Jet physics program at RHIC

(Finite temperature and density QCD)

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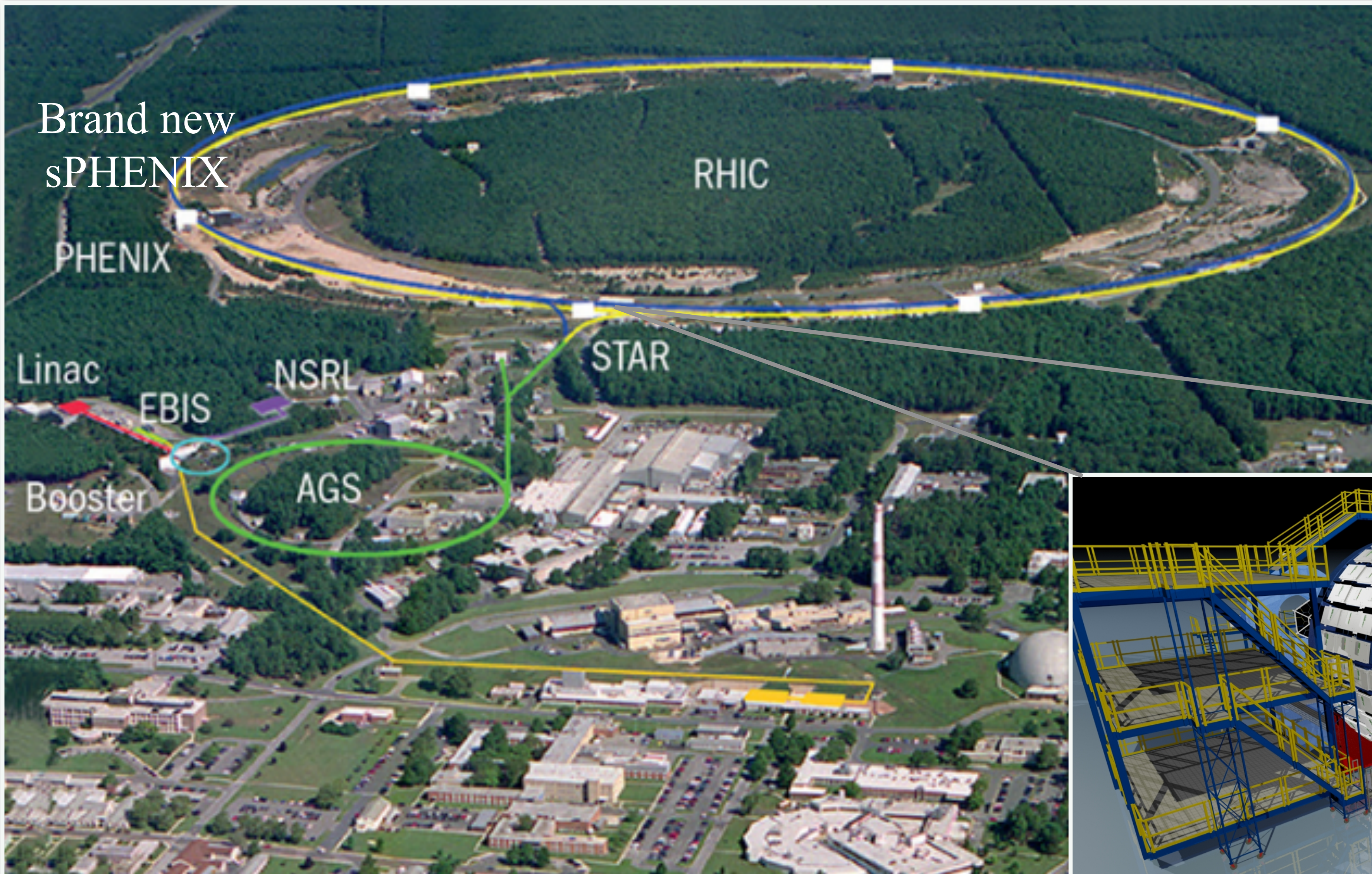
Light Cone 2021: Physics of Hadrons on the Light Front, Nov 29 - Dec 4, 2021

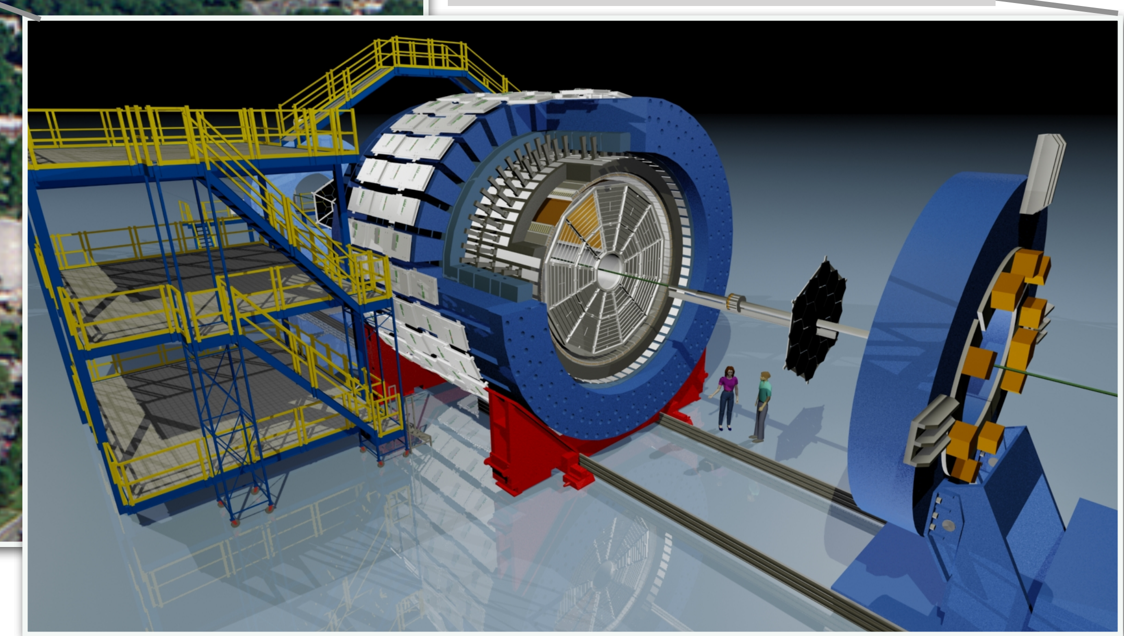
RHIC experiment

RHIC accelerator



BNL, New York, USA

STAR detectors



- Center of energy: 7.7 to 200 GeV
- Hot-dense QCD medium study: Au+Au, Cu+Cu, U+U, Ru+Ru, and Zr+Zr
- Cold QCD medium study: p+Au, and d+Au
- QCD vacuum in p+p collisions

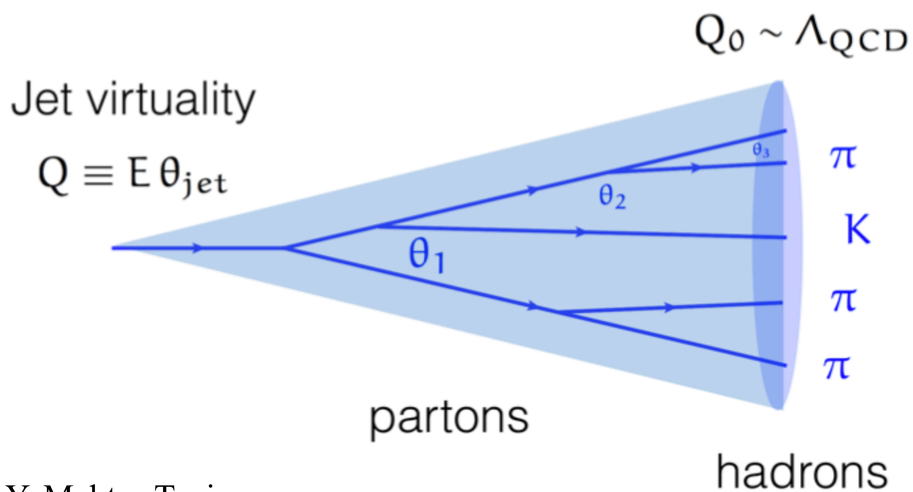
Jets in vacuum

(In p+p collisions)

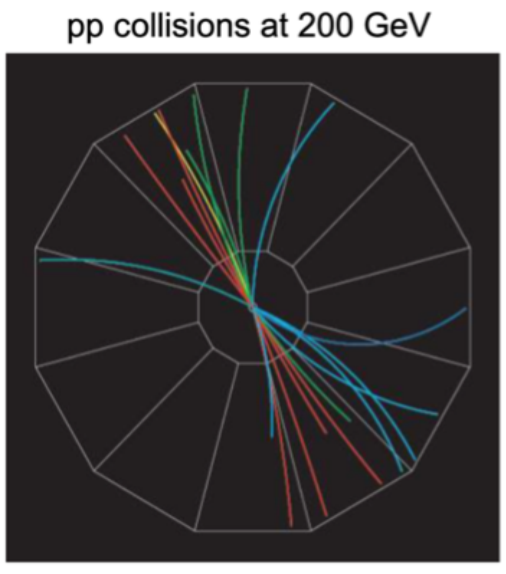
Jets in vacuum

Jet measurement in p+p collisions

Vacuum timelike parton shower



Y. Mehtar-Tani:
NPA 956 (2016) 168-175



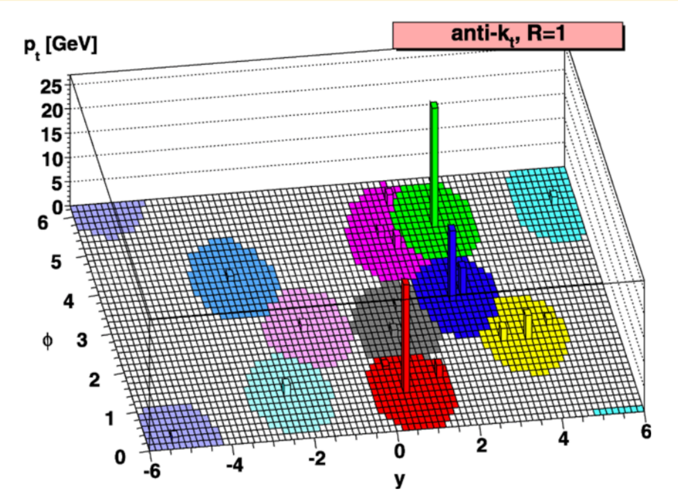
In experiment:

anti-k_T sequential recombination algorithm

$$d_{ij} = \min\,(p_{T,i}^{-2}, p_{T,j}^{-2})\frac{\Delta R_{ij}^2}{R^2},$$

and, $d_{iB} = p_{T,i}^{-2}$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$



Salam, EPJC (2010) 67: 637–686

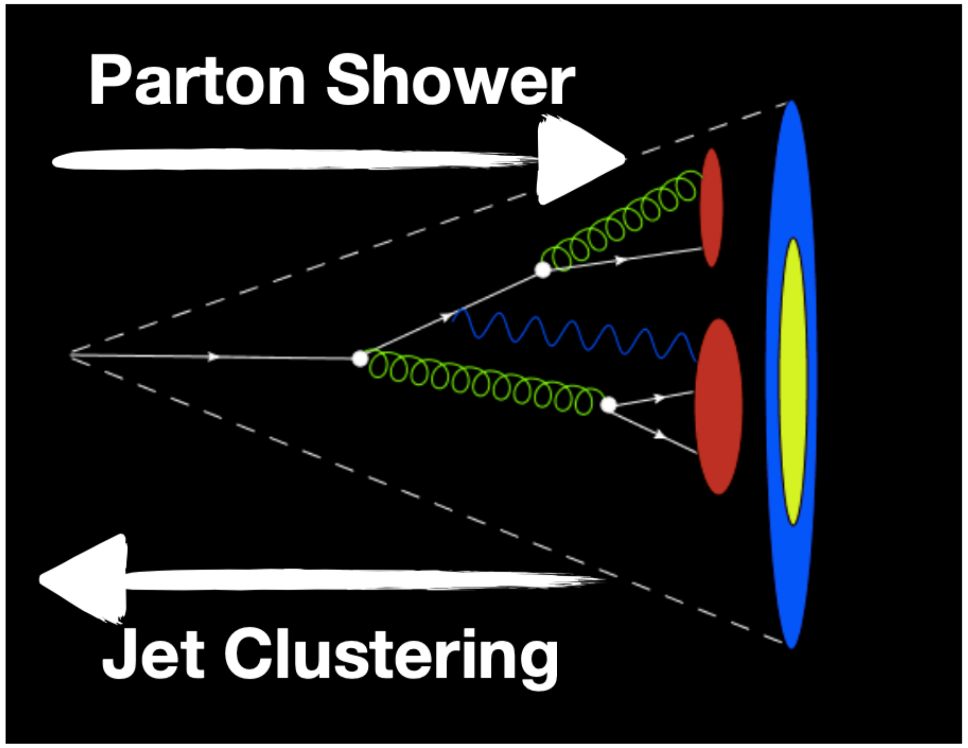
- pQCD and non-pQCD effects at RHIC
- To constrain parameters in parton shower models
- Vacuum-baseline for heavy-ion collisions (finite-temperature QCD medium)

Jet substructure measurement in p+p collisions

SoftDrop jet grooming:

IRC/Sudakov-safe

Lakoski, Marzani, and Thaler; PRD 91, 111501(R) (2015)



Courtesy: Raghav Elayavalli

Declustering jet branching history by removing soft branch until it satisfies the condition:

$$z_g = \frac{\min\,(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}(R_g/R_{jet})^{\beta}$$

$\beta = 0$;

$z_{cut} = 0.1$ → no angular dependence; soft branch at least 10% of total momentum of the pair

Kinematics of each branching:

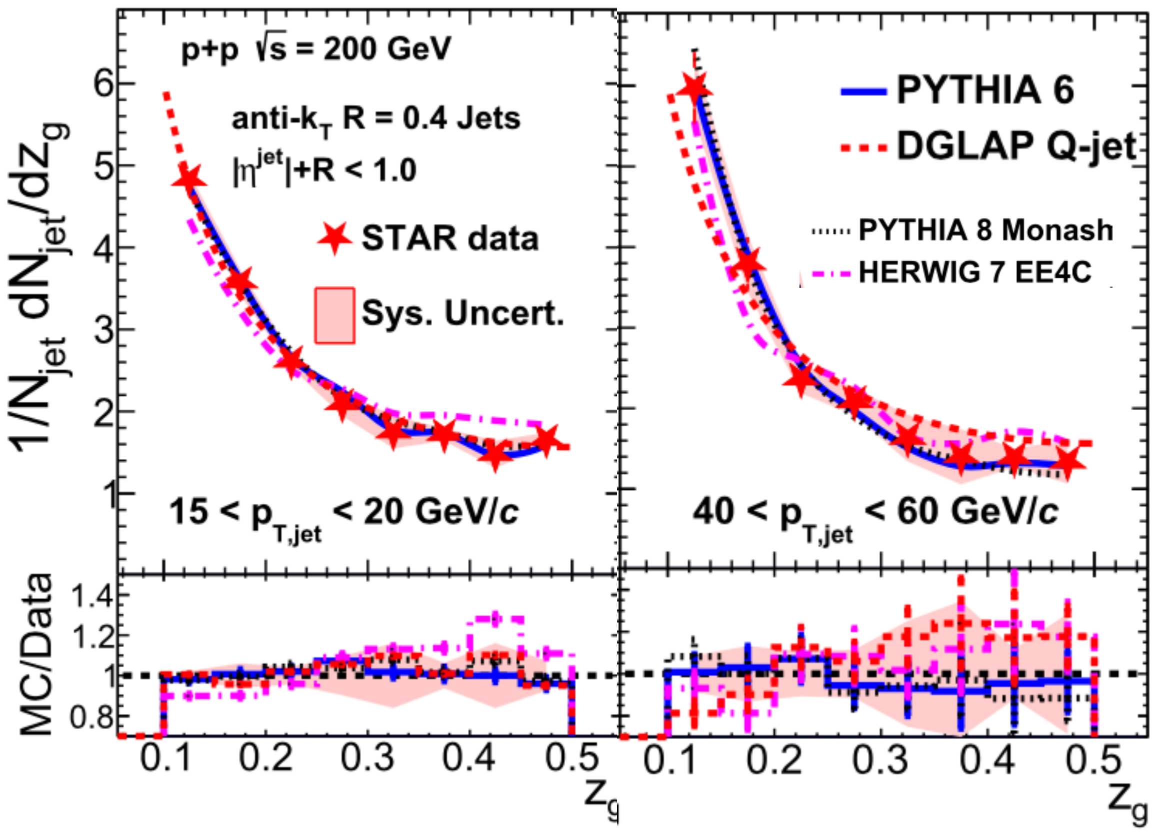
- Groomed jet radius, R_g
- Groomed momentum sharing, z_g

Vacuum splitting in p+p collisions at $\sqrt{s} = 200$ GeV

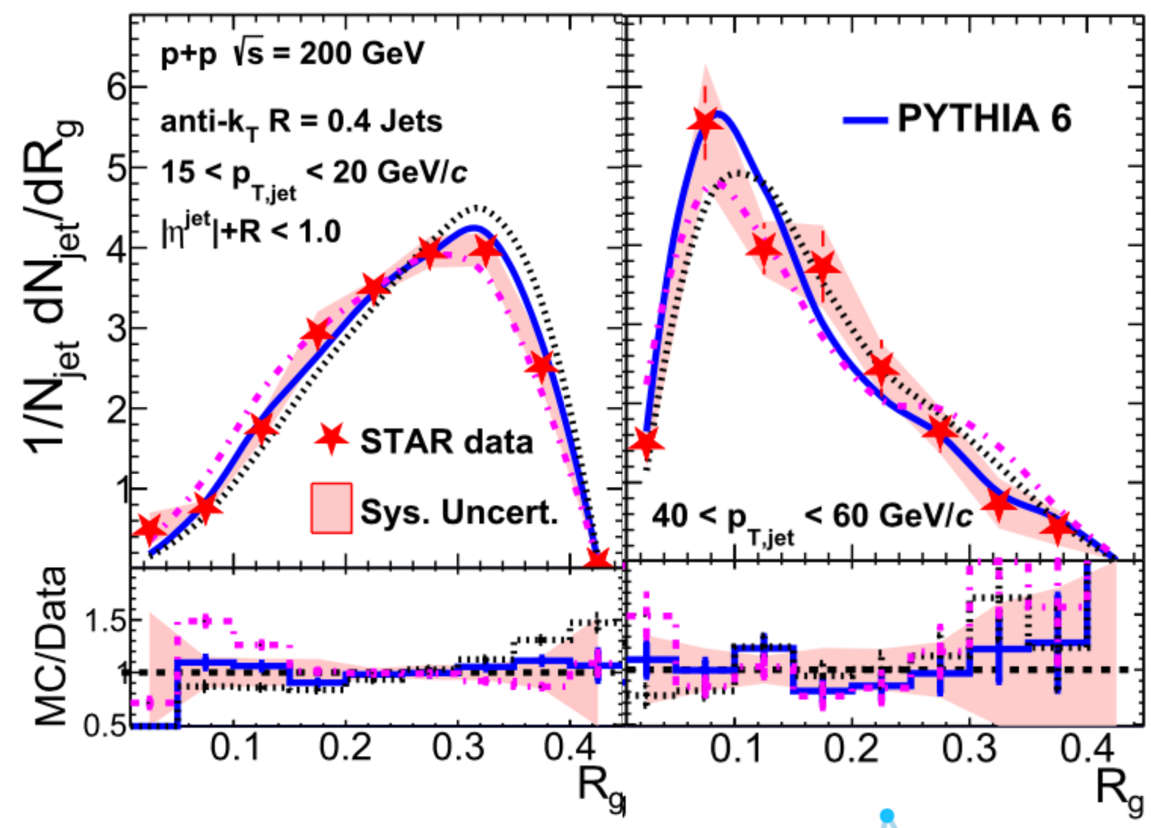
STAR: PLB 811 (2020) 135846

Groomed jet substructure observables

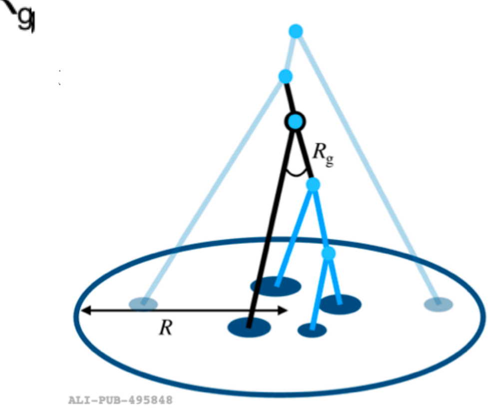
Groomed momentum sharing (z_g)



Groomed jet radius (R_g)



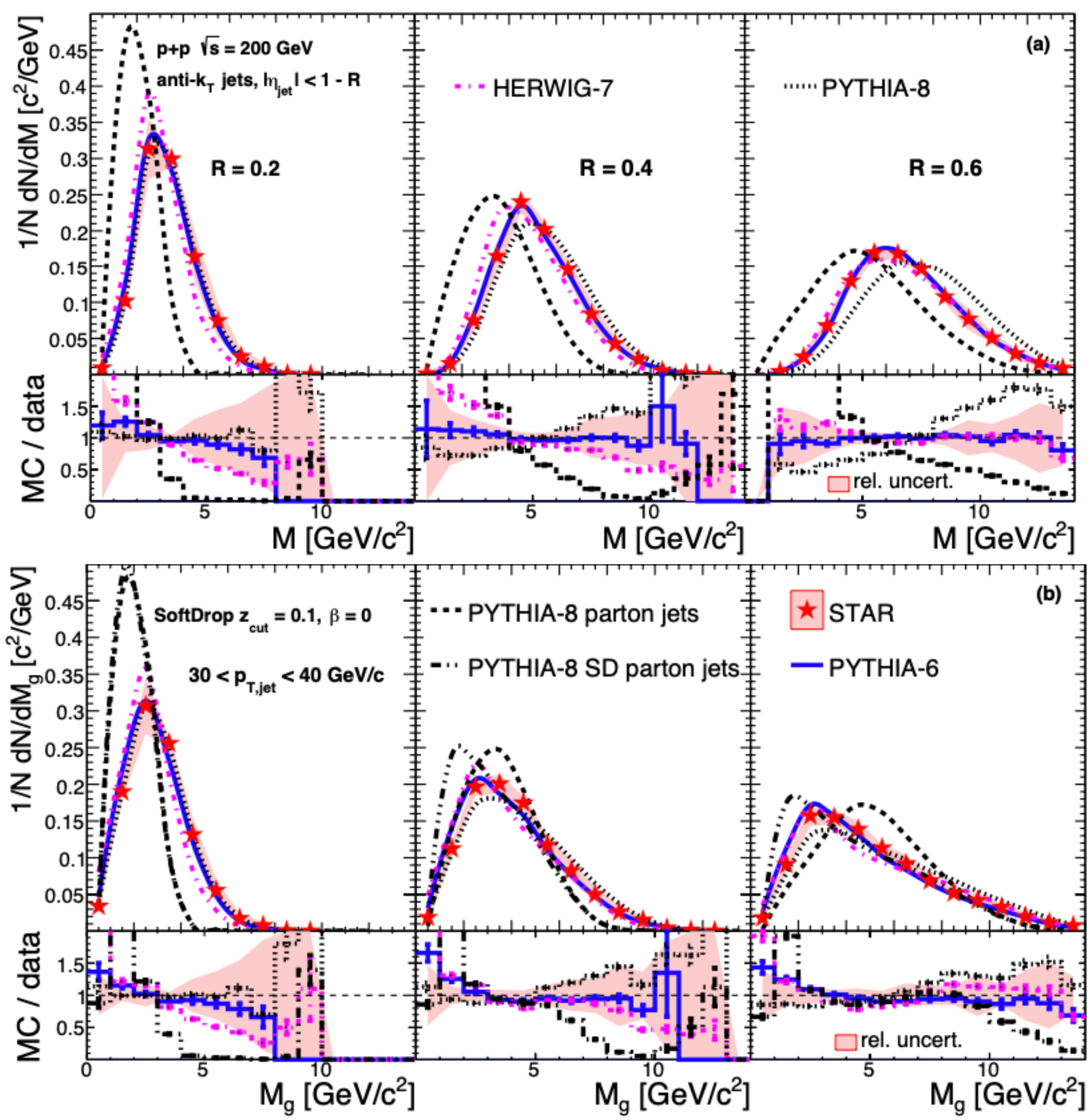
- z_g follows DGLAP splitting kernel
- Unlike z_g, R_g shows a dependence on $p_{T,jet}$ above 25 GeV/c
- At higher $p_{T,jet} \rightarrow$ narrower substructure with asymmetric splitting in a jet
- STAR-tuned PYTHIA-6 Perugia 2012 describes the jet substructure observables at RHIC



Jet mass in vacuum

p+p collisions $\sqrt{s} = 200$ GeV

STAR, arXiv: 2103.13286 (Accepted by PRD)



- Ungroomed Jet mass: $M = |\sum_{i \in \text{jet}} p_i|$

- Groomed jet mass: $M_g = |\sum_{i \in \text{jet}} p_g|$

$p_g \rightarrow$ momentum of the constituent in a groomed jet

- Mean and width increase:
  - With jet R $\rightarrow$ inclusion of wide-angle radiation
  - With jet p_T $\rightarrow$ increasing radiation phase-space
- M_g is smaller than M

  Reduction of soft radiations
- STAR tuned PYTHIA-6 Perugia 2012 well-describes the measurements

Jets in heavy-ion collisions at RHIC: Jet quenching

RHIC early measurements

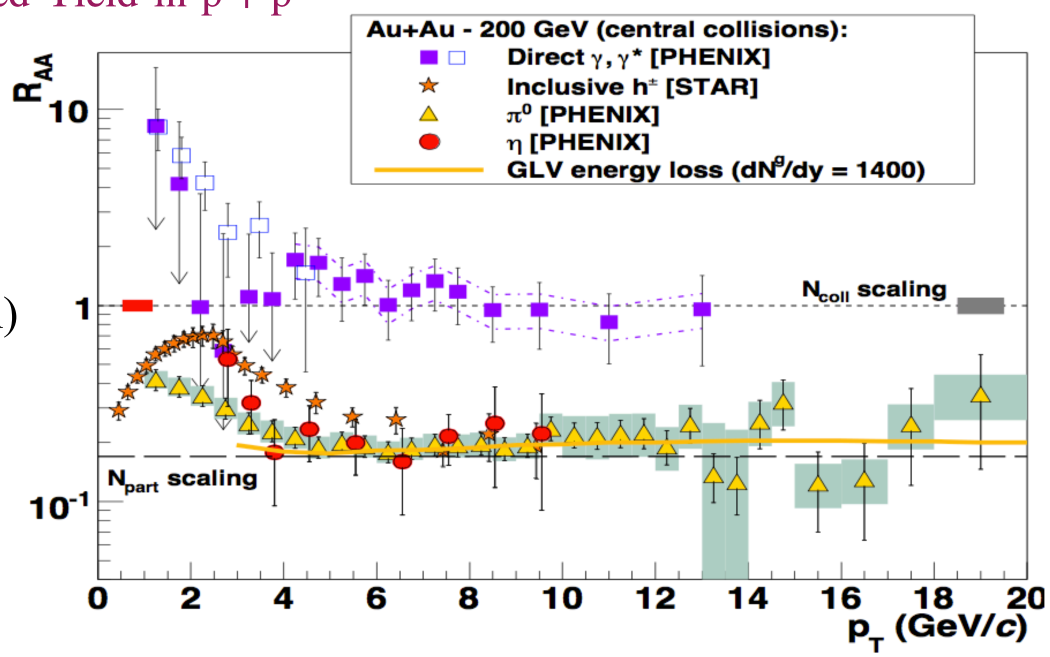
Discovery of "jet quenching" at RHIC

$$R_{AA} = \frac{\text{Yield in A + A}}{\text{Normalized Yield in p + p}}$$

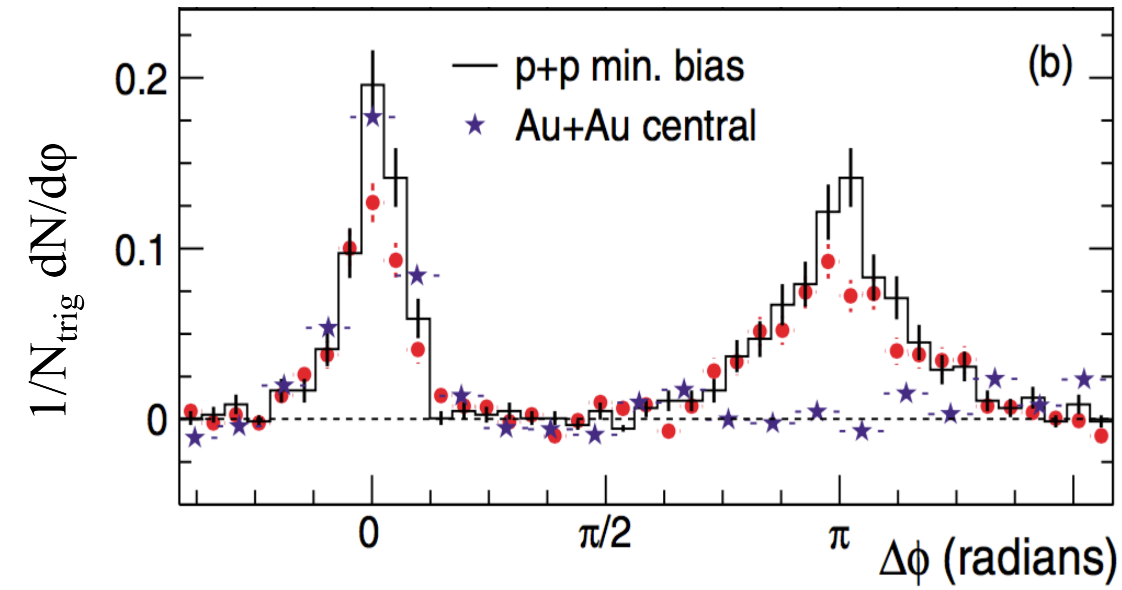
$R_{AA} > 1$
(Enhancement)

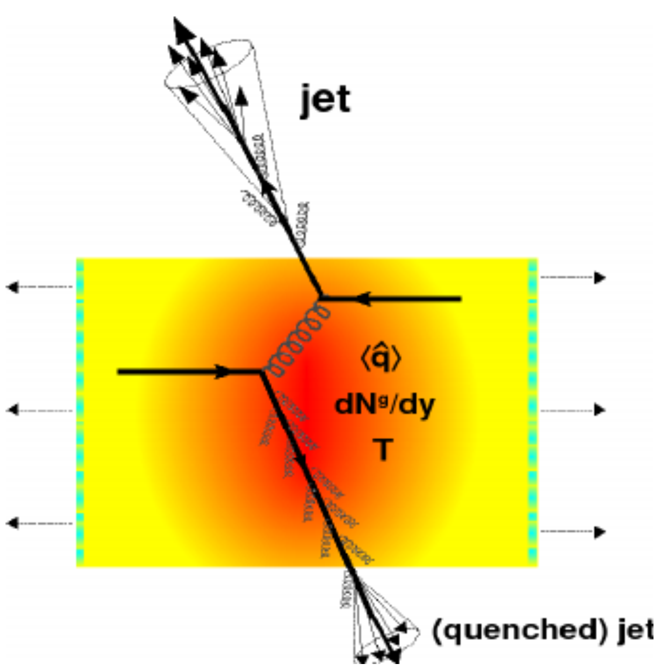
$R_{AA} = 1$
(No suppression)

$R_{AA} < 1$
(Suppression)



STAR: PRL 91, 072304 (2003)





- Suppression of inclusive charged/neutral hadrons at high-p_T
- Away-side jet suppression
- No suppression of direct photons

Confirmed at the LHC…

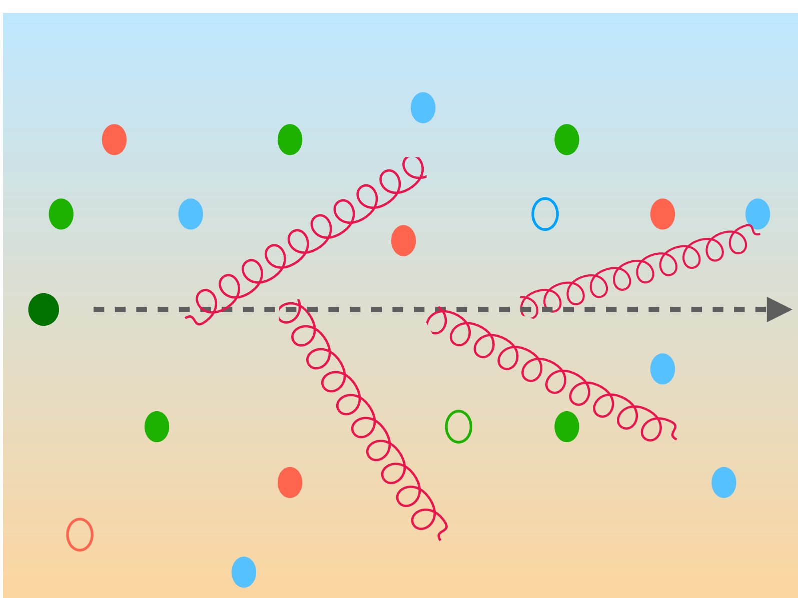
Indication of hot-dense QCD medium (QGP)

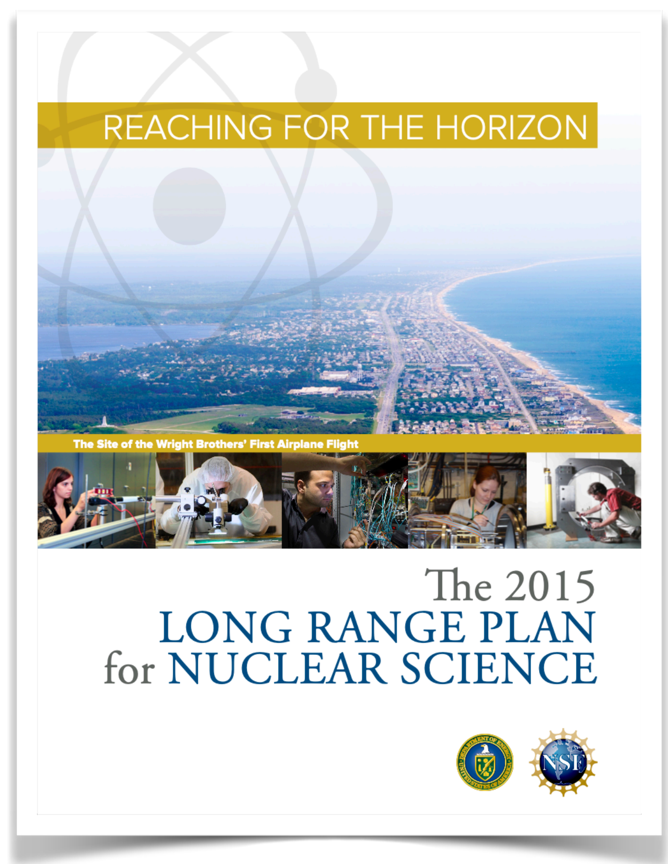
Jet quenching physics and beyond

Physics probed by jet quenching in finite-temperature QCD medium:

- What is the medium response to an excitation?
- How can we quantify the parton energy loss in the medium?
- Reduction of jet-medium coupling α_s
- Modification of jet shape inside the medium
- Large-angle deflection of recoil jet and p_T-broadening in the medium

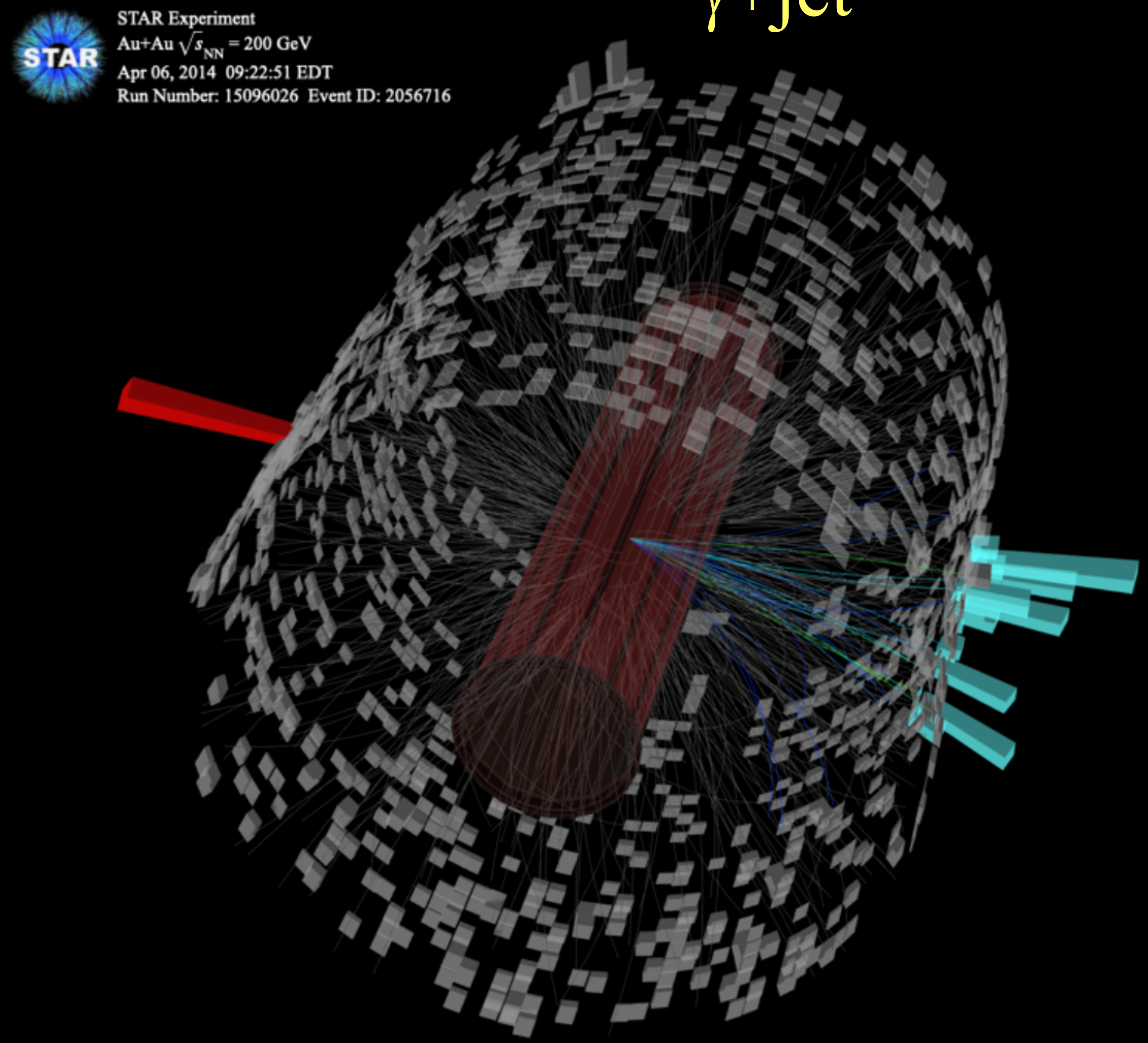
Inner workings of QGP



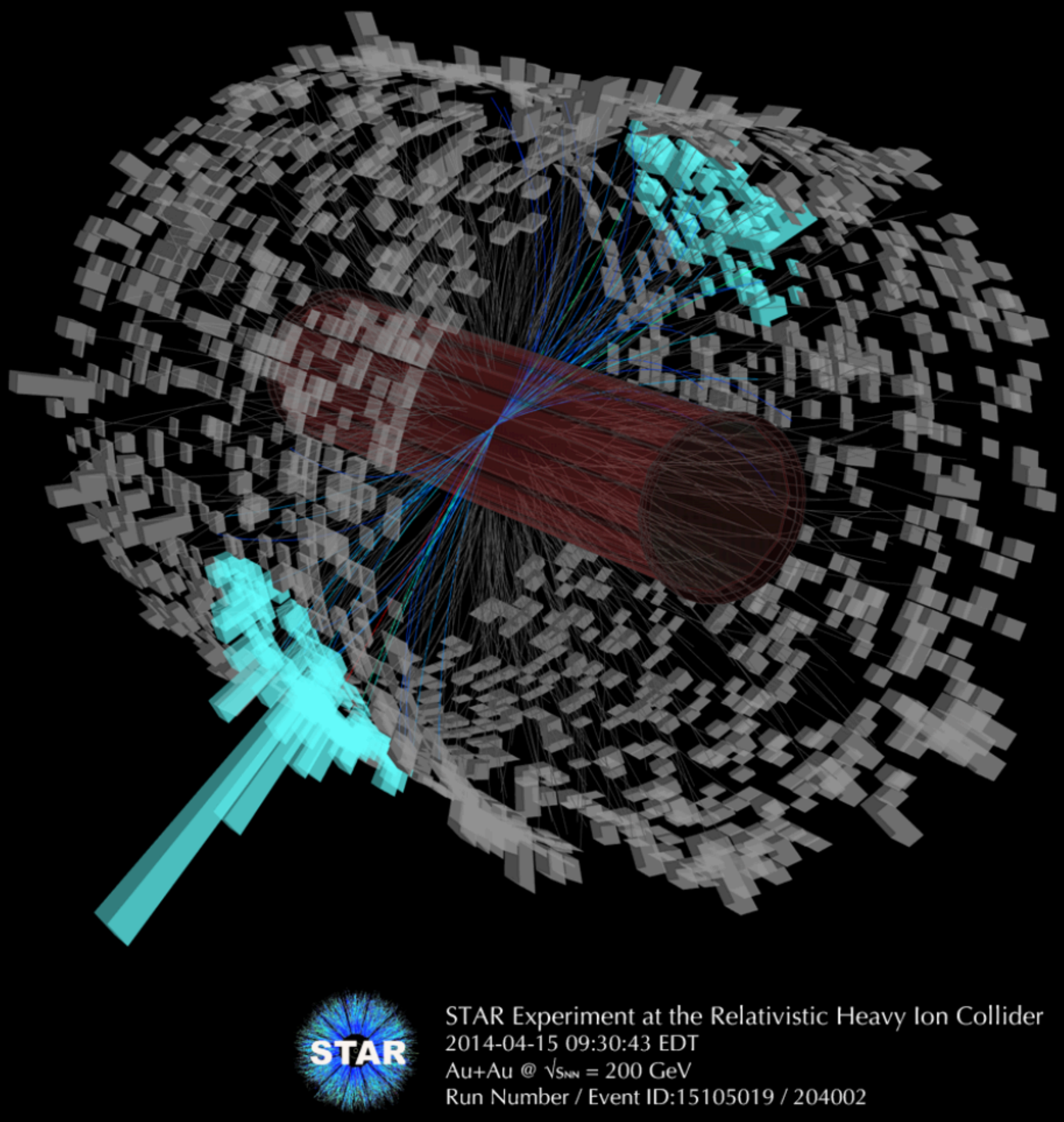


Jet program at STAR

γ+jet

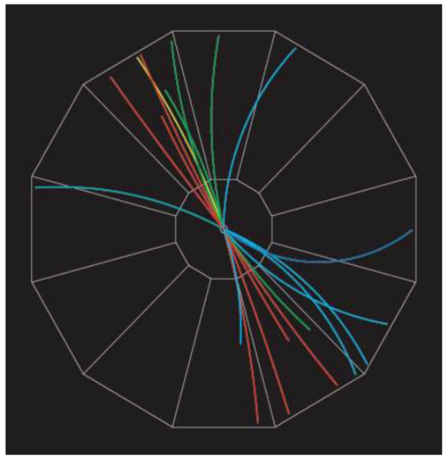


dijet



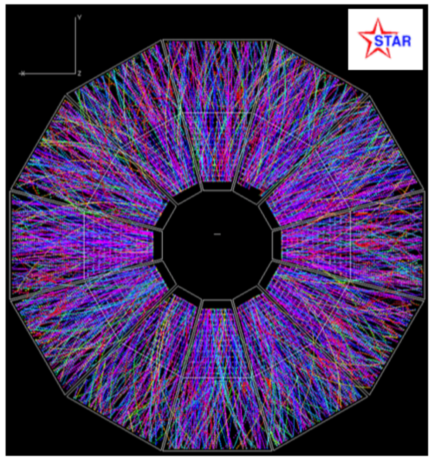
Experimental techniques to measure jets in heavy-ion collisions

pp collisions at 200 GeV



$p + p \rightarrow \text{jet} + \text{jet}$

AuAu collisions at 200 GeV



$\text{Au} + \text{Au} \rightarrow \text{X}$

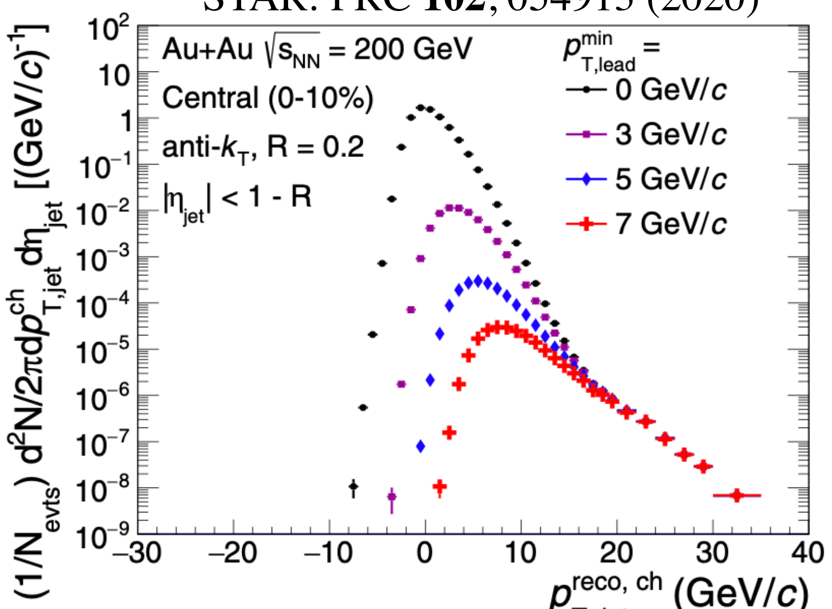
- In heavy-ion collisions: large uncorrelated soft background

  Different techniques used to mitigate and correct

Using minimum leading constituent $p_{\rm T}$ cut-off

Inclusive jet measurement

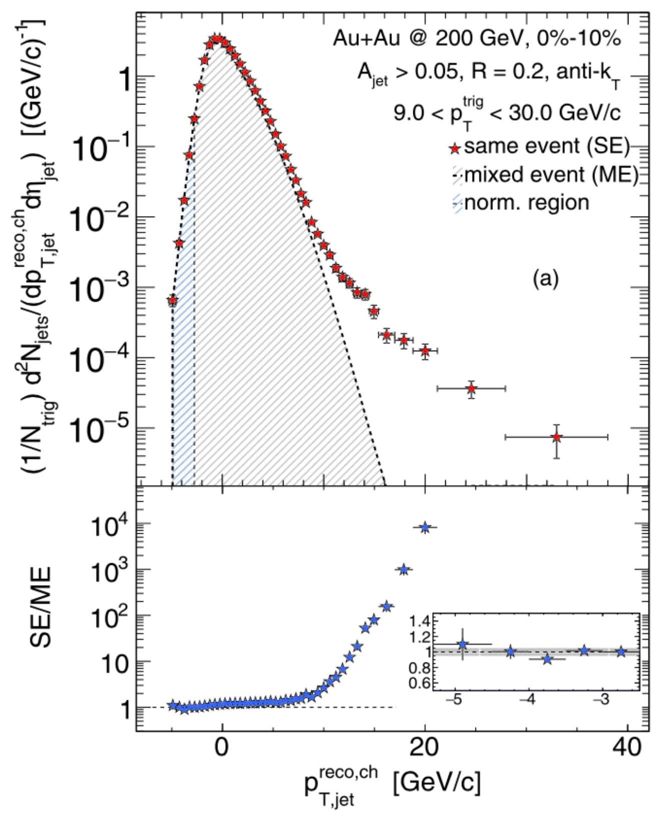
STAR: PRC **102**, 054913 (2020)



Using mixed event

Semi-inclusive jet measurement

STAR: PRC 96, 024905 (2017)



- Unfolding procedure to correct jet $p_{\rm T}$ spectra

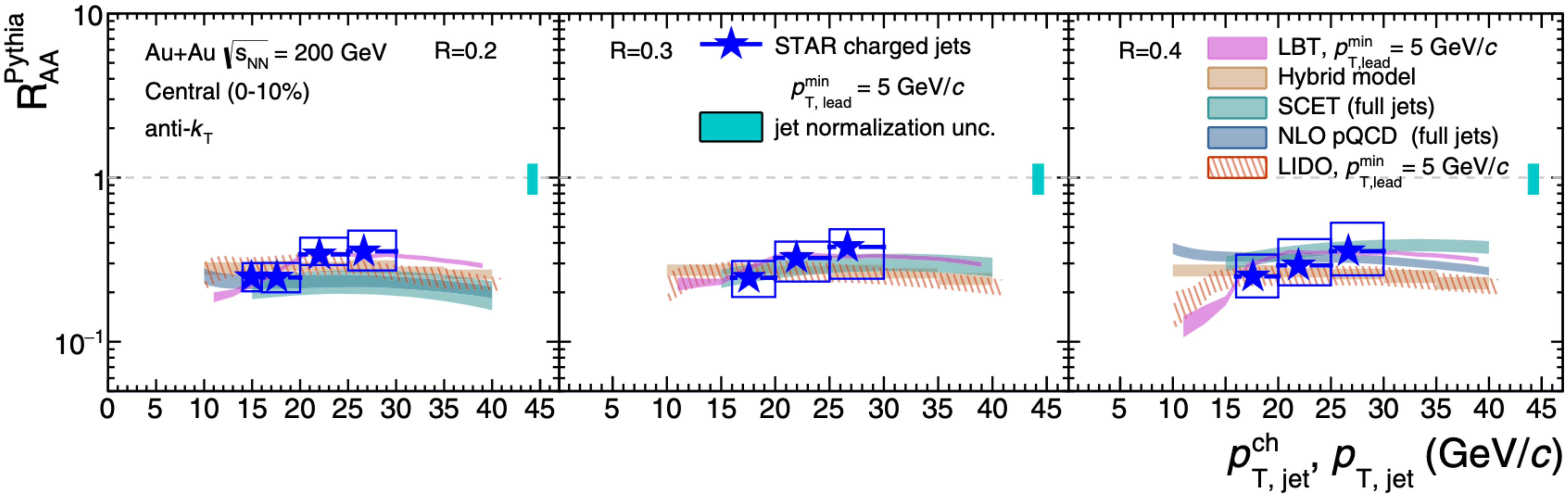
  By factorizing heavy-ion background and detector effects

Inclusive charged-jet suppression at RHIC

$$R_{AA}^{Pythia}(p_{T,jet}) = \frac{1}{< T_{AA} >} \frac{Y(p_{T,jet})^{AA}}{Y(p_{T,jet})^{pp-Pythia}}$$

$< T_{AA} > \rightarrow$ Nuclear thickness factor

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



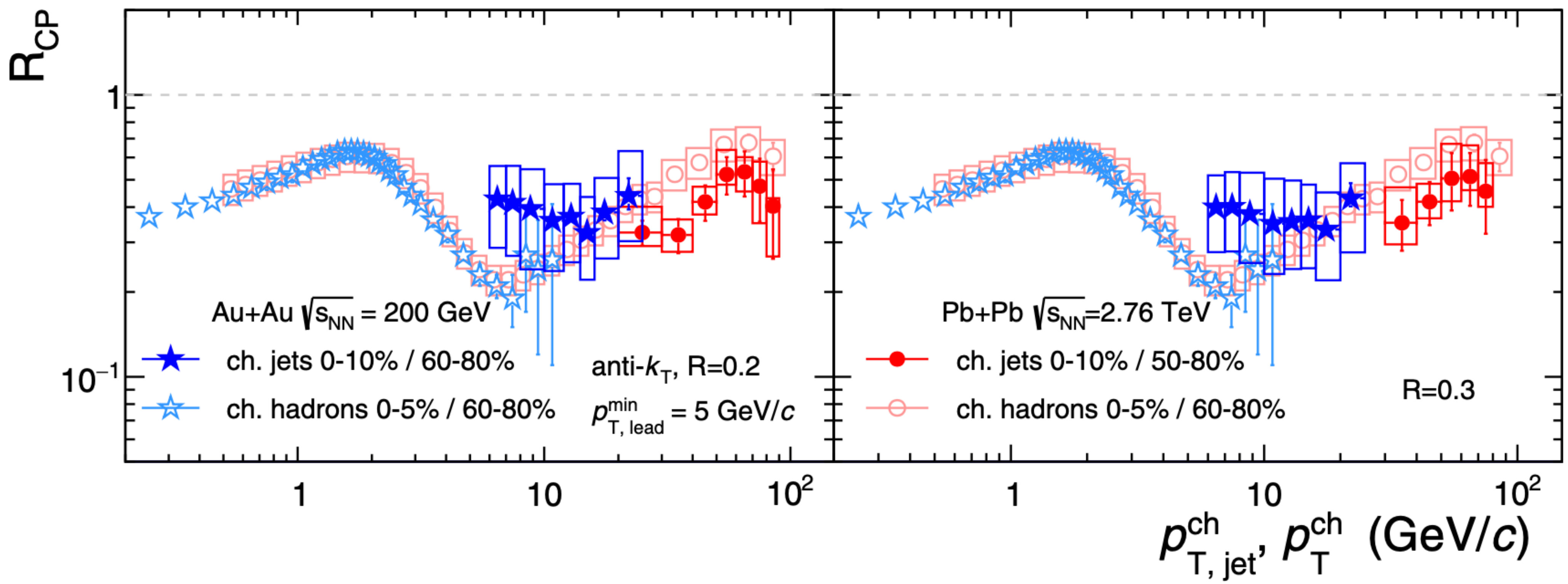
- Strong suppression of inclusive charged-jet yield in central collisions
- R_{AA} shows no jet R dependence
- Different theory predictions consistent with the data (within uncertainties)

Inclusive charged-jet suppression (RHIC vs. LHC)

$$R_{CP}\,(p_{T,jet}) = \frac{1}{< T_{AA} >} \frac{Y(p_{T,jet})^{central}}{Y(p_{T,jet})^{peripheral}}$$

$< T_{AA} > \rightarrow$ Nuclear thickness factor

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

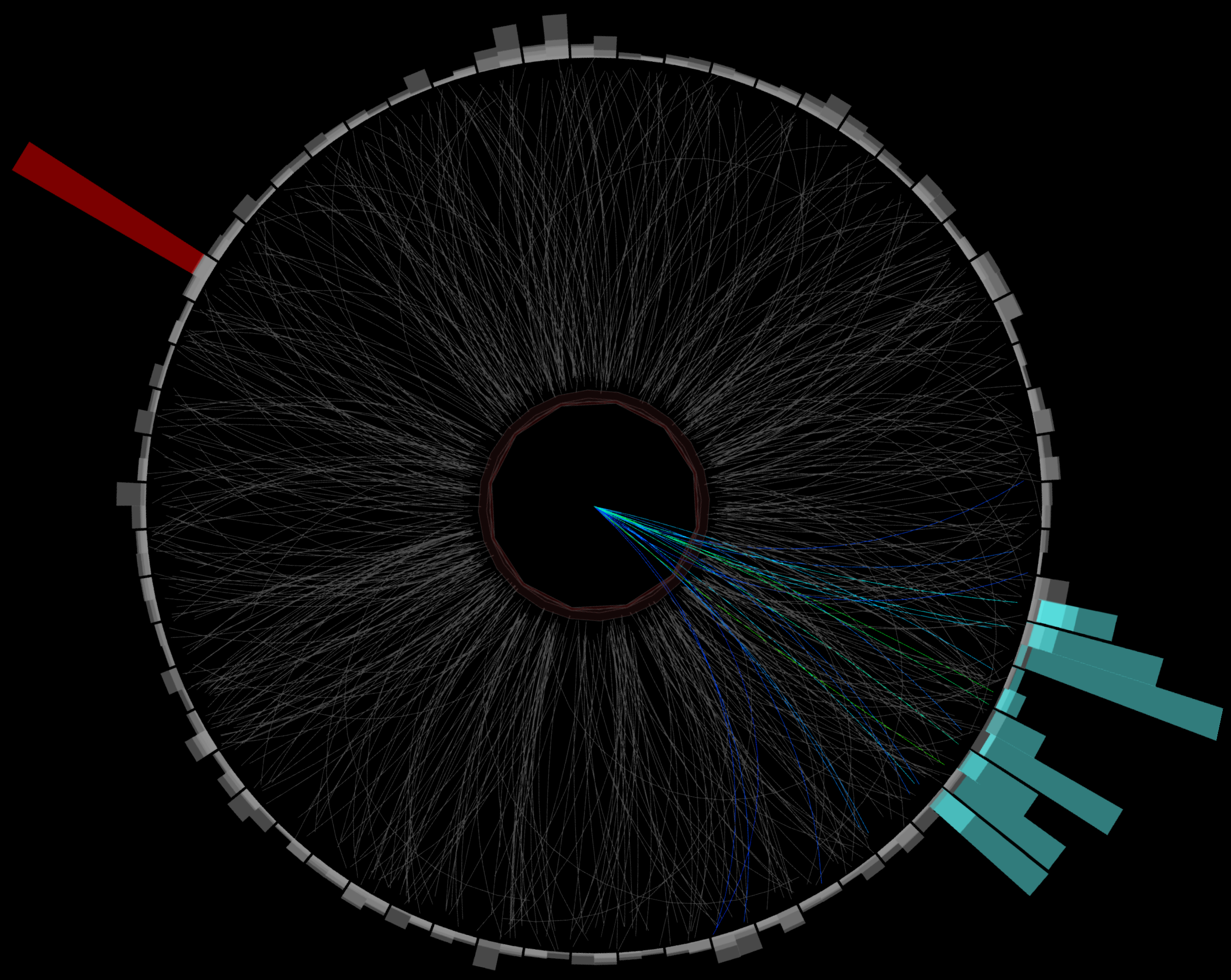


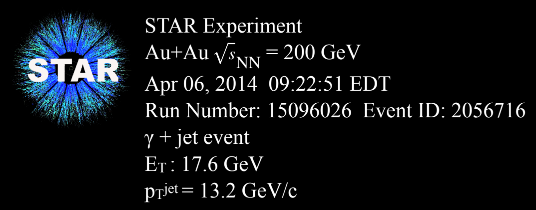
- Strong suppression of inclusive charged-jet yield in central with respect to peripheral collisions
- R_{CP} shows no jet R dependence
- Similar level of suppression between inclusive charged hadron and jet yield (within the same p_T interval)
- Same level of suppression at RHIC and the LHC (although different p_T interval)

Full jet R_{CP} measurement will access higher jet p_T at RHIC.

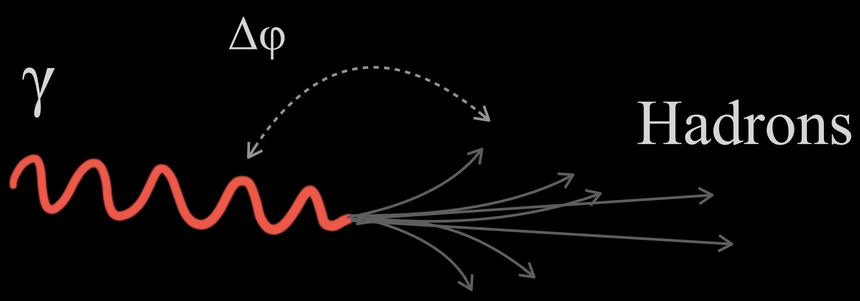
γ+jet measurement at RHIC

STAR γ+jet event display

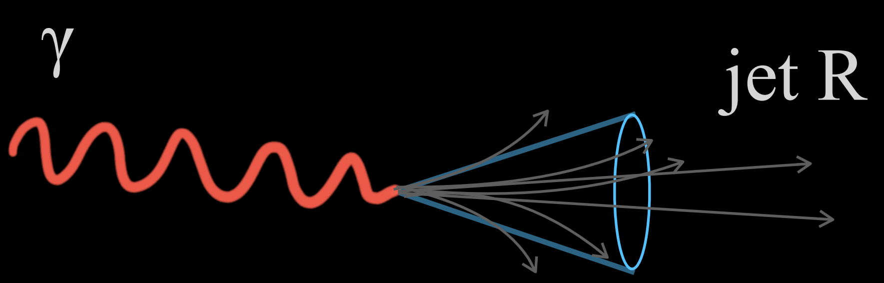




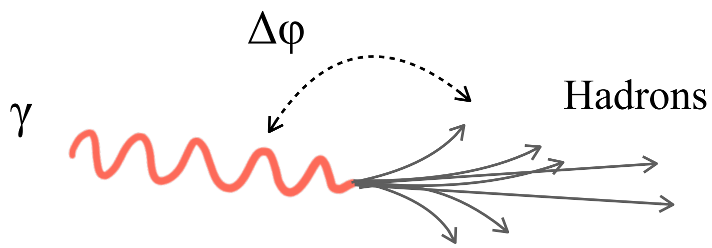
Jet-like γ+hadron correlation



γ+Jet reconstruction



RHIC jet-like γ+hadron correlations measurements

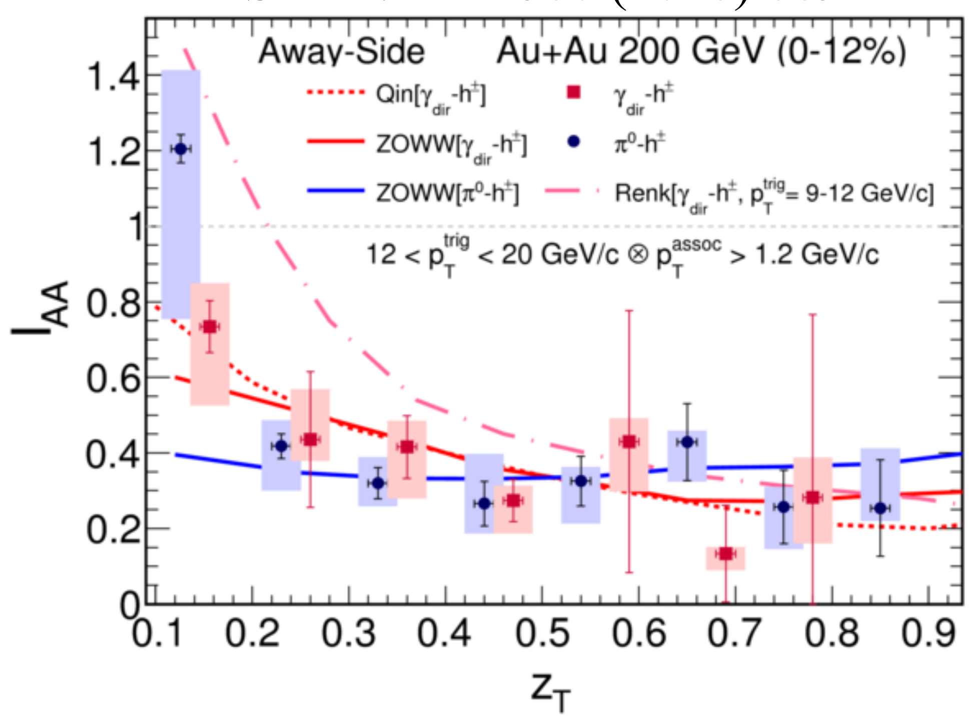


$$I_{AA}(z_T) = \frac{Y(z_T)^{A+A}}{Y(z_T)^{p+p}}$$

$$z_T = \frac{p_T^{assoc}}{p_T^{trig}}$$

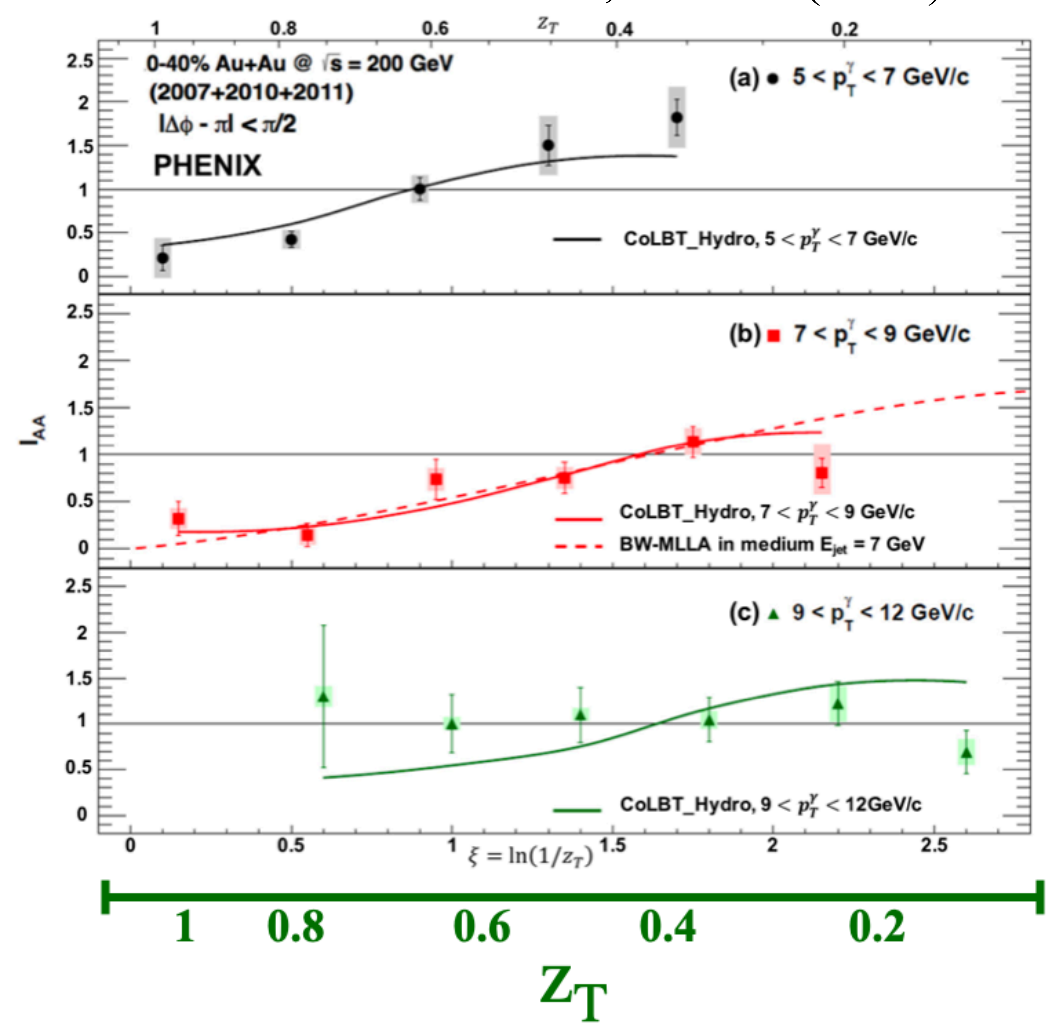
p_T^{γ}: 12-20 GeV

STAR: PLB 760 (2016) 689



p_T^{γ}: 5-12 GeV

PHENIX: PRC **102**, 054910 (2020)

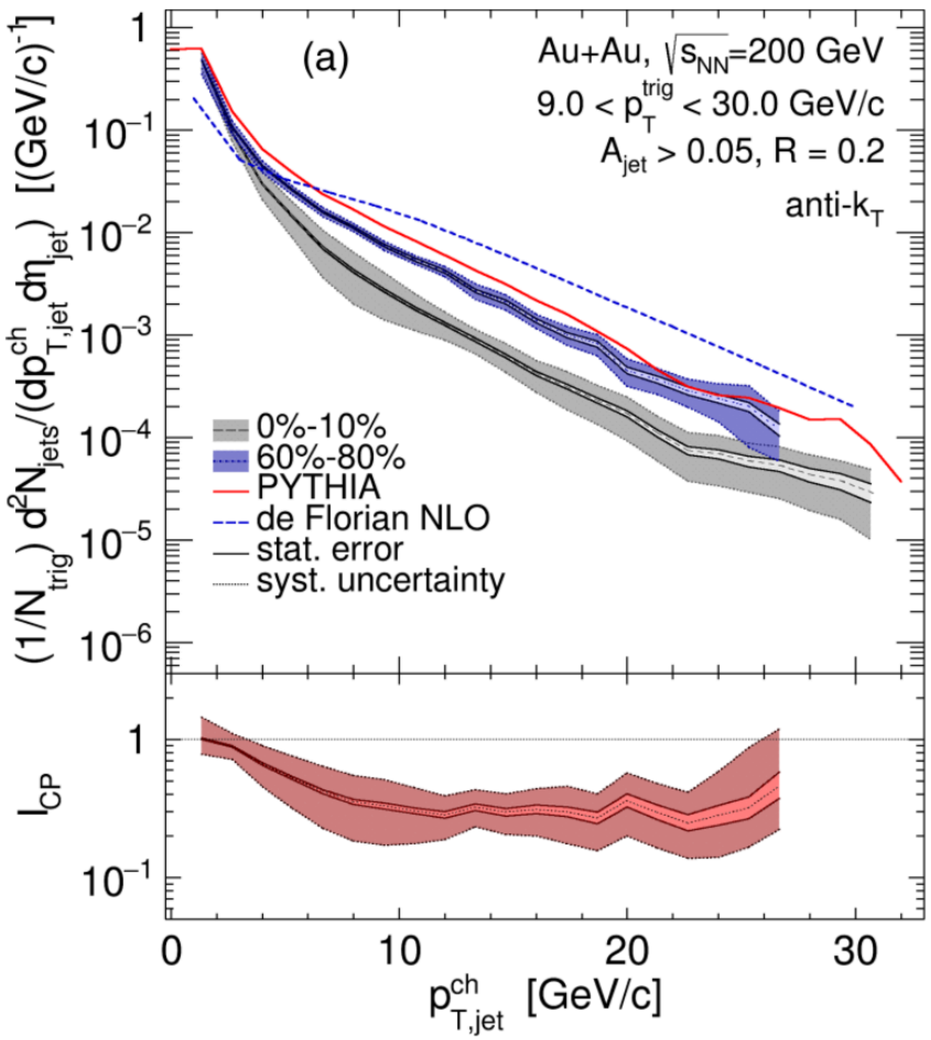


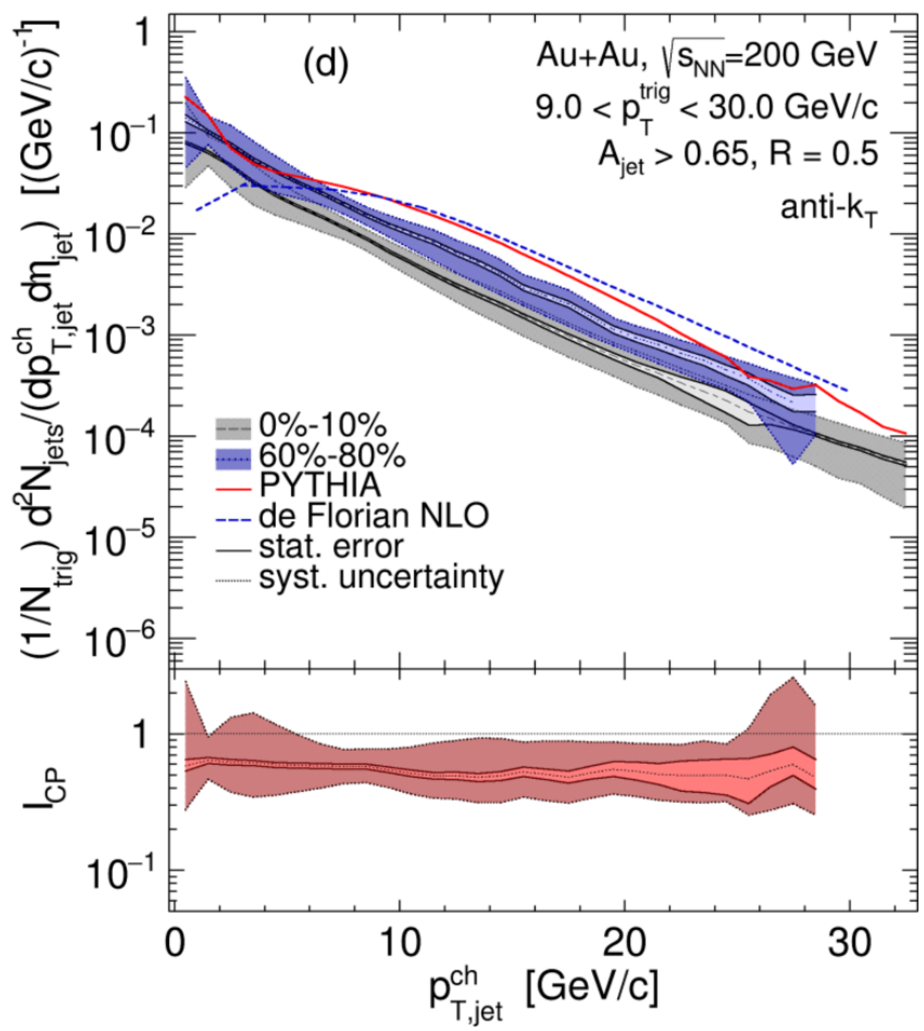
- Strong suppression at high z_T
- A tendency of enhancement (> 1) towards low z_T (soft particles)
- CoLBT-hydro: jet-induced medium excitations → thermal nature of the produced soft particles

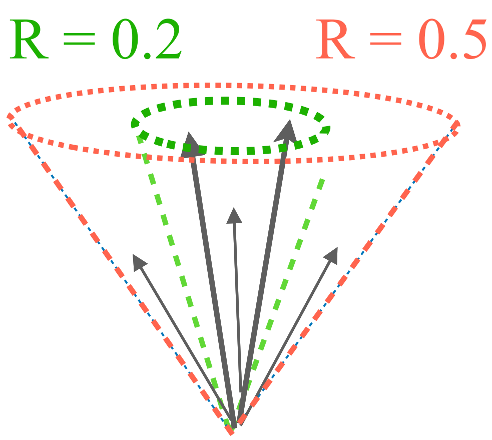
Semi-inclusive h+jet measurement

STAR: PRC 96, 024905 (2017)

STAR experiment



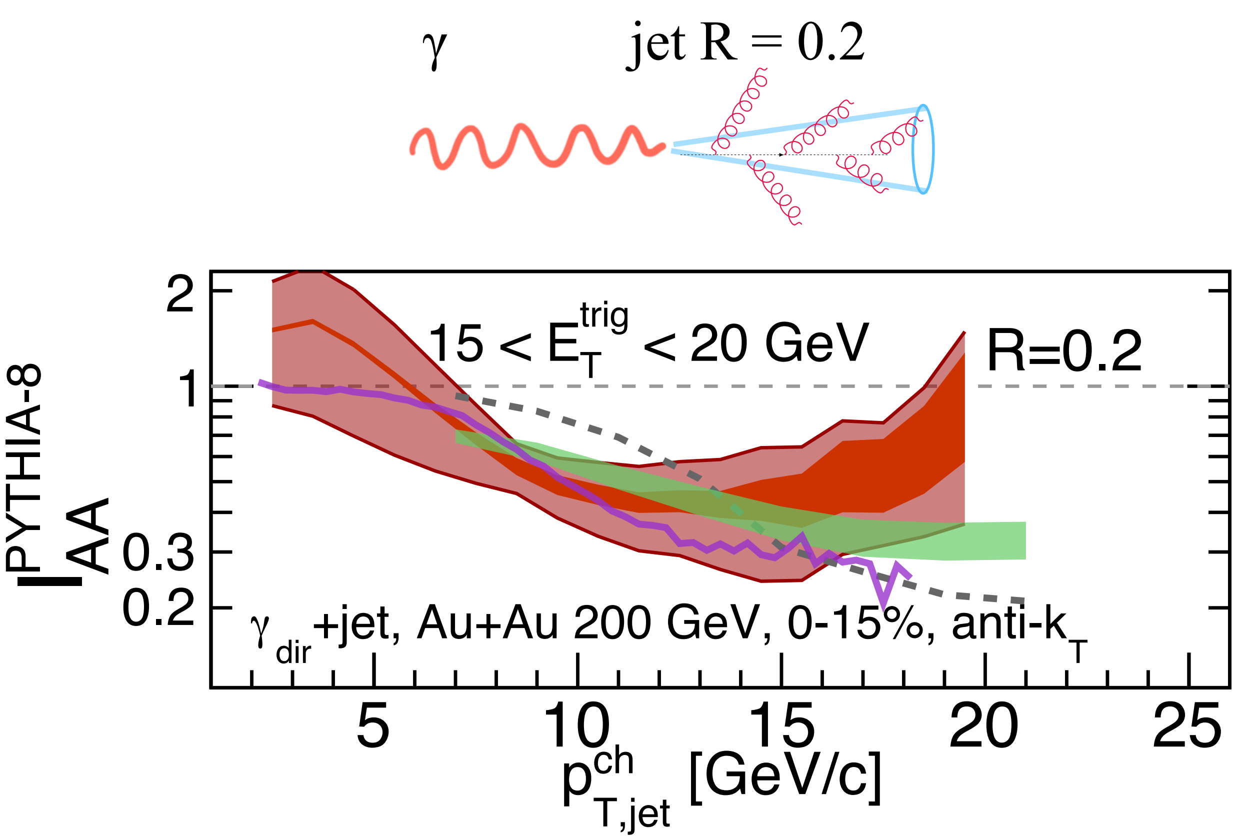


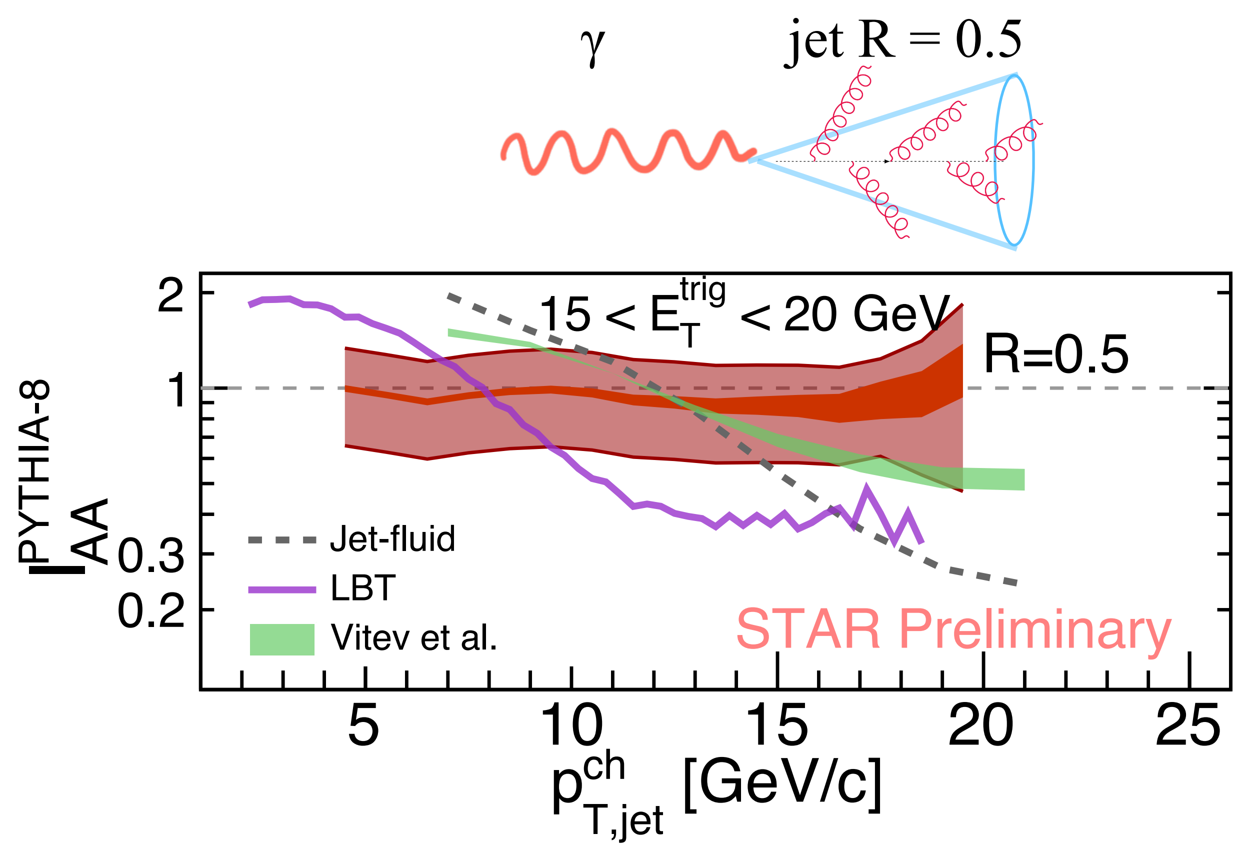


- I_{CP} shows p_T-dependence of suppression
- Within uncertainty, I_{CP} is consistent for two jet radii

Semi-inclusive γ+jet measurement

STAR experiment





- p_T-dependence of suppression is different between theory predictions and data
- A hint of jet *R* dependence of suppression

Expect improvement in precision with data-taking in Run23-25

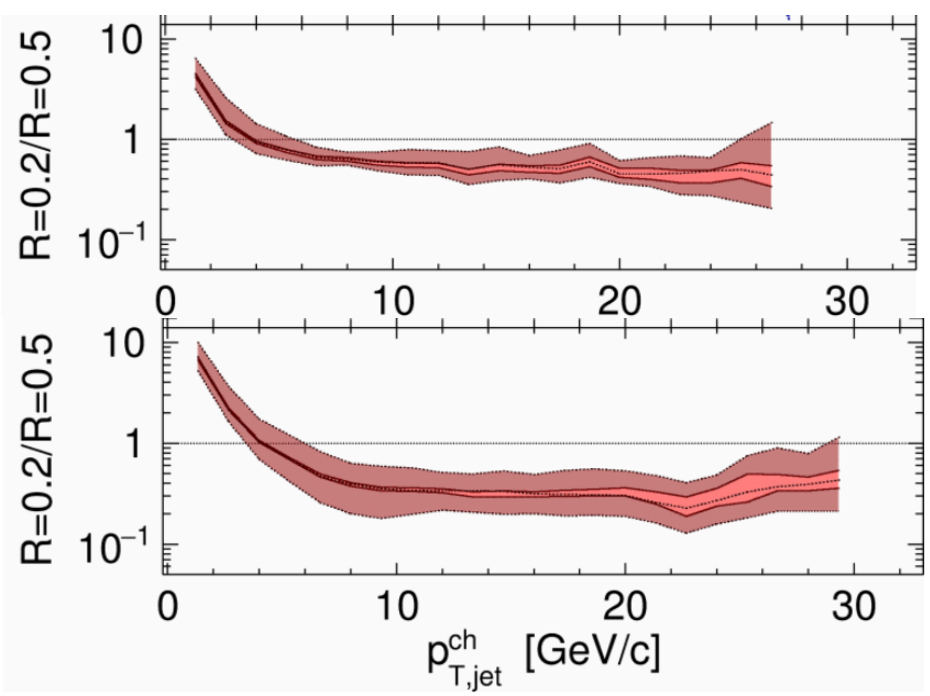
Jet-fluid: jet shower + medium response [Chang, et al., PRC 94 (2016), 024902]
LBT: coupled LBT+hydro [Chen, et al., PLB 777 (2018) 707]
Vitev: Soft Collinear Effective Theory [Sievert, et al., PLB 795 (2019) 502]

Intra-jet broadening in heavy-ion collisions

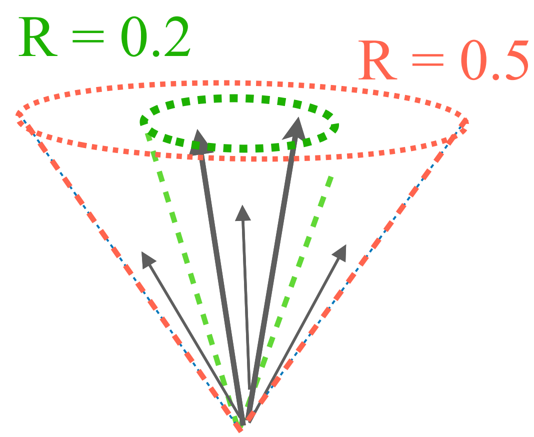
Yield ratio for R=0.2 to 0.5 and comparison between A+A and p+p

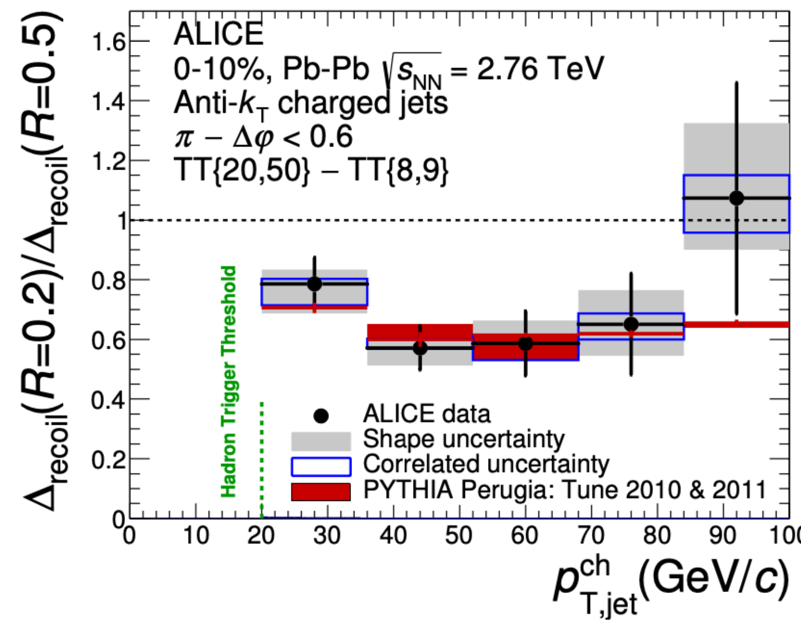
LHC/ALICE measurement Pb+Pb 2.76 TeV

STAR semi-inclusive h+jet



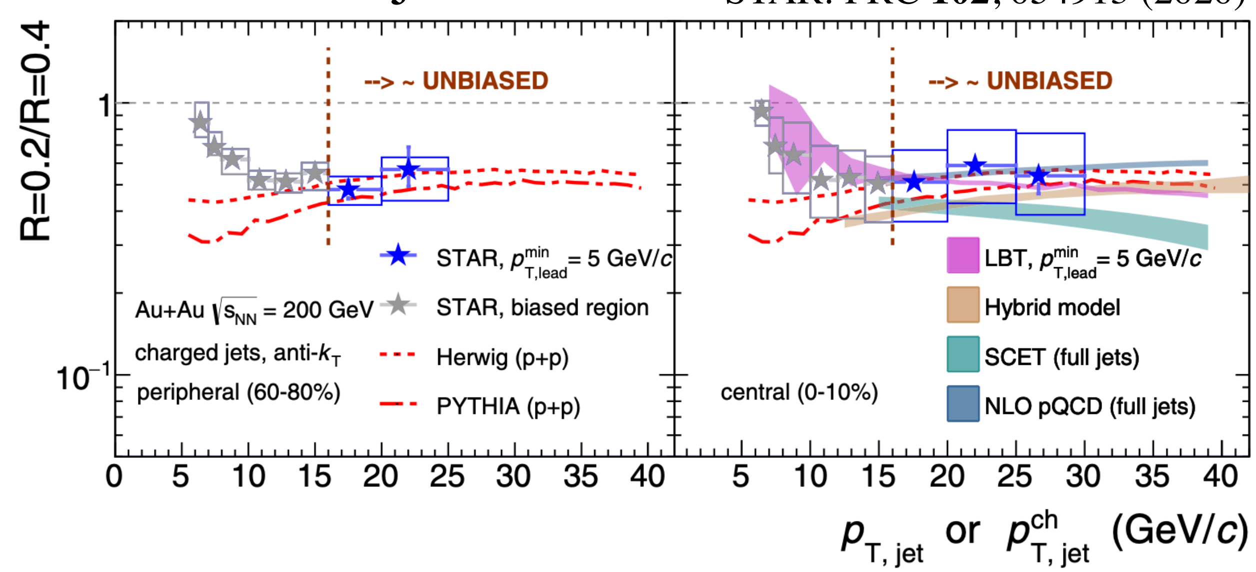
Jet-shape: spread of energy inside a jet





Inclusive jet

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



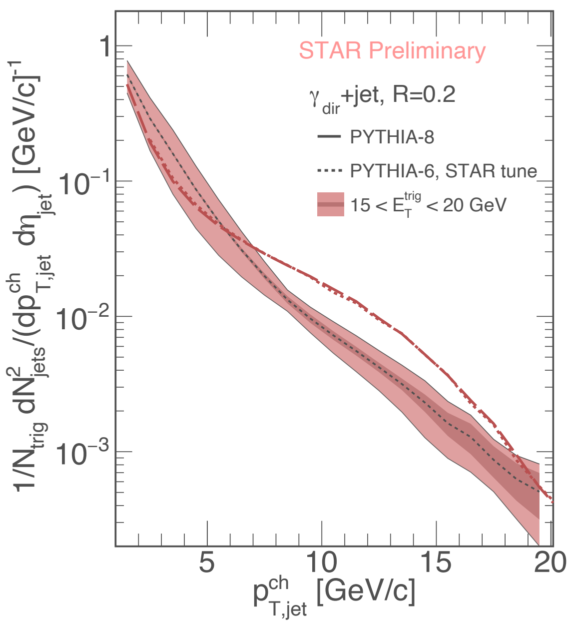
No hints of intra-jet broadening in central heavy-ion collisions at RHIC and the LHC

Parton energy loss: RHIC vs LHC jet measurements

Let us investigate recent measurements of jet yield suppression at RHIC and LHC.

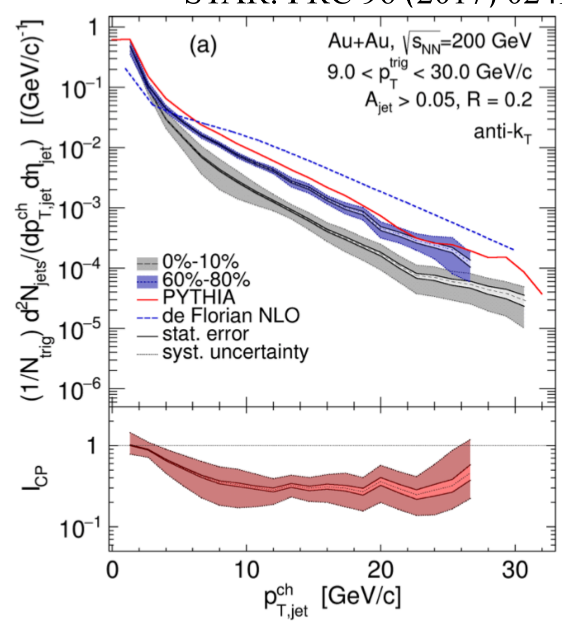
STAR/RHIC

Semi-inclusive γ+jet

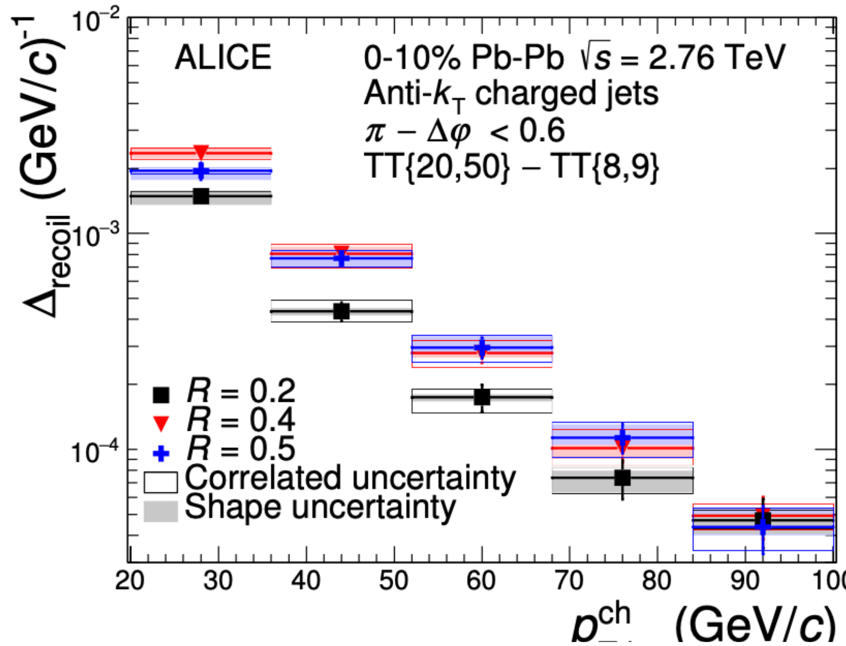


Semi-inclusive h+jet

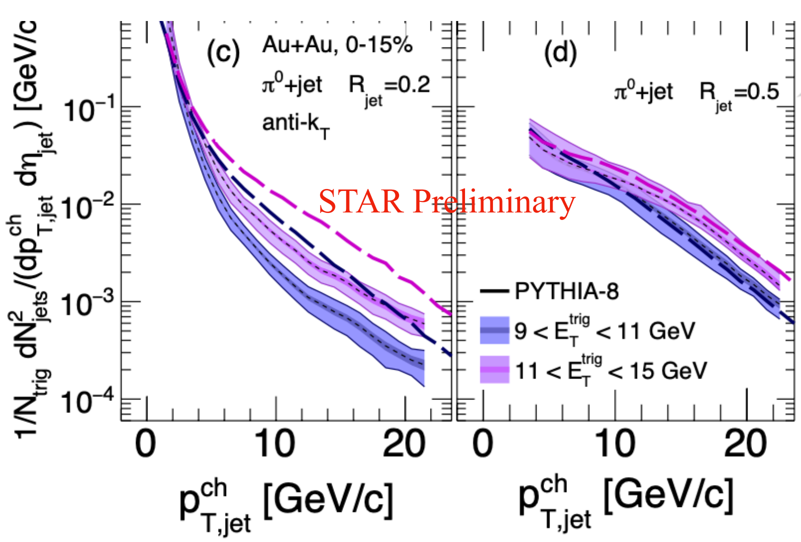
STAR: PRC 96 (2017) 024905



Semi-inclusive h+jet

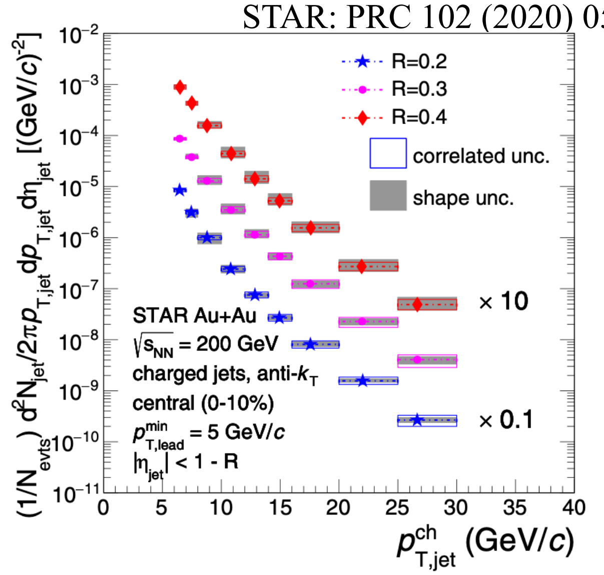


Semi-inclusive π^0+jet



Inclusive jet

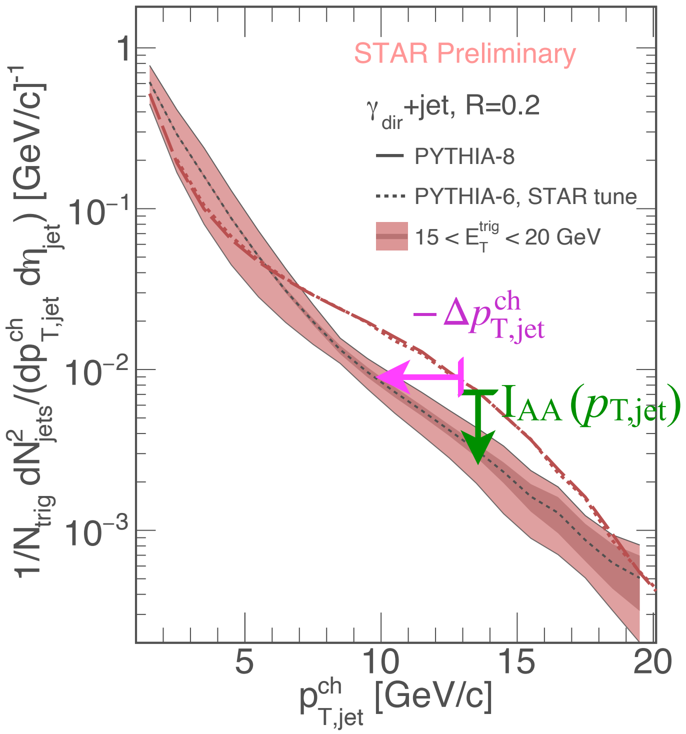
STAR: PRC 102 (2020) 054913

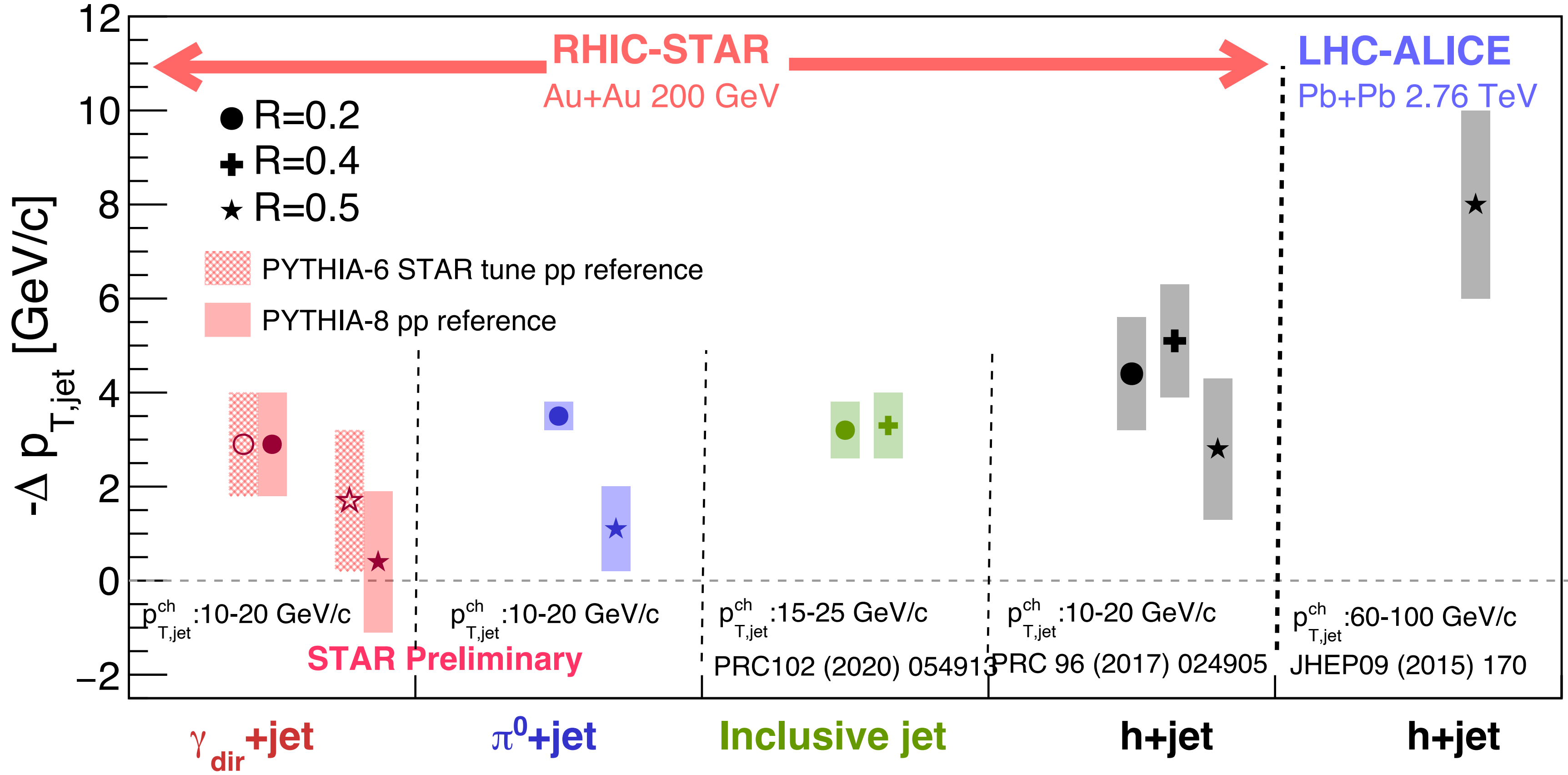


Calculate horizontal jet p_T shift from all these measurements

Charged jet p_T-spectrum shift : RHIC vs. LHC

Characterization of average out-of-cone parton energy loss





Another way to quantify jet-quenching:

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

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

Note:

- $p_{T,jet}$ ranges at RHIC and the LHC are different in the plot
- Only charged-jets are compared here

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

RHIC Jet results in a nutshell

- Jet-induced medium excitations and parton energy loss in QGP
- A hint of jet R dependence of suppression
- An indication of smaller in-medium energy loss at RHIC than the LHC

Future exploration:

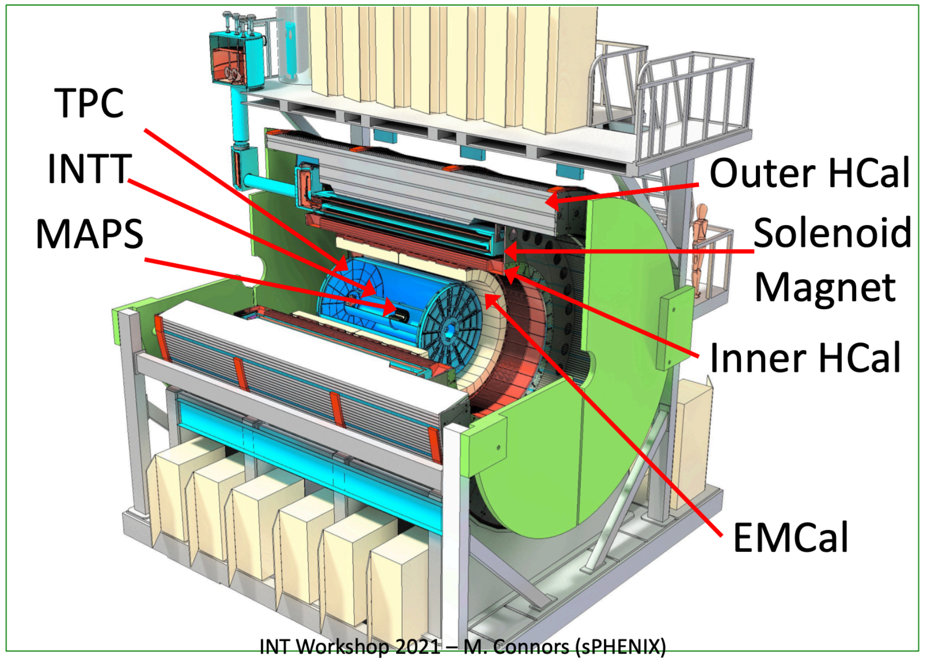
- Certainly need precision measurements at RHIC
- Also need to explore new measurement

Upcoming RHIC experiments and data-taking plan

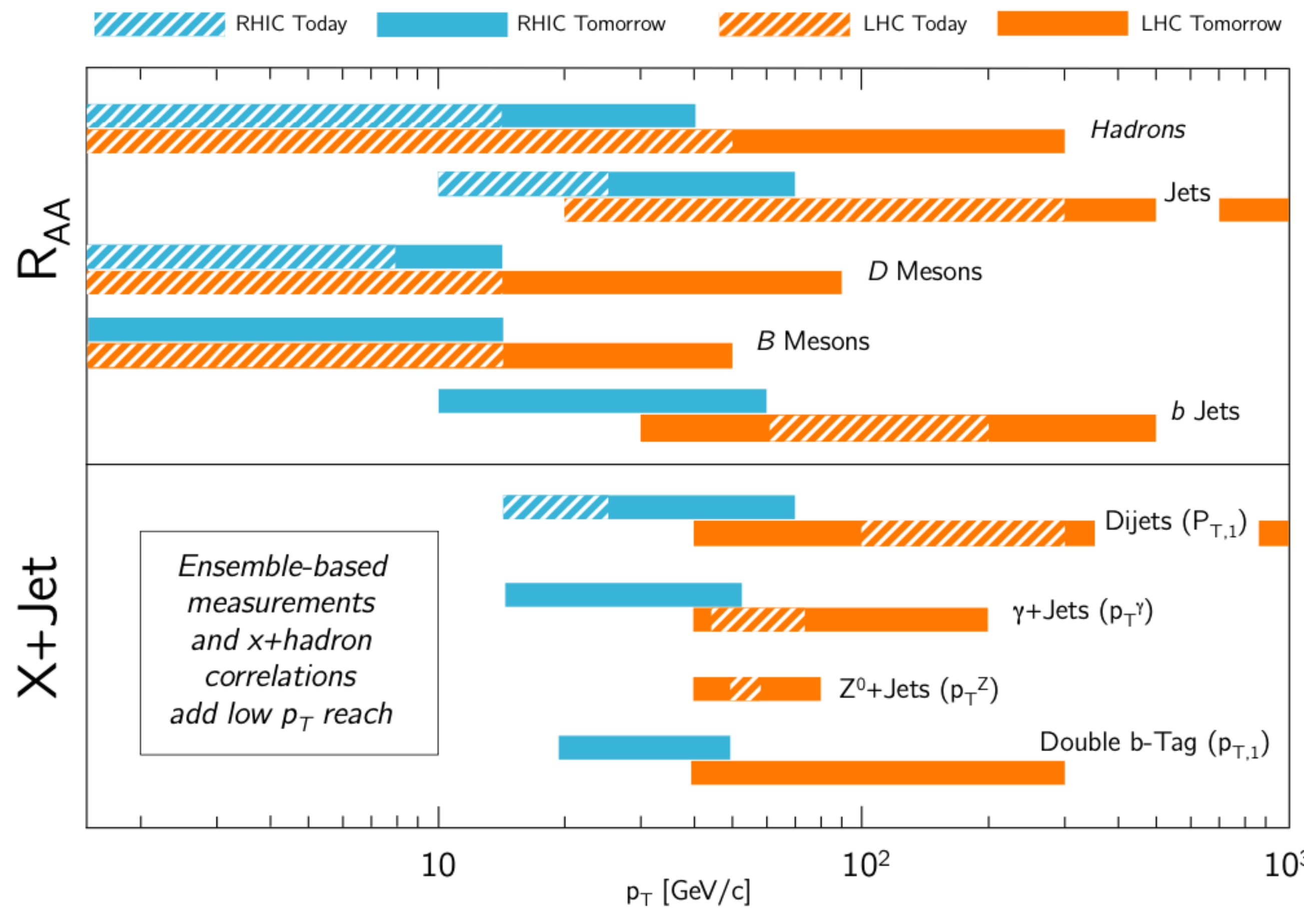
New sPHENIX experiment at RHIC

Brand new experiment

sPHENIX detectors



RHIC and LHC complementarity



Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\|z\|<10$ cm	Samp. Lum. $\|z\|<10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

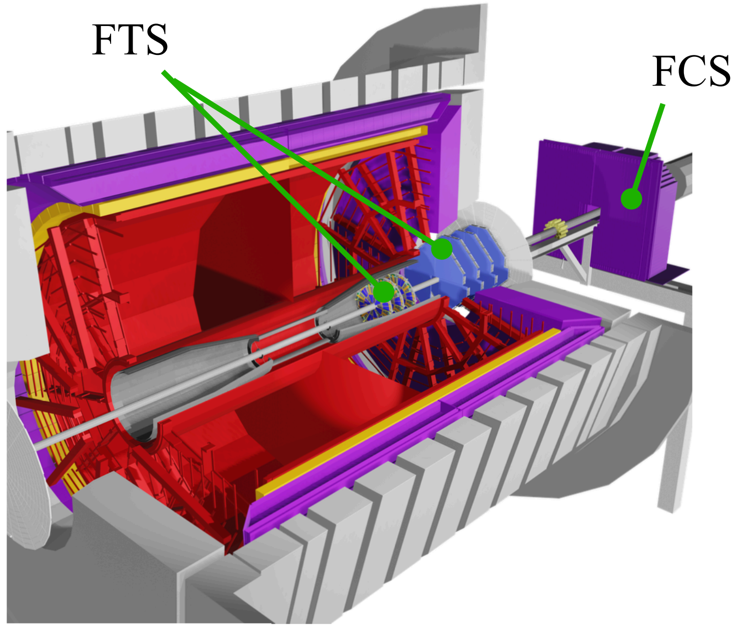
Megan Connors (GSU): INT workshop 2021

Precision hard probes measurements

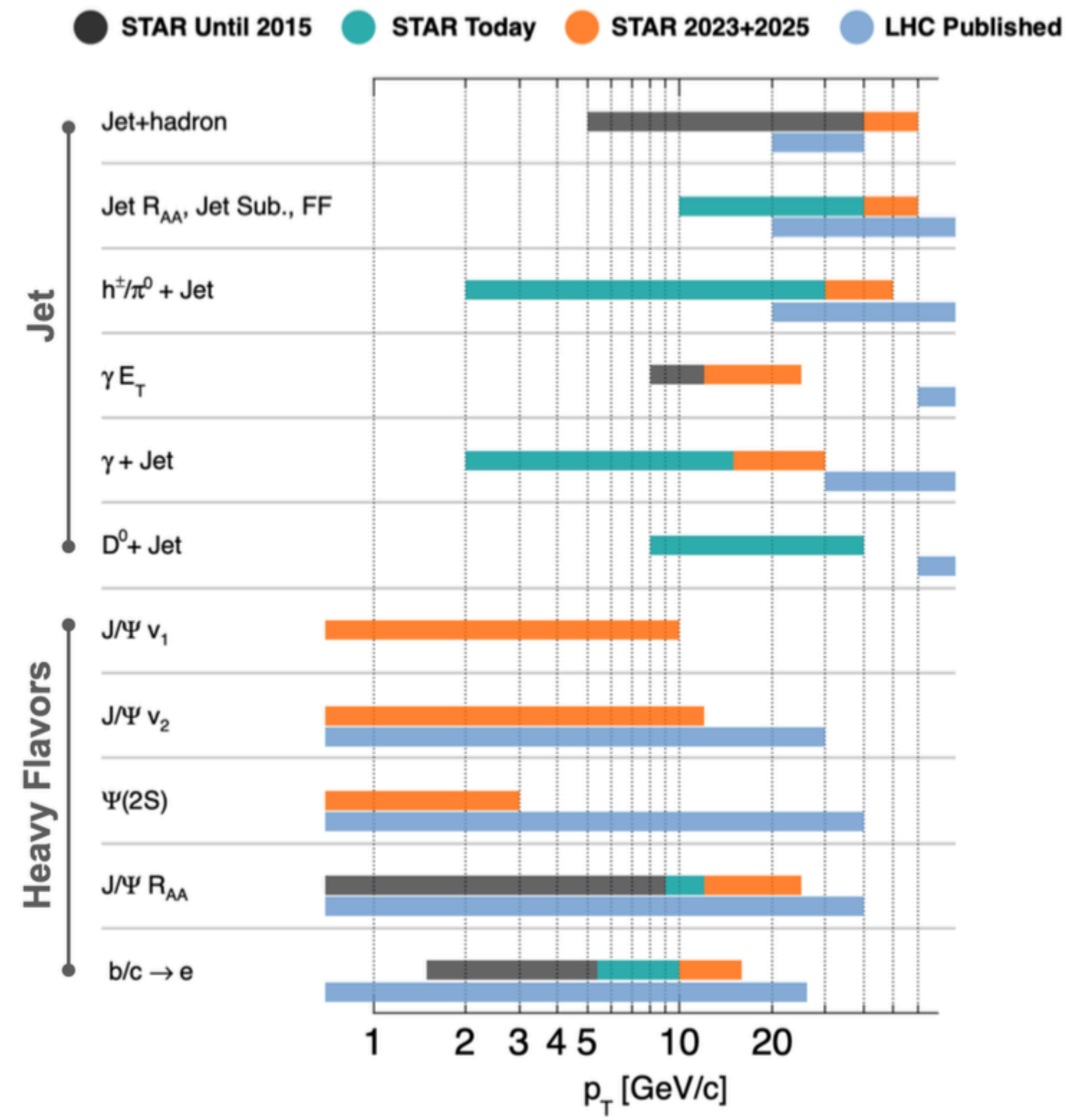
γ+jet, dijet, heavy-flavor jets, etc.

STAR 2023-2025 run plan and physics program

STAR experiment and its forward detector upgrade



Kinematic coverage for hard-probes



Run plan

2021	2022	2023	2024	2025
Completion of BES-II [FXT program]	**p+p 510 GeV** [16 Cryo-weeks] 400 pb^{-1}	**Au+Au** $\sqrt{s_{NN}}$ **= 200 GeV** [28 Cryo-weeks] 31 pb^{-1}	**p+p** $\sqrt{s}$ **= 200 GeV** [28 Cryo-weeks] 235 pb^{-1} **p+Au** $\sqrt{s_{NN}}$ **= 200 GeV** 1.3 pb^{-1}	**Au+Au** $\sqrt{s_{NN}}$ **= 200 GeV** [28 Cryo-weeks] 31 pb^{-1}

|⟵ STAR forward detectors upgrade ⟶ (2022–2025)

It includes Hot-QCD and Cold-QCD STAR programs.

- Hot-QCD program: Study the microstructure of the QGP
  Precision jet and heavy-flavor measurements

Summary and outlook

- p+p measurements to study vacuum shower and baseline for heavy-ion measurements
- Learn important information on jet-medium interaction in the QGP
- Need of precision measurements at RHIC

sPHENIX with precision measurements and STAR experiments complement
to study finite temperature QCD medium in upcoming RHIC runs

New RHIC results will be shown at Quark Matter 2022 in Poland.

Thank you!