γ+jet and π^0+jet in central Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV in STAR

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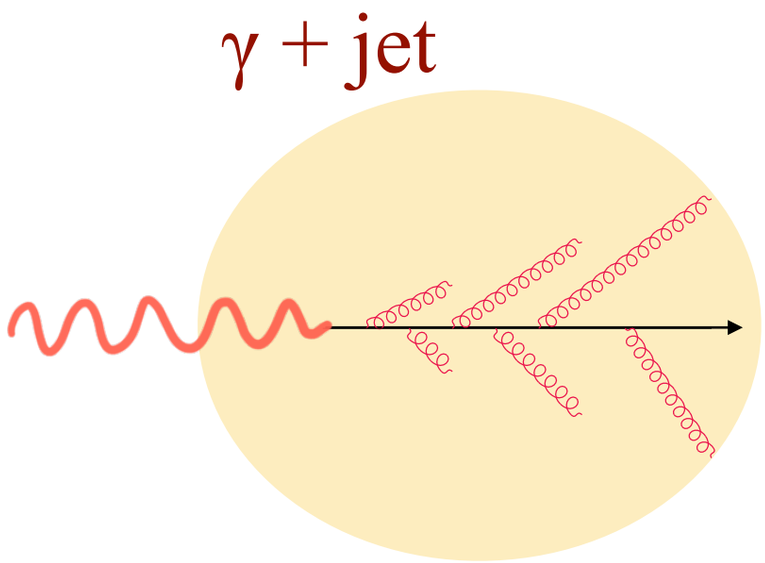
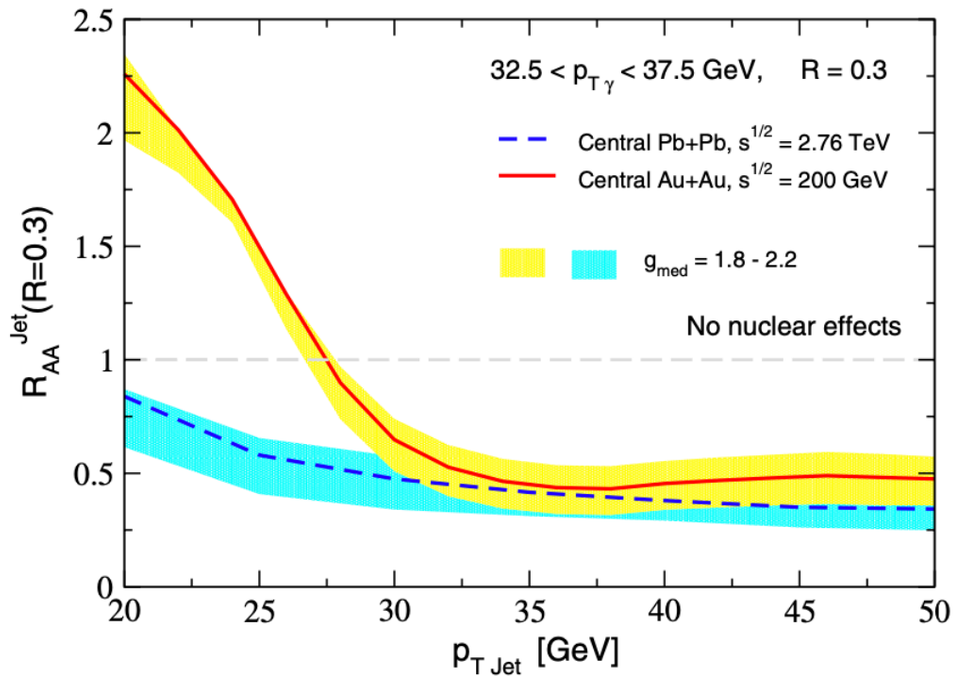
γ+jet in heavy-ion collisions





[Dai et al., PRL 110, 142001]

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

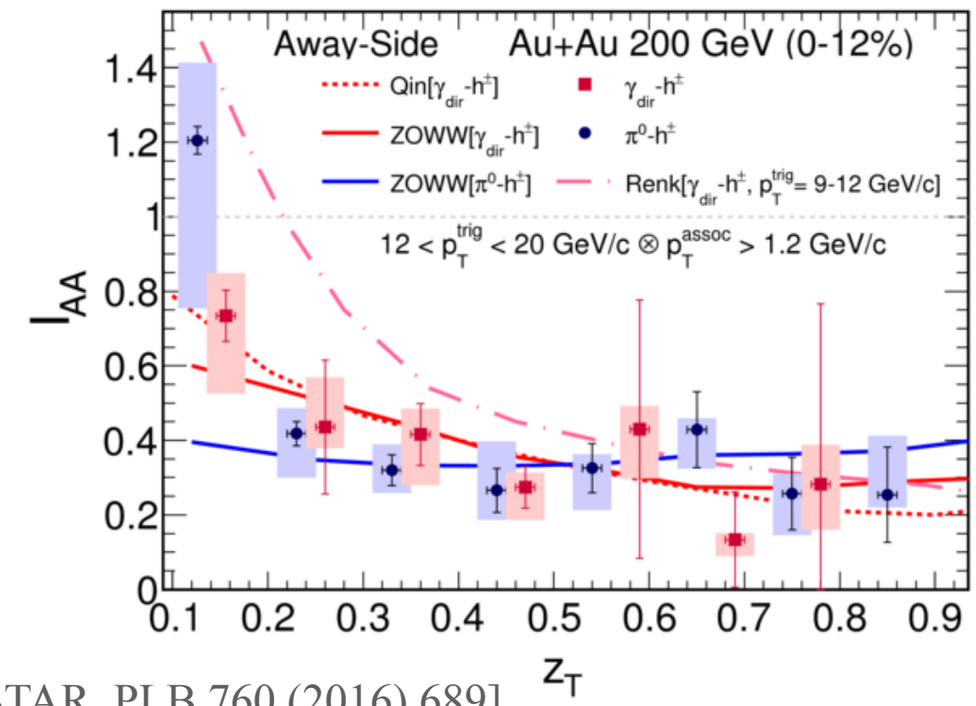
  However, NLO effects generates p_T-imbalance; calculable

- Comparison of γ+jet at RHIC and the LHC: valuable tool to explore jet quenching

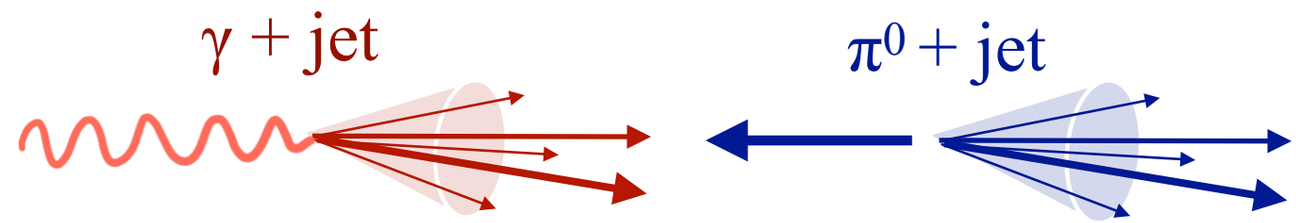
[X. N. Wang et al., PRL 77 (1996) 231; T. Luo, et al., PLB 782 (2018) 707]

γ+jet and π^0+ jet measurements in STAR

STAR: jet-like correlation measurement



[STAR, PLB 760 (2016) 689]



Comparison between γ+jet and π^0+jet:

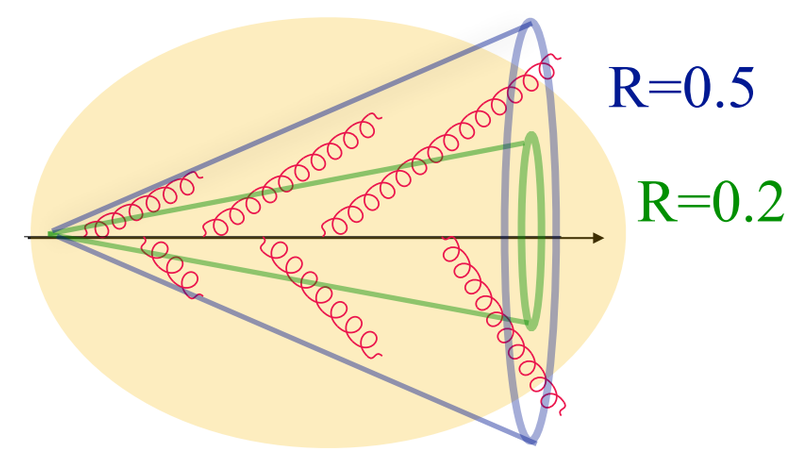
- Vary quark vs. gluon of recoil jets
- Vary recoil mean path length

Two challenges:

- Discrimination of γ/π^0 trigger
  [STAR, PLB760 (2016) 689–696]

  Resolved using STAR colorimeter system
- Uncorrelated jets in recoil jets region
  [STAR, PRC 96 no. 2, (2017) 024905]

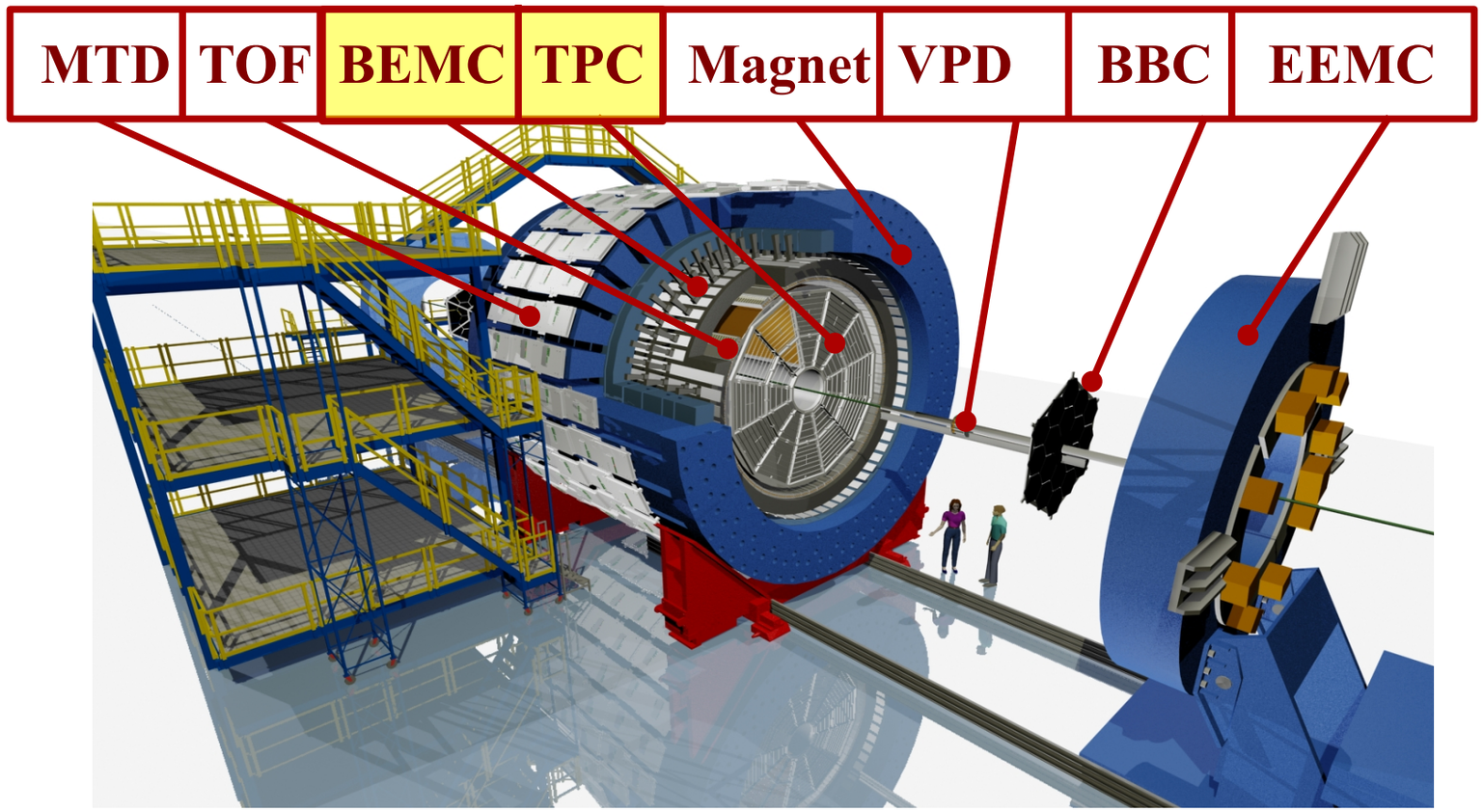
  Resolved using Mixed Event (ME) method



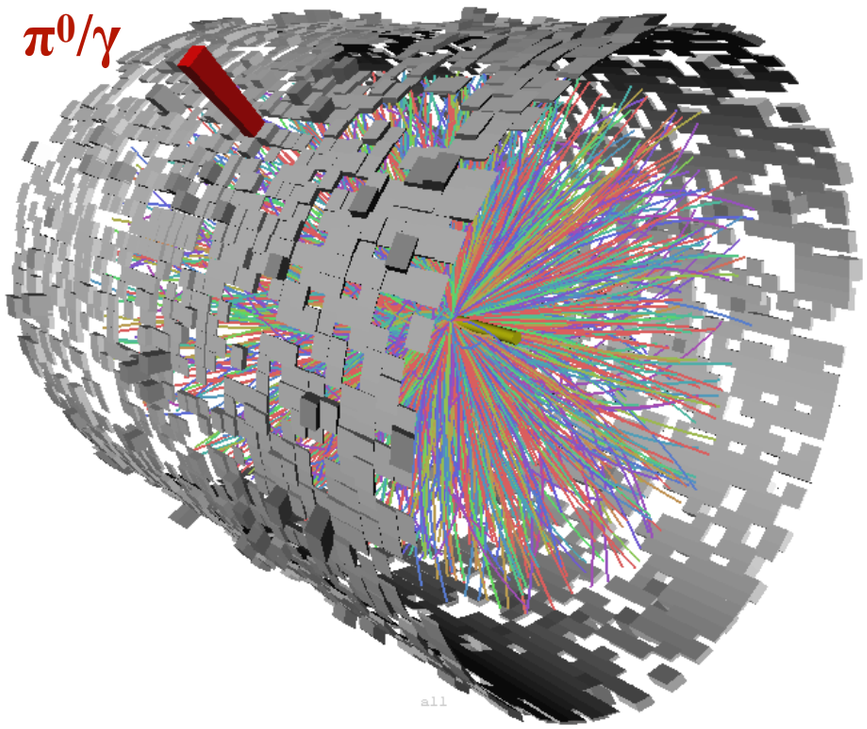
In this talk

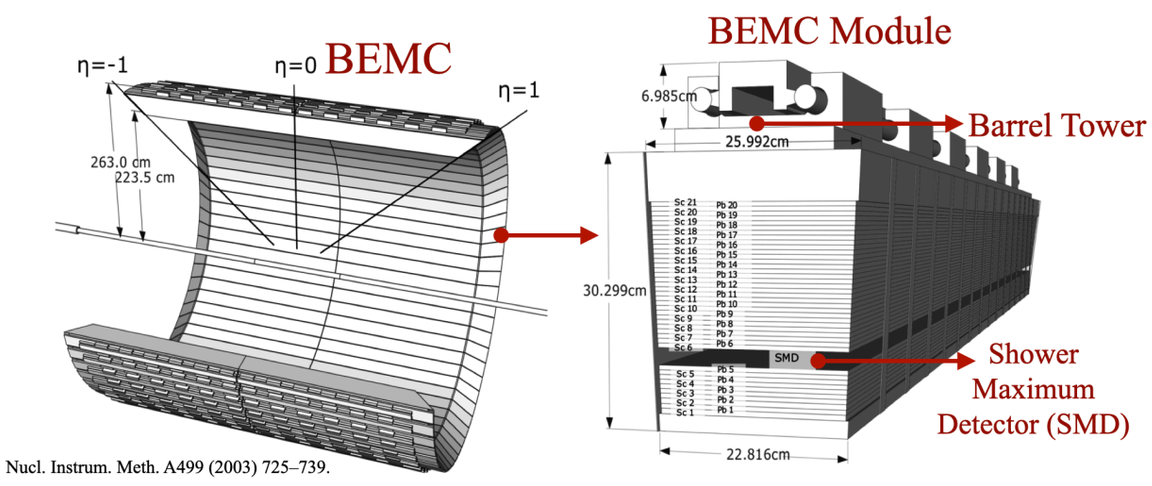
- Recoil jet yield suppression for jet R =0.2 and 0.5
- Modification of jet shape
- Jet energy loss due to quenching: RHIC vs. LHC

STAR detectors and online trigger



Online trigger: BEMC High Tower (HT) trigger to select events of large energy depositions





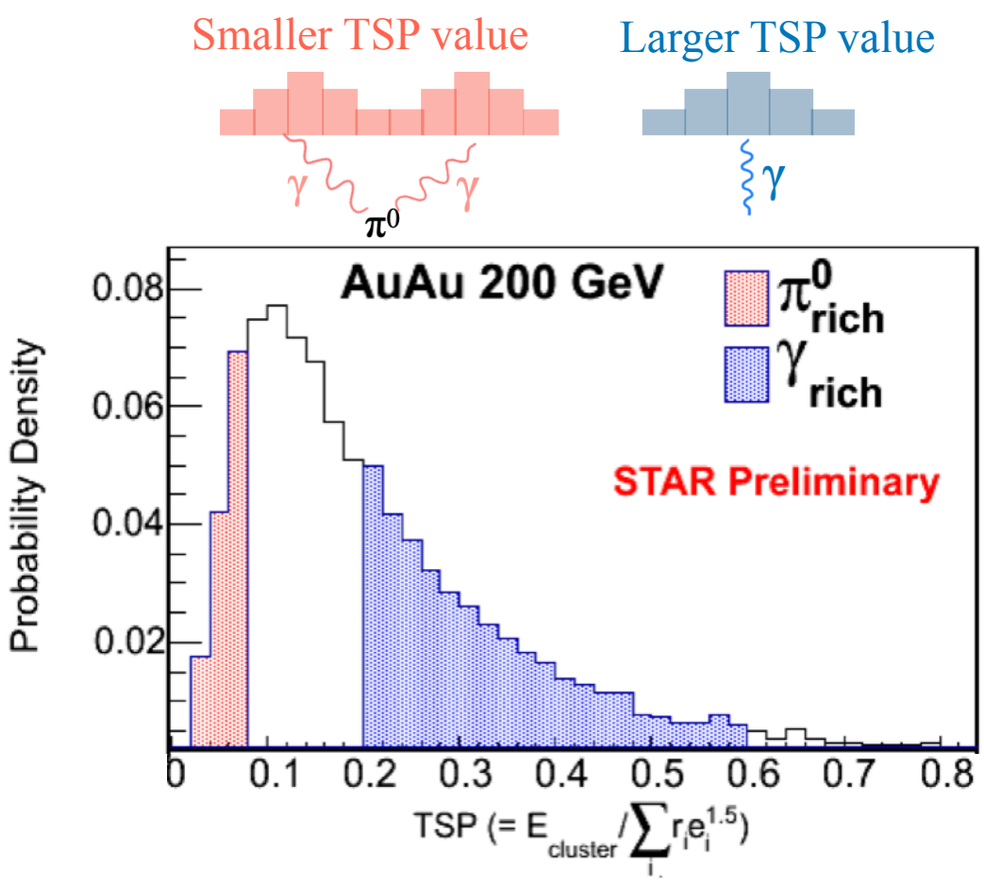
Nucl. Instrum. Meth. A499 (2003) 725–739.

- Au+Au $\sqrt{s_{NN}}$ = 200 GeV (Year 2014 data)
- Integrated luminosity: 13 nb^{-1}
- 0-15% central collisions

γ_{dir}/π^0 discrimination and offline trigger

- HT trigger to select γ/π^0 events using BEMC
- Shower Maximum Detector (SMD)
  → Provides spatial resolution for electromagnetic shower
  → Discrimination between γ_{dir} and π^0 using TSP method

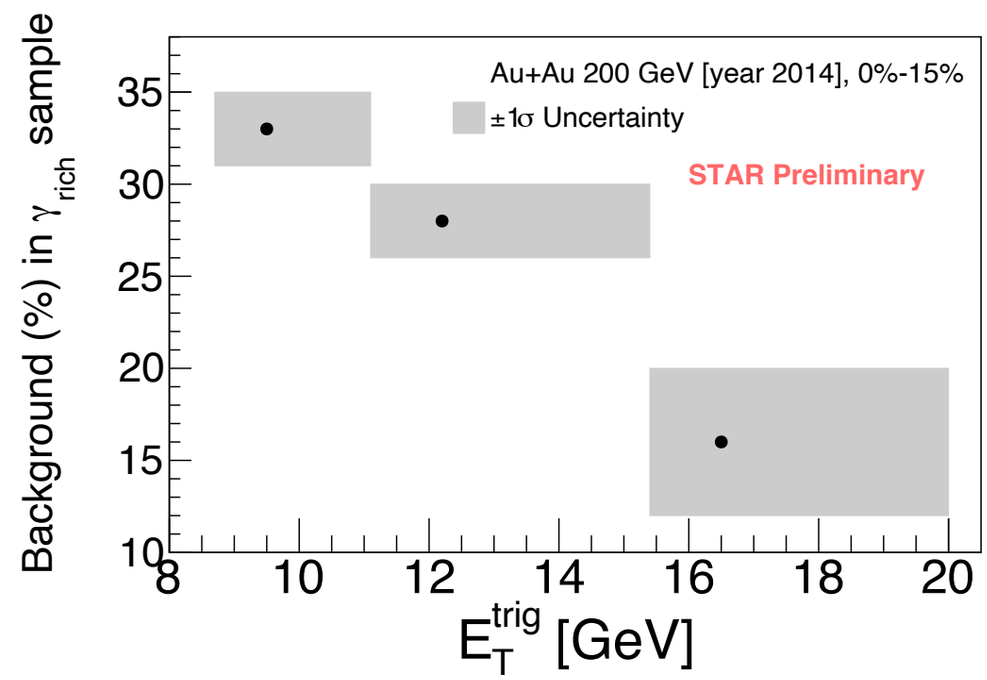
Transverse Shower Profile (TSP) distribution



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

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

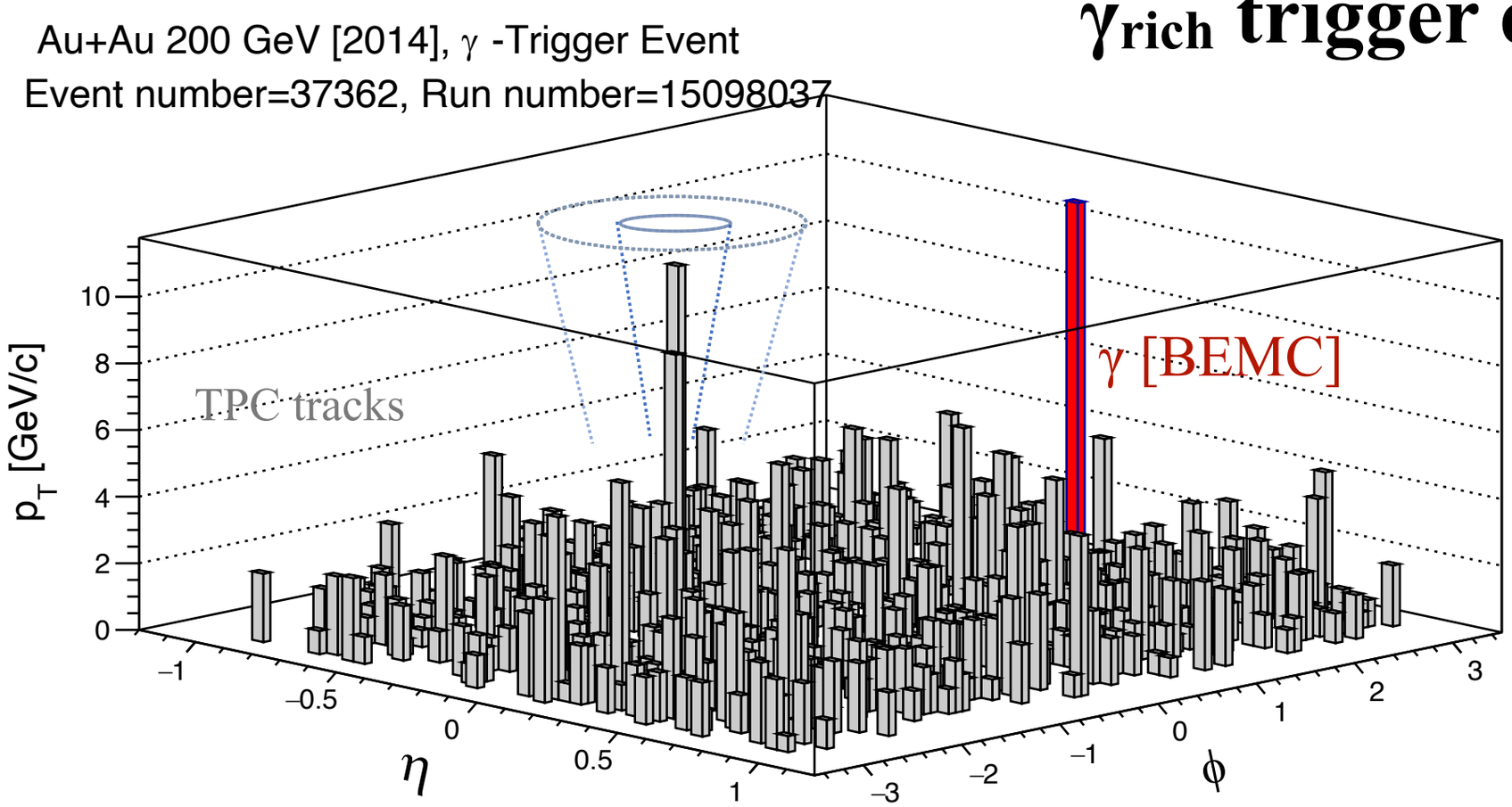
Background (%) in γ_{rich}-sample



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

Charged jet reconstruction

γ_{rich} trigger event



Charged jet reconstruction

- Constituent charged tracks: $p_T^{track} < 30$ GeV/c; $|\eta| < 1$
- Anti-k_T algorithm [FastJet]; jet R =0.2 and 0.5
- Recoil jet region: $\phi^{trig} - \phi^{jet} \in [3\pi/4, 5\pi/4]$
- $|\eta_{jet}| < 1\text{-}R$

Corrections and uncertainties

Event-by-event correction:

- Uncorrelated background energy density (ρ)

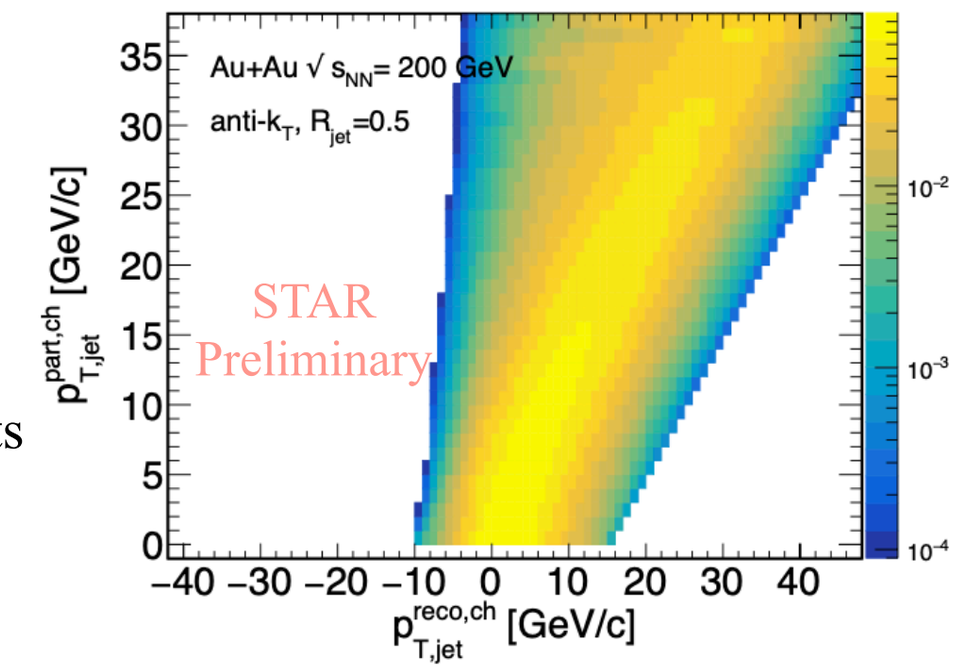
$$p_{\mathrm{T,jet}}^{\mathrm{reco,ch}} = p_{\mathrm{T,jet}}^{\mathrm{raw,ch}} - \rho \times A;$$

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

Ensemble-level correction:

- Uncorrelated jet yield correction: Mixed Event approach
- Jet Energy Scale (JES) smearing correction: Unfolding
  - Factorize instrumentation and background fluctuation effects
  - Unfolding: SVD; iterative Bayesian

Combined response matrix, R=0.5

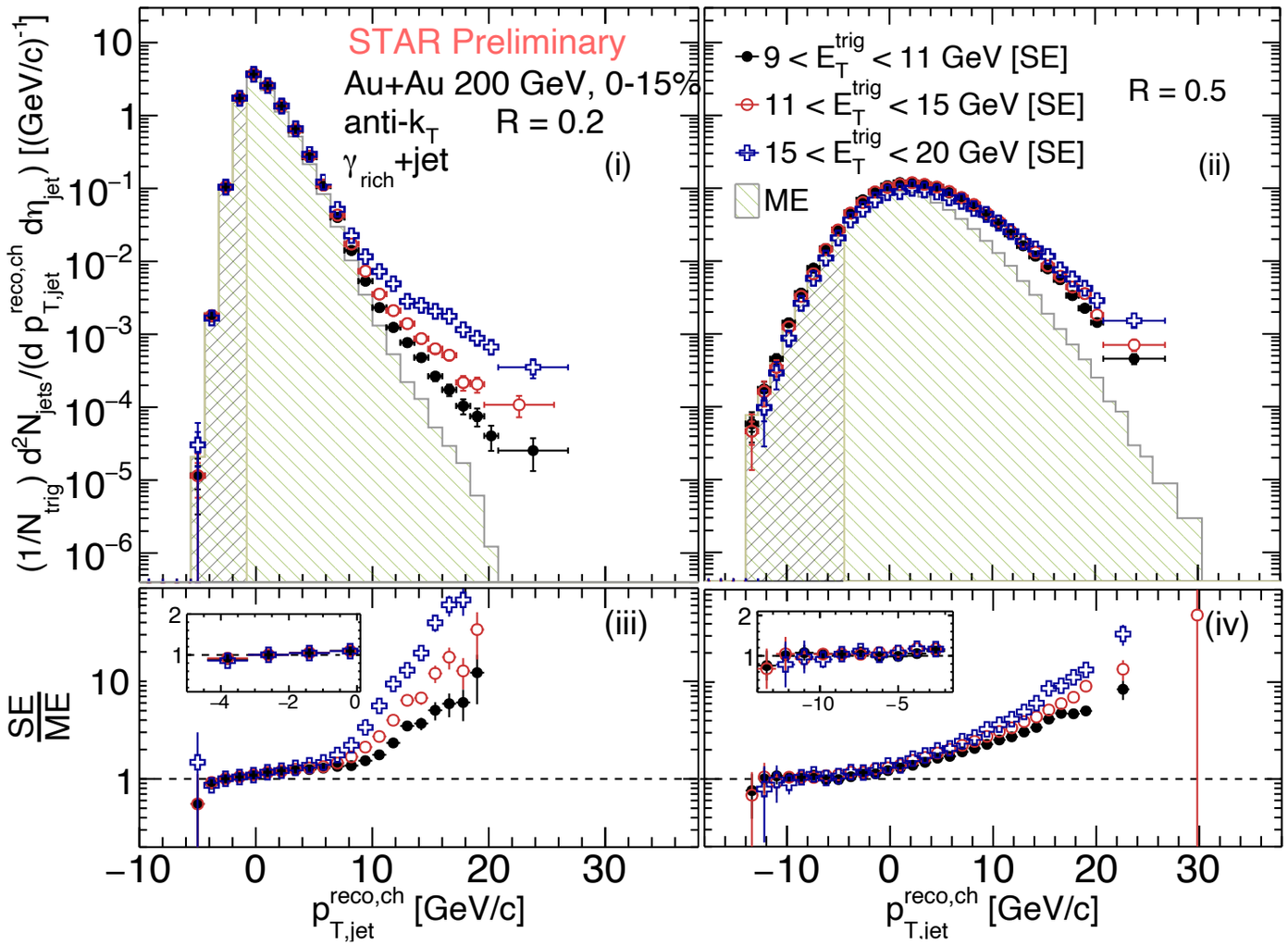


Main contributions to systematic uncertainties

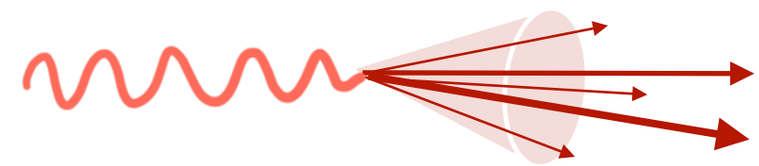
- Unfolding (iteration parameter and prior variation)
- Choice of ME normalization region
- Instrumentation effects [largest effect: tracking efficiency]
- Direct photon purity

Semi-inclusive γ_{rich} +jet $p_{T,jet}^{reco,ch}$ distribution

R=0.2 **R=0.5**



γ + jet



Recoil charged jet

- Same Event (SE): Uncorrelated jets + correlated jets
- Mixed Event (ME): Uncorrelated (combinatorial) jets

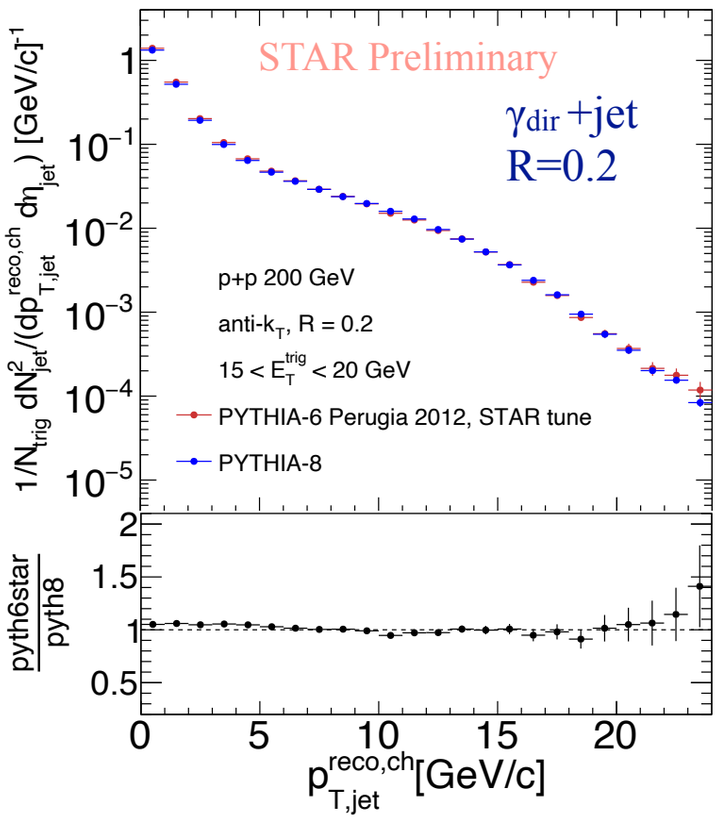
- $p_{T,jet}^{reco,ch} < 0$: yield independent of E_T^{trig}
  ME reproduces shape of SE
- $p_{T,jet}^{reco,ch} > 0$: yield dependent of E_T^{trig}
  SE dominates over ME at high-$p_{T,jet}^{raw,ch}$

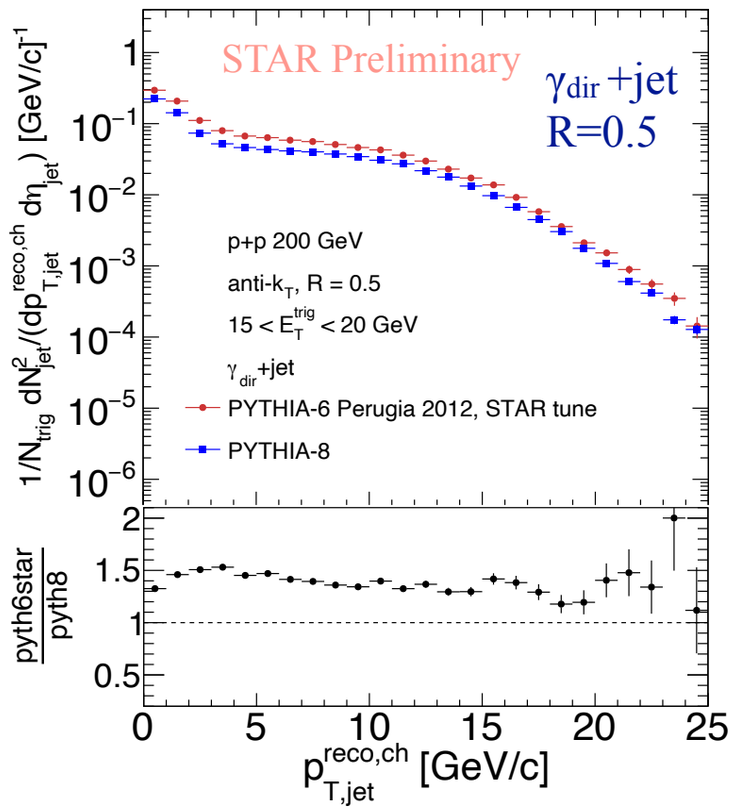
- ME normalization: crosshatching region
- Correction for uncorrelated yield: ME subtraction
- Correction for JES smearing: Unfolding

$p+p$ reference for this measurement

γ_{dir} +jet and π^0+jet p+p reference:

- STAR data: insufficient statistical precision for this analysis at present
- Use PYTHIA validated by STAR measurements





Two versions of PYTHIA:

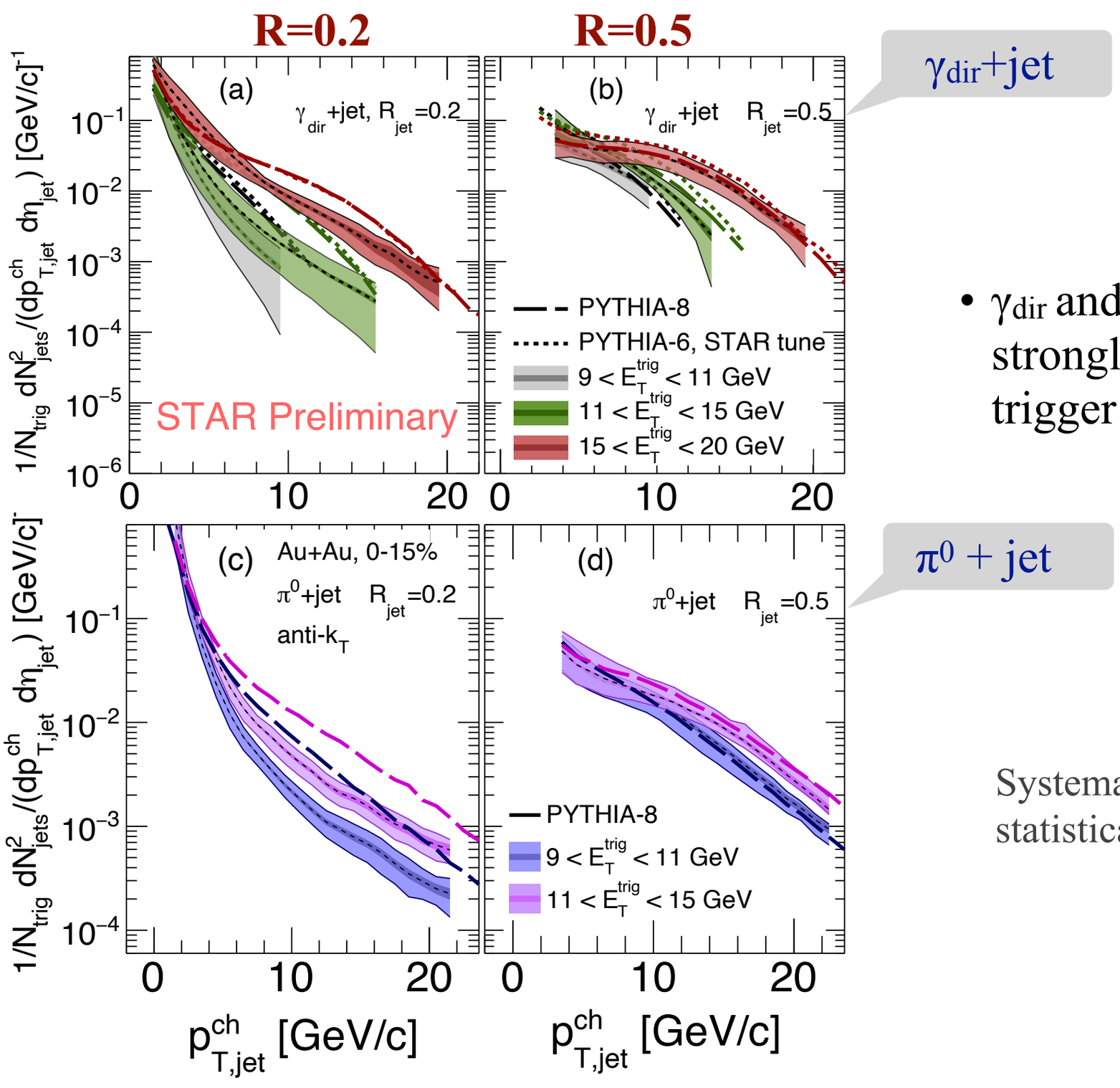
- PYTHIA8 Tune 4C:
  used for QM2019 presentation of this analysis
- PYTHIA6 Perugia 2012 STAR tune:
  validation by STAR p+p data
  [STAR, Phys. Rev. D 100, 052005 (2019)]

We will show both references to illustrate differences.

For γ_{dir} +jet:

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

Corrected semi-inclusive 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

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

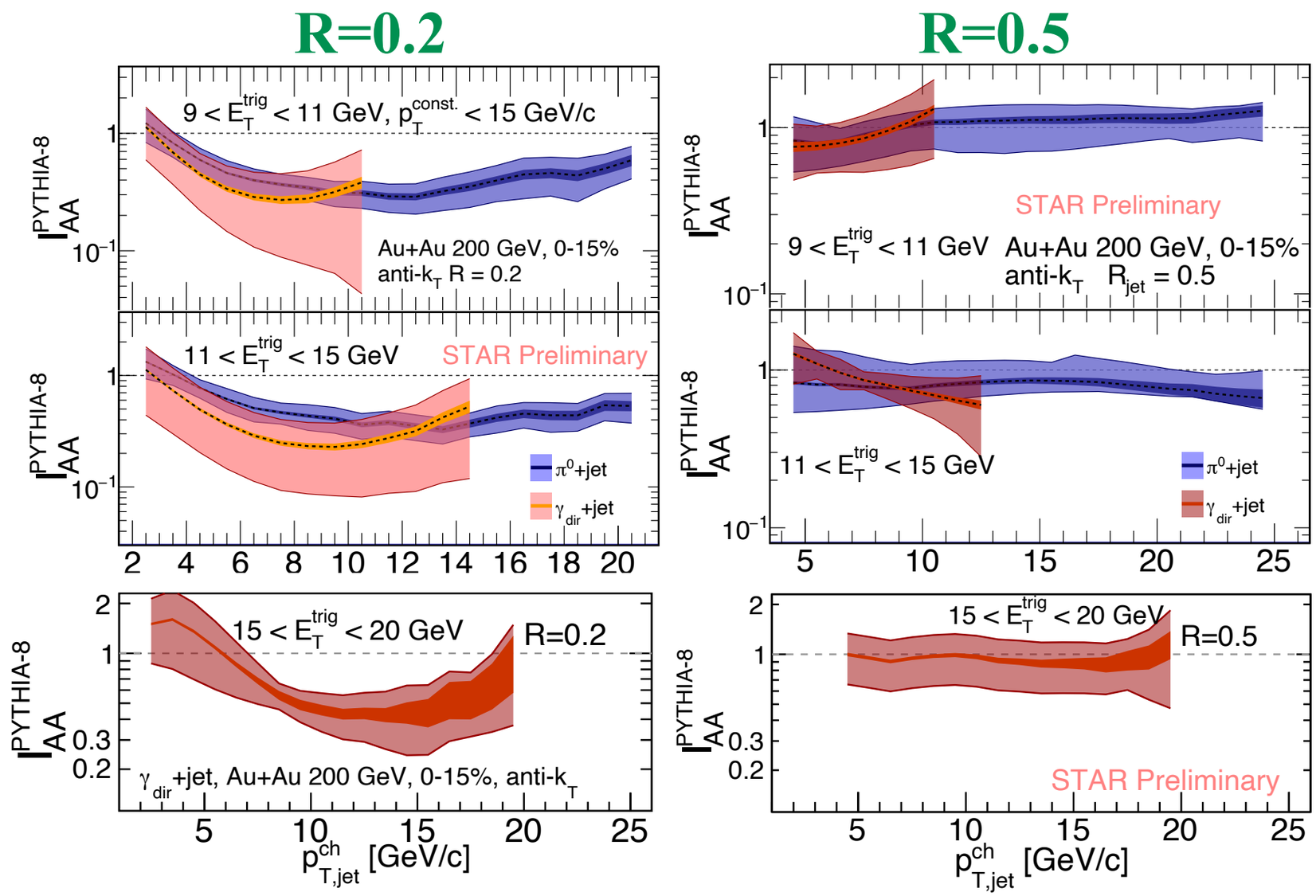
Recoil jet yield suppression for R=0.2 and 0.5

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

$Y(p_{T,jet}^{ch}) \rightarrow$ 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

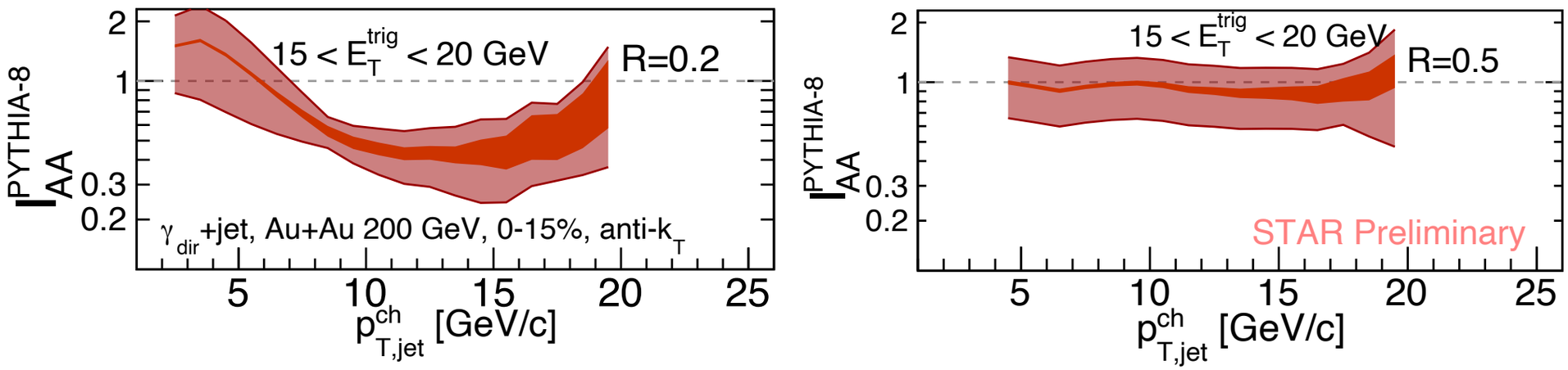


- γ_{dir}+jet and π^0+ jet show similar level of suppression
- No significant trigger E_T dependence
- Larger recoil jet yield suppression for R=0.2 than R=0.5

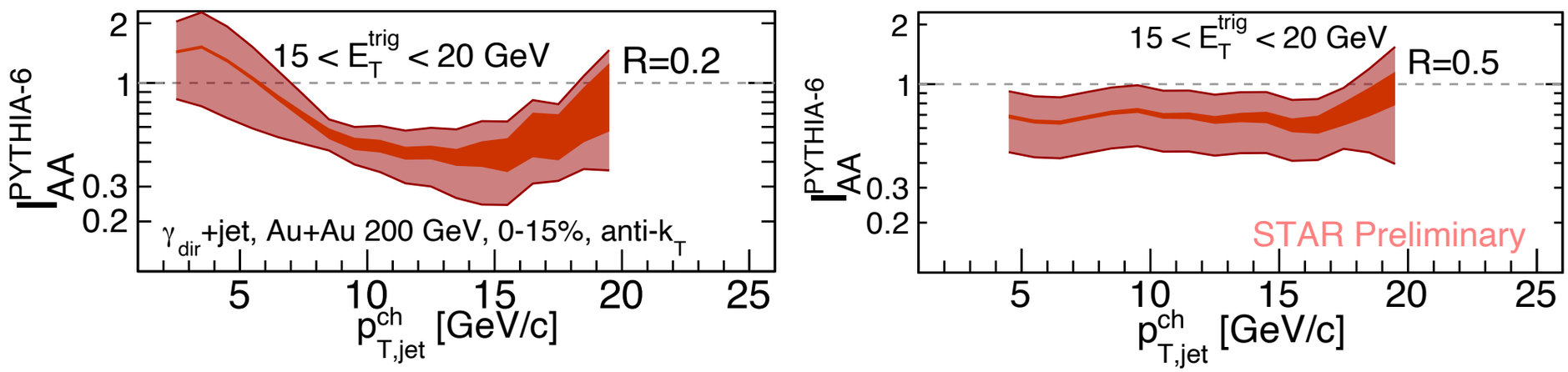
Recoil jet yield suppression: *PYTHIA-6 STAR vs PYTHIA-8*

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

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



pp reference: PYTHIA-6 STAR tune



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

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

Recoil jet yield suppression: *Data vs. Model*

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

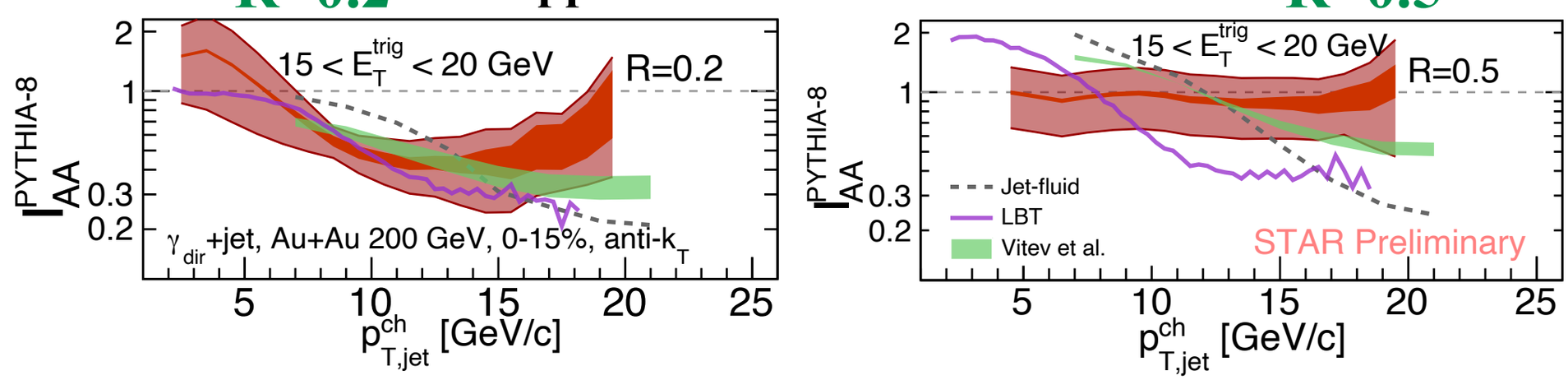
Comparison to Theory

Jet-fluid: jet shower + medium response [Chang, et al., PRC 94 (2016), 024902]

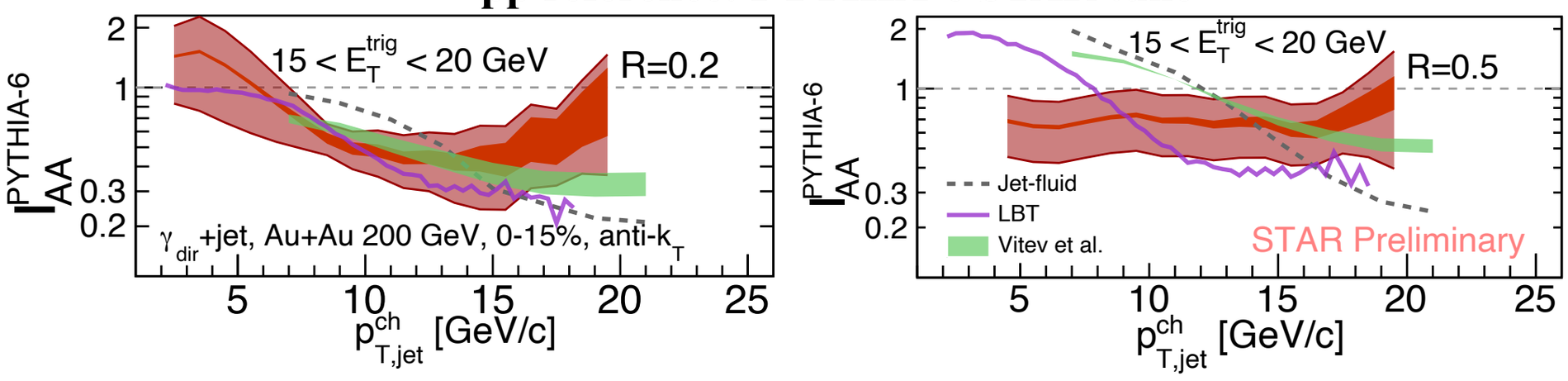
LBT: coupled LBT+hydro [Chen, et al., PLB 777 (2018) 707]

All order in opacity [Sievert, et al., PLB 795 (2019) 502]

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



pp reference: PYTHIA-6 STAR tune



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

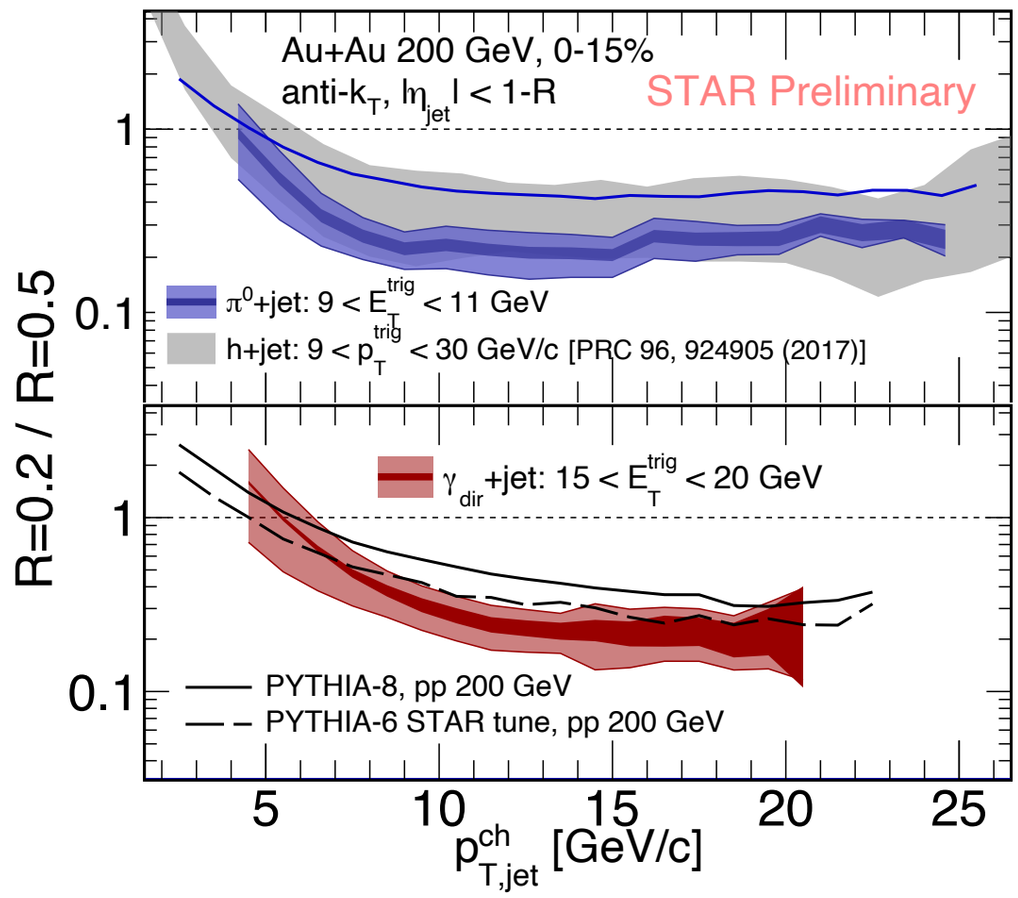
p_T-dependence of suppression is different in theory predictions and data.

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

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

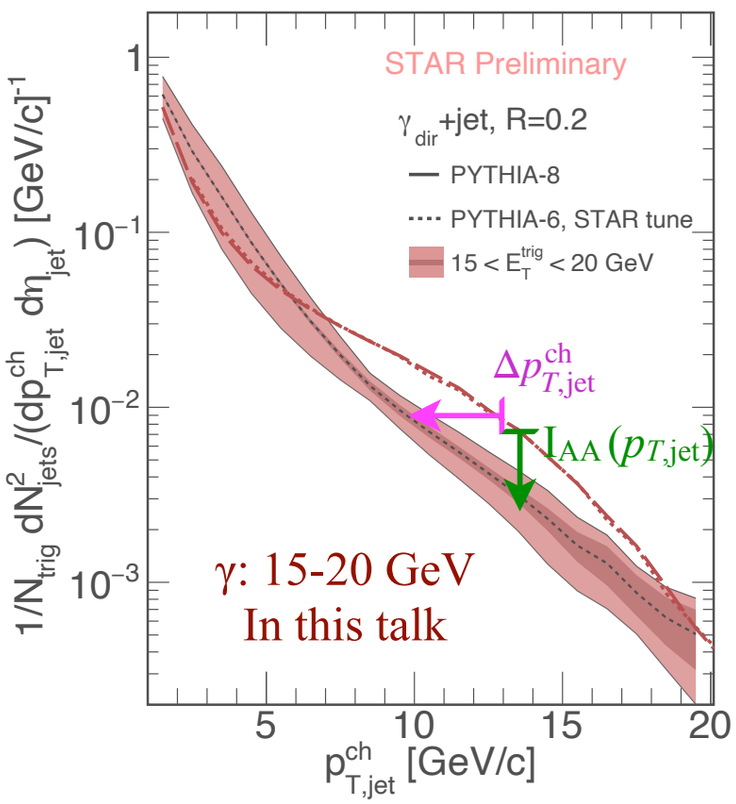
Systematic (lighter band) and statistical (darker band) uncertainties

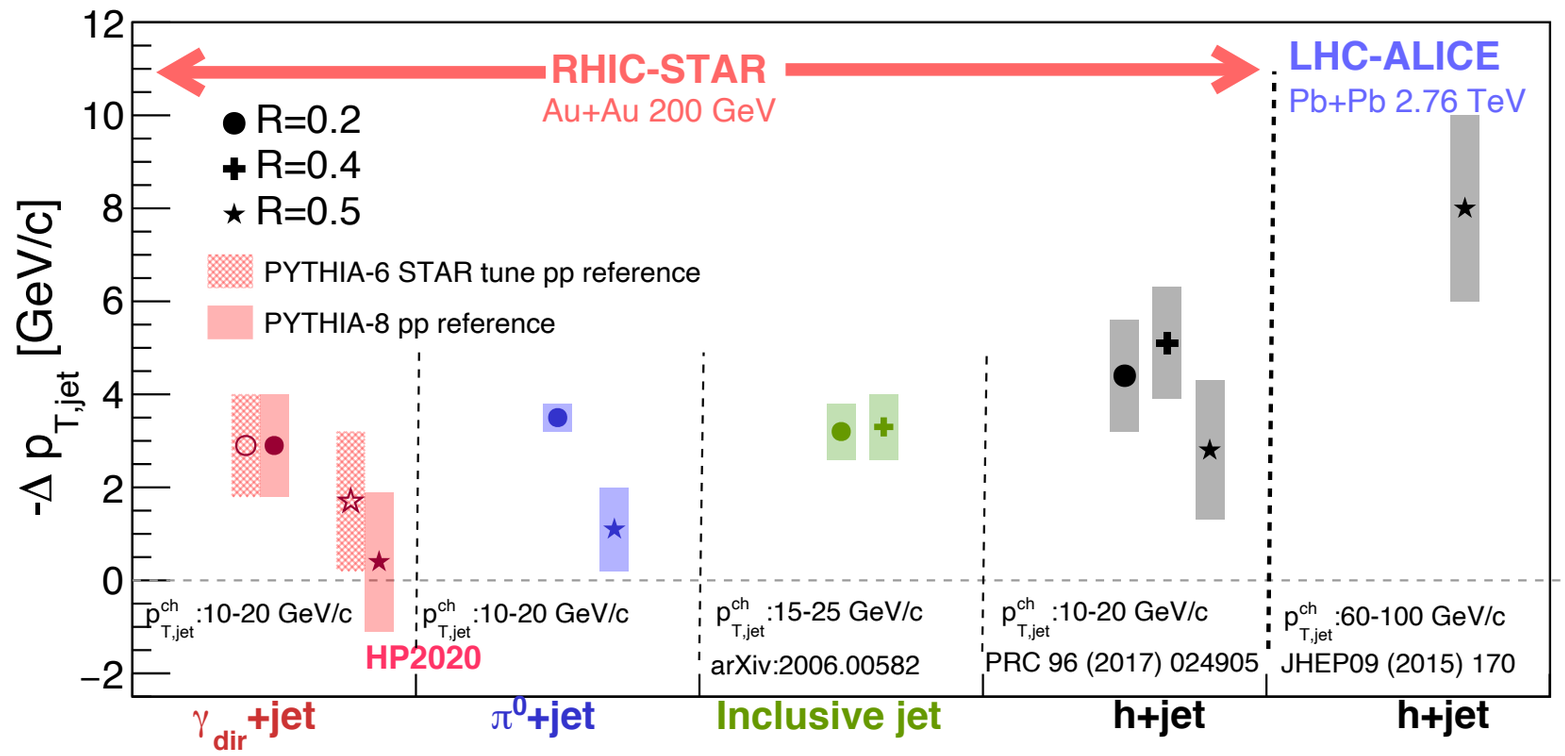


- γ_{dir} +jet consistent with PYTHIA-6 STAR tune → would indicate no significant in-medium broadening
- Quantitative difference: PYTHIA-6 STAR tune vs. PYTHIA-8
- π^0 + jet and hadron+jet are consistent

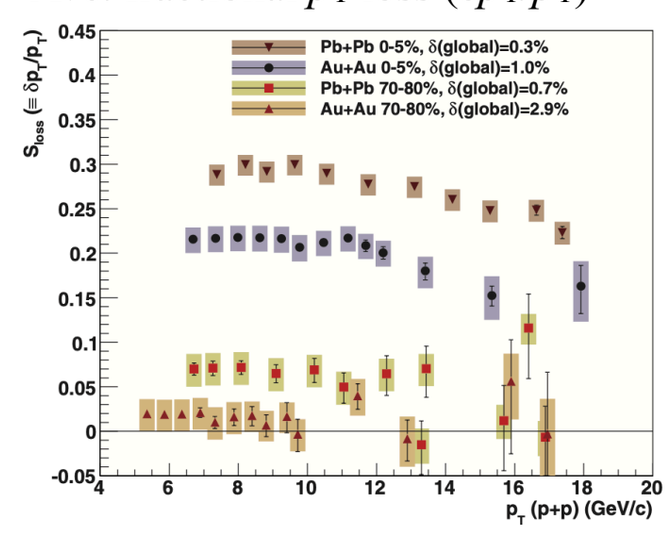
Jet p_T-spectrum shift : RHIC vs. LHC

Characterization of average out-of-cone parton energy loss





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



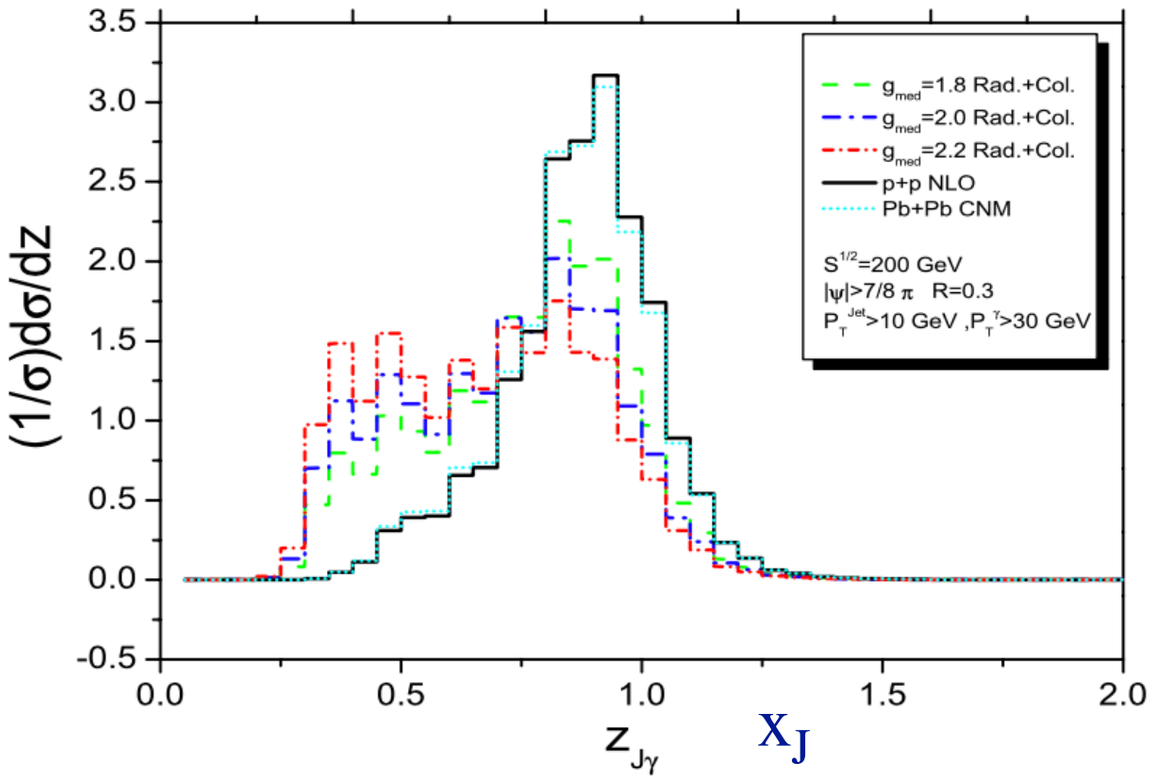
- π^0 PHENIX δp_T : ~2-3 GeV/c within p_T :10-18 GeV/c

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

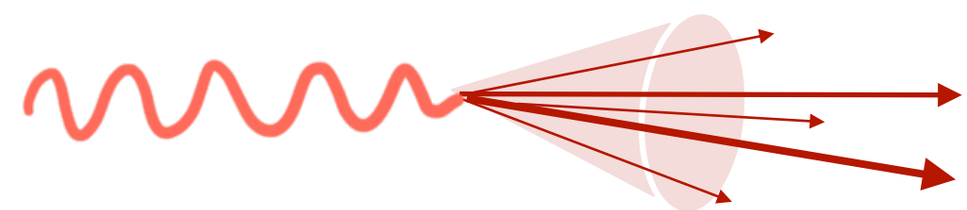
Indication of smaller in-medium energy loss at RHIC than the LHC

γ_{dir} + jet measurement in STAR (outlook)

(Dai, Vitev and Zhang, PRL **110**, 142001)



γ + jet



$$x_J = \frac{p_{T,jet}}{E_T^{\gamma}}$$

Ongoing in STAR:

- x_J : $9 < E_T^{trig} < 20$ GeV [poster ID#253 by Annika Ewigleben]
- p+p $\sqrt{s}$ = 200 GeV: γ_{dir}+jet and π^0+jet

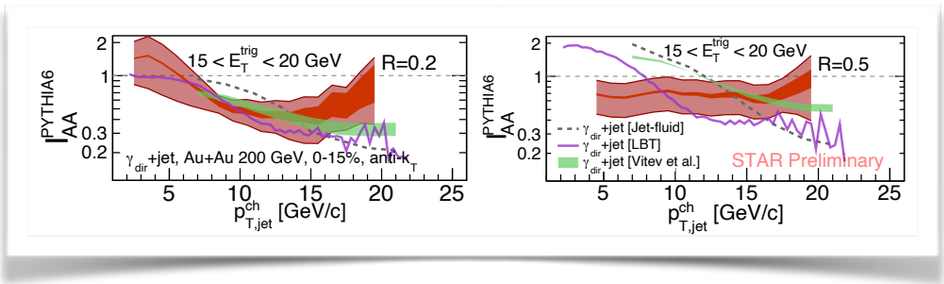
Summary

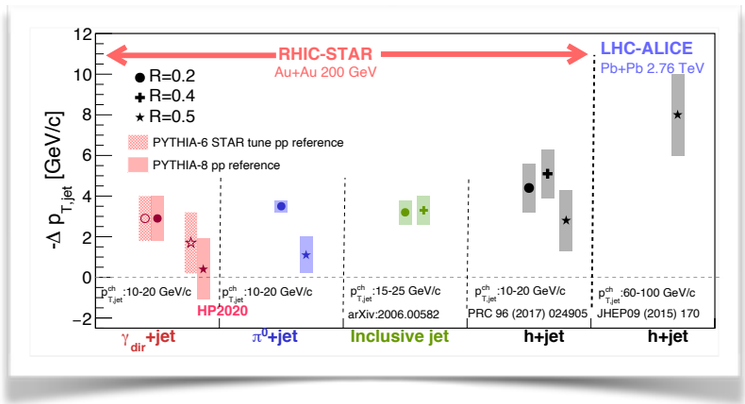
First measurement of γ_{dir}+jet and π^0+jet spectra in central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

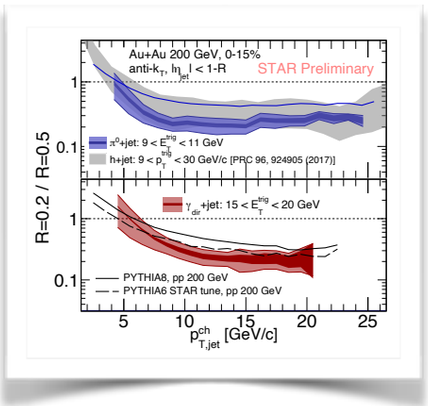
- p+p reference: PYTHIA-6 STAR tune, PYTHIA-8
- Recoil jet yield suppression: similar magnitude for γ_{dir}+jet and π^0+jet
  - Theoretical calculations do not reproduce p_T dependence

    Jet-fluid, LBT and All-order opacity
- Jet energy loss at RHIC
  - Consistent between measurement channels (inclusive, γ_{dir}+jet and π^0+jet)
  - Indication of being smaller than the LHC
- R-dependence of suppression; jet shape modification

  PYTHIA-6 (STAR) vs PYTHIA-8 give different pictures; to be resolved with measured p+p reference







Thank you!