Medium-induced jet broadening and acoplanarity using semi-inclusive photon+jet and π^0+jet measurements in STAR

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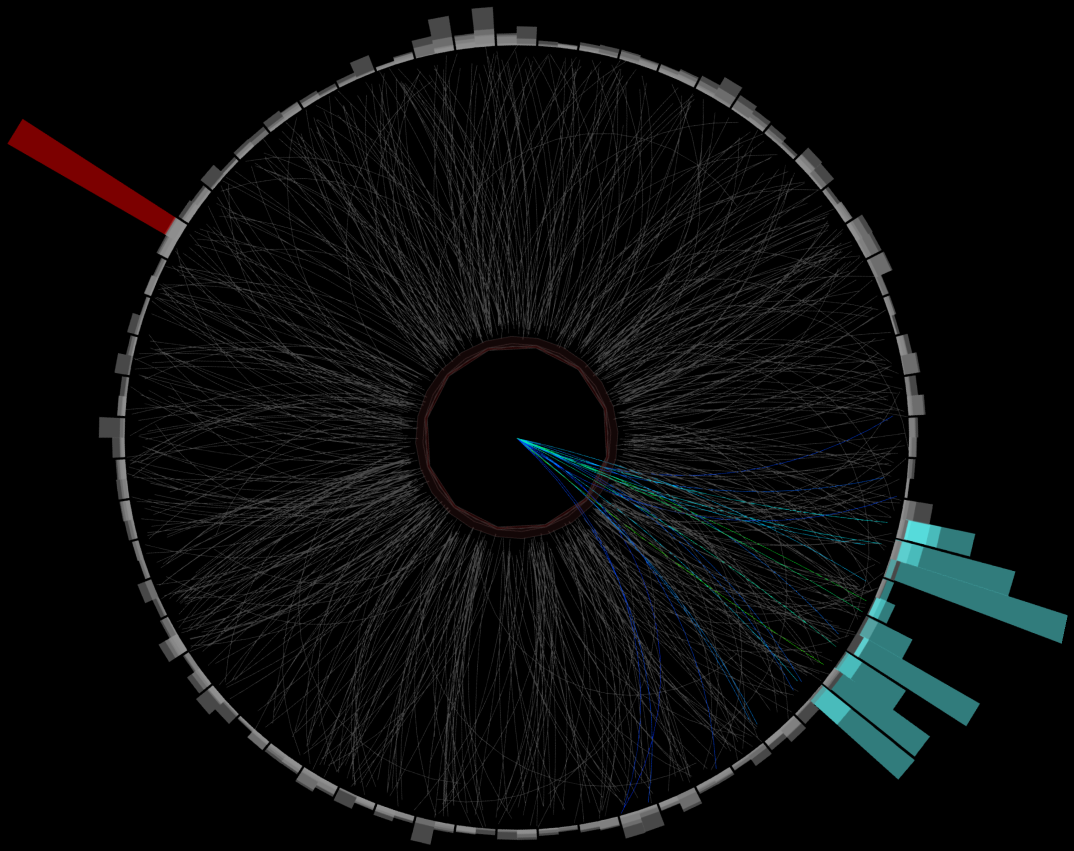
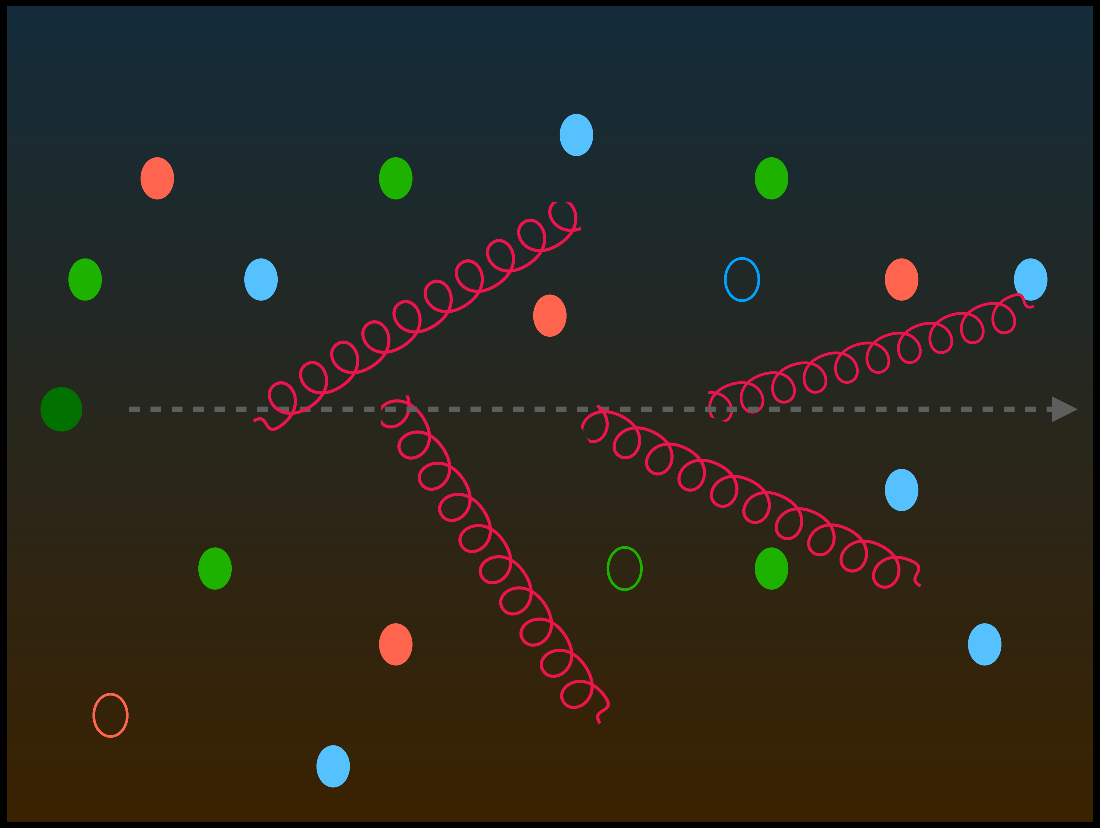


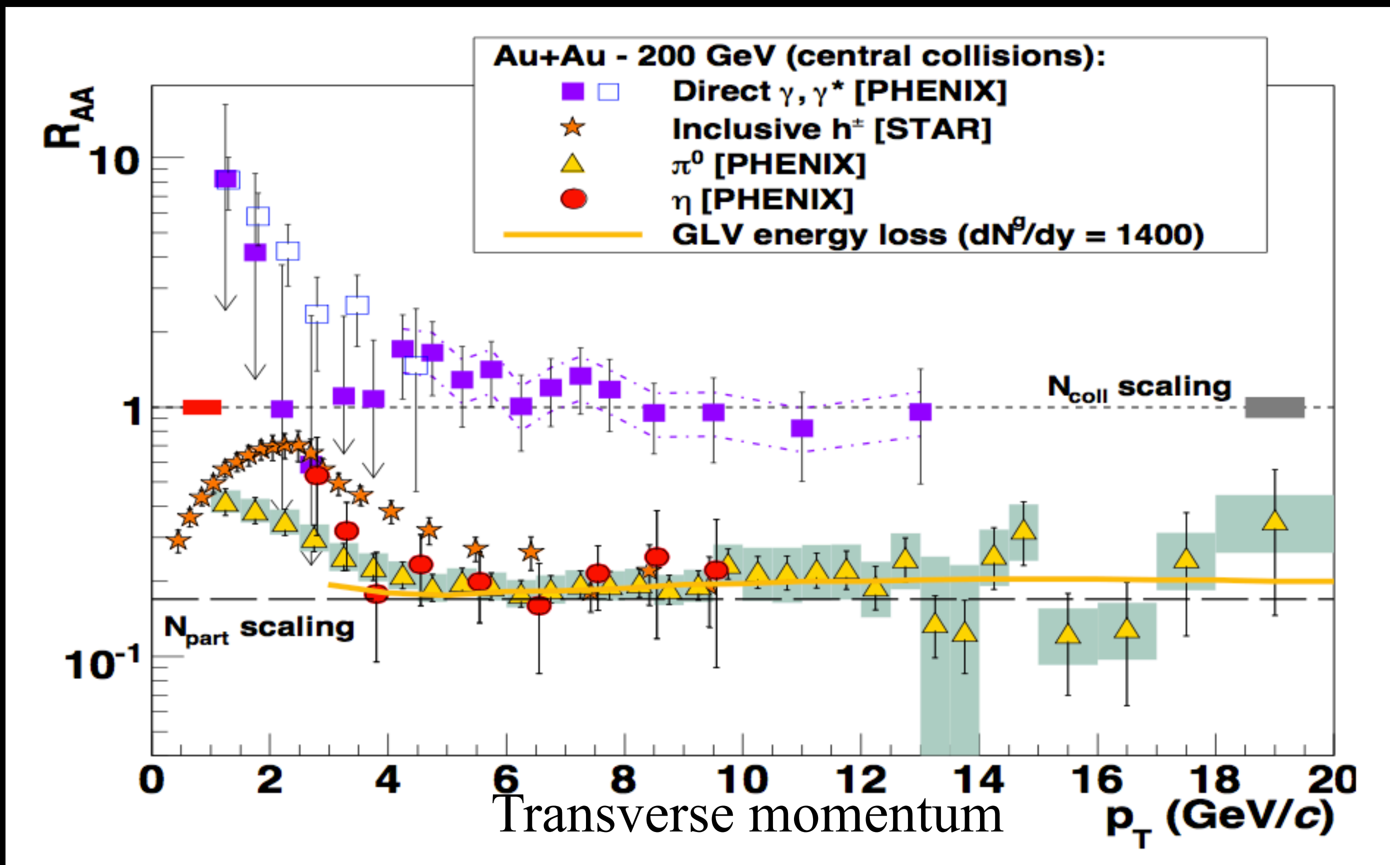


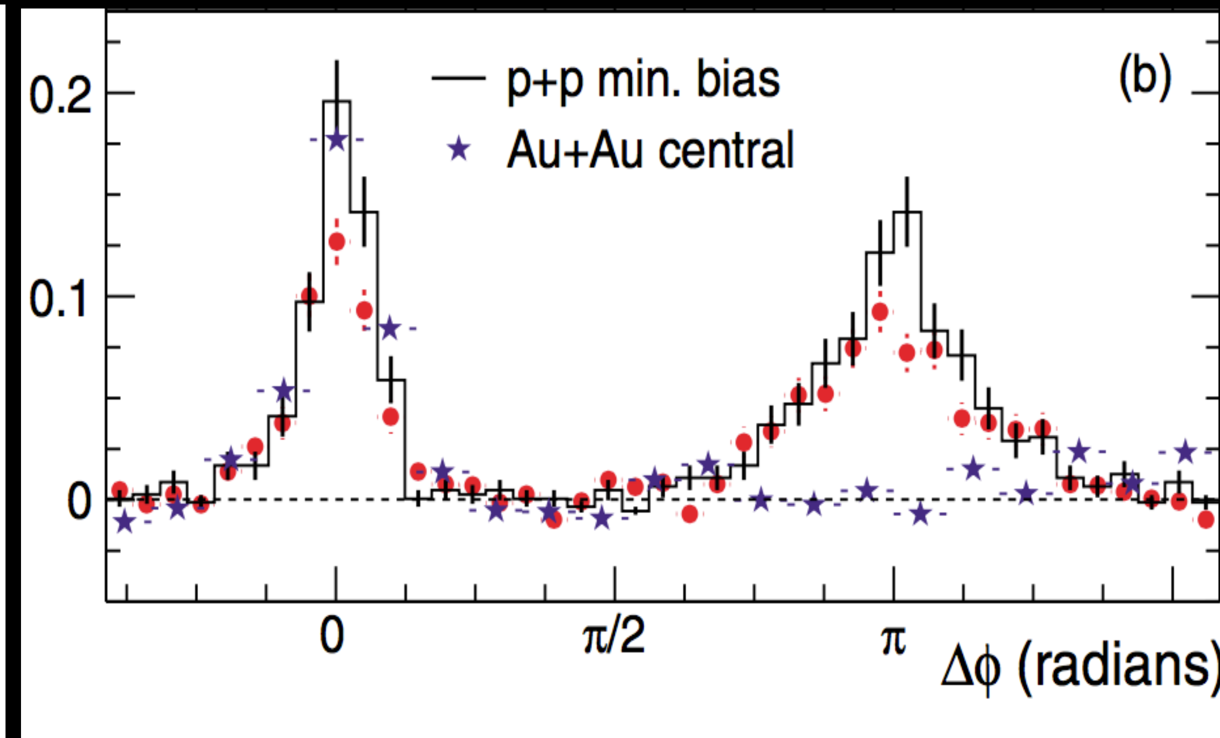
How does an energetic quark/gluon interact with the finite temperature QCD medium?

What can this tell us about the QGP?

Experimental evidence of jet quenching

First evidence of jet quenching at RHIC





STAR: PRL 91, 072304 (2003)

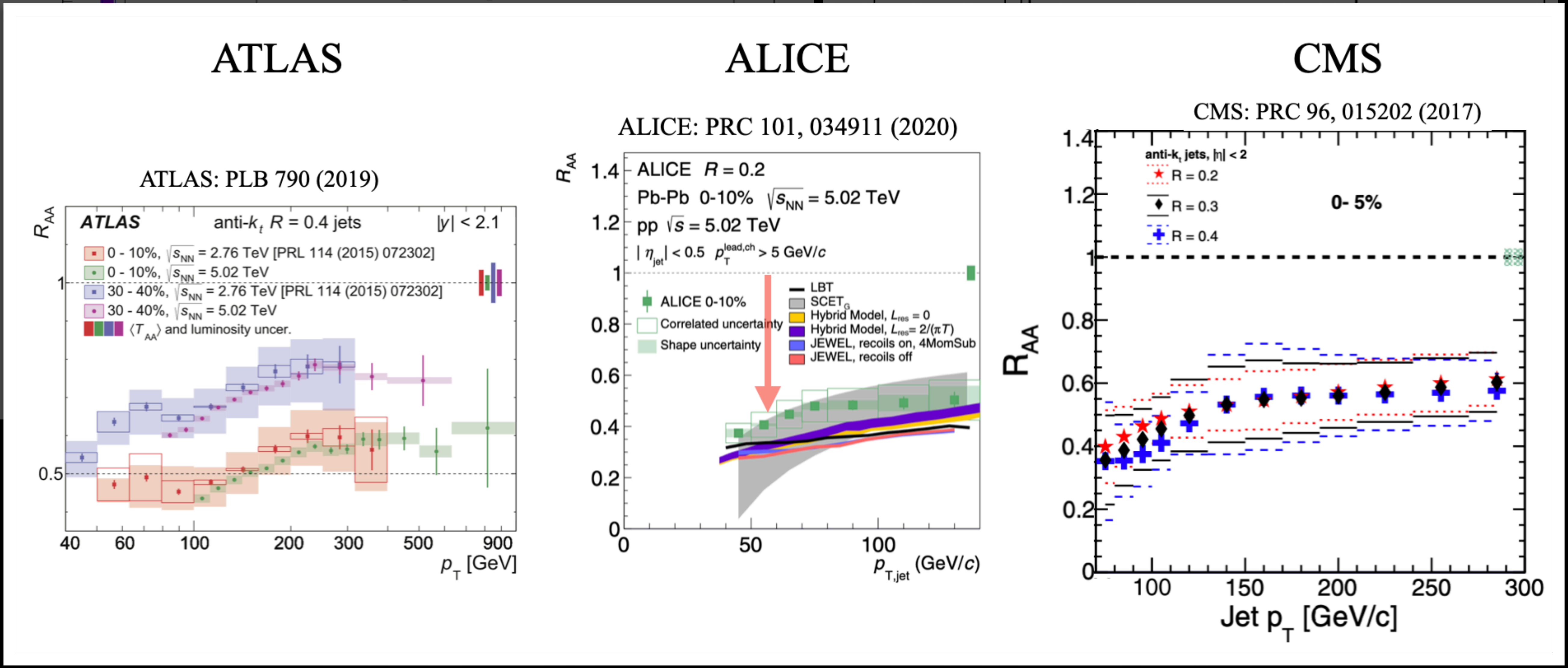
PHENIX: PRC 75 (2007) 024909

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

Signature of Quark-Gluon Plasma at RHIC

Experimental evidence of jet quenching

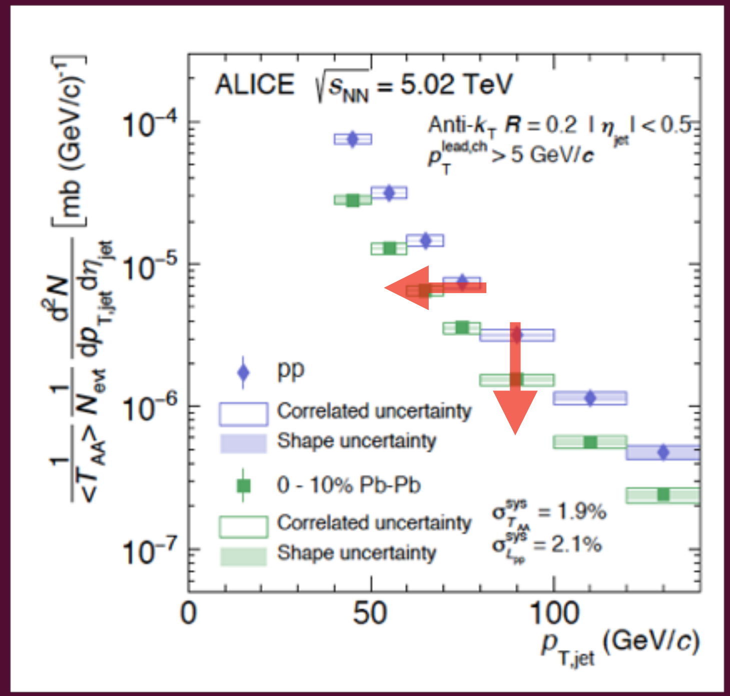
First evidence of jet quenching at RHIC

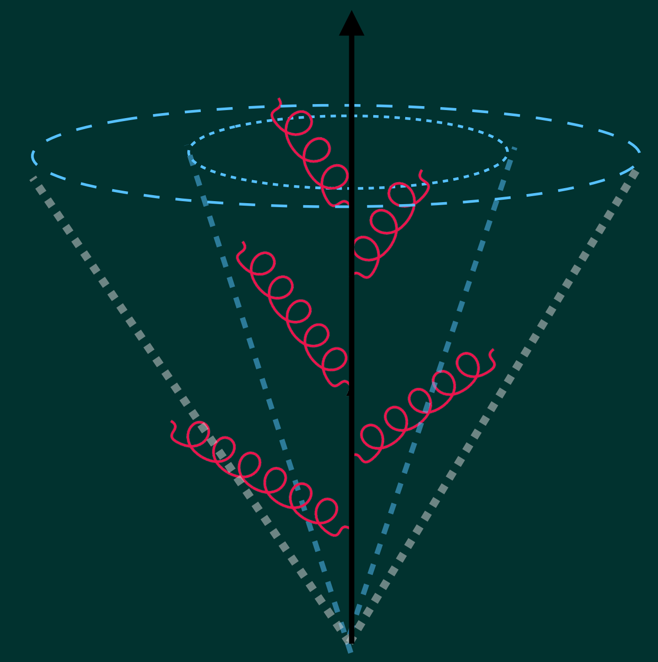


Signature of Quark-Gluon Plasma at LHC

Consequences of jet quenching

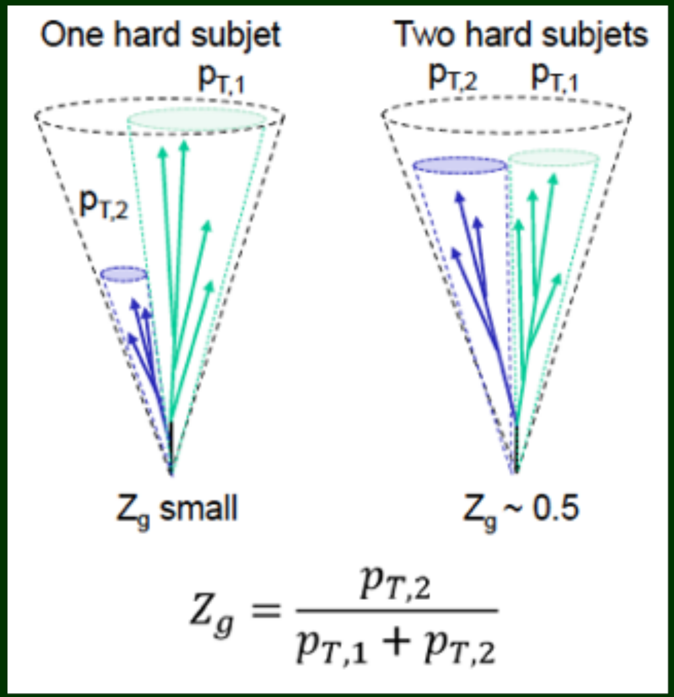
Energy loss

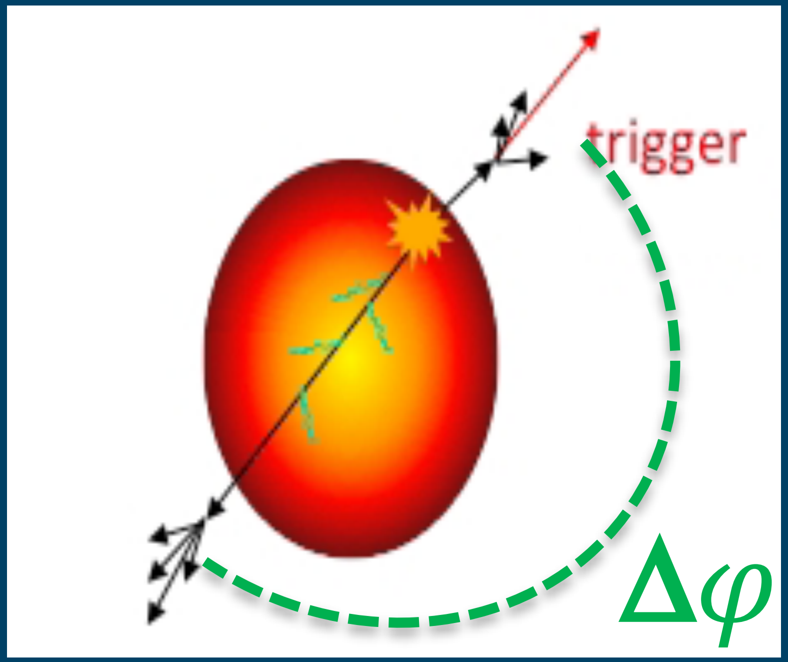




Large angle radiation

Modification of jet substructure





Jet deflection

Nihar Sahoo, SDU

γ+jet and h+jet measurements in STAR

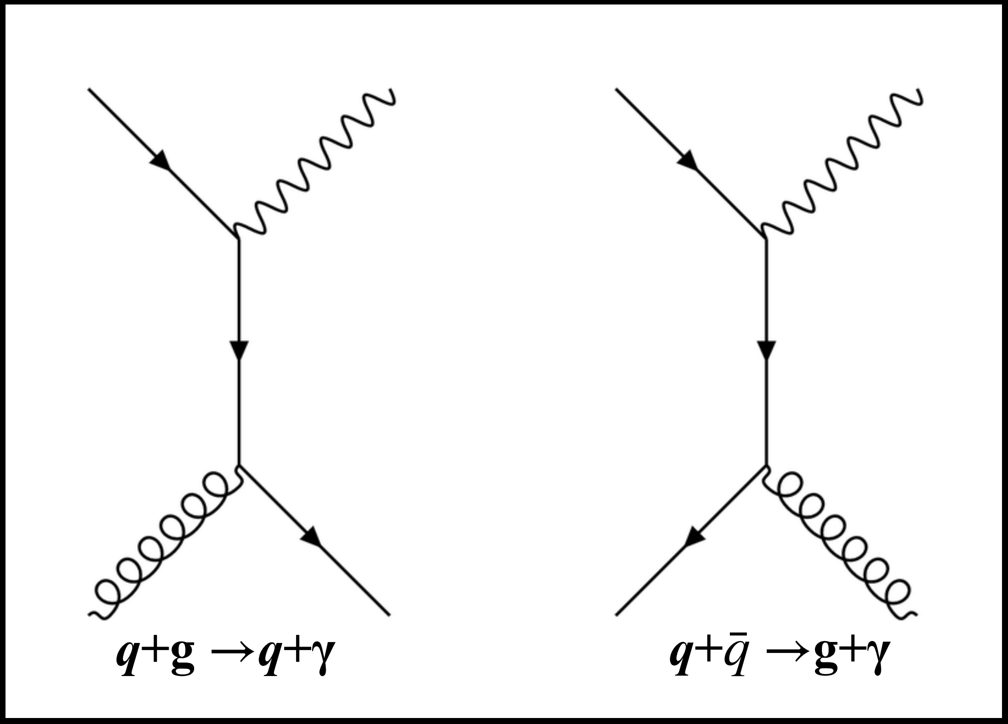
To explore more on jet quenching…

Derek Anderson's QM2022 talk: https://indico.cern.ch/event/895086/contributions/4717079/

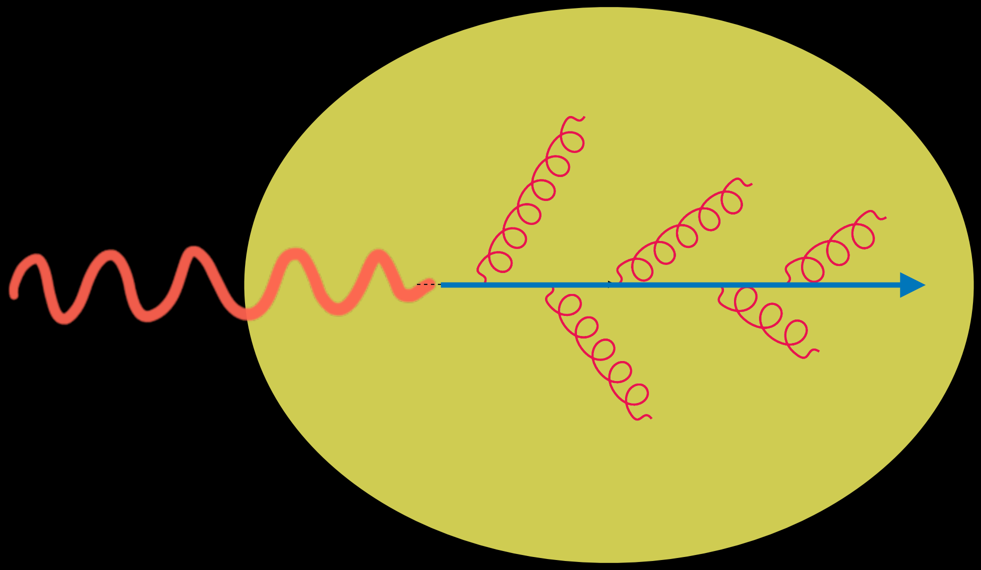
On jet-acoplanarity, NRS's QM2022 poster: https://indico.cern.ch/event/895086/contributions/4721355/

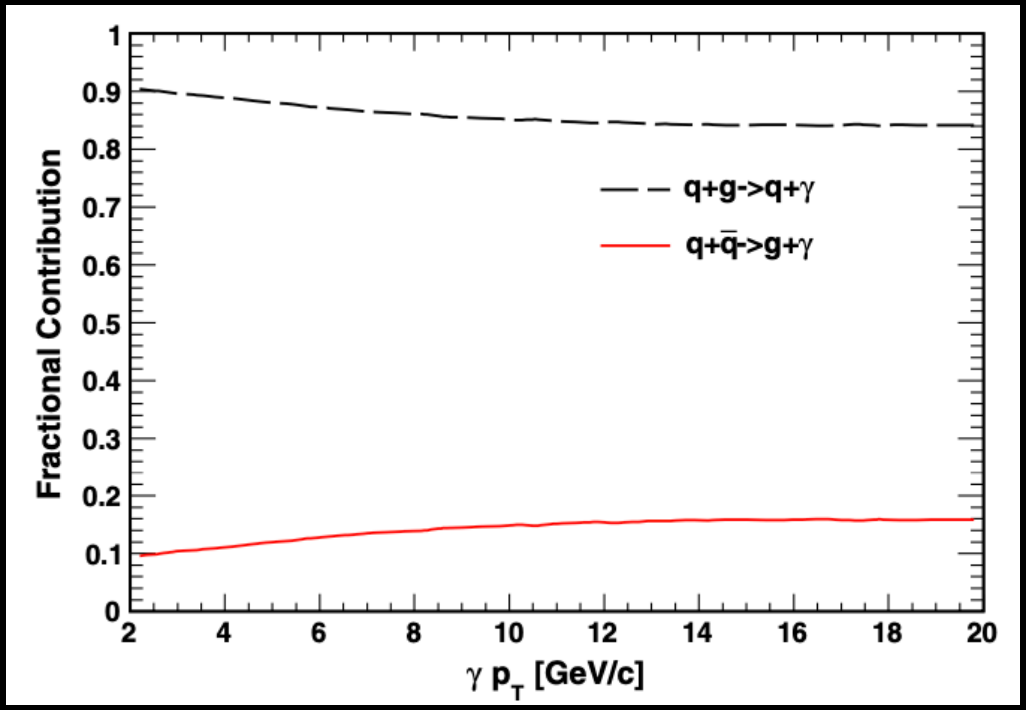
γ+jet in heavy-ion collisions

LO QCD process for prompt photon production



γ+jet in QGP





PHENIX: PRD 82, 072001 (2010)

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

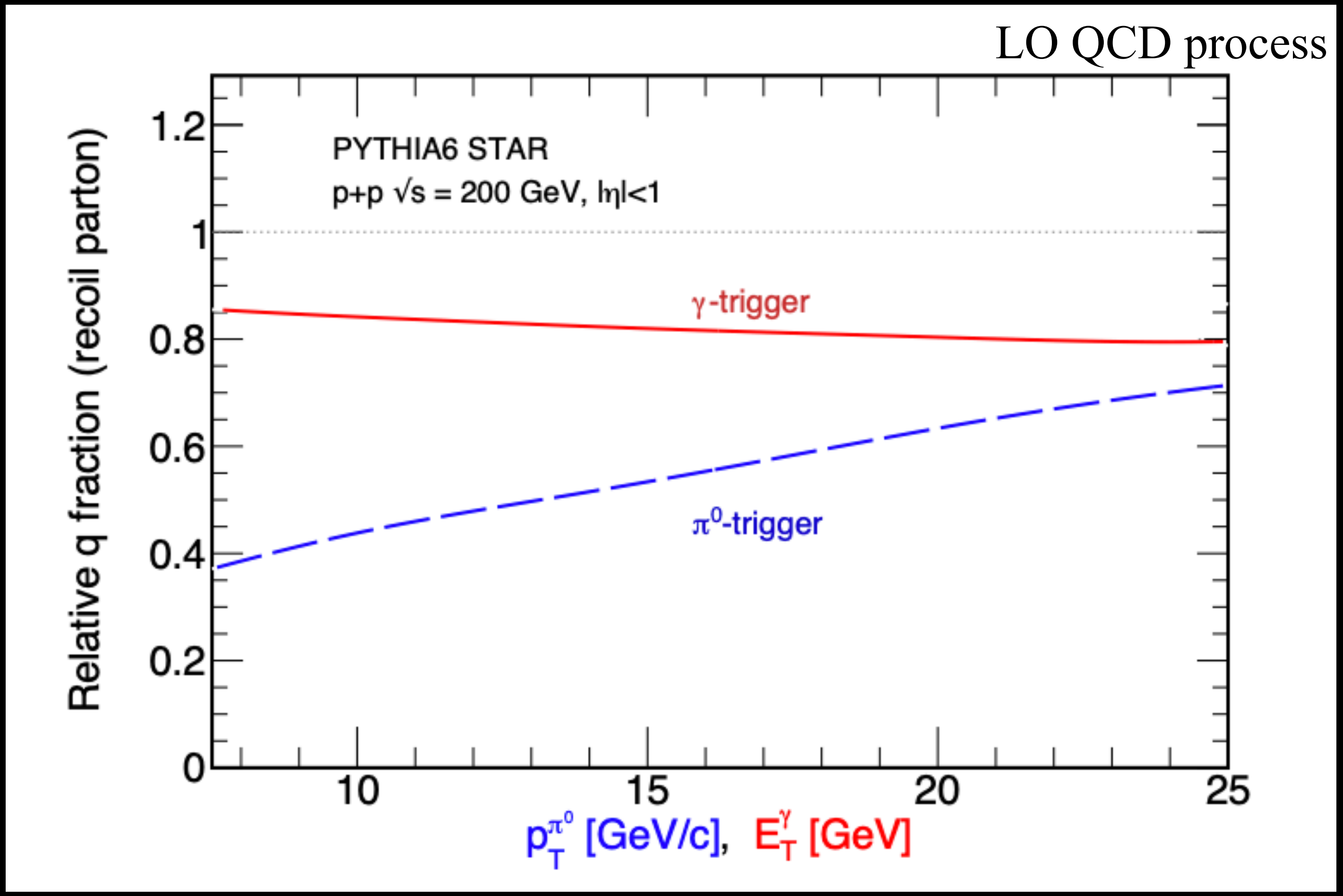
γ+jet and hadron+jet measurements at RHIC

γ+jet processes:

$q+g \rightarrow q+\gamma$
$q+\bar{q} \rightarrow g+\gamma$

π^0+jet processes:

$q+\bar{q} \rightarrow g+g$
$q+q \rightarrow q+q$
$q+\bar{q} \rightarrow q+\bar{q}$
$q+g \rightarrow q+g$
$g+g \rightarrow g+g$
$g+g \rightarrow q+\bar{q}$



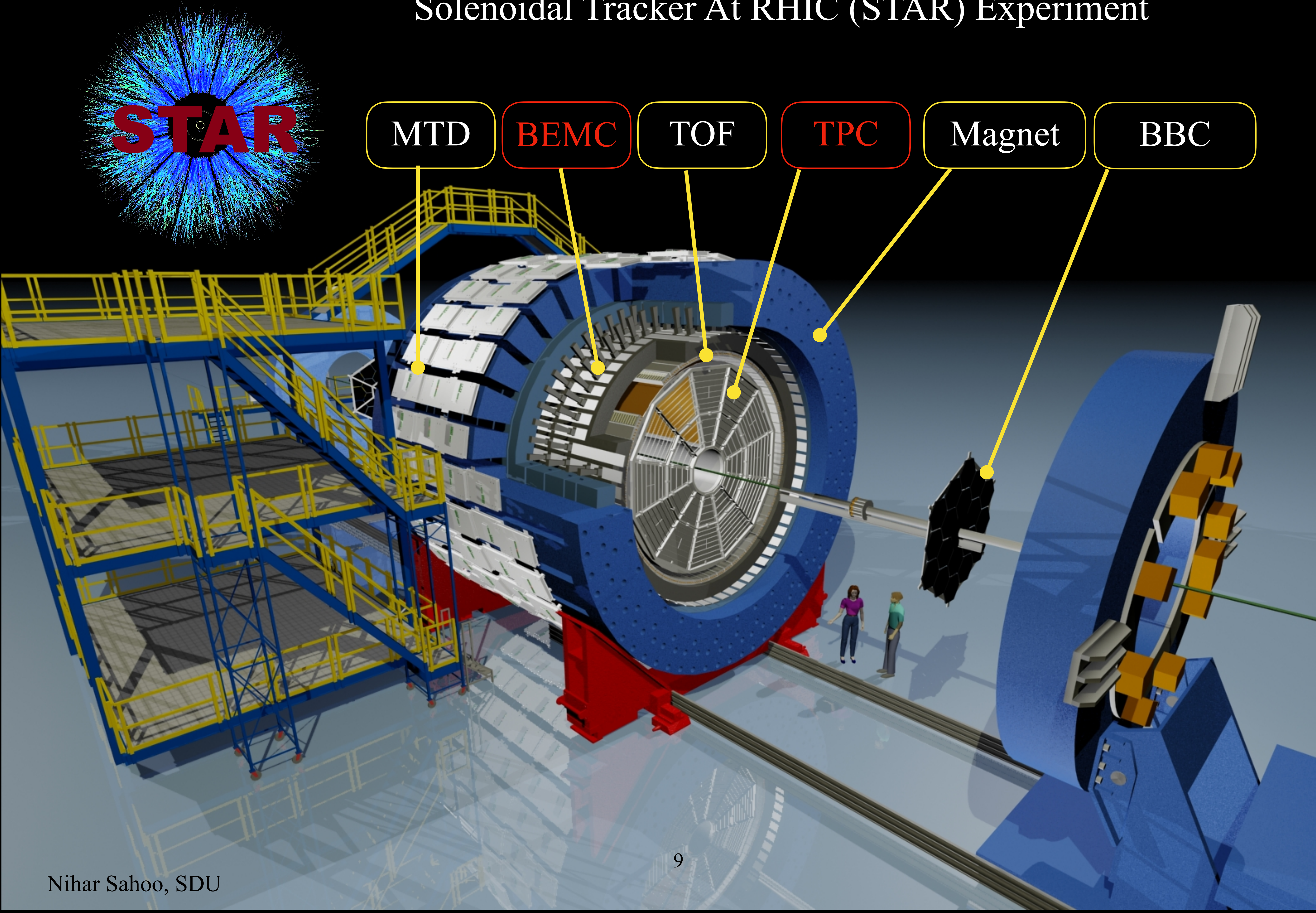
Using STAR BEMC/ SMD detector and shower shape analysis technique, both γ +jet and π^0 +jet can be studied.

Comparison between γ+jet and π^0/hadron+jet [trigger bias]

q/g recoil jets (C_A/C_F = 9/4) and vary recoil mean path length

Two challenges in this measurement:
1) γ/π^0 discrimination and 2) measurement of recoil jet

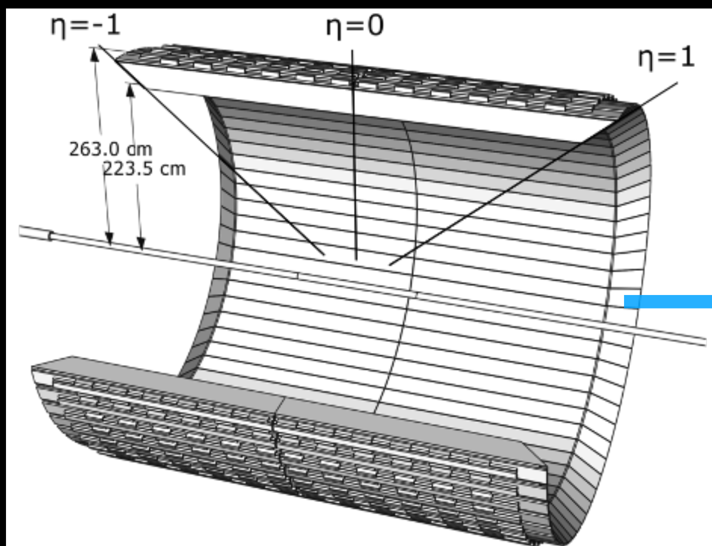
Solenoidal Tracker At RHIC (STAR) Experiment

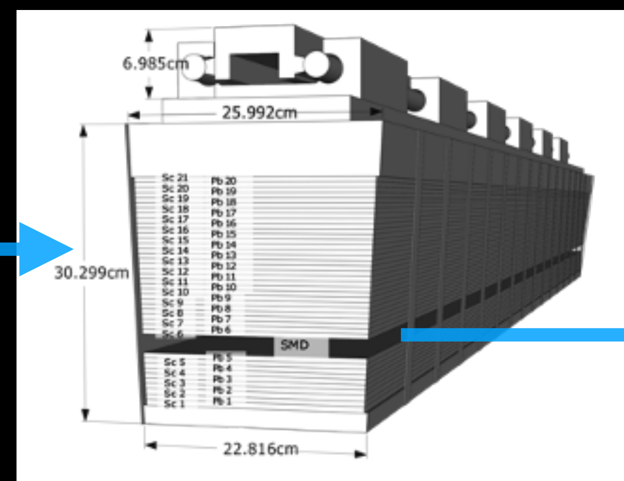


γ identification in STAR experiment at RHIC

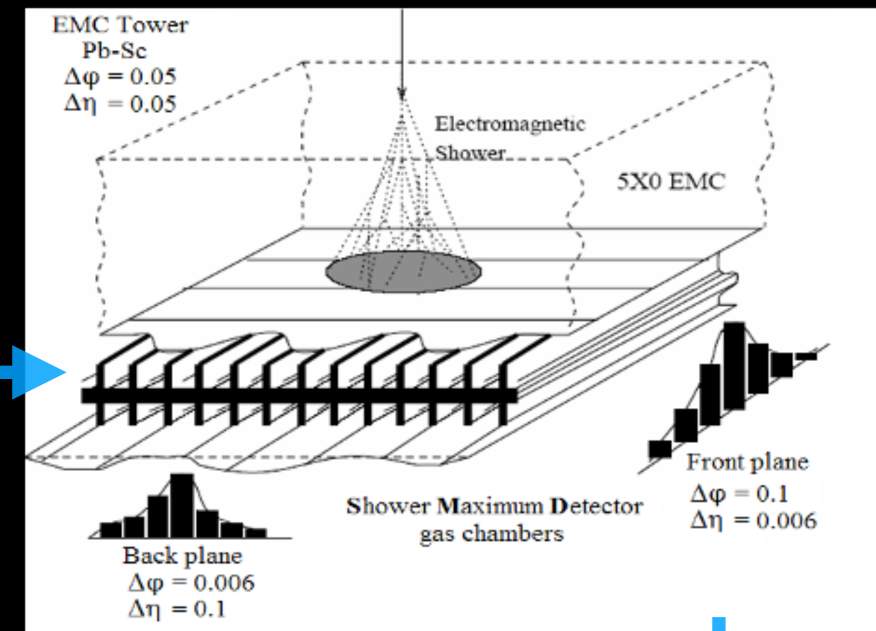
γ/π^0 identification technique

STAR Calorimeter detector



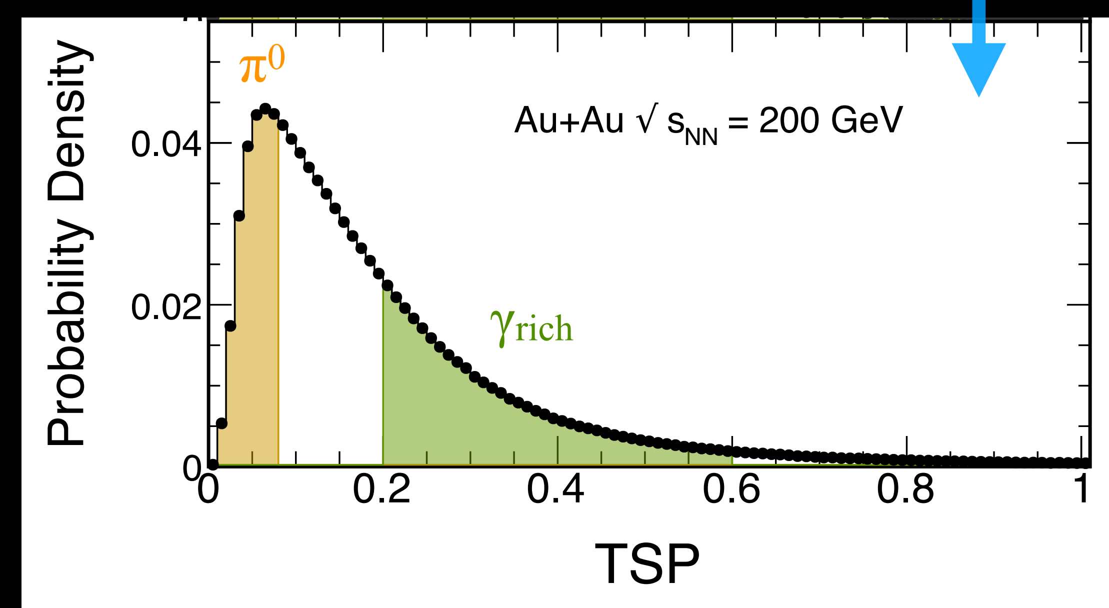


Shower maximum detector (SMD)



- Special online trigger to identify photon-like cluster in BEMC (L2gamma)
- Clustering algorithm using calorimeter detector system and method to discriminate π^0/γ at high-p_T

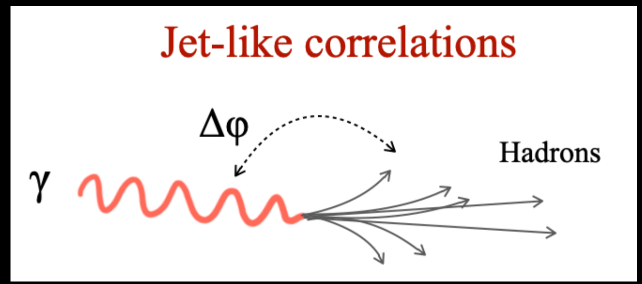
$$\mathrm{TSP} = \frac{E_{\mathrm{cluster}}}{\sum_i r_i e_i^{1.5}}$$



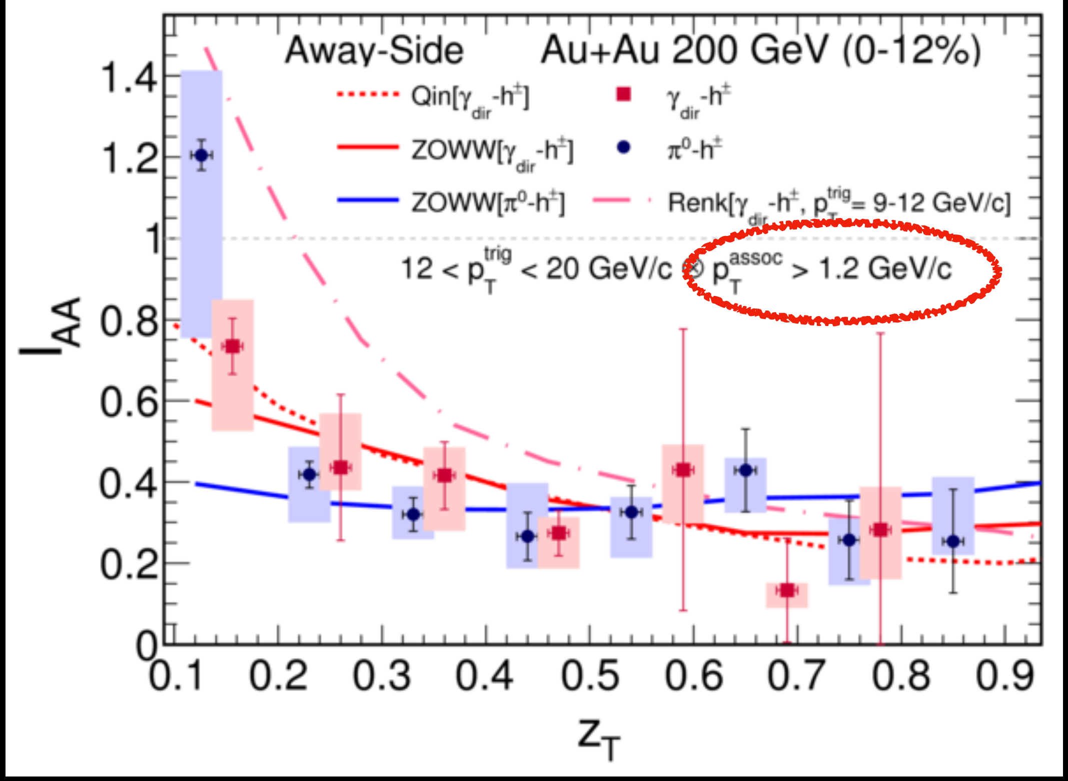
Jet-induced medium excitation in QGP

Experimental observation

$$I_{AA} = \frac{D(z_T)^{AuAu}}{D(z_T)^{pp}}$$



STAR: PLB 760 (2016) 689



γ+hadrons: Strong suppression at high z_T

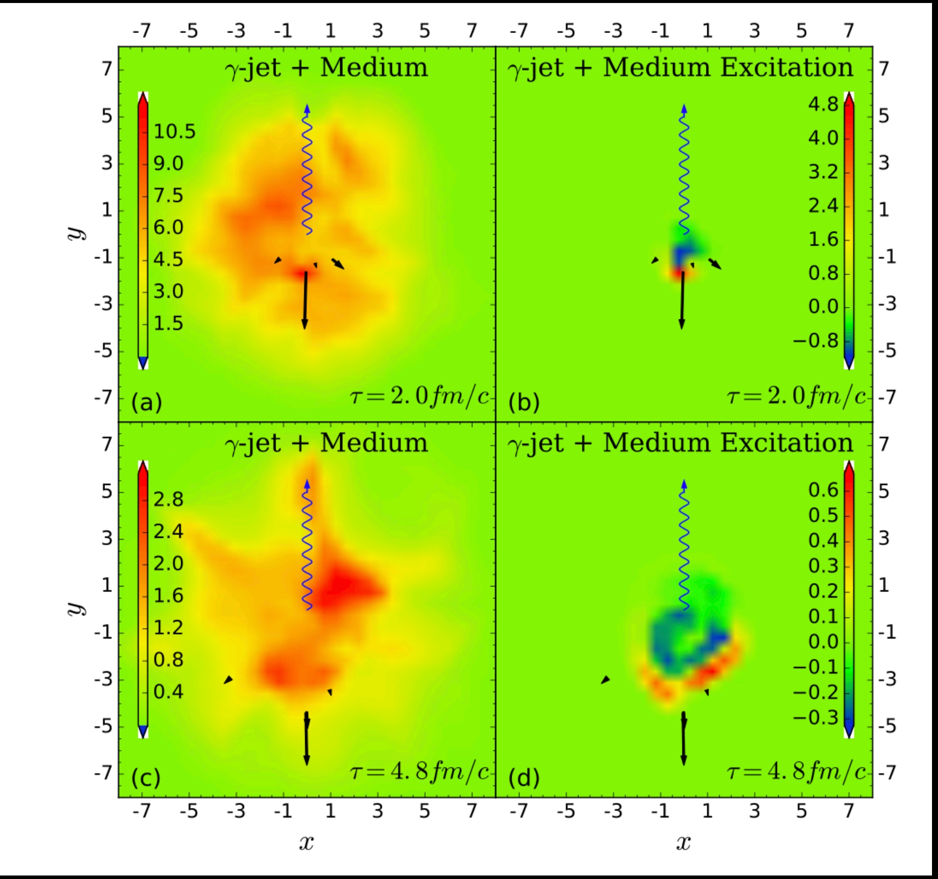
Challenge: How can we study soft-gluon radiations?

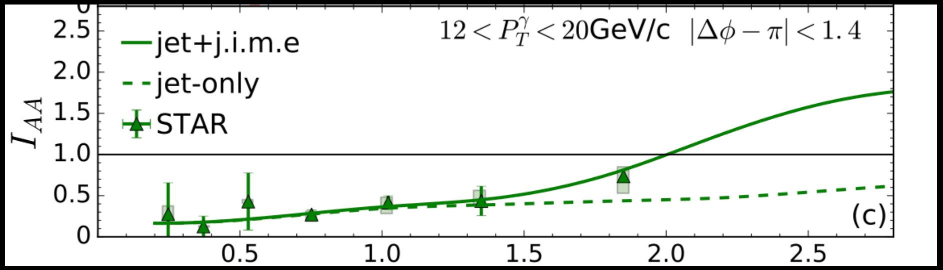
Hadron observables are frag. bias; for unbiased measurement → Need to reconstruct jet)

Theoretical development (CoLBT-hydro)

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

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





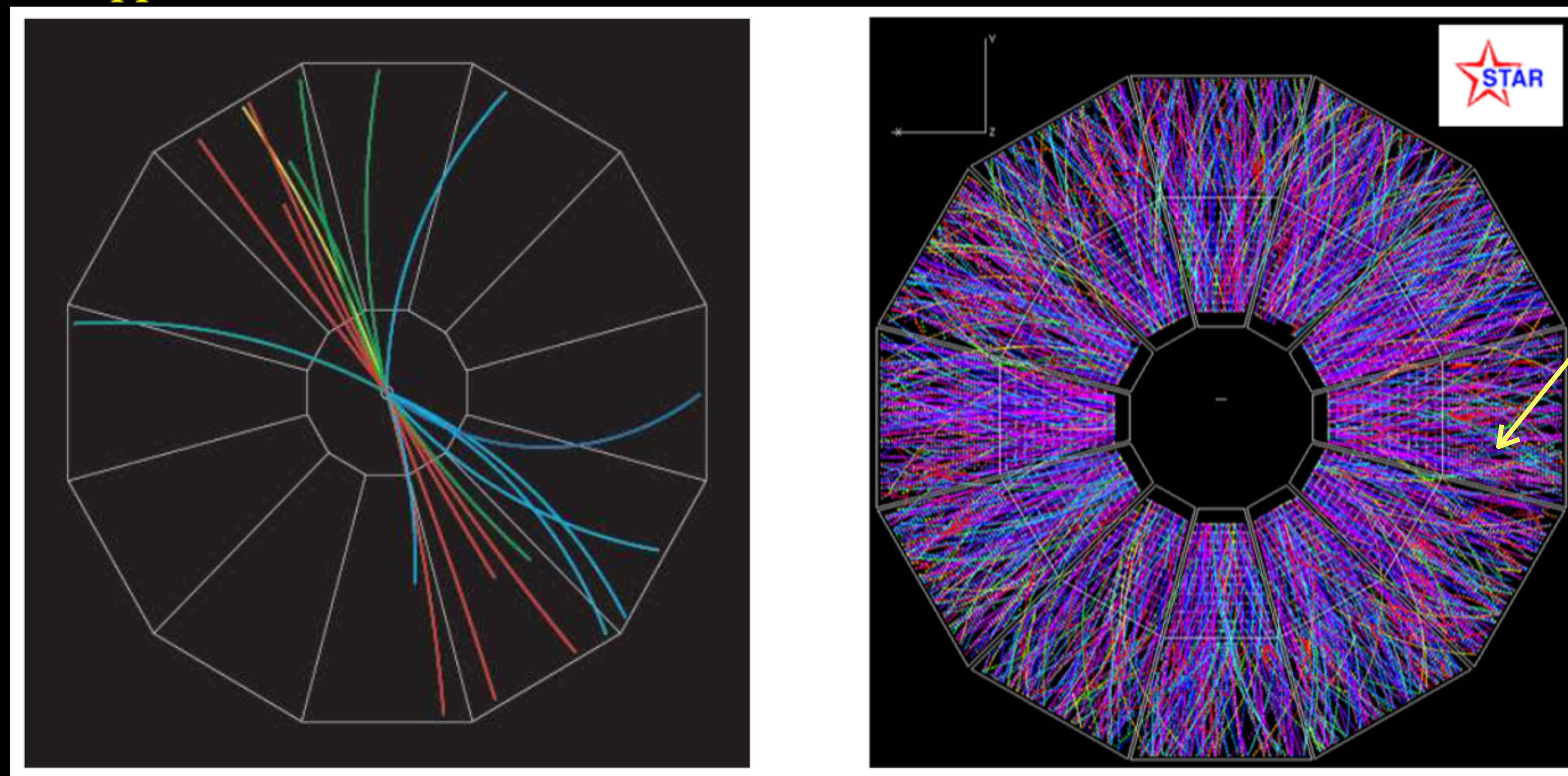
Wake

Depletion of soft hadrons in γ direction

→ Diffusion wake left behind by the jet in QGP

Uncorrelated background in Heavy-ion collisions

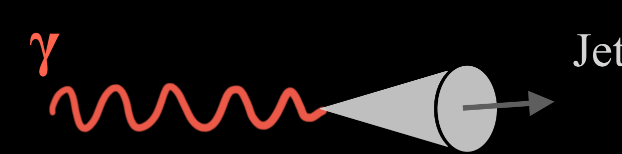
pp collisions at 200 GeV | AuAu collisions at 200 GeV

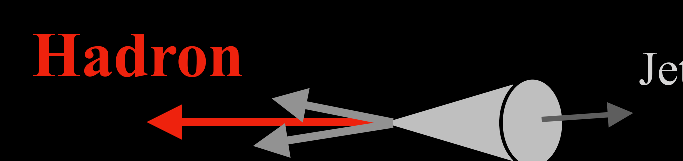


Uncorrelated background

$p + p \rightarrow \mathrm{jet} + \mathrm{jet}$ | $\mathrm{Au} + \mathrm{Au} \rightarrow \mathrm{X}$

Uncorrelated jet background effects:
i) jet yield → Mixed event subtraction
ii) jet pt-smearing → Unfolding procedure





Semi-inclusive distributions of charged jets recoiling from high p_T γ and π^0/hadron

Uncorrelated background jet yield correction in HIC

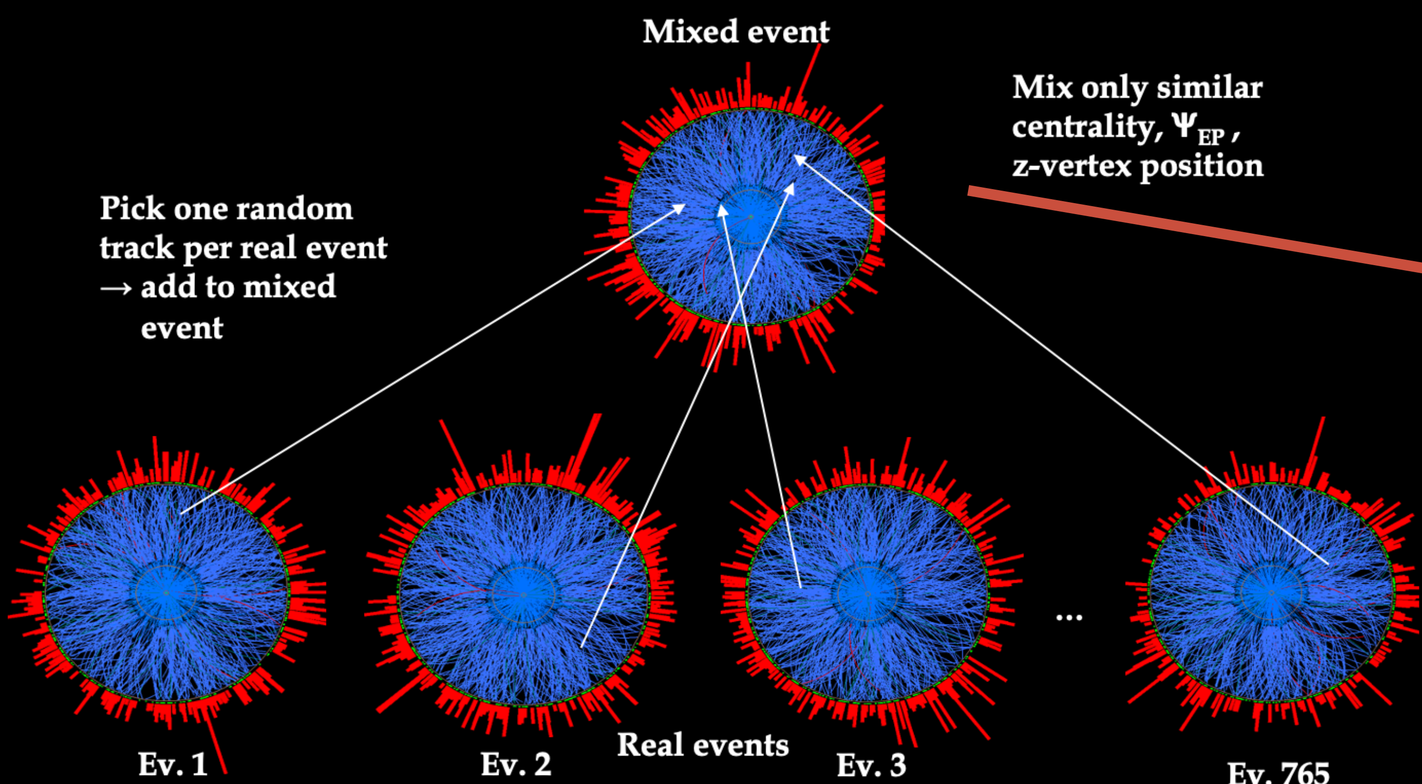
Semi-inclusive recoil jets: $$\frac{1}{N_{trig}} \cdot \frac{dN_{jet}}{dp^{ch}_{T,jet}}\Bigg|_{p_T^{trig}} = \left(\frac{1}{\sigma^{A+A\to trig}} \cdot \frac{d\sigma^{A+A\to trig+jet}}{dp^{ch}_{T,jet}}\right)\Bigg|_{p^{ch}_{T,jet}}$$

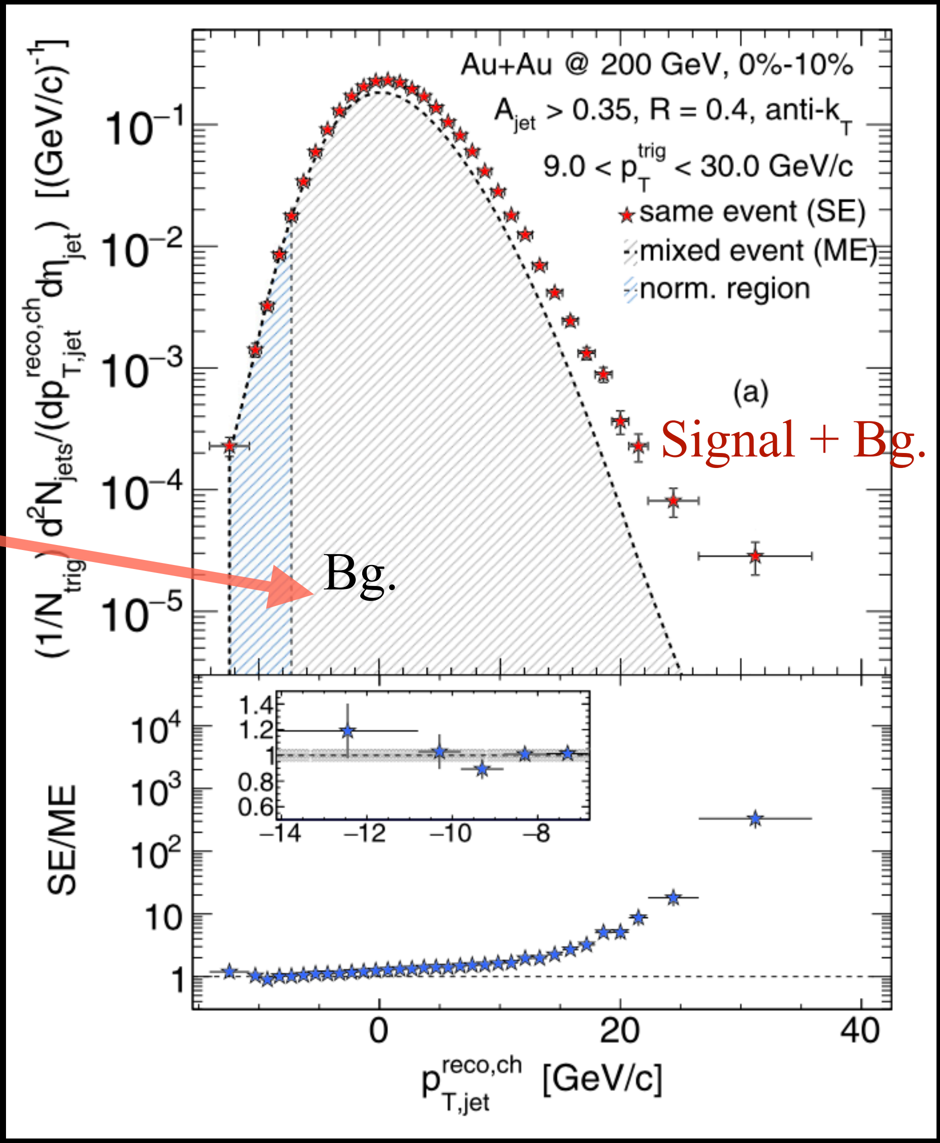
Trigger particle → γ / π^0 / ch. hadron

STAR: PRC 96 (2017) 024905

Uncorrelated background: mixed events

STAR Collaboration,
Phys. Rev. C 96 (2017), 024905

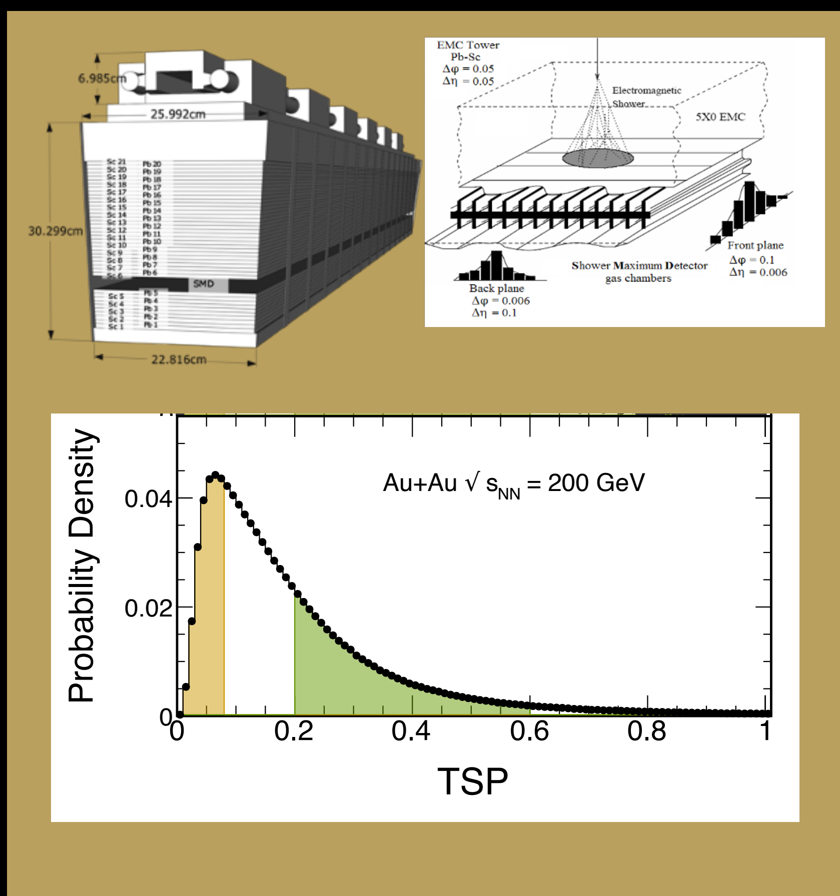




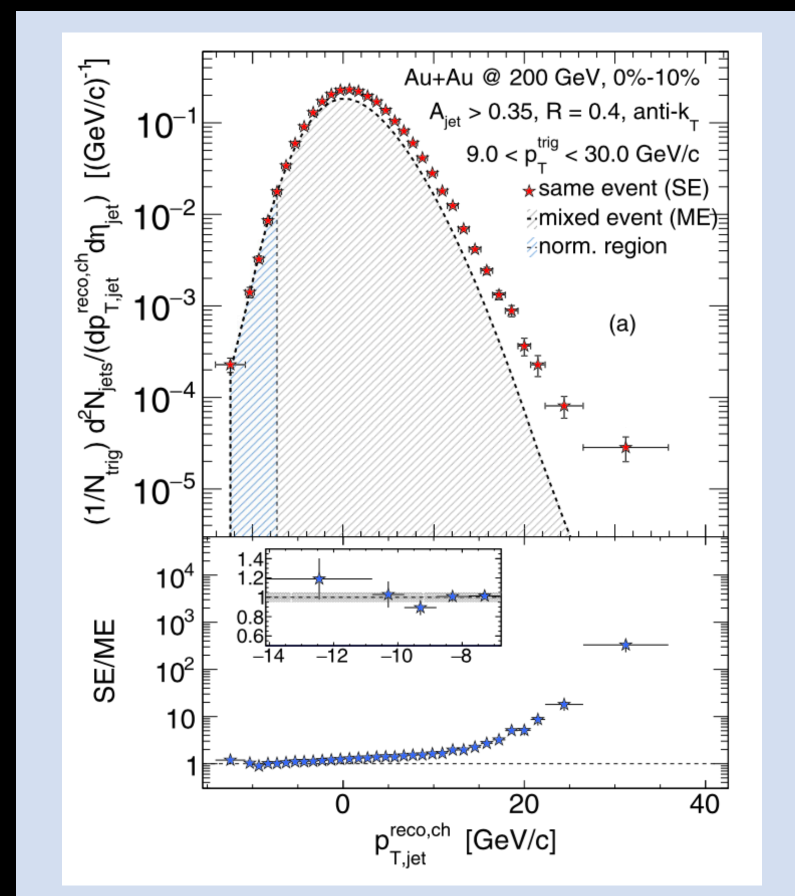
Data-driven method to correct for uncorrelated jet backgrounds

Semi-inclusive γ+jet measurement at RHIC

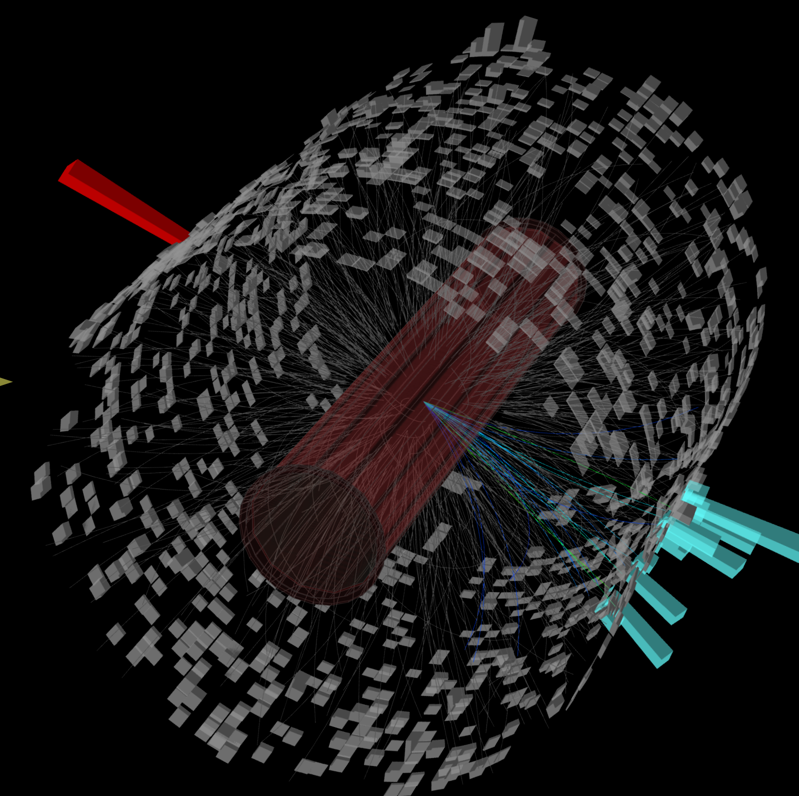
Method to discriminate
π^0/γ at high-p_T



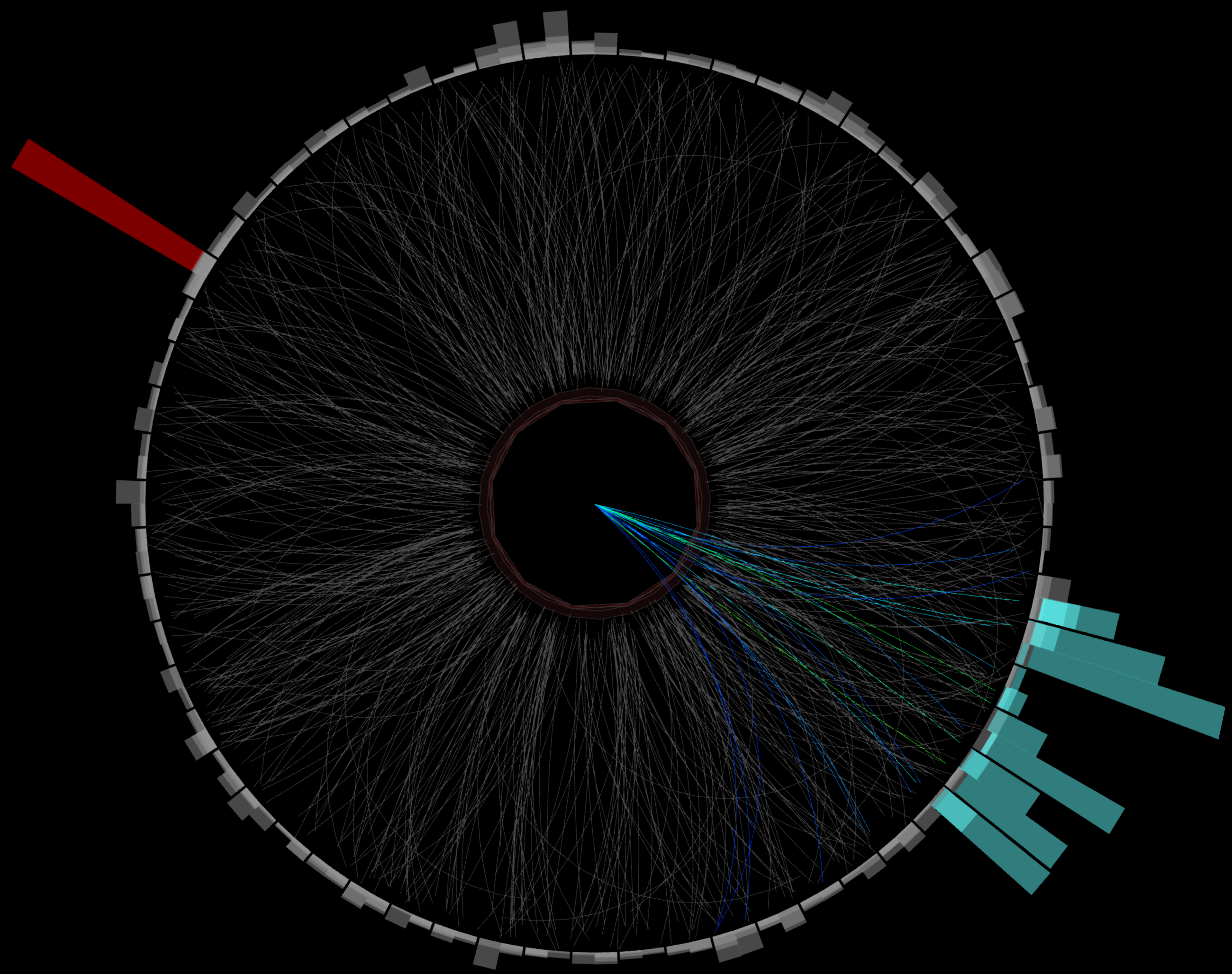
Data-driven method to correct
uncorrelated jet background yield

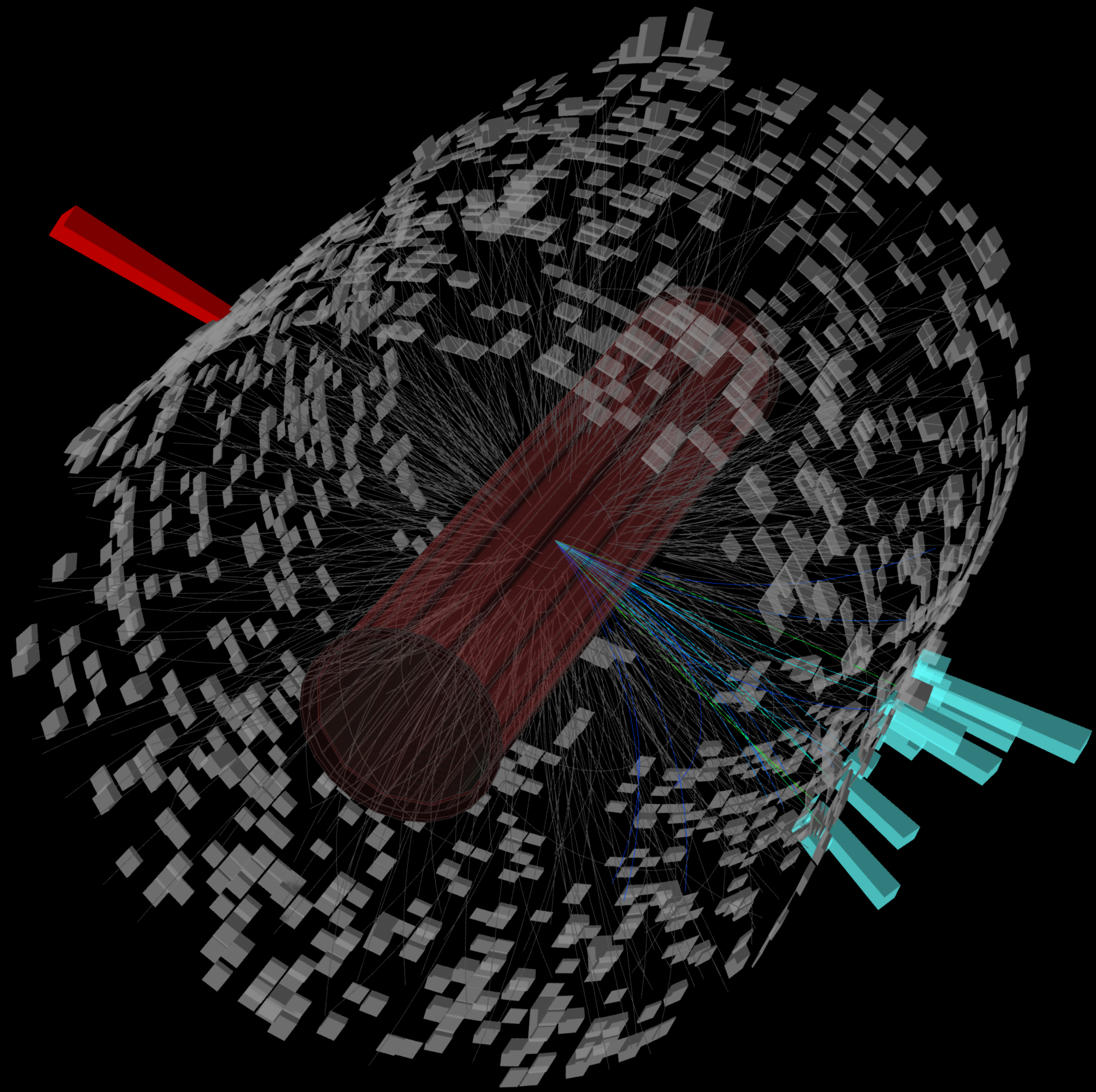


Semi-inclusive γ+jet
measurement in STAR



γ + jet event-display in Au+Au collisions





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
p_T^{jet} = 13.2 GeV/c

This talk: charged-particle recoil jets
Full jet analysis TBD

γ+jet and h+jet measurements in STAR and corrections

Au+Au (2014): 13 nb^{-1} ; p+p (2009): 23 pb^{-1}

- Trigger E_T ranges:

  γ trigger: 9-11, 11-15, 15-20 GeV

  π^0 trigger: 9-11, 11-15 GeV

- Jet resolution parameter R = 0.2 and 0.5

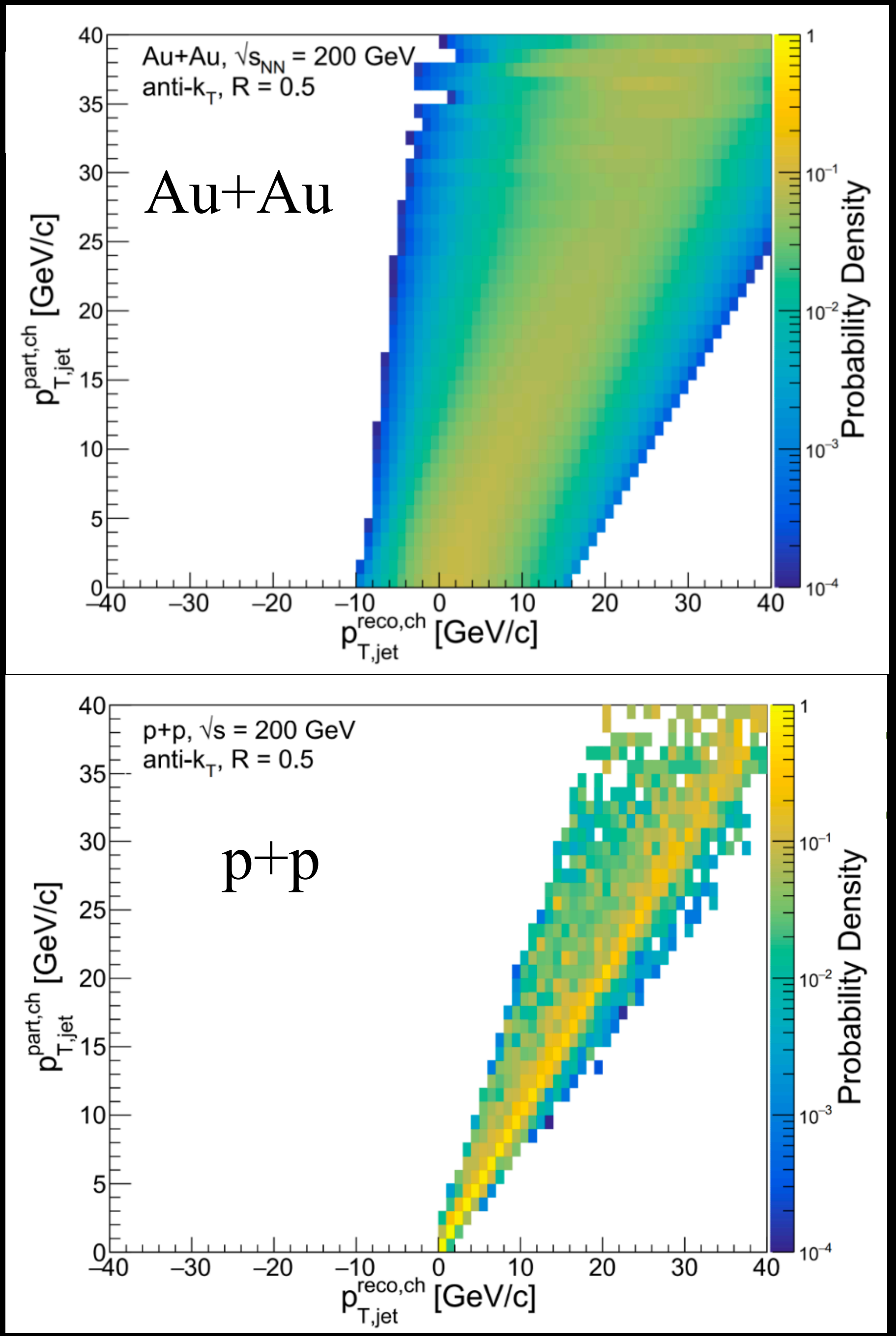
- p_T-smearing correction:
  - Event-by-event correction:

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

$$\rho = \mathrm{median}\{\frac{p_{\mathrm{T,jet}}^{\mathrm{raw}}}{A_{\mathrm{jet}}}\} ;$$

A: Area of the jet

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

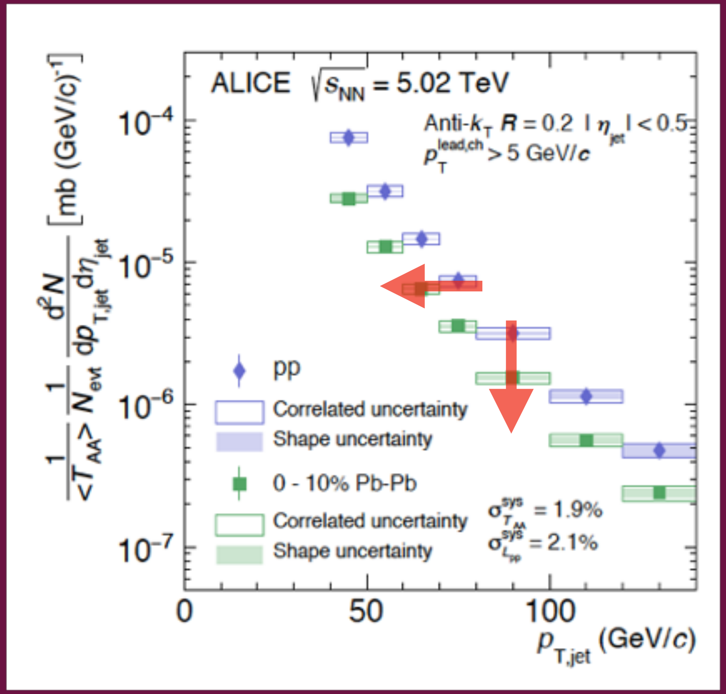


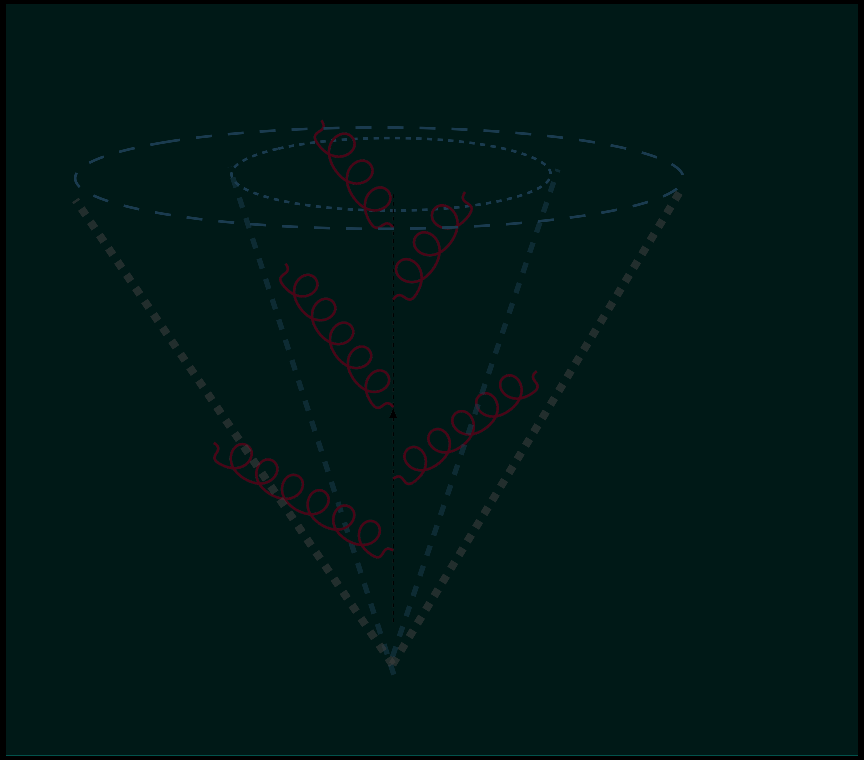
- Statistical and unfolding precisions are acutely related

What have we observed?

Consequences of jet quenching

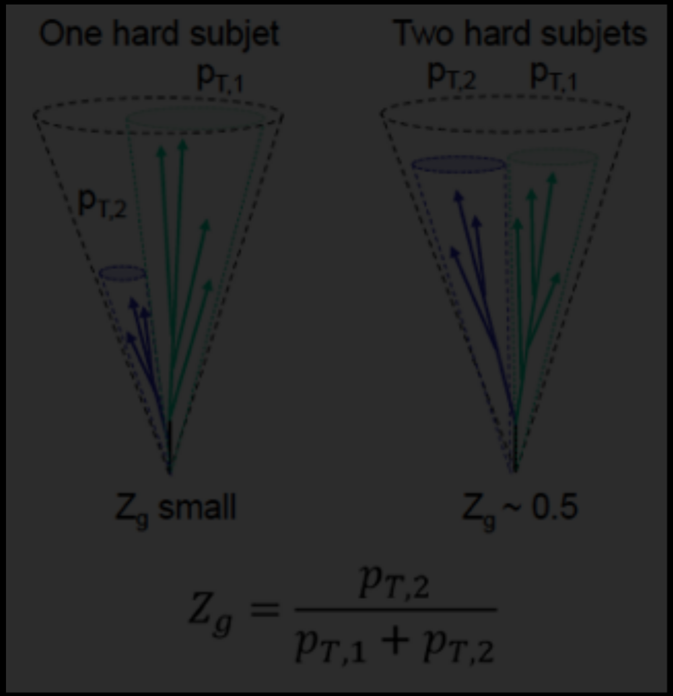
Energy loss

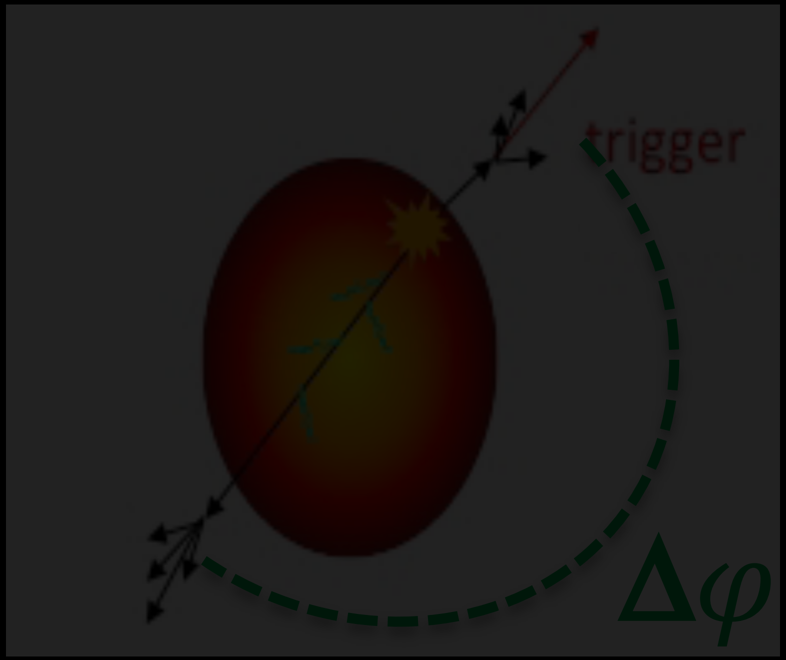




Large angle radiation

Modification of jet substructure



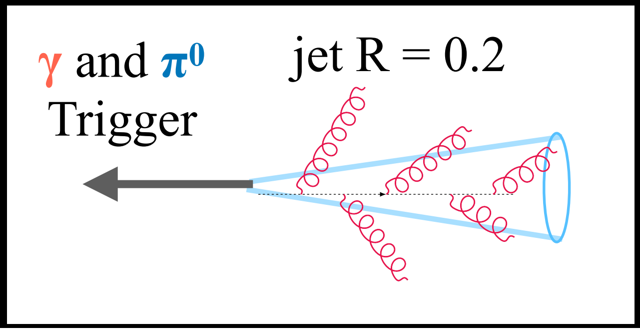


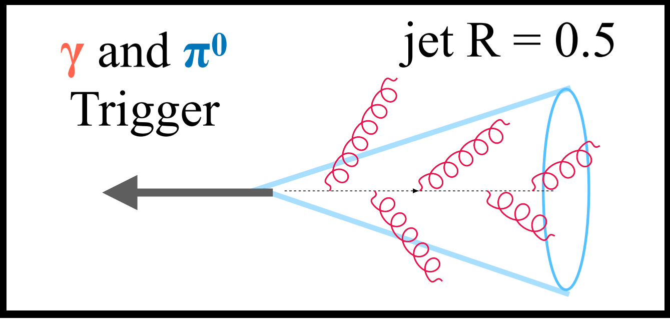
Jet deflection

Nihar Sahoo, SDU

Semi-inclusive recoil jet suppression in Au+Au relative to p+p: I_{AA}

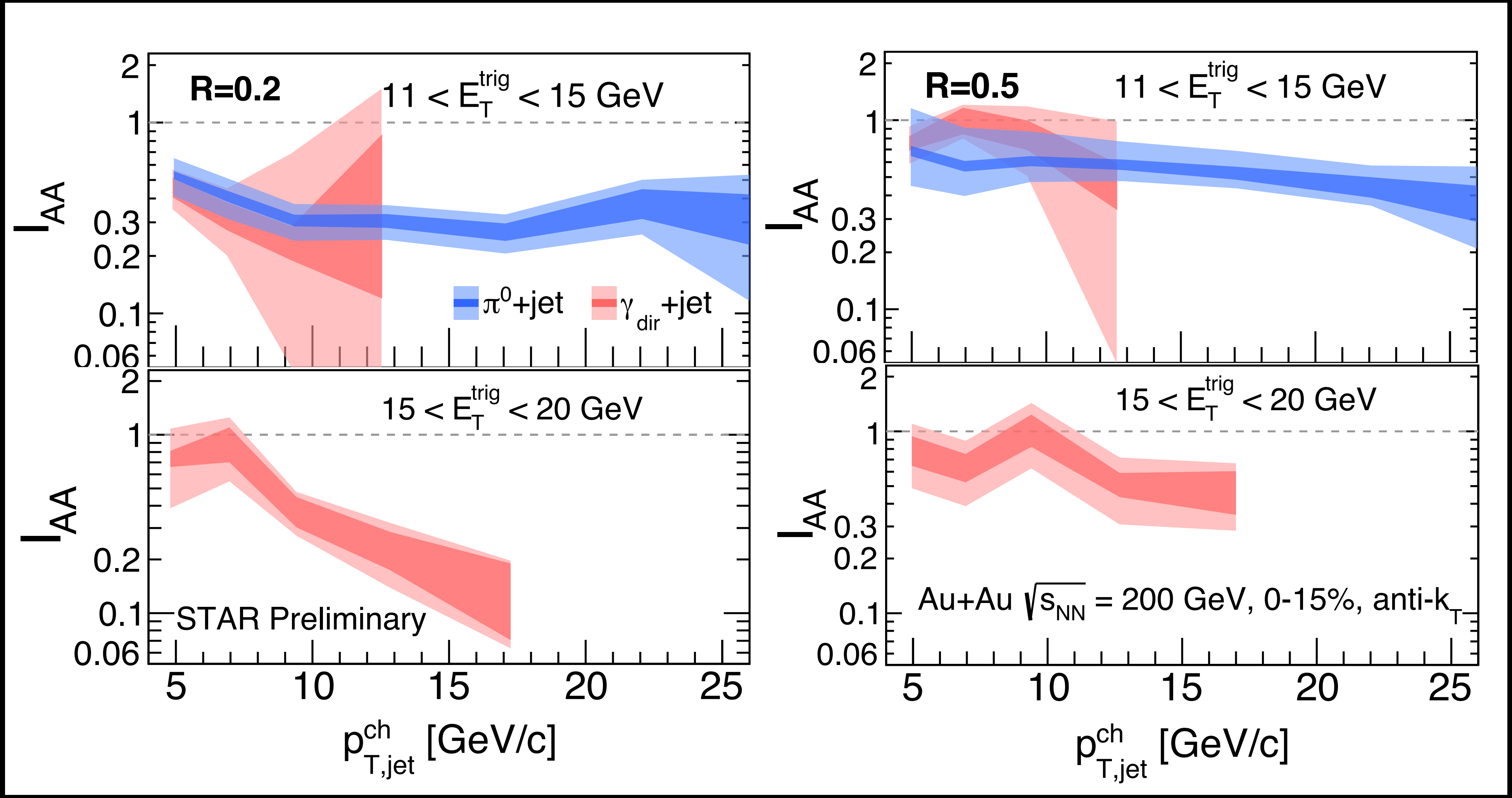
QM2022: Derek Anderson





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

p+p data are used for vacuum reference

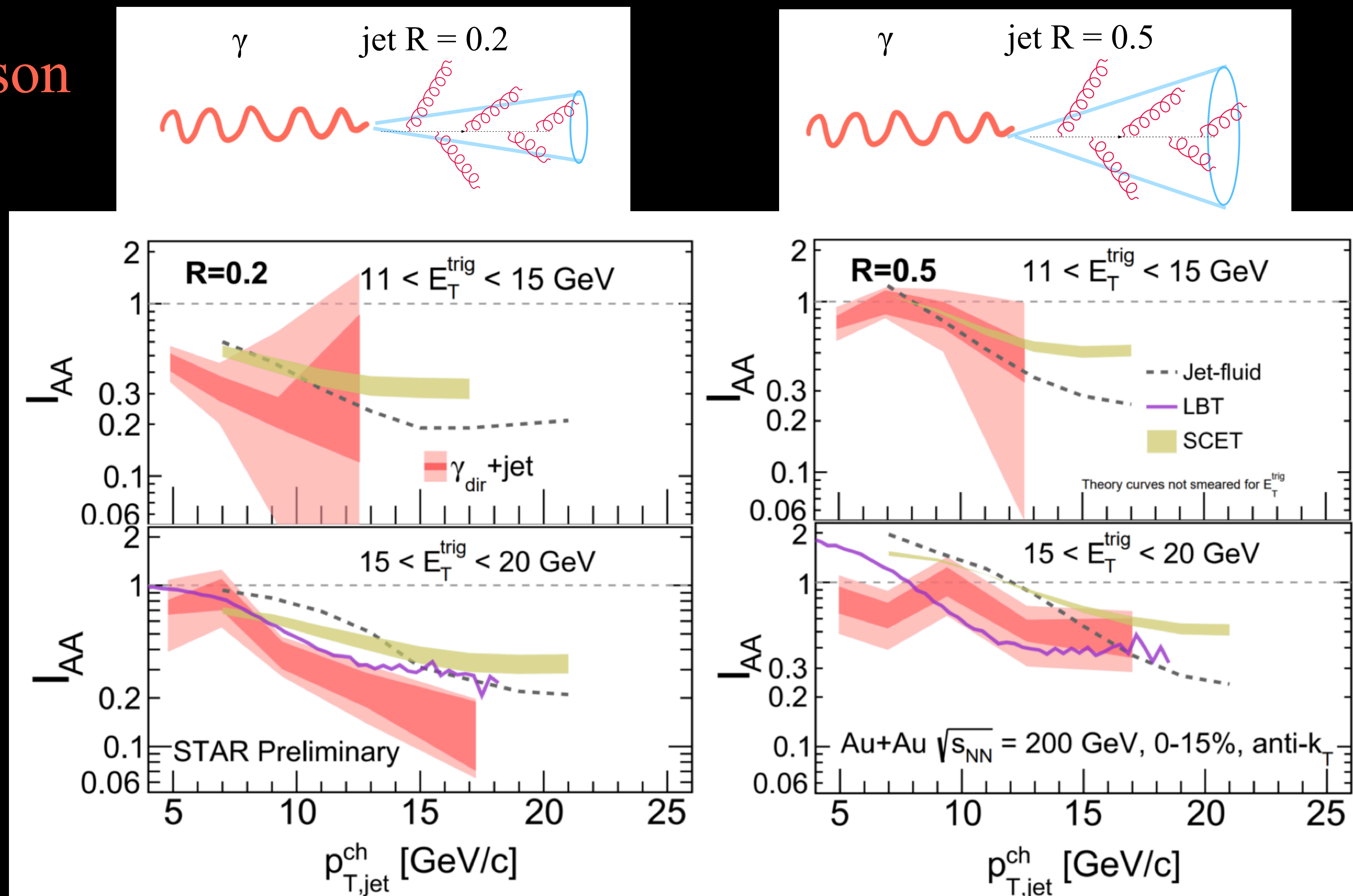


Recoil jets with smaller jet R more suppressed than large R

γ+jet and **π⁰+jet** I_{AA} are consistent within uncertainties

Semi-inclusive recoil jet suppression in Au+Au relative to p+p: I_{AA}

Theory comparison



QM2022: Derek Anderson

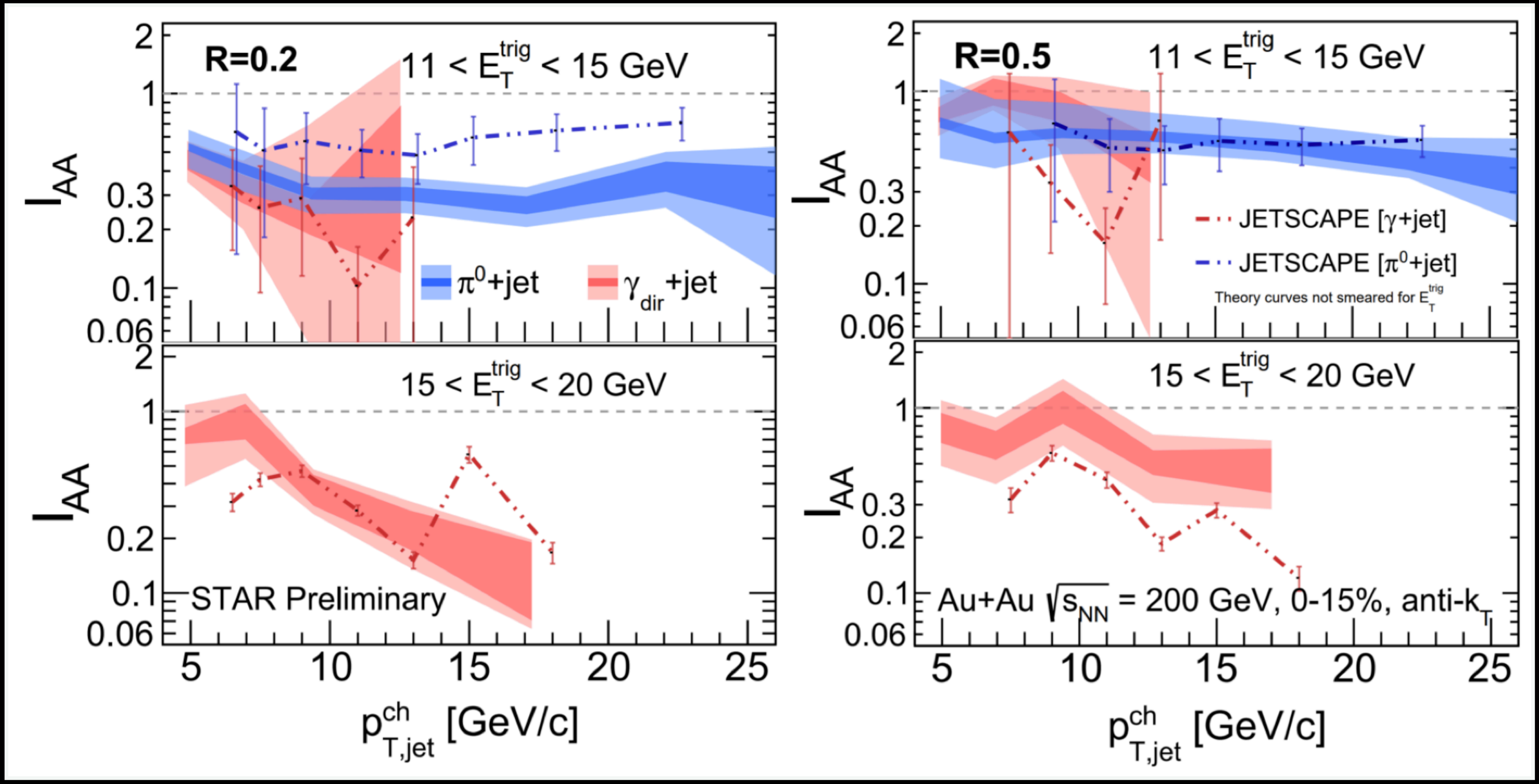
Theory curves follow p_T dependent trend.

Suppression magnitude differs some cases.

[Jet-Fluid] N.-B. Chang, G.-Y. Qin, PRC **94**, 024902 (2016)
[LBT] T. Luo, S. Cao, Y. He, X.-N. Wang, PLB **782**, 707 (2018)
[SCET] M. D. Sievert, I. Vitev, and B. Yoon, PLB **795**, 502 (2019)

Semi-inclusive recoil jet suppression in Au+Au relative to p+p: I_{AA}

JETSCAPE comparison



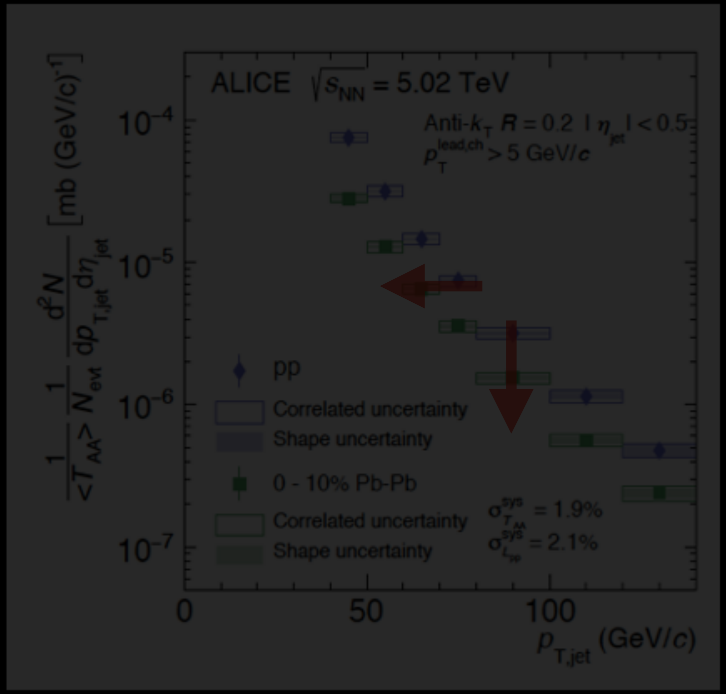
JETSCAPE: Need more statistics for better comparison

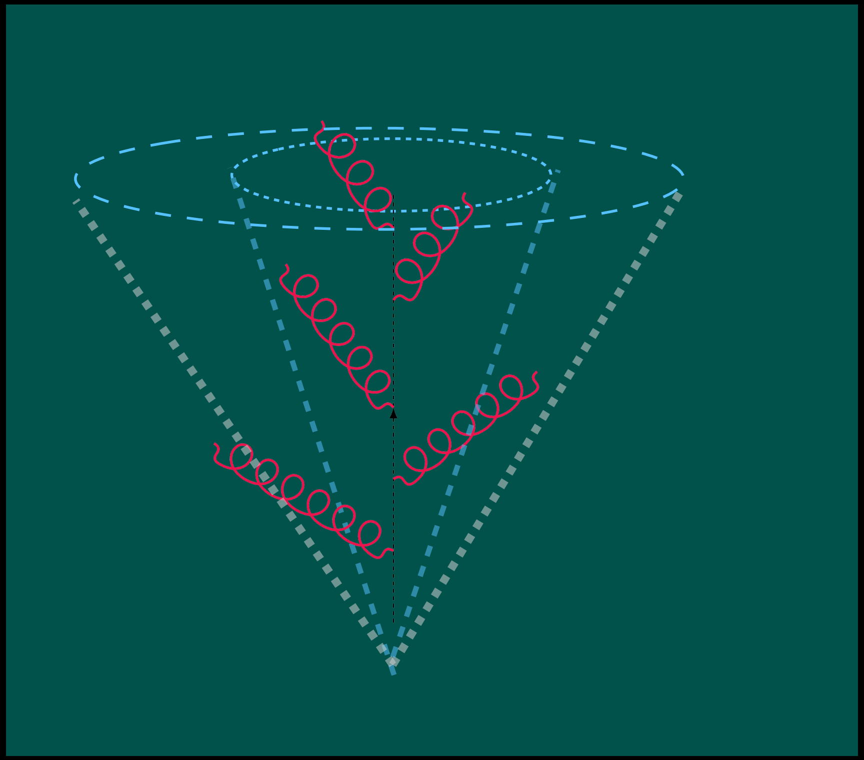
Thanks to Chathuranga and Abhijit for JETSCAPE calculation.

QM2022: Derek Anderson

Consequences of jet quenching

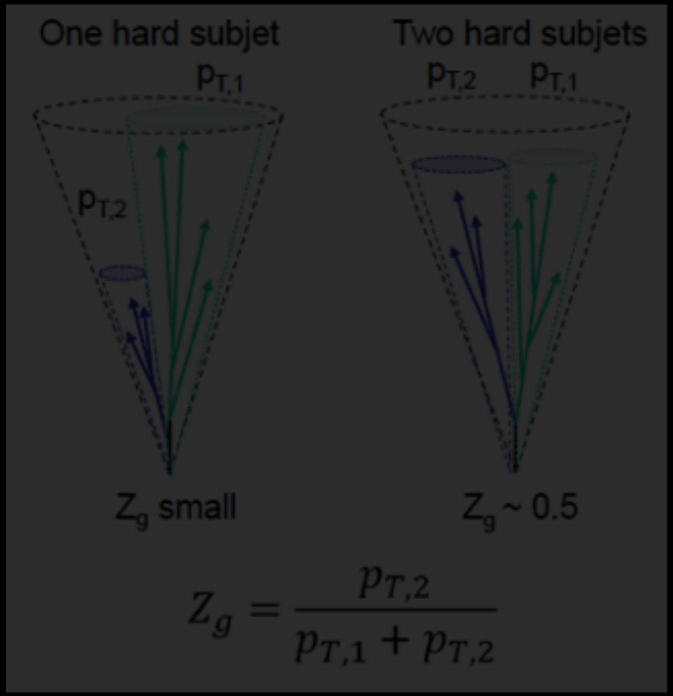
Energy loss

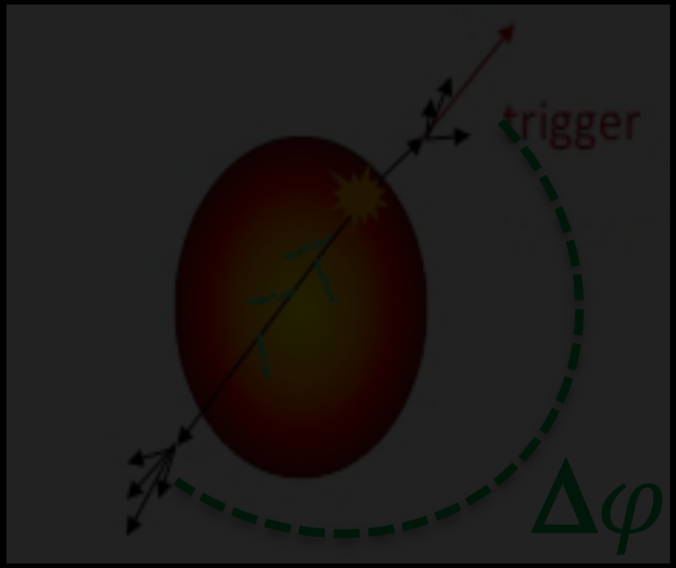




Large angle radiation

Modification of jet substructure

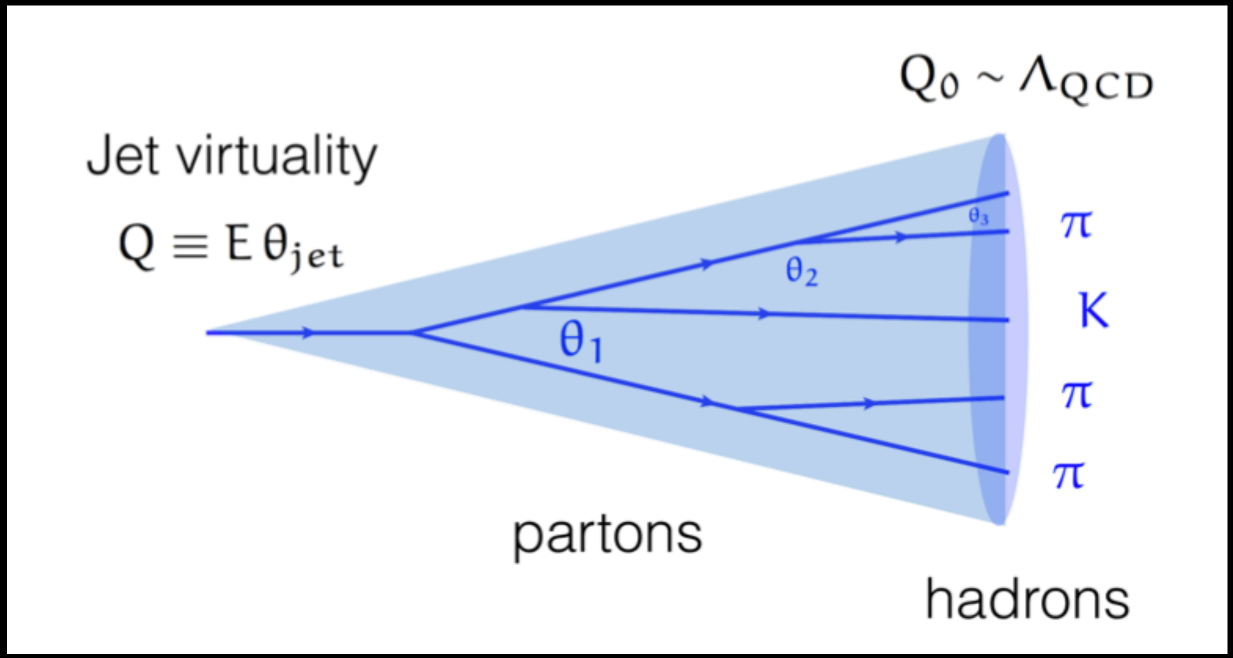




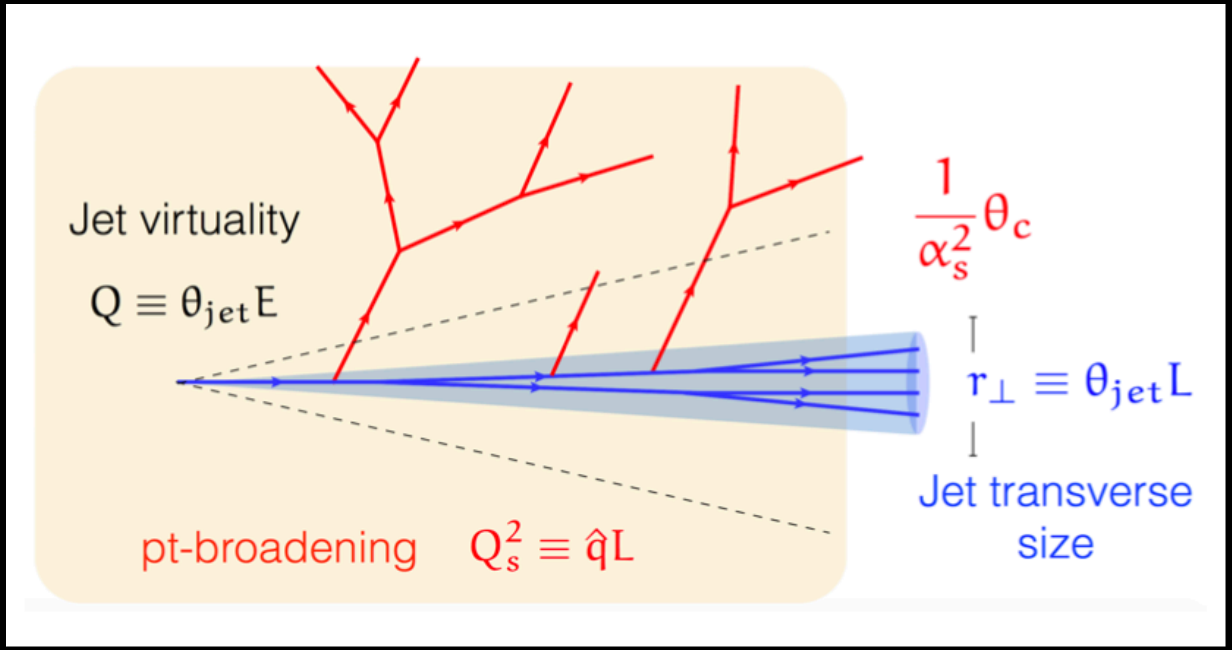
Jet deflection

R-dependence of jet yield: jet shape modification

Vacuums parton shower



Medium-induced gluon radiation



Yacine Mehtar-Tani, arXiv: 1602.01047

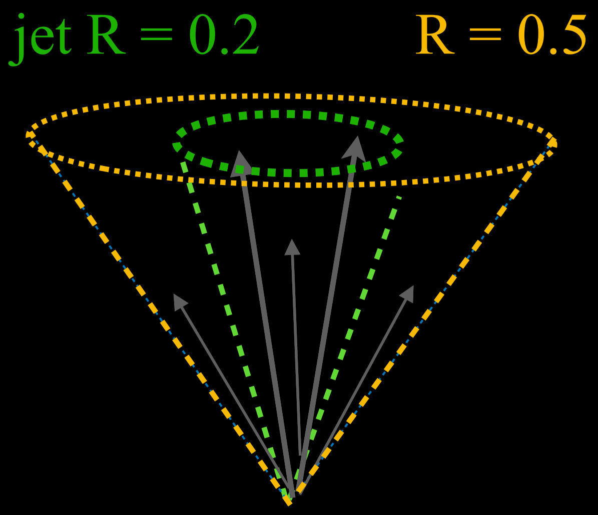
Simultaneous effect of vacuum shower and medium-induced gluon radiation

Jet shape: spread of energy inside a jet

Strategy:

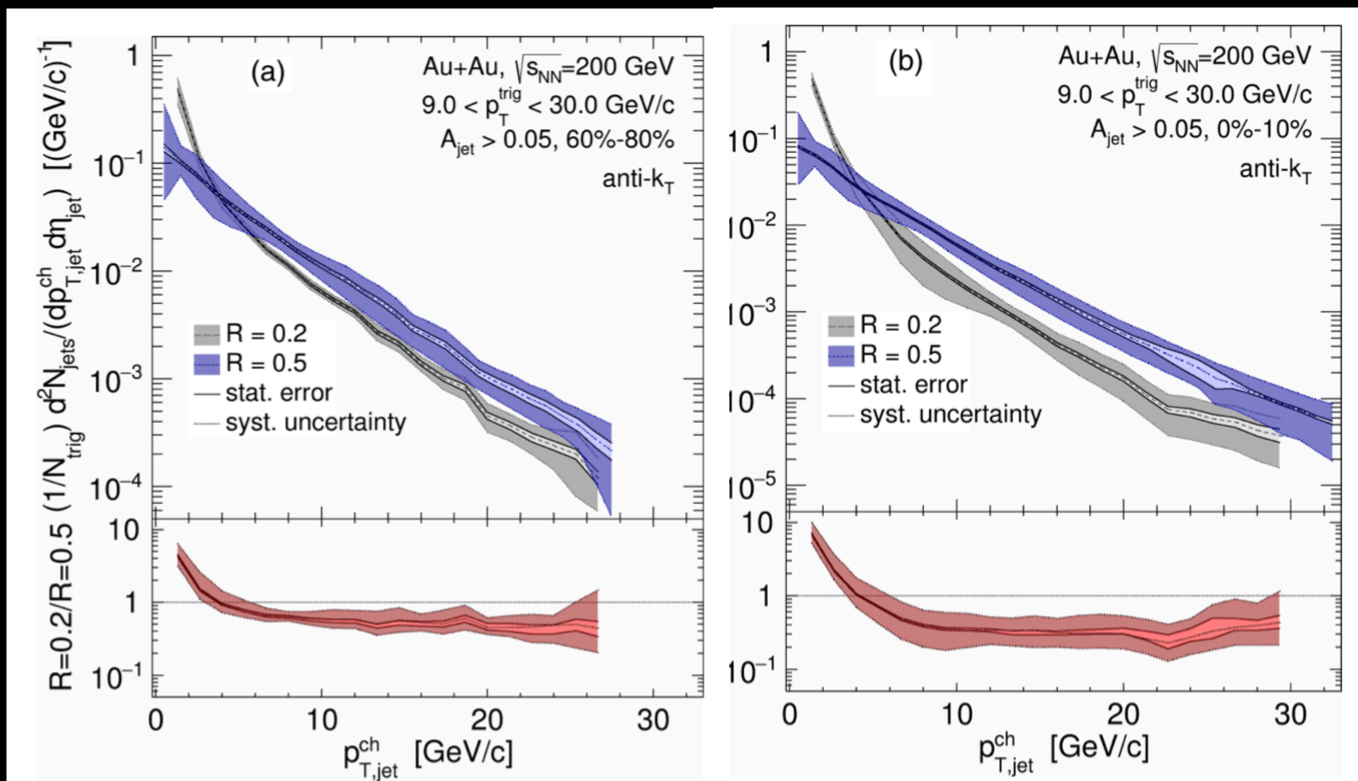
- Take jet yield ratio of smaller over large-R in the same system
- And compare with p+p and heavy-ion collisions

$$\mathfrak{R}^{\text{small}-R}_{\text{large}-R} = \frac{Y(p_T^{\text{jet,ch}})^{\text{small}-\text{R}}}{Y(p_T^{\text{jet,ch}})^{\text{large}-\text{R}}}$$

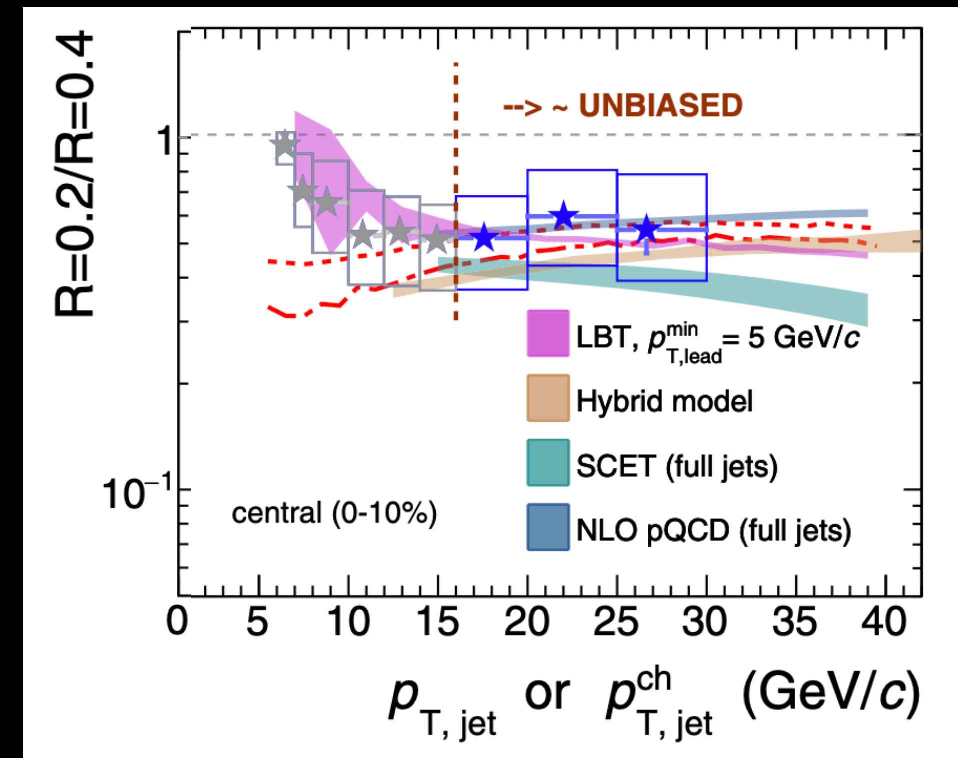


Jet shape modification: previous measurements

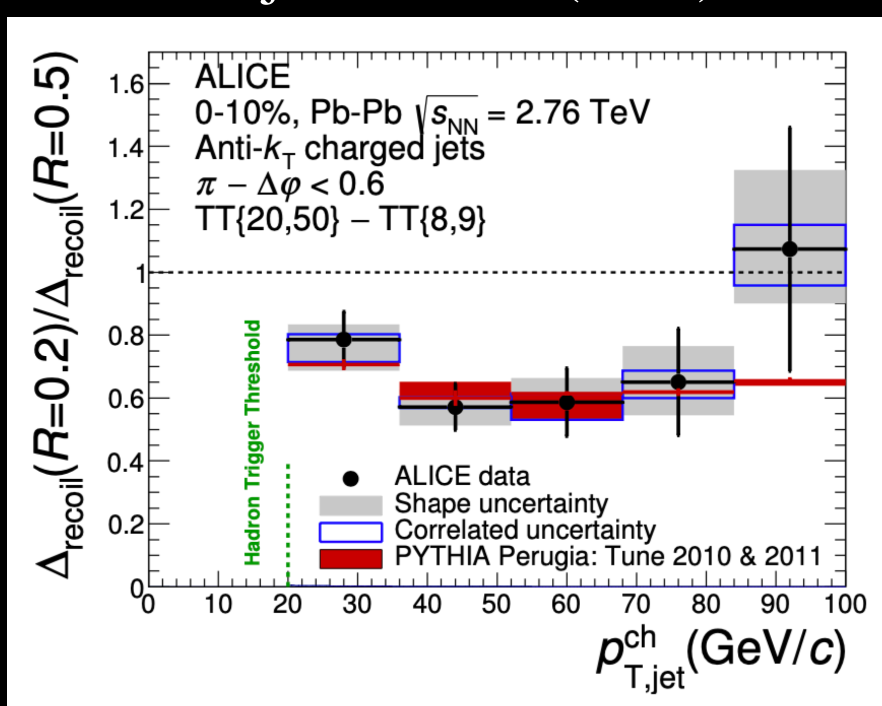
STAR semi-inclusive h+jet: PRC 96, 024905 (2017)



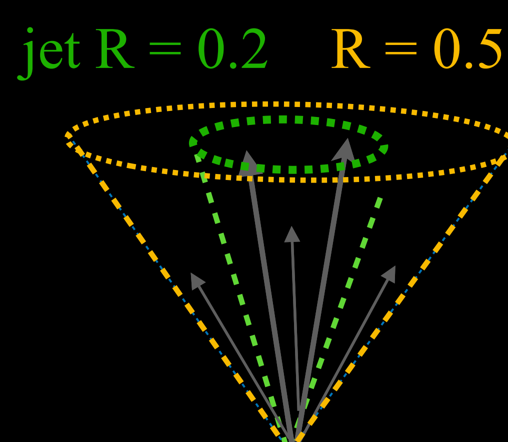
STAR Inclusive jet: PRC **102**, 054913 (2020)



ALICE h+jet : JHEP09(2015)170

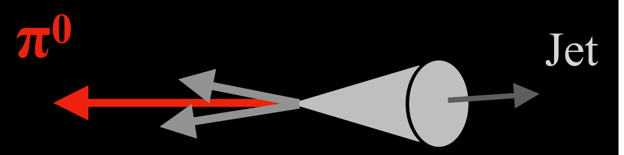


Jet-shape: spread of energy inside a jet

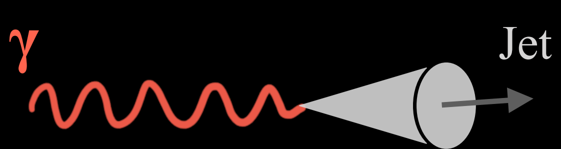


No clear indication of intra-jet broadening

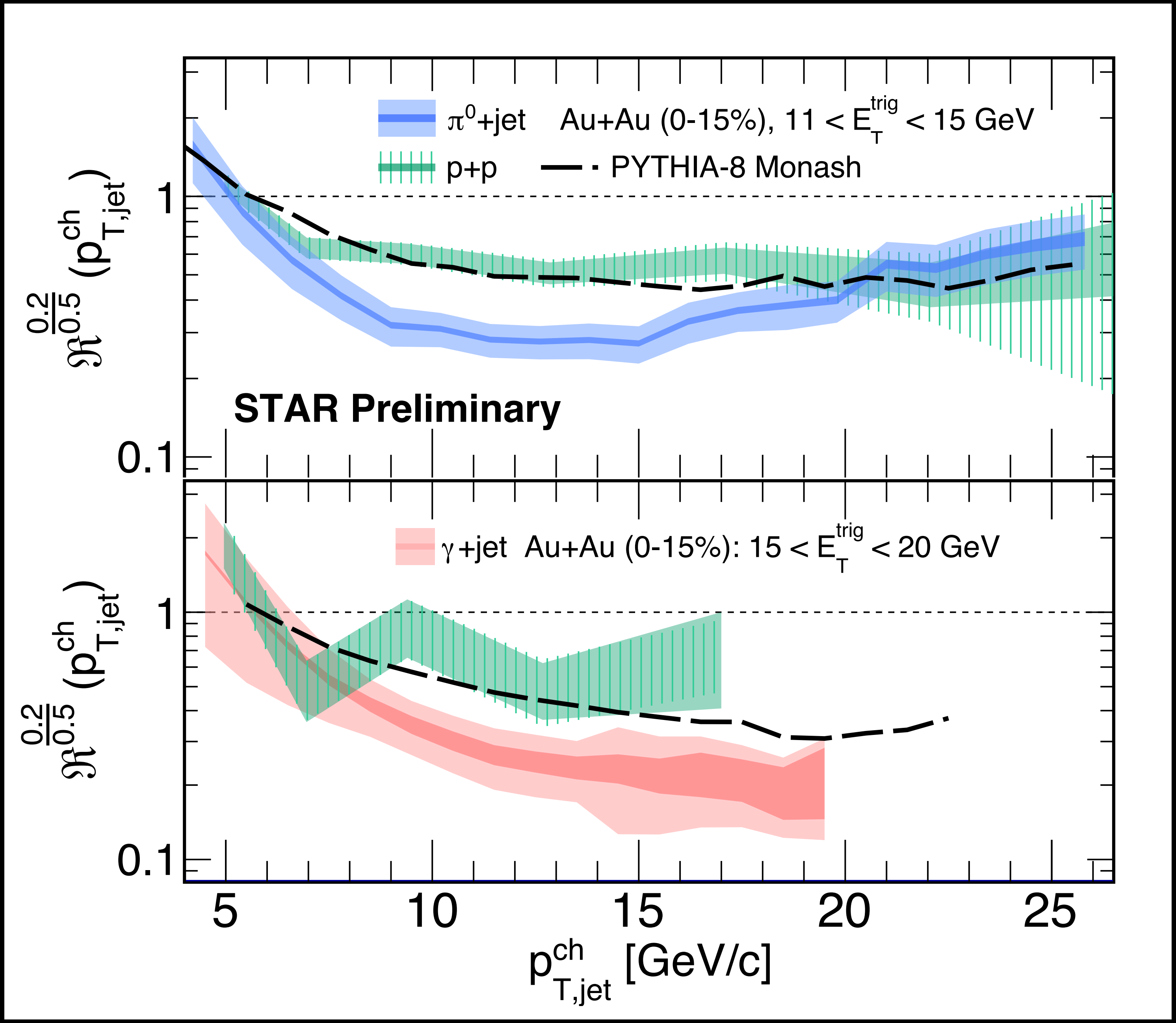
R-dependence of jet yield: jet shape modification in QGP



$$\mathfrak{R}^{\,\text{small}-R}_{\,\text{large}-R} = \frac{Y(p_T^{\text{jet,ch}})^{\text{small}-R}}{Y(p_T^{\text{jet,ch}})^{\text{large}-R}}$$

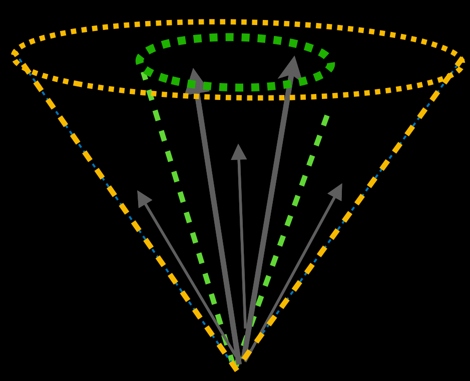


Derek Anderson, QM2022



Jet-shape: spread of energy inside a jet

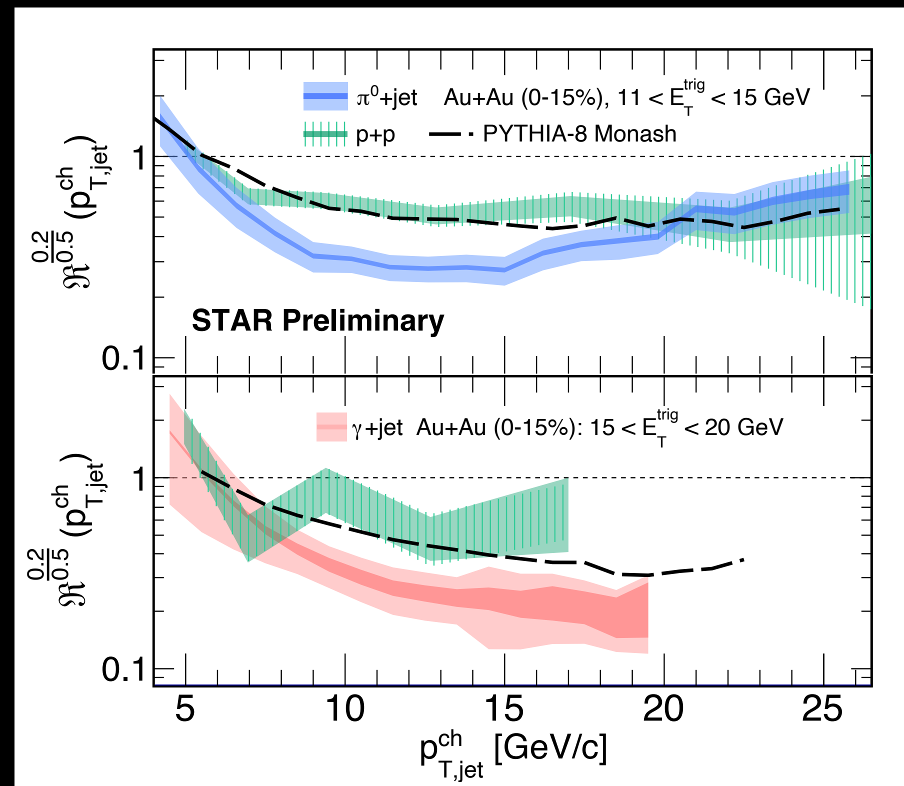
jet R = 0.2 R = 0.5

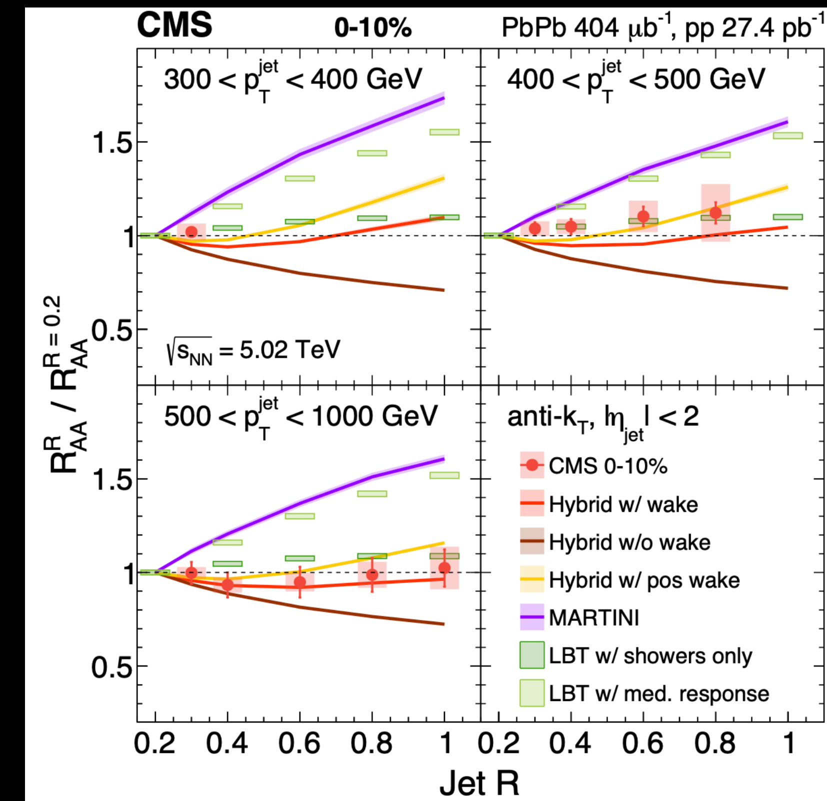


First indication of jet shape modification due to medium induced gluon radiations at RHIC

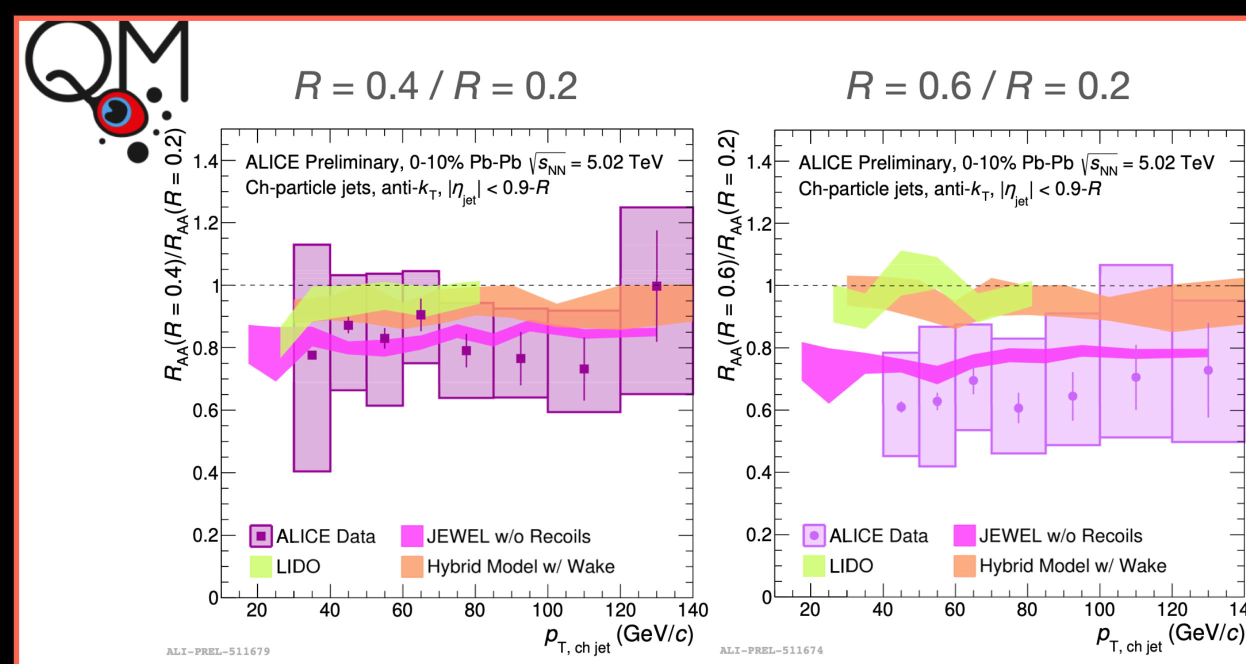
Jet R dependence of yield suppression

Both STAR and CMS:
Small R →more suppressed
Large R →Less suppressed





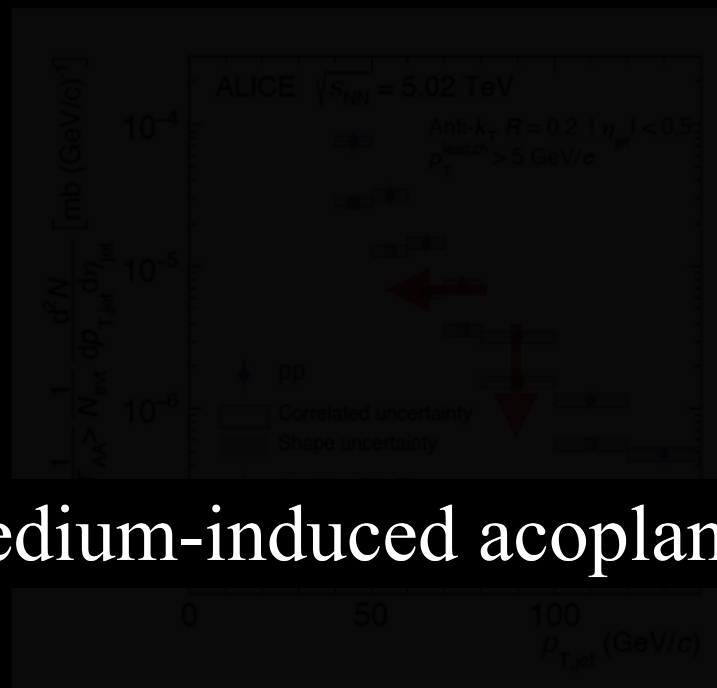
ALICE Inclusive jet using ML:
Large R → more suppressed

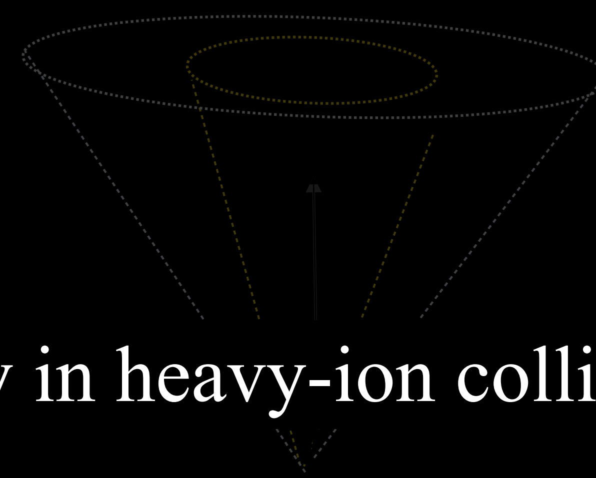


Different measurement biases and kinematic ranges. Consistent picture or tension?

Consequences of jet-quenching

Energy loss

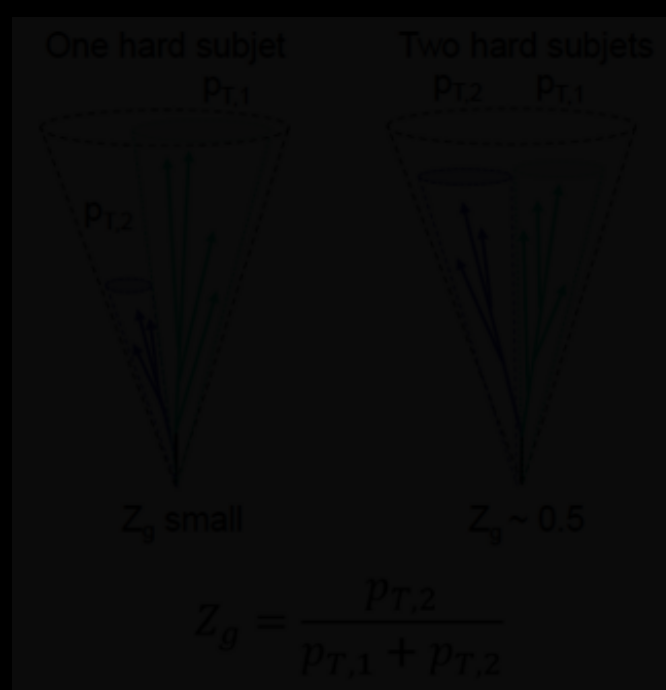


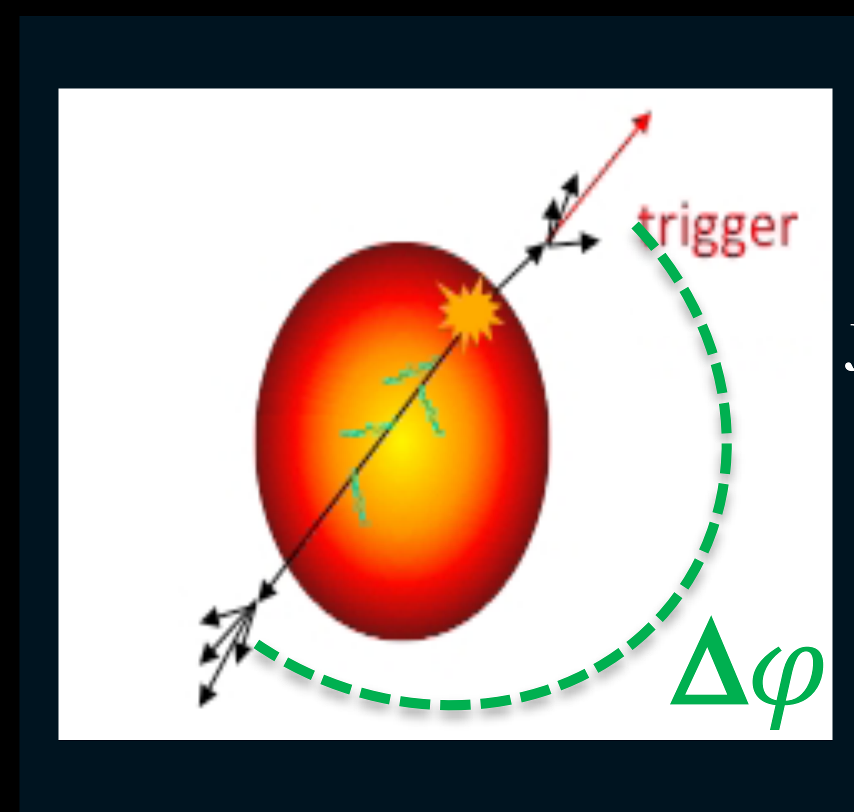


Large angle radiation

Medium-induced acoplanarity in heavy-ion collisions…

Modification of jet substructure

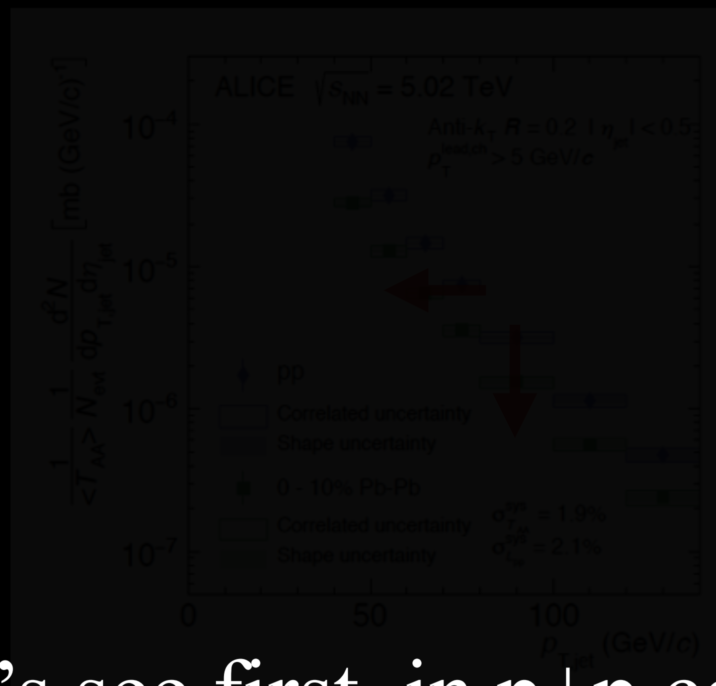


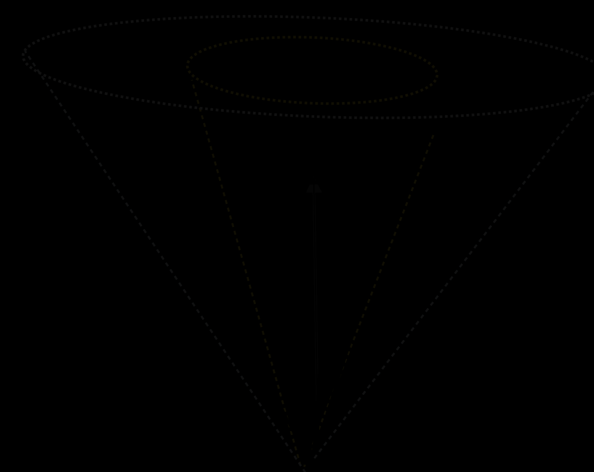


Jet-deflection

Consequences of jet-quenching

Energy loss

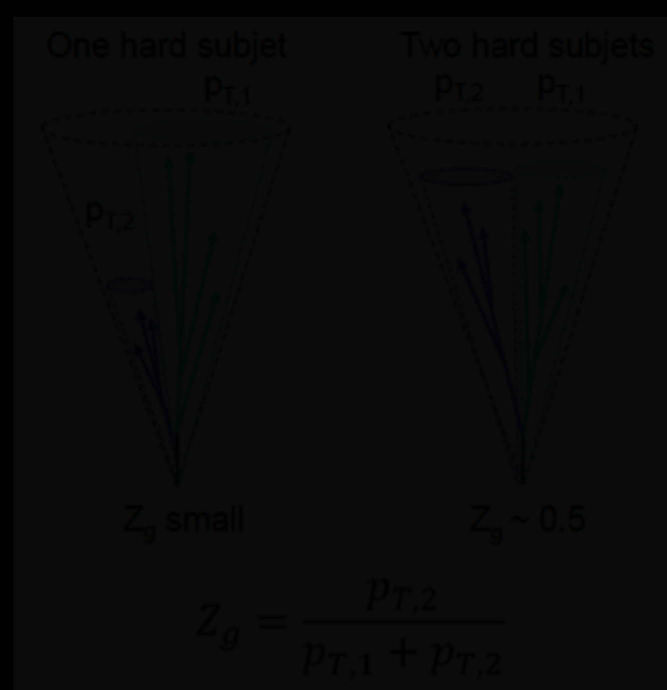


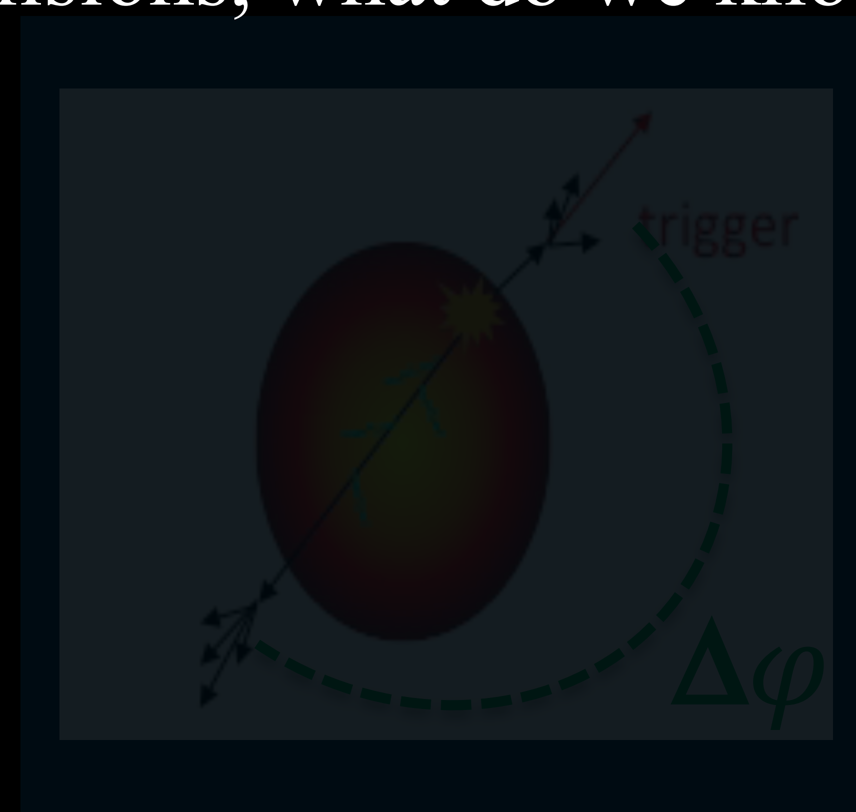


Large angle radiation

Let's see first, in p+p collisions, what do we know?

Modification of jet substructure





Jet-deflection

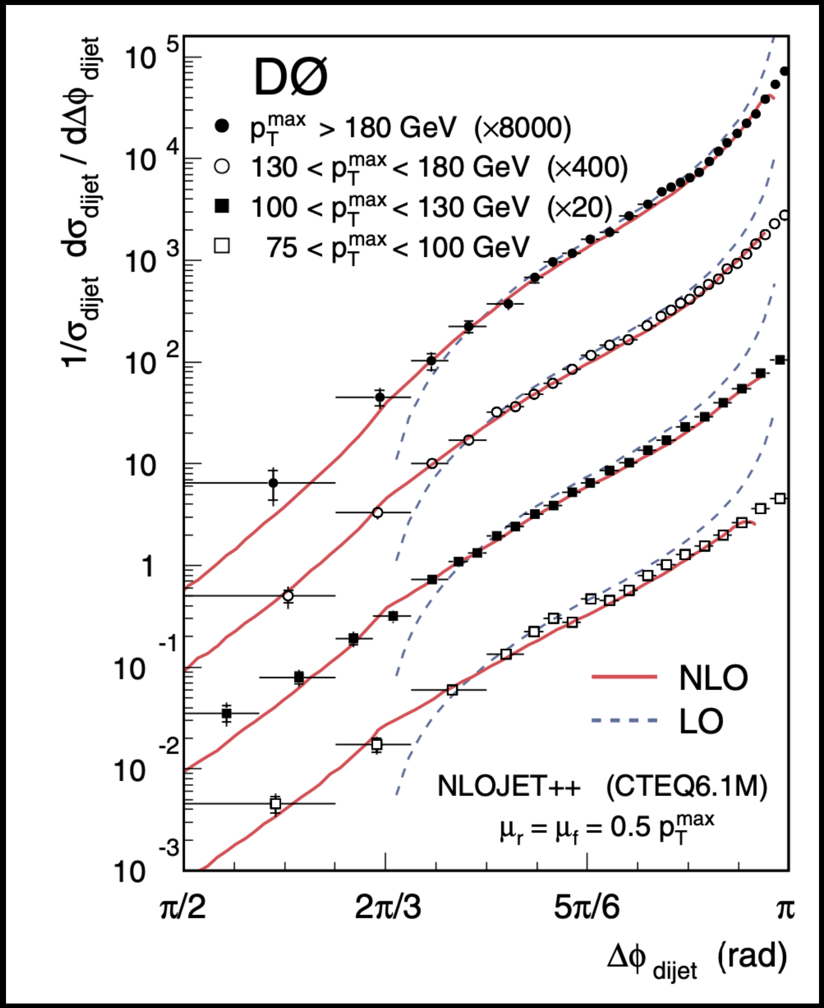
Dijet acoplanarity measurement in vacuum

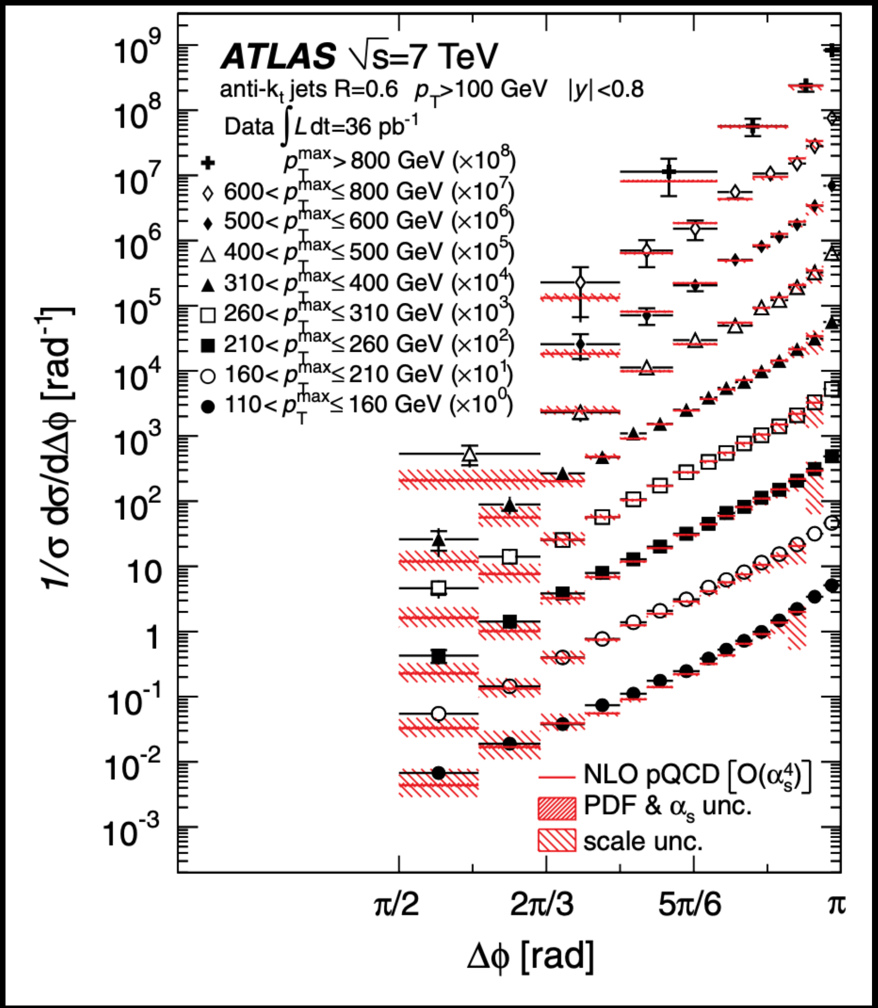
Dijet measurement at mid-rapidity

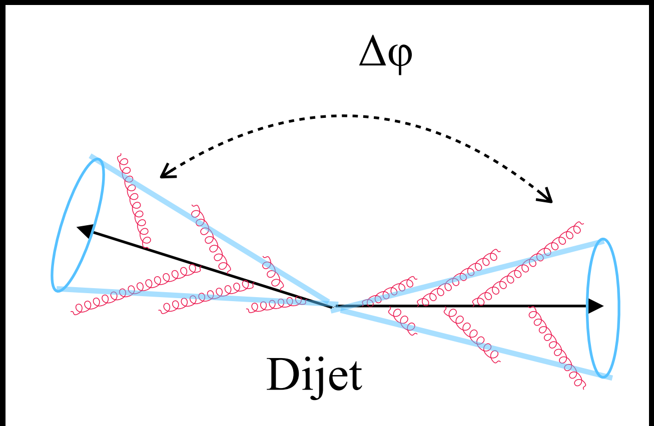
Tevatron: $p + \bar{p}$ at $\sqrt{s} = 1.96$ TeV
D0: PRL **94,** 221801 (2005)

LHC : p+p at $\sqrt{s} = 7$ TeV
ATLAS: PRL 106, **172002** (2011)

CMS: PRL 106, 122003 (2011)







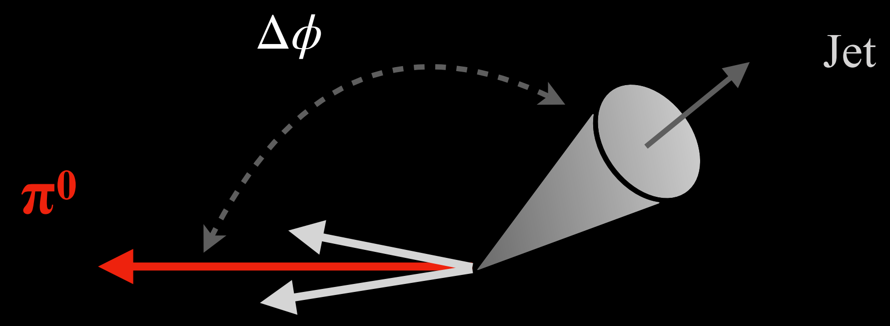
- Well-described by NLO pQCD
- Multi-parton radiation dominates at small angle

Semi-inclusive trigger+jet azimuthal correlations in p+p collisions

[A different measurement in comparison with Tevatron and LHC measurements]

$$\left.\frac{1}{\mathrm{N_{trig}}}\cdot\frac{\mathrm{d^2N_{jet}}}{\mathrm{dp_{T,jet}d}(\Delta\phi)}\right|_{\mathrm{E_T^{trig}}} = \left.\left(\frac{1}{\sigma^{\mathrm{A+A\rightarrow trig}}}\cdot\frac{\mathrm{d}^2\sigma^{\mathrm{A+A\rightarrow trig+jet}}}{\mathrm{dp_{T,jet}d}(\Delta\phi)}\right)\right|_{\mathrm{E_T^{trig}}}$$

$\pi^0 + \mathrm{jet}$

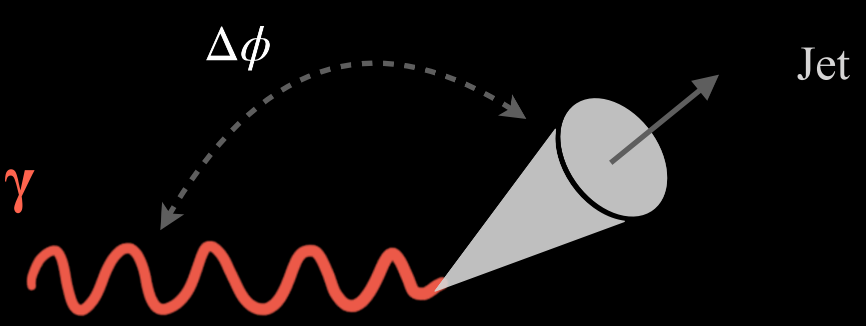


p+p 200 GeV

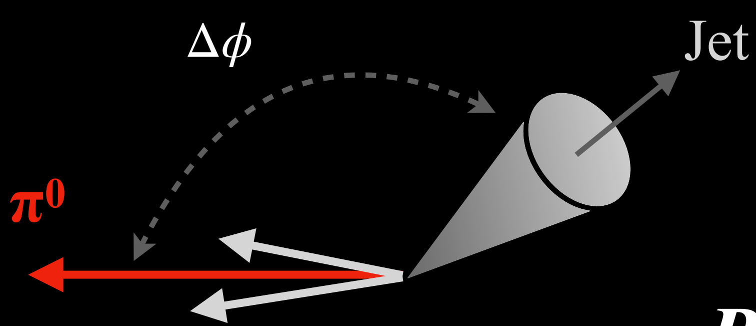
π^0 trigger: $\mathbf{9} < E_{\mathrm{T}}^{\mathrm{trig}} < \mathbf{11\ GeV}$

Recoil jet p_T: 5-10, 10-15, 15-20 GeV/c

$\gamma + \mathrm{jet}$

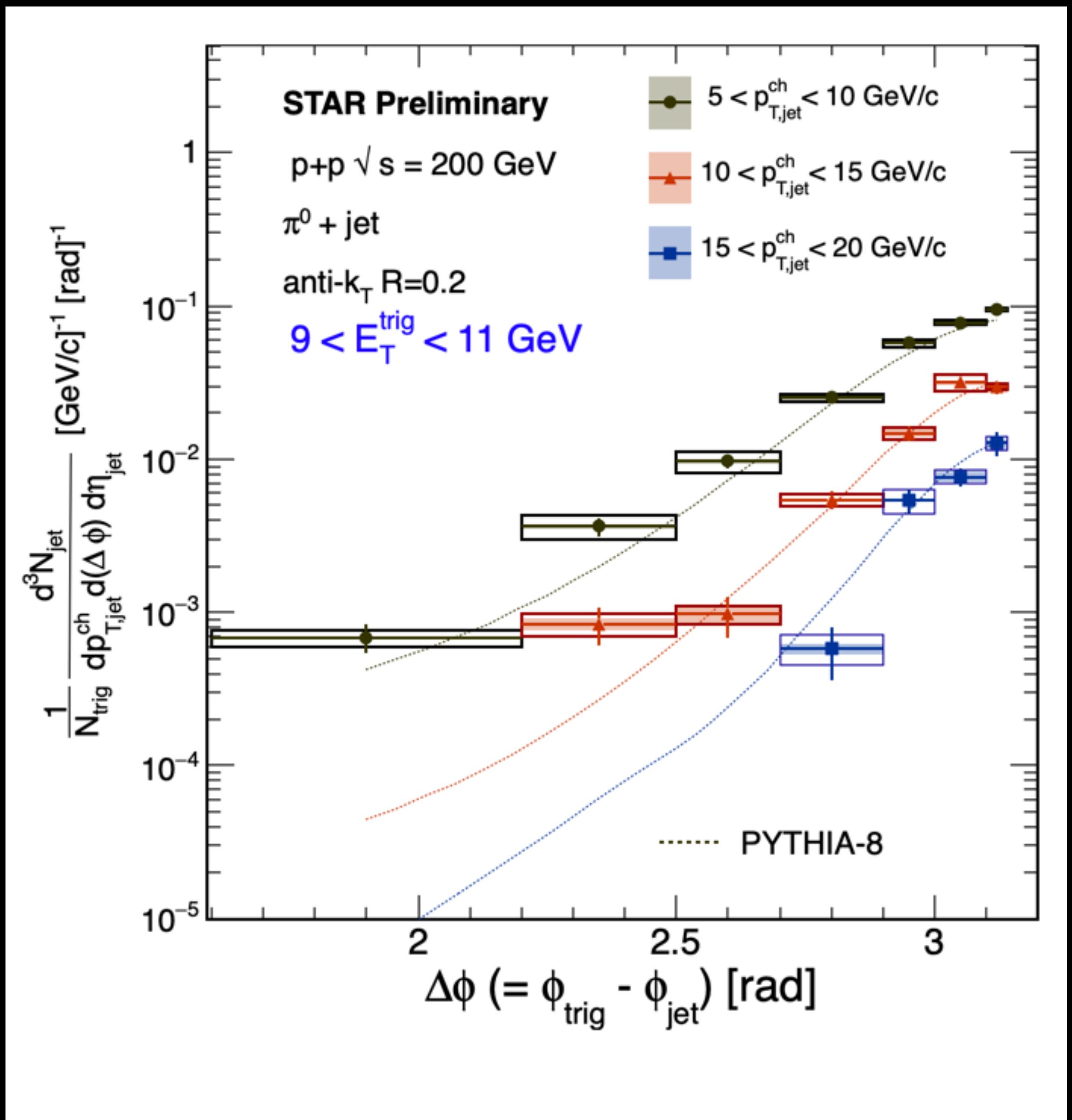


Semi-inclusive π^0+jet azimuthal correlation in p+p collisions

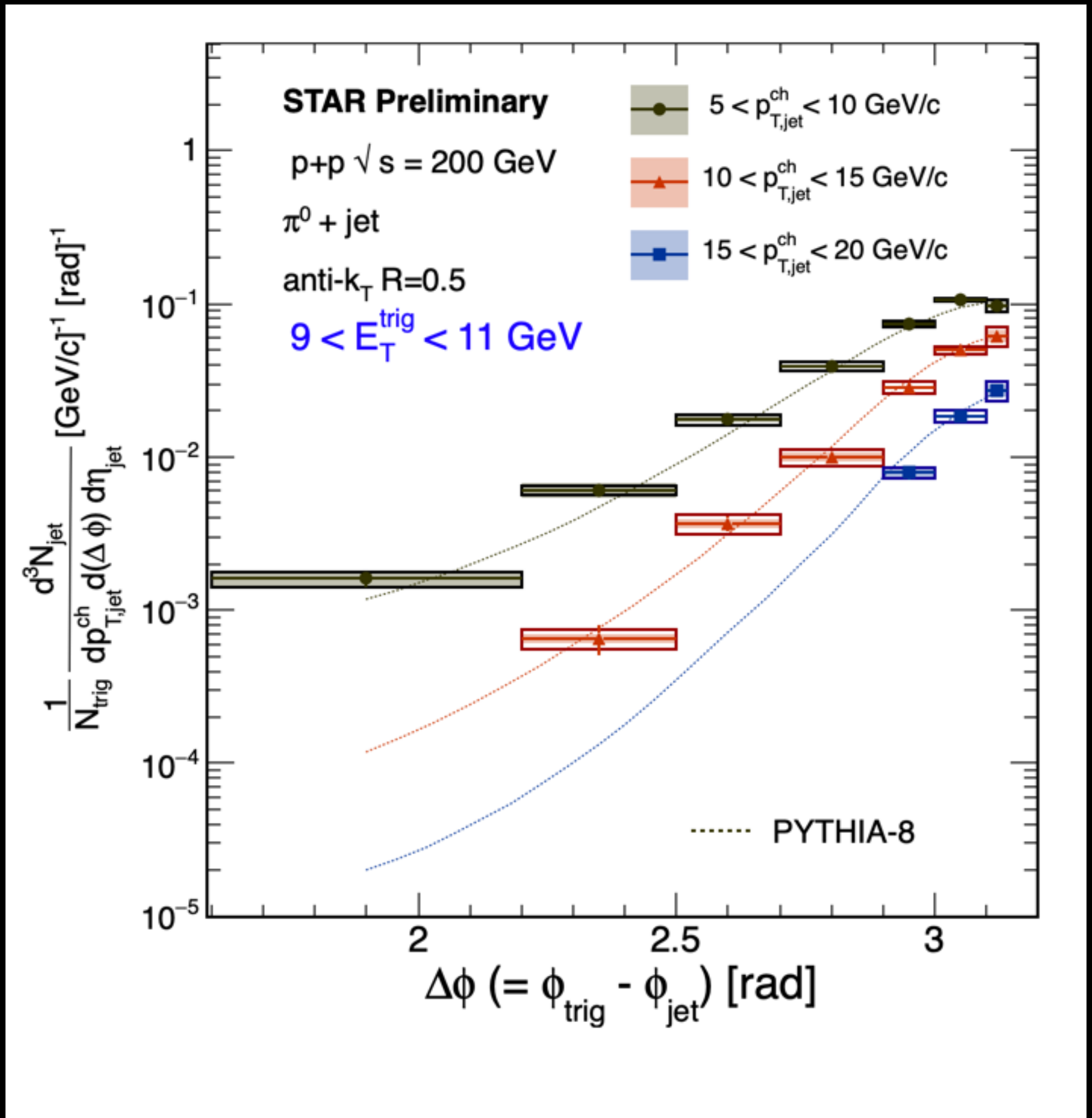


$$9 < E_T^{\mathrm{trig}} < 11 \text{ GeV}$$

***R*=0.2**



***R*=0.5**

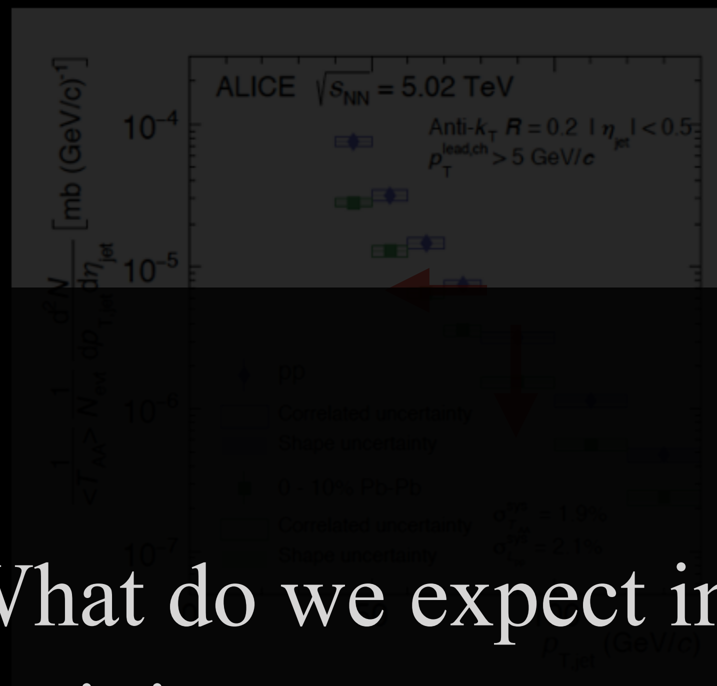


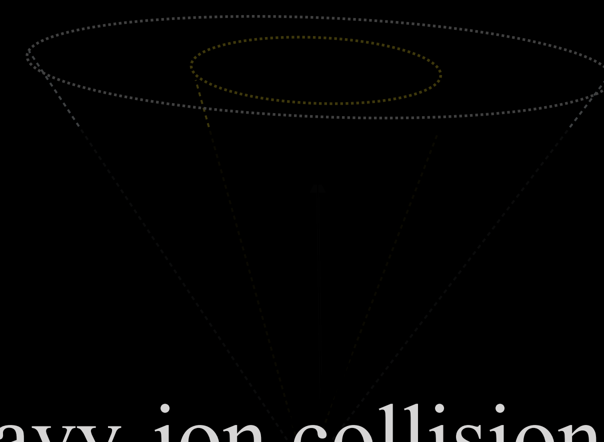
$$\Delta\phi = \phi_{\mathrm{trig}} - \phi_{\mathrm{jet}}$$

Shape and magnitude of p+p data comparable with PYTHIA-8

Consequences of jet-quenching

Energy loss



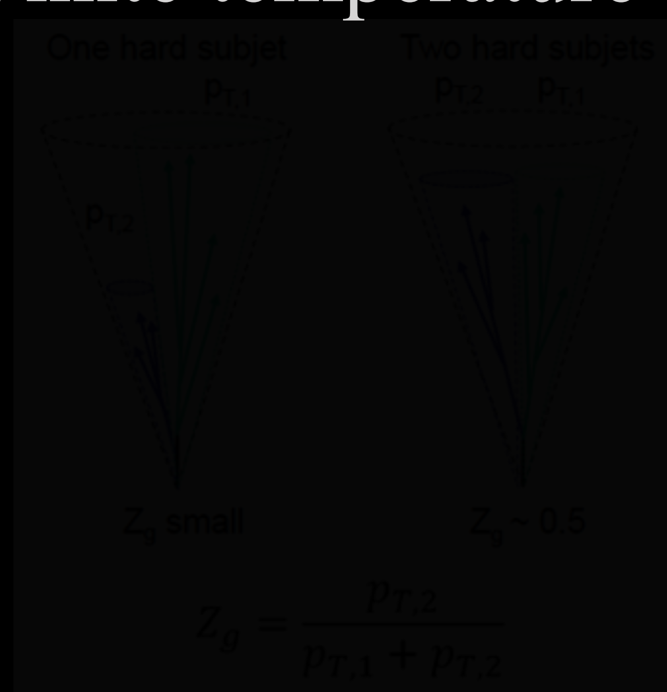


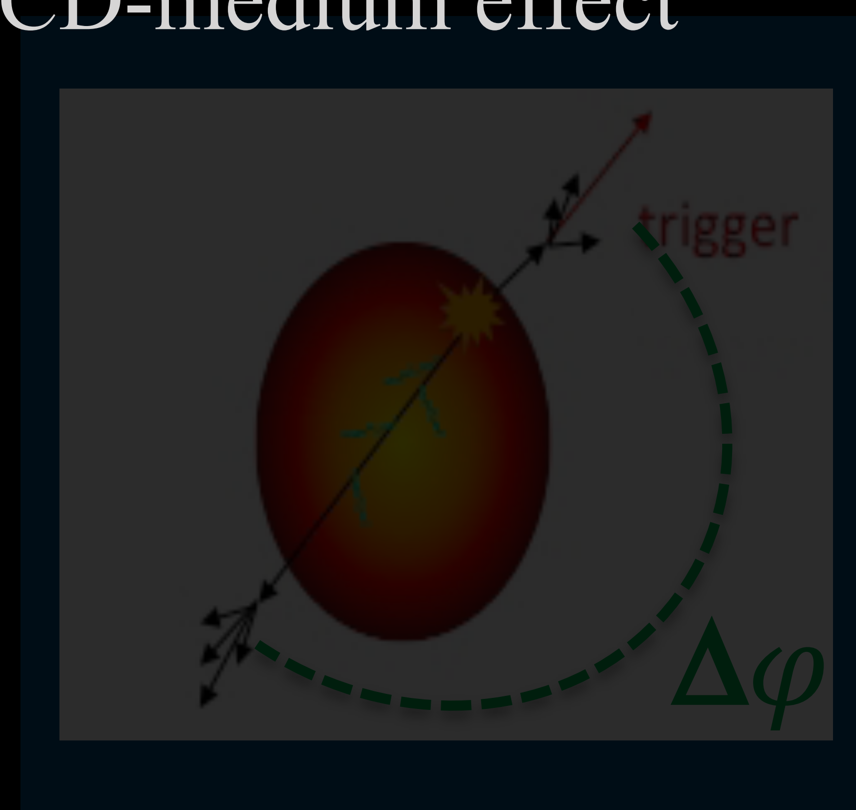
Large angle radiation

What do we expect in heavy-ion collisions?

Finite temperature QCD-medium effect

Modification of jet substructure





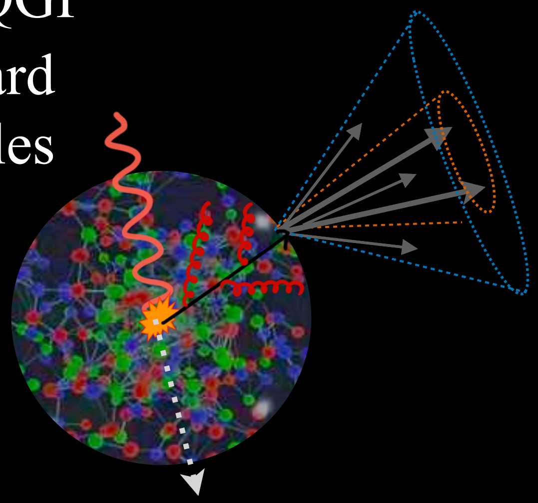
Jet-deflection

Physics mechanisms for acoplanarity of γ+jet in heavy-ion collisions

- Rutherford Scattering: Energetic parton resolves microstructure of QGP

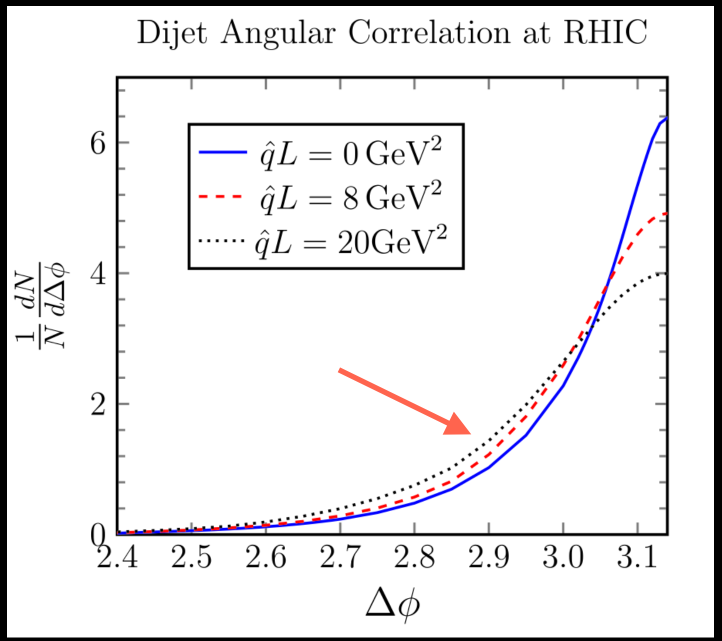
Large-angle deflection of hard partons off quasi-particles

D'Eramo, Rajagopal, Yin, JHEP 01 (2019) 172;
D'Eramo, et. All, JHEP 05 (2013) 031

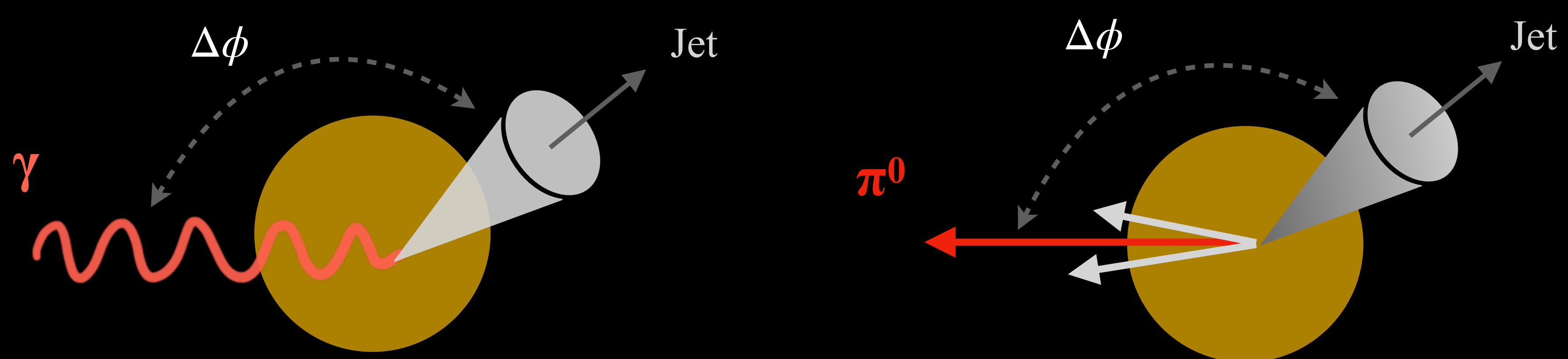


A. Mueller et al,
PLB 763 (2016) 208

- Vacuum soft gluon radiation
- Medium effect: multiple scattering and medium induced gluon radiation



Measuring two probes in STAR experiment

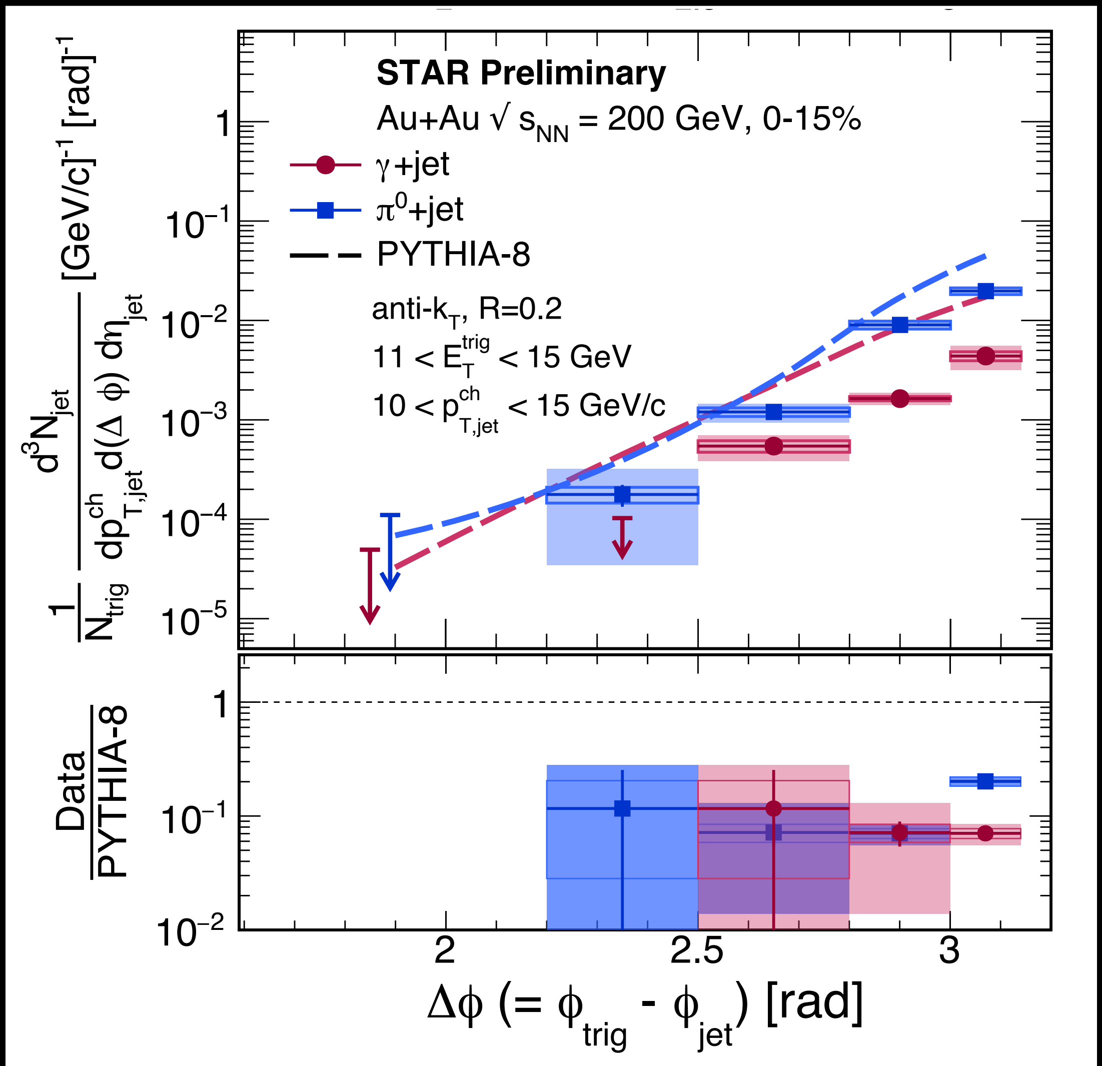


Azimuthal correlations between trigger particle and recoil jet: $\Delta\phi = \phi_{\mathrm{trig}} - \phi_{\mathrm{jet}}$

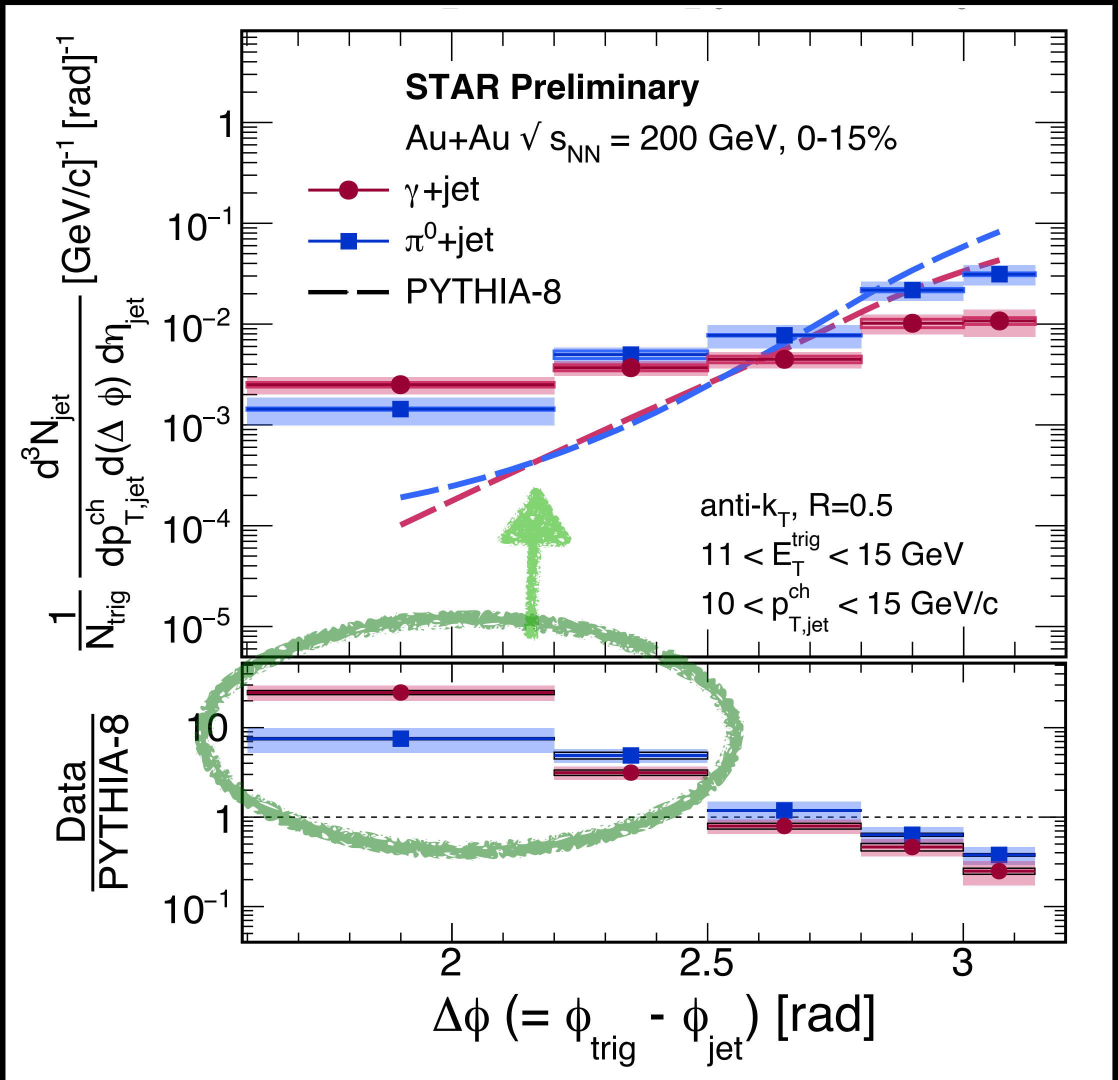
Semi-inclusive γ+jet and π^0+jet azimuthal correlation in Au+Au collisions

$11 < E_T^{trig} < 15$ GeV

***R*=0.2**

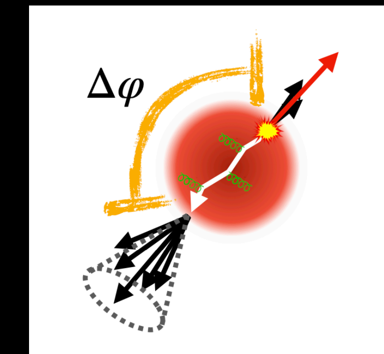


***R*=0.5**

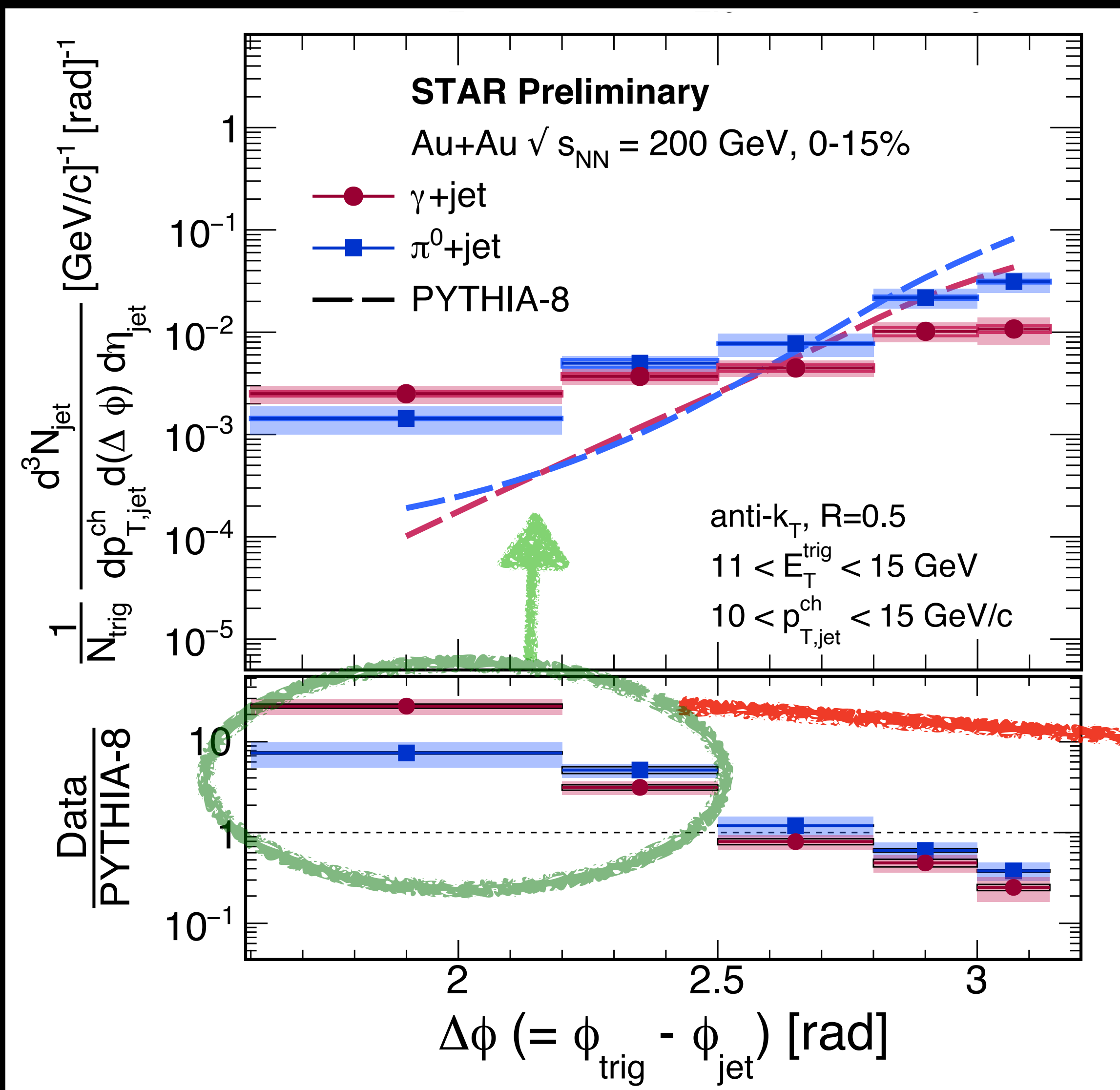


First evidence of significant medium-induced acoplanarity in QGP for jets with R=0.5

Medium-induced jet acoplanarity at RHIC and LHC

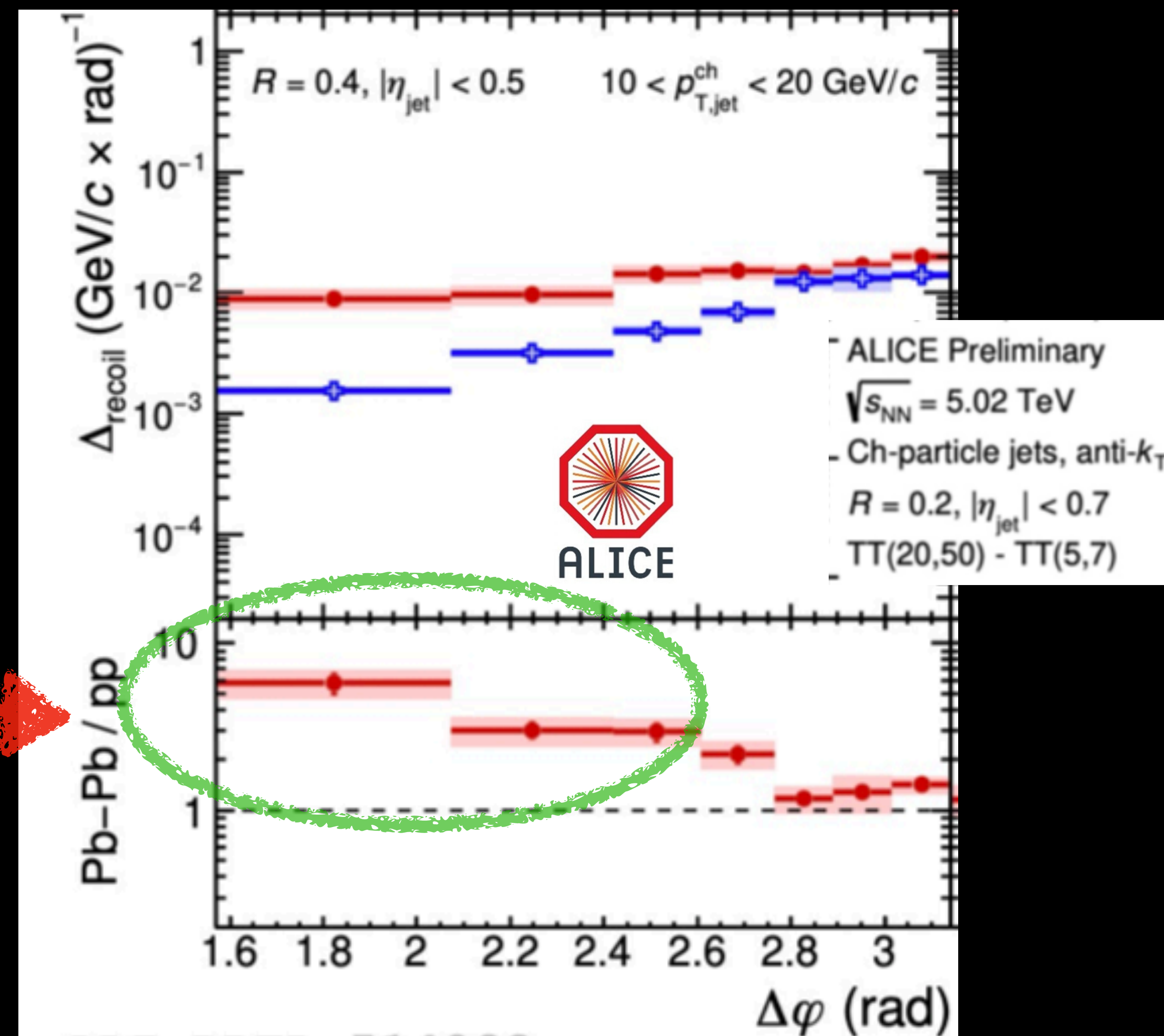


STAR γ+jet and π⁰+jet



- Mixed-event subtraction method
- Jet R=0.5

ALICE h+jet



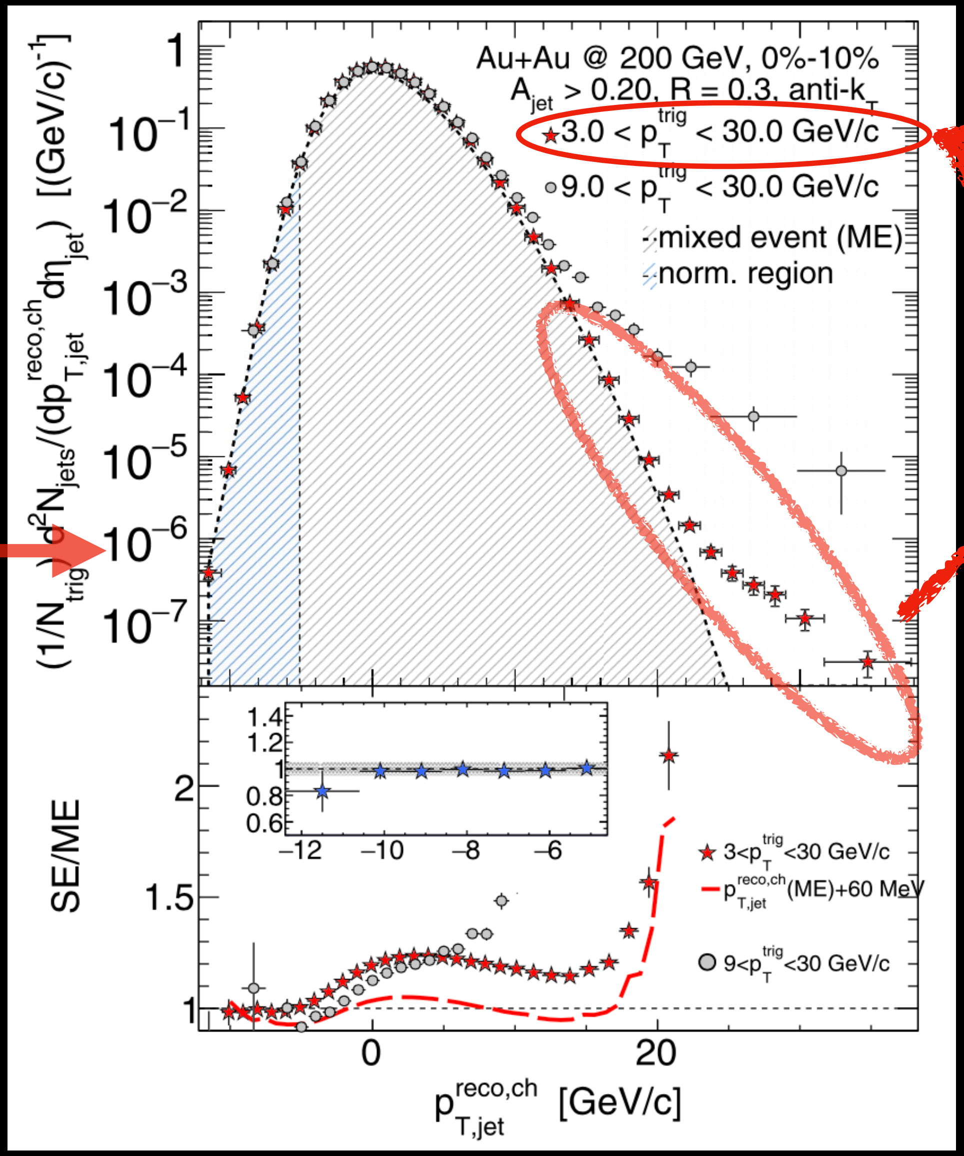
- TT(20,50) - TT(5,7)
- Jet R=0.4

Same observation: Medium-induced acoplanarity with jet ($p_T \sim 10$ GeV/c) and large R (0.4-0.5)
What happened to larger Sudakov broadening at the LHC?

MPI in heavy-ion collisions and its effects

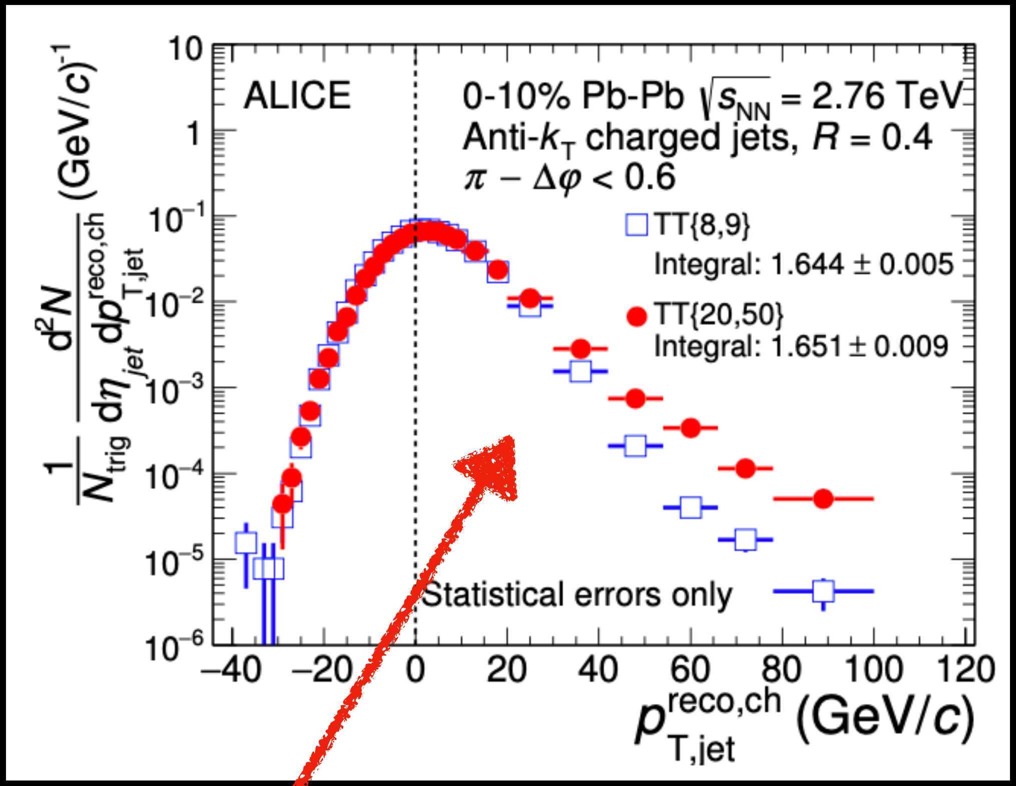
Multiple parton interactions (MPI): uncorrelated jets contribution to high-Q^2 processes
Independent of trigger p_T and $\Delta\phi$

STAR h+jet: PRC 96 (2017) 024905

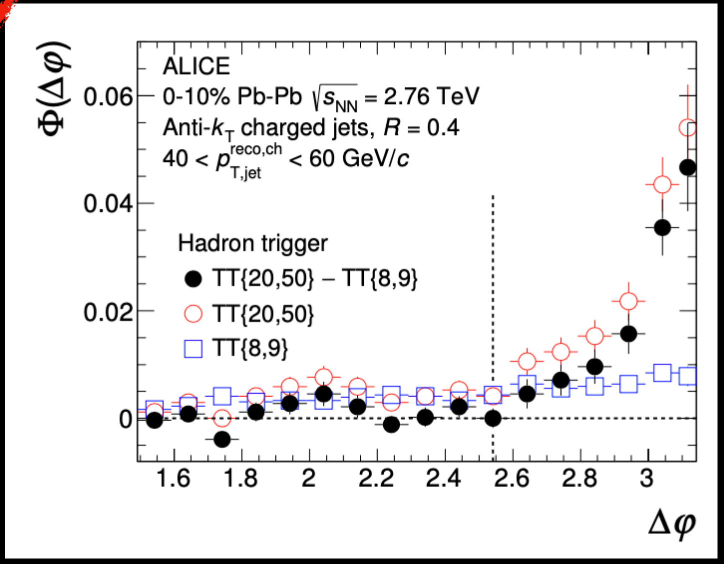


Negligible contribution with lower trigger p_T range

ALICE h+jet : JHEP09(2015)170

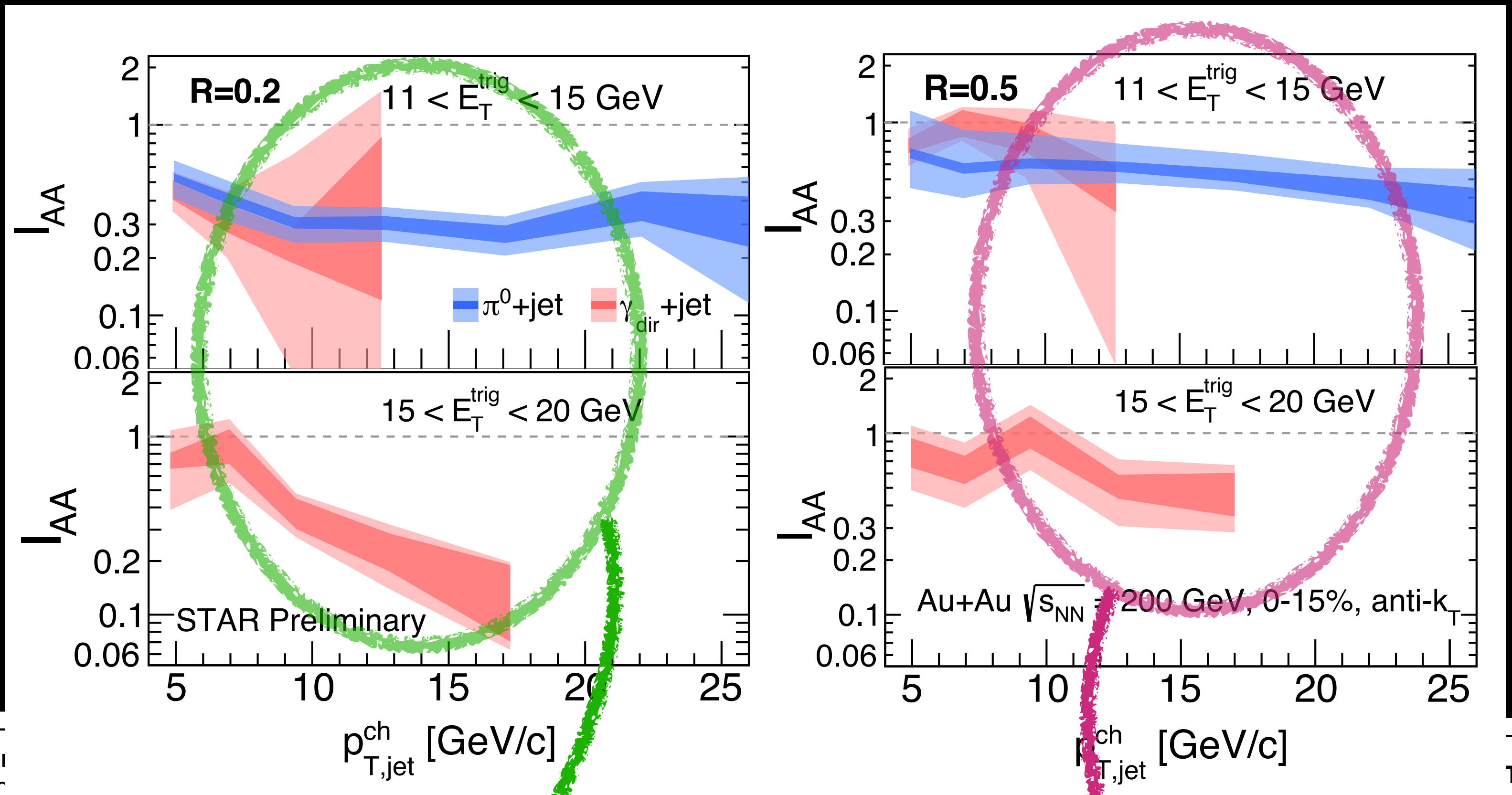


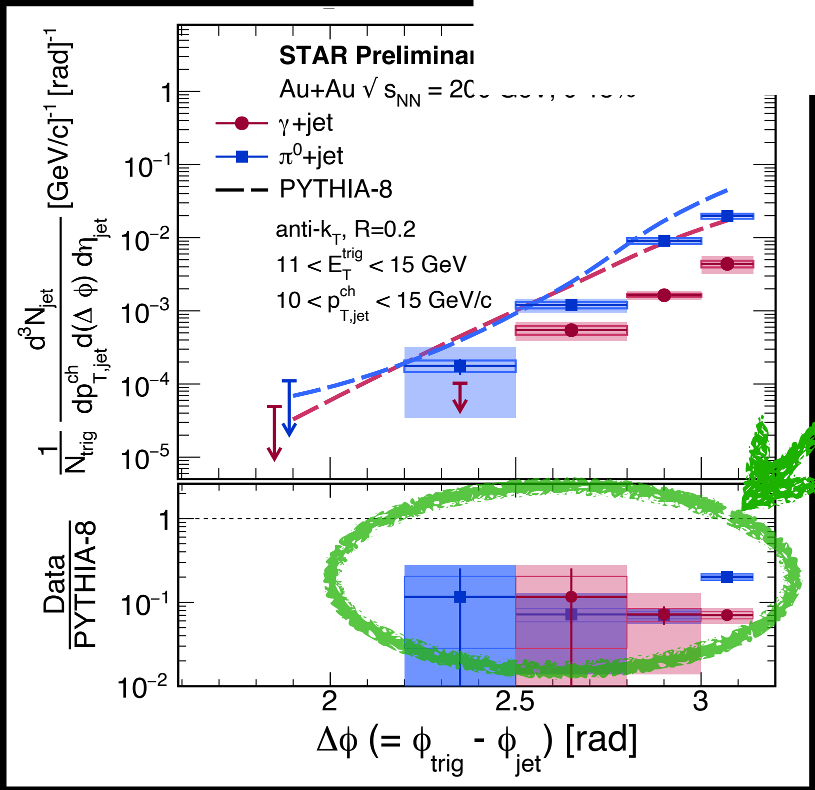
Full subtraction of MPI due exclusive trigger p_T ranges



Two different approaches

Jet suppression vs. medium-induced jet acoplanarity

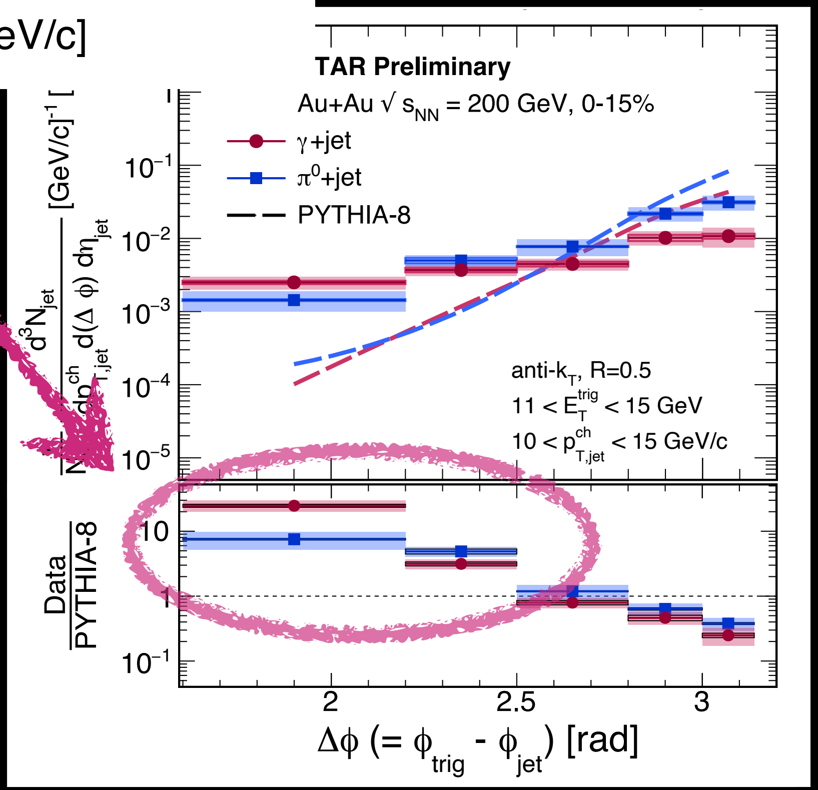




Strong yield suppression

Relatively less yield suppression

With high acoplanarity

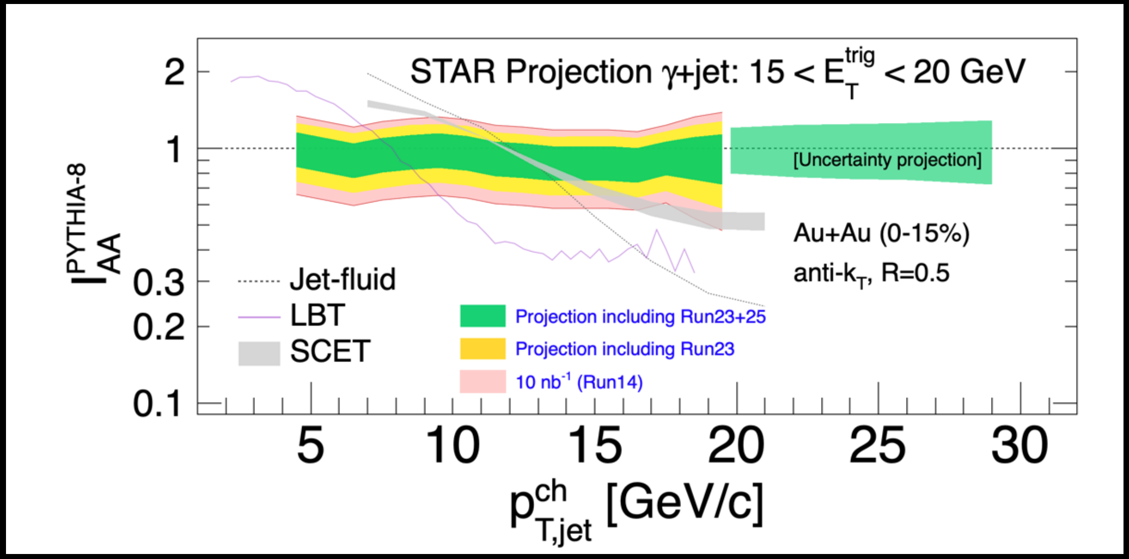


Need to understand the QCD medium effect…

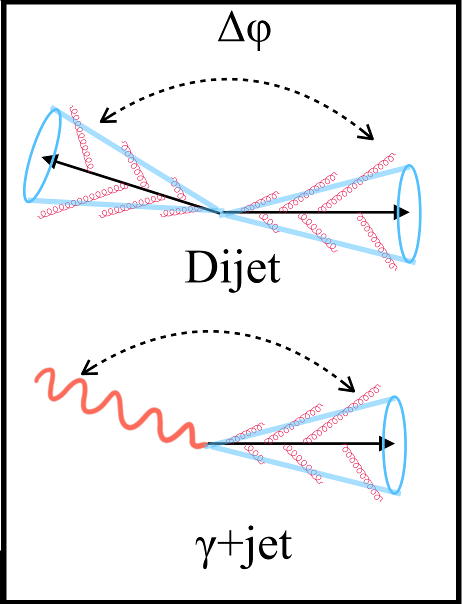
Future measurements…

Future RHIC Beam Use Request (BUR) for 2023-2025

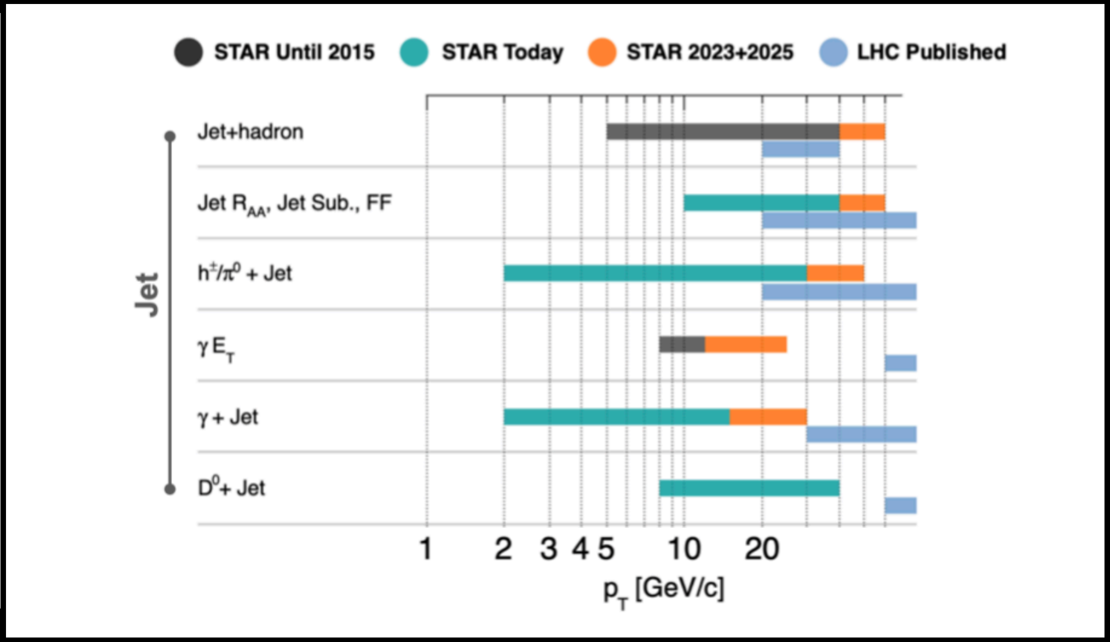
STAR γ+jet measurement proposal



Acoplanarity measurements

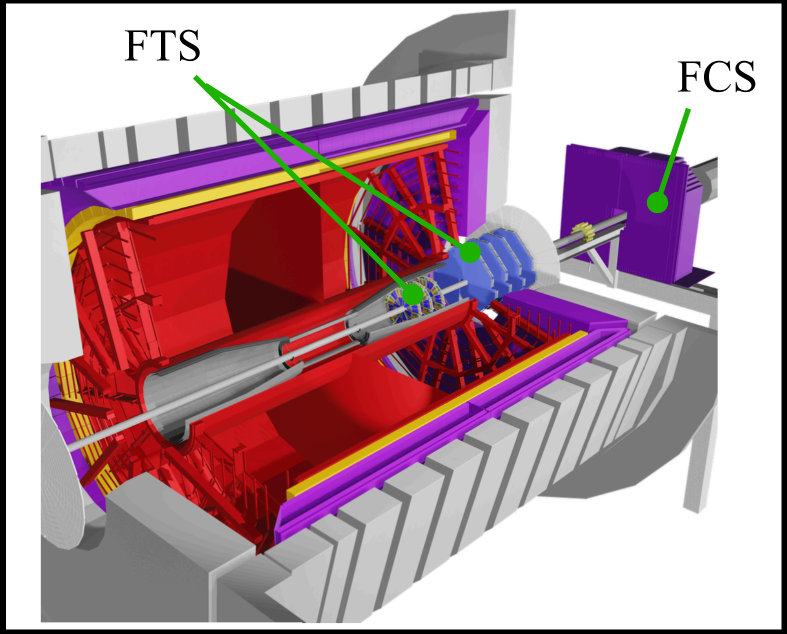


BNL NPP 2021 PAC meeting:
https://indico.bnl.gov/event/11308/



RHIC experiments (sPHENIX and STAR) plan to take high lumi data

- For Au+Au [2023+2025] and p+p [2024] 200 GeV (also p+Au)
- Crucial for γ+jet and other jet measurements
- STAR forward detectors upgrade program to study cold QCD physics

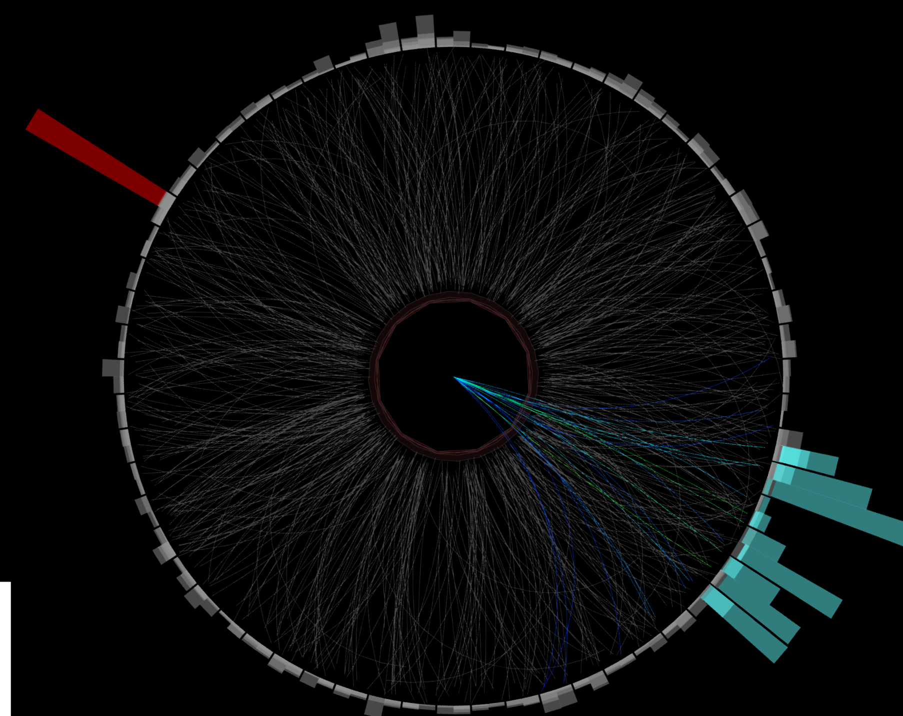


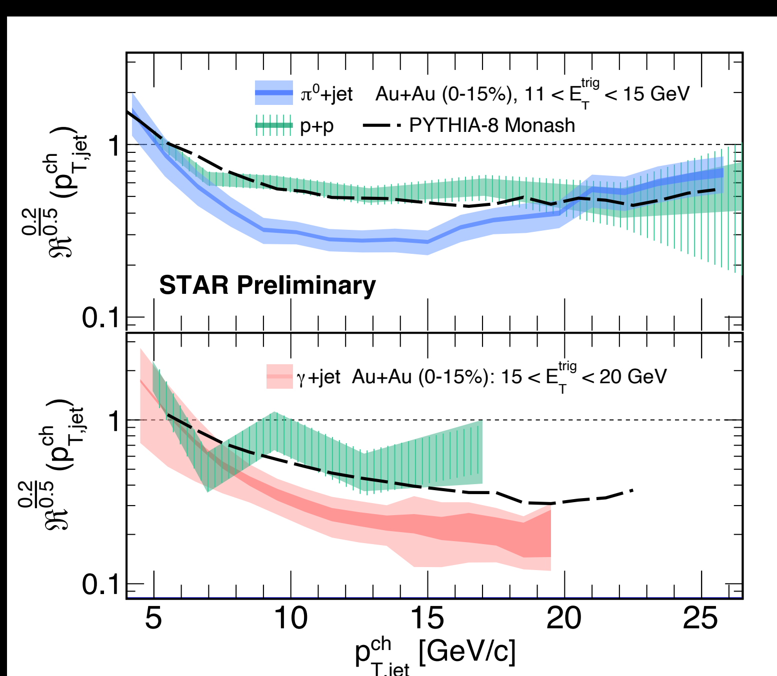
Summary and outlook

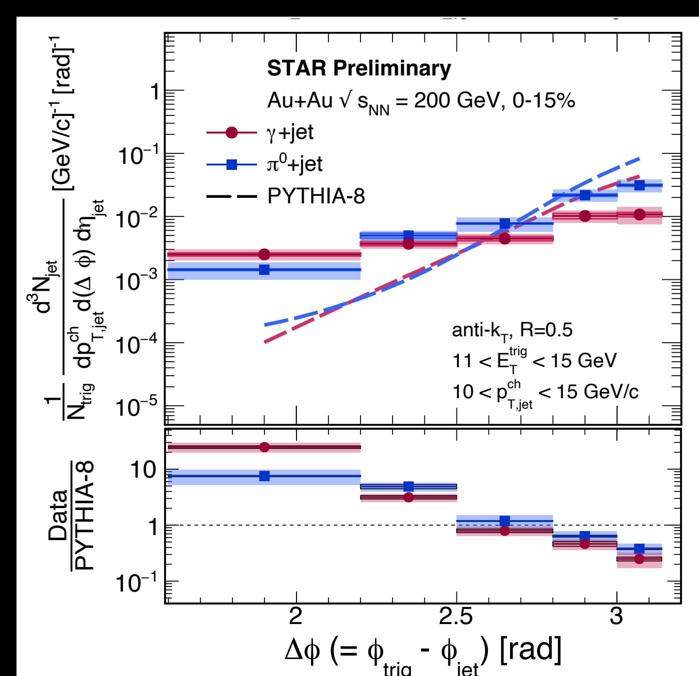
First observation of intra-jet broadening and medium-induced jet acoplanarity in heavy-ion collisions

Upcoming heavy-Ion runs and the future experiment is crucial for a definitive and incisive understanding of the QCD matter

γ + jet event display





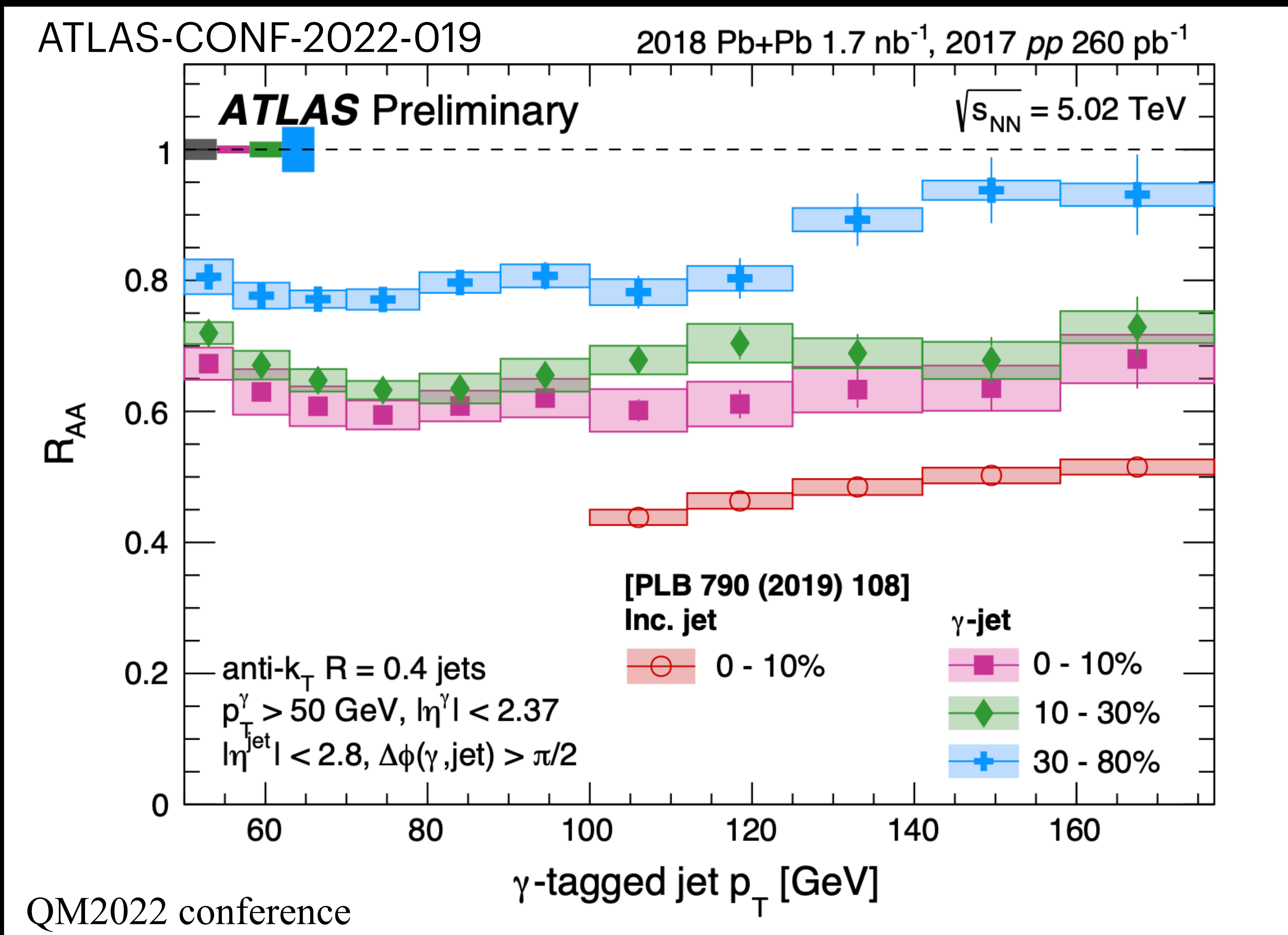


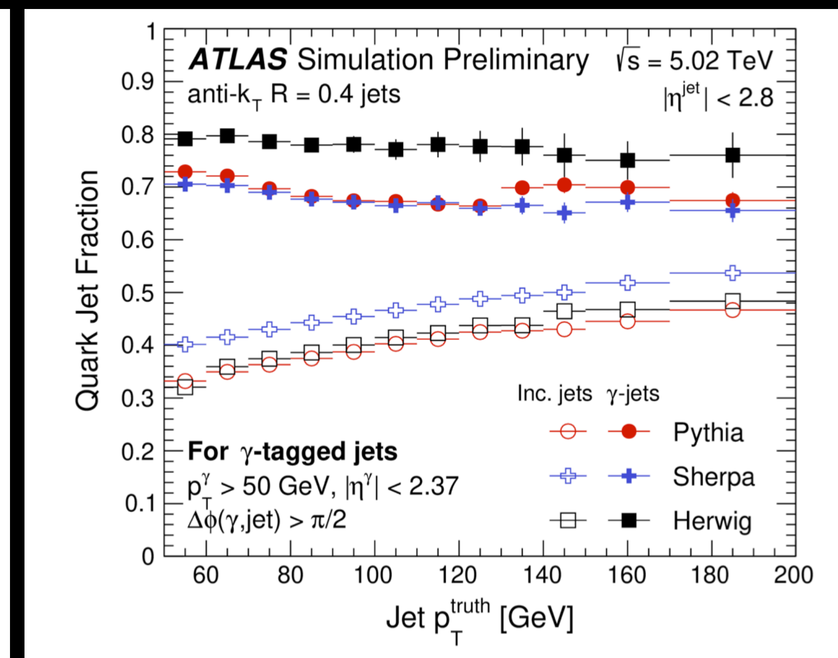
Thank you!

Backup

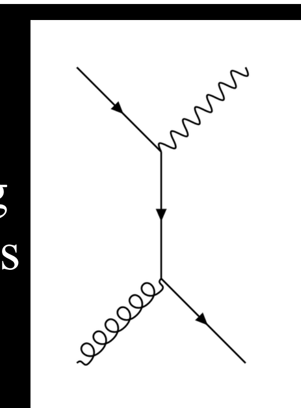
ATLAS (LHC) measurement

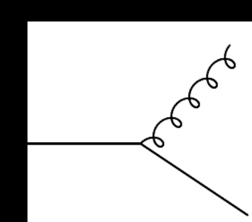
Inclusive jet vs γ+jet in Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV



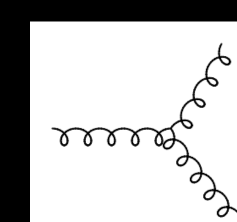


Dominating γ+jet process





$C_F = 3/4$



$C_A = 3$

Indication of $C_A/C_F = 9/4$ effect in quark vs. gluon jet