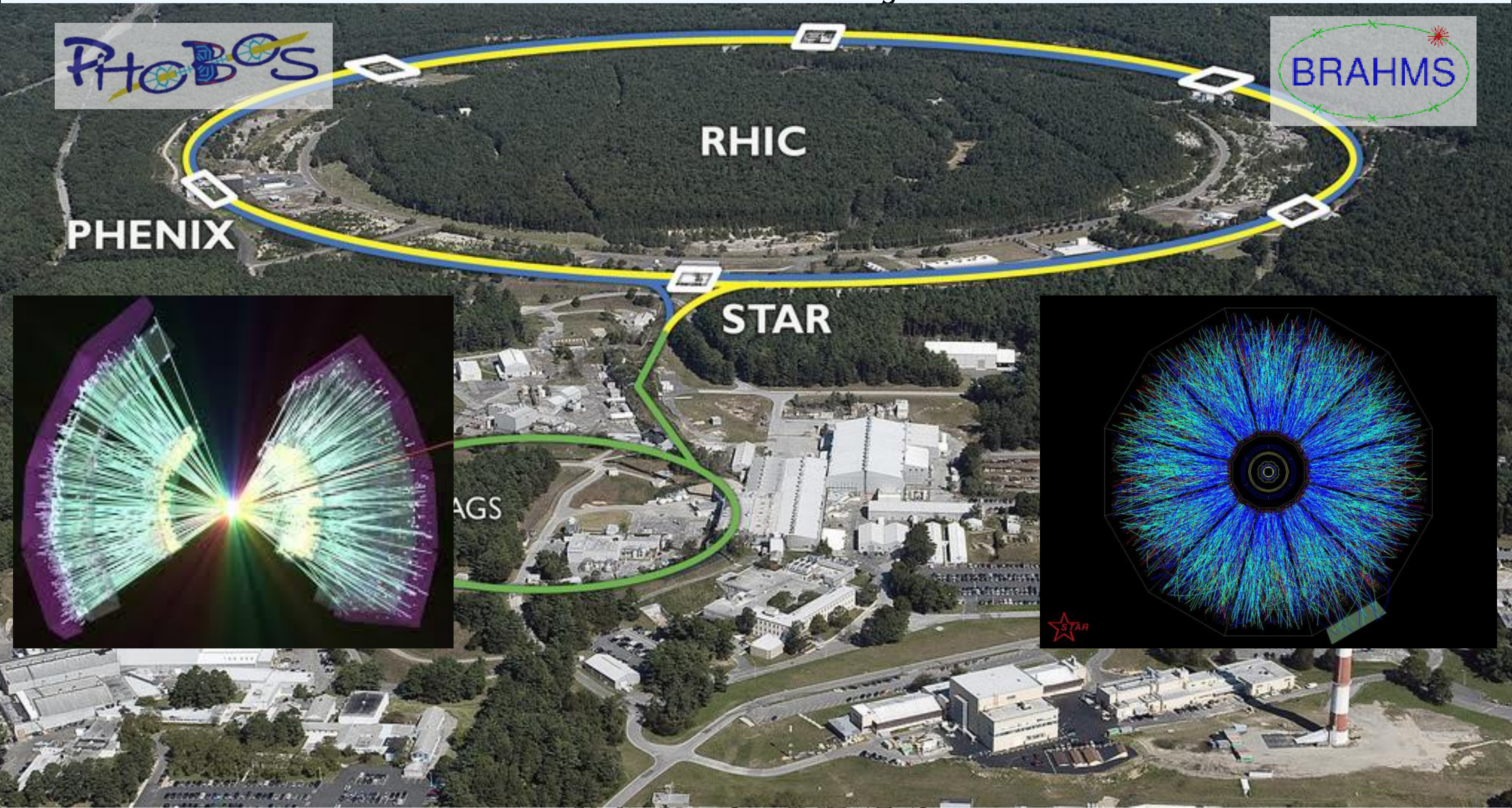
# Jet Studies at RHIC

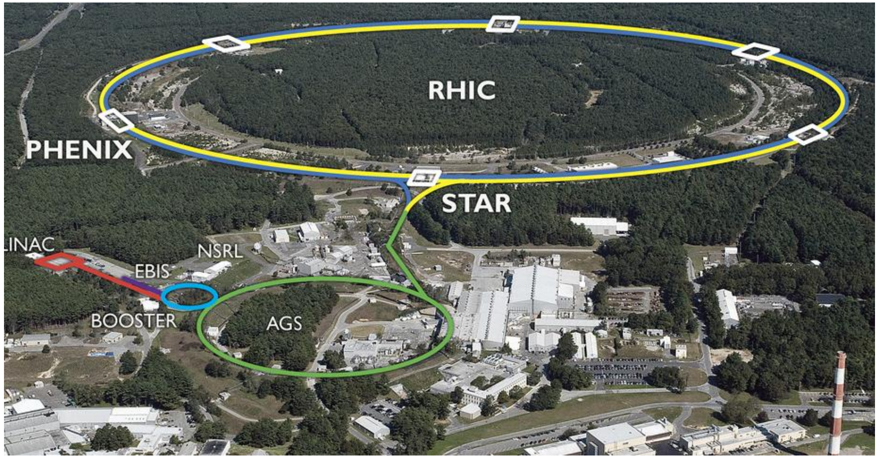
*Kolja Kauder*

Precision Spectroscopy of QGP Properties with Jets and Heavy Quarks (INT-17-1b)

# The Relativistic Heavy Ion Collider



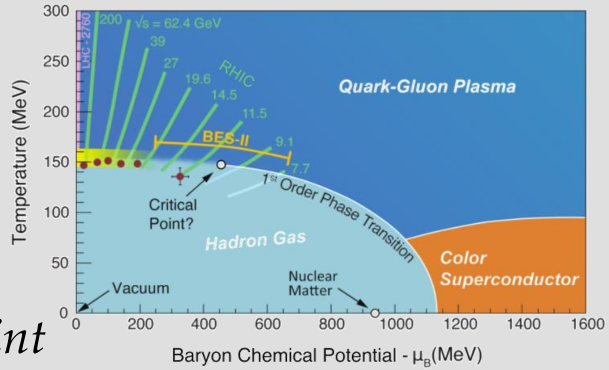
# The **R**elativistic **H**eavy **I**on **C**ollider




**HI Collisions at $\sqrt{s_{NN}}$=200 GeV**
**- Au+Au,** Cu+Cu, Cu+Au, U+U, Cu+Au
- Isobars (Ru+Ru & Zr+Zr, planned)

**Small Systems:**
- p+p, p+Au, p+Al, d+Au, $^3$He+Au

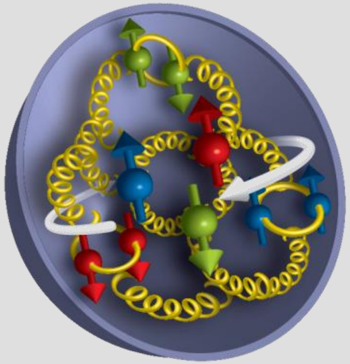
Not Covered:
BES, BES-2 (7.7 – 62 GeV)



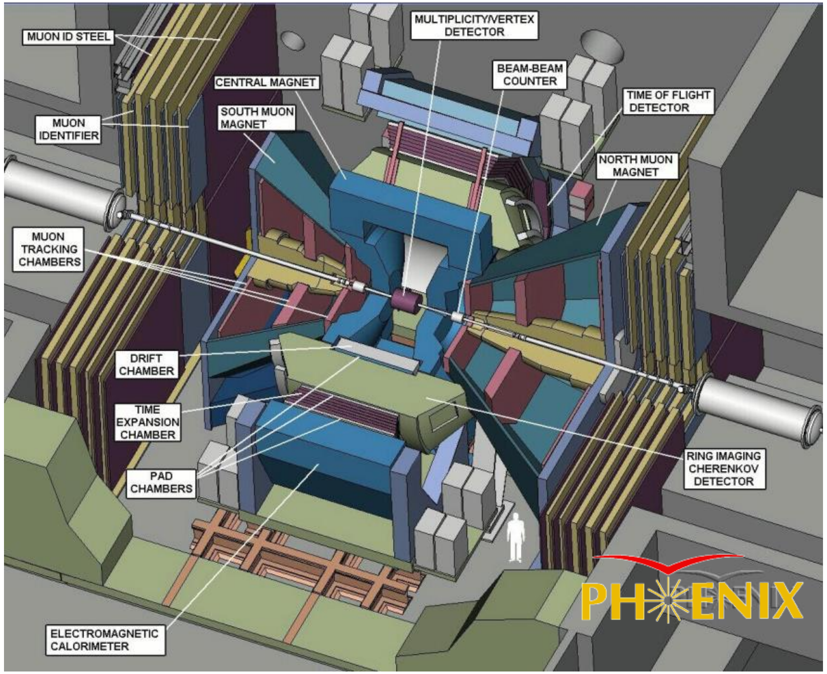

*Search for Critical Point*

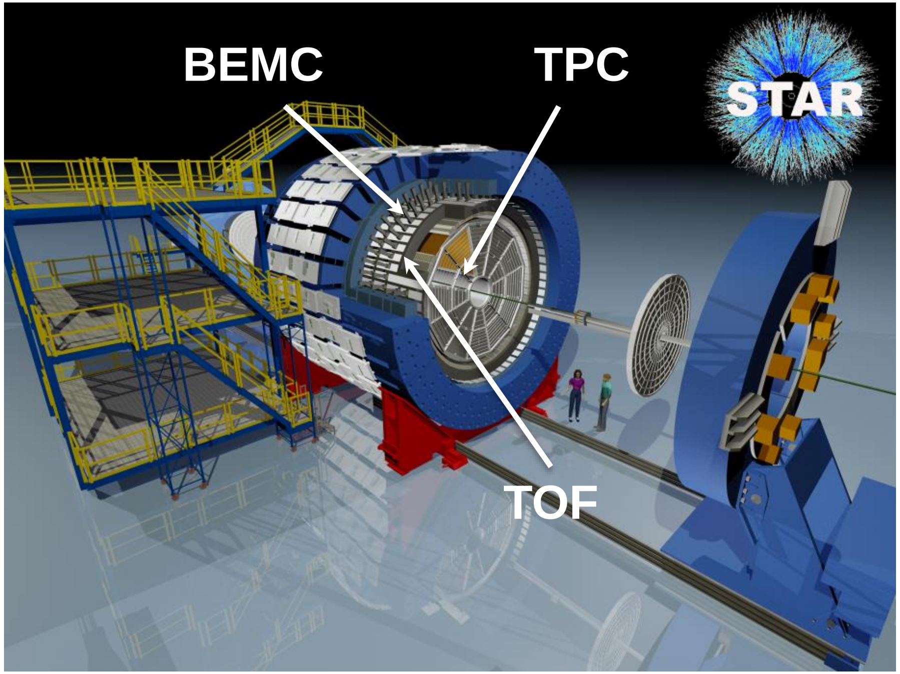
Not Covered:
Polarized p+p program (up to 510 GeV)

*Proton Spin Puzzle*



# Detectors



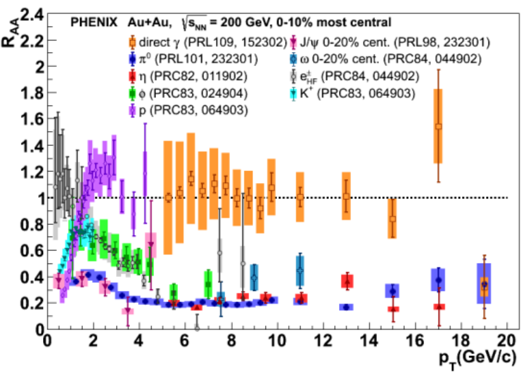

Focus on **Rare Probes**
- High DAQ rate
- Specialized sub-detectors
- Small acceptance

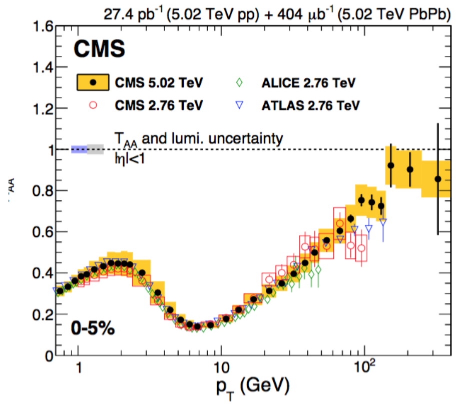
Focus on **Uniform Acceptance**
- $2\pi \times |\eta| < 1$ (and more)
  for tracking, PID, EM Calorimetry

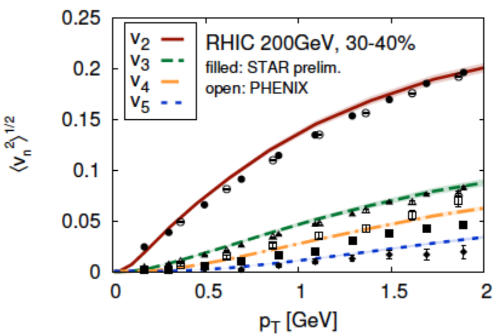
# RHIC and the LHC

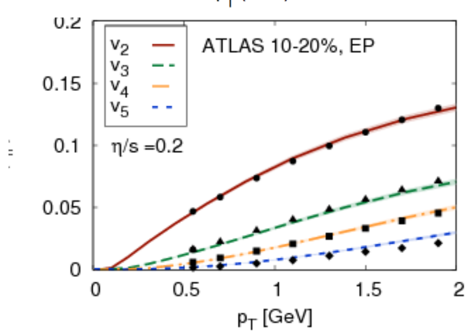
- Larger $Q^2$, new probes (Z, W, …) in "similar" QGP
  → Stronger model constraints

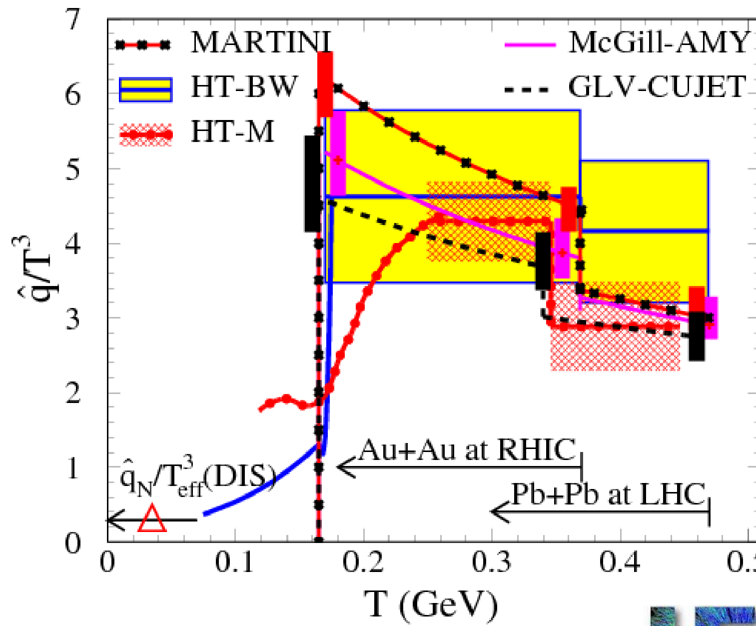
- Qualitative differences?



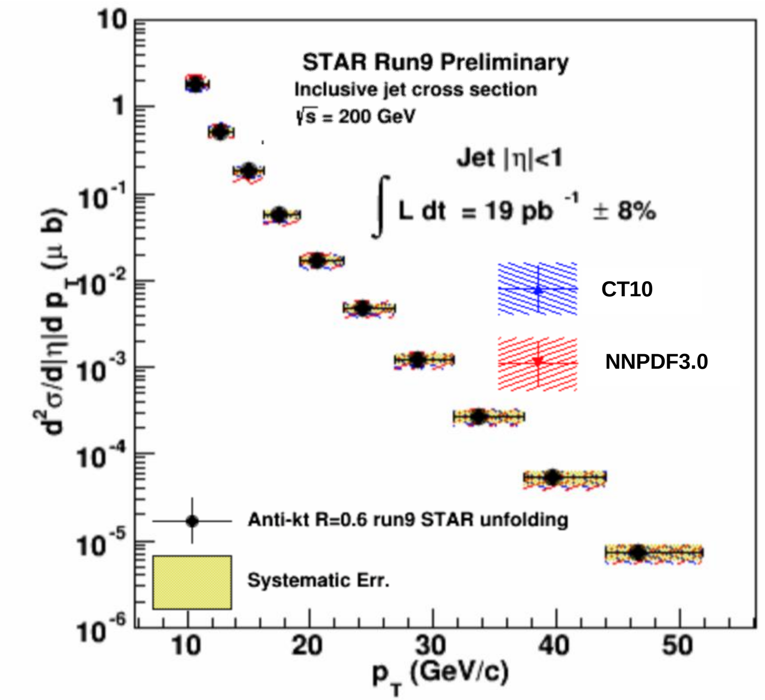



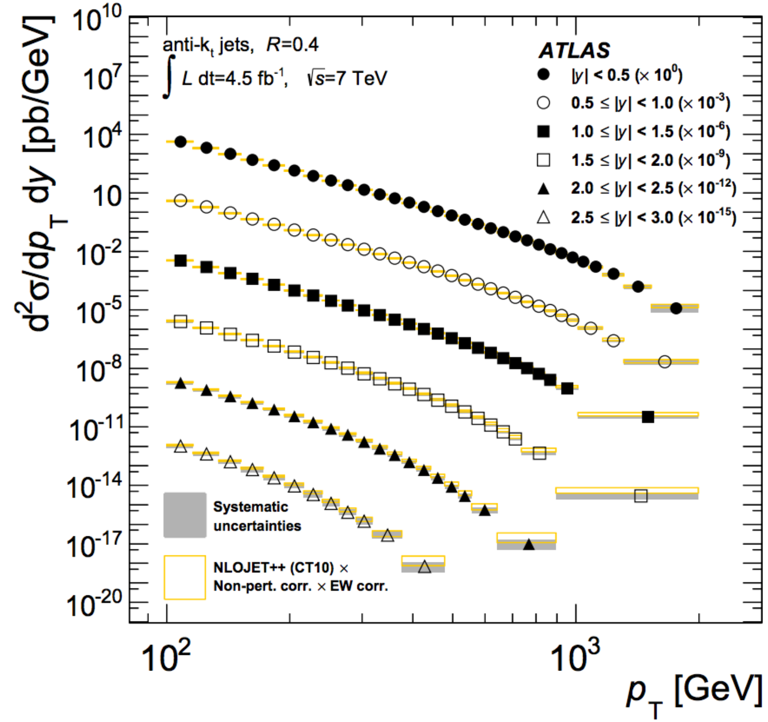




JET Collaboration

# Kinematic Reach



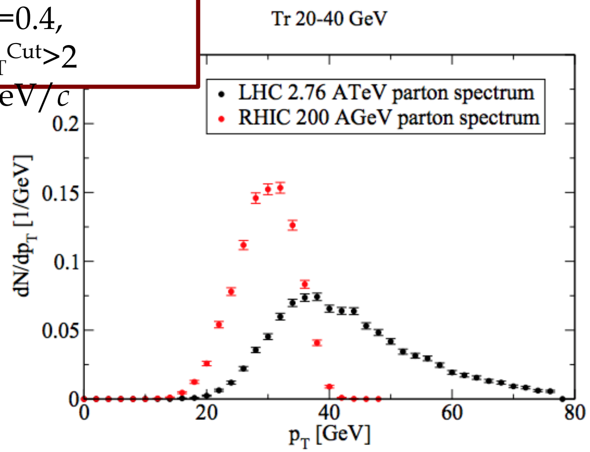

RHIC: $p_T^{Jet}$ <~ 50 GeV/*c*
LHC: $p_T^{Jet}$ > 1000 GeV/*c*
… But a steep spectrum has its benefits

*PoS(DIS2015)203*

*JHEP 02 (2015) 153*

# Unique RHIC Strengths

R=0.4, $p_T^{Cut}>2$ GeV/*c*

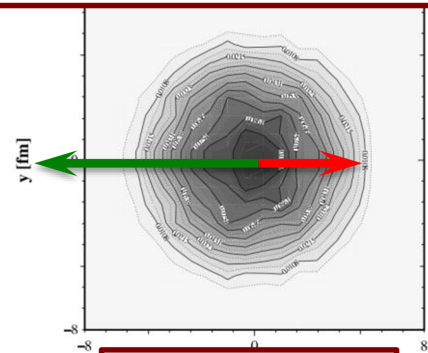



Recoil $p_T$ off a 20-40 GeV trigger

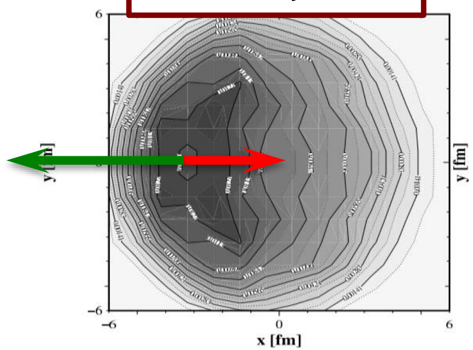
Steeply falling spectrum
→ Good correlation between jet and original energy!

*YaJEM, T. Renk*
*arXiv:1212.0646, PRC 87, 024905 (2013),*
*PRC 85, 064908 (2012), PRC 87, 024905 (2013)*

LHC Imbalanced Dijets

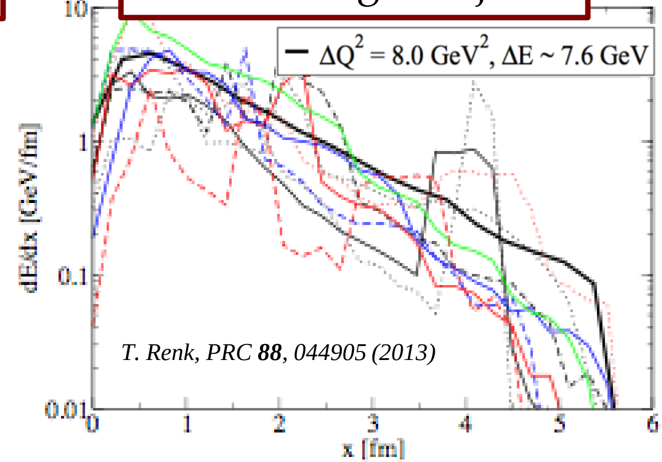



RHIC Jet-h




Path Length Control?

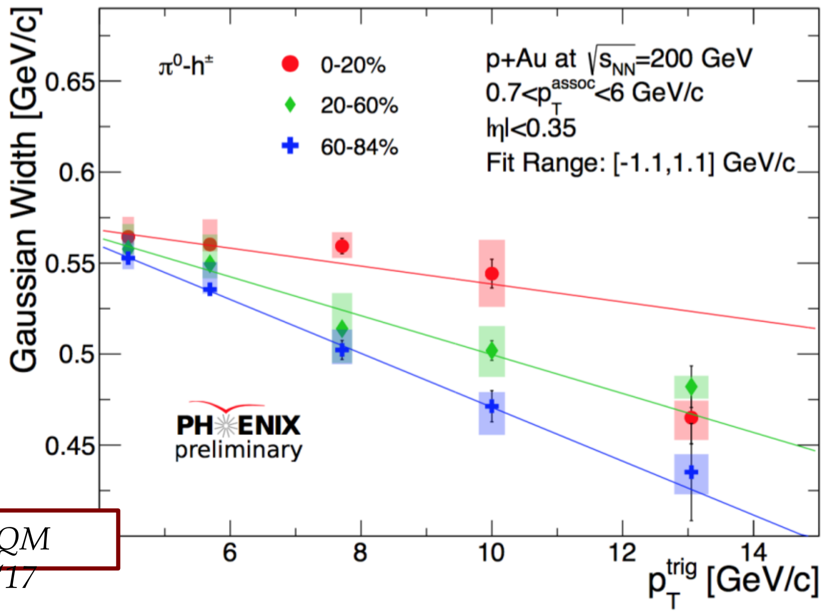
120 GeV gluon jet




LHC: Larger energy loss at early times
→ more diffusion
→ larger angles

# Single-Particle Correlations

# Di-Hadron Correlations in small systems

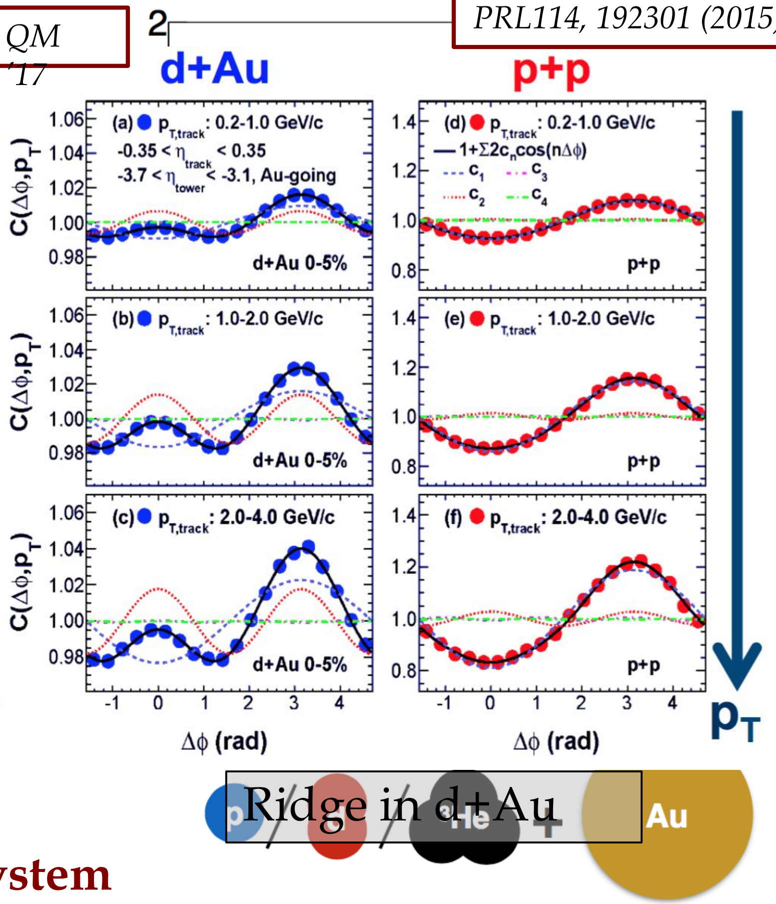



QM '17

Gaussian widths in p+Au (and p+Al) show interesting centrality dependence
→ Interpretations ongoing

QM '17

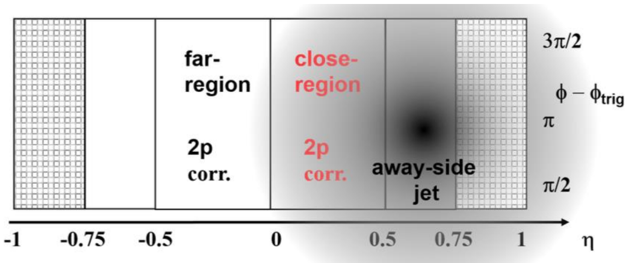
*PRL114, 192301 (2015)*

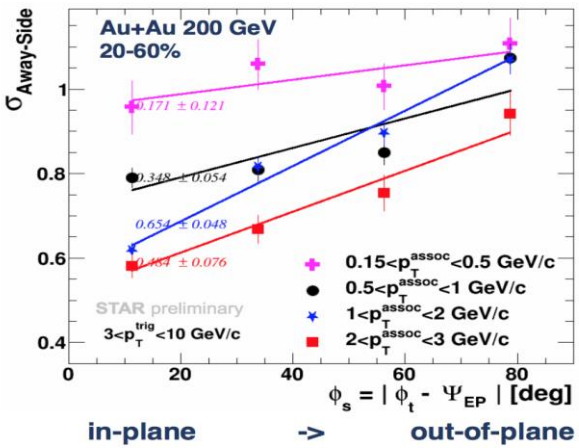


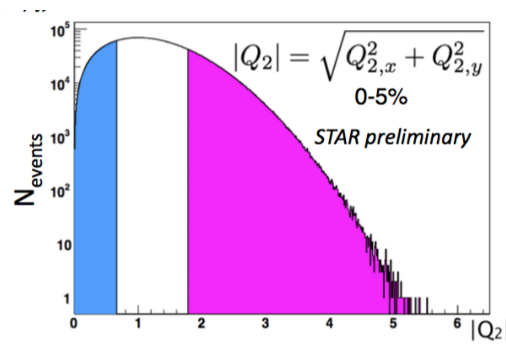

Ridge in d+Au

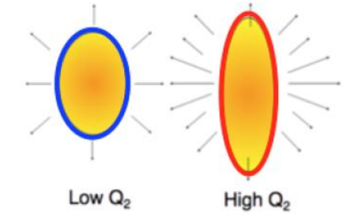
***p/d*+A is no longer just a baseline or a simple system**

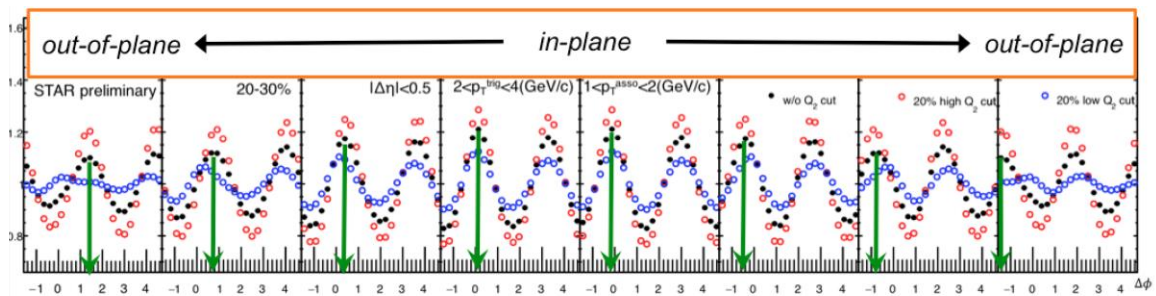
# Di-Hadrons in Au+Au – EP dependence




- Broadening in-plane → out-of-plane

- Event Shape Engineering:
  → Enhance Effect

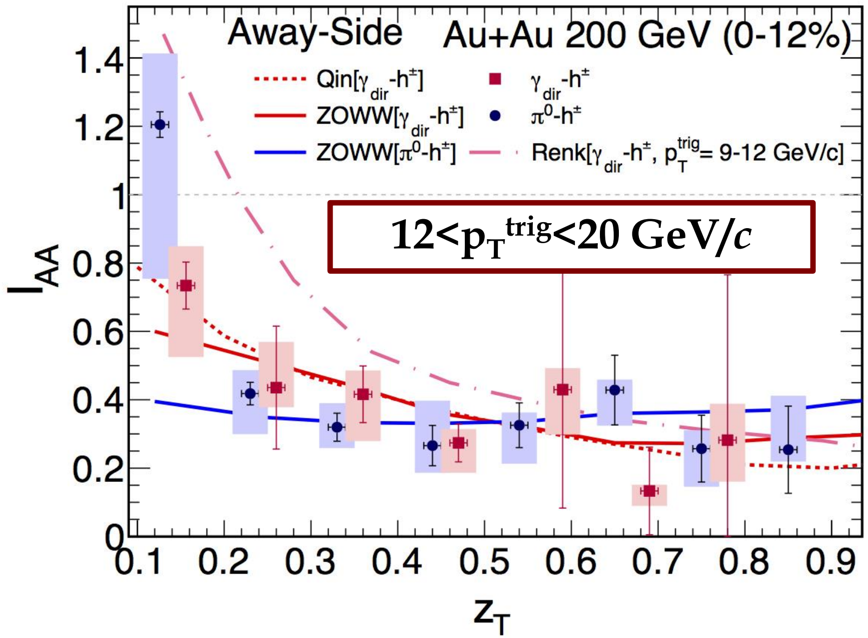
**Path-length dependence of energy loss**

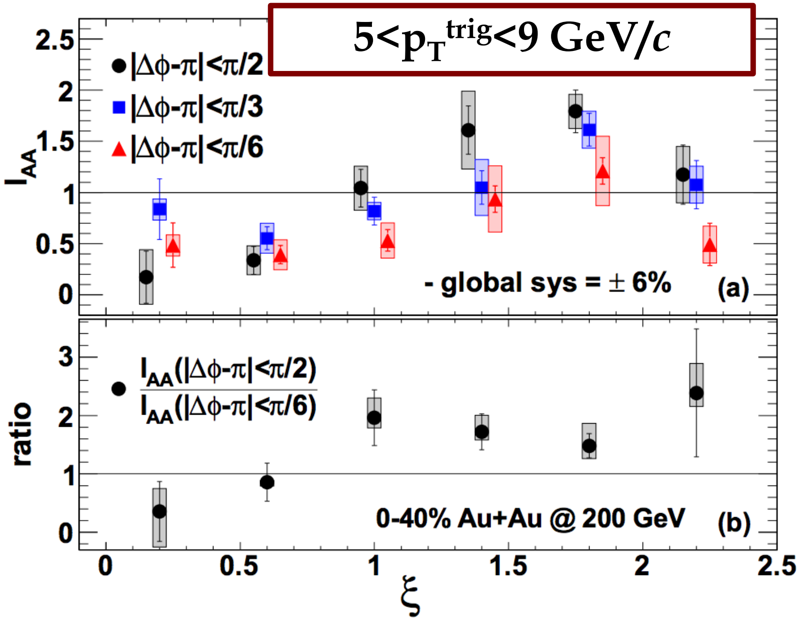
QM '17

# Direct-γ+Hadron in Au+Au

*STAR, PLB 760 (2016) 689*

*PHENIX, PRL 111, 032301 (2013)*

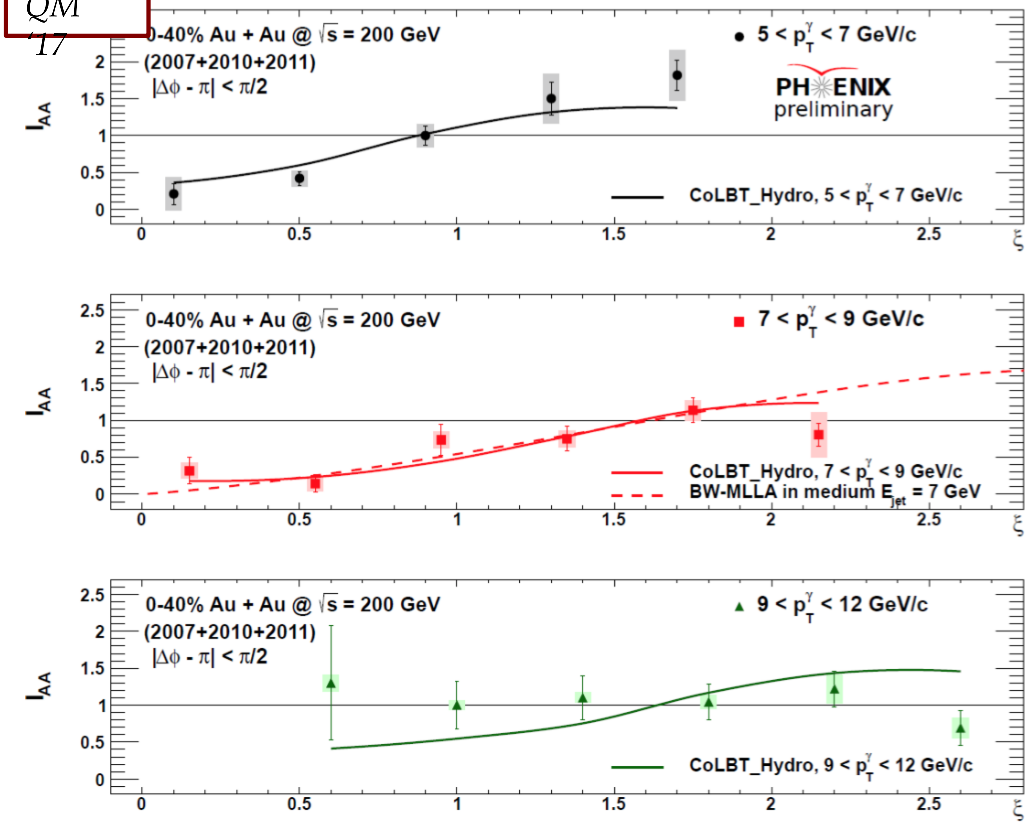


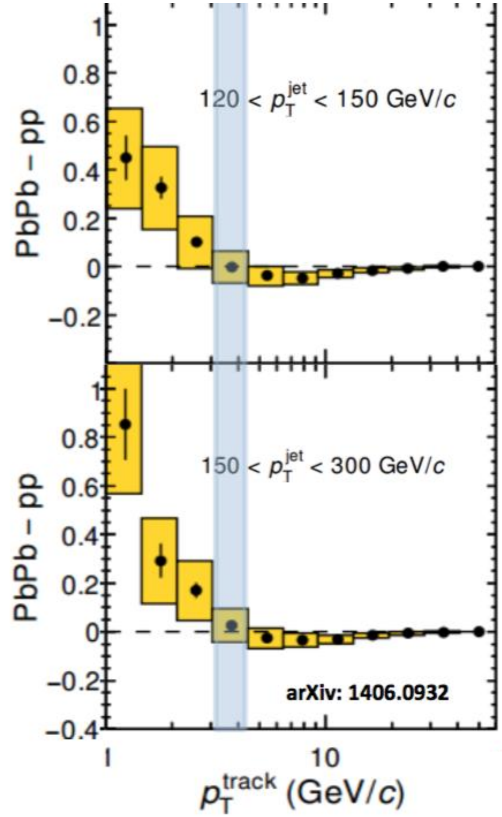

- STAR: Suppression for all measured $z_T$
- PHENIX: Clear enhancement at large $\xi$ ( = small $z_T$)
- Points to: transition depends on $p_T^{assc}$, not $z_T$

# Transition Point

*QM '17*




*CMS, PRC* ***90*** *(2014) 024908*

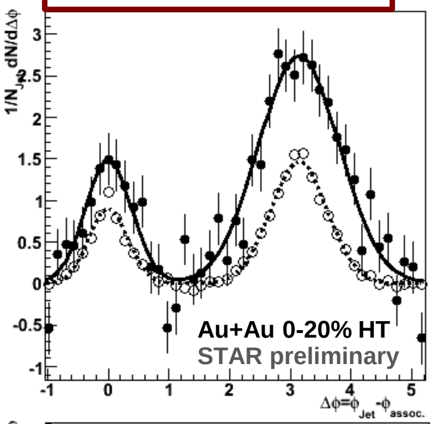



- Transition not at fixed $\xi$

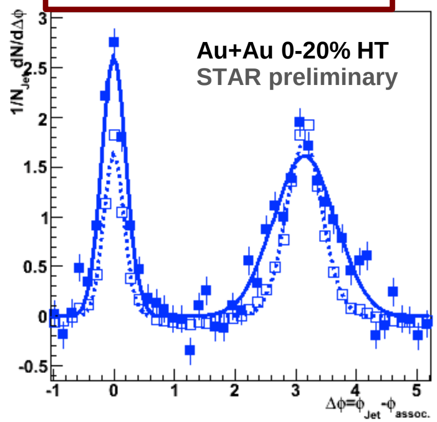
- LHC: $p_T^{assc} \sim 3$ GeV/$c$
- RHIC: $p_T^{assc} = ?$

# Transition Point from Jet+hadron

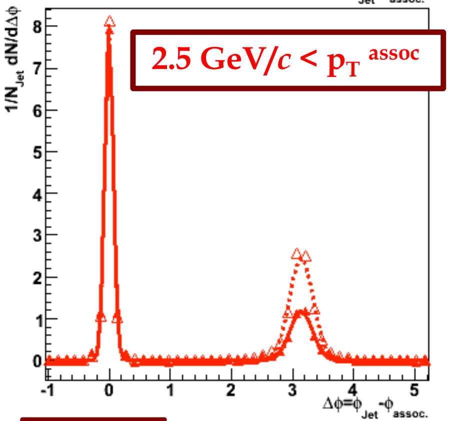
0.2 < $p_T^{assoc}$ <1 GeV/*c*




1 < $p_T^{assoc}$ <2.5 GeV/*c*

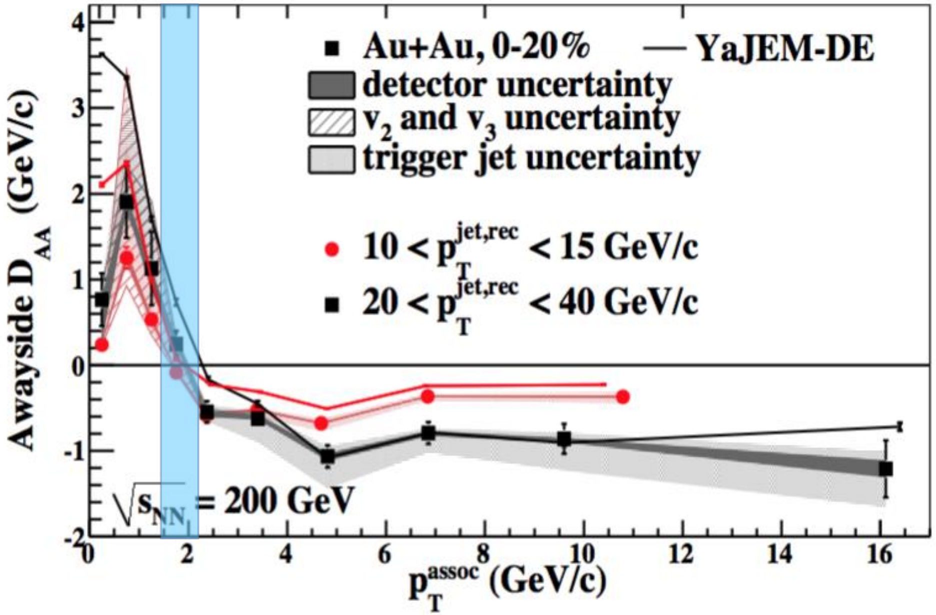



2.5 GeV/*c* < $p_T^{assoc}$




*QM '11*

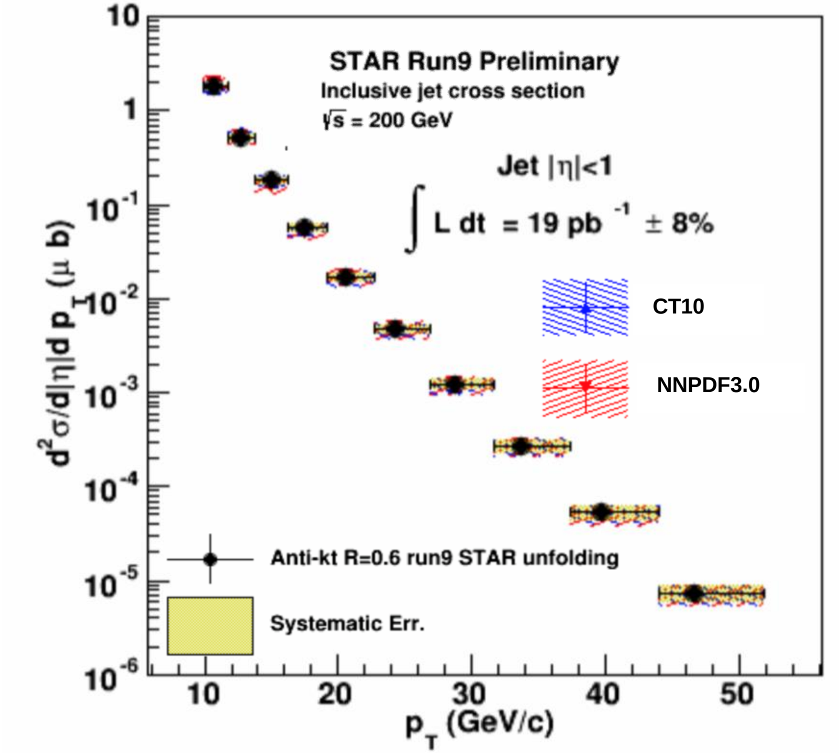
*STAR, PRL* ***112****, 122301 (2014)*

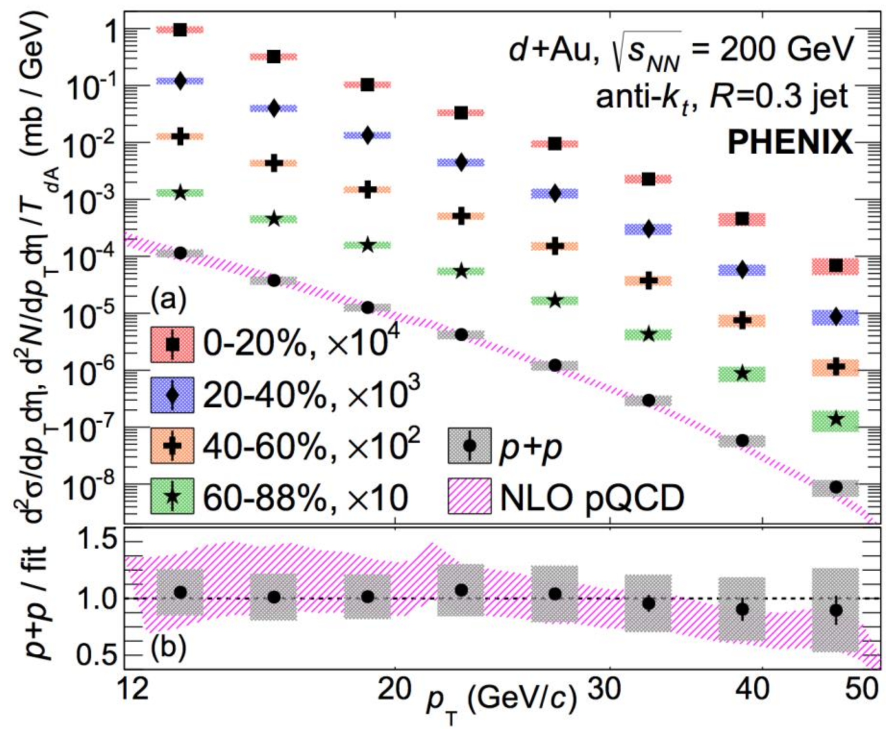



RHIC: $p_T^{assc} \sim 2$ GeV/*c*!

# Reconstructed Jets

# Jet Cross Section in p+p and d+Au



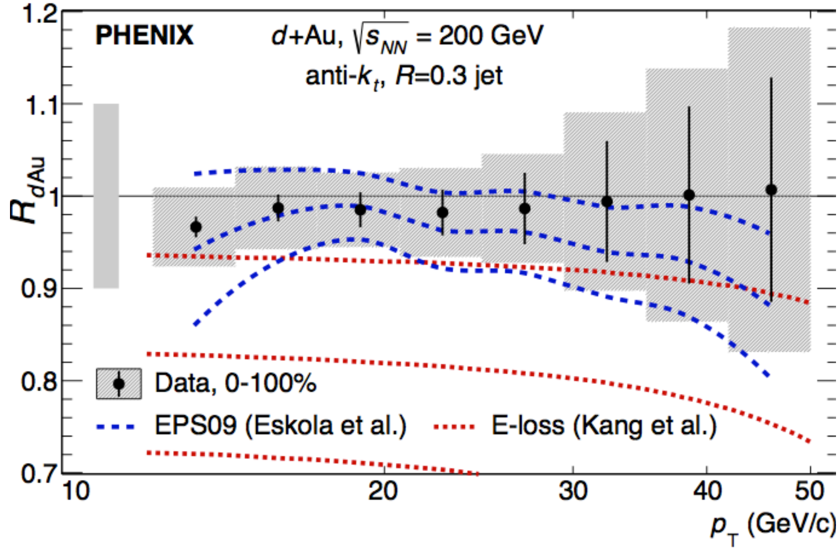



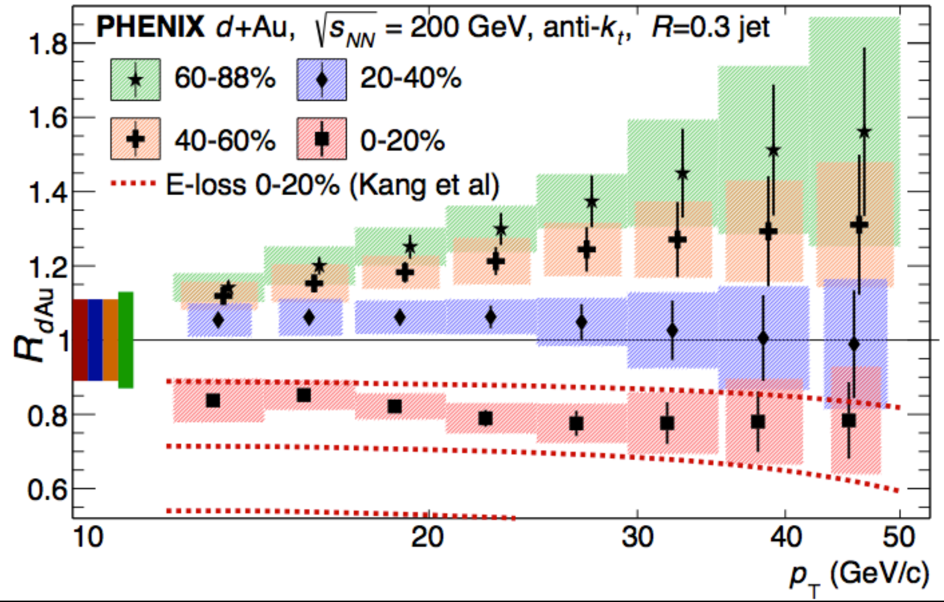

PoS(DIS2015)203

High-precision baseline, well described in NLO
→ Calibrated probe

PRL116, 122301 (2016)

# Jets in d+Au



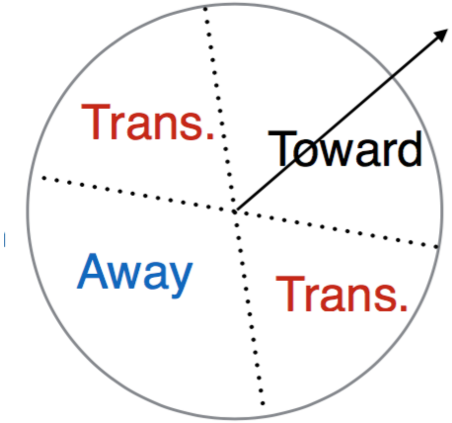

Minimum bias jets show no energy loss

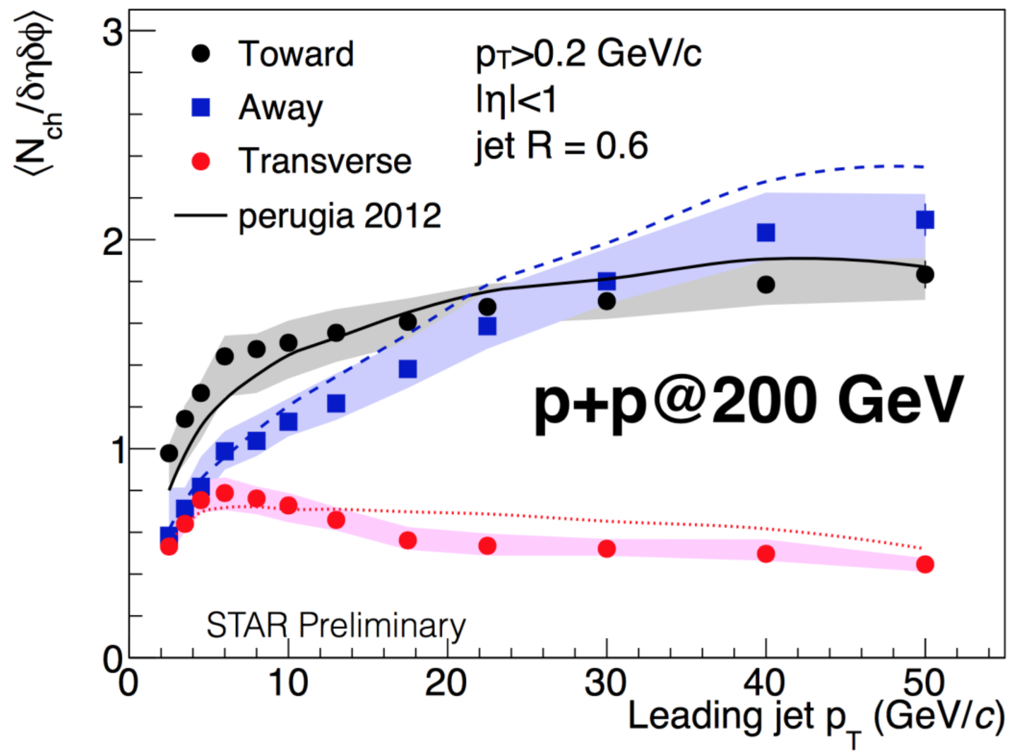
- Surprising centrality dependence
- Peripheral: High-$p_T$ enhancement
- Central: High-$p_T$ suppression
- Challenge to conventional models.

***p/d*+A is no longer just a baseline or a simple system**

*PRL116, 122301 (2016)*

# Underlying Event Activity in p+p



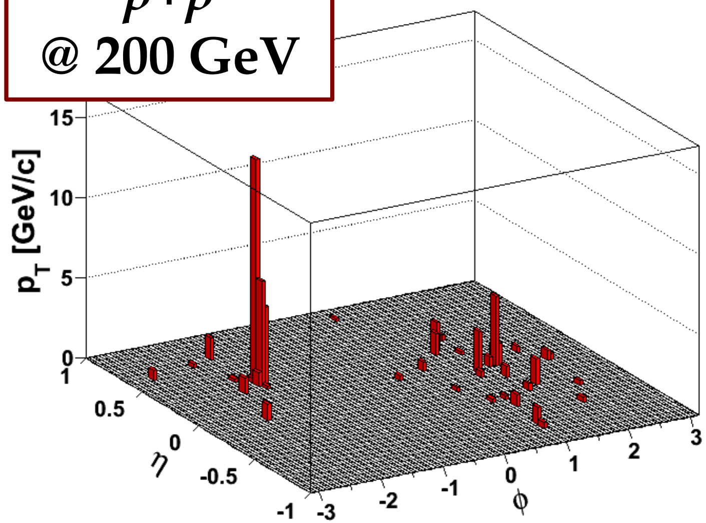




- Transverse charged particle multiplicity slightly decreases for higher leading jet $p_T$
- PYTHIA perugia 2012 over-predicts transverse charged multiplicity by 25% +/- 15%

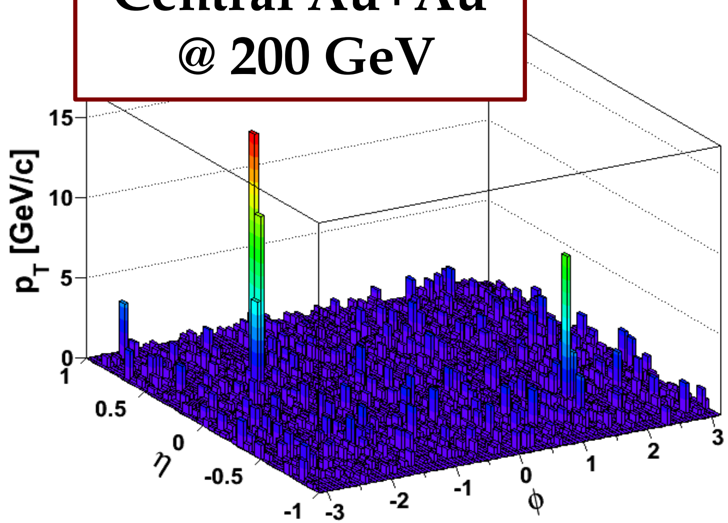
QM '17

# The Underlying Heavy Ion Event

*p+p*
**@ 200 GeV**




**Central Au+Au**
**@ 200 GeV**



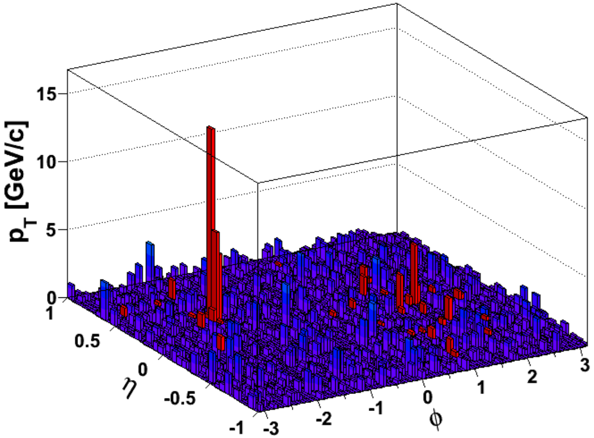

- $< \Sigma\, p_T >$ in an R=0.4 cone is **~25 GeV/c**
- Intra-event fluctuations: **~6 GeV/c**
- 20 GeV fluctuations are rare (~3σ)
  – but 20 GeV jets are rare as well
- Challenge to identify "true" hard scatters

# Comparing A+A to p+p

- Subtract average density:

$$p_T^{\text{Jet}} = p_T^{\text{rec}} - \rho A$$

- Fluctuations, Detector Effects: **Embed reference**
    - p+p in Au+Au
    - PYTHIA in GEANT




*pp* @ **Au+Au**

Two Approaches:

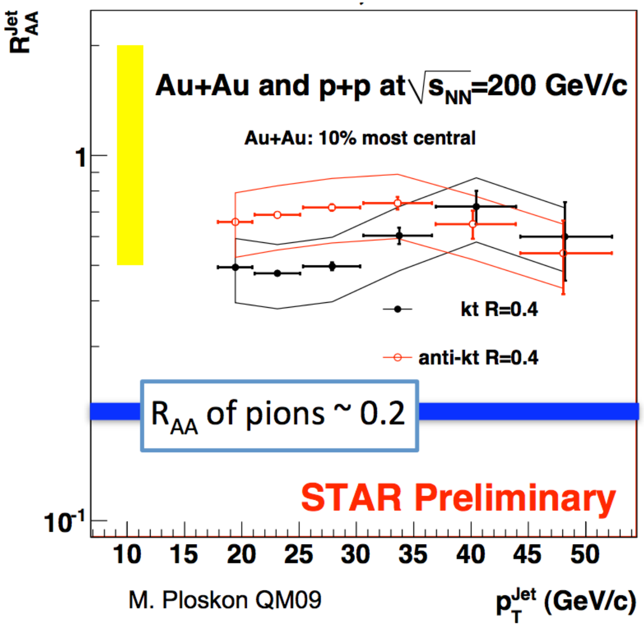
- Compare at **detector level**:
  + Simple, robust
  + No additional systematics
  - Hard to compare to theory

- Unfold (invert response)
  → Compare at **particle level**
  + Facilitate model comparison
  - Complex, sensitive

# Inclusive Jet $R_{AA}$

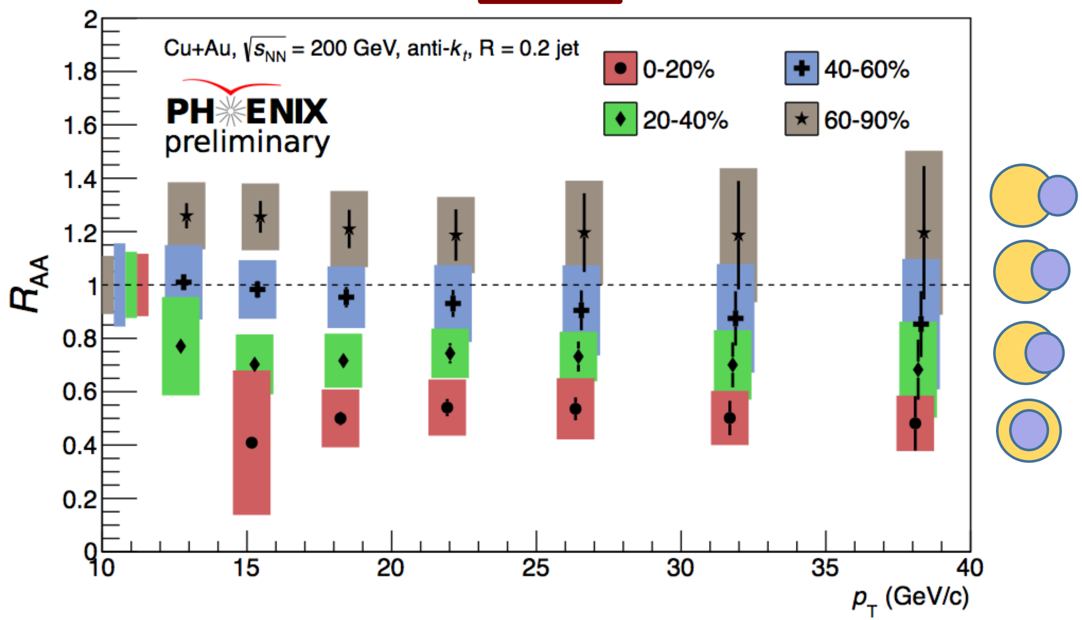
*QM '09*

**R=0.4**



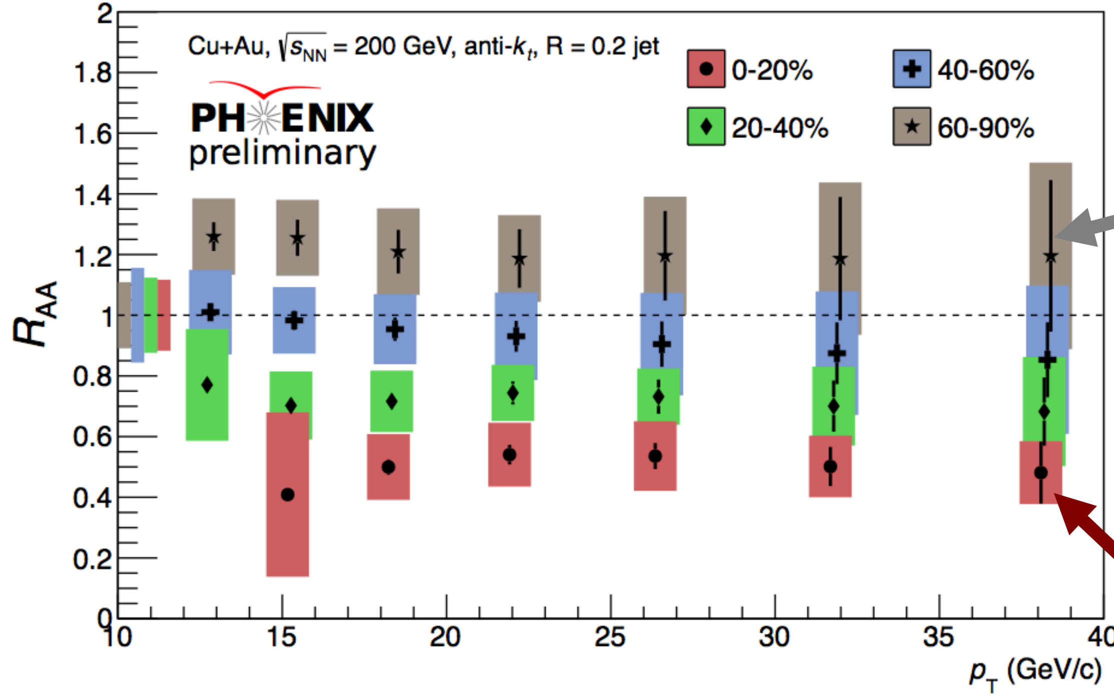

**R=0.2**

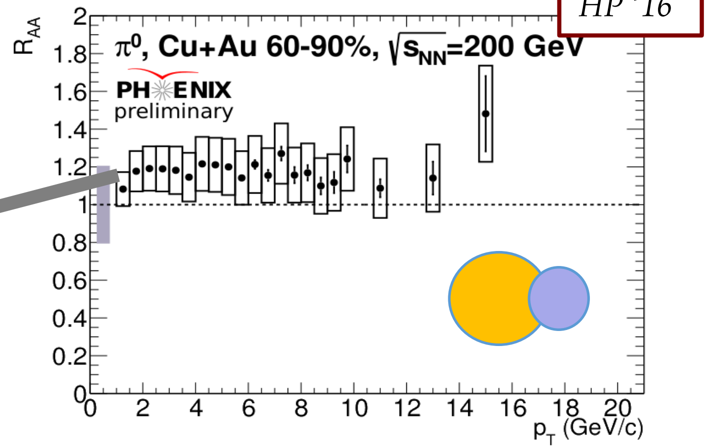
*HP '16*

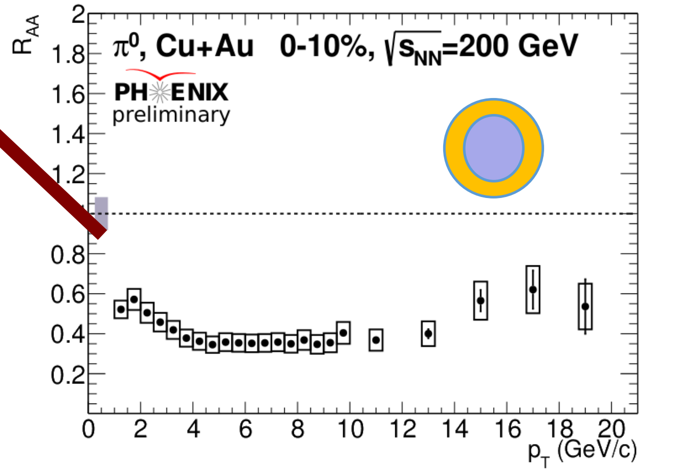



- Jets suppressed by ~factor of 2 in central Cu+Au collisions.
- Suppression shows **no $p_T$ dependence**,
    - similar to LHC at much higher energies.

# Inclusive Jet $R_{AA}$



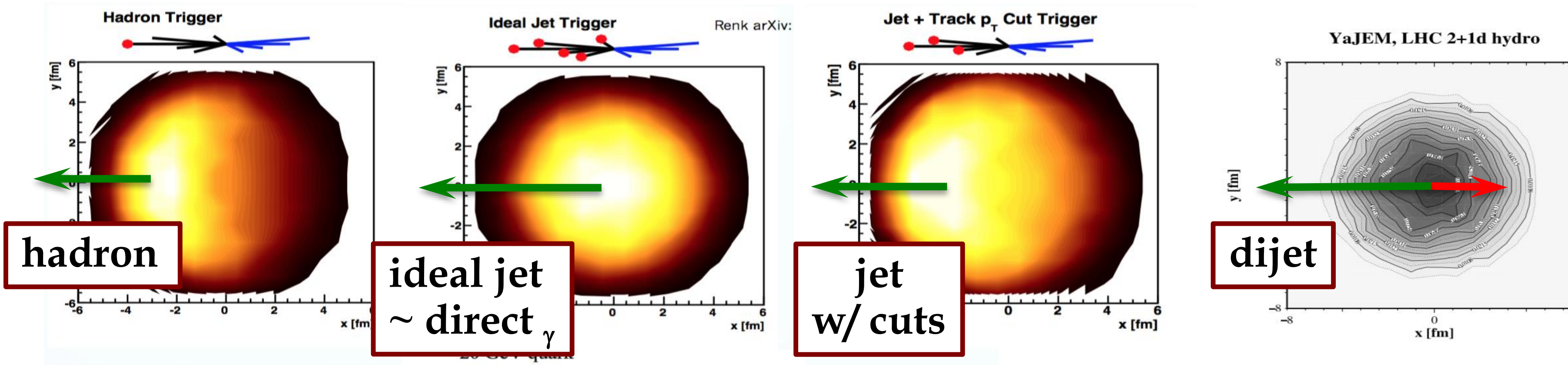

- R=0.2: Comparable to $\pi^0$ $R_{AA}$

HP '16

# A+A: Geometries and Strategies

YaJEM: *T. Renk arXiv:1212.0646, PRC 85, 064908 (2012), PRC 87, 024905 (2013)*

**RHIC** **LHC Dijets**




**Selecting a hard scatter:**

- High-$p_T$ hadron
- High-$p_T$ direct photon
- Jet, with cuts
- LHC: Geometry ~unaffected

**Exploit bias at RHIC for Jet Geometry Engineering**

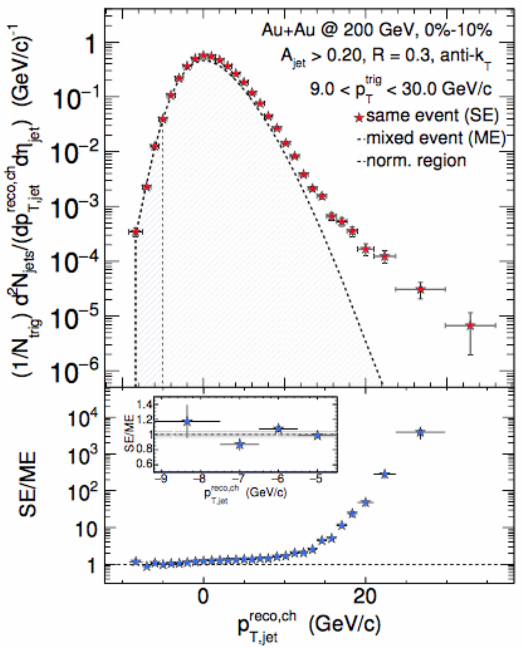
**Analyze the recoil**

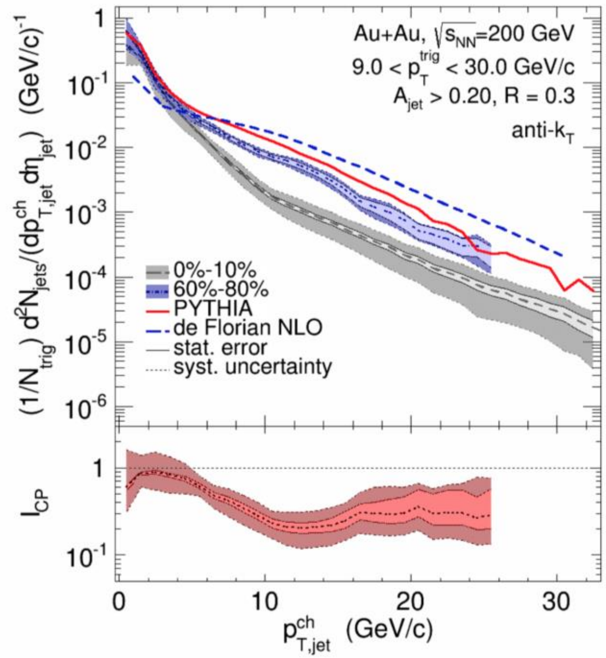
- Correlation
- Semi-inclusive jets
  → maximum path length
- Jet, with cuts
  → shorter path length?

# h-Triggered Recoil Jets

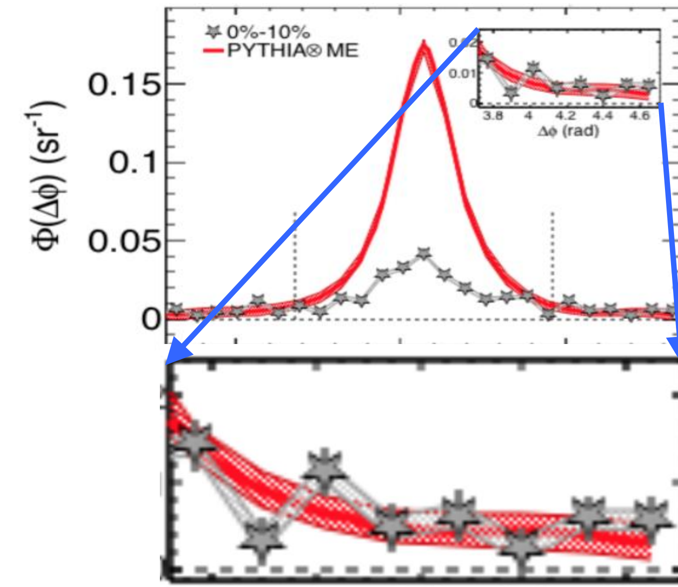
*arXiv:1702.01108*

**Raw** **R=0.3** **Unfolded**




**Recoil jets azimuthal distribution**




- $h^{+/-}$-triggered charged recoil jets:
  → $I_{CP}$ shows strong suppression (~0.2-0.3 for R=0.3)

- New limit on large-angle Molière scattering in central Au+Au

# γ-Triggered Recoil Jets

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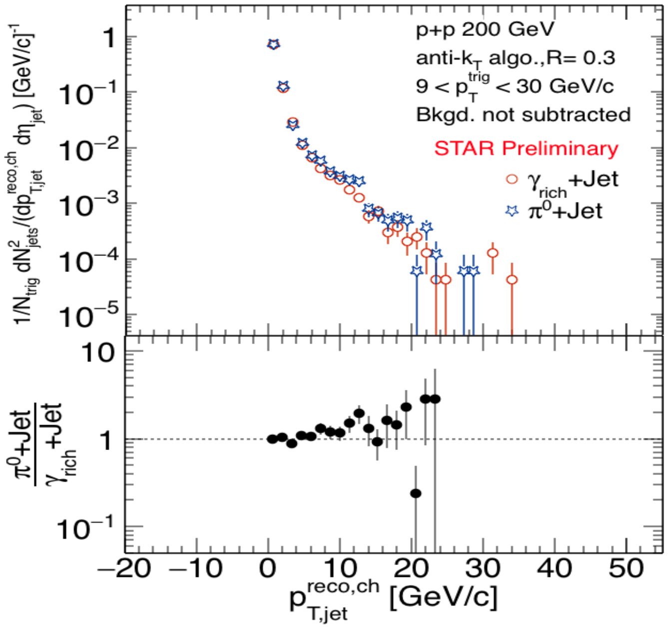
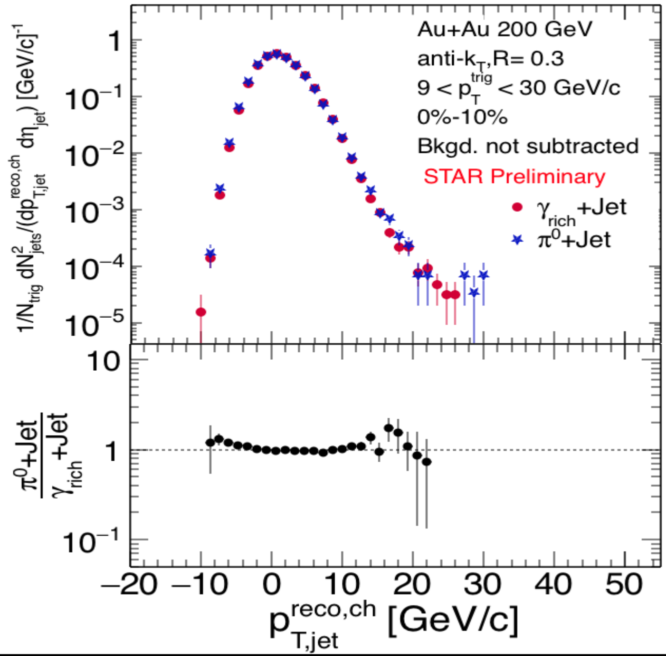
**p+p**




**Au+Au**




Purity of $\gamma_{dir}$ :
p+p ~**40%**
Au+Au (0-10%) ~**70%**

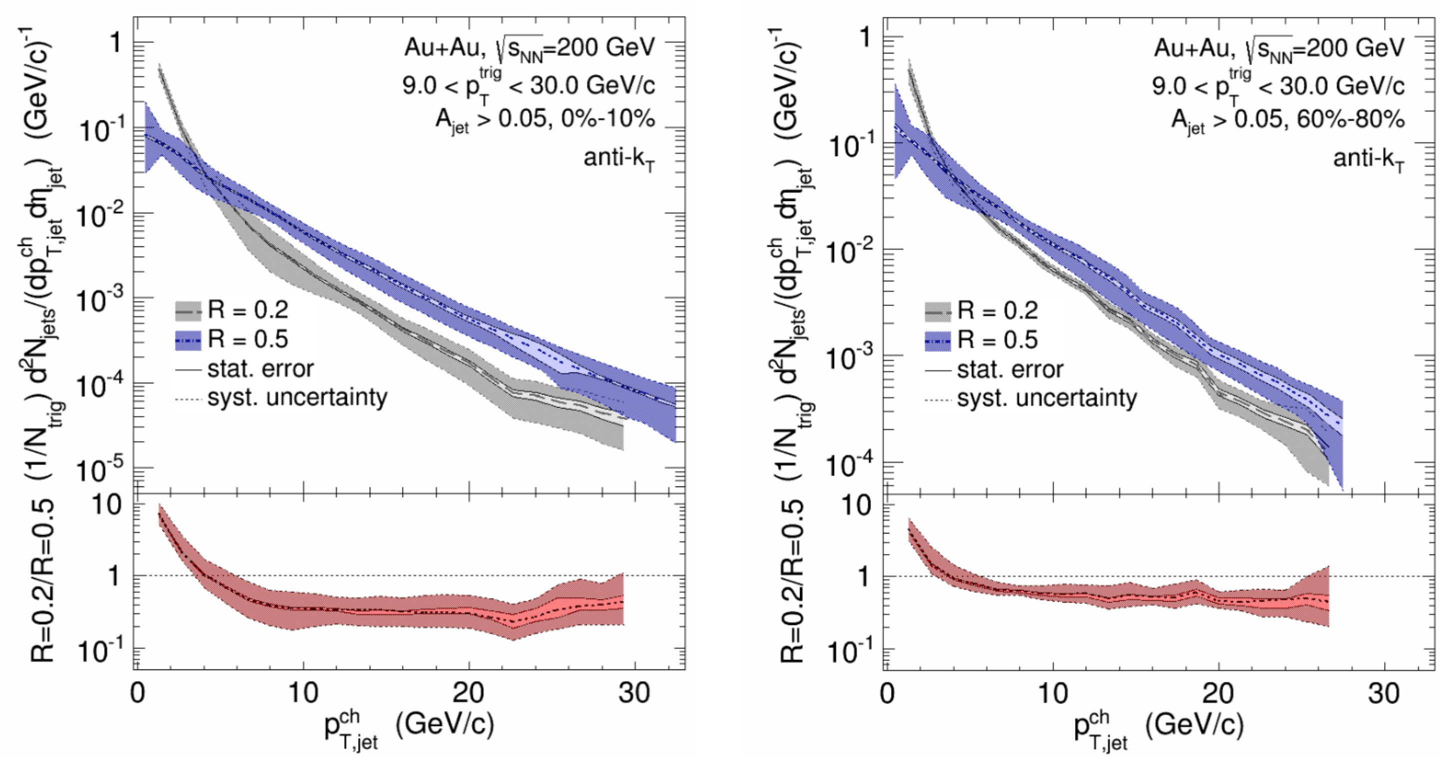
- p+p: Modest difference between □$^0$ and γ-rich triggers
- To extract medium effects for □$^0$+jet vs. γ+jet for p+p need full corrections, detailed study and large statistics

# Shapes and Internal Structures

# h-Triggered Recoil Jets

*arXiv:1702.01108*

**0-10%** **R=0.2 vs. R=0.5** **60-80%**




- Medium-induced broadening between *R*=0.2 and *R*=0.5

# Di-Jet Imbalance

**"Hard Core" Selection**

High Tower trigger $E_T$>5.4 GeV

$p_T^{Cut}$ = 2 GeV/$c$

→ Reduce background

→ Reduce combinatorial jets

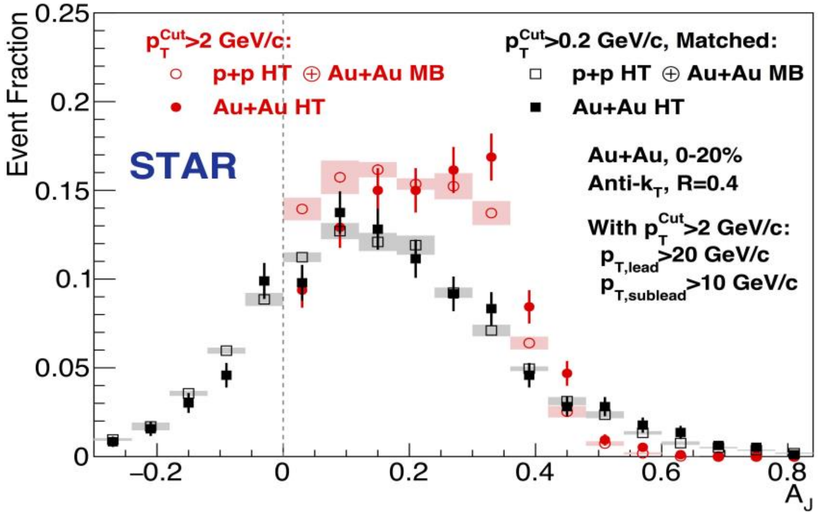
Jet $p_T^{Lead}$>20 GeV/c

Jet $p_T^{SubLead}$>10 GeV/$c$

Recover soft component:

**match to $p_T^{Cut}$ = 0.2 GeV/$c$**

Compared at detector level



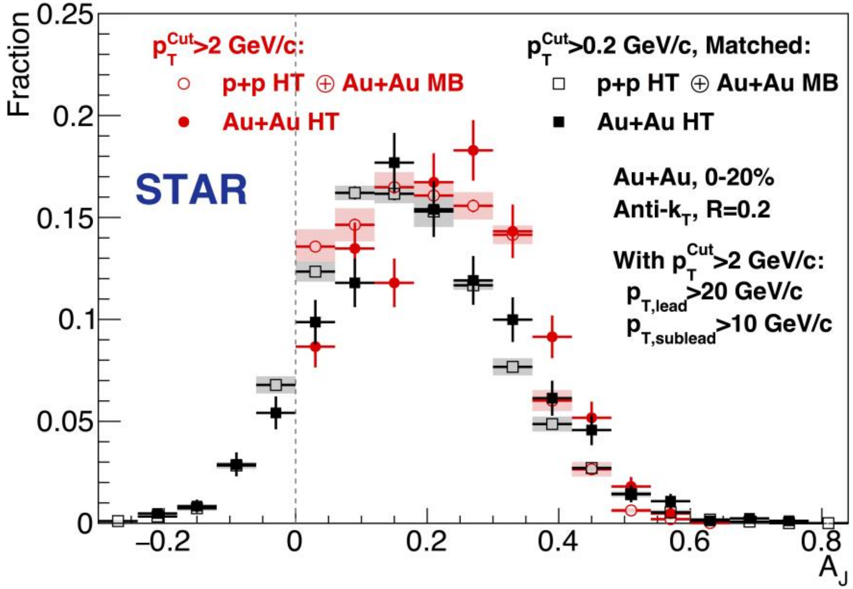

$$A_J = \frac{p_T^{\rm Lead} - p_T^{\rm SubLead}}{p_T^{\rm Lead} + p_T^{\rm SubLead}}$$

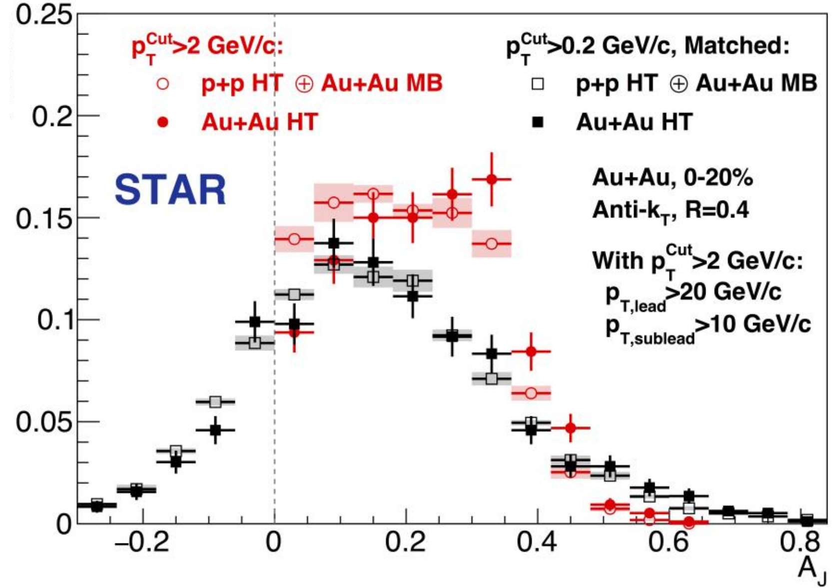
*arXiv:1609.03878*

- Au+Au di-jets more imbalanced than p+p for "hard core" selection
- p+p balance recovered in matched di-jets for R=0.4

# Di-Jet Imbalance

**R=0.2** | **R=0.2 vs. R=0.4** | **R=0.4**



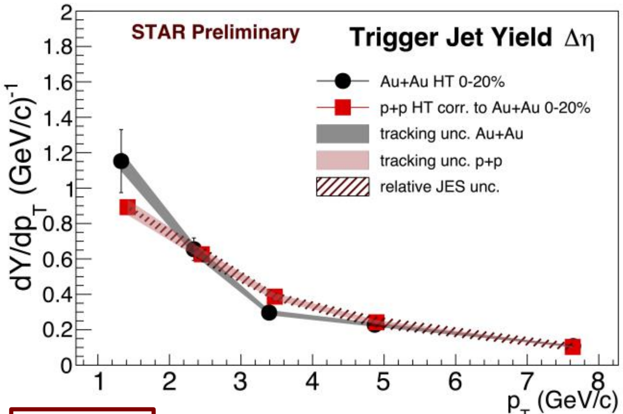



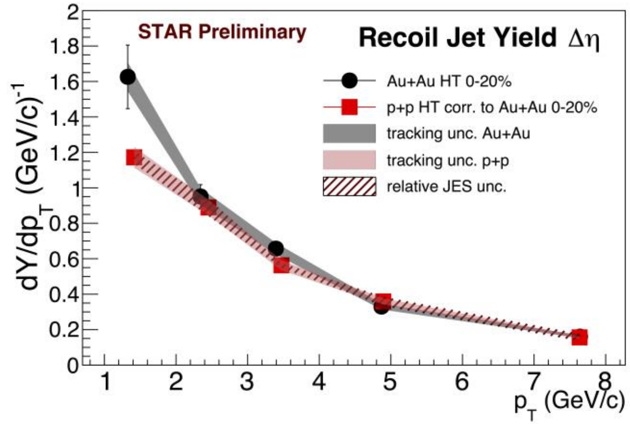

- p+p balance **no longer recovered**
- Energy shifted outward, yet remains inside 0.4
- Leading or sub-leading jet? $A_J$ can't answer

*arXiv:1609.03878*

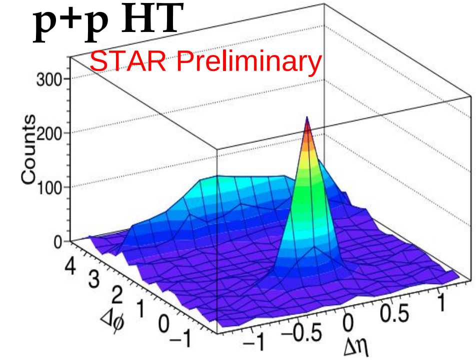
# Di-Jet+Hadron Correlations

Updated Hard Core selection:
**Trigger Jet contains HT** with $E_T$>6 GeV

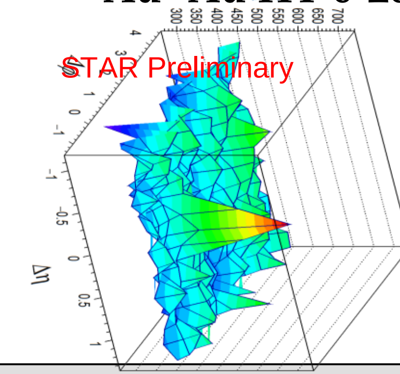



**p+p HT**




**Au+Au HT 0-20%**

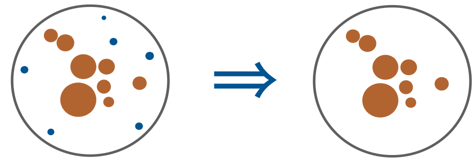



*QM '17*

- No modification relative to p+p on the trigger side → Surface Bias
- Hints of excess soft yield on the recoil side
- Integration over balanced jets (no $A_J$ cut) may dilute recoil suppression

# Groomed Momentum Sharing $z_g$

- Soft Drop: Remove wide angle soft radiation

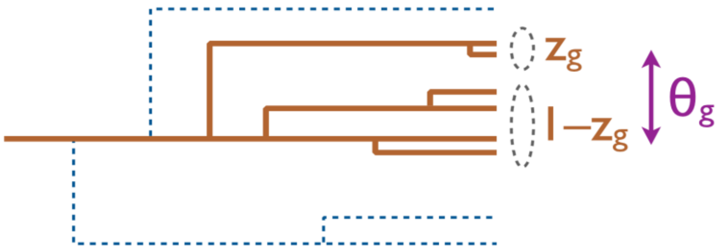


Soft Drop Condition:

$$z > z_{\text{cut}}\,\theta^{\beta}$$

energy threshold (→ $z_{\text{cut}}$)

angular exponent (→ $\beta$)




Based on declustering an angular-ordered tree

With **β=0** and Cambridge/Aachen:

**"Groomed Momentum Sharing"**

**Relative z of the softer prong**

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

In vacuum:

$$\frac{d\sigma}{dz_g} \propto \overline{P_i}(z_g) + \mathcal{O}(\alpha_s^2)$$

(the $\mathcal{O}(\alpha_s^2)$ term is struck through)

**$P_i$: AP splitting functions**

~ independent of $\alpha_s$

~ independent of $p_T$ (in UV limit)

~ independent of quark/gluon jet

Connection to fundamental QCD

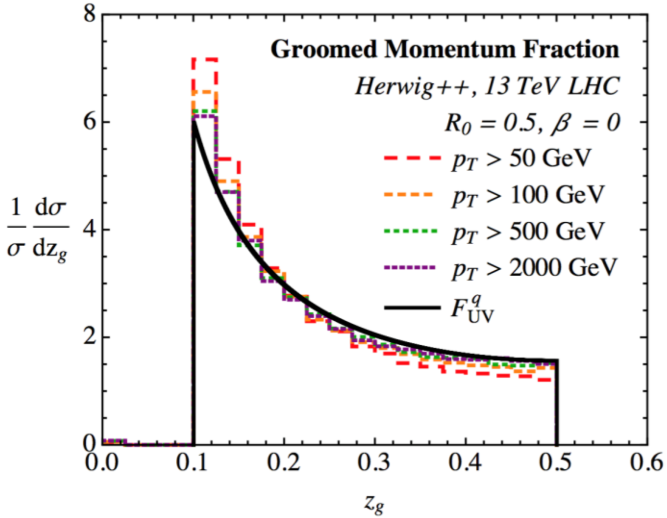
*J. Thaler*
*ALICE Jet Workshop (2015)*

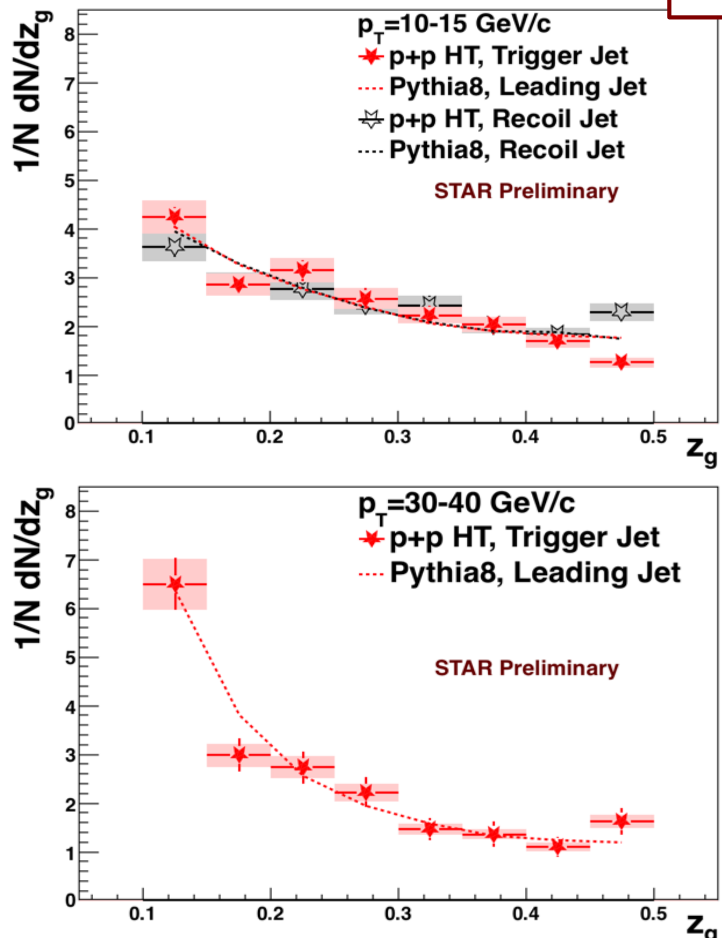
*Larkoski et al.,*
*PRD 91, 111501 (2015)*

# $z_g$ in p+p at 200 GeV

*Larkoski et al.,*
*PRD 91, 111501 (2015)*

*HP '16*

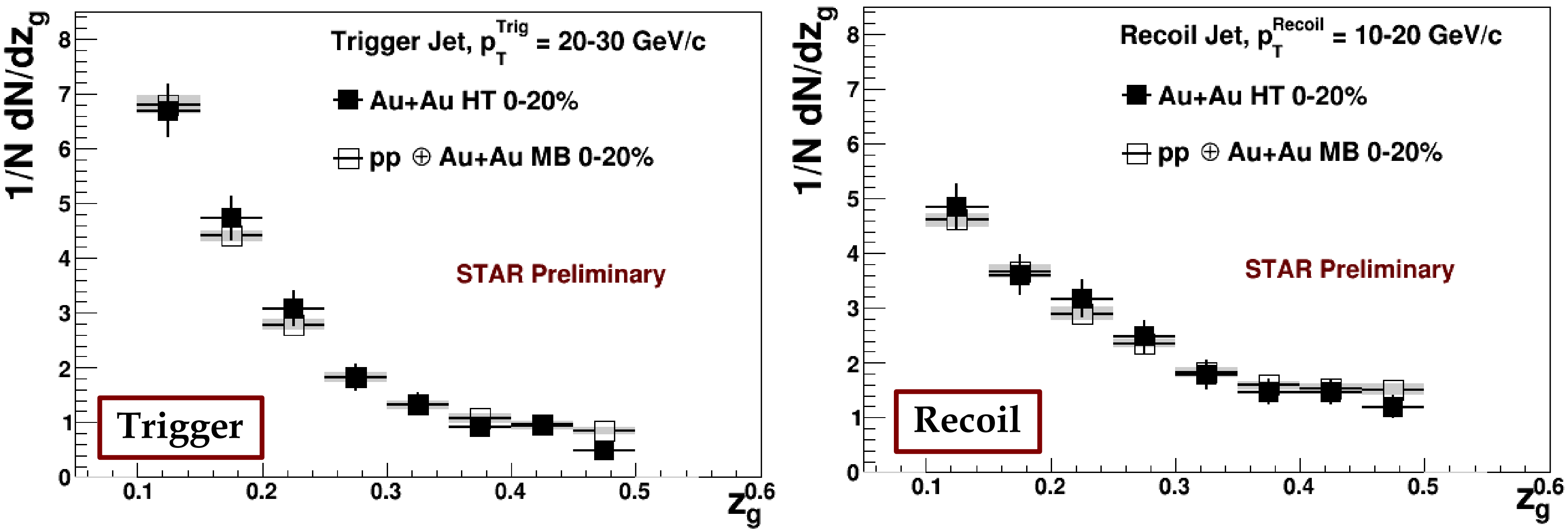



- Bin-by-bin correction to particle level
- Good agreement with PYTHIA in $p_T$=10-40 GeV/*c*

# Di-Jet $z_g$ in Au+Au and p+p

*HP '16*

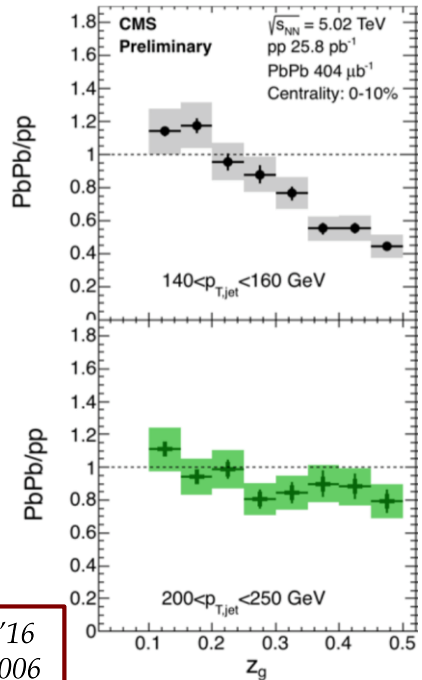



$z_g$ found in matched jets with $p_{T,cut} > 0.2$ GeV/$c$
Trigger Jet contains HT with $E_T$>5.4 GeV

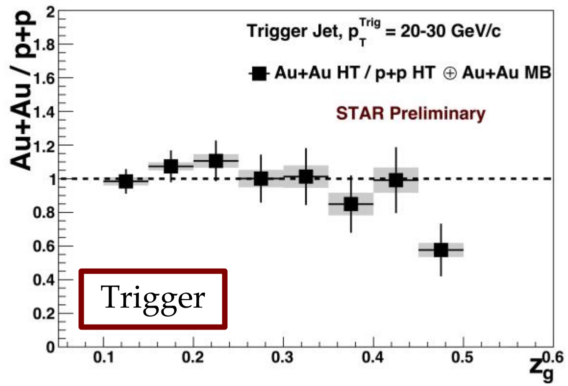
- No significant splitting modification on near- or away-side
  – but $A_J$ is modified!

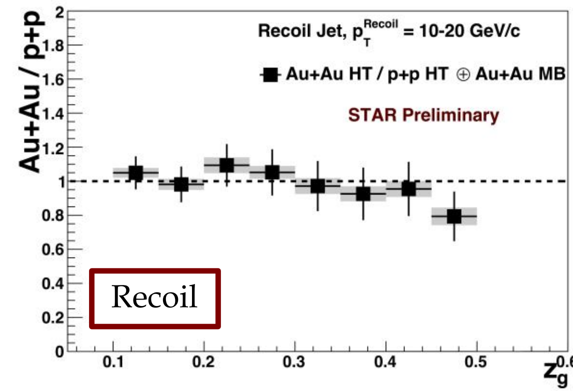
# Contrast to LHC

*HP '16*




*BOOST '16*
*HIN-16-006*




- STAR Biased Di-Jets: No $z_g$ modification found

- CMS Inclusive Jets: Significant modification in central Pb+Pb below 250 GeV/c

Possible Reasons:

- Split as measured with $z_g$ occurs outside the medium?
  - Or before formation?
- Splitting function not affected by medium interactions?
- Other explanations?

# Summary

- **RHIC offers unparalleled flexibility and unique strengths for jet studies**

- **Small Systems p+p, p+A, d+A, $^3$He+A:**

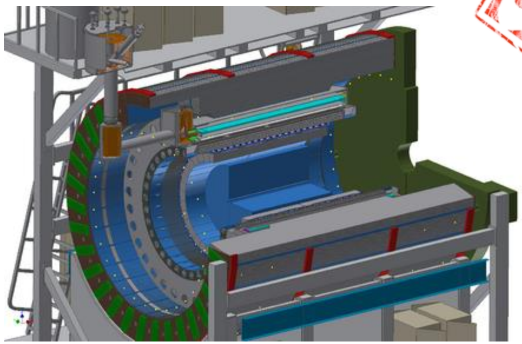
  *p*/*d*+A no longer just a baseline, nor a simple system

- **Large Systems Au+Au, Cu+Au, U+U:**
  - Common theme across all inclusive and differential measurements of E-loss:

    Energy redistributed to larger angles and softer particles
    - LHC: Lost quickly to large angles
    - RHIC: Can be recovered at small R for some selections

  - Interesting contrast to LHC data in splitting via $z_g$

# The Future



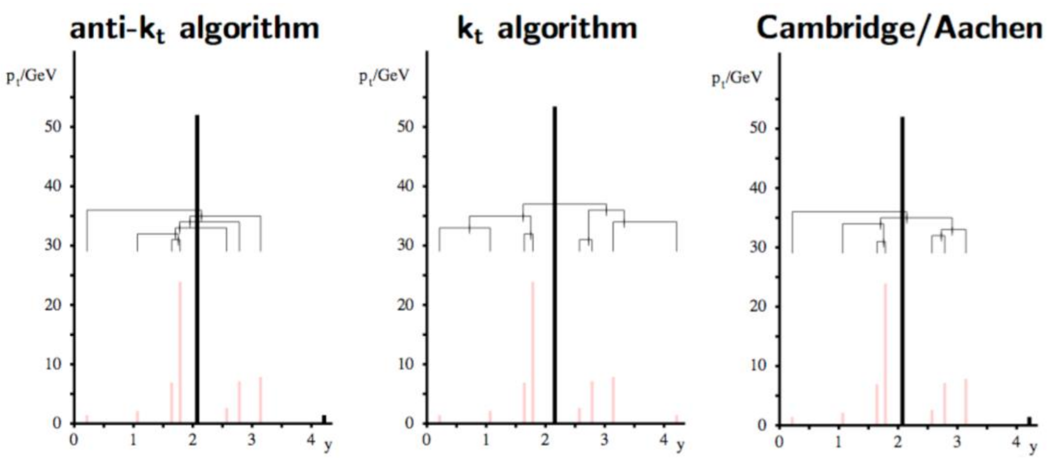
- State-of-the-art jet detector at RHIC
  - uniform acceptance
  - HCAL and EMCal
- High Statistics
  - $10^7$ jets above 20 GeV
  - $10^4$ direct $\gamma$ above 20 GeV
- CD0!

- Interdisciplinary: physicists, computer scientists, statisticians
- Mission: Comprehensive software framework for systematic, rigorous, unified comparison of theory and experiment

# BACKUP

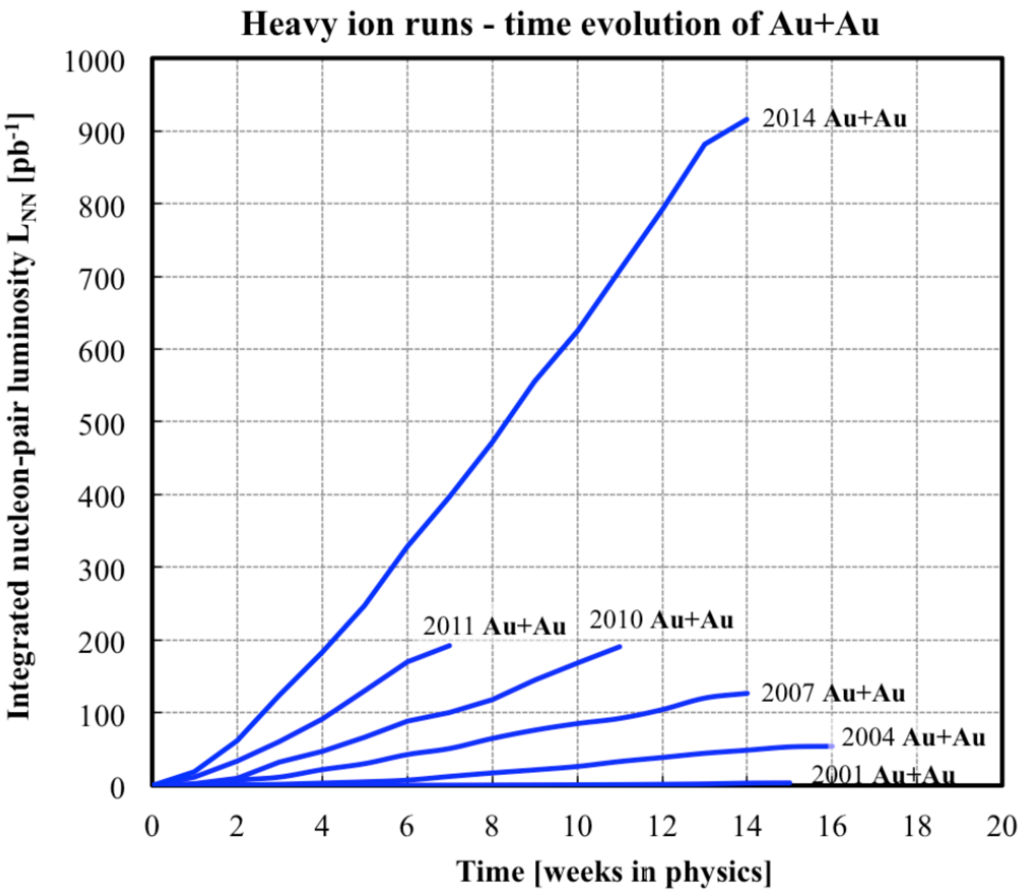
# Sequential recombination algorithms

1. Calculate **distance $d_{ij}$** between two particles and **beam distance $d_{iB}$** for all particles
2. Find **smallest** of all $d_{ij}$, $d_{iB}$
3. If it's a $d_{ij}$, **recombine** particles $i$&$j$. If it's a $d_{iB}$, call particle $i$ a **jet**
4. **Repeat** until no particles are left




- Resulting clusters are **jets**.
  - **Operational** definition. No unambiguous jet definition exists!
- Advantages:
  - Minimize sensitivity to hadronization: **IR-safe** and **collinear-safe** algorithm and instrumentation
  - Measure energy flow: connect to dynamics of **partons**
  - Comparison to **QCD** calculations beyond event generators

**FastJet3**
*M. Cacciari and G. Salam*
*Phys. Lett. B 641, 57 (2006)*



Heavy ion runs - time evolution of Au+Au
Integrated nucleon-pair luminosity $L_{NN}$ [$pb^{-1}$]
1000
900
800
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
18
20
Time [weeks in physics]
2014 Au+Au
2011 Au+Au
2010 Au+Au
2007 Au+Au
2004 Au+Au
2001 Au+Au

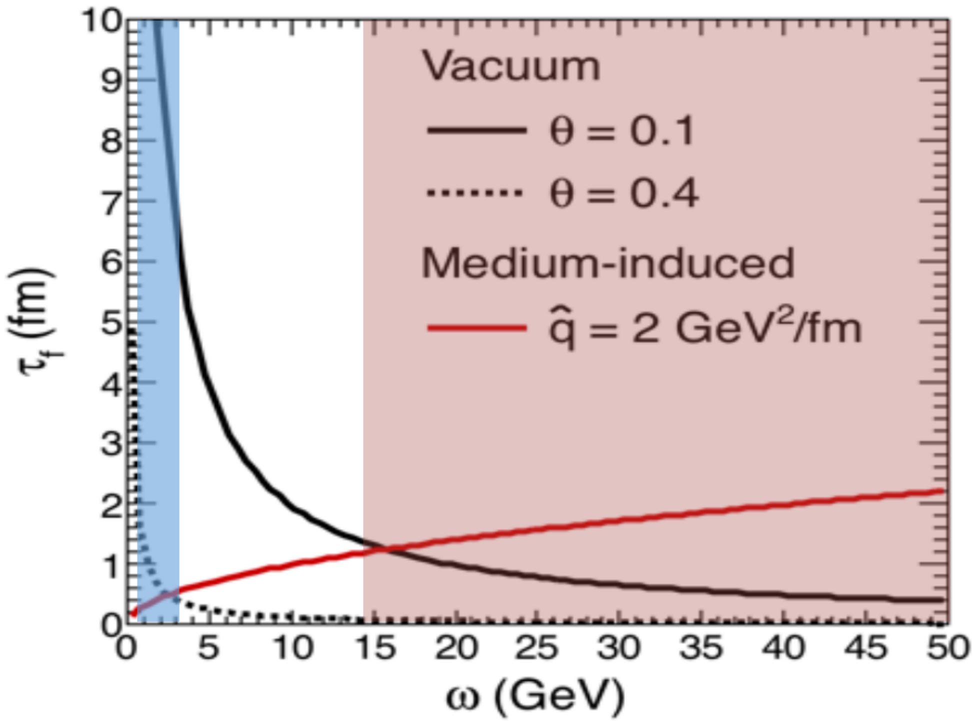
# $z_g$ – RHIC vs LHC

Vacuum and medium formation times

Hard medium-induced radiation happens late in the shower

$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

$$\tau_f^{med} \cong \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$$




Phase space covered for $z_g$=0.1

STAR

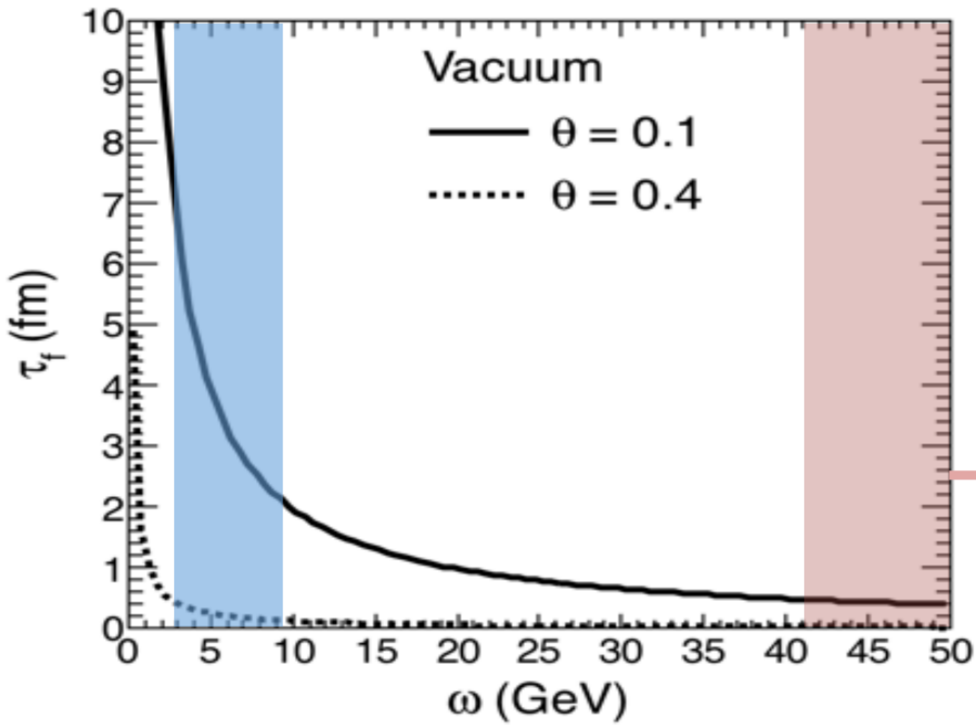
CMS

At RHIC can only see medium for rare large angle emissions or even splittings. Larger $z_{cut}$ and/or $\Delta R_{12}$ selection would increase sensitivity

# $z_g$ – RHIC vs LHC

Vacuum formation time of gluons with certain energy

$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$




Phase space covered for

$z_g$=0.3

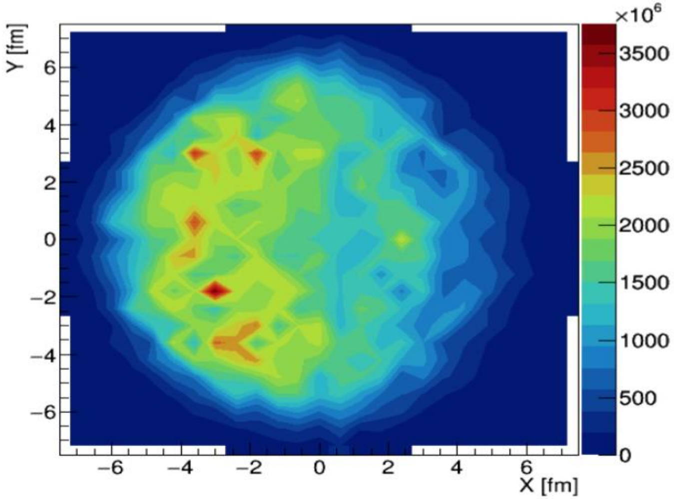
STAR

CMS

STAR and CMS are probing very different formation times. No overlap

# YaJEM Calculation for STAR Dijets (First Look)

$p_{T1} > 20$ & $p_{T2} > 10$




**Courtesy of Kirill Lapidus**

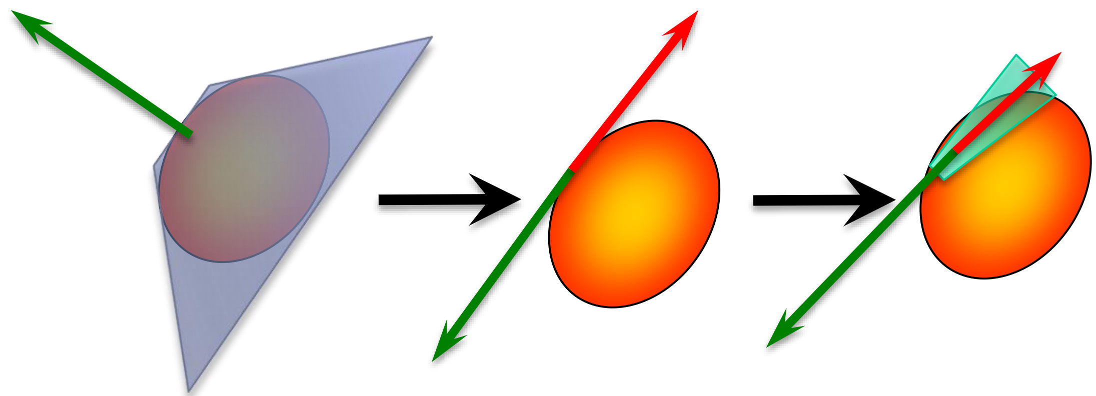
**1D hydro**
R = 0.4
constituent bias 2 GeV
5.5 hard track in either of two jets
back-to-back

Signs of creation hot spots shift by 2-4 fm

Needs further investigation
-- Be mindful of fluctuations and hydrodynamic expansion

$p_T^{SubLead}$ & Constituent $p_T$ → **systematically** dial in the **path length** of the recoil jet

Dijet Imbalance = Recoil E-loss?
Found a **"sweet spot"**
Lost energy seems to be
**contained within R=0.4**



**Matching:** *Differentially* study
- Broadening – *jet-by-jet*
- Softening – *jet-by-jet*