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

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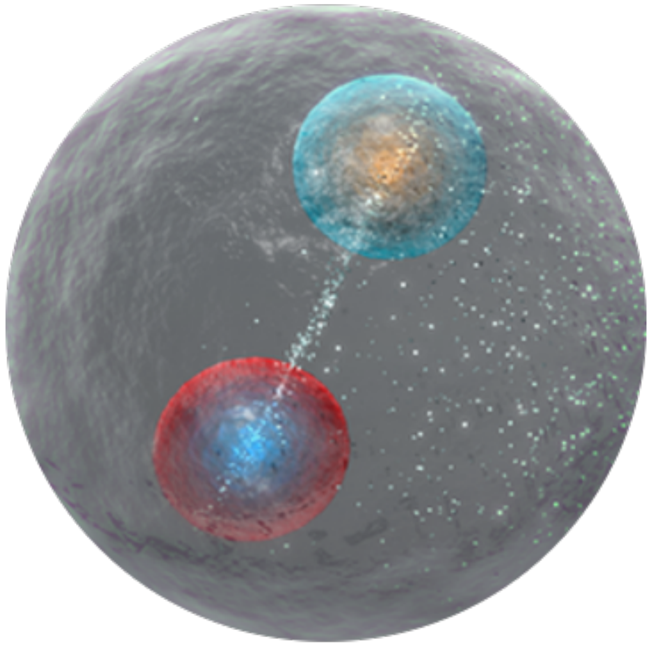
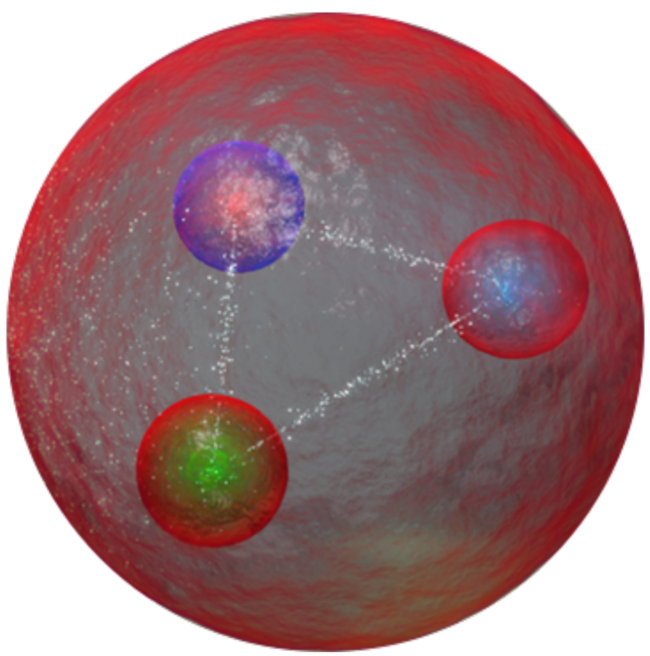
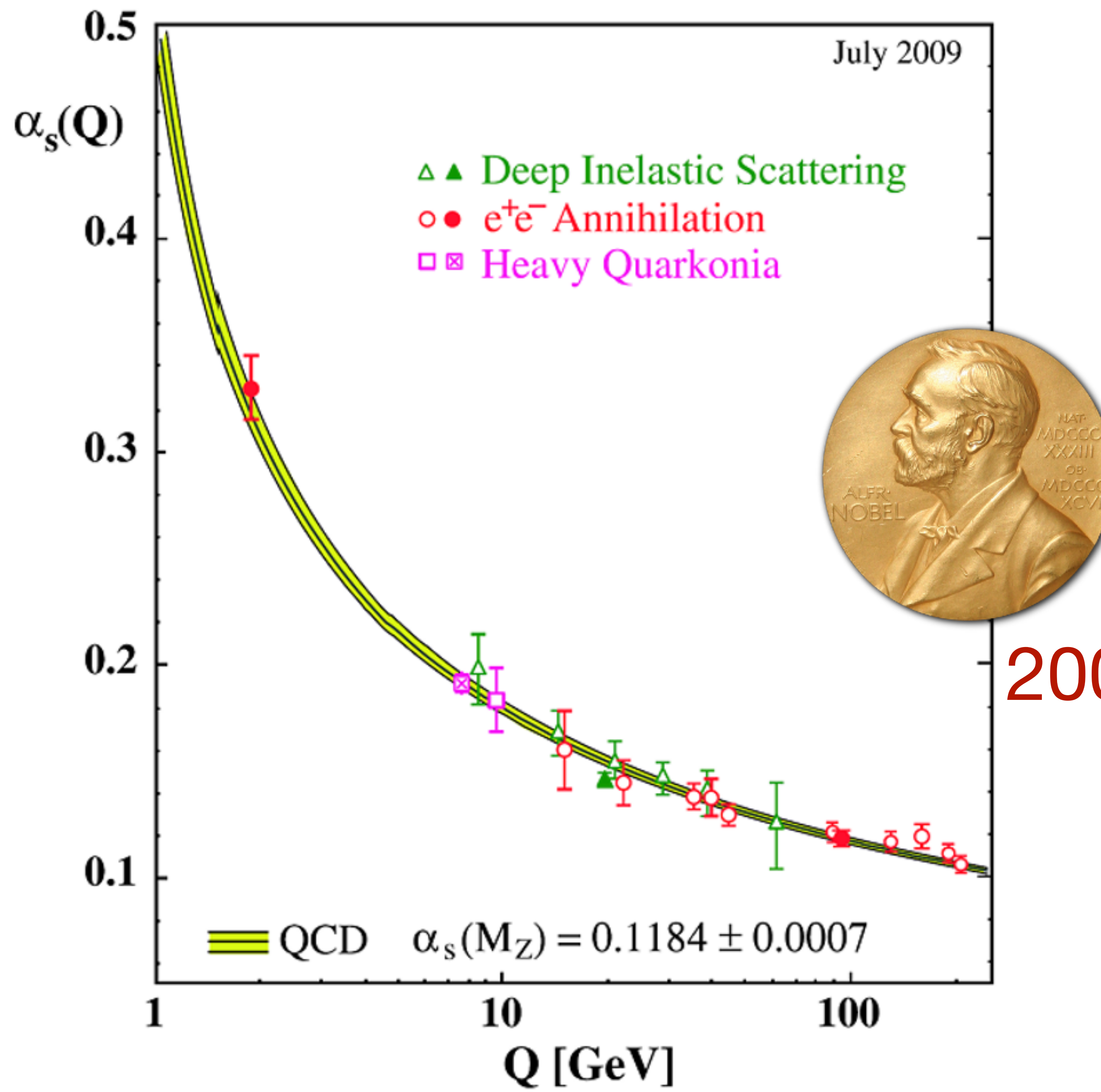
- *Introduction*
- *Signatures of* $\gamma\gamma \rightarrow l^+l^-$ *in UPC*
- $\gamma\gamma \rightarrow l^+l^-$ *production in non-UPC*
- *Summary and outlook*

第一届“粤港澳”核物理论坛

Confinement





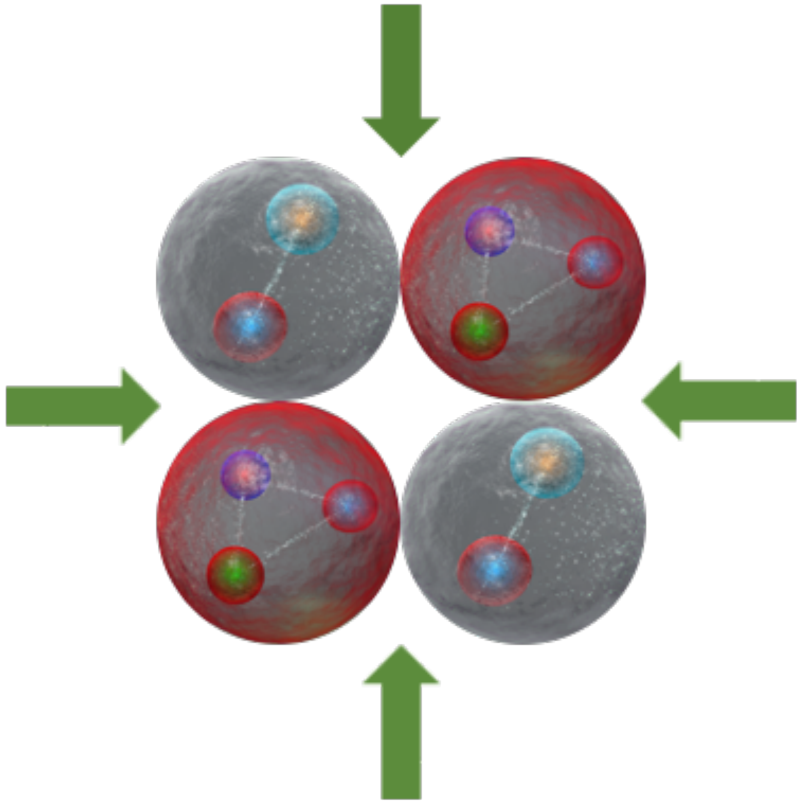


2004

NO free quark in nature!

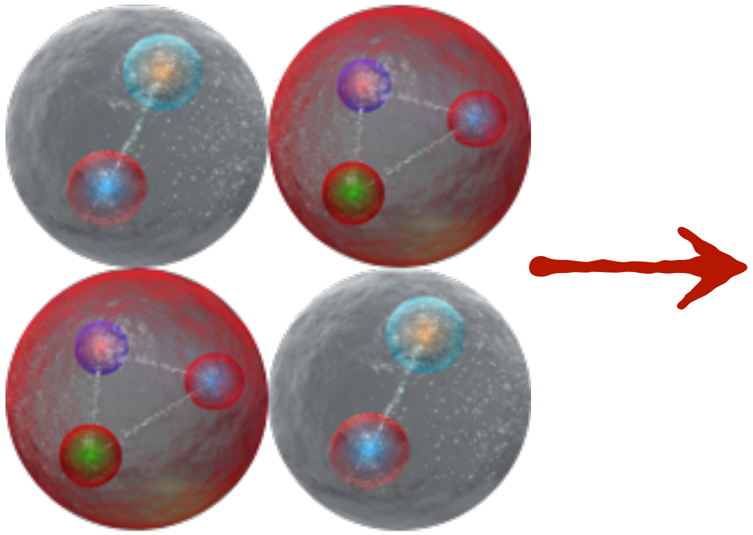
Confinement ⟹ Deconfinement

Pressure

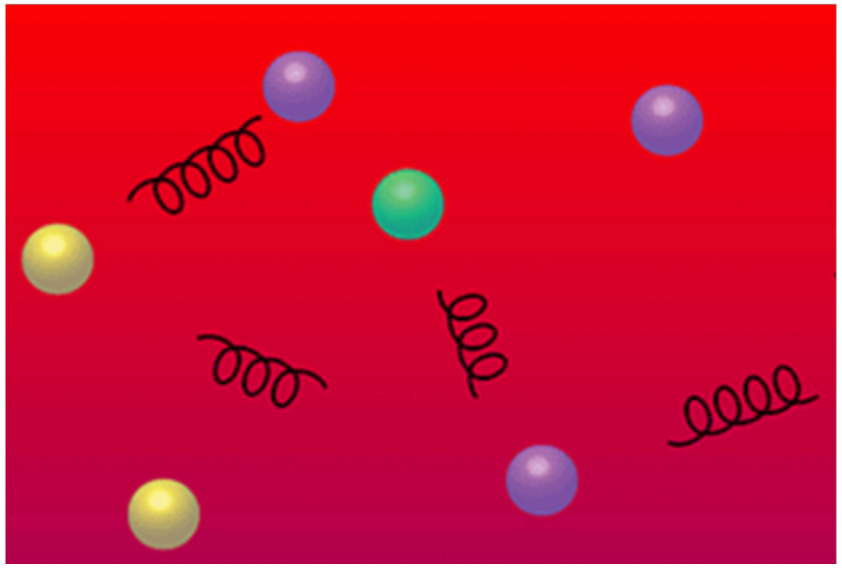


OR

Heat

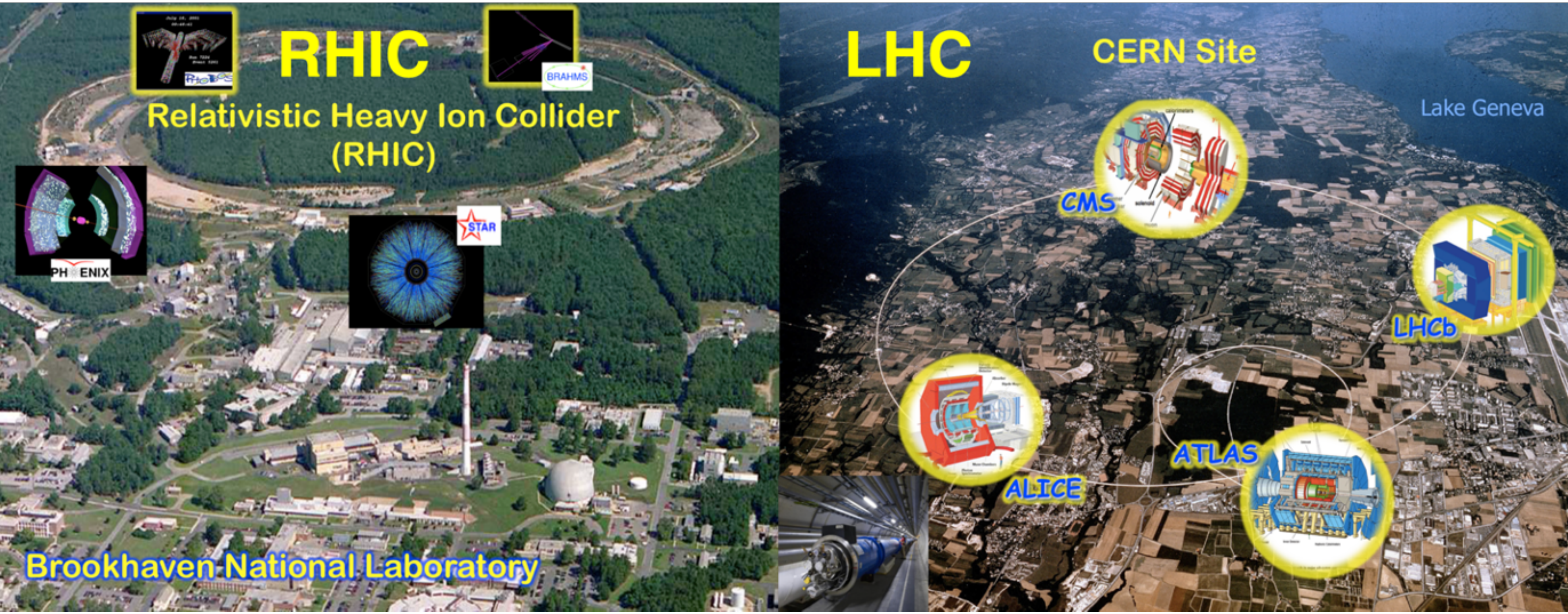


Quark Gluon Plasma



- Deconfinement
- Thermalization

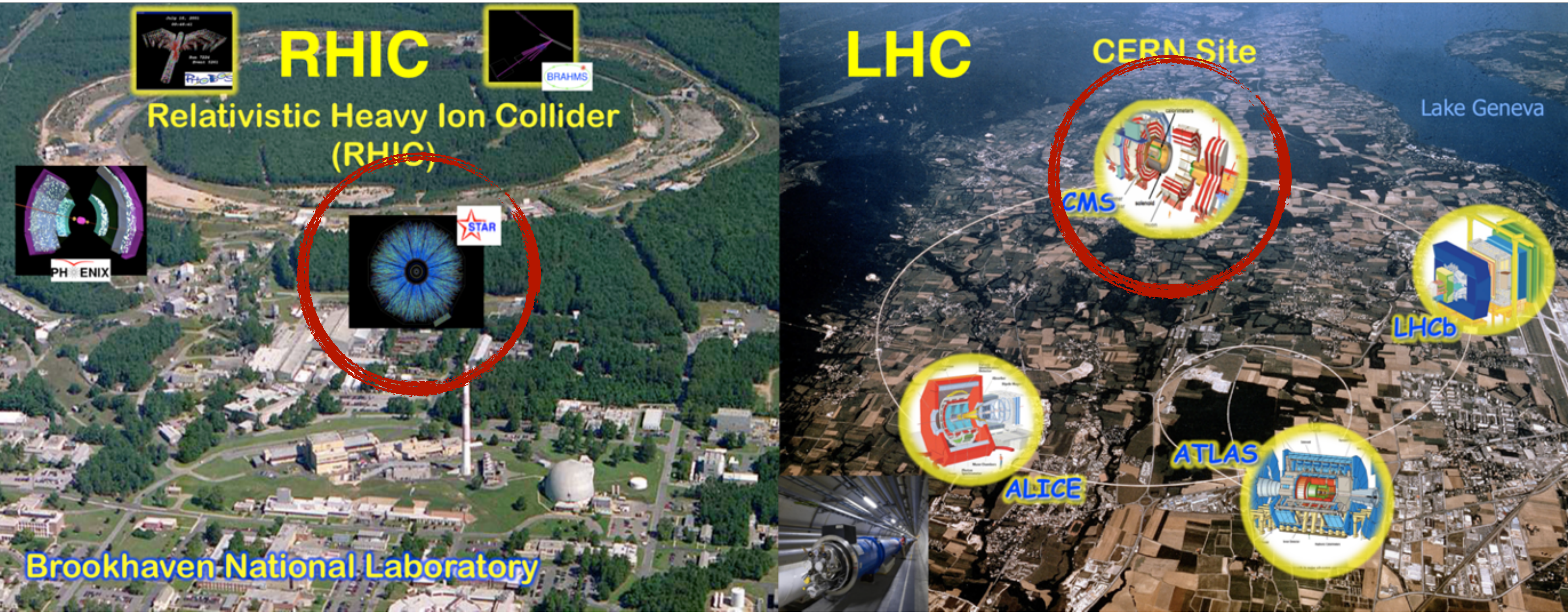
Creating QGP in laboratory



$99.995\% \times c$ $99.999999\% \times c$

“Little Bang”

Creating QGP in laboratory



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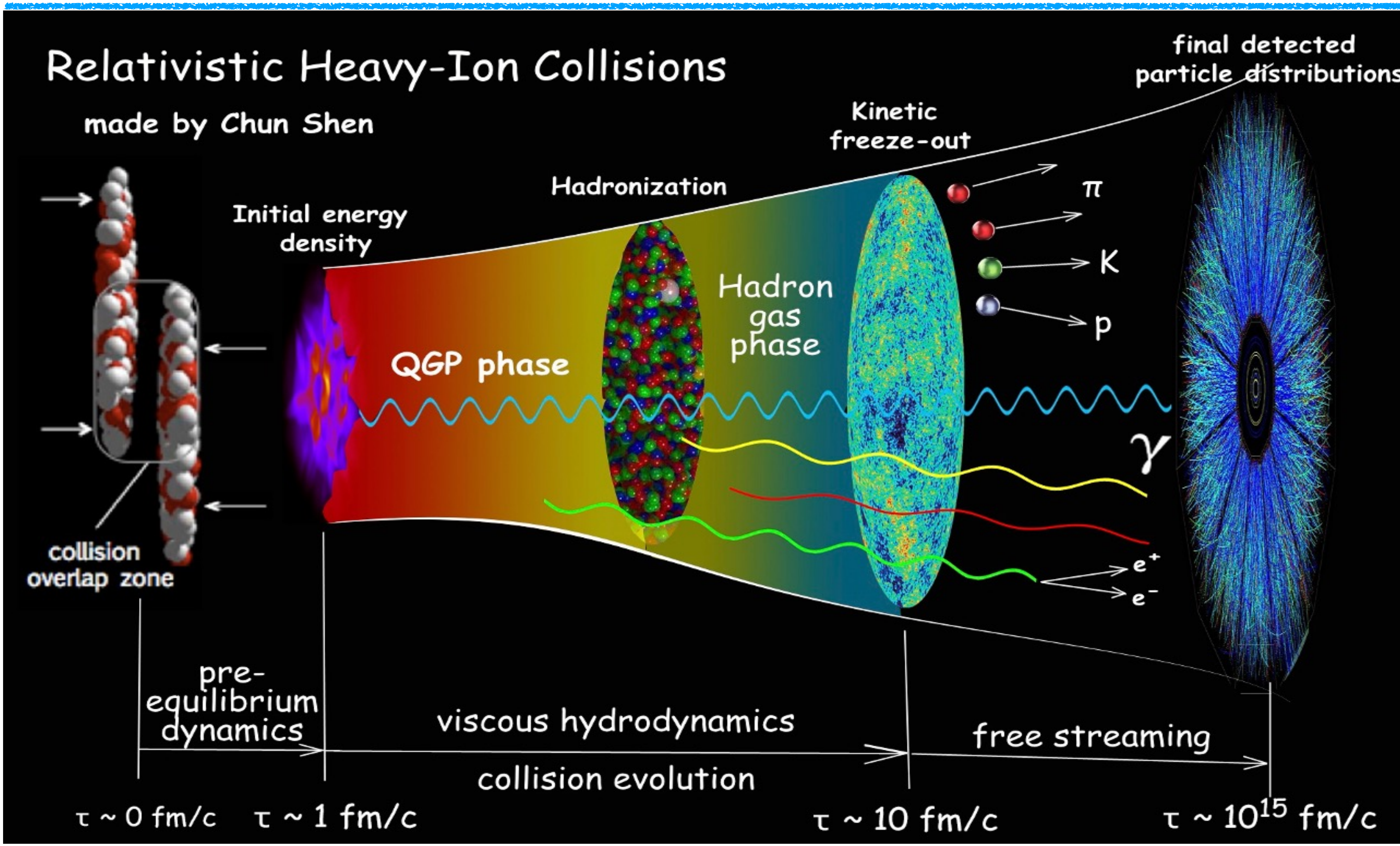
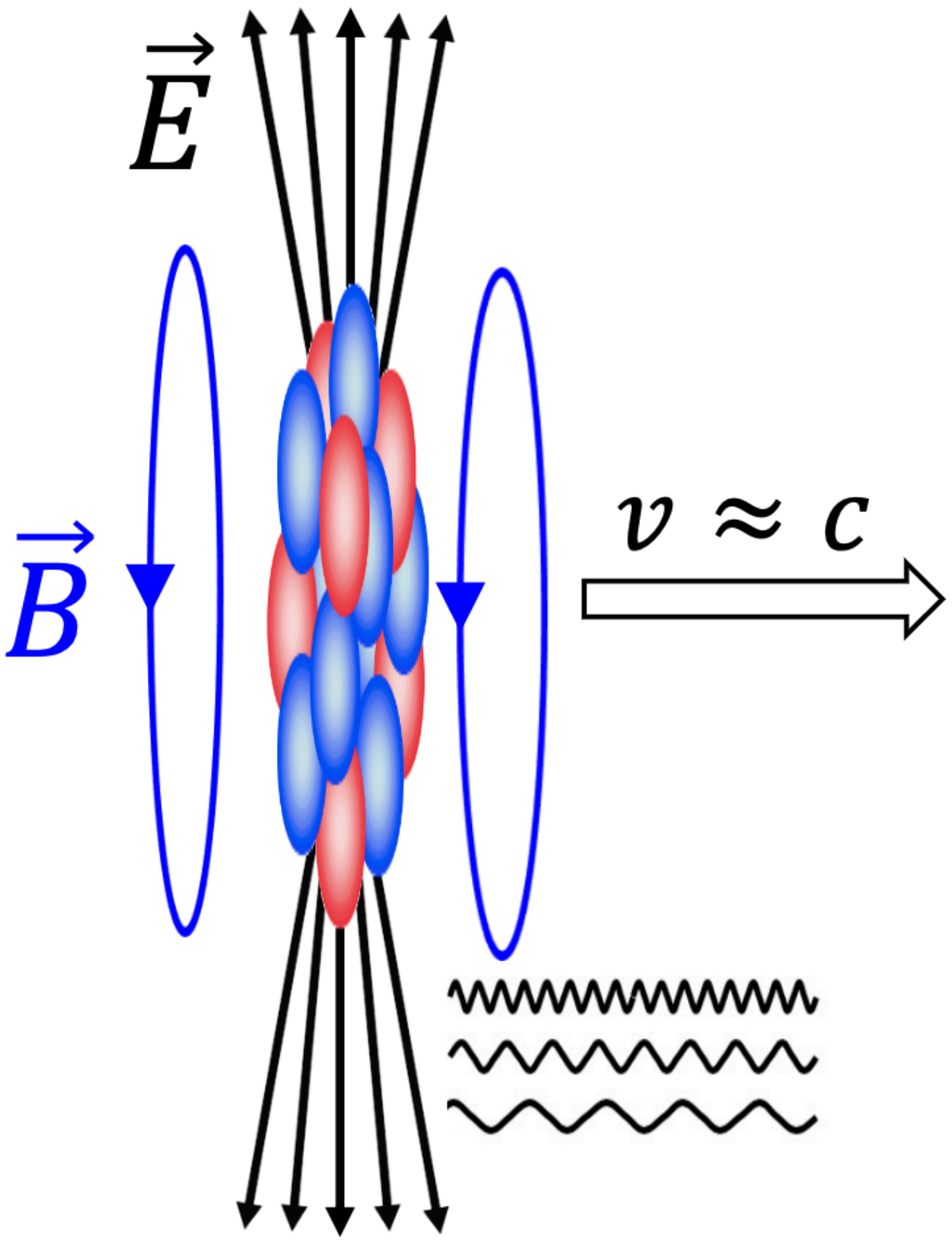
"Little Bang"

Relativistic heavy-ion collisions



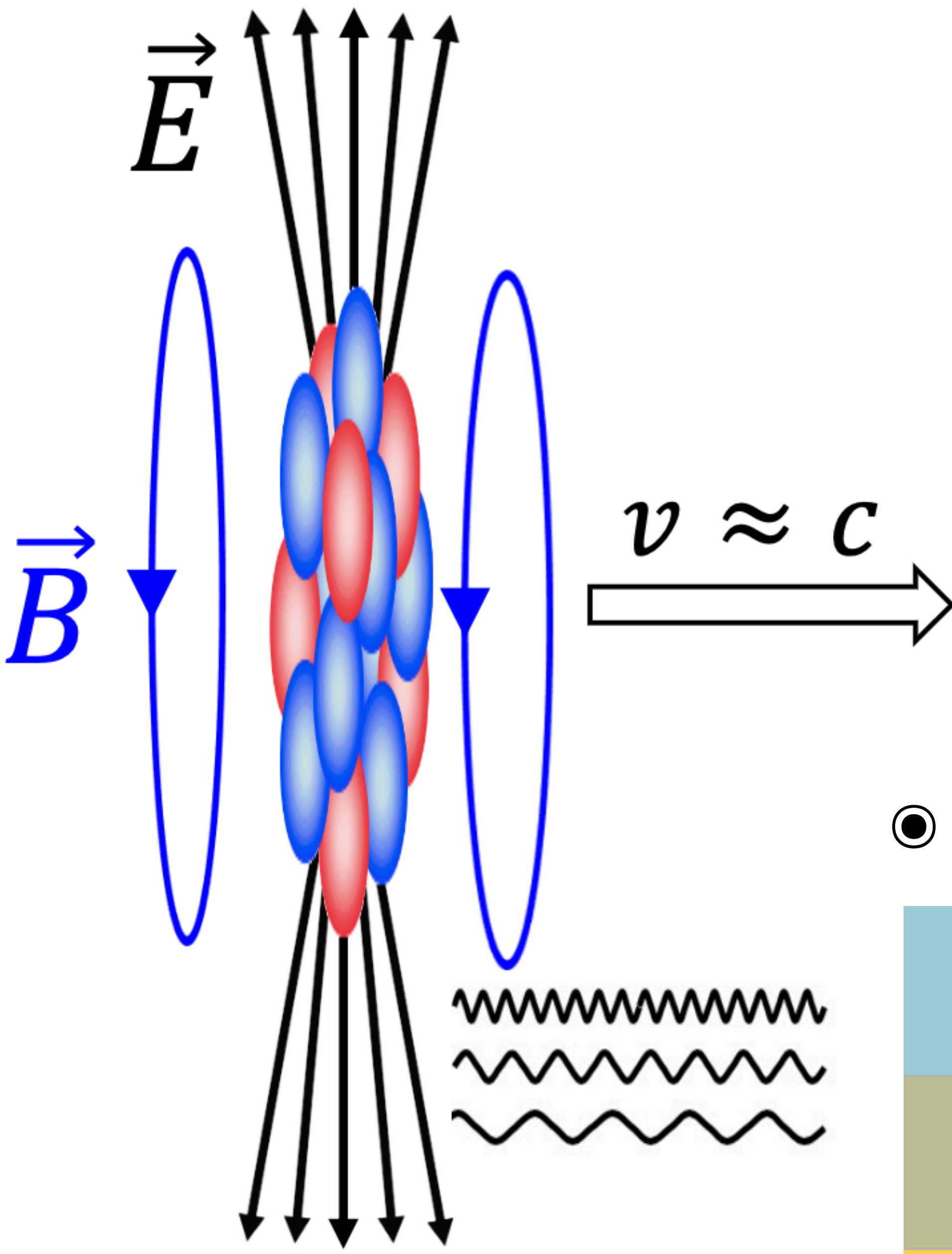
“Little Bang”

Not just a hadron collider



- Equivalent Photon Approximation
  - Proposed in 1924 by Fermi
  - Photon Flux ∝ Z^2

Not just a hadron collider



- Equivalent Photon Approximation
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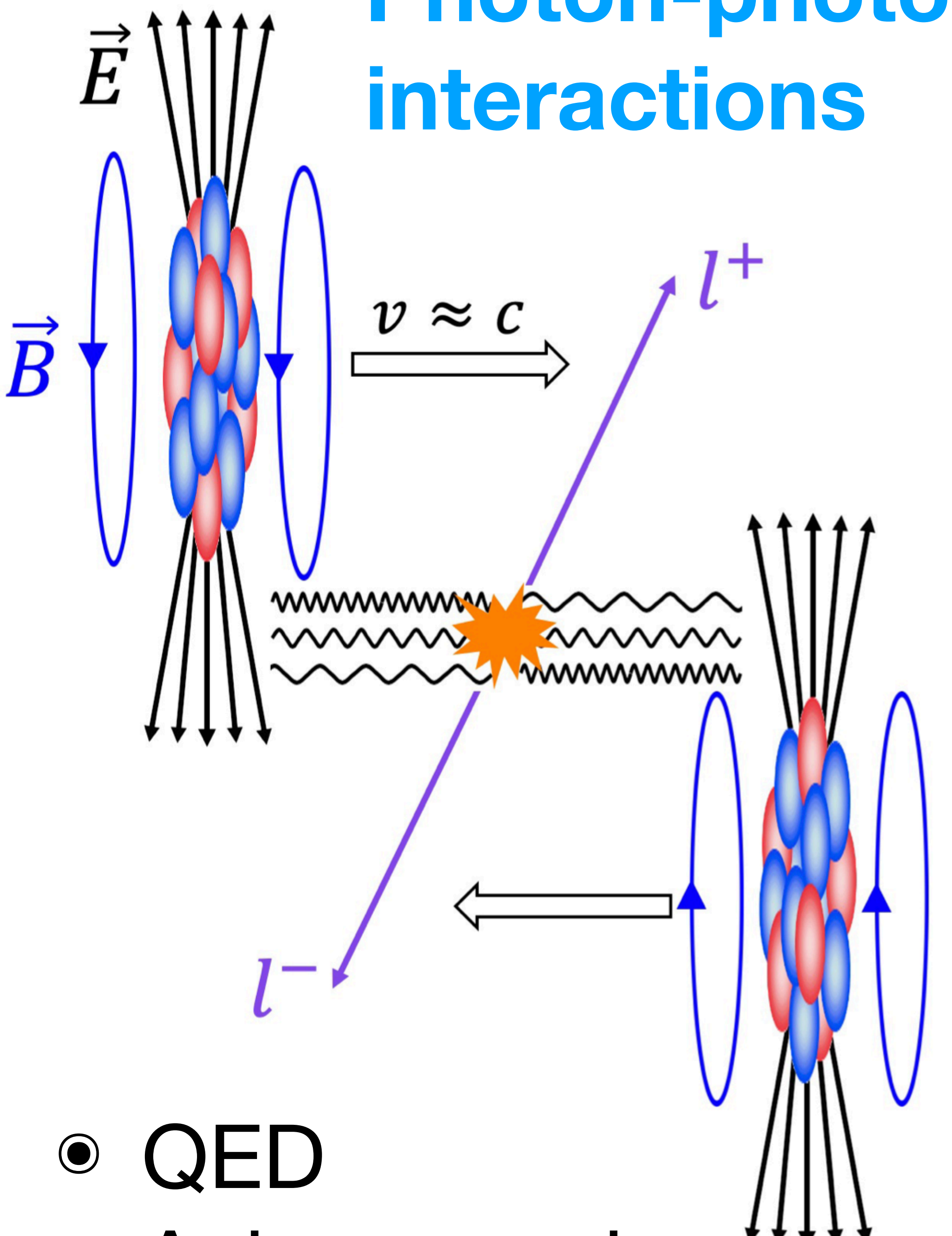
  - Photon Flux $\propto Z^2$

- Photon kinematics

maximum energy $E_{\gamma,max}$~$\gamma(\hbar c/R)$	**80 GeV in Pb+Pb@LHC 3 GeV in Au+Au@RHIC**
typical p_T (& virtuality) p_{Tmax} ~ $\hbar c/R$	**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!)**

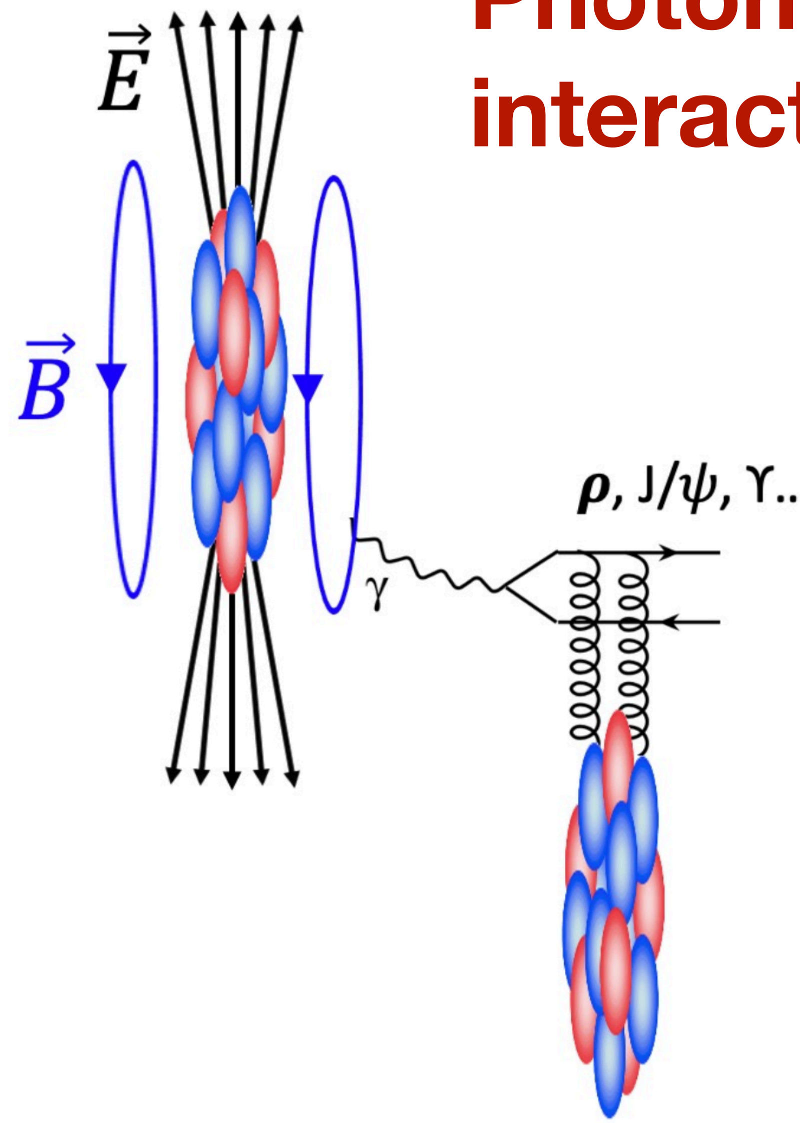
Not just a hadron collider

Photon-photon interactions



- QED
- Axion search

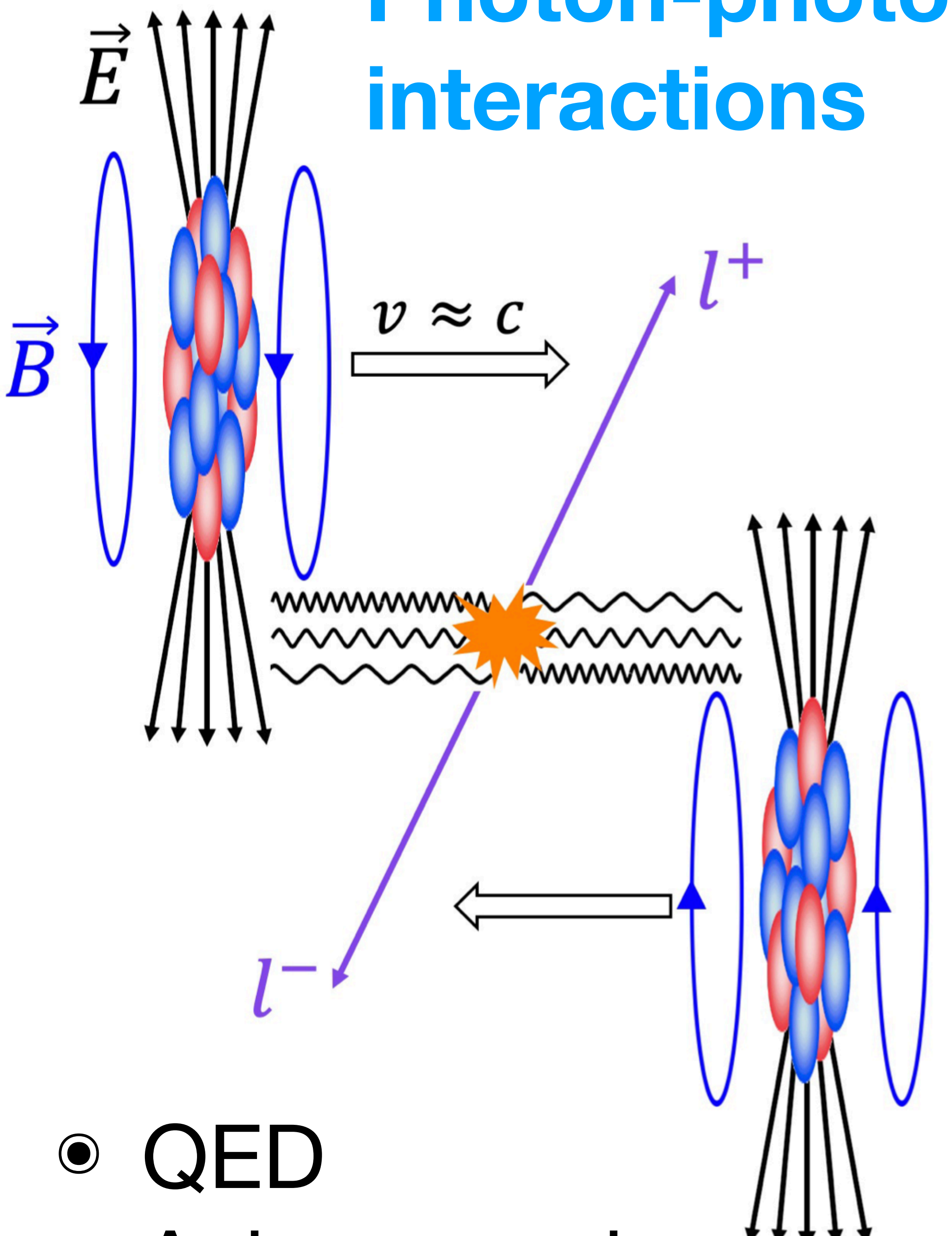
Photon-nuclear interactions

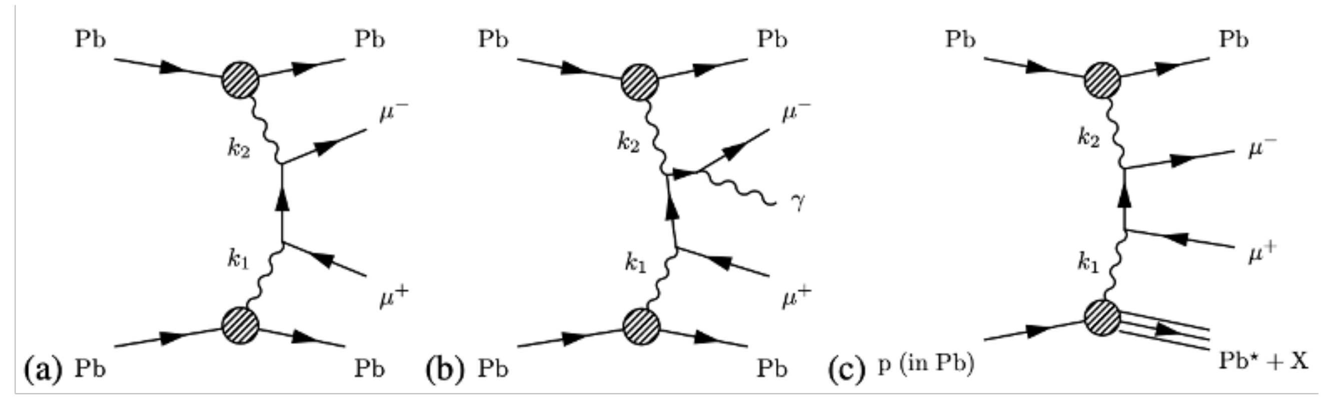


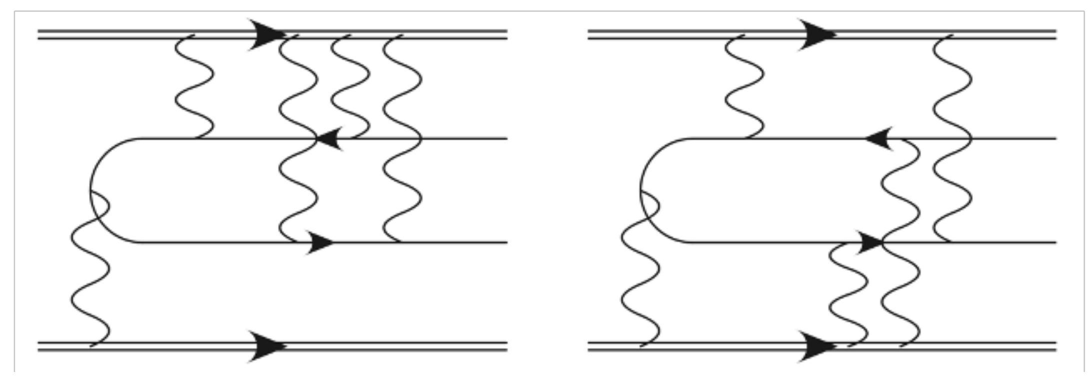
- Little “EIC”

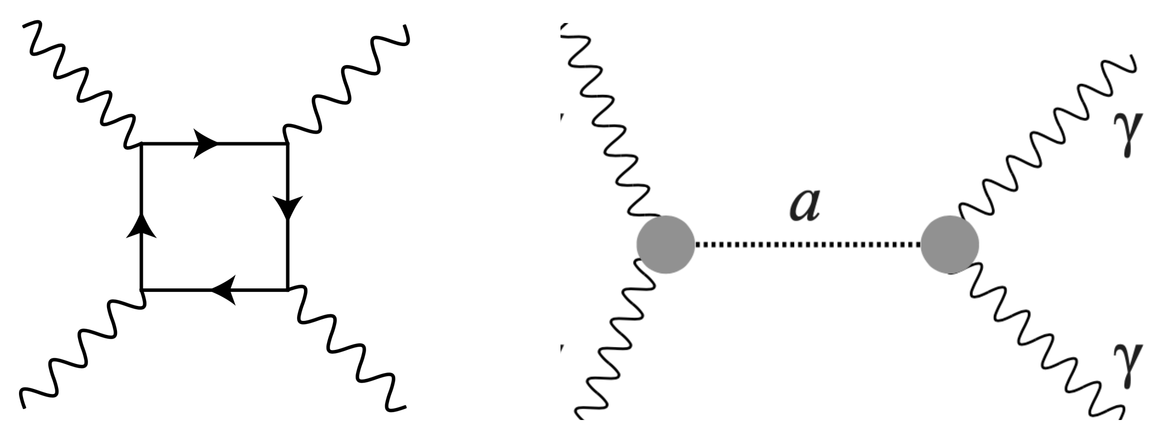
Not just a hadron collider

Photon-photon interactions





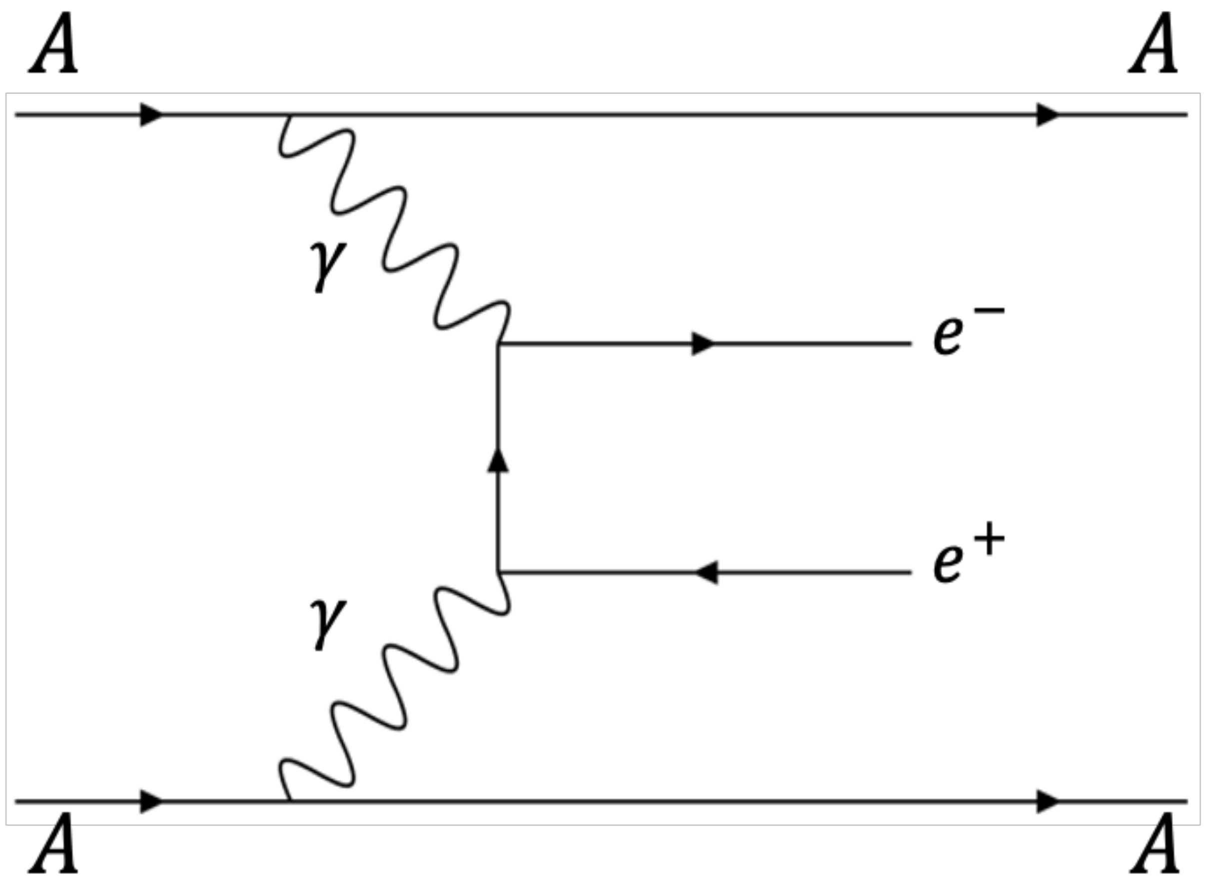




- QED
- Axion search

STAR, PRC 70 (2004) 031902; PRL 121 (2018) 132301; PRL 127 (2021) 052302
ATLAS, Nat. Phys. 13 (2017) 852; PRL 121 (2018) 212301; PRL 123 (2019) 052001; PRC 104 (2021) 024906
CMS, PRL 127 (2021) 122001

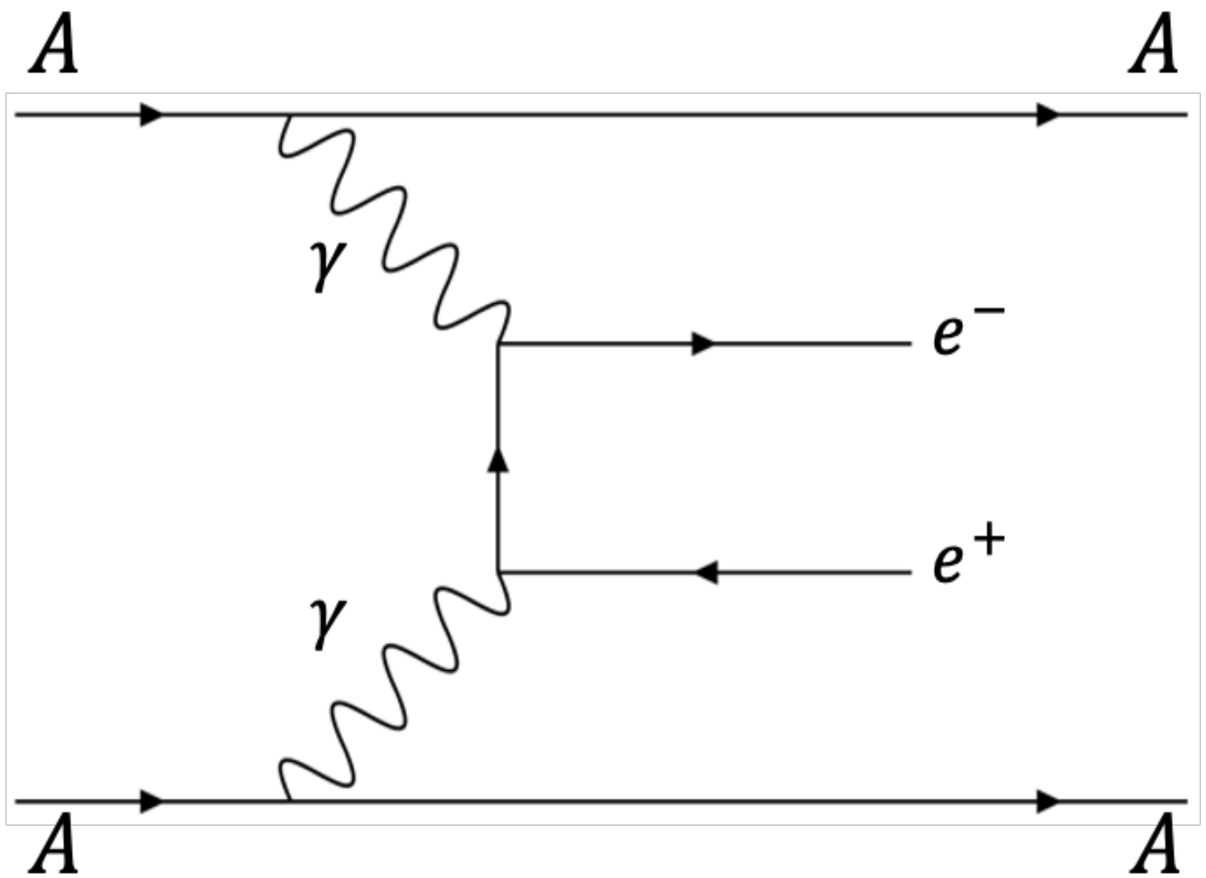
Breit-Wheeler process



- **Breit-Wheeler process:** converting **real** photon into e^+e^-
  - Proposed in 1934

Breit & Wheeler, Phys. Rev. 46 (1934) 1087

Breit-Wheeler process



1934, Breit and Wheeler, **Collision of two light Quanta to create matter and antimatter (e^+e^-)**

rather than exact relations. It is also hopeless to try to observe the pair formation in laboratory experiments with two beams of x-rays or γ-rays meeting each other on account of the smallness of σ and the insufficiently large available densities of quanta. In the considerations of Williams, however, the large nuclear electric fields lead to large densities of quanta in moving frames of reference. This, together with the large number

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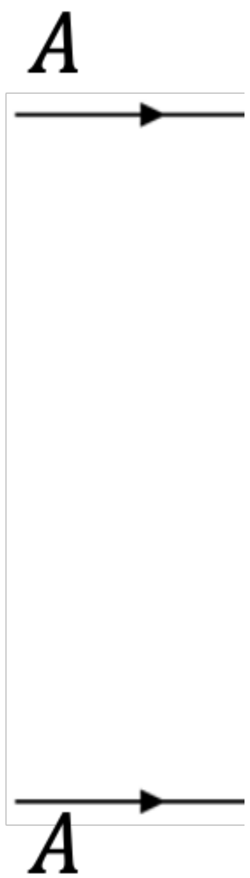
Breit-Wheeler process

Light into matter

Nature Photon 8 (2014) 496



Oliver Pike explains to *Nature Photonics* that the so far elusive electron–positron pair production from light may now be possible using existing technology.

Why work on Breit–Wheeler pair production?

The Breit–Wheeler process is the production of an electron–positron pair from the collision of two photons. Being the inverse of Dirac annihilation, it is the simplest mechanism by which light can be converted into matter. The process also has wide significance for areas of high-energy astrophysics, including the radiation fields of compact objects, the cut-off of cosmic rays propagating over intergalactic distances and the various mechanisms of gamma-ray burst emission. We have long been interested in the physics of such systems and approaches for replicating their behaviour in the laboratory. When we performed order-of-magnitude estimates to assess how existing laser facilities could be used to study the fundamental processes relevant to these systems, we were surprised to discover that Breit–Wheeler pair production may finally be observable 80 years after it was theoretically predicted.

How can pair production be done in the laboratory?

Detecting the Breit–Wheeler process has proved extremely difficult, because of the high energy threshold for the reaction: the product of the two photon energies must be at least $(511\ \text{keV})^2$. In the past, this requirement has been too demanding, and consequently the process has completely eluded observation. By using a unique combination of gamma- and X-ray sources, our scheme is the first capable of promoting a sufficient number of photons above the threshold. The high-energy photons collide inside a hohlraum; the photon–photon collisions occur in vacuum. In other words, this experiment would be the first in which light interacts with itself with no massive particles present.

Where should the experiment be conducted?

We have tailored the scheme for specific laser facilities. The experiment is well suited to those where hohlraum experiments are performed, such as the National Ignition Facility (NIF), Omega EP and the Orion laser; these facilities have highly energetic long-pulse systems and will soon (after the imminent commissioning of the ARC system at NIF) all have powerful short-pulse capabilities. However, the experiment could also be performed at much smaller optical laser facilities, such as Astra Gemini and the Berkeley Lab Laser Accelerator, which are routinely used to produce high-quality wakefields. In this case, the hohlraum radiation could be replaced by X-ray fields created by laser irradiation of solid targets; these fields can be both energetic and intense even for relatively low laser energies when short pulse lengths are used. Finally, free-electron laser facilities, such as the Linac Coherent Light Source, could also host a variant of this experiment in which the X-ray beam acts as the second source of photons.

What is the expected performance of pair production?

The number of Breit–Wheeler pairs produced depends on the system used. The

Ed Hill, Steve Rose and Oliver Pike (left to right) with Felix Mackenroth (not pictured) have proposed a way to use existing facilities to produce electron–positron pairs by colliding photons.

detection method would be to use a magnetic field to isolate the positrons, and then use Čerenkov glass in combination with an intensified CCD (charge-coupled device) to collect their signature radiation.

Are the implications only fundamental, or are they also applied?

The primary motivation behind this work is the first-time detection of a fundamental physical process. In addition, successfully implementing the experiment would represent the first two-photon collider, which may ignite interest in the concept in the high-energy-physics community. As with any pure-science experiment, it may lead to further applications, but at this stage these remain unclear.

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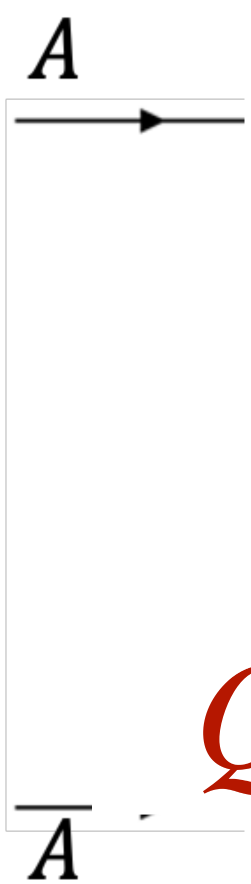
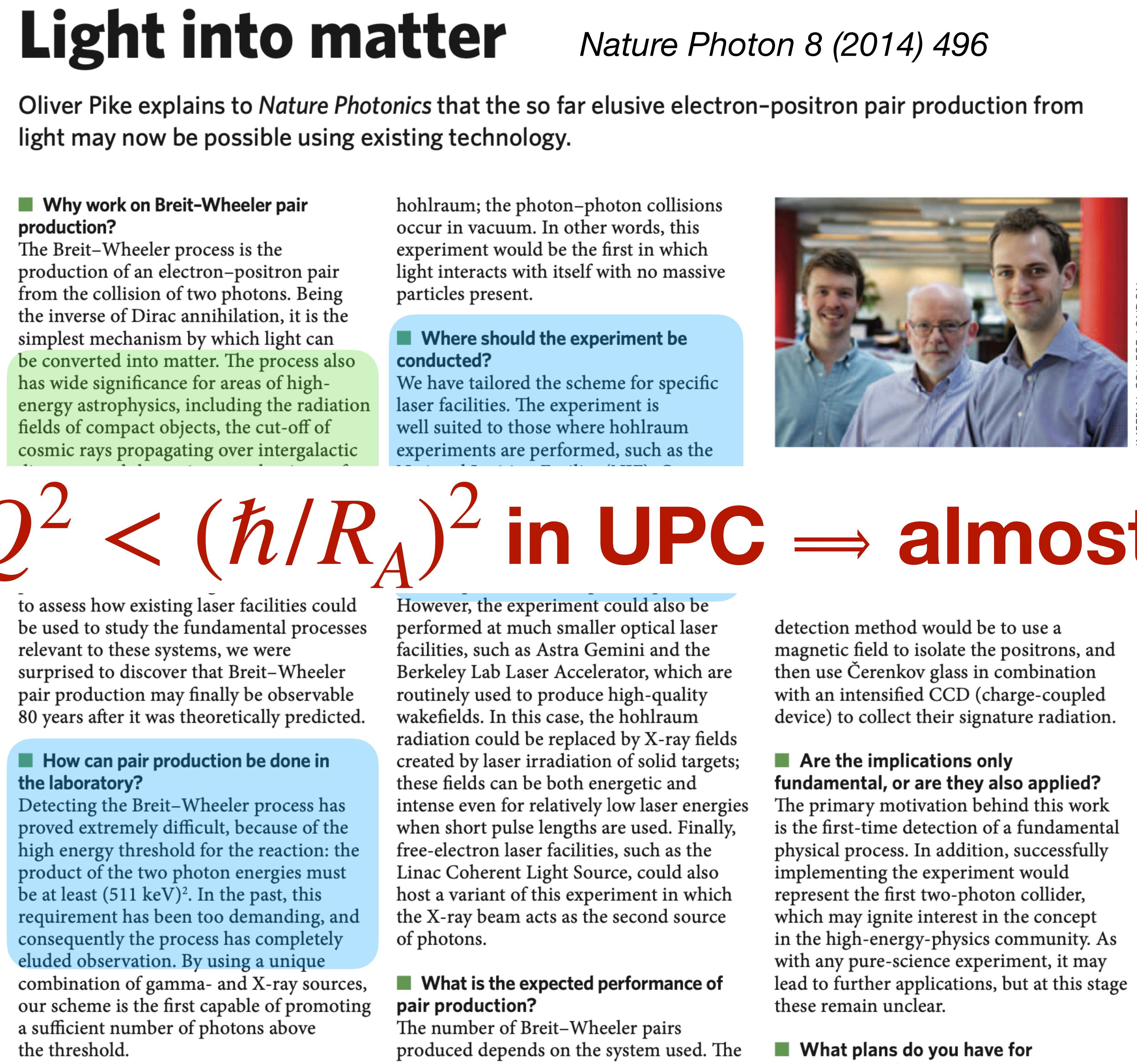
Breit-Wheeler process





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IMPERIAL COLLEGE LONDON

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$Q^2 < (\hbar/R_A)^2$ in UPC $\Longrightarrow$ almost real

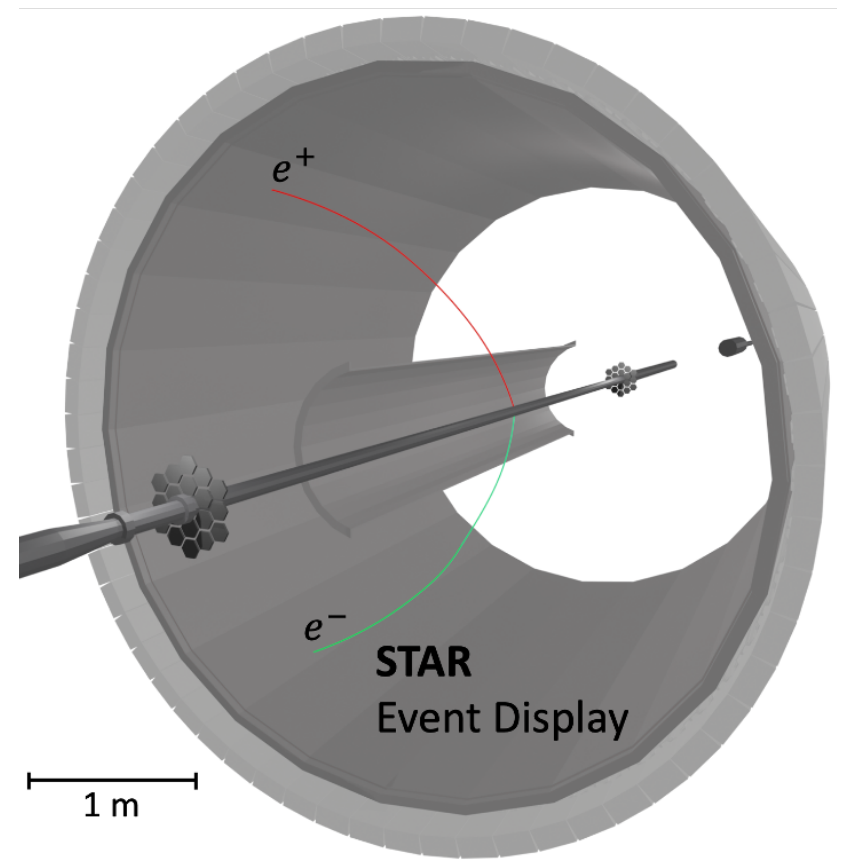
- **Breit** … nto e^+e^-
  - Prop …

4) 1087

Distinctive features of $\gamma\gamma \rightarrow l^+l^-$

- Exclusive production of l^+l^- pair

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



Distinctive features of $\gamma\gamma \rightarrow l^+l^-$

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- Smooth mass spectrum

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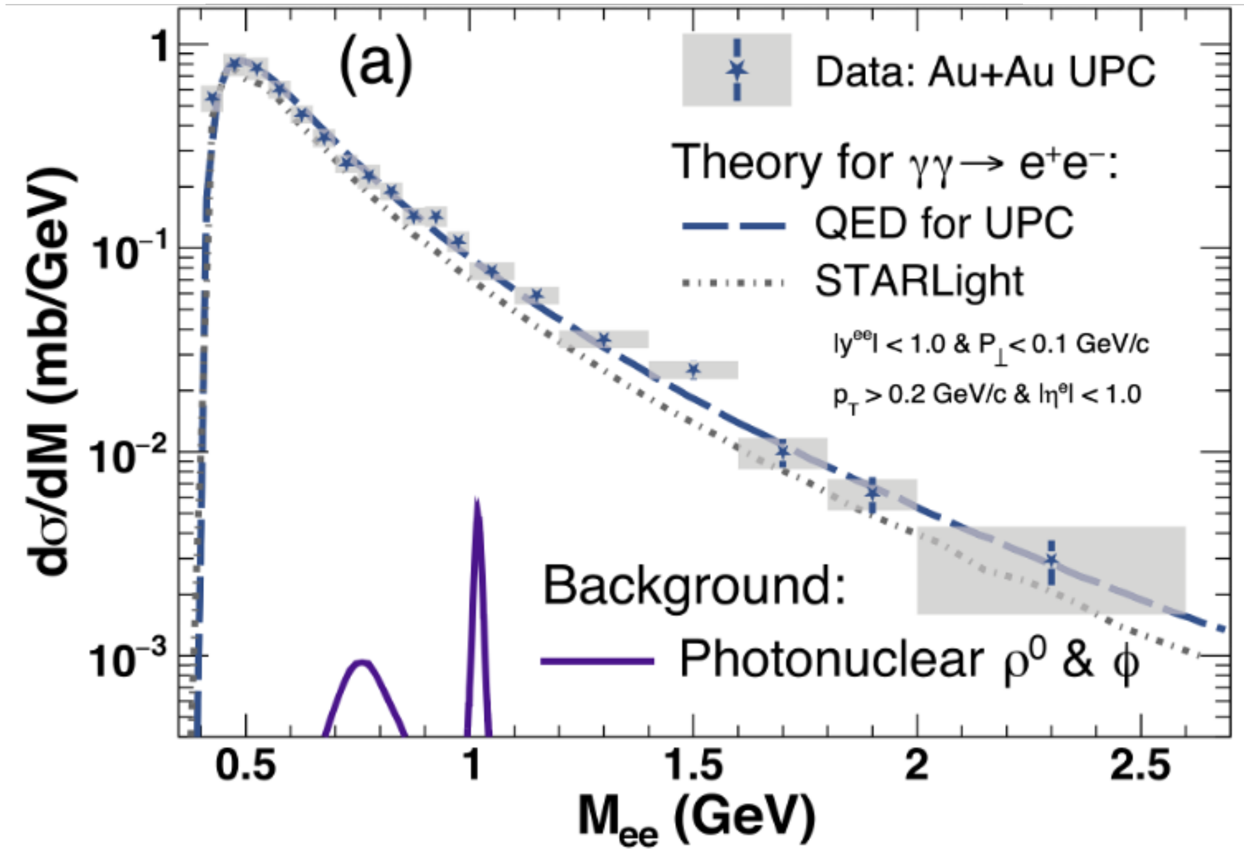

Distinctive features of $\gamma\gamma \rightarrow l^+l^-$

- 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
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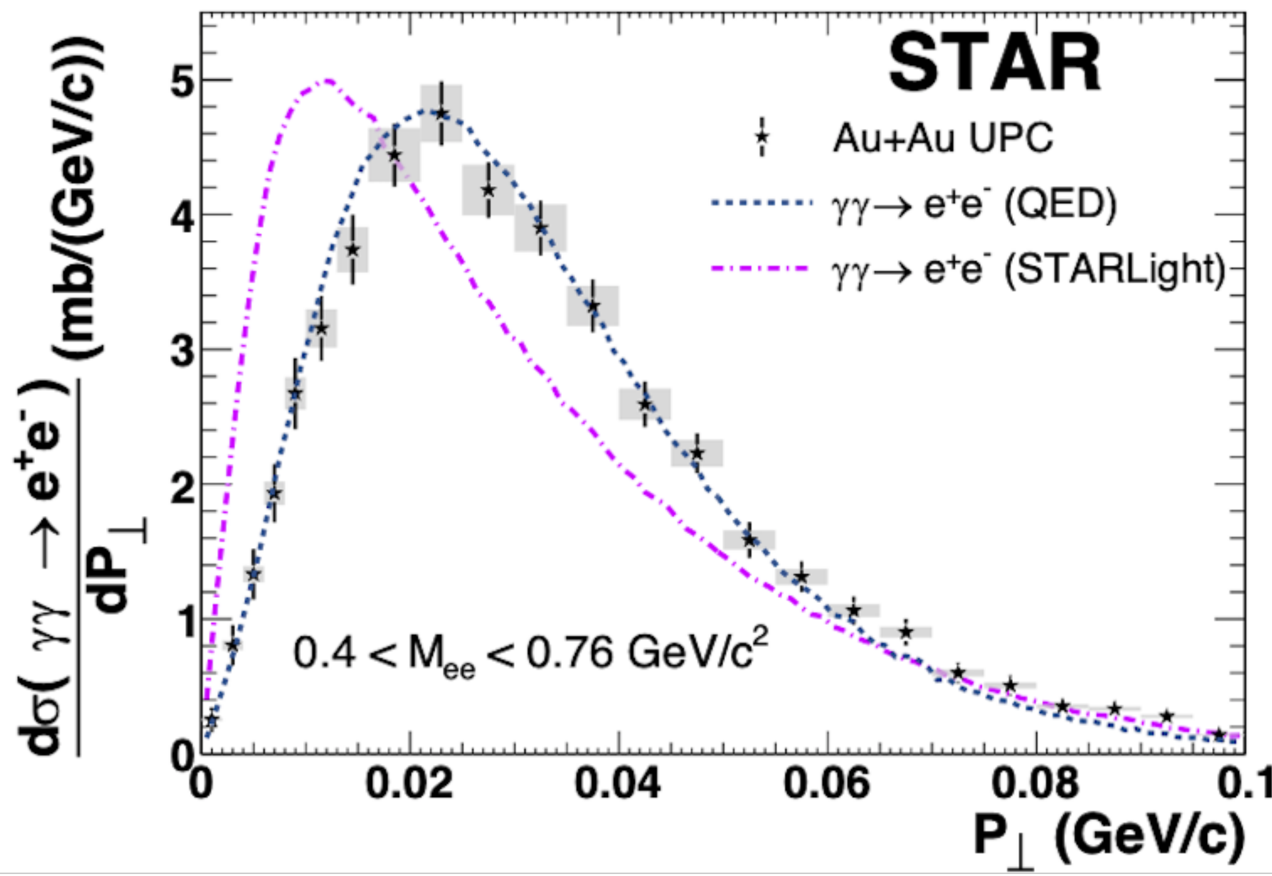

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- Exclusive production of l^+l^- pair
- Smooth mass spectrum
- Concentrated at low p_T
  - Back to back in transverse plane
- Individual l^+/l^- preferentially aligned along beam axis
  - Highly virtual photon interactions should have an isotropic distribution
  - θ': angle between l^+ and beam axis in pair rest frame

STAR, PRL 127 (2021) 052302
Zha et al., PLB 800 (2020) 135089
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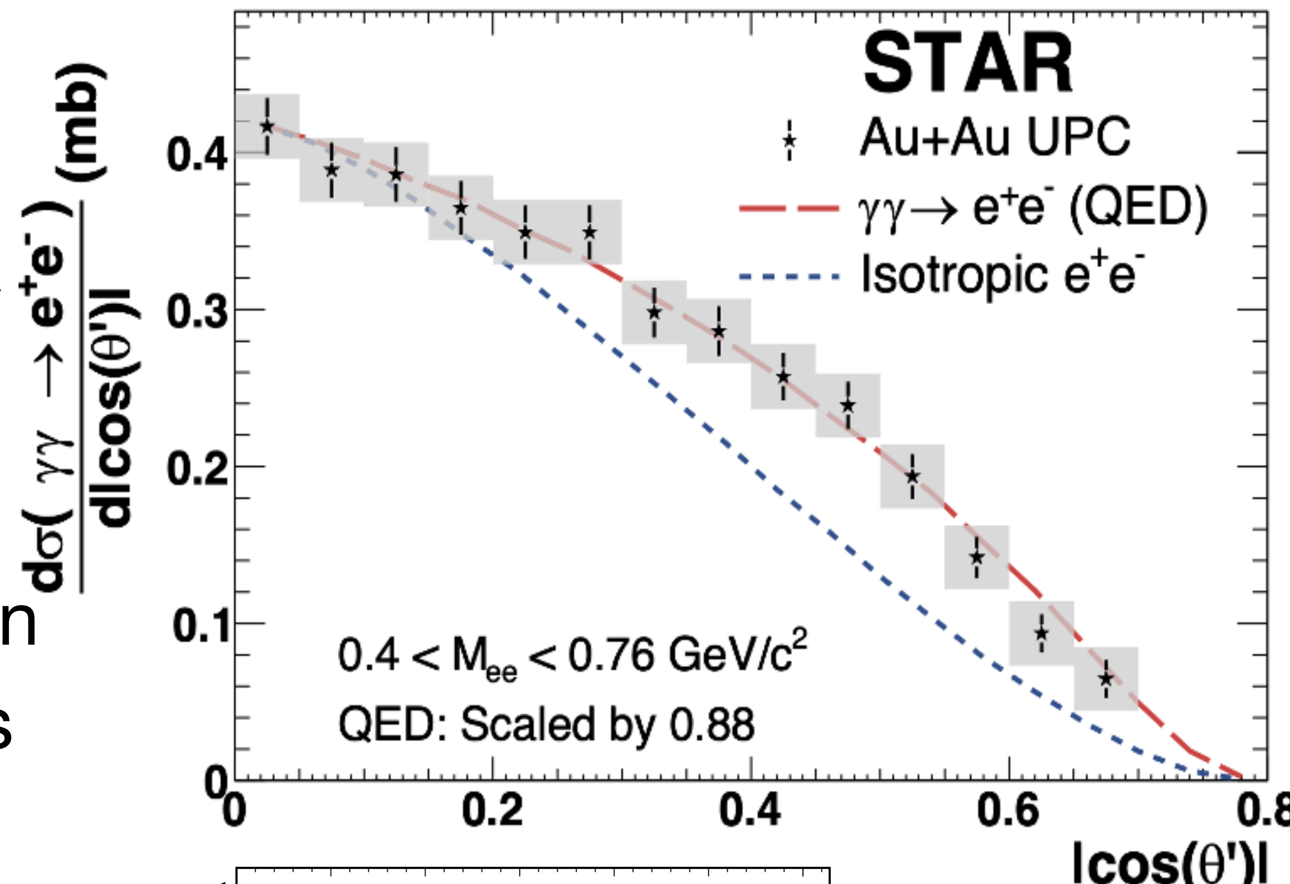
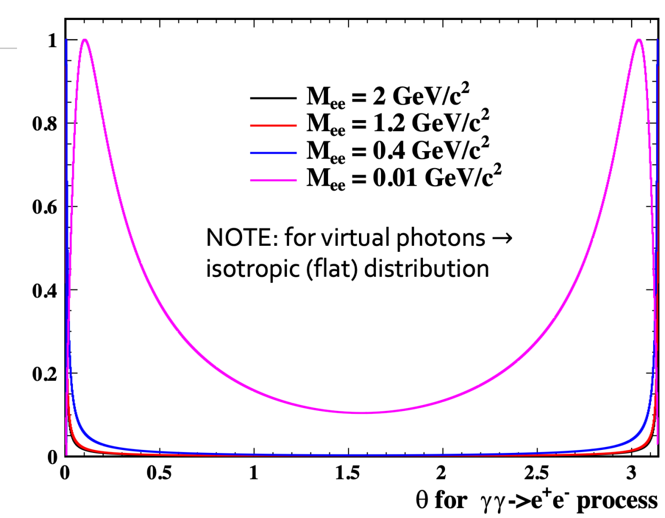
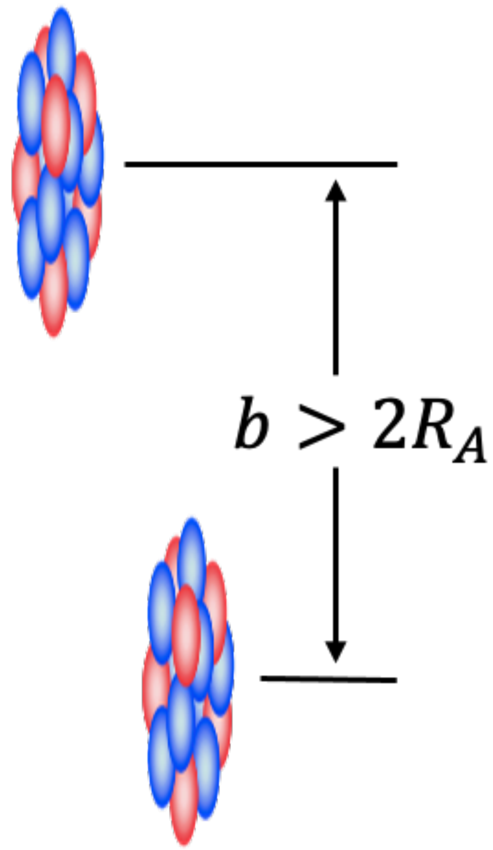
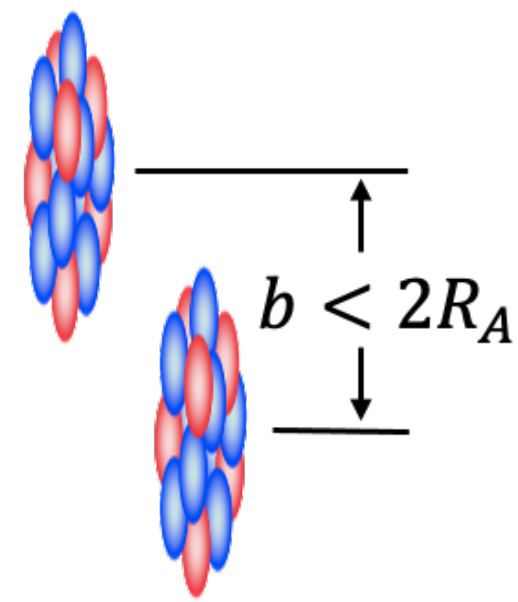
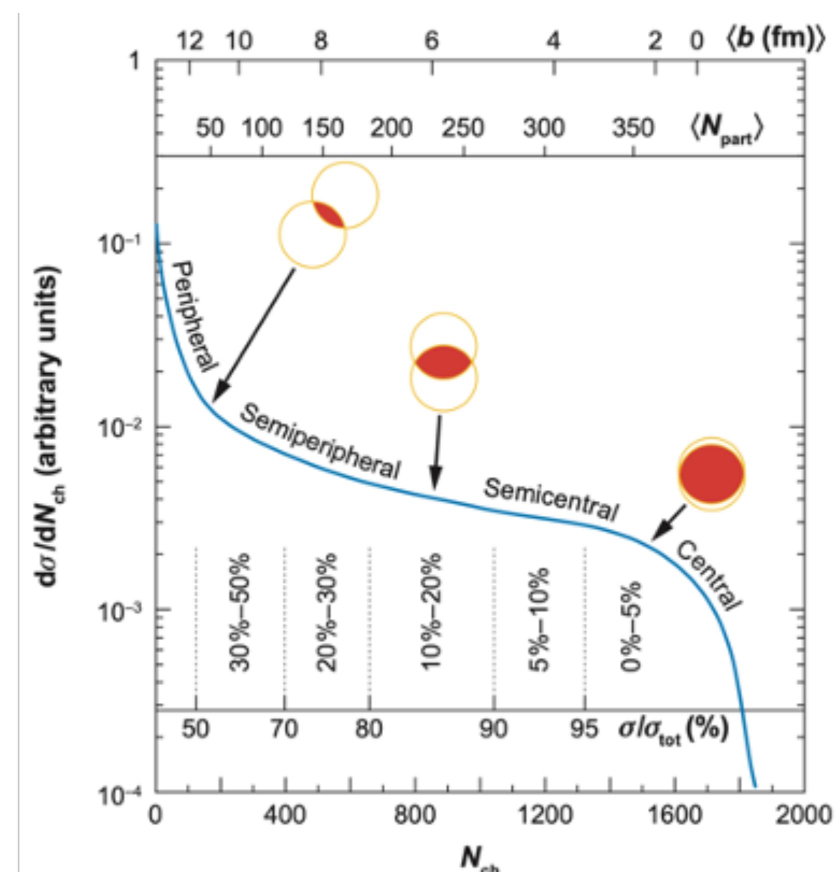




From UPC to hadronic collisions

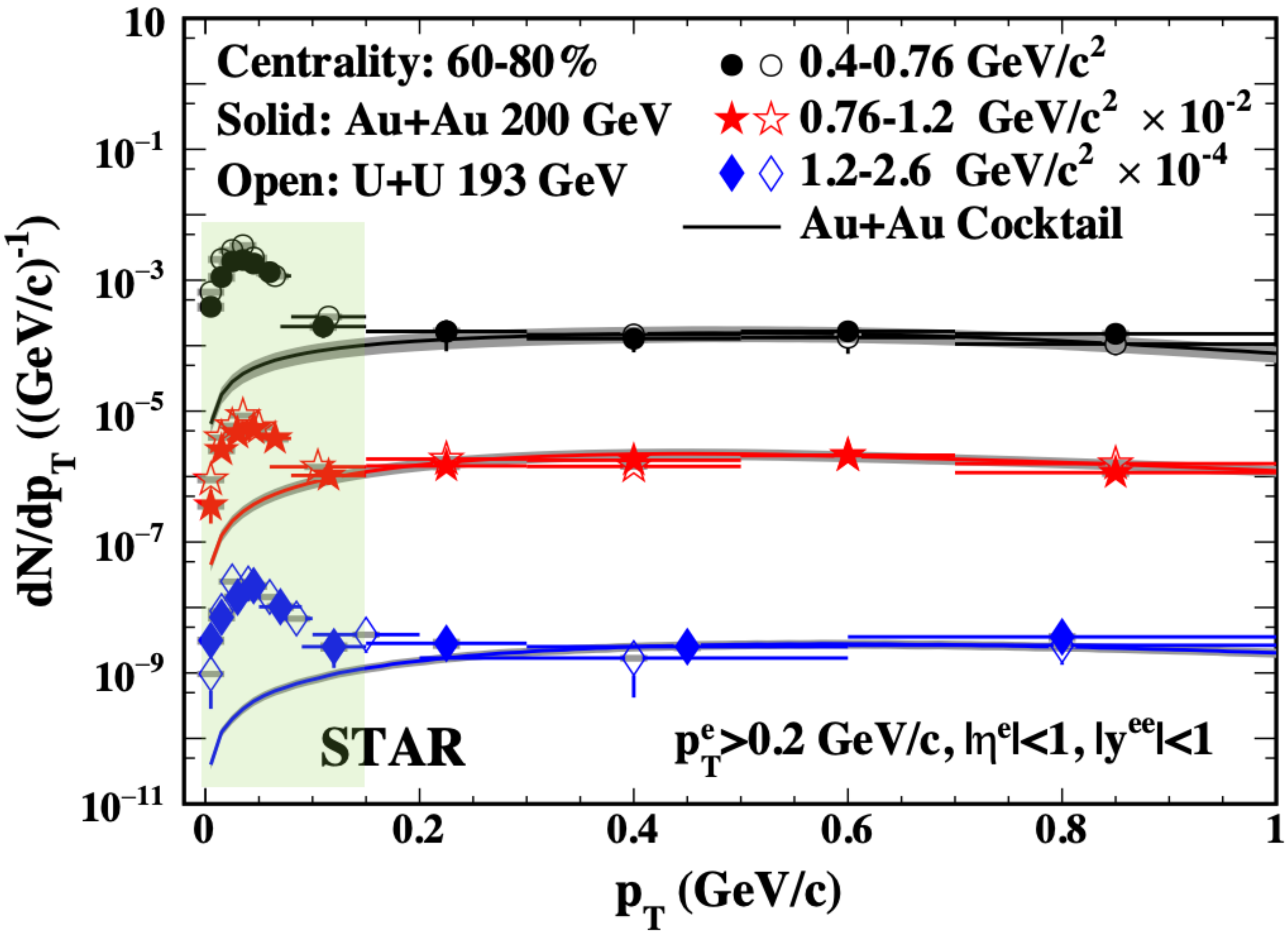


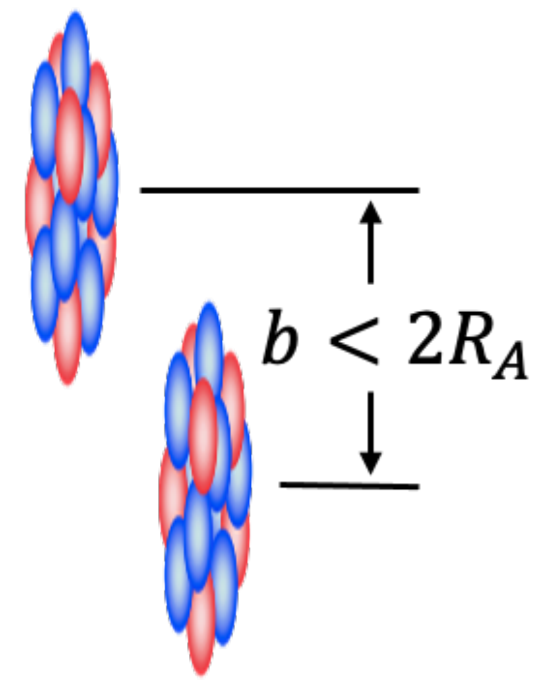




Concentrated at low p_T

STAR, PRL 121 (2018) 132301





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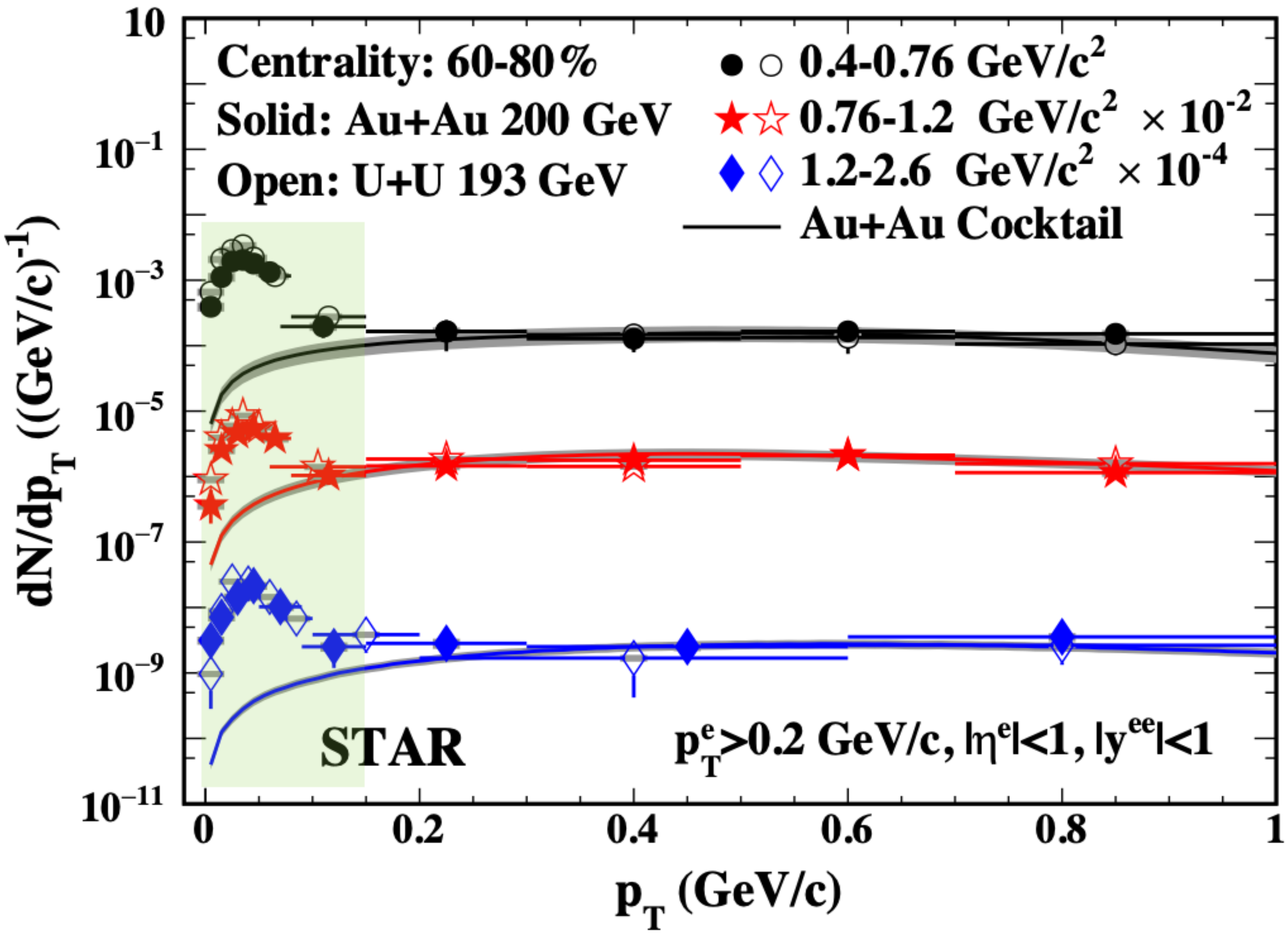
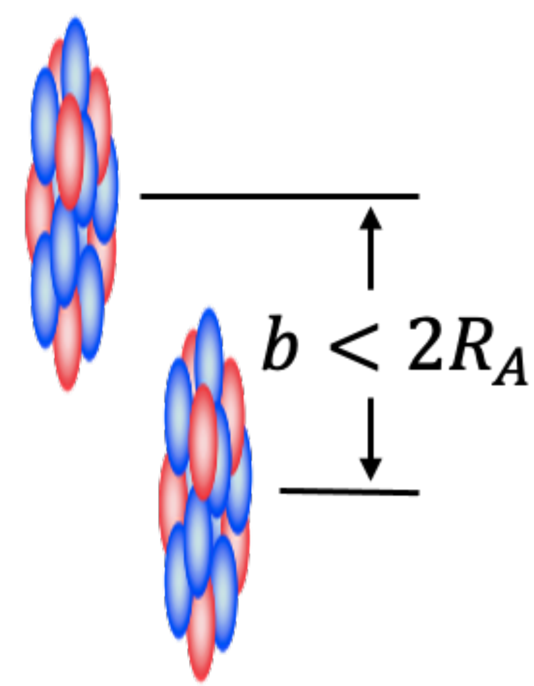
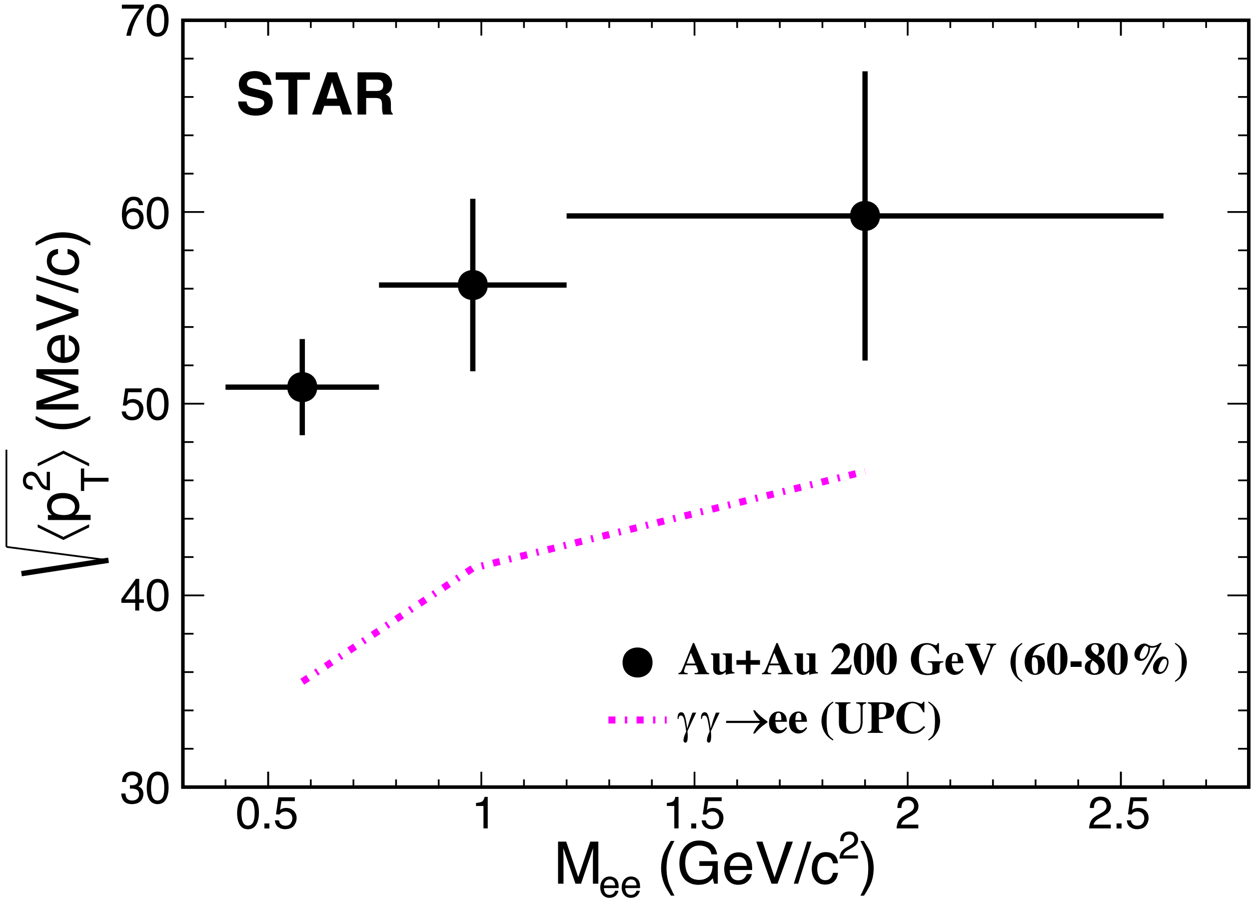




Unexpectedly observed $\gamma\gamma \rightarrow l^+l^-$ in hadronic collisions

Modification of lepton pairs

STAR, PRL 121 (2018) 132301



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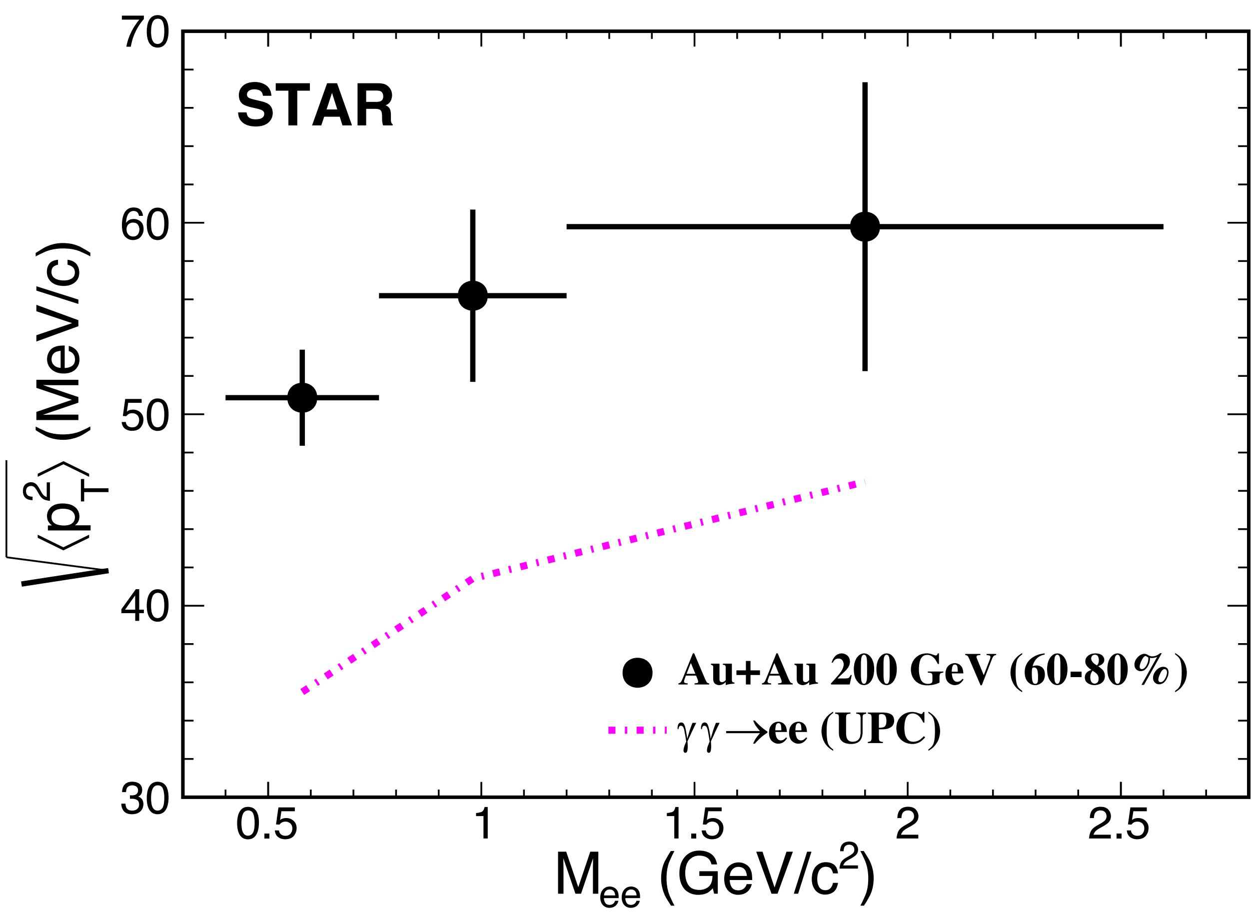
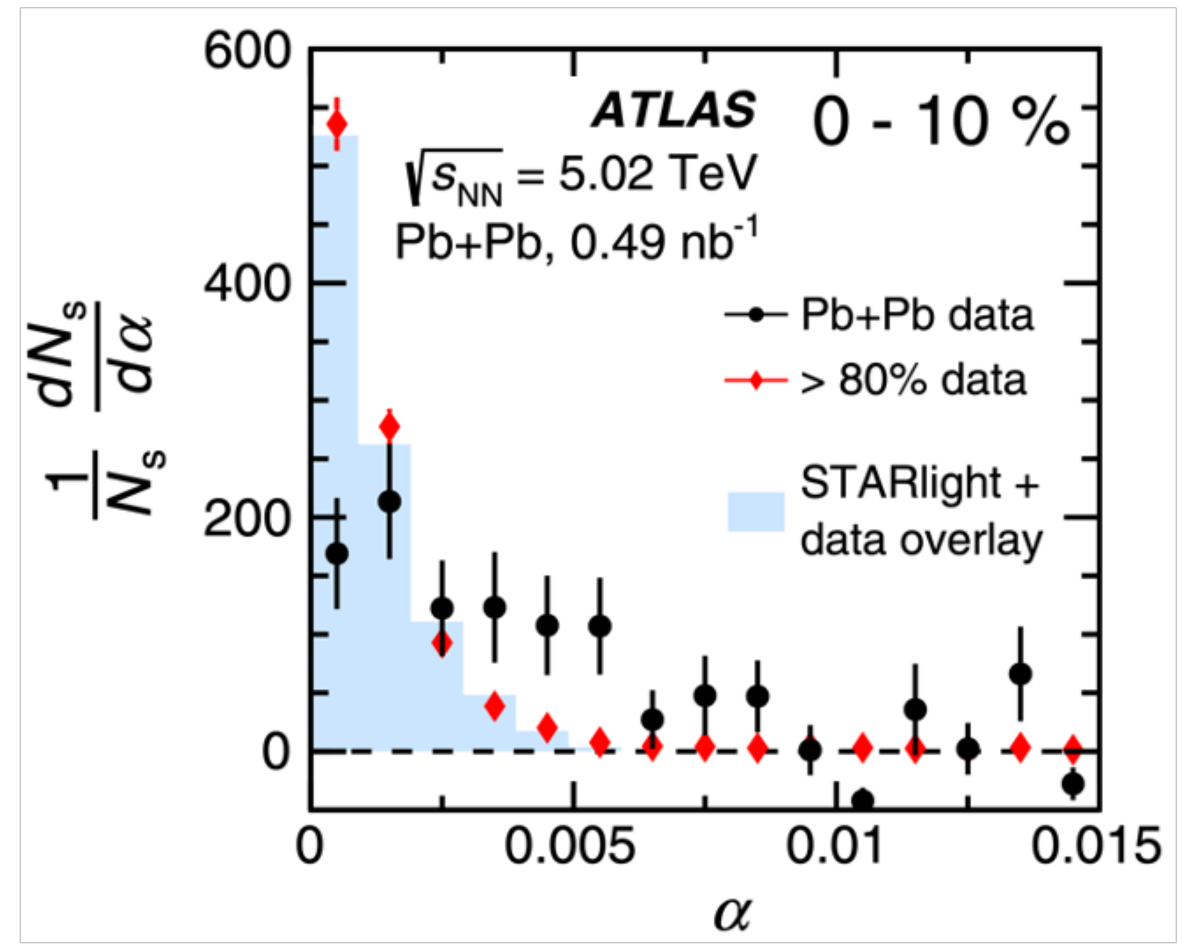
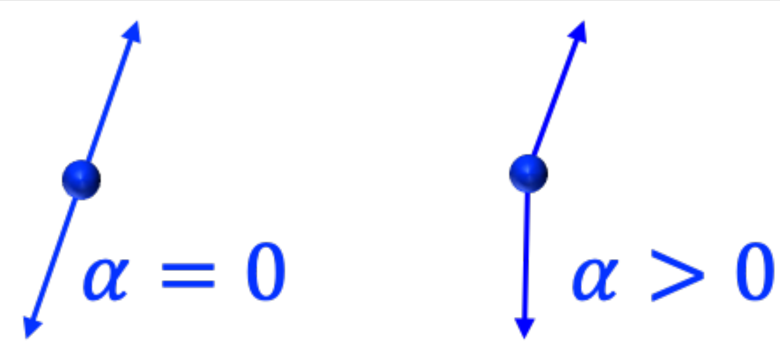


ATLAS, PRL 121 (2018) 212301



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



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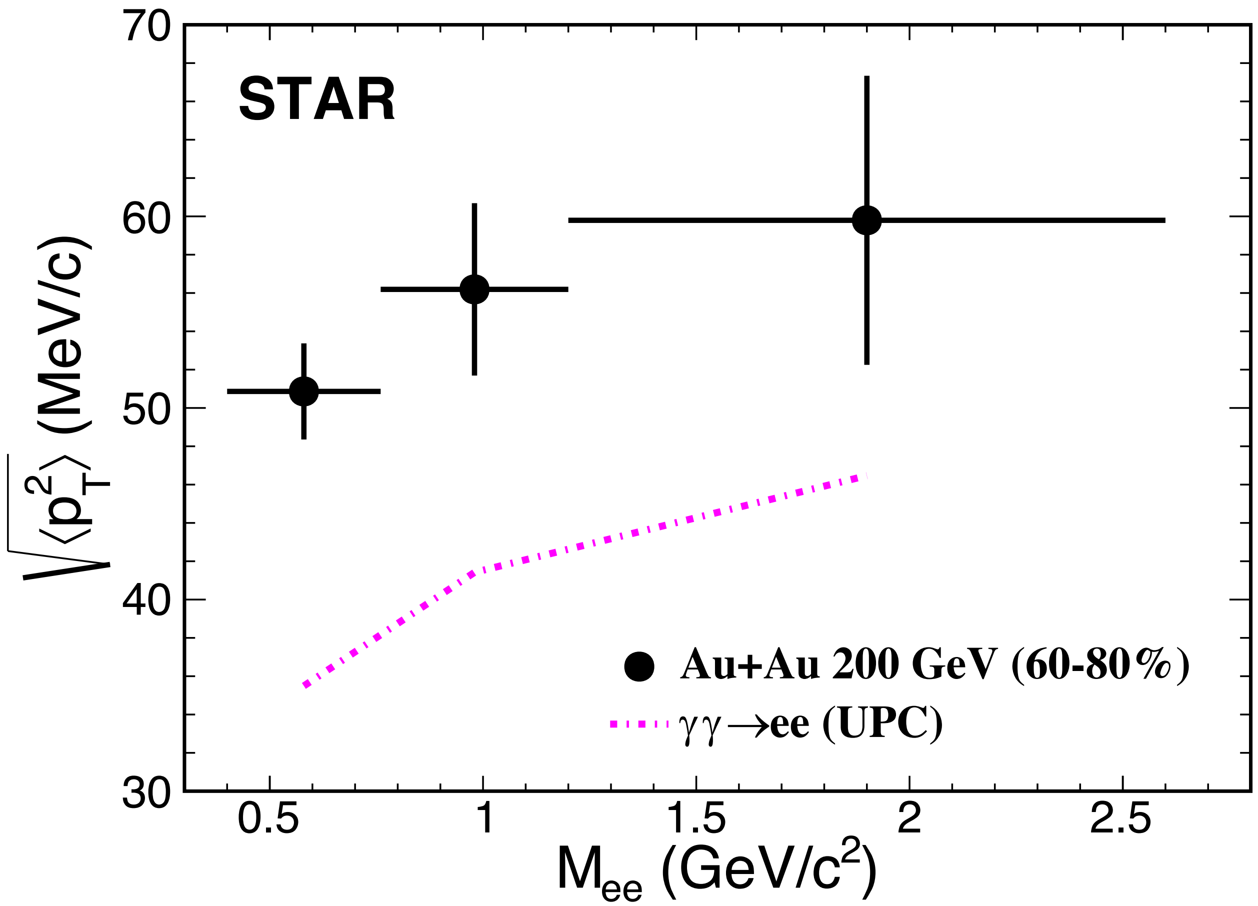

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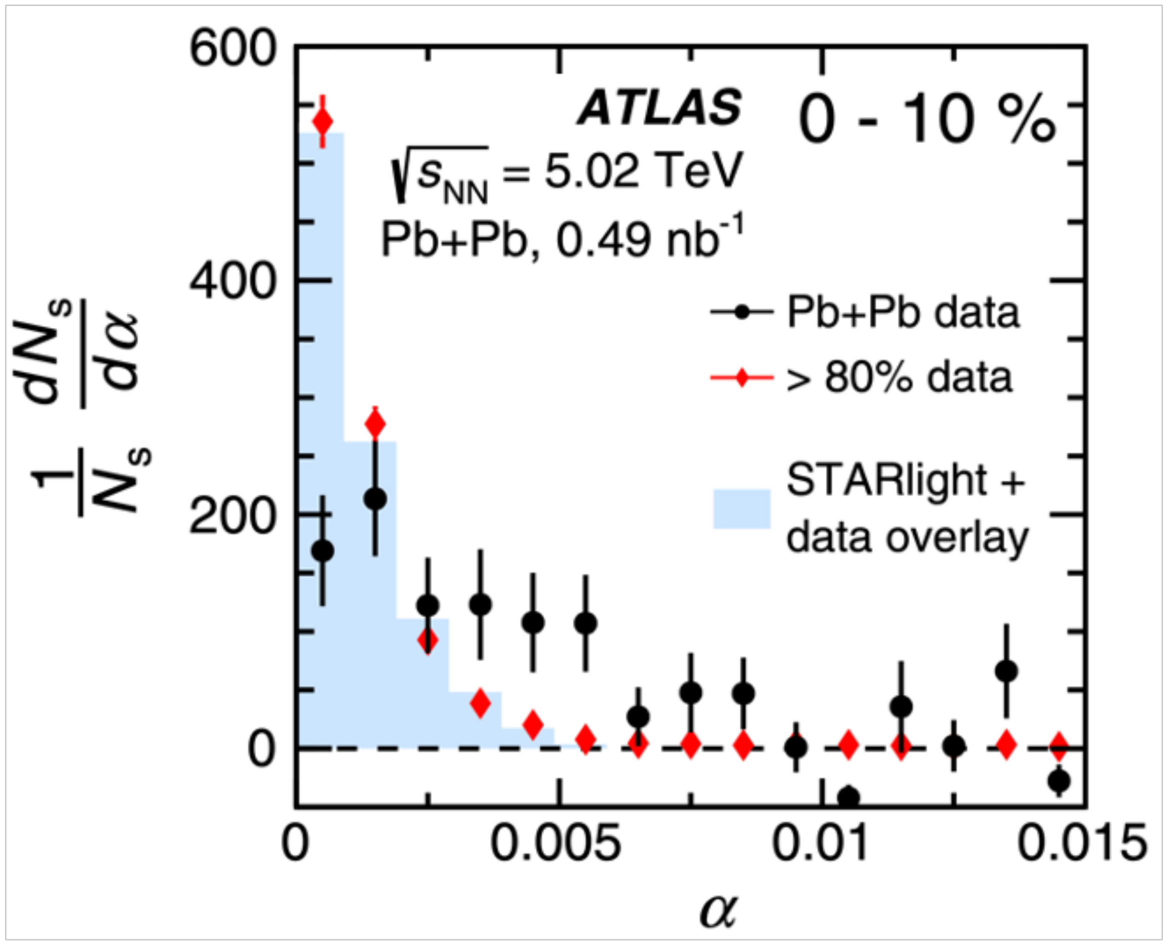

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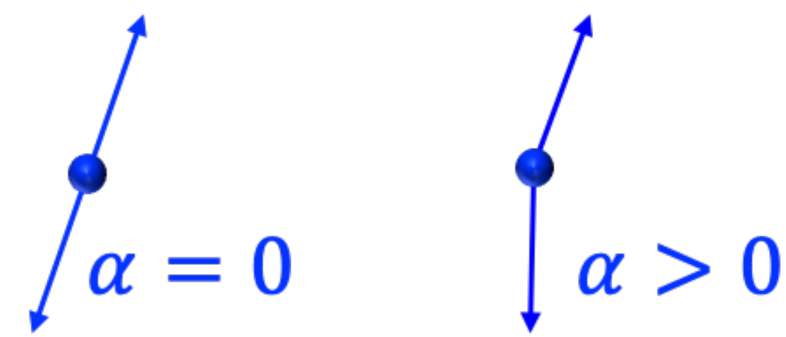
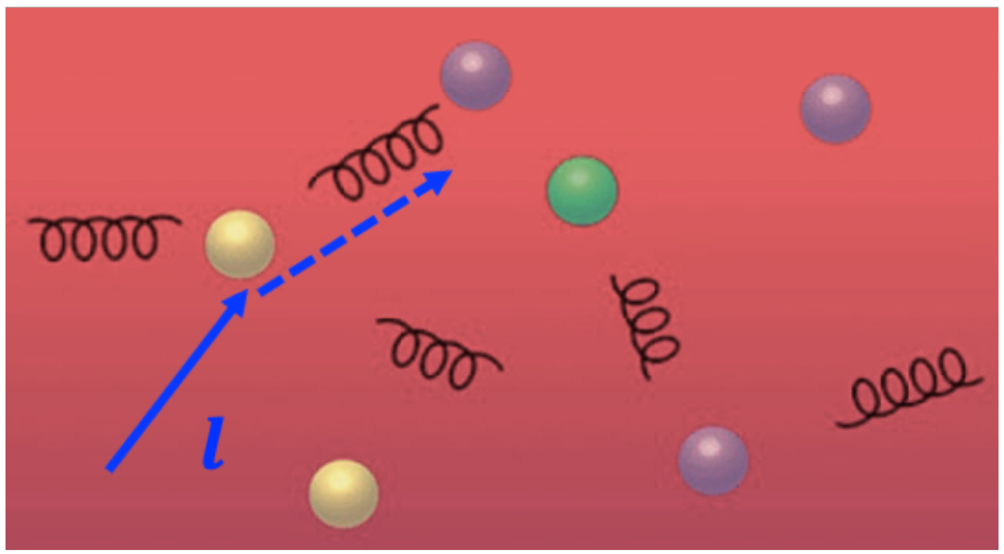


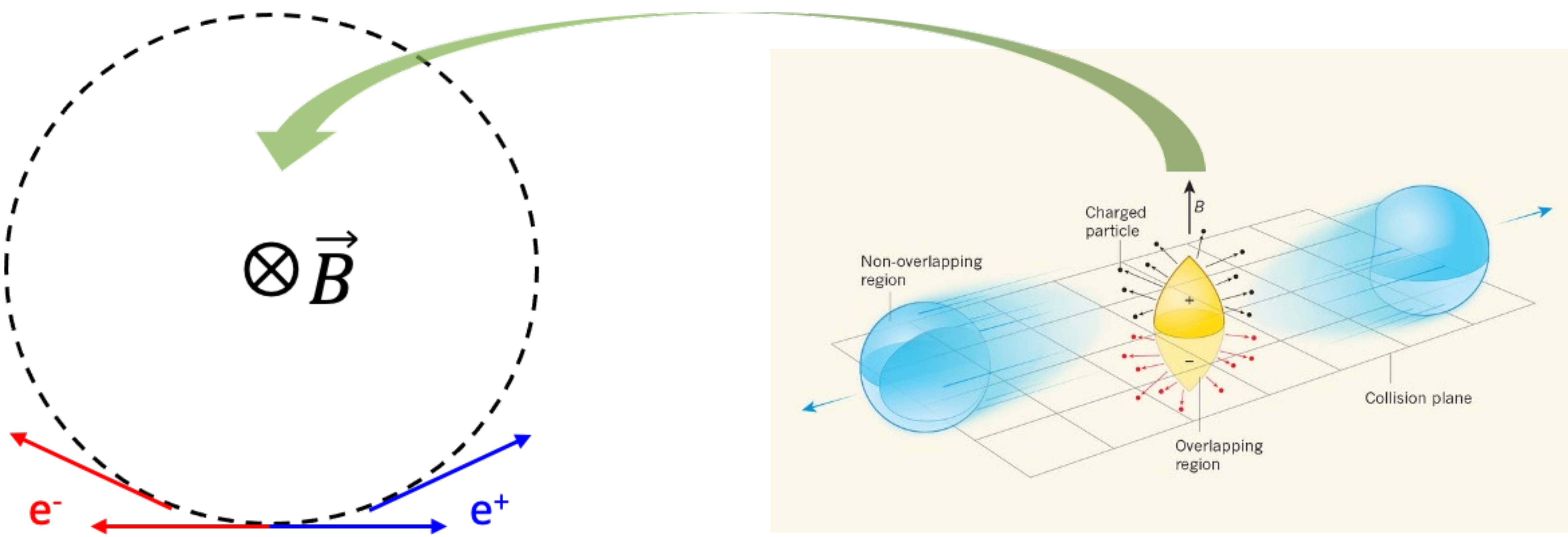
- Back-to-back correlation becomes weaker towards central collisions

Puzzle of the physics origin

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

Final-state effect?





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Zha et al., PLB 800 (2020) 135089

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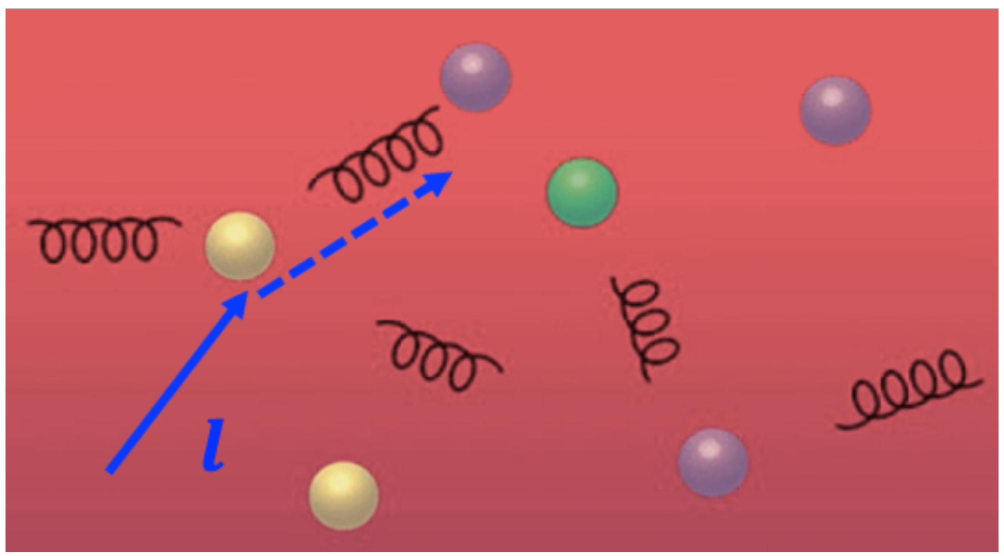
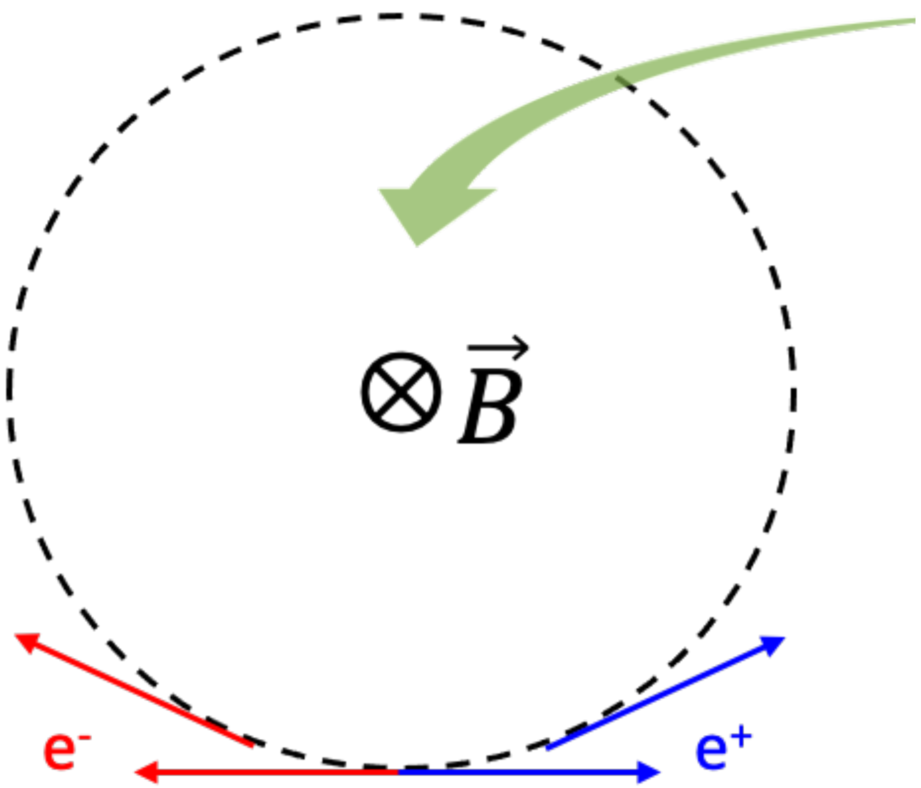
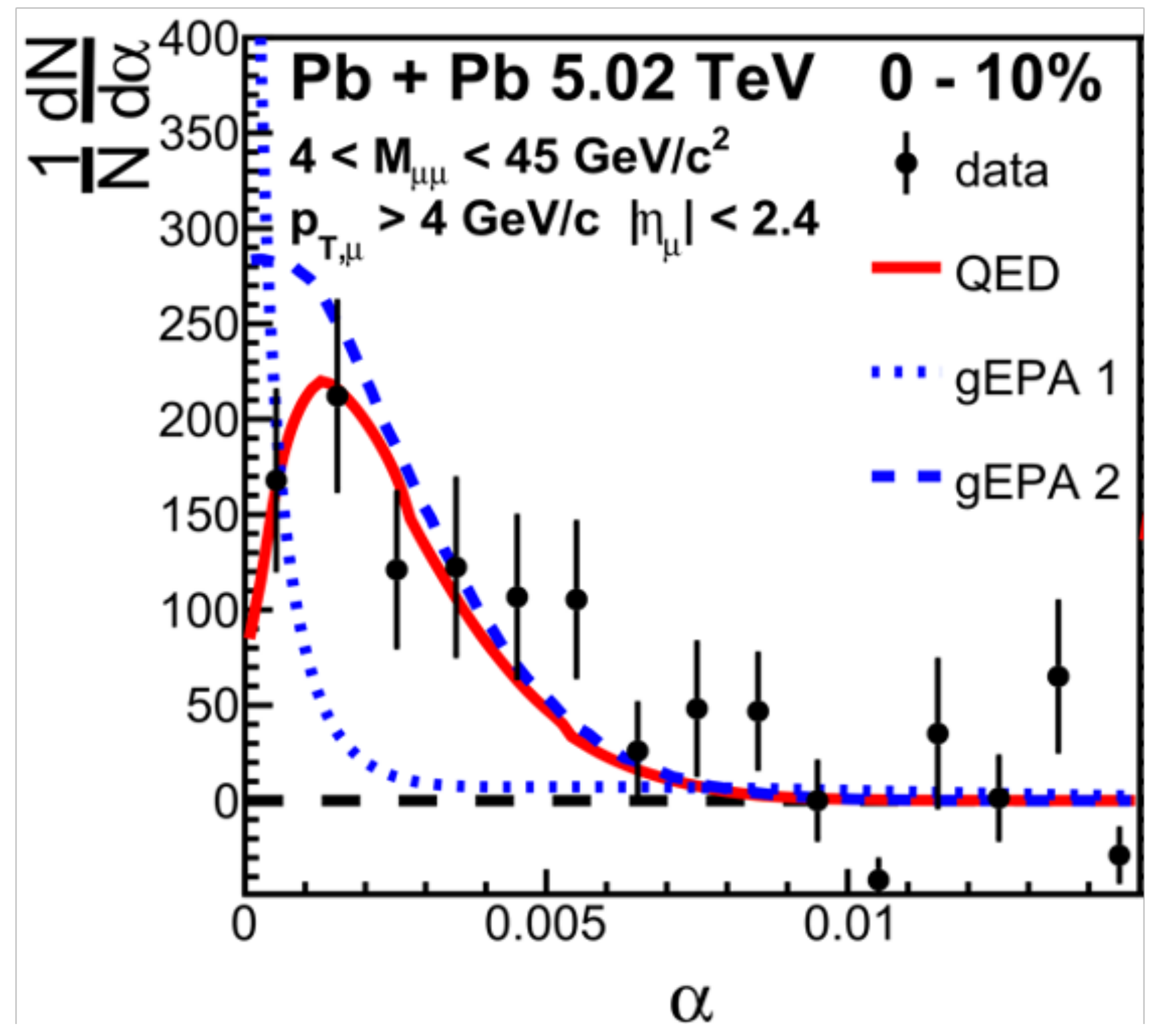


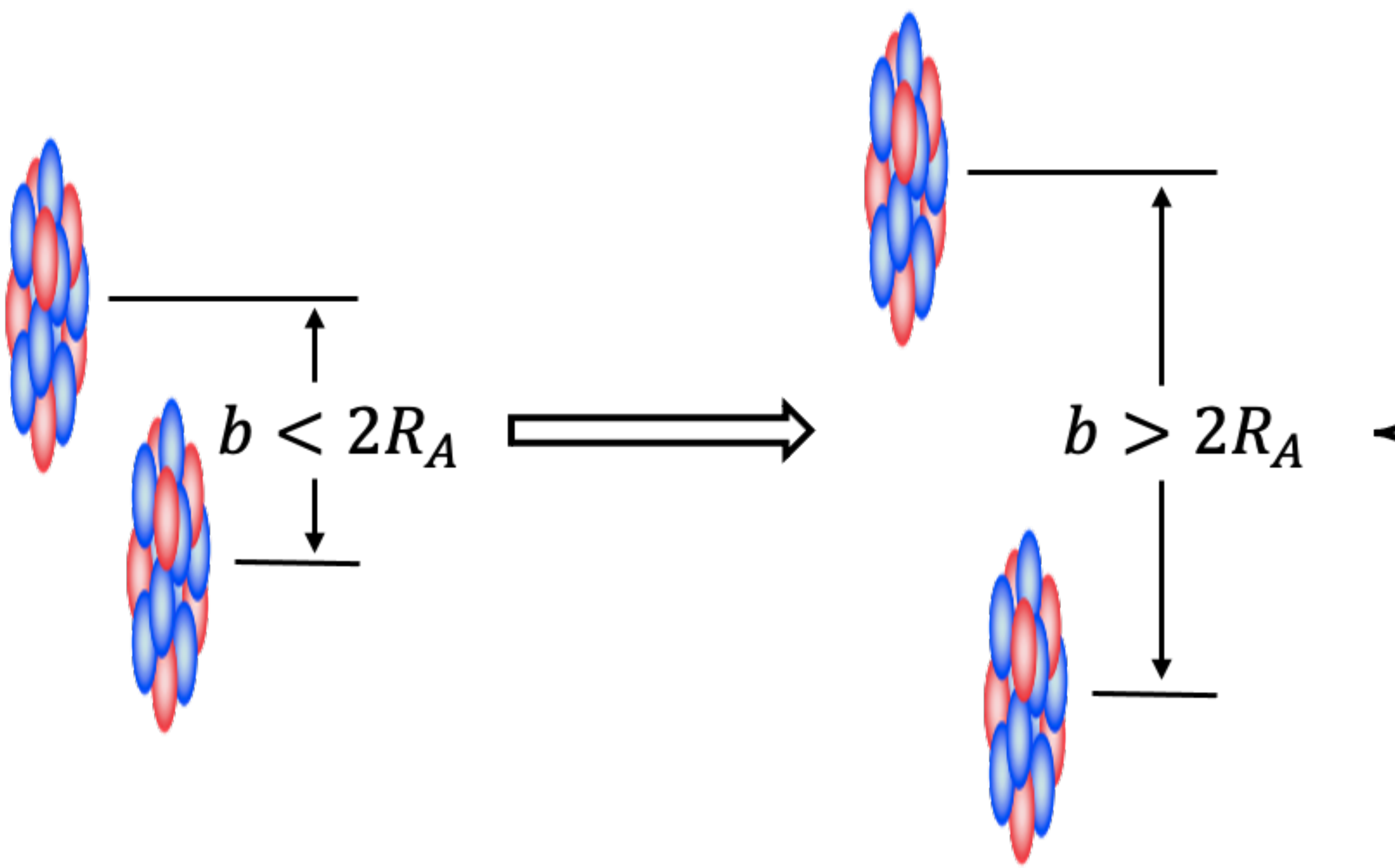


Initial-state effect?



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

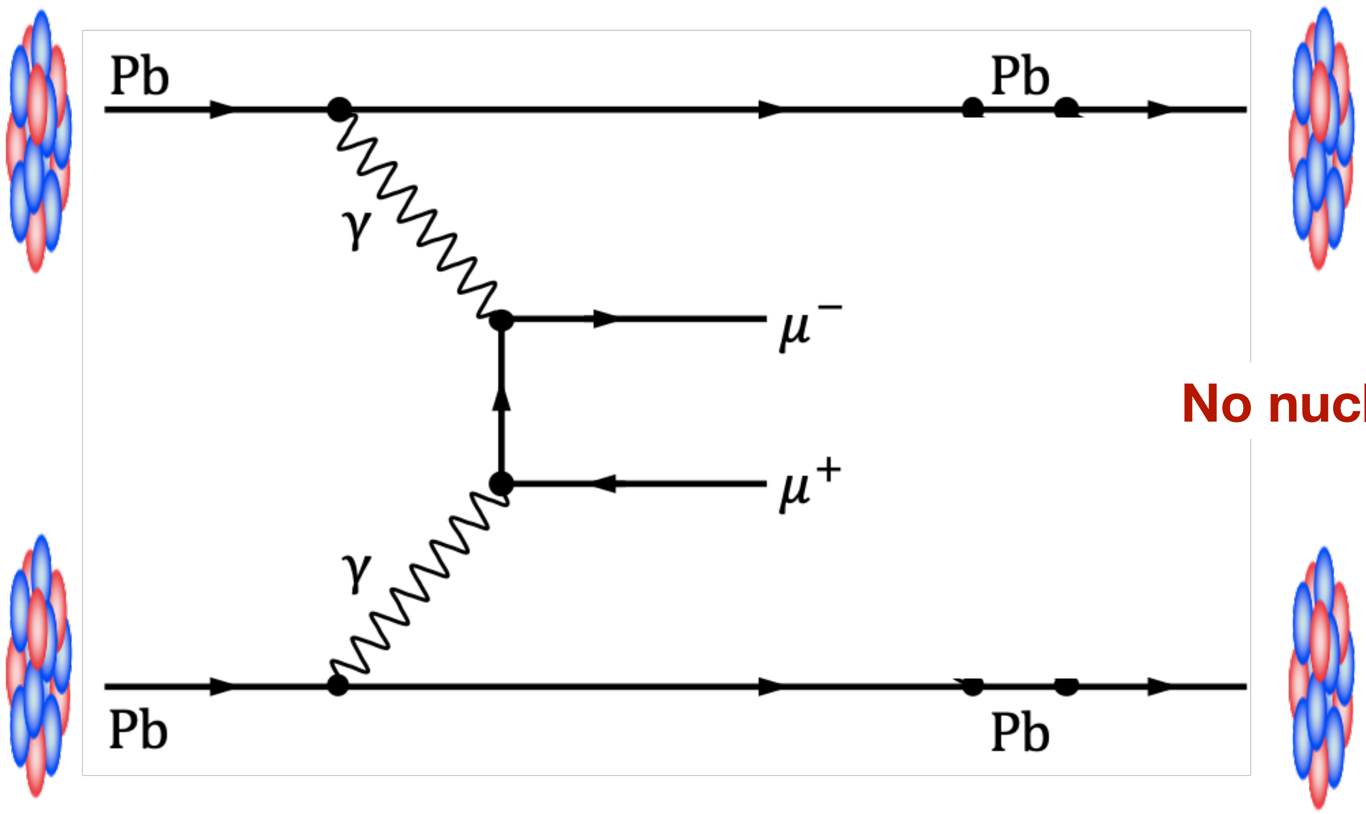
Experimentally explore the puzzle



Turn off hot medium

Control ***b***

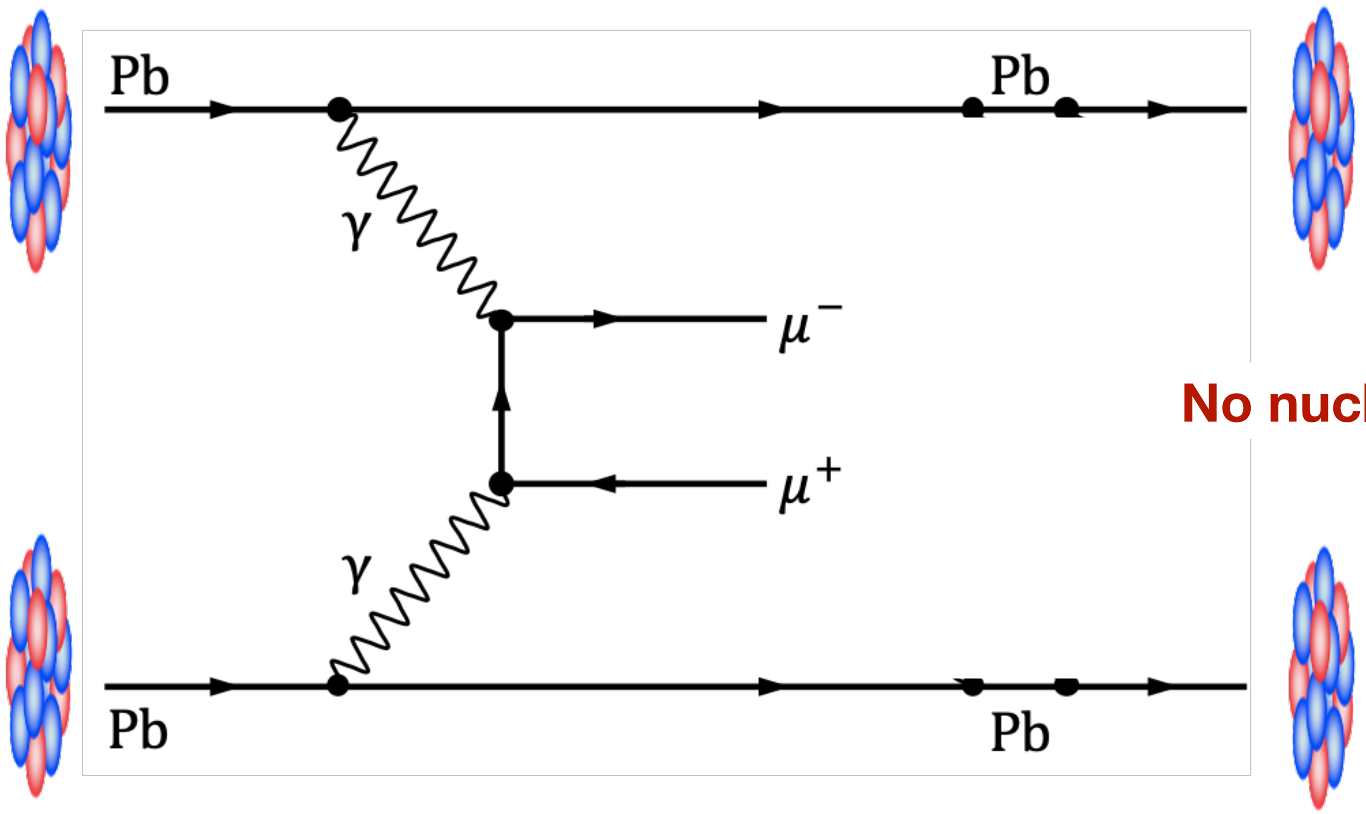
Control ***b*** in UPC



No nucleus breakup

Control *b* in UPC

Nuclei **may** exchange soft photon(s) $\Longrightarrow$ nuclear dissociation



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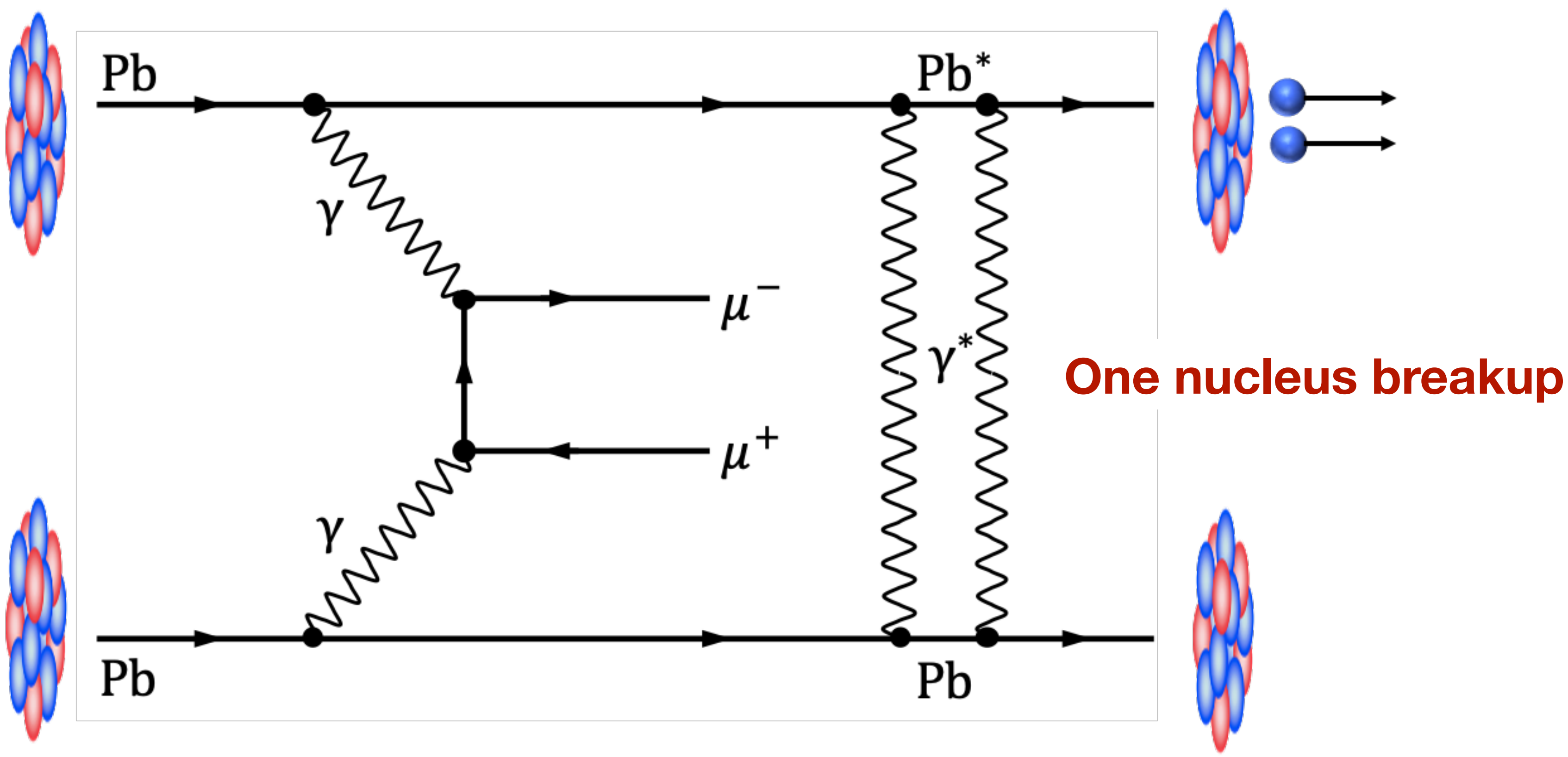

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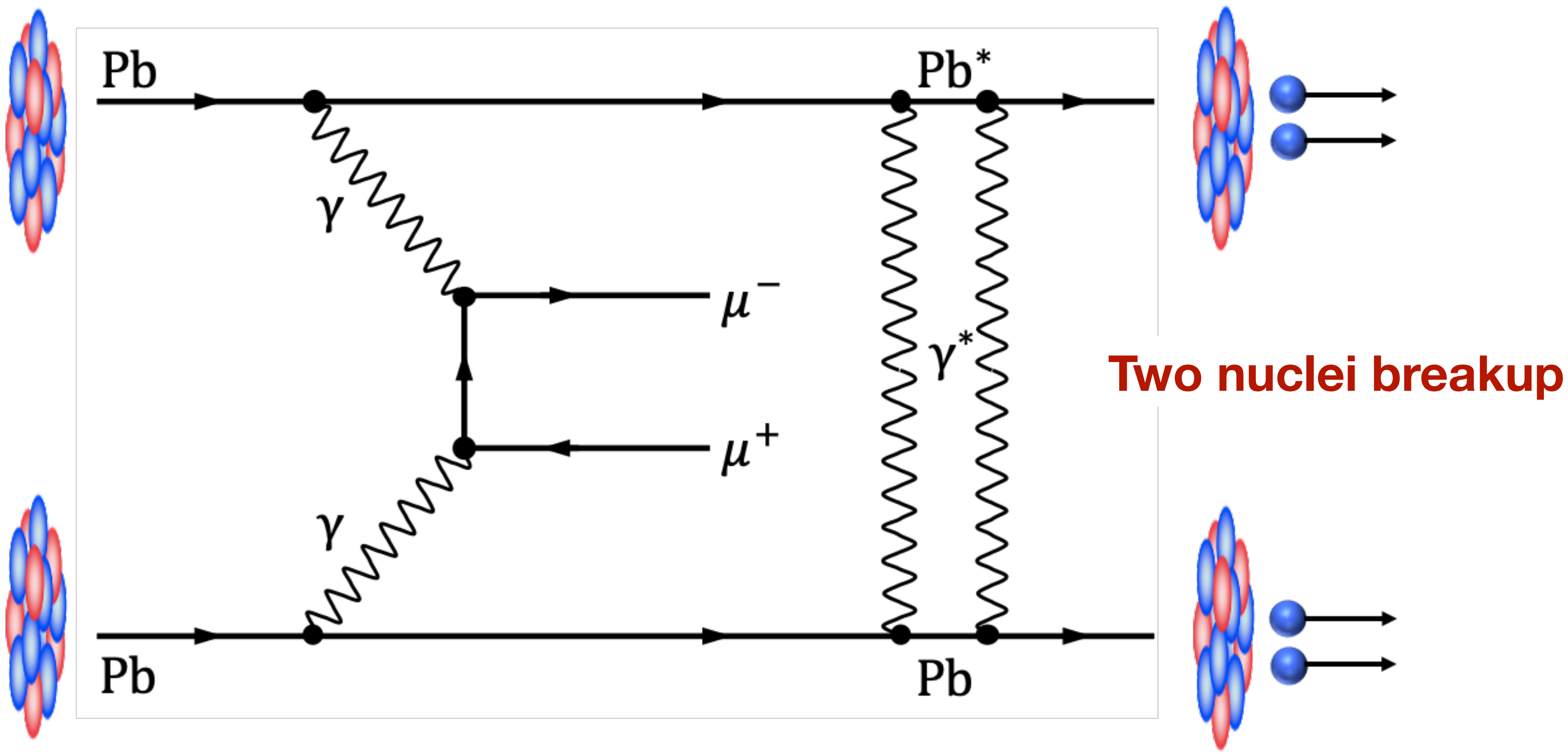

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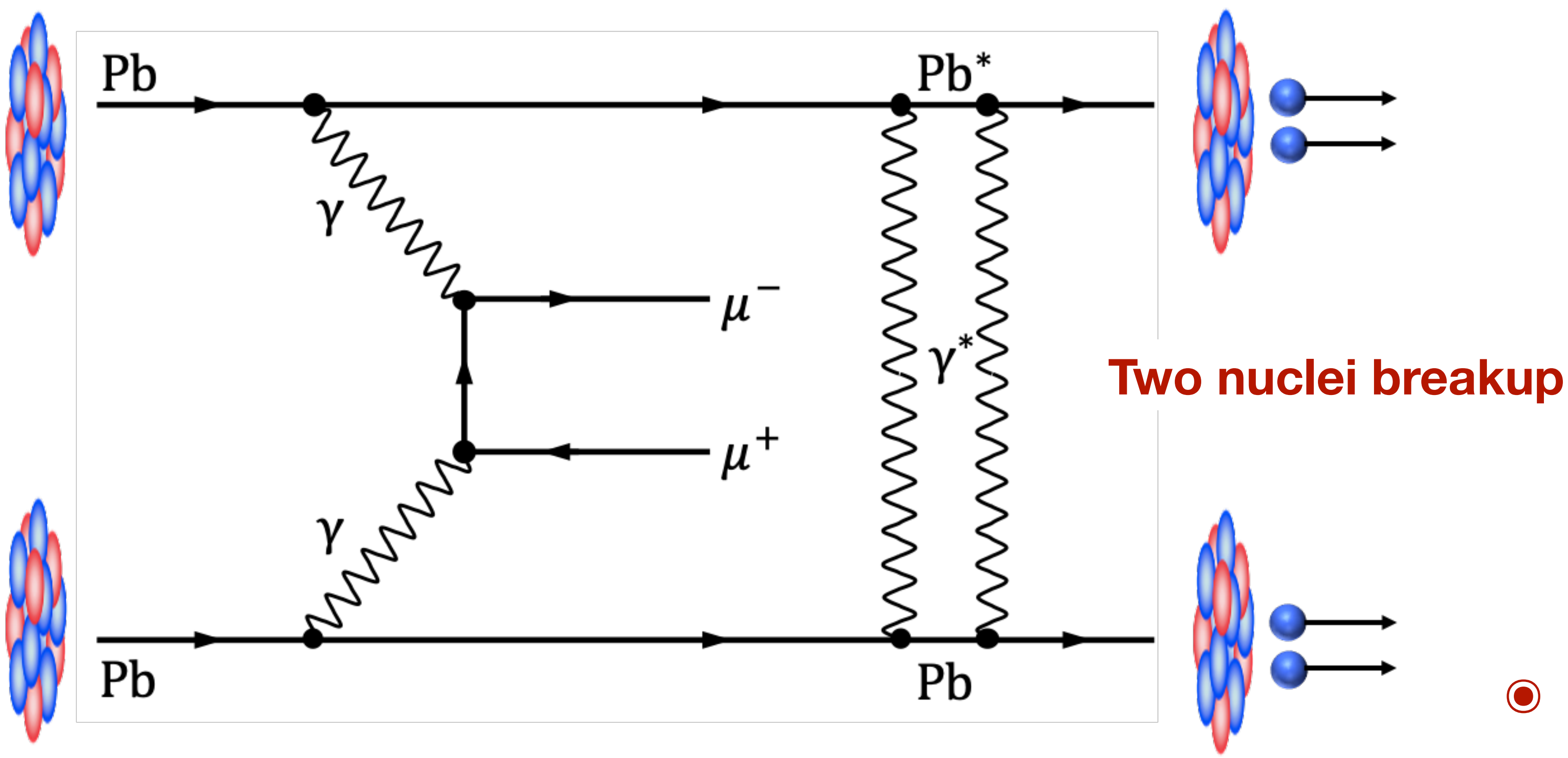
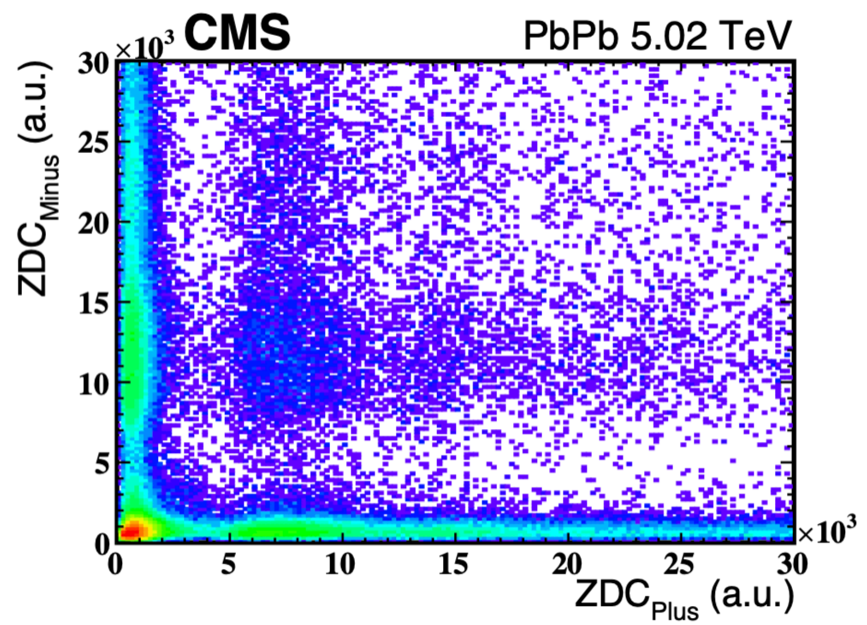
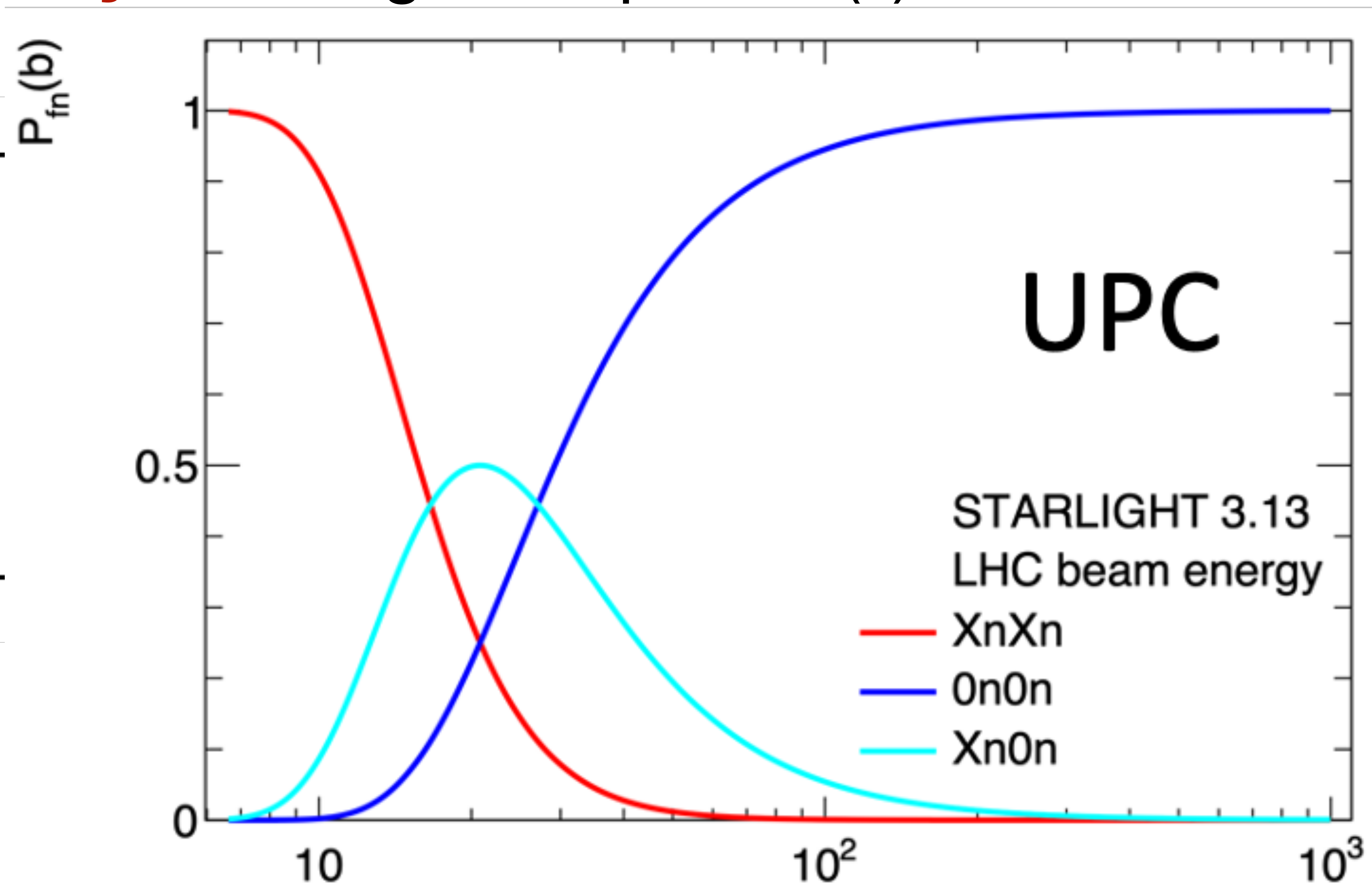




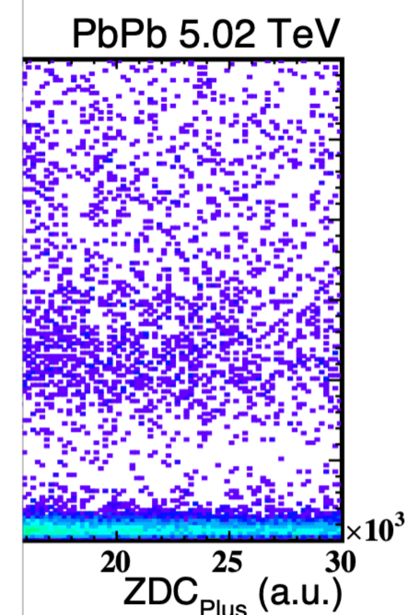
- Zero Degree Calorimeter
  - $|\eta| > 8.3$
  - ~140 m from IP

Control *b* in UPC

Nuclei **may** exchange soft photon(s) ⟹ nuclear dissociation



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

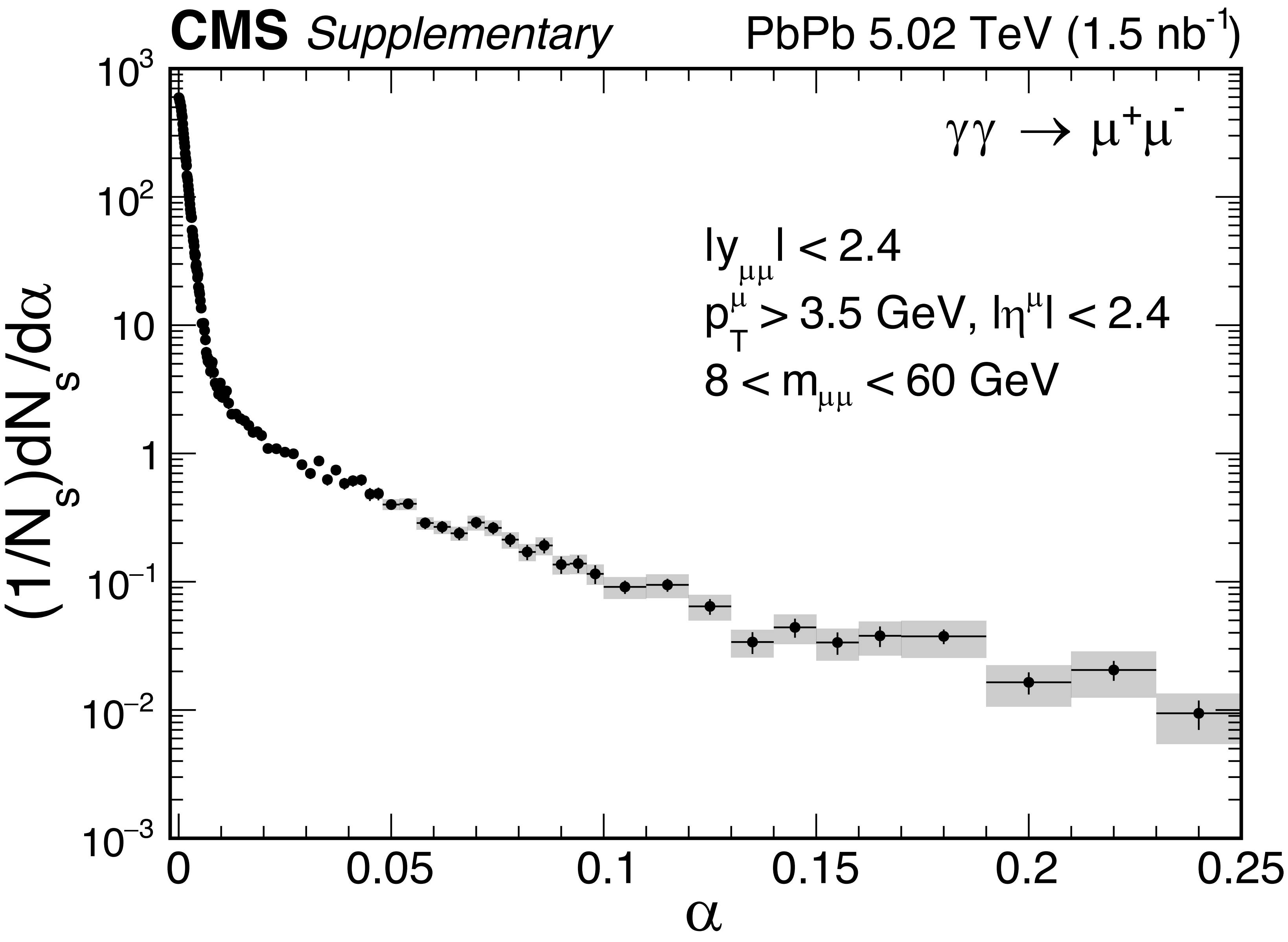


Calorimeter

m IP

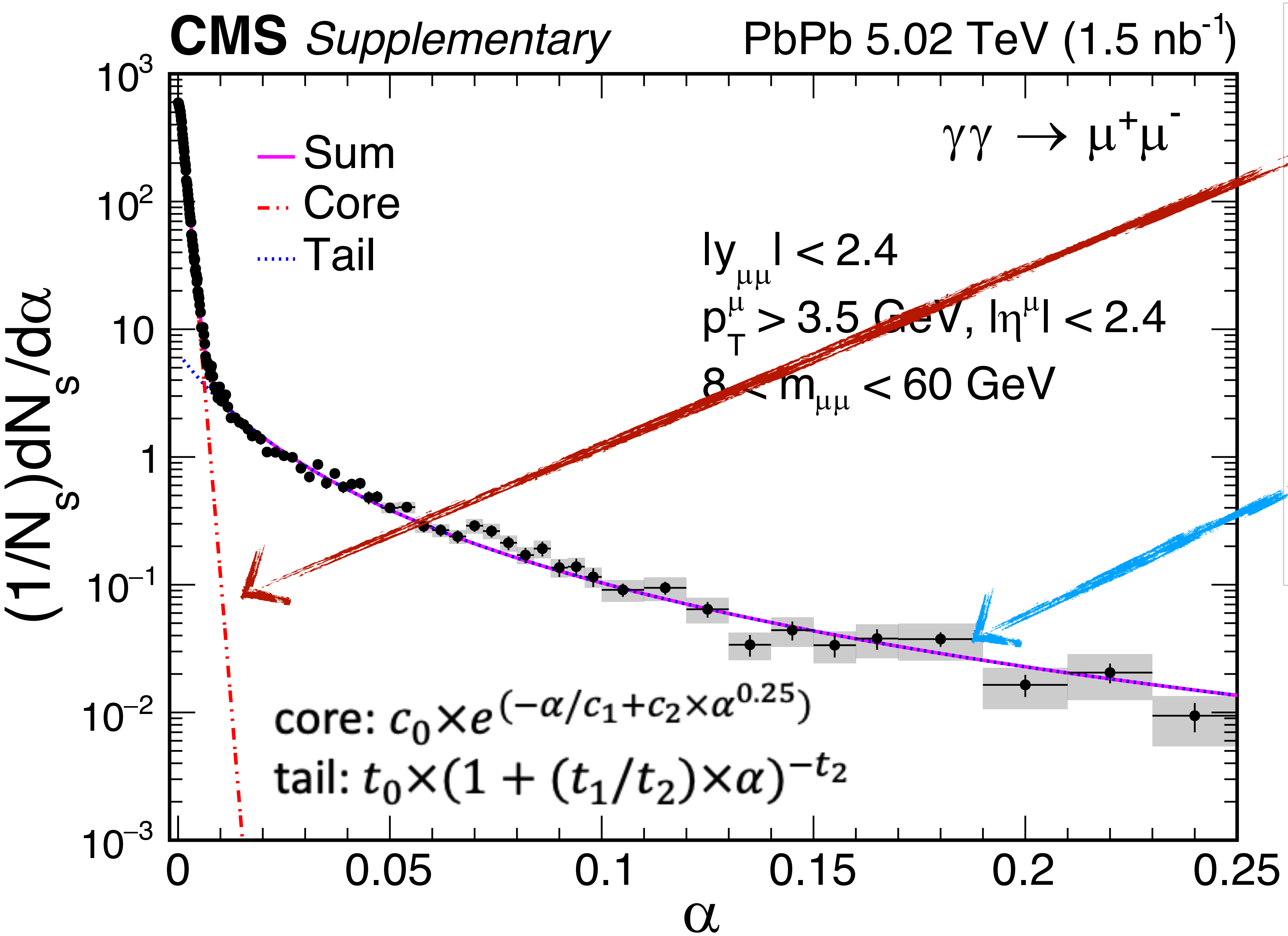
$$b_{XnXn} < b_{0nXn} < b_{0n0n}$$

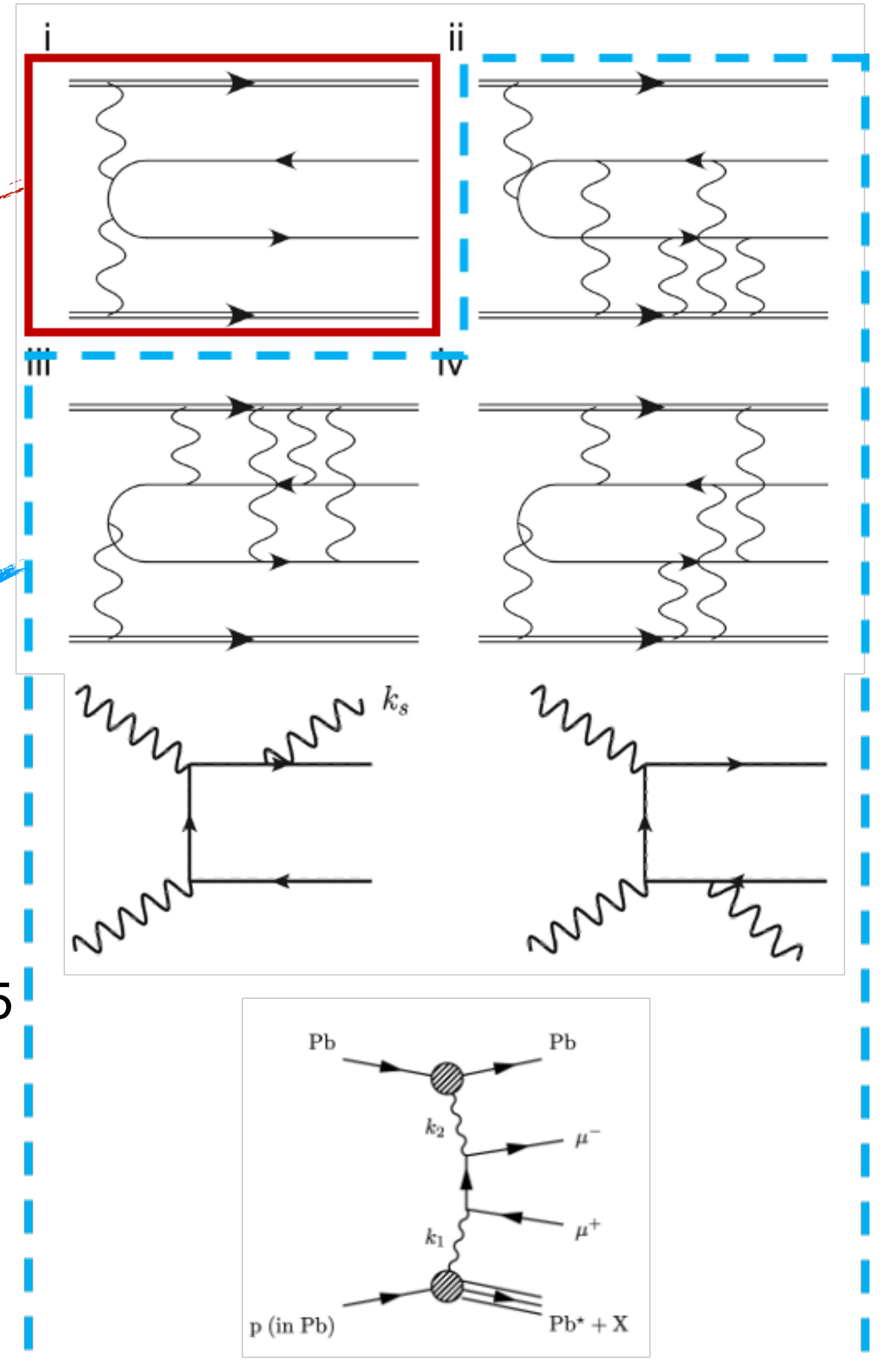
α spectrum in UPC



CMS, PRL 127 (2021) 122001

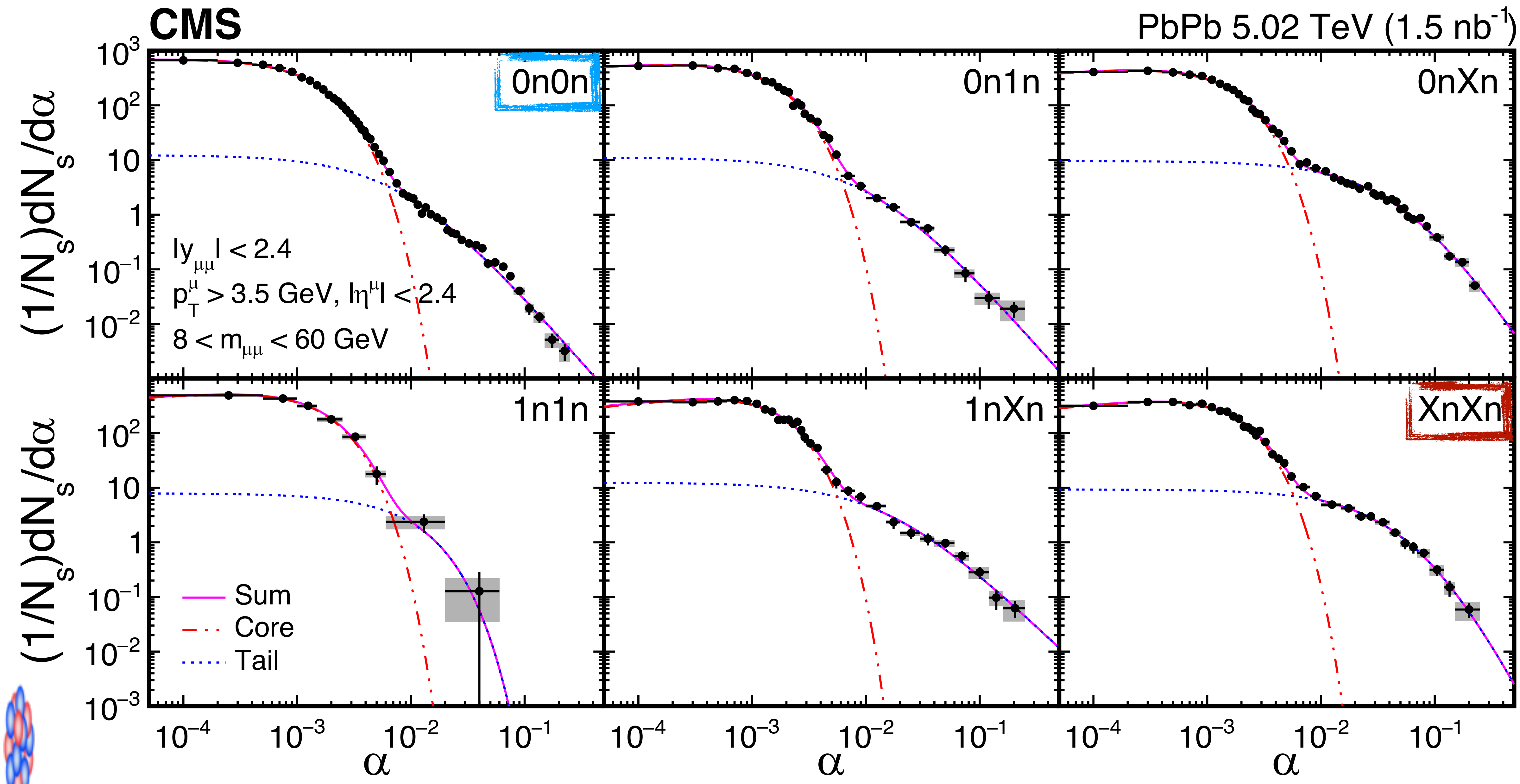
α spectrum in UPC





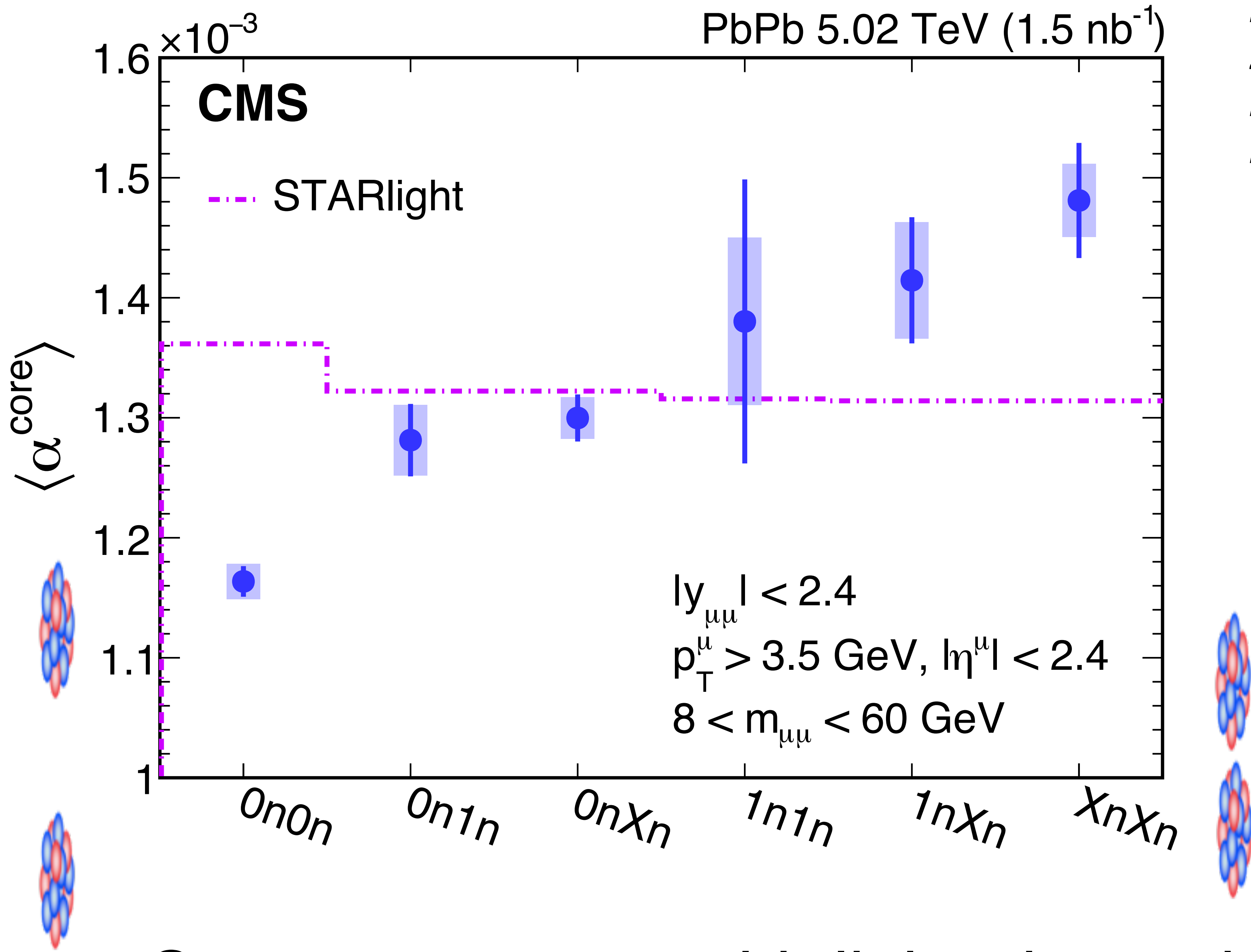
Decouple α spectrum with empirical function

α spectrum vs. neutron multiplicity

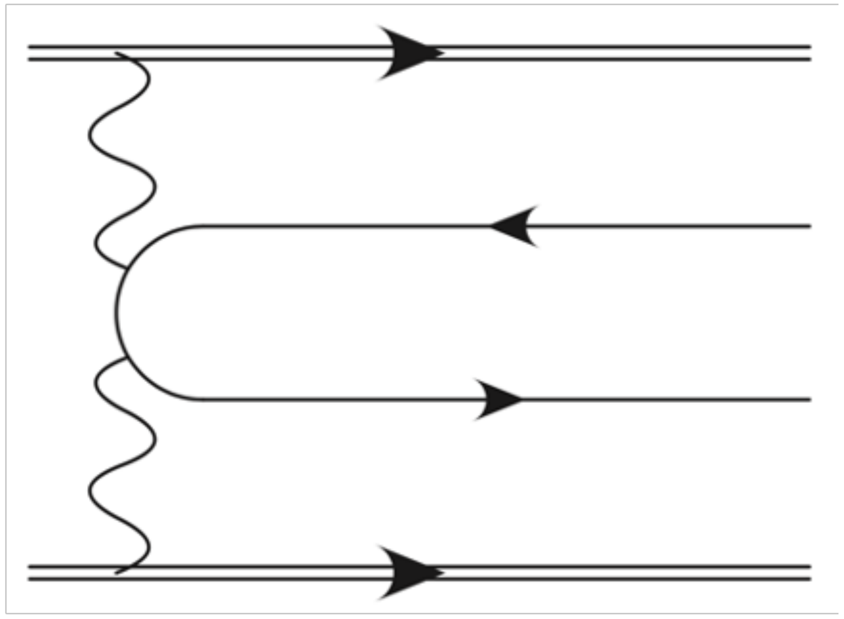


- 0n0n (fewer neutrons) ⟹ XnXn (more neutrons)
  - Tail contribution becomes larger

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

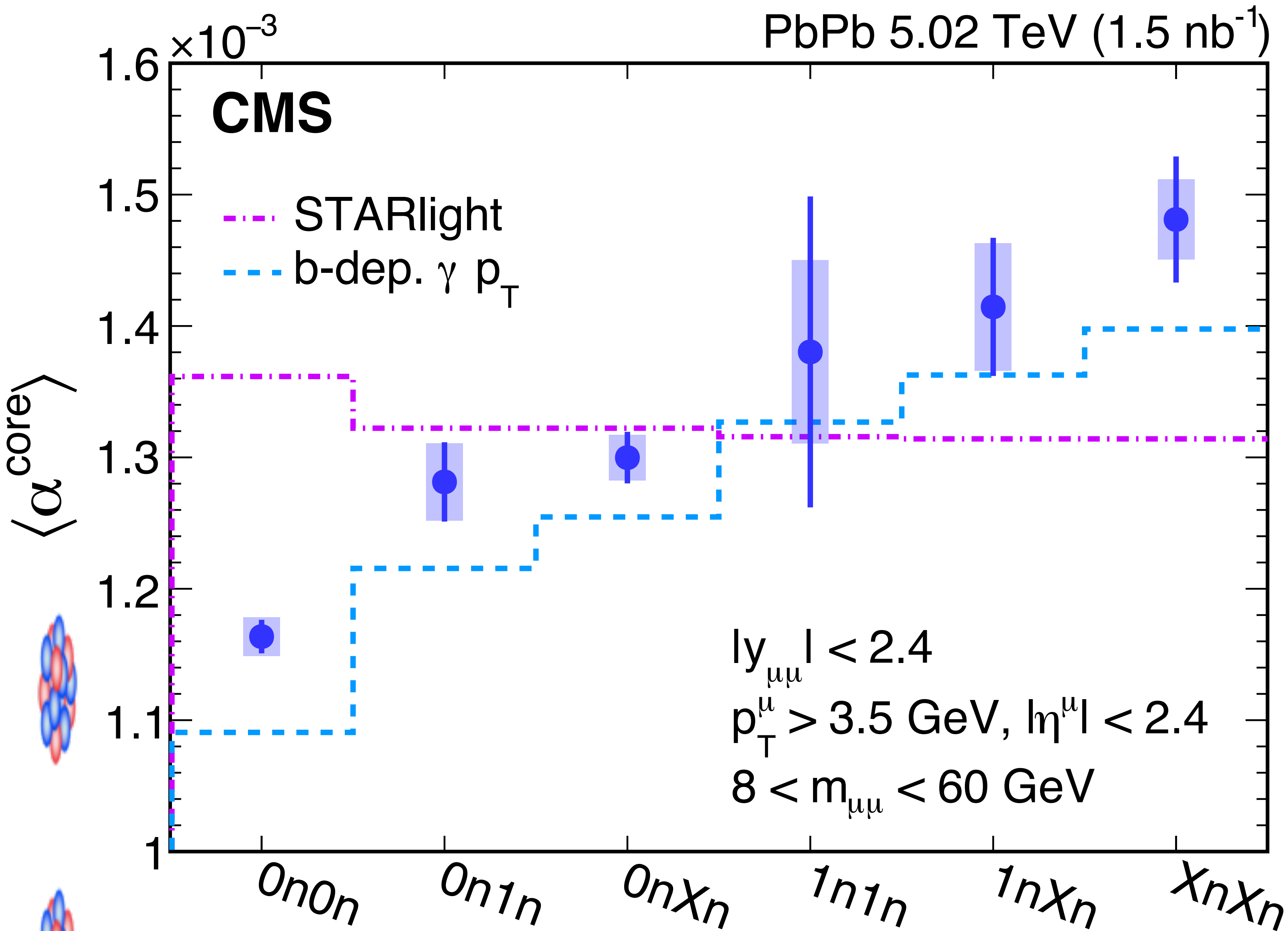


Klein et al., Comput. Phys. Commun. 212 (2017) 258
Klein et al., PRL 122 (2019) 132301
Brandenburg et al., arXiv:2006.07365

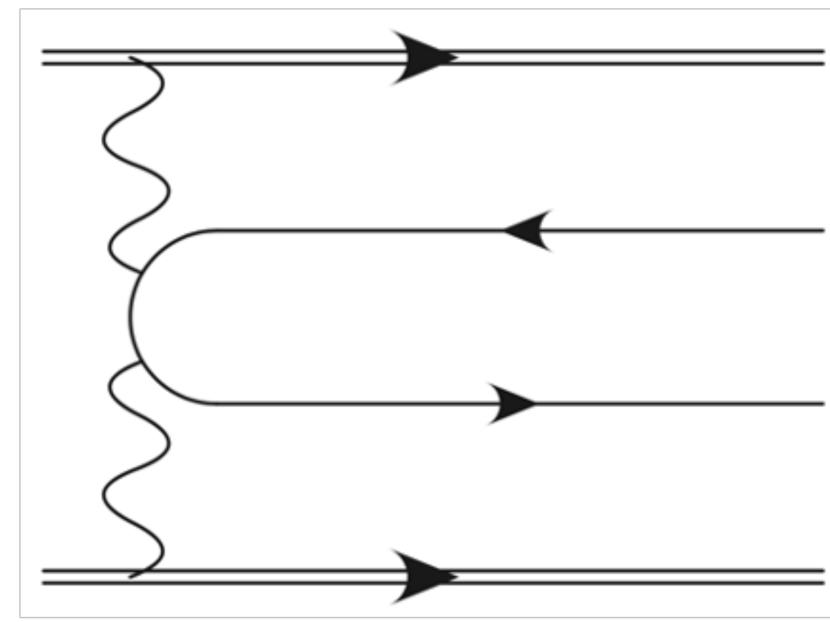


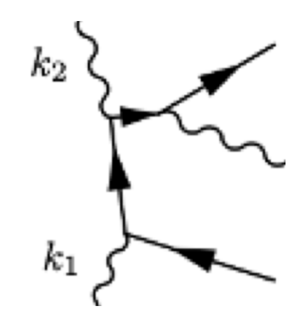
- Strong neutron multiplicity dependence of $\langle \alpha^{core} \rangle$
  - ***b*** dependence of initial photon p_T

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



Klein et al., Comput. Phys. Commun. 212 (2017) 258
Klein et al., PRL 122 (2019) 132301
Brandenburg et al., arXiv:2006.07365



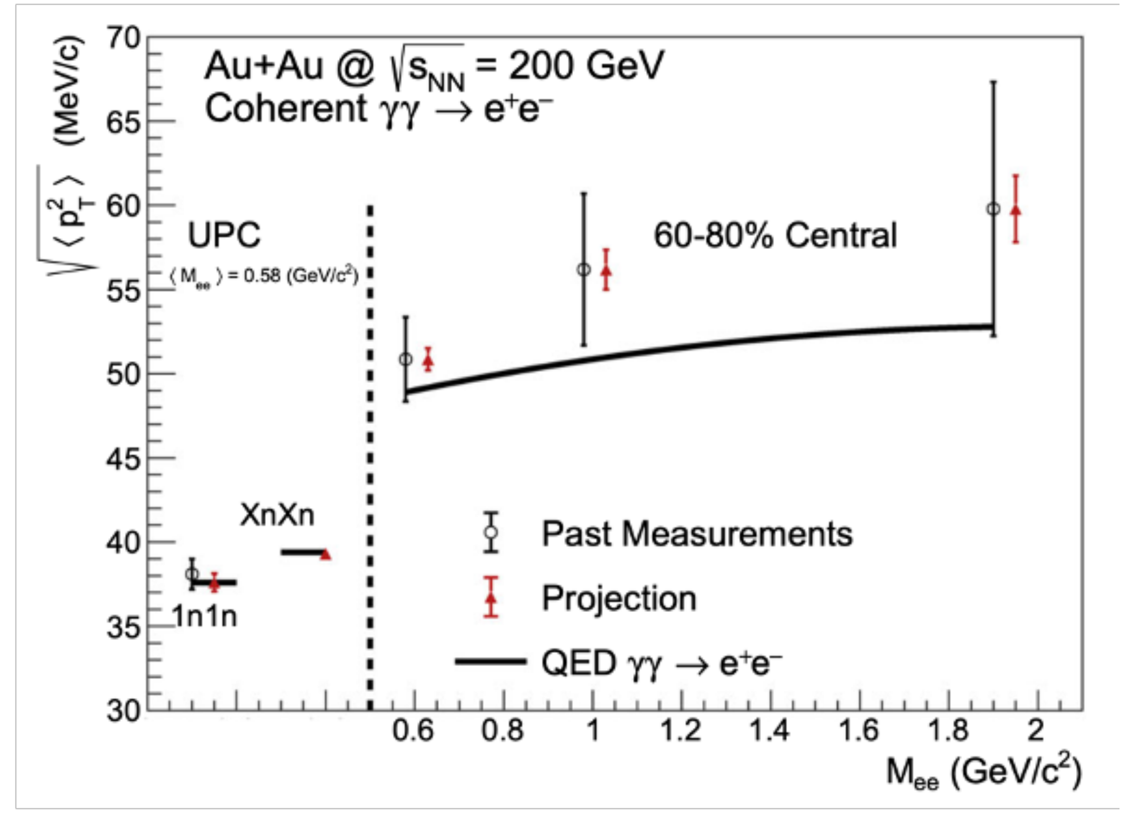


- Qualitatively described by a leading order QED model
  - Systematically lower than data could be caused by lacking HO corrections

CMS, PRL 127 (2021) 122001

Roadmap to QGP EM properties

- The ***b*** dependence of photon p_T should be considered to explore QGP EM properties
  - RHIC run 2023-2025
  - LHC run3 & 4



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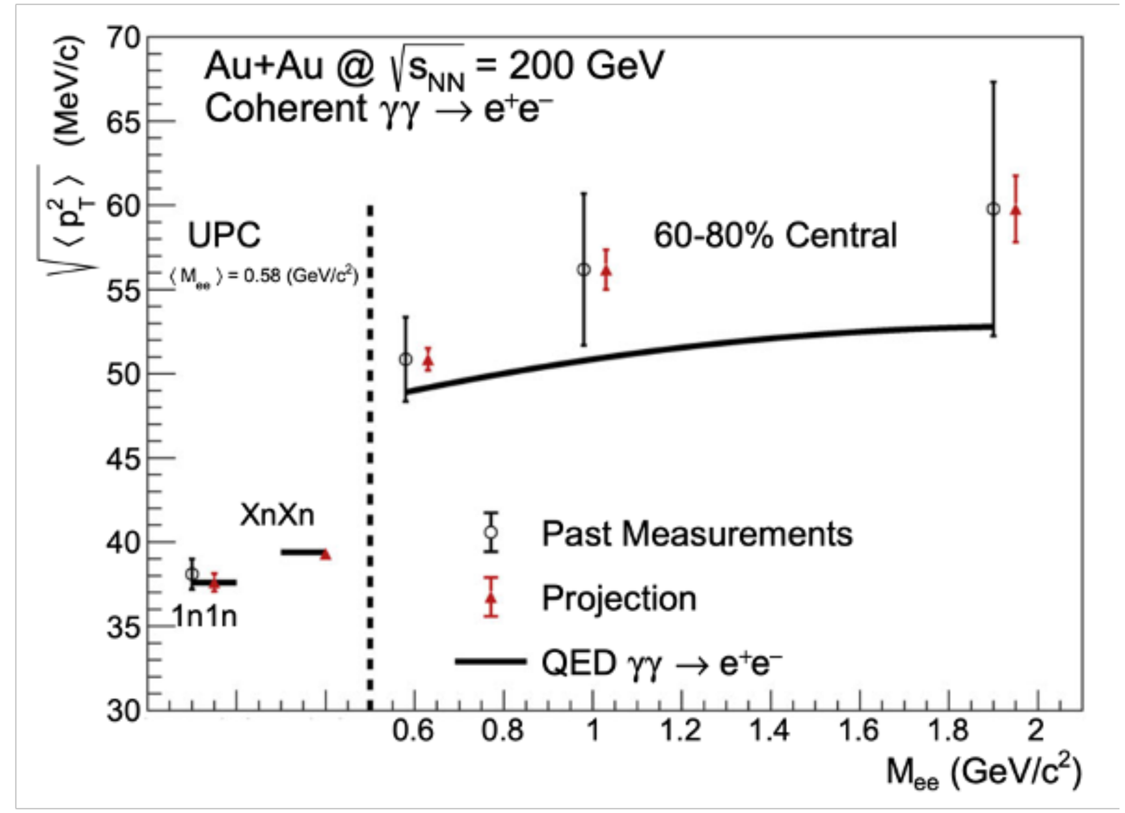
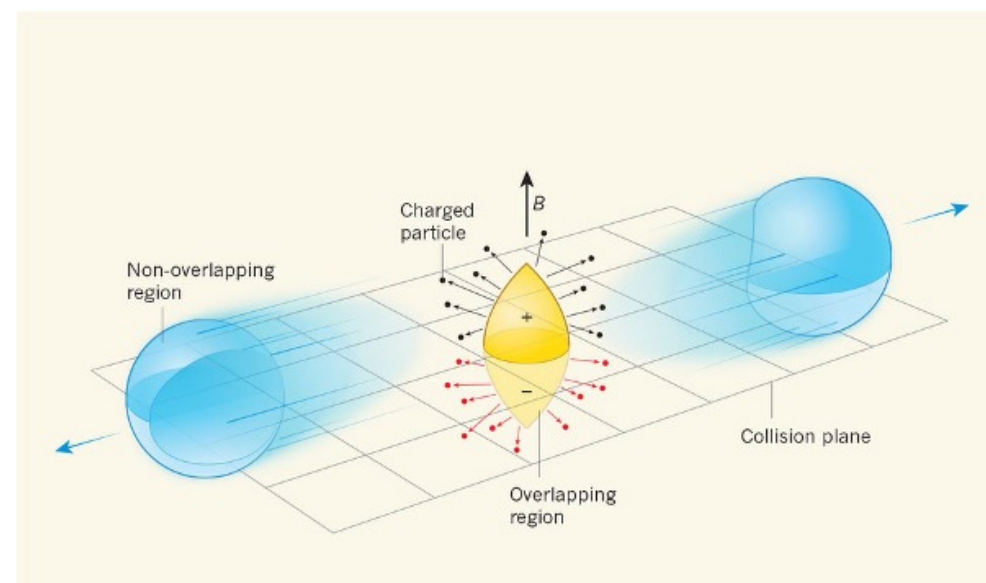
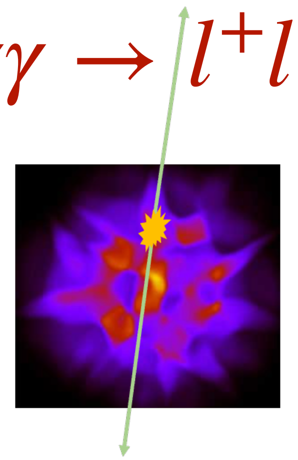


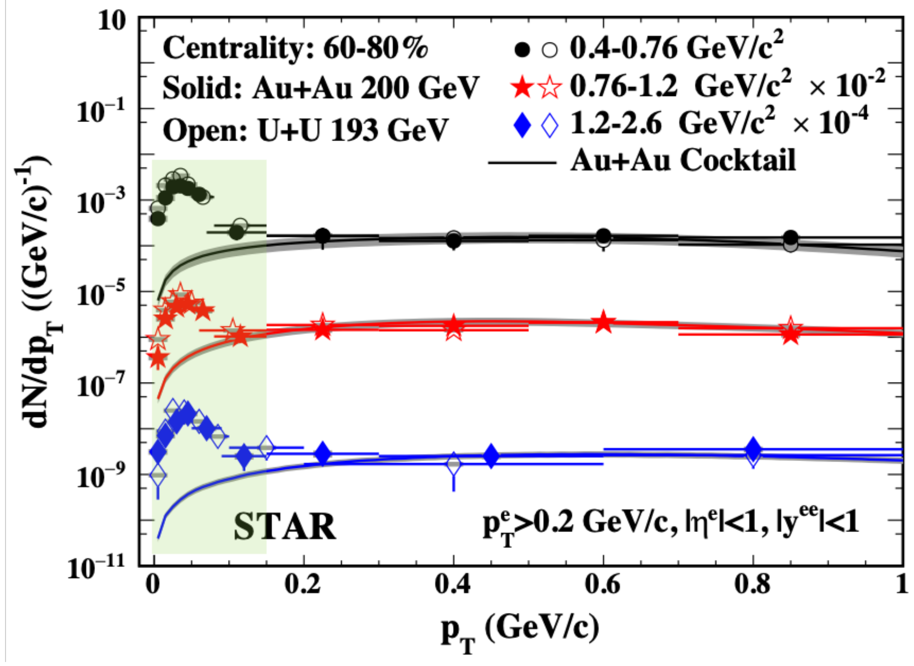
- $\langle p_T \rangle$ or $\langle \alpha \rangle$ w.r.t. event plane
  - In plane > out of plane $\Longrightarrow$ Magnetic field
  - In plane < out of plane $\Longrightarrow$ Multiple scattering



Summary

- First observation of Breit-Wheeler process in non-UPC
  - Probe QGP medium using $\gamma\gamma \rightarrow l^+l^-$





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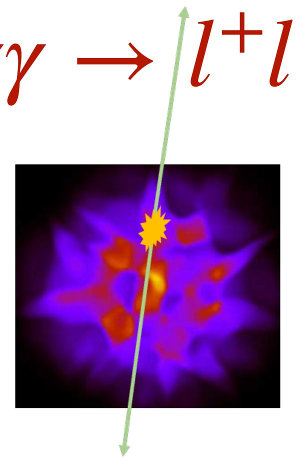
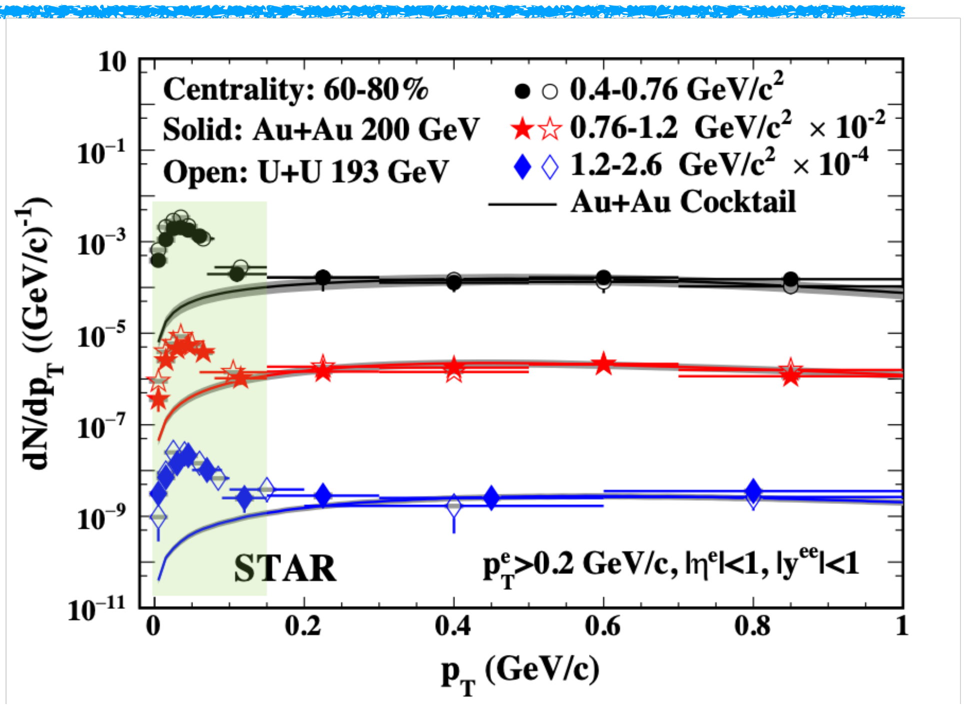
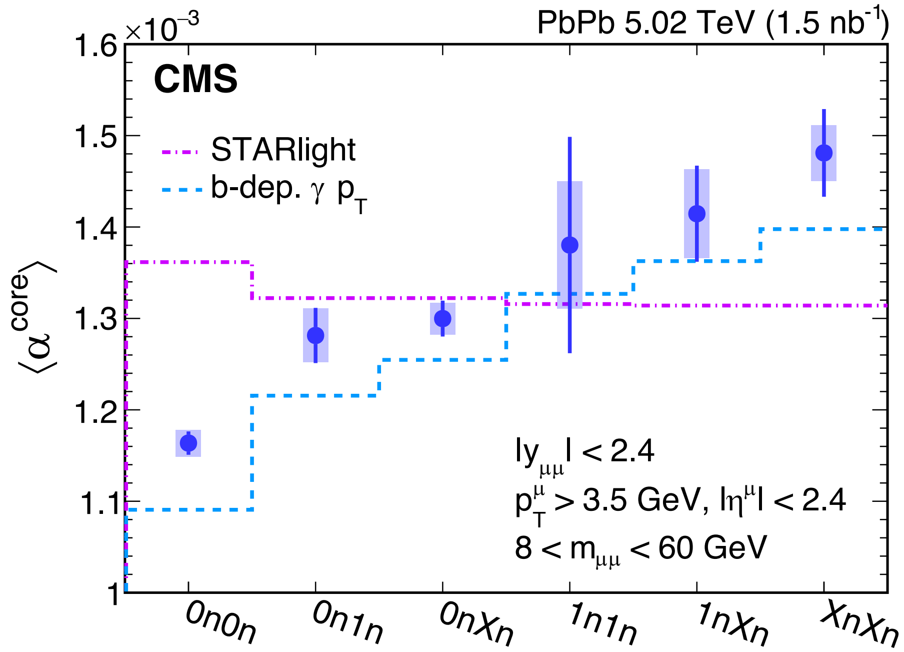




- First observation of *b* dependence of photon p_T
  - Controllable reference for probing QGP EM effects



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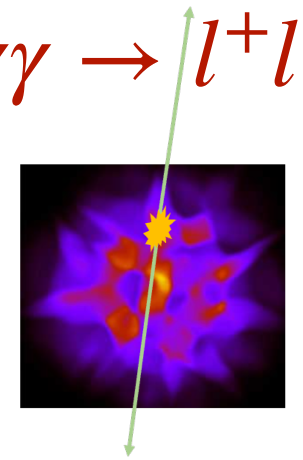

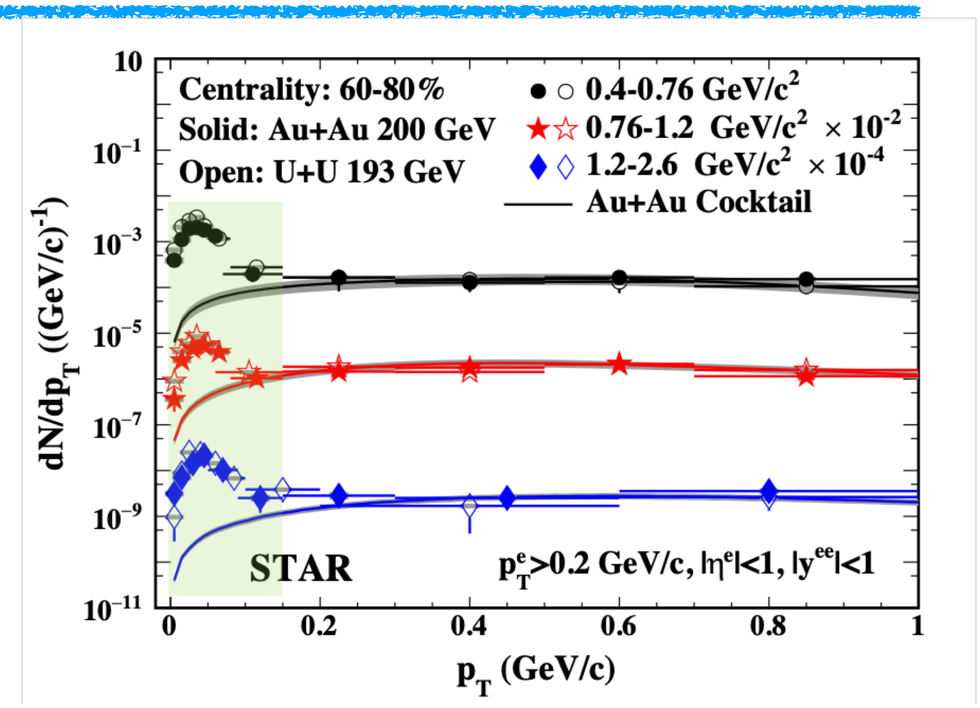

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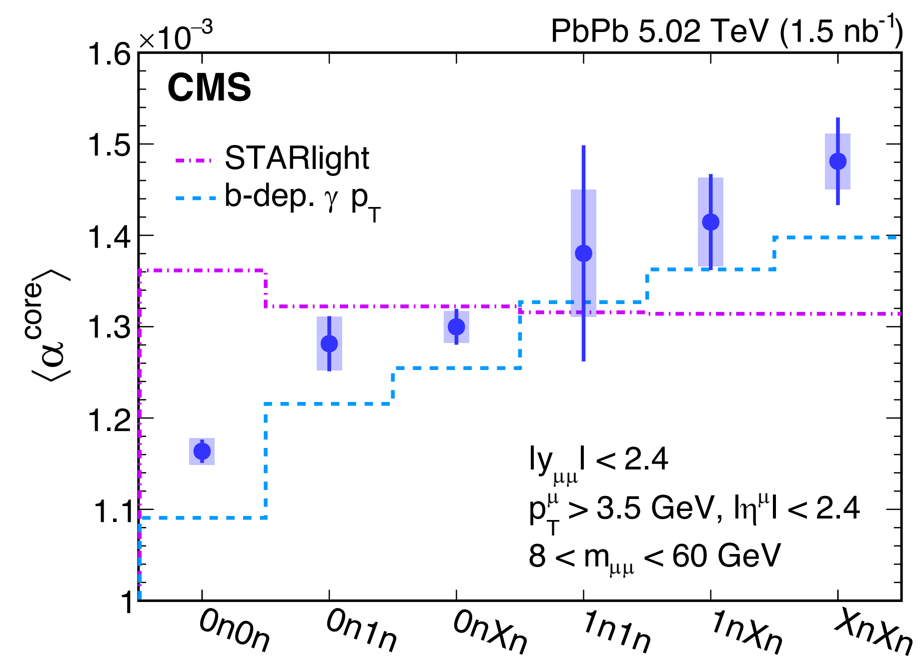


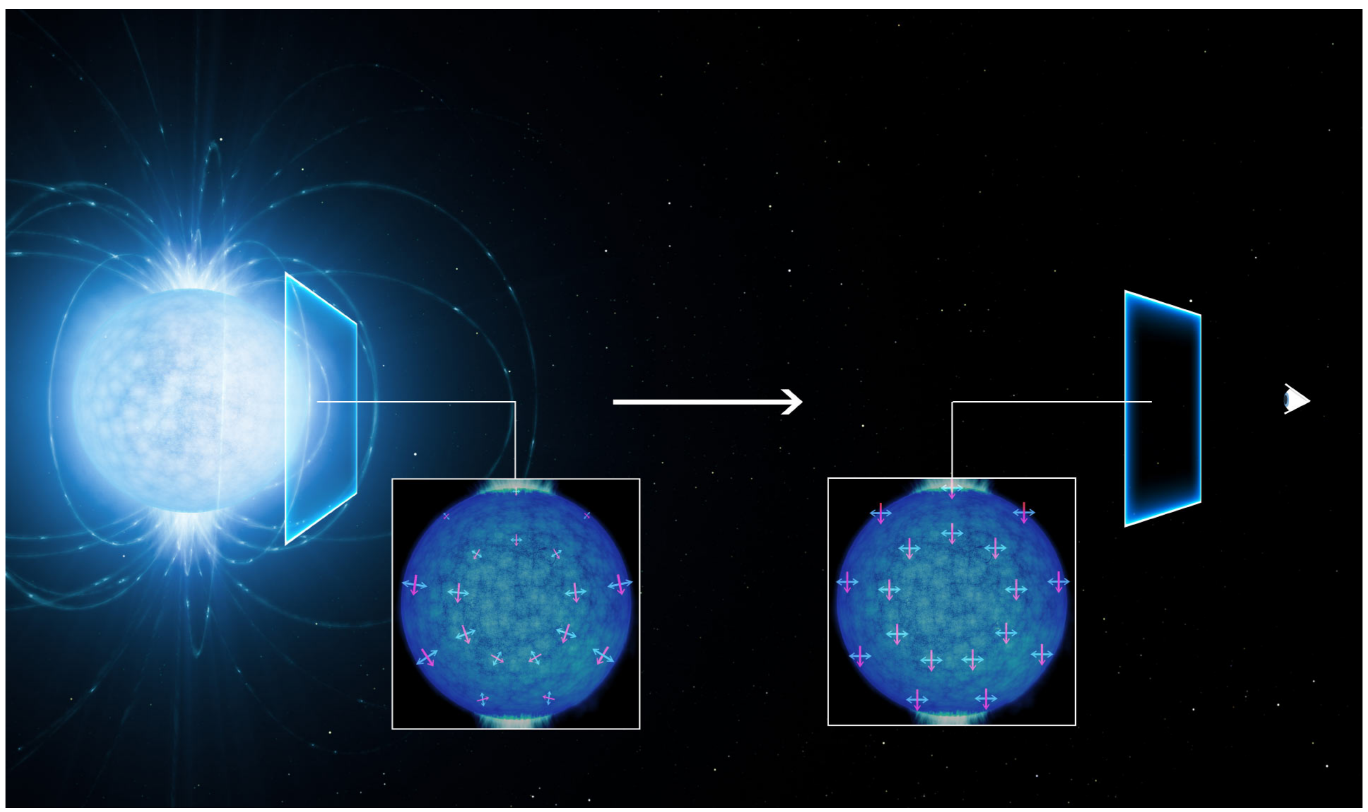
- Quantitatively study QGP EM properties at RHIC and LHC in next few years

Backups

Vacuum birefringence

Vacuum birefringence : Predicted in 1936 by Heisenberg & Euler. Index of refraction for γ interaction with $\vec{B}$ field depends on relative polarization angle i.e. $\boldsymbol{\Delta\sigma = \sigma_{\parallel} - \sigma_{\perp} \neq 0}$

Discovered on Nov. 2, 2016



Requires extremely strong $\vec{B}$

Neutron stars are the very dense remnant cores of massive stars that have exploded as supernovae at the ends of their lives.

They also have extreme magnetic fields — billions of times stronger than that of the Sun — that permeate their outer surface and surroundings. These fields are so strong that they even affect the properties of the empty space around the star.

Normally a vacuum is thought of as completely empty, and light can travel through it without being changed.

But in quantum electrodynamics (QED), the quantum theory describing the interaction between photons and charged particles such as electrons, space is full of virtual particles that appear and vanish all the time.

Very strong magnetic fields can modify this space so that it affects the polarization of light passing through it.

"According to QED, a highly magnetized vacuum behaves as a prism for the propagation of light, an effect known as vacuum birefringence," said team member Dr. Roberto Mignani, from INAF Milan in Italy.

Among the many predictions of QED, however, vacuum birefringence so far lacked a direct experimental demonstration.

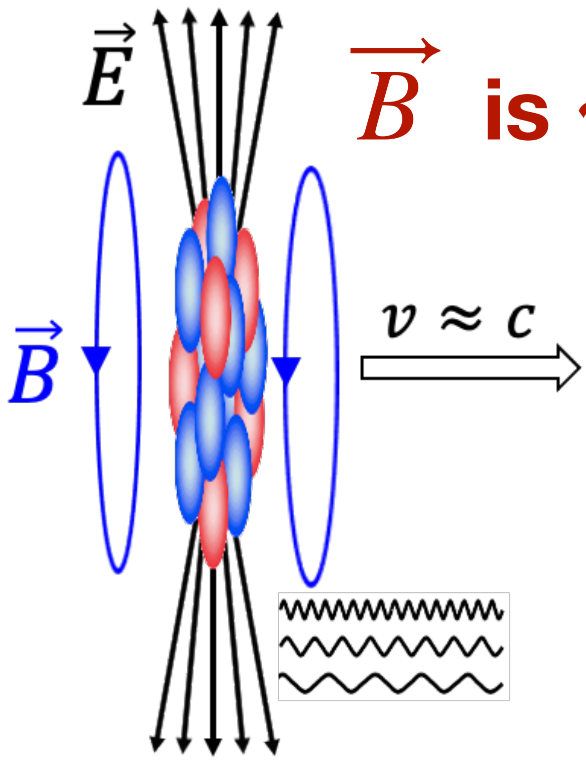
Attempts to detect it in the laboratory have not yet succeeded in the 80 years since it was predicted in by Werner Heisenberg and Hans Heinrich Euler.

"This effect can be detected only in the presence of enormously strong magnetic fields, such as those around neutron stars," said team member Dr. Roberto Turolla, from the University of Padua in Italy.

"This shows, once more, that neutron stars are invaluable laboratories in which to study the fundamental laws of nature."

Mon. Notices Royal Astron. Soc., 465 (2017) 492

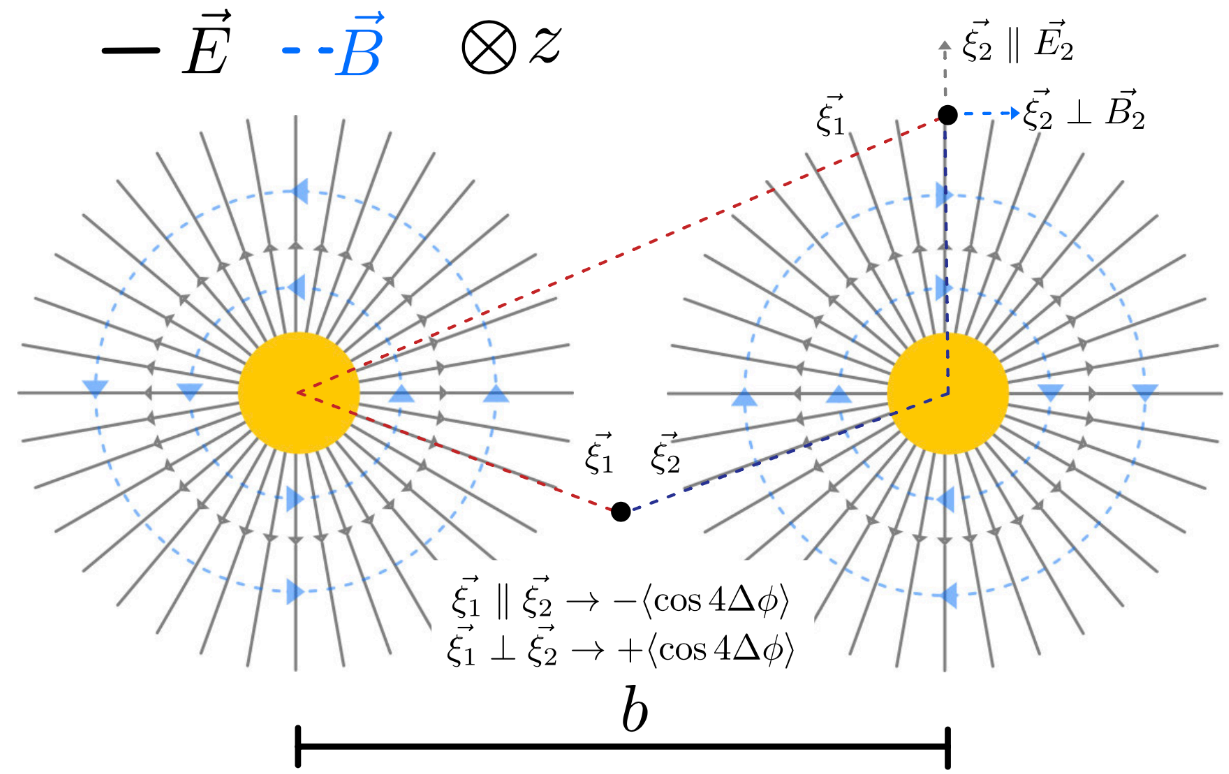
Vacuum birefringence in lab



$\vec{B}$ **is ~10[15]T at RHIC**

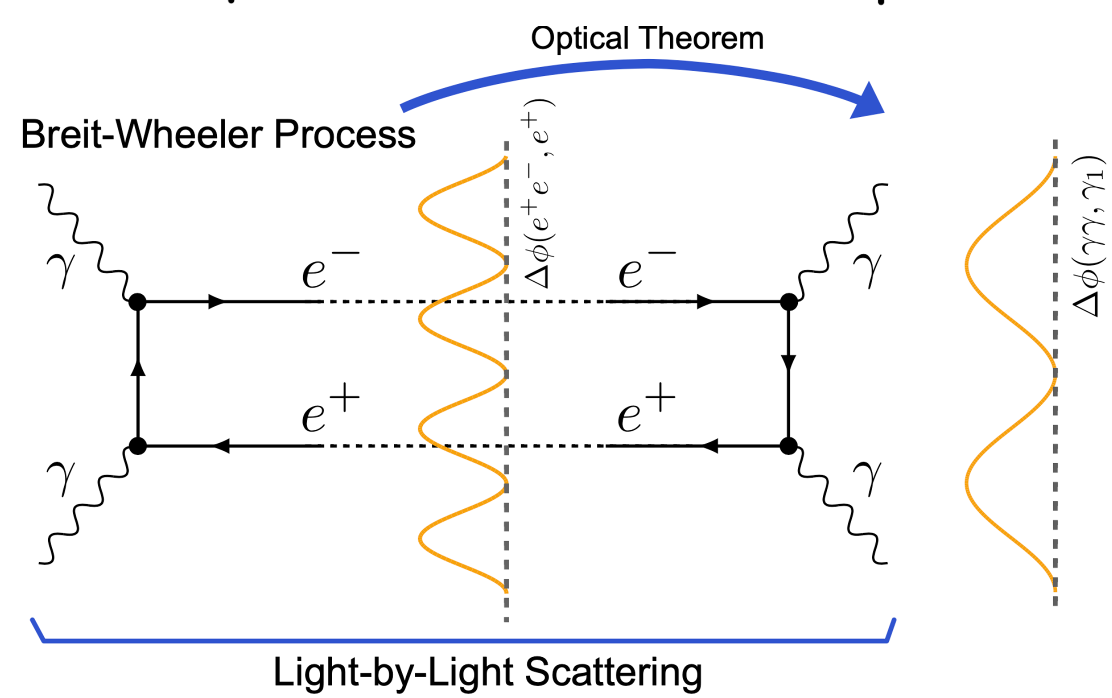
$$\vec{E} \perp \vec{B} \perp \vec{v}$$

C. Li et al., Phys. Lett. B 795, 576 (2019)
Brandenburg et al., EPJA 57 (2021) 299



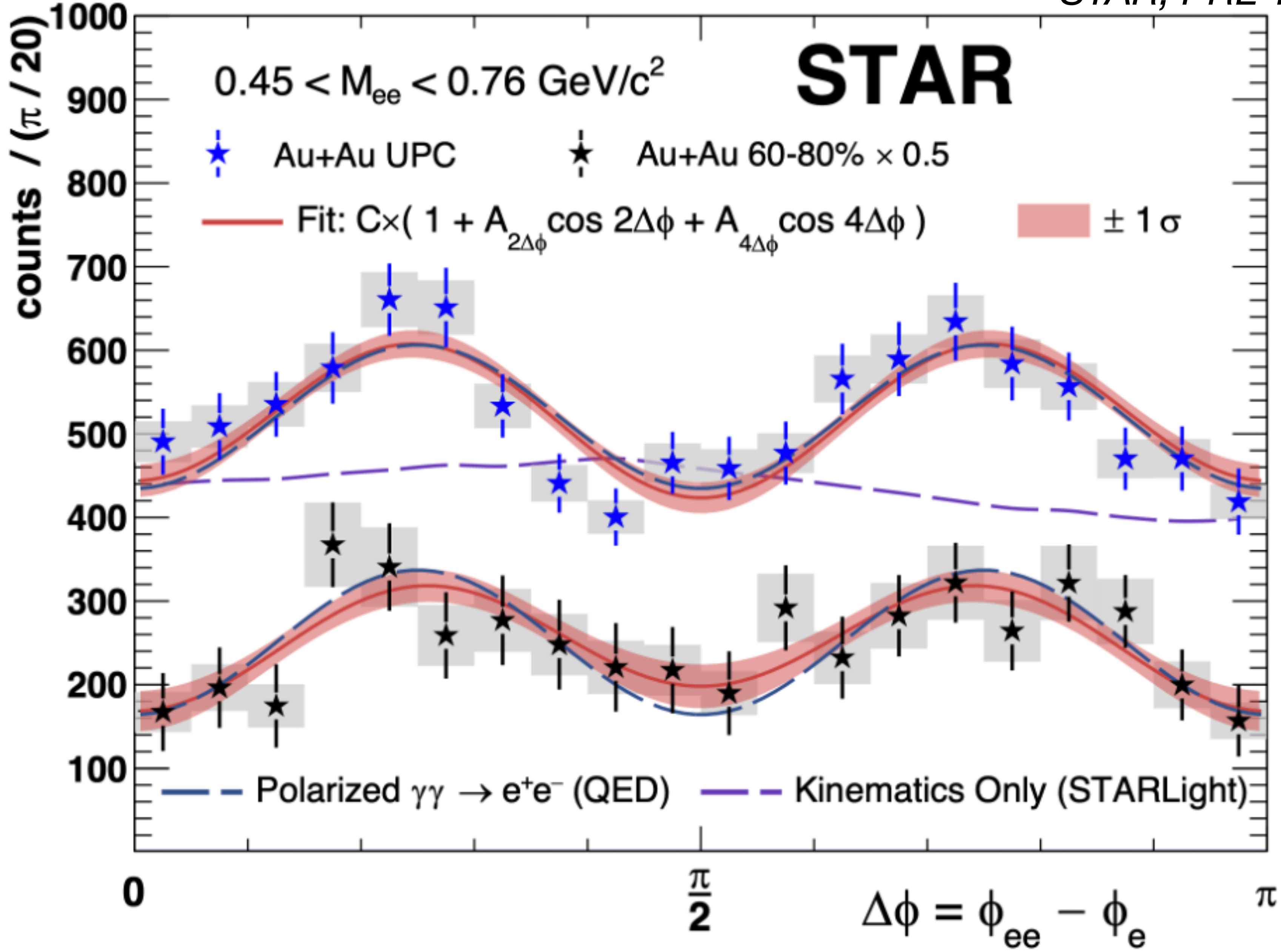
- Photon polarization direction ($\vec{\xi}$) is parallel to $\vec{E}$
- Recently realized, $\Delta\sigma = \sigma_{\parallel} - \sigma_{\perp} \neq 0$ lead a $cos(4\Delta\phi)$ modulation in polarized $\gamma\gamma \to l^+ l^-$
  - $cos(2\Delta\phi) \propto m_l^2 / p_{T,l}^2$

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



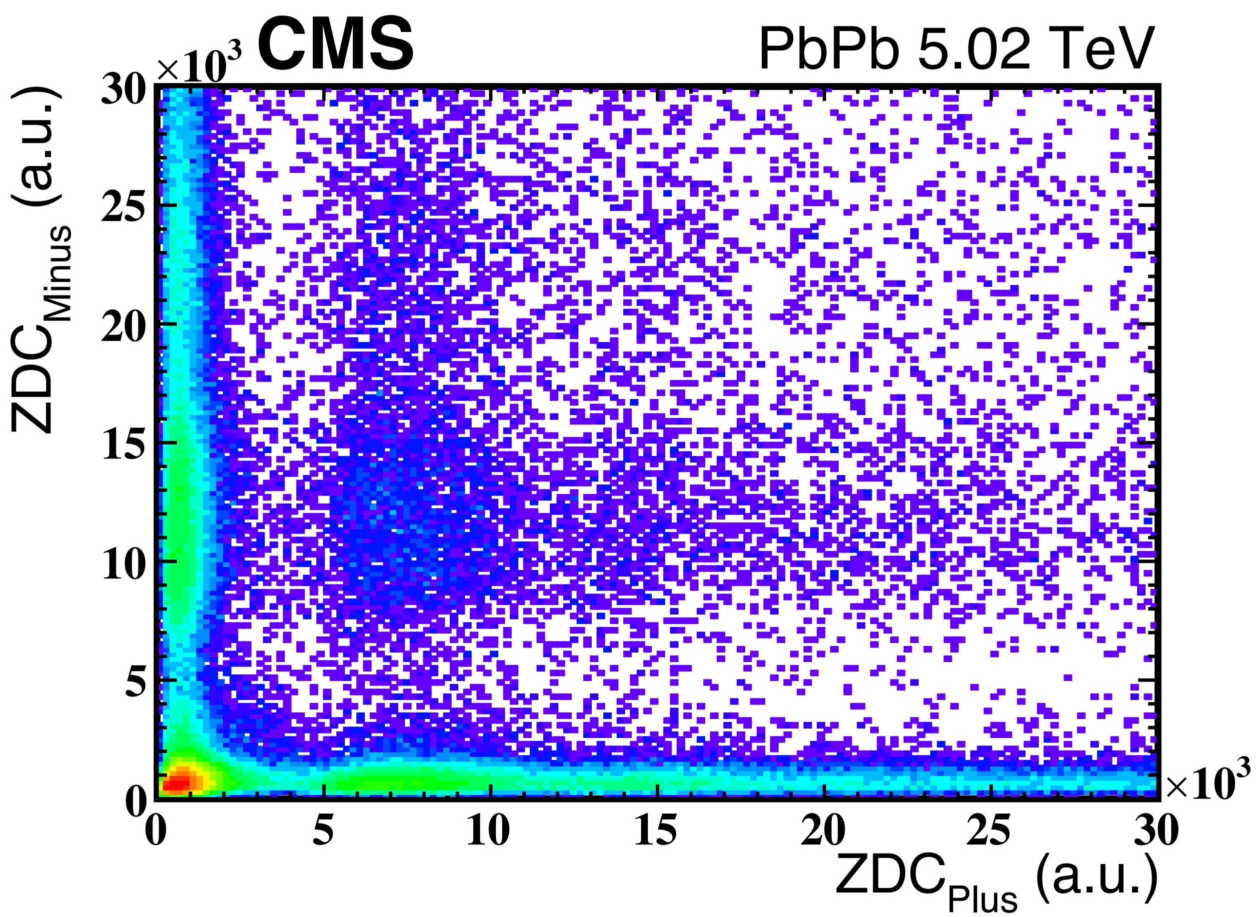
Vacuum birefringence in lab

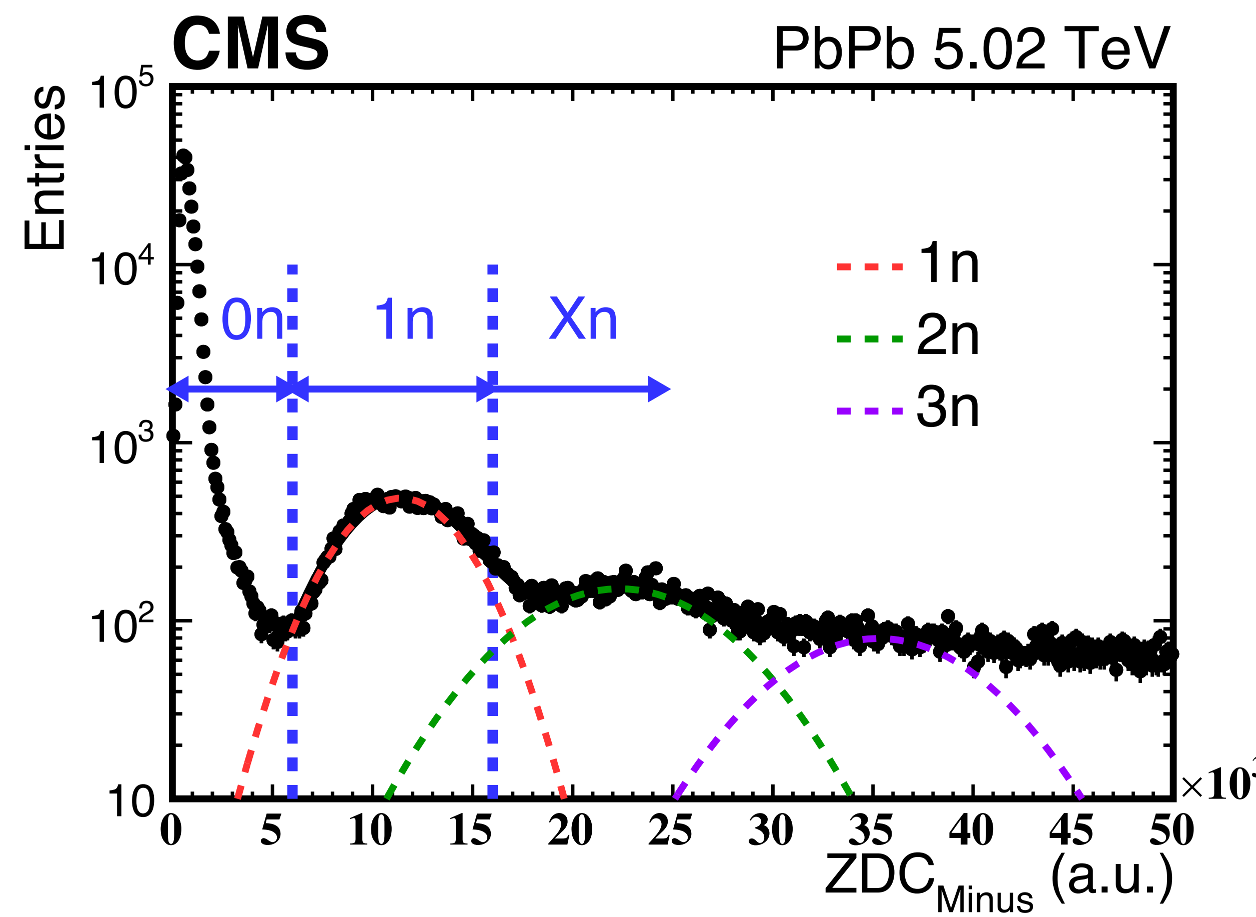
STAR, PRL 127 (2021) 052302



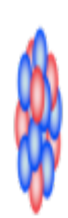
- First **earth-based** observation (6.7σ level) of vacuum birefringence
  - Experimental evidence of linearly polarized photons

Determine neutron multiplicity



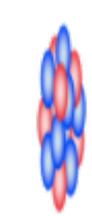


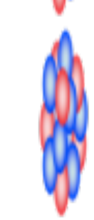
- Straight cuts to disentangle neutrons
  - 0n0n, 0n1n, 0nXn, 1n1n, 1nXn, XnXn (X≥2)



Fewer neutrons

More neutrons

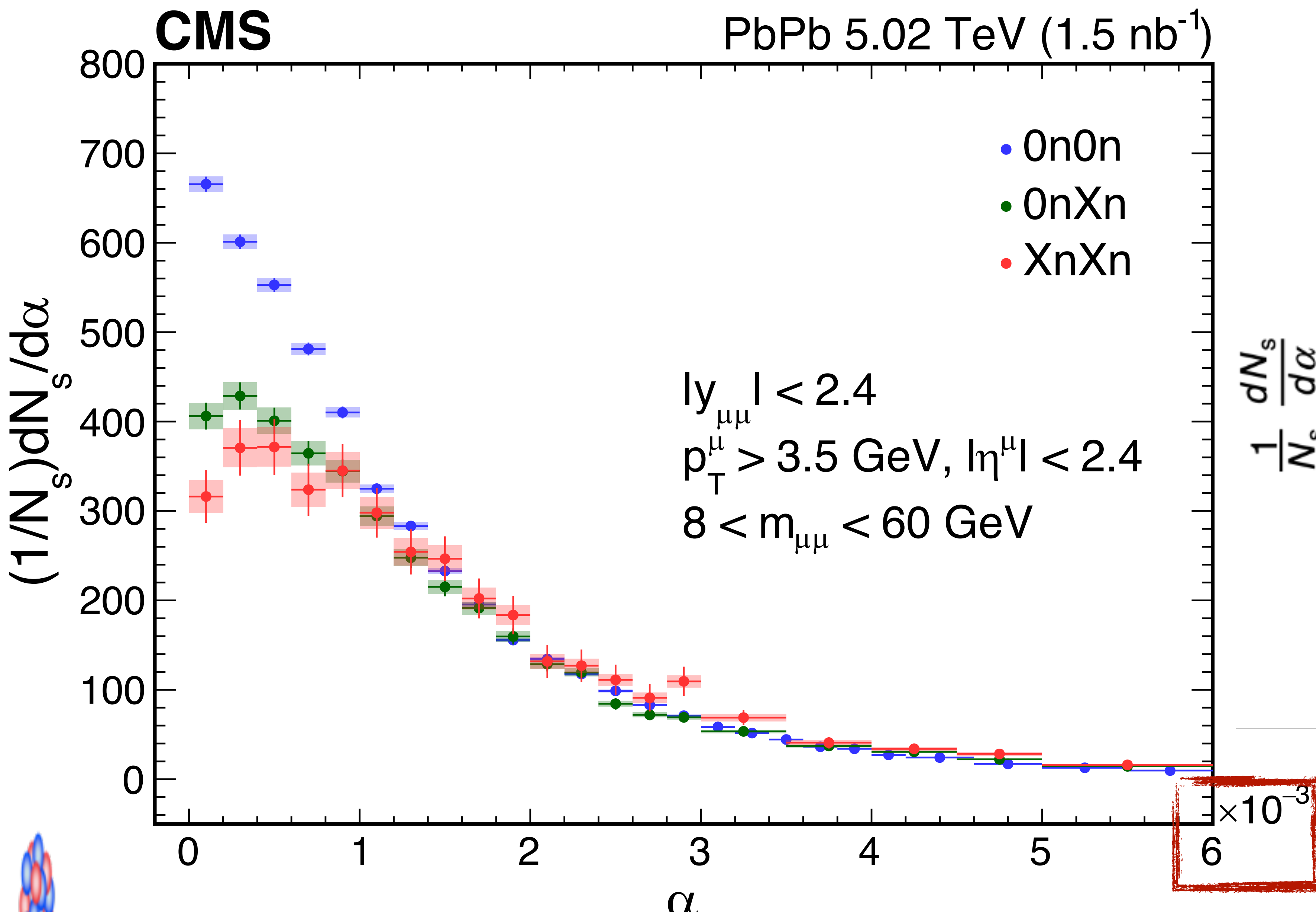


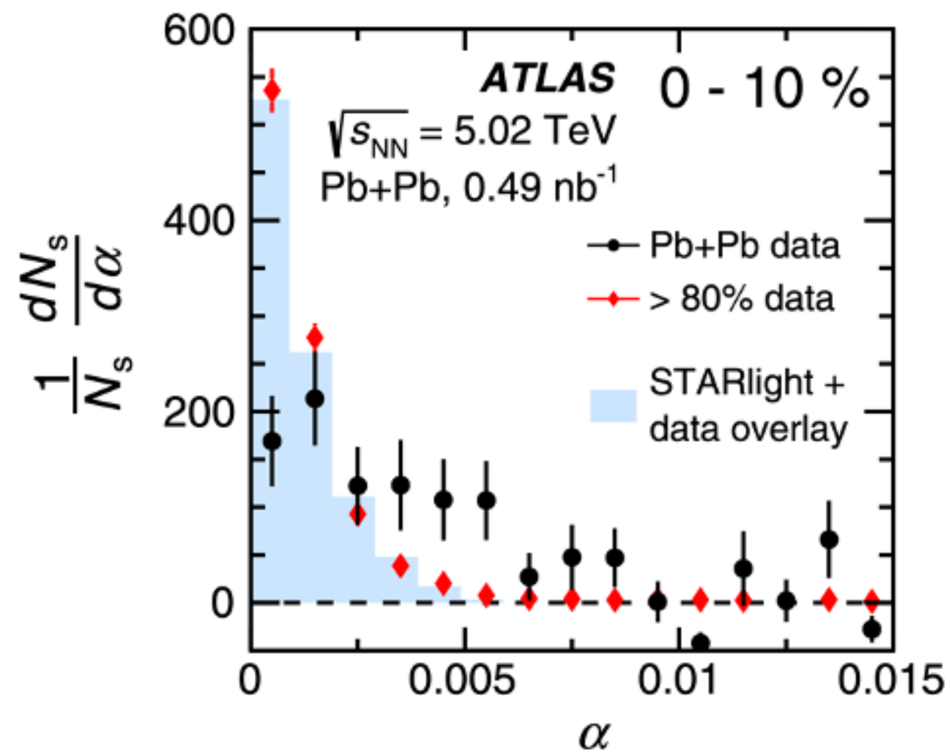


CMS, PRL 127 (2021) 122001

α spectrum vs. neutron multiplicity

CMS, PRL 127 (2021) 122001





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