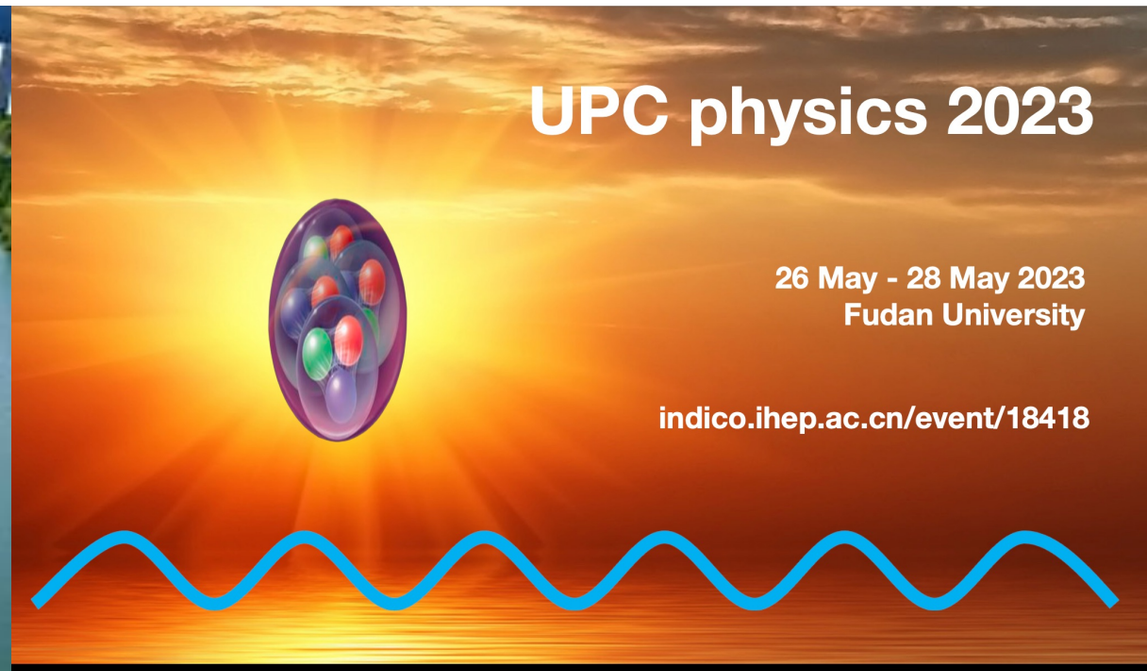
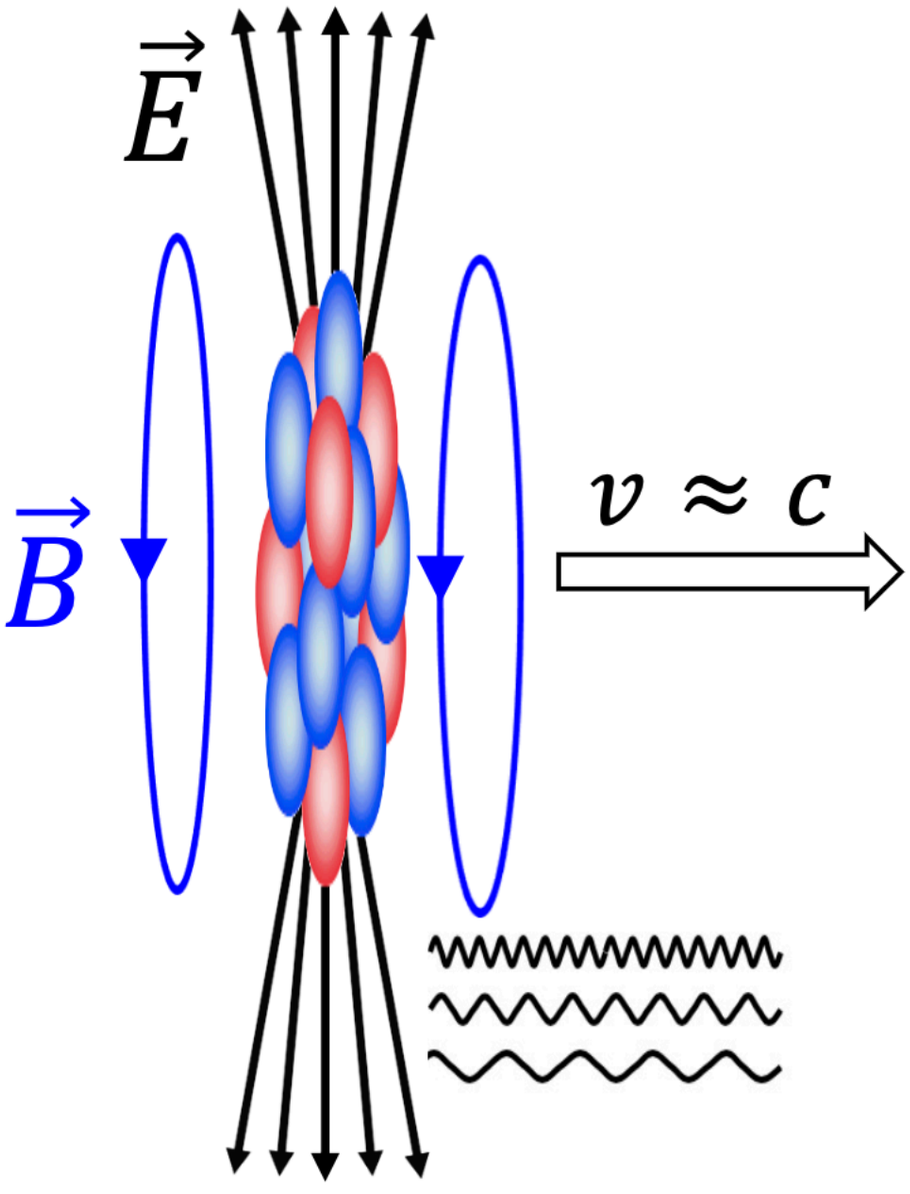
Impact parameter dependence of photon-induced processes in heavy-ion collisions

杨 帅

华南师范大学

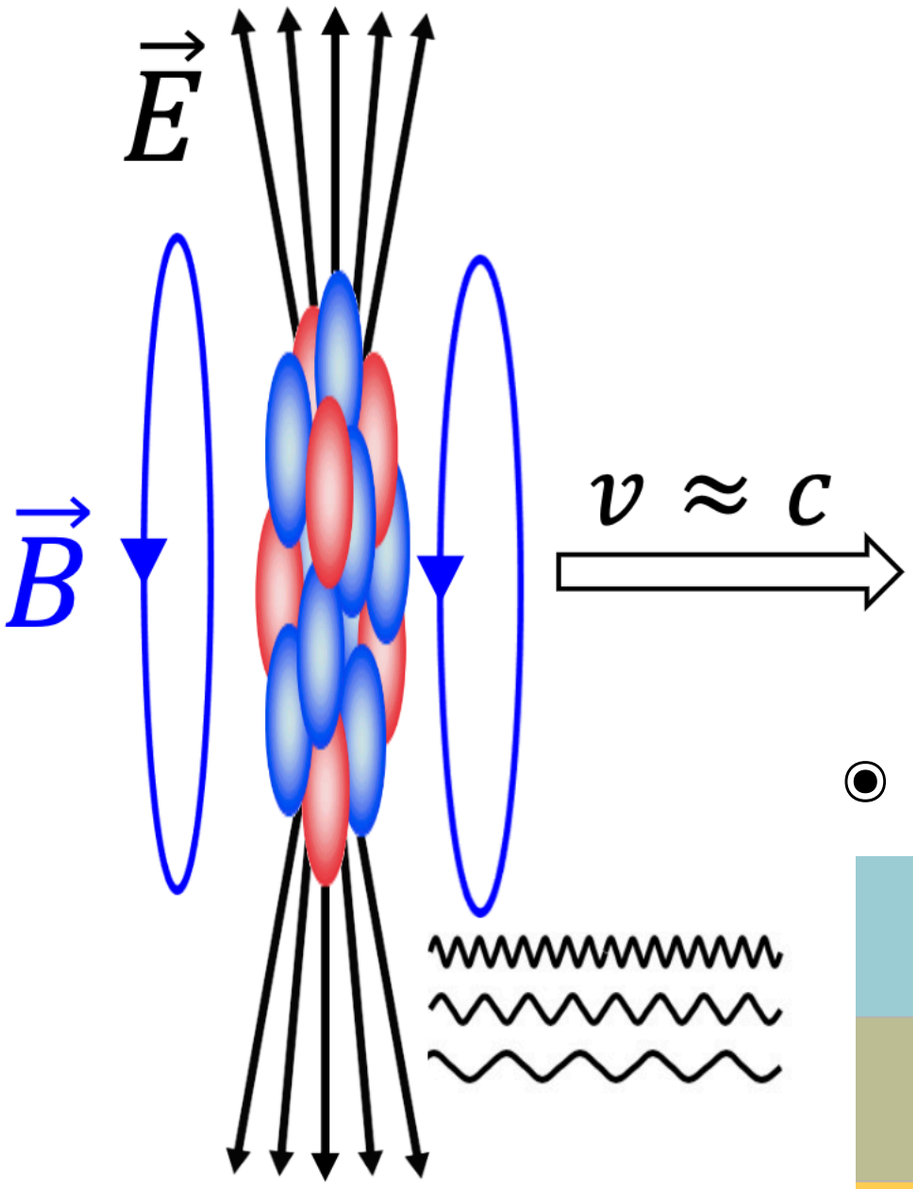


Equivalent photon



- Equivalent Photon Approximation
  - Photon Flux ∝ Z^2
  - p_T < ~30 MeV (Q^2~0)

Equivalent photon



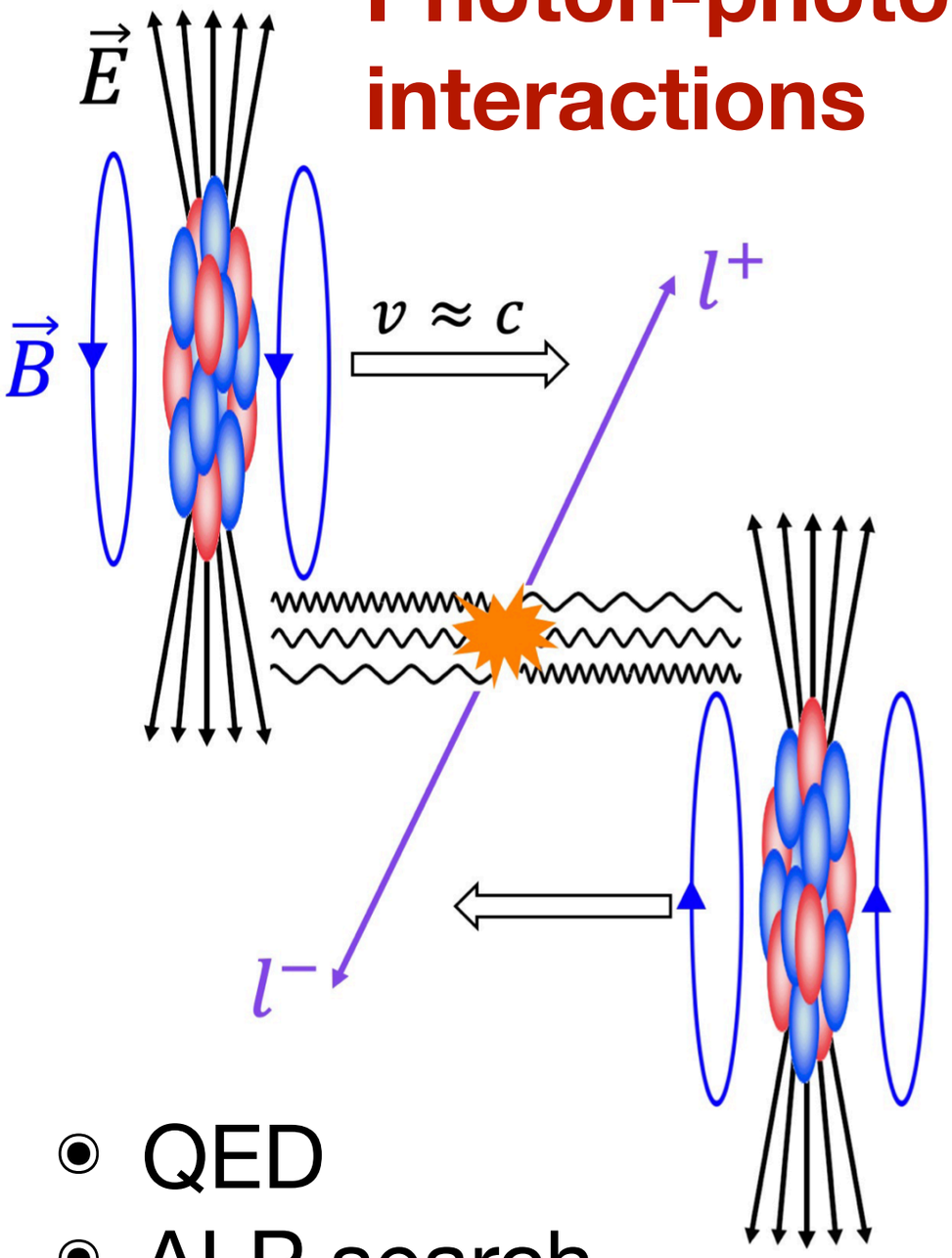
- Equivalent Photon Approximation
  - Photon Flux ∝ Z^2
  - p_T < ~30 MeV (Q^2~0)

- Photon kinematics

maximum energy $E_{\gamma,max} \sim \gamma(\hbar c/R)$	**80 GeV in Pb+Pb@LHC** **3 GeV in Au+Au@RHIC**
typical p_T (& virtuality) $p_{Tmax} \sim \hbar c/R$	**O(30) MeV @ RHIC & LHC**
Coherent strengths (rates) scale as **Z^2**: nuclei >> protons	Flux of photons on other nucleus ~ **Z^2**, flux of photons on photons ~ **Z^4 (45M!)**

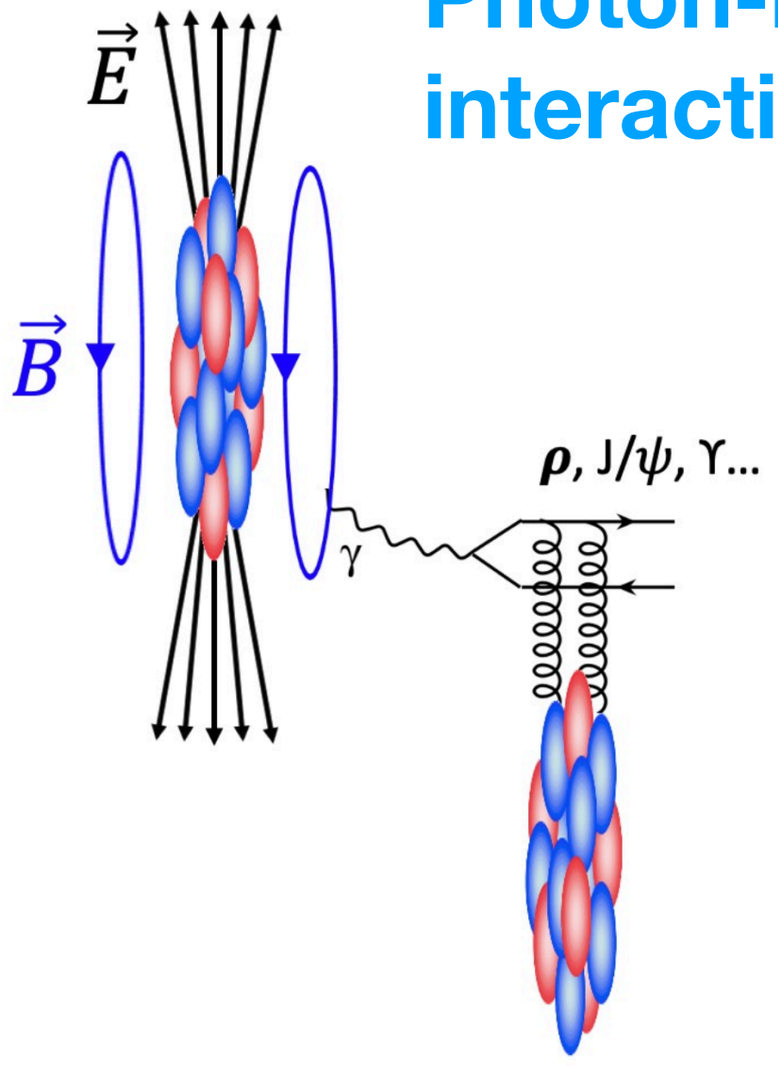
Photon interactions

Photon-photon interactions



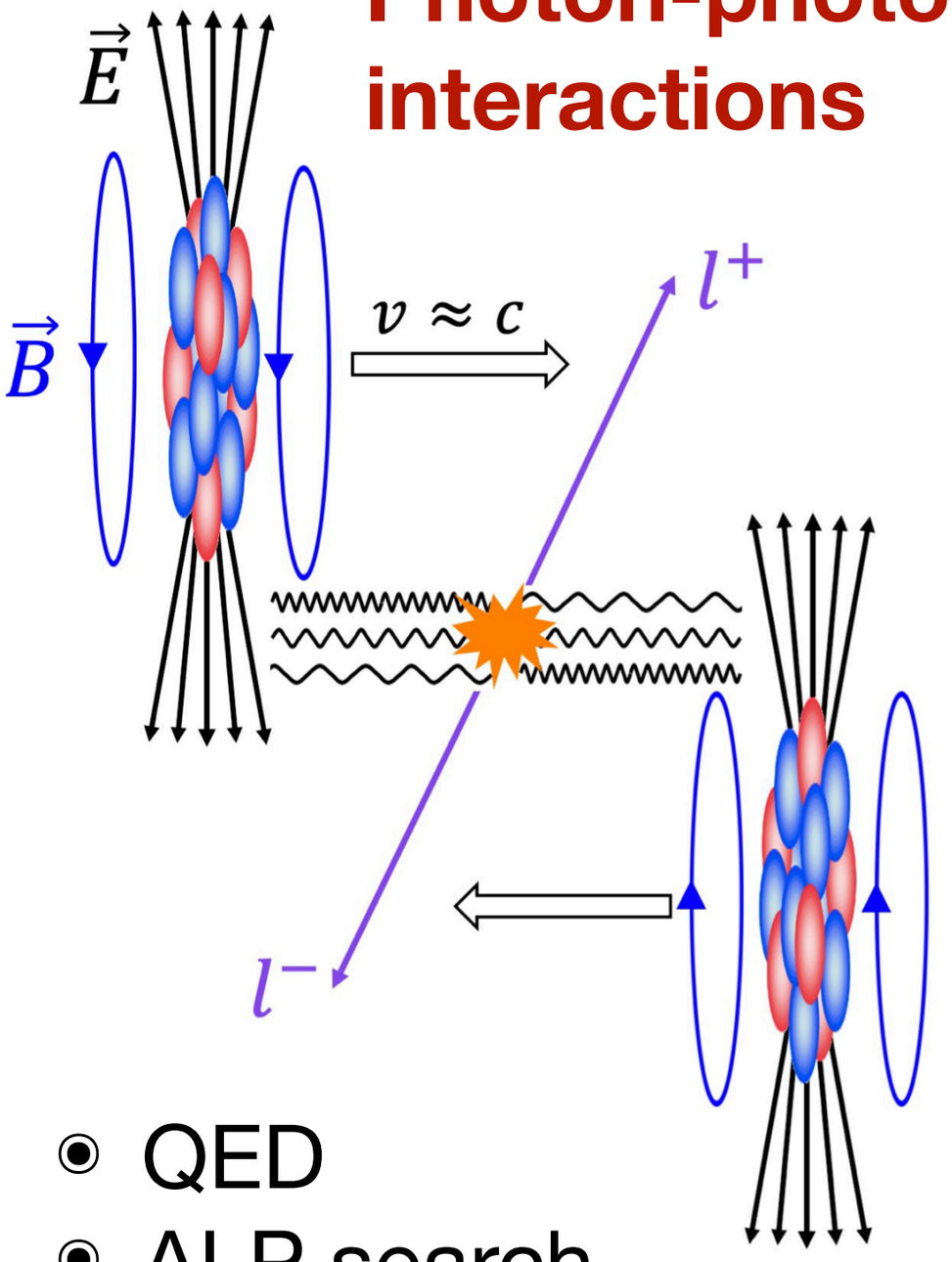
- QED
- ALP search

Photon-nuclear interactions

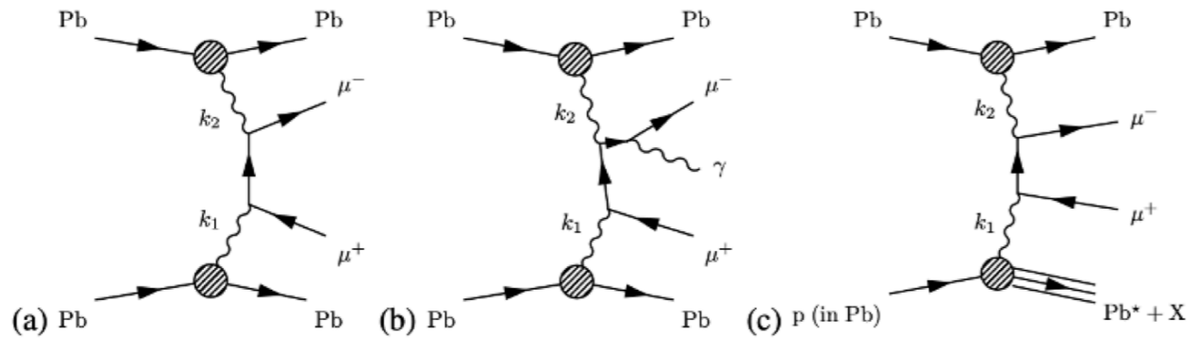


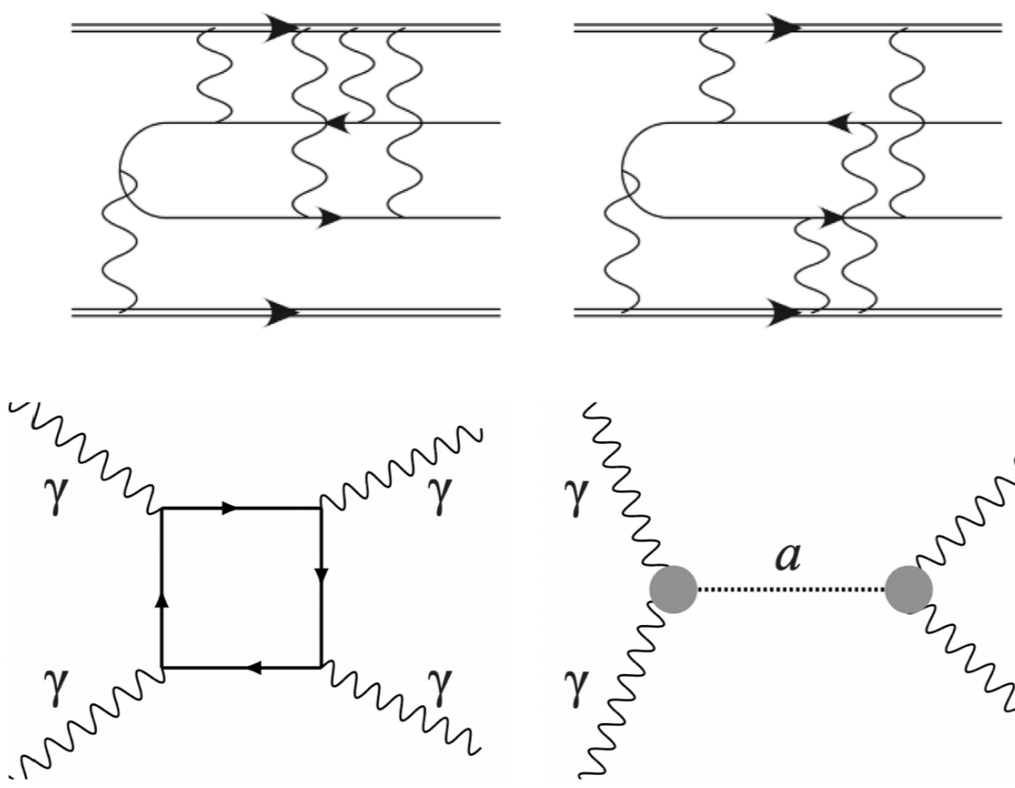
- Little “EIC”

Photon interactions



- QED
- ALP search

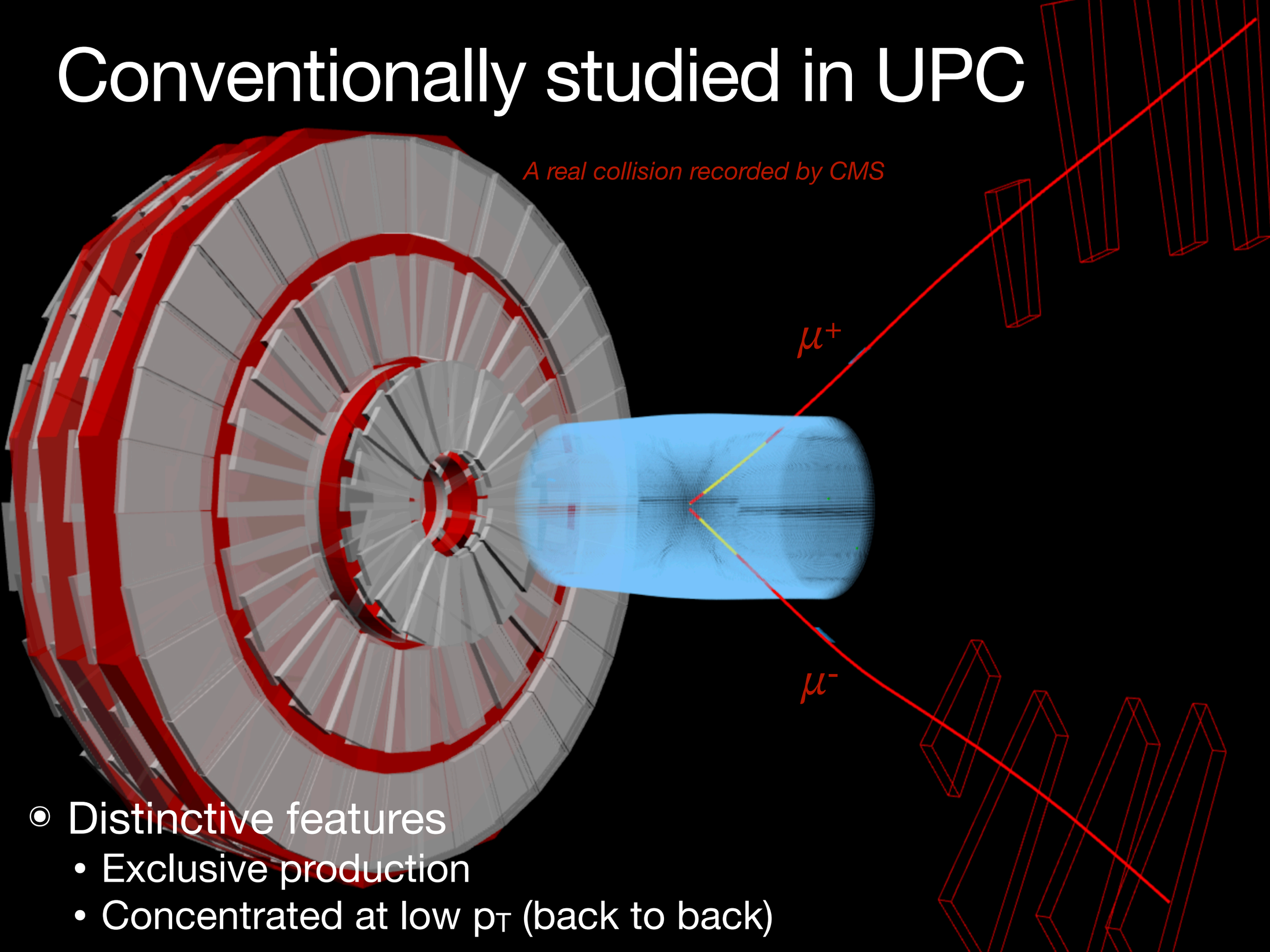




STAR, PRC 70 (2004) 031902; PRL 121 (2018) 132301; PRL 127 (2021) 052302
ATLAS, Nat. Phys. 13 (2017) 852; PRL 121 (2018) 212301; PRL 123 (2019) 052001; PRC 104 (2021) 024906
CMS, PRL 127 (2021) 122001

Conventionally studied in UPC

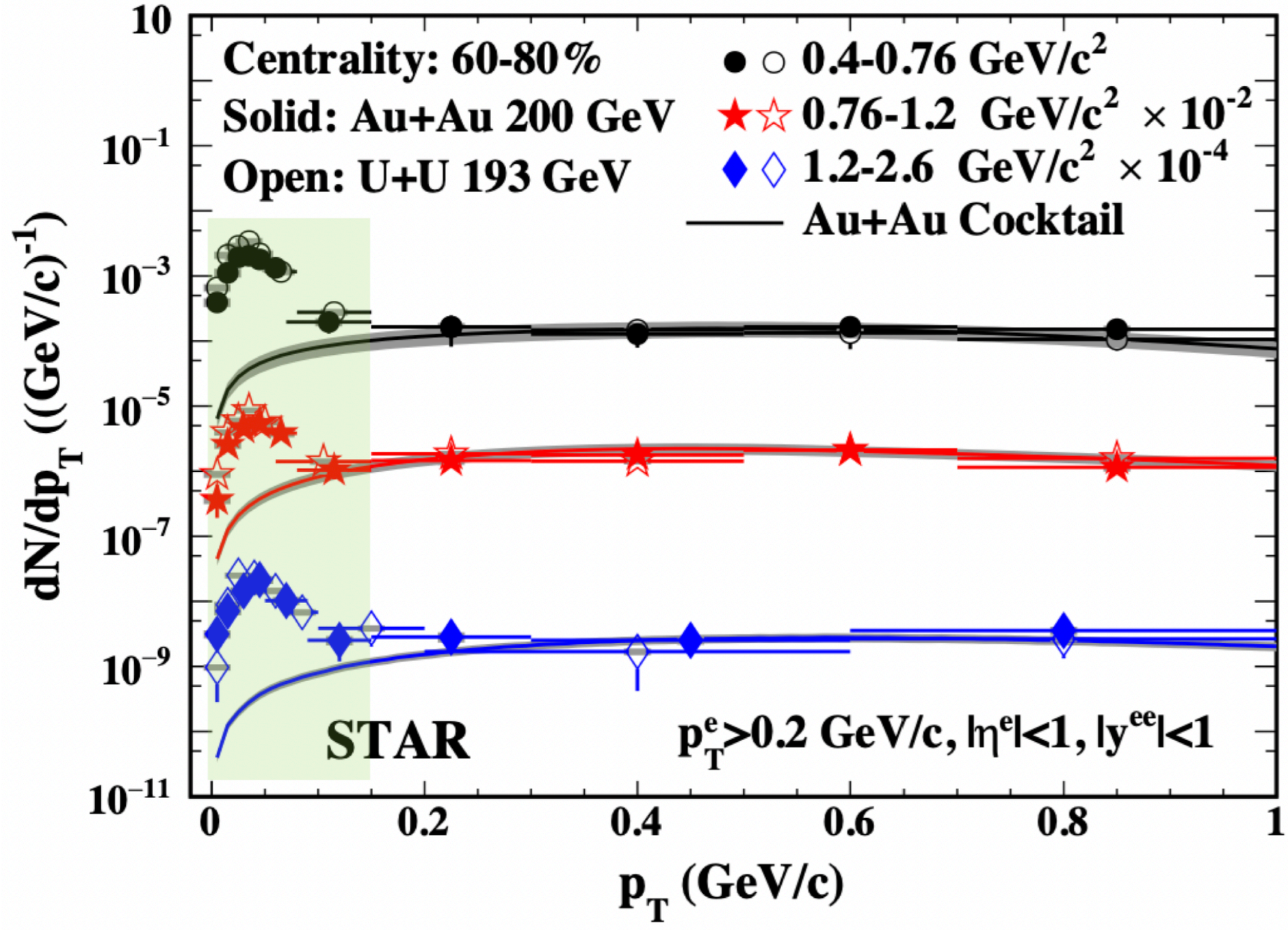
A real collision recorded by CMS

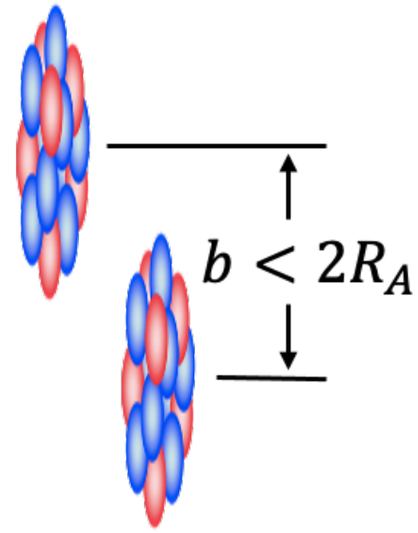


- Distinctive features
  - Exclusive production
  - Concentrated at low p_T (back to back)

Observed in hadronic collisions

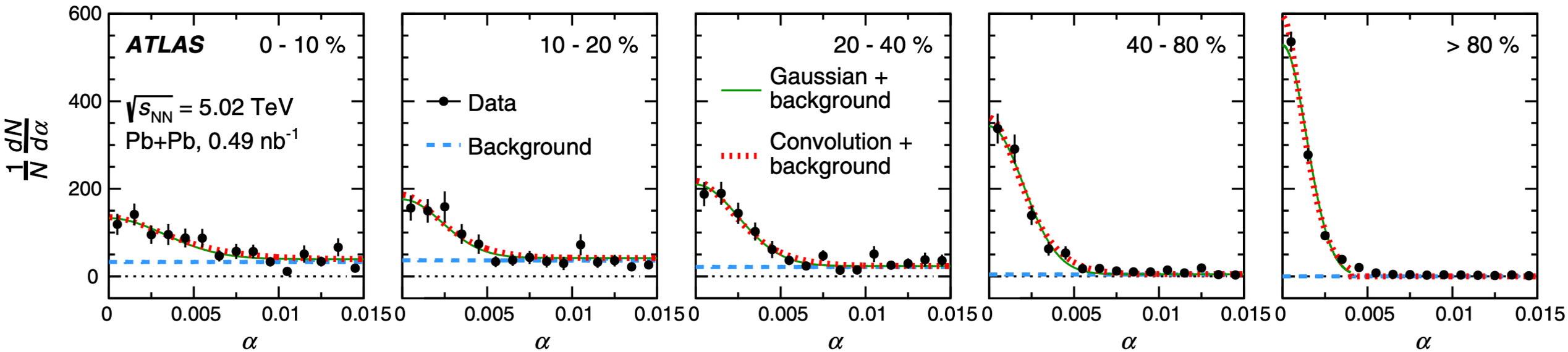
STAR, PRL 121 (2018) 132301





Modification of lepton pairs

ATLAS, PRL 121 (2018) 212301

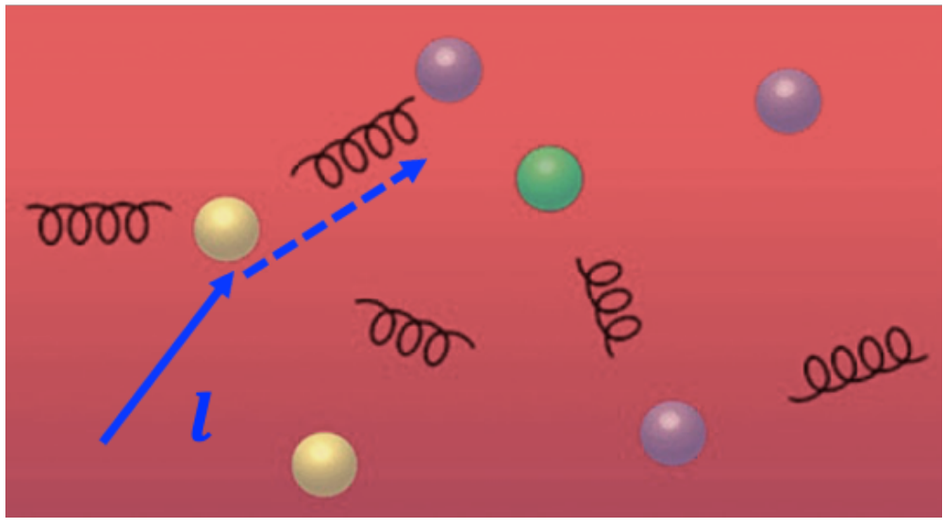


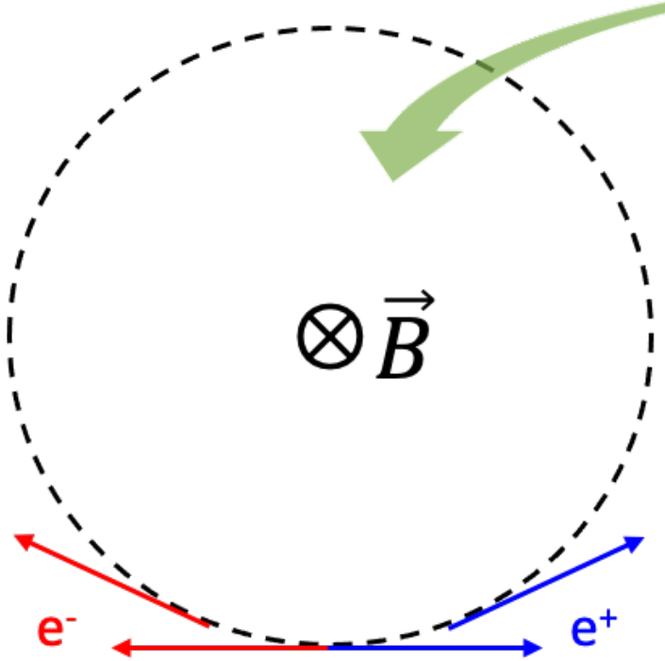
- Back-to-back correlation becomes weaker towards central collisions

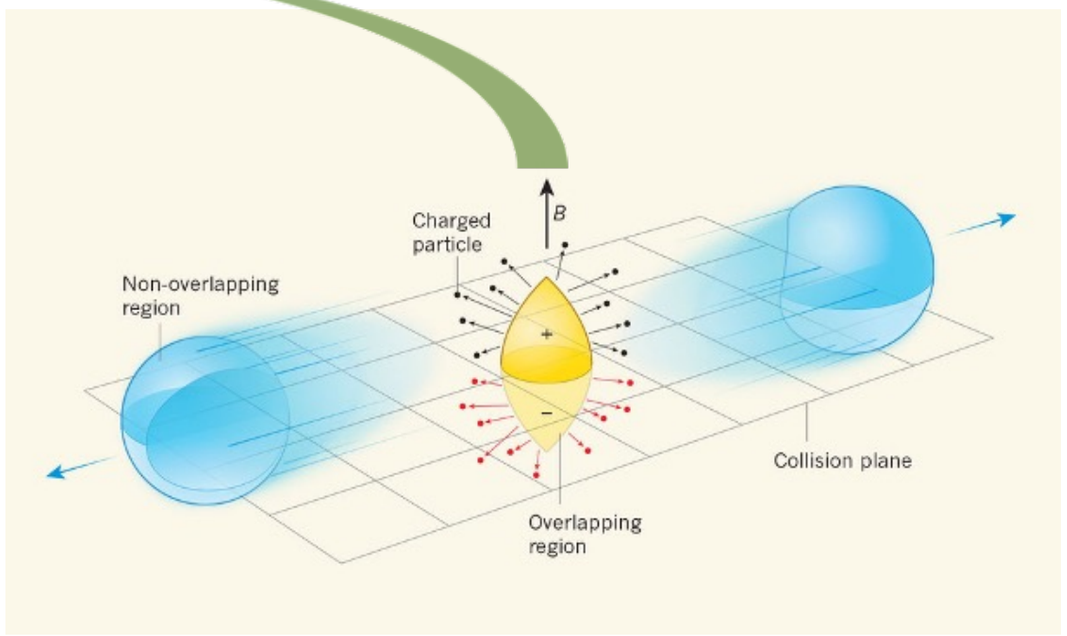
Puzzle of the physics origin

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

Final-state effect?





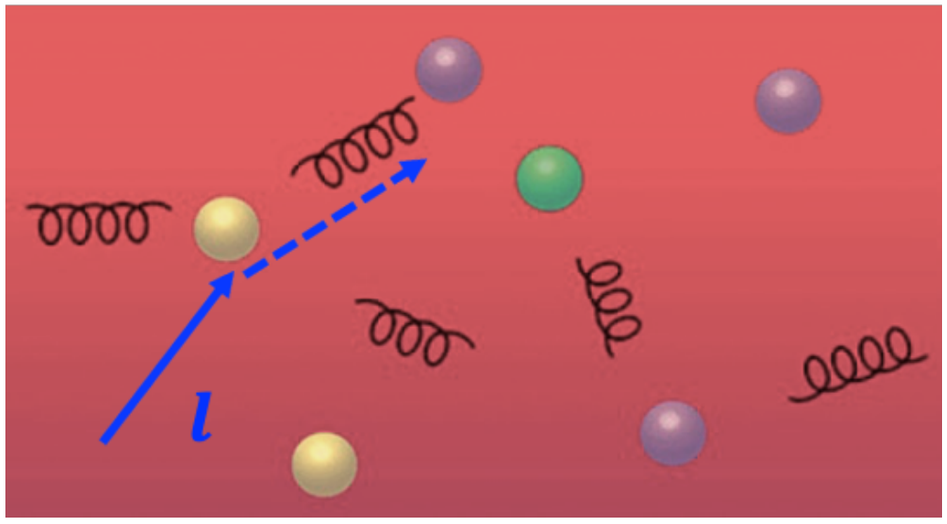


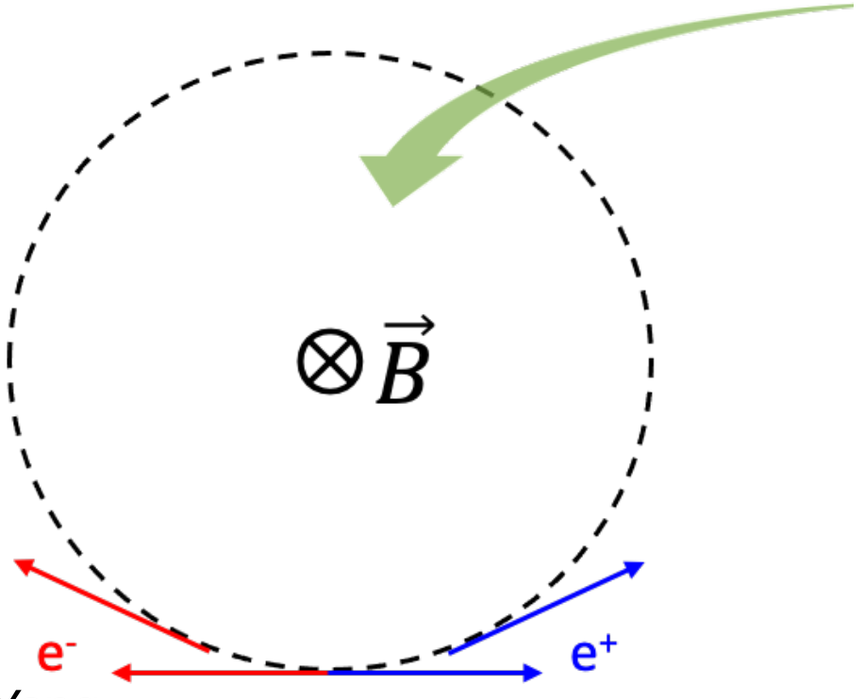
Puzzle of the physics origin

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

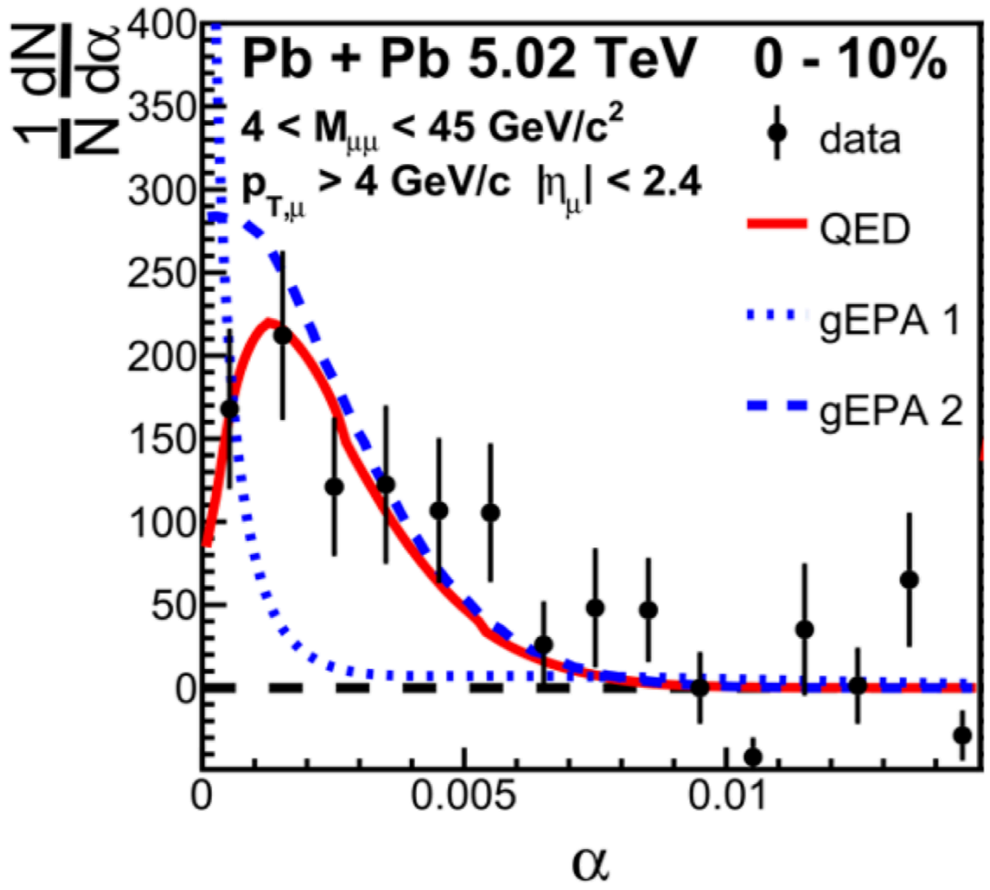
Zha et al., PLB 800 (2020) 135089
Li et al., PRD 101 (2020) 034015
Wang et al., PRD 104 (2021) 056011

Final-state effect?



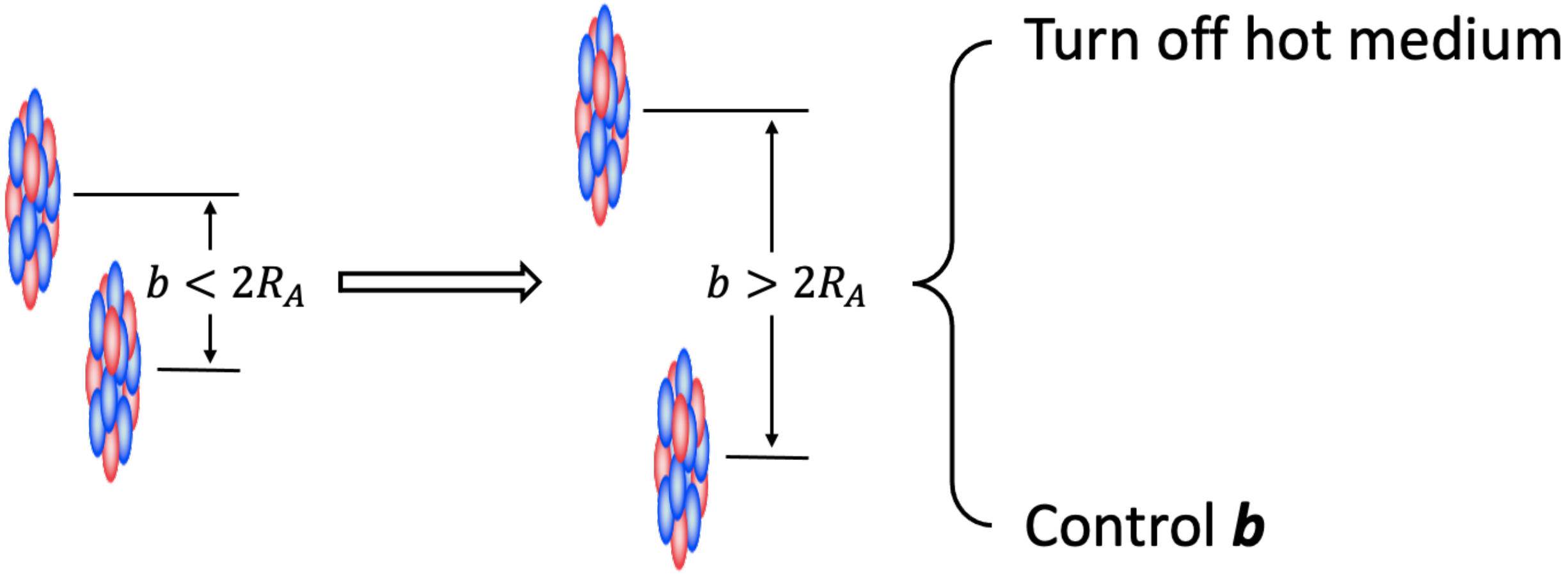


Initial-state effect?



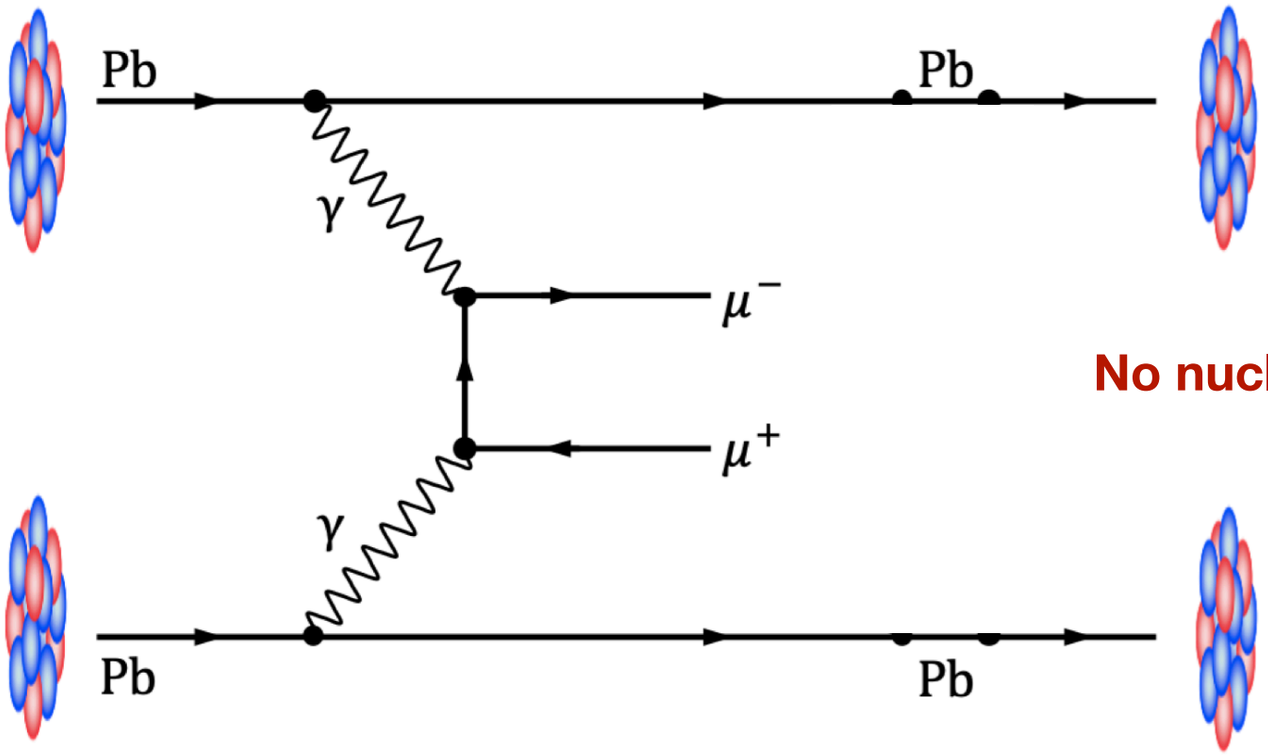
- Described by lowest-order QED without medium effect
  - ***b*** dependence of initial photon p_T

Experimentally explore the puzzle



Control ***b*** in UPC

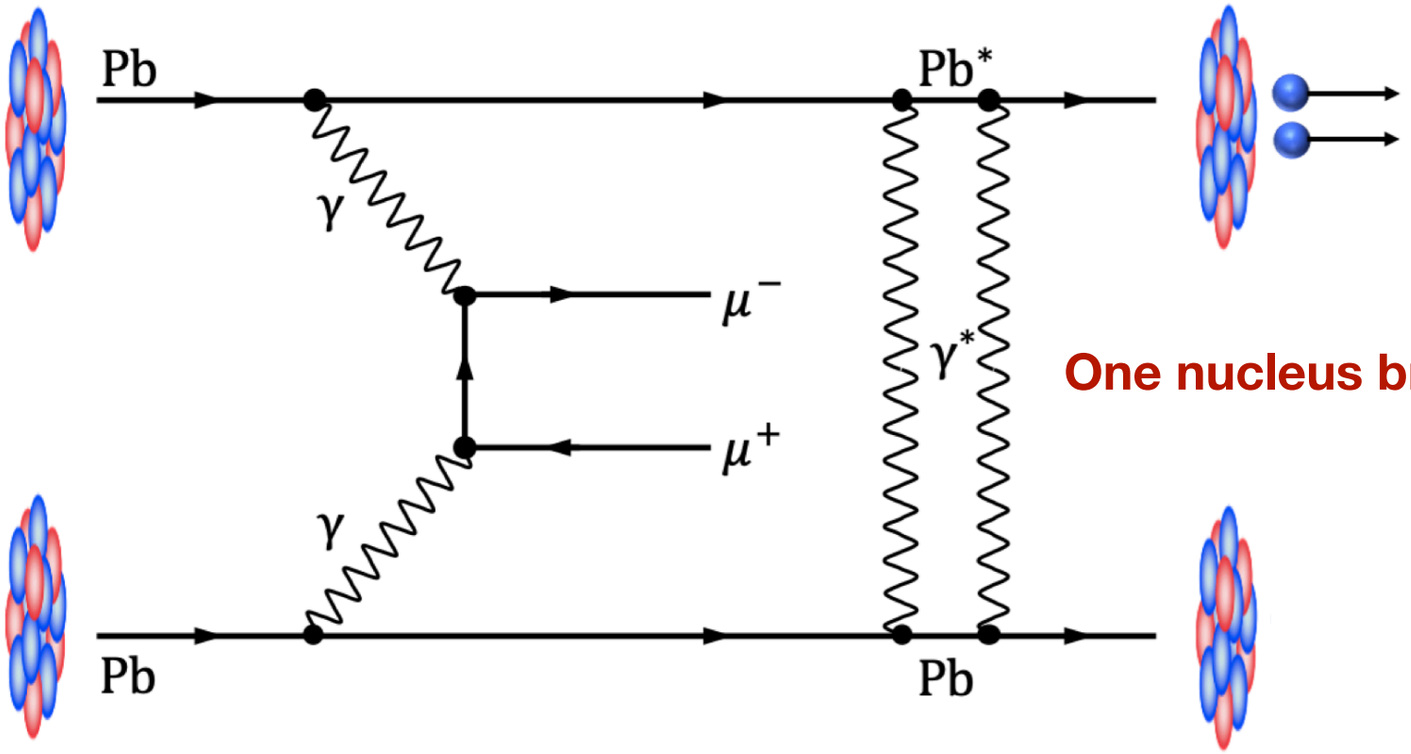
Nuclei **may** exchange soft photon(s) $\Longrightarrow$ nuclear dissociation



No nucleus breakup

Control ***b*** in UPC

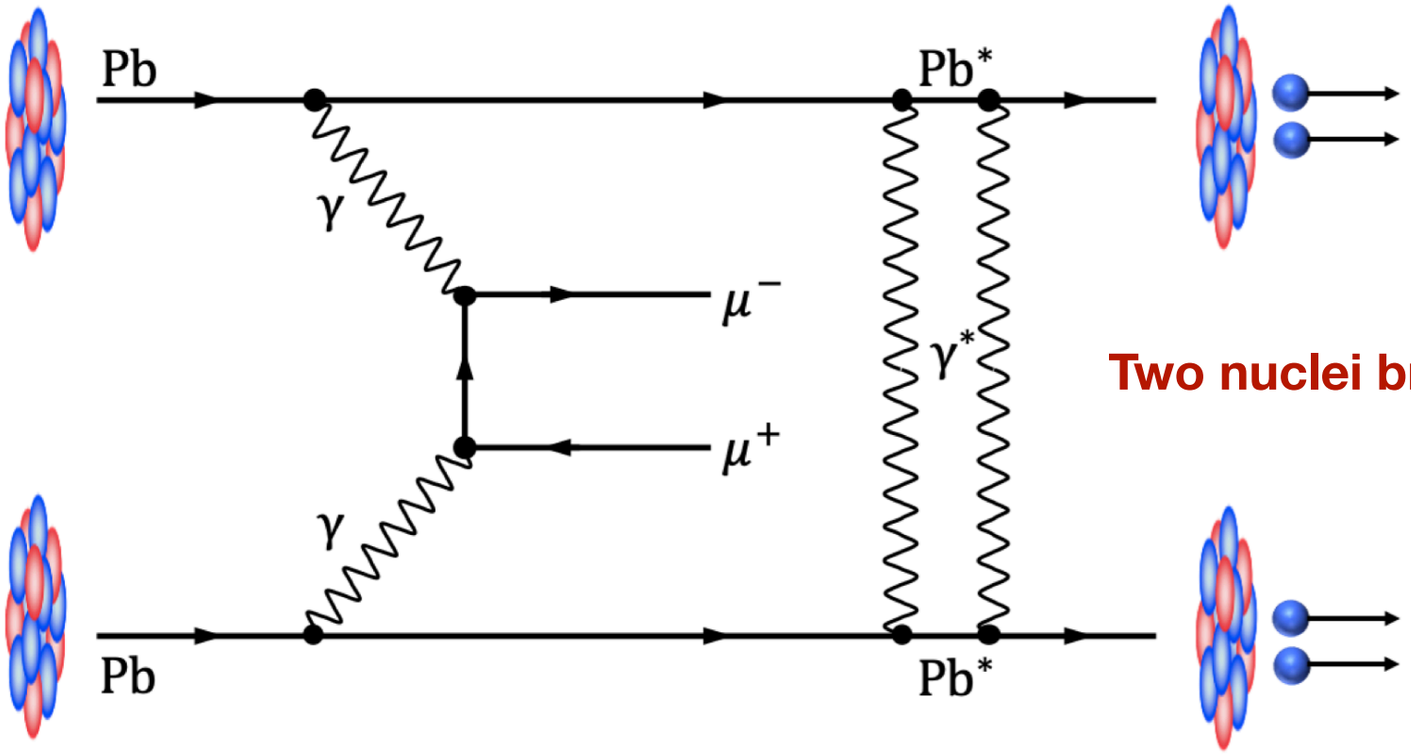
Nuclei **may** exchange soft photon(s) $\Longrightarrow$ nuclear dissociation



One nucleus breakup

Control ***b*** in UPC

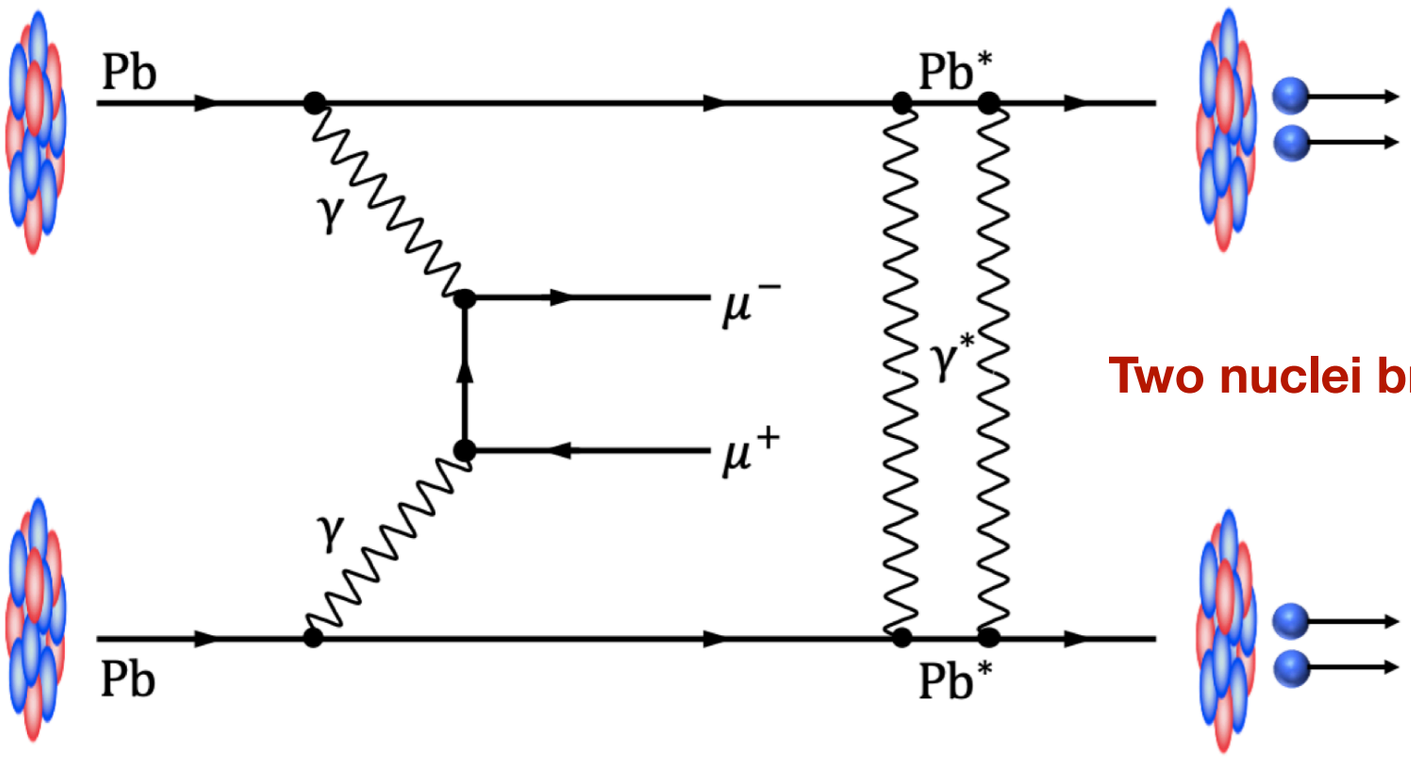
Nuclei **may** exchange soft photon(s) $\Longrightarrow$ nuclear dissociation



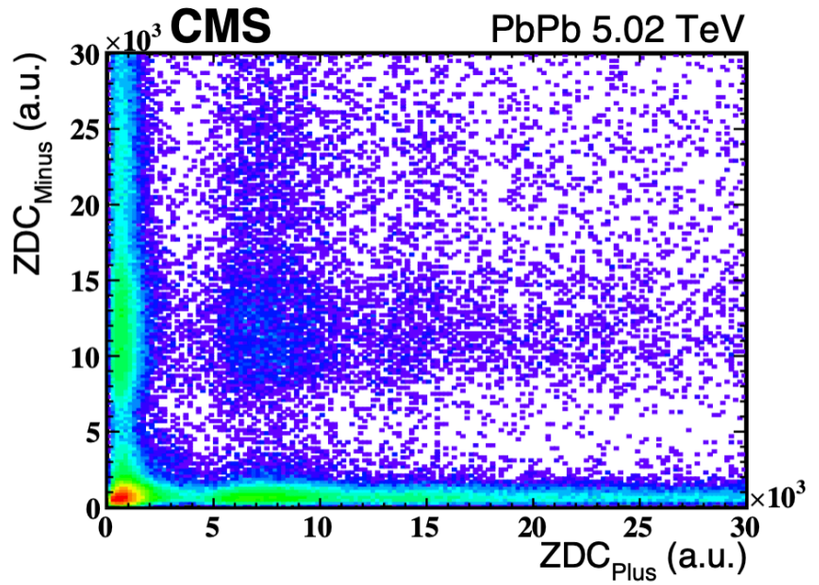
Two nuclei breakup

Control ***b*** in UPC

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



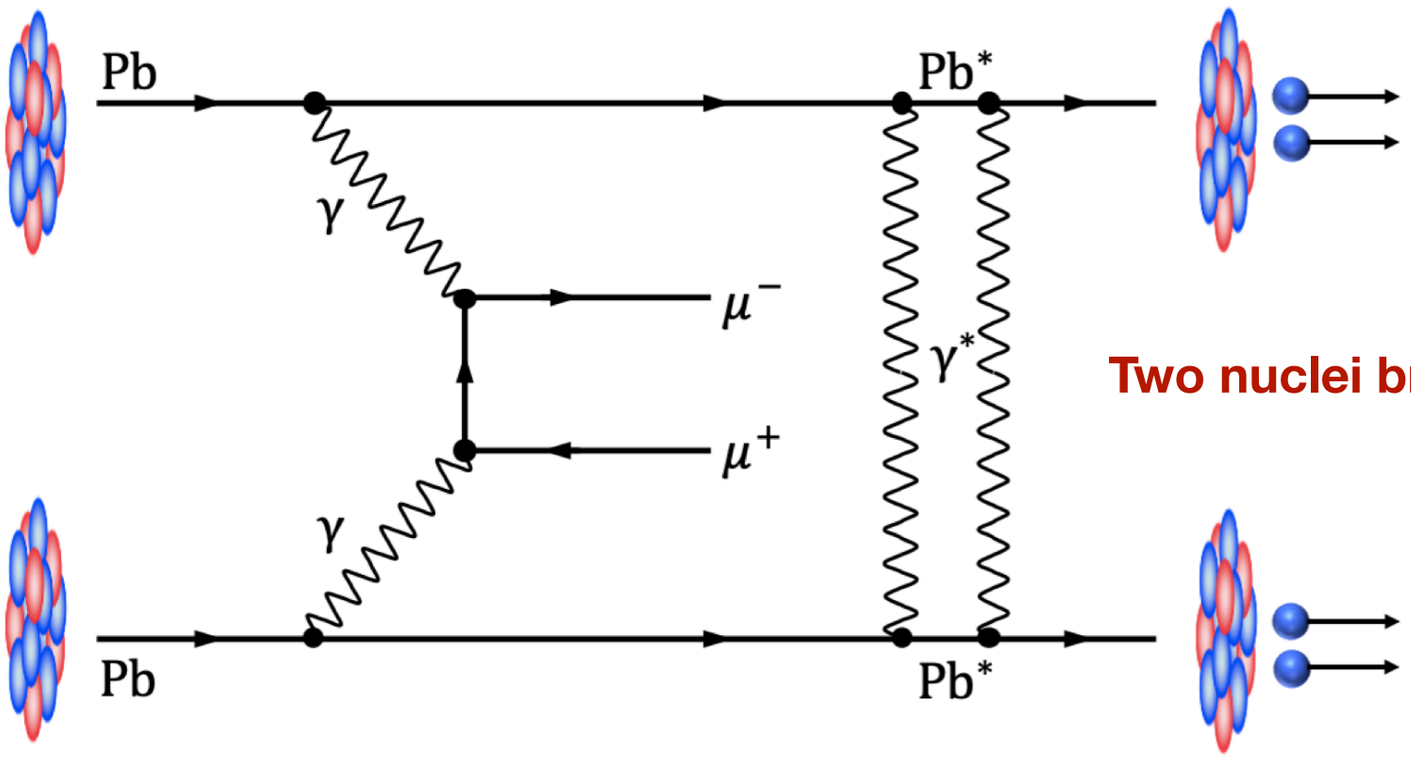
Two nuclei breakup



- Zero Degree Calorimeter

Control ***b*** in UPC

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



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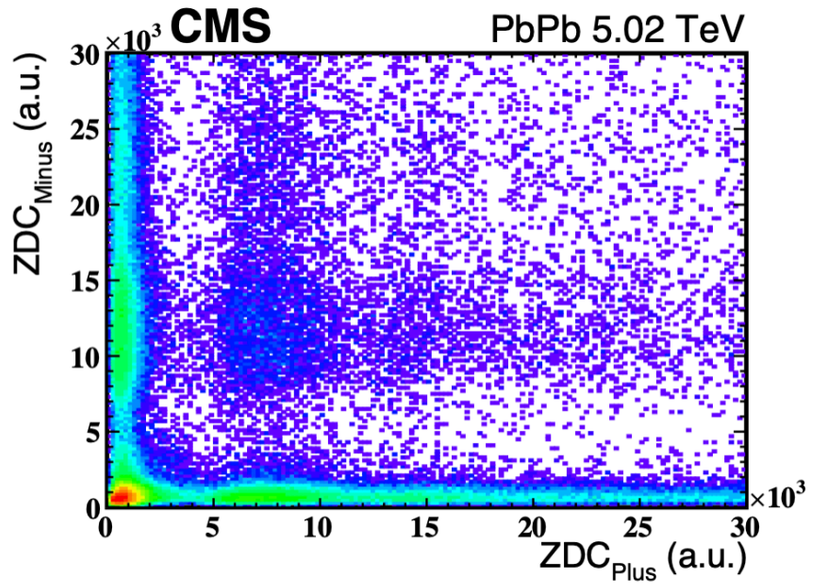
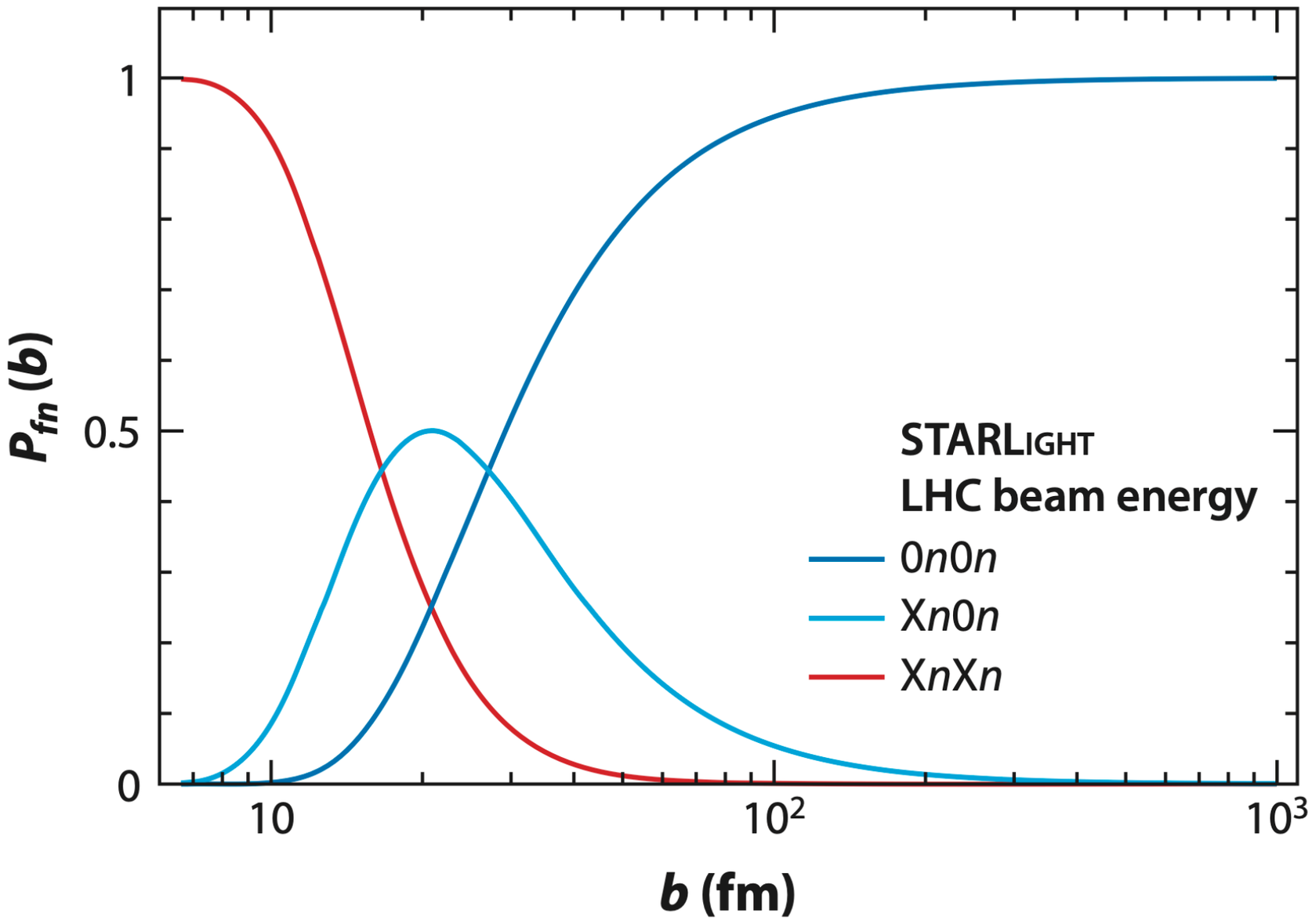


- Zero Degree Calorimeter

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

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

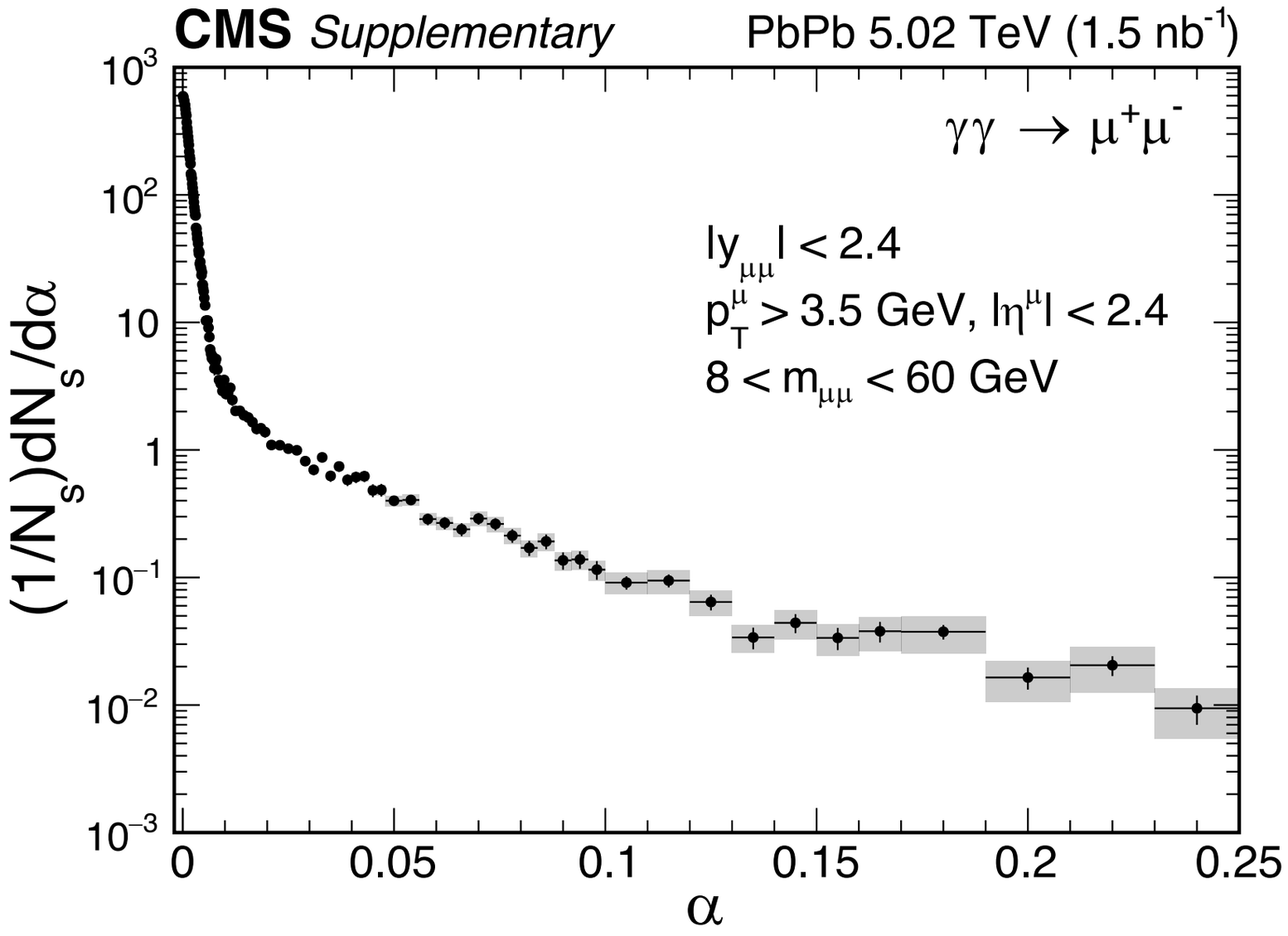
Control ***b*** in UPC



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

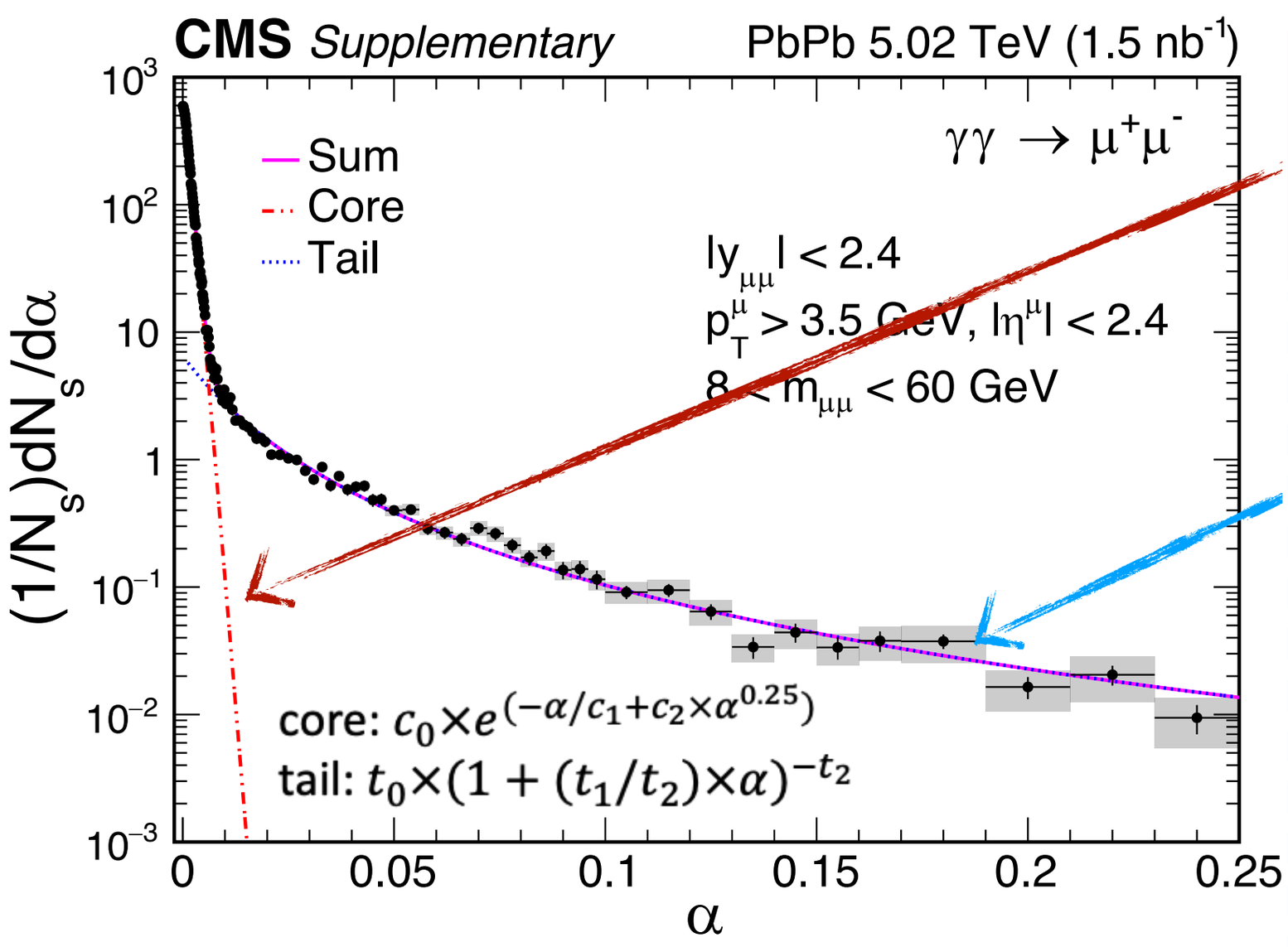
$$b_{XnXn} < b_{0nXn} < b_{0n0n}$$

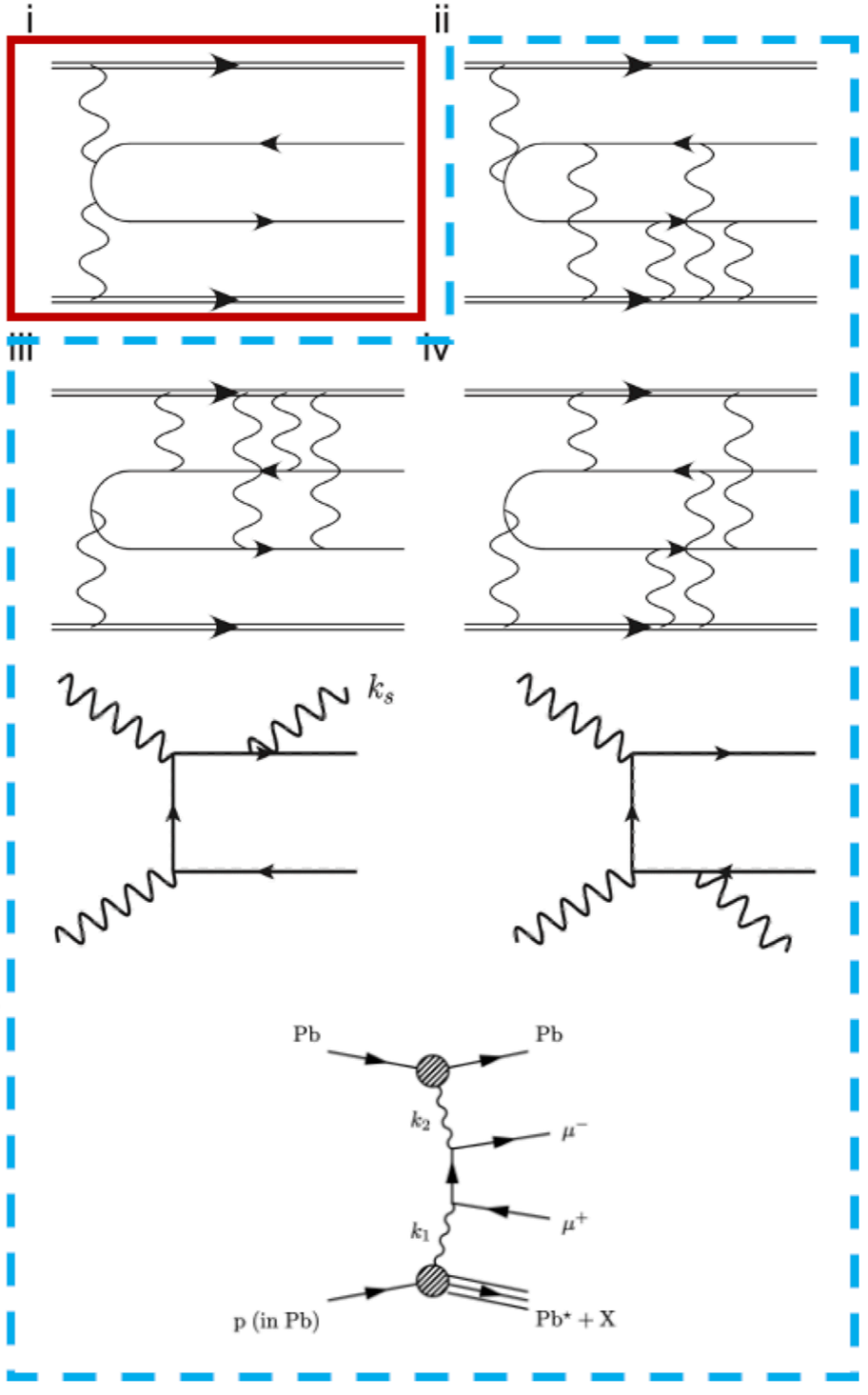
α spectrum in UPC



CMS, PRL 127 (2021) 122001

α spectrum in UPC

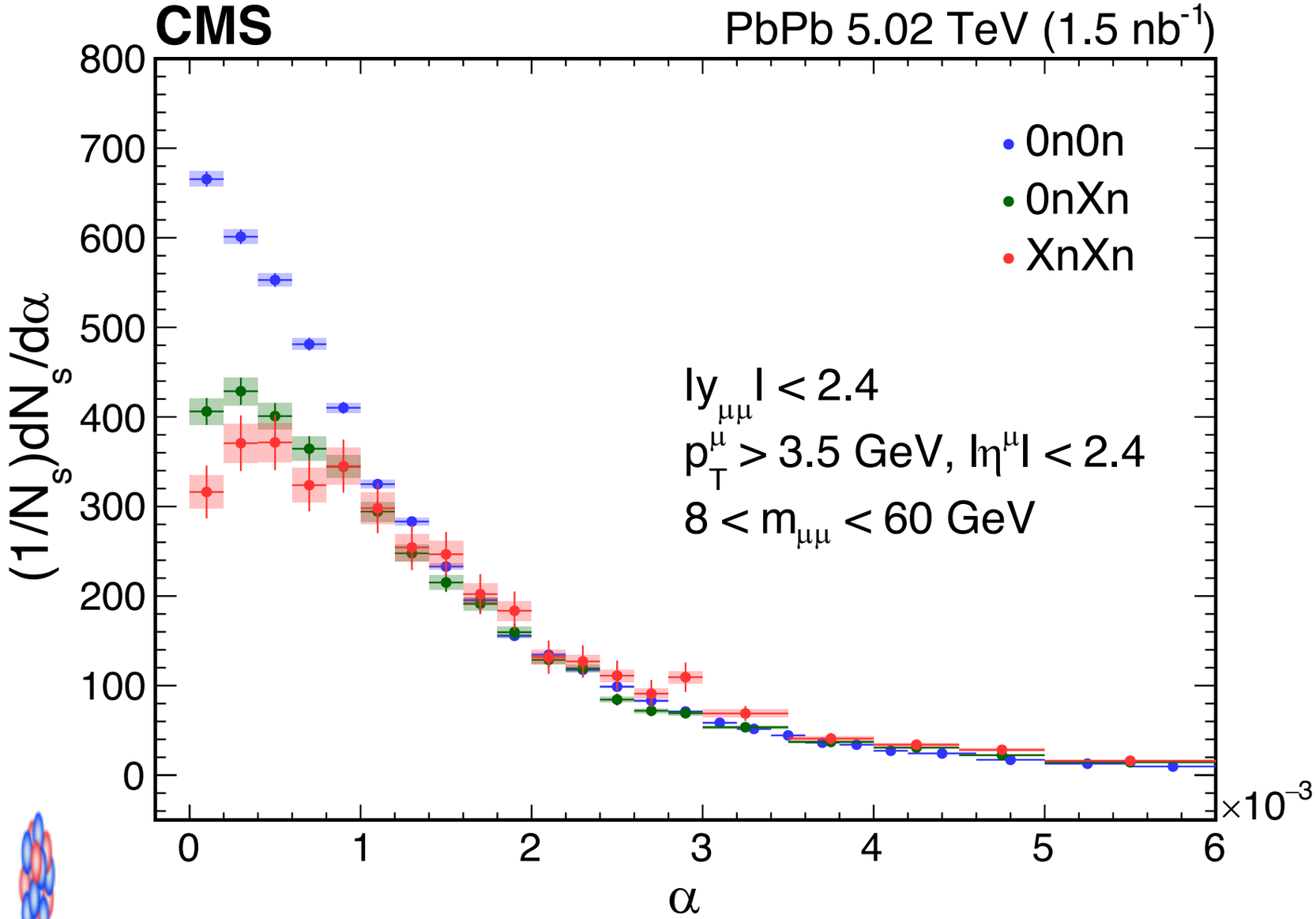




Decouple α spectrum with empirical function

CMS, PRL 127 (2021) 122001

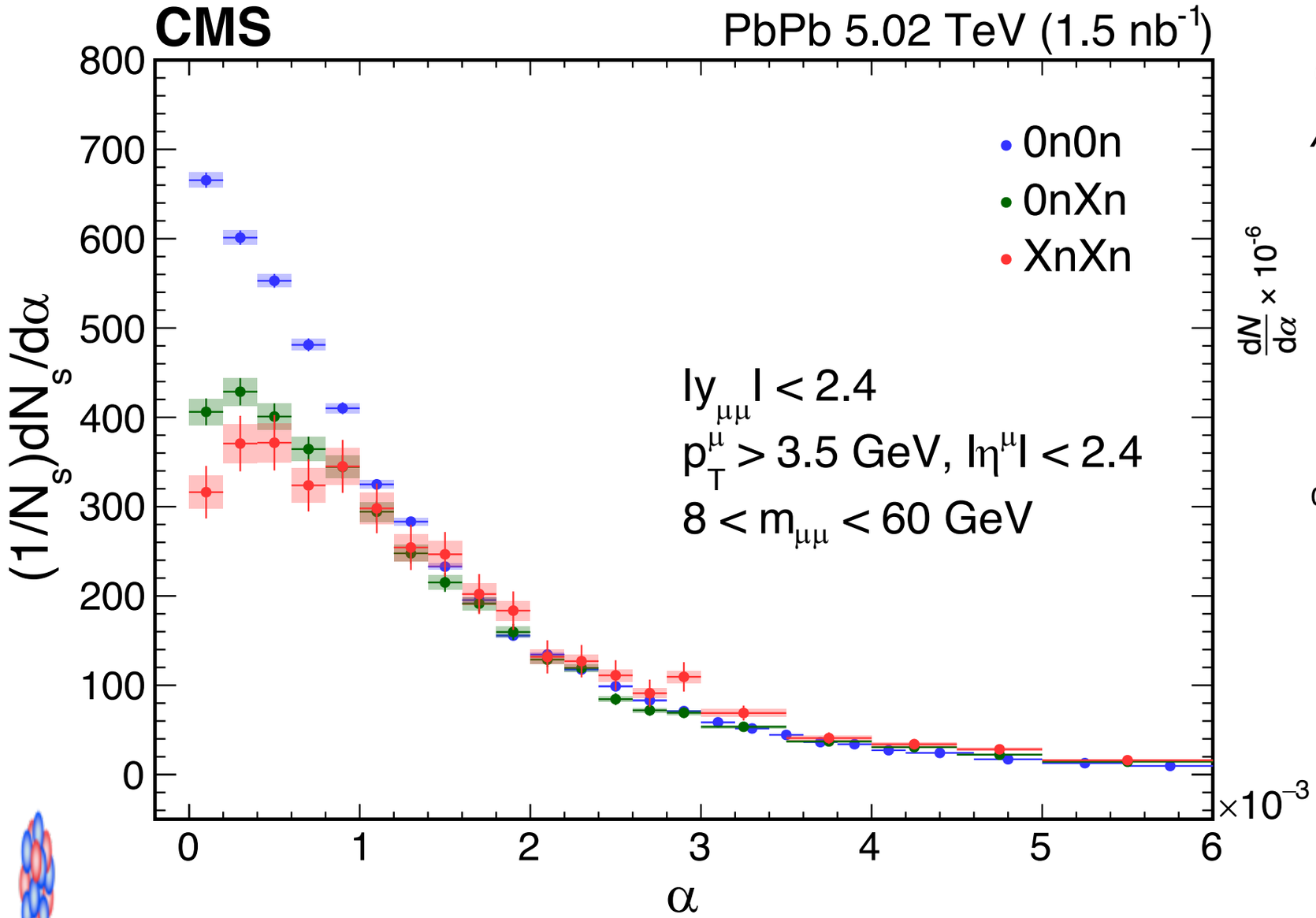
α spectrum vs. neutron multiplicity



CMS, PRL 127 (2021) 122001

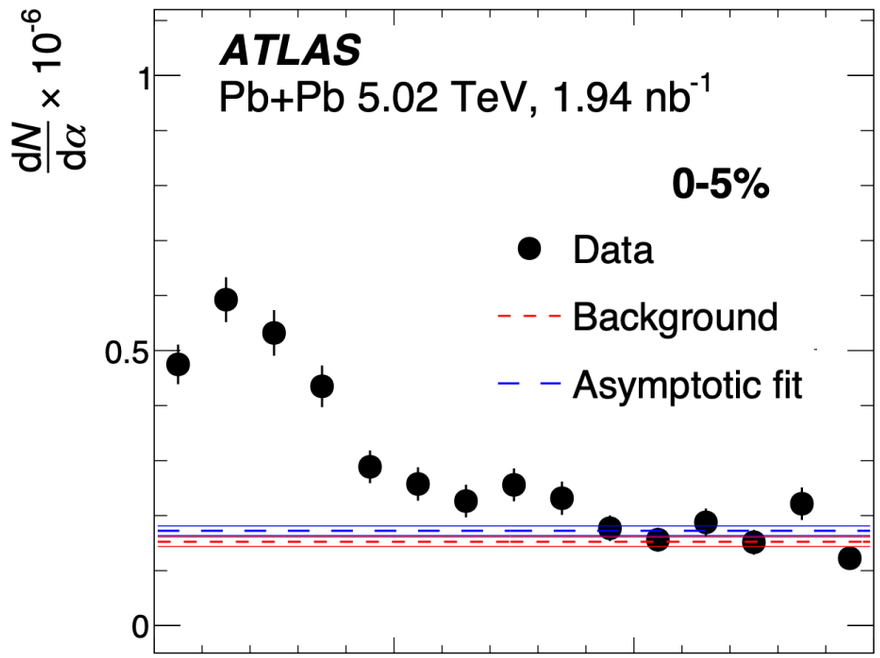
- 0n0n (fewer neutrons) $\Longrightarrow$ XnXn (more neutrons)
  - α spectrum becomes broader

α spectrum vs. neutron multiplicity



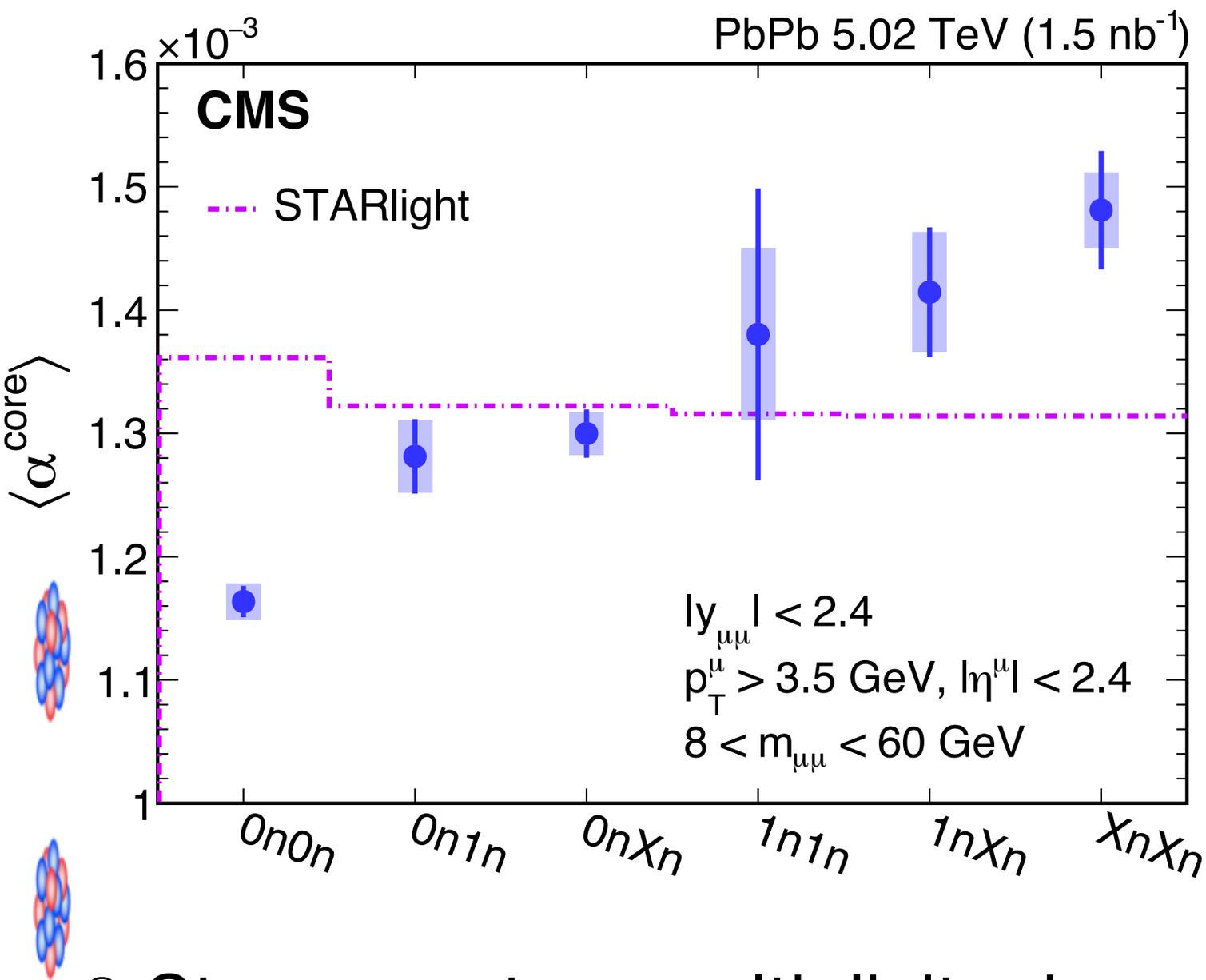
CMS, PRL 127 (2021) 122001

ATLAS, PRC 107 (2023) 054907

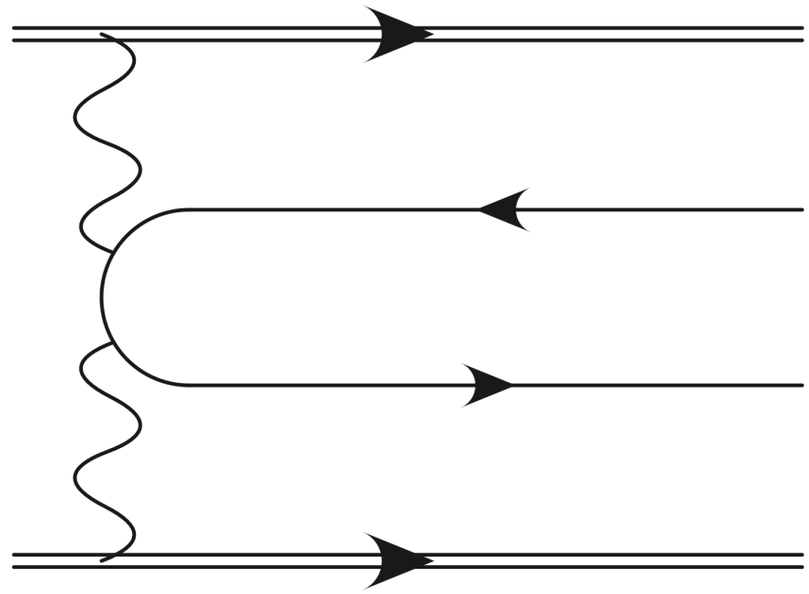


- 0n0n (fewer neutrons) $\Longrightarrow$ XnXn (more neutrons)
  - α spectrum becomes broader
  - Seems has depletion in the very small α

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

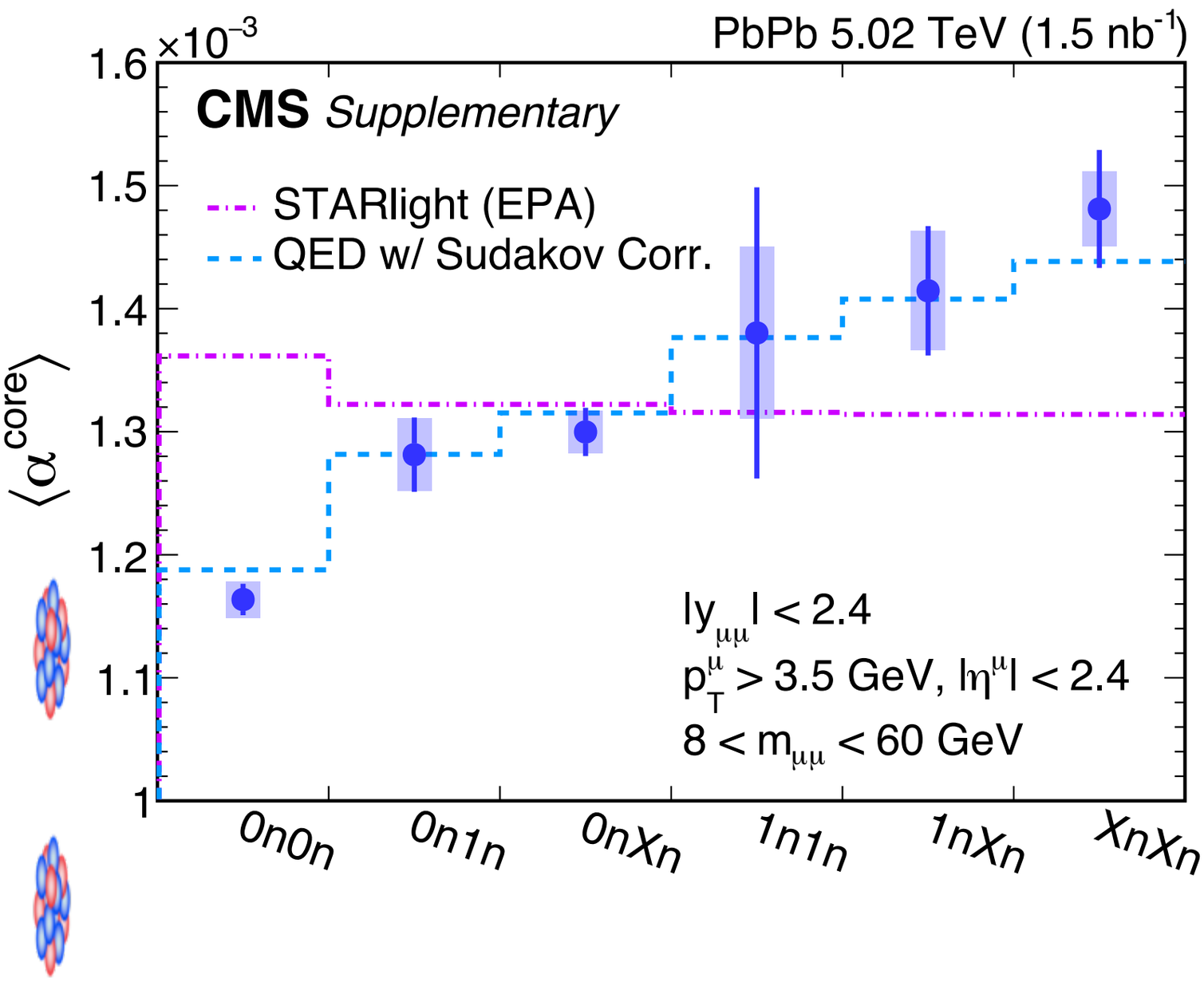


Klein et al., Comput. Phys. Commun. 212 (2017) 258
Klein et al., PRL 122 (2019) 132301
Brandenburg et al., arXiv:2006.07365



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

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



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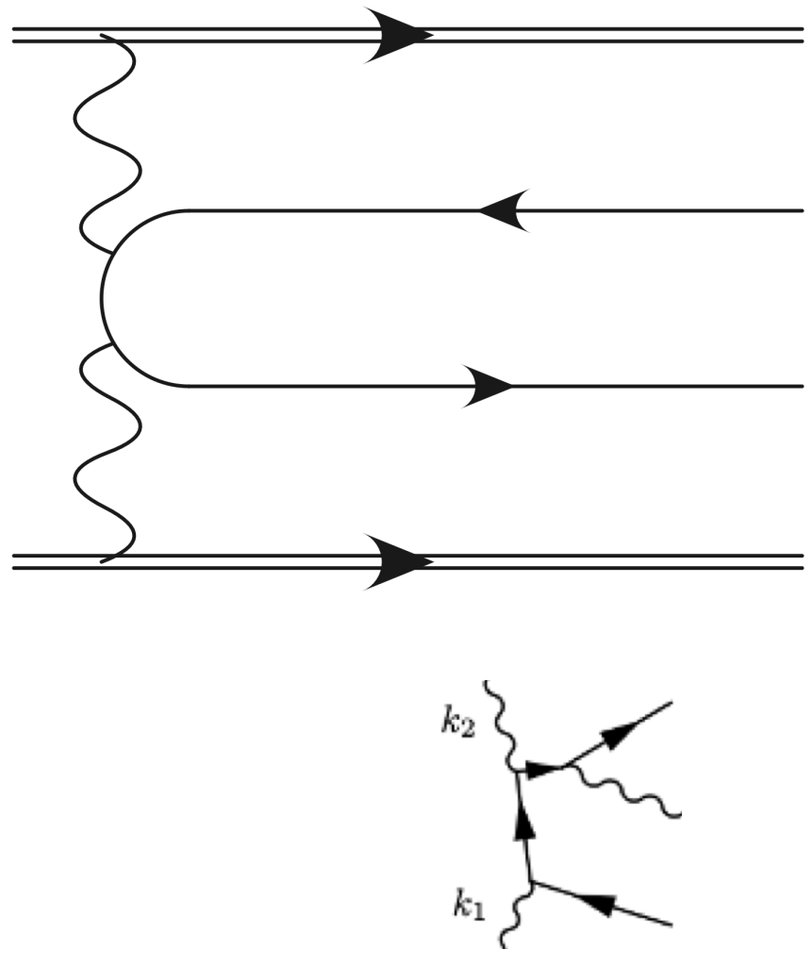
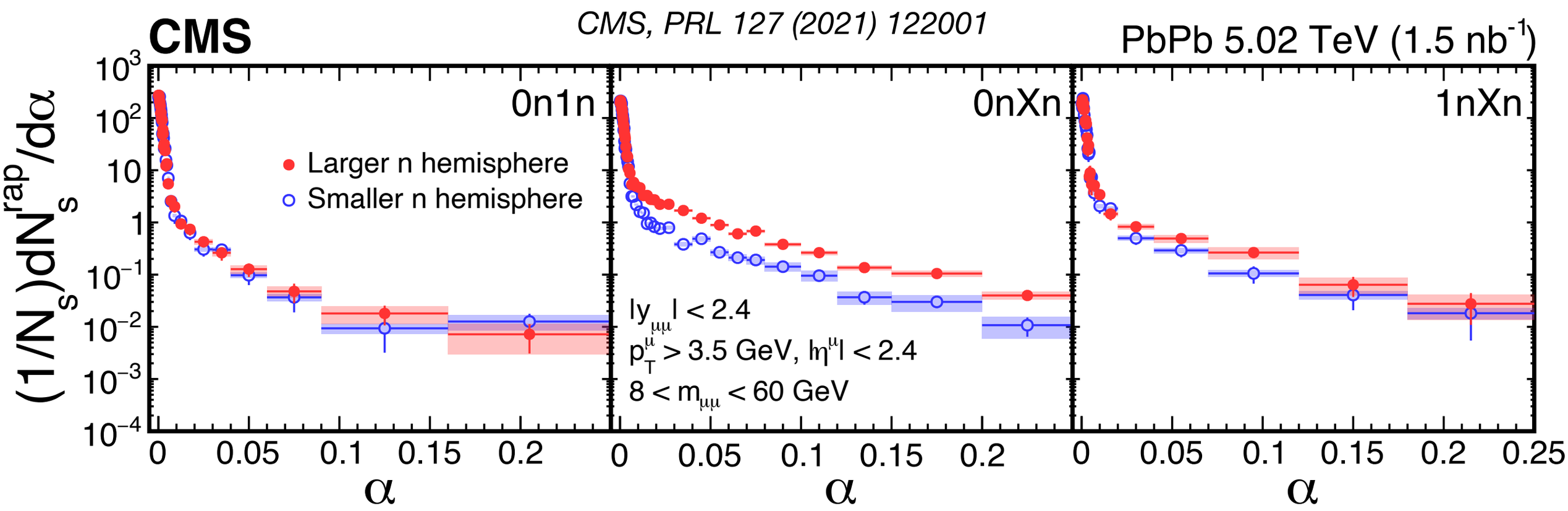
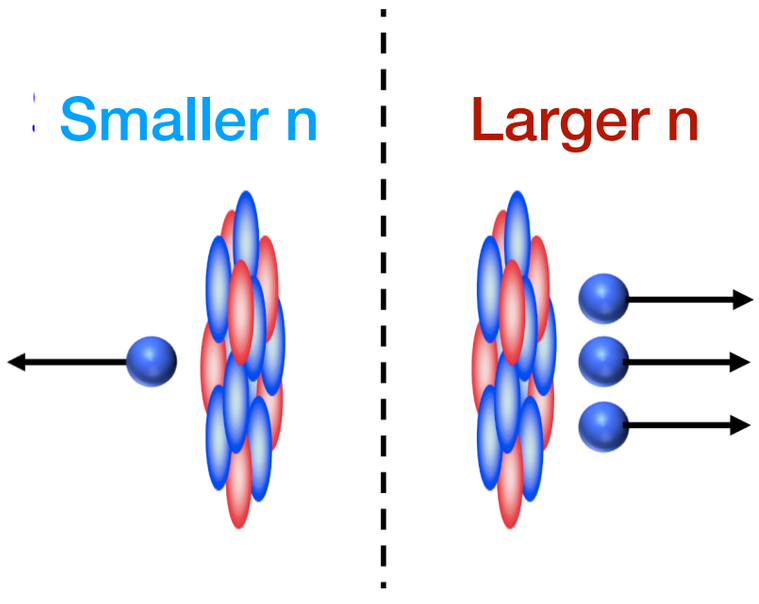


- Qualitatively described by a leading order QED model

Rapidity dependence of α spectra

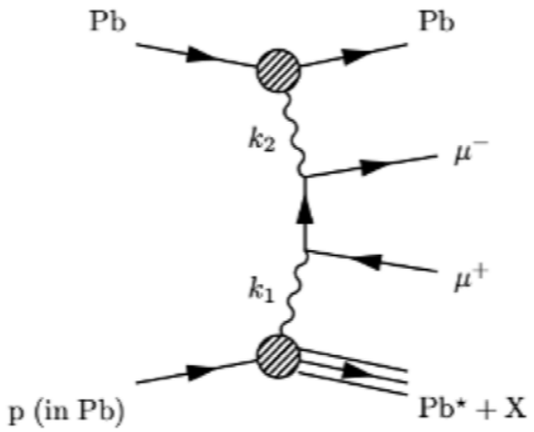


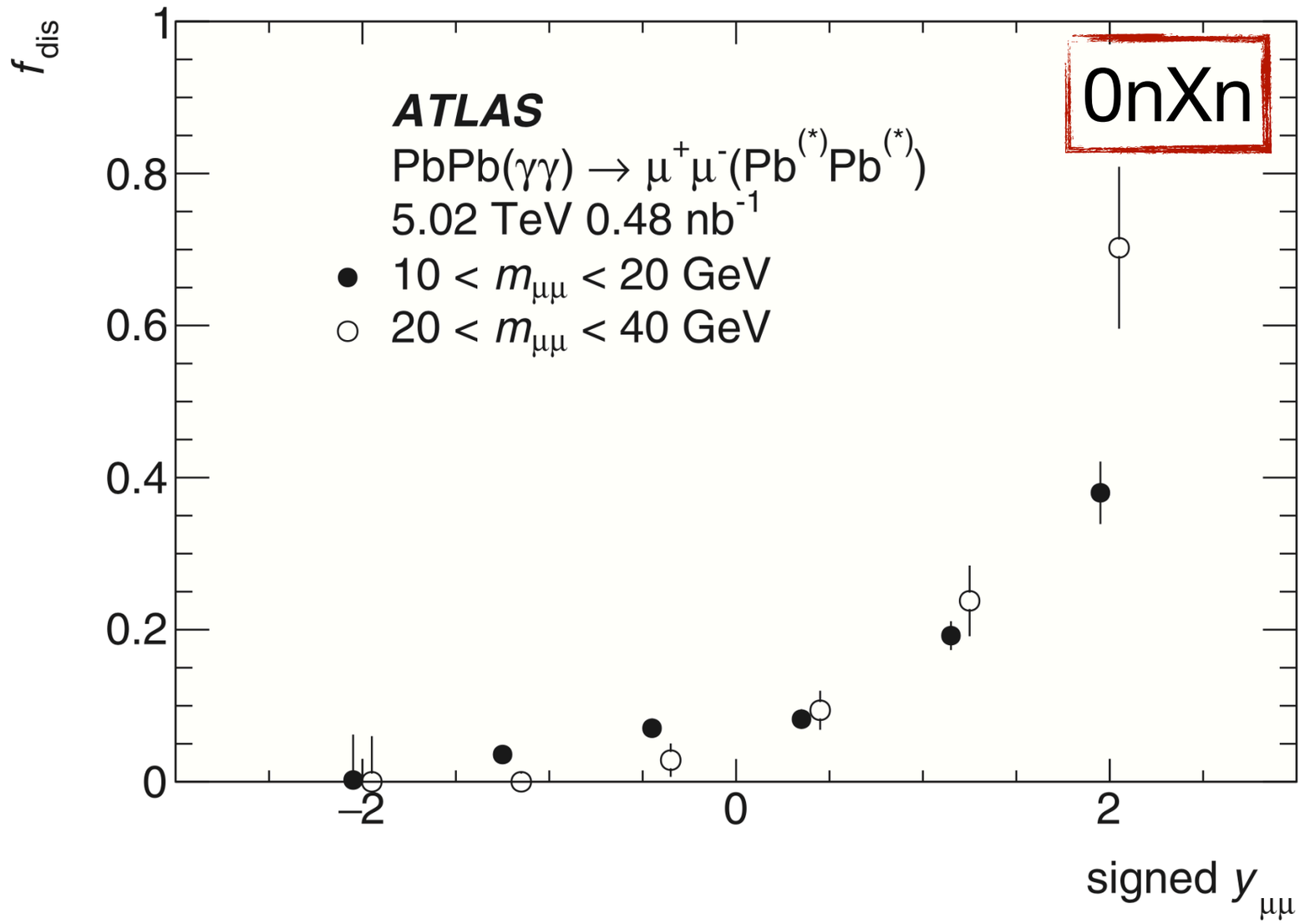


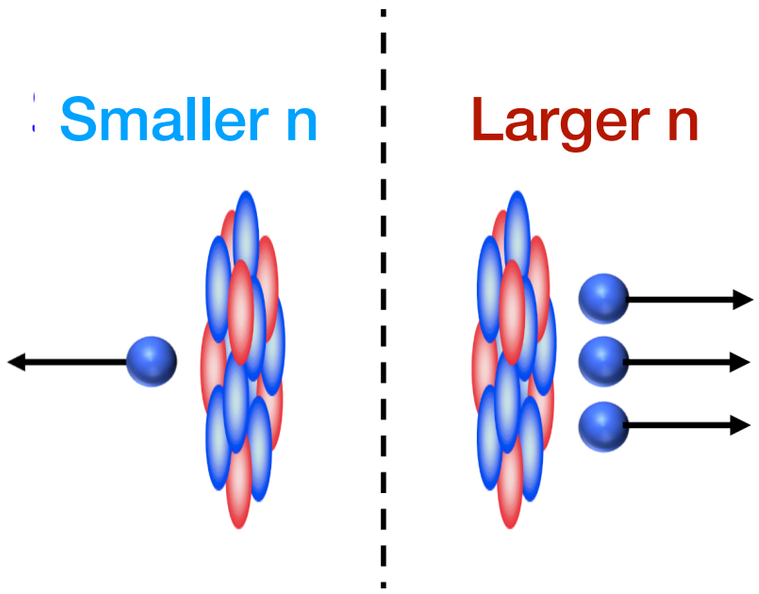
- For the tail contribution
  - Larger n hemisphere > Smaller n hemisphere

Rapidity dependence of α spectra

ATLAS, PRC 104 (2021) 024906





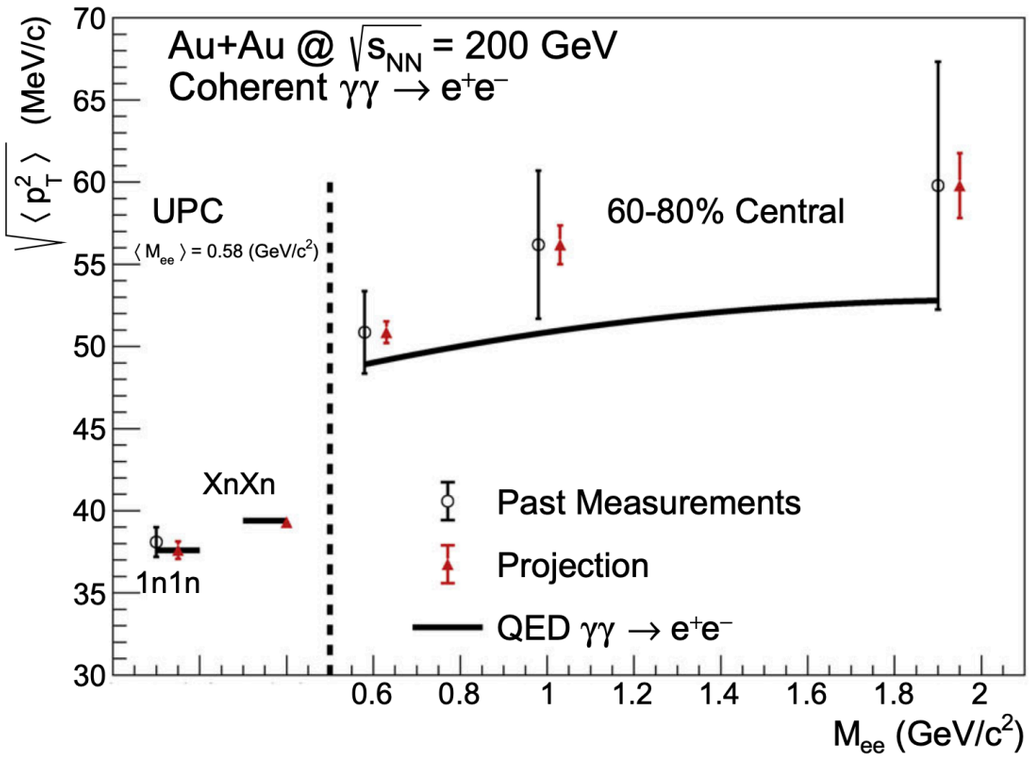


- Similar observation by ATLAS

Impact to explore QGP EM properties

Brandenburg et al., EPJA 57 (2021) 299

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



Impact to explore QGP EM properties

Brandenburg et al., EPJA 57 (2021) 299

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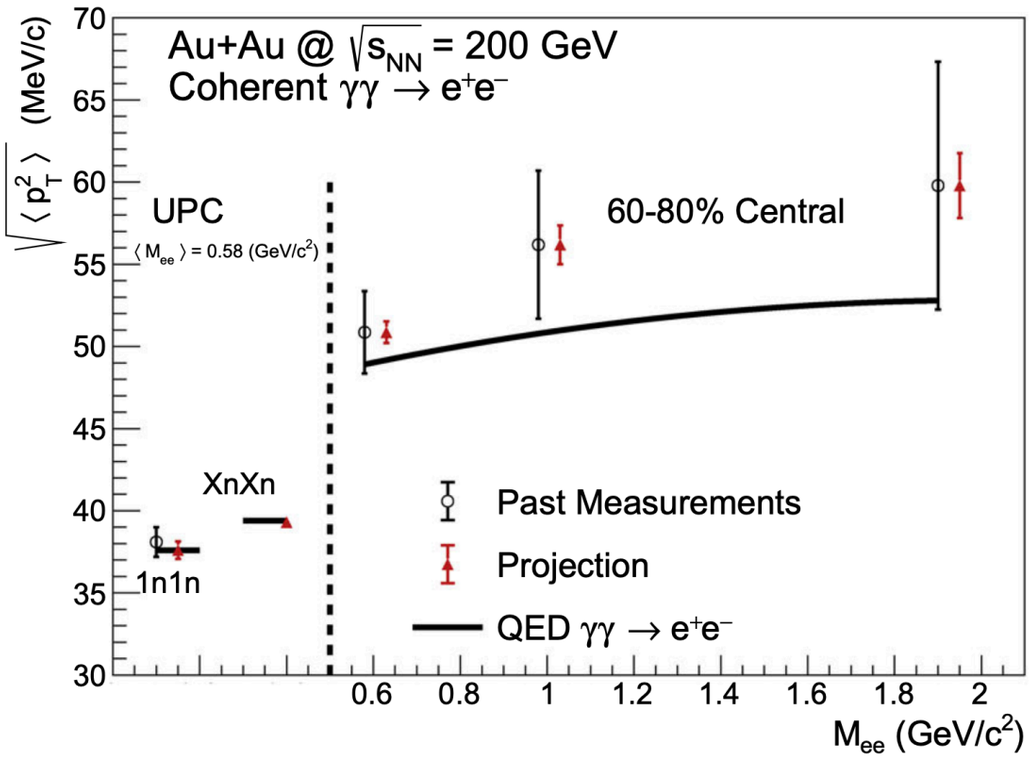
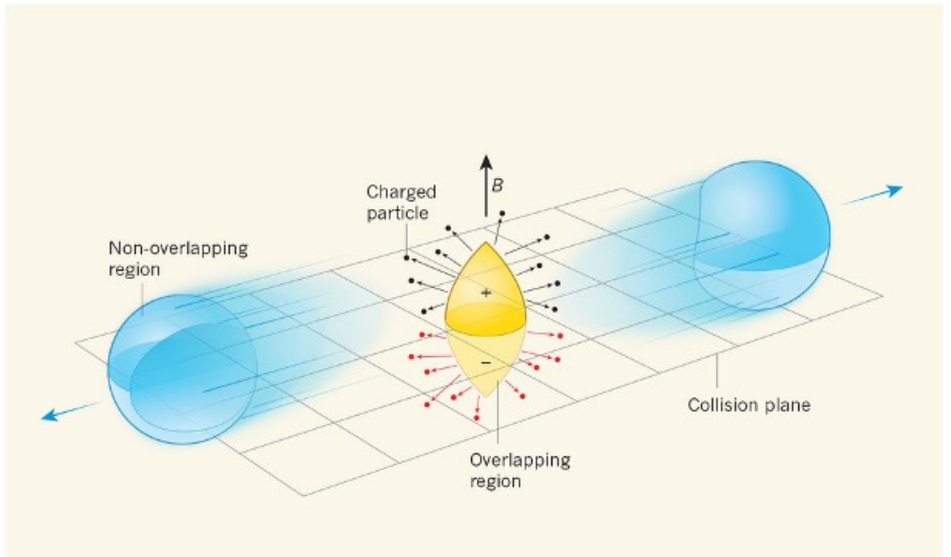
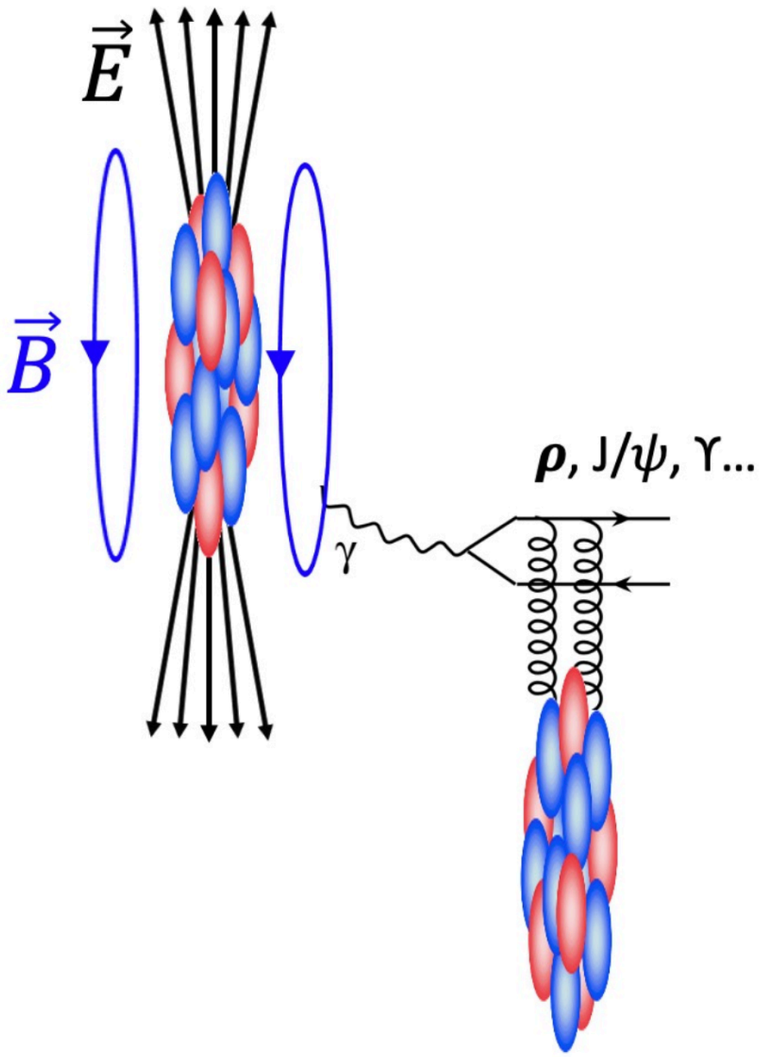


- $\langle p_T \rangle$ or $\langle \alpha \rangle$ w.r.t. event plane
  - In plane > out of plane $\Longrightarrow$ Magnetic field
  - In plane < out of plane $\Longrightarrow$ Multiple scattering

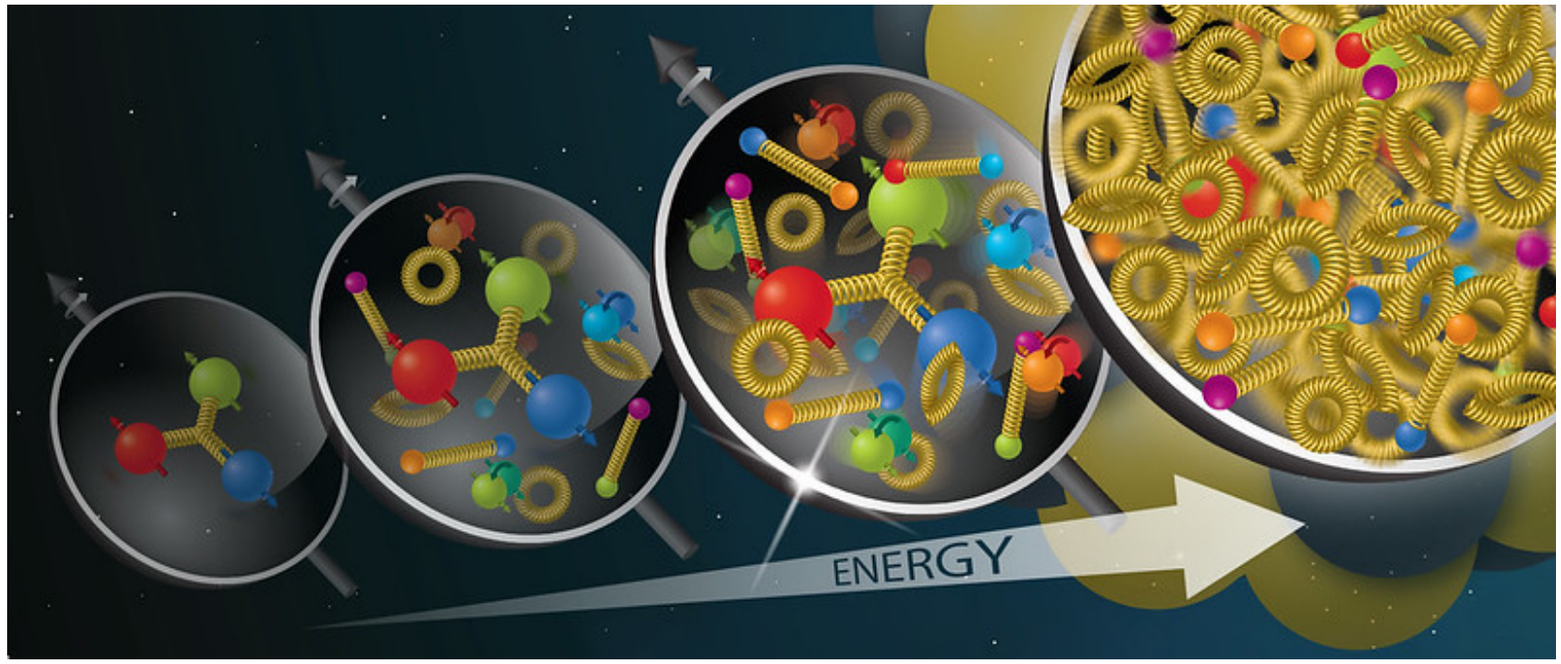


ATLAS, PRC 107 (2023) 054907

Impact to image the nuclear



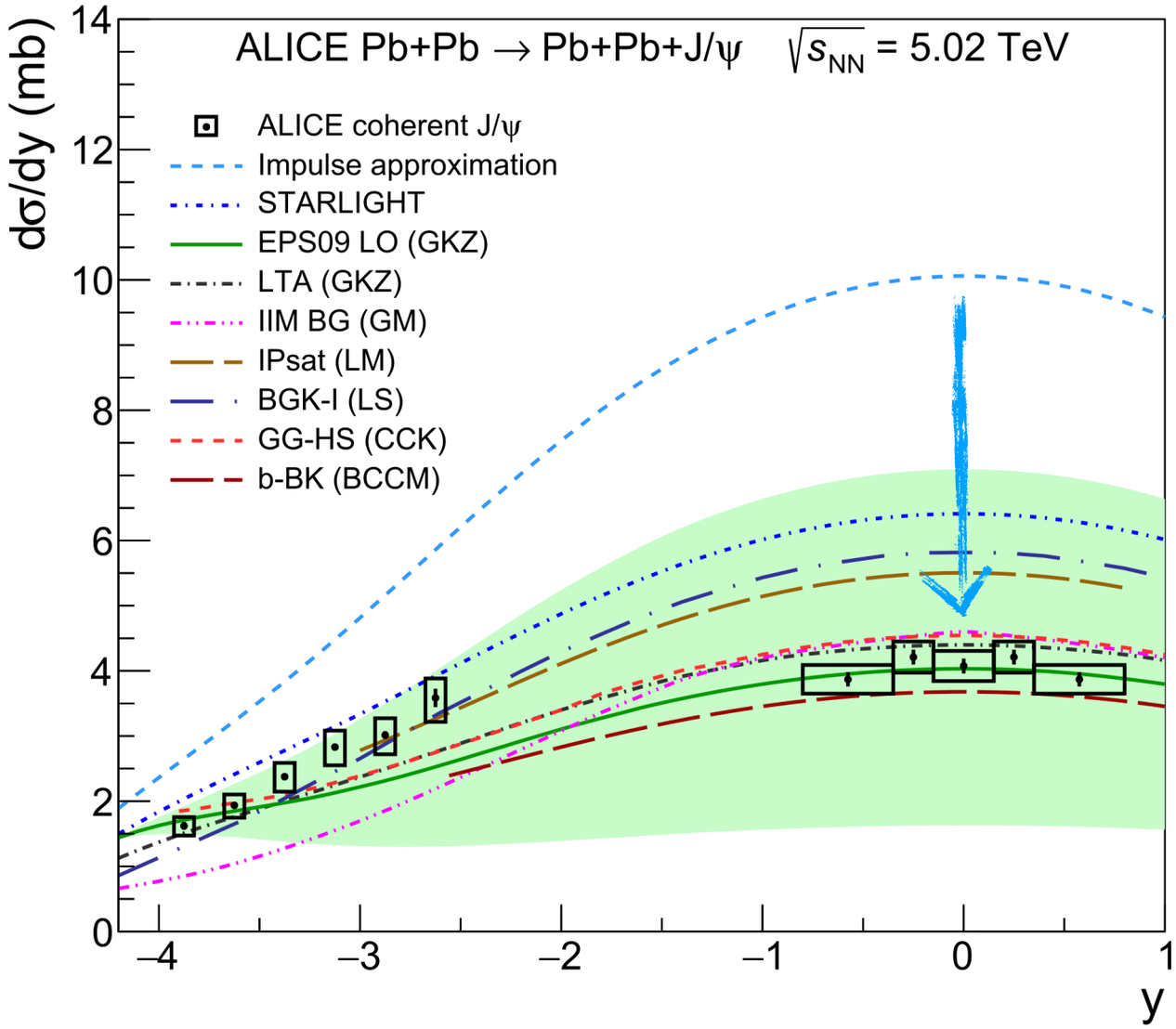
$$\frac{d\sigma(\gamma A \to VA)}{dt}|_{t=0} \propto [xG_A(x,Q^2)]^2$$



Middle Rapidity → Forward Rapidity

Impact to image the nuclear

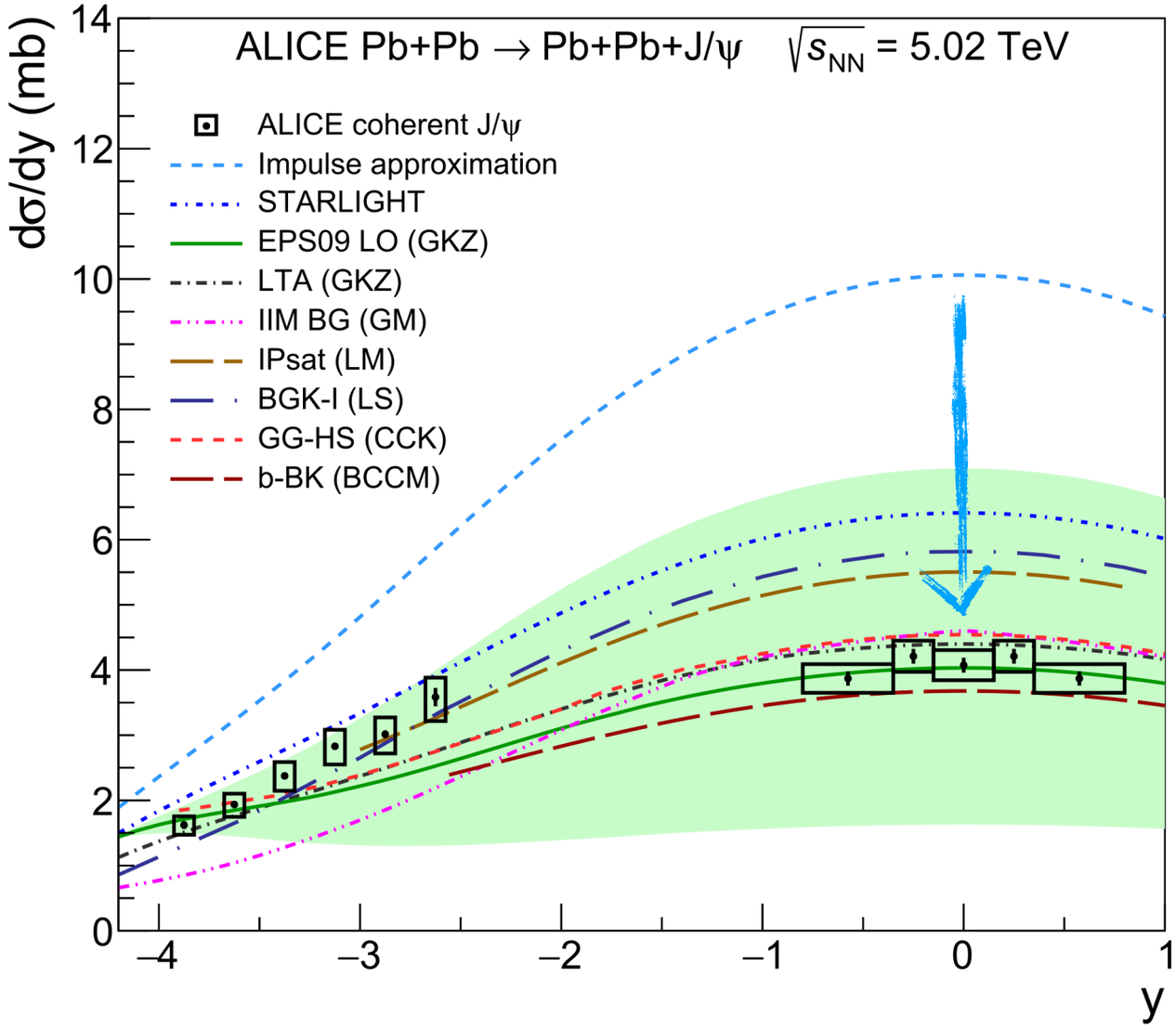
ALICE, PLB 798 (2019) 134926
ALICE, EPJC 81 (2021) 712



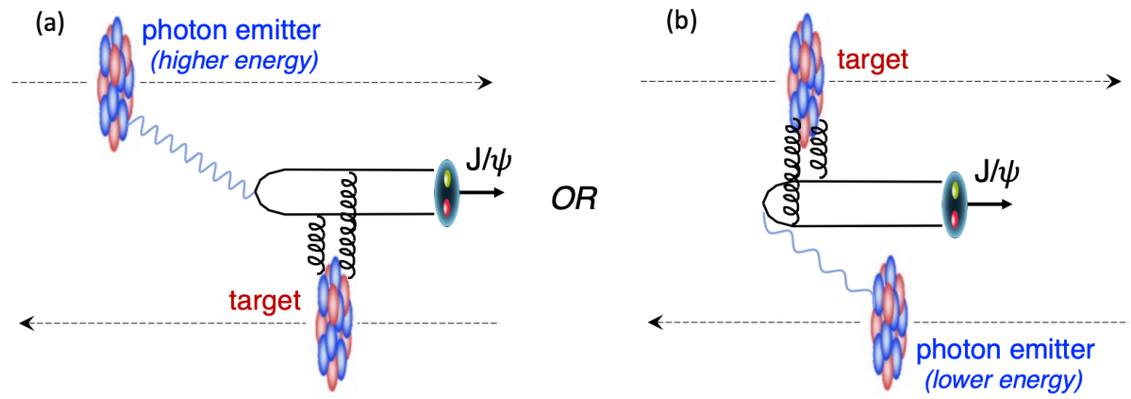
- Nuclear gluon suppression factor $R_g^{Pb} = 0.64 \pm 0.04$ at $x \sim 10^{-3}$

Impact to image the nuclear

ALICE, PLB 798 (2019) 134926
ALICE, EPJC 81 (2021) 712



- Nuclear gluon suppression factor $R_g^{Pb} = 0.64 \pm 0.04$ at $x \sim 10^{-3}$
- Two-way ambiguity in A+A UPC

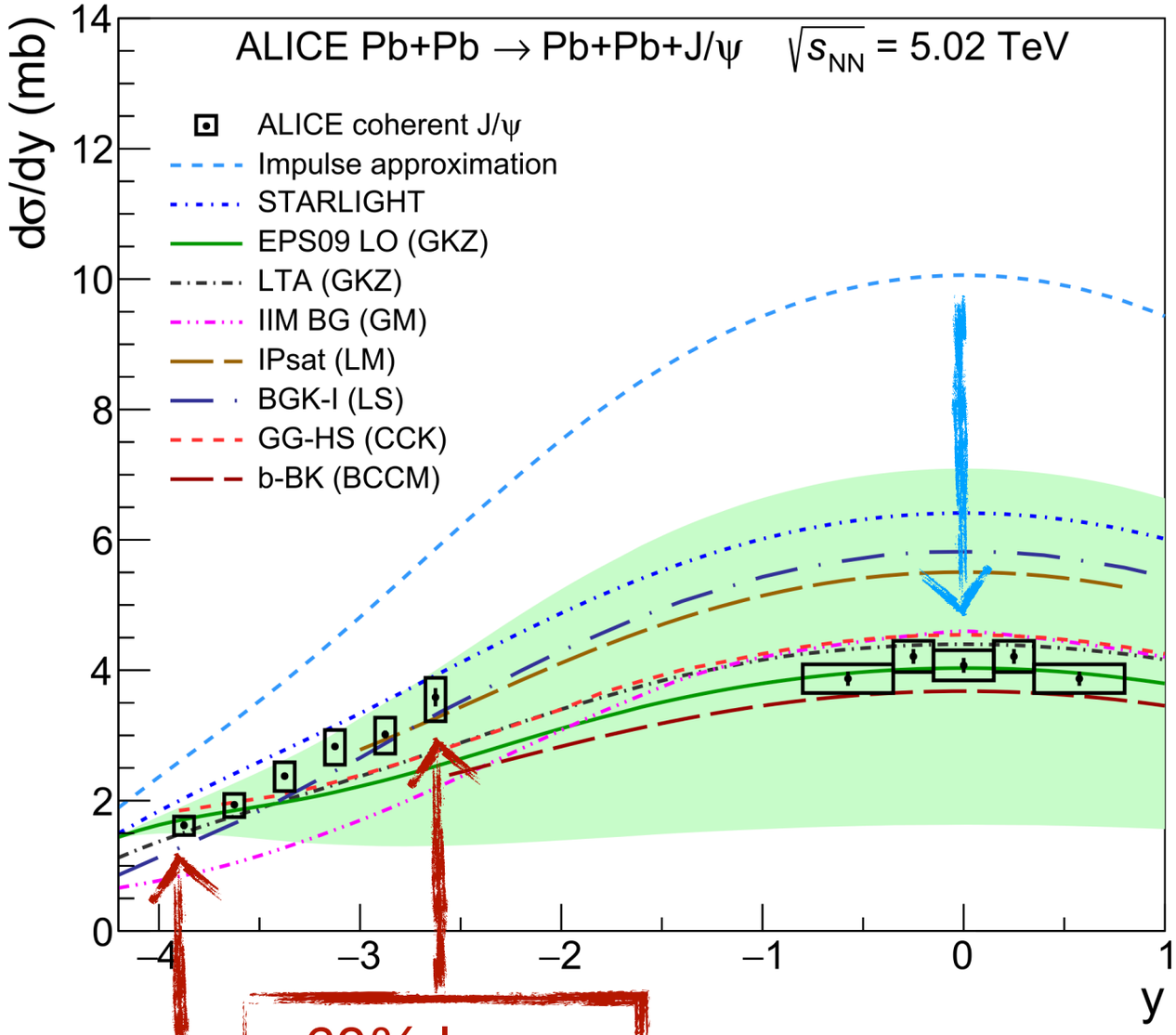


$$x = \frac{M_{J/\psi}}{2E_{beam}} e^{-y} \qquad x = \frac{M_{J/\psi}}{2E_{beam}} e^{+y}$$

$$\frac{d\sigma_{AA\to AA'J/\psi}}{dy} = N_{\gamma/A}(\omega_1) \cdot \sigma_{\gamma A\to J/\psi A'(\omega_1)} + N_{\gamma/A}(\omega_2) \cdot \sigma_{\gamma A\to J/\psi A'(\omega_2)}$$

Impact to image the nuclear

ALICE, PLB 798 (2019) 134926
ALICE, EPJC 81 (2021) 712



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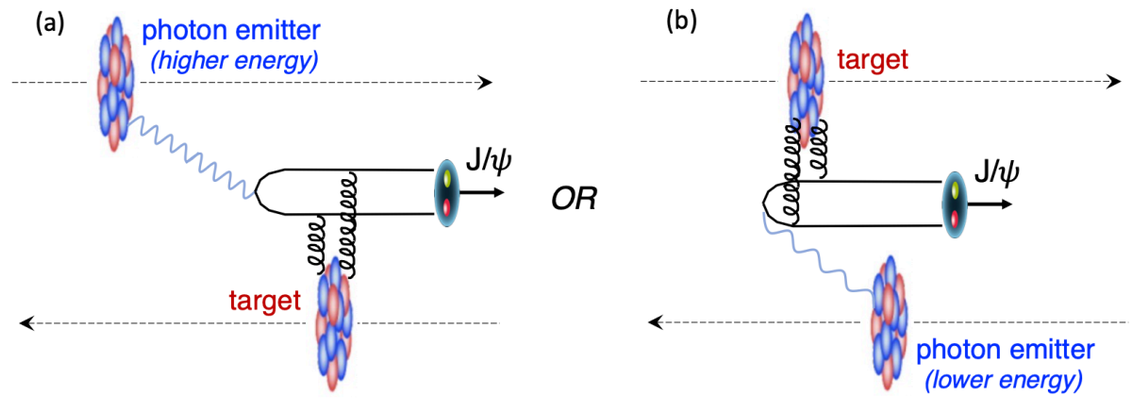

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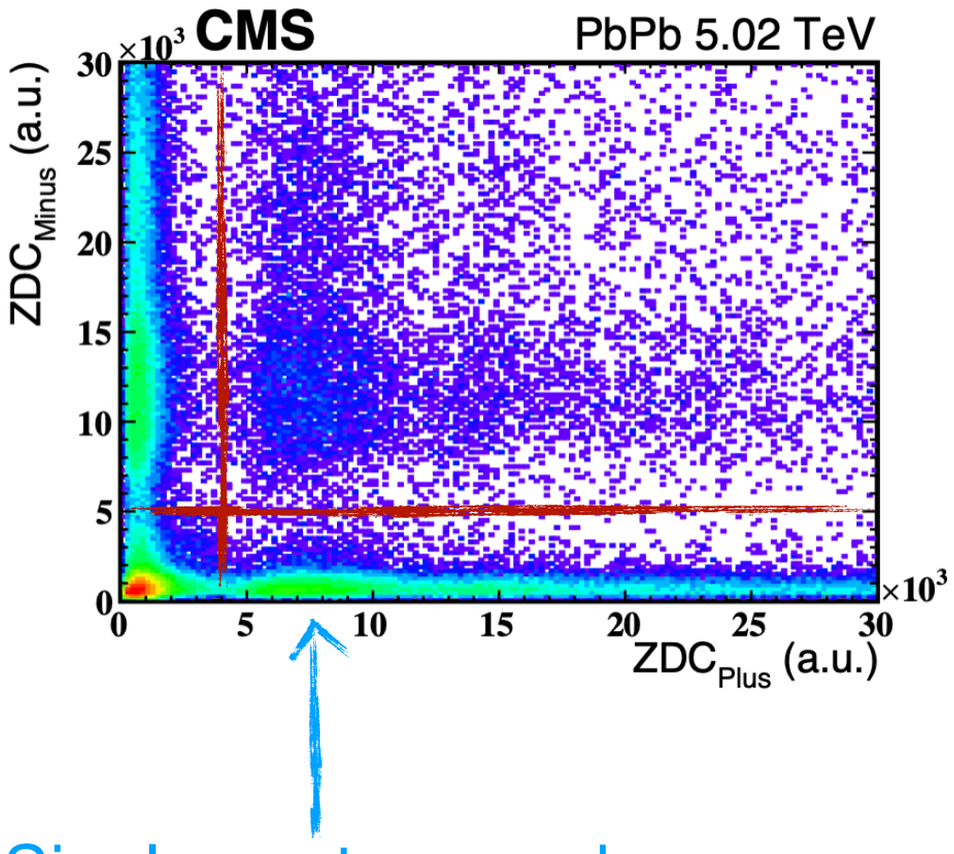
See Zaochen's talk tomorrow

Impact to image the nuclear

Guzey *et al.*, EPJC 74 (2014) 2942

CMS, PRL 127 (2021) 122001



Single neutron peak

$$\frac{d\sigma^{0n0n}_{AA\to AA'J/\psi}}{dy} = N^{0n0n}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0n0n}_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_2)}$$

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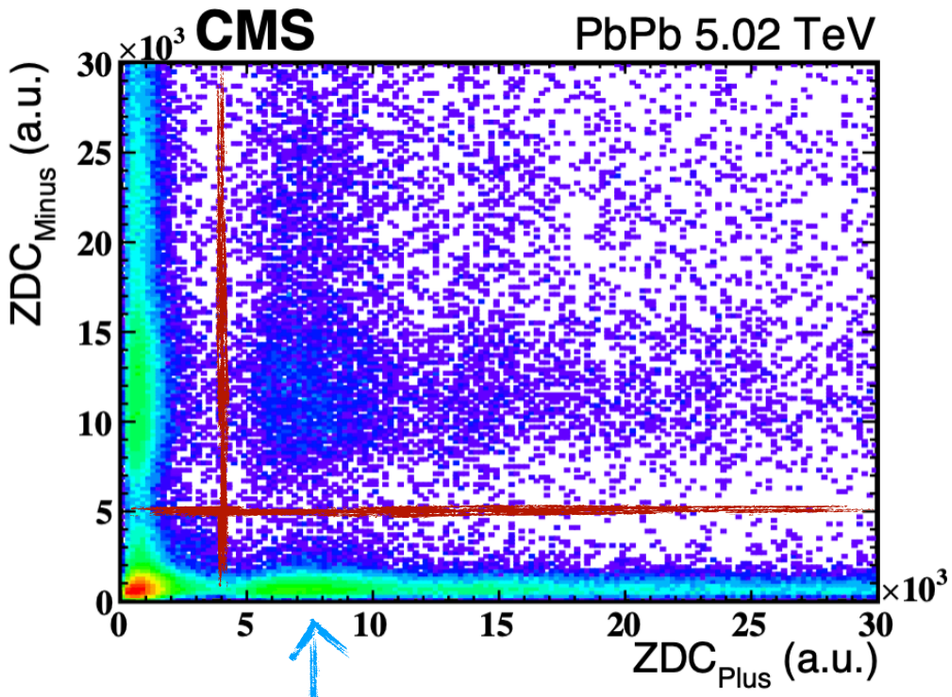
Guzey *et al.*, EPJC 74 (2014) 2942

CMS, PRL 127 (2021) 122001



Single neutron peak

Experimental measurements

$$\frac{d\sigma^{0n0n}_{AA\to AA'J/\psi}}{dy} = N^{0n0n}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0n0n}_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_2)}$$

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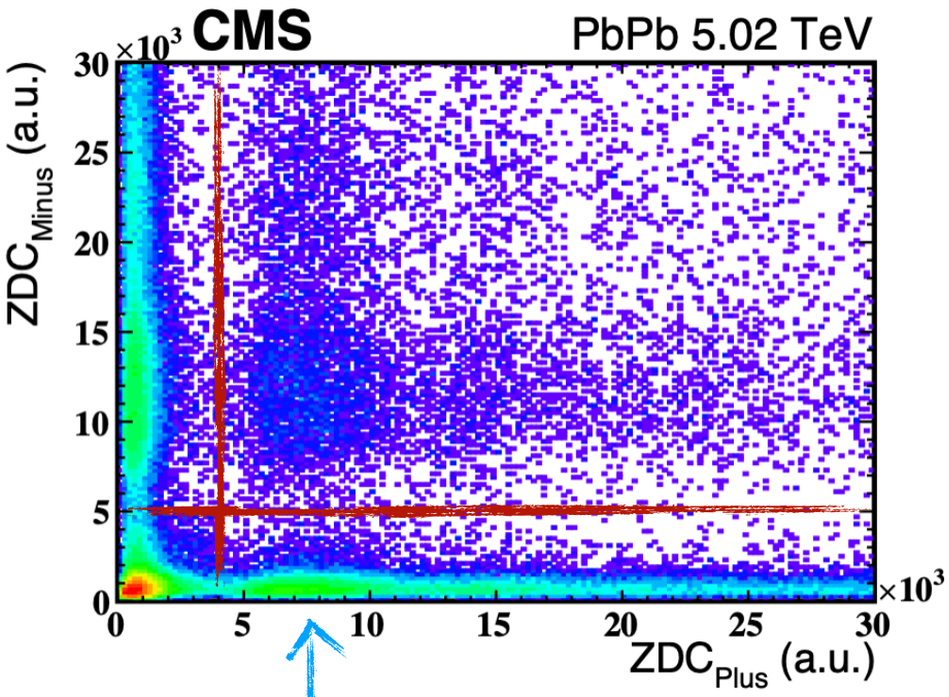

Single neutron peak

Experimental measurements

Photon flux from theory

$$\frac{d\sigma^{0n0n}_{AA\to AA'J/\psi}}{dy} = N^{0n0n}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0n0n}_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_2)}$$

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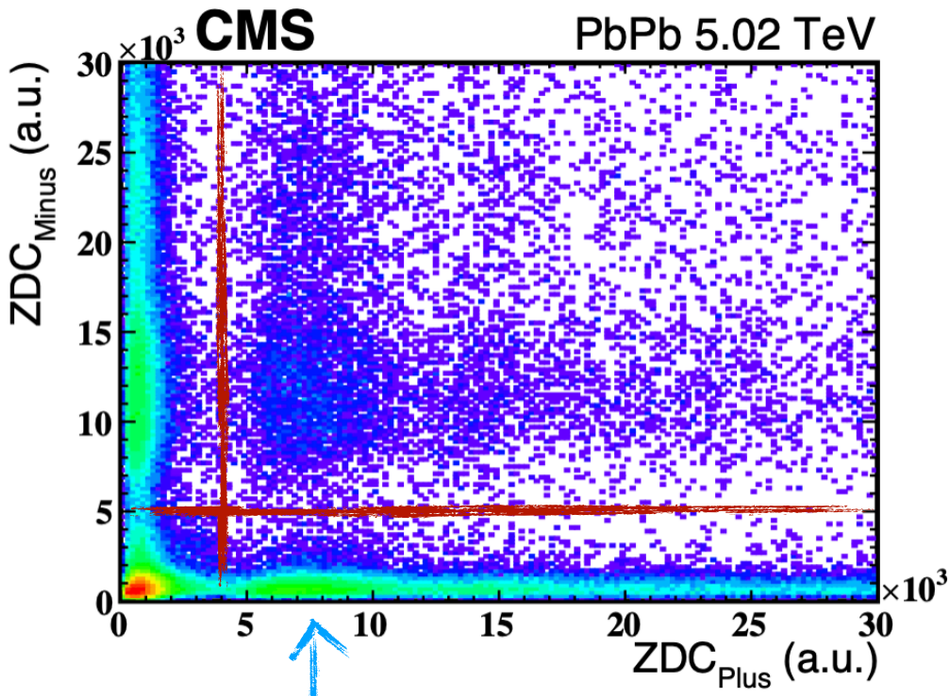

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What we need!

↓

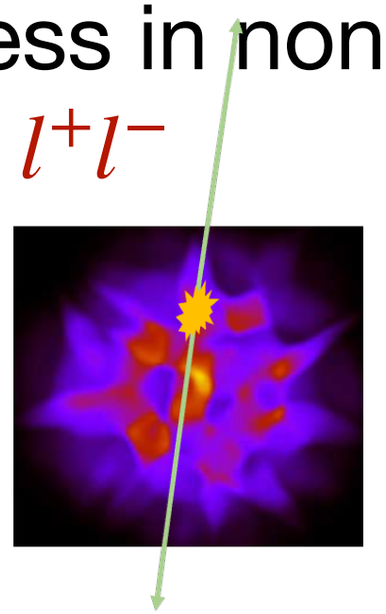
Solve the "two-way ambiguity"

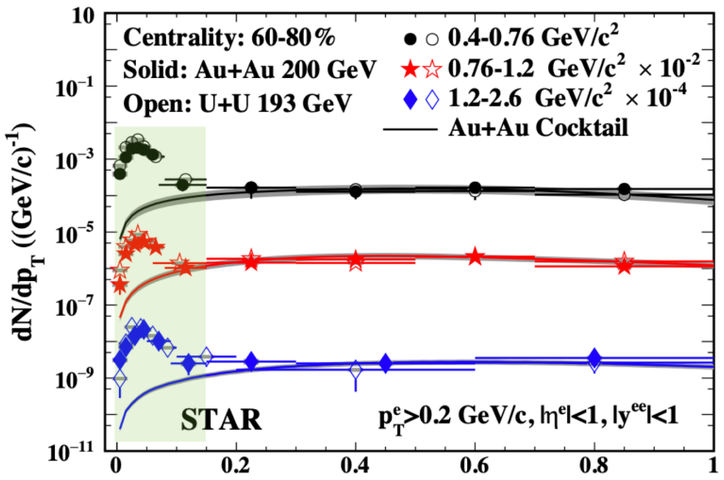
↓

Probe gluons at *small x* in heavy nucleus!

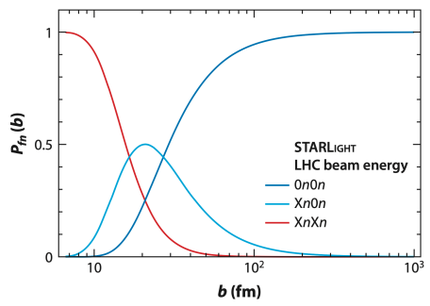
Summary

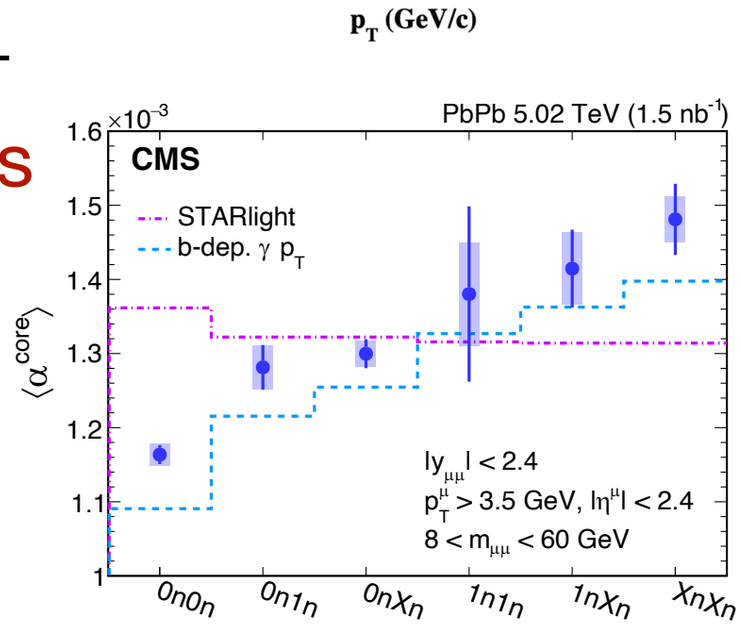
- Observed Breit-Wheeler process in non-UPC
  - Probe QGP medium using $\gamma\gamma \rightarrow l^{+}l^{-}$





- Observed of *b* dependence of photon p_T
  - Precise reference for probing QGP EM effects

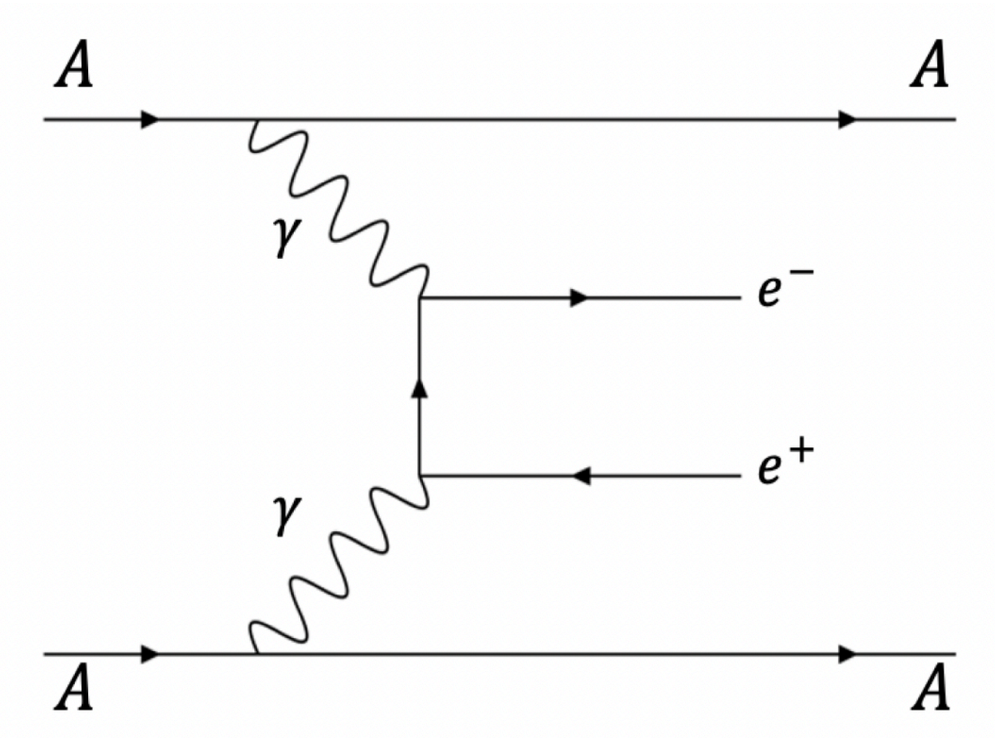




- New tool of exploring small x physics from b dependence of photoproduced vector mesons

Backups

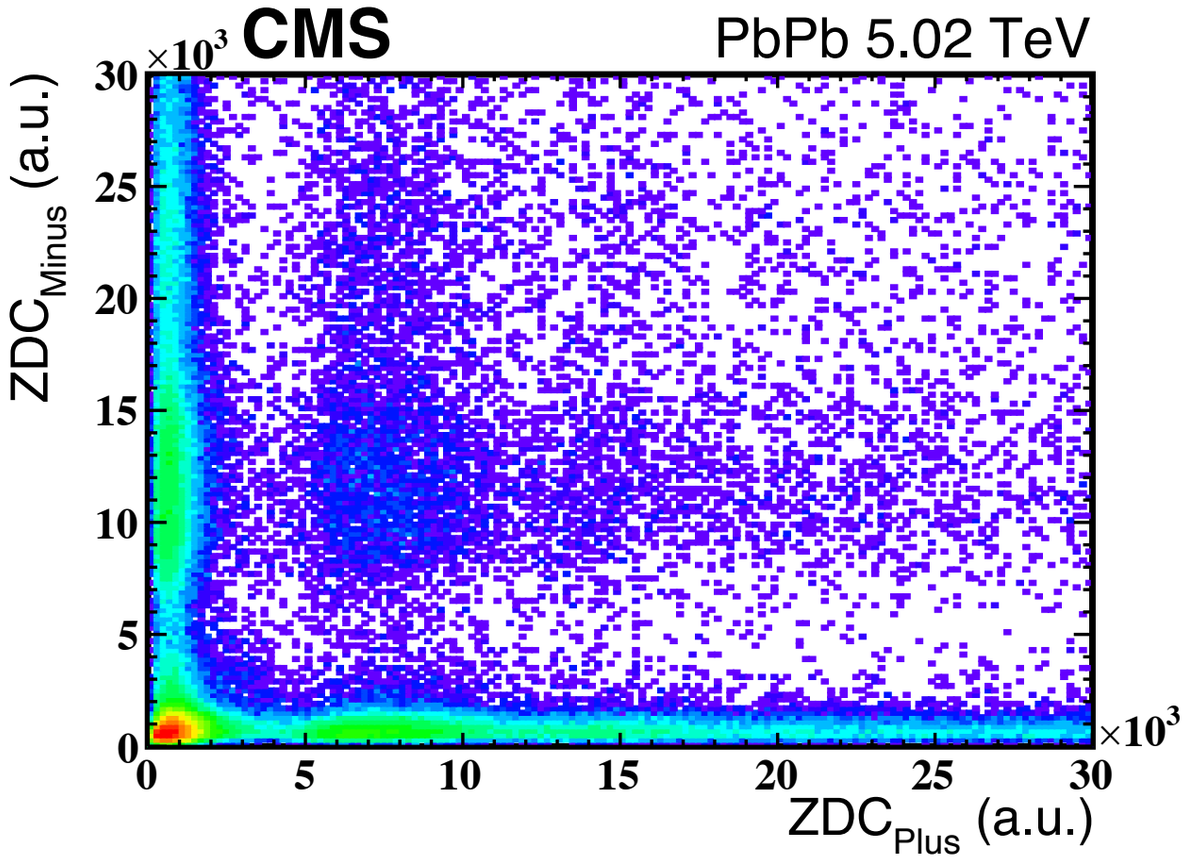
Breit-Wheeler process

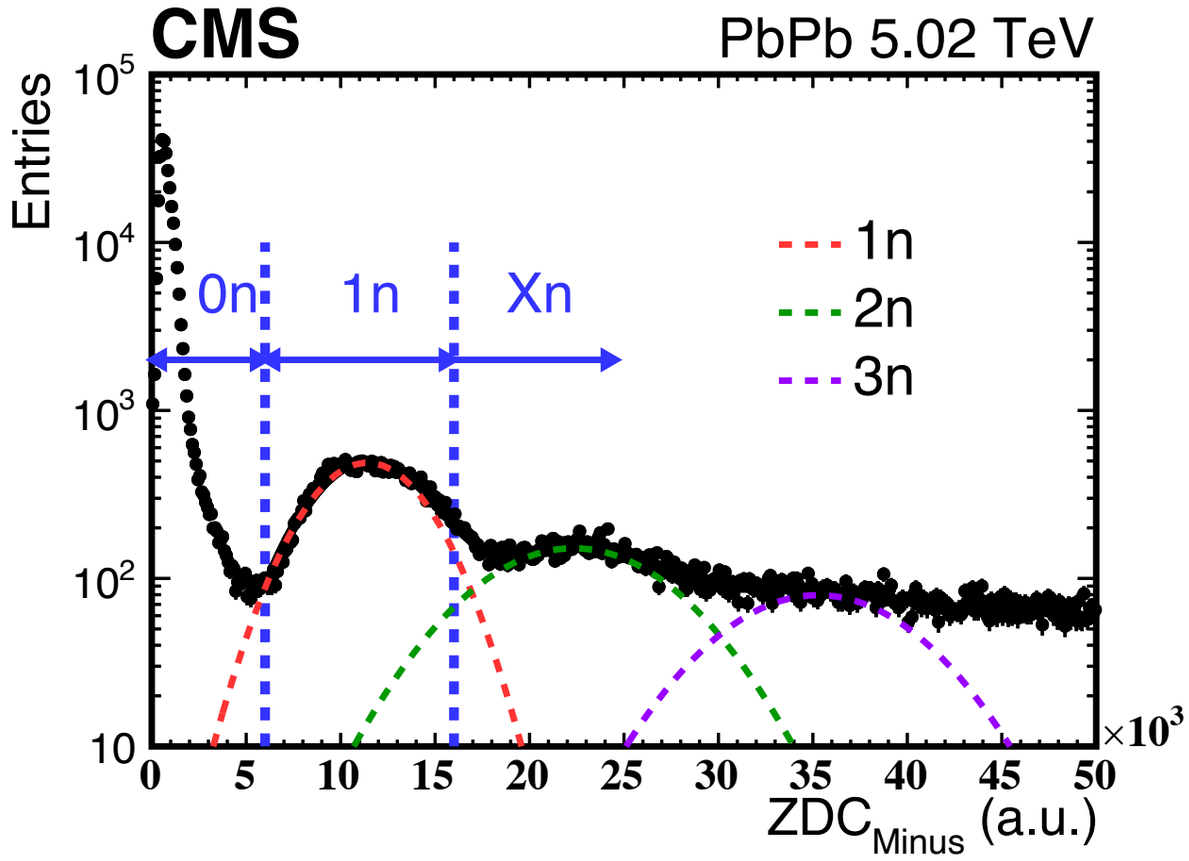


- **Breit-Wheeler process:** converting **real** photon into e^+e^-
  - Proposed in 1934 *[Breit & Wheeler, Phys. Rev. 46 (1934) 1087]*

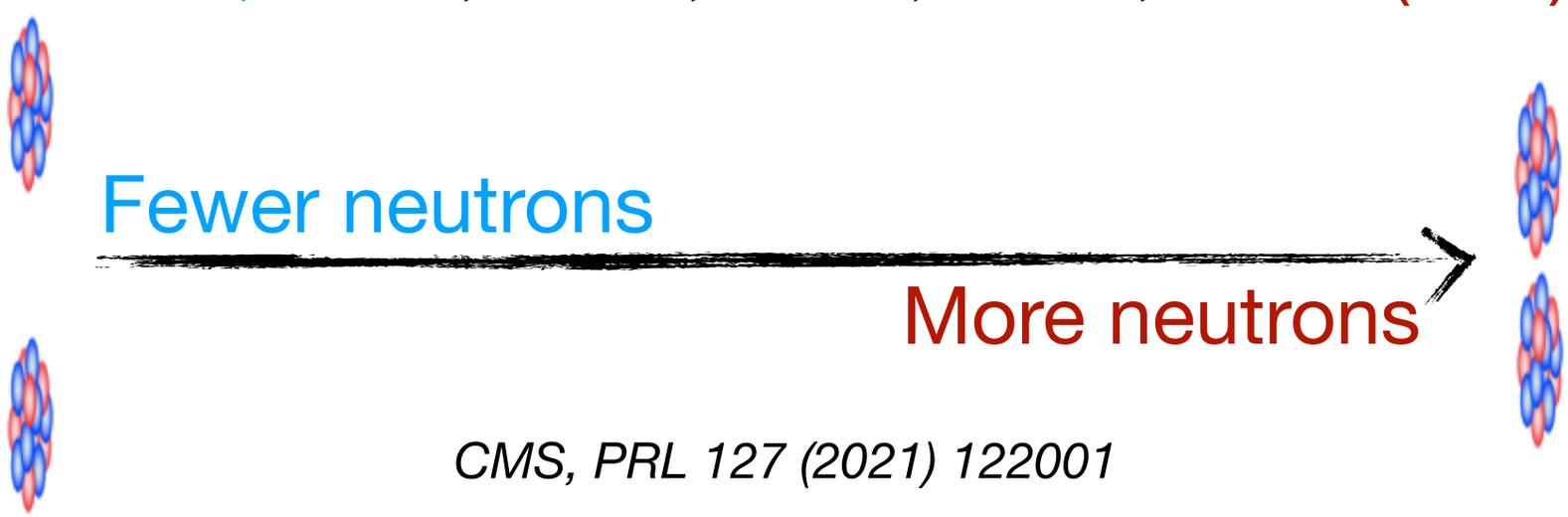
$$Q^2 < (\hbar/R_A)^2 \textbf{ in UPC} \Longrightarrow \textbf{almost real}$$

Determine neutron multiplicity

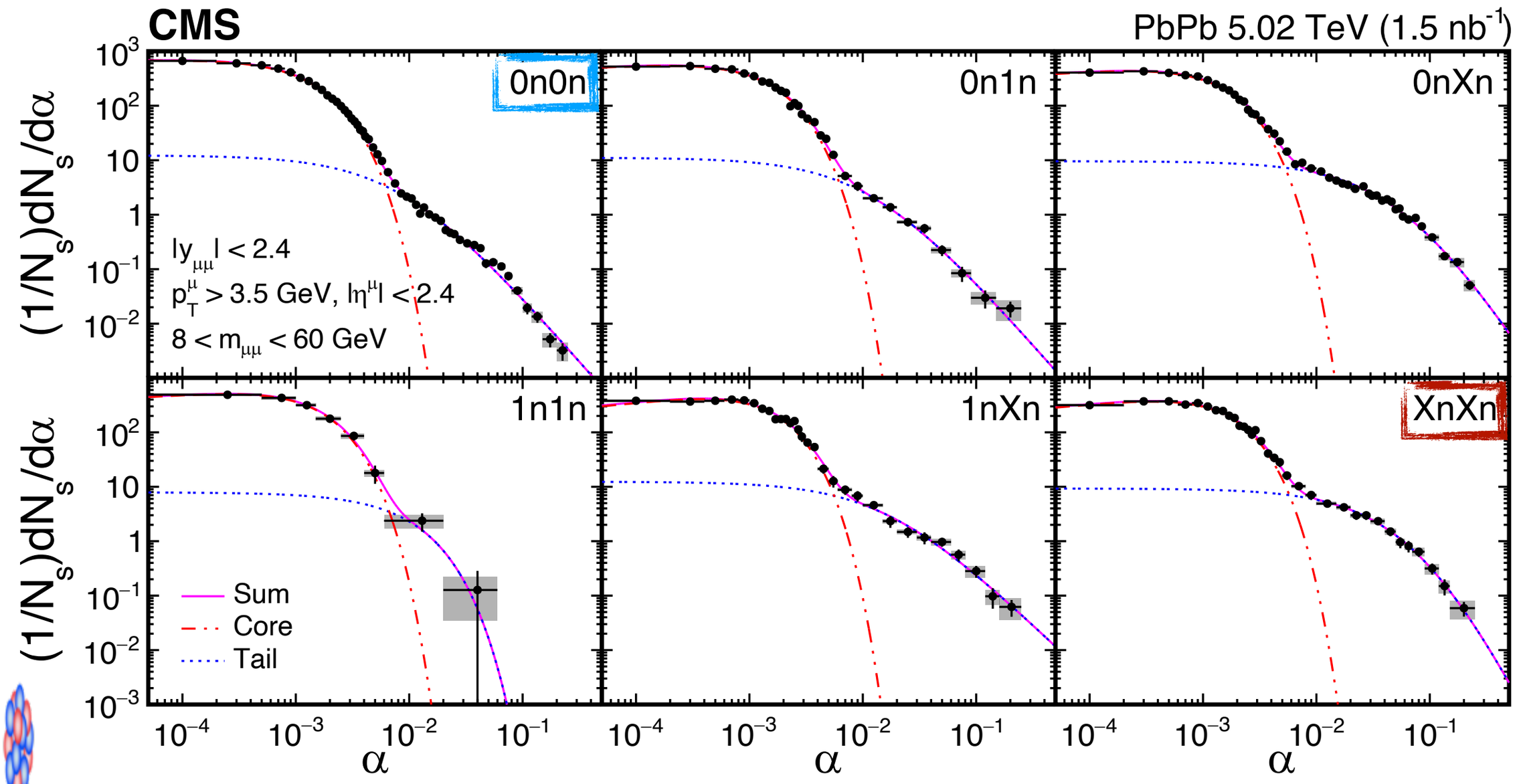




- Straight cuts to disentangle neutrons
  - 0n0n, 0n1n, 0nXn, 1n1n, 1nXn, XnXn (X≥2)



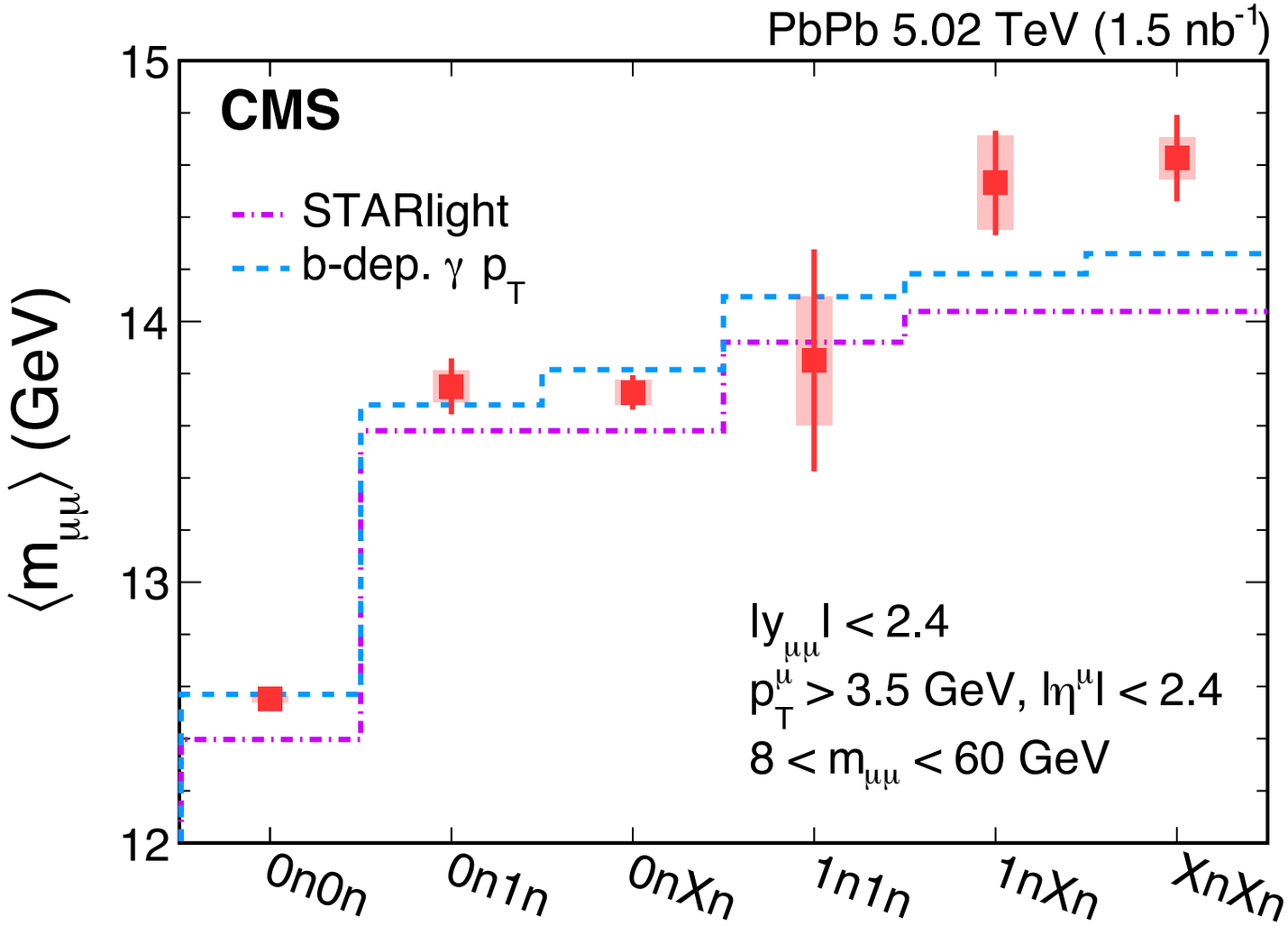
α spectrum vs. neutron multiplicity



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

$\langle M_{\mu\mu} \rangle$ 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

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

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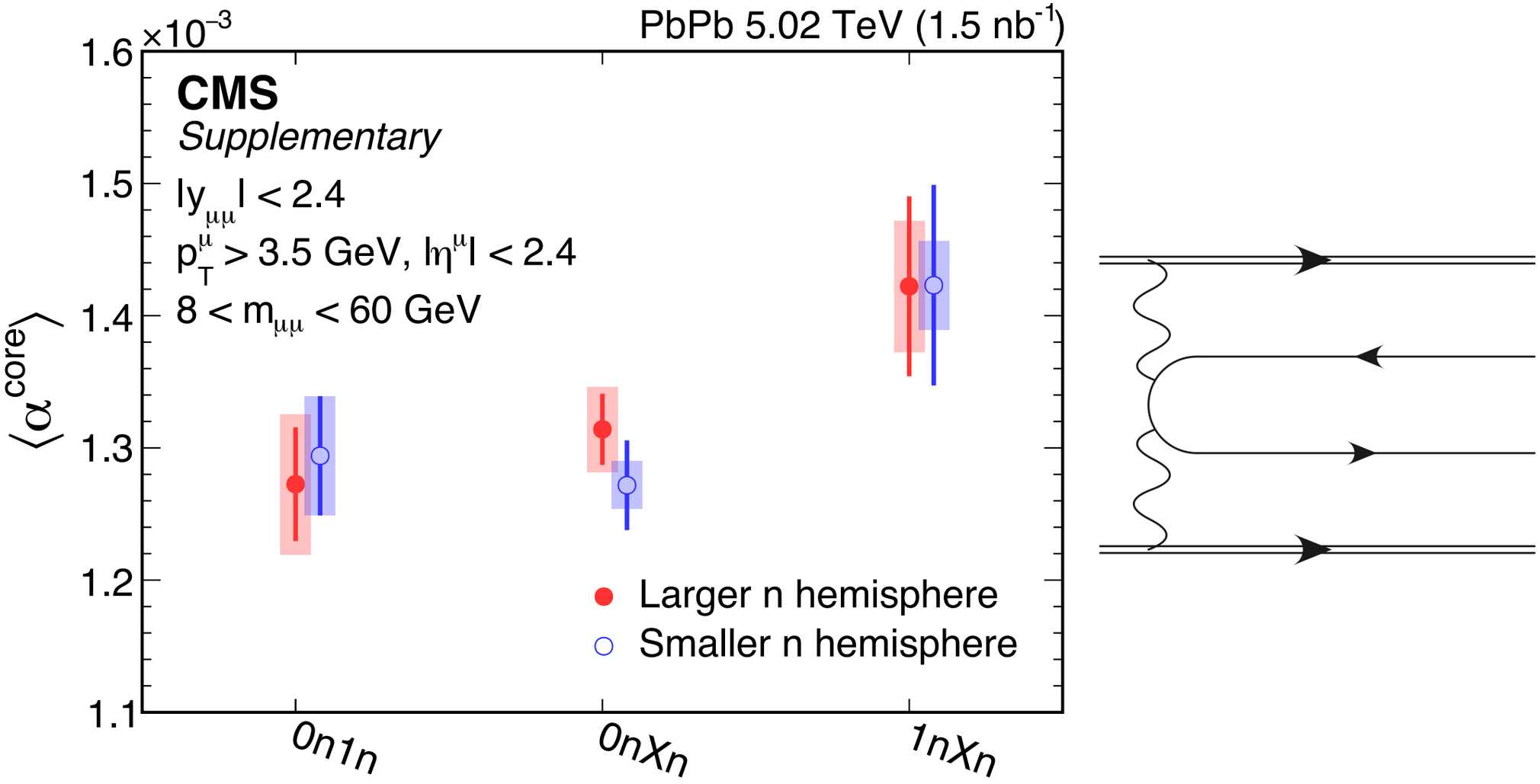
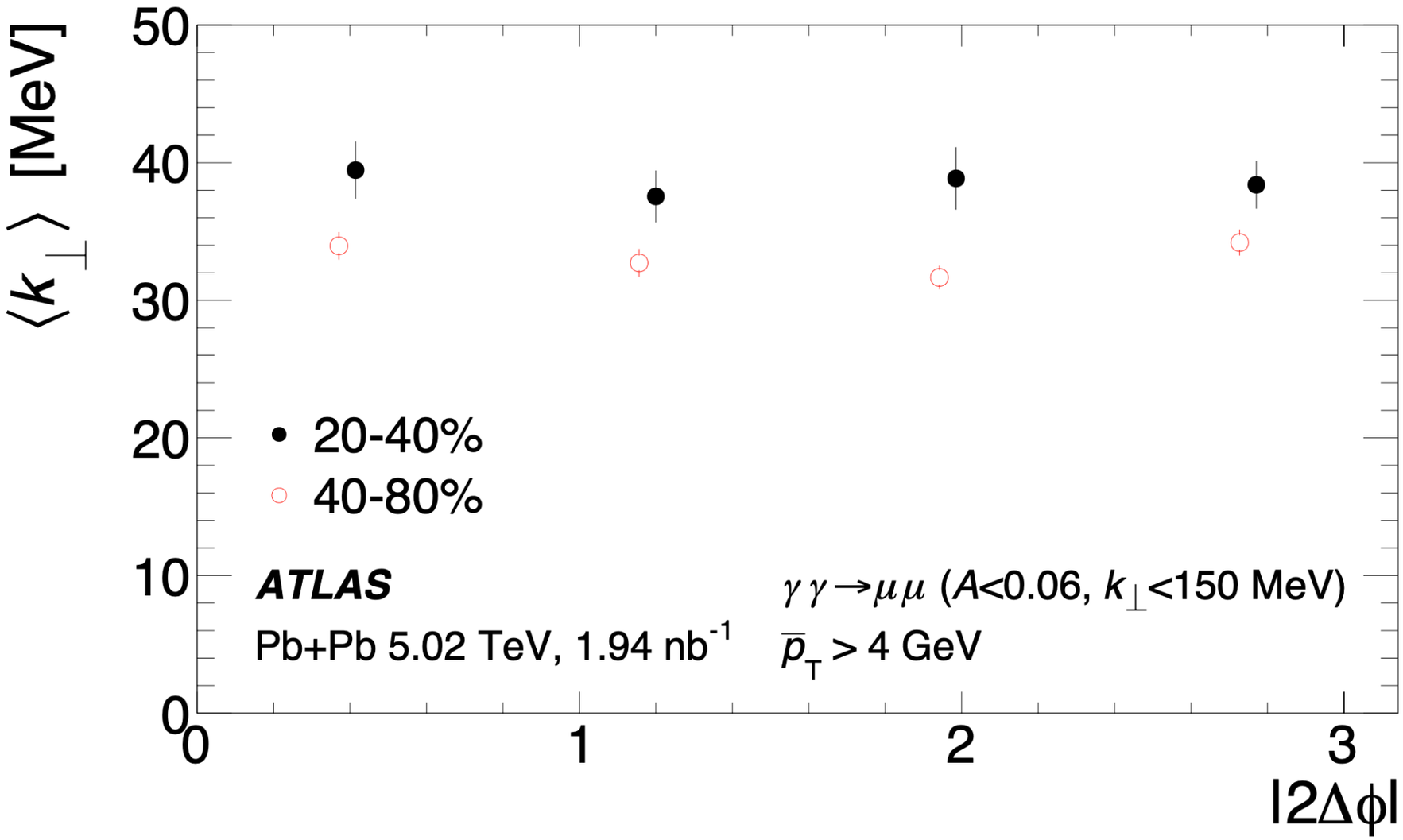


- $\langle \alpha^{\text{core}} \rangle$ has no rapidity dependence
  - Core dominantly comes from LO $\gamma\gamma$ scatterings

Event plane dependence

ATLAS, arXiv:2206.12594



$$|2\Delta\phi| \equiv \left|2\left(\phi_{\mu\mu} - \Psi_2\right)\right| \qquad \phi_{\mu\mu} = \frac{1}{2}\left(\phi_1 + \pi + \phi_2\right)$$

$$k_\perp \equiv \frac{1}{2}\left(p_{\mathrm{T}1} + p_{\mathrm{T}2}\right)\left(\pi - |\phi_1 - \phi_2|\right) = \pi\alpha\bar{p}_{\mathrm{T}}$$