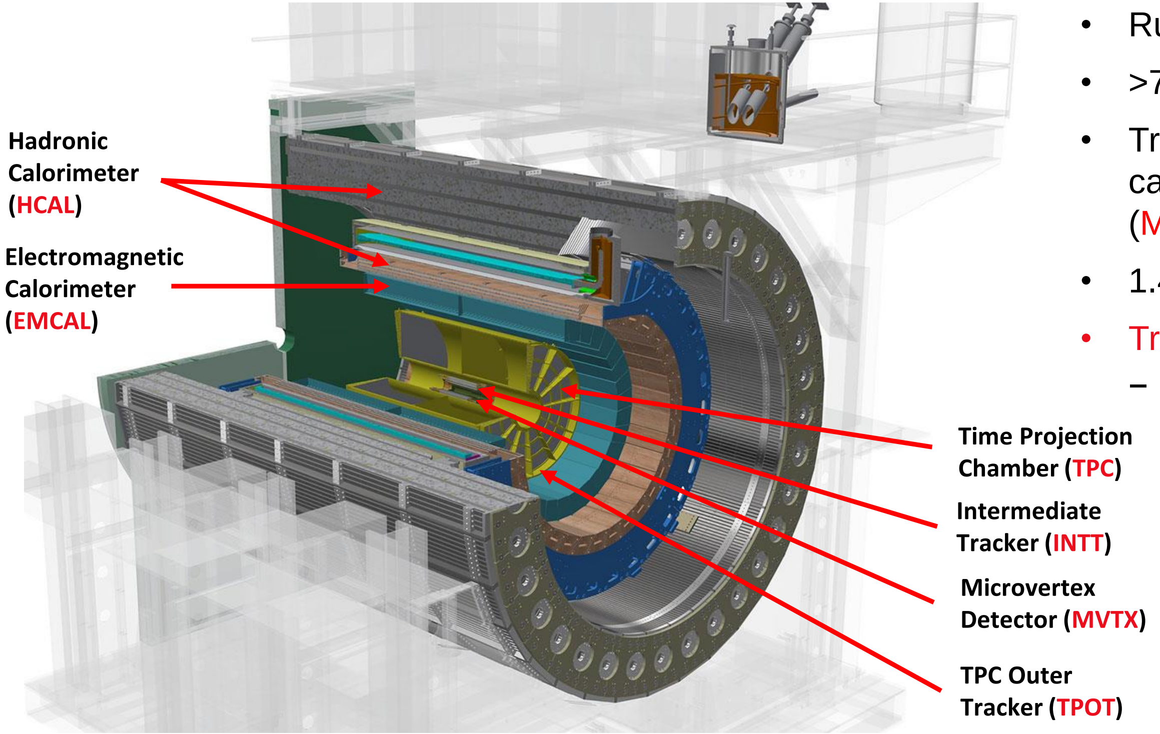
Heavy-Flavor tagged jets at sPHENIX

Jakub Kvapil for the sPHENIX collaboration

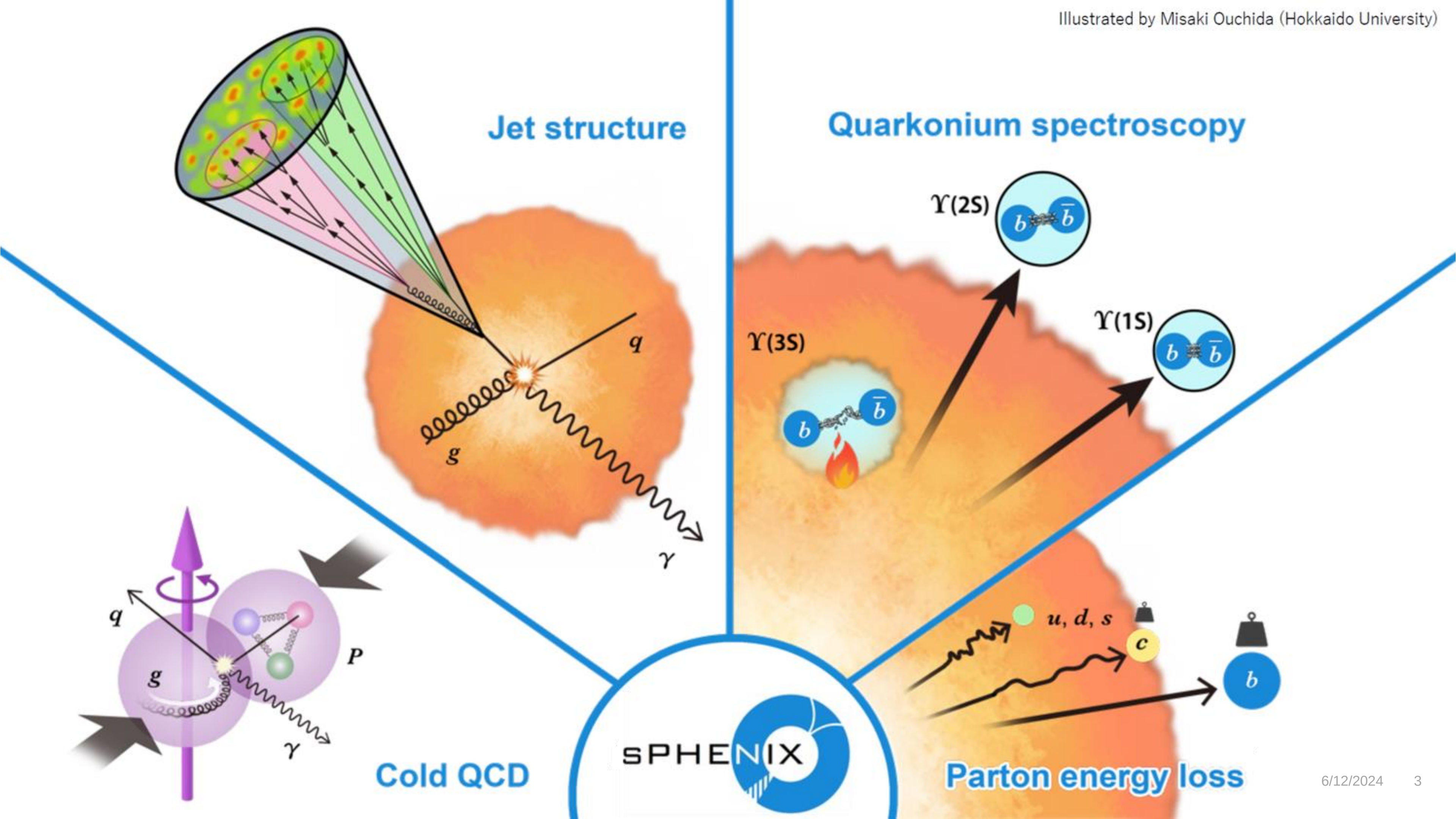
2024 RHIC/AGS Annual Users' Meeting

LA-UR-24-25617

sPHENIX experiment

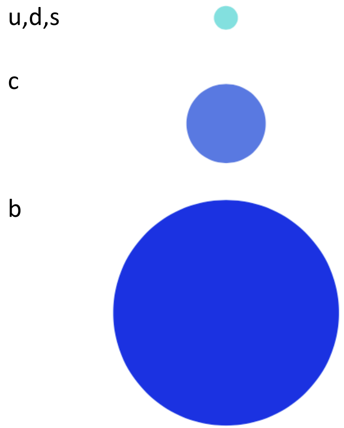


- Running period 2023-2025
- >7m long, >5m high, 1000 tons
- Tracking detectors (MVTX, INTT, TPC, TPOT), calorimeters (EMCAL, HCAL), and endcaps (MBD, sEPD, ZDC, SMD)
- 1.4 T Magnetic Field, $|\eta| \leqslant 1.1$
- Tracking detectors capable of streamed readout
  - Hybrid DAQ supporting 15 kHz triggering

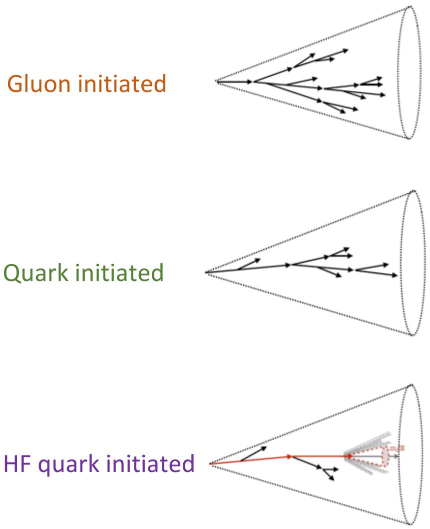

Illustrated by Misaki Ouchida (Hokkaido University)
Jet structure
q
g
γ
Quarkonium spectroscopy
Υ(2S)
b b̄
Υ(1S)
b b̄
Υ(3S)
b b̄
Cold QCD
q
g
P
γ
sPHENIX
Parton energy loss
u, d, s
c
b

Physics motivation

- Heavy-flavor (HF) hadrons
  - Heavy quarks (charm and beauty) are mostly produced in hard partonic scatterings processes in the early stages of the collisions.
  - Because of their large mass, the production cross section can be calculated using pQCD down to low p_{T}.
  - Excellent probe for Quark-Gluon Plasma (QGP) as they are produced before QGP is formed and experience the entire QGP evolution



Physics motivation



- HF-tagged jets
  - Give direct access to the initial parton kinematics
  - Provide further constraints on pQCD-based models
  - Quark initiated jets
  - Information on heavy-quark energy loss in the QGP
    - Collisional energy loss might be significant
    - Redistribution of lost energy
    - Measurement of radiative energy loss – dead cone effect
- HF hadronization, fragmentation, and its modification by QGP, and flow
  - Jet substructure provides additional information, complementary to RAA and v2
- Comparing to past RHIC measurements
  - sPHENIX offers high rate, precise tagging, and full calorimetry jets
- Comparing to past LHC measurements
  - sPHENIX offers temperature closer to T0, lower fraction of gluon splitting

Different HF tagging methods

1. Impact parameter method
   - Selecting jets containing one or more displaced tracks from the primary vertex
   - High efficiency, lower purity
   - Works very well in pp, p-A. A-A might be challenging

   A. Track counting method [this talk]
      - First step, simple to deploy, usually lower purity
      - arXiv:1211.4462 [CMS], arXiv:2110.06104 [ALICE]

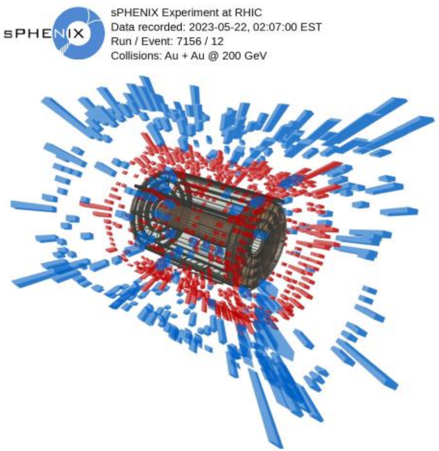
   B. Data-driven track probability method
      - Next step, requires deep knowledge of detector performance, higher purity
      - arXiv:1211.4462[CMS], arXiv:2110.06104[ALICE], arXiv:1002.4224[D0], arXiv:0311003[DELPHI]

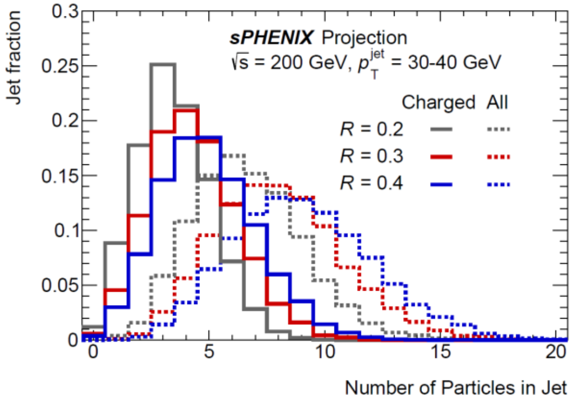
Different HF tagging methods

2. Secondary vertex reconstruction
   - Constrains on topology and vertex invariant mass
   - Can be used to separate prompt (c) and non-prompt (b) signals
   - Helps to constraint the background
   - arXiv:2110.06104[ALICE], arXIV:1211.4462[CMS]
3. HF-hadron tagging
   - Requires fully reconstructed HF-hadron inside a jet
   - Looking at hadronic [this talk] or (semi-)leptonic HF decays channels to tag the jet
   - High purity, lower efficiency
   - Allows the study of additional HF-jet substructure variables ($z_{||}$) and modification of other ($g,\ p_T D,$ $z_g,\ R_g,\ n_{SD},\ \ln 1/\theta$)
   - arXiv:2204.10167[ALICE], arXiv:1911.01461[CMS]

Particle flow

- Almost half of the jet energy is carried by the neutral particles
  - The importance to study full jets
  - sPHENIX has the first mid-rapidity HCAL at RHIC!
- Initial implementation of particle flow at sPHENIX to connect charged tracks and calorimeter information





Track counting method

- One of the “simplest” methods to start with
  - Only requires a track and primary vertex
  - This method was used in the sPHENIX performance studies

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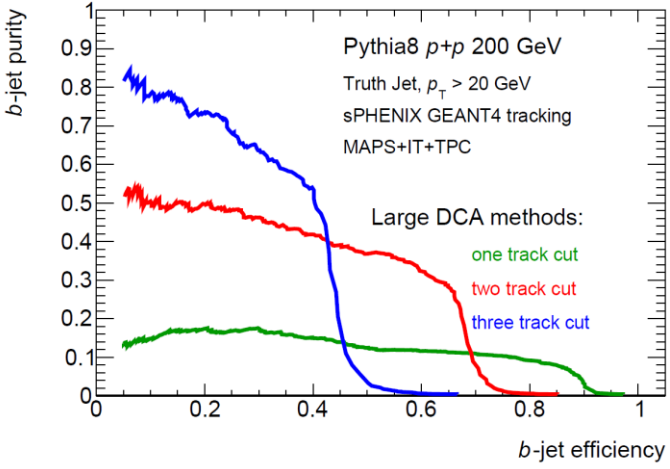

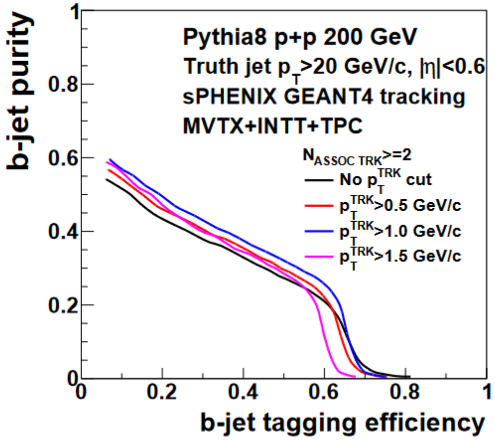

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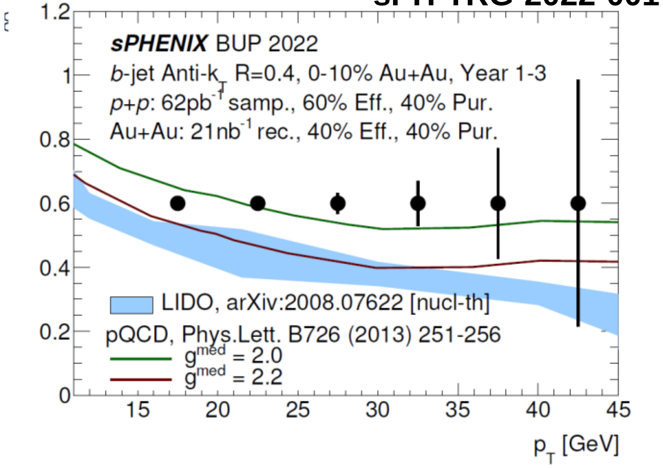
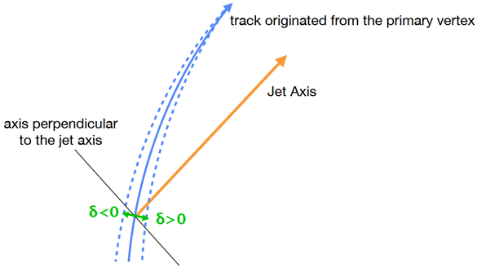


Track counting method

1. The main discriminator is the signed significance of track-to-primary-vertex DCA in transverse plane $SDCA_{\mathrm{xy}}$
   - $SDCA_{\mathrm{xy}} = sgn\left(\overrightarrow{p_{xy}^{jet}} \cdot \overrightarrow{DCA_{xy}^{jet}}\right) \frac{|\overrightarrow{DCA_{xy}}|}{unc(|\overrightarrow{DCA_{xy}}|)}$
   - The significance is defined as DCA in transverse plane between the track and the primary vertex divided by its uncertainty
   - The sign is defined as a signum (sgn) of the scalar product of the jet axis and the DCA vector
     - Tracks originating from primary vertex should have $\mathrm{sgn}(x) = 0$
     - due to limited resolution, they will have both $\mathrm{sgn}(x) = +1$ and $\mathrm{sgn}(x) = -1$ values
     - Track originating from secondary decays will have $\mathrm{sgn}(x) = +1$



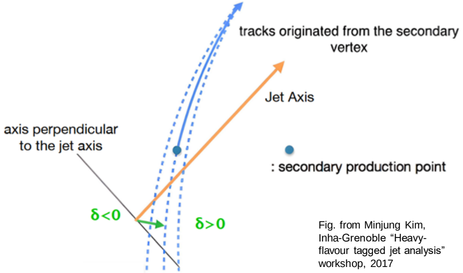
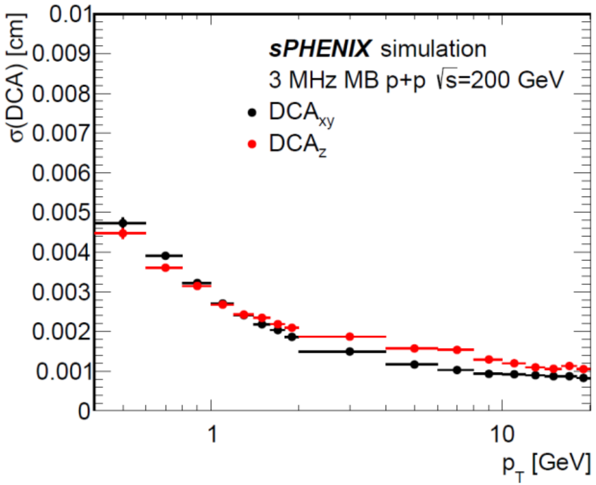


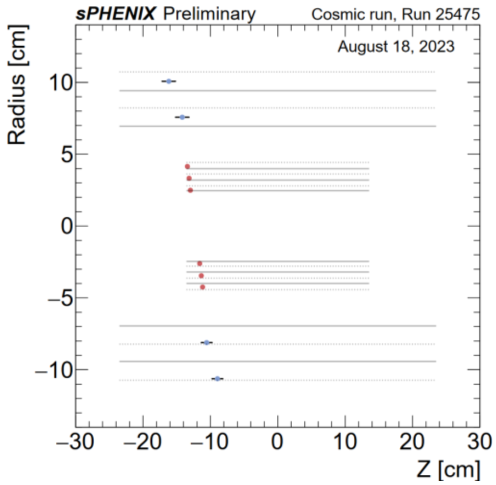
Fig. from Minjung Kim, Inha-Grenoble "Heavy-flavour tagged jet analysis" workshop, 2017

Simulation Sample/Jet-Track Selection

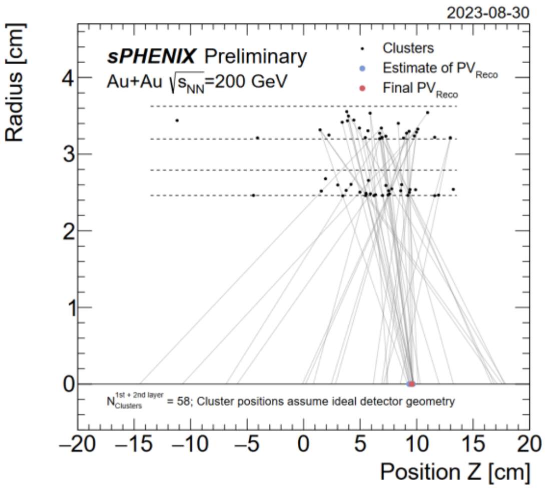
- Simulation configuration:
  - PYTHIA 8 + GEANT 4, pp 200 GeV, HardQCD:all, $\hat{Q} = 7\ \mathrm{GeV}/c$, without pile up
- Jet selection:
  - Anti-k_T, E-scheme, $R = 0.4$, $p_{\mathrm{T,jet}}^{\mathrm{truth}} \geq 10\ \mathrm{GeV}/c$, $p_{\mathrm{T,jet}}^{\mathrm{reco}} \geq 5\ \mathrm{GeV}/c$
- Track selection:
  - $p_{\mathrm{T,track}} \geq 500\ \mathrm{MeV}/c$
- For the $SDCA_{\mathrm{xy}}$ calculation further track selection is required:
  - $\chi^2/nDOF < 5$
  - TPC clusters ≥ 30
  - INTT clusters ≥ 2
  - MVTX clusters ≥ 3



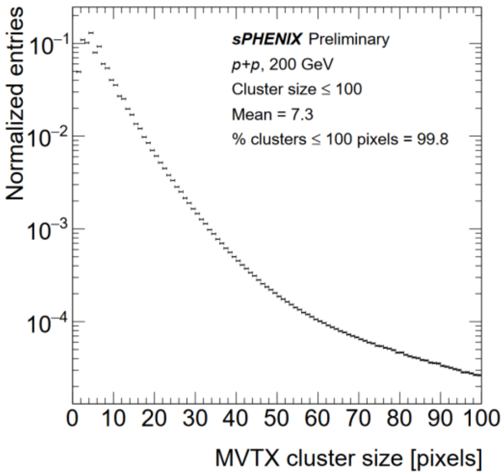
Large progress made during commissioning



2023 cosmic, silicon alignment



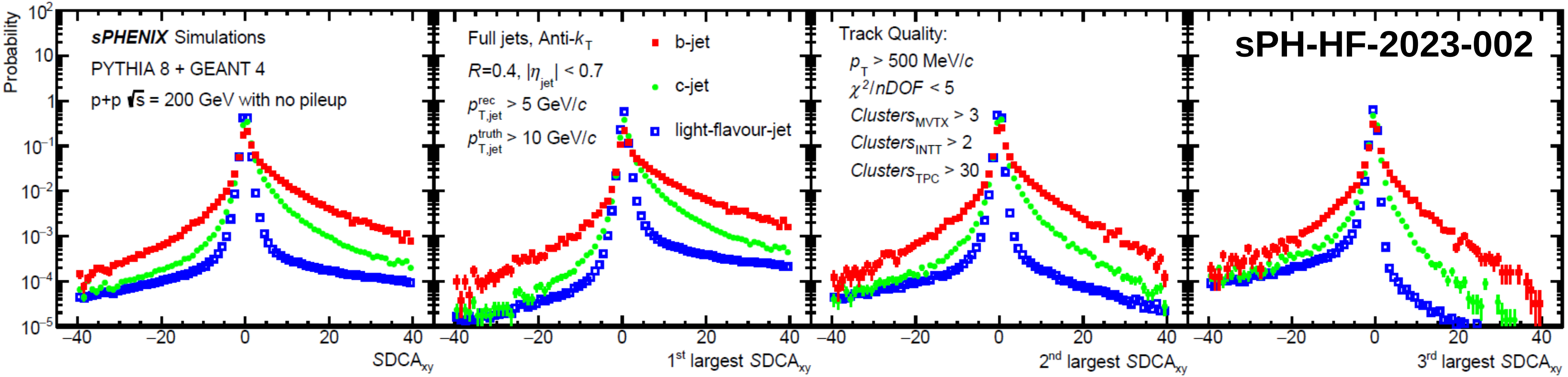
2023 ion run, MVTX-Only
PV estimation



2024 proton data, cluster size
Consistent with ALICE and CMS

$SDCA_{xy}$ probabilities

- Signed significance ($SDCA_{xy}$) probability of tracks, and $SDCA_{xy}$ of the first-, second-, and third- most significant track
- Clear separation of flavours



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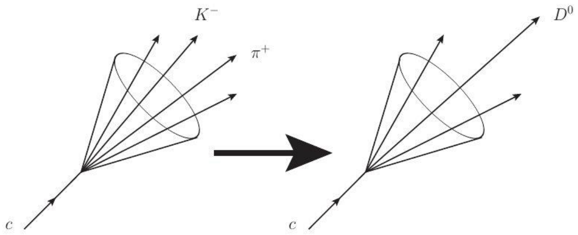
Next steps

1. First look at HF-tagged full jets using particle flow at sPHENIX
2. Optimize the track selection and jet tagger under the Run24 condition, including the pile up and apply in 2024 on p+p data
3. Tune the track and jet selection to achieve high purity and efficiency
4. Implement Jet Probability method
5. Introduce the machine learning to further improve the performance

HF hadron tagging

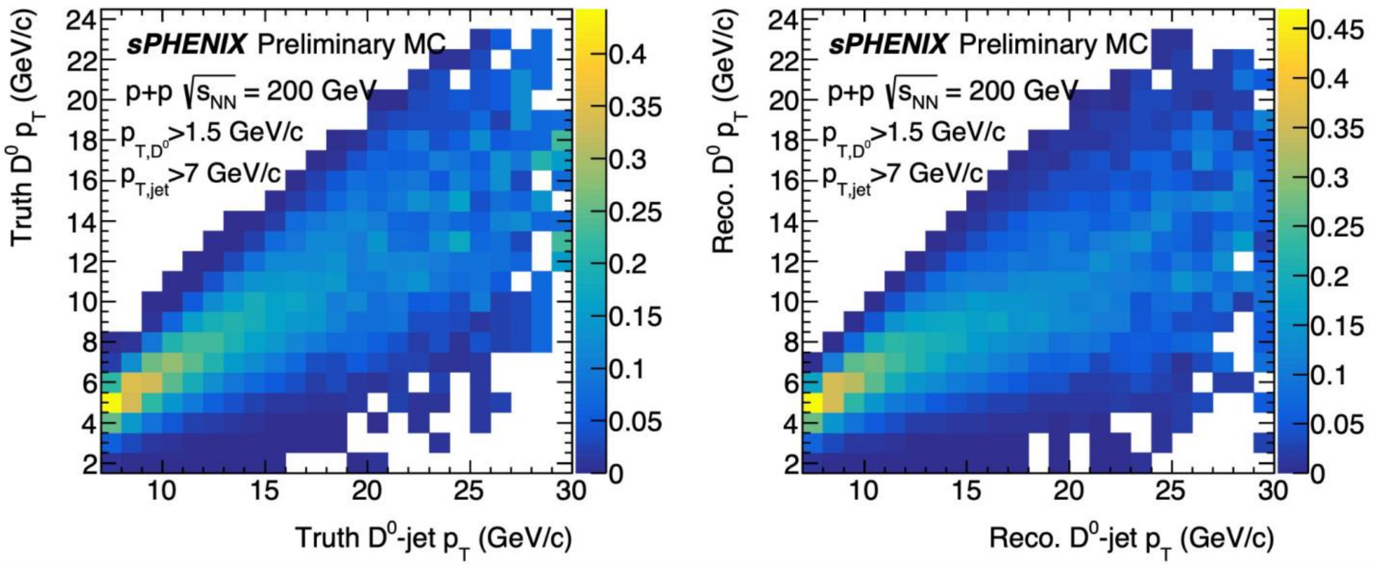
- Better jet background rejection
- Allow study of jet spectrum down to low pT
- Heavy-quark initiated jet structure and parton shower

1. D mesons are reconstructed via $D^0 \rightarrow K^-\pi^+$exploiting sPHENIX excellent tracking capabilities
2. D-meson decay daughters are removed from the particle list and replaced by the D-meson 4-momentum vector
3. Jet is tagged as D-meson tagged if there is a fully reconstructed D0 particle inside the jet



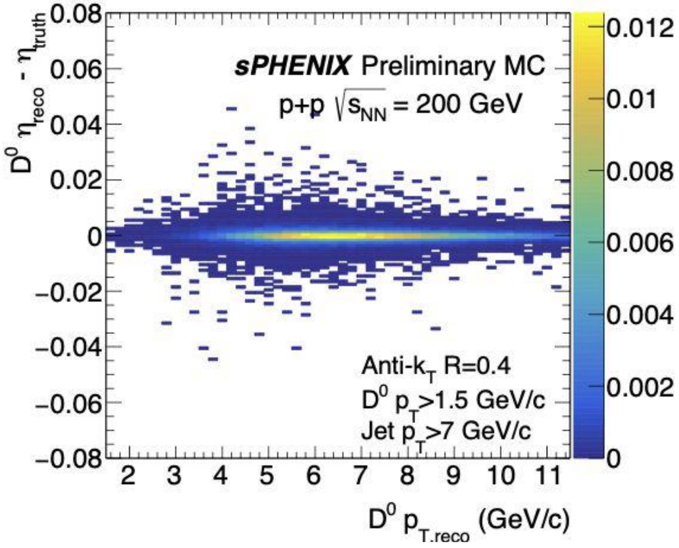
HF hadron tagging

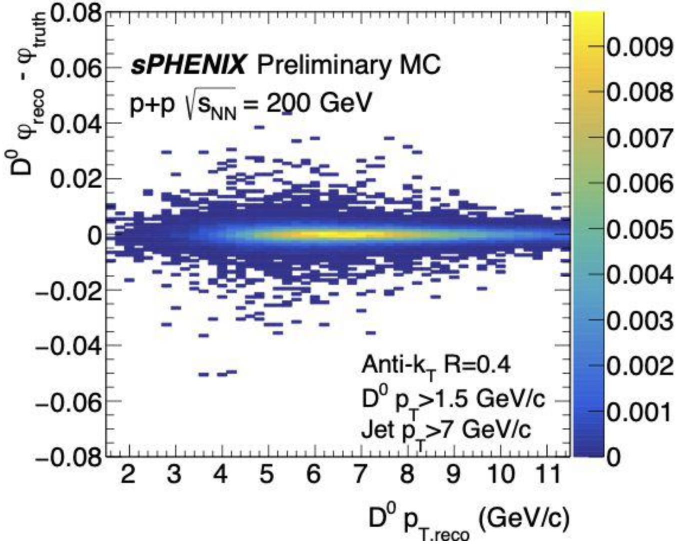
- Jet tagging successfully implemented
- Next step: Commissioning of the full framework



HF hadron tagging

- Angular resolution is a key element in the study of heavy-flavor jet structure





Summary

- sPHENIX is the first detector with full calorimetry in mid rapidity at RHIC
- sPHENIX started collecting first pp data
  - Data reconstruction, calibration, and alignment underway
  - DCA resolution < 40 um crucial for separation of prompt and non-prompt D-meson
- Focus on commissioning the particle flow and pp data
- Multiple HF jet tagging strategies were explored

Thank you for your attention