Prospects for UPC at the LHC

Peter Steinberg, BNL ALICE-USA meeting, Yale University / May 31, 2024

What happens at very large impact parameters when large nuclei "miss" each other?

Stripped nuclei have very strong EM fields (B=O(1015) T!)

Z=82 packed into a subatomic volume traveling ultra relativistic speeds (Lorentz contracted)!

Classical fields can be understood as a source of nearly-real high energy photons!

A powerful QCD laboratory is also a powerful QED laboratory!

Fermi, Landau, von Weiszacker, Williams

Equivalent Photon Approximation A nucleus moving at nearly the speed of light has almost transverse electromagnetic fields; the electric and and magnetic fields have absolute value and are perpendicular to each other. The same \mathcal{L} observer can not distinguish between these transverse electromagnetic fields and an equivalent swarm of photons, see Fig-S.1 Equating the energy flux of the electromagnetic fields through a transverse plane

"Exclusive γγ" processes INTRODUCTION. – THE ELASTIC SCATTERING OF TWO PHOTONS IN VACUUM (γ γ process that proceeds at least \mathbf{v}

lepton decays

rare QED processes BSM physics

is provide clean environment for study of QED & BSM proc is proviac cican chwitonnicht ior staay or QLD & Dolvi proc

Photonuclear processes of virtualities, virtualit probability for hard diffraction consistent with approxar nroceace that the distinct \sim enitting nucleus either does not break up or

end during the next decade.

"exclusive"/elastic vector meson production: nuclear geometry nuclear PDFs/GPDs parton saturation?

3. Data analysis inelastic hadron and jet production: nuclear PDFs $parton$ saturation? from the position of the track in the PC outside the DC and the parton saturation?

to blovide similar capabilities t $s \sim \sqrt{1-\Delta}$ with the tracks in the event. This gave an event vertex verte Photonuclear processes provide similar capabilities to ep/eA machines! eral of the crucial directions of HERA research can be

with the following characteristics:

Electron-ion collider (BNL & JLab)

Partonic and spatial structure of nucleons & nuclei: $W_{\nu\rho} \sim 140 \text{ GeV}$

Mark Strikman - thurs parallel

The UPC opportunity

- **• The EIC is going to be the next major generational machine for the NP community**
	- Detailed studies of PDFs and nPDFs
	- Spatial imaging of nucleons and nuclei
	- Search for new QCD physics at low x
	- Photon-initiated BSM physics (e.g. weak mixing angle, $e\rightarrow\tau$)
- **• UPCs offer well-understood beams of nearly-real photons that provide access to pertinent QCD physics**
	- nPDFs, spatial imaging, saturation
- **• They also provide opportunities to HEP that (so far) are unique, even at the LHC**
	- BSM physics with dileptons or diphotons
- **• They even offer one of the "smallest" collective systems that can inform our understanding of the QGP**
- **• Our collider detectors at the LHC are excellent for this task**
	- Large acceptance (ATLAS/CMS $|n|$ < 2.4, ALICE $|n|$ < 0.8 and n = -2.5-4, LHCb η=2-4.5) and flexible detectors with powerful triggering (or no need…)

exclusive dileptons ("γγ luminosity")

2 photon flux, 2 approaches hence this sets a lower bound on the survival factor in any physically reasonable approach. Given this, we will also briefly review of uncertainty review of uncertainty review of uncertainty α \bullet is individual equipped values. The \bullet collisions in particular, this separation is beyond the reach of \mathbf{r} and \mathbf{r} thiv gonne of that a significant fraction of elastic PI significant fraction of elastic PI scattering of the s m, \mathcal{L} approactive that are simply of \mathcal{L}

$$
\sigma_X = \int \frac{d^2N}{dk_1 dk_2} \hat{\sigma}(k_1, k_2, \dots) dk_1 dk_2
$$
 for dileptons we use well-known
Breit-Wheeler cross section formula (Brodsky et al, 1971)

for dileptons we use well-known

*d*2*N dk*1*dk*² ⁼ [∫]*b*1>*R*¹ *d*2 *^b*¹ [∫]*b*2>*R*² *d*2 *b*² *n*(*k*1, *b*1)*n*(*k*2, *b*2) *P*fn(*b*) (1 − *P*H(*b*)) **point like charge with radial cutof** forward neutron topology (no) hadronic interaction: Glauber calculation **STARlight: 2 Theory 2.1 Elastic photon–initiated production in hadron collisions: recap** The basic formalism follows that described in for example [26]. That is, the elastic photon– initiated cross section in *N*1*N*² collisions is given in terms of the equivalent photon approxima-*N*1*N*2!*N*1*X N*² = Z ^d*x*1d*x*² *ⁿ*(*x*1)*n*(*x*2)^ˆ !*^X* , (1) where *Ni* denotes the parent particle, and the photon flux is *ⁿ*(*xi*) = *↵* ^Z d2*qi*? Ç *q*² (¹ *xi*)*FE*(*Q*² in terms of the transverse momentum *qi*? and longitudinal momentum fraction *xi* of the parent **2 Theory 2.1 Elastic photon–initiated production in hadron collisions: recap** The basic formalism follows that described in for example [26]. That is, the elastic photon– initiated cross section in *N*1*N*² collisions is given in terms of the equivalent photon approximation (EPA) [34] by = where *Ni* denotes the parent particle, and the photon flux is *ⁿ*(*xi*) = *↵ ⇡*² *xi* ^Z d2*qi*? *q*2 *i*? + *x*² *ⁱ ^m*² *Ni* Ç *q*² *i*? *q*2 *i*? + *x*² *ⁱ ^m*² *Ni* (¹ *xi*)*FE*(*Q*² *ⁱ*) + *x*2 *i* 2 *FM* (*Q*² *i*) å **SuperChic:** Comput.Phys.Commun. 212 (2017) 258-268 . Z R Z

<u>xutions u</u> i? $\frac{1}{2}$ *k*n vr *i*? form fa particle carried by the photon. The modulus of the photon virtuality, *Q*² **charge distributions using known form factors**

SciPost Phys. 11, 064 (2021)

an exclusive dimuon event

11 highest mass dimuon event in 2015 dataset - $m_{\mu\mu}$ = 173 GeV

an exclusive dielectron event

 $p_T^{\rm e1}$ $= 8.2 \text{ GeV}$ $p_T^{e2} = 7.4$ GeV

Exclusive dilepton processes & dissociation

 $PhPh(\gamma\gamma) \rightarrow \mu^+ \mu^- (Ph^{(\star)}ph^{(\star)})$ is the primary signal Breit-Wheeler process $PbPb(\gamma\gamma) \rightarrow \mu^+\mu^-(Pb^{(\star)}Pb^{(\star)})$ is the primary signal Breit-Wheeler process

 $\mathcal{F}_{\mathcal{F}}$ is diagrams for the (a) leading-order PbPb() and (b) next-to-leading-order $\mathcal{F}_{\mathcal{F}}$

 $PbPb(\gamma\gamma) \rightarrow \mu^+\mu^-\gamma(Pb^{(\star)}Pb^{(\star)})$ is a radiative process (still signal!) photons in the final state. Dissociative processes, where one photon is emitted by charged constituents of

a nucleon, as shown in Figure 1(c), are also neglected by most models, in part due to the fact that the fact t

 $Pb + N/Pb(\gamma\gamma) \rightarrow \mu^+\mu^- X(Pb^\star Pb^{(\star)})$ is **dissociative** background process

How exclusive is "exclusive"? **2°sPb, the FWHM of the incident "quasi-monochromatic photon beam" was determined to be ALL MEV we have the straight E the energy region** \mathcal{L} **is the energy intervals of** \mathcal{L}

Exclusive processes can still excite the nuclei, via secondary photon exchange, depending on impact parameter

o, b ,,:Ao $Pb+Pb$ 2018, 0.8 μb^{-1} / "k, ~ 1Loreniz line $\begin{array}{ccc} & 1 & 1 & 1 \end{array}$ Fig. 2. **Partial photoneutron** cross sections (~:,,., cry, =. and ~7, 3° of 19~Au. We also show the descending part of the unique Lorentz line corresponding **to parameters** tpven in table 3. 1 10 $E_{\rm C}^{\rm ZDC}$ [n] 0 10000 20000 30000 Counts *ATLAS* Preliminary end the UPC selection and this paper have been obtained from experiments performed from MB selection with the photon-monochromator developed by Tzara and \uparrow A detailed description of the measurements of the photon energy resolution *AE/E* and of the number of the number of $\mathbb T$ and $\mathbb T$ and $\mathbb T$ photons traversing the photons of the photons of the photons of t target has been given elsewhere 2,3). A summary of the general technique is given here. Positons are created in a gold target then deflected and energy analyzed by means of the magnetic and a set of variable width. On passing the variable width. On passing the variable width. \bigwedge annihilation target of λ are positons of the positons are posi annihilated-in-flight thus creating a"quasi-monochromatic" photon beam of energyE. The remainder are swept out of the photon beam and captured in a Faraday cup 2-4). The photon beam and captured in a Faraday cup 2-4). \overline{a} series of \overline{a} $E_C^{\text{2DC}}[n]$

"Giant dipole resonance": all protons vibrating against all neutrons

 \rightarrow knocks out 1-4n

which we can "count" in our zero degree calorimeters!

ZDC selections in exclusive γγ→µµ

ZDCs can easily distinguish 0n from 1n, 2n or more neutrons

Typically make a selection at ~0.4 of the neutron energy to divide no activity (0*n*) from 1 or more (X*n*)

We can then classify events by their neutron topology:

- **OnOn** no neutrons on either side
- **Xn0n/0nXn** neutrons on one side
- **XnXn** neutrons on both sides

ZDC fragmentation in STARlight

Selecting ZDC topologies selects impact parameter ranges! (exploited by several of the results I will show soon!)

Dissociative contributions from *ℓℓ* **acoplanarity**

*p*Te > 2.5 GeV, |ηe|<2.47,*p*Tee < 2 GeV

0n0n signal distributions beautifully described after including QED showering! griai distributibris beautifully describe Events / bin width

Xn0n and XnXn require contribution from dissociative processes d Yn Yn roquiro d XnXn <u>require</u> contribution fr i
Di $\frac{1}{2}$ issociative prod

Both ee and µµ observe steady rise with |yee|, relative to STARlight Both ee and $\mu\mu$ observe steady rise with $|v_{\text{ee}}|$, relative to STARIigh The shaded area represents the total uncertainty of the data, excluding the 2% luminosity uncertainty. R_o th µان
اسداد µ

STARlight tends to underpredict data while, SuperChic has the correct s iARiight tends to underpredict data while, SuperChic has the cori
spectral shape, but overpredicts data. 120 N hi ta (

ZDC selections test the *impact parameter dependence* of the photon fluxes. s test the imnact parameter $\frac{m \cdot p \cdot \sigma}{0.2}$ lependence of the photon f $\begin{array}{ccccccc} 0.2 & & & & 0.2 \end{array}$

ATLAS sees expected modifications on <u>longitudinal</u> distributions: $m_{\mu\mu}$ and $y_{\mu\mu}$: selecting one or both ZDCs to fire makes the mass distribution harder CMS sees clear trans wered broadening in acoplanarity and increased mean m_u $p_{\mu\mu}$ [GeV] as event selections require more neutrons in the ZDCs pected modifications on <u>ior</u> $t_{\rm th}$, alternalization, and the dashed line corresponds to the dashed state of the dashed sta litualital aistribution 10 20 30 40 50 60 10 20 30 0 10 20 30 40 50 60 *<u><u></u>*</u> 10 20 30 40 50 60 \boldsymbol{q}

generated to the target of the target initial photons of the target of linear nolarization of initial photons o sum and difference vectors!
nelse a separation in the distribution in the distribution of the distribution of the distribution of the distributio $\mathbf{S}_{\mathbf{a}}$ and magnetic field angle is closely related to the three contributions of the theorem STAR demonstrated impact of linear polarization of initial photons, as a correlation between the momentum su tions and a continuum of the public international comparations of the public state of Λ possible public lines as a correlation between the momentum sum and difference vectors! A new tool in UPC physics.

Non-exclusive µµ from γγ initial idea
 in the shear viscosity of the viscosity of the viscosity of the viscosity of the viscosity of the
 internal shear viscosity of the viscosity

The same $\mu\mu$ process can occur in non-UPC Pb+Pb collisions, albeit accompanied by hadronic backgrounds (esp. heavy flavor): are the outgoing muons sensitive to initial (e.g. B field) or final (QGP) effects?

Non-exclusive µµ from γγ 0.5 0.5

1 oun**d**ls ا
ا brogressively broader than UPC, and even "dips" at 1 ds (heavy flavor & Drell-Yan), the opening and distribution at b<R becomes progressively broader than UPC, and even "dips" at α~0 1 After accounting for backgrounds (heavy flavor & Drell-Yan), the opening angle 5 α Best understood so far as a QED interference effect

1

BSM physics

- **•** Anomalous magnetic moment of tau leptons $a_\tau = (g_\tau 2)/2$ sensitive to **physics beyond the standard model** ent of tau ledtons i $\frac{1}{2}$. Pape is produced the $\frac{1}{2}$. $\frac{1}{2}$. $\frac{1}{2}$. $\frac{1}{2}$ r d modal \blacksquare for experimental realization and importantly show that
	- Large mass of the tau increases sensitivity to new physics by $(m_\tau/m_\mu)^2$ relative to muon g-2 (e.g. at BNL & FNAL) precision. The LHC cross-section enjoys a *Z*⁴ enhancement (*Z* = 82 for Pb), with over one million ! ⌧ ⌧ ton beams require future datasets (Belle-II) or proposed \blacksquare $g(x) = \frac{1}{2}$ DOVSICS OV IM₅/M_uj² tensor *^µ*⌫ = i[*^µ,* ⌫]*/*2 structure of the fermion current
- **• Three channels available: eµ, µ+track, µ+3 tracks**
	- CMS focuses on μ +3 tracks in 2015 data (404 μ b⁻¹), with no ZDC selections *fits for a^τ using variation of σ(γγ*→*ττ)*
	- ATLAS uses all 3 channels in 2018 (1.44 nb-1), requiring 0n0n and cluster veto to suppress dissociative and hadronic backgrounds
		- *fits for a^τ using modifications to p*T*(µ) distributions, using µµ to normalize photon flux*

ATLAS: 3 channels

- **• Observed 95% CL limits from a^τ** ∈ **(−0.057, 0.024)** \mathcal{F} at \mathcal{F} \mathcal{F} from \mathcal{F} $\mathcal{F$ σ s from a $_\tau$ \in (–0.057, 0.024) and from the f
	- Limits similar to that extracted from DELPHI in 2004 $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ experiments at $\frac{1}{2}$
	- Expecting substantial improvements from Run 3 & 4 data!

advarice by iooking in the full nume fulling.
And final states insing events w/ few extra tracks, paramarata states, asing svents *in* for Sxtra trashe Figure 10: Observed and predicted *N*tracks distributions for events passing the SR selection but CMS made a dramatic advance by looking in the full Run 2 lumi, combining the e*µ*, e*t*h, *µt*h, and *t*h*t*^h final states together. The inclusive diboson background using a combination of leptonic and final states, using events w/ few extra tracks to the result of the global fit performed with the *m*vis distributions in the SRs, and the signal eter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and

light-by-light scattering

Candidate Event: Light-by-Light Scattering
Run: 366994 Event: 453765663 2018-11-26 18:32:03 CEST

Light by light scattering very soft transverse momenta (*p*^T . 0.1 GeV). Since each photon flux scales as the square of the ion charge *Z*² , *gg* scattering cross sections in PbPb collisions are enhanced by a factor of

Signal process is the observation of two photons and no other activity. Gignal production and chool validit of two priotons and no other adtivity. Signal process is the observation of two photons and no other activity.

 $\frac{1}{2}$ TIUWGVGI, GIGULI However, electron pairs can mimic photons if we don't see their tracks.

Also, there are gluon-mediated processes with two-photon final states ("central exclusive production", or CEP) When \mathcal{E} and first evidence of \mathcal{E} reported by the ATLAS experiment \mathcal{E} and \mathcal{E} with a set of \mathcal{E} with a

γγ acoplanarity

γγ acoplanarity ($A_Φ=1-ΔΦ/π$) used to reject or enhance backgrounds: signal dominates in A_Φ<0.01

CEP backgrounds typically estimated using data-driven approaches, and requiring ZDC strongly enhances these

BSM physics using LbyL cross-section measurement currently exists. The cross-sections marked with † are those used as input to the extraction of the CM phyciae ucin \bigcup \longrightarrow \bigcup

Light-by-light scattering is sensitive to the production of axion-like $particles (ALP)$ $\text{TE} \text{prod}_{\text{S} \text{ = } \text{C}^{\text{S}}} \text{prod}_{\text$ \overline{Pb} \overline{Pb} \overline{Pb} \overline{Pb} \overline{Pb}

 $\frac{1}{2}$ theo. uncertainties used Joint working group starting to perform accounting for correlations. \sim detailed combination measurements

Phys. Rev. D, 99:056016, 2019. doi: 10.1103/PhysRevD. σ $\sigma_{\text{meas.}}$ - 115 \pm 15 (stat.) \pm 11 $\mathbf{S} = 115 \pm 10 \text{ nb}$ **s** $= 115 \pm 19$ nb, at $+\frac{3}{\mu}$ $\left(\frac{\mu}{2}\right)$ $+\frac{3}{\mu}$ $\left(\frac{\mu}{2}\right)$ the α $\left(\frac{\mu}{2}\right)$ $\sigma_{\text{meas.}}^{\text{fid.}} = 115 \pm 15 \text{ (stat.)} \pm 11 \text{ (syst.)} \pm 3 \text{ (lumi.)} \pm 3 \text{ (theo.)} \text{ nb}$

 $J_{\rm max}$ Important offort for a noncommutativity. *Phys. Rev. D*, 101(9):095035, 2020. f kom \overline{I} \overline{I} mportant offer the oxideding for poternation.
from LHC runs 3 & 4 trooting full potontial Important effort for extracting full potential $\frac{1}{2}$ uncertainty is still found to be the statistical uncertainty is still found to be the theorem is still found to be the stil

Pb

γ

γ

Pb(*)

a

γ

γ

Pb(*)

Pb

spatial and momentum parton structure of nucleons and nuclei

CMS Experiment at LHC, CERN Data recorded: Sat Nov 28 01:35:16 2015 CET Run/Event: 262777 / 9332894 Lumi section: 98 Orbit/Crossing: 25546801 / 1572

324 *PHENIX Collaboration / Physics Letters B 679 (2009) 321–329*

occur when the nuclei are separated by impact parameters larger than the sum of the nuclear radii. $invariant mass = 3.13 GeV$ 9216 modules with 4 cm × 4 cm × 40 cm, 14*.*4*X*0), at a radial dis-

forward direction. The reconstructed invariant mass of the two leptons is about the *J/* mass. LHC experiments have a broad variety of results on vector meson (ρ,ψ,Υ) in Pb+Pb (γ+A) and p+Pb (γ+p) collisions! results on ve **/** \mathbf{F} **)** complies:

Momentum & spatial structure

Sensitivity to shadowing $\& \quad \frac{1}{2} \mathbf{X} \mathbf{X} \mathbf{X} \mathbf{X} \mathbf{X} \mathbf{X}$ $\mathbf{X} \mathbf{U} \mathbf{X} \mathbf{X} \mathbf{X}$ Target final state *|f* i 6= initial state *|i*i square of gluon density: sensitivity to shadowing &
saturation physics cross sections sensitive to saturation physics

 $\sum_{i=1}^{\infty} \mathcal{L} \left(\mathcal{L} \mathcal{L} \left(\mathcal{L} \mathcal{L} \right) \right)$ and $\sum_{i=1}^{\infty} \mathcal{L} \left(\mathcal{L} \mathcal{L} \left(\mathcal{L} \right) \right)$ $d^2\sigma$ *dYdt* ∝ (*xG*(*x*)) 2

measured p–p dielectron rate [34] at *m*inv *>* 2 GeV*/c*² to the 8%

Incoherent/Breakup

select collisions well centered in the fiducial area of the central

 $\mathbb{E} \left[\begin{array}{cc} 1 & 1 \end{array} \right]$ \mathbb{E} characterised by \mathbb{V} $\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$ $\frac{1}{t_1}$ $\frac{1}{t_2}$

 $\begin{array}{c} \begin{array}{c} \end{array}$

h*i|A|i*i

 t_1 t_2

Fig. 1 Diffractive *J/*ψ meson production in electron proton colli- $\mathbf{a} \sim^* A \times I/A$ $\frac{d\sigma}{d\sigma}$ \sim $1/4\gamma^*A\rightarrow VA$ _{\sim} \sim \sim $\frac{d\sigma}{d\sigma}$ \sim dt $\frac{1}{2}$ $\frac{1}{2$ energy of [√]*^s* [≈] 318 GeV, data recorded at a lower centre $e(k')$ $\frac{1}{\gamma^*(q)}$ $\sum_{j=1}^{N}$ ments at HERA and fixed target experiments [26, 27]. The elastic and proton-dissociative cross sections $\mathcal{L}_{\mathcal{L}}(\mathcal{D}')$ *t* $\left(\frac{1}{2} \right)$ elastic production: proton survives incoherent production: p/A, RIP \mathbb{R} $\frac{1}{2}$ $\left| \left\langle \mathcal{A} \right\rangle \Omega \right|$ **Experimental matrix** $\frac{1}{\sqrt{2\pi}}$ $p(P)$ Rapidity gap between *J/* and target remnants $\bm{q} \bm{\varrho} \equiv \sigma_{\text{incoherent}} \sim \sum |\langle f|\mathcal{A}|i\rangle|^2.$ $f \neq i$ $=$ \sum *f* $=\sum \langle i|\mathcal{A}|f\rangle^\dagger \langle f|\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^\dagger \langle i|\mathcal{A}|i\rangle$ Average over initial states: $|A|^2$ _{Ω} $|\langle A \rangle$ dσ/dt $e(h)$ $\lambda \in \mathbb{R}^{n \times (q)}$ \mathcal{S} is the state \mathcal{S} of \mathcal{S} and \mathcal{S} are \mathcal{S} of \mathcal{S} and \mathcal{S} real size \mathcal{S} / \mathcal{V} probing fixed target configuration ⌦ $p(P)$ in the same $p(F)$ $\mathrm{d}\sigma^{\gamma^* A\to V\!A}$ d*t* $\sim |\langle {\cal A}^{\gamma^*A\to V\!A}\rangle_\Omega|^2$ Cross section probes average b dependence of the scattering dissociative (incoherent) α maniyasaan, 2016
 $e(k)$ $\qquad \qquad$ \qquad $e(k')$ No net color charge transfer Rapidity gap between *J/* and target remnants $\| \setminus \setminus \setminus \setminus \|$ *f* 6=*i* .
ب
سي \sim $f(A \rightarrow VA \setminus \bigcap_{\alpha} |2$ elastic: sensitive to average $\sigma_{\text{incoherent}} \sim \sum_{f \neq i} |\langle f | \mathcal{A} | \iota \rangle|^2$ h*i|A|f* i *†* h*f |A|i*ih*i|A|i*i \mathcal{A} average over initial states: \mathcal{A} ϵ itions $\|\sigma\|_A^2\rangle_{\Omega}-|\langle A\rangle_{\Omega}|^2$ spatial extent of object $e(k)$ \overline{S} ^{*i*}₁ $W_{\gamma p}$ J/ψ $\mathbb{A}(P) \stackrel{\geq}{=}$ incoherent ⇠ h*|A|*2i⌦ *[|]*h*A*i⌦*[|]* **Incoherent cross section = variance of** *A*
 A dσ/dt |t| Coherent/Elastic Incoherent/Breakup t₁ t_{2 t+1} t₃ t₄ $\mathrm{d}\sigma^{\gamma^*A\to VA}$ and the target configuration fluctuations in target configurations in target configurations of $\mathrm{d}\sigma^{\gamma^*A\to VA}$ $\frac{1}{16}$ 1978, 1978, Pumplin, Phys.Rev. Caldwell, Phys.Rev. Caldwell, Phys.Rev. Caldwell, Phys.Rev. Caldwell, Phys.Rev. Caldwell, **Fig. 11** Alternatives **Fig. 2** It is the colli-type events contained by a large rapidity by a large rapid by a large rapidity gap on the colli-type events contained by a large rapid by a large rapid by a large rapid by a sions: (*a*) elastic *J/*_{*w*} production in which the production in which the production in the proton state and production in the proton state Γ $\begin{aligned} \text{SIN} \text{ = } \sum_{f} \langle \text{ = } \rangle \rangle \end{aligned}$ dashed line are soft photons that may excite the nuclei but do not lead to particle production in the central rapidity region. Both diagrams contain at least one photon and $e(k)$ and Q^2 impact $e(k')$ 18*X*0) and two sectors of lead-glass Cerenkov calorimeter (PbGl, ˇ $\gamma^*(q)$ tance of ∼ 5 m from the beam line. $T = \frac{1}{2}$ ultra-peripheral Au events were tagged by $\mathcal{A}^{\mathcal{A}}_{\mathcal{A}}$ detection at \overline{M} and $\overline{3}$ are $\overline{3}$ hadronic calorimeters S_1 m up γp and γ interaction point that measure that measure that \mathbb{Z} from the Au[⋆] Coulomb dissociation with [∼] 20% energy resolution and cover |θ| *<* 2 mrad, which is a very forward region.³ \blacksquare trigger set up for the first time in \mathbb{R} either side of the central arm. GQE and C are both of C is the C $\frac{r}{\sqrt{a}}$ The Background $\mathcal{F}_{\mathcal{B}}$ trigger effects in the Au collisions is a $\mathcal{F}_{\mathcal{B}}$ $\mathcal{S}^{\mathcal{S}}$ and the BBC trigger has an inefficiency of $\mathcal{S}^{\mathcal{S}}$ which is the most peripheral nuclear reactions could be \sim a potential background for \sim $(1/4)^2$ on $(1/4)^2$ $\left| \begin{array}{ccc} \vert & \vert & \vert & \vert \end{array} \right|$ in the final state of the final state \mathcal{S} structure of the position of the PC hits and EMCal clusters as- \mathcal{F} the tracks in the event vertex in the event. This gave an event vertex \mathcal{F} $\mathbf{A} = \left\{ \begin{array}{l} \mathbf{A} & \mathbf{A} \\ \mathbf{B} & \mathbf{A} \end{array} \right.$ reduction in the resolution is expected in this analysis because of $\frac{1}{2}$ (1) A standard offline vertex cut |*vtxz*| *<* 30 cm was required to $\begin{bmatrix} \mathbb{R} & \mathbb{R} \end{bmatrix}$ sensitive to fluctuations Schenke & Mantyasaari, 2016

Beautiful connection between HERA (& eventual EIC) physics and the urgent needs of the RHIC/LHC heavy ion program!

J/ψ measurements & NLO theory rements \blacksquare

 \sim Denig calculated, to potentially allow nd a to be productively used for PDF/sh NLO cross sections being calculated, to potentially allow J/ψ data to be productively used for PDF/shadowing extraction

$$
\mathcal{M}^{\gamma N} \propto \langle O_1 \rangle_V^{1/2} \int\limits_{-1}^1 dx \left[T_g(x,\xi) F^g(x,\xi,t) + T_q(x,\xi) F^{q,S}(x,\xi,t) \right] \qquad \leftarrow \text{GPDs!}
$$

important progress towards including weeter mesons into PDFs Large scale dependence (and perhaps ALICE/LHCb tension) but

Probing nuclear shadowing with J/ψ

J/ψ cross sections can be turned into photonuclear cross sections using selections on the ZDC, method now used by both ALICE & CMS.

 Comparison with "impulse approximation" gives empirical estimate of nuclear shadowing effects on J/ψ production

Prospects for J/Ψ in ATLAS

Newly commissioned TRT trigger let ATLAS accumulate large sample of exclusive J/ψ using full acceptance of our tracker.

Analysis ramping up but excited about continuous coverage over wide rapidity range - should help resolve theoretical puzzles!

STAR: probing nuclear geometry w/ ρ⁰ energies [42] produces a Australia Romano s stattering with the processing

The shape of the shape of the shape of conductive dips in \mathcal{D} F^{-2} obecnied with coberant o \sim μ \sim 00000 vour with donorum μ Diffractive dips in $-t = p_T^2$ observed with coherent ρ bands show the sum in quadrature of all systematic uncertainties listed

target. The candidary of principles the Topic of great interest for $\mathbf f$ of the gold nucleus via two-dimensional Fourier transformation and *d*σ*/dt*. RHIC beam energies are high enough that, for ρ⁰ photoproduction at middle the local density distribution and μ *XnXn* and 1*n*1*n* diffraction patterns shown in Fig. 8. The integration α limited to the region α of β and β an photo production, and with differing sensitivity to saturation effects **2** arounds from incoherent processes groundo nominioonoront processes) in Table V and the statistical errors, which are shown as vertical lines. Topic of great interest for the EIC, also with ϕ & J/ψ, in both DIS and photo production, and with differing sensitivity to saturation effects emitted by any of the two ions. (but important backgrounds from incoherent processes)

arXiv:2204.01625

STAR: coherent ρ⁰→ππ

Just as with dileptons, polarization offers a unique **A+A** collision handle on imagine the nucleus with vector mesons $A_1 + B_2 + A_3 = A_4 + A_4$ selected increding the pulsive is the pairs of the **pairs in the servite** \mathbf{a} , \mathbf{b} , \mathbf{a} handle on imagine the nucleus with vector mesons

 $\cos \phi = (p_{T1} + p_{T2}) \cdot (p_{T1} - p_{T2}) / (|p_{T1} + p_{T2}| \times |p_{T1} - p_{T2}|)$

sheeds in ATA (not in pTA) which are also sensitive the set the construction of th effects in A+A (not in p+A) which are also sensitive $A_2 \rightarrow$ to nuclear geometry (via itts to -t distributions) Linear polarized photons lead to distinct interferometric to nuclear geometry (via fits to -t distributions)

in U+U) show a definite interference effect due to the non-locality of the pion wave functions. **Yajin Zhou, Thurs parallelIsaac Upsal, Tues parallel**

Impact parameter dependence from ALICE

Brand new result from ALICE on these quantum interference effects as a function of "centrality"!

Comparisons with models that treat the ρ production as the scattering of color dipole off of a CGC

The interference increases at smaller impact parameters

photonuclear jet production

Run: 286717 Event: 36935568 nucleus collisions at the LHC. The resulting high rates demonstrate that some key directions in small x research $2013 - 11 - 2003.30.37$ UEST Pb+Pb, $\sqrt{s_{NN}} = 5.02$ TeV t_{t} the particles will thus be significant in the set collisions that $\frac{1}{\text{t}}$

Studies of small x deep inelastic scattering at HERA substantially improved our understanding of strong interactions at high energies. Among the key findings of HERA were the direct observation of the rapid growth of the small x structure functions over a wide range of virtualities, Q2, and the observation of a significant probability for hard diffraction consistent with approximate scaling and a logarithmic Q² dependence ("leading twist" dominance). HERA also established a new \mathcal{C} son production – described by the QCD factorization theorem and related to generalized parton distributions

The importance of nonlinear QCD dynamics at small $x \in \mathbb{R}^n$ is one of the focal points of the focal points of the focal points of the \mathbb{R}^n *e.g.* Ref. [1]). Analyses suggest that the strength of the interactions, especially when a hard probe directly couples to gluons, approaches the maximum possible strength – the black disk limit – for ^Q² [≤] ⁴ GeV2. These values are relatively small, with an even smaller \mathcal{L} difficult to separate perturbative and nonperturbative effects at small x and Q2. Possible new directions for further experimental investigation of this regime include higher energies, nuclear beams and studies of the longitudinal virtual photon cross section, σL. The latter two options were discussed for HERA [2, 3]. Unfortunately, it now seems that HERA will stop operating in two years with no further measurements along these lines except perhaps of σL. One might therefore expect that experimental investigations in this direction would

The purpose of this letter is to demonstrate that sev-

 $p_T^2 = 60$ GeV

kinematics can be readily identified by the hermetic LHC detectors, ATLAS and CMS. In this paper we consider the feasibility of studies in two of the direcΣ*γ*Δ*η*

 $p_T^1 = 73$ GeV

where the photon carries momentum fraction \mathcal{L}^{1} use jets to directly probe nuclear PDFs Xn0n topology enhances events, verified by "gap"

inelastic photonuclear processes

Σ*γ*Δ*η*

Run: 286717 Event: 43643466 2015-11-26 09:53:40 CEST Pb+Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

soft inelastic collisions are typically modeled using VDM: ρ+A does a "small" hadronic system show collective behavior like p+A & pp?

3D flow in photon-nucleus collisions? γ

photons interact hadronically via fluctuations in quark-antiquark pair

3D simulation of a photon-nucleus collision!

emitted photons are almost on mass shell, with virtuality α is the radius of the radius of the charge, with virtuality α

Does this system show "flow" like in heavy ions or proton-proton? For mumber a system snow flow fike in neavy lons or proton-proton α
Simulations suggest possible, but need to work in full 3D!

> https://www.bnl.gov/newsroom/news.php?a=120817 Phys. Rev. Lett. **129**, 252302

Extracting flow contributions

Two particle correlations of charged particles to extract v_2

Template method has been successfully used to extract flow coefficients from pp data, based on use of a lower multiplicity sample

Collective flow in γ+A?

 v_2 and v_3 observed - with no observed multiplicity dependence, and lower than p+Pb and pp

Signs of collectivity (QGP) in **γ+Pb**? **γ+p** does not show this!

Great interest for people excited about physics at the EIC, esp. high density QCD effects

Hydrodynamics can *predict* the data, after being tuned to pp/pPb

Phys. Rev. C 104, 014903 (2021)

Collective flow in γ+A?

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In the experience of s prior en 1996. For New York because because

Great interest for people excited about physics at the EIC, esp. high density QCD effects of the decreasing lifetime of the hydrodynamic phase.

Hydrodynamics can *predict* the data, after being tuned to pp/pPb collisions, which results in the smaller $\sum_{i=1}^n$ is play for the stronger longitude str

Lower values of v_2 reflect a more comb raidoo of vz rondot a moro COLIPACTIBULAISIALE compact initial state

Radial flow from mean *p***^T** PHYSICAL REVIEW LETTERS 129, 252302 (2022)

be the esme in unualeus as lisions as in *pe the same in y-nucleus collisions as in* extrapolated to $\mathcal{O}_\mathbf{C}$ and $\mathcal{O}_\mathbf{C}$ is a definition smaller than the markers, are statistical uncertainties and shaded \bm{n} -Bauel en die Collisions. FIG. 1. The charged hadron pseudorapidity distributions Also predicts expansion will be the same in γ -nucleus collisions as in calculations are compared with experimental data from the compared with experimental data from the ρ roton the comparison the comparison of ρ roton the comparison the comparison of ρ roton the comparison of ρ roton functions of charged hadron multiplicity in p \mathbf{F} (dashed lines) in p \mathbf{F} (dashed lines) in p \mathbf{F} p*roton-*nucleus collisions at same N_{ch} \mathcal{L} , the p \mathcal{L} p \mathcal{L} p \mathcal{L} p \mathcal{L} , the p \mathcal{L} p results are compared by \mathcal{L}

 m omentum to he similar in som pseudoraam to be omnigt to be the sense momentum to be similar in some regions, but not all - hints of 3D flow! ATLAS recently measured this, and observes average transverse

Summary

- **• "Light"ning tour of what can be done with UPC at the LHC**
- **• Photon-photon processes**
	- electrons, muons, tau lepton pairs, photon-pairs
	- Probing both QED and BSM physics

• Photonuclear processes

- Jet production to probe nuclear PDFs
- Soft hadron production studies of collectivity (full circle back to the hadronic program!)
- Exclusive vector meson is already providing a wealth of insight, which will only increase with integrated luminosity

• LHC Run 3 finally began in 2023

- Expect x3 more data than in Run 2 (2015-2018)
- New detector capabilities from the Phase 1 upgrades
- Lots of new exciting results to come!

• I didn't even get to the Pb+p program (or O+O or p+O)

- Interesting workshop coming up at CERN interested in this
- "Physics with high-luminosity proton-nucleus collisions at the LHC Workshop" https://indico.cern.ch/event/1389579/

6 Summary **ALICE streaming data is a UPC dream**