Direct Photon Production from Concurrent Minijet-Hydrodynamics Evolution

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Motivation and Overview

- Jets with relatively low-p_T (mini-jets) $\longrightarrow$ can continuously deposit energy-momentum into the medium

- Direct photons are probes of the quark-gluon plasma (QGP)

- They are emitted throughout the space-time evolution and escape largely unmodified

- How does continuous minijet(hard) energy loss affect direct photon observables?

- We investigate how a concurrent minijet+hydro evolution impacts:
  - Direct photon spectra
  - Photon elliptic flow (v_2)

- Framework: IP-Glasma + MUSIC + UrQMD + dedicated photon module, with minijet dynamics from a hybrid model

Introduction to Minijets:

- Hard parton scattering $\rightarrow$ outgoing partons $\rightarrow$ shower/fragment $\rightarrow$ jets[1,2]

- Mini-jets with relatively low transverse momentum:

$$p_T \sim \mathcal{O}(4\text{-}10) \text{ GeV}$$

- Produced in initial hard pQCD scatterings
- Intermediate regime:
  - between soft bulk medium and rare high-p_T jets
- If $x_{\text{stop}} > \tau_0$:

$\Rightarrow$ slow thermalization $\Rightarrow$ persistent energy-momentum source during hydro

Wake, Credit: Edmont, Wikimedia
Commons, CC BY-SA 3.0

[1] Busza, Rajagopal, van der Schee, Ann.Rev.Nucl. (2018)
[2] Solana, Gulhan, Milhano, Pablos, Rajagopal, JHEP (2014)

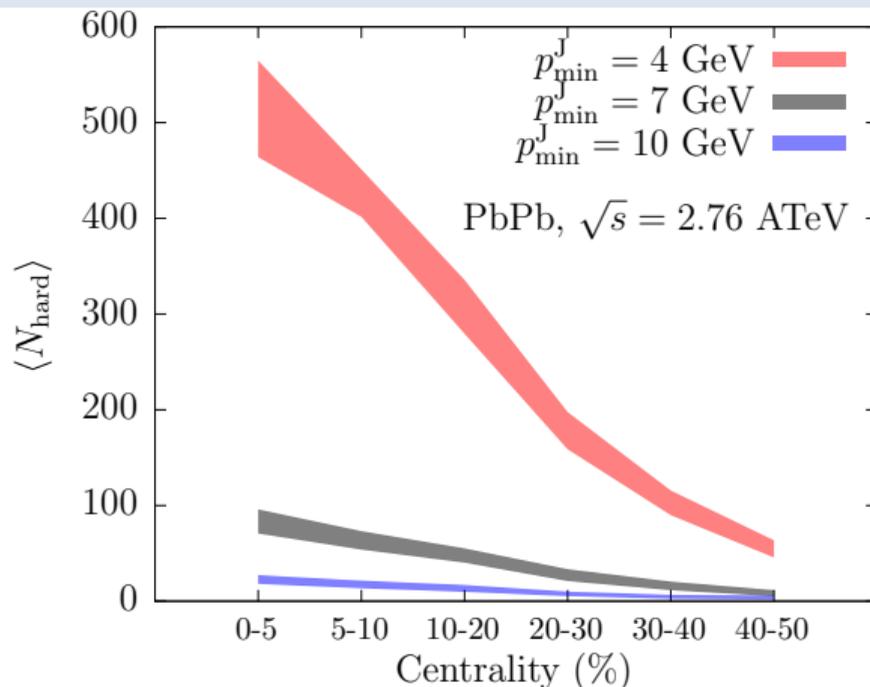# Choice of the jet transverse momentum

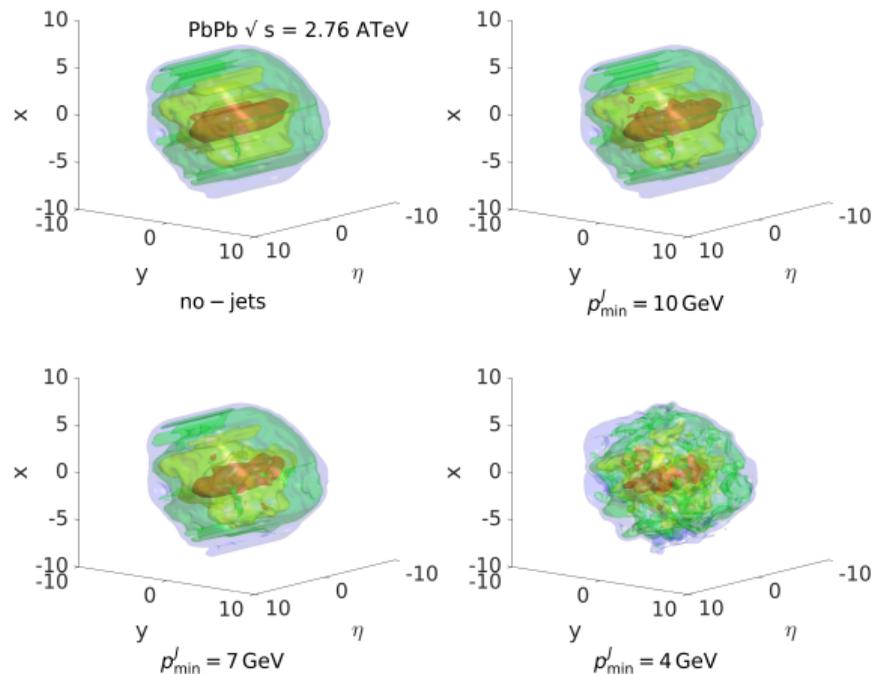Figure: Ref. Pablos, Singh, Jeon, Gale, PRC (2022)

Modified Hydro Evolution

Figure: Snapshots of the 3D isotherms. Ref. Pablos, Singh, Jeon, Gale, PRC (2022)

Minijets: How They Affect the Medium

- Continuous energy–momentum deposition into the QGP fluid
- Induces *spikier* hydrodynamic fields:
  - Additional event-by-event fluctuations
- Affects final-state multiplicity:
  - Mini-jets add entropy
  - To keep realistic $dN_{ch}/d\eta$, initial entropy must be reduced
- Minijet momenta are randomly oriented:
  - $\Rightarrow$ tend to reduce collective flow
- Impact on transport extraction:
  - To reproduce measured v_n,
  - Presence of minijets favors lower QGP η/s

[1] Pablos, Singh, Jeon, Gale, PRC (2022)

$p_J^{\min}$ [GeV]	s_{factor}	η/s
4	0.45	0.02
7	0.82	0.10
10	0.90	0.125
No jets	0.915	0.13

- Mini-jets require adjusting:
  - initial entropy
  - shear viscosity
- Direct photons can help constrain these effects

Direct Photons as Probes of the QGP

- Categorized according to their origins [1]:

  - Prompt Photons $\implies$ Produced in initial hard partonic scatterings (e.g., Compton scattering $qg \to q\gamma$ and annihilation $q\bar{q} \to g\gamma$)

  - Thermal Photons $\implies$ QGP $\oplus$ hadronic gas

  - Decay Photons $\implies$ hadron decays (subtracted experimentally)

- Direct photons are defined as:

$$\text{Direct photons} = \text{Prompt photons} \oplus \text{Thermal photons}$$

[1] Jean-François Paquet, Thesis (2016)

Simulation Framework
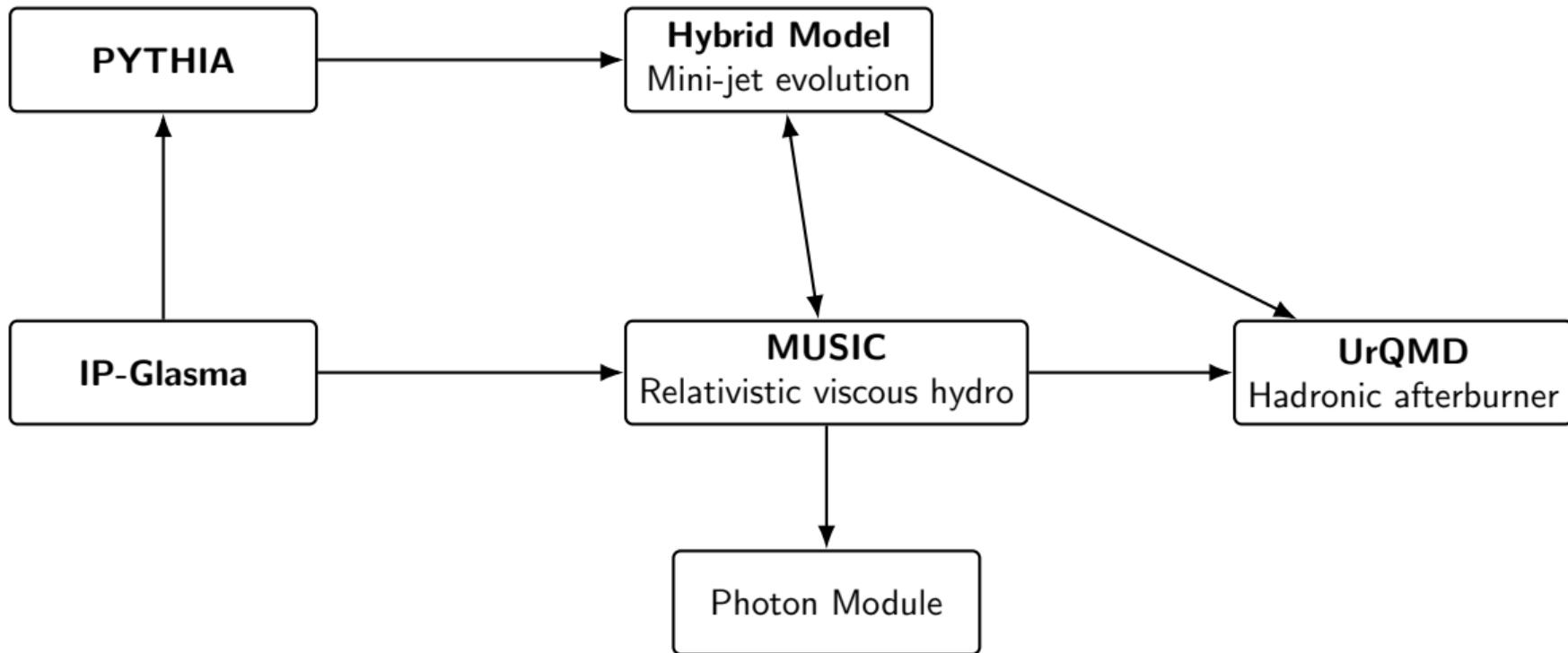
Hybrid Strong/Weak Coupling

- Scale separation [1]
  - Hard jet production and splittings: perturbative QCD (DGLAP)
  - Jet-medium interactions: strongly coupled dynamics
- Model assumptions
  - Soft exchanges
  - Vacuum-like splittings: DGLAP splitting probabilities

Energy-loss rate [2]

$$\frac{1}{E_{\text{in}}} \frac{dE}{dx} = -\frac{4x^2}{\pi\, x_{\text{stop}}^2\, \sqrt{x_{\text{stop}}^2 - x^2}}$$

Stopping distance

$$x_{\text{stop}} = \frac{1}{2\, \kappa_{\text{sc}}}\, \frac{E_{\text{in}}^{1/3}}{T^{4/3}}$$

[1] Chesler and Rajagopal, PRD (2014)

[2] Solana, Gulhan, Milhano, Pablos, Rajagopal, JHEP(2014)

IP-Glasma Initial Conditions with Concurrent Minijets

- **Bulk initial state from IP-Glasma[1,2]**:
  - CGC-based description of the colliding nuclei
  - Generates fluctuating energy–momentum density profiles
  - Hydrodynamic initialization at

$$\tau_0 = 0.4 \text{ fm}$$

- **Mini-jets from hard scatterings**:
  - Produced by PYTHIA

- **Concurrent minijet–hydrodynamic evolution**:
  - Hybrid strong/weak-coupling description of jet propagation
  - Lost energy is deposited into the medium as a source term[3]:

$$\partial_\mu T^{\mu\nu}_{\text{fluid}} = J^\nu_{\text{minijets}}$$

[1] Scott McDonald, Thesis (2020)
[2] Gelis, Iancu, Jalilian-Marian, Venugopalan, ARNPS (2010)
[3] Pablos, Singh, Jeon, Gale, PRC (2022)

How We Calculate Direct Photons

- **Prompt photons**
  - Computed using a baseline prompt photon spectrum from $p+p$ collisions
  - Scaled to Pb+Pb collisions using binary collision scaling:

$$\frac{dN_{\mathrm{prompt}}^{\gamma}}{dp_T}\bigg|_{AA} = \frac{dN_{\mathrm{prompt}}^{\gamma}}{dp_T}\bigg|_{pp} \times N_{\mathrm{coll}}$$
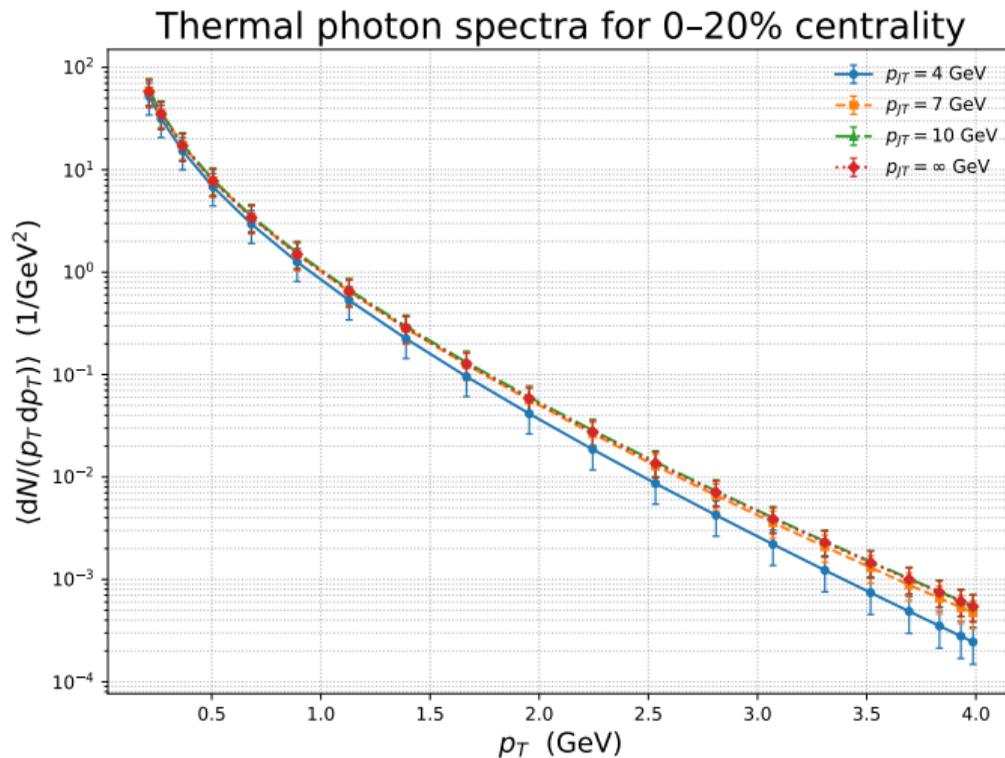
- **Thermal photons**
  - The full hydrodynamic evolution is stored: $T(x)$, $u^{\mu}(x)$, $\pi^{\mu\nu}(x)$, etc
  - Local thermal emission rates are evaluated at each space-time point
  - The total thermal yield is obtained by integrating the rates over the 4-volume:

$$E\frac{dN_{\mathrm{th}}^{\gamma}}{d^3p} = \int d^4x \, \left(E^* \frac{dR^{\gamma}}{d^3p^*}\right)\left(T(x), u^{\mu}(x)\right)$$

- Emission is terminated at a temperature:

$$T_{\mathrm{sw}} = 105 \text{ MeV}$$

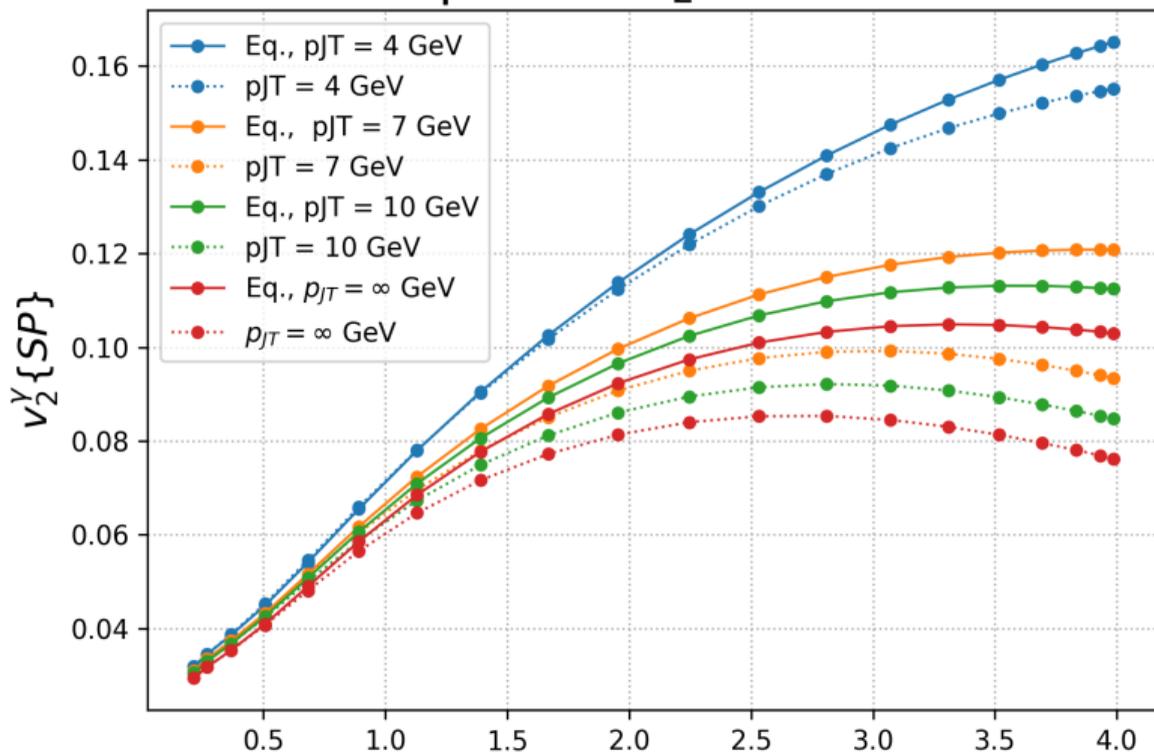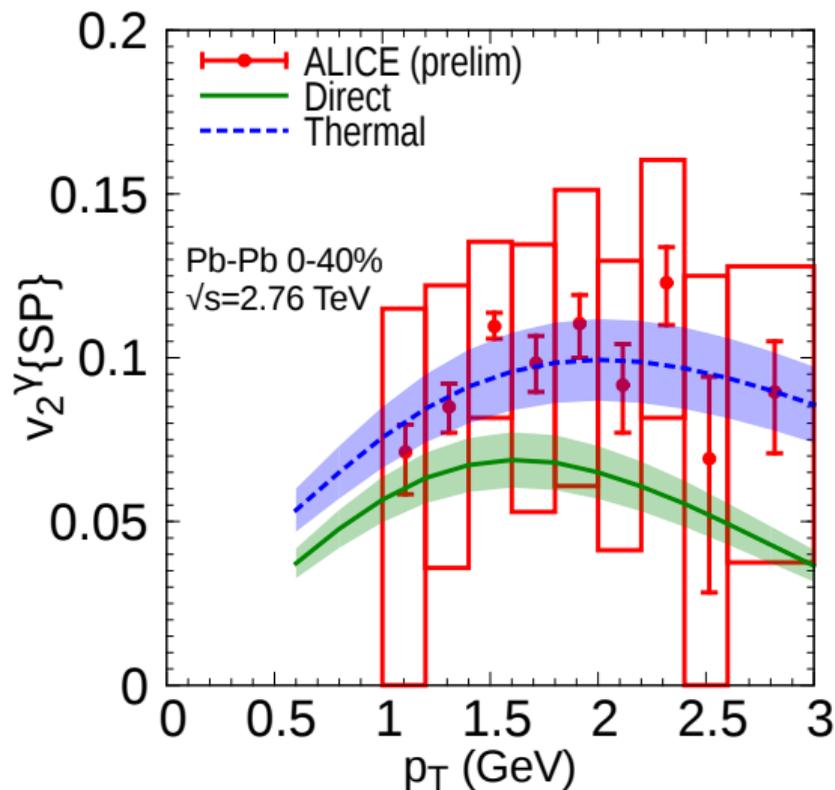# Preliminary Results: Photon Spectra (Central)

Thermal photon spectra for 0–20% centrality
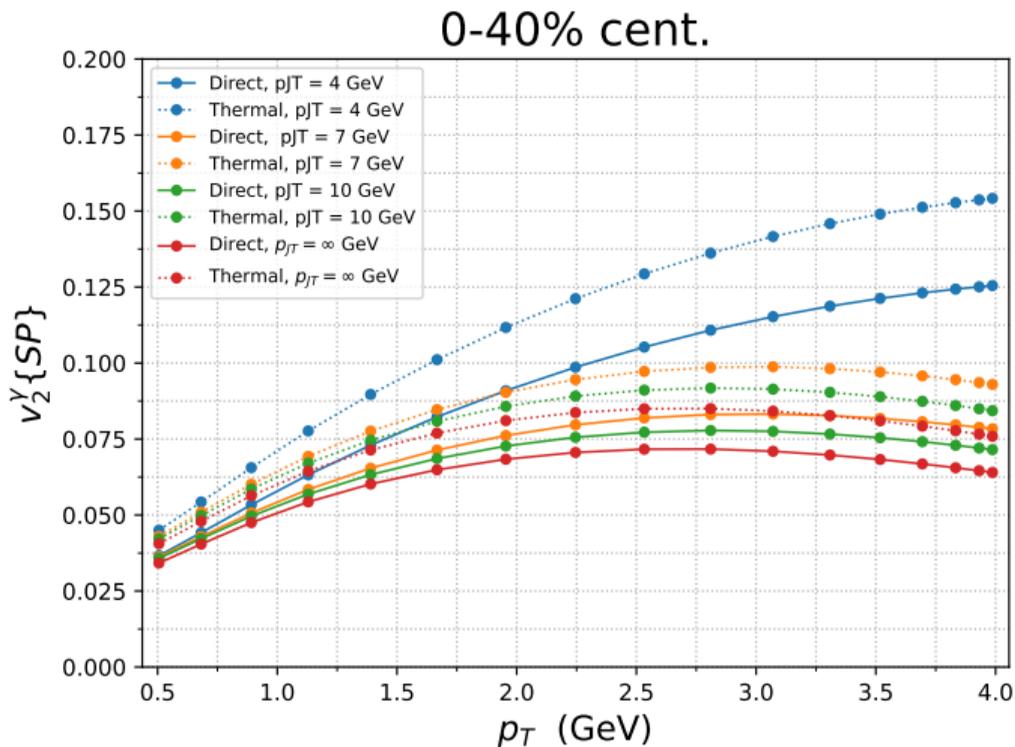
0-40% cent.

Thermal photon v_2 for 0-40% cent

Summary

- We studied direct photon production in a hybrid minijet+hydro framework:
  - IP-Glasma + MUSIC + UrQMD
  - Minijets from PYTHIA with hybrid strong/weak-coupling energy loss
- Mini-jets significantly impact:
  - Hydrodynamic fields and fluctuations
  - Photon yields and elliptic flow
  - Interpretation of QGP transport coefficients
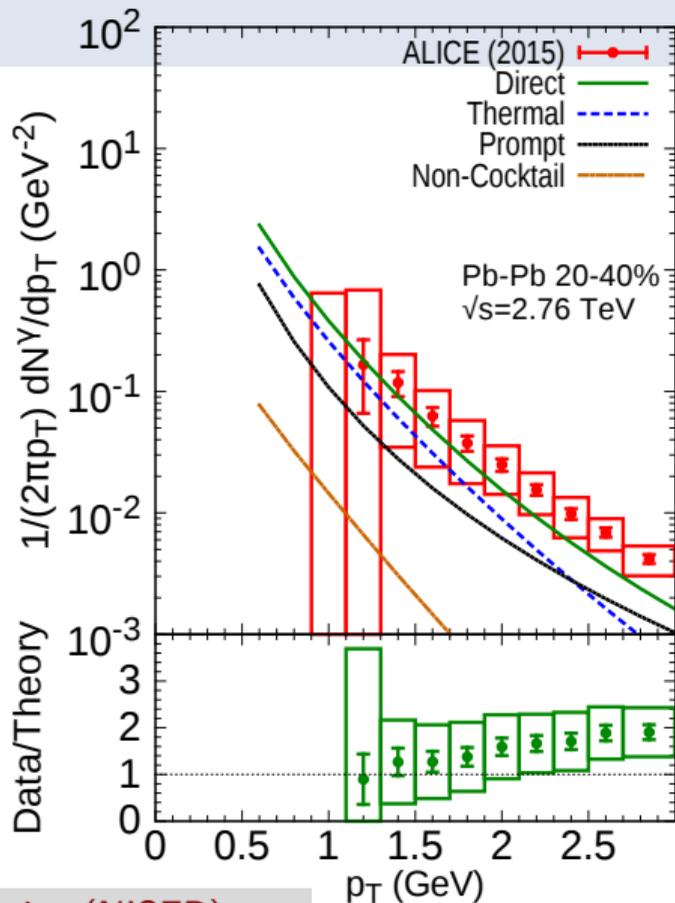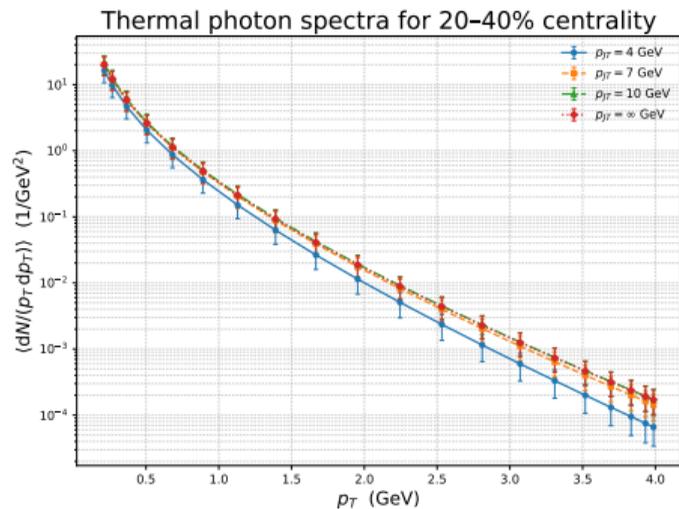- Direct photons provide an effective probe of minijet dynamics and medium evolution
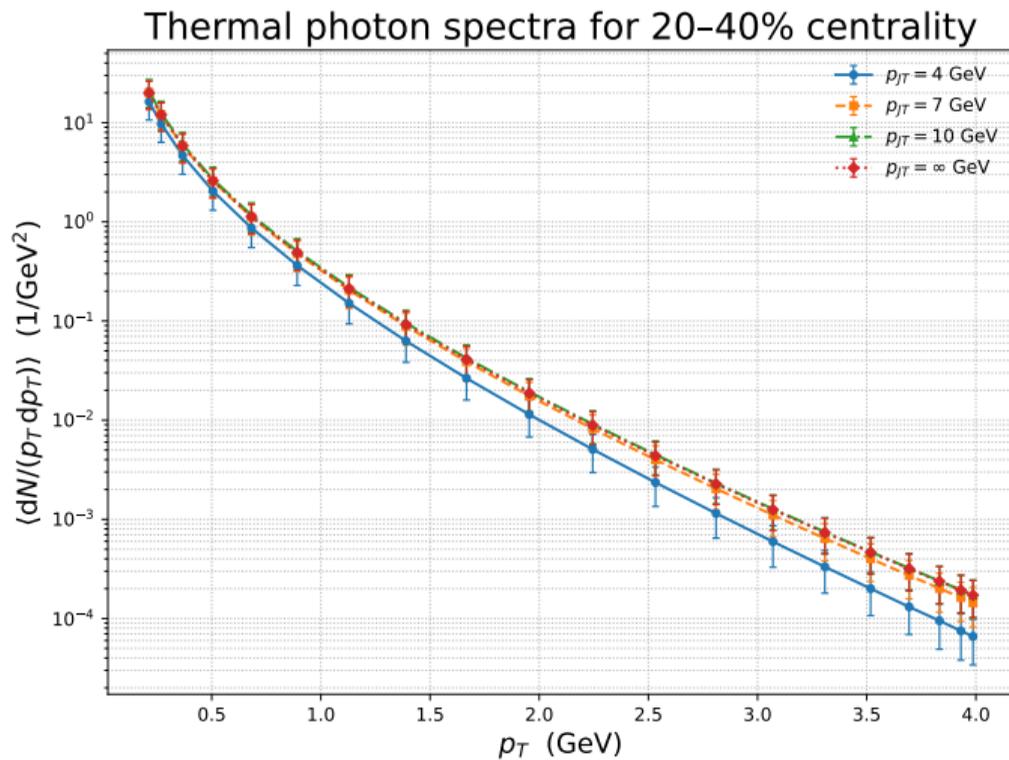
Comparison with previous results
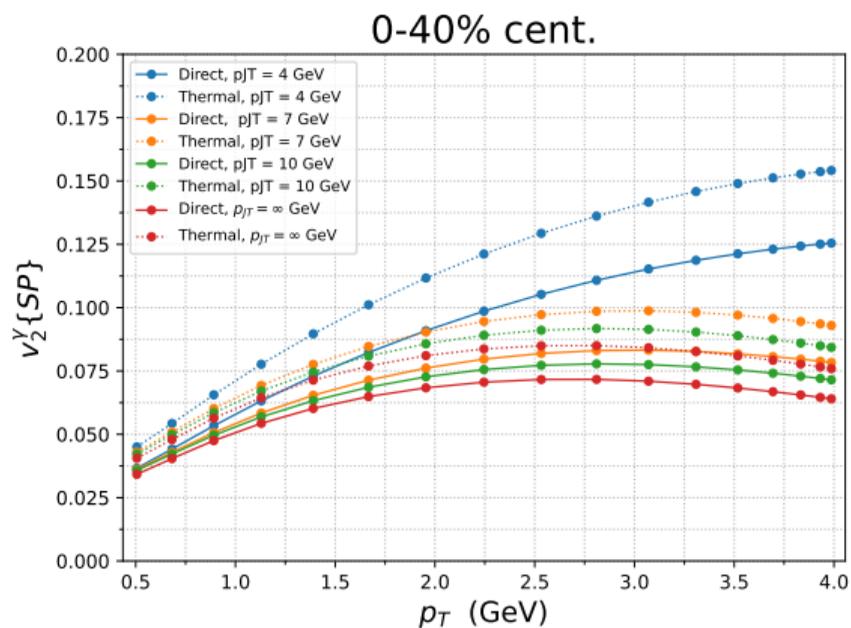
Comparison with previous results 1:

Thermal photon spectra for 0–20% centrality

Comparison with previous results 2:

Thermal photon spectra for 20-40% centrality
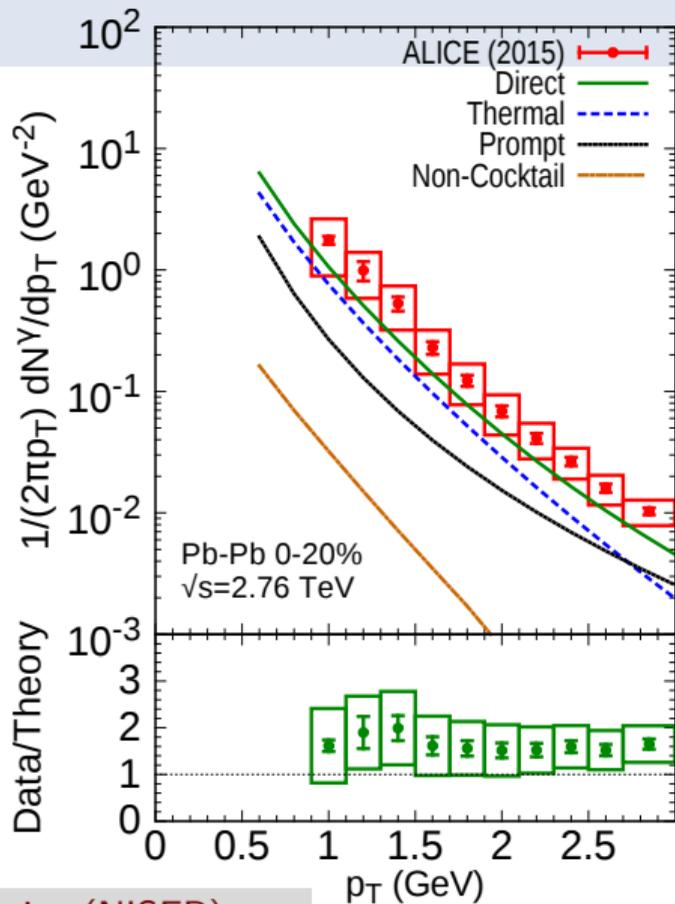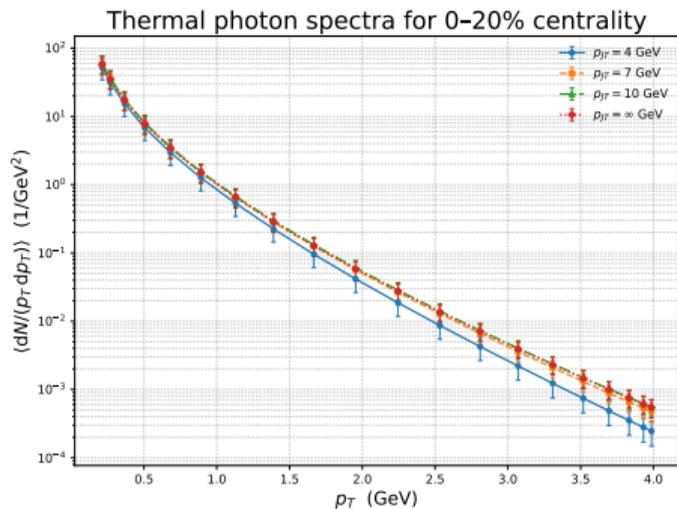
Preliminary Results: Photon Spectra (Semi-central)

Thermal photon spectra for 20–40% centrality

Evolution of energy density-weighted average temperature

Soham Banerjee (NISER)
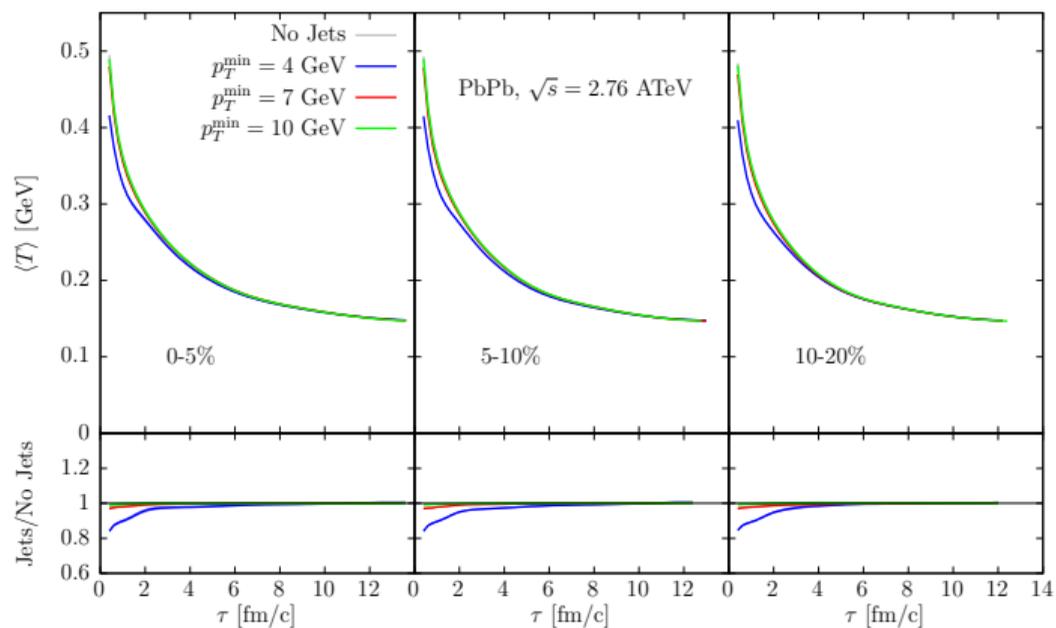
Evolution of energy density-weighted average momentum anisotropy