Photon-photon physics in heavy ion collisions

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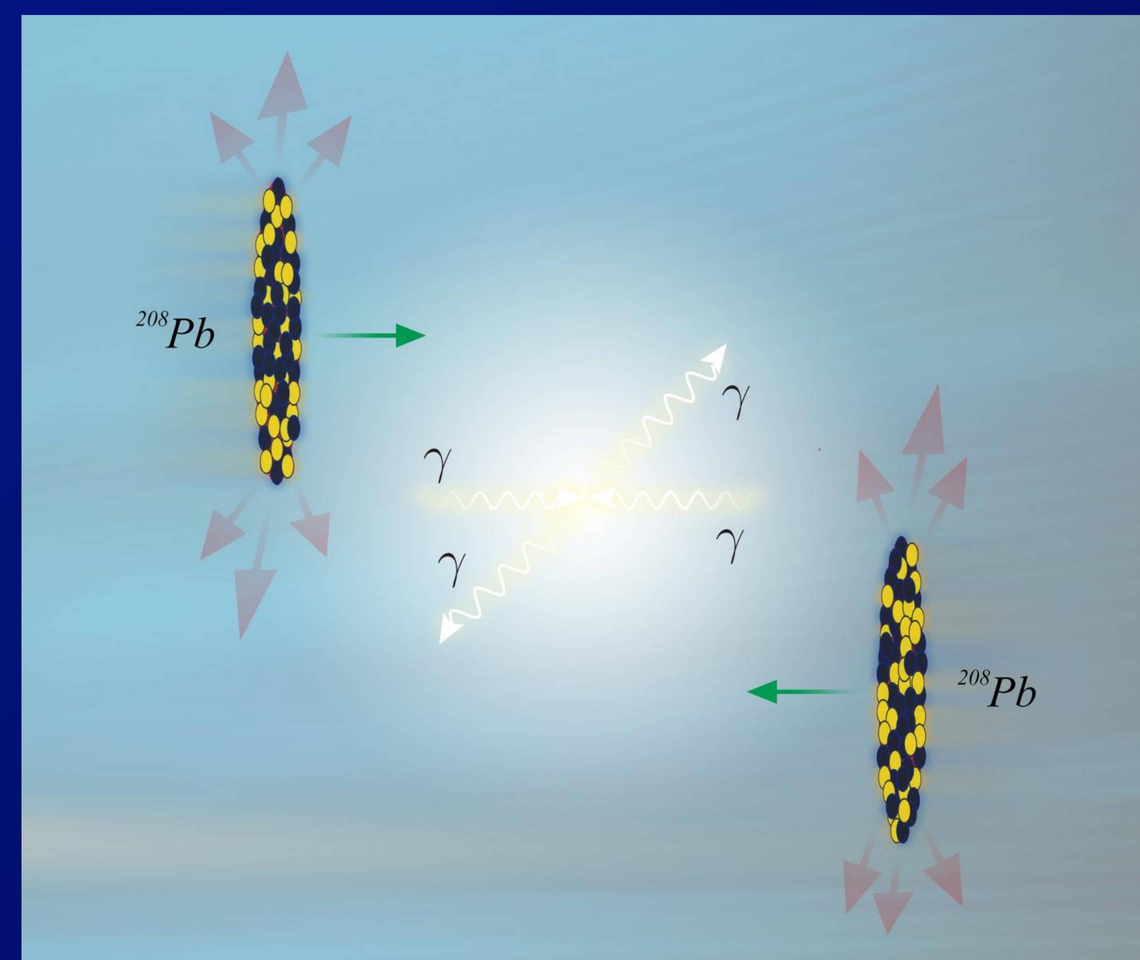
WILHELM UND ELSE HERAEUS-STIFTUNG



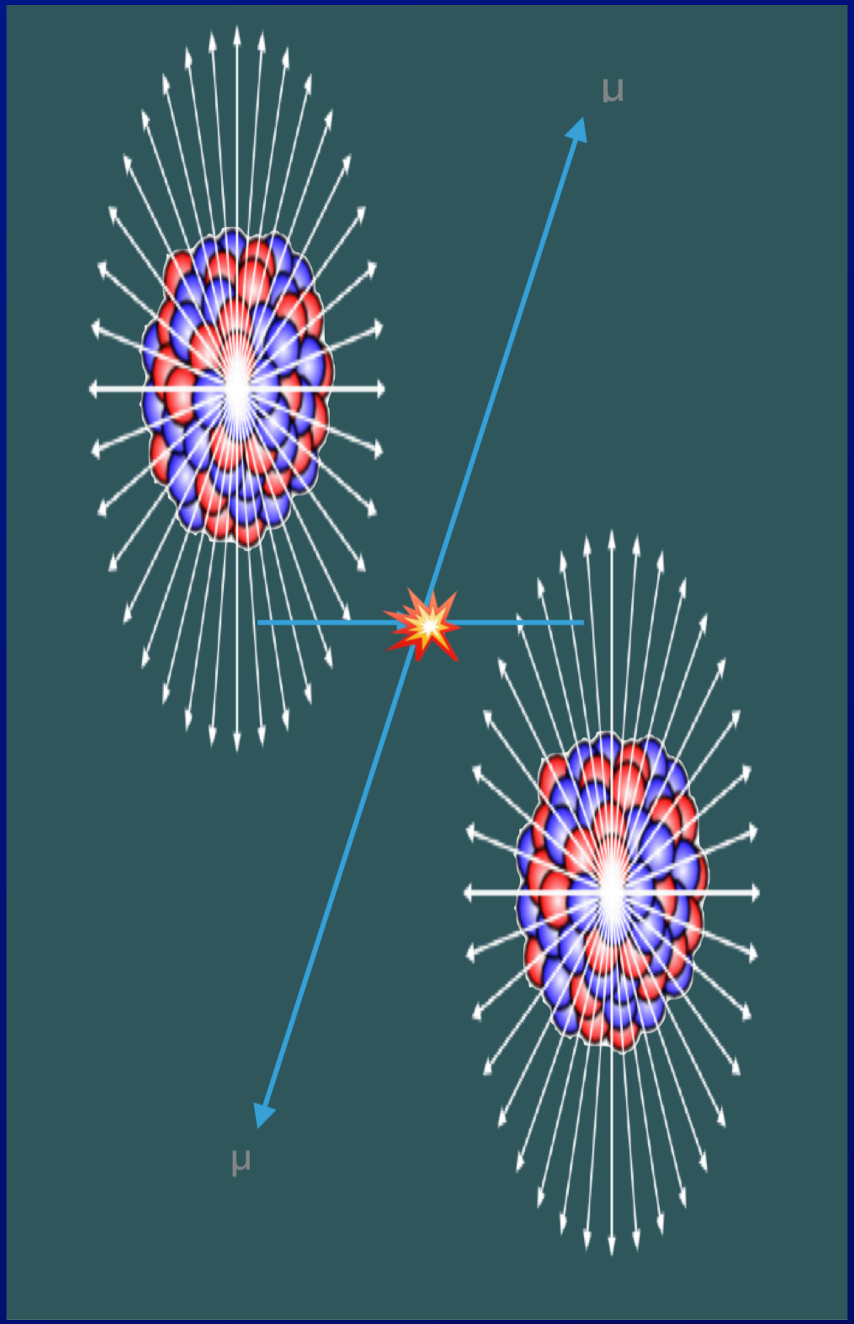
Outline

- Introduction
  - Nuclei as sources of quasi-real photons
- Control measurements: exclusive dilepton
  - ATLAS and STAR e^+e^-
- Light-by-light scattering
  - Measurements, Limits on ALP production
- $\tau^+\tau^-$ and τ g-2 measurement
  - ATLAS & CMS results
- Photon k_T distributions
  - CMS: μ+μ- acoplanarity vs # forward neutrons
  - ATLAS: $\gamma+\gamma \rightarrow \mu\mu$ in hadronic A+A collisions
- γ+A → jets advertisement
- Summary

Introduction

- **Weizsacker & Williams + Jackson + … :**
  - Highly relativistic particles act as sources of ~ real photons
- **Finger physics:**
  - When $\lambda > R/\gamma$, or equivalently $E \lesssim \hbar c\ \gamma/R$, the photons are emitted coherently
  - At LHC, Pb+Pb @ 5.02 TeV, coherence condition is $E \lesssim 80$ GeV
  - (Coherent) Photon flux $\propto Z^2$
    - $\gamma+\gamma$ luminosity $\propto Z^4$
- **During heavy ion operation, the LHC is also a Large Photon Collider**

$\Rightarrow \sqrt{s} > 100$ GeV



EPA, STARlight, geometry

- **Until recently, calculations of the photon flux in UPC collisions started with textbook formula**
  - photon flux density for given energy, *k* at a perpendicular distance, $r_\perp$

$\Rightarrow$ $$N(k,b) = \frac{Z^2\alpha}{\pi^2}\frac{k}{(\hbar c)^2}\frac{1}{\gamma^2}\left[K_1^2(x) + \frac{1}{\gamma^2}K_0^2(x)\right] \qquad x \equiv \frac{k r_\perp}{\gamma \hbar c}$$

$\Rightarrow$ correlation between $r_\perp$ and energy

EPA, STARlight, geometry

- Until recently, calculations of the photon flux in UPC collisions started with textbook formula
  - photon flux density for given energy, *k* at a perp. distance, $r_\perp$

$$\Rightarrow \quad N(k,b) = \frac{Z^2\alpha}{\pi^2}\frac{k}{(\hbar c)^2}\frac{1}{\gamma^2}\left[K_1^2(x) + \frac{1}{\gamma^2}K_0^2(x)\right] \qquad x \equiv \frac{k r_\perp}{\gamma\,\hbar c}$$

$\Rightarrow$ correlation between $r_\perp$ and energy

- geometric convolution w/ no-hadronic interaction factor
  - e.g. STARlight formula for γ+γ:

$$\Rightarrow \quad \frac{d^2N_{\gamma\gamma}(k_1,k_2)}{dk_1dk_2} = \int\int d^2b_1 d^2b_2^2 P_{\mathrm{NOHAD}}(|\vec{b_1}-\vec{b_2}|)N(k_1,\vec{b}_1)N(k_2,\vec{b}_2)$$

- But, in textbook or literature, handling of $r_\perp < R$, unsettled

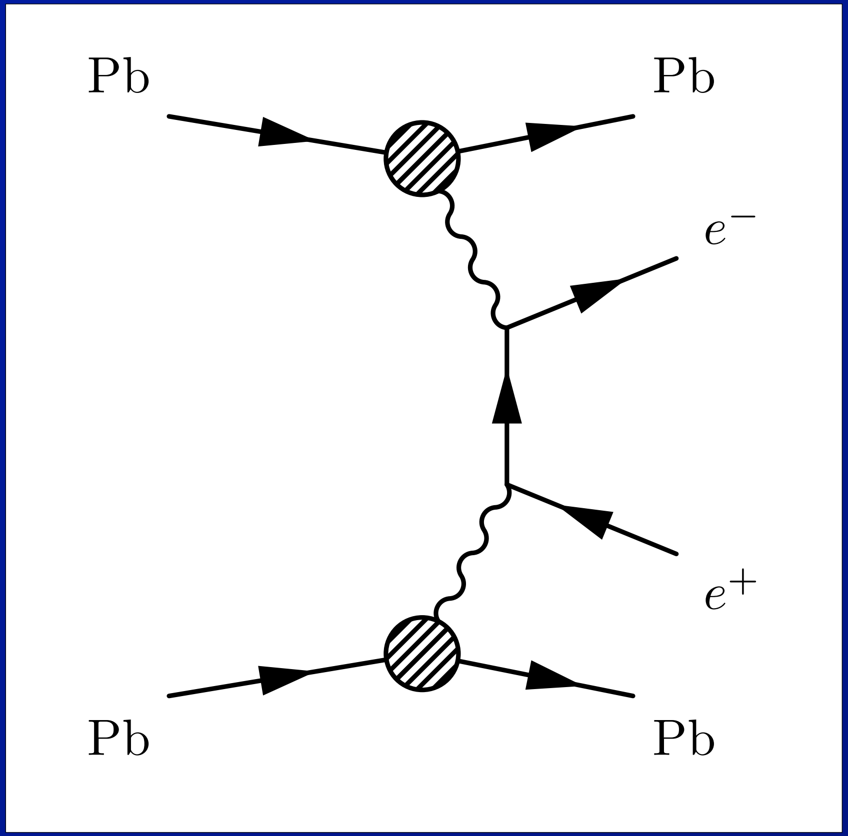
$\Rightarrow$ For example, STARlight neglects photons w/ $r_\perp < R$

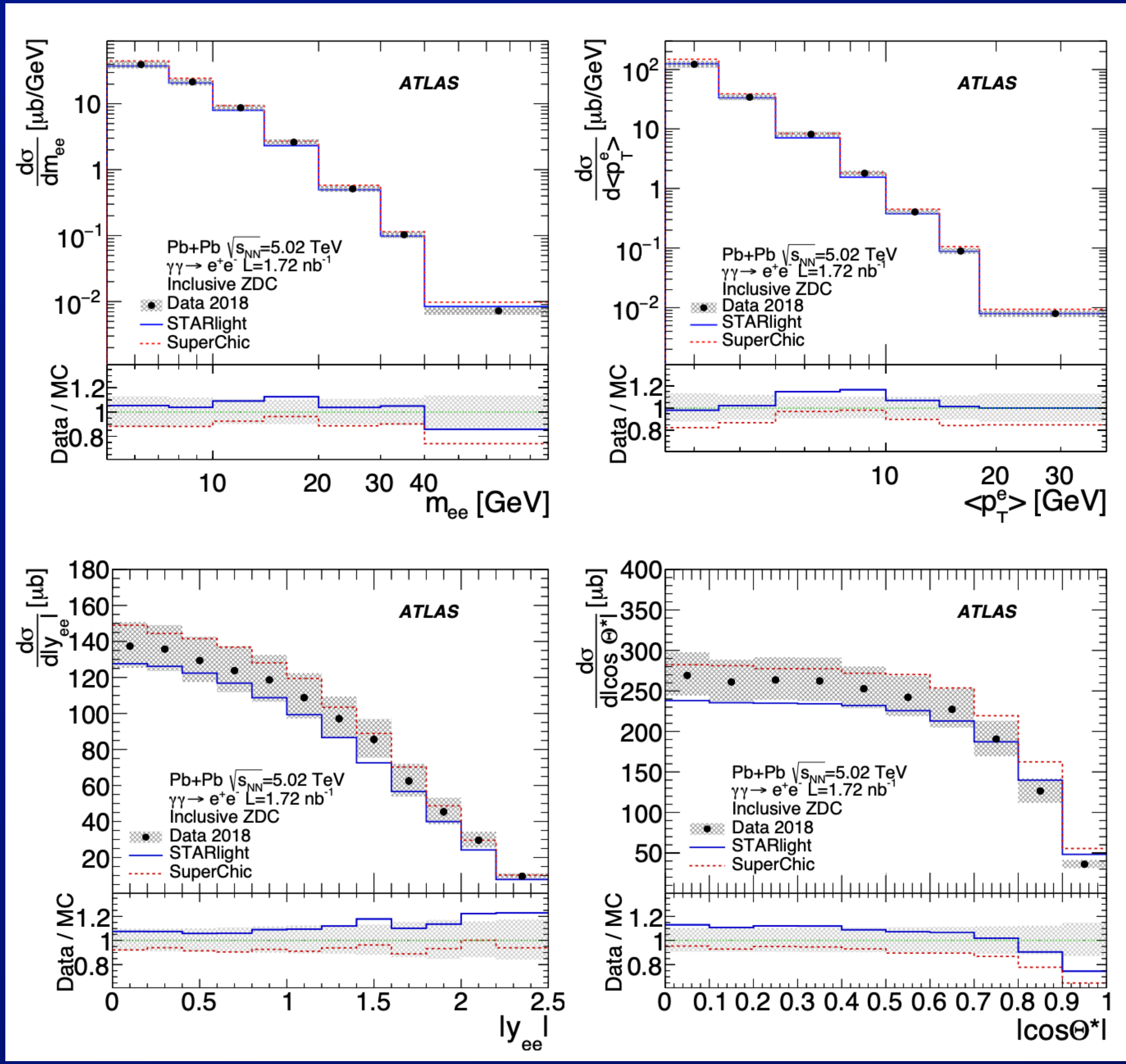
$\Rightarrow$ SuperChic does not

γ+γ production of dileptons

Dilepton production in γ+γ collisions

- At leading order in QED the γ+γ → l^+l^- process is simple





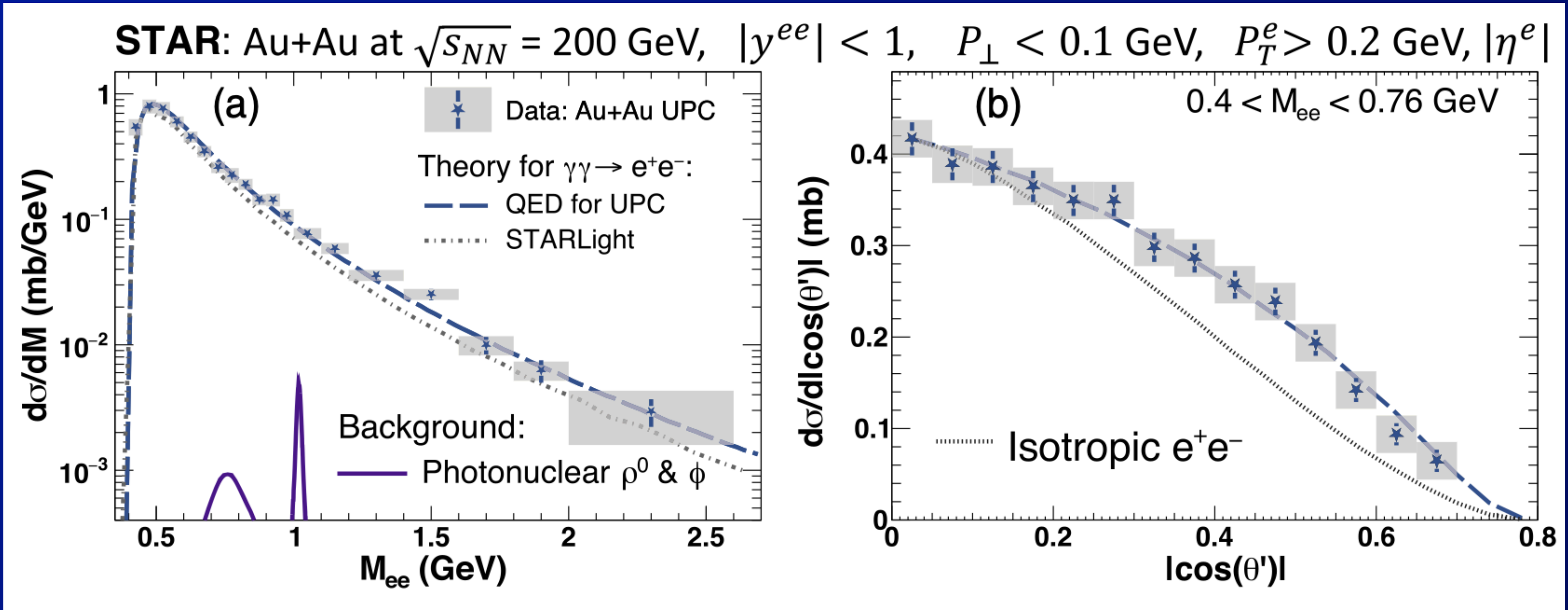
- Well-established calculations
- High-statistics measurements
- Good agreement with theory**

⇒ Declare success

ATLAS UPC e^+e^-
JHEP 06 (2023) 182

STAR exclusive e^+e^-

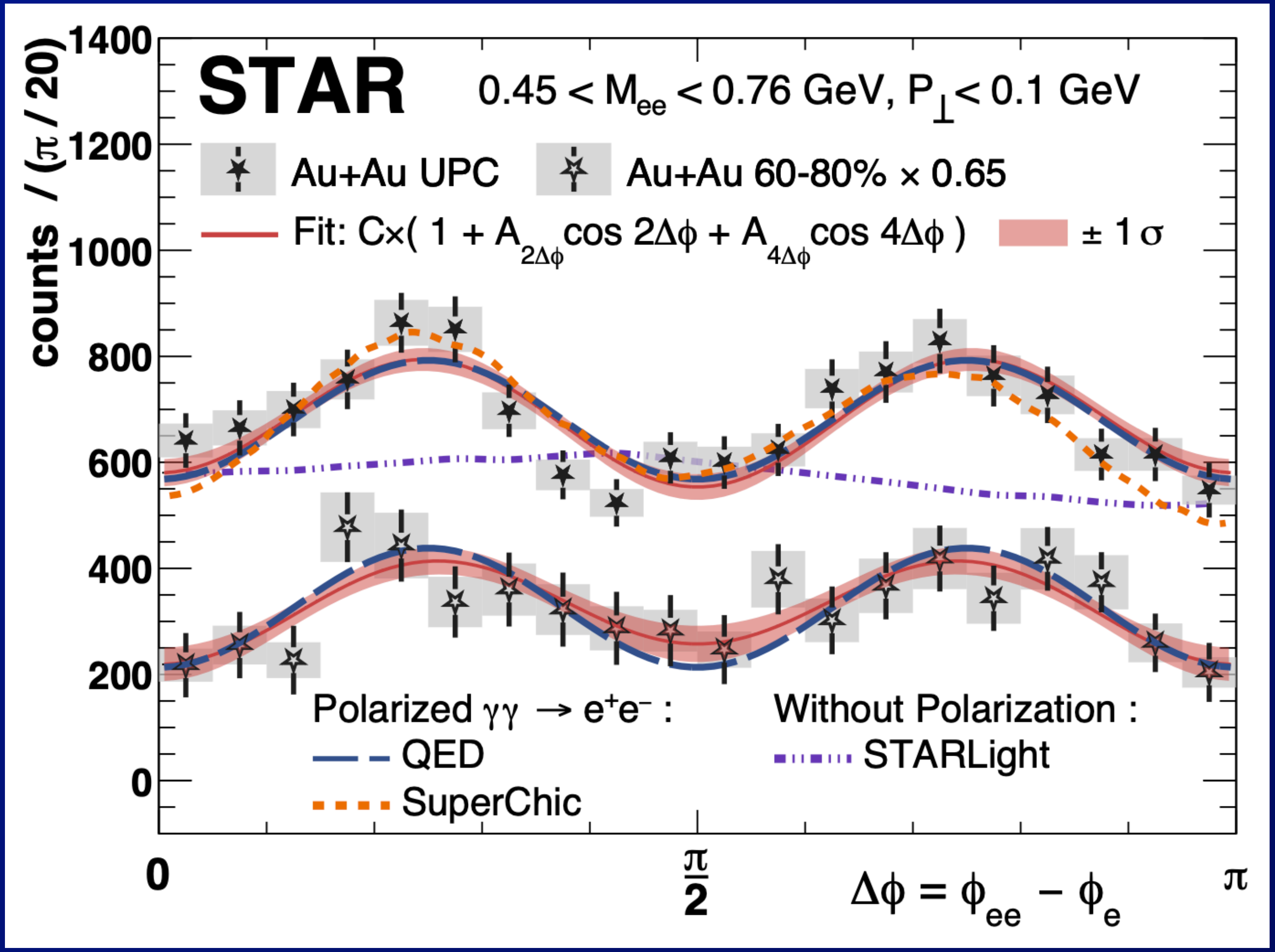
- **STAR UPC $\gamma+\gamma \to e^+e^-$ in 200 GeV Au+Au (L_{int} = 70 μb^{-1})**
  - $0.4 < M_{ee} < 2.6$ GeV, $p_{Tee} < 0.1$ GeV, $|y_{ee}| < 1$
- **Compared to STARLight and "QED" calculation**
  - ⇒STARLight slightly underpredicts data
  - ⇒QED calculation agrees well with data



PRL 127, 052302 (2021)

STAR exclusive e^+e^-

- **First measurement of the angular correlation between lepton pair p_T vector and lepton ϕ angles**
  - possible due to the low electron p_T values and << material

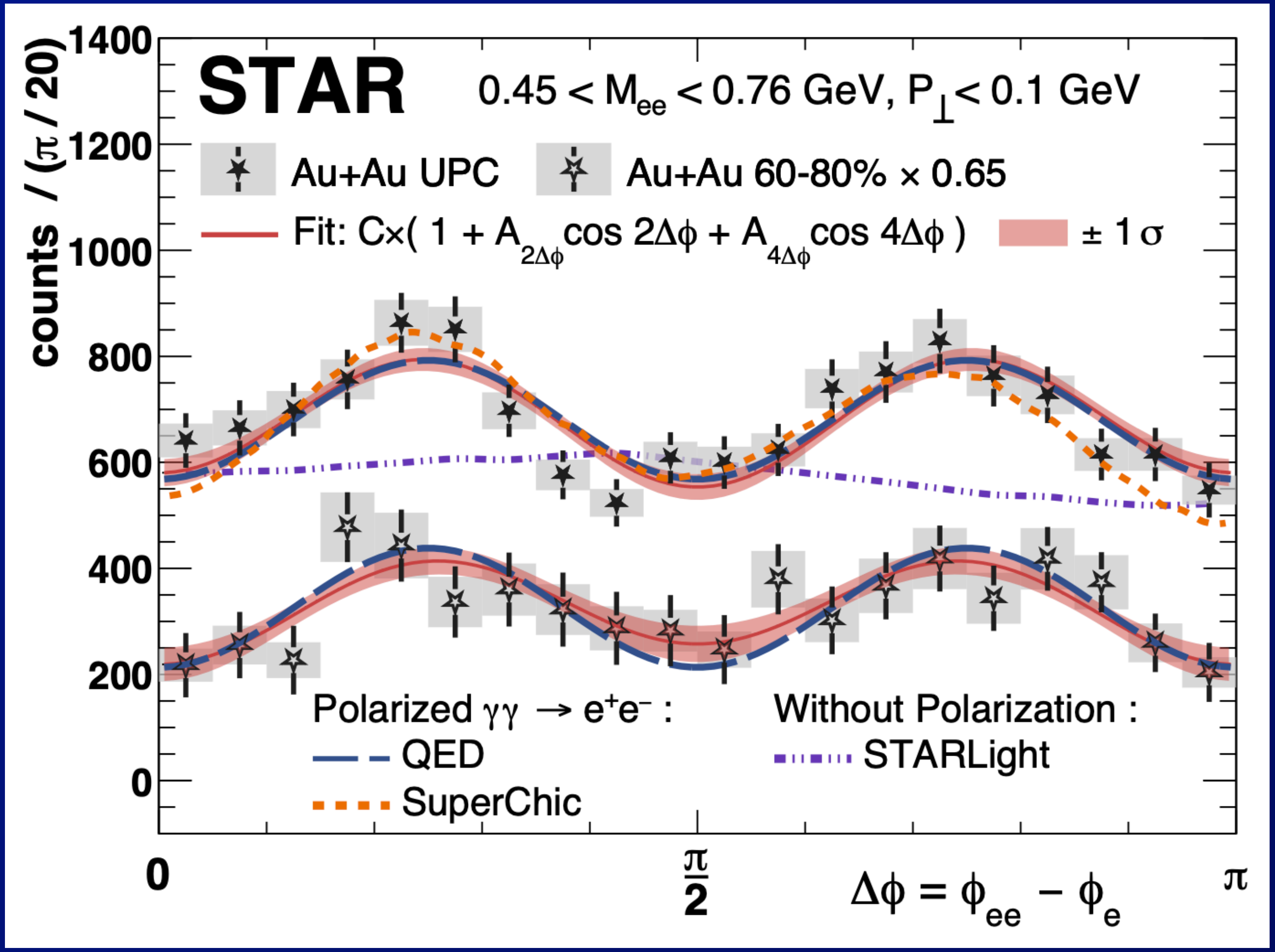


STAR exclusive e^+e^-

- First measurement of the angular correlation between lepton pair p_T vector and lepton ϕ angles
  - possible due to the low electron p_T values and << material

- Compare to calculations:
  - Reasonable agreement with QED and SuperChic

  ⇒ QED: $\cos(4\Delta\phi)$ modulation from linear polarization of the photons

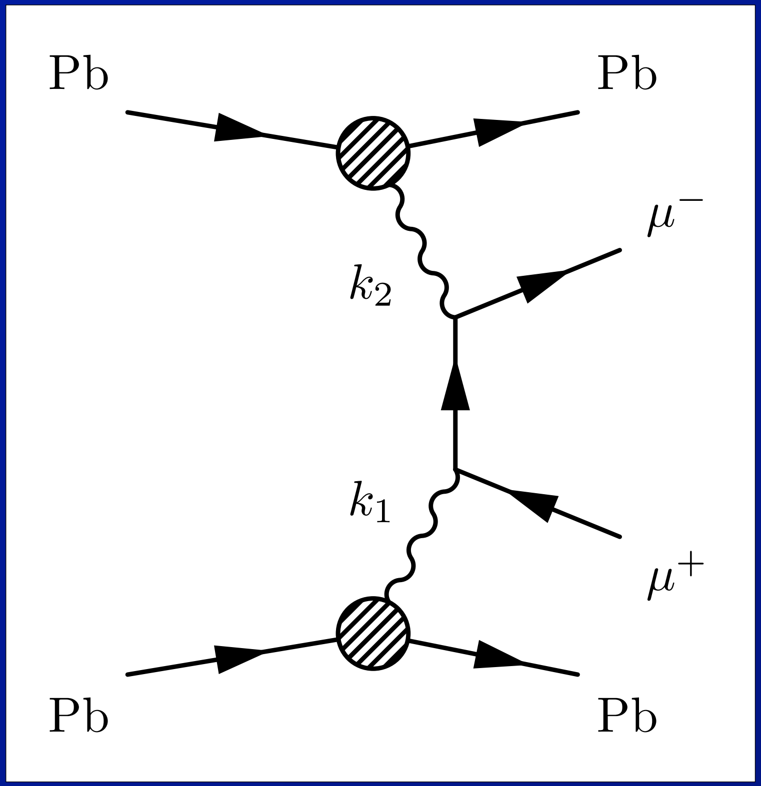


γ+γ scattering and forward neutrons

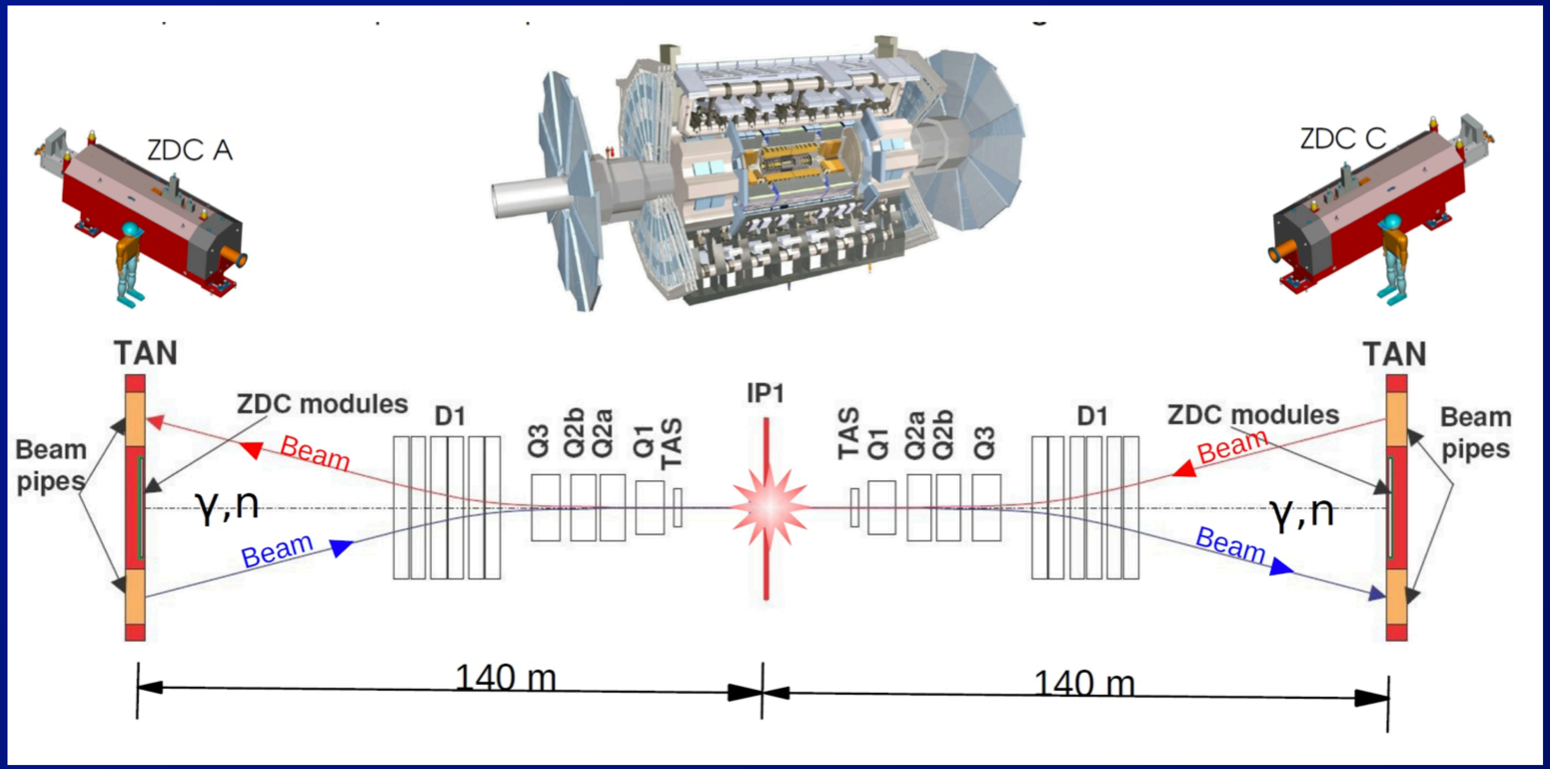
Nuclear breakup via Coulomb Excitation

- In Pb+Pb γ+γ, coherent photons dominate

⇒Nominally: no forward neutrons in 0 degree calorimeters



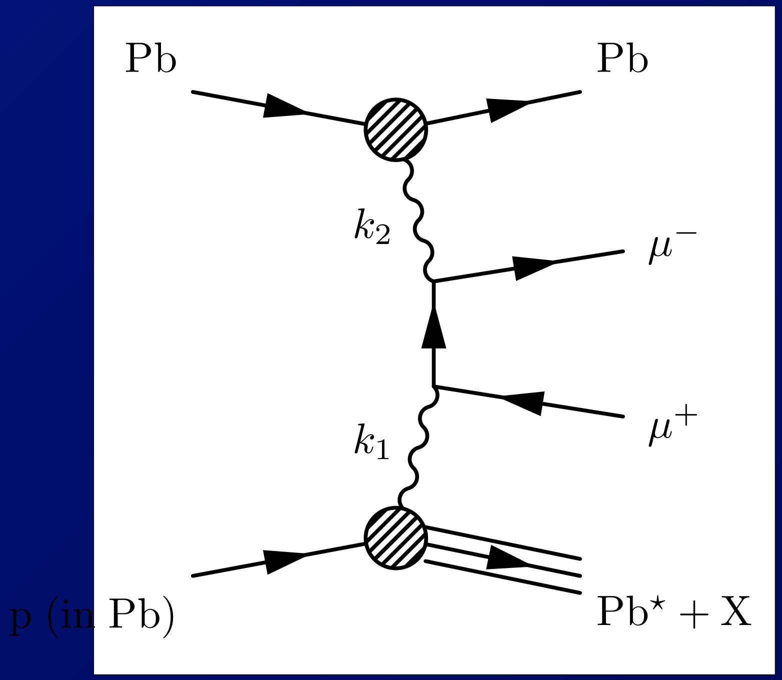
"0n0n"



- However, long-range EM interactions can induce giant dipole resonance++

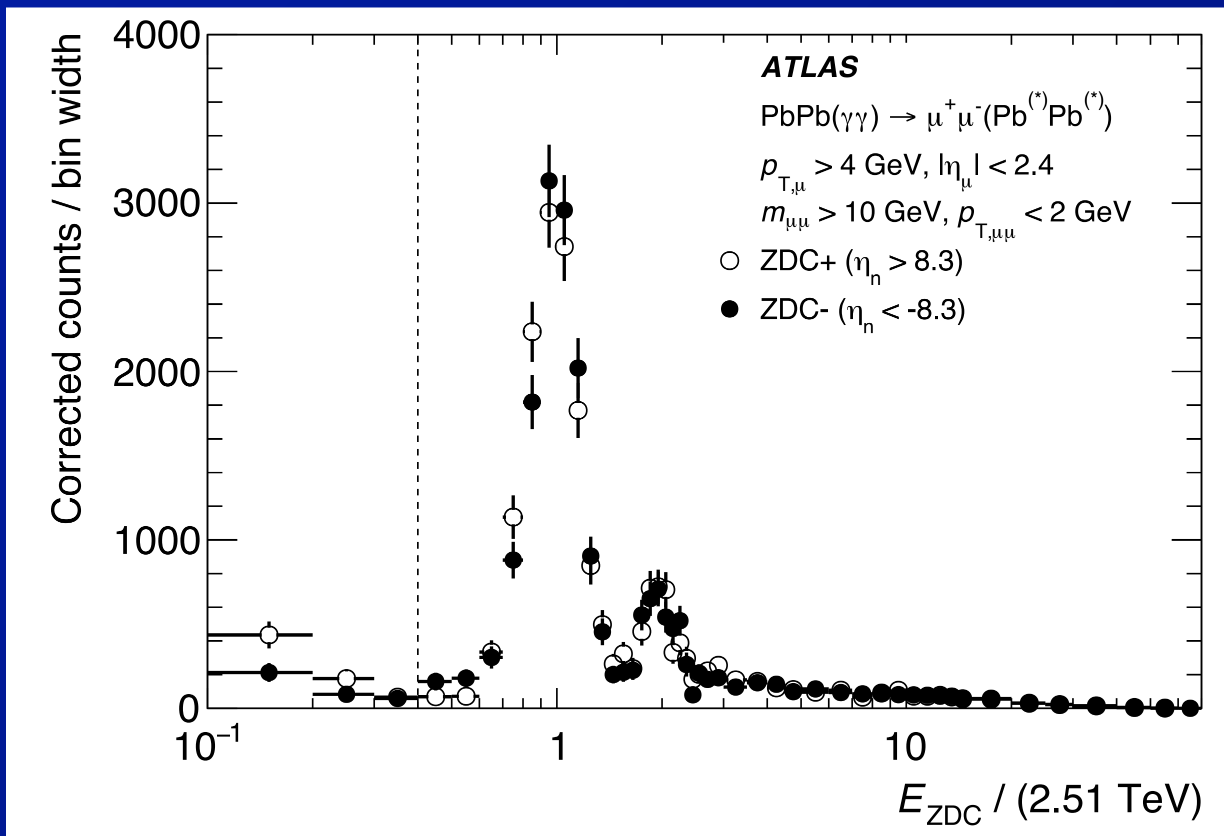
⇒Emission of 1 or more neutrons by one or both nuclei

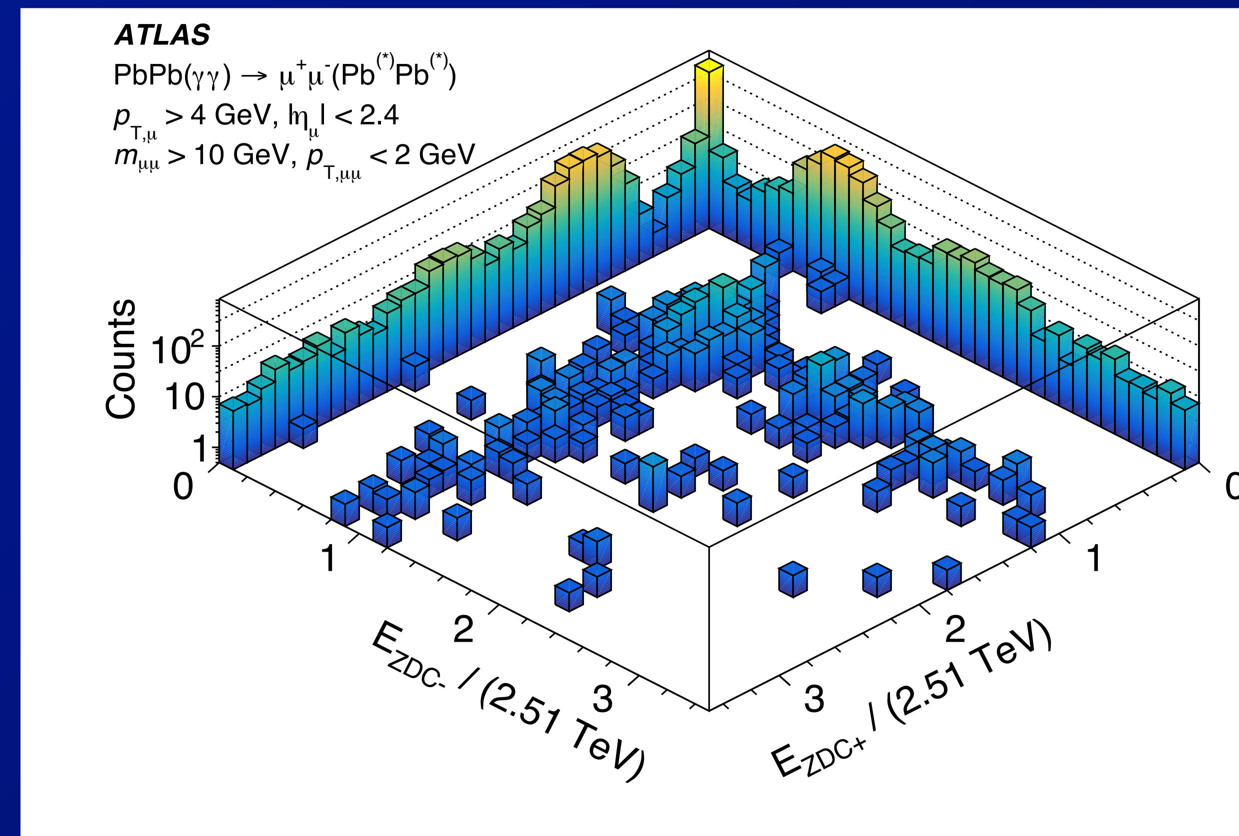
⇒Explore with ATLAS γ+γ→μ+μ-



γ+γ→μ⁺μ⁻, nuclear breakup

- Event topology as seen in the two ZDCs

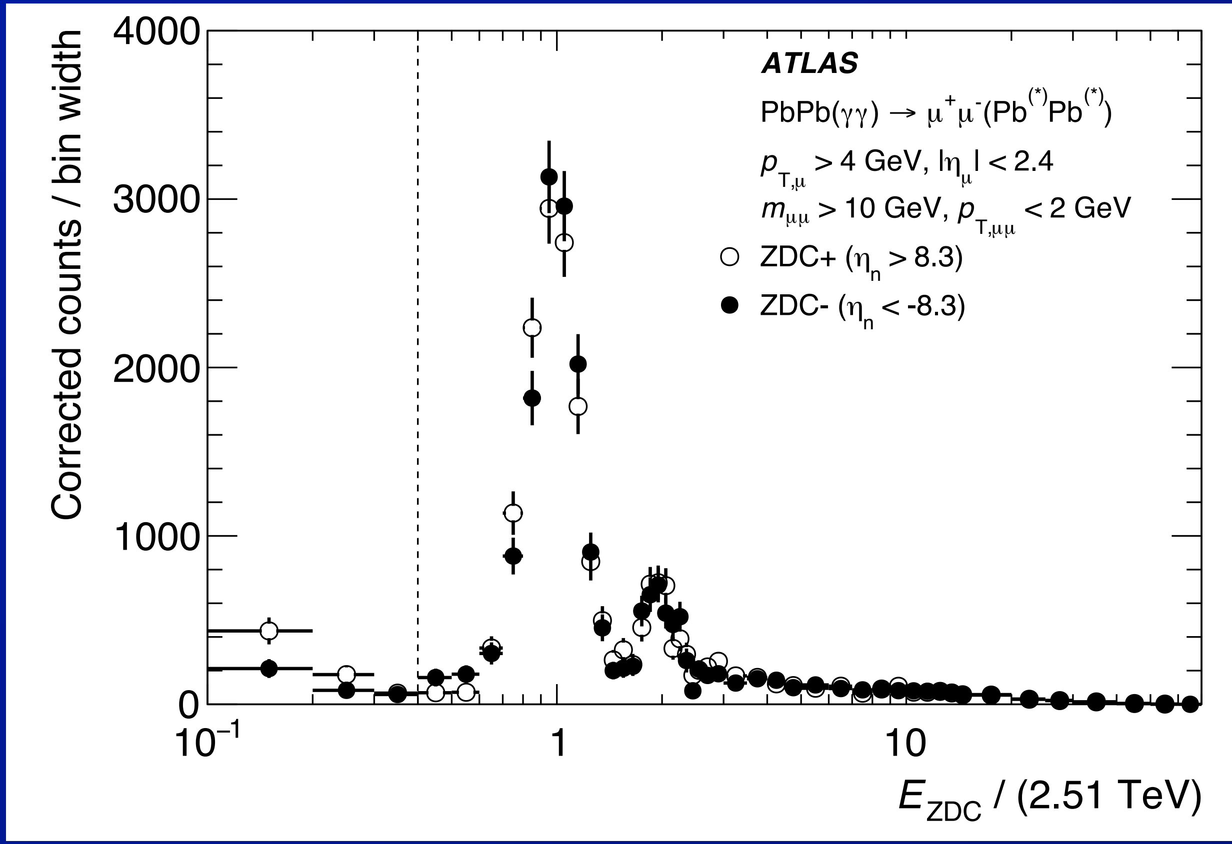


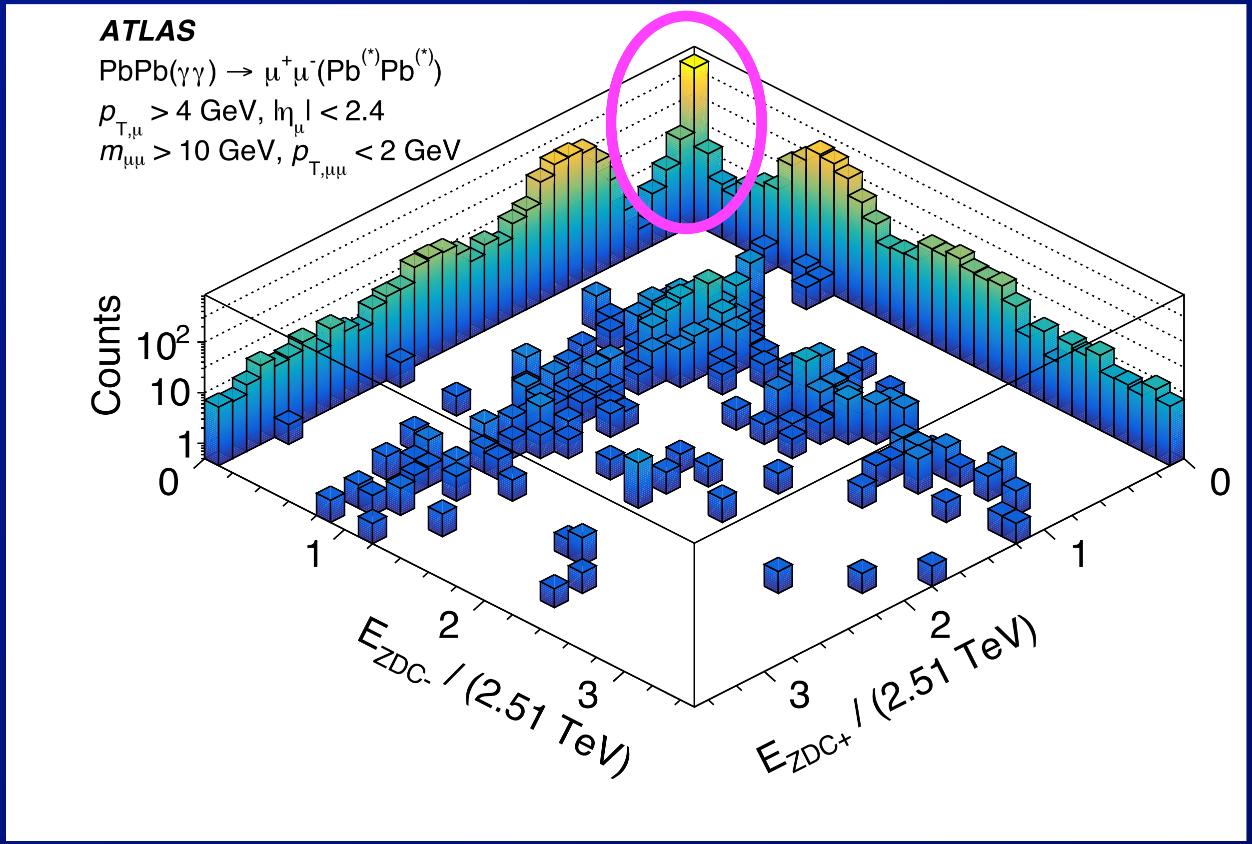


Phys. Rev. C 104 (2021) 024906

$\gamma+\gamma \rightarrow \mu^+\mu^-$, nuclear breakup

- Event topology as seen in the two ZDCs





– 0n0n - no neutrons in either ZDC

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γ+γ→μ⁺μ⁻, nuclear breakup

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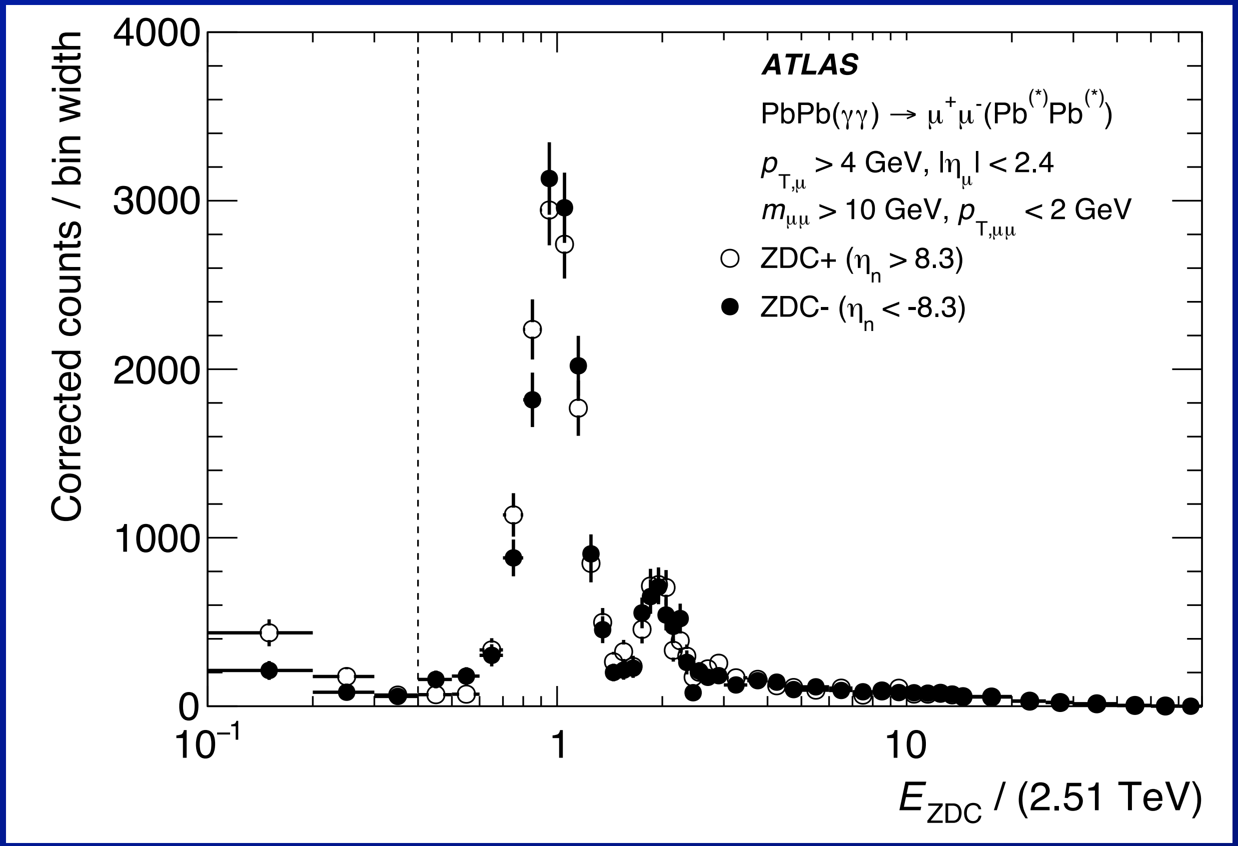
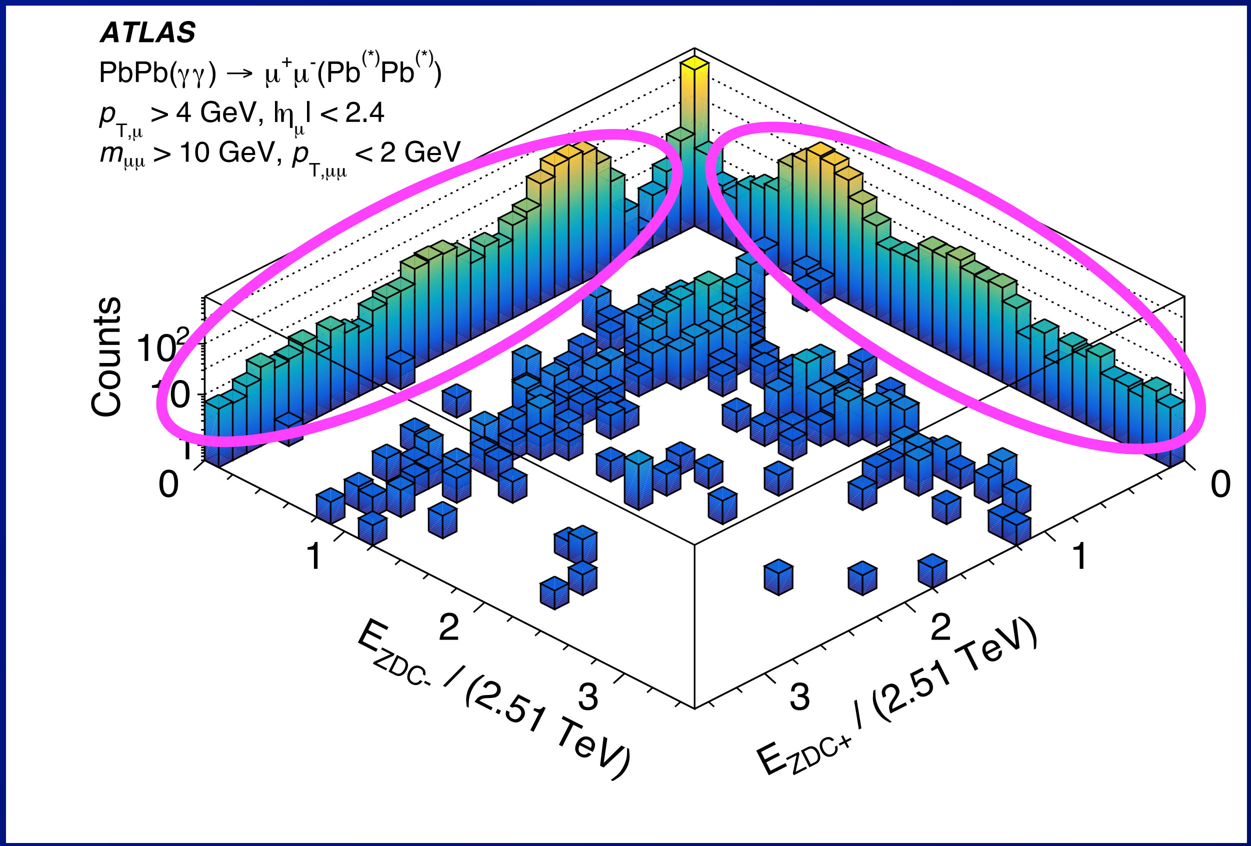




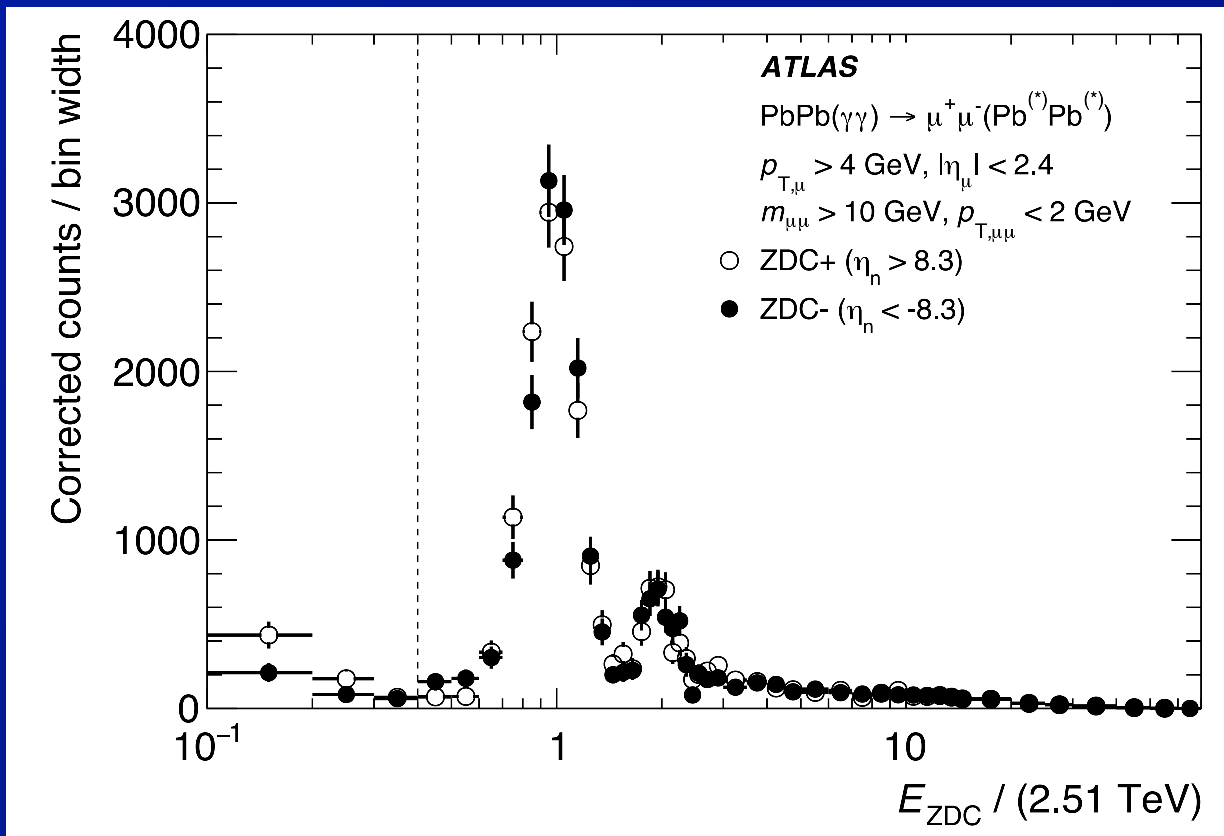
– 0nXn

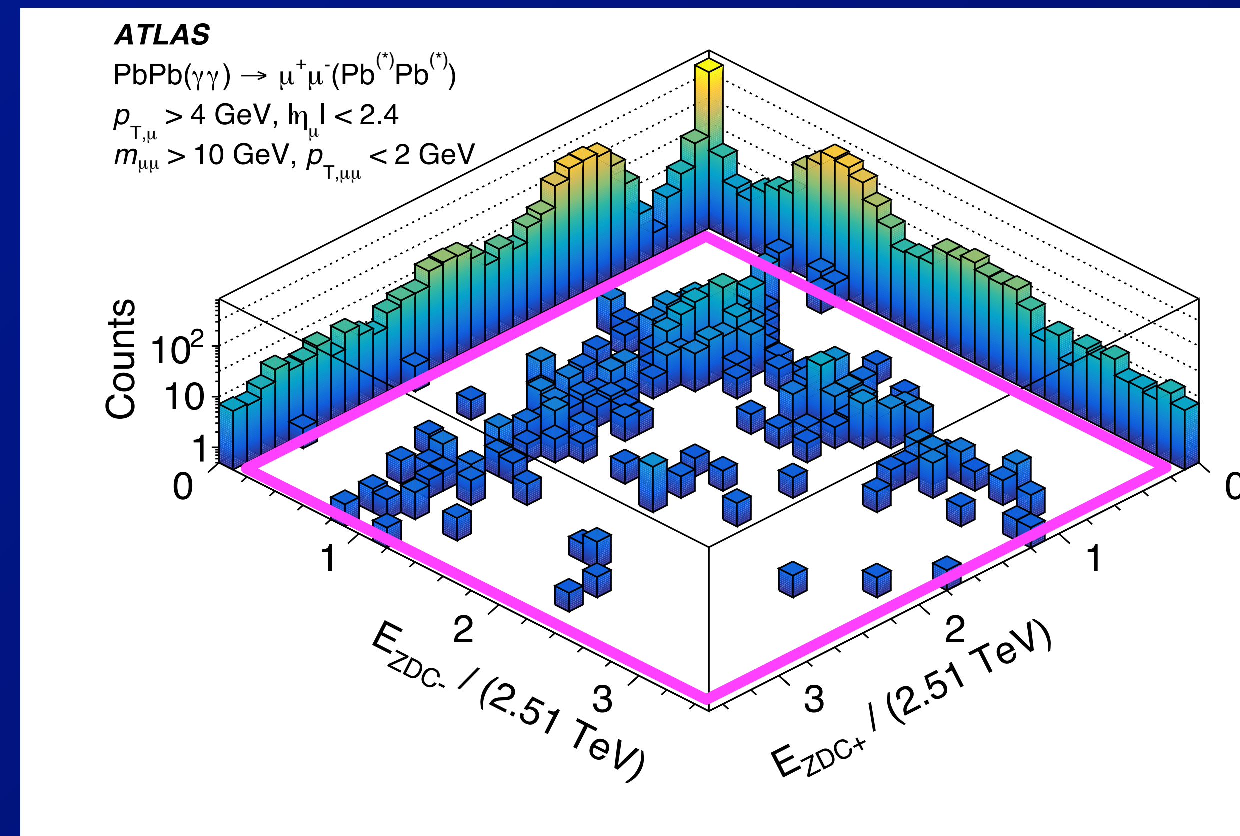
⇒ 0 neutrons in one

⇒ ≥ 1 in the other

$\gamma+\gamma \to \mu^+\mu^-$, nuclear breakup

- Event topology as seen in the two ZDCs



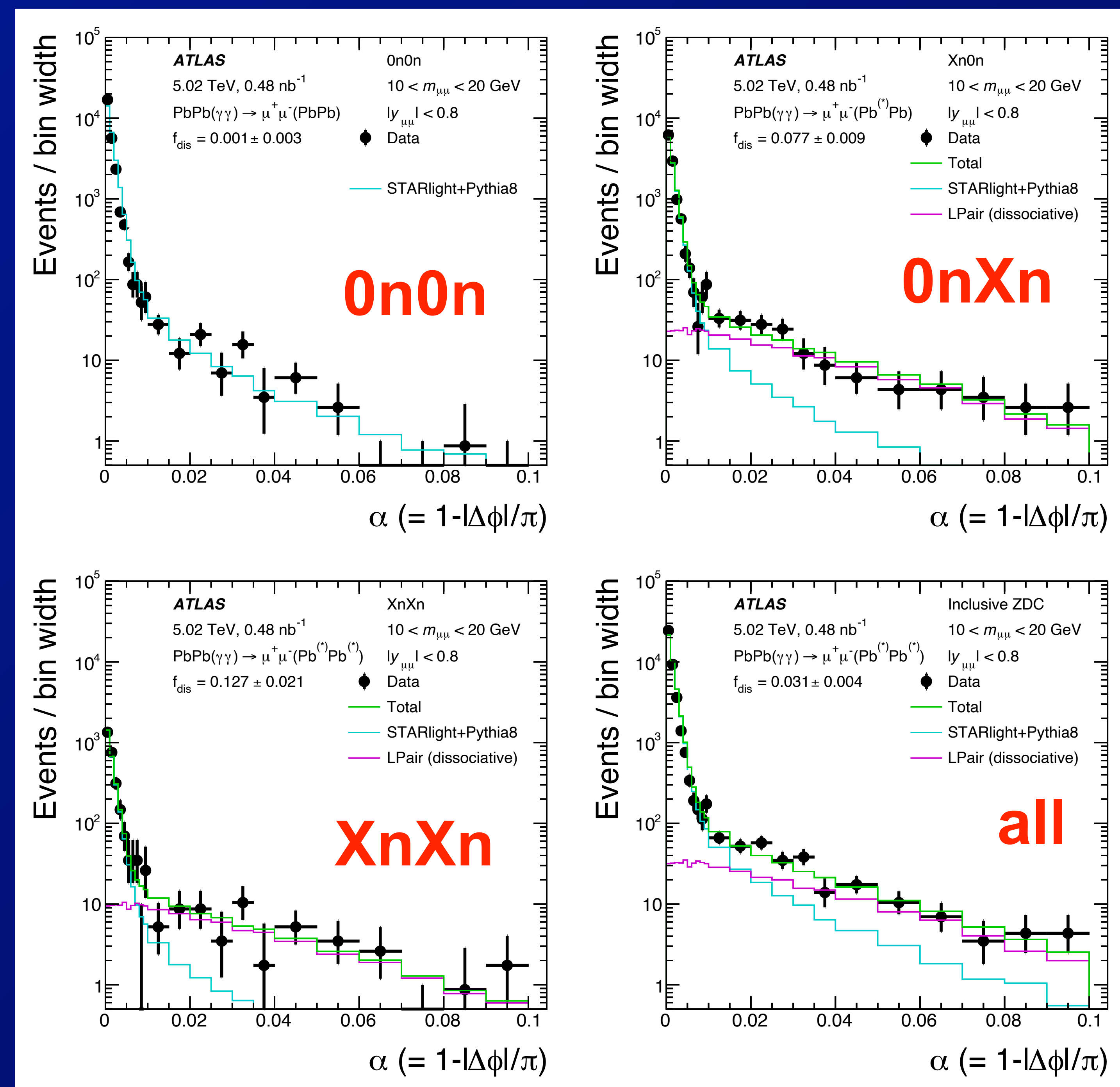


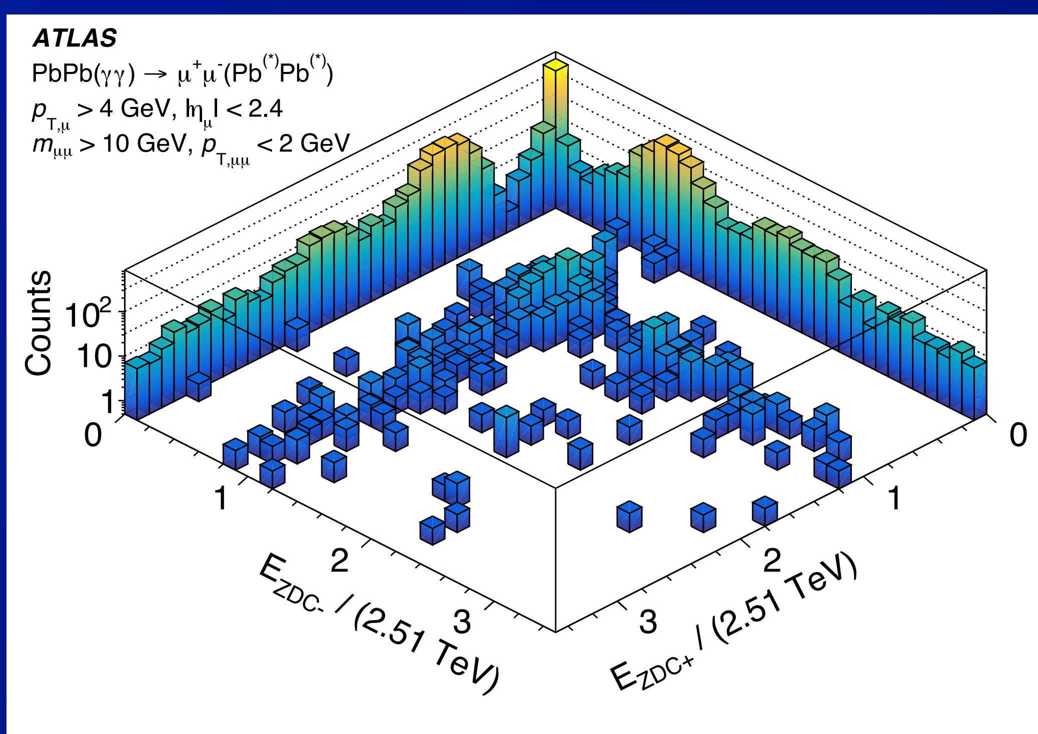
– XnXn

⇒≥ 1 neutrons in both

$\gamma+\gamma\rightarrow\mu^+\mu^-$, nuclear breakup

- **Dimuon acopolanarity distributions** $\alpha = 1 - \frac{\Delta\phi}{\pi}$
  - for different topologies
    - ⇒Large-acoplanarity tails change shape for different neutron topologies





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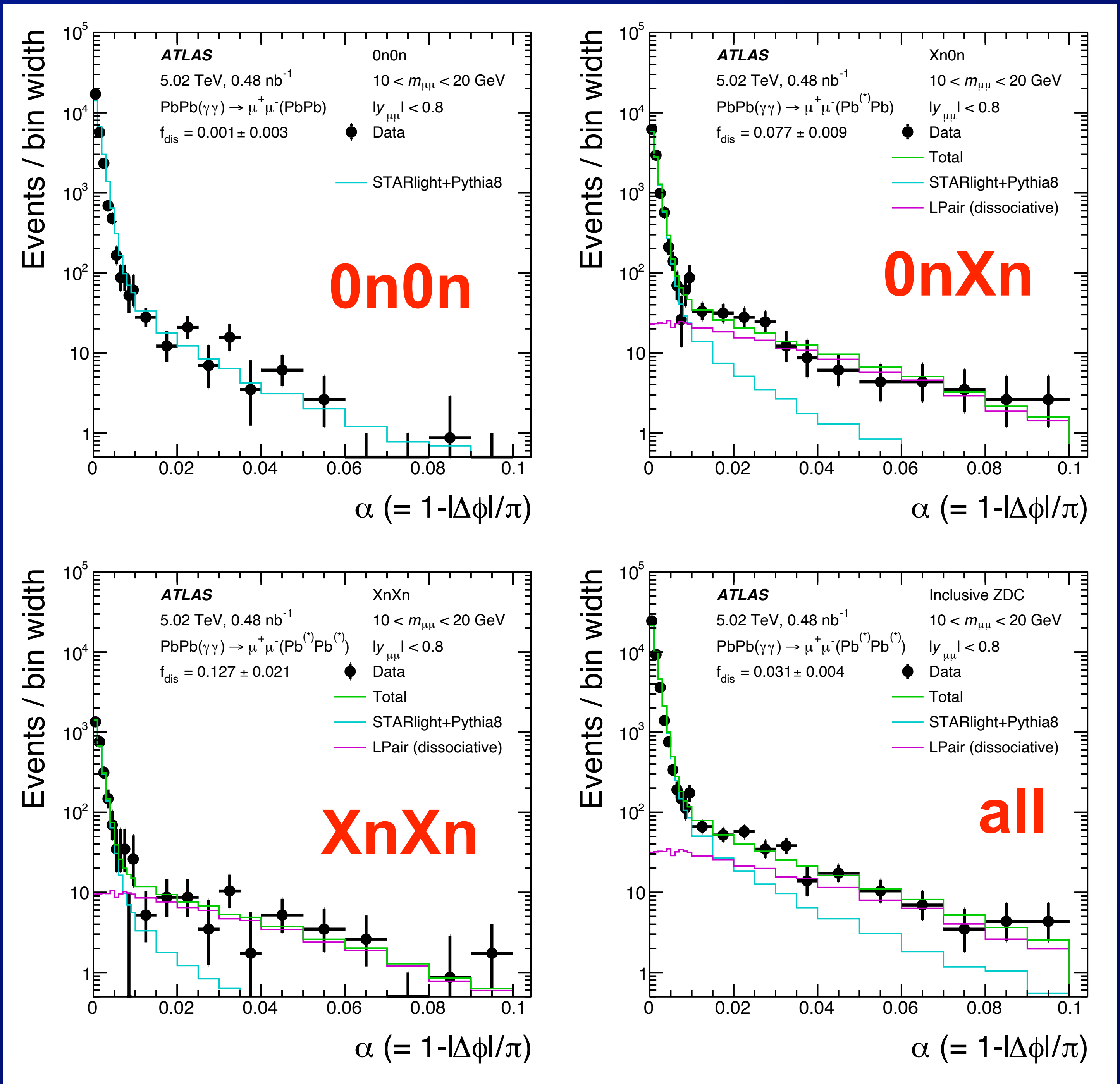

- **Dominant effect:**
  - Dissociative emission of photons *a la* pp
    - ⇒ Described by LPair

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γ+γ→μ⁺μ⁻, nuclear breakup

- **Dimuon acopolanarity distributions**

$$\alpha = 1 - \frac{\Delta\phi}{\pi}$$

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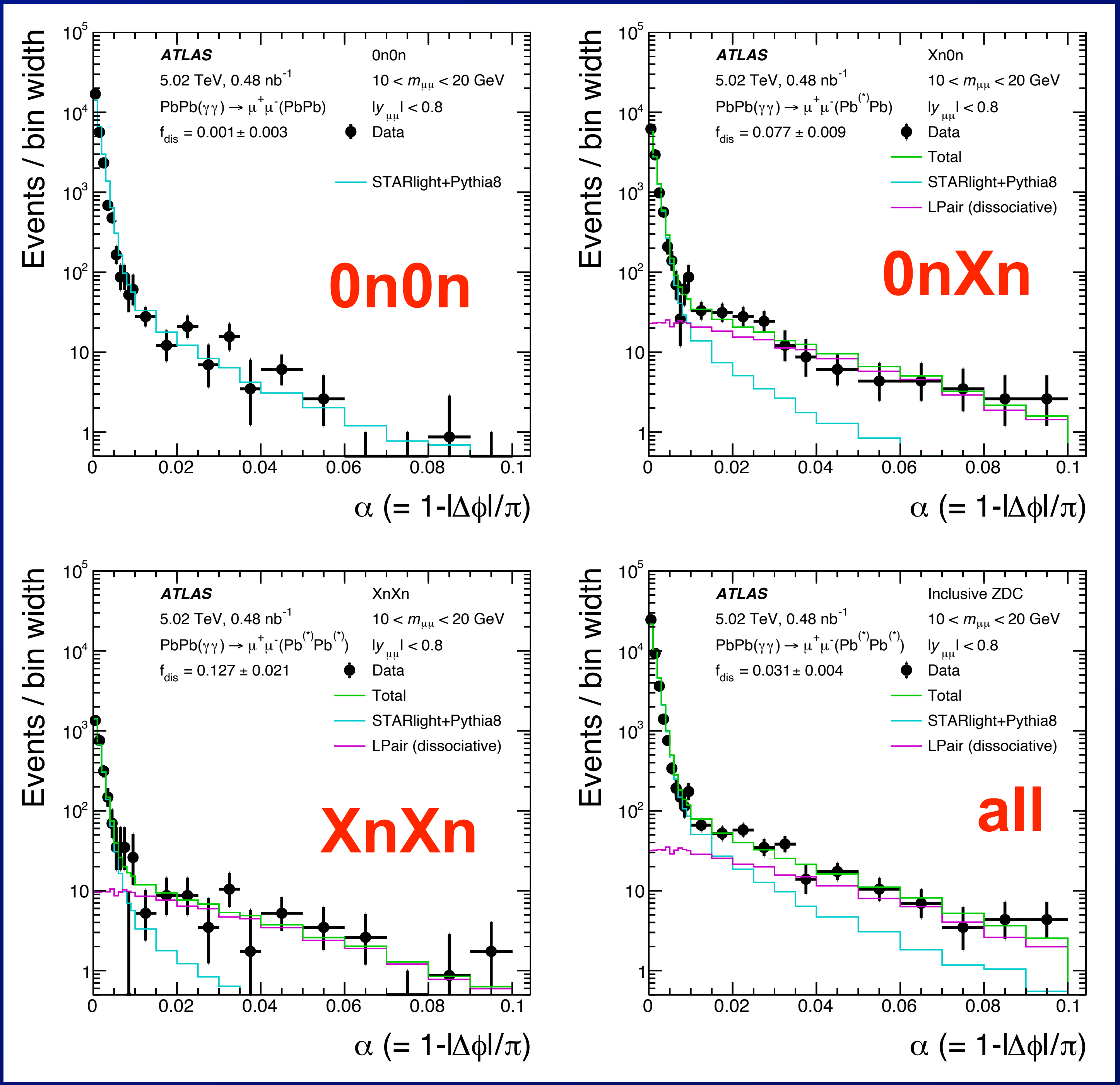

- **More generally**
  - Forward neutron rejection (i.e. 0n0n requirement) reduces γγ backgrounds
    - ⇒γ+A, diffractive, dissociative γ

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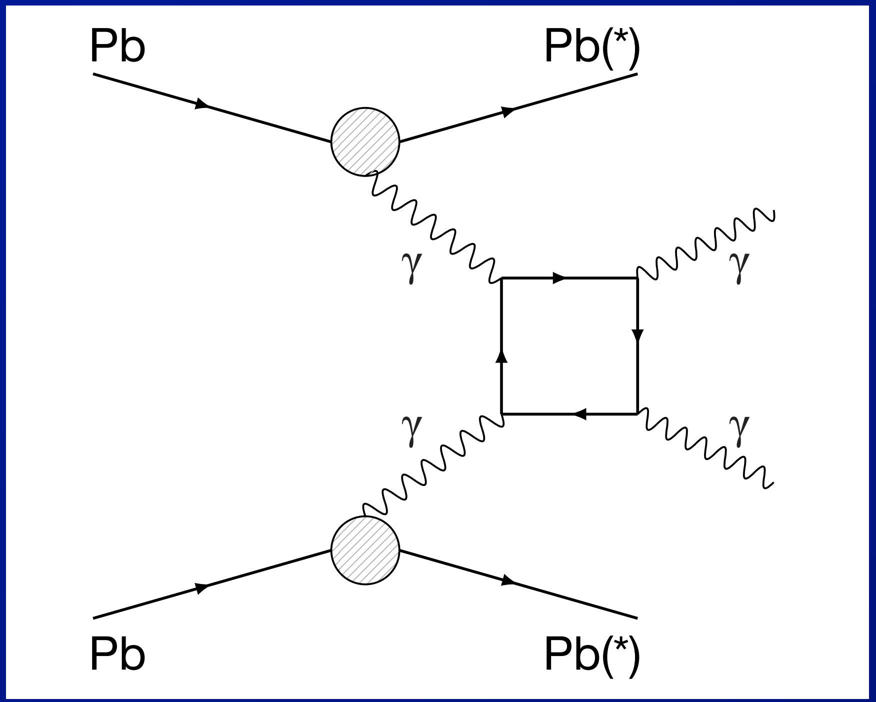
Light-by-light scattering

Light-by-light

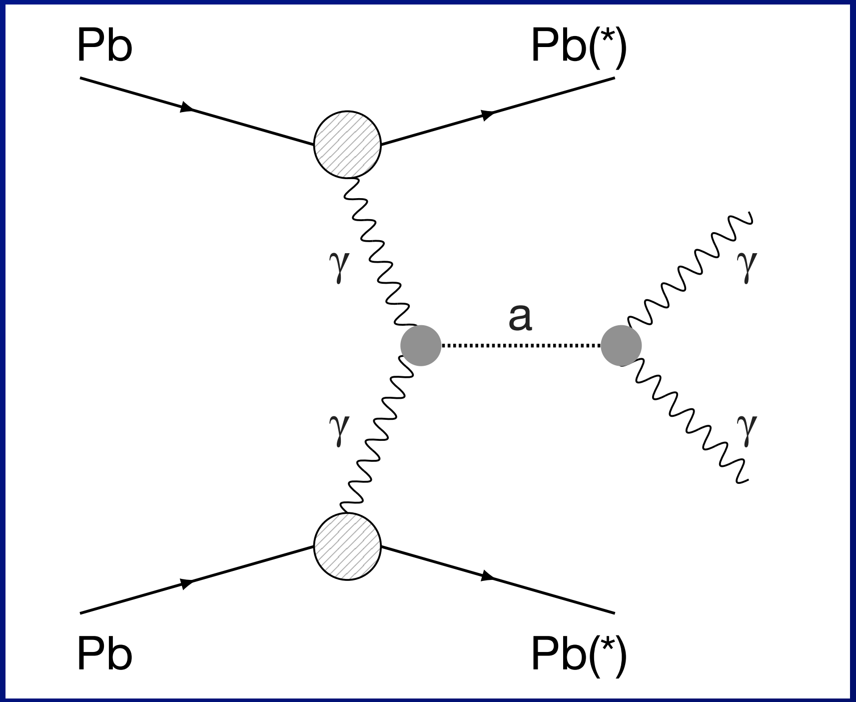
- Light-by-light scattering of (≈) real photons was discovered @ LHC
  - by both ATLAS and CMS
  - now being used to search from BSM physics

  ⇒e.g. axion-like particles (ALP)

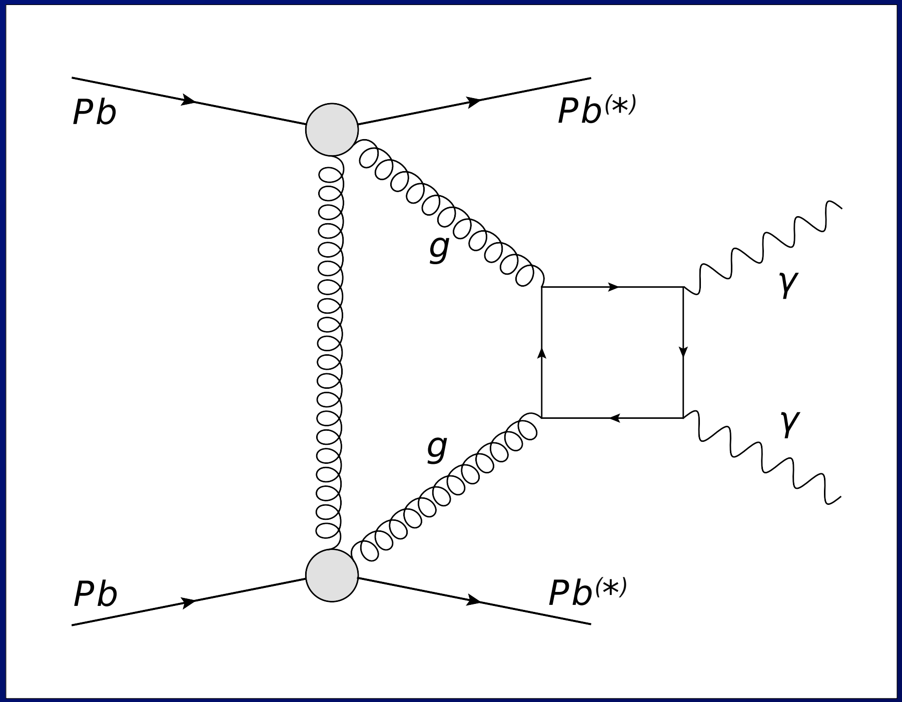
- Diagrams for three processes:



SM L-by-L



L-by-L ALP



CEP g+g→γγ (Background)

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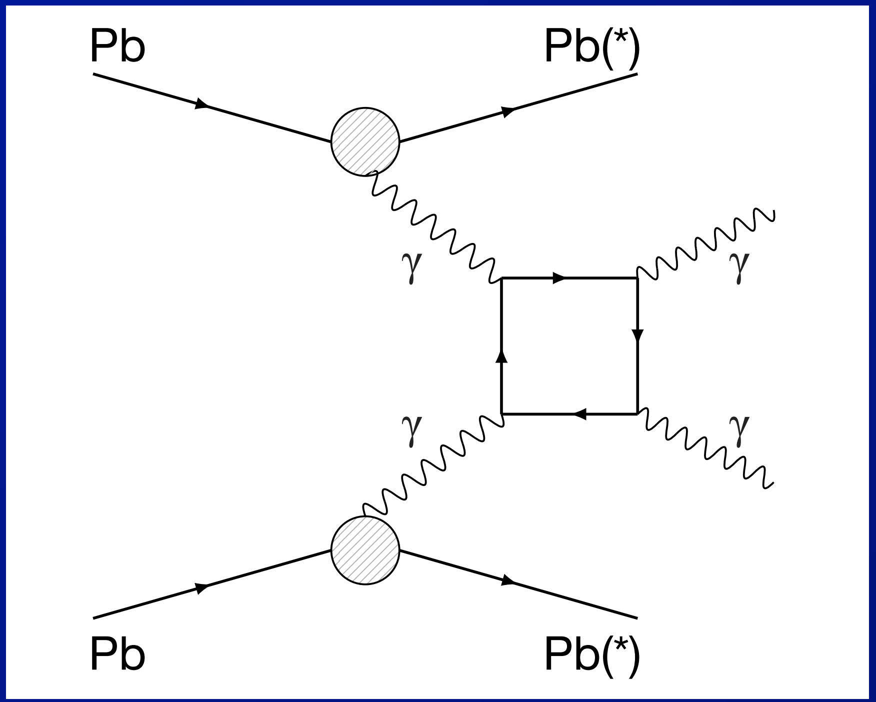
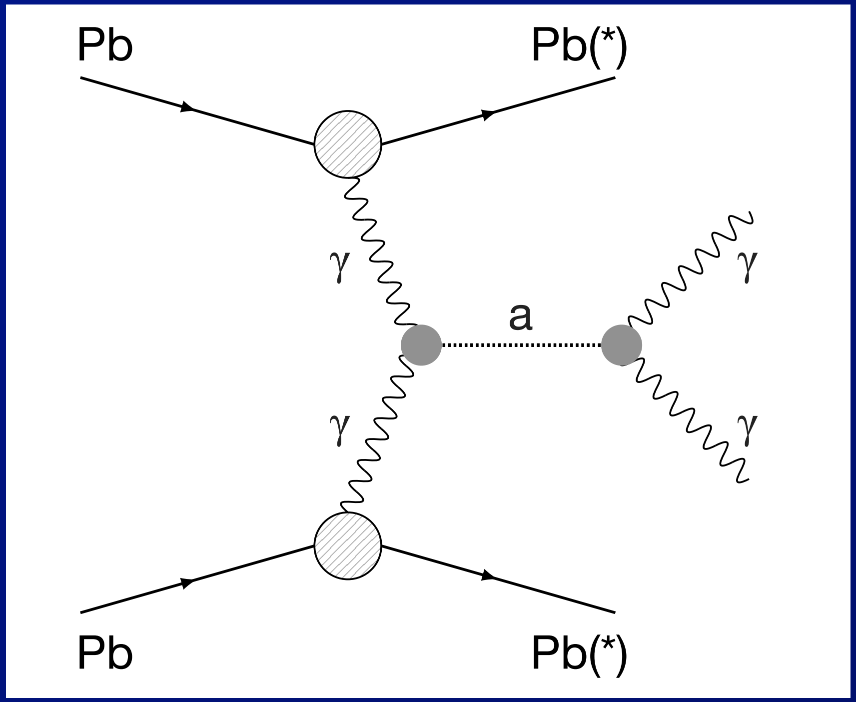
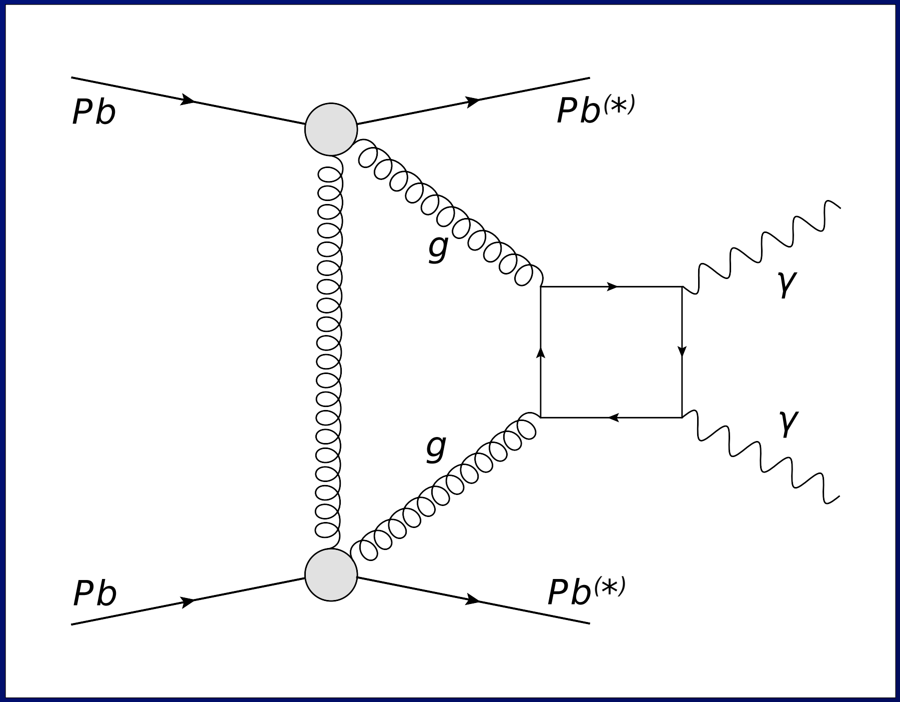
- **Diagrams for three processes:**



SM L-by-L



L-by-L ALP



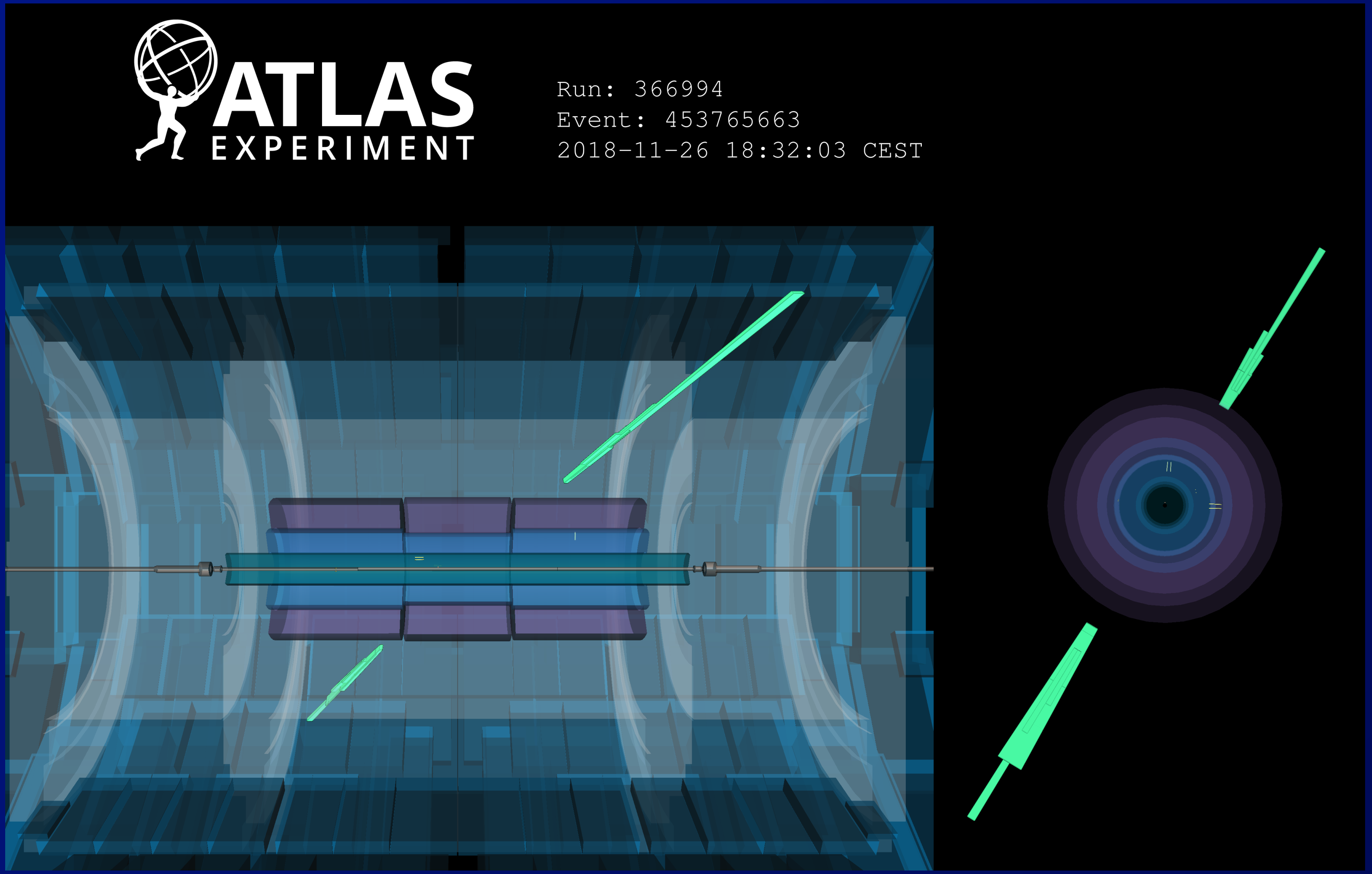
CEP g+g→γγ

nuclear breakup likely

ATLAS Light-by-Light Observation

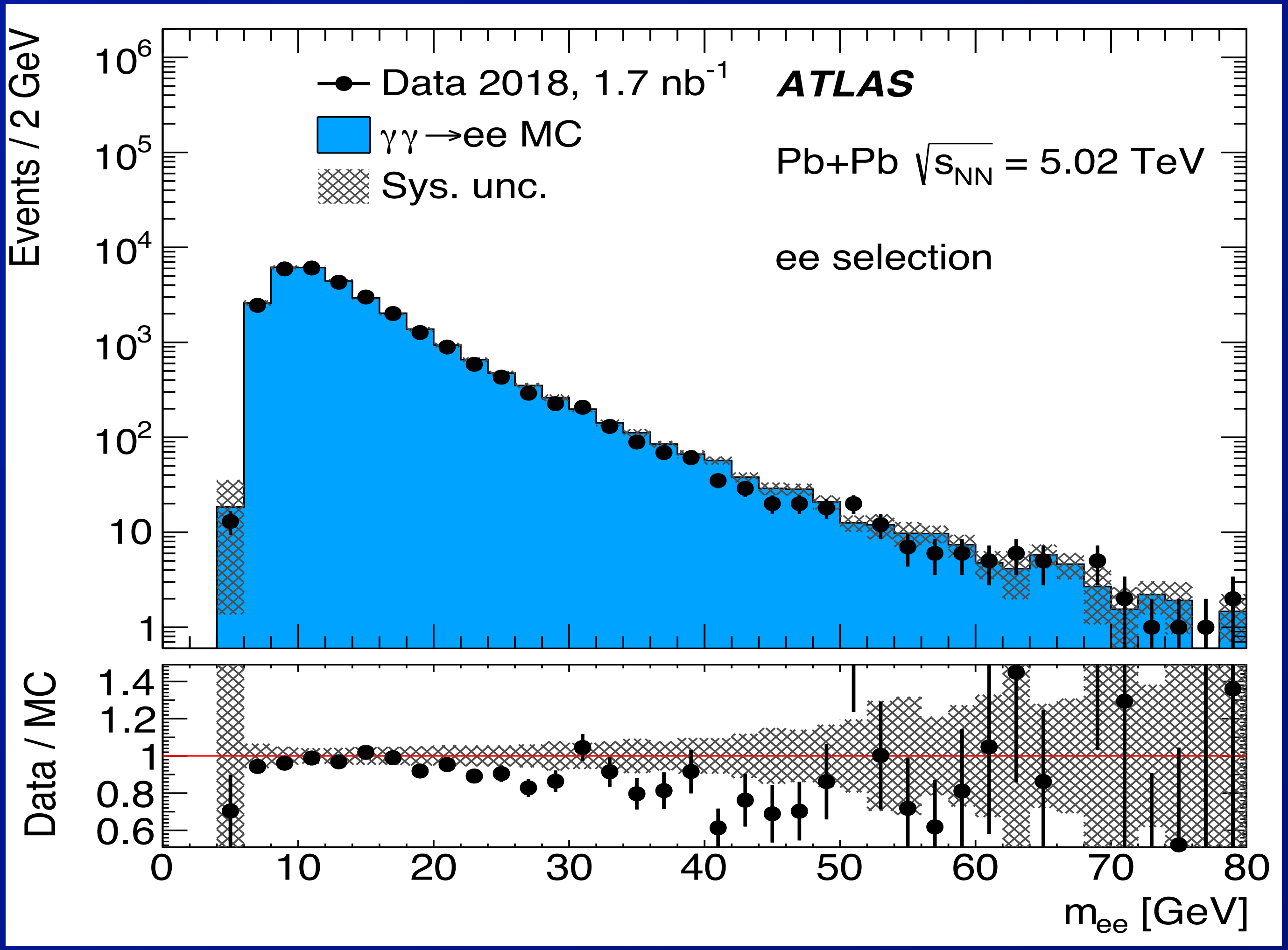
- Using 2018 data, Pb+Pb @ 5.02 TeV (1.7 nb^{-1})
- Exclusive γγ events (no tracks):
  - $E_{T\gamma} > 2.5$ GeV, $|\eta|_\gamma < 2.37$ (excl 1.37-1.52)
  - $m_{\gamma\gamma} > 5$ GeV
  - $p_{T\gamma\gamma} < 1(2)$ GeV, $A_\phi < 0.01$

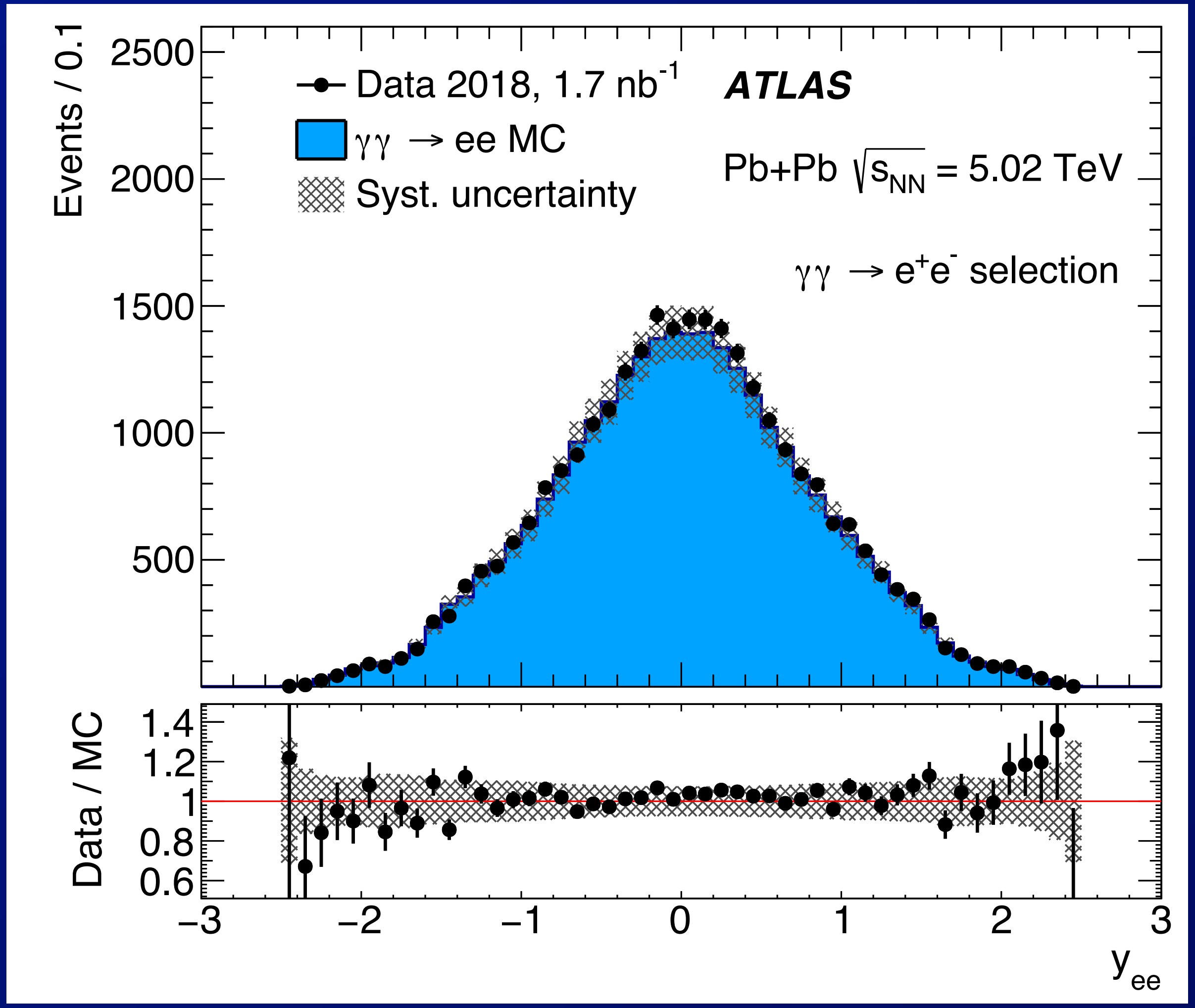
Phys. Rev. Lett. 123 (2019) 052001



ATLAS Light-by-Light Observation

- exclusive e^+e^- used to validate EM energy scale, trigger & reco. efficiencies

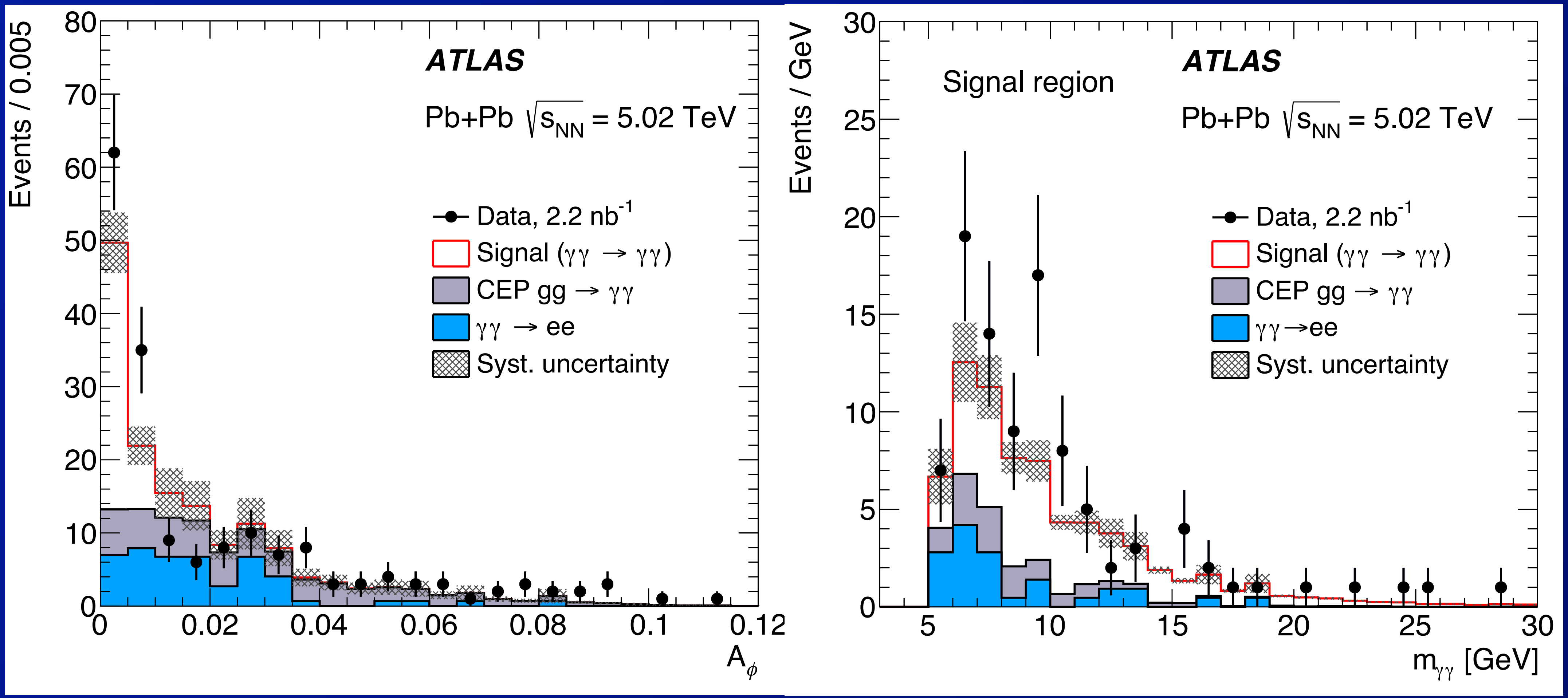




Phys. Rev. Lett. 123 (2019) 0520

ATLAS Light-by-Light Observation

- CEP bkgd from MC, normalized w/ data, $A_\phi > 0.01$



- 97 events observed, background: 27 ± 5

⇒σ_{fid} = 120 nb ±17 (stat.) ±13 (syst.) ± 4 (lumi.)

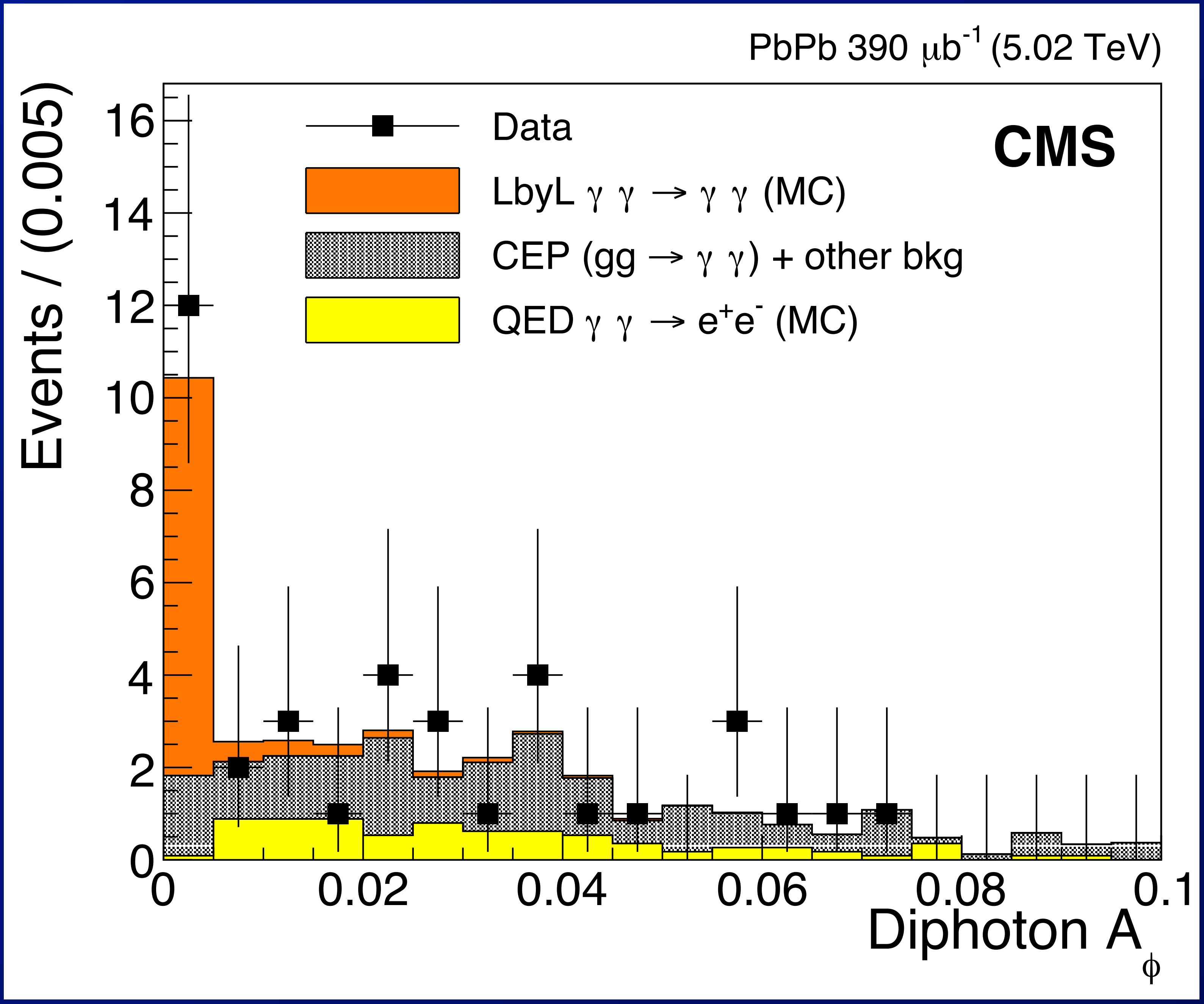
- Ratio to theory(ies):

⇒ (combining) 1.5 ± 0.3

PRL 123 (2019) 052001

CMS Light-by-Light measurement

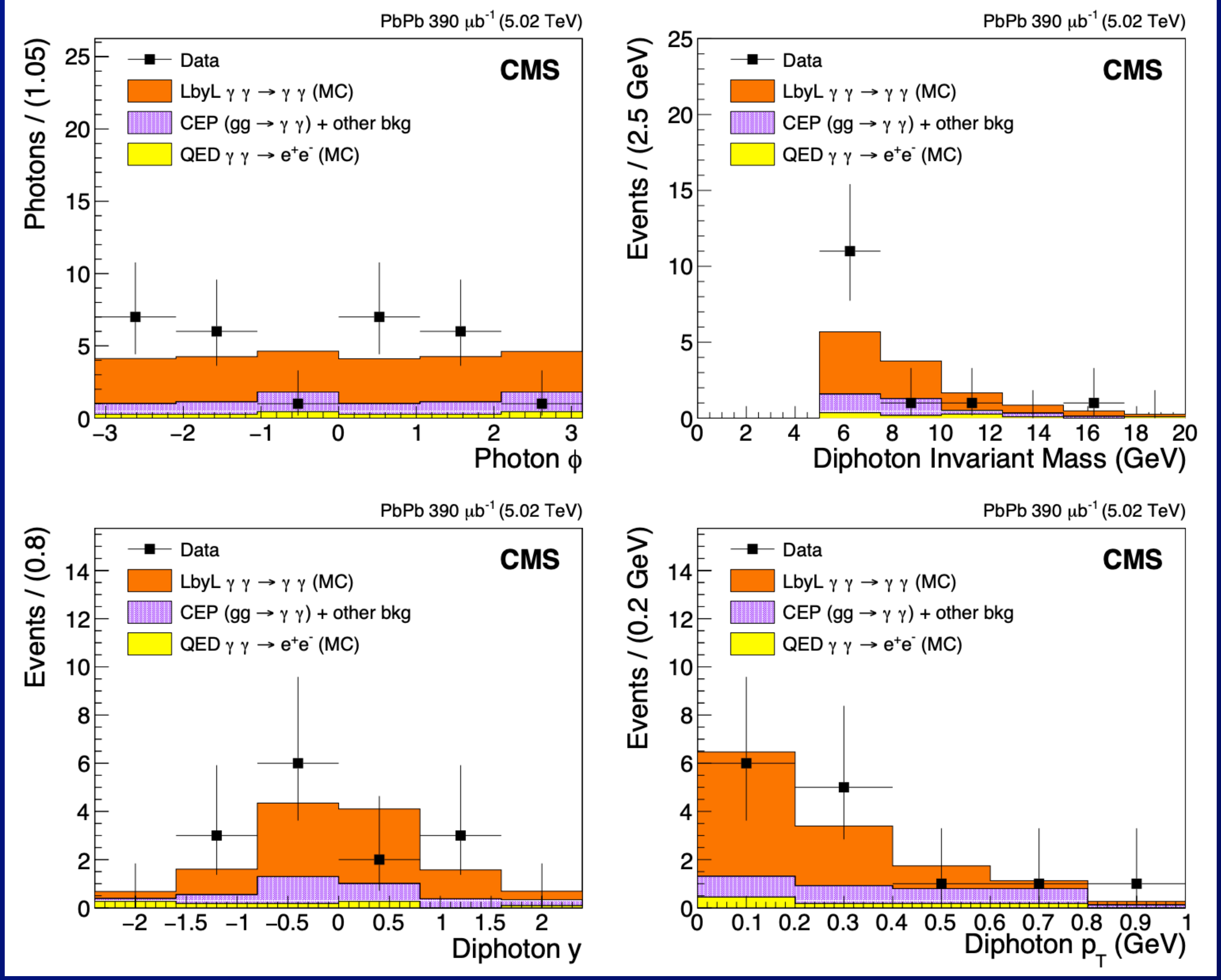
- Using 2015 data set (0.39 nb^{-1})
- Exclusive $\gamma\gamma$ events
  - $E_{T\gamma} > 2$ GeV, $|\eta|_\gamma < 2.4$
  - $p_{T\gamma\gamma} < 1$ GeV, $A_\phi < 0.01$
- Estimate CEP background using $A_\phi > 0.02$



Phys. Lett. B 797 (2019) 134826

CMS Light-by-Light measurement

- Using 2015 data set (0.39 nb^{-1})
- Exclusive γγ events
  - $E_{T\gamma} > 2$ GeV, $|\eta|_\gamma < 2.4$
  - $p_{T\gamma\gamma} < 1$ GeV, $A_\phi < 0.01$



Phys. Lett. B 797 (2019) 134826

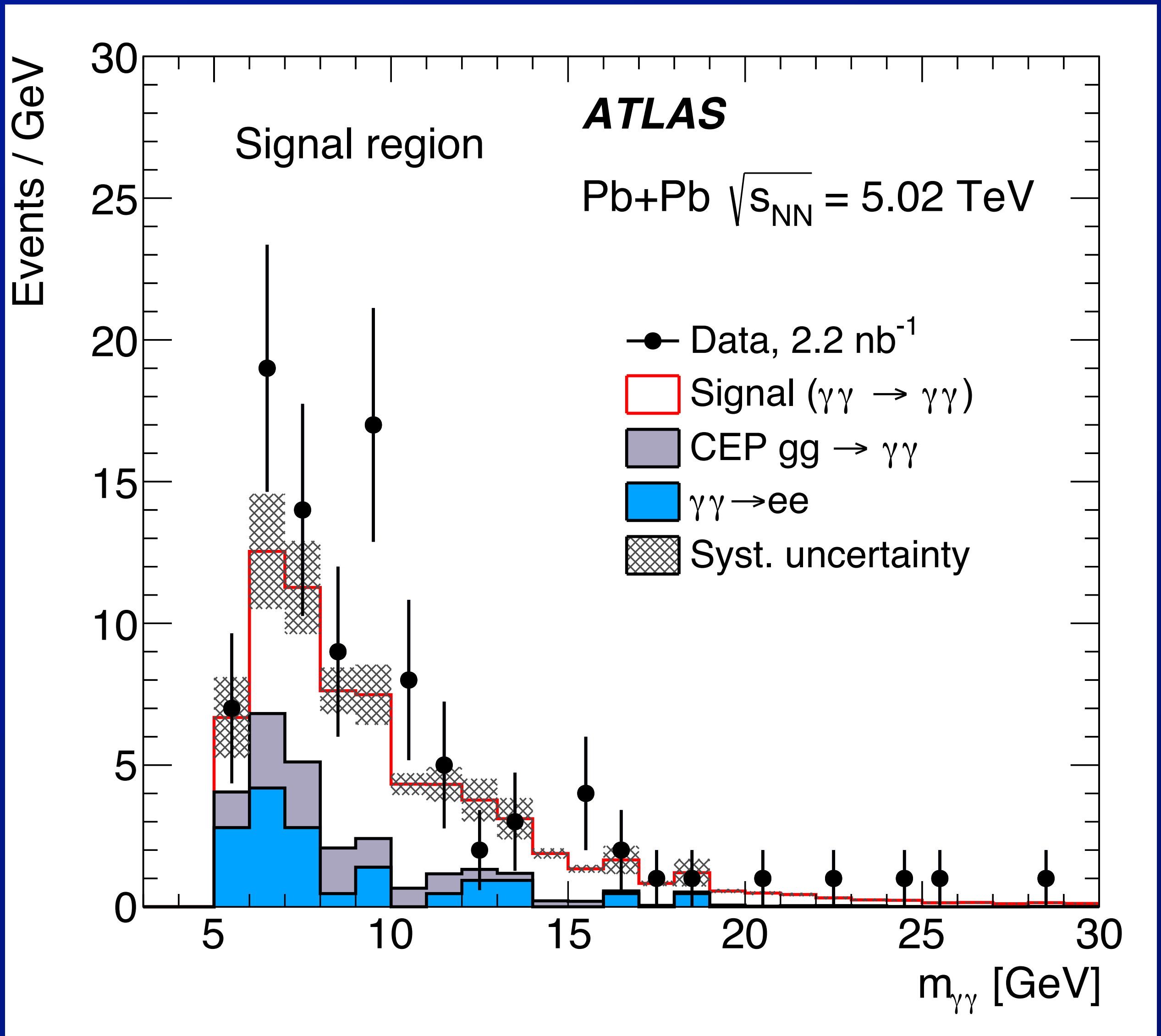
- Result: 14 L-by-L candidates
  - 9 ± 0.1 expected
  - 3.0 ± 1.1 CEP bkgd
  - 1.0 ± 0.3 e^+e^- bkgd

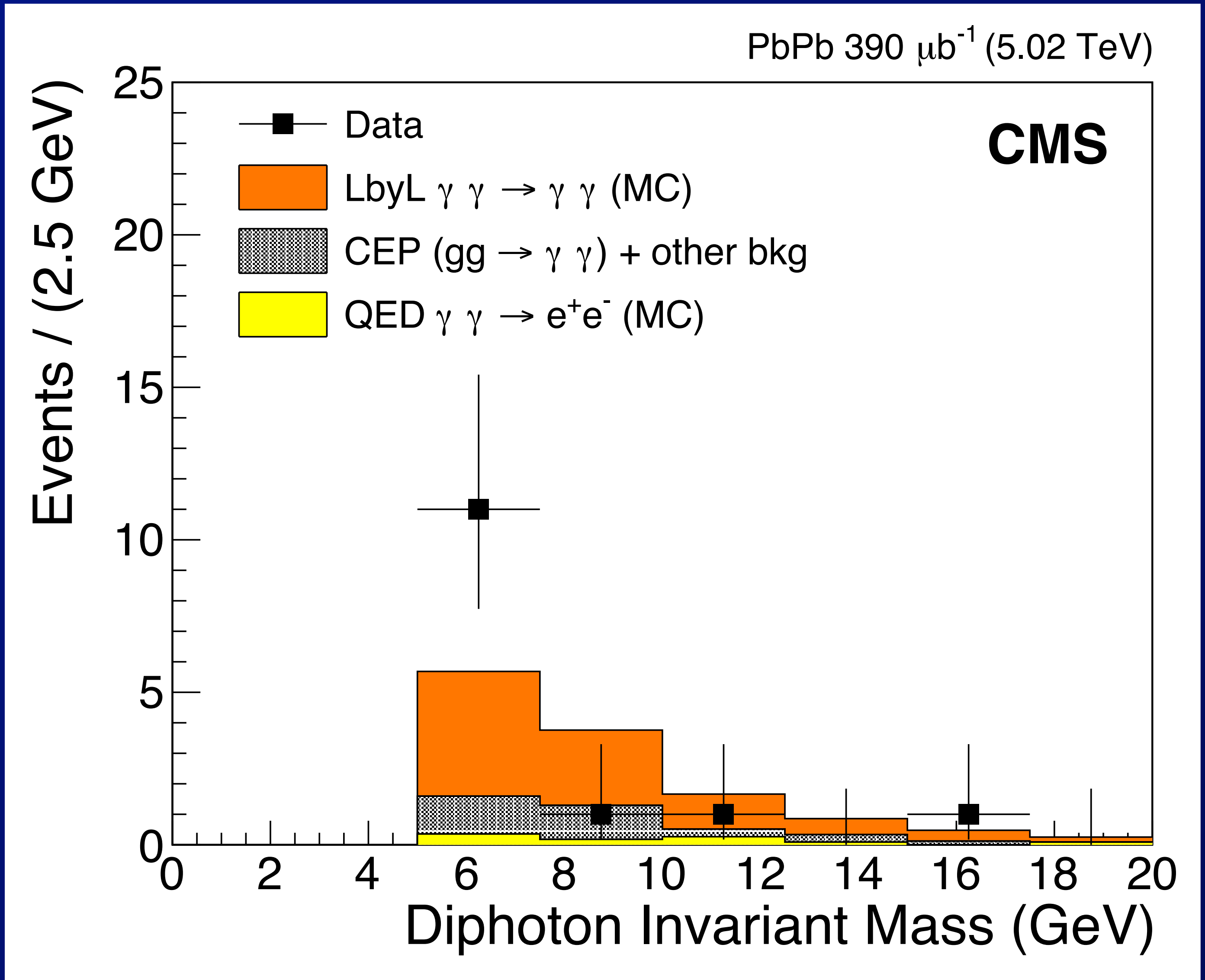
⇒ σ_{fid} = 120 ± 46 (stat) ± 28 (syst) ± 12 (theo) nb

⇒ Theoretical: $\sigma_{fid}(\gamma\gamma \to \gamma\gamma)$ = 116 ± 12 nb.

ALP searches

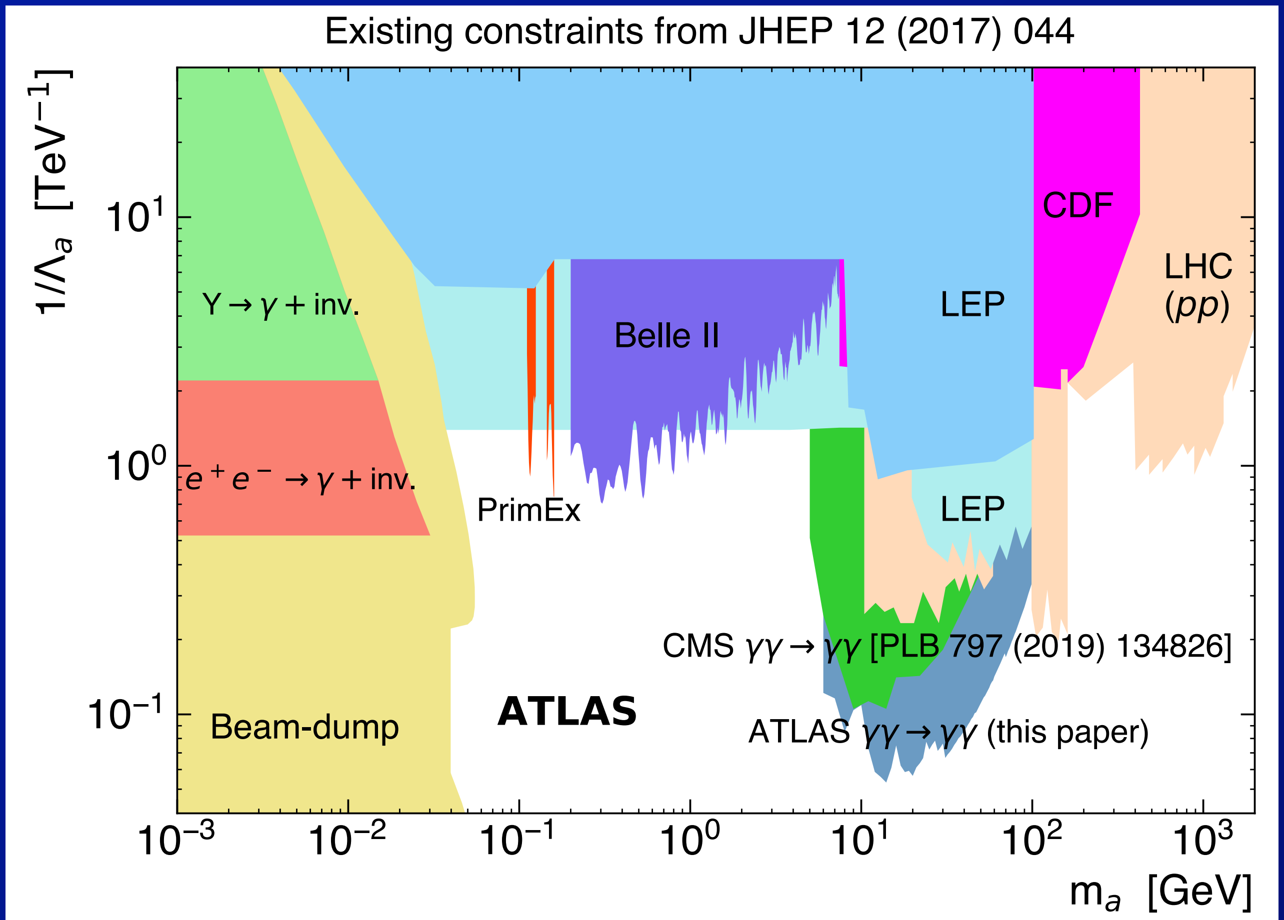
- **ALP searches:**
  - Look for narrow resonances in $m_{\gamma\gamma}$ distribution
    - ⇒ Both ATLAS and CMS data consistent with background-only hypothesis

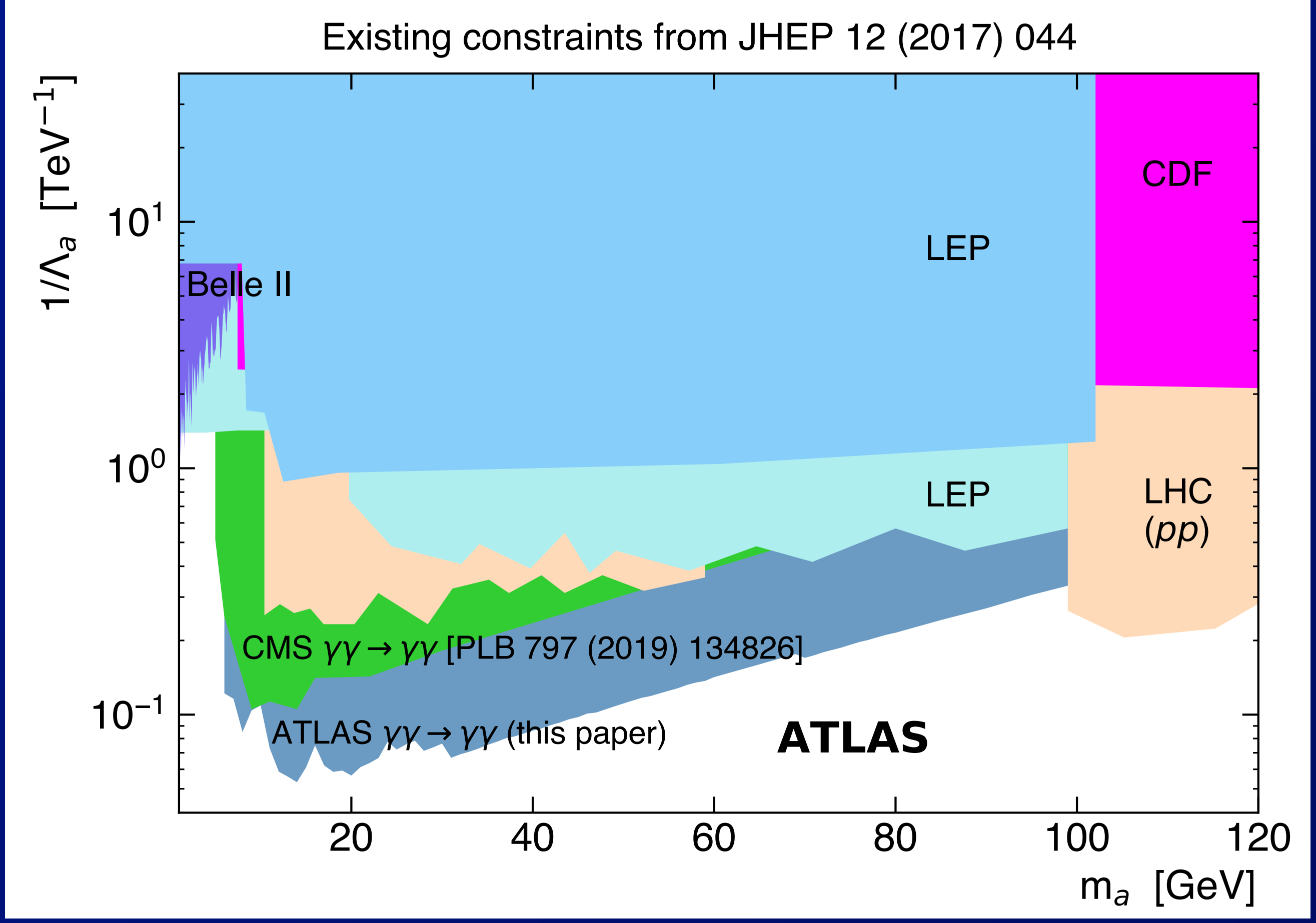




ATLAS and CMS limits on ALP in γγ

- **LHC measurements in UPC light-by-light:**
  - **CMS and ATLAS constraints on γγ→ALP**





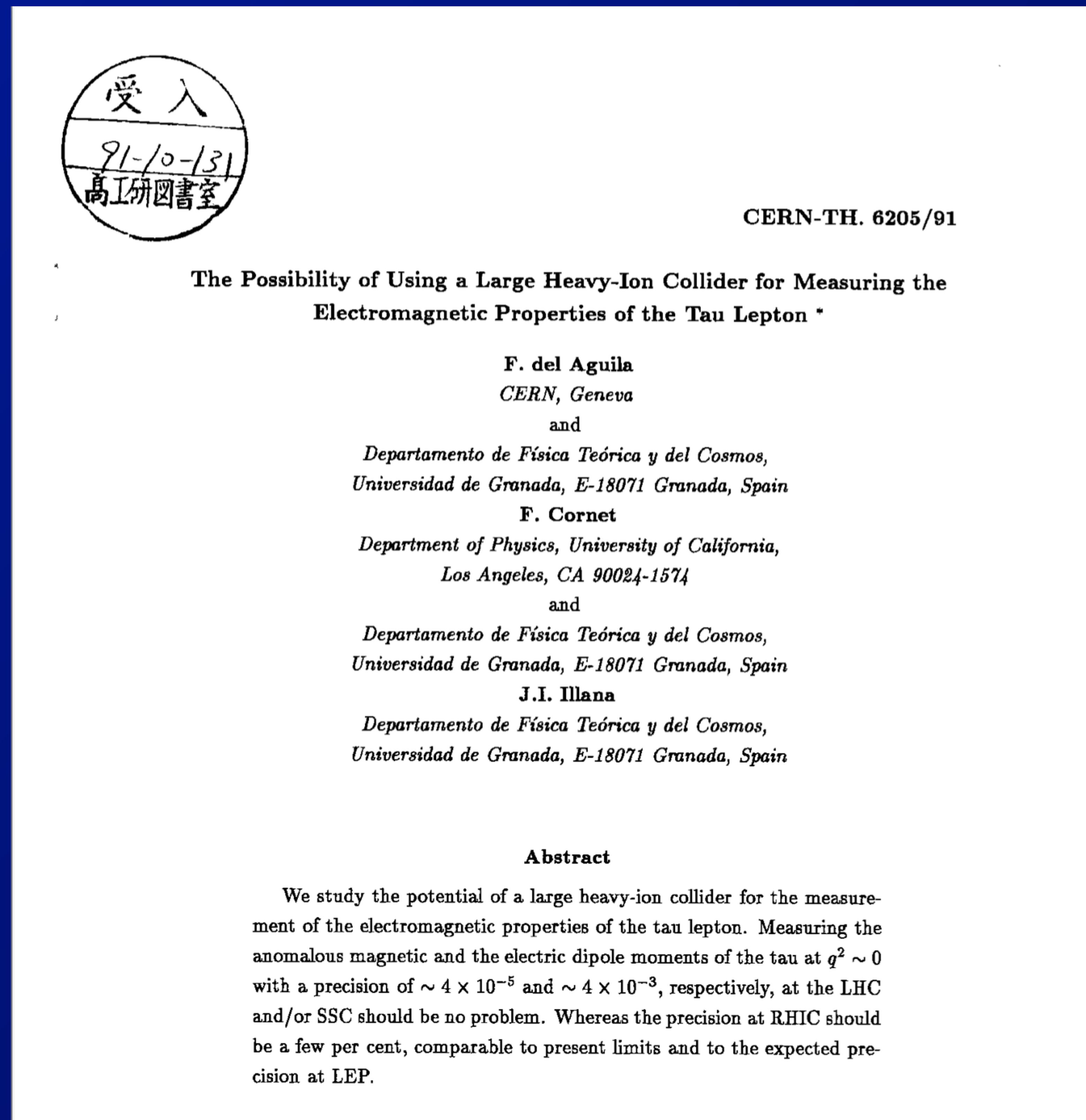
⇒**LHC light-by-light data provide improved constraints on ALP production in mass range 5-100 GeV**

– **Note: no combination (yet) of ATLAS and CMS data**

$\tau^+ \tau^-$ and τ g-2

UPC collisions and $\tau^+ \tau^-$ production

- Studying tau properties in ultra-peripheral collisions is an old idea



CERN-TH. 6205/91

The Possibility of Using a Large Heavy-Ion Collider for Measuring the Electromagnetic Properties of the Tau Lepton *

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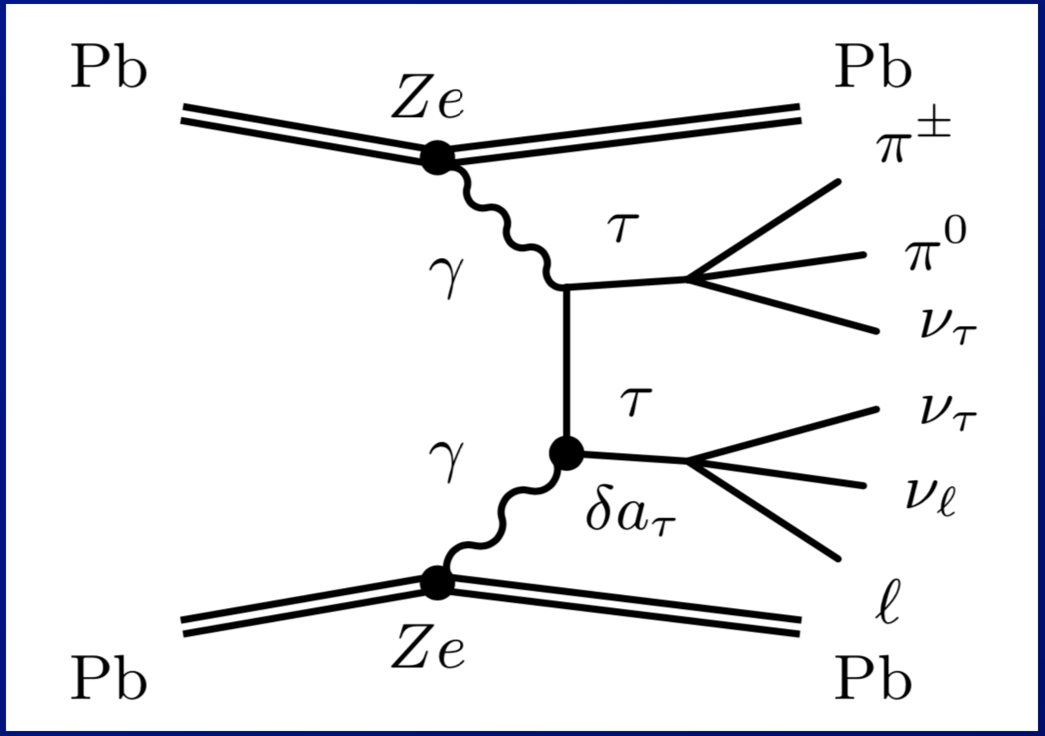
Abstract

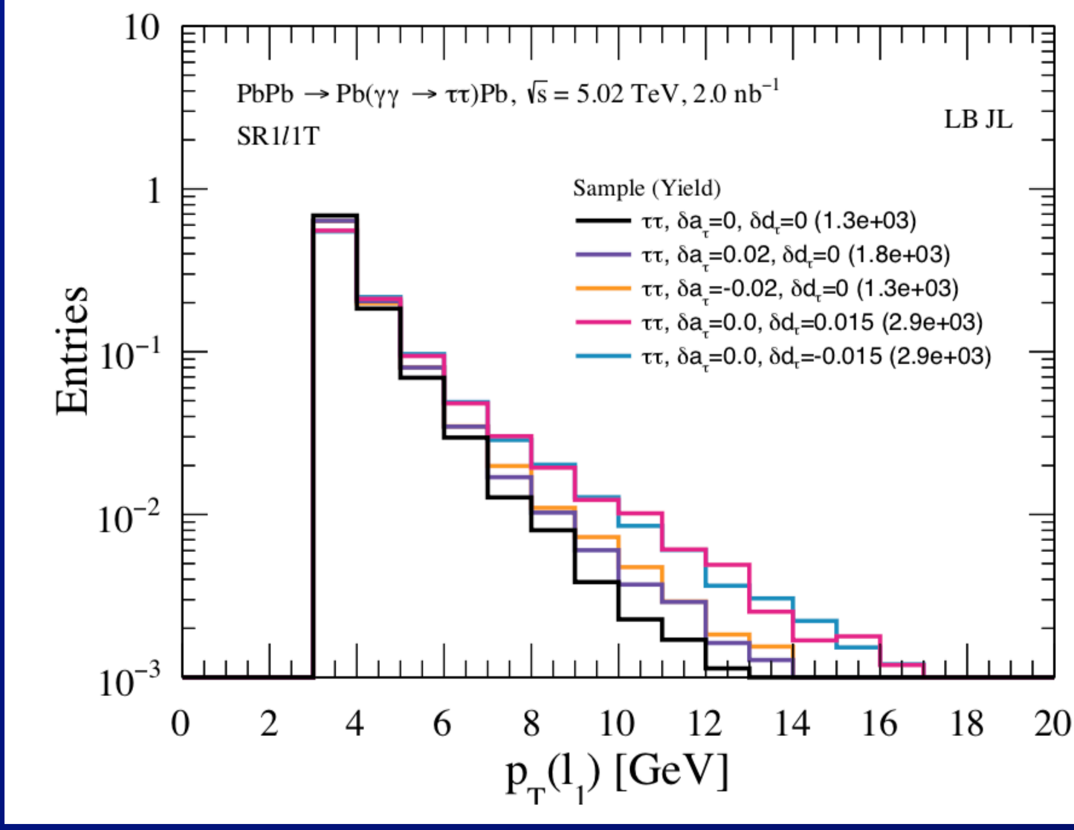
We study the potential of a large heavy-ion collider for the measurement of the electromagnetic properties of the tau lepton. Measuring the anomalous magnetic and the electric dipole moments of the tau at $q^2 \sim 0$ with a precision of $\sim 4 \times 10^{-5}$ and $\sim 4 \times 10^{-3}$, respectively, at the LHC and/or SSC should be no problem. Whereas the precision at RHIC should be a few per cent, comparable to present limits and to the expected precision at LEP.

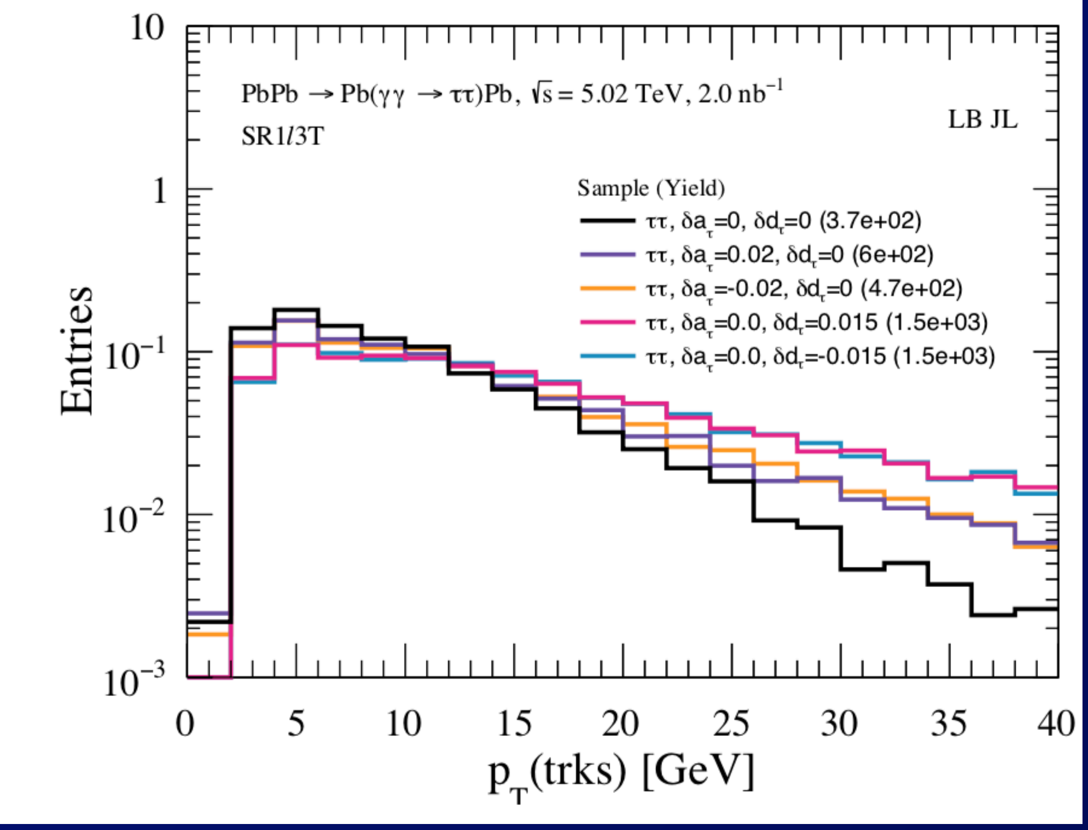
tau g-2 and UPC $\tau^+\tau^-$ production

- **Beresford and Liu:**
  - tau g-2 measurements could be made using UPC $\gamma+\gamma \rightarrow \tau^+\tau^-$
  - mass increases sensitivity to BSM physics

  ⇒ the kinematics of the taus & decay products are sensitive to BSM physics





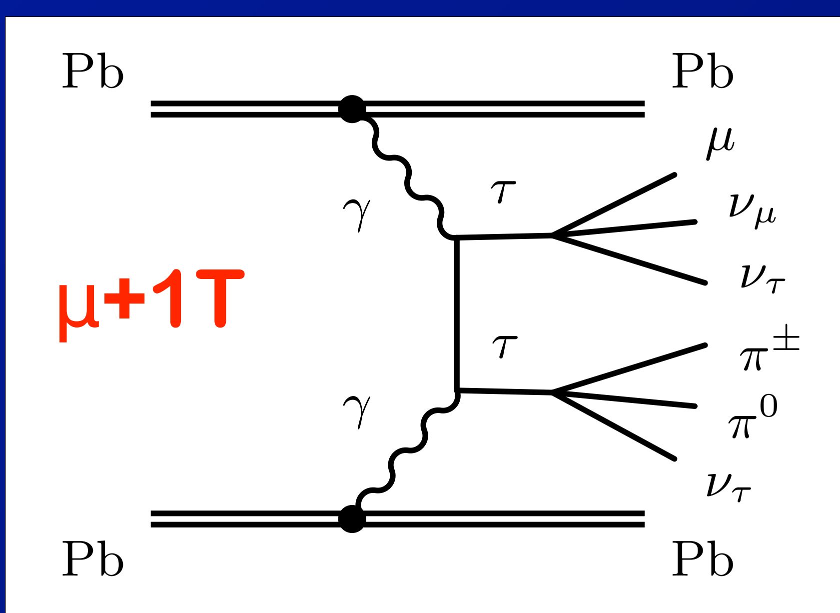


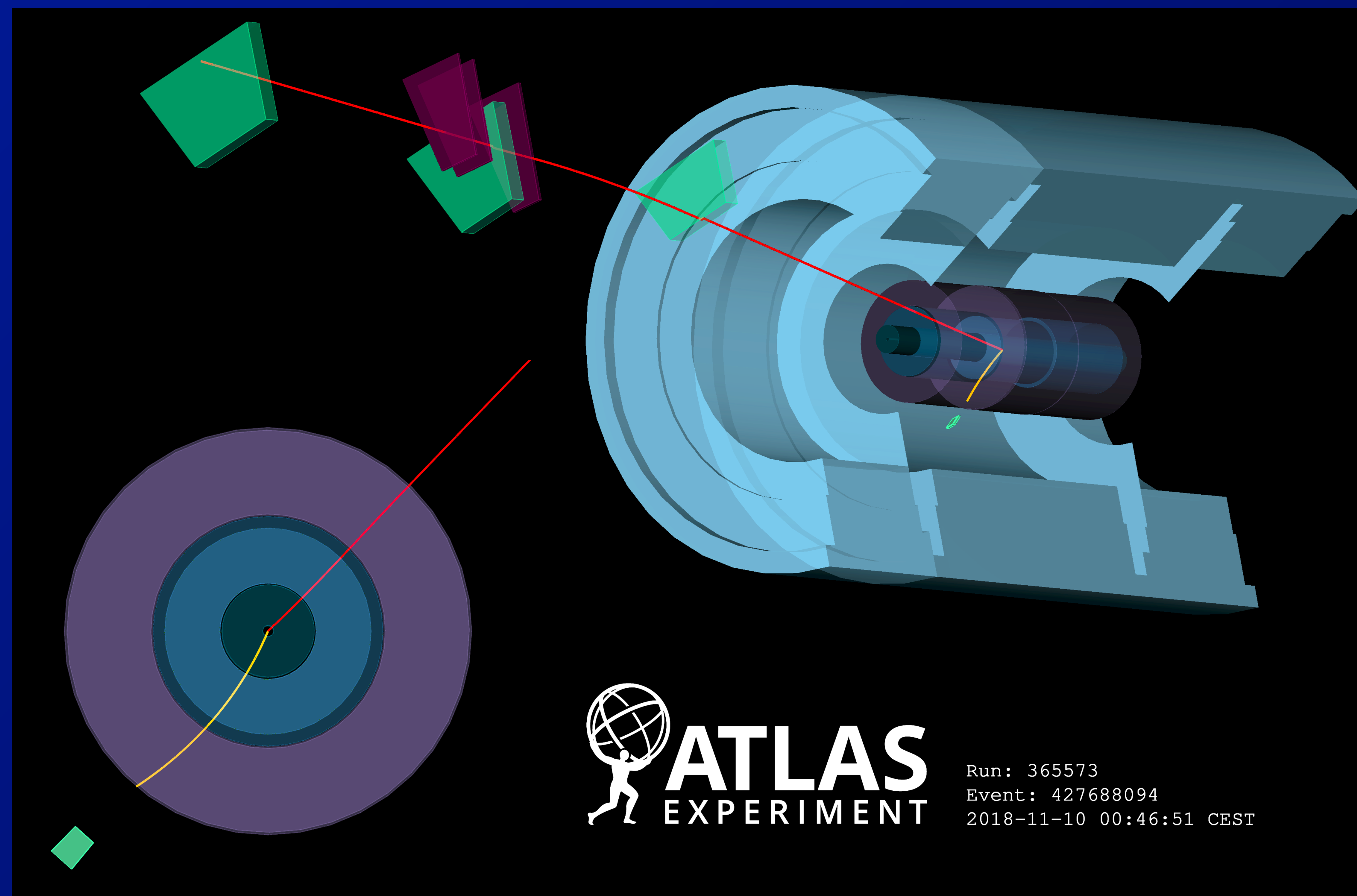
ATLAS $\gamma\gamma \to \tau\tau$ observation

- ATLAS used three signal CRs to select events with 2 τ decays

ATLAS γγ→ττ observation

- ATLAS used three signal channels/regions to select events with 2 τ decays
  - Muon + 1 track





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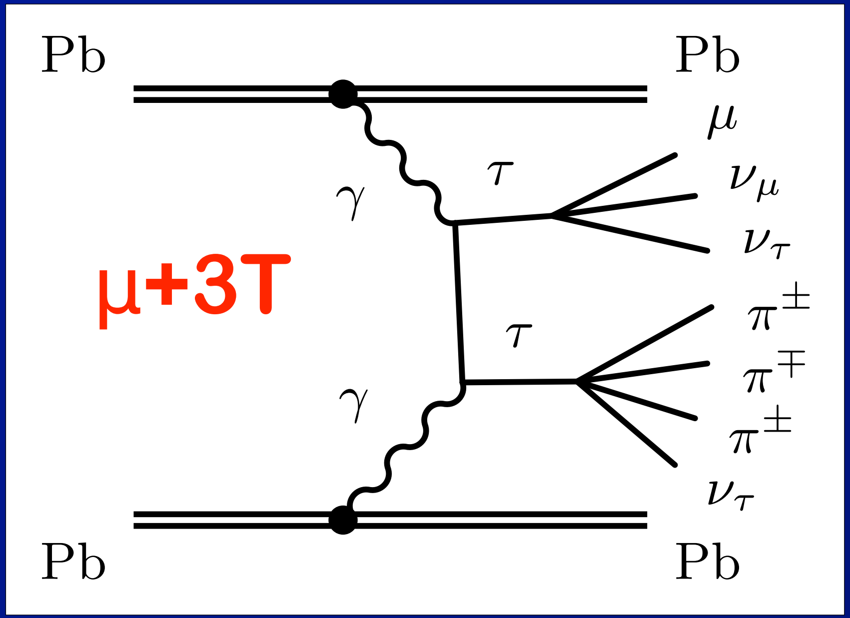
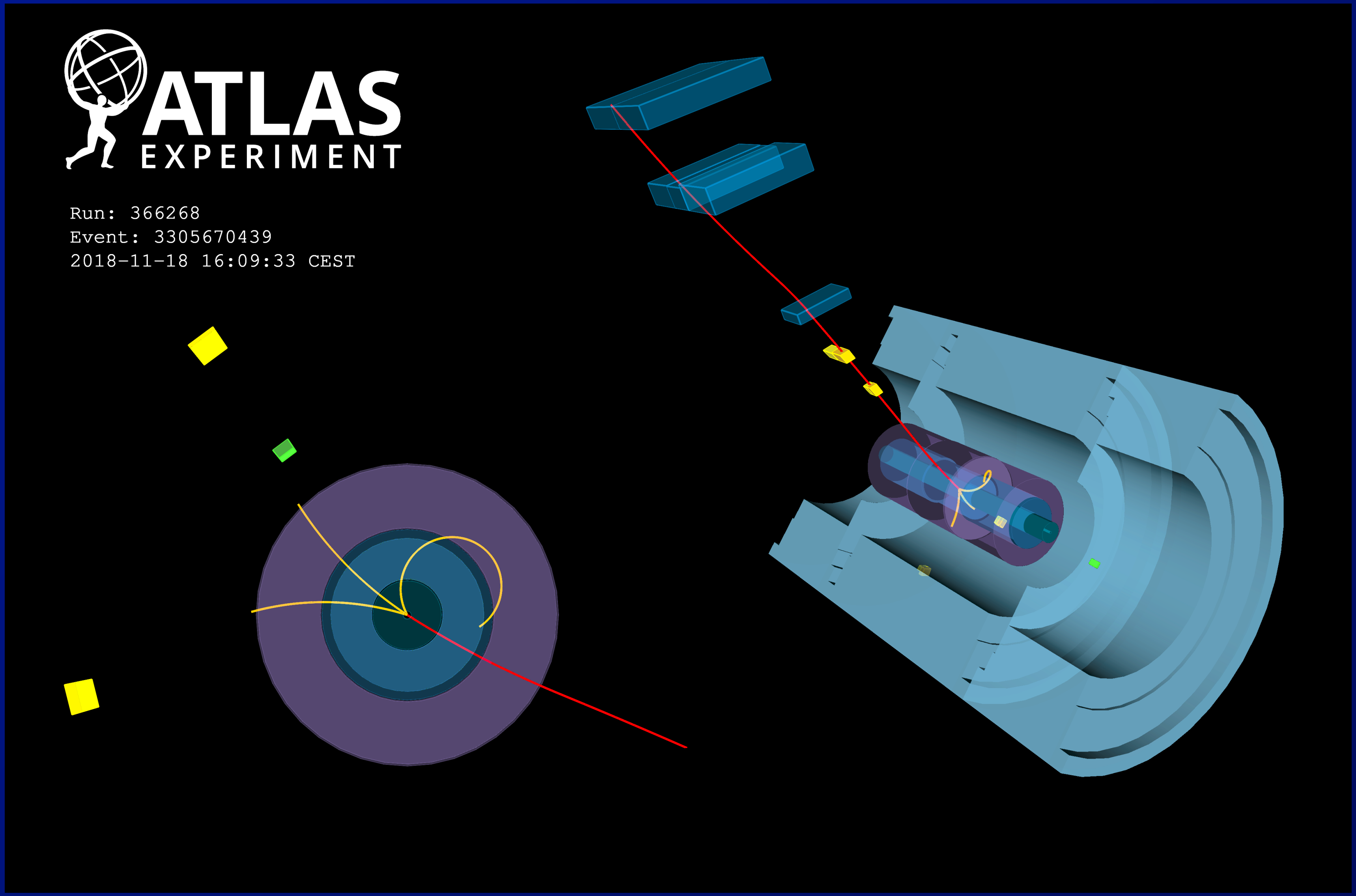
ATLAS γγ→ττ observation

- ATLAS used three signal channels/regions to select events with 2 τ decays
  - Muon + 3 tracks





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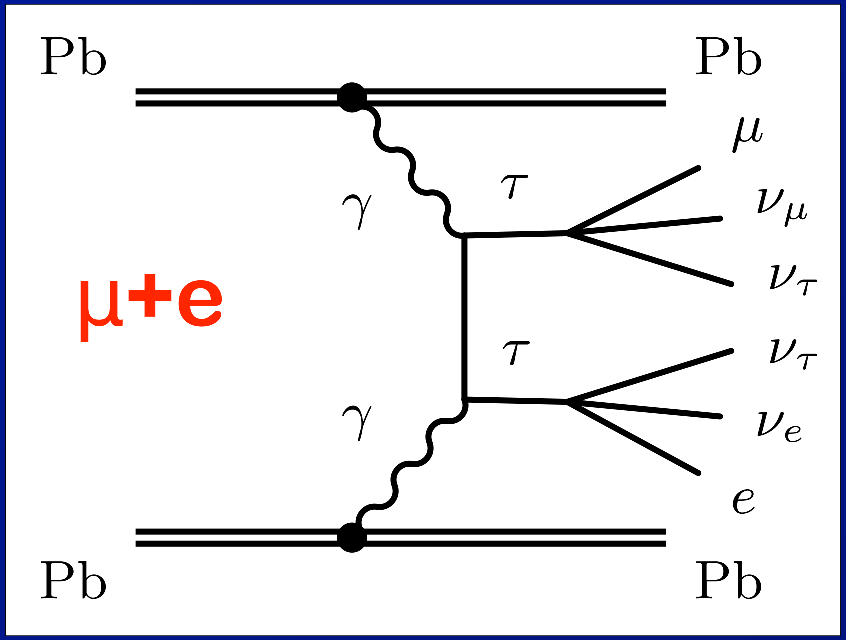
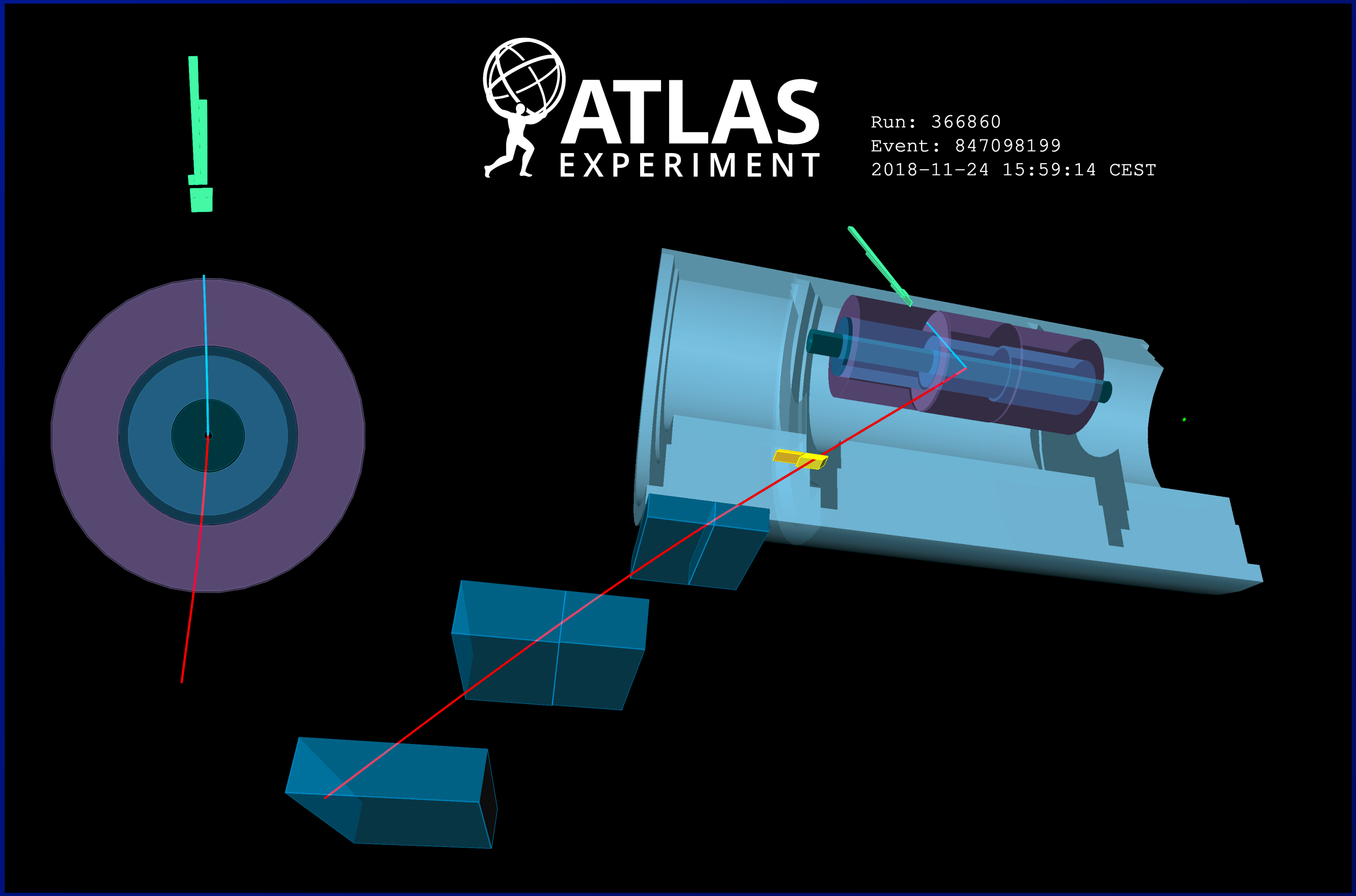
ATLAS γγ→ττ observation

- ATLAS used three signal channels/regions to select events with 2 τ decays
  - Muon + electron





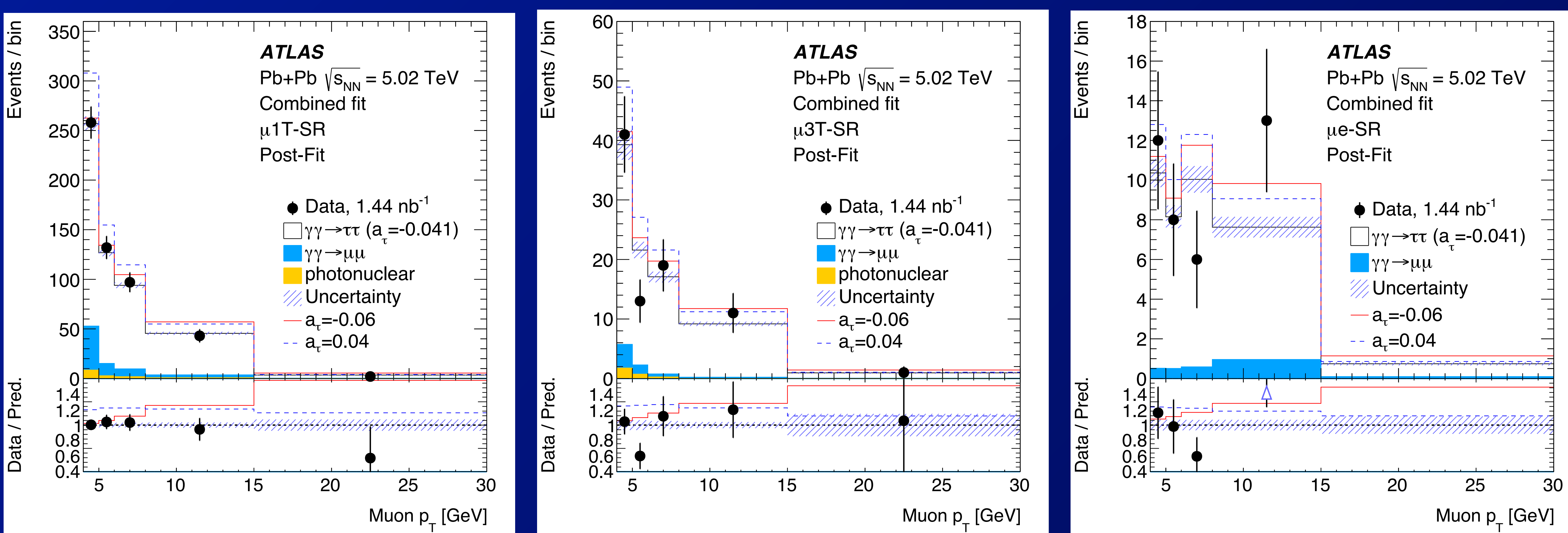
Phys. Rev. Lett. 131 (2023) 151

ATLAS γγ→ττ observation

- **Simultaneous analysis of 3 signal channels**
  - 3 control regions to constrain backgrounds

  ⇒ Expected backgrounds < 15% in all three channels
- **LL Fit to a_τ assuming γττ coupling** $F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i}{2m_\tau}\sigma^{\mu\nu}q_\nu$
  - Similar parameterization to LEP analyses

  ⇒ $a_\tau \equiv (g_\tau - 2)/2 = -0.041$, $a_\tau^{SM} = 0.0012$

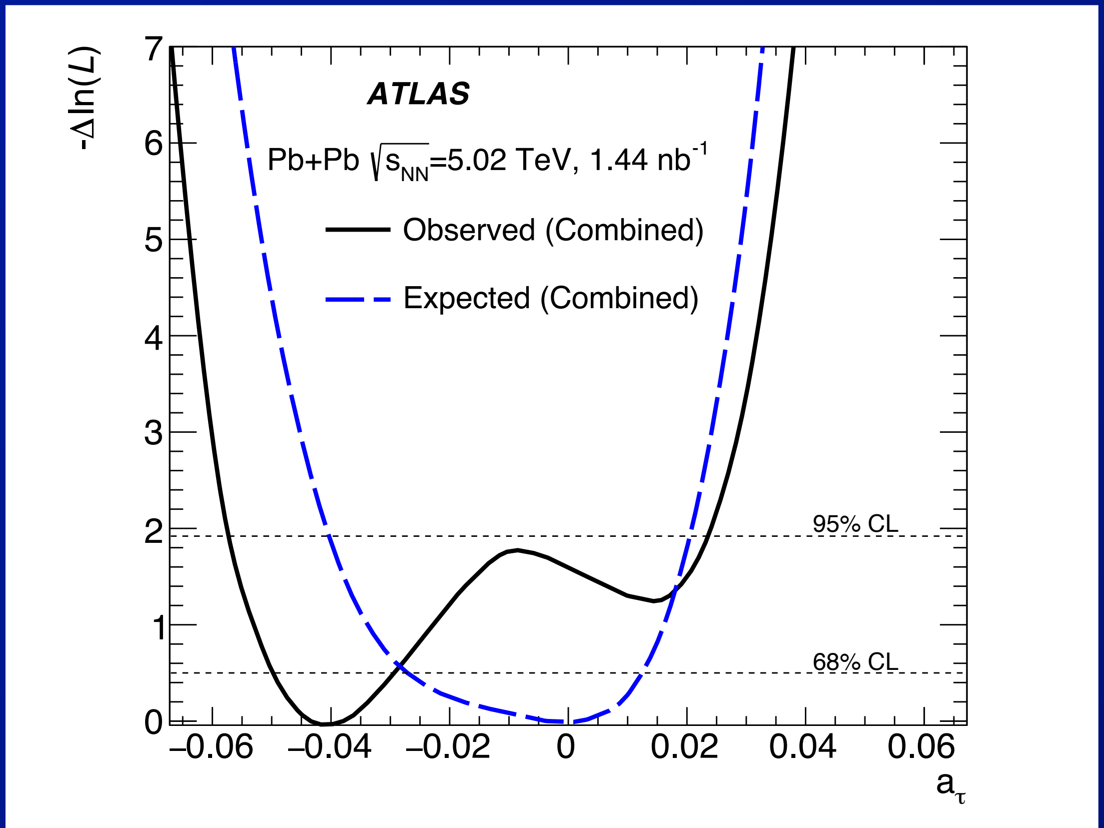


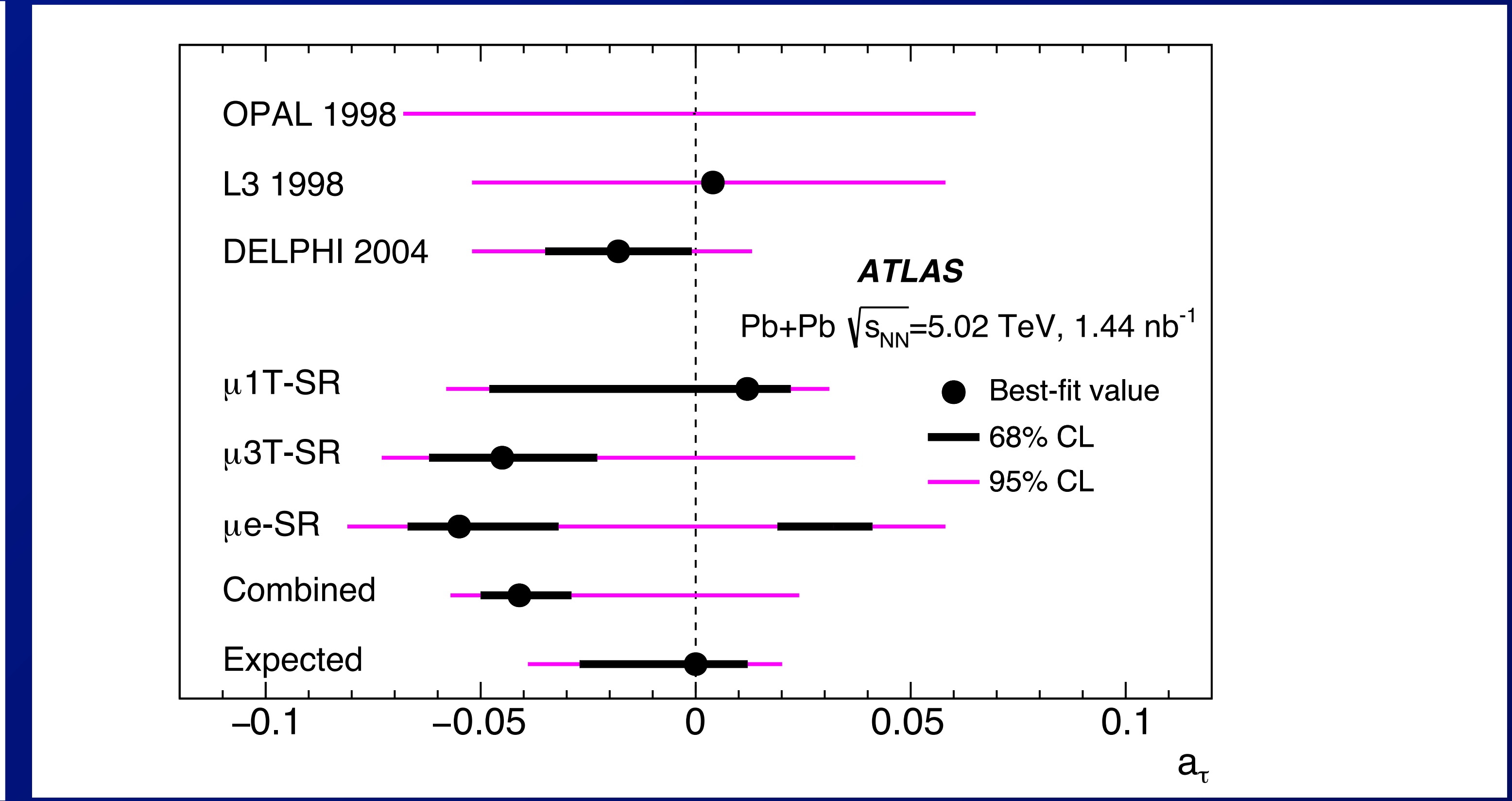
Phys. Rev. Lett. 131 (2023) 151802

ATLAS $\gamma\gamma\rightarrow\tau\tau$ observation

- LL Fit to a_τ assuming $\gamma\tau\tau$ coupling $F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i}{2m_\tau}\sigma^{\mu\nu}q_\nu$
- "Standard" evaluation of 68% and 95% CLs
  - But interference between SM and BSM processes make the 95% CLs "unusual"

⇒ Allow non-zero positive and negative a_τ





⇒ Use of muon p_T distributions makes result less sensitive to uncertainties in photon flux

CMS $\gamma\gamma \to \tau\tau$ observation

- CMS measurement focused on the μ+3 track channel

  ⇒ Directly constrain one of the tau decays

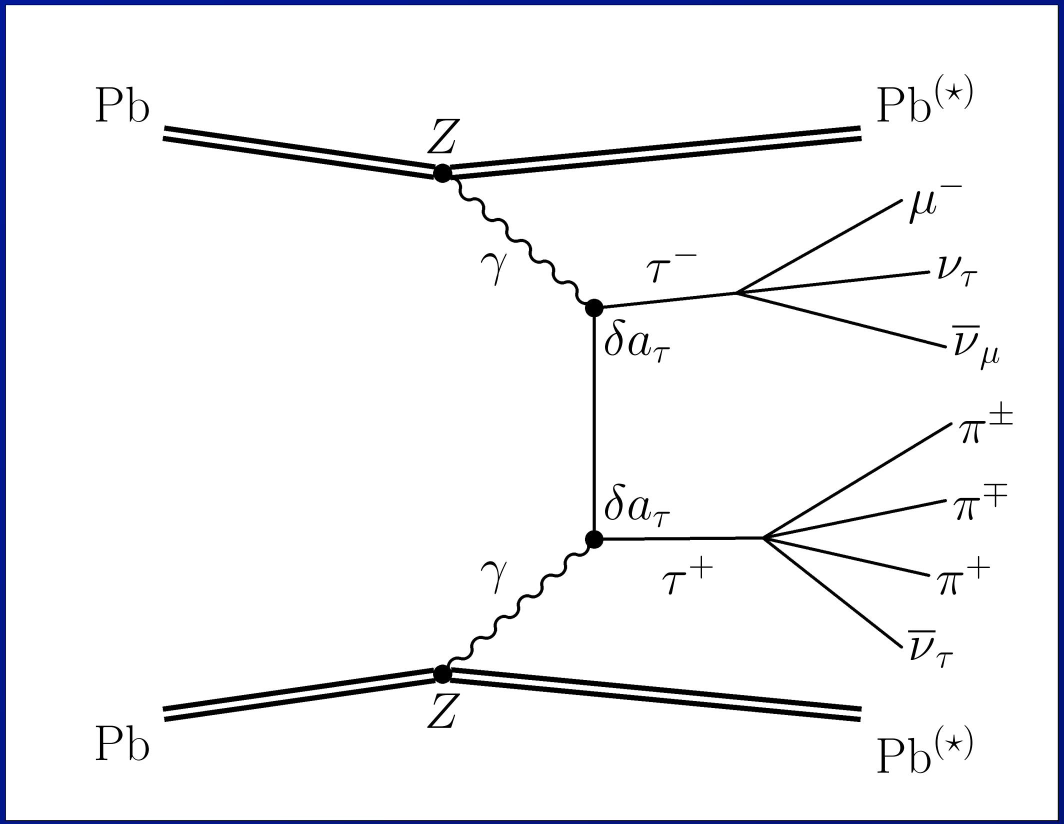
- Less luminosity (0.4 nb^{-1}), but lower p_T threshold on muon:

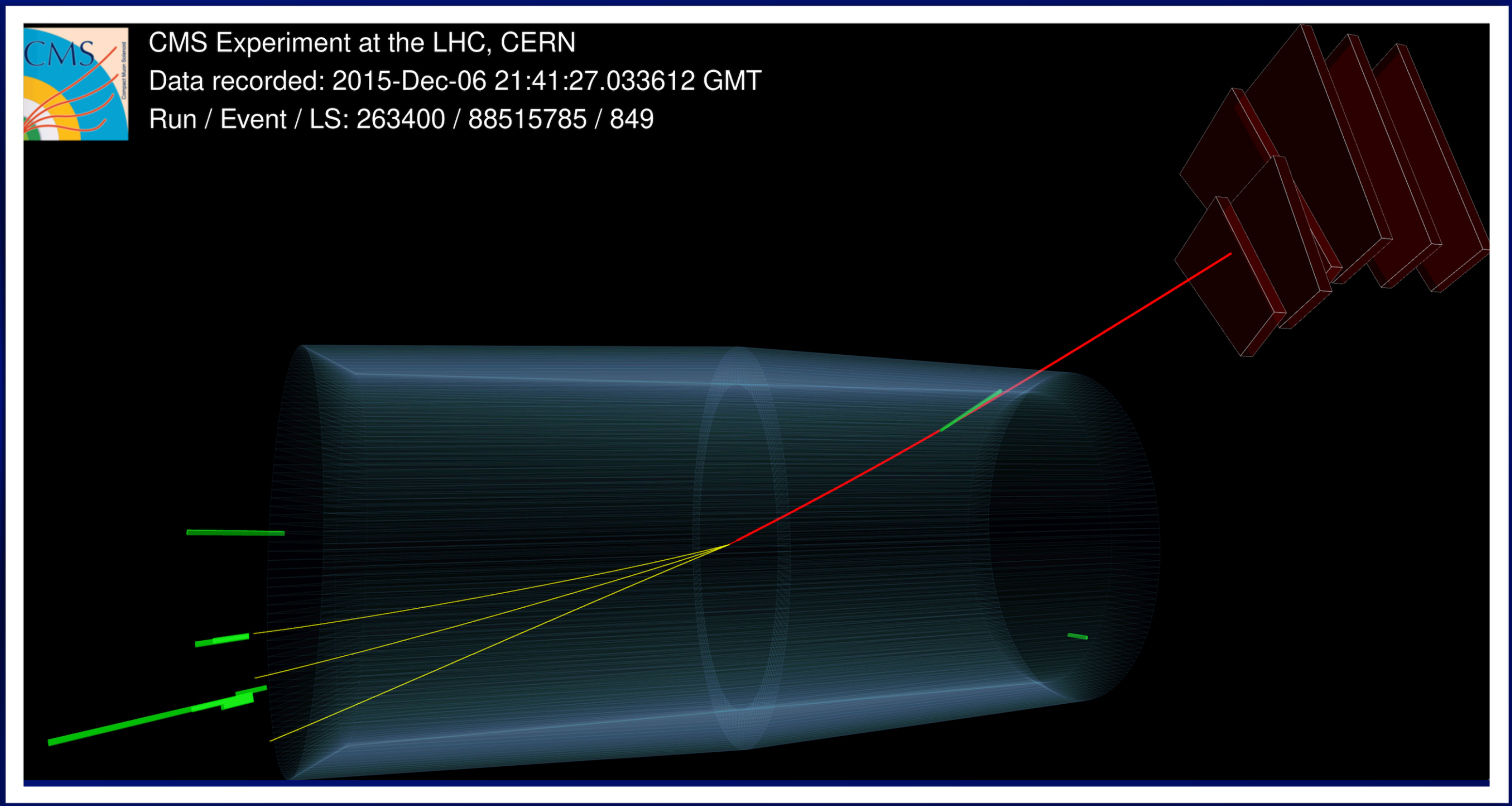
  – $p_{T\mu}$ > 3.5 GeV for $|\eta_\mu|$ < 1.2,

  – $p_{T\mu}$ > 2.5 GeV for 1.2 < $|\eta_\mu|$ < 2.4

  ⇒ Similar statistical precision on σ_{fid} as the ATLAS measurement

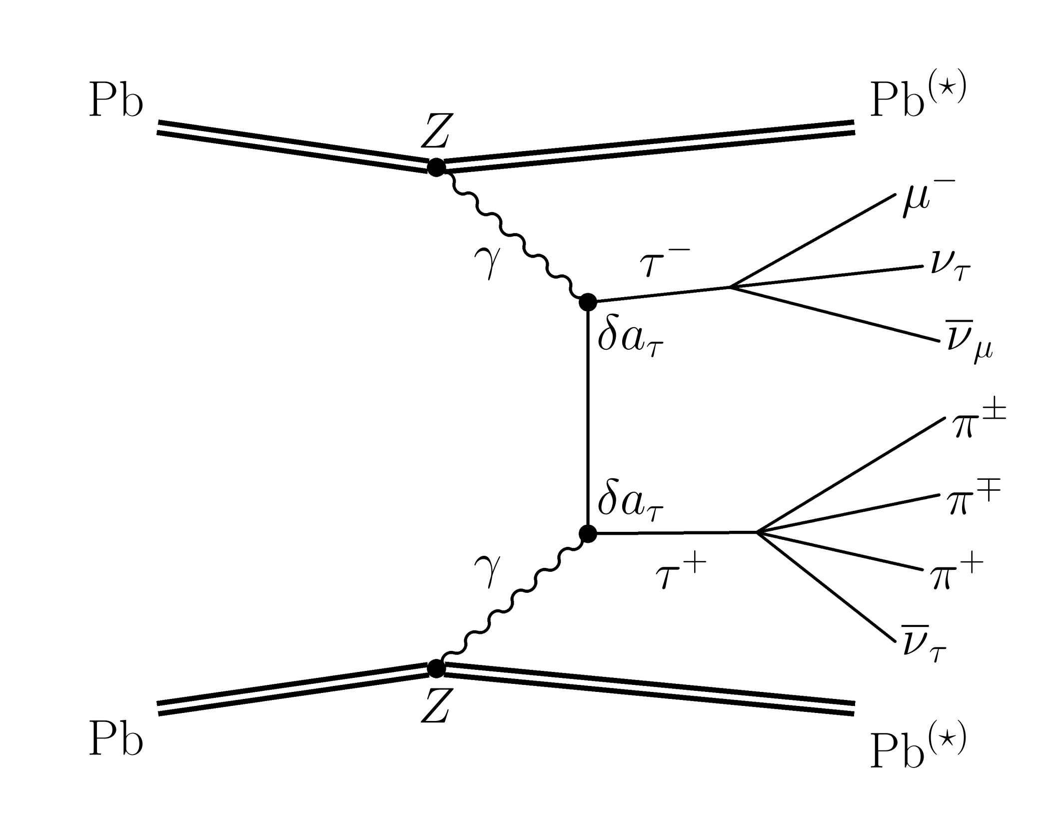
  ⇒ But by fitting σ_{fit}, sensitive to photon flux





CMS γγ→ττ observation

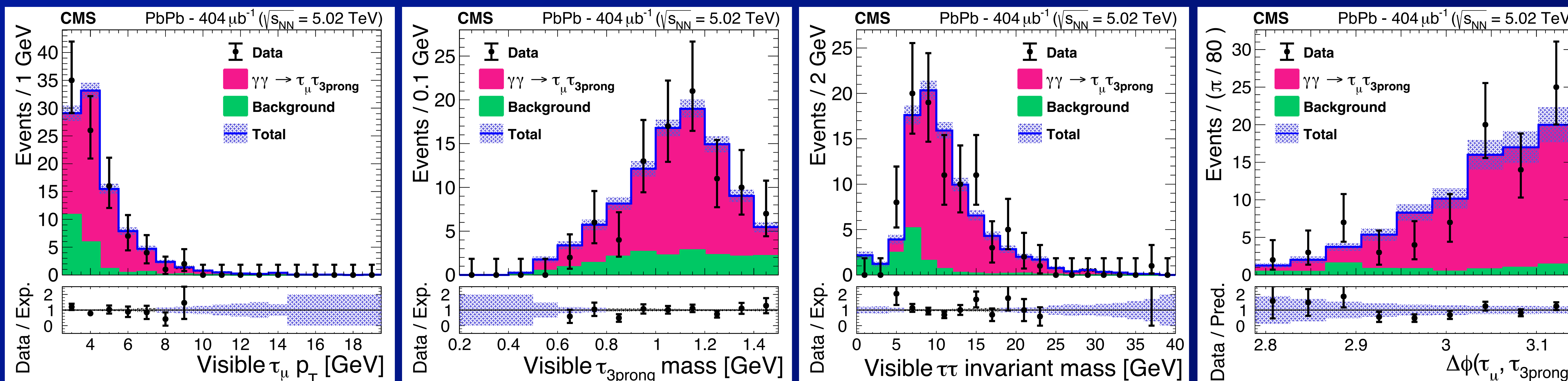
- CMS measurement focused on the μ+3 track channel
  - ⇒ Directly constrain one of the tau decays
- Less luminosity ($0.4\ nb^{-1}$), but lower p_T threshold on muon:
  - – $p_{T\mu} > 3.5$ GeV for $|\eta_\mu| < 1.2$,
  - – $p_{T\mu} > 2.5$ GeV for $1.2 < |\eta_\mu| < 2.4$
  - ⇒ Similar statistical precision on σ_{fid} as the ATLAS measurement
  - ⇒ But by fitting σ_{fit}, sensitive to photon flux



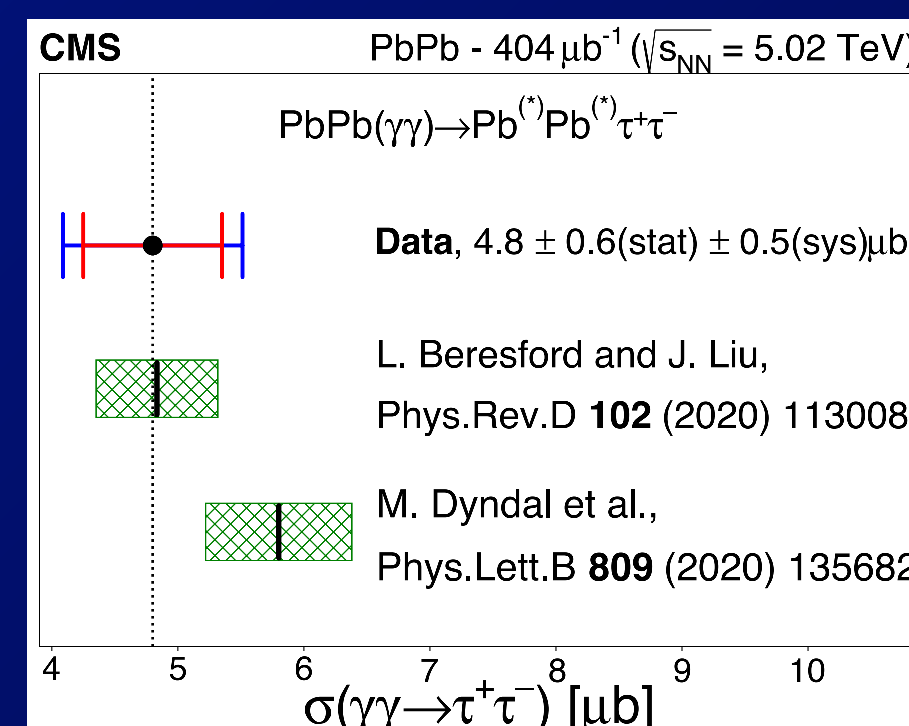
Muon selection	$p_T > 3.5$ GeV for $\lvert\eta\rvert < 1.2$ $p_T > 2.5$ GeV for $1.2 < \lvert\eta\rvert < 2.4$
Pion selection	$p_T > 0.5$ GeV for the leading $p_T > 0.3$ GeV for the (sub-)subleading $\lvert\eta\rvert < 2.5$
τ_{3prong} selection	$p_T^{vis} > 2$ GeV and $0.2 < m_\tau^{vis} < 1.5$ GeV

CMS γγ→ττ observation

- Clean $\gamma\gamma \rightarrow \tau^+\tau^-$ signal with low bkgd (@ small $m_{\tau\tau}$)
  - 3 CR regions at higher track multiplicity, and/or higher E_{HF}^{lead} used to constrain background



- From fit to μ-3T Δφ distribution
  - ⇒ N_{sig} = 77 ± 12
  - ⇒SM ratio: r = 0.99 (+0.16) (-0.14)
  - ⇒A_τ = 0.001 (+0.055) (-0.089) 68% CL



$\gamma+\gamma$ production of dileptons: A closer look

B-depedence of photon k_T

- The photon k_T distribution has only recently been a subject of significant focus & effort.
  - Typically related to nuclear Form factor

⇒e.g. in STARlight:

$$\frac{dN(k, p_T)}{dp_T} = \frac{2F^2(Q^2 = p_T^2)p_T^3}{(2\pi)^2((k/\gamma)^2 + p_T^2)^2}.$$

- But this formula (not unique to STARlight) loses correlation between the photon k_T and $r_\perp$

⇒required by physics (see arXiv 2207.05595.pdf)

- $r_\perp$ and/or b-dependence of photon k_T distribution the subject of much recent work by multiple groups

Photon k_T in dilepton production

- Recent calculation by Zha, Brandenburg, Tang, Xu
  - Using formalism from Hencken, Trautmann, Baur
- Start from EM potential of the two nuclei

$$A_1^\mu(k_1,b) = -2\pi(Z_1e)e^{ik_1^\tau b_\tau}\delta(k_1^\nu u_{1\nu})\frac{F_1(-k_1^\rho k_{1\rho})}{k_1^\sigma k_{1\sigma}}u_1^\mu,$$

$$A_2^\mu(k_2,0) = -2\pi(Z_2e)e^{ik_2^\tau b_\tau}\delta(k_2^\nu u_{2\nu})\frac{F_2(-k_2^\rho k_{2\rho})}{k_2^\sigma k_{2\sigma}}u_2^\mu$$

Zha *et al*, Phys. Lett. B 800 (2020) 135089

Photon k_T in dilepton production

- **Recent calculation by Zha, Brandenburg, Tang, Xu**
  - Using formalism from Hencken, Trautmann, Baur
- **Start from EM potential of the two nuclei**
  - Then, using S-matrix analysis (not QED) obtain “gEPA”

$$A_1^{\mu}(k_1, b) = -2\pi(Z_1 e)e^{ik_1^{\tau}b_{\tau}}\delta(k_1^{\nu}u_{1\nu})\frac{F_1(-k_1^{\rho}k_{1\rho})}{k_1^{\sigma}k_{1\sigma}}u_1^{\mu}$$

$$A_2^{\mu}(k_2, 0) = -2\pi(Z_2 e)e^{ik_2^{\tau}b_{\tau}}\delta(k_2^{\nu}u_{2\nu})\frac{F_2(-k_2^{\rho}k_{2\rho})}{k_2^{\sigma}k_{2\sigma}}u_2^{\mu}$$

$$\sigma = 16\frac{Z^4e^4}{(4\pi)^2}\int d^2b\int\frac{dw_1}{w_1}\frac{dw_2}{w_2}\frac{d^2k_{1\perp}}{(2\pi)^2}\frac{d^2k_{2\perp}}{(2\pi)^2}\frac{d^2q_{\perp}}{(2\pi)^2}$$
$$\times\frac{F(-k_1^2)}{k_1^2}\frac{F(-k_2^2)}{k_2^2}\frac{F^*(-k_1'^2)}{k_1'^2}\frac{F^*(-k_2'^2)}{k_2'^2}e^{-i\vec{b}\cdot\vec{q}_{\perp}}$$
$$\times\Big[(\vec{k}_{1\perp}\cdot\vec{k}_{2\perp})(\vec{k}'_{1\perp}\cdot\vec{k}'_{2\perp})\sigma_s(w_1,w_2)$$
$$+(\vec{k}_{1\perp}\times\vec{k}_{2\perp})(\vec{k}'_{1\perp}\times\vec{k}'_{2\perp})\sigma_{ps}(w_1,w_2)\Big]$$

Zha *et al*, Phys. Lett. B 800 (2020) 135089

Photon k_T in dilepton production

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  - Using formalism from Hencken, Trautmann, Baur
- **Start from EM potential of the two nuclei**
  - then, using S-matrix analysis (not QED) obtain "gEPA"
  - has explicit Fourier term involving the A+A impact parameter, b

$$A_1^\mu(k_1, b) = -2\pi(Z_1 e)e^{ik_1^\tau b_\tau}\delta(k_1^\nu u_{1\nu})\frac{F_1(-k_1^\rho k_{1\rho})}{k_1^\sigma k_{1\sigma}}u_1^\mu,$$

$$A_2^\mu(k_2, 0) = -2\pi(Z_2 e)e^{ik_2^\tau b_\tau}\delta(k_2^\nu u_{2\nu})\frac{F_2(-k_2^\rho k_{2\rho})}{k_2^\sigma k_{2\sigma}}u_2^\mu$$

$$\sigma = 16\frac{Z^4 e^4}{(4\pi)^2}\int d^2 b \int \frac{dw_1}{w_1}\frac{dw_2}{w_2}\frac{d^2 k_{1\perp}}{(2\pi)^2}\frac{d^2 k_{2\perp}}{(2\pi)^2}\frac{d^2 q_{\perp}}{(2\pi)^2}$$
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$$\times \left[(\vec{k}_{1\perp}\cdot\vec{k}_{2\perp})(\vec{k}'_{1\perp}\cdot\vec{k}'_{2\perp})\sigma_s(w_1, w_2)\right.$$
$$\left.+ (\vec{k}_{1\perp}\times\vec{k}_{2\perp})(\vec{k}'_{1\perp}\times\vec{k}'_{2\perp})\sigma_{ps}(w_1, w_2)\right]$$

Zha *et al*, Phys. Lett. B 800 (2020) 135089

Photon k_T in dilepton production

- Recent calculation by Zha, Brandenburg, Tang, Xu
  - Using formalism from Hencken, Trautmann, Baur
- Start from EM potential of the two nuclei
  - Alternatively, perform the actual QED computation:

$$A_1^{\mu}(k_1, b) = -2\pi(Z_1 e)e^{ik_1^{\tau}b_{\tau}}\delta(k_1^{\nu}u_{1\nu})\frac{F_1(-k_1^{\rho}k_{1\rho})}{k_1^{\sigma}k_{1\sigma}}u_1^{\mu},$$

$$A_2^{\mu}(k_2, 0) = -2\pi(Z_2 e)e^{ik_2^{\tau}b_{\tau}}\delta(k_2^{\nu}u_{2\nu})\frac{F_2(-k_2^{\rho}k_{2\rho})}{k_2^{\sigma}k_{2\sigma}}u_2^{\mu}$$

$$\sigma = \int d^2b \frac{d^6P(\vec{b})}{d^3p_+d^3p_-} = \int d^2q \frac{d^6P(\vec{q})}{d^3p_+d^3p_-}\int d^2b e^{i\vec{q}\cdot\vec{b}},$$

$$\begin{aligned}\frac{d^6P(\vec{q})}{d^3p_+d^3p_-} &= (Z\alpha)^4\frac{4}{\beta^2}\frac{1}{(2\pi)^6 2\epsilon_+ 2\epsilon_-}\int d^2q_1 \\ &F(N_0)F(N_1)F(N_3)F(N_4)[N_0N_1N_3N_4]^{-1} \\ &\times \mathrm{Tr}\{(\not{p}_- + m)[N_{2D}^{-1}\not{u}_1(\not{p}_- - \not{q}_1 + m)\not{u}_2 + \\ &N_{2X}^{-1}\not{u}_2(\not{q}_1 - \not{p}_+ + m)\not{u}_1](\not{p}_+ - m)[N_{5D}^{-1}\not{u}_2 \\ &(\not{p}_- - \not{q}_1 - \not{q} + m)\not{u}_1 + N_{5X}^{-1}\not{u}_1(\not{q}_1 + \not{q} - \not{p}_+ \\ &+ m)\not{u}_2]\},\end{aligned}$$

with

$$\begin{aligned}&N_0 = -q_1^2, N_1 = -[q_1 - (p_+ + p_-)]^2, \\ &N_3 = -(q_1 + q)^2, N_4 = -[q + (q_1 - p_+ - p_-)]^2, \\ &N_{2D} = -(q_1 - p_-)^2 + m^2, \\ &N_{2X} = -(q_1 - p_+)^2 + m^2, \\ &N_{5D} = -(q_1 + q - p_-)^2 + m^2, \\ &N_{5X} = -(q_1 + q - p_+)^2 + m^2,\end{aligned}$$

Zha *et al*, Phys. Lett. B 800 (2020) 135089

Photon k_T in dilepton production

- **Recent calculation by Zha, Brandenburg, Tang, Xu**
  - Using formalism from Hencken, Trautmann, Baur
- **Start from EM potential of the two nuclei**
  - Alternatively, perform the actual QED computation:
  - Which also has the explicit Fourier term involving the impact parameter, b

$$A_1^\mu(k_1, b) = -2\pi(Z_1 e)e^{ik_1^\tau b_\tau}\delta(k_1^\nu u_{1\nu})\frac{F_1(-k_1^\rho k_{1\rho})}{k_1^\sigma k_{1\sigma}}u_1^\mu,$$

$$A_2^\mu(k_2, 0) = -2\pi(Z_2 e)e^{ik_2^\tau b_\tau}\delta(k_2^\nu u_{2\nu})\frac{F_2(-k_2^\rho k_{2\rho})}{k_2^\sigma k_{2\sigma}}u_2^\mu$$

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with

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Zha *et al*, Phys. Lett. B 800 (2020) 135089

Photon k_T in dilepton production

- Recent calculation by Zha, Brandenburg, Tang, Xu
  - Using formalism from Hencken, Trautmann, Baur
- Start from EM potential of the two nuclei
  - both gEPA and QED calculations have b-dependent "broadening" of the dilepton p_T distributions

⇒more on this later

$$A_1^\mu(k_1, b) = -2\pi(Z_1 e)e^{ik_1^\tau b_\tau}\delta(k_1^\nu u_{1\nu})\frac{F_1(-k_1^\rho k_{1\rho})}{k_1^\sigma k_{1\sigma}}u_1^\mu,$$

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Zha *et al*, Phys. Lett. B 800 (2020) 135089

Photon Wigner Distribution

- An alternative calculation has been performed by Klein *et al,* and Klusek-Gawenda *et al:*

$$xf_\gamma(x,k_T;b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp\cdot b_\perp} xf_\gamma(x,k_T;\Delta_\perp).$$

$$xf_\gamma(x,k_T;\Delta_\perp) = xh_\gamma(x,k_T;\Delta_\perp) = \frac{4Z^2\alpha}{(2\pi)^2}\frac{q_\perp\cdot q'_\perp}{q^2q'^2}F_A(q^2)F_A(q'^2)$$

$q_\perp = k_T - \Delta_\perp/2$, $q'_\perp = k_T + \Delta_\perp/2$

$q^2 = q_\perp^2 + x^2m_p^2$

- *S*tarting from the photon Wigner distribution
  - describe the correlation between photon k_T and $r_\perp$
  - using formalism developed for PDFs (Belitsky, Ji, Yuan)

Phys. Rev. D 102 (2020) 9, 094013

Photon Wigner Distribution

- An alternative calculation has been performed by Klein *et al* starting from the photon Wigner distribution
  - describe the correlation between photon k_T and $r_\perp$
  - using formalism developed for PDFs (Belitsky, Ji, Yuan)

  ⇒ Also see Fourier term, but now for single nucleus

$$xf_\gamma(x, k_T; b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \cdot b_\perp} xf_\gamma(x, k_T; \Delta_\perp).$$

$$xf_\gamma(x, k_T; \Delta_\perp) = xh_\gamma(x, k_T; \Delta_\perp) = \frac{4Z^2\alpha}{(2\pi)^2} \frac{q_\perp \cdot q'_\perp}{q^2 q'^2} F_A(q^2) F_A(q'^2)$$

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Phys. Rev. D 102 (2020) 9, 094013

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  - describe the correlation between photon k_T and $r_\perp$
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⇒ Also see Fourier term, but now for single nucleus

⇒ Non-trivial dependence of photon WF on b, k_T

$$xf_\gamma(x,k_T;b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp\cdot b_\perp} xf_\gamma(x,k_T;\Delta_\perp).$$

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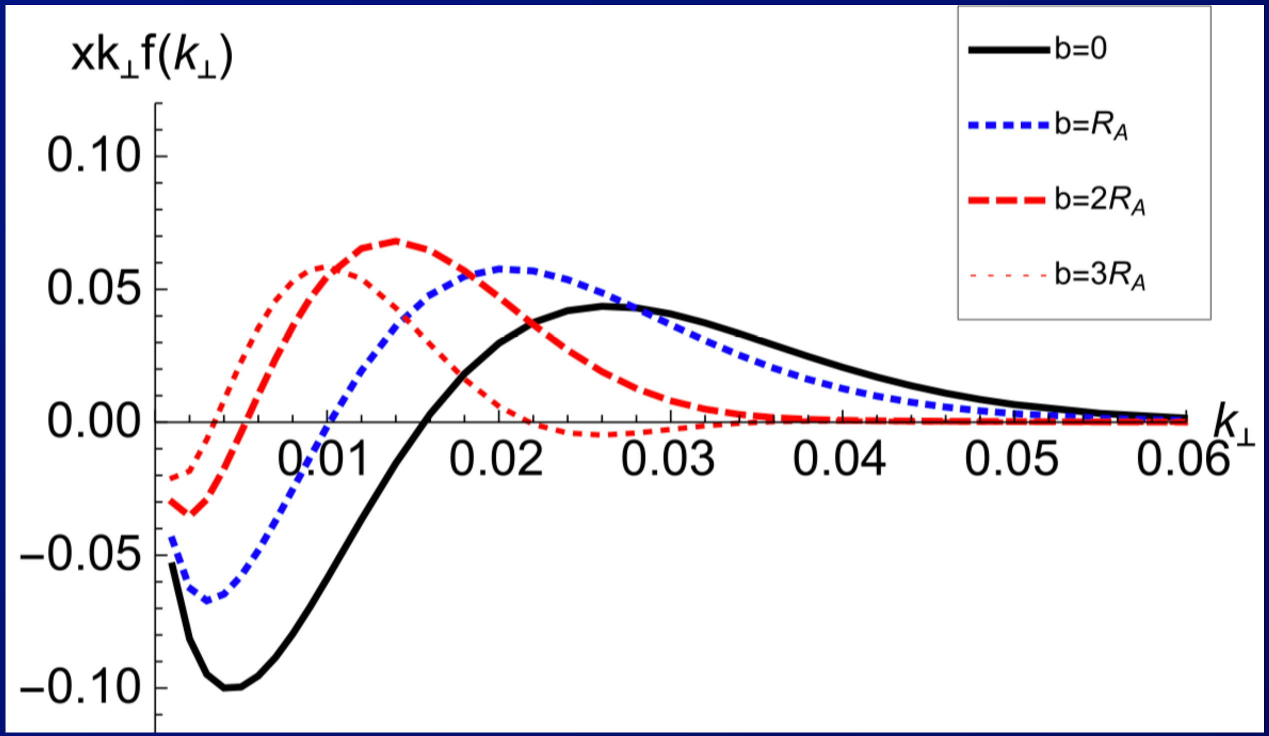
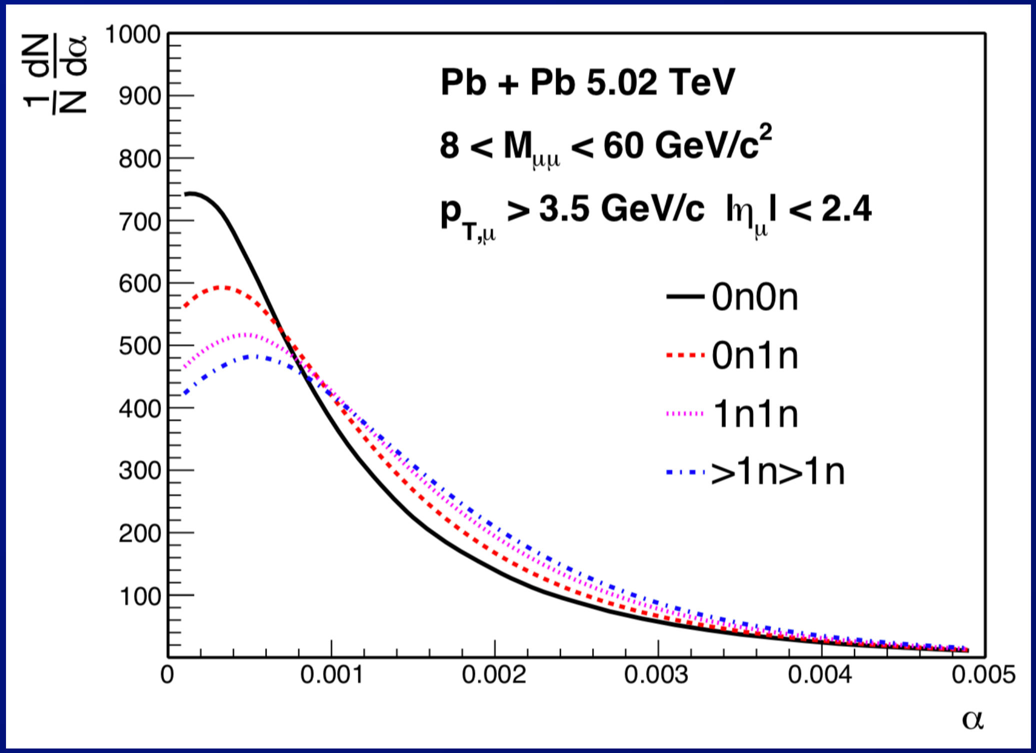


Phys. Rev. D 102 (2020) 9, 094013

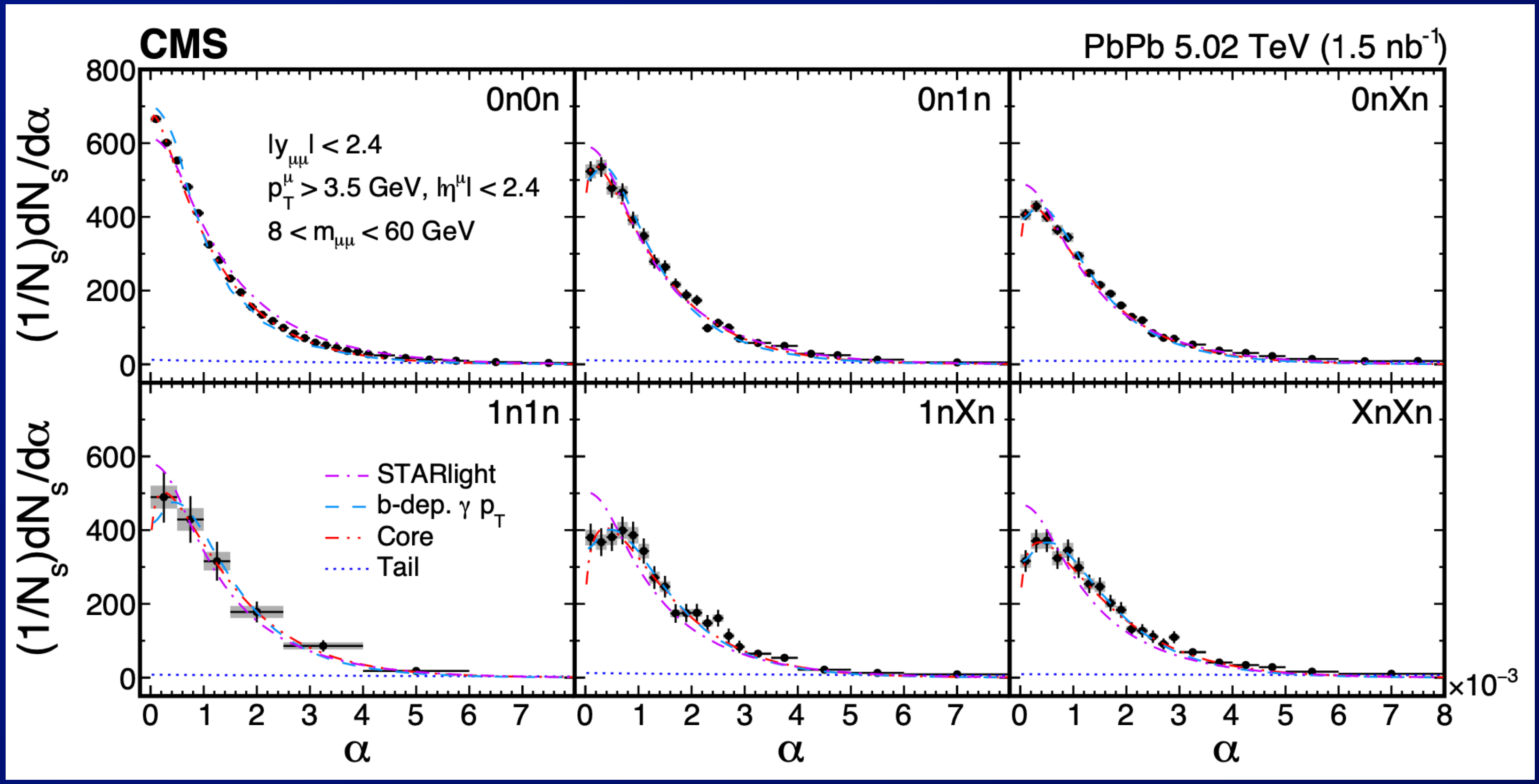
Nuclear breakup, and photon k_T

Brandenburg et al, arXiv:2006.07365

- b-dependence of Coulomb excitation, forward neutrons
- + b dependence of photon kT
  - ⇒ Broadening of dilepton acoplanarity with increasing nuclear breakup (# neutrons)



- Observed by CMS



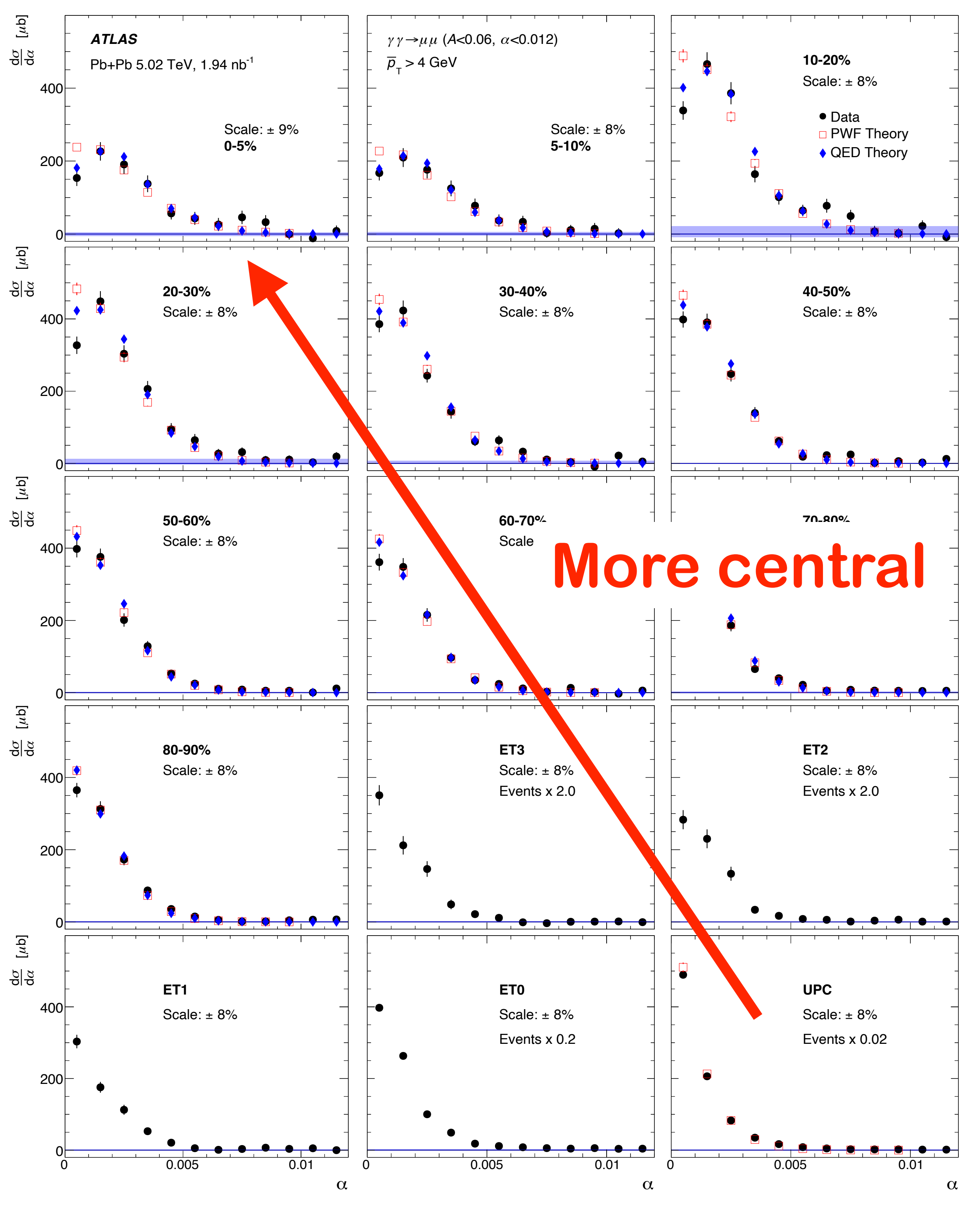
Phys. Rev. Lett. 127, 122001 (2021)

γ+γ dilepton production in hadronic Pb+Pb

- ATLAS studied γ+γ → $\mu^+\mu^-$ in hadronic Pb+Pb collisions
  - Goal: use tight Δφ correlation of muons as EM probe of the quark gluon plasma

⇒ See a centrality-dependence of $\mu^+\mu^-$ acoplanarity distribution

⇒ Magnetic field? Collisional?



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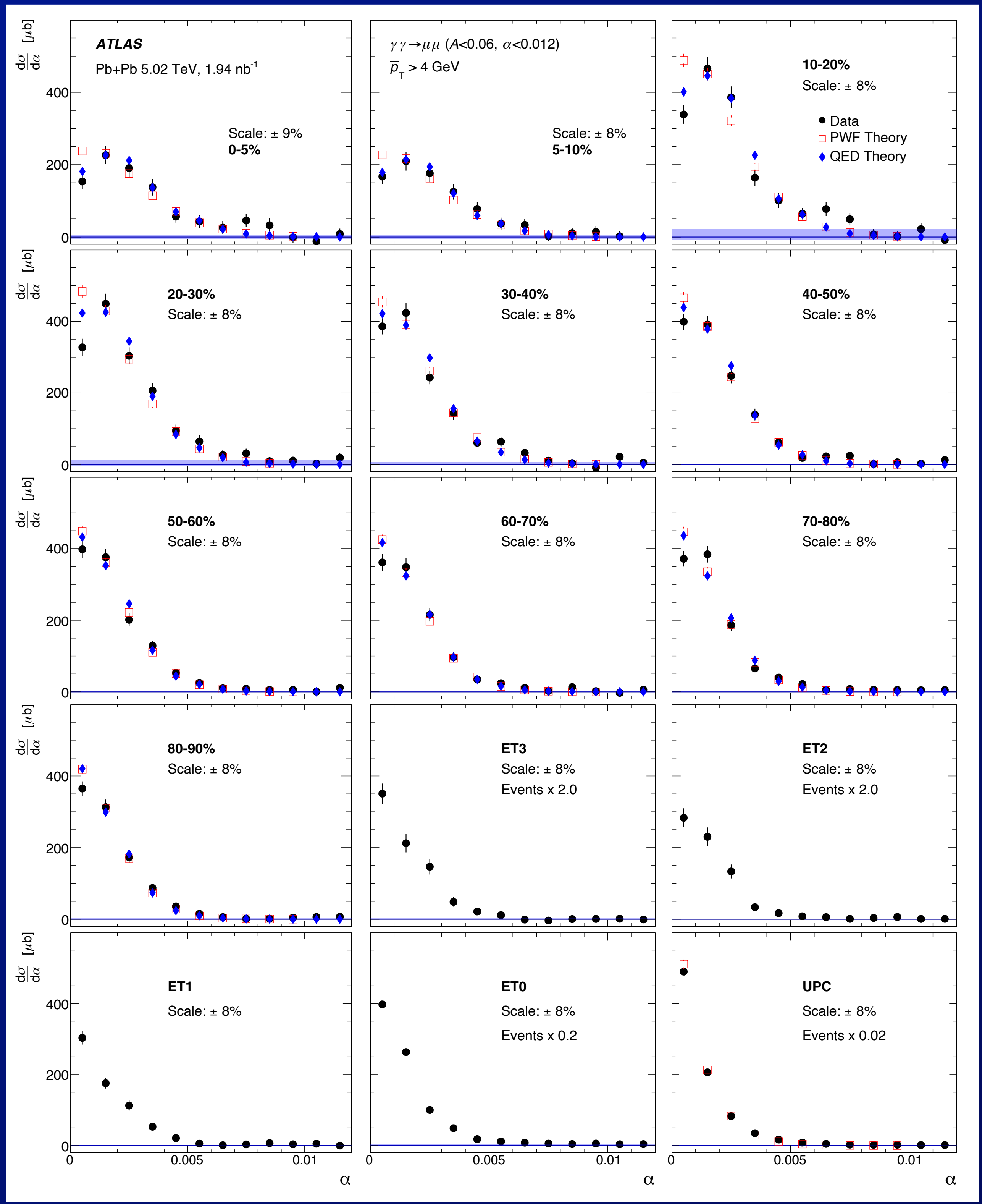
  ⇒See a centrality-dependence of $\mu^+\mu^-$ acoplanarity distribution

  ⇒Magnetic field? Collisional?



- In fact, data are reproduced by calculations including b-dependence of the photon k_T distribution

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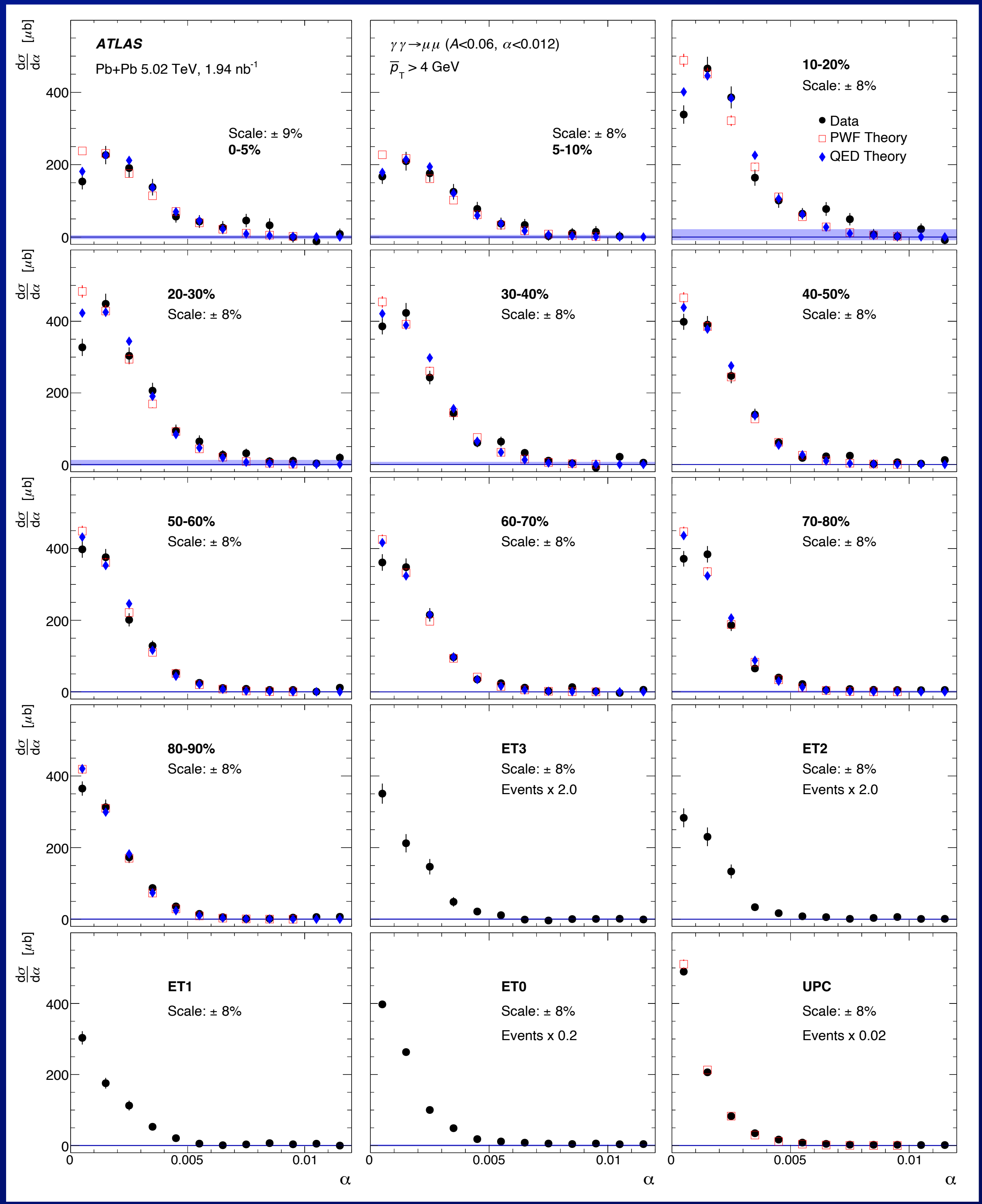
  - Goal: use tight Δφ correlation of muons as EM probe of the quark gluon plasma

  ⇒ See a centrality-dependence of $\mu^+\mu^-$ acoplanarity distribution

  ⇒ Magnetic field? Collisional?



- **In fact, data are reproduced by calculations including b-dependence of the photon k_T distribution**

  ⇒ May provide new/competitive method to probe the electromagnetic structure of nuclei.

Summary, Observations

- LHC (and RHIC) are high-luminosity photon colliders
  – Can study $\gamma+\gamma$ scattering with $\sqrt{s} > 100$ GeV
  – Photon fluxes can be calculated ab initio
  – But important details still under study
  ⇒ Especially photon k_T and correlation with $r_\perp$ and b
- $\gamma+\gamma \rightarrow$ dilepton data provide important tests of theory
  – But there are complications/interesting physics
  ⇒ Photon k_T and impact parameter dependence
  ⇒ Dissociative γ emission
  ⇒ Higher-order processes (didn't discuss)
  – $\gamma+\gamma \rightarrow$ dileptons in hadronic Pb+Pb collisions a new topic
- $\gamma+\gamma$ processes are being used for SM and BSM tests
  – Light-by-light, ALP limits
  – τ g-2
  ⇒ more will come: e.g. WW, bbbar, exotics, …