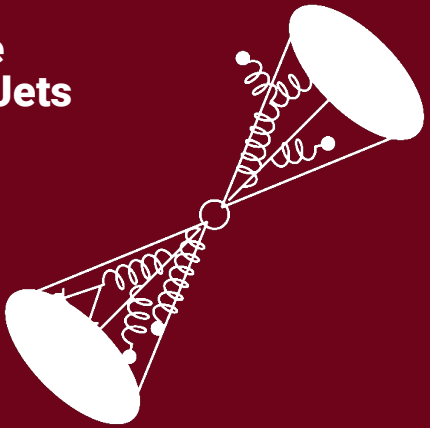
Jets in Hot-and-Cold Nuclear Matter

Chris McGinn

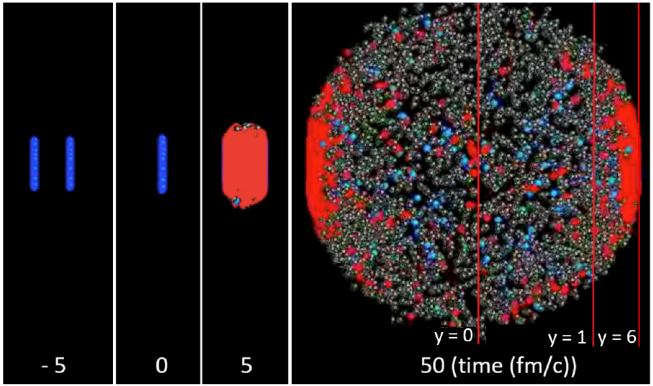
EMMI: Probing the Early Stages with Jets

16 July 2026



MITHIG's work is supported by US DOE-NP

Schematic of Heavy Ion Collisions

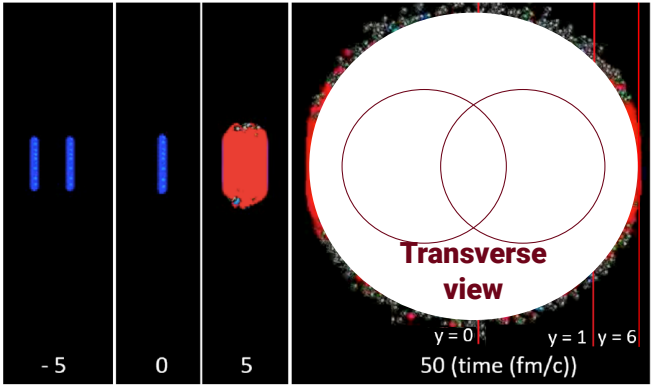


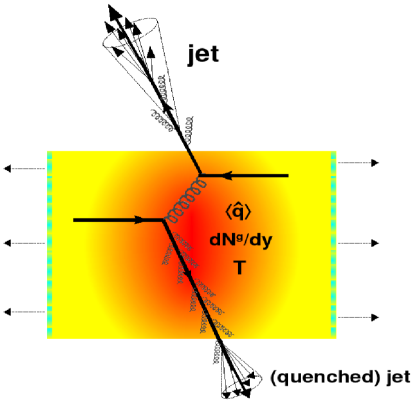
Still via Ann.Rev.Nucl.68 (2018)

Full video via Yen-jie Lee, Wit Busza, and Andre Yoon

1. Lorentz-contracted nuclei inbound
2. Initial collision
3. After some formation time, Quark Gluon Plasma (QGP) - hydrodynamics takes over
4. After some longer time, freezeout and hadronization

Probing the Quark Gluon Plasma with Jets

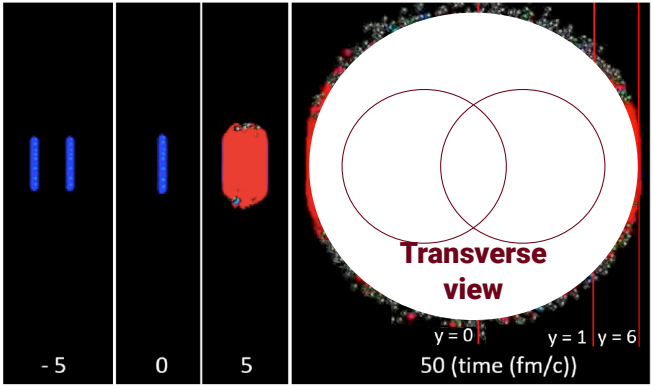


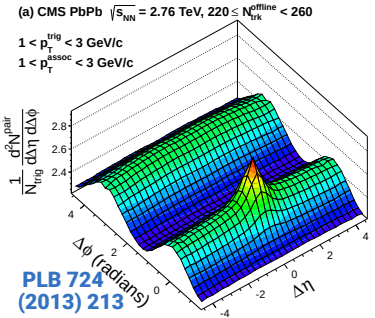


Via D. d'Enterria

- Hard-scattered partons act as QGP probe
  - Energy loss observed in jets taken as possible sign of QGP formation

Geometry to Momentum Space Correlations





Initial state geometry in AA → long range correlations via hydro.

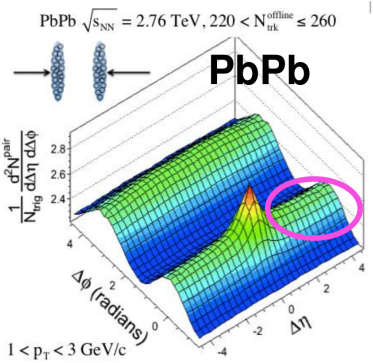
$\sim 1 + 2\,\Sigma_n v_n^2 \cos(n\Delta\phi)$

v_2 → **ellipticity**

- **Long-range correlations taken as possible sign of QGP formation**

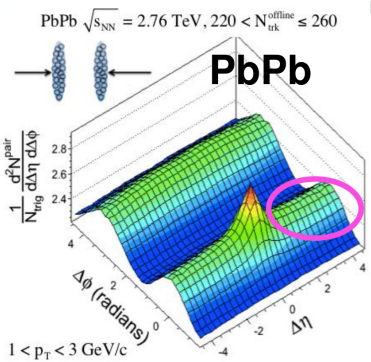
A Droplet of Plasma in Small Systems?

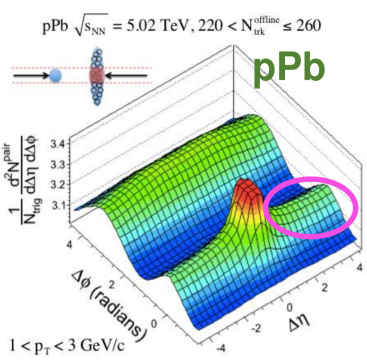
PLB 724 (2013) 213



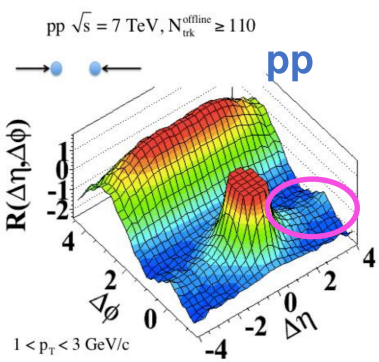
A Droplet of Plasma in Small Systems?

PLB 724 (2013) 213



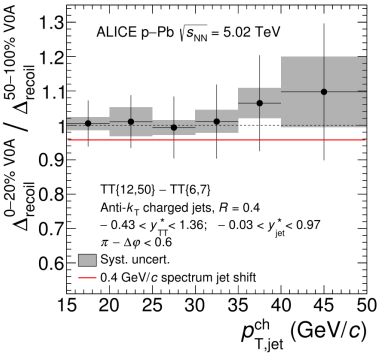


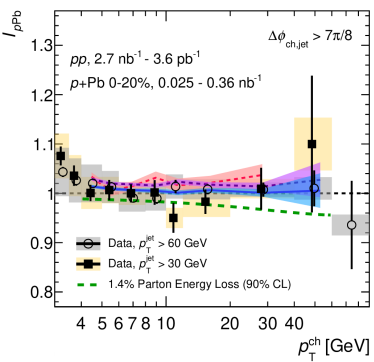
PLB 765 (2017) 193

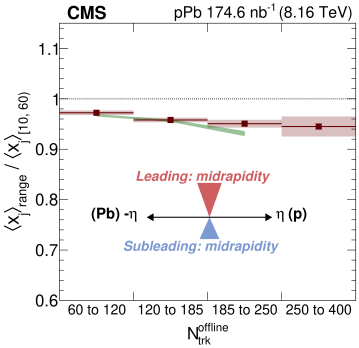


- **Observable phenomena in collision systems of all sizes!**
- **Possible signature of QGP droplet formation in small systems?**

Where Is Quenching in Small Systems?







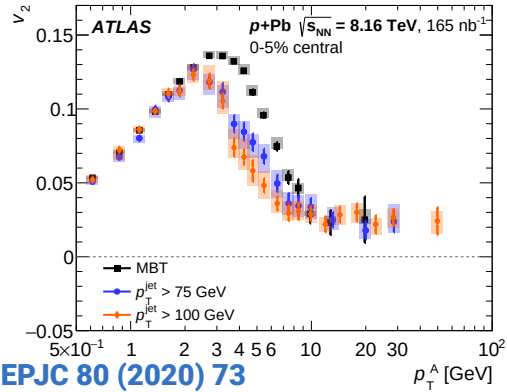
PLB 783 (2018) 95

PRL 131 (2023) 072301

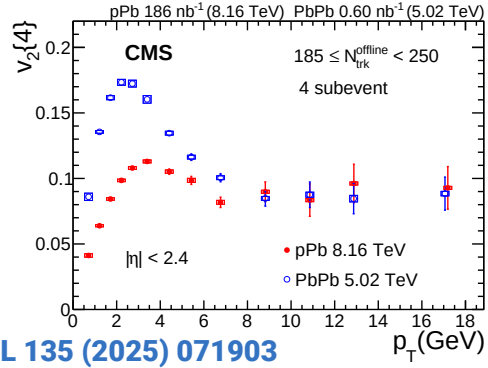
JHEP 07 (2025) 118

- Many independent searches for quenching in pPb have returned no indications
- ALICE, ATLAS, and CMS have all set stringent limits w/ dijet x_J, jet-hadron correlations

High-p_T v_2 in pPb



EPJC 80 (2020) 73



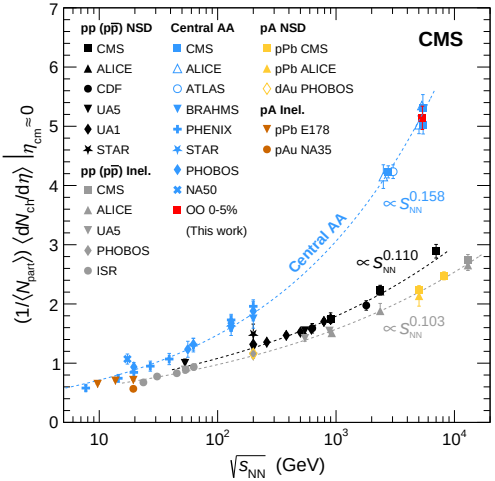
PRL 135 (2025) 071903

- **CMS and ATLAS both see a high-p_T v_2 in pPb**
- **High-p_T v_2 in PbPb was explained by models with path-length dependent energy loss**
  - **But no jet energy loss in pPb is detected**
  - **Open question: do we understand the origins of high-p_T v_2?**

The Case for Light Ion Collisions

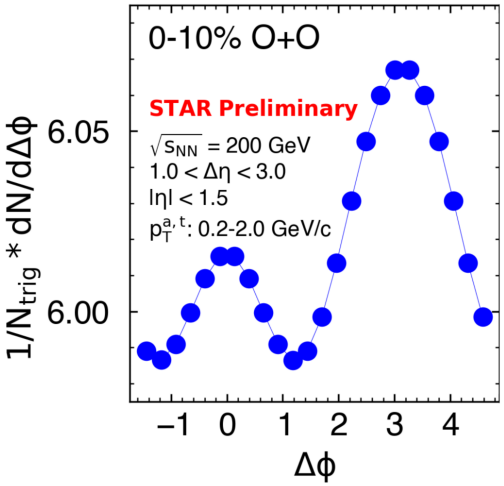
Light ions to bridge the gap

- N_{part} **comparable with pA**
- **No longitudinal asymmetry**
- **Greater transverse area of collision**
- **Reduced bias in centrality selections**



Submitted PLB

Flow Measurements in OO with STAR

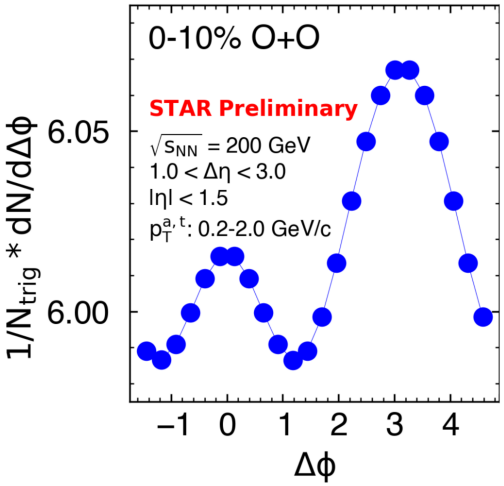


Sijie Zhang, QM2025

STAR took OO collisions in 2021

- **Clear long-range correlation signature!**

Flow Measurements in OO with STAR



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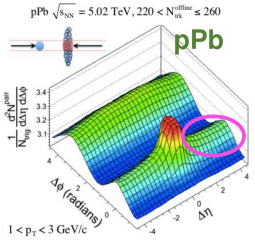

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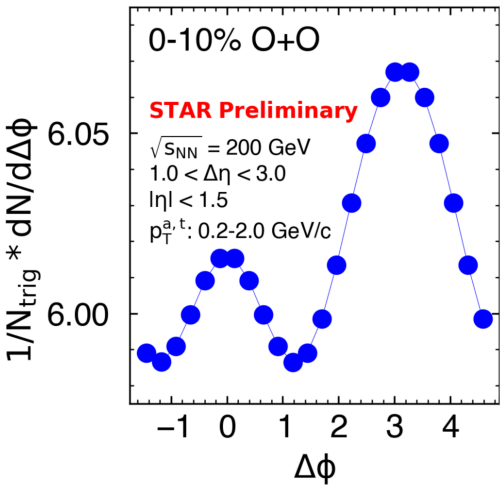

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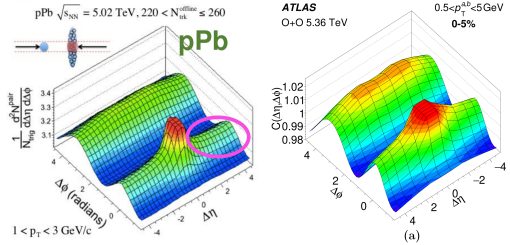
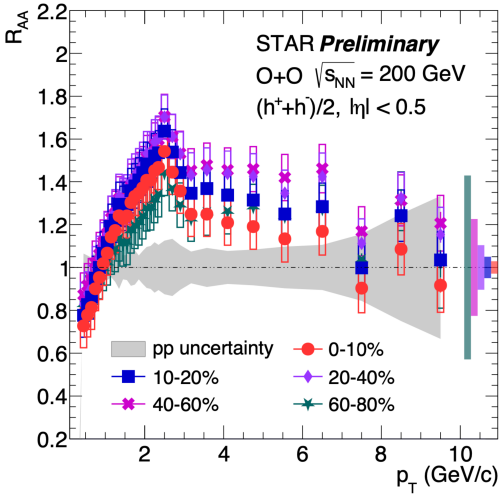


- **Also seen w/ later LHC datataking**
- **What about quenching signatures?**

Quenching Search in OO from STAR

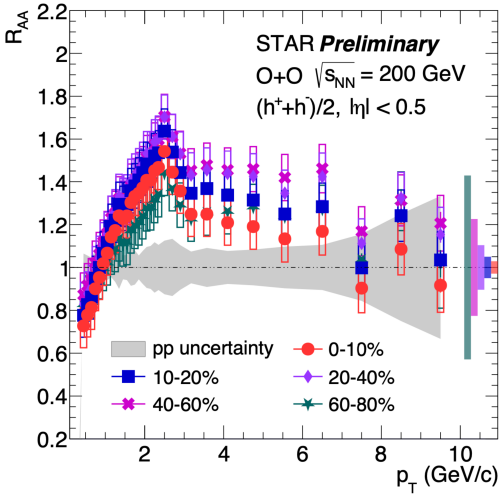


Sijie Zhang, QM2025

Initial quenching search inconclusive

- **Significant normalization uncertainties**

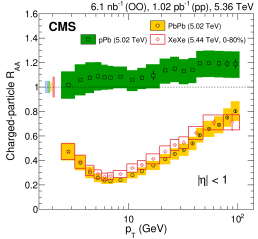
Quenching Search in OO from STAR



Sijie Zhang, QM2025

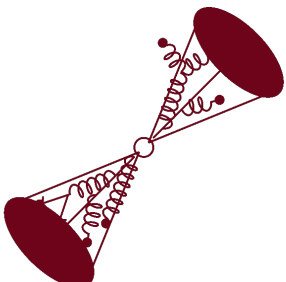
Initial quenching search inconclusive

- **Significant normalization uncertainties**
- **Compare w/ pA hadron R_{pA}**



- **Other initial studies (hadron-triggered I_{CP}) also inconclusive**

Light Ions Data at the LHC and 2025 Results

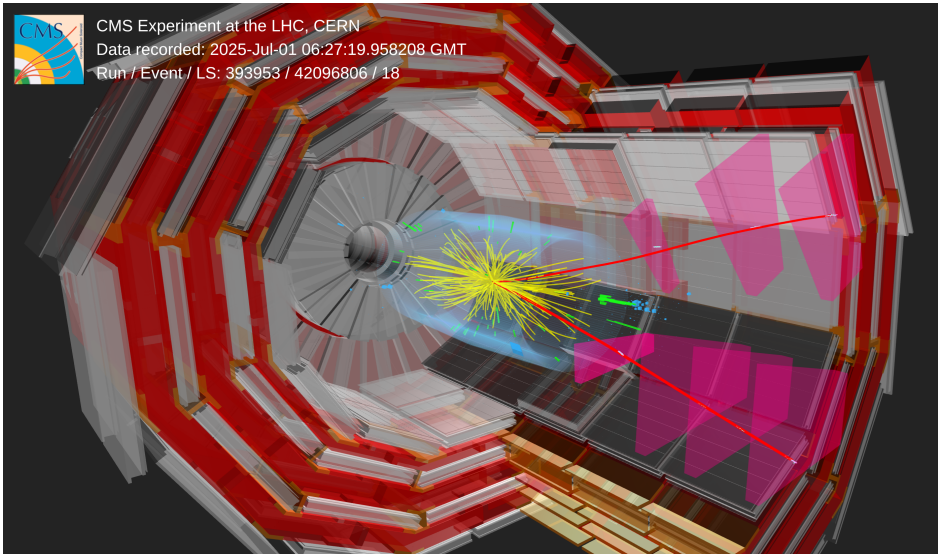


New Light Ions at the LHC

	Jul		Aug						Sep				
Wk	27	28	29	30	31	32	33	34	35	36	37	38	39
Mo	30	7	14	21	28	4	11	18	25	1	8	15	22
Tu	O ion setting up	Ne-Ne run								MD 2			
We		ZDCs out											
Th	MD 1b	VdM program									Jeune G.		
Fr													
Sa	O-O & p-O Ions run												
Su													

3 short runs in July 2025 →

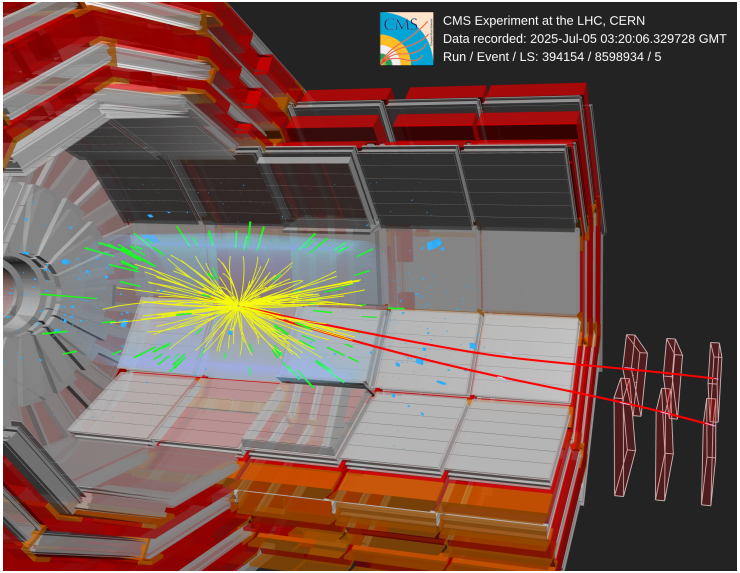
LHC Datataking for pO,



Data taken July 1st-3rd

pO event displays via CDS

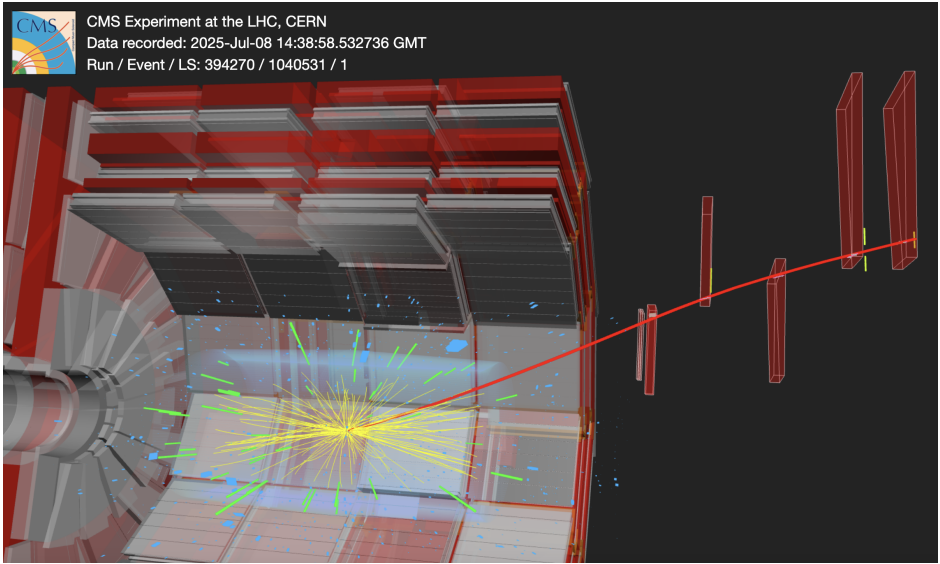
LHC Datataking for pO, OO,



Data taken July 5th-7th

OO event displays via CDS

LHC Datataking for pO, OO, and NeNe!



Data taken July 8th-9th

NeNe event displays via CDS

Luminosity Delivered in Light Ions at the LHC

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Wk	27	28	29	30	31	32	33	34	35	36	37	38	39
Mo	30	7	14	21	28	4	11	18	25	1	8	15	22
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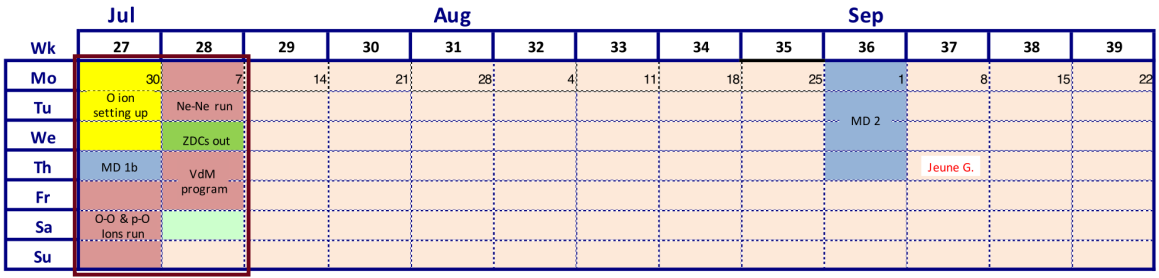

OO

(nb^{-1})	target	delivered	ratio
ATLAS	**0.8**	8.2	10.3
ALICE	**0.5**	5.15	10.3
CMS	**0.8**	9.4	11.8
LHCb	**0.5**	5.75	11.5

NeNe

(nb^{-1})	target	delivered	F
ATLAS	0.1	1.0	10
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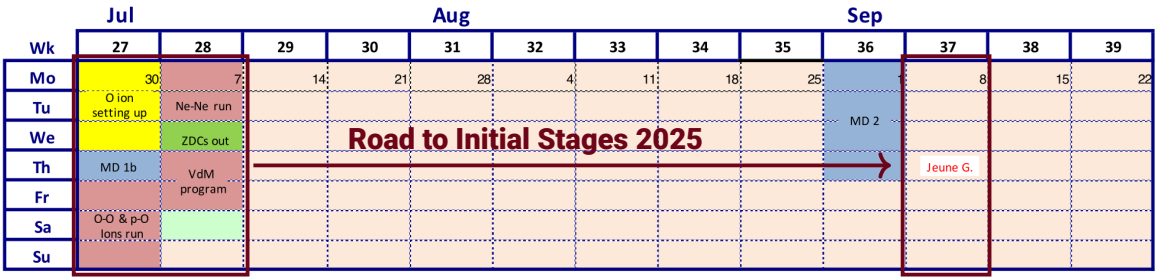
Via LHC report at Sept. Jamboree

Luminosity Delivered in Light Ions at the LHC



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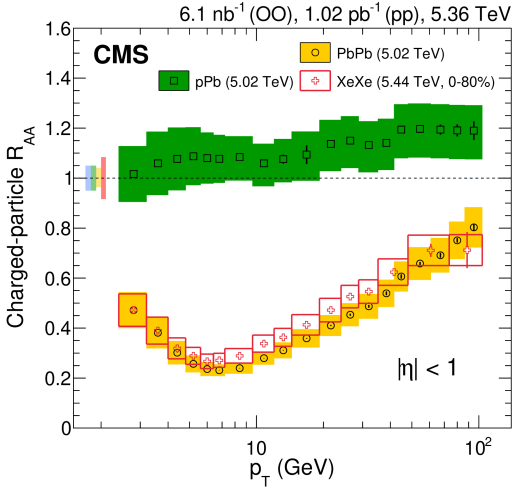
Will we see the onset of quenching?

Via LHC report at Sept. Jamboree

CMS Charged-Particle R_{AA} in OO



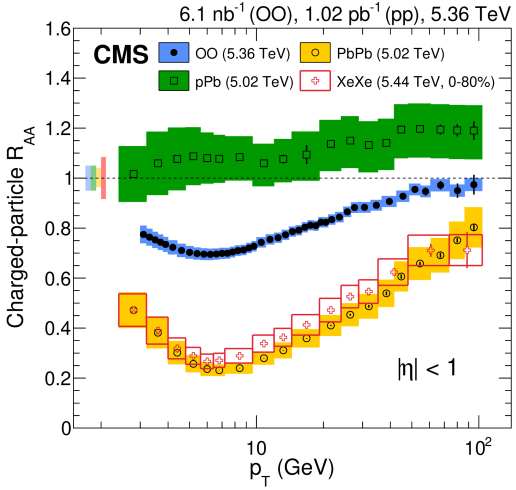
CMS charged-particle spectra

- **Measure inclusive in centrality → avoid Glauber modeling**
- **Take R_{AA} definition as:**

$$R_{AA} = \frac{1}{A^2} \frac{d\sigma_{OO}/dp_T}{d\sigma_{pp}/dp_T}$$

Adapted from PRL 136 (2026) 162301

CMS Charged-Particle R_{AA} in OO



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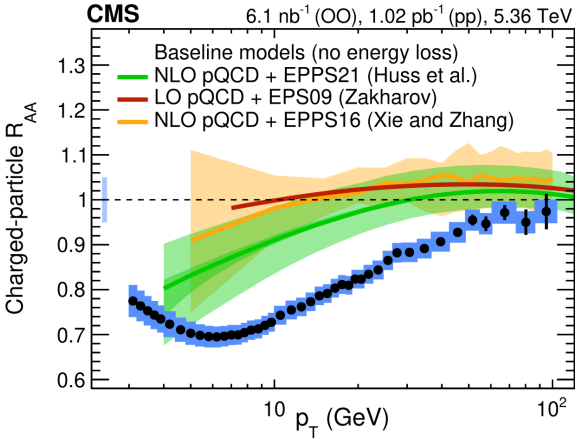
$$R_{AA} = \frac{1}{A^2} \frac{d\sigma_{OO}/dp_T}{d\sigma_{pp}/dp_T}$$

- **Suppression, $\sim 7\sigma$ significance**
- **$\sim$0.69 at 6 GeV**

Adapted from PRL 136 (2026) 162301

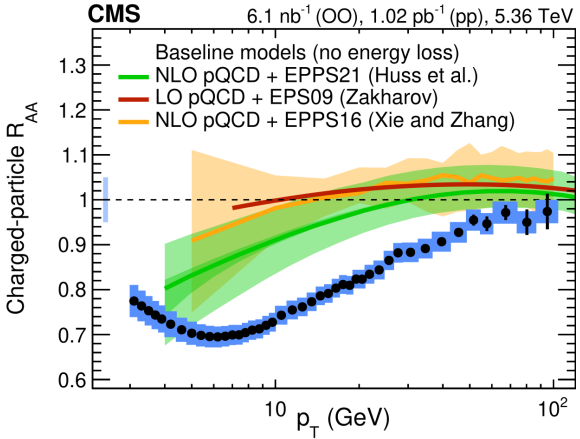
Comparison to Baseline without Quenching

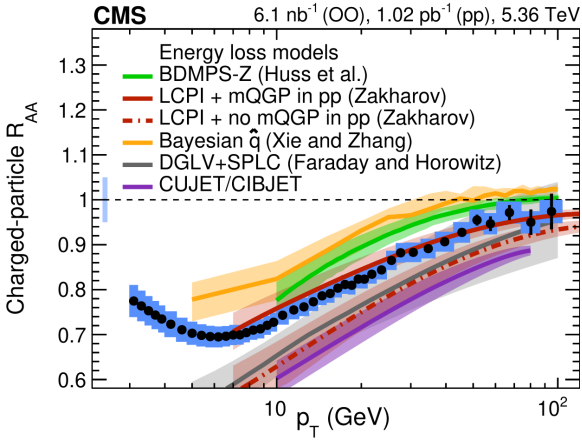


Adapted from PRL 136 (2026) 162301

- **nPDF effects can explain some fraction of observed suppression**
- **This measurement alone insufficient for quenching observation**
- **EPPS21 approximately 2σ from data**
  - **pO data crucial for constraining nPDFs!**

Comparisons To Quenching Models

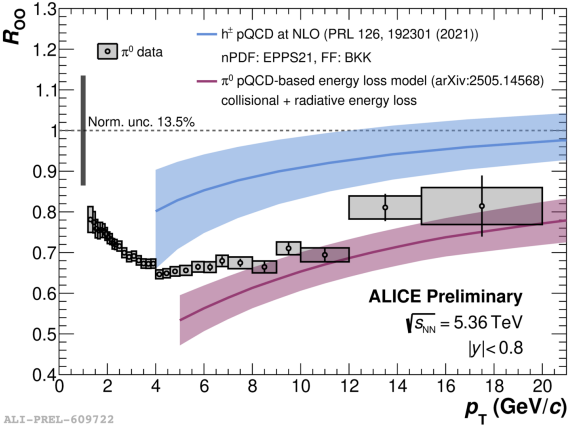




Adapted from PRL 136 (2026) 162301

- **However, data is clearly best described with quenching models!**

Preliminary ALICE π^0 R_{AA} in OO

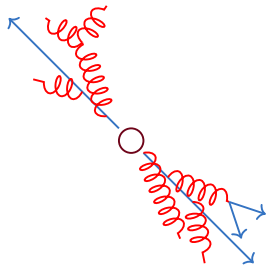


ALICE Preliminary

- **Significant suppression observed in independent measurement!**
- **Comparison w/ CMS must come with caveats**
  - **π^0 vs. all charged-particles**
  - **Different acceptance in η**
- **Qualitative agreement in overall suppression with CMS**
- **Shared limitations from nPDF effects**
  - **Stay tuned; ALICE resolves!**

Dijet Balance as a Quenching Probe

Consider a qq hard-scattering:



- **Parton will fragment+hadronize**

Dijet Balance as a Quenching Probe

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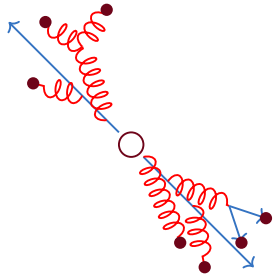

- **Parton will fragment+hadronize**
- **We have focused on hadrons**

Dijet Balance as a Quenching Probe

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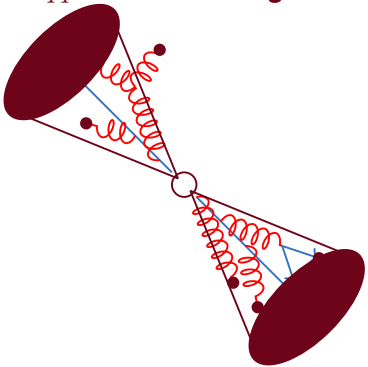

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- **What about at the jet level?**

Dijet Balance as a Quenching Probe

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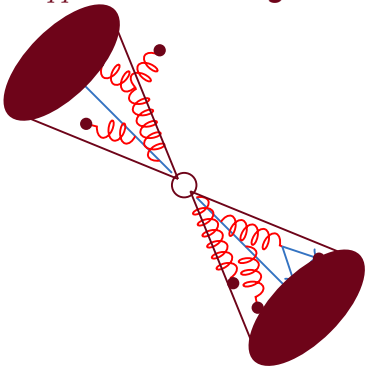
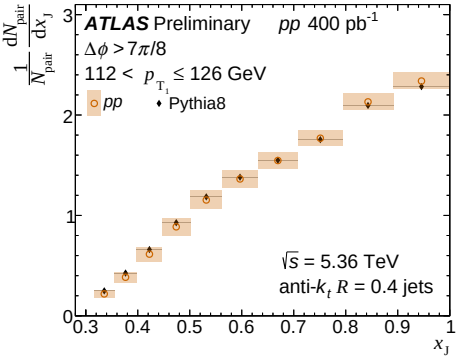


- **Parton will fragment+hadronize**
- **We have focused on hadrons**
- **What about at the jet level?**

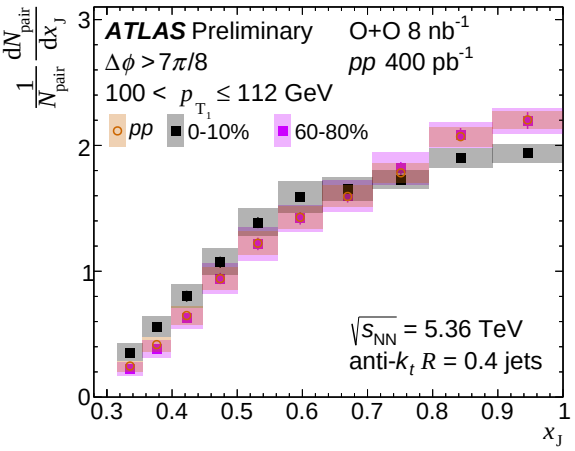
Consider x_J = $p_{T,SubleadingJet}$ / $p_{T,LeadingJet}$

Via ATLAS-CONF-2025-010



- **Well-modeled by PYTHIA in pp**

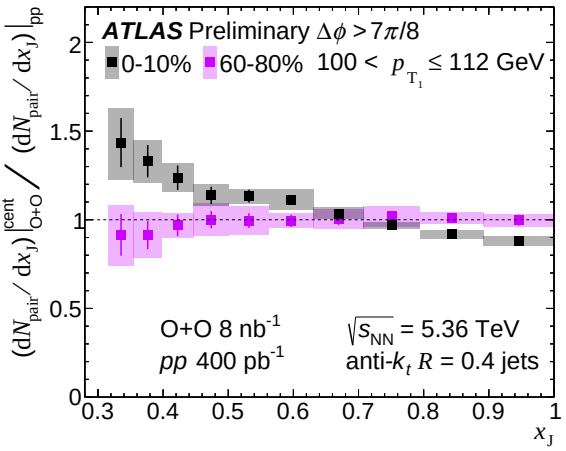
Preliminary Dijet Balance in OO with ATLAS



ATLAS-CONF-2025-010

- **Jet measurements have reduced sensitivity to nPDFs**
- **Differential in centrality → stronger quenching potential**

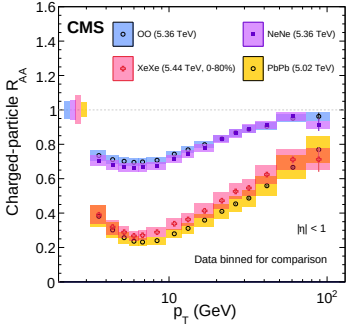
Preliminary Dijet Balance in OO with ATLAS

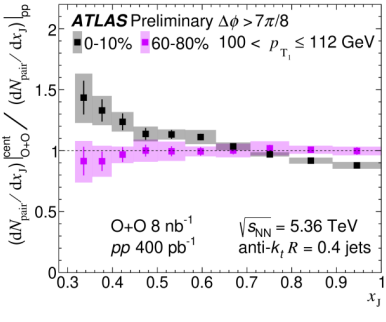


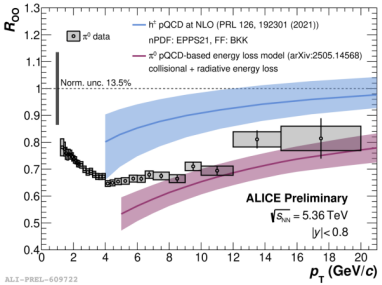
ATLAS-CONF-2025-010

- **Jet measurements have reduced sensitivity to nPDFs**
- **Differential in centrality → stronger quenching potential**
- **Uncertainties highly correlated → cancel in ratio**
- **Centrality-dependent enhancement of asymmetric x_J!**

Big Picture in 2025: Quenching Models Preferred

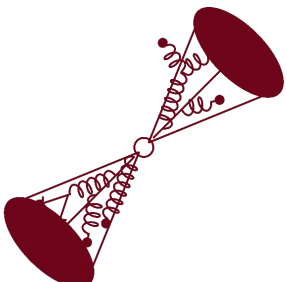






- **Each experiment's results come with caveats regarding significance of quenching**
- **Considered together, a strong case for the formation of a QGP**

Light Ions Results in 2026



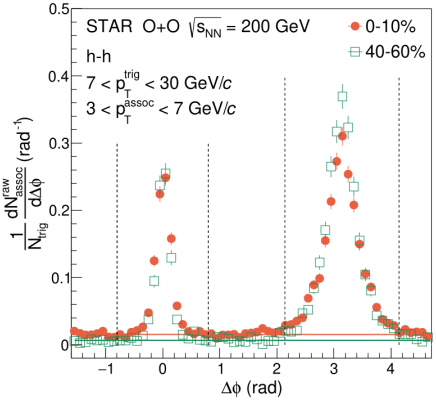
Explosion of Results from Light Ions

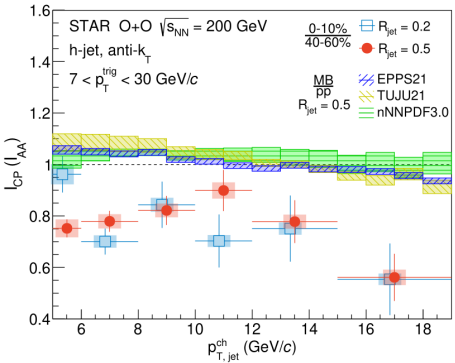
From SQM to HardProbes, an incomplete selection:

- **dN/dη from ATLAS, CMS, and ALICE**
- **Flow results from ATLAS, CMS, ALICE, and LHCb**
- **HF production from LHCb and HF flow results from ALICE**
- **Many new results in strangeness from ALICE at SQM and CMS at HP**
- **New quarkonia measurements with CMS Upsilon and ALICE J/Psi**

New STAR Evidence of Quenching (I)

Submitted PRL, supersedes preliminary shown earlier





- **Re-analysis of hadron-hadron and hadron-jet correlations in 2021 OO data**
- **Study w/ I_{CP}, using 40-60% centrality as a reference**
  - **Similar to R_{AA}, except per trigger hadron and no pp reference**

New STAR Evidence of Quenching (II)

Submitted PRL, supersedes preliminary shown earlier

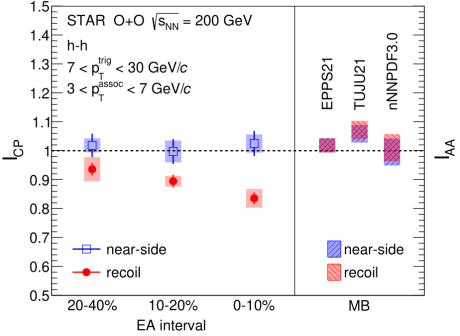


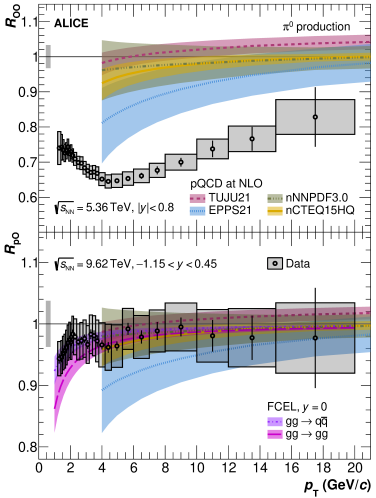
TABLE I. Significance of recoil yield suppression in h-h and h-jet correlations in the 0-10% EA population, compared to several different choices of no–quenching baseline. See text for details.

Baseline	h-h recoil	h-jet, $R = 0.5$	h-jet, $R = 0.2$
Unity	4.3σ	4.3σ	3.5σ
h-h near side	3.3σ	N/A	N/A
EPPS21	4.0σ	4.8σ	3.5σ
TUJU21	5.2σ	4.9σ	3.7σ
nNNPDF3.0	2.7σ	5.0σ	3.7σ

- **Left: Hadron-hadron I_{CP}, integrated over p_T, w/ MB nPDF expectation.**
- **Right: Significance of deviation from unity under different nPDF assumptions**
- **Emergent light-ions quenching picture shared between RHIC and the LHC!**

New ALICE Evidence of Quenching w/ π^0

Submitted PRL, supersedes 2025 preliminary shown earlier



ALI-PUB-636169

- Reduced luminosity uncertainty + added pO data

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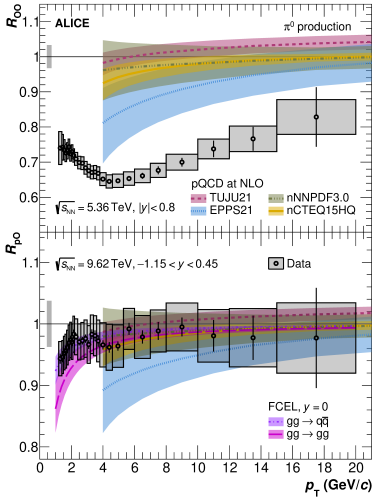
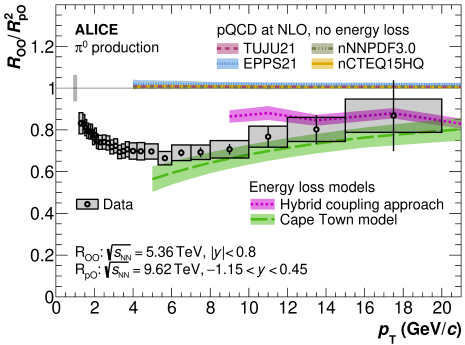


ALI-PUB-636169

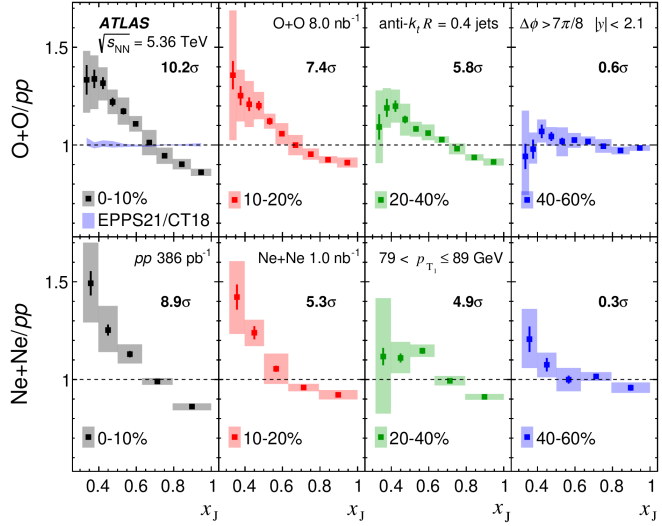
- **Reduced luminosity uncertainty + added pO data**
- **$R_{OO}/ R_{pO}{}^2 \rightarrow$ nPDF effects largely cancel!**
- **Achieved 4.9σ significance**



ALI-PUB-636174

New ATLAS Observation of Quenching w/ Dijets

Submitted PRL, supersedes 2025 preliminary shown earlier

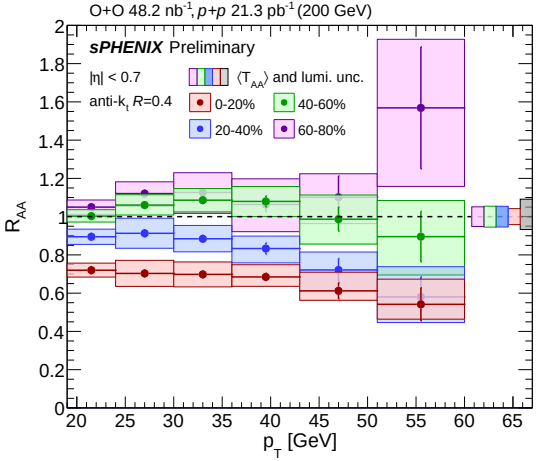


Updates from the preliminary:

- **Added NeNe data (bottom row)**
- **Took ratio of x_J in light ions w/ pp**
  - **Accounts for correlations in syst.**
- **Significance exceeds 5σ compared to nPDFs; quenching observed!**

sPHENIX Inclusive Jet R_{OO}

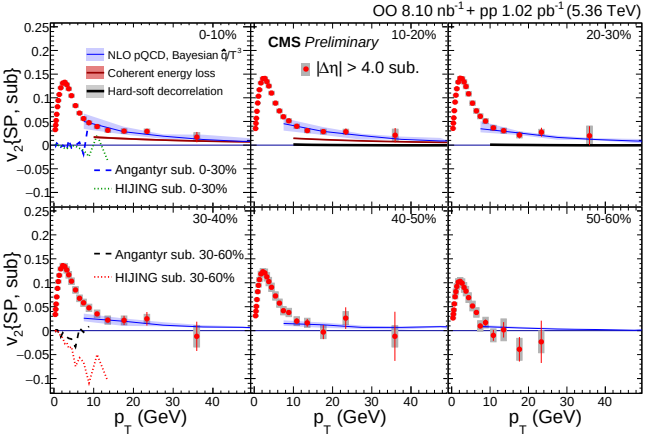
sPH-CONF-JET-2026-02



- **Measured inclusive jet spectra in OO**
  - **Extracted nuclear modification factor**
- **Centrality-dependent suppression**
- **N.B. this data was taken in February 2026!**
  - **Just 4 months to measurement**

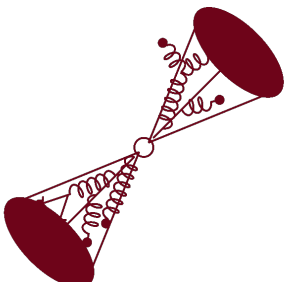
CMS High-p_T v_2 in OO

CMS-PAS-HIN-26-005



- **Recall: high-p_T v_2 in pPb w/o observable quenching**
- **Via CMS measurement, we have high-p_T v_2 in OO**
- **Need to disentangle quenching v. other contributions to signal**
  - **Challenge: can we describe PbPb, OO, and pPb simultaneously?**

Future Directions



So You Found Quenching: Now What?

With quenching established, we can move to jets-as-probes.

Light ions can offer advantages over heavy ions; 2 examples:

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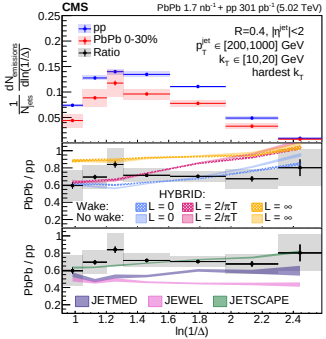
Light ions can offer advantages over heavy ions; 2 examples:

- **Reduced backgrounds, improved substructure measurements**



Submitted PRL

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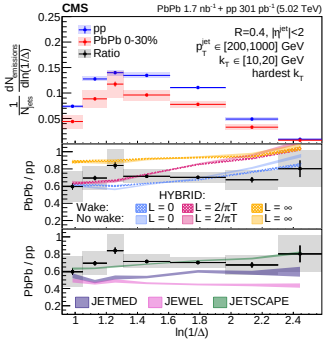
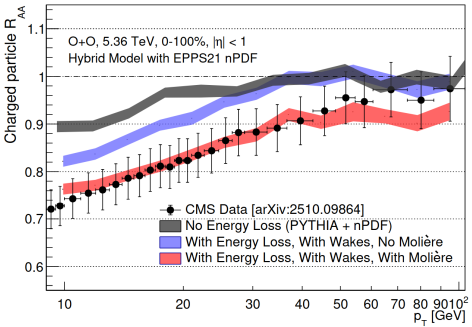


Submitted PRL

- **Changes in relative importance of physics effects**



Kudinoor et al.

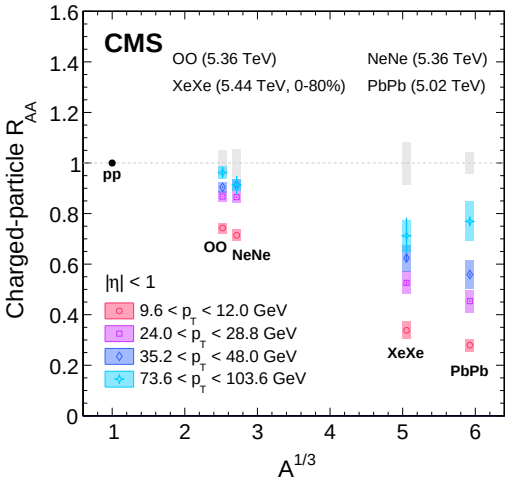
Isolating Initial Stages w/ System Scans?

- Several talks w/ calculations of energy loss from QGP v. pre-QGP phase
  - PbPb, OO (w/ interest in pPb!)
- Is there an observable where a system scan isolates pre-QGP effects?

Isolating Initial Stages w/ System Scans?

- **Several talks w/ calculations of energy loss from QGP v. pre-QGP phase**
  - **PbPb, OO (w/ interest in pPb!)**
- **Is there an observable where a system scan isolates pre-QGP effects?**
- **System size scans already in-hand**
  - **Is this set of nuclei optimal for you?**

Submitted PLB



Future Prospects for Light Ions at the LHC (I)

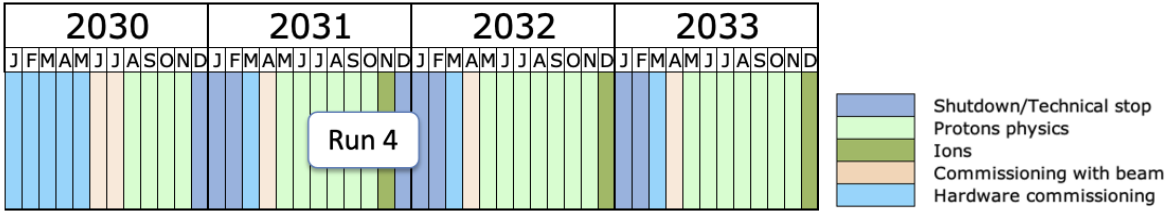
If you are interested in more light ions data, some considerations:

- **Two items that ease the constrained-resources problem (neither guaranteed):**
  1. **Pilot runs akin to the July 1st-9th period of 2025 (and XeXe in 2017!)**
  2. **Second source+injector system for easier system switches (and asymm. collisions)**

- **We should be advocating collectively as a field for both of the above**

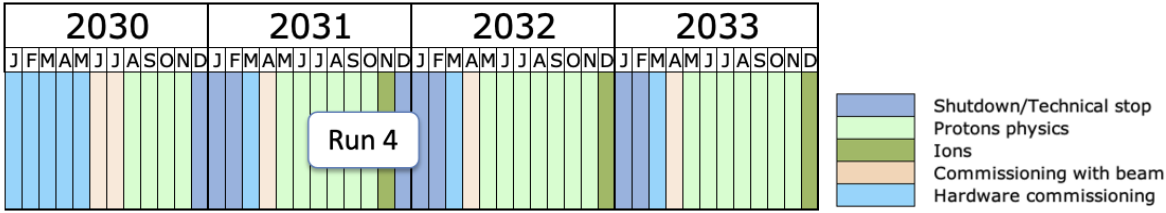
- **Otherwise, we have our designated run periods in Run 4 and Run 5**
  - **Based on previous presentations from ALICE, ALICE 3 in Run 5 strongly prefers PbPb**
  - **Our opportunity, if any, is therefore in Run 4, which coincides nicely with many upgrades**

Future Prospects for Light Ions at the LHC (II)



3 dedicated heavy-ion periods, with detector upgrades generally improving η coverage:

Future Prospects for Light Ions at the LHC (II)



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- **One of these three run periods should be pPb (asymmetric, forward-η coverage!)**
- **One should be PbPb for new analyses in heavy ions enabled with upgrades**

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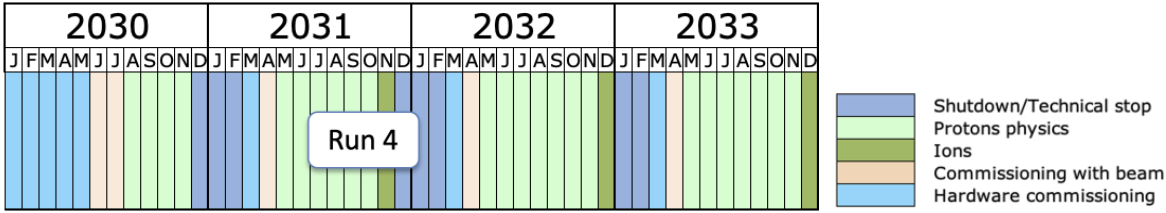
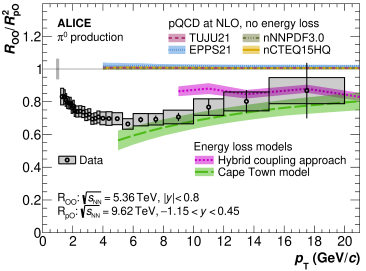
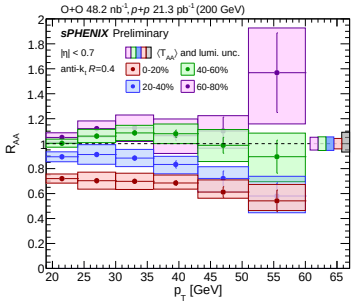


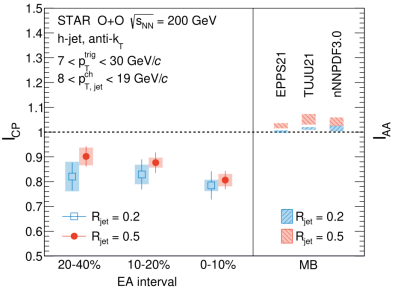
3 dedicated heavy-ion periods, with detector upgrades generally improving η coverage:

- **One of these three run periods should be pPb (asymmetric, forward-η coverage!)**
- **One should be PbPb for new analyses in heavy ions enabled with upgrades**
- **Remaining: if PbPb, doubles Run 4 statistics but will likely lag Run 3 total**
  - **A dedicated period for a new ion species should be considered as an alternative**

Conclusion



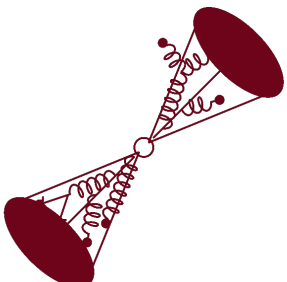




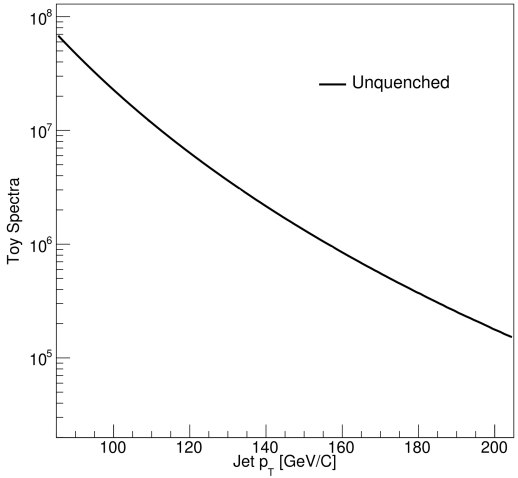
- **Consistent picture at RHIC and LHC: light ions data indicates quenching**
- **New directions with existing data: substructure, system-size scans**
- **More exciting opportunities w/ future runs at the LHC!**
  - **We should be carefully exploring options in Run 4**

What would the people in this room like to see (now and future) from experiment?

Backup

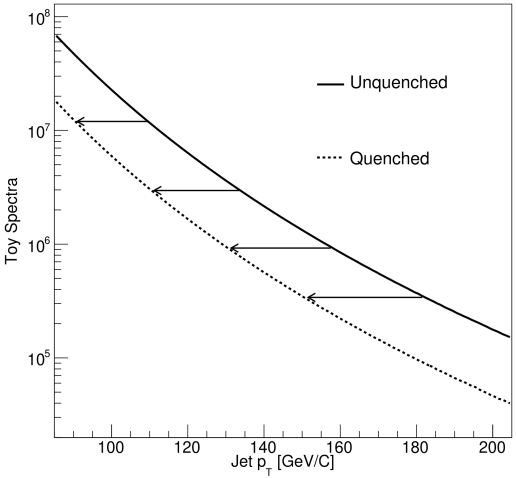


Energy Loss and Spectra



$$R_{AA}\ (R_{pA}) = \frac{\text{Spectra in AA (pA)}}{\text{Spectra in pp, scaled by \# of nucleon-nucleon collisions}}$$

Energy Loss and Spectra



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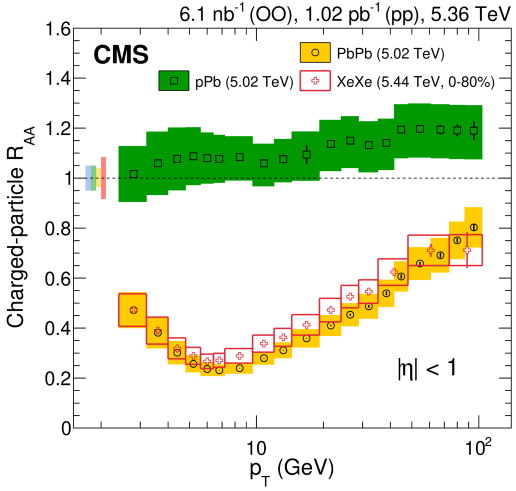
Quenching shifts spectra left $\rightarrow$ R_{AA} (R_{pA}) suppressed!

Energy Loss and Spectra



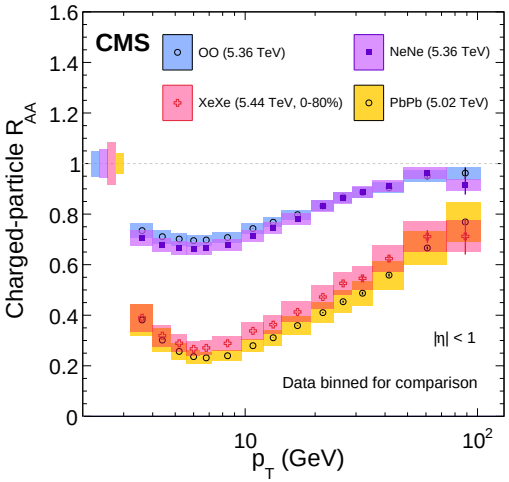
R_{AA} (R_{pA}) = **Spectra in AA (pA) / Spectra in pp, scaled by # of nucleon-nucleon collisions**

Quenching shifts spectra left →
R_{AA} (R_{pA}) suppressed!

No such shift observed in R_{pA}

Adapted from PRL 136 (2026) 162301

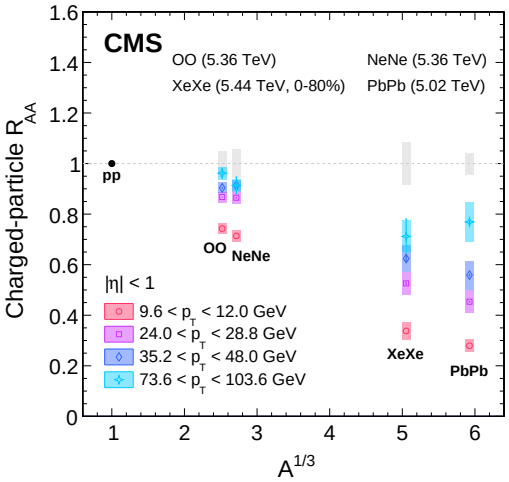
Measurement of R_{AA} in NeNe Collisions



Submitted PLB

- Measured charged-particle R_{AA} in NeNe collisions!
- Slight increase in observed suppression
  - O: 16 nucleons
  - Ne: 20 nucleons
- Need to take normalization uncertainties seriously!

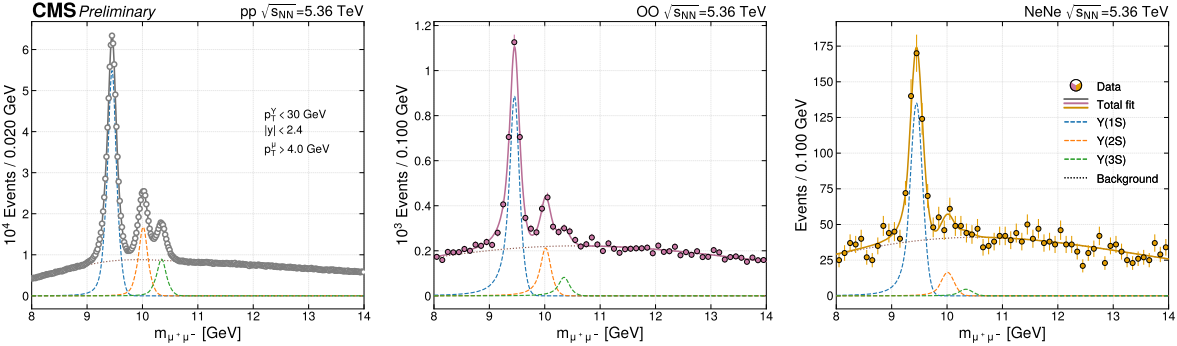
Dependence of R_{AA} vs. $A^{1/3}$



Submitted PLB

- LHC AA quenching data now spans many systems!
- We can now consider ordering in A^n
- Plot vs. $A^{1/3}$ as a path-length proxy
  - Qualitative linearity on inspection
- Important follow-ups:
  - pO data for nPDF constraints
    - (ATLAS first look!)
  - Centrality-differential R_{AA}

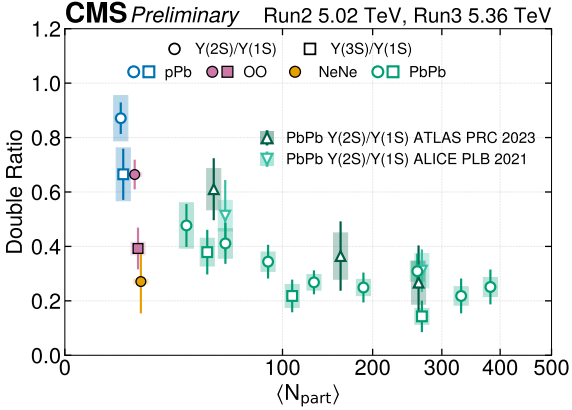
Upsilon 1s, 2s, and 3s with CMS



CMS-PAS-HIN-25-015

- **Sequential quarkonia suppression → different mechanism than quenching**
- **Offered here as parallel evidence of miniature QGP formation**

Upsilon Suppression in OO and NeNe with CMS



CMS-PAS-HIN-25-015

- **Significant suppression for 2s/1s and 3s/1s in OO**
  - **2s/1s suppression observed in NeNe**
- **Suppression appears intermediate between pPb and PbPb**
- **All probes of QGP formation being pursued in light ions!**