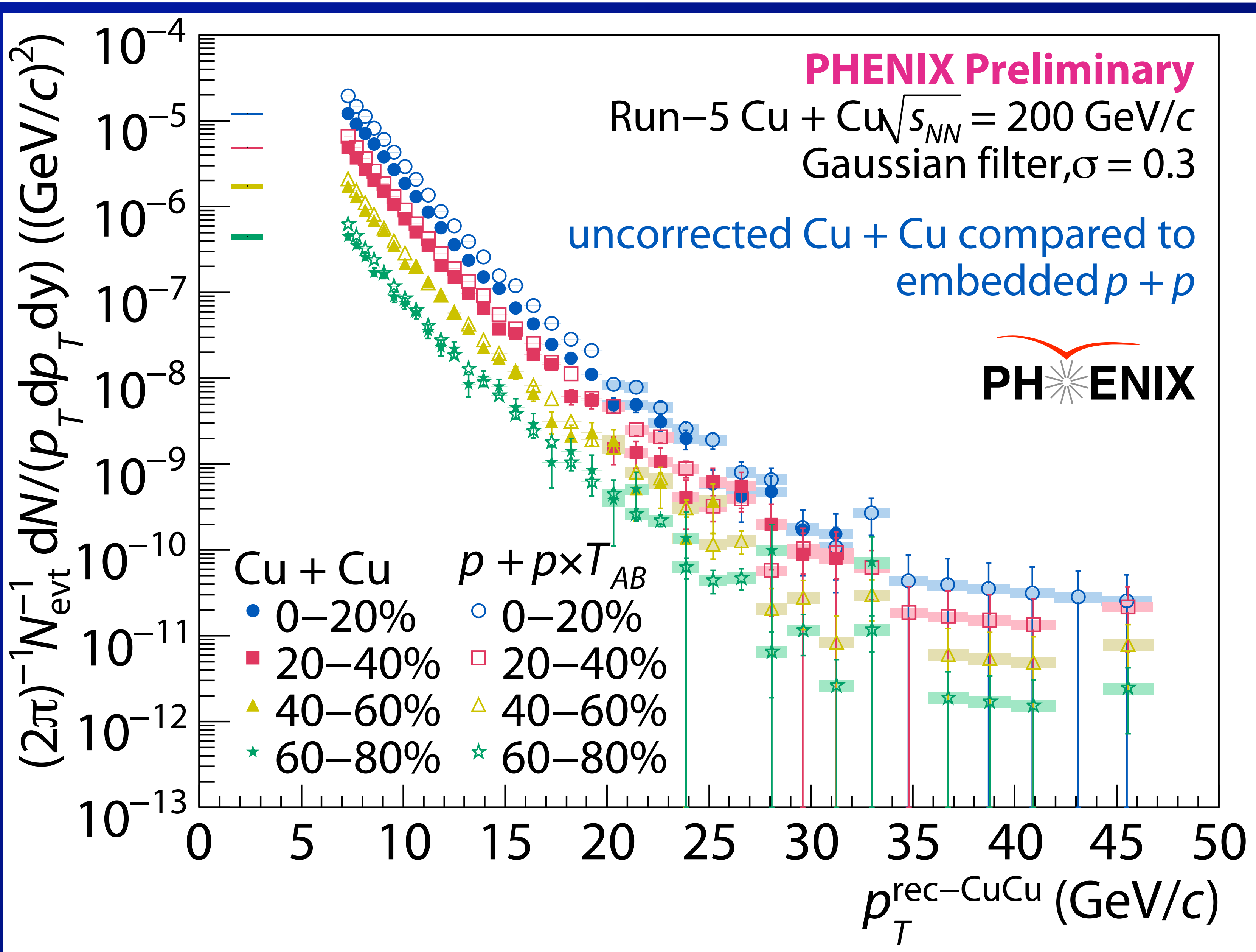


Unfolded Cu+Cu R_{AA}



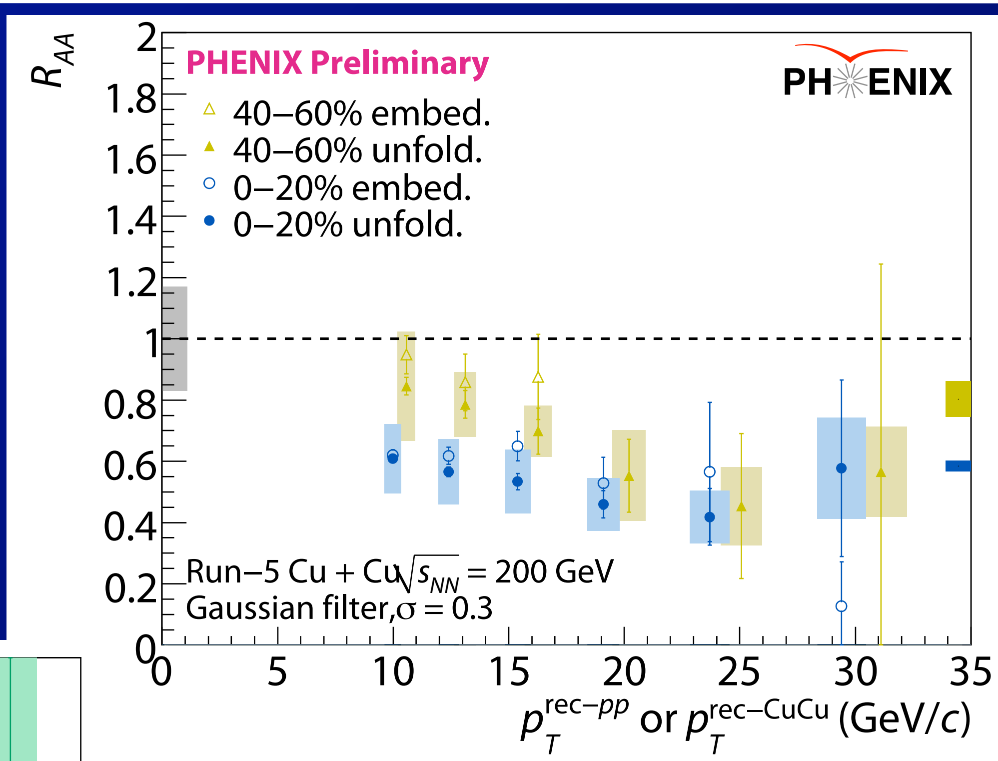
- **Three systematic errors quoted**
  - Normalization (mostly p-p, Cu-Cu relative E scale)
  - Centrality dependent (unfolding vs embedding)
  - Bin-by-bin unfolding systematic error

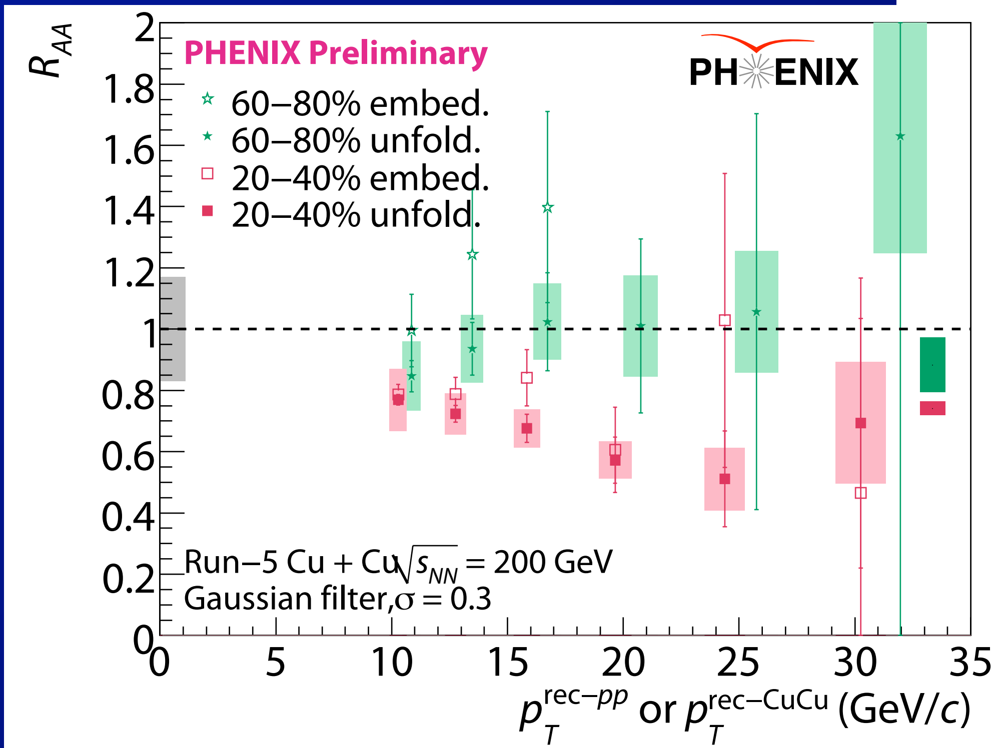
Cu-Cu, Embedded p-p Comparison



Unfolding / Embedding R_{AA} Comparison

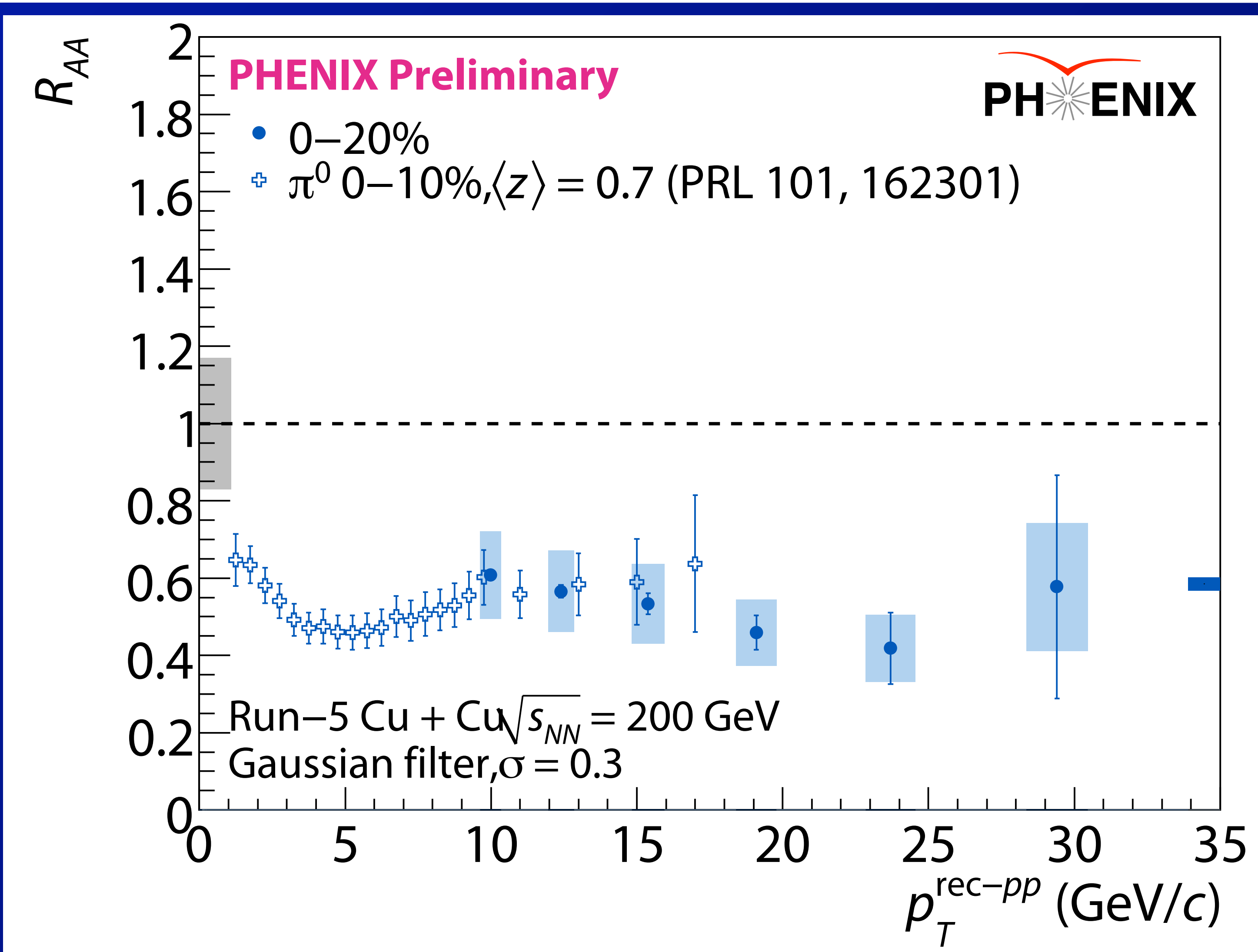
Beware:
Unfolding and embedded have different p_T scales (OK if R_{AA} ~ flat)





Good agreement between two different methods

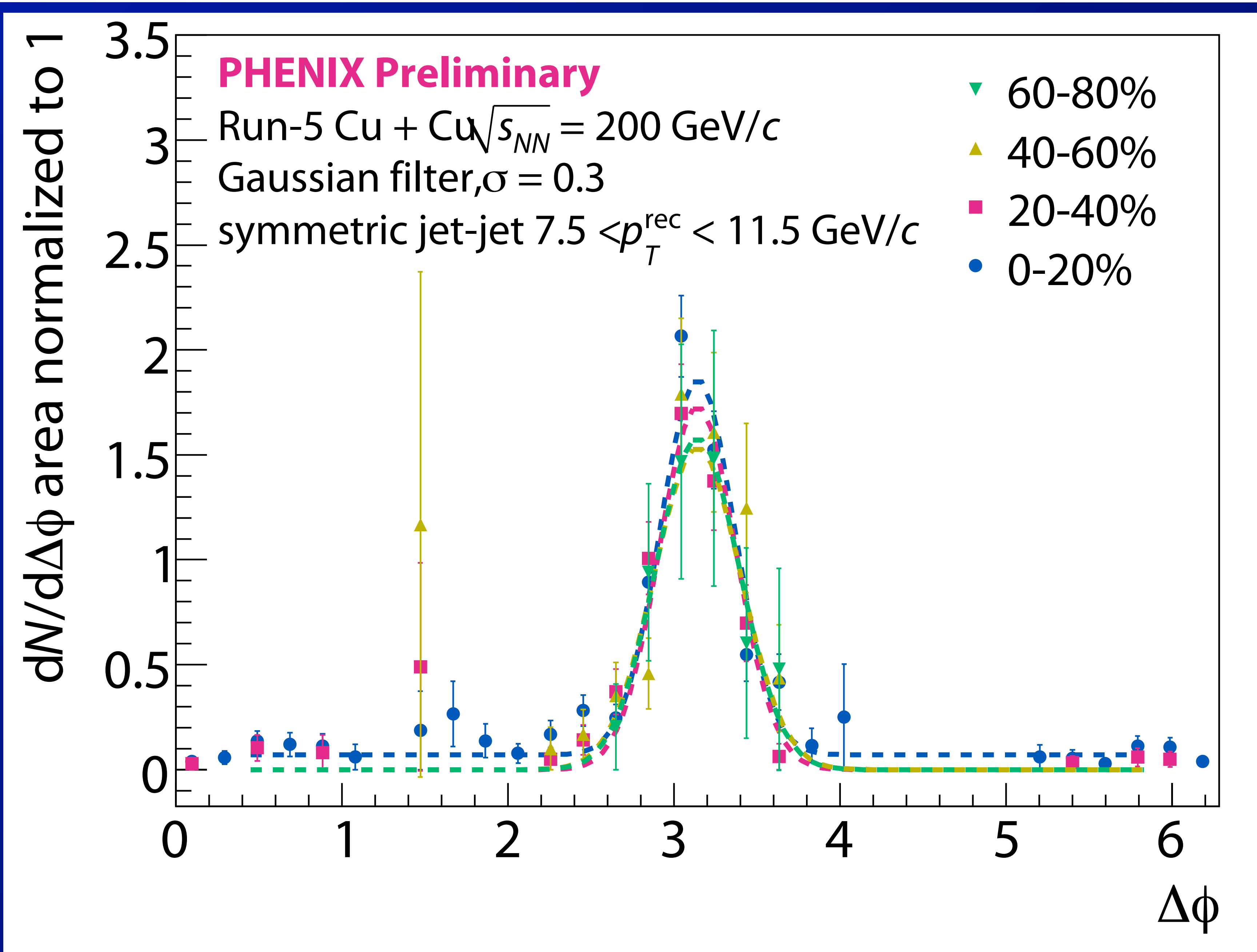
Cu+Cu Jet, π^0 R_{AA} Comparison



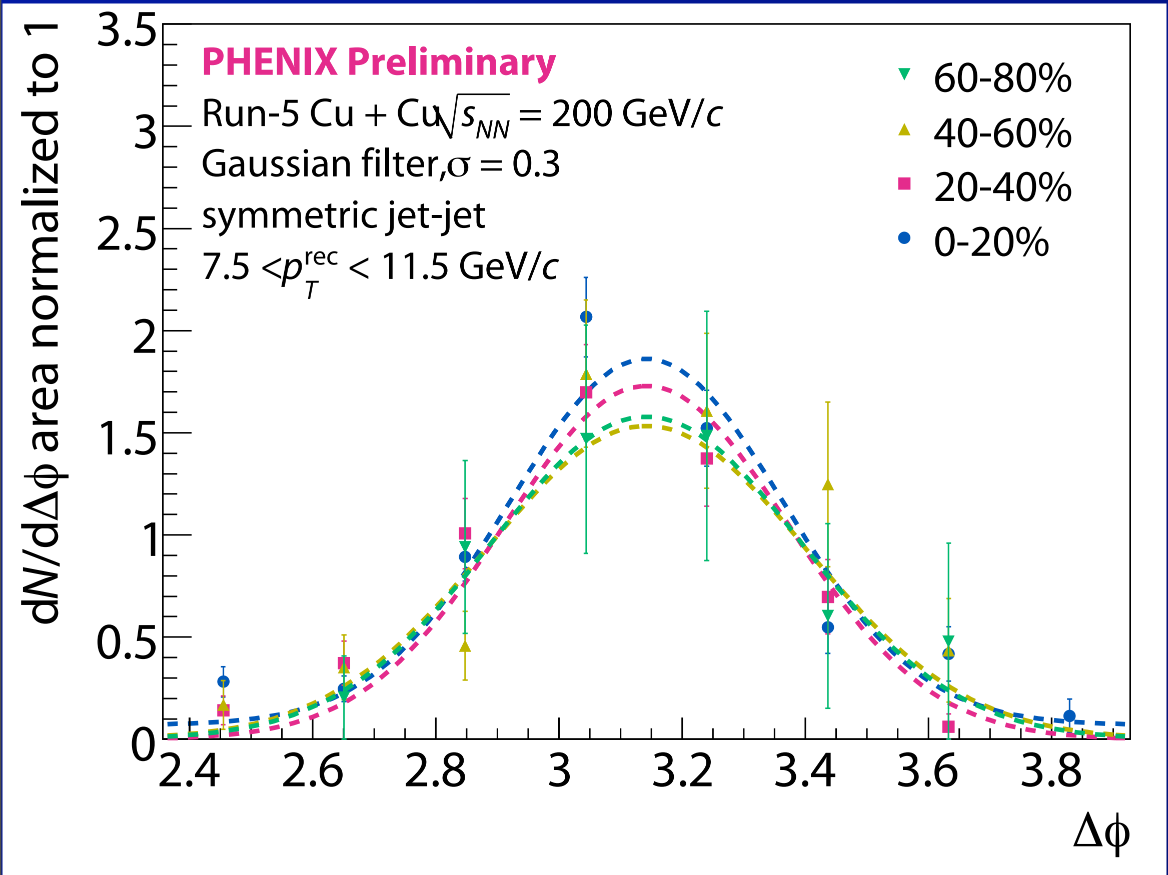
Beware:
π^0 R_{AA} shown at π^0 p_T scale $\langle z \rangle \sim 0.7$

- Jet RAA comparable to π^0 R_{AA}.
  - Only partial overlap in normalization syst. err.

Cu+Cu Di-jet Δφ Distribution



Cu+Cu Di-jet Δφ Distribution (2)



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 apparent broadening of di-jet Δφ distribution between peripheral and central Cu+Cu**
  - Consistent with substantial suppression?

Summary

- First PHENIX measurement of jet cross-section in proton-proton collisions @ 200 GeV/c.
- Measurement of Cu+Cu jet spectra, R_{AA}
  - Using two different procedures. Good agreement.
  - Jet R_{AA} shows significant jet "suppression".
- Measurement of Cu+Cu di-jet $\Delta\phi$ distribution
  - No apparent broadening, change in $\Delta\phi$ width
- R_{AA} and $\Delta\phi$ results suggest we are not "seeing" quenched jets
  - Due to algorithm, "Out of cone radiation", collisional energy loss, other ? We don't know
- It's still early in A+A jet measurement program, beware over-interpreting results …

PHENIX: To-do

- We expect to soon have for Cu+Cu:
  - Fragmentation functions, hadron J_T distributions, di-jet E_T balance, absolutely normalized $\Delta\phi$
    - ⇒Working on the (2-dimensional) unfolding
- Clearly a very high priority is performing Cu+Cu measurement w/ different Gaussian σ.
  - But, we have another approach to angular weight too.
- In p-p test our understanding of jet energy scale
  - Use techniques from CDF/D0 (e.g.)
    - ⇒di-jet balance to check Monte-Carlo
    - ⇒γ-jet to calibrate jet energy scale
- Apply to Au+Au (more high-energy data!)
- Use full jets + hadrons for medium response.
- Use another algorithm (anti-k_T?), first in Cu+Cu

Thoughts / My perspective (2)

- I am pinning all my hopes on progress in understanding jet quenching on full jet measurements
  1. For physics reasons (above and below)
  2. Sociological reasons

➡ Break the field out of the "rut" we are in and force us to address the fundamental physics questions

➡ How do partons lose energy?

➡ How do they interact in medium?

➡ "Where" does lost energy go?

➡ <u>And NOT "what is $\hat{q}$?"</u>

Thoughts / My perspective (2)

- At QM2008, I argued in so many words that we are not attacking jet quenching scientifically.
  - But I wasn't sufficiently blunt.

⇒ We are not attacking jet quenching scientifically.

⇒ Instead of asking the right questions and trying to answer them, we are trying to fit the physics into our chosen/preferred answers.

Thoughts / My perspective (3)

- Q#1: "How do partons lose energy?"
- Improved version: "what happens to quarks & gluons in medium?"
  - Radiative energy loss?
  - Collisional energy loss?
  - Conversion into other partons
  - Deflection in chromomagnetic fields?
  - Lost in black holes, …

    ⇒ Currently our answers are ~ entirely based on theoretical prejudice.

    ⇒ I hope Jet R_{AA} + FF will provide some model-independent insight.

Thoughts / My perspective (4)

- Q#2: "How do partons interact with the medium?"
  - Weak coupling (i.e. via 2→2, 2→3 processes + formation/interference)?
  - Strong coupling (something else)?
  - Non-perturbatively (via intermediate hadron-like states)?
    - ⇒We have data that indicates this is an important question to answer
    - ⇒We need a strategy to answer this question with new/better data.

Thoughts / My perspective (4)

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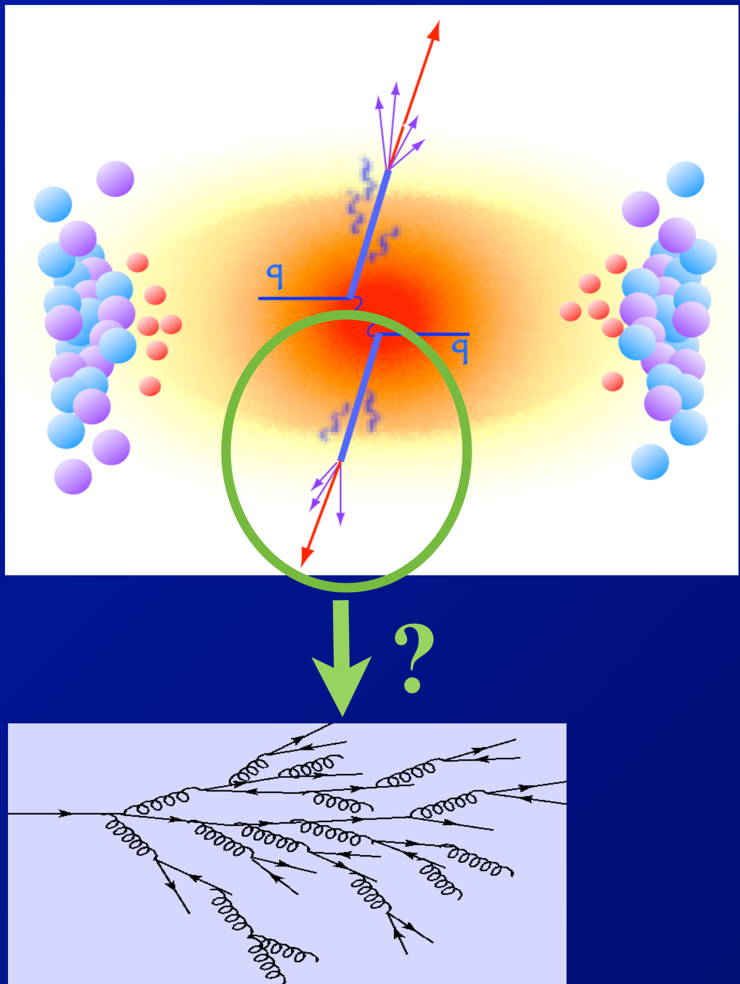
    - ⇒We have data that indicates this is an important question to answer
      - » We need a strategy to answer this question with new/better data.

Q#2: One (crude) attempt

From BNL seminar july 2008

Physics of jet quenching



- **Crucial question:**
  - Does parton evolution in medium look anything like a “normal” parton shower?
- **Attempt to distinguish**
  - Weakly coupled radiative + collisional energy loss
  - Strongly coupled/non-perturbative quenching
- **Hard to tell looking only at hadrons**
  - Need to see jet (or not!)

Thoughts / My perspective (5)

Suppose we conclude based on experimental evidence that the physics of quenching is weakly coupled:

- Q#2.5: Is original Gyulassy-Wang model on which all subsequent calculations rely correct?
- Q#2.5.5 If so, which is the right limit?
  - Thick medium (BDMPS)
  - Thin medium (opacity expansion)
  - In-between (?)
    - ⇒Should be decided on basis of empirical evidence not prejudice

Thoughts / My perspective (6)

Suppose quenching is weakly coupled and the thick-medium limit applies

- Is AMY analysis of formation lengths correct?
- Can parton energy loss really be treated separately from fragmentation?
  - Or is evolution of FF in the medium the right/only way?
- etc...
- My opinion:
  - much of what we should be doing here is formulating such questions and laying out a path to answering them.

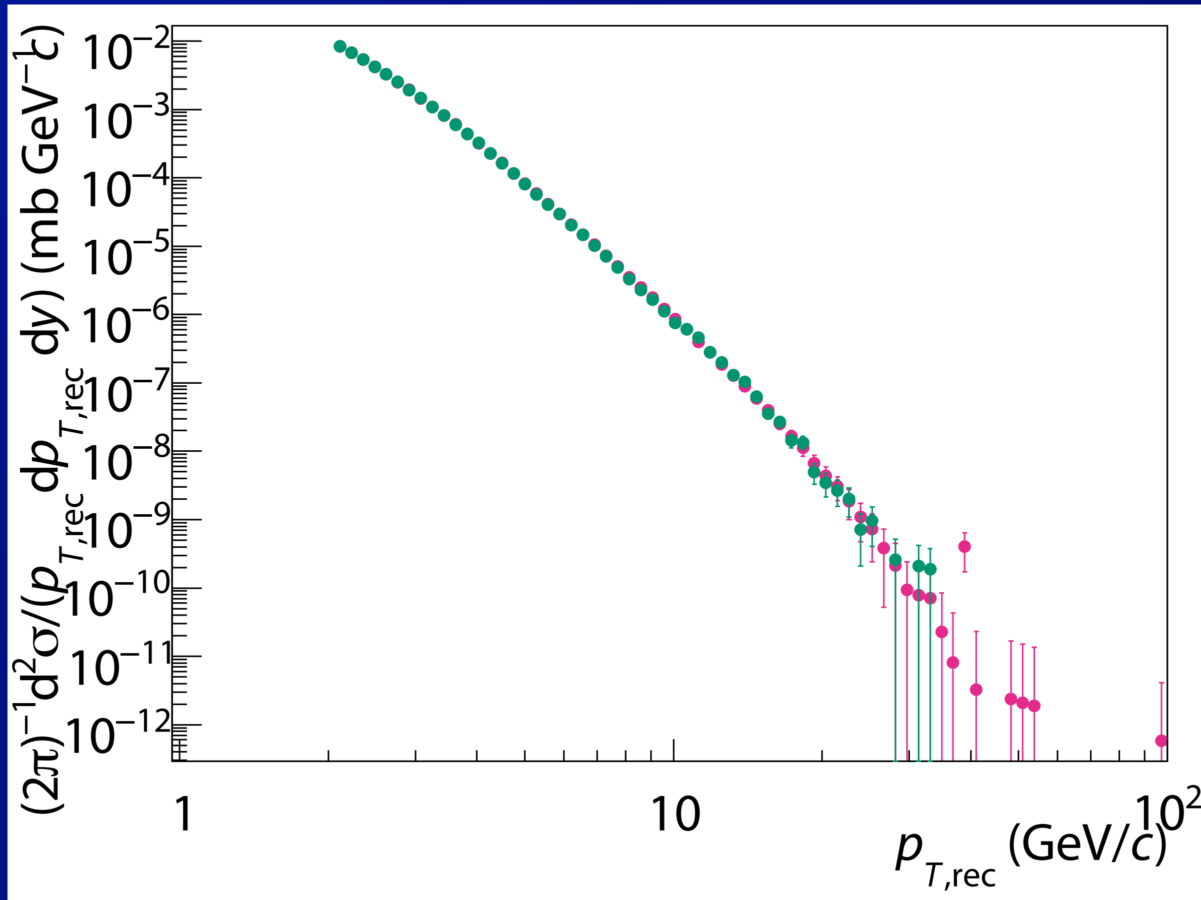
Back to PHENIX

- PHENIX will continue to develop:
  - Full jet measurments
    - ⇒ And full set of correlations with other observables.
  - (direct) gamma-hadron / gamma-jet
  - v_2 at high p_T
- With upgrades
  - Jets (via tracking) with VTX
    - ⇒ $|\eta| < 1.2$
  - Charm (D) and bottom at high p_T
  - High-p_T photons, π^0 in larger acceptance
    - ⇒ $\sim 2 < |\eta| < \sim 3$ with $\Delta\varphi = 2\pi$

Backup

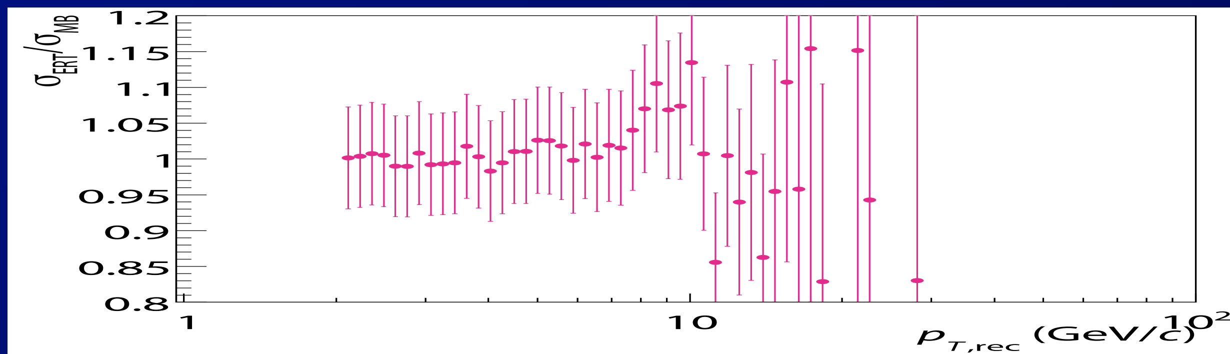
p-p, Triggered vs Min-bias Comparison

- Above p-p data from Level-1 4x4 tower trigger



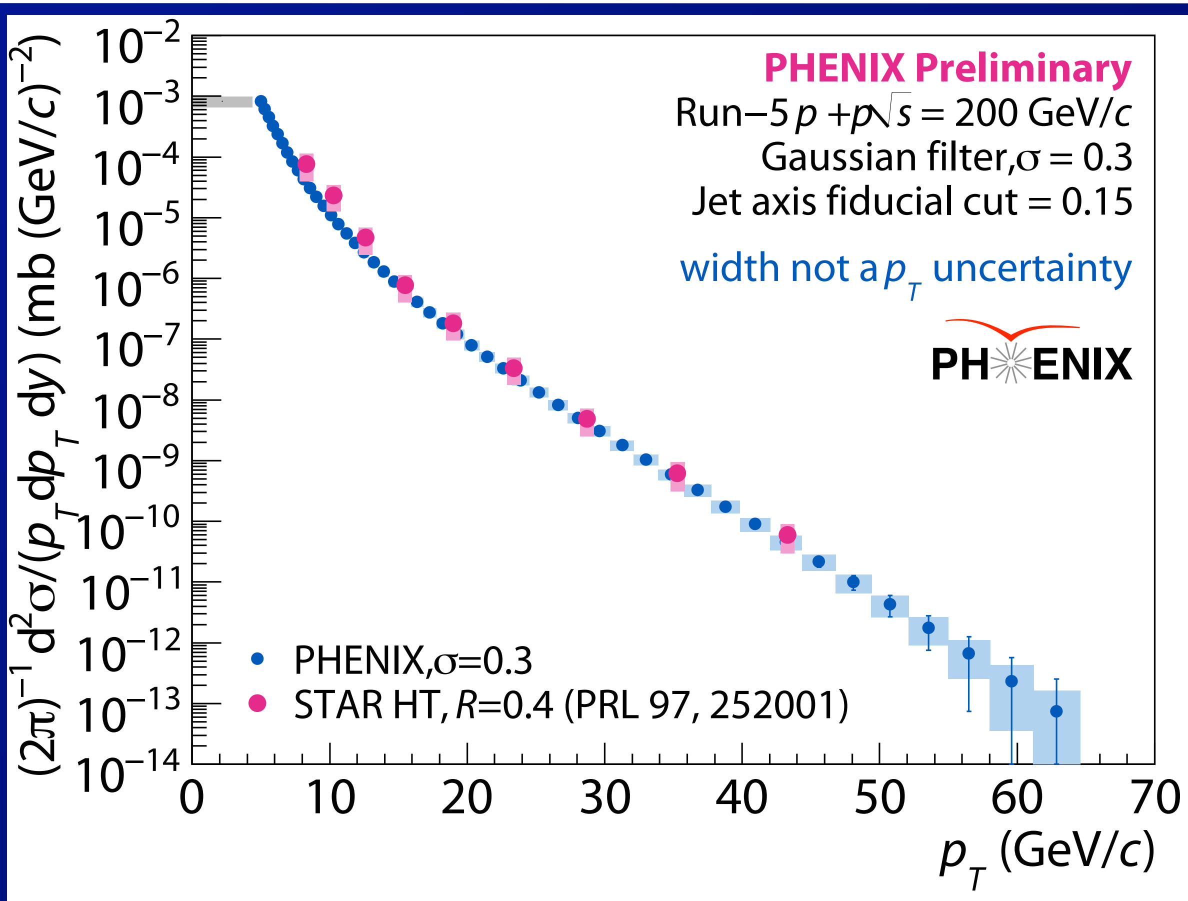
- Here we show comparison with min-bias trigger.

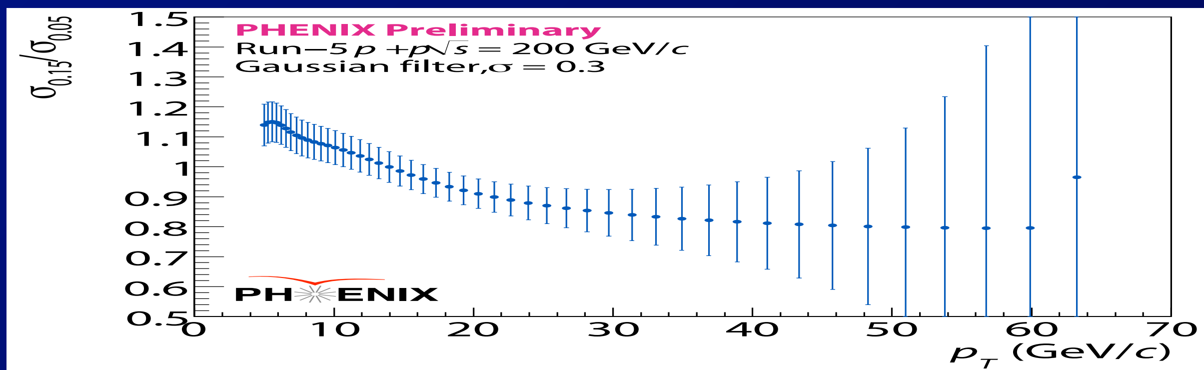
- Agreement within <~ 10%



p-p: Acceptance Systematics

- How well does PHENIX have edge effects under control?
- For all above results, apply fiducial cut
  - Jet 0.05 away from edge
- Suppose we tighten cut
  - Jet 0.15 away from edge
- Re-do analysis
  - Consistent within 15 - 20%



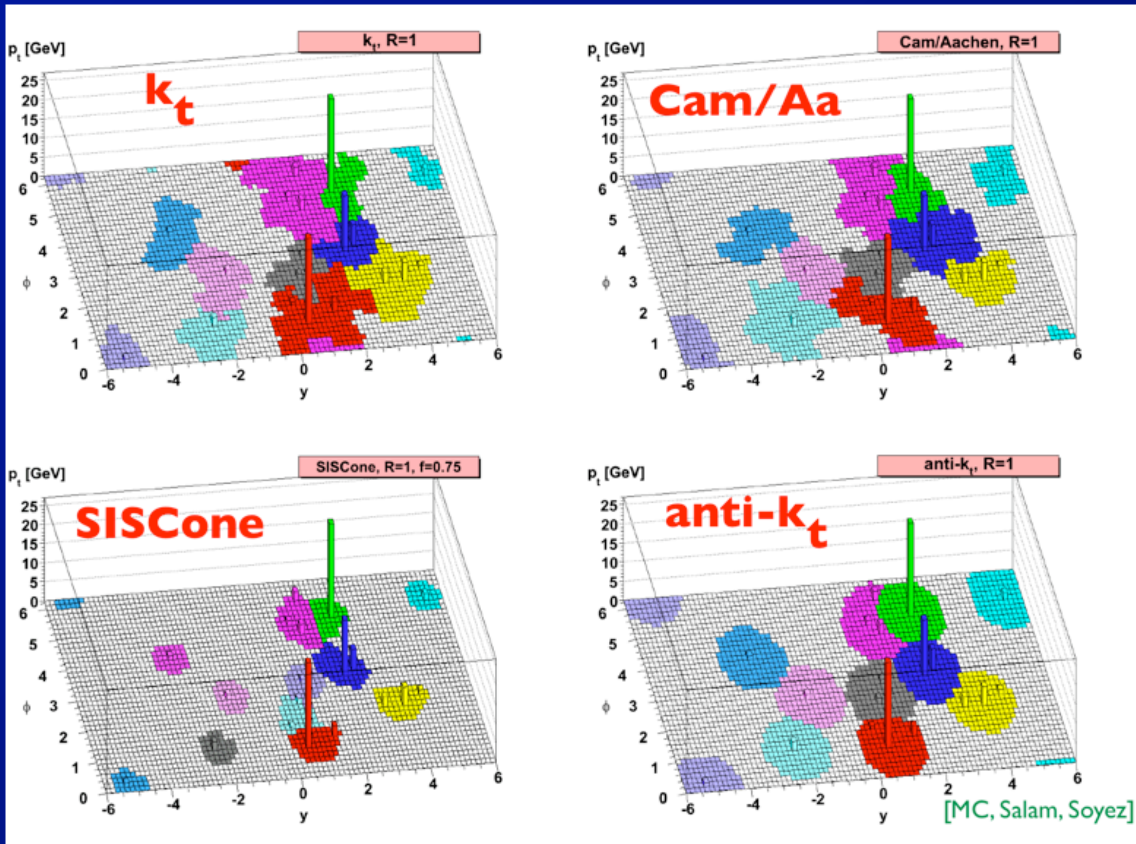


Fake Jet Rejection: Bias?

- Obvious question:
  - Doesn't fake jet rejection bias jet sample?
- Answer:
  - Potentially, yes.
    - ⇒But, better to measure R_{AA} for jets we know how to find (w/ vacuum-like parton shower, than introduce systematics from fake jets.
      - » If we see suppression, we have learned something important already
  - And, as we have shown, fake rejection has small effect in Cu+Cu above ~ 10-12 GeV
    - ⇒But, we expect much larger effects in Au+Au
    - ⇒Best to understand potential biases, consequences of fake jet rejection in Cu+Cu.

Recent Improved Jet Algorithms

- Recent progress in development of (practical) infrared-safe, collinear-safe jet algorithms

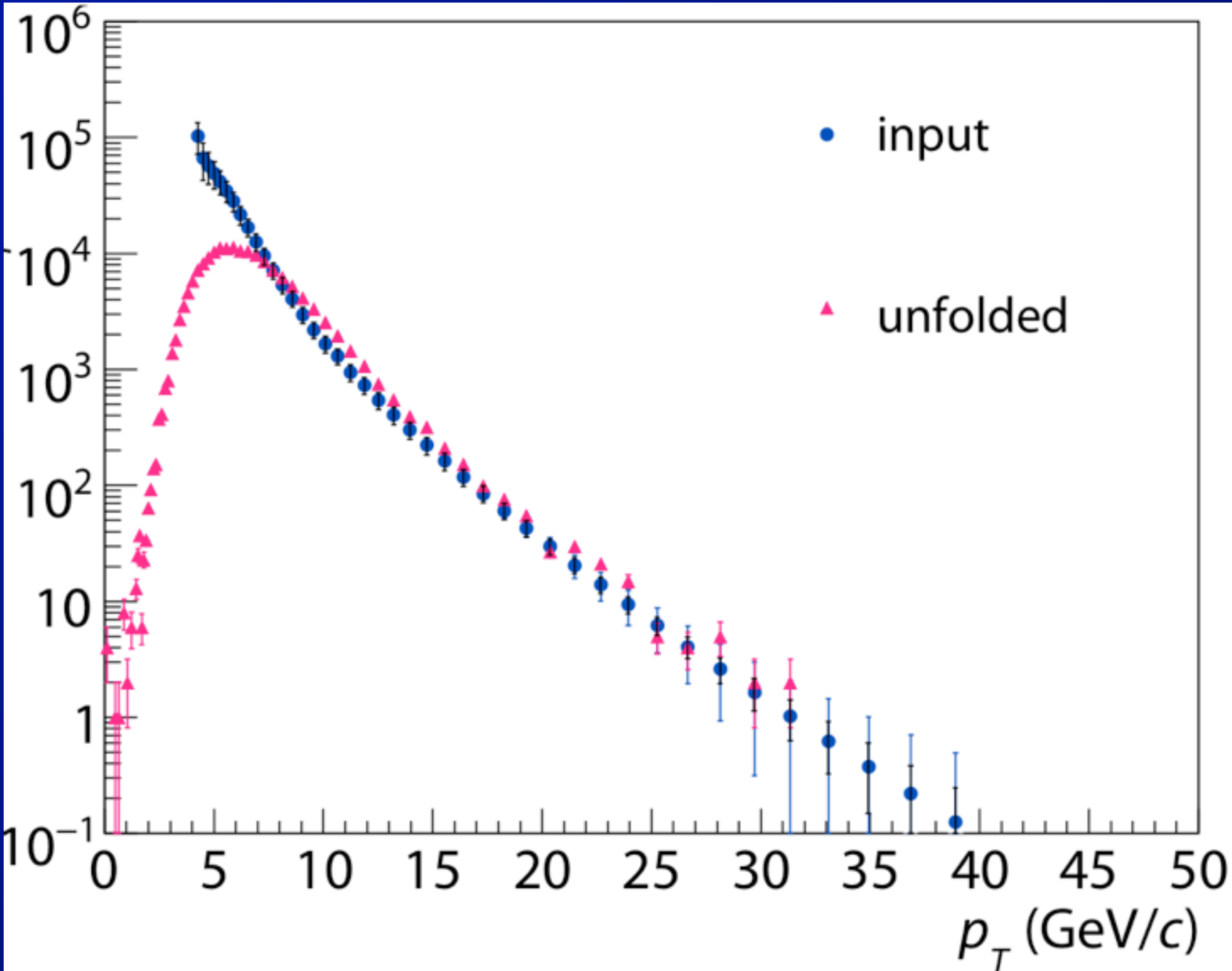


Cacciari,
Salam,
Soyez

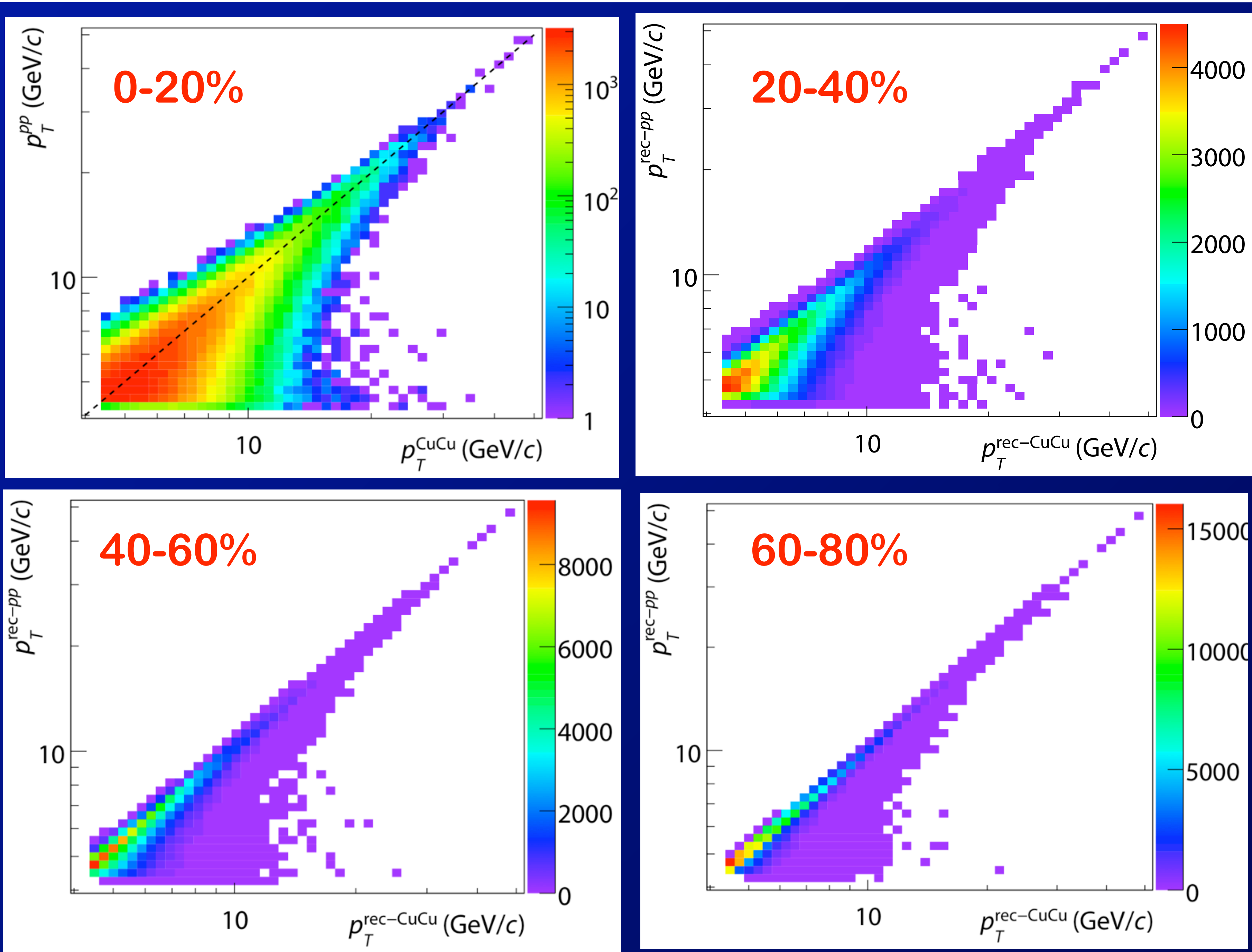
- “No-brainer” that we should try anti-k_T and C/A with filter for comparison to Gaussian filter

➡Impact of PHENIX acceptance needs study.

Cu-Cu Unfolding: Before/After



p-p into Cu-Cu: Embedding Response



Gaussian Filter: Jet E_T Correction

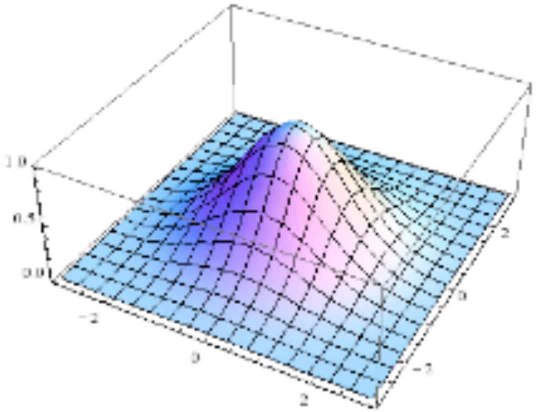
- The Gaussian filter output is more like an "energy flow" variable than true jet energy.
  - But, there is a well-defined expansion that allows corrections to the Gaussian filter to be calculated.

$$
\begin{aligned}
E_T^{filt}(\eta_0,\phi_0) &= \int\int d\phi d\eta \frac{d^2E_T}{d\eta d\phi} = \int\int d\phi d\eta \frac{d^2E_T}{d\eta d\phi} e^{-R^2/2\sigma^2} e^{+R^2/2\sigma^2} \\
&= \int\int d\phi d\eta \frac{d^2E_T}{d\eta d\phi} e^{-R^2/2\sigma^2} \left(1 + \frac{R^2}{2\sigma^2} + \frac{R^4}{8\sigma^4} + \ldots\right) \\
&= \int\int d\phi d\eta \frac{d^2E_T}{d\eta d\phi} e^{-R^2/2\sigma^2} + \int\int d\phi d\eta \frac{d^2E_T}{d\eta d\phi} \frac{R^2}{2\sigma^2} e^{-R^2/2\sigma^2} + \ldots \\
&\equiv p_T^0 + p_T^1 + p_T^2 + \ldots
\end{aligned}
$$

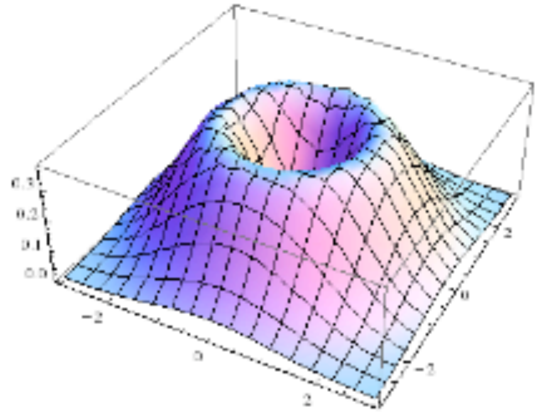
  - Gaussian filter is just the first term in this expansion.
  - Evaluate the second term to assess how much the filter is distorting the jet energy measurement.

Gaussian Filter: Jet E_T Correction (2)

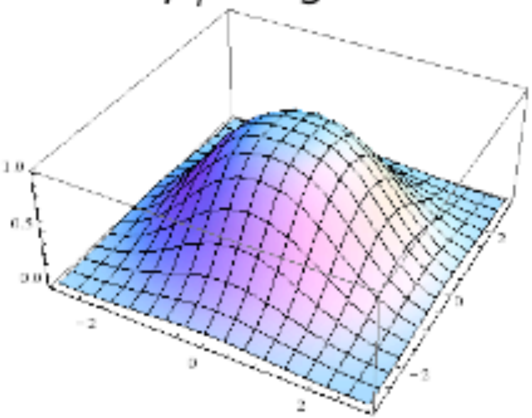
In pictures:



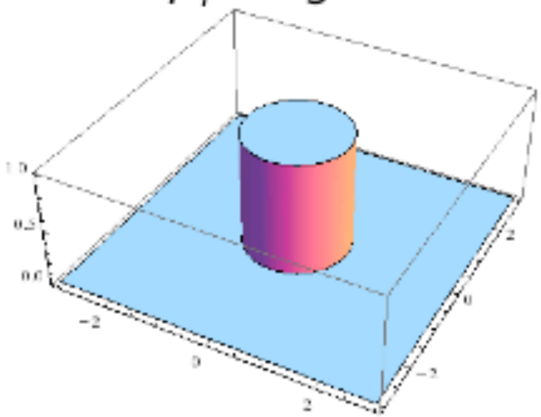
p_T^0 weight



p_T^1 weight



$p_T^0 + p_T^1$ weight



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Gaussian Filter: Jet E_T Correction (3)