Converting light into matter: using the Breit-Wheeler process to probe QGP

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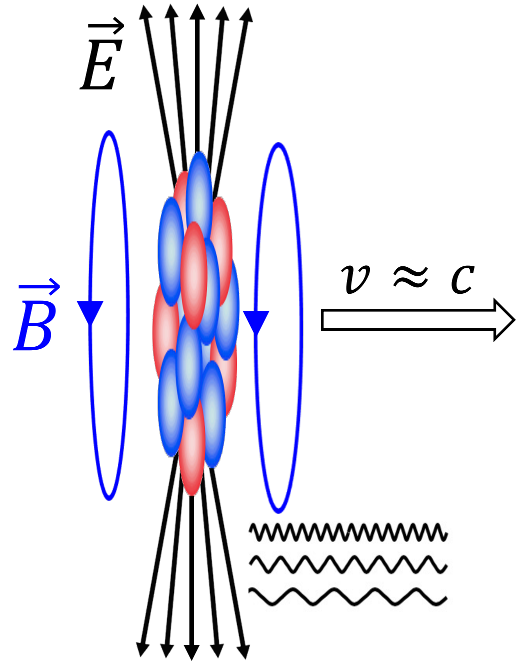
Based on the following works:
CMS, [PRL 127 (2021) 122001]
STAR, [PRL 127 (2021) 052302]
STAR, [PRL 121 (2018) 132301]

- *Introduction*
- *Signatures of* $\gamma\gamma \rightarrow l^{+}l^{-}$ *in UPC*
- $\gamma\gamma \rightarrow l^{+}l^{-}$ *production in non-UPC*
- *Probing QGP EM properties*
- *Summary and outlook*

Equivalent photon



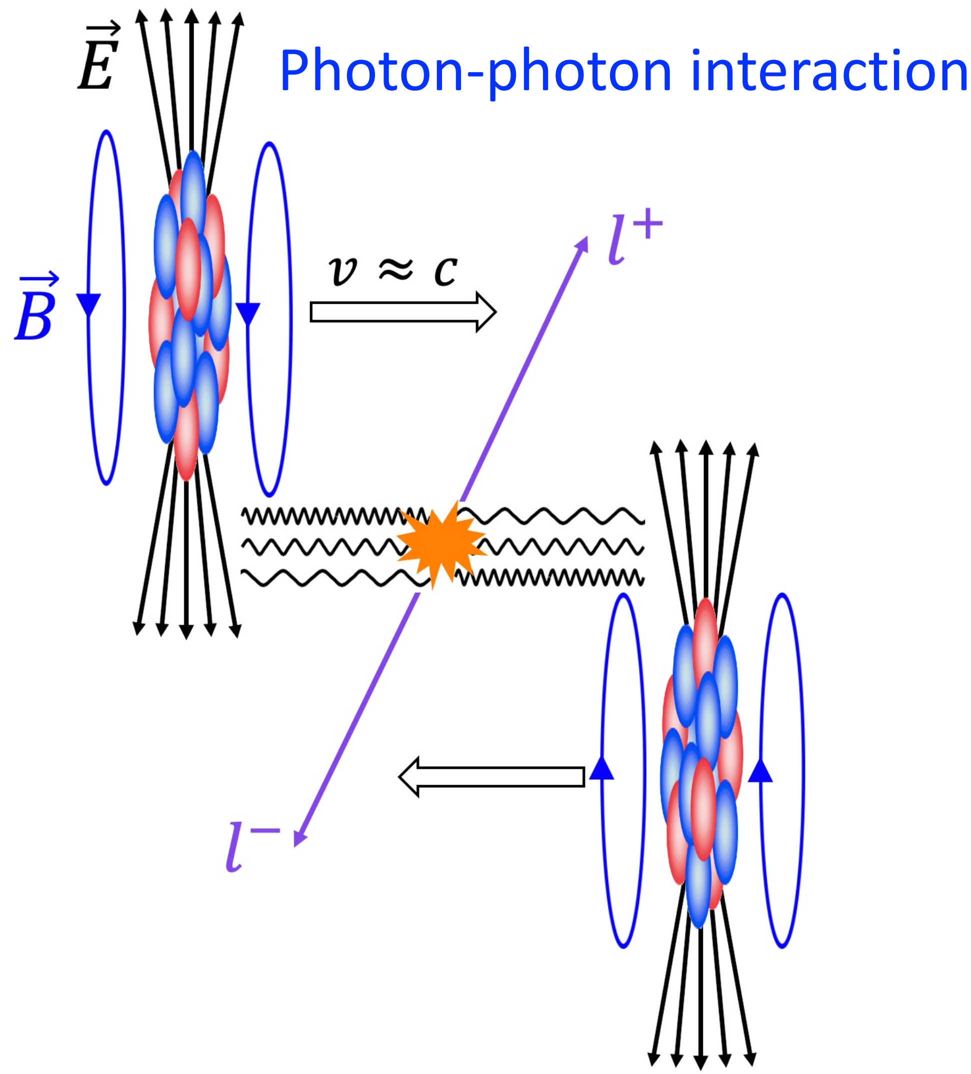
➢ Equivalent Photon Approximation

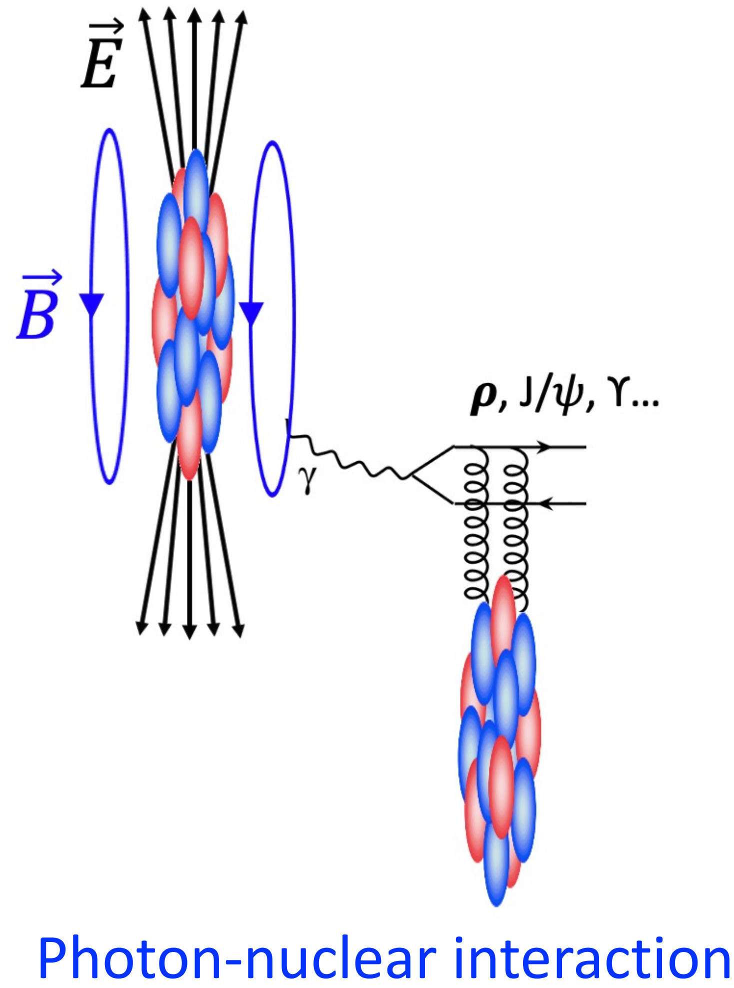
- Proposed in 1924 by Fermi
- Photon flux $\propto Z^2$

➢ Photon kinematics

- $\omega < \frac{\hbar\gamma}{R_A}$ (3 GeV @ RHIC, 80 GeV @ LHC)
- $p_T < \frac{\hbar}{R_A}$ ($\mathcal{O}$(30) MeV/c @ RHIC, LHC)

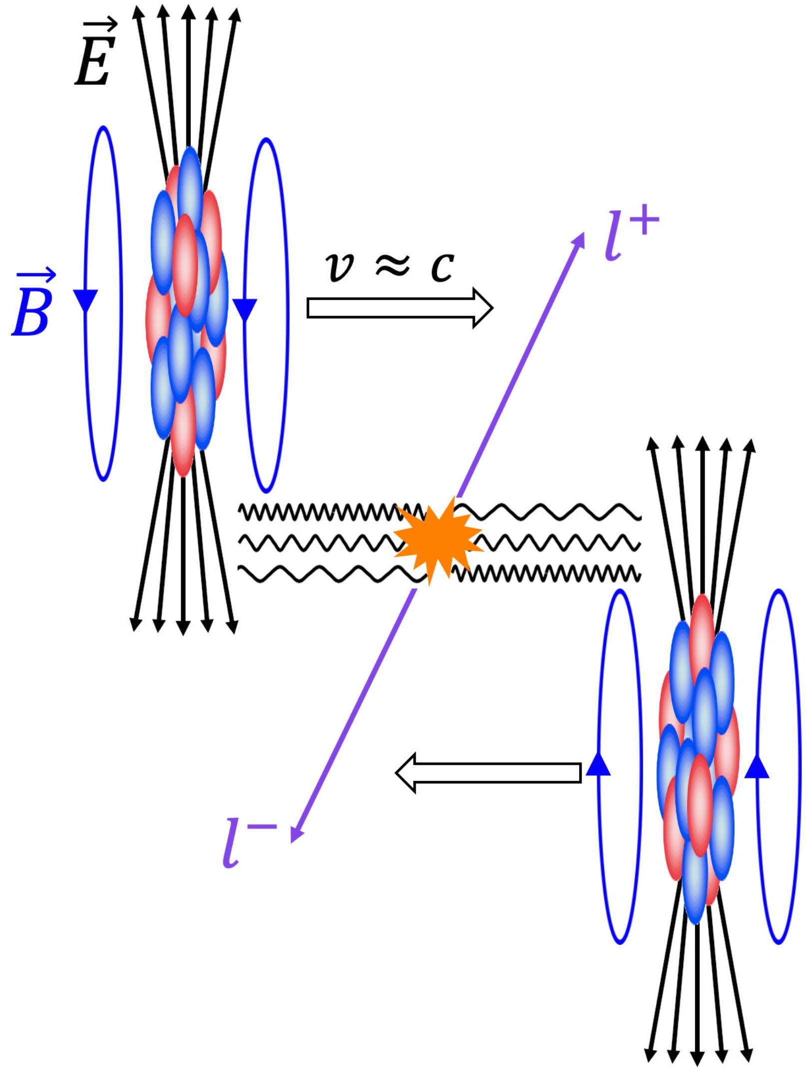
Ultraperipheral collisions (UPC)

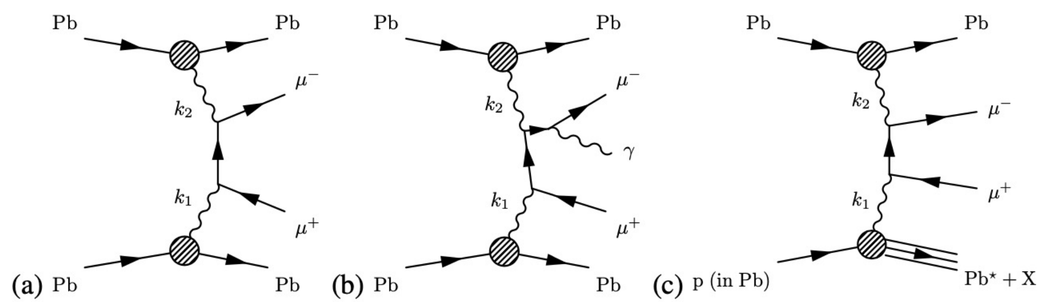


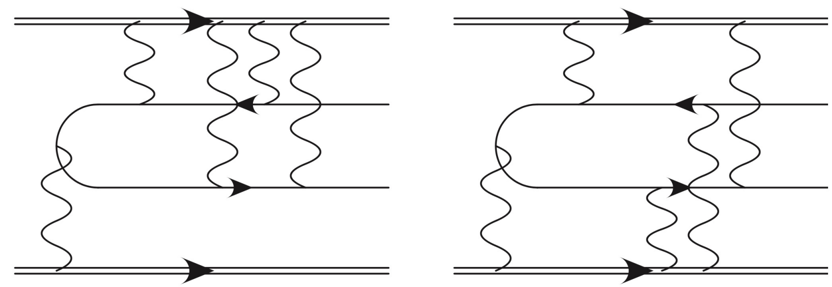


Photon-photon interactions

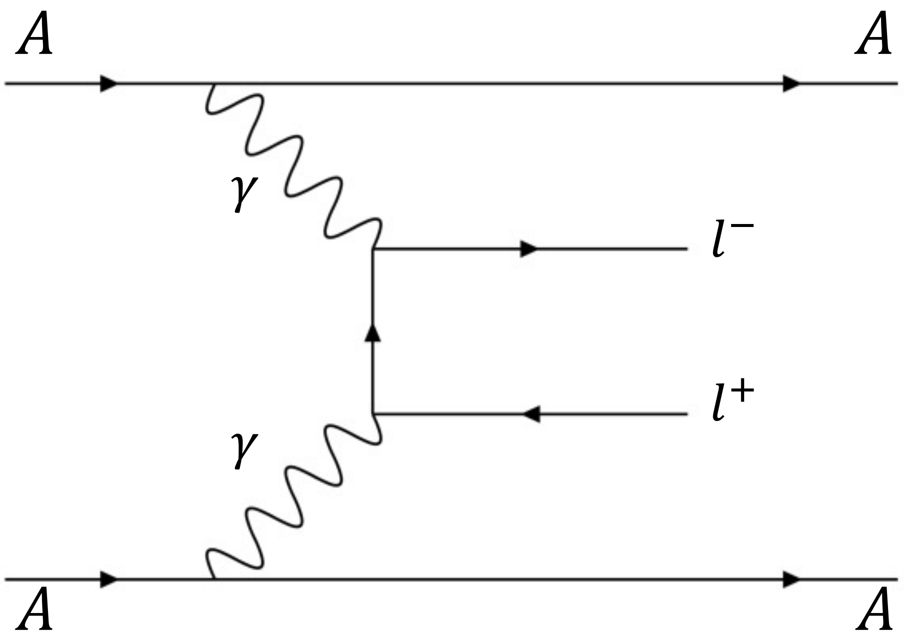
G. Baur et al., Phys. Rep. 453 (2007) 1
ATLAS, PRC 104 (2021) 024906







Breit-Wheeler process



- Breit-Wheeler process: converting **real** photon into e^+e^-
  - Proposed in 1934
  - $Q^2 < (\hbar/R_A)^2$ in UPC $\longrightarrow$ almost real
  - Several distinctive features

Modeling of $\gamma\gamma \rightarrow l^+ l^-$

- **Photon flux:** $n(k,r) = \frac{4Z^2\alpha}{k}\left|\int \frac{d^2q_\perp}{(2\pi)^2} q_\perp \frac{F(q)}{q^2} e^{iq_\perp \cdot r}\right|^2$

S. Klein et al., CPC 212 (2017) 258
W. Zha et al., PLB 781 (2018) 182

- How to convolute two photons into $l^+ l^-$?

STARlight formalism:

$$\sigma(A + A \rightarrow A + A + l^+ l^-) = \int_{R_A}^{\infty} \pi r_1 d^2 r_1 \int_{R_A}^{\infty} \pi r_2 d^2 r_2 \int_0^{2\pi} d\phi\, N(k_1, r_1) N(k_2, r_2) \sigma(\gamma\gamma \rightarrow l^+ l^-)$$

- Integrate ***b*** out ⟹ No ***b*** dependence of photon (lepton pair) p_T
- Radius cutoff ⟹ ~20% less yield & insensitive to form factor

Modeling of $\gamma\gamma \rightarrow l^+l^-$

- Photon flux: $n(k,r) = \frac{4Z^2\alpha}{k}\left|\int \frac{d^2q_\perp}{(2\pi)^2} q_\perp \frac{F(q)}{q^2} e^{iq_\perp \cdot r}\right|^2$

S. Klein et al., CPC 212 (2017) 258
W. Zha et al., PLB 781 (2018) 182
S. Klein et al., PRD 102 (2020) 094013
W. Zha et al., PLB 800 (2020) 135089
M. Klusek-Gawenda, PLB 814 (2021) 136114
R. Wang et al., PRD 104 (2021) 056011

Models in market

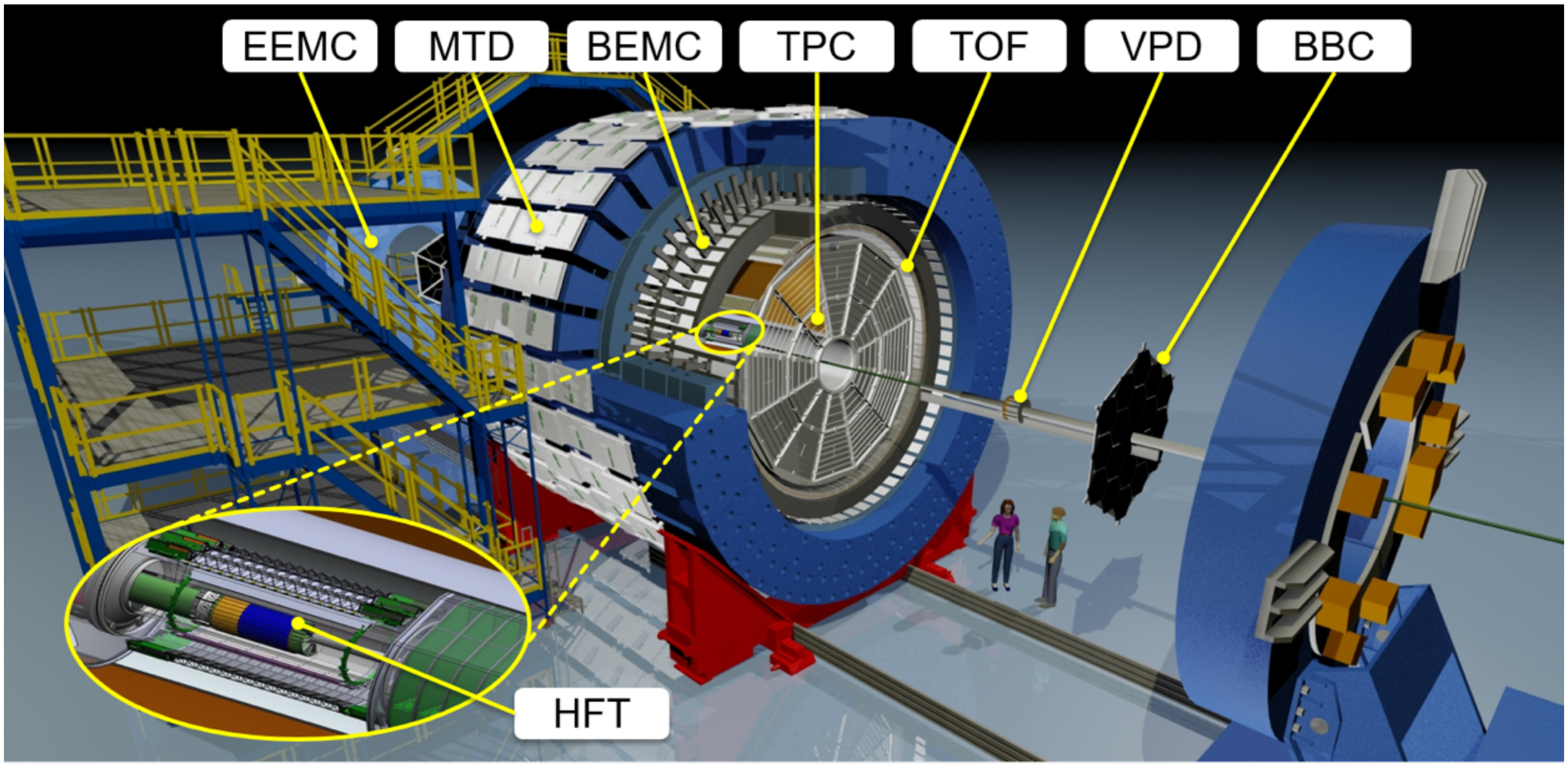
	STARlight	**gEPA**	**QED**
Form Factor	Point-like	Woods-Saxon	Woods-Saxon
γ intensity(***b***)	✓	✓	✓
γ p_T(***b***)	✗	✓	✓
l^+l^- inside nucleus	✗	✓	✓
HO contribution	✗	✗	✗ ✤

✤ Being addressed in calculations

No single available model covers all aspects

The STAR detector

- Acceptance: $|\eta|<1$, $0<\phi<2\pi$

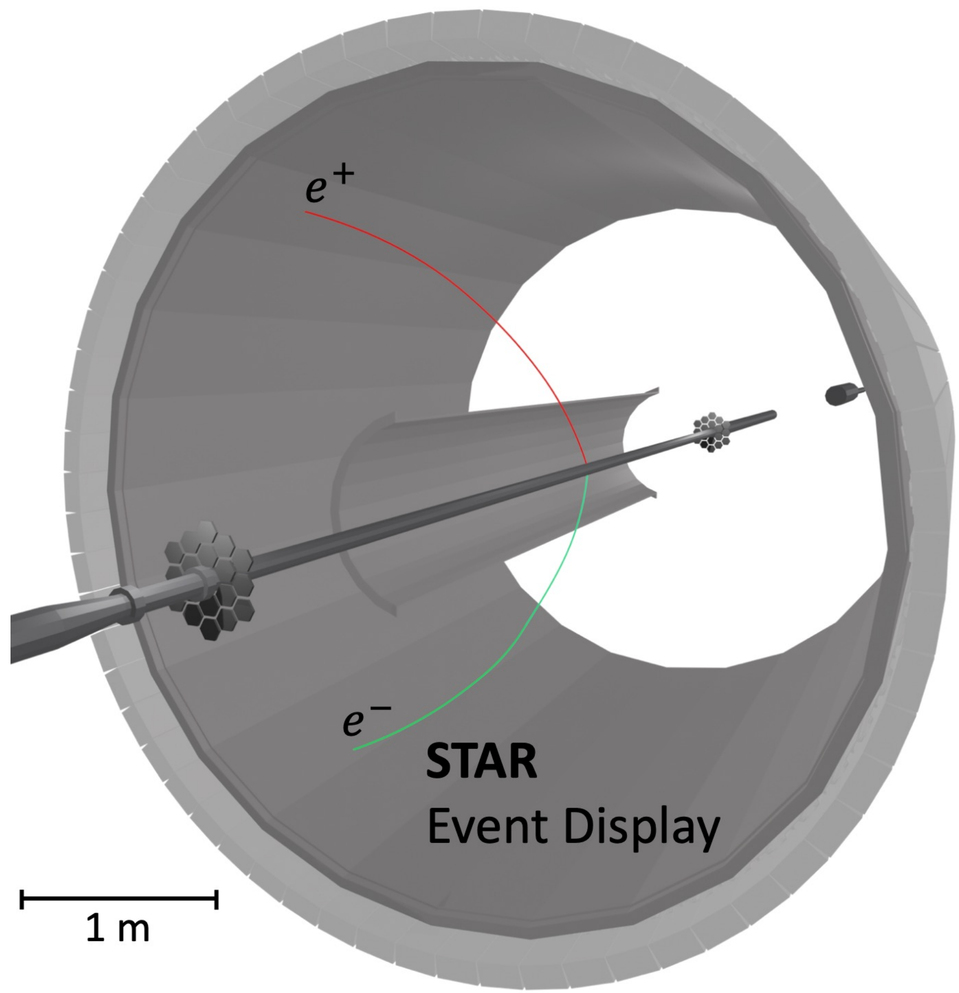


- Time Projection Chamber: tracking, momenta, and dE/dx
- Time-of-Flight: velocity

Signatures of $\gamma\gamma \to l^+l^-$

- Exclusive production of l^+l^- pair

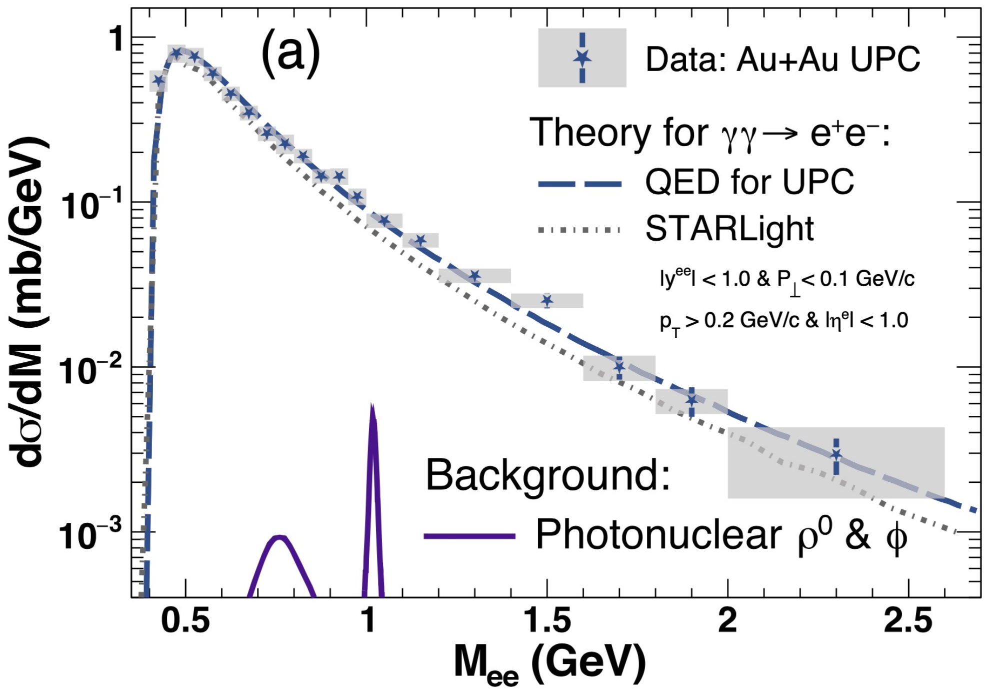
STAR, PRL 127 (2021) 052302



Signatures of $\gamma\gamma \rightarrow l^+l^-$

- Exclusive production of l^+l^- pair
- Smooth mass spectrum

STAR, PRL 127 (2021) 052302
W. Zha et al., PLB 800 (2020) 135089
S. Klein et al., CPC 212 (2017) 258

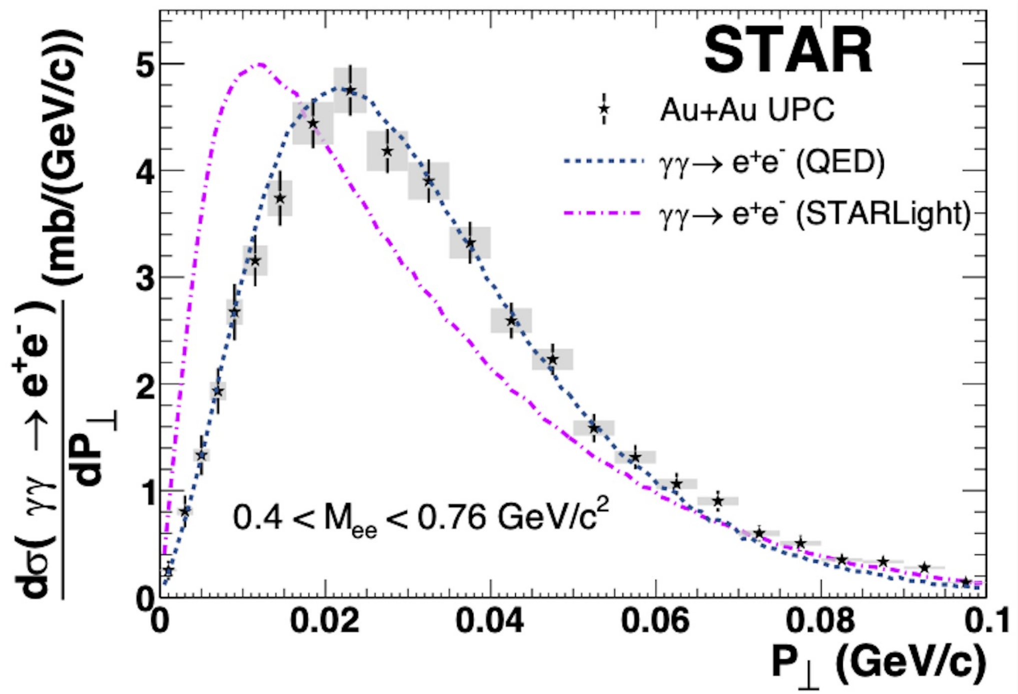


- l^+l^- production inside nucleus
  - QED (✓)
  - STARlight (X)

Signatures of $\gamma\gamma \rightarrow l^+l^-$

- Exclusive production of l^+l^- pair
- Smooth mass spectrum
- Concentrated at low p_T
  - Back-to-back in transverse plane

STAR, PRL 127 (2021) 052302
W. Zha et al., PLB 800 (2020) 135089
S. Klein et al., CPC 212 (2017) 258

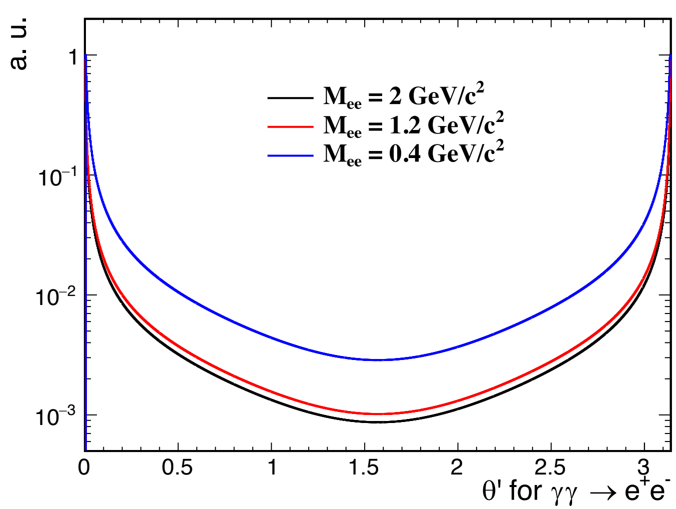


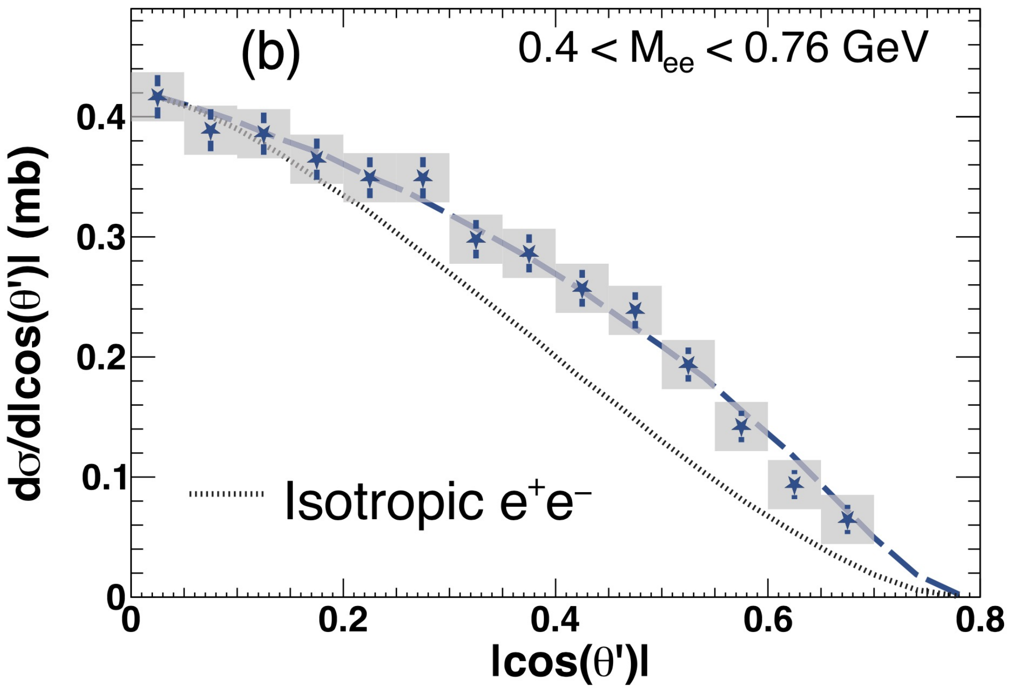
- *b* dependence of photon p_T
  - QED (✓)
  - STARlight (✗)

Signatures of $\gamma\gamma \rightarrow l^+l^-$

STAR, PRL 127 (2021) 052302
W. Zha et al., PLB 800 (2020) 135089
S. Klein et al., CPC 212 (2017) 258

- Exclusive production of l^+l^- pair
- Smooth mass spectrum
- Concentrated at low p_T
  - Back-to-back in transverse plane
- Individual l^+/l^- preferentially aligned along beam axis

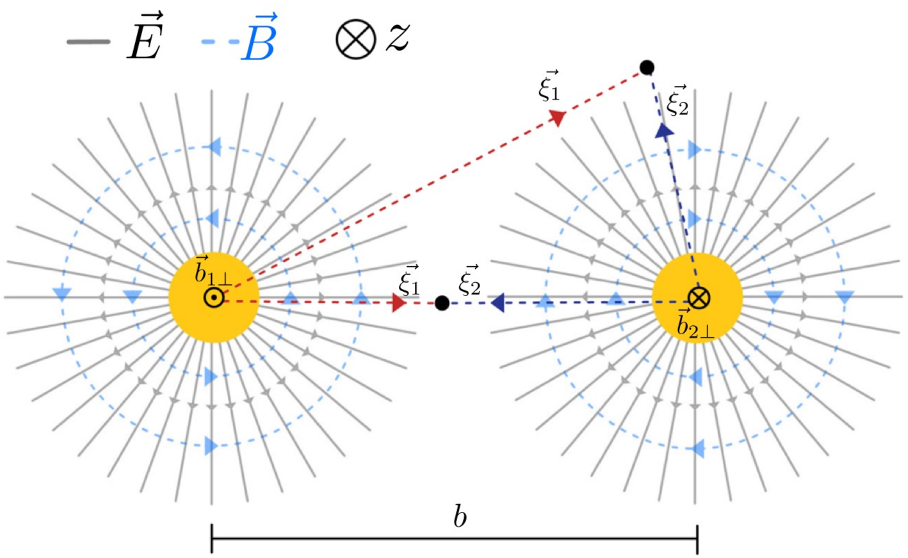




- θ': angel between e^+ and beam axis in pair rest frame

Linearly polarized photons

$$\vec{E} \perp \vec{B} \perp \vec{v}$$



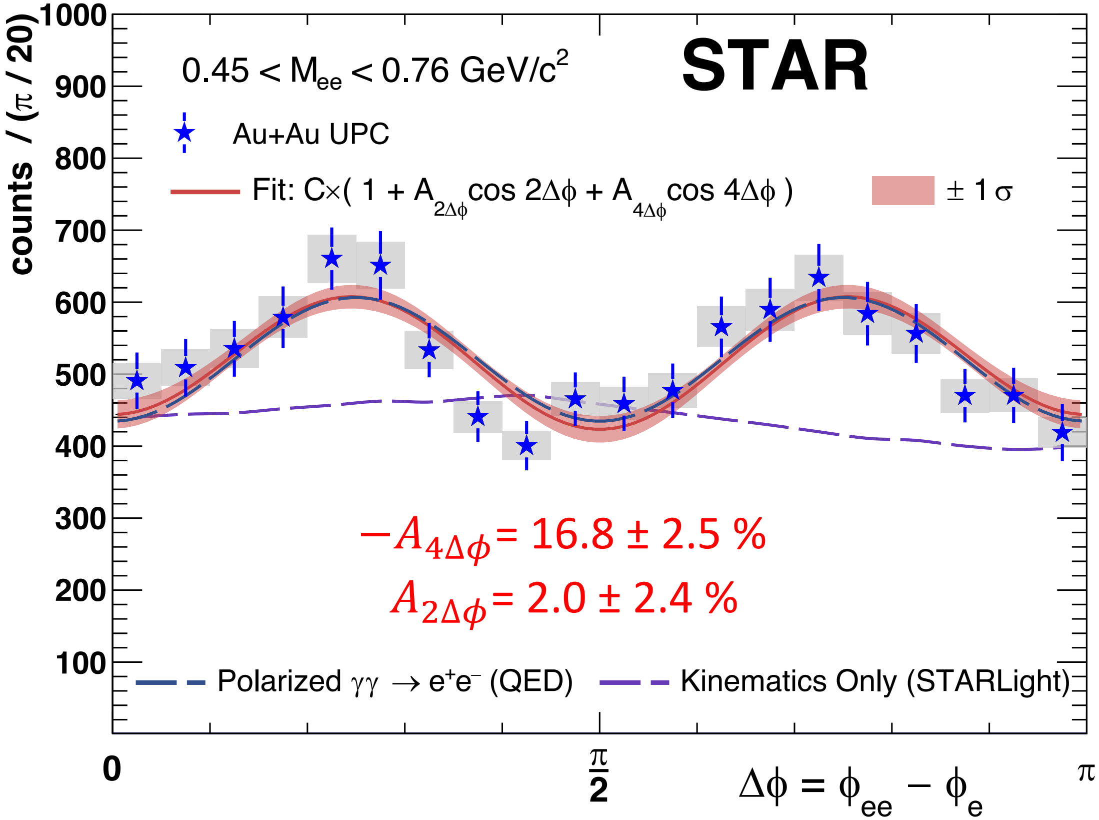
- Photon polarization direction ($\vec{\xi}$) is parallel to $\vec{E}$
- Recently realized, collision of linearly polarized photons lead to a cos(4$\Delta\phi$) modulation
  - cos(2$\Delta\phi$) $\propto m_l^2/p_{T,l}^2$

C. Li et al., PLB 795 (2019) 576
J. D. Brandenburg et al., EPJA 57 (2021) 299

$$\Delta\phi = \Delta\phi[(l^+ + l^-), (l^+ - l^-)]$$
$$\approx \Delta\phi[(l^+ + l^-), l^+]$$

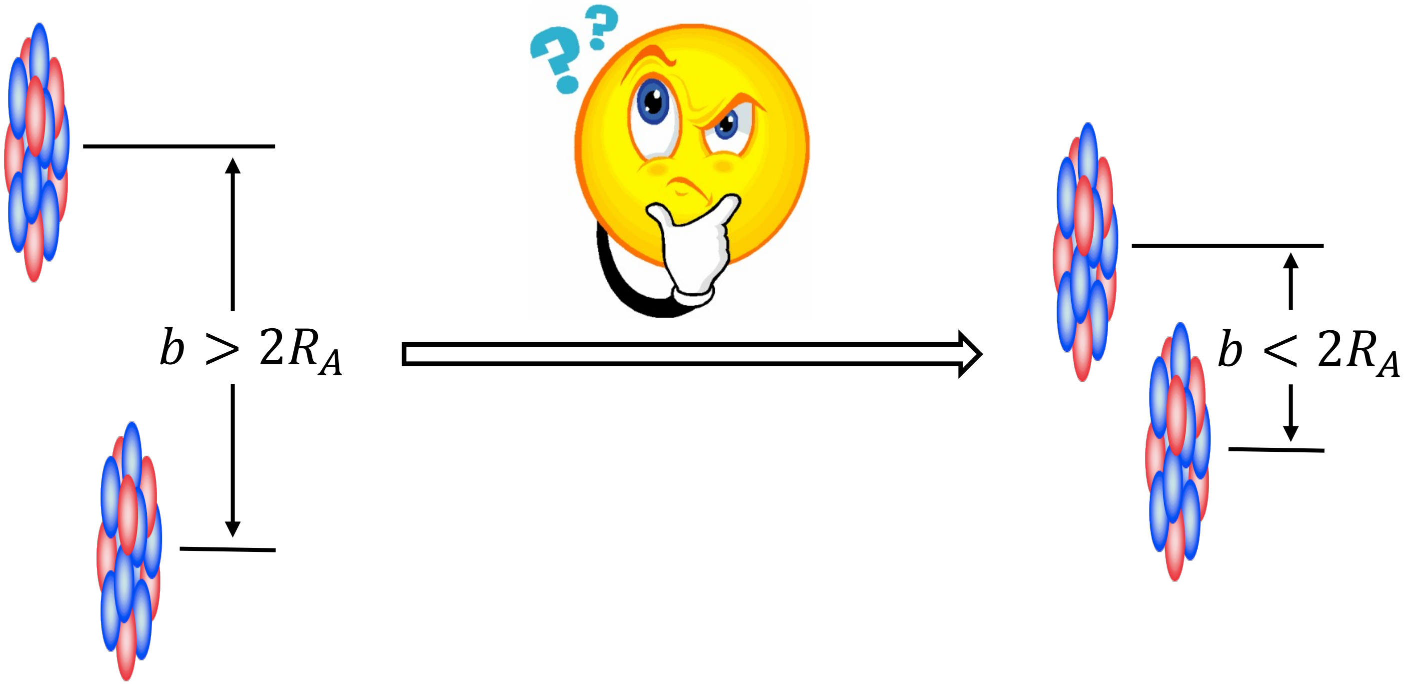
Linearly polarized photon

STAR, PRL 127 (2021) 052302



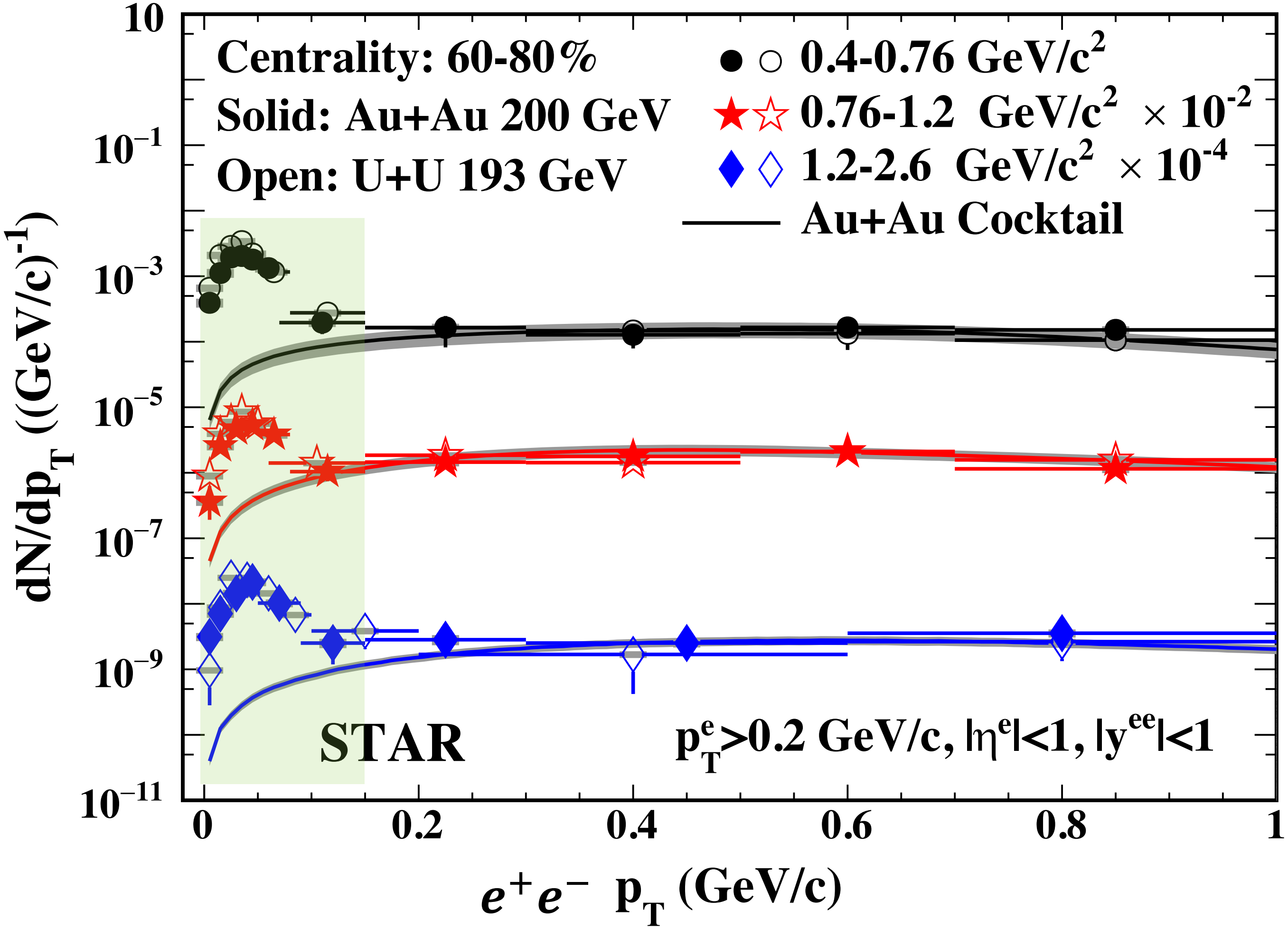
- Firstly observed 6.7 σ cos $4\Delta\phi$ modulation
  - Experimental evidence of linearly polarized photons
  - Analogous to vacuum birefringence

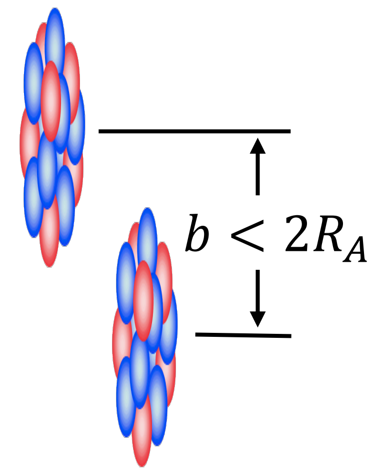
From UPC to hadronic collisions



Concentrated at low p_T

STAR, PRL 121 (2018) 132301

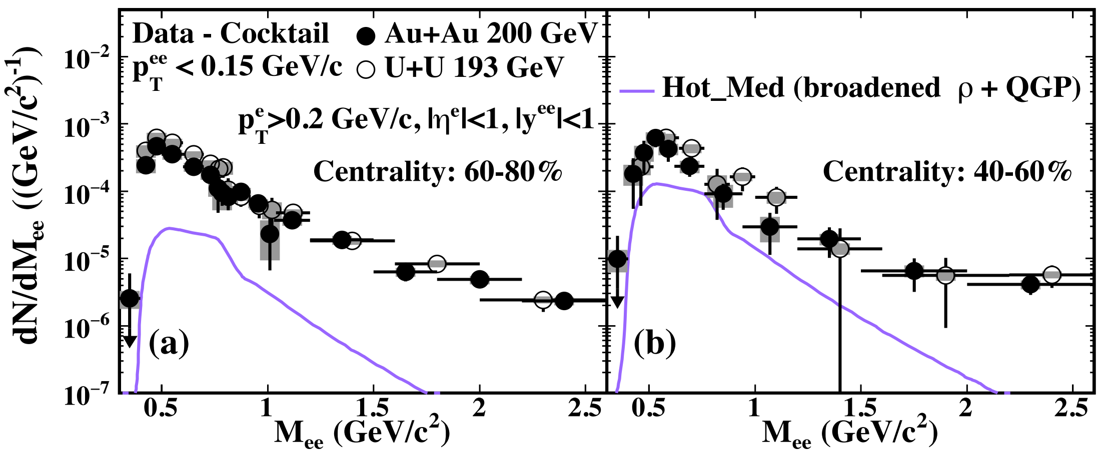




Excess mass spectra

STAR, PRL 121 (2018) 132301

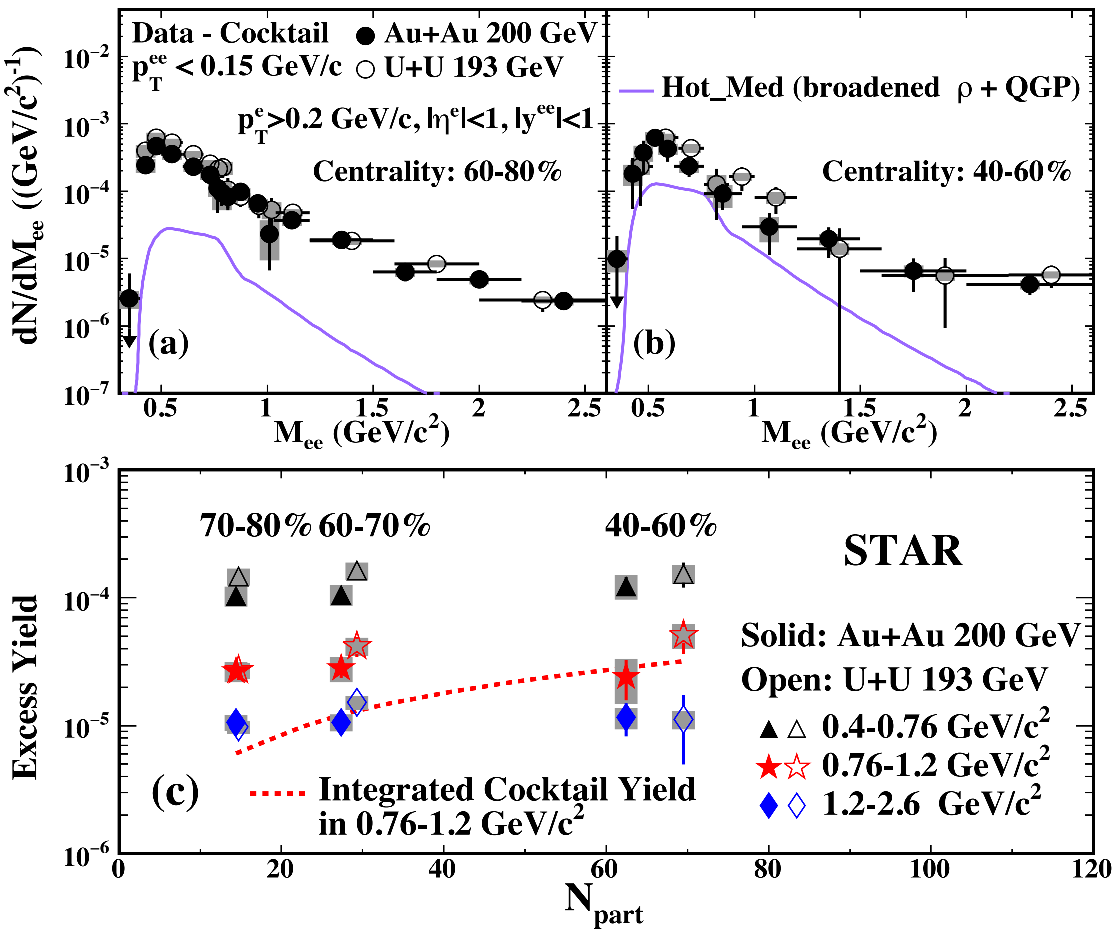
Excess = data - cocktail



- Smooth mass spectra
  - In-medium broadened ρ (✗)

Excess mass spectra

STAR, PRL 121 (2018) 132301

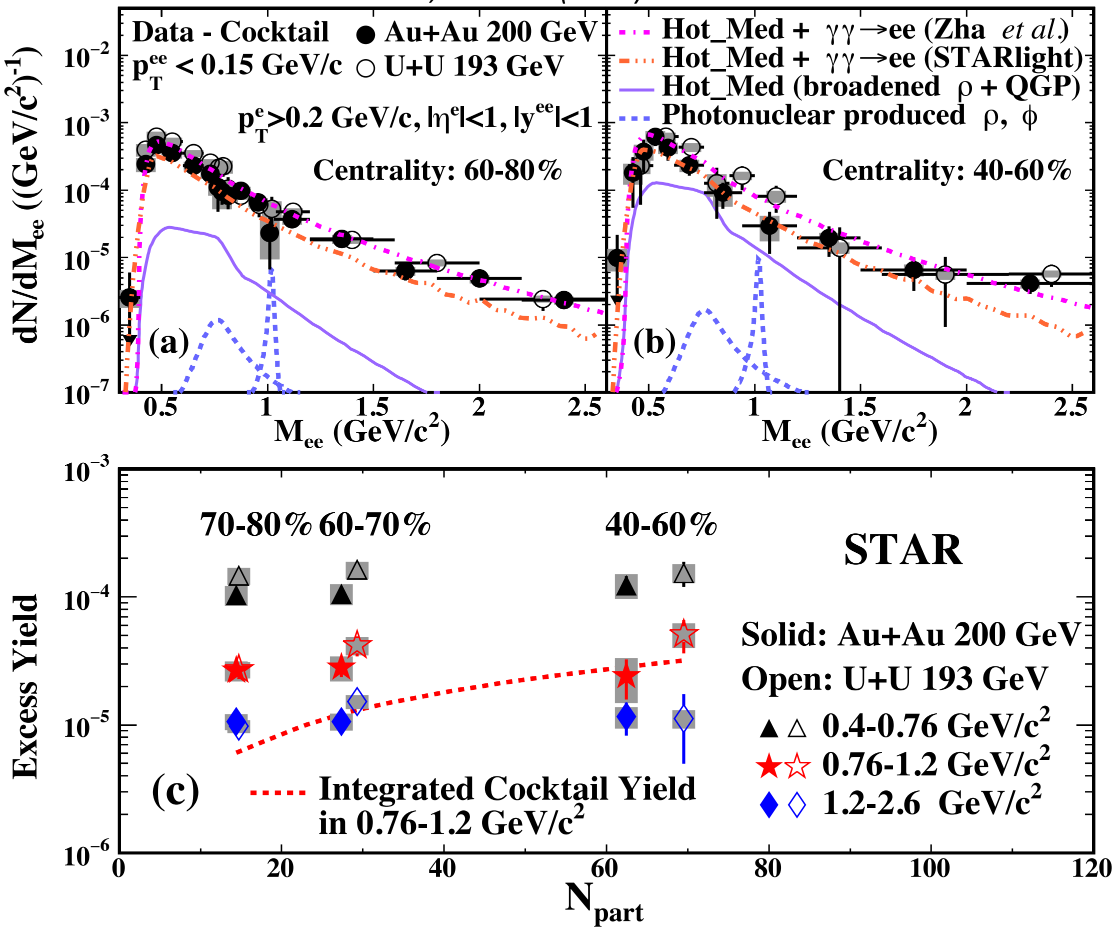


Excess = data - cocktail

- Smooth mass spectra
  - In-medium broadened ρ (✓)
  - Weak centrality dependence of excess yield

Excess mass spectra

STAR, PRL 121 (2018) 132301
W. Zha et al., PLB 781 (2018) 182
S. Klein et al., CPC 212 (2017) 258

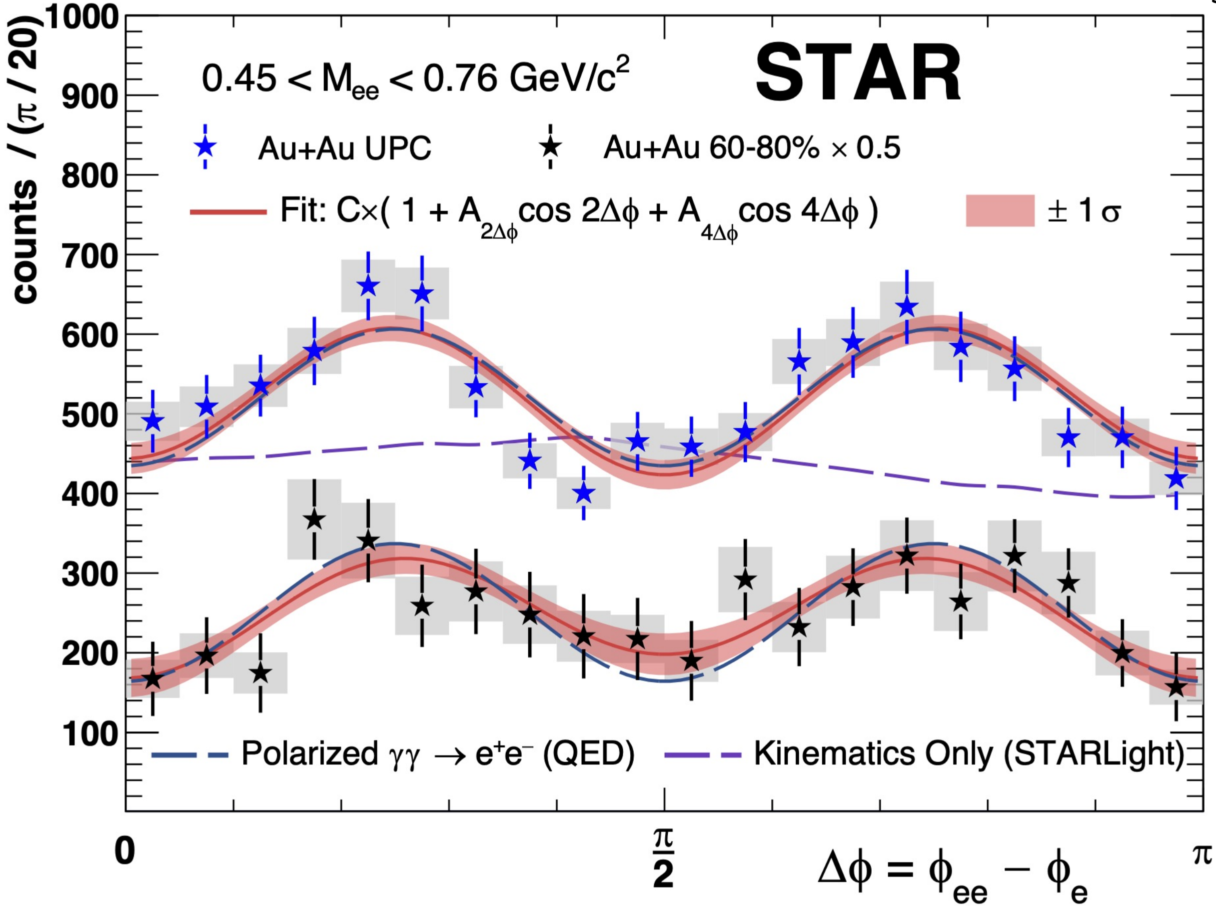


Excess = data - cocktail

- Smooth mass spectra
  - In-medium broadened ρ (✗)
  - Weak centrality dependence of excess yield
  - Negligible photoproduced vector meson contribution
  - Described by photon photon scattering models

Similar ϕ modulation

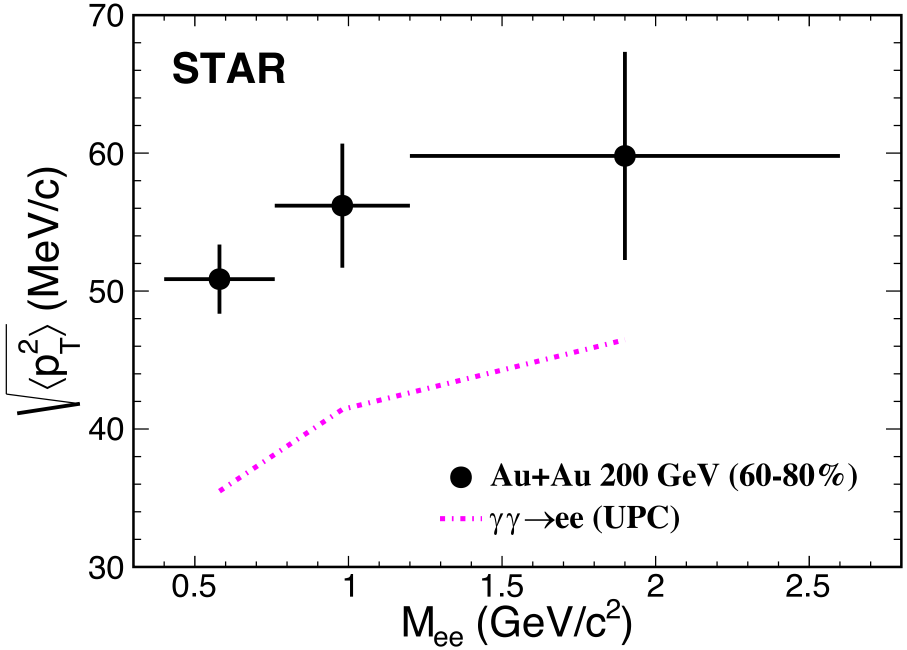
STAR, PRL 127 (2021) 052302



$-A_{4\Delta\phi}$= 27 ± 6 % in 60-80%

Modification of lepton pairs

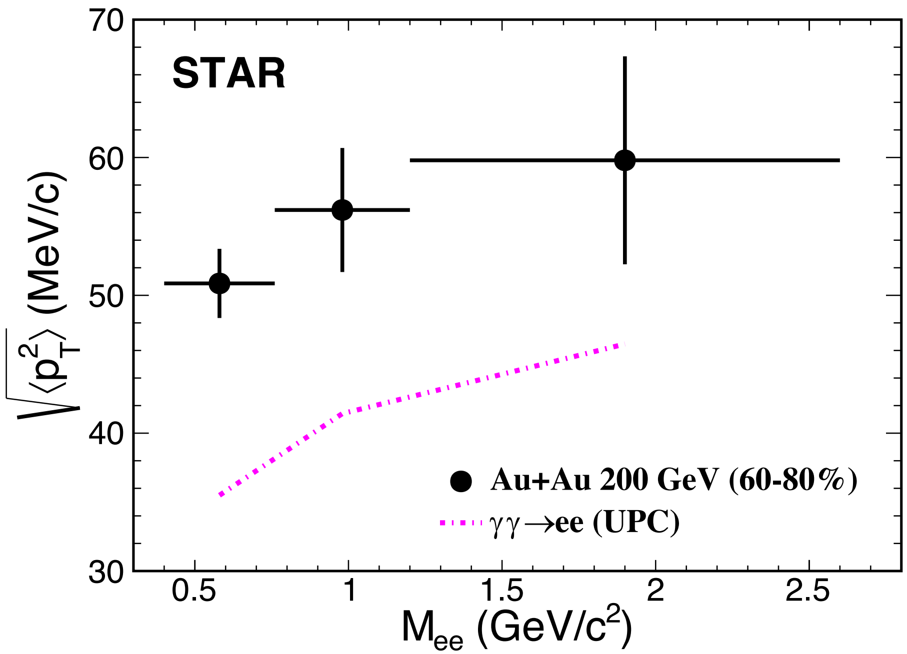
STAR, PRL 121 (2018) 132301



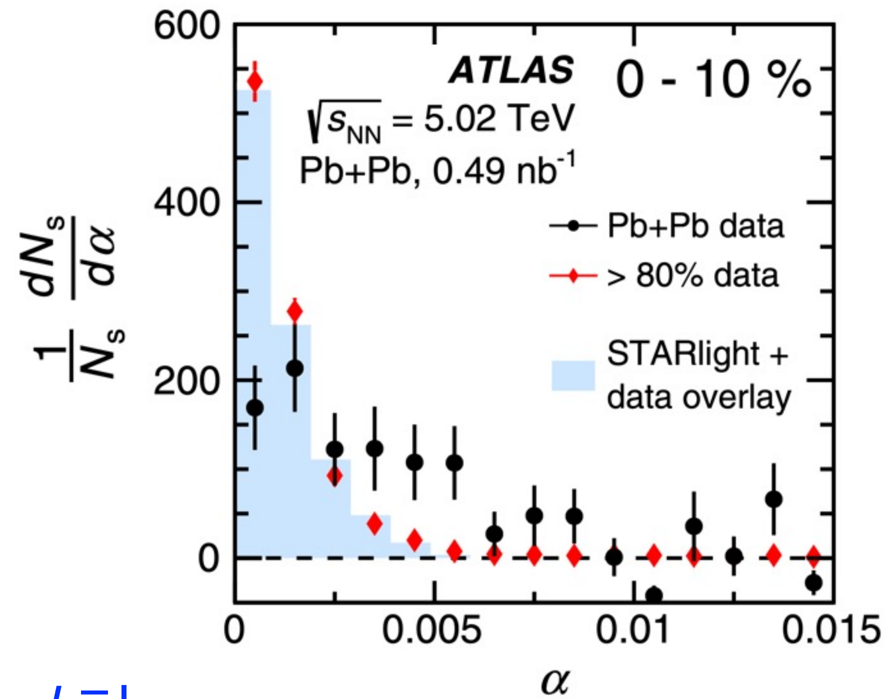
- ➢Back-to-back correlation becomes weaker towards central collisions

Modification of lepton pairs

STAR, PRL 121 (2018) 132301



ATLAS, PRL 121 (2018) 212301



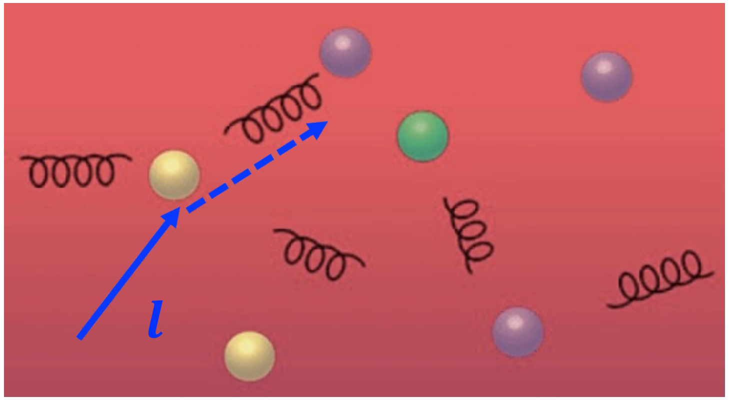
$$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi}, \alpha \propto p_T^{l^+ l^-}$$

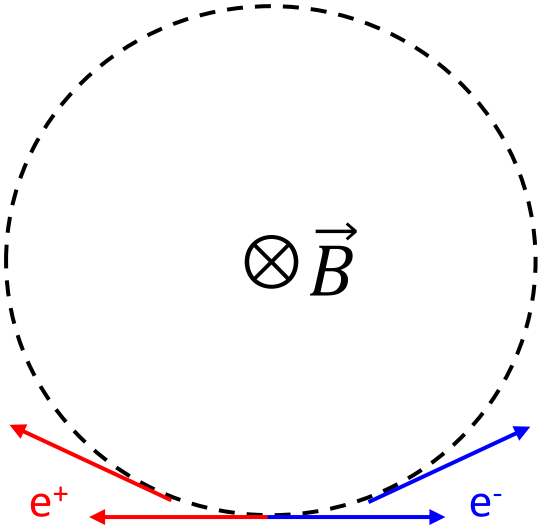
- ➢ Back-to-back correlation becomes weaker towards central collisions

Puzzle of the physics origin

STAR, PRL 121 (2018) 132301
ATLAS, PRL 121 (2018) 212301

Final-state effect?



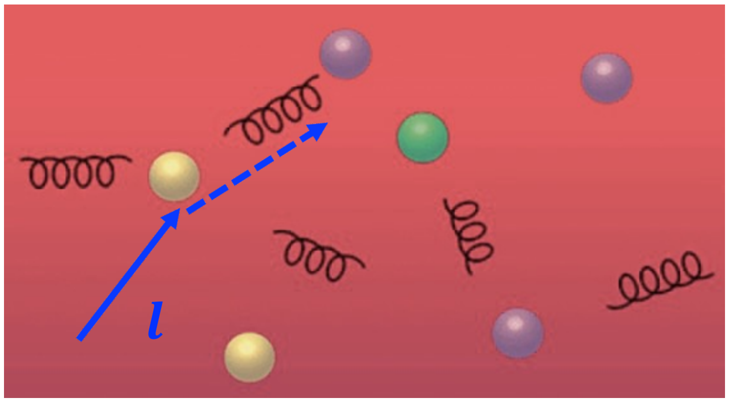


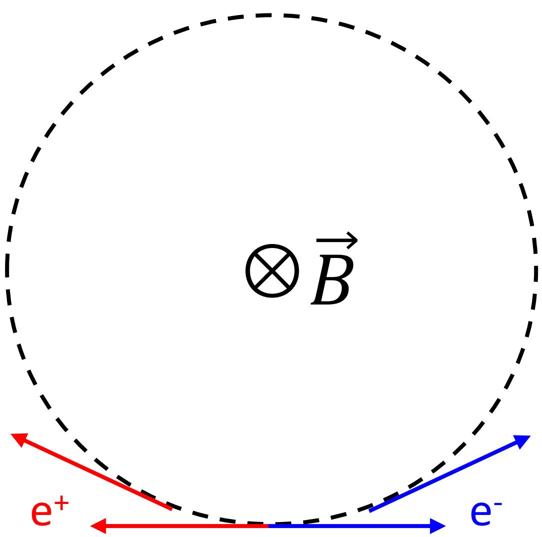
Puzzle of the physics origin

STAR, PRL 121 (2018) 132301
ATLAS, PRL 121 (2018) 212301

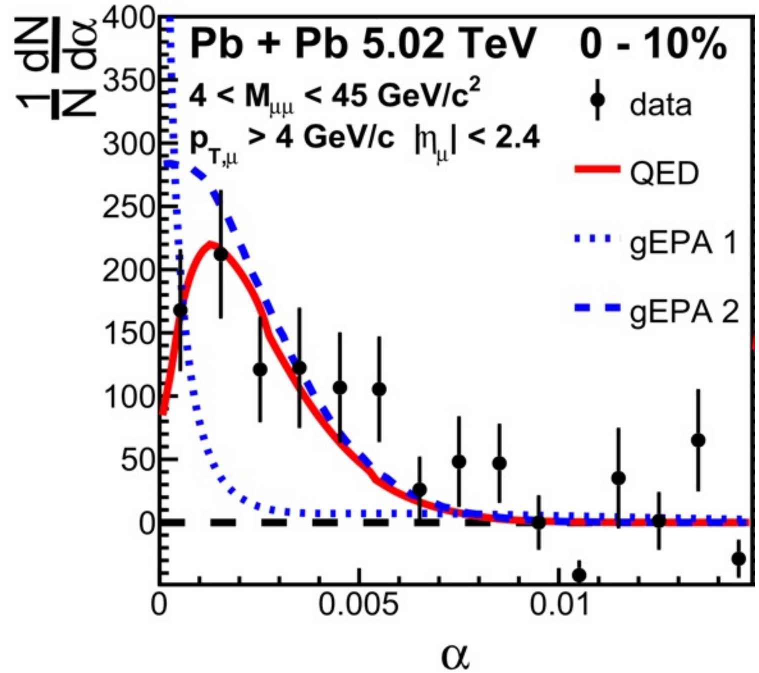
W. Zha et al., PLB 800 (2020) 135089

Final-state effect?



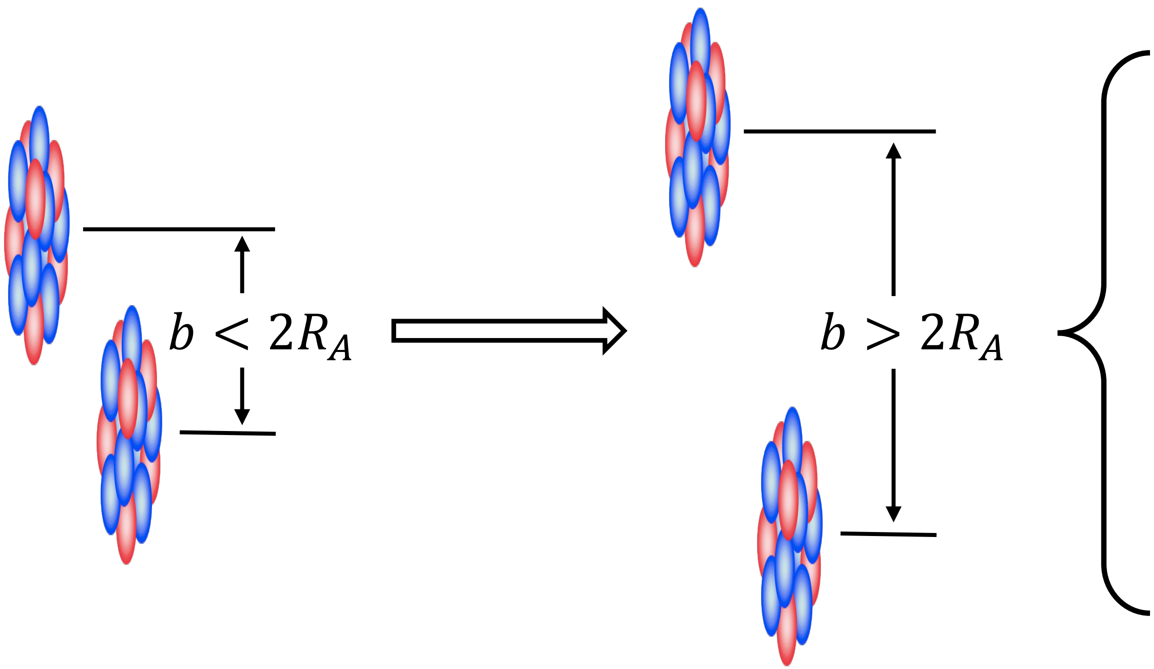


Initial-state effect?



- Described by lowest-order QED without medium effect
  - ***b*** dependence of initial photon p_T

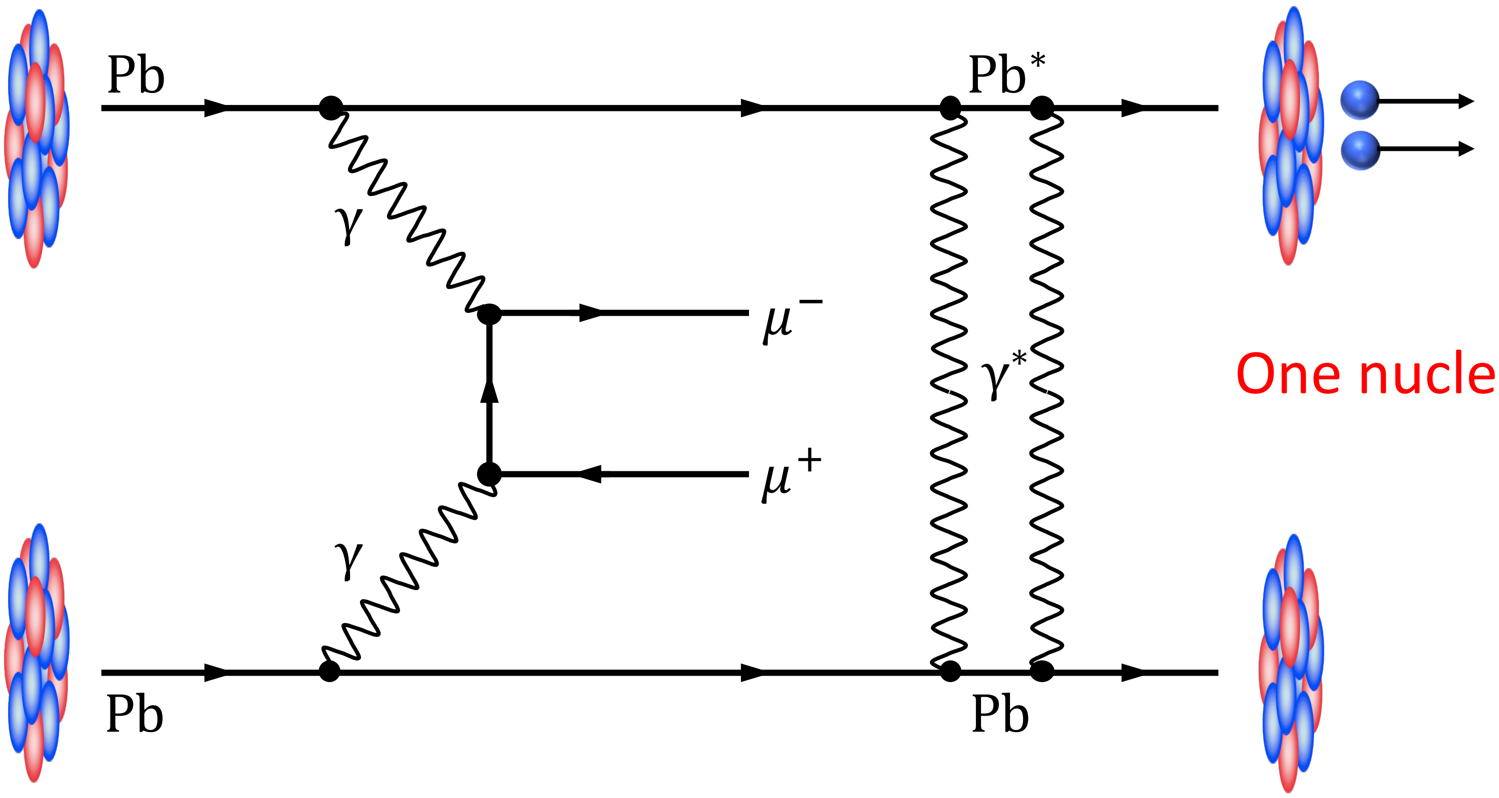
Experimentally explore the puzzle



Turn off hot medium

Control $\boldsymbol{b}$

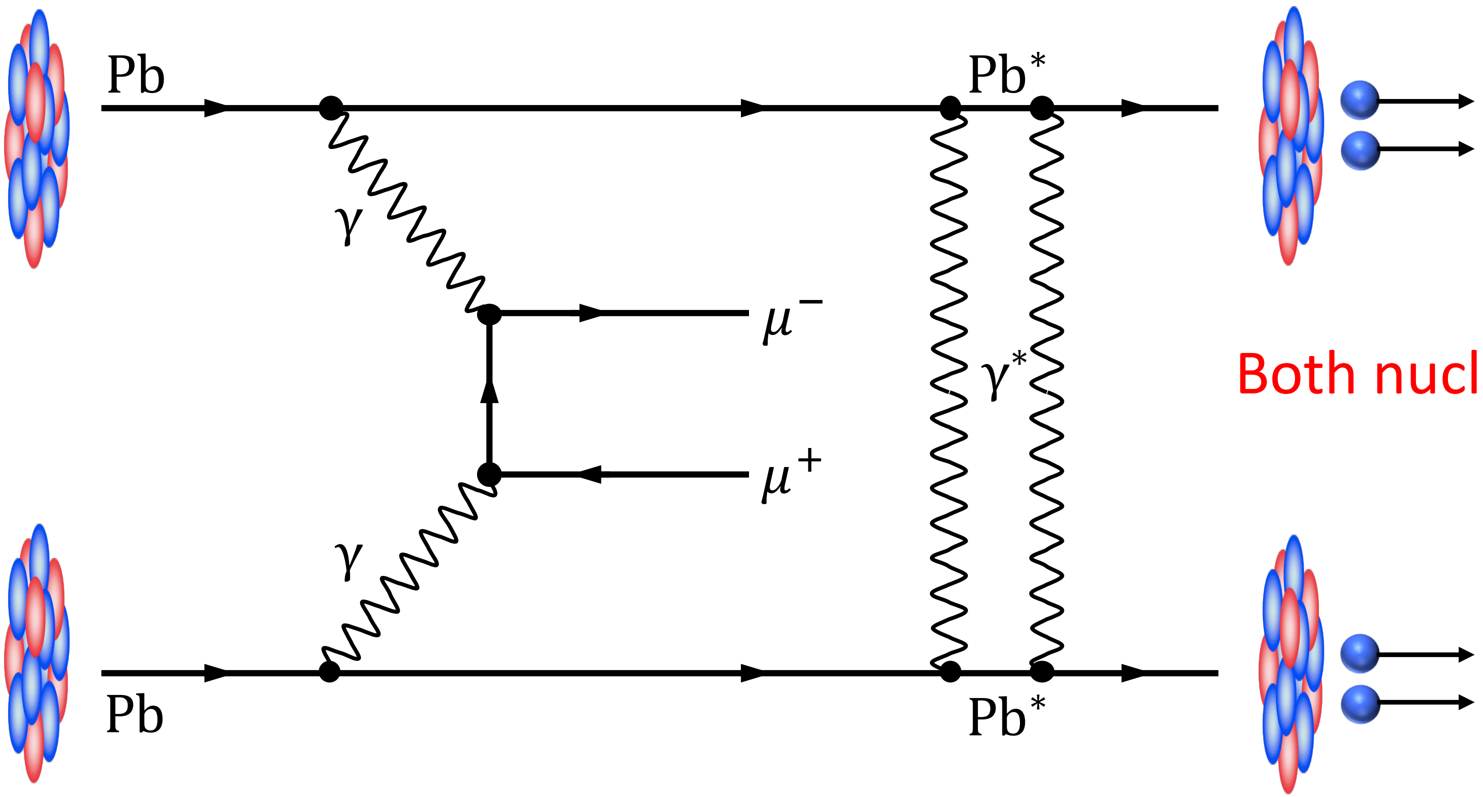
Nuclear dissociation



One nucleus breakup

➢Nuclei may exchange soft photons ⟶ nuclear dissociation

Nuclear dissociation

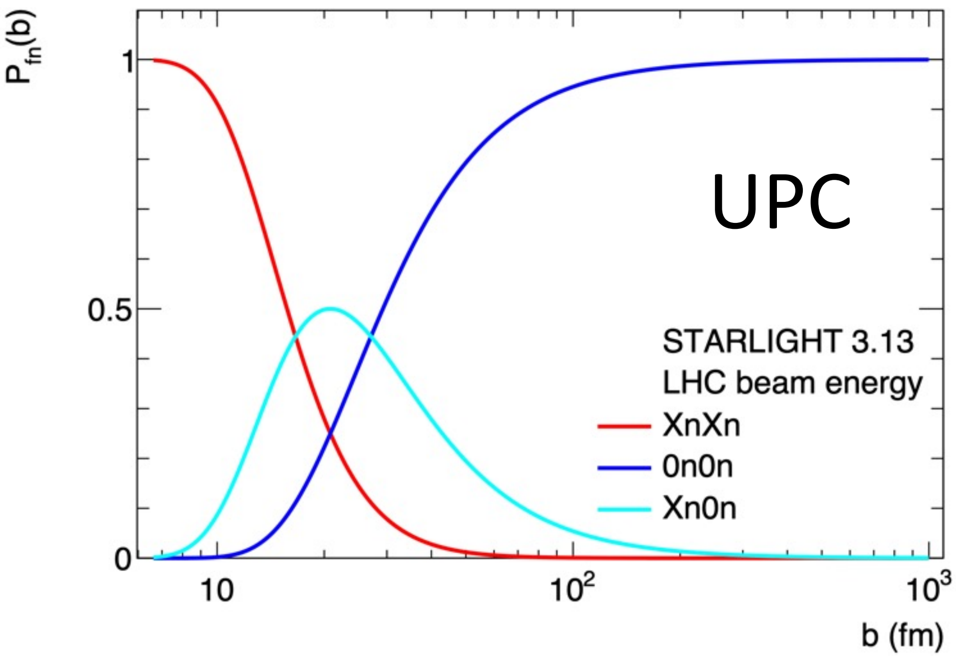


Both nuclei breakup

- Nuclei may exchange soft photons ⟶ nuclear dissociation

Control "centrality" in UPC

S. Klein and P. Steinberg, Ann. Rev. Nucl. Part. Sci. 70 (2020) 323

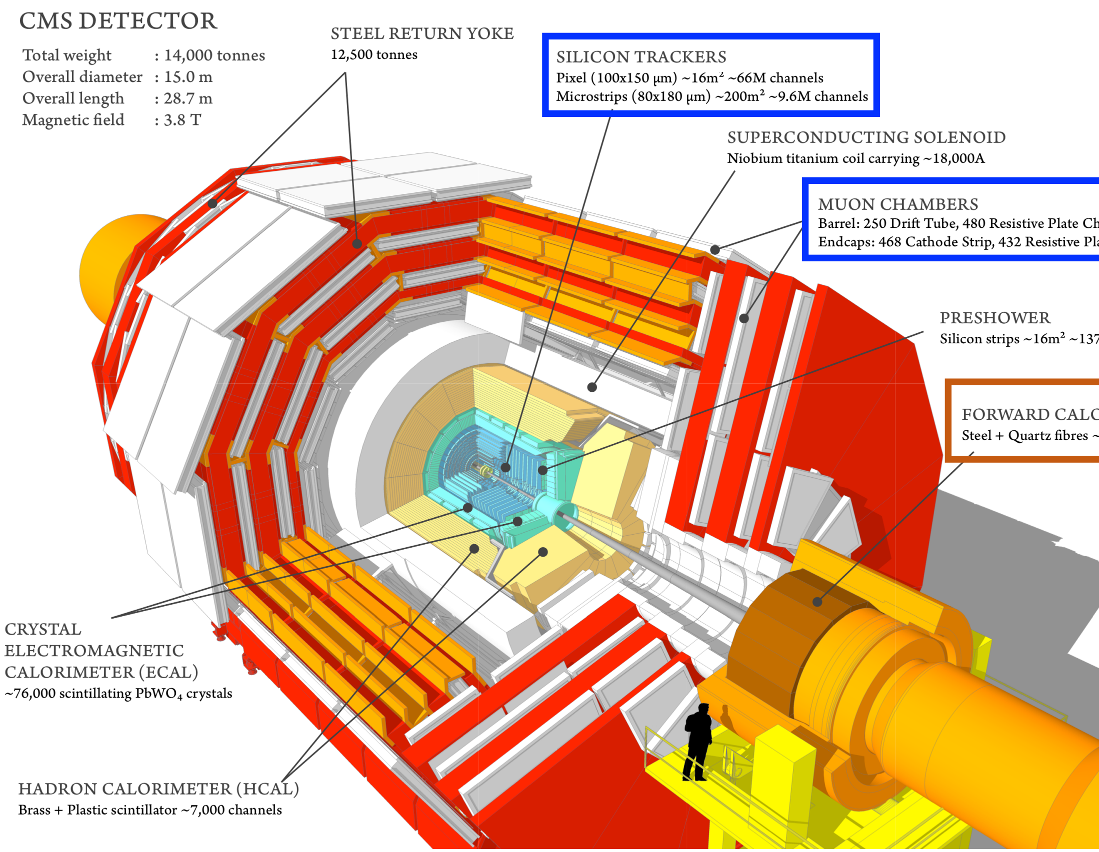


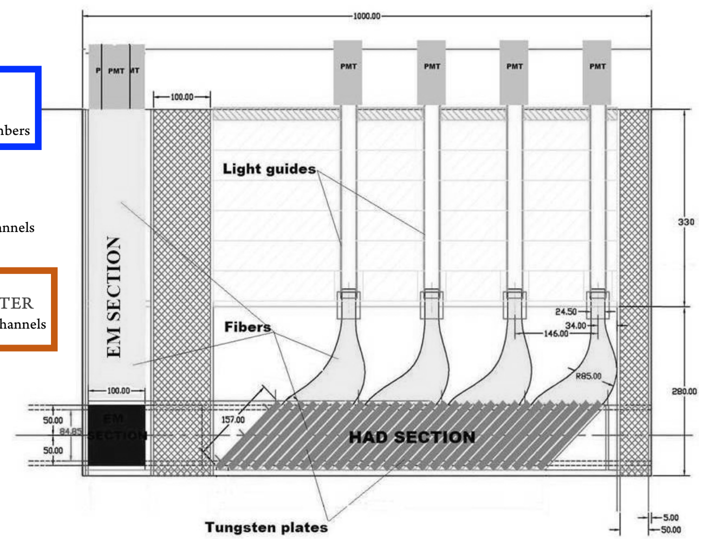
- Bearing analogy to centrality
  - $b_{XnXn} < b_{0nXn} < b_{0n0n}$

$$N(k) = \int d^2b N(k,b) P_{0\text{had}}(b) P_1(b) P_2(b)$$

$$\text{, where } P_i(b) \propto 1/b^2$$

The CMS detector



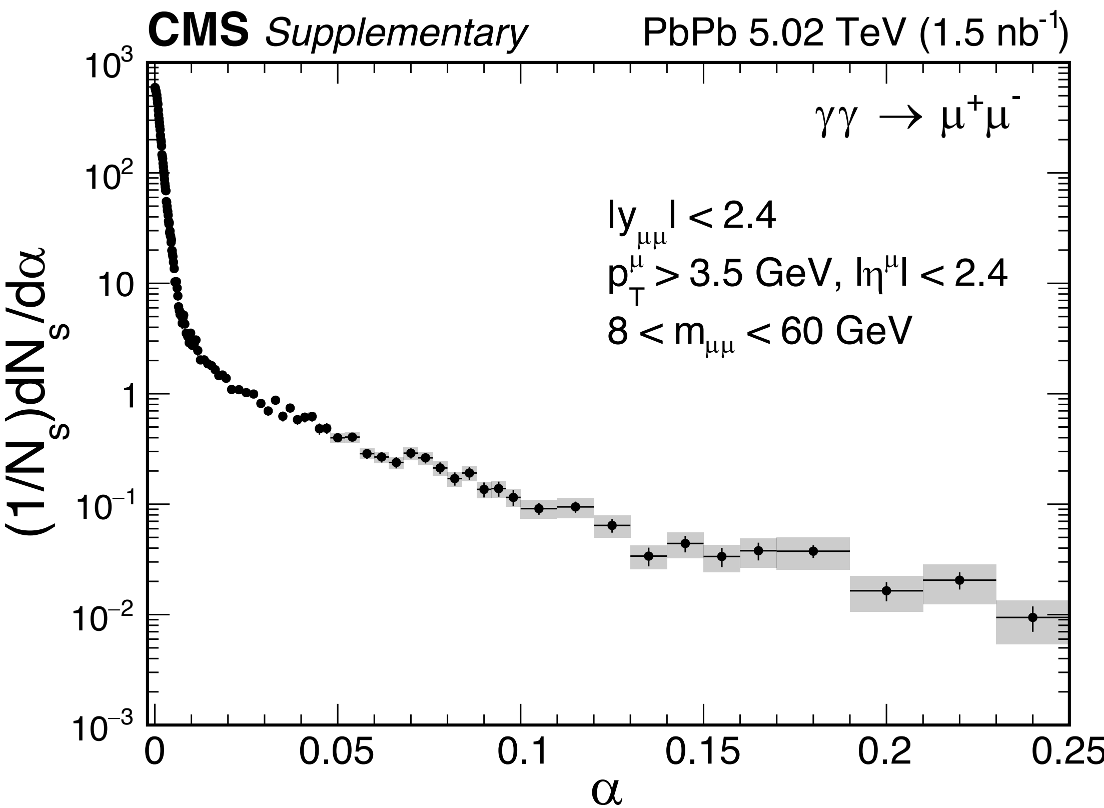


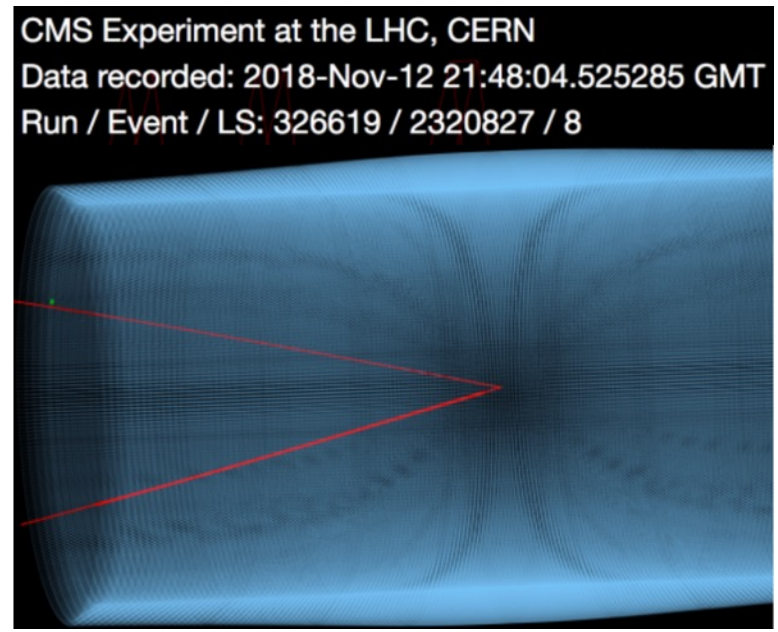
Zero Degree Calorimeter
$|\eta|$>8.3, ~140m from IP

- HF: reject hadronic collisions
- Tracker + Muon chamber: muon identification
- ZDC: Neutron detection

α distribution in UPC

CMS, PRL 127 (2021) 122001



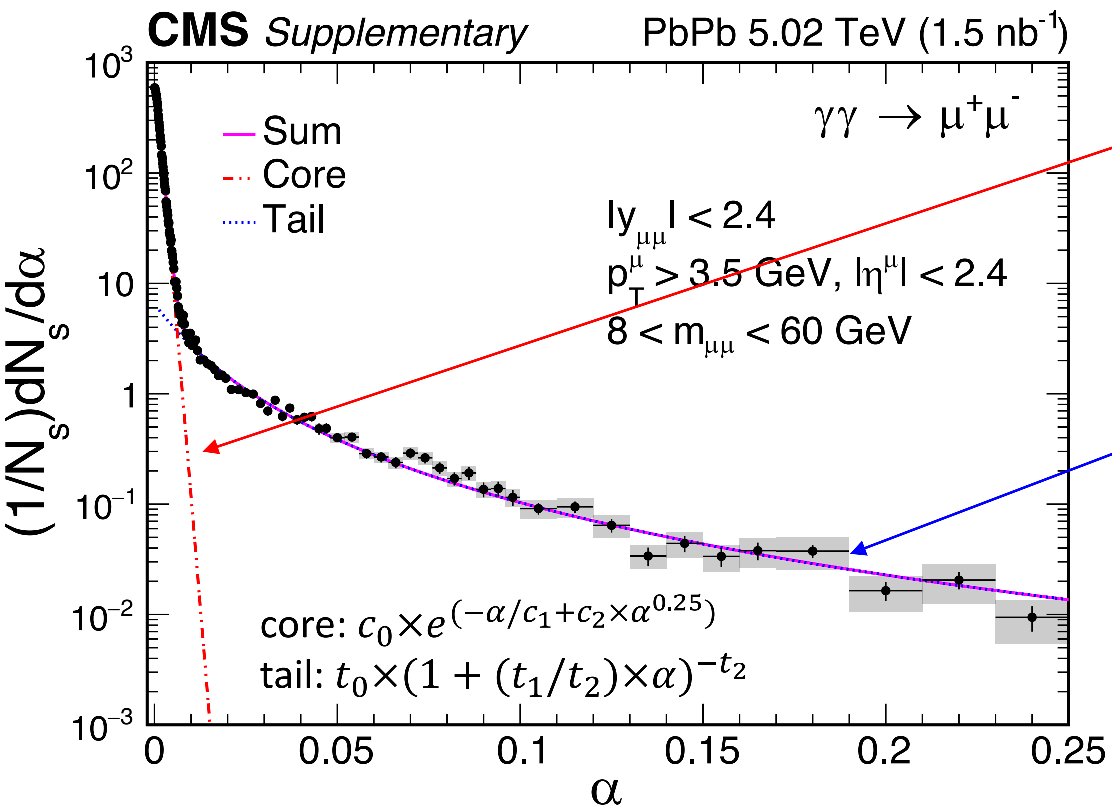


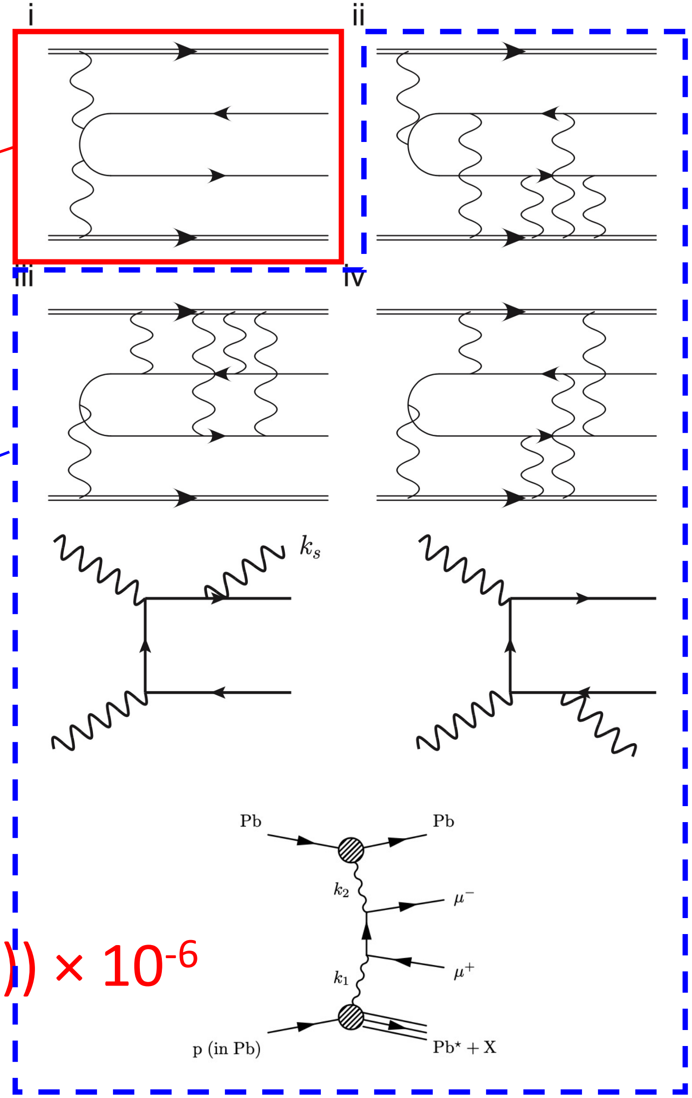
- Narrow core + Long tail

$$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi}, \alpha \propto p_T^{l^+l^-}$$

α distribution in UPC

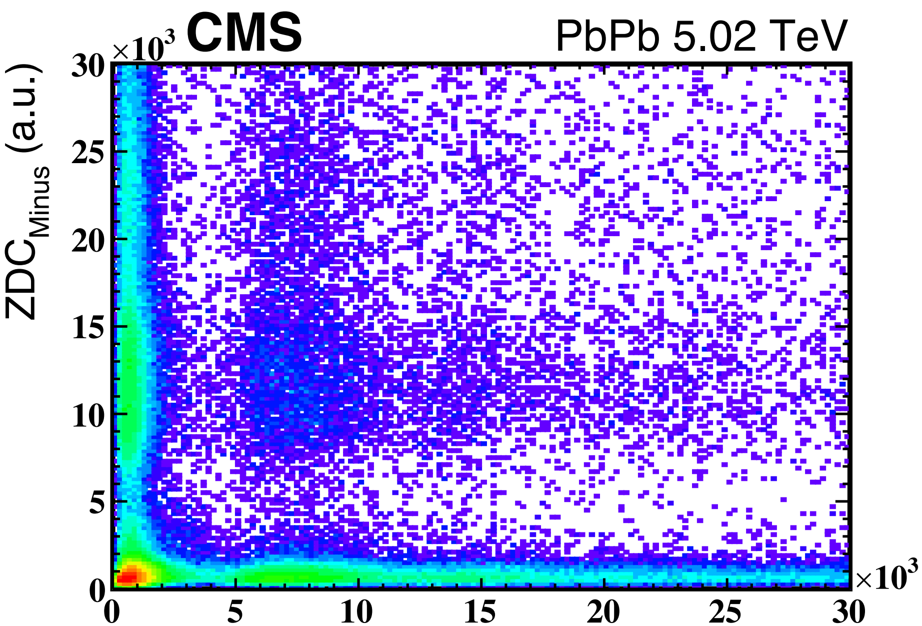
CMS, PRL 127 (2021) 122001



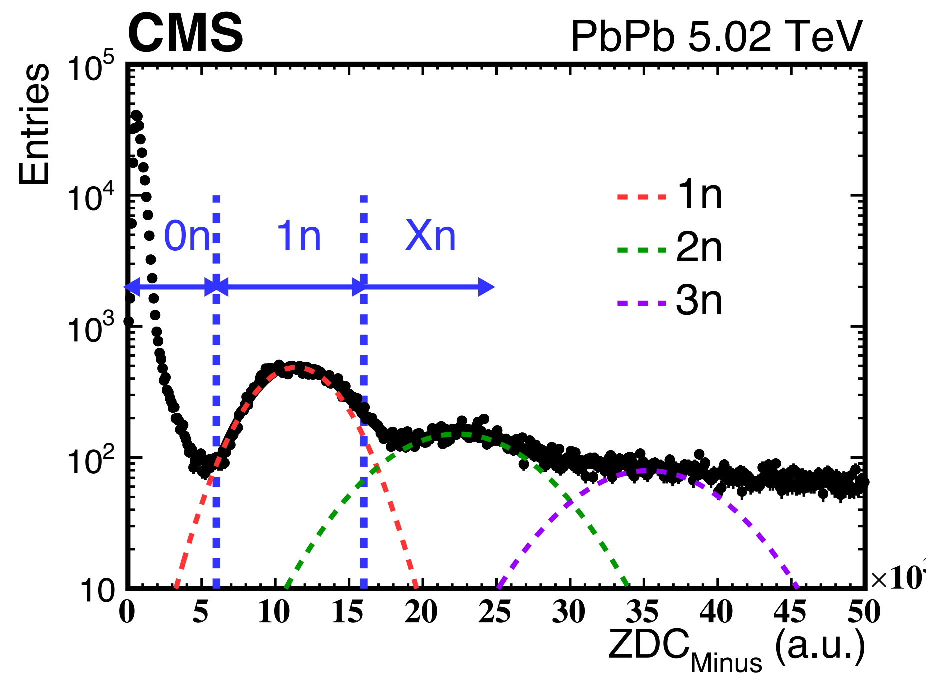


- Decouple α spectrum:
  - Data: $\langle \alpha^{core} \rangle$ = (1227 ± 7 (stat) ± 8 (syst)) × 10^{-6}
  - STARlight: $\langle \alpha^{core} \rangle$ = 1350 × 10^{-6}

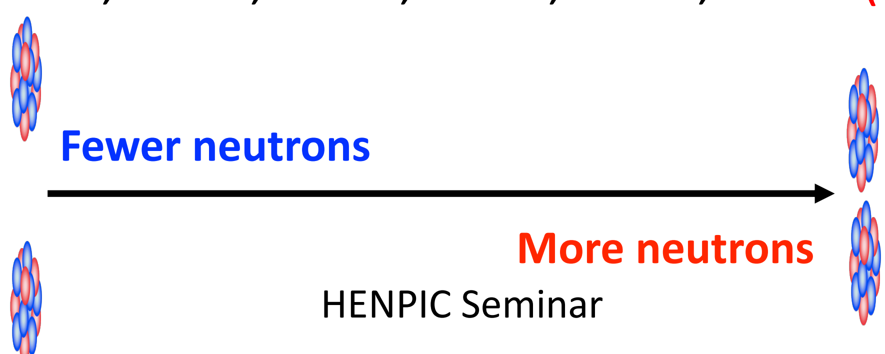
Determine neutron multiplicity



CMS, PRL 127 (2021) 122001

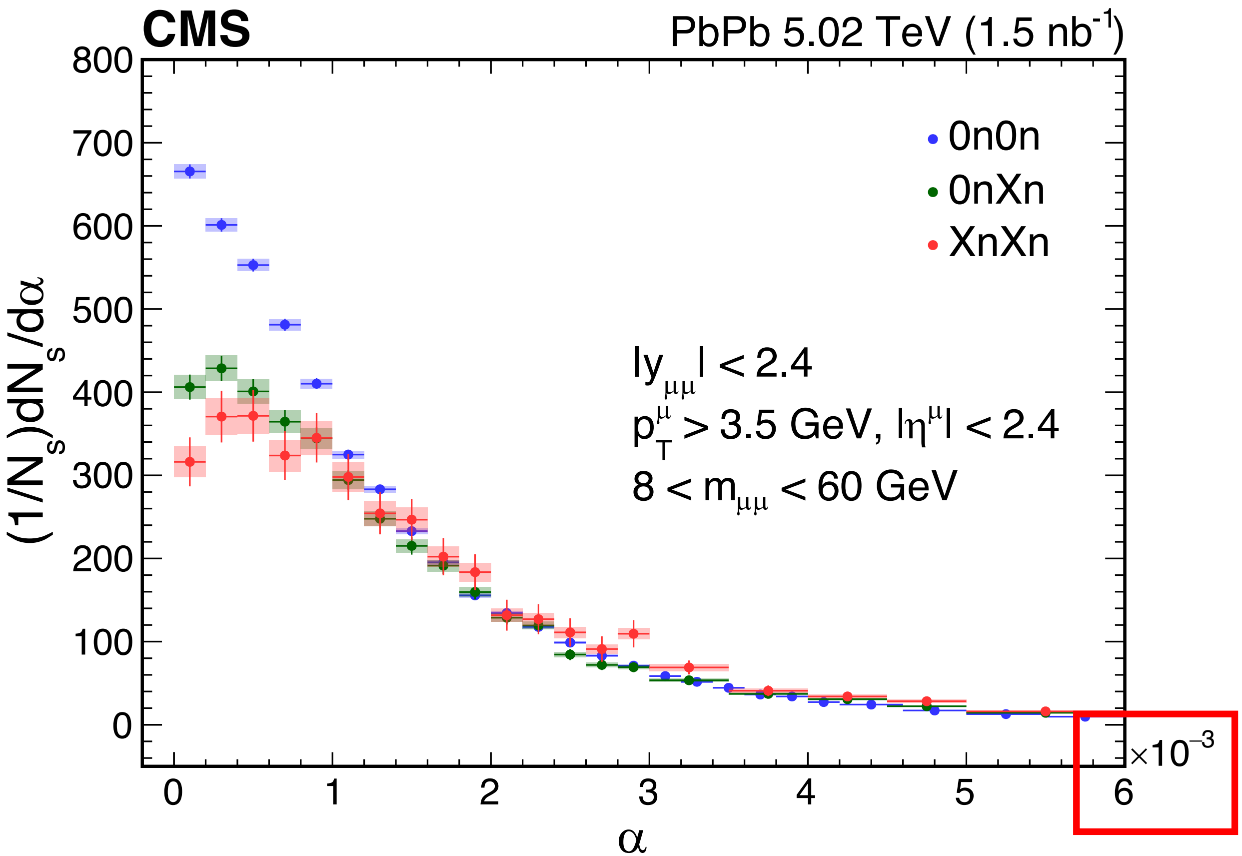


- Straight cut to disentangle neutrons
  - 0n0n, 0n1n, 0nXn, 1n1n, 1nXn, XnXn (X≥2)



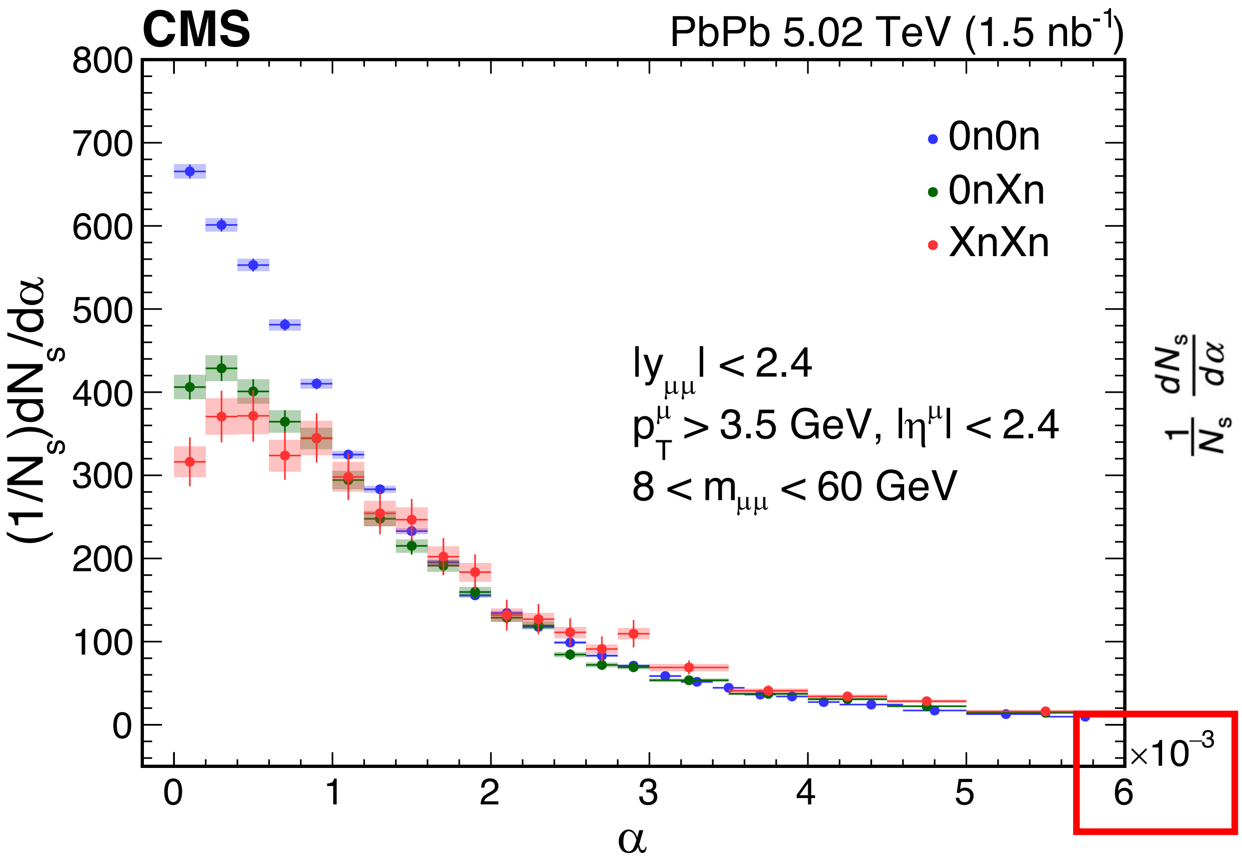
α spectrum vs. neutron multiplicity

CMS, PRL 127 (2021) 122001

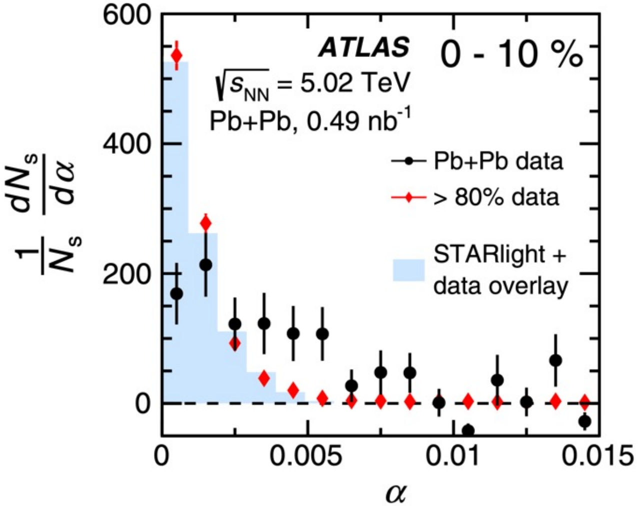


- 0n0n (fewer neutrons) $\Longrightarrow$ XnXn (more neutrons)
  - α spectrum becomes broad

α spectrum vs. neutron multiplicity

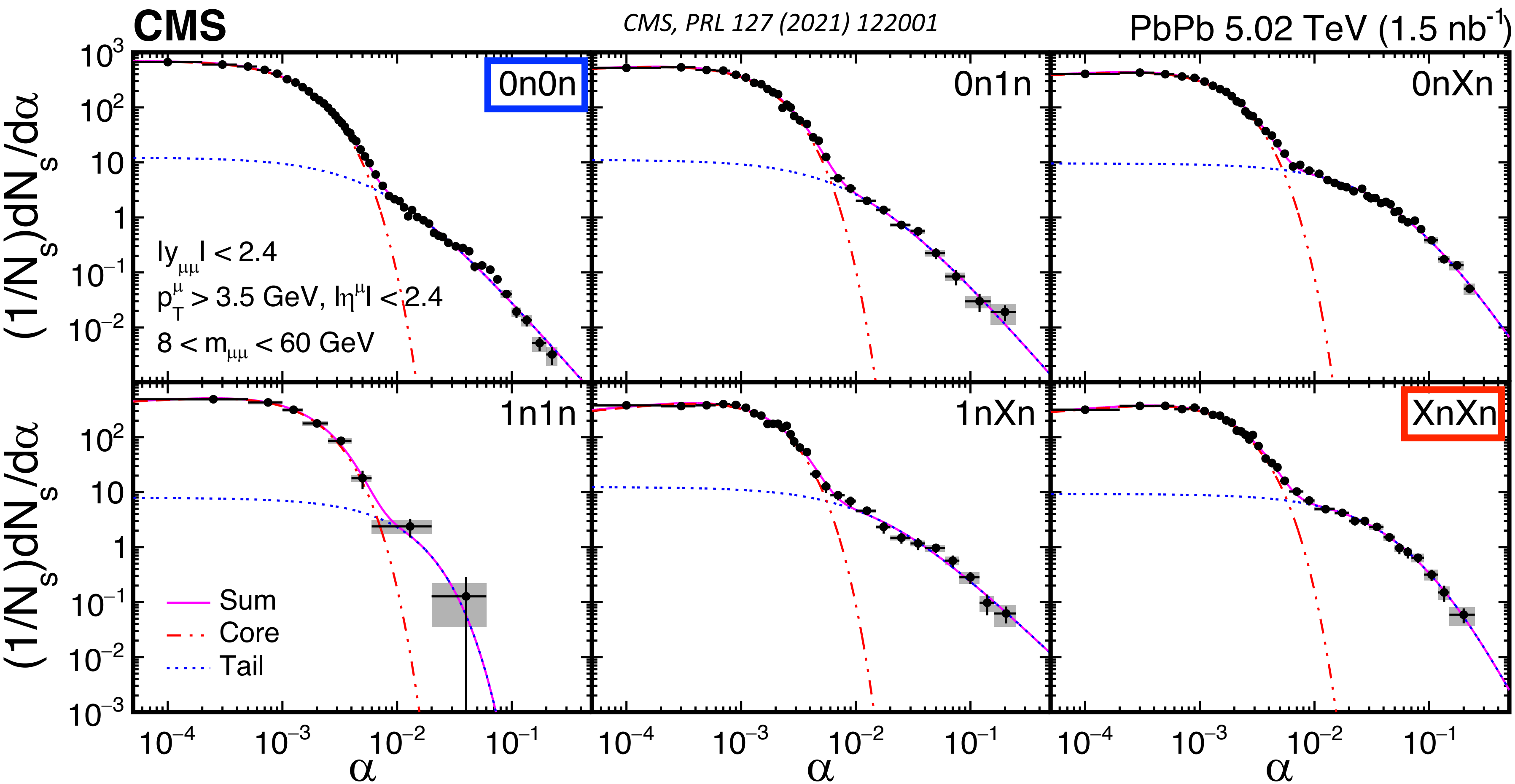


CMS, PRL 127 (2021) 122001
ATLAS, PRL 121 (2018) 212301



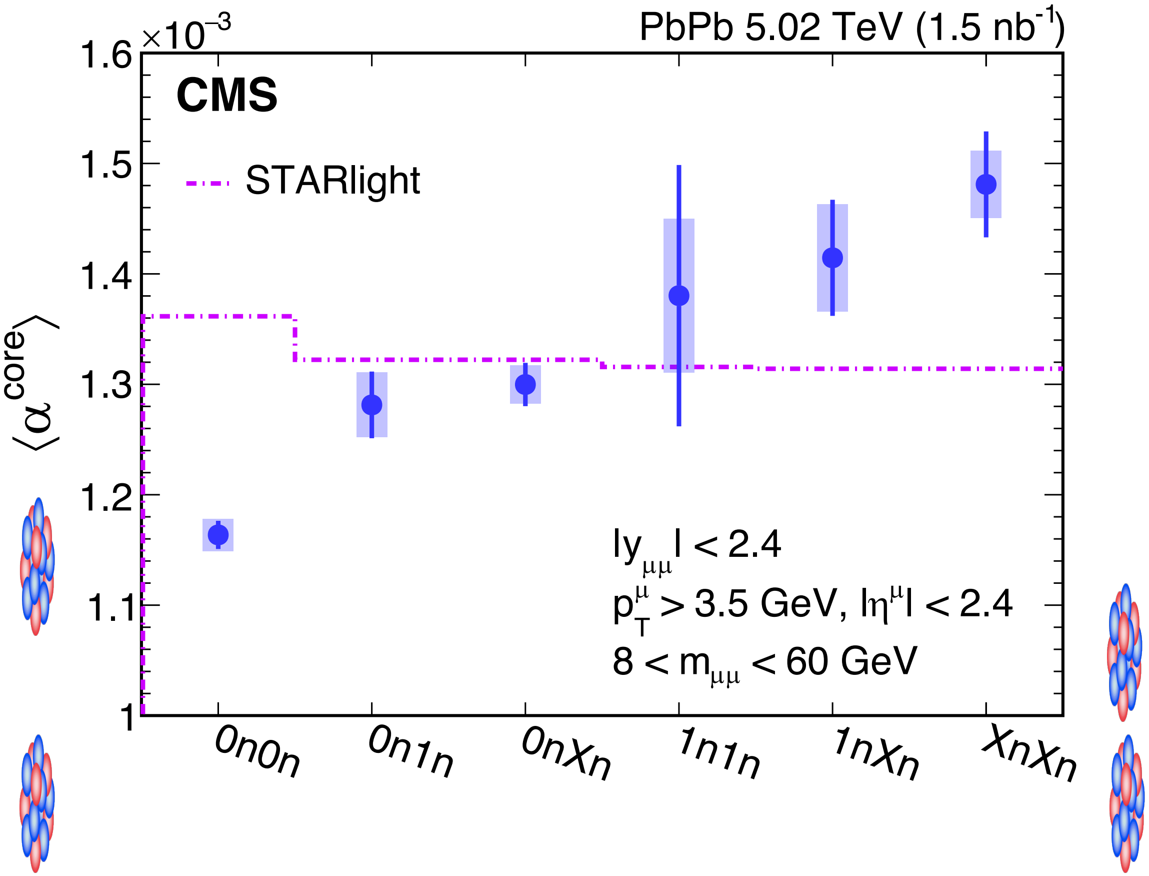
- 0n0n (fewer neutrons) $\Longrightarrow$ XnXn (more neutrons)
  - α spectrum becomes broad
  - Seems has depletion in the very small α

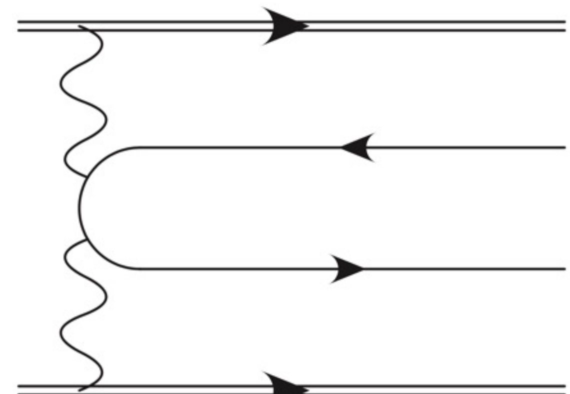
α spectrum vs. neutron multiplicity



- 0n0n (fewer neutrons) $\Longrightarrow$ XnXn (more neutrons)
  - Tail contribution becomes larger

$\langle \alpha^{\text{core}} \rangle$ vs. neutron multiplicity

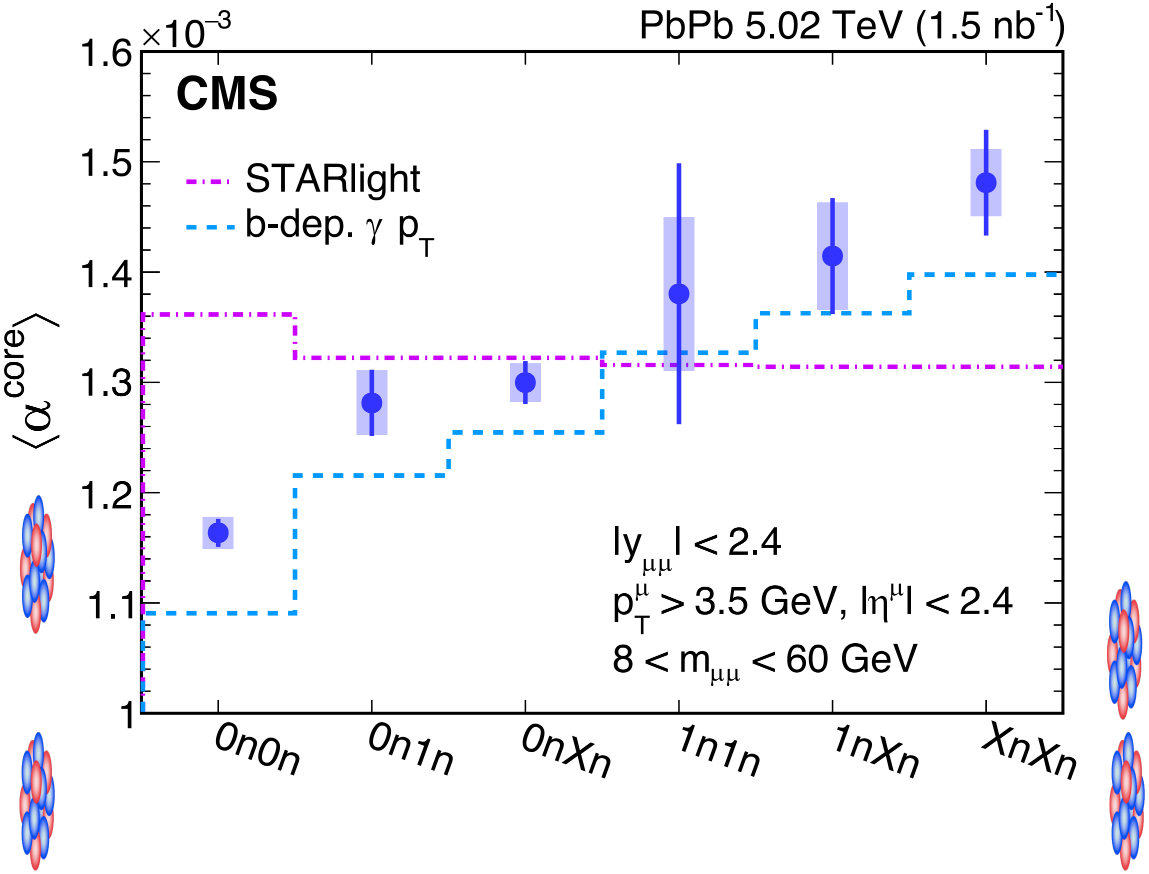


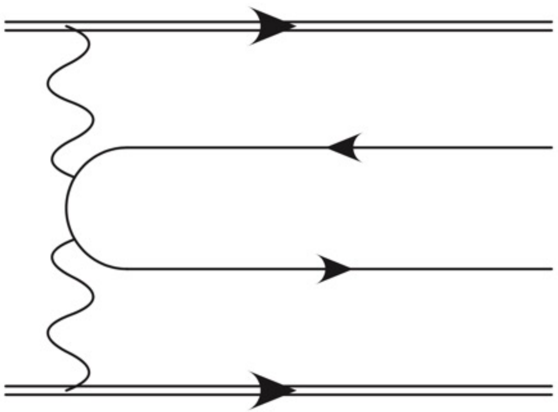


CMS, PRL 127 (2021) 122001

- Strong neutron multiplicity dependence of $\langle \alpha^{\text{core}} \rangle$
  - Deviation from constant: 5.7σ
  - ***b*** dependence of initial photon p_T

$\langle\alpha^{core}\rangle$ vs. neutron multiplicity



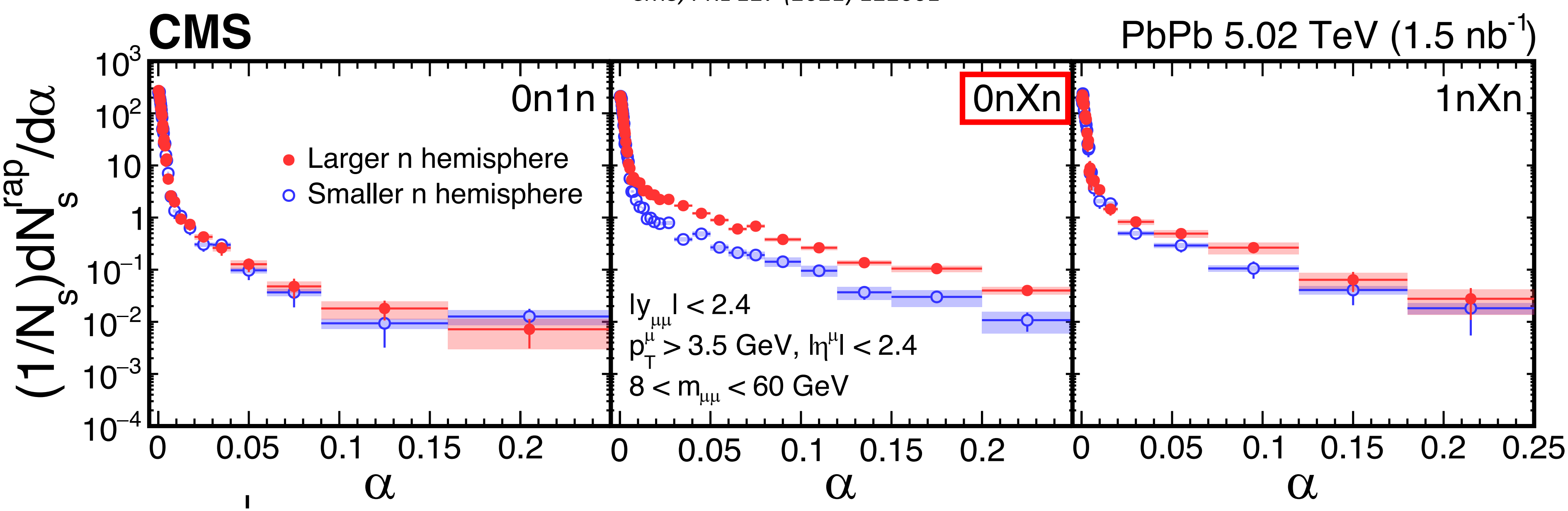


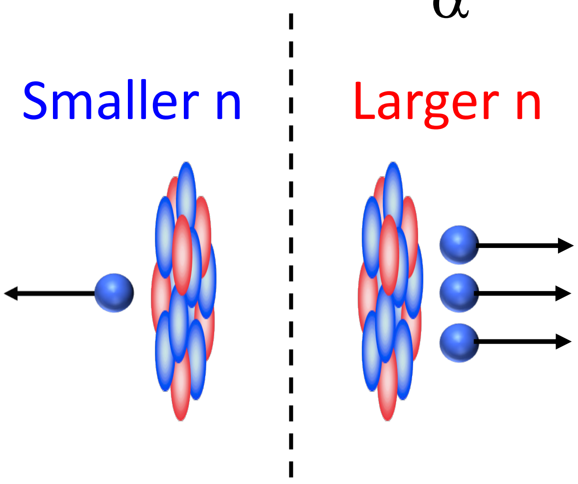
CMS, PRL 127 (2021) 122001
J. Brandenburg et al., arXiv: 2006.07365

- Qualitatively described by a leading order QED model
  - Systematically lower than data could be caused by lacking HO corrections, e.g. Sudakov effect correction *[S. Klein et al., PRL 122 (2019) 132301]*

Rapidity dependence of α spectrum

CMS, PRL 127 (2021) 122001

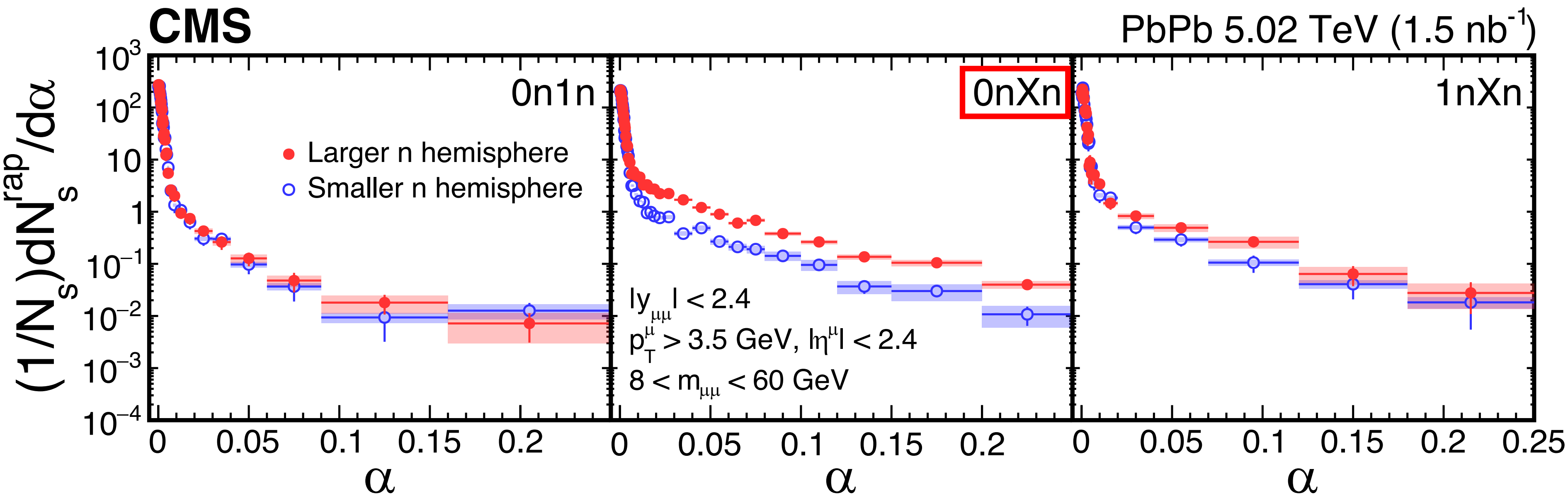


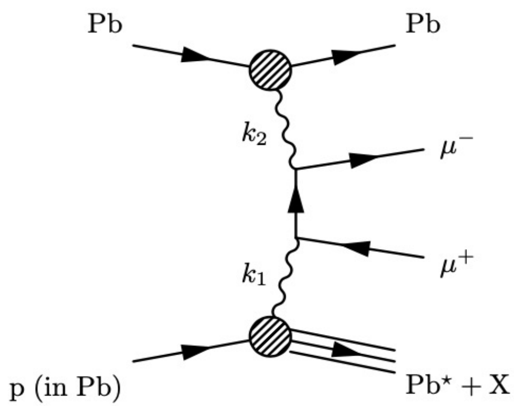


- In 0nXn, the tail contribution
  - Larger n hemisphere > Smaller n hemisphere

Rapidity dependence of α spectrum

CMS, PRL 127 (2021) 122001



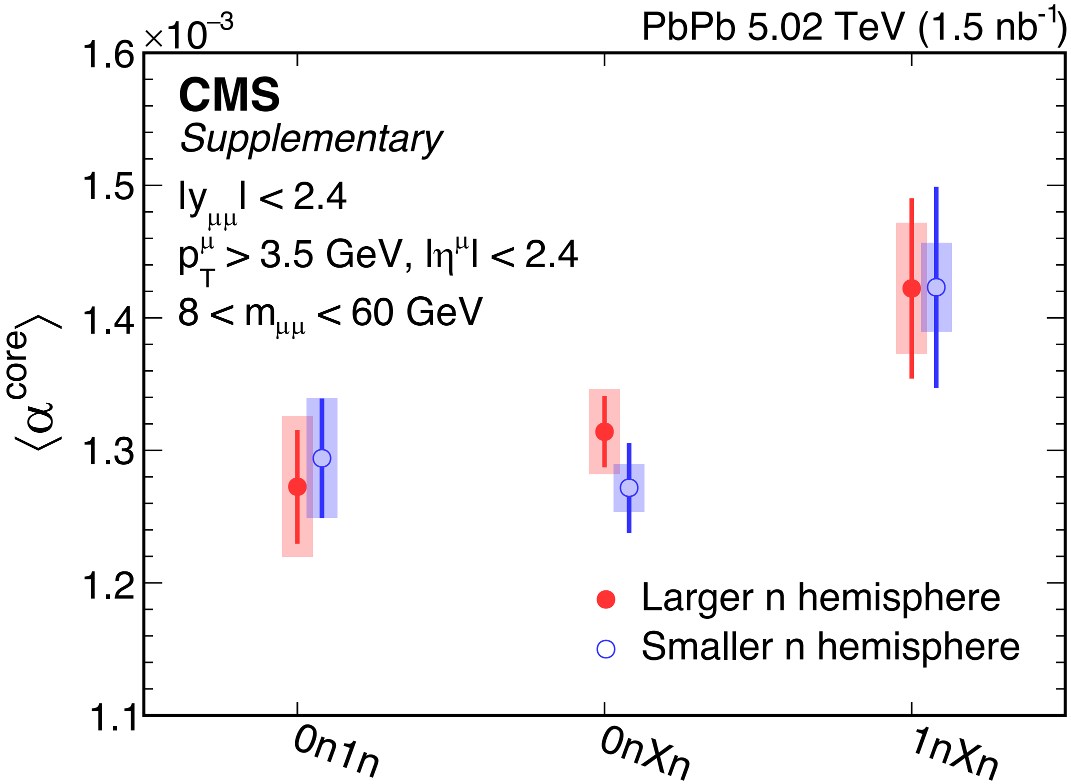


ATLAS, PRC 104 (2021) 024906

- Only the tail in 0nXn has significant rapidity dependence! Why?
  - UPC needs to move from EPA to full QED including HO effects

Rapidity dependence of $\langle \alpha^{\text{core}} \rangle$

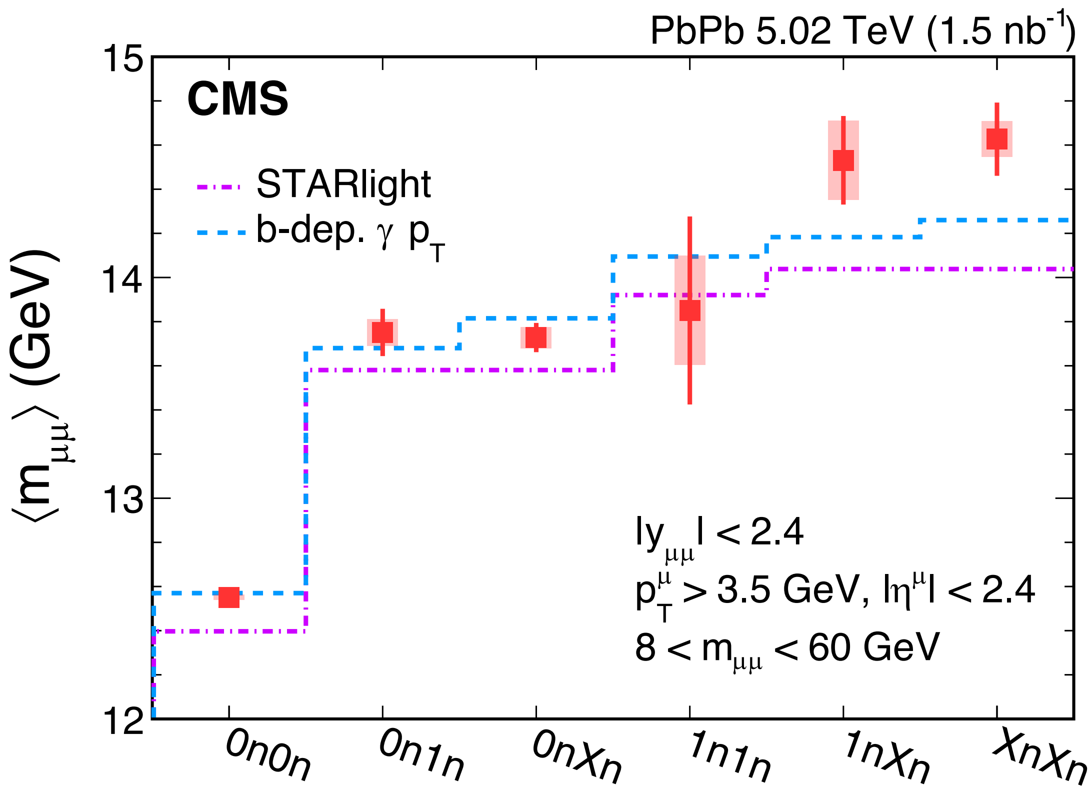
CMS, PRL 127 (2021) 122001



- $\langle \alpha^{\text{core}} \rangle$ has no rapidity dependence
  - Core dominantly comes from LO $\gamma\gamma$ scattering
  - Core function is reliable

$\langle M_{\mu\mu} \rangle$ vs. neutron multiplicity

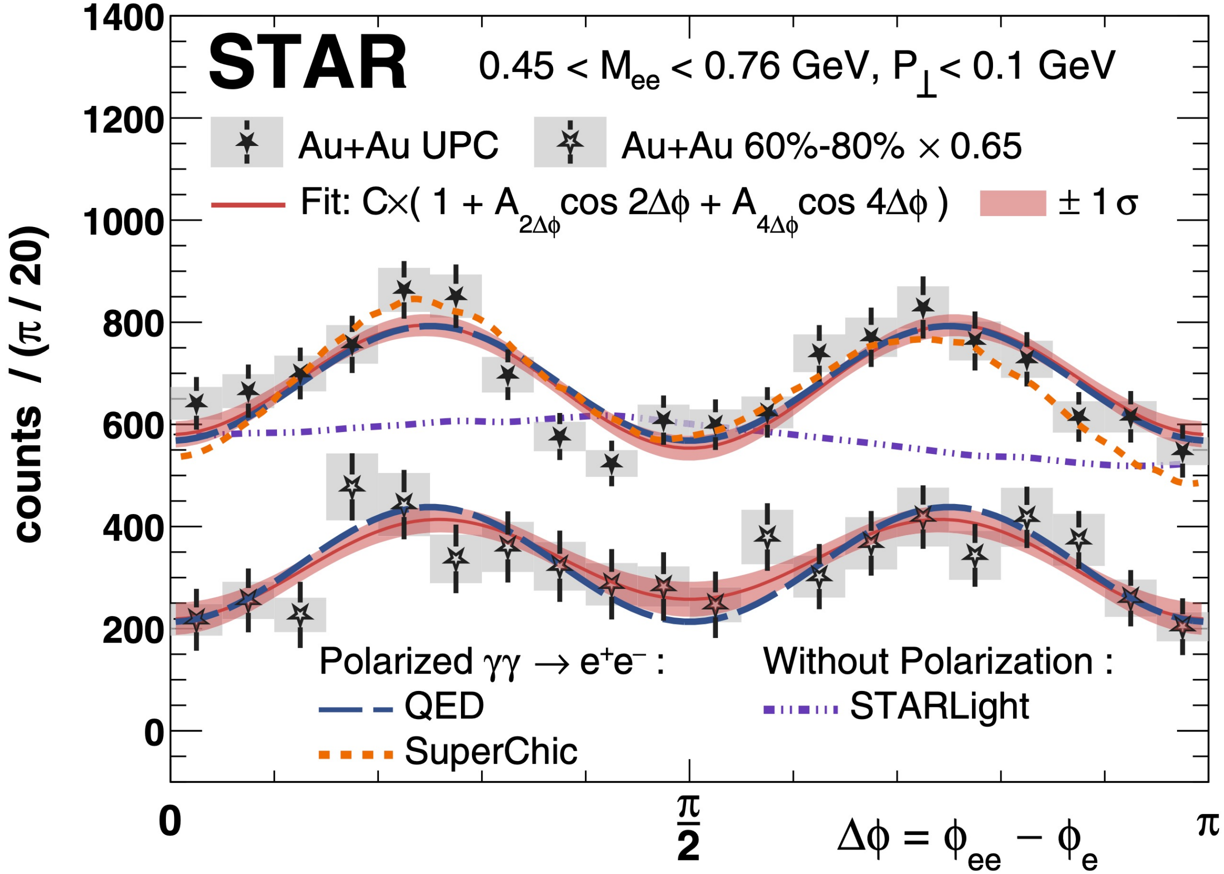
CMS, PRL 127 (2021) 122001



- Strong neutron multiplicity dependence of $\langle m_{\mu\mu} \rangle$
  - Deviation from constant: $\gg 5\sigma$
  - ***b*** dependence of initial photon energy

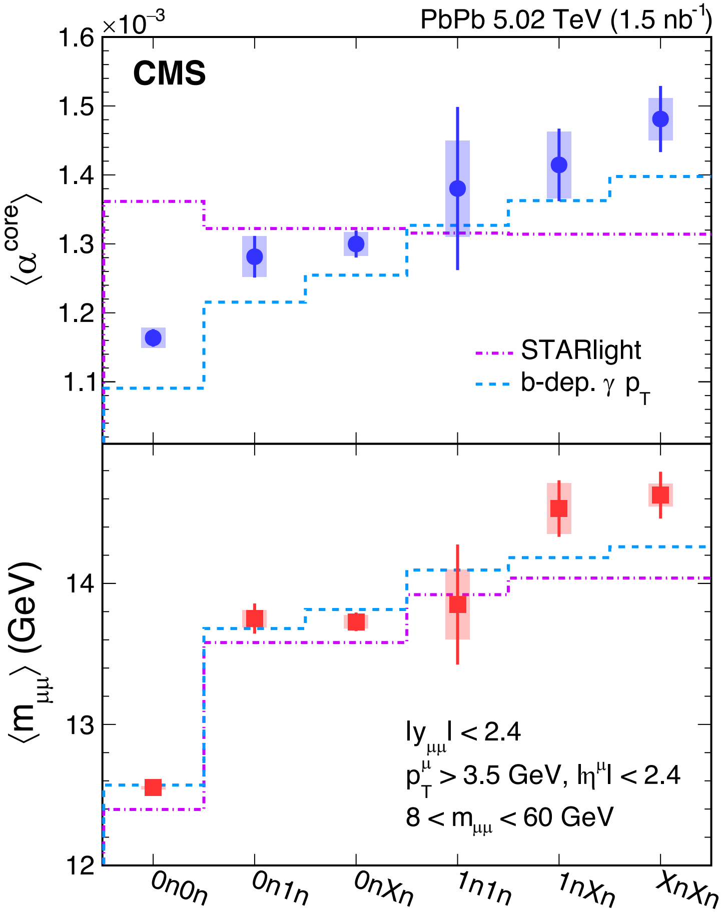
Take home message

- First observation of **linear polarization of photons** via $\cos 4\Delta\phi$ modulation



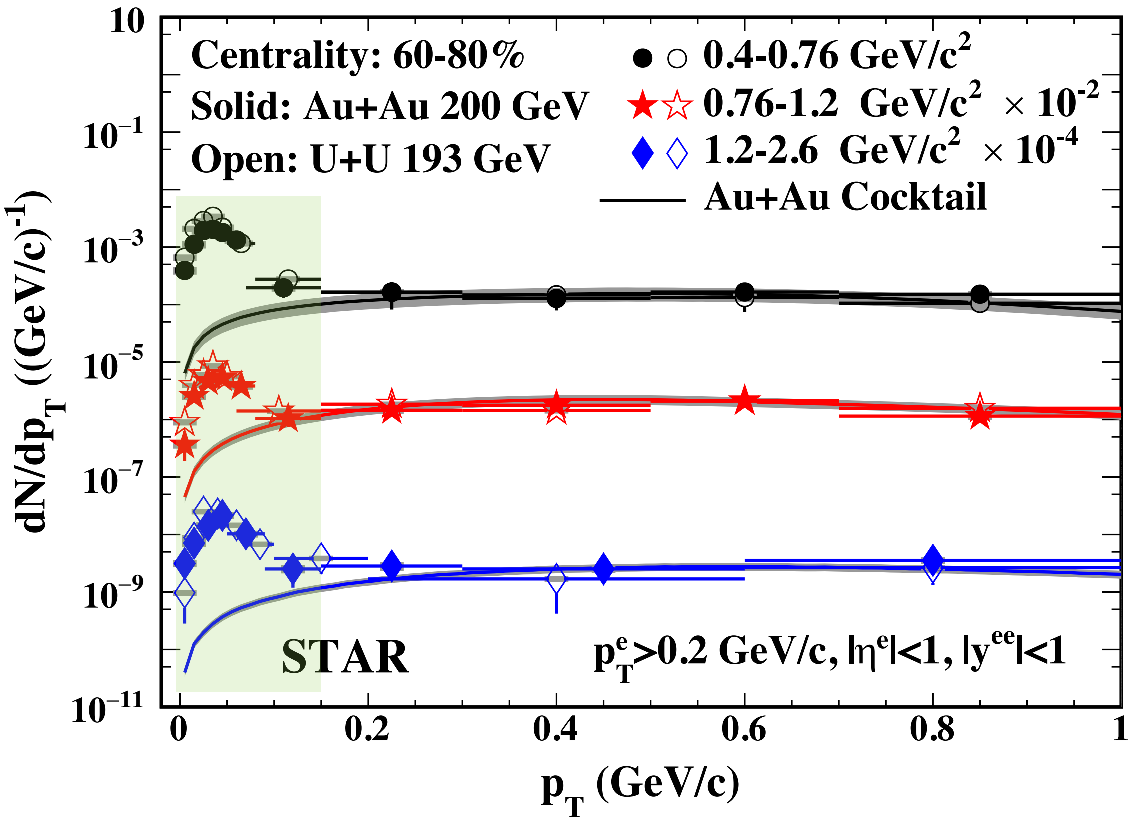
Take home message

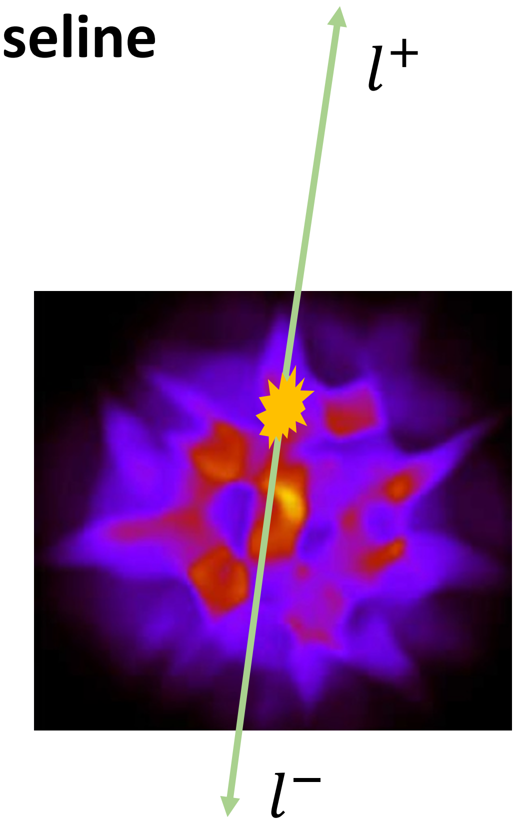
- First observation of ***b* dependence of photon p_T and energy**
  - Direct constraint on models of initial photon flux
  - Controllable reference for searching possible final-state EM effects



Take home message

- First observation of **photon-photon collisions in non-UPC**
  - Probe QGP medium **with appropriate baseline**

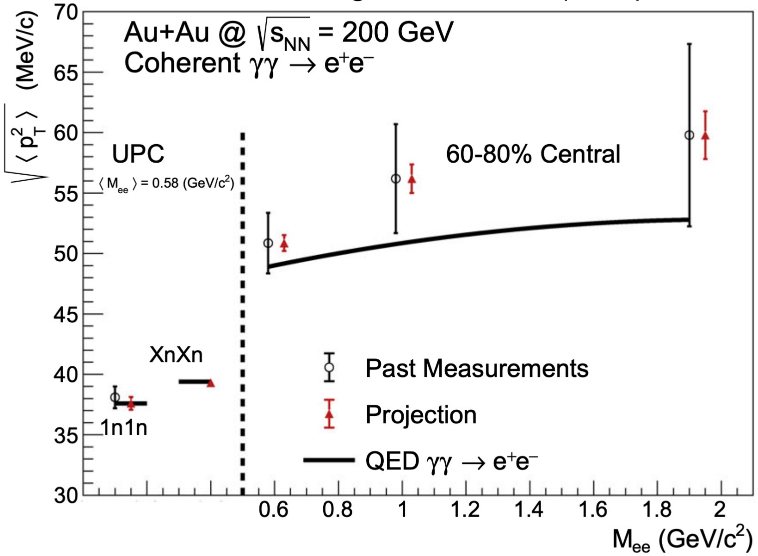




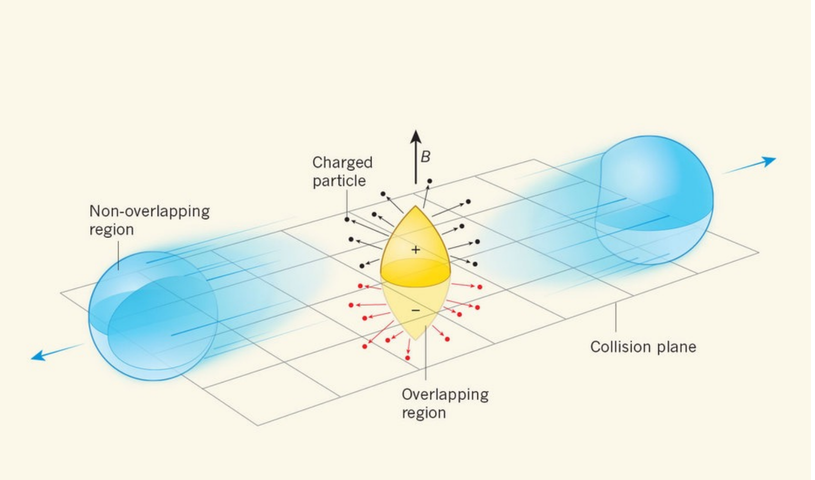
Roadmap to QGP EM properties

- The ***b*** dependence of photon p_T should be considered to explore QGP EM properties
  - RHIC run 2023-2025

J. D. Brandenburg et al., EPJA 57 (2021) 299



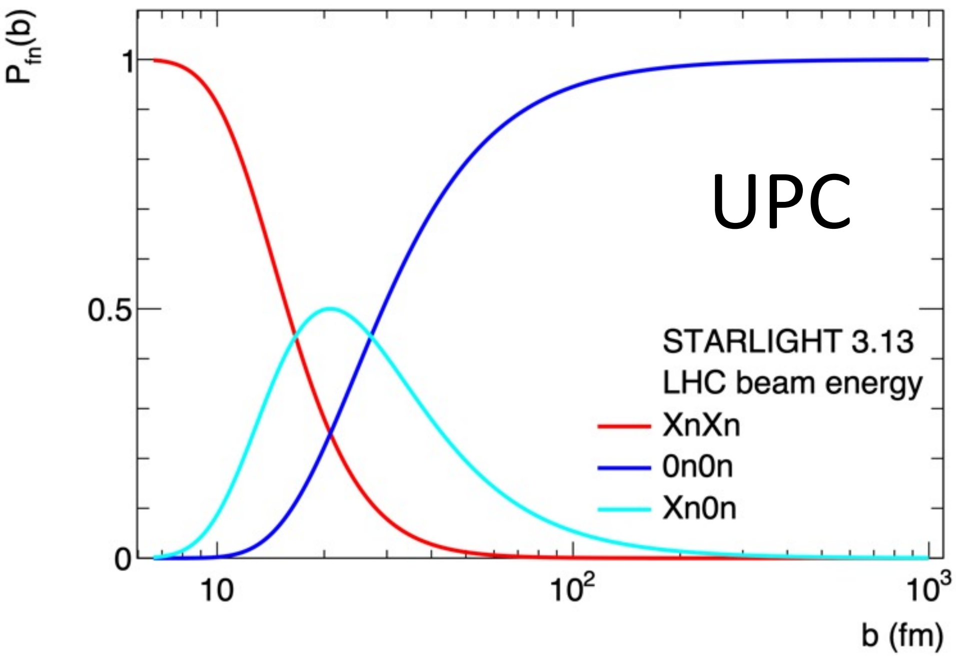
- $\langle p_T \rangle$ or $\langle \alpha \rangle$ w.r.t. event plane
  - In plane > out of plane $\Longrightarrow$ Magnetic field
  - In plane < out of plane $\Longrightarrow$ Multiple scattering



Backup

Why CMS?

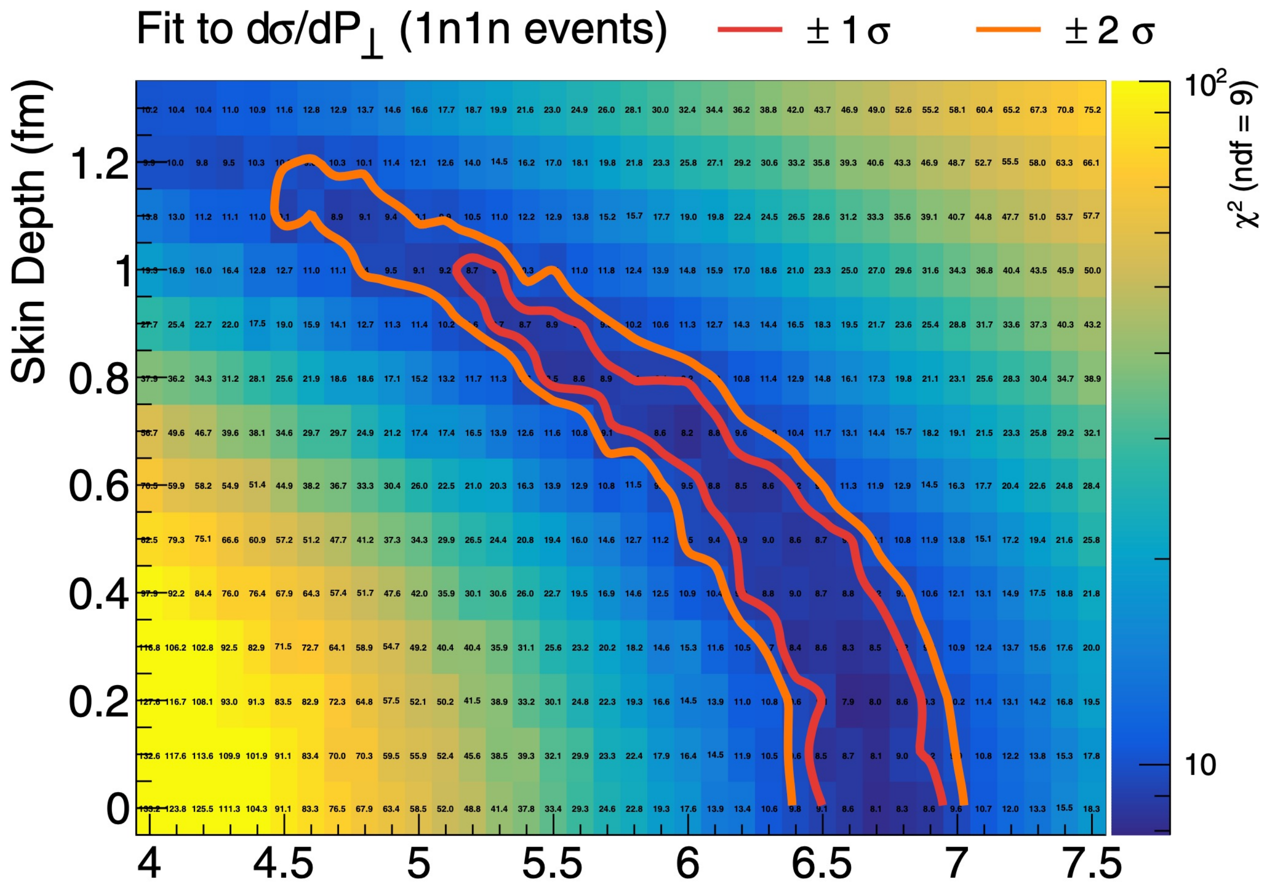
S. Klein and P. Steinberg, arXiv: 2005.01872



- Bearing analogy to centrality
  - $b_{XnXn} < b_{0nXn} \ll b_{0n0n}$

- CMS triggers UPC events containing μ regardless neutron dissociation
- STAR ONLY triggers UPC events with $N_n \geq 1$ in each side

Constrain nuclear charge distribution

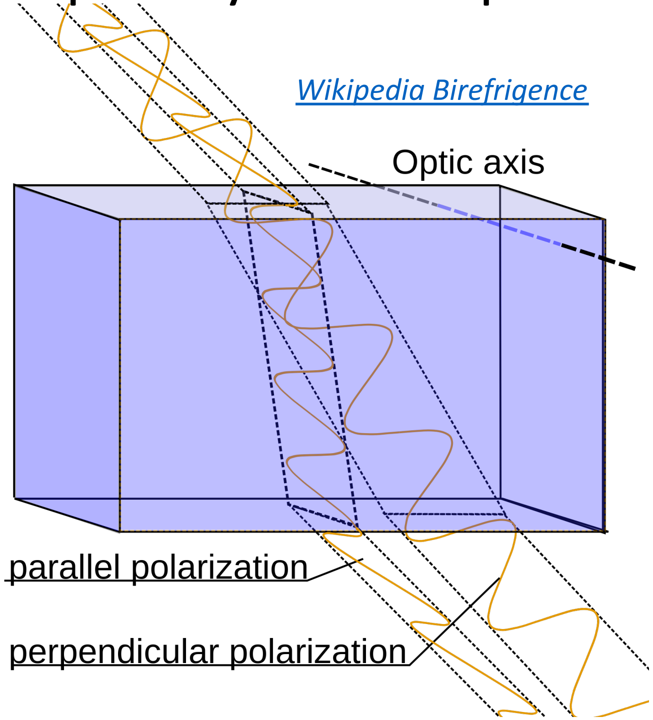


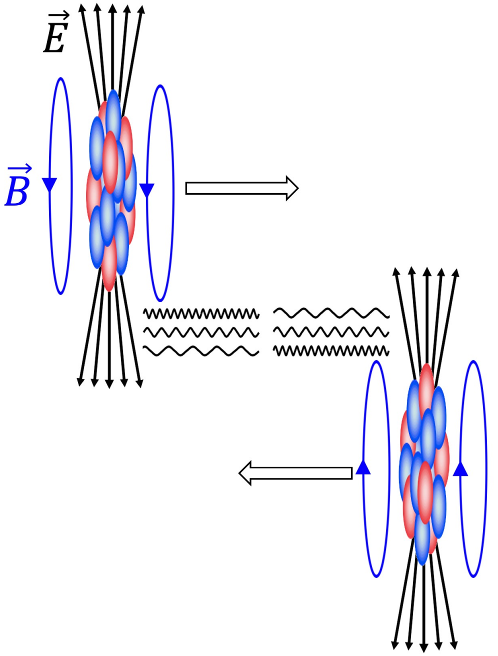
J. D. Brandenburg et al., EPJA 57 (2021) 299

- ➢ The nuclear charge distribution is assumed to follow a continuous charge distribution given by a Woods-Saxon distribution

Vacuum birefringence

- **Optical birefringence**: $n_{\parallel}(extraordinary) \neq n_{\perp}(ordinary)$ in optically anisotropic materials $\Longrightarrow$ wave splitting





- **Vacuum birefringence**: refractive index of photon progating in extremely strong $\vec{B}$ field depends on relative polarization angle $\Longrightarrow \cos(n\Delta\phi)$ modulation of polarized $\gamma\gamma \to l^{+}l^{-}$