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STAR

Jet substructure in *p*+*p* and *p*+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at STAR



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10th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions June 3, 2020

Jet mass



Majumder, Putschke, Phys.Rev. C 93 (2016) 054909.

What we measure

[~ initial hard parton virtuality!]

- * **Partonic mass**, M_{parton} :
 - Magnitude of 4-momentum between 0 and scale, Q
- * Reconstructed jet mass, $M_{jet} = \left| \sum p_i \right| = \sqrt{E^2 p^2}$:
 - Magnitude of constituent 4-momentum sum for given R

SIAR

Motivation - heavy ion collisions

 Recent ALICE A+A measurement:

★ Jet mass ~ virtuality ~

Jets with different

masses resolve

- Jet mass is sensitive to different implementations of partonic energy loss
- $\frac{dN}{dM_{ch jet}} (c^2/GeV)$ $80 < p_{T, ch jet} < 100 \text{ GeV/}c$ ALICE 0.2 0-10% Pb-Pb **v**s_{NN} = 2.76 TeV PYTHIA Perugia 2011 **Q-PYTHIA** JEWEL + PYTHIA 0-10% Pb-Pb Recoil on Recoil off 10 $M_{\rm ch\,jet}~({\rm GeV}/c^2)$ **RHIC Jet Probes** Resolution [1/fm] creasing virtuality LHC Jet Probes **QGP** Influence Thermal Mass G Perfect Fluid Only 0.6 T [GeV] 0.3 0.4 0.5

ALICE, Phys.Lett. B 776 (2018) 249

Reaching for the Horizon: The 2015 Long Range Plan for Nuclear Science

medium at different scales

resolution

Motivation - p+p, p+Au collisions **star**

★ p+p measurements done mostly at LHC¹⁻⁷
 No measurement yet at RHIC!
 → further tune MCs

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<sup>1</sup>ATLAS, JHEP 05 (2012) 128
<sup>2</sup>ATLAS, Phys.Rev.Lett. 121 (2018) 092001
<sup>3</sup>ATLAS, tech. rep. ATLAS-CONF-2018-014 (2018)
<sup>4</sup>CDF, Phys.Rev. D 85 (2012) 091101
<sup>5</sup>CMS, JHEP 05 (2013) 090
<sup>6</sup>CMS, Eur.Phys.J. C 77 (2017) 467
<sup>7</sup>CMS, JHEP 10 (2018) 161
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- * ALICE observes no modification of jet mass in p+Pb at 5.02 TeV for 60 < $p_{T,jet}$ < 120 GeV/c w.r.t. PYTHIA, HERWIG
- ★ No measurement yet at RHIC! \rightarrow modification at RHIC?



★ Unexpected PHENIX R_{d+Au} enhancement for peripheral, ★ Unexpected PHENIX R_{d+Au} enhancement for peripheral,

Motivation - p+p, p+Au collisions **STAR**

suppression for central

- are jets modified at RHIC?
- Jet mass may be sensitive to cold QCD effects, e.g. if initiating parton loses energy traversing the nucleus
- *p+p* and *p+Au* serve as vacuum and cold QCD baselines for future STAR Au+Au studies



The Solenoidal Tracker at RHIC (STAR)



Relativistic Heavy Ion Collider (RHIC) collides p+p, p+Au beams at $\sqrt{s_{NN}} = 200$ GeV

Time Projection Chamber (TPC): momenta of charged tracks

Barrel Electromagnetic Calorimeter (BEMC): neutral energy deposits + provides online trigger (Jet Patch: $E_T^{patch} > 7.4$ GeV)

Inner Beam-Beam Counter (iBBC): forward detector (3.4 < $|\eta|$ < 5.0) cf. TPC $|\eta|$ < 1 east/Au-going side activity used as centrality proxy in *p*+Au



The Solenoidal Tracker at RHIC (STAR)



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east/Au-going side activity used as centrality proxy in p+Au

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Jet mass resolution



STAR, Phys.Rev. D 100 (2019) 052005

Jet Mass Scale (JMS) shift from unity: mostly from track loss ¹⁰⁰ Jet Mass Resolution (JMR) p_T -independent!

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Unfolding

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- Correct for finite detector resolution effects
- effects
 Correction procedure:
 Iterative Bayesian from
 RooUnfold (4 iterations)
 - M dependent on p_T
 → 2D unfolding
 → 4D response
 - Correct p_T , M, and correlation simultaneously

4D jet mass response matrix



Tim Adye in Proceedings, PHYSTAT 2011, CERN, edited by Prosper and Lyons, CERN-2011-006, pp. 313-318.

Systematic uncertainties

Sources include (decreasing magnitude):

 Unfolding

 (maximum envelope of the following):

- Iteration parameter variation: 2 or 6
- Prior variation:
 *p*_T, *M* spectra varied
 independently
- * Tracking efficiency uncertainty of 4%¹
- Tower gain uncertainty of 3.8%¹
- Hadronic correction
 variation: from nominal
 100%² to 50%



Total systematic uncertainty is a quadrature sum of the four sources

¹STAR, Phys.Rev. D 100 (2019) 052005 ²STAR, Phys.Rev.Lett. 115 (2015) 092002

Jet mass as a function of $p_{T,jet}$



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Jet mass as a function of $p_{T,jet}$



RHIC-tuned **PYTHIA-6** describes data

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Jet mass as a function of $p_{T,jet}$



HERWIG-7 <u>underpredicts</u> and PYTHIA-8 <u>overpredicts</u> (EE4C) ← LHC → (Monash)

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SoftDrop grooming



Larkoski, Marzani, Soyez, Thaler, JHEP 05 (2014) 146

Groomed momentum fraction



- * Recover the universal 1/z behavior starting from $p_T \sim 25$ GeV/c
- * **PYTHIA-6** and **PYTHIA-8** describe data
- HERWIG-7 predicts harder splitting

Groomed jet radius



- * R_g reflects momentum-dependent narrowing of jet structure
- * **PYTHIA-6** describes data
- * **PYTHIA-8** predicts larger groomed jet angular scale

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Groomed jet mass



Grooming suppresses non-perturbative effects, decreasing jet mass - in particular, at higher $p_{T,jet}$

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Groomed jet mass



RHIC-tuned **PYTHIA-6** describes data

HERWIG-7 underpredicts and PYTHIA-8 overpredicts

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Conclusions - p+p

RHIC-tuned PYTHIA-6: jet substructure data is well-described

LHC-tuned HERWIG-7, PYTHIA-8: opportunity for further tuning

First inclusive *p*+*p* jet mass measurements at RHIC

Jet mass increases with increased phase space (jet p_T), consistent with pQCD expectations

SoftDrop groomed mass is observed to be closer to ungroomed parton level mass; Consistent substructure picture via $M_g \sim z_g R_g^2$







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David Stewart, June 2, 12:55 CDT, D4

- Test event activity dependence using the inner BBC on the Au-going (east) side
- Embed PYTHIA+GEANT events into p+Au MB background, unfold without event-by-event UE subtraction
- Assess additional systematics due to our embedding procedure and the enhanced background in *p*+Au

Veronica Verkest, June 2, 7:30 CDT, poster session

Jet mass: low EA



p+p and p+Au 50-100% event activity are comparable p+Au low-EA ~ p+p !

Groomed jet mass: low EA STAR



Groomed jet mass in p+p and p+Au 50-100% event activity are comparable p+Au low-EA ~ p+p !

Jet mass: high EA



Low- and high-EA mass ratio is unity within systematic and statistical uncertainties

No significant modification to the jet mass is observed in *p*+Au!

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Groomed jet mass: high EA



Low- and high-EA mass ratio is unity within systematic and statistical uncertainties \rightarrow core of the jets is unmodified

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Conclusions - p+Au

First inclusive *p*+Au jet mass measurements at RHIC

Overall, we observe no contribution of CNM effects to the jet mass in p+Au collisions, suggesting p+p-like fragmentation, no jet modification

Suggests that centrality-dependent modification of jet yields observed by PHENIX is not due to modification of the internal structure of jets themselves.





Conclusions



First inclusive p+p, p+Au jet mass measurements at RHIC

p+p: RHIC-tuned PYTHIA-6: jet substructure data are well described LHC-tuned HERWIG-7, PYTHIA-8: opportunity for further tuning

p+Au: no contribution of CNM effects to the (groomed) jet mass, suggesting p+p-like fragmentation

Outlook

 z_g , R_g in p+Au — are competing modifications canceled in M_g ?

Narrow event activity selections to enhance potential CNM effects

Study jet radius dependence in p+Au to compare to p+p

Au+Au to study hot nuclear matter effects on jet substructure, e.g. jet mass!



Sudakov structure of jet mass



Sudakov structure of jet mass



MC tunes

PYTHIA-6.4.28: Perugia 2012 tune. "This combination overestimates the inclusive π^{\pm} yields by up to 30% for $p_T < 3$ GeV/c, when compared to the previously published STAR measurements at $\sqrt{s} = 200$ GeV [47,48]. To compensate, a single parameter in the Perugia 2012 PYTHIA tune, PARP(90), was reduced from 0.24 to 0.213. PARP(90) controls the energy dependence of the low-p_T cut-off for the UE generation process."¹

PYTHIA-8.23: Monash tune²

¹STAR, Phys.Rev. D 100 (2019), 052005
²Skands, Carrazza, Rojo, Eur.Phys.J. C 74 (2014), 3024
³Gieseke, Rohr, Siodmok, Eur.Phys.J. C 72 (2012), 2225

HERWIG-7: LHC-UE-EE-4-CTEQ6L1 underlying event tune³

Note: relatively stable particles are left undecayed until interaction with the detector material in the GEANT-3 simulation. These "stable" particles include $\pi^0, \pi^{\pm}, \eta, K^+, K^0_S, K^0_L, \Sigma^{\pm}, \bar{\Sigma}^{\pm}, \Lambda, \bar{\Lambda}, \Xi^-, \bar{\Xi}^+, \Omega^-, \bar{\Omega}^+$

Quark and gluon fractions



Gluon jets have larger mass than quark jets ($C_A/C_F = 9/4$) Majority of jets are quark-initiated in this kinematic regime













Groomed jet mass systematics



Systematic uncertainties are reduced from ungroomed case

Groomed jet mass as a function of R



Groomed mean mass less sensitive to radius / p_T variation

Groomed jet mass as a function of R



Groomed jet mass as a function of R



Comparing high-EA p+Au to p+p







PYTHIA-8 Angantyr (heavy ions)



PYTHIA-8.219 p+p and PYTHIA-8.219 p+Au (Angantyr) use the same tune (Monash) Weak decays turned off to be consistent with the PYTHIA-6 used in the measurement

PartonLevel:MPI = on PartonLevel:ISR = on PartonLevel:FSR = on HadronLevel:Hadronize = on