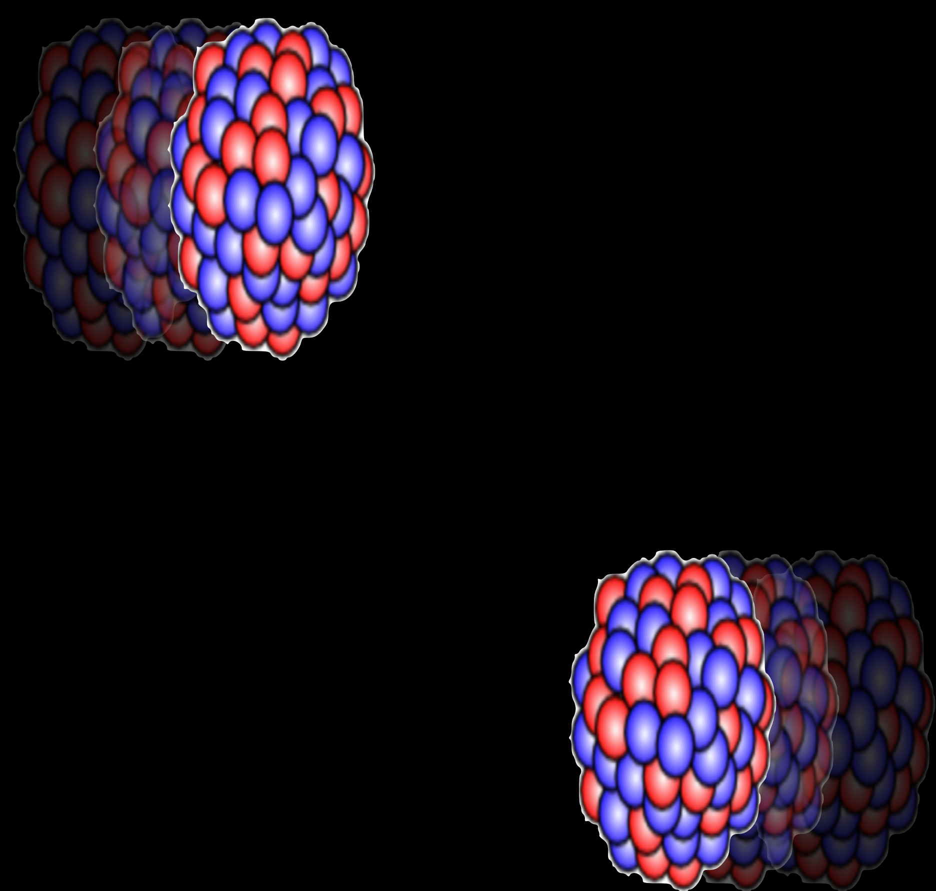
Prospects for UPC at the LHC

Peter Steinberg, BNL

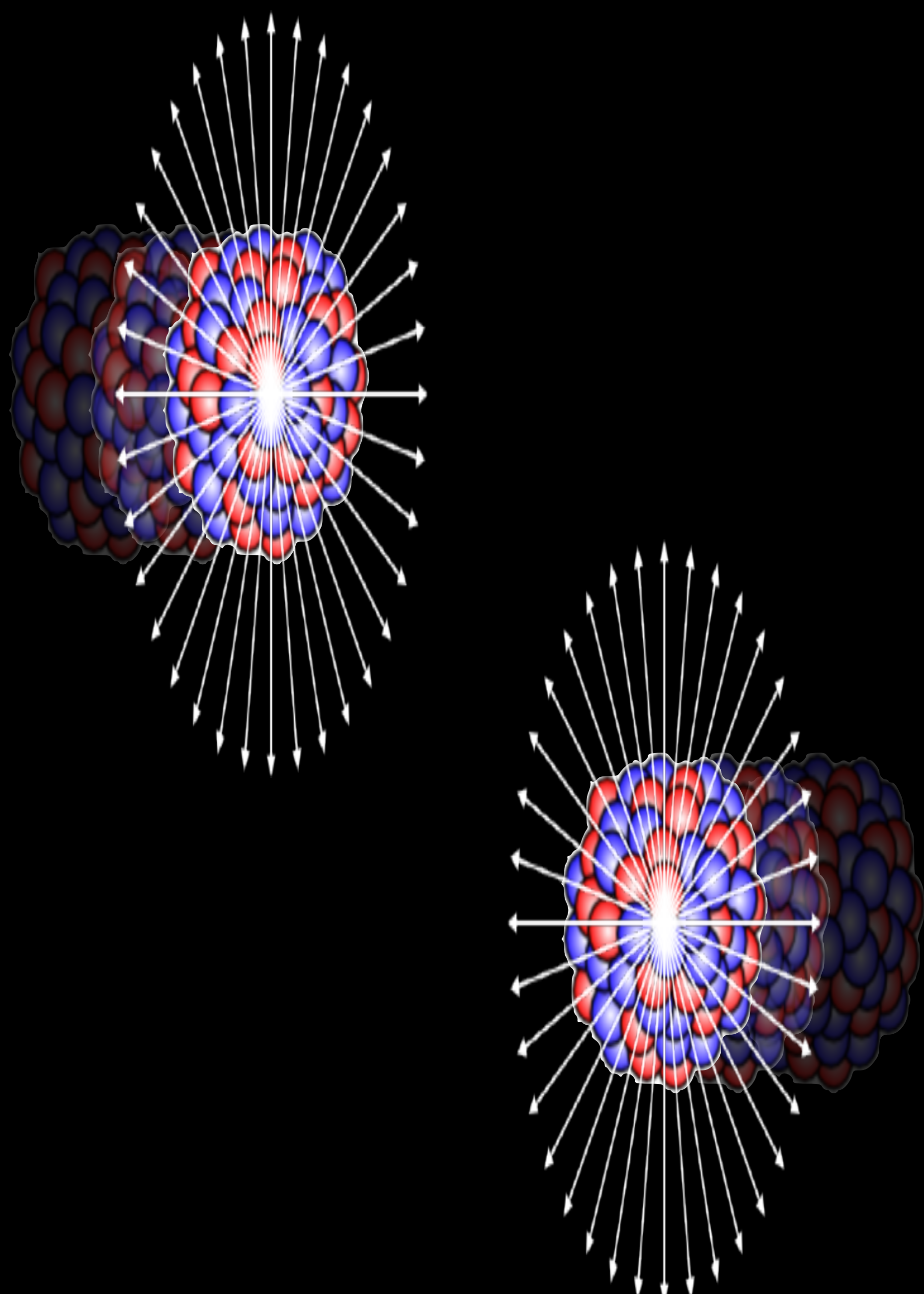
ALICE-USA meeting, Yale University / May 31, 2024

Brookhaven National Laboratory

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



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



Stripped nuclei have
<u>very</u> strong EM fields
(B=O(10^{15}) T!)

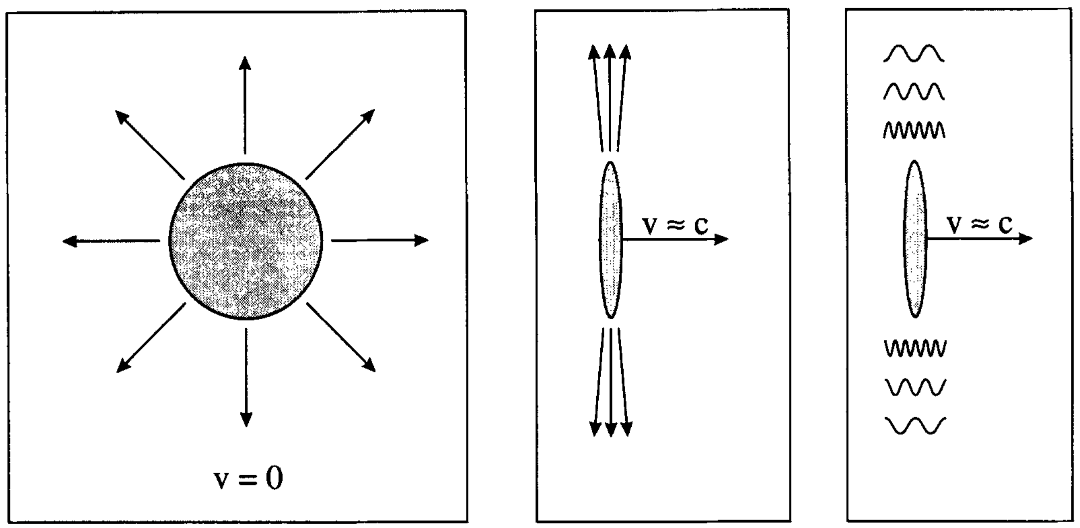
Z=82 packed into a subatomic volume traveling ultra relativistic speeds (Lorentz contracted)!

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

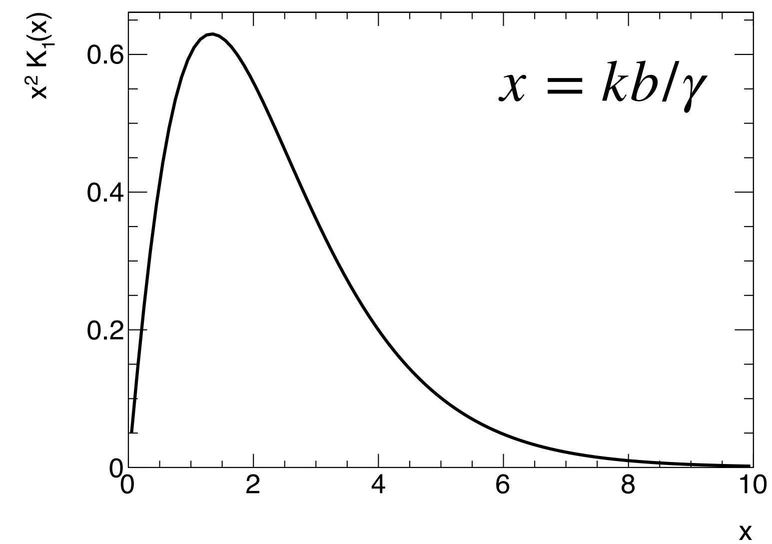
Equivalent Photon Approximation



For a point charge:

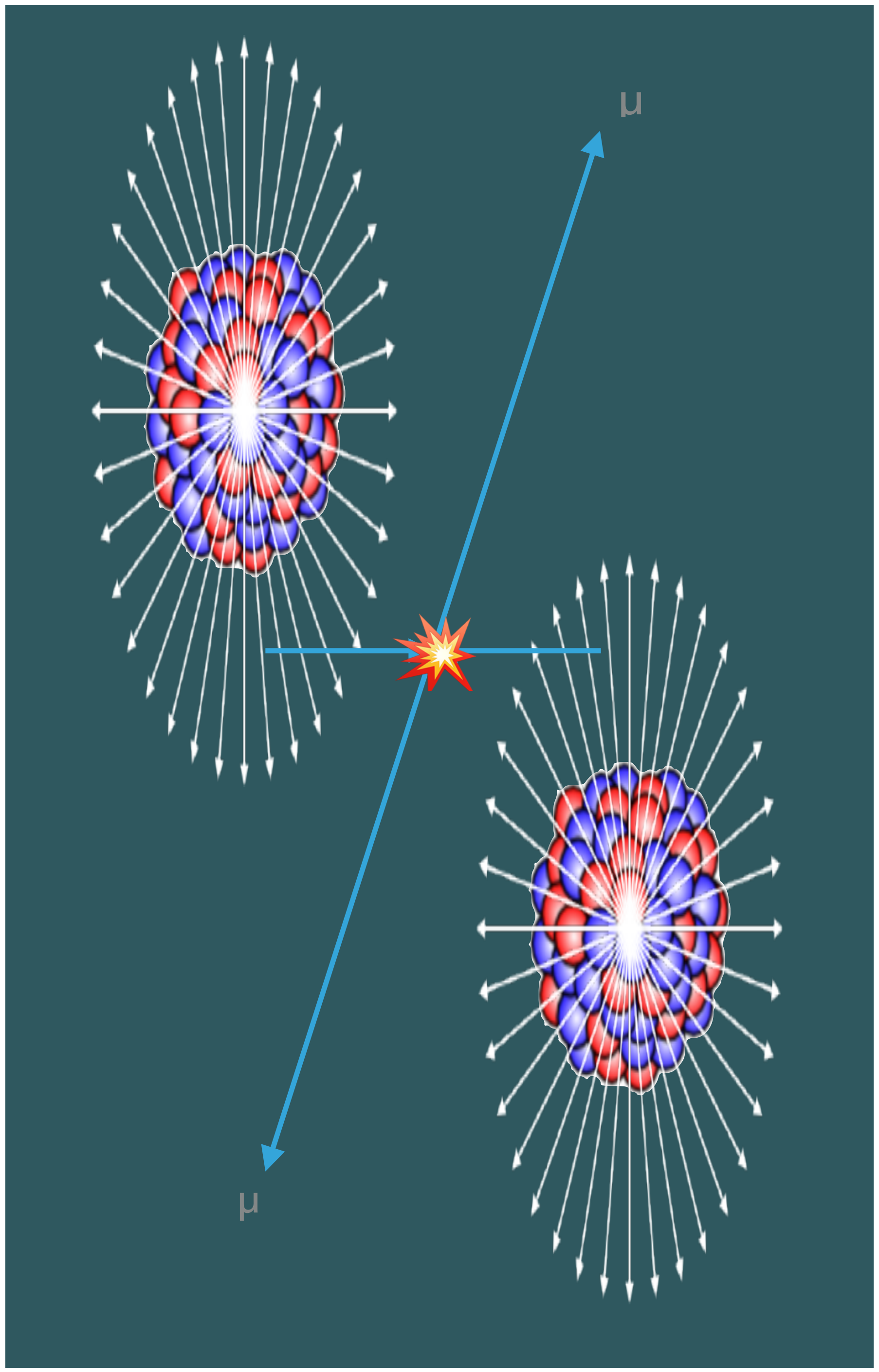
$$n(k,b) = \frac{d^3N_\gamma}{d^2b\,dk} \propto \frac{\alpha Z^2}{kb^2} f(kb/\gamma)$$

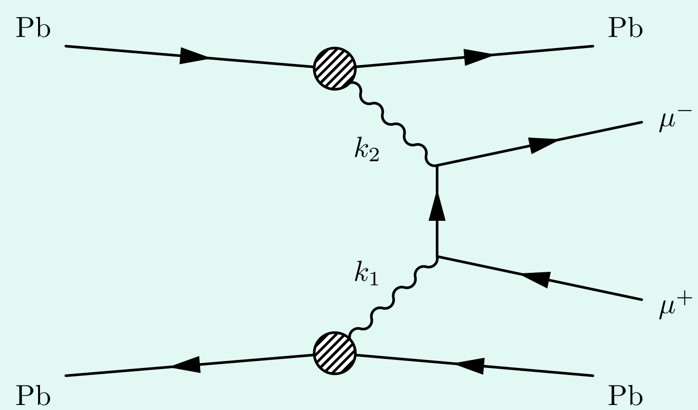
energy depends on radial distance:
the lower the b, the harder the spectrum!



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

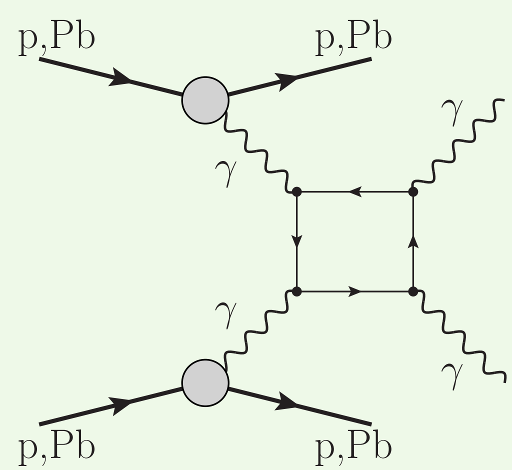




lepton pair production

(Breit-Wheeler formula, Brodsky et al 1971)

γγ “luminosity”
lepton decays



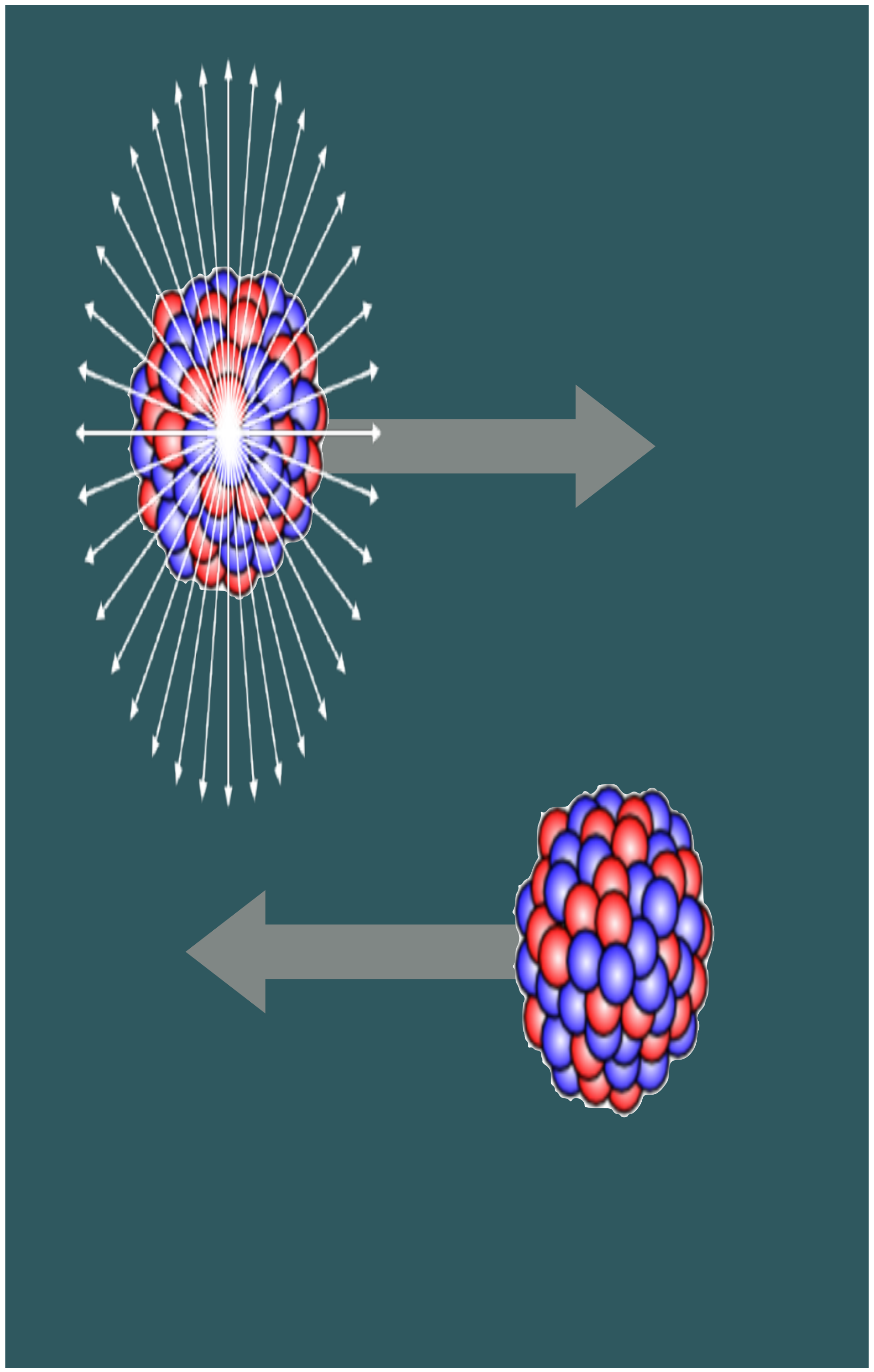
photon pair production

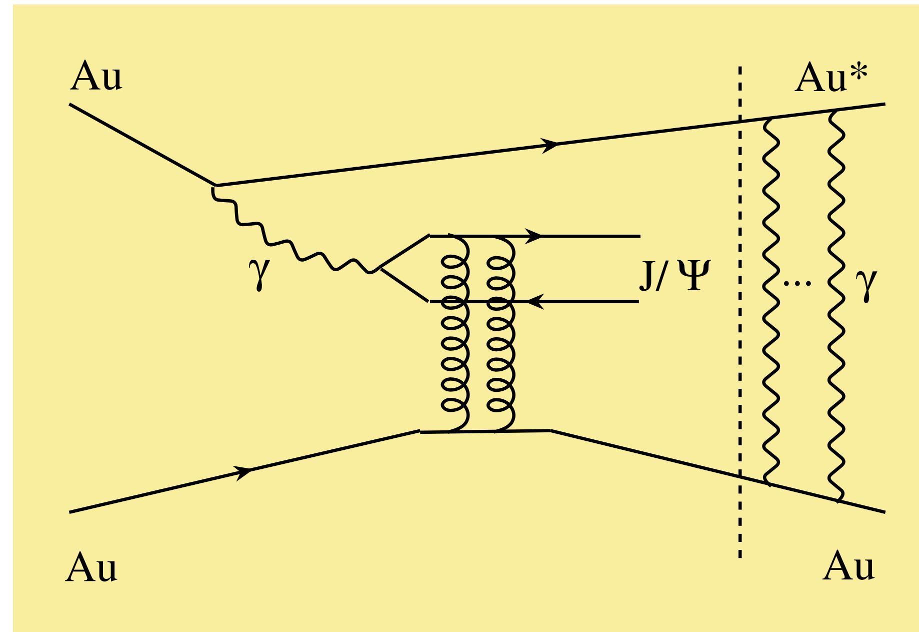
(via quark, lepton, W, BSM? loops)

rare QED processes
BSM physics

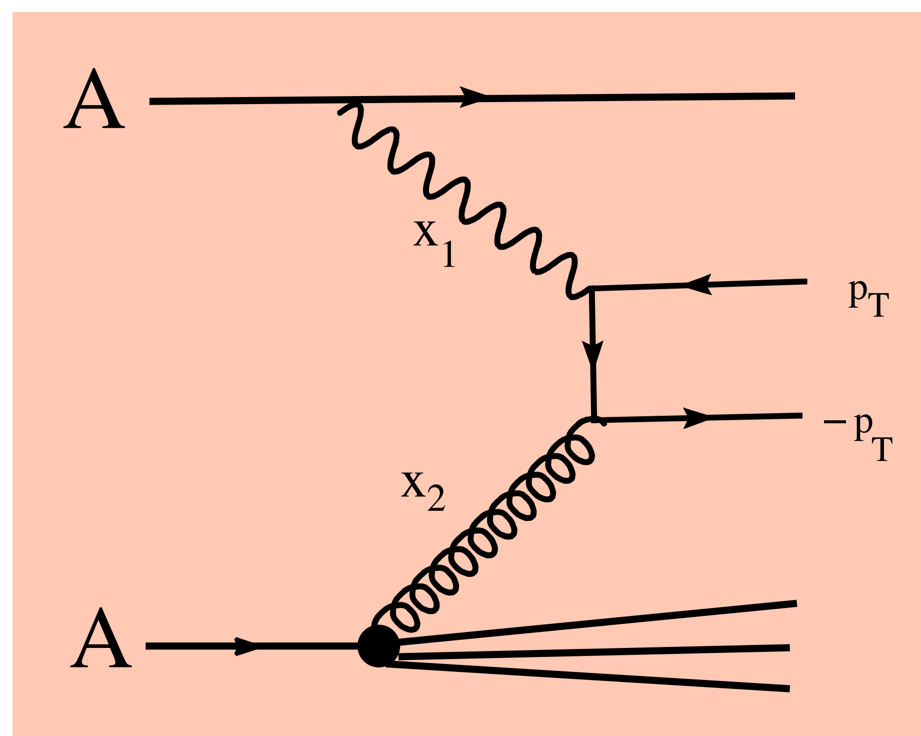
Heavy ion collisions provide clean environment for study of QED & BSM processes

Photonuclear processes





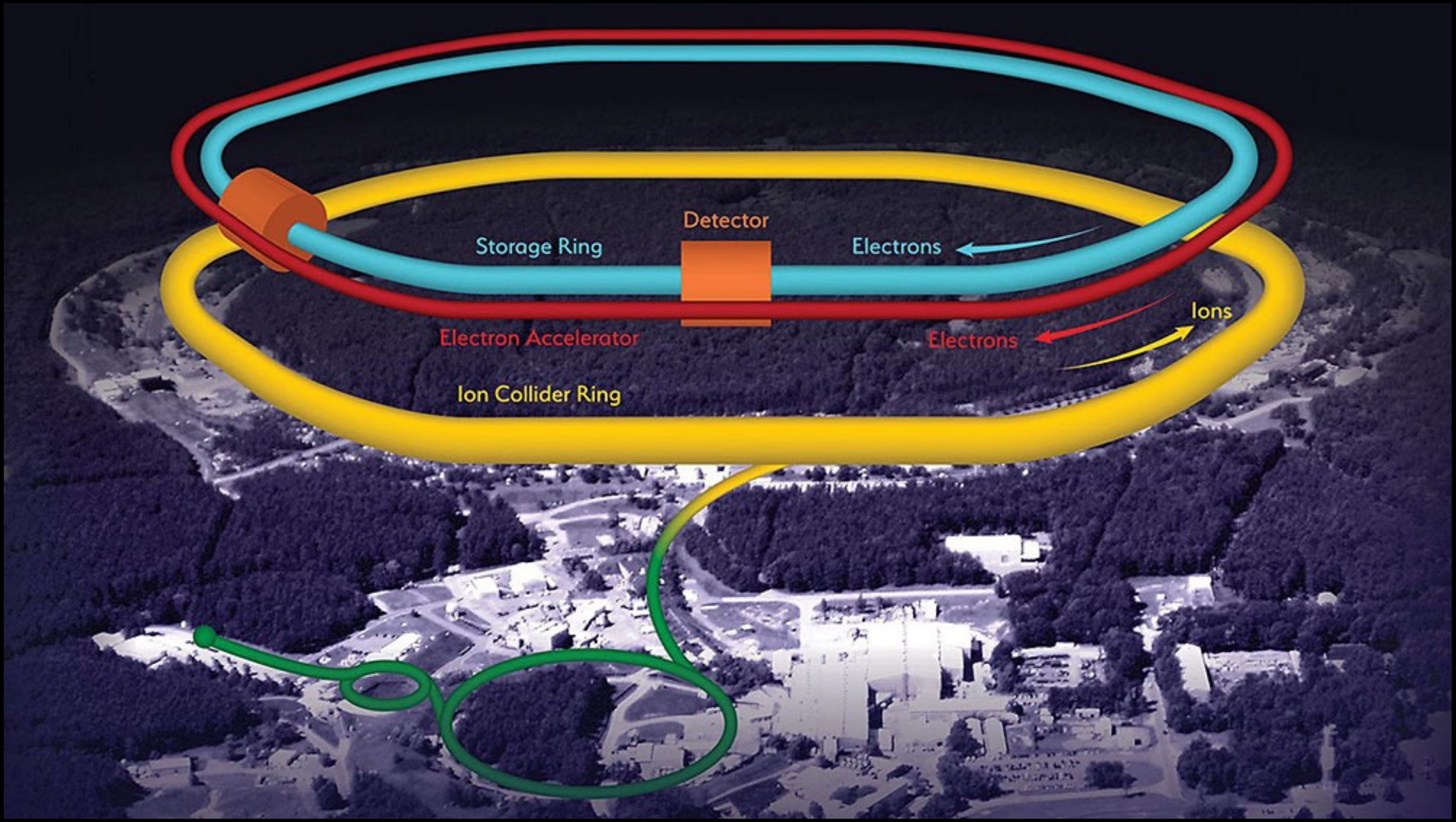
"exclusive"/elastic vector meson production:
nuclear geometry
nuclear PDFs/GPDs
parton saturation?



inelastic hadron and jet production:
nuclear PDFs
parton saturation?

Photonuclear processes provide similar capabilities to ep/eA machines!

Electron-ion collider (BNL & JLab)



Partonic and spatial structure of nucleons & nuclei:
$W_{\gamma p}$ ~ 140 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 <u>well-understood</u> 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 $|\eta|<2.4$, ALICE $|\eta|<0.8$ and $\eta=-2.5$-4, LHCb $\eta=2$-4.5) and flexible detectors with powerful triggering (or no need…)

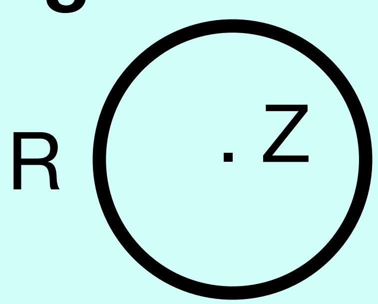
exclusive dileptons (“γγ luminosity”)

2 photon flux, 2 approaches

$$\sigma_X = \int \frac{d^2N}{dk_1 dk_2} \hat{\sigma}(k_1, k_2, \dots) dk_1 dk_2$$

for dileptons we use well-known Breit-Wheeler cross section formula (Brodsky et al, 1971)

STARlight:



$$\frac{d^2N}{dk_1 dk_2} = \int_{b_1>R_1} d^2b_1 \int_{b_2>R_2} d^2b_2 \; n(k_1, b_1) n(k_2, b_2) \; P_{\mathrm{fn}}(b) \; (1 - P_{\mathrm{H}}(b))$$

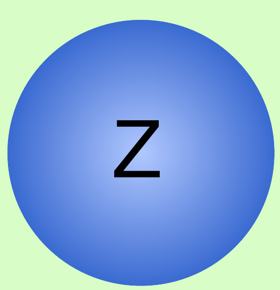
forward neutron topology

(no) hadronic interaction: Glauber calculation

point like charge with radial cutoff

Comput.Phys.Commun. 212 (2017) 258-268

SuperChic:



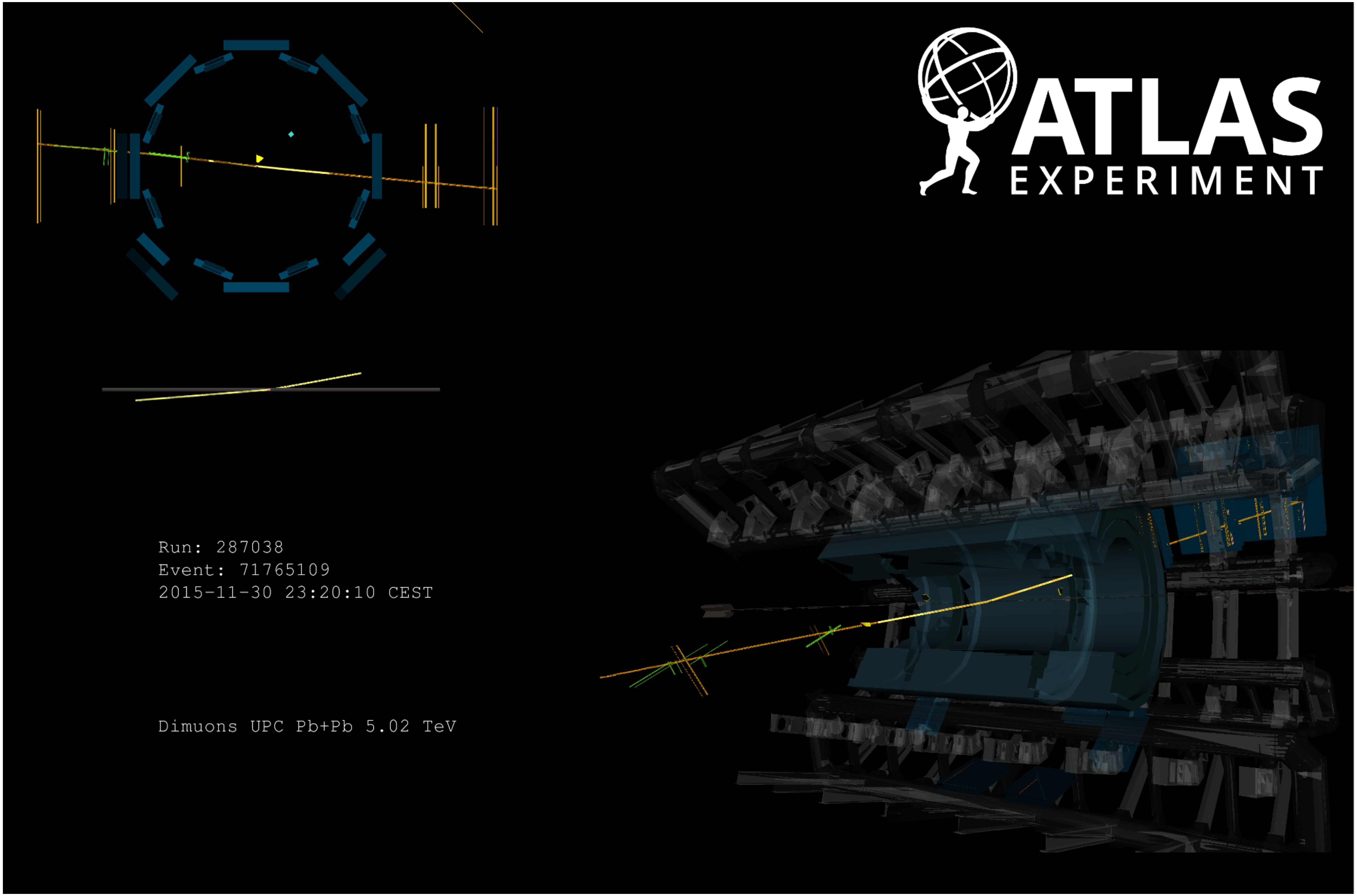
$$\sigma_{N_1N_2 \to N_1XN_2} = \int \mathrm{d}x_1 \mathrm{d}x_2 \, n(x_1) n(x_2) \hat{\sigma}_{\gamma\gamma \to X}$$

$$n(x_i) = \frac{\alpha}{\pi^2 x_i} \int \frac{\mathrm{d}^2 q_{i_\perp}}{q_{i_\perp}^2 + x_i^2 m_{N_i}^2} \left(\frac{q_{i_\perp}^2}{q_{i_\perp}^2 + x_i^2 m_{N_i}^2} (1 - x_i) F_E(Q_i^2) + \frac{x_i^2}{2} F_M(Q_i^2) \right)$$

charge distributions using known form factors

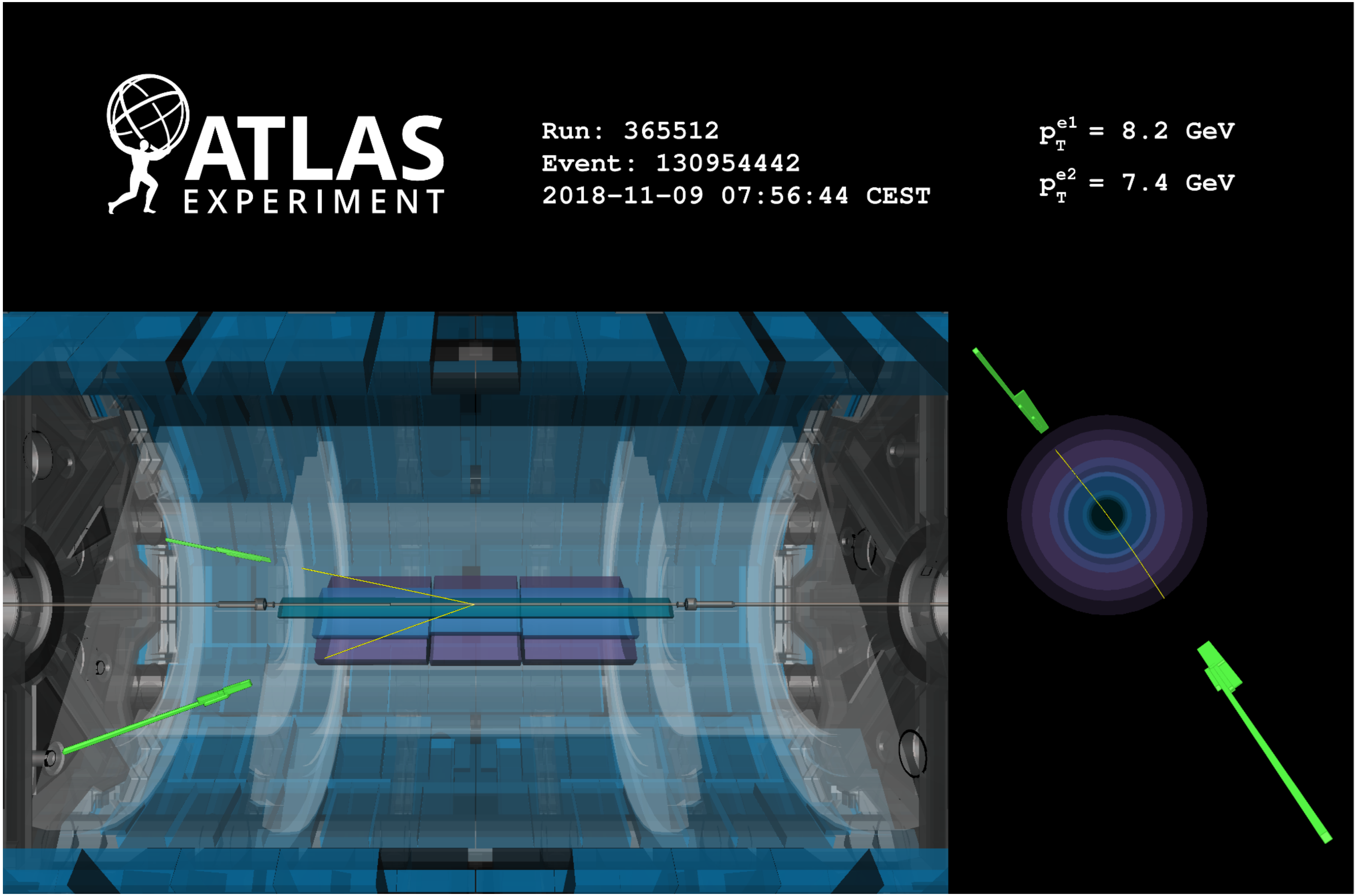
SciPost Phys. 11, 064 (2021)

an exclusive dimuon event

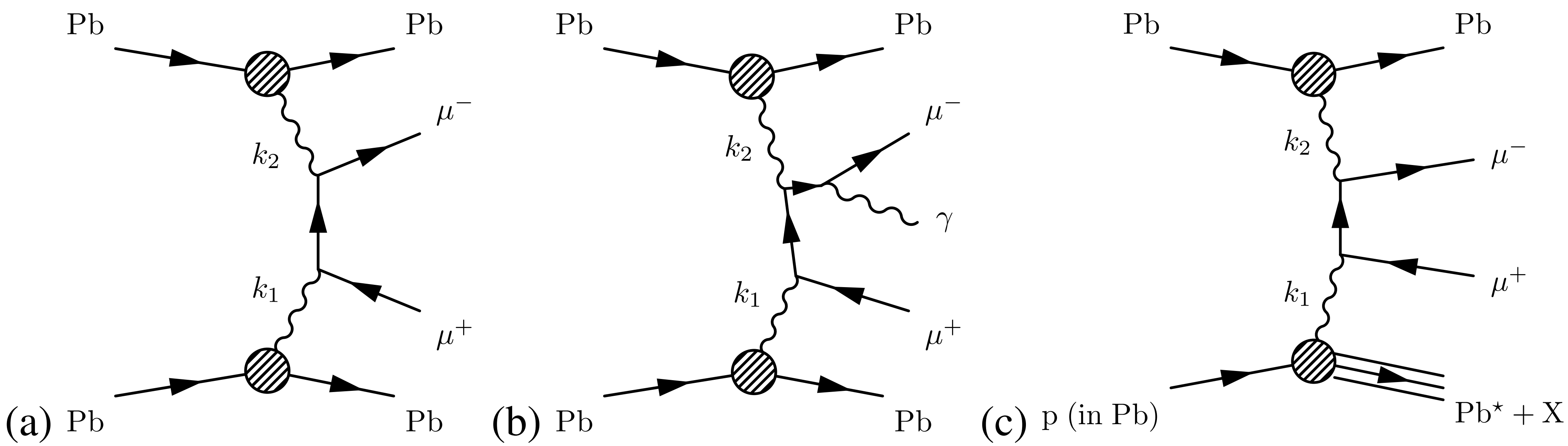


highest mass dimuon event in 2015 dataset - $m_{\mu\mu}$ = 173 GeV

an exclusive dielectron event



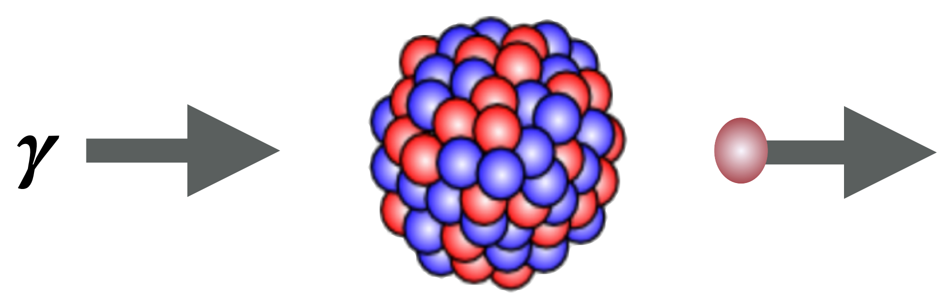
Exclusive dilepton processes & dissociation



$\mathrm{PbPb}(\gamma\gamma) \to \mu^+\mu^-(\mathrm{Pb}^{(\star)}\mathrm{Pb}^{(\star)})$ is the primary signal Breit-Wheeler process
$\mathrm{PbPb}(\gamma\gamma) \to \mu^+\mu^-\gamma(\mathrm{Pb}^{(\star)}\mathrm{Pb}^{(\star)})$ is a radiative process (still signal!)
$\mathrm{Pb} + \mathrm{N}/\mathrm{Pb}(\gamma\gamma) \to \mu^+\mu^- X(\mathrm{Pb}^{\star}\mathrm{Pb}^{(\star)})$ is **dissociative** background process

How exclusive is “exclusive”?

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



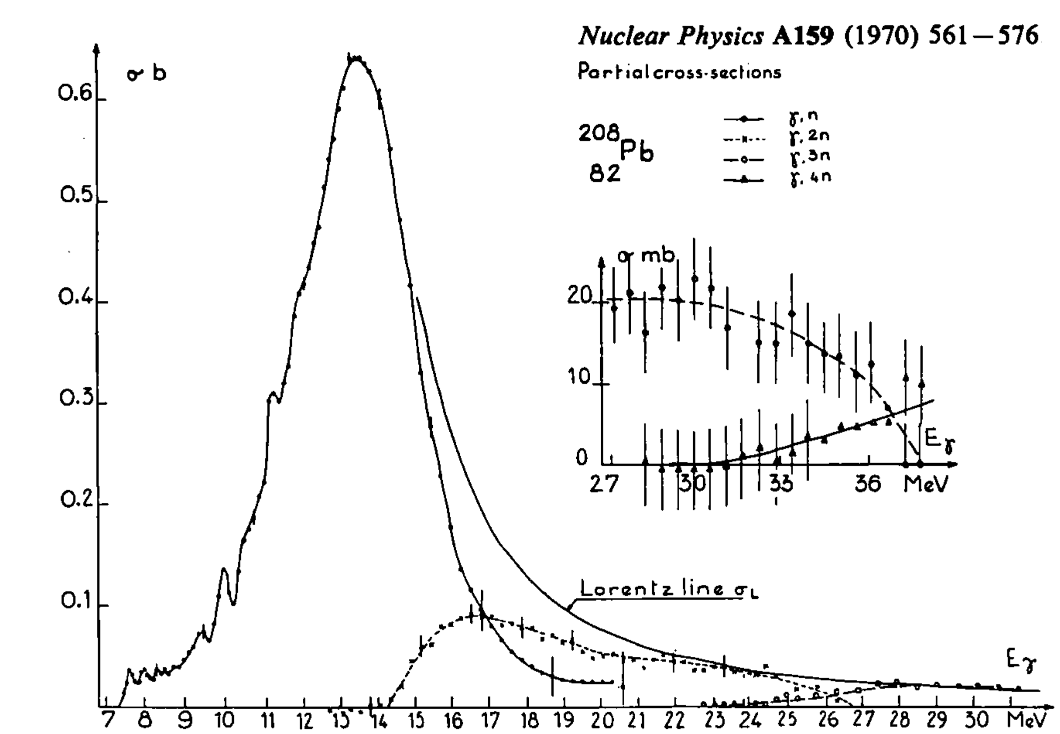
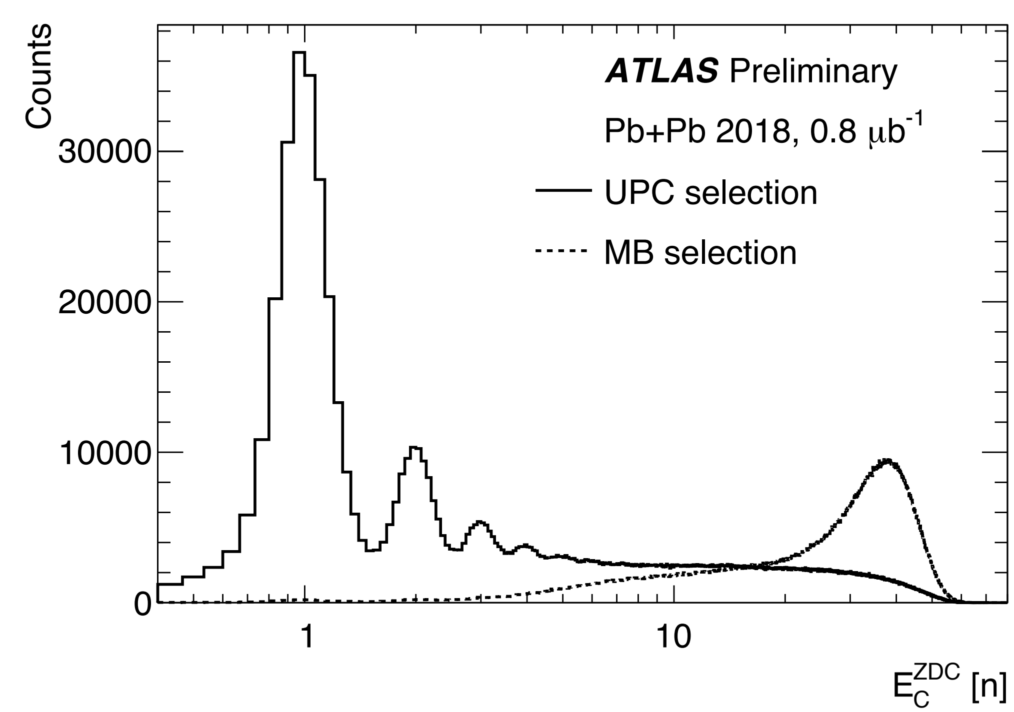


Fig. 1. Partial photoneutron cross sections $\sigma_{\gamma,n}$, $\sigma_{\gamma,2n}$, $\sigma_{\gamma,3n}$, and $\sigma_{\gamma,4n}$ of ^{208}Pb. We also show the descending part of the unique Lorentz line giving the best fit to the experimental $\sigma_{\gamma,T}(E)$ curve.

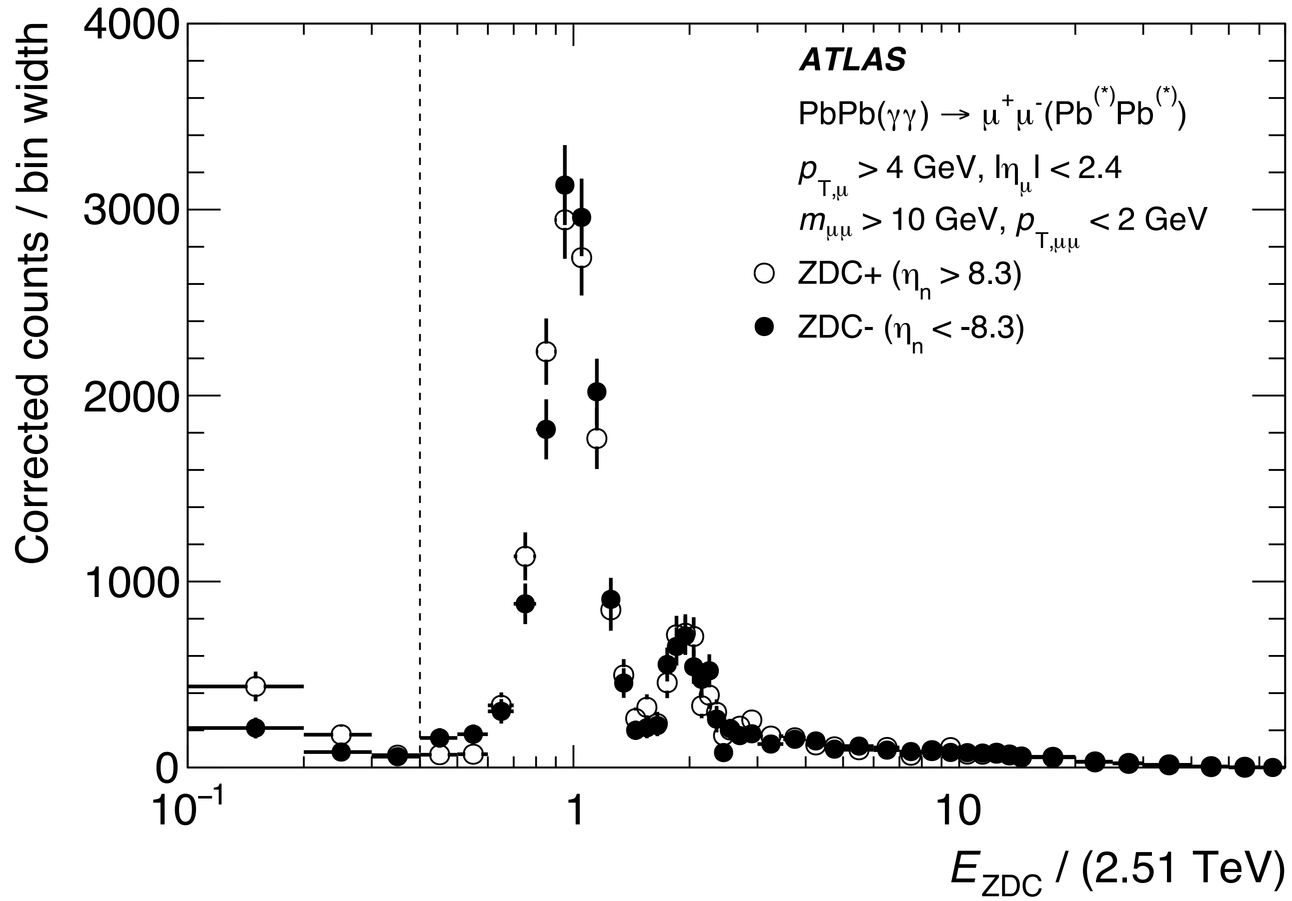
“Giant dipole resonance”: all protons vibrating against all neutrons

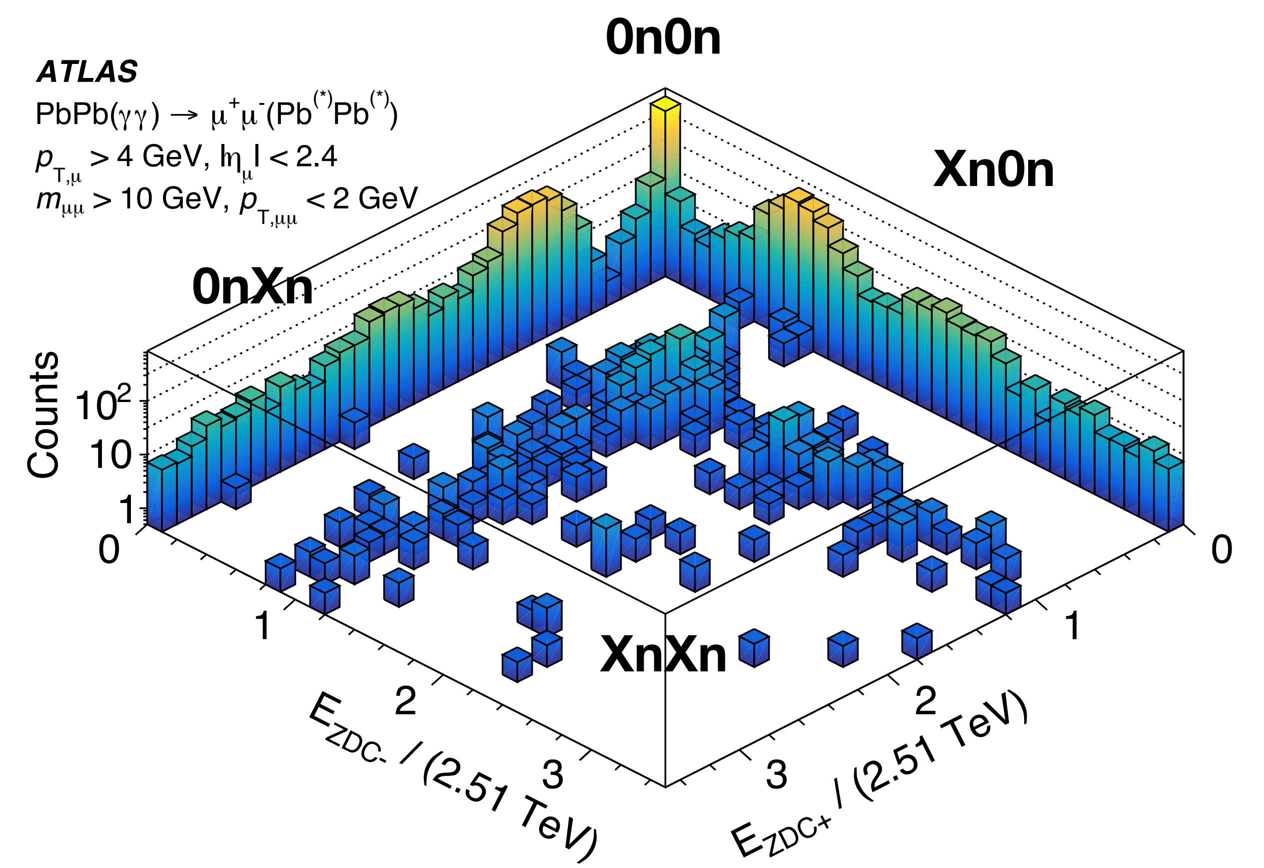
→ knocks out 1-4n

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

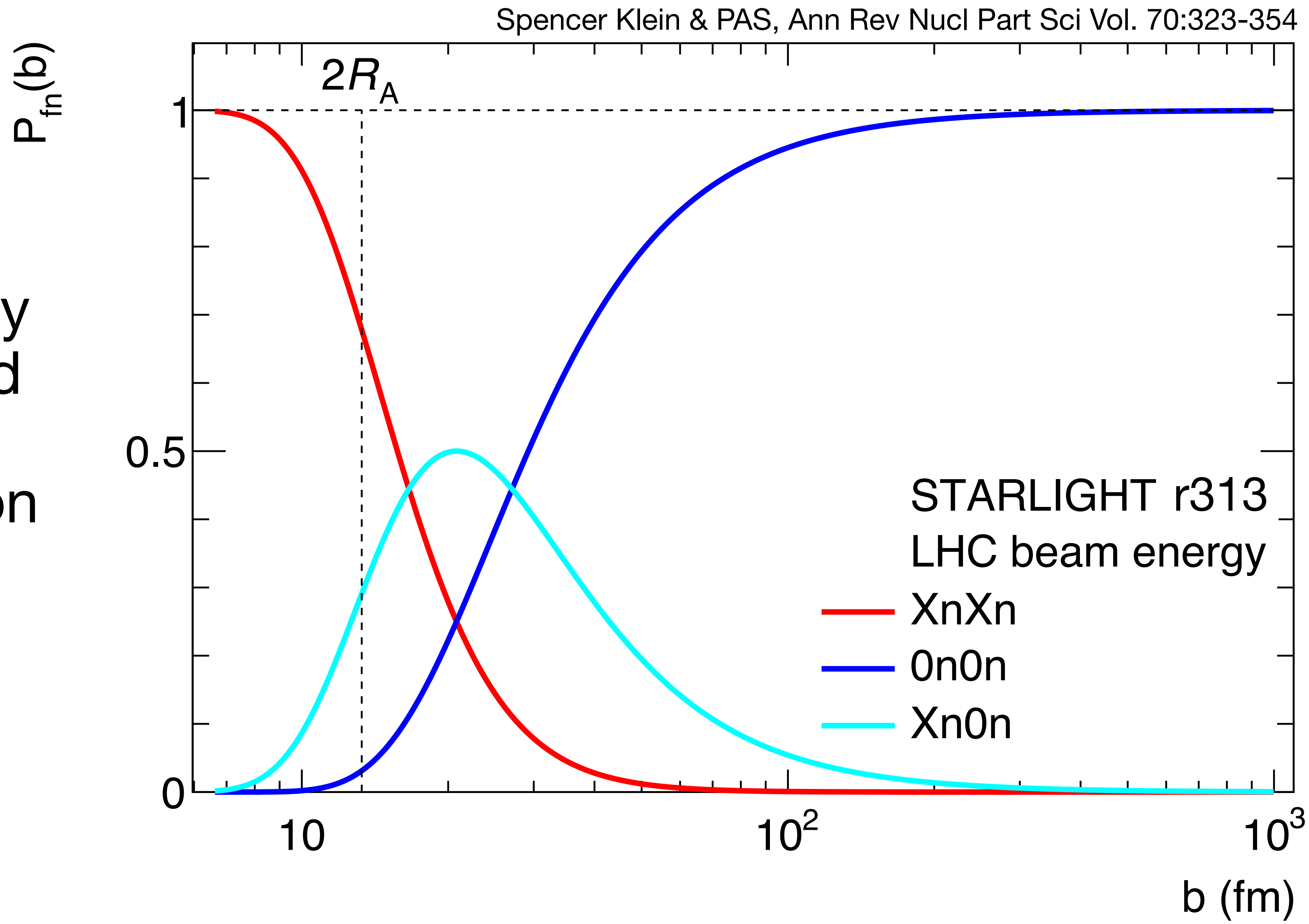
Typically make a selection at ~0.4 of the neutron energy to divide no activity (0*n*) from 1 or more (X*n*)

We can then classify events by their neutron topology:

- **0n0n** - no neutrons on either side
- **Xn0n/0nXn** - neutrons on one side
- **XnXn** - neutrons on both sides

ZDC fragmentation in STARlight

probability of forward neutron production

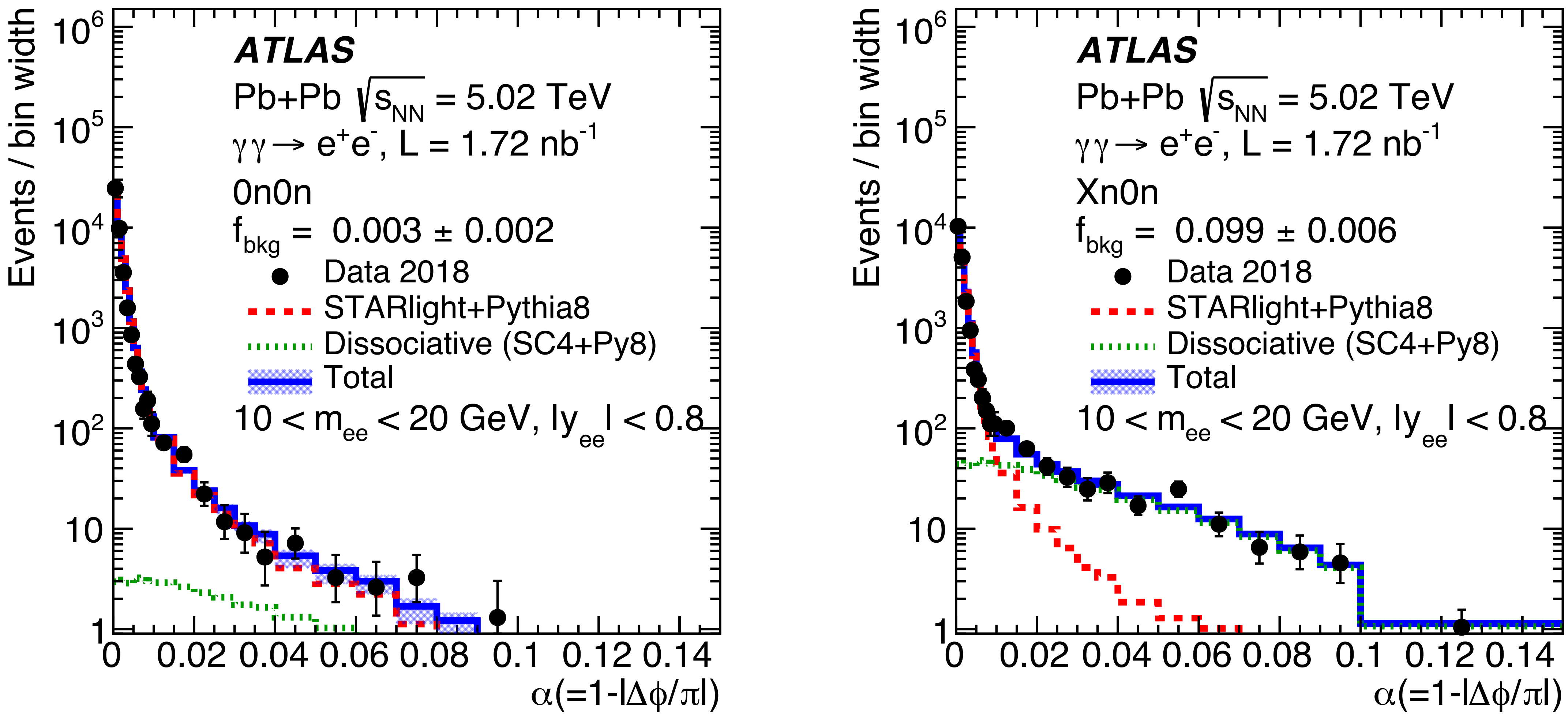


Selecting ZDC topologies selects impact parameter ranges!
(exploited by several of the results I will show soon!)

Dissociative contributions from $\ell\ell$ acoplanarity

$p_{Te} > 2.5$ GeV, $|\eta_e|<2.47$, $p_{Tee} < 2$ GeV

mostly "back to back", so $\alpha = 1 - \left|\frac{\Delta\phi}{\pi}\right| \sim 0$

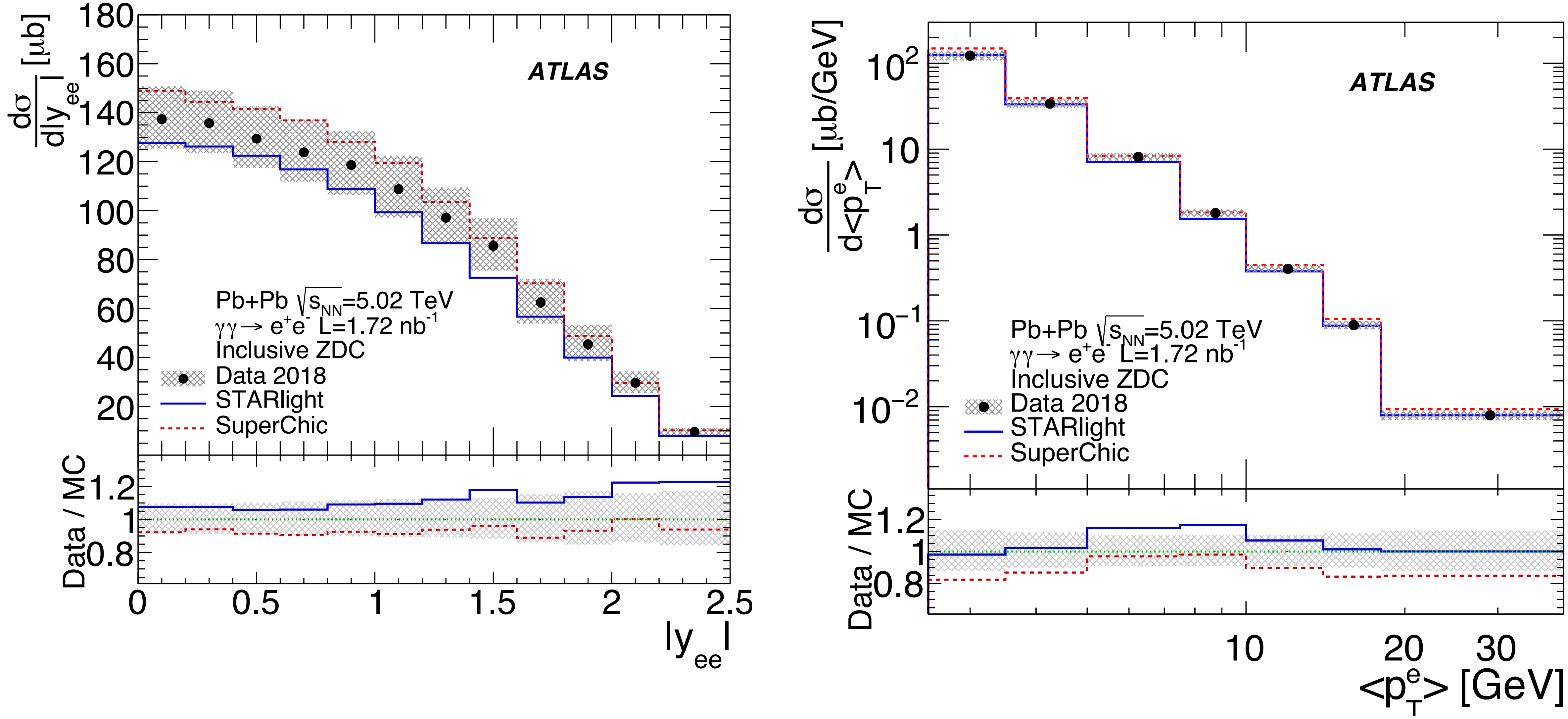


0n0n signal distributions beautifully described after including QED showering!

Xn0n and XnXn <u>require</u> contribution from dissociative processes

ee: rapidity and $<p_T^e>$

$p_{Te} > 2.5$ GeV, $|\eta_e|<2.47$, $m_{ee} > 5$ GeV, $p_{Tee} < 2$ GeV

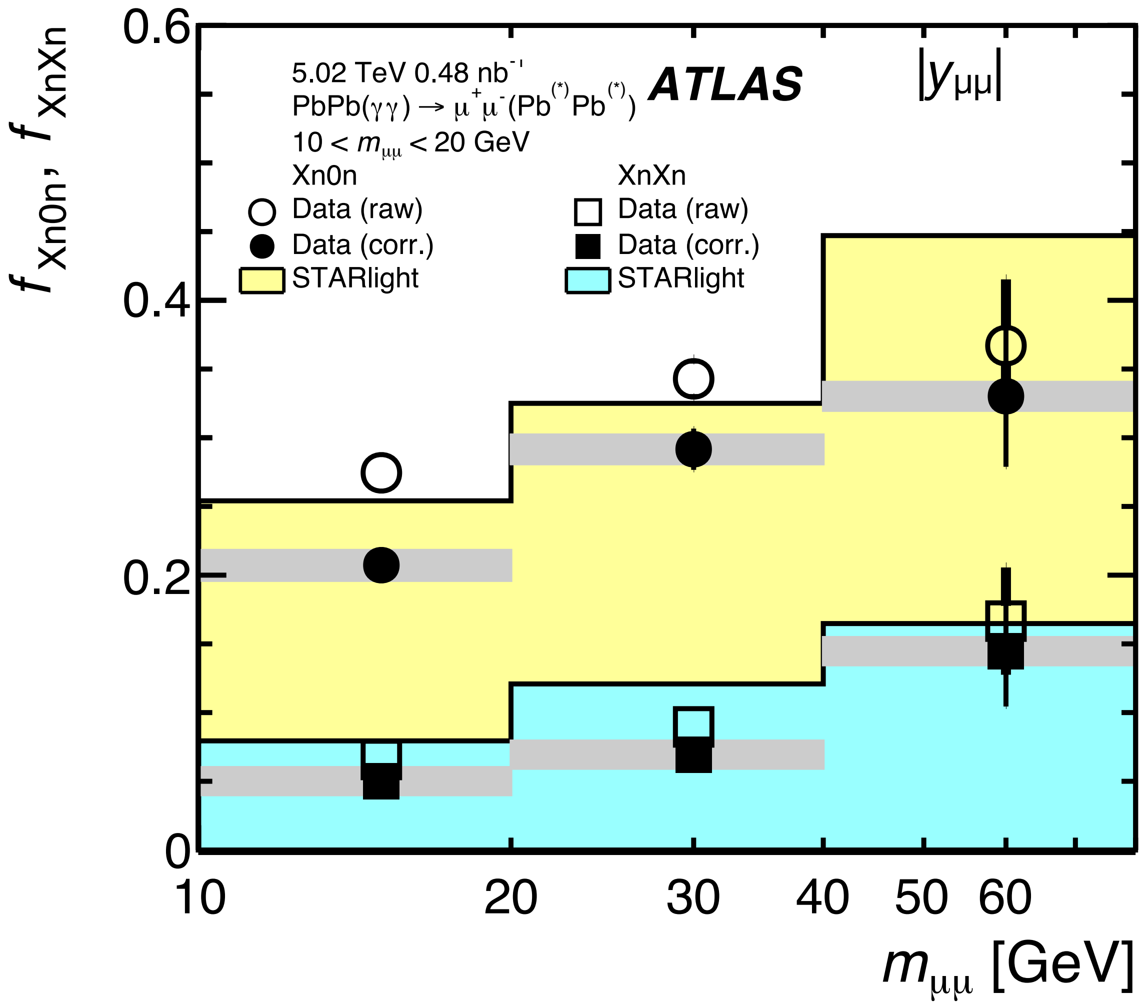


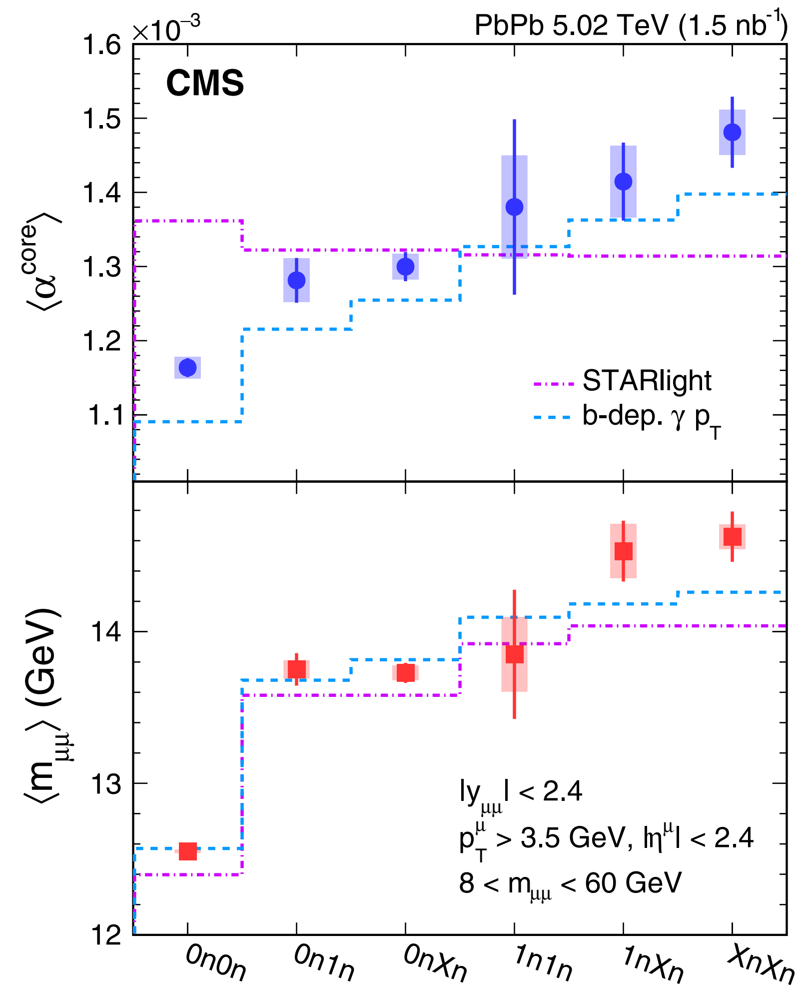
Both ee and μμ observe steady rise with $|y_{ee}|$, relative to STARlight

STARlight tends to underpredict data while, SuperChic has the correct spectral shape, but overpredicts data.

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

Impact of ZDC selections





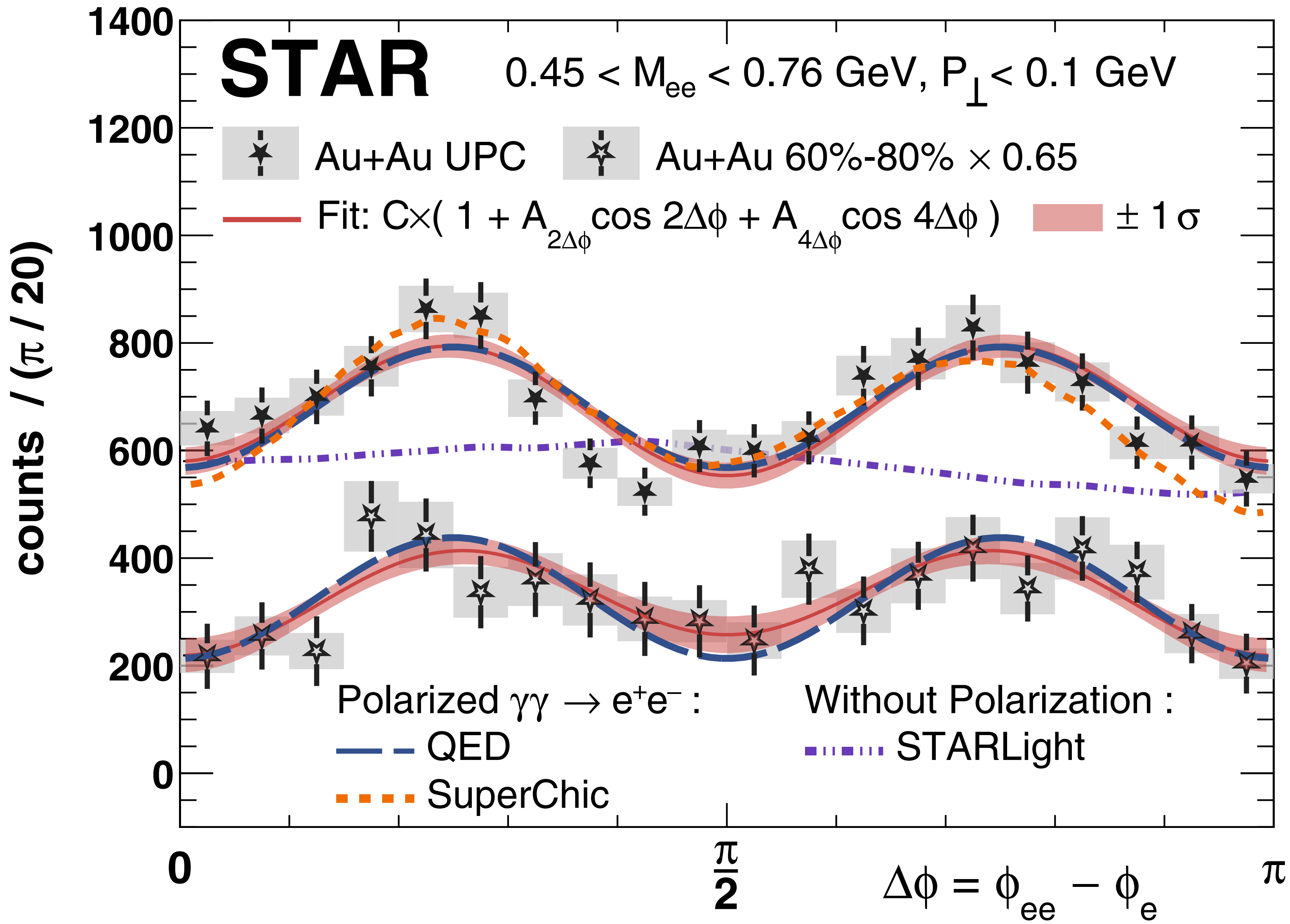
ZDC selections test the impact parameter dependence of the photon fluxes.

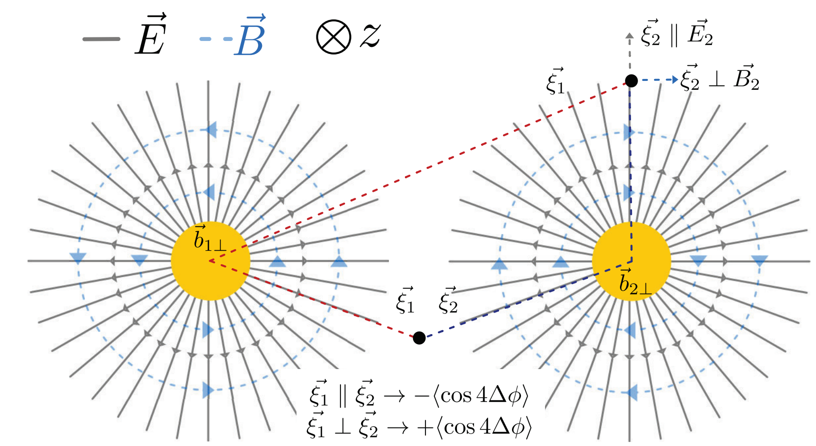
ATLAS sees expected modifications on longitudinal distributions: $m_{\mu\mu}$ and $y_{\mu\mu}$: selecting one or both ZDCs to fire makes the mass distribution harder

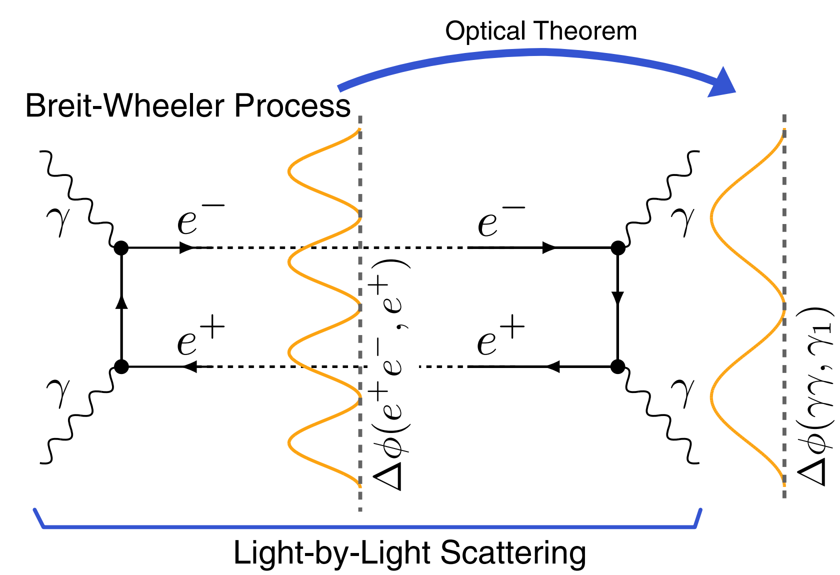
CMS sees clear transverse broadening in acoplanarity and increased mean $m_{\mu\mu}$ as event selections require more neutrons in the ZDCs

STAR: polarization in UPC e+e-

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



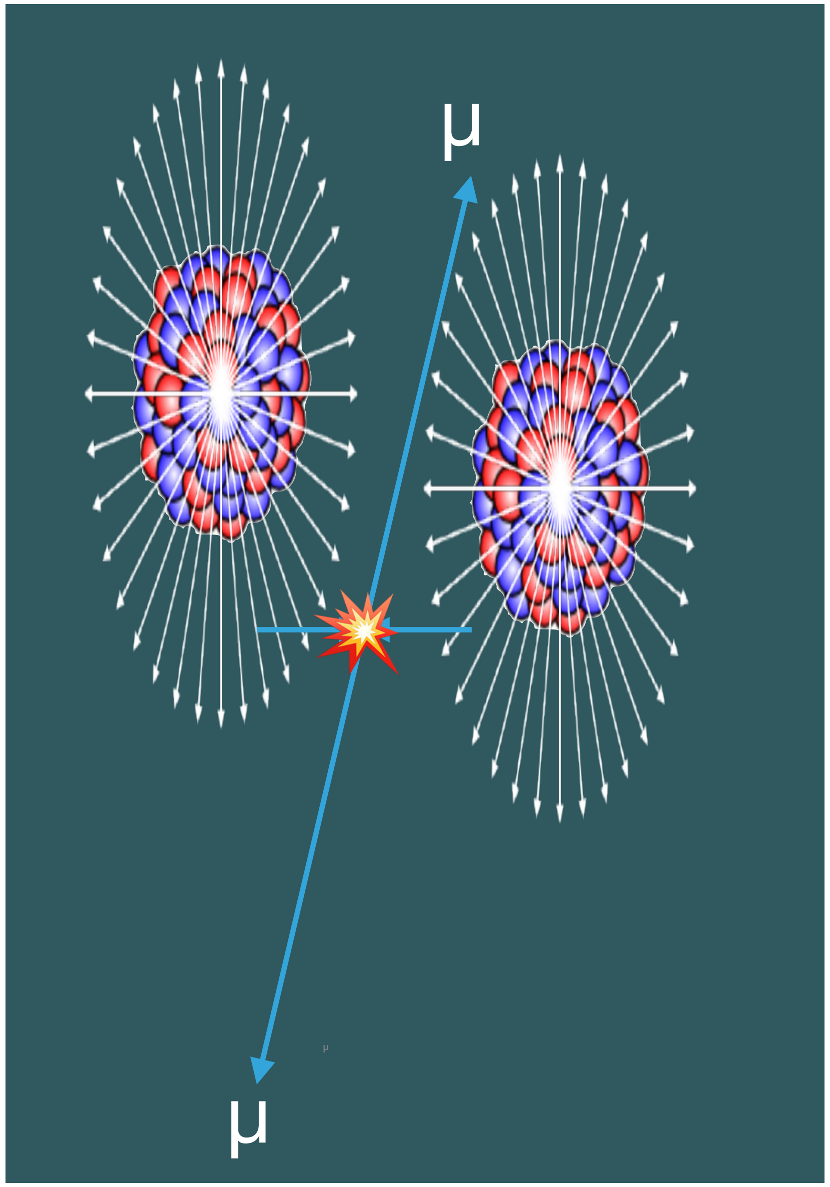


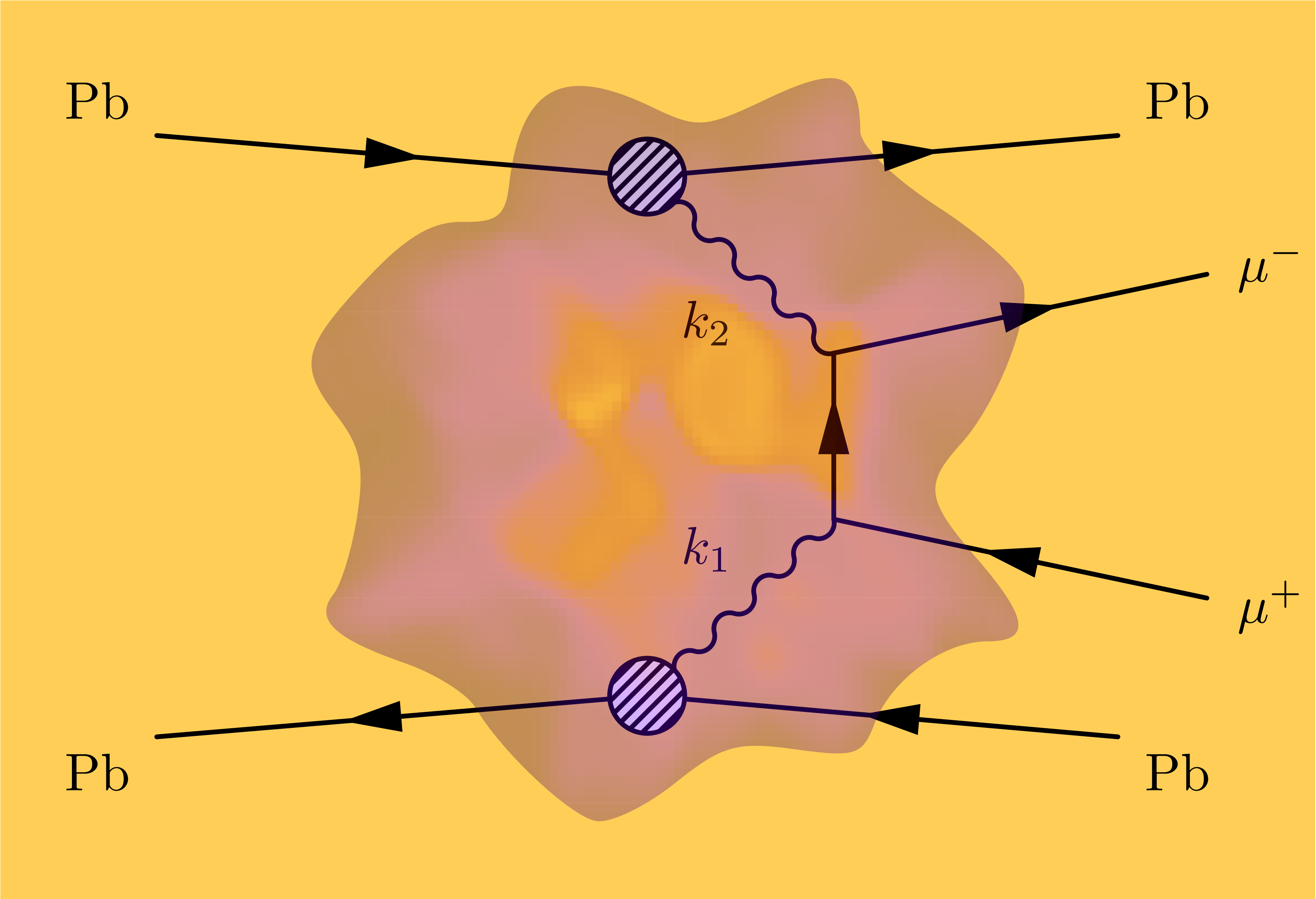


STAR demonstrated impact of linear polarization of initial photons, as a correlation between the momentum sum and difference vectors! A new tool in UPC physics.

Phys. Rev. Lett. 127, 052302

Non-exclusive μμ from γγ

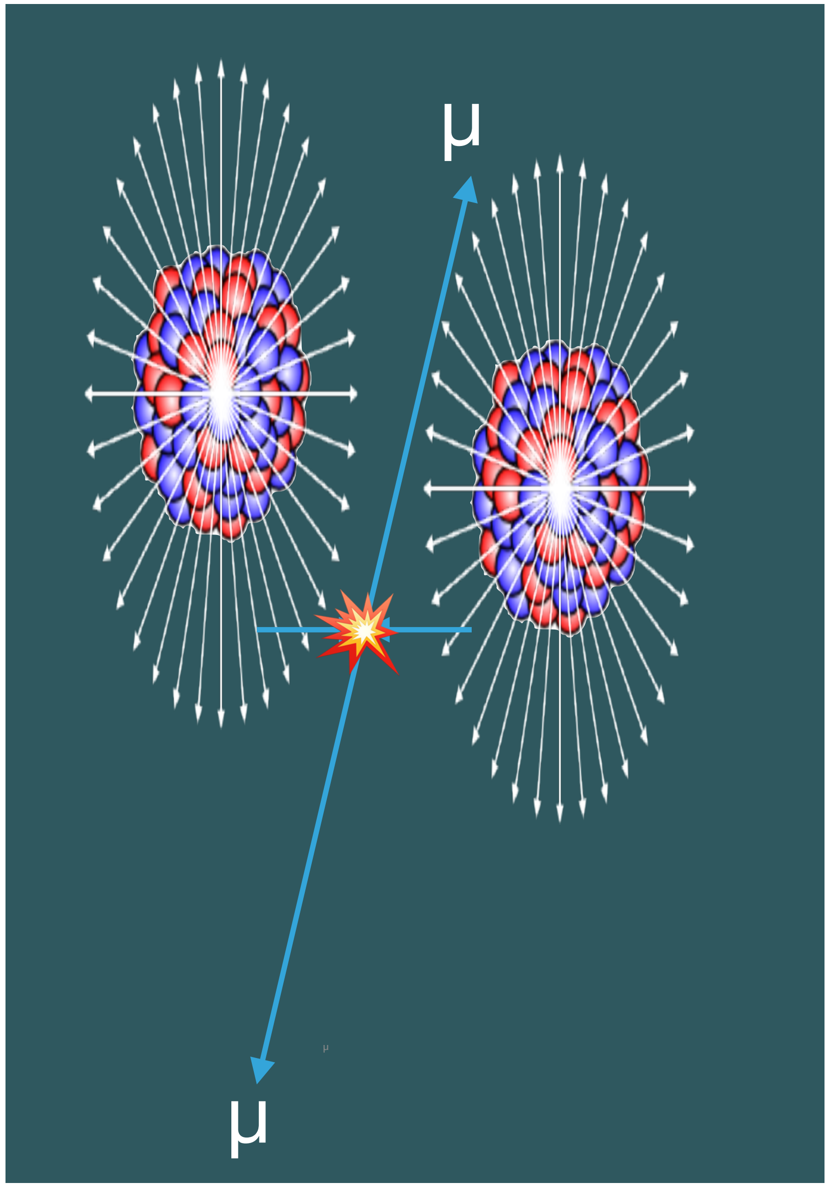


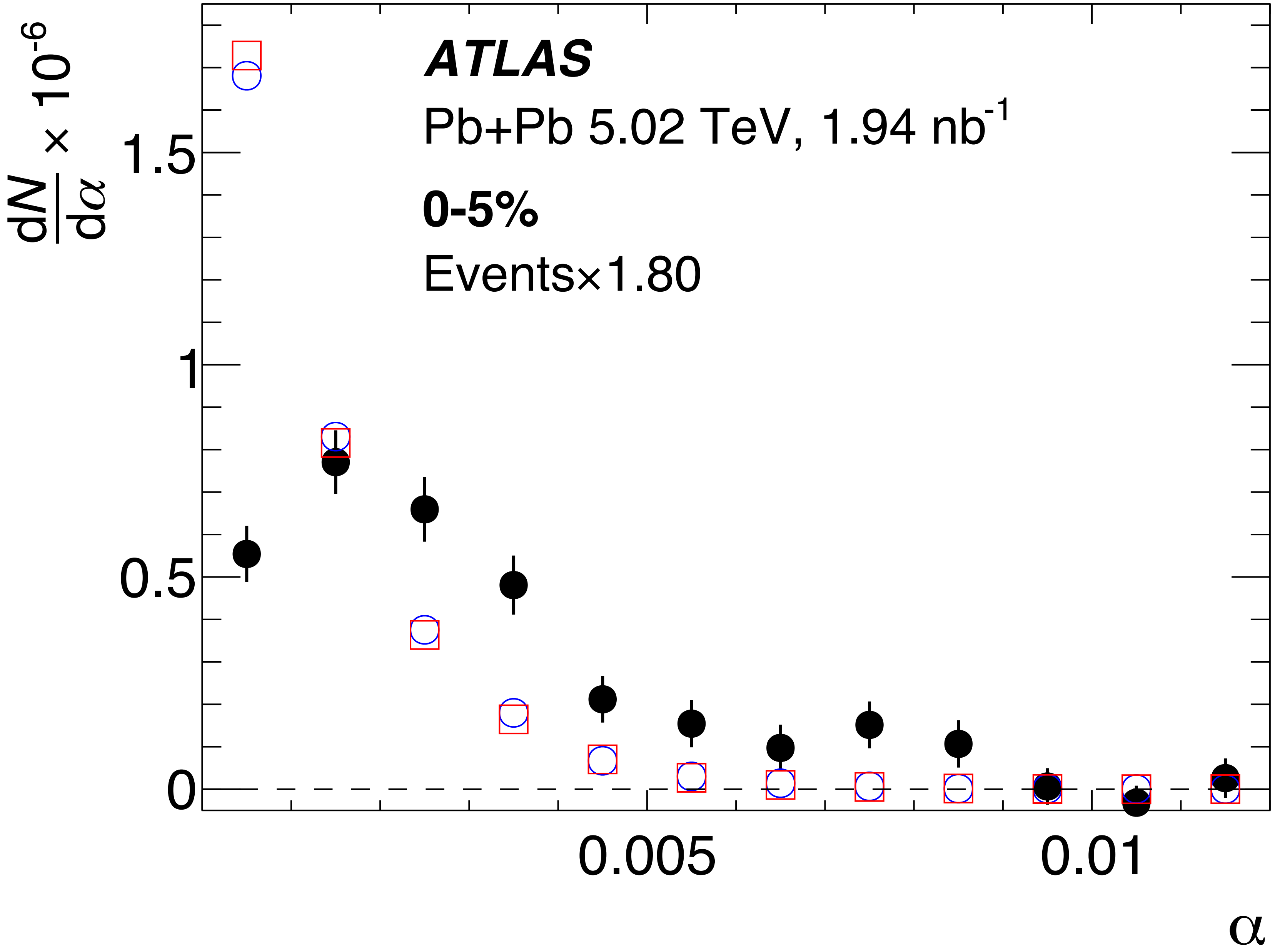


The same μμ process can occur in non-UPC Pb+Pb collisions,
albeit accompanied by hadronic backgrounds (esp. heavy flavor):
are the outgoing muons sensitive to initial (e.g. B field) or final (QGP) effects?

Phys. Rev. C **107**, 054907 (2023)

Non-exclusive μμ from γγ



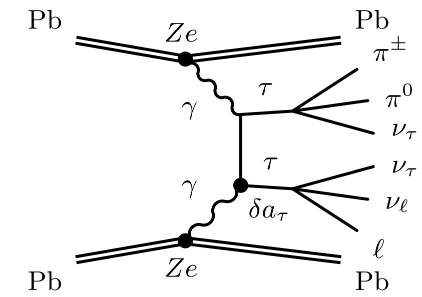


After accounting for backgrounds (heavy flavor & Drell-Yan), the opening angle distribution at b<R becomes progressively broader than UPC, and even "dips" at α~0

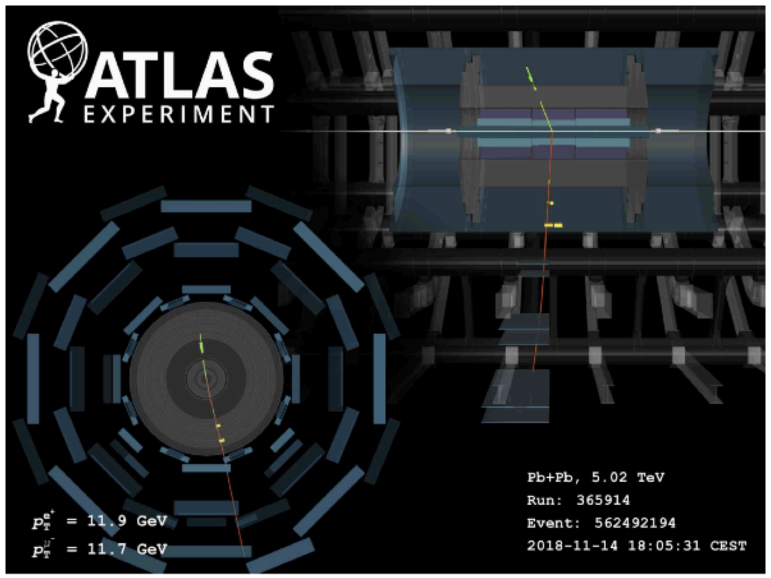
Best understood so far as a QED interference effect

BSM physics

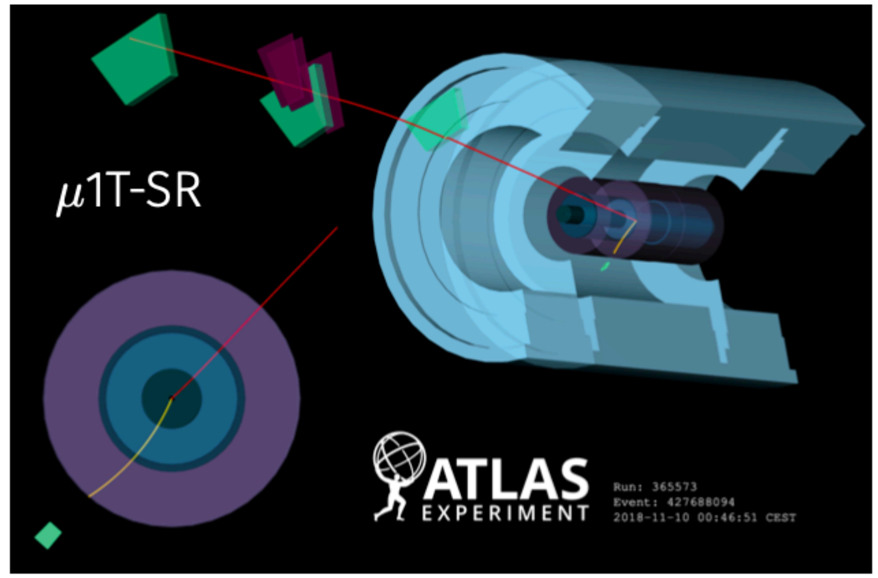
a_τ from $\tau^+\tau^-$ in Pb+Pb



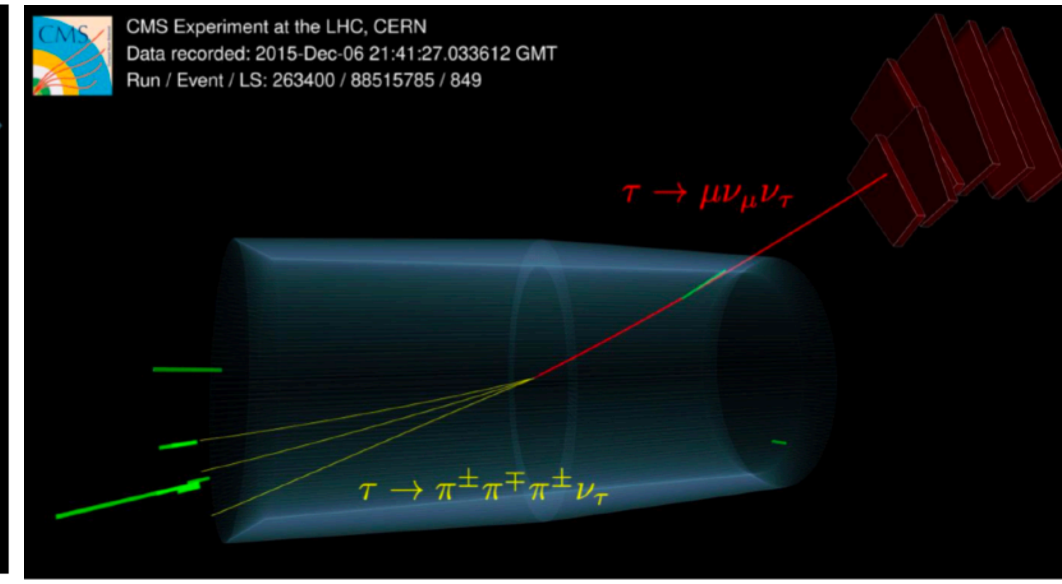
μe



μ+1 track



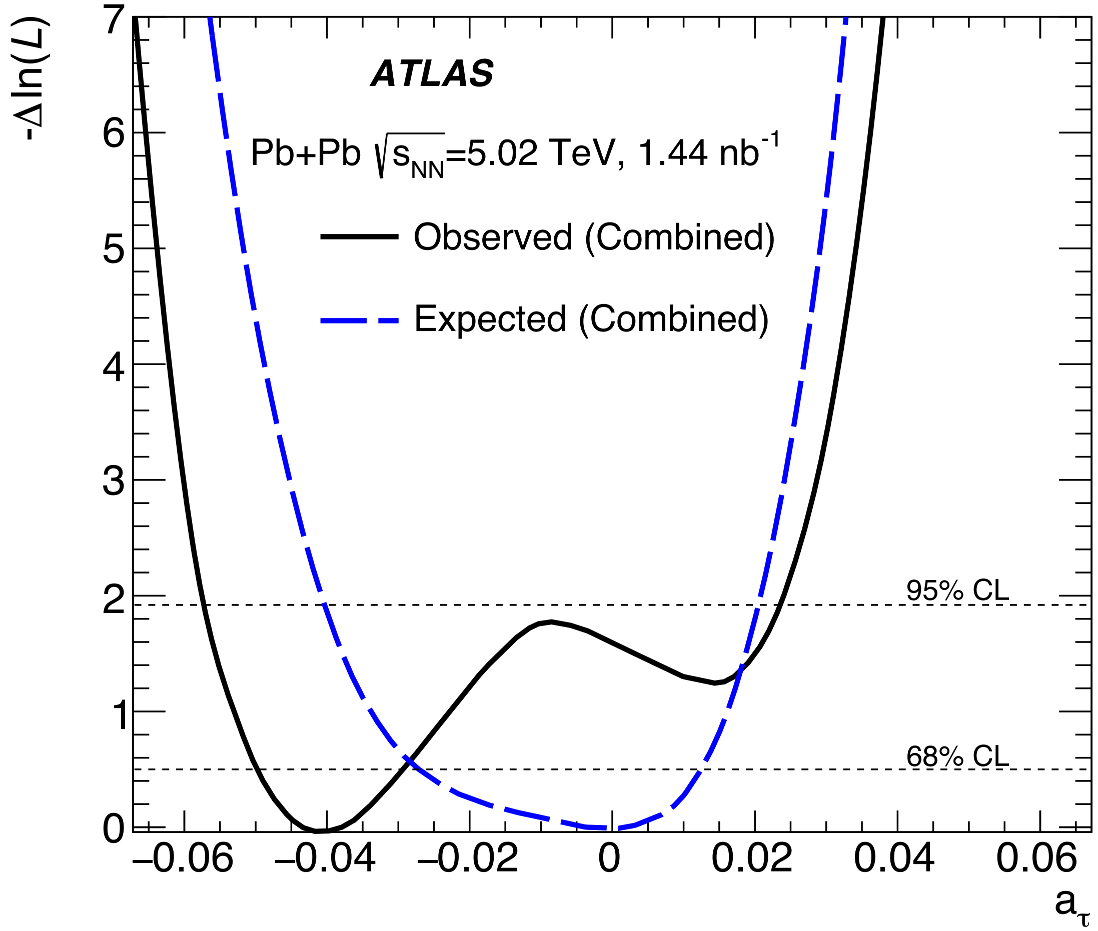
μ+3 track

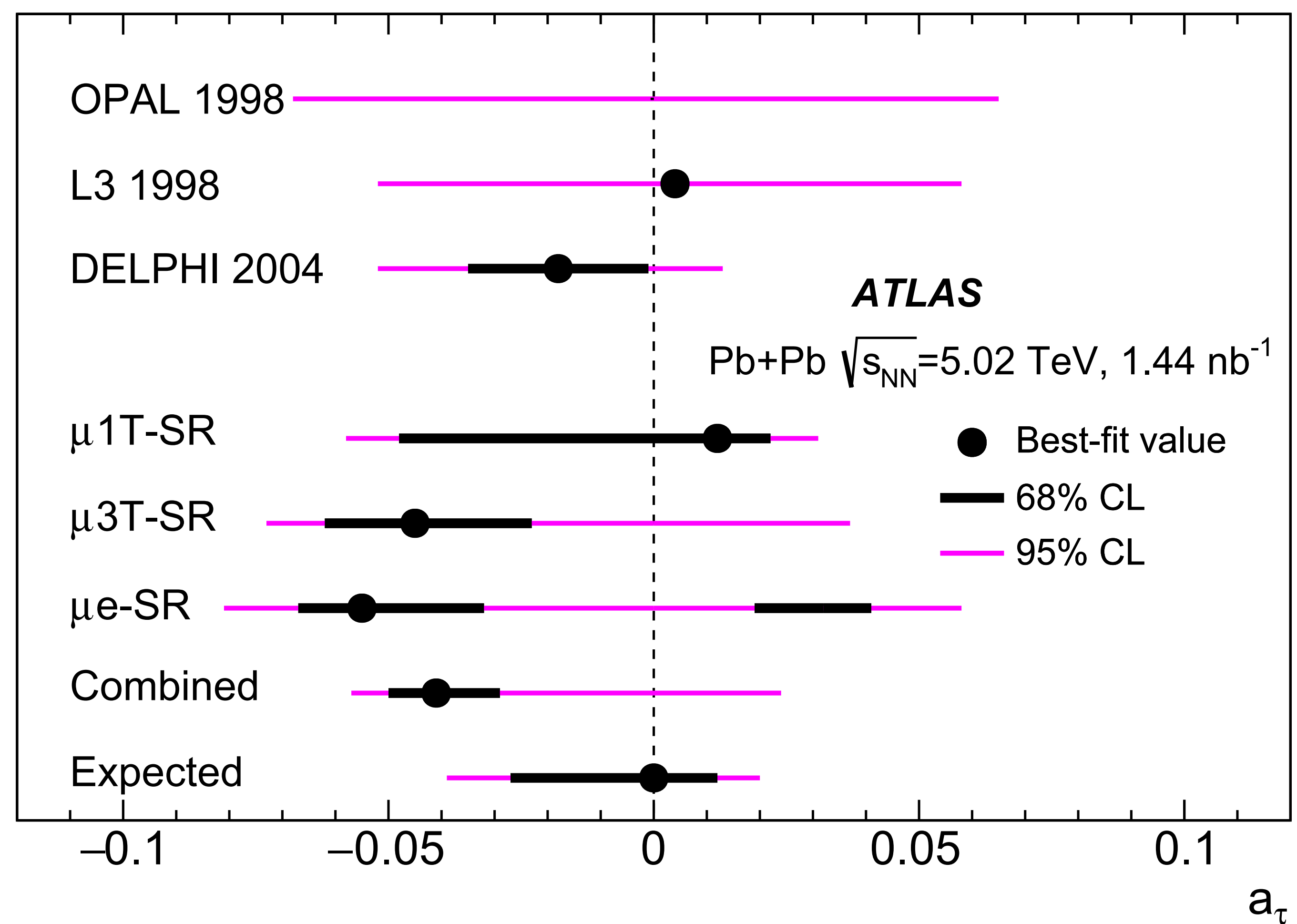


- **Anomalous magnetic moment of tau leptons $a_\tau=(g_\tau-2)/2$ sensitive to physics beyond the standard model**
  - Large mass of the tau increases sensitivity to new physics by $(m_\tau/m_\mu)^2$ relative to muon g-2 (e.g. at BNL & FNAL)

- **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*

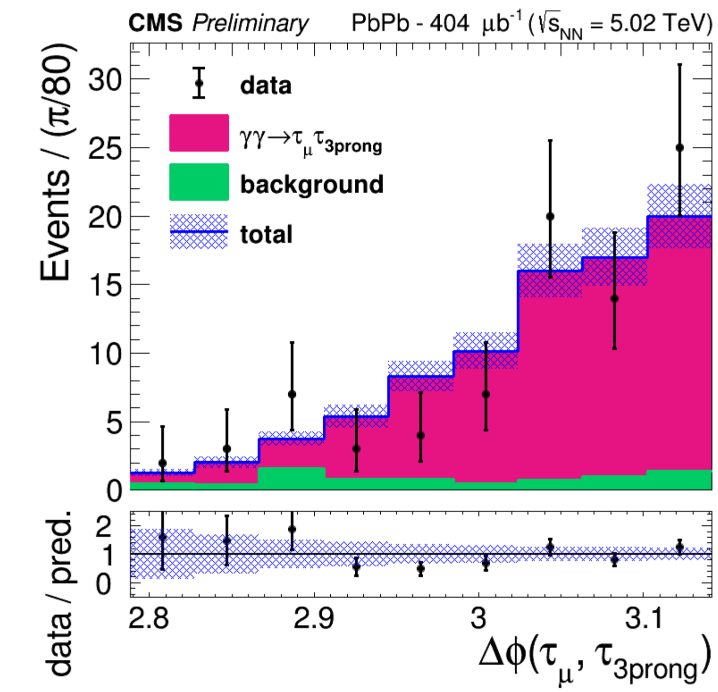
ATLAS: 3 channels

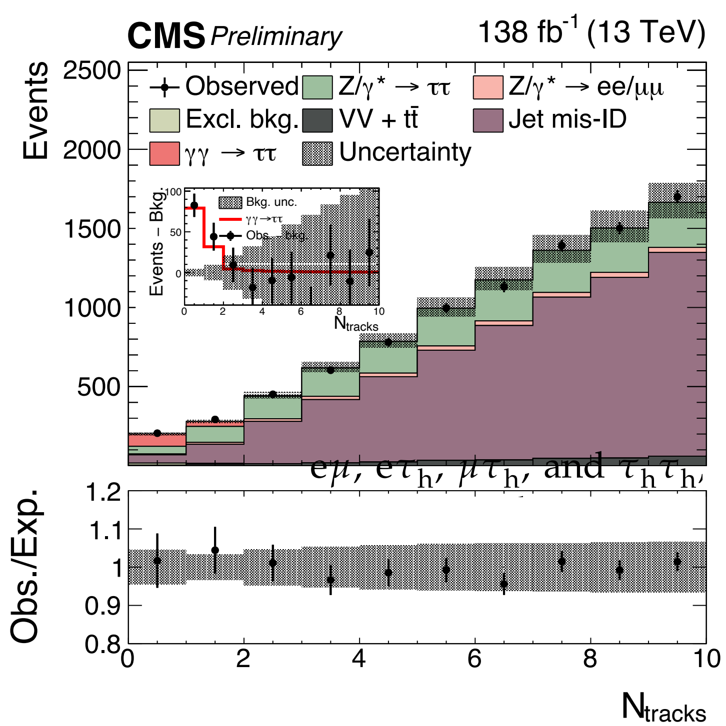


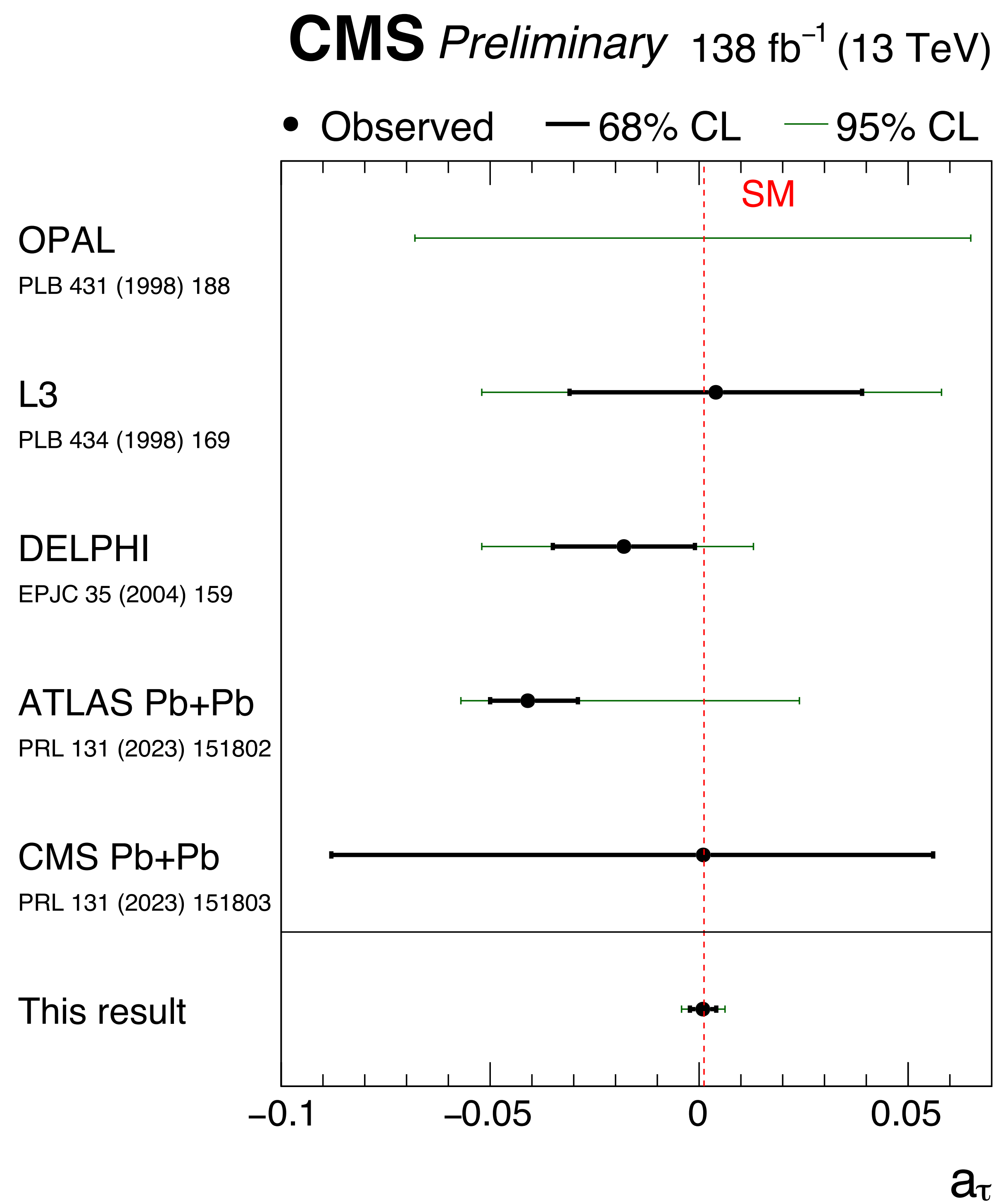


- **Observed 95% CL limits from $a_\tau \in (-0.057, 0.024)$**
  - Limits similar to that extracted from DELPHI in 2004
  - Expecting substantial improvements from Run 3 & 4 data!

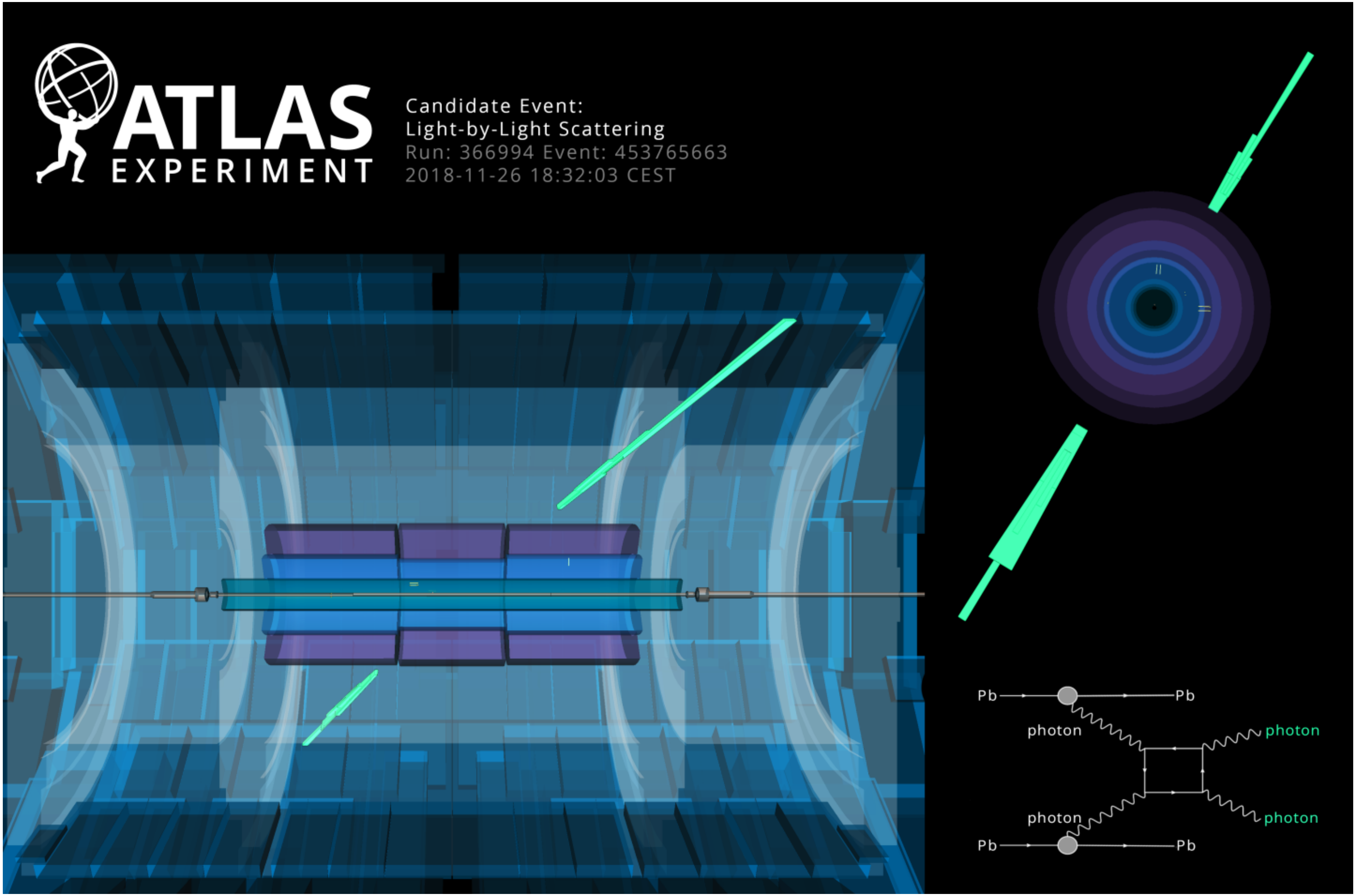
CMS results a_τ in Pb+Pb AND pp



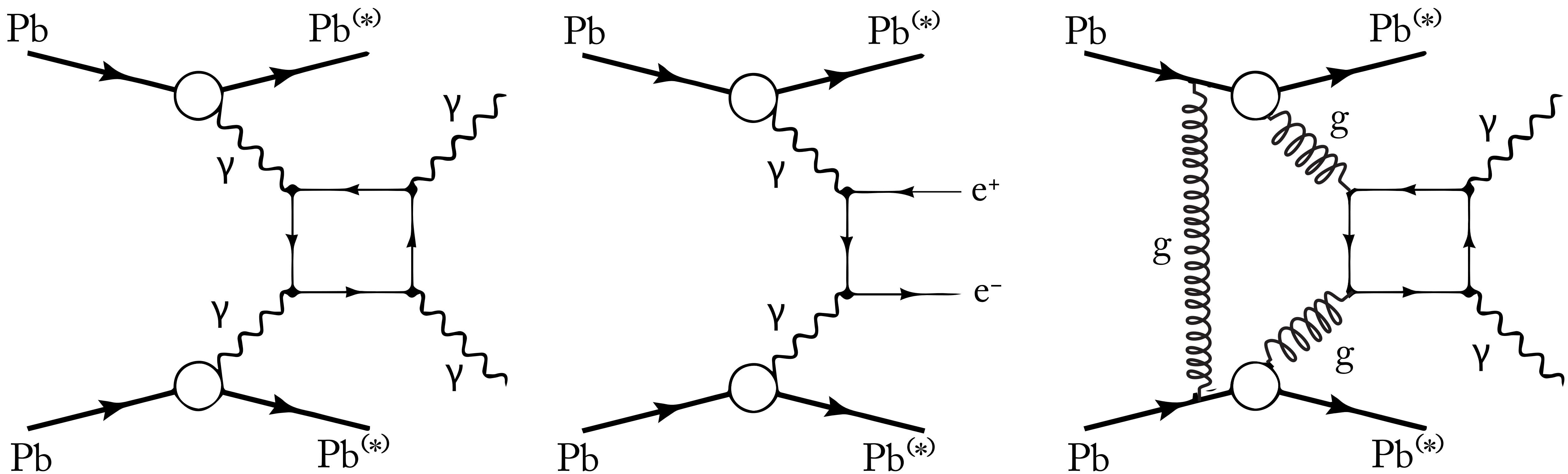




CMS made a dramatic advance by looking in the full Run 2 lumi, using a combination of leptonic and final states, using events w/ few extra tracks


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

Light by light scattering

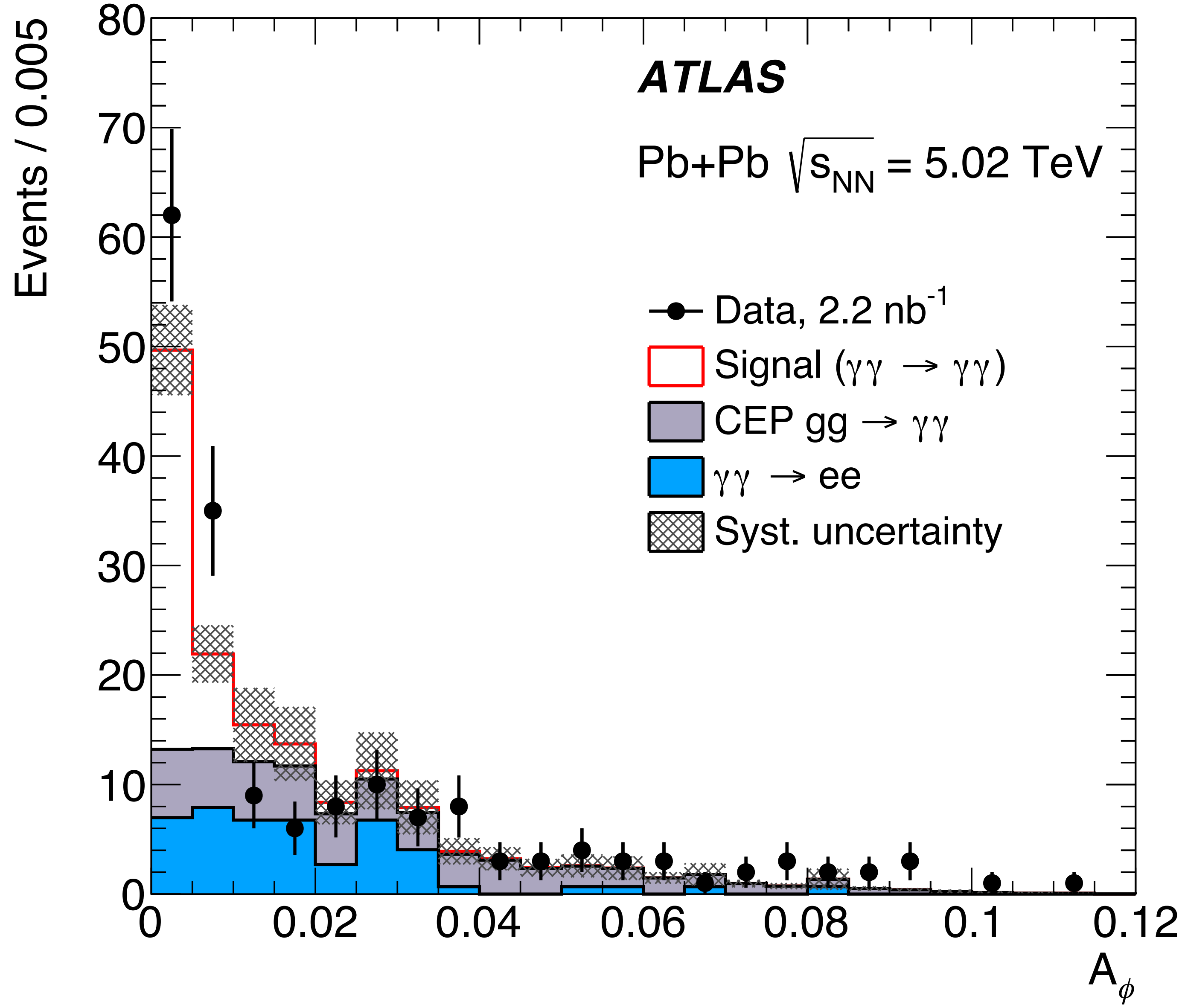


Signal process is the observation of two photons and no other activity.

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)

γγ acoplanarity

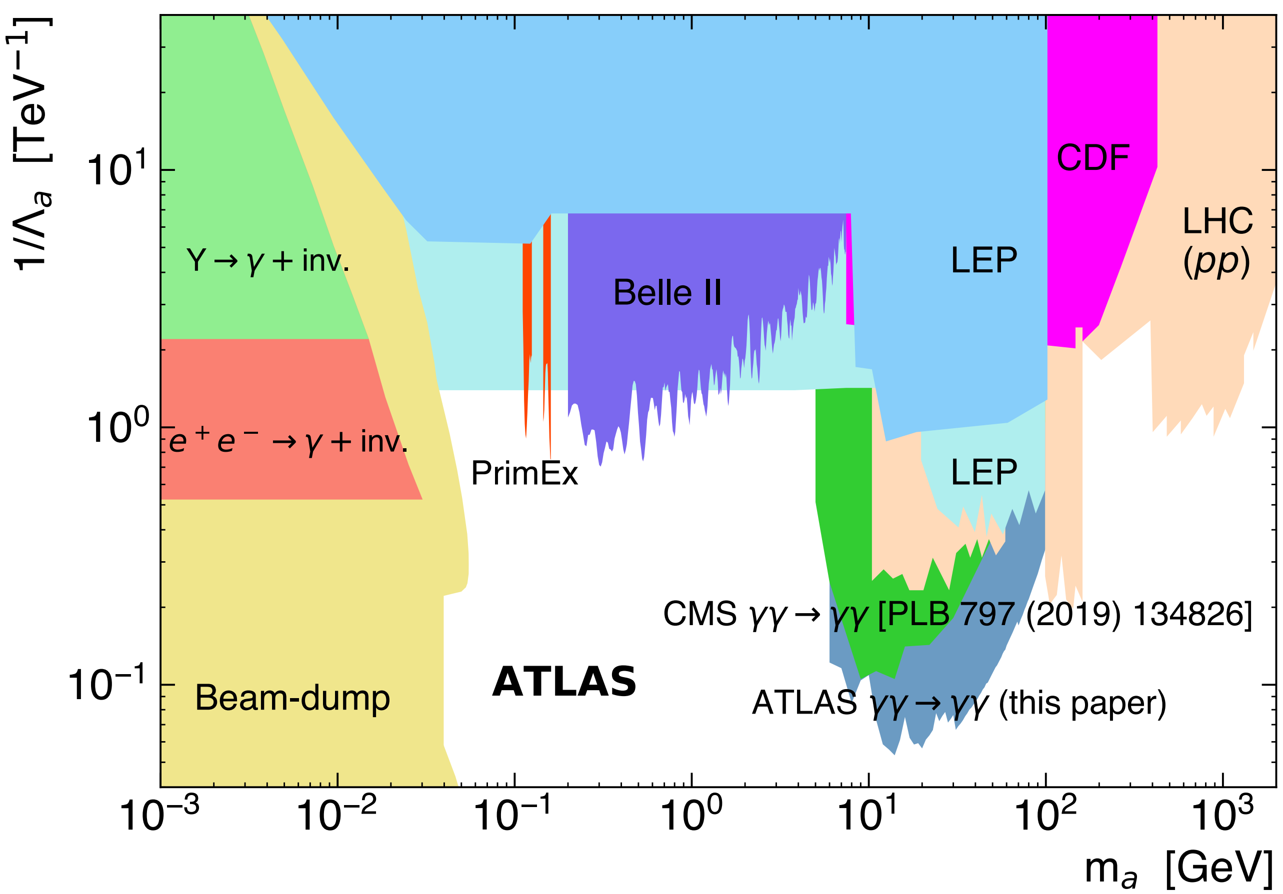


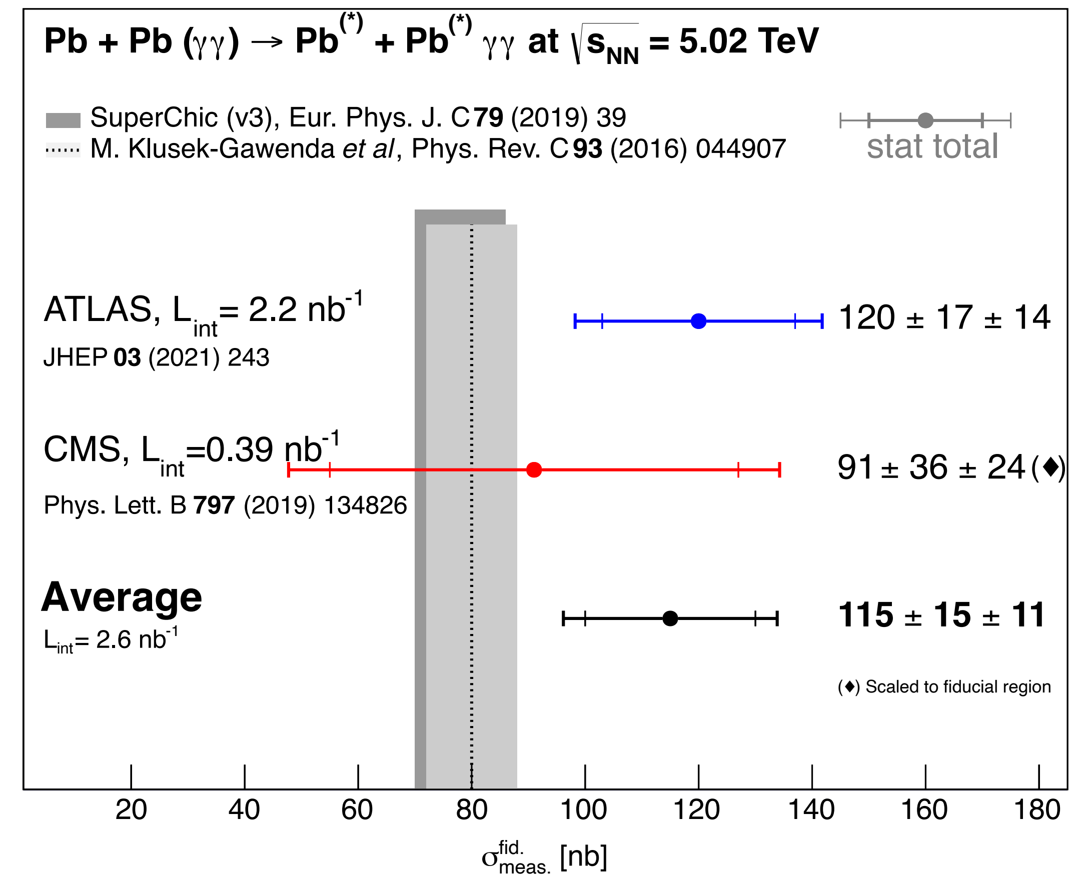
γγ acoplanarity ($A_\phi = 1 - \Delta\phi/\pi$) used to reject or enhance backgrounds: signal dominates in $A_\phi < 0.01$

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

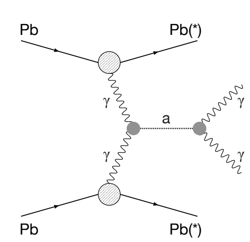
BSM physics using LbyL

Existing constraints from JHEP 12 (2017) 044





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



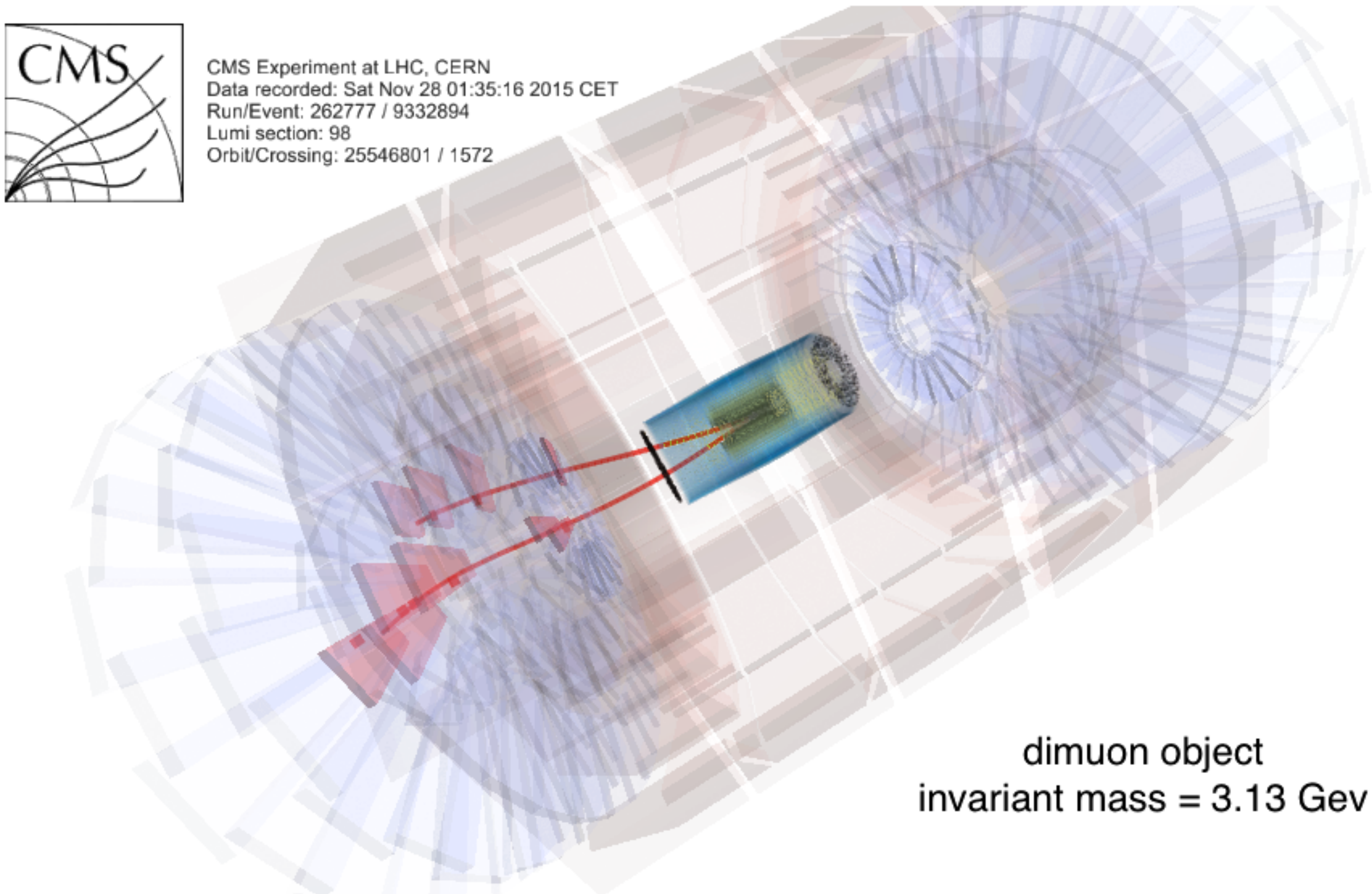
STARlight 2.0 used to generate mass distributions to test for significant excess: none found so data used to set 95% CL upper limits on cross section & coupling

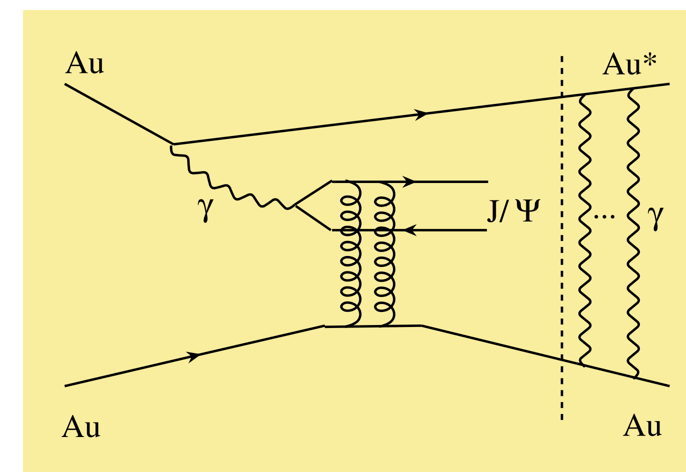
Joint working group starting to perform detailed combination measurements accounting for correlations.

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

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

spatial and momentum parton structure of nucleons and nuclei



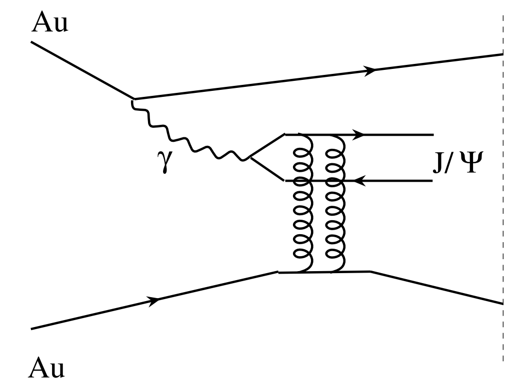


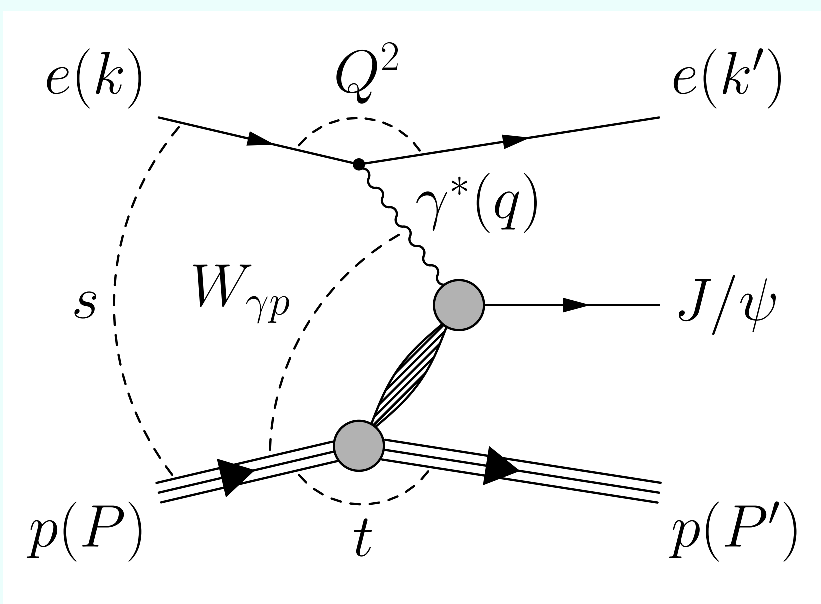
LHC experiments have a broad variety of results on vector meson (ρ,ψ,ϒ) in **Pb+Pb** (**γ+A**) and **p+Pb** (**γ+p**) collisions!

Momentum & spatial structure

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

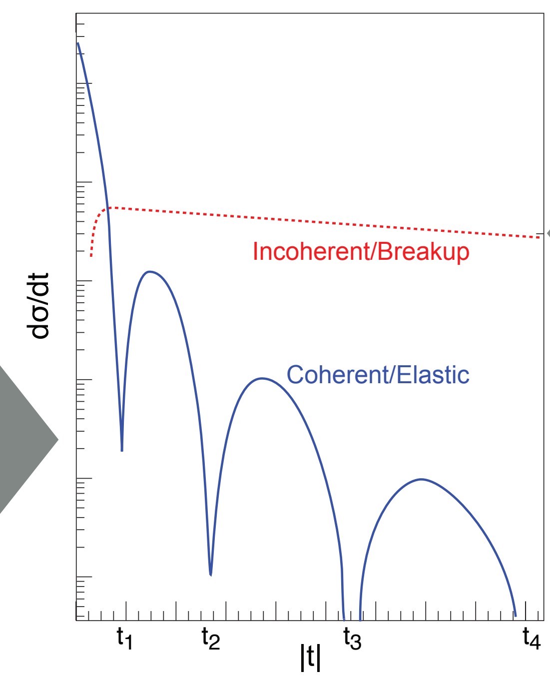
$$\frac{d^2\sigma}{dYdt} \propto \left(xG(x)\right)^2$$

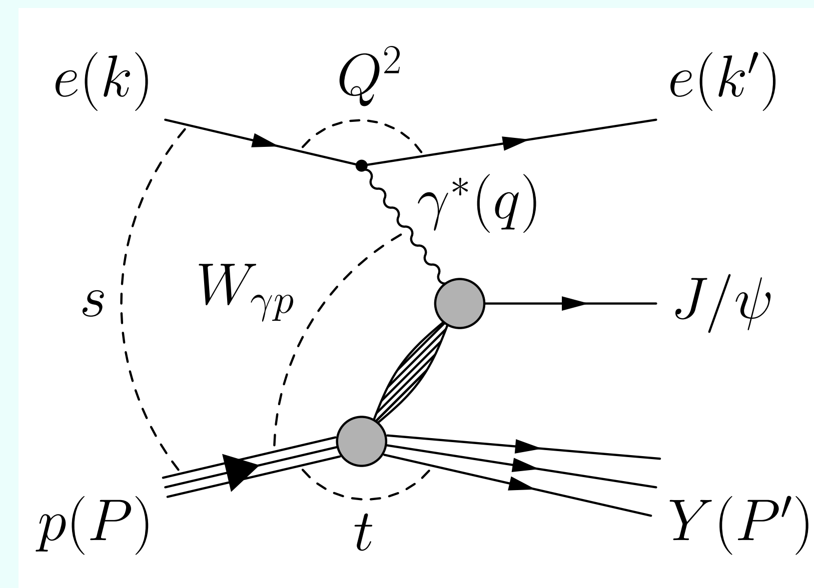




elastic production: proton survives

Schenke & Mantyasaari, 2016





incoherent production: p/A, RIP ☠️

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

elastic: sensitive to average spatial extent of object

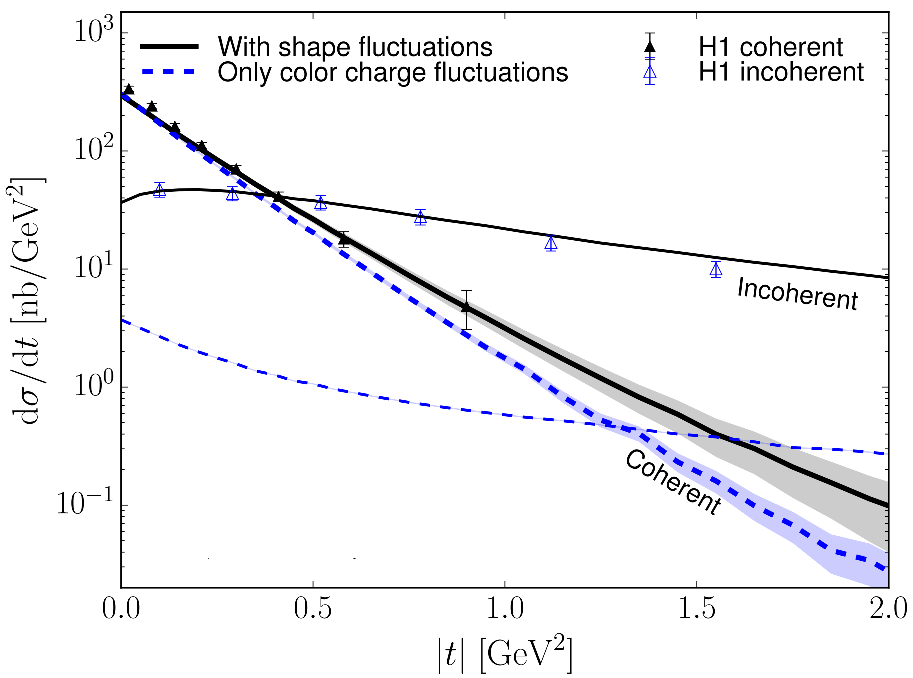
$$\sigma_{\text{incoherent}} \sim \sum_{f \neq i} |\langle f|\mathcal{A}|i\rangle|^2$$
$$= \sum_f \langle i|\mathcal{A}|f\rangle^\dagger \langle f|\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^\dagger \langle i|\mathcal{A}|i\rangle$$

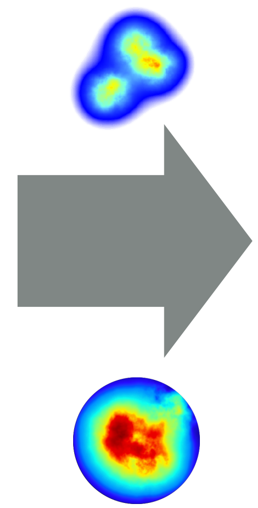
dissociative (incoherent) sensitive to fluctuations

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

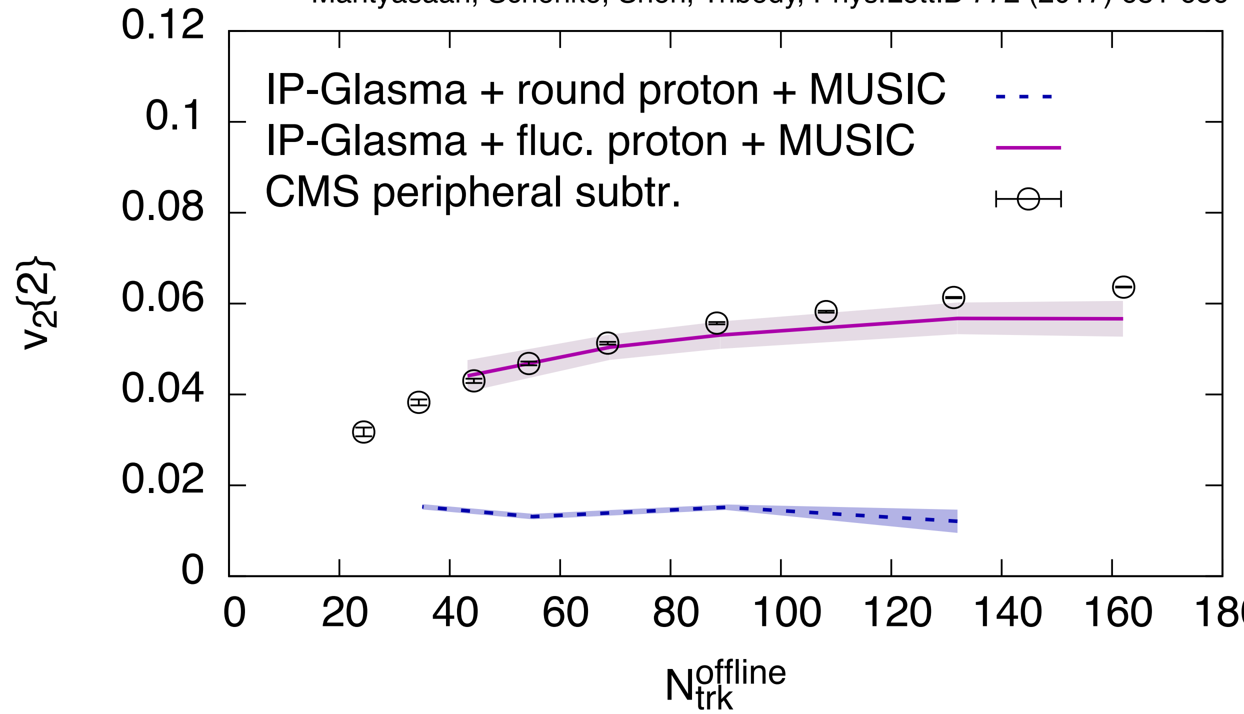
Imaging the nucleon (γ+p)

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





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



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

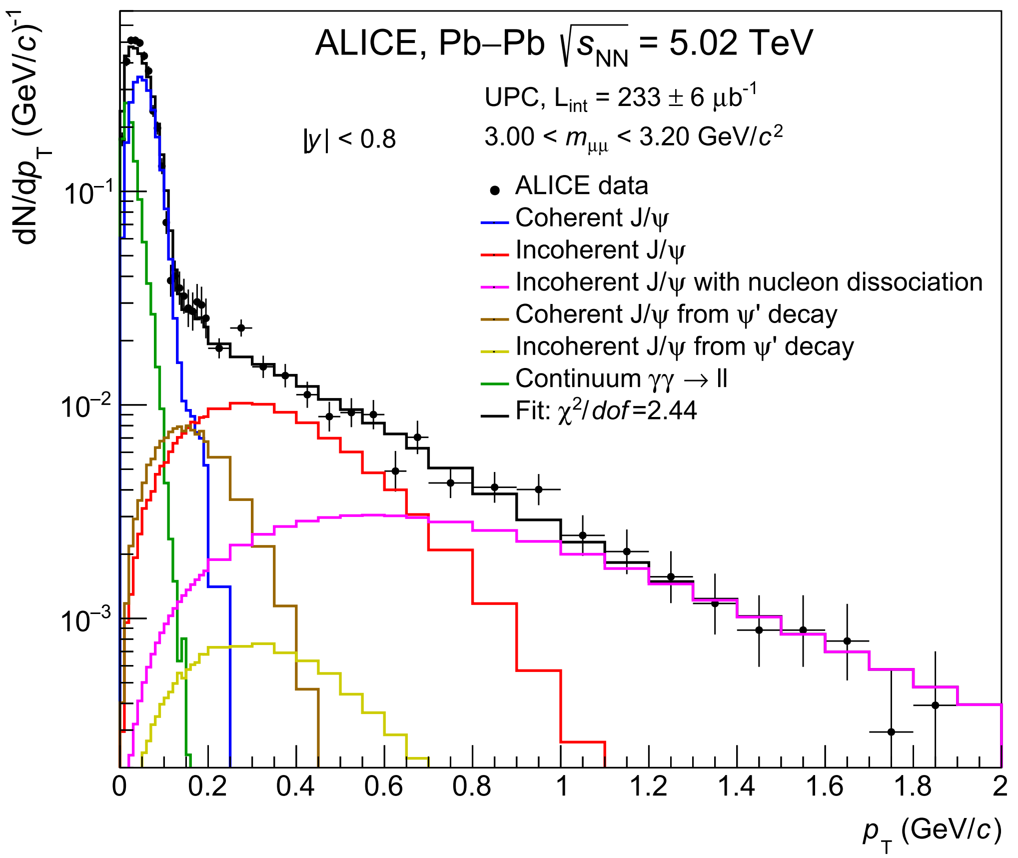
Same fluctuations have been succesfully incorporated into hydro calculations for pp

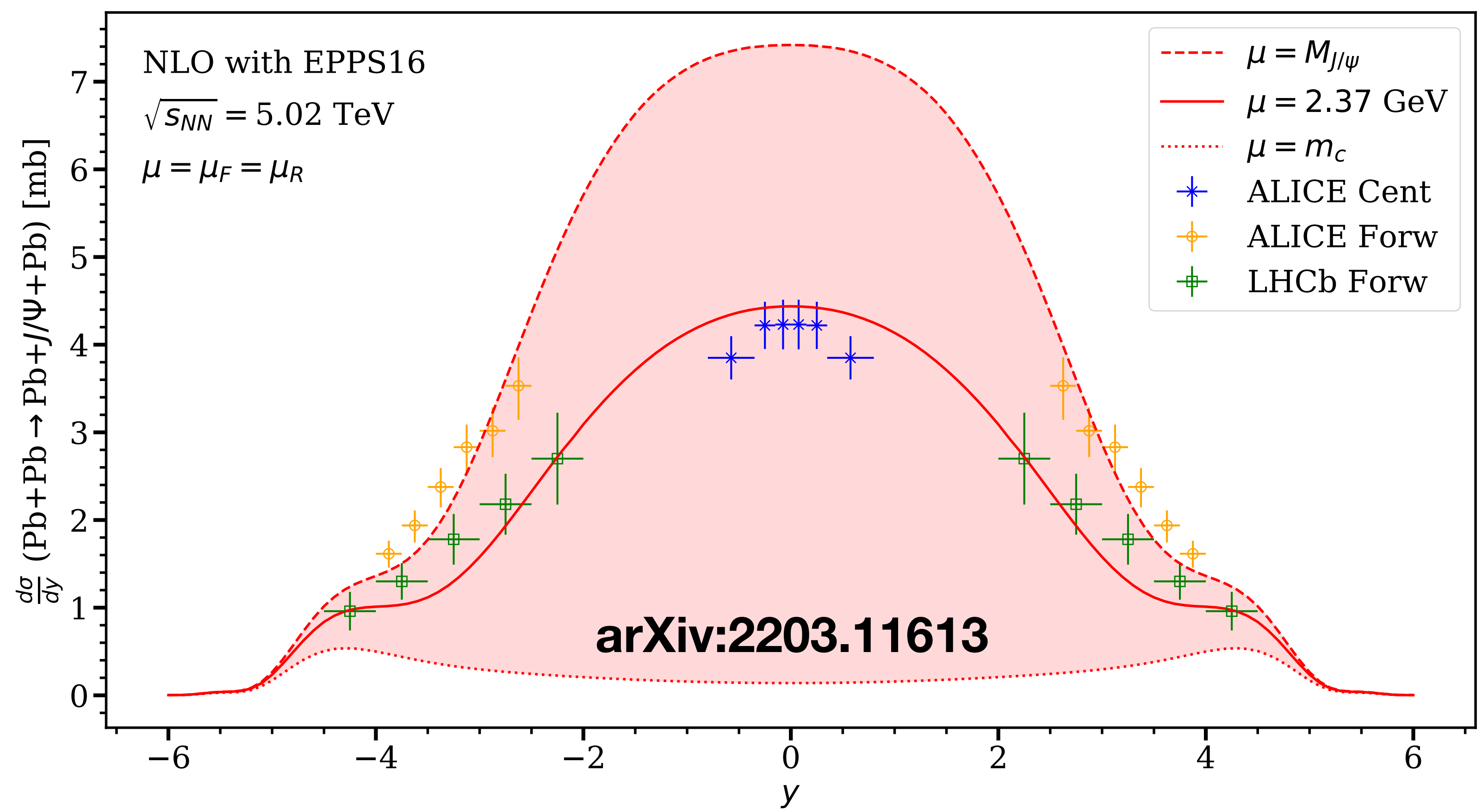
Beautiful connection between HERA (& eventual EIC) physics and the urgent needs of the RHIC/LHC heavy ion program!

J/ψ measurements & NLO theory

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

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





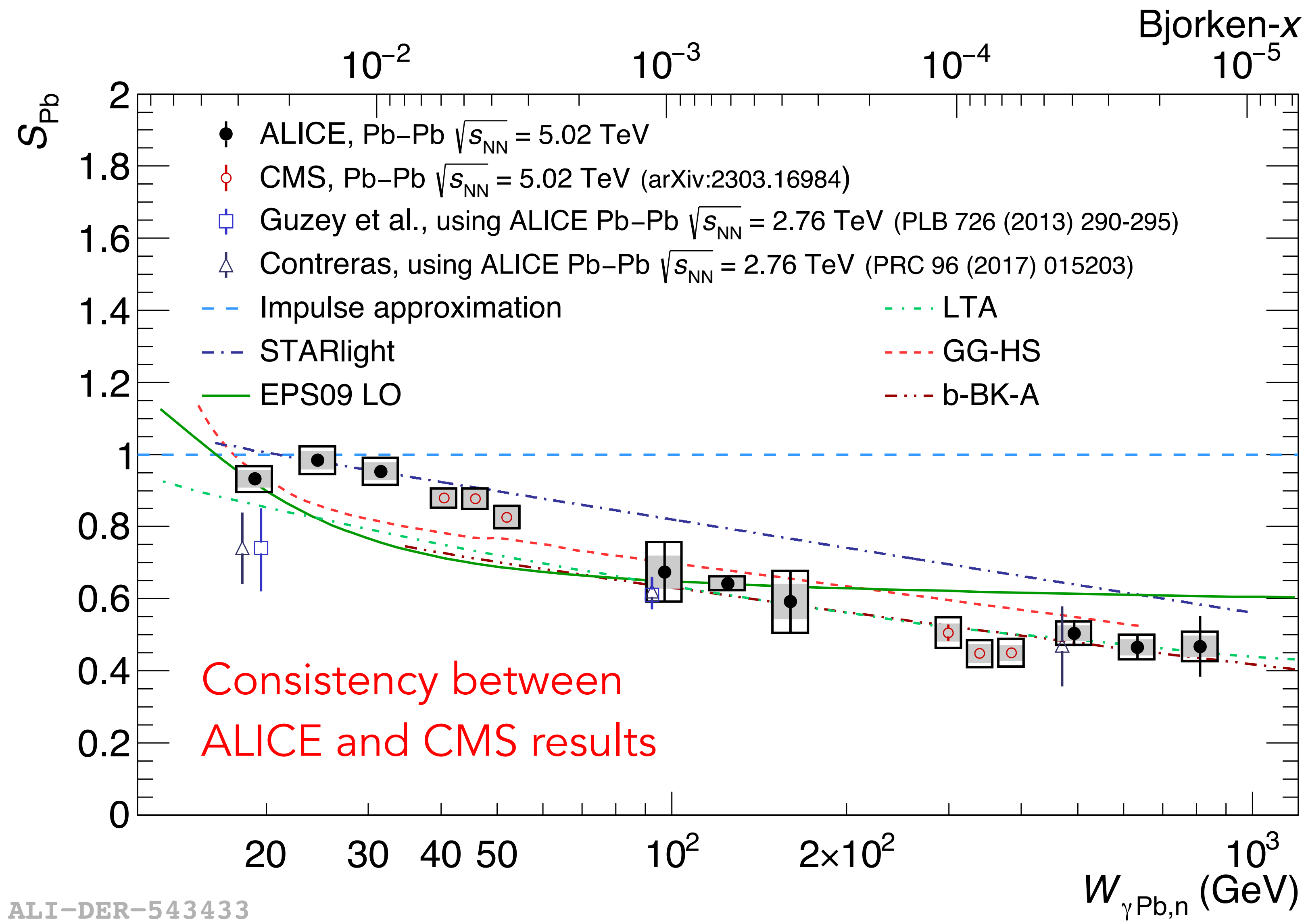
NLO cross sections being calculated, to potentially allow J/ψ data to be productively used for PDF/shadowing extraction

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

←GPDs!

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

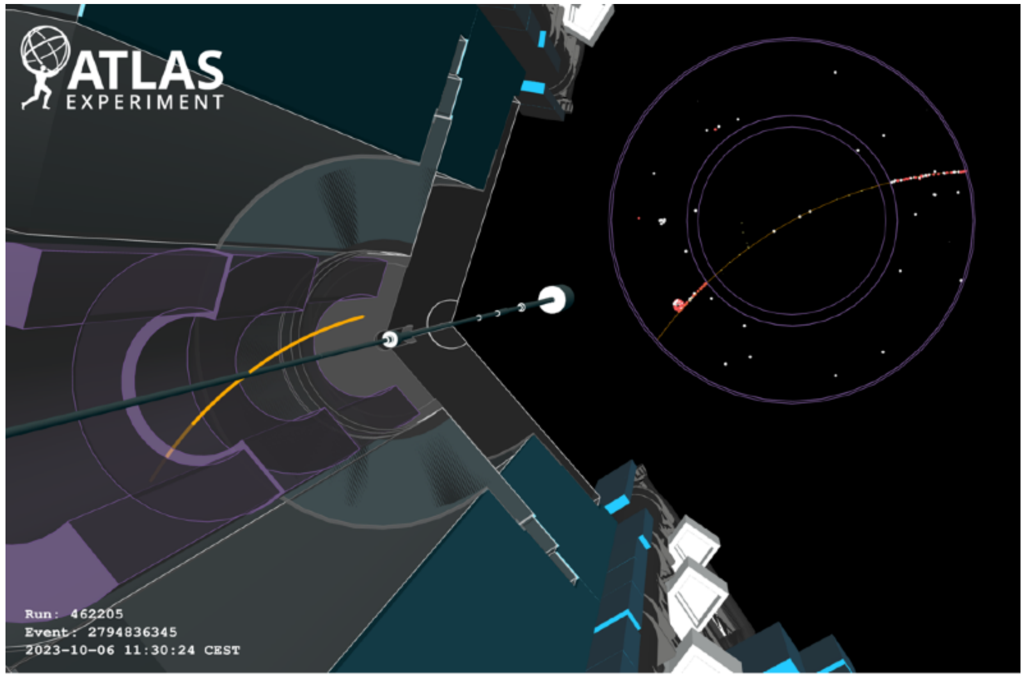
Probing nuclear shadowing with J/ψ



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

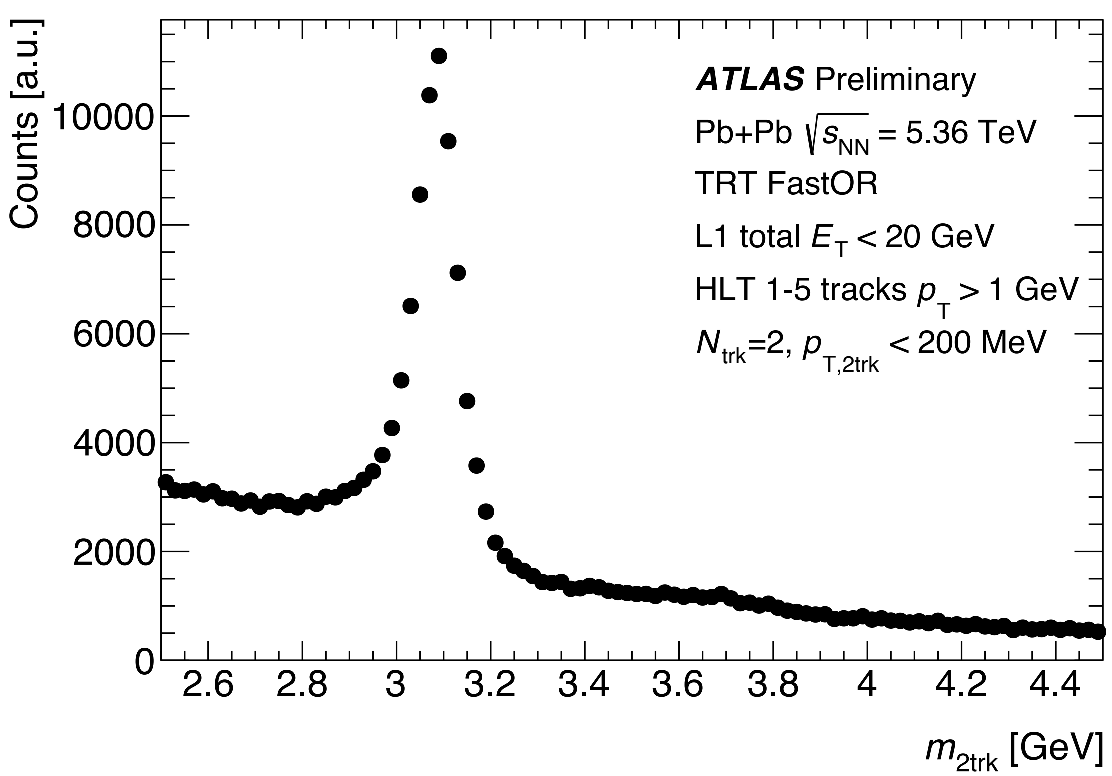
Comparison with “impulse approximation” gives empirical estimate of nuclear shadowing effects on J/ψ production

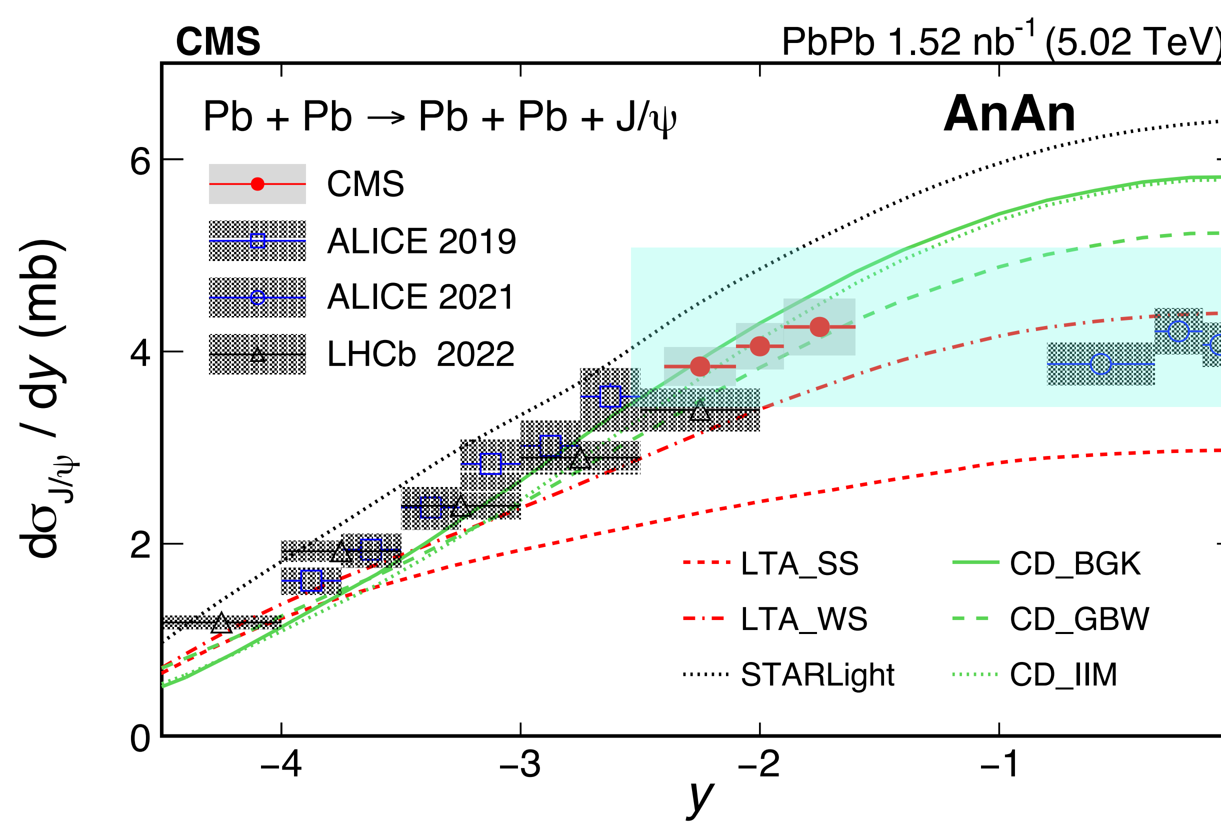
Prospects for J/Ψ in ATLAS



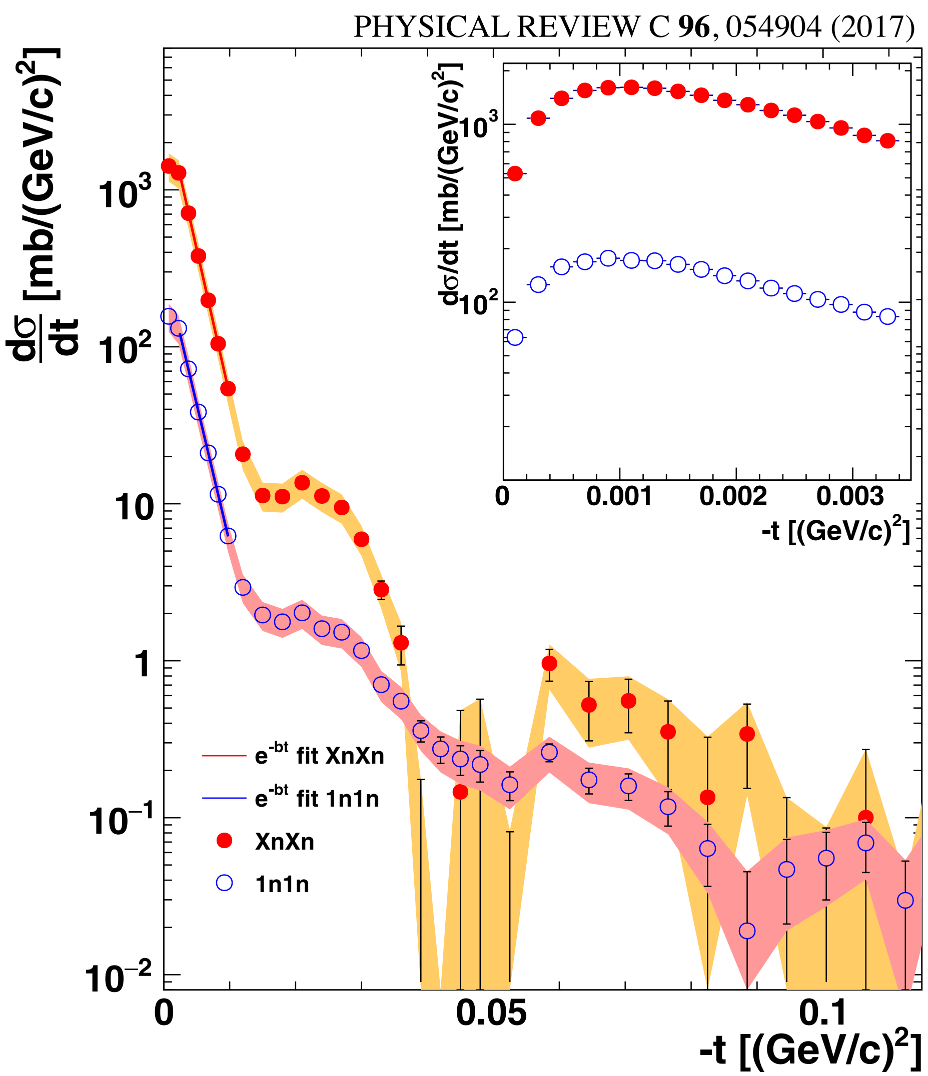
Newly commissioned TRT trigger let ATLAS accumulate large sample of exclusive J/ψ using full acceptance of our tracker.

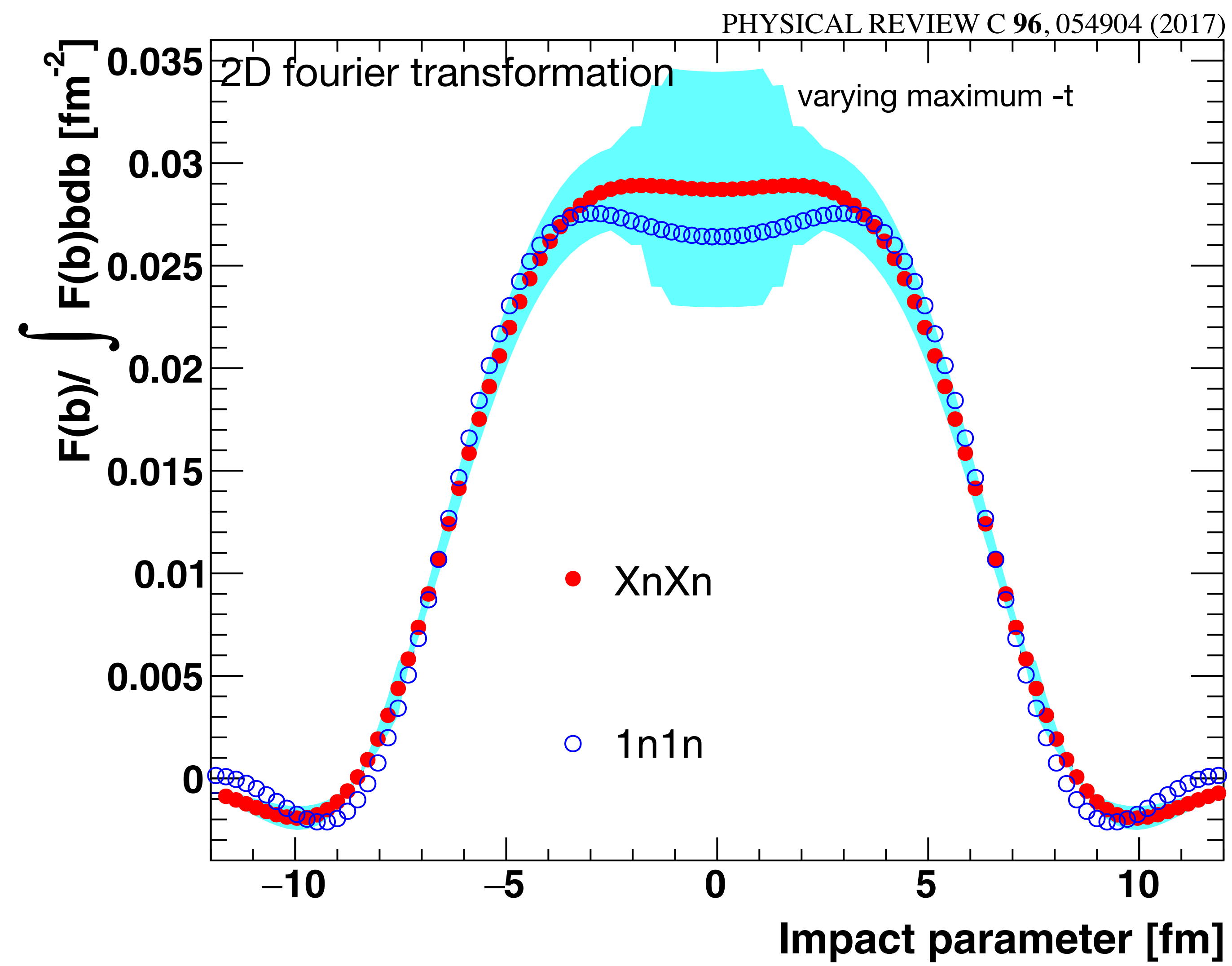
Analysis ramping up but excited about continuous coverage over wide rapidity range - should help resolve theoretical puzzles!





STAR: probing nuclear geometry w/ ρ^0



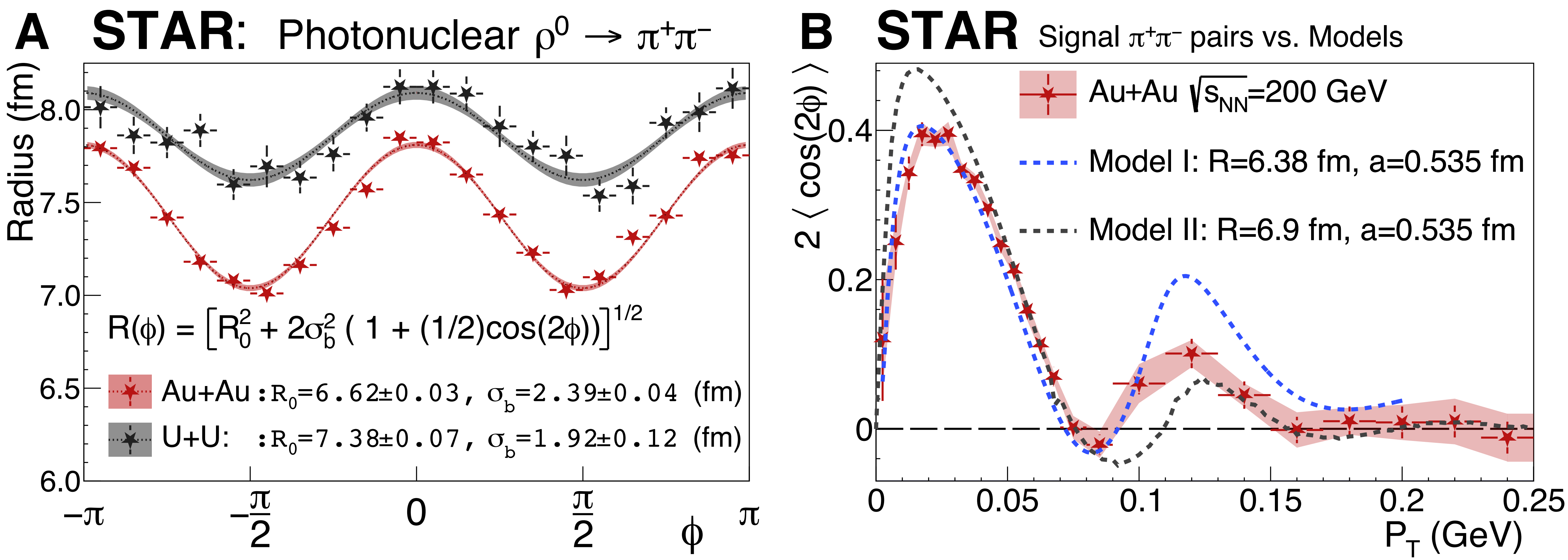


Diffractive dips in $-t = p_T^2$ observed with coherent ρ

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)

arXiv:2204.01625

STAR: coherent $\rho^0 \rightarrow \pi\pi$

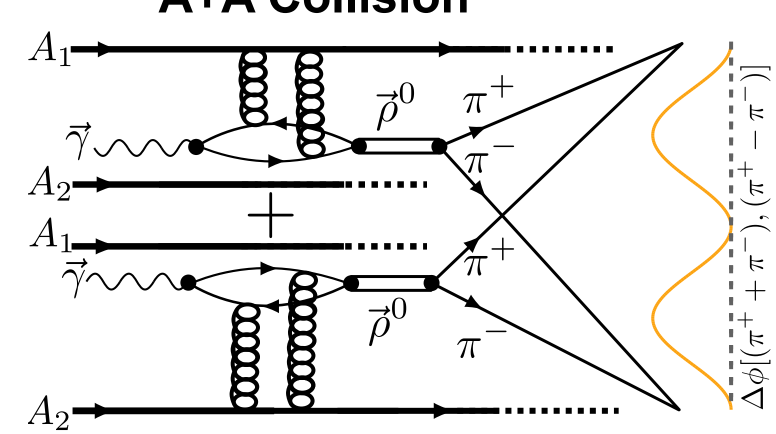


Just as with dileptons, polarization offers a unique handle on imagine the nucleus with vector mesons

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

Linear polarized photons lead to distinct interferometric effects in A+A (not in p+A) which are also sensitive to nuclear geometry (via fits to -t distributions)

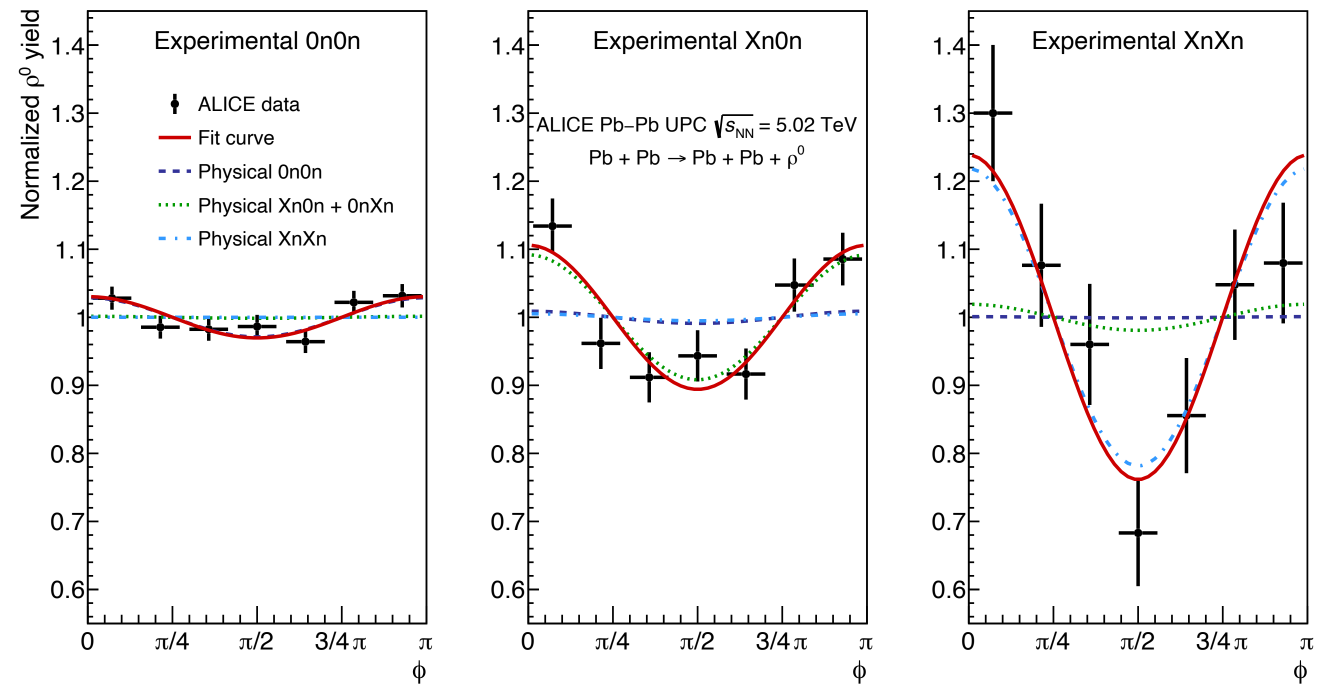
A+A Collision



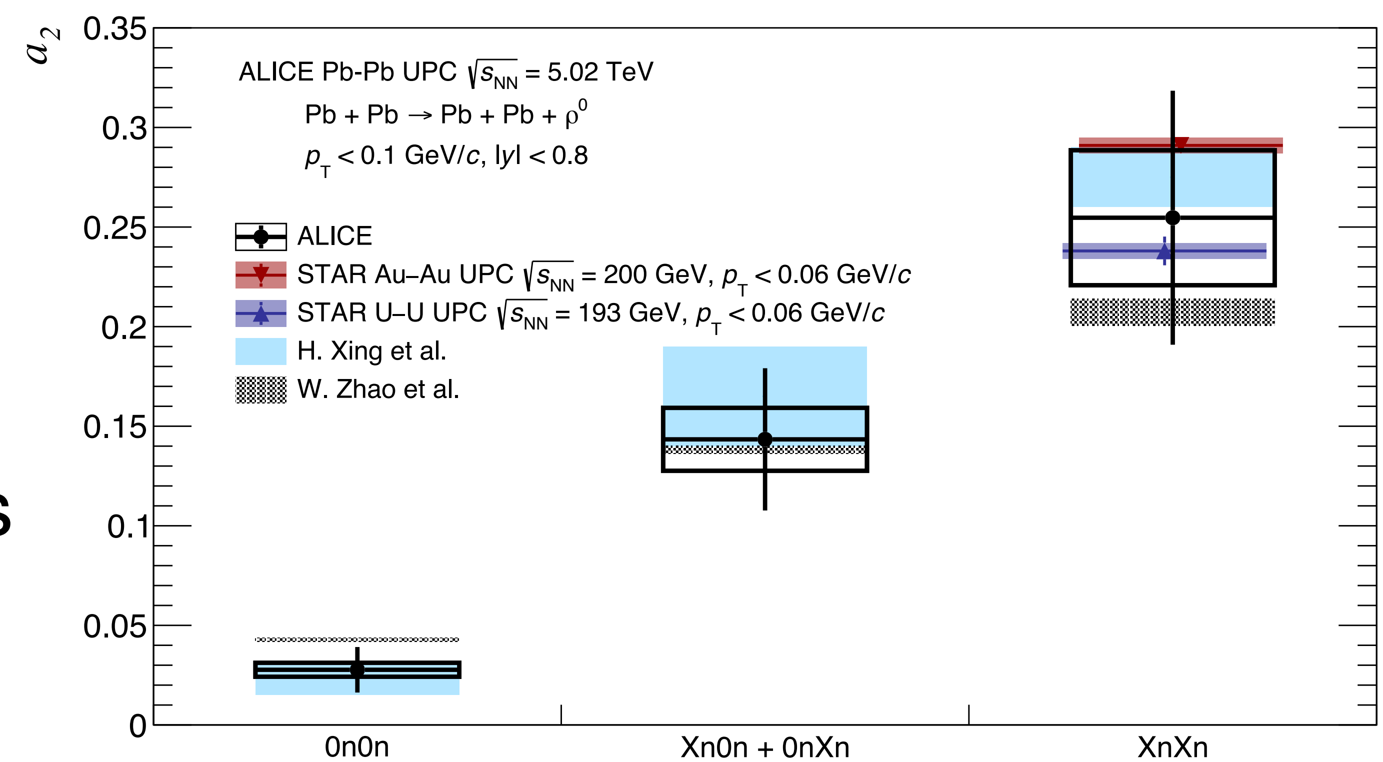
Isaac Upsal, Tues parallel
Yajin Zhou, Thurs parallel

Impact parameter dependence from ALICE

arXiv:2405.14505

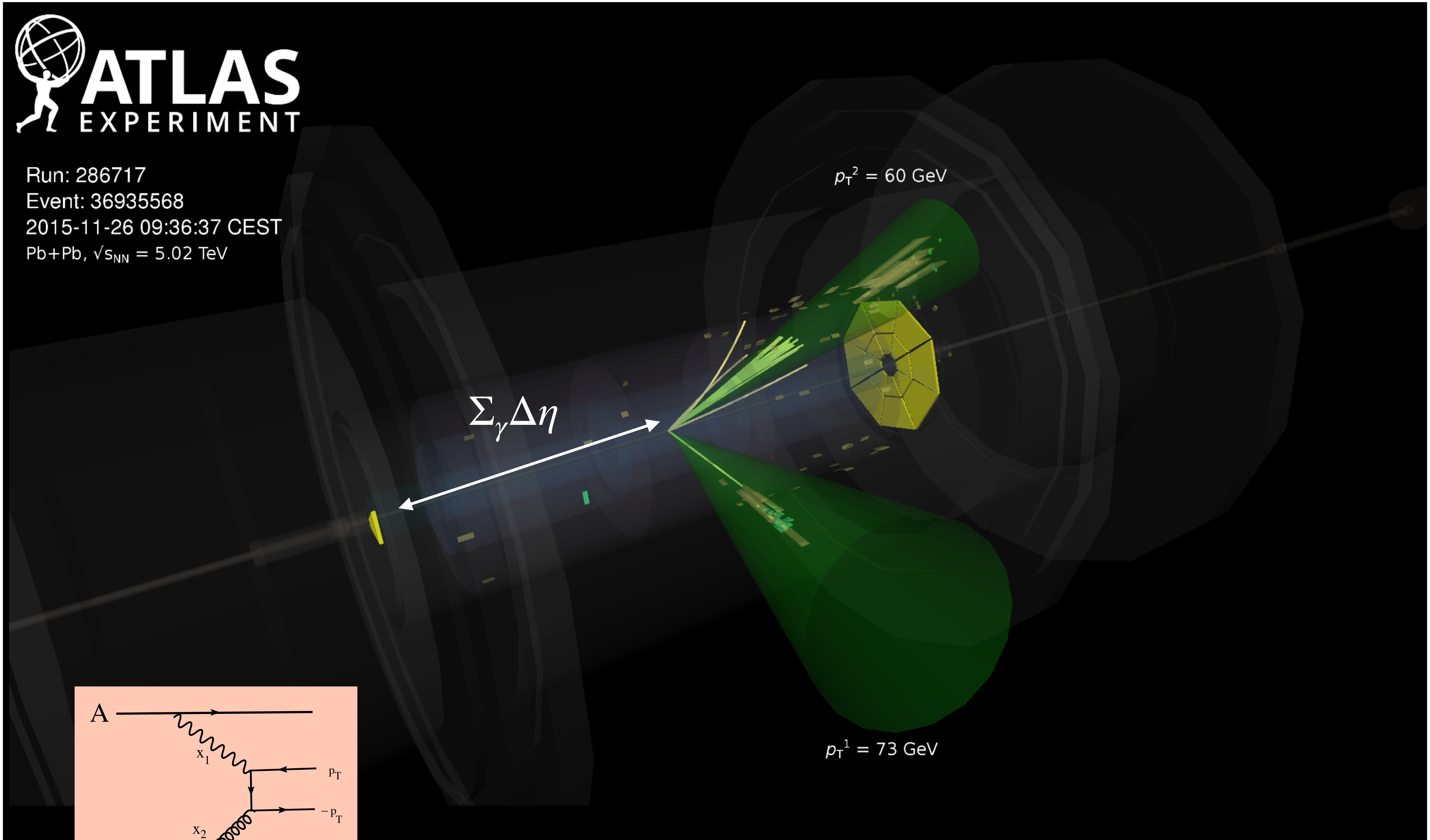


Brand new result from ALICE on these quantum interference effects as a function of “centrality”!



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



use jets to directly probe nuclear PDFs

Xn0n topology enhances events, verified by “gap”

ATLAS: Triple differential UPC dijets

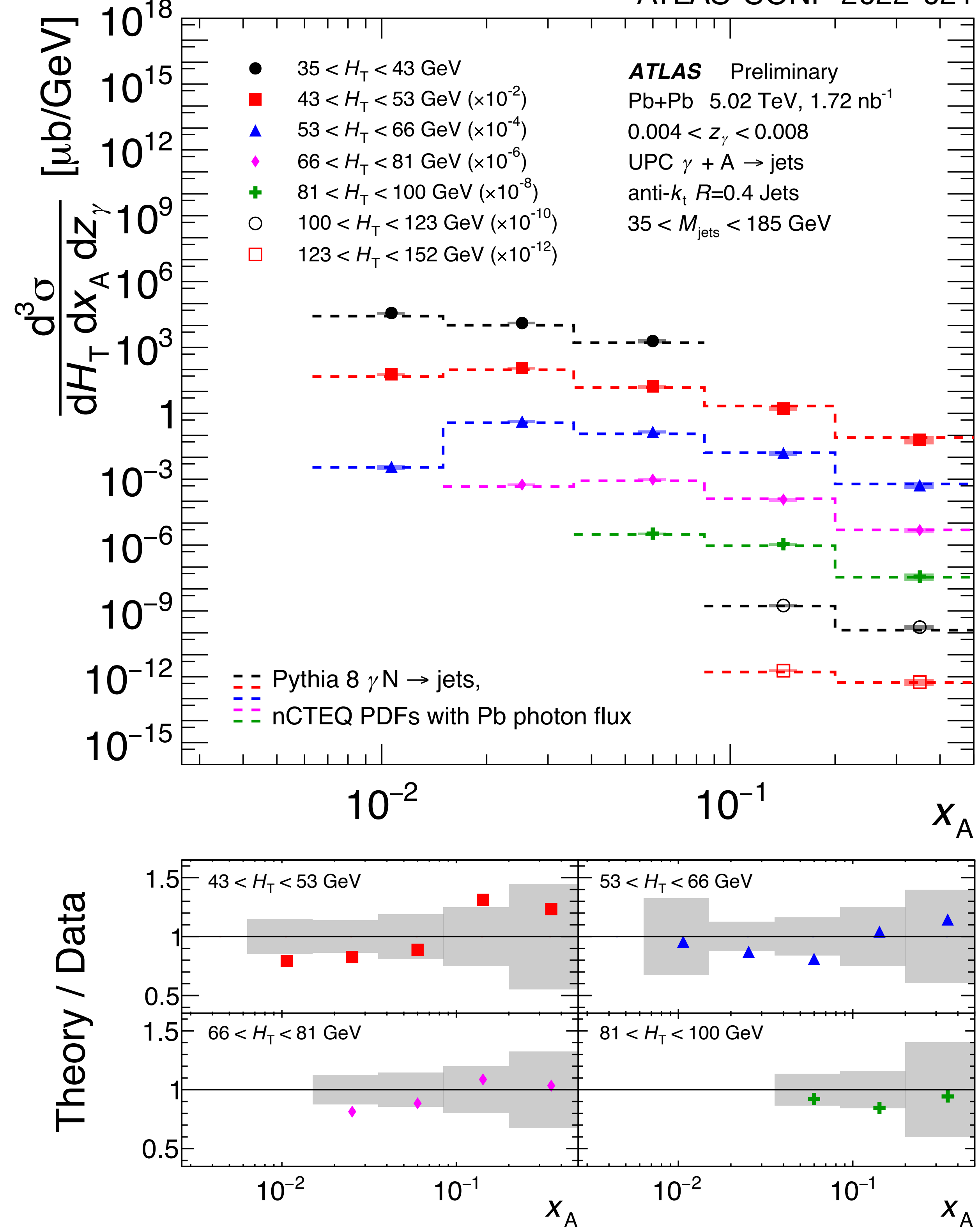
- **Use ZDC as part of primary trigger**
  - Require gaps to ensure photonuclear topology
- **Use jets to define kinematic variables akin to variables used in deep inelastic scattering**

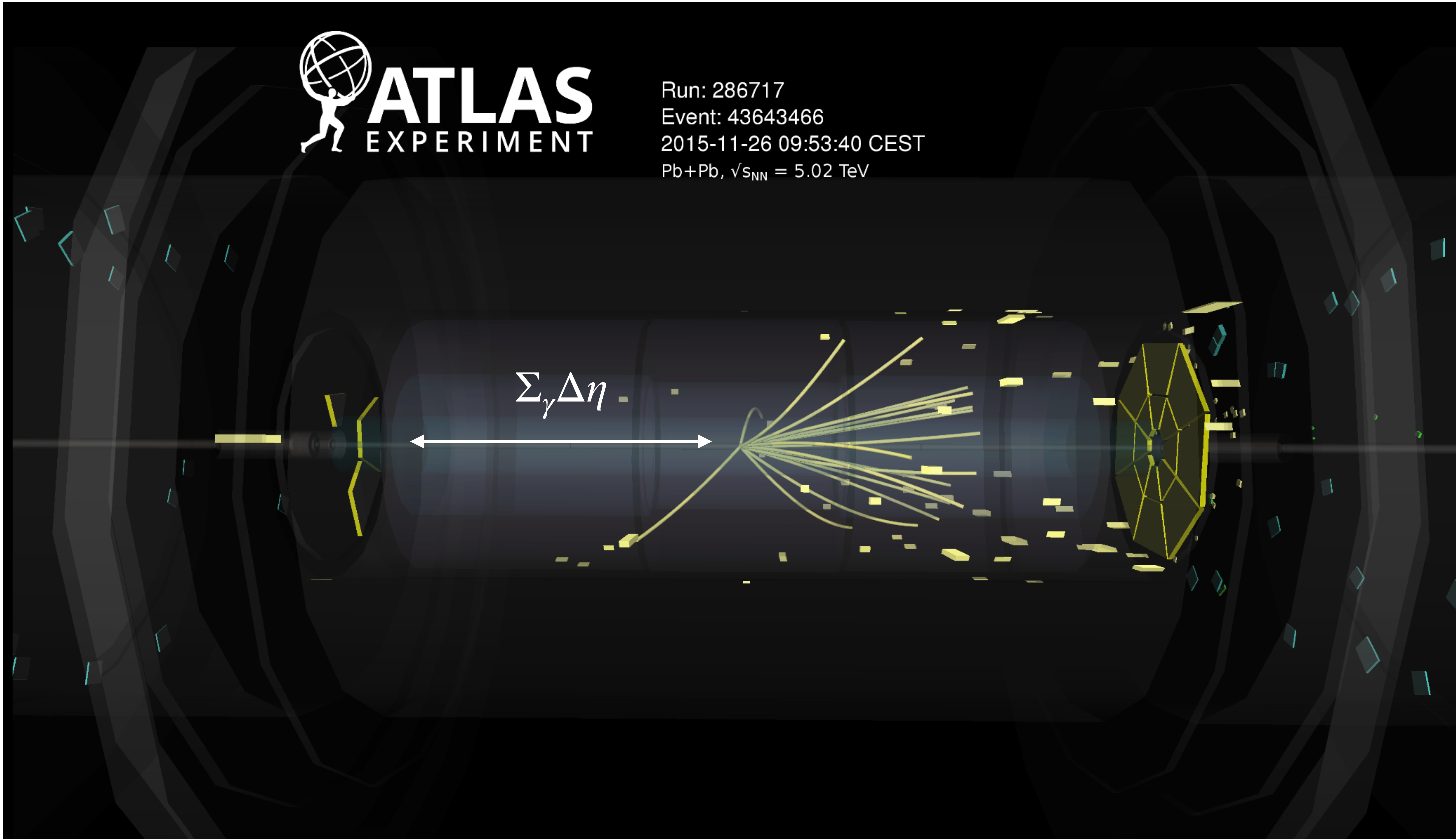
$$H_T \equiv \sum_i p_T^i \qquad x_A \equiv \frac{M_{jets} e^{-y_{jets}}}{\sqrt{s_{NN}}} \qquad z_\gamma \equiv \frac{M_{jets} e^{+y_{jets}}}{\sqrt{s_{NN}}}$$

"Q2" "xy"

- **Selections on zγ 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
- **Final results are complete and paper is in preparation!**

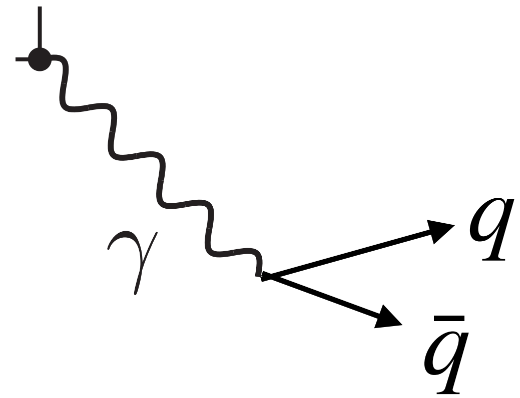
ATLAS-CONF-2022-021

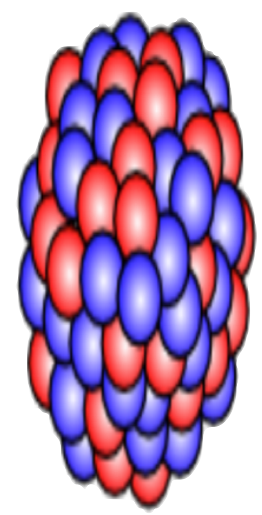




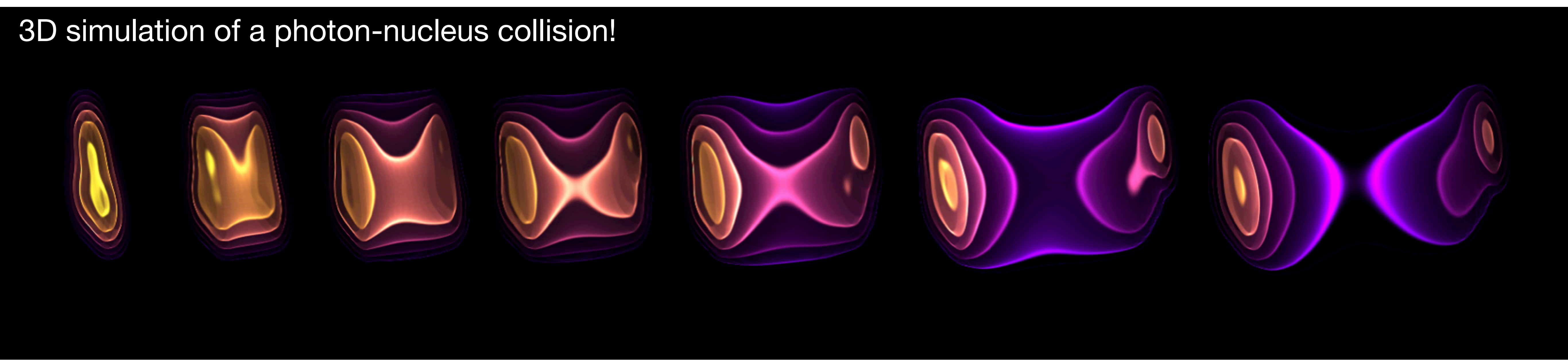
soft inelastic collisions are typically modeled using VDM: ρ+A
does a “small” hadronic system show collective behavior like p+A & pp?

3D flow in photon-nucleus collisions?





photons interact hadronically via
fluctuations in quark-antiquark pair

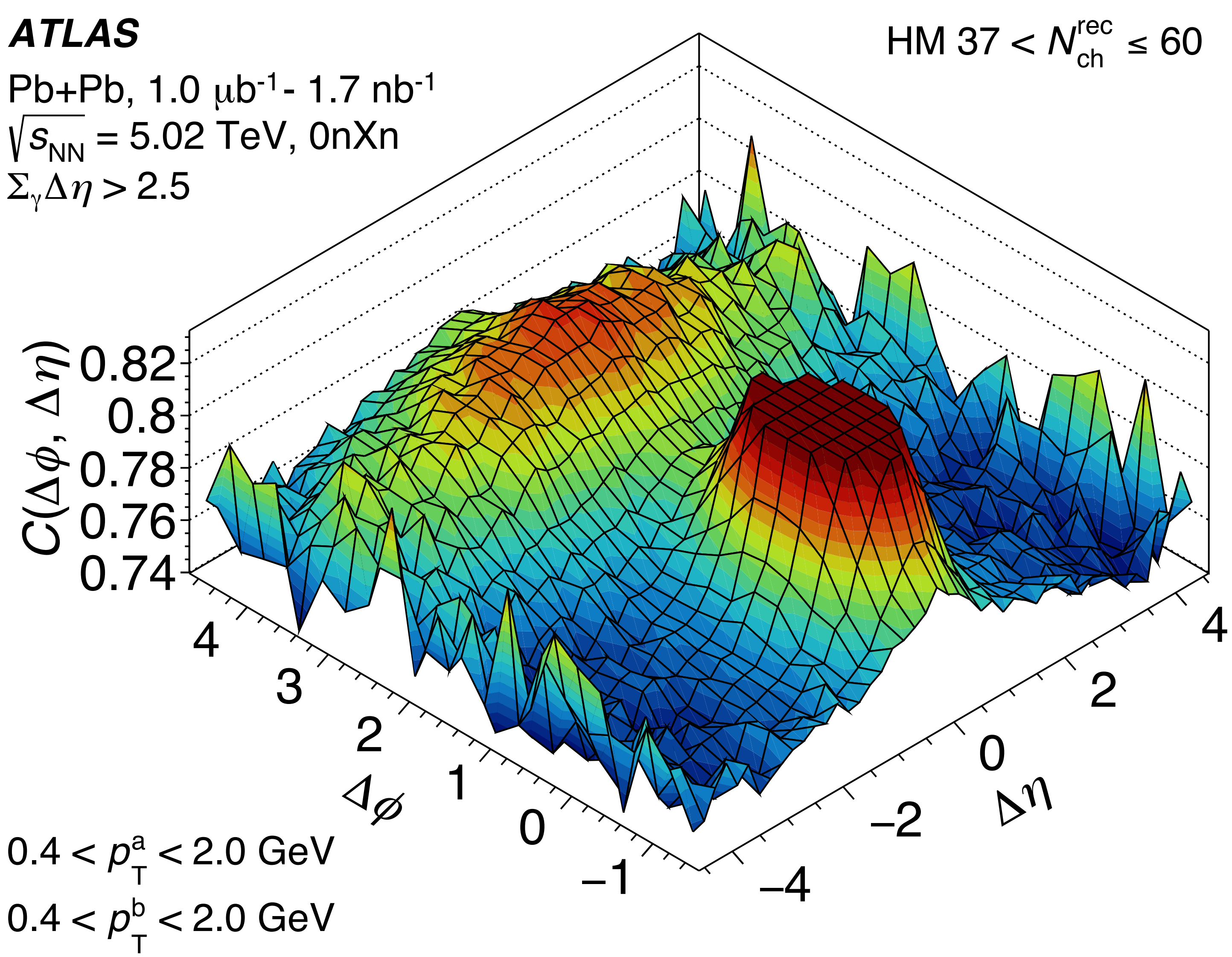


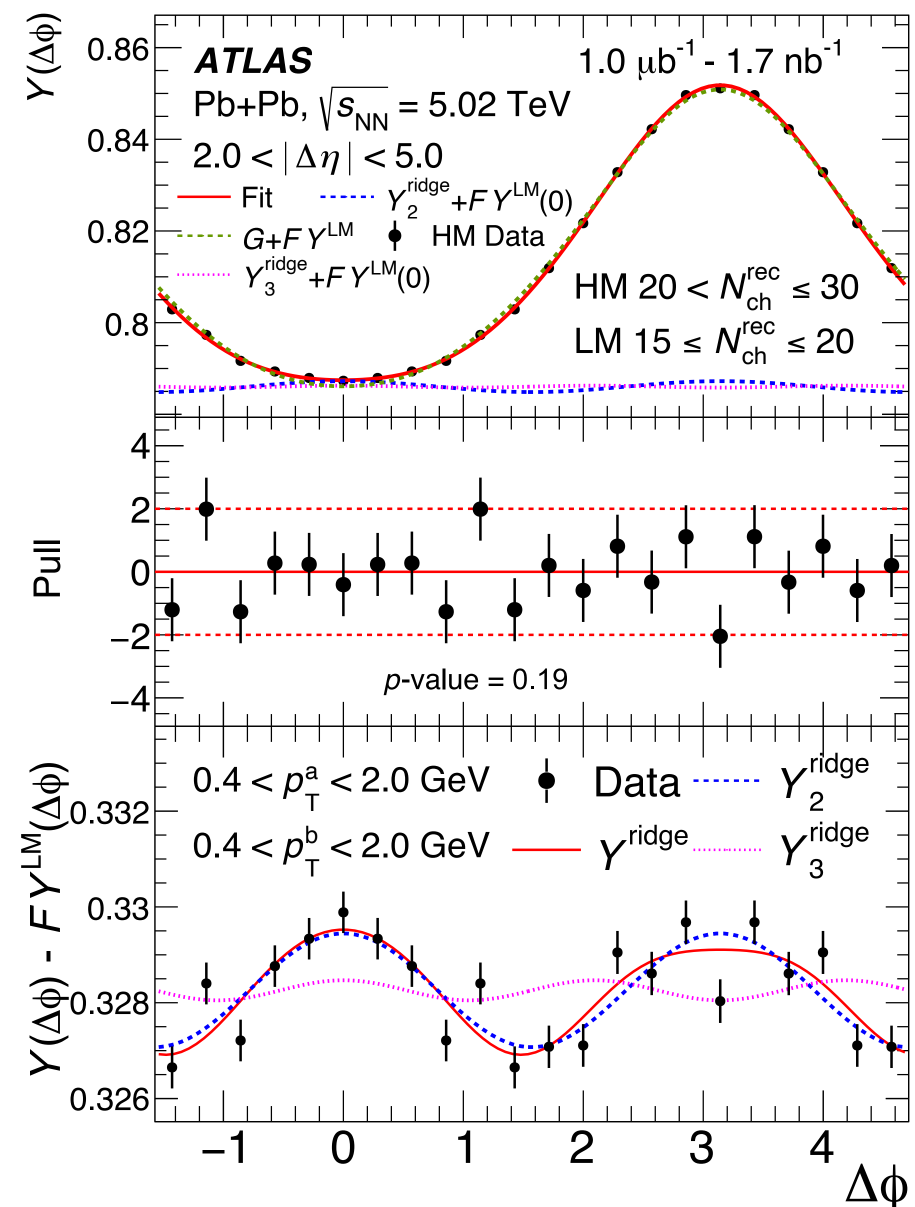
Does this system show “flow” like in heavy ions or proton-proton?
Simulations suggest possible, but need to work in full 3D!

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

Phys. Rev. C 104, 014903 (2021)

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

Phys. Rev. C 104, 014903 (2021)

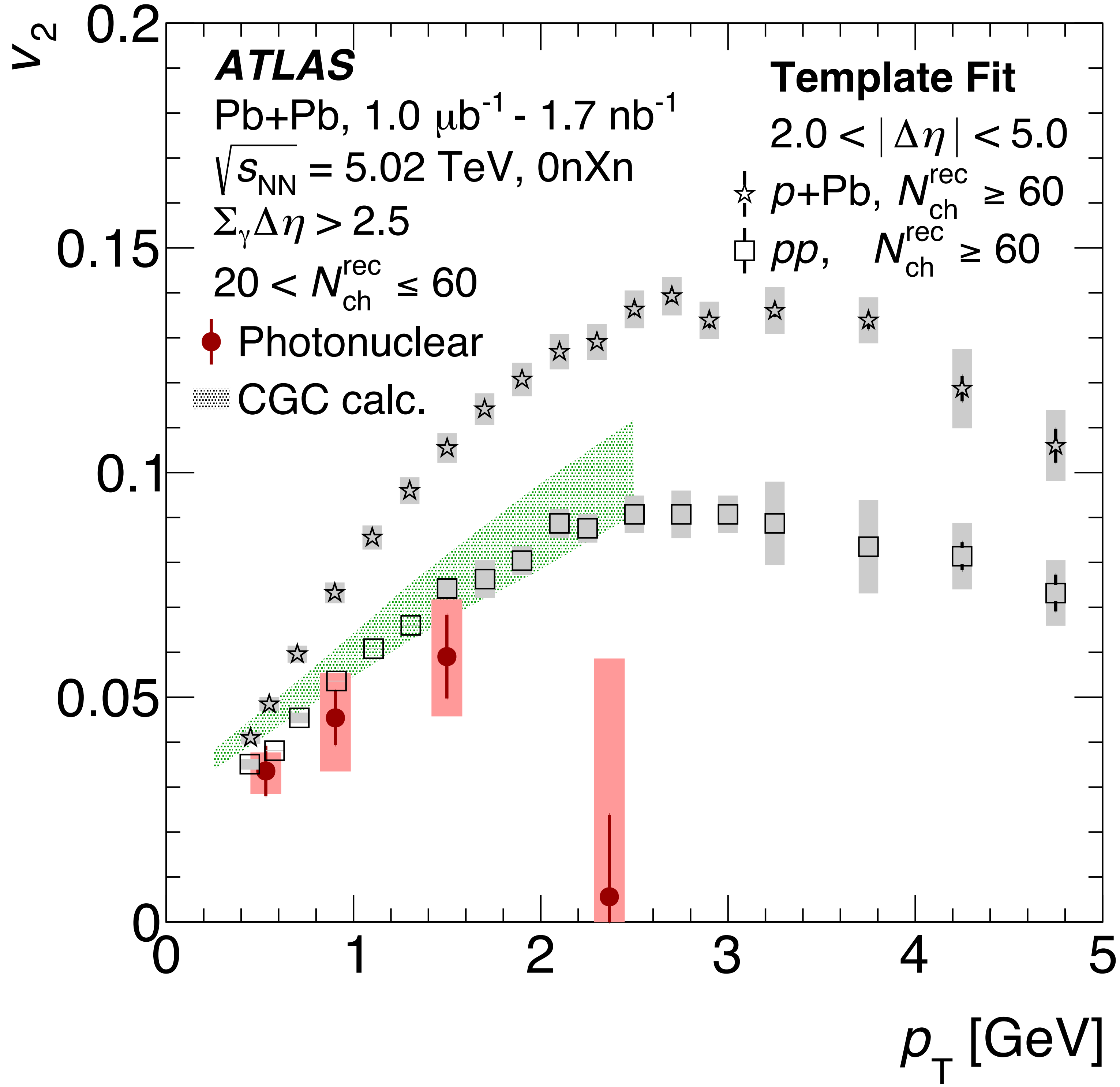
Collective flow in γ+A?

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



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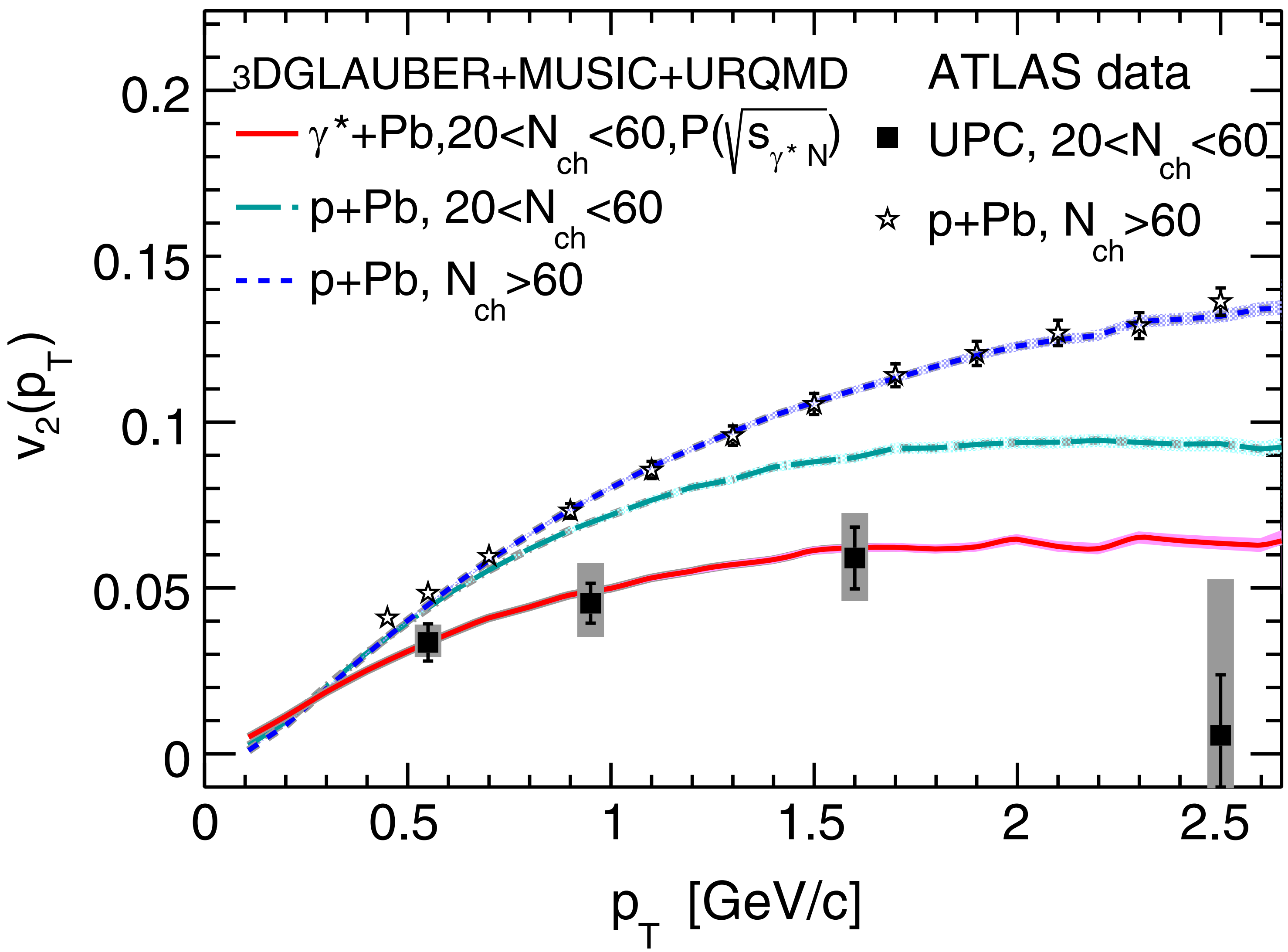
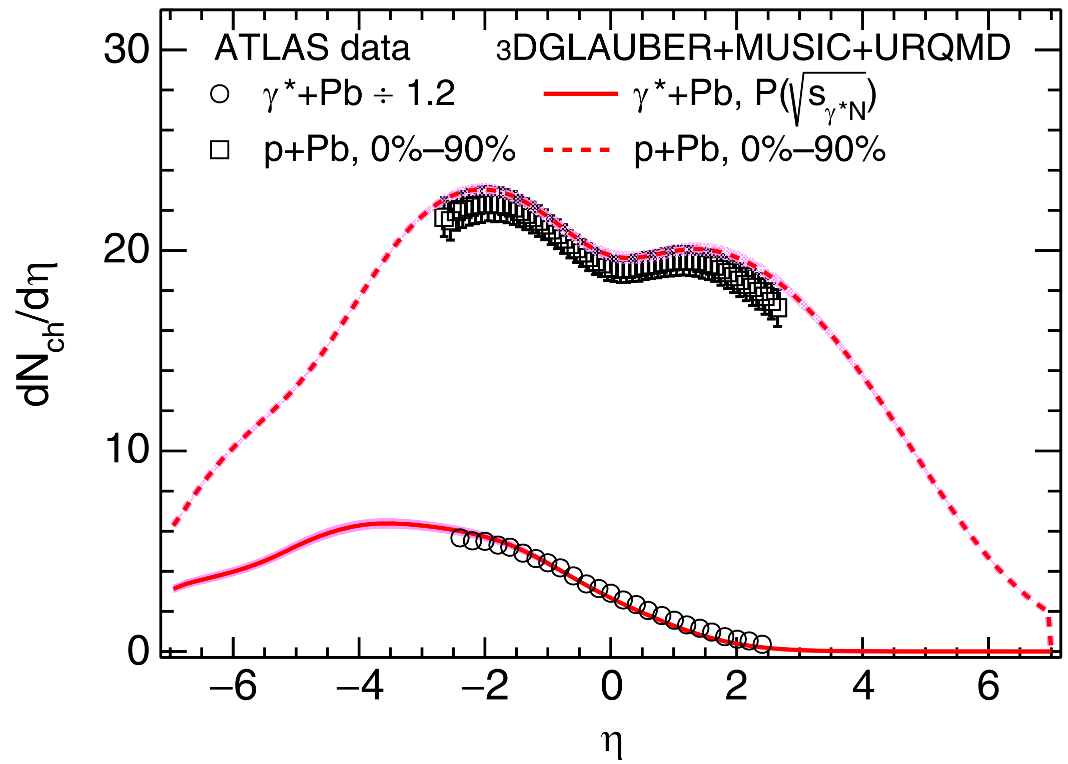
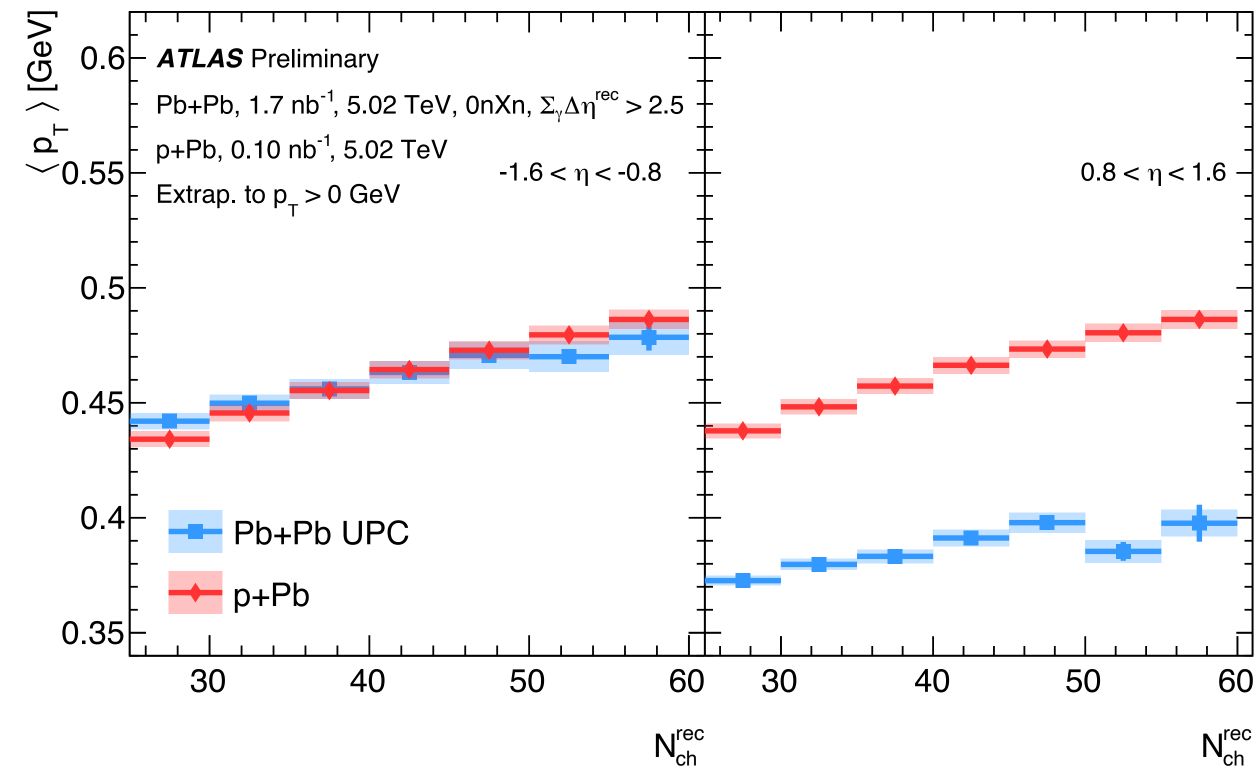
Phys. Rev. Lett. **129**, 252302



Lower values of v_2 reflect a more compact initial state

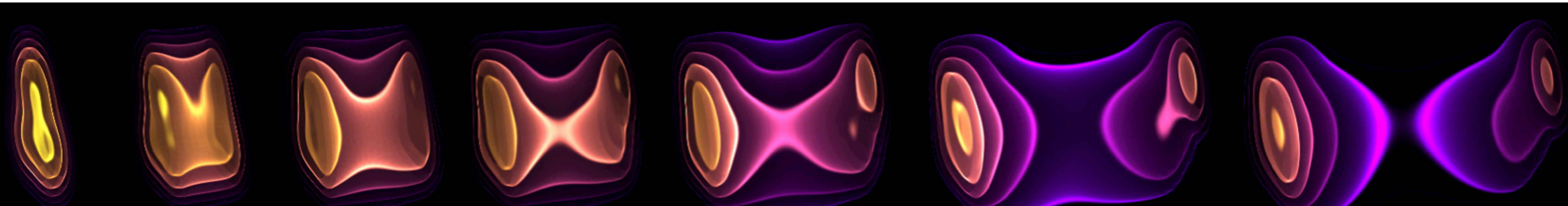
Radial flow from mean p_T





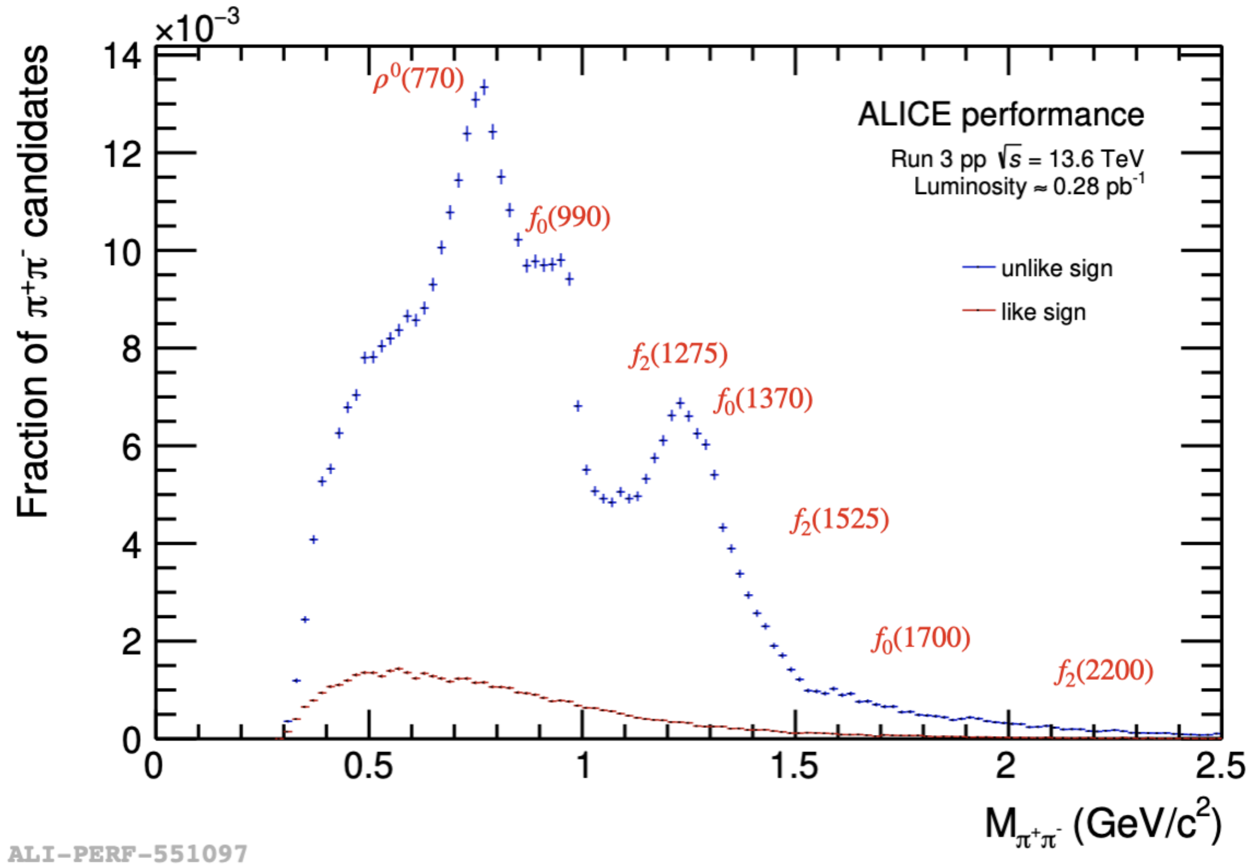
Also predicts expansion will be the same in ***γ***-nucleus collisions as in *proton*-nucleus collisions at same N_{ch}

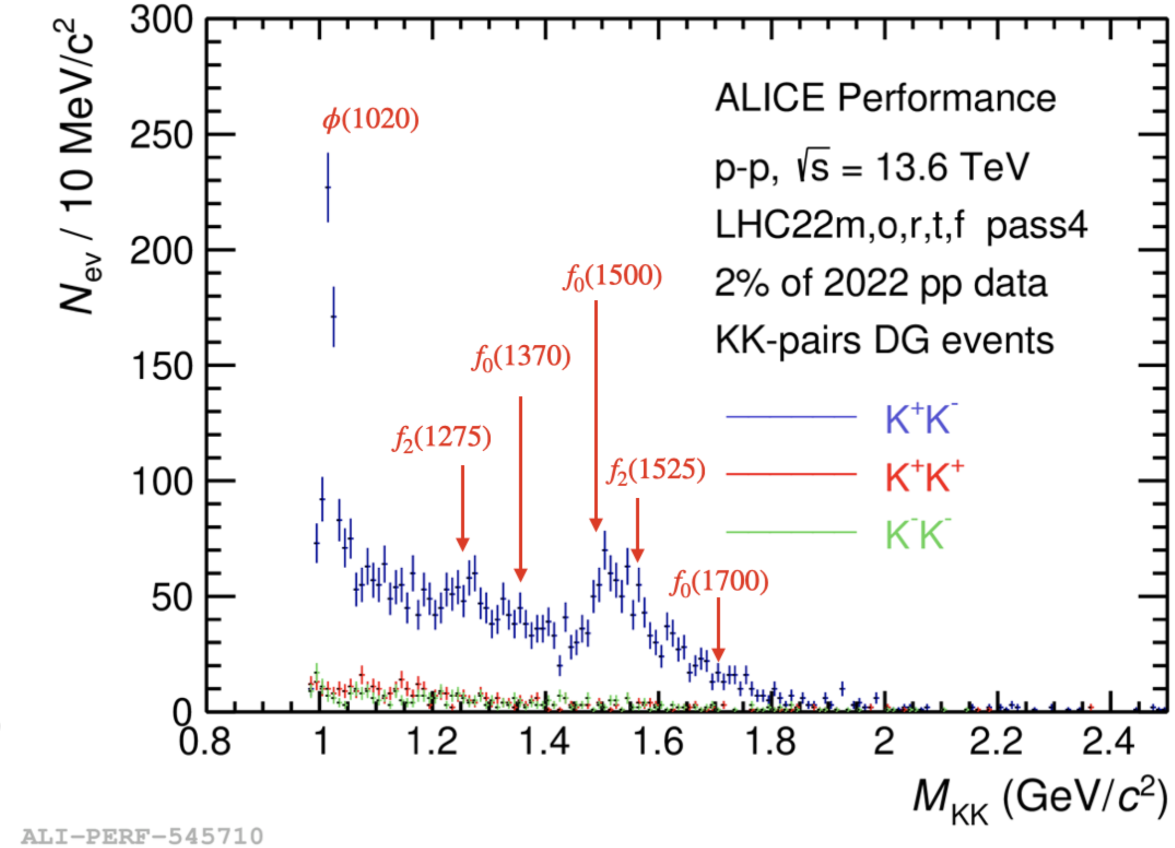
ATLAS recently measured this, and observes average transverse momentum to be similar in some regions, but not all - hints of 3D flow!



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/





ALICE streaming data is a UPC dream