Measurements of strong QED interactions at RHIC and LHC

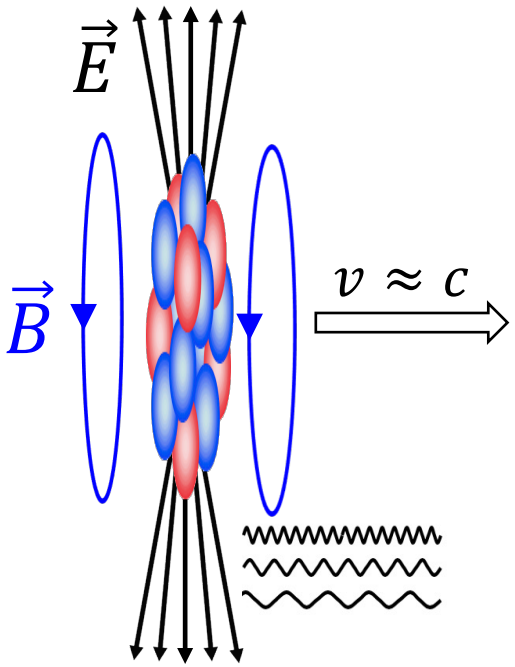
Shuai Yang

Rice University

Center for Frontiers in Nuclear Science Workshop series

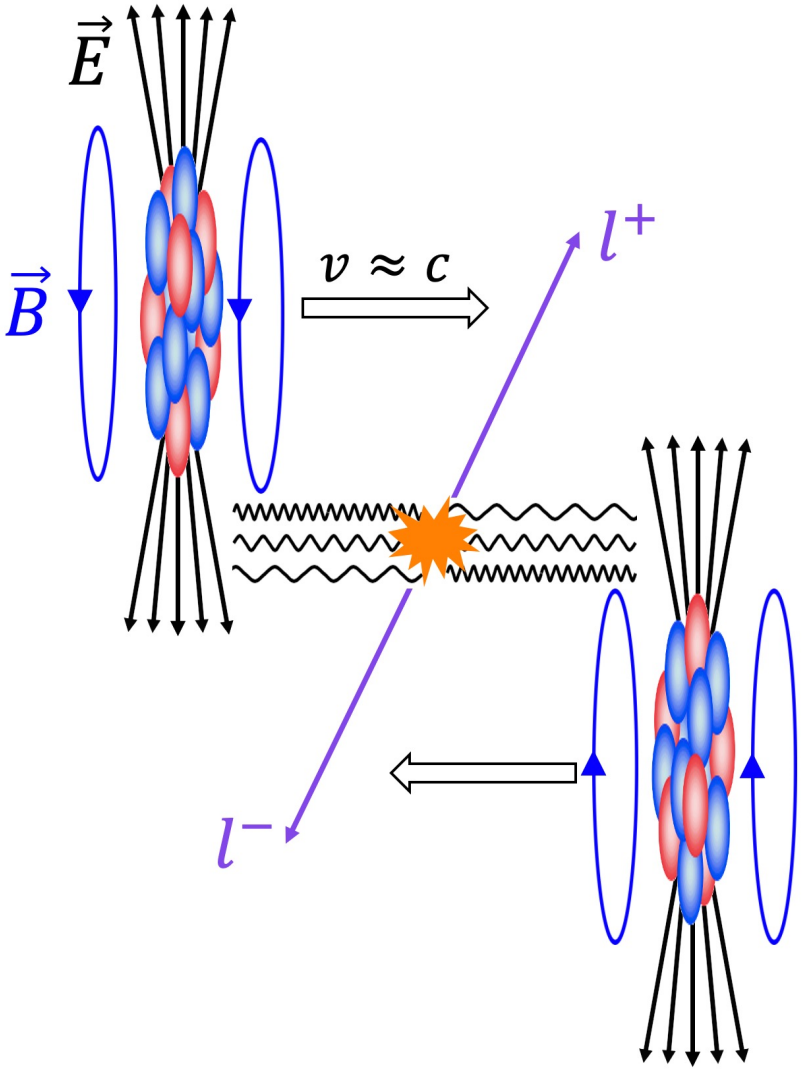
Workshop: RHIC Science Programs Informative Toward EIC in the Coming Years

Equivalent photon

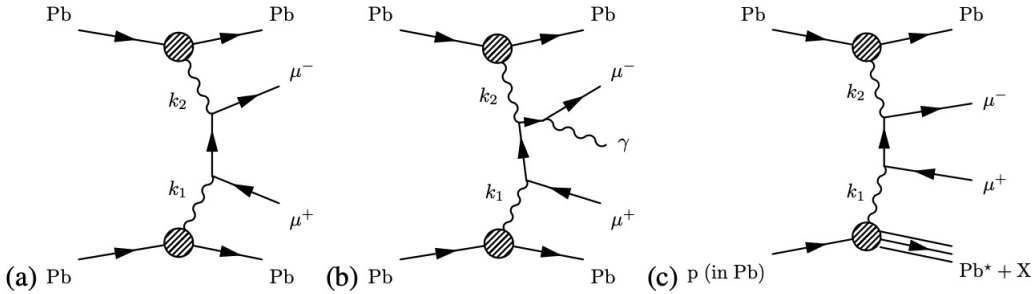


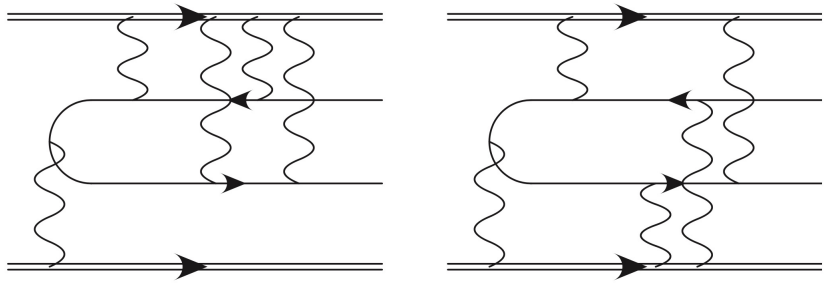
- Ultra-relativistic charged nuclei produce highly contracted EM field
- Equivalent Photon Approximation
  - Quasi-real photon
- Photon kinematics
  - $\omega < \frac{\hbar\gamma}{R_A}$ (3 GeV @ RHIC, 80 GeV @ LHC)
  - $p_T < \frac{\hbar}{R_A}$ ($\mathcal{O}$(30) MeV @ RHIC, LHC)

Photon-photon collisions



Baur et al., Phys. Rep. 453 (2007) 1
ATLAS, arXiv:2011.12211





✤ LbyL is not covered by this talk, see backup and Peter's talk in April CFNS workshop

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

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

Klein et al., CPC 212 (2017) 258
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 $\Longrightarrow$ No ***b*** dependence of photon (lepton pair) p_T
- Radius cutoff $\Longrightarrow$ ~20% less yield & insensitive to form factor

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

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

Klein et al., CPC 212 (2017) 258
Zha et al., PLB 781 (2018) 182
Klein et al., PRD 102 (2020) 094013
Zha et al., PLB 800 (2020) 135089

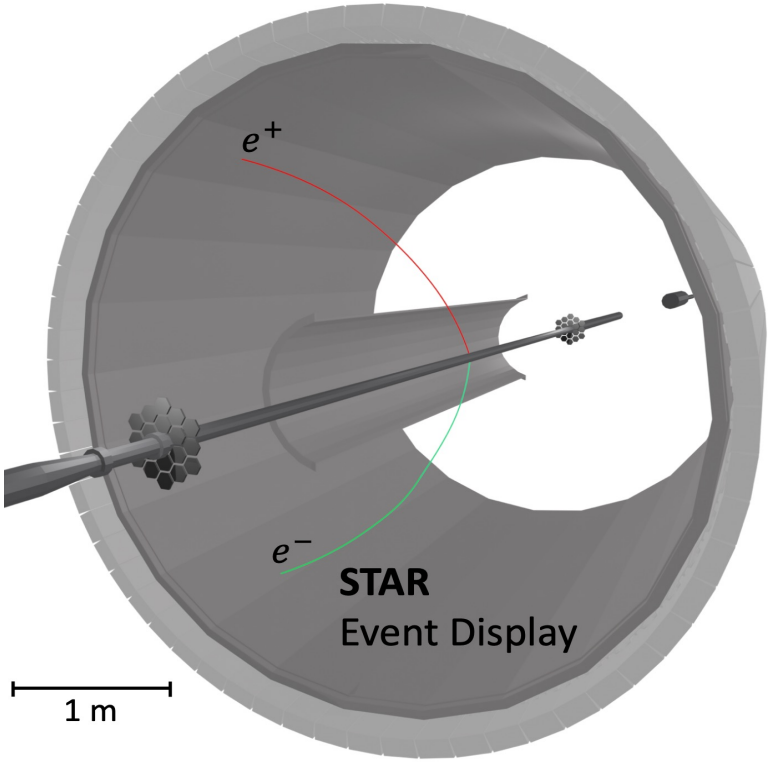
Models in market

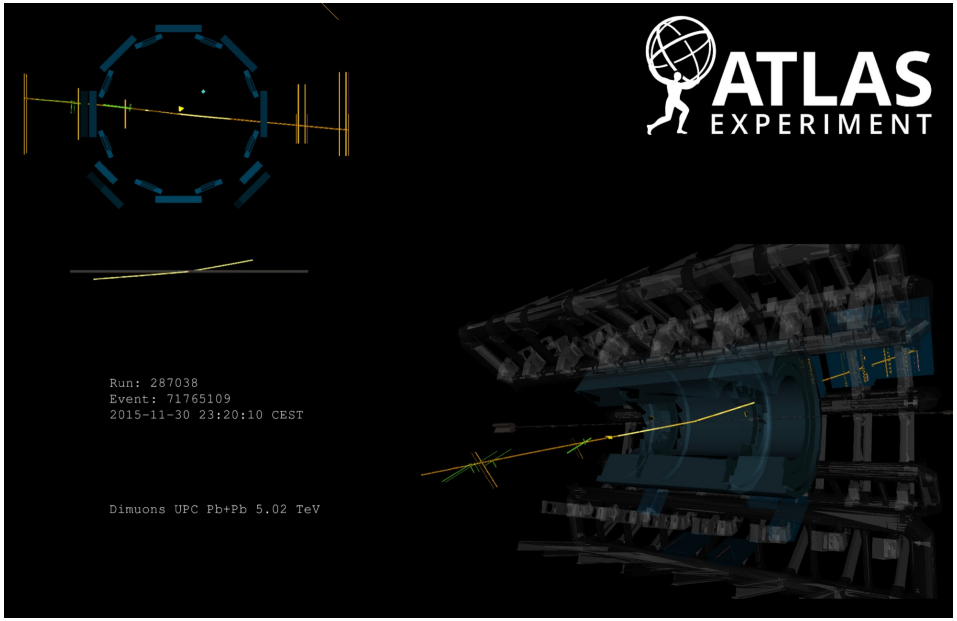
	STARlight	**gEPA**	**QED**
Form Factor	Point-like	Woods-Saxon	Woods-Saxon
γ intensity(***b***)	✓	✓	✓
γ p_T(***b***)	✗	✓	✓
l^+l^- inside nucleus	✗	✓	✓
HO contribution	✗	✗	✗ ✤

✤ Being addressed in calculations

No single available model covers all aspects

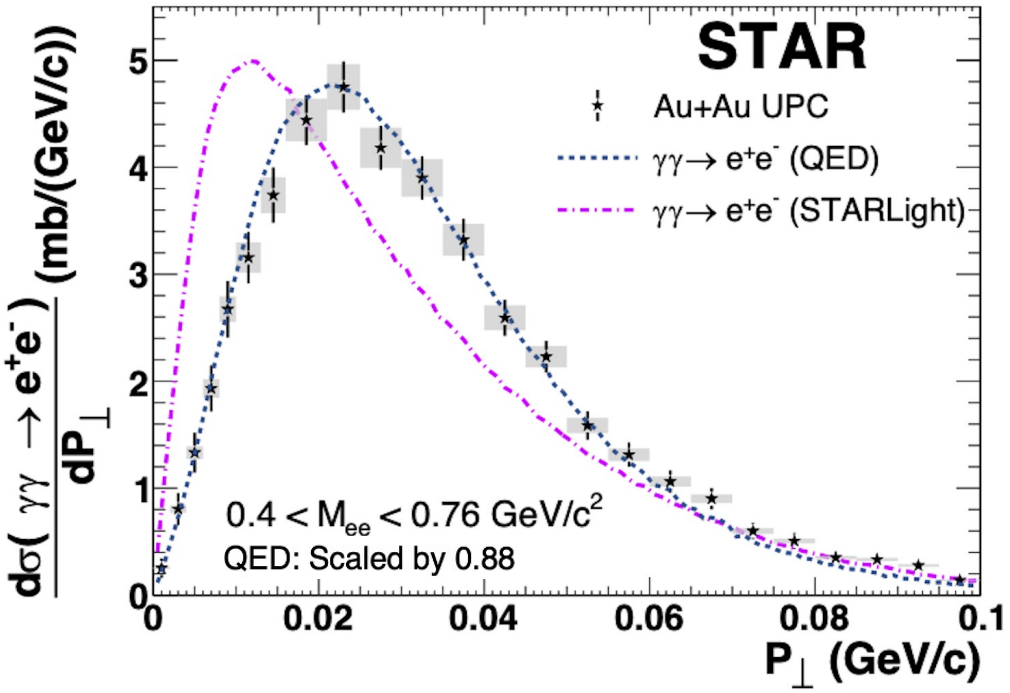
Exclusive $\gamma\gamma \rightarrow l^+l^-$ production





Total cross section at RHIC

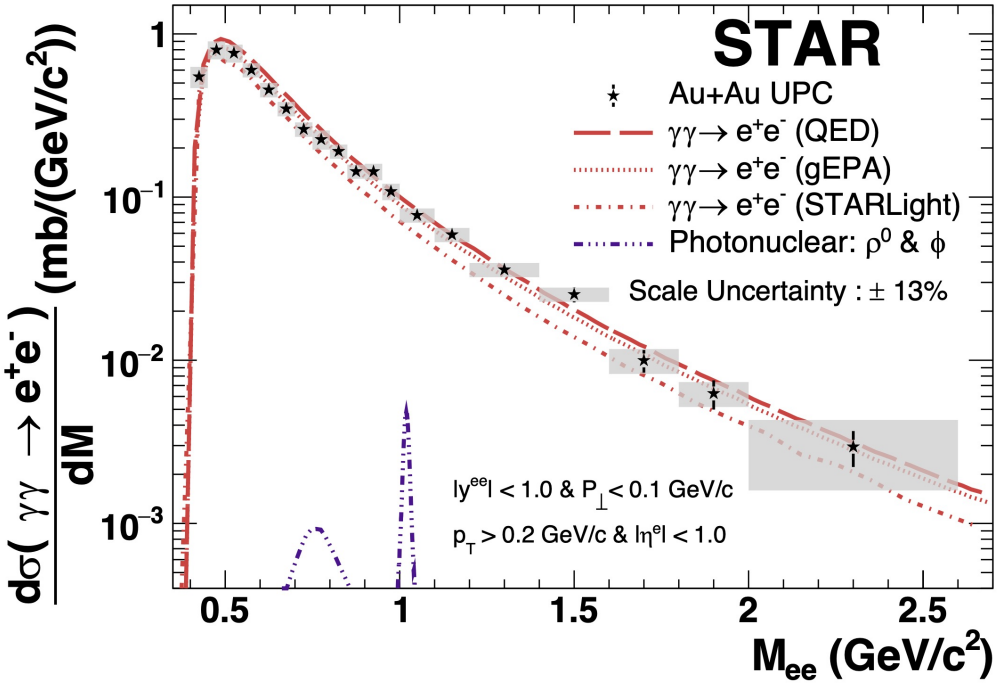
STAR, arXiv: 1910.12400
Klein et al., CPC 212 (2017) 258
Zha et al., PLB 800 (2020) 135089



- Concentrated at low p_T
- Significant difference between STARlight and QED at $p_T \approx 0$
  - Virtuality for e^+e^- channel?
  - *b* dependence of photon p_T*?*

Total cross section at RHIC

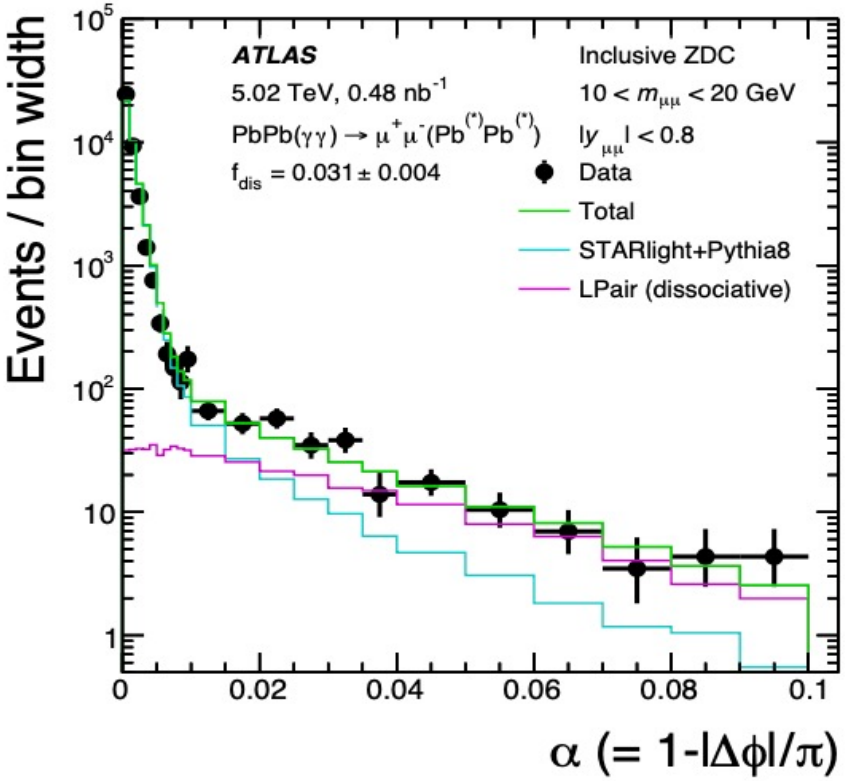
STAR, arXiv: 1910.12400
Klein et al., CPC 212 (2017) 258
Zha et al., PLB 800 (2020) 135089



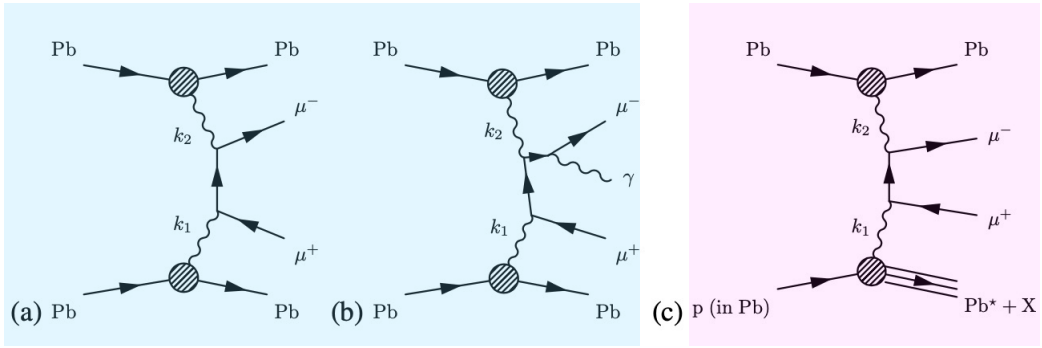
- Smooth mass spectrum
- l^+l^- production inside nucleus
  - QED, gEPA (✓)
  - STARlight (✗)

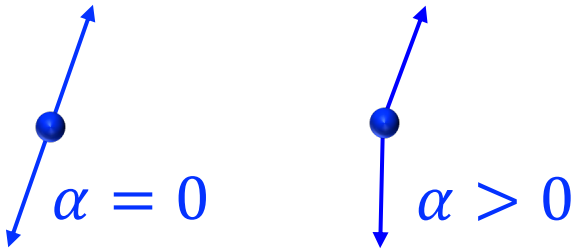
Total cross section at LHC

ATLAS, arXiv:2011.12211



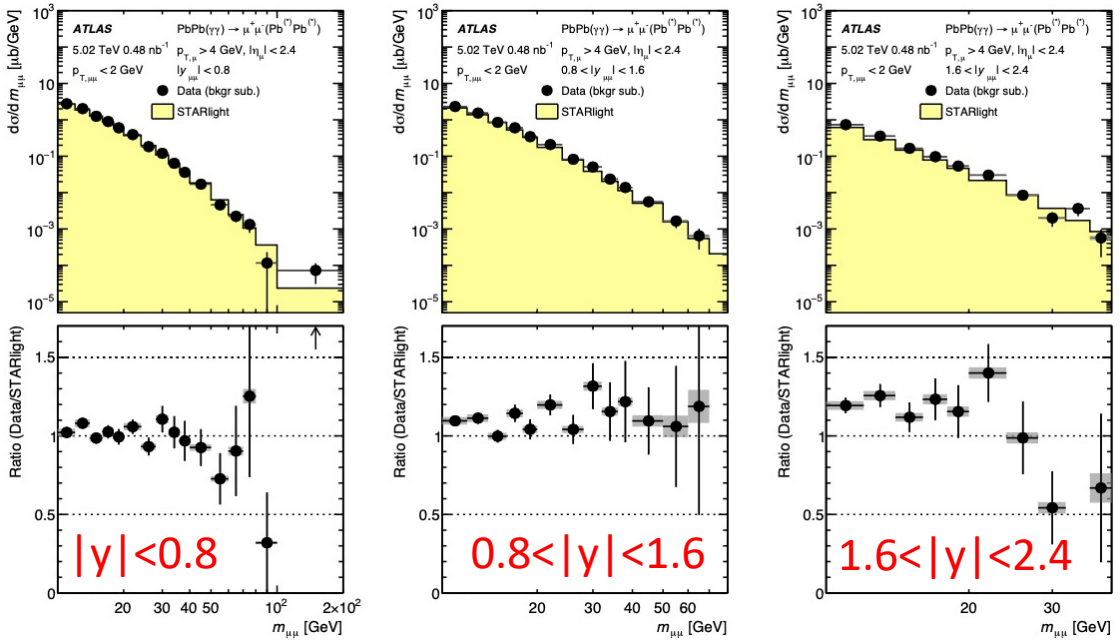
STARlight + Pythia8 **LPair**





Total cross section at LHC

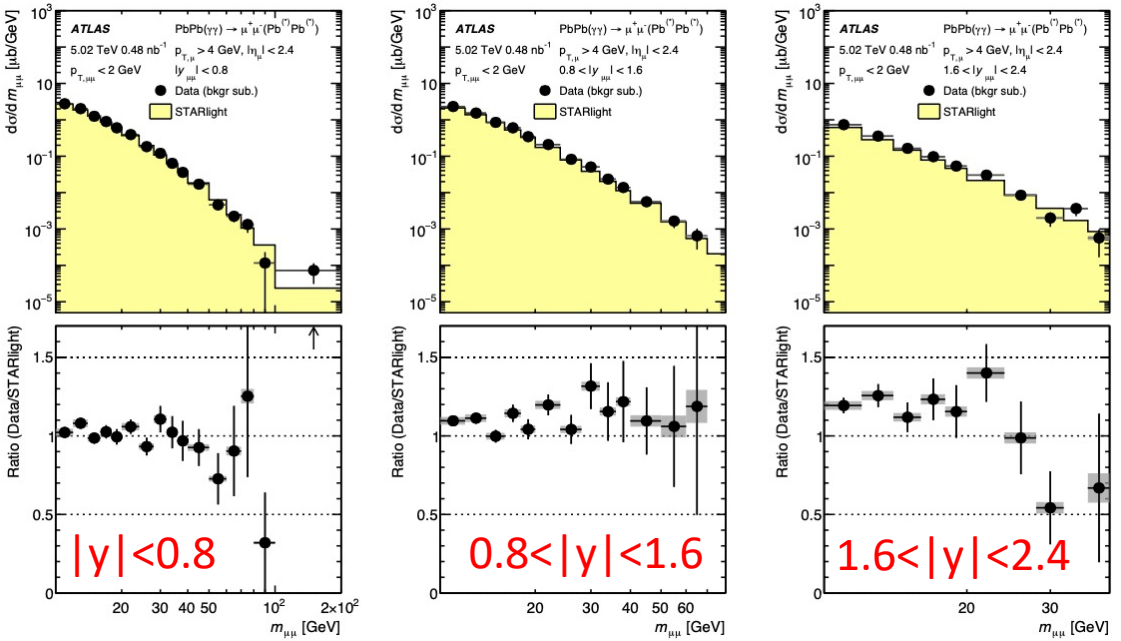
ATLAS, arXiv:2011.12211

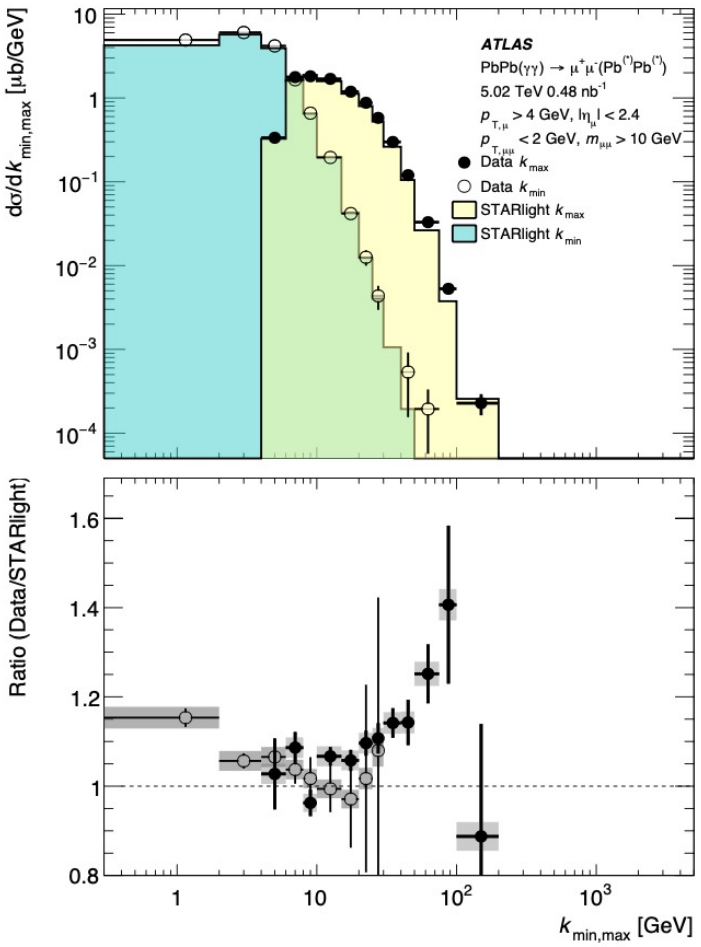


- Good agreement with STARlight at mid y, but systematic increase at higher y
  - STARlight should underestimate ~20% l^+l^- rates

Total cross section at LHC

ATLAS, arXiv:2011.12211



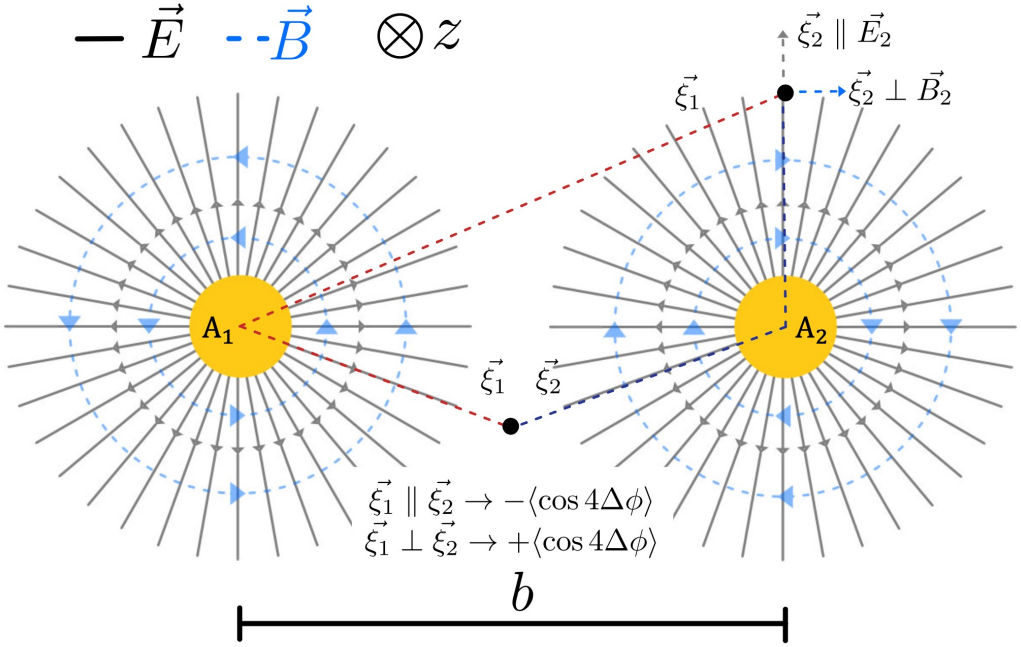


- Good agreement with STARlight at mid y, but systematic increase at higher y
  - STARlight should underestimate ~20% l^+l^- rates

- $k_{min,max} = \frac{m_{\mu\mu}}{2} e^{\pm y_{\mu\mu}}$

Linearly polarized photons

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



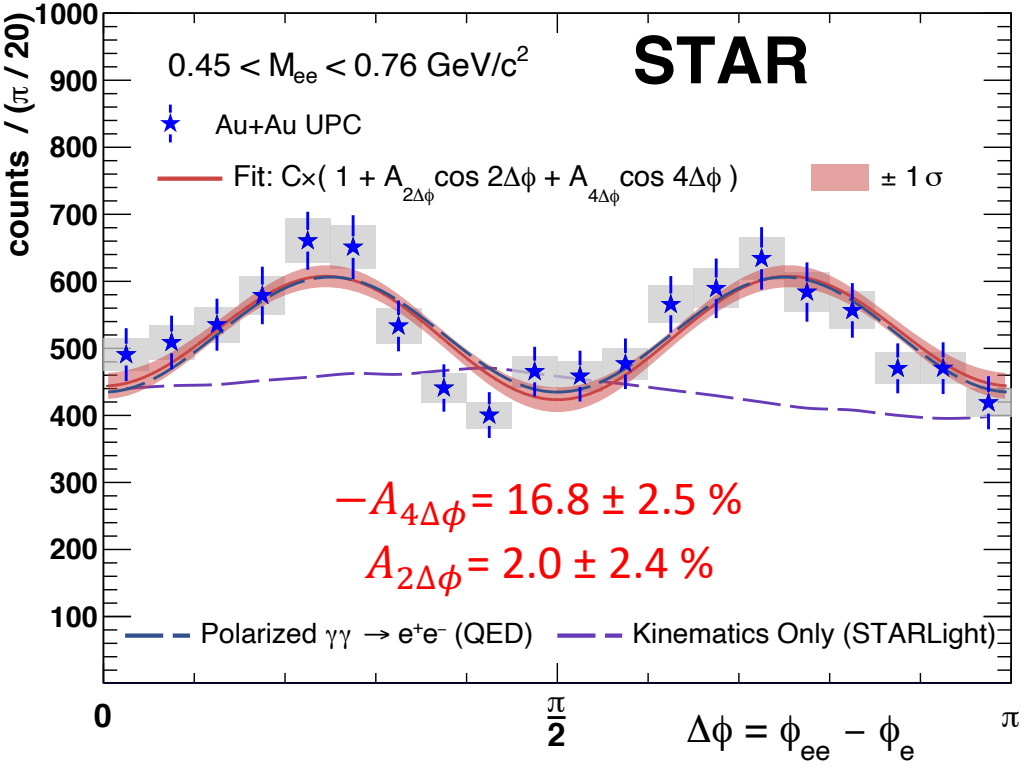
J.D. Brandenburg, CFNS workshop 2021.04

- 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 *[Li et al., PLB 795 (2019) 576]*
  - $\cos(2\Delta\phi) \propto m_l^2/p_{T,l}^2$

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

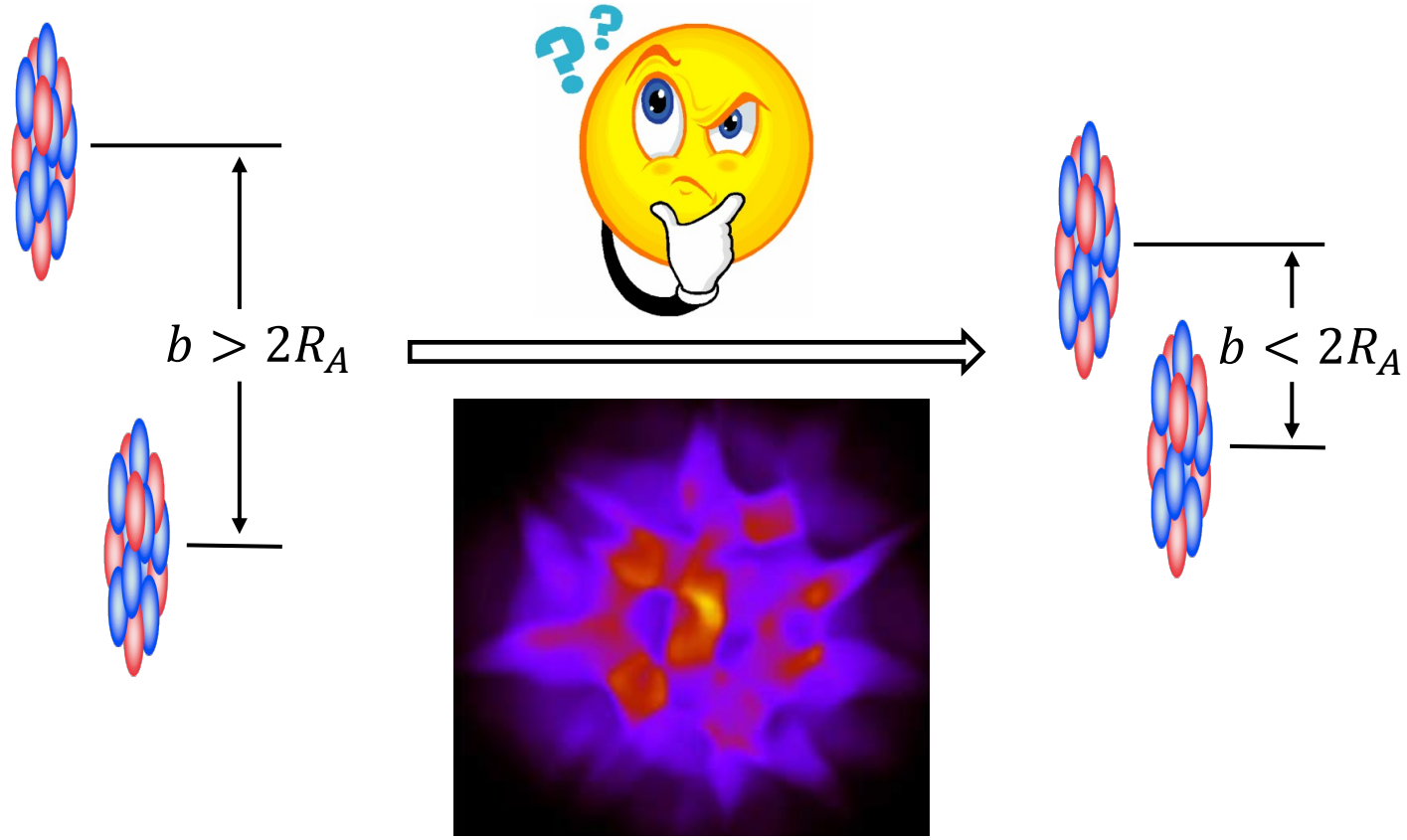
Linearly polarized photons

STAR, arXiv: 1910.12400



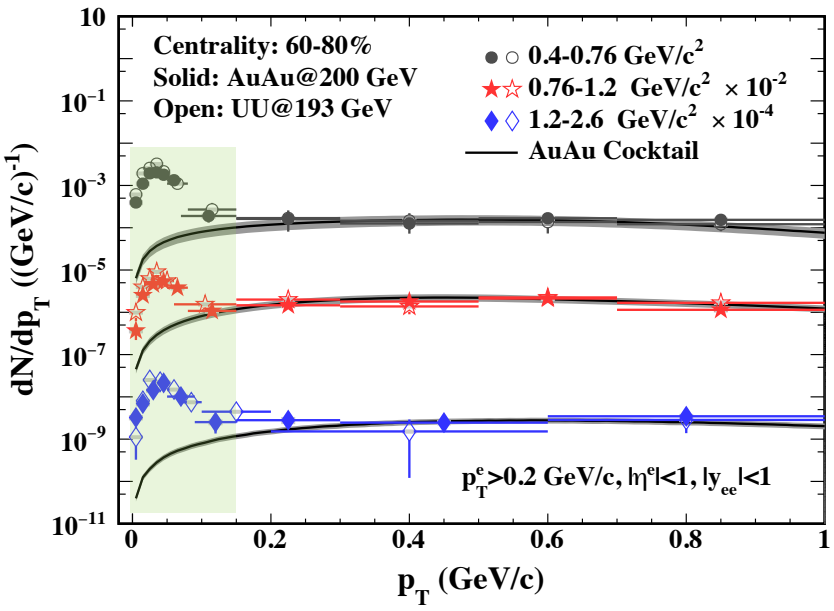
- Firstly observed 6.7 σ cos $4\Delta\phi$ modulation
  - Experimental evidence of linearly polarized photons
  - Analogous to vacuum birefringence

From UPC to hadronic collisions

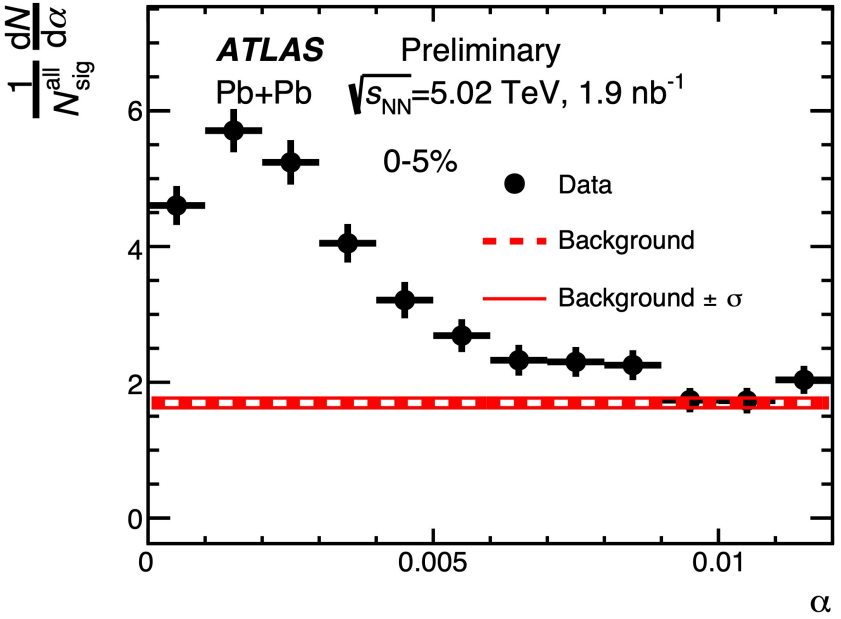


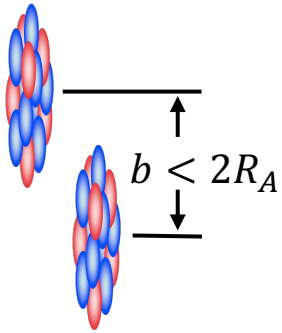
Non-exclusive $\gamma\gamma \rightarrow l^+l^-$ production

STAR, PRL 121 (2018) 132301

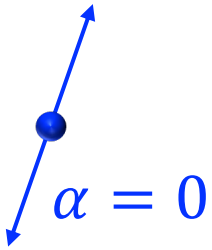


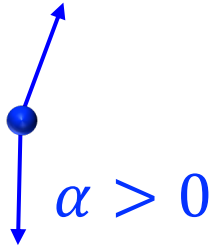
ATLAS, PRL 121 (2018) 212301; ATLAS-CONF-2019-051





$$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$

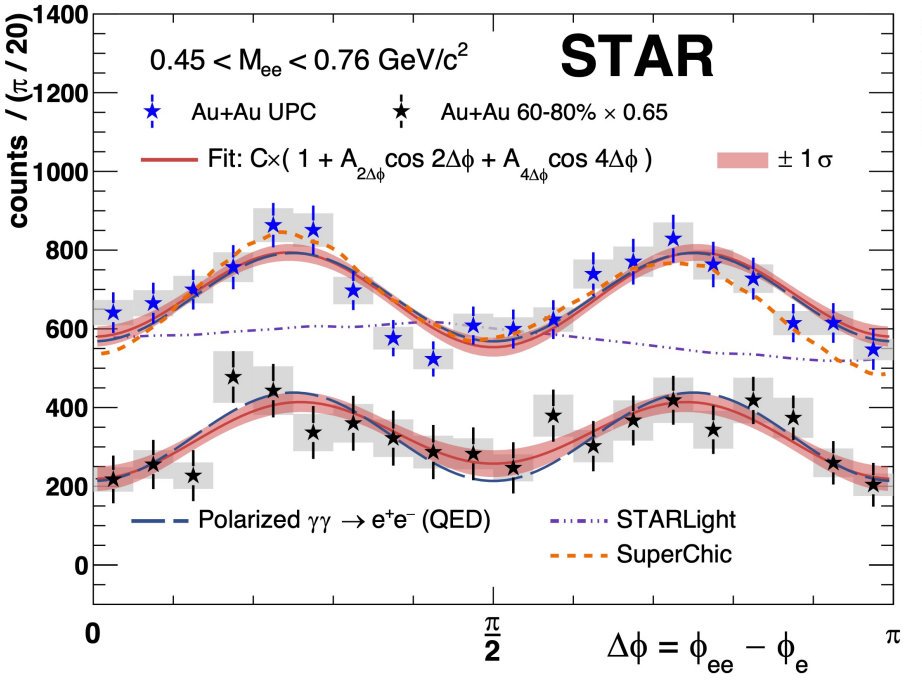




Non-exclusive $\gamma\gamma \rightarrow l^+l^-$ production

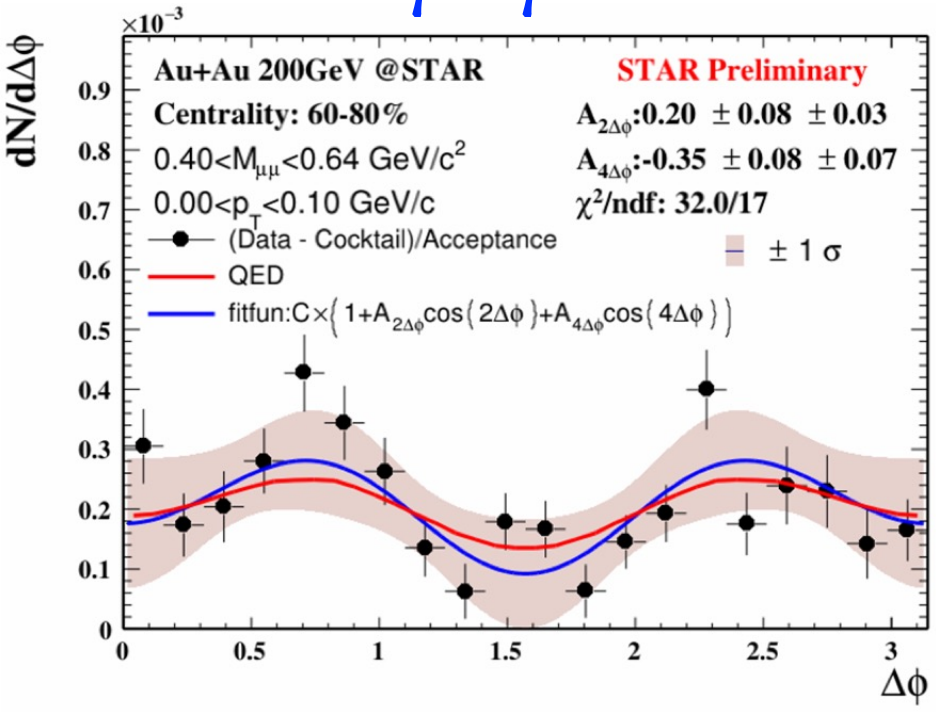
STAR, arXiv: 1910.12400

e^+e^-



J. Zhou, sQM 2021

$\mu^+\mu^-$

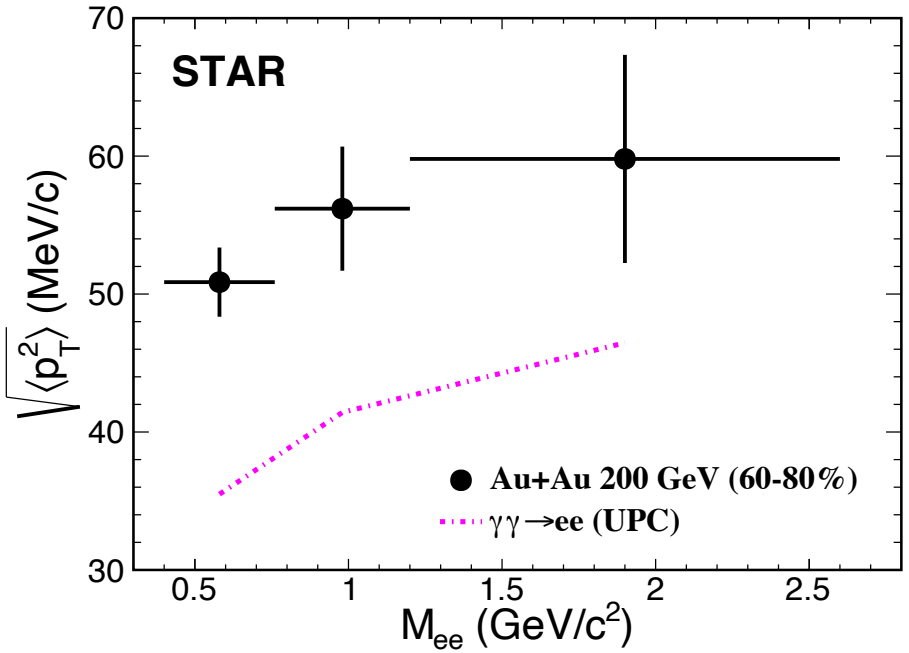


- Consistent with 0 cos $2\Delta\phi$ modulation in e^+e^-
- **Observed 2.3σ $cos\ 2\Delta\phi$ modulation in $\mu^+\mu^-$**

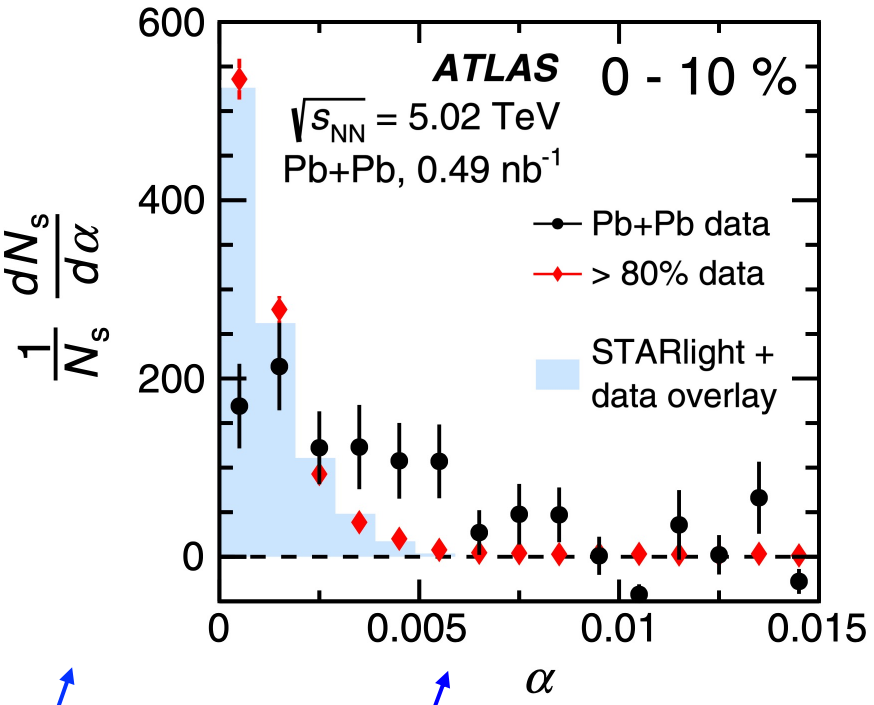
$$\cos(2\Delta\phi) \propto m_l^2/p_{T,l}^2$$

Modification of lepton pairs

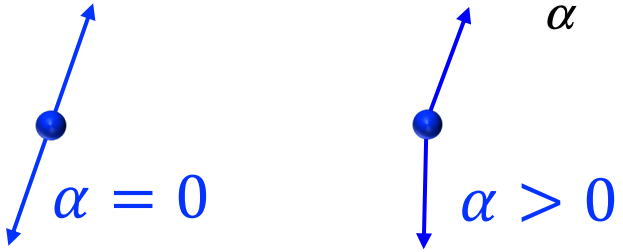
STAR, PRL 121 (2018) 132301



ATLAS, PRL 121 (2018) 212301



$$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$

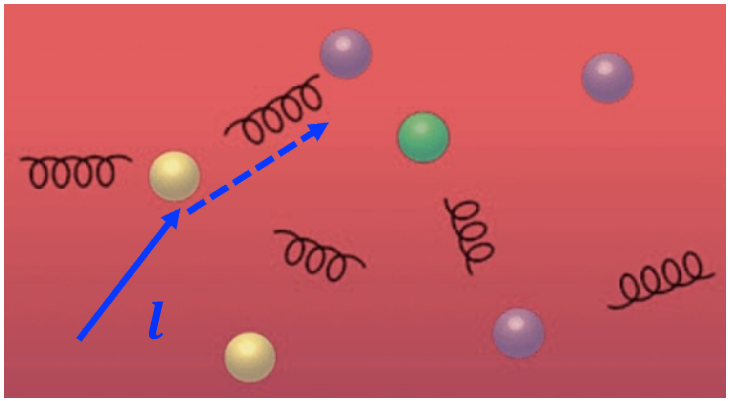


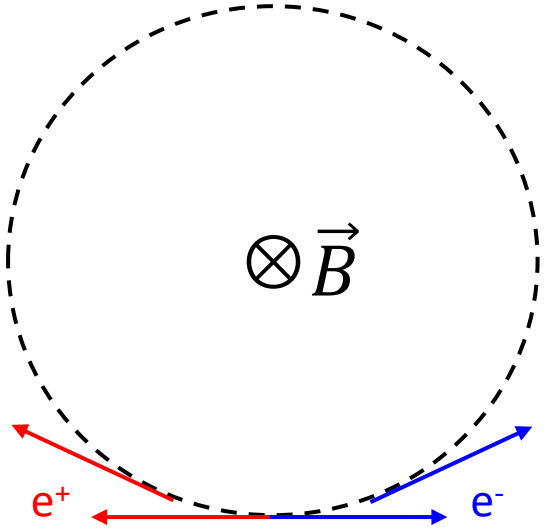
- Back-to-back correlation becomes weaker towards central collisions

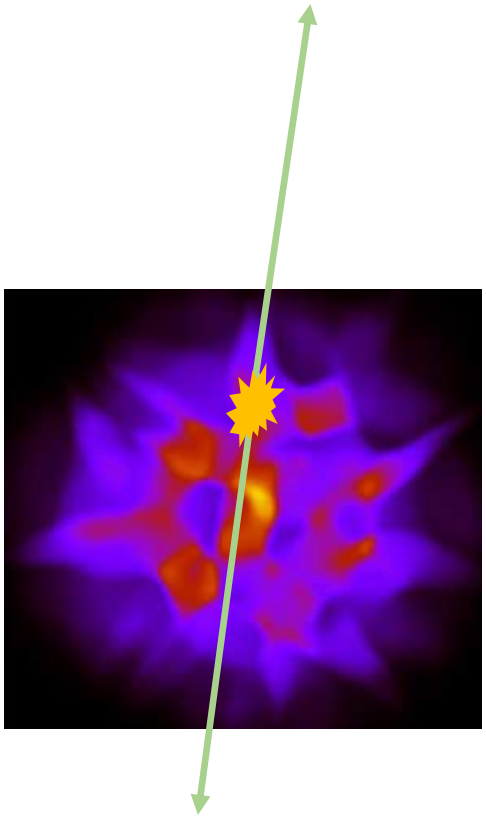
Puzzle of the physics origin

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

Final-state effect?





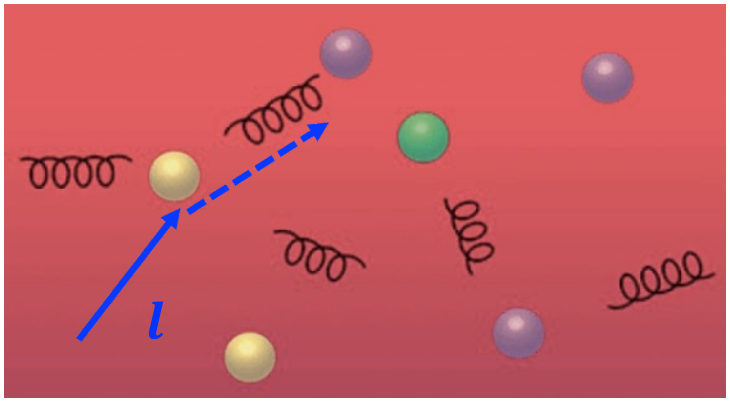


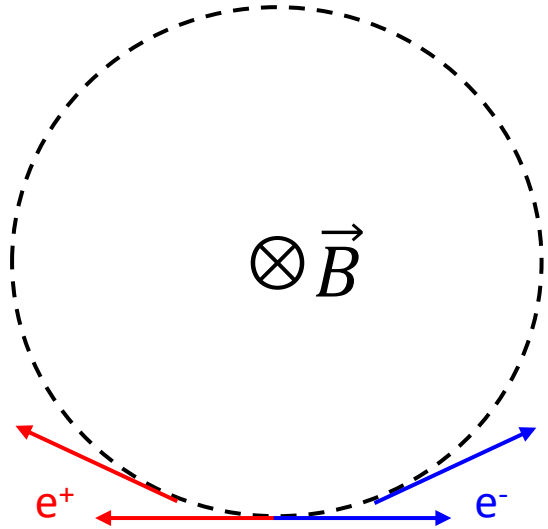
Puzzle of the physics origin

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

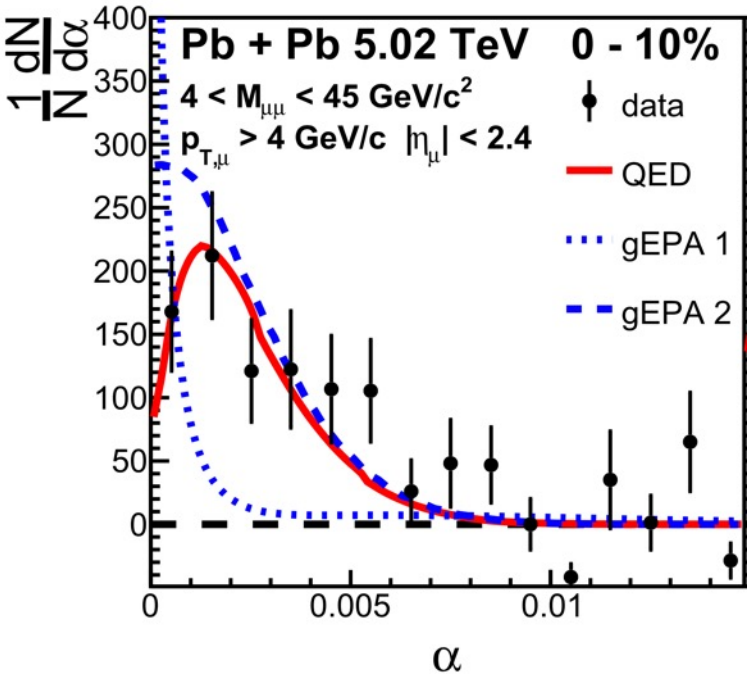
Zha et al., PLB 800 (2020) 135089

Final-state effect?



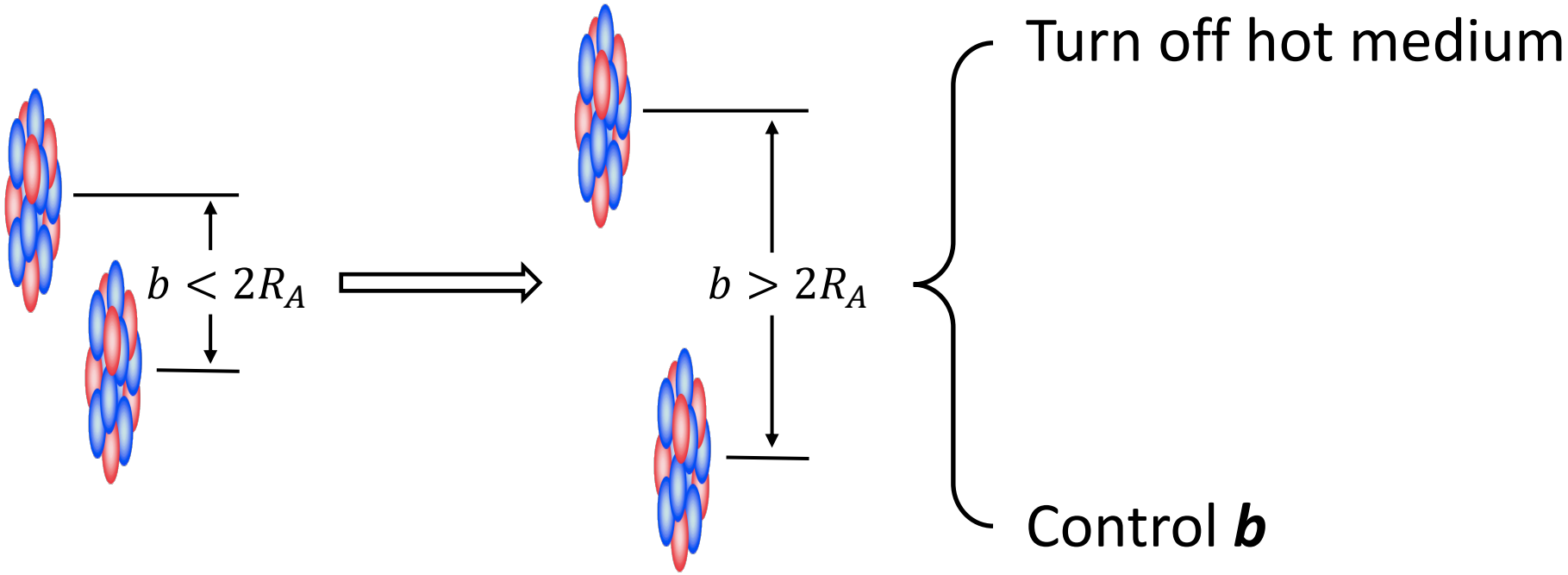


Initial-state effect?

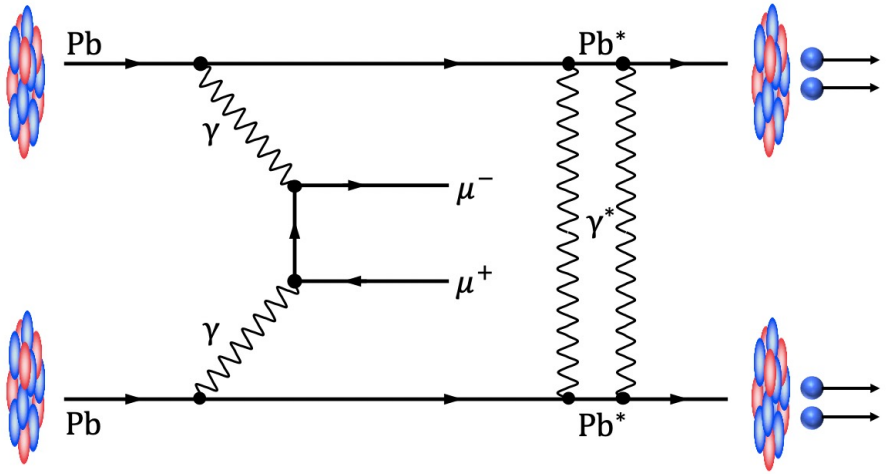


- Described by **lowest-order** QED without medium effect
  - ***b*** dependence of initial photon p_T

Experimentally explore the puzzle

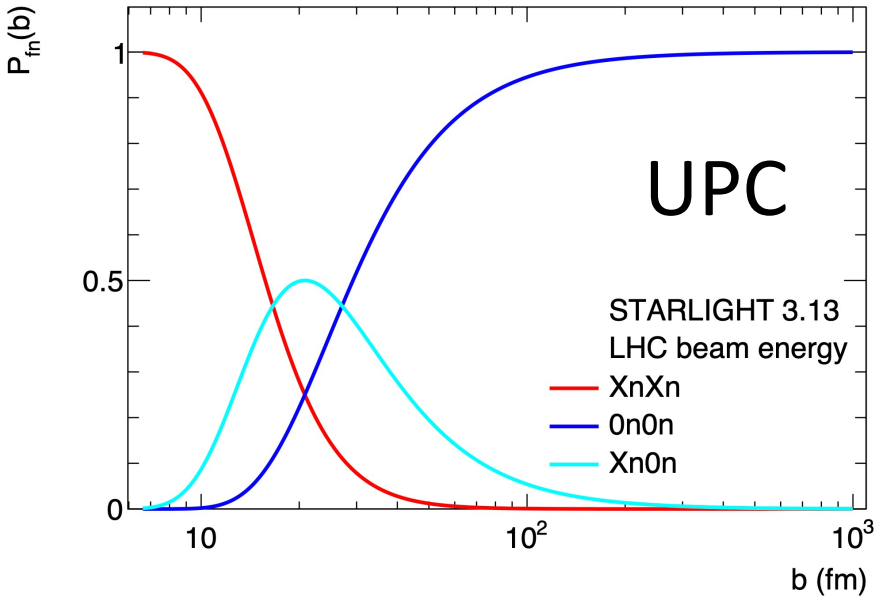


Control “centrality” in UPC



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

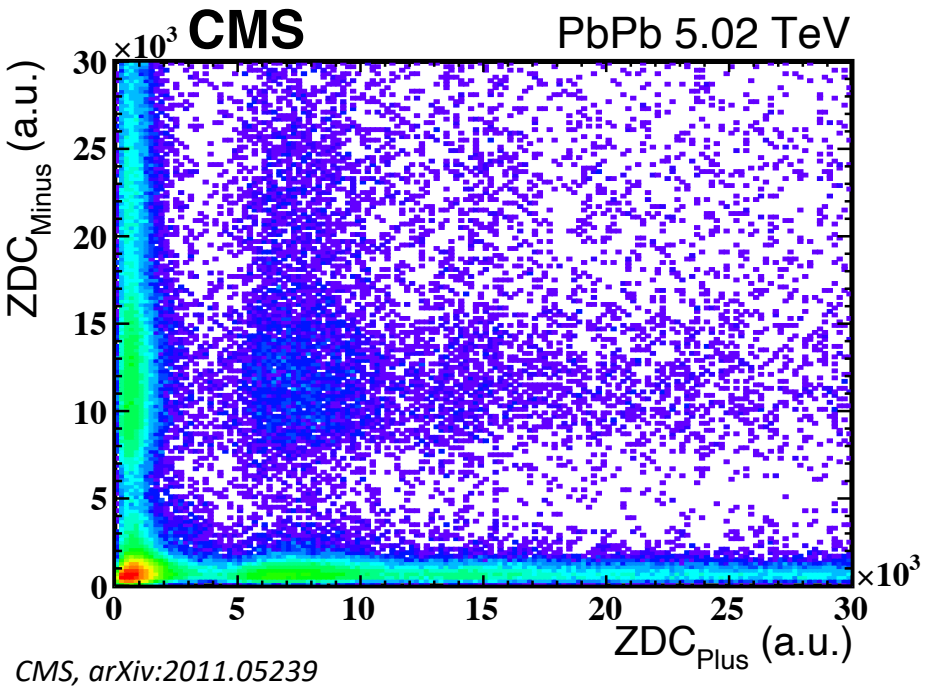
, where $P_i(b) \propto 1/b^2$

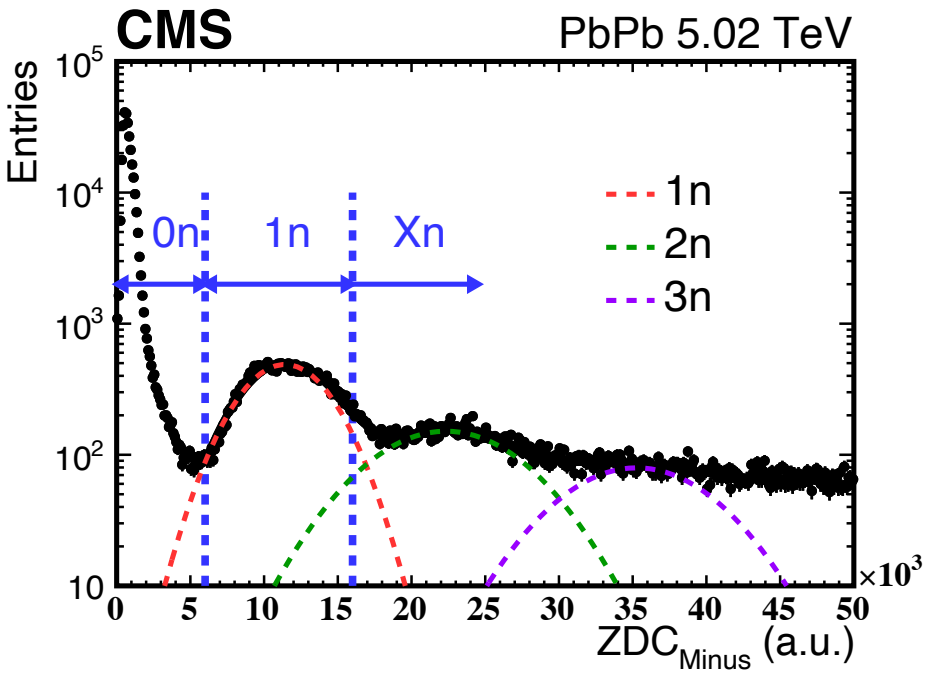


- Bearing analogy to centrality
  - $b_{XnXn} < b_{0nXn} < b_{0n0n}$

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

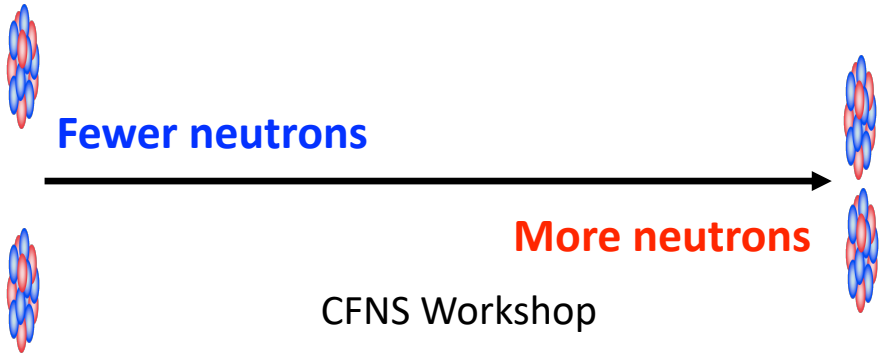
ZDC selections





CMS, arXiv:2011.05239

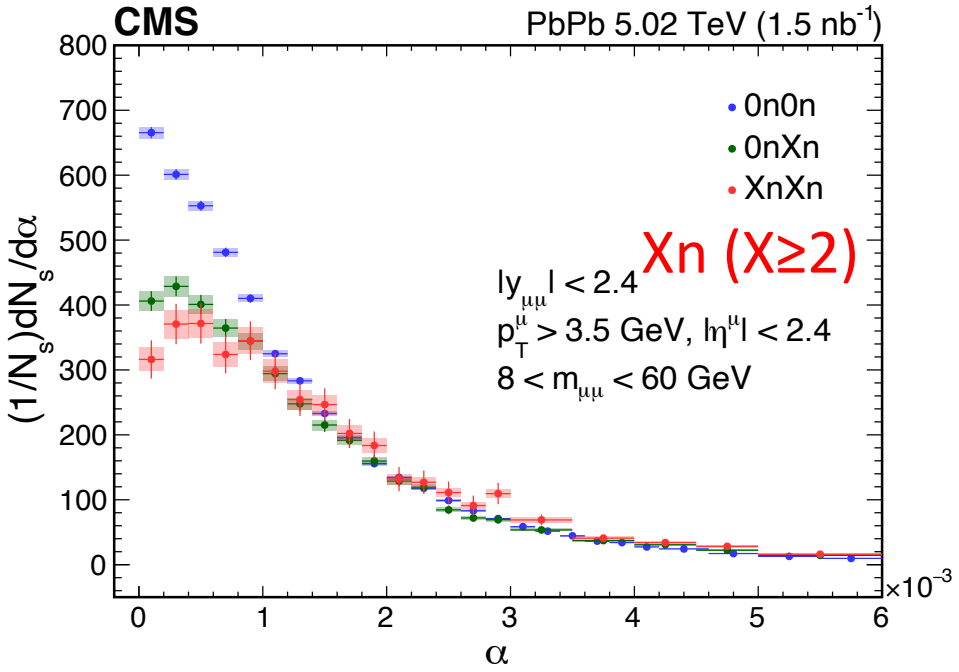
- Straight cut to disentangle neutrons
  - 0n0n, 0n1n, 0nXn, 1n1n, 1nXn, XnXn (X≥2)



α spectrum vs. neutron multiplicity

CMS, arXiv:2011.05239

UPC

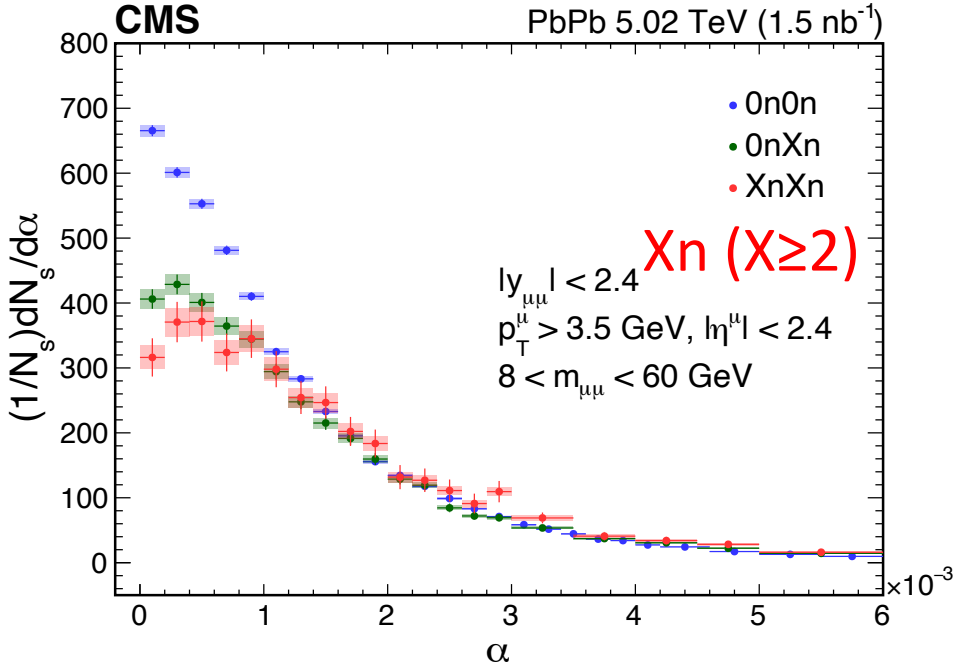


- 0n0n (fewer neutrons) $\Longrightarrow$ XnXn (more neutrons)
  - α spectrum becomes broad

α spectrum vs. neutron multiplicity

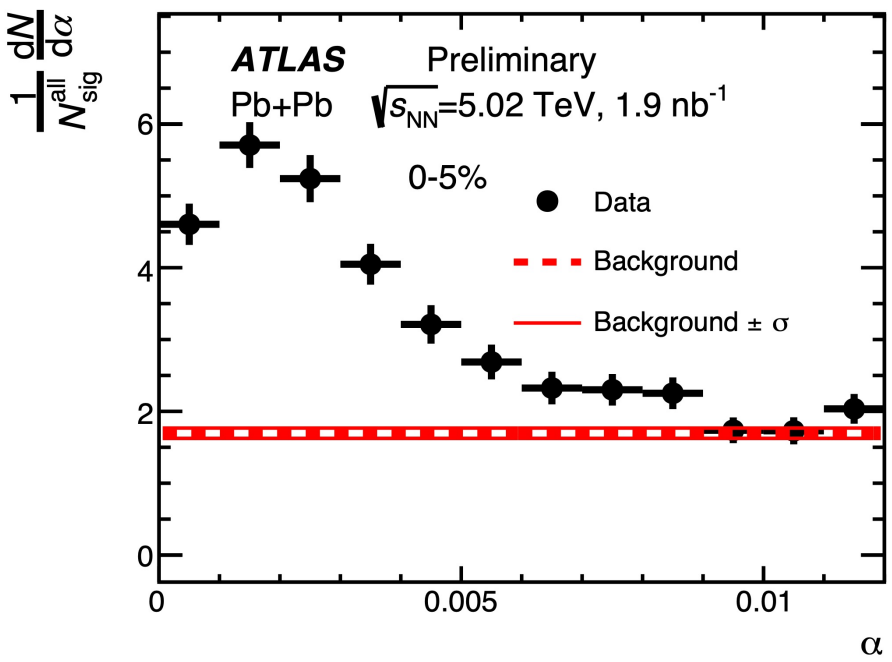
CMS, arXiv:2011.05239

UPC



ATLAS-CONF-2019-051

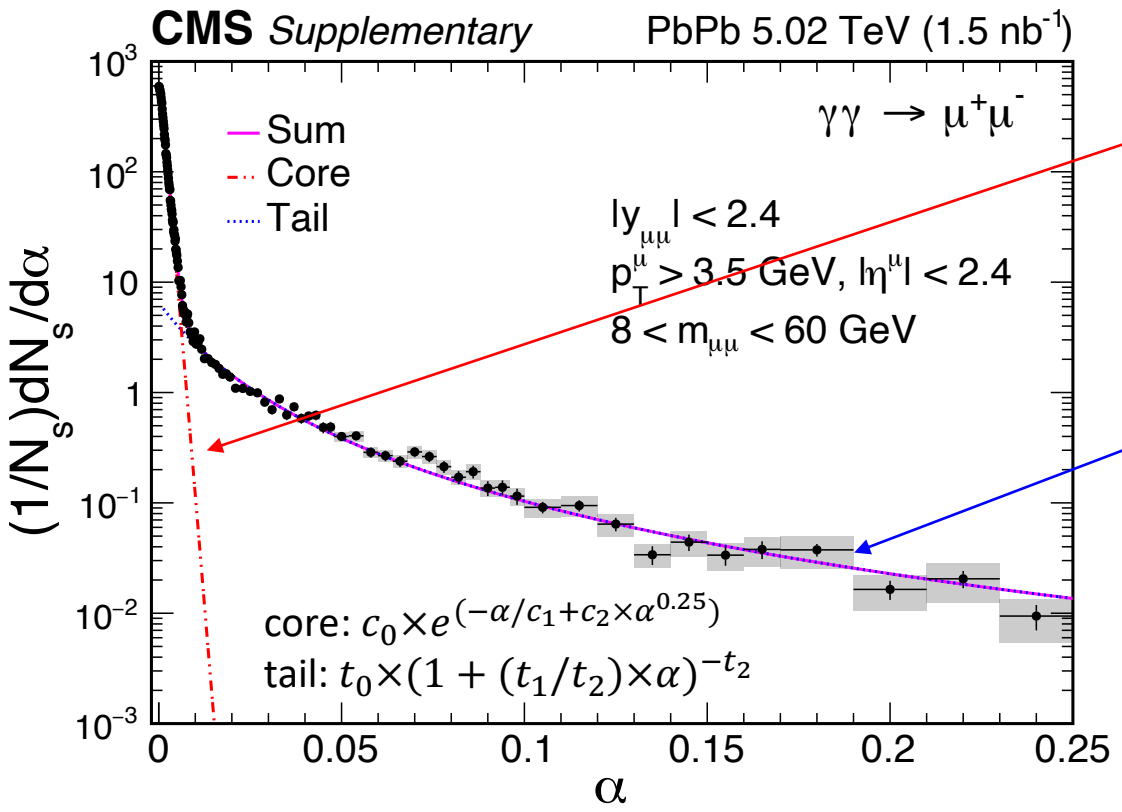
Hadronic Collisions

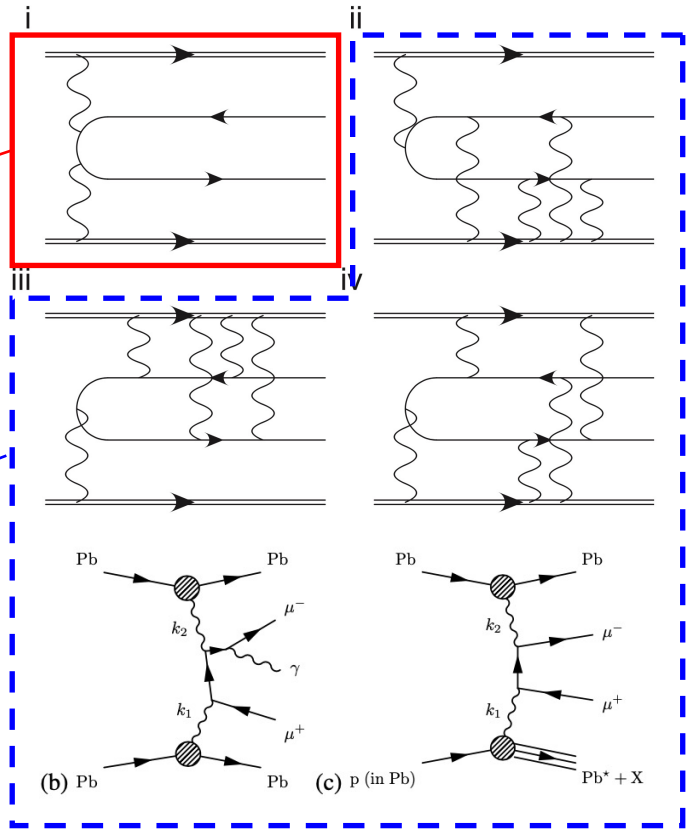


- 0n0n (fewer neutrons) $\Longrightarrow$ XnXn (more neutrons)
  - α spectrum becomes broad
  - Similar depletion in XnXn class with that in hadronic collisions at very small α

Decouple leading-order component

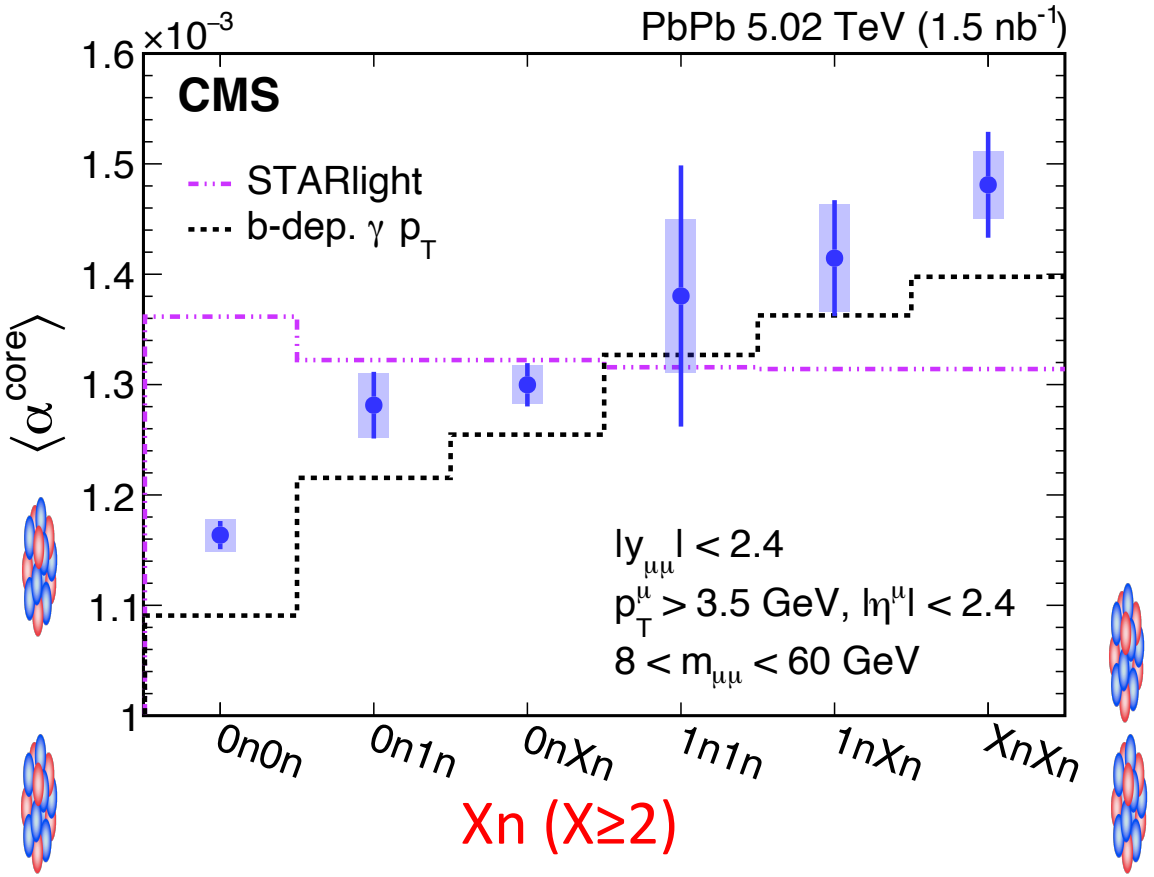
CMS, arXiv:2011.05239



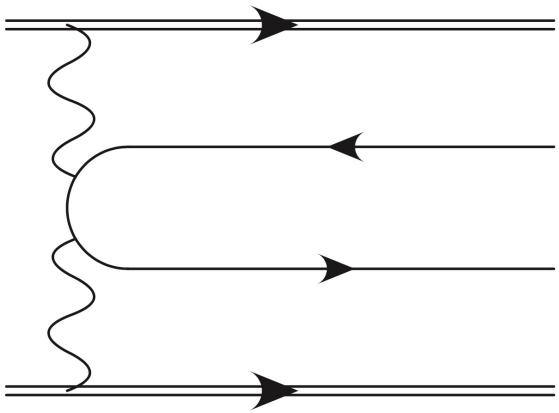


- Decouple α spectrum:
  - Data: $\langle \alpha^{\text{core}} \rangle$ = (1227 ± 7 (stat) ± 8 (syst)) × 10^{-6}
  - STARlight: 1350 × 10^{-6}

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



CMS, arXiv:2011.05239

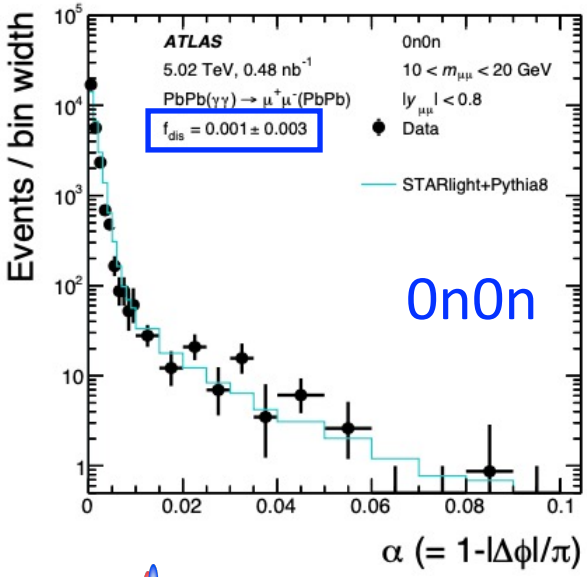


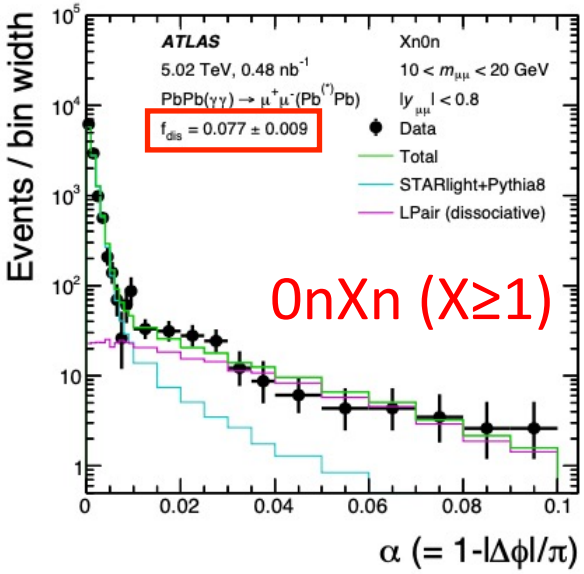
- Strong (5.7 σ) neutron multiplicity dependence of $\langle \alpha^{\text{core}} \rangle$
  - ***b*** dependence of initial photon p_T
  - Qualitatively described by a leading order QED model

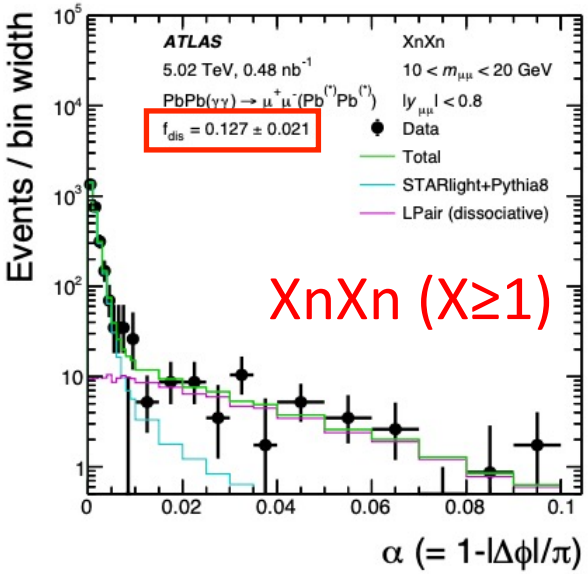
 Brandenburg et al., arXiv: 2006.07365

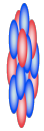
HO contribution vs. neutron multiplicity

ATLAS, arXiv:2011.12211

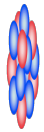


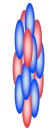


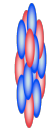




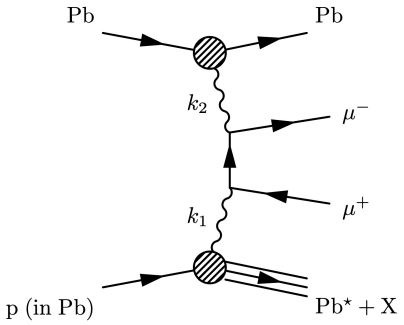
Fewer neutrons



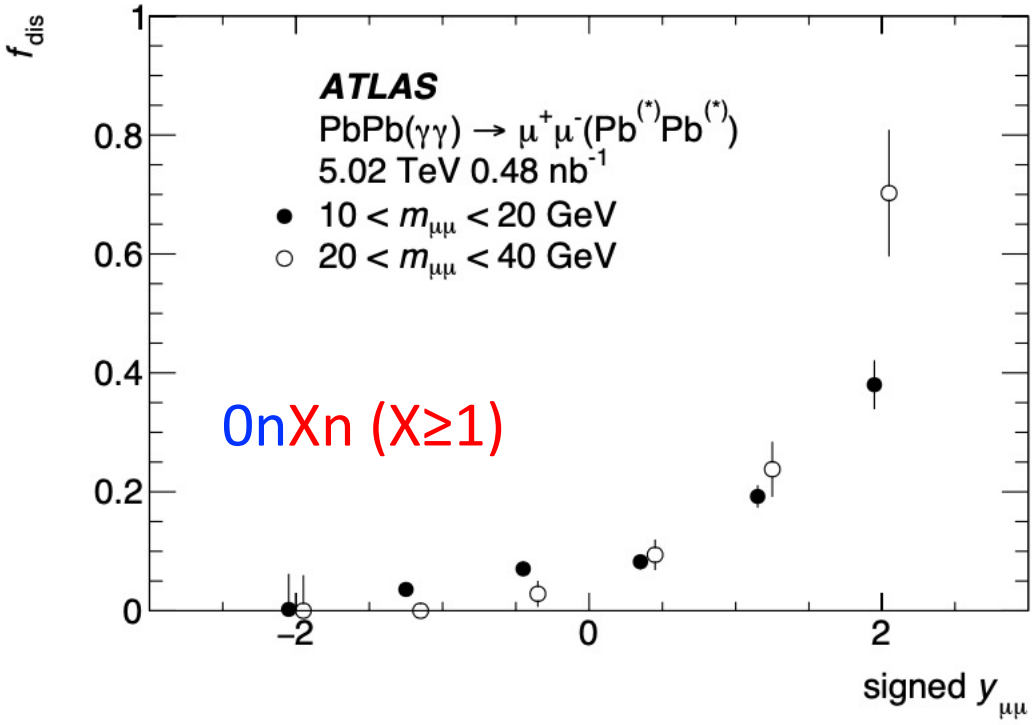




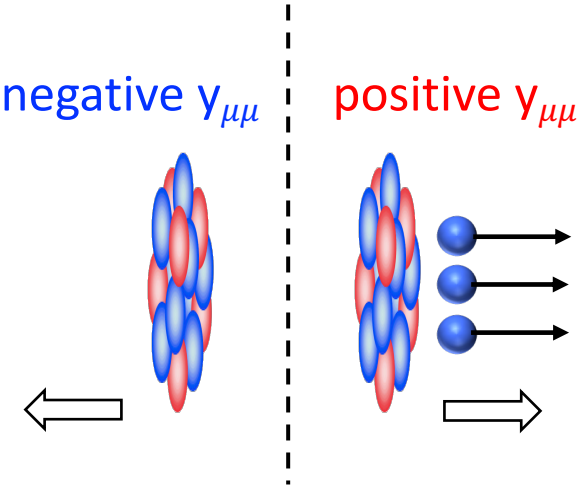
More neutrons



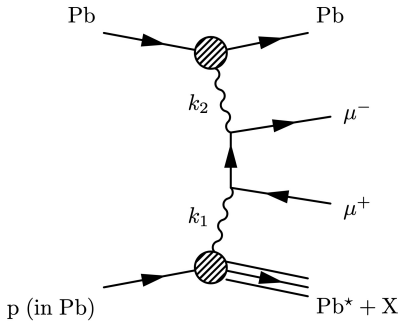
HO contribution vs. rapidity



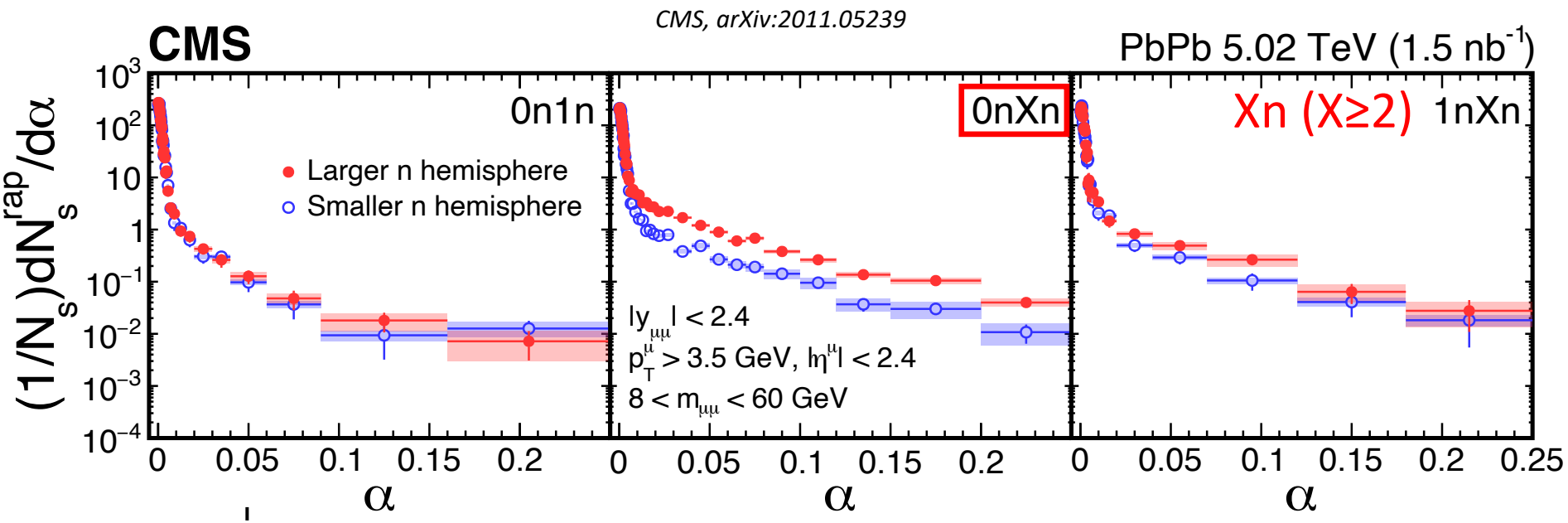
ATLAS, arXiv:2011.12211

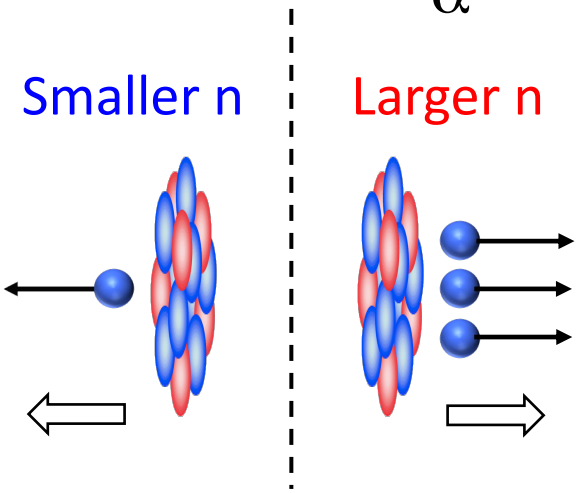


- Increase HO contribution (dissociative assumption) vs. signed $y_{\mu\mu}$



HO contribution vs. rapidity

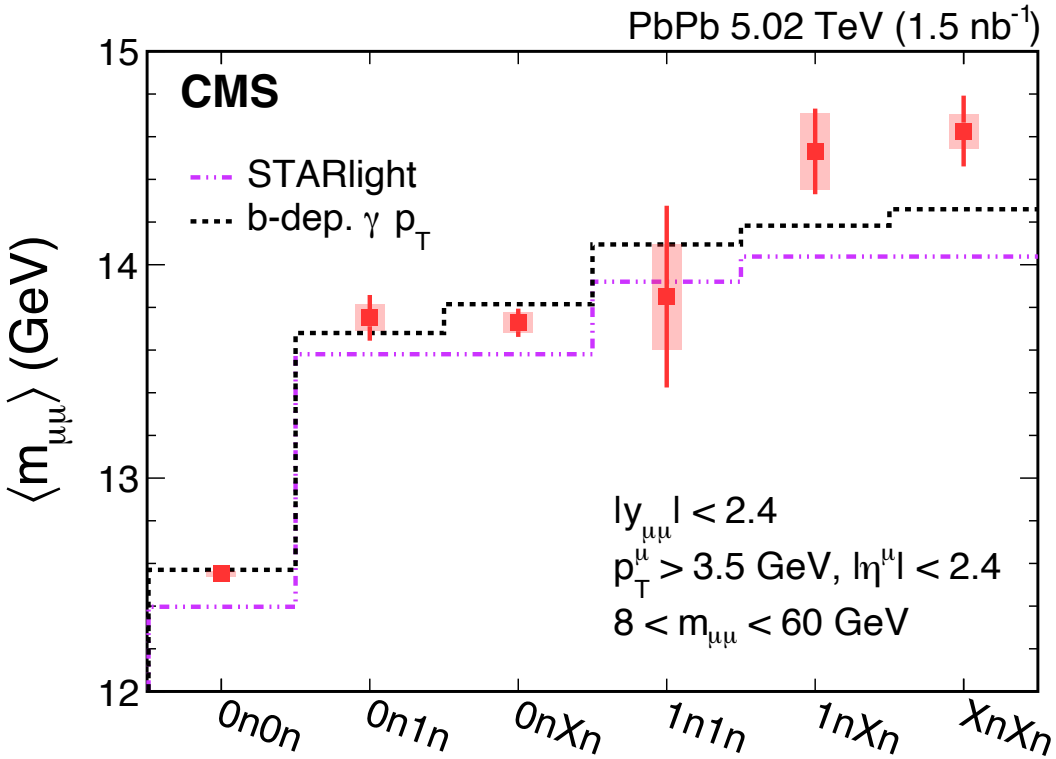




- In 0nXn, the tail contribution
  - Larger n hemisphere > Smaller n hemisphere
- **Only the tail in 0nXn has rapidity dependence**
  - Other HO process(es) play a role?

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

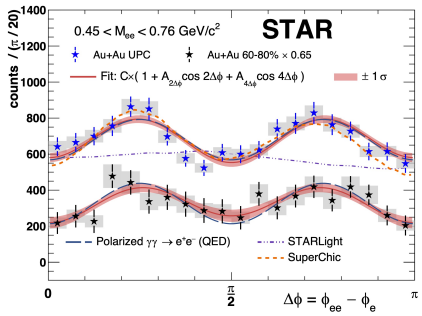
CMS, arXiv:2011.05239

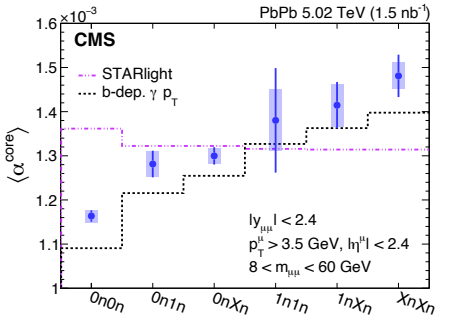


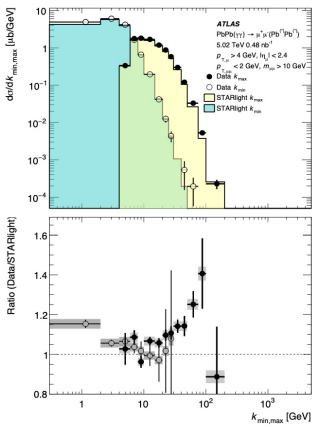
- Strong neutron multiplicity dependence of $\langle m_{\mu\mu} \rangle$
  - Deviation from constant: $\gg 5\sigma$
  - ***b*** dependence of initial photon energy

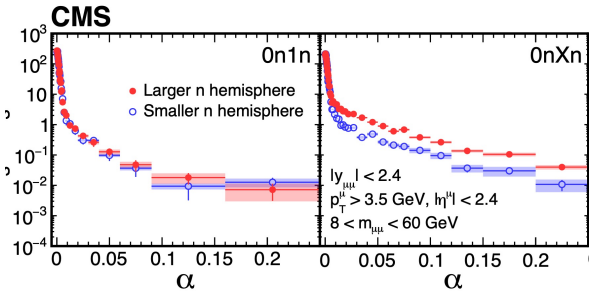
Summary

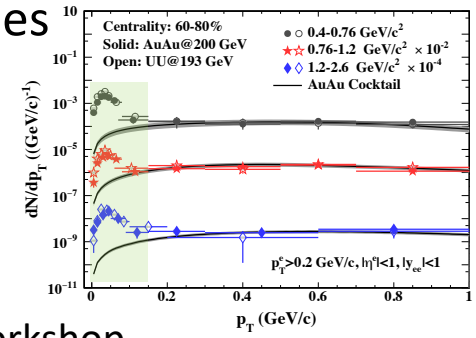
- Exclusive l^+l^- production
  - Linearly polarized photon
  - *b* dependence of photon p_T
  - Advanced generator needed for current/future precise data
    - Photon kinematics (PDF)
    - Higher-order $\gamma\gamma$ interactions
- Non-exclusive l^+l^- production
  - Opportunity to study QGP EM properties
  - Require precise baseline

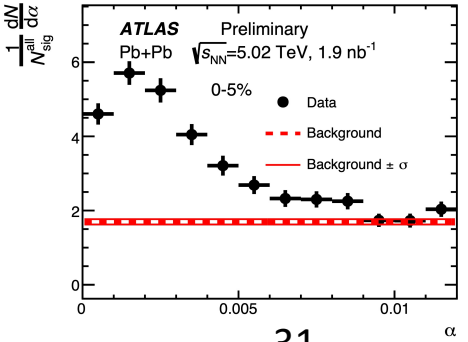






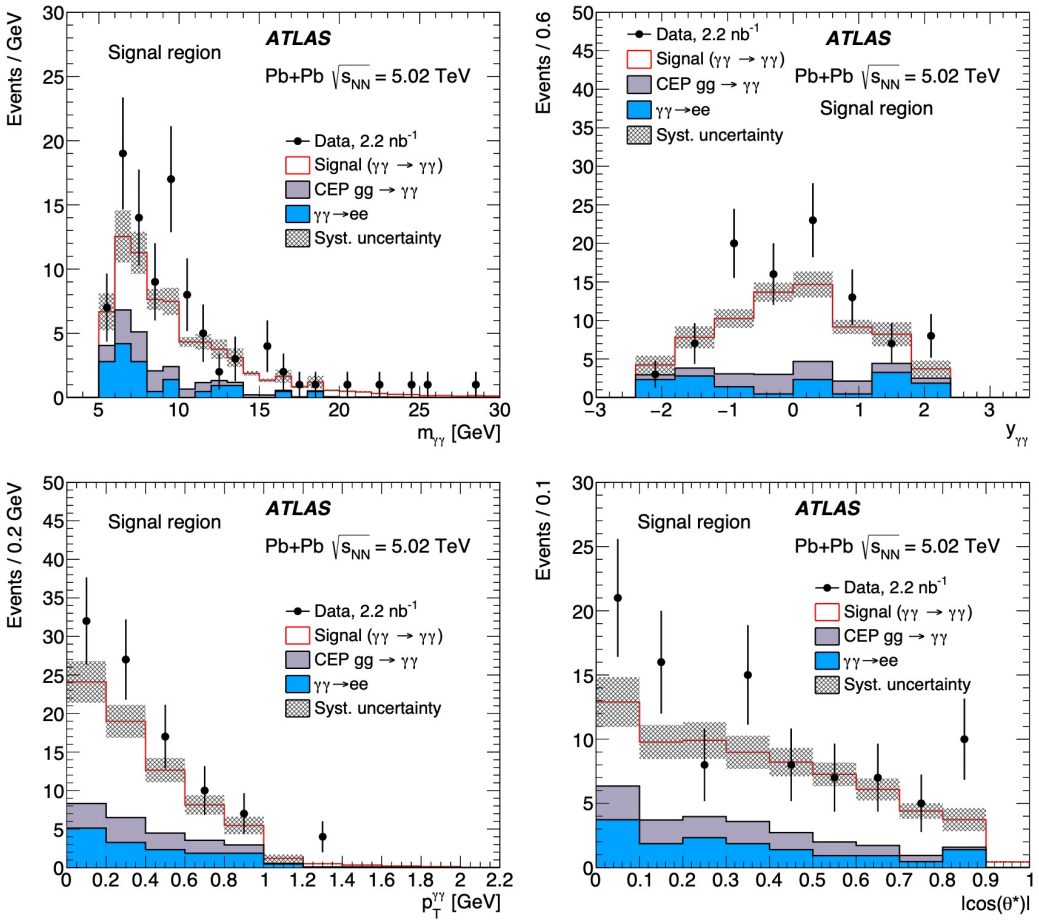






Backup

Light-by-light scattering

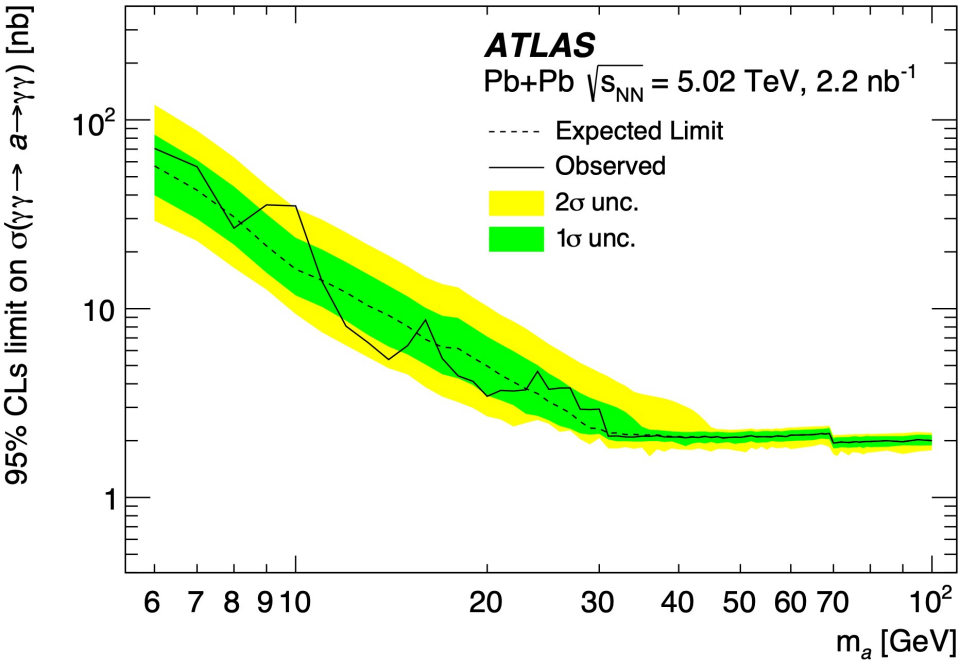


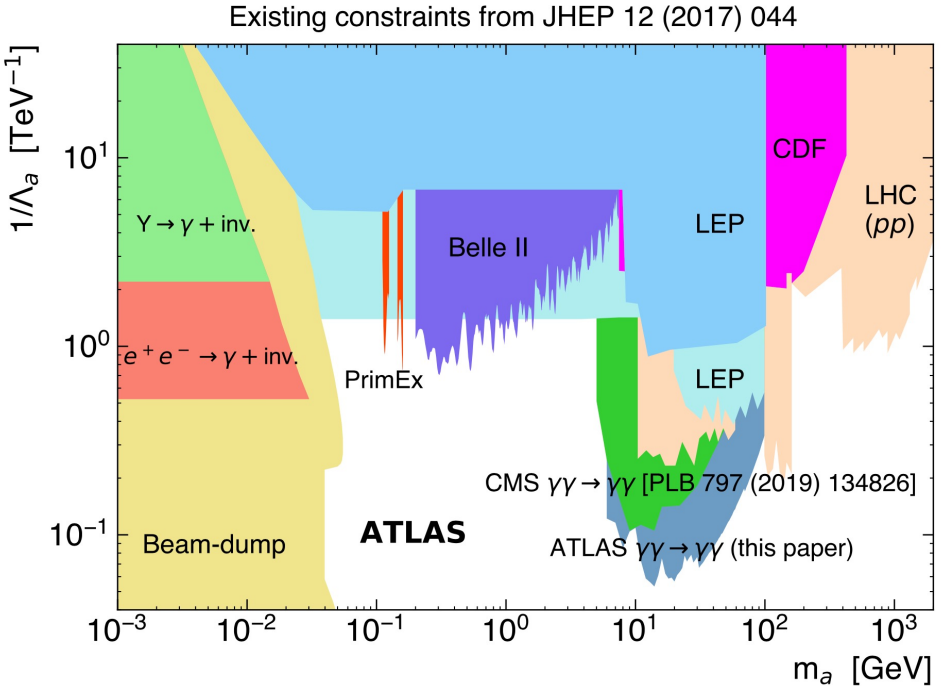
ATLAS, JHEP 03 (2021) 243

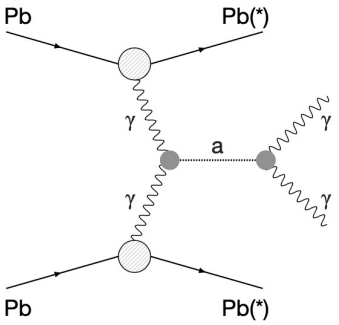
- Generally good agreement with model, but indication of a systematic excess

Light-by-light scattering

ATLAS, JHEP 03 (2021) 243

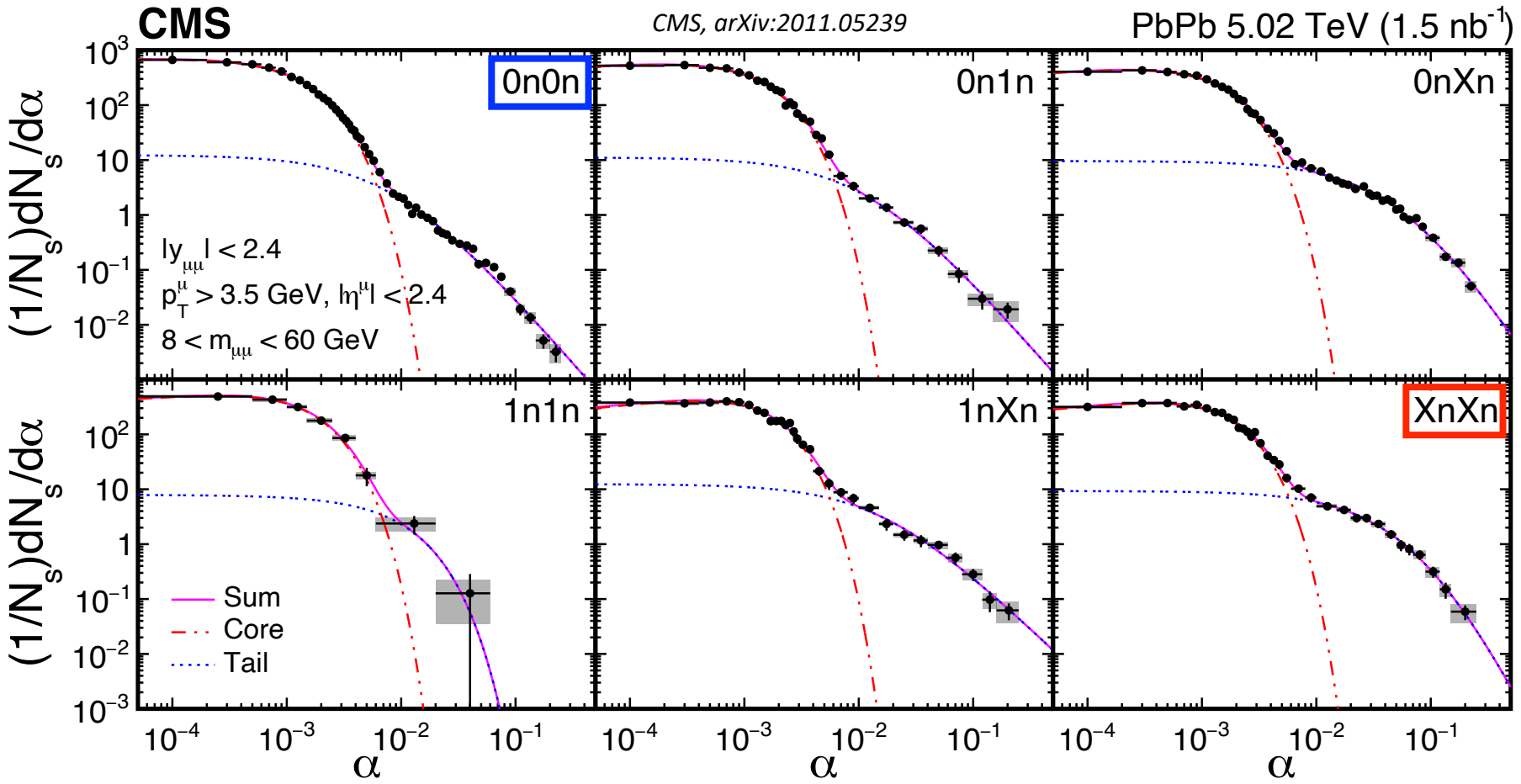






- No ALP observed
- Most stringent limits set for cross section and coupling

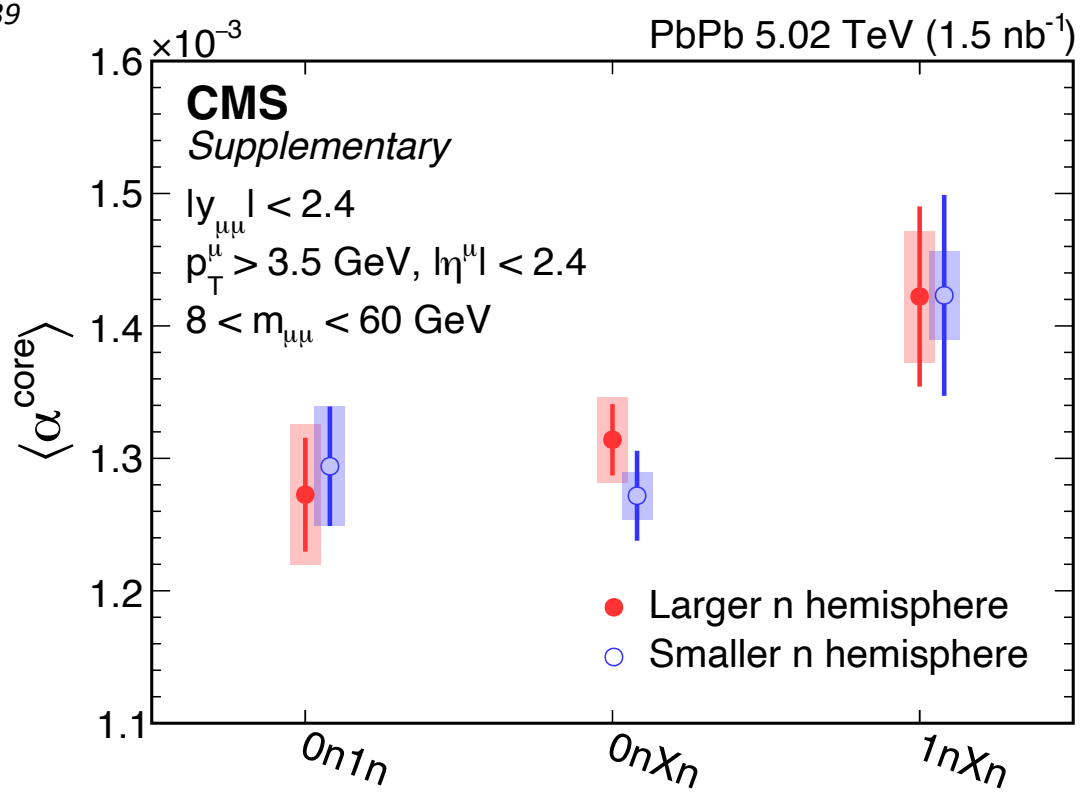
α spectrum vs. neutron multiplicity



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

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

CMS, arXiv:2011.05239

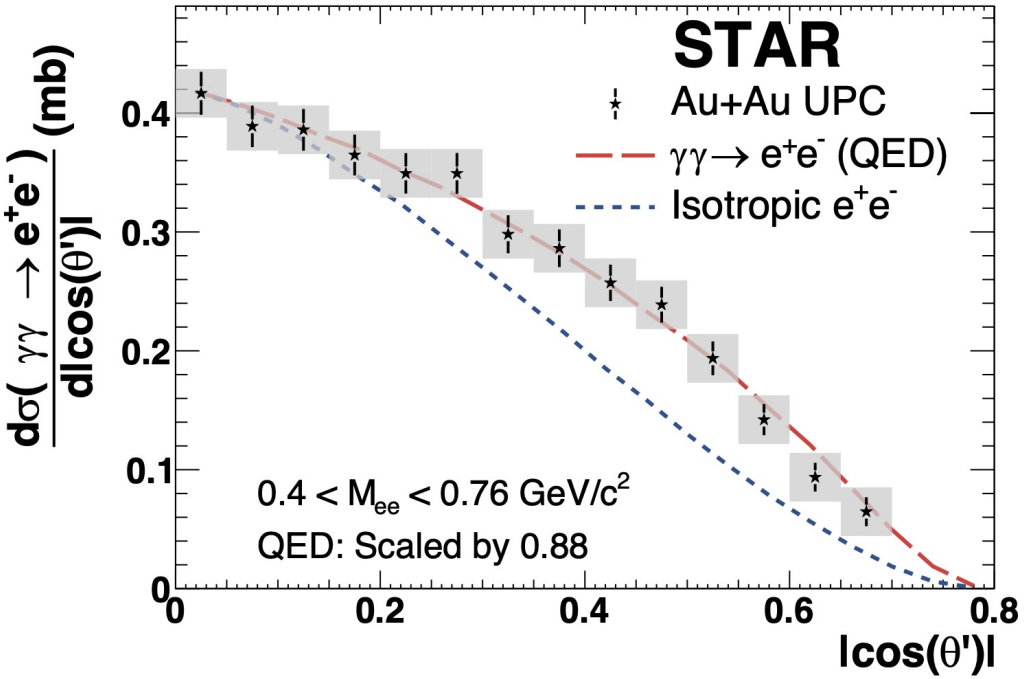


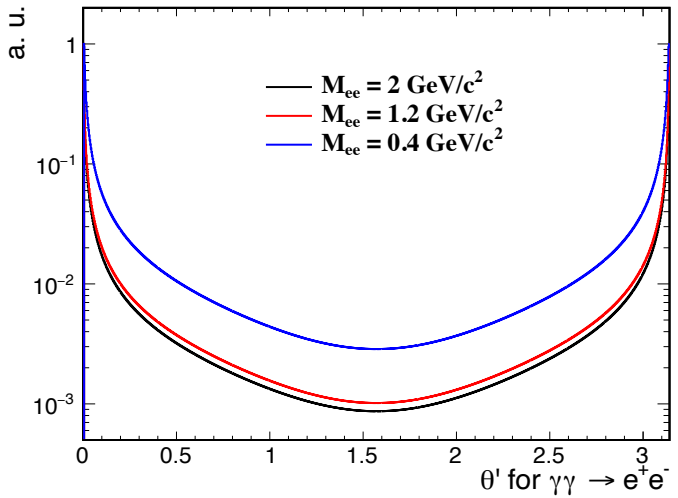
- $\langle \alpha^{\mathrm{core}} \rangle$ has no rapidity dependence
  - Core dominantly comes from LO $\gamma\gamma$ scattering
  - Core function is reliable

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

STAR, arXiv: 1910.12400

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

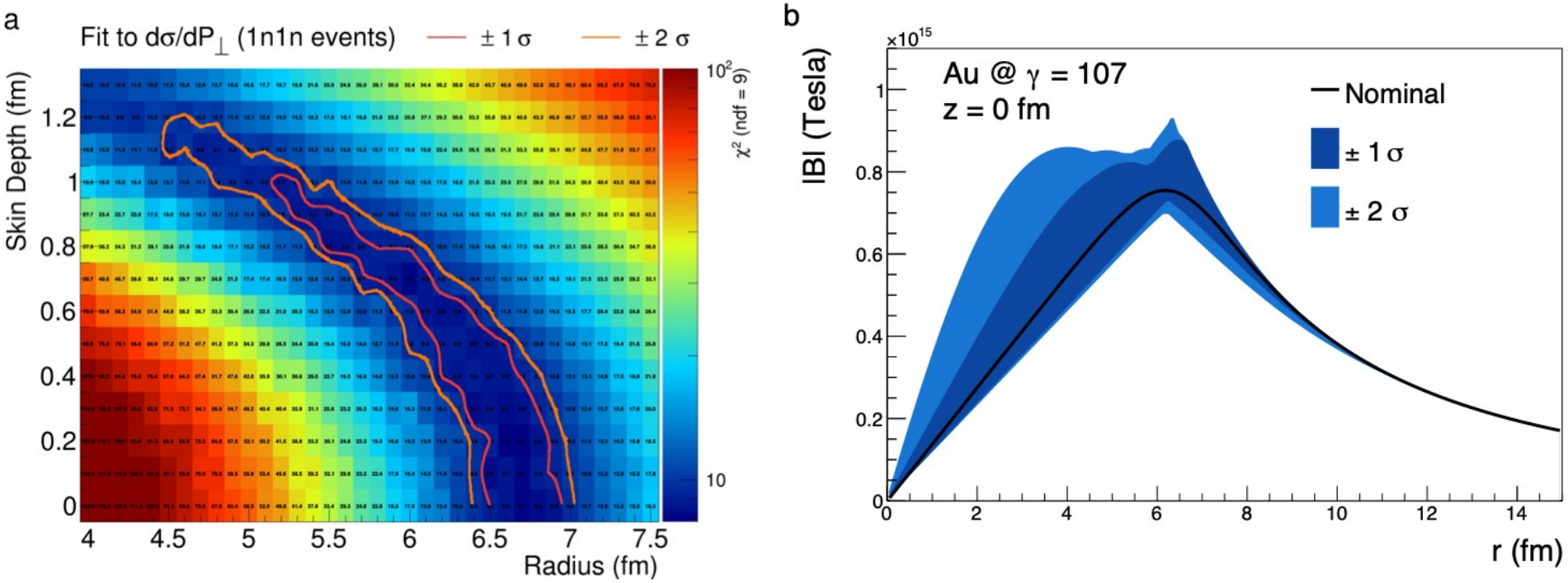




➢Individual l^+/l^- preferentially aligned along beam axis

EM filed mapping

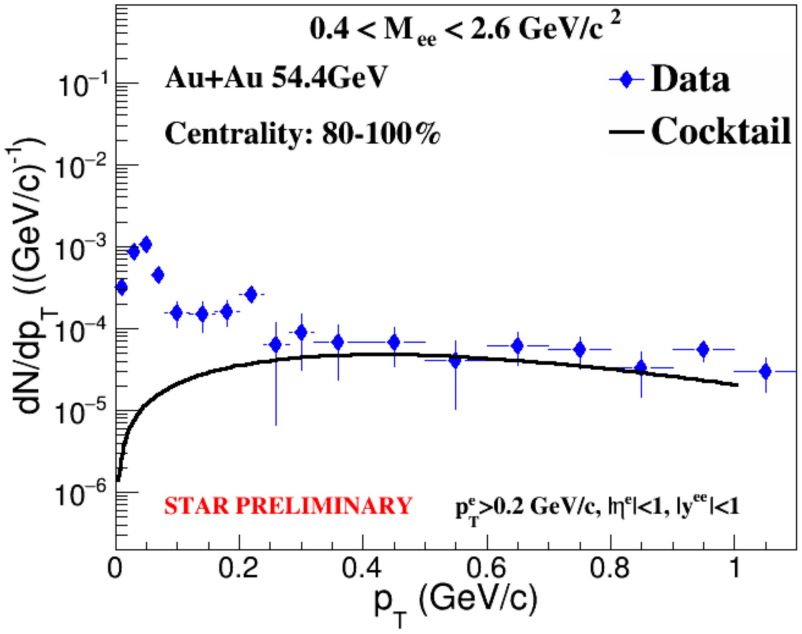
Brandenburg et al., arXiv: 2103.16623



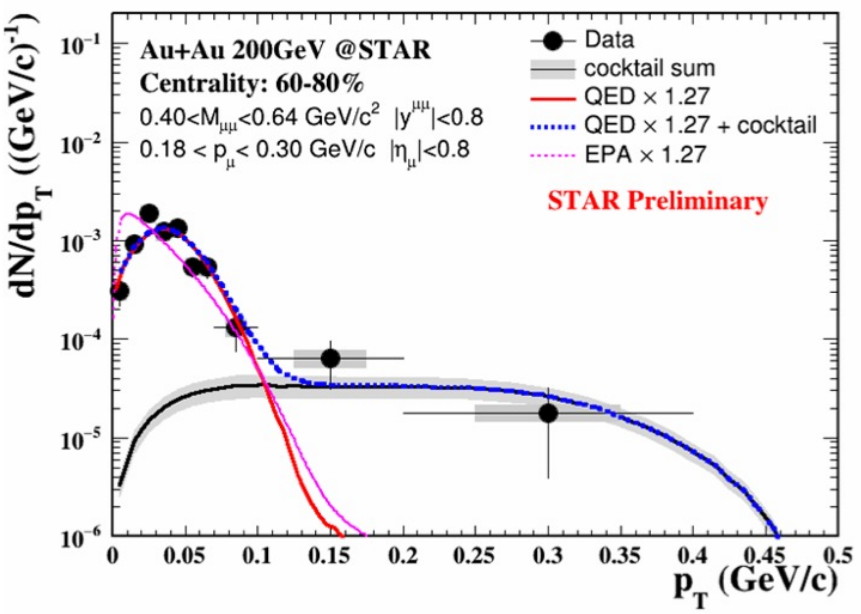
- Fit to STAR's measurement of $\gamma\gamma \rightarrow e^{+}e^{-}$ in UPC
- Map charge distribution and magnetic filed

Non-exclusive $\gamma\gamma \rightarrow l^+l^-$ at RHIC

X.F. Wang, Initial Stages 2021



J. Zhou, sQM 2021



- Indication for additional peak from semi-coherent $\gamma\gamma$ interactions
- New measurement of $\gamma\gamma \rightarrow \mu^+\mu^-$ in 60-80% AuAu collisions