Probing QGP by semi-inclusive γ+jet measurement in STAR

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BNL Nuclear Physics Seminar
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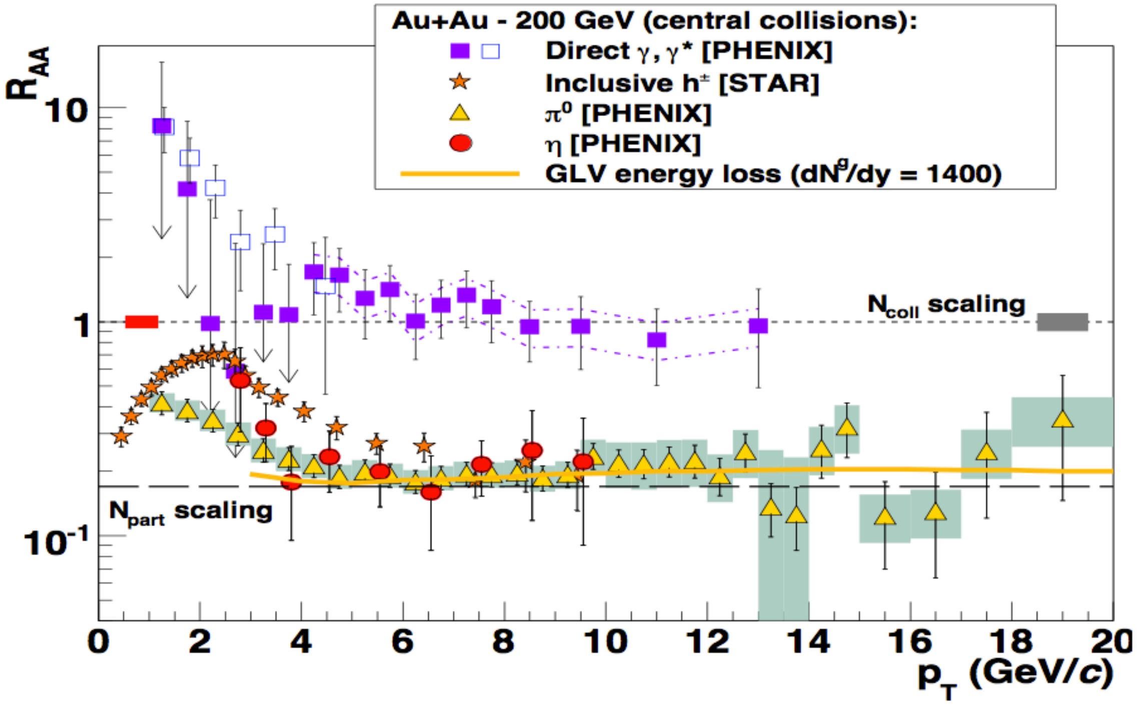
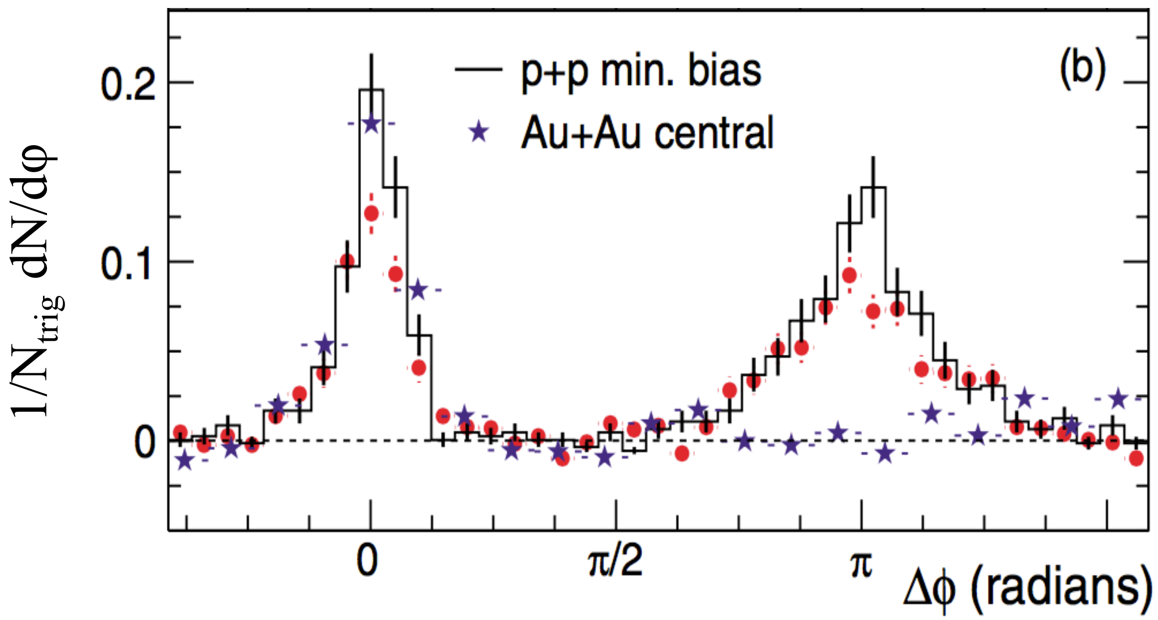
Jet quenching at RHIC

RHIC early measurements



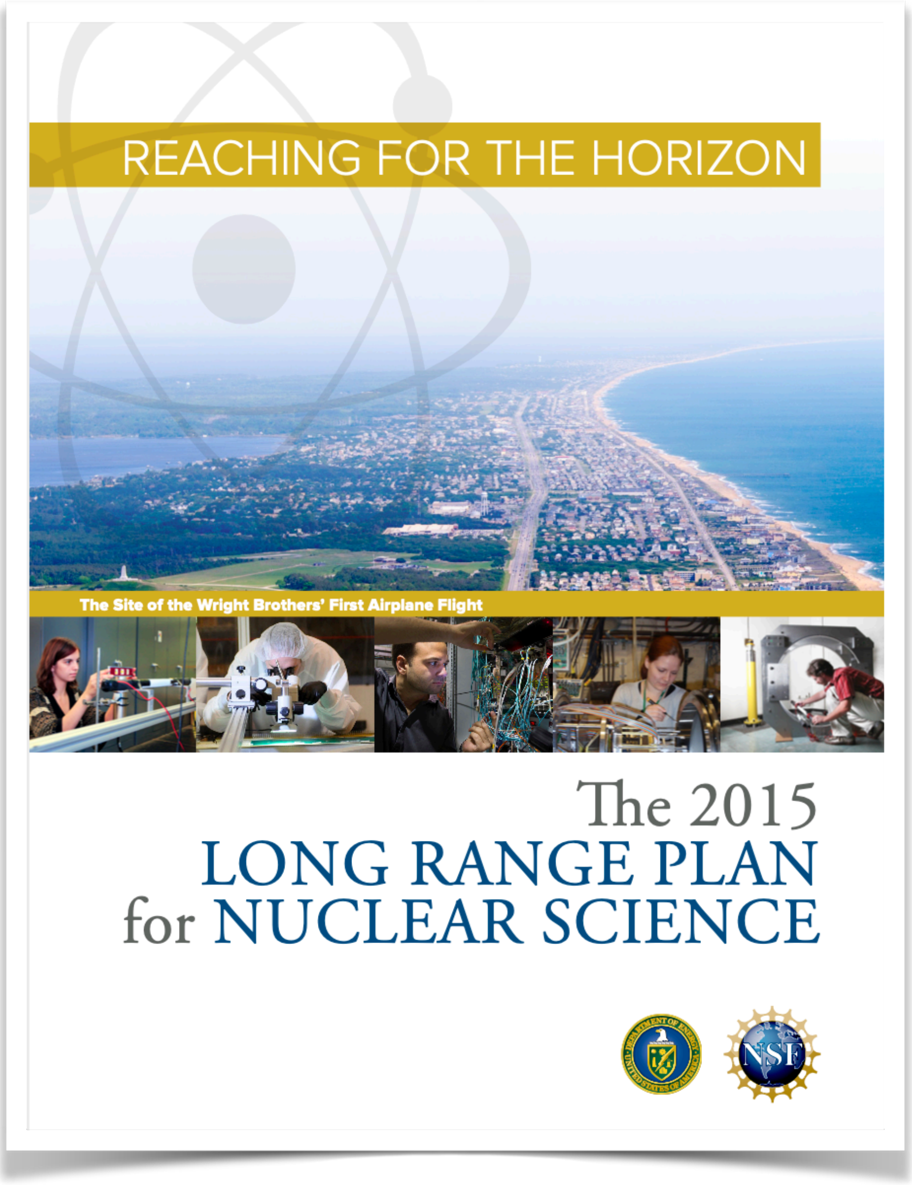
STAR: PRL 91, 072304 (2003)



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

Indication of hot-dense QCD medium (QGP)

RHIC scientific mission



REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

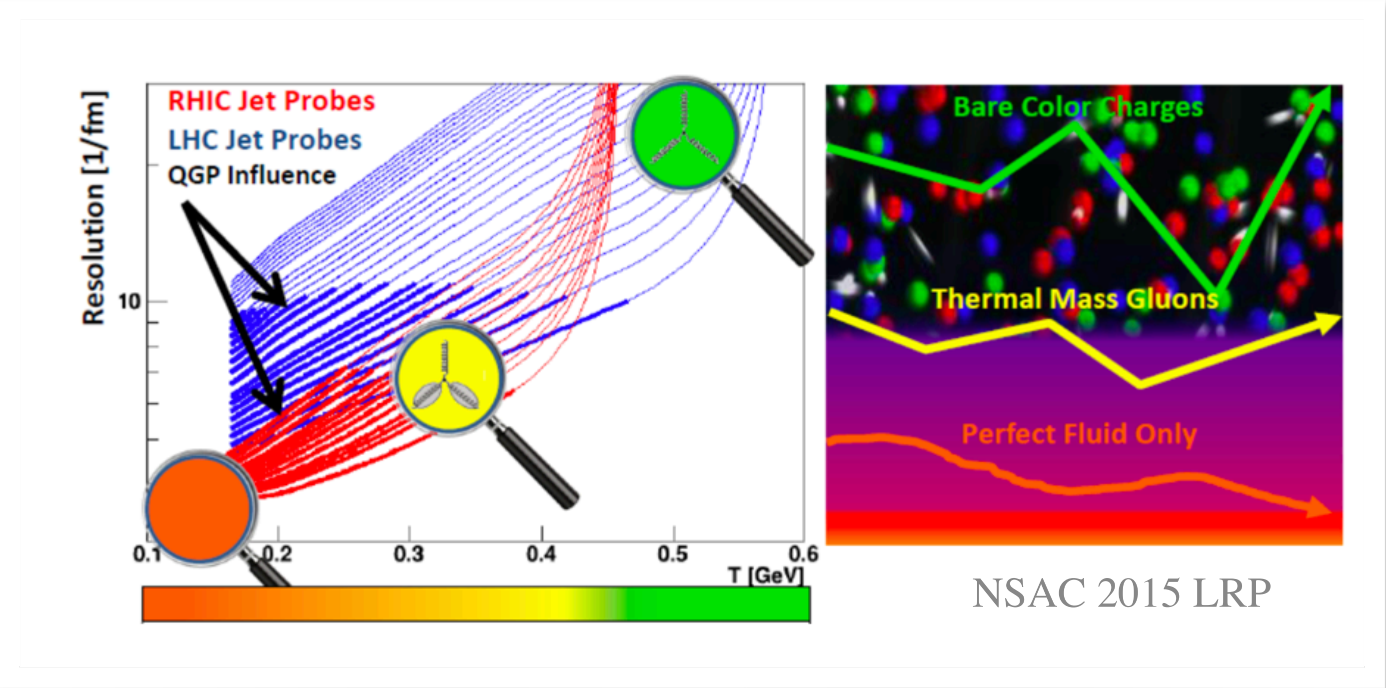
The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

Two central goals:

1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales

2) Map the phase diagram of QCD

Jet probes for the Quark-Gluon Plasma



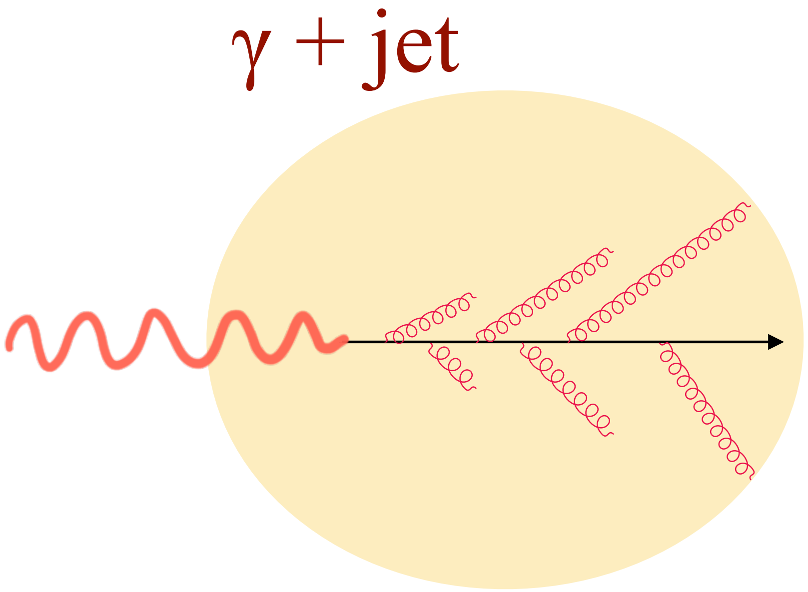
NSAC 2015 LRP

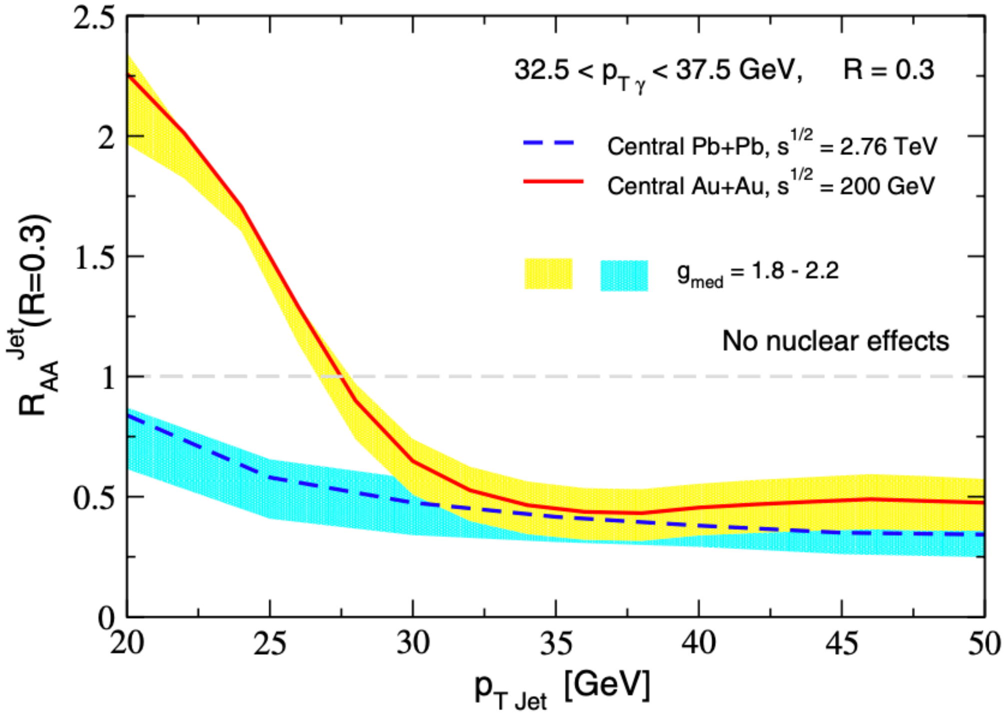
- Underlying mechanisms of jet-quenching at RHIC energy
- Microscopic structure of the QGP as a function of the resolution scale

Some perceptive inquiries on jet quenching:

- Quantitative evaluation of parton energy loss
- Redistribution of lost energy inside the medium
- RHIC vs. LHC [reduction of jet-medium coupling α_s]
- Jet quenching in a small system
- Modification of jet shape inside QGP
- Large angle deflection of recoil jet in QGP

γ+jet in heavy-ion collisions





[Dai et al., PRL 110, 142001]

- γ does not interact strongly in QGP → recoil jet is a "tomographic probe"

  However, NLO effects generate p_T-imbalance; calculable

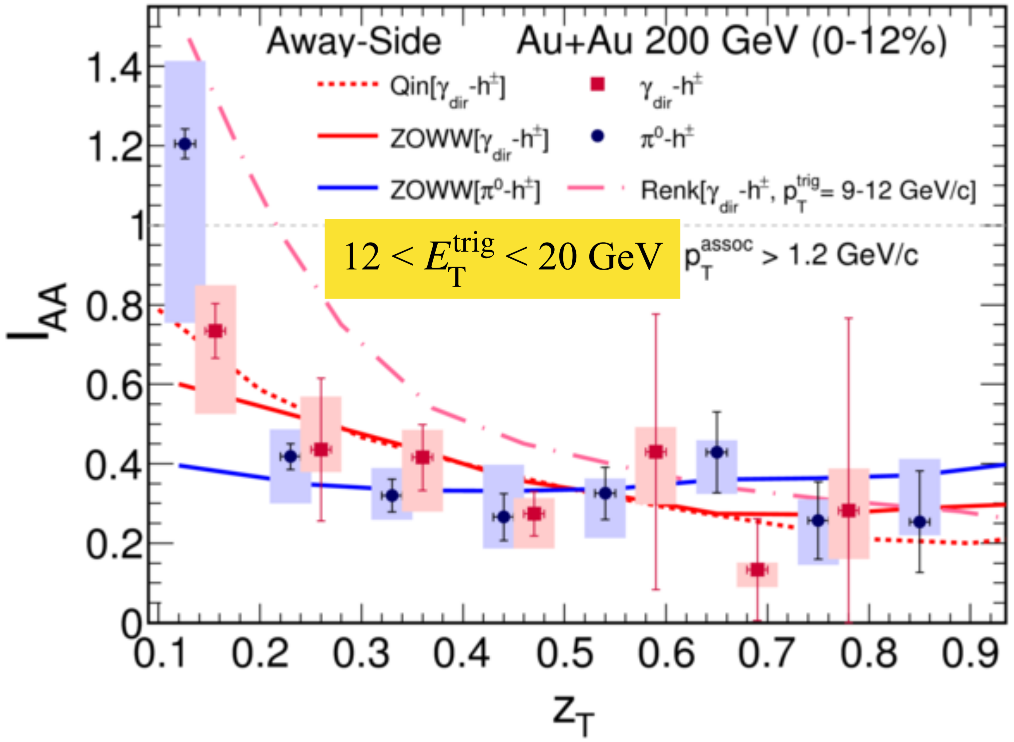
- Comparison of γ+jet at RHIC and the LHC: a valuable tool to explore jet quenching
- Comparison between γ+jet and π^0+jet

  q/g recoil jets and vary recoil mean path length

Jet-like γ+hadron and π⁰+hadron correlations measurements

[STAR, PLB 760 (2016) 689]

STAR: jet-like correlation measurement



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

$$z_T = \frac{p_{T,i}{}^{hadron}}{p_T{}^{trig}}$$

Lost energy reappears predominantly at low transverse momentum, regardless of trigger energy

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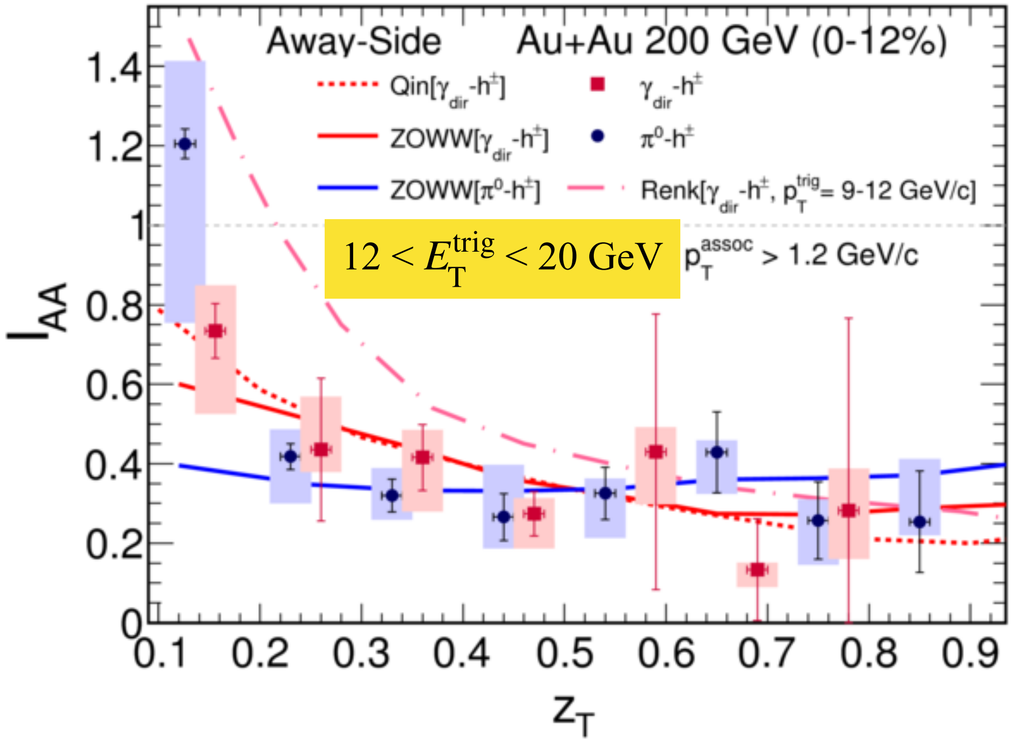

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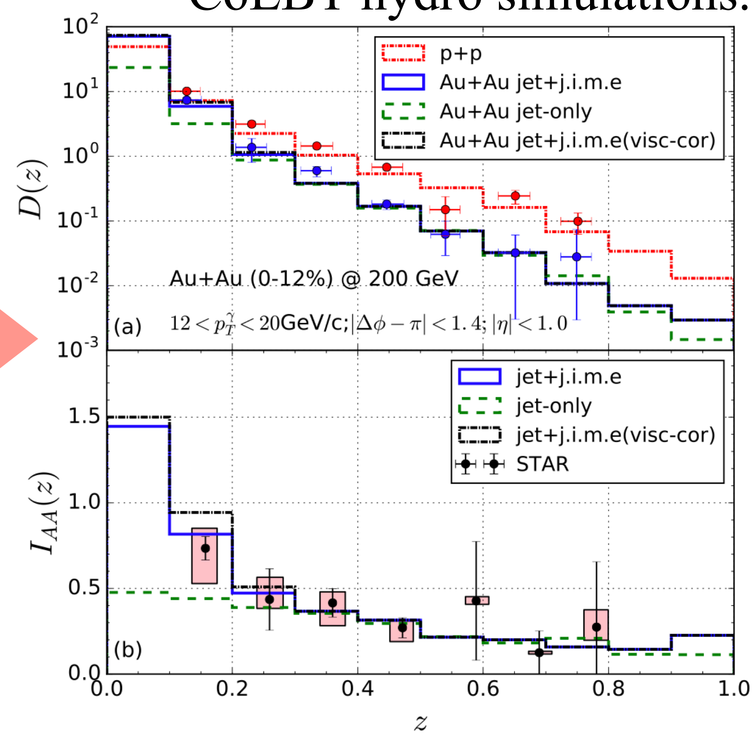
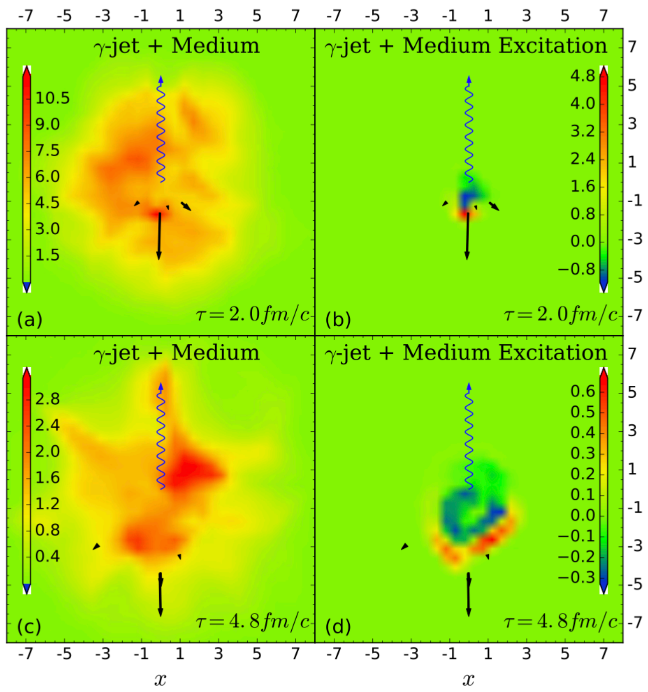
Theoretical development (CoLBT-hydro)

W. Chen *et al.*, PLB 777 (2018) 86–90

Jet transport and jet-induced medium excitation in CoLBT-hydro simulations.





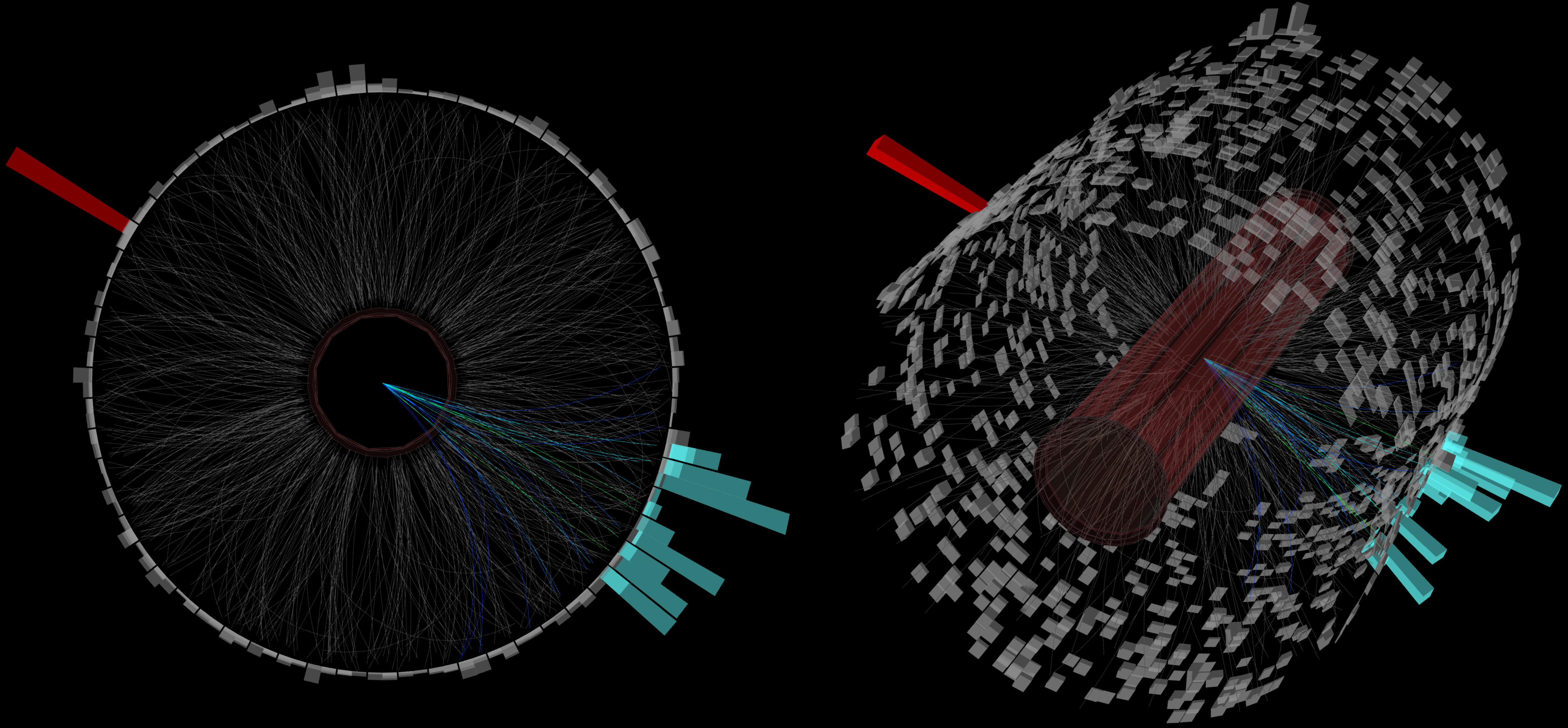
Depletion of soft hadrons in γ direction

→ Diffusion wake left behind by the jet in QGP

Data can be well reproducible by this model

A differential measurement by reconstructing recoil jet is needed to understand jet quenching.

γ+jet measurement in STAR



STAR Experiment
Au+Au $\sqrt{s_{NN}}$ = 200 GeV
Apr 06, 2014 09:22:51 EDT
Run Number: 15096026 Event ID: 2056716
γ + jet event
E_T : 17.6 GeV

Experimental challenges for γ+jet measurement

Two major challenges:

- Discrimination of γ/π^0 trigger events
- Uncorrelated jets

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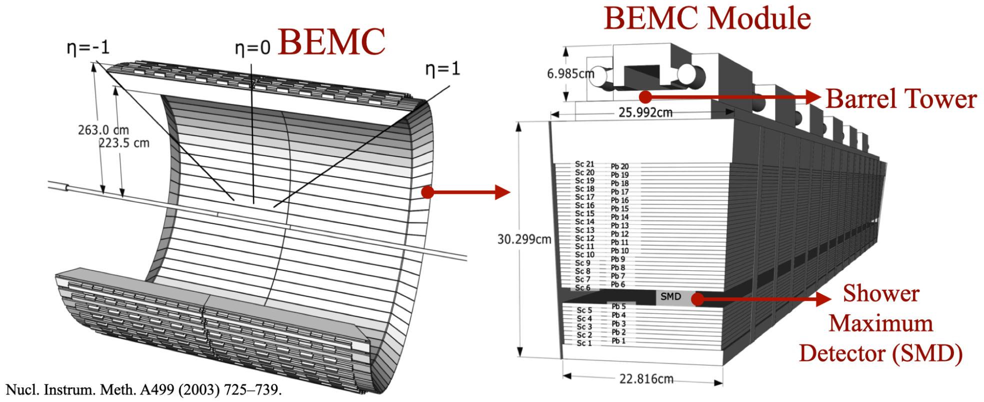
HT trigger to select γ/π^0 events using BEMC (L2gamma)



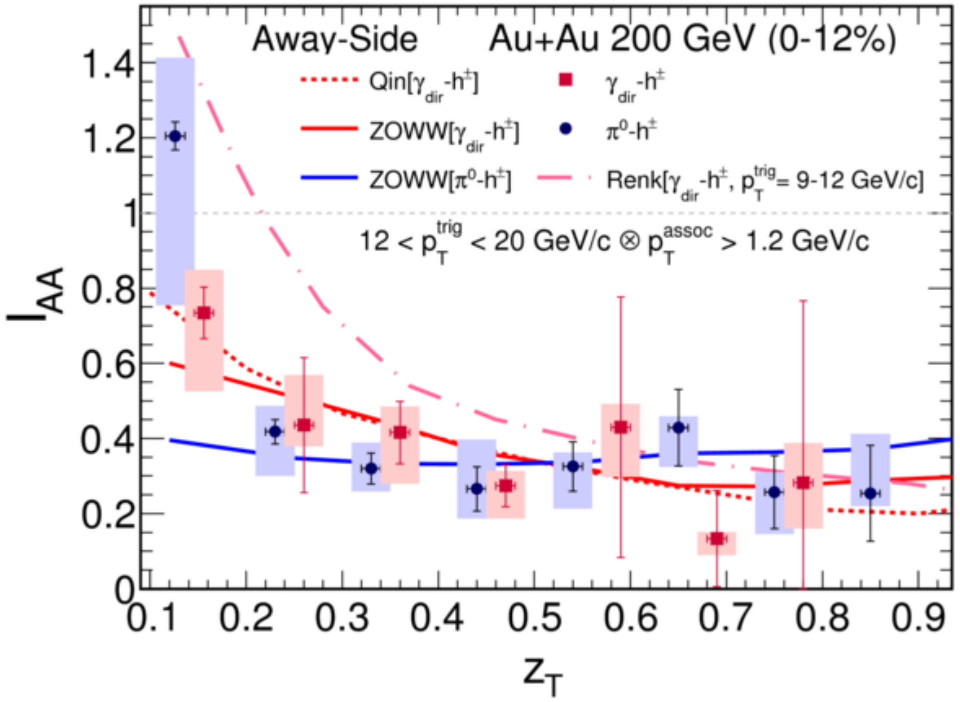
Nucl. Instrum. Meth. A499 (2003) 725–739.

BEMC and BSMD: Better η-φ spatial resolution

Jet-like Δφ correlation measurement

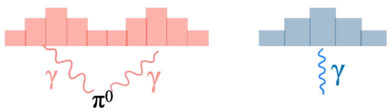
$12 < \gamma E_T^{trig} < 20$ GeV

[STAR, PLB 760 (2016) 689]

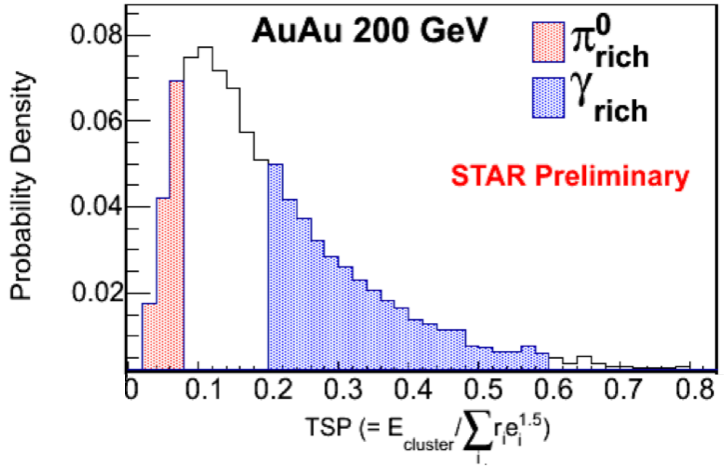


Smaller TSP value

Larger TSP value



Transverse Shower Profile (TSP) distribution



$$\mathrm{TSP} = \frac{E_{cluster}}{\sum_i r_i e_i^{1.5}}$$

$E_{cluster}$: Cluster energy
r_i : distance of the SMD strips from the center of cluster
e_i : individual SMD strip energies

All techniques are developed in STAR

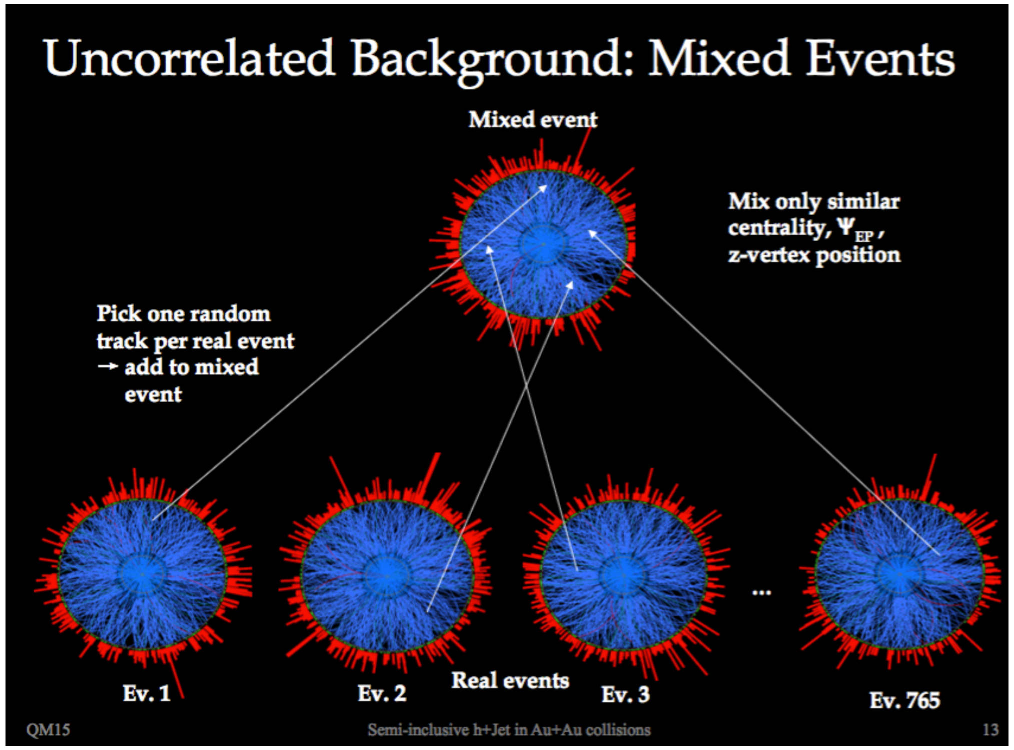
Besides, we can also trigger $\gamma E_T^{trig} > 20$ GeV but it needs some R&D

- γ dominates over π^0 at high E_T^{trig} (> ~15 GeV)

Experimental challenges for γ+jet measurement

Two major challenges:

- Discrimination of γ/π^0 trigger events
- Uncorrelated jets



Uncorrelated Background: Mixed Events

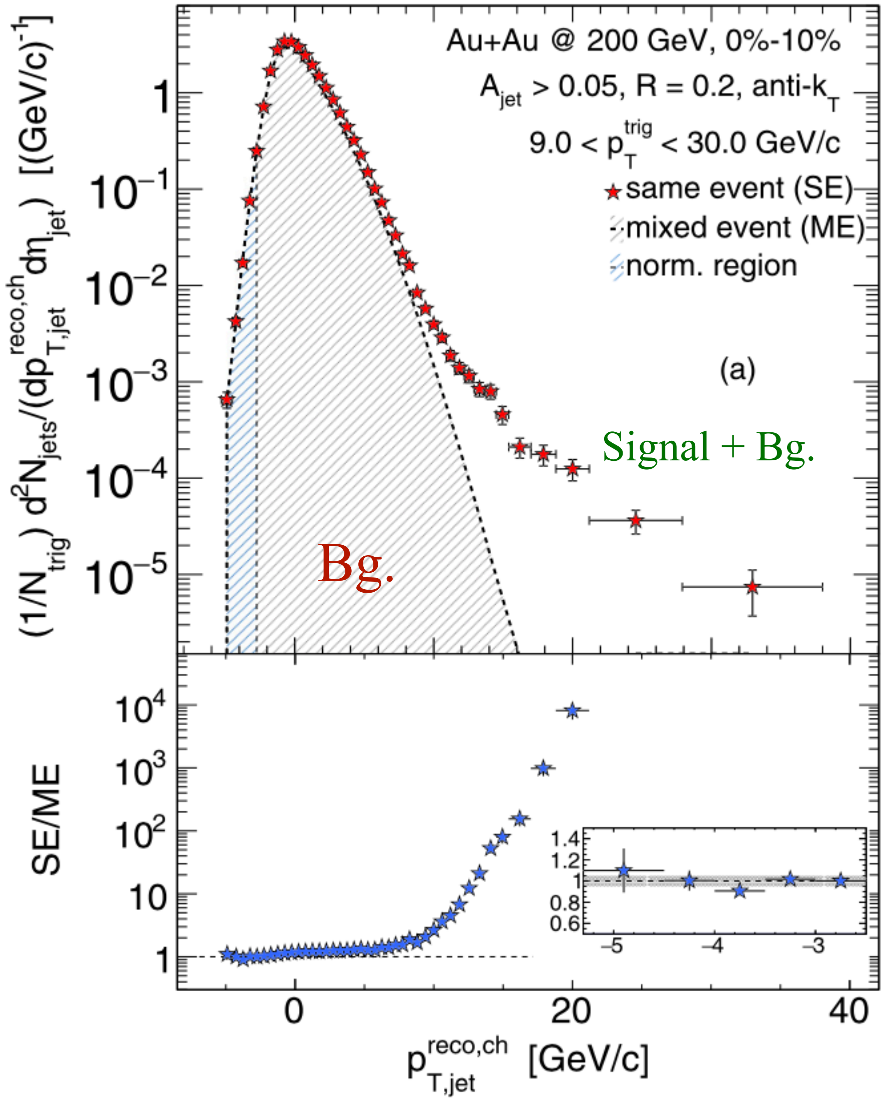
Mix only similar centrality, Ψ_{EP}, z-vertex position

Pick one random track per real event → add to mixed event

Procedures are developed in STAR

Semi-inclusive h+jet: Unbiased procedure to select recoil jet

STAR, PRC 96 no. 2, (2017) 024905



Same Event (SE): Signal + Uncorrelated jet

Mixed Event (ME): Uncorrelated jet

Both have the same background energy density

Need to subtract normalized ME uncorrelated jet spectrum from that of SE

Experimental challenges for γ+jet measurement

Two major challenges:

- Discrimination of γ/π^0 trigger events
- Uncorrelated jets

Solved

Other corrections:

Event-by-event correction

- Uncorrelated background energy density (ρ)

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

$$\rho = \mathrm{median}\{\frac{p_{\mathrm{T,jet}}^{\mathrm{raw}}}{A_{\mathrm{jet}}}\}\ ; \qquad \text{A: Area of the jet}$$

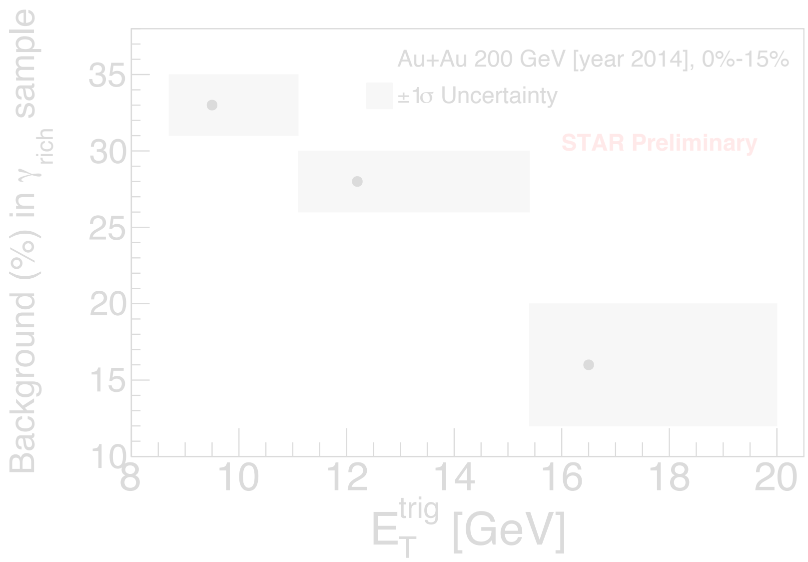
Ensemble-level correction

- Jet Energy Scale (JES) smearing correction: Unfolding
  - Factorize instrumentation and background fluctuation effects
  - Unfolding: SVD; iterative Bayesian

Statistical and unfolding precisions are acutely related

Main contributions to systematic uncertainties

- Instrumentation effects [Unfolding]
- Direct photon purity



- $\gamma_{\mathrm{rich}} = \gamma_{\mathrm{dir}} + \pi^0$ decays photons; γ_{dir} purity → 65-88% between $E_{\mathrm{T}}^{\mathrm{trig}}$: 9-20 GeV
- π^0_{rich} :~95% pure
- $E_{\mathrm{T}}^{\mathrm{trig}}$ bins in this measurement: 9-11, 11-15, 15-20 GeV

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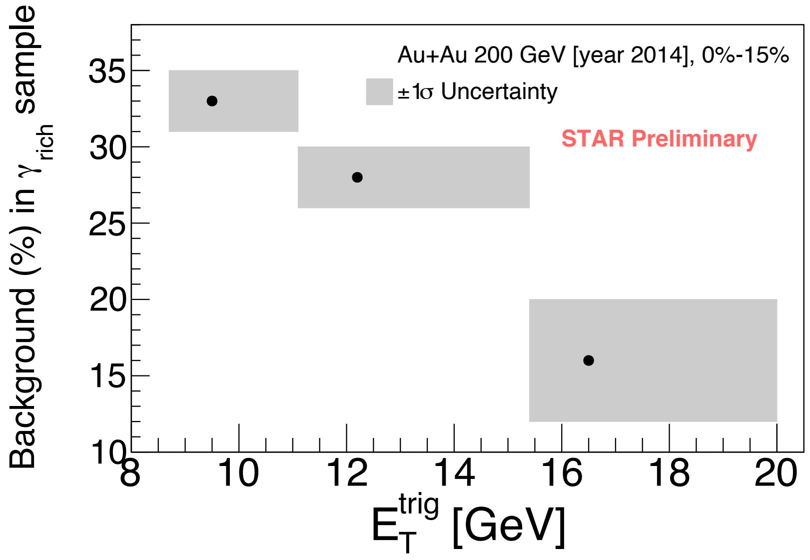

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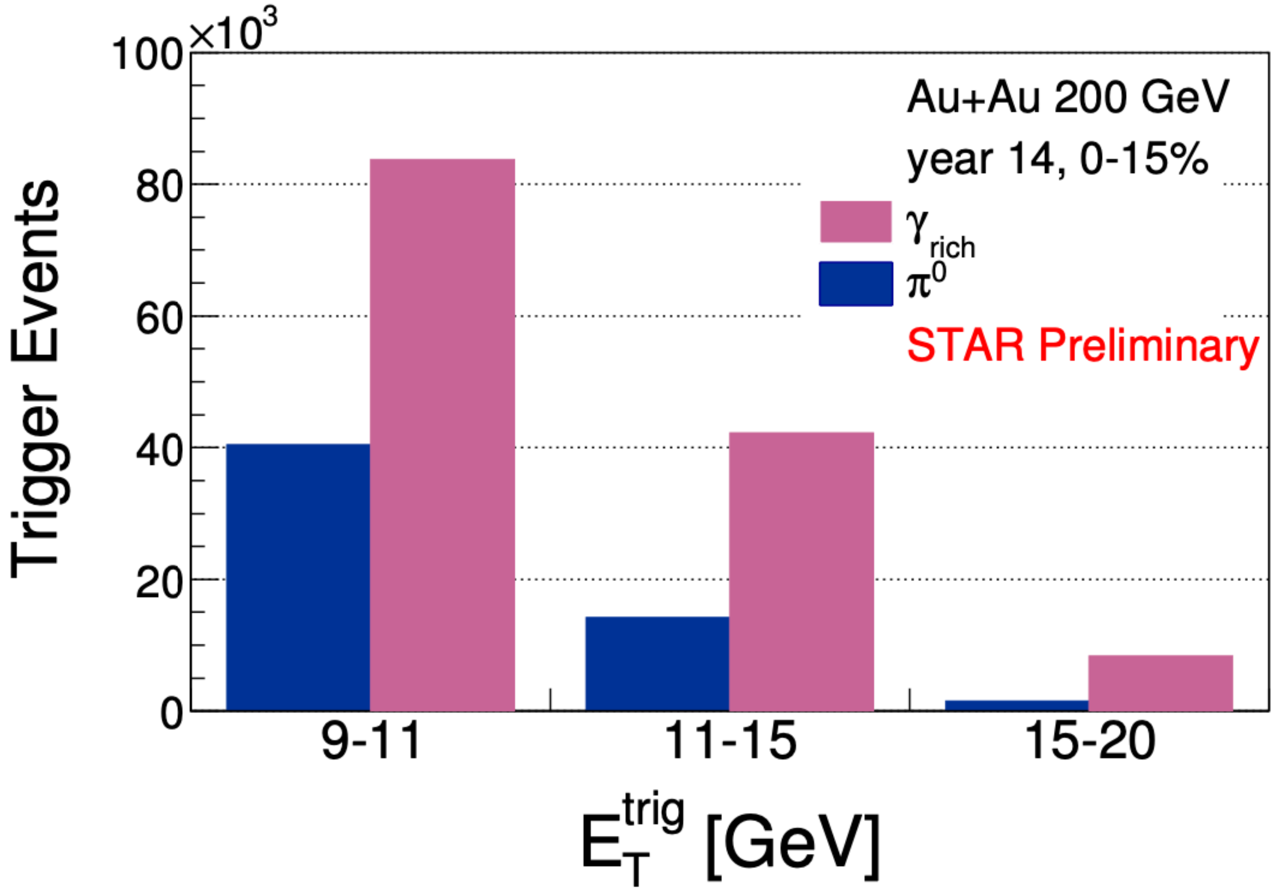
γ and π^0 trigger event statistics



Year 2014 Au+Au $\sqrt{s_{NN}} = 200$ GeV

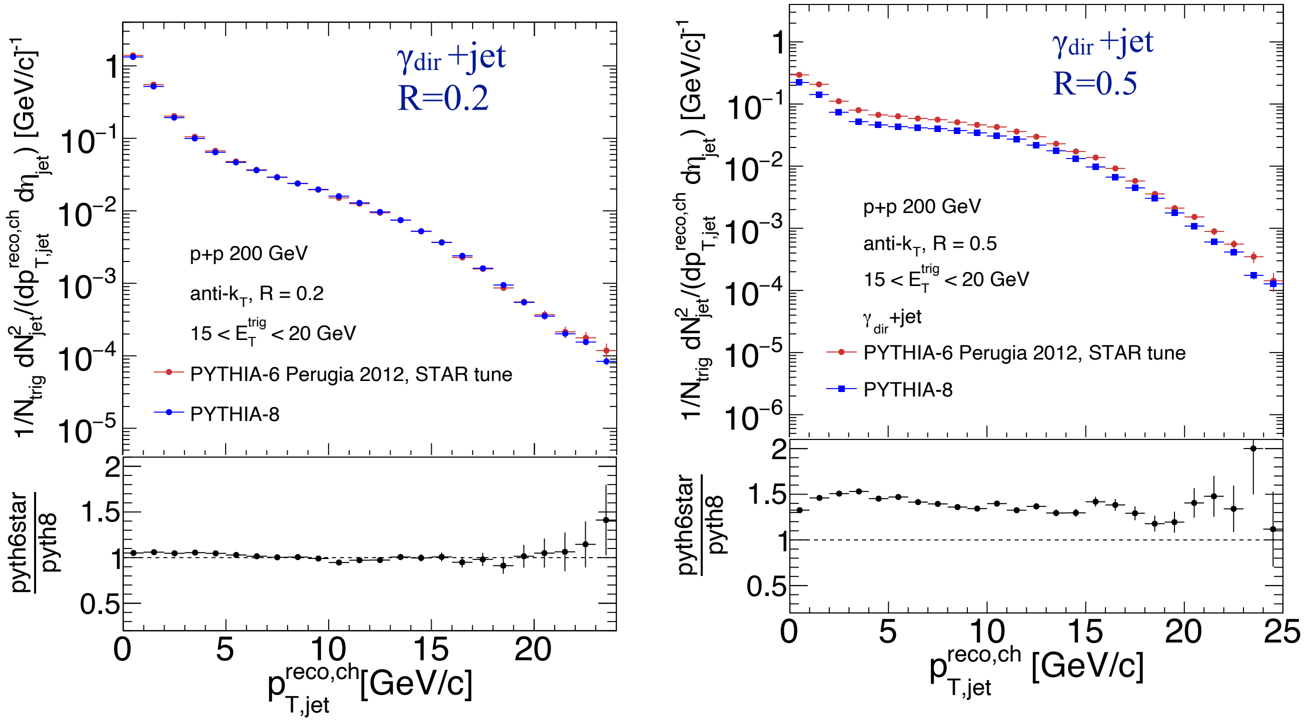
- high-p_T Lumi. 9.9 nb^{-1}
- We also have roughly the same statistics from 2016

- γ $E_T >$ 20 GeV → 1.4k events [not analyzed]
- Certainly, it can be measured with higher lumi.

γ+jet measurement: *p*+*p* reference

γ_{dir}+jet and π^0+jet p+p reference (ongoing)

- STAR data: insufficient statistical precision for this analysis at present
  - Year-2009 with 26 pb^{-1} (ongoing and will be finalized soon)
  - Proposed plan for 2024 p+p run: 235 pb^{-1} (huge impact on our p+p baseline)
- Use PYTHIA validated by STAR measurements



Two versions of PYTHIA:

- PYTHIA8 Tune 4C
- PYTHIA6 Perugia 2012 STAR tune: validation by STAR p+p data
  [STAR, Phys. Rev. D 100, 052005 (2019)]

Both references to illustrate the differences

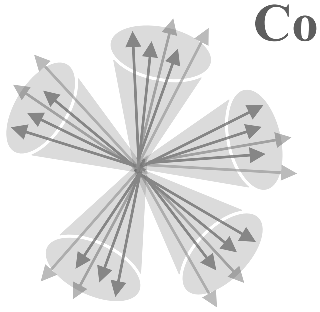
For γ_{dir}+jet:

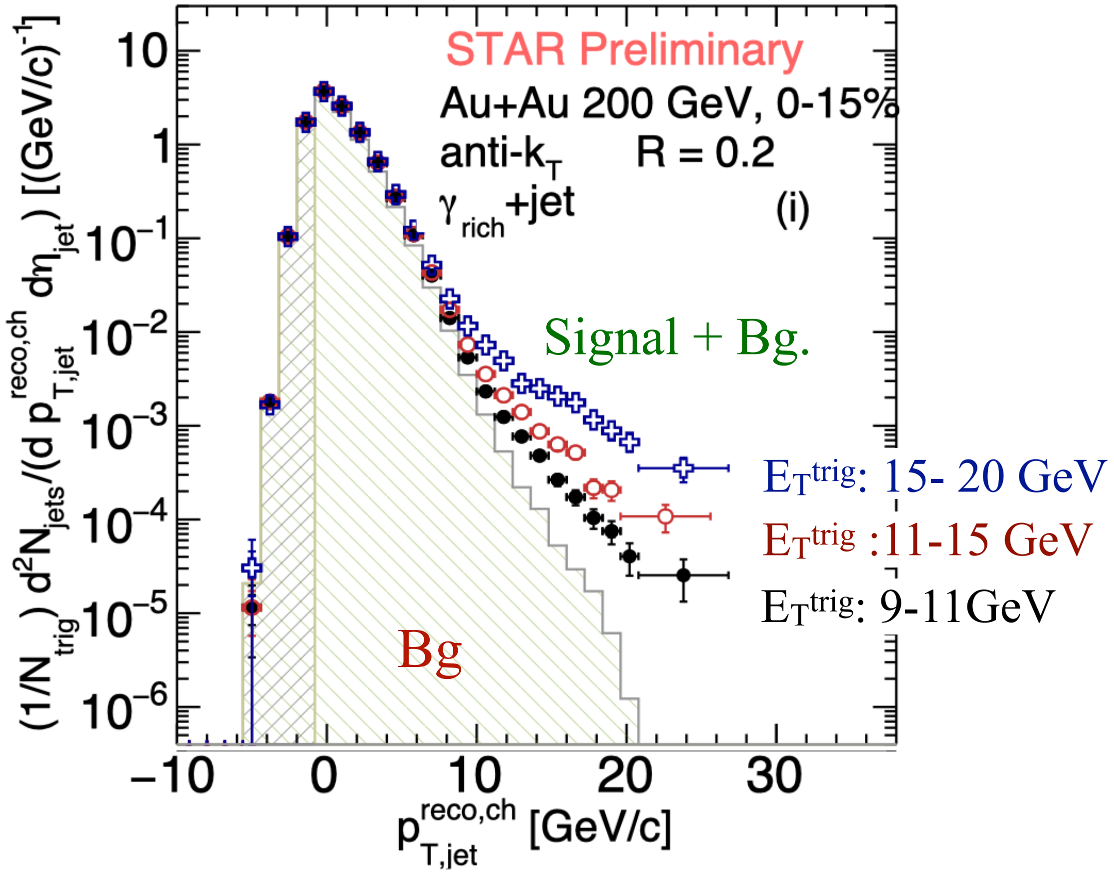
- R=0.2: negligible differences
- R=0.5: 10-40% differences

Semi-inclusive γ_{rich}+jet p_T spectra in heavy-ion collisions

γ + jet in a SE

Combinatorial jets in ME



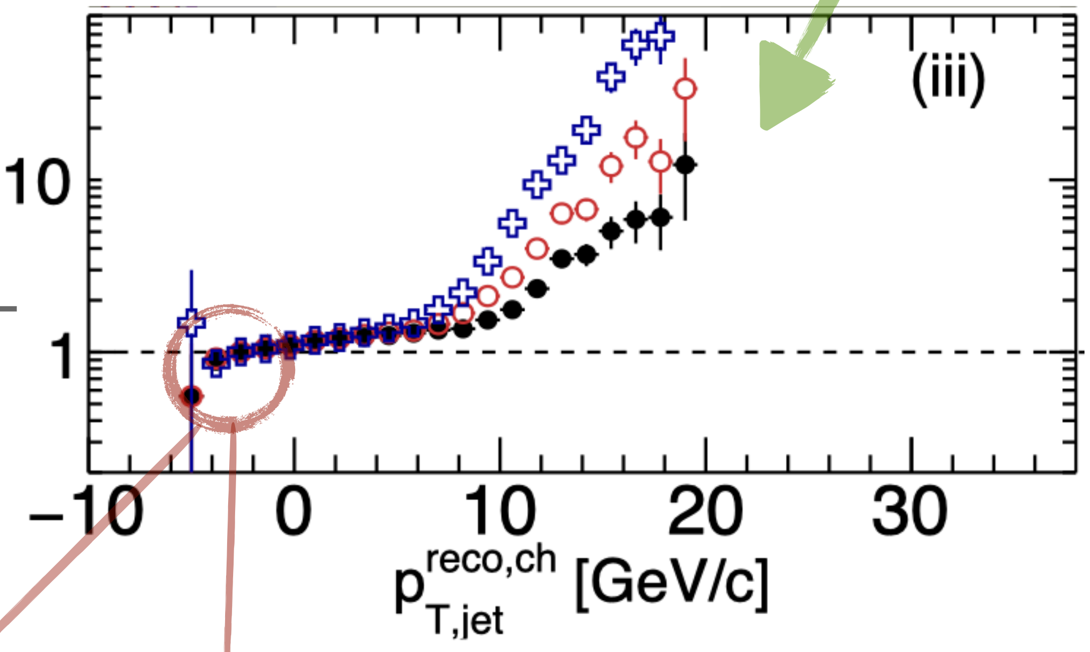


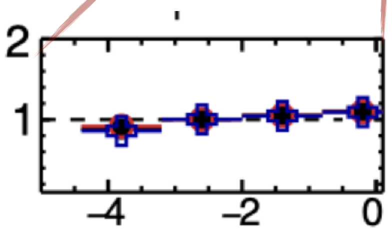
$$p_{T,jet}^{reco,ch} = p_{T,jet}^{raw,ch} - \rho \times A$$

Same Event: Signal + Bg. jet
Normalized Mixed Event: Bg. jet

$$\frac{\text{Signal + Bg.}}{\text{Bg.}}$$

$p_{T,jet}^{reco,ch} > 0$: yield dependent of E_T^{trig}
(recoil jets dominate)

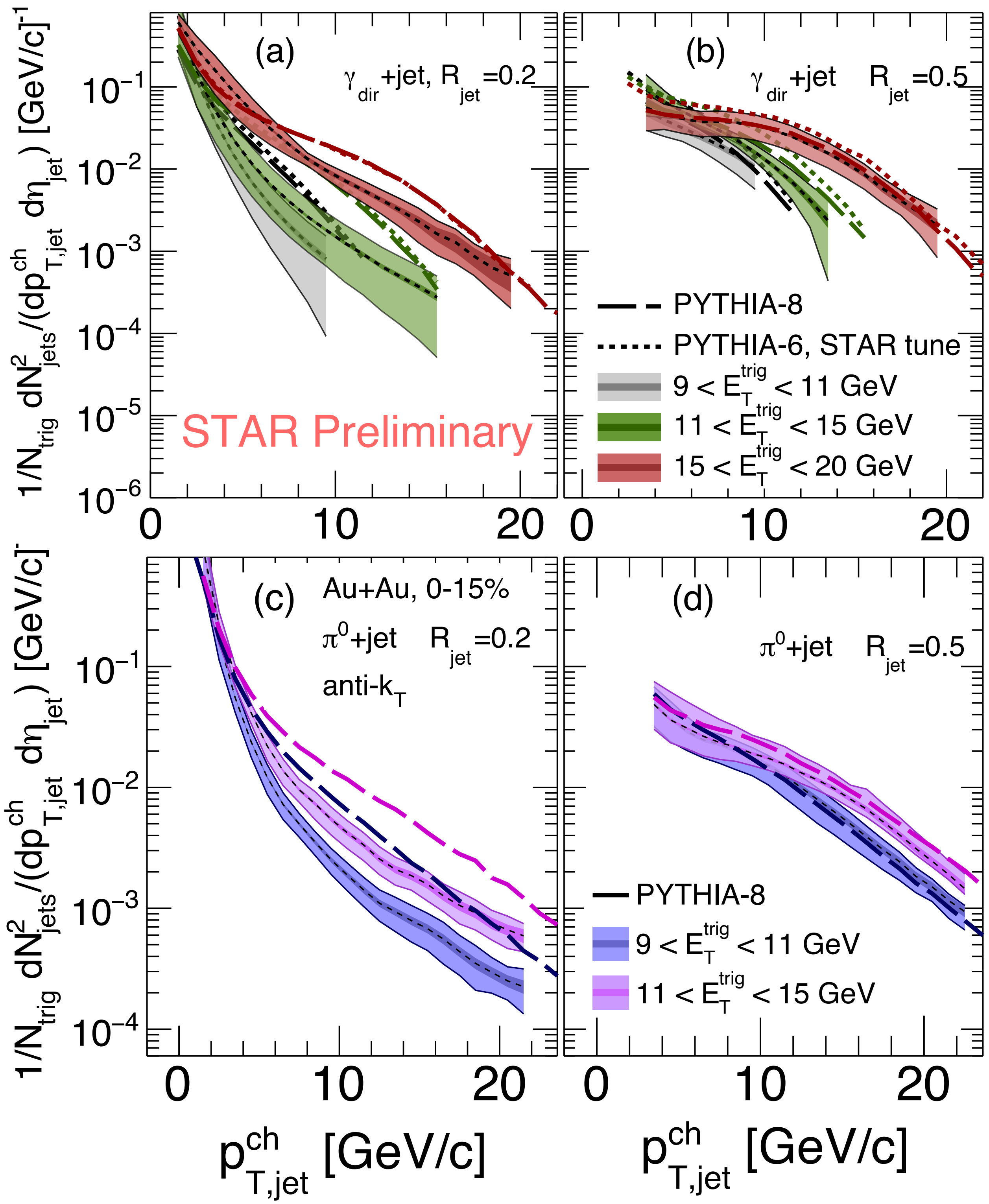




$p_{T,jet}^{reco,ch} < 0$: yield independent of E_T^{trig}
(Background jets contribution)

Recoil jet contribution dominates over background at high-$p_{T,jet}^{reco,ch}$ and the same for π^0+jet.

γ_{dir}+jet and π^0+jet p_T spectra

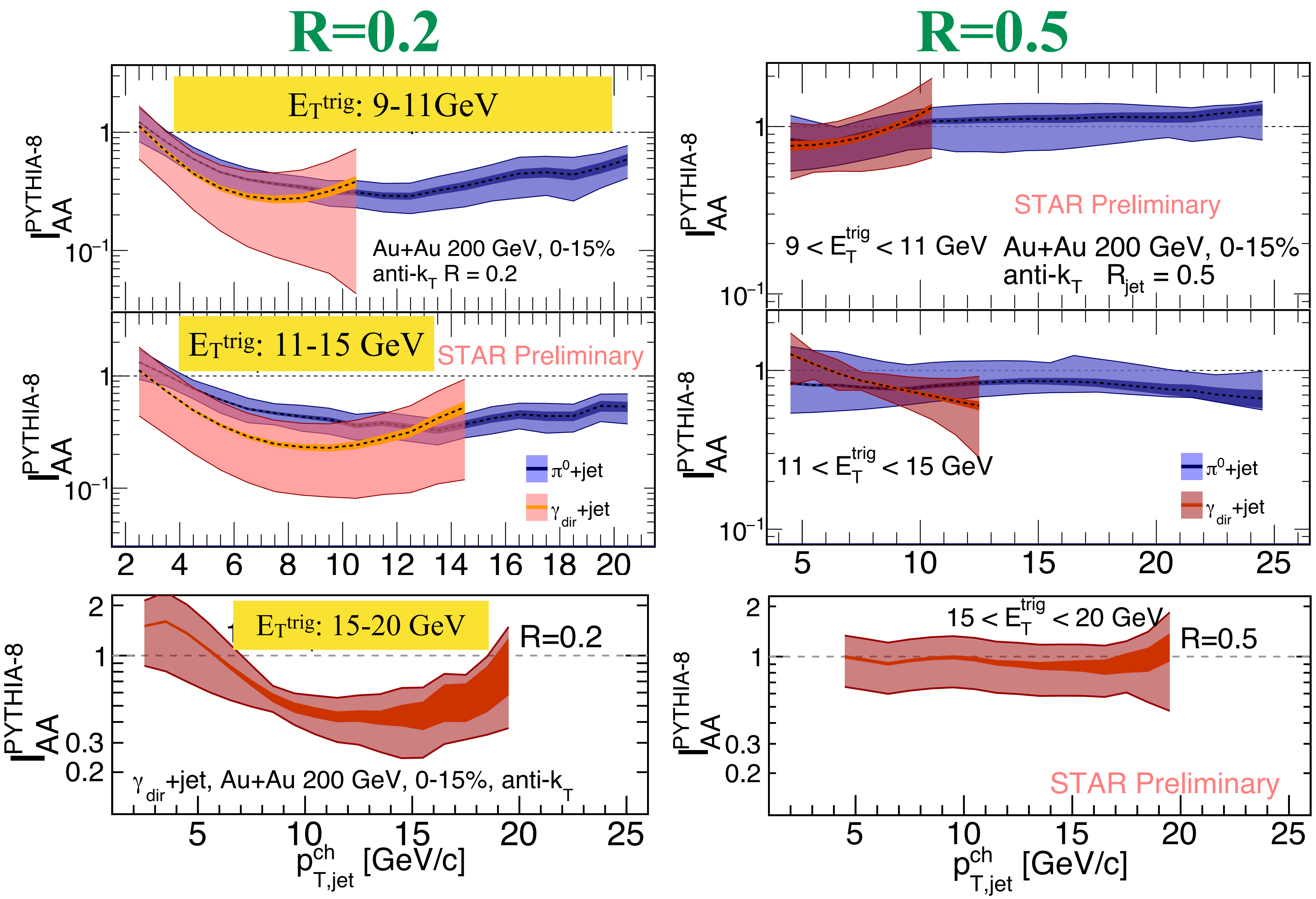


γ_{dir}+jet

π^0+jet

- γ_{dir} and π^0 trigger recoil jet p_T spectra strongly dependent on jet R and trigger E_T

Recoil jet yield suppression for R=0.2 and 0.5



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

$Y(p_{T,jet}^{ch})$ → Per trigger recoil jet yield as a function $p_{T,jet}^{ch}$

$p+p$ reference: PYTHIA-8

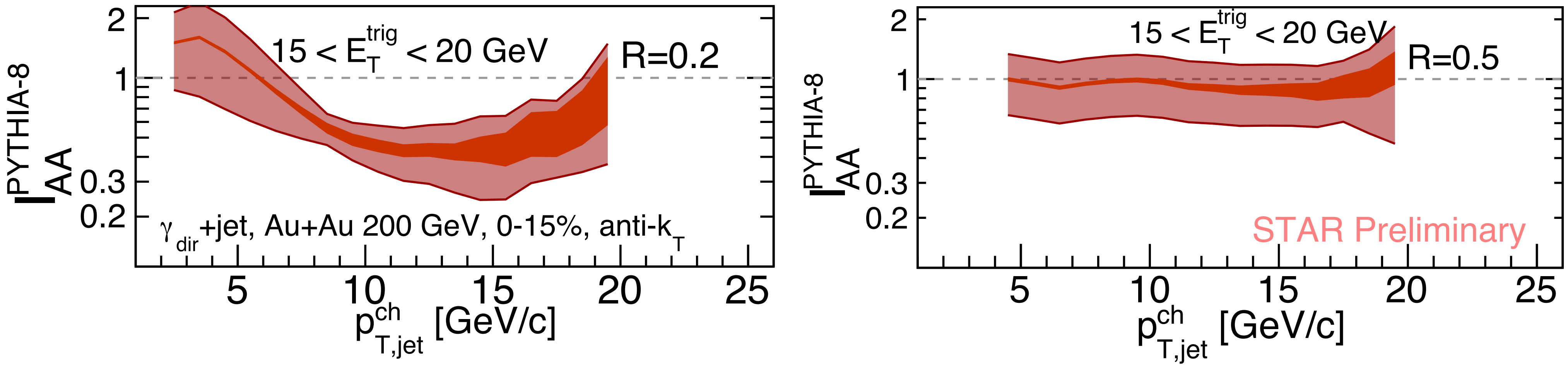
Systematic (lighter band) and statistical (darker band) uncertainties

- γ_{dir}+jet and π^0+ jet show a similar level of suppression
- No significant trigger E_T dependence
- Larger recoil jet yield suppression for R=0.2 than R=0.5

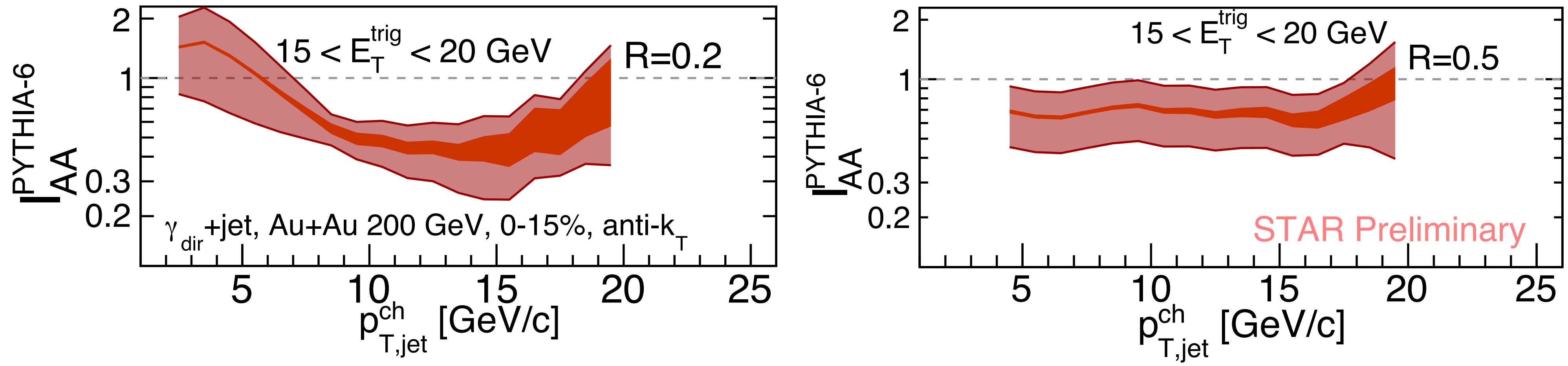
Recoil jet yield suppression: *PYTHIA-6 STAR vs PYTHIA-8*

$\gamma_{\rm dir}$+jet: $15 < E_{\rm T}^{\rm trig} < 20$ GeV

R=0.2 **pp reference: PYTHIA-8** **R=0.5**



pp reference: PYTHIA-6 STAR tune



PYTHIA-6 STAR tune vs PYTHIA-8:

- R=0.2: negligible change
- R=0.5: significant shift in central value but consistent within other systematic uncertainties

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

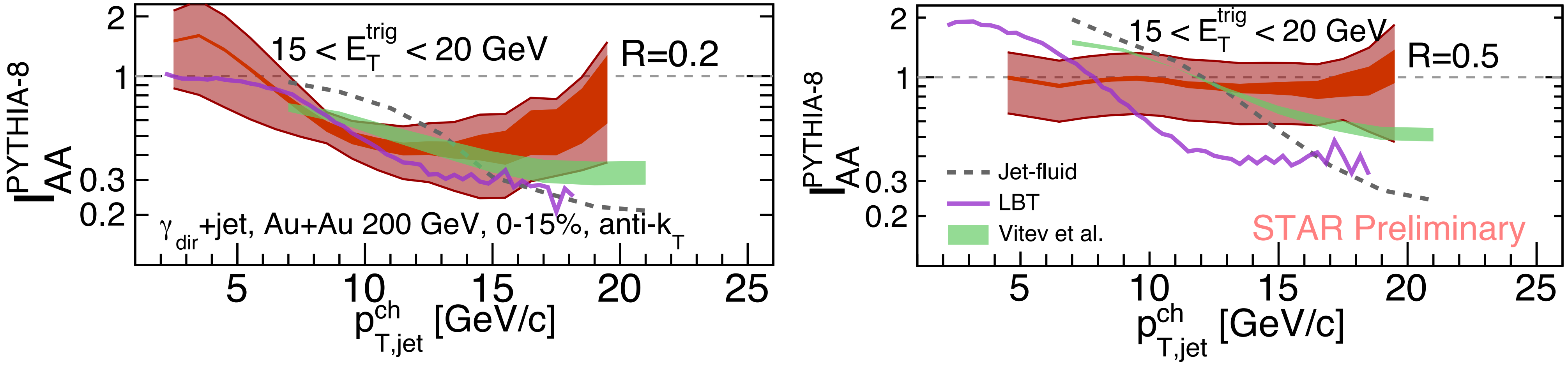
Recoil jet yield suppression: *Data vs. Model*

γ_{dir}+jet: $15 < E_T^{\mathrm{trig}} < 20$ GeV

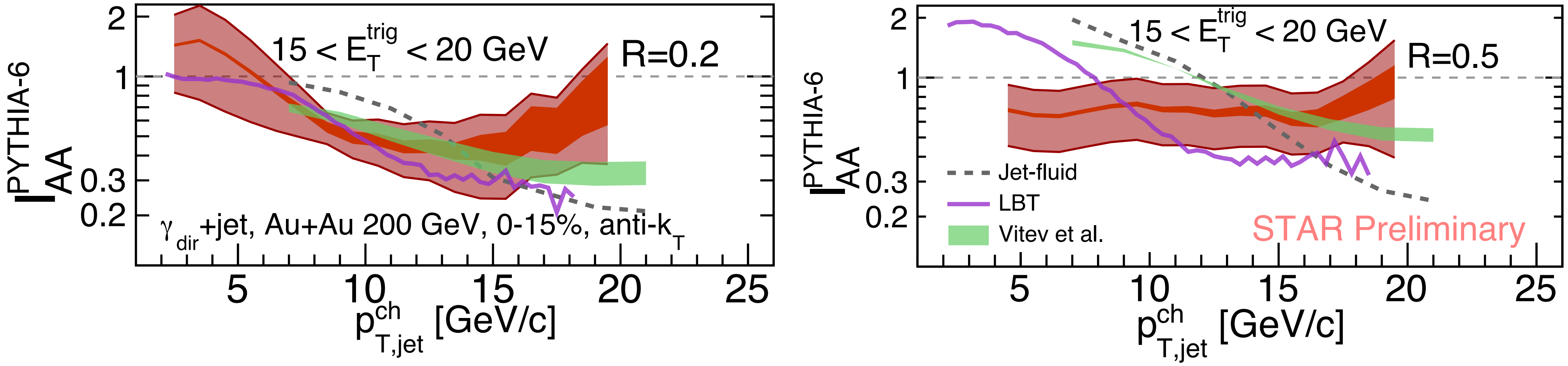
Comparison to Theory

Jet-fluid: jet shower + medium response	[Chang, et al., PRC 94 (2016), 024902]
LBT: coupled LBT+hydro	[Chen, et al., PLB 777 (2018) 707]
Vitev: Soft Collinear Effective Theory	[Sievert, et al., PLB 795 (2019) 502]

R=0.2 **pp reference: PYTHIA-8** **R=0.5**



pp reference: PYTHIA-6 STAR tune



p_T-dependence of suppression is different in theory predictions and data.

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

Measurement of jet radial profile

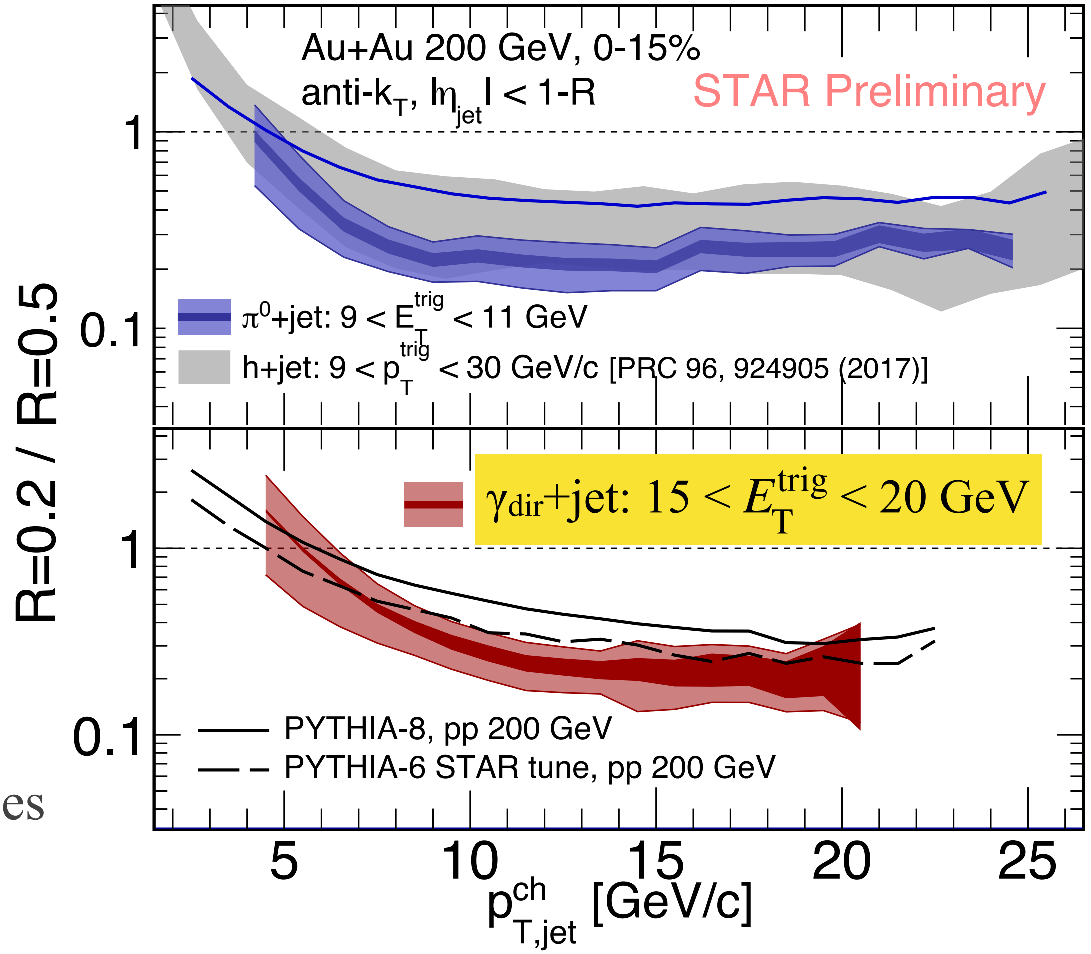
- Ratio of recoil jet yields R=0.2/R=0.5
- Jet radial profile in vacuum requires ratio < 1 in pp collisions (PYTHIA)
- In-medium modification of jet shape? Compare p+p and Au+Au

LHC p+p

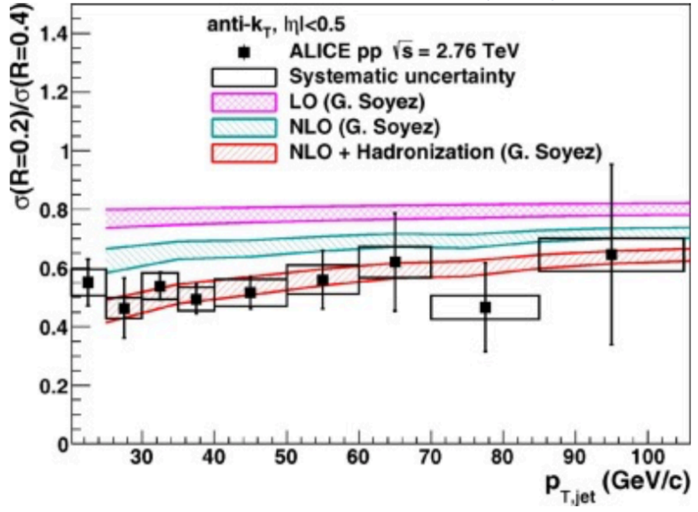
$$\frac{Y\ (p_{T,jet}^{ch})^{R=0.2}}{Y\ (p_{T,jet}^{ch})^{R=0.5}}$$

$Y(p_{T,jet}^{ch})$ → Per trigger recoil jet yield as a function $p_{T,jet}^{ch}$

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

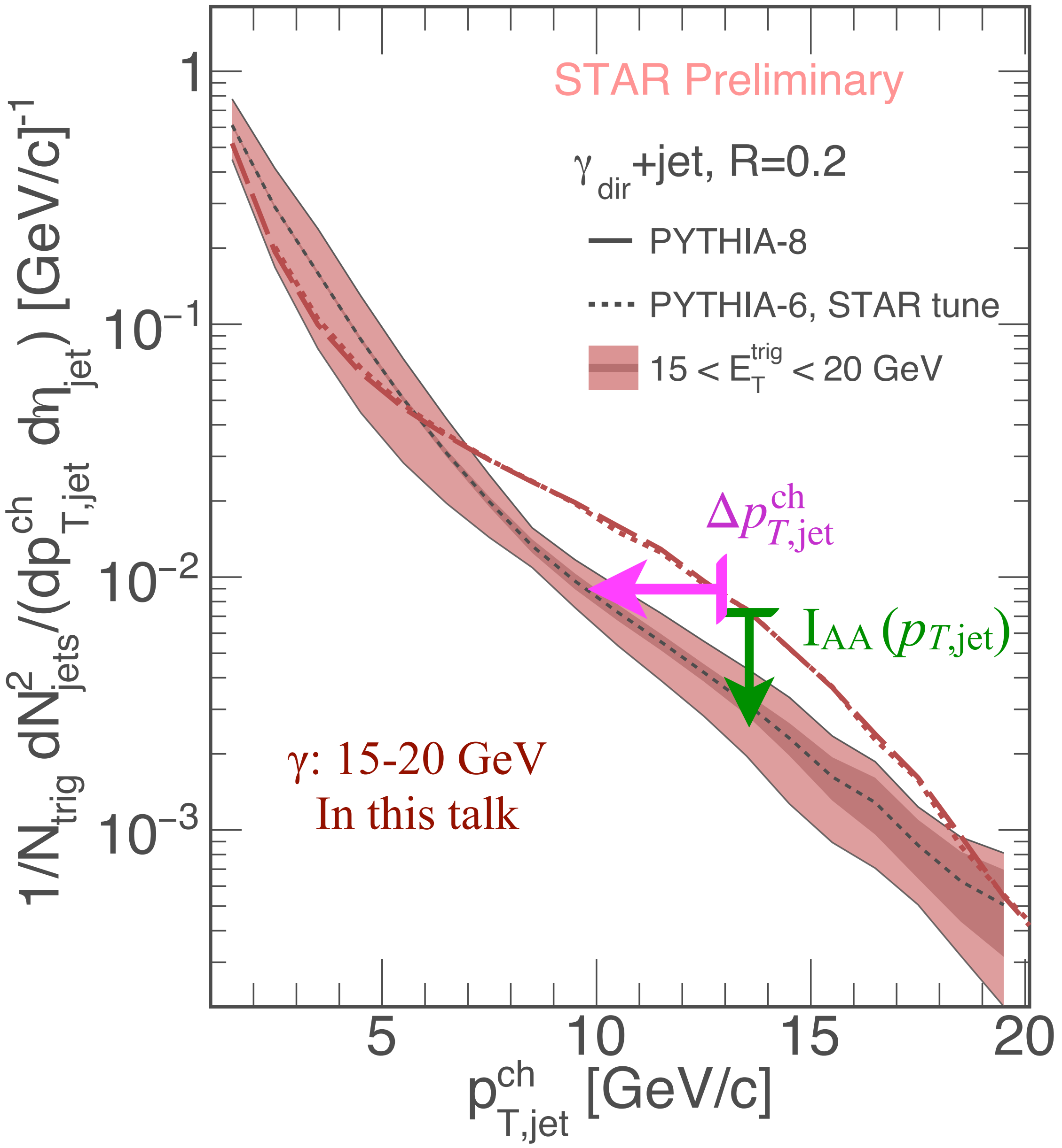


ALICE: PLB 722 (2013) 262–272



- γ_{dir} +jet consistent with PYTHIA-6 STAR tune
  - would indicate no significant in-medium broadening
- Quantitative difference: PYTHIA-6 STAR tune vs. PYTHIA-8

Jet-quenching: jet p_T-spectrum shift



Jet-quenching observables:

I_{AA} or R_{AA} at fixed jet p_T → $I_{AA}(p^{ch}_{T,jet}) = \dfrac{Y(p^{ch}_{T,jet})^{Au+Au}}{Y(p^{ch}_{T,jet})^{p+p}}$

Convolute the effect of energy loss with spectrum shape

Another way to quantify jet-quenching:

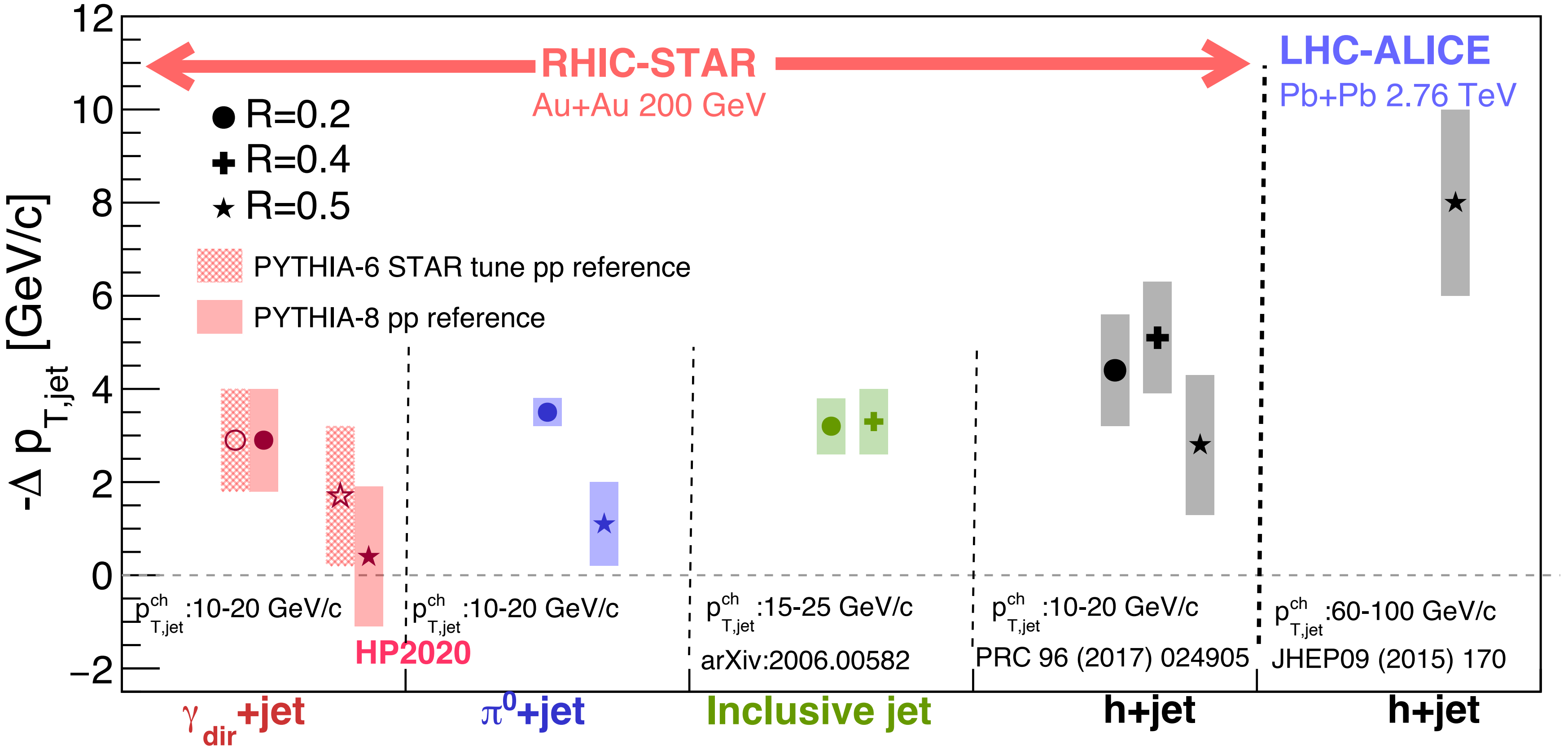
Jet p_T shift ($\Delta p^{ch}_{T,jet}$)

$\Delta p^{ch}_{T,jet} = (\Delta p_{T,jet})_{p+p} - (\Delta p_{T,jet})_{Au+Au}$

Initial parton energy loss can also be characterized by jet p_T shift

Jet p_T-spectrum shift : RHIC vs. LHC

Characterization of average out-of-cone parton energy loss

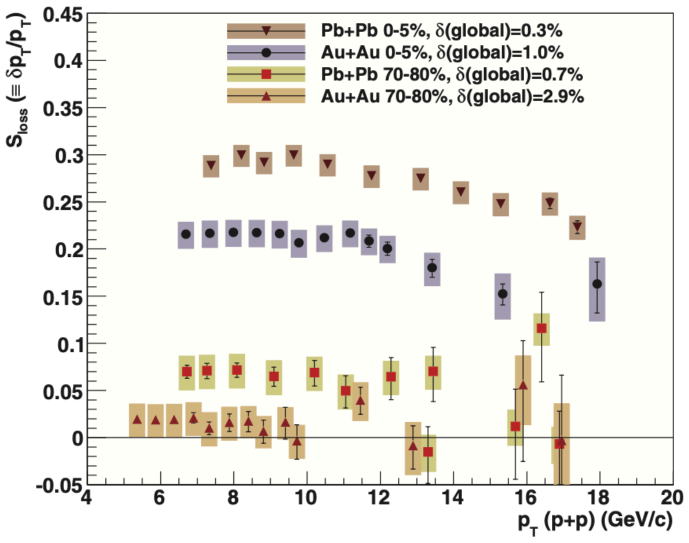


Note here also different kinematic coverage

- π^0 PHENIX δp_T : ~2-3 GeV/c within p_T :10-18 GeV/c

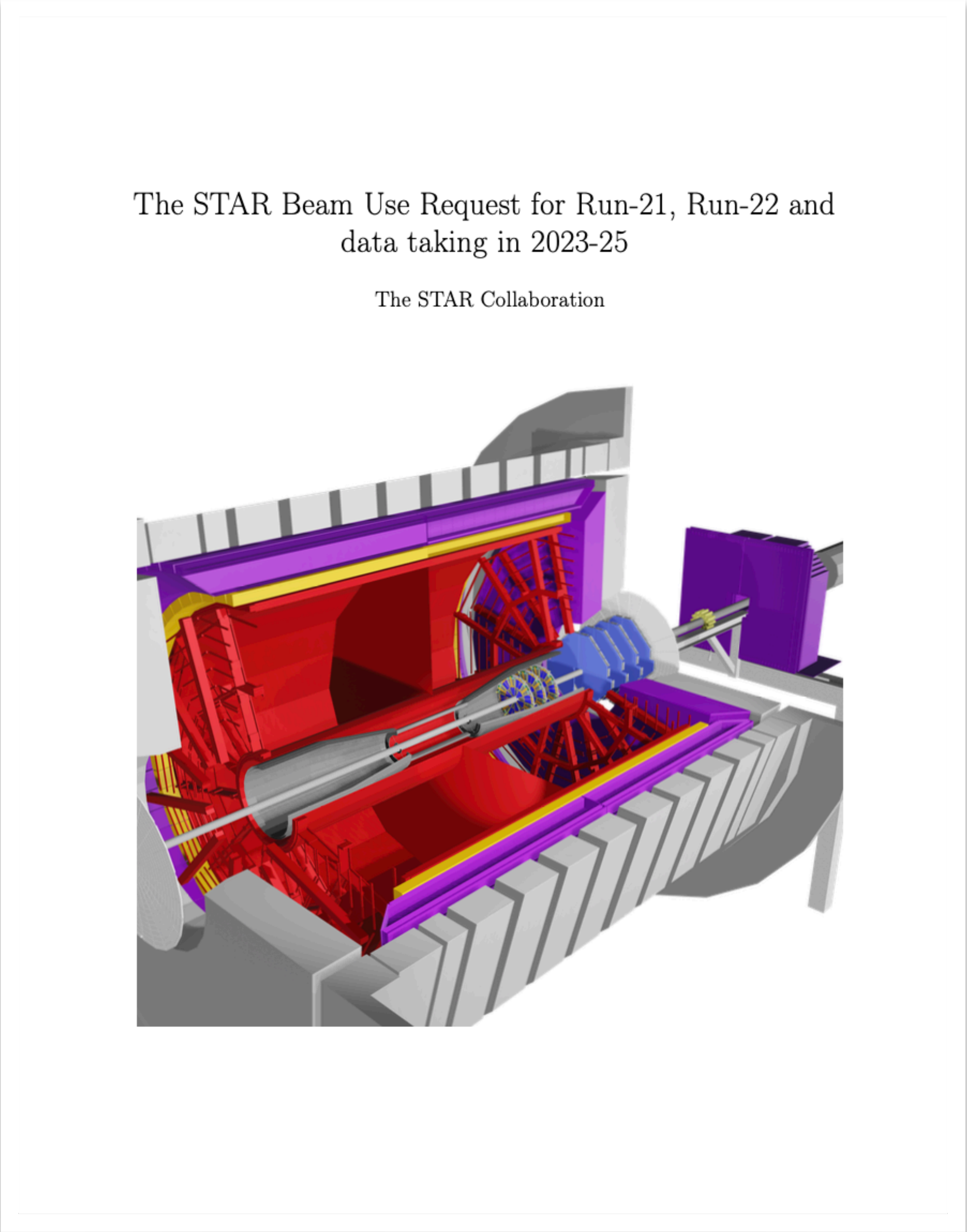
  Similar to STAR jet measurements [PHENIX, PRC **87**, 034911 (2013)]

PHENIX: Inclusive π^0 p_T spectrum:
Ave. fractional p_T loss ($\delta p_T/p_T$)



Indication of smaller in-medium energy loss at RHIC than the LHC

Microstructure of QGP: Jet Probes



The STAR Beam Use Request for Run-21, Run-22 and
data taking in 2023-25

The STAR Collaboration

https://indico.bnl.gov/event/7881/

Section

2.4 Exploring the Microstructure of the QGP (Run-23 and Run-25 Au+Au)

One of the questions…

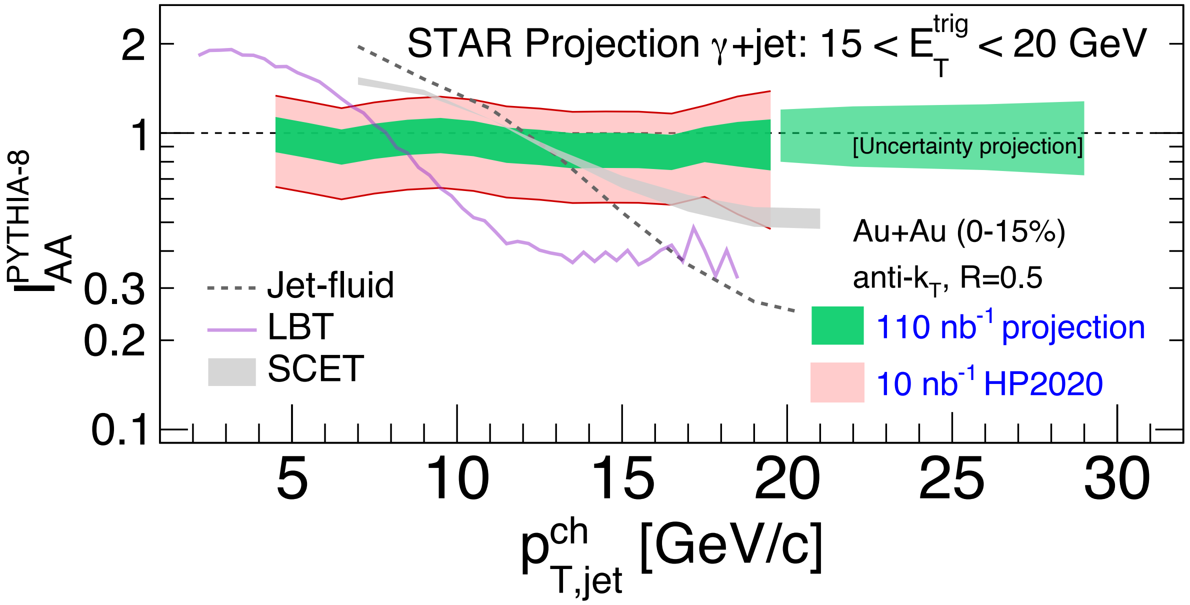
What are the underlying mechanisms of jet quenching at RHIC energies? What do jet probes tell us about the microscopic structure of the QGP as a function of resolution scale?

With detectors:

- BEMC: $|\eta| < 1$
- EEMC: $1 < \eta < 2$
- TPC (iTPC) : $|\eta| < 1.5$
- Forward Tracking: $2.5 < \eta < 4$

Future projection: γ+jet measurement in STAR

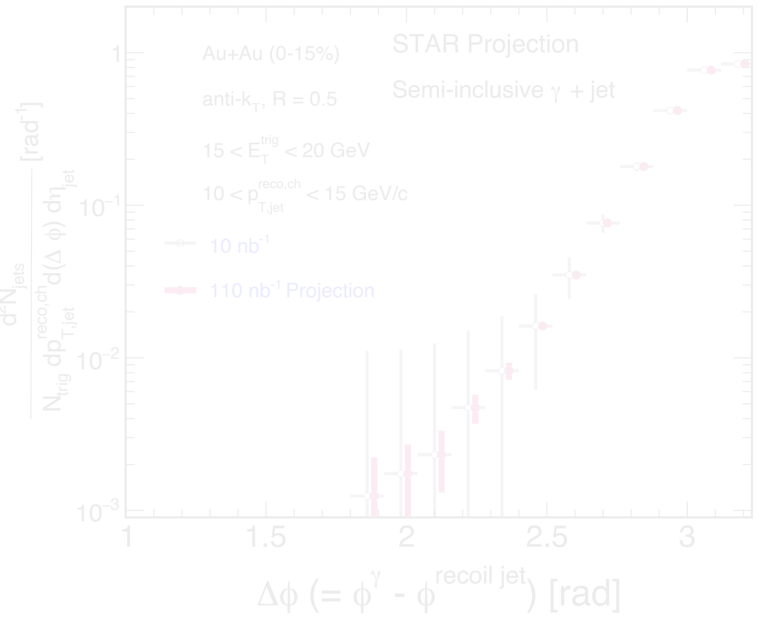
1. High precision I_{AA} measurement with extended jet p_T and at higher E_T^{trig} [to resolve theory predictions]



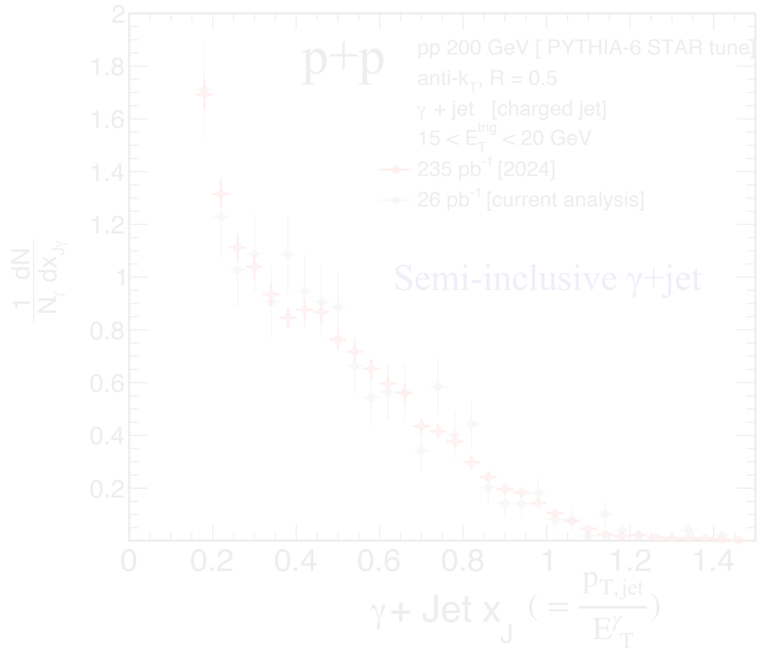
year	minimum bias [$\times 10^9$ events]	high-p_T int. luminosity [nb^{-1}] all vz	|vz|<70cm	|vz|<30cm
2014 2016	2	26.5	19.1	15.7
2023	10	43	38	32
2025	10	58	52	43

- Precision measurement for p+p reference
- Full jet measurement using BEMC
- Also mid- and forward-rapidity measurement in p+Au collisions [cold-QCD matter effect]

2. Large angle deflection measurement [to explore microstructure of QGP]

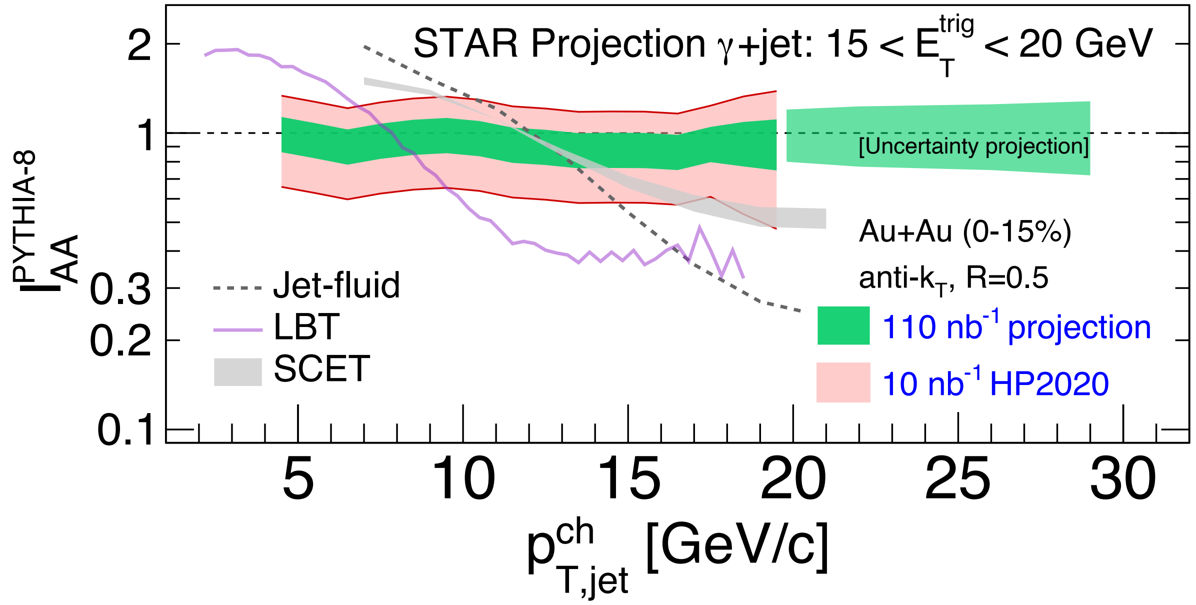


3. γ+jet p_T-balance [to study jet-quenching more differential way]

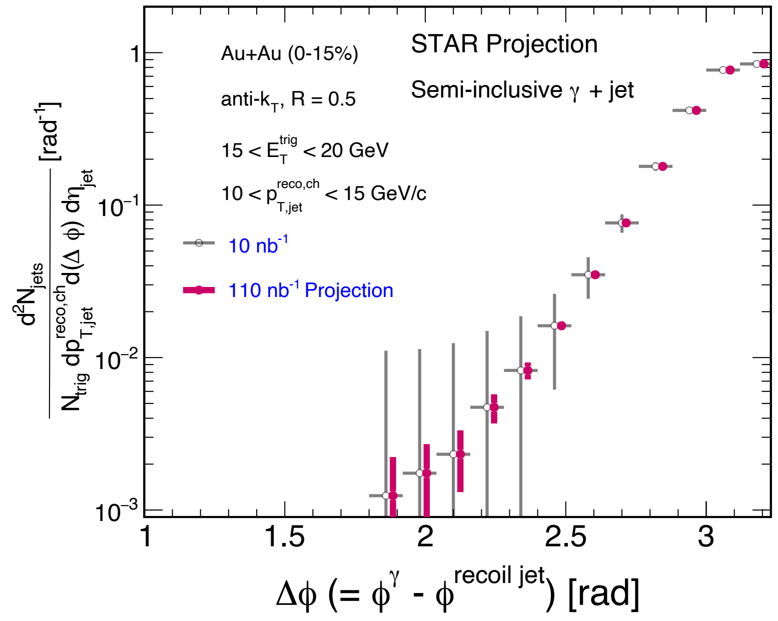


Future projection: γ+jet measurement in STAR

1. High precision I_{AA} measurement with extended jet p_T and at higher E_T^{trig} [to resolve theory predictions]

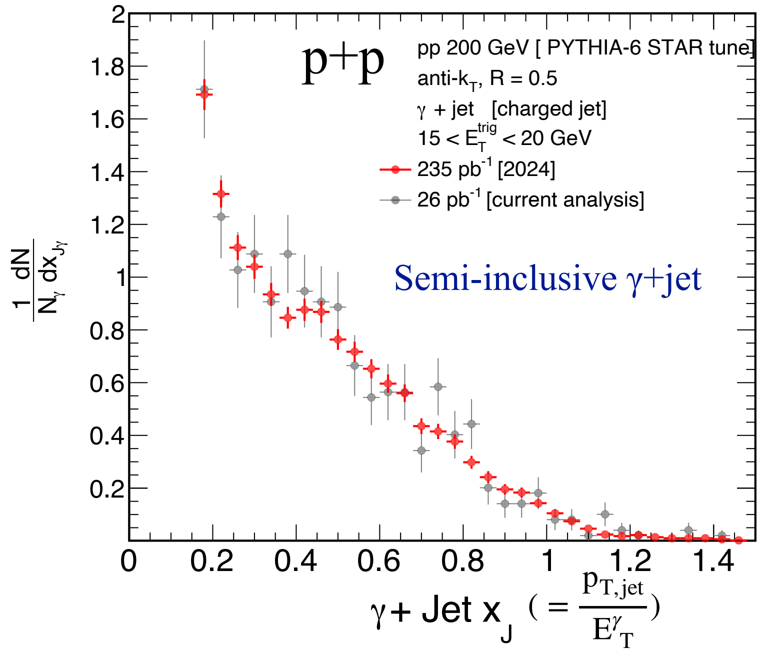


2. Large angle deflection measurement [to explore microstructure of QGP]



year	minimum bias [$\times10^9$ events]	high-p_T int. luminosity [nb^{-1}]		
		all vz	$\lvert vz\rvert<70$cm	$\lvert vz\rvert<30$cm
2014 2016	2	26.5	19.1	15.7
2023	10	43	38	32
2025	10	58	52	43

3. γ+jet p_T-balance [to study jet-quenching more differential way]



- Precision measurement for p+p reference
- Full jet measurement using BEMC
- Also mid- and forward-rapidity measurement in p+Au collisions [cold-QCD matter effect]

Summary and outlook

- Developed all the methods and techniques in recent years for semi-inclusive γ+jet measurement in STAR
- The current challenge is high precision p+p reference (and also Au+Au data)
  - Aim for the year 2024 p+p data taking (235 pb^{-1})
  - p+p reference: PYTHIA-6 STAR tune *vs.* PYTHIA-8
- Preliminary results show:
  - Recoil jet yield suppression: similar magnitude for γ_{dir}+jet and π^0+jet
  - Theoretical calculations do not reproduce p_T dependence
  - R-dependence of suppression
  - Jet energy loss at RHIC: indication of being smaller than the LHC

Run23-25 heavy-Ion (along with Run24 p+p) runs would be crucial for definitive and incisive conclusion on our observation in STAR…

Thank you!

Backup

Extraction of γ_{dir}+jet from γ_{rich}+jet

Per trigger jet yield of γ_{dir} at a given jet p_T :

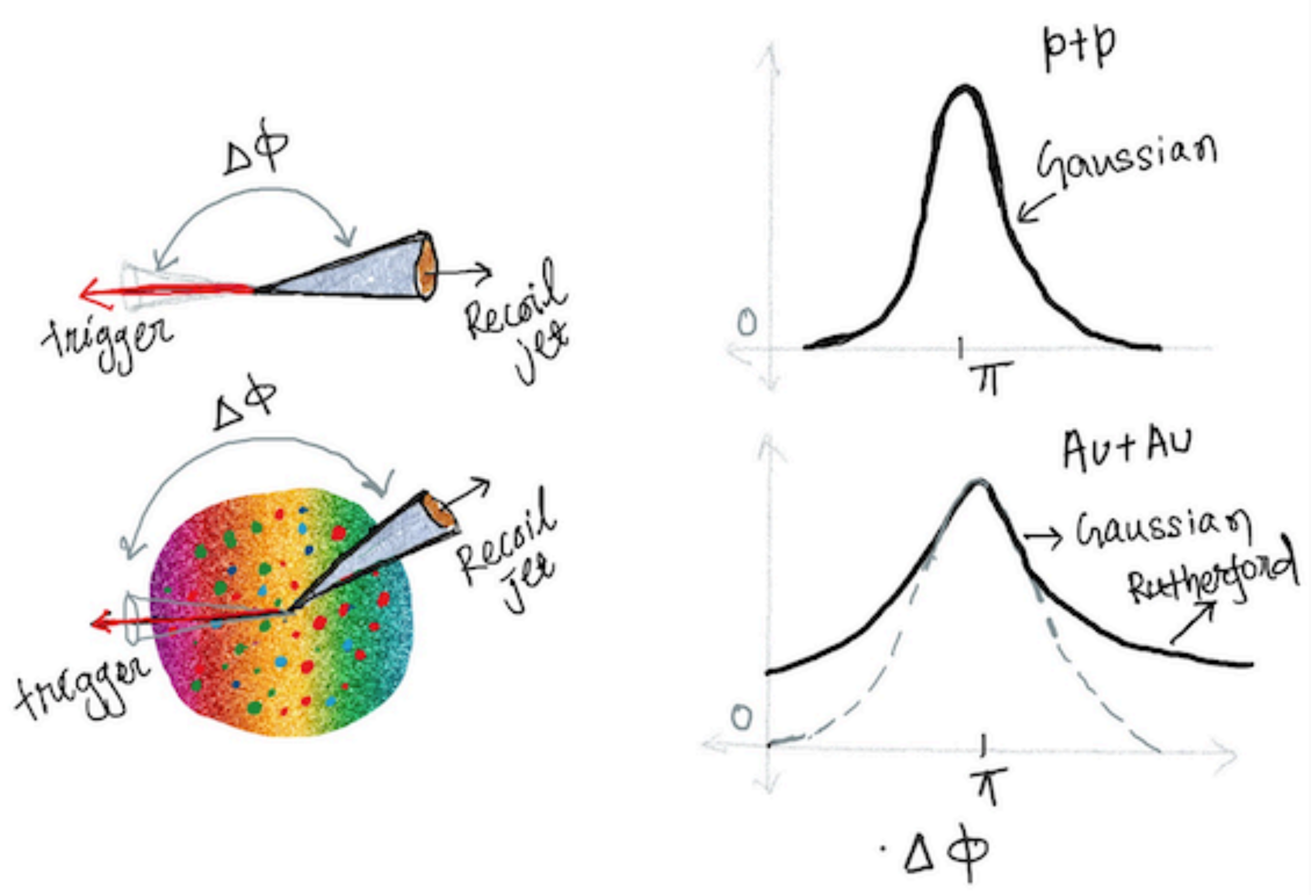
$$\mathscr{D}_{\gamma_{\mathrm{dir}}}(\mathrm{p_T}) = \frac{\mathscr{D}_{\gamma_{\mathrm{rich}}}(\mathrm{p_T}) - \mathrm{R_{impurity}} \cdot \mathscr{D}_{\pi^0}(\mathrm{p_T})}{1 - \mathrm{R_{impurity}}}$$

$\mathscr{D}_{\gamma_{\mathrm{rich}}}(\mathrm{p_T})$: per trigger jet yield of γ_{rich} at a given jet p_T

$\mathscr{D}_{\pi^0}$ $(\mathrm{p_T})$: per trigger jet yield of π^0 at a given jet p_T

R_{impurity} : π^0 impurity in γ_{rich} sample

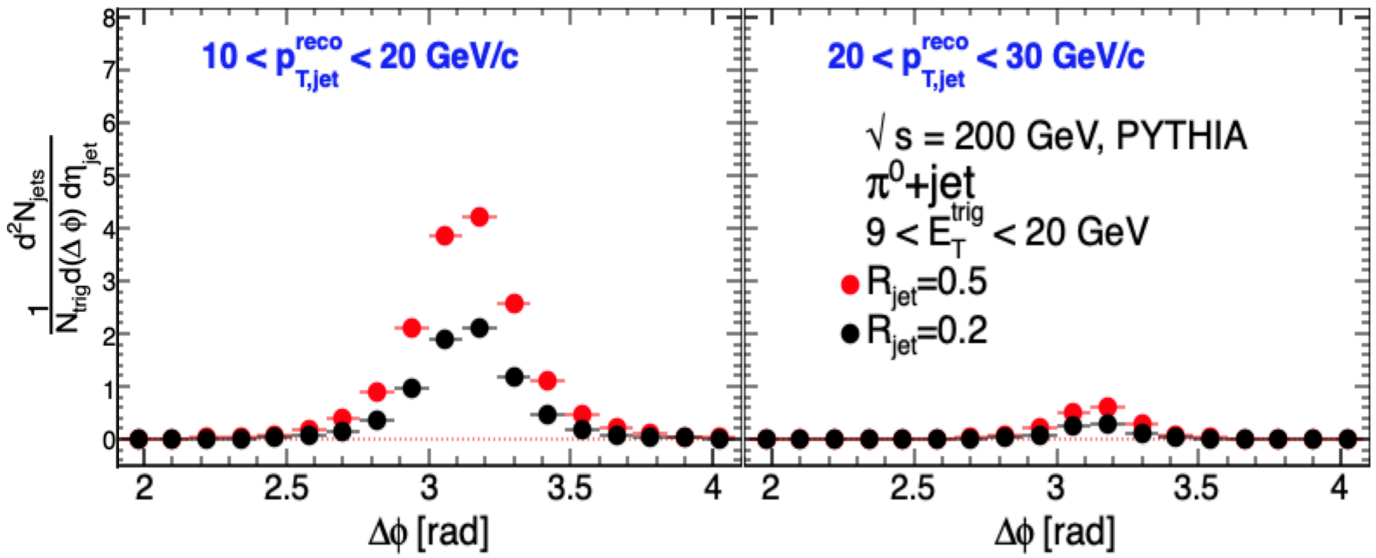
Search for the large angle deflection

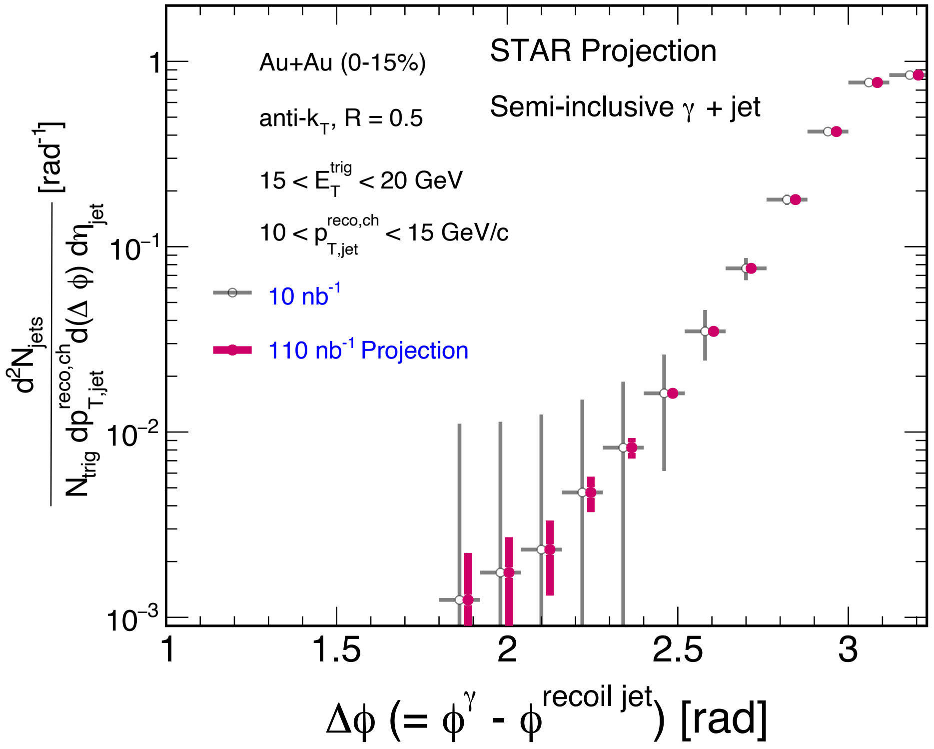


At small angle ⟶Gaussian Shape
At large angle ⟶Rutherford Scattering

Scattering of a recoil-jet off quasi-particles in the QGP → Intra-jet broadening (Δφ)

Large angle deflection measurement [to explore microstructure of QGP]





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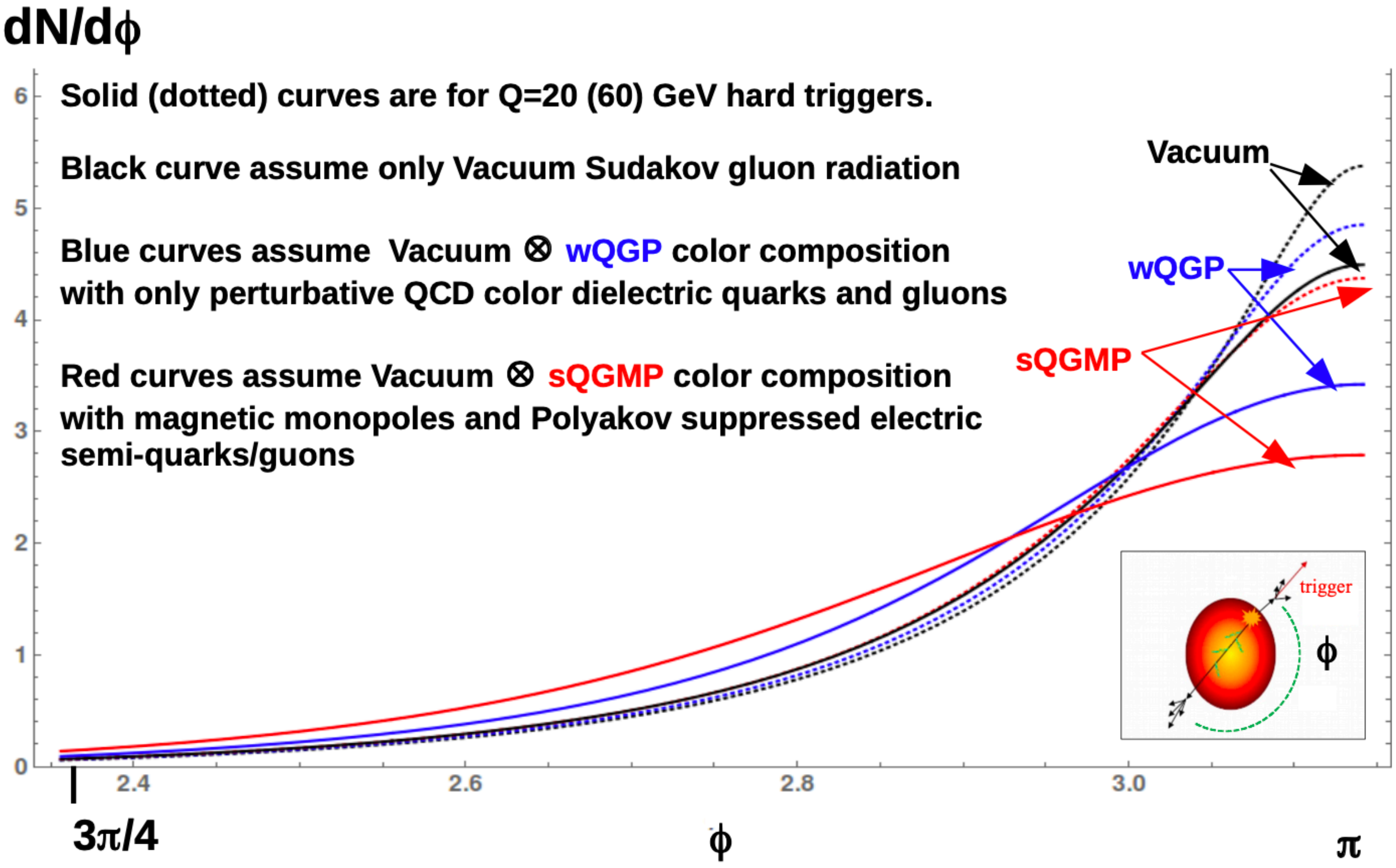

Solid (dotted) curves are for Q=20 (60) GeV hard triggers.

Black curve assume only Vacuum Sudakov gluon radiation

Blue curves assume Vacuum ⊗ wQGP color composition with only perturbative QCD color dielectric quarks and gluons

Red curves assume Vacuum ⊗ sQGMP color composition with magnetic monopoles and Polyakov suppressed electric semi-quarks/guons