UPC@LHC contributions to EIC science

Peter Steinberg, BNL

Mini-town meeting, 8 Sept 2022

Brookhaven National Laboratory

https://www.symmetrymagazine.org/article/a-collision-of-light

UPC before the EIC

- **The RHIC & LHC UPC programs have embarked on an ambitious program of photon-photon and photo-nuclear physics**

- **To date, many results from the LHC on a broad range of topics, several of which have clear relevance to the EIC program**
  - Dileptons - “luminosity” & BSM physics (tau)
  - Light-by-light - sensitive to BSM physics
  - Vector mesons - gluon momentum and spatial distributions, hot spots within the nucleon
  - Jets - nPDFs, gluon polarization
  - Hadron “collectivity” (correlations from parton saturation)

- **All of these will be advanced by the ~10x increase in luminosity expected in LHC Runs 3 and 4**

ATLAS: Triple differential UPC dijets

- **Use ZDC as part of primary trigger**
  - Require gaps to ensure photonuclear topology

- **Use jets to define kinematic variables akin to DIS variables**

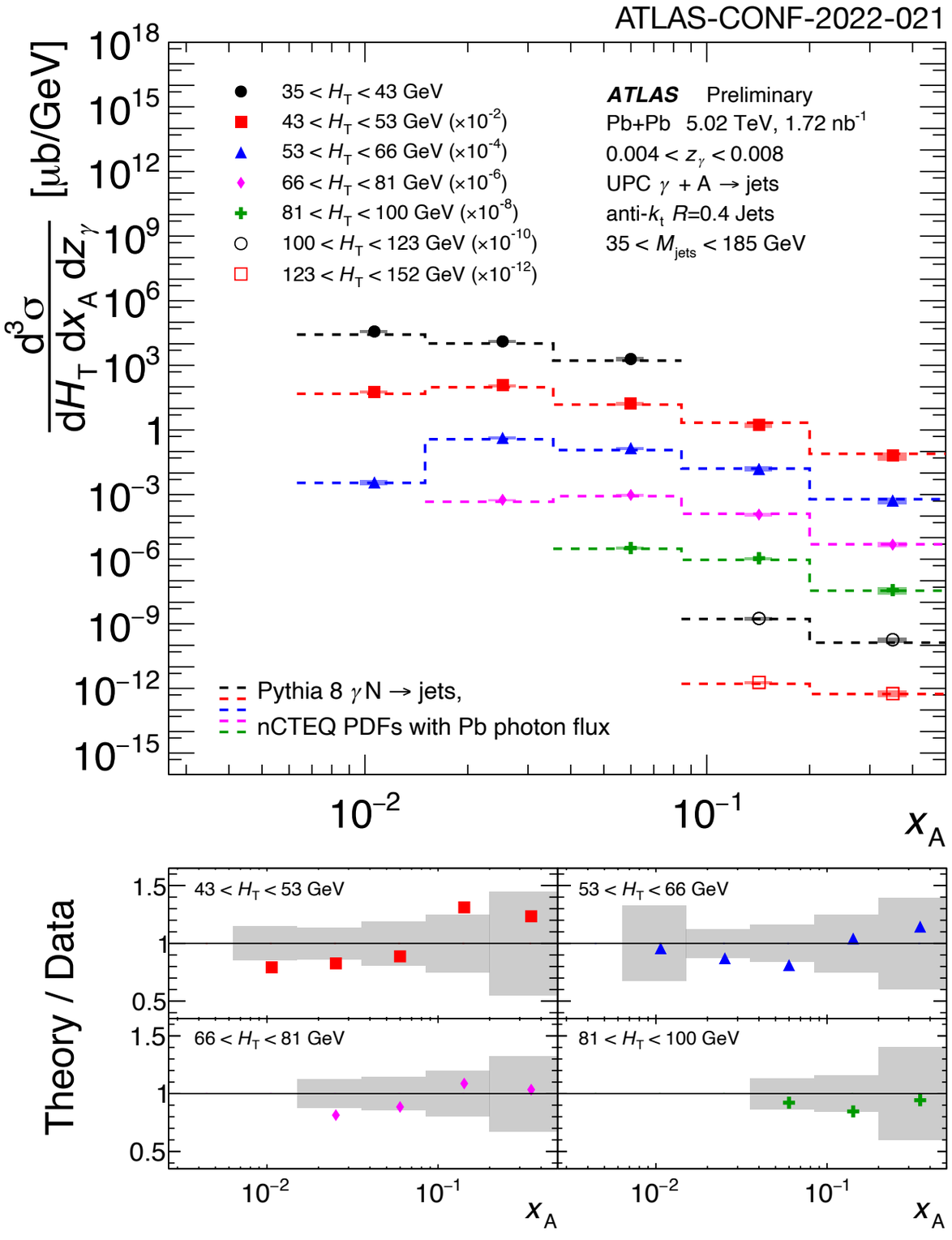
$$H_T \equiv \sum_i p_T^i \qquad x_A \equiv \frac{M_{jets} e^{-y_{jets}}}{\sqrt{s_{NN}}} \qquad z_\gamma \equiv \frac{M_{jets} e^{+y_{jets}}}{\sqrt{s_{NN}}}$$

"Q^2" "xy"

- **Selections on z_γ to minimize acceptance affects**

- **Triple differential cross sections can be compared to Pythia8 using nCTEQ PDFs**
  - Reweighed Pb photon flux
  - Modeled correction to account for requiring Xn0n

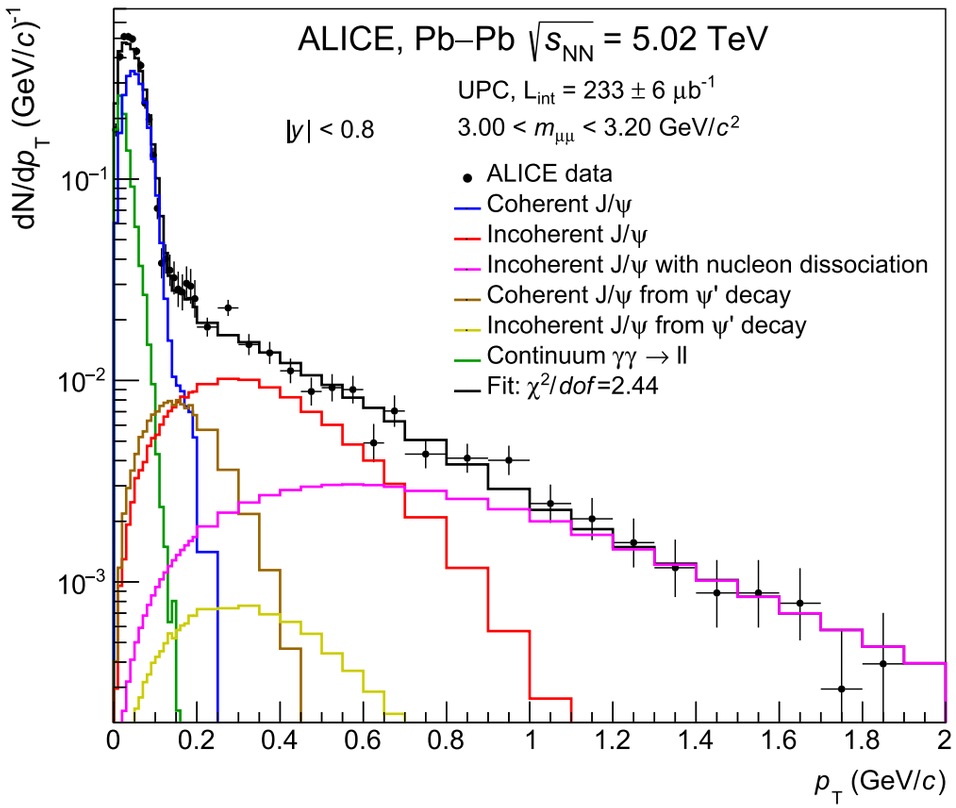
- **Results not yet finalized, but offer prospects for first detailed direct studies of nPDFs**

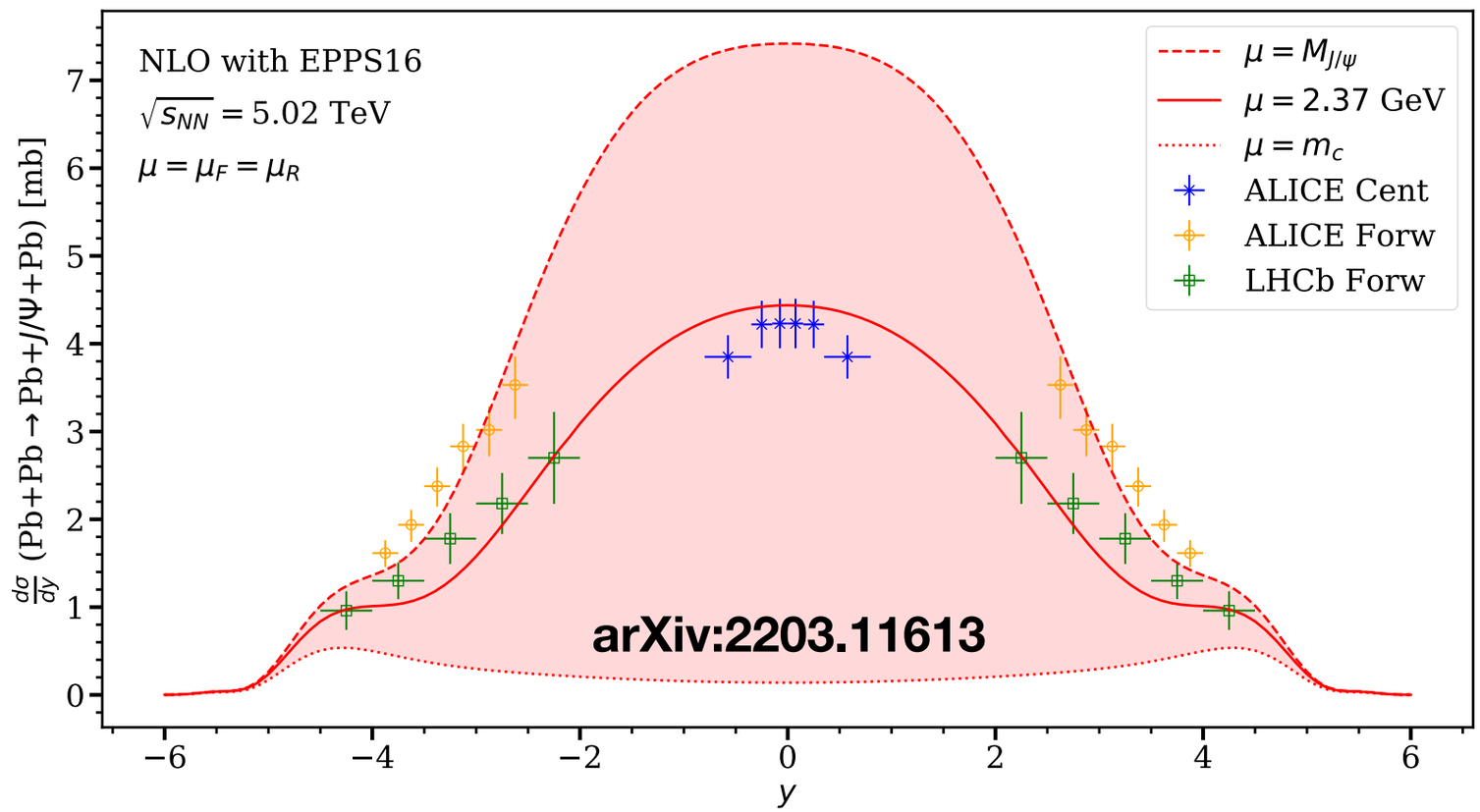


J/ψ measurements & NLO theory

LHCb arXiv:2107.03223
ALICE: Eur. Phys. J C (2021) 81:712

$$\frac{d\sigma^{AA\to AVA}}{dy} = \left[k\frac{dN_\gamma^A(k)}{dk}\sigma^{\gamma A\to VA}(k)\right]_{k^-} + \left[k\frac{dN_\gamma^A(k)}{dk}\sigma^{A\gamma\to AV}(k)\right]_{k^+}$$





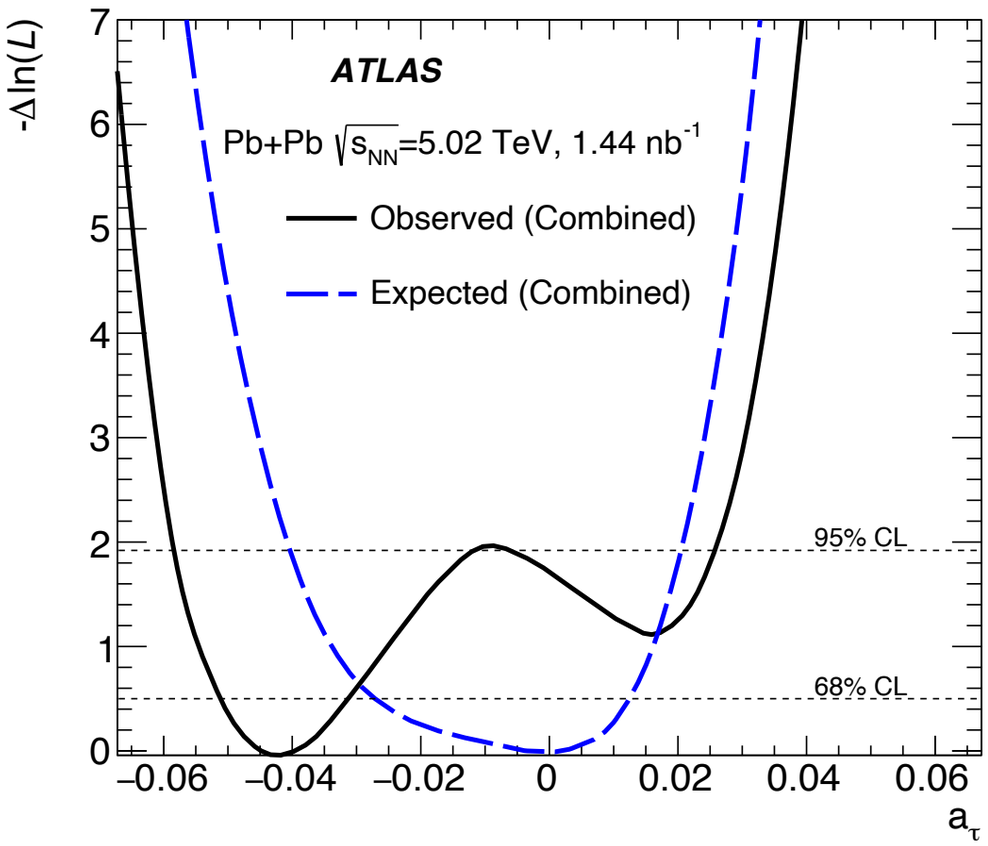
NLO cross sections being calculated, to potentially allow J/ψ data to be productively used for PDF/shadowing extraction

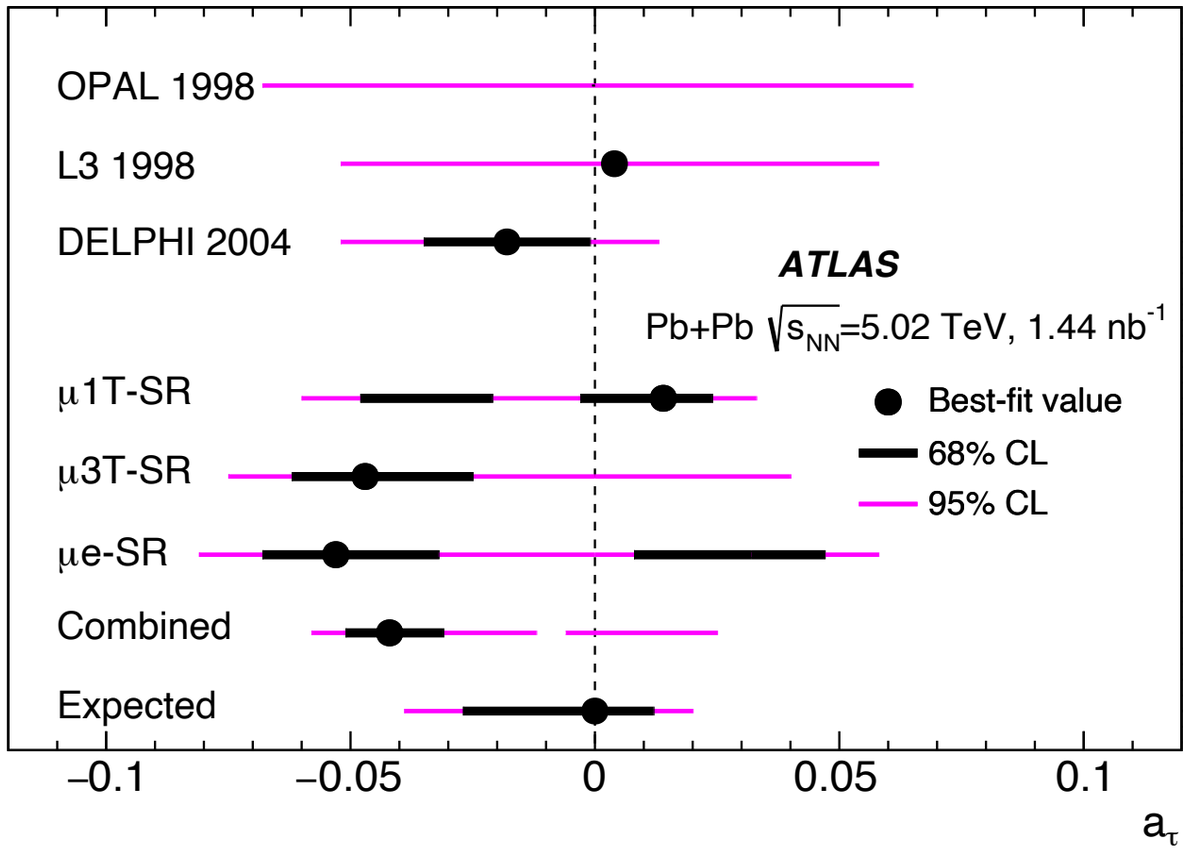
$$\mathcal{M}^{\gamma N} \propto \langle O_1\rangle_V^{1/2} \int_{-1}^{1} dx \left[T_g(x,\xi)F^g(x,\xi,t) + T_q(x,\xi)F^{q,S}(x,\xi,t)\right]$$

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

NEW arXiv:2204.13478

ATLAS: tau g-2

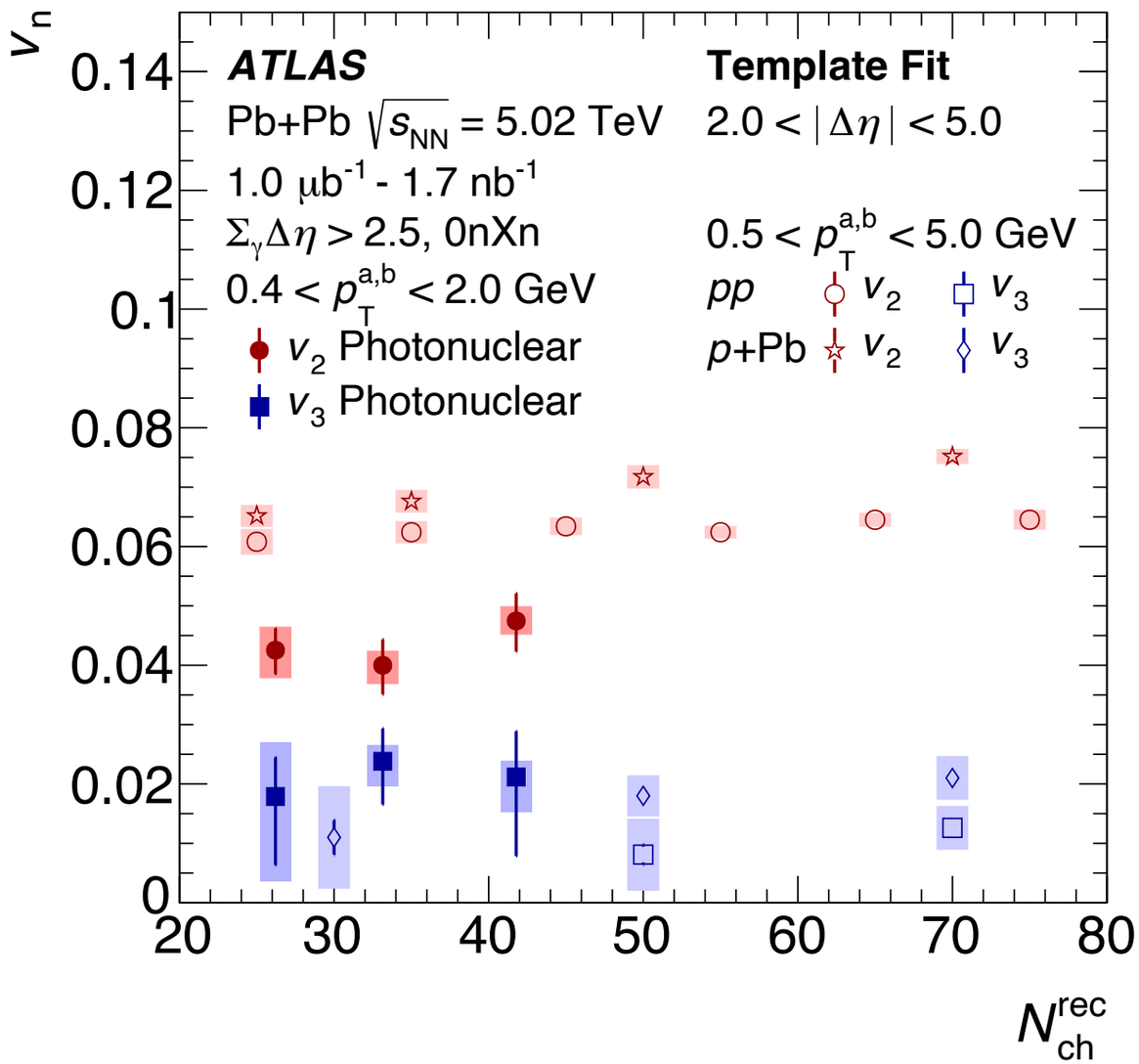


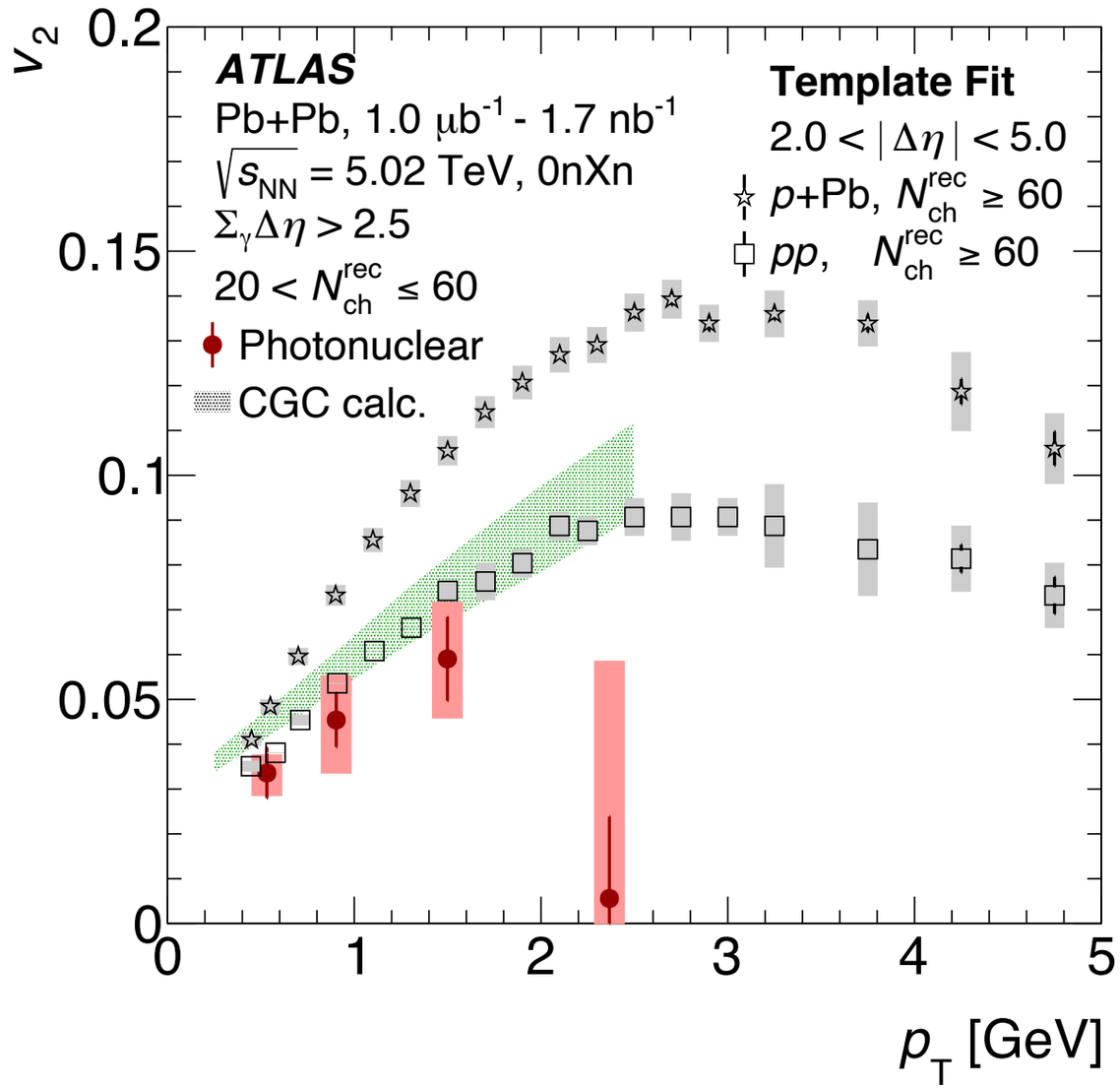


- **likelihoods as a function of a_τ derived using profile likelihood fit**
  - templates from Dyndal et al (PLB 809 (2020) 135682)
- **Observed 95% CL limits from $a_\tau \in$ (–0.058, –0.012) ∪ (–0.006, 0.025)**
  - Double interval from interference of SM & BSM amplitudes
  - Limits similar to that extracted from DELPHI in 2004
  - Also expecting substantial improvements from Run 3 & 4 data!

Phys. Rev. C 104, 014903 (2021)

Flow coefficients 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**? New CMS result (arXiv: 2204.13486) on **γ+p** does subtract non-flow contributions and reports no evidence of collectivity in that system.

CGC calculation (Shi et al) also describes these data, and has also been applied to EIC

Ben Gilbert, Tues parallel
Jamal Jalilian-Marian, Tues parallel

Benefits to the EIC program

- **LHC does not replace the EIC program**
  - probes higher s, higher Q^2 and lower x

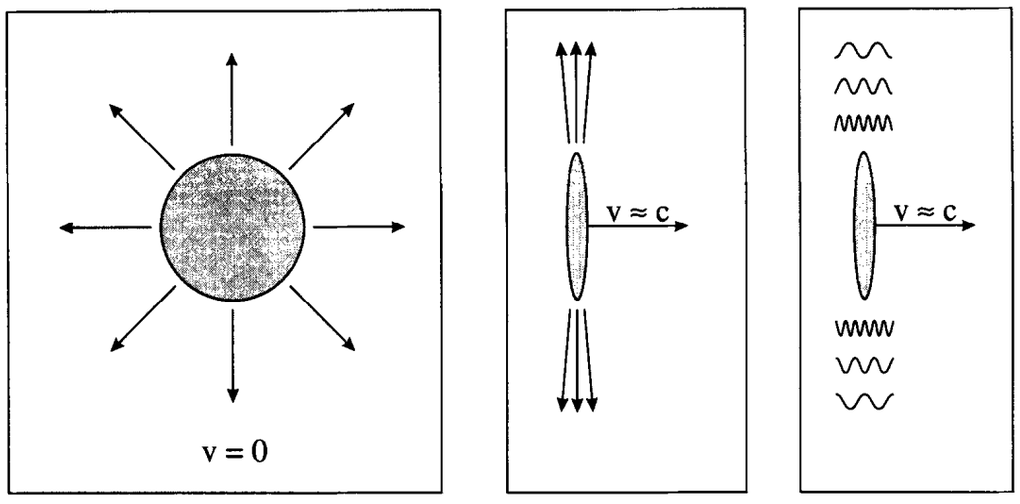
- **However, it will be vast data set, with a rich set of phenomena, many of which have not been analyzed yet**

- **Every measurement will improve our understanding of physics backgrounds, analysis techniques, systematic uncertainties, limitations of theoretical models, etc.**
  - Most of the experiments have ZDCs, which have been found to be more useful than originally expected (e.g. for geometry)

- **Like everything at the LHC, far too much physics with far too few people**
  - Could the US provide more effort to the LHC UPC program, as a transitional activity before the EIC?
  - RHIC also will have a UPC program, but with much lower s

Extra slides

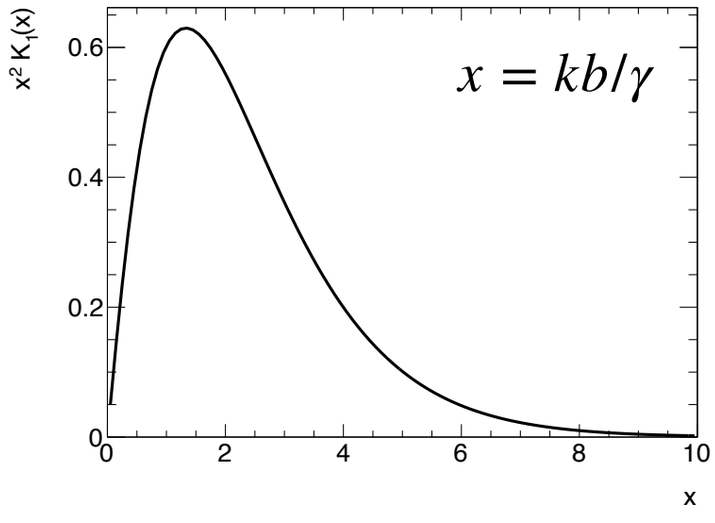
Equivalent Photon Approximation



For a point charge:

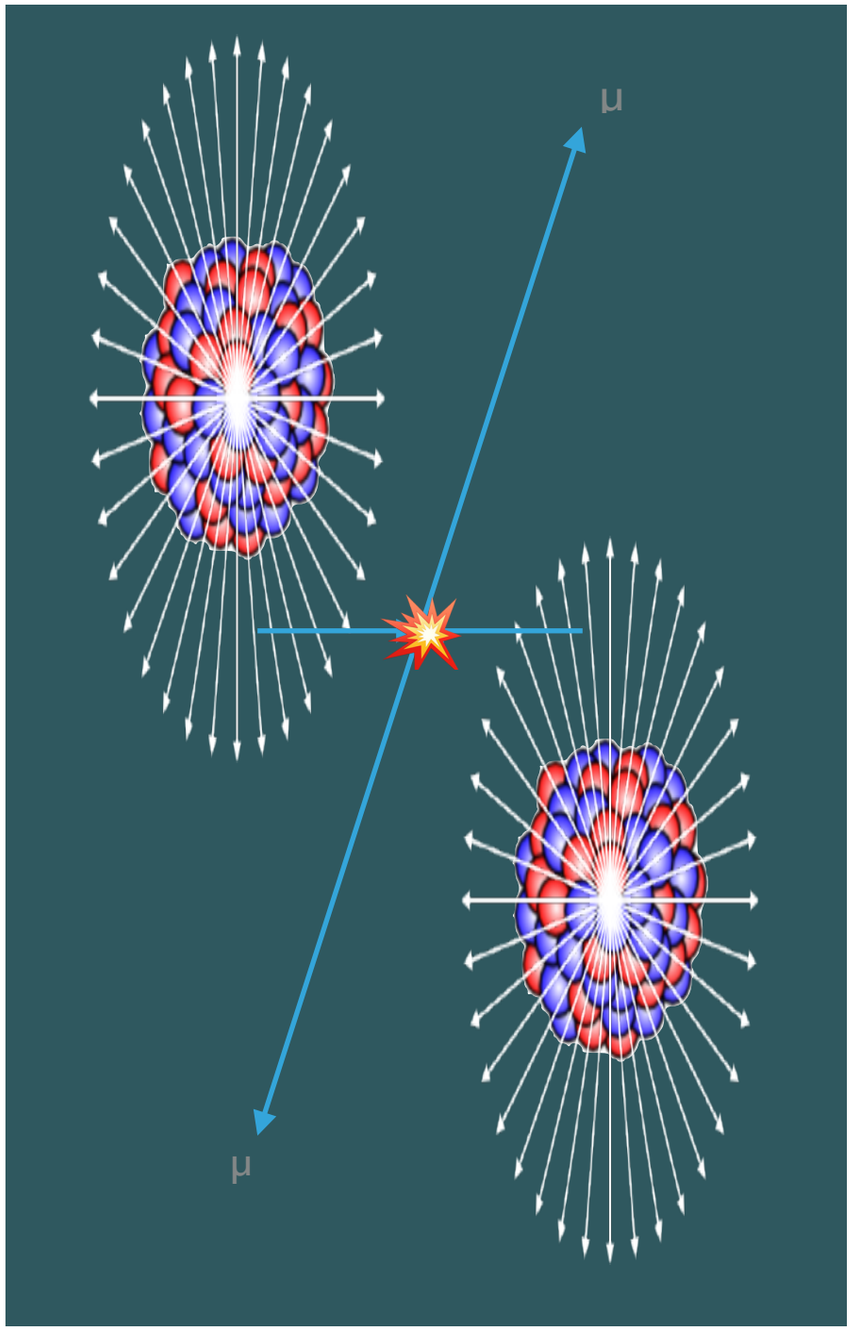
$$n(k,b) = \frac{d^3N_\gamma}{d^2b\,dk} \propto \frac{\alpha Z^2}{kb^2} f(kb/\gamma)$$

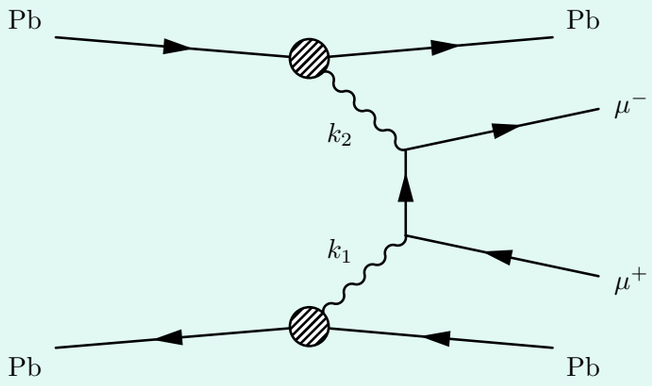
energy depends on radial distance:
the lower the b, the harder the spectrum!



maximum energy $E_{\gamma,max} \sim \gamma(\hbar c/R)$	**80 GeV in Pb+Pb@LHC** **3 GeV in Au+Au@RHIC**
typical p_T (& virtuality) $p_{Tmax} \sim \hbar c/R$	**O(30) MeV @ RHIC & LHC**
Coherent strengths (rates) scale as **Z^2**: nuclei >> protons	Flux of photons on other nucleus ~ **Z^2**, flux of photons on photons ~ **Z^4 (45M!)**

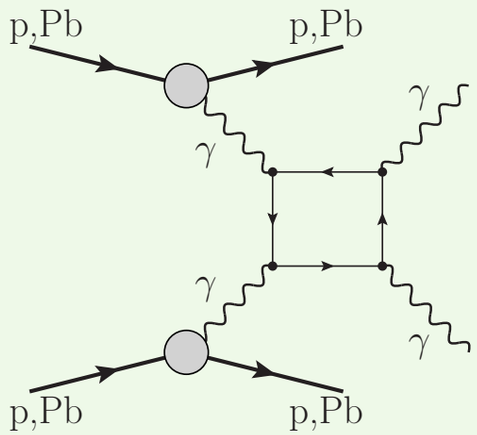
Exclusive γγ processes





lepton pair production
(Breit-Wheeler formula, Brodsky et al 1971)

γγ “luminosity”
lepton decays

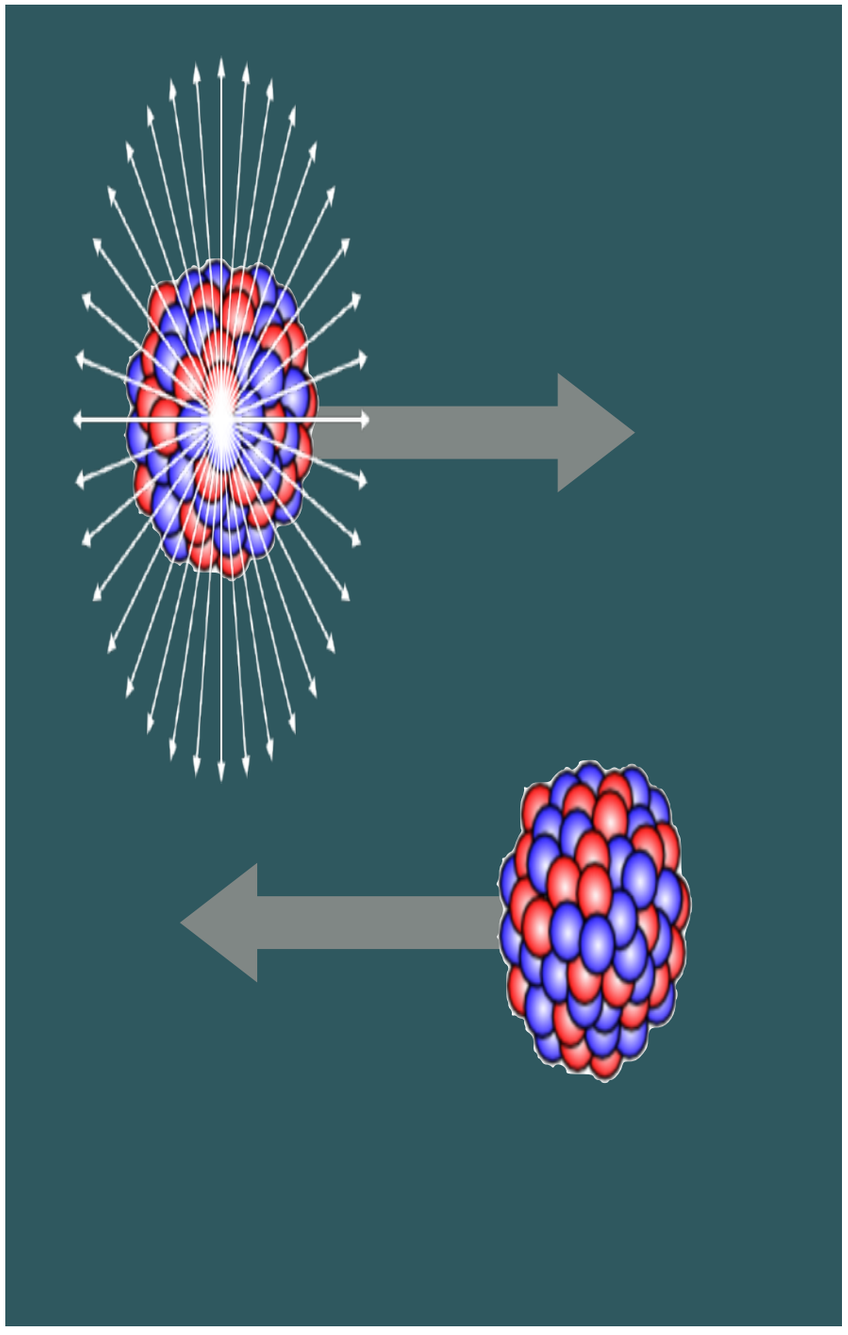


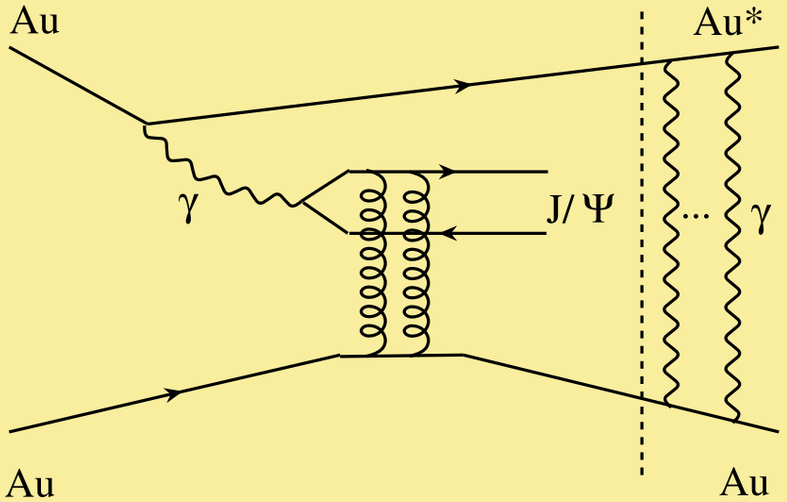
photon pair production
(via quark, lepton, W, BSM? loops)

rare QED processes
BSM physics

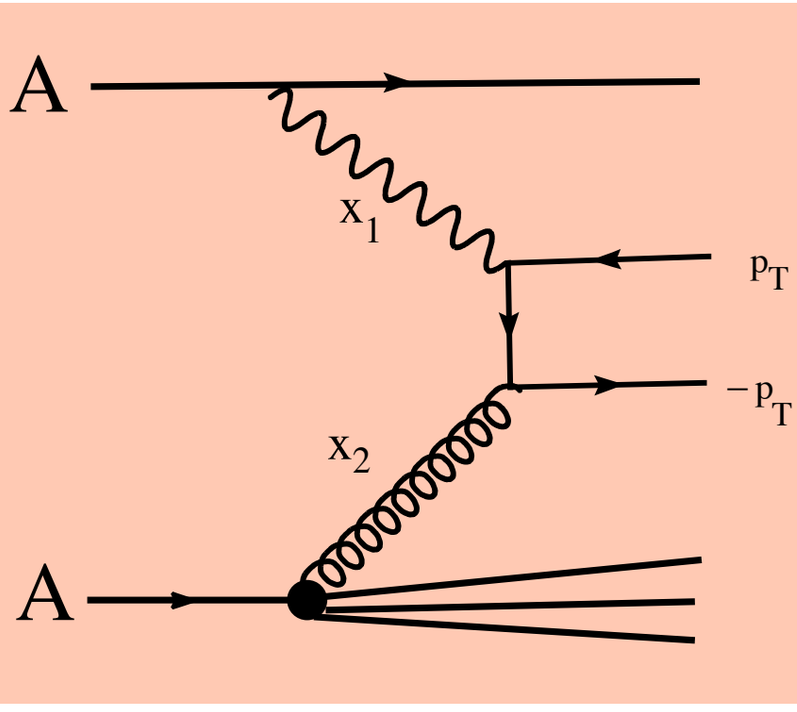
Heavy ion collisions are excellent QED & BSM laboratories!

Photonuclear processes





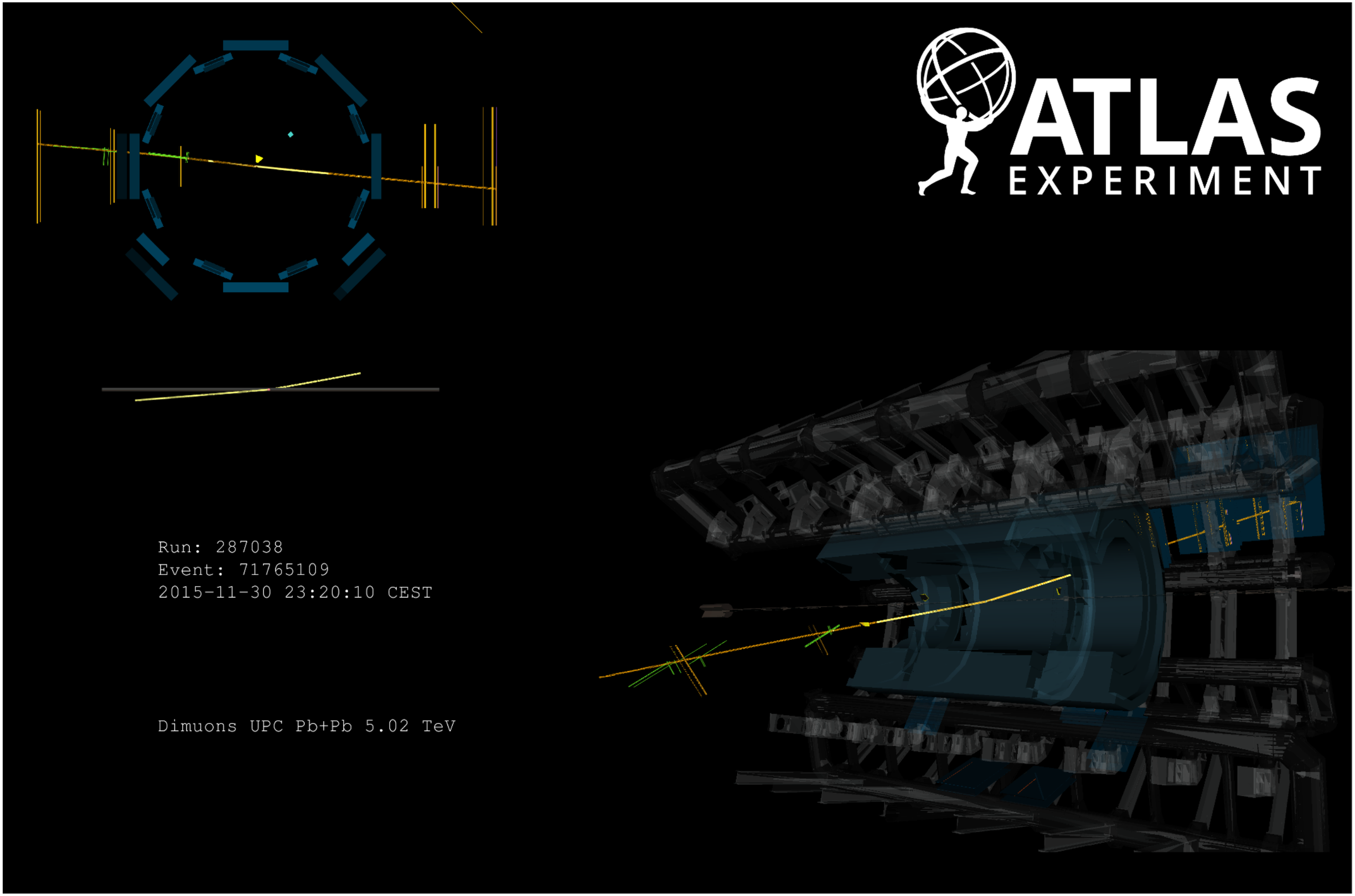
“exclusive”/elastic
vector meson production:
nuclear geometry
nuclear PDFs/GPDs
parton saturation?



inelastic hadron and
jet production:
nuclear PDFs
parton saturation?

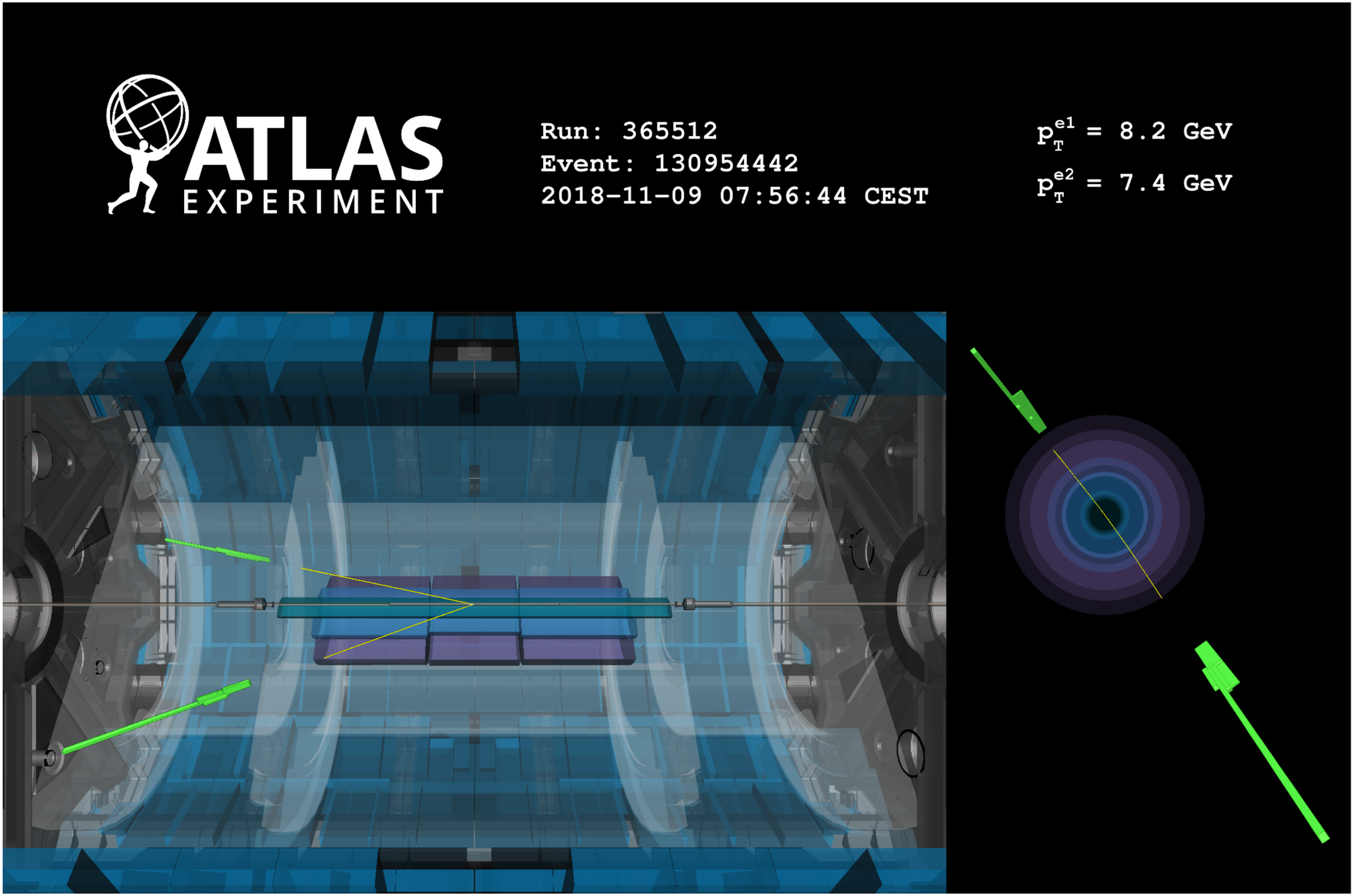
Photonuclear processes provide similar capabilities to ep/eA machines!

an exclusive dimuon event



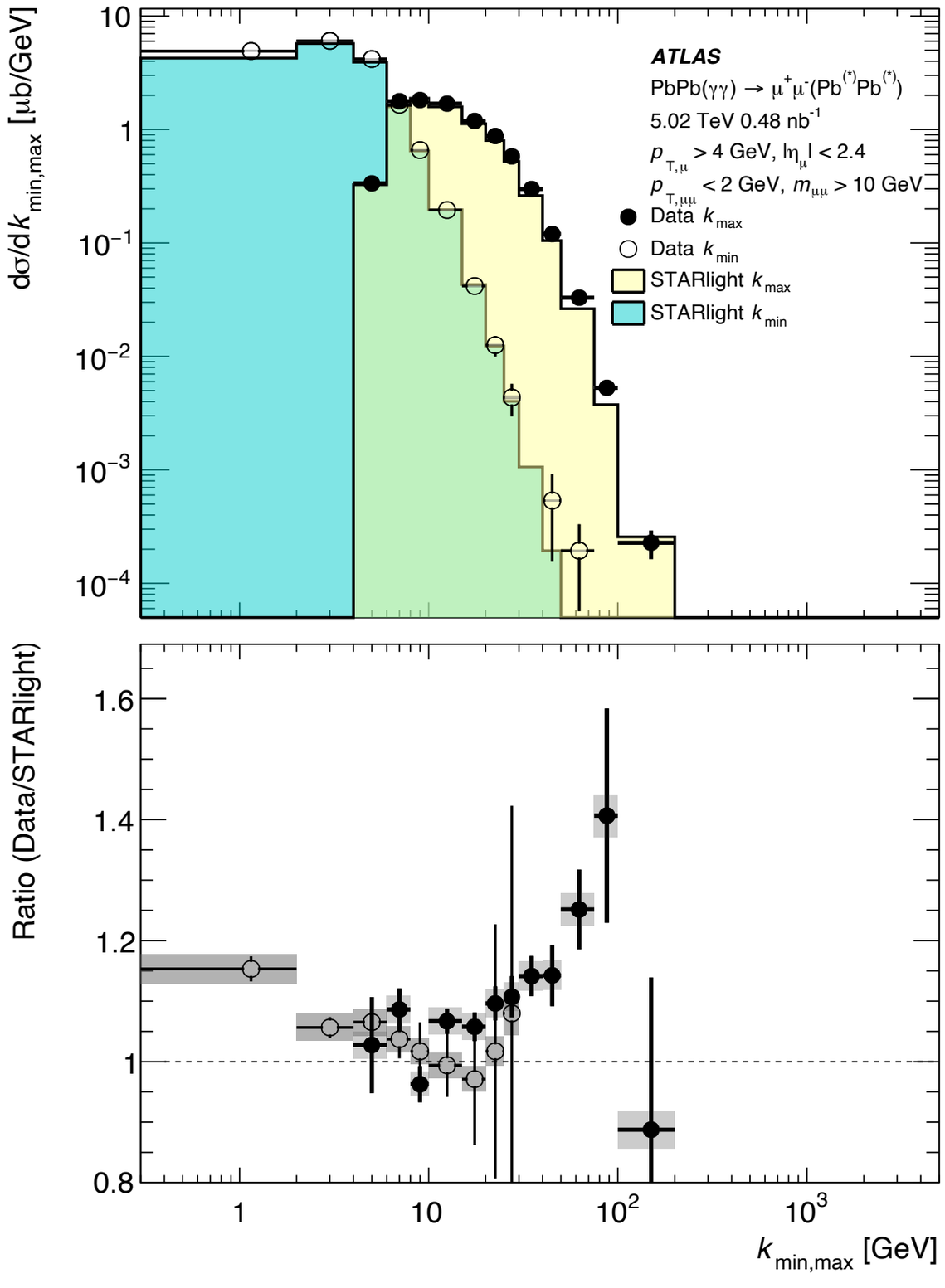
highest mass dimuon event in 2015 dataset - $m_{\mu\mu}$ = 173 GeV

an exclusive dielectron event



Phys. Rev. C 104, 024906 (2021)

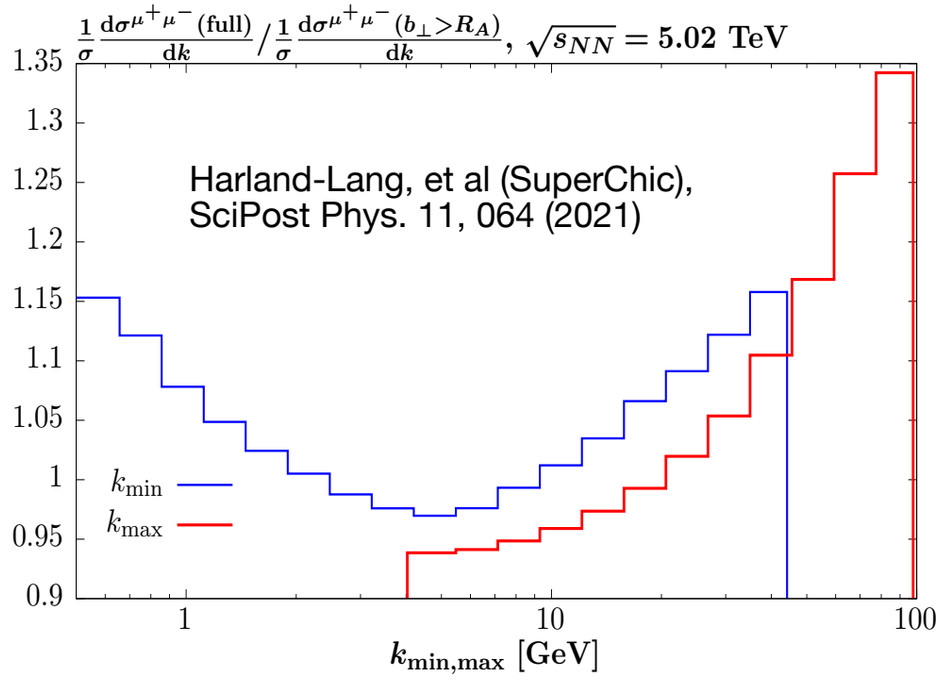
Photon energy distributions



Can combine $m_{\mu\mu}$ and $y_{\mu\mu}$ to estimate incoming photon energies!

$$k_{1,2} = (m_{\mu\mu}/2)\exp(\pm y_{\mu\mu})$$

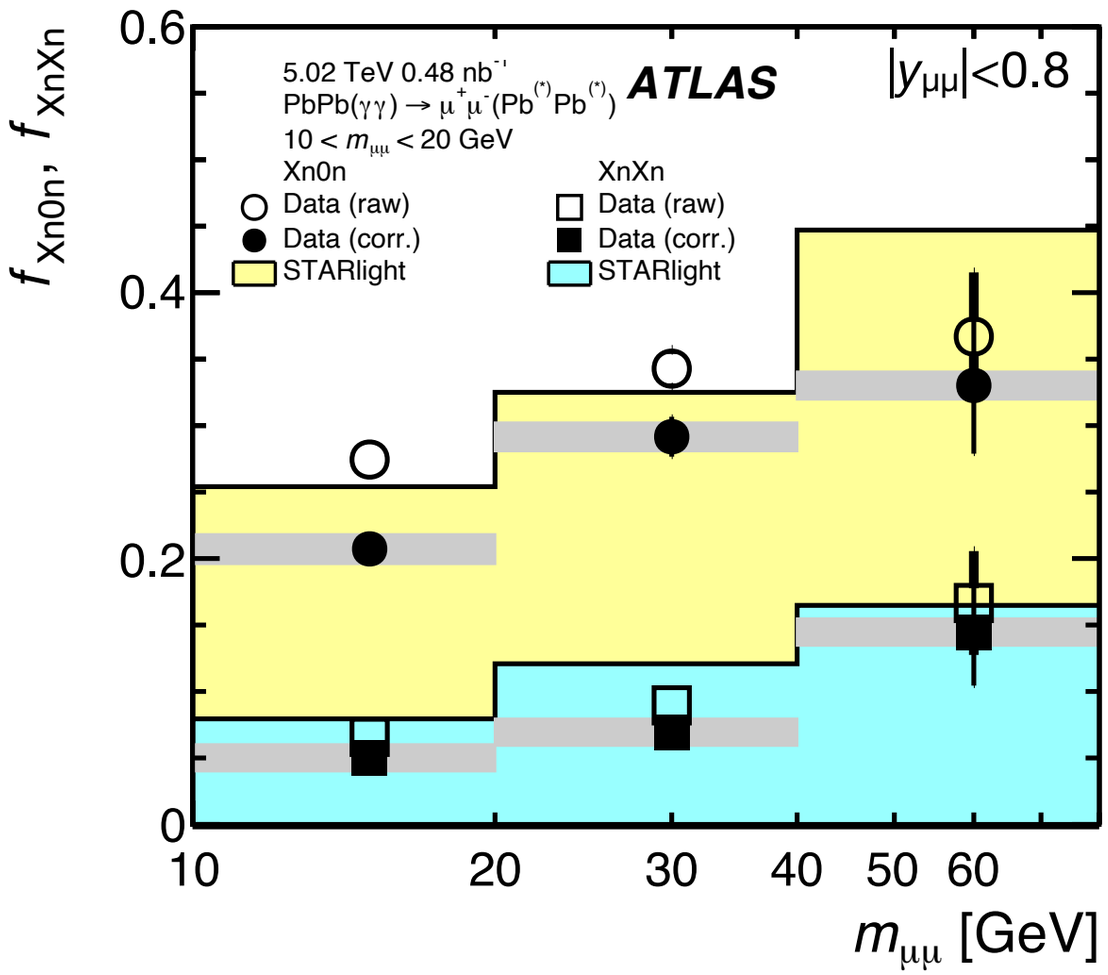
Overall good agreement but clear enhancements at low and high k: consistent with relaxing impact parameter cuts in STARlight (Harland-Lang, et al)

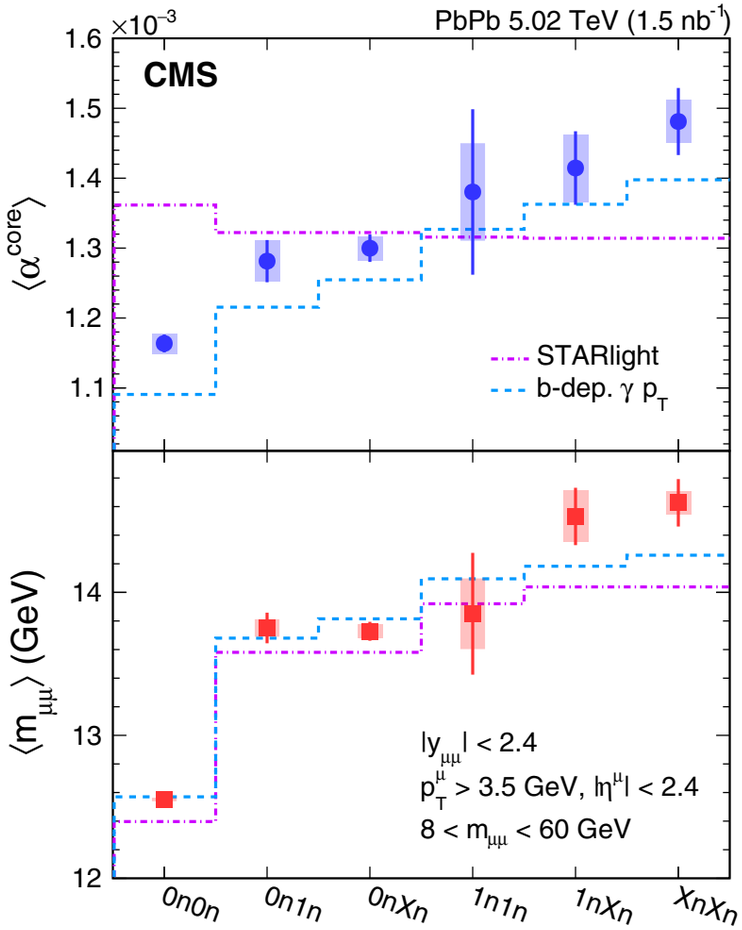


$p_{T\mu} > 4$ GeV, $|\eta_\mu|<2.4$, $m_{\mu\mu} > 10$ GeV, $p_{T\mu\mu} < 2$ GeV

ATLAS: Phys. Rev. C 104, 024906 (2021)
CMS: PRL 127, 122001 (2021)

Impact of ZDC selections





ZDC selections test the impact parameter dependence of the photon fluxes.

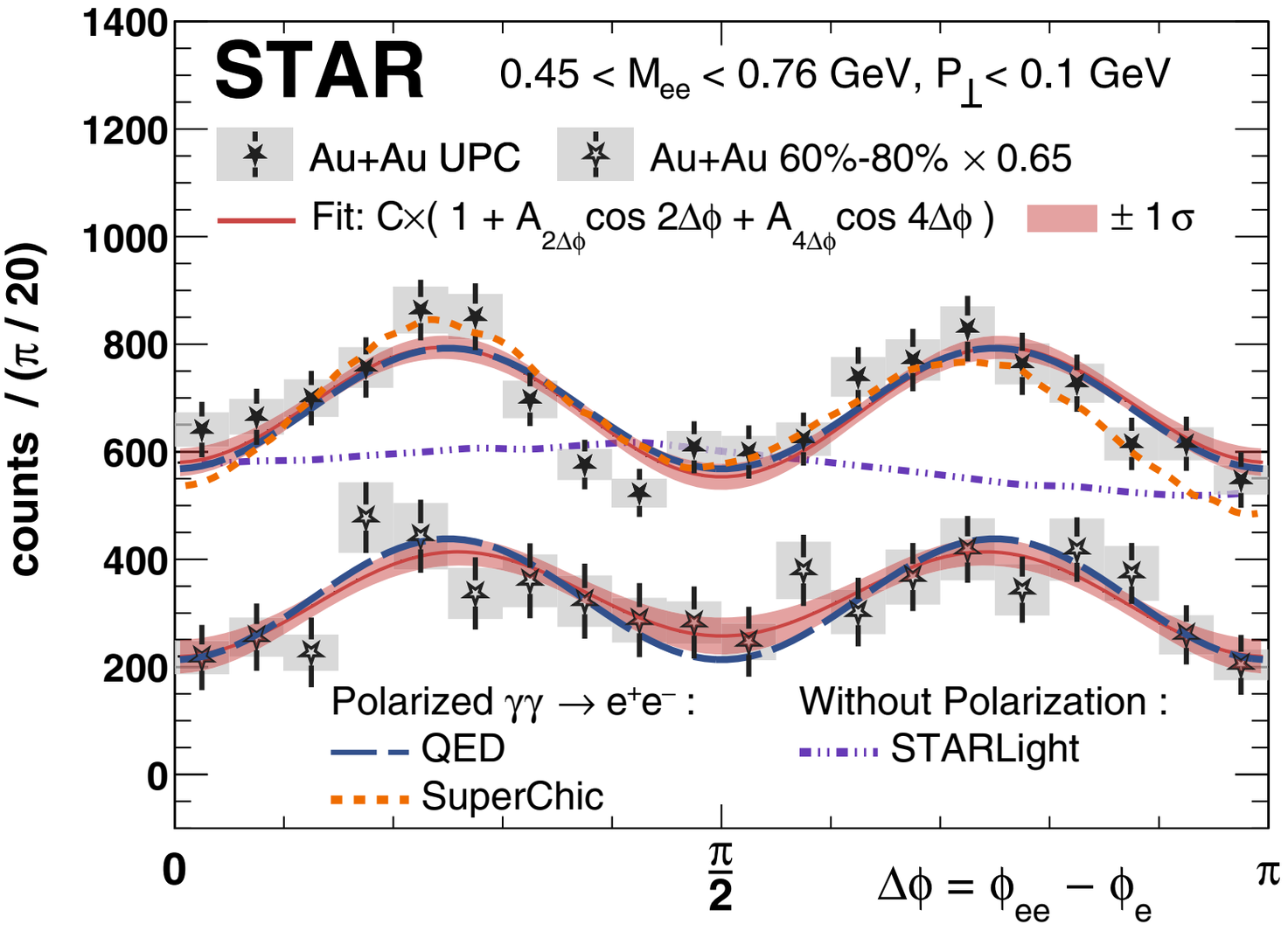
ATLAS sees expected modifications on <u>longitudinal</u> distributions: $m_{\mu\mu}$ and $y_{\mu\mu}$: selecting one or both ZDCs to fire makes the mass distribution harder

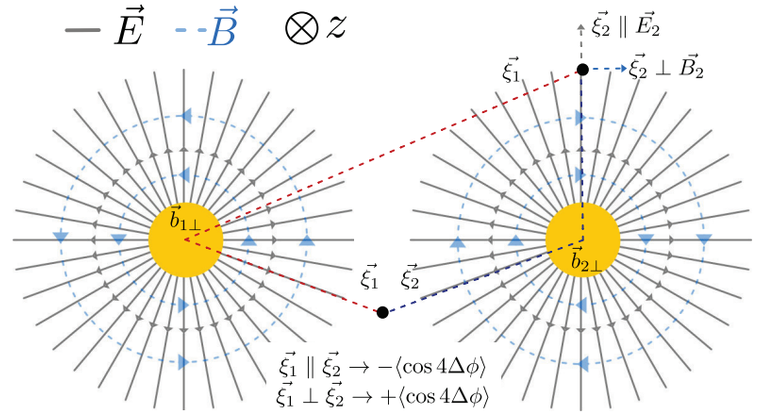
CMS sees clear <u>transverse</u> broadening in acoplanarity and increased mean $m_{\mu\mu}$ as event selections require more neutrons in the ZDCs

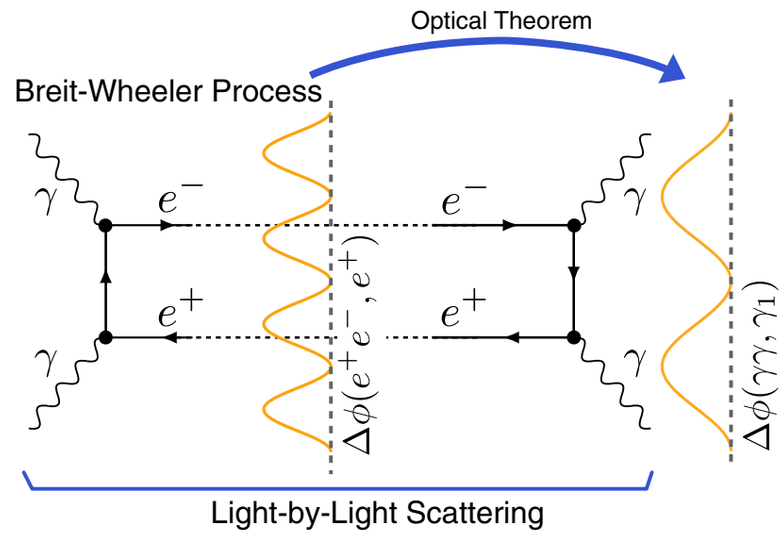
Irais Bautista Guzman, Tuesday parallel
Iwona Grabowska Bold, Weds parallel

STAR: polarization in UPC e+e-

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



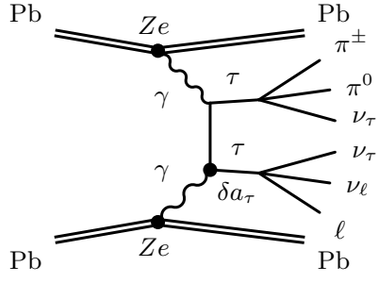




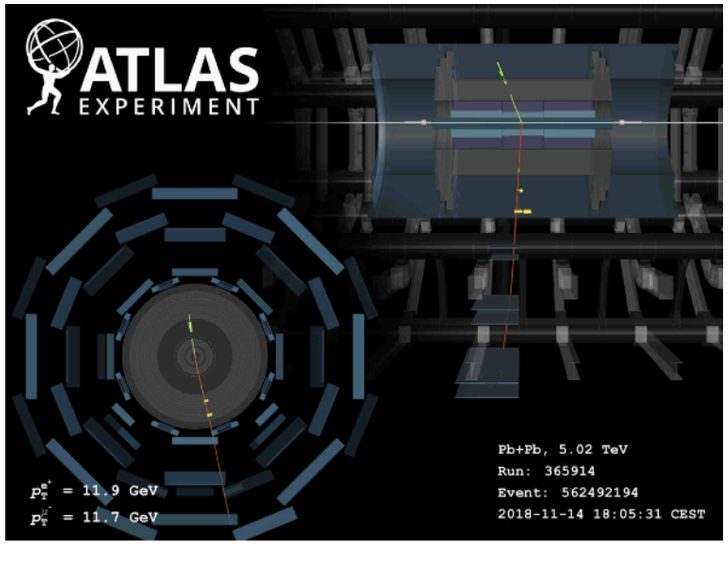
STAR demonstrated impact of linear polarization of initial photons, as a correlation between the momentum sum and difference vectors! Observation implies clear predictions for γγ

Phys. Rev. Lett. 127, 052302

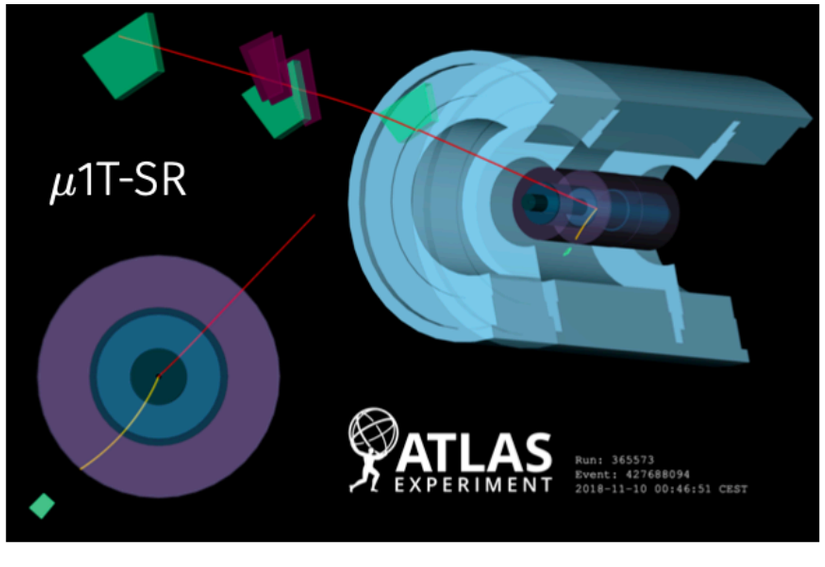
a_τ from $\tau^+\tau^-$ in Pb+Pb



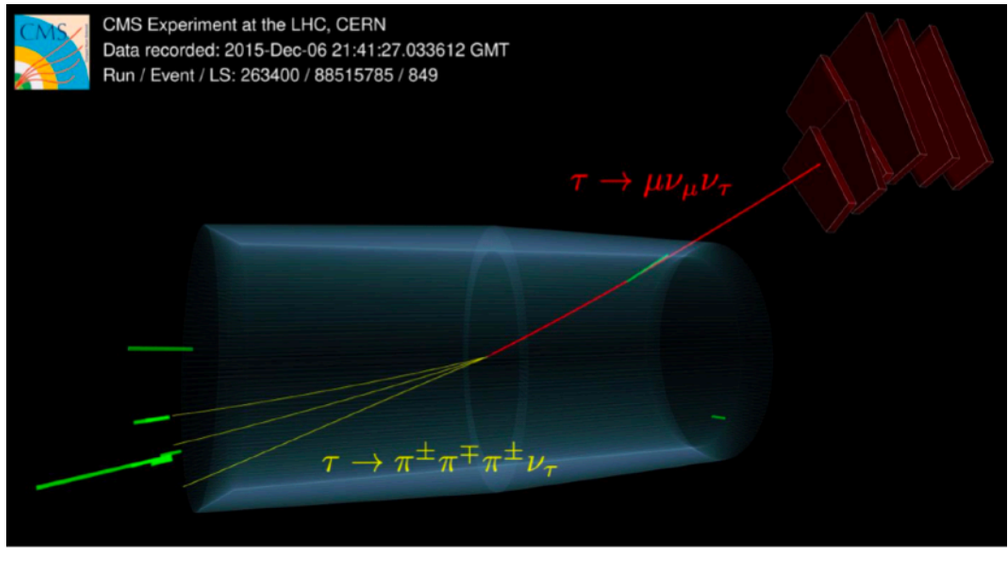
μe



μ+1 track



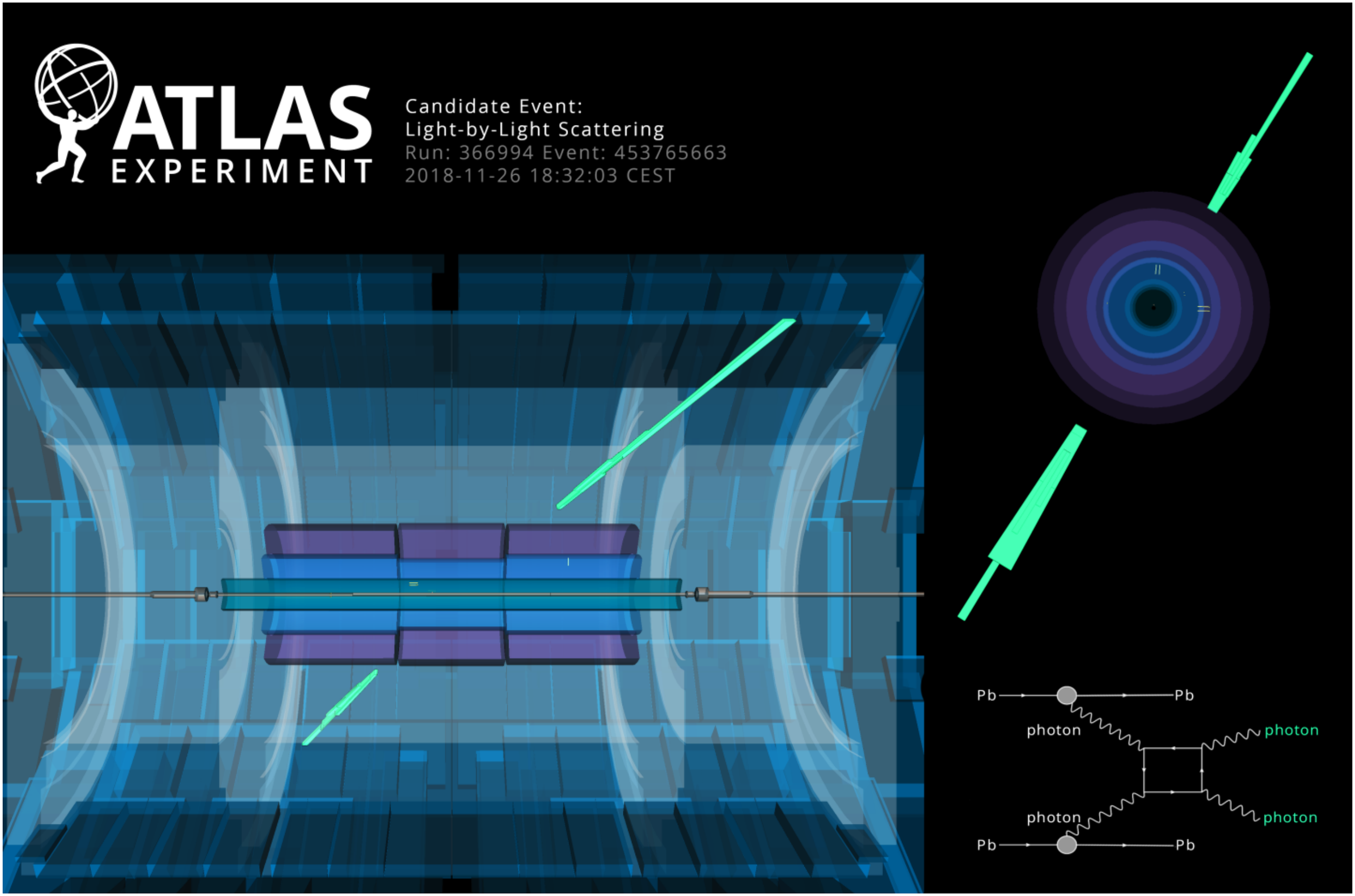
μ+3 track



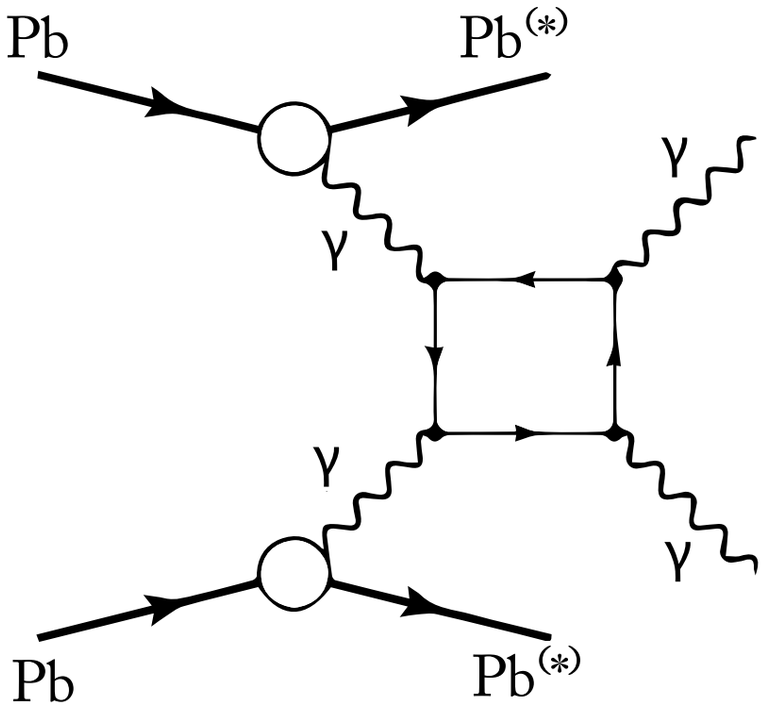
- **Anomalous magnetic moment of tau leptons sensitive to physics beyond the standard model**
  - Development of theory frameworks in 2019/2020, and new measurements from CMS (preliminary) and ATLAS (final) from Run 2 Pb+Pb data from LHC!

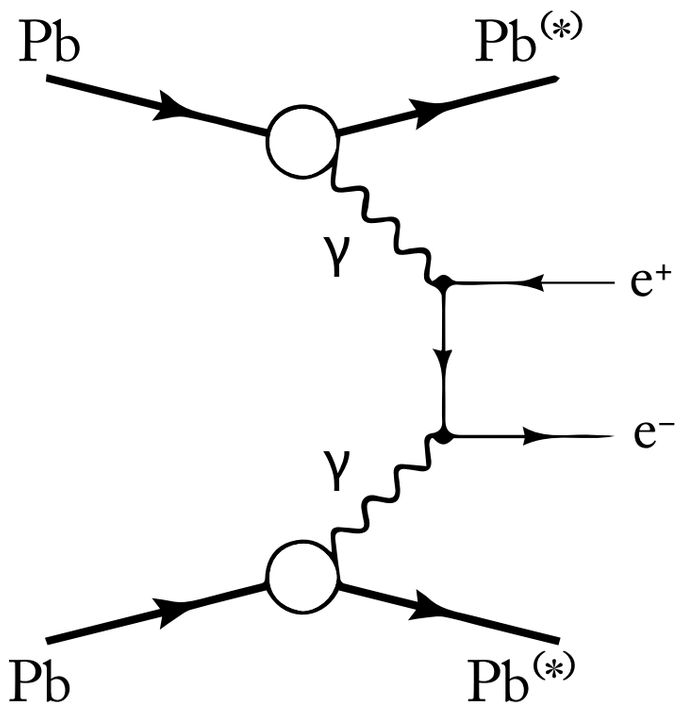
- **Three channels available: eμ, μ+track, μ+3 tracks**
  - CMS focuses on μ+3 tracks in 2015 data (404 μb^{-1}), with no ZDC selections
    - *fits for a_τ using variation of $\sigma(\gamma\gamma \to \tau\tau)$*
  - ATLAS uses all 3 channels in 2018 (1.44 nb^{-1}), requiring 0n0n and cluster veto to suppress dissociative and hadronic backgrounds
    - *fits for a_τ using modifications to $p_T(\mu)$ distributions, using μμ to normalize photon flux*

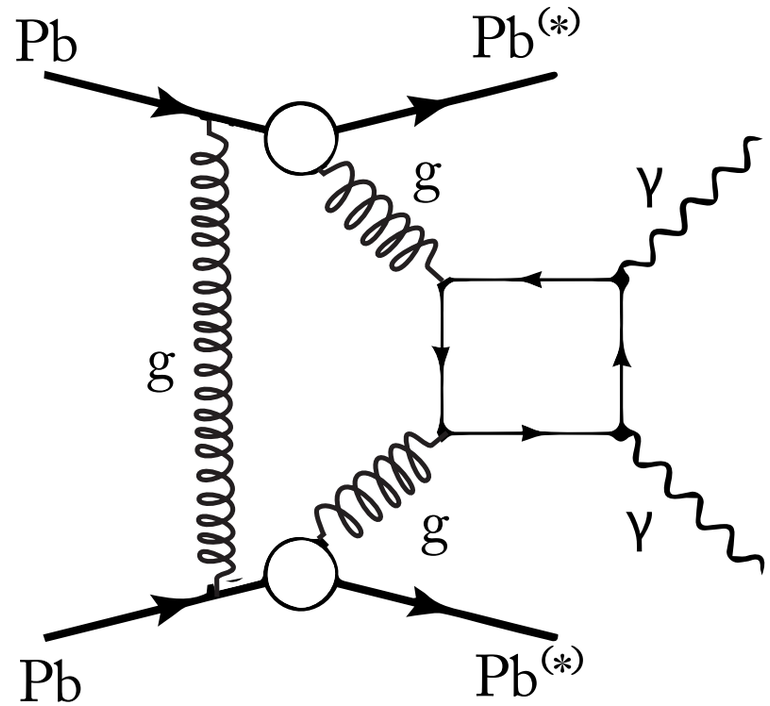
light-by-light scattering



Light by light scattering





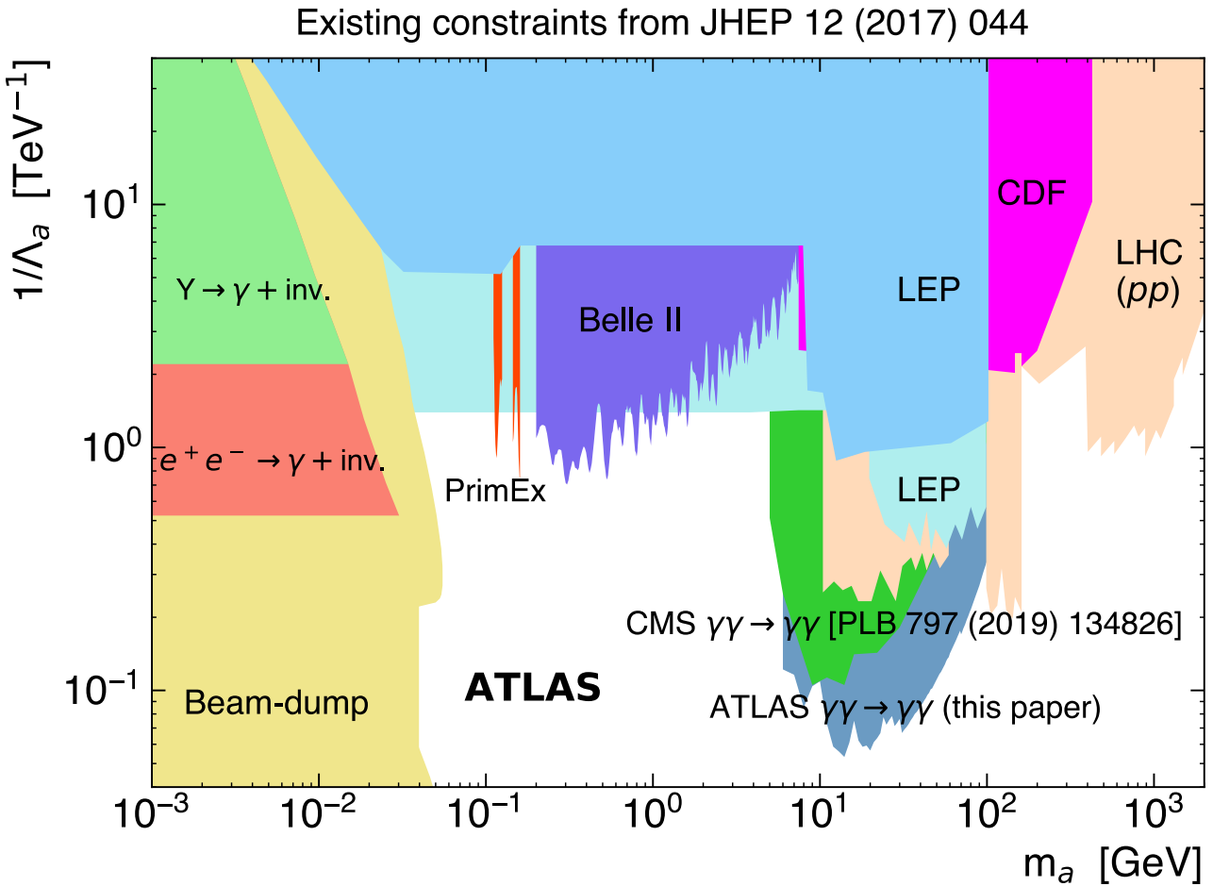


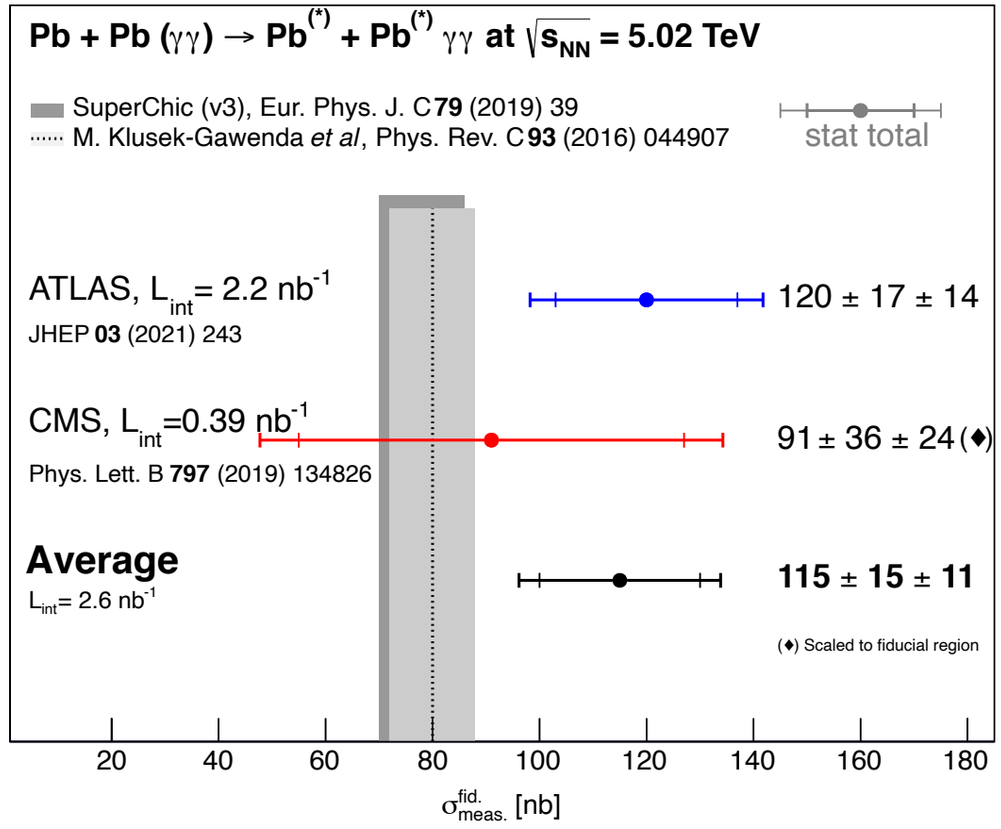
Signal process is the observation of two photons and no other activity.

However, electron pairs can mimic photons if we don't see their tracks.

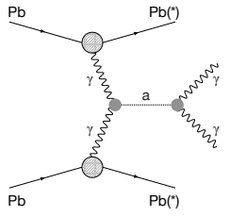
Also, there are gluon-mediated processes with two-photon final states (Central exclusive production, or CEP)

BSM physics using LbyL





Light-by-light scattering is sensitive to the production of axion-like particles (ALP)



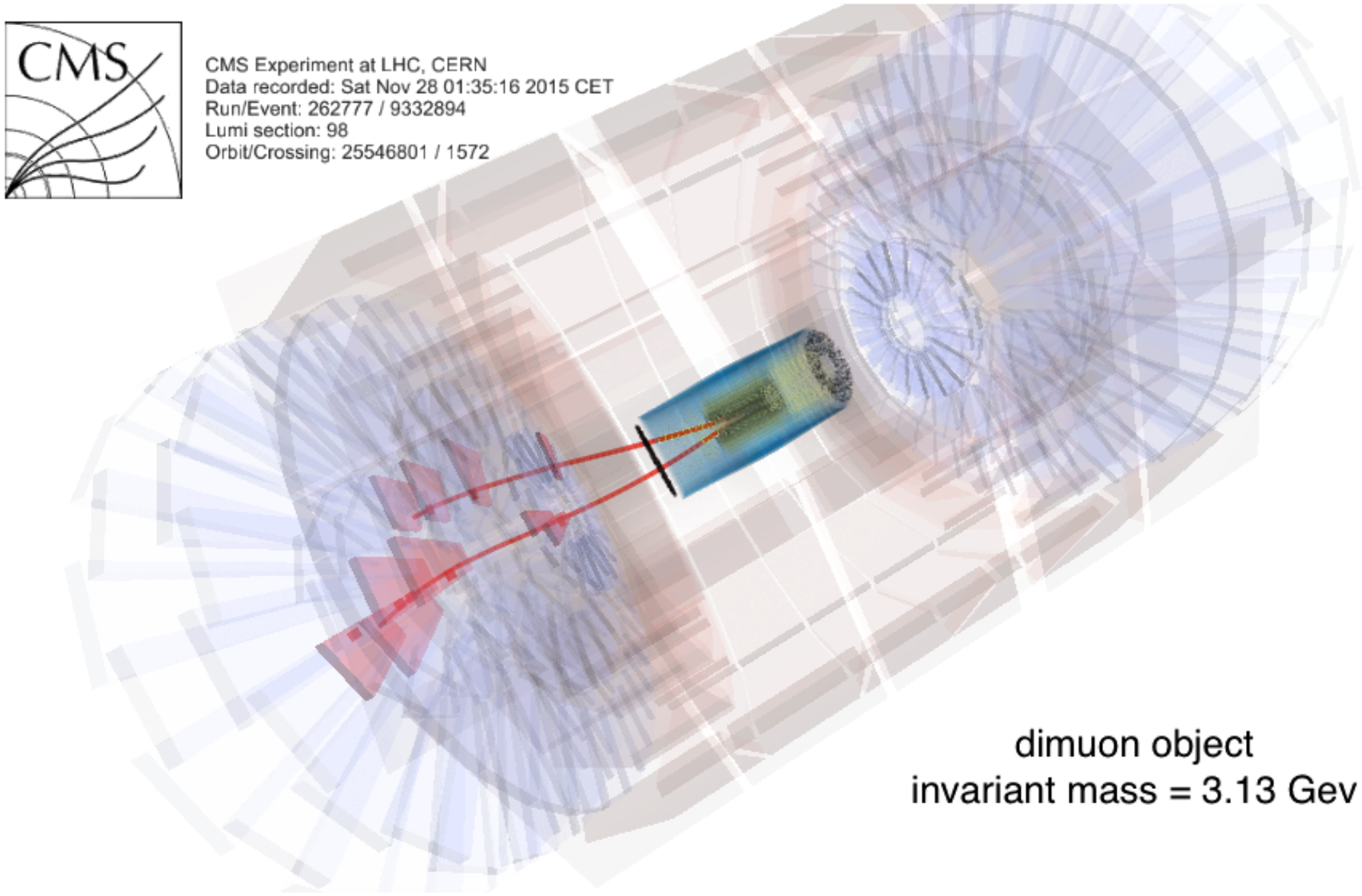
STARlight 2.0 used to generate mass distributions to test for significant excess: none found so data used to set 95% CL upper limits on cross section & coupling

Joint working group starting to perform detailed combination measurements accounting for correlations.

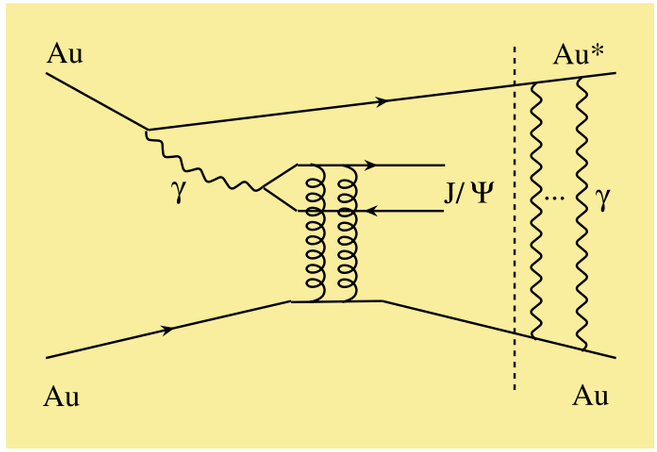
$$\sigma^{\text{fid.}}_{\text{meas.}} = 115 \pm 15\ (\text{stat.}) \pm 11\ (\text{syst.}) \pm 3\ (\text{lumi.}) \pm 3\ (\text{theo.})\ \text{nb}$$
$$= 115 \pm 19\ \text{nb},$$

Important effort for extracting full potential from LHC runs 3 & 4

elastic photonuclear processes



dimuon object
invariant mass = 3.13 Gev

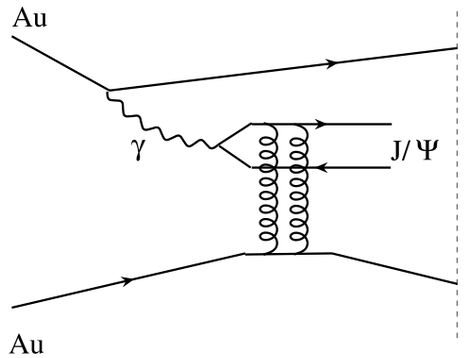


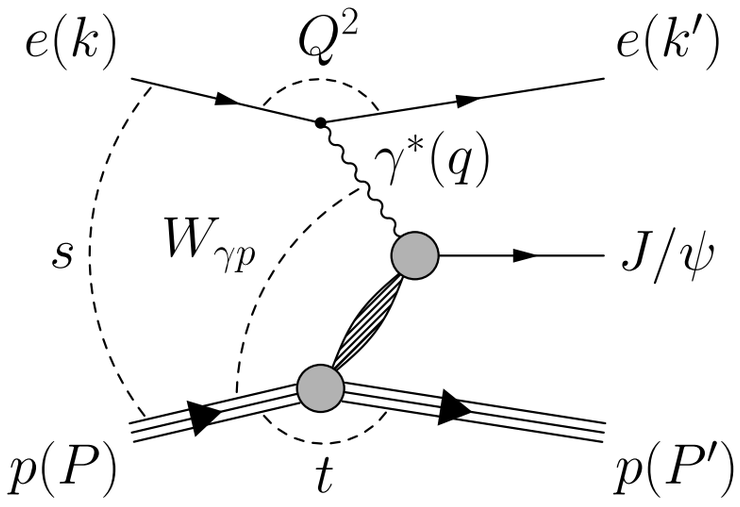
LHC experiments have a broad variety of results on vector meson (ρ,ψ,ϒ) in **Pb+Pb** (**γ+A**) and **p+Pb** (**γ+p**) collisions!

Momentum & spatial structure

cross sections sensitive to square of gluon density: sensitivity to shadowing & saturation physics

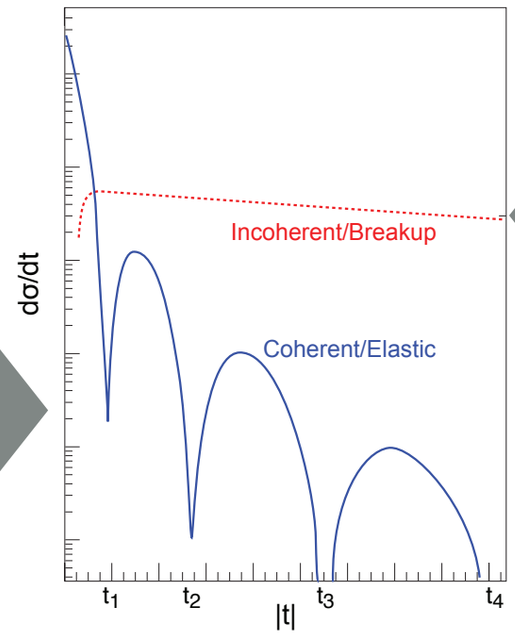
$$\frac{d^2\sigma}{dYdt} \propto \left(xG(x)\right)^2$$

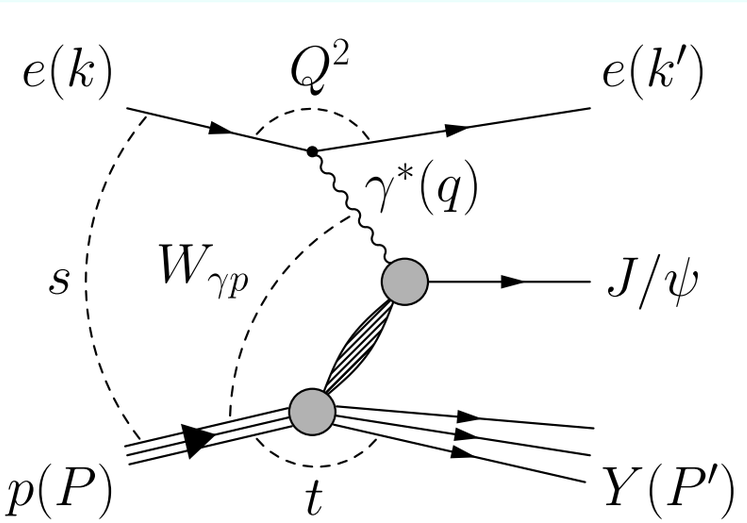




elastic production: proton survives

Schenke & Mantyasaari, 2016





incoherent production: p/A, RIP ☠️

$$\frac{\mathrm{d}\sigma^{\gamma^* A\to VA}}{\mathrm{d}t} \sim \left|\left\langle \mathcal{A}^{\gamma^* A\to VA}\right\rangle_\Omega\right|^2$$

elastic: sensitive to average spatial extent of object

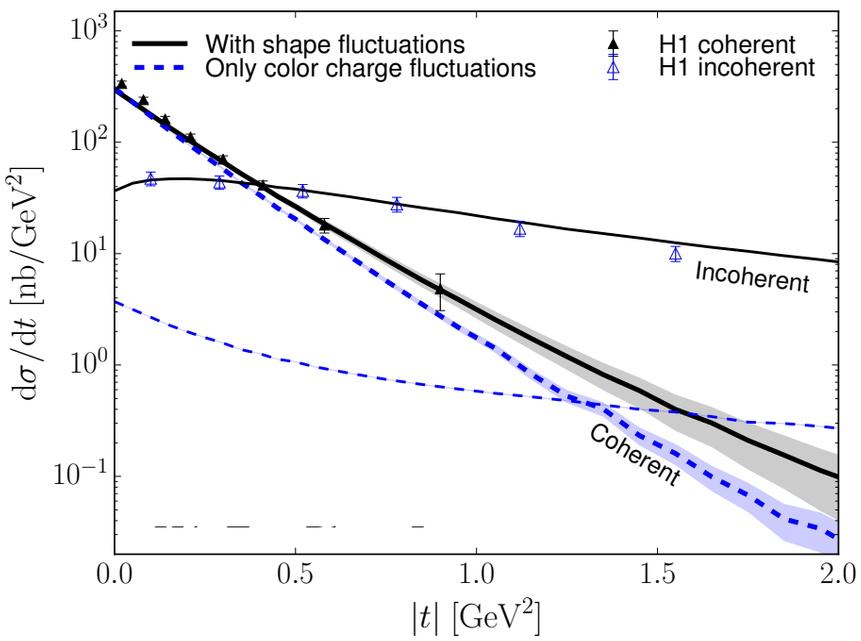
$$\sigma_{\text{incoherent}} \sim \sum_{f\neq i} |\langle f|\mathcal{A}|i\rangle|^2 = \sum_f \langle i|\mathcal{A}|f\rangle^\dagger\langle f|\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^\dagger\langle i|\mathcal{A}|i\rangle$$

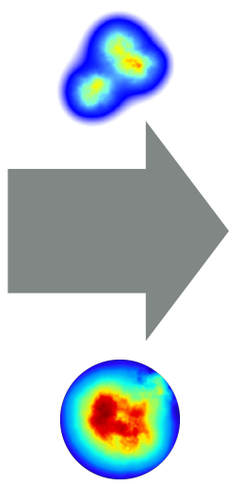
dissociative (incoherent) sensitive to fluctuations

$$\sim \left\langle|\mathcal{A}|^2\right\rangle_\Omega - \left|\left\langle\mathcal{A}\right\rangle_\Omega\right|^2$$

Imaging the nucleon

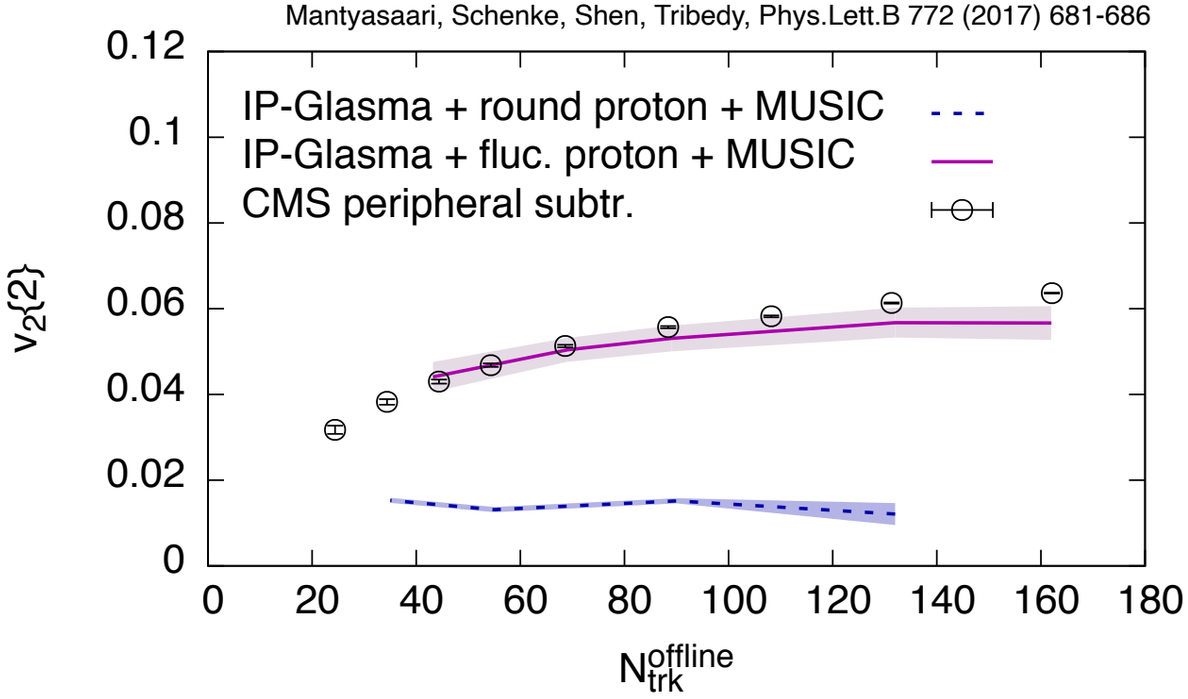
Mantyasaari & Schenke, Phys. Rev. Lett. 117, 052301 (2016)





Fluctuating hot spots in proton needed to describe dissociative ("incoherent") J/ψ photoproduction

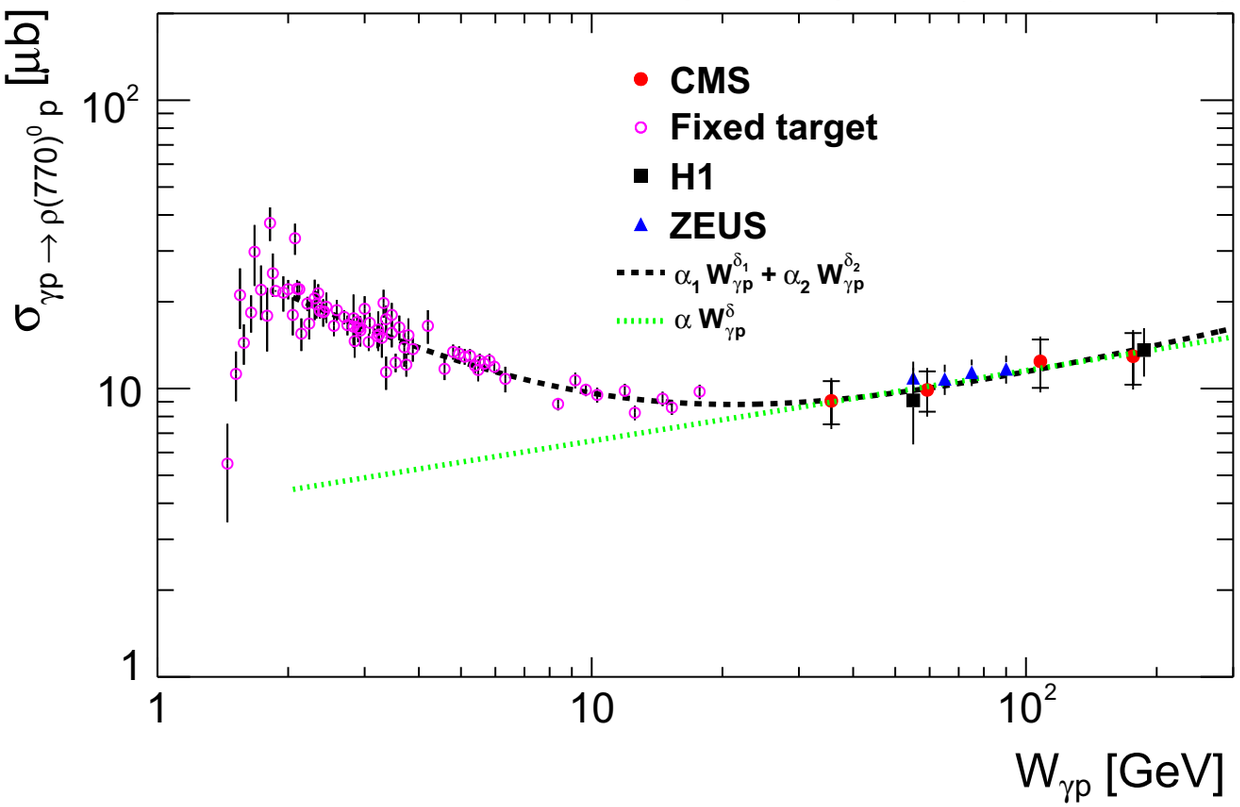
Mantyasaari, Schenke, Shen, Tribedy, Phys.Lett.B 772 (2017) 681-686

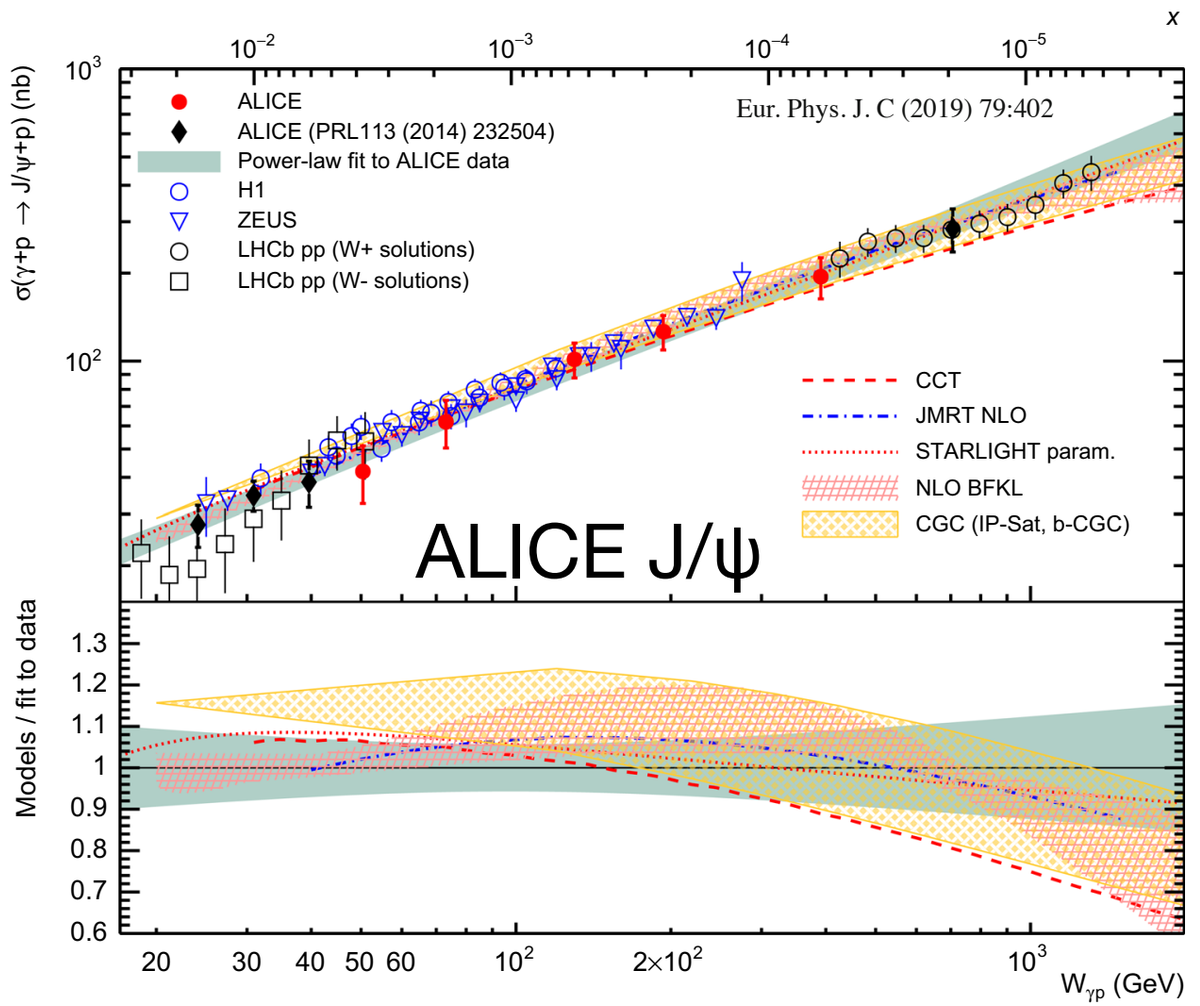


Same fluctuations have been succesfully incorporated into hydro calculations for pp

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

Vector mesons in p+Pb: γ+p



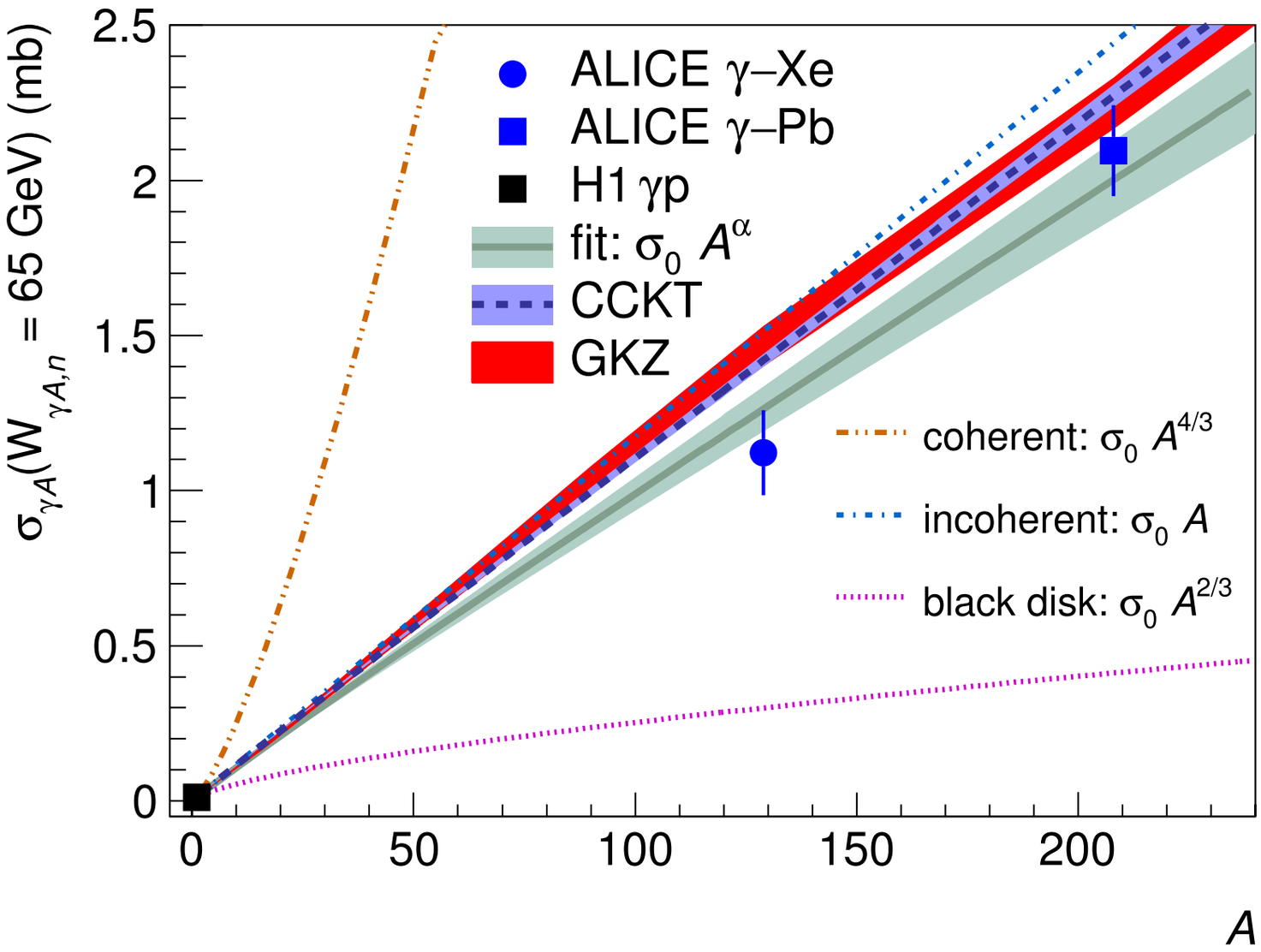


Exclusive vector meson photoproduction in UPC p+Pb provides full characterization of kinematics: $W_{\gamma p}^2 = 2E_p M_V \exp(-y_V)$

Limited statistical precision so far, but excellent compatibility with HERA, and will be powerful tool for studying saturation physics in nucleon

Michael Krelina, Weds parallel
Diego Stocco, Weds parallel

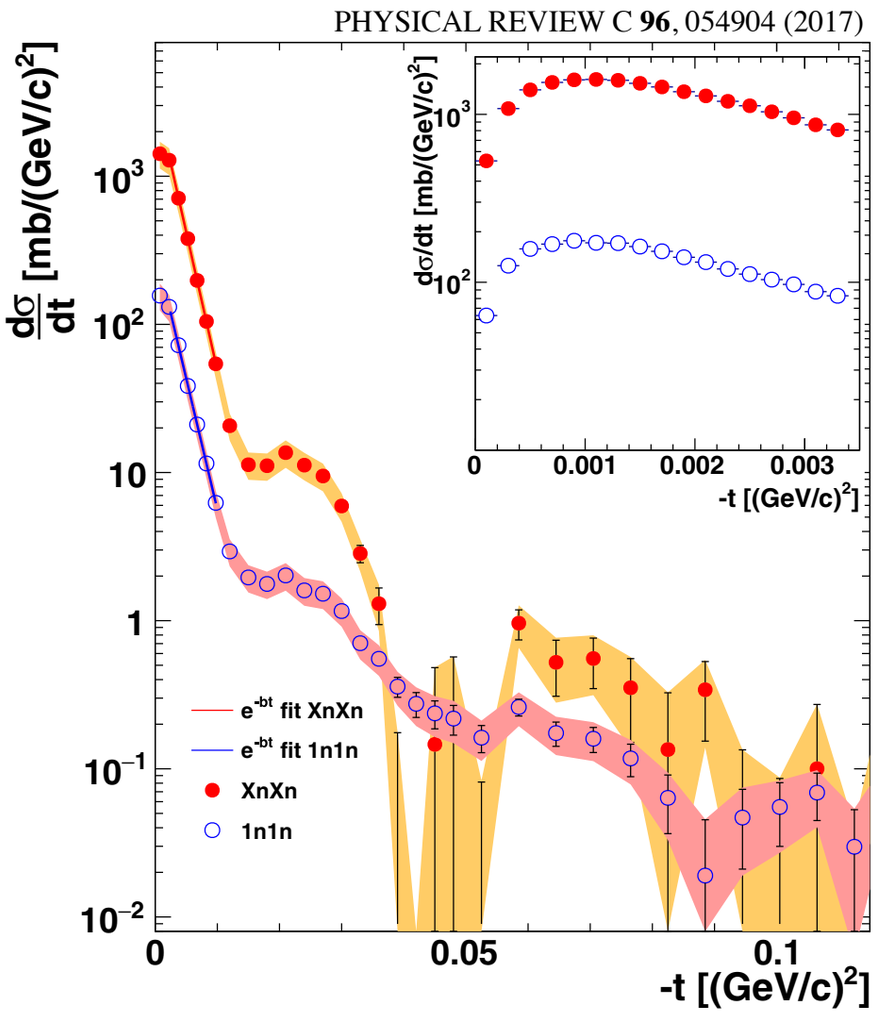
ALICE: coherent ρ^0 in Pb+Pb & Xe+Xe



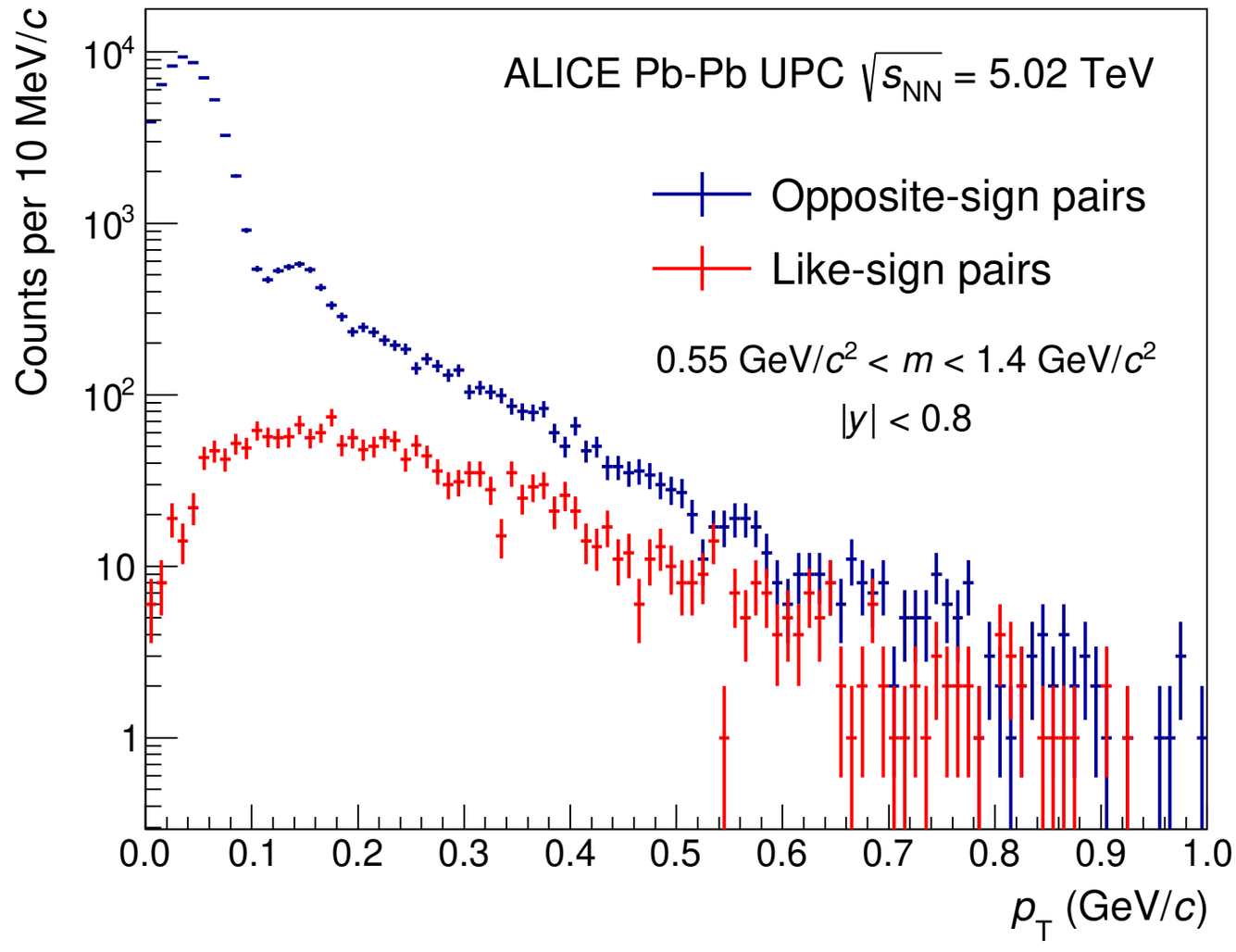
A-dependence provides insight into shadowing on nuclei. Huge deviation from coherent production, interpreted as "incoherent+enormous shadowing"

Probing nuclear geometry with ρ^0

STAR

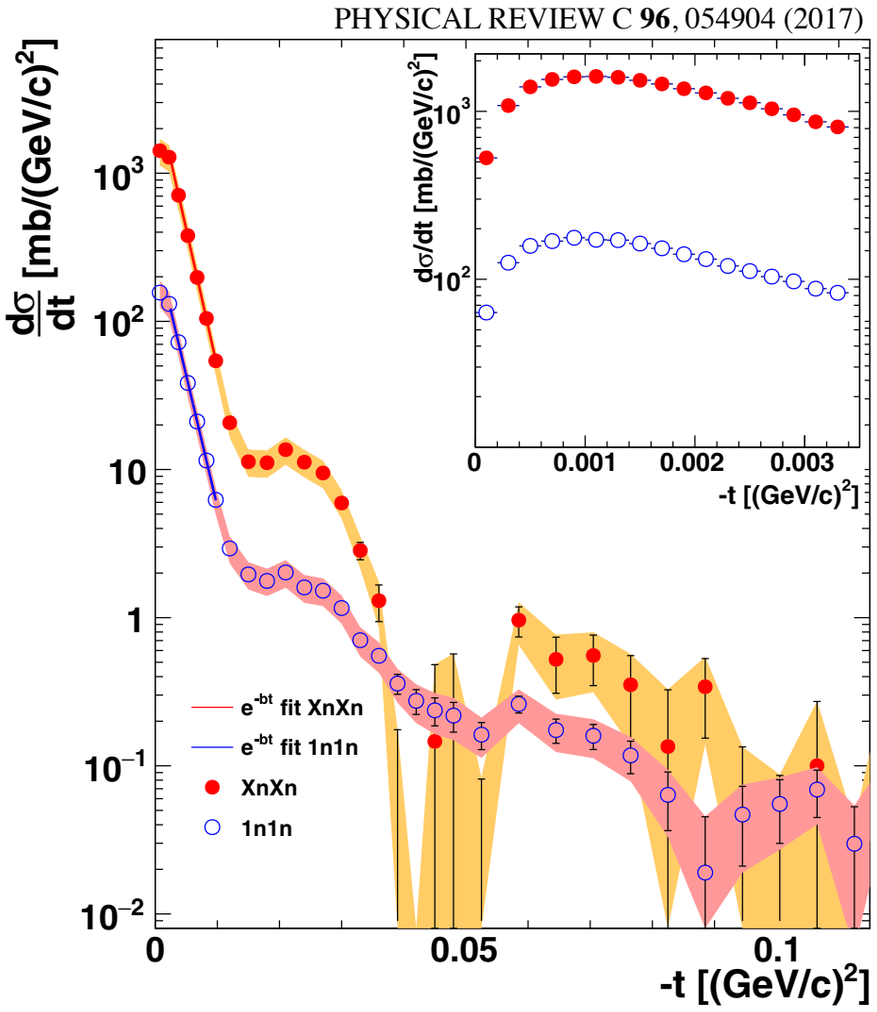


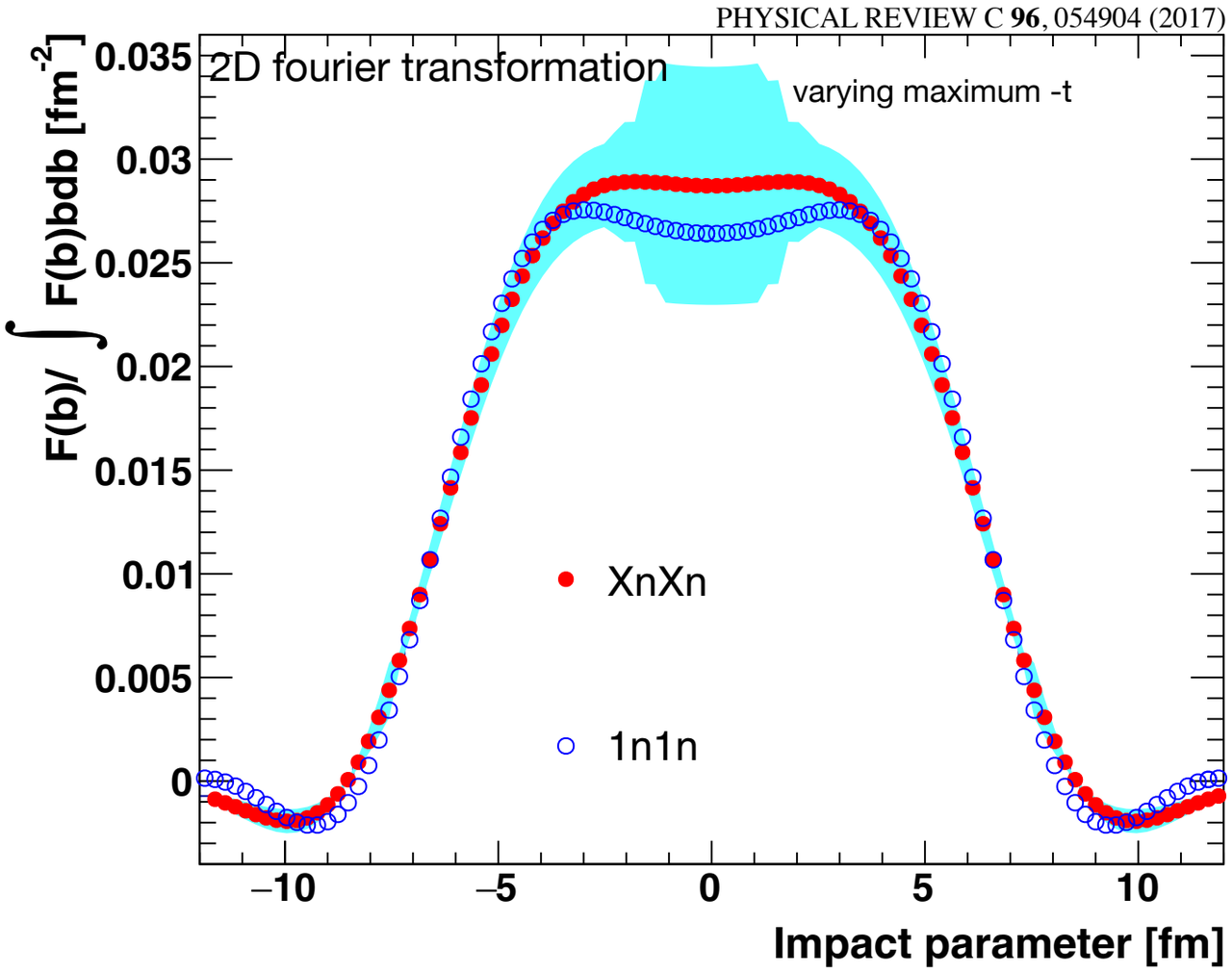
ALICE: JHEP 06 (2020) 035



Diffractive dips in $-t = p_T^2$ observed with coherent ρ in UPC at both RHIC (STAR) and the LHC (ALICE)

STAR: probing nuclear geometry w/ ρ^0



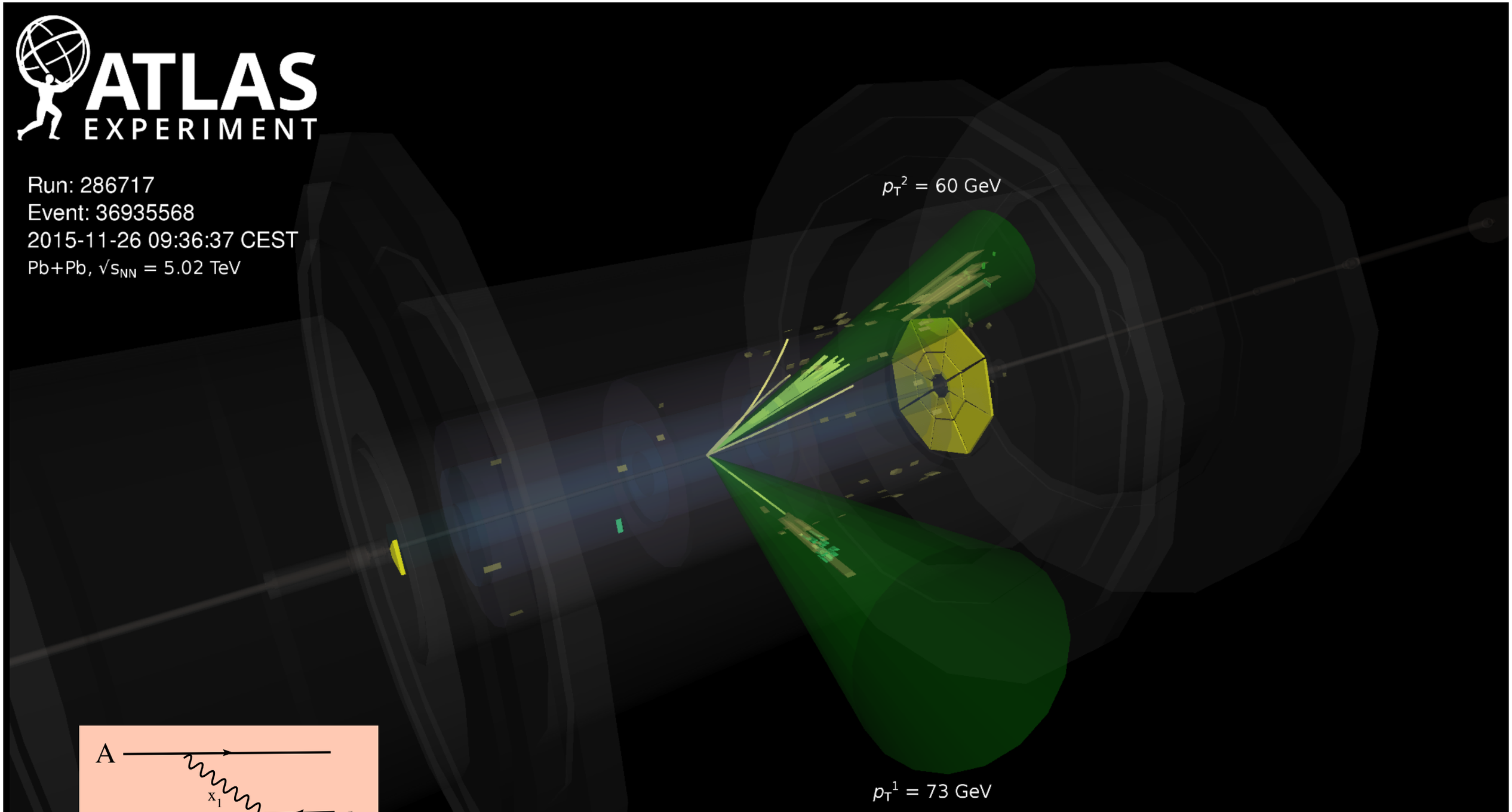


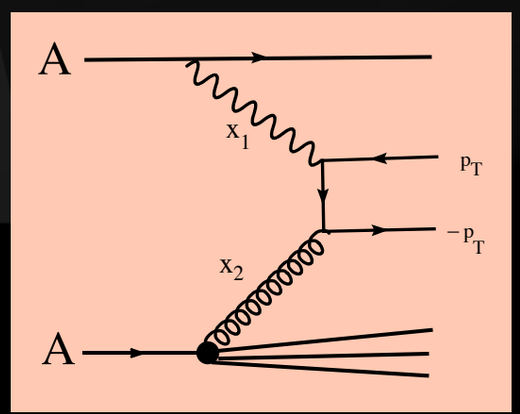
Diffractive dips in $-t = p_T^2$ observed with coherent ρ

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 (but important backgrounds from incoherent processes)

Kong Tu (diffractive VM), Alex Jentsch (FF), Weds

photonuclear jet production

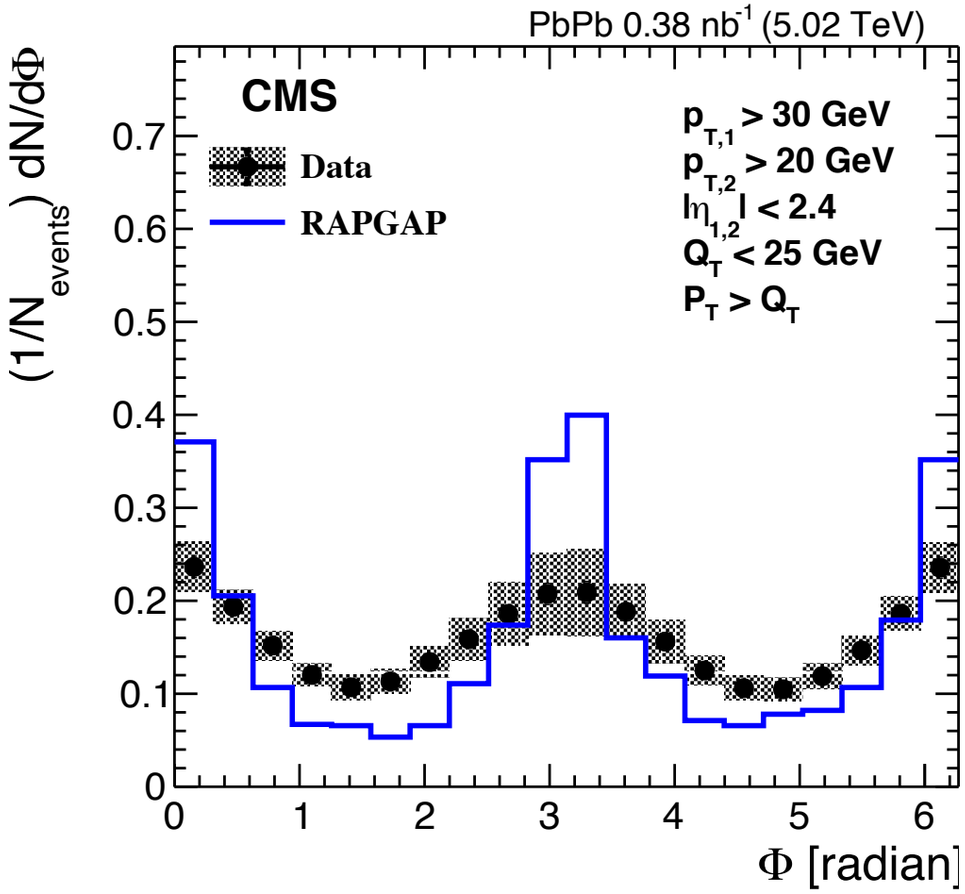


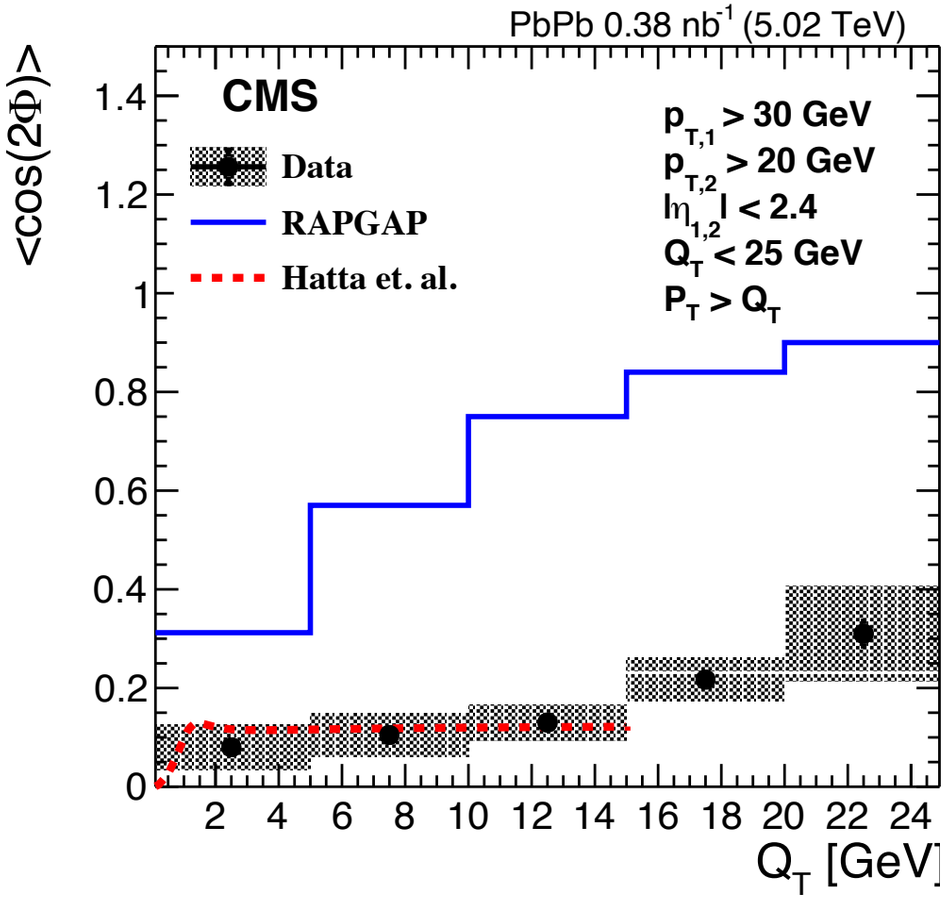


use jets to directly probe nuclear PDFs
Xn0n topology enhances events, verified by gap

NEW CMS-HIN-18-011

CMS: dijet correlations in γ+Pb





CMS studies azimuthal angle between the sum and difference vectors for jets in (strict) dijet γ+Pb events, unfolded to correct for experimental detector effects

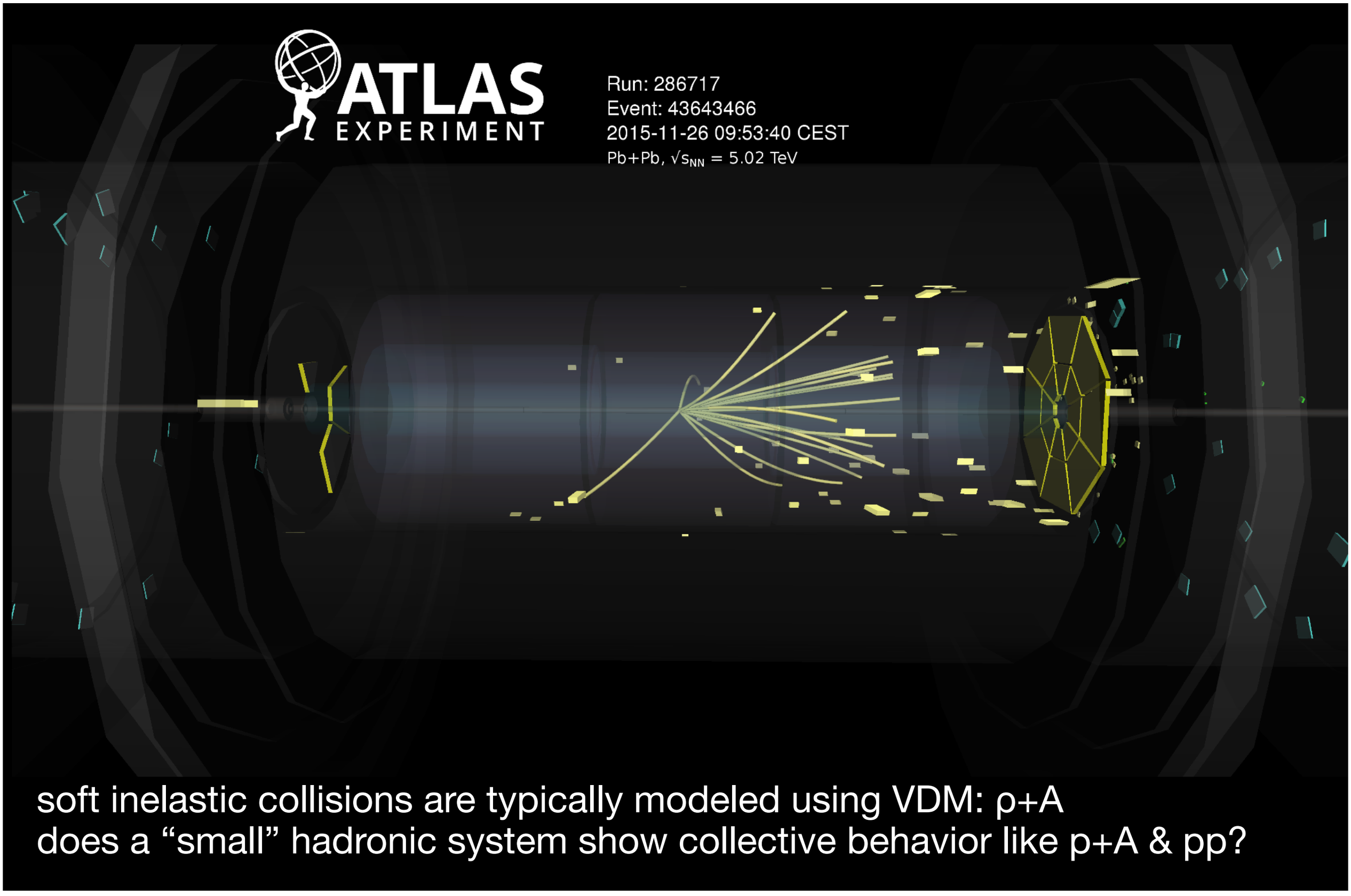
$$\vec{Q}_T = \vec{p}_{T,1} + \vec{p}_{T,2} \qquad \vec{P}_T = (\vec{p}_{T,1} - \vec{p}_{T,2})/2 \qquad \cos(\Phi) = \frac{\vec{P}_T \cdot \vec{Q}_T}{\left|\vec{P}_T\right| \left|\vec{Q}_T\right|}$$

(cf. STAR)

Very different than ep (RAPGAP), and should be sensitive to elliptically polarized gluons, or even saturation physics — and is not fully explicable with FSR

M. Murray, Weds paralle

inelastic photonuclear processes



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

What you should know about UPC

- **Ultraperipheral collisions are providing a new physics program based on γγ, γ+Pb and γ+p collisions**
  - Sit “alongside” the hadronic HI (QGP) physics program at RHIC and the LHC
  - Clean environment allowing precise measurements

- **Results being shown at DIS include**
  - Dileptons (ee, μμ, ττ) - photon luminosity, geometric dependence of photon fluxes
  - Impact of linear photon polarization
  - BSM searches with ττ & γγ final states - already competitive with previous searches, and much more Run 3/4 data coming
  - Vector mesons - parton structure and spatial imaging
  - Photonuclear jets - measurements of nPDFs, studies of gluon polarization
  - Collectivity in hadronic photonuclear final states

- **Excellent synergies between RHIC & LHC**

- **Previews of the EIC physics program in the decade before EIC!**