

Motivation and predictions for O-O and p-O collisions

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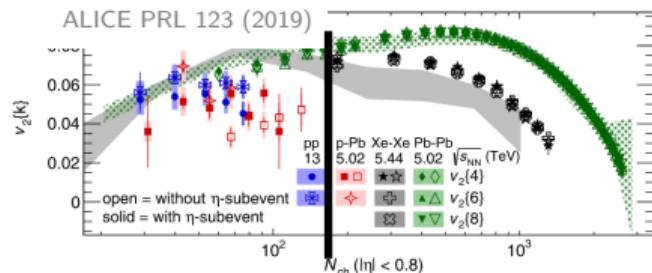


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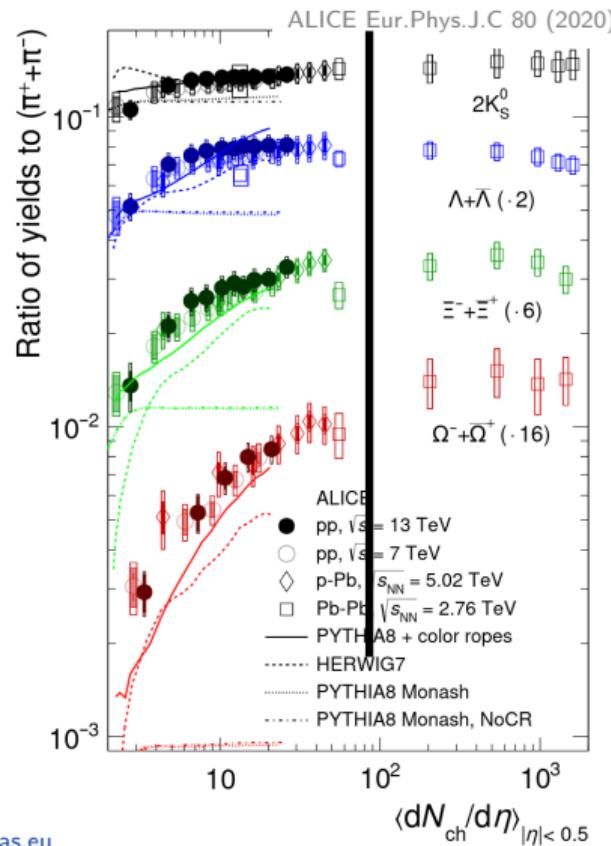


Small systems ($dN_{\text{ch}}/d\eta < 100$ and $N_{\text{part}} < 30$) are interesting

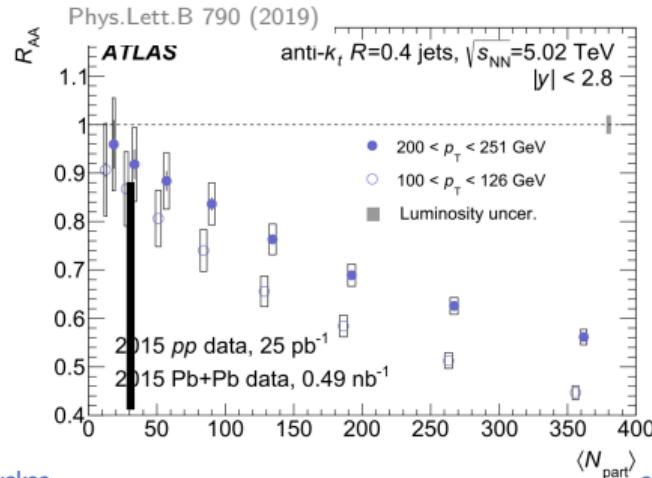
“Flattening” of v_n



Change in strangeness enhancement

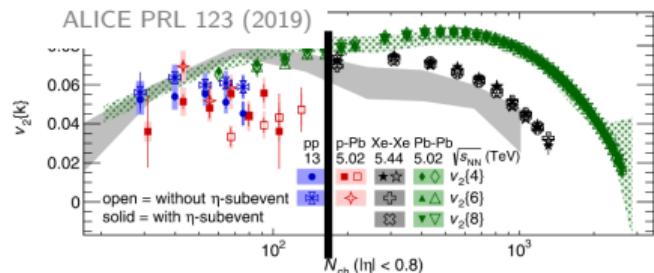


Disappearance of jet quenching

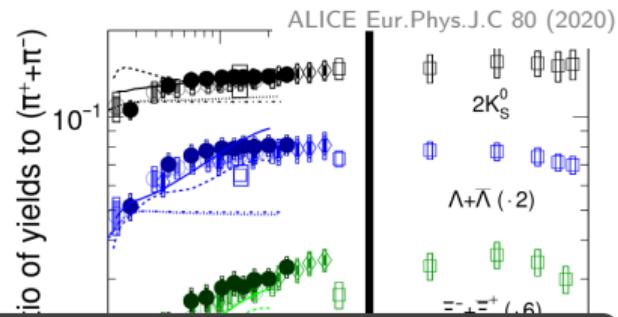


Small systems ($dN_{\text{ch}}/d\eta < 100$ and $N_{\text{part}} < 30$) are interesting

“Flattening” of v_n

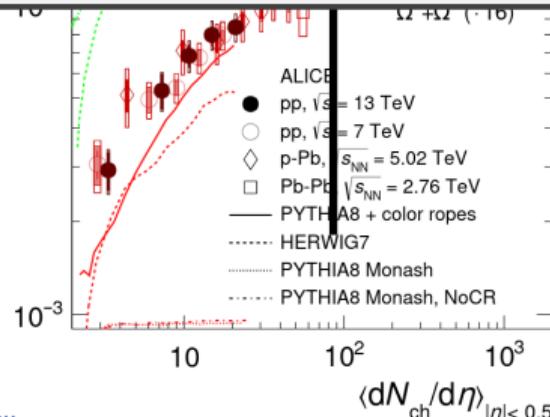
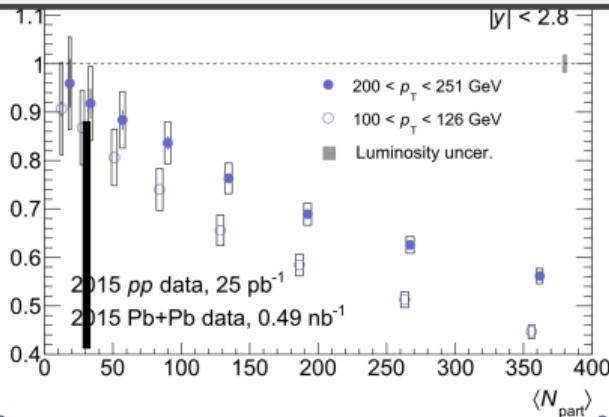


Change in strangeness enhancement



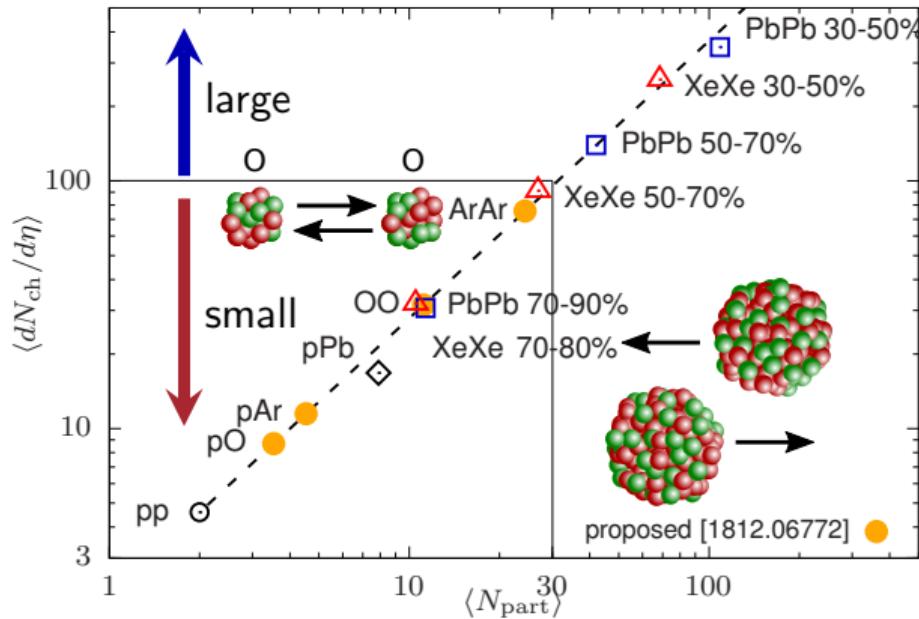
Disappearance of jet quenching

We must either validate or disprove QGP picture in small systems.



System size scan with light-ion collisions

- RHIC: pp, pAl, pAu, dAu, ${}^3\text{He}\text{Au}$, CuCu, CuAu, AuAu, UU (RuRu, ZrZr, OO)
- LHC: pp, pPb, XeXe, PbPb (OO,pO), SMOG2: pNe, pHe, pAr, PbNe



${}^{16}_8\text{O} {}^{16}_8\text{O}$ sits in a "sweet spot" between pPb and PbPb .

Timeline of oxygen runs

- 2017 HL-LHC workshop and 2018 CERN Yellow report [1] established scientific case for oxygen collisions at LHC.
- 2021 Topical workshop “Opportunities of OO and $p\text{O}$ collisions at LHC”
 - Technical feasibility at LHC.
 - QCD medium in very small systems.
 - Energy loss of high- p_T partons.
 - Muon puzzle in cosmic ray physics.
- Summary document Brewer, AM, van der Schee arXiv:2103:01939.
- 2021 STAR collected $\mathcal{L}_{\text{OO}} = 32 \text{ nb}^{-1}$ at $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$
- Jun 2024 planned OO ($\sim 7 \text{ TeV}$) and $p\text{O}$ ($\sim 9.9 \text{ TeV}$) run ($\sim 1 \text{ week}$) at LHC.
Luminosity targets: $\mathcal{L}_{\text{OO}} \approx 0.5 \text{ nb}^{-1}$ (ALICE, ATLAS, CMS), $\mathcal{L}_{p\text{O}} \approx 1.5\text{-}2 \text{ nb}^{-1}$ (low pileup ATLAS/LHCf, LHCb), $\mathcal{L}_{p\text{O}} > 5 \text{ nb}^{-1}$ (ALICE, CMS).

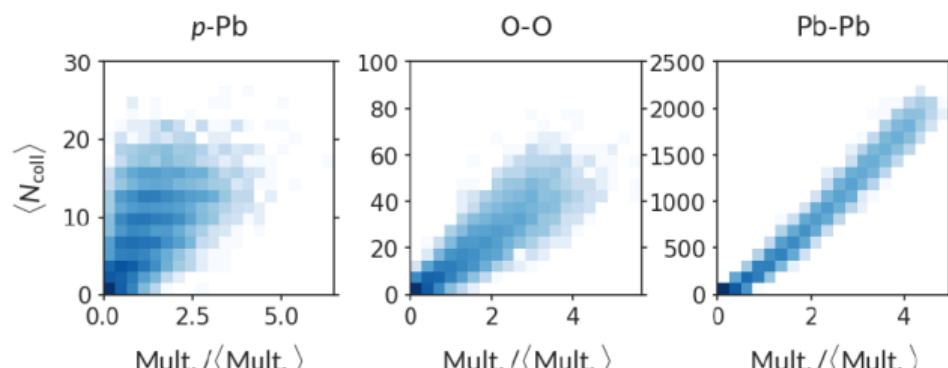


Oxygen run is important test for future runs with light-ions in Run 5 and beyond.

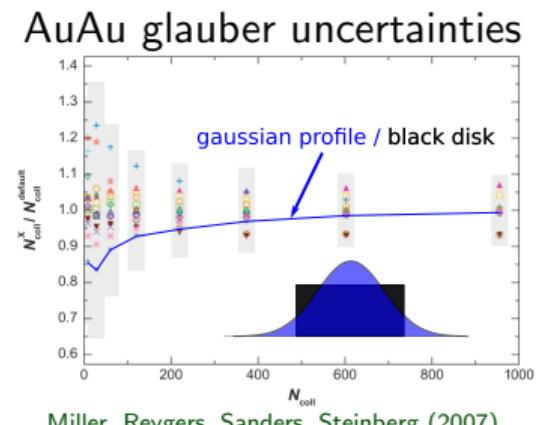
Advantages of OO for small system studies

OO is different from PbPb and $p\text{Pb}$ at the same $dN_{\text{ch}}/d\eta$

- Better defined geometry compared to peripheral PbPb.
- Can use minimum bias OO $\langle N_{\text{part}} \rangle \sim 10$.
- Stronger multiplicity and N_{coll} correlation than pPb
- Symmetric system \Rightarrow no rapidity mismatch with pp reference.



Ke and Vitev 2204.00634

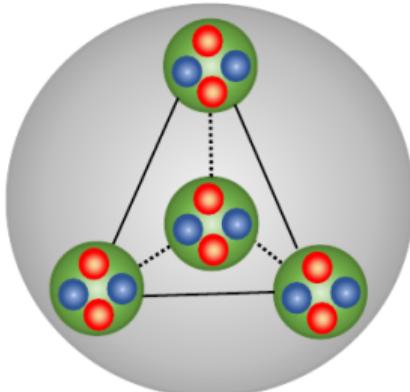


Oxygen will be the first common ion species between LHC and RHIC!

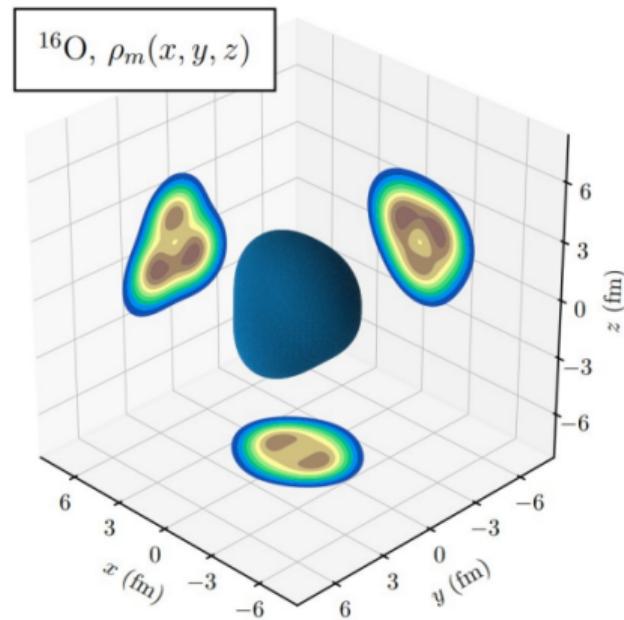
Initial state and soft dynamics of small system

Oxygen nuclear structure

α clustering in $^{16}_8\text{O}$



Behera et al. 2110.04016



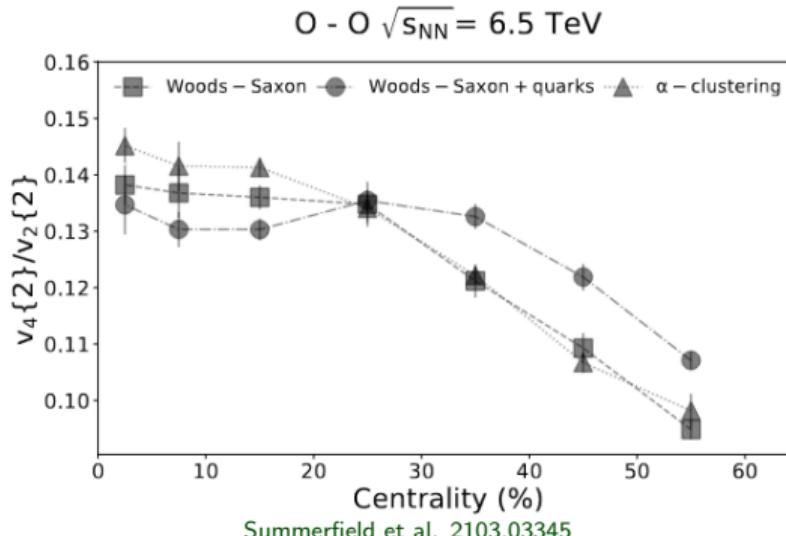
from Giacalone's plenary on Wednesday

We can anchor oxygen nuclear structure on independent ab-initio computations!

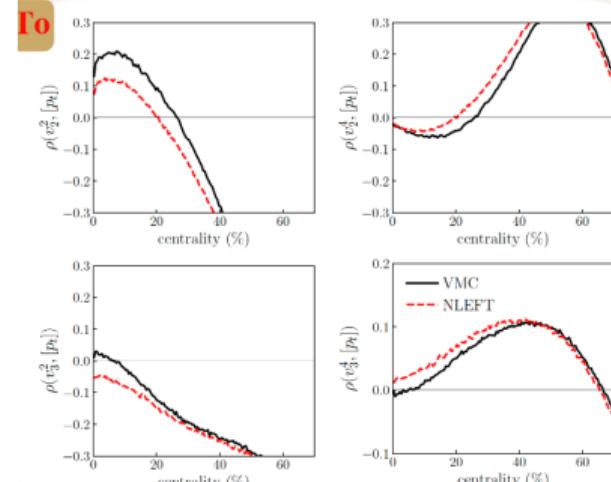
Initial oxygen geometry and fluctuations

- α -clustering suppresses $v_3\{2\}/v_2\{2\}$ and enhances $v_4\{2\}/v_2\{2\}$ (opposite to subnucleonic fluctuations).
- Higher-order v_n - p_T correlators also sensitive to nuclear structure.

Flow for different structure models



Flow-momentum correlations



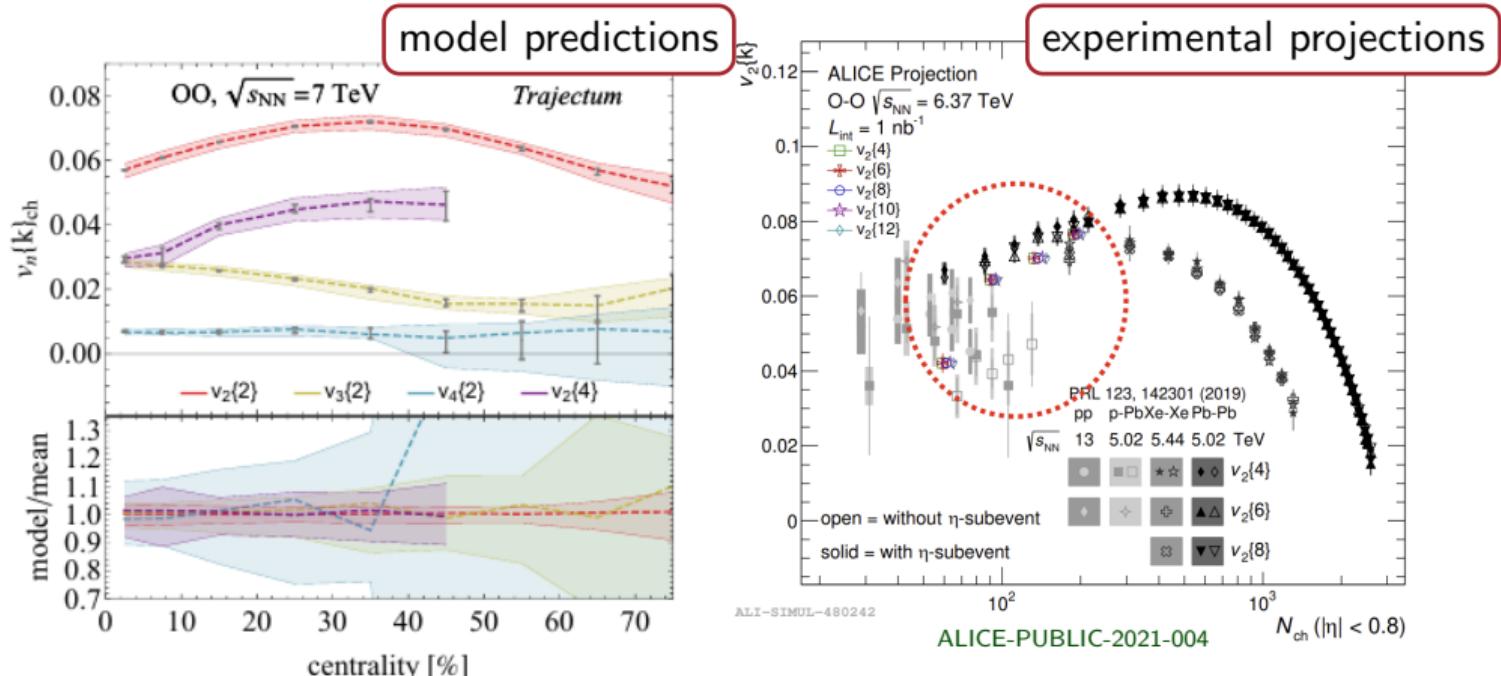
Nielsen's parallel

For predictions for global properties with AMPT, see Behera et al. 2110.04016

We can experimentally validate nuclear structure in model-independent way.

Precise measurements of collectivity in OO collisions

$\mathcal{L}_{OO} \approx 1 \text{ nb}^{-1}$ sufficient to measure up to 12-particle correlations



Nijs and van der Schee, 2110.13153, van der Schee's parallel

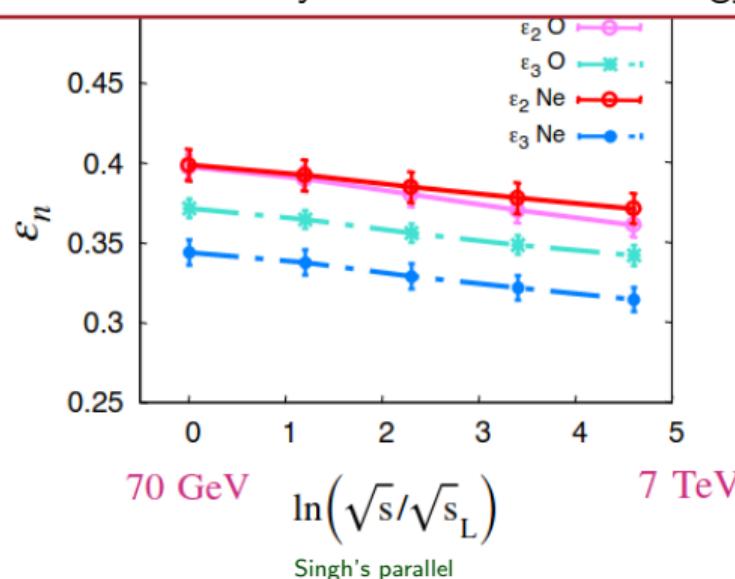
Small system comparison in Run 3: pp , pPb , pO , OO , and peripheral $PbPb$.

We can study the origin of persistent collectivity among $N_{ch} < 100$ particles.

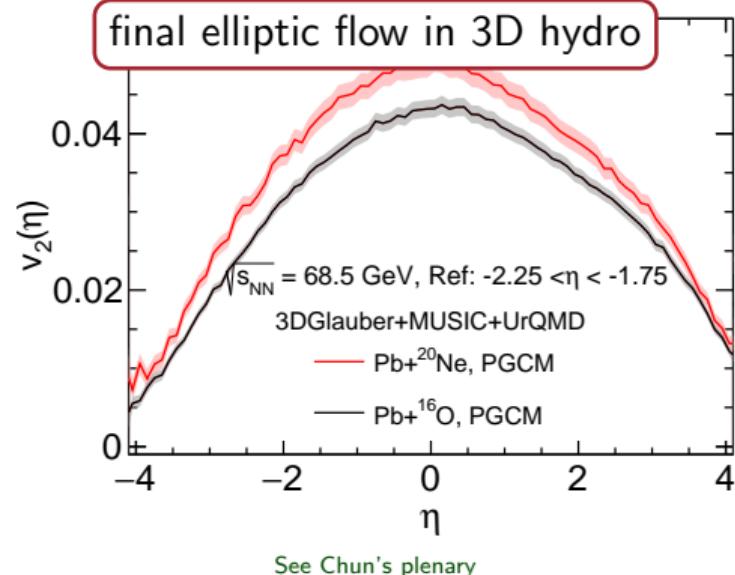
Rapidity dependence studies with oxygen collisions

- LHC (7000 GeV), RHIC (200 GeV), SMOG2 fixed-target (70GeV)
⇒ *large range of beam and pseudo-rapidities*
- Collisions at different energies will test JMWLK evolution of initial geometry

initial eccentricity as a function of energy



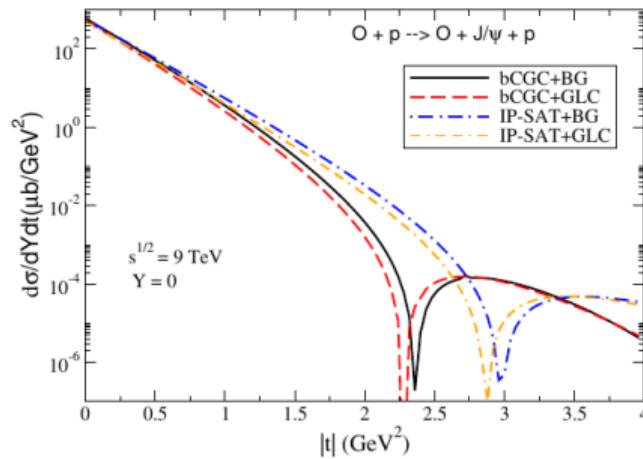
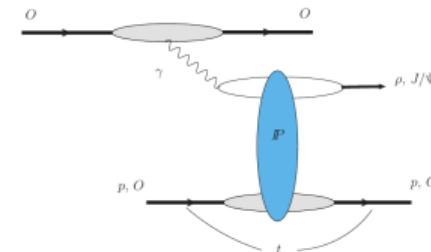
final elliptic flow in 3D hydro



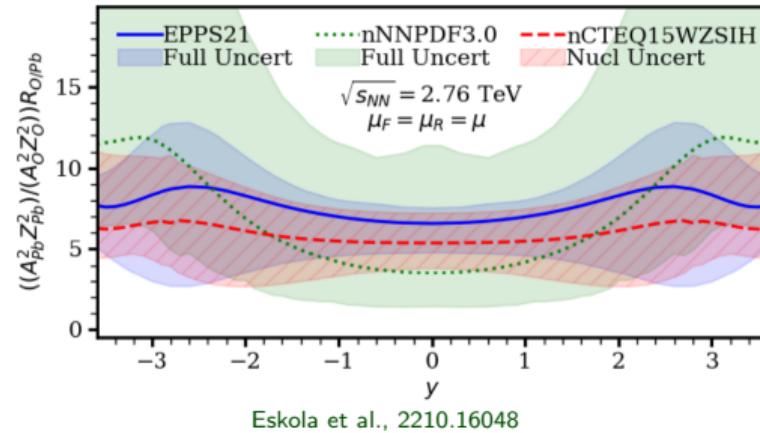
Unique chance to study Bjorken-x and \sqrt{s} evolution in the same ion system.

Exclusive photo-production of J/ψ in UPC pO and OO

- Ultra-peripheral collisions sensitive to nuclear and subnuclear structure see Giacalone's plenary
- Ratio of ions tame scale uncertainty of NLO computations see Eskola's plenary



Goncalves, Moreira, Santana, 2210.11911



For photoproduction in EIS, see Mantysaari et al. 2303.04866

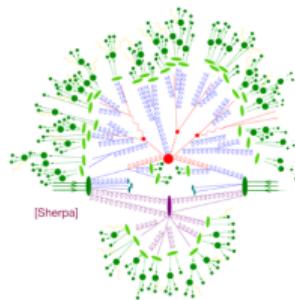
Ultra-peripheral OO and pO measurements will bring complementary information.

Hard Probes in OO and pO

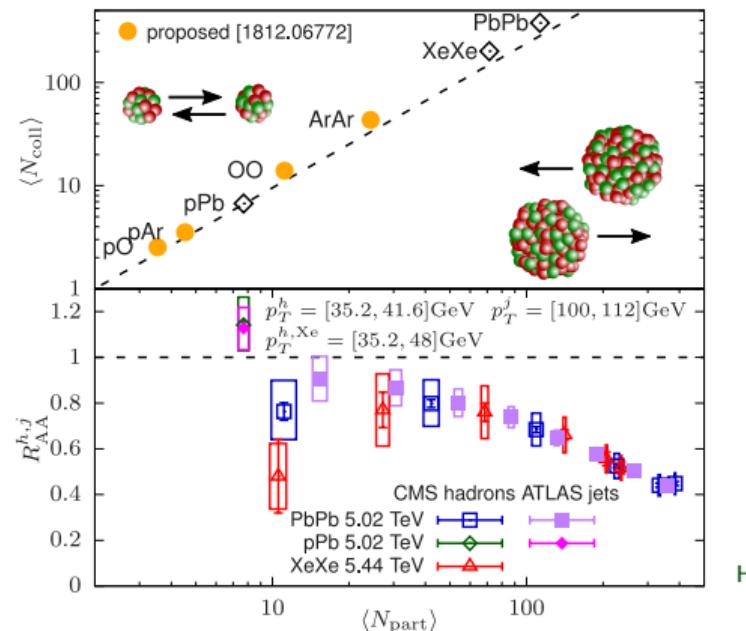
The puzzle of high p_T parton rescattering in small systems

No direct evidence of high- p_T hadron or jet suppression in small systems.

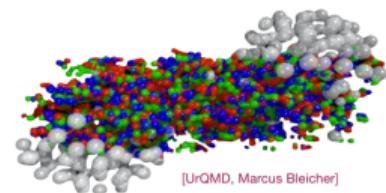
HEP



[Sherpa]



HIP



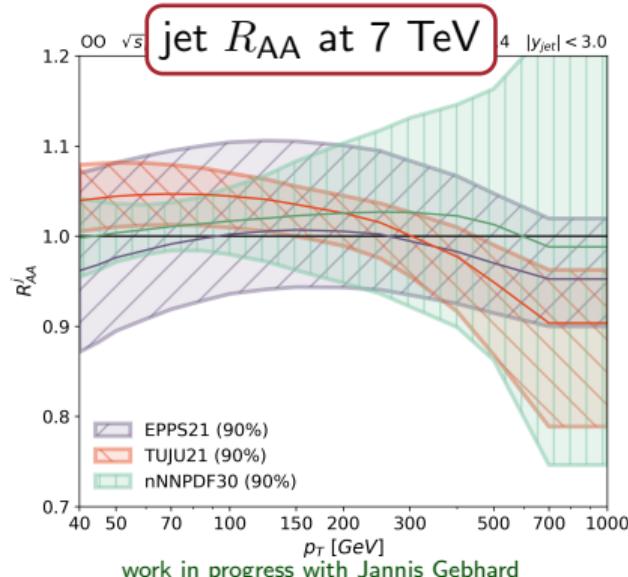
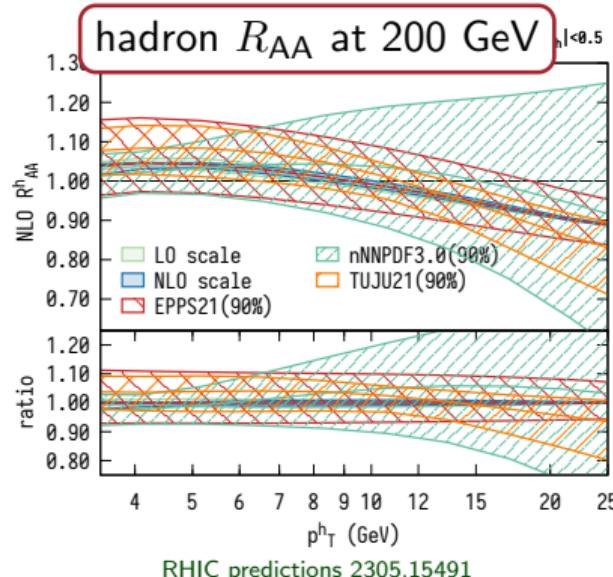
[UrQMD, Marcus Bleicher]

Understanding hard probes is crucial in reconciling HEP and HIP pictures.

Minimum-bias hadron and jet baseline for OO at $\sqrt{s_{NN}} = 0.2 \text{ TeV}$ and 7 TeV

In min. bias we can use accurate pQCD computations to find no-energy-loss baseline

$$R_{\text{AA}, \text{ min bias}}^{h,j}(p_T) = \frac{1}{A^2} \frac{d\sigma_{\text{AA}}^{h,j}/dp_T}{d\sigma_{pp}^{h,j}/dp_T} = \frac{\text{hadron interaction diagram}}{16^2 \times \text{jet interaction diagram}}$$

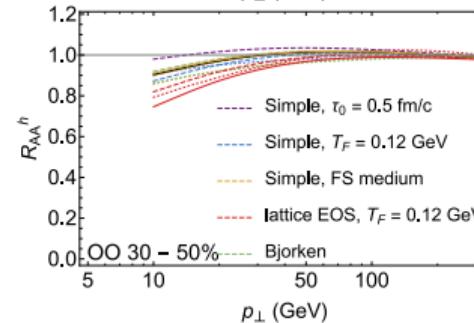
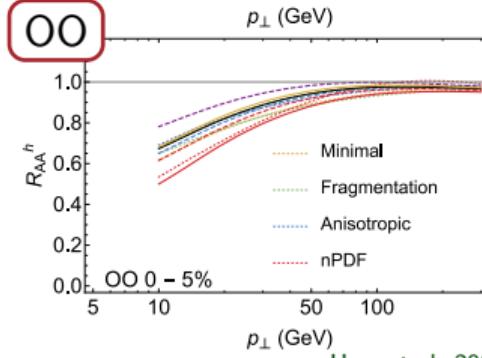
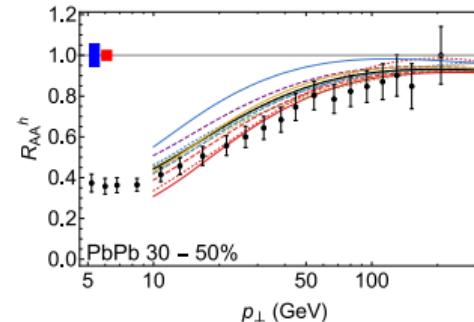
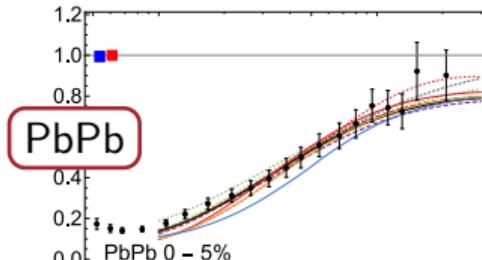


nPDF uncertainties are important systematics for measuring small energy loss!

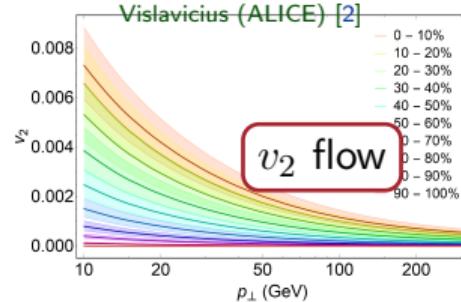
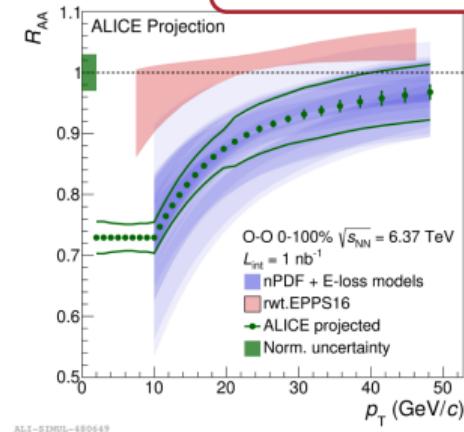
Energy loss and elliptic flow predictions in OO: Part I

We drastically varied background medium evolution and energy loss formulas

min. bias OO



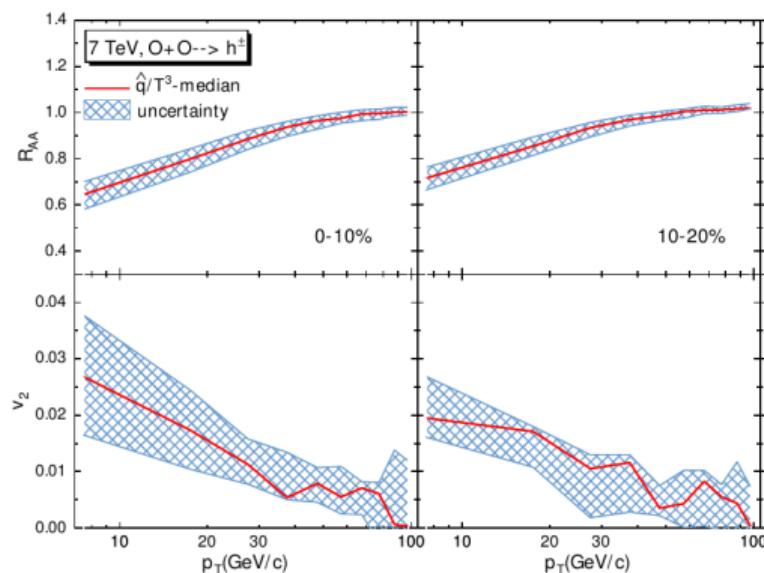
Huss et al. 2007.13754, 2007.13758



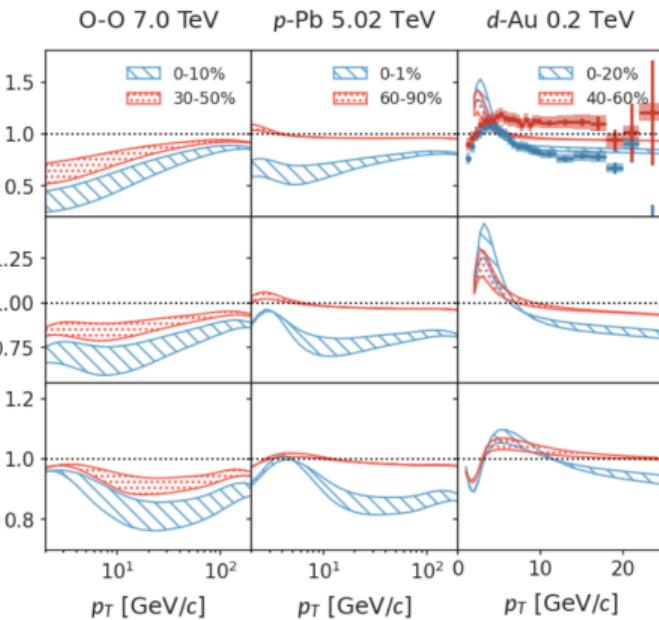
Measurable energy loss signal in $10 \text{ GeV} < p_T < 50 \text{ GeV}$ region at the LHC.

Energy loss and elliptic flow predictions in OO: Part II

Independent computations in high-twist and Soft-Collinear-Effective-Theory.



Xie, Ke, Zhang, Wang, 2208.14419



Ke and Vitev 2204.00634

For heavy flavour in light ions see Kolb  's plenary and Katz et al. 1907.03308

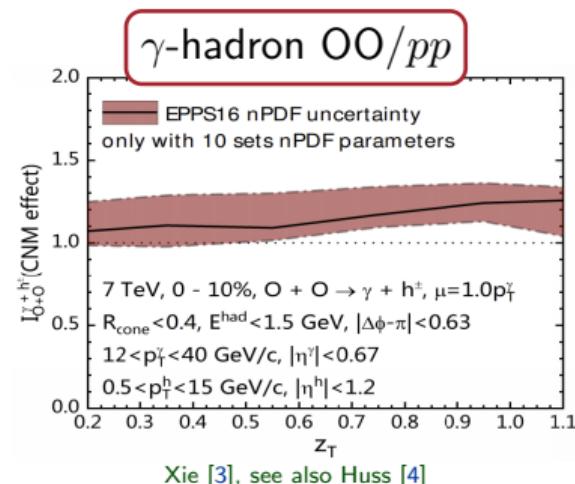
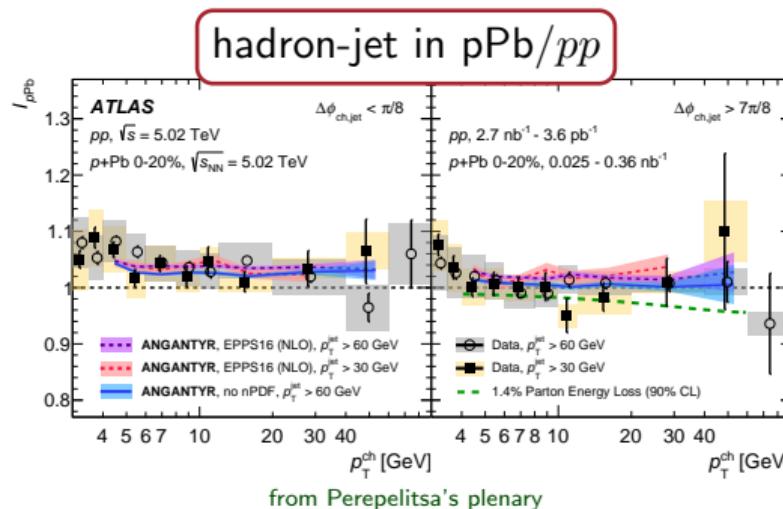
Significant hadron suppression predicted for OO by different computations.

Coincidence measurements with trigger observables

Semi-inclusive observables ($h + j$) are normalized to the trigger yield (j):

$$I_{\text{AA}}(p_T) = \frac{N^{pp \rightarrow j+X}}{N^{AA \rightarrow j+X}} \frac{dN^{AA \rightarrow h+j+X}/dp_T}{dN^{pp \rightarrow h+j+X}/dp_T}$$

Proposed as precision observable for small systems



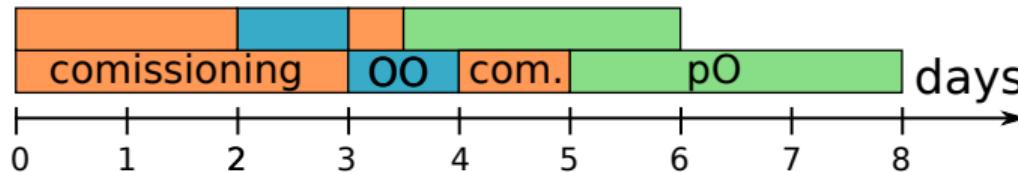
Important to know the no-energy-loss baseline!

pp references in LHC Run 3

- Tentative collision energies in Run 3

| | <i>pp</i> | <i>pPb, pp</i> | <i>PbPb, pp</i> | <i>OO</i> | <i>pO</i> |
|------------|-----------|----------------|-----------------|-----------|-----------|
| \sqrt{s} | 13.6 TeV | 8.54 TeV | 5.36 TeV | 6.8 TeV | 9.62 TeV |

- *Currently no corresponding pp reference planned for OO and pO.*



- The ratio to *pp* spectra cancels large **theoretical and experimental** uncertainties.

$$R_{\text{AA, min bias}}^{h,j}(p_T) = \frac{1}{A^2} \frac{d\sigma_{\text{AA}}^{h,j}/dp_T(6.37 \text{ TeV})}{\underbrace{d\sigma_{\text{pp}}^{h,j}/dp_T(5.02 \text{ TeV})}_{\text{measured}} \times \underbrace{\frac{d\sigma_{\text{pp}}^{h,j}/dp_T(6.37 \text{ TeV})}{d\sigma_{\text{pp}}^{h,j}/dp_T(5.02 \text{ TeV})}}_{\text{scaling factor}}}$$

- Three alternatives to *pp* reference

Brewer, Huss, AM, van der Schee [2108.13434]

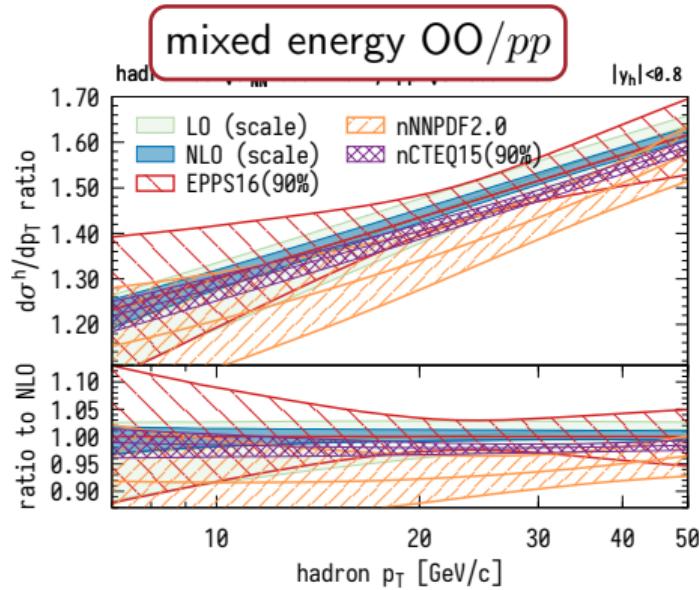
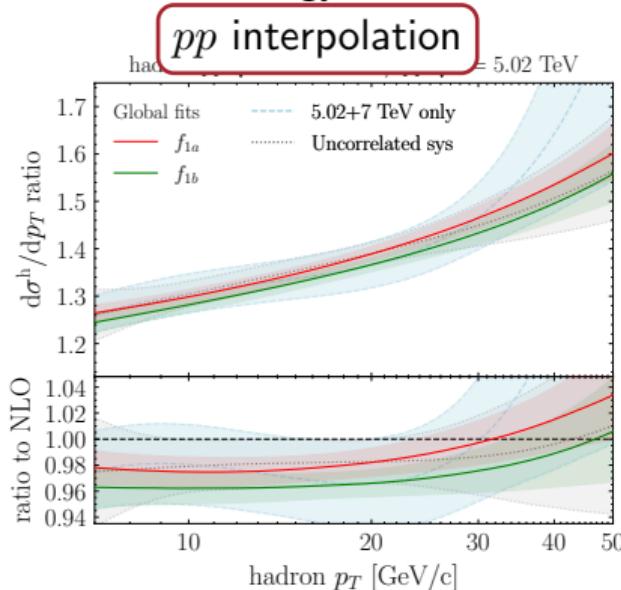
Hadron R_{AA} without same energy pp reference

- 1 Compute pp reference perturbatively



- 2 Interpolate measured data

- 3 Take mixed-energy ratio

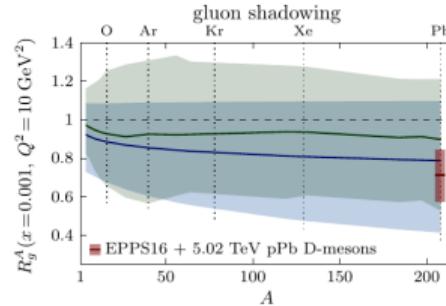
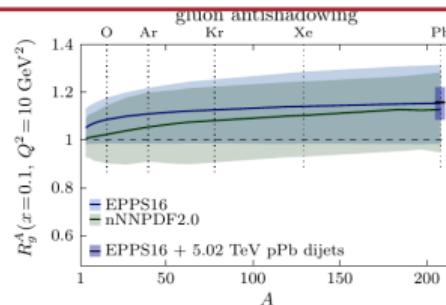


nPDF uncertainties likely the dominant uncertainty in the baseline.

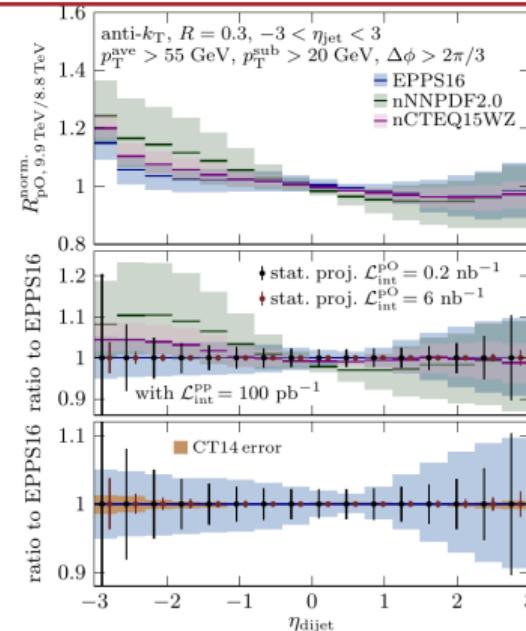
Nuclear parton distribution functions (nPDFs) for oxygen nucleus

No available ^{16}O data for global nPDF fits, LHC data only for ^{208}Pb .

A parametrization dependence



dijet mixed energy double $p\text{O}/pp$ ratio



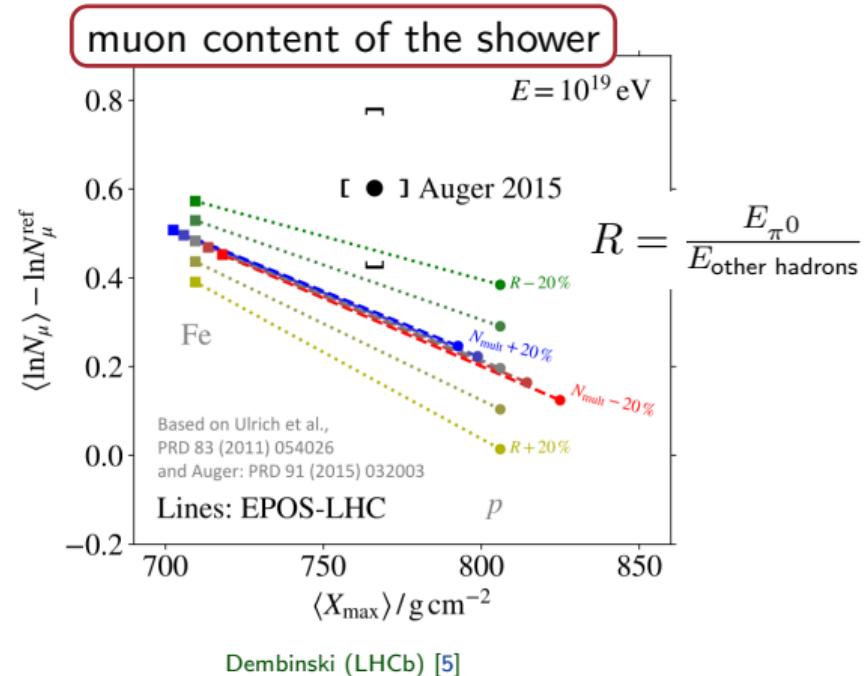
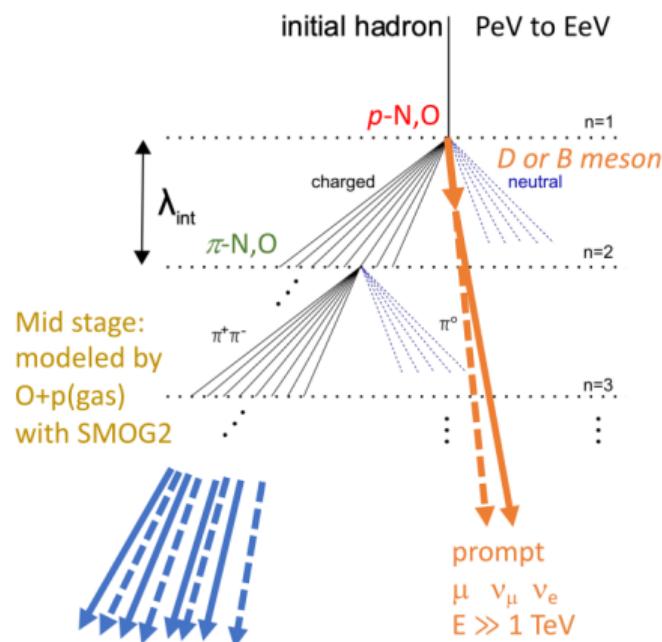
Paakkinen 2111.05368

pO run would improve constrains on gluon modification in light nuclei.

Cosmic ray physics at LHC

Muon puzzle in cosmic ray showers

- More muons observed in cosmic ray showers than expected in models.
- But large hadronic uncertainties at primary production vertex, e.g. pO or pN .

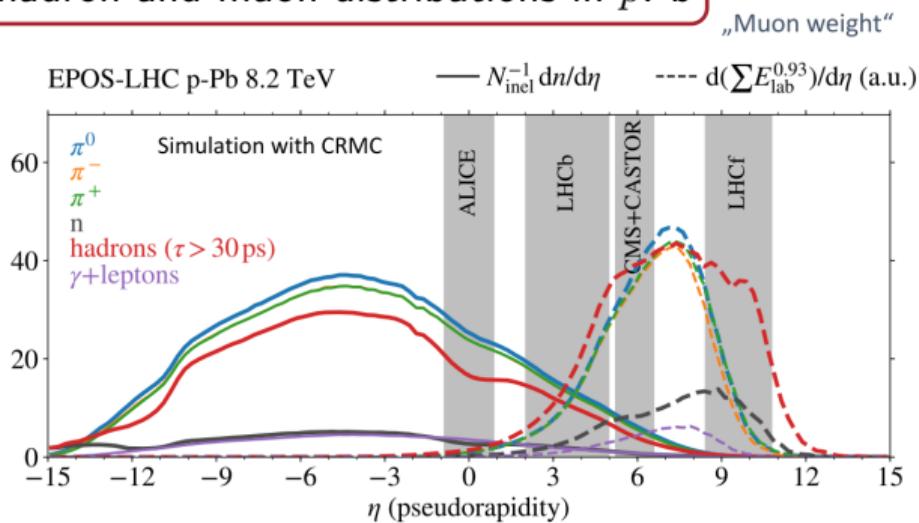


Forward $\sqrt{s_{NN}} = 9.9 \text{ TeV } pO$ collisions would probe $E > 10^{16} \text{ eV}$ shower kinematics.

Forward physics reach at LHC

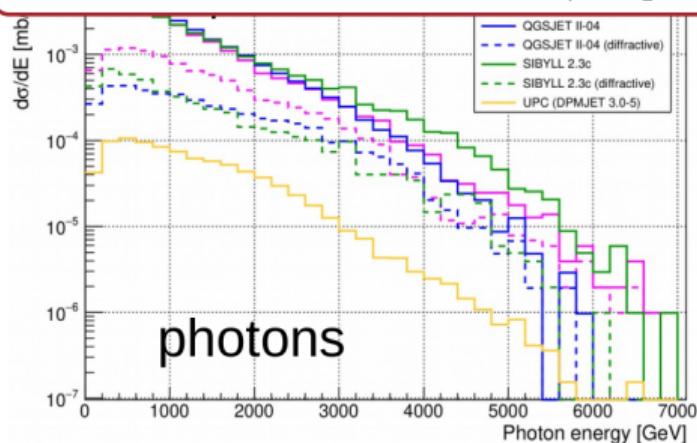
- LHCb can take data in OO and $p\bar{O}$ collisions at full efficiency Dembinski (LHCb) [5].
- Fixed target $\sqrt{s_{NN}} = 81 \text{ GeV}$ $O\bar{p}$ collisions possible at SMOG2 Graziani (LHCb) [6].
- LHCf measures γ, π^0, n in unique forward rapidity region $\eta > 8.4$ Menjo (LHCf) [7].

hadron and muon distributions in $p\bar{\text{Pb}}$



Dembinski (LHCb) [5]

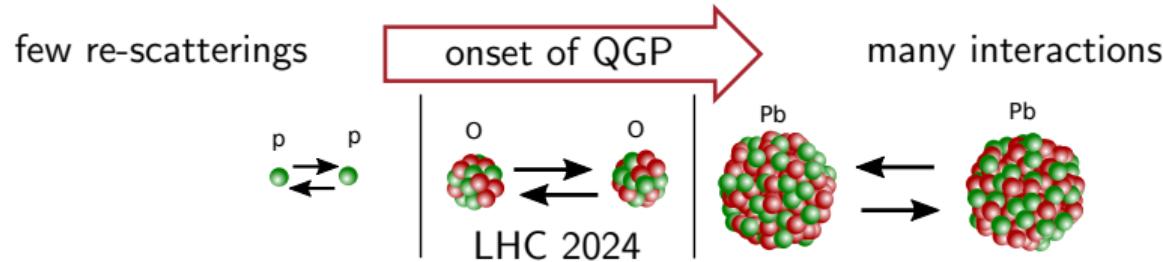
inelastic, diffractive and UPC γ in $p\bar{O}$



Tiberio (LHCf) [8]

Cosmic ray community strongly supports $p\bar{O}$ at largest collision energies in Run 3.

Conclusions and outlook



A short multi-purpose run of OO and $p\bar{O}$ would address several outstanding issues:

- The origin of ubiquitous collective phenomena in small collision systems.
- Modification of hard probes in light nuclei collisions (nPDF and rescattering).
- Indispensible hadronic data for cosmic ray shower modelling.

There are many great theoretical predictions and experimental projections!

Great  opportunities ahead!

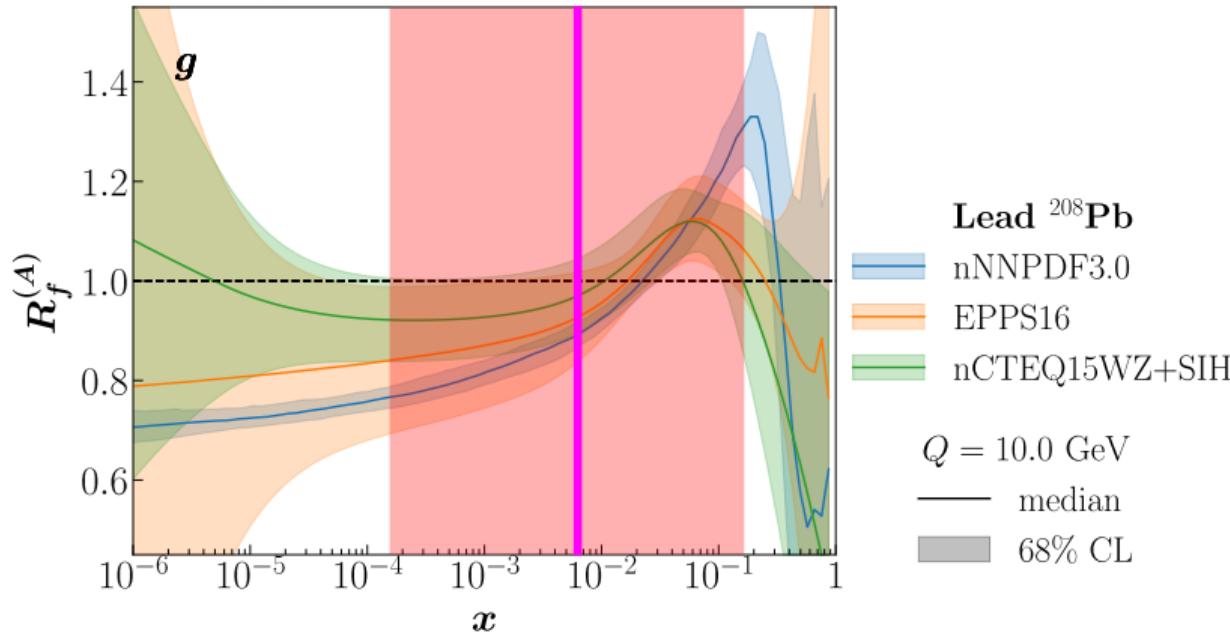
Bibliography I

- [1] Z. Citron et al. Report from Working Group 5. *CERN Yellow Rep. Monogr.*, 7:1159–1410, 2019, 1812.06772.
- [2] Vytautas Vislavicius. ALICE goals and projections for hard probes measurements. Feb 2021. URL <https://cds.cern.ch/record/2751544>.
- [3] Man Xie. γ -hadron spectra in $p + \text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$. Feb 2021. URL <https://cds.cern.ch/record/2751496>.
- [4] Alexander Yohei Huss. Discovering partonic rescattering in light nucleus collisions. Feb 2021. URL <https://cds.cern.ch/record/2751492>.
- [5] Hans Peter Dembinski. Oxygen beams and LHCb: prospects of pO and OO collisions for nuclear and astroparticle physics. Feb 2021. URL <https://cds.cern.ch/record/2751548>.
- [6] Giacomo Graziani. Oxygen beams and LHCb: prospects of collisions with fixed-targets. Feb 2021. URL <https://cds.cern.ch/record/2751549>.
- [7] Hiroaki Menjo. LHCf achievements at pp and pPb. Feb 2021. URL <https://cds.cern.ch/record/2751672>.
- [8] Alessio Tiberio. LHCf motivations and prospects of p-O collisions. Feb 2021. URL <https://cds.cern.ch/record/2751673>.

Semi-inclusive measurements and their nPDF dependence

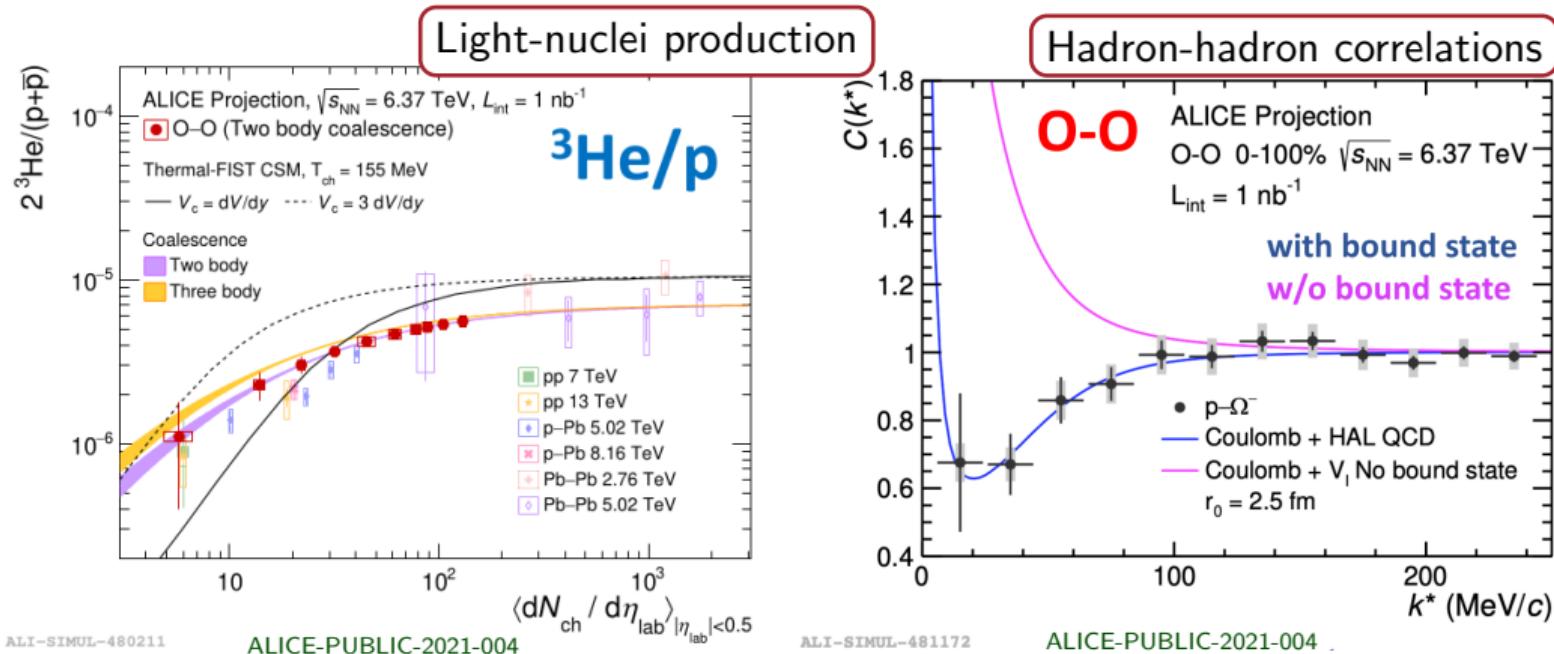
Inclusive normalization depends on different x range than coincidence cross-section!

$$\frac{1}{N_{\text{trig}}^{\text{AA}}} \frac{d^2 N_{\text{jet}}^{\text{AA}}}{dp_{T,\text{jet}}^{\text{ch}} d\eta_{\text{jet}}} \Big|_{p_{T,\text{trig}} \in \text{TT}} = \left(\frac{1}{\sigma^{\text{AA} \rightarrow h+X}} \cdot \frac{d^2 \sigma^{\text{AA} \rightarrow h+\text{jet}+X}}{dp_{T,\text{jet}}^{\text{ch}} d\eta_{\text{jet}}} \right) \Big|_{p_{T,h} \in \text{TT}}$$
$$x_A = \frac{p_T}{\sqrt{s}} (e^{y_j} + e^{y_h})$$
$$x_B = \frac{p_T}{\sqrt{s}} (e^{-y_j} + e^{-y_h})$$



Light nuclei production and hadron-hadron correlations in OO

- Deuteron, ^3He and hypertriton production in small systems.
- Femtoscopy measurements in OO for studying $p - \Omega^-$ bound state formation.



OO will provide important novel insight on hadronic physics.