Photon Mediated Processes from Strong Electromagnetic Fields

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APS Topical Group on Hadronic Physics

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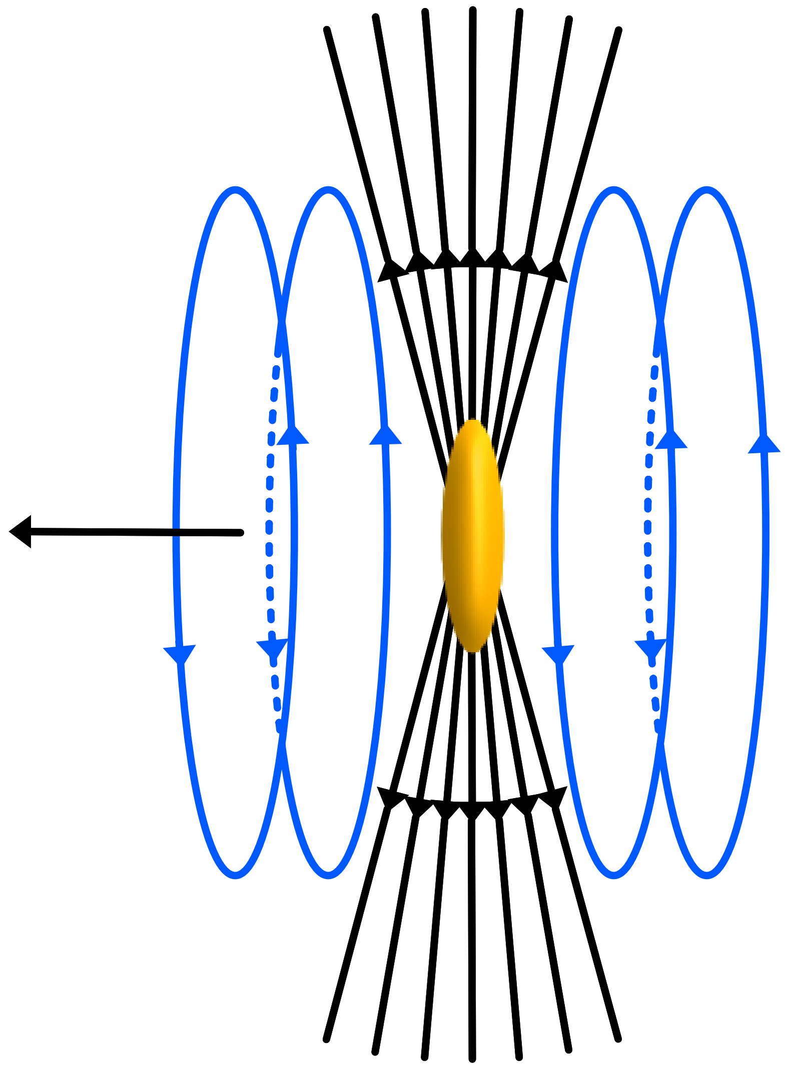


BROOKHAVEN NATIONAL LABORATORY

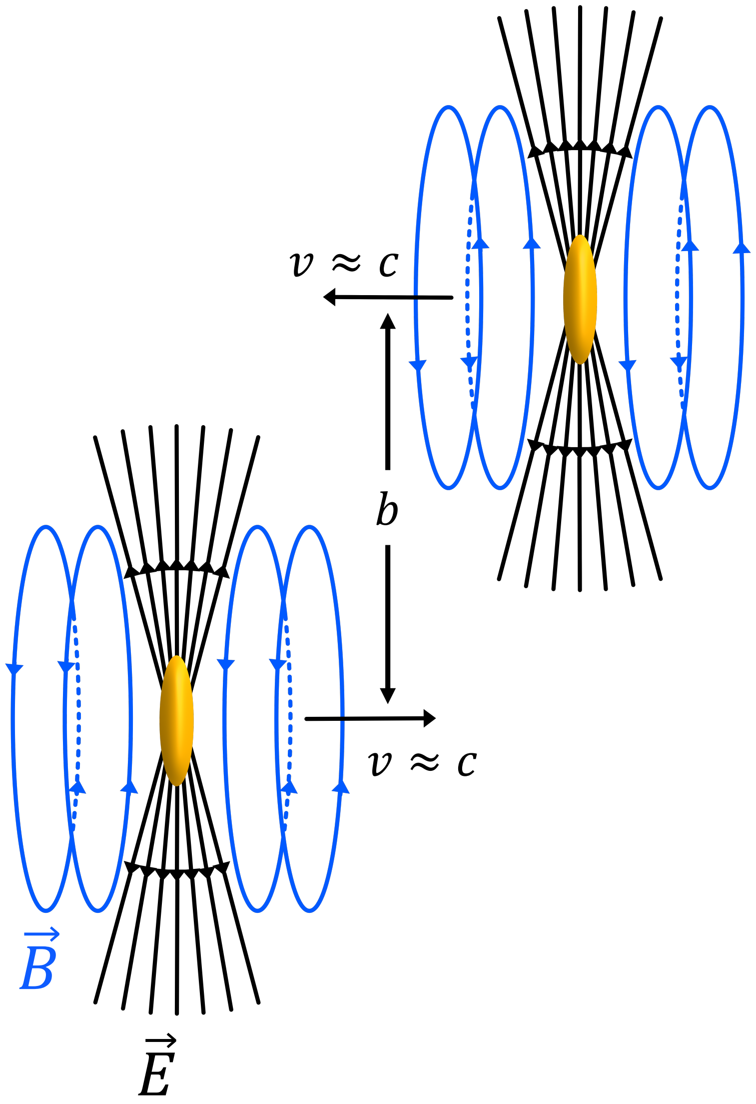
Center for Frontiers in Nuclear Science

Photon Mediate Processes in HICs

- Photons from Strong Fields
- Recent Experimental Catalysts
  - Photon-mediated processes in Hadronic collisions
  - Transverse Momentum Broadening
  - Photon Polarization
- Two-photon processes
  - Mapping electromagnetic field
  - Axion Search
- Photo-nuclear processes
  - Photon-polarization (a new observable)
- Summary and a Look Forward

Based on:
"**Mapping the Electromagnetic Fields of Heavy-Ion Collisions with the Breit-Wheeler Process**"
JDB, W Zha, Z Xu
arXiv:2103.16623

Photons from Strong Fields in Heavy-Ion Collisions



Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic field

Weizäcker-Williams *Equivalent Photon Approximation* (EPA):
→ In a specific phase space, transverse EM fields can be quantized as a flux of **quasi-real photons**

Weizsäcker, C. F. v. *Zeitschrift für Physik* 88 (1934): 612

$$n \propto \vec{S} = \frac{1}{\mu_0}\,\vec{E}\times\vec{B} \approx \left|\vec{E}\right|^2 \approx \left|\vec{B}\right|^2$$

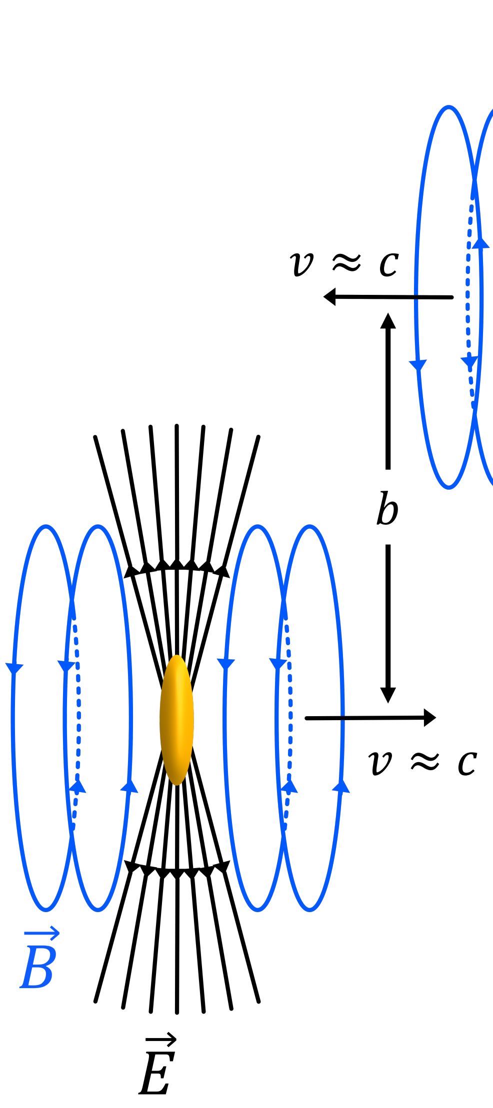
Recent experimental result

→ Breakdown of traditional EPA?

- **Test the assumption used in common EPA implementations**
- **Compare with full QED calculations**

Experimental Catalysts

Photons from Strong Fields in Heavy-Ion Collisions



Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic fields

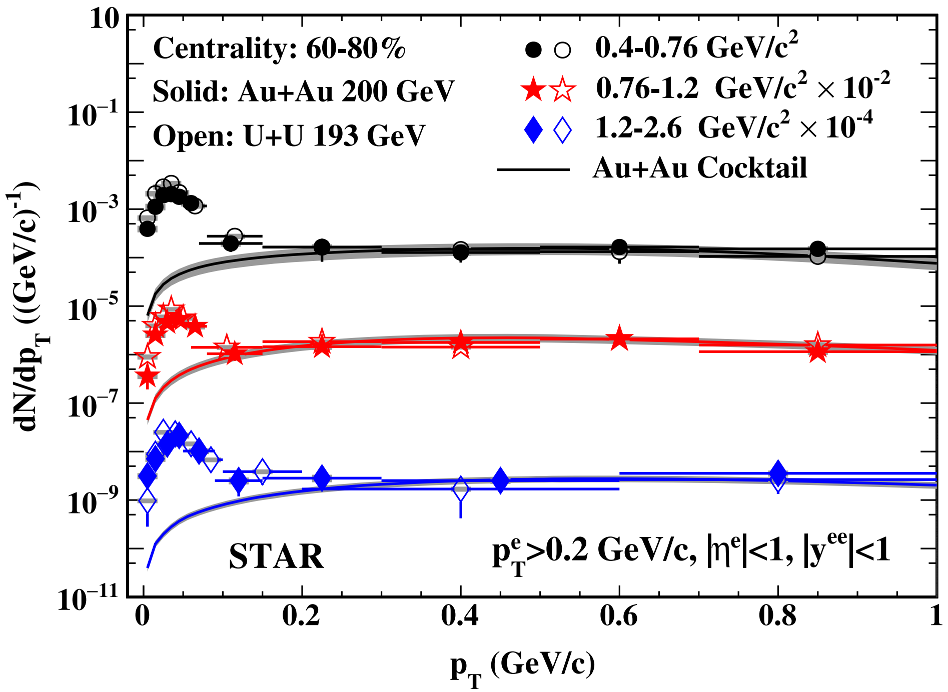
- $\gamma\gamma \rightarrow l^+l^-$: photon-photon fusion
  - One photon from the field of each nucleus interacts
  - Second order process in α
  - $Z\alpha \approx 1$ $\rightarrow$ High photon density with highly charged nuclei

- $\gamma\mathbb{P} \rightarrow \rho^0, J/\psi, etc.$: Photo-nuclear production of vector mesons ($J^P = 1^-$)
  - Photon from the EM field of one nucleus fluctuates to a $q\bar{q}$ pair, interacts with pomeron
  - Photon quantum numbers $J^{PC} = 1^{--}$

S. J. Brodsky, T. Kinoshita, and H. Terazawa, Phys. Rev. D **4**, 1532 (1971).
M. Vidović, M. Greiner, C. Best, and G. Soff, Phys. Rev. C **47**, 2308 (1993).

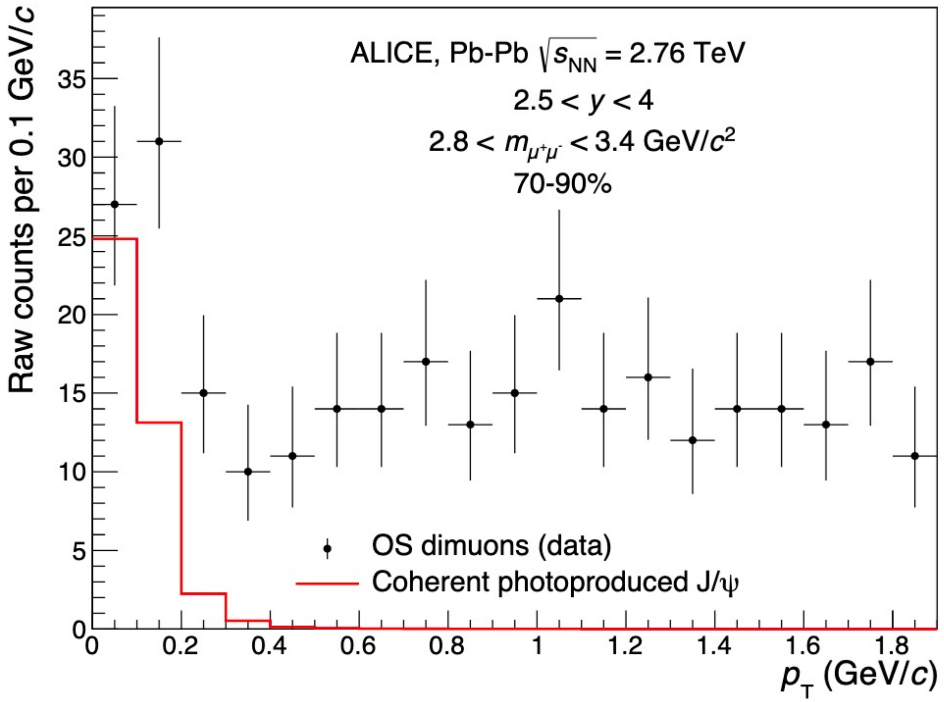
Photo-Processes in **Hadronic Collisions**

$\gamma\gamma \rightarrow l^+l^-$ in 60 – 80% Central



STAR Collaboration, PRL.121(13), 132301 (2018).

$\gamma\mathbb{P} \rightarrow J/\psi$ in 70 – 90% Central



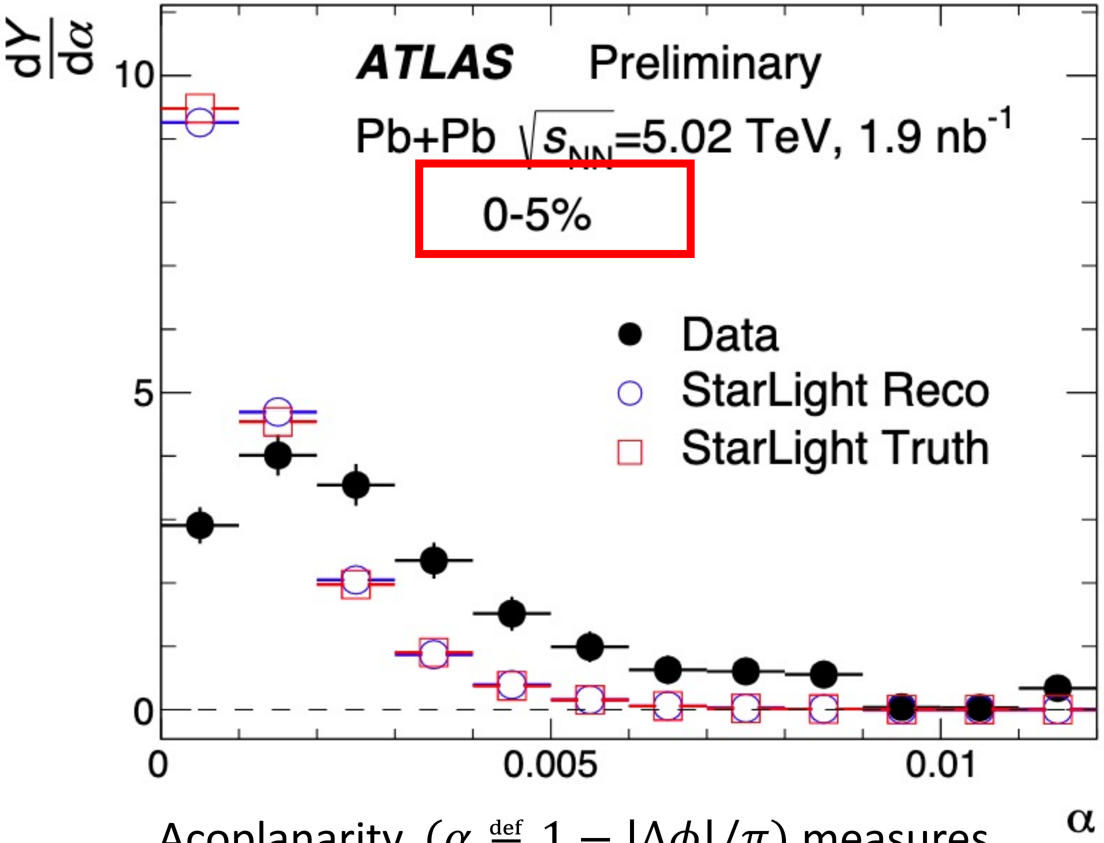
J. Adam *et al.* (ALICE Collaboration) Phys. Rev. Lett. 116, 222301

- Significant excess yields at low transverse momentum
  - Very small photon p_T from coherent EM field
- Clear signature of photon mediated processes, even in hadronic collisions

Photon-Photon processes in **Central Collisions**

- ATLAS: able to measure $\gamma\gamma \rightarrow \mu^{+}\mu^{-}$ <u>even in central collisions</u>

ATLAS-CONF-2019-051



Acoplanarity, ($\alpha \stackrel{\text{def}}{=} 1 - |\Delta\phi|/\pi$) measures how back-to-back is the pair

- Stringent test of impact parameter dependence in <u>$b \rightarrow 0$ fm collisions</u>
- Significant broadening of α in central collisions compared to STARLight

What is the source of this broadening?

 ATLAS, Phys. Rev. Lett. 121, 212301 (2018)

Photon-Photon processes in **Central Collisions**

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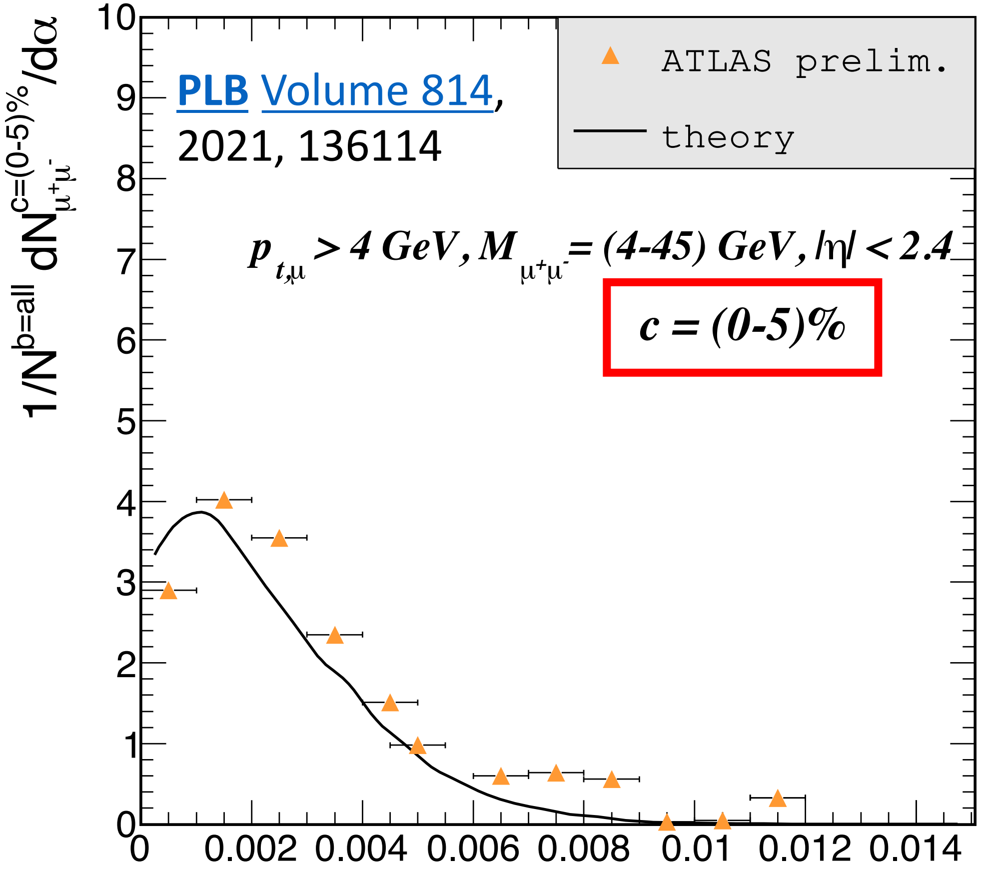


Acoplanarity, ($\alpha \stackrel{\text{def}}{=} 1 - |\Delta\phi|/\pi$) measures how back-to-back is the pair

- Stringent test of impact parameter dependence in $b \rightarrow 0$ fm collisions
- Significant broadening of α in central collisions compared to STARLight
- Well describe by full QED & Wigner function calculations
  - $\rightarrow$ Both yield and α distribution
- Access photon Wigner distribution
  - $\rightarrow$ Photon Flux in terms of $n(\omega, b, q)$

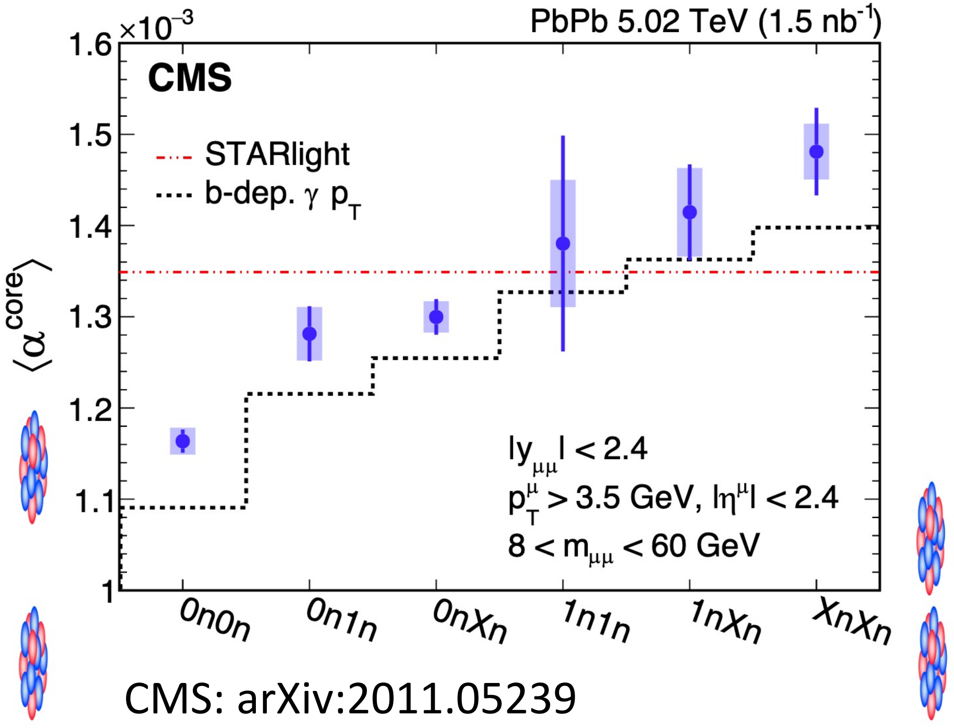
Can we be sure it is not primarily a final state effect (interaction with QGP)?

S. R. Klein, et. al, PRL. 122, (2019), 132301
ATLAS PRL. 121 (2018) , 212301

ATLAS, Phys. Rev. Lett. 121, 212301 (2018)

Testing **Impact Parameter Dependence**

Creative new ways to test **impact parameter dependence** of photons in UPC



CMS: arXiv:2011.05239

Other unique measurements from STAR, ATLAS, ALICE …

- Use neutron spectra to access impact parameter dependence

Neutron Spectra in UPC ⇔ Glauber in HICs

- Strong impact parameter dependence

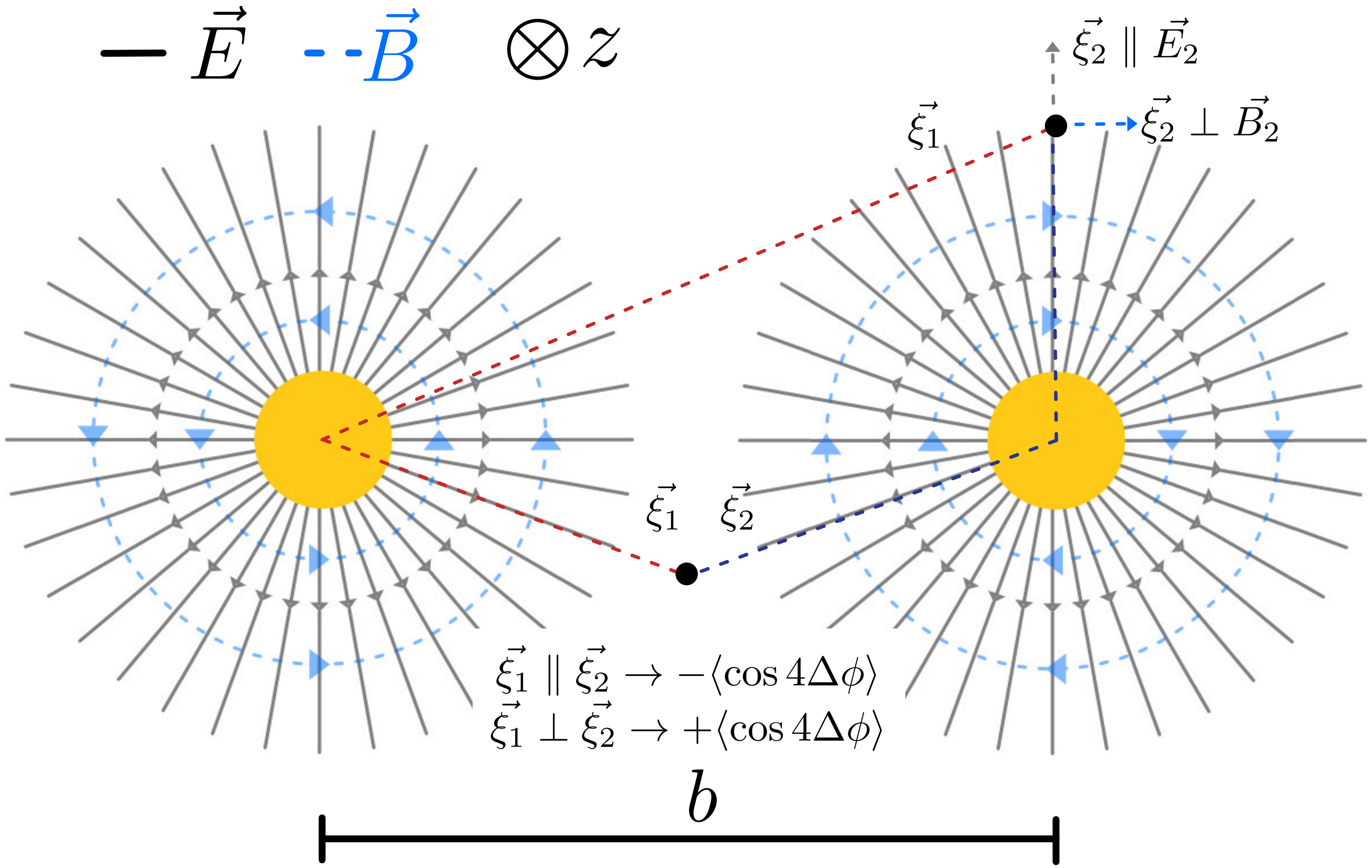
→ Traditional EPA fails to describe data

→ Trend agrees with full QED calculations

What do we learn?

→ **Photon momenta results from field geometry**

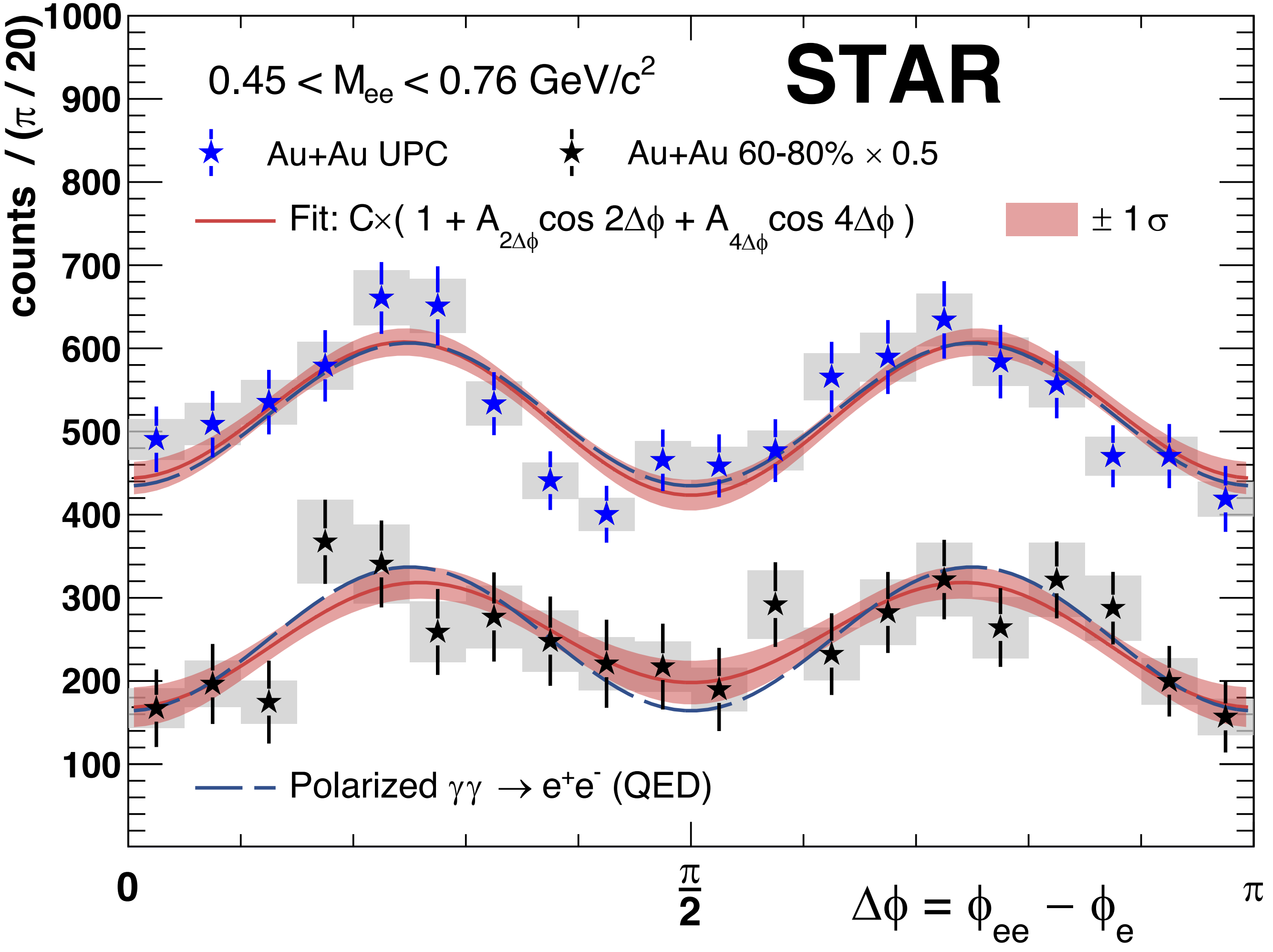
Photon Polarization



Photon Polarization:

- Polarization vector is defined by the semi-classical EM fields
- Experimental signature of polarization: $\cos 4\phi$ modulation
- Final $\cos 4\phi$ modulation depends precisely on the field strength and extent in space

Photon Polarization



C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)
Li, C., Zhou, J. & Zhou, Y. Phys. Rev. D 101, 034015 (2020).

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Vacuum polarization effect, first laboratory evidence for vacuum birefringence

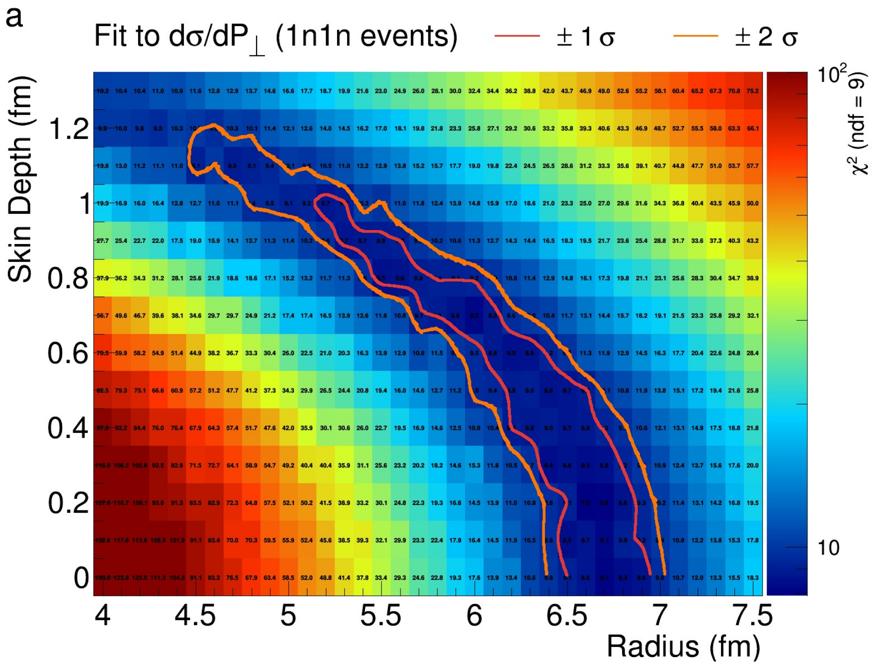
STAR, arXiv : 1910.12400
JDB, W Zha, Z Xu, arXiv:2103.16623
Phys. Rev. D 90, 045025
Thesis J Toll, ProQuest.https://search.proquest.com/docview/301990593/

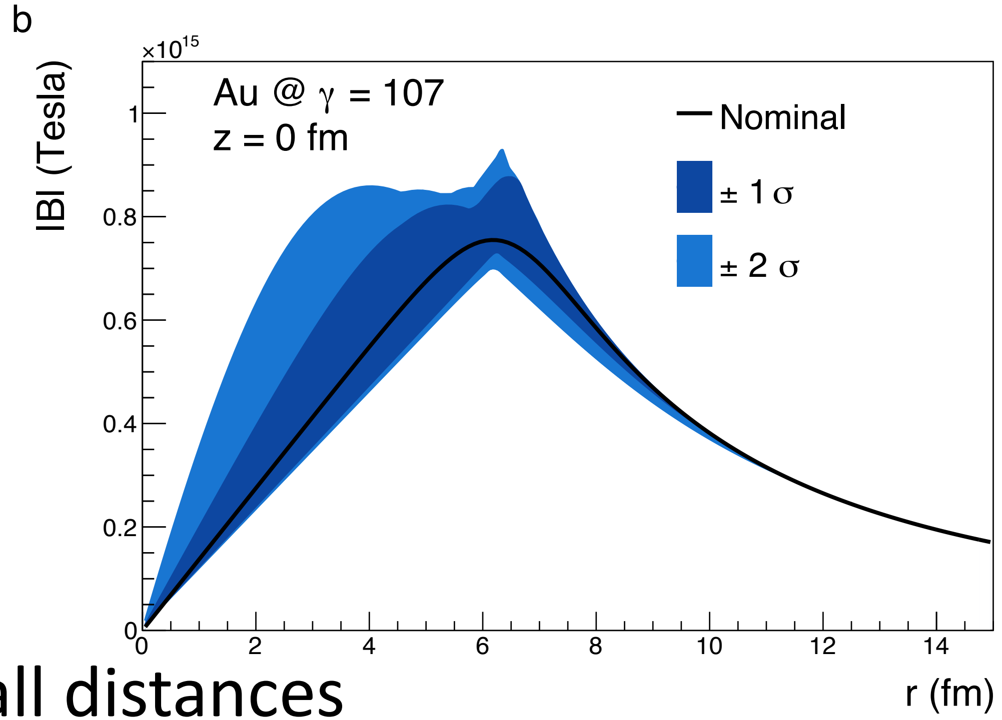
Applications

Mapping of EM Field Distribution

STAR, arXiv : 1910.12400
JDB, W Zha, Z Xu, arXiv:2103.16623

- Using STAR's measurement of $\gamma\gamma \rightarrow e^{+}e^{-}$ (in UPC)
- Precision transverse momentum + polarization = constrain field map in 2D





- Much stronger field possible at small distances
  - More measurements needed to constrain event-by-event fluctuations of EM fields
- **Novel input for magnetic-field driven phenomena**

Light-by-Light Scattering & the **Search for Axions**

- Light-by-Light scattering through Axion-like particles:

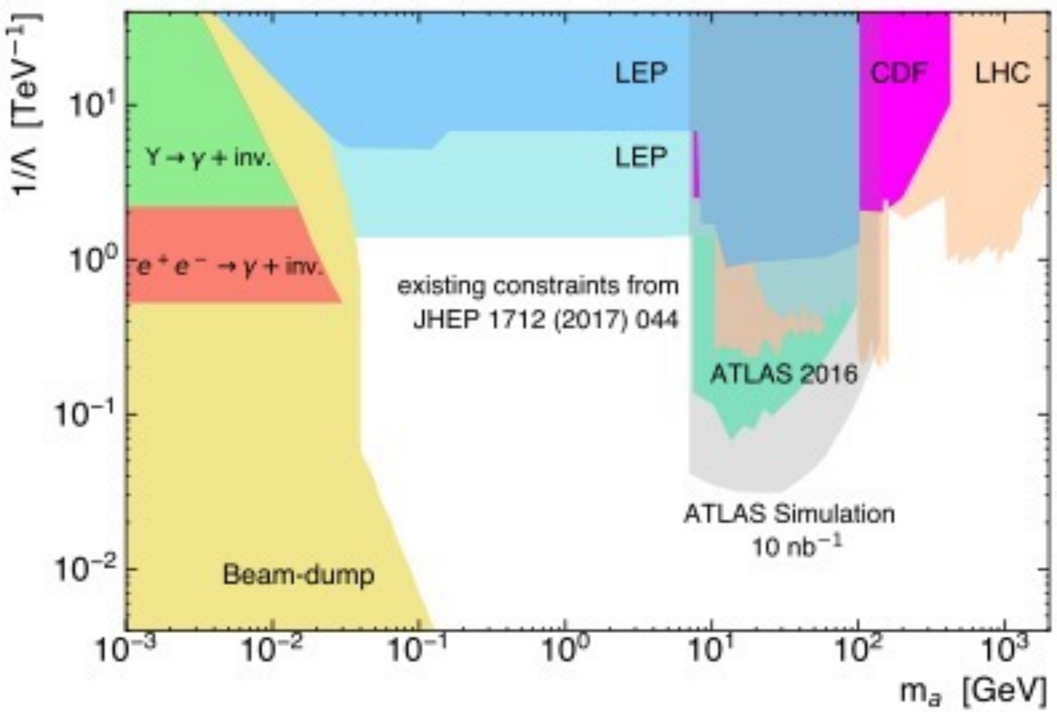
$$\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$$

Photon-ALP Lagrangian density[1]:

$$\mathcal{L}_{a\gamma\gamma} = \frac{1}{4\Lambda} a F^{\mu\nu} \tilde{F}_{\mu\nu} = \frac{1}{\Lambda} a \mathbf{E} \cdot \mathbf{B}$$

- Due to quantum spin-momentum correlations, axion production should be correlated with impact parameter direction (due to $\boldsymbol{E} \cdot \boldsymbol{B}$ coupling)
- Access through photon polarization sensitive differential measurements
- More direct than total cross section

JDB, W Zha, Z Xu, arXiv:2103.16623



Prospects for Measurements of Photon-Induced Processes in Ultra-Peripheral Collisions of Heavy Ions with the ATLAS Detector in the LHC Runs 3 and 4 - CERN Document Server. http://cds.cern.ch/record/2641655/files/.

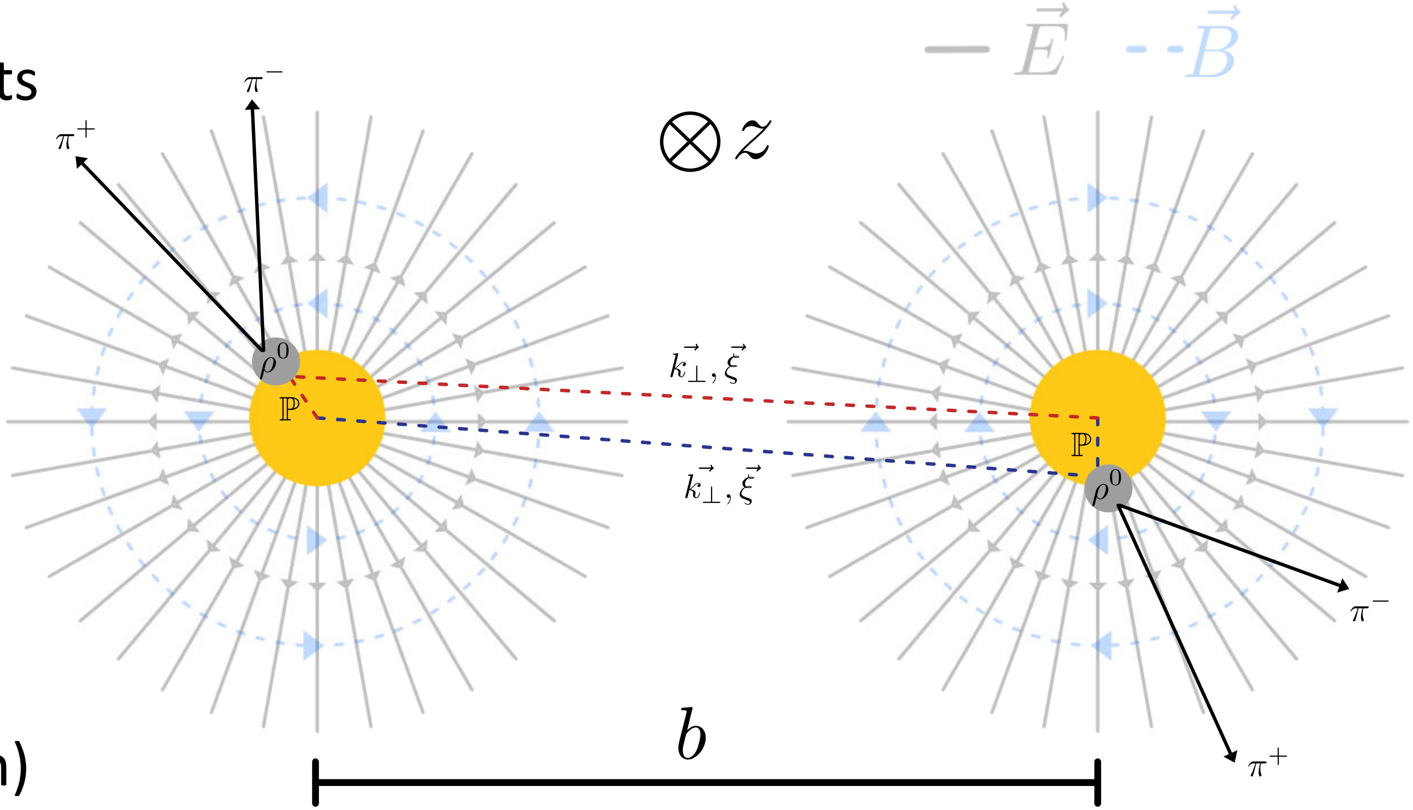
1. Bauer, M., Neubert, M. & Thamm, A. Collider probes of axion-like particles. *J. High Energ. Phys.* **2017**, 44 (2017).

ATLAS, *Nature Physics* 13 (2017), 852
ATLAS, Phys. Rev. Lett. **123**, 052001 (2019).
CMS, Physics Letters B **797**, 134826 (2019).

Photonuclear Polarization Interference Effect

- Nuclei “take-turns” emitting photon vs. Pomeron

- Diffractive Photonuclear measurements
  → mainstay since HERA
  Eur.Phys.J.C46:585-603,2006
  Phys.Rev.D 50 (1994) 5518-5534
  Phys.Lett.B 483 (2000) 23-35



Access to photon polarization interference is sensitive to:

→ Details of nuclear geometry (gluon distribution)

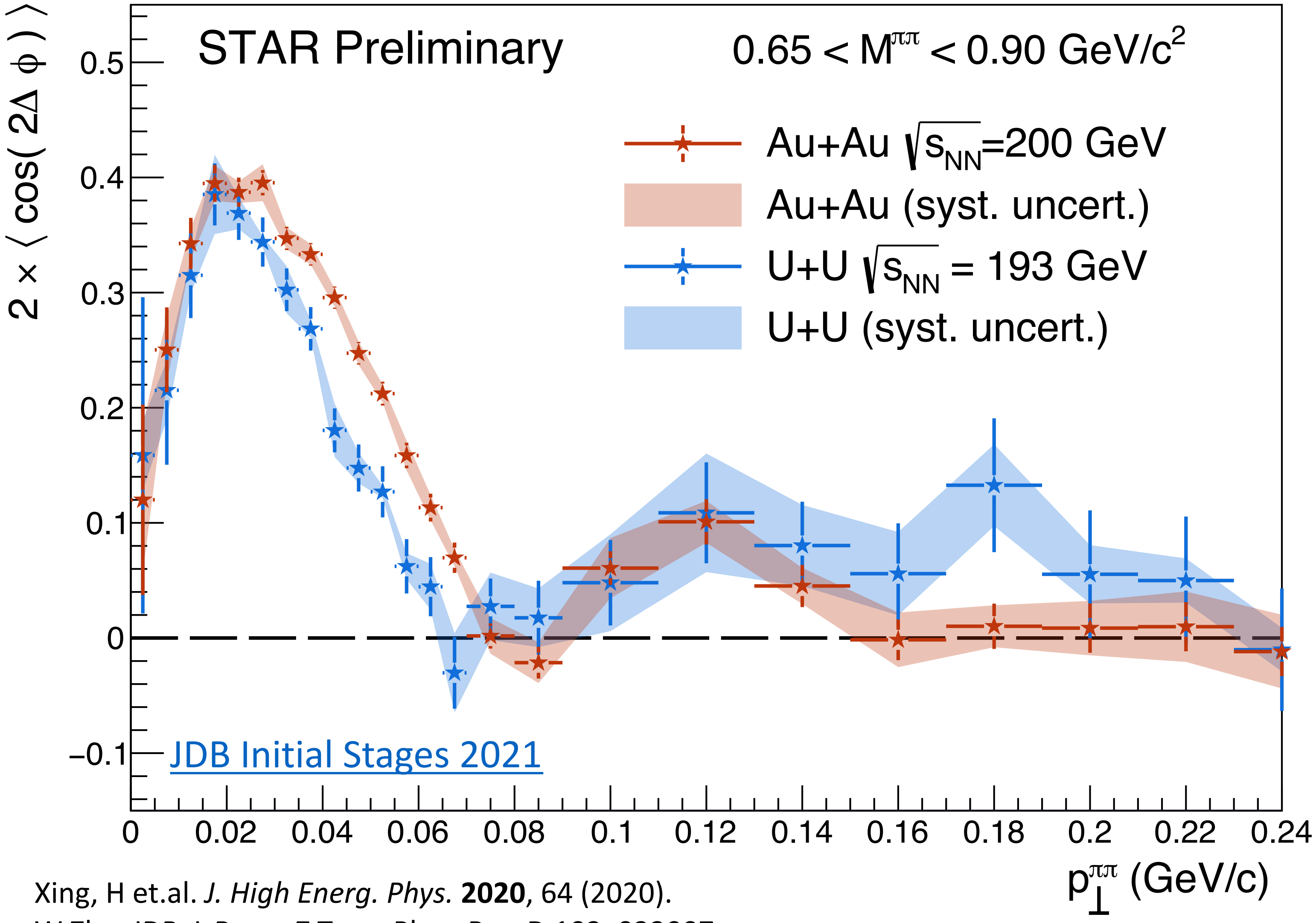
→ Impact Parameter (spatial distribution)

Polarization interference → $\cos 2\phi$ modulation, <u>A new tool for studying nuclei</u>

[JDB Initial Stages 2021]

[1] Xing, H et.al. *J. High Energ. Phys.* **2020**, 64 (2020).

$\cos 2\Delta\phi$ $vs.\, \rho^0\ p_T$ in U+U and Au+Au



Xing, H et.al. *J. High Energ. Phys.* **2020**, 64 (2020).
W Zha, JDB, L Ruan, Z Tang, Phys. Rev. D 103, 033007

- Strong $\cos 2\Delta\phi$ modulation observed at $p_T < \sim 60$ MeV/c – similar to Au+Au
- Systematic uncertainty shown in blue band
- U+U and Au+Au show similar structure
- Details of interference sensitive to gluon distribution within nuclei

Summary and Outlook

- New experimental results → crucial input for theoretical treatment
  - Lots of progress, sadly can only show a few results

More details in JDB, W Zha, Z Xu arXiv:2103.16623

Summary and Outlook

- New experimental results → crucial input for theoretical treatment
  - Lots of progress, sadly can only show a few results
- Photon polarization and Transverse momentum broadening ($\gamma\gamma \rightarrow l^+l^-$)

→ Novel input: Map in 2D the ultra-strong EM fields

→ More measurements needed to constrain event-by-event fluctuations

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Summary and Outlook Thank you!

- New experimental results → crucial input for theoretical treatment
  - Lots of progress, sadly can only show a few results
- Photon polarization and Transverse momentum broadening $(\gamma\gamma \rightarrow l^+l^-)$

→ Novel input: Map in 2D the ultra-strong EM fields

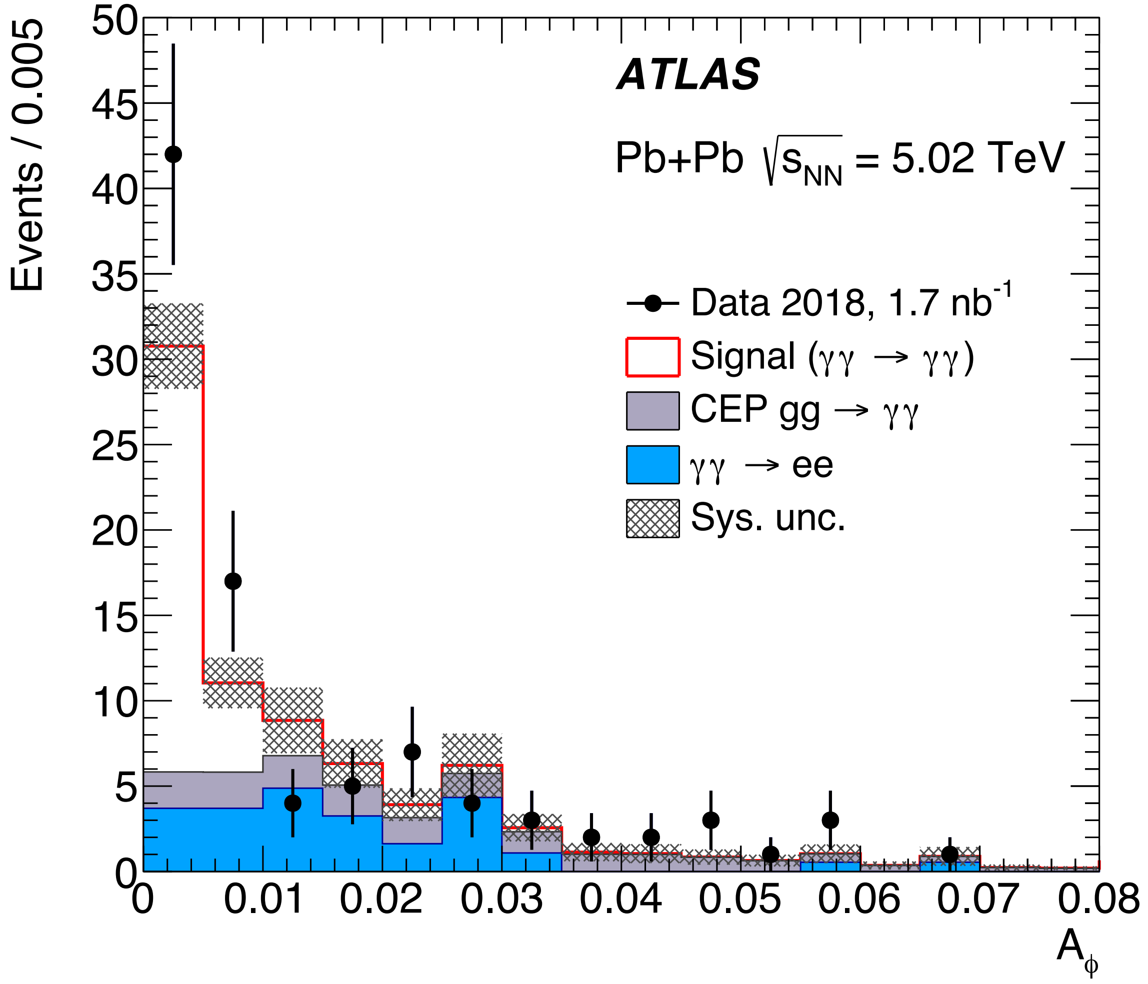
→ More measurements needed to constrain event-by-event fluctuations

- Photon polarization in Light-by-Light scattering: Provide differential approach + more sensitivity for axion-like particle searches
- Photon polarization interference in photonuclear interactions

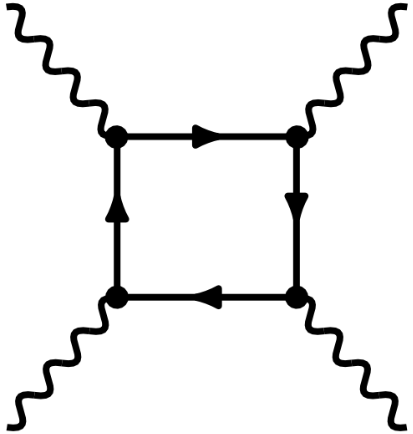
→ New observable for a long-standing process + important for the future (EIC)

More details in JDB, W Zha, Z Xu [arXiv:2103.16623](https://arxiv.org/abs/2103.16623)

Light-by-Light Scattering



ATLAS Observed Light-by-Light Scattering in UPCs:



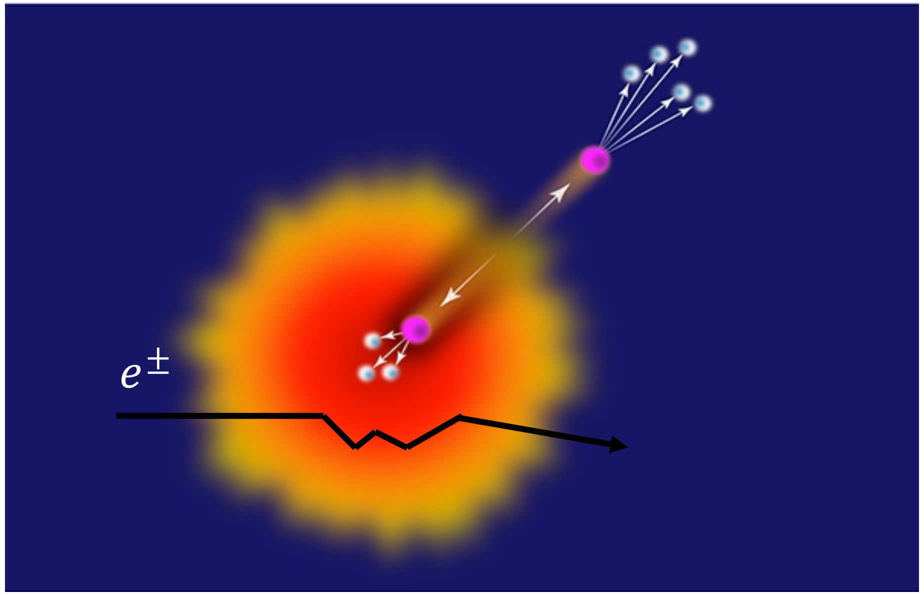
- Purely quantum mechanical process (α_{em}^4)
- Light-by-Light scattering involves real photons by definition
- Standard Model process proceeds through loop of charged particles (lepton, quarks, $W^{\pm}$)

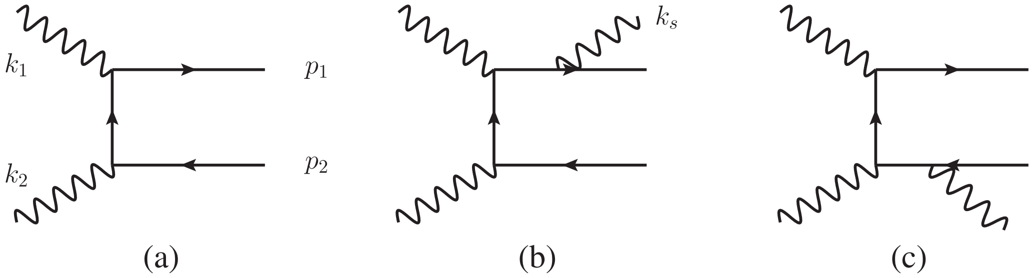
ATLAS, *Nature Physics* 13 (2017), 852
ATLAS, Phys. Rev. Lett. **123**, 052001 (2019).
CMS, Physics Letters B **797**, 134826 (2019).

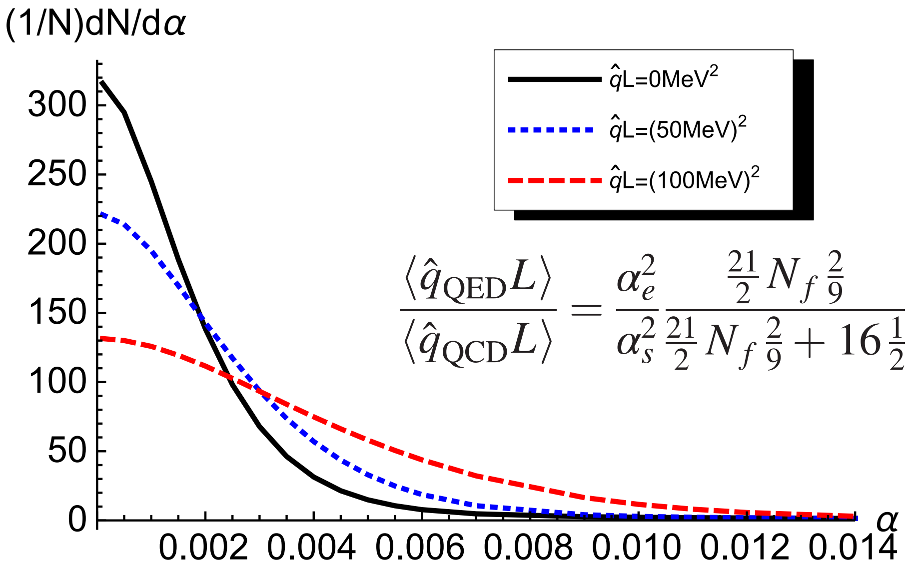
[1] S. R. Klein, et. al, Phys. Rev. Lett. 122, (2019), 132301
[2] ATLAS Phys. Rev. Lett. 121 (2018) , 212301

Coulomb Scattering through QGP

- Charged particles may scatter off charge centers in QGP, modifying primordial pair $P_\perp$?







$$\frac{\langle \hat{q}_{\mathrm{QED}} L\rangle}{\langle \hat{q}_{\mathrm{QCD}} L\rangle} = \frac{\alpha_e^2}{\alpha_s^2} \frac{\frac{21}{2} N_f \frac{2}{9}}{\frac{21}{2} N_f \frac{2}{9} + 16\frac{1}{2}} = \frac{\alpha_e^2}{\alpha_s^2} \times \frac{7}{15},$$

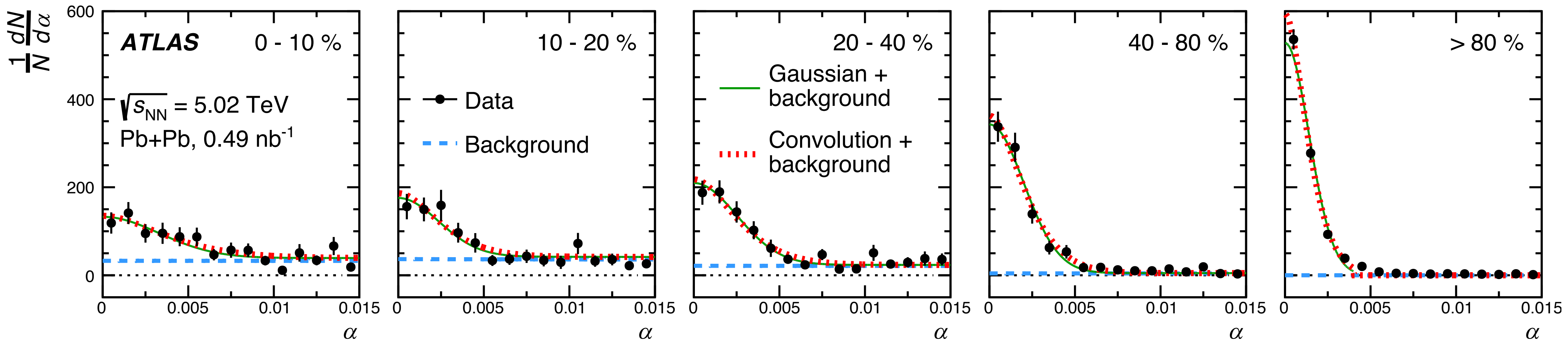
Assumptions:

1. Primordial distribution given by STARLight
2. Daughters traverse medium

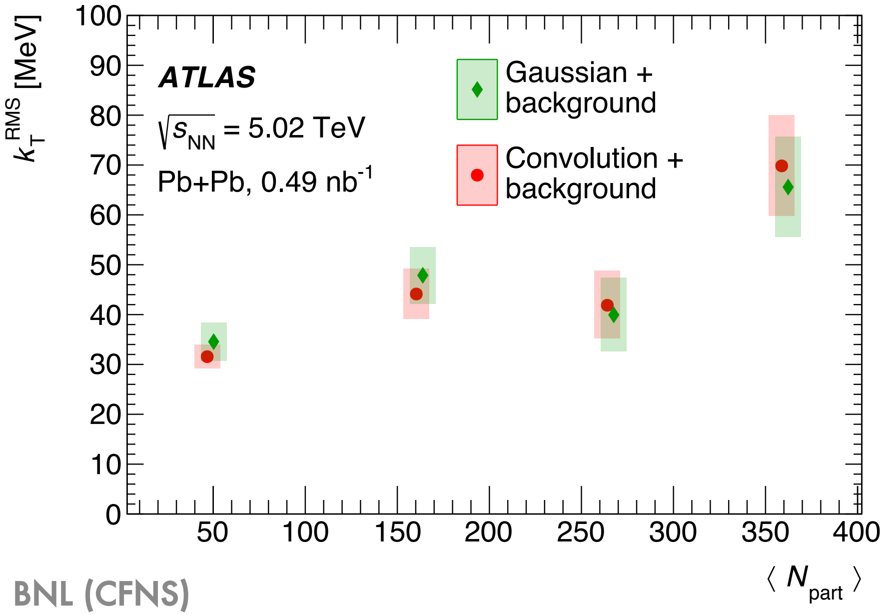
ATLAS Measurement of $\gamma\gamma \rightarrow \mu^+\mu^-$

arXiv:1806.08708

Phys. Rev. Lett. 121, 212301 (2018)



- Describe the broadening in terms of UPC curve + kick from Coulombic multiple scattering (in QGP)
- Fits to data: $k_T^{RMS} \approx 40 - 50$ MeV
- No significant centrality dependence, maybe a hint in last bin
- Very different kinematics range than STAR dielectrons, $\vec{B}$ field / coulomb scattering may not be mutually exclusive descriptions



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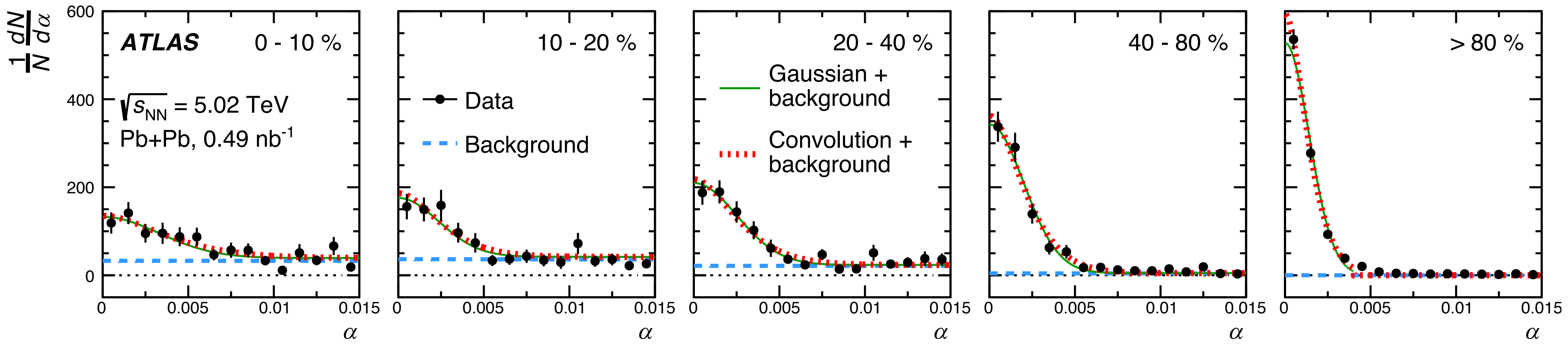

- Describe the broadening in terms of UPC curve + kick from Coulombic multiple scattering (in QGP)
- Fits to data: $k_T^{RMS} \approx 40 - 50$ MeV
- New data (QM19): significant centrality dependence!
- Very different kinematics range than STAR dielectrons, $\vec{B}$ field / coulomb scattering may not be mutually exclusive descriptions