Recent CMS light ions results

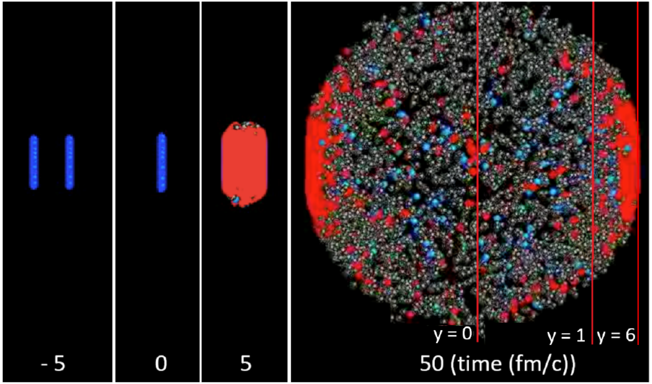
Chris McGinn

BNL NP Seminar

14 October 2025

MITHIG group's work was supported by US DOE-NP

Schematic of Heavy Ion Collisions



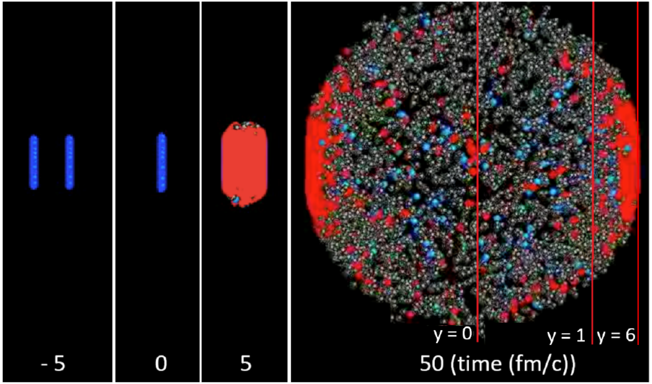
1 2 3 4

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



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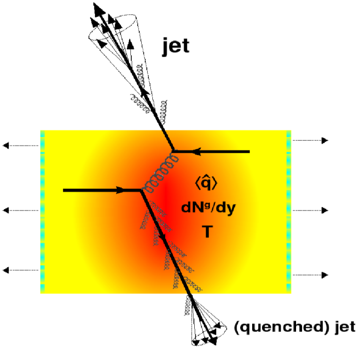
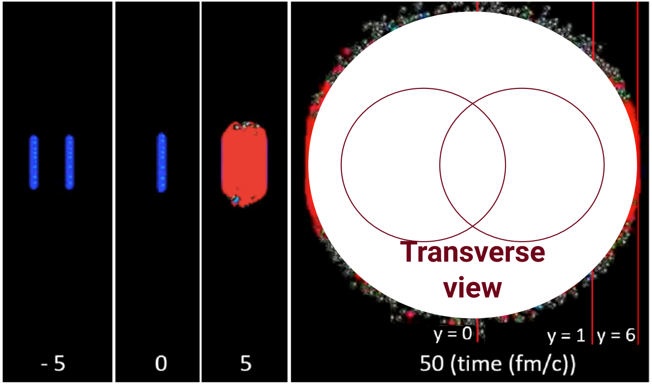


Via D. d'Enterria

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

Geometry to Momentum Space Correlations



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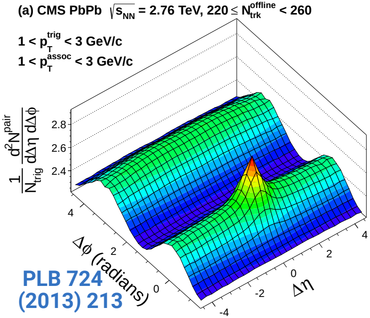


PLB 724 (2013) 213

Initial state geometry in AA $\rightarrow$ long range correlations via hydro.

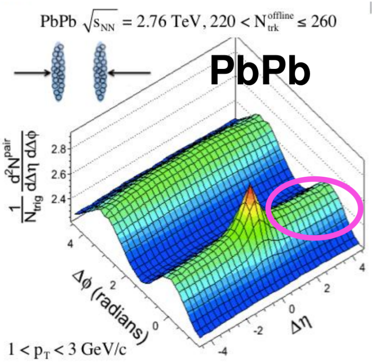
$\sim$ **1 + 2** $\Sigma_n v_n^2$**cos**$(n\Delta\phi)$

v$_2$ $\rightarrow$ **ellipticity**

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

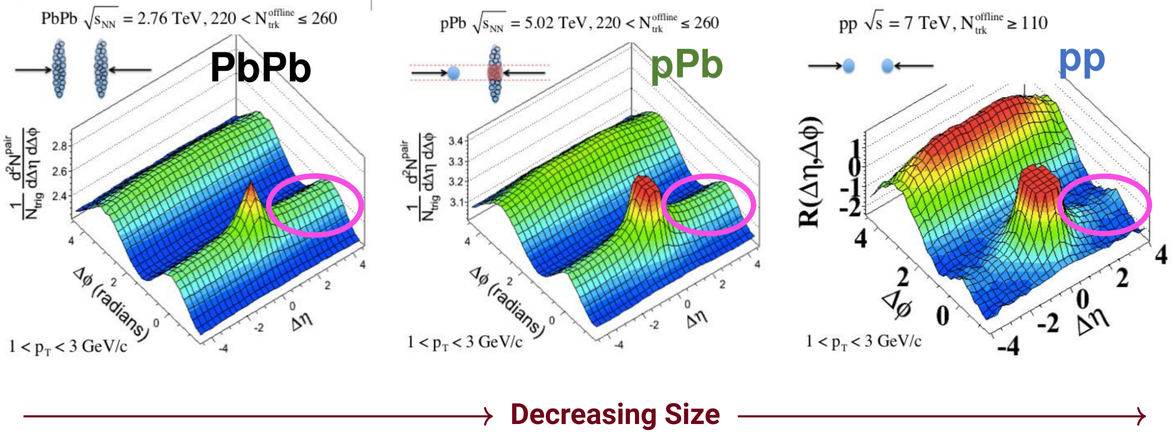
A Droplet of Plasma in Small Systems?

PLB 724 (2013) 213



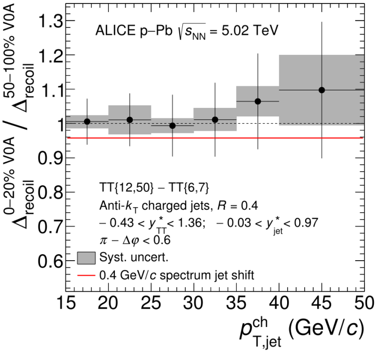
A Droplet of Plasma in Small Systems?

PLB 724 (2013) 213 PLB 765 (2017) 193

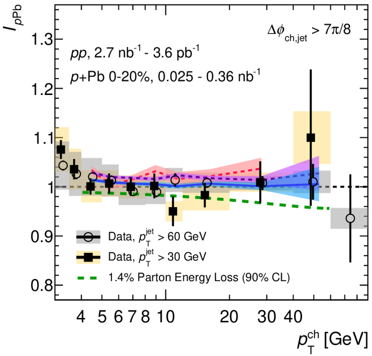


- **Observable phenomena in collisions systems of all sizes!**
- **Possible signature of QGP droplet formation in small systems?**

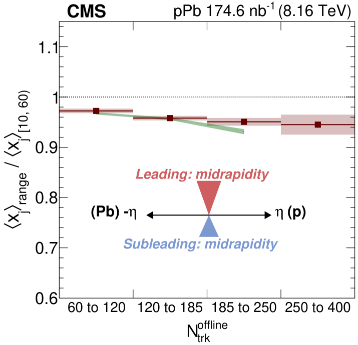
Complication: Where Is Quenching?



PLB 783 (2018) 95



PRL 131 (2023) 072301



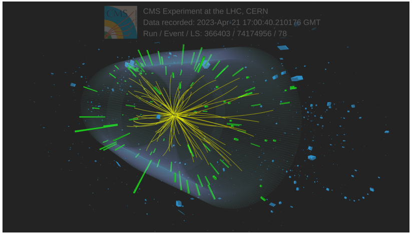
JHEP 07 (2025) 118

- **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**

Probing Many Geometries at the LHC

Increasing Size

pp

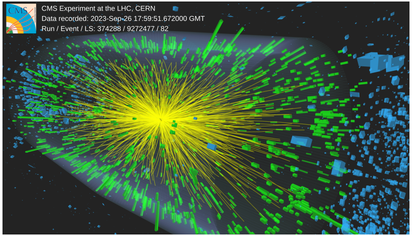


γPb (UPCs)

pPb

XeXe

PbPb



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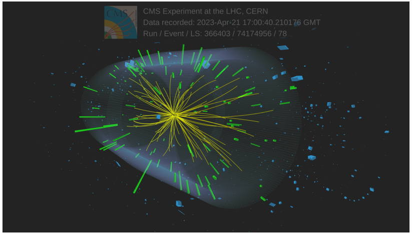

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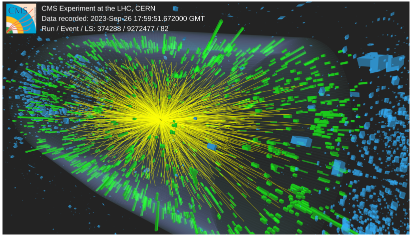

See flow-like v_2

Probing Many Geometries at the LHC

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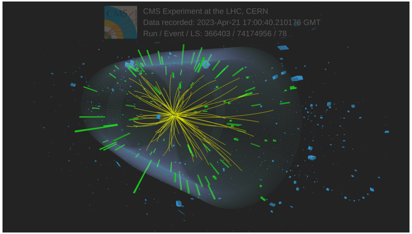

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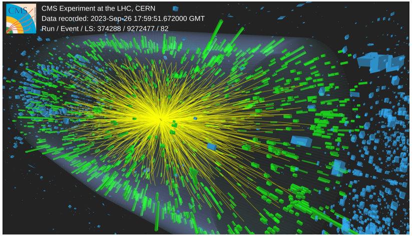


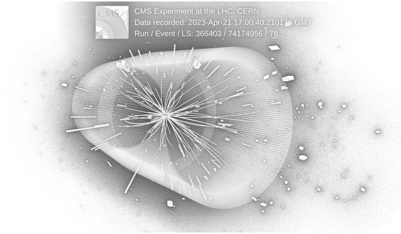
See flow-like v_2

See quenching

Probing Many Geometries at the LHC

Increasing Size

pp



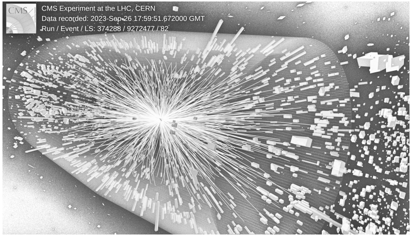
γPb
(UPCs)

pPb
pO

OO
NeNe

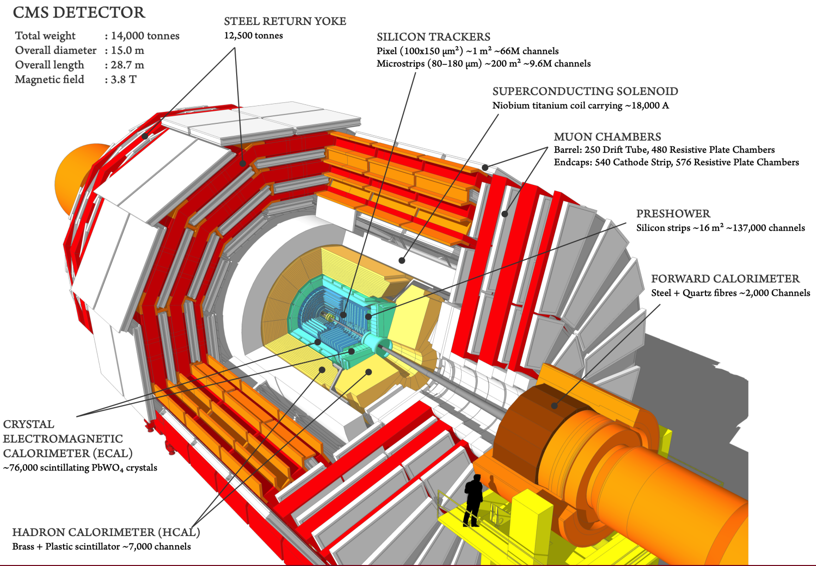
XeXe

PbPb



1. **Study the relationship between system-size and particle production w/ $dN/d\eta$**
2. **Probe the nuclear structure with v_2 and v_3 in each system**
3. **Search for partonic energy loss in light ions**

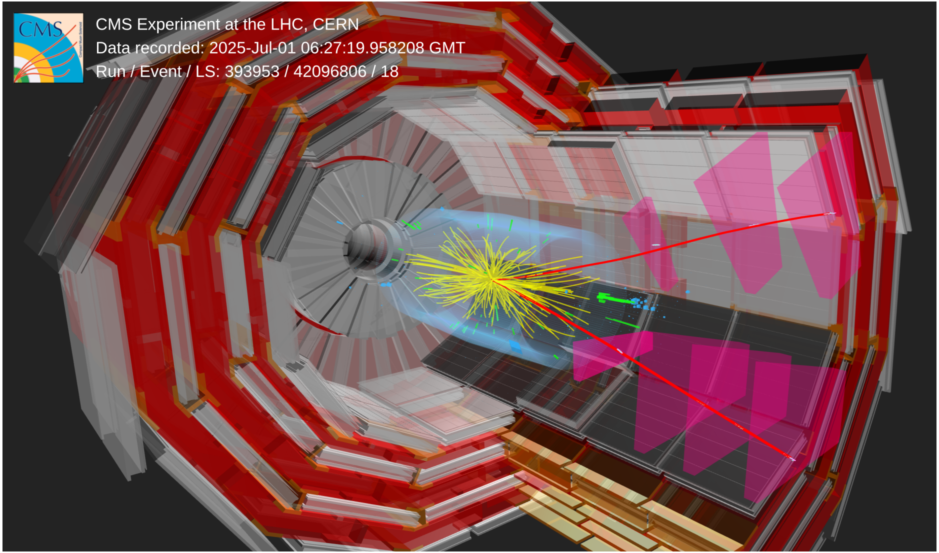
The CMS Detector



Study of HI enabled by The CMS Detector

- Silicon trackers for charged hadrons
- ECAL for photons / π^0
- HCAL for neutrals
- Forward calorimeters for centrality
- Muon chambers and ZDC (used minimally in these analyses)

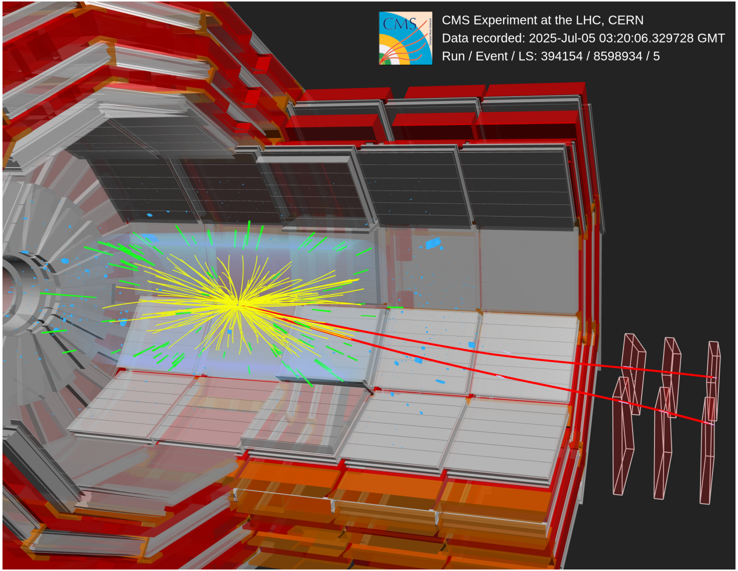
Datataking for pO,



Data taken July 1st-3rd

pO event displays via CDS

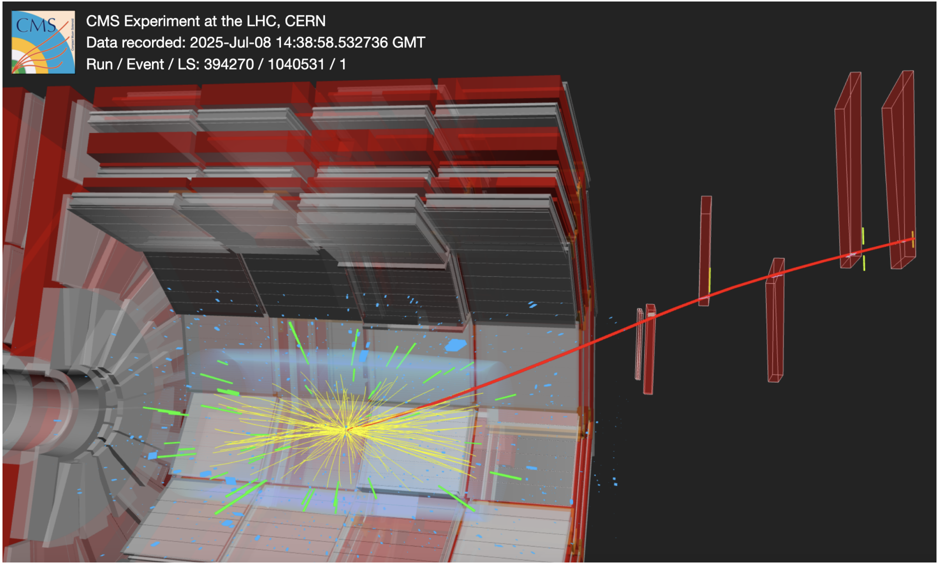
Datataking for pO, OO,



Data taken July 5th-7th

OO event displays via CDS

Datataking for pO, OO, and NeNe!



Data taken July 8th-9th

NeNe event displays via CDS

Luminosity Delivered in Light Ions

Wk	27 (Jul)	28	29	30	31 (Aug)	32	33	34	35	36 (Sep)	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													

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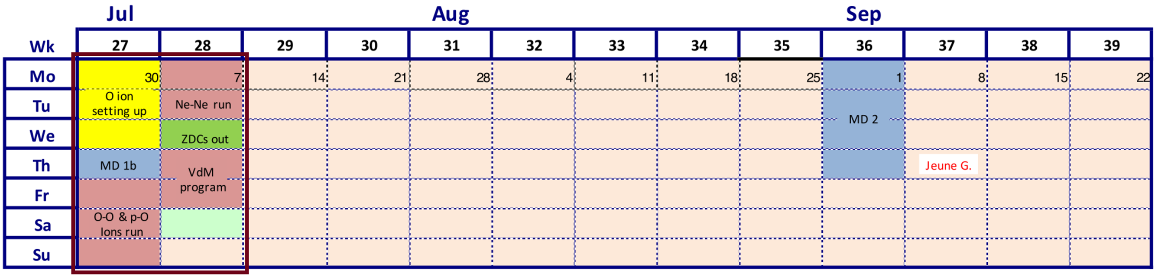

OO

(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
ALICE	0.1	0.91	9.1
CMS	0.1	0.91	9.1
LHCb	0.1	0.61	6.1

Only experiment w/ VdM in NeNe!

Via LHC report at Sept. Jamboree

Luminosity Delivered in Light Ions

	Jul				Aug					Sep			
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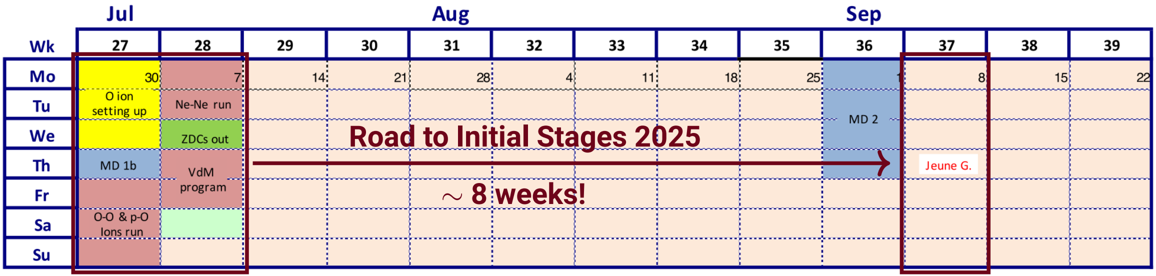

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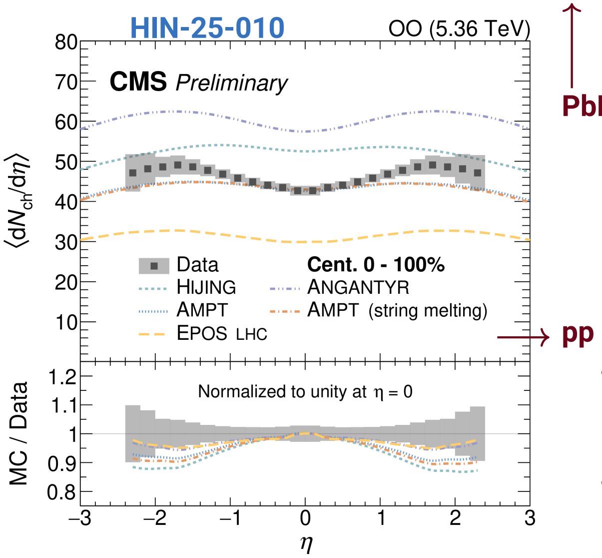
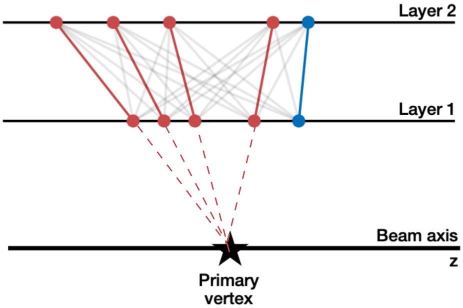
Via LHC report at Sept. Jamboree

$dN/d\eta$ in Light Ions

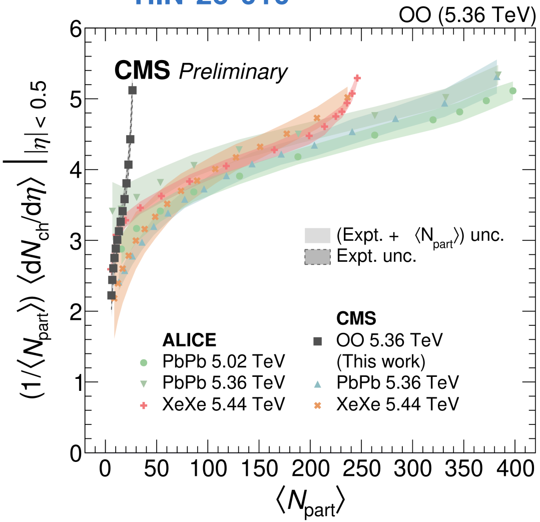




- **Measured with pixel tracklet combinations from inner silicon layers**
- **$\sim$40-50 depending on η in OO**
  - **Compare w/ just $\sim$6 in pp**
  - **$\sim$600 in PbPb (off plot scale!)**

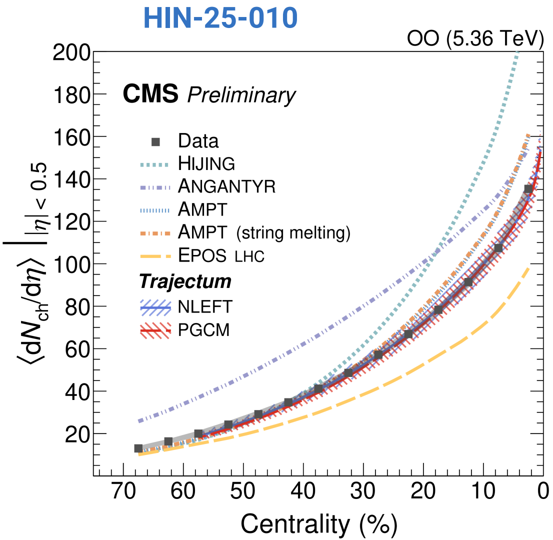
N_{part} dependence of $dN/d\eta$

HIN-25-010



- N_{part} scaled average $dN/d\eta$ in N_{part} bins
- Observe a steep slope as a function of N_{part} compared to other species
- At central-most OO, achieve density akin to heavy-ions
  - Full nuclear-overlap $\rightarrow$ similar particle production per nucleon

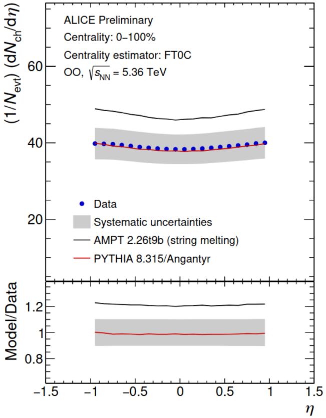
Centrality dependence of $dN/d\eta$

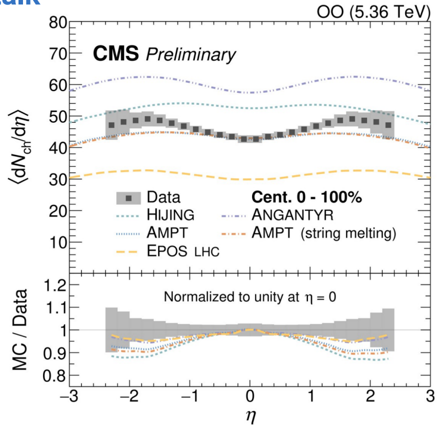


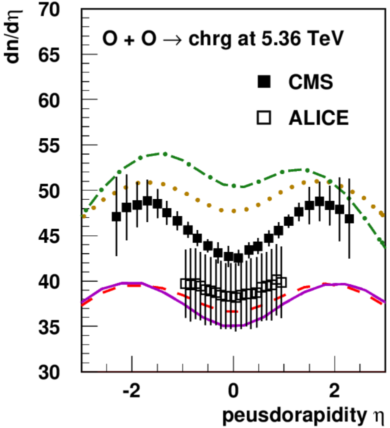
- **Comparing w/ models as a function of centrality**
- **Hydro. models w/ different nuclear structure assumptions (Trajectum) show good agreement**
  - **Note: restricted to mid-rapidity, $|\eta| < 0.5$**
- **MC EPOS LHC and HIJING fare worse - important input for tuning!**

Comparisons with ALICE

Via T. Pierog ISMD talk

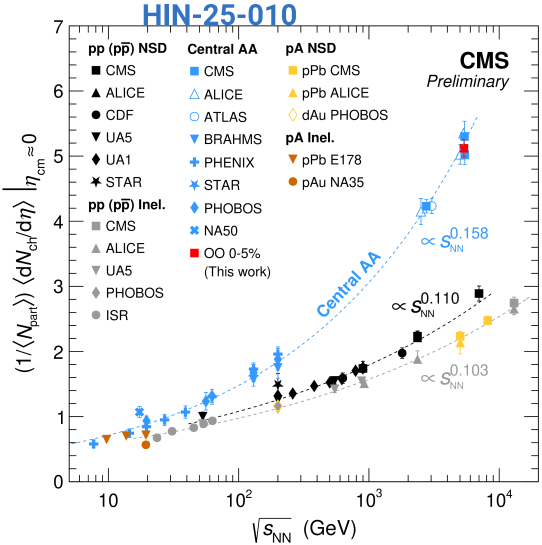






- Comparison just a the $dN/d\eta$ level, no Glauber modeling
- Results consistent between 1-2σ; already being studied by modeling community!

OO $dN/d\eta$ in the Global Picture



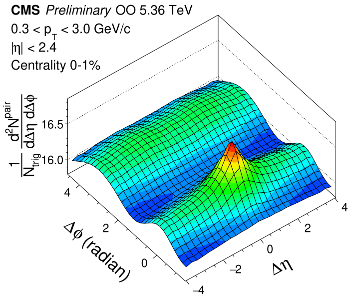
- **OO $\rightarrow$ heavy-ions like particle production**
- **Not simply an incoherent superposition of proton-proton collisions**
  - **Rather, energy more efficiently converted to final-state multiplicities**

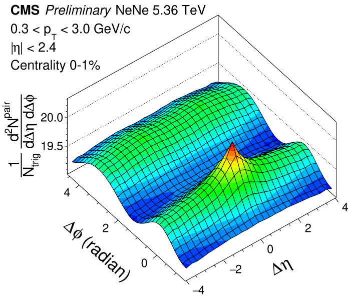
Motivating Flow in Light Ions

- **Do we see collectivity in light-ions?**

Motivating Flow in Light Ions

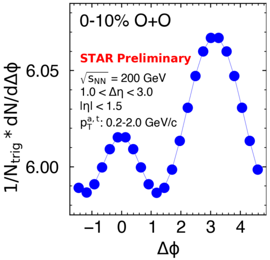
- Do we see collectivity in light-ions? (Answer: Yes!)





CMS-HIN-25-009

Via S. Zhang QM Talk

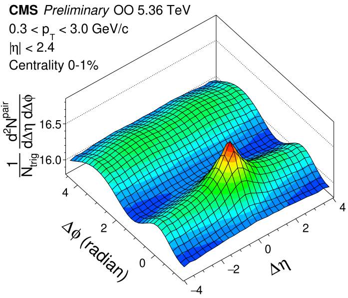


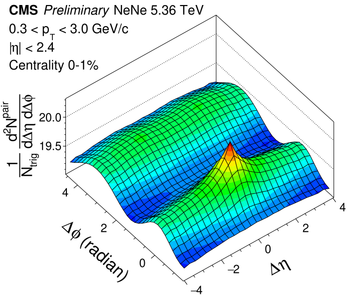
Known from STAR!

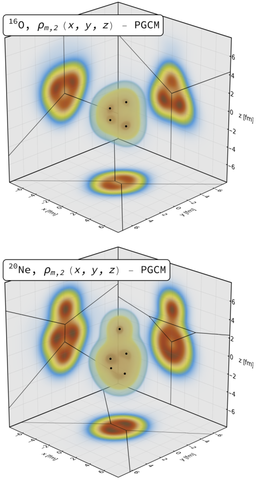
- How do the signs of collectivity evolve w/ centrality in light-ions compared to heavy-ions?

Motivating Flow in Light Ions

- **Do we see collectivity in light-ions? (Answer: Yes!)**







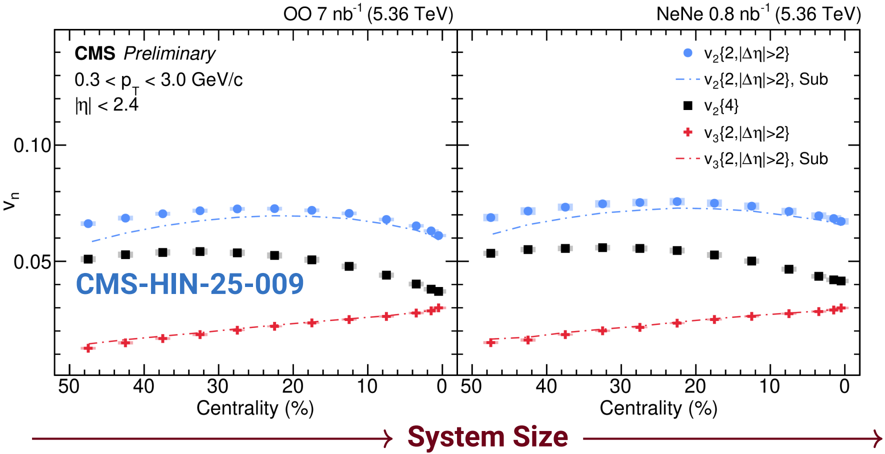
CMS-HIN-25-009

- **How do the signs of collectivity evolve w/ centrality in light-ions compared to heavy-ions?**

- **OO/NeNe: similar nucleon numbers, but different geometry**
  - **Should imprint on v_2 ratio; are we sensitive?**
  - **Like STAR probe of U-deformation, Nature 635 (2024) 8037**

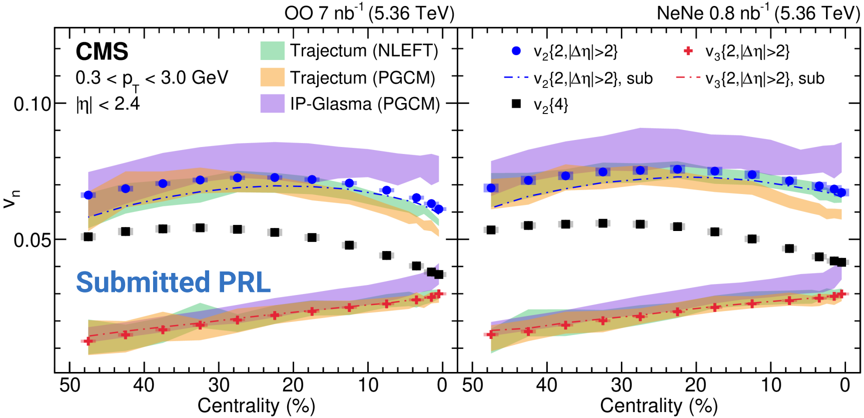
PRL 135 (2025) 012302

Measuring $v_{n\{n\}}$ in OO and NeNe



- **Measured $v_2\{2\}$ +$v_3\{2\}$ w/ and w/o subtraction, and $v_2\{4\}$ in OO and NeNe**
- **v_2 behavior qualitatively similar to heavy-ions expectation**
- **v_3 strictly increasing as centrality $\rightarrow$ 0% contra HI; impact of fluctuations?**

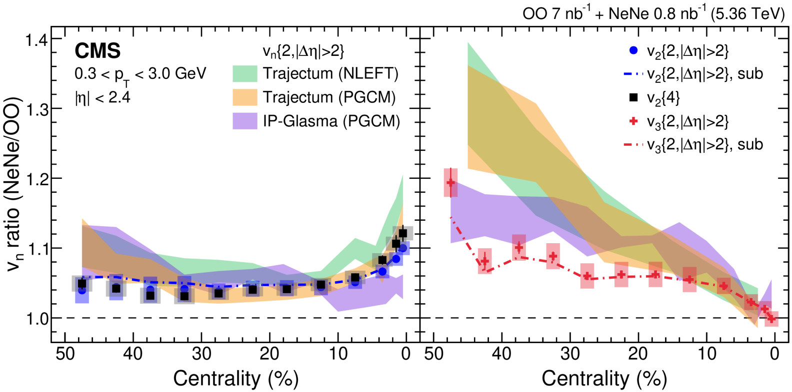
Comparing v_2 with Models

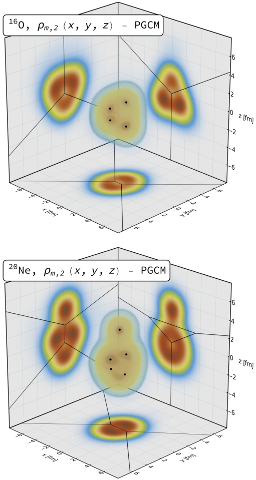


System Size

- **Reasonable qualitative agreement observed with hydro models in OO and NeNe**
  - **NLEFT appears modestly better than PGCM**
- **IP-Glasma+PGCM fares worse; impact of greater fluctuation in initial conditions?**

Ratio of $v_2\{2\}$ in OO and NeNe



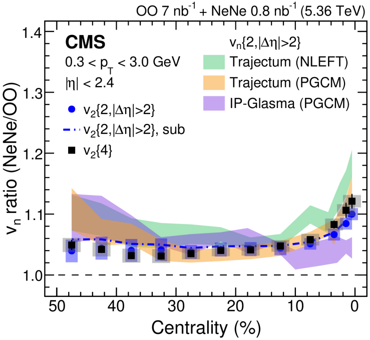


- **Uptick in $v_2\{2\}$ as centrality $\rightarrow$ 0%**
- **Indicative of nuclear deformation present in neon!**
  - **'Bowling pin' structure compared to more symmetric oxygen**

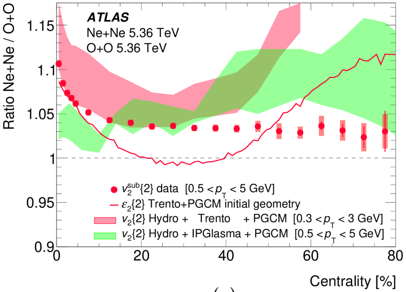
PRL 135 (2025) 012302

Comparing to ATLAS and ALICE

Note: Flipped x-axis!

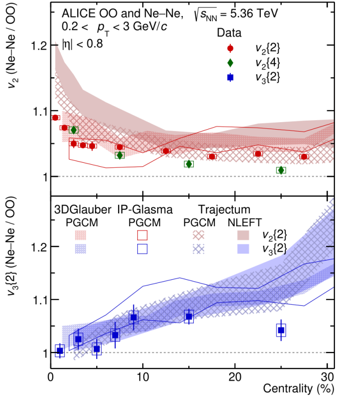


Submitted PRL



(a)

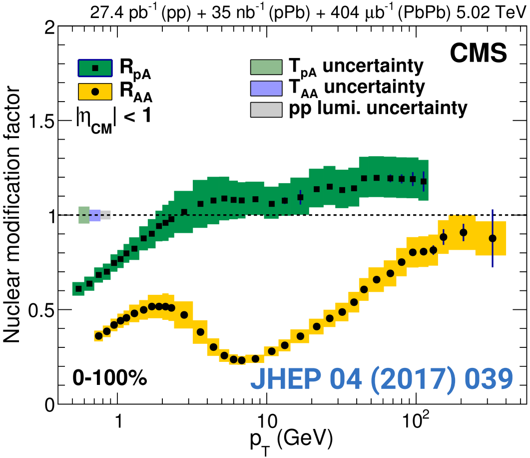
Submitted Phys. Rev. C



Submitted PRL

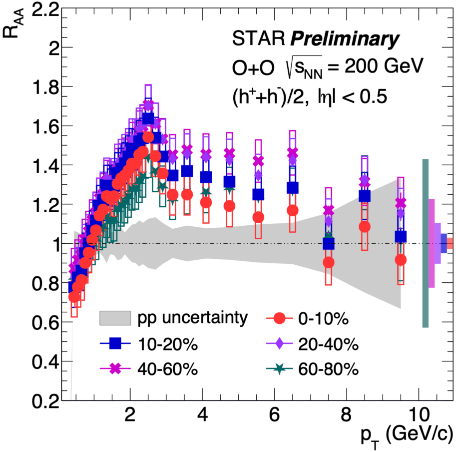
- Qualitatively consistent trend across all three experiments in OO/NeNe v_2 vs centrality
- All pointing towards sensitivity to nuclear deformation via correlations

Motivating a Quenching Search in Light Ions



- One manifestation of quenching → high-p_T particle suppression
- Long-observed in AA, absent in pA
- Measure in light ions to establish where quenching effects turn-on

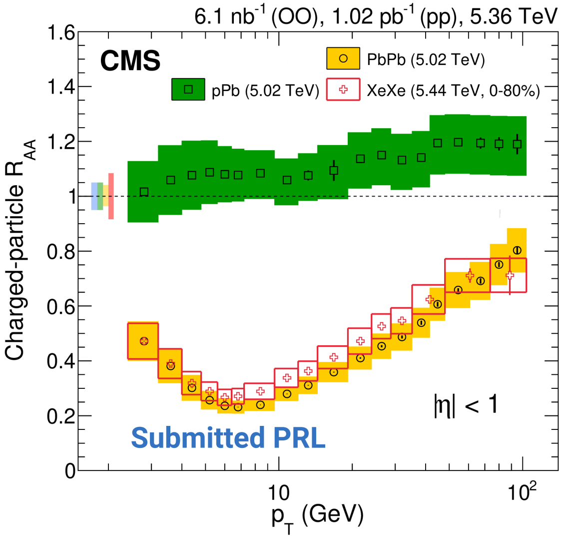
Existing Results from STAR at RHIC



Via S. Zhang QM Talk

- STAR R_{AA} above unity, but with significant uncertainties
- Uncertainties come from Glauber normalization for centrality bins
- Can we be more precise looking inclusively? What about higher p_T?

OO Charged Particle R_{AA}

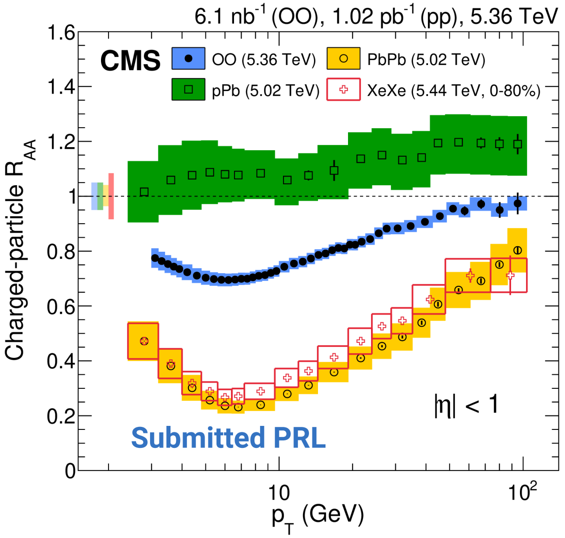


- **Measure inclusive in centrality to avoid Glauber modeling**
- **R_{AA} definition as:**

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

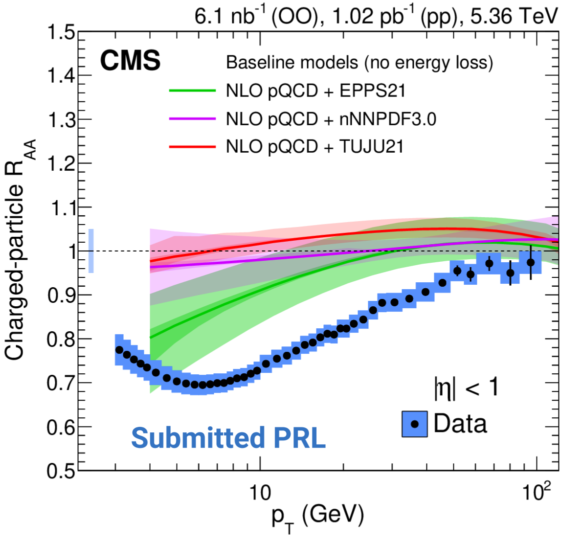
- **Any guesses?**

OO Charged Particle R_{AA}



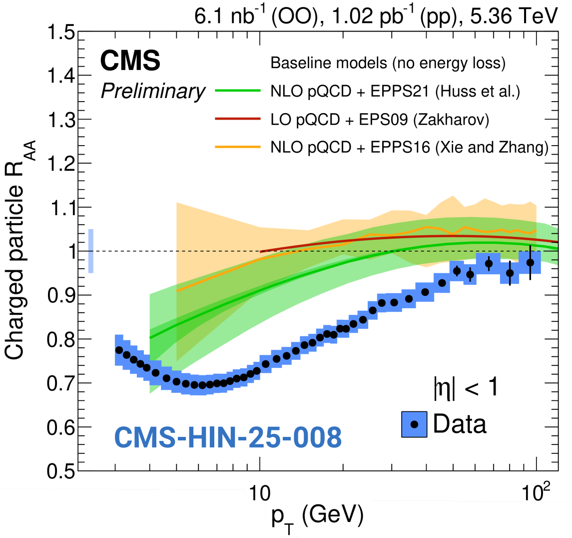
- **Observe a significant suppression!**
  - **$\sim 7\sigma$ deviation from unity at minimum**
  - **Roughly 0.69 at 6 GeV**

Baseline without Quenching Effects



- **nPDF effects can explain some fraction of observed suppression**
- **As a result, cannot declare light-ions quenching observed (yet!)**
- **EPPS21 nPDFs approximately 2σ from data**
  - **pO data will prove crucial for constraining nPDFs**

Comparison with Quenching Models

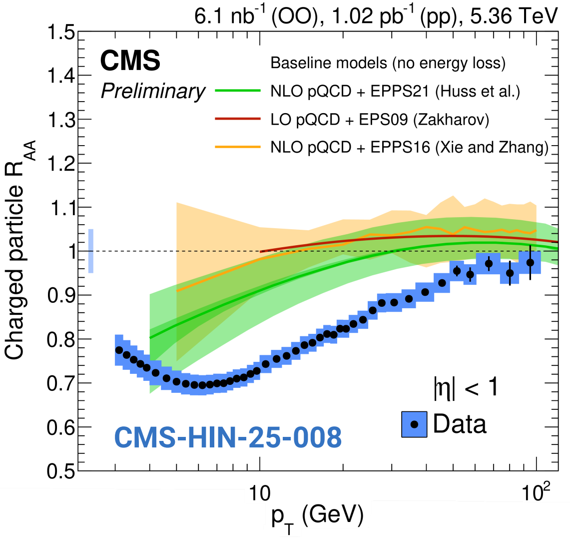


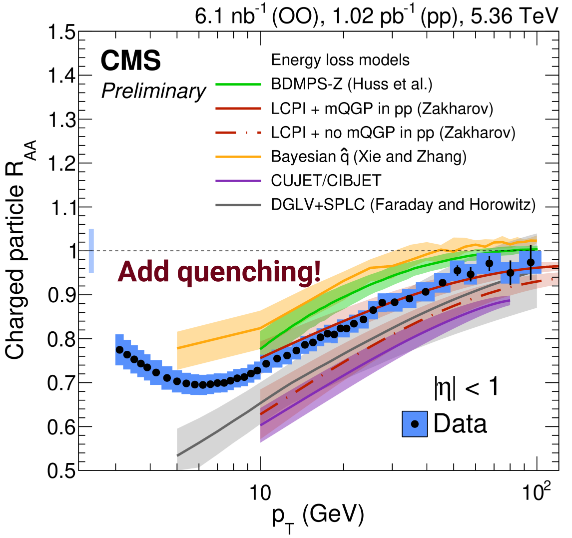
Three baselines w/o quenching:

1) NLO pQCD + EPPS21
2) LO pQCD + EPS09
3) NLO pQCD + EPPS16

None describe the data

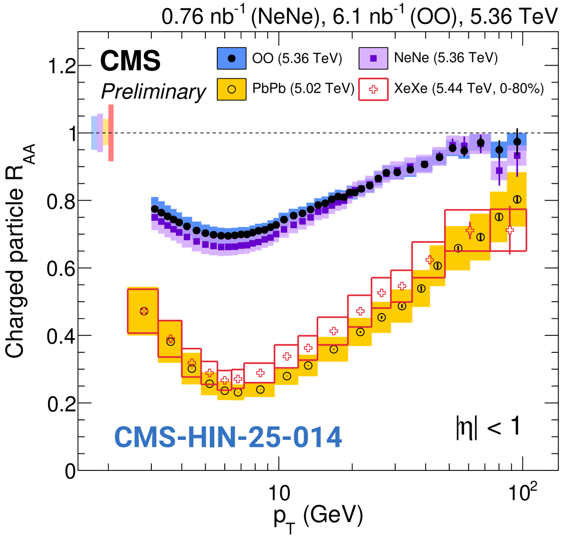
Comparison with Quenching Models





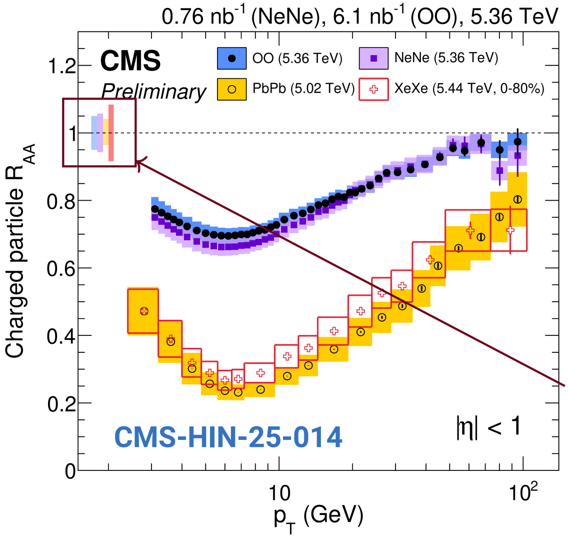
Data is best described w/ quenching effects!

R_{AA} in NeNe Collisions



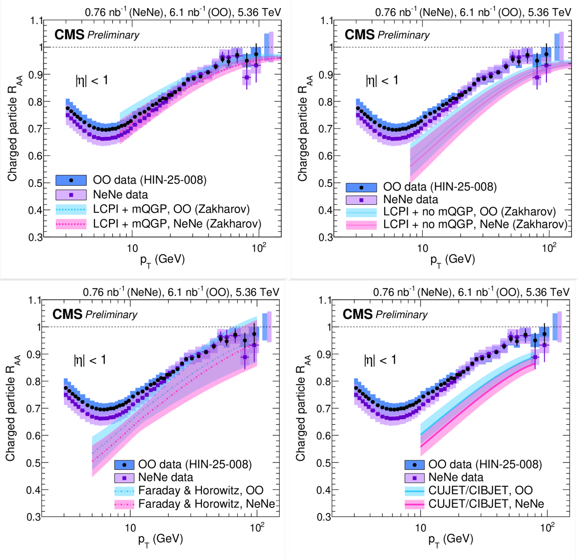
- **NeNe R_{AA} measured in identical binning as OO**
- **Slight increase in observed suppresion**
  - **O: 16 nucleons**
  - **Ne: 20 nucleons**

R_{AA} in NeNe Collisions



- **NeNe R_{AA} measured in identical binning as OO**
- **Slight increase in observed suppresion**
  - **O: 16 nucleons**
  - **Ne: 20 nucleons**
- **Need to take normalization uncertainties seriously!**

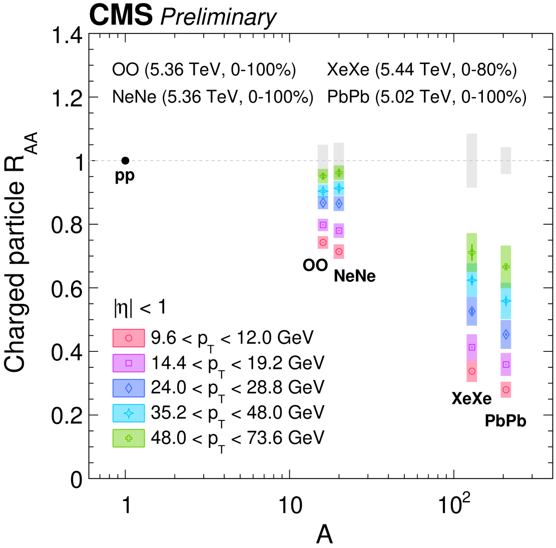
NeNe R_{AA} Model Comparisons



CMS-HIN-25-014

- NeNe model comparisons made simultaneous to OO comparisons
- Models consistently predict rough ordering observed in data
- What does the A dependence of quenching look like?

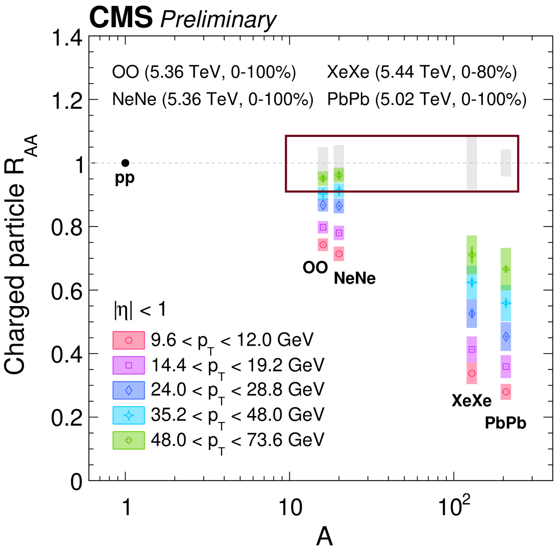
R_{AA} Dependence on A



CMS-HIN-25-014

- **LHC AA quenching data now spans many systems!**
- **Rough ordering in A observed**

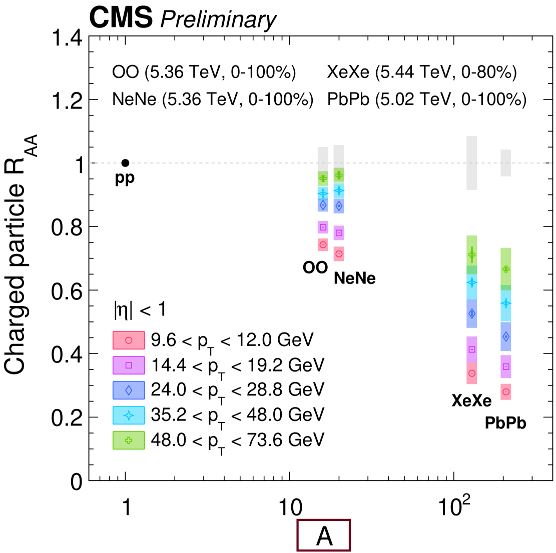
R_{AA} Dependence on A



CMS-HIN-25-014

- **LHC AA quenching data now spans many systems!**
- **Rough ordering in A observed**
  - **Still must take normalization uncertainty seriously**

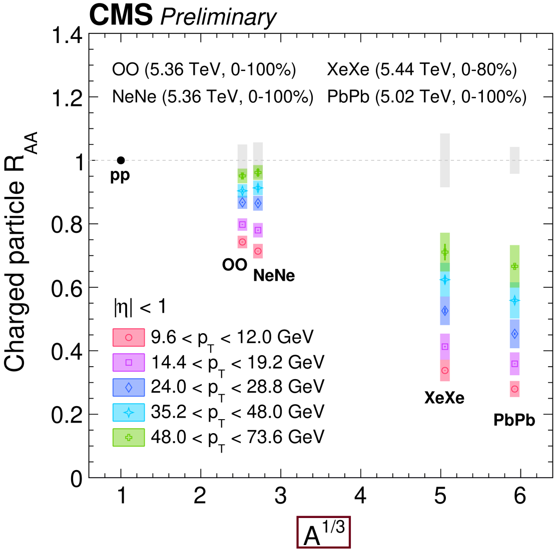
R_{AA} Dependence on A



CMS-HIN-25-014

- **LHC AA quenching data now spans many systems!**
- **Rough ordering in A observed**
  - **Still must take normalization uncertainty seriously**
- **A may not be the most natural x-axis**
  - **What about $A^{1/3}$ (path-length proxy)?**

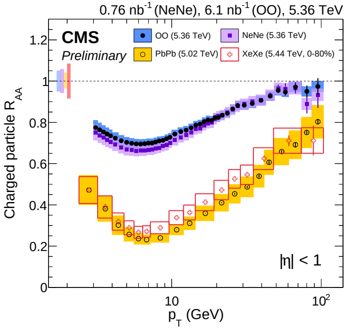
R_{AA} Dependence on $A^{1/3}$



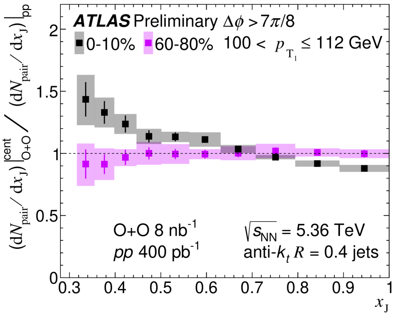
CMS-HIN-25-014

- **RAA $A^{1/3}$ dependence plausibly linear**
- **Path-length dependence picture emerging**
- **Caveat: quenching favored in OO/NeNe**
  - **However, nPDFs cannot be excluded at greater than 2σ**
  - **Scans in A^n may be premature**
- **Follow-ups:**
  - **pO data for nPDF constraints**
  - **Centrality-differential R_{AA}**

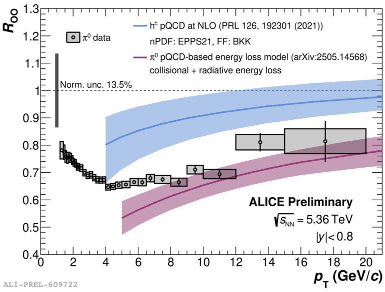
Quenching in Small Systems



CMS-HIN-25-014



ATLAS-CONF-2025-010

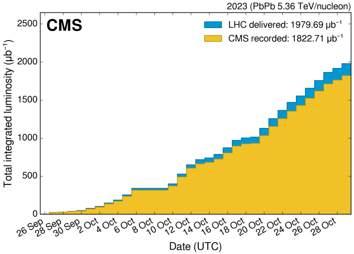


ALICE IS25 Briefing

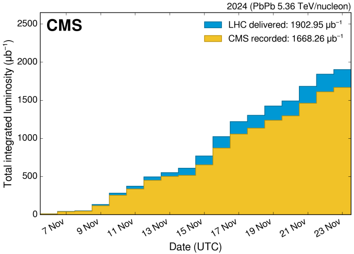
- **ATLAS, ALICE, and CMS light-ions measurements all favor quenching**
  - **Global evidence stronger than CMS results alone**
  - **Fast analysis from all three experiments made this advance possible!**

2023+2024 Integrated Luminosity for PbPb and pp ref.

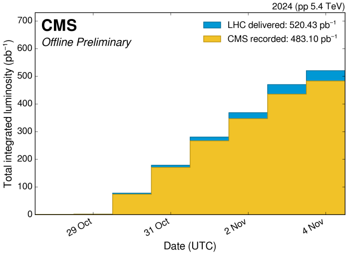
Via LUM TWiki



PbPb 2023



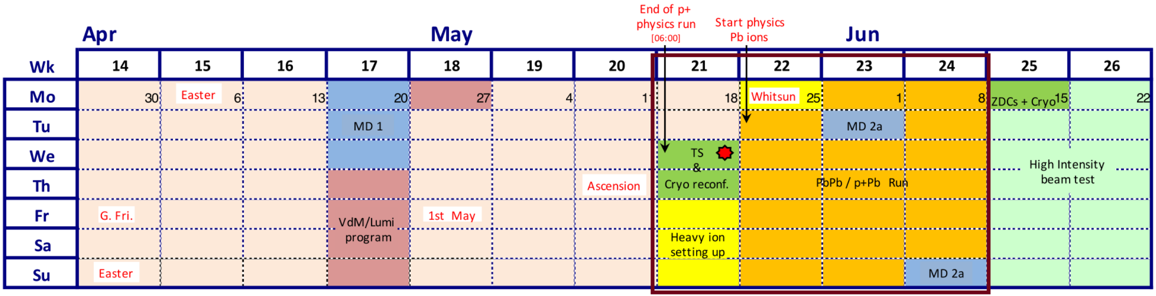
PbPb 2024



pp ref. 2024

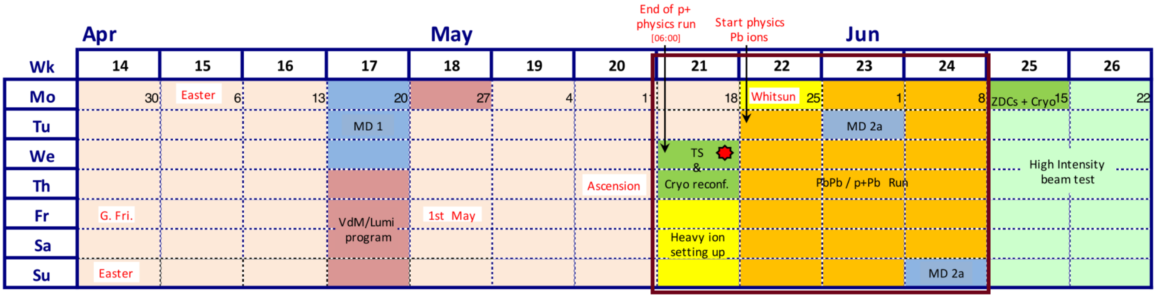
- Recorded PbPb total $\sim 3.5\ \text{nb}^{-1}$, per above, or about halfway to our $7\ \text{nb}^{-1}$ target
- Reference pp sample delivered last year, $\sim$1.5x our Run 2 reference from 2017
- Per-fill peak luminosity improved in 2024 over 2023; optimistic for 2025

Future Prospects

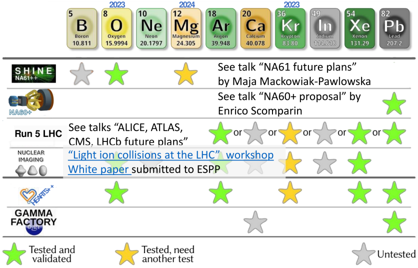


↑ **2026 LHC schedule**

Future Prospects



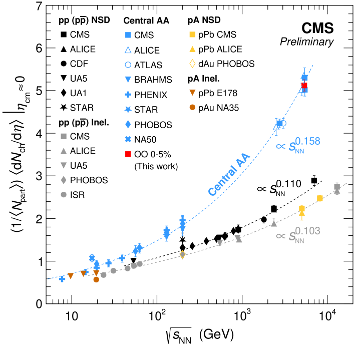
↑ **2026 LHC schedule**

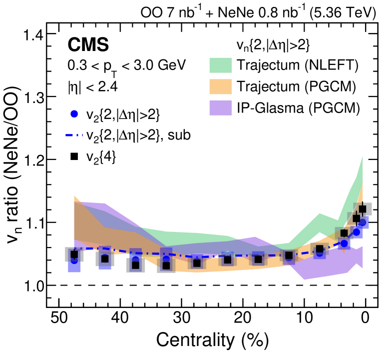


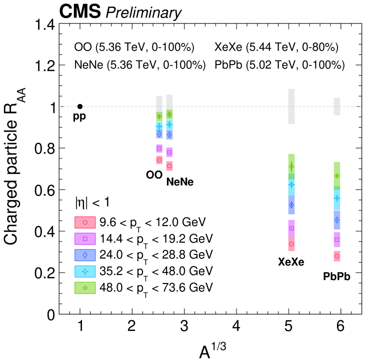
← **Alt. ions via Via Town Hall contribution from R.A. Fernandez**

Alt. ions an option if we hit our PbPb target in 2025

Summary







- **Measurement of bulk particle-production suggests OO is akin to heavy-ions**
- **Flow measurements in OO and NeNe are a new tool for nuclear structure**
- **New results suggest quenching present in light-ions!**