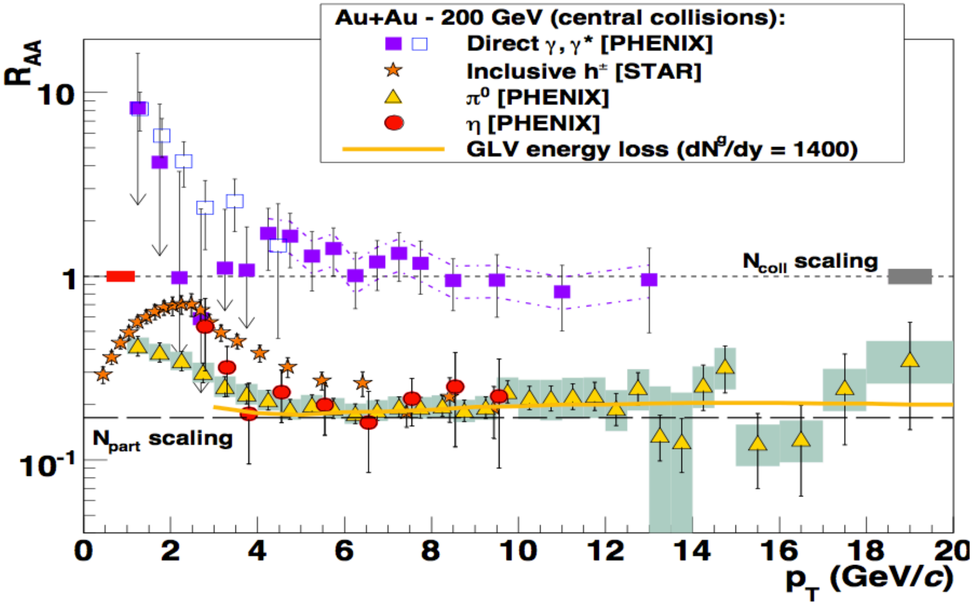
Recent jet results in Heavy-Ion collisions at RHIC

Nihar Ranjan Sahoo
Shandong University

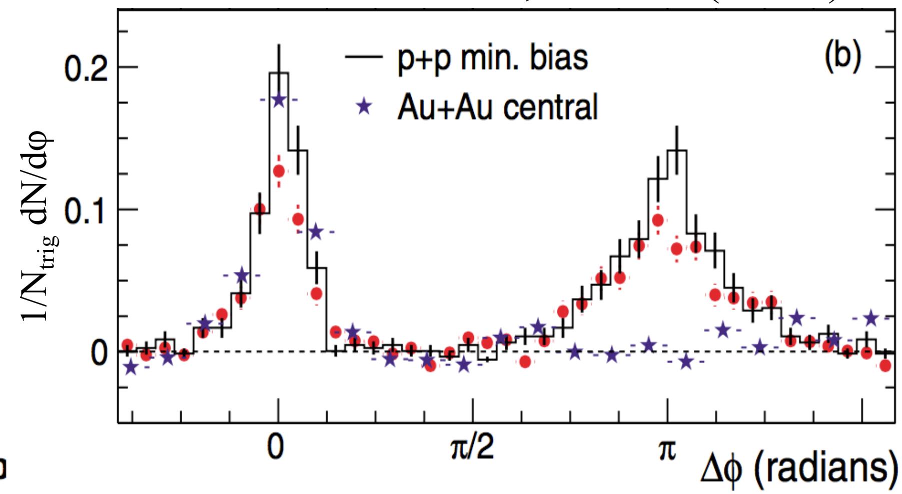
QPT 2019, Enshi, China
Aug 17-20, 2019

Jet quenching in RHIC

Early RHIC measurements



STAR: PRL 91, 072304 (2003)



- Suppression of inclusive charged/neutral hadrons at high-p_T
- No suppression of vector-bosons (γ, W, Z)
- Away-side jet suppression

Indication of Hot-dense QCD medium (QGP)

What we want to study about the jet-quenching in HIC?

Quantitative understanding of parton energy loss in QCD medium

- Parton energy loss as a function of path length, color factor, initial parton energy, etc.
- Redistribution of lost energy inside the medium [Jet radius/medium]
- RHIC vs. LHC [dependence on temp. and initial gluon density]

  What about lower beam energy in HIC? Any threshold for pQCD?
- Modification jet shape inside a finite temp. QCD medium

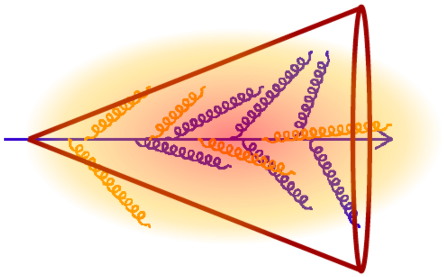
Important to understand QCD at finite temperature(QGP)

Many theoretical developments are still underway for a deeper understanding of the heavy-Ion data…

Let’s focus on RHIC heavy-Ion results…

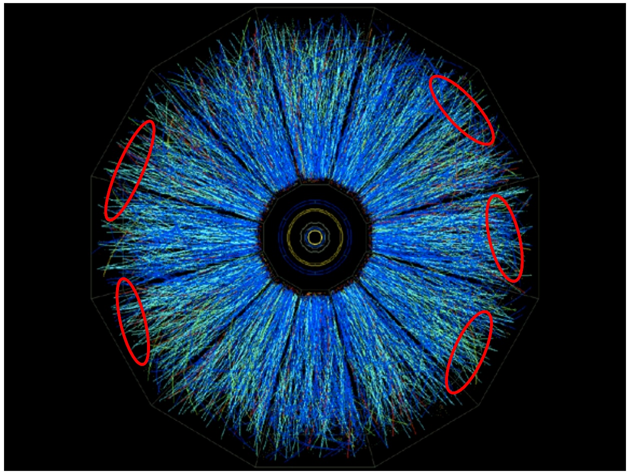
Challenges in heavy-ion collisions to study jet

In hot-dense QCD medium: simultaneous effect of vacuum shower and medium-induced gluon radiation



Au+Au collisions

In Heavy-Ion collisions:
Soft-background fluctuations and uncorrelated jet background contributions make life difficult



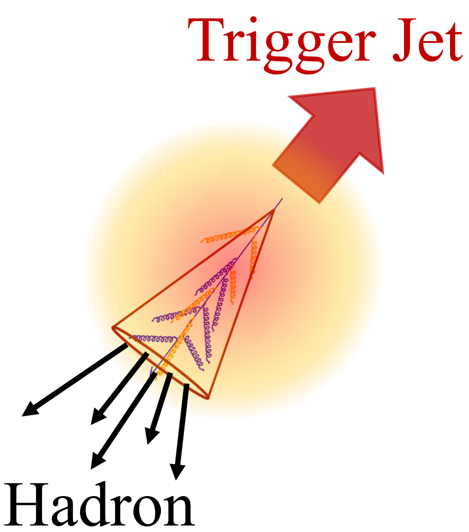
Recently, in STAR (PHENIX) experiment we developed some techniques to overcome these huddles.

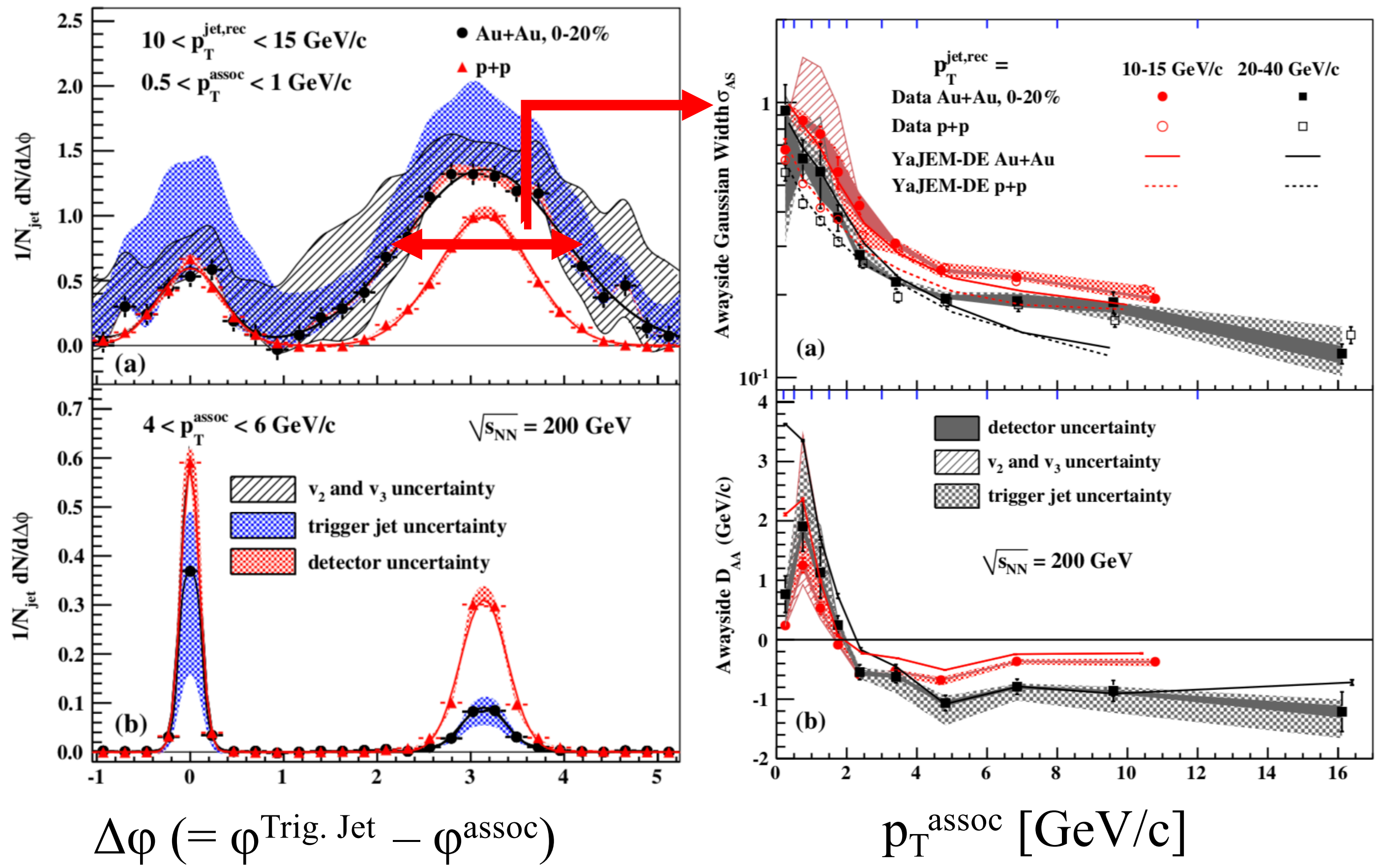
- Jet+hadron, γ+hadron, h+Jet, γ+Jet, Dijet, Inclusive jet, SoftDrop-grooming, etc.

(All are not covered due to the time limit, only selected results.)

Jet + hadron correlations

STAR: PRL112, 122301 (2014)





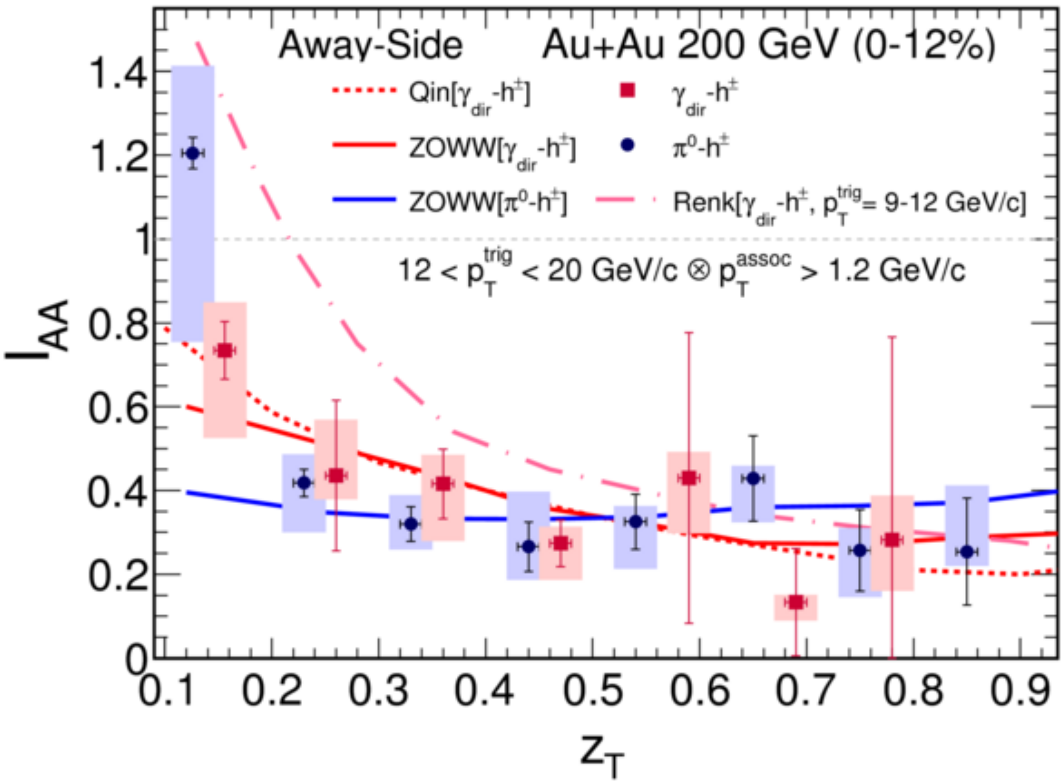
High-p_T balanced by Low p_T enhancement

Away-side jet width →medium-induced broadening

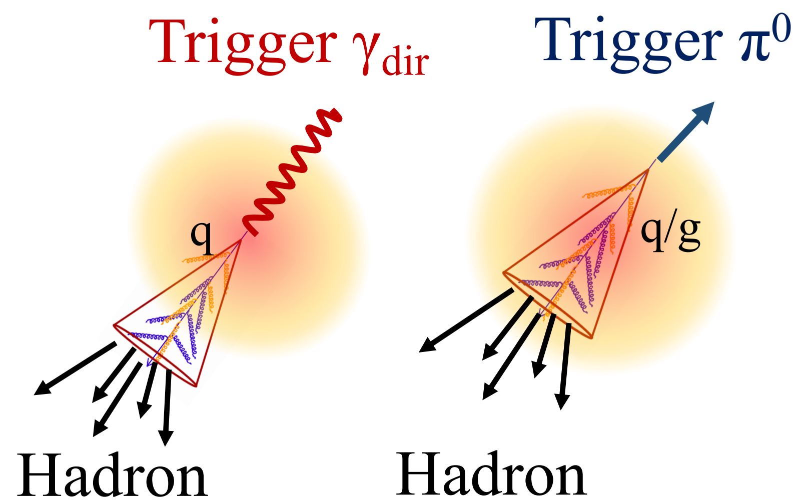
Jet-like γ_{dir}+hadron and π^0+hadron correlations

$$I_{AA}(x) = \frac{Y^{Au+Au}(x)}{Y^{p+p}(x)}$$

STAR: PLB 760 (2016) 689



Trigger Bias:
Color factor and path length effect?



$z_T = p_{T,i}{}^{h}/p_T{}^{trig}$

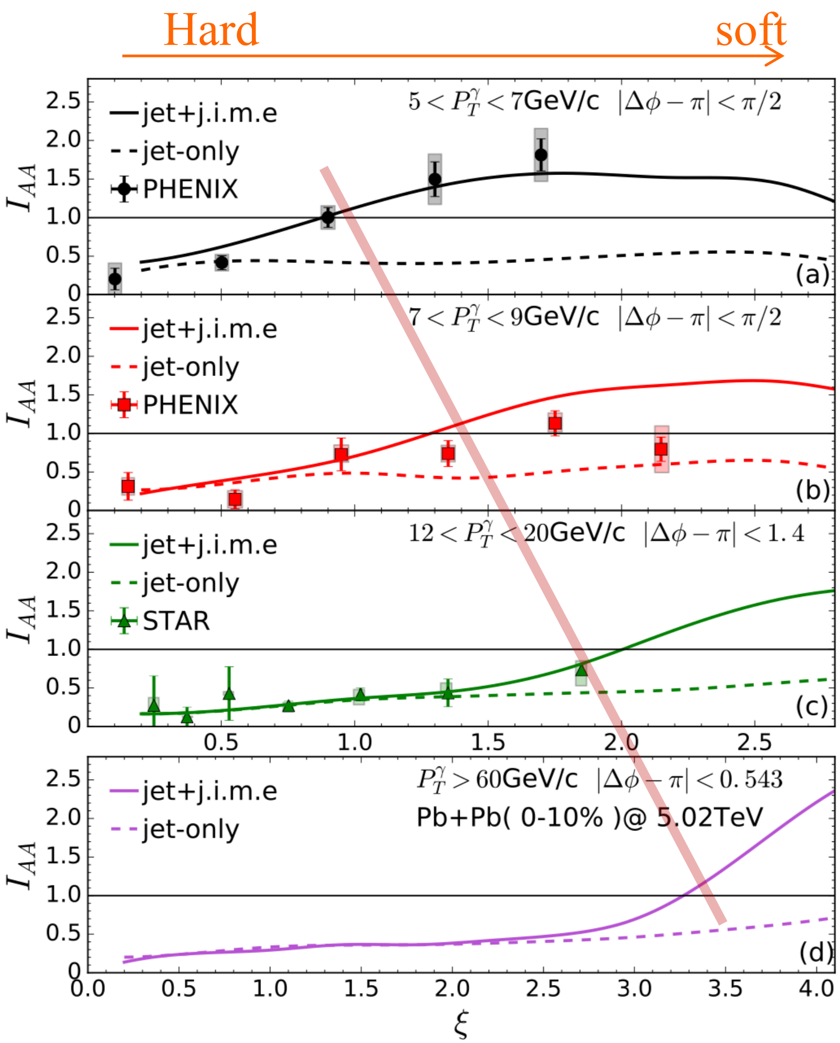
- Soft associated particles are less suppressed compared with high pT

  Consistent with Jet+hadron correlation result
- Within uncertainty, no trigger (γ_{dir}/ π^0) bias can be observed

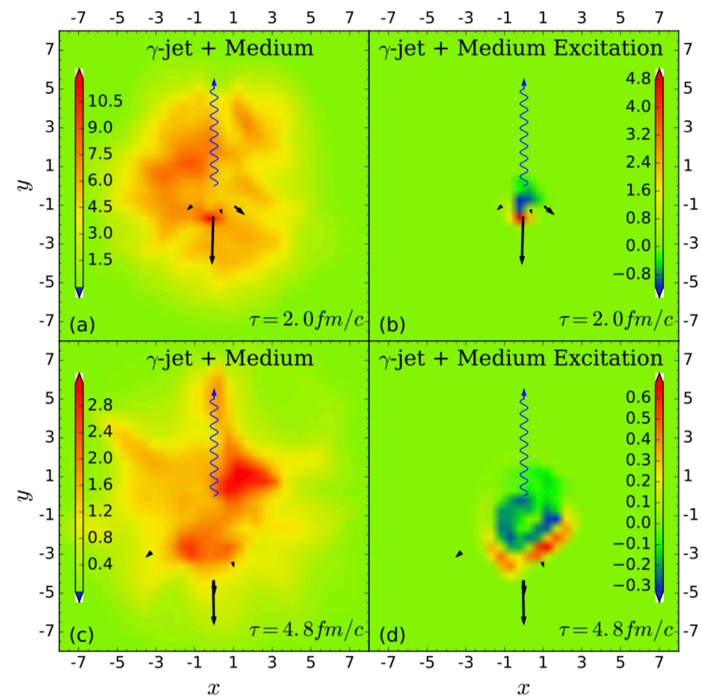
Jet-like γ_{dir}+hadron correlation: Theory comparison

W. Chen, et al. PLB 777, 86 (2018)

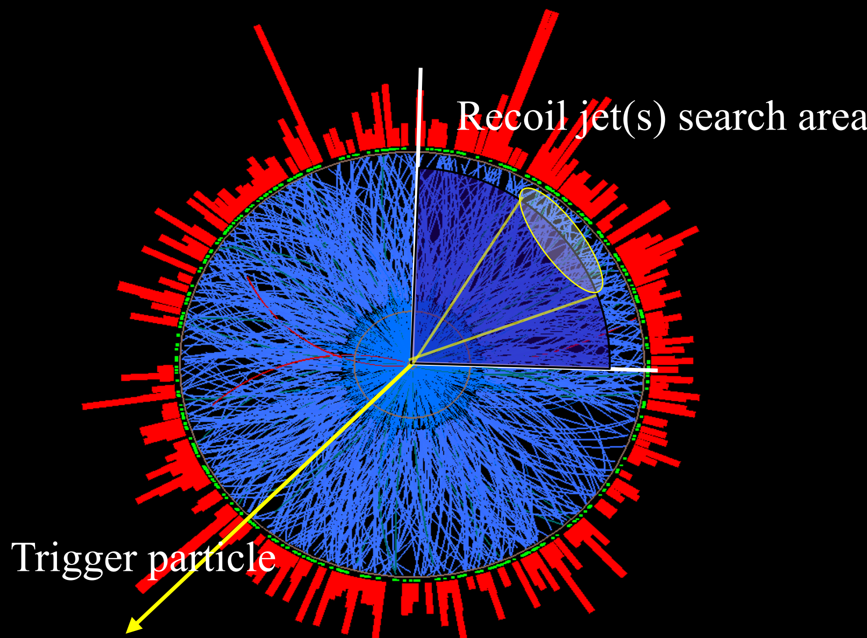
Coupled linear Boltzmann Transport and 3+1D hydro (CoLBT-hydro)



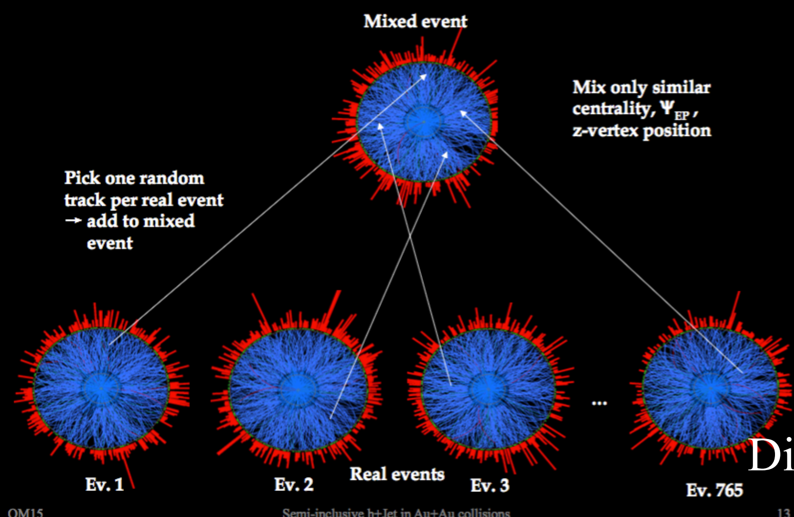
- Enhancement of soft hadrons due to jet-induced medium excitation



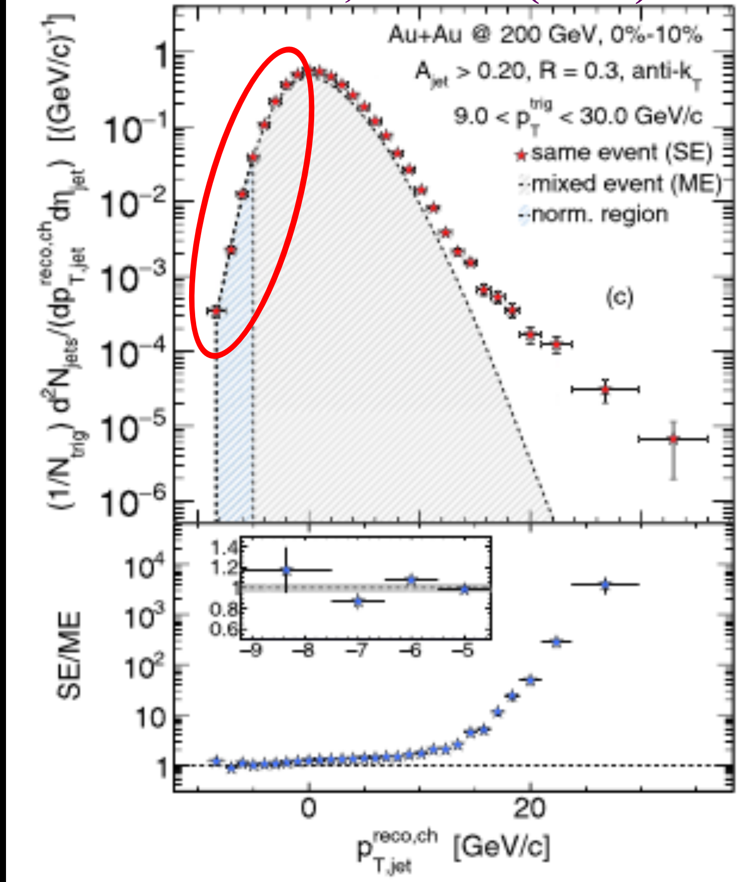
h+jet in STAR experiment



Uncorrelated Background: Mixed Events



PRC 96, 024905 (2017)

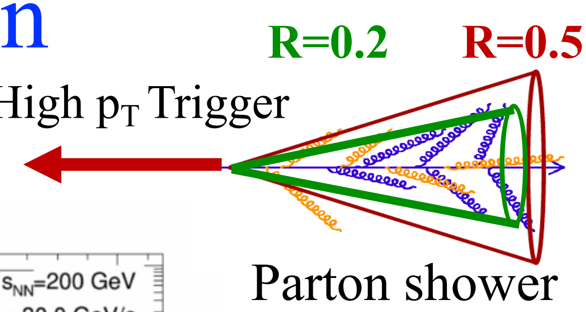


$$p_{\mathrm{T,jet}}^{\mathrm{reco,ch}} = p_{\mathrm{T,jet}}^{\mathrm{raw,ch}} - \rho \cdot A$$

Distribution matches with mixed event background.

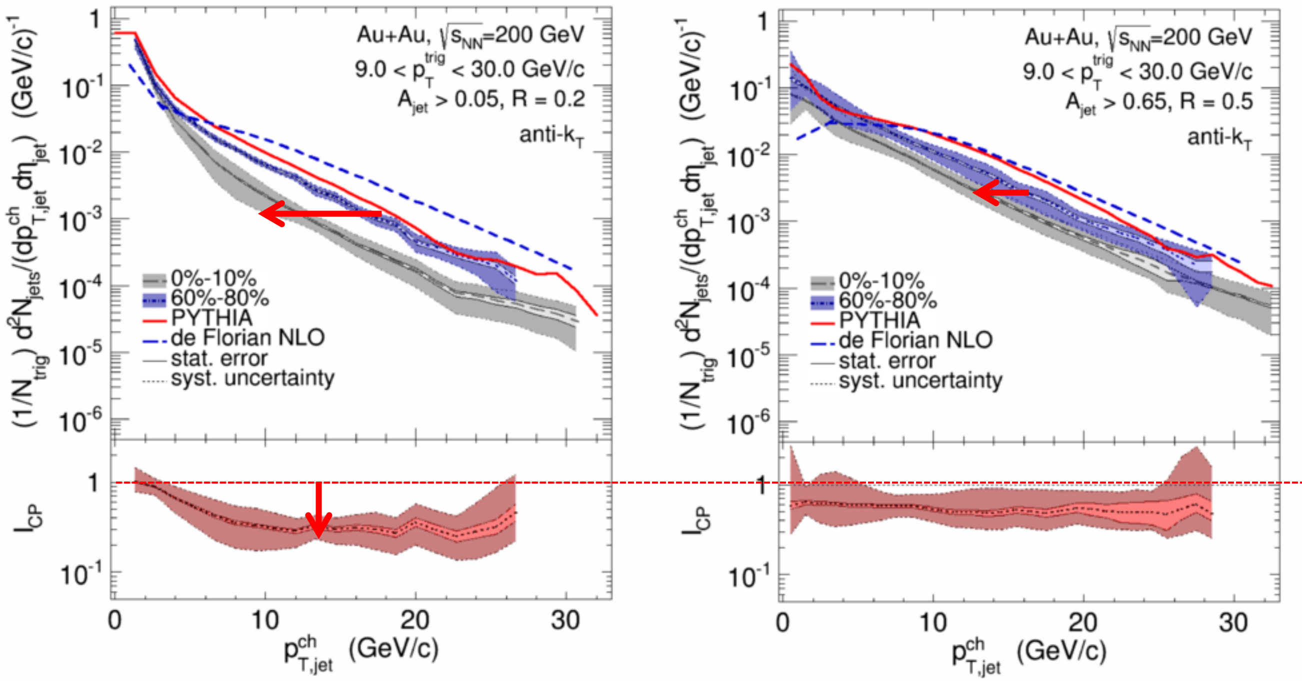
h+Jet yield suppression

STAR:PRC 96, 024905 (2017)



Ratio Per trigger yield

Jet R= 0.2 **Jet R= 0.5**



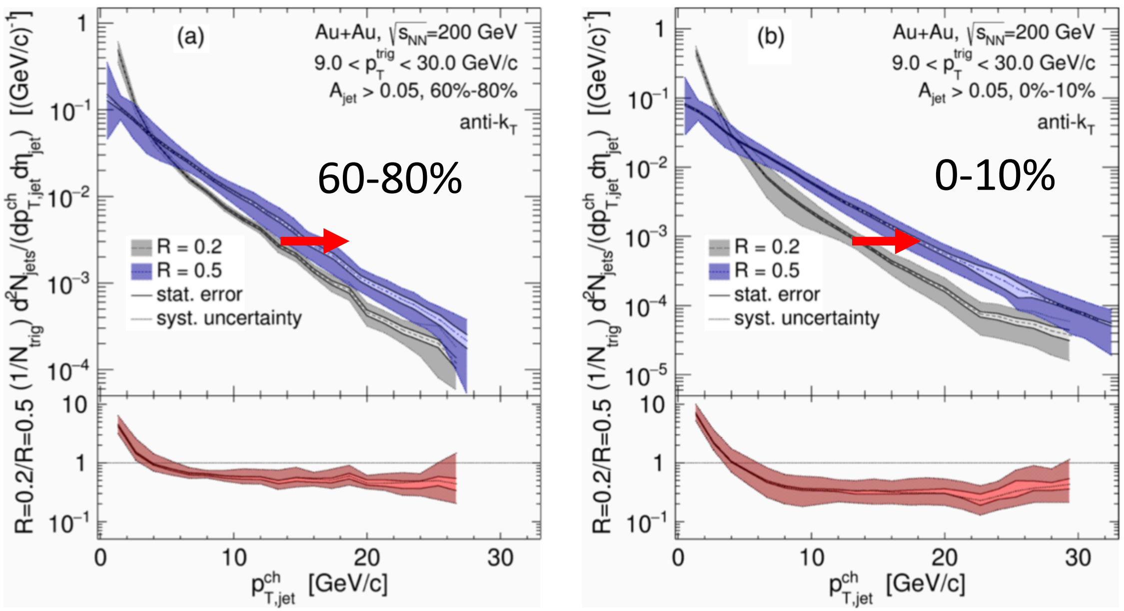
Transverse momentum of the recoil jet in GeV/c

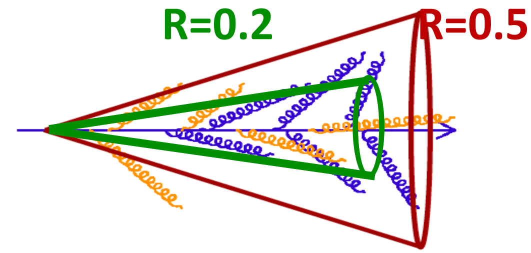
- Energy transported out of the cone due to jet-quenching (Partonic energy loss)

Modification of jet shape: h+jet

Medium induced broadening!

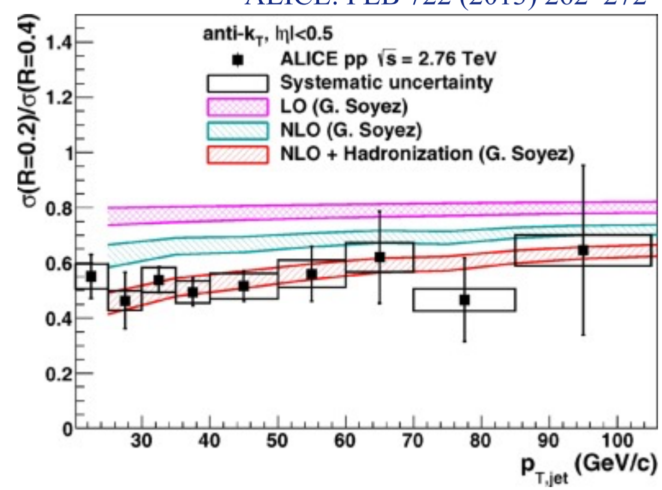
STAR:PRC 96, 024905 (2017)





Intrajet distribution of energy transverse to the jet axis

ALICE: PLB 722 (2013) 262–272



- Horizontal pT-shift between 10-20 GeV/c:
  - 60-80%: 2.9 ± 0.4(stat) ± 1.9(sys) GeV/c
  - 0-10%: 5.0 ± 0.5(stat) ± 2.3(sys) GeV/c
  - Consistent within uncertainty

No evidence of broadening of the jet shower due to jet quenching like in p+p and Pb+Pb at LHC

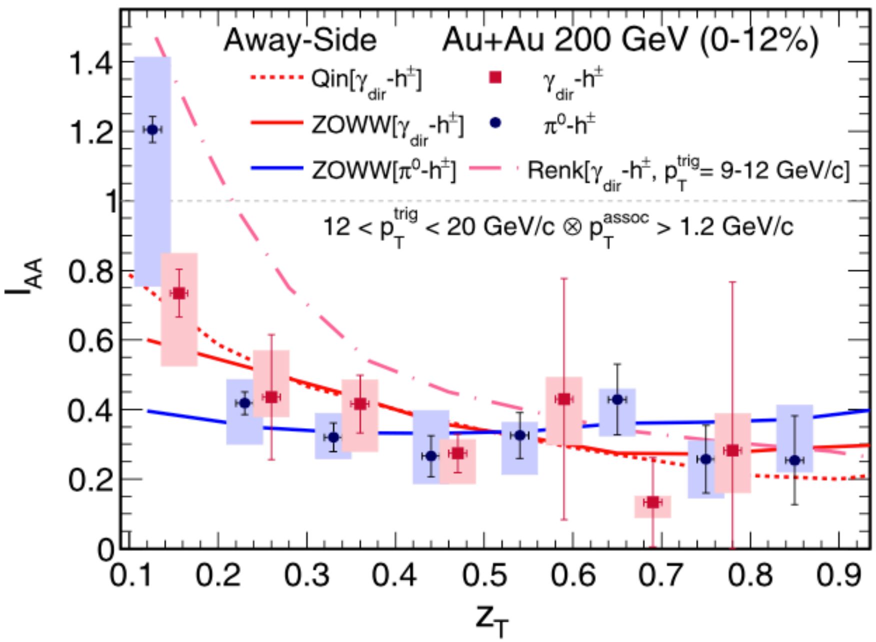
Two important tools developed in STAR

γ_{dir}+hadron and π^0+hadron correlation

$h^{\pm}$+jet

STAR: PLB 760 (2016) 689

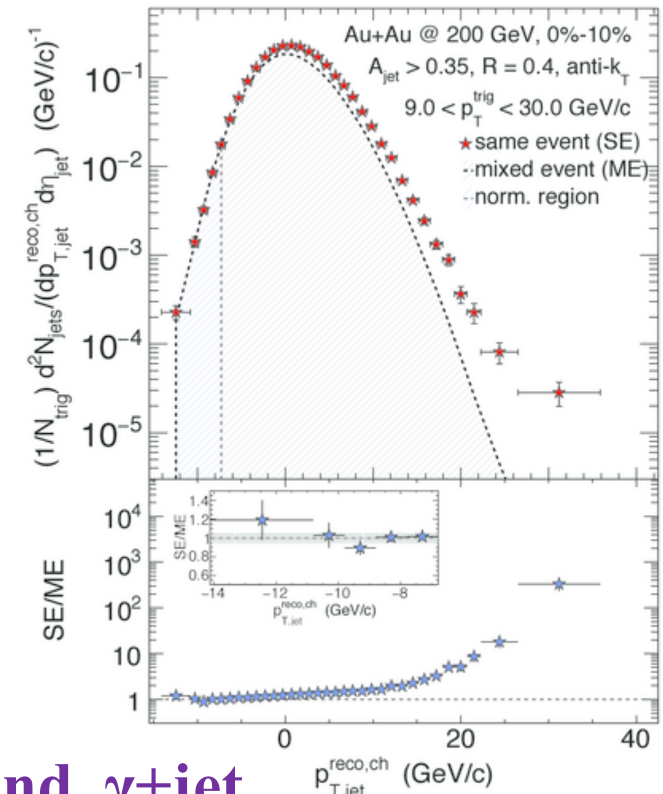
- γ_{dir}/π^0: trigger and discrimination



$$I_{AA}(p_T, z_T) = \frac{Y^{\text{Au+Au}}(p_T, z_T)}{Y^{\text{p+p}}(p_T, z_T)}$$

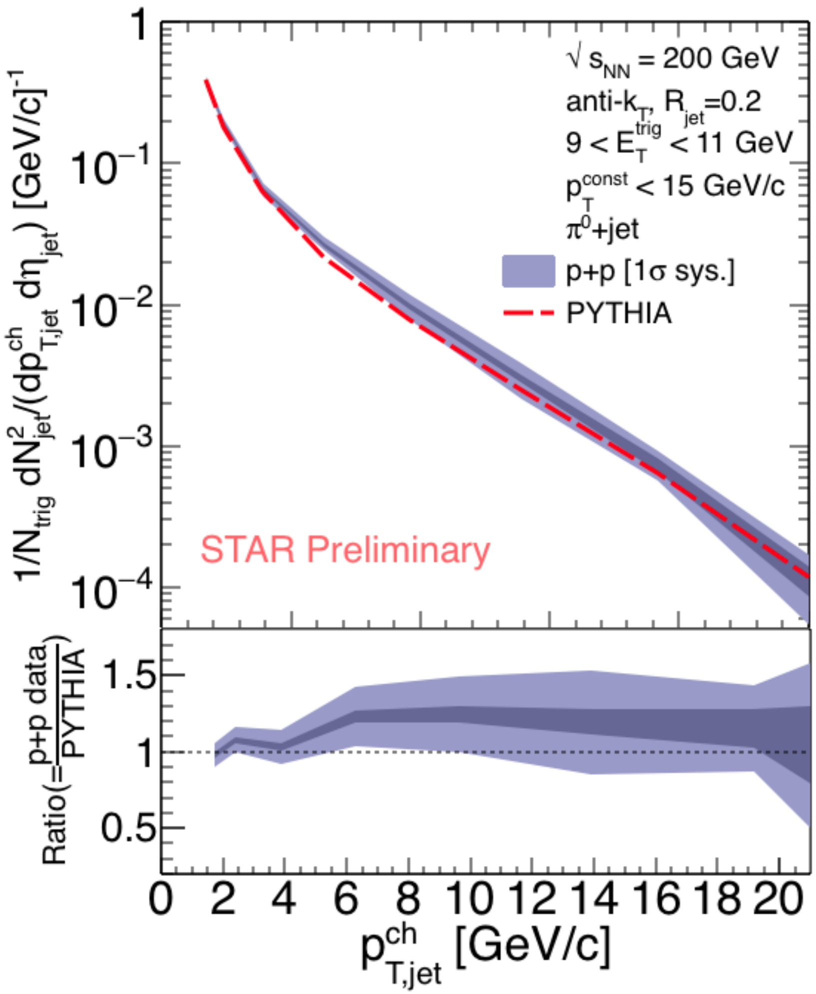
STAR:PRC 96, 024905 (2017)

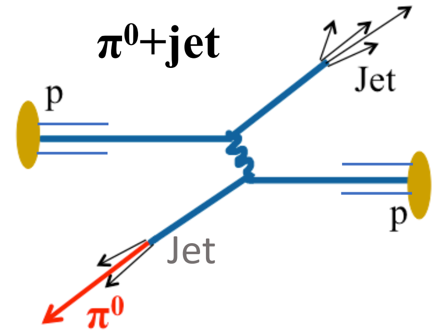
- Handel over uncorrelated background jet
- Final recoil jet correction (Unfolding)



Splicing these two analyses → **π^0+jet and γ+jet**

π^0-trigger charged recoil jets in p+p collisions



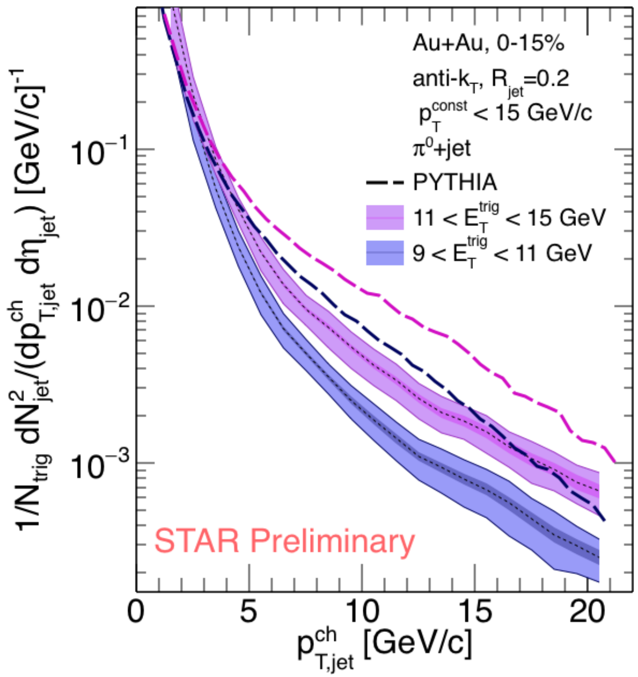


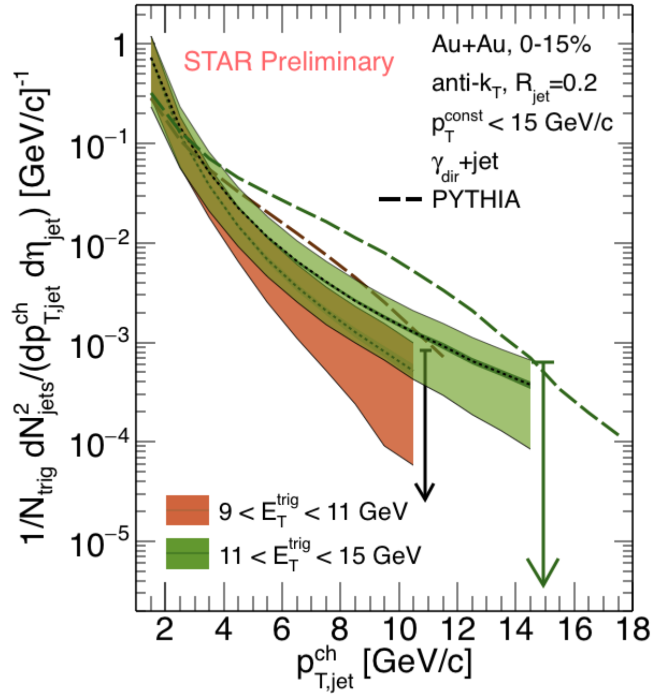
- p+p $\sqrt{s_{NN}}$ = 200 GeV/c
- π^0 triggers with $9 < E_T^{trig} < 11$ GeV, fully unfolded charged jets
- π^0-triggered charged-jet spectrum consistent with PYTHIA8.

Nihar Sahoo: HP2018 talk

γ_{dir}+jet and π^0+jet in Au+Au collisions

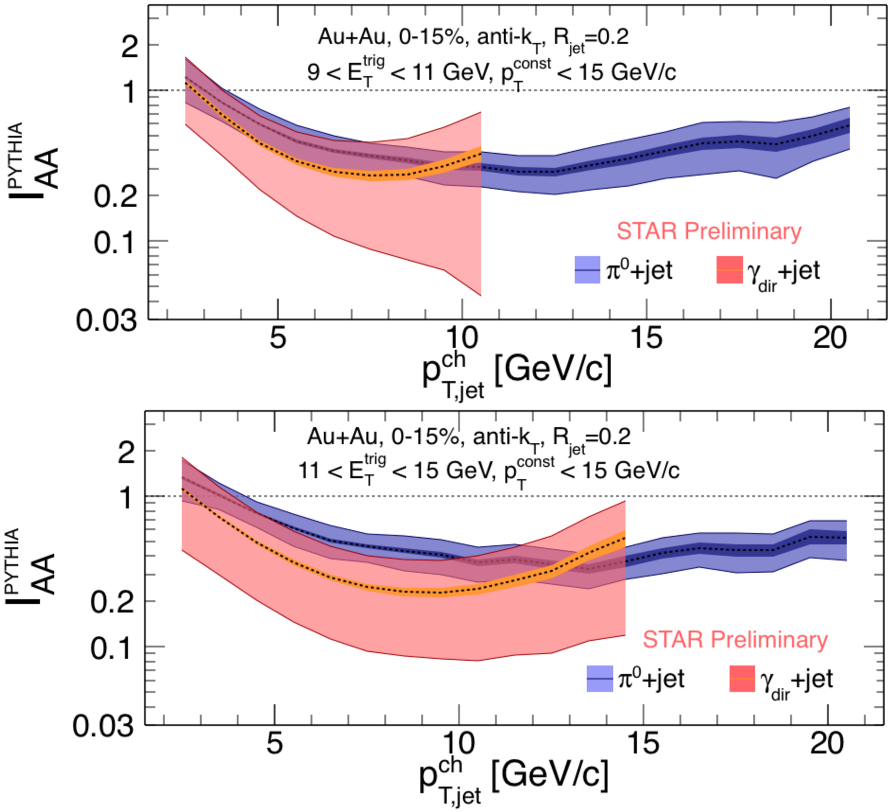
Nihar Sahoo: HP2018 talk





- A clear difference between recoil-jet spectra for different π^0 trigger-E_T: $9 < E_T^{trig} < 11$ GeV vs. $11 < E_T^{trig} < 15$ GeV
- Indication of difference between γ_{dir} trigger recoil-jet
- Clear suppression with respect to pp reference (PYTHIA8)

Recoil jet yield suppression: γ_{dir}+jet vs. π^0+jet



Nihar Sahoo: HP2018 talk

$$I_{AA} = \frac{Y(p_{T,jet}^{ch})^{Au+Au}}{Y(p_{T,jet}^{ch})^{p+p}}$$

I_{AA}^{PYTHIA}: PYTHIA as p+p reference

[Systematic uncertainty has been improved in the current study for QM2019]

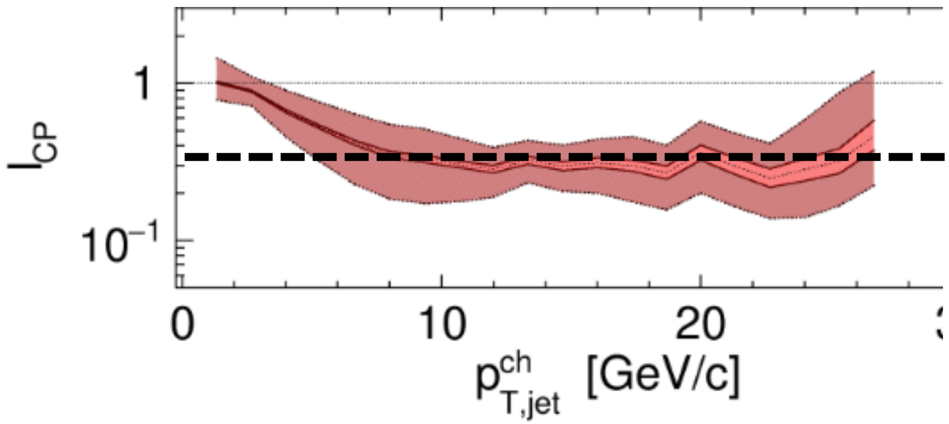
- I_{AA}^{PYTHIA} is the ratio of per triggered recoil jet yield in central Au+Au collisions to PYTHIA
- Clear suppression for both trigger types with respect to PYTHIA8
- Similar level of suppression in γ_{dir}+jet and π^0+jet, within uncertainties

Comparison of $h^{\pm}$+jet to π^0+jet

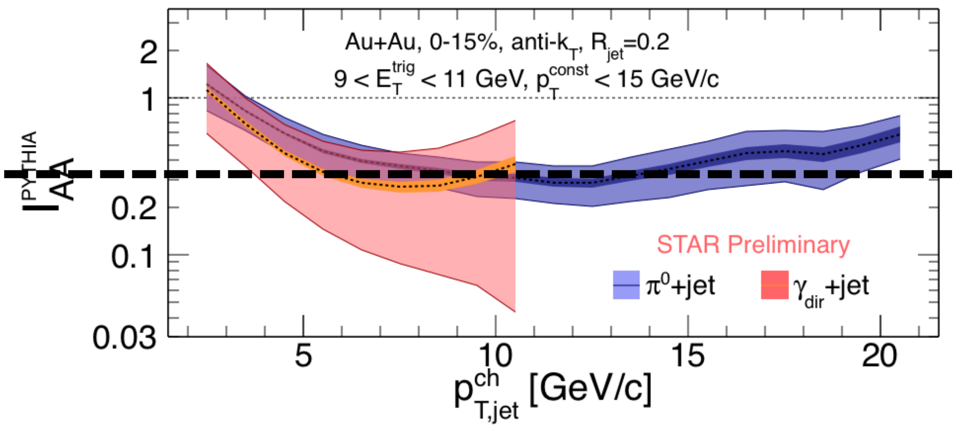
Au+Au 200 GeV

STAR: PRC **96**, 024905 (2017)

$h^{\pm}$+jet: $9 < p_T^{trig} < 30$ GeV/c



This analysis: $9 < E_T^{trig} < 11$ GeV



Systematic (lighter band) and statistical (darker band) uncertainties

- Same level of suppression above $p_{T,jet}^{ch} > 9$ GeV/c
  - $h^{\pm}$+jet is I_{CP}, whereas π^0+jet is I_{AA}^{PYTHIA}

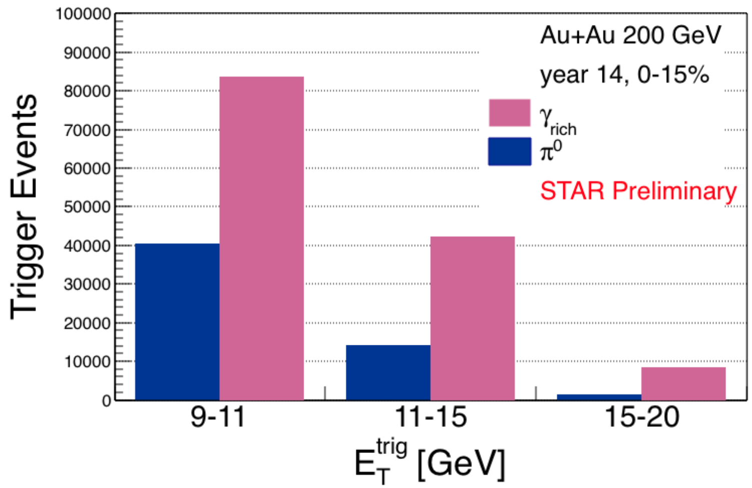
Recoil jet yield suppression: γ_{dir}+jet vs. π^0+jet

Two jet radii

- R=0.2 and 0.5 [to explore medium-induced broadening]

Three trigger E_T bins of γ_{dir} and π^0

- $9 < E_T^{trig} < 11$ GeV
- $11 < E_T^{trig} < 15$ GeV
- $15 < E_T^{trig} < 20$ GeV [STAR capability of γ_{dir} measurement at very high E_T^{trig}]



Results will be shown in Quark Matter 2019, Wuhan.

Dijet symmetry in Au+Au

Background fluctuations in Au+Au

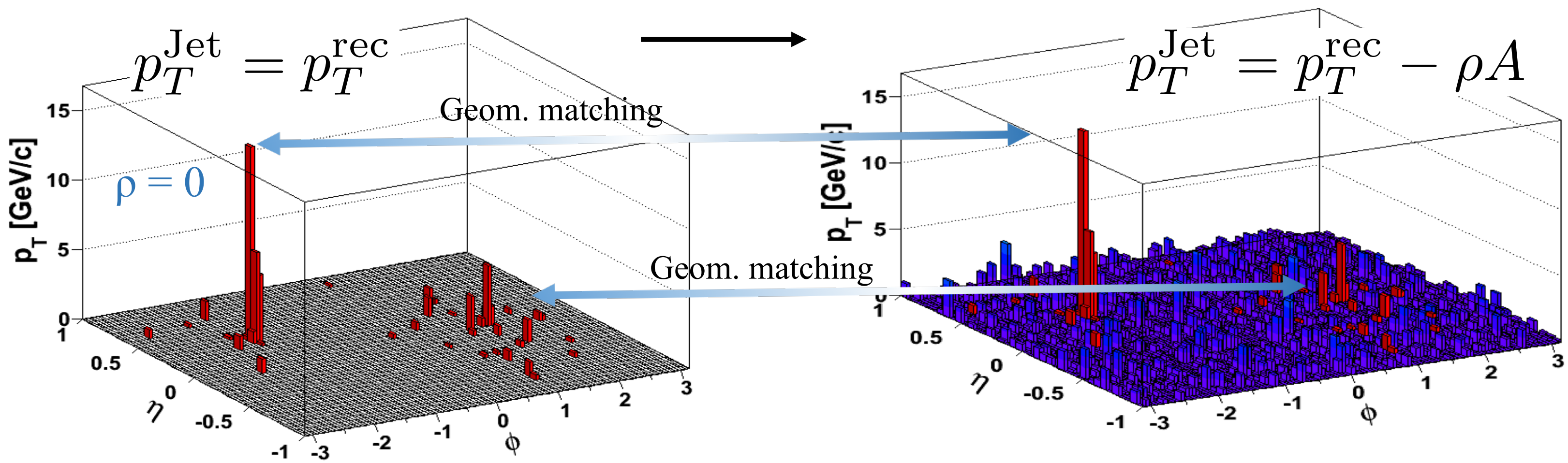
p_T^{Cut}=2 GeV/*c*

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

p+p HT

Rerun jet-finding algorithm anti-k_T on these events

p+p HT $\otimes$Au+Au MB



Transverse momentum imbalance for back-to-back di-jet pairs

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

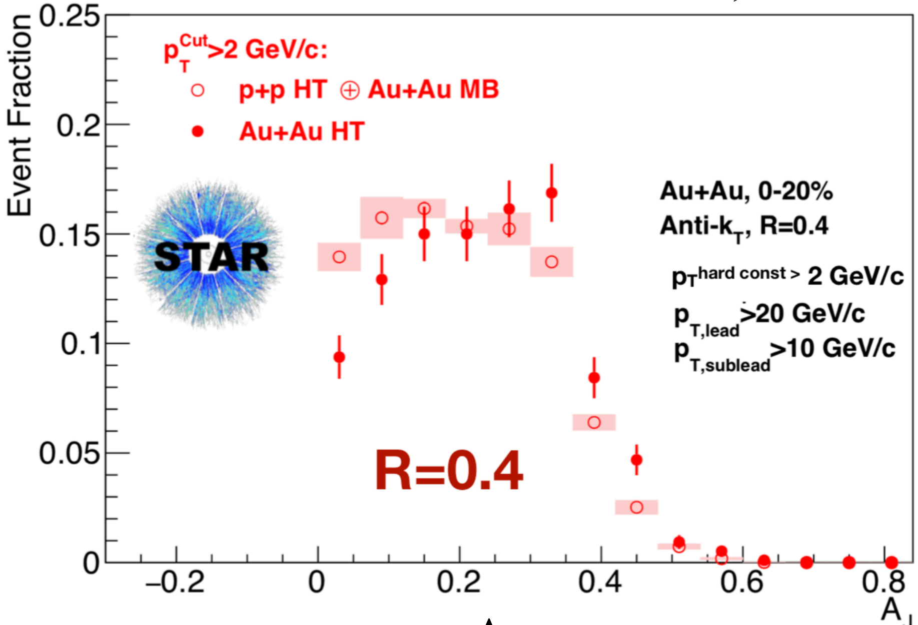
- Calculate "matched" $|A_J|$ with constituent $p_{T,cut}$>0.2 GeV/c and with geometrical matching condition $\Delta R < 0.4$

Dijet asymmetry in Au+Au

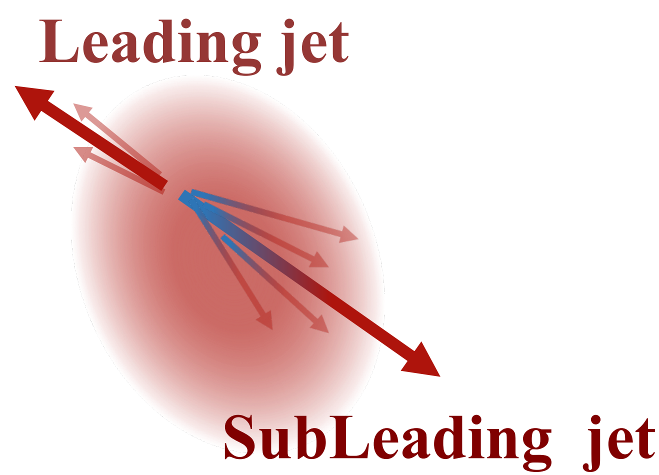
Transverse momentum imbalance for back-to-back di-jet pairs

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

STAR: PRL 119, 062301 (2017)



A_J



Hard core ($p_T^{\mathrm{const.}}$ > 2 GeV/c) di-jet noticeably imbalanced w.r.t p+p

Dijet asymmetry in Au+Au

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

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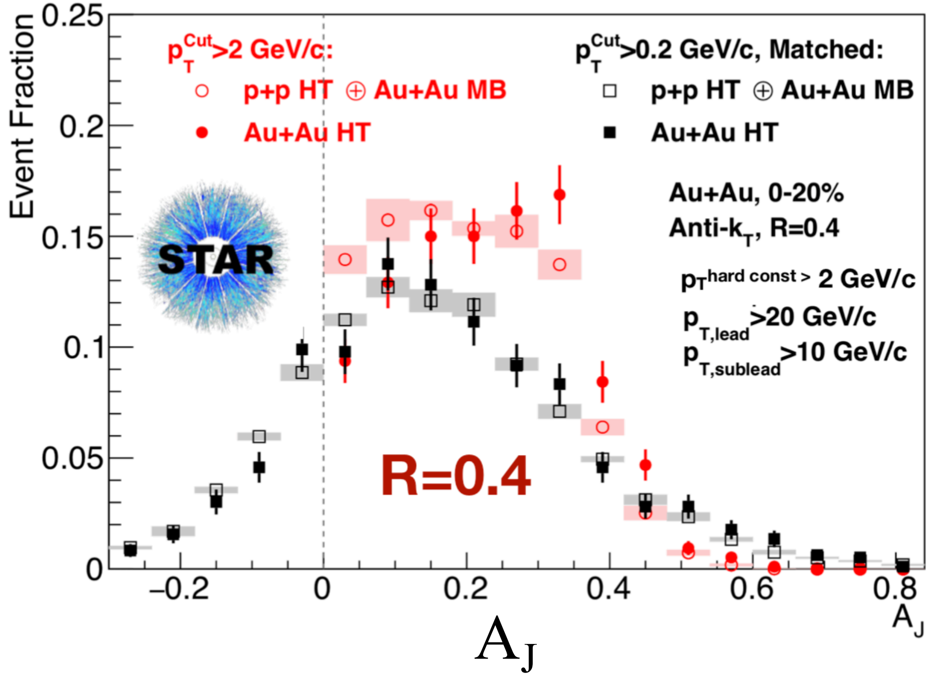
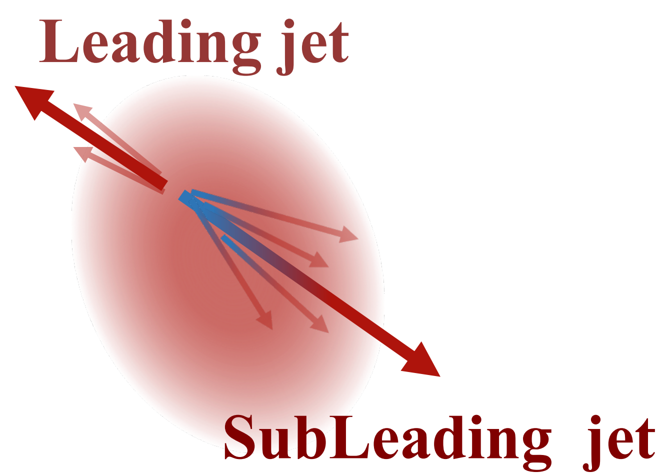




Hard core ($p_T^{\text{const.}}$ > 2 GeV/c) di-jet noticeably imbalanced w.r.t p+p

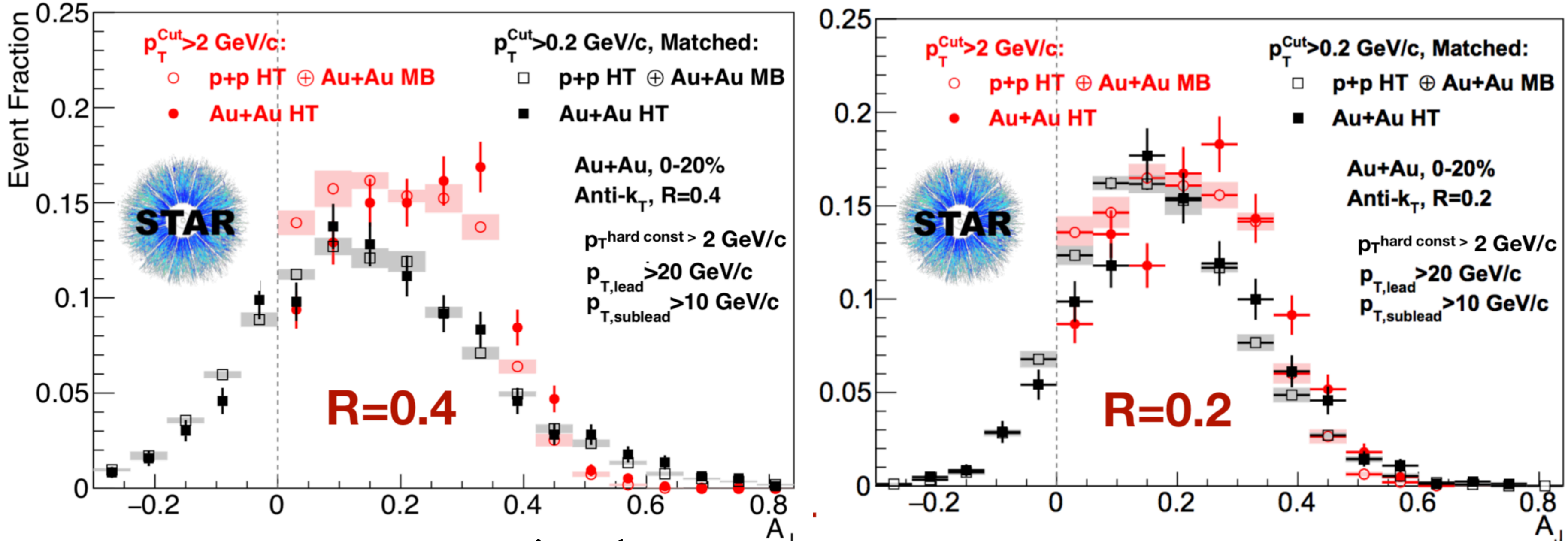
But, including soft particles ($p_T^{\text{const.}}$ > 0.2 GeV/c), balance recovered to a level of p+p for R=0.4 (What about smaller R = 0.2?)

Dijet asymmetry in Au+Au

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

STAR: PRL 119, 062301 (2017)

Balance no longer restored to a level of p+p for R=0.2, including soft particles ($p_T^{\text{const.}} > 0.2$ GeV/c)



Jet suppression by

- Broadening of jet from R=0.2 to 0.4
- Softening of jet constituents

What is the threshold of recovery?

Summary and outlook

Progress after the discovery of jet-quenching at RHIC

- Several attempts for detail information of jet quenching in HIC

  STAR/PHENIX: Jet+hadron, γ+hadron, h+Jet, γ+Jet, Dijet, Inclusive jet, SoftDrop-grooming, etc.

- Experimental techniques are developed to handle Heavy-Ion challenges

  Soft background fluctuations, uncorrelated jet bg., etc

- Still many open questions to answer for understanding jet-quenching in a finite temperature QCD medium (QGP)

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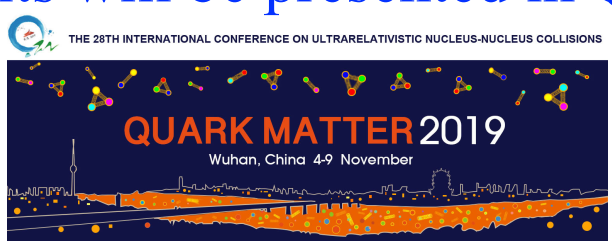
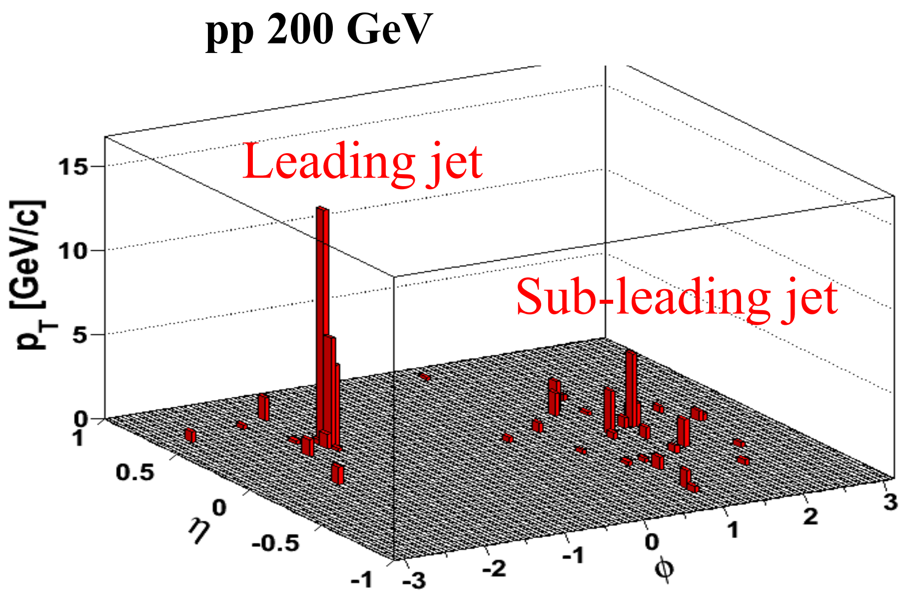
(New results will be presented in QM2019, Wuhan)



Thank you!
谢谢!

BackUp

Di-Jet imbalance



Di-jet Selection:

Jet p_T^{Lead}>20 GeV/c

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

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

Constituent $p_T^{\text{Cut}} > 2$ GeV/*c*

(Reduce background and combinatorial jets compared with including constituent $p_T^{\text{Cut}} > 0.2$ GeV/*c*)

Transverse momentum imbalance for back-to-back di-jet pairs

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

What is the background effect in Au+Au collisions?