Jet Quenching at RHIC and LHC

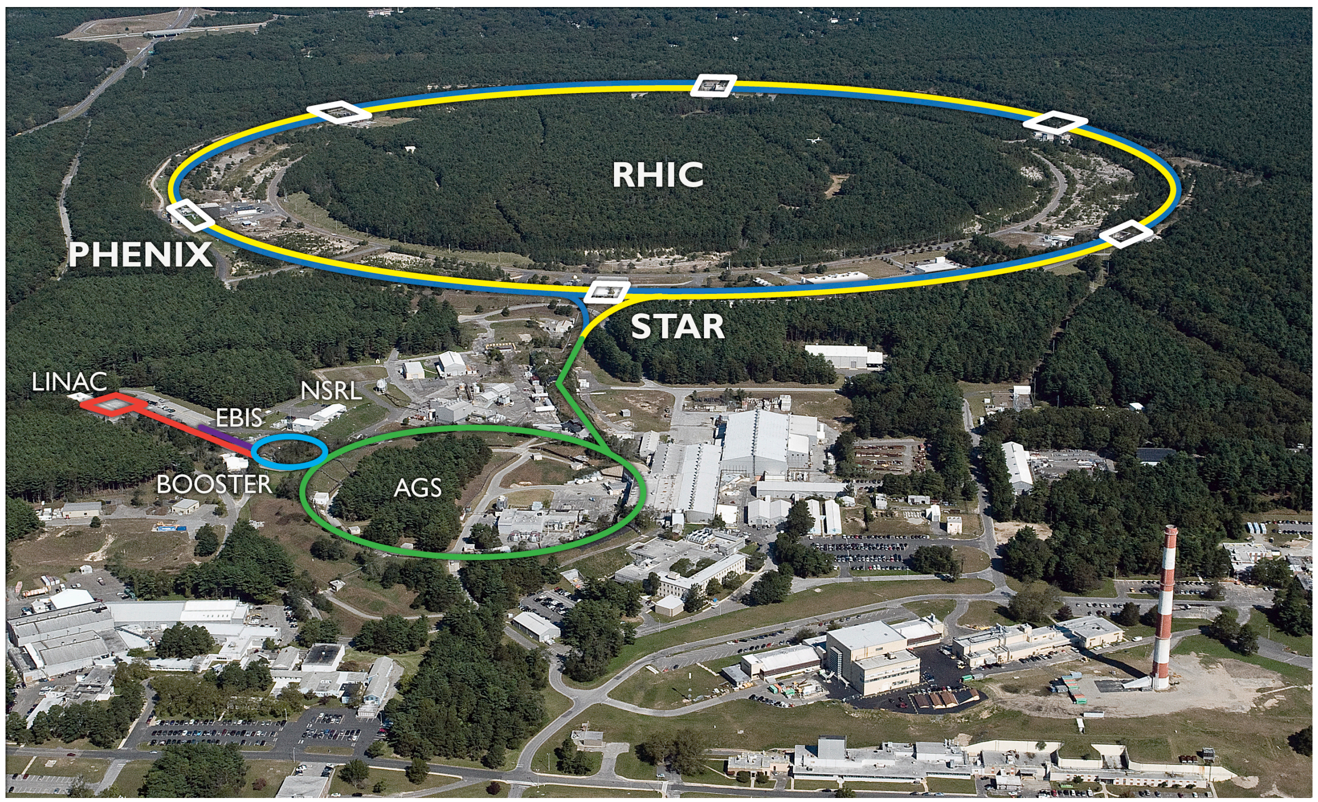
An Experimental Observation

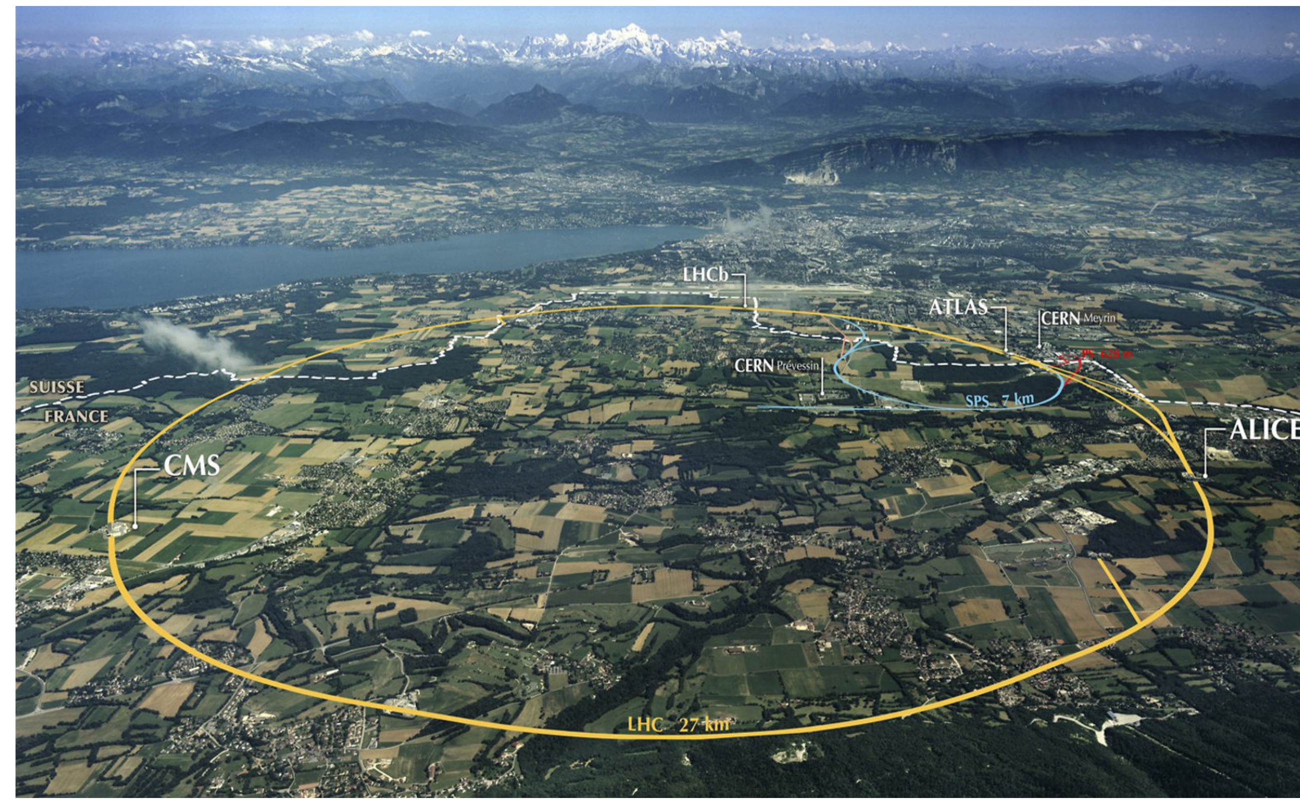
Raghav Kunnawalkam Elayavalli
(Wayne State University)

Open Symposium: The space-time structure of jet quenching: Theory and Experiment

12-16 August 2019
GSI Helmholtzzentrum für Schwerionenforschung GmbH

Jet Quenching at RHIC and LHC

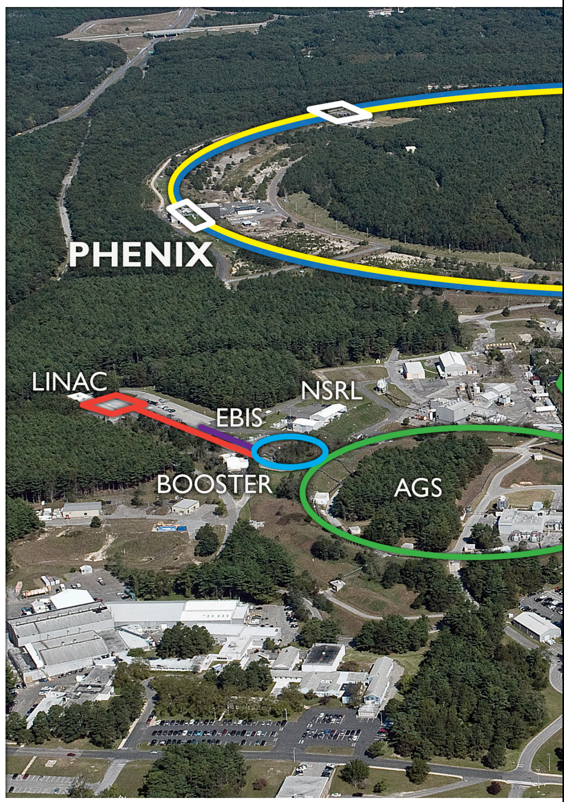


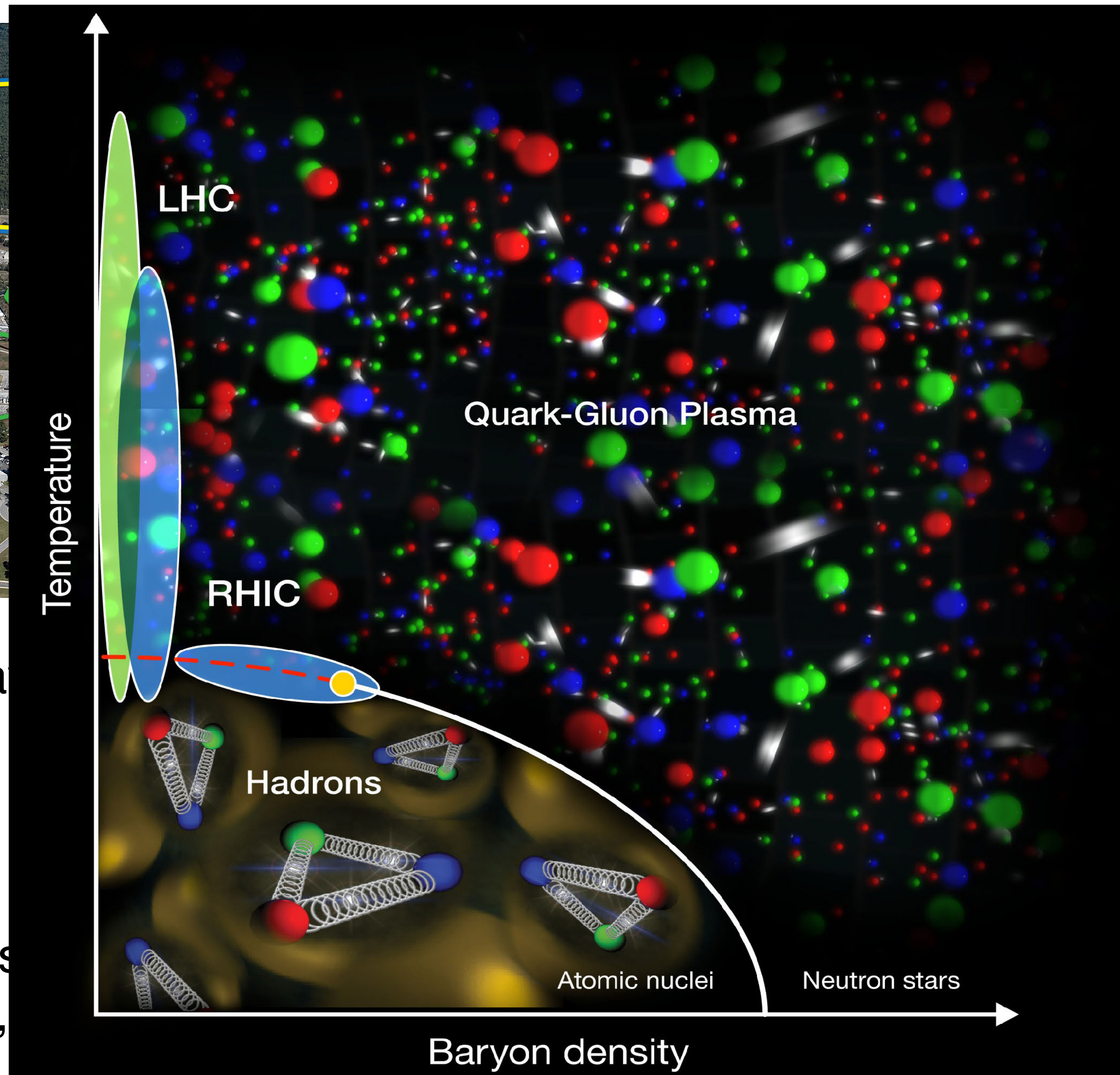


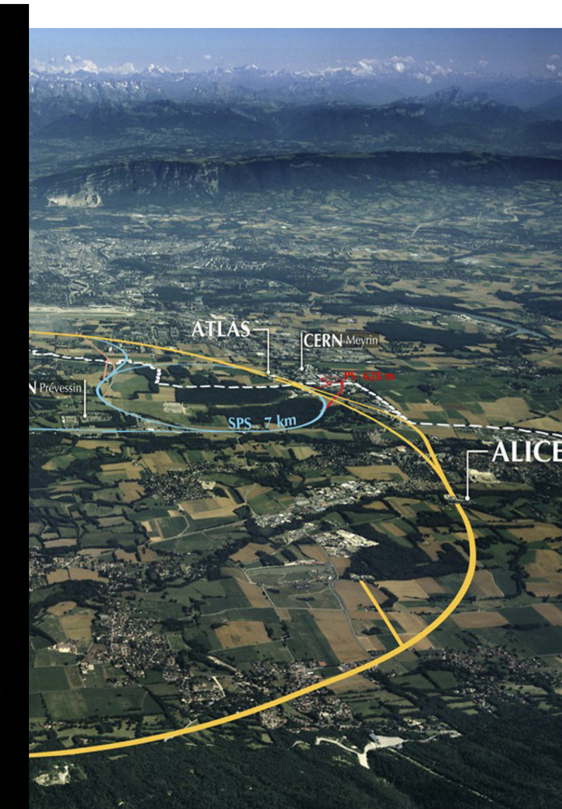
- Relativistic Heavy Ion Collider
- $\sqrt{s_{NN}} = 7.7 - 200$ GeV
- Particle Species - p+p, p+Au, d+Au, Au+Au, Cu+Au, Ur+Ur, etc…

- Large Hadron Collider
- $\sqrt{s_{NN}} = 2.76,\ 5.02$ TeV
- Particle Species - p+p, p+Pb, Pb+Pb, Ar+Ar

Jet Quenching at RHIC and LHC

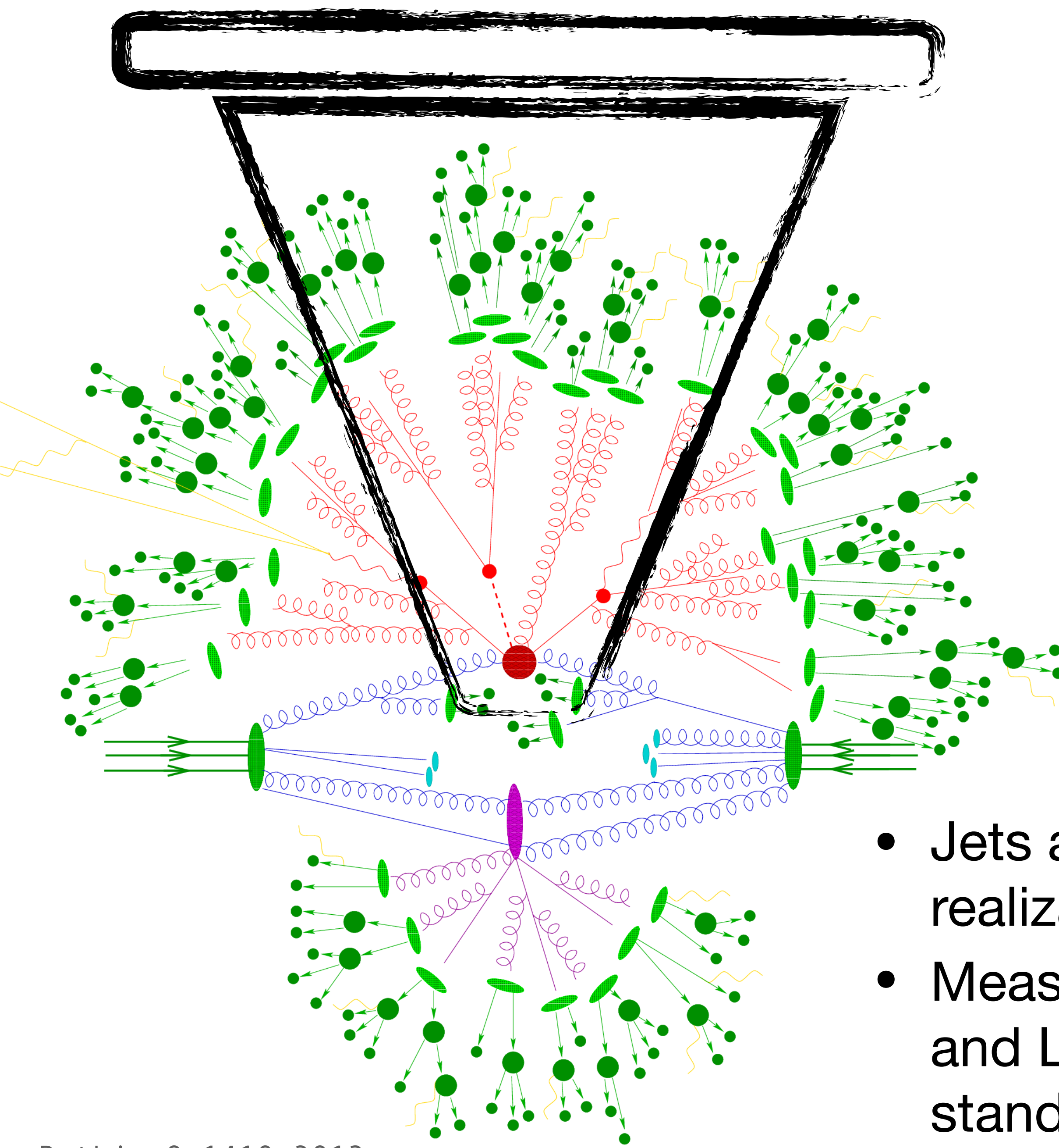


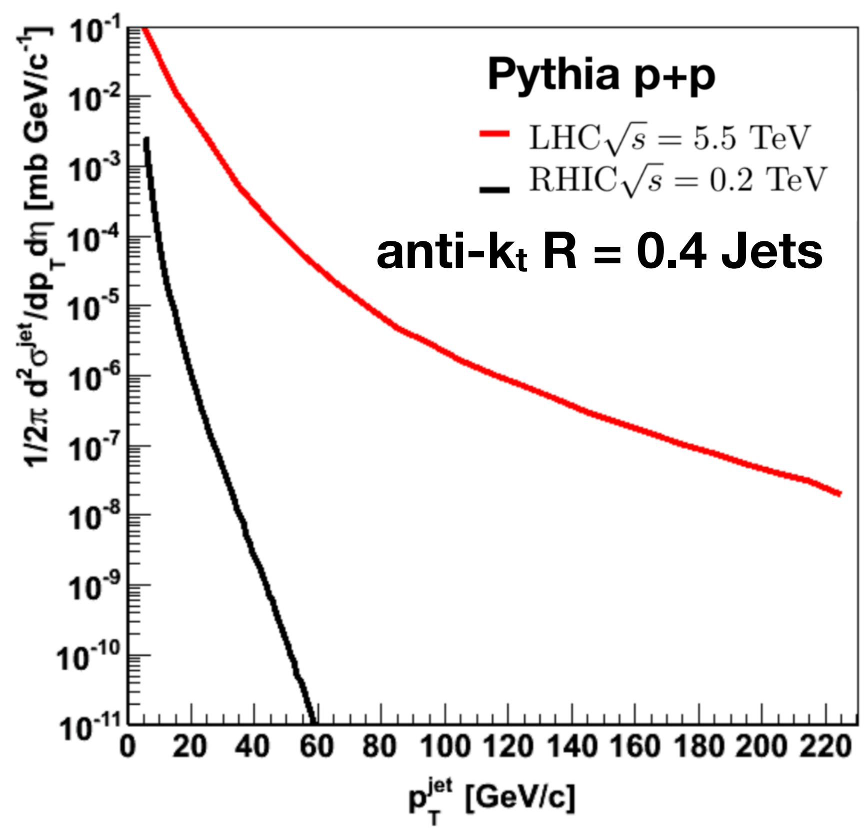




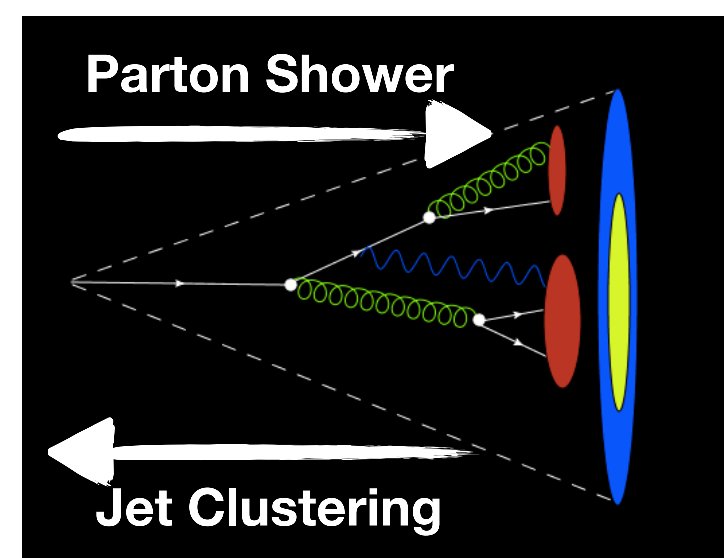
- Relativistic Hea…
- $\sqrt{s_{NN}} = 7.7 -$ … TeV
- Particle Specie… …, p+Pb, Pb+Pb, Au+Au, Cu+Au, …

Jet Quenching at RHIC and LHC



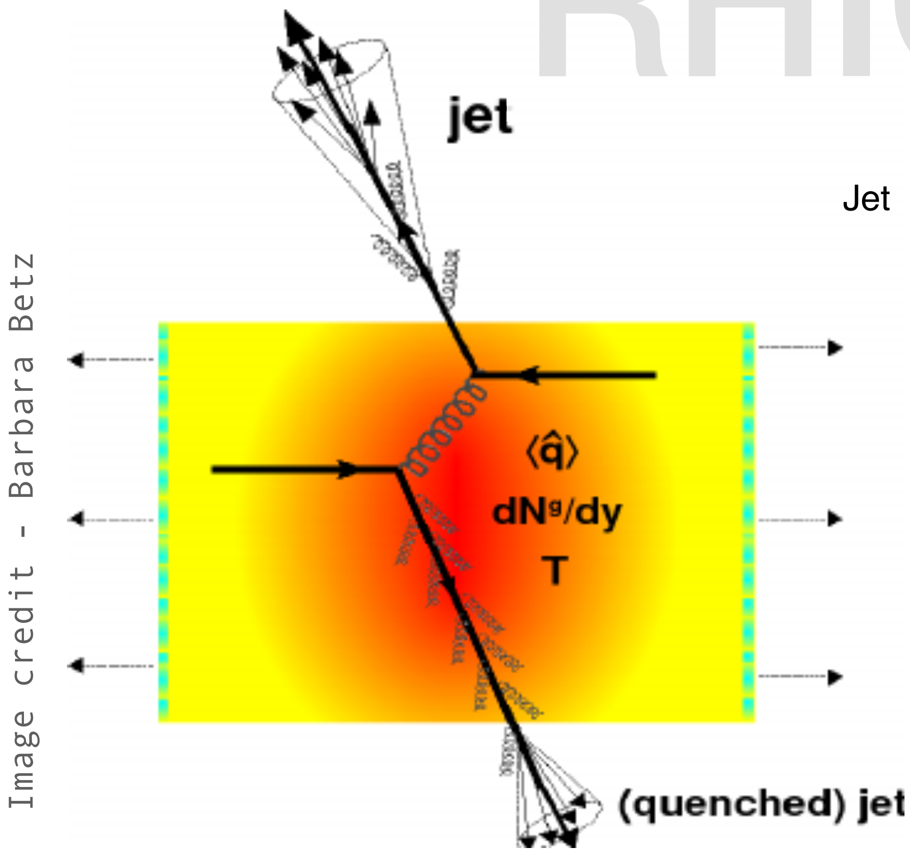


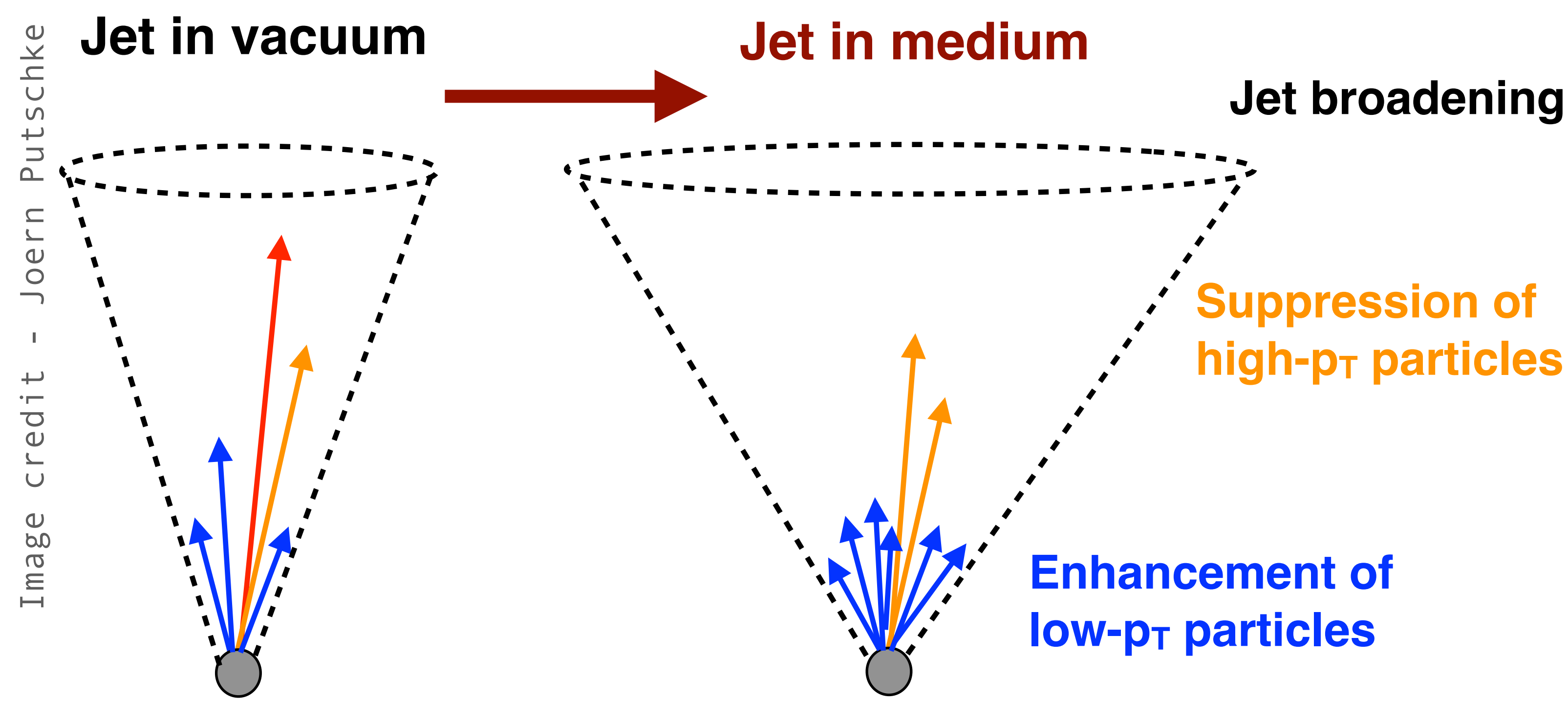
- Jets are an algorithmic realization of a parton shower
- Measurements from RHIC and LHC use the now standard anti-kt algorithm w/ a jet resolution parameter/jet radius R



Pythia-8 1410.3012
Höche 1411.4085
Fastjet CERN-PH-TH/2011-297

Jet Quenching at RHIC and LHC





- Hard scattered parton emanating from a high q^2 process with early formation time probes the evolution of the QGP
- Modifications of jet properties w.r.t a reference (pp/pA) seen as interaction with QGP

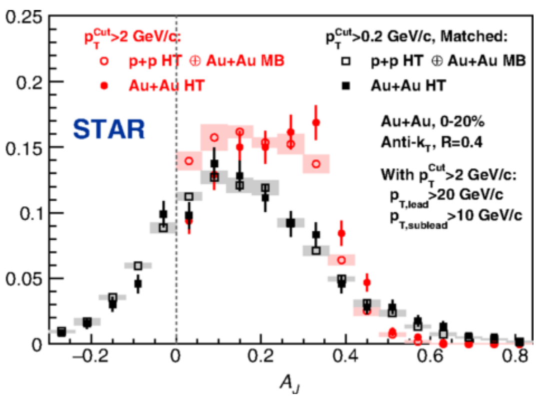
Mechanisms of energy loss - pQCD-like multiple gluon radiations, medium induced scatterings (inelastic), AdS/CFT energy loss, color coherence/decoherence, modified partonic splitting functions etc…

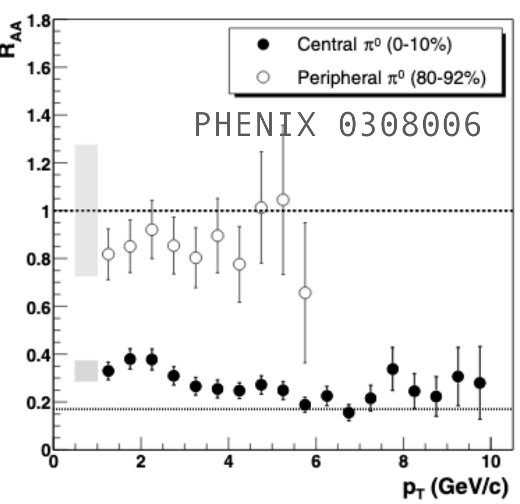
See the next two talks by Yacine and Korinna!

Qin, Wang, 1511.00790 Weidemann 0908.2306 Solano et al 1405.3864 Mehtar-Tani 1602.01047 Zapp et al. 1212.1599

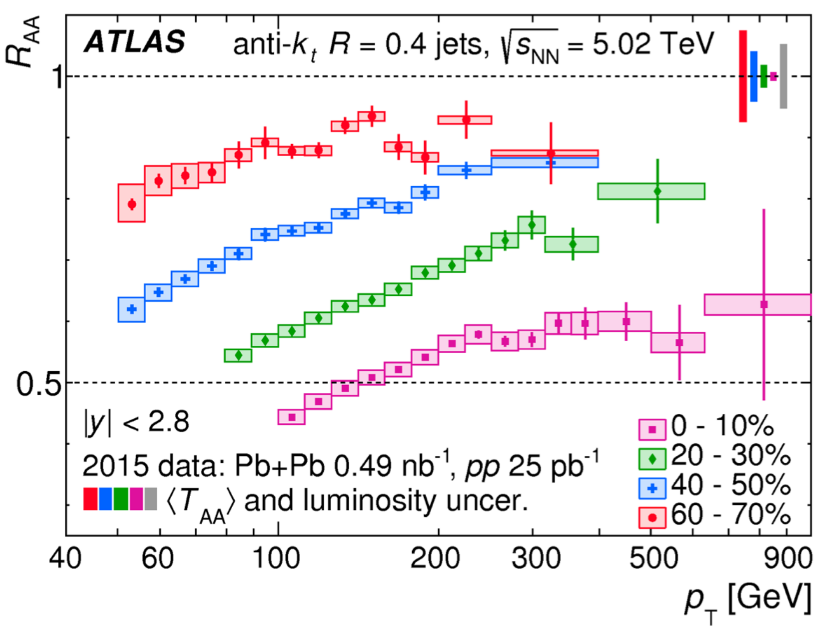
Jet Quenching at RHIC and LHC

STAR 1609.03878

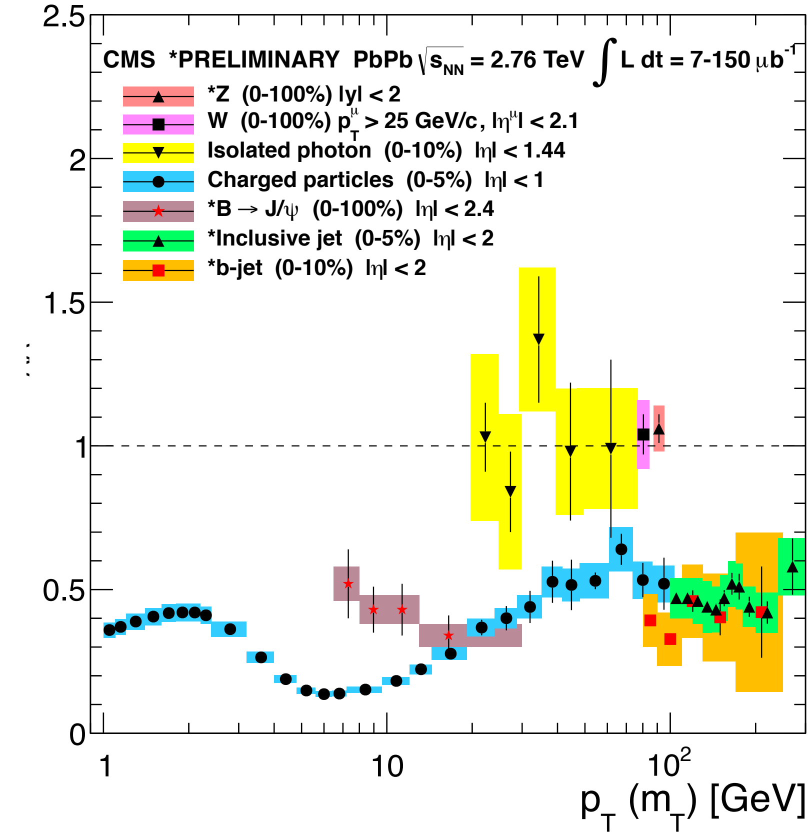




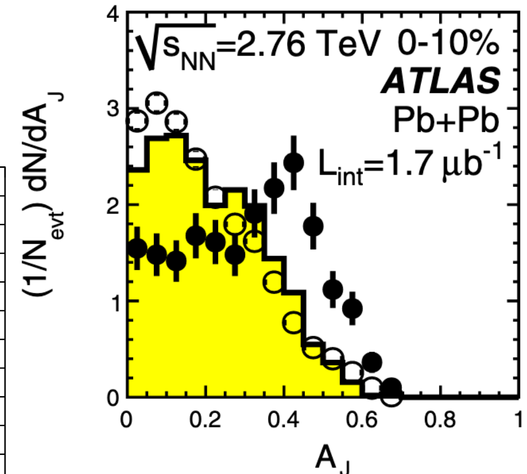
ATLAS 1805.05635

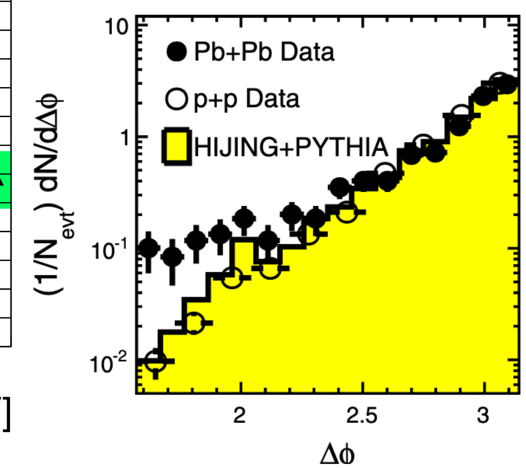


CMS R_{AA} QM-17 compilation



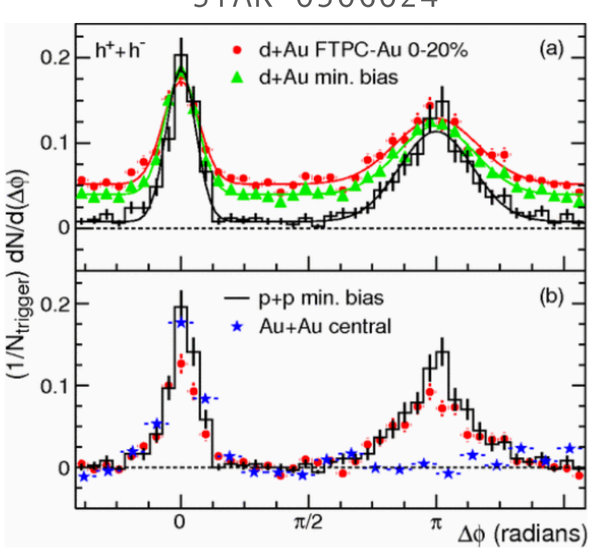
ATLAS 1011.6182



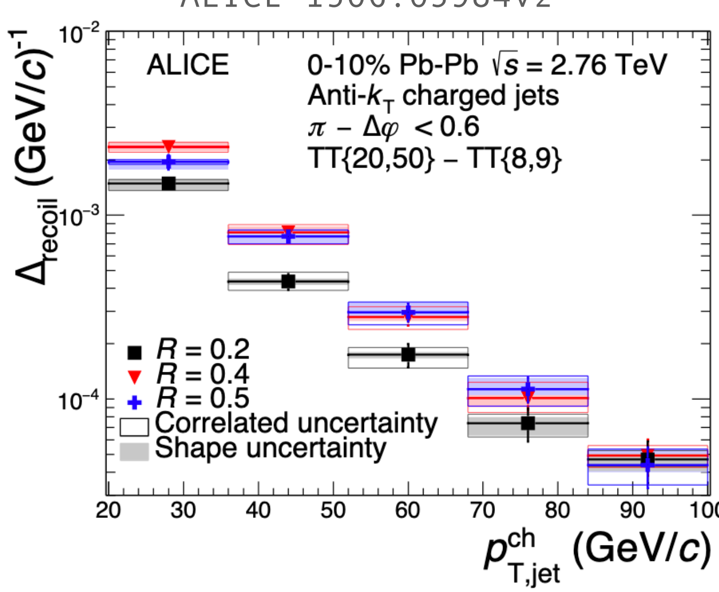


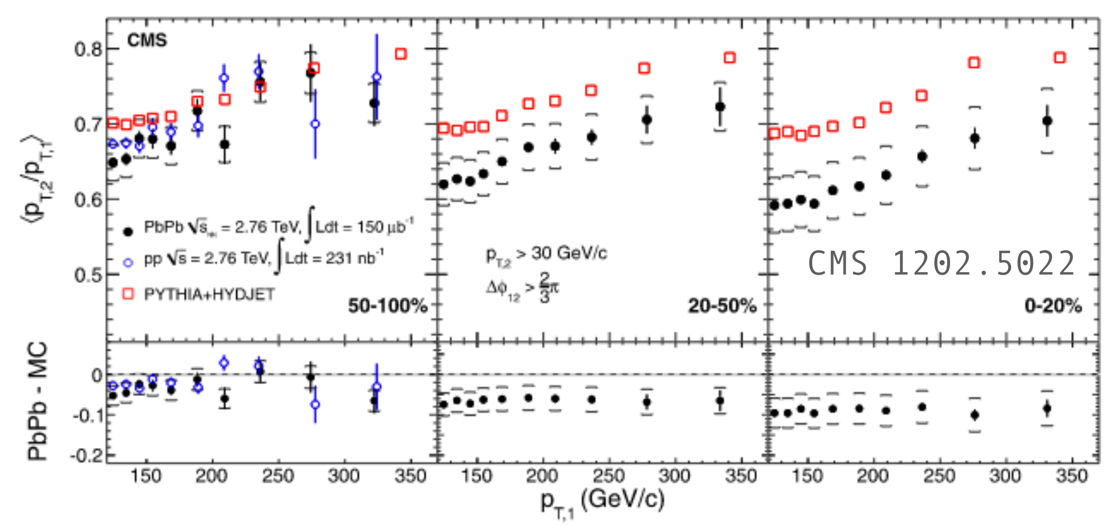
and many more ...

STAR 0306024



ALICE 1506.03984v2





What do early jet measurements inform us on jet quenching

- Colored probes are opaque whereas QGP appearing transparent to EW probes (γ, Z, W)
    - R_{AA} Nuclear modification factor (comparing yield in AA w.r.t binary collisions scaled pp) for γ/Z ~ 1, hadrons ~ 0.2 and **Jet R_{AA} ~ 0.5** (even at high p_T! With mild momentum dependence)
- **Large momentum asymmetry** in Di-jet and γ/Z+Jet pairs - Highlights need for and use of calibrated probes with good reference predictions
- Large (Δϕ) spread of quenched energy - Broadening effect
- Flavor dependence on quenching - Observation of sequential suppression in heavy resonance production, whilst heavy flavor jets are quenched at similar rates as light flavor jets (Not discussed in this talk)

ATLAS Heavy Ion Publications

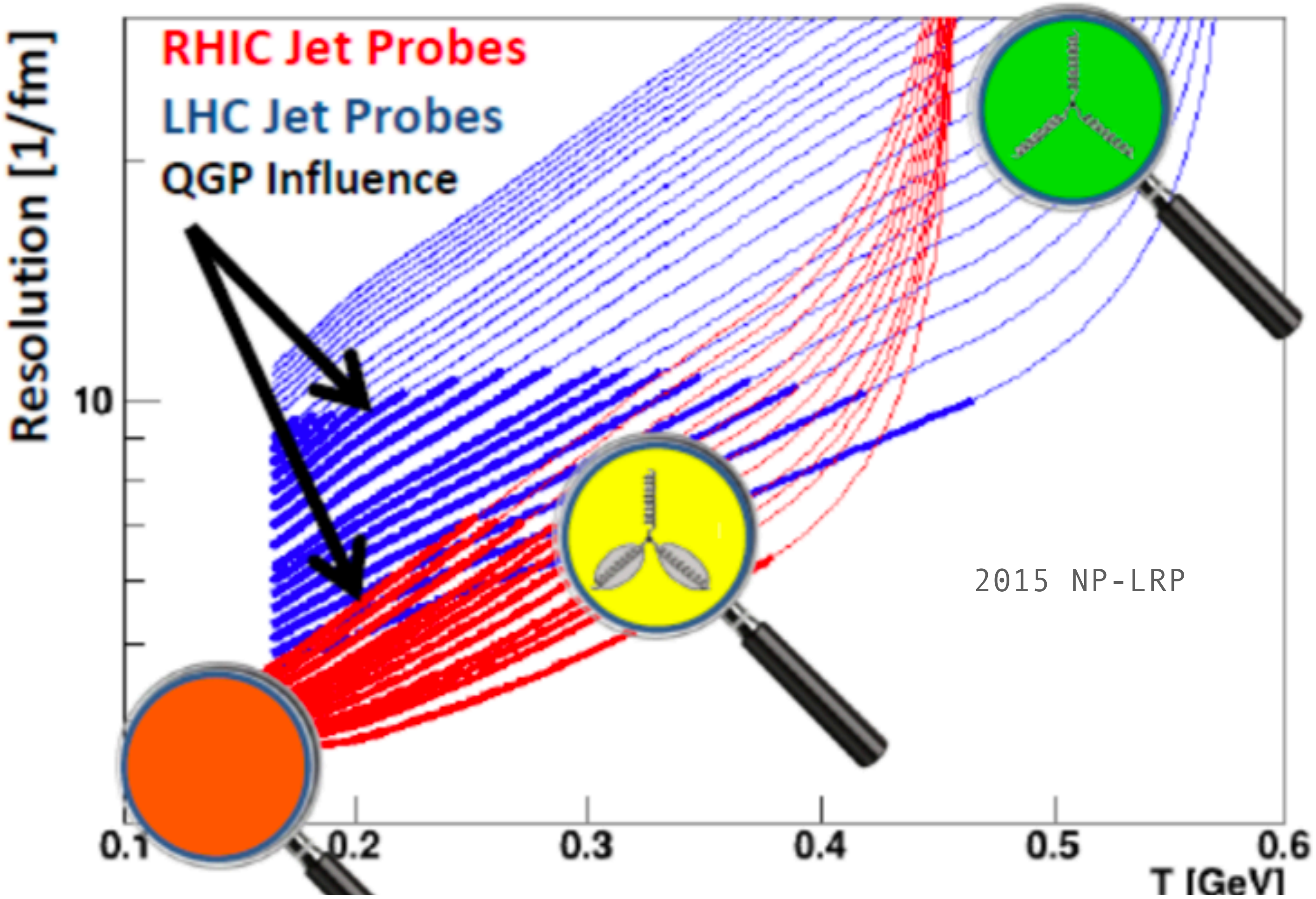
ALICE Heavy Ion Publications

CMS Heavy Ion Publications

STAR Publications

PHENIX Publications

What do we want to measure?



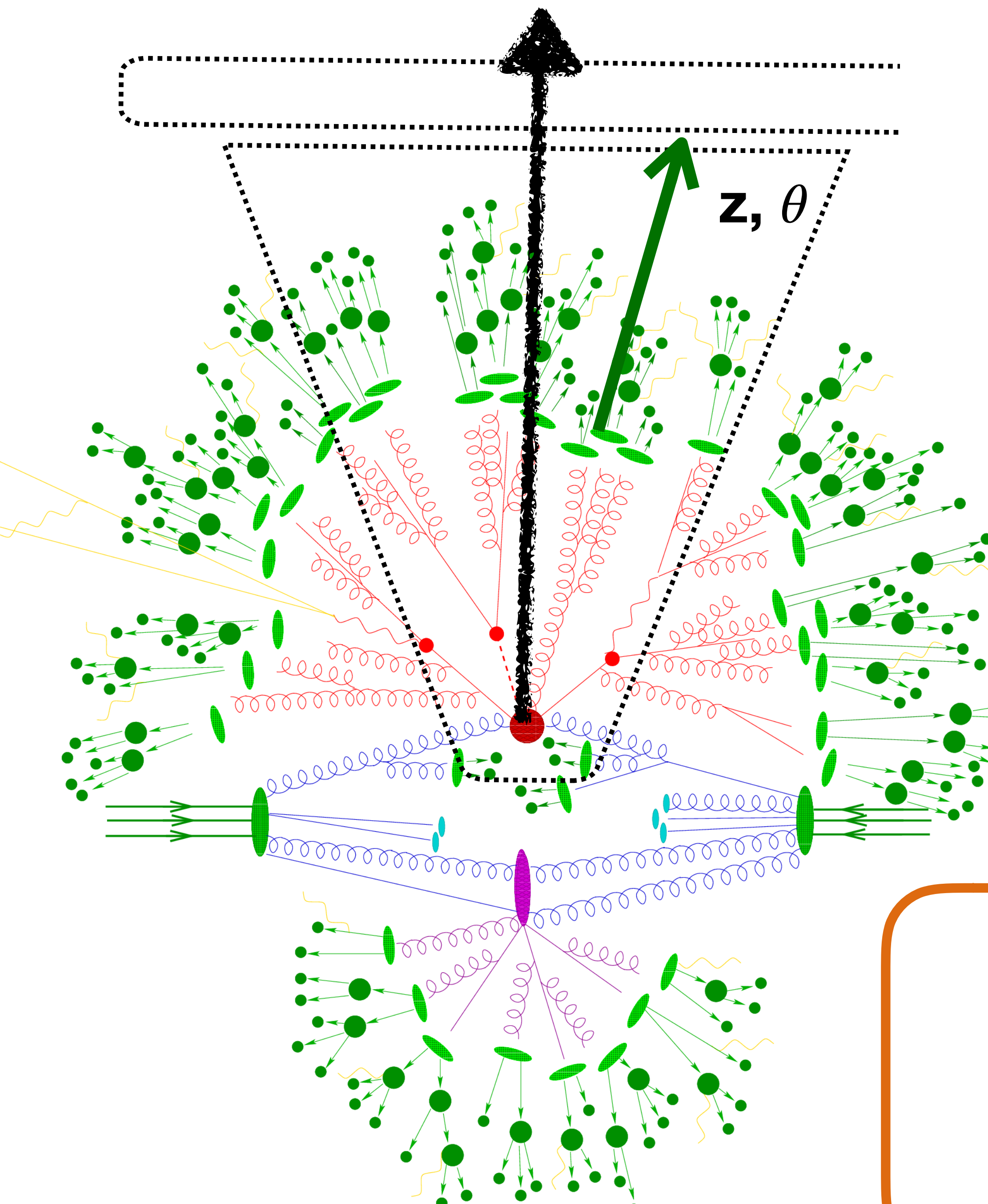
Microscopic properties of the QGP Medium - structure at varying scales

Interaction of the jet with the medium could depend on the resolution scale

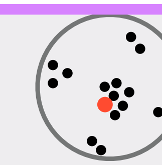
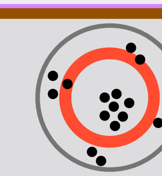
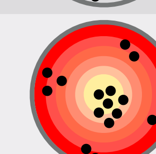
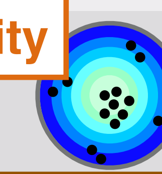
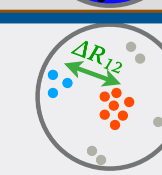
Partonic energy loss via a differential study in momentum scale and angular scale

Jet substructure measurements

Table taken from Jesse Thaler



Fragmentation Functions	Classic Jet Shapes	Groomed Observables
		
Single hadron	*All hadrons*	*Subset of hadrons*

fragmentation function	$D(z) = \left\langle \sum_{i \in \text{jet}} \delta(z - p_{ti}/p_{t,\text{jet}}) \right\rangle_{\text{jets}}$	
differential jet shape	$\rho(r) = \frac{1}{p_\perp^{\text{jet}}} \sum_{k \text{ with } \Delta R_{kJ} \in [r, r+\delta r]} p_\perp^{(k)}\,,$	
girth ≡ broadening	$g = \frac{1}{p_\perp^{\text{jet}}} \sum_{k \in J} p_\perp^{(k)} \Delta R_{kJ}\,,$	
jet mass, groomed & ungroomed	$m^2 = \left(\sum_{i \in (\text{sub})\text{jet}} p_i^\mu \right)^2$	
z_g, ΔR_{12}	$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} > z_{\text{cut}} \left(\frac{\Delta R_{1,2}}{R_J} \right)^\beta$	

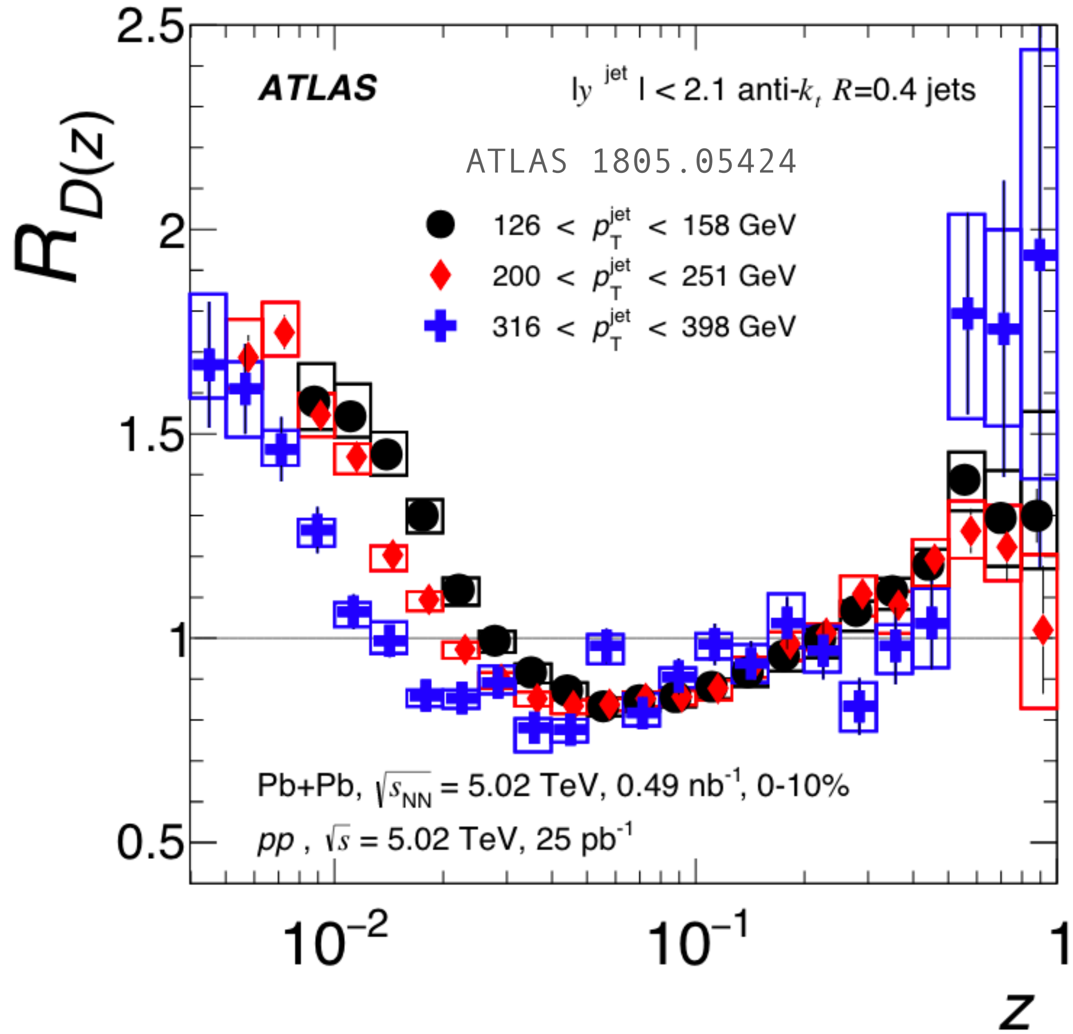
Jet Mass ~ $z\theta^2$ ~ Virtuality

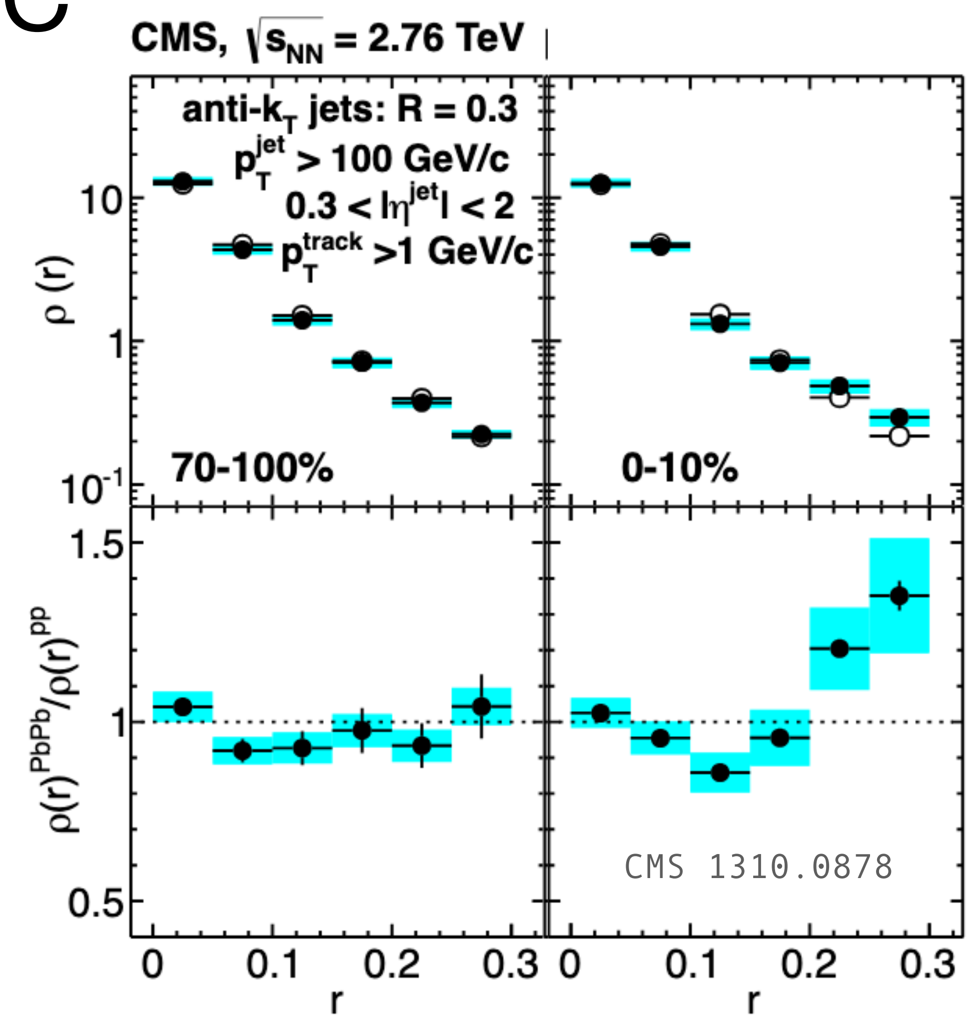
z_g ~ Splitting Function
ΔR_{12} ~ opening angle
(of the *hardest* split)

For SoftDrop see
Ladorzki et al
JHEP 1405 (2014) 146

Intra-jet particle production

At LHC



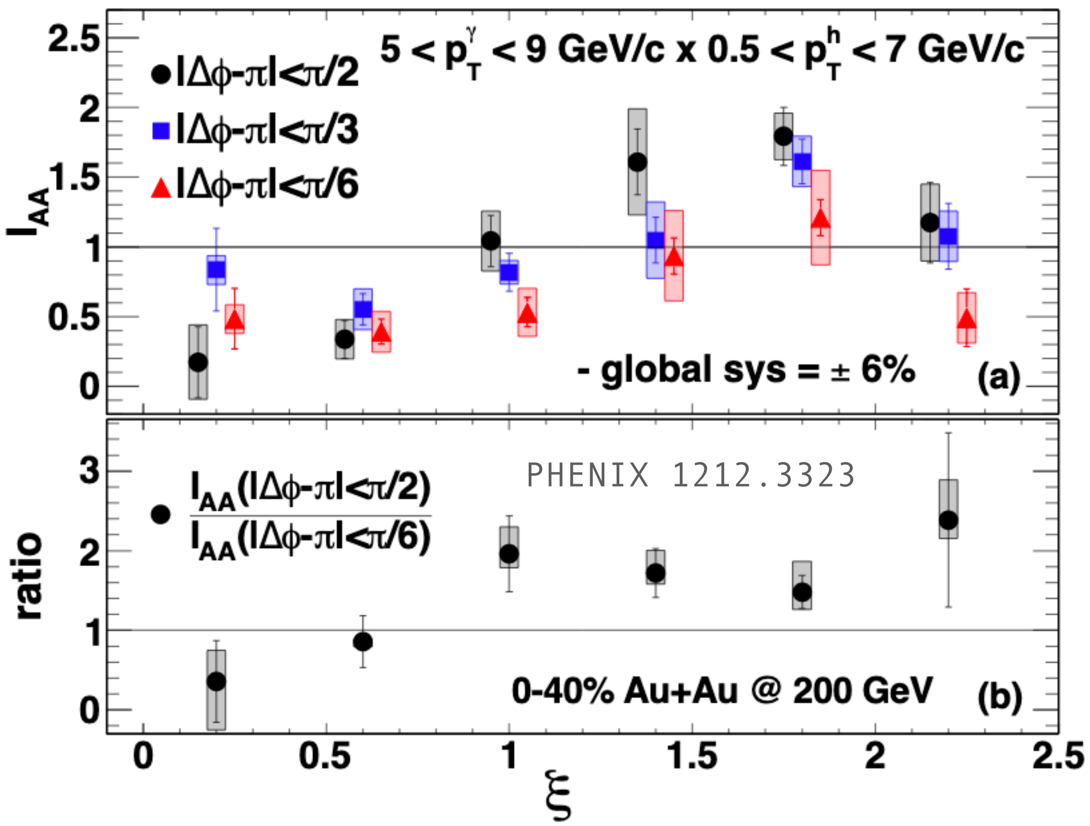


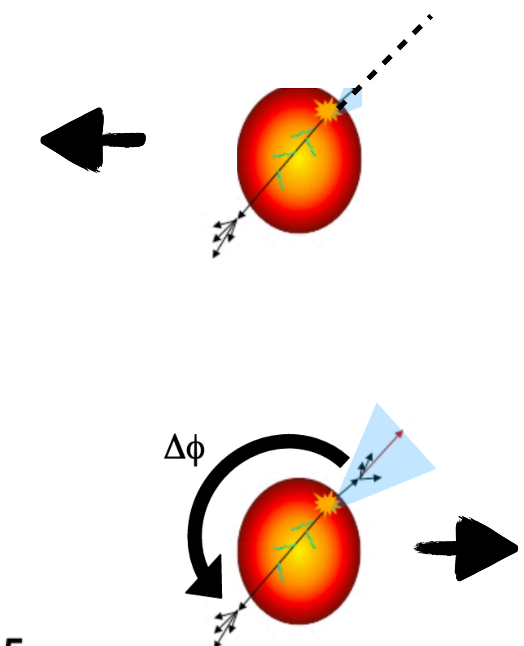
<u>Fragmentation functions and Jet Shapes</u>

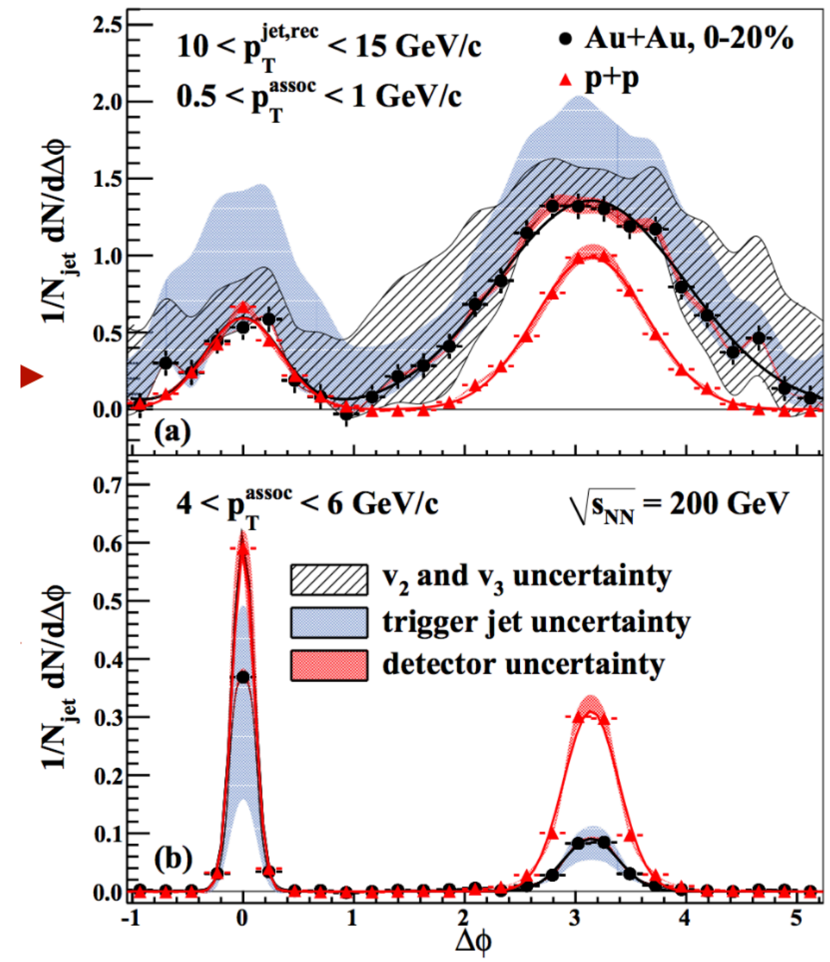
- Enhancement of low z hadrons around the edges of the jet cone (and extending beyond) at similar p_T (3.5 GeV) - points to a medium scale!
- Interesting observation of possible enhancement at high z - Convolution of effects including varying parton flavor and kinematic selection

Jet/γ-Hadron correlations

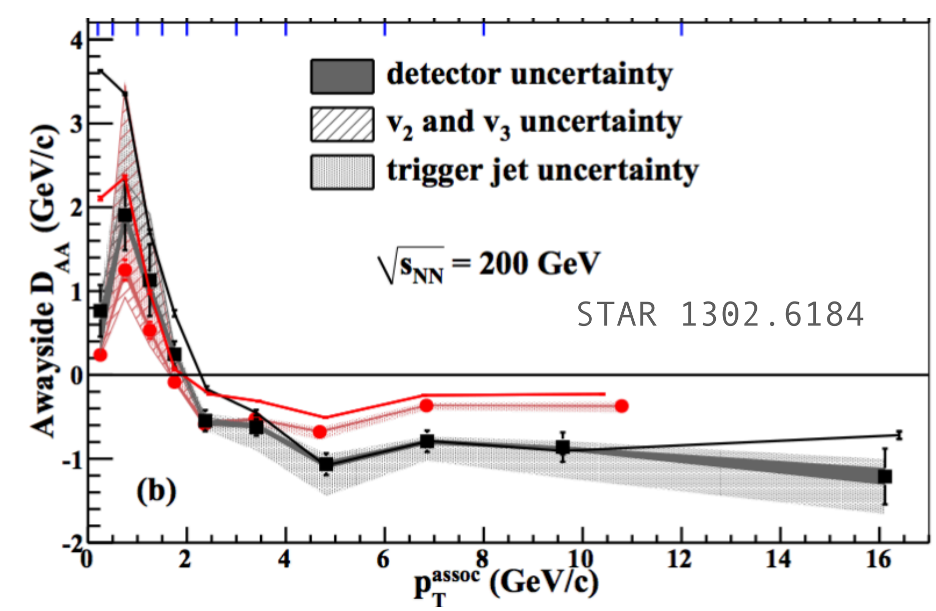
At RHIC





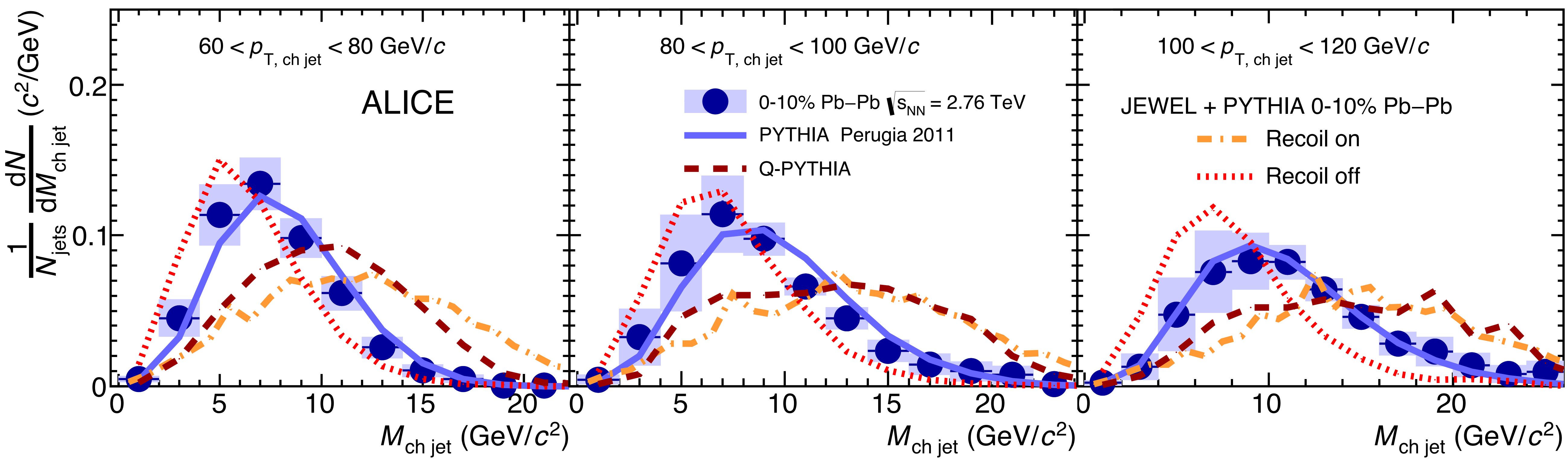


- Suppression of low ξ (high p_T tracks) recoiling off photons
- Clear and consistent signal of enhancement and broadening of recoil jet's low p_T constituents.
- Energy lost by high p_T (> 2GeV) constituents recovered by low p_T (0.2-2 GeV) excess
- Medium scale (2GeV vs 3.5GeV at LHC) smaller at RHIC as expected



Jet Mass ~ zθ^2

ALICE 1702.00804

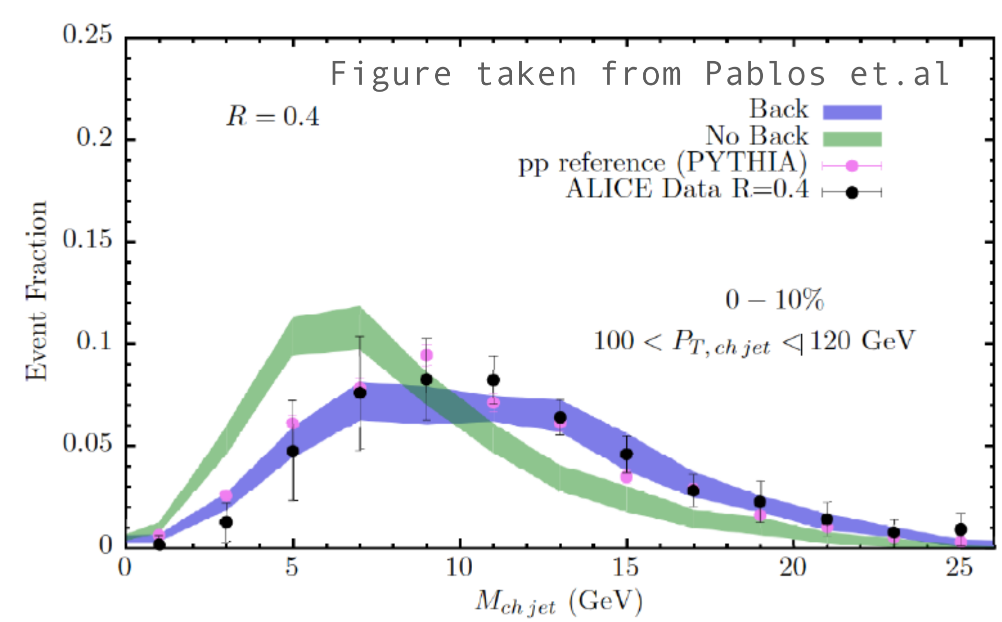


Experimental access to virtuality via jet mass measurements
→ Access to both relevant pQCD quantities: Energy and Virtuality!

Indication of slightly reduced jet mass/lower virtuality in PbPb collisions for lower energetic jets < 100 GeV/c

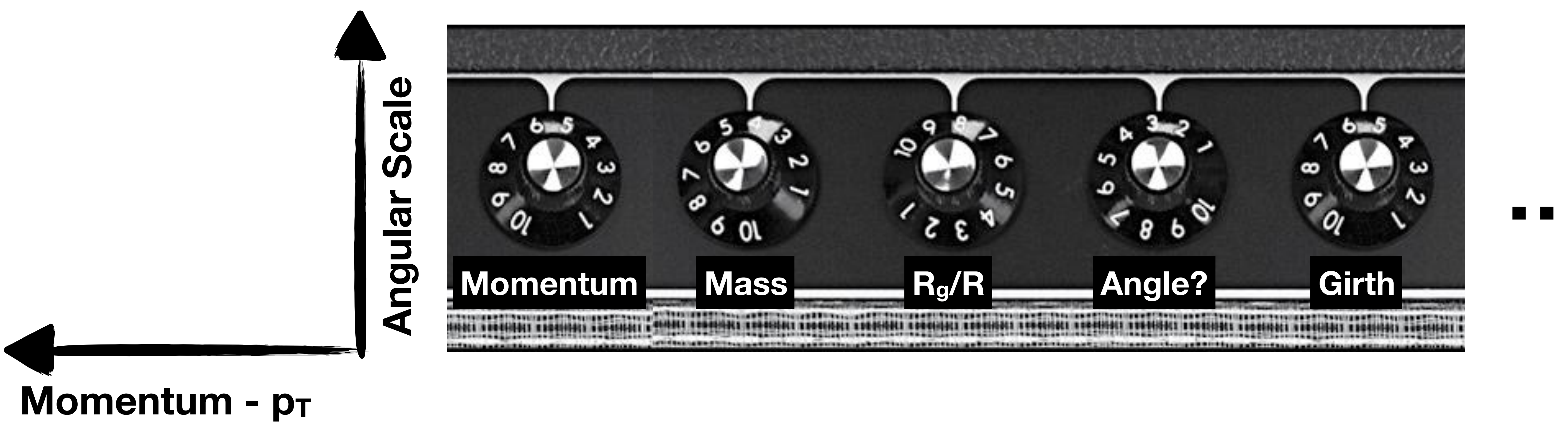
Cancelling effects from medium modifications of the shower and medium response?

Jet Mass at RHIC - work in progress!



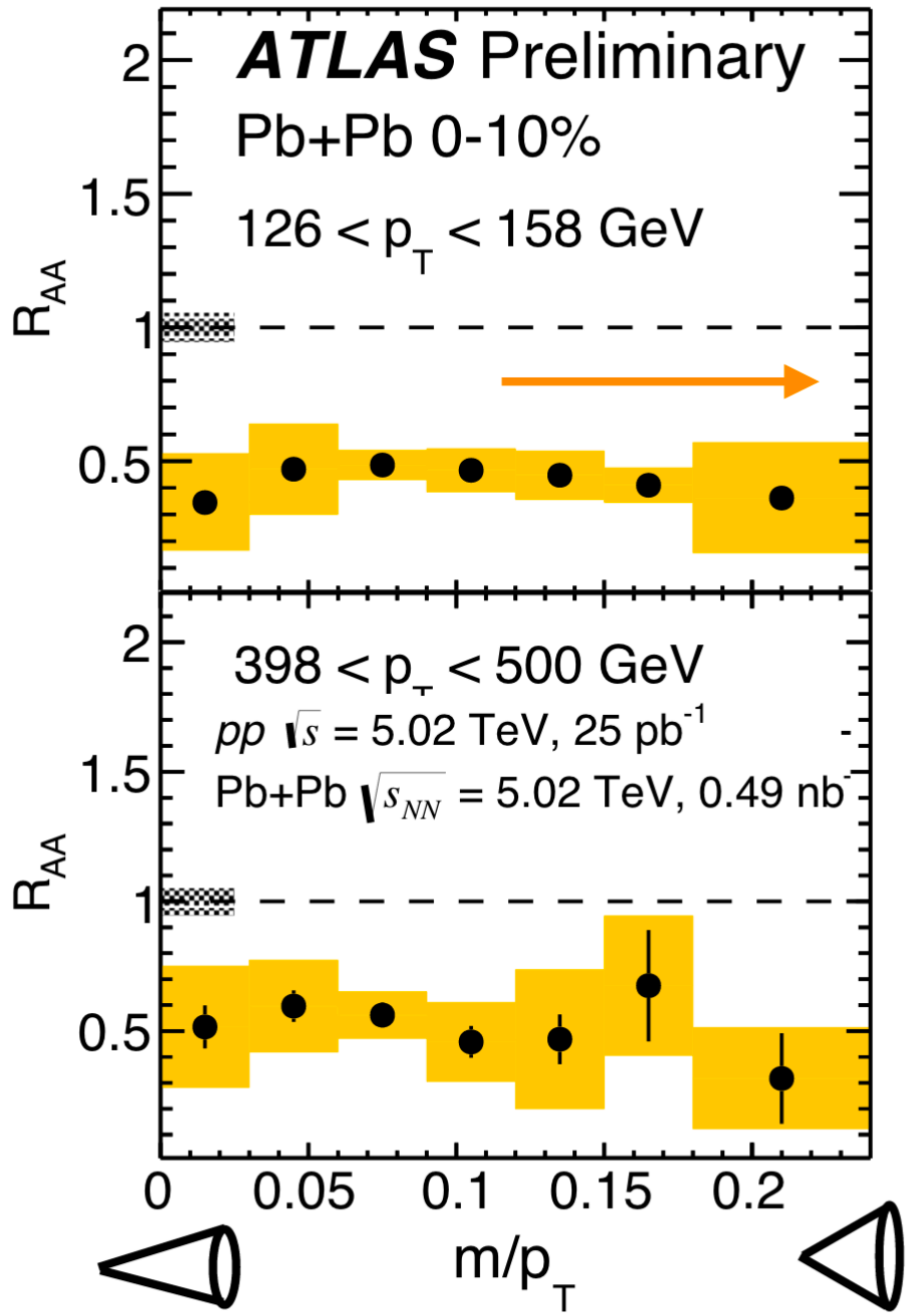
Key Idea
Use jet-substructure as a selection tool

Identify jet observable(s) sensitive to the parton shower kinematics

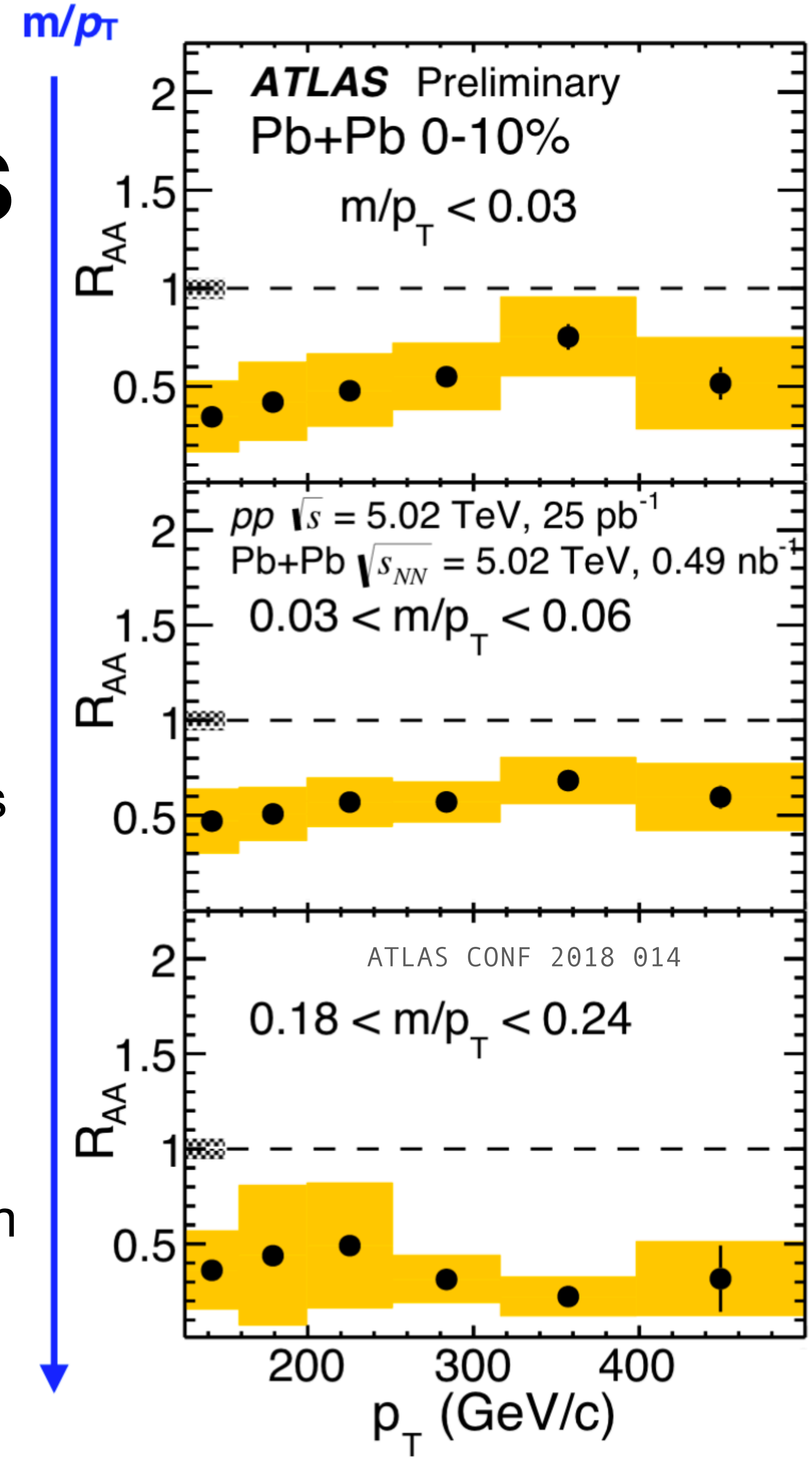


Partonic energy loss via a differential study in momentum scale and angular scale

R_{AA} for various Mass selections



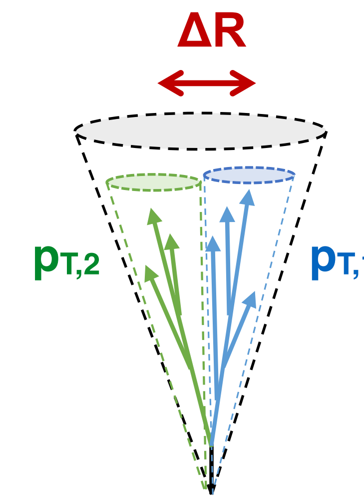
- Observe no significant effect of varying m/p_T
- Jet p_T possibly too high?
- m/p_T bins include jets of varying mass/ smeared resolution scales?
- Mass cancellation effects from quenching vs medium response possible?



Figures taken from Laura Haver's talk at WWND 2019

Tools from HEP

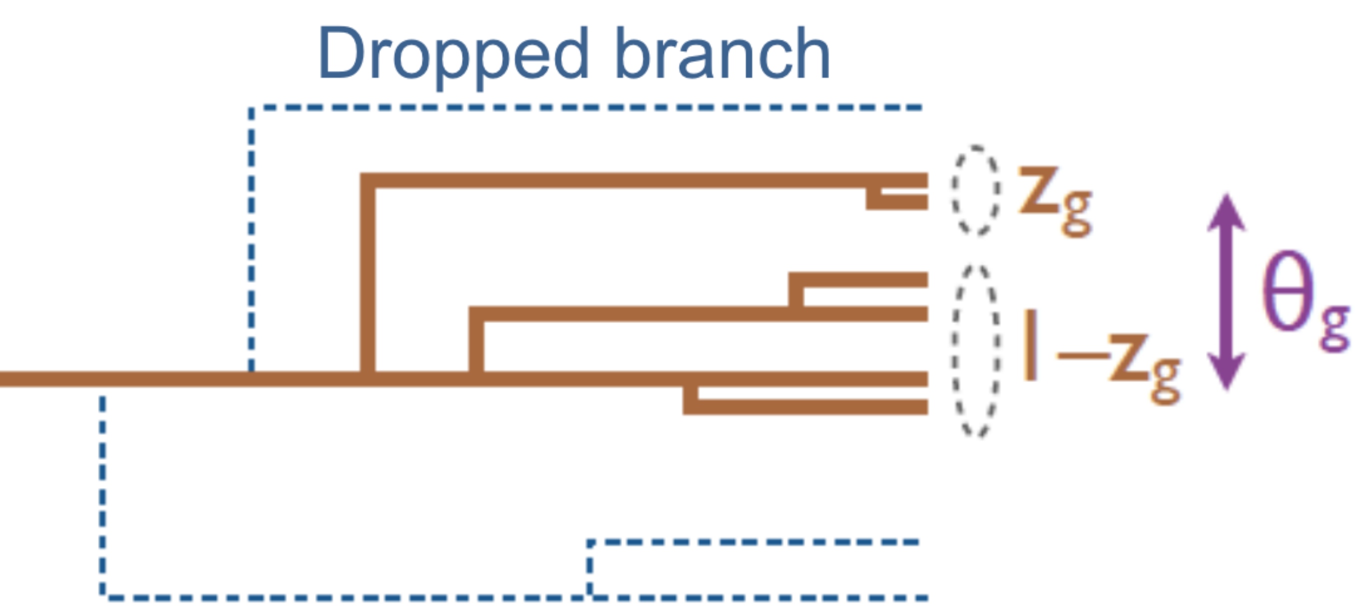
Grooming -> Splitting

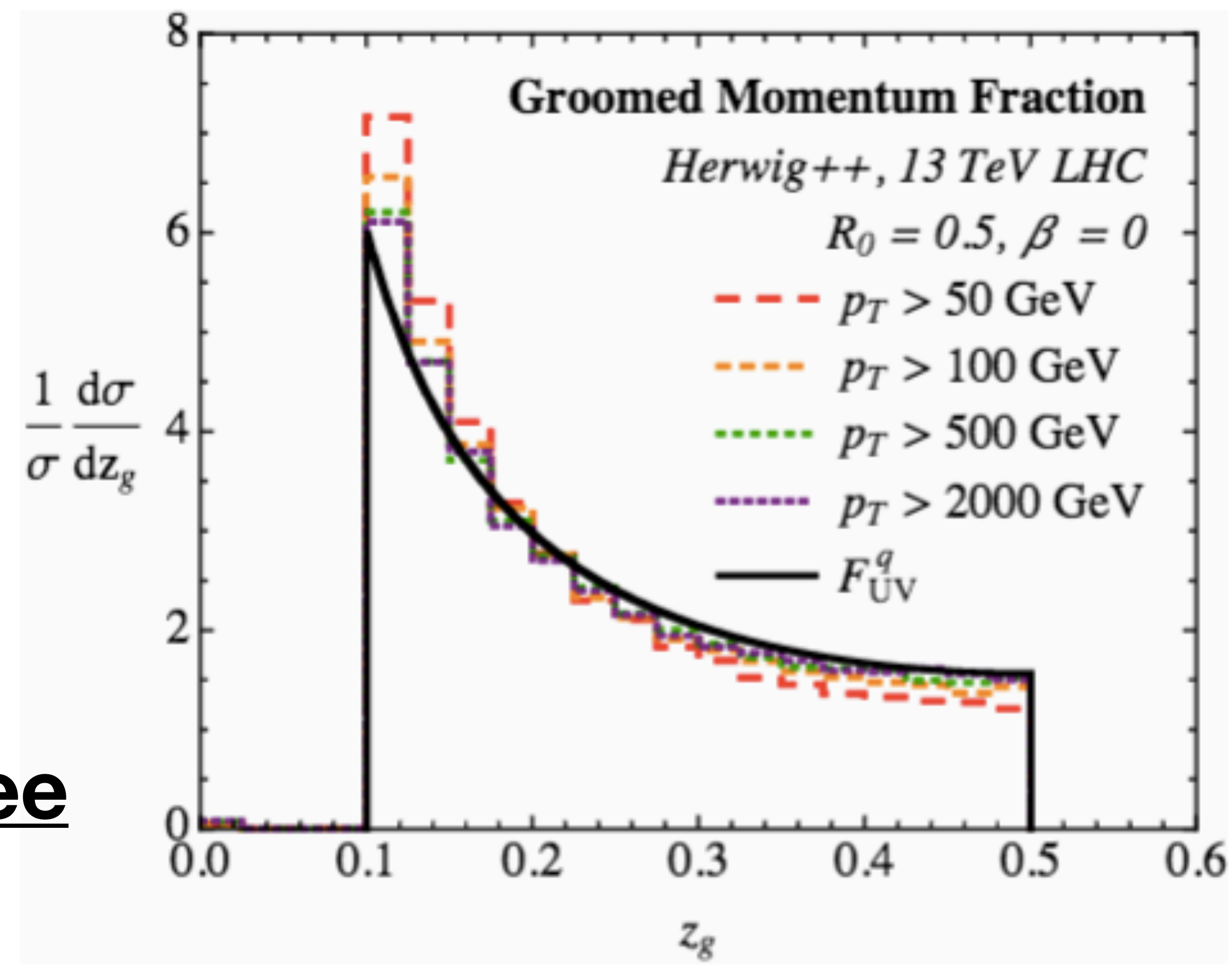


z_g (groomed shared momentum fraction) :

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

$z_{cut} = 0.1$, $\beta = 0$

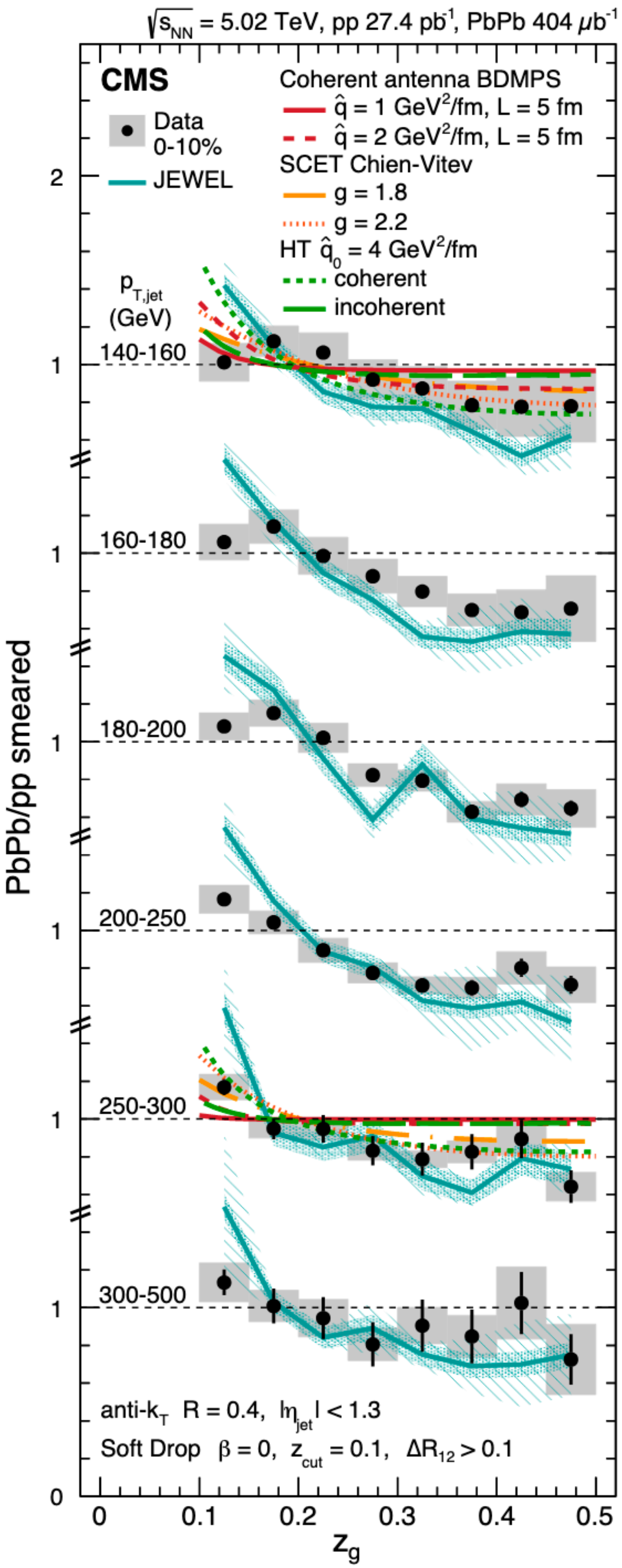


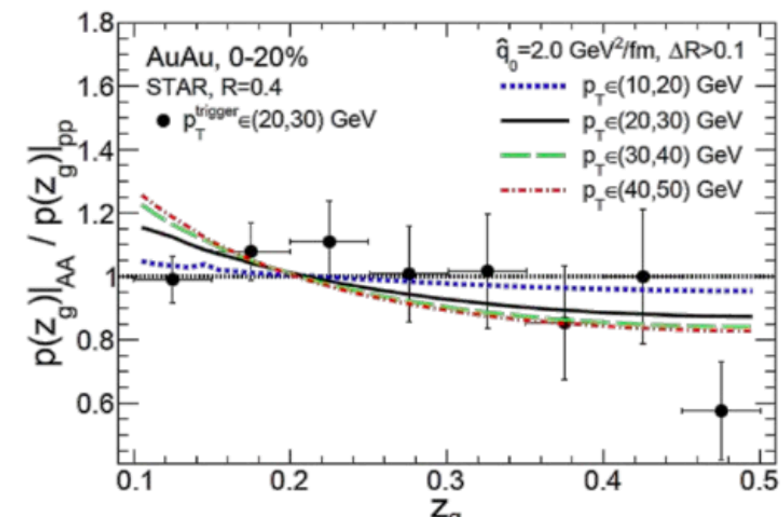


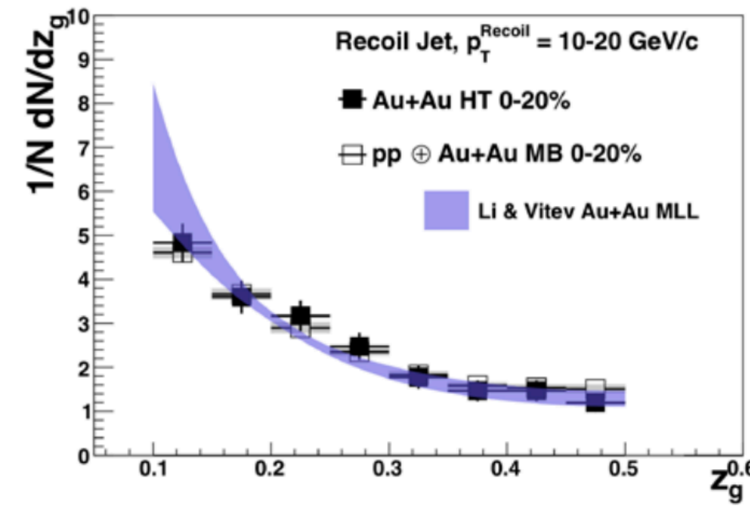
- Walking backwards along a reclustered **angular ordered tree**

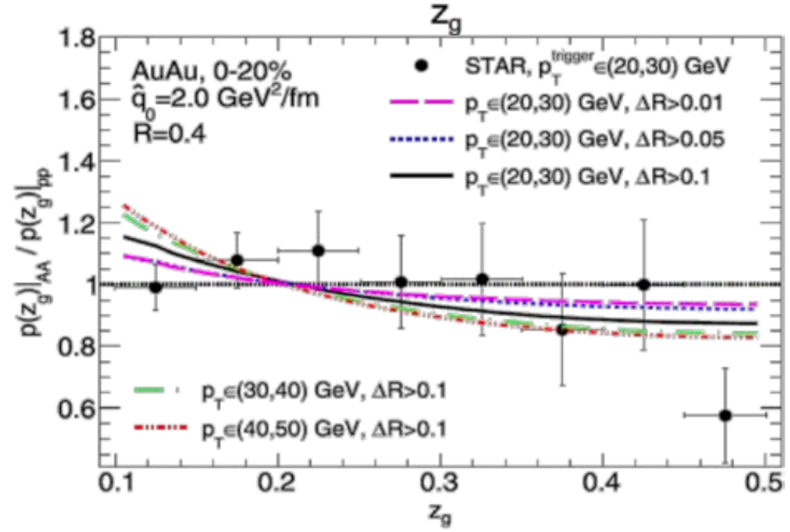
SoftDrop splitting functions

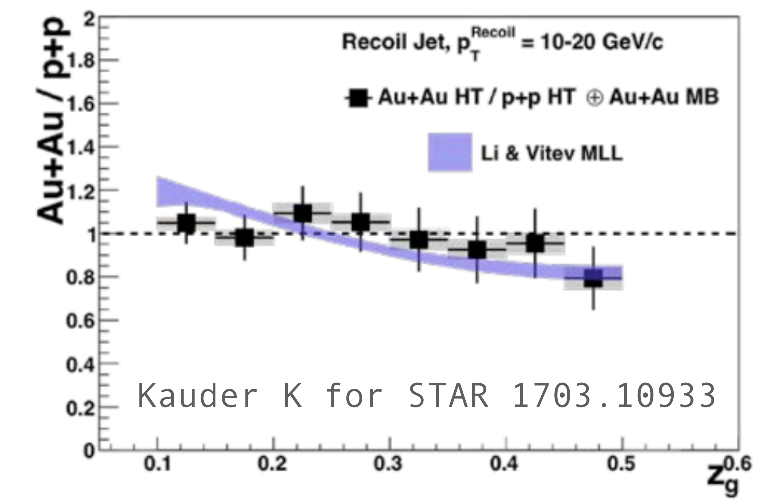
CMS 1708.09429







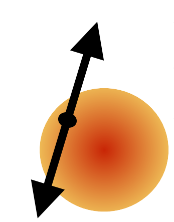




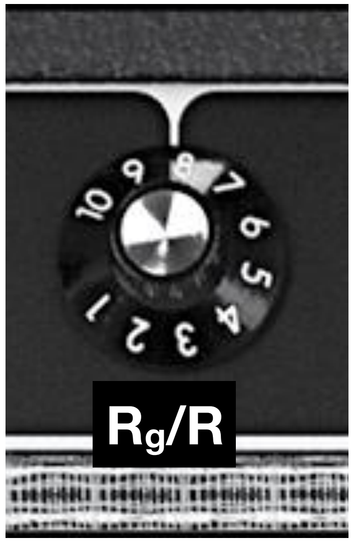
- Self-normalized distributions of z_g shows significant modifications at the LHC
- Dijets at RHIC show no significant modification leading towards jets that have vacuum-like hardest split via softdrop

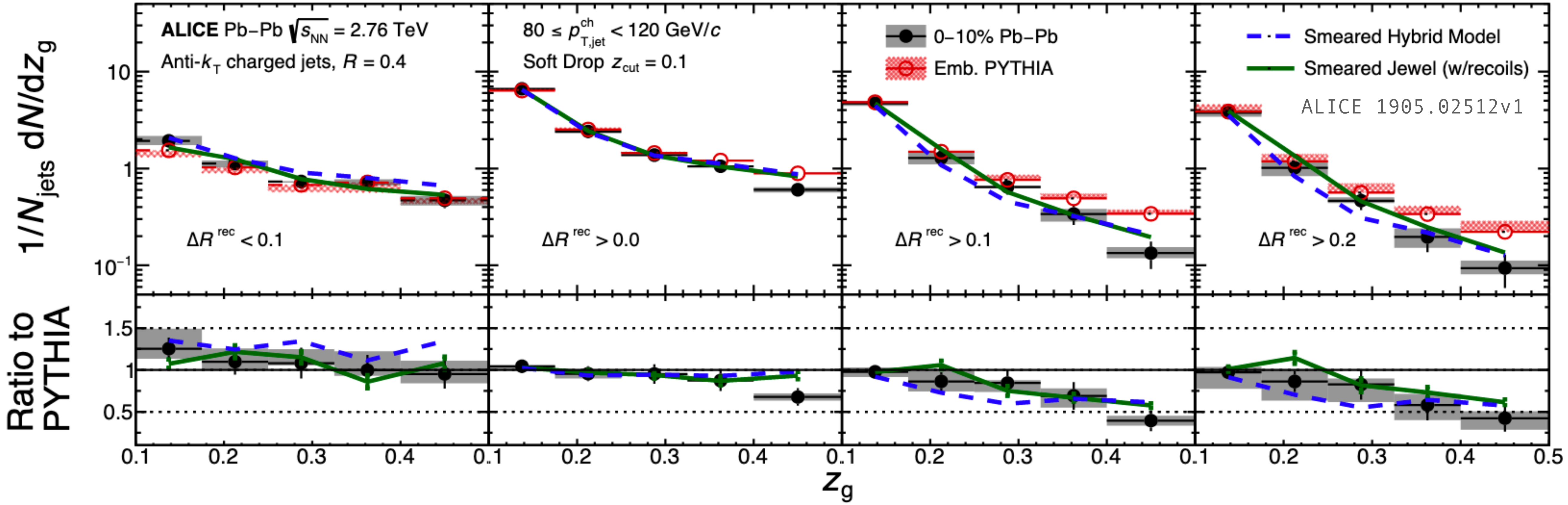
"Jet Geometry Engineering" via constituent p_T cut

$t_f \approx 1/(p_T^{sub}\theta_{SJ}^2)$
~ few fm
~ (biased) medium length



Softdrop splitting at varying opening angles

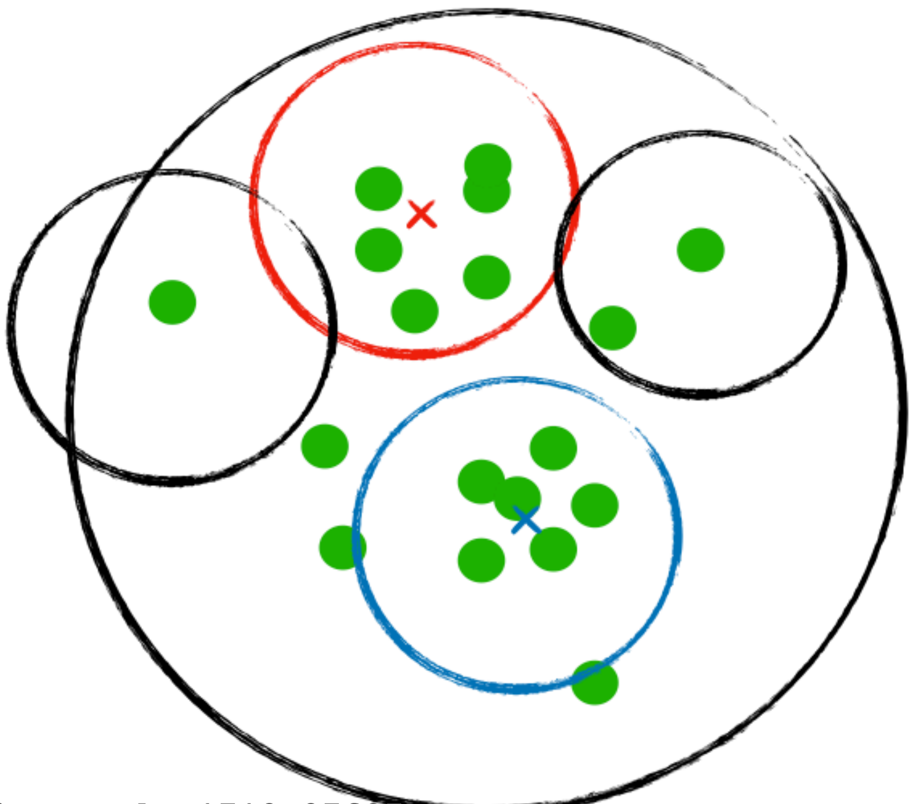




- Suppression of wide angle z_g splits and enhancement of narrow angle z_g
- MC models are generally able to reproduce the trend but further systematic studies are needed to discriminate these models

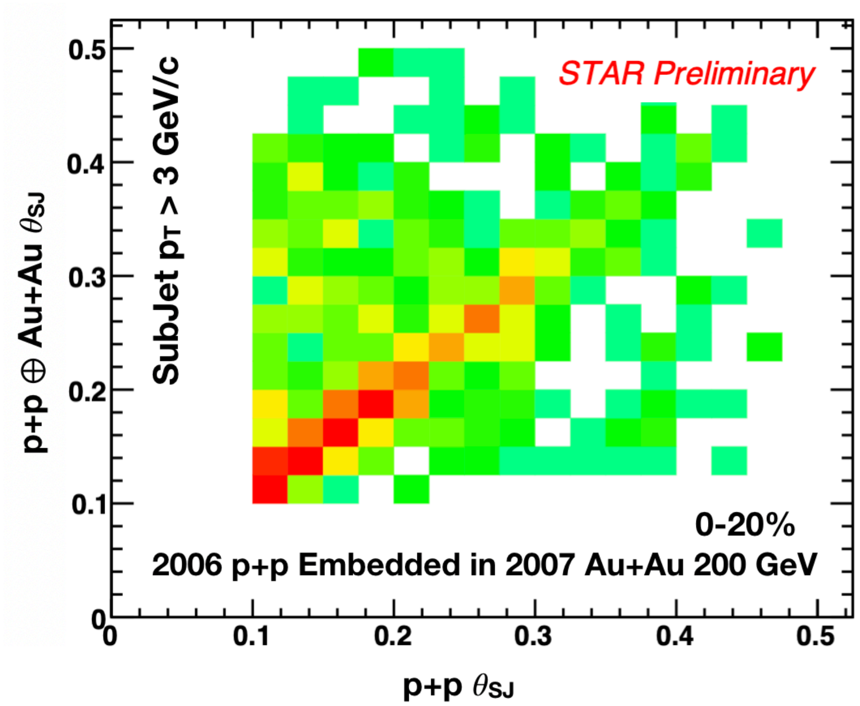
Utilizing subjets of smaller R

Need techniques and observables that are robust to underlying event background especially at RHIC



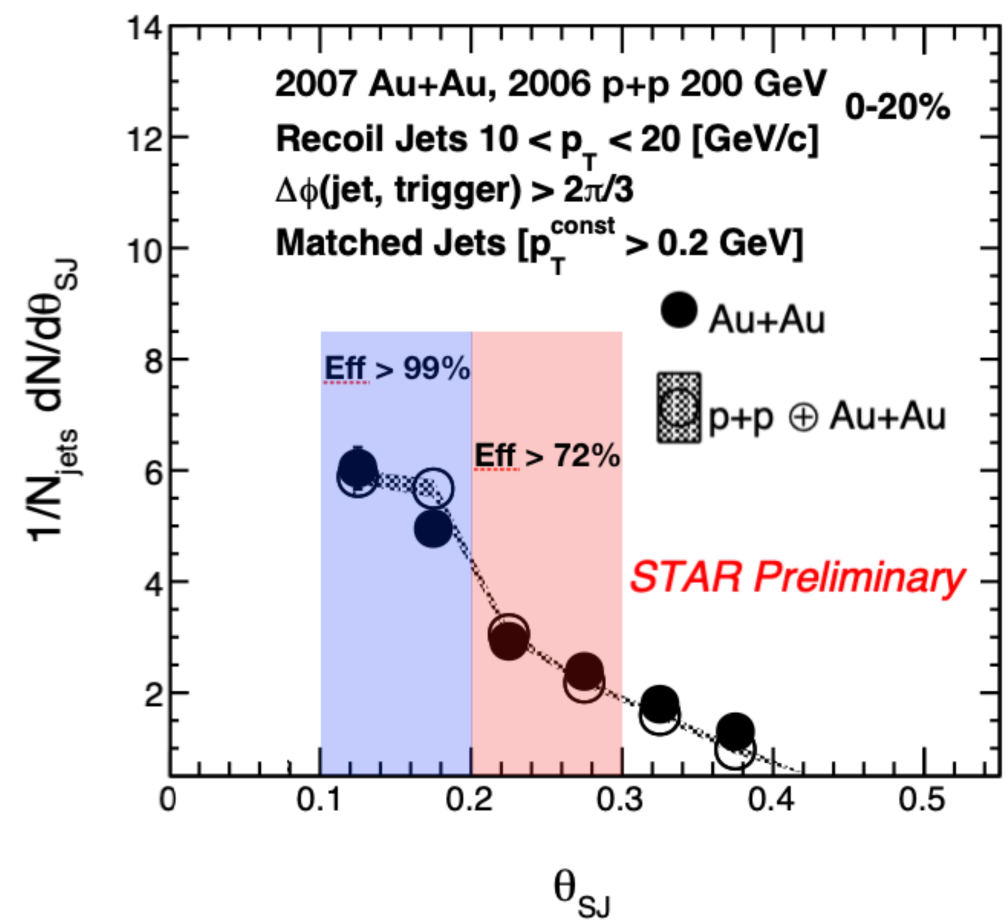
Apolinario et al. 1710.07607

- Recluster jet constituents with a smaller radius - identify regions of jet-like features within the mother jet
- Choose the **leading** and **subleading** SubJets
- z_{SJ} = **Blue p_T** / (**Blue p_T** + **Red p_T**)
- θ_{SJ} = **Δ R (Blue Axis, Red Axis)**



anti-k_t R^{jet} = 0.4
Ch+Ne Jets, |η|+R^{jet} < 1.0
20.0 < p_T < 30.0 [GeV/c]
Recoil jets $\Delta\phi_{jet, HT}$ > 2π/3
Constituent-subtracted jets
Berta, P et al. JHEP 06 (2014) 092

- θ_{SJ} (w/ R=0.1 SubJets) **less sensitive to AuAu underlying event**



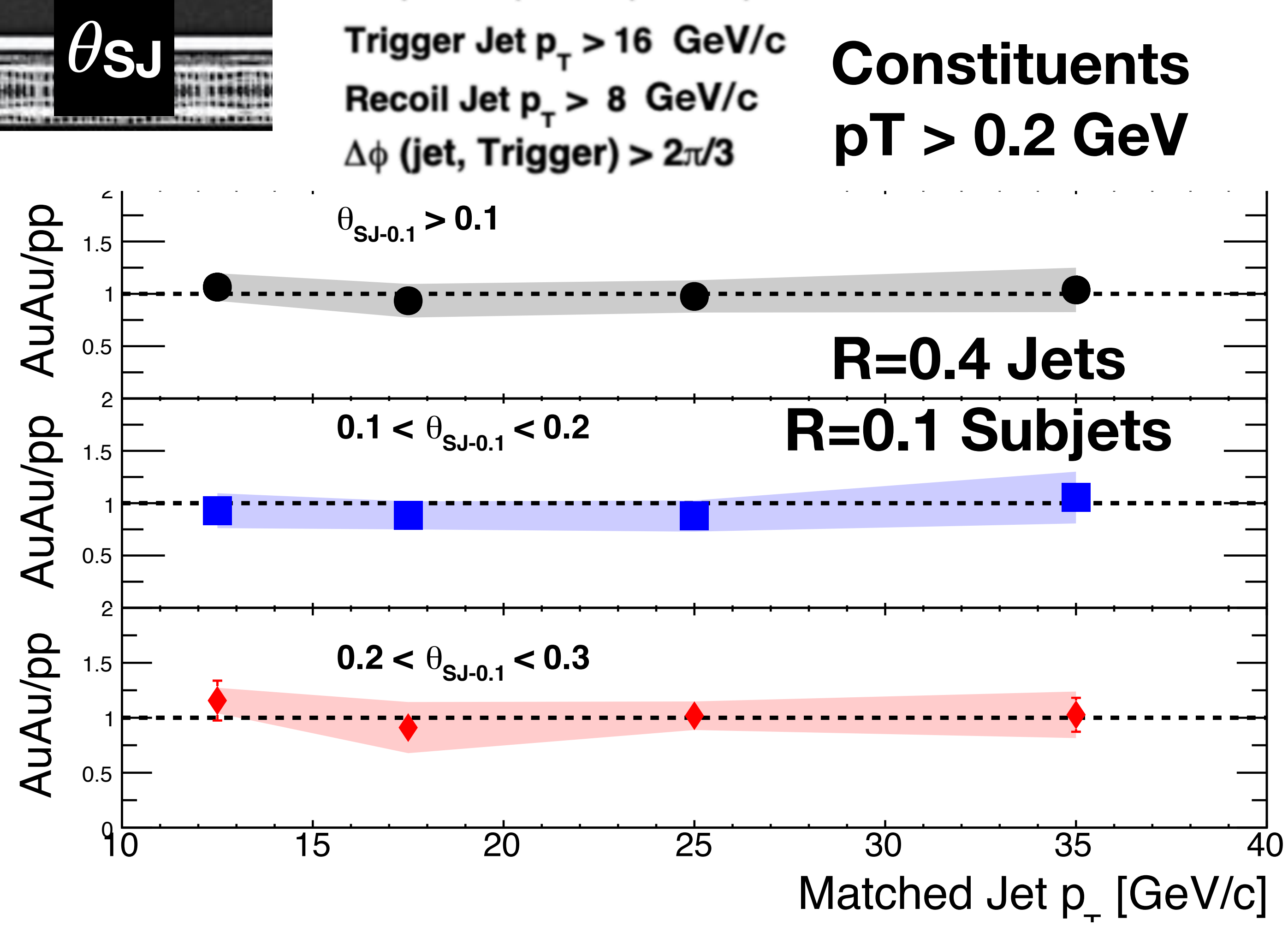
RKE for STAR 1903.12115

Jet Quenching at varying opening angles

Constituents pT > 0.2 GeV

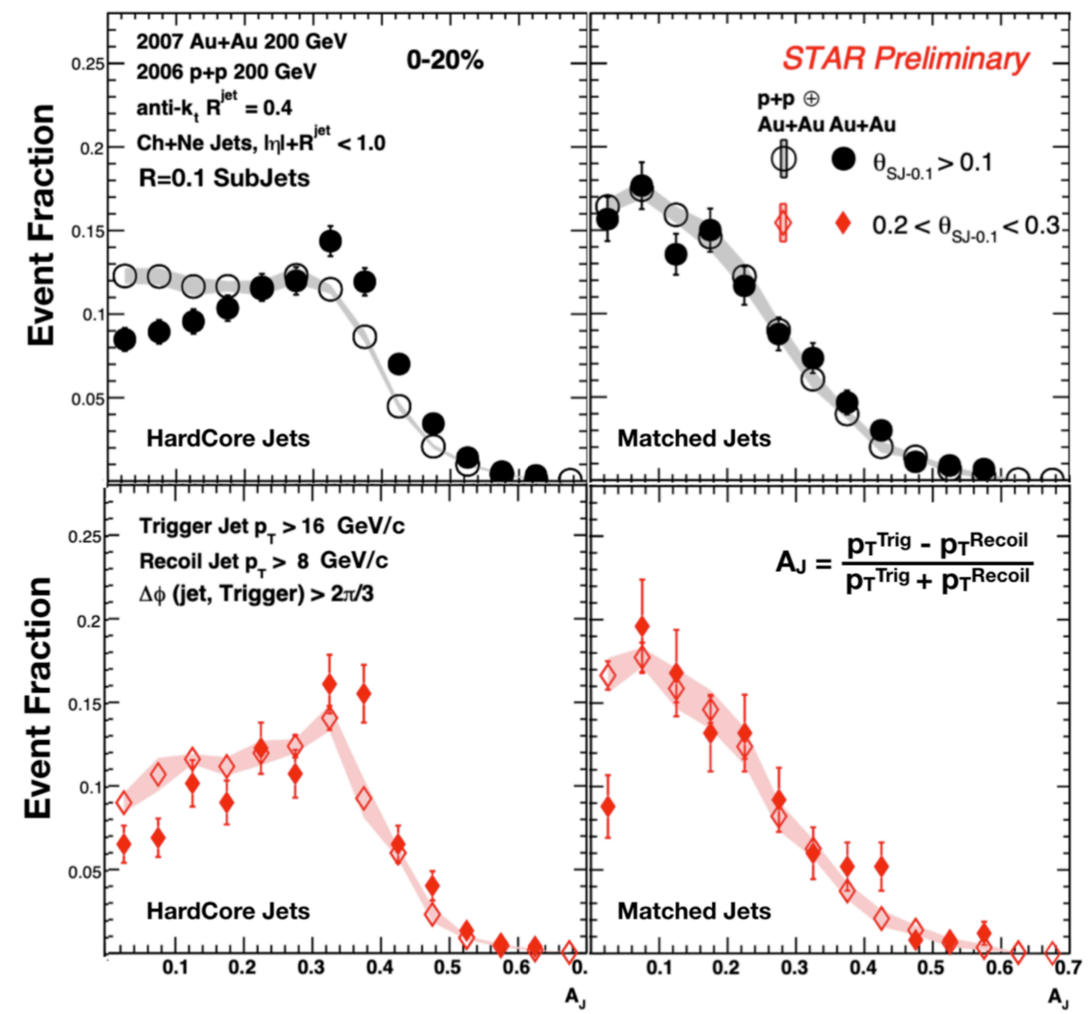
R=0.4 Jets

R=0.1 Subjets



Constituents pT > 2 GeV

Constituents pT > 0.2 GeV



RKE for STAR 1903.12115

- With the Dijet selection at STAR, we don't observe any significant differences in jet quenching and energy recovery between θ_{SJ} selections
- Given later splits and Jet Geometry Engineering and surface bias, first split most likely outside the medium and resulting modification is **Soft gluon (0.2-2 GeV) radiation from a single color charge!**

Conclusions

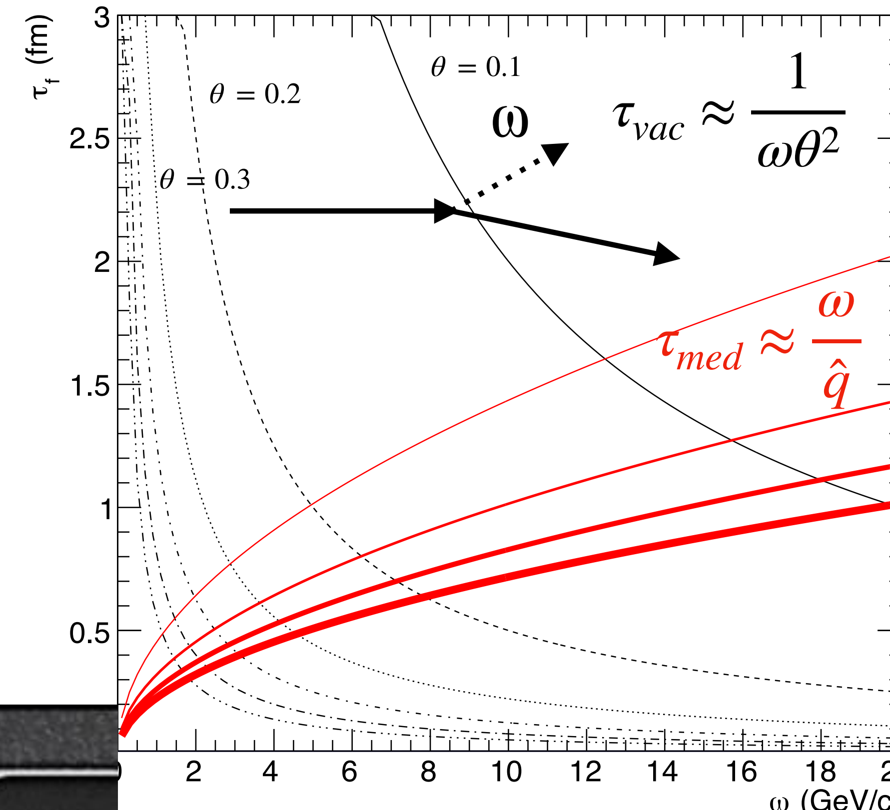
- Utilize jet substructure and measurements of angular scale <=> resolution scales and differentially study microscopic properties of the QGP

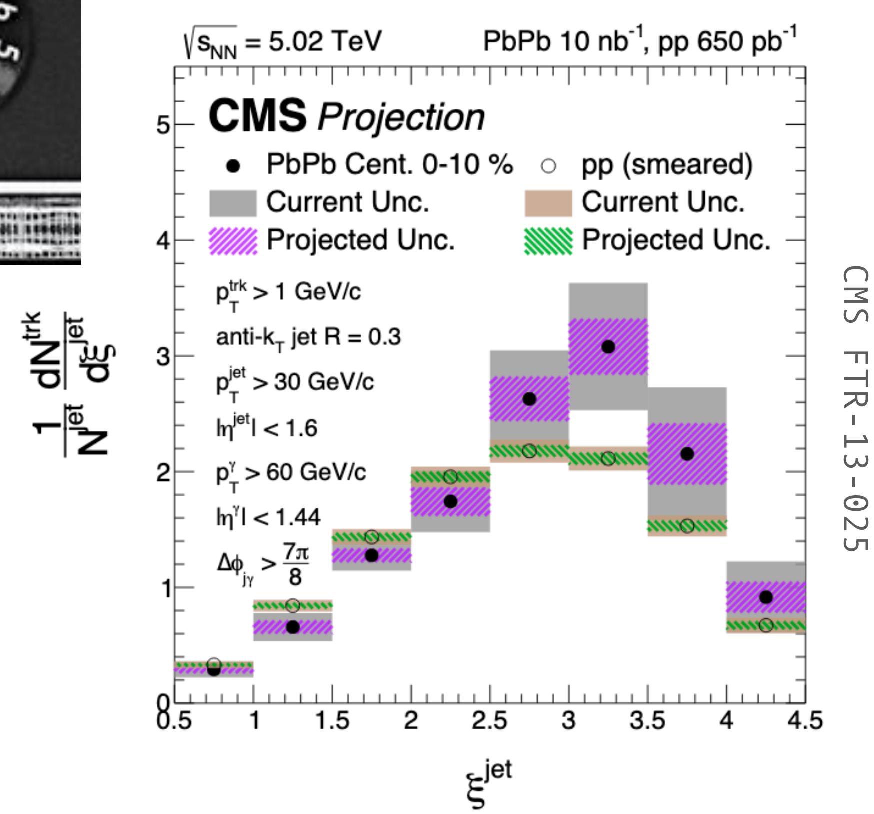
- Complementarity of measurements at RHIC and LHC are crucial for this purpose - Similar measurements at similar kinematics but varying medium temperature and energy density
  - At LHC - the lost energy is found in low pT particles around the hemisphere
  - At RHIC - Depending on your event selection, you can recover the lost energy in particles 0.2 - 2 GeV within the jet cone!

- Jet substructure measurements offer sensitivity to description of jet-medium interactions and ability to discriminate between MC models

Moving forward

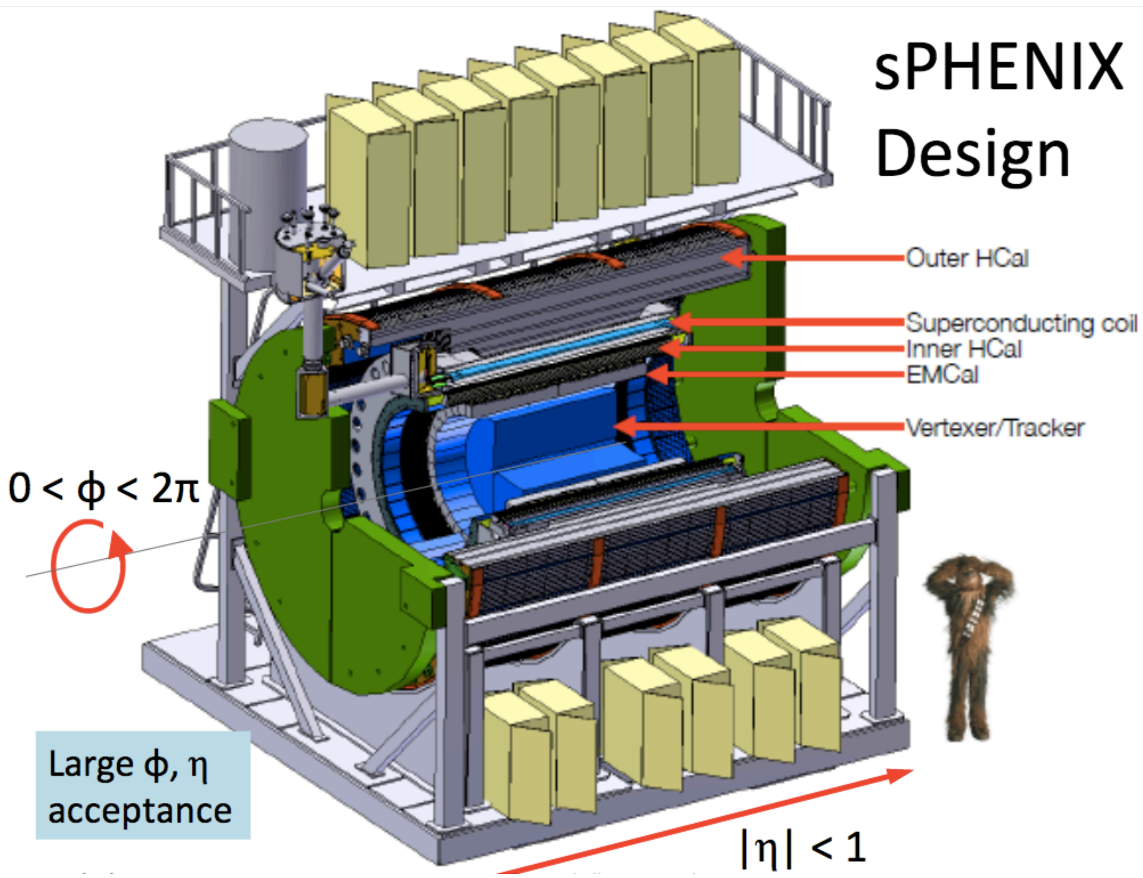
- Game of high statistics - 2018 Data from LHC and 2014 and 2016 data from RHIC
  - Differential studies in both momentum and angular scales
  - Enhance rare hard probes high pT prompt photons/Zs recoiling off jets
  - Jet-Hadron Chemistry and its modifications leading towards hadronization studies
  - Systematic mapping of the splitting phase space within jets - via formation time arguments

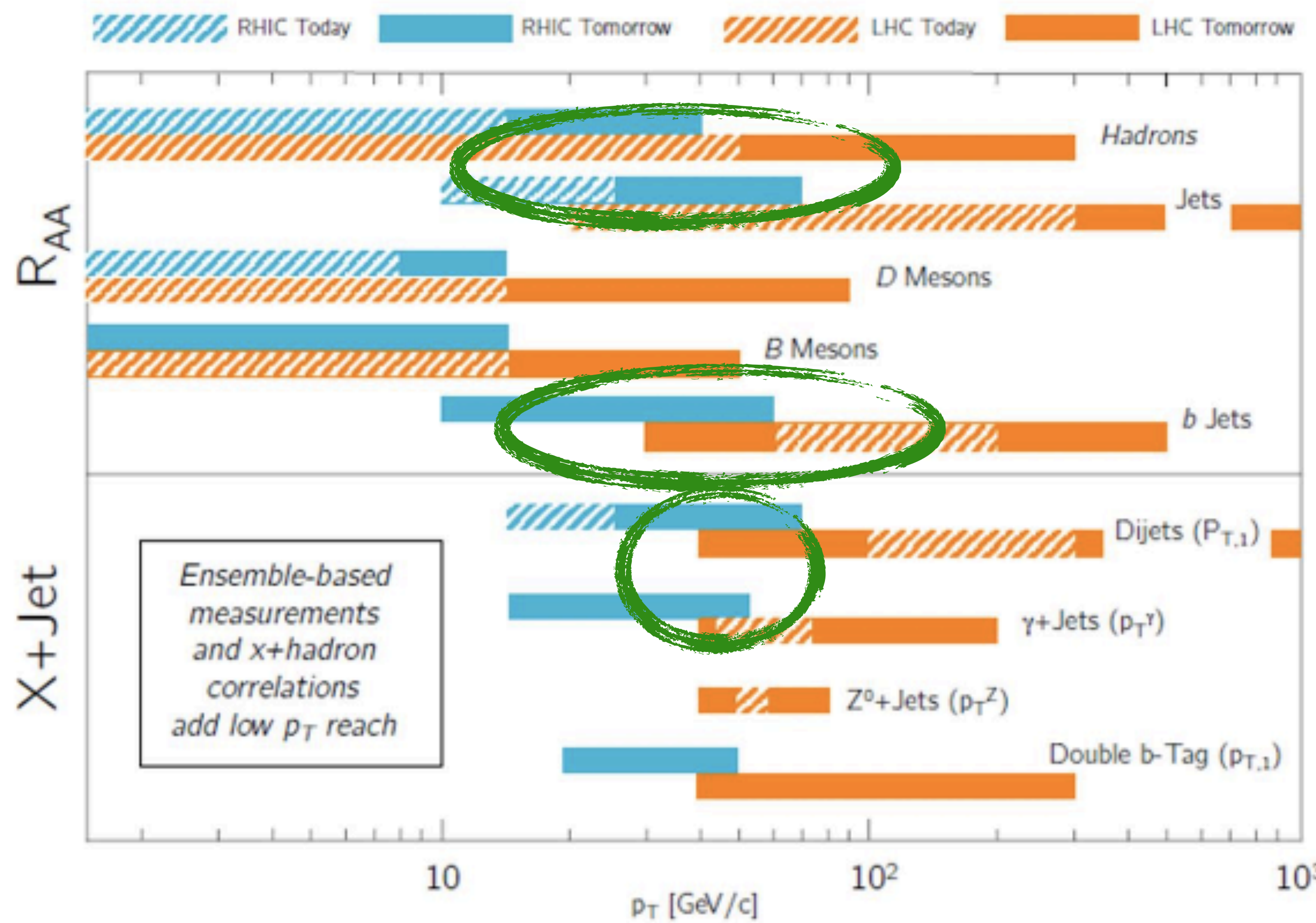




- High luminosity LHC - expect an order of magnitude increase in statistics along with enhancements in detector technologies - reduced uncertainties

Looking towards the future at RHIC - sPHENIX





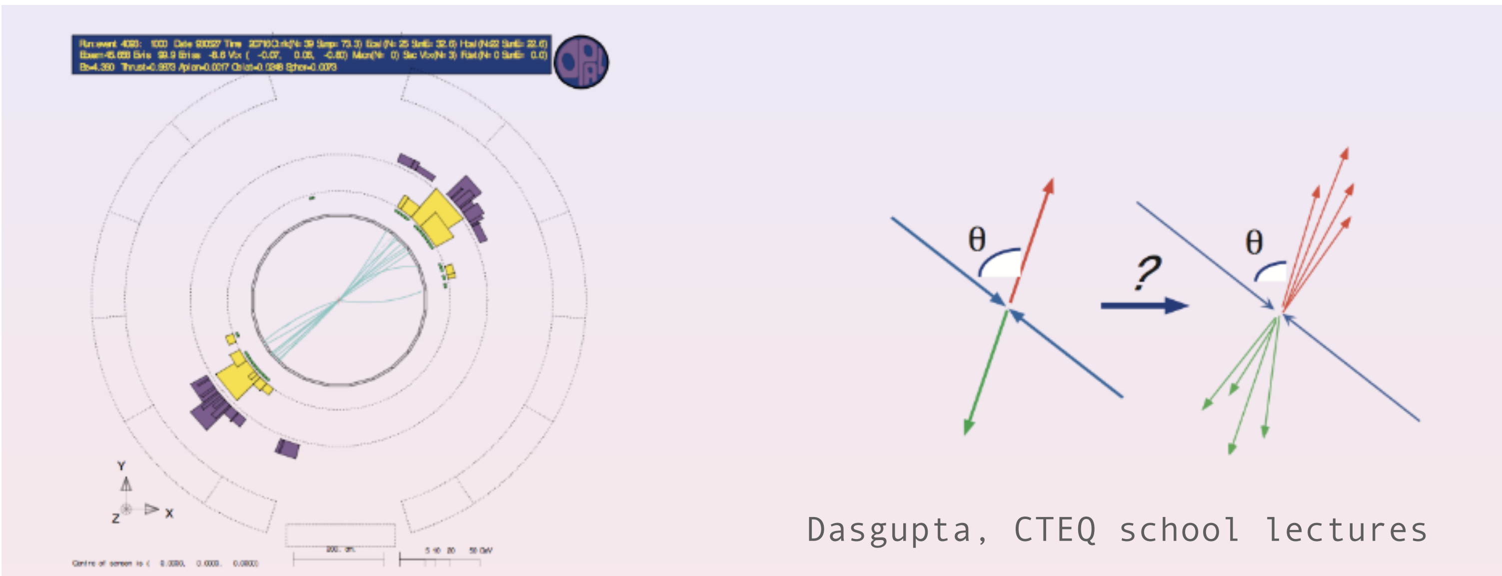
Timescale ~2023 data-taking

Figure Credit - Gunther Roland

- LHC capability at RHIC energy - fast/continuous readout
- Kinematic overlap -> RHIC/LHC complementarity

Backup slides

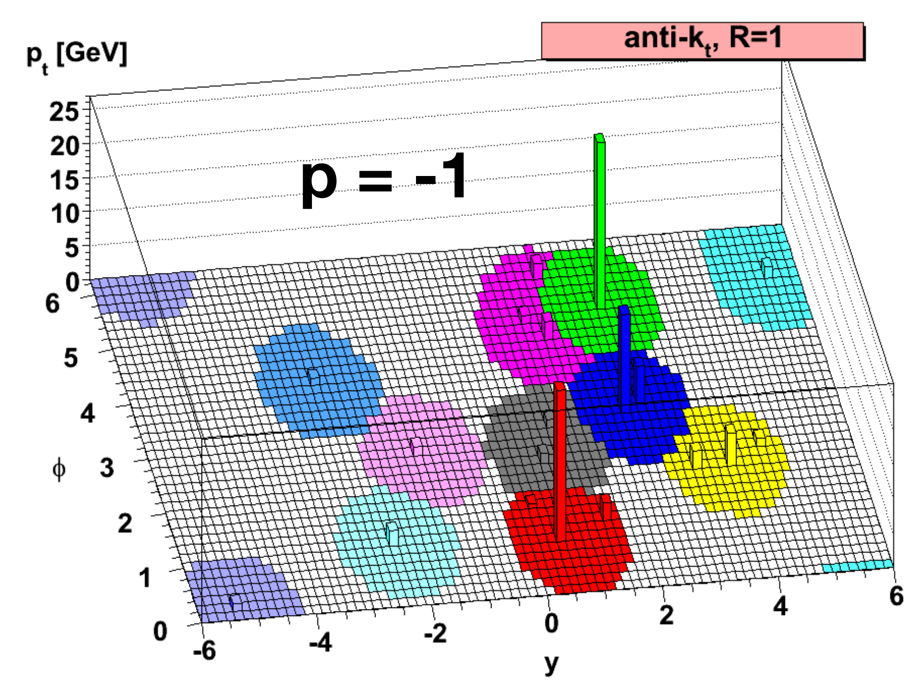
Origin story of Jets



Jets (narrow collections of particles) in e+ e- collisions were the first verification of quarks, gluons and confinement

Clustering algorithms converts particles to jets infrared and collinear safe algorithms are a necessary agreement between theory and experiment

$$d_{ij} = \min(\mathrm{k}_{\mathrm{t,i}}^{2\mathrm{p}}, \mathrm{k}_{\mathrm{t,j}}^{2\mathrm{p}})\ \Delta \mathrm{R}_{\mathrm{ij}}^{2}/\mathrm{R}^{2}$$
$$d_{iB} = k_{t,i}^{2p};\ p = -1,\ 0,\ 1$$



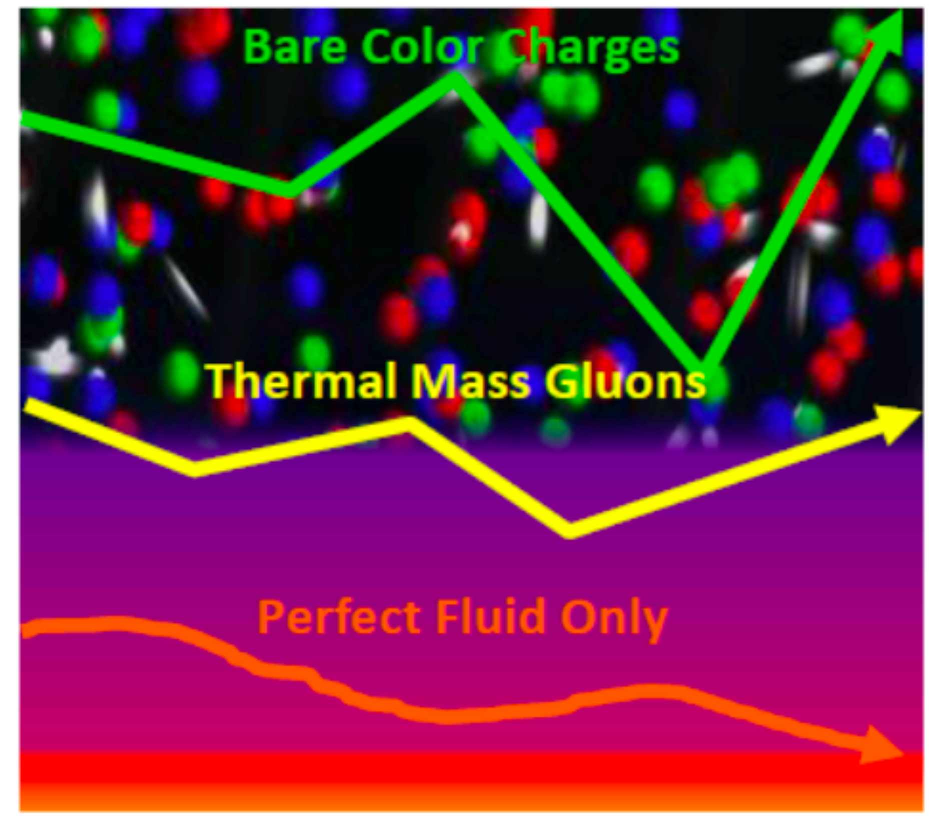
What did we expect?

Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J.D.Bjorken, FERMILAB-Pub-82/59-THY

hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

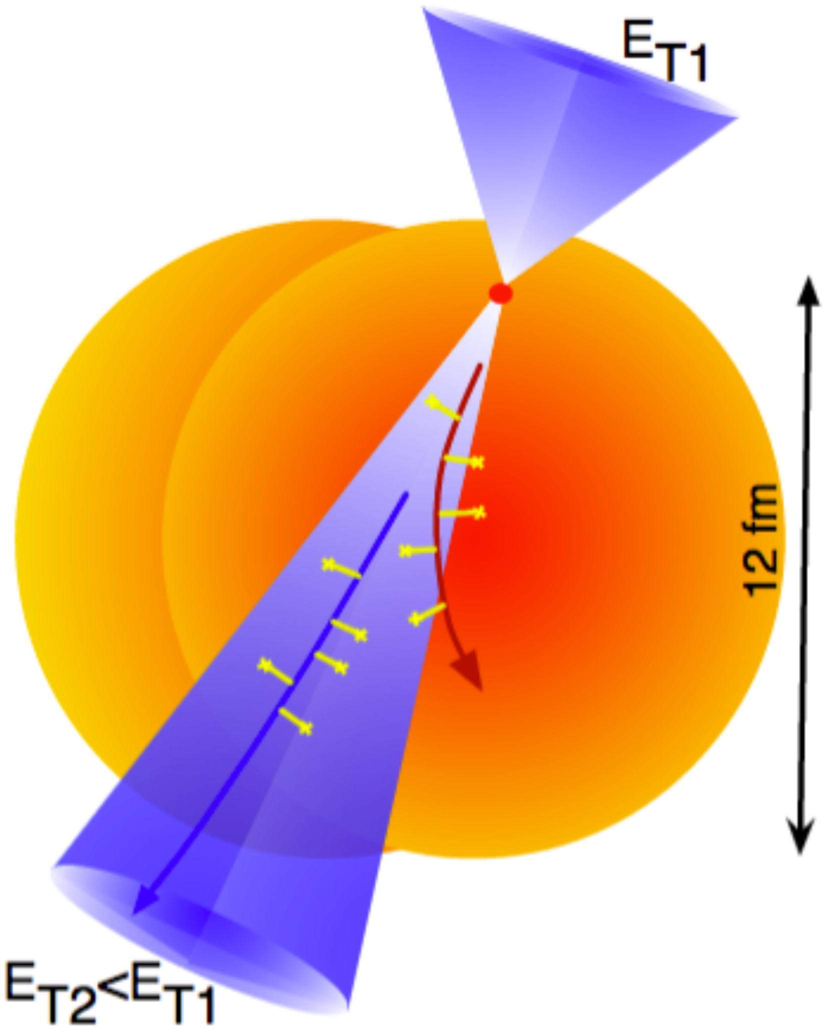
Image credit - 2015 LRP

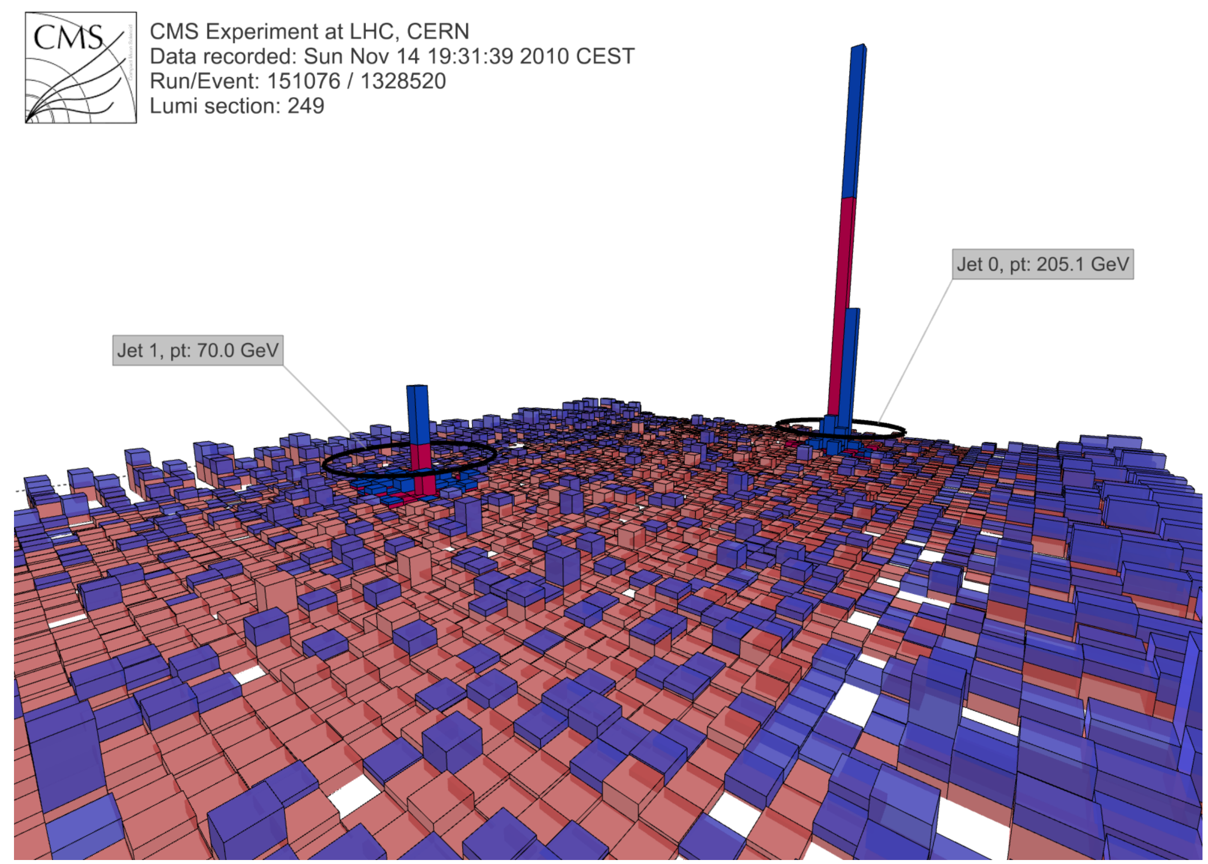


- High pT particle/jet yield suppressed and energy loss
- Modification of the hard scattered partons due to scatterings in the medium - could affect both jet axis and distributions of jet constituents

Experimentally measuring Jet Quenching

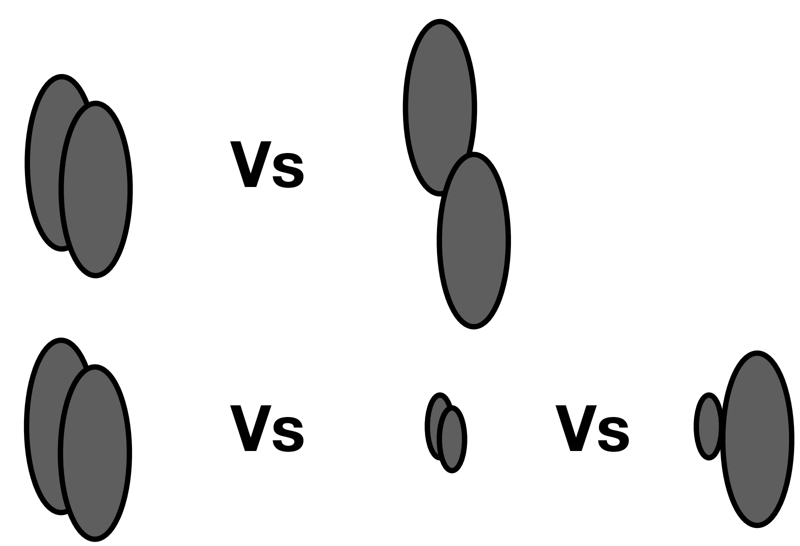
Image credit - Guilherme Milhano



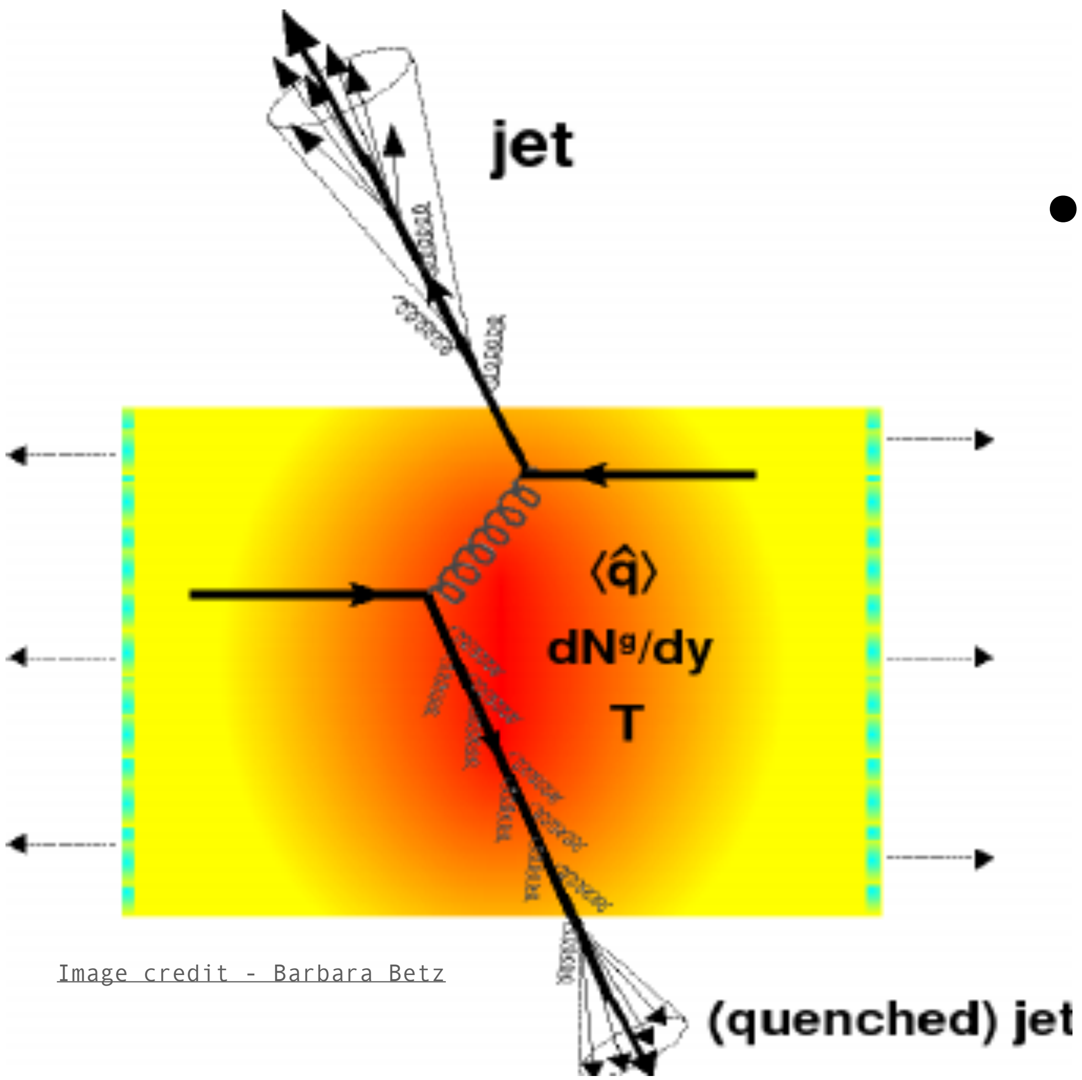


In comparisons of jet observables to a reference

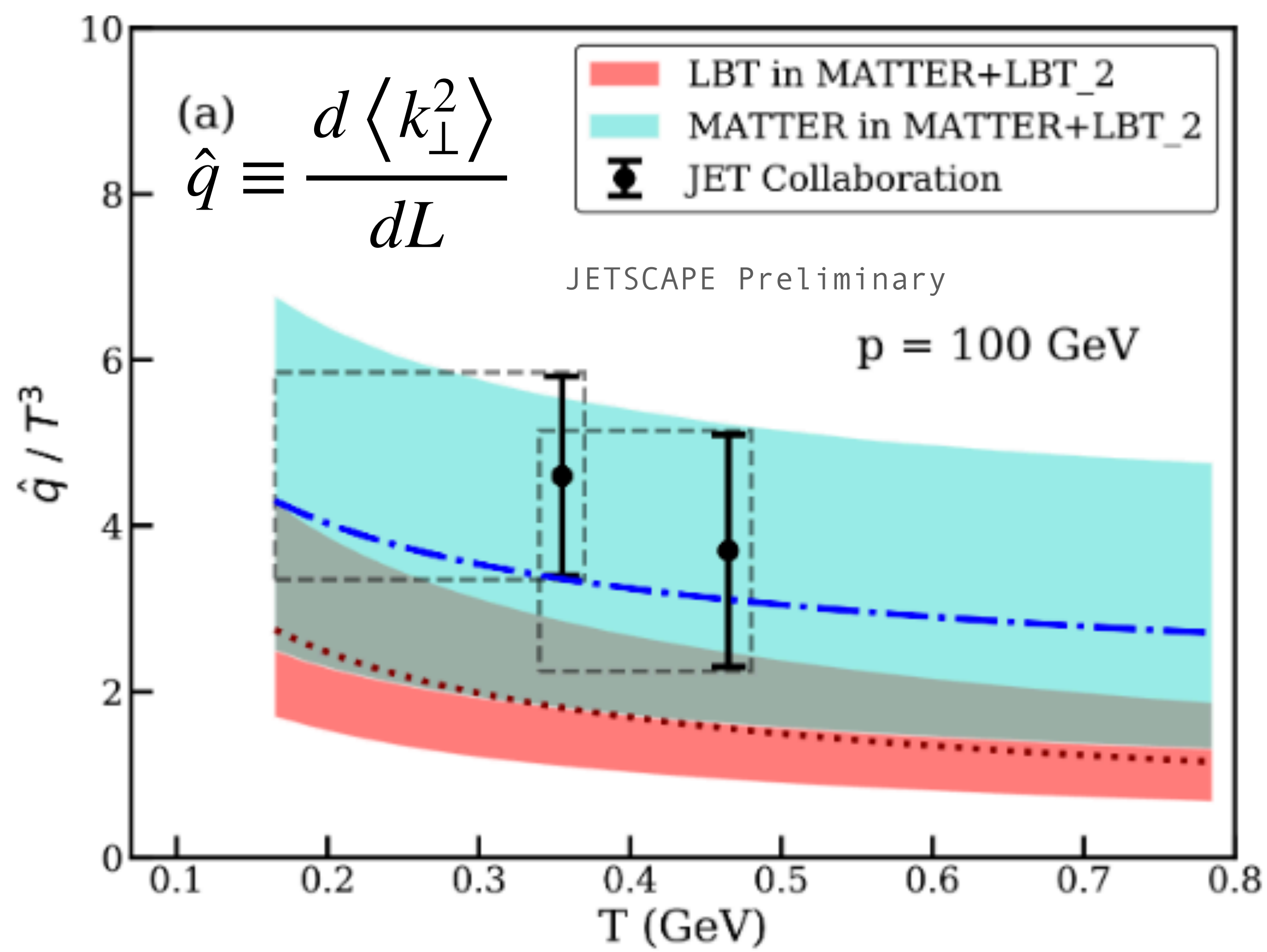
- Central vs Peripheral collisions
- A+A vs p+p or p+A (with the assumption that medium induced modifications are weaker or non-existent in the latter systems)



Jets and the QCD Medium

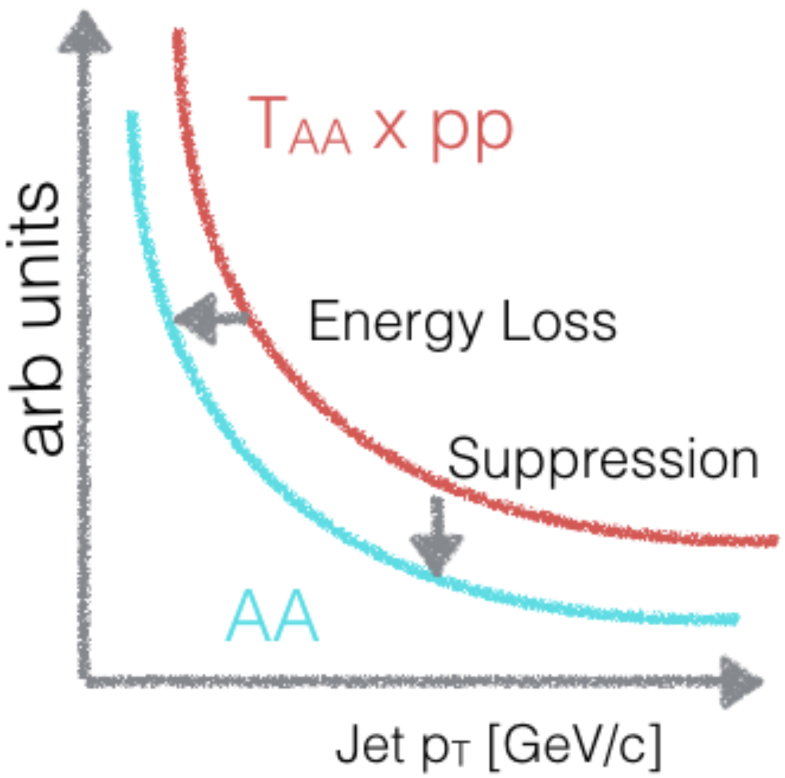


- Parton Energy loss is also dependent on both the momentum and the resolution scale

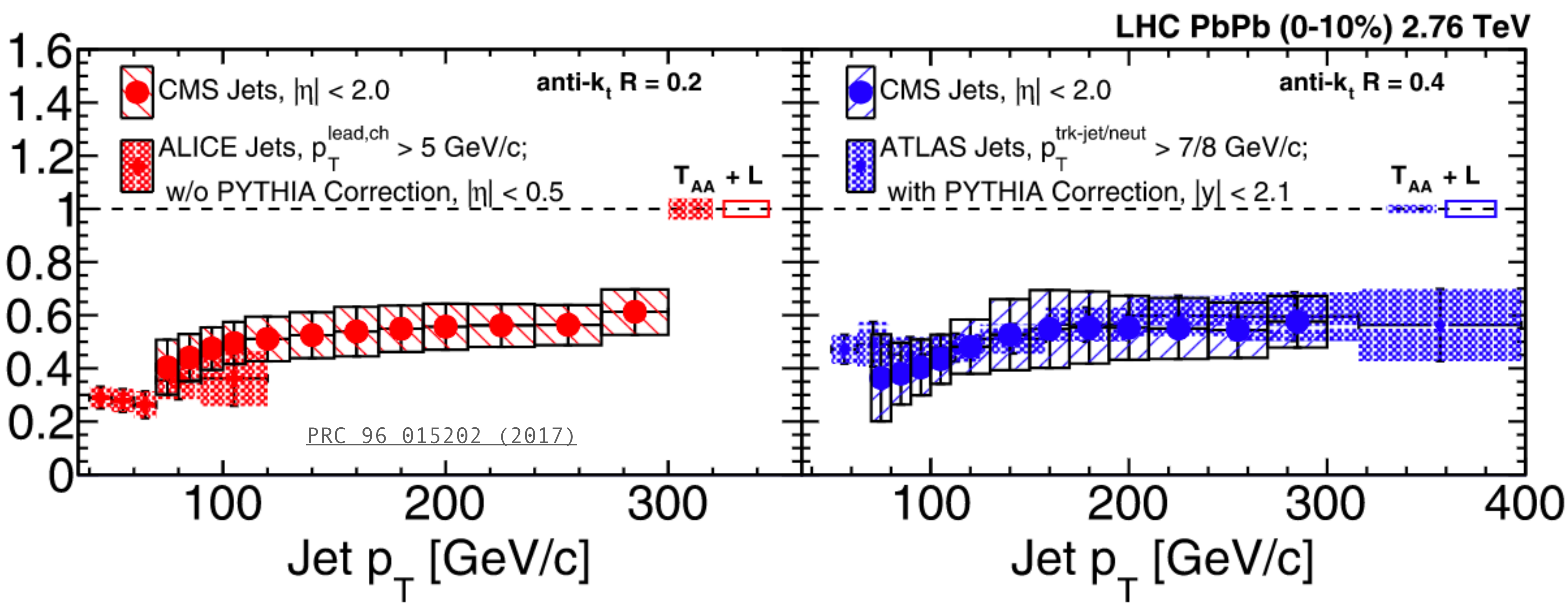


Goal is to understand energy loss (macro medium properties) - we can utilize similar measurements to study micro medium properties

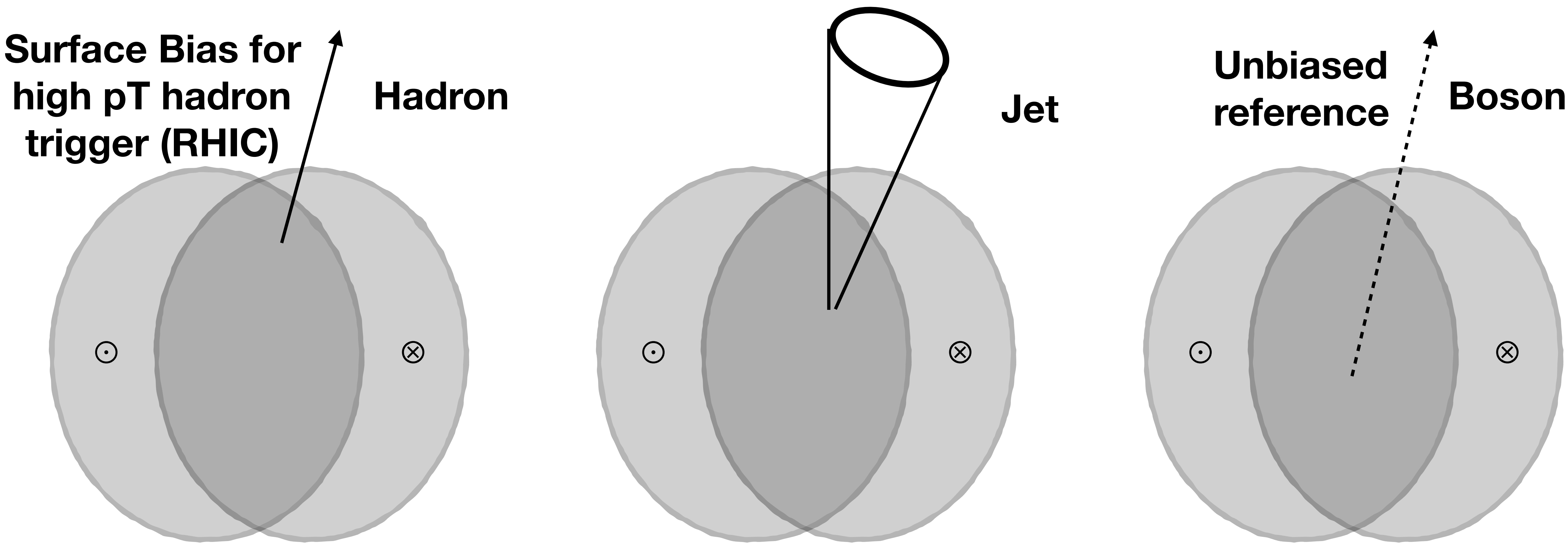
Modification of Inclusive Jets

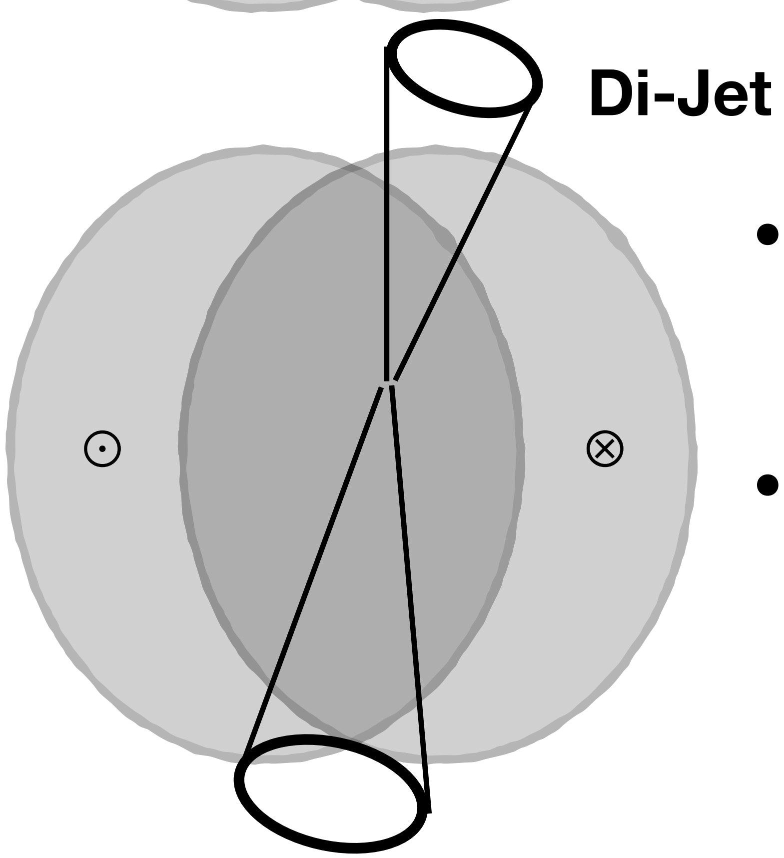


- Unfolded to particle level - facilitate comparisons between experiments and w/ theory/MC models
- Glauber model provides us with NBinary to go from pp to AA
- Within exp-uncertainties RAA consistent for R 0.2~0.4 jets

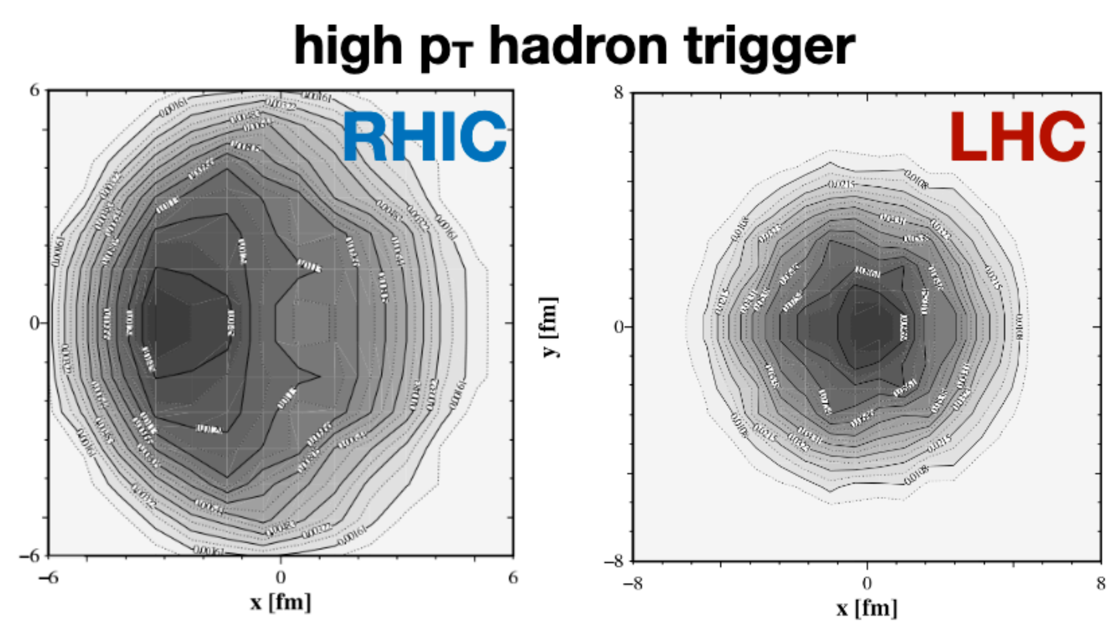


Not all events are created equal



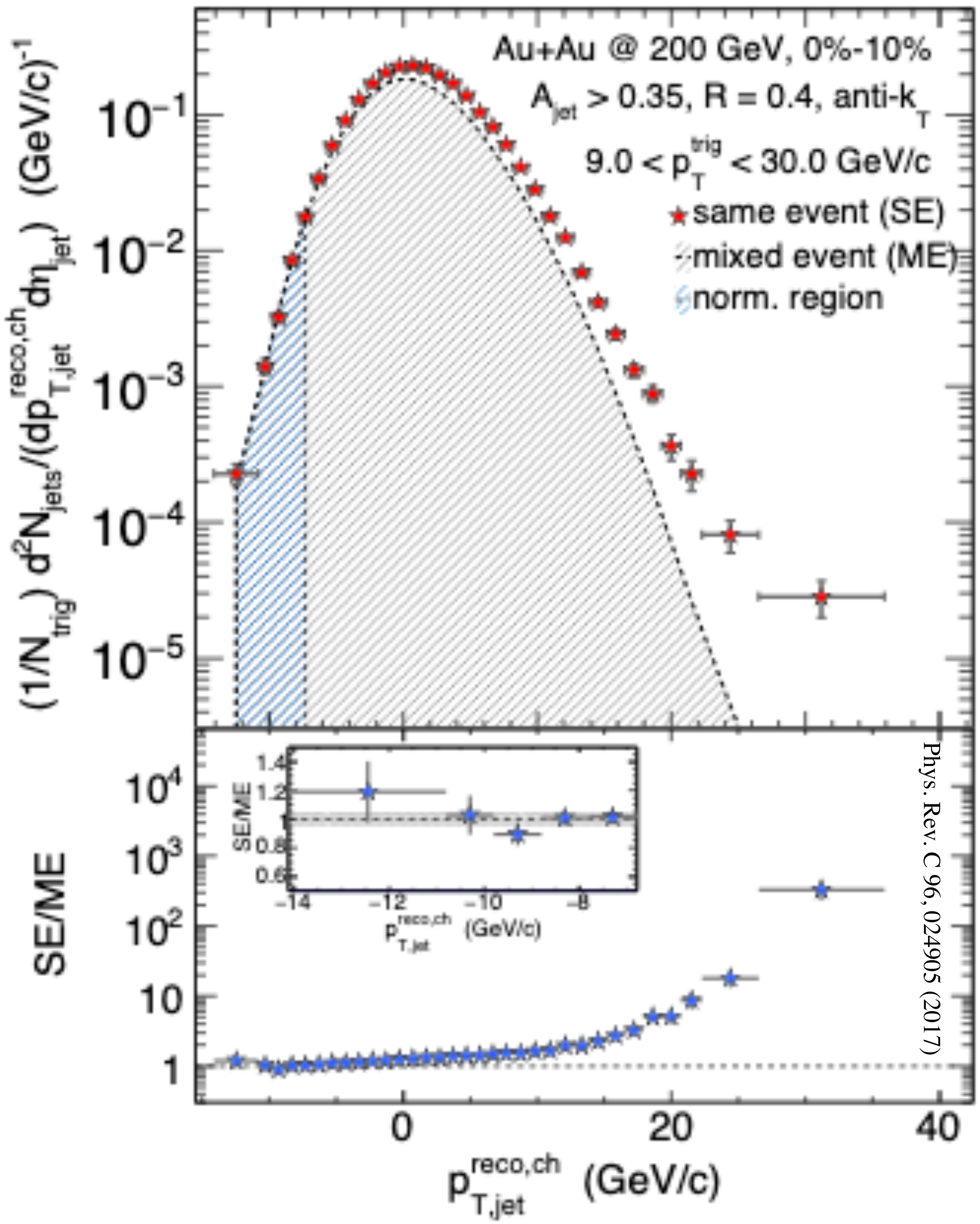


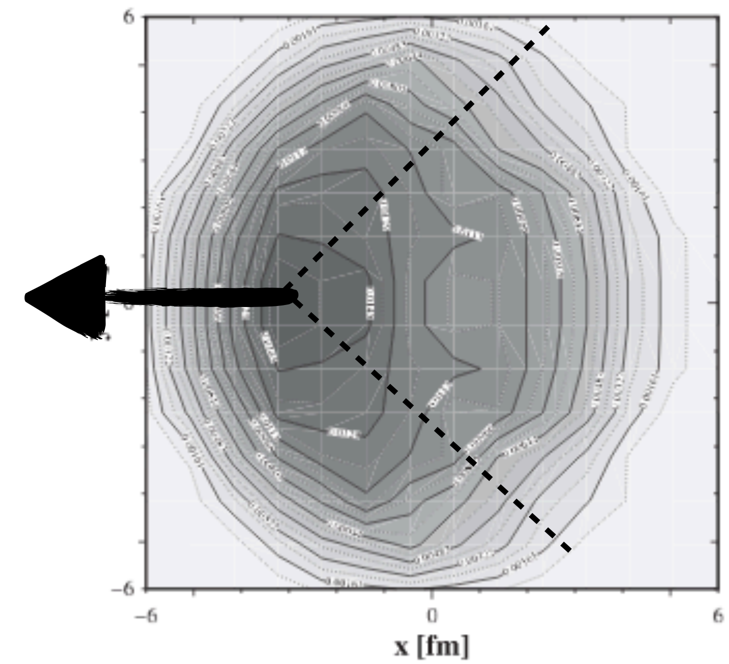
- Each of these event selections come with their own biases
- Important to understand their effect on an observable



Renk, PRC 85 064908 (2012), 87 024905 (2013)

Semi-Inclusive recoils

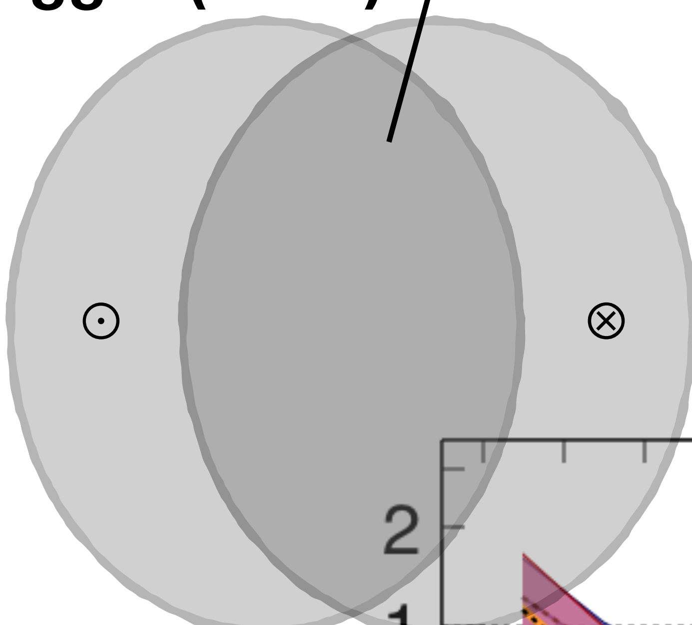




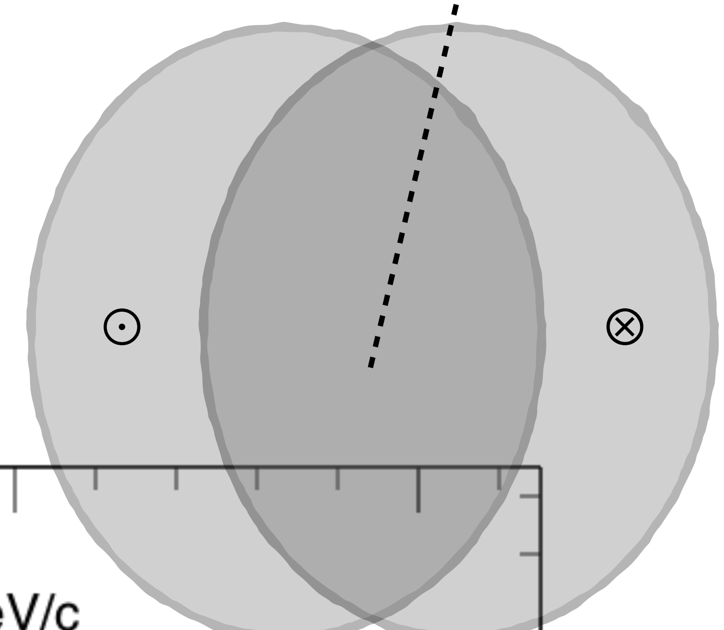
Renk, Phys.Rev. C 87, 024905 (2013)

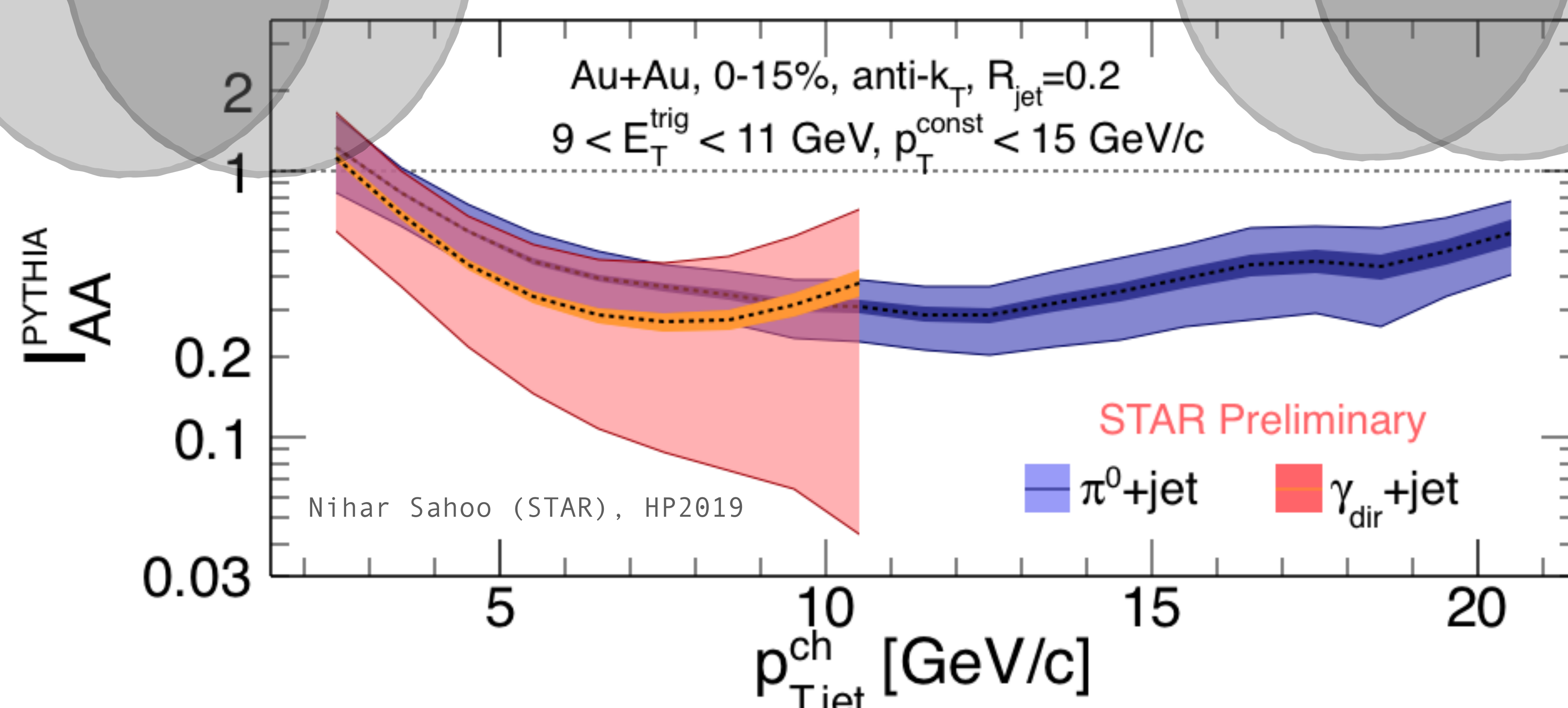
- No selection on recoil jet momenta
- Statistical correction of the combinatorial jet yields via mixed events

Comparing pion triggered vs photon triggered recoils



- Similar levels of suppression for direct photon recoils and hadron recoils

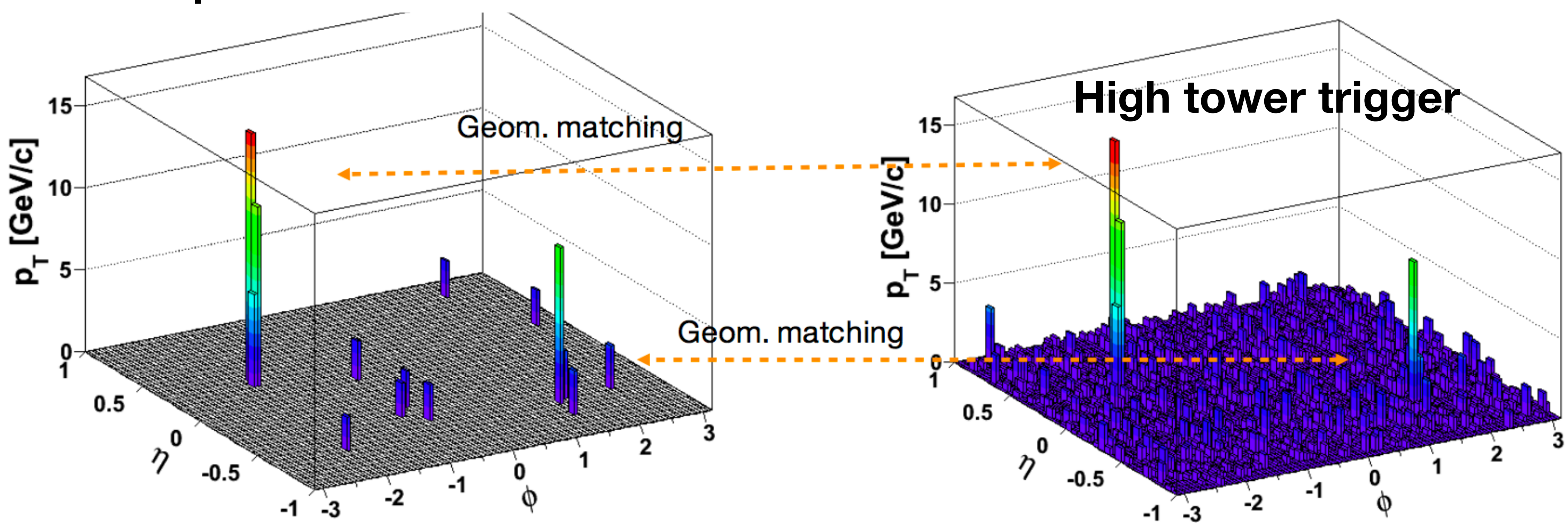




STAR Jet Selection

Hard Core jets
$p_T^{const} > 2$ GeV/c
$p_T^{Lead\text{-}jet} > 16$ GeV/c
$p_T^{Recoil\text{-}jet} > 8$ GeV/c

Matched jets
$p_T^{const} > 0.2$ GeV/c
ΔR (jet, HC-jet) < 0.4

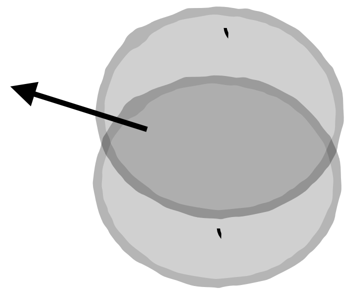


Hard Core selection → **removes almost all background**

geometric matching → **no combinatoric jets, recover all constituents**

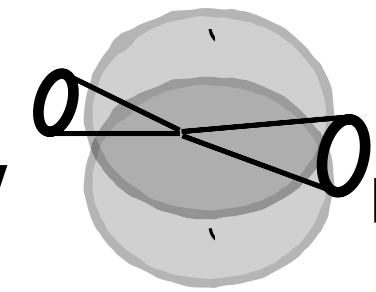
STAR, PRL 119 062301 (2017)

Semi-Inclusive vs Biased Dijet



Hadron trigger 9-30 GeV
R=0.2 R=0.5 Jets

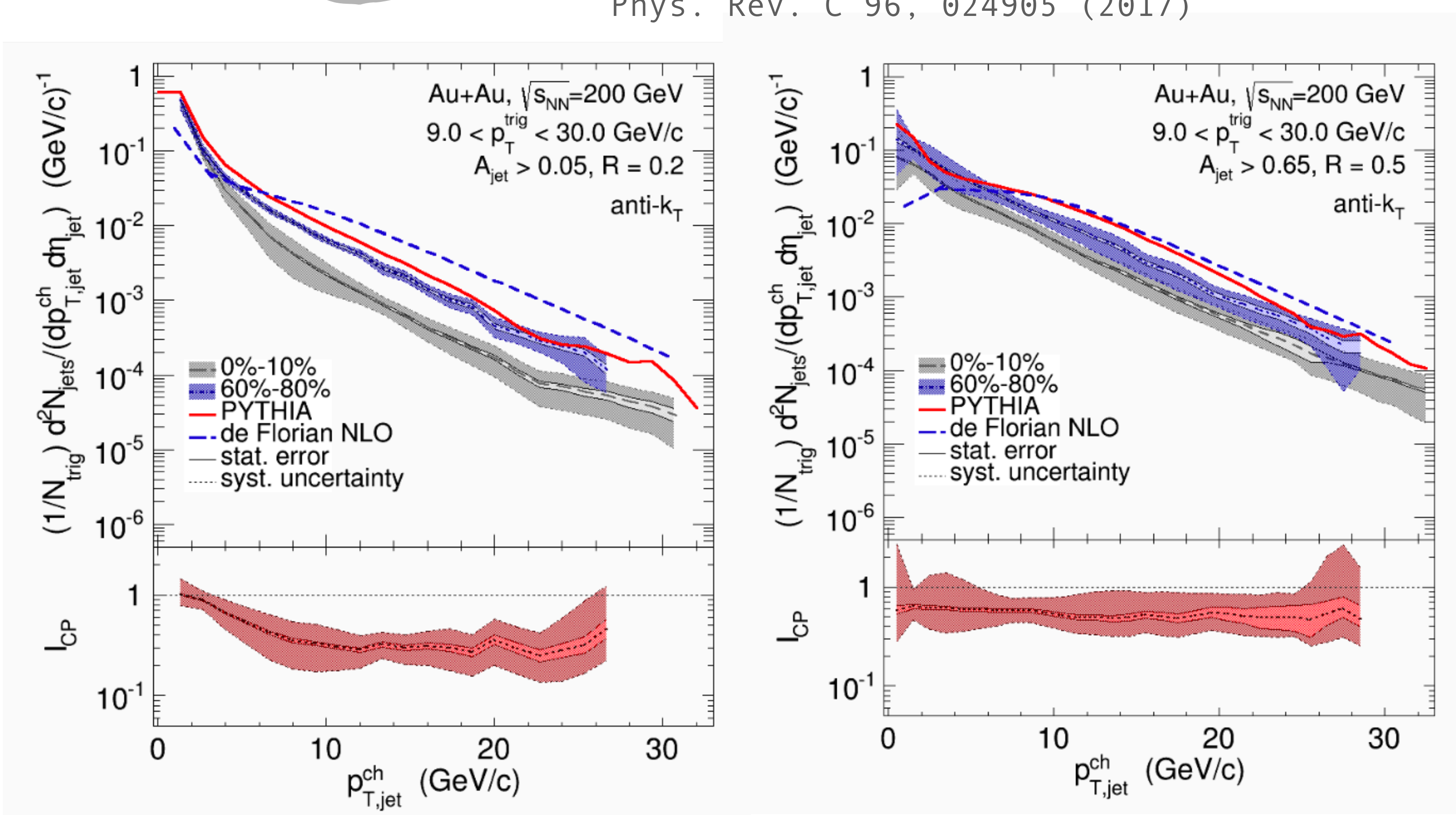
Trigger Jet pT > 20 GeV

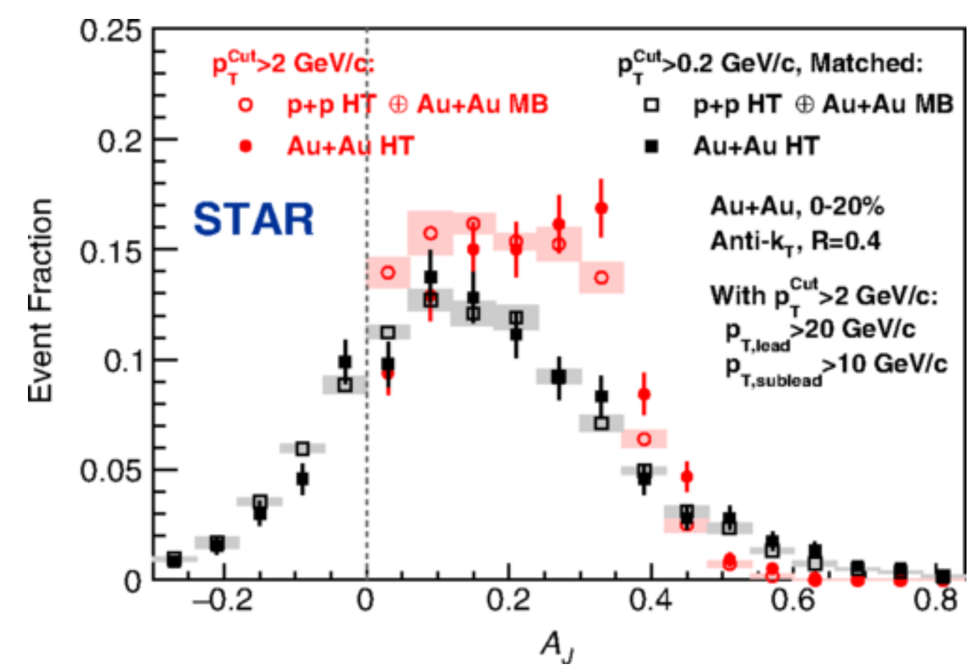


Recoil Jet pT > 10 GeV

STAR, PRL 119 062301 (2017)

Phys. Rev. C 96, 024905 (2017)

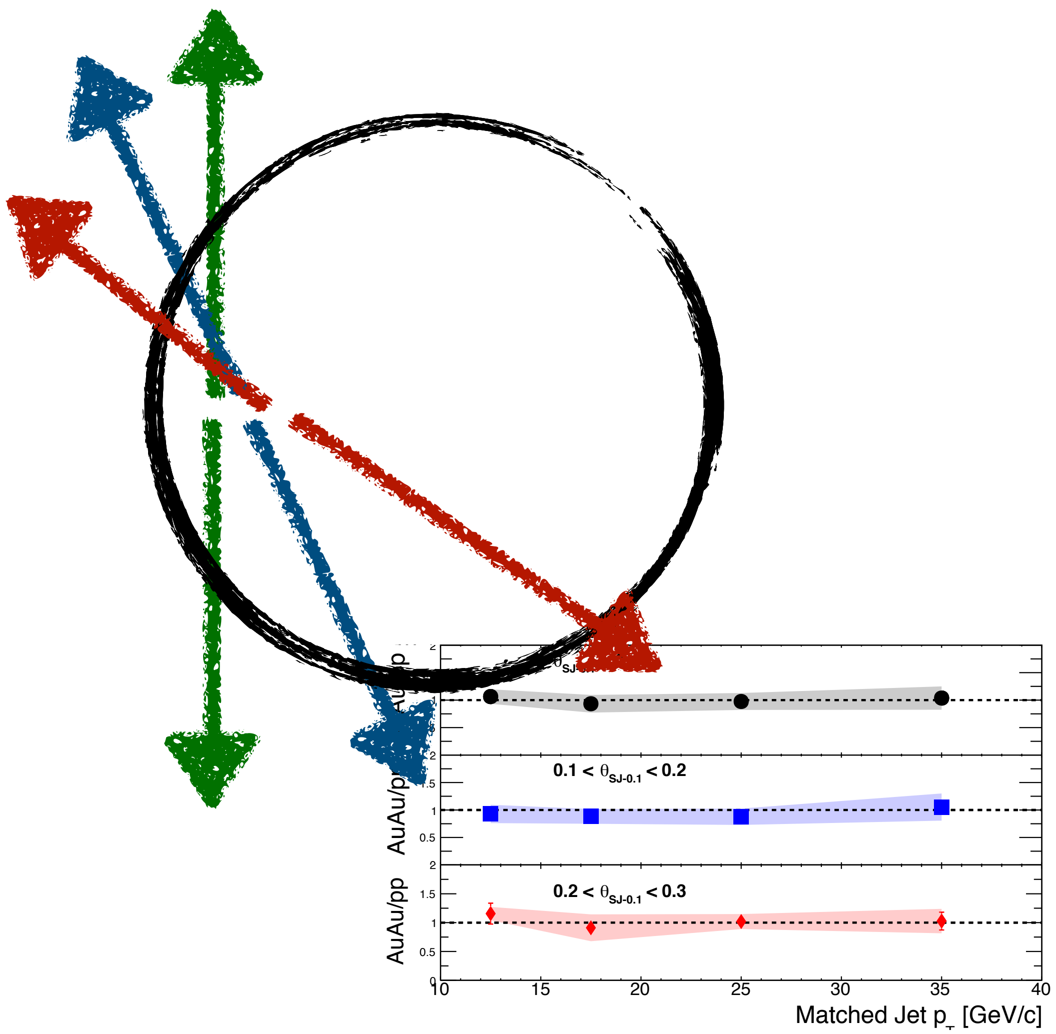


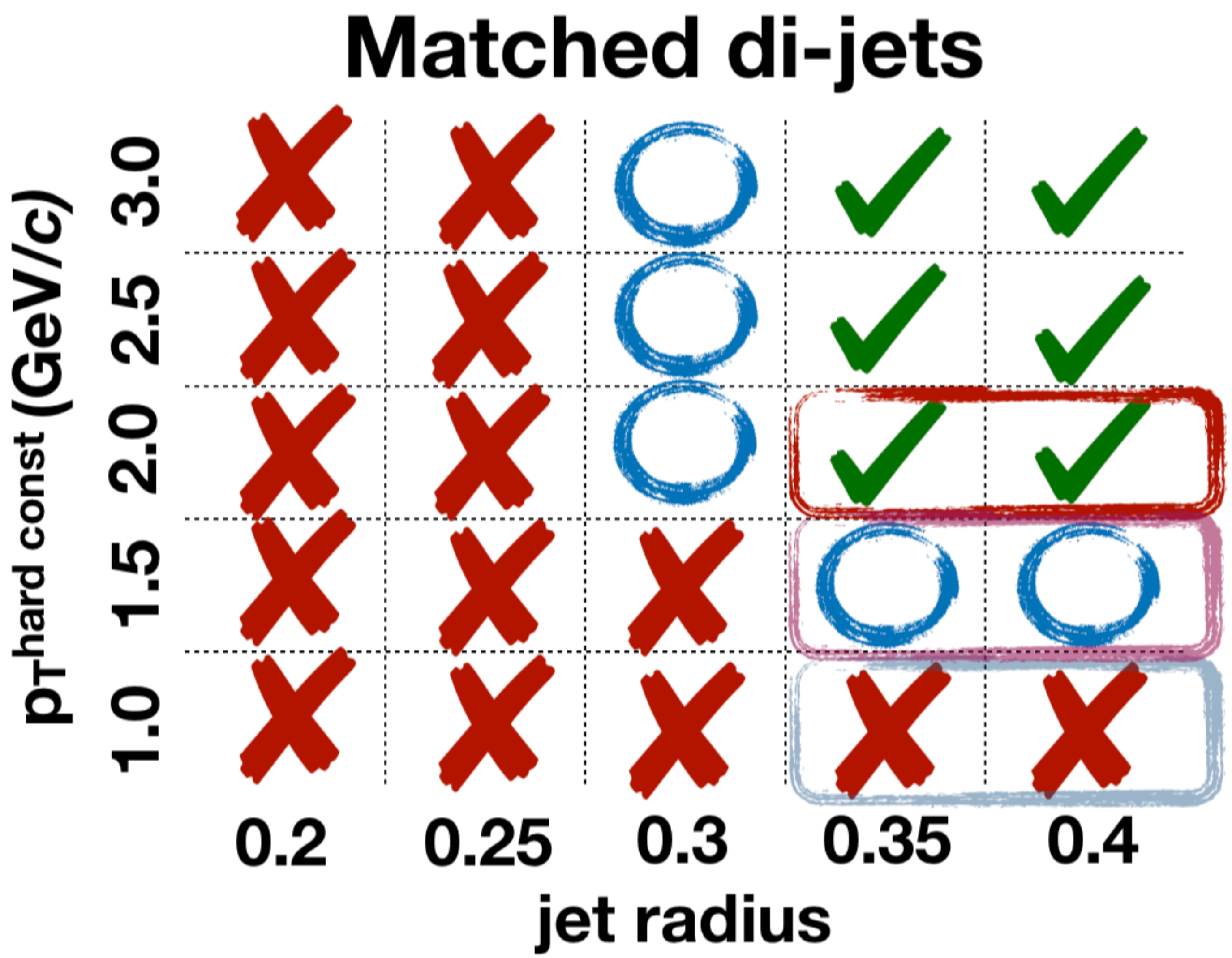


The recoil coincidence yield for R=0.2 (left) jets are suppressed compared to R=0.5 (right) [p_T shifts for R=0.2 : -4.4 +/- 0.2 +/- 1.2 and R=0.5 : -2.8 +/- 0.2 +/- 1.5]

- Jets with constituents pT > 2 GeV are imbalanced compared to pp
- Reduce threshold to 0.2 GeV, geometrically match and they are balanced!
- Quenched energy is recovered within R=0.4 radius

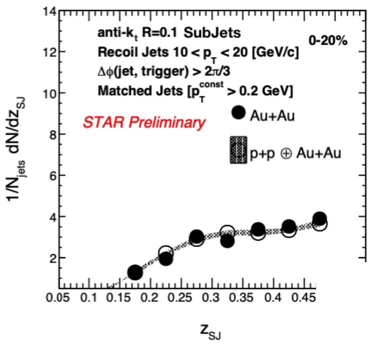
Jet Geometry Engineering

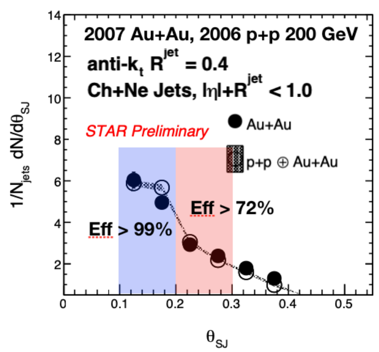


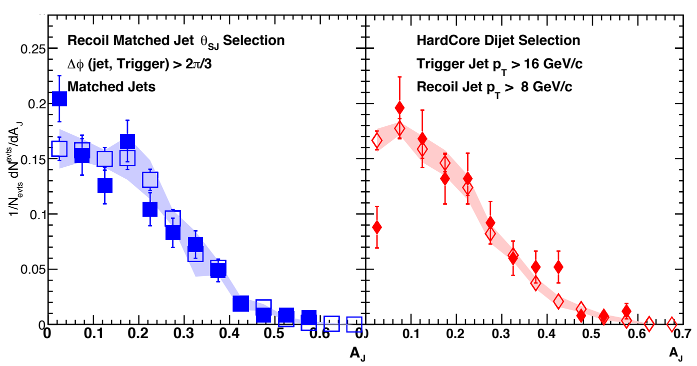


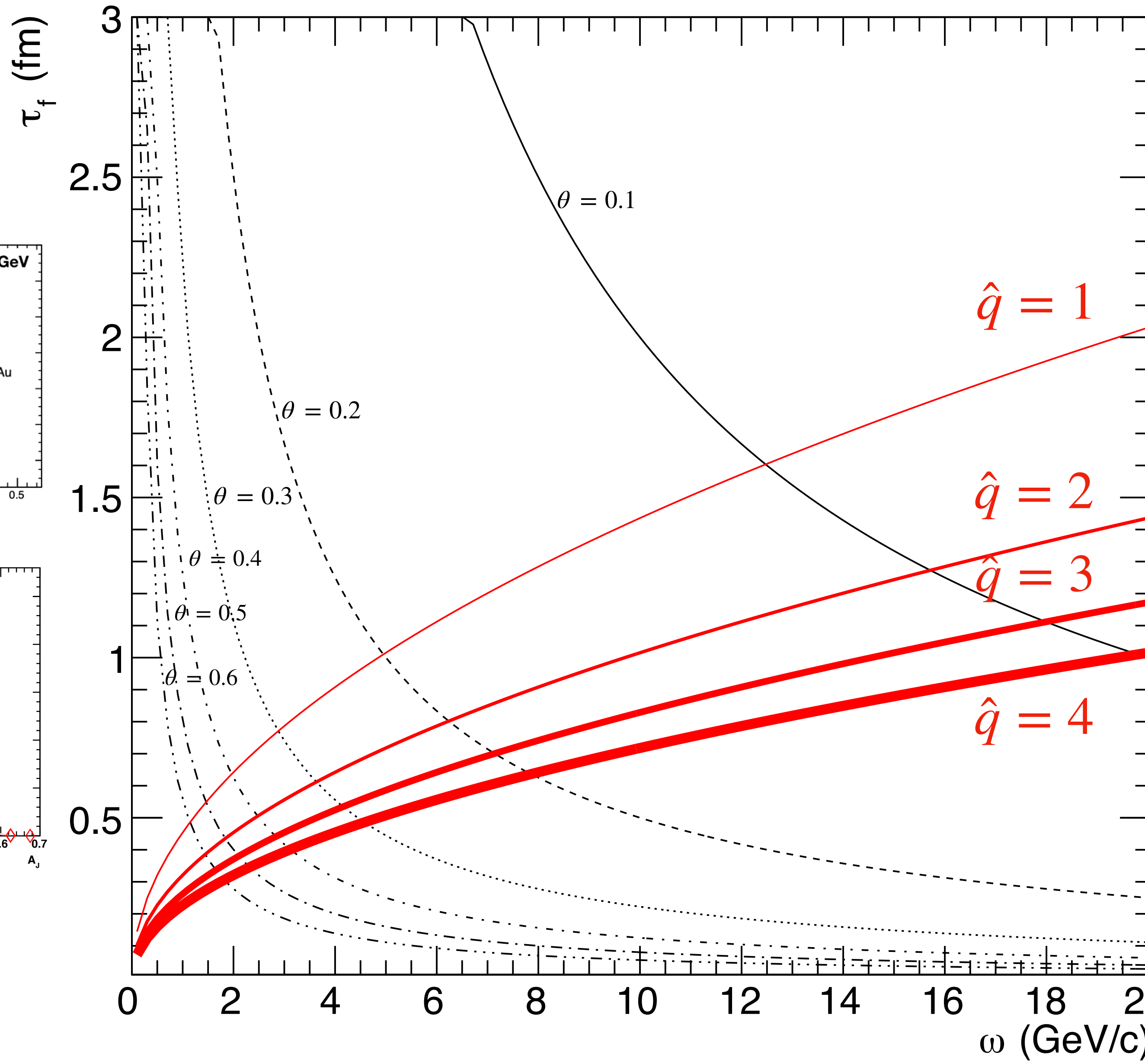
- Consistent picture of jet quenching at RHIC emerging
- We end up selecting dijets with a smaller path length in the medium with a higher constituent threshold

Formation time argument



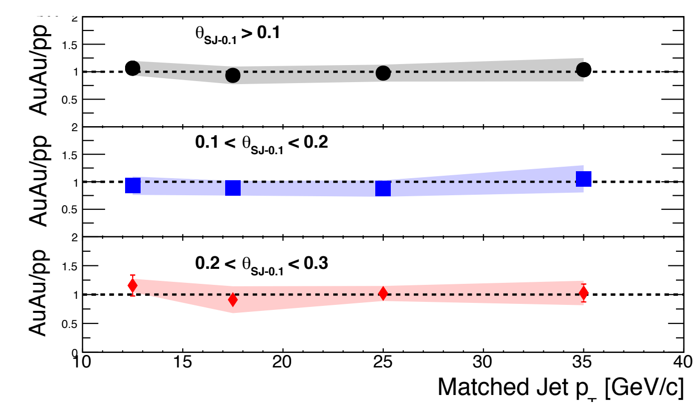






$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

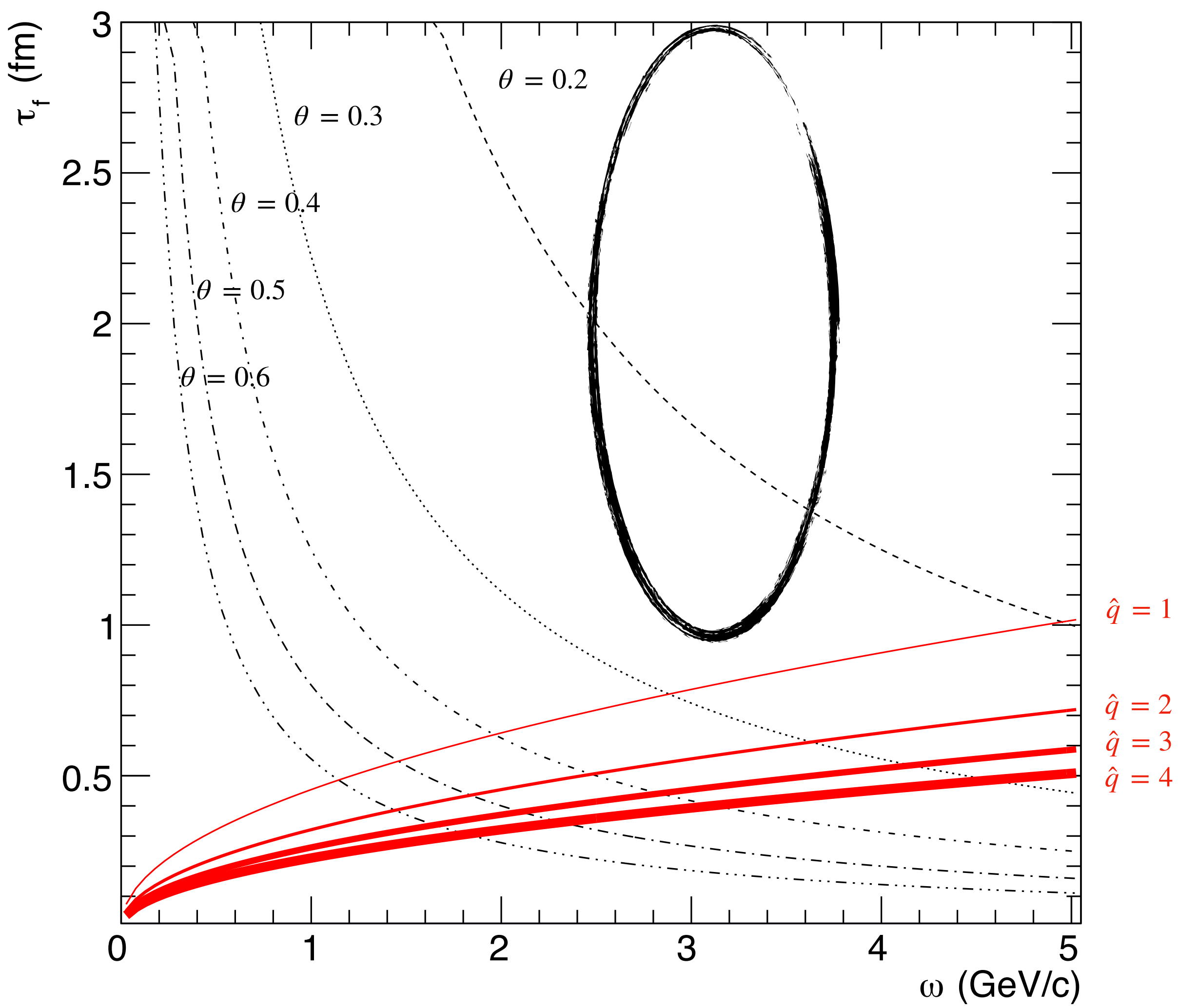
$$\tau_f^{med} \cong \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$$

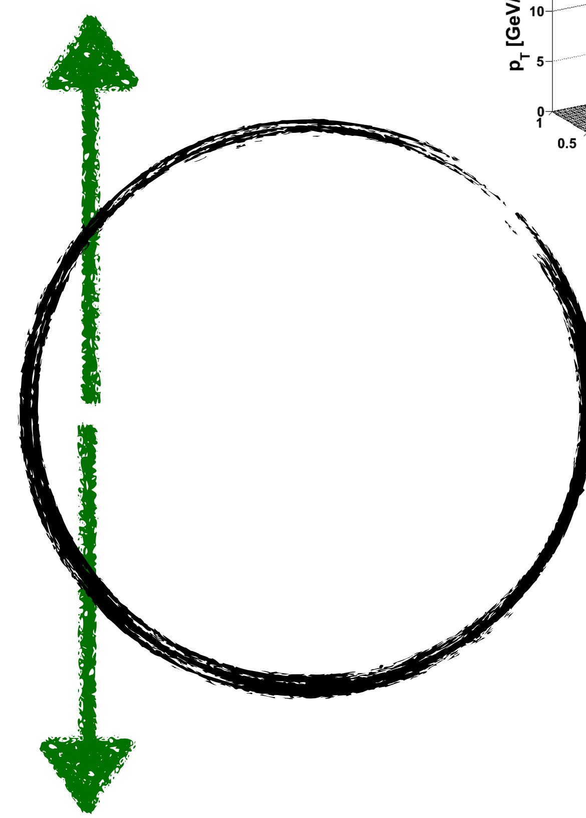


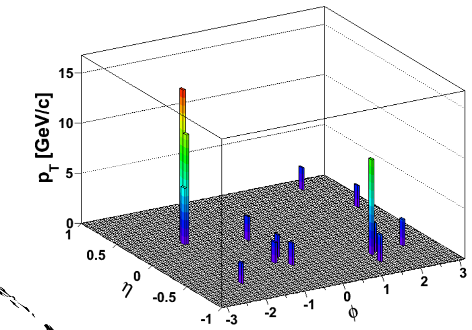
- Jet substructure observables are similar for both pp+AA and AA - vacuum like fragmentation
- No differences between wide/ narrow jets in Aj/Recoil Yield

- Given our zSJ tends towards a mean of 0.35, we can say ω ~ several GeV/c
- [Rough estimation] Wide jets are formed a couple of fermi whereas Narrow jets are roughly formed a few fermi after collision

Putting the two together



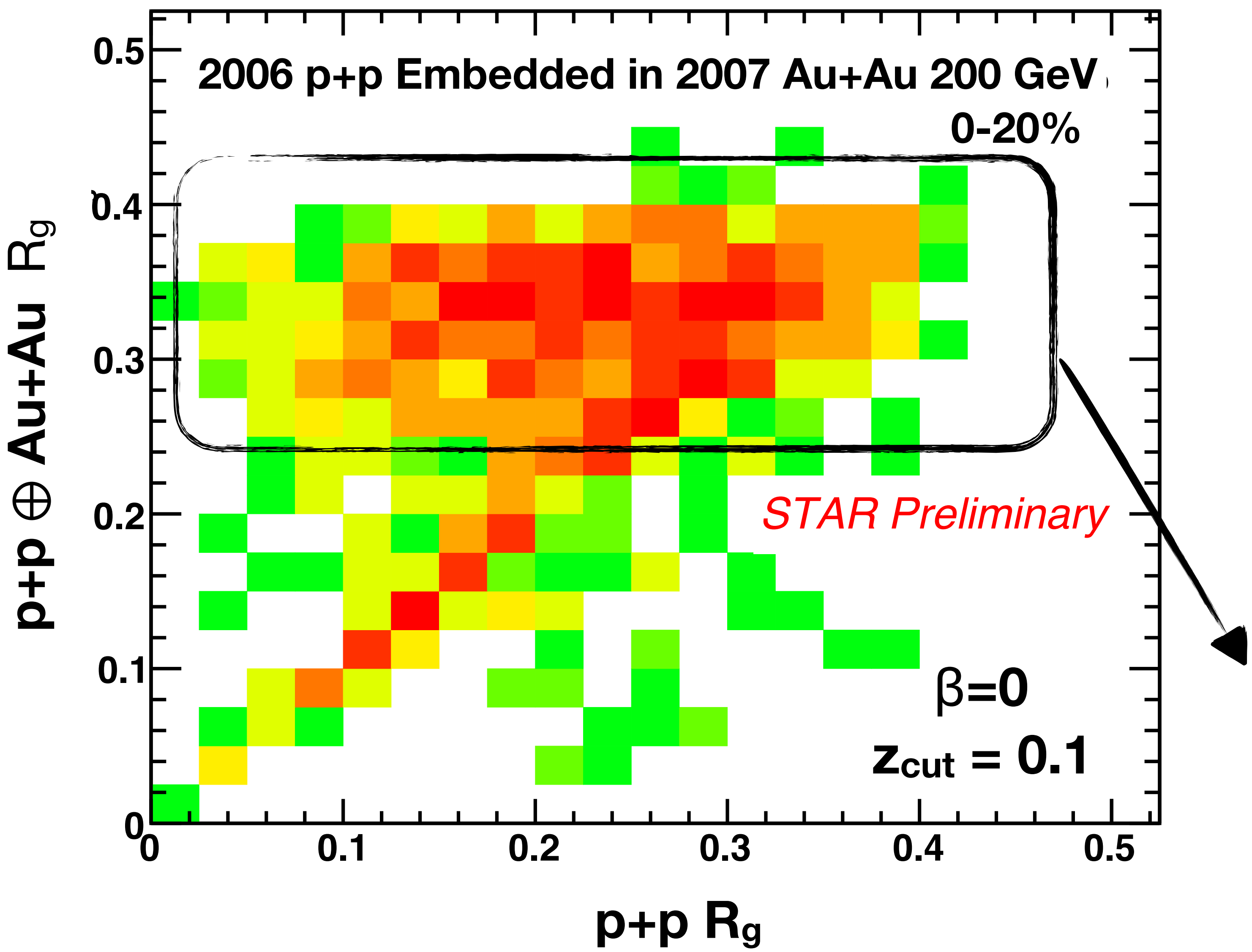




HardCore Dijet selection

Given later splits and Jet Geometry Engineering and surface bias, first split most likely outside the medium and resulting modification is **Soft gluon (0.2-2 GeV) radiation from a single color charge!**

SoftDrop R_g in the presence of a Heavy Ion event



anti-k_t R^{jet} = 0.4

Ch+Ne Jets, $|\eta|+R^{jet} < 1.0$

$20.0 < p_T < 30.0$ [GeV/c]

Recoil jets $\Delta\phi_{jet, HT} > 2\pi/3$

Constituent-subtracted jets

Berta, P et al. JHEP 06 (2014) 092

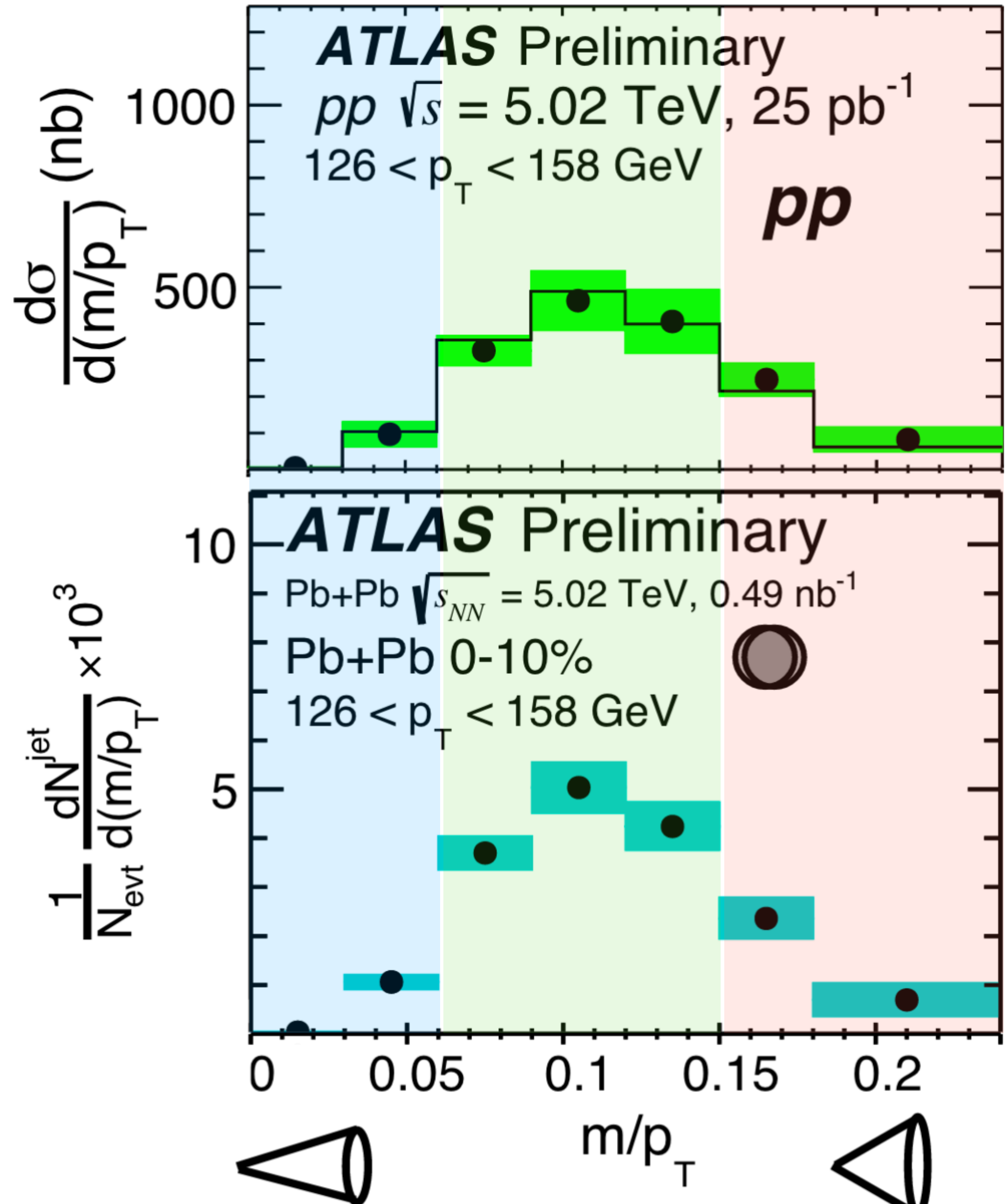
SoftDrop R_g sensitive to background fluctuations

We need an observable that is more **robust** to the AuAu fluctuating underlying event but still **sensitive** to jet kinematics

ATLAS Jet m/pT

- m/p_T is essentially related to the overall size of the momentum weighted jet constituents
- Easier to unfold - reduced dependence on jet p_T
- Requires model comparisons and a bit of thought to directly translate it to a resolution scale

ATLAS-CONF-2018-014

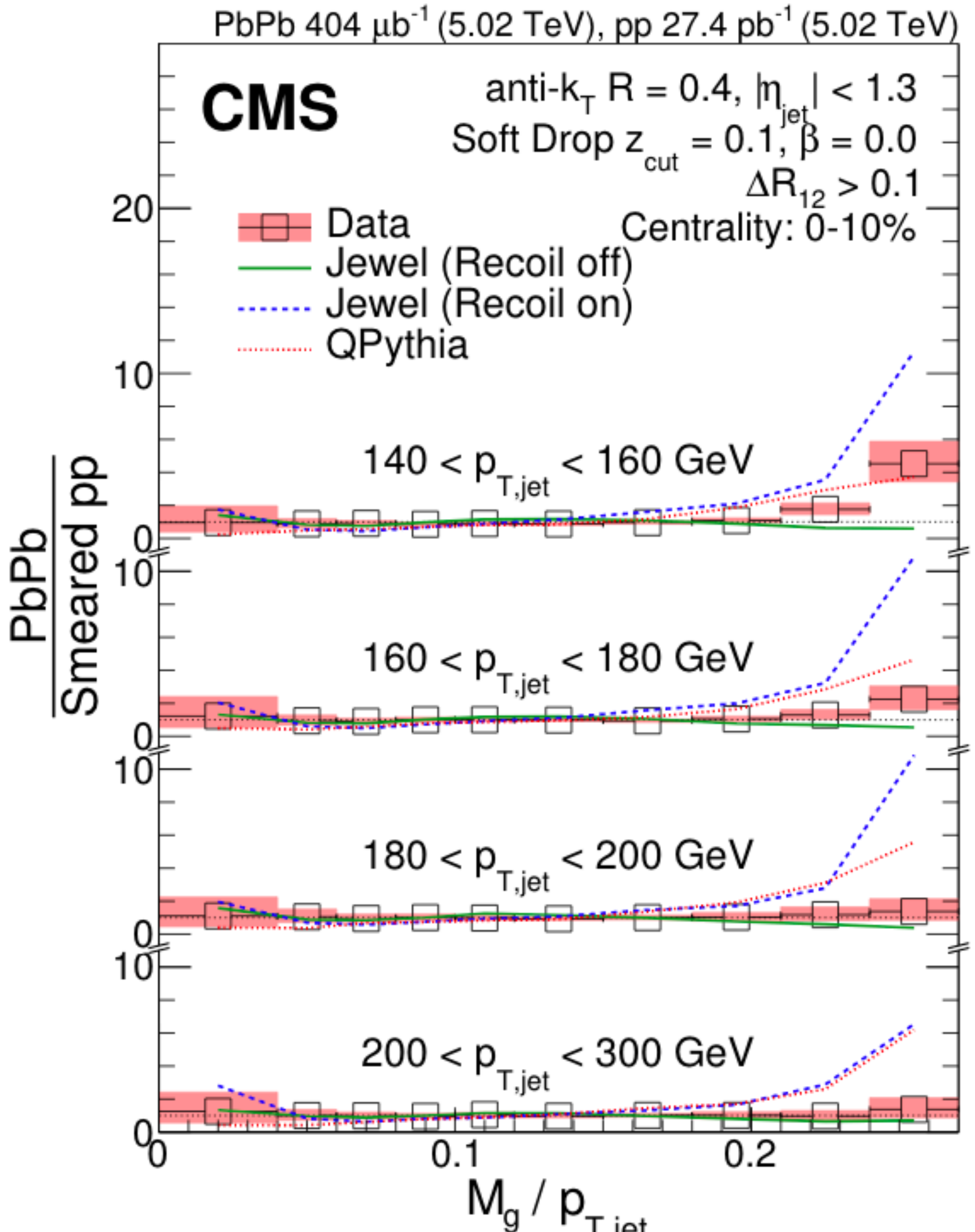


Figures taken from Laura Haver's talk at WWND 2019

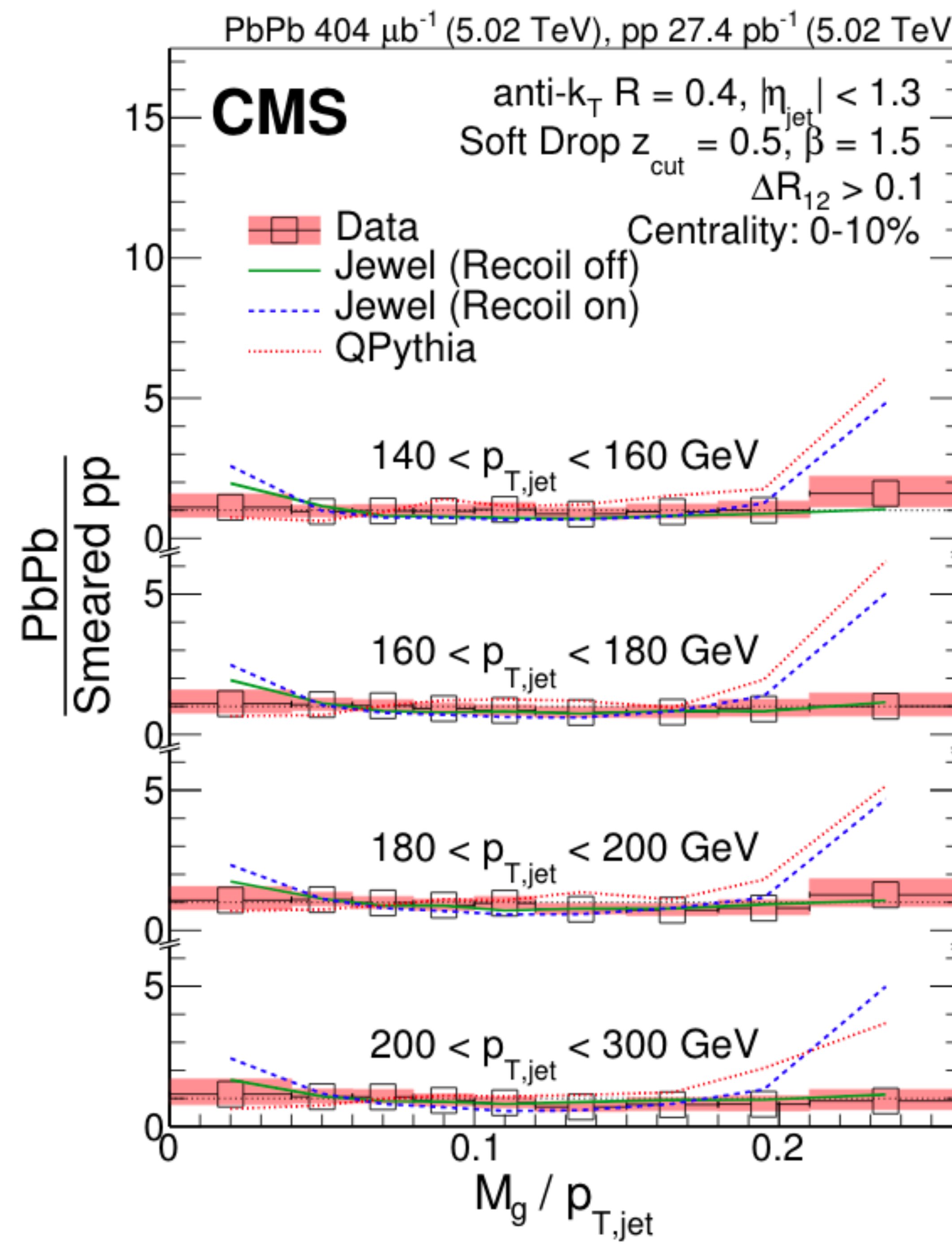
CMS Groomed M_g/p_T

Hints of modification at large M_g/p_T but not as large as MC models.
No modifications in the core!

- Soft exterior grooming

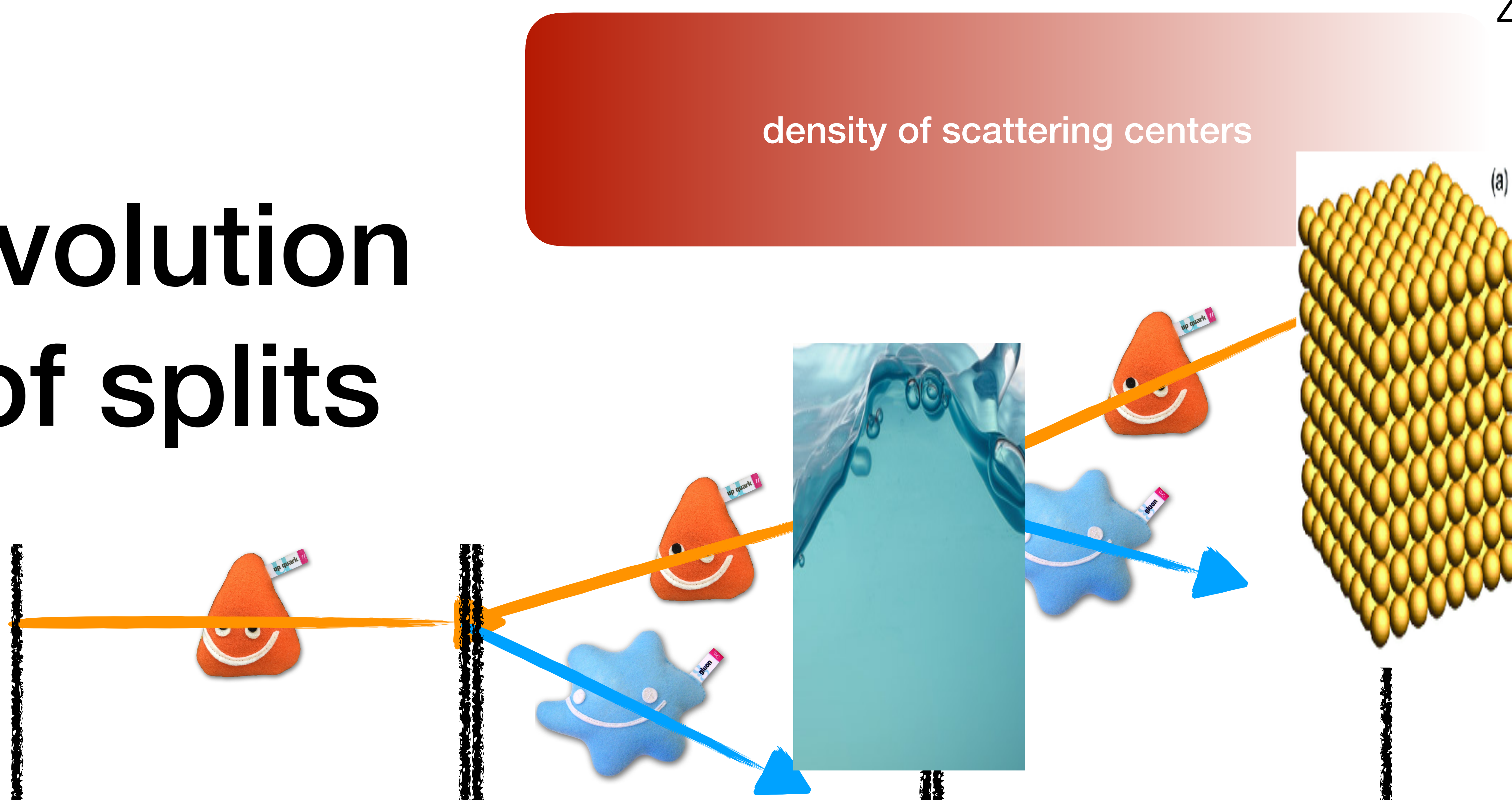


- Core grooming



CMS, JHEP 10 (2018) 161

evolution of splits



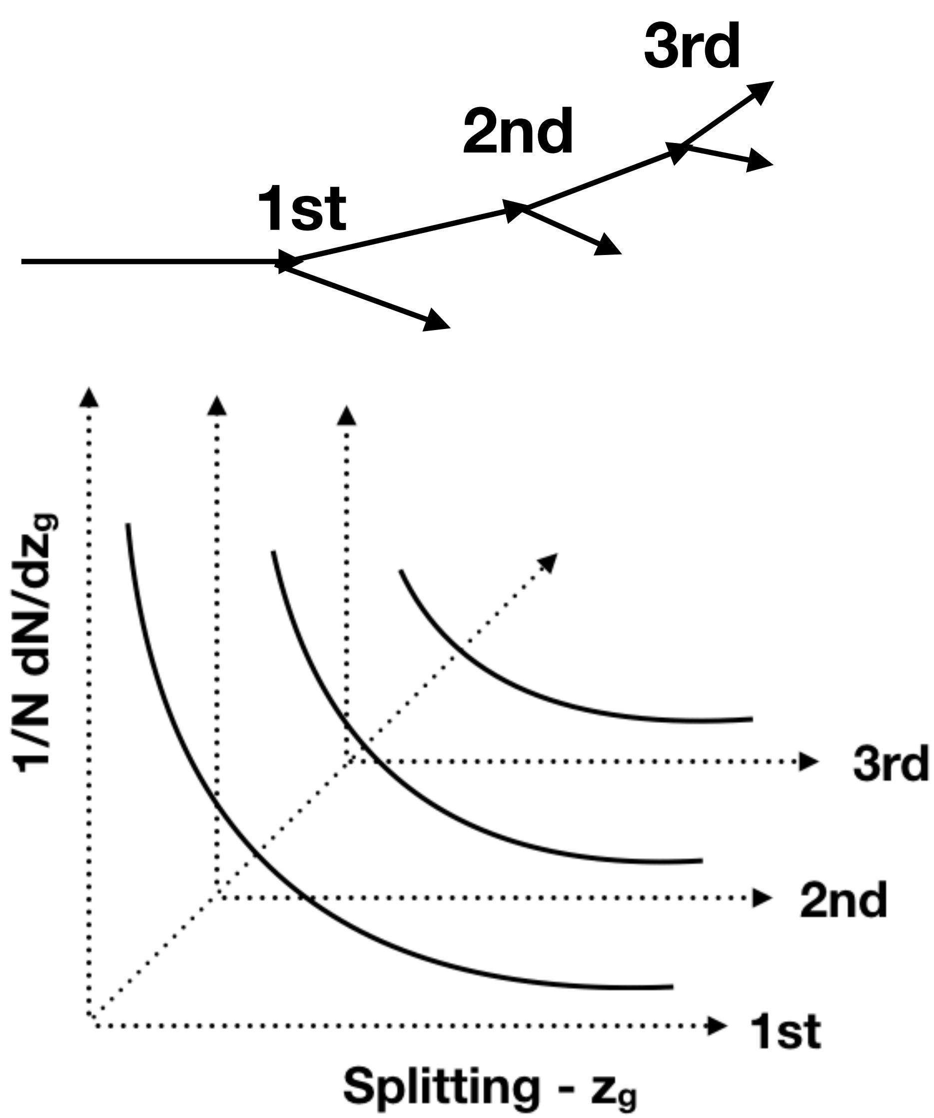
Very early formation times - Does not see any medium activity

Depending on the split - first interaction with the medium

Medium expansion occurring concurrently with jet evolution

Measuring the parton shower

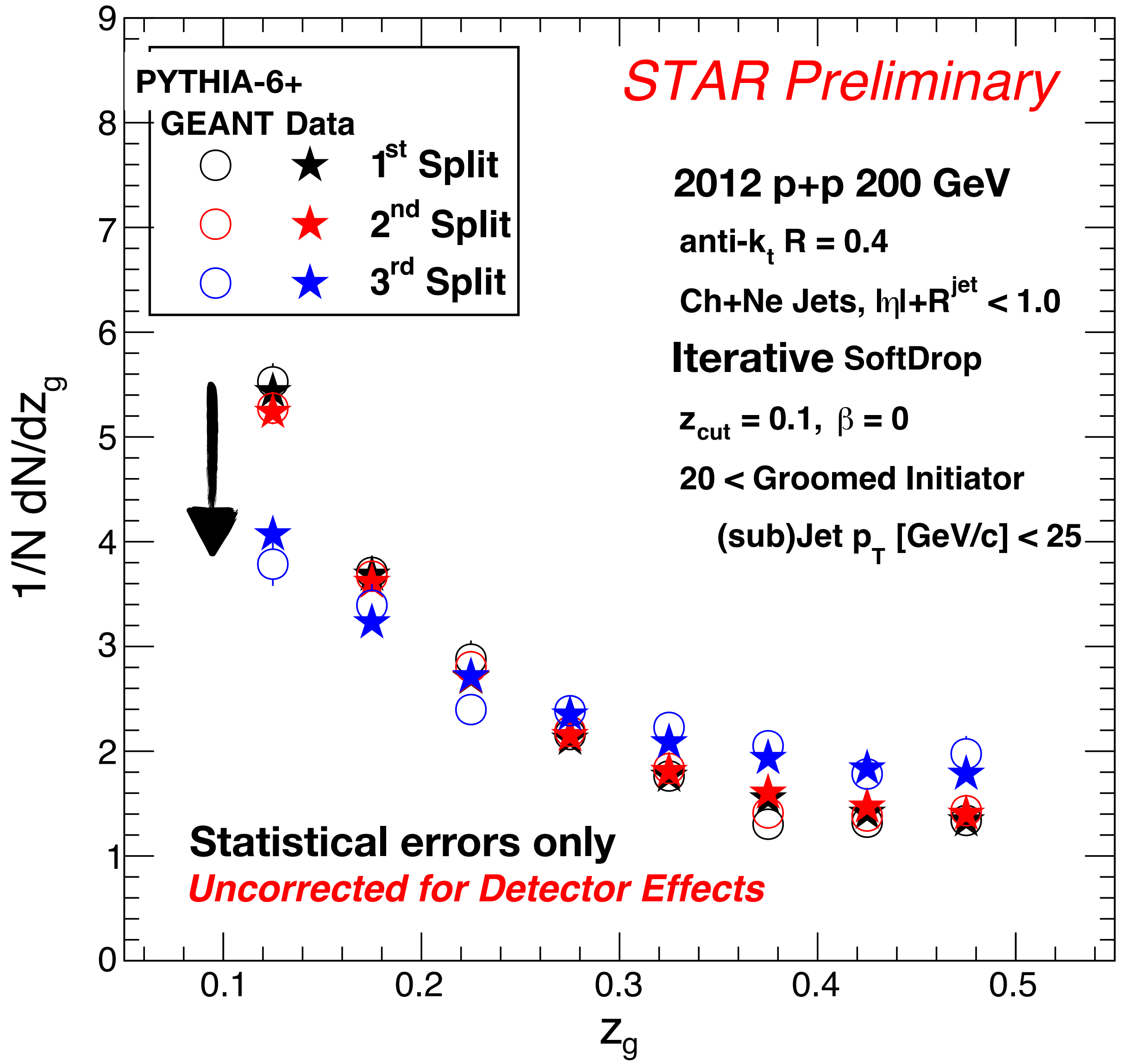
Opportunity to study self similarity of splittings within jets

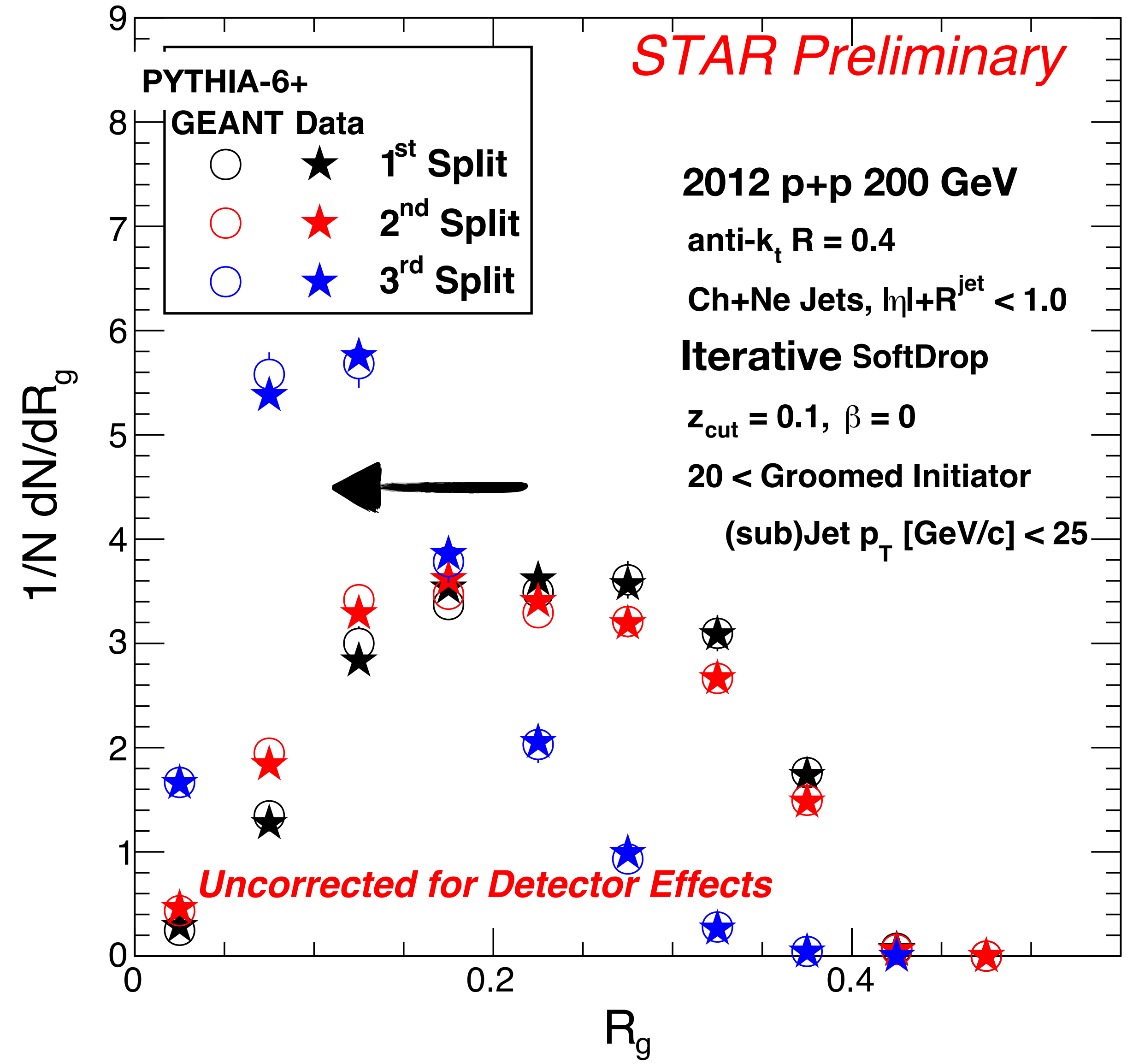


- **<u>Given a split (initiator p_T)</u>**, what are the z_g, R_g for 1st, 2nd and 3rd splits? Follow a split…
- Compare these at varying initiator kinematics (direct handle on splits)
- <u>Indirect constraint on jet kinematics</u>

Iterative Jet Substructure

RKE for STAR, 1906.05129





- **1st and 2nd splits are similar** in both z_g and R_g
- **3rd split is significantly constrained** in phase space/ angular scale - Deviation from universal *1/z behavior*