

# Jet quenching and Heavy Flavor dynamics in small systems

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Thank you to Carlota Andres, Jasmine Brewer, Florian Cougoulic, Xiaojian Du, Elena Ferreiro, Gian Michele Innocenti, Carlos Salgado, Deepa Thomas, Urs Wiedemann, and Nima Zardoshti for advice and illuminating discussions.



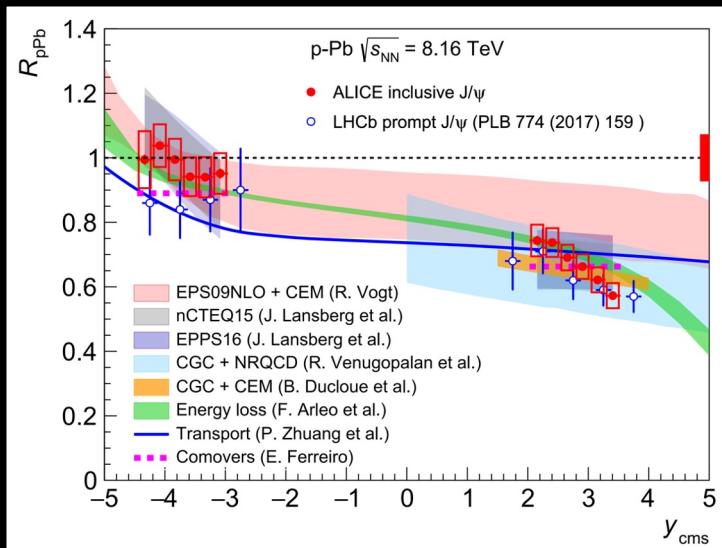
**IGFAE**  
Instituto Galego de F sica de Altas Enerx as



**XUNTA  
DE GALICIA**



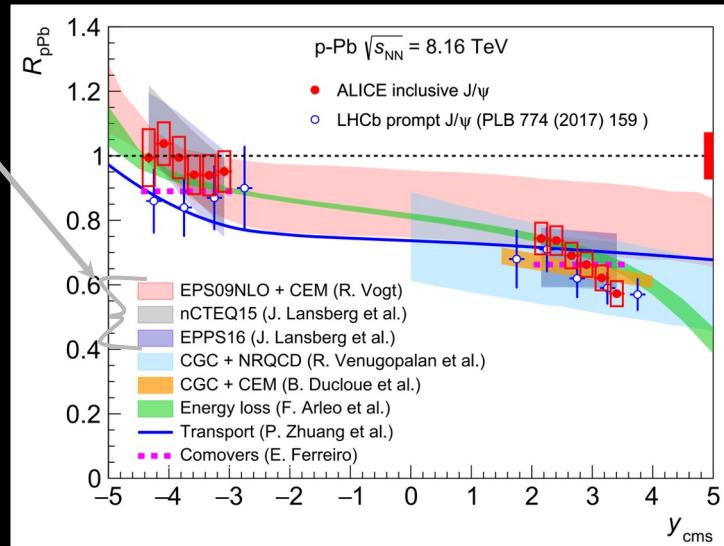
# Are there competitive non-plasma $J/\psi$ suppression mechanisms?



$$R_{pPb}(y_{cms}, p_T) = \frac{\frac{d^2 \sigma_{pPb}^{J/\psi}}{dy_{cms} dp_T}}{A_{Pb} \frac{d^2 \sigma_{pp}^{J/\psi}}{dy_{cms} dp_T}}$$

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Nuclear modification  
of PDFs  
(Marquet, Tue)



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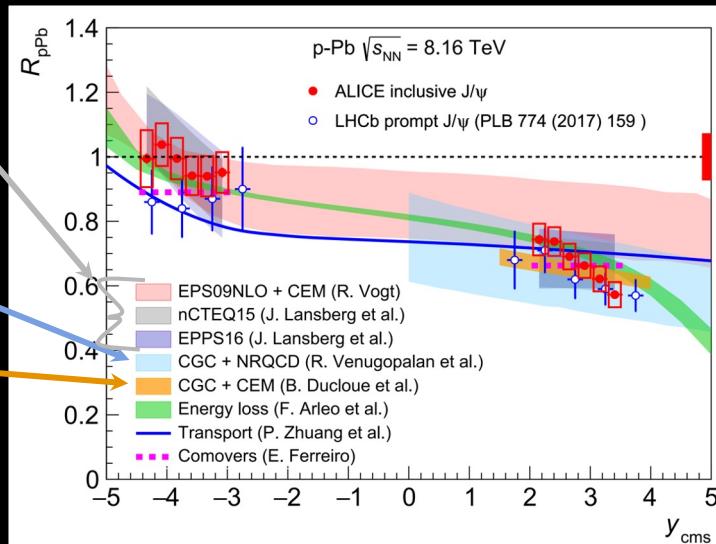
eeeee

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Gluon saturation

Gluon saturation  
+ hadronization



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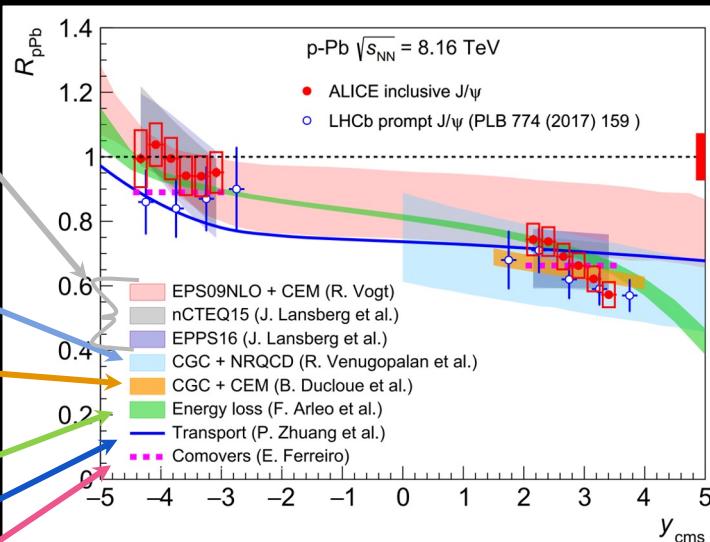
Gluon saturation

Gluon saturation  
+ hadronization

Fully coherent gluon  
radiation

Hot and cold

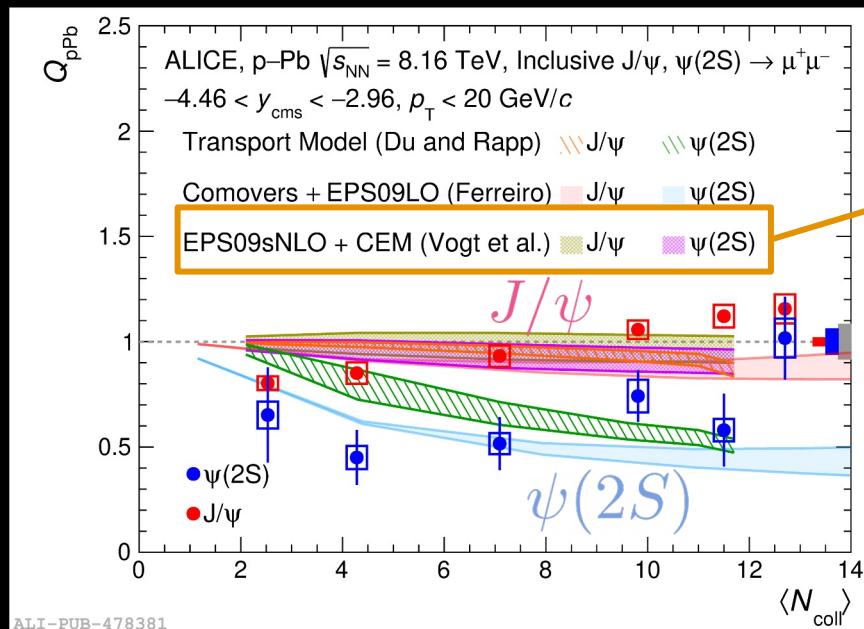
Dissociation



$$R_{pPb}(y_{cms}, p_T) = \frac{\frac{d^2 \sigma_{pPb}^{J/\psi}}{dy_{cms} dp_T}}{A_{Pb} \frac{d^2 \sigma_{pp}^{J/\psi}}{dy_{cms} dp_T}}$$

Initial- and final-state  
effects describe p-  
going direction  
suppression.

# Need final-state effects for $\psi(2S)$



No final state - no difference  
between  $J/\psi$  and  $\psi(2S)$

Experimental results:

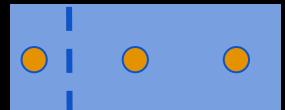
- Thomas ([overview](#))
- Trzeciak ([STAR](#))
- Wang ([LHCb](#))
- Lofnes ([ALICE](#))
- Acharya ([ALICE](#))

# Jet Quenching

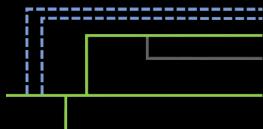
in small systems

Do we know what  
to expect?

Existing  
calculations

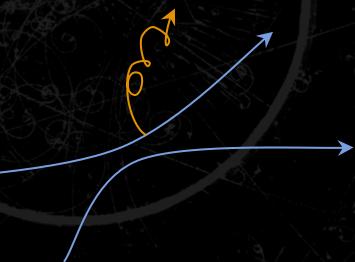


Beyond  $R_{AA}$

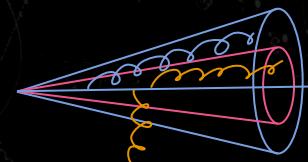


How can HF  
help?

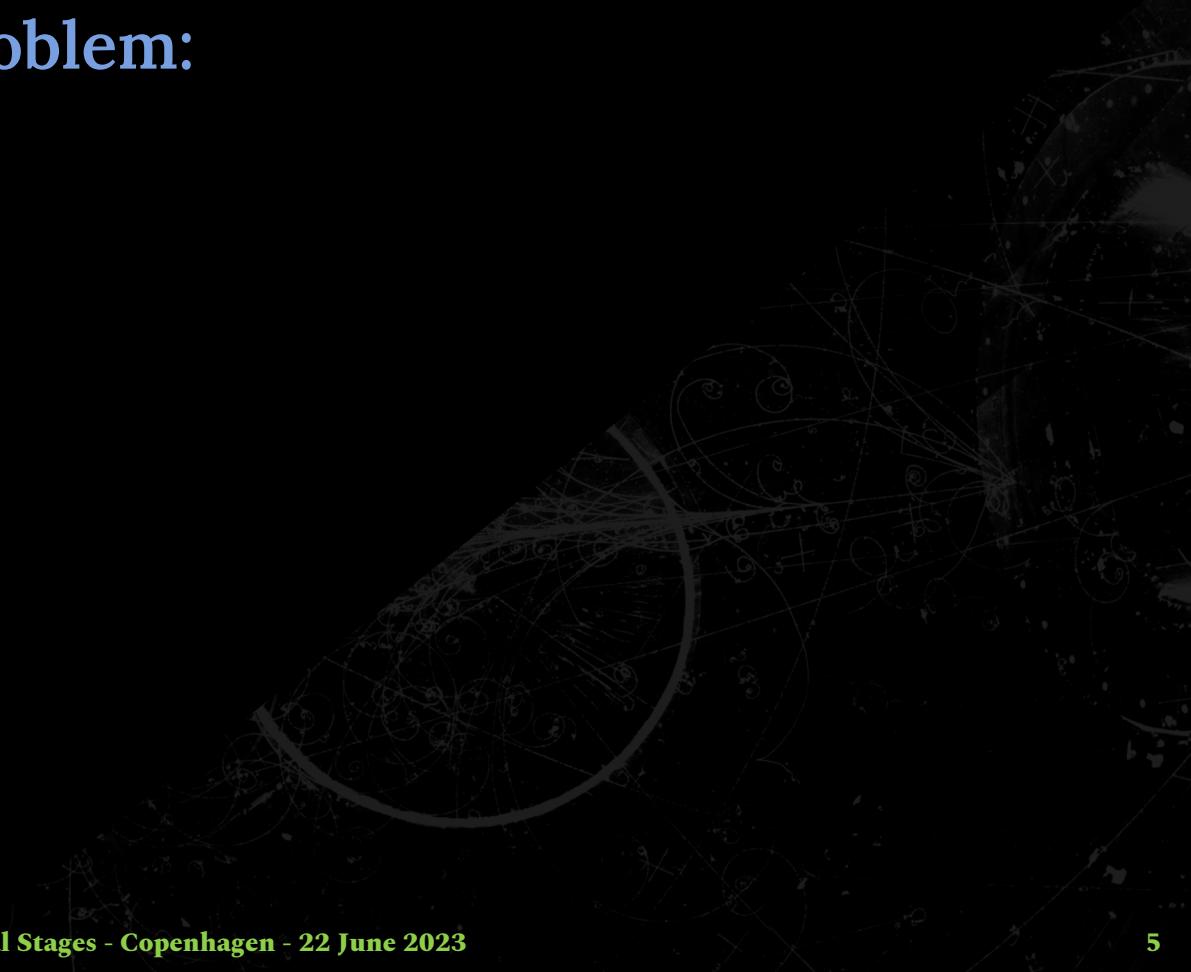
Intermediate- $p_T$



More physics

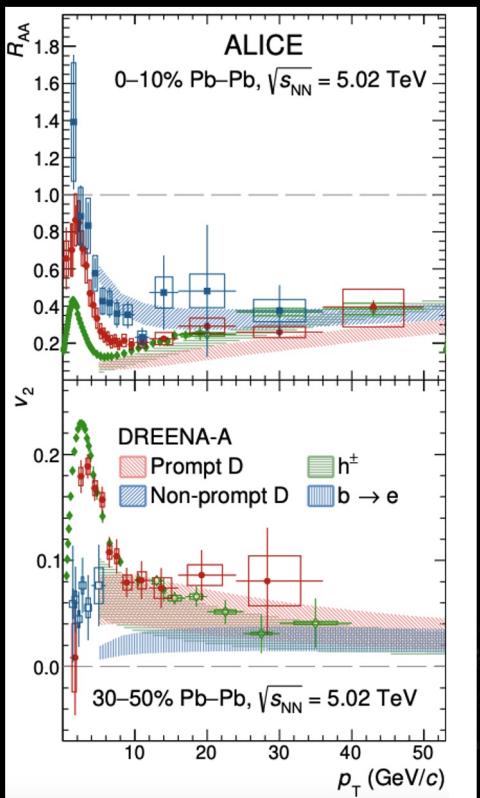


# A phrasing of the problem:



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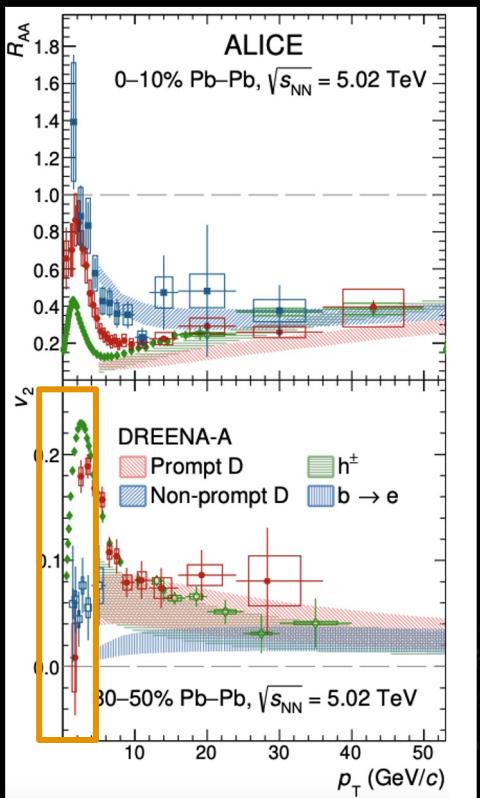
Self-consistent paradigm in AA:



# A phrasing of the problem:

Self-consistent paradigm in AA:

Strong-coupling:  
Multiple interactions

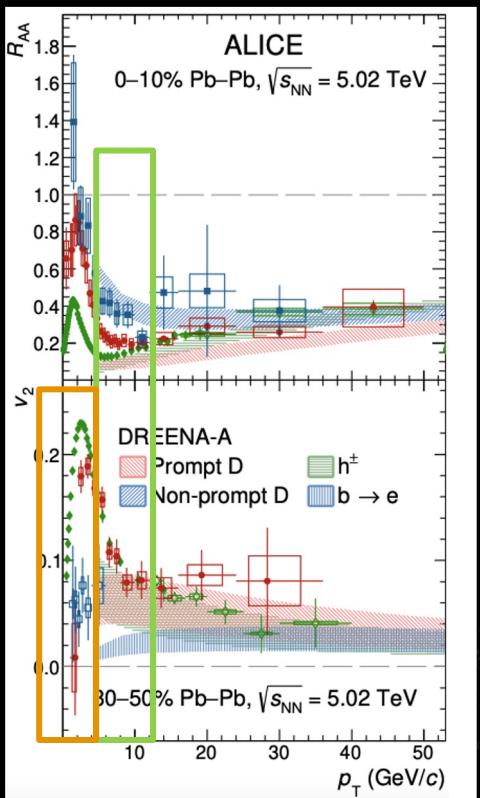


# A phrasing of the problem:

Self-consistent paradigm in AA:

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Kinetic transition:  
Few interactions



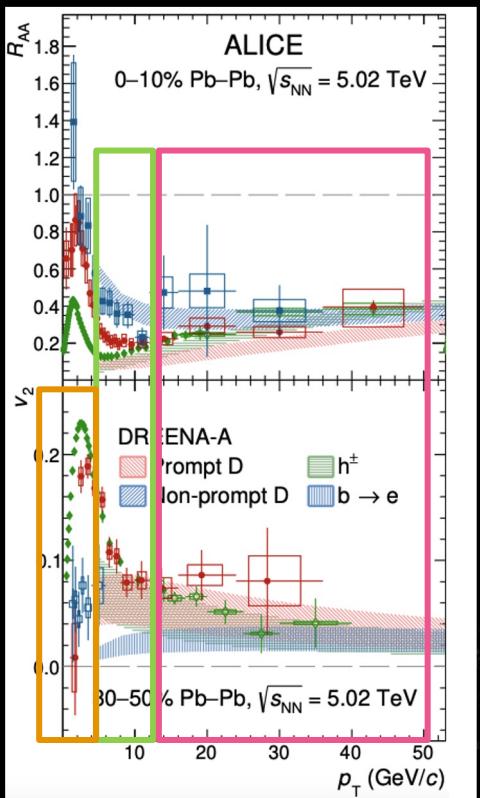
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Self-consistent paradigm in AA:

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Path length-dependent  
energy loss



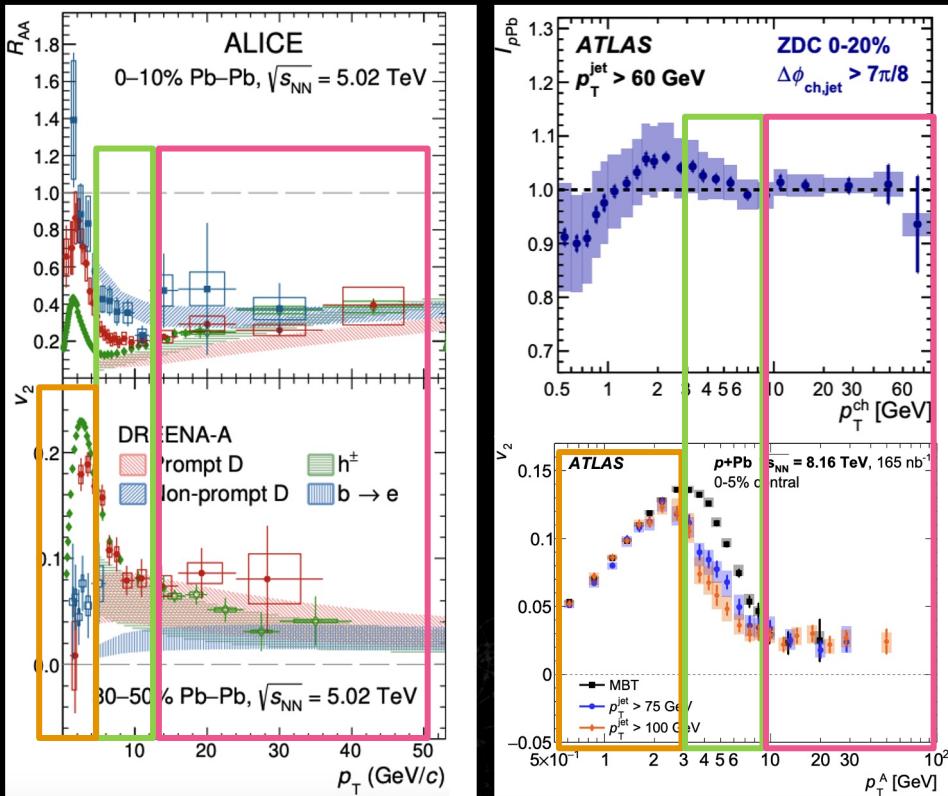
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Unclear interpretation  
in small systems

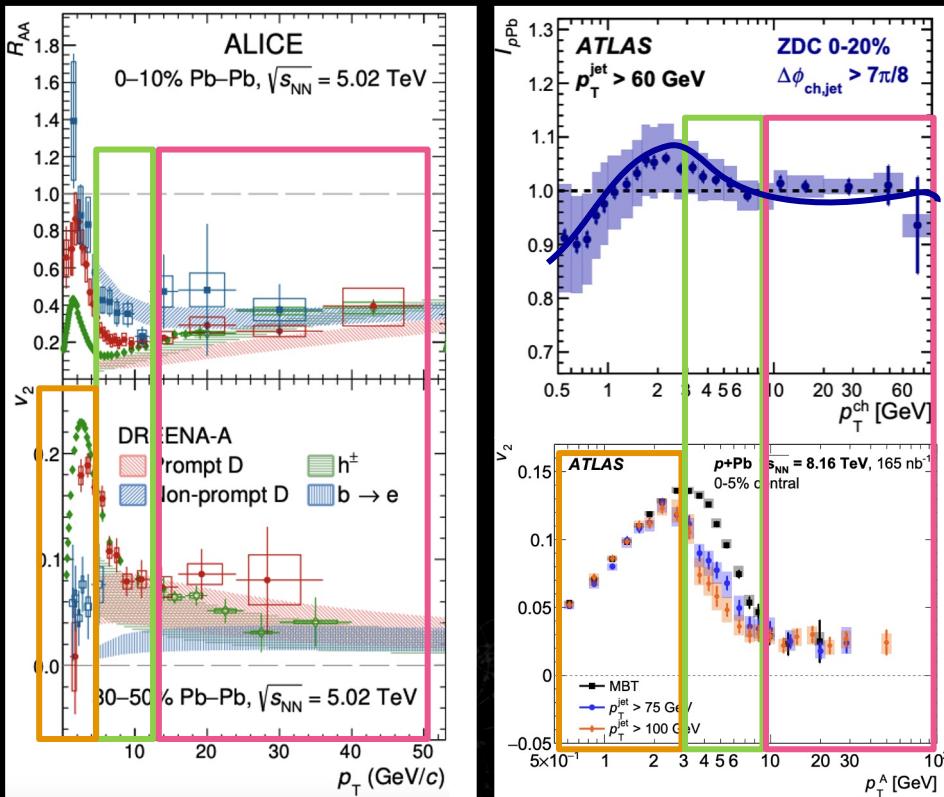
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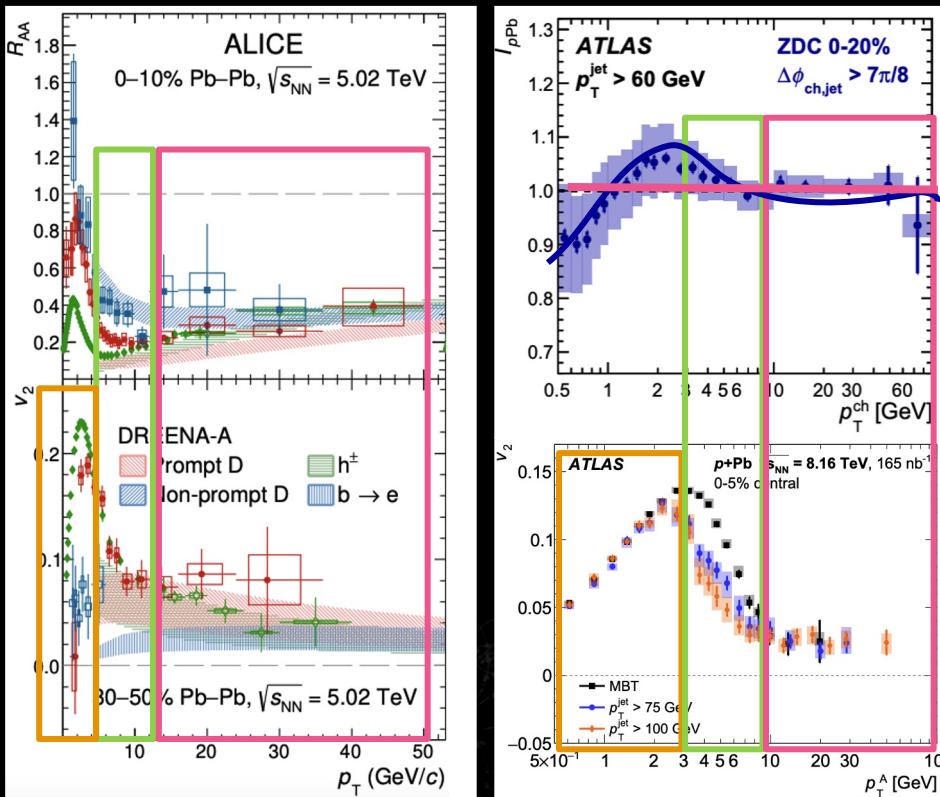
# A phrasing of the problem:

Self-consistent paradigm in AA:

**Strong-coupling:**  
Multiple interactions

**Kinetic transition:**  
Few interactions

**Path length-dependent energy loss**



Unclear interpretation  
in small systems

An E-loss description of  $v_2$   
and  $R_{AA}$  is non-trivial in AA

Sensitive to:  
-starting time  
-temperature profile  
-hadronization

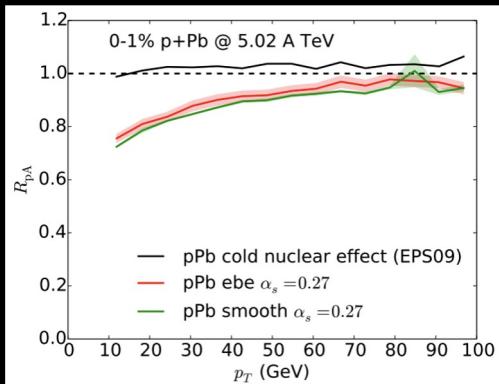
See backups

# Start by varying the pathlength



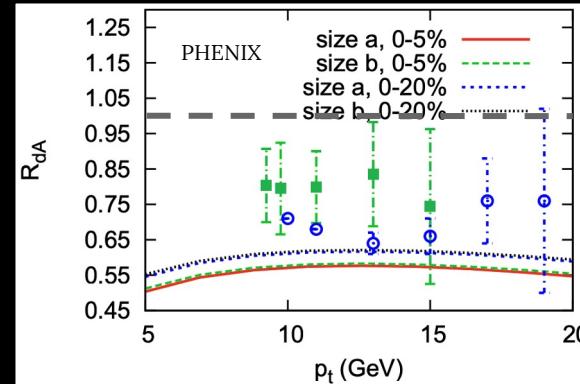
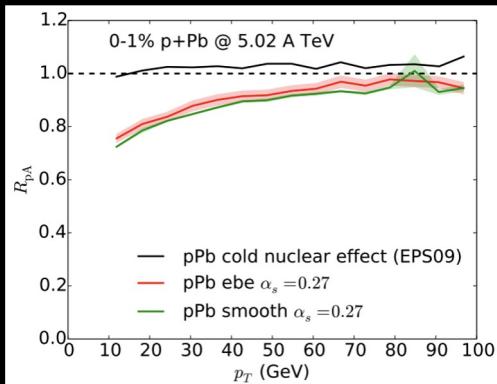
# Start by varying the pathlength

Energetic partons +  
MARTINI



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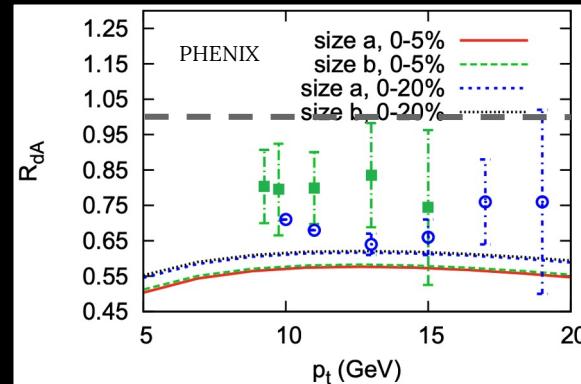
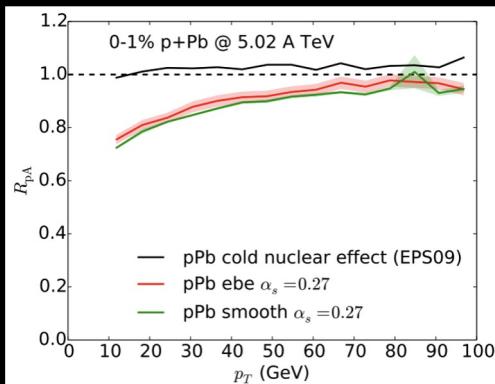
Energetic partons +  
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Enhanced energy  
loss near  $T_c$

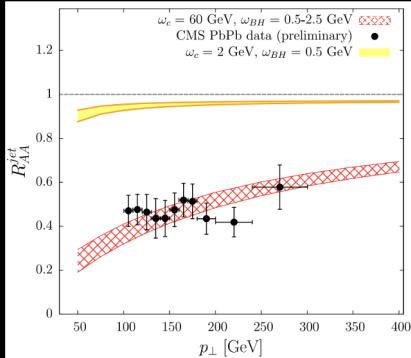
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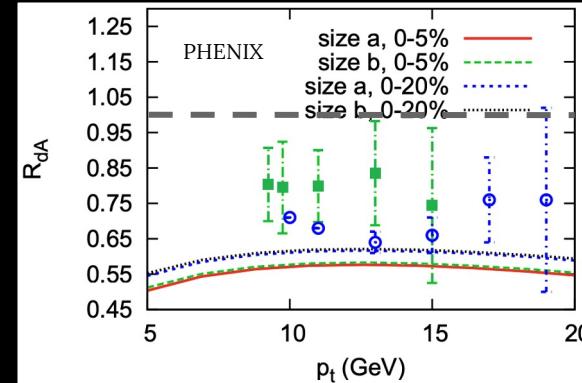
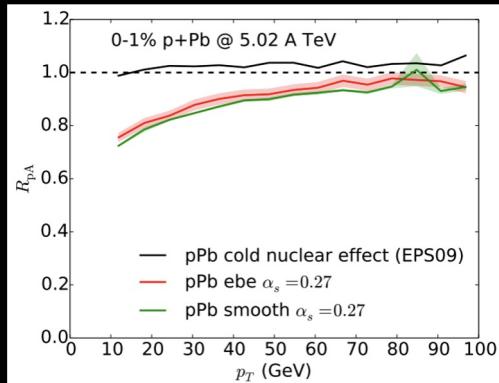
Enhanced energy  
loss near  $T_c$

Estimate energy and  
length scales,  
multiple soft  
scattering

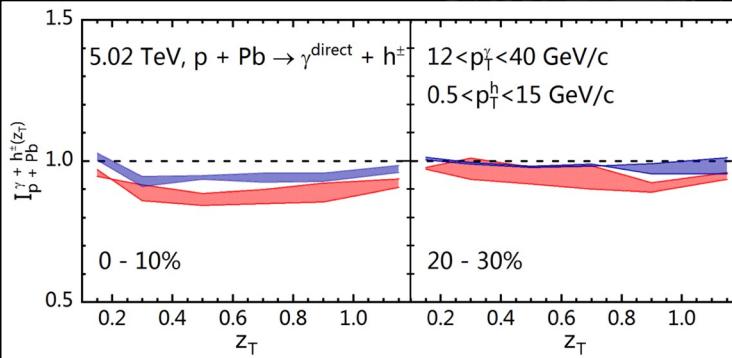
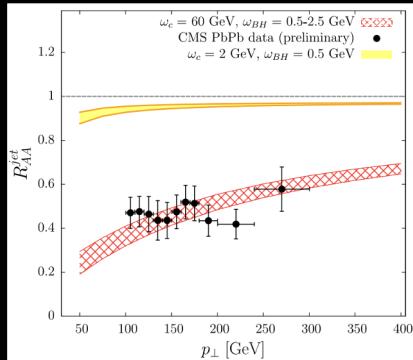


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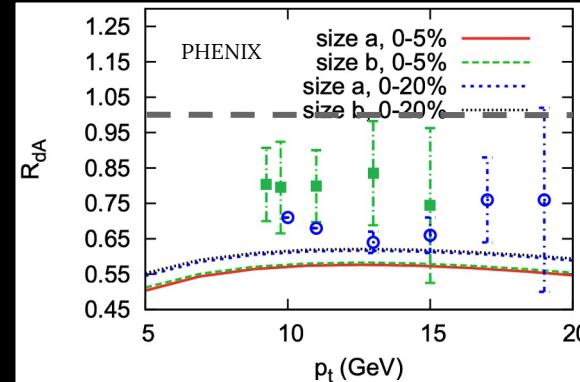
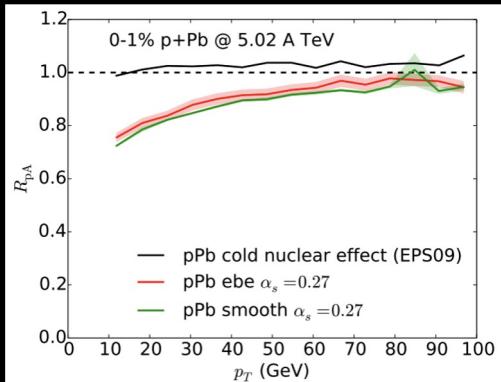


Enhanced energy  
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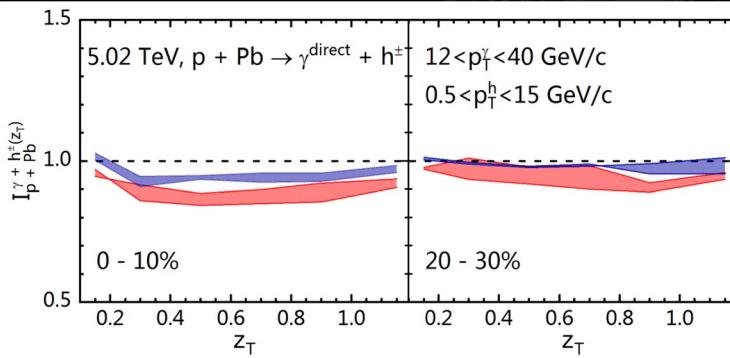
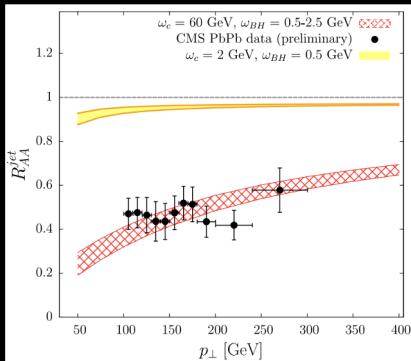
Higher-twist  
energy loss

# Start by varying the pathlength

Energetic partons +  
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Estimate energy and  
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scattering

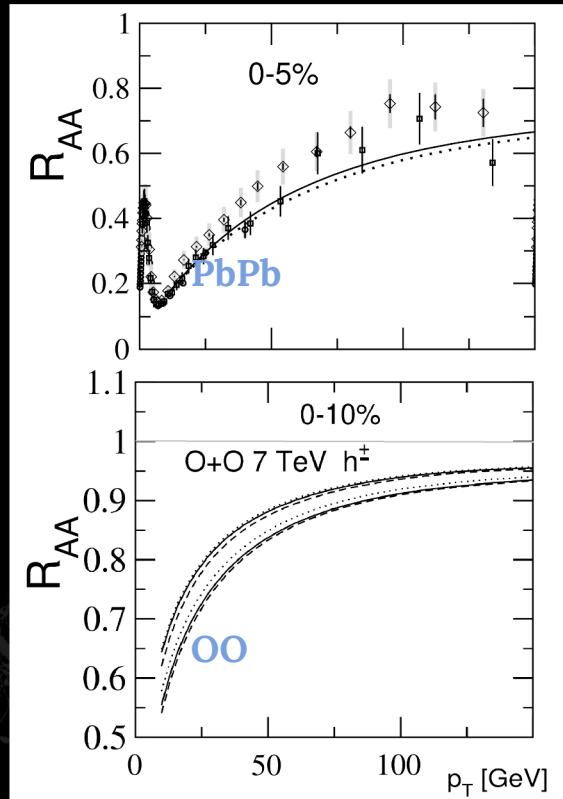
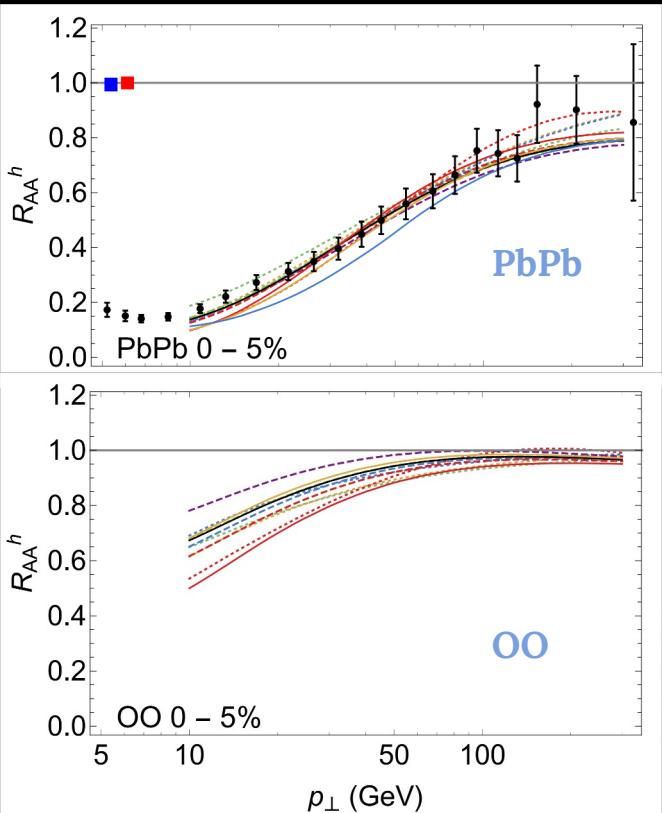


Caveat:  
Centrality  
determination  
is non-trivial  
(see backups)

Enhanced energy  
loss near  $T_c$

Higher-twist  
energy loss

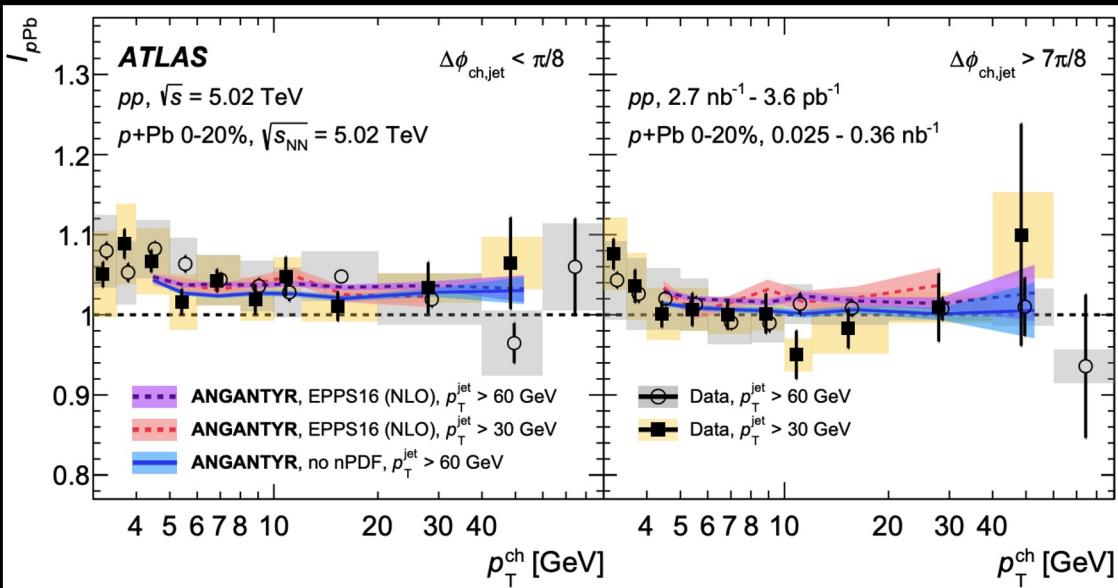
# Lighter ions



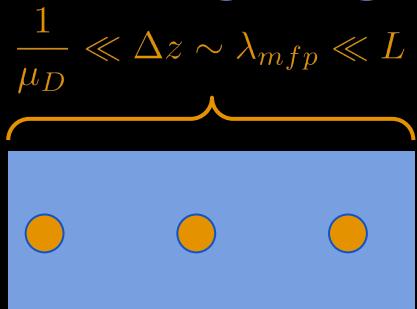
# No quenching?

ANGANTYR with  
string-shoving OFF

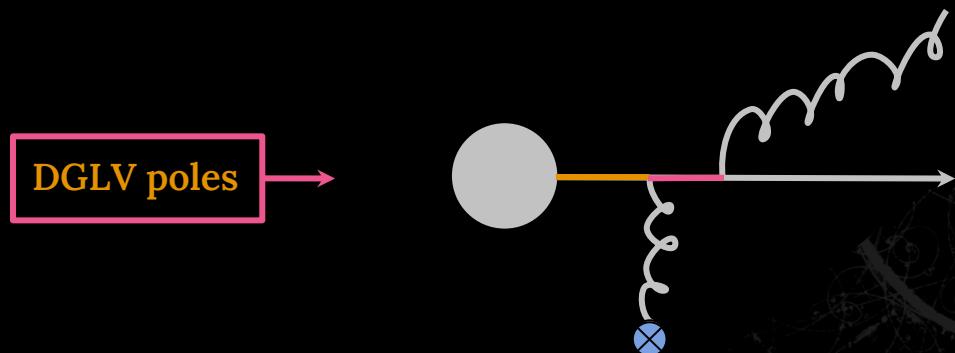
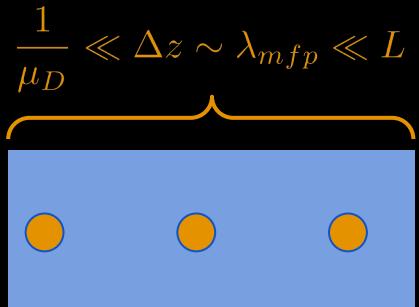
Caveat: 0-20% bin in  
pPb is quantitatively  
different to 0-5%



# Relaxing large-L approximation

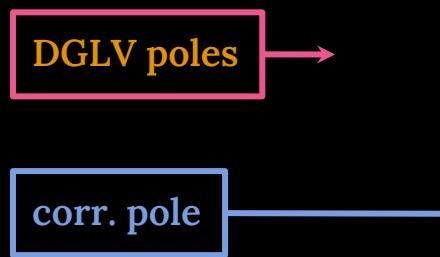


# Relaxing large- $L$ approximation



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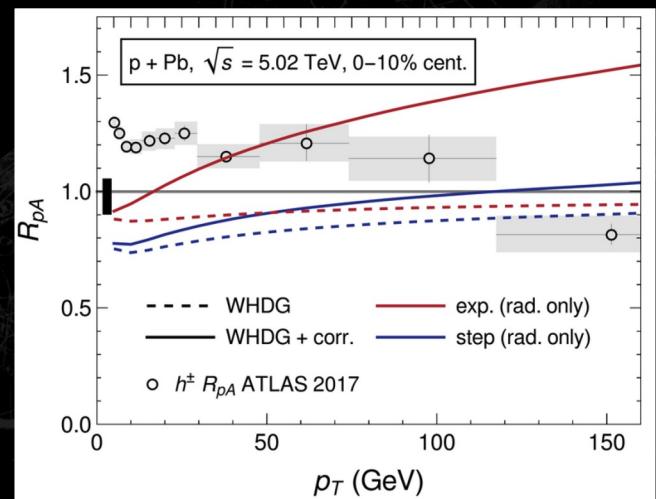
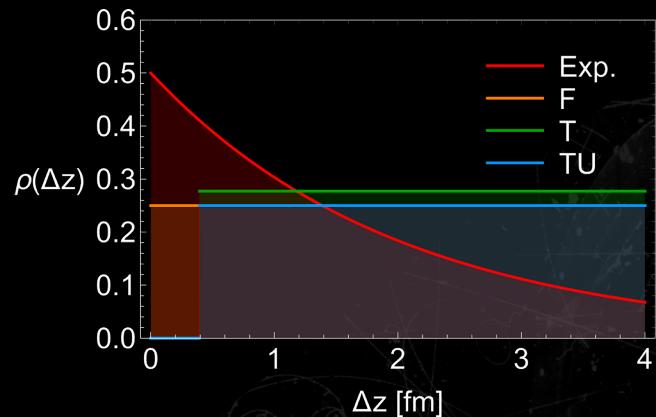
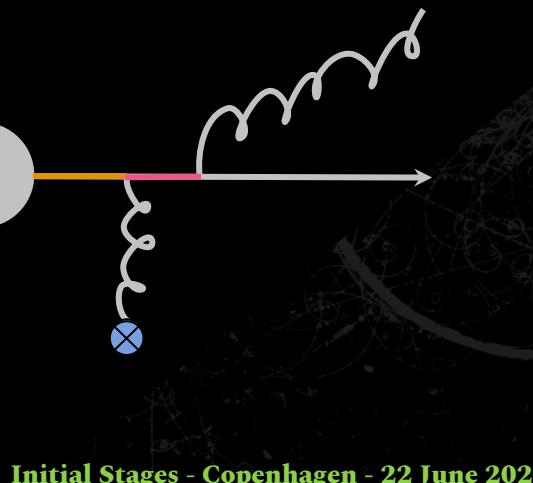
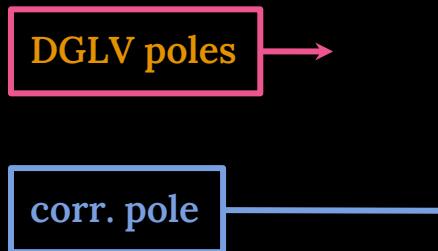
$$\frac{1}{\mu_D} \ll \Delta z \sim \lambda_{mfp} \ll L$$
$$\frac{1}{\mu_D} \ll \lambda_{mfp}$$



# Relaxing large- $L$ approximation

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

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



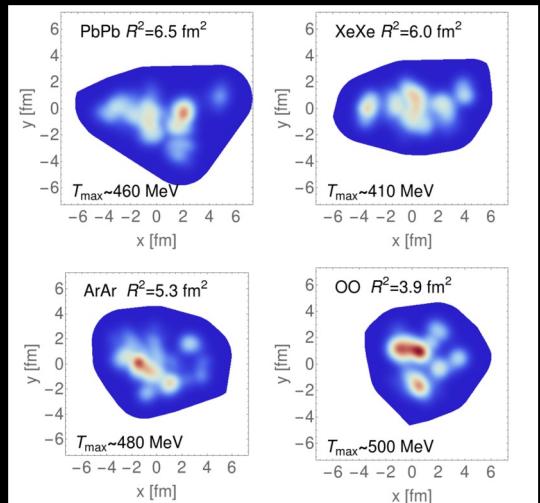
# Small is not the only problem

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



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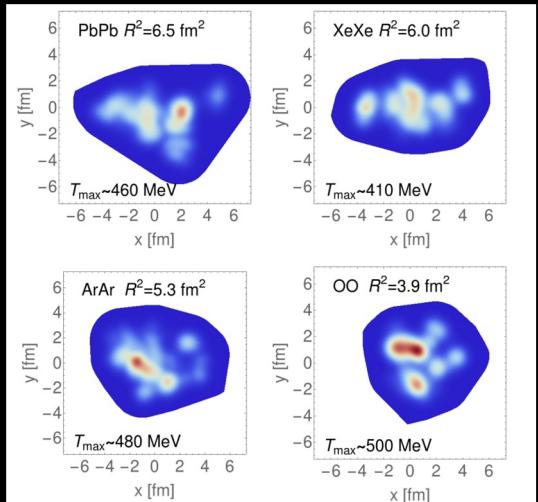


Smaller systems are hotter at the same multiplicity

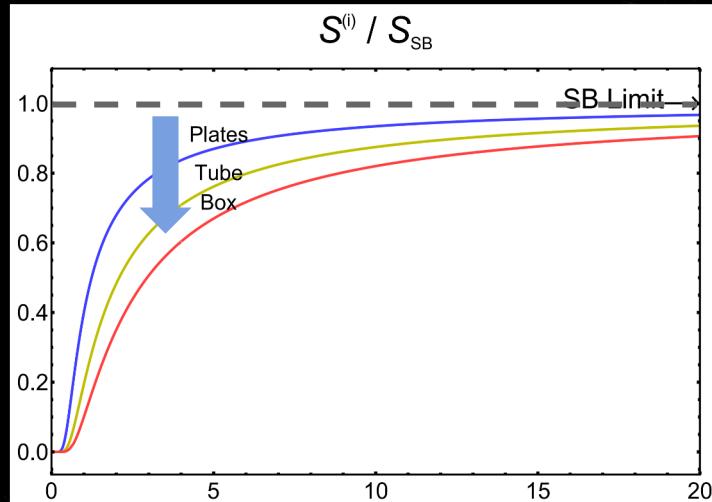
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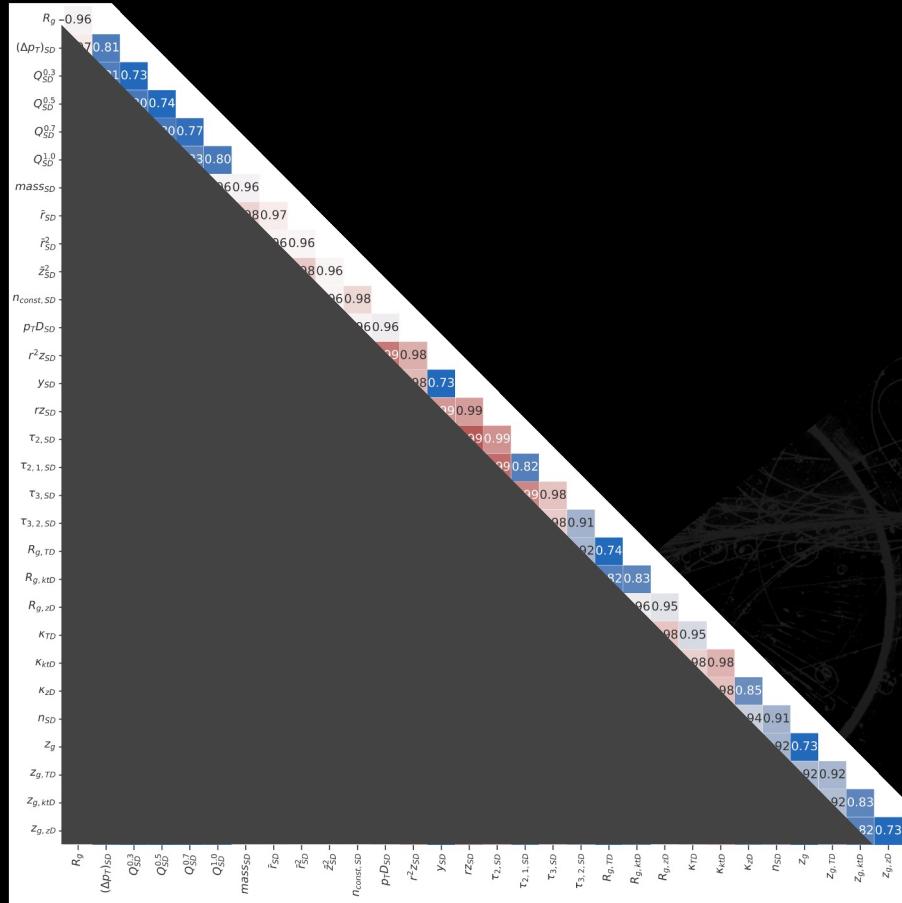


Single, massless, non-interacting, scalar field in a finite box

# The future of quenching studies in small systems

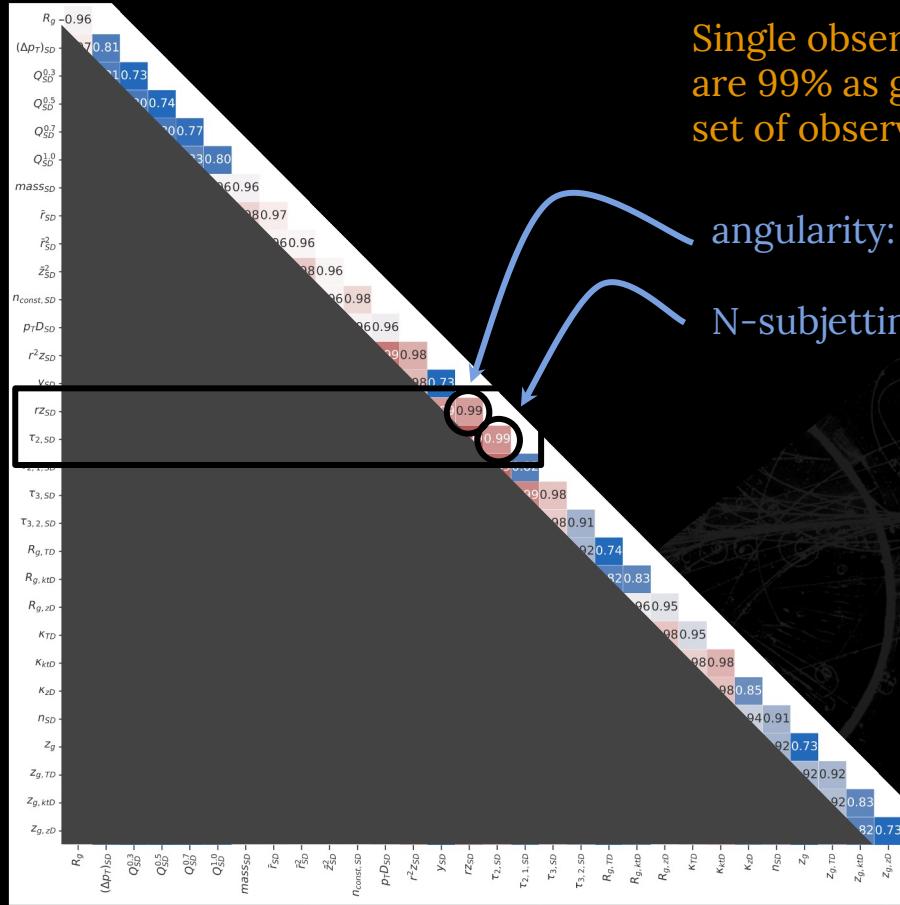
# Beyond $R_{AA}$

- (1) Train a BDT on all observables to distinguish quenched from unquenched
- (2) cf single and pairs of observables



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- (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

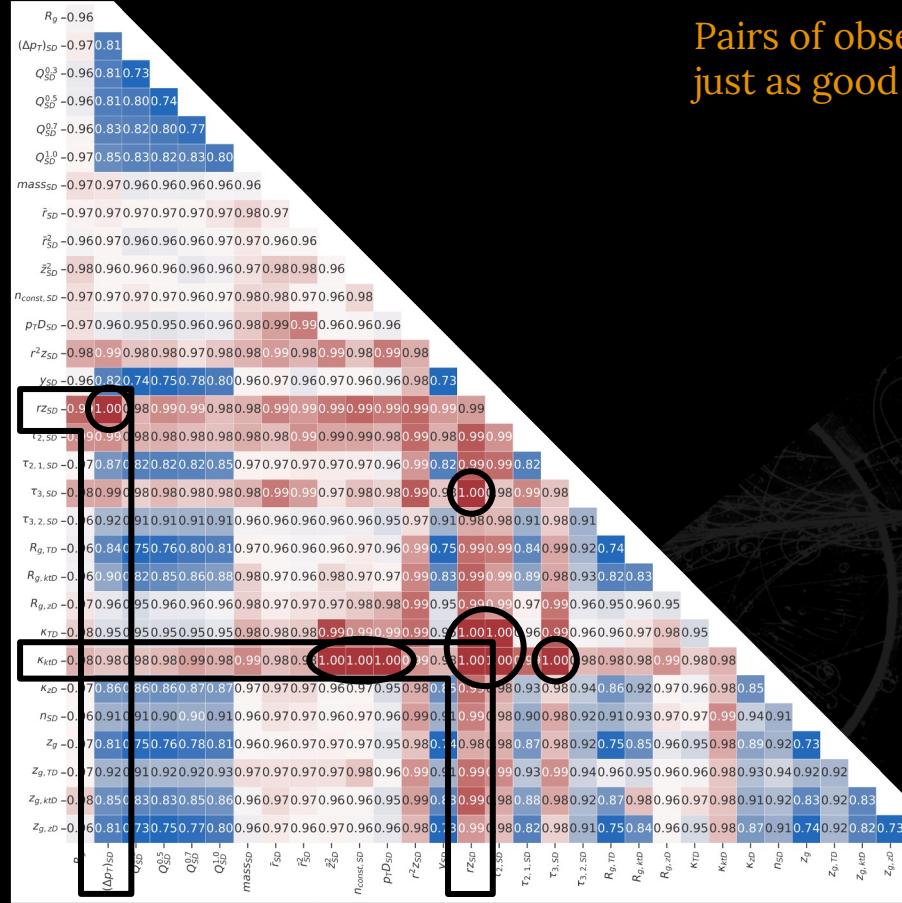
angularity:  $r z_{SD} = \lambda_{1,SD}^1$

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

# Beyond $R_{AA}$

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

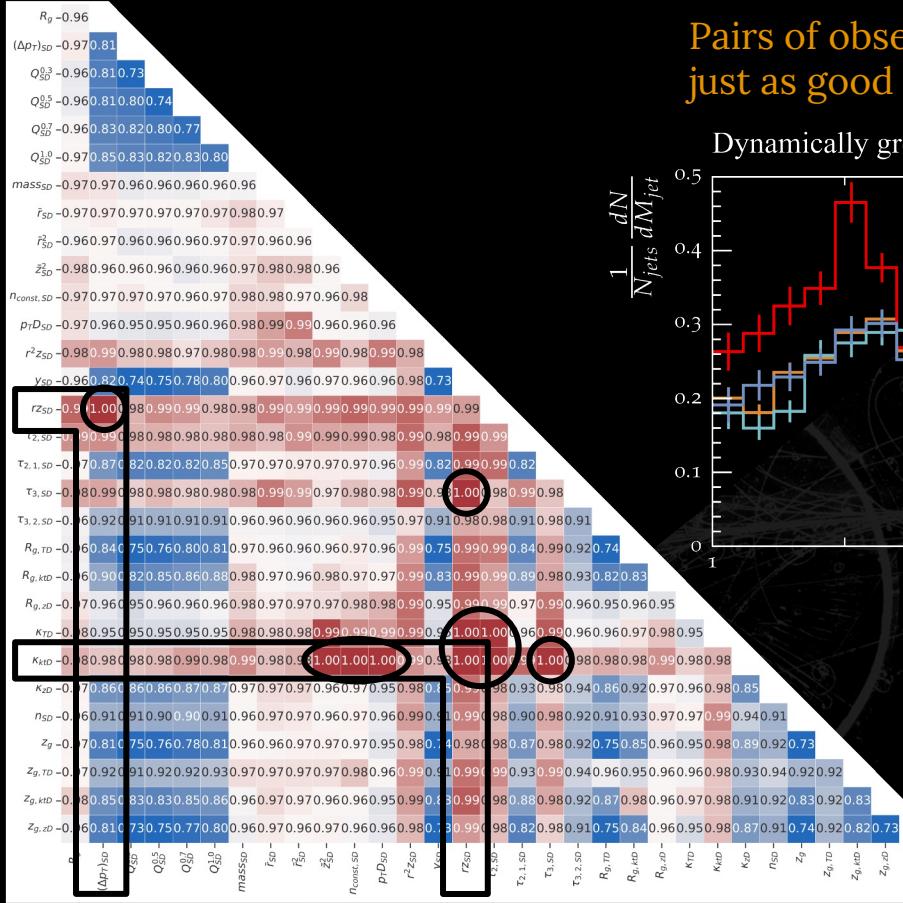
(2) cf single and pairs  
of observables



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

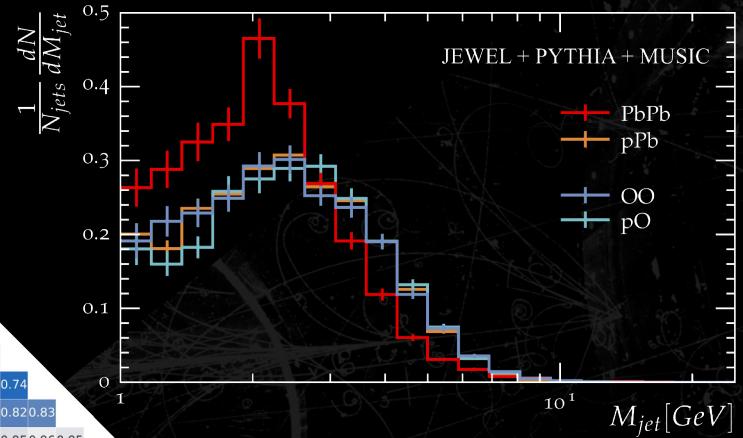
# Beyond $R_{AA}$

- (1) Train a BDT on all observables to distinguish quenched from unquenched
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Pairs of observables that are just as good as the full set

Dynamically groomed jets,  $a = 0.1$



JEWEL-2.4.0 on (2+1)D background

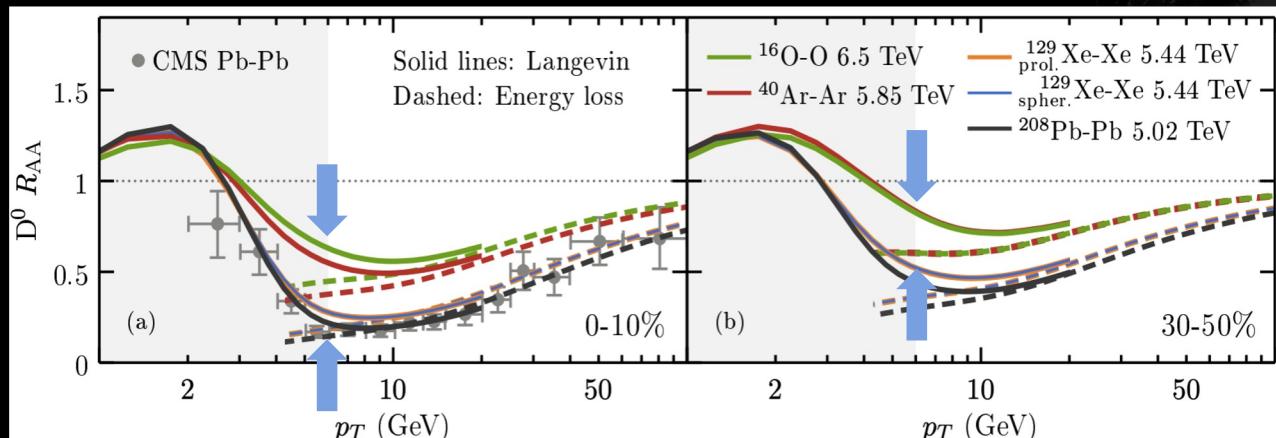
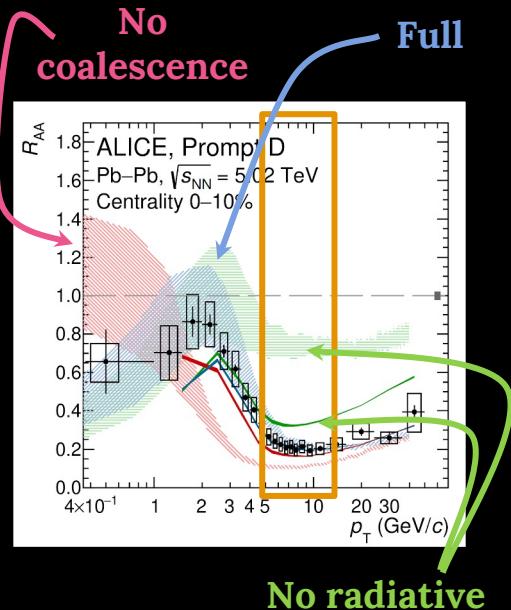
# How can heavy flavor help?

Produced early:

- Easy to tag
- Track evolution

Additional physics

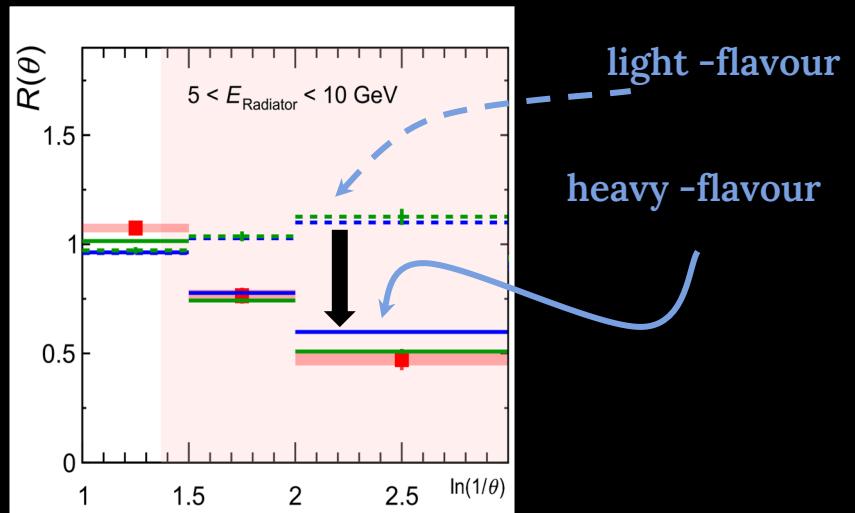
# Heavy flavor and Intermediate $p_T$



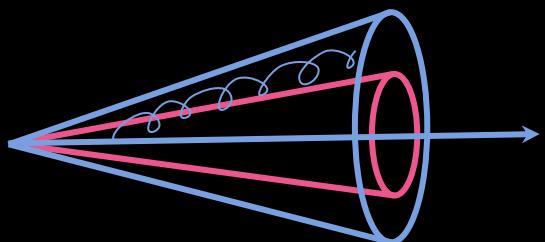
Lower  $p_T$  has more discriminating power between energy-loss mechanisms

Critical in small systems  
NB! Need control over centrality

# The dead cone

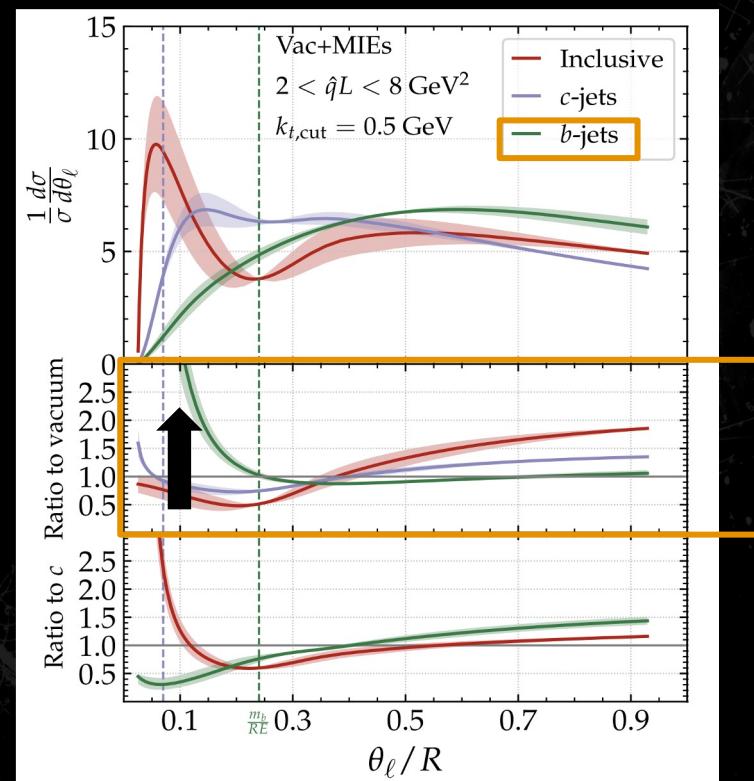
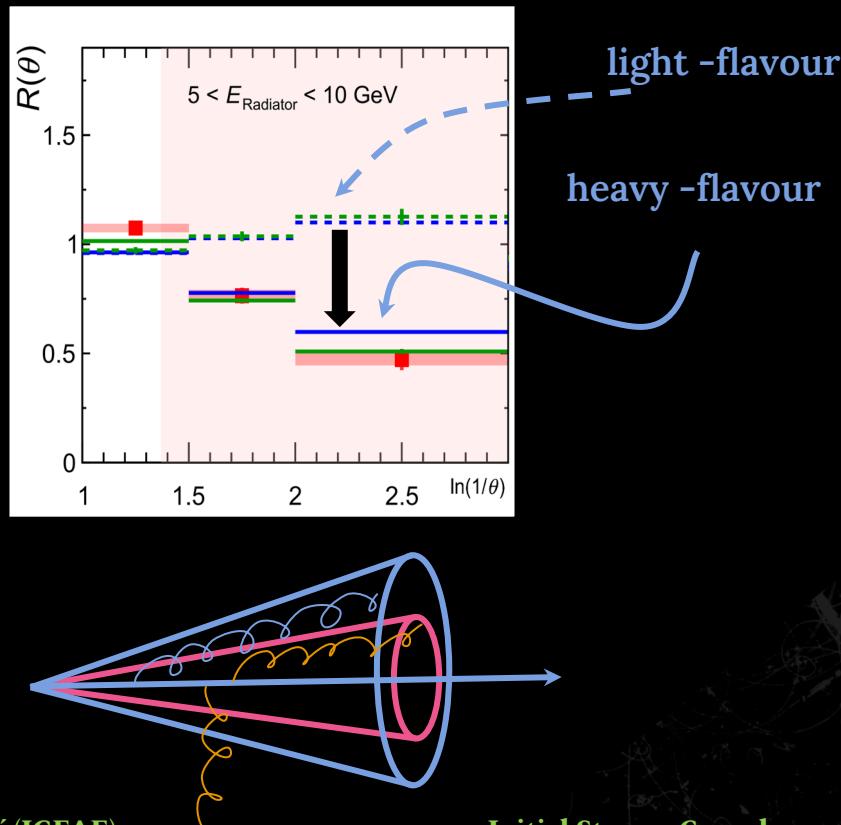


light -flavour  
heavy -flavour



# The dead cone

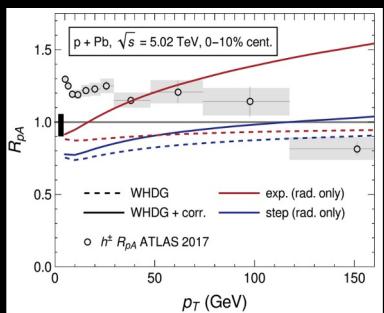
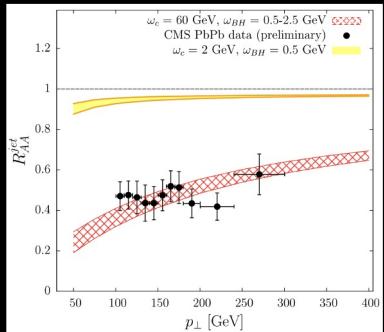
In-medium radiation fills the dead cone



# Summary

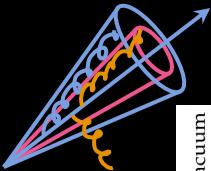
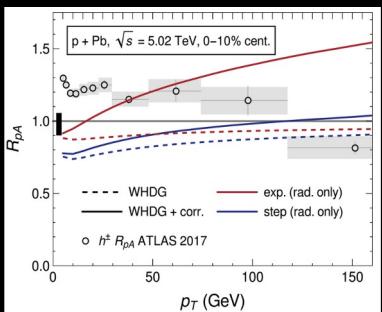
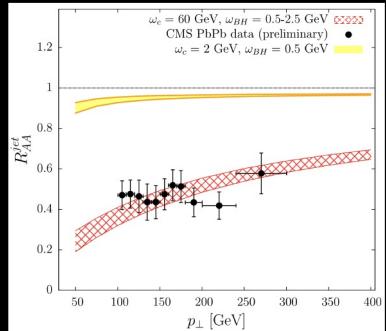
# Summary

Can compute RAA in  
small systems -  
problematic

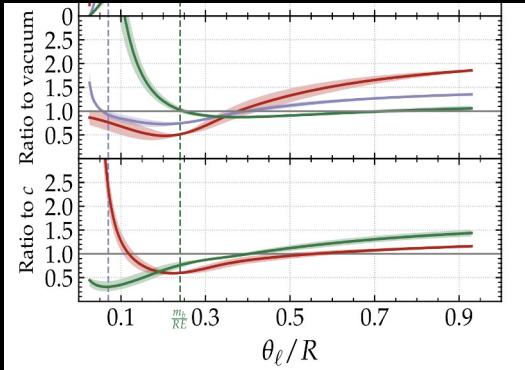


# Summary

Can compute RAA in  
small systems -  
problematic



“New” observables are  
game-changers

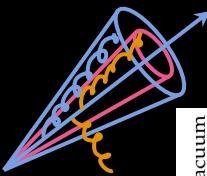
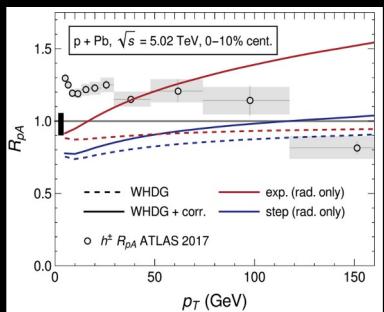
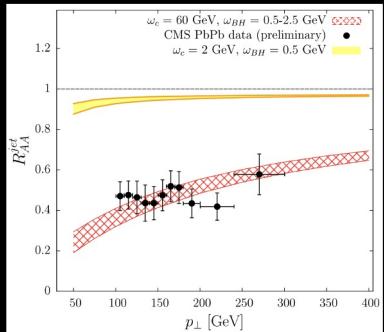


$\kappa_{TD}$	-0.98	0.95	0.95	0.95	0.95	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.95	1.00	1.00	0.96	0.99	0.99
$\kappa_{KD}$	-0.98	0.98	0.98	0.98	0.99	0.98	0.99	0.98	0.98	0.99	0.99	0.99	0.98	1.00	1.00	0.99	1.00	0.99
$K_{SD}$	-0.97	0.86	0.86	0.86	0.87	0.87	0.87	0.90	0.97	0.97	0.97	0.97	0.95	0.98	0.85	0.99	0.98	0.93
$n_{SD}$	-0.96	0.91	0.91	0.91	0.90	0.90	0.91	0.90	0.96	0.97	0.97	0.97	0.96	0.99	0.91	0.99	0.98	0.90
$Z_g$	-0.97	0.81	0.75	0.76	0.78	0.81	0.96	0.96	0.97	0.97	0.97	0.97	0.95	0.98	0.74	0.98	0.98	0.87
$Z_{g, TD}$	-0.97	0.92	0.91	0.92	0.92	0.93	0.97	0.97	0.97	0.97	0.98	0.96	0.99	0.91	0.99	0.99	0.93	0.95
$Z_{g, kTD}$	-0.98	0.85	0.83	0.83	0.85	0.86	0.96	0.97	0.97	0.96	0.96	0.95	0.99	0.83	0.99	0.98	0.89	0.98
$Z_{g, zD}$	-0.96	0.81	0.73	0.75	0.77	0.80	0.96	0.97	0.97	0.96	0.96	0.95	0.99	0.83	0.99	0.98	0.82	0.98

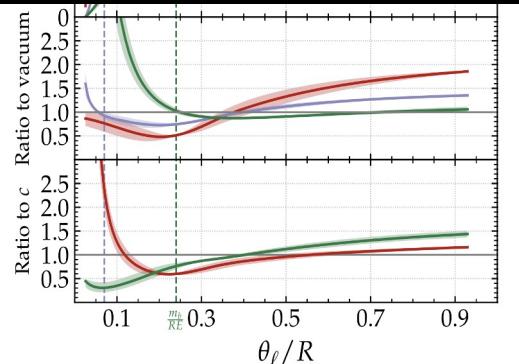


# Summary

Can compute RAA in small systems - problematic

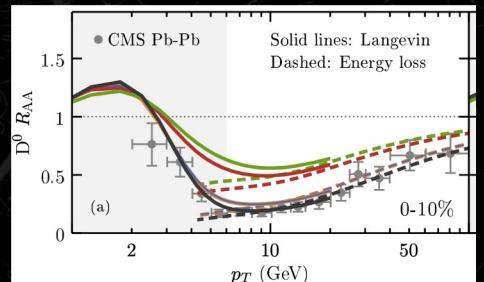
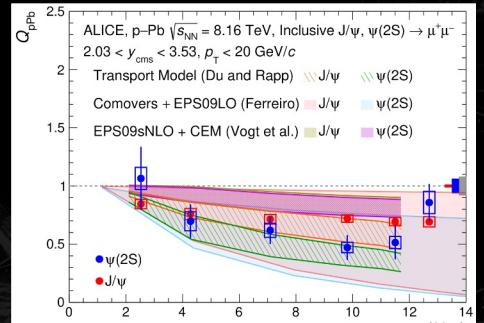


“New” observables are game-changers



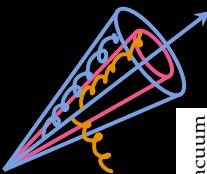
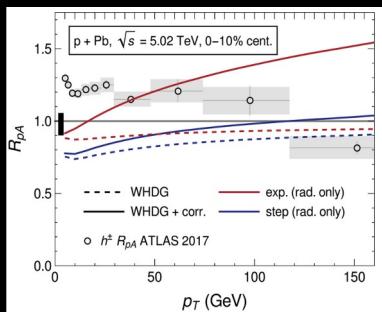
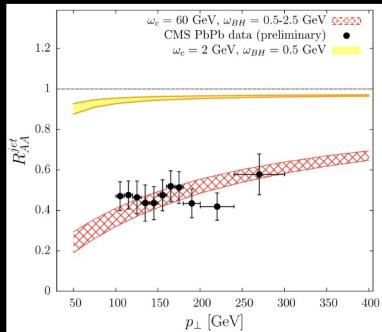
$\kappa_{TD}$	-0.980	0.950	0.950	0.950	0.950	0.980	0.980	0.980	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	
$\kappa_{KD}$	-0.980	0.980	0.980	0.990	0.980	0.990	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	
$K_{SD}$	-0.970	0.860	0.860	0.860	0.870	0.870	0.870	0.870	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970	
$n_{SD}$	-0.960	0.910	0.910	0.900	0.900	0.910	0.960	0.970	0.970	0.960	0.970	0.960	0.970	0.960	0.990	0.990	0.980	0.990	0.980	0.980	
$Z_g$	-0.970	0.810	0.750	0.760	0.780	0.810	0.960	0.960	0.970	0.970	0.970	0.970	0.950	0.98	0.74	0.980	0.980	0.870	0.980	0.980	
$Z_{g,TD}$	-0.970	0.920	0.910	0.920	0.920	0.930	0.970	0.970	0.970	0.970	0.980	0.96	0.99	0.91	0.990	0.990	0.93	0.95	0.95	0.95	
$Z_{g,KD}$	-0.980	0.850	0.830	0.830	0.850	0.860	0.960	0.970	0.970	0.960	0.960	0.950	0.99	0.83	0.99	0.980	0.89	0.980	0.980	0.980	
$Z_{g,zD}$	-0.960	0.810	0.730	0.750	0.770	0.800	0.960	0.970	0.970	0.960	0.960	0.960	0.98	0.730	0.990	0.980	0.82	0.980	0.980	0.980	
$R_g$	( $\Delta p_T/z_0$ )	$Q_{SD}^{0.3}$	$Q_{SD}^{0.5}$	$Q_{SD}^{0.7}$	$Q_{SD}^{0.9}$	$mass_{SD}$	$\tilde{f}_{SD}$	$\tilde{f}_{SD}^2$	$\tilde{z}_{SD}$	$\rho D_{SD}$	$r^2 z_{SD}$	$y_{SD}$	$r z_{SD}$	$T_{2,SD}$	$T_{3,SD}$	$T_{4,SD}$	$T_{5,SD}$	$T_{6,SD}$	$T_{7,SD}$	$T_{8,SD}$	$T_{9,SD}$

Heavy flavor will be key:  
Calibrate CNM & leverage intermediate-  $p_T$

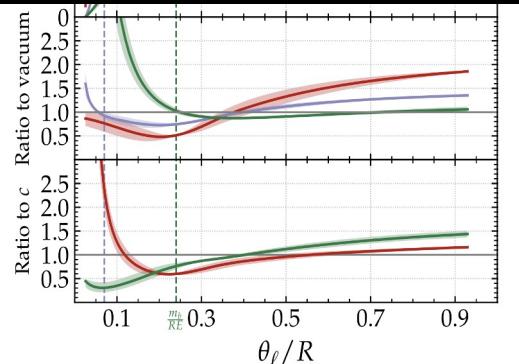


# Summary

Can compute RAA in small systems - problematic



“New” observables are game-changers

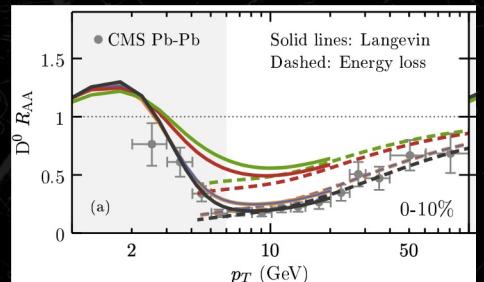
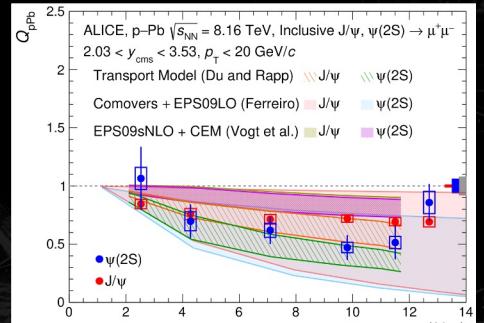


$K_{TD}$	-0.980	0.950	0.950	0.950	0.950	0.980	0.980	0.980	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990
$K_{SD}$	-0.980	0.980	0.980	0.990	0.980	0.990	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980
$K_{Zg}$	-0.970	0.860	0.860	0.860	0.870	0.870	0.870	0.870	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970	0.970
$n_{SD}$	-0.960	0.910	0.910	0.900	0.900	0.910	0.960	0.970	0.970	0.960	0.970	0.960	0.990	0.91	0.990	0.980	0.900	0.980	0.980
$Z_g$	-0.97	0.810	0.750	0.760	0.780	0.81	0.960	0.960	0.970	0.970	0.970	0.970	0.950	0.98	0.74	0.980	0.98	0.87	0.980
$Z_{g, TD}$	-0.970	0.920	0.910	0.920	0.920	0.930	0.970	0.970	0.970	0.970	0.980	0.96	0.99	0.91	0.990	0.990	0.93	0.95	0.95
$Z_{g, kTD}$	-0.980	0.850	0.830	0.830	0.850	0.860	0.960	0.970	0.970	0.960	0.960	0.950	0.99	0.83	0.99	0.980	0.89	0.980	0.980
$Z_{g, zD}$	-0.960	0.810	0.730	0.750	0.770	0.80	0.960	0.970	0.970	0.960	0.960	0.96	0.98	0.73	0.99	0.98	0.82	0.980	0.980

Tusind tak!

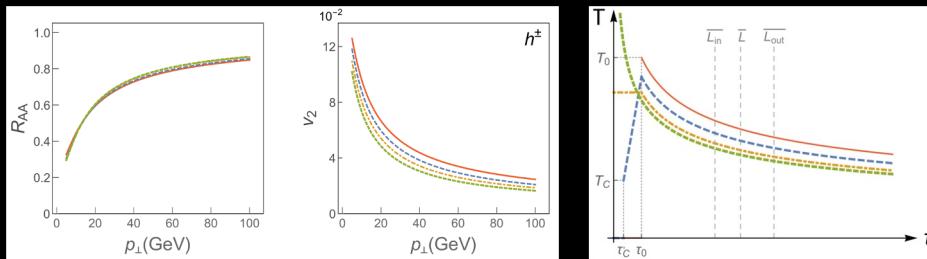
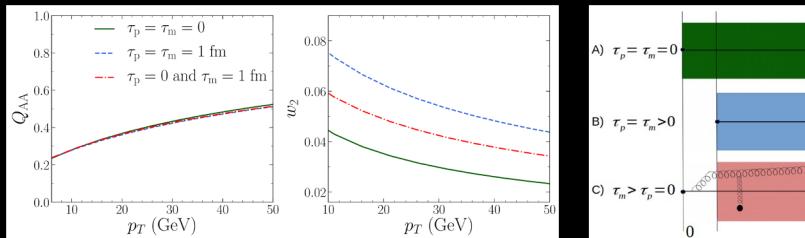
Initial Stages - Copenhagen - 22 June 2023

Heavy flavor will be key:  
Calibrate CNM & leverage intermediate-  $p_T$

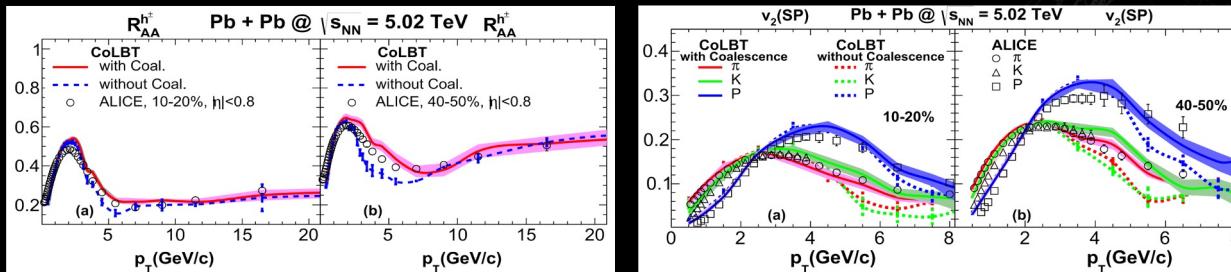


# Backups

# Description of $R_{AA}$ and $v_2$ is non-trivial in AA



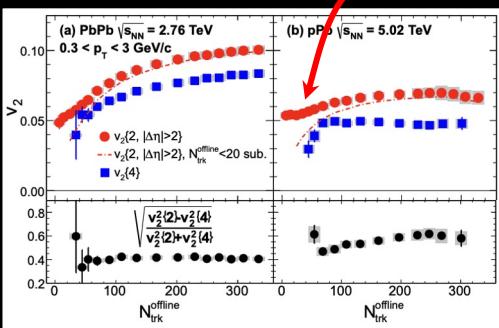
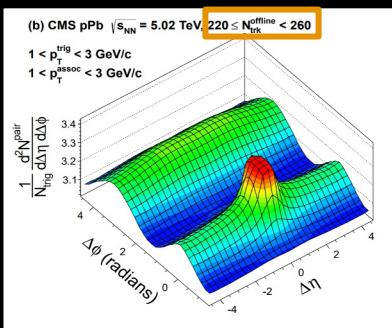
Sensitivity to the nature of radiation in the early stages



Or sensitivity to late-time temperature profile?

Or do you need comprehensive hadronization picture?

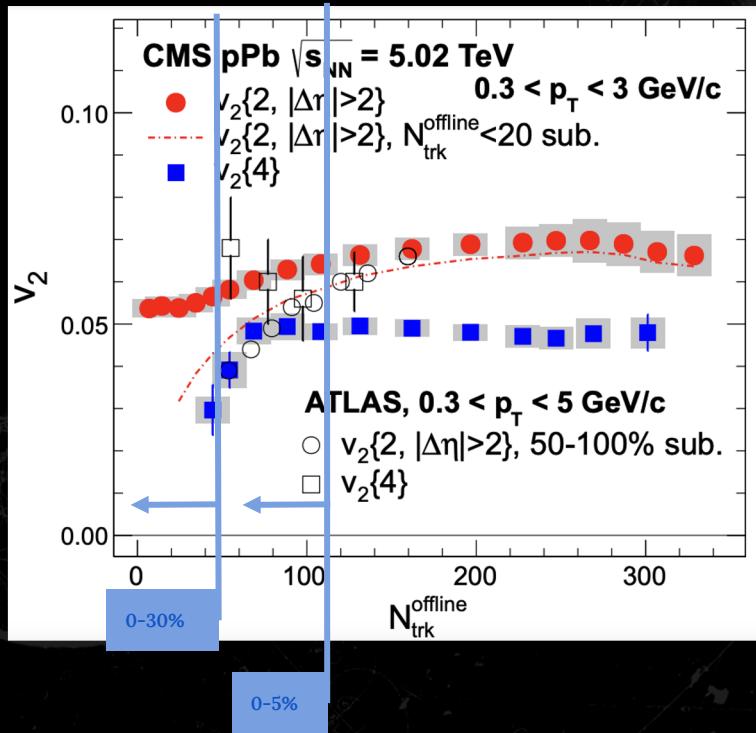
# $R_{AA}$ , $v_2$ , and Centrality



Subtract low mult-data (match ATLAS)

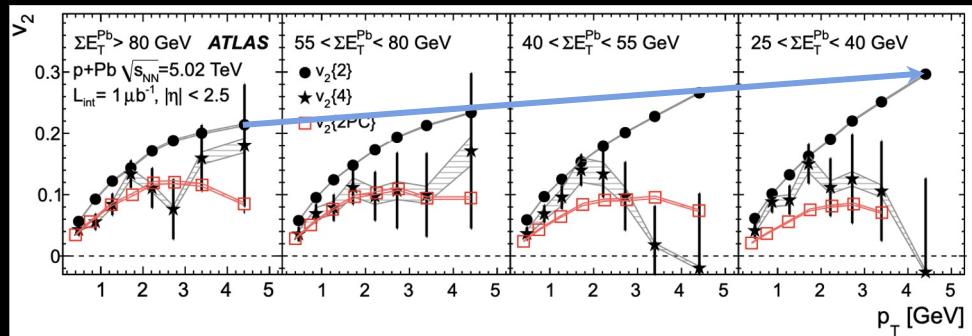
$N_{\text{trk}}$ bin	PbPb data			pPb data		
	$\langle \text{Centrality} \rangle$ ± RMS (%)	$\langle N_{\text{trk}} \rangle$	$\langle N_{\text{corrected}} \rangle$	Fraction	$\langle N_{\text{trk}} \rangle$	$\langle N_{\text{trk}} \rangle$
[0, ∞)	92±4	10	13±1	1.00	40	50±2
[0, 20)	92±4	10	13±1	0.31	10	12±1
[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	210±9	0.03	109	132±6
[120, 150)	67±3	134	253±11	0.02	132	159±7
[150, 185)	64±3	167	4 × 10 <sup>-3</sup>	162	195±9	
[185, 220)	62±2	202	5 × 10 <sup>-4</sup>	196	236±10	
[220, 260)	59±2	239	299±13	6 × 10 <sup>-5</sup>	232	280±12
[260, 300)	57±2	279	350±15	3 × 10 <sup>-6</sup>	271	328±14
[300, 350)	55±2	324	405±18	1 × 10 <sup>-7</sup>	311	374±16

0-0.00631% bin



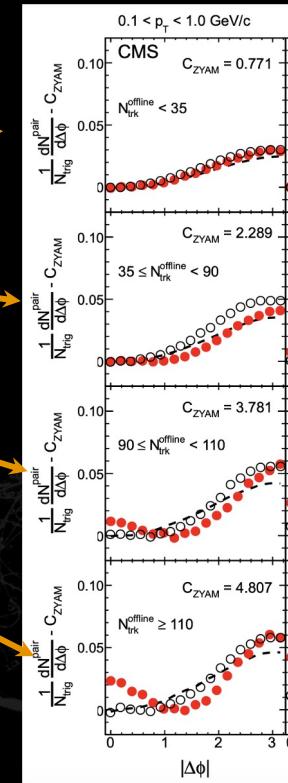
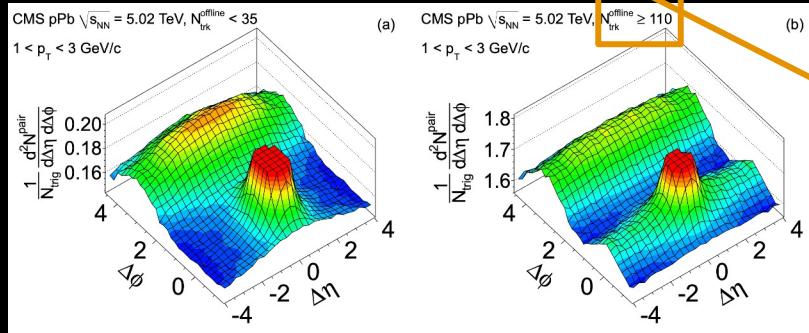
# $R_{AA}$ , $v_2$ , and Centrality (Alternative - ATLAS)

$\Sigma E_T^{\text{Pb}}$ range [GeV]	$\langle \Sigma E_T^{\text{Pb}} \rangle$ [GeV]	range in fraction of events [%]	$\langle N_{\text{ch}}^{\text{rec}} \rangle$ (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)

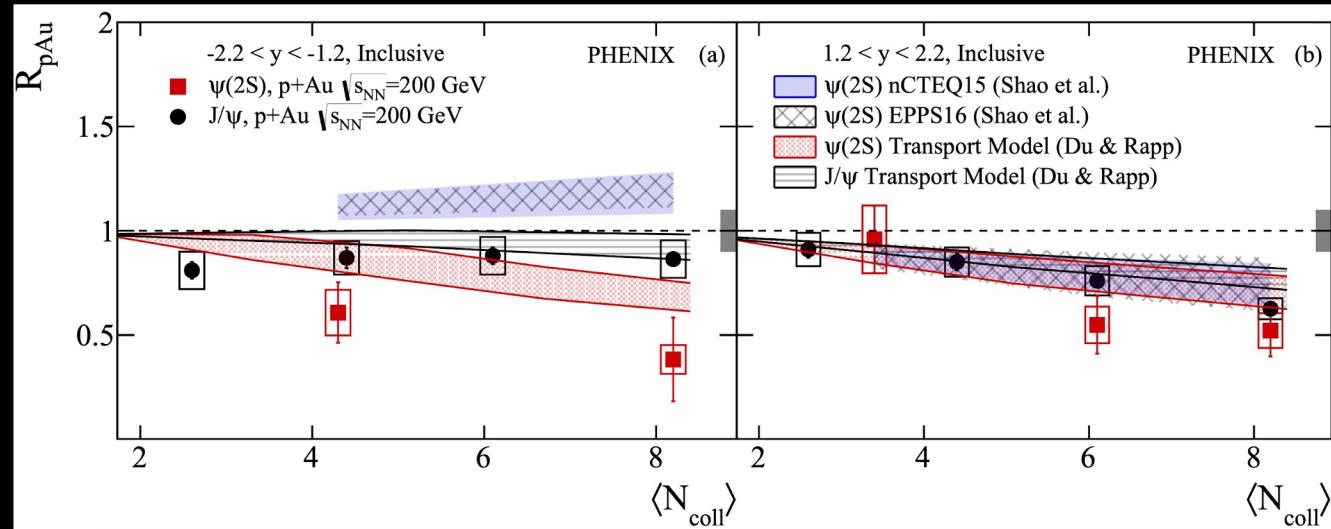


# $R_{AA}$ , $v_2$ , and Centrality (Alternative - peripheral)

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

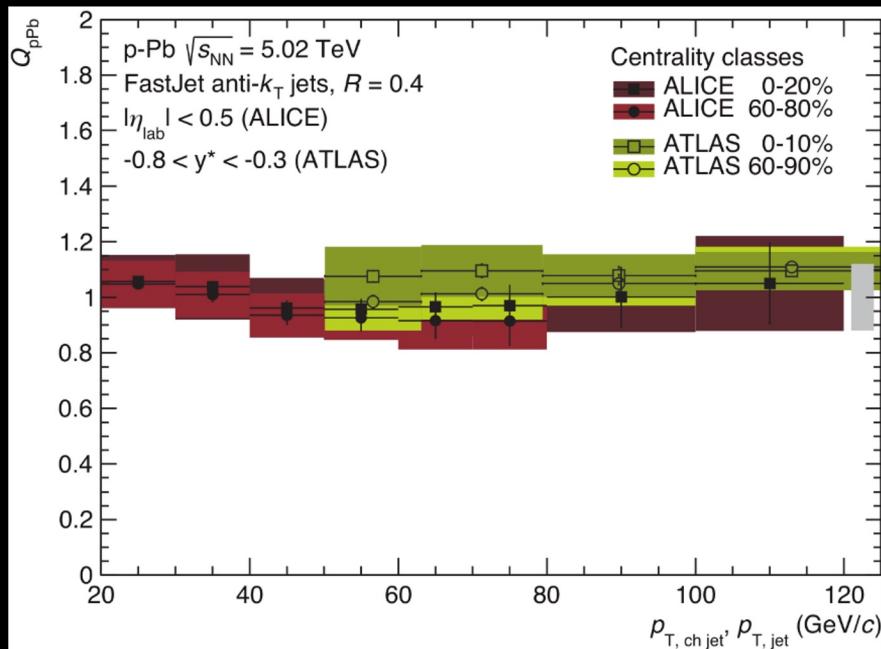


# Sequential $J/\psi$ and $\psi(2S)$



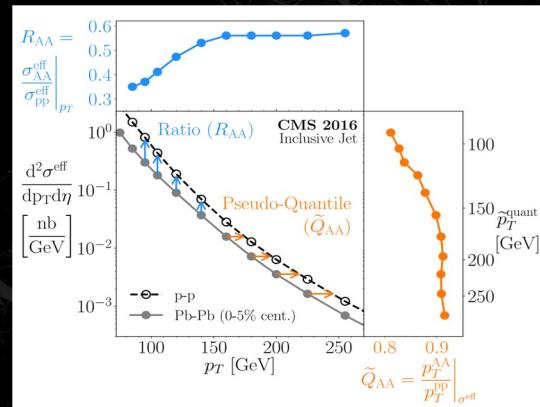
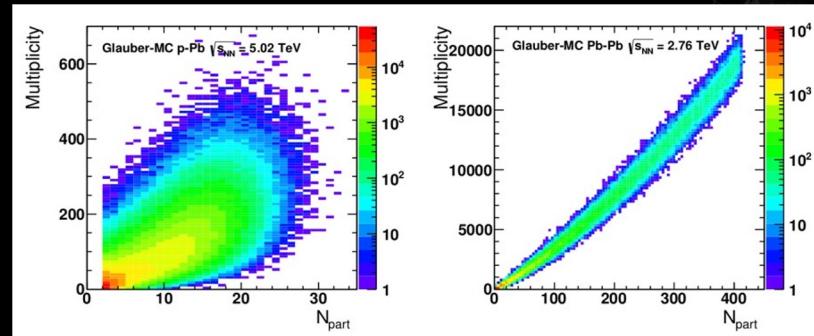
PHENIX Pb-going direction shows separation between  $J/\psi$  and  $\psi(2S)$

# $R_{AA}$ in p-Pb

ALICE: *Eur Phys J C* 76 (2016) 5, 271

# Why $R_{AA}$ is not ideal for small systems

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



# Dead cone prediction in AA

