Heavy-ion phenomenology and small systems at UCT

QGP@Mzansi

Coleridge Faraday
University of Cape Town, South Africa

NITheCS
National Institute for Theoretical and Computational Sciences

National Research Foundation

The Horowitz Group at UCT

We study the high-temperature, multi-particle limit of QCD—the *quark-gluon plasma* (QGP)—with a focus on connecting theory and experiment, QGP formation in small systems, and the foundations of thermal field theory.

Students

PhD: Cole Faraday, Rens Roosenstein

Master's: Nia O'Callaghan, Tiaan van der Merwe, Jack Brand, Jarryd Bath

3rd year: Ditiro Nkuna (graduated)

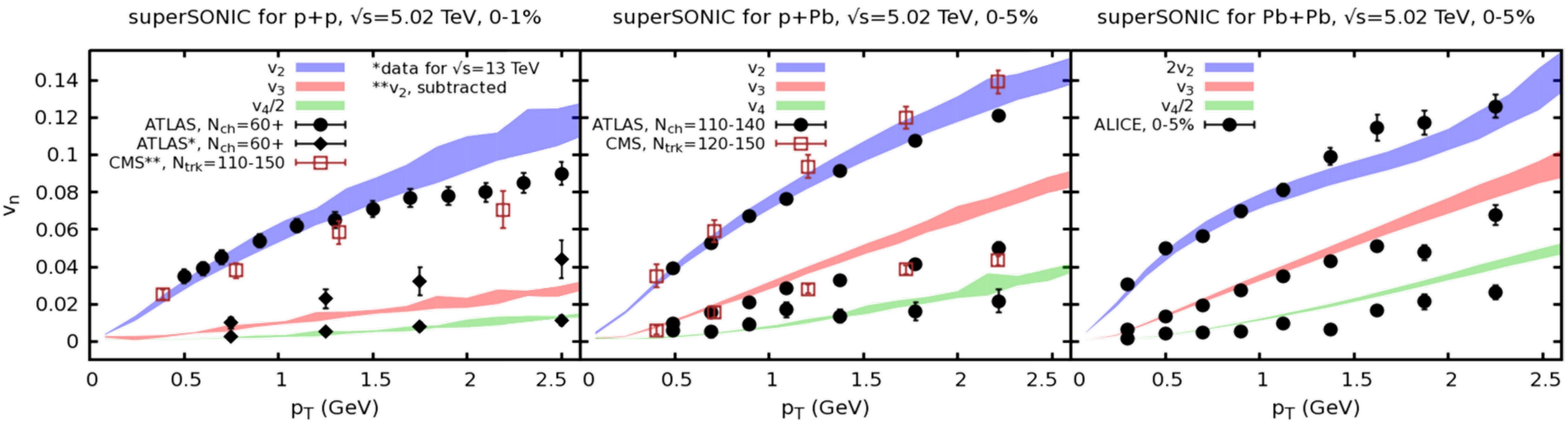
Big questions in small systems

- **Does a quark-gluon plasma form in small systems?**

Big questions in small systems

- **Does a quark-gluon plasma form in small systems?**

Soft observables say… **YES**
… as long as you're at high enough multiplicity



pp *p*Pb PbPb

Weller et al., PLB 774 (2017) 351-356

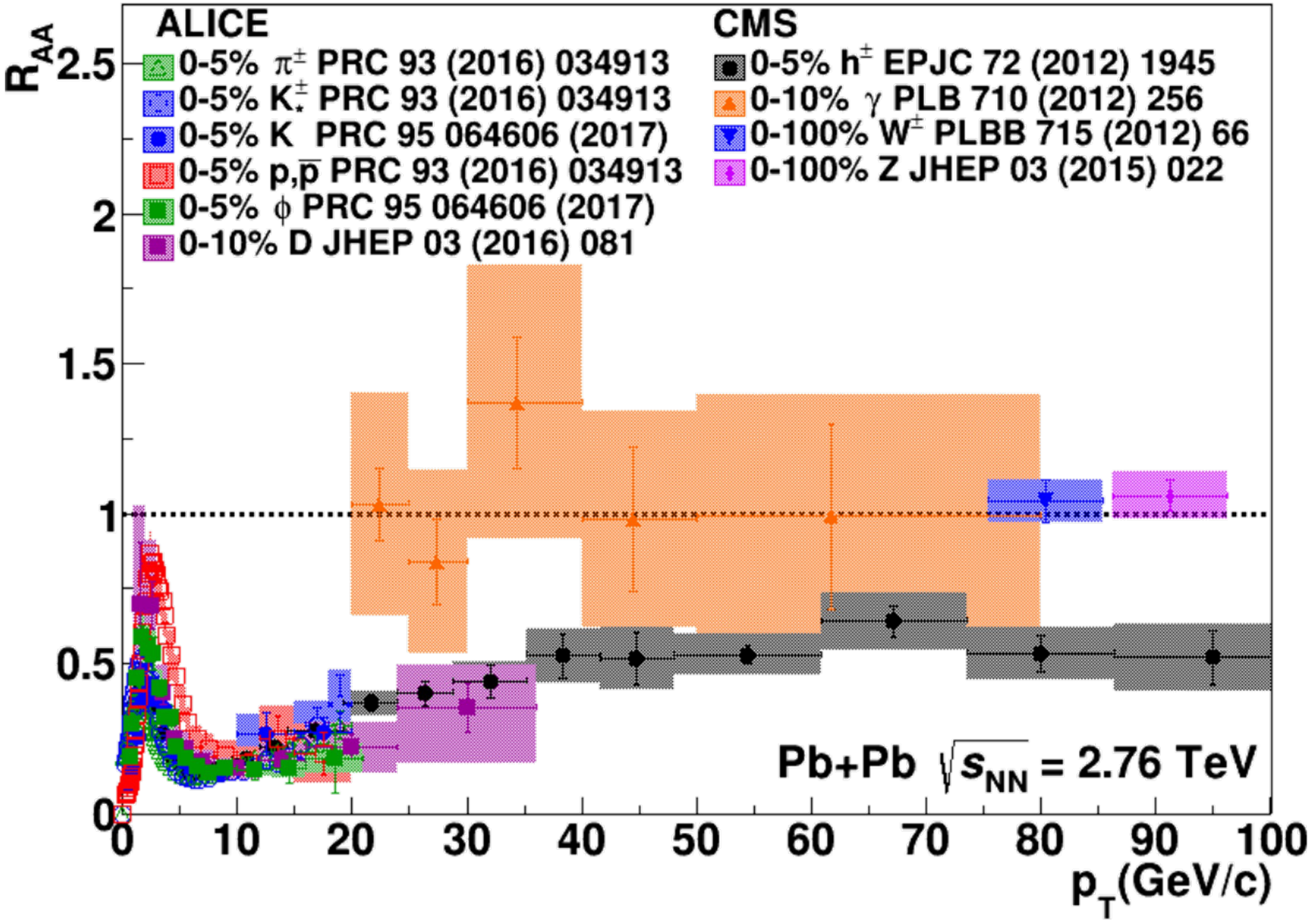
Big questions in small systems

How does this QGP in small systems, if it is formed, differ from that in large systems?

Weller et al., PLB 774 (2017) 351-356

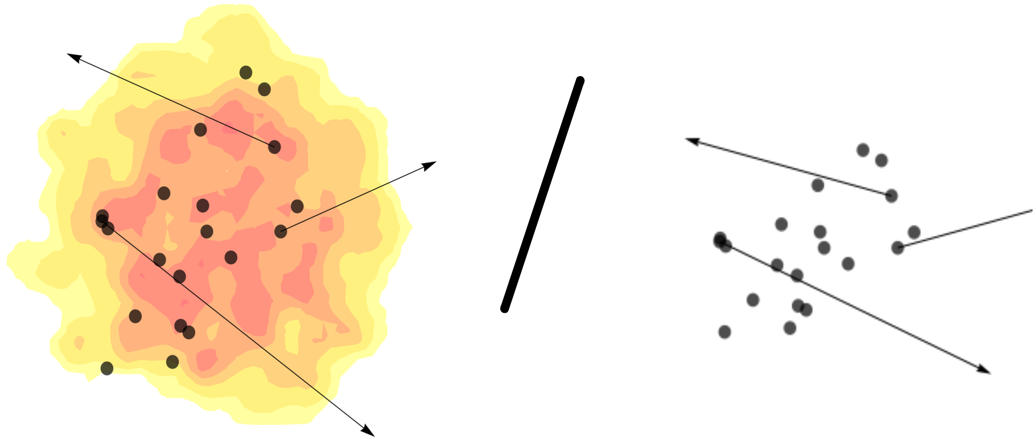
Energy loss in small systems

From large systems, we expect that QGP => partonic energy loss



$$R_{AA}(p_T) = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

$=$



M. Connors, C. Nattrass, R. Reed, and S. Salur, Rev. Mod. Phys. **90**, 025005 (2018).

Energy loss in small systems

From large systems, we expect that QGP => partonic energy loss; however, …

There are mixed signals for energy loss in *p* / *d* + A

ATLAS *JHEP* 07, 074 (2023)

PHENIX *Nature Phys.* 15, 214–220 (2018)

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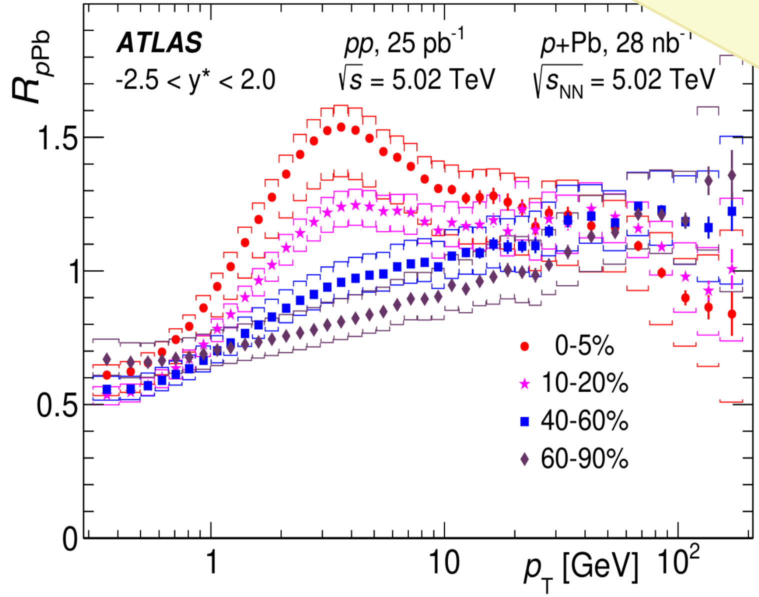
Glauber



No energy loss?

ATLAS *JHEP* 07, 074 (2023)

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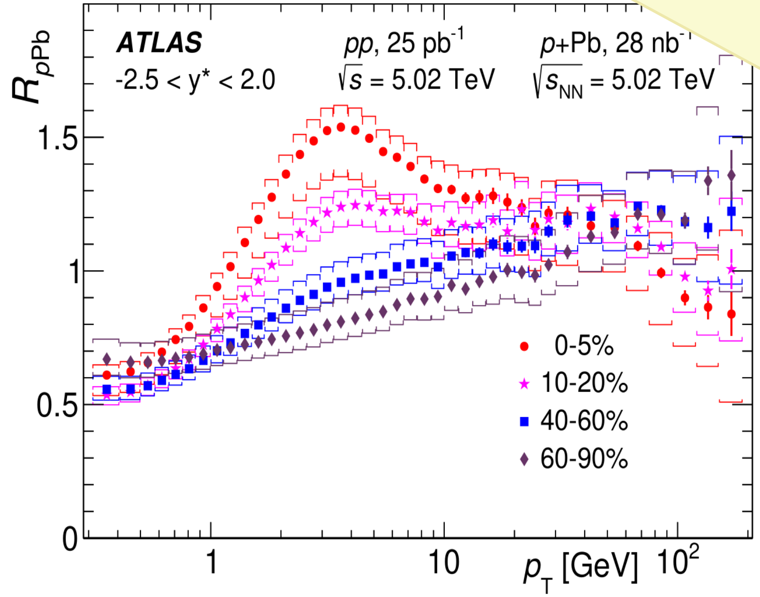
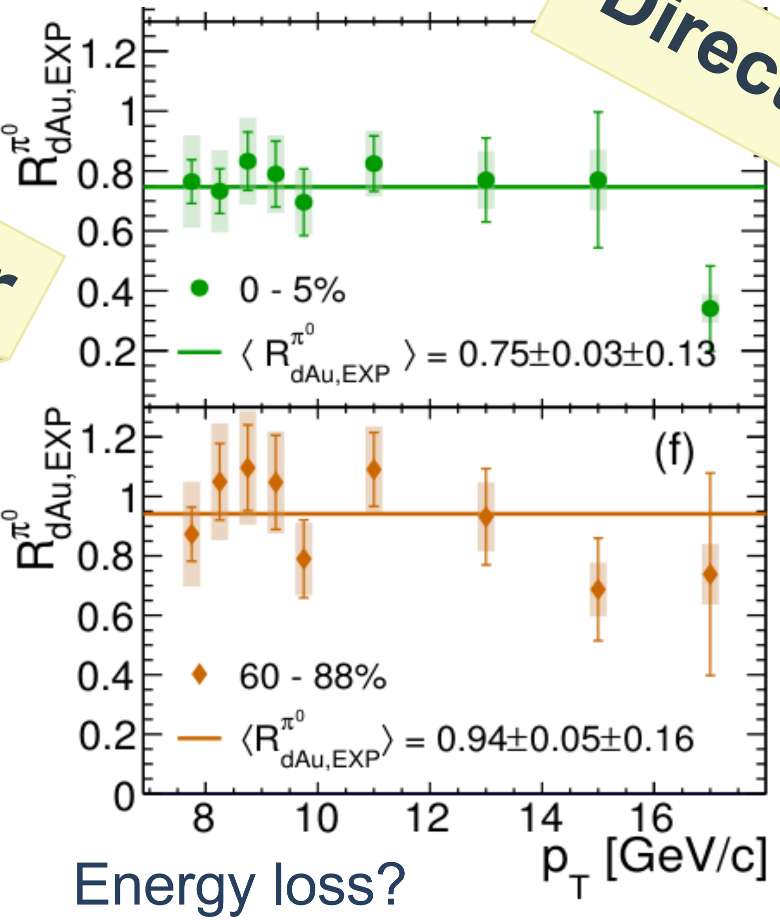


No energy loss?

ATLAS *JHEP* 07, 074 (2023)

Direct γ



Energy loss?

PHENIX *Nature Phys.* 15, 214–220 (2018)

Energy loss in small systems

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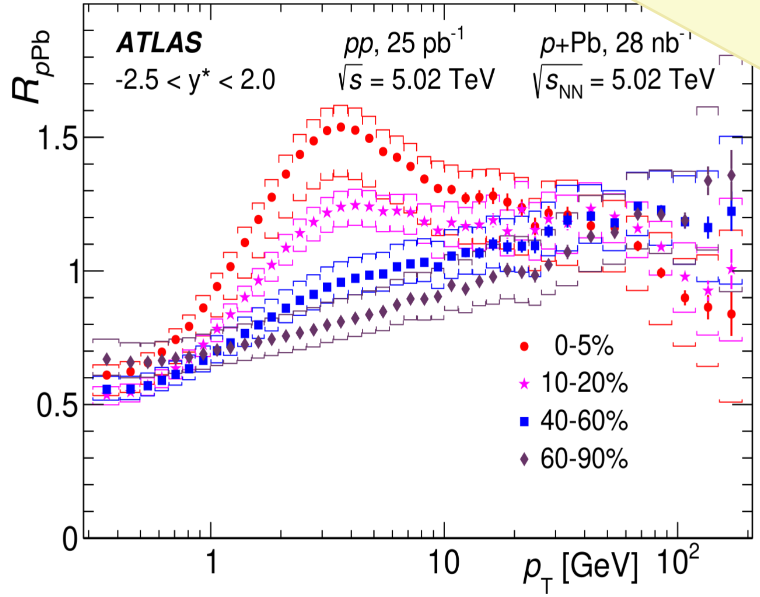

No energy loss?

ATLAS *JHEP* 07, 074 (2023)

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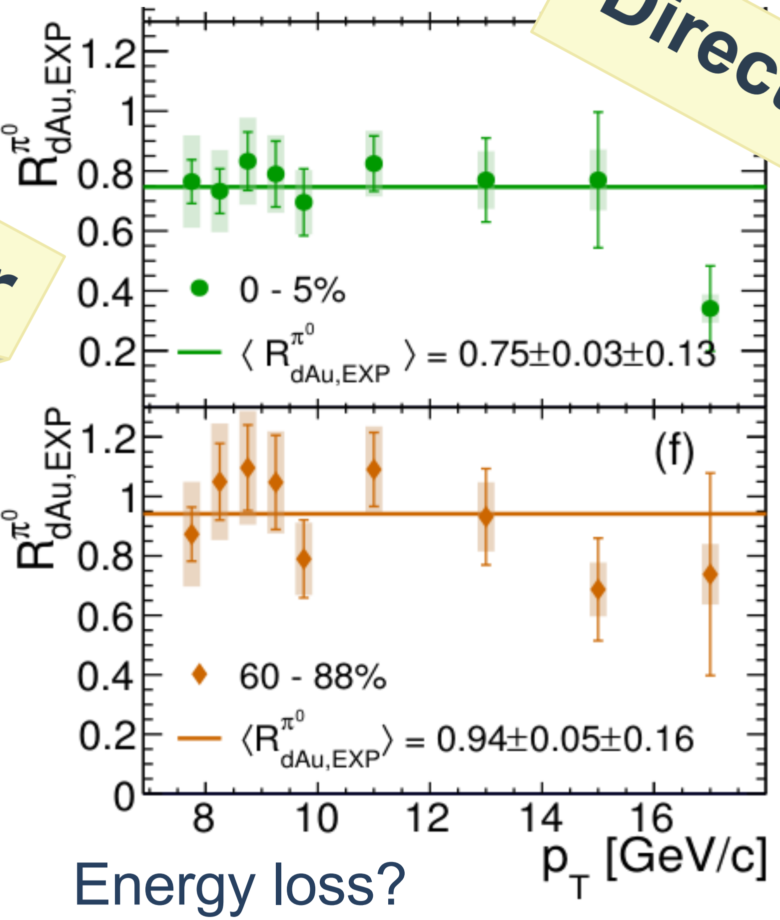
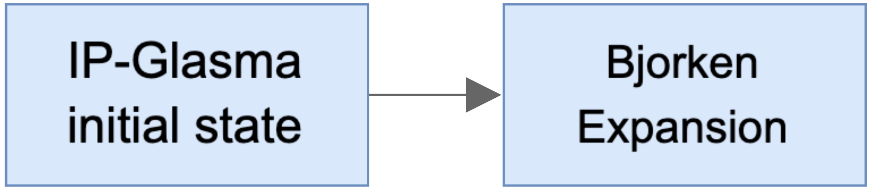


Energy loss?

- **Results are unclear! What to do?**
- **Theoretical input needed!**

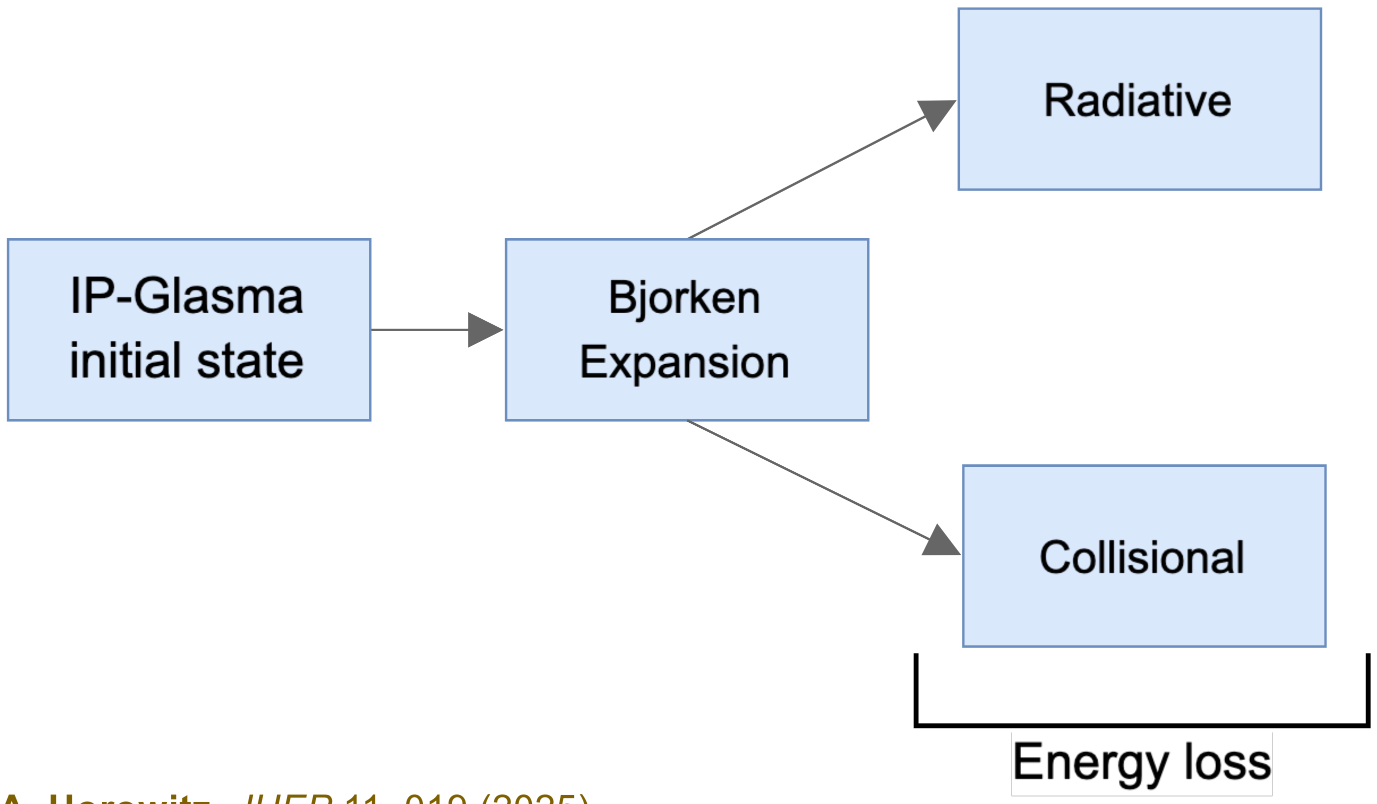
PHENIX *Nature Phys.* 15, 214–220 (2018)

Physics model



CF, W. A. Horowitz, *JHEP* 11, 019 (2025)

Physics model



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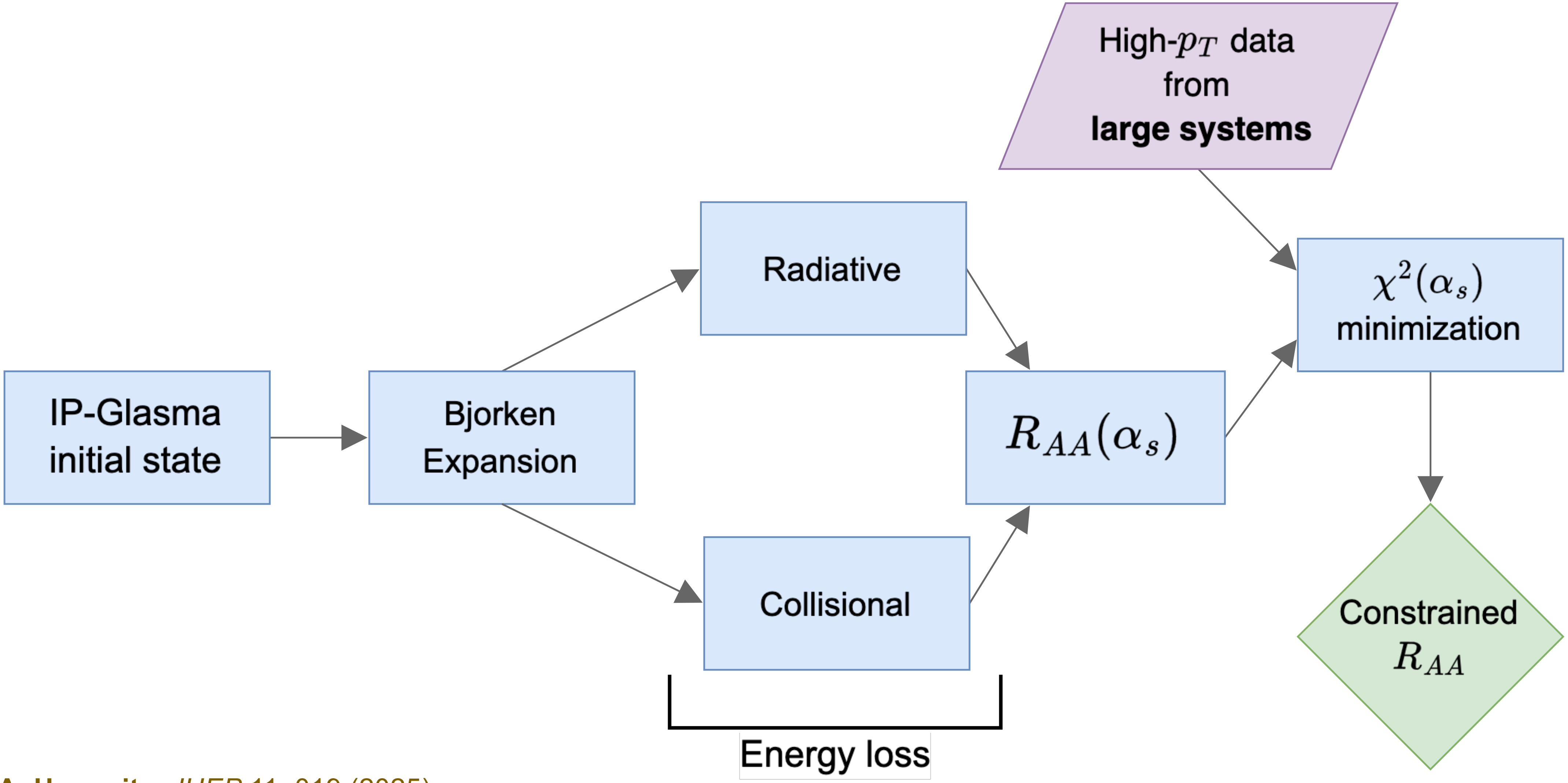

CF, W. A. Horowitz, *JHEP* 11, 019 (2025)

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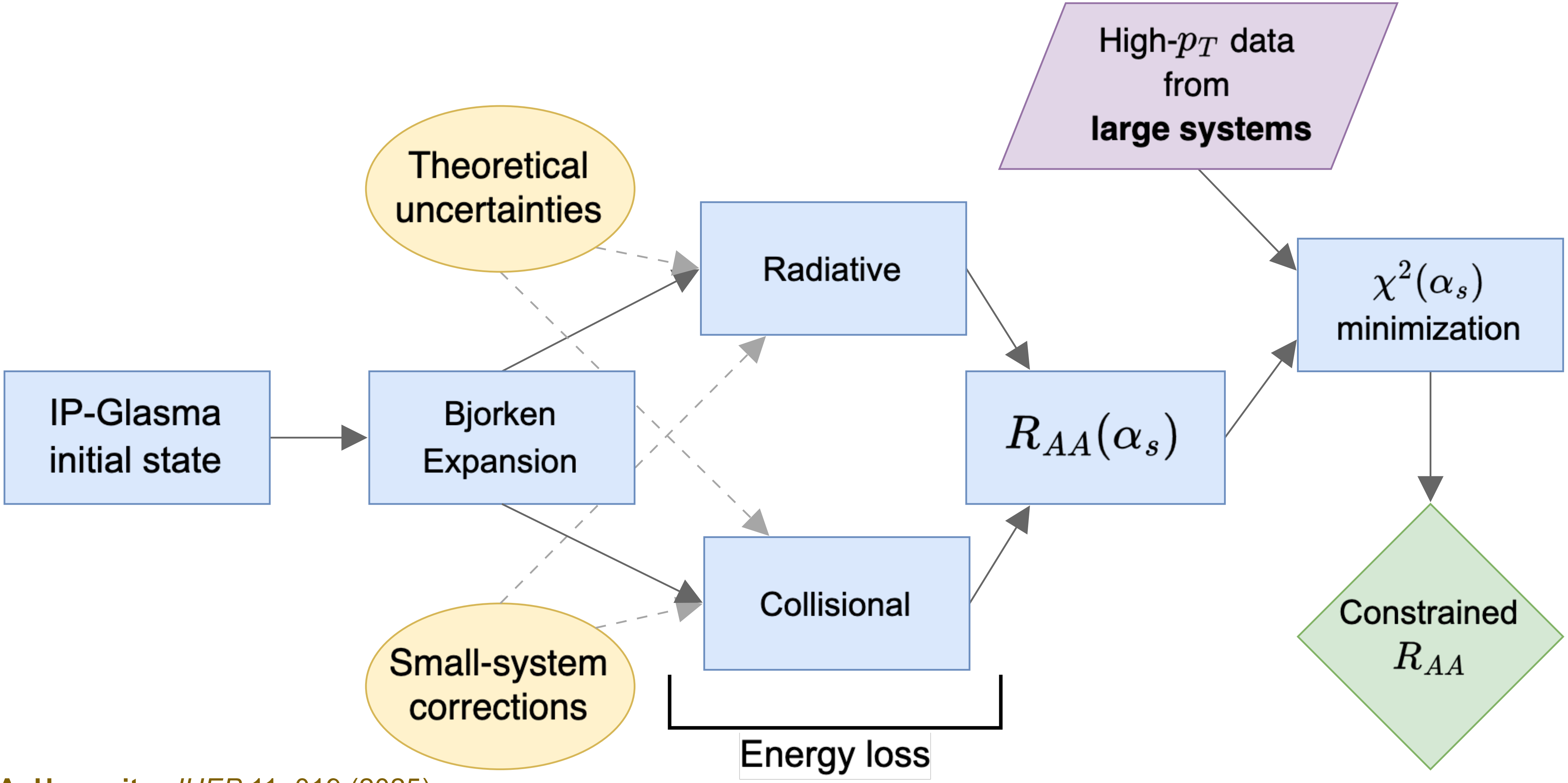
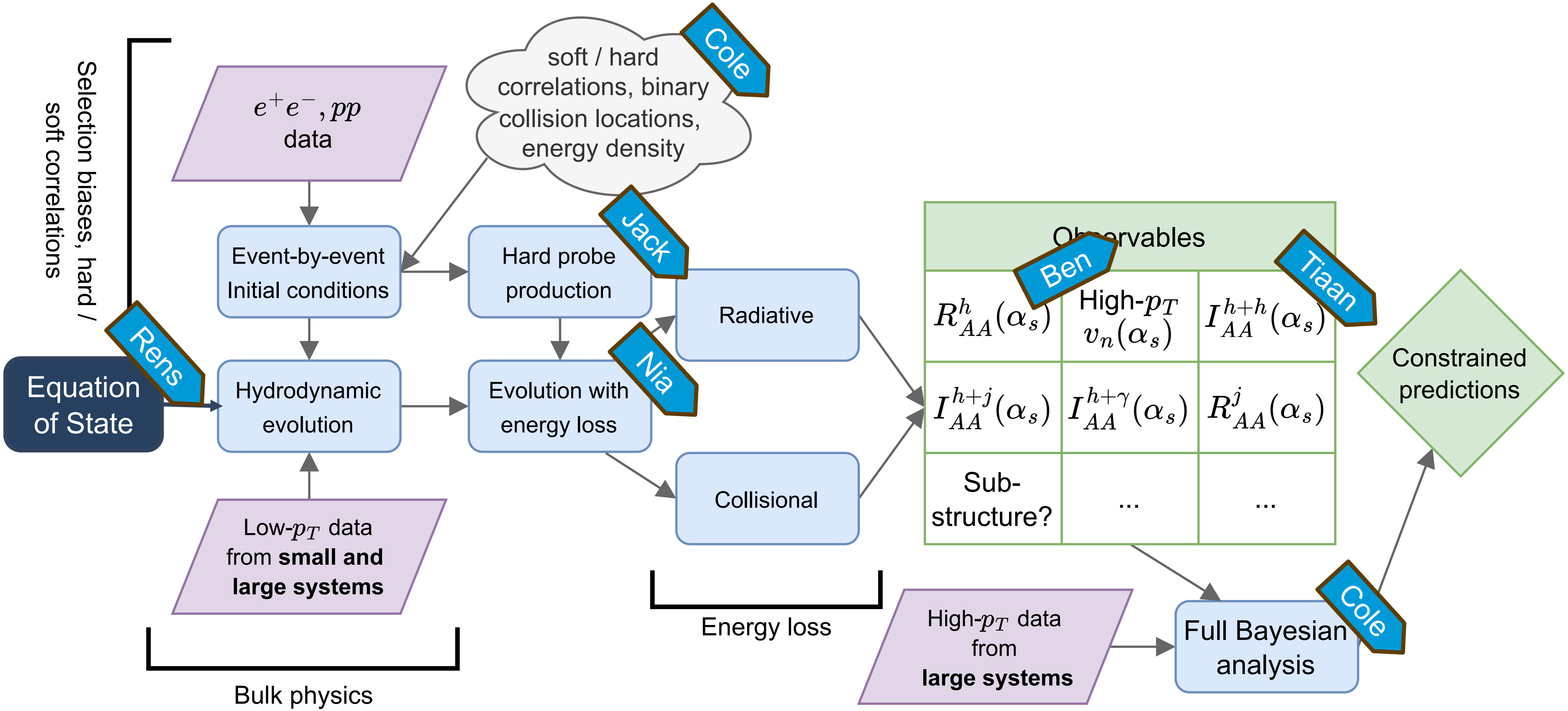
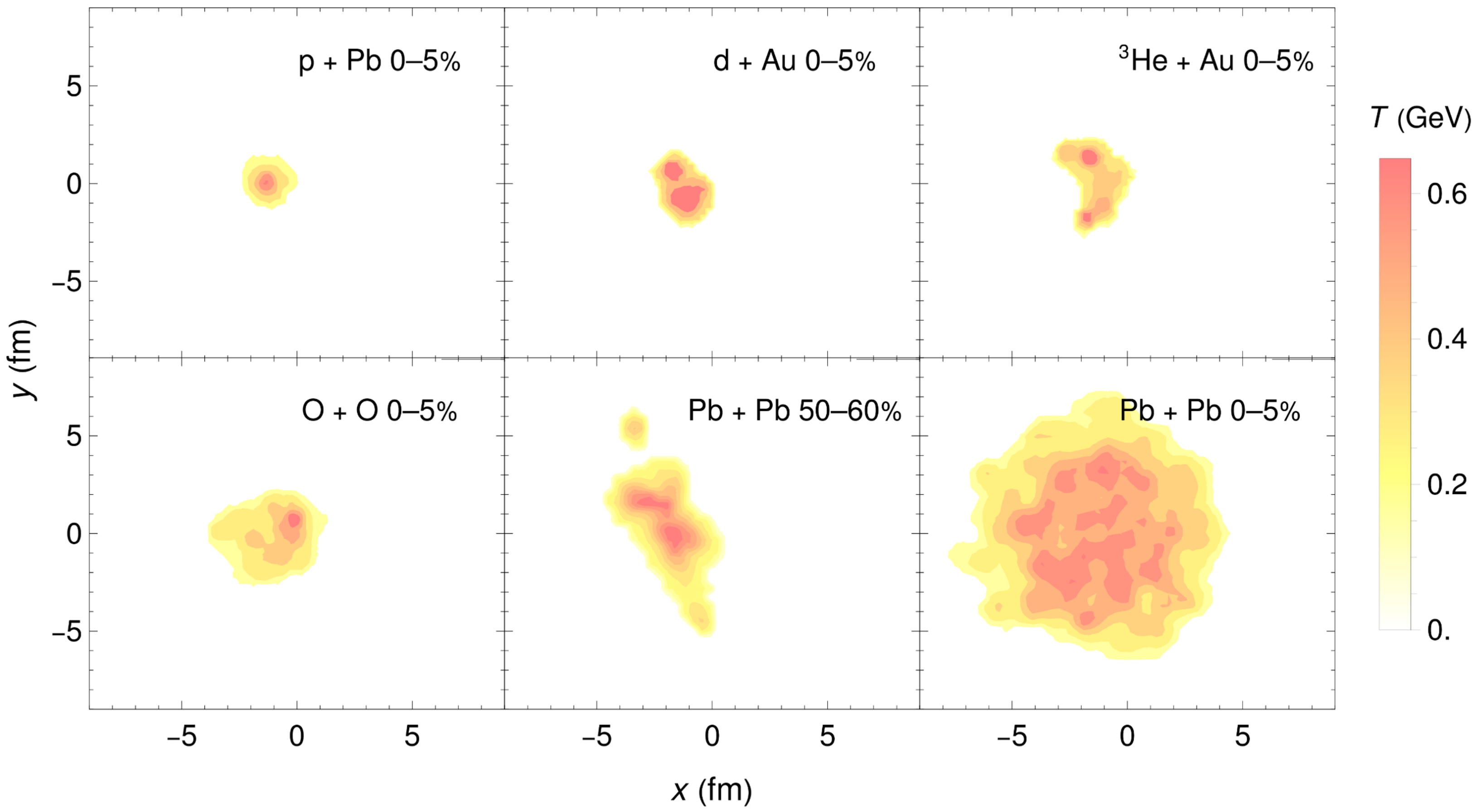


CF, W. A. Horowitz, *JHEP* 11, 019 (2025)

Work in progress

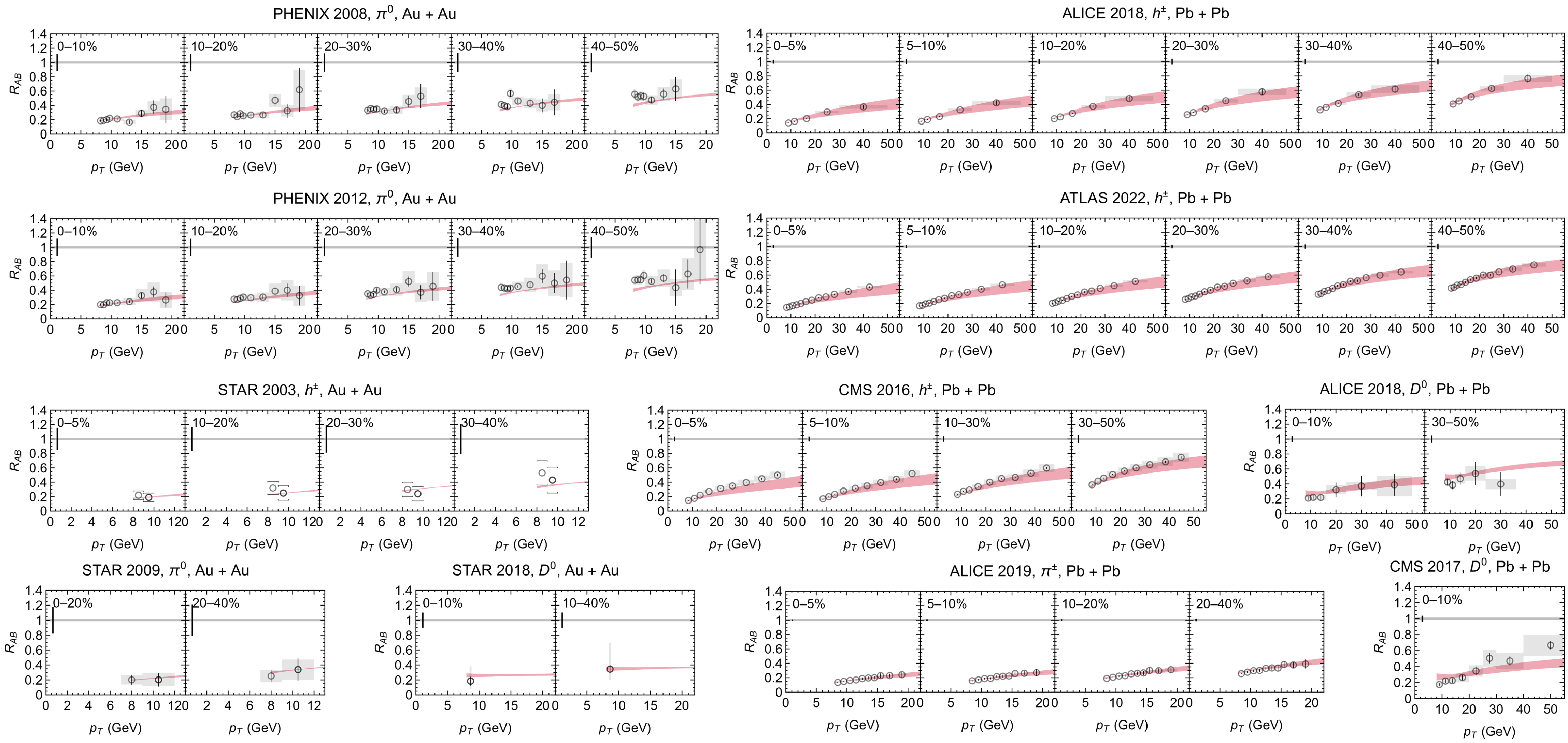


Strategy

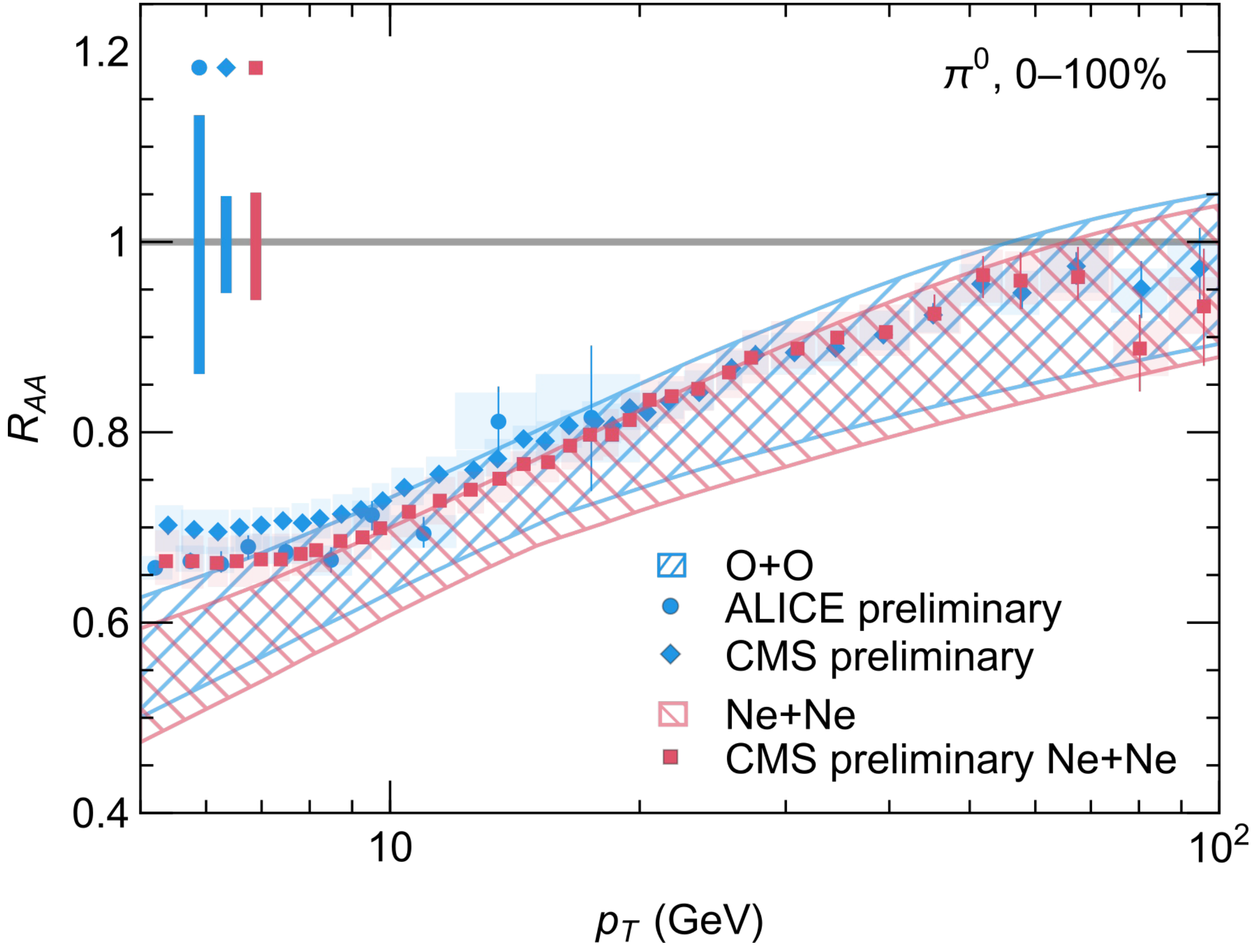


- Fit the model on large-system data
- Then make predictions for small systems data

All results post-fitting, 295 data points



Predictions for light ions

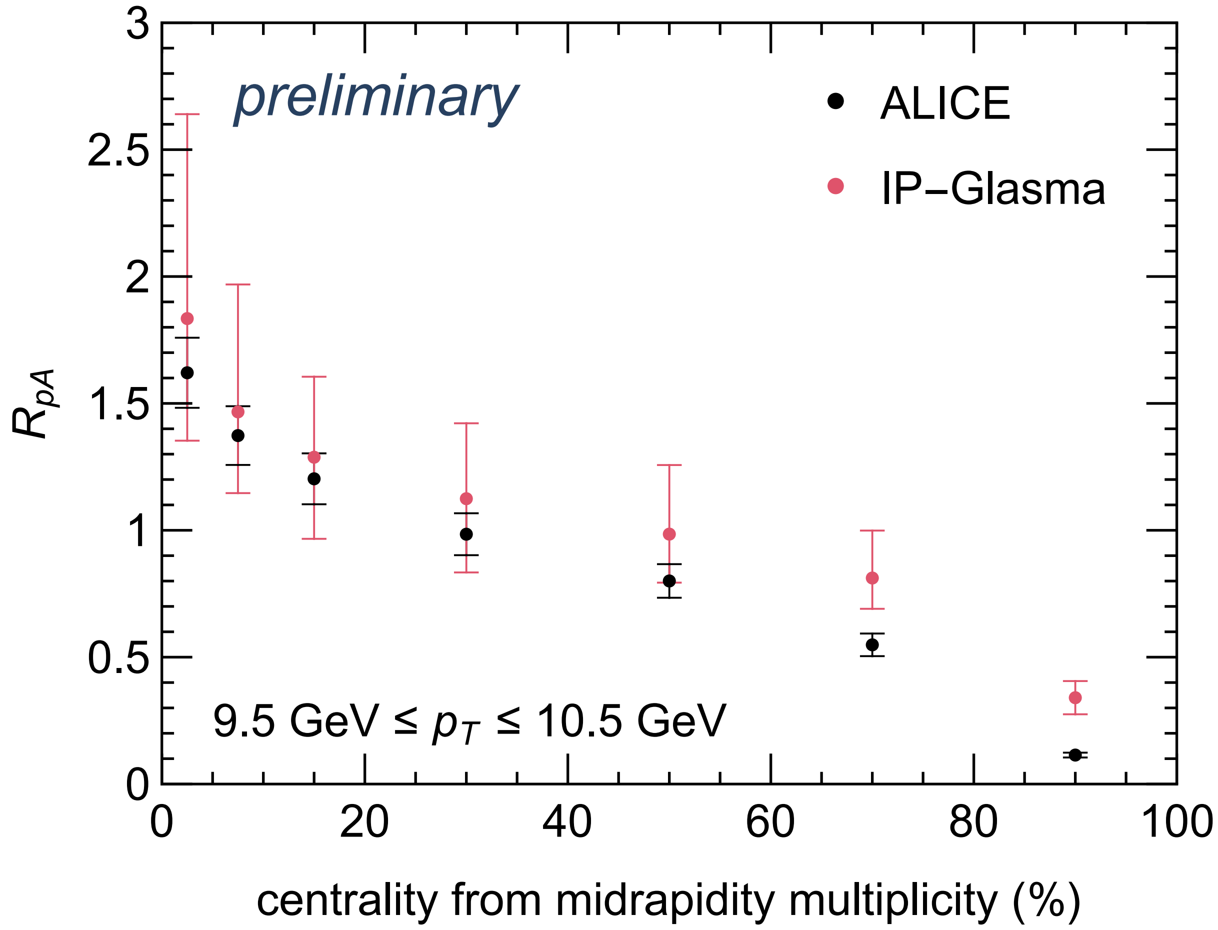


- Overall, good agreement between predictions and data!
- Missing physics for $p_T \lesssim 10\ \mathrm{GeV}$
  - Medium-modified hadronization

CF, W. A. Horowitz, *JHEP* 11, 019 (2025)

Towards understanding *pA*

- Use IP-Glasma to generate both the soft and intermediate spectra
- Ability to capture hard-soft correlations and selection bias effects
- Uncertainties are from Bayesian posterior of HERA data (could be reduced in the future by adding in pA / pp data)
- *Future*: add energy loss, see if a consistent picture of hard + soft can coexist



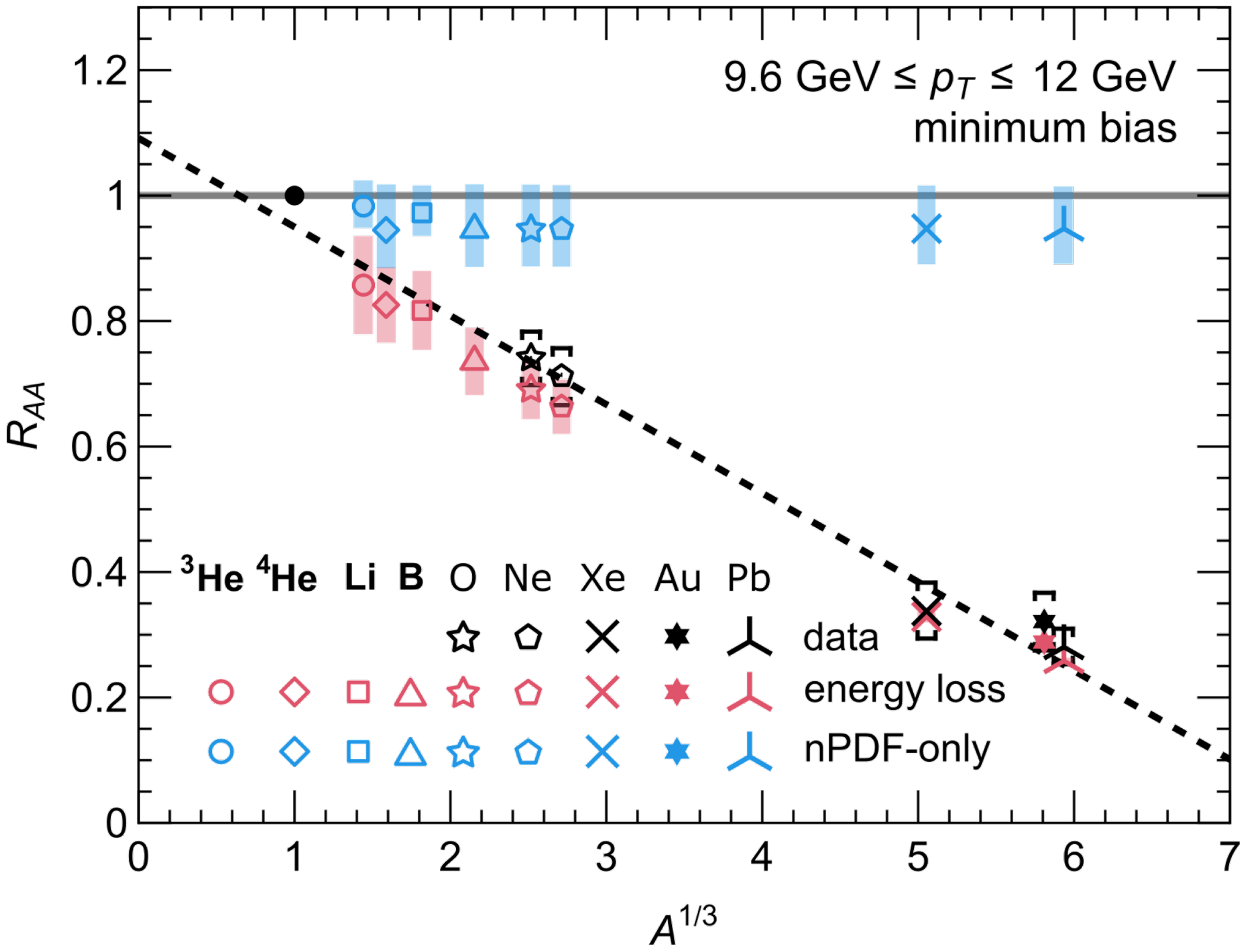
CF, W. A. Horowitz, B. Schenke *ongoing work*

ALICE, Phys. Rev. C **91**, 064905 (2015).

Can we go smaller?

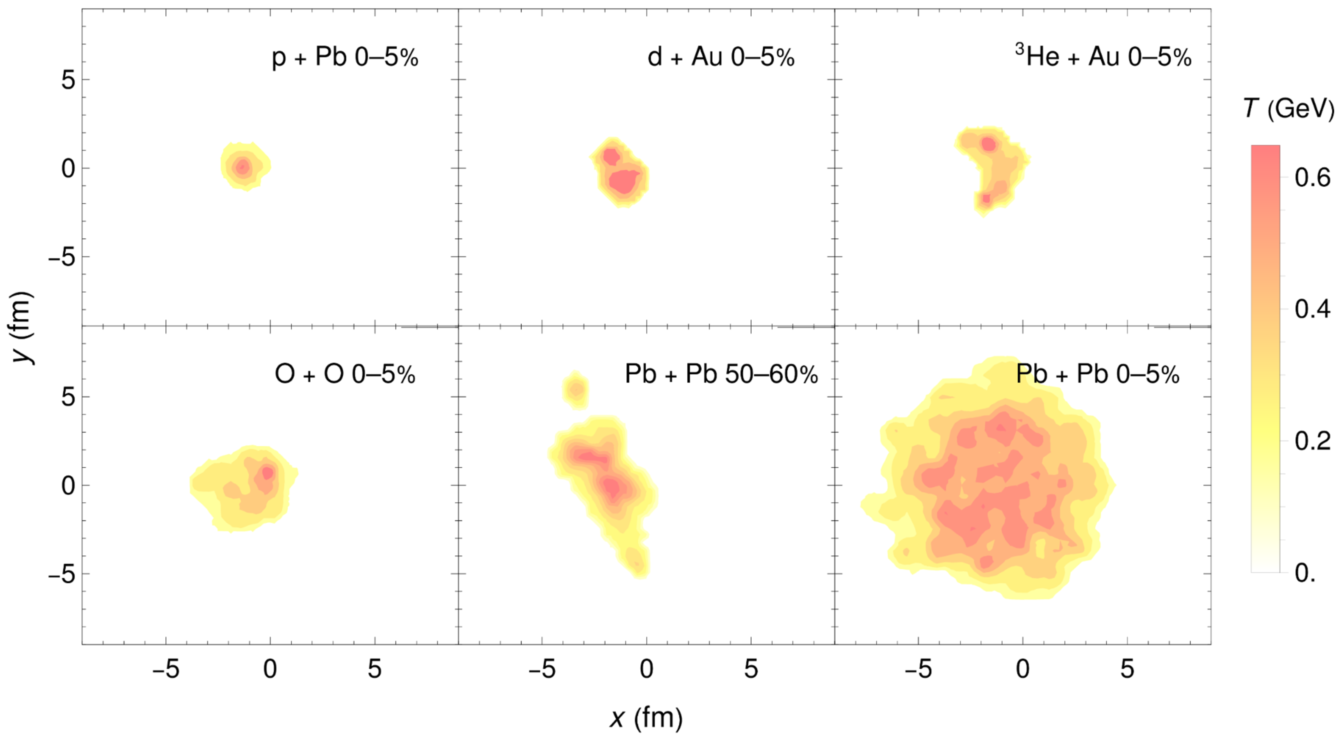
- 3-He and 6-Li offer the most “bang-for-buck” in terms of discovering energy loss in very small systems (i.e. small nPDF effects and uncertainties)
- Would also be interesting to test onset of hydro, non-hydro modes, etc.

CF, B. Bert, J. Brand, W. Vogelsang, and **W. A. Horowitz**, arXiv:2512.17832 [hep-ph] (2025).



Concluding remarks

- Understanding QGP in small systems is one of the most interesting open questions in high energy nuclear physics



- *What is the smallest droplet of QGP?*
- *How many particles are needed for collectivity?*
- *How does the "standard model" of heavy-ions extrapolate to smaller systems?*

Thank you!

Modelling parton and charged hadron production spectra in hadronic collisions

QGP @ Mzanzi

Jack Brand

Department of Physics, University of Cape Town

26 January 2026

Abstract

- We reproduced LO pQCD differential cross-sections for light parton $(u, \bar{u}, d, \bar{d}, s, \bar{s}, g)$ and charged meson $(\pi^{\pm}, K^{\pm}, p, \bar{p})$ production
- Used contemporary parton distribution functions (PDFs) and fragmentation functions.
- Compared with experimental data of p+p at $\sqrt{s} = 630$ GeV.

Introduction

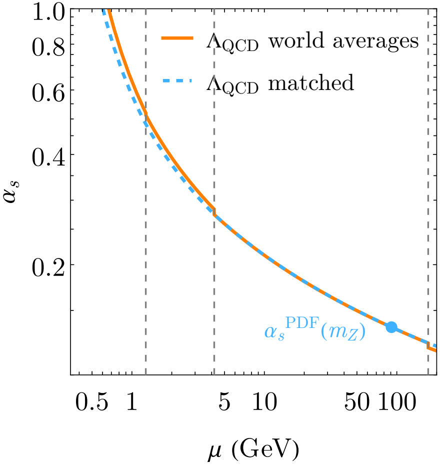
In pQCD, processes with final-state hadrons are described in terms of[1]

- Perturbative hard-scattering cross-sections $\frac{d\sigma^{AB\to f\to h}}{dX}$
- Non-perturbative universal functions $f_f^A(x, Q^2)$, $D_{f\to h}(z, \mu_F^2)$

[1] Collins, Soper, & Sterman (1989), arXiv:hep-ph/0409313

Strong Coupling Constant

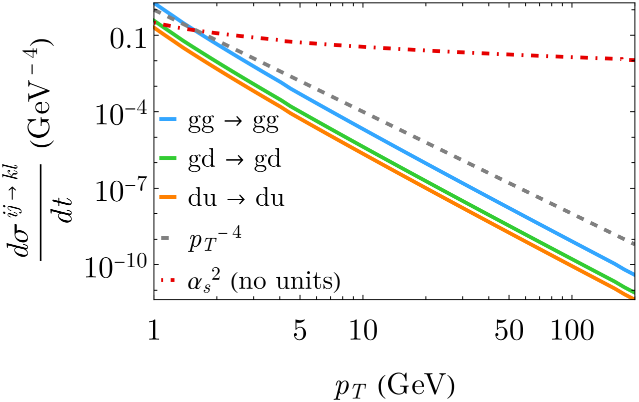
$$\alpha_s(\mu) = \frac{4\pi}{\beta_0 \ln\left(\mu^2/\Lambda^2_{\text{QCD}}(N_f)\right)}, \qquad \beta_0 = 33 - 2N_f \qquad (1)$$



Parton Interaction Spectra

LO interaction cross-section of a hard 2-to-2 QCD vertex[1]:

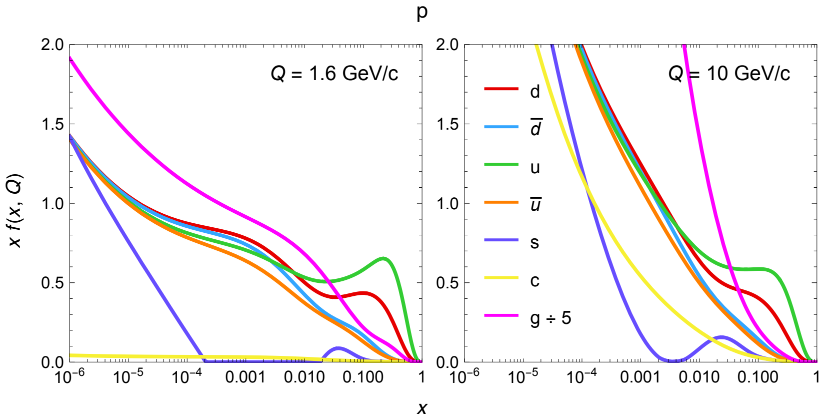
$$\frac{d\hat{\sigma}^{ij\to kl}}{d\hat{t}}(\hat{s},\hat{t},\hat{u}) = \frac{\pi\alpha_s^2}{\hat{s}^2}\left|\left\langle\mathcal{M}^{ij\to kl}(\hat{s},\hat{t},\hat{u})\right\rangle\right|^2 \tag{2}$$



[1] Combridge, Kripfganz, & Ranft (1977)

Parton Distribution Functions

- We used the CT18LO global fit[1].



[1] Yan, Hou, Nadolsky, & Yuan (2023), arXiv:2205.00137 [hep-ph]

Parton Production Spectra

- Parton pairs (k, l) produced back-to-back in the transverse plane have the LO cross-section[1]

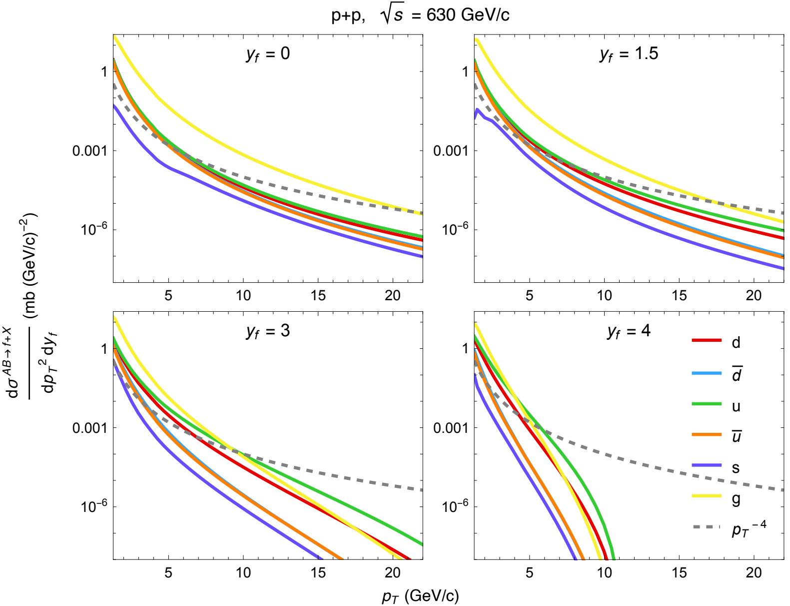
$$\frac{d\sigma^{AB\to kl+X}}{dp_T^2\,dy_1\,dy_2} = \sum_{i,j} x_1 f_i^A(x_1,Q^2)\;x_2 f_j^B(x_2,Q^2)\;\frac{d\hat{\sigma}^{ij\to kl}}{d\hat{t}} \tag{3}$$

- So the inclusive cross-section to produce parton f is

$$\frac{d\sigma^{AB\to f+X}}{dp_T^2\,dy_f} = \int dy_1\,dy_2 \sum_{\langle k,l\rangle} \frac{d\sigma^{AB\to kl+X}}{dp_T^2\,dy_1\,dy_2} \times \left[\delta_{kf}\delta(y_f - y_1) + \delta_{lf}\delta(y_f - y_2)\right]\frac{1}{1+\delta_{kl}} \tag{4}$$

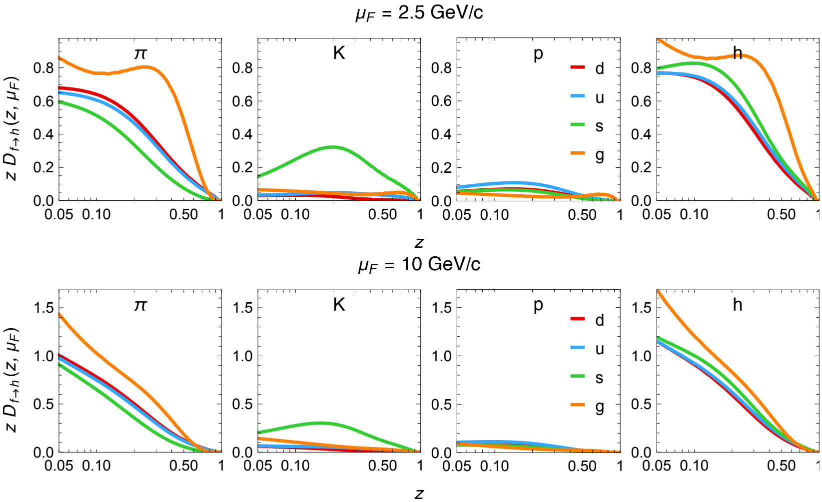
[1] Eskola & Honkanen (2003), arXiv:hep-ph/0205048

Parton Production Spectra



Fragmentation Functions

- We used the DSS dataset[1], containing $\pi^{\pm}$, $K^{\pm}$ and $p, \bar{p}$ fragmentation functions from NLO combined analyses.



[1] de Florian, Sassot, & Stratmann (2007), arXiv:hep-ph/0703242

Hadron Production Spectra

The inclusive cross-section to produce hadron h is[1]

$$\frac{d\sigma^{AB\to h+X}}{dq_T^2\,dy} = K(\sqrt{s})\,J(m_T,y)\sum_f \int \frac{dz}{z^2} D_{f\to h}(z,\mu_F^2)\,\frac{d\sigma^{AB\to f+X}}{dp_T^2\,dy_f}\bigg|_{p_T^2,y_f} \tag{5}$$

- $K(\sqrt{s})$ is the NLO factor
- The parton cross-section is evaluated at

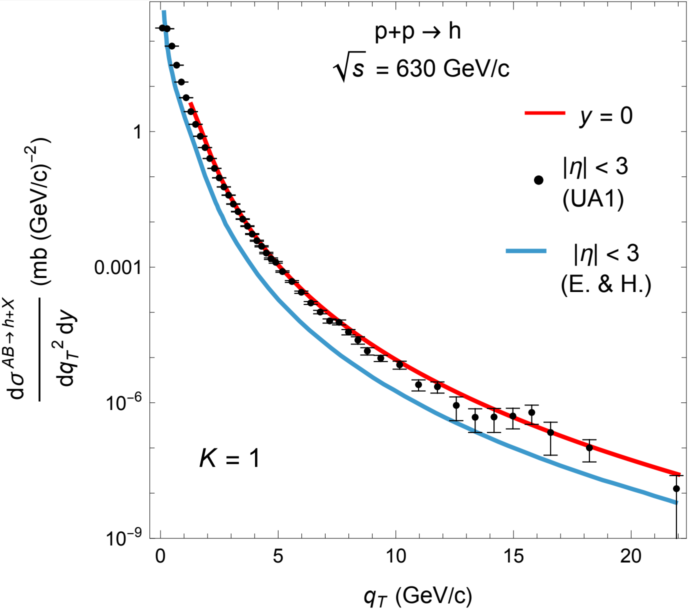
$$p_T = \frac{q_T}{z} J(m_T,y)\,, \quad y_f = \operatorname{arcsinh}\left(\frac{m_T}{q_T}\sinh y\right)$$

- The integral bounds are

$$\frac{2m_T}{\sqrt{s}}\cosh y \;\le\; z \;\le\; \min\left(1,\; \frac{q_T}{p_0} J(m_T,\, y)\right)$$

[1] Eskola & Honkanen (2003), arXiv:hep-ph/0205048

Hadron Production Spectra



Thank you!

Questions

DIHADRON CORRELATIONS AS PROBES OF THE QUARK-GLUON PLASMA

Tiaan van der Merwe

Assoc Prof. William Horowitz

UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

QUARK GLUON PLASMA AND HEAVY ION COLLISIONS

Relativistic pancake

Quarks and gluons interact with each other within the QGP

We observe particles that are created and modified via the quark-gluon interaction

Smash two Pb atoms together

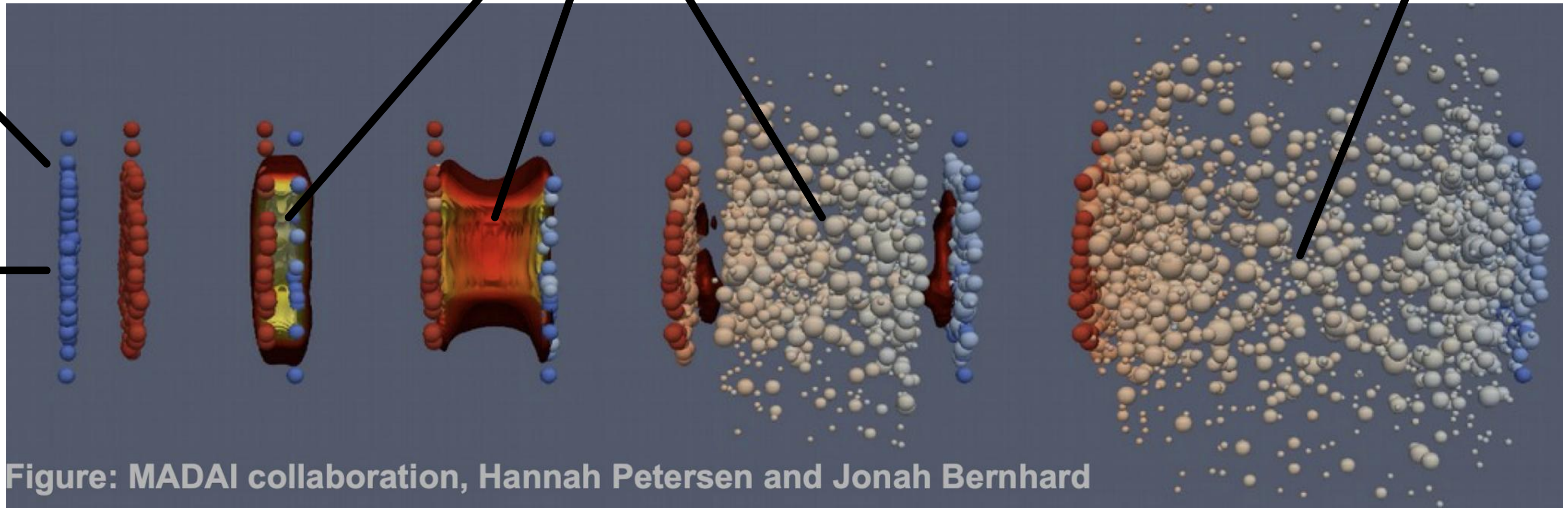


Figure: MADAI collaboration, Hannah Petersen and Jonah Bernhard

t

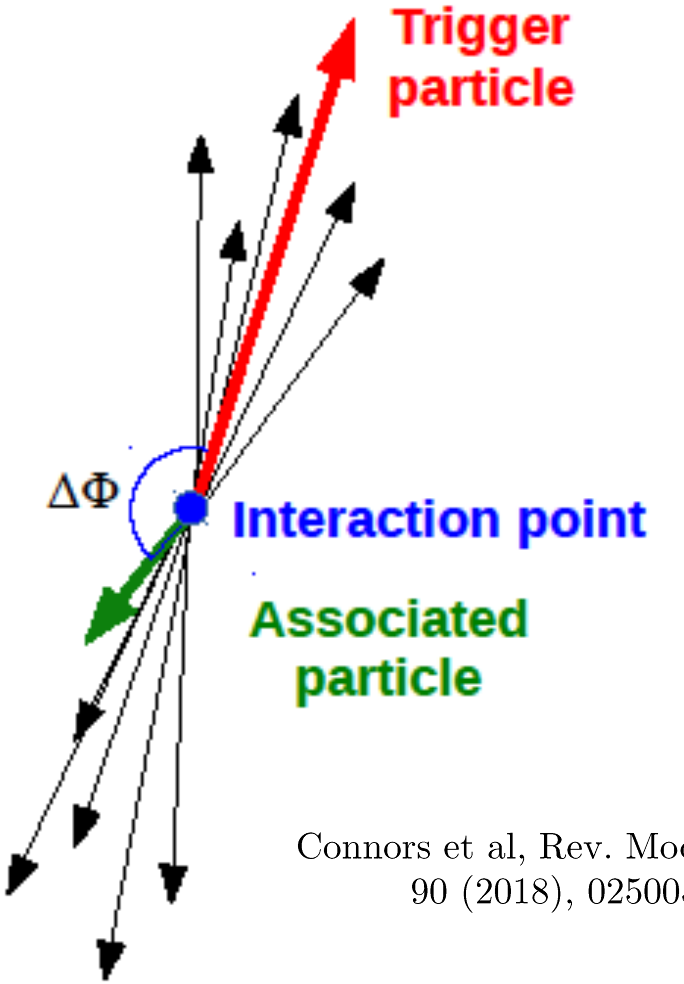
$\sim 10^{-23}$ s

DIHADRON CORRELATIONS

- A hard parton scattering produces two partons that are separated by $\Delta\phi = \pi$ in the transverse plane (back-to-back).
- The partons are modified by in-medium interactions: one might lose more energy than the other, and one can "bend" relative to the other.
- Partons fragment and hadronize into hadrons

A high-p_T hadron ⇒ trigger hadron

The lower p_T hadrons ⇒ associate hadrons

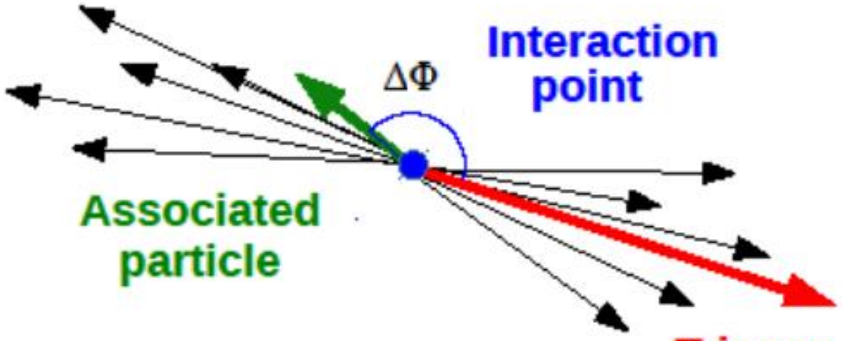


Connors et al, Rev. Mod. Phys. 90 (2018), 025005

DIHADRON CORRELATIONS

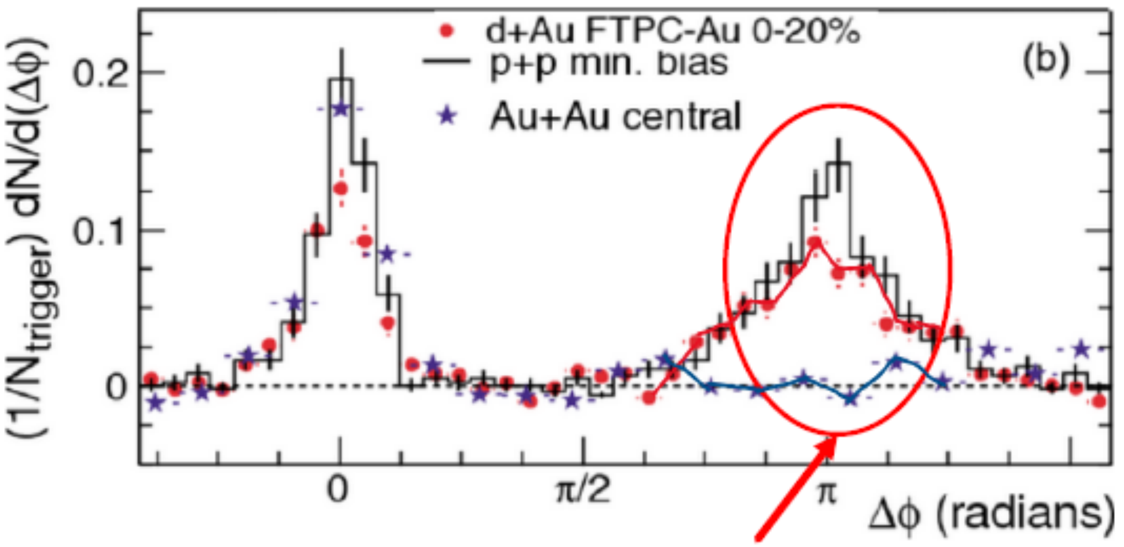
Count the number of trigger particles and associate particles for different momenta, pseudorapidity and azimuthal angle, and compare pp to AA.

Build correlation functions with the yields.



Connors et al, Rev. Mod. Phys. 90 (2018), 025005

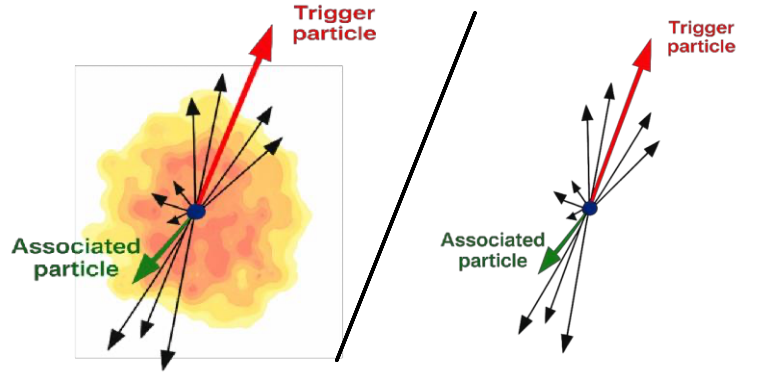
STAR Collaboration, Phys. Rev. Lett. 91 (2003) 072304

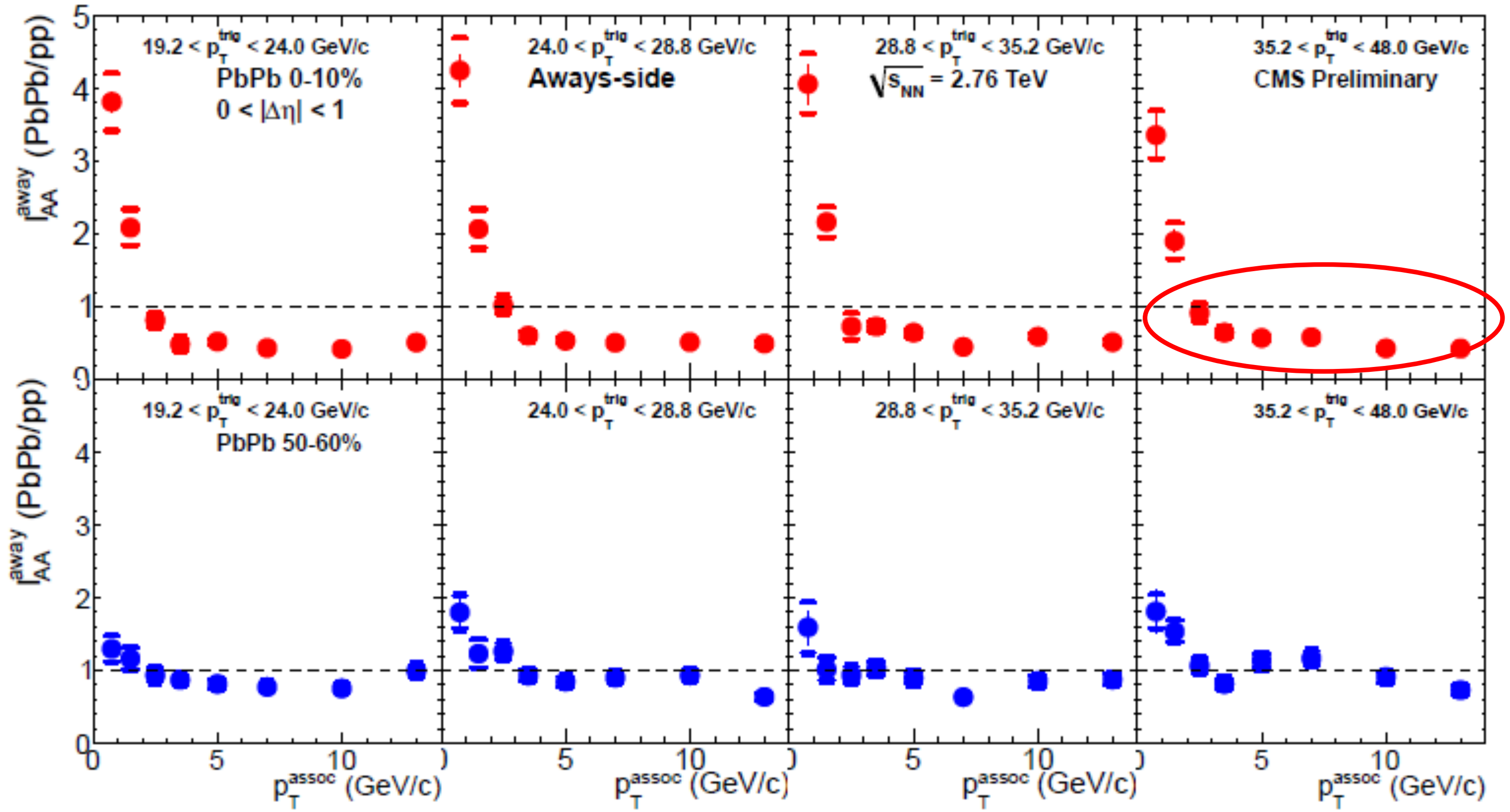


Correlation peaks at π, corresponding to back-to-back parton pairs originating in hard scatter

KEY OBSERVABLE: DIHADRON SUPPRESSION FACTOR I_{AA}

$$I_{AA} = \frac{\text{Per-trigger Yield of Associate Particles in AA}}{\text{Per-trigger Yield of Associate Particles in pp}} =$$





Suppression of associate particles at high-p_T!

CMS Collaboration, Nuclear Physics A 904–905 (2013) 451c–454c

MONTE CARLO + ANALYTICAL APPROACH

Medium modelling

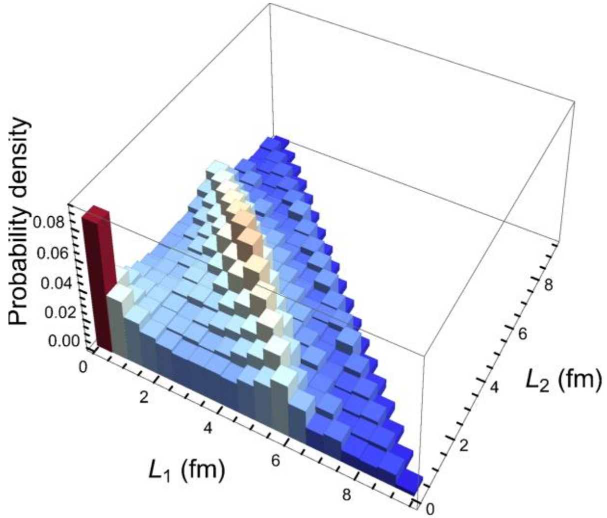
Energy loss:

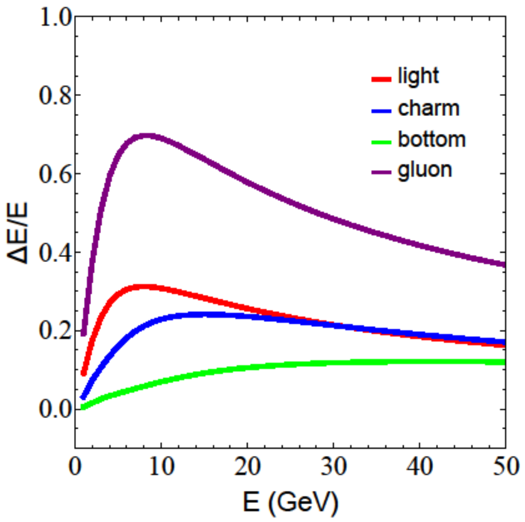
- Radiative energy loss: DGLV formula
- Collisional energy loss: HTL framework

Energy loss calculated as a function of parton energy, path length, and medium temperature

Geometry

- Simple geometry model: Optical Glauber Model
- Will extend to hydrodynamic backgrounds





Self generated (2025)

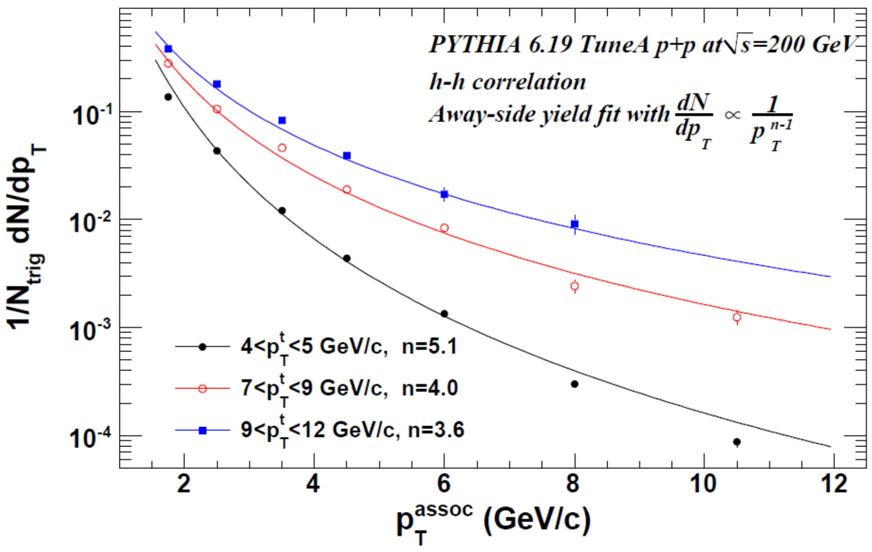
Hard probe production

PYTHIA:

- Model associate and trigger hadrons with Pythia
- Build baseline p+p dihadron correlations

Medium modifications:

- Couple Pythia to in-medium energy loss



Jiangyong Jia et. al, Phys. Rev. C 84 (2011) 034904

Pythia Production → Energy loss → Geometry → Observable

OUTLOOK + CONCLUSIONS

- Energy loss is a key signal of the formation of QGP in heavy-ion collisions, with dihadron correlations providing a sensitive and differential probe of medium effects.
- This project aims to deliver publication-quality results within the first year of the MSc, with a dedicated focus on interpretation and journal submission in the second year.
- Quantitative constraints on QGP properties, strong coupling constant α_s and the jet transport coefficient $\hat{q}$, will be extracted from measurements of the I_{AA}
- Extending these studies to small collision systems offers the opportunity to address a central open question in the field: **does a QGP also form in small systems?**

QUESTIONS?

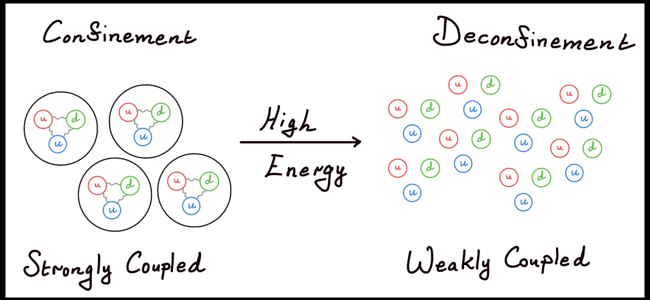
$R_{AA} \otimes v_n$ FROM ENERGY LOSS IN SMALL SYSTEMS

BEN BERT

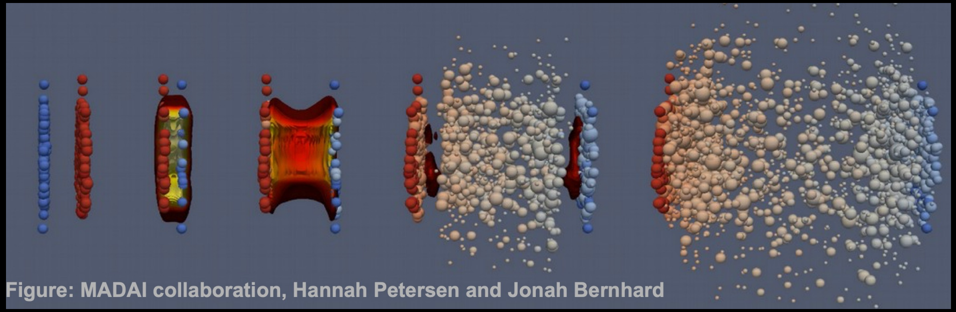
NITheCS
National Institute for Theoretical and Computational Sciences
CERN
South African Institute of Physics
NRF National Research Foundation
iThemba LABS Laboratory for Accelerator Based Sciences

NUCLEAR FIREBALL PHYSICS

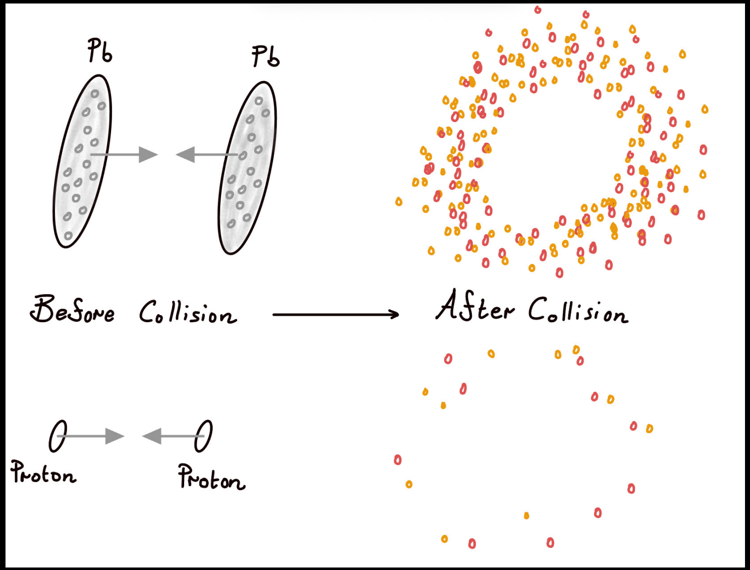
Deconfinement from QCD

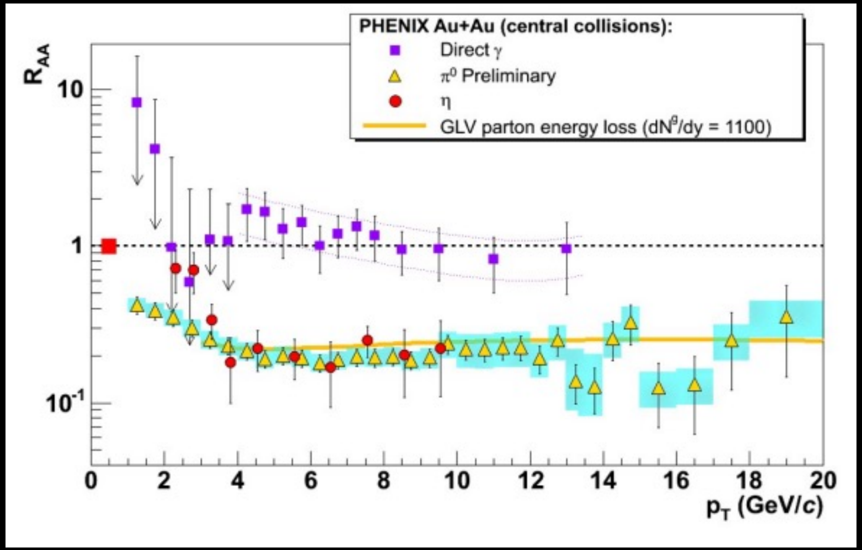


Deconfined matter leads to collective behavior, known as QGP



OBSERVABLE OF INTEREST 1: R_{AA}



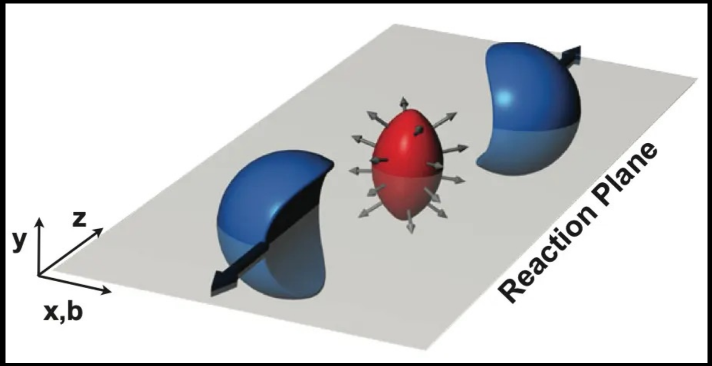


Tadaaki Isobe. *AIP Conf. Proc.*, 842:56–58, 2006

$$R_{AA} \equiv \frac{dN^{AA}/dp_T}{N_{coll}\, dN^{pp}/dp_T}$$

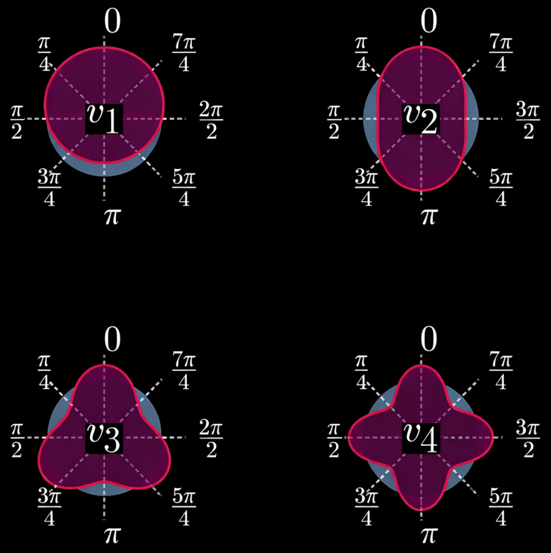
$$R_{AA} \approx 1 - \Delta E/E$$

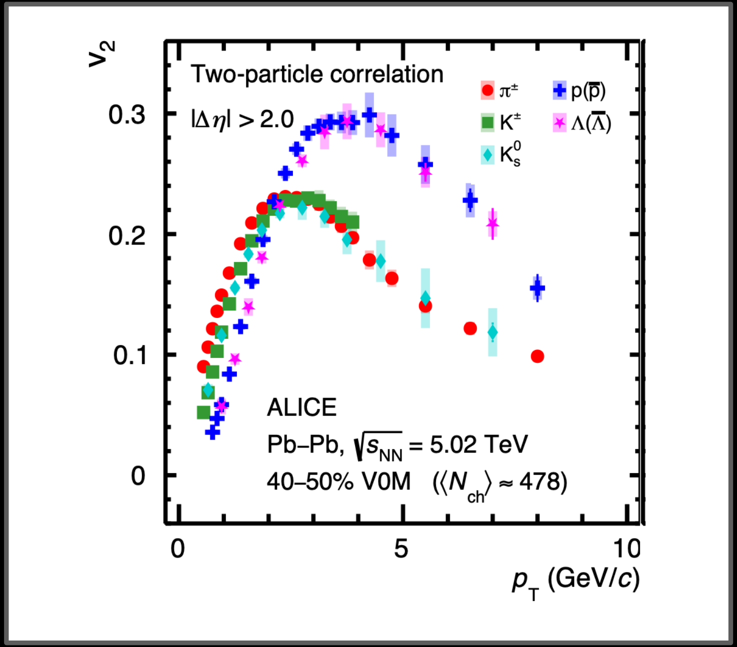
OBSERVABLE OF INTEREST 2: v_n



https://arxiv.org/pdf/1102.3010

$$\frac{R_{AA}^{h,k}(p_T,\phi)}{R_{AA}^{h,k}(p_T)} = 1 + 2\sum_{n=1}^{\infty} v_n^k \cos\left(n\left[\phi - \psi_n^k\right]\right)$$

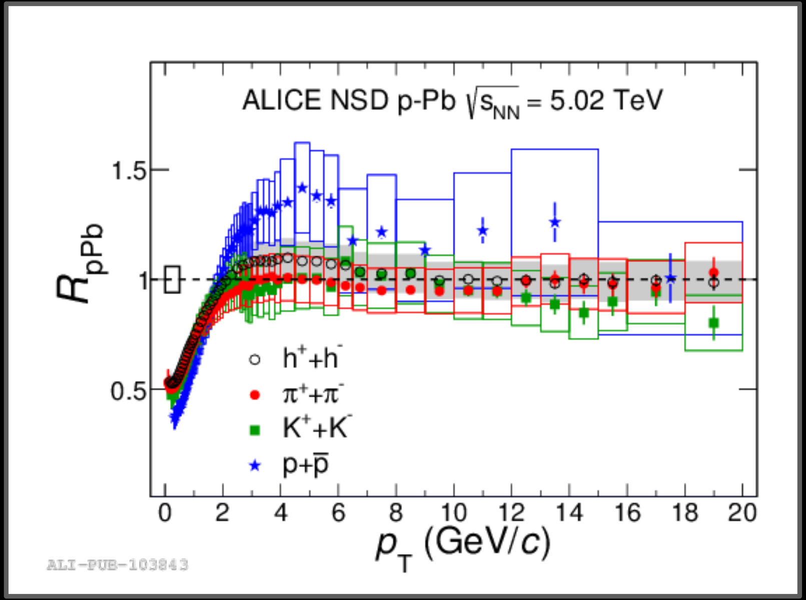




https://arxiv.org/pdf/2411.09323

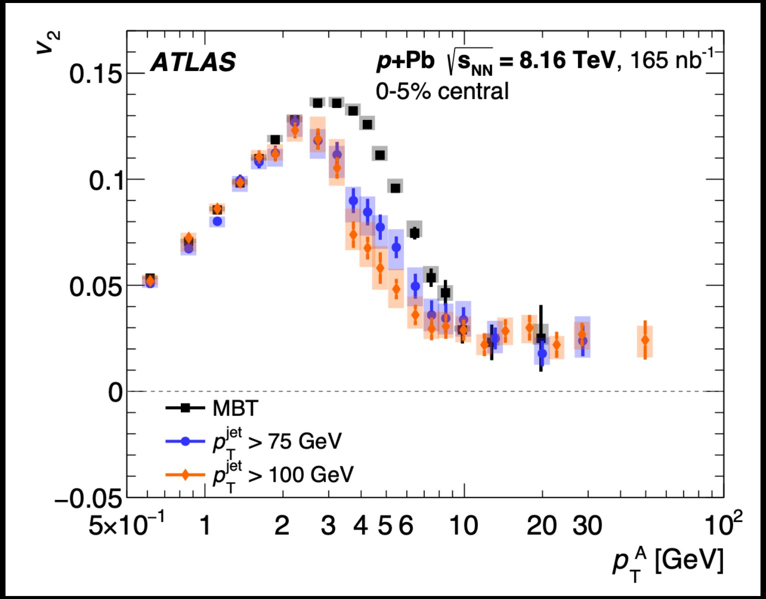
IS THERE A QGP IN SMALL SYSTEMS?

https://arxiv.org/abs/1609.05665



$R_{pPb} \approx 1$

https://arxiv.org/pdf/1910.13978

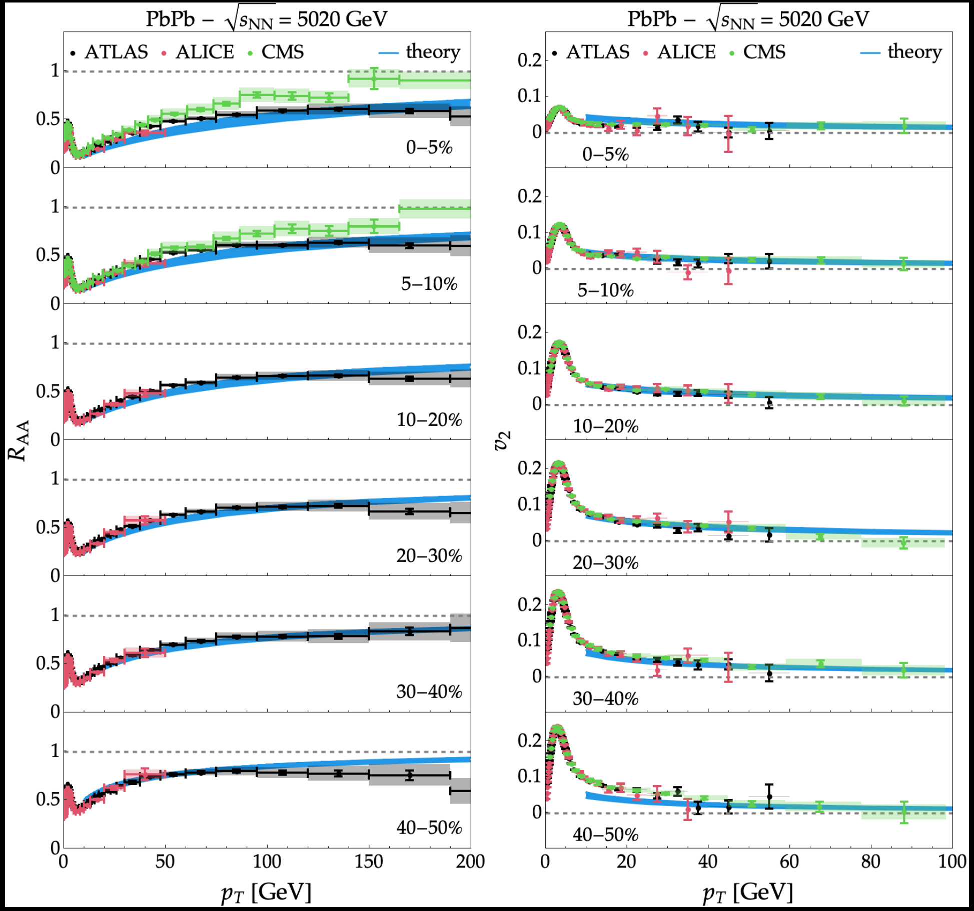


$v_2 \neq 0$

CONSTRAINING OUR MODEL TO LARGE SYSTEM DATA

Large system data

Experiment	Collision system	Hadron species	Obseravble
ALICE [94]	PbPb	D^0	R_{AA}
ALICE [63]	PbPb	$h^{\pm}$	R_{AA}
ALICE [95]	PbPb	$\pi^{\pm}$	R_{AA}
ATLAS [64]	PbPb	$h^{\pm}$	R_{AA}
CMS [62]	PbPb	$h^{\pm}$	R_{AA}
CMS [96]	PbPb	D^0	R_{AA}
ALICE [97]	PbPb	D	v_2
ALICE [58]	PbPb	$h^{\pm}$	v_2
ATLAS [78]	PbPb	$h^{\pm}$	v_2
CMS [81]	PbPb	D^0	v_2
CMS [56]	PbPb	$h^{\pm}$	v_2
CMS [82]	PbPb	D^0	v_2
CMS [83]	PbPb	D^0	v_2
PHENIX [98]	AuAu	π^0	R_{AA}
PHENIX [85]	AuAu	π^0	R_{AA}



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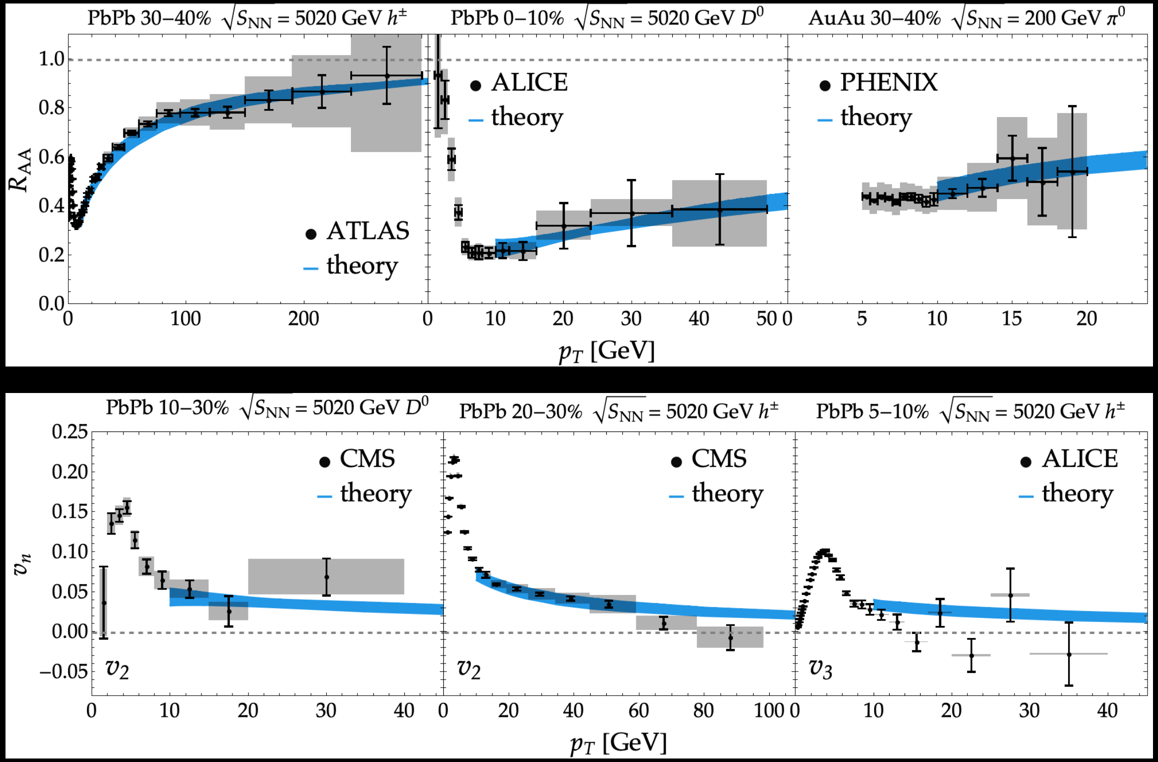
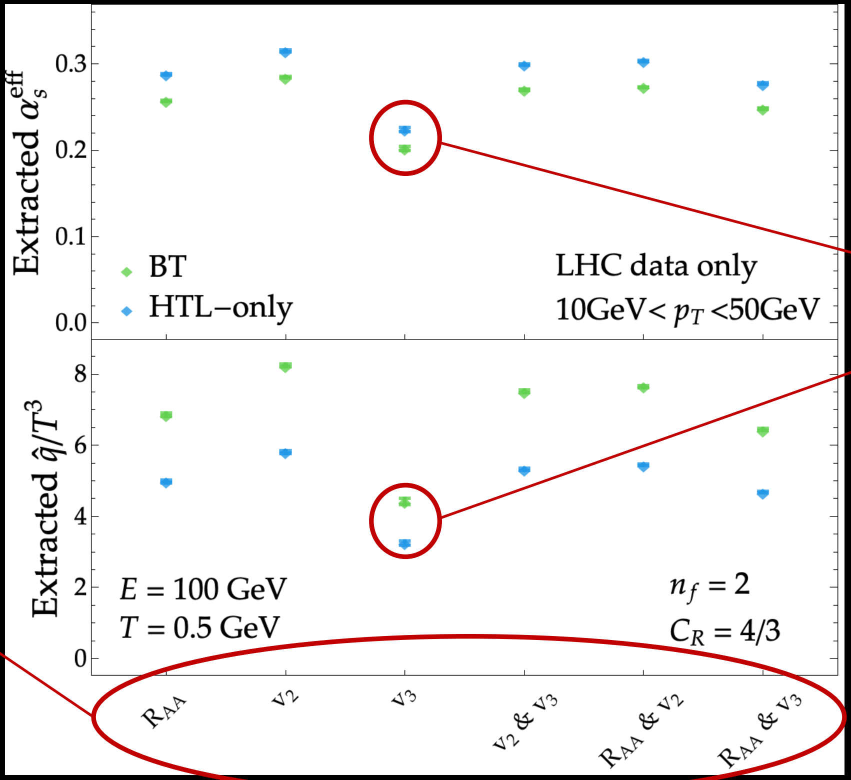


TENSION IN v_3 DATA

$$\chi^2\left(\alpha_s^{\text{eff.}}\right) \equiv \sum_{i,j}^{N} \left[y_i - \mu_i\left(\alpha_s^{\text{eff.}}\right)\right] \left(C^{-1}\right)_{ij} \left[y_j - \mu_j\left(\alpha_s^{\text{eff.}}\right)\right]$$

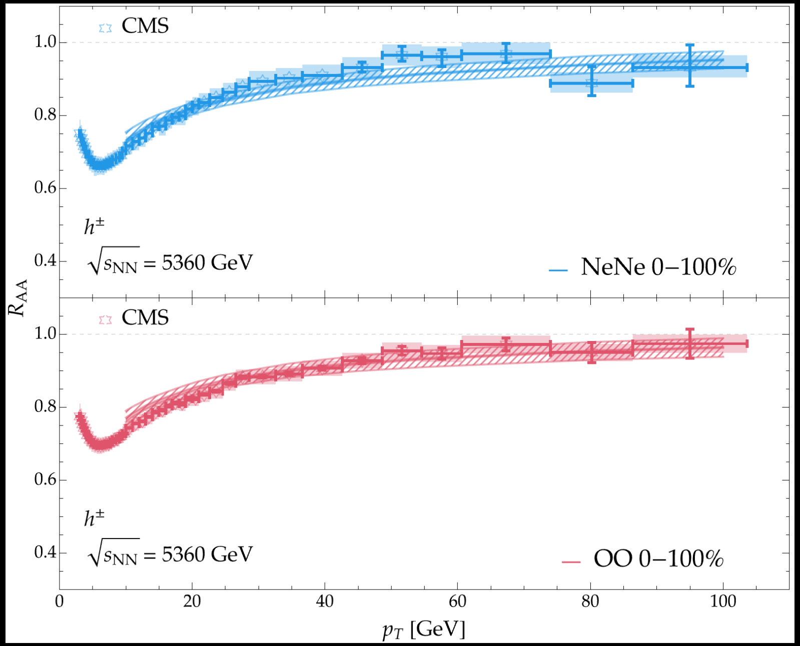
Constrain model on
a subset of all observables



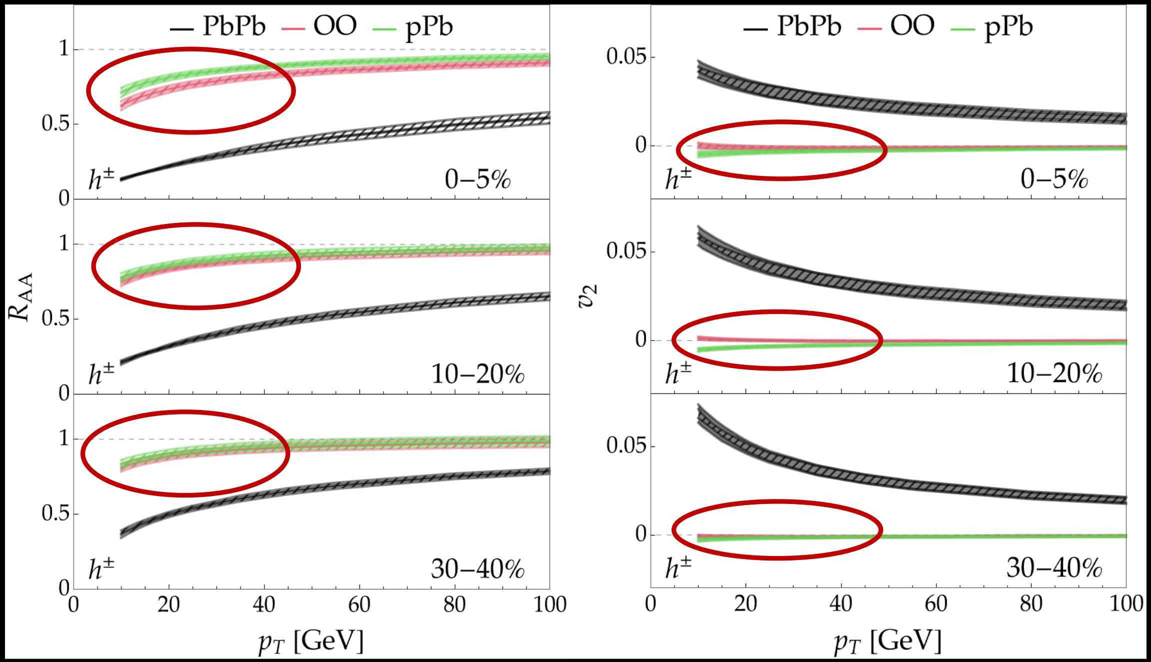
Small α_s and $\hat{q}$ are needed
to describe the v_3 data

SMALL SYSTEM PREDICTIONS

Really good agreement in R_{OO} and R_{NeNe} !



$R_{AA} < 1$ and ~0 v_2 in small systems?



CONCLUSION

1. QGP formation is well established in large systems
2. Our energy less model is constrained to large systems
3. Some QGP signatures are present in small systems
4. There is a strong tension in the v_3 data
5. Excellent agreement between our model and data in R_{OO} and R_{NeNe}
6. We predict $R_{AA} < 1$ and ~0 v_2 in small systems