Fragmentation Function of Charged Pions in Jets using JetScape

McKenna Sleeth
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U.S. DEPARTMENT of ENERGY

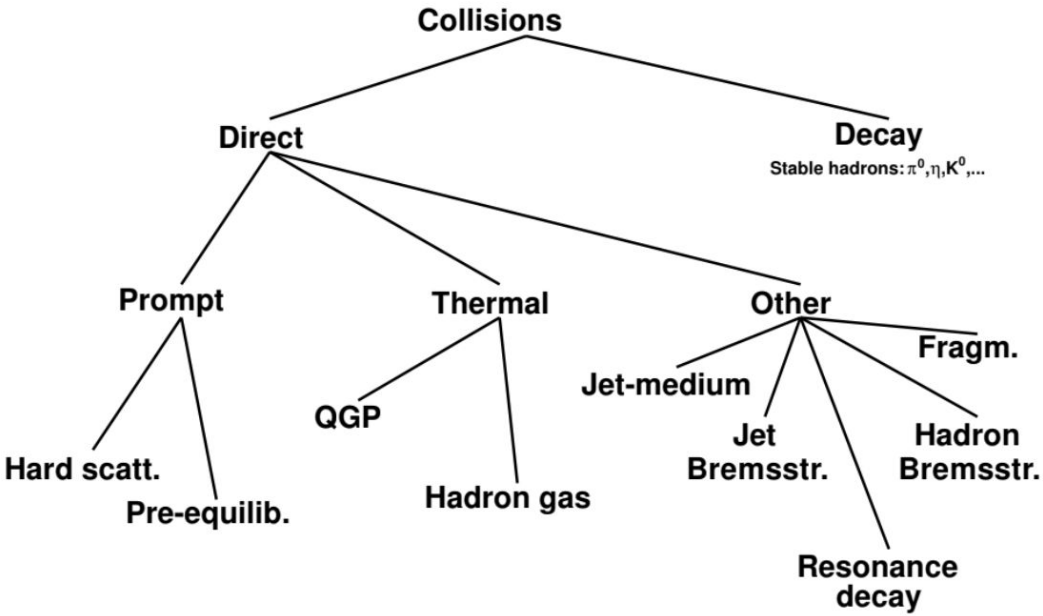
VANDERBILT UNIVERSITY

Motivation and Goal

- Multiple interactions can produce photons in a particle collision

- Some are only produced in heavy-ion collisions (e.g. QGP thermal photons, etc)

Types of Photons in Heavy-Ion Collisions



G. David. Rep. Prog. Phys. 27;83(4):046301(2020)

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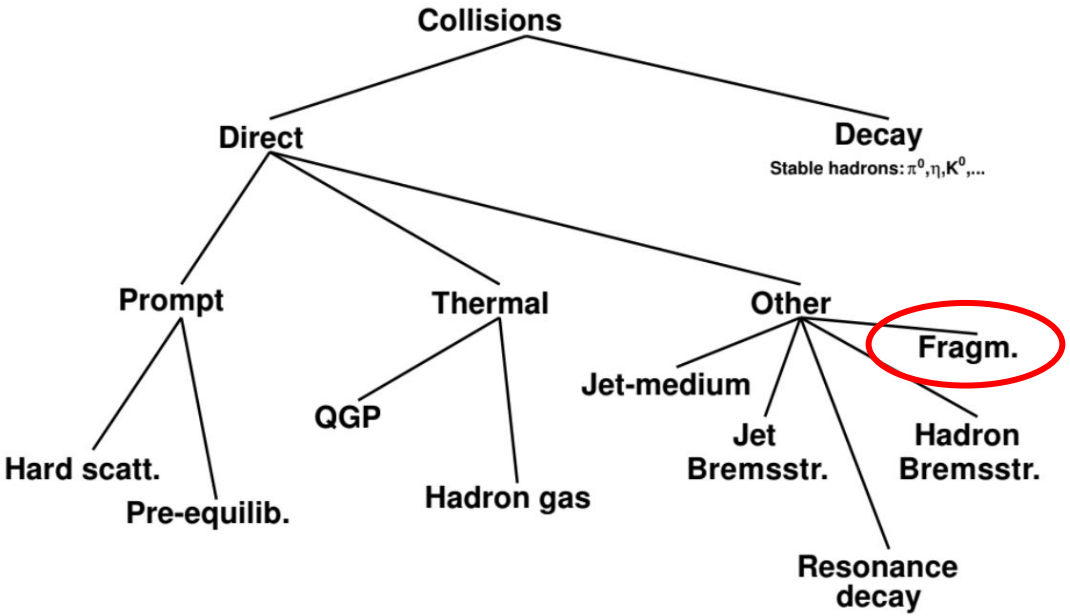
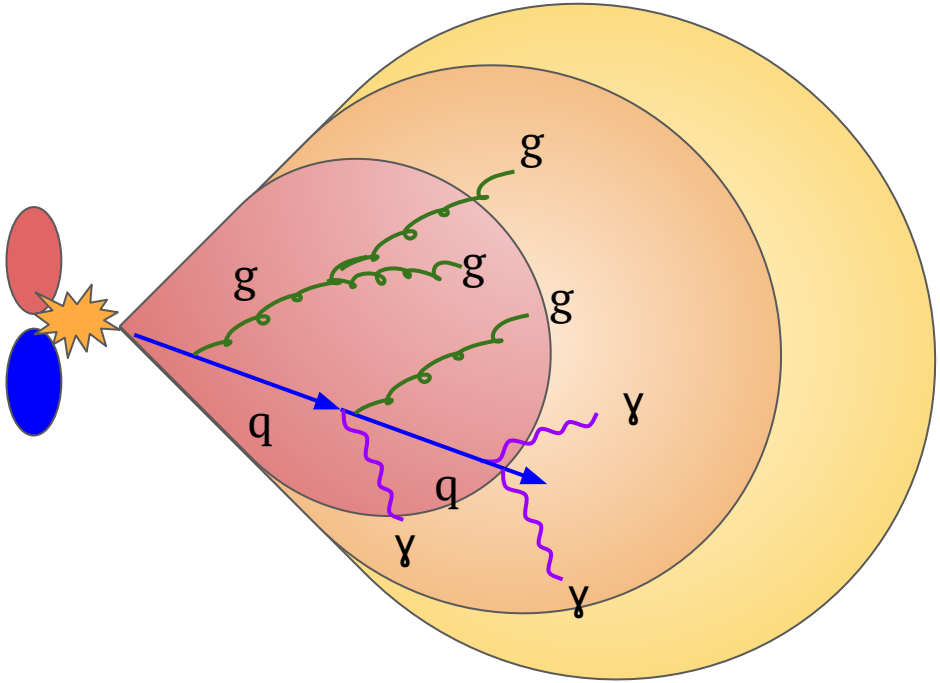


G. David. Rep. Prog. Phys. 27;83(4):046301(2020)

Motivation and Goal

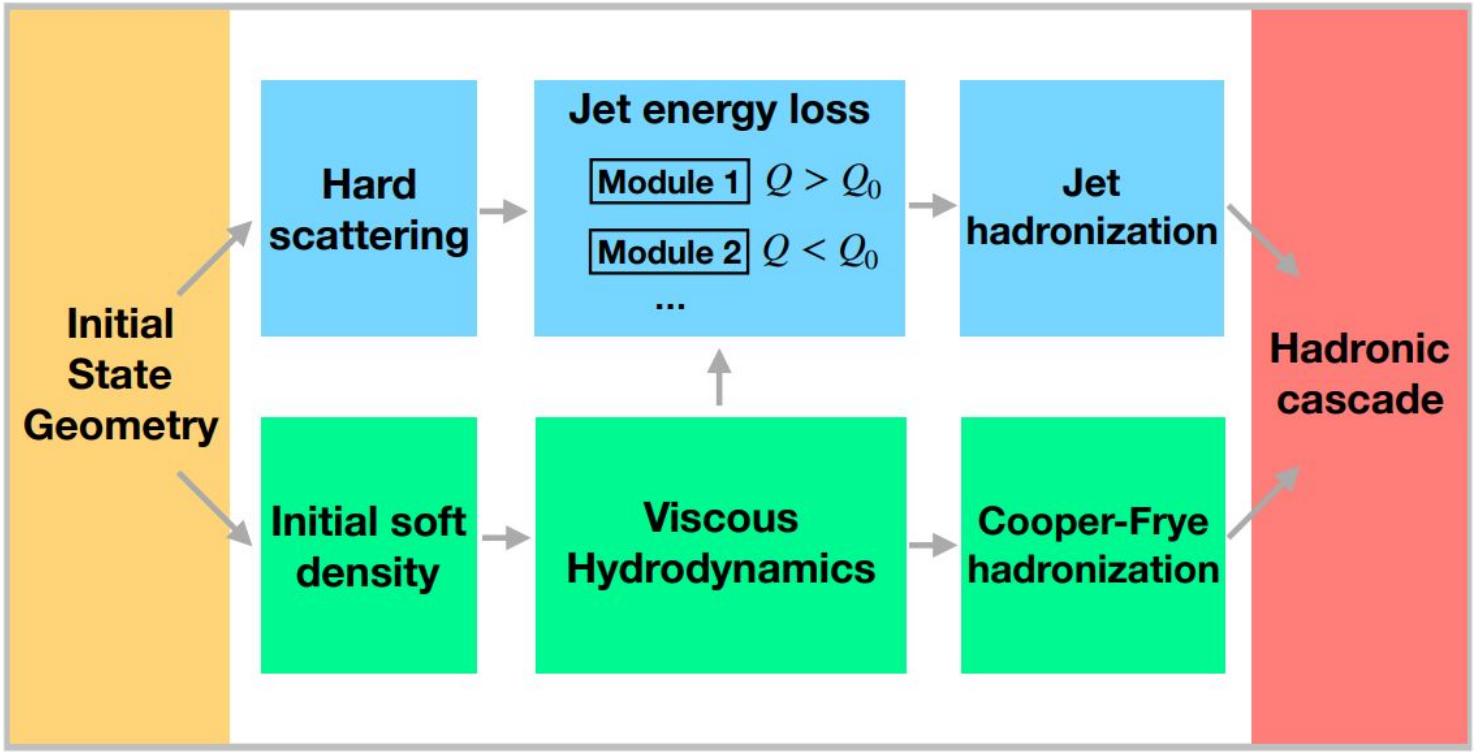
Parton Energy Loss in the QGP:



- Fragmentation photons radiate from quarks, and take a fraction of the momentum of that quark
- It is unknown how well current models can account for medium-induced photons or non-pQCD fragmentation

JETSCAPE Framework

J. Mulligan, JETSCAPE Framework (2019)



JETSCAPE Framework

- Packages:
  - TRENTO: Initial Conditions
  - PYTHIA: Hard Process Monte Carlo
  - FREESTREAM: Pre-Equilibrium Dynamics
  - MUSIC: Hydrodynamics
  - ISS: Soft-particlization
  - SMASH: Hadronic Transport
  - MATTER + LBT: Energy Loss

JETSCAPE Framework

- Parameters of my simulations:
  - CM Energy: 200 GeV (RHIC)
  - Centrality: 0-10% (minimal v_2 effects)
  - Hard QCD enabled
  - Prompt Photons disabled
  - Hadron Decay disabled
  - SMASH only decays enabled

Recreating JETSCAPE Observables

- Soft Sector: Flow harmonics (v_2 , v_3), pion p_T spectra

$$v_n\{2\} = \sqrt{c_n\{2\}}$$

$$c_n\{2\} = \langle\langle 2 \rangle\rangle$$

$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)}$$

$$Q_n \equiv \sum_{i=1}^{M} e^{in\phi_i}$$

- Hard Sector: Charged pion cross section, R_{AA}

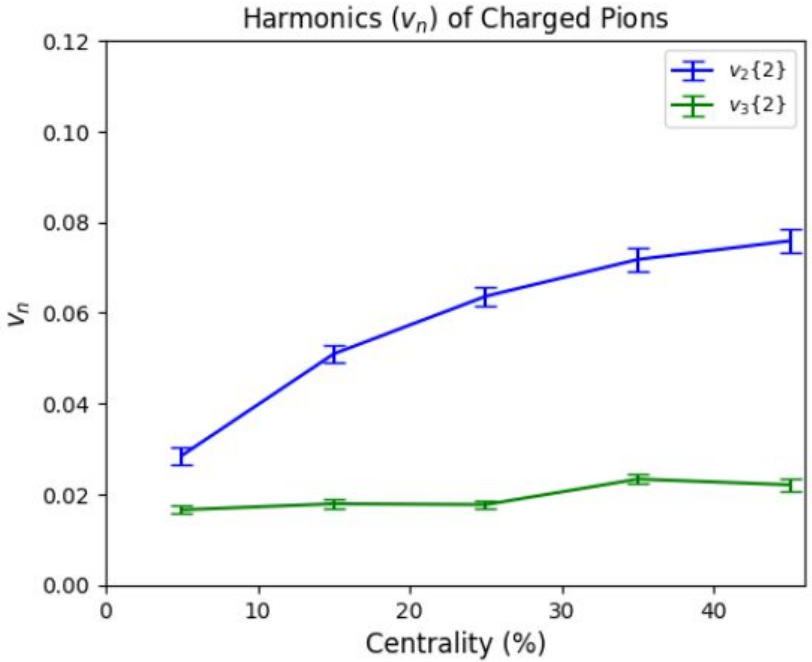
$$\frac{1}{2\pi p_T}\frac{d^2\sigma}{d\eta dp_T} = \frac{1}{2\pi p_T^{avg}}\sigma^{PP}\frac{d^2N}{d\eta dp_T}$$

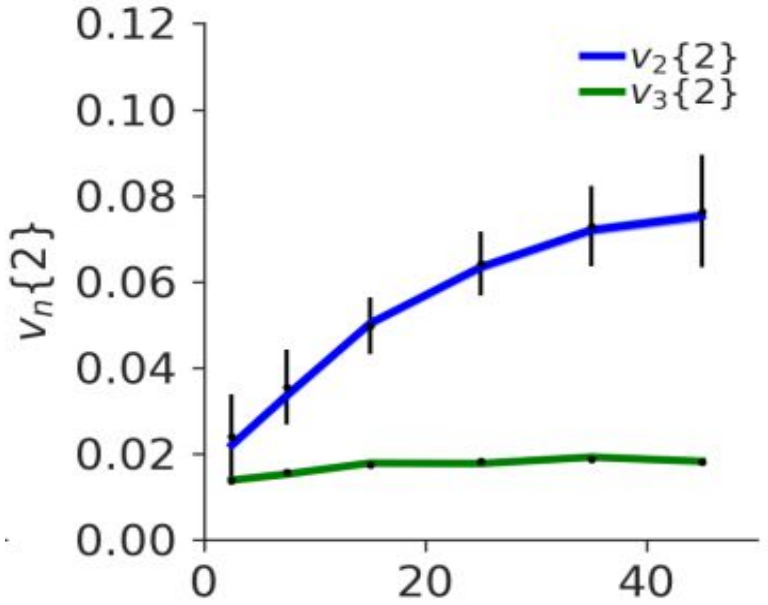
$$R_{AA}(p_T, y; b) = \frac{d^2N_{AA}/dydp_T}{\langle T_{AA}(b)\rangle \times d^2\sigma/dydp_T}$$

Recreating JETSCAPE Observables

- Soft Sector: Flow harmonics (v_2 , v_3)

(JETSCAPE. *Phys.Rev.C* 103 (2021) 5, 054904)

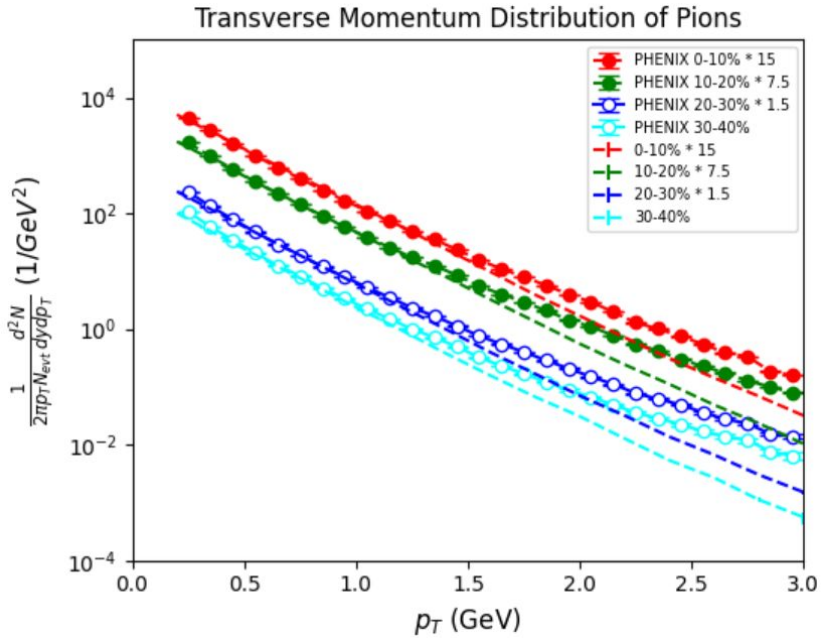




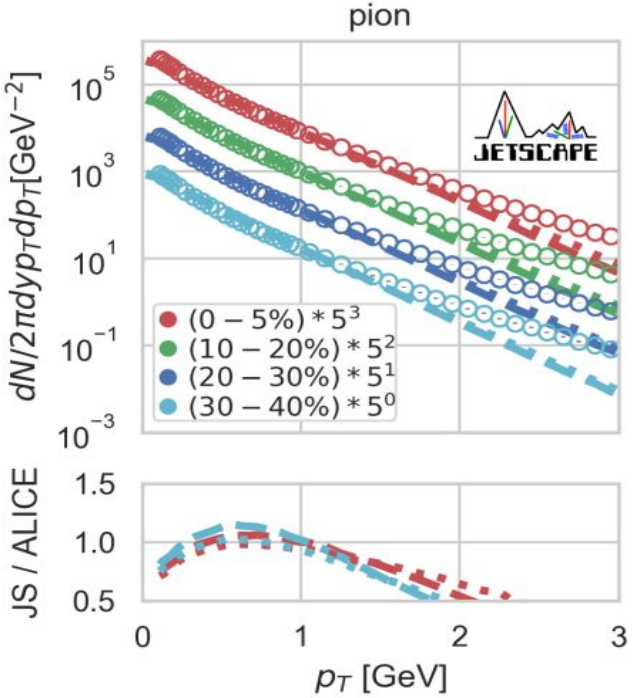
Recreating JETSCAPE Observables

(JETSCAPE. *Phys.Rev.C* 103 (2021) 5, 054904)

- Soft Sector: Pion p_T Spectra



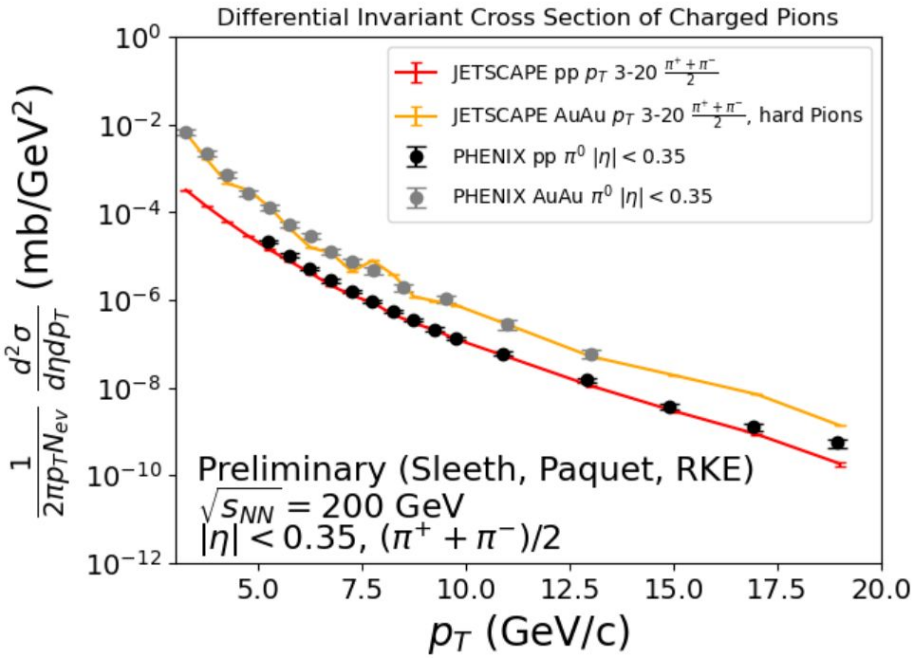
(PHENIX. PHYS. REV. C 69, 034909 (2004))

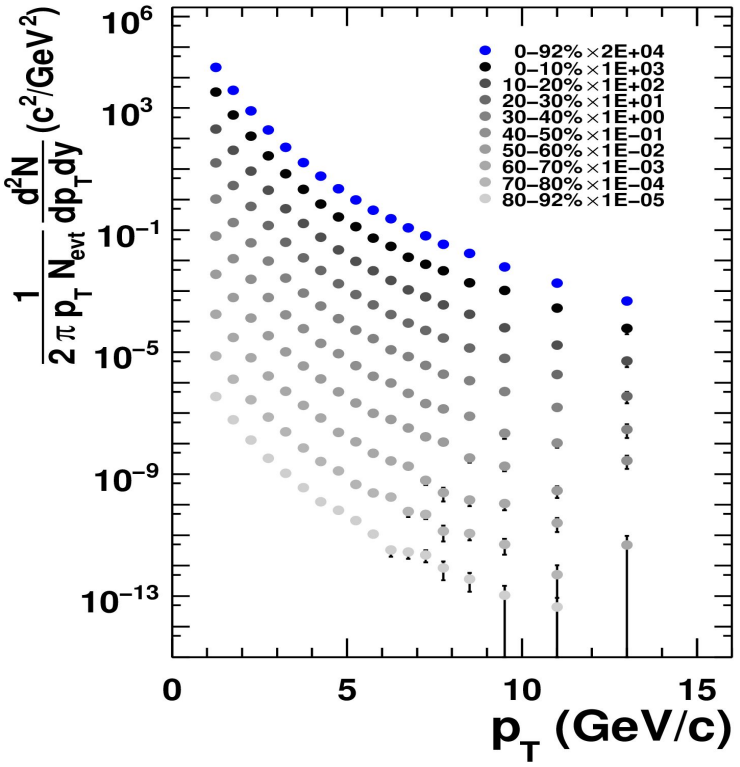


Recreating JETSCAPE Observables

(S. Adler, *Phys.Rev.C* 76 (2007) 034904)

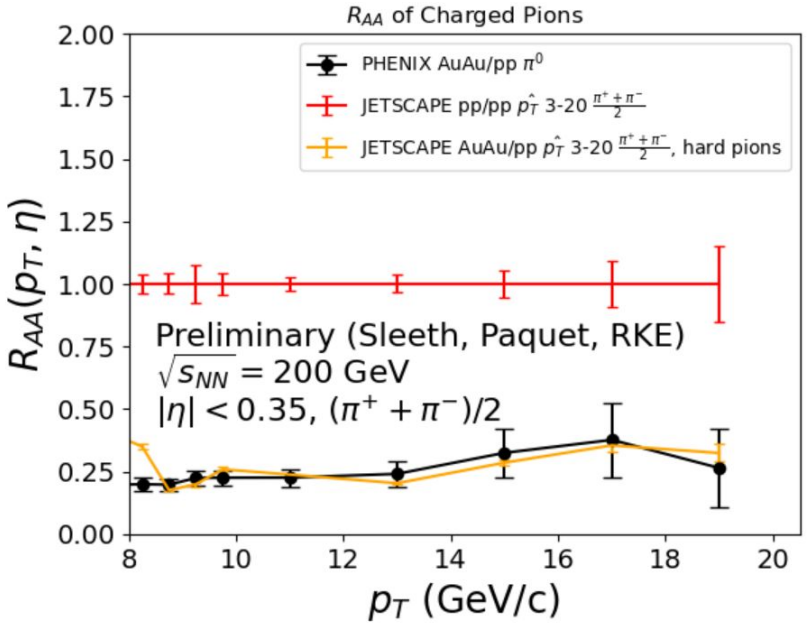
- Hard Sector: Charged pion cross section



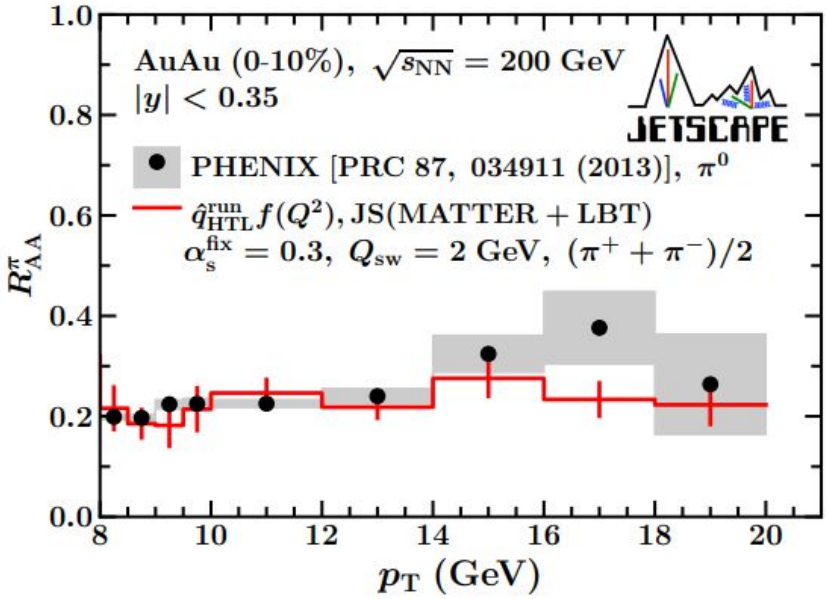


Recreating JETSCAPE Observables

- Hard Sector: Charged pion R_{AA}



(JETSCAPE. *Phys.Rev.C* 107 (2023) 3, 034911)



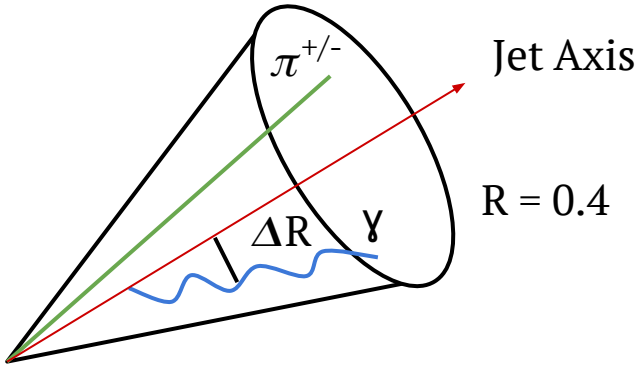
Jet Observables

- Momentum Fraction (z):

$$z = \frac{p_T^{\pi}}{p_T^{jet}}$$

- Distance Between Particle and Jet Axis (ΔR):

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

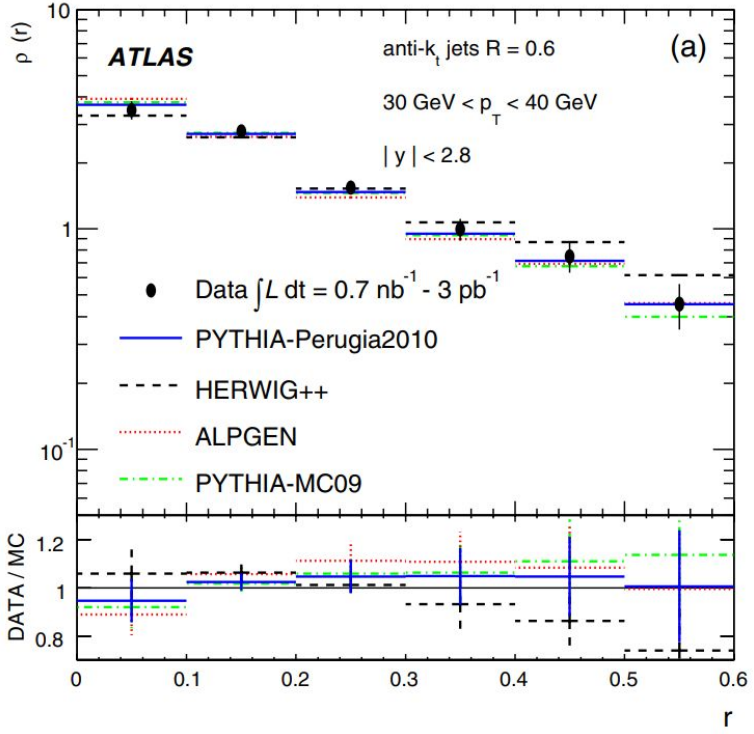


$$\eta = ln(\frac{E + p_z}{E - p_z})$$

$$\phi = tan^{-1}(p_y/p_x)$$

These are Ensemble Observables Quantify Signal vs Background

Jet Observable in Publications



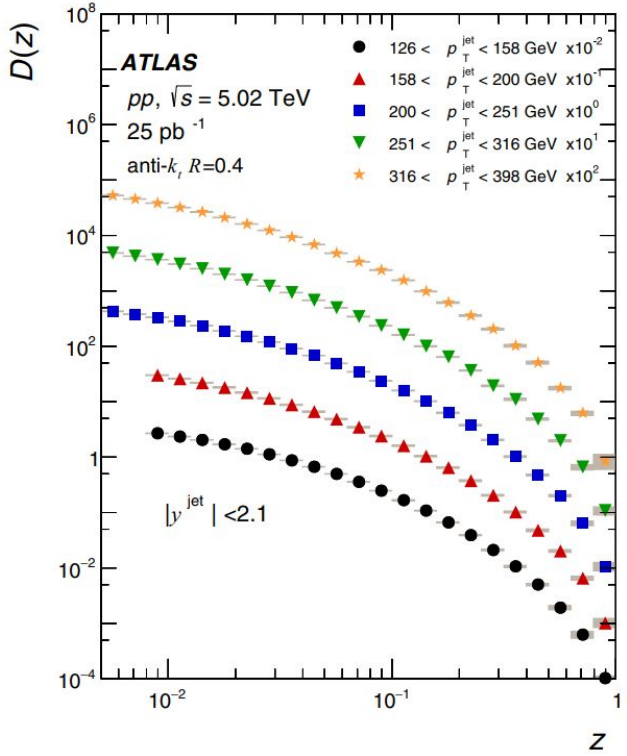
- **Measurements of ρ(r) in pp collisions from ATLAS detector at LHC**

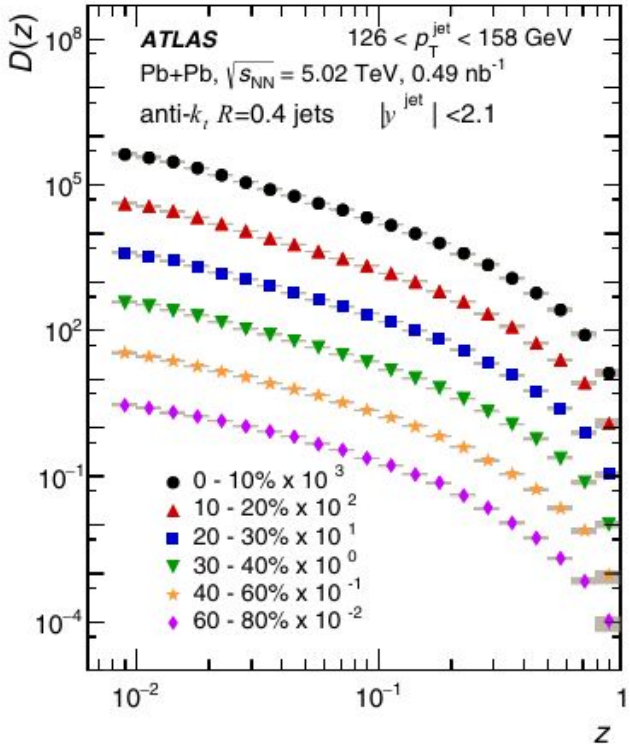
$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N^{\text{jet}}}\sum_{\text{jets}}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)}$$

ATLAS, Phys. Rev. D 83, no. 5 (2011): 052003

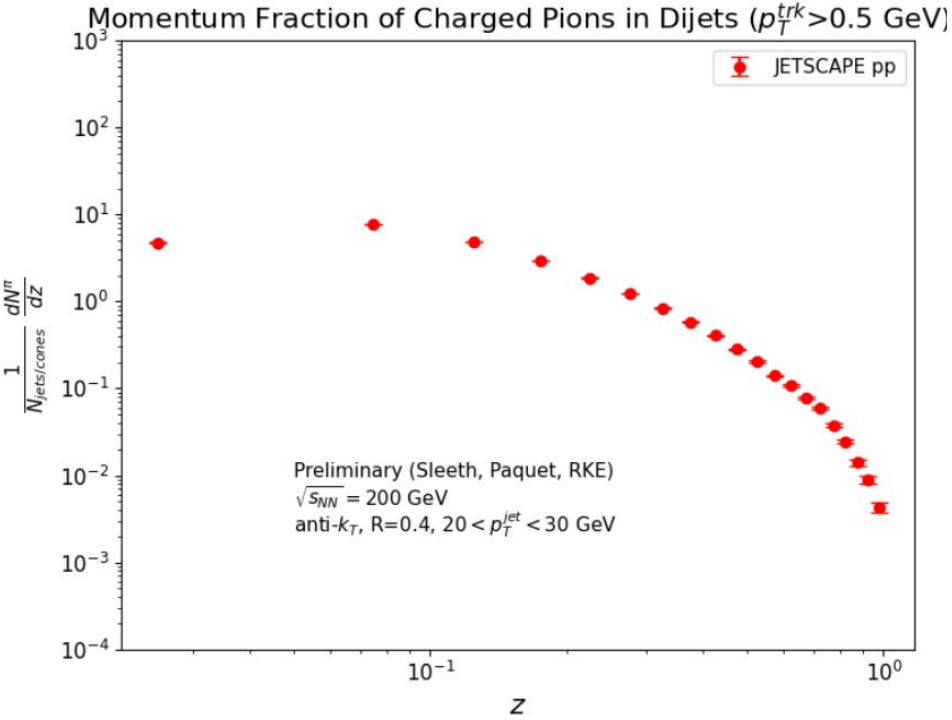
Grid Cone Background Subtraction

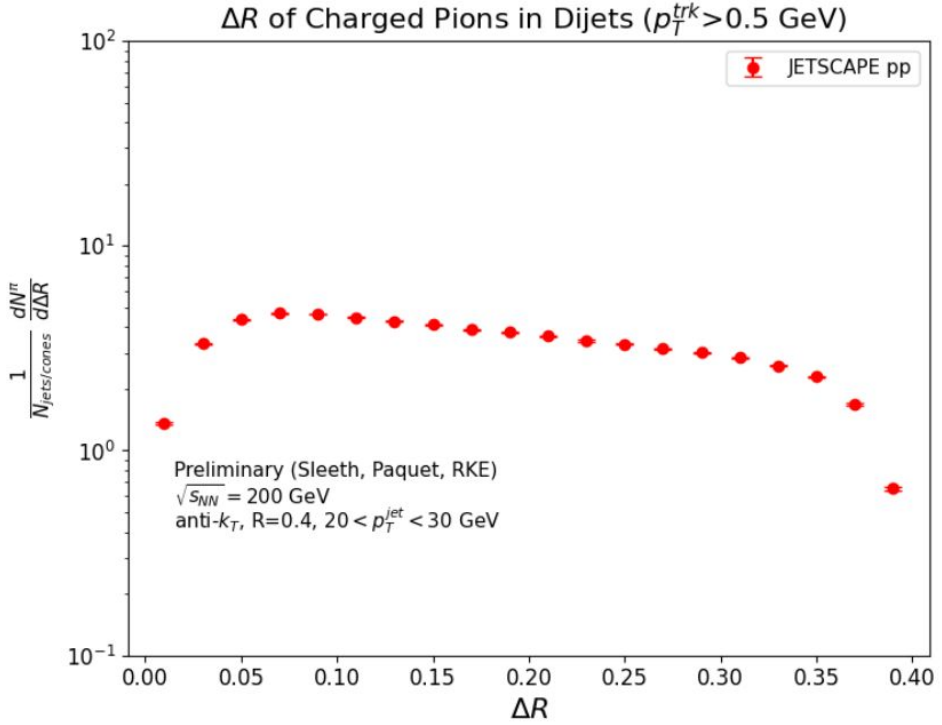
(ATLAS, Phys. Rev. C 98, no. 2 (2018): 024908)



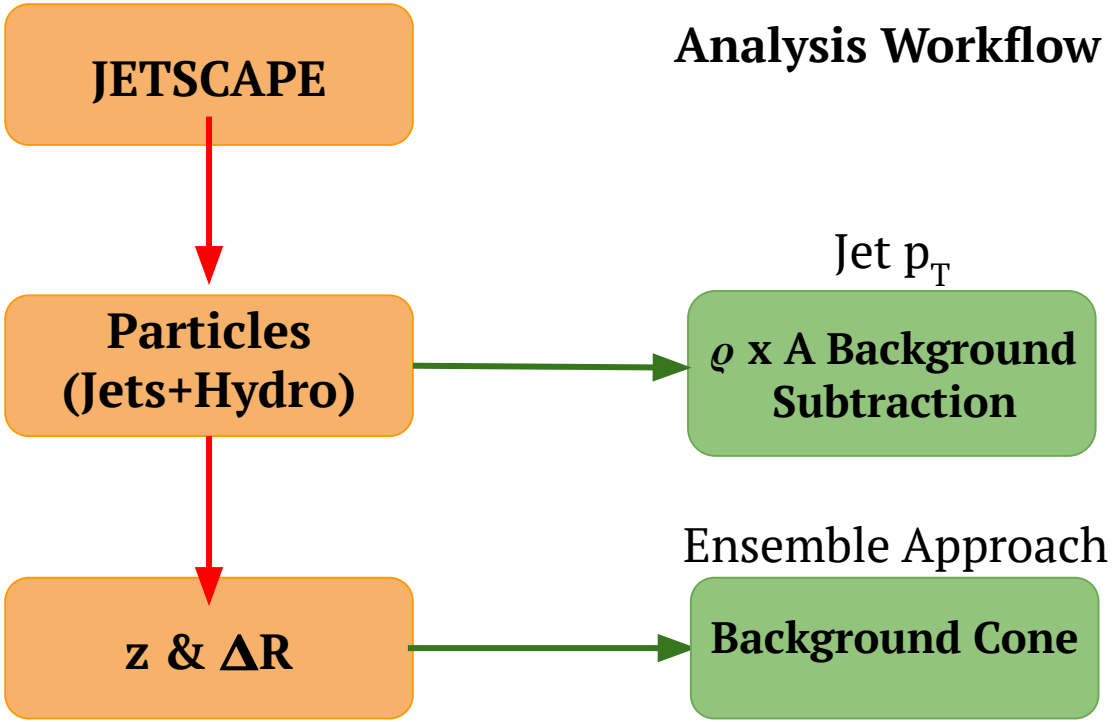


Momentum Fraction and ΔR - pp





Background Subtraction Method



Background Estimation Methods:

- Perpendicular Cones
- Reflected Cones
- Grid Cones

Jet p_T Background Subtraction

- Broad subtraction method from FASTJET3 area-based energy density estimation:

$$p_T^{subtr.jet} = p_T^{jet} - \rho A$$

- Where ϱ is the background density, and is defined by:

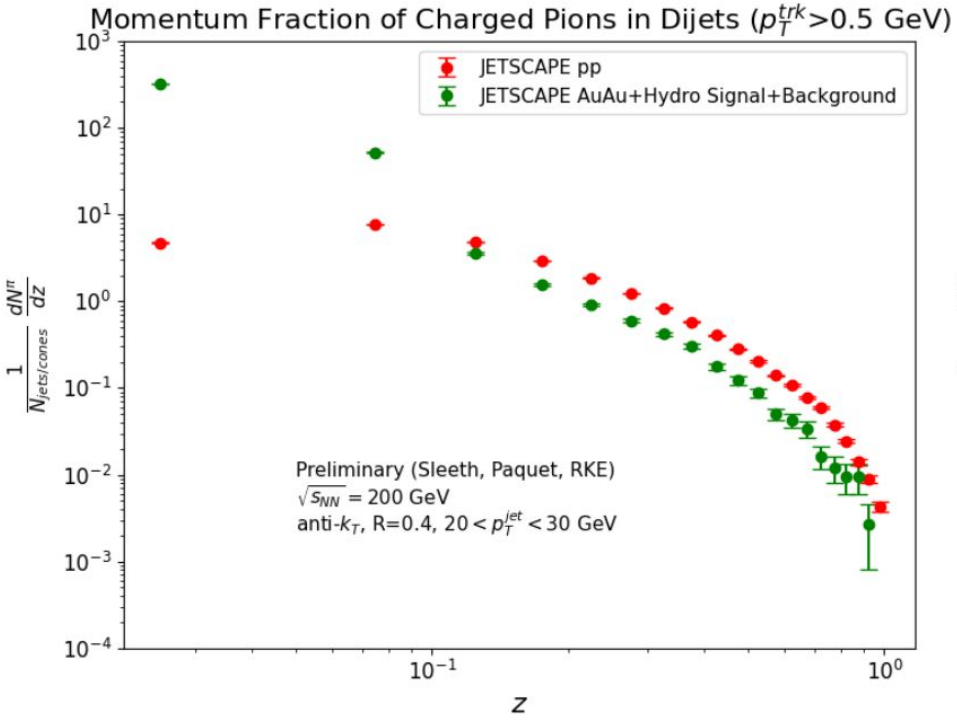
$$\rho = \text{median}\left[\left\{\frac{p_{tj}}{A_j}\right\}\right]$$

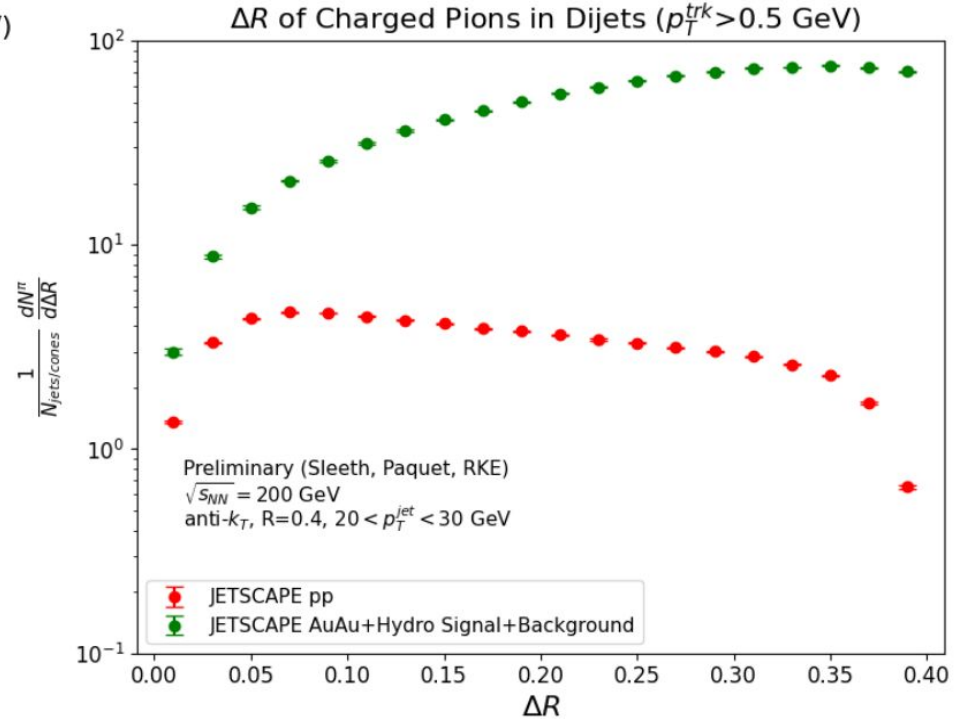
p_{tj} is the scalar p_t calculated for each k_T clustered jet j

A_j is the area of that jet calculated from ghost particles (that do not contribute to p_t)

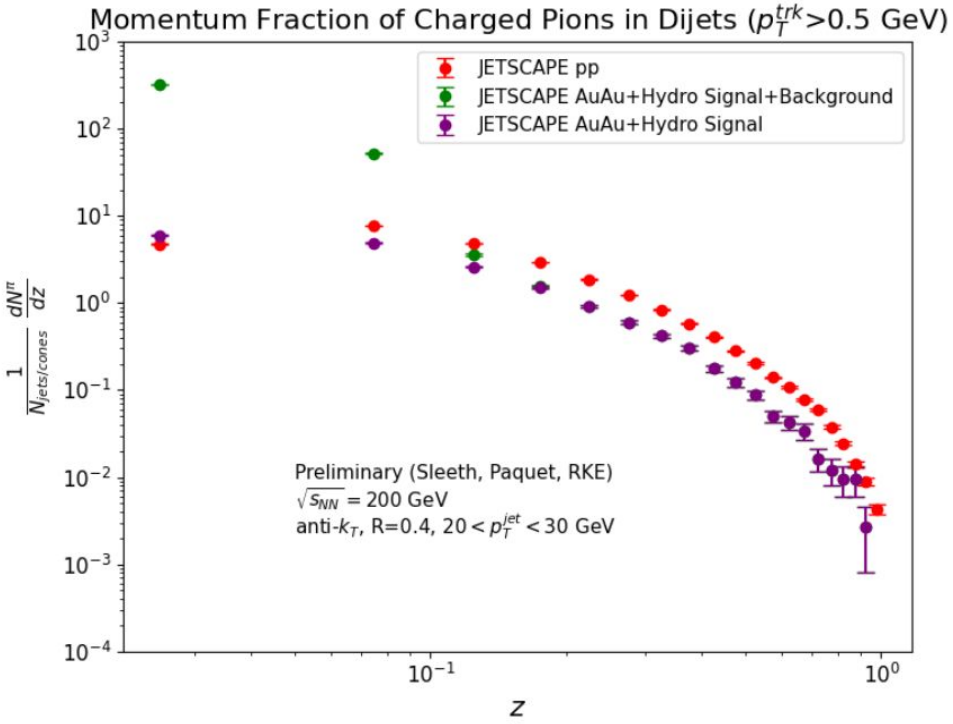
Cacciari & Salam. Phys. Lett. B 659, no. 1-2 (2008): 119-126

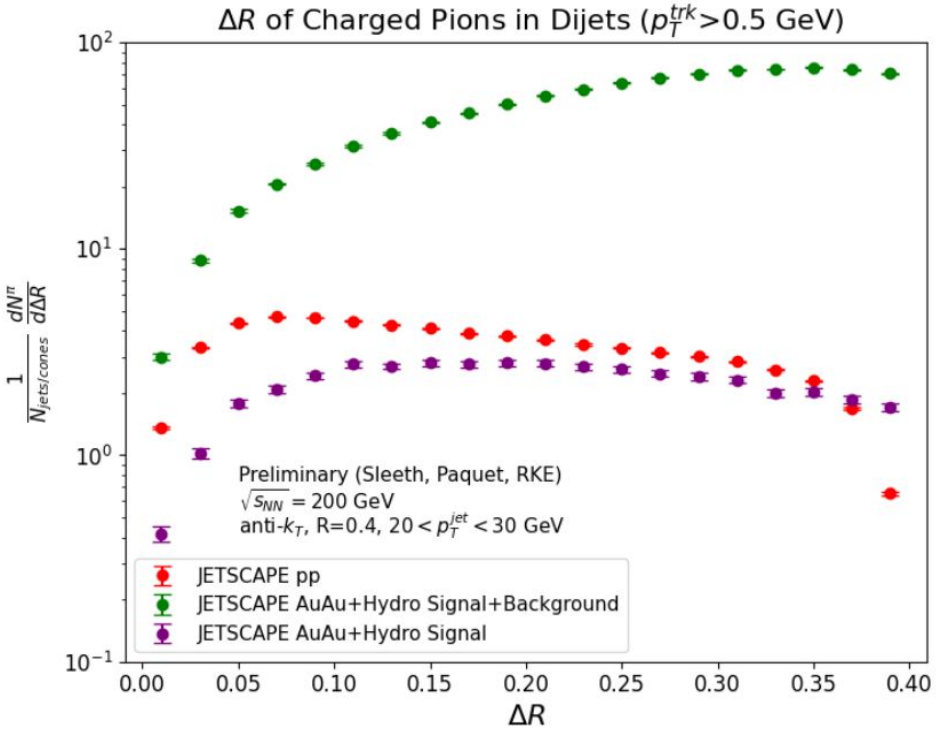
Momentum Fraction and ΔR - AuAu+Hydro Signal+Background



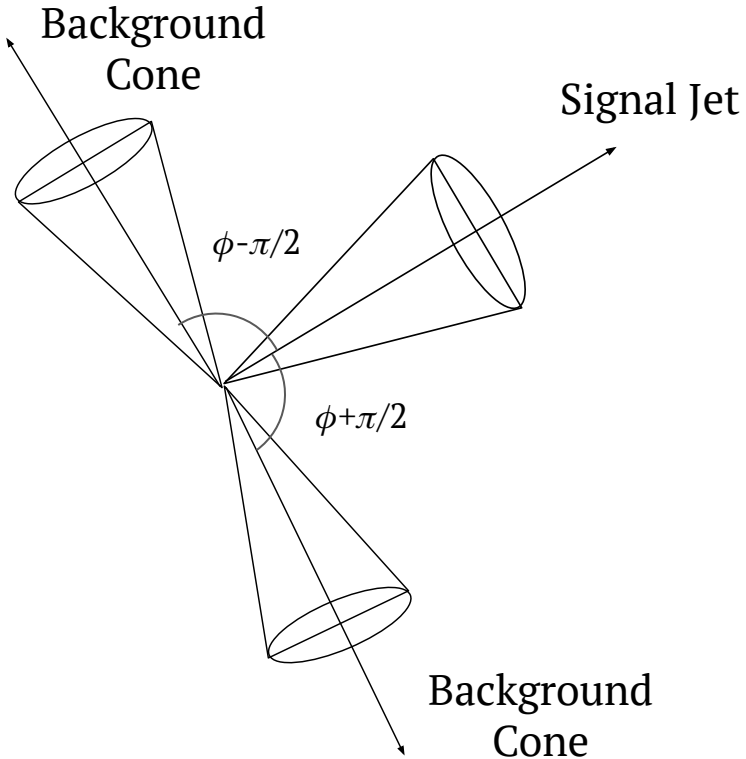


Momentum Fraction and ΔR - AuAu+Hydro Signal





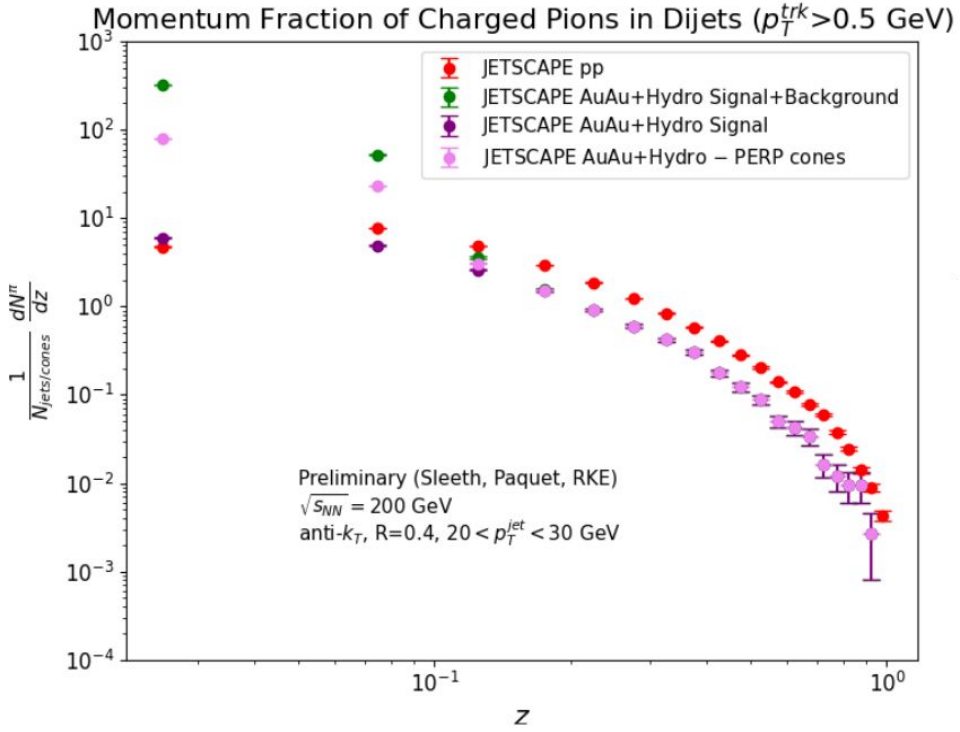
Perpendicular Cone Background Subtraction

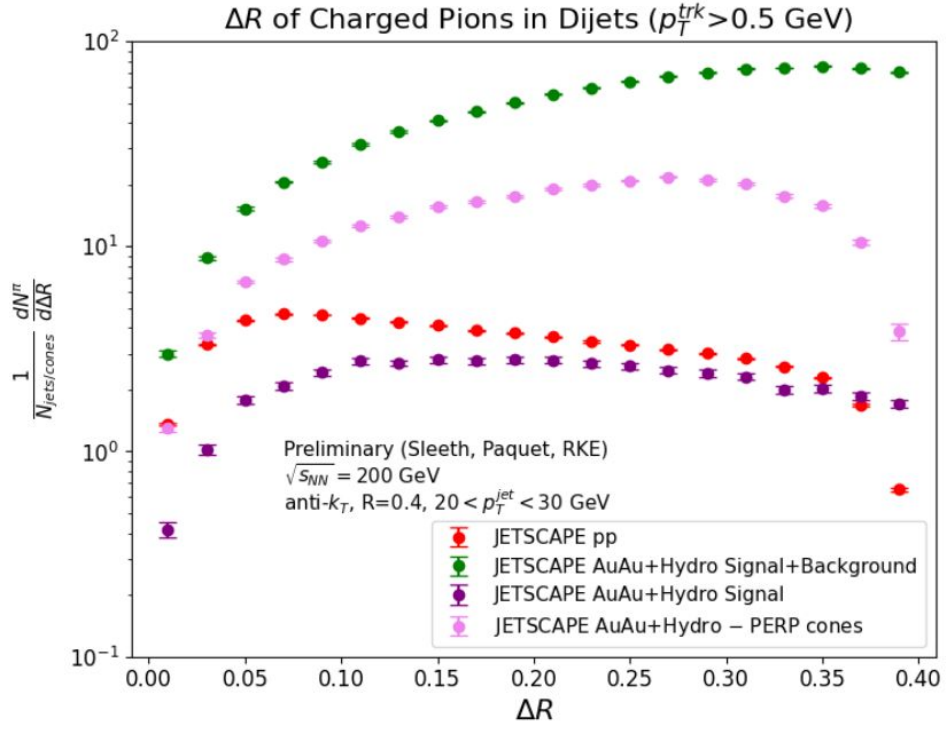


- Places two cones that are perpendicular (+π/2 and -π/2) in ϕ to the original jet ϕ, the jet η stays the same
- Used in ALICE jet-hadron correlation publication

(ALICE. J. High Energ. Phys. 2012, 53 (2012))

Momentum Fraction and ΔR - Perpendicular Cones

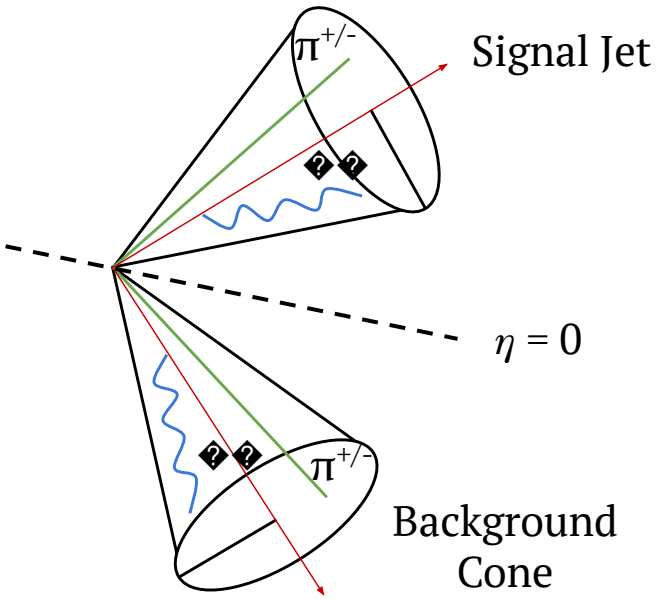




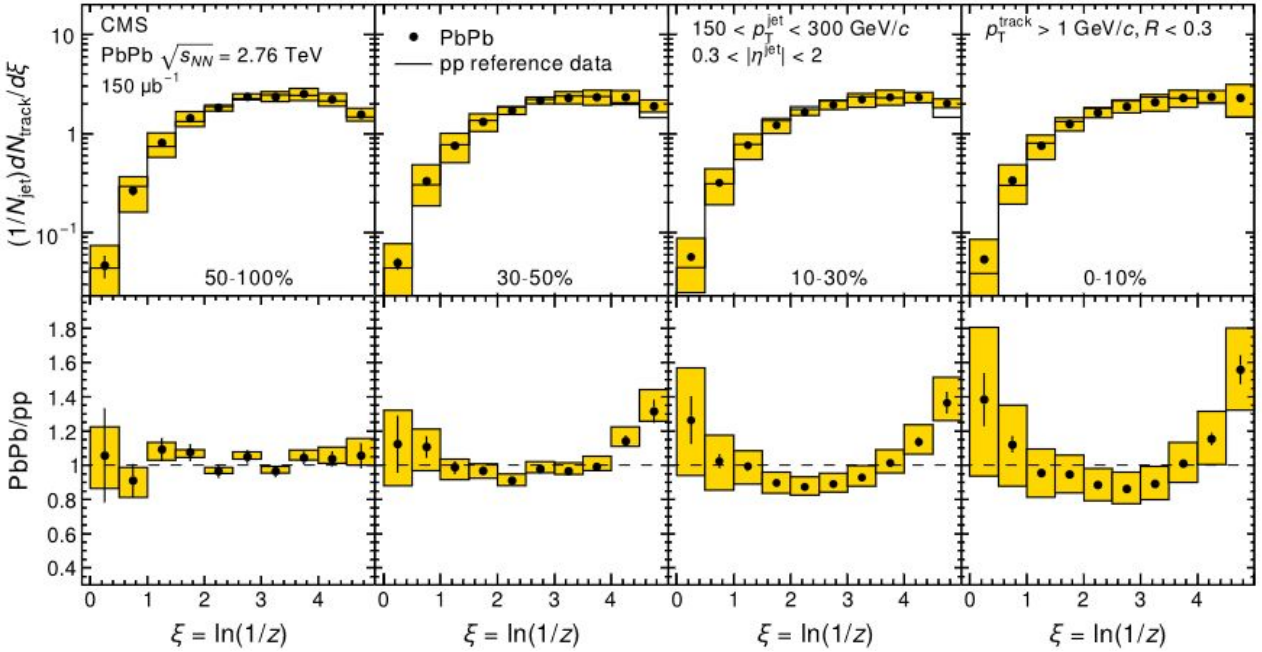
Reflected Cone Background Subtraction

- Reflects the original jet about η=0 axis
- Excludes jets within $|\eta|$ < R (jet radius) to avoid overlap between signal and background regions
- Used in CMS Fragmentation Function Publications

CMS, Jour. High En. Phys. 2012, no. 10 (October 2012): 87



Reflected Cone Method Background Subtraction

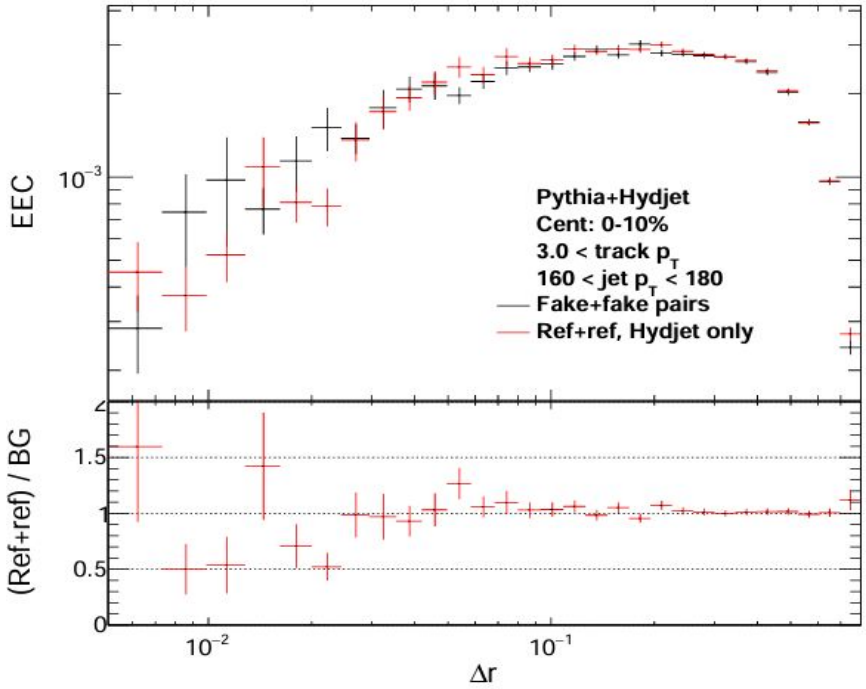


CMS, Jour. High En. Phys. 2012, no. 10 (October 2012): 87

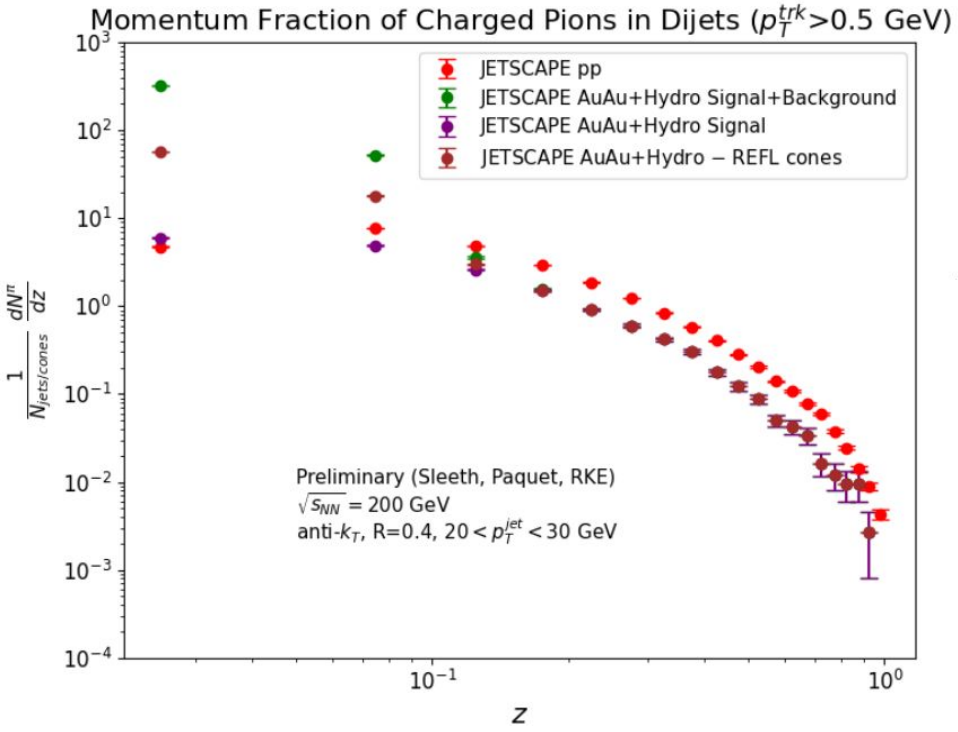
Modified Reflected Cone Background Subtraction

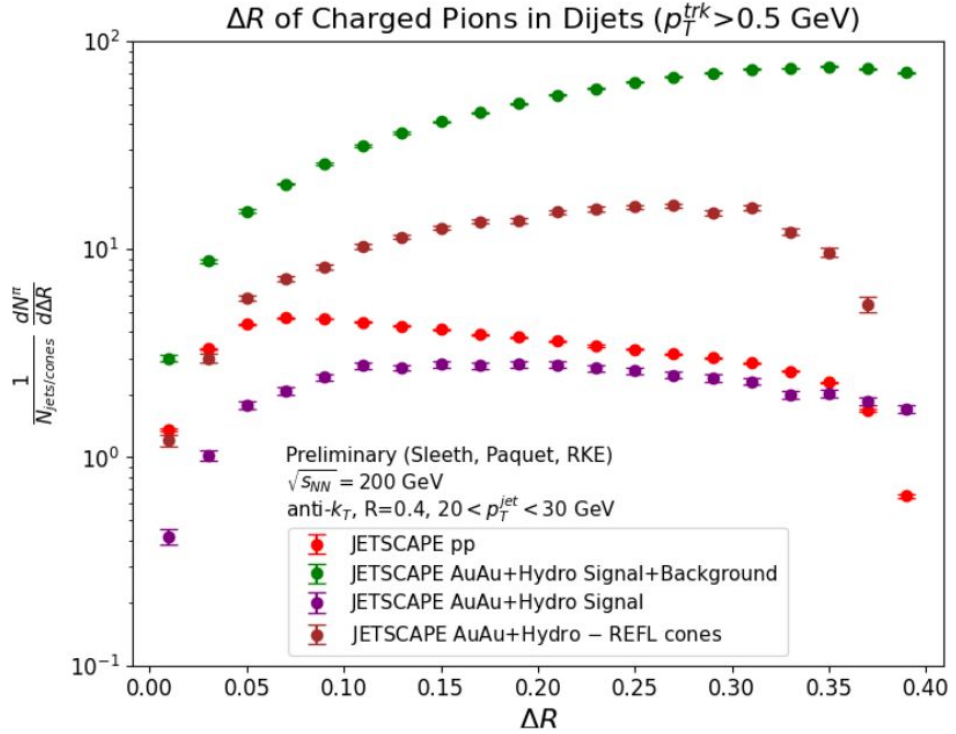
- Excludes jets within these criteria:
  - If $|\eta_{jet}| > R$: $\eta_{cone} = -\eta_{jet}$
  - If $-R =< \eta_{jet} < 0$: $\eta_{cone} = \eta_{jet} + 2R$
  - If $0 =< \eta_{jet} =< R$: $\eta_{cone} = \eta_{jet} - 2R$
- This set of criteria was used for EEC calculations

(Jussi, V. *INT WORKSHOP INT-21R-2B.*)



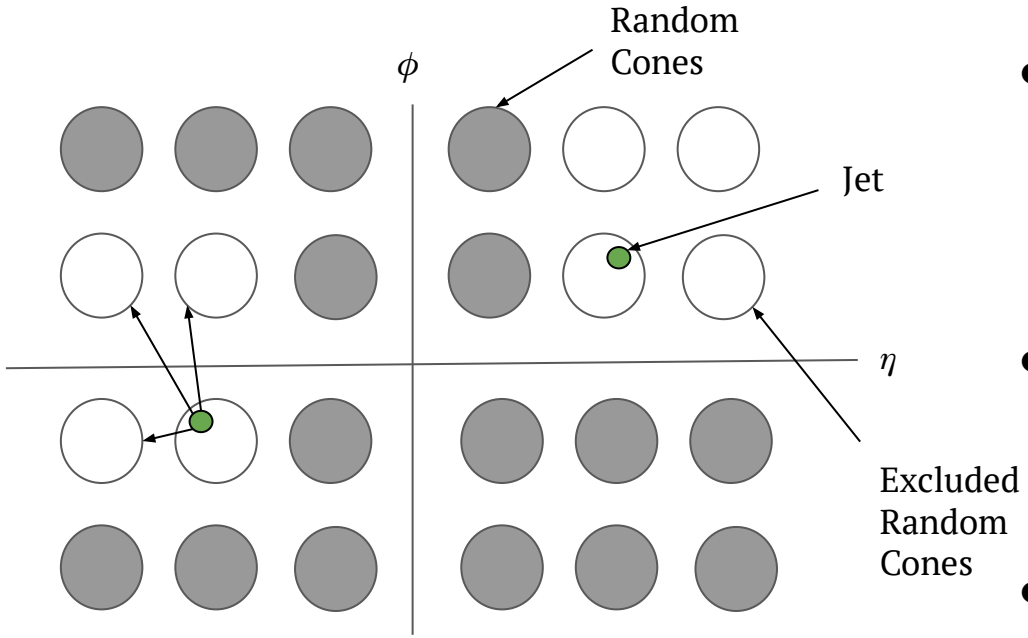
Momentum Fraction and ΔR - **Reflected Cones**





Grid Cone Background Subtraction

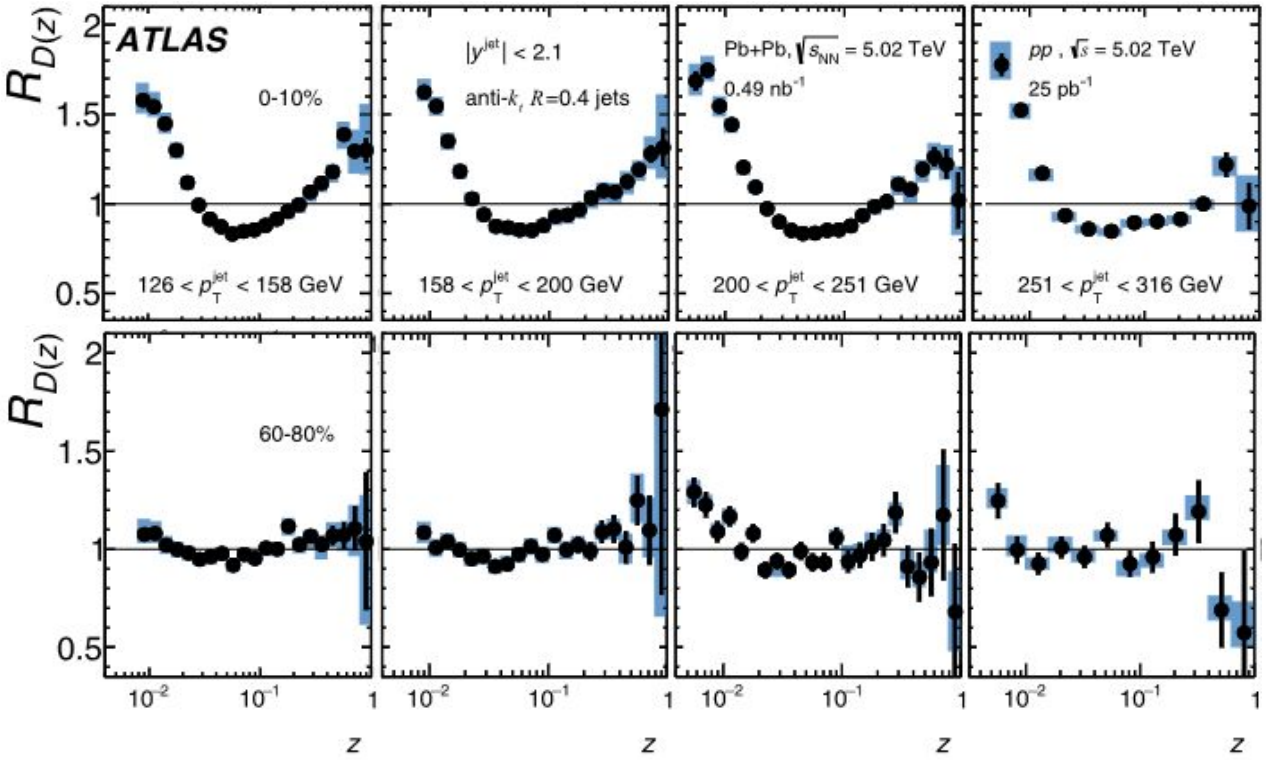
ATLAS, Phys. Rev. C 98, no. 2 (2018): 024908



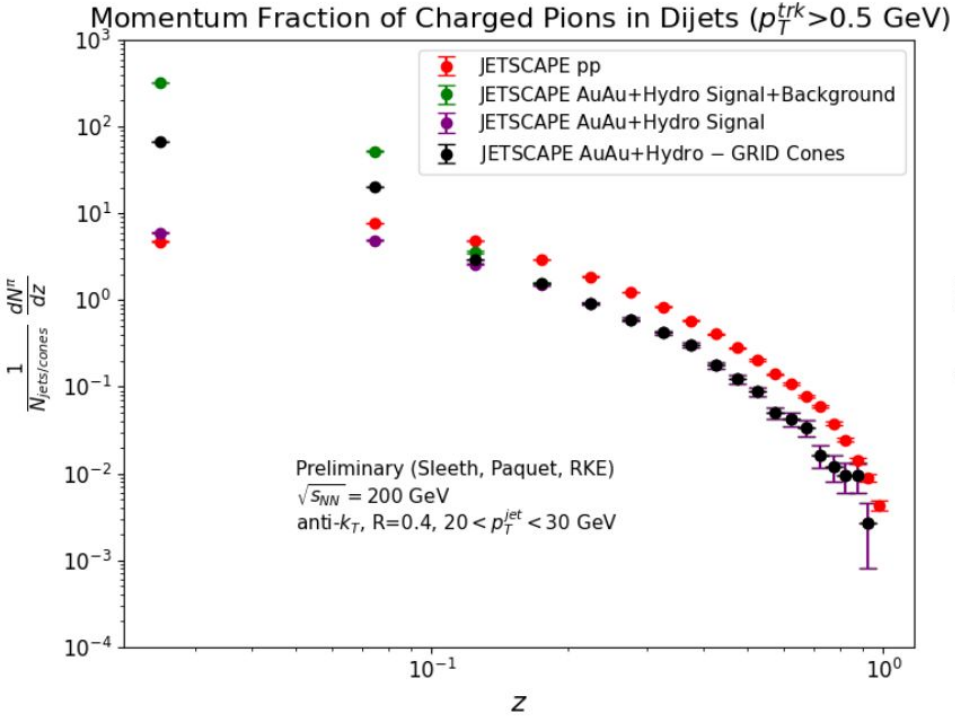
- Places cones in a grid spanning $|\eta| < 1.1$, and $\Delta\phi < 2\pi$ (ATLAS inner detector acceptance) and with radii of R = 0.4
- Charged particles of above $p_T = 6$ GeV will be excluded as well as cones within $\Delta R > 0.4$ of the jet
- Used in ATLAS Fragmentation Function Publications

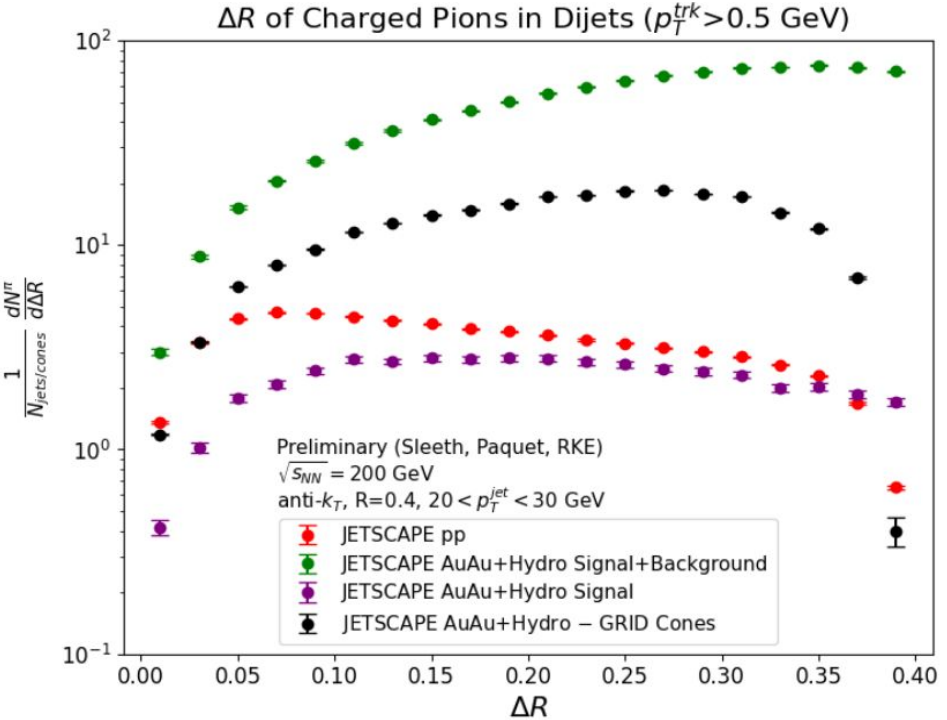
Grid Cone Background Subtraction

ATLAS, Phys. Rev. C 98, no. 2 (2018): 024908



Momentum Fraction and ΔR - **Grid Cones**





Summary

- First study of jet fragmentation and jet shape at RHIC energies using JETSCAPE
- Original plan was to study energy loss of jets through FF and jet shape of fragmentation photons, but needed a baseline → charged pions in jets
- Background subtraction methods from LHC do not work for background at RHIC for these observables → need to have a good one for future measurements
- Supported by DOE Awards DE-SC0024660 and DE-SC0024347

References

- David, Gabor. "Direct real photons in relativistic heavy ion collisions." Reports on Progress in Physics 83, no. 4 (2020): 046301.
- J. H. Putschke et al. The JETSCAPE framework. 3 2019.
- Mulligan, James. “The JETSCAPE Framework.” Presentation at the Jet Tools Conference, University of Bergen, Norway, May 15, 2019. https://indico.cern.ch/event/771644/contributions/3417051/attachments/1844419/3025548/Jetscape_Bergen.pdf.
- CMS collaboration, S. Chatrchyan et al., "Measurement of jet fragmentation into charged particles in pp and PbPb collisions at √sNN = 2.76 TeV," Journal of High Energy Physics 2012, no. 10 (October 2012): 87, https://doi.org/10.1007/JHEP10(2012)087.
- ATLAS Collaboration, "Study of jet shapes in inclusive jet production in pp collisions at √s = 7 TeV using the ATLAS detector," Physical Review D 83, no. 5 (2011): 052003, doi:10.1103/PhysRevD.83.052003
- ATLAS Collaboration. "Measurement of jet fragmentation in Pb+Pb and p+p collisions at √sNN = 5.02 TeV with the ATLAS detector." Physical Review C 98, no. 2 (2018): 024908. https://doi.org/10.1103/PhysRevC.98.024908

Backup

Observables

- Soft Sector: Flow harmonics (v_2 , v_3), pion p_T spectra

$$v_n\{2\} = \sqrt{c_n\{2\}}$$

$$c_n\{2\} = \langle\langle 2 \rangle\rangle$$

$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)}$$

$$Q_n \equiv \sum_{i=1}^{M} e^{in\phi_i}$$

- Hard Sector: Charged pion cross section, R_{AA}

$$\frac{1}{2\pi E}\frac{d\sigma}{dEdy} = \frac{1}{2\pi E_{avg}}\sigma_{PP}\frac{dN}{dEdy}$$

$$dN = \Delta N = \frac{N_\gamma}{N_{event}}$$

$$dy = \Delta y = y_{max} - y_{min}$$

$$dE = \Delta E = E_2 - E_1$$

$$E_{avg} = \frac{E_2 + E_1}{2}$$

Observables

Simulation Data Sets:

pp	10M Events	230138 Jets
AuAu+nPDF	10M Events	632 Jets
AuAu nPDF+Hydro	100k Events	14736 Subtr. Jets
AuAu+nPDF Quenched	10M Events	19416 Jets

Overview

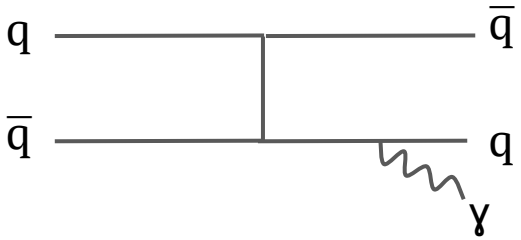
- Motivation and Goal
- JETSCAPE Framework
- Observables
- Results:
  - Charged Pions
  - Fragmentation Photons
- Summary
- References

Analysis Parameters

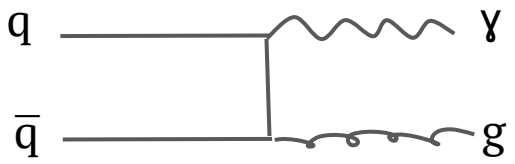
- Particle pseudorapidity: |1.1|
- Jet pseudorapidity: |1.1 - R|
- Azimuthal acceptance: 2π
- Jet radius: R = 0.4
- $20 < p_T^{jet} < 30$ GeV

Motivation and Goal

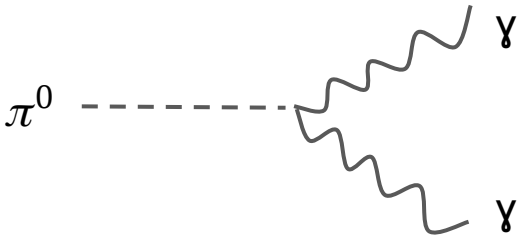
Fragmentation:



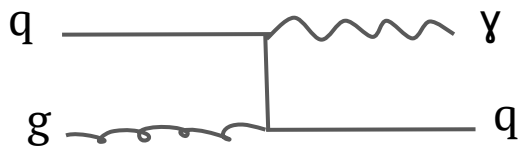
$q\bar{q}$ Annihilation:



Neutral Pion (Hadron) Decay:

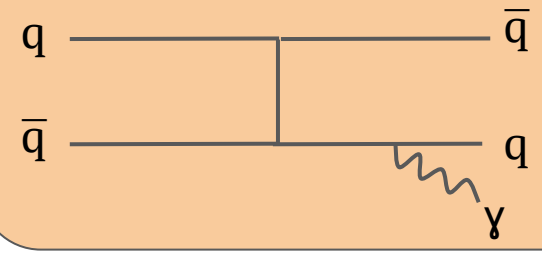


Hard QCD Compton Scattering:

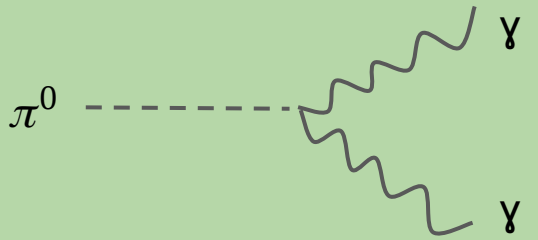


Motivation and Goal

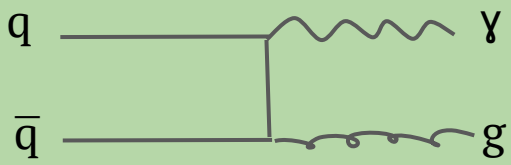
Fragmentation:



Neutral Pion (Hadron) Decay:



$q\bar{q}$ Annihilation:



Hard QCD Compton Scattering:

Results

- Momentum fraction (z) and Distance (ΔR) between charged pion and jet axis

WIP: Photon momentum fraction from jet:
- pp
- AuAu Jets+nPDF
- AuAu Jets+nPDF+Hydro

WIP: Photon deltaR from jet:
- pp
- AuAu Jets+nPDF
- AuAu Jets+nPDF+Hydro

My JETSCAPE Configuration

- For AuAu Jets+Hydro: $\hat{p_T}$ between 15-100 GeV
  - nReuseHydro: 10 orders of magnitude less than nEvents (one hydro per 10 jets)
  - TRENTO: Parameters follow JETSCAPE publication of soft sector, centrality 0-10%
  - PYTHIA: HardQCD:all = on, PromptPhoton:all = off, Au nPDF EPS09LOR, HadronLevel:Decay = off
  - FREESTREAM: Parameters follow JETSCAPE publication of Au soft sector
  - MUSIC: Parameters follow JETSCAPE publication of Au soft sector
  - iSS: Parameters follow JETSCAPE publication of Au soft sector, repeated samples = 1
  - SMASH: Only decays enabled
  - MATTER: Parameters follow JETSCAPE publication of AuAu (hard sector)
  - LBT: Parameters follow JETSCAPE publication of AuAu (hard sector)

JETSCAPE Framework

- For AuAu Only Hydro:
  - nReuseHydro = 100 orders of magnitude less than nEvents (100 hydro events)
  - TRENTO: Soft sector parameters, 0-10% centrality
  - FREESTREAM: Soft sector parameters
  - MUSIC: Soft sector parameters
  - iSS: Soft sector parameters
  - SMASH: Only decays enabled

JETSCAPE Framework

- For AuAu Only Jets:
  - nReuseHydro >> nEvents (not necessary?)
  - TRENTO: Soft sector parameters, 0-10% centrality
  - PYTHIA: HardQCD:all = on, PromptPhoton:all = off, Au nPDF EPS09LOR, HadronLevel:Decay = off
  - MATTER: Hard sector AuAu parameters
  - LBT: Hard sector AuAu parameters

Observables

- Background subtraction methods:
  - FASTJET rho*A background jet pT subtraction
  - Full background subtraction:
    - Jets+nPDF+Hydro (quenching) - Only Hydro (random cone)
    - Ratios (show plots?):
      - Jets+nPDF+Hydro (no quenching) / Jets+nPDF (no quenching)
      - Jets+nPDF+Hydro (quenching) / Jets+nPDF (quenching)