Mandelstam Institute for Theoretical Physics
MITP

Jet substructure

for ~~in~~ small systems

with JEWEL

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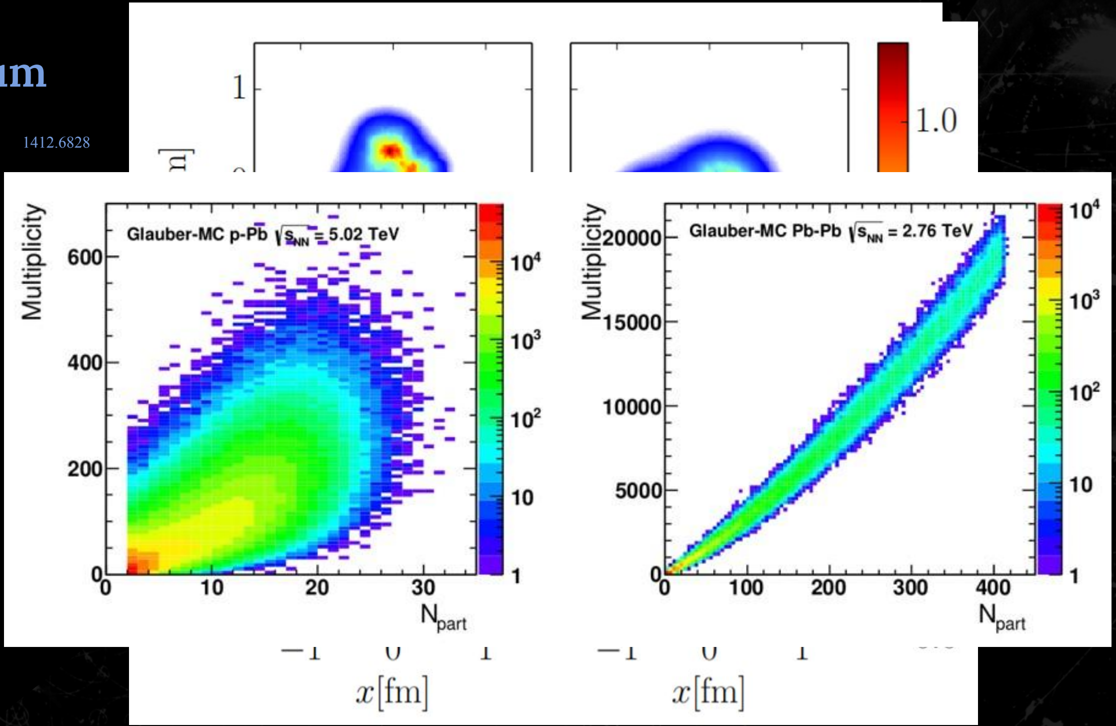
Thank you to Carlota Andres, Rithya Kunnawalkam-Elayavalli, Wilke van der Schee, and Martha Verweij for advice and illuminating conversations.

Why R_{AA} is the worst (in small systems)

- Reliance on a reference system
- Steeply falling production spectrum
  - Survival bias
  - Sensitive to PDFs and nPDFs
- Sensitive to initial condition
  - Geometry
  - Momentum anisotropy
- Sensitive to jet fragmentation
- Supposed to quantify ΔE, but
  - ΔE ← L ← N_{coll} : uncontrolled
  - ΔE = ΔE(T) : T is uncontrolled

1812.05111
1607.01711



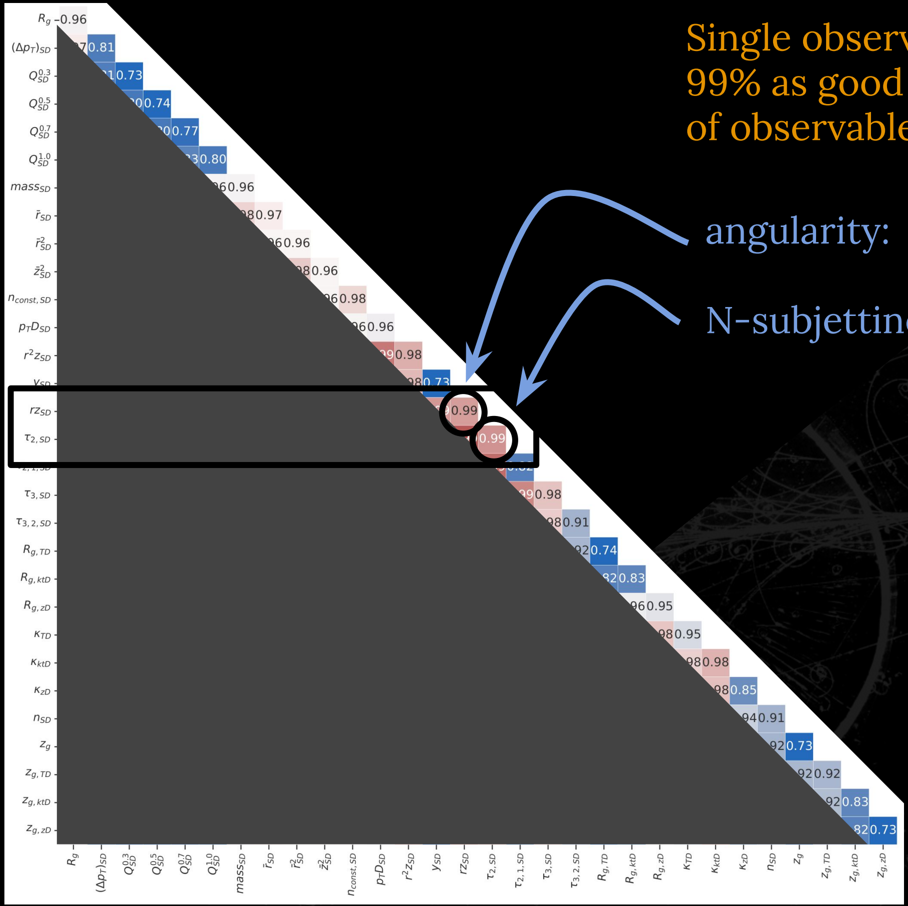
$$R_{AA}(p_T) = \frac{1}{\langle T_{AA}\rangle}\frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

Can we do something else?

Beyond R_{AA}

(1) Train a BDT on all observables to distinguish quenched from unquenched

(2) cf single and pairs of observables



Single observables that are 99% as good as the full set of observables

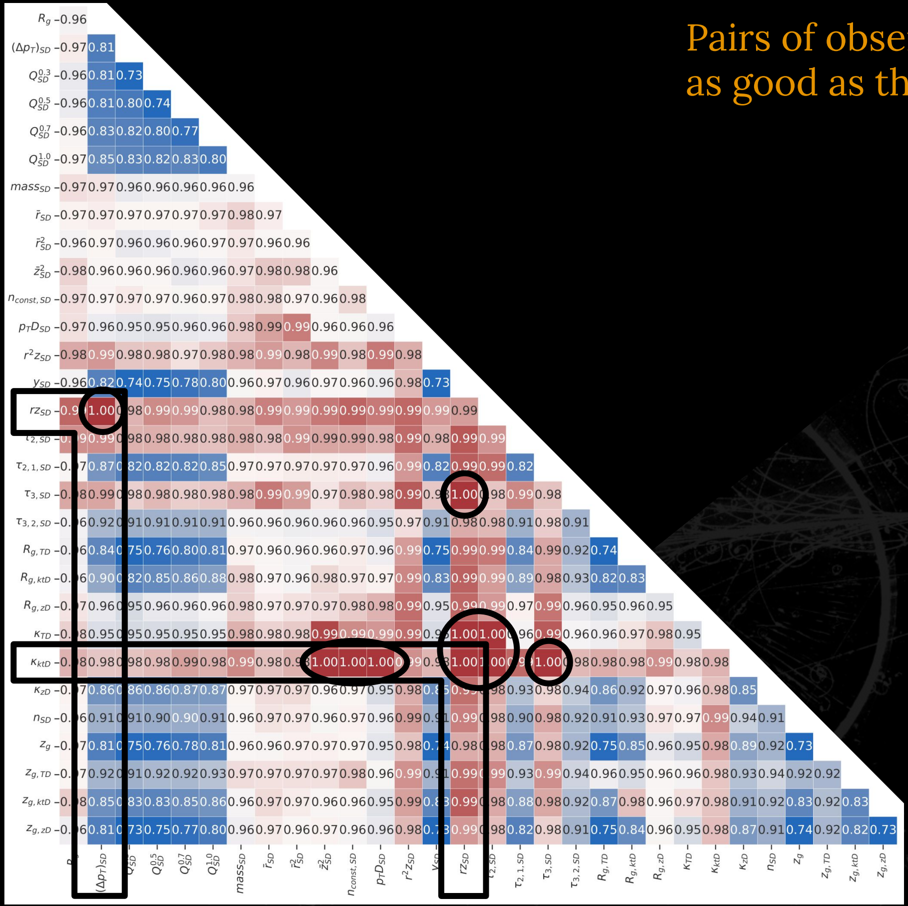
angularity: $rz_{SD} = \lambda^1_{1,SD}$

N-subjettiness: $\tau_{2,SD}$

Beyond R_{AA}

(1) Train a BDT on all observables to distinguish quenched from unquenched

(2) cf single and pairs of observables

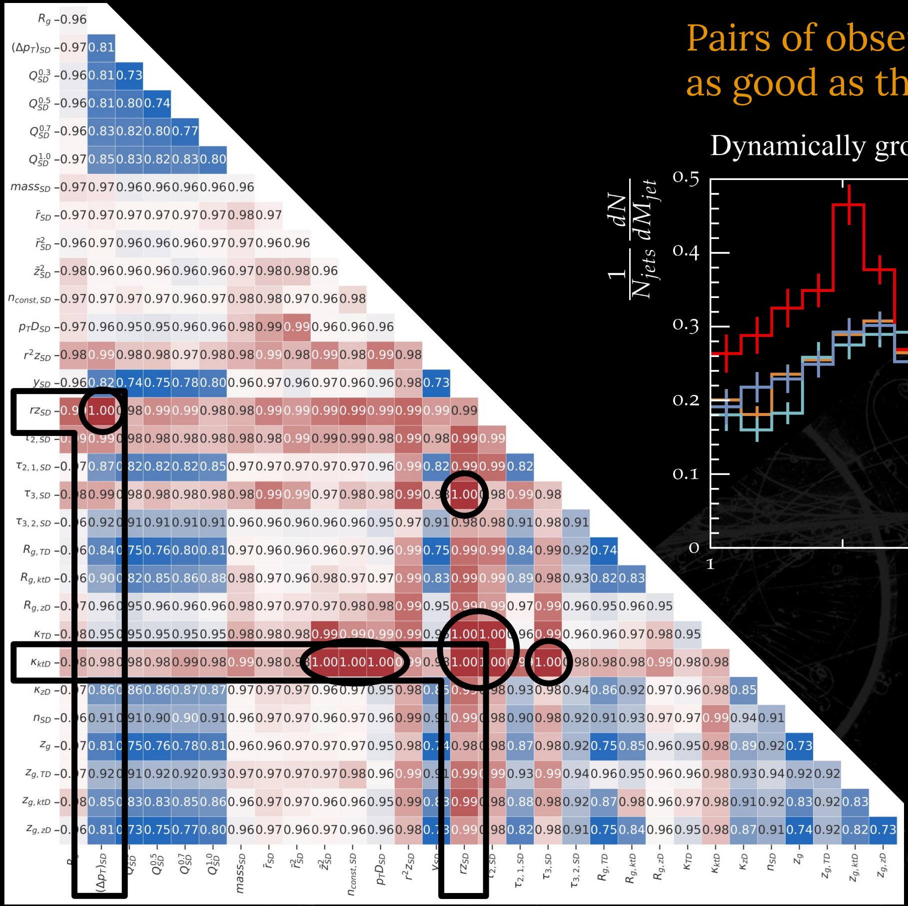


Pairs of observables that are just as good as the full set

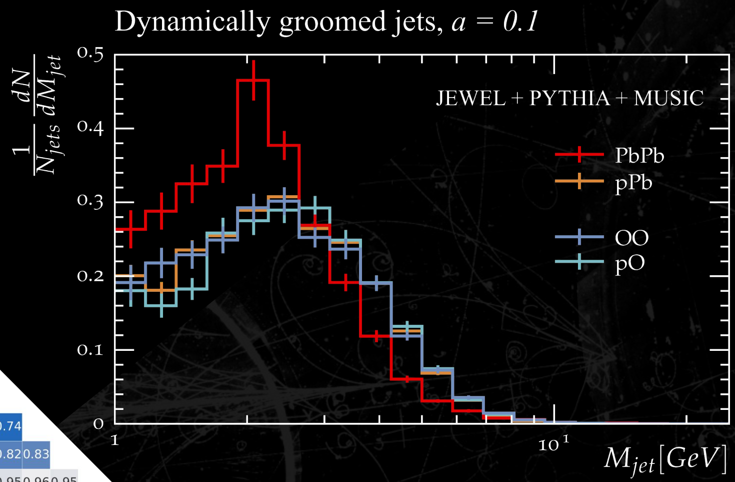
Beyond R_{AA}

(1) Train a BDT on all observables to distinguish quenched from unquenched

(2) cf single and pairs of observables



Pairs of observables that are just as good as the full set



JEWEL-2.4.0 on (2+1)D background

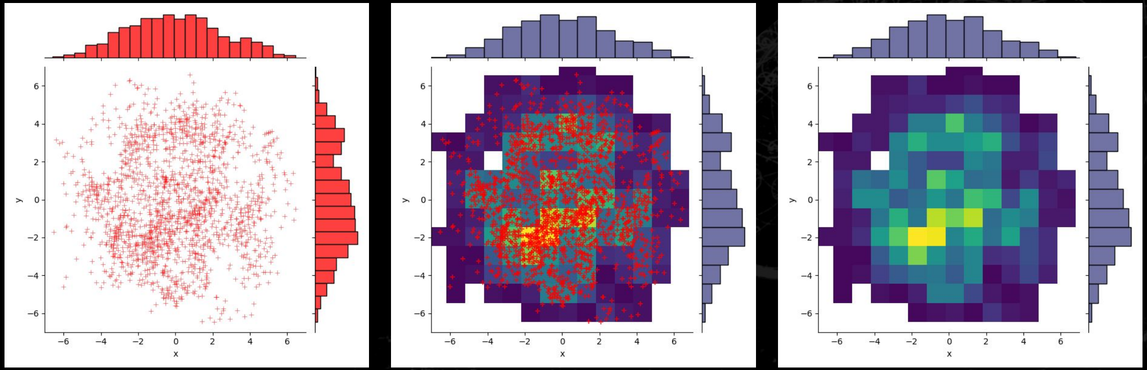
Hydro interface for JEWEL

```
gh repo clone isobelkolbe/jewel-2.4.0-2D
```

New jewel-2.4.0-hydro-2D:

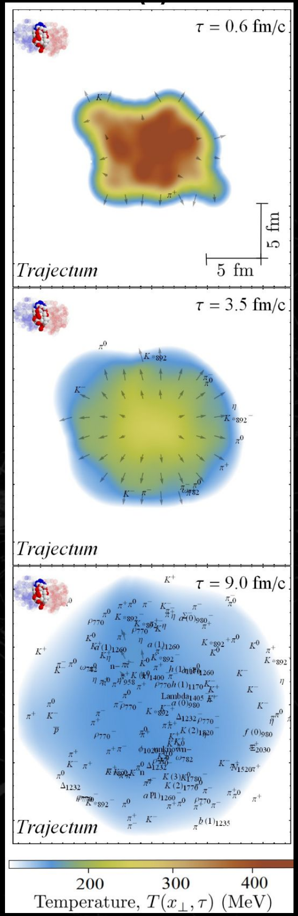
- Built on jewel-2.4.0-simple
  - Similar use of temperature and velocity for scattering centers
  - Similarly separable from main jewel code.
- Can include *any* (2+1)D background with T and (u_x, u_y) information
- Jet production location from N_{coll} information
- Subtleties with density determination

$$n_{eff} = \frac{n_0}{\cosh \eta - \sinh \eta \cos \theta}$$

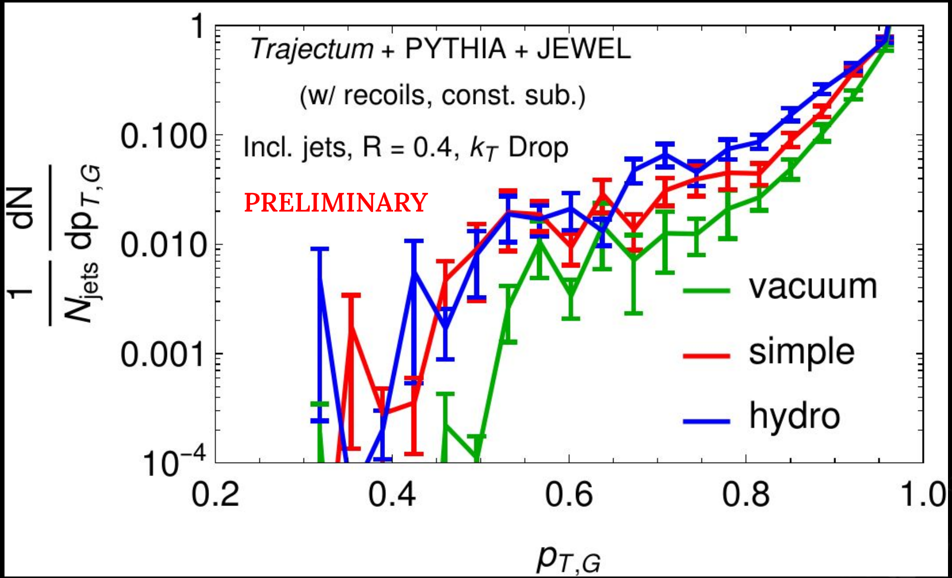


Trajectum

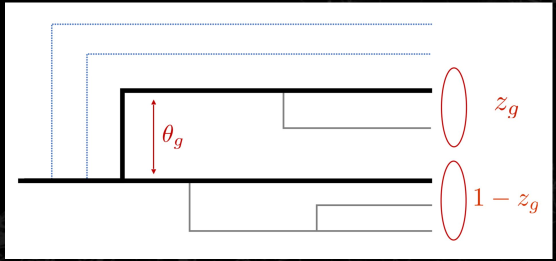
- Utrecht / CERN / MIT
- Contains:
  - Initial stage (Trento)
  - pre-eq.
  - Hydro
  - Freeze-out
  - Hadron phase
- Fast
- Bayesianized parameter lists



Ultra-preliminary results - groomed pT

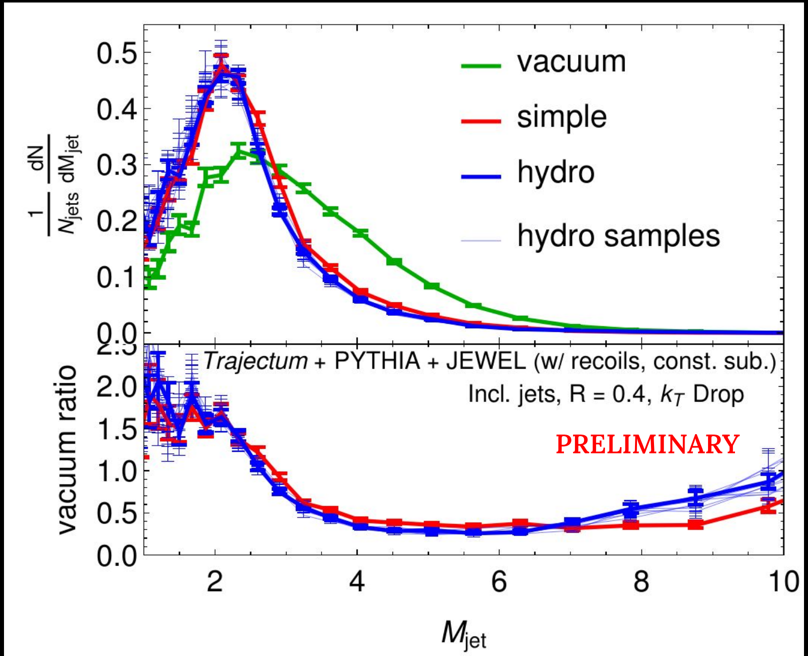


Dynamical Grooming (1911.00375)



$$\kappa^{(a)} = \frac{1}{p_{\rm T}} \max_{i \in \text{C/A seq.}} \left[z_i (1 - z_i)\, p_{{\rm T},i} \left(\frac{\theta_i}{R} \right)^a \right]$$

Ultra-preliminary results - Jet Mass

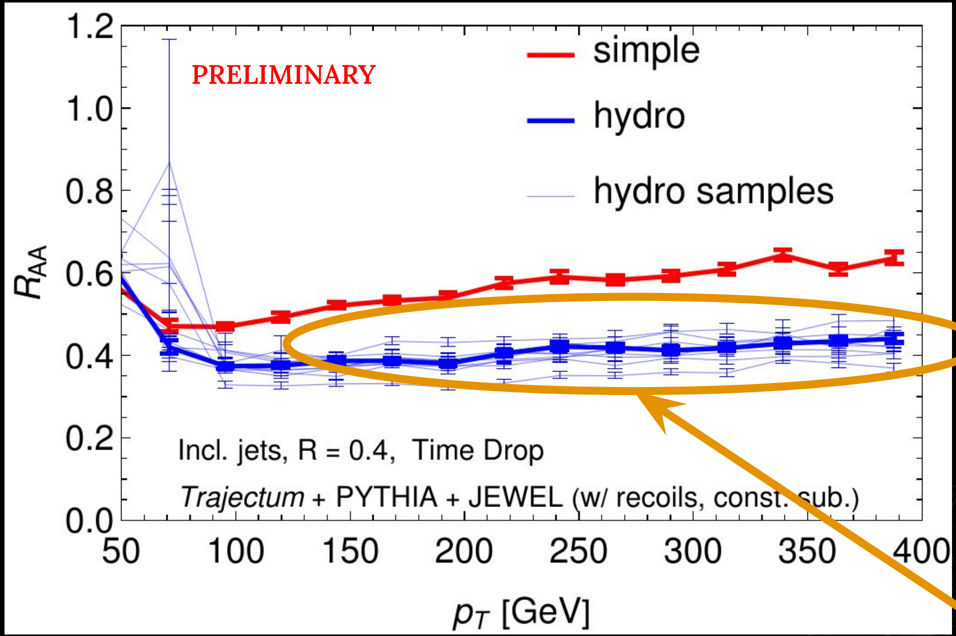


Simple: Standard JEWEL medium.

Hydro: 1k JEWEL events each on 500 *Trajectum* profiles.

Hydro samples: 200k JEWEL events on each of 10 randomly chosen *Trajectum* profiles.

Ultra-preliminary results - R_{AA}



Simple: Standard JEWEL medium.

Hydro: 1k JEWEL events each on 500 *Trajectum* profiles.

Hydro samples: 200k JEWEL events on each of 10 randomly chosen *Trajectum* profiles.

All normalized to JEWEL vacuum.

Really need ensemble

What (other) physics can we do with this?

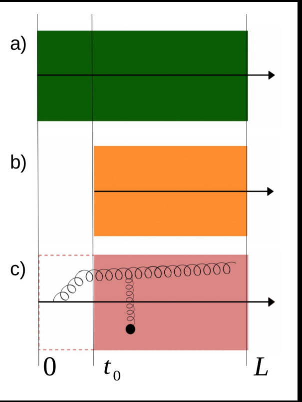
- **Initial goal:** Explore new observables in a variety of collision geometries.
- Explore *any* medium effect on jets:
  - Time-delays
  - Flowing medium
- Realistic R_{AA} vs v_2 in AA (more work)

What does the modification of high-p_T partons look like in small systems?

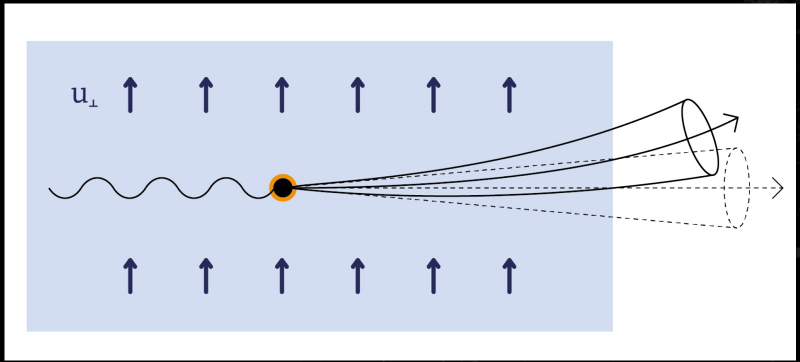
What role do initial state fluctuations play on jet properties?

How do other environments affect jets?

2112.04593



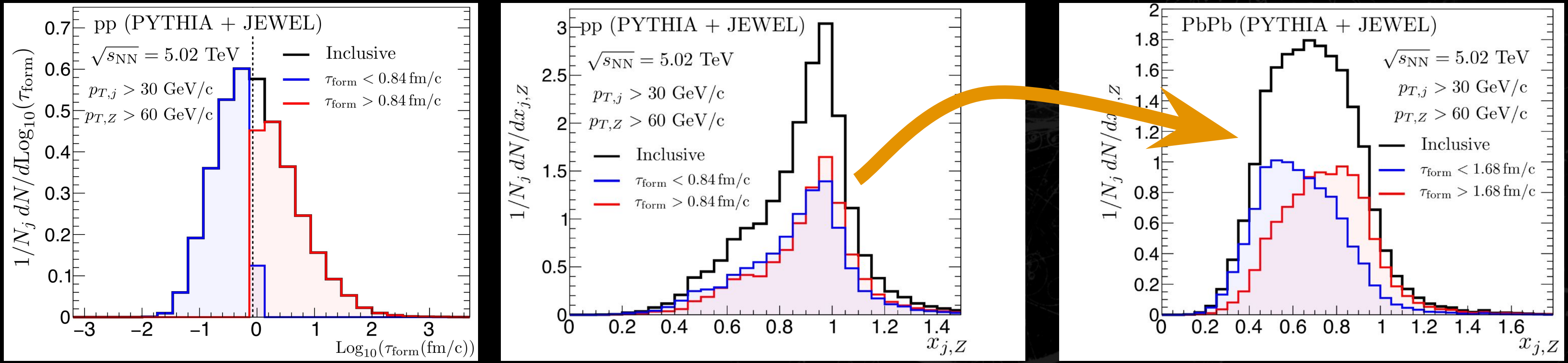
2104.09513



Backups

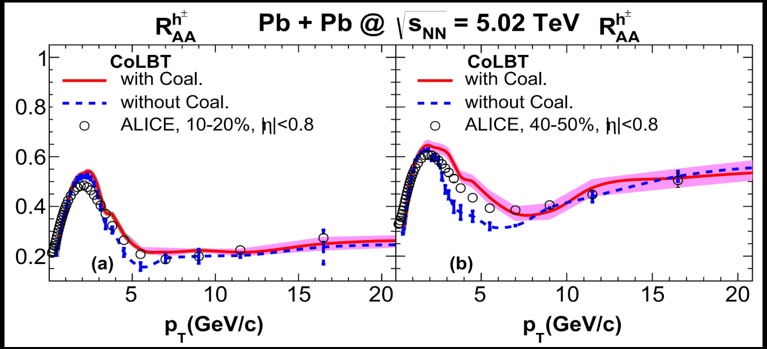
Need a space-time picture

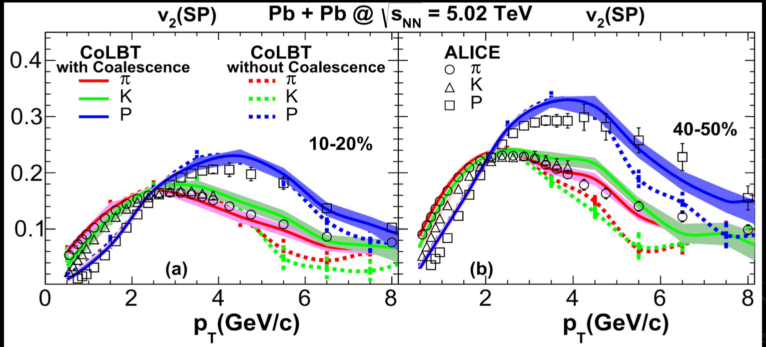
Time reclustering: $d_{ij} = \min\left(p_{T,i}^{2p}, p_{T,j}^{2p}\right)\frac{\Delta R_{ij}^2}{R^2} \xrightarrow{p=0.5} p_{T,i}\theta^2 \sim \frac{1}{\tau_{form}}$



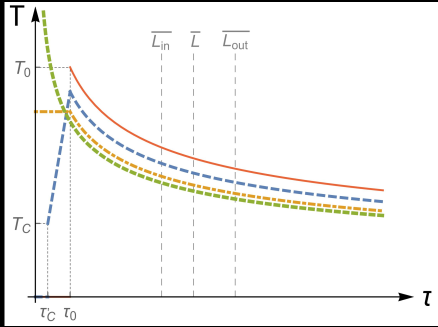
Andres *et.al.*: 2211.10161 | Zigic *et.al.*: 1908.11866 | Zhao *et.al.*: 2103.14657 | Mehtar-Tani et.al:2402.07869

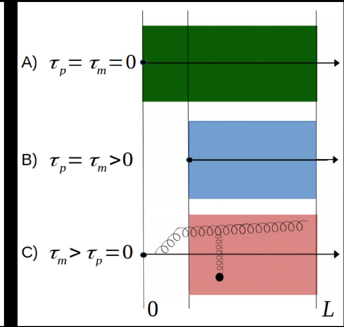
$R_{AA} \otimes v_2$ non-trivial even in AA

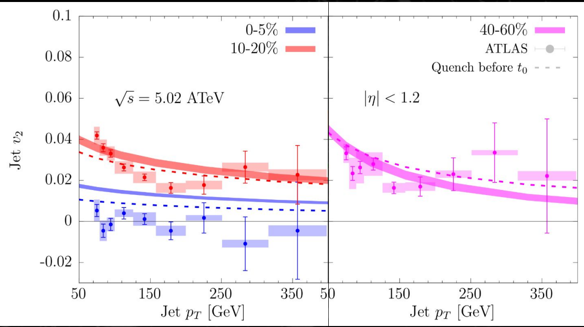


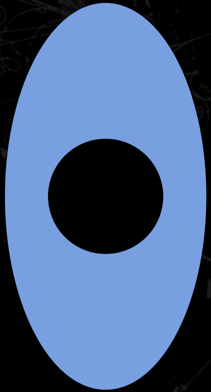


Sensitive to hadronization





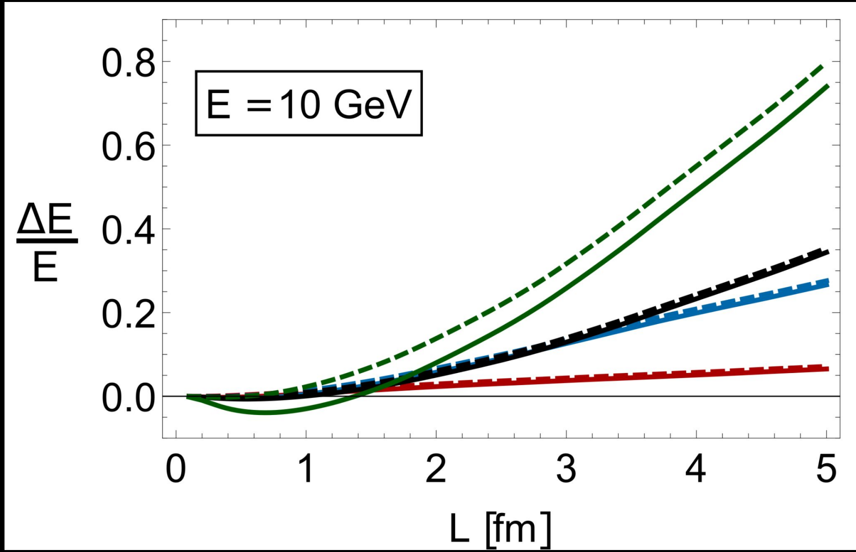


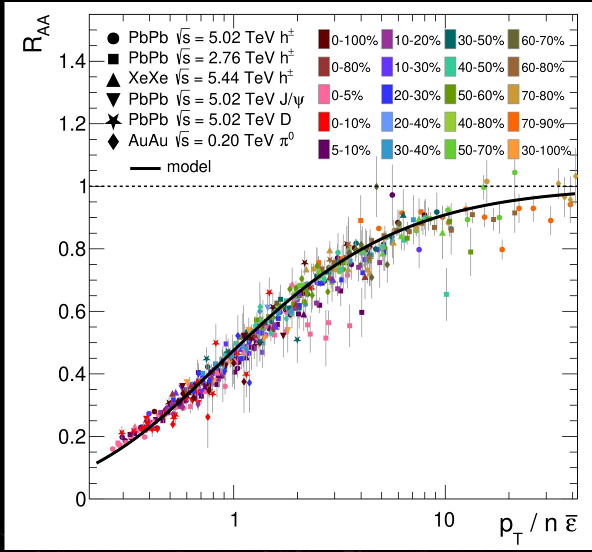


Sensitive to late-time temperature profile?

Sensitive to the nature of radiation in the early stages

What is the pathlength dependence?





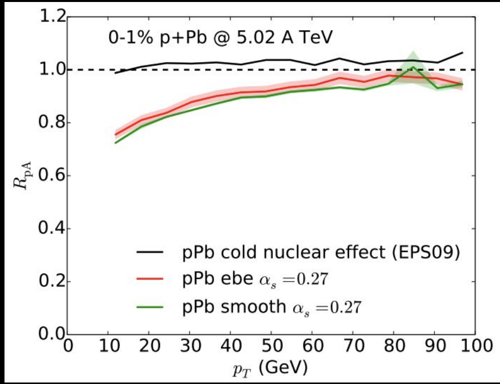
$$\langle \epsilon \rangle = L^{\beta}$$

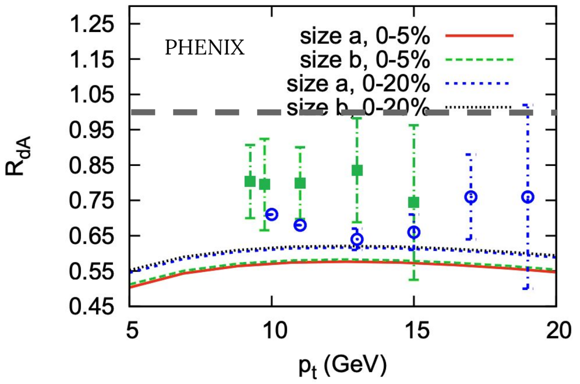
$$\beta = 1.02^{+0.09}_{-0.06}$$

Start by varying the pathlength

Caveat: Centrality determination is non-trivial (see backups)

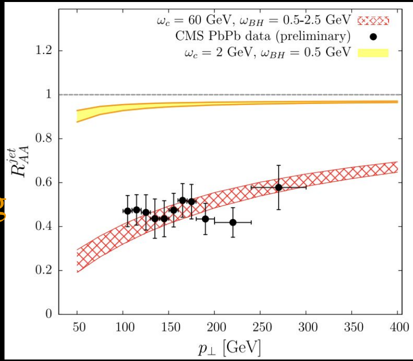
Energetic partons + MARTINI

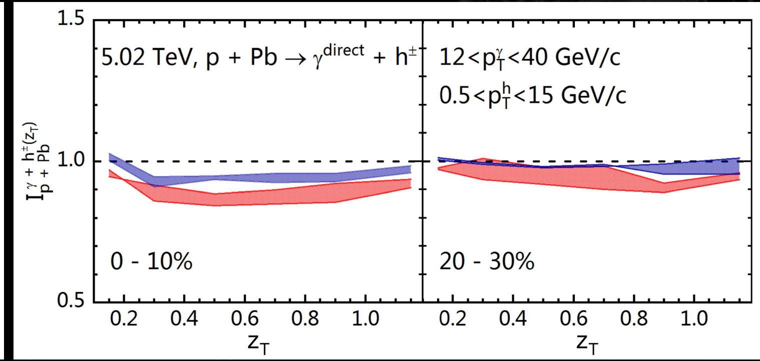




Enhanced energy loss near T_c

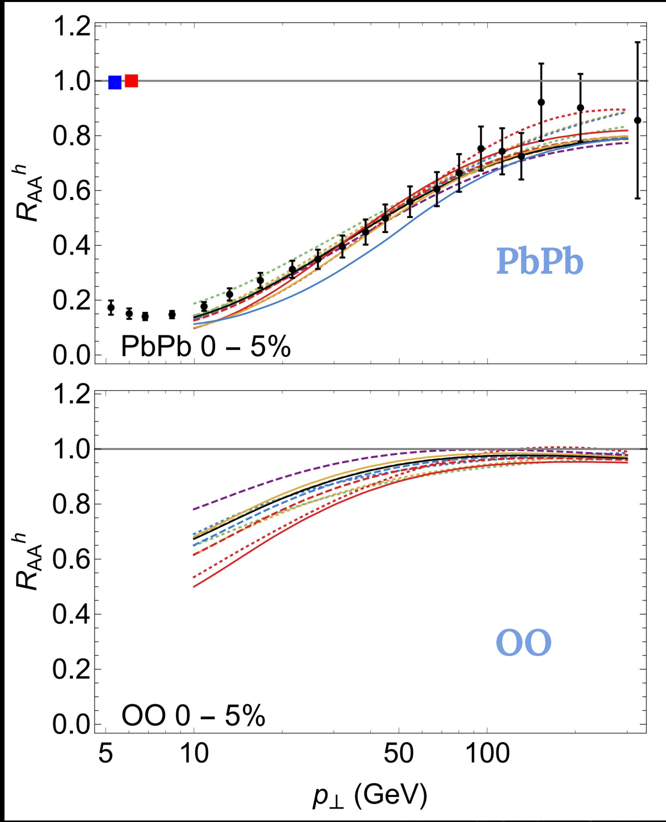
Estimate energy and length scales, multiple soft scattering

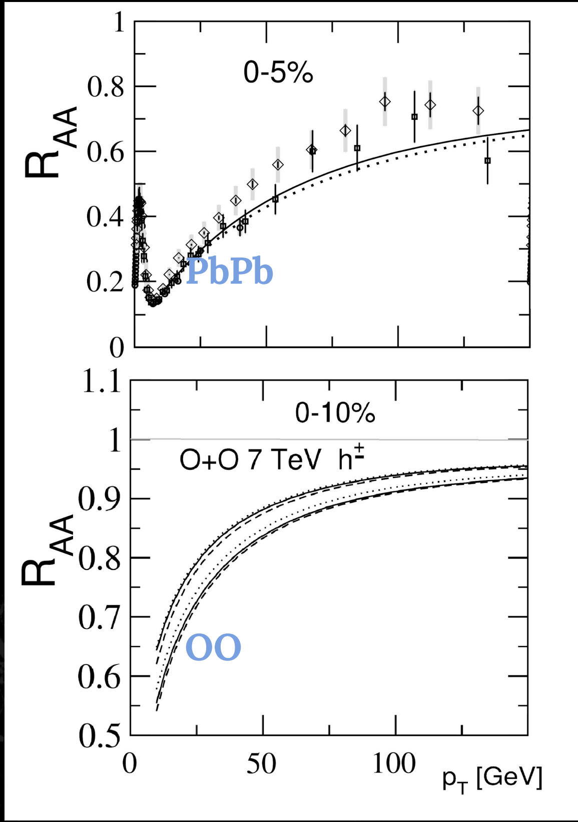




Higher-twist energy loss

Lighter ions

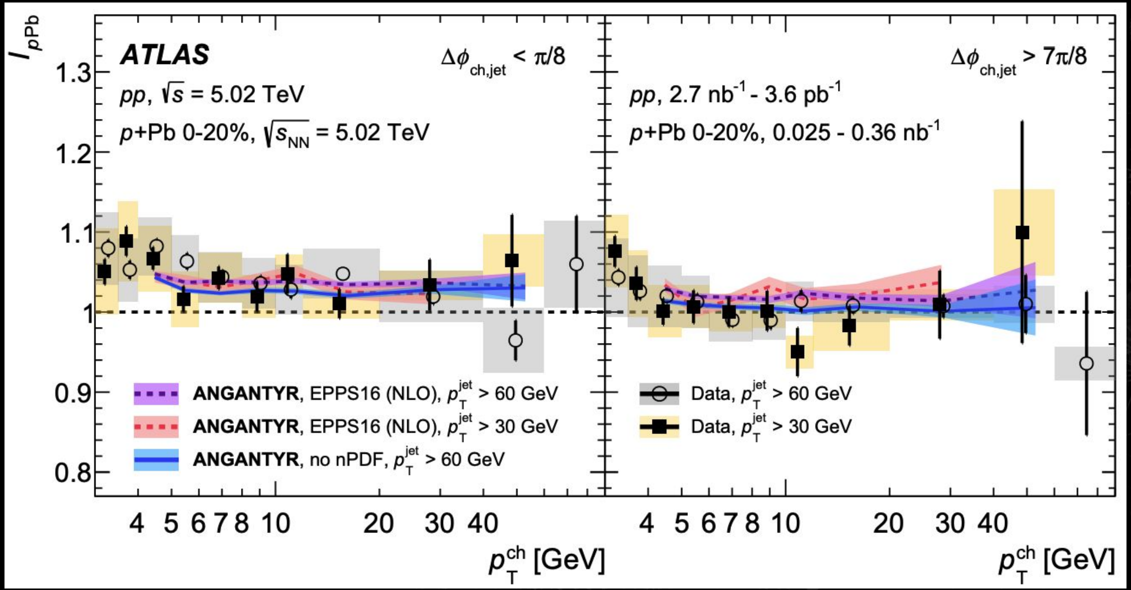


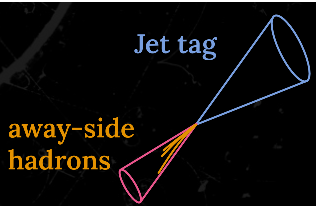


No quenching?

ANGANTYR with string-shoving OFF

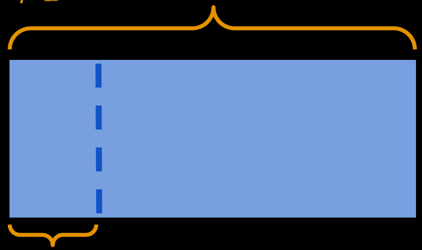
Caveat: 0-20% bin in pPb is quantitatively different to 0-5%



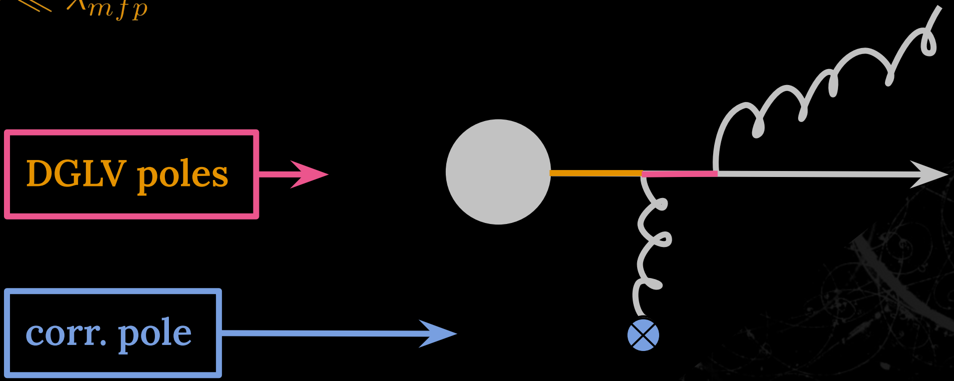


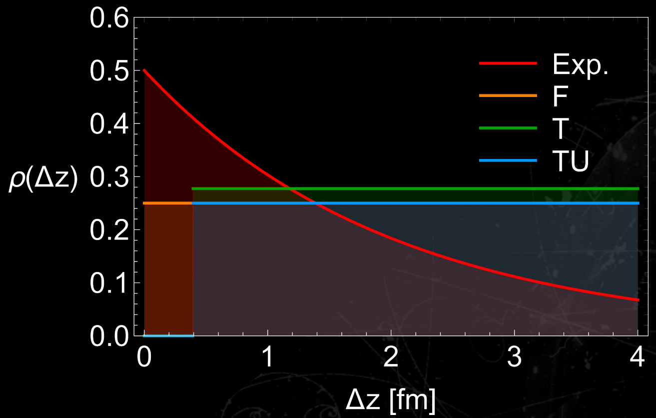
Relaxing large-L approximation

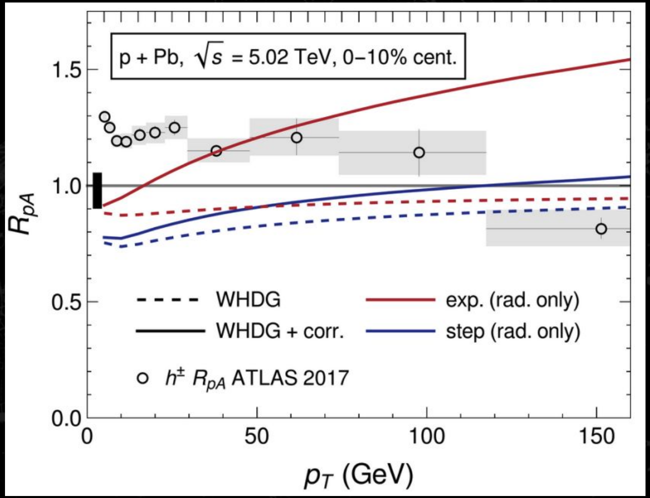
$$\frac{1}{\mu_D} \ll \Delta z \sim \lambda_{mfp} \ll L$$



$$\frac{1}{\mu_D} \ll \lambda_{mfp}$$



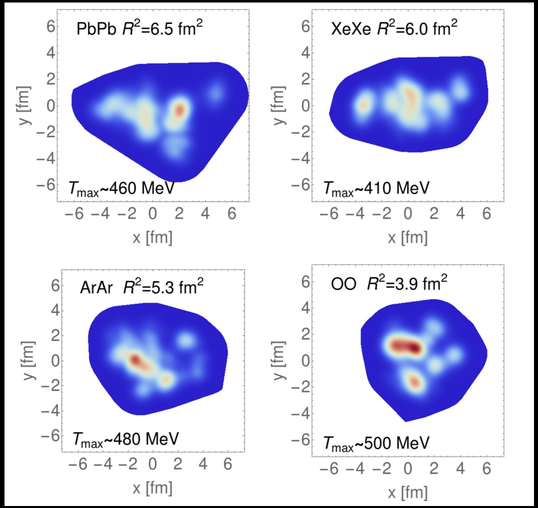


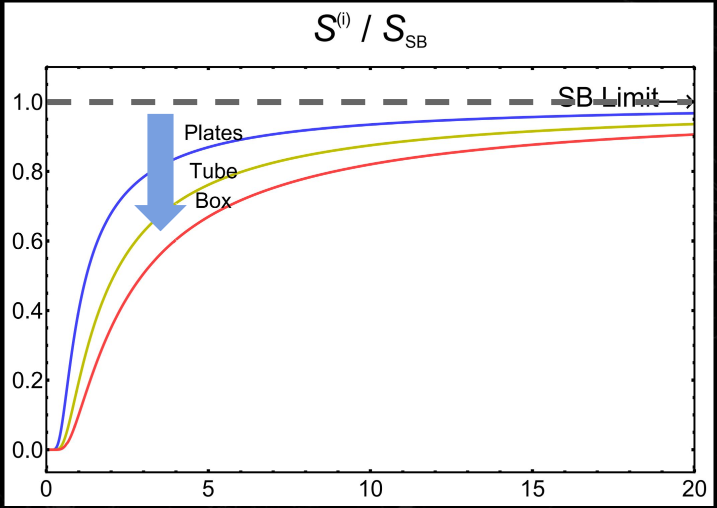


Small is not the only problem

$$\lambda_{mfp} \sim \frac{1}{\rho\sigma} \sim \frac{1}{g^2 T}$$

$$\mu_D \sim gT$$



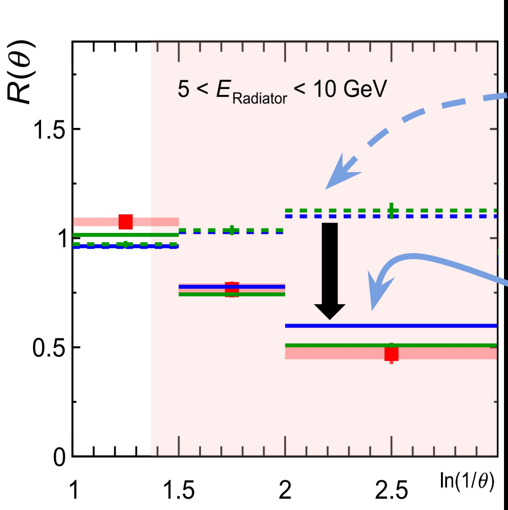


Smaller systems are hotter at the same multiplicity

Single, massless, non-interacting, scalar field in a finite box

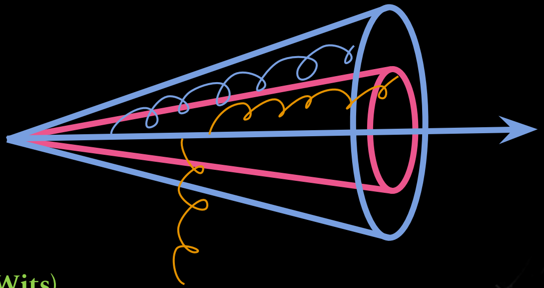
The dead cone

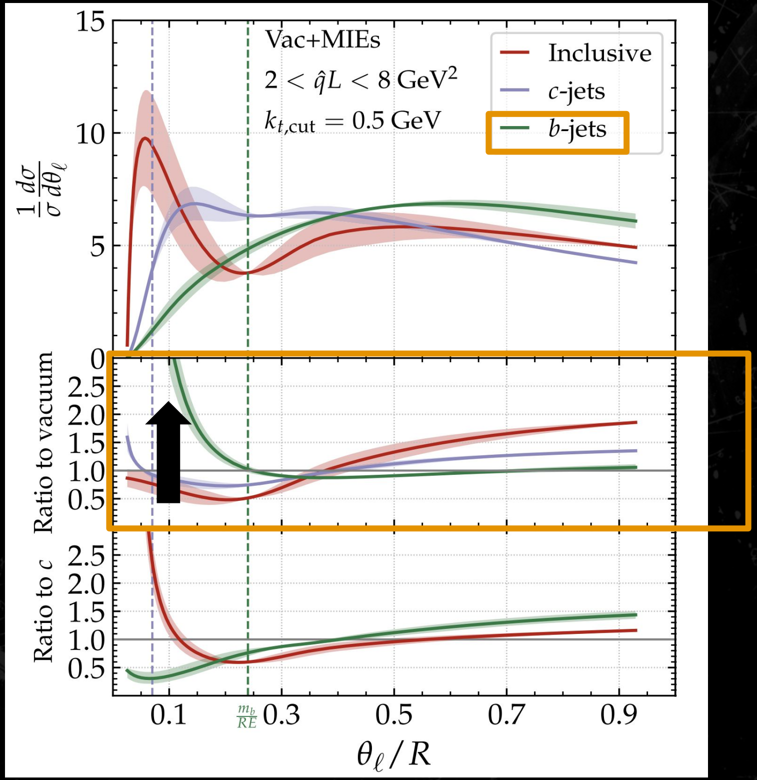
In-medium radiation fills the dead cone



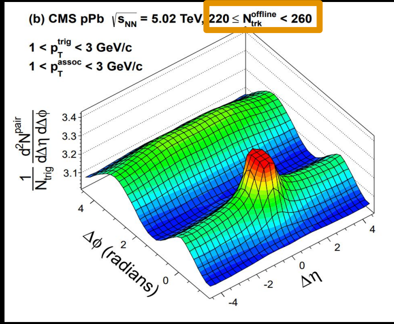
light -flavour

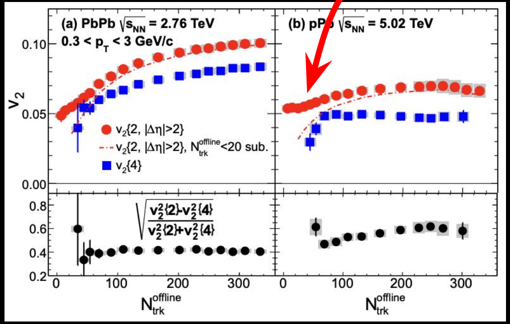
heavy -flavour





R_{AA}, v_2, and Centrality





Subtract low mult-data (match ATLAS)

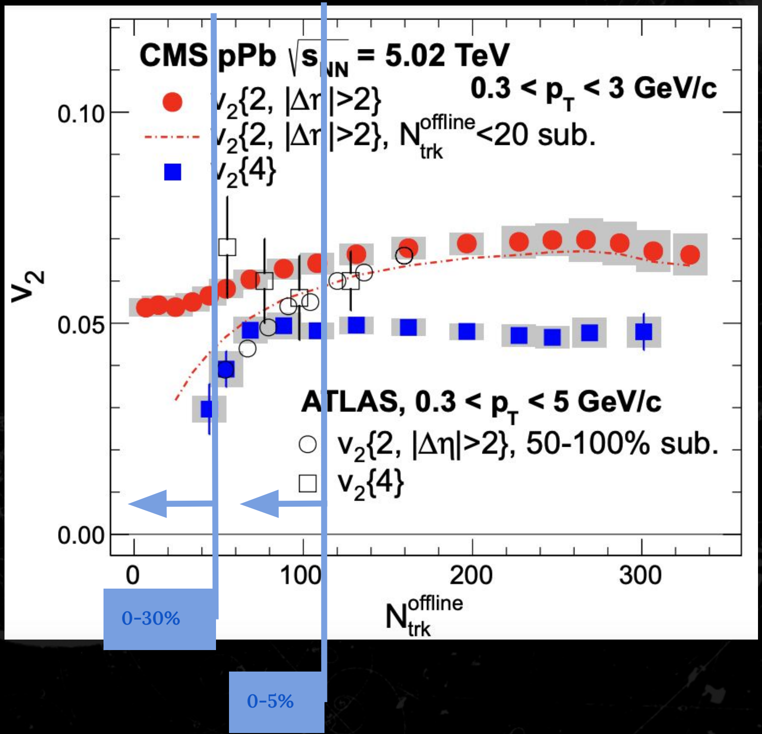
$N_{trk}^{offline}$ bin	PbPb data ⟨Centrality⟩ ± RMS (%)	⟨$N_{trk}^{offline}$⟩	⟨$N_{trk}^{corrected}$⟩	pPb data Fraction	⟨$N_{trk}^{offline}$⟩	⟨$N_{trk}^{corrected}$⟩
[0, ∞)				1.00	40	50±2
[0, 20)	92±4	10	13±1	0.31	10	12±1
[20, 30)	86±4	24	30±1	0.14	25	30±1
[30, 40)	83±4	34		0.12	35	42±2
[40, 50)	80±4	44		0.10	45	54±2
[50, 60)	78±3	54		0.09	54	66±3
[60, 80)	75±3	69	87±4	0.12	69	84±4
[80, 100)	72±3	89		0.07	89	108±5
[100, 120)	70±3	109		0.03	109	132±6
[120, 150)	67±3	134		0.02	132	159±7
[150, 185)	64±3	167	210±9	4×10^{-3}	162	195±9
[185, 220)	62±2	202	253±11	5×10^{-4}	196	236±10
[220, 260)	59±2	239	299±13	6×10^{-5}	232	280±12
[260, 300)	57±2	279	350±15	3×10^{-6}	271	328±14
[300, 350)	55±2	324	405±18	1×10^{-7}	311	374±16

0-50%

0-30%

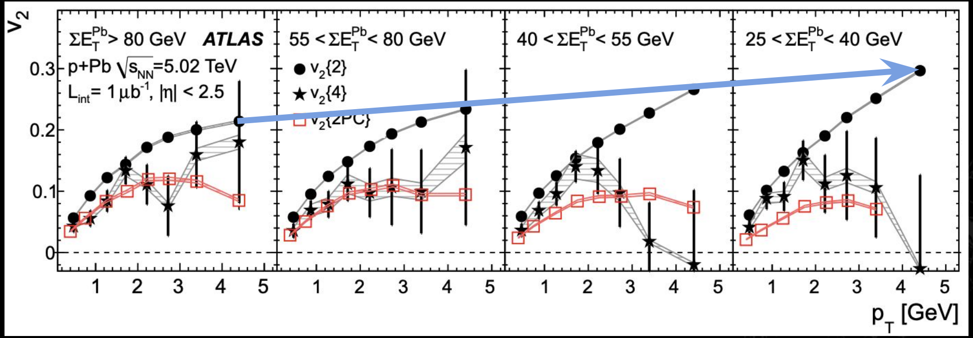
0-10%

0-0.00631% bin



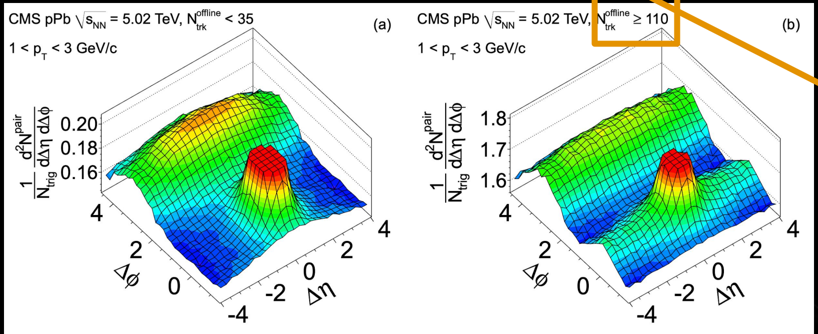
R_{AA}, v_2 , and Centrality (Alternative - ATLAS)

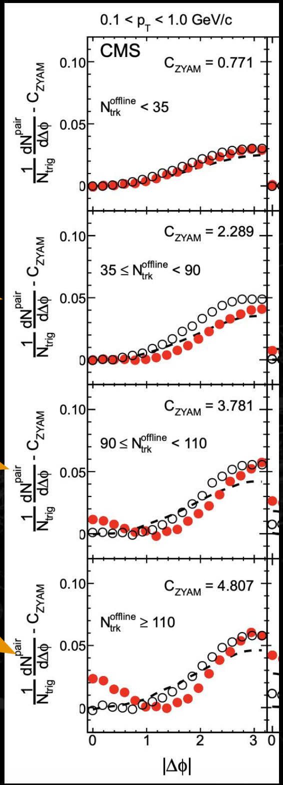
ΣE_T^{Pb} range [GeV]	$\langle \Sigma E_T^{Pb} \rangle$ [GeV]	range in fraction of events [%]	$\langle N_{ch}^{rec} \rangle$ (RMS)
> 80	93.7	0–1.9	134 (31)
55–80	64.8	1.9–9.1	102 (26)
40–55	46.7	9.1–20.0	80 (23)
25–40	31.9	20.0–39.3	60 (20)
10–25	16.9	39.3–70.4	37 (17)
< 10	4.9	70.4–100	16 (11)



R_{AA}, v_2 , and Centrality (Alternative - peripheral)

Multiplicity class ($N_{trk}^{offline}$)	Fraction (%)	$\langle N_{trk}^{offline} \rangle$	$\langle N_{trk}^{corrected} \rangle$
Minimum Bias	100.0	40.6	53.4±2.9
$N_{trk}^{offline} < 35$	50.4	17.1	23.5±1.3
$35 \leq N_{trk}^{offline} < 90$	41.9	56.3	75.6±4.1
$90 \leq N_{trk}^{offline} < 110$	4.6	98.2	114.3±6.2
$N_{trk}^{offline} \geq 110$	3.1	128.2	149.1±8.1

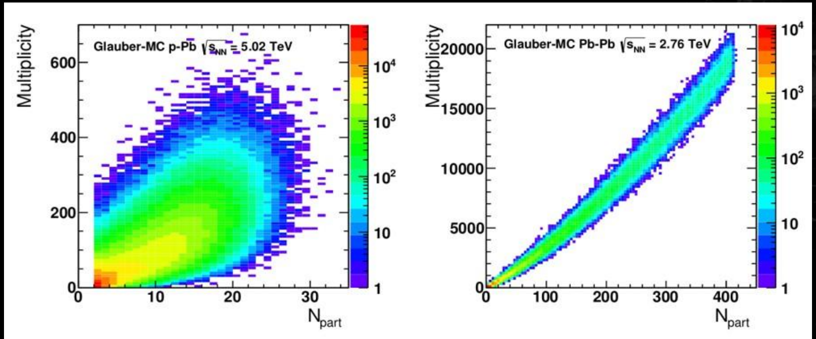


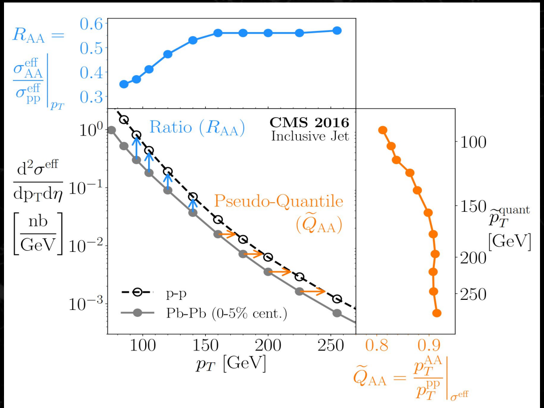


Correlated yield

Why R_{AA} is not ideal for small systems

- Reliance on a reference system
- Steeply falling production spectrum
  - Sensitive only to large ΔE
  - Sensitive to PDFs and nPDFs
  - Species-dependent
- Sensitive to initial condition
  - Geometry
  - Momentum anisotropy
- Sensitive to jet fragmentation
- Supposed to quantify ΔE, but
  - $\Delta E \leftarrow L \leftarrow N_{coll}$: uncontrolled
  - $\Delta E = \Delta E(T)$: T is uncontrolled





Dead cone prediction in AA