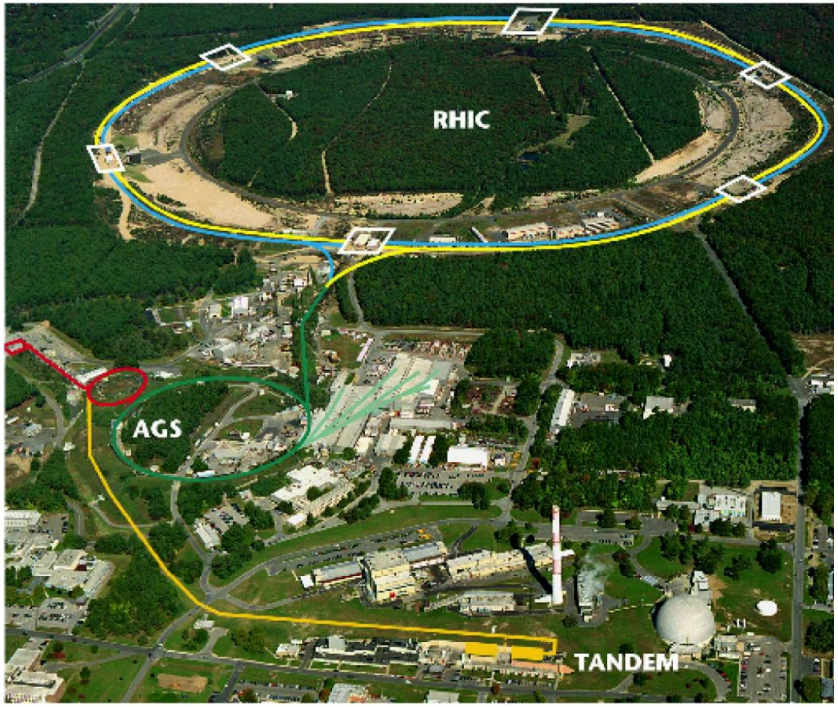
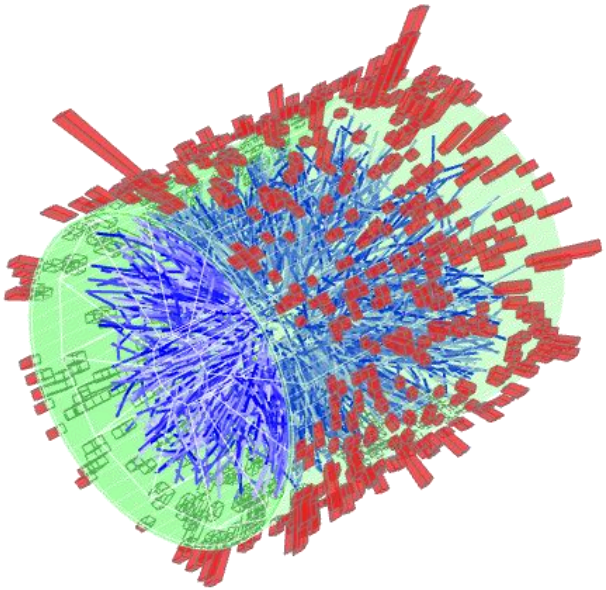
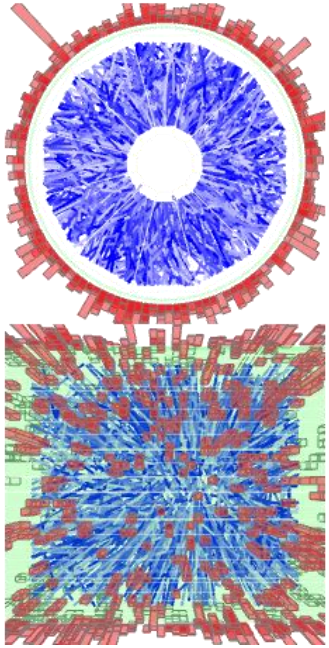






Jet Measurements with STAR

with a focus on jet reconstruction

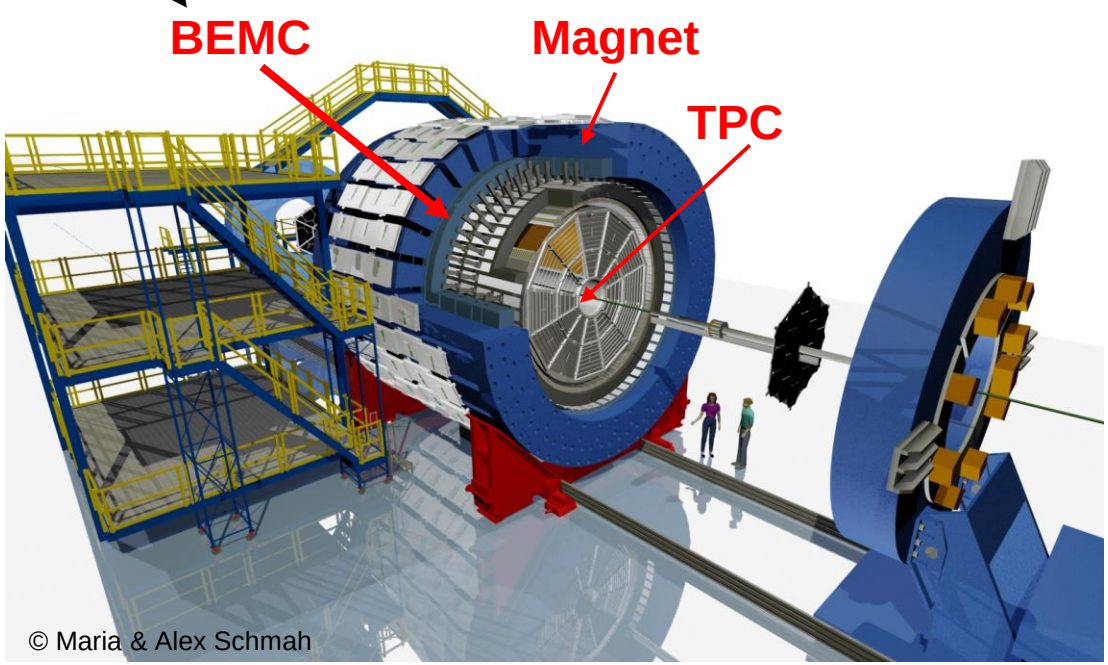
Kolja Kauder *for the STAR Collaboration*
June 8, 2016

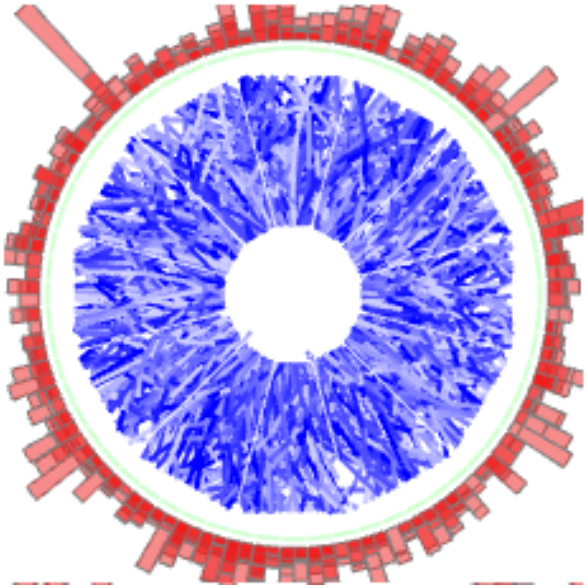
STAR

High Tower: Online Trigger
$E_T > 5.4$ GeV
in one tower
$\Delta\varphi \times \Delta\eta = 0.05 \times 0.05$

Charged and neutral particles:

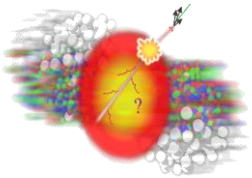
- Full azimuthal acceptance
- Extended pseudorapidity acceptance $|\eta|<1$





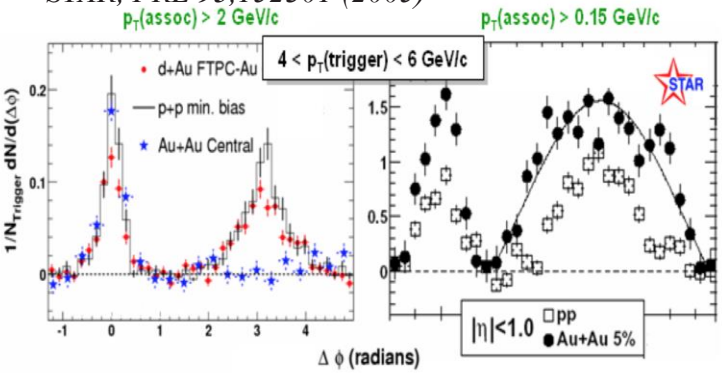
Au+Au, 200 GeV

Correlations: Jet Quenching beyond R_{AA}



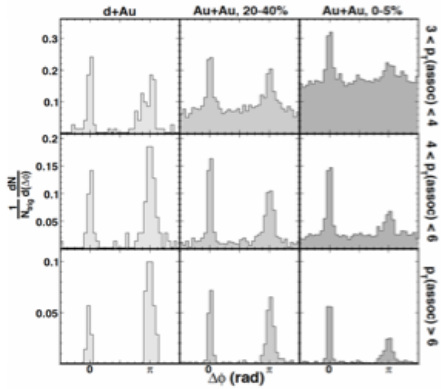
Di-hadron

*STAR, PRL **91**, 072304 (2003)*
*STAR, PRL **95**,152301 (2005)*



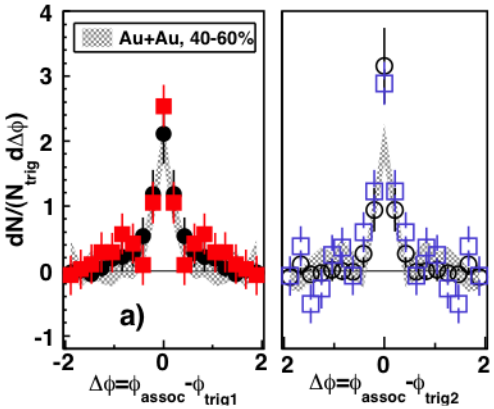
Di-Jets

*STAR, PRL **97**, 162301 (2006)*



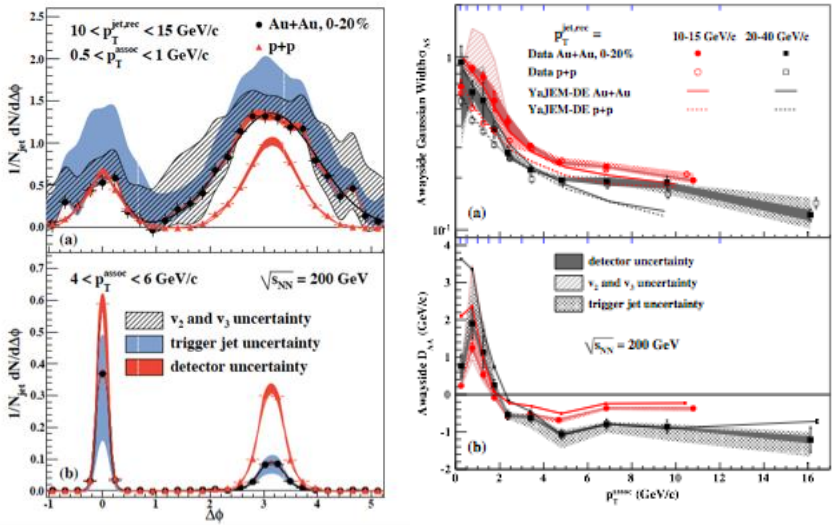
2+1

*STAR, PRC **83**, 061901 (2011)*



Jet-hadron

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



- Hadron Correlations: Dependence on hadronization
- Goal: **partonic** E-loss
- All Correlations: Ensemble-based
  "jets lose x amount of energy *on average*"
- Goal: **jet-by-jet** E-loss
  "*this* jet lost x amount of energy

Implementation:

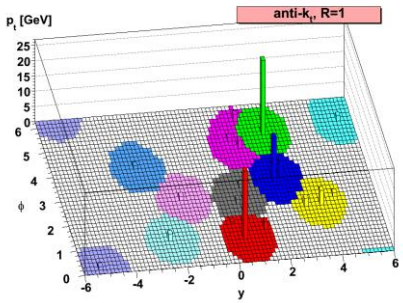
FastJet3

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

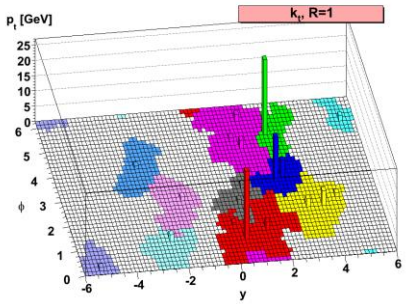
Jet Finding

Sequential Clustering:

- **anti-k_T**, R=0.2—0.5

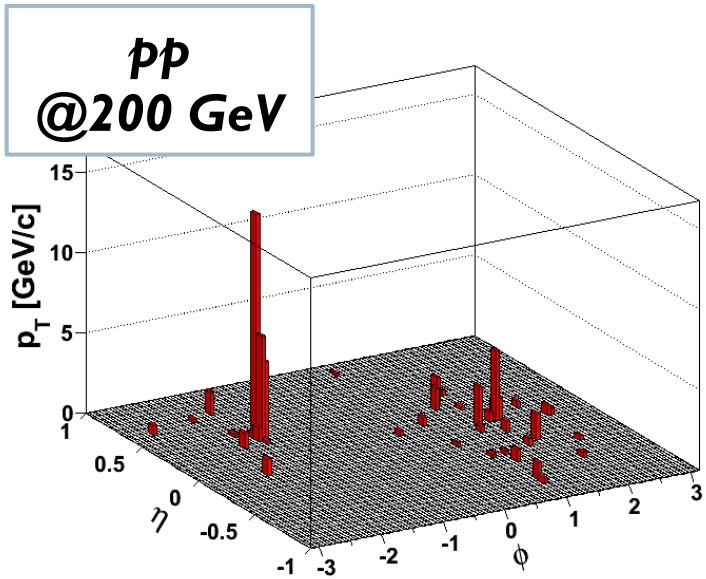


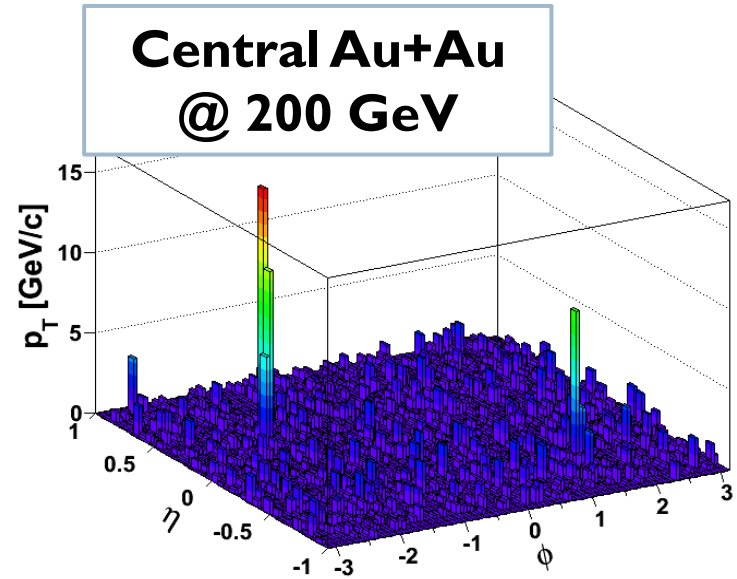
- average energy density: k_T algorithm, same R



- 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

The Underlying Heavy Ion Event





- Can still *find* a "jet", but does it come from a hard scattering?
- And if so, how to determine the parton energy?

$< \Sigma\, p_T >$ in an R= 0.4 cone is on the order of ~25 GeV/*c*

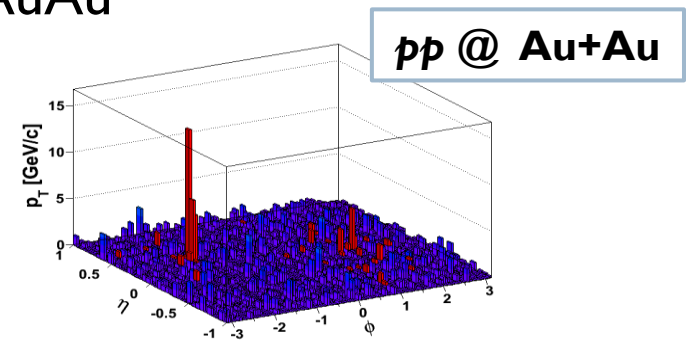
Intra-event fluctuations: ~6 GeV/*c*

Background

- Subtract average density:

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

- Fluctuations and Detector Effects: **Embed** reference in AuAu



→ Compare on **detector level**
→ Or **unfold** response matrix to **particle level**

20 GeV fluctuations are rare (~3σ)
– but 20 GeV jets are rare as well

→ How to select hard scatters?

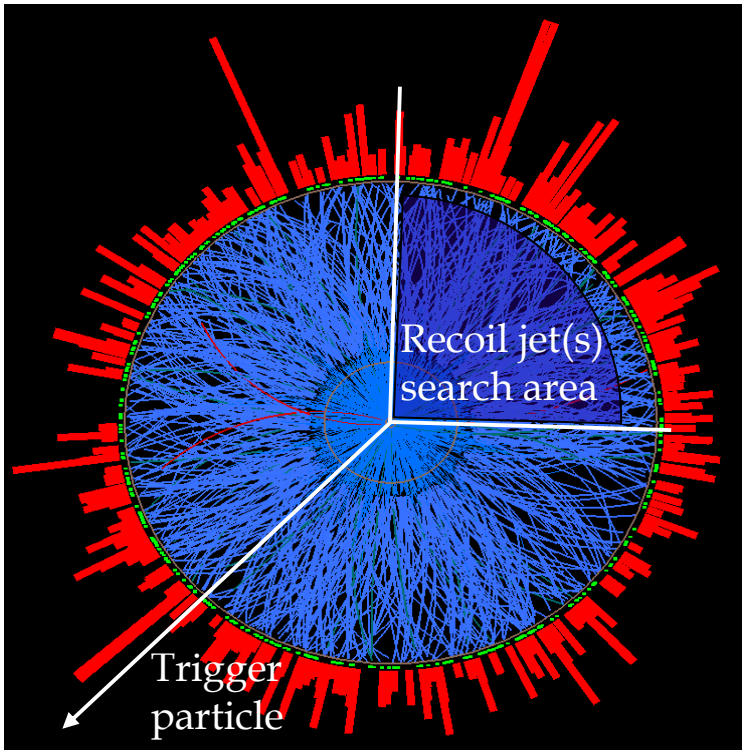
Focus on "coincidence" measurements

- **Hadron-Jet correlations**
  Surface bias for trigger, but away-side is bias-free
- **Di-Jet Asymmetry**
  tangential bias
  → *jet geometry engineering*

Alternative: ***direct*** *γ*
→ *see Nihar Sahoo's talk*

A. Schmah, HP 2015

Semi-Inclusive Recoil Jets



Semi-inclusive yield of (charged) jets recoiling from a high-p_T hadron trigger

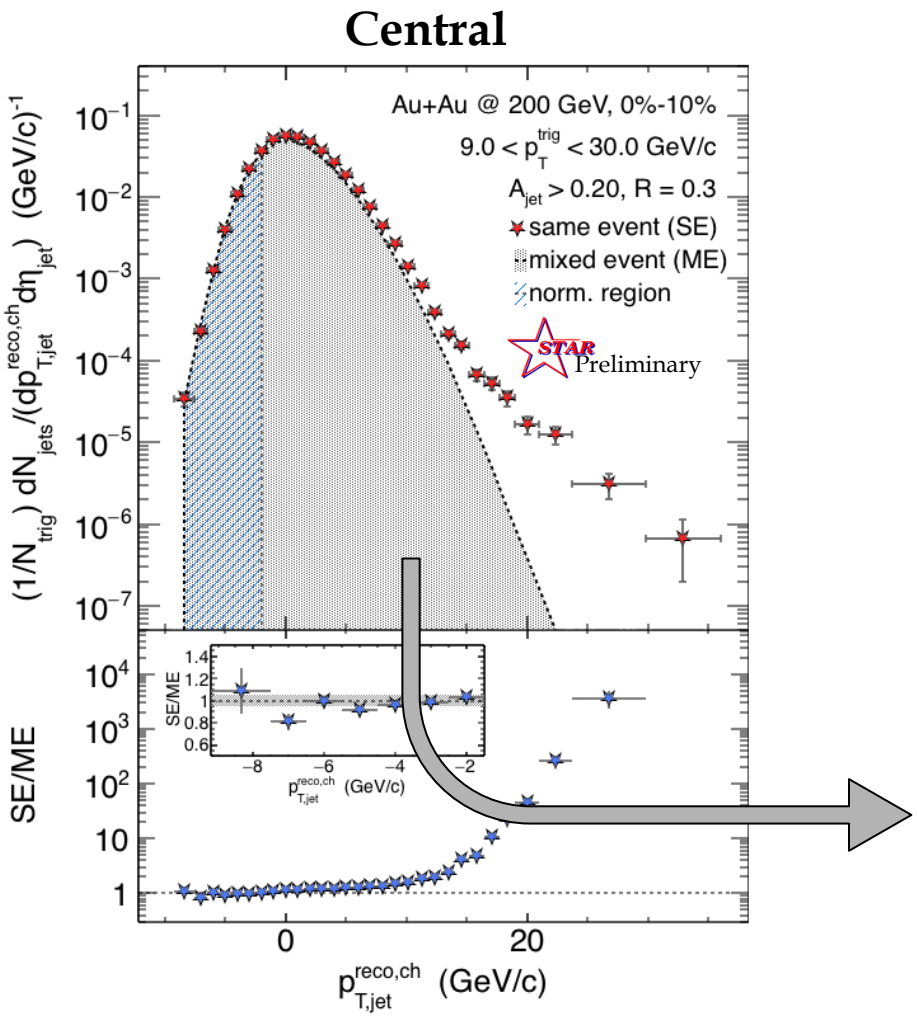
$$\frac{1}{N^h_{trig}}\frac{dN_{jet}}{dp_{T,jet}} = \frac{1}{\sigma^{pp\to h+X}}\frac{d\sigma^{pp\to h+jet+X}}{dp_{T,jet}}$$

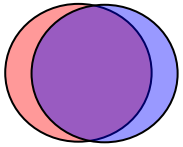
Measured Calculable in pQCD

Phys.Rev. D79 (2009) 114014
arXiv:0904.4402

- Trigger on high p_T hadron → Selection of a high p_T process
- Use all jet candidates on the other azimuthal hemisphere within +/- 45 degrees → **no fragmentation bias on recoil side**!
- Combinatorial background determined via mixed events

Charged Raw Recoil Jet Spectrum: Central Au+Au

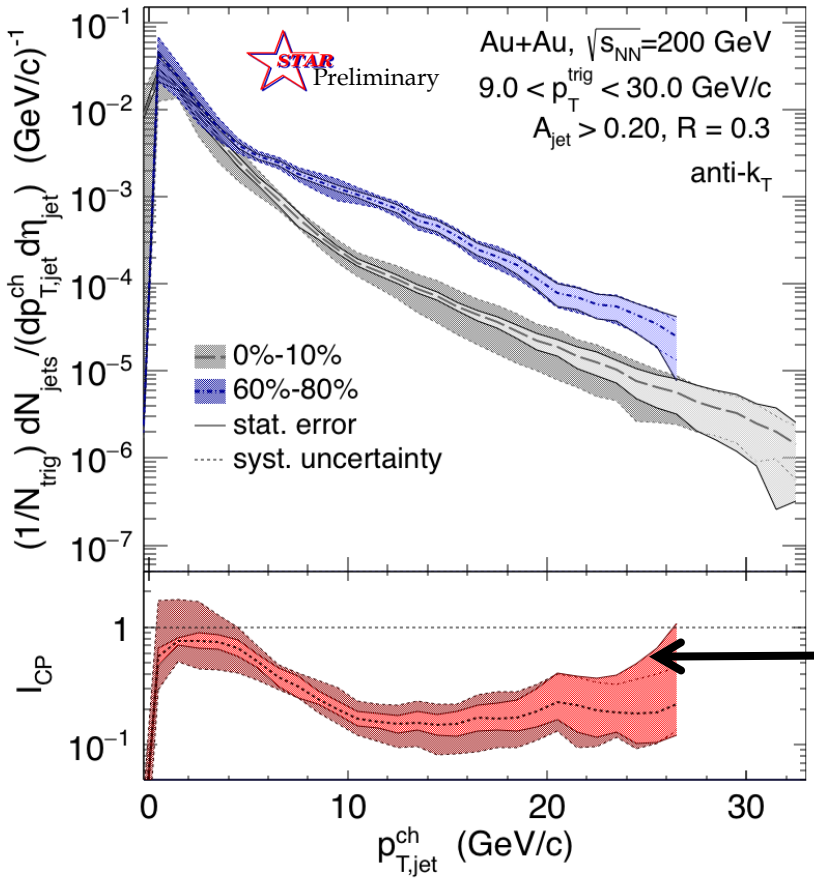




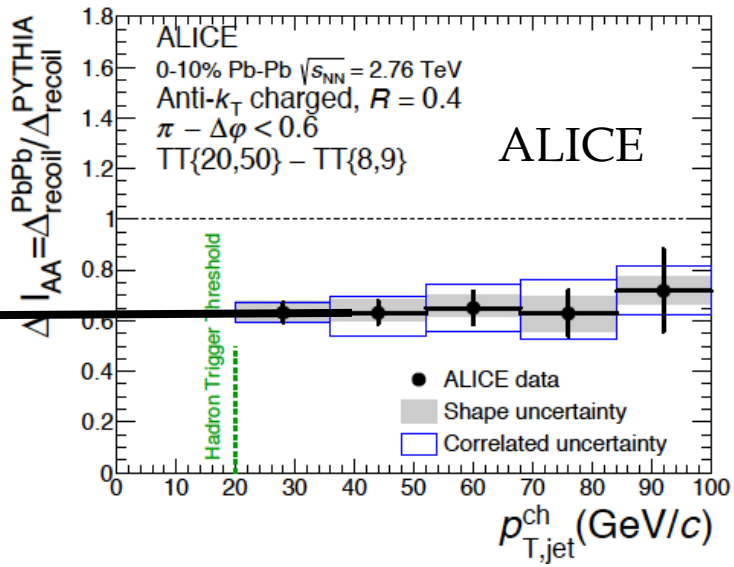
- Excellent description of low p_T SE spectrum with ME
- Normalization region varied systematically
- Significant jet signal at p_T - $\rangle$ A > 10 GeV/c

Combinatorial jet background → statistically described by mixed event technique

Comparison Central-Peripheral: I_{CP}



- Significant suppression (~0.2) at p_T > 10 GeV/c, close to 1 at low p_T
- **Larger suppression** compared to LHC energies! (caveat: **different R**)

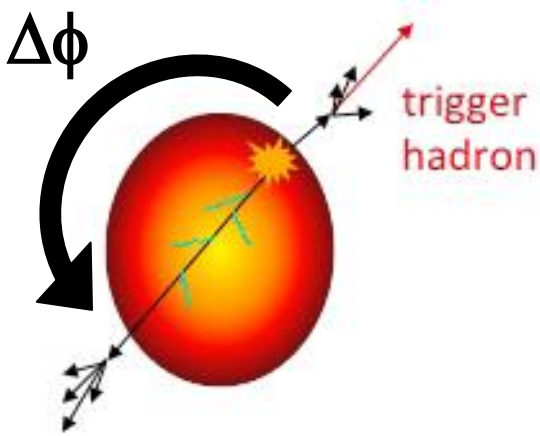


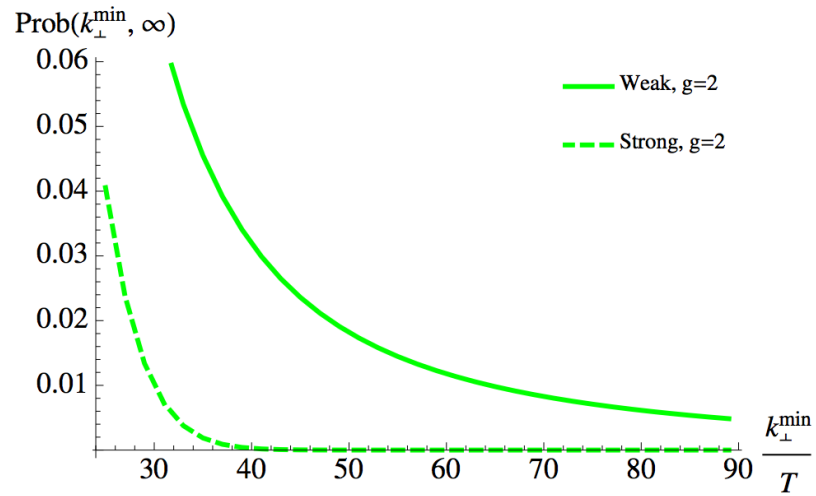
- Errors show combined systematics

arXiv:1506.03984 [nucl-ex]

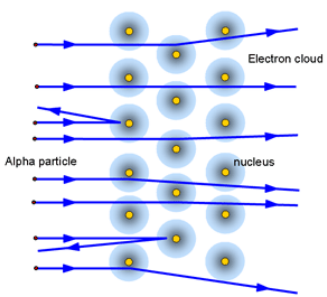
Large Angle Scattering off the QGP?

JHEP 1305 (2013) 031

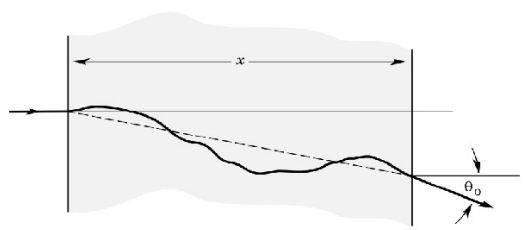




Discrete scattering centers or effectively continuous medium?



"Weak"
multiple scattering



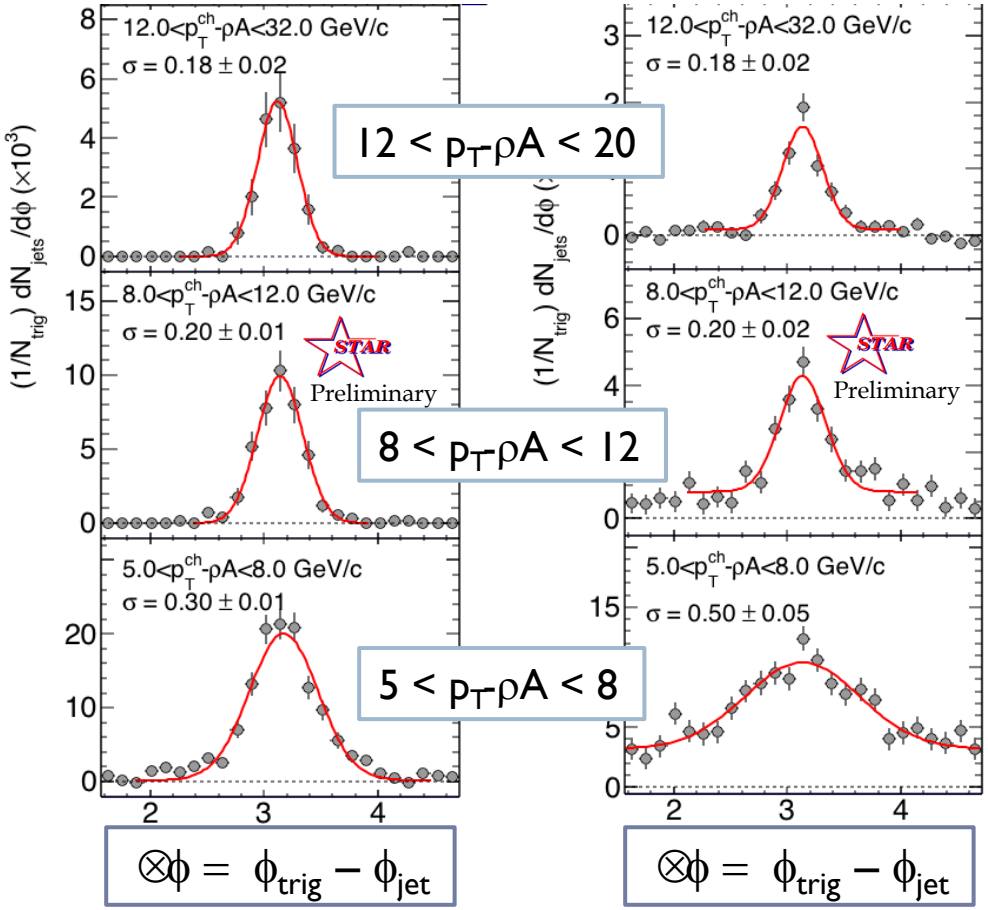
"Strong"
Continuous E-loss

- Scattering probability can give us important information about coupling
  → strongly/weakly coupled QGP
  → quasiparticles?

Δϕ at R = 0.3

Peripheral

Central



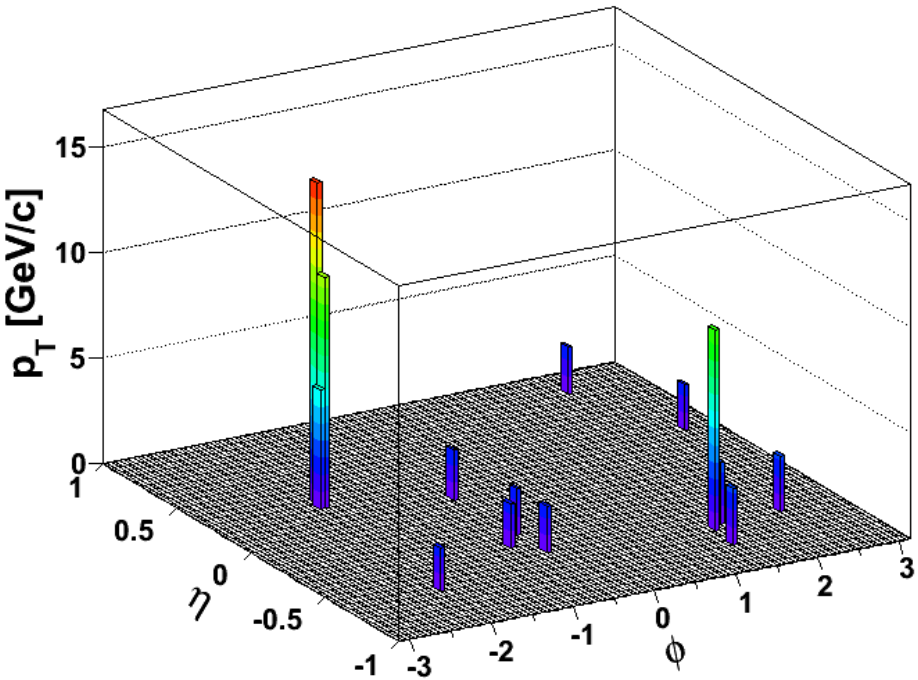
High recoil jet p_T:

→ Same width for both centralities

$5 < p_T\text{-}\rho A < 8$ GeV/c:

→ Significant difference
→ Normalization? BG? Flow?
→ More studies needed

Trigger **and** Away-Side Jets (Biased) Di-Jet Selection



Constituent p_T^{Cut} = 0.2 GeV/*c*

Constituent p_T^{Cut} = 2 GeV/*c*

→ Reduce BG

→ Reduce combinatorial jets

Di-jet Selection:

Jet p_T^{Lead}>20 GeV/c

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

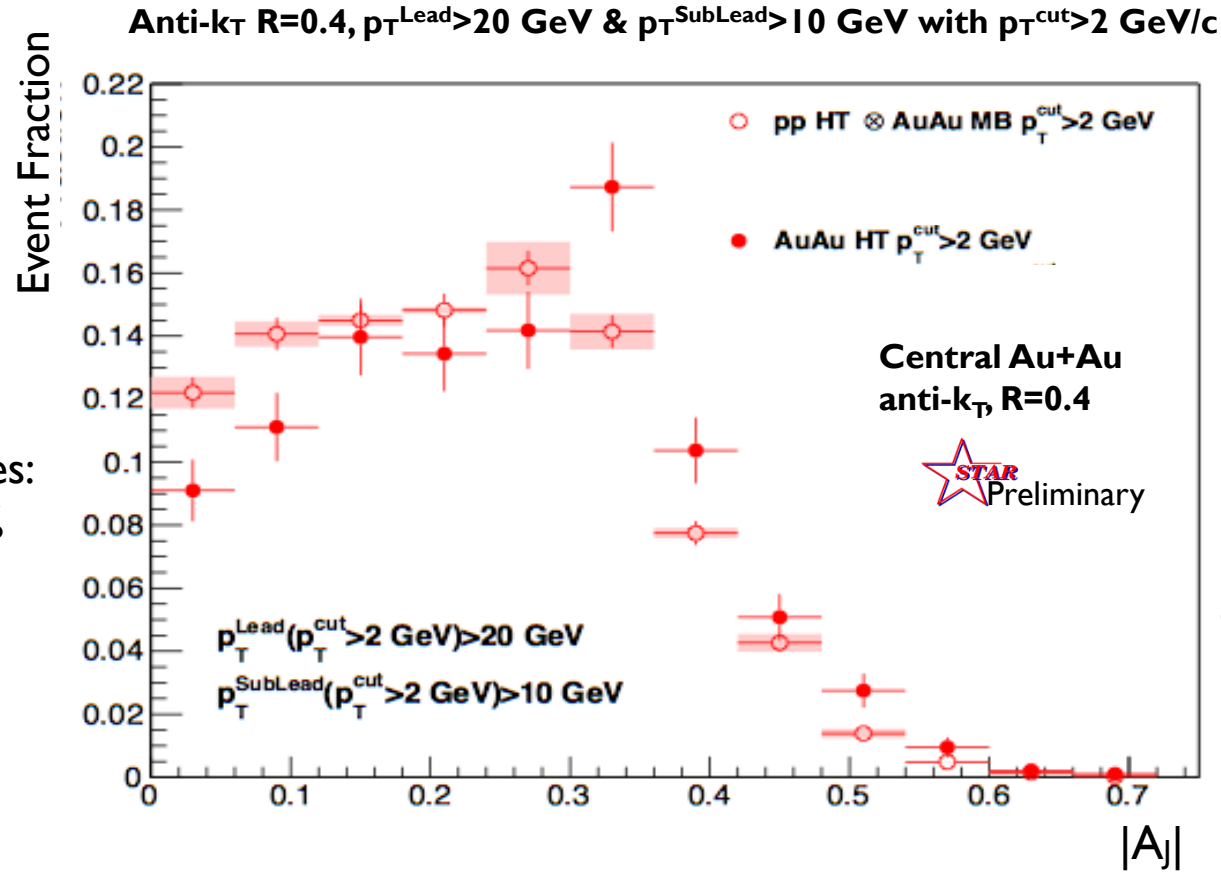
$|\Delta\phi-\pi|<0.4$

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

*ATLAS, PRL **105**, 252303*
*CMS, PRC **84**, 024906 (2011)*

KK, HP 2015

Di-Jet Imbalance A_J
Central Au+Au, R=0.4



Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

p-value < 10^{-4}
(stat. error only)

Pearson's χ^2-test
N.D. Gagunashvili, arXiv:physics/0605123

Au+Au di-jets more imbalanced than p+p for p_T^{cut}>2 GeV/c

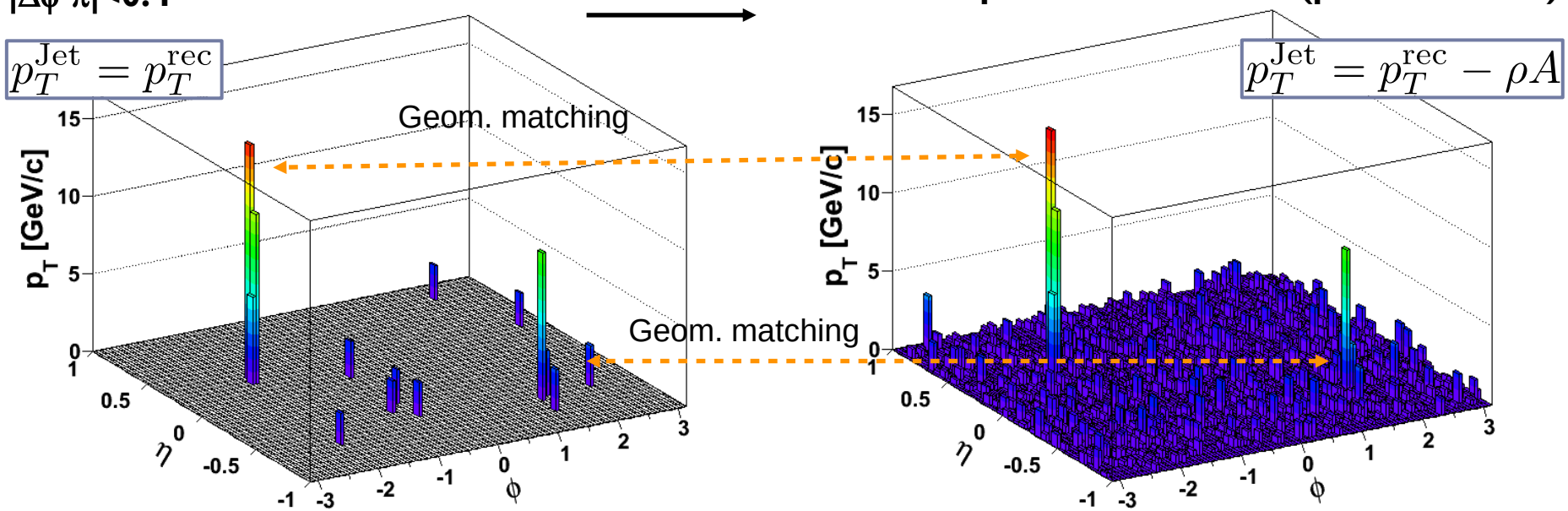
Can the balance be restored?

Matched Di-jets w/o Constituent p_T Cut

p_T^{Cut}=2 GeV/c
p_T^{Lead}>20 GeV/c
$p_T^{SubLead}$>10 GeV/c
$|\Delta\phi-\pi|$<0.4

Rerun jet-finding algorithm anti-k_T on **these events**

p_T^{Cut}=0.2 GeV/c
p_T^{Lead}>20 GeV/c (p_T^{Cut}=2 GeV/c)
$p_T^{SubLead}$>10 GeV/c (p_T^{Cut}=2 GeV/c)



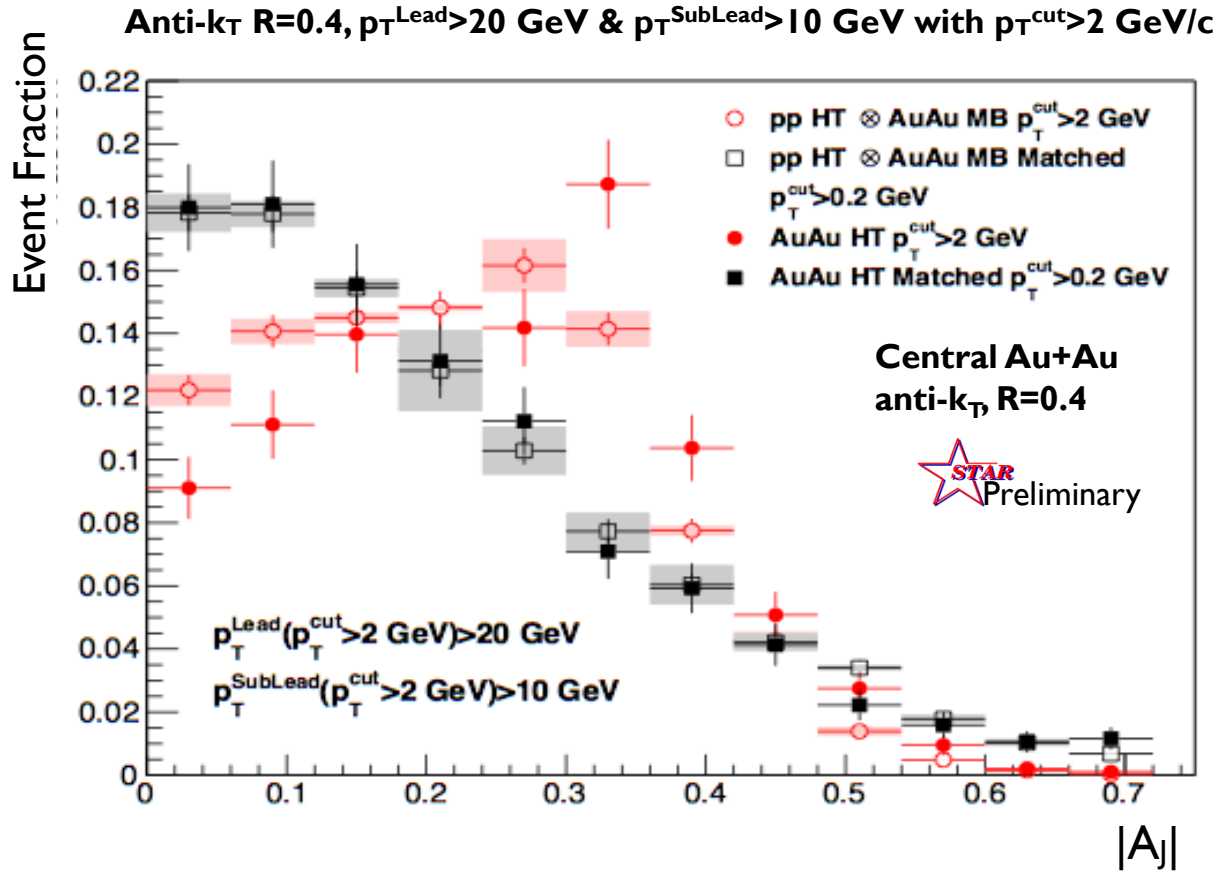
Keep this jet selection

Calculate "matched" $|A_J|$ with constituent $p_{T,cut}$>0.2 GeV/c.

Geom. matching: $\Delta R<0.4$

Di-Jet Imbalance A_J
Central Au+Au, R=0.4

Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%



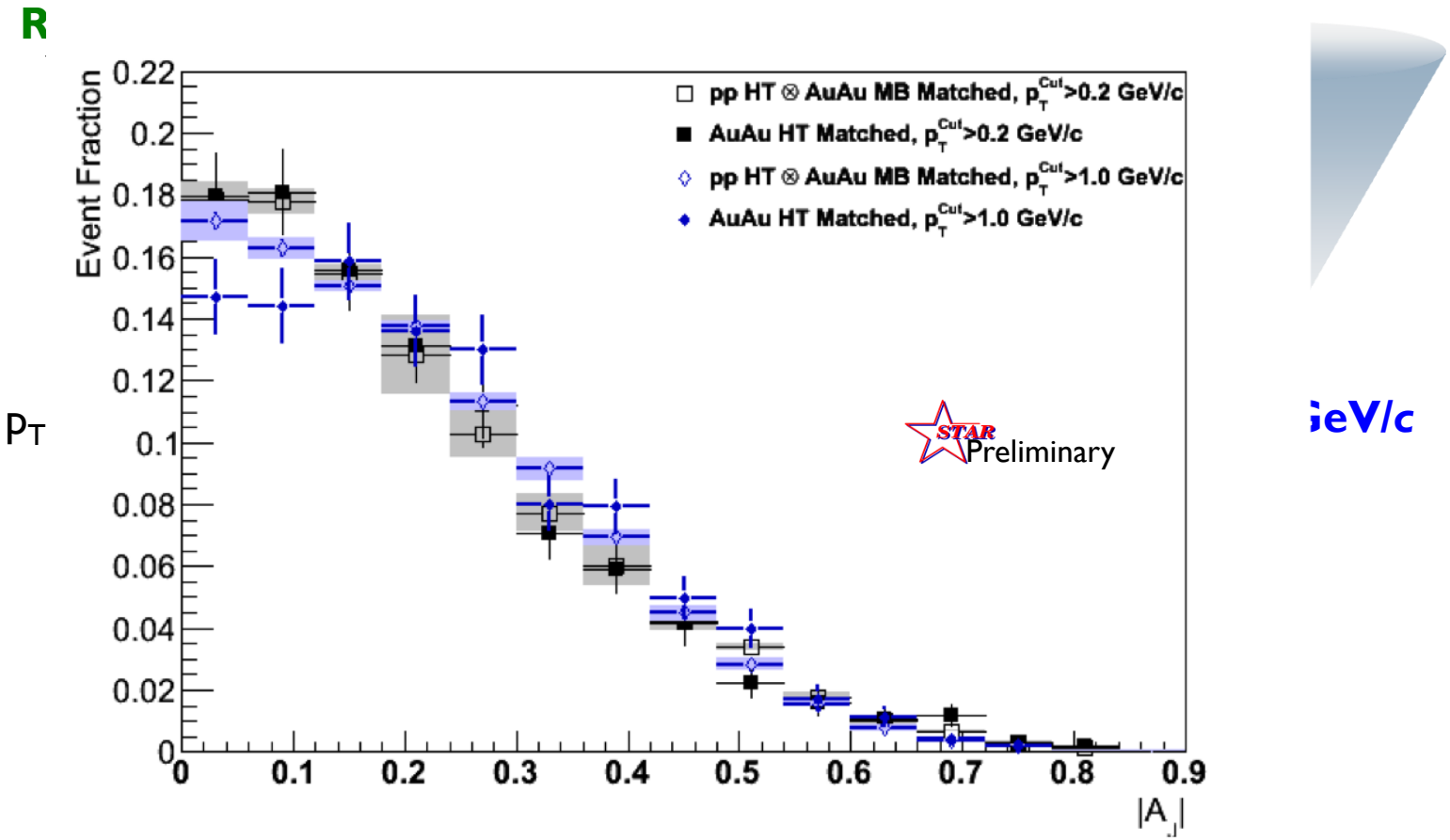
p-value < 10^{-4} (stat. error only)

p-value = 0.8 (stat. error only)

Au+Au di-jets more imbalanced than p+p for p_T^{cut}>2 GeV/c

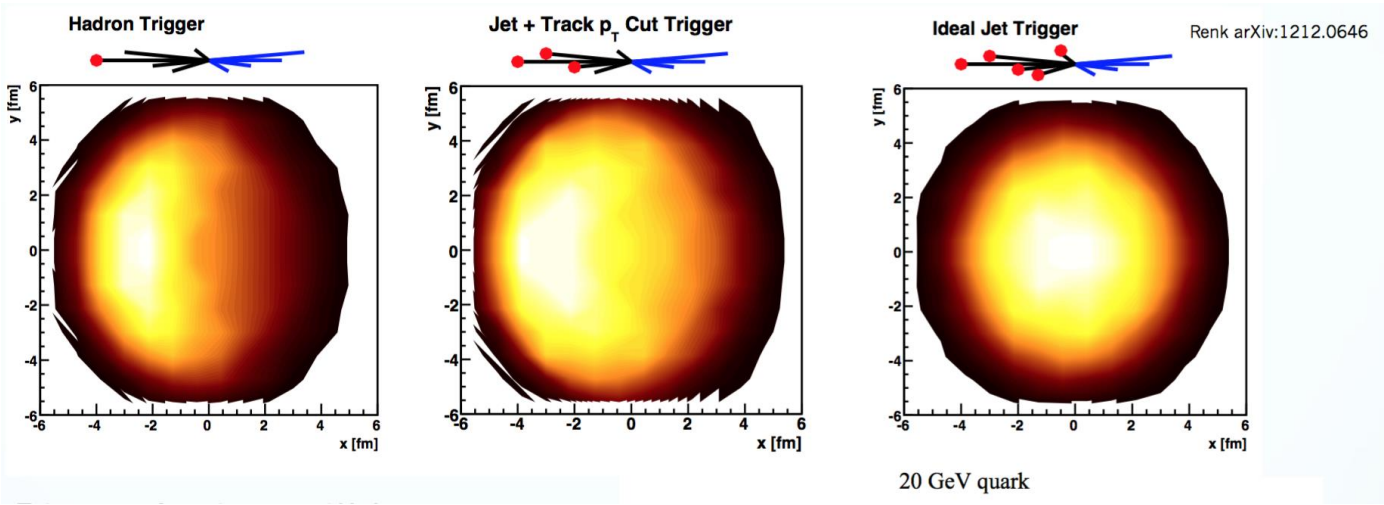
Au+Au A_J ~ p+p A_J for matched di-jets (R=0.4)

Differential Measurements

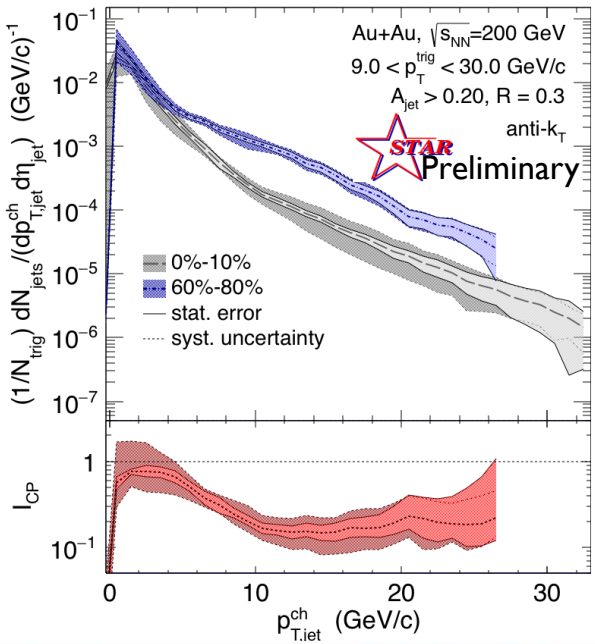


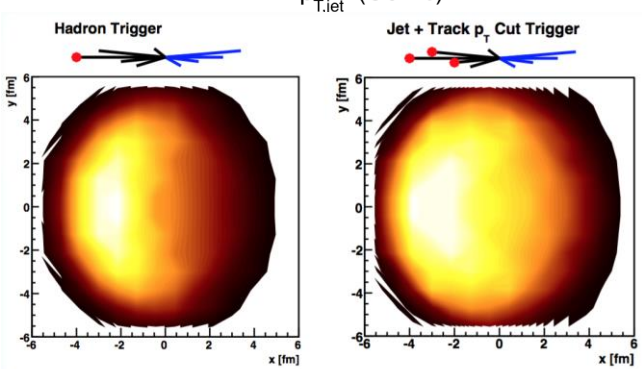
A Consistent (Qualitative) Picture
Focus on: Jet Softening

- All measurements π^0, h-jet, γ^{dir}, A_J, and jet-h consistent with suppression of high-z fragments
  - → Particularly jet-h and A_J suggest balancing at low-z
  - → Near-side is affected differently, but recoil always has long path length
  - → Need to compare at the same parton p_T and hadron z_T

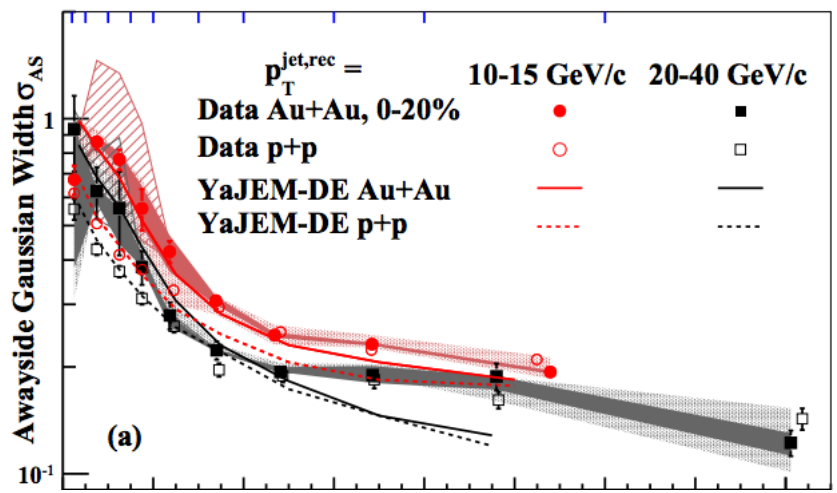


A Consistent (Qualitative) Picture
Focus on: Jet Broadening





- h-Jet: Away-Side Jet cross section of **narrow** jets is suppressed
  → Suggests **broadening** beyond R=0.3
- Differential Di-Jet Imbalance: Broadening



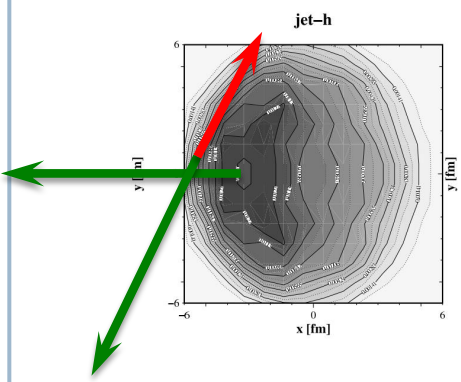
PRL 112 (2014) 12, 122301

A Tool to Control Path Length

Biased Di-Jet A_J: "Lost" energy of the dijets is recovered in a jet of R=0.4 for p_T^{Cut} = 0.2 GeV/c

Interpretation:

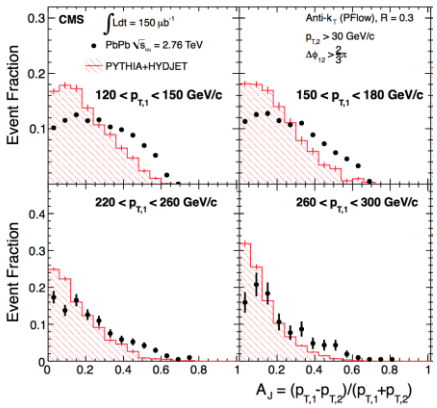
(Constituent) p_T^{Cut} = 2 GeV/c
+ High Tower (5.5 GeV)
+ (Jet) p_T^{Lead}>20 GeV/c
→ Surface Bias



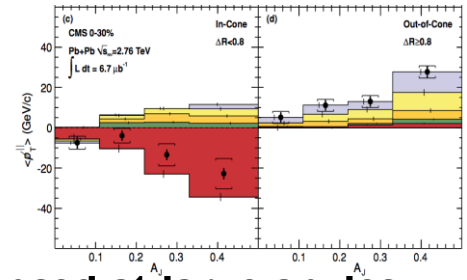
STAR:
p_T^{lead}>15 GeV/c
p_T^{cut}>2 GeV/c
T. Renk, PRC 87, 024905 (2013)

+ (Recoil) $p_T^{SubLead}$>10 GeV/c
→ Path Length Control

Contrast to LHC:

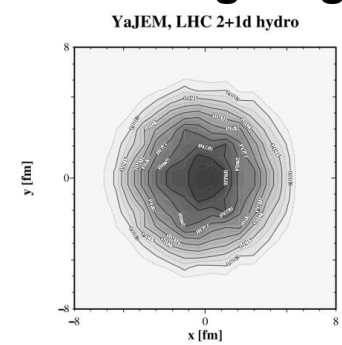


*CMS, PRC **84**, 024906 (2011)*



Large imbalance, balanced at large angles

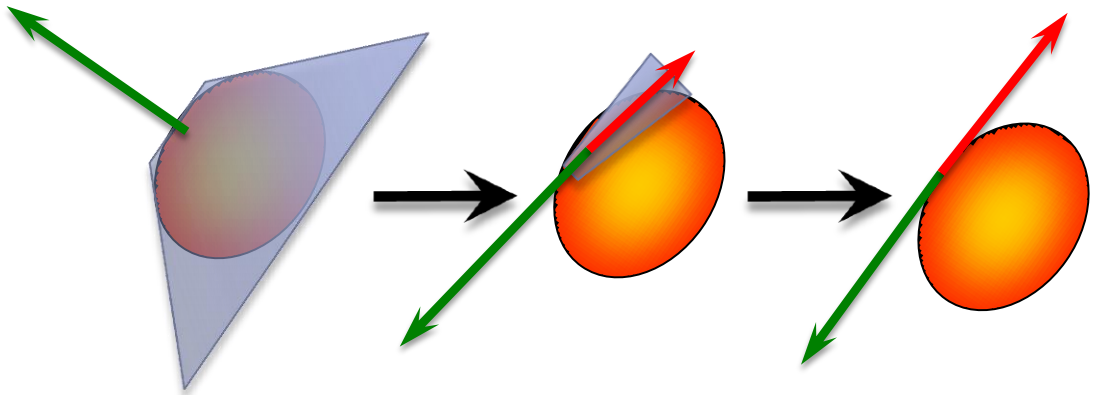
LHC:
A_J Dijet Trigger
T. Renk, PRC 85, 064908 (2012)



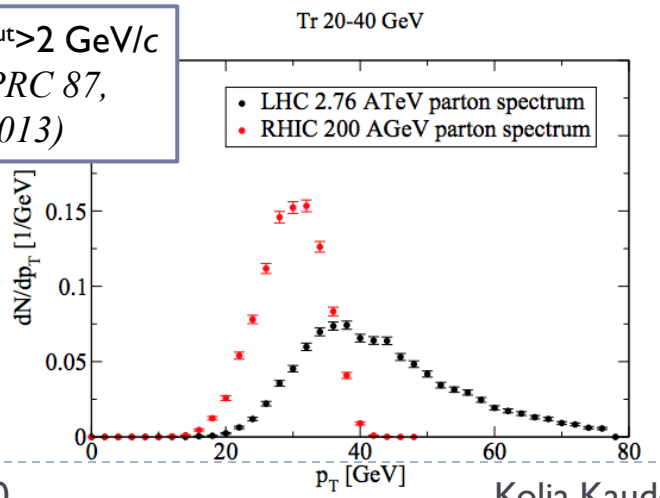
- **"Unbiased" di-jet selection**
  → longer path lengths
  & Larger energy loss at early times
  → more diffusion in medium

Unique Opportunity for **Jet Geometry Engineering** at RHIC

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



R=0.4,p_T^{Cut}>2 GeV/c
T. Renk, PRC 87, 024905 (2013)



A RHIC Strength!
Good correlation between jet and parton energy for these jets

Summary

- Hadron-Jet: Jet reconstruction of recoil jet
  → no fragmentation bias on recoil side
  - Suppression at 20 GeV/c (~0.2) is larger compared to LHC energies (caveat: different R)
  - $\Delta\phi$ shows no difference between central and peripheral, except for lowest p_T (interpretation needs more studies)

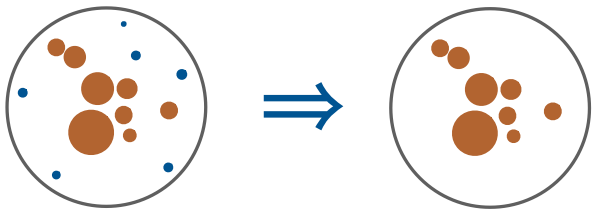
- A_J: Jet reconstruction of leading and recoil jet
  → Energy loss *jet-by-jet* instead of ensemble-based
  - "Lost" energy seems **contained within R=0.4 and low p_T**
  - Imbalance remains for smaller cone or higher constituent cutoff

    → Observed **Broadening** and **Softening** *jet-by-jet*

Bonus Slides

Bonus: Soft-Drop Grooming

- Remove wide angle soft radiation

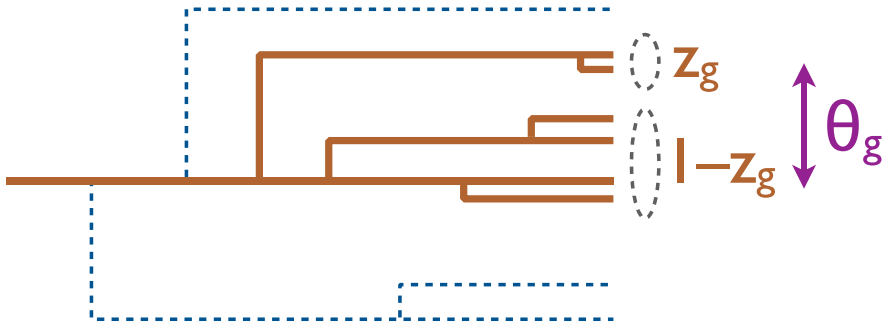


Soft Drop Condition:

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

energy threshold

angular exponent



Based on declustering an angular-ordered tree

Interesting for:

- groomed energy, groomed radius
- *pp*, jet mass, …
- Focus here:

"Groomed Momentum Sharing"

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

p_T fraction carried by smaller sub-jet after grooming

J. Thaler
ALICE Jet Workshop, Yale

Larkoski et al.,
Phys. Rev. D 91, 111501 (2015)

Measuring the AP Splitting Function

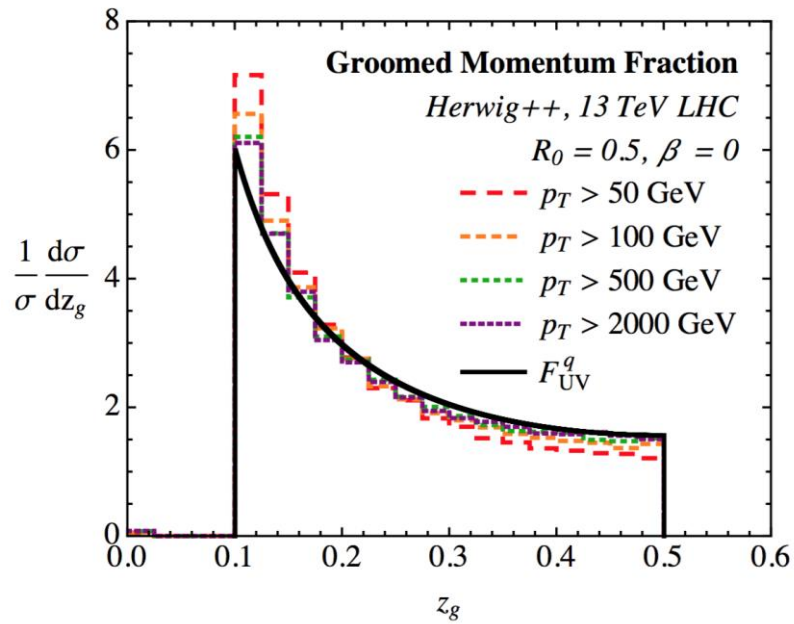
Role of β:
β>0 - IRC safe
β<0 - (IR)C unsafe
β=0 - IRC unsafe – but Sudakov-safe

$$\text{For } \beta = 0, z_g > z_{\text{cut}} :$$

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

P_i: Appropriate Altarelli-Parisi splitting function (symmetrized)

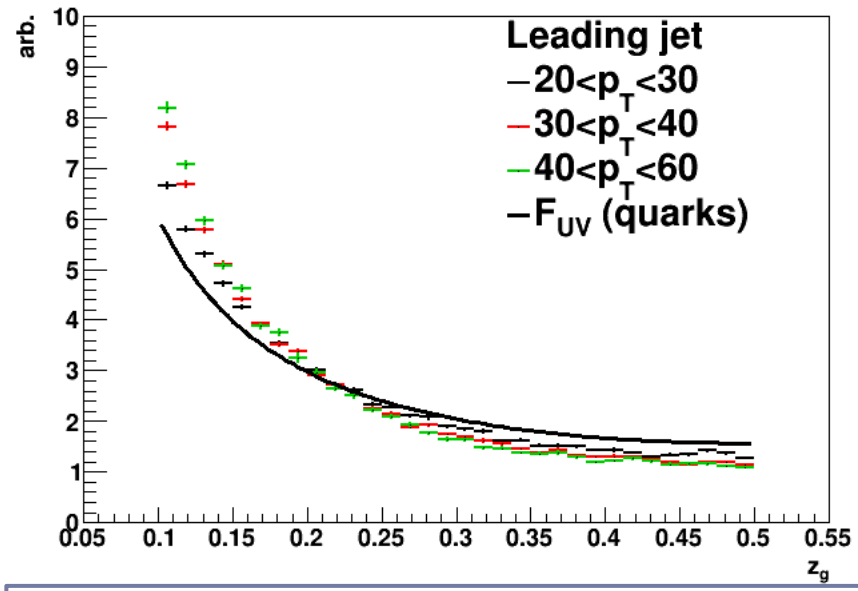
(q->qg, g->gg, g->qg)

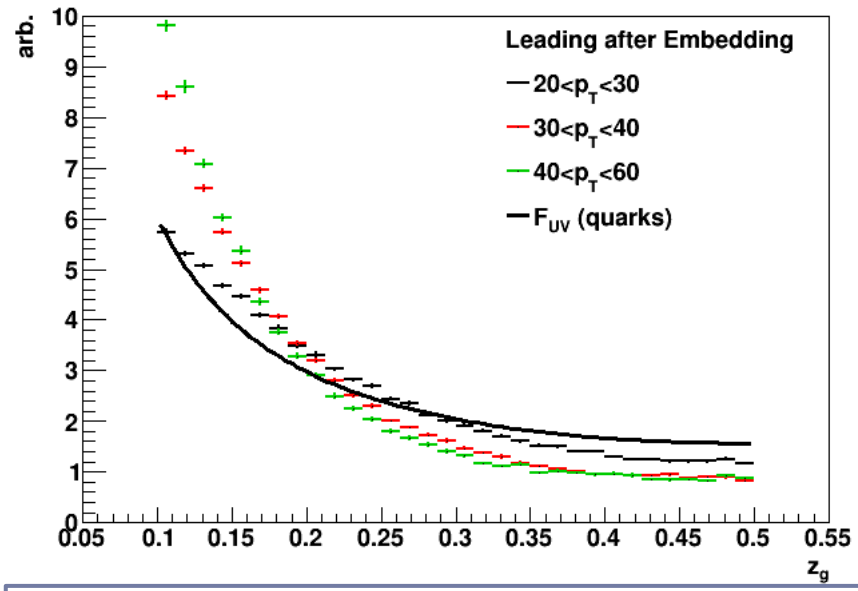


~ independent of α_s
~ independent of p_T (in UV limit)

~ same for quarks and gluons
~ weak p_T dependence at RHIC

PYTHIA @ RHIC





PYTHIA8 *pp* at 200 GeV
Leading anti-k_T Jets, R=0.4
reclustered with C/A

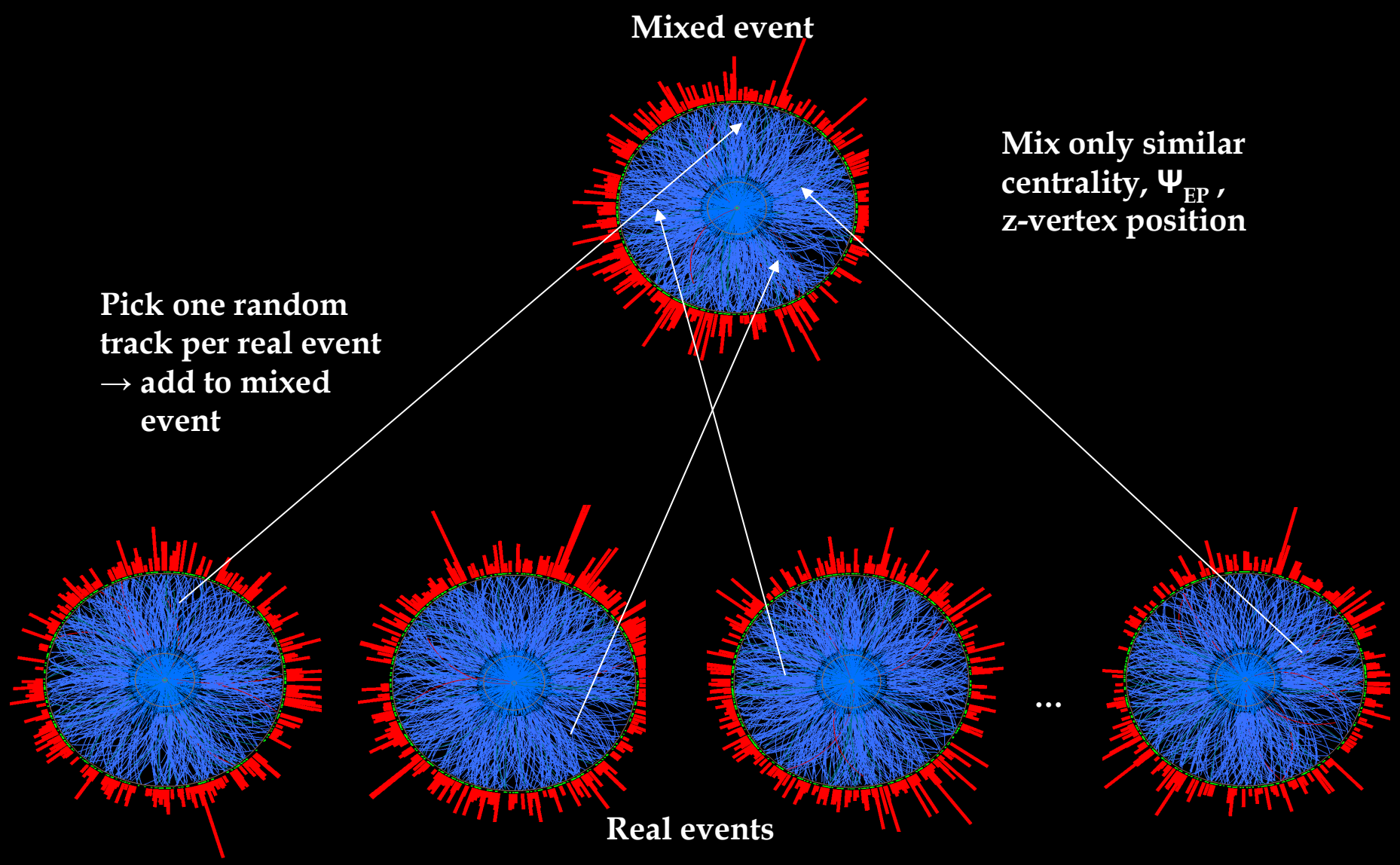
- Some difference from theory
  - maybe due to "small" R
- Z_g becomes p_T-indep. above 30 GeV

Same jets embedded
Fake Au+Au mocks up multiplicity, spectra, energy densiy

- Fairly benign background effect
- Shape and mild p_T dependence good for unfolding

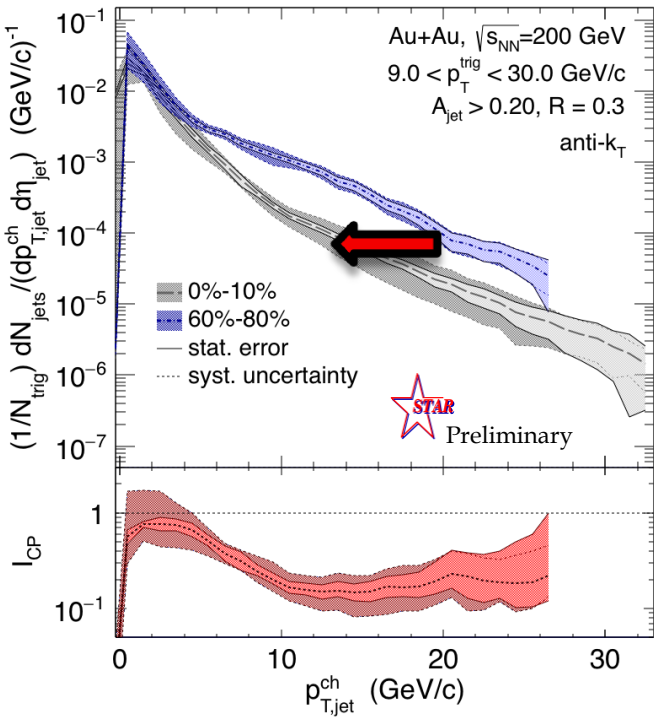
Backup

Mixed Event Generation for Jets

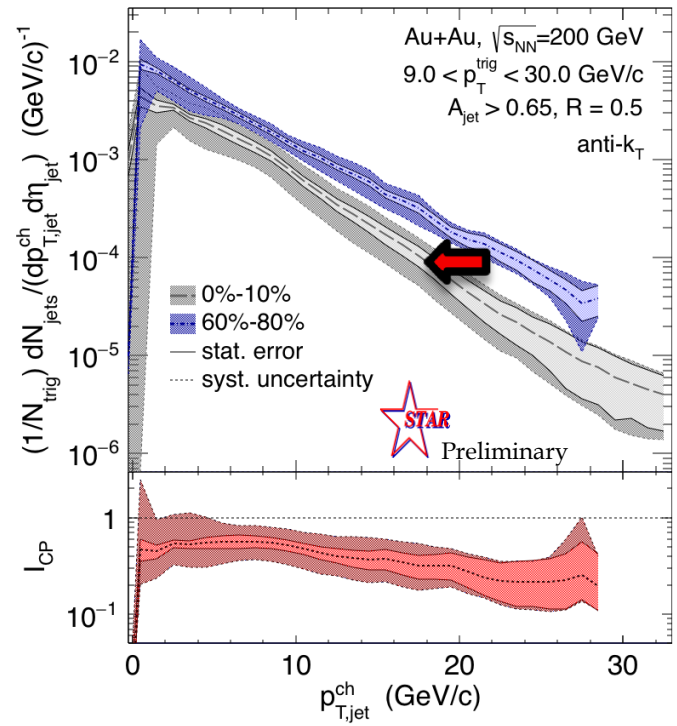


Recoil yield suppression

R=0.3



R=0.5



Calculate spectrum shift

- requires distributions ~ exponential, ratio ~ flat

Spectrum Shift Periph/pp ➔Central			
	$p^{ch}_{T,jet}$ range [GeV]	**Shift R=0.3 [GeV]**	**Shift R=0.5 [GeV]**
Au+Au @ 200 GeV	[10,20]	**-6.3** ± 0.6 ± 0.8	**-3.8** ± 0.5 ± 1.8
Pb+Pb @ 2.76 TeV *ALICE arXiv:1506.03984*	[60,100]		**-8** ± 2

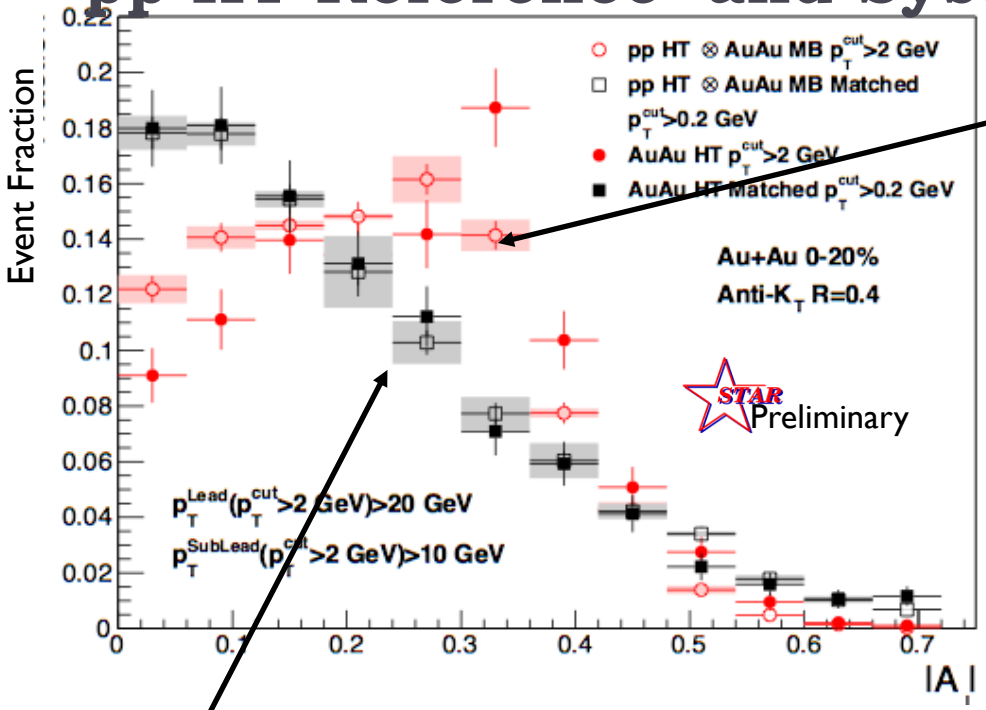
RHIC: smaller shift for larger R

R=0.5: smaller shift at RHIC than LHC

Out-of-cone energy transport ?

- comparison requires similar trigger bias ➔ theory calculation

pp HT Reference and Systematic Errors



Reference:

pp HT ⊗ AuAu MB

Embed pp HT randomly into AuAu 0-20% minimum bias event, adjusted for relative tracking efficiency between pp HT Y06 and AuAu HT Y07

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

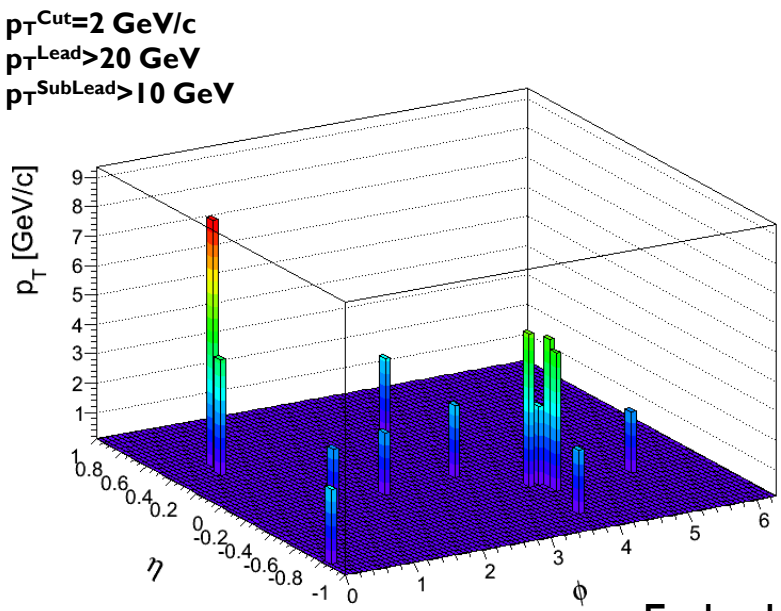
Systematic Uncertainties (Analogous to Jet-Hadron Corr.)

- Tracking efficiency uncertainties 6%
- Relative Tower energy scale uncertainty 2%
- Background/vn: Null-Hypothesis Method1 vs. Method2
- Remaining uncertainties negligible

Null-Hypothesis: Balance Restored by Uncorrelated BG?

Method 1: Random Cone (RC):

Take di-jet pair p_T^{Cut}>2 GeV/c (w/o low p_T)



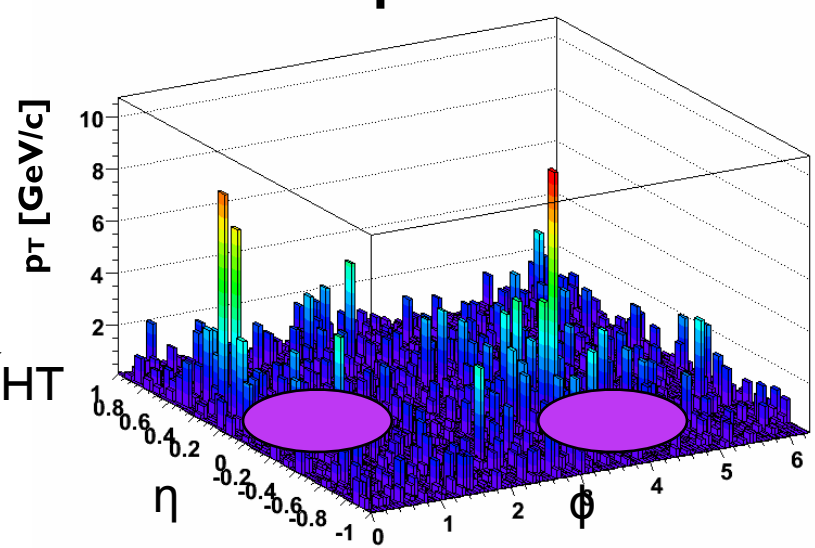
Embed randomly the two Jet vectors into a central Au+Au MB event

Calculate $|A_J|$ with p_T^{Cut}>0.2 GeV/c using cone of R

Method 2: EtaCone (EC):

Take di-jet pair p_T^{Cut}>2 GeV/c (w/o low p_T)

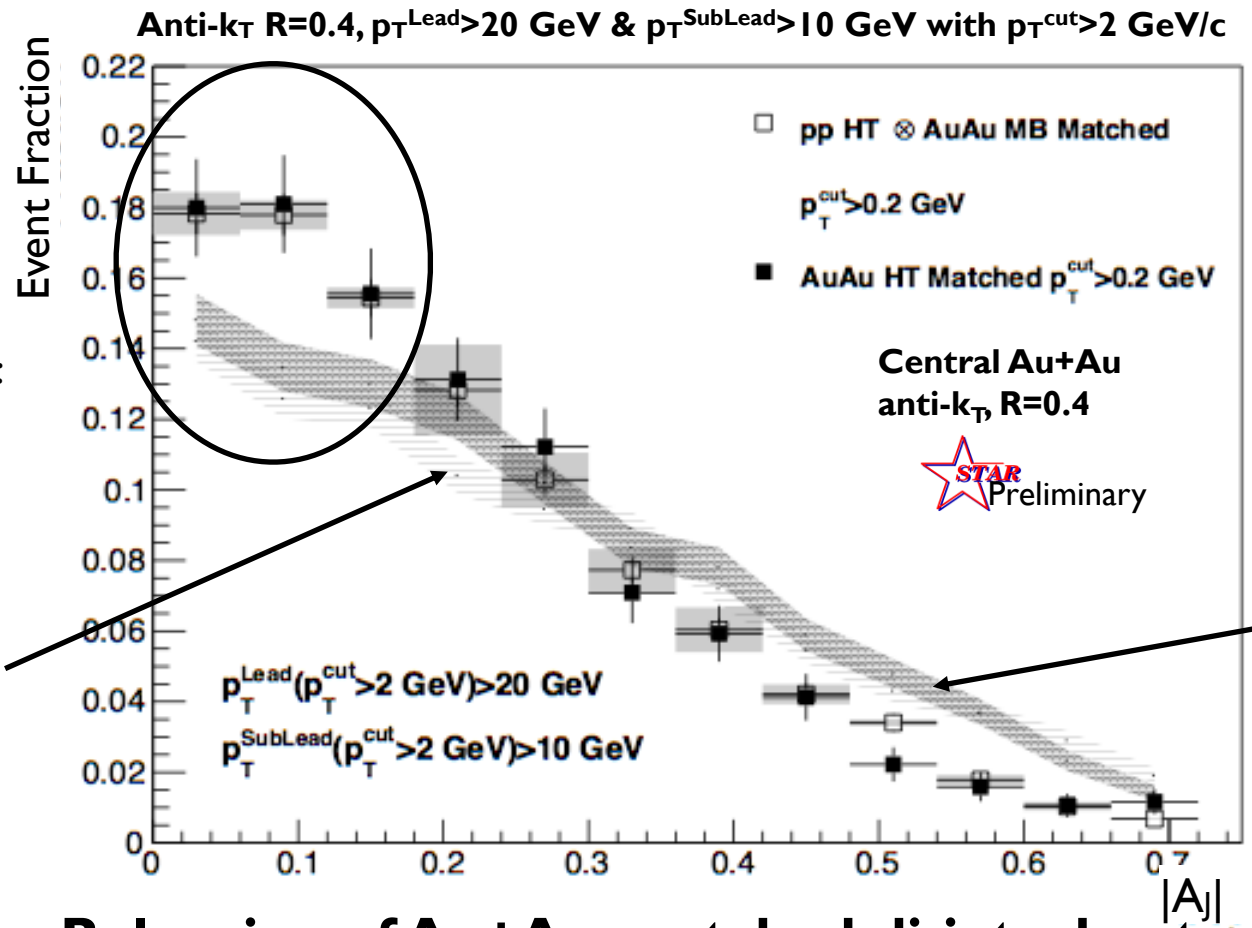
Embed the two Jet vectors into a Au+Au HT event, 2R away from reconstructed di-jet pair in that event



Effect of Background Fluctuations

Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

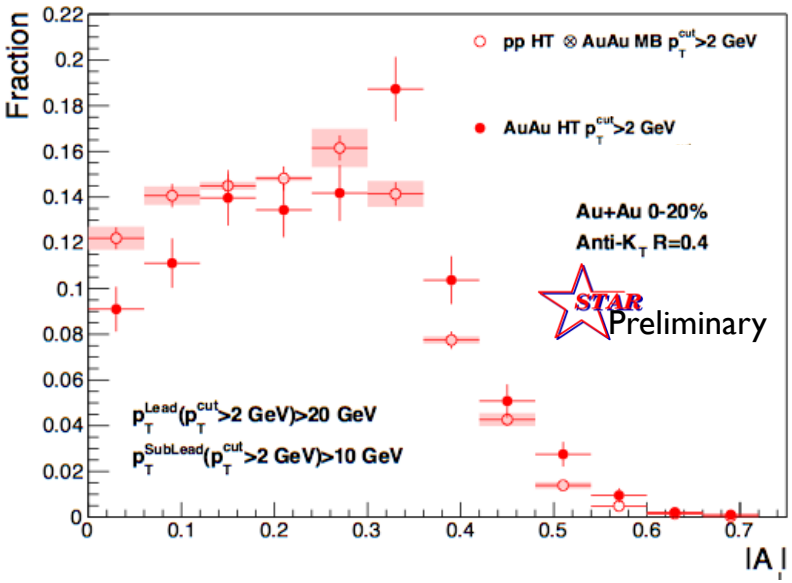
Method 1 (RC)

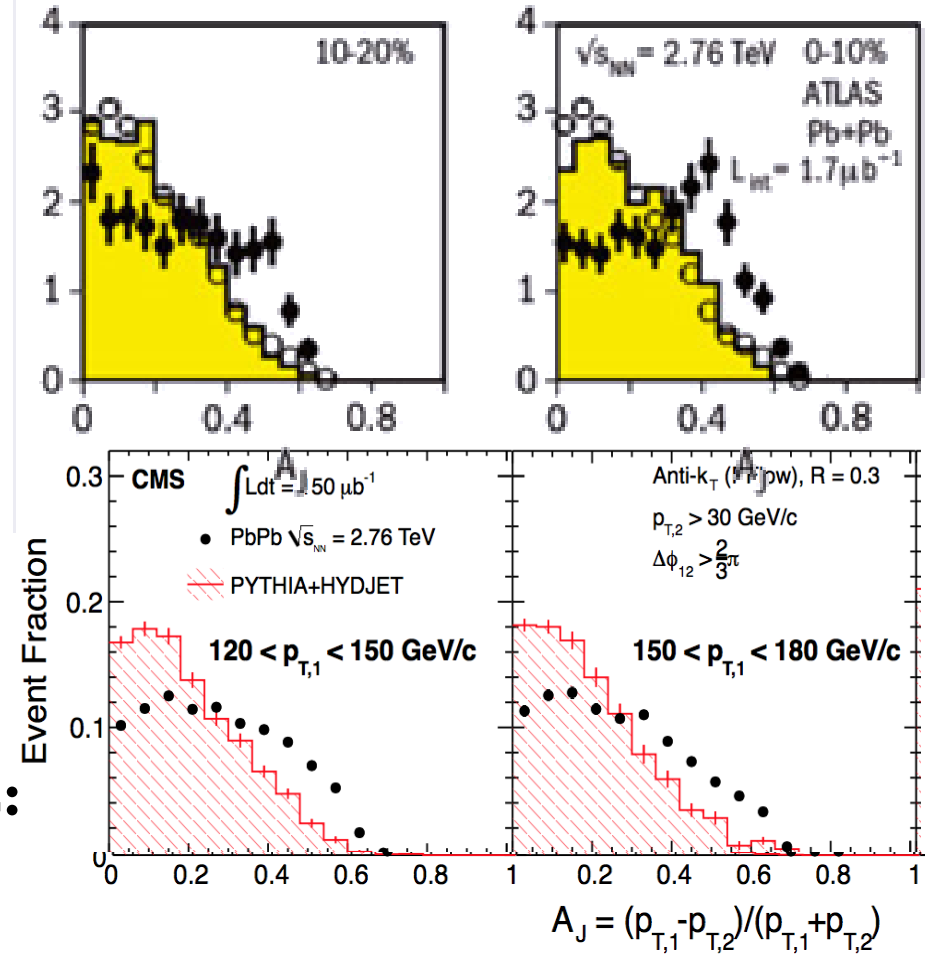


Method 2 (EC)

Balancing of Au+Au matched di-jets due to correlated signal yield in a cone of R=0.4

Contrast and Compare



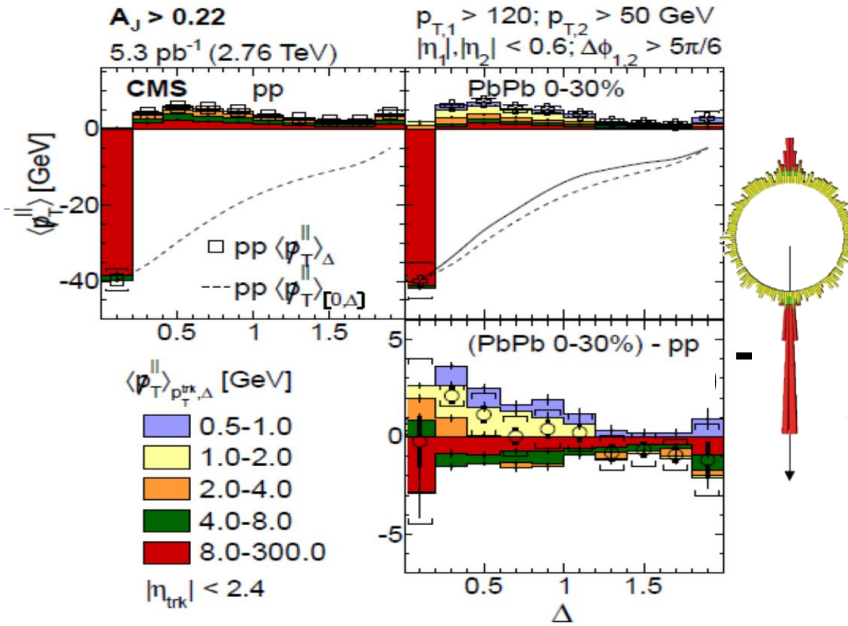


"Hard Core": Similar to LHC:

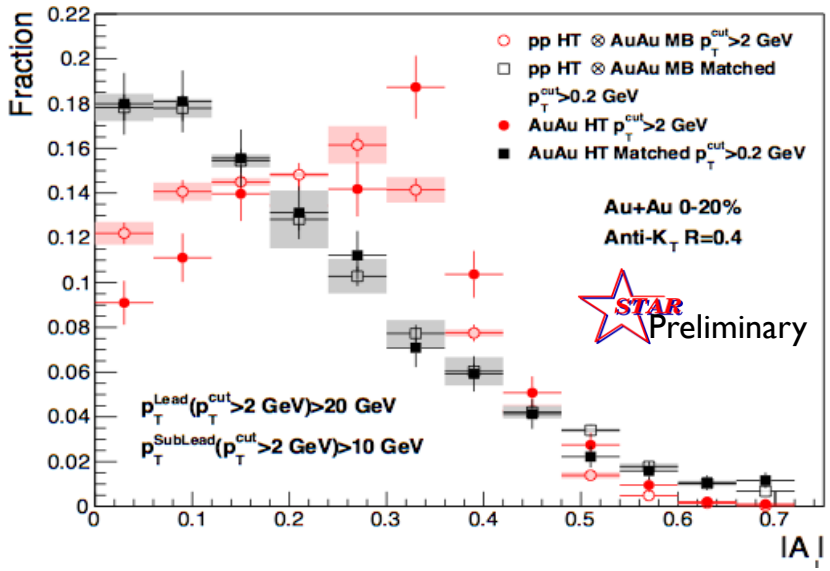
clear imbalance compared to *pp*

ATLAS, PRL ***105****, 252303*
CMS, PRC ***84****, 024906 (2011)*

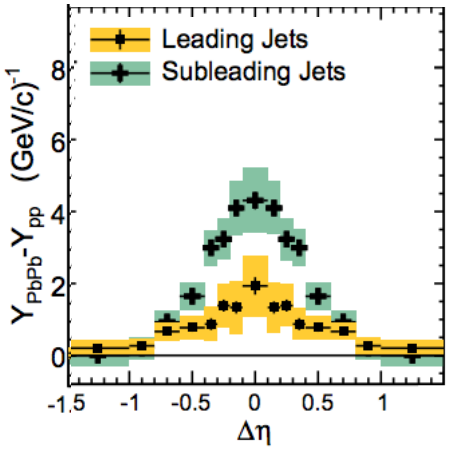
Contrast and Compare II Missing Energy



LHC: Shifted to large angles



RHIC: Contained in R=0.4
Shifted to lower p_T



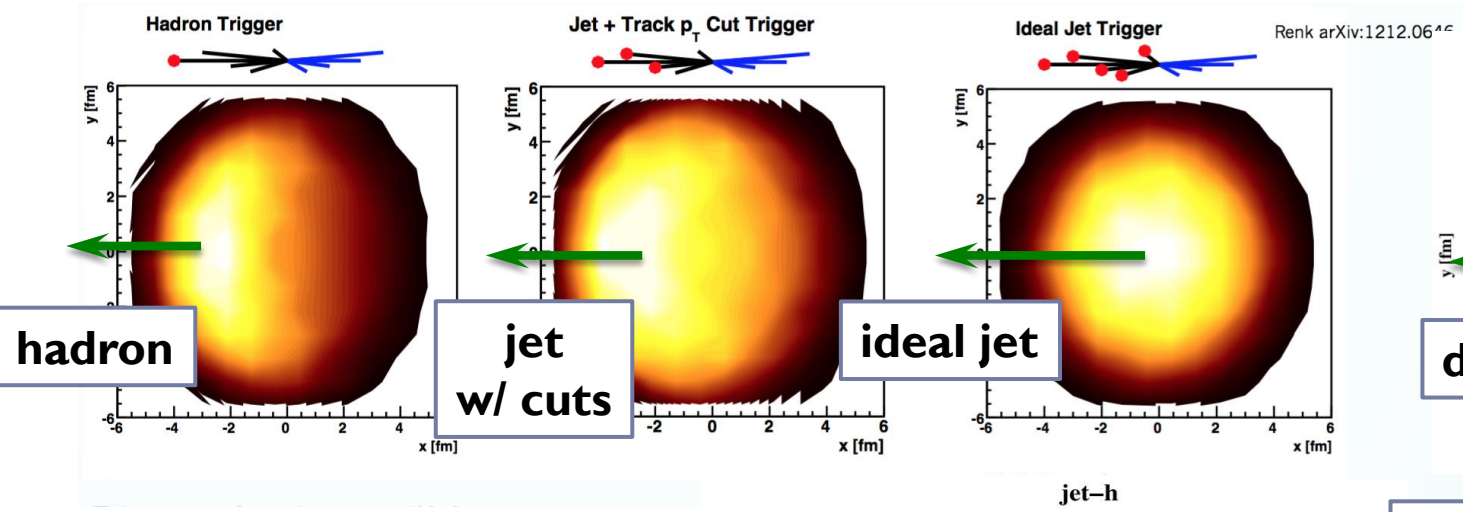
Jet-like yield out to |ΔR|~1

CMS, JHEP 01 (2016) 006
CMS, JHEP 1602 (2016)

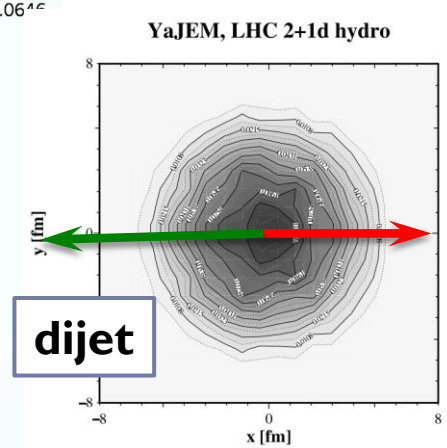
Geometric Biases

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

STAR

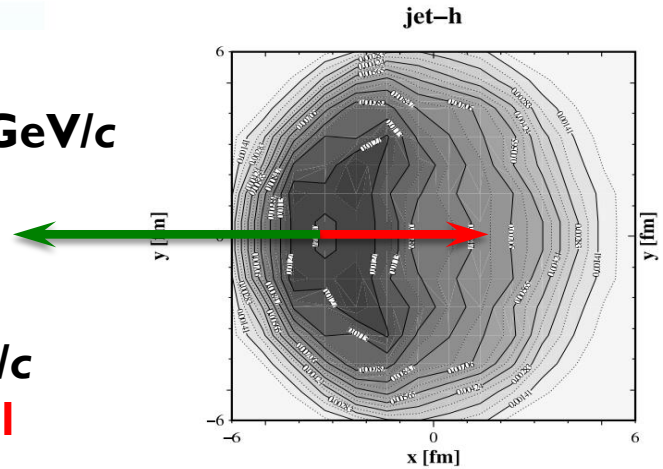


LHC Dijets



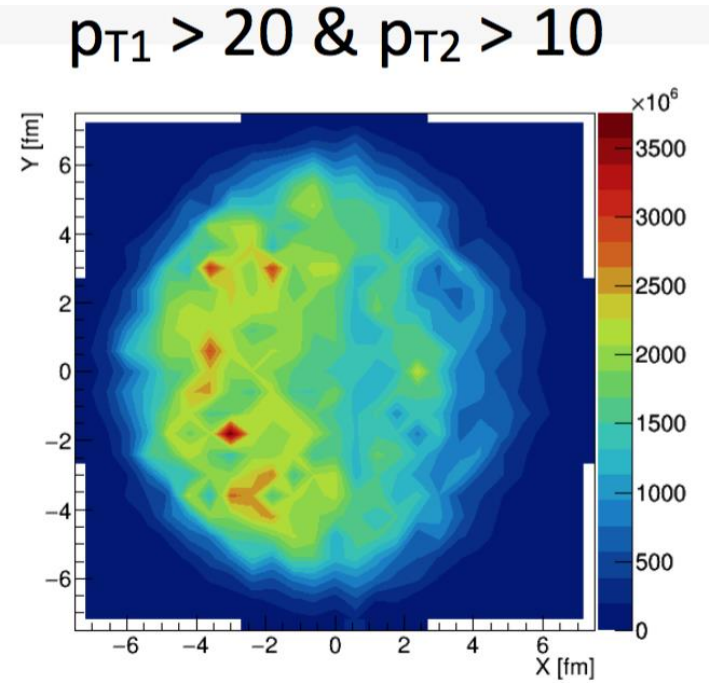
STAR Interpretation:

(Constituent) p_T^{Cut} = 2 GeV/c
+ High Tower
+ (Jet) p_T^{Lead}>20 GeV/c
→ Surface Bias
+ (Recoil) $p_T^{SubLead}$>10 GeV/c
→ Path Length Control



LHC:
"Unbiased" di-jet selection
→ longer path lengths & larger energy loss at early times
→ more diffusion in medium

YaJEM Calculation for STAR Dijets (First Look)



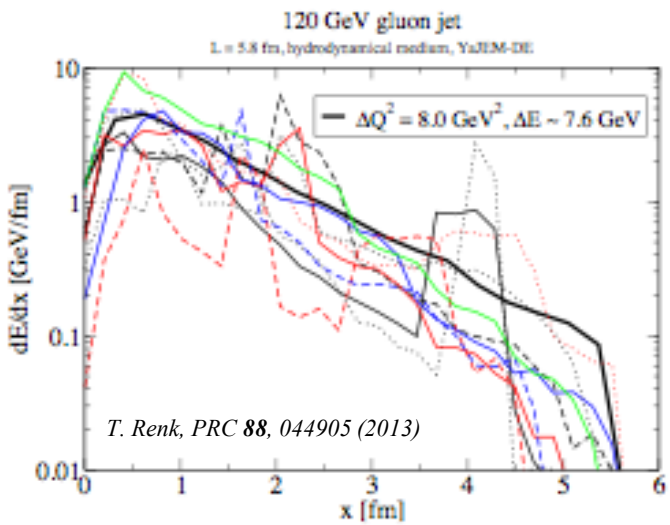
Courtesy of Kirill Lapidus

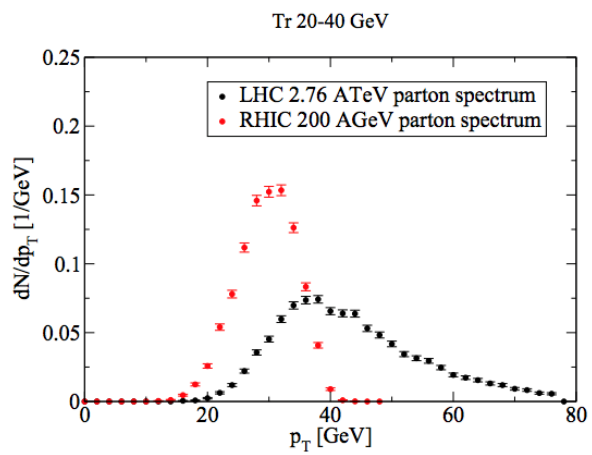
1D hydro
R = 0.4
constituent bias 2 GeV
5.5 hard track in either of two jets back-to-back

Signs of creation hot spots shift by 2-4 fm

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

RHIC vs LHC





LHC:

Larger energy loss at early times
→ more diffusion in medium
→ larger angles

RHIC:

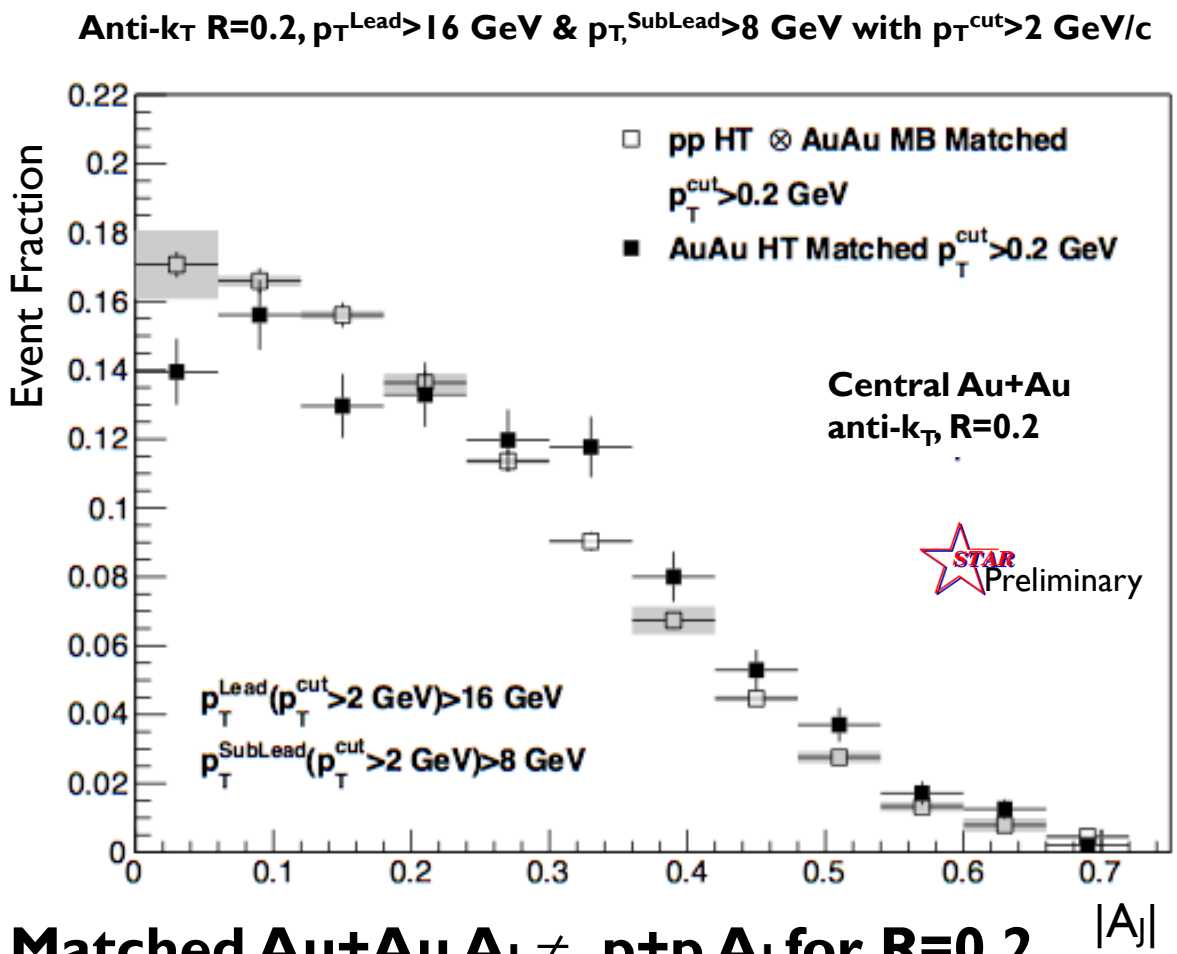
Quenched energy closer to initial parton/jet direction. Can utilize biases for systematic exploration.
→ (easier) to study soft gluon radiation

RHIC Advantage:
Steeply falling spectrum
→ Good correlation between jet and original energy

R=0.4,p_T^{Cut}>2 GeV/c
T. Renk, PRC 87, 024905 (2013)

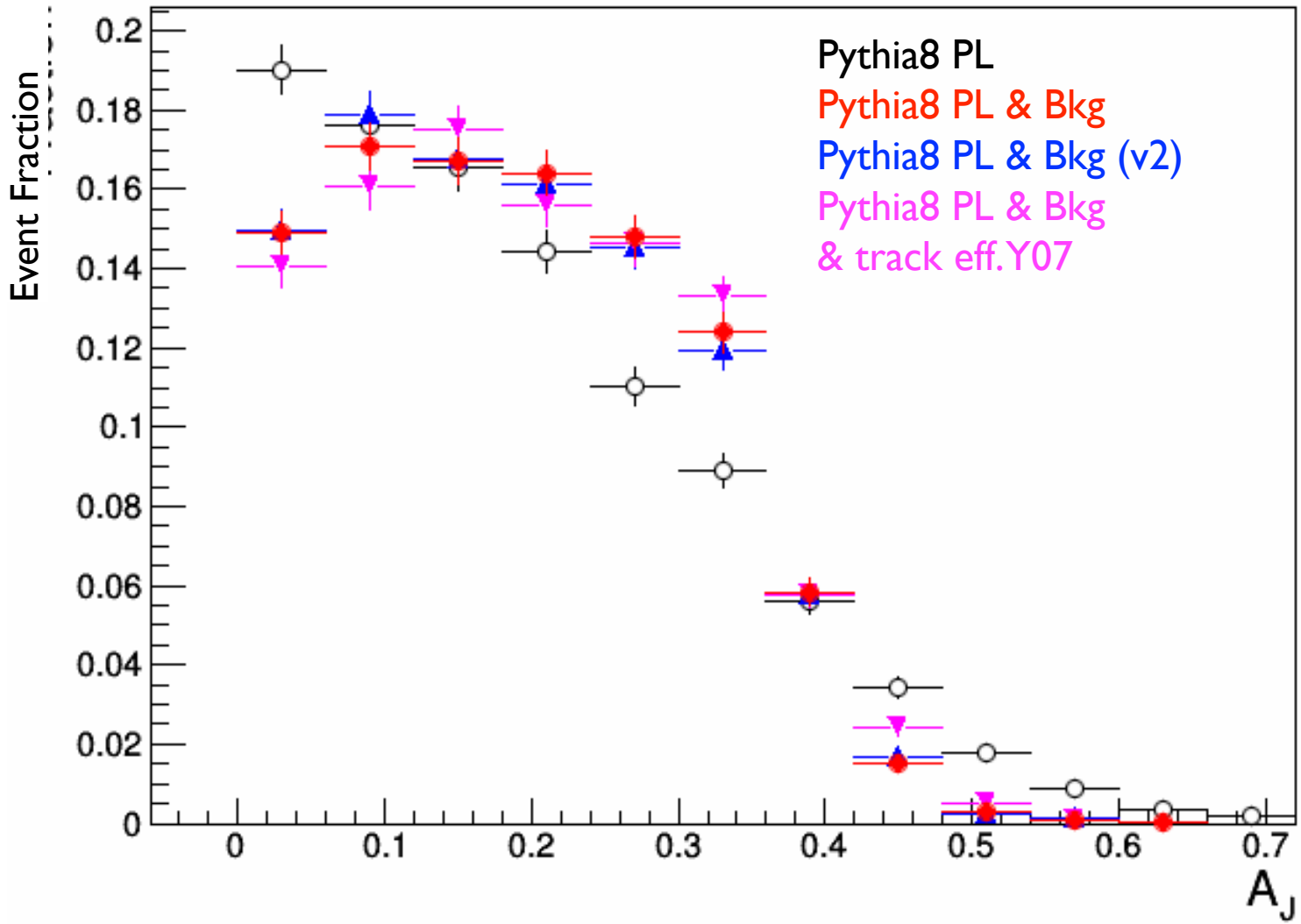
Di-Jet Imbalance A_J
Central Au+Au, R=0.2

Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%



p-value < 10^{-10} (stat. error only)

p-value < 10^{-4} (stat. error only)

Matched Au+Au $A_J \neq$ p+p A_J for R=0.2
→ (recoil) Jet broadening in 0.2 − 0.4

PYTHIA8 Particle Level (PL) and Toy Bkg. Model