sPHENIX

Beam Use Request for Runs 23-25

BNL NPP Physics Advisory Committee (PAC) Meeting

2 June 2022

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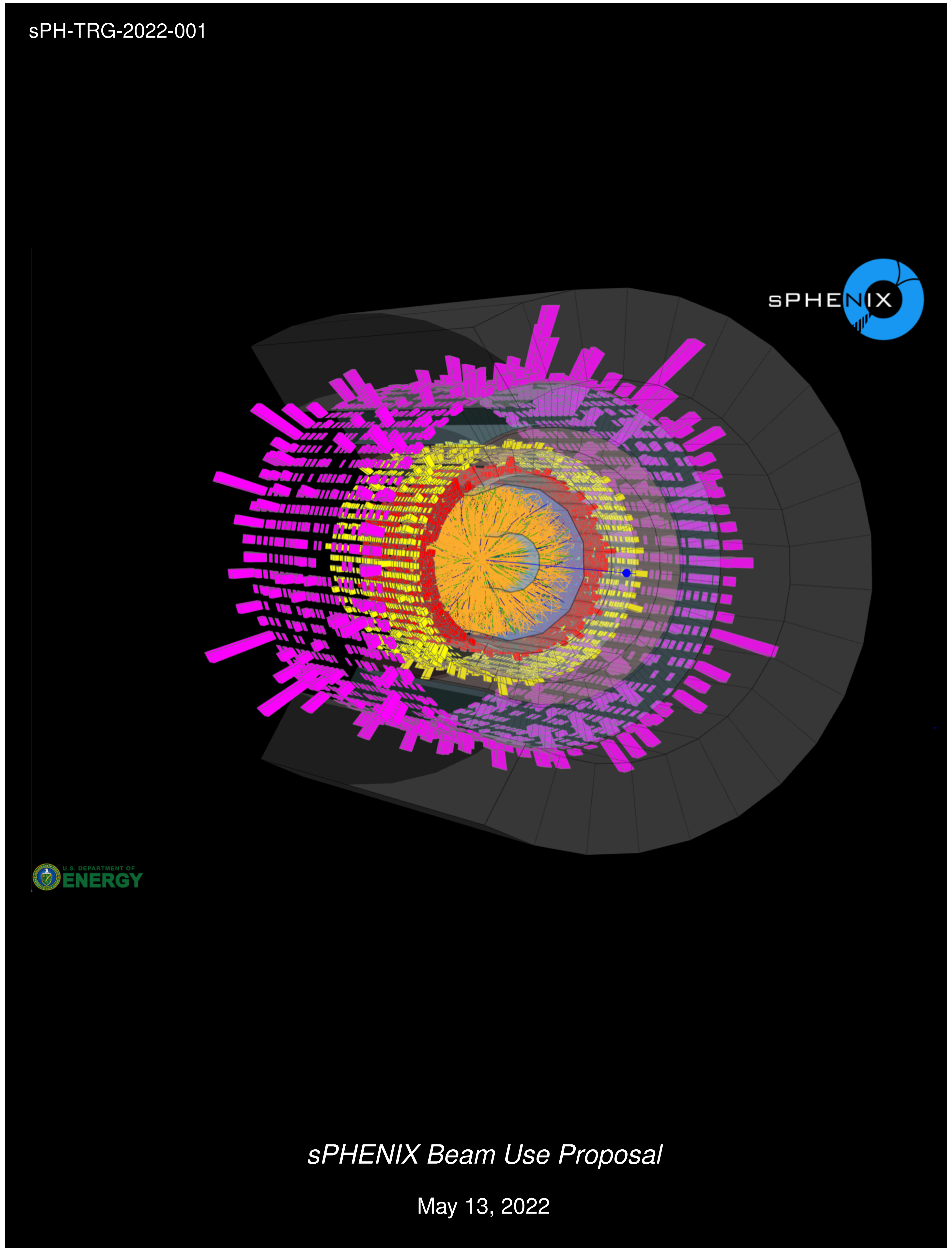


sPHENIX science

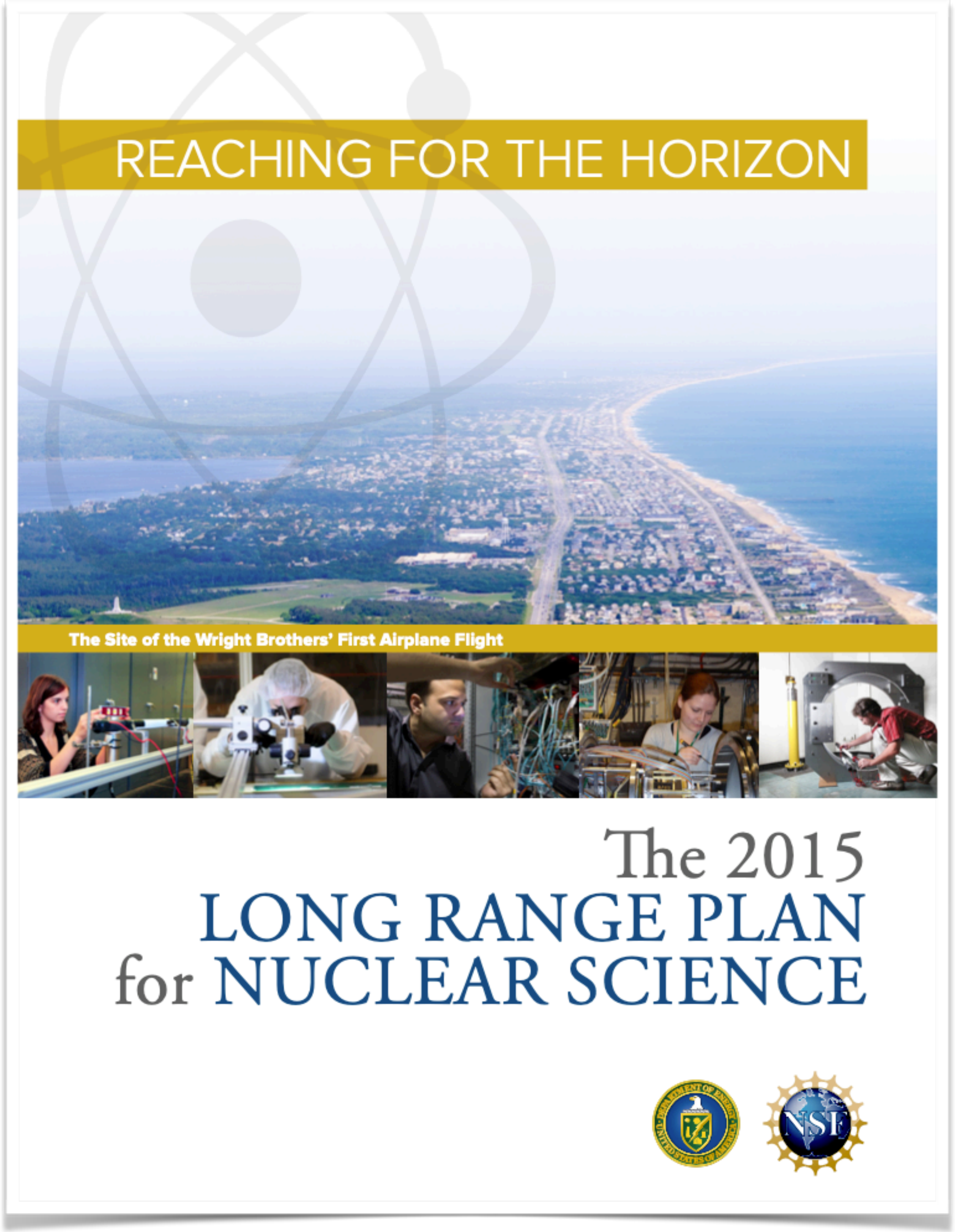
sPHENIX is the first new detector at *any* hadron collider in over a decade!

sPHENIX has unique, purpose-built capabilities never before deployed at RHIC

sPHENIX is going to put the remarkable QGP under a state-of-the-art microscope …

…and complete the scientific journey started at RHIC over twenty years ago!

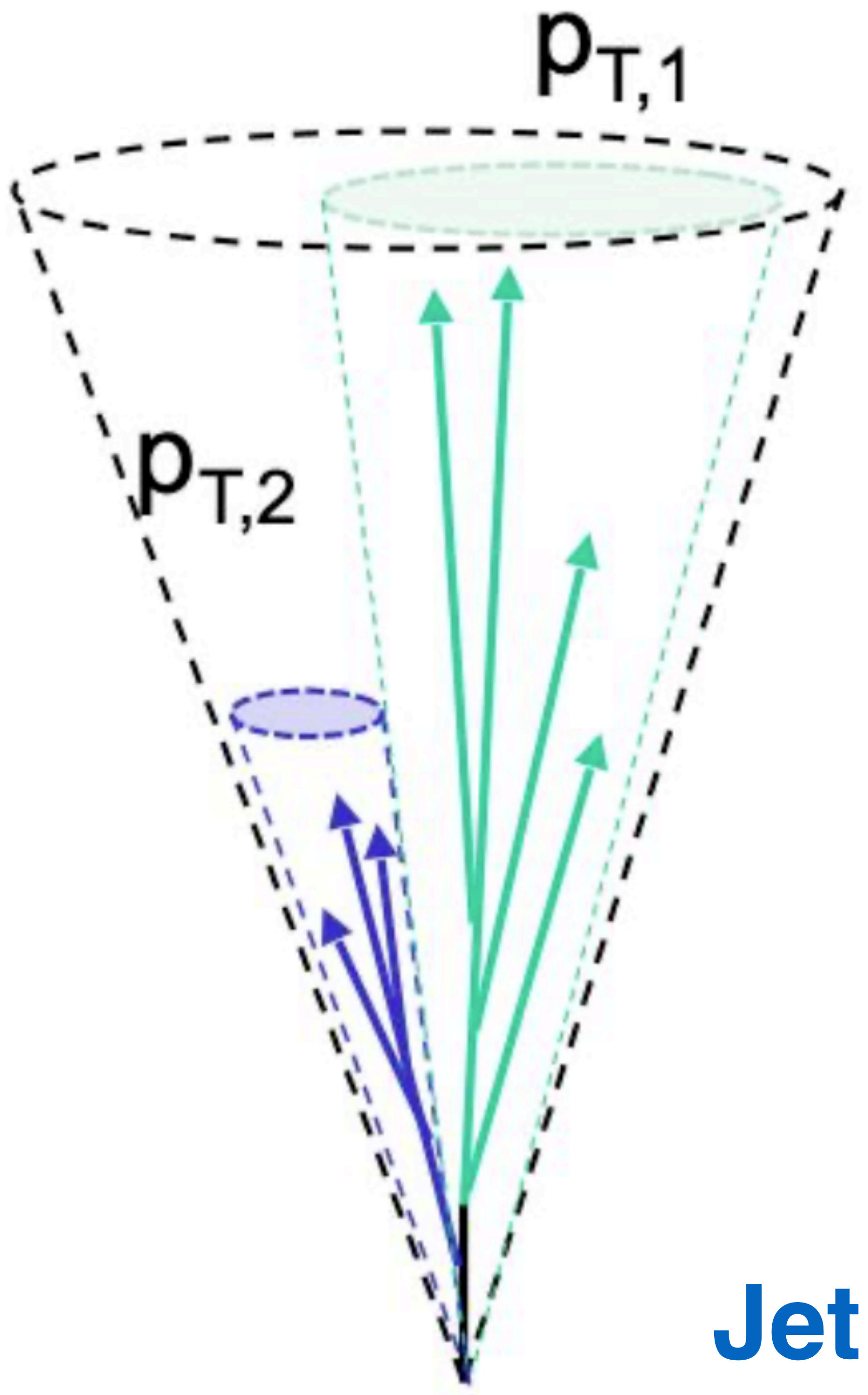
sPHENIX science



There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**

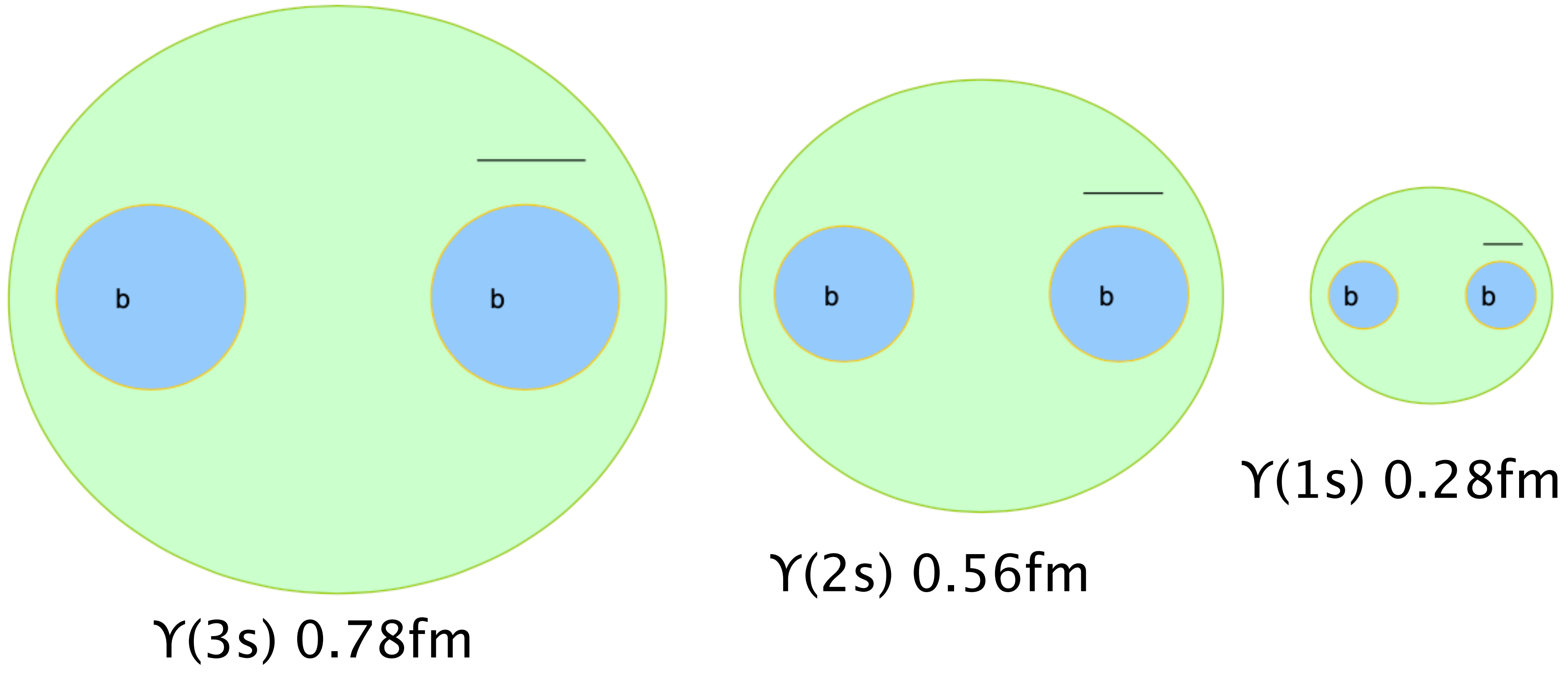
2015 US NP LRP

sPHENIX recognized by the U.S. Nuclear Physics community as the *essential* tool for QGP microscopy at RHIC



Jet structure

vary momentum/angular scale of probe



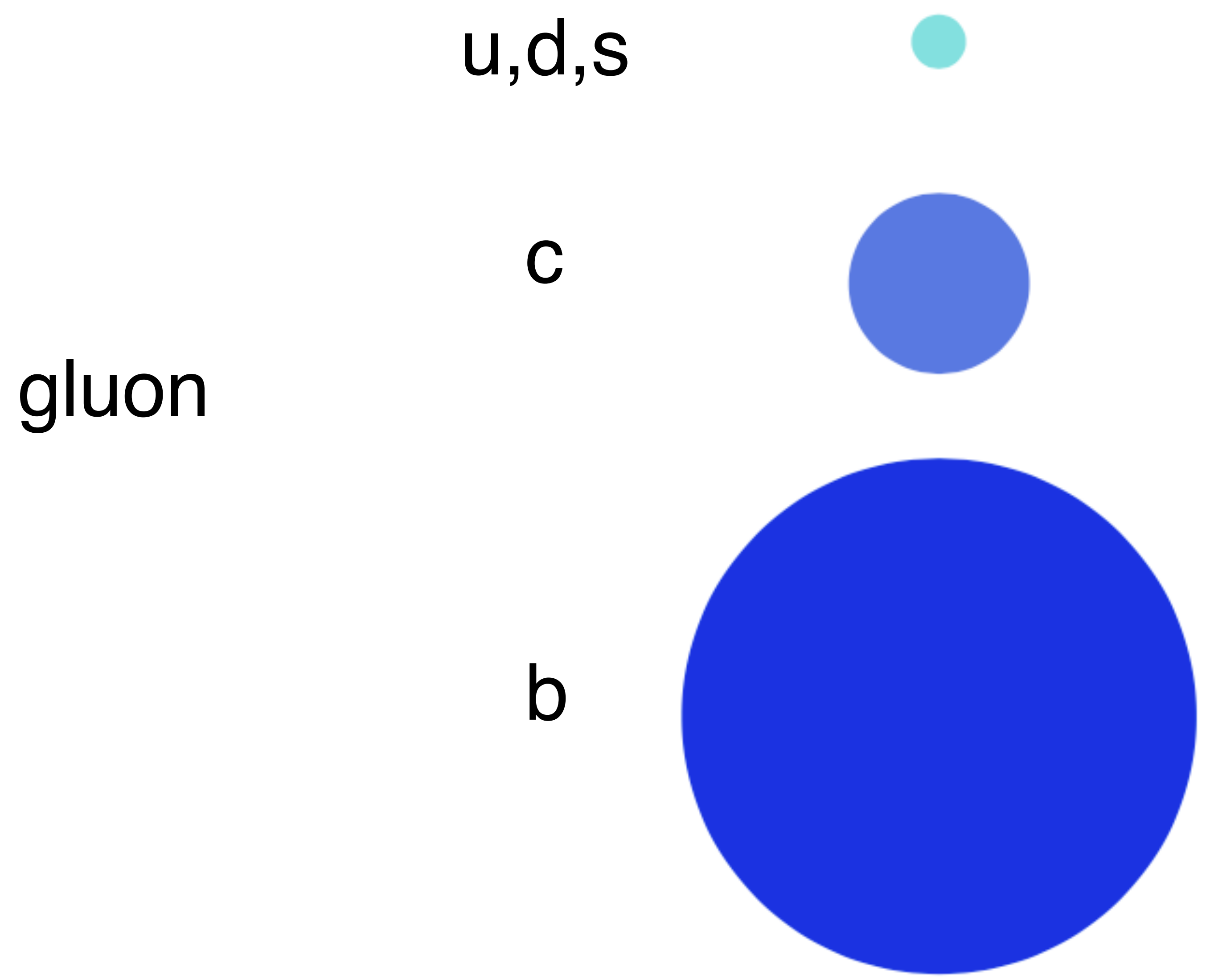
Quarkonium spectroscopy

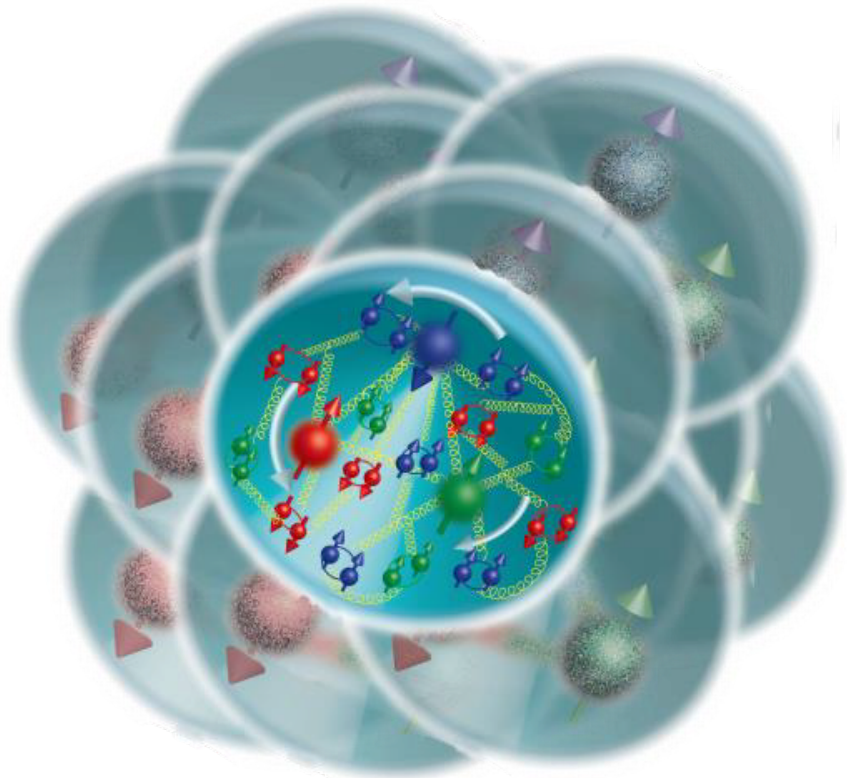
vary size of probe

sPHENIX

Parton energy loss

vary mass/momentum of probe





Cold QCD

study proton spin, transverse-momentum, and cold nuclear effects

Proposed run plan 2023-2025

Table 1: Summary of the sPHENIX Beam Use Proposal for years 2023–2025, as requested in the charge. The values correspond to 24 cryo-week scenarios, while those in parentheses correspond to 28 cryo-week scenarios. The 10%-*str* values correspond to the modest streaming readout upgrade of the tracking detectors. Full details are provided in Chapter 2.

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}
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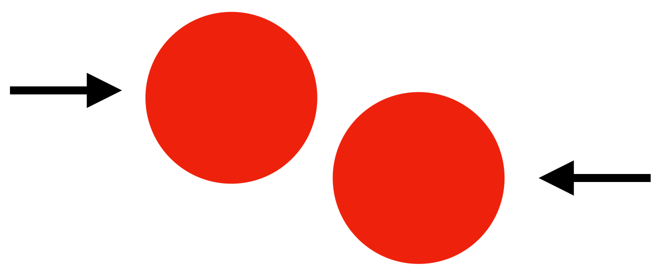
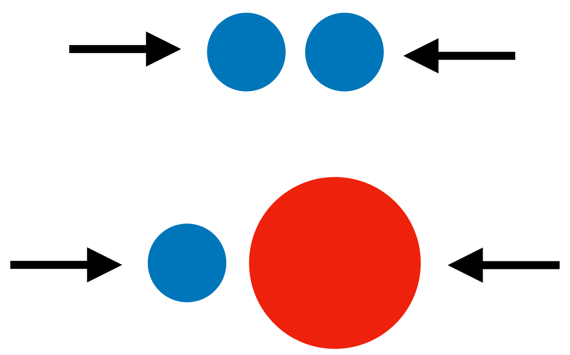
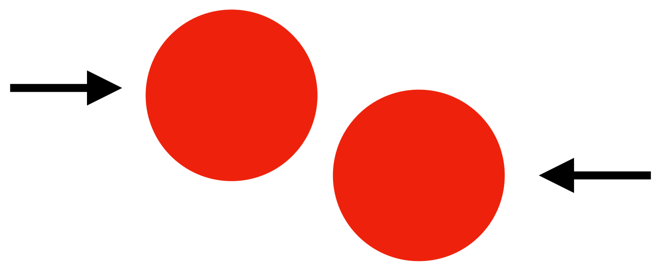


Year-1



Year-2



Year-3

- Focus on core science mission of sPHENIX and RHIC
- Minimization of risk guides ramp-up, commissioning and running conditions
- Maximize science output for investment (in MIE, 1008 facility upgrades, RHIC ops, U.S. HI research programs)
- Note: requested collision species and luminosity unchanged compared to 2020 and 2021 Beam Use Proposals

➡ stable physics and commissioning plan for years sPHENIX

BUP 2022, Sec 2

Year-1: commissioning and first physics

Weeks	Designation
0.5	Cool Down from 50 K to 4 K
2.0	Set-up mode 1 (Au+Au at 200 GeV)
0.5	Ramp-up mode 1 (8 h/night for experiments)
11.5	sPHENIX Initial Commission Time
9.0 (13.0)	Au+Au Data taking (Physics)
0.5	Controlled refrigeration turn-off
24.0 (28.0)	Total cryo-weeks

Table 2.2: Year 2023 run plan for 24 (28) cryo-weeks with Au+Au 200 GeV collisions.

Year-1 (2023) serves to commission all detector subsystems and full detector operations, and to validate the calibration and reconstruction operations essential to delivering the sPHENIX science in a timely manner. Close coordination with C-AD will be required in the ramp-up of RHIC luminosity and optimization of beam operations to achieve these goals in a safe manner, enabling full exploitation of RHIC luminosity in Year-2 and Year-3. Year-1 will also allow collection of a Au+Au data set enabling sPHENIX to repeat and extend measurements of "standard candles" at RHIC.

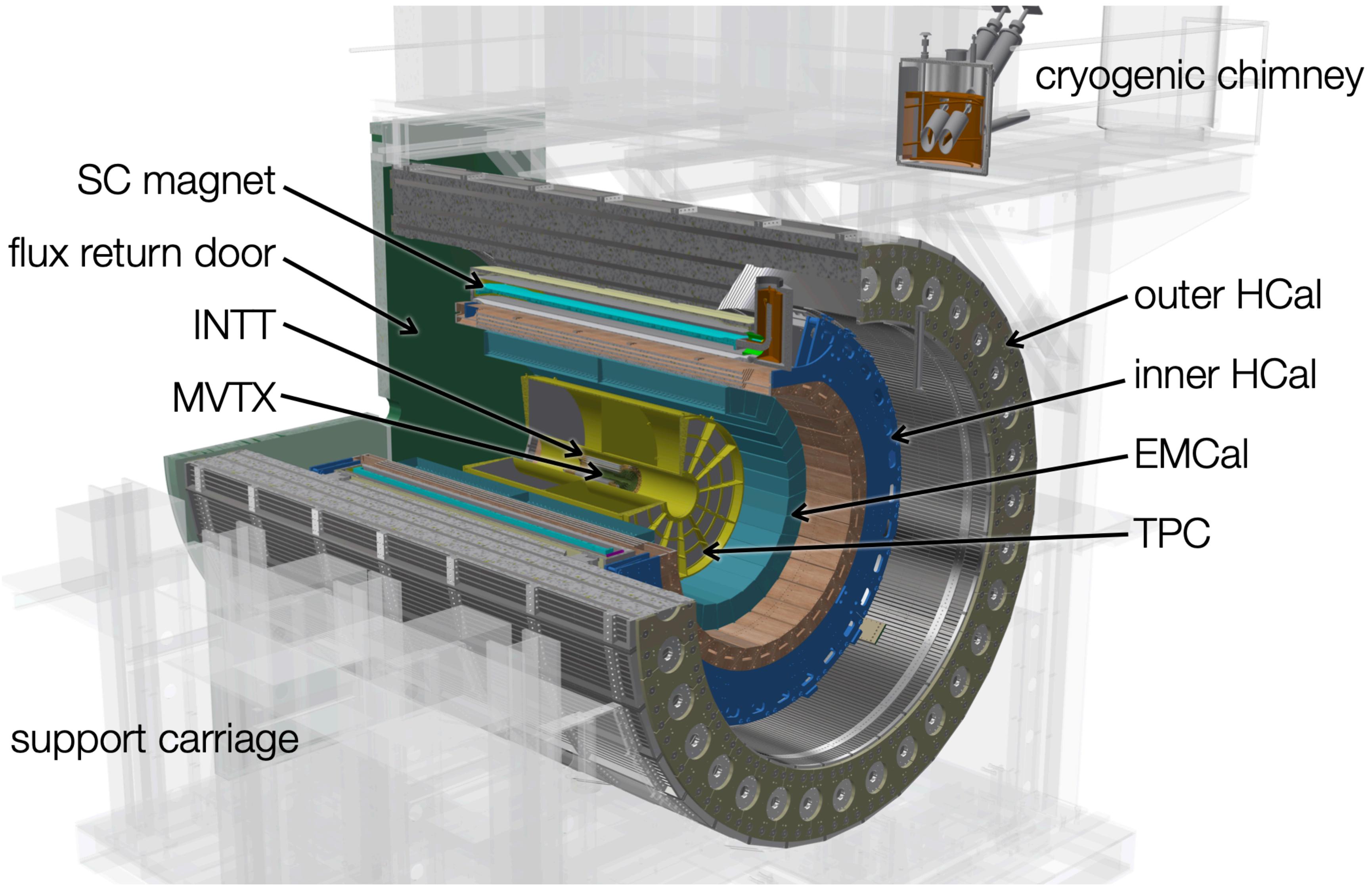
- Proposed Year-1 running includes critical time for safe commissioning

➡ followed by 9 (13) weeks of high luminosity data-taking for full validation of sPHENIX physics performance, measurement of standard candles and first new physics

Commissioning plan

Weeks	Details
2.0	low rate, 6-28 bunches
2.0	low rate, 111 bunches, MBD L1 timing
1.0	low rate, crossing angle checks
1.0	low rate, calorimeter timing
4.0	medium rate, TPC timing, optimization
2.0	full rate, system test, DAQ throughput
12.0	**total**

Table 3.1: Timeline for sPHENIX commissioning period in 2023, the first year of operation.



- Commissioning will require close coordination with C-AD to ramp-up luminosity and optimize beam / detector operations
  - ➡ timing in the MBD - minimum-bias trigger for Year-1 data-taking
  - ➡ optimizing crossing angle (crucial for lowering pileup while providing narrow *z* vertex distribution)
  - ➡ timing in the calorimeters
  - ➡ initial operation of tracking detectors, including alignment study, move to MB-triggered mode
  - ➡ increasing to full rate as requested for physics running to follow

Year-2: *p+p* baseline and *p+A* physics

	Weeks	Designation
	0.5	Cool Down from 50 K to 4 K
p+p	2.0	Set-up mode 1 ($p^{\uparrow}p^{\uparrow}$ at 200 GeV)
p+p	0.5	Ramp-up mode 1 (8 h/night for experiments)
p+p	12.0 (16.0)	Data taking mode 1 ($p^{\uparrow}p^{\uparrow}$ Physics)
	1.0	Move DX magnets
p+Au	2.0	Set-up mode 2 ($p^{\uparrow}$+Au at 200 GeV)
p+Au	0.5	Ramp-up mode 2 (8 h/night for experiments)
p+Au	5.0	Data taking mode 2 ($p^{\uparrow}$+Au Physics)
	0.5	Controlled refrigeration turn-off
	24.0 (28.0)	Total cryo-weeks

Table 2.3: Year 2024 run plan for 24 (28) cryo-weeks with $p^{\uparrow}p^{\uparrow}$ and $p^{\uparrow}$+Au 200 GeV collisions.

Year-2 (2024) will see commissioning of the detector for $p+p$ collisions and collection of large $p+p$ and $p+$Au data sets. The $p+p$ data are critical as reference data for the Au+Au physics. As a separate scientific objective, due to the transverse polarization of the proton beams, the $p+p$ data together with $p+$Au data will allow for substantial new studies of cold QCD physics. We highlight that a modest streaming readout upgrade of the tracking detectors [10%-*str*], requiring no additional hardware, will greatly extend this physics program in $p+p$ and $p+$Au running.

- Critical transversely polarized *p+p* and *p+*Au running as an unbiased data reference for Au+Au and for the Cold QCD program
- Still requires commissioning for triggers, new beam conditions, etc.
- Streaming readout of tracker (10% of delivered lumi) enables unprecedented heavy-flavor program at RHIC

Critical impact of *p+p* running (1/2)

- Large luminosity *p+p* reference data underpins the sPHENIX science program
  - ➡ for many unique, flagship measurements (separated Upsilon states, *b*-jets, photon+jets), the yield in *p+p* is smaller than in central Au+Au - limiting factor
  - ➡ large luminosity of *p+p* data also provides *systematic* uncertainty reduction - *in situ* gamma+jet energy scale calibration, etc.
  - ➡ decrease in *p+p* reference data results in **increased statistical and systematic uncertainties** for many measurements

Critical impact of *p+p* running (2/2)

- In 2021, sPHENIX was asked to prepare a BUP under a 20 cryo-week scenario in 2024
  - ➡ under that scenario, sPHENIX prefered to remove all *p*+Au running (with large, unrecoverable loss in physics) just to preserve the needed *p+p* luminosity
  - ➡ we thank the PAC for their strong recommendation to keep 28 cryoweeks
- On May 5th, C-AD posted a revised set of *p+p* luminosity projections, with a -20% decrease, which we are working to understand
  - ➡ the projections in the BUP use the previous values from 2019-2022
  - ➡ sPHENIX has a serious concern about the impact of this potential reduction on this physics program
  - ➡ we stress the importance of a **full 28 cryoweek run** (if not longer) in 2024 to allow sPHENIX to record a **large integrated luminosity of *p+p* data**

BUP 2022, Sec 4.1

Year-3: golden physics dataset

Weeks	Designation
0.5	Cool Down from 50 K to 4 K
2.0	Set-up mode 1 (Au+Au at 200 GeV)
0.5	Ramp-up mode 1 (8 h/night for experiments)
20.5 (24.5)	Au+Au Data taking (Physics)
0.5	Controlled refrigeration turn-off
24.0 (28.0)	Total cryo-weeks

Table 2.4: Year 2025 run plan for 24 (28) cryo-weeks with Au+Au 200 GeV collisions.

...

141 *billion* minimum-bias events in 2023+2025!

|z| < 10cm, 28 cryoweek scenarios

- Year-3 focuses on the collection of a very large Au+Au dataset for measurements of jets and heavy flavor observables with *unprecedented statistical precision*

➡ successful commissioning with Au+Au collisions in Year-1 allows sPHENIX to take full advantage of cryoweeks in Year-3 for physics

Hard process yields

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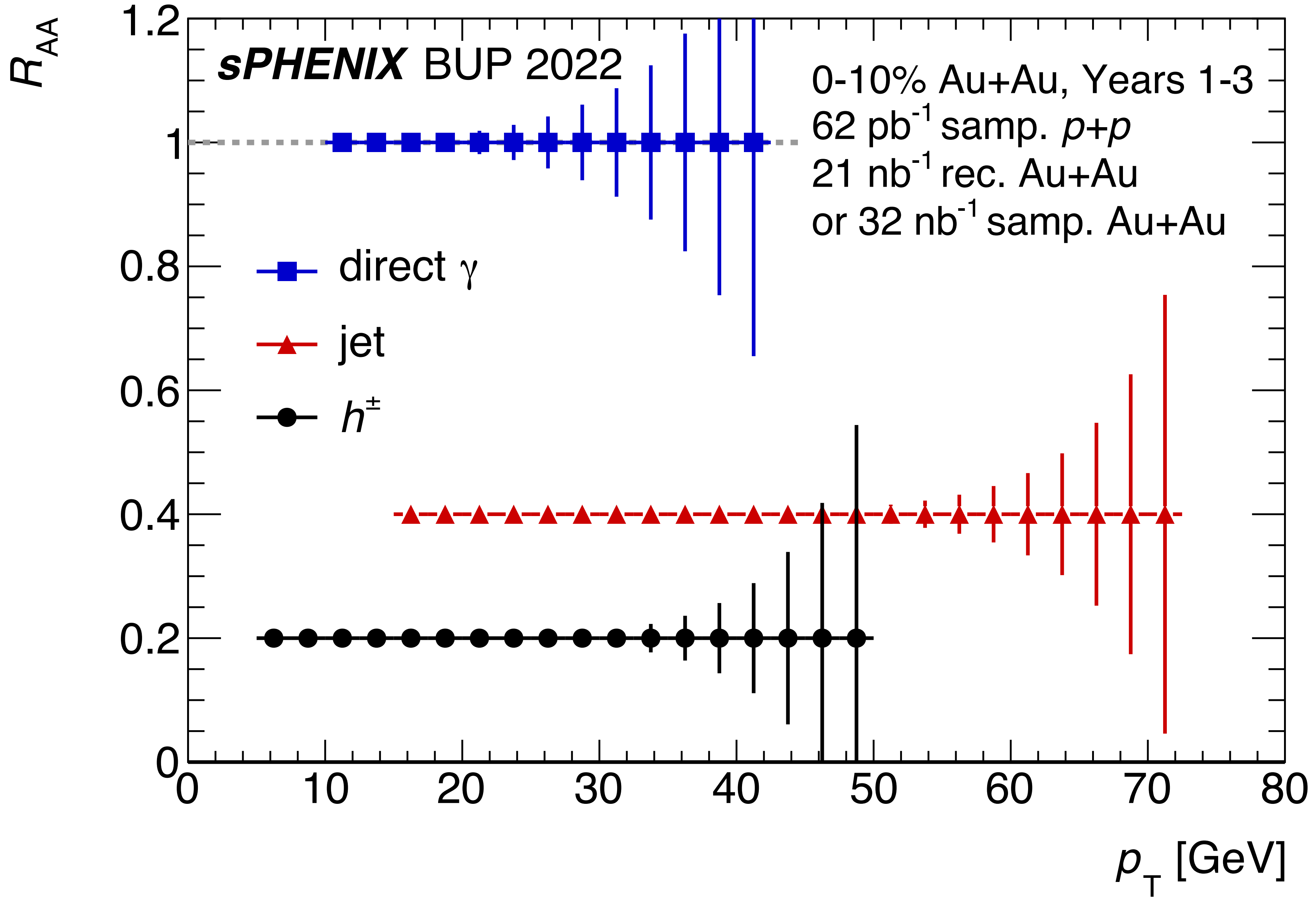

Signal	Au+Au 0–10% Counts	p+p Counts
Jets $p_T > 20$ GeV	22 000 000	11 000 000
Jets $p_T > 40$ GeV	65 000	31 000
Direct Photons $p_T > 20$ GeV	47 000	5 800
Direct Photons $p_T > 30$ GeV	2 400	290
Charged Hadrons $p_T > 25$ GeV	4 300	4 100

Table 4.1: Projected counts for jet, direct photon, and charged hadron events above the indicated threshold p_T from the sPHENIX proposed 2023–2025 data taking. These estimates correspond to the 28 cryo-week scenarios.

- Large luminosity for inclusive R_{AA} measurements (*left*) and detailed study (*right*)
  - ➡ **reconstructed jets** to ~70 GeV - fate of R_{AA} at very high p_T
  - ➡ **charged particles** to ~45 GeV - fragmentation functions out to high-z
  - ➡ **direct photons** to ~40 GeV - precise check of nuclear geometry

Jets: structure & correlations

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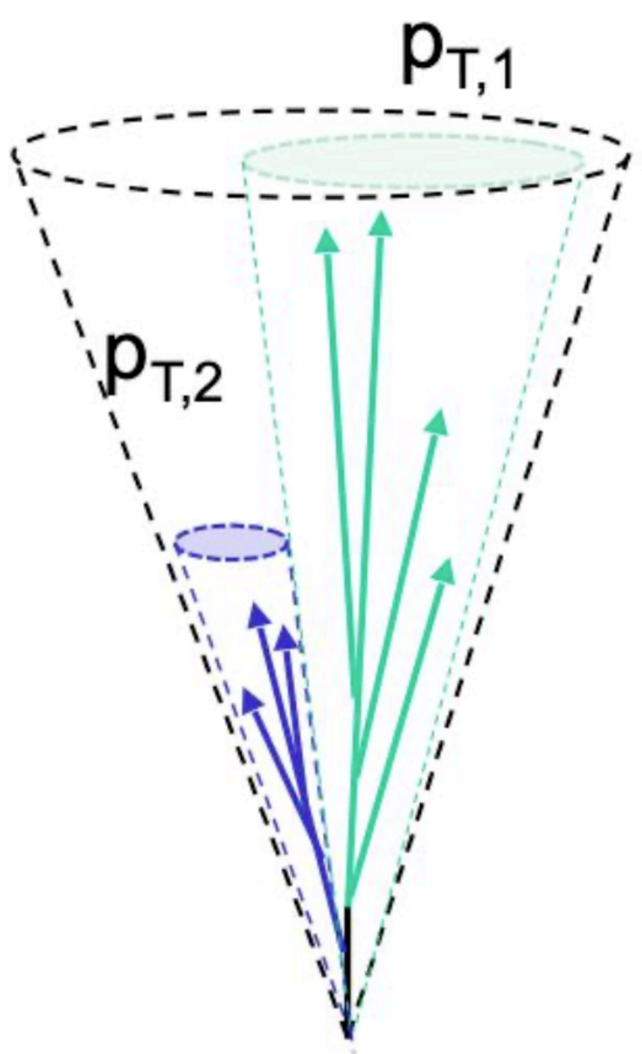
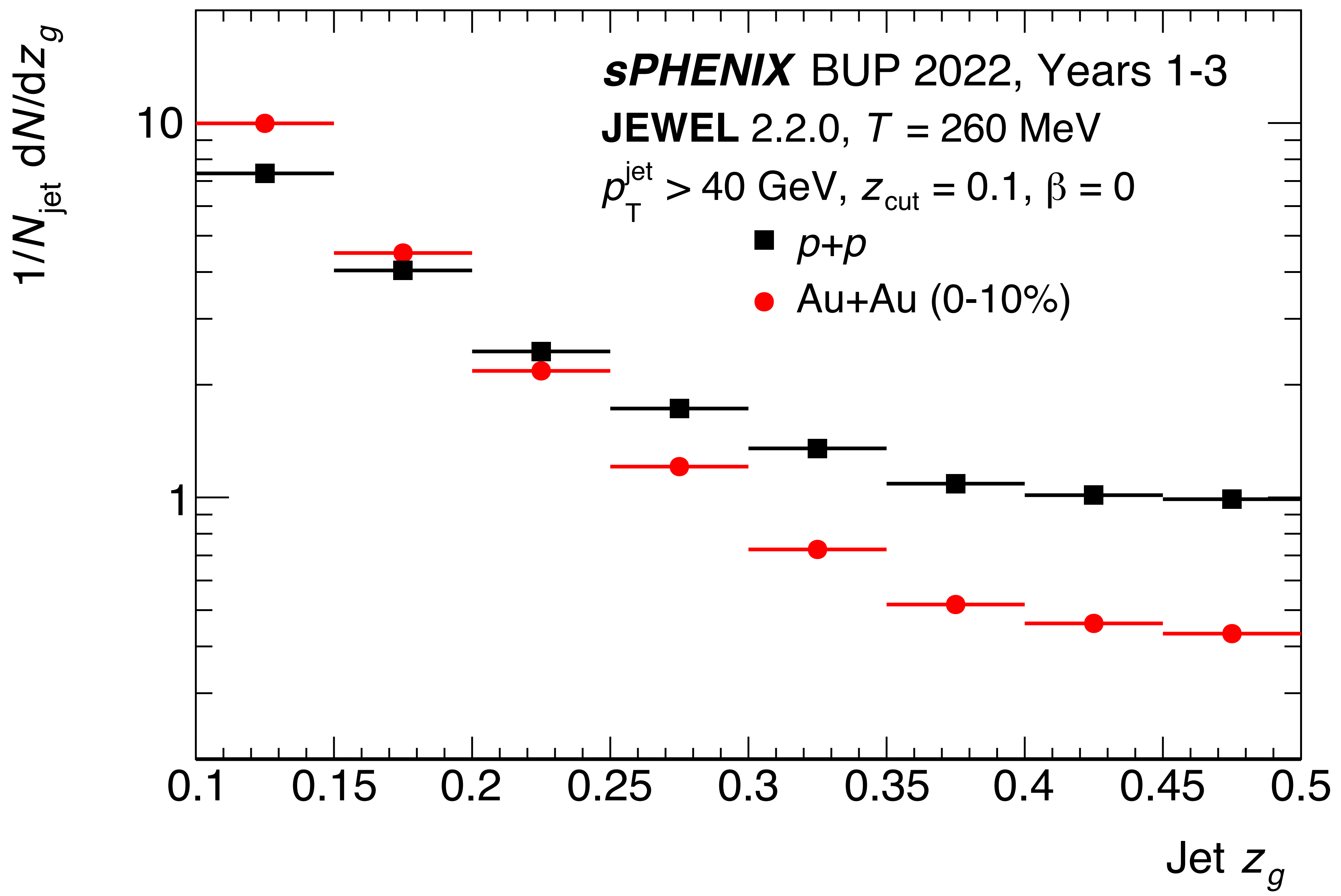
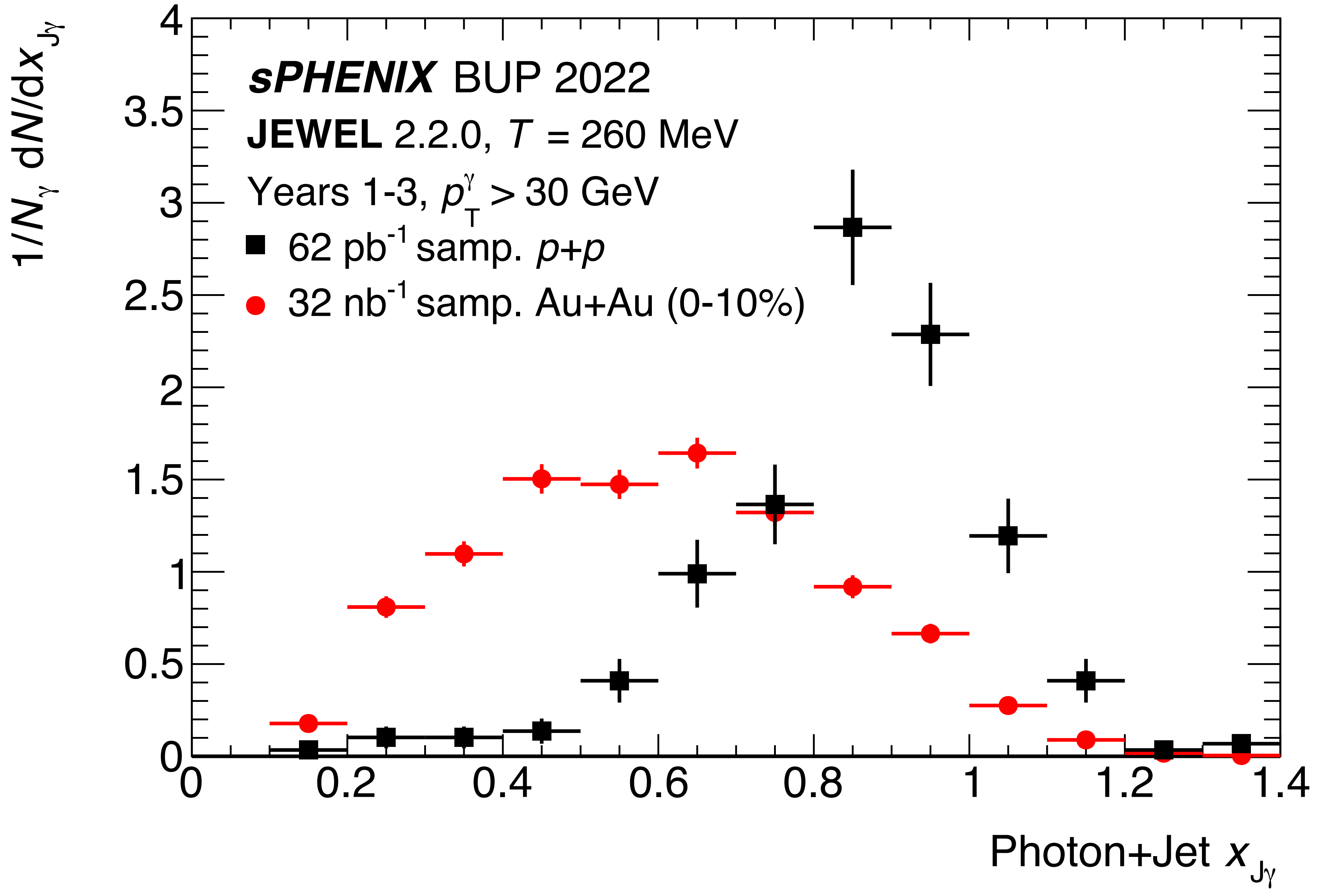




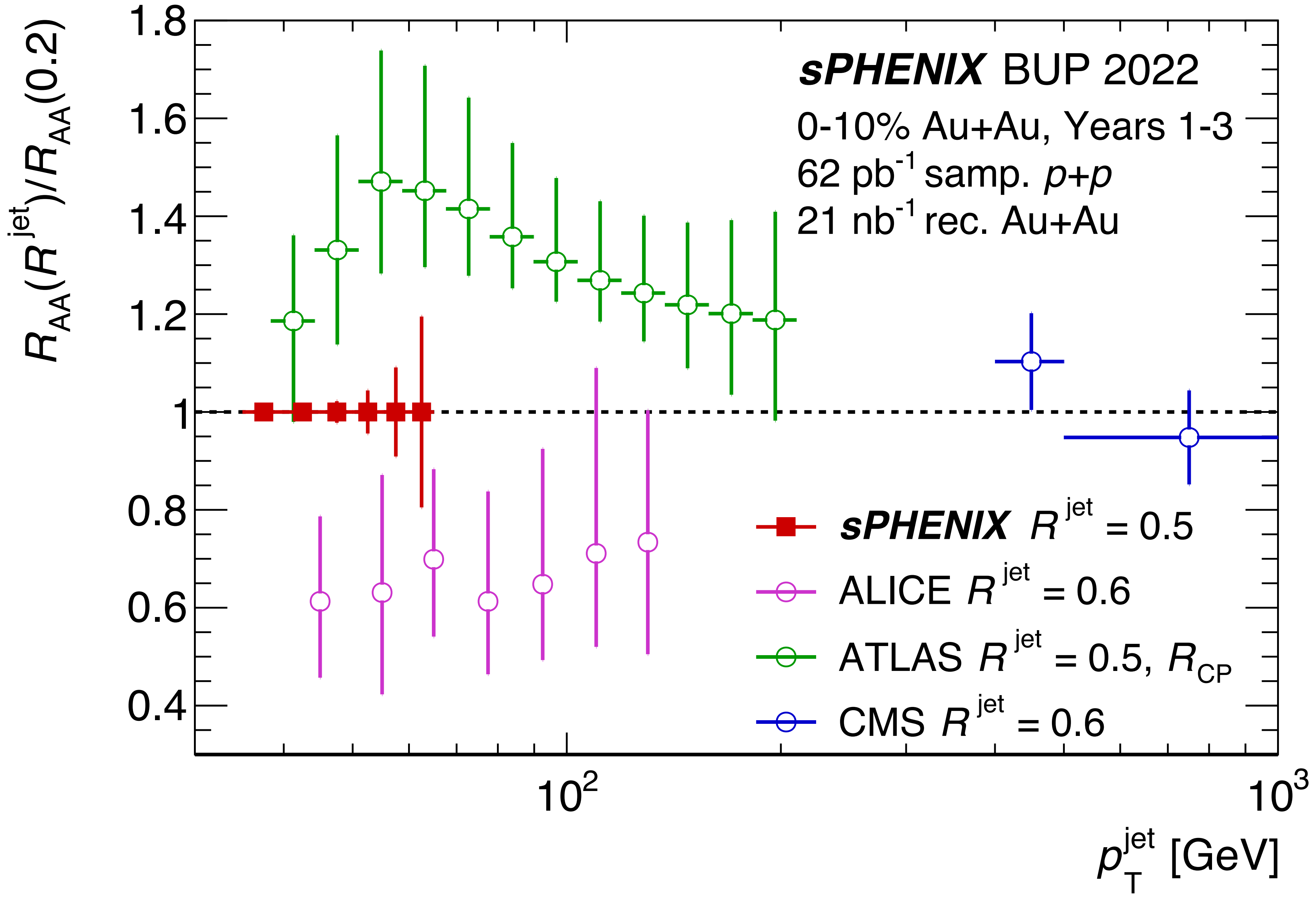


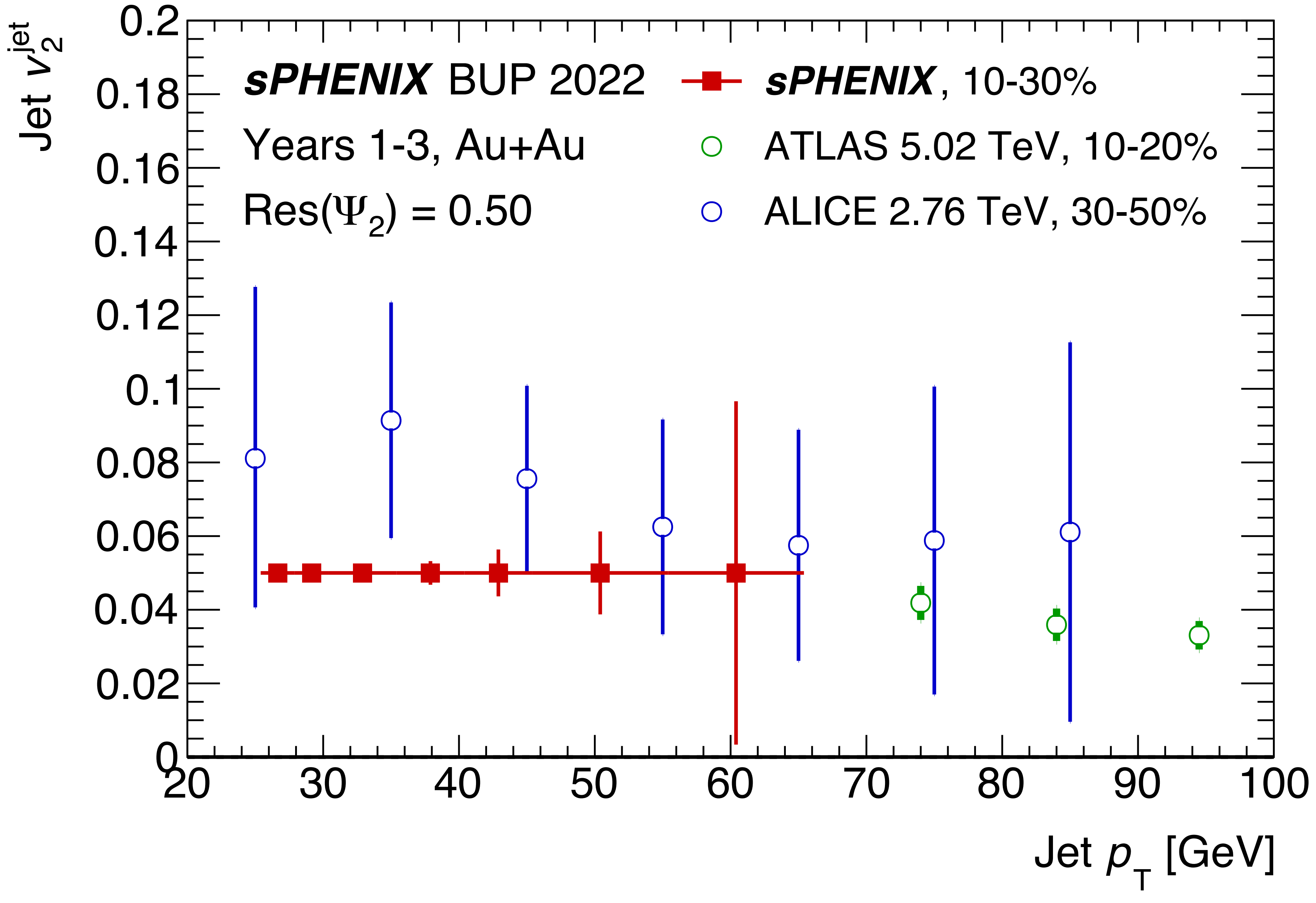
- Statistical projections for ***p+p*** and **0-10% Au+Au** (shape taken from JEWEL)

➡ *Left*: subjet fraction z_g for >40 GeV jets - very large yield for inclusive jet (sub-)structure - full variety of measurements limited only by our creativity!

➡ *Right*: γ+jet p_T balance mapped in *detail* (distribution of energy loss values, not just averages)

Jets: open questions from LHC





- Jet R-dependence and jet v_n - key info on shape modification and geometry dependence

  ➡ but difficult to measure at LHC in region where these effects may be large (<100 GeV)
- *Left*: projected **R_{AA}(0.5)/R_{AA}(0.2) double ratio** in 0-10% events
- *Right*: statistical projection of **jet v_n** in 10-30% events

Upsilons: melting of the three states

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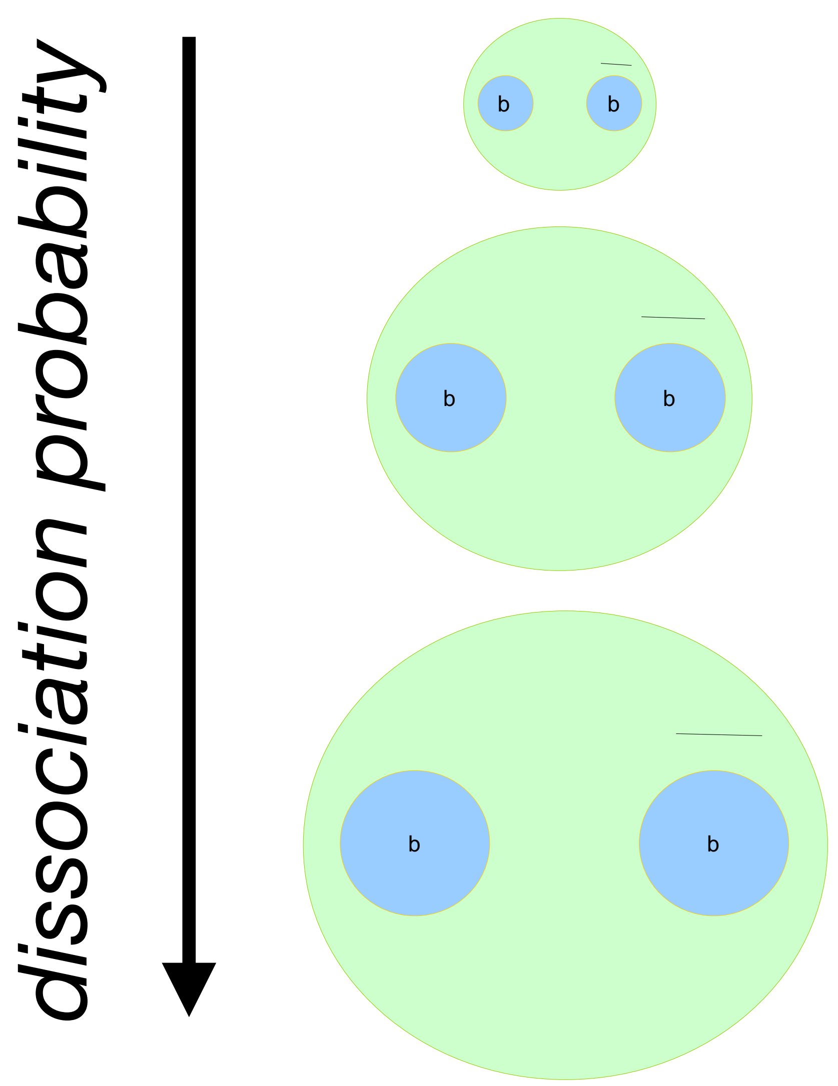

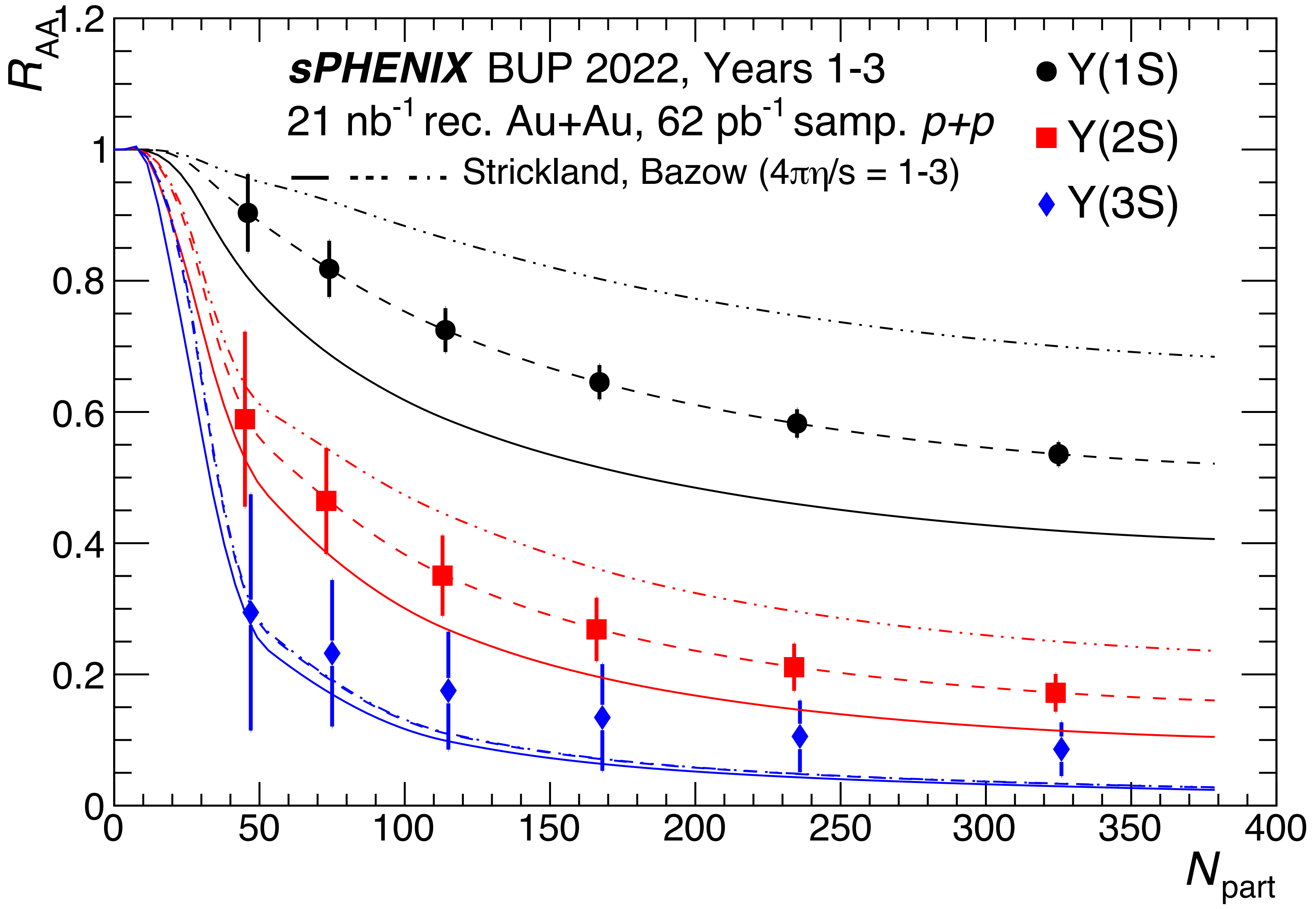

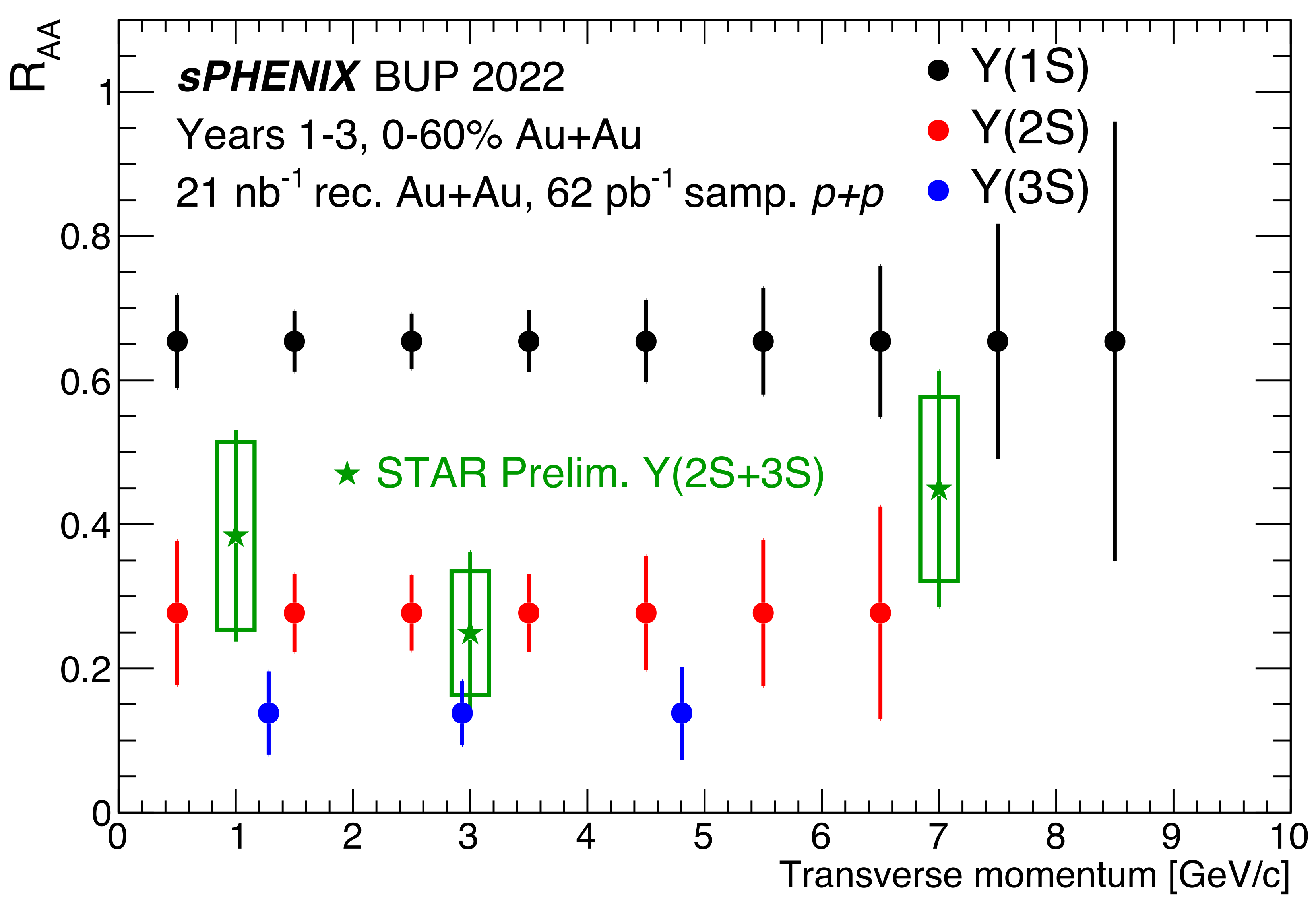

- Detailed centrality dependence (*left*) and p_T-dependence (*right*) for separated Υ states

➡ given the observation of $R_{AA}(3S)/R_{AA}(2S)$ ~ 0.5 at the LHC, we can project an observable $\Upsilon(3S)$ yield

➡ sPHENIX has the unique opportunity to discover the fate of the $\Upsilon(3S)$ at RHIC!

HF: open heavy flavor

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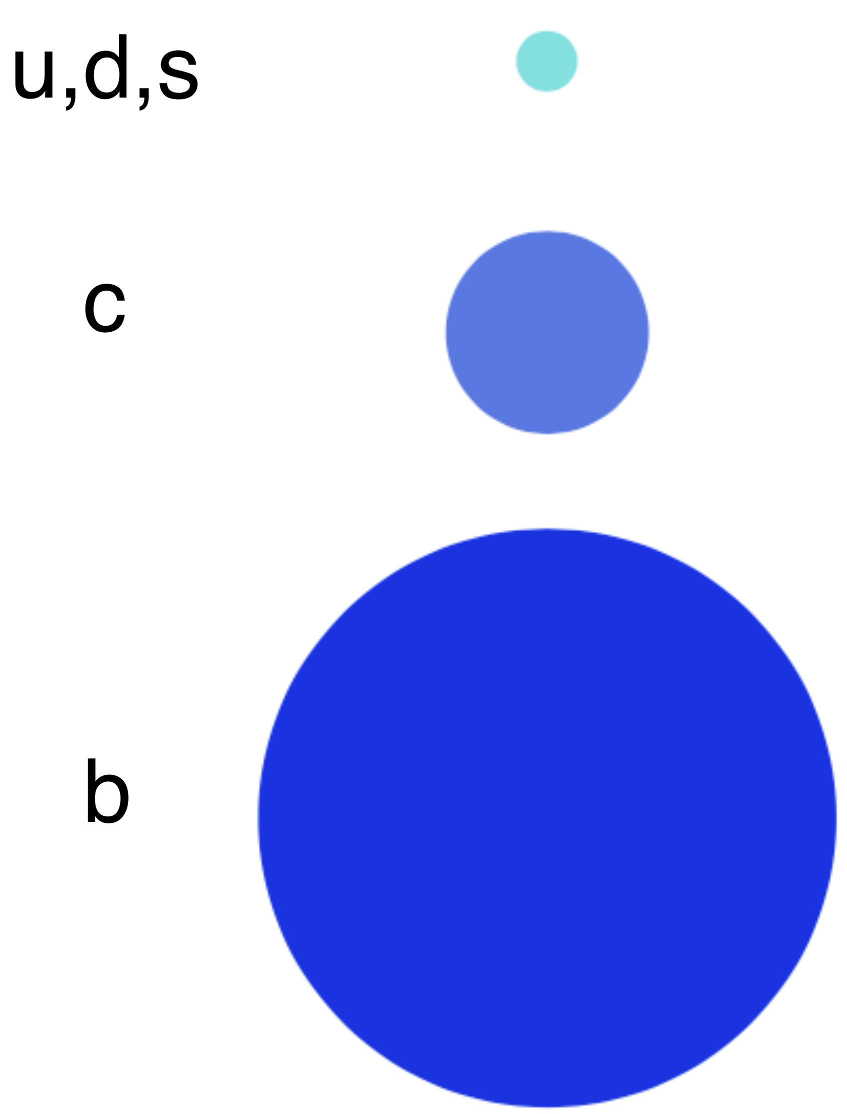
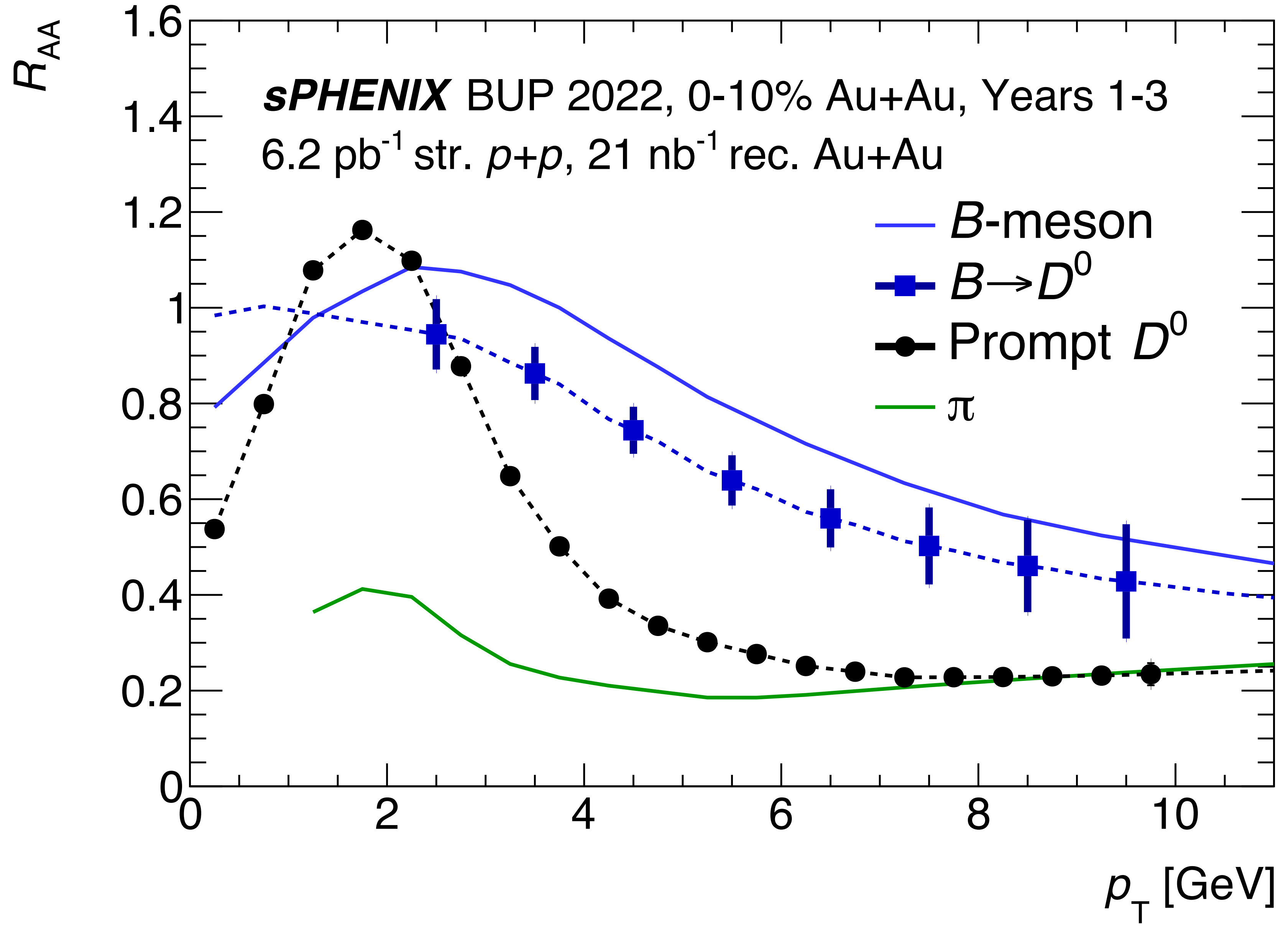
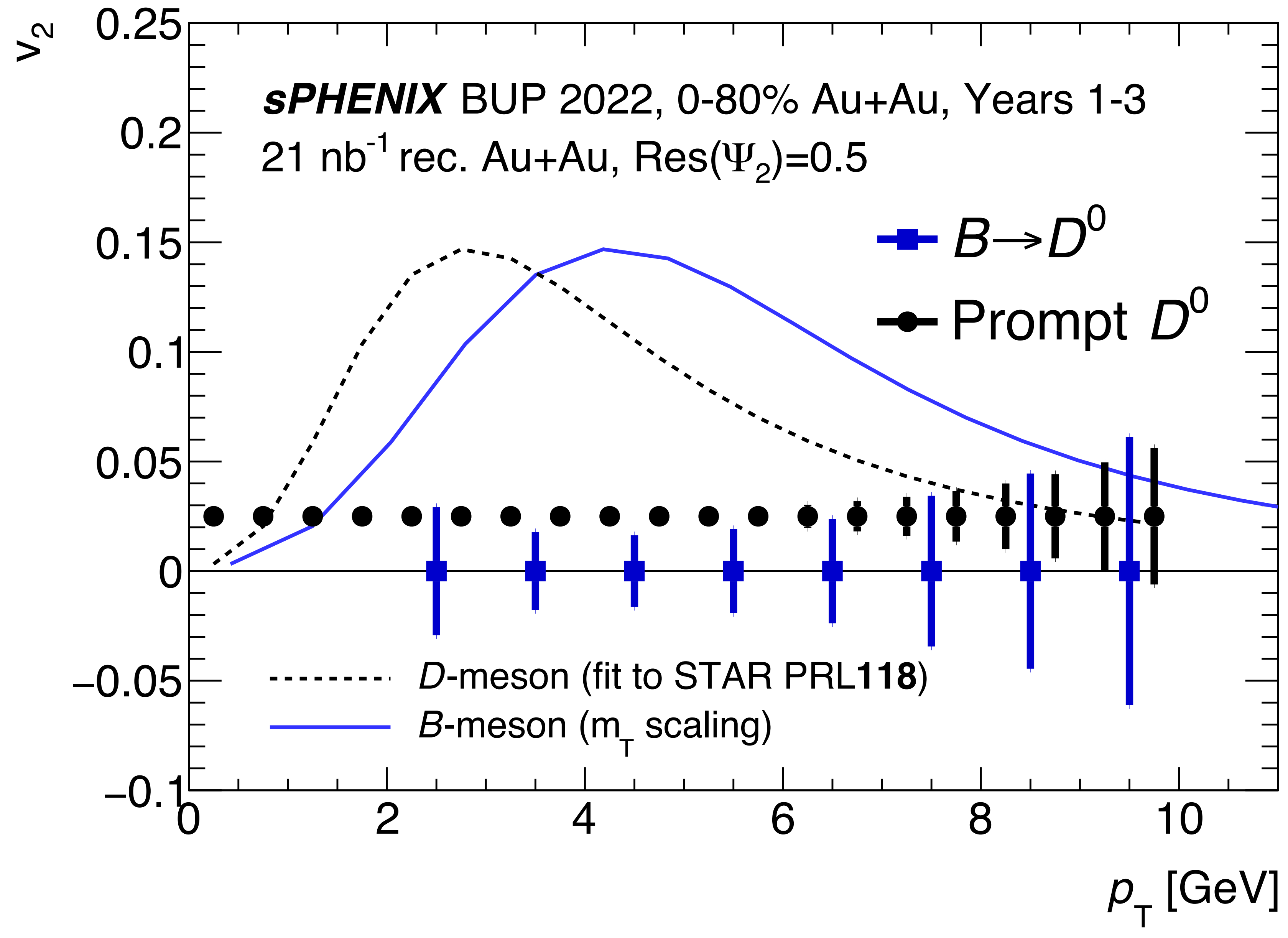


★ enabled by streaming readout





- Broad measurements of the production (*left*) and azimuthal modulation (*right*) of fully reconstructed HF hadrons
  - ➡ shown here: **prompt** D^0 (down to 0 GeV) and $B \to D^0$
  - ➡ precise measurements over a large kinematic range to isolate how the mass effect evolves with p_T

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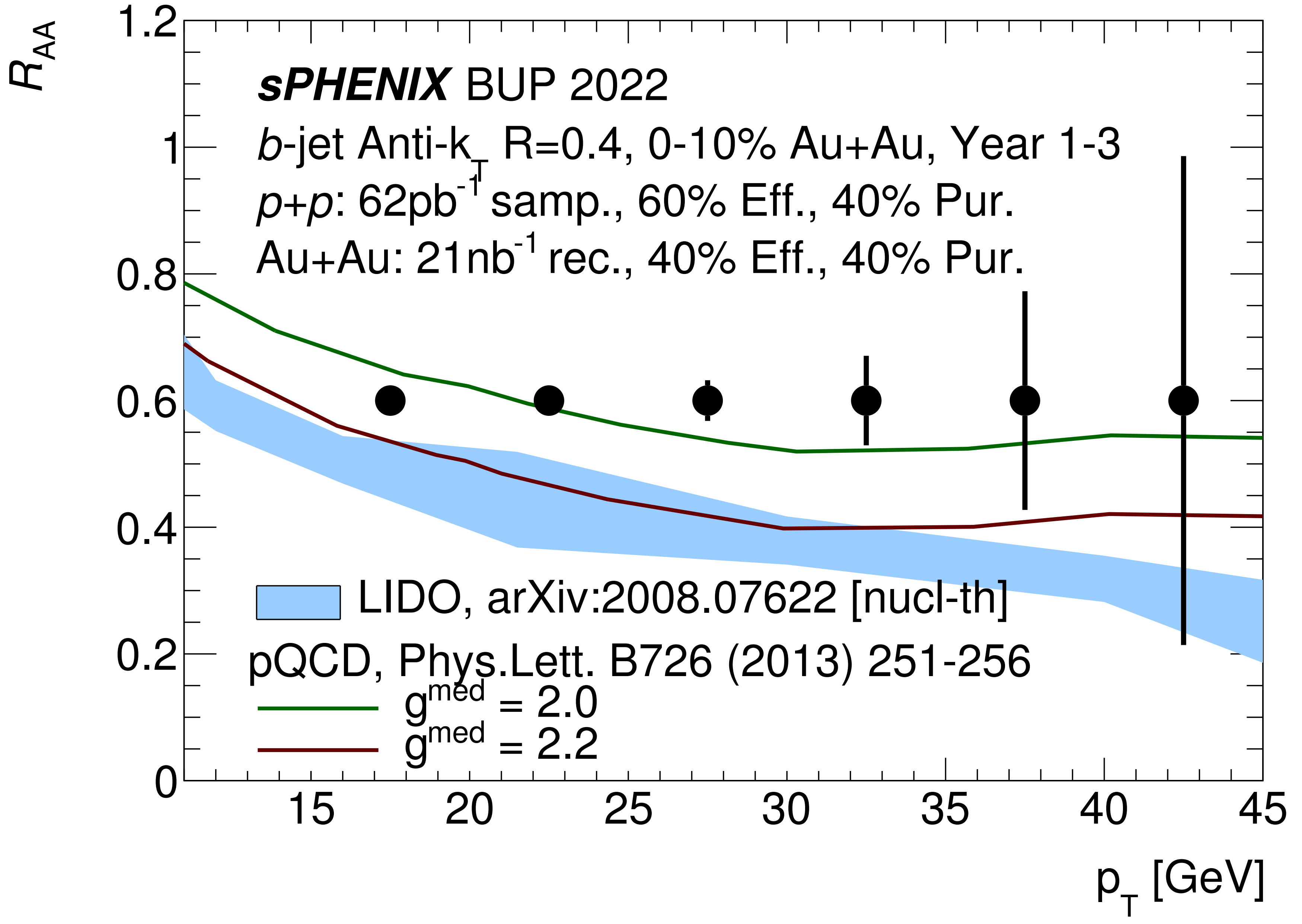
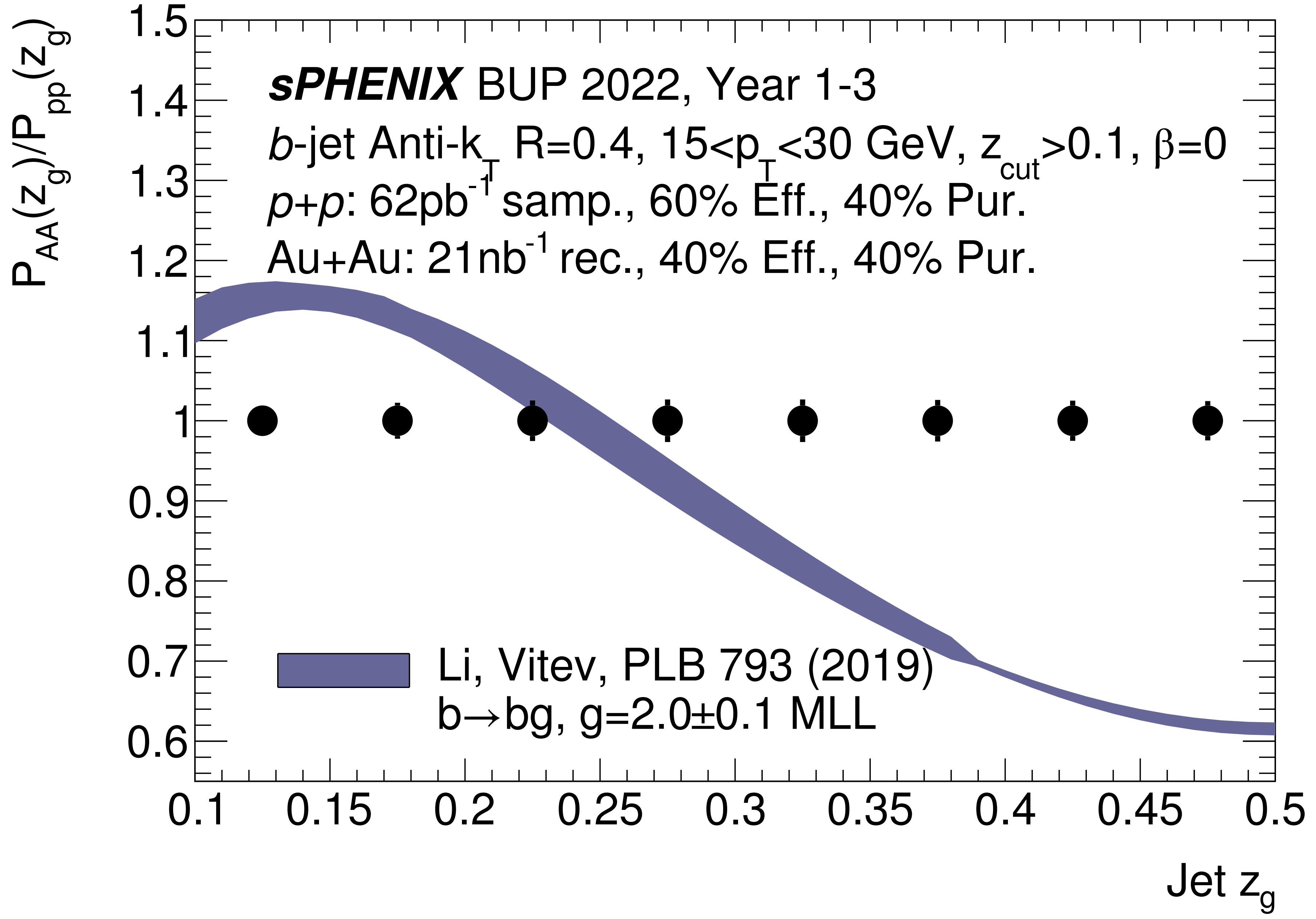
HF: *b*-tagged jets

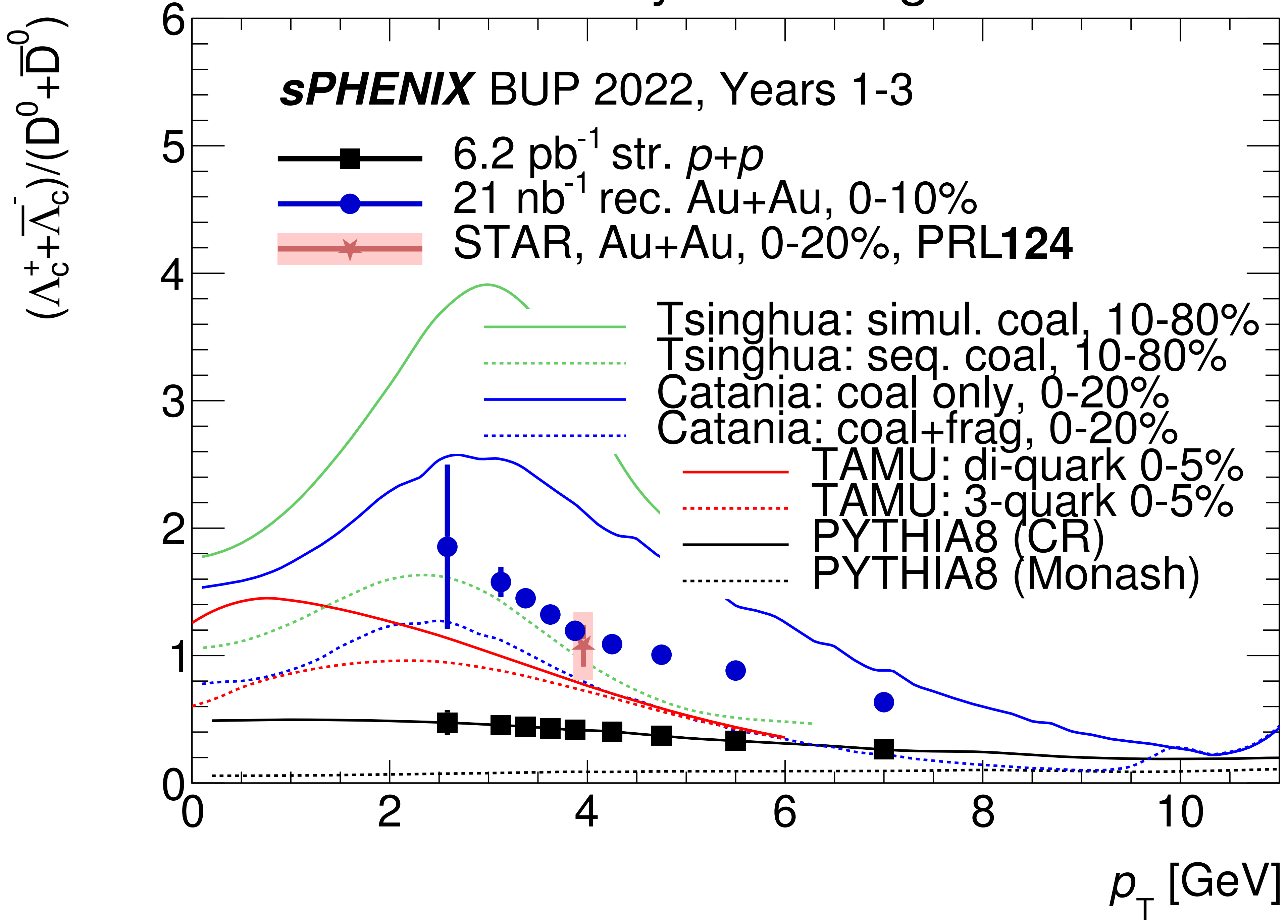


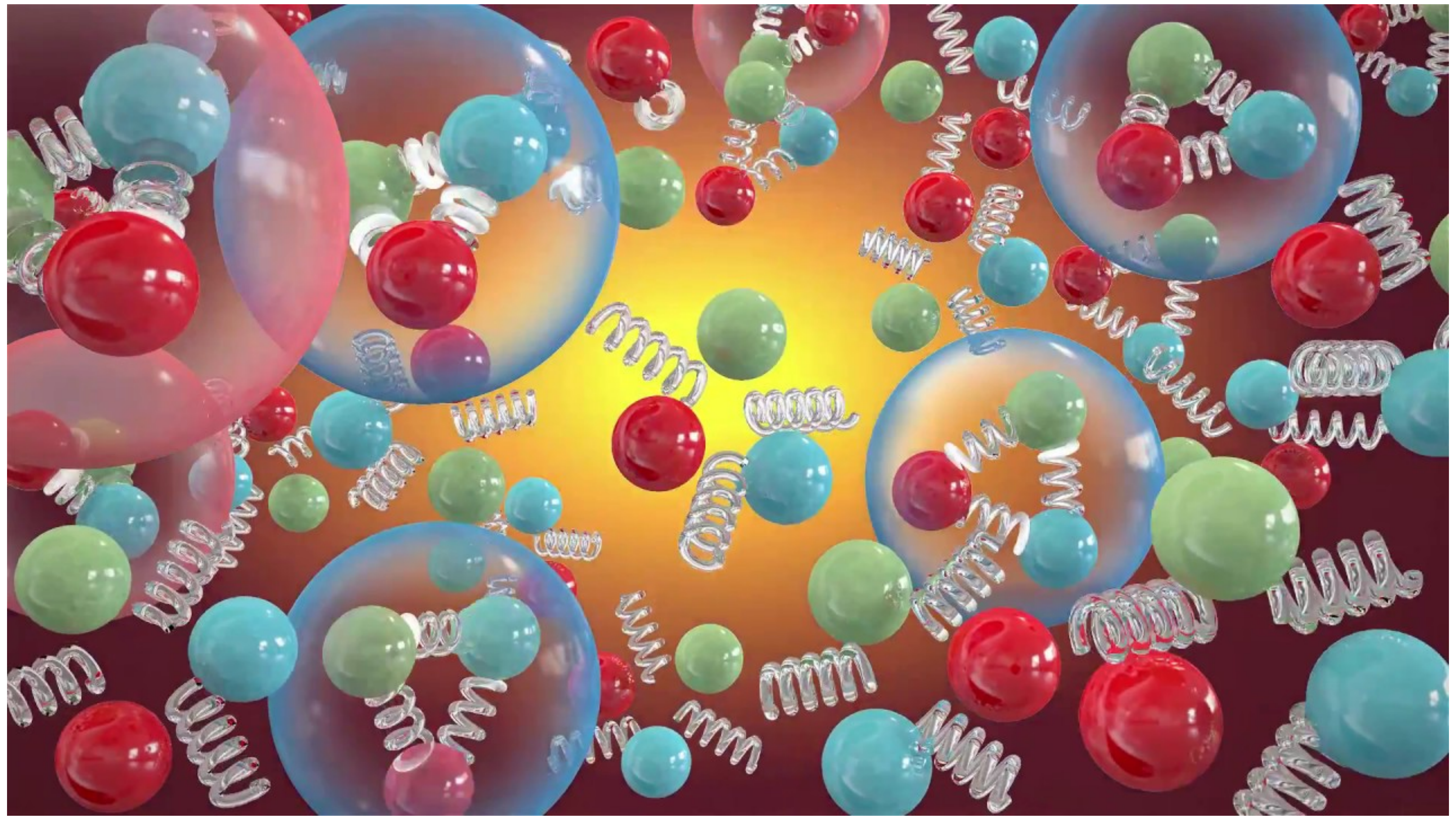


- At higher *b*-quark p_T, precision tracking enables the tagging of *b*-jets
  ➡ completely new channel at RHIC - unique sPHENIX capability!
- *Left*: statistical projection of ***b*-jet R_{AA}**, studies show good purity/efficiency
- *Right*: sufficiently large yield to look at *b*-jet structure, e.g. **ratio of z_g** in Au+Au/*p*+*p*

HF: hadronization in medium

★ enabled by streaming readout





- Address in-medium hadronization of heavy quarks
- One type of measurment - relative abundance of heavy-flavor baryons and mesons

➡ *above*: indications of Λ_c/D^0 enhancement at RHIC - sPHENIX can explore this in detail

➡ and also measure the real *p*+*p* data baseline

p+A and *p*+*p*: hard process yields

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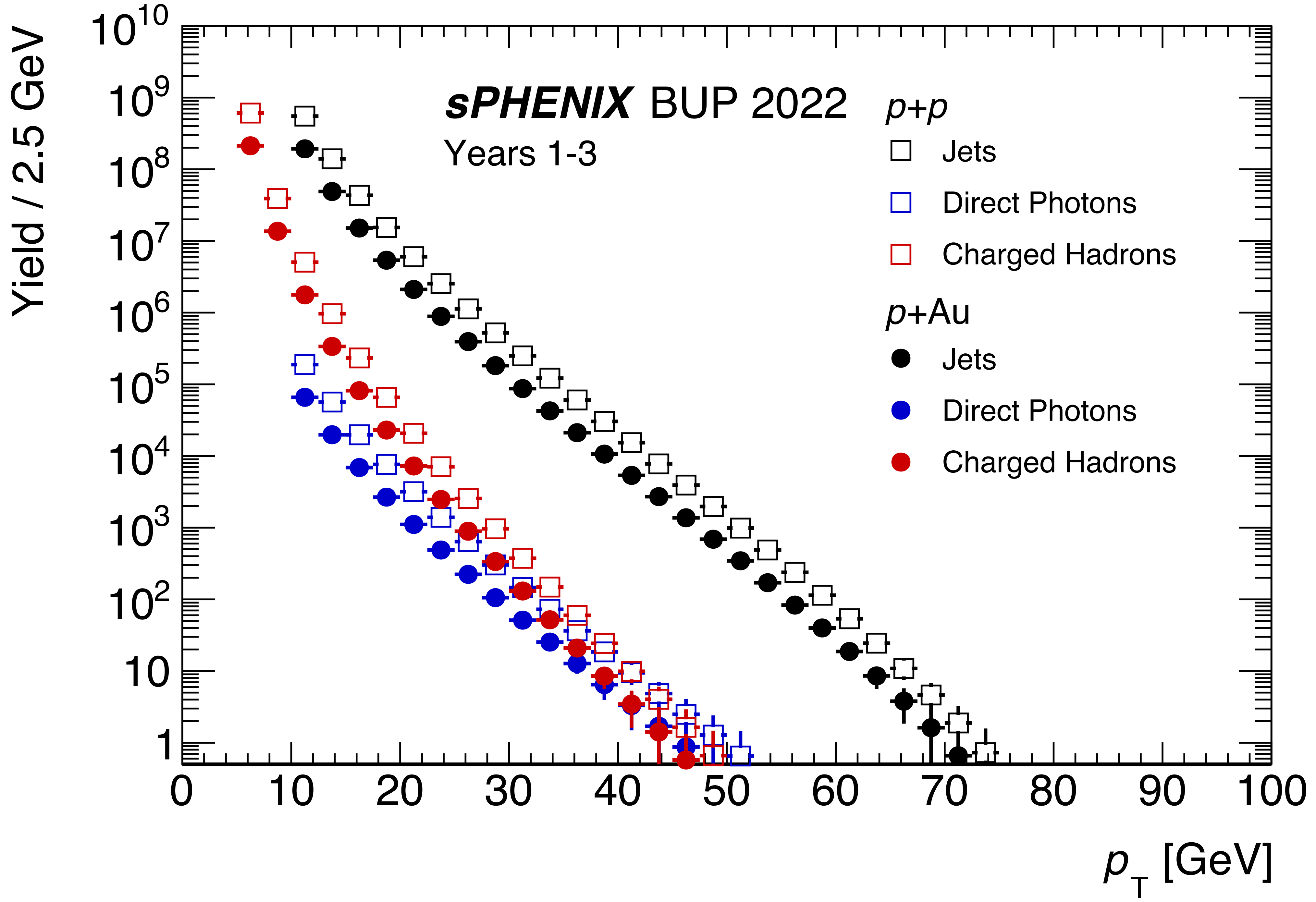
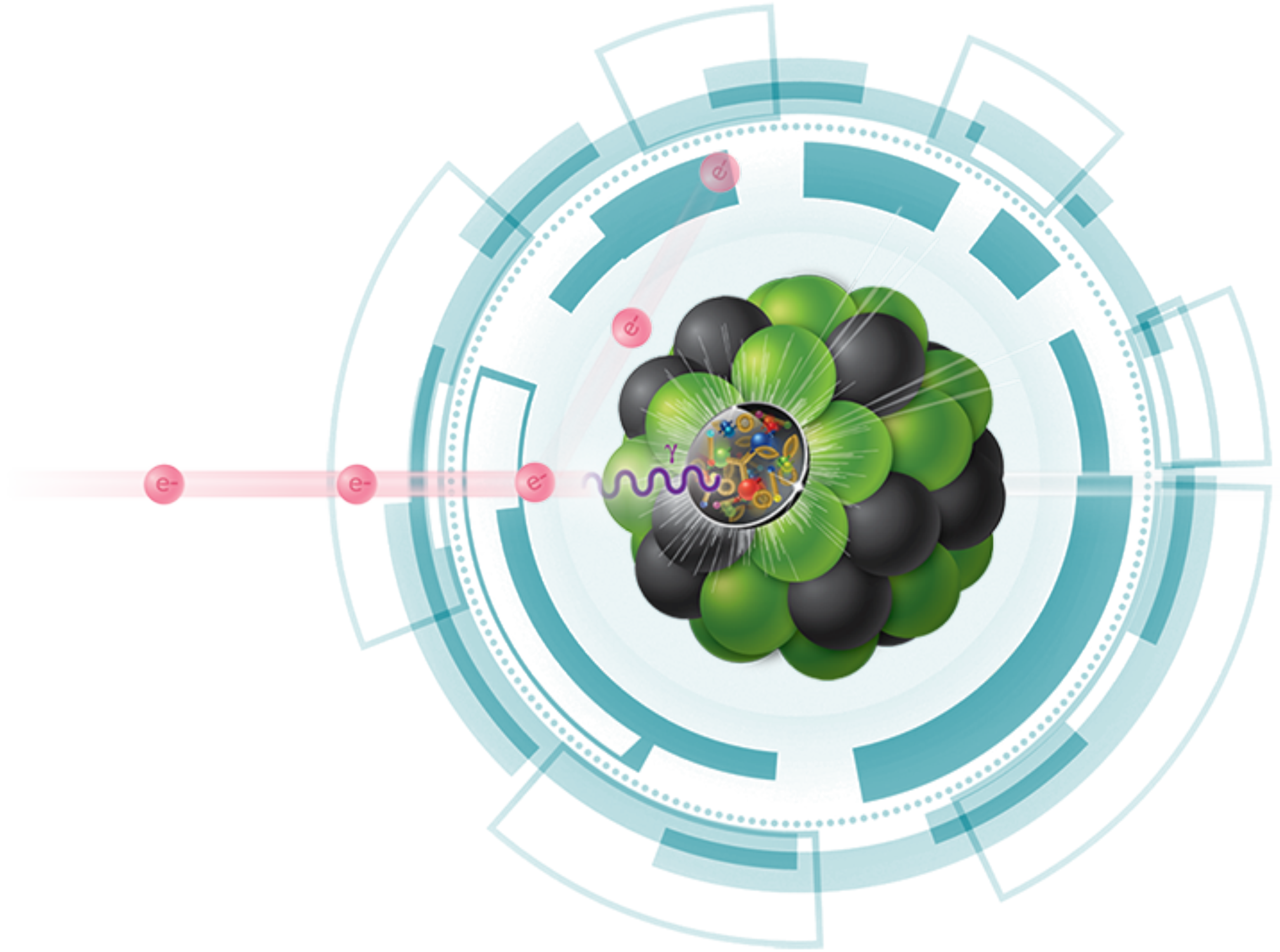
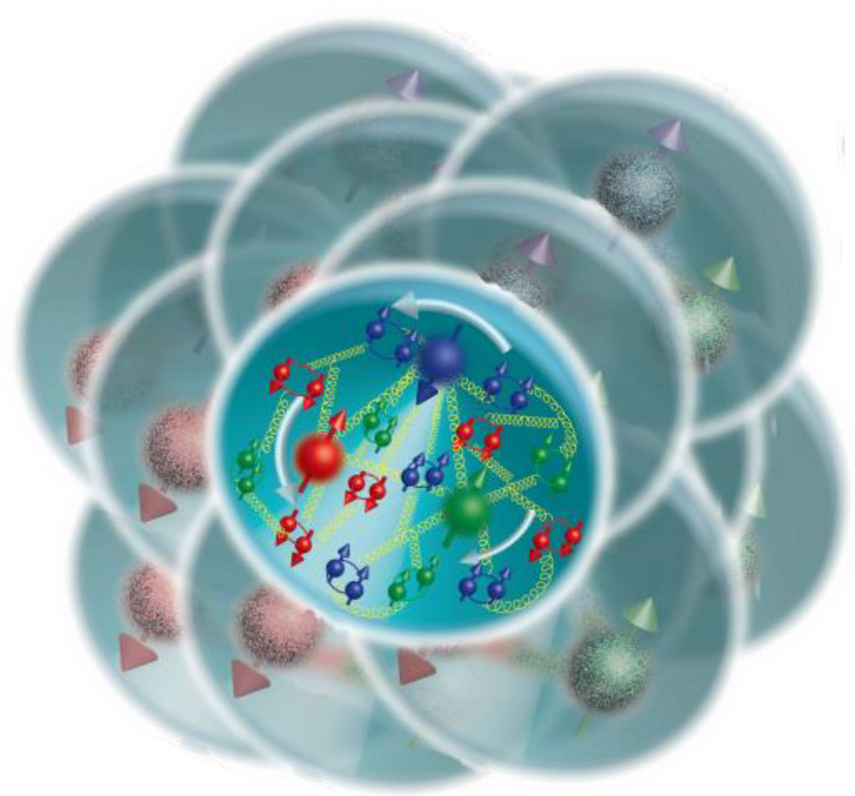


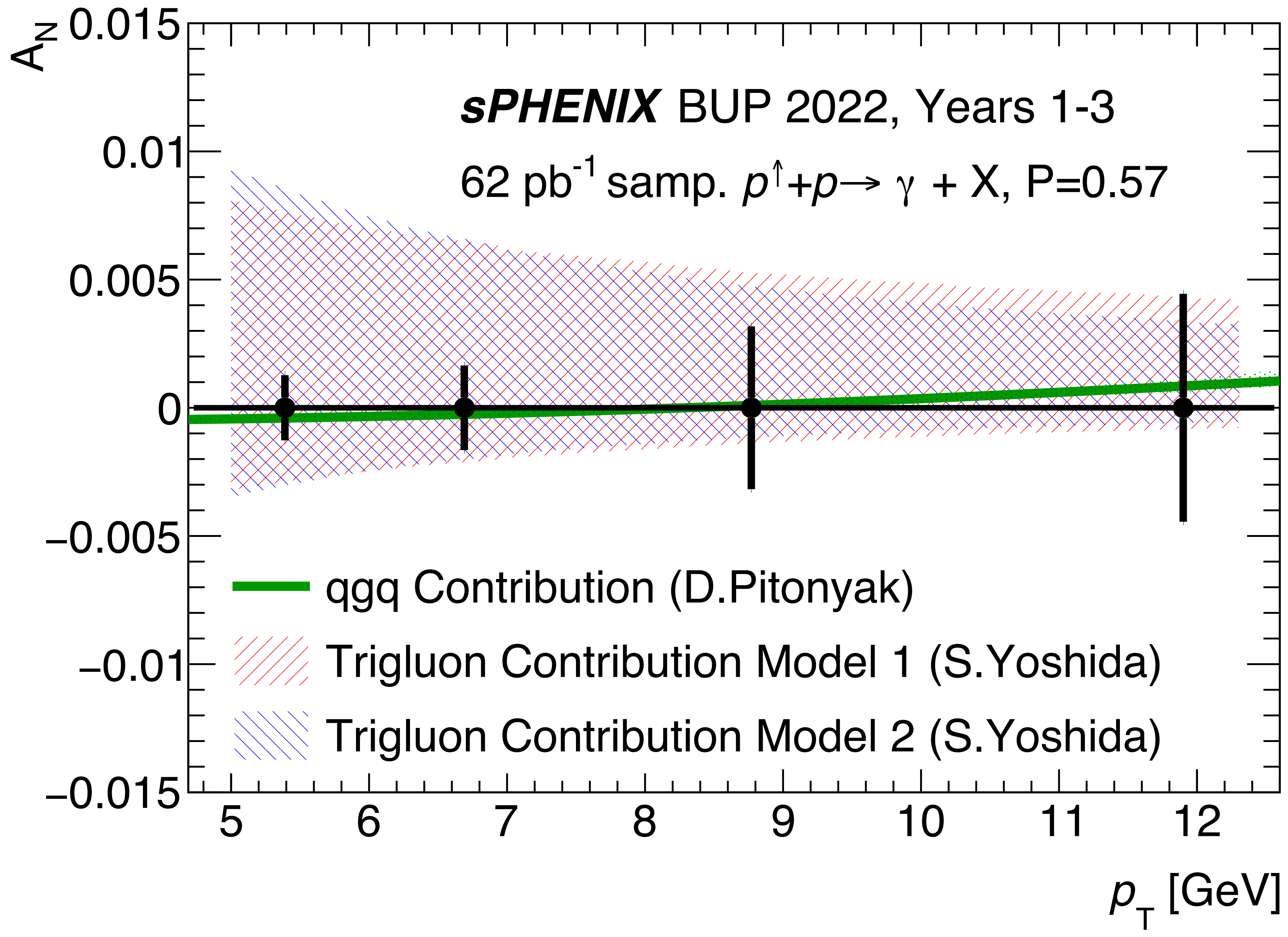


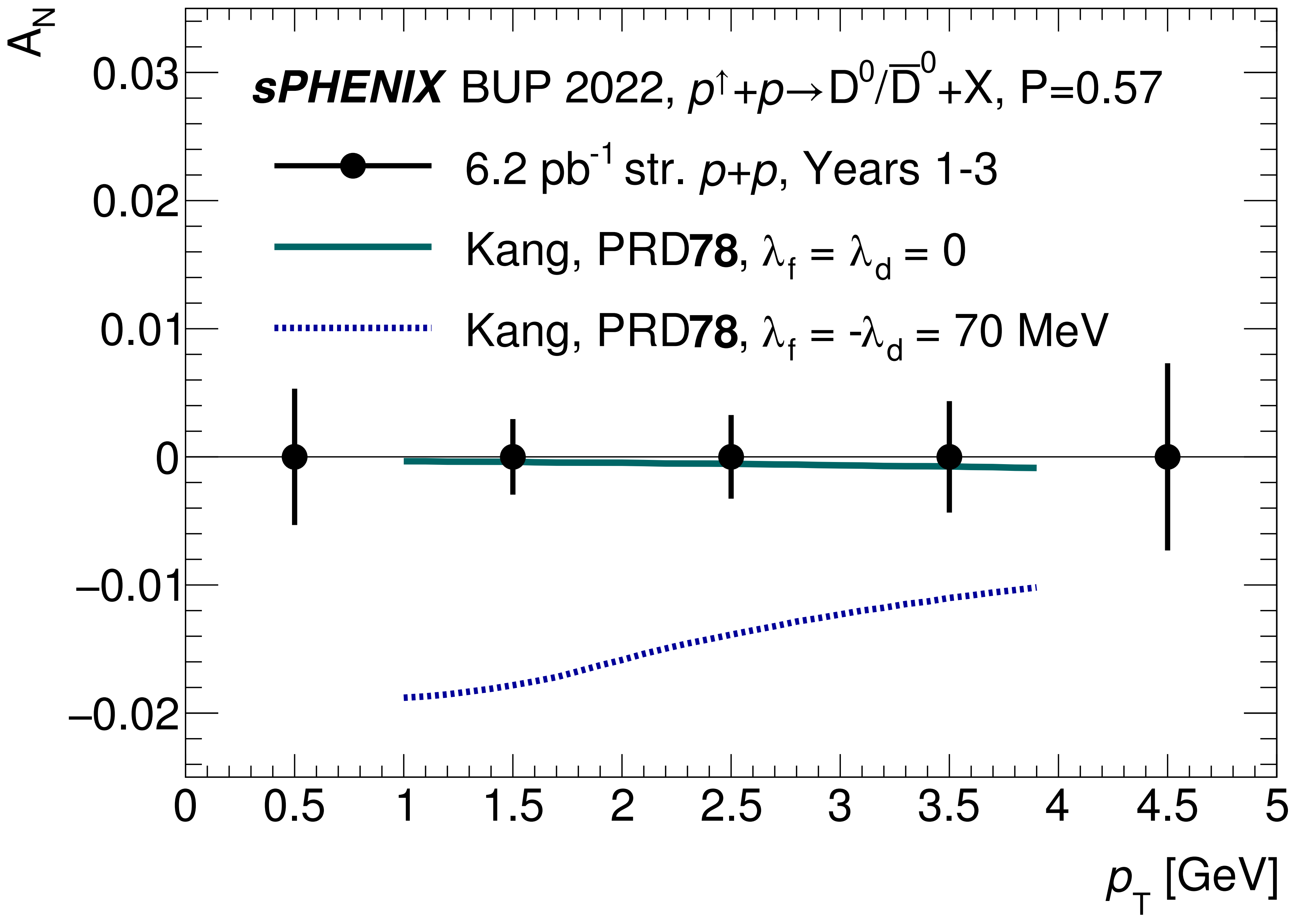
- *Above*: large yields for unpolarized *p*+A physics & unbiased *p*+*p* data reference
  - ➡ nuclear PDF modification extending deep into EMC region & cold nuclear energy loss
  - ➡ measurements looking towards EIC, including EIC Detector-1 instrumentation - e.g. hadronization in nuclear medium via jet structure

p+*p*: polarized observables

★ enabled by streaming readout





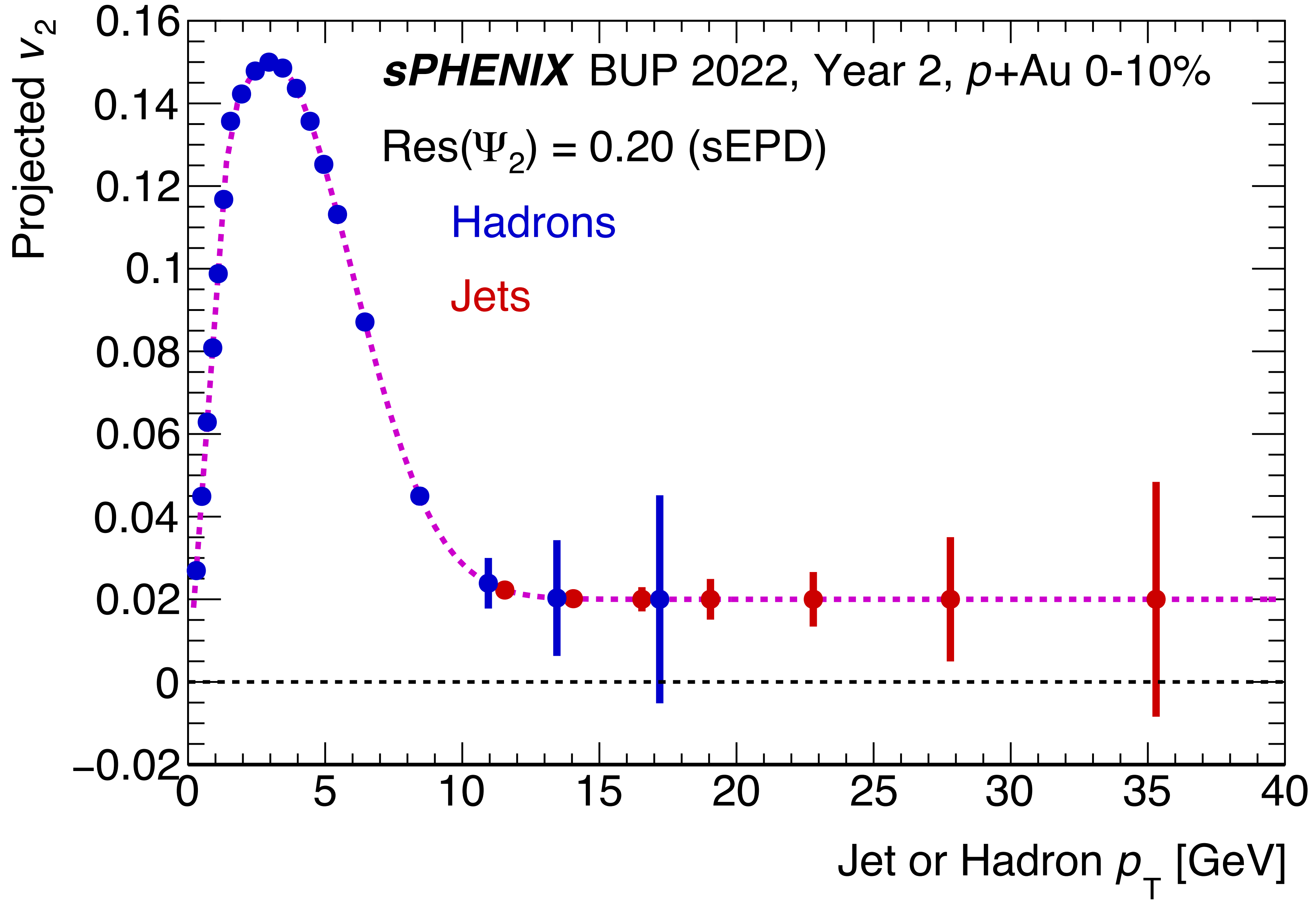


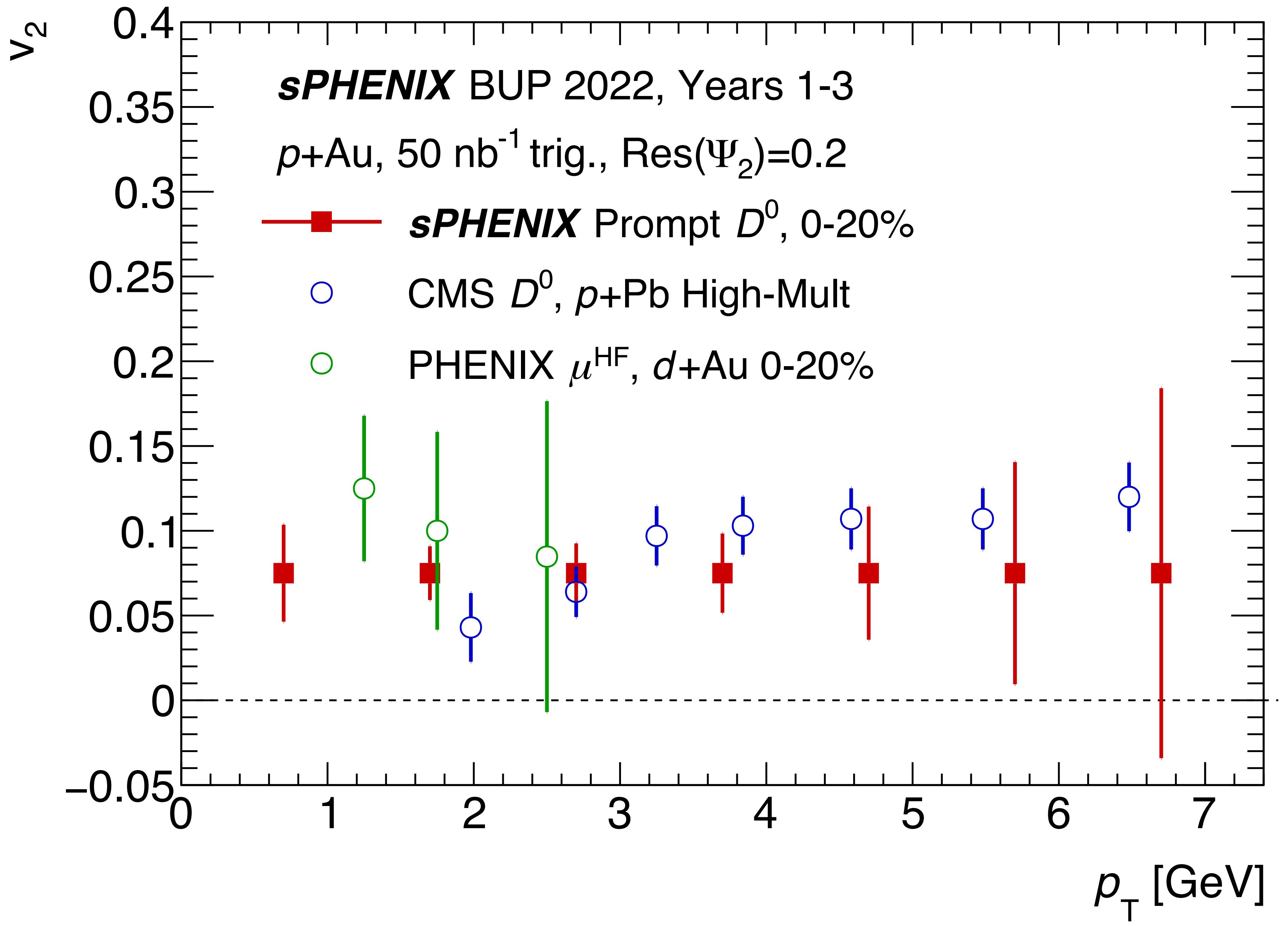
- Use sPHENIX capabilities for TSSA of direct photons (left) and heavy flavor hadrons (right) - probe gluon dynamics in transversely polarized nucleons through tri-gluon correlation function

➡ connected with the poorly constrained gluon Sivers TMD function

➡ check universality with HF A_N at the EIC

p+A: collective behavior





- Detailed azimuthal anisotropy for light and heavy flavor probes in *p*+Au

  ➡ key open question on the origin of collectivity in small systems

- *Left*: projected v_2 for **hadrons** and **jets** (& large stats for track-only analyses - cumulants, etc.)
- *Right*: HF flow poorly constrained at RHIC *p*/*d*+Au - major impact from **sPHENIX** D^0

sPHENIX Outlook

The sPHENIX Beam Use Proposal outlines a specific plan to deliver the promised physics in 2023-2025

Exciting physics program requires dedicated detector & machine commissioning time

Sufficient luminosity for large *p+p* data sample critical to success of scientific program

It is our last opportunity at RHIC to collect an *archival dataset* with *unprecedented experimental capability!*

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