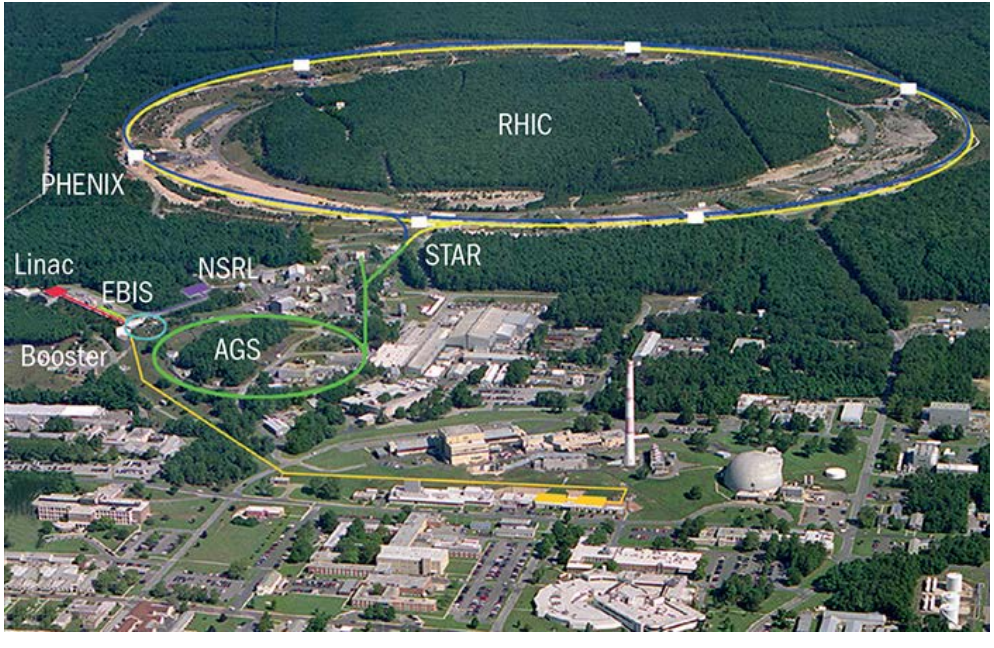
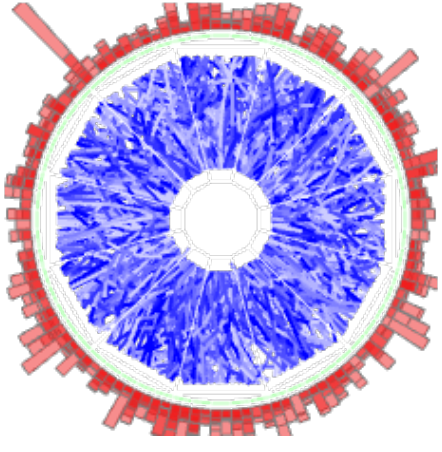
Jet Substructure Measurements in STAR

Kolja Kauder



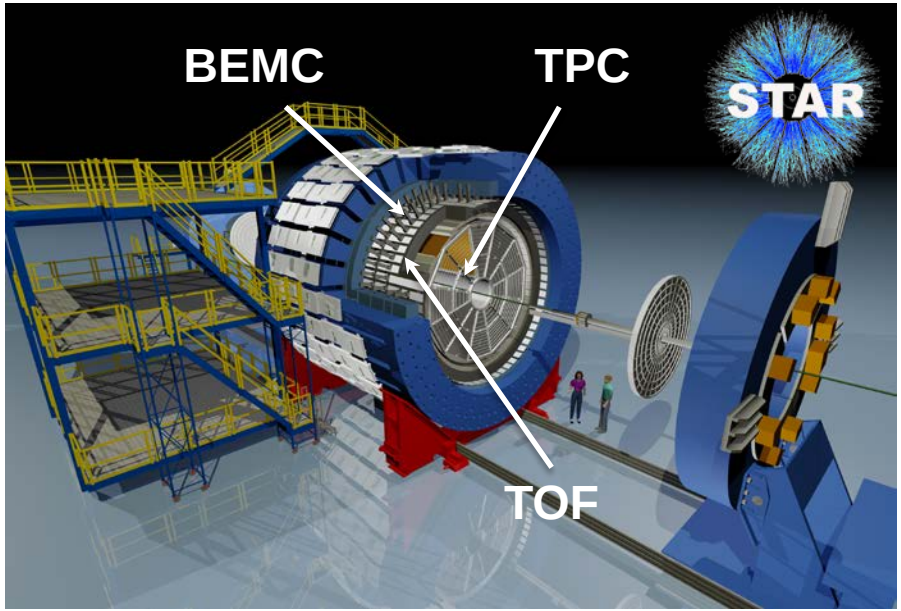


RHIC & AGS Users' Meeting 2018, BNL

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

The Solenoidal Tracker at RHIC



Core Systems for Jets:

- **$2\pi \times |\eta| < 1$ acceptance:**
  charged particles (TPC)
  neutral particles (BEMC)

Additional Capabilities:

Particle ID:

- Charged (TPC dE/dx, TOF)
- γ identification (BSMD)
- Heavy flavor (HFT)

→ *See A. Jentsch, Wed 9am*

Many collision systems small and large

Muons (MTD)

Event Plane (EPD) NEW

…

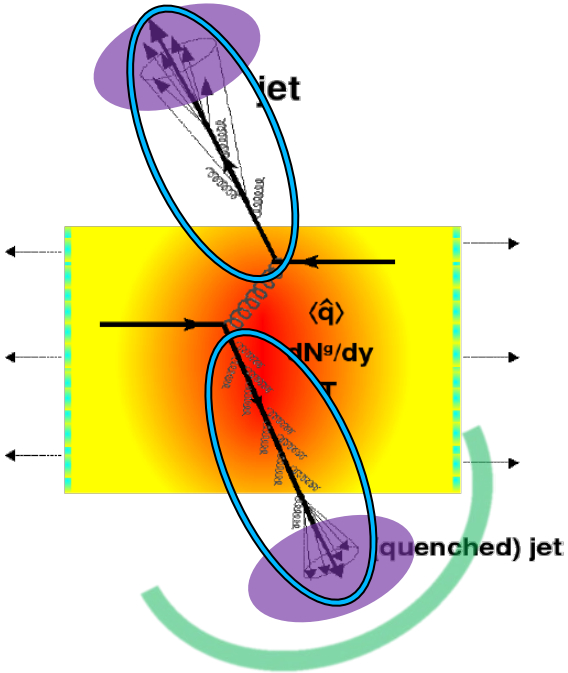
Jets and Jet Substructure in HIC

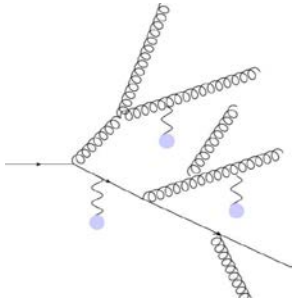
Traditional Questions: **Energy Flow**

- How much energy is (left) in the jet?
- And where did it go?

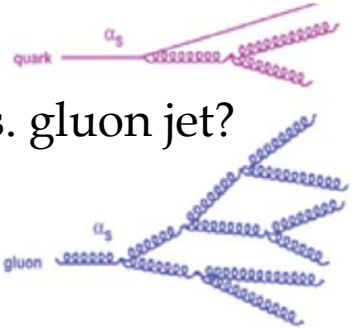
Substructure: **Focus on Shower**

- Where did energy flow **inside** the jet?
- Is the shower modified?

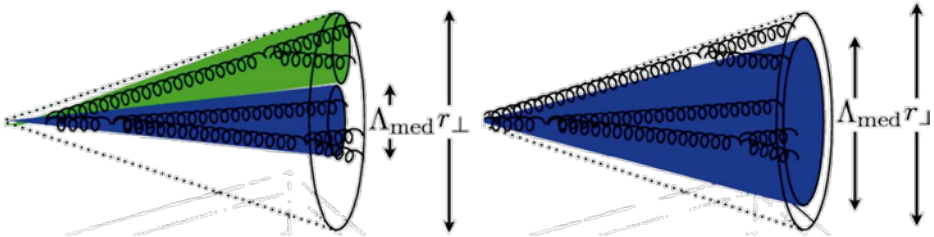




Splitting kernel?

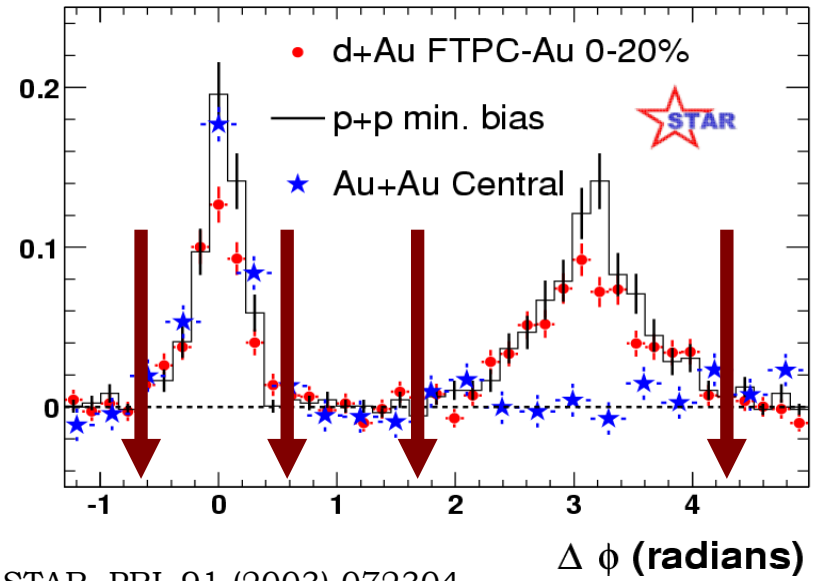


Quark vs. gluon jet?

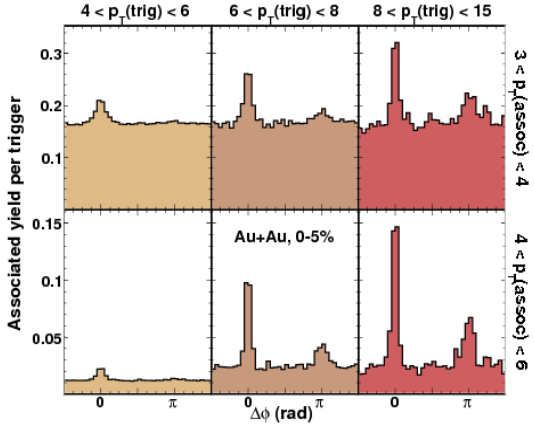


De-coherent vs coherent E-loss?

"Jet" "Substructure"



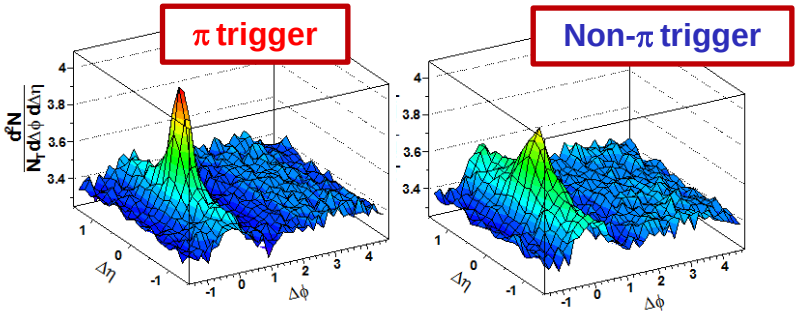
STAR, PRL 91 (2003) 072304



STAR, PRL 97 (2006) 162301

Narrow, vacuum-like Dijets

STAR, PLB751 (2015) 233-240

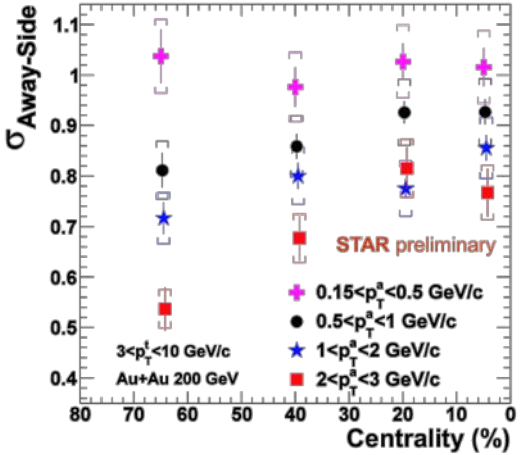


- Narrow, vacuum-like Near-Side
- Broadened, softened Away-Side

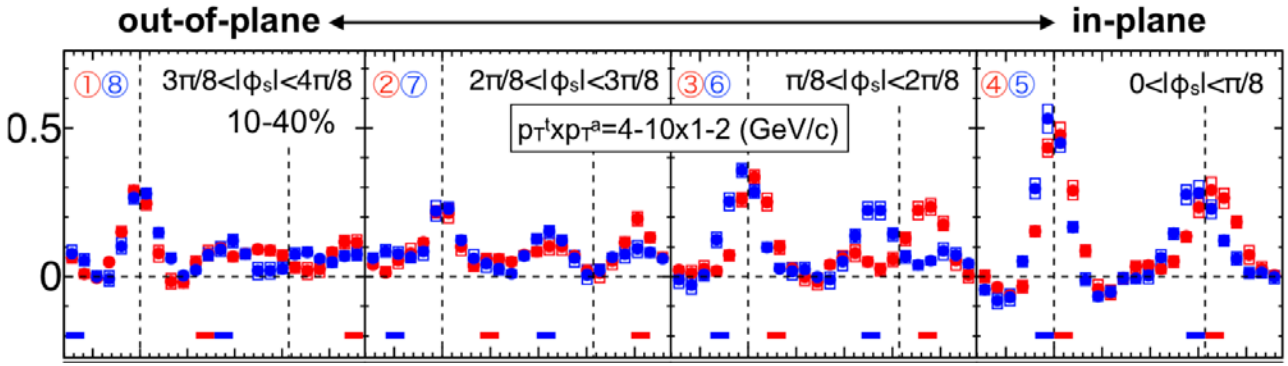
Broader NS for non-π triggers could access quark/glue difference

Recent Di-hadron Results

Kun Jiang, QM2018

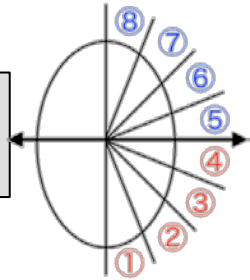


Ryo Aoyama, QM2018



- Away-Side broadening after flow subtraction

- Strong AS deformation as a function of Event Plane (and Shape)



Di-hadron correlations offer great insights into jet substructure - but here we will focus on reconstructed jets

Jet Reconstruction

Sequential Clustering:

1. Calculate a **distance d_{ij}** between two particles and a **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 and j. If it's a d_{iB}, call particle i a **jet**
4. Repeat from step 2 until no particles are left

De-facto standard. For substructure: also provides **cluster history**

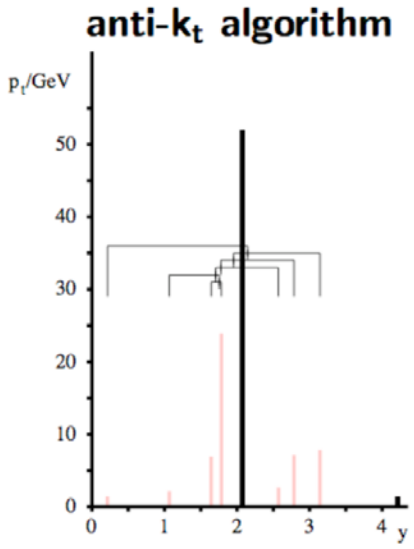
Resulting clusters are **jets**.

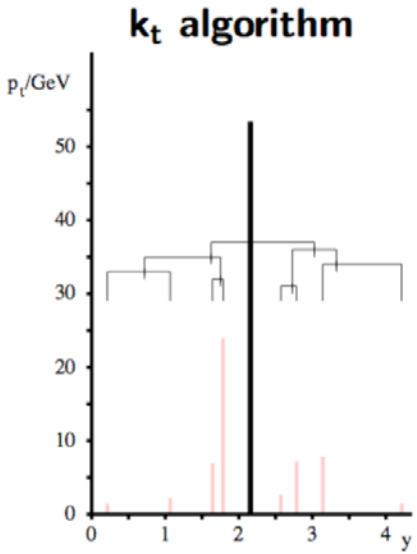
- **Operational** definition. No unambiguous jet definition exists!

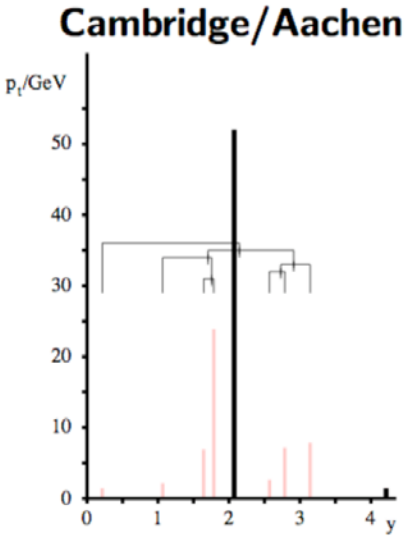
Advantages:

- 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

Distance Measures $d_{ij} = f(p_{T,i}, p_{T,j})\,(\Delta y^2 + \Delta\phi^2) / R^2$







$f = \min(1/p_{T,i}^2, 1/p_{T,j}^2)$

- merge to **hardest**
- seed on "real" jets
- circular leading jets

$f = \min(p_{T,i}^2, p_{T,j}^2)$

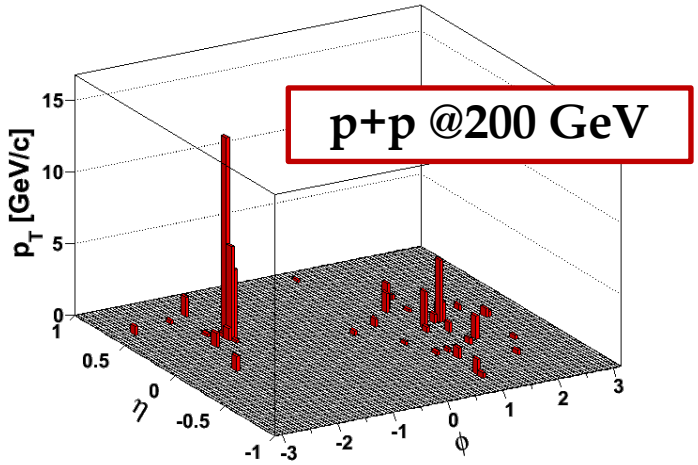
- merge to **softest**
- good characterization of "background" jets

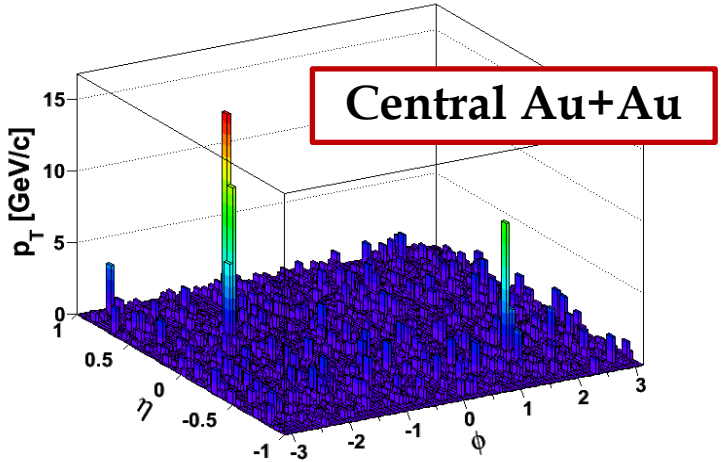
$f = 1$

- merge to **closest**
- angular ordering → relevant later!

M. Cacciari , HP '16

Jets in Heavy Ions



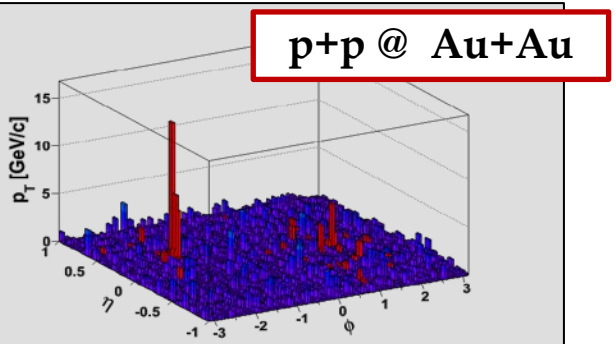


Pedestal Subtraction:

- **Area-based**: $p_T^{\mathrm{Jet}} = p_T^{\mathrm{rec}} - \rho A$
- Substructure: Some observables sensitive to soft, large angle radiation → exploring alternatives (e.g. **constituent subtraction**)

Fluctuations:

- Response from Embedding:



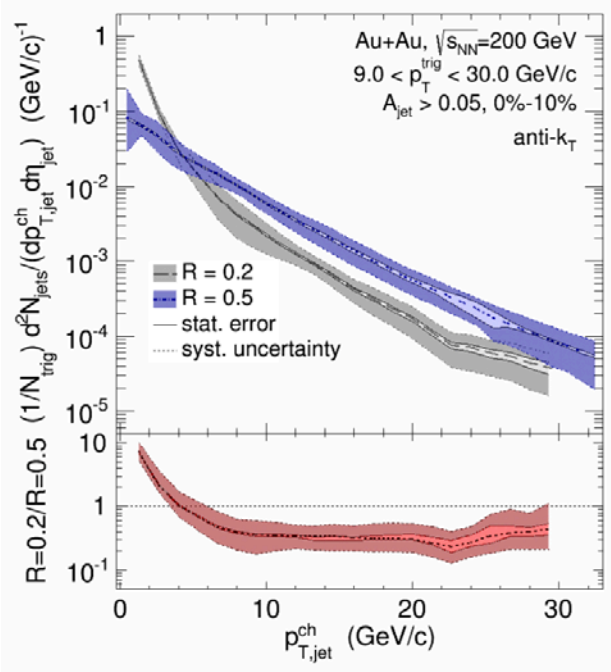
- Compare at **detector level**
- Or **unfold to particle level**
  … if possible

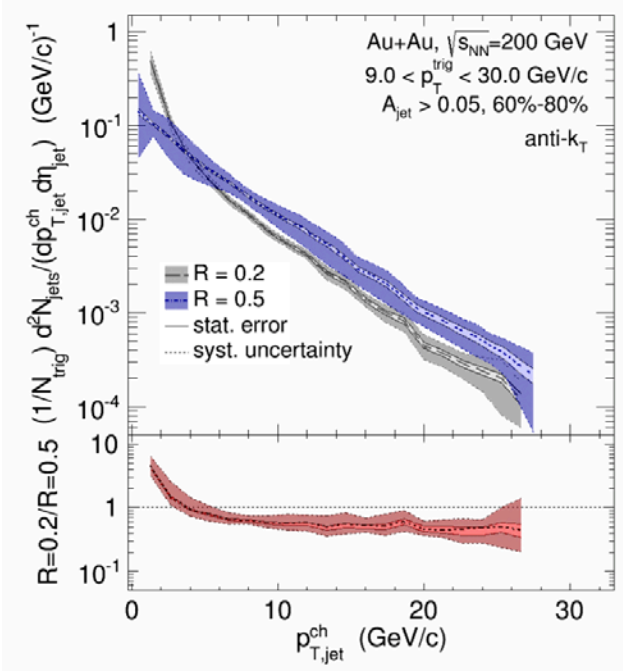
Hadron+Jet "Substructure" (Shape)

0-10%

R=0.2 vs. R=0.5

60-80%





NB: STAR/ALICE approach to **jet shape**, ALICE, PLB 722, 262 (2013)

Compare and contrast to: CMS, PLB 730, 243 (2014)

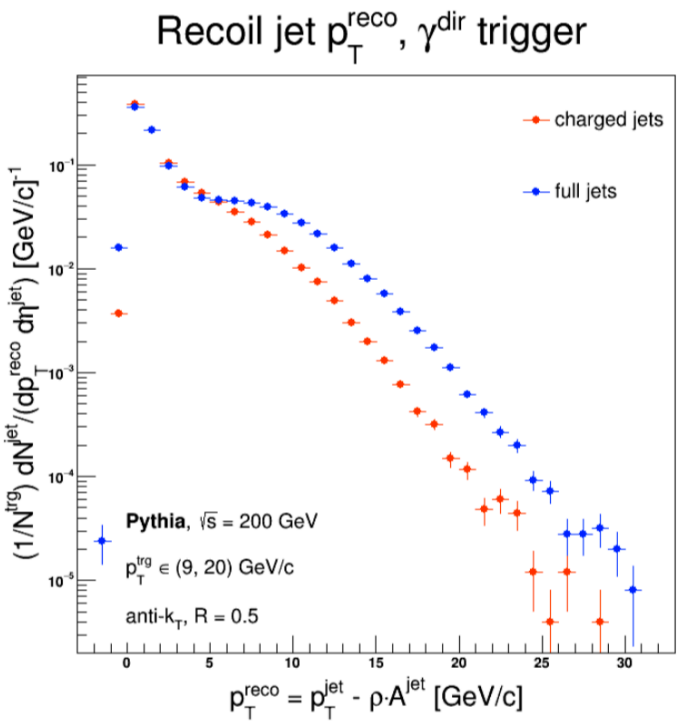
ATLAS, EPJC77, 379 (2017)

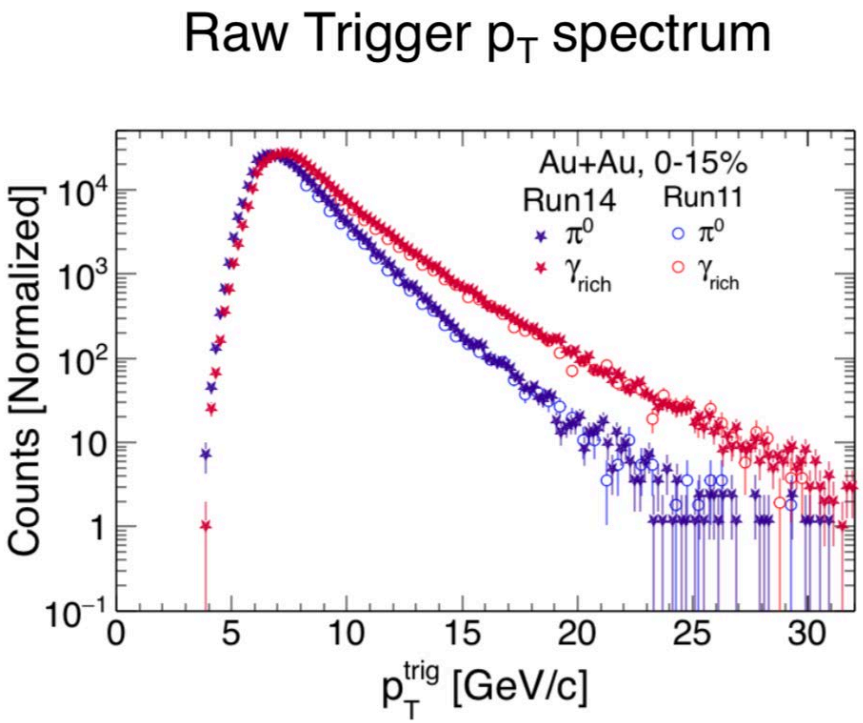
- Medium-induced broadening between R=0.2 and R=0.5

STAR, PRC 96 (2017) 24905

See also N. Elsey, this morning

Outlook: γ+Jet



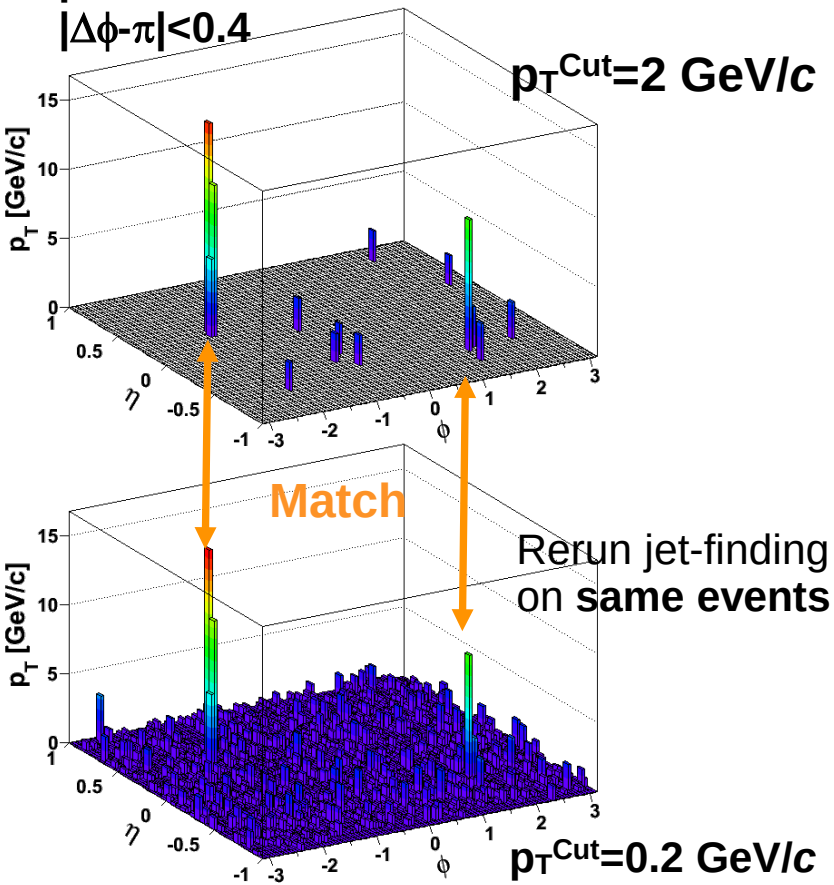


Repeating this analysis with the "golden probe" – stay tuned

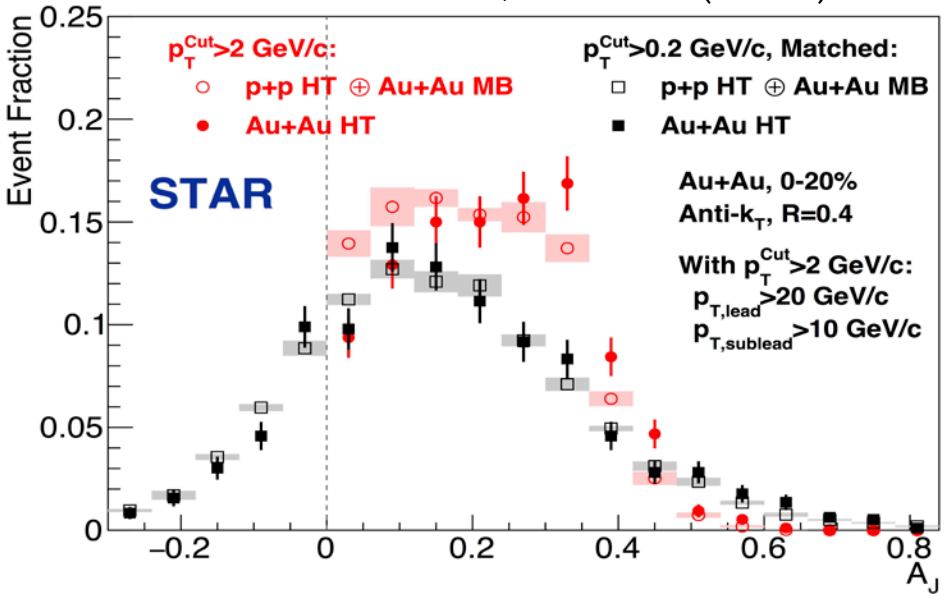
See D. Anderson, Wed, 12pm

Jet-by-Jet with hard cores

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



STAR PRL 119, 062301 (2014)



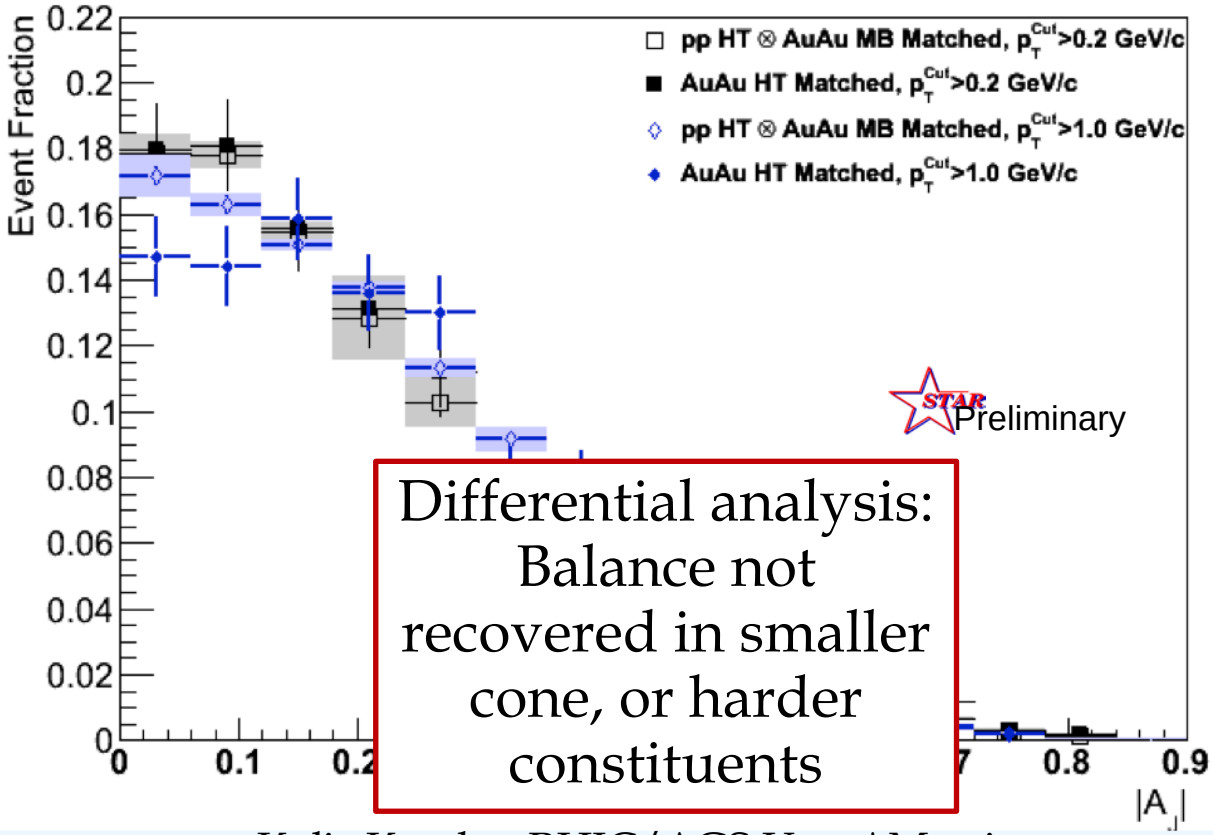
$$A_J = \frac{p_T^{\mathrm{Lead}} - p_T^{\mathrm{SubLead}}}{p_T^{\mathrm{Lead}} + p_T^{\mathrm{SubLead}}}$$

See also N. Elsey, this morning

- Imbalance in "hard cores" restored in matched di-jets for R=0.4

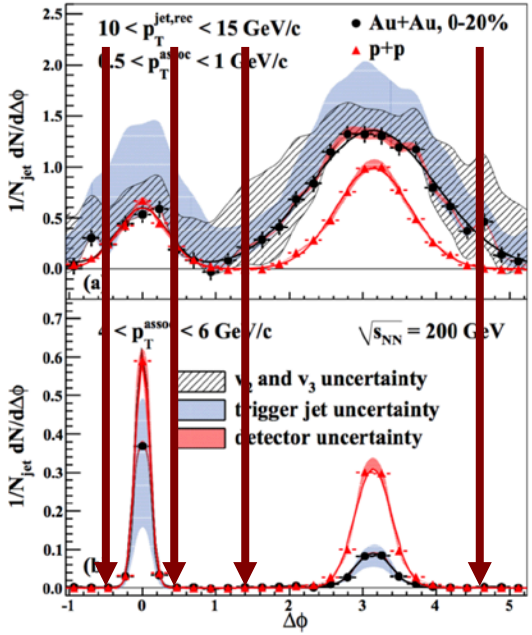
Angular and Spectral "Substructure"

R=0.2 R=0.4 R=0.4

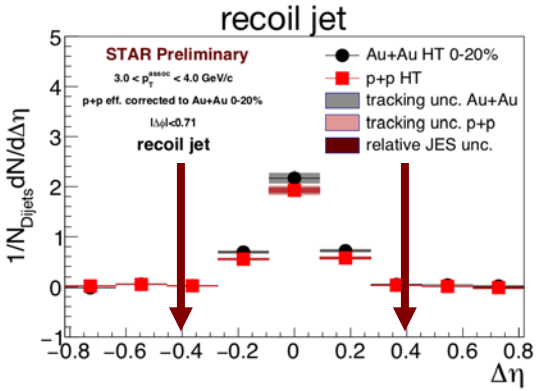


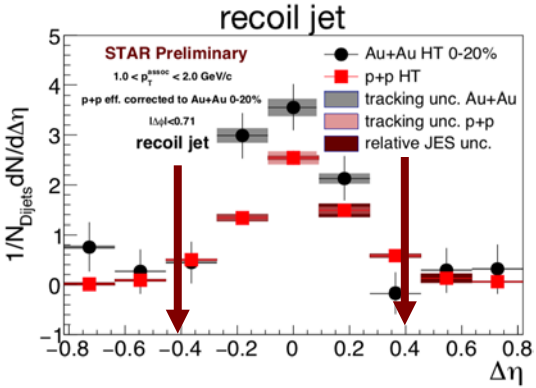
Differential analysis: Balance not recovered in smaller cone, or harder constituents

(Di)Jet+Hadron "Substructure"



See N. Elsey, this morning



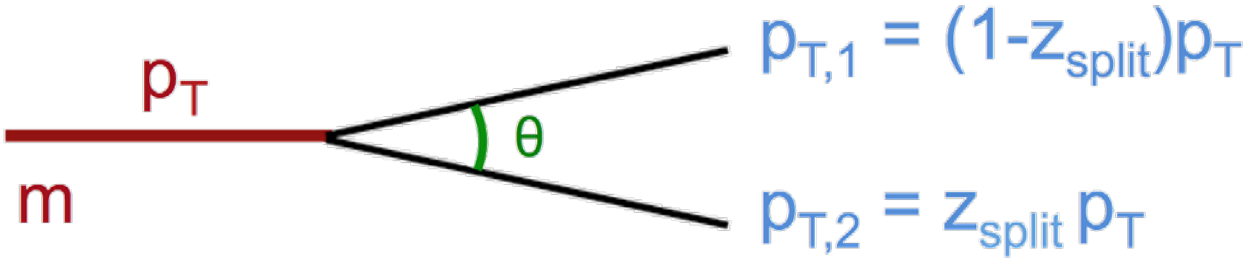


Now want to focus on jet-by-jet, pQCD style, IRC-safe substructure observables

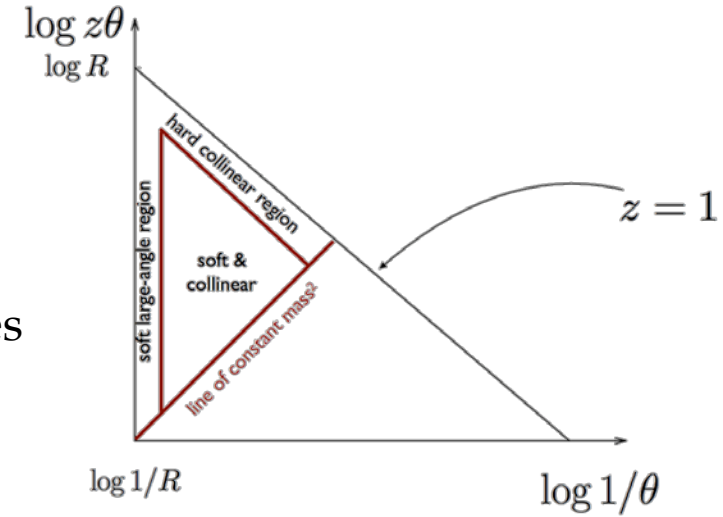
- ***but don't dismiss correlations and traditional shapes***

Jet Substructure

Cartoon by M. Verweij

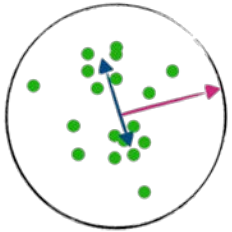


Lund Diagram:
B. Anderson et al., Z Phys C 43, 625 (1989)



Two scales for incoming parton: **m, p_T**

Two scales for the split: **z, θ**

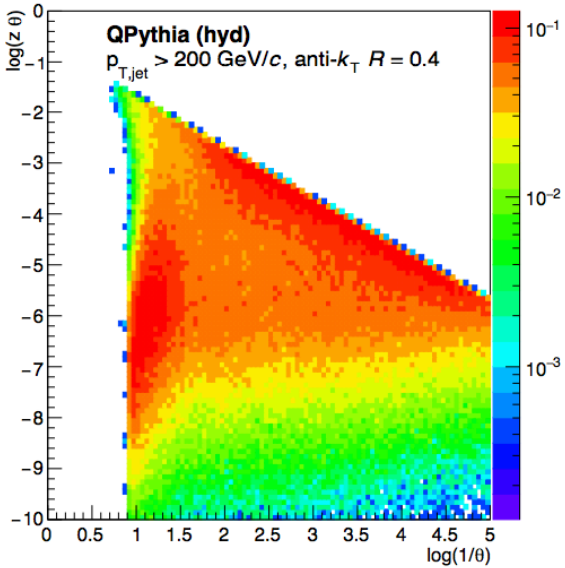


Program: Characterize with experimentally robust observables

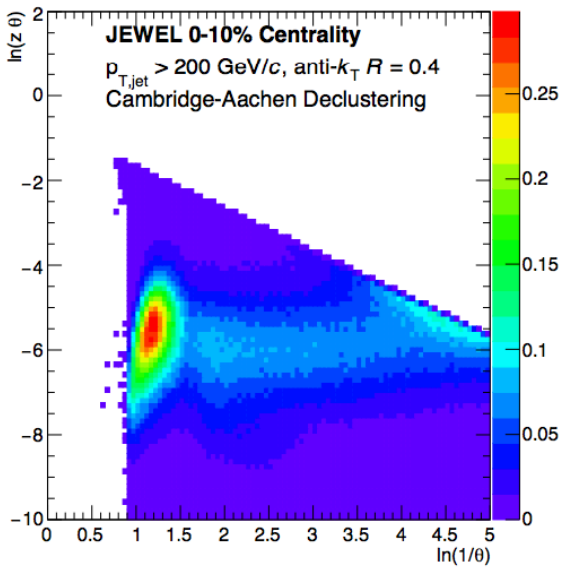
Cartoon by R. Kunnawalkam Elayavalli

Tantalizing MC Results

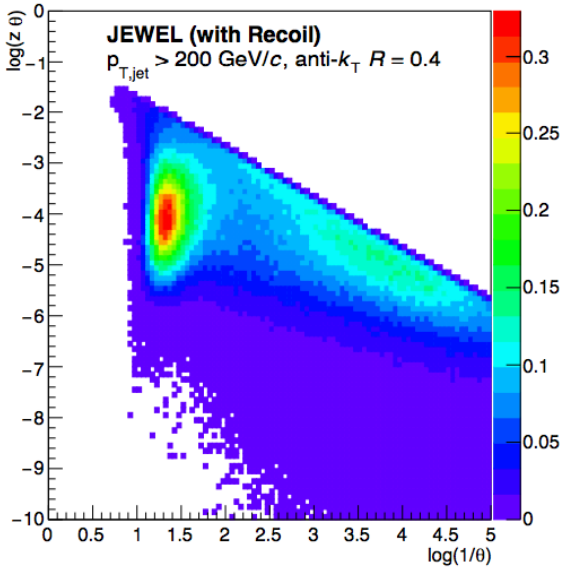
QPYTHIA



JEWEL (wo/ recoil)



JEWEL (w/ recoil)



- Promise of strong model disambiguation
- Let's assemble ingredients

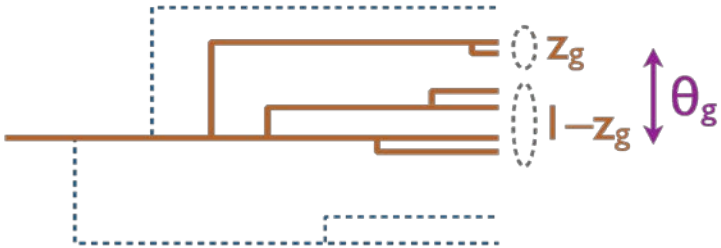
MC Study by K. Tywoniuk et al.
Details: JETSCAPE Winter School 2018

Groomed Momentum Sharing z_g

- Soft Drop: Remove wide angle soft radiation

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

energy threshold — angular exponent



Based on declustering an angular-ordered tree

With β=0 and Cambridge/Aachen:
"Groomed Momentum Sharing"
Relative z of the softer prong

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

J. Thaler
ALICE Jet Workshop (2015)

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

In vacuum:

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

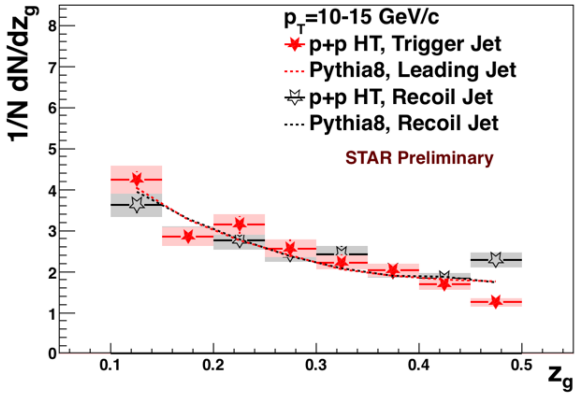
P_i: AP splitting functions

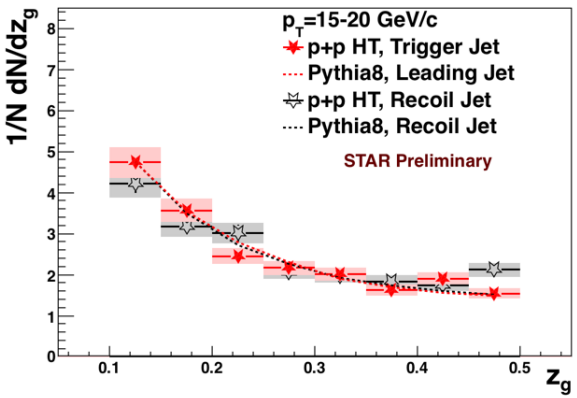
~ independent of α_s
~ independent of p_T (in UV limit)
~ independent of quark/gluon jet
Connection to fundamental QCD

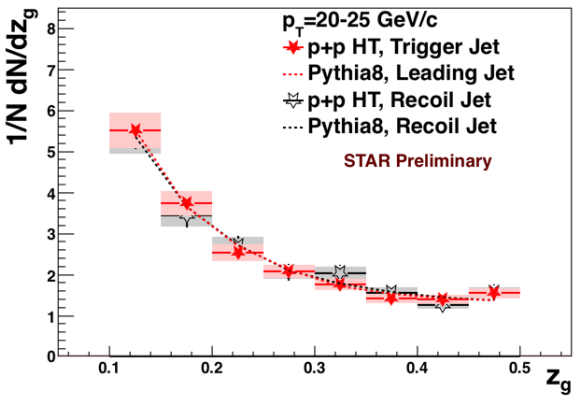
Particle Level z_g in p+p

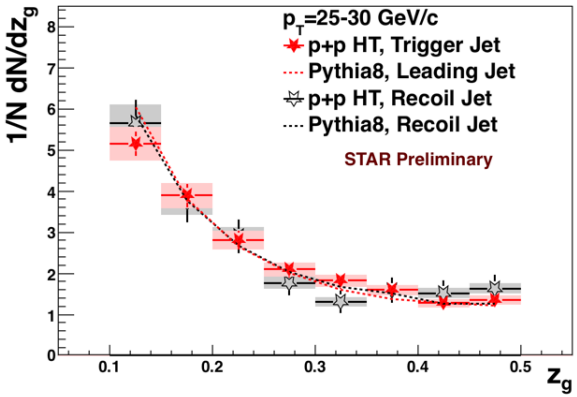
Bin-by-bin corrected

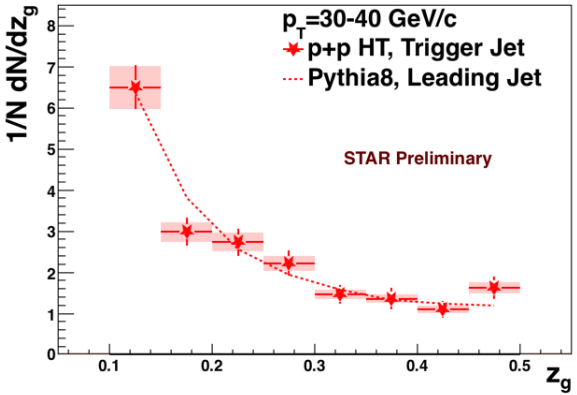
KK, HP16, QM17









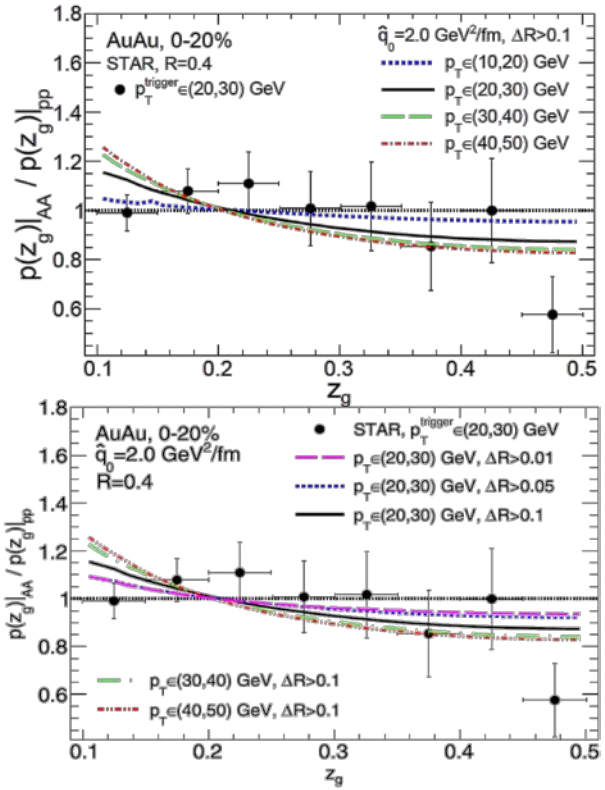


- Mild p_T dependence above ~20 GeV/c
- Well described by Pythia

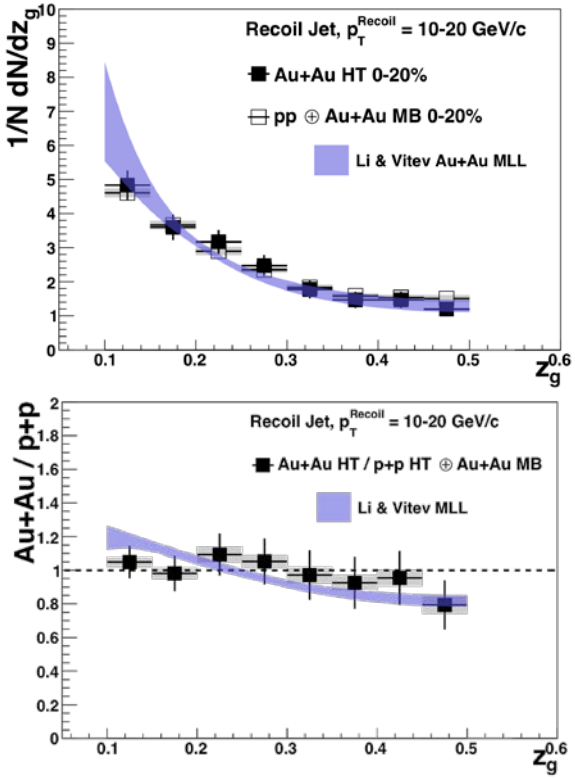
Upcoming:
Larger data set + unfolding
→ z_g up to **50+ GeV/*c***

Jet Substructure: z_g in Hard Core Jets

KK, HP16, QM17



Ning-Bo Chang
et al. QM18

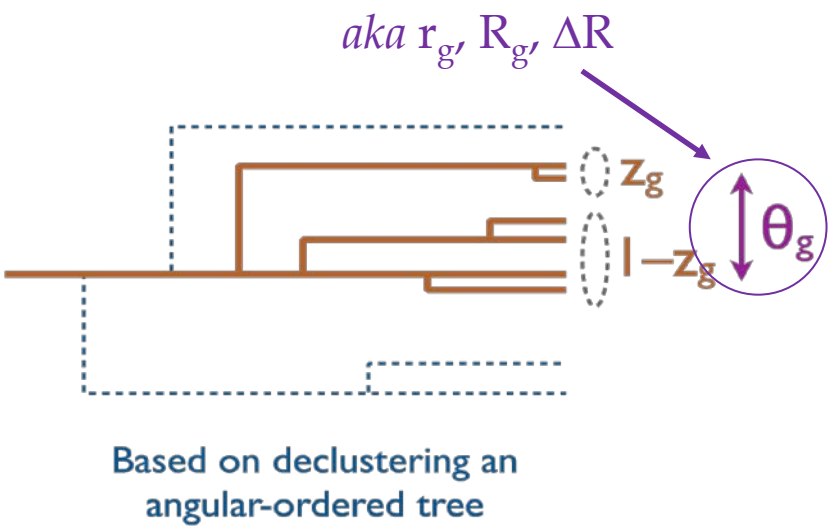


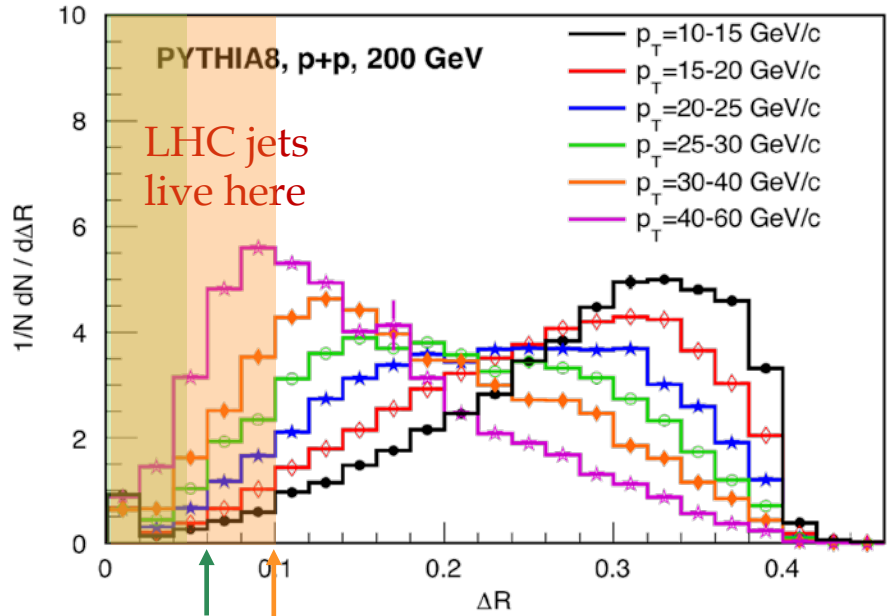
Li & Vitev
arXiv: 1801.0008

- No significant modification on trigger and recoil side of hard-core dijets
- Theoretical models capture this well
- More statistics: Test downward slope

Modelers: Be mindful of cuts and detector effects

Groomed jet radius r_g





STAR BEMC (but tracking is dominant)

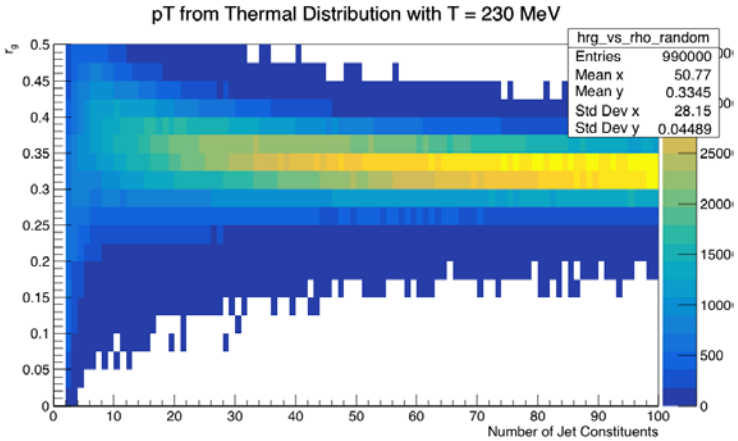
CMS resolution constraint

- Expected narrowing with p_T
- Good resolution in RHIC's kinematic range

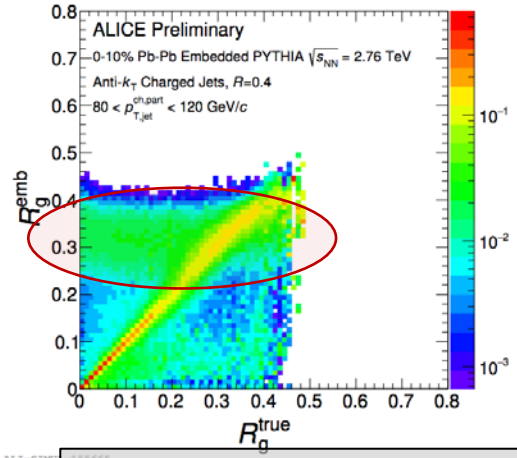
- Even plays to RHIC's strengths!
- What about HI background?

r_g in a Thermal Background

R. Kunnawalkam Elayavalli



ALICE< Harry Andrews, QM '18



ALICE, $80<p_T<120$
Effect potentially more severe in STAR's kinematic range

- Toy background creates a peak purely determined by jet parameters

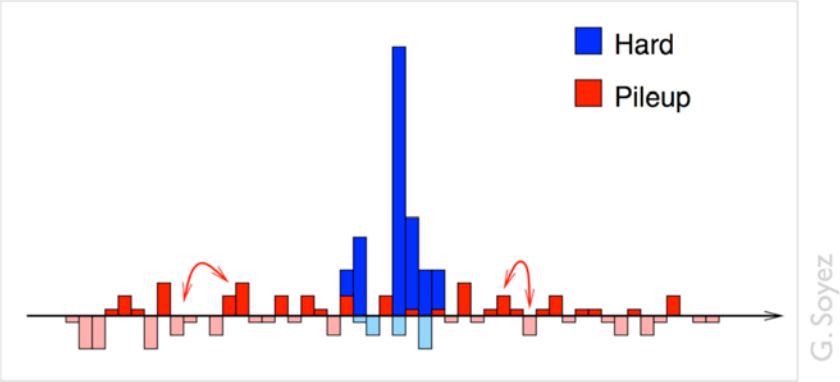
- With signal present, significant structures remain – difficult to disentangle w/o truth info

SoftDrop's biggest strengths are intimately tied to Cambridge/Aachen, because C/A follows angular ordering – but HI background is not angular ordered

Mitigation/Alternatives

Possible mitigation options

1. Increase z_{cut}
2. Introduce additional cuts
3. Alternatives to C/A?
4. More sophisticated background subtraction (e.g. constituent subtraction)?

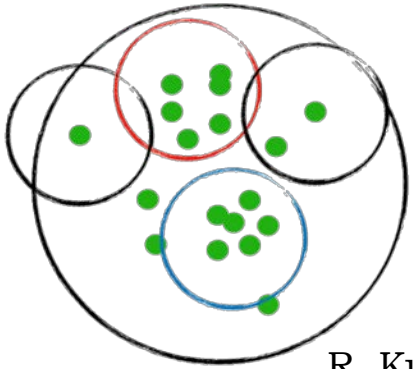


M. Cacciari , HP '16

"Generic **experimental characterisation of jets in HI** collisions, even **in the absence of universally valid theoretical descriptions**, can and should be a **priority**" - *M. Cacciari , HP '16*

Possible alternatives to characterize angular scale:

- Jet **mass** (in the works), girth, …
- Small subjets (in the works)

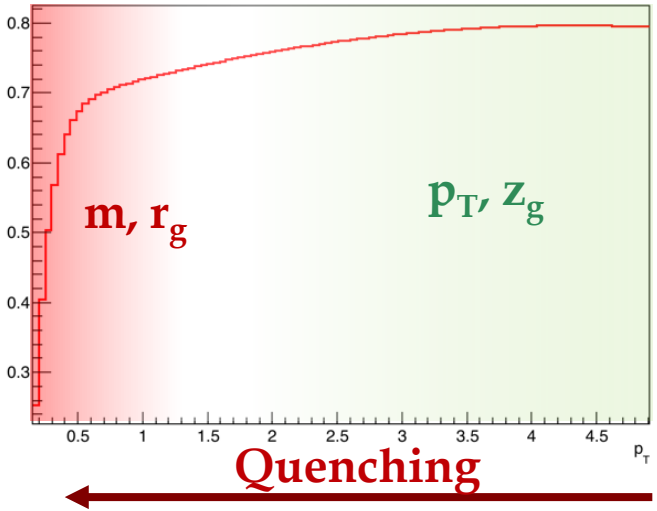


Cartoon by R. Kunnawalkam Elayavalli

Challenges in Unfolding

1) Substructure: z, θ, E, two jets,…
   → **dimensionality** grows → need to carefully factorize
2) What is the **truth level**?
   → Hard-core, trigger cuts etc. done at detector level
   → Inclusive measurements may not be possible
   … or desirable (e.g. jet geometry engineering)

3) **vacuum != medium jets**



Possible solutions:

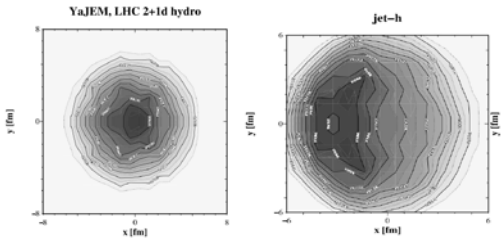
- Detector Level comparison (ratios help)
- Rethink response construction
- Bracket response using multiple models

JETSCAPE 1.0

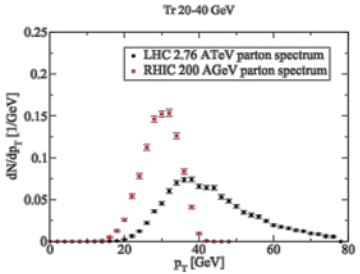
See J. Putschke, Thu 11:30 am

Summary

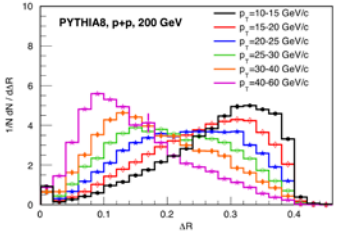
- **STAR and RHIC offer unique strengths and capabilities for jet and jet substructure studies**



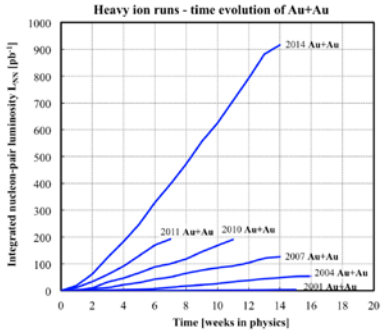
Jet Geometry Engineering



Tight parton--jet correspondence



Sensitivity to substructure



Flexibility and Luminosity

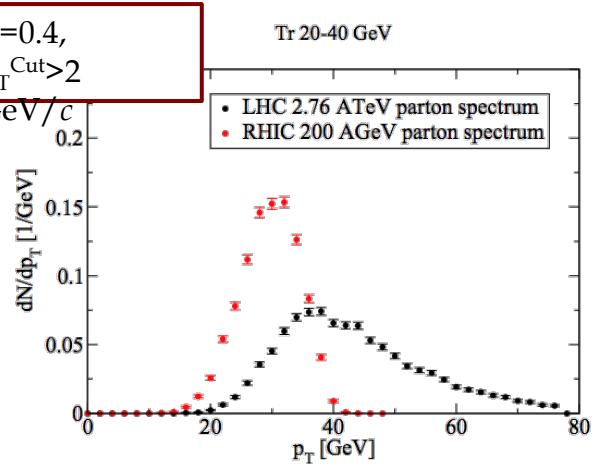
- **An ambitious program of traditional, 1st , and 2nd generation observables is well underway**
  - Book your ticket to Aix-les-Bains!

HARD PROBES 2018

BACKUP

Unique RHIC Strengths

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

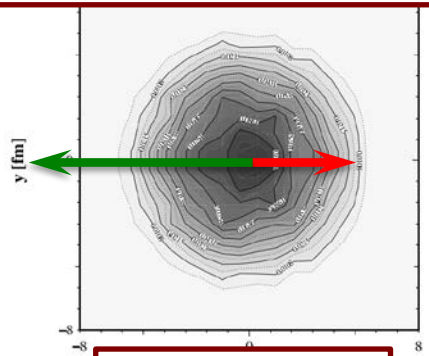


Recoil p_T off a 20-40 GeV trigger

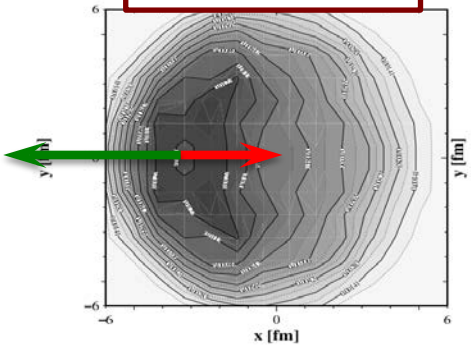
Steeply falling spectrum
→ Good correlation between jet and original energy!

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

LHC Imbalanced Dijets

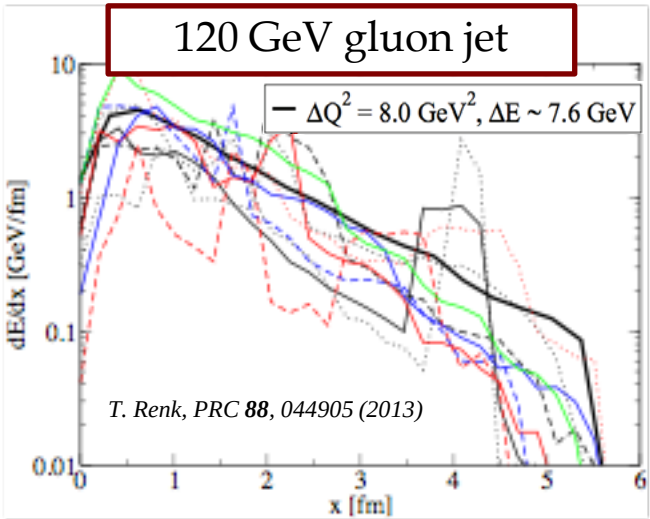


RHIC Jet-h



Path Length Control?

120 GeV gluon jet

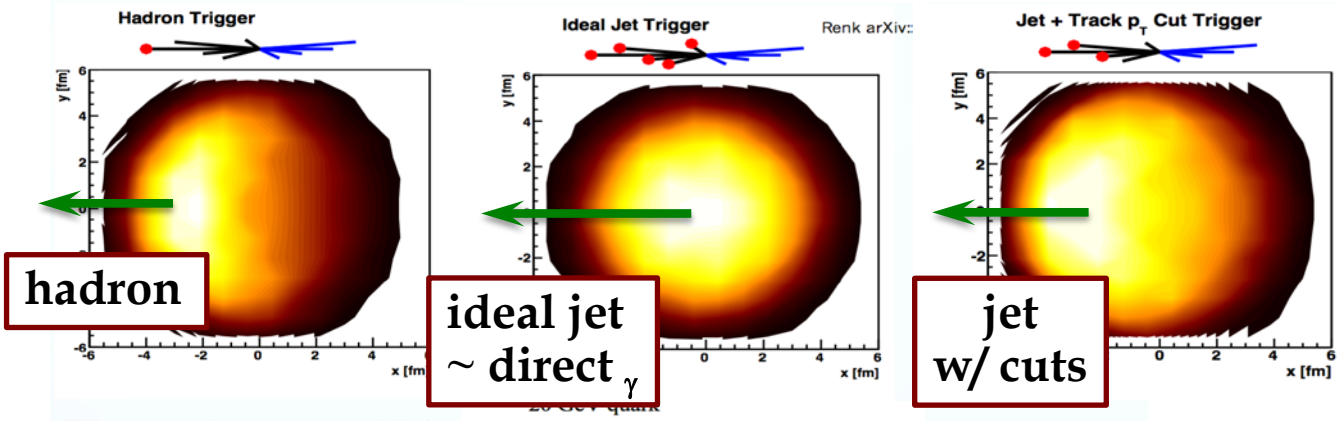


LHC: Larger energy loss at early times
→ more diffusion
→ larger angles

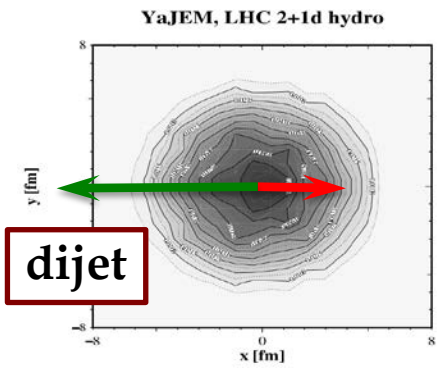
A+A: Geometries and Strategies

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

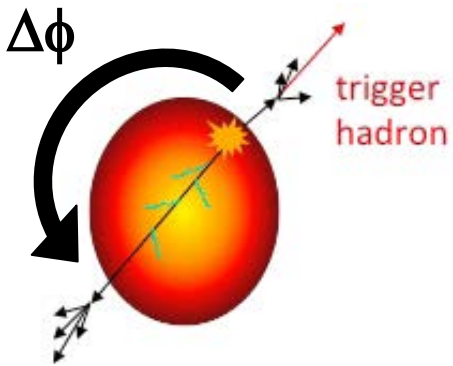
Exploit bias at RHIC for Jet Geometry Engineering

Analyze the recoil

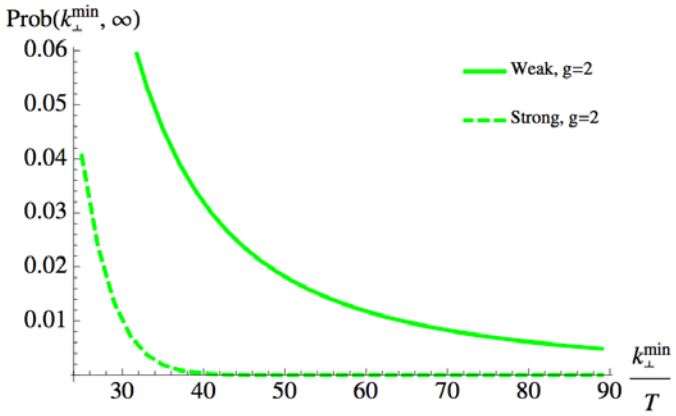
- Correlation
- Semi-inclusive jets
  → maximum path length
- Jet, with cuts
  → shorter path length?

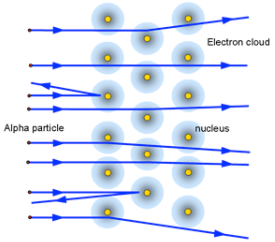
Large Angle Scattering off the QGP?

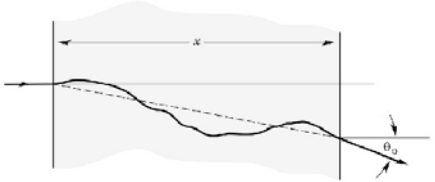
JHEP 1305 (2013) 031



Discrete scattering centers or effectively continuous medium?







"Weak"
multiple scattering

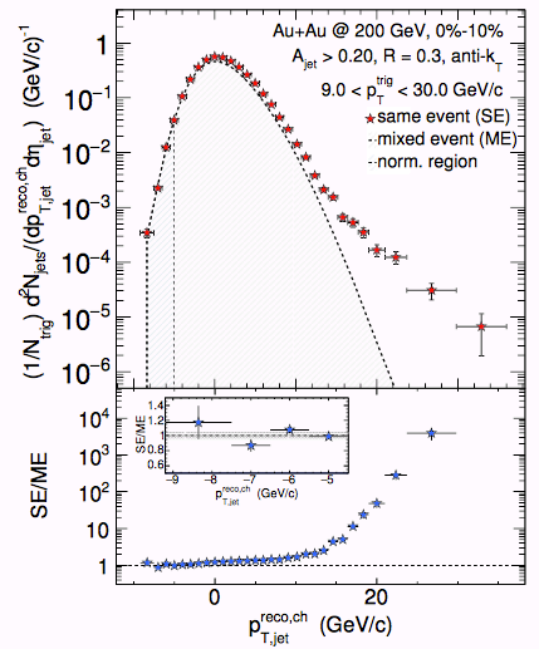
"Strong"
Continuous E-loss

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

h-Triggered Recoil Jets

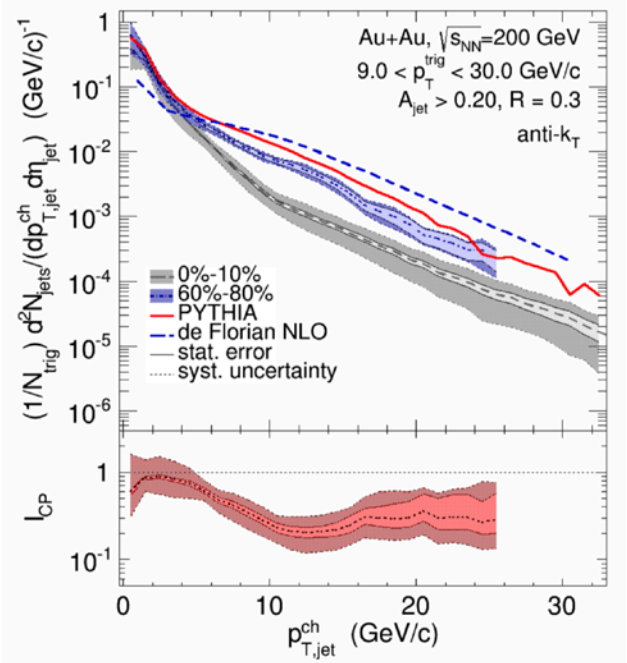
arXiv:1702.01108

Raw

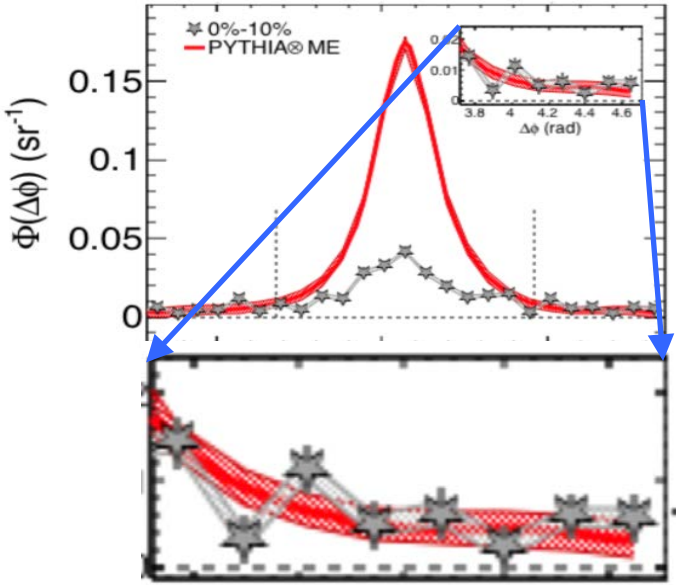


R=0.3

Unfolded



Recoil jets azimuthal distribution

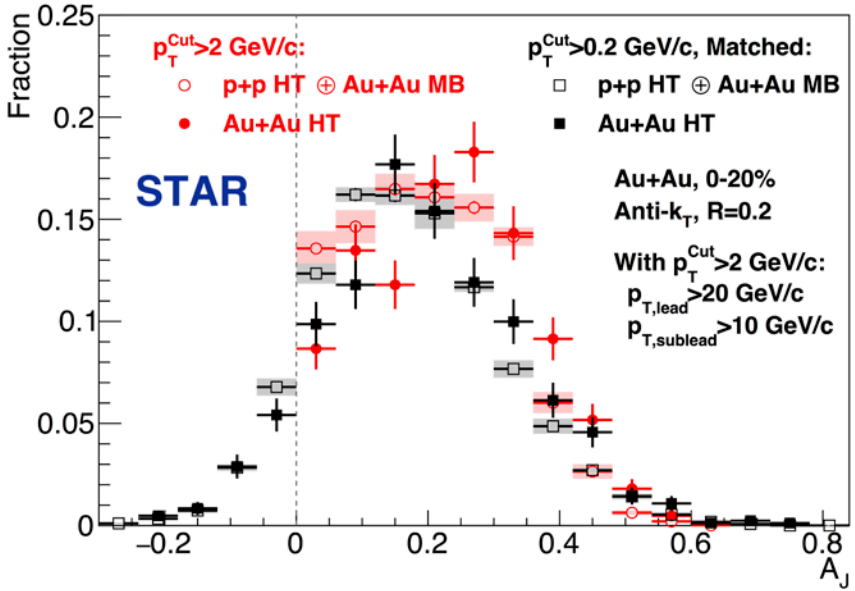


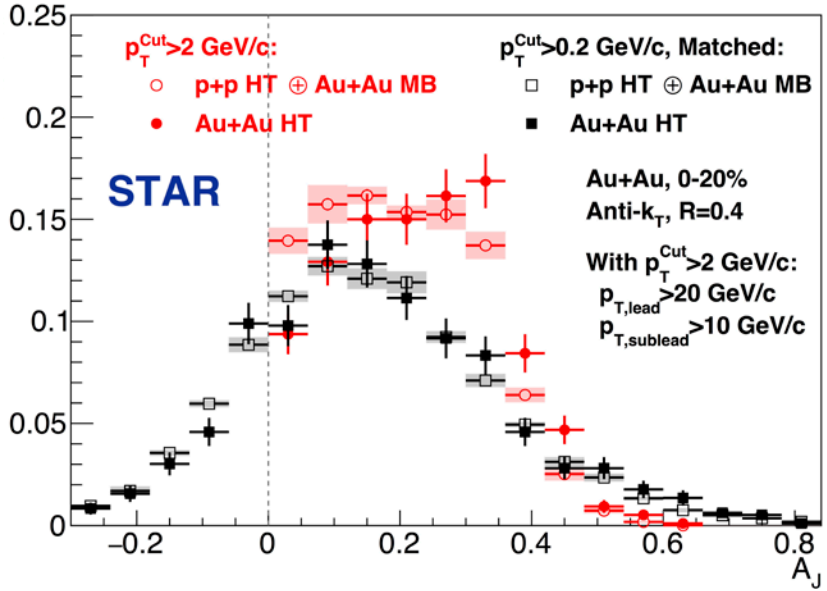
- $h^{+/-}$-triggered charged recoil jets:
  → I_{CP} shows strong suppression (~0.2-0.3 for R=0.3)

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

Di-Jet Imbalance

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



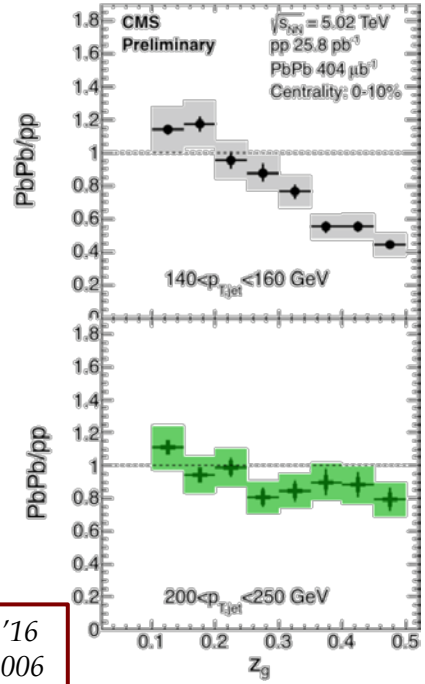


- p+p balance **no longer recovered**
- Energy shifted outward, yet remains inside 0.4
- Leading or sub-leading jet? A_J can't answer

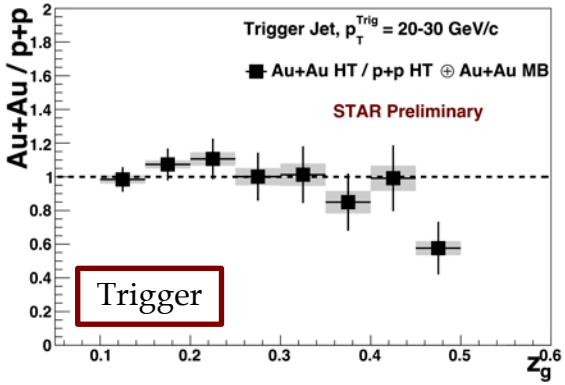
arXiv:1609.03878

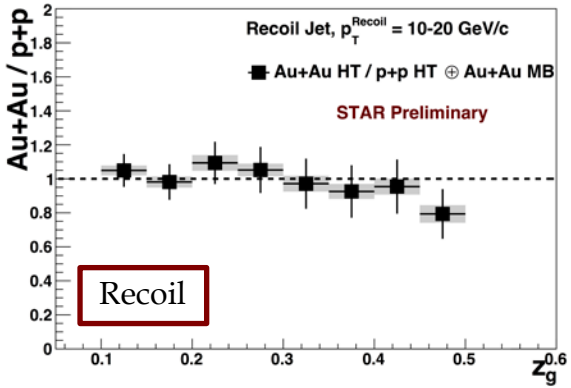
Contrast to LHC

HP '16



BOOST '16
HIN-16-006





- STAR Biased Di-Jets: No z_g modification found

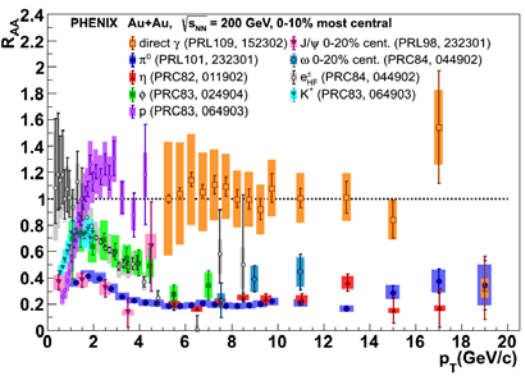
- CMS Inclusive Jets: Significant modification in central Pb+Pb below 250 GeV/c

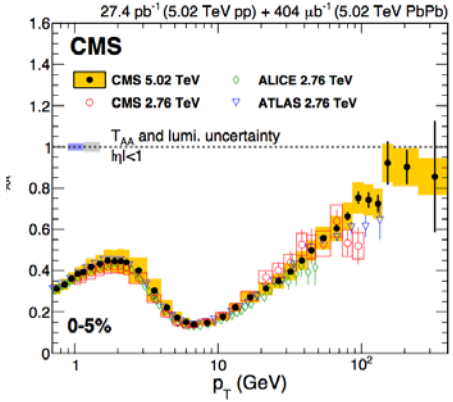
Possible Reasons:
- Split as measured with z_g occurs outside the medium?
  - Or before formation?
- Splitting function not affected by medium interactions?
- Other explanations?

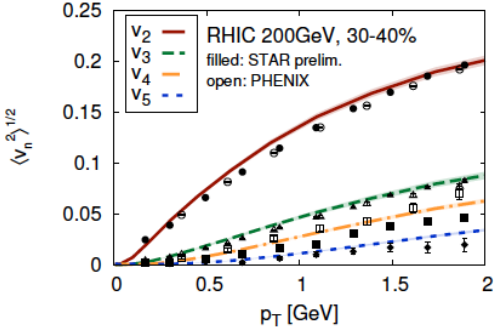
RHIC and the LHC

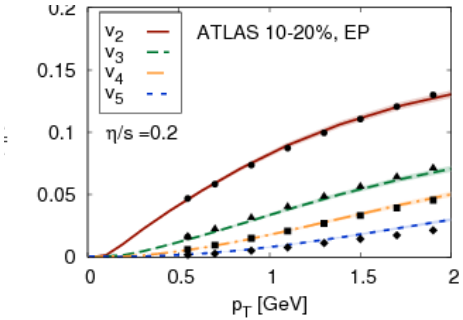
- Larger Q^2, new probes (Z, W, …) in "similar" QGP
  → Stronger model constraints

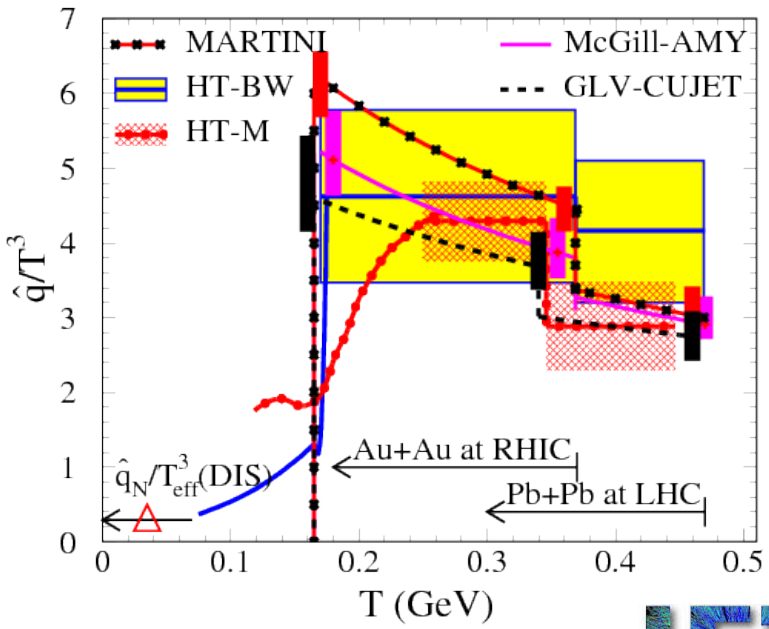
- Qualitative differences?











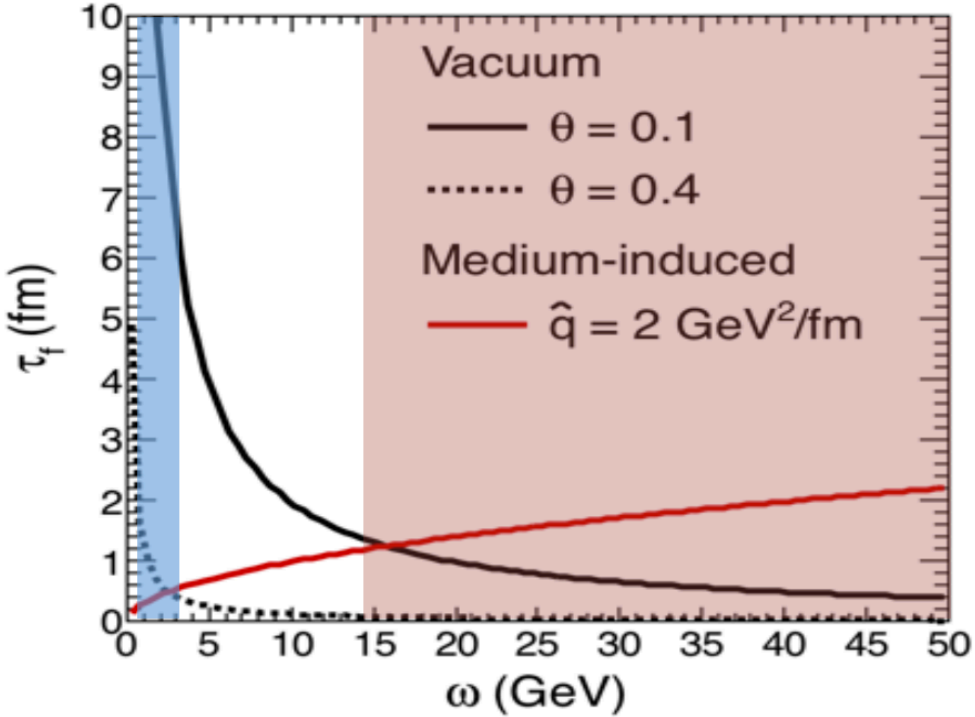
z_g – RHIC vs LHC

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

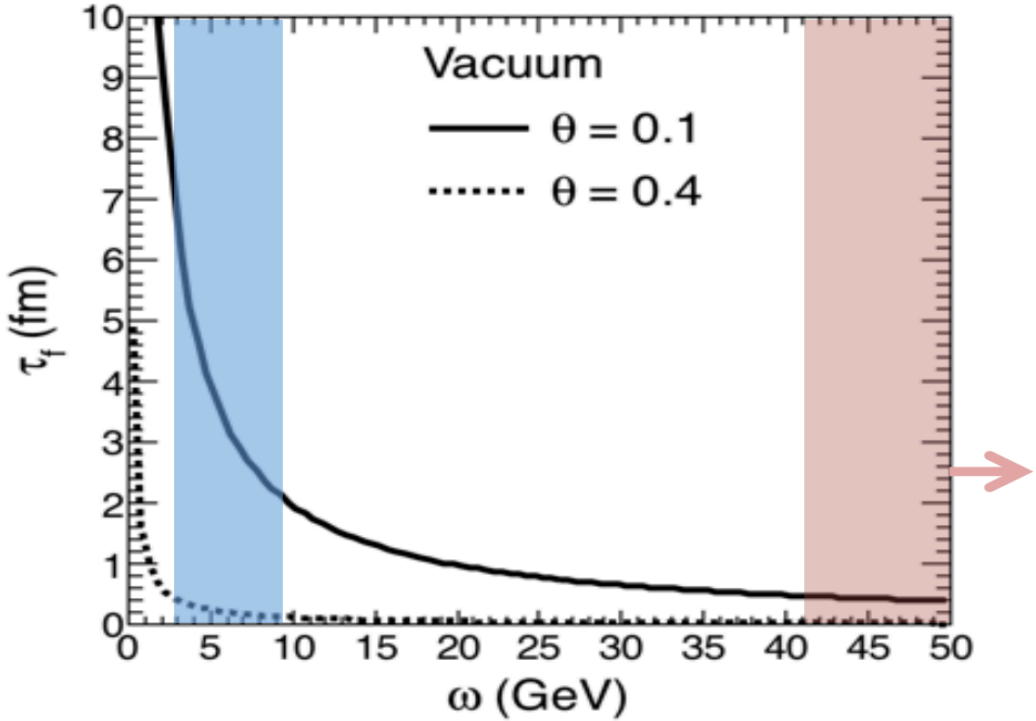
CMS

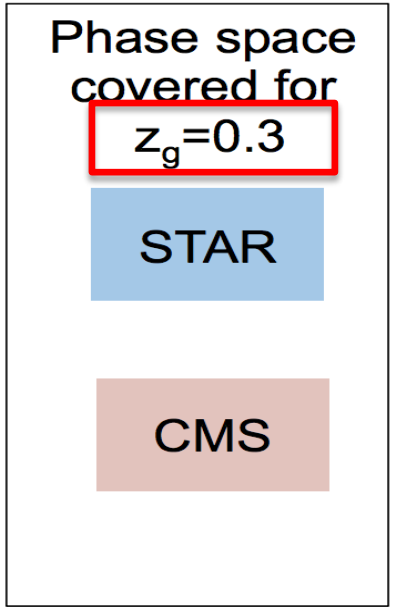
At RHIC can only see medium for rare large angle emissions or even splittings. Larger z_{cut} and/or ΔR_{12} selection would increase sensitivity

z_g – RHIC vs LHC

Vacuum formation time of gluons with certain energy

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





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