$\gamma\gamma \rightarrow \mathrm{l}^{+}\mathrm{l}^{-}$ production at RHIC and at the LHC in hadronic collisions

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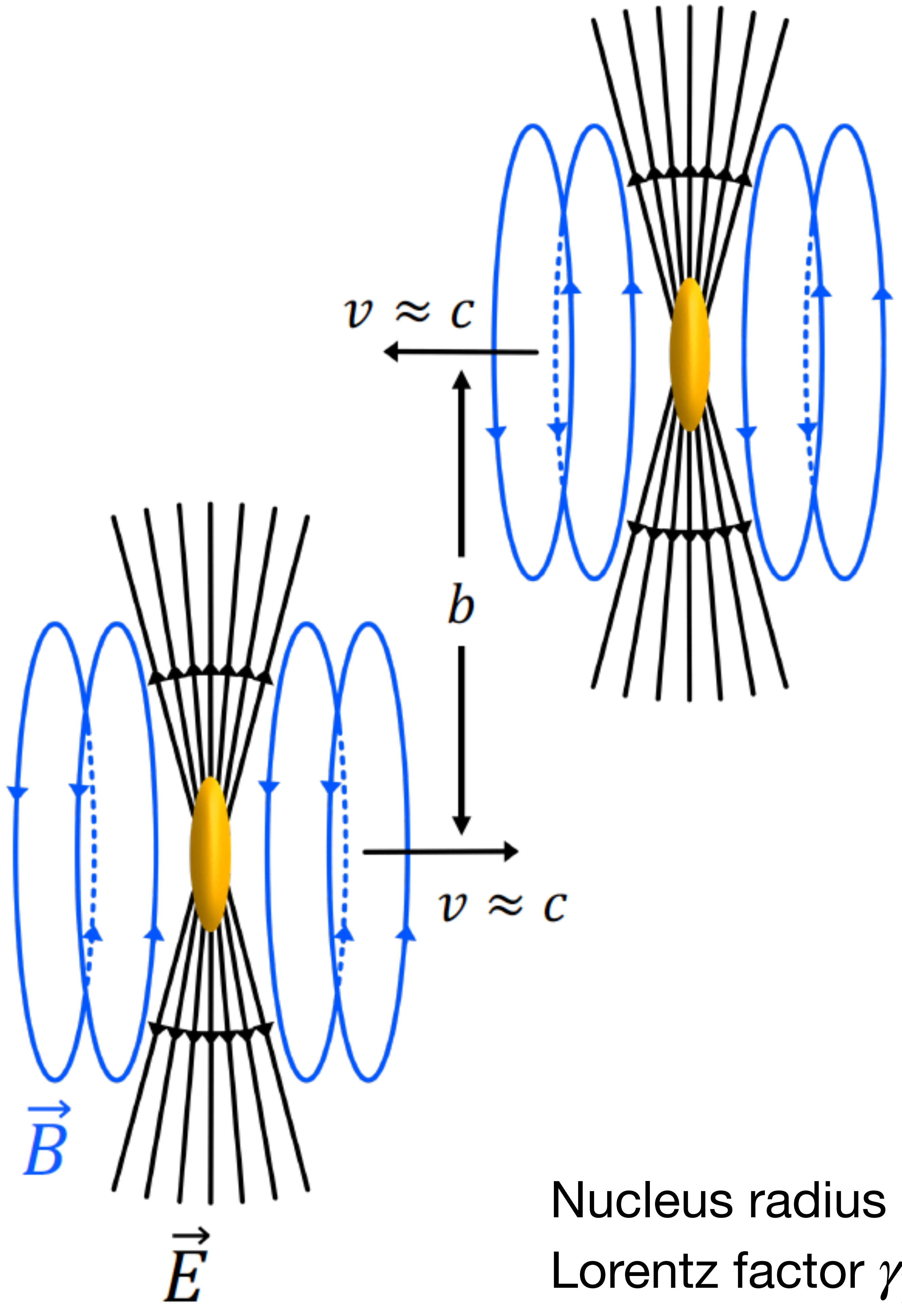
GDR QCD Workshop on coherence/incoherence in hadronic & diffractive collisions at DIS and at hadron colliders
Orsay - 11.10.2023

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

The strongest electromagnetic fields



Nucleus radius R
Lorentz factor γ_L

In heavy-ion collisions

$$E_{max} = \frac{Ze\gamma}{b^2} \approx 5 \times 10^{16} - 10^{18} \text{ V/cm}$$
$$B_{max} \sim 10^{14} - 10^{16} \text{ T}$$

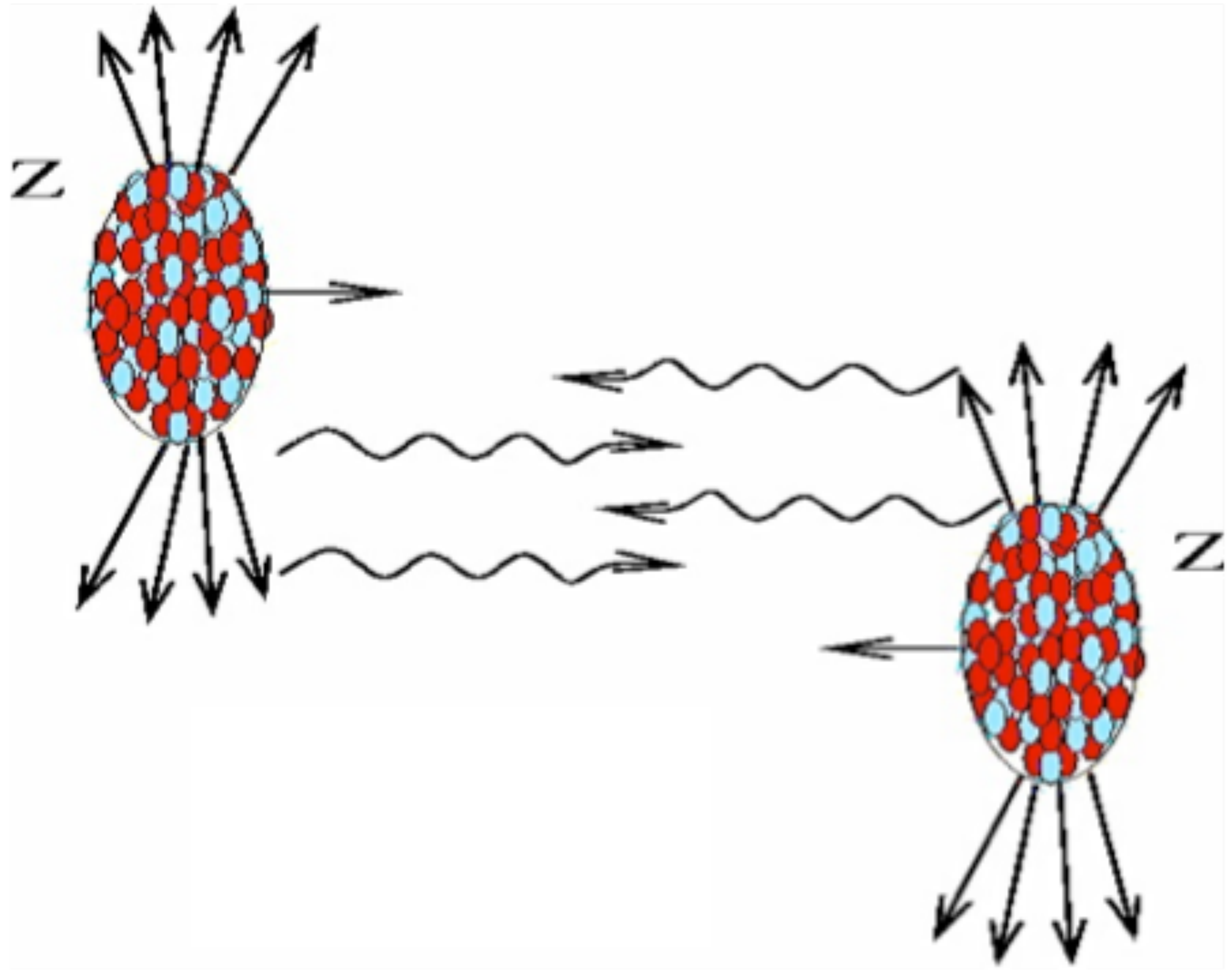
Strongest fields in the universe but very short lifetime
→ Must be treated in terms of photon quanta

Source of quasi-real photons generated coherently

- Z^2 dependence of the photon flux
- Maximum energy $\omega_{\gamma,max} \sim \gamma_L(\hbar c/R)$
  80 GeV in Pb—Pb@LHC, 3 GeV in Au—Au@RHIC
- Typical transverse γ momentum $p_{T,\gamma}$ very small (~30 MeV)
  $\omega/\gamma_L \lesssim p_{T,\gamma} \lesssim 1/R \ll \omega$

J. D. Brandenburg, W. Zha, Z. Xu, Eur. Phys. J. A57 (2021) 299
X. Wang et al, Phys. Rev. C 107 (2023) 044906

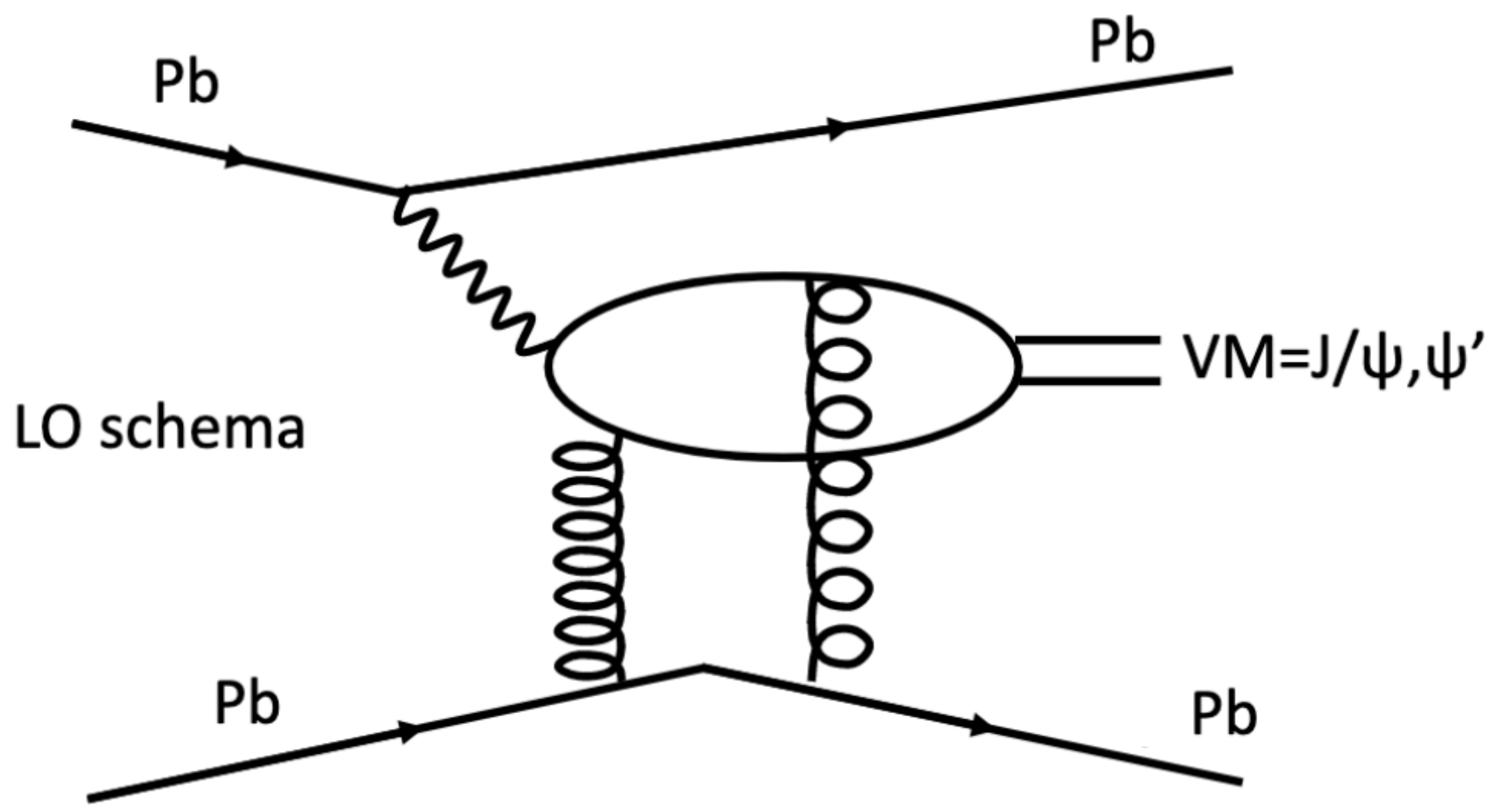
Photon induced processes in heavy-ion collisions



Flux on photons $\sim Z^2$

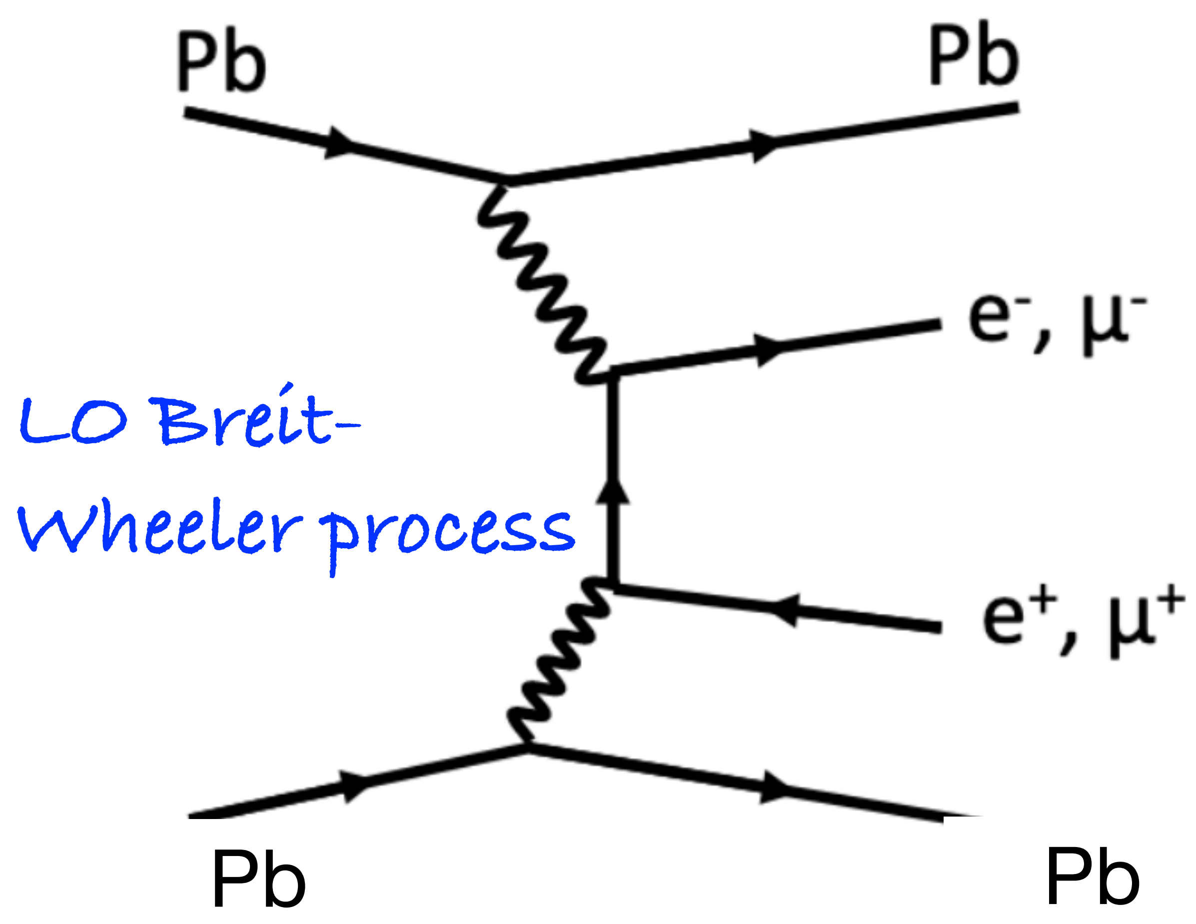
Flux on photons on photons $\sim Z^4$

Production of vector mesons



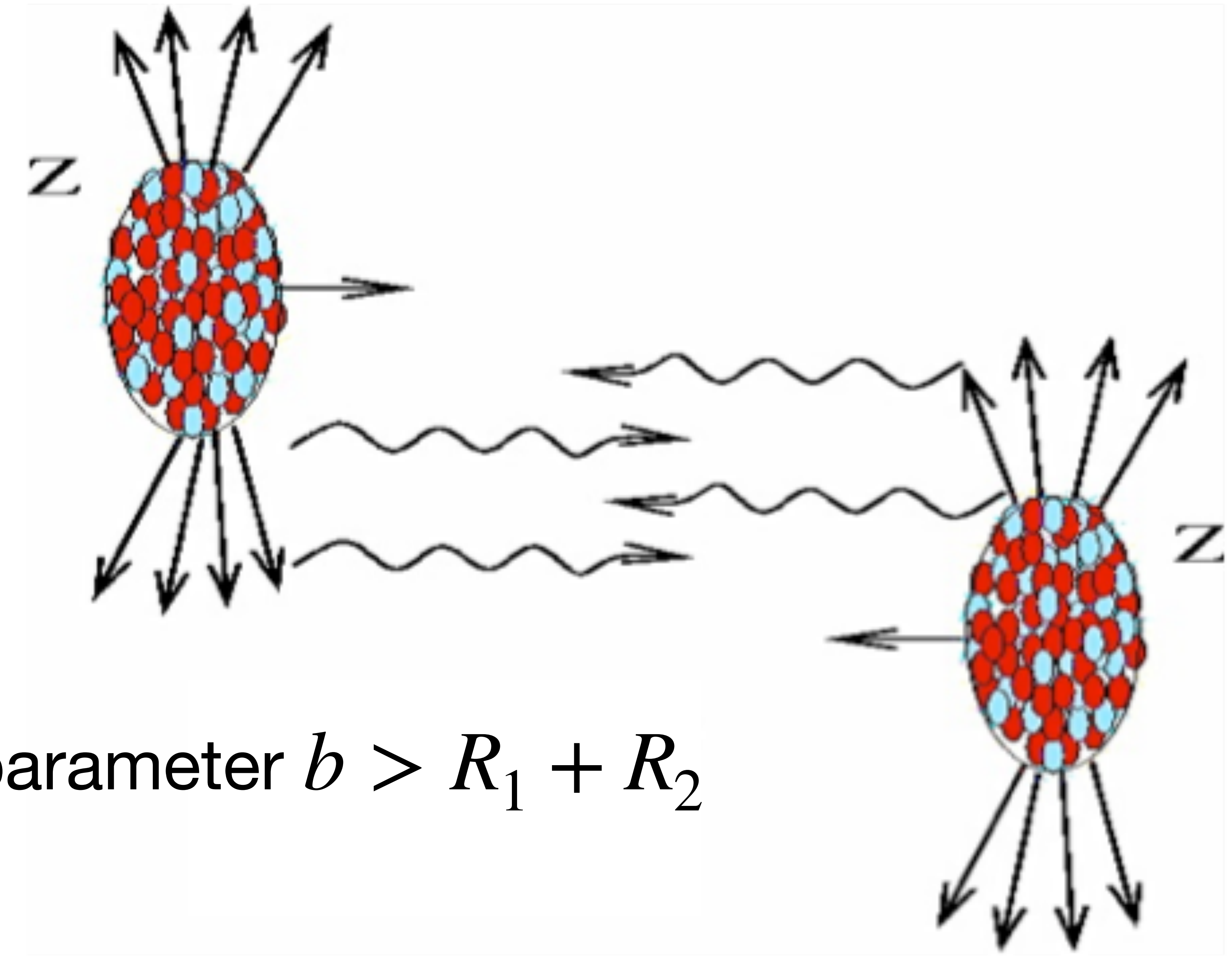
→ Access to gluon distributions in nucleus

Dilepton production



→ test QED, map EM field

Ultra-peripheral heavy-ion collisions (UPCs)



Impact parameter $b > R_1 + R_2$

Clean environment without hadronic interaction

A lot of publications for $\gamma\gamma \rightarrow \mathrm{l}^+\mathrm{l}^-$ in UPCs

- **PHENIX Au—Au at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV**

  $2 < m_{\mathrm{e^+e^-}} < 6.2$ GeV/c^2 Phys. Lett. B679 (2009) 321

- **STAR Au—Au at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV**

  $0.14 < m_{\mathrm{e^+e^-}} < 0.26$ GeV/c^2 Phys. Rev. C70 (2004) 031902
  $0.4 < m_{\mathrm{e^+e^-}} < 2.7$ GeV/c^2 Phys. Rev. Lett 127 (2021) 052302

- **ALICE Pb—Pb at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV**

  $4 < m_{\mathrm{e^+e^-}} < 10$ GeV/c^2 Eur. Phys. J. C 73 (2013) 2617

- **ATLAS Pb—Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV**

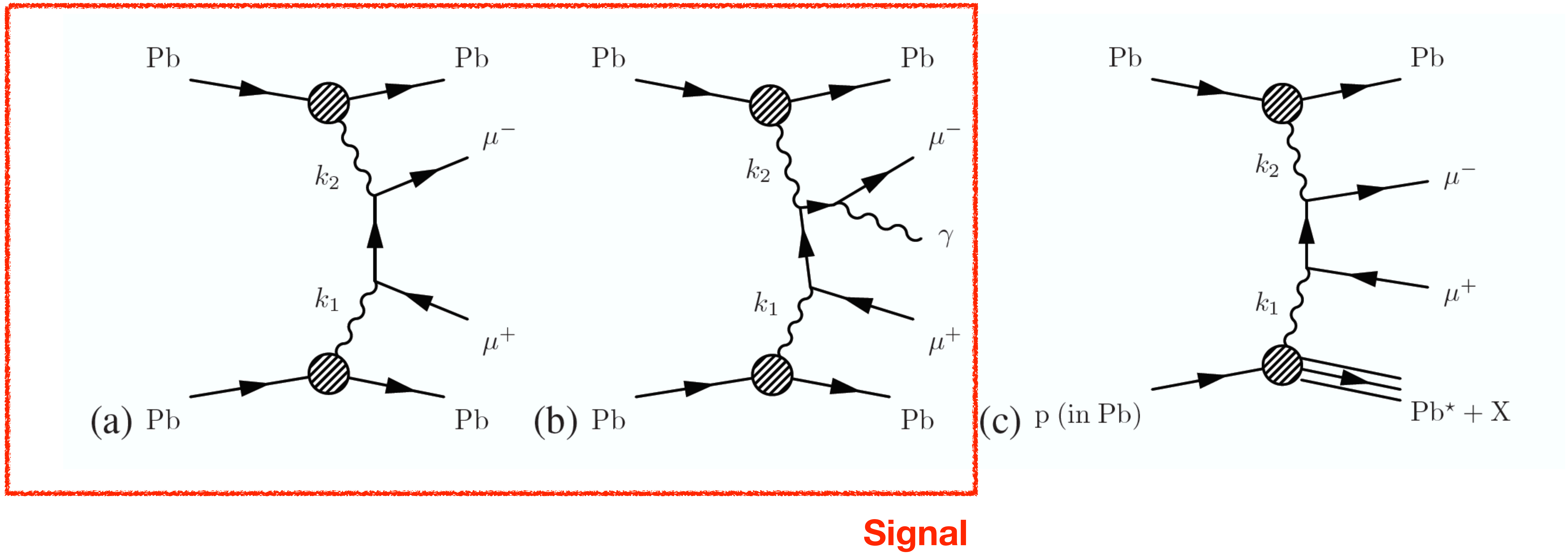
  $10 < m_{\mu^+\mu^-} < 80$ GeV/c^2 Phys. Rev. C 104, 024906 (2021)
  $5 < m_{\mathrm{e^+e^-}} < 90$ GeV/c^2 JHEP06 (2023) 182

- **CMS Pb—Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV**

  $5 < m_{\mathrm{e^+e^-}} < 100$ GeV/c^2 CMS Phys. Lett. B 797 (2019) 134826
  $8 < m_{\mu^+\mu^-} < 60$ GeV/c^2 CMS Phys. Rev. Lett 127 (2021) 122001

Note: also measurements in pp collisions at $\sqrt{s} =$ 7 and 13 TeV at the LHC

Exclusive dilepton processes & dissociation in UPCs

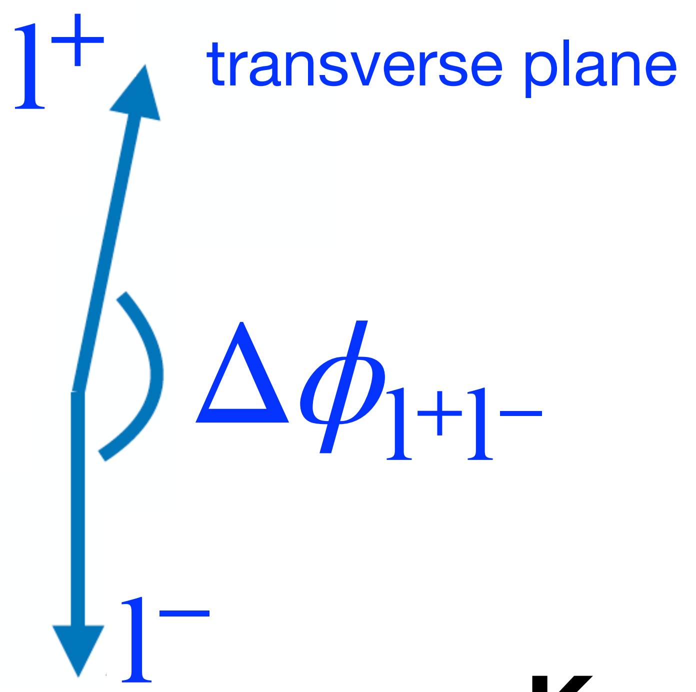


(a) Leading order $\gamma\gamma \rightarrow l^+l^-$ production = primary Breit-Wheeler process
implemented in STARlight, SuperChic, LO QED calculations, Wigner approaches

(b) Higher order final state, not existing in any MCs, under study in calculations (but not included in final comparison with data)
e.g. STAR: Pythia8 used on top to STARlight calculations

(c) Dissociative processes subtracted: one photon emitted not coherently by charged constituents of the nucleus
not coherently enhanced, larger $p_{T,\gamma}$

Dilepton acoplanarity



$$\alpha_{l^+l^-} = 1 - \frac{\Delta\phi_{l^+l^-}}{\pi}$$

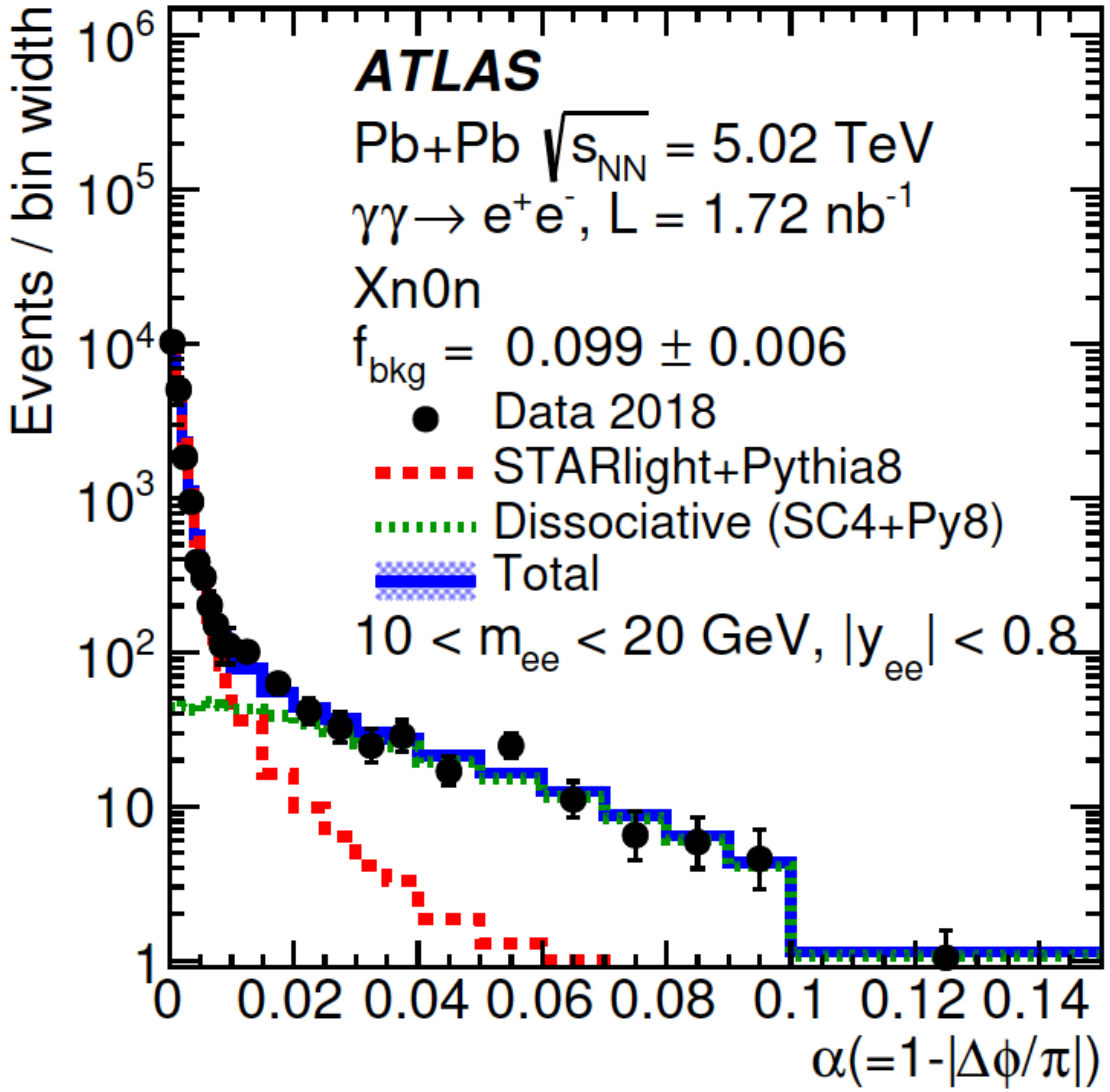
Key tool for distinguishing between these processes

$\alpha_{l^+l^-} = 0$: Lepton back-to-back in transverse plane
(p_{T,l^+l^-} small)
LO Breit-Wheeler process dominant

$\alpha_{l^+l^-} > 0$: higher-order contributions in tail of red distributio

$\alpha_{l^+l^-}$ large: nuclear dissociative processes

Dissociative background subtracted via $\alpha_{l^+l^-}$ fits (simple (CMS) or more involved (ATLAS))



Results in *inclusive* UPCs

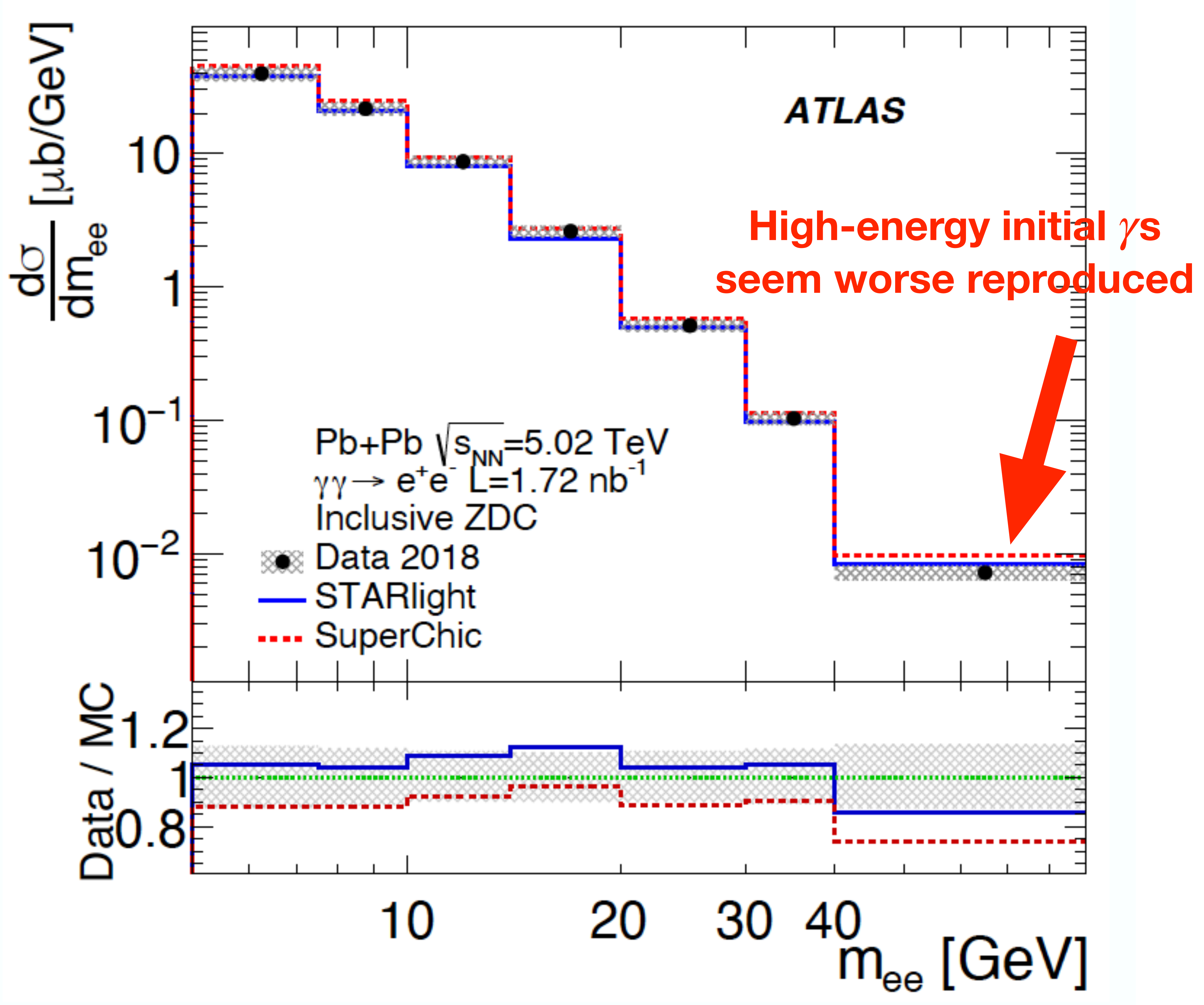
As a function of:

- $m_{l^+l^-}$ = centre-of-mass energy of colliding $\gamma\gamma$
- $y_{l^+l^-} = y_{\gamma\gamma}$
- $|\cos(\Theta^*)|$ with Θ^* scattering Dimuon angles in the $\gamma\gamma$ centre-of-mass frame (back-up)

Reasonably well described by calculations

UPCs Pb—Pb $\sqrt{s_{NN}} = 5.02$ TeV

$5 < m_{e^+e^-} < 90$ GeV/c², $|\eta_e| < 2.5$



ATLAS, JHEP06 (2023) 182

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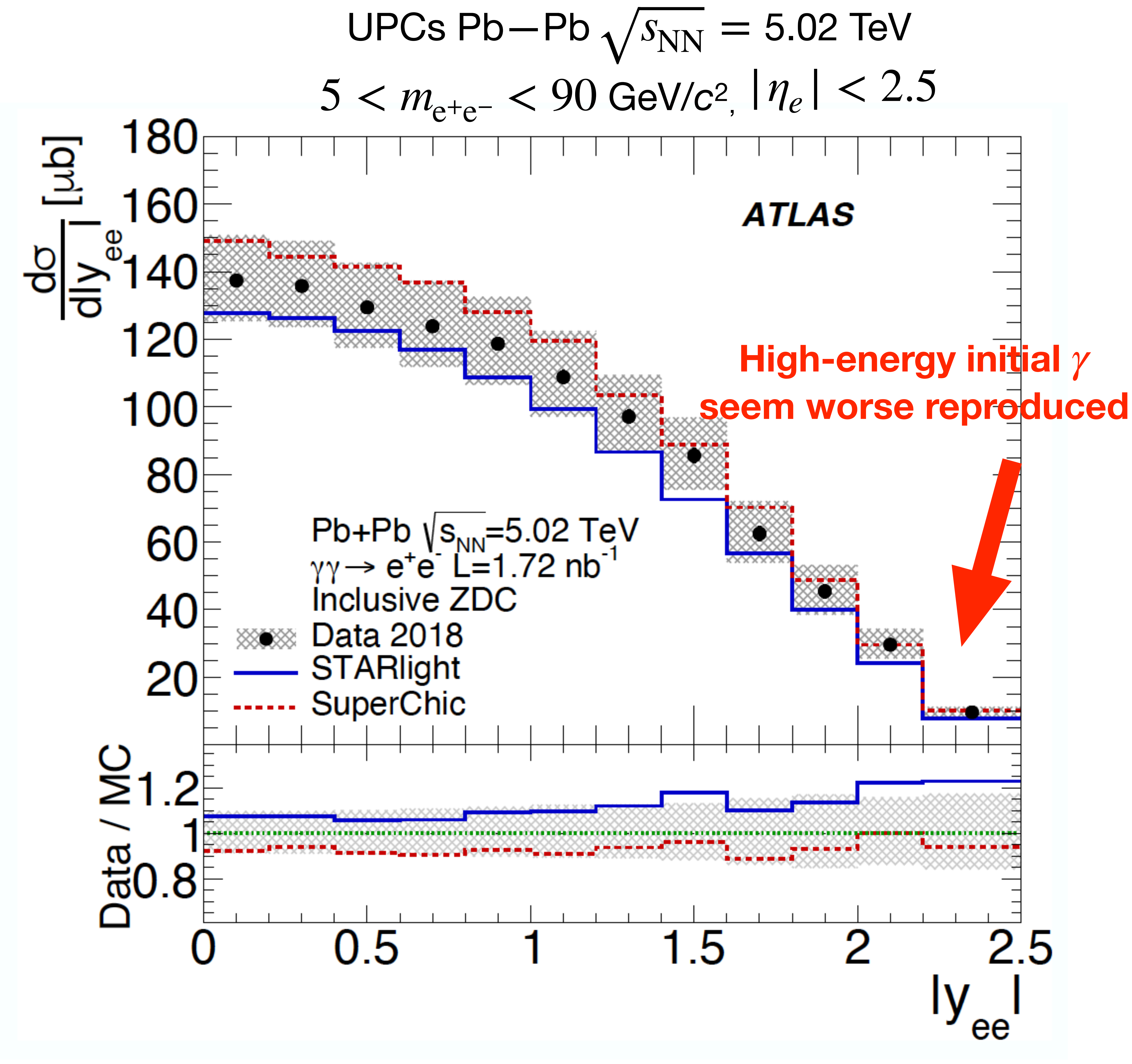


ATLAS, JHEP06 (2023) 182

Results in *inclusive* UPCs

UPCs Pb—Pb $\sqrt{s_{NN}}$ = 5.02 TeV

$m_{\mu^+\mu^-} > 10$ GeV/c^2, $|\eta_\mu| < 2.4$

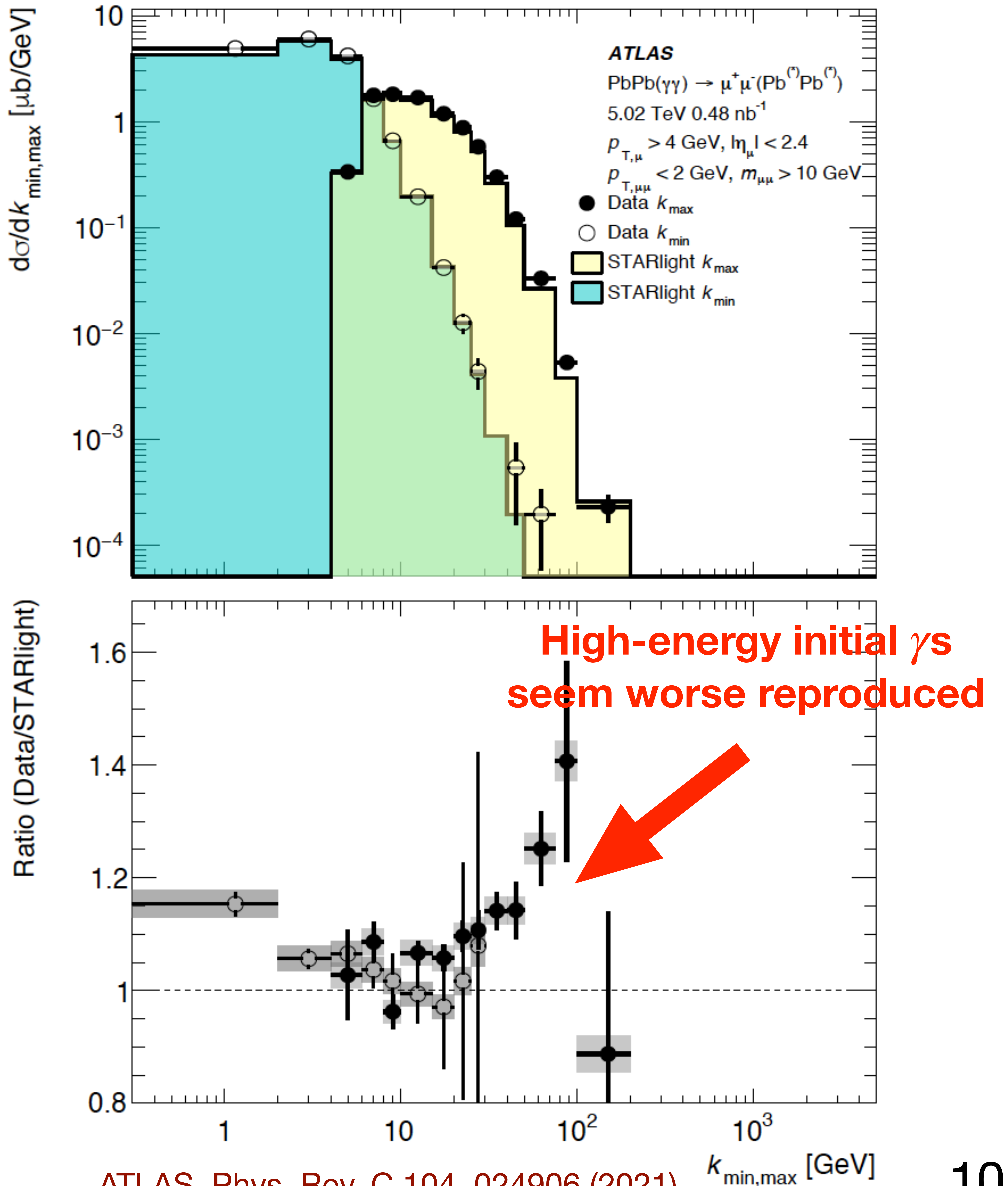
As a function of:

- $m_{l^+l^-}$ = centre-of-mass energy of colliding $\gamma\gamma$
- $y_{l^+l^-} = y_{\gamma\gamma}$
- $|\cos(\Theta^*)|$ with Θ^* scattering Dimuon angles in the $\gamma\gamma$ centre-of-mass frame

Reasonably well described by calculations

$m_{l^+l^-}$ & $y_{l^+l^+}$ **use to estimate photon energies**

$$\omega_{1,2} = k_{1,2} = (m_{l^+l^-}/2)\exp(\pm y_{l^+l^-})$$

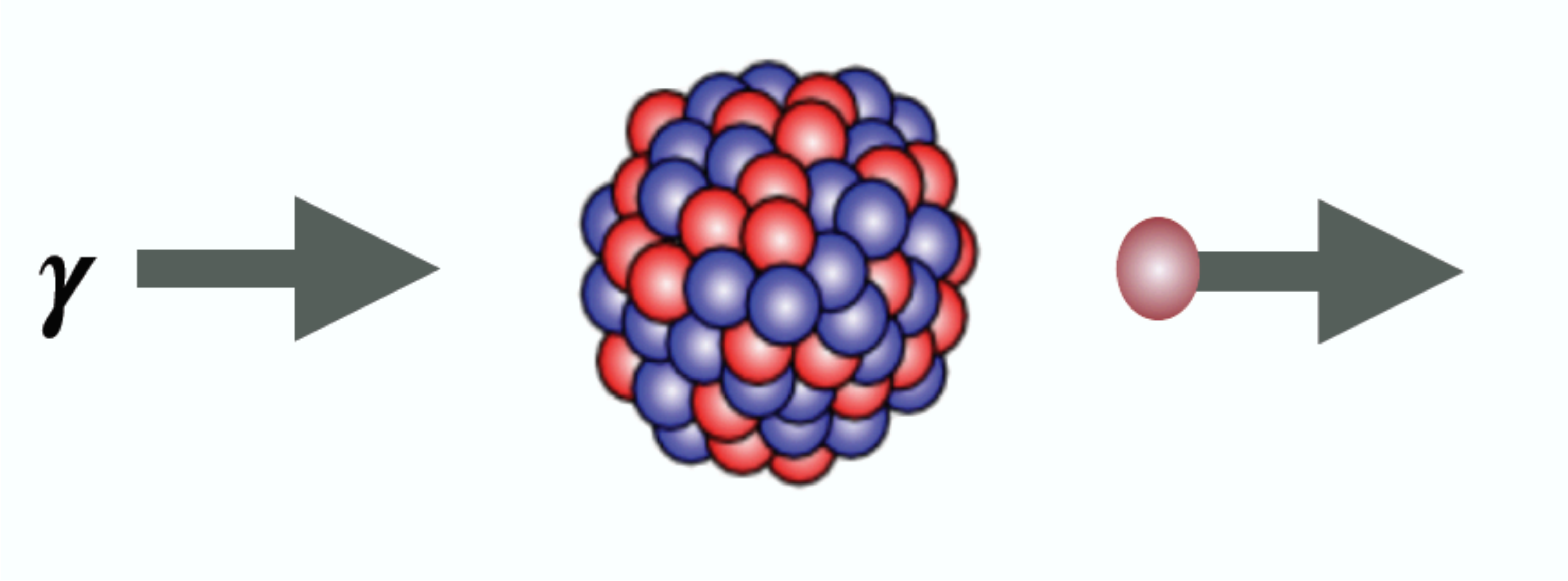


ATLAS, Phys. Rev. C 104, 024906 (2021)

Varying impact parameter in UPCs

Excitation of the nuclei possible
through secondary photon exchange

"Giant dipole resonance"
All protons vibrating against all neutrons
→ Knocks out 1-4 neutrons



Neutrons can be "count" in zero degree calorimeters

Varying impact parameter in UPCs

S. Klein, P. Steinberg,
Annu. Rev. Nucl. Part. Sci. 70(1), 323 (2020)

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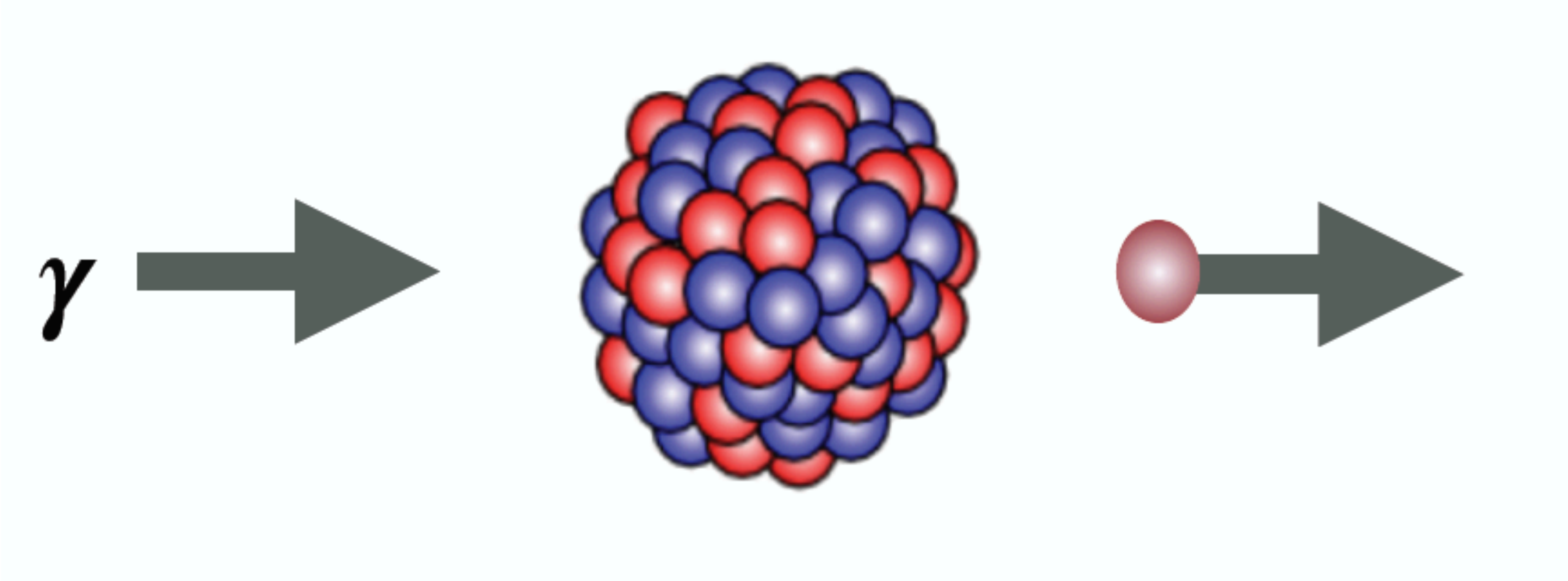
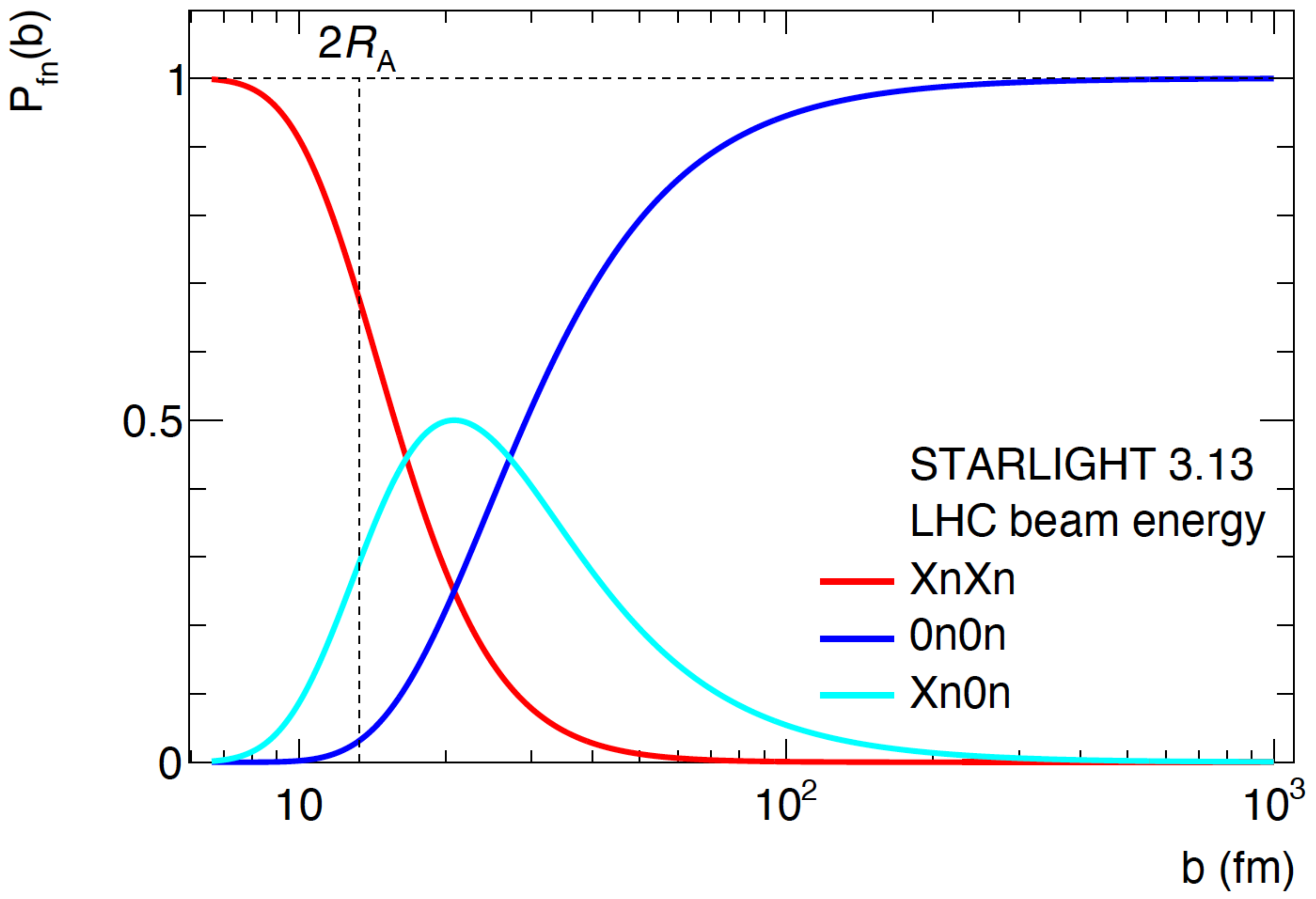




Neutrons can be "count" in zero degree calorimeters

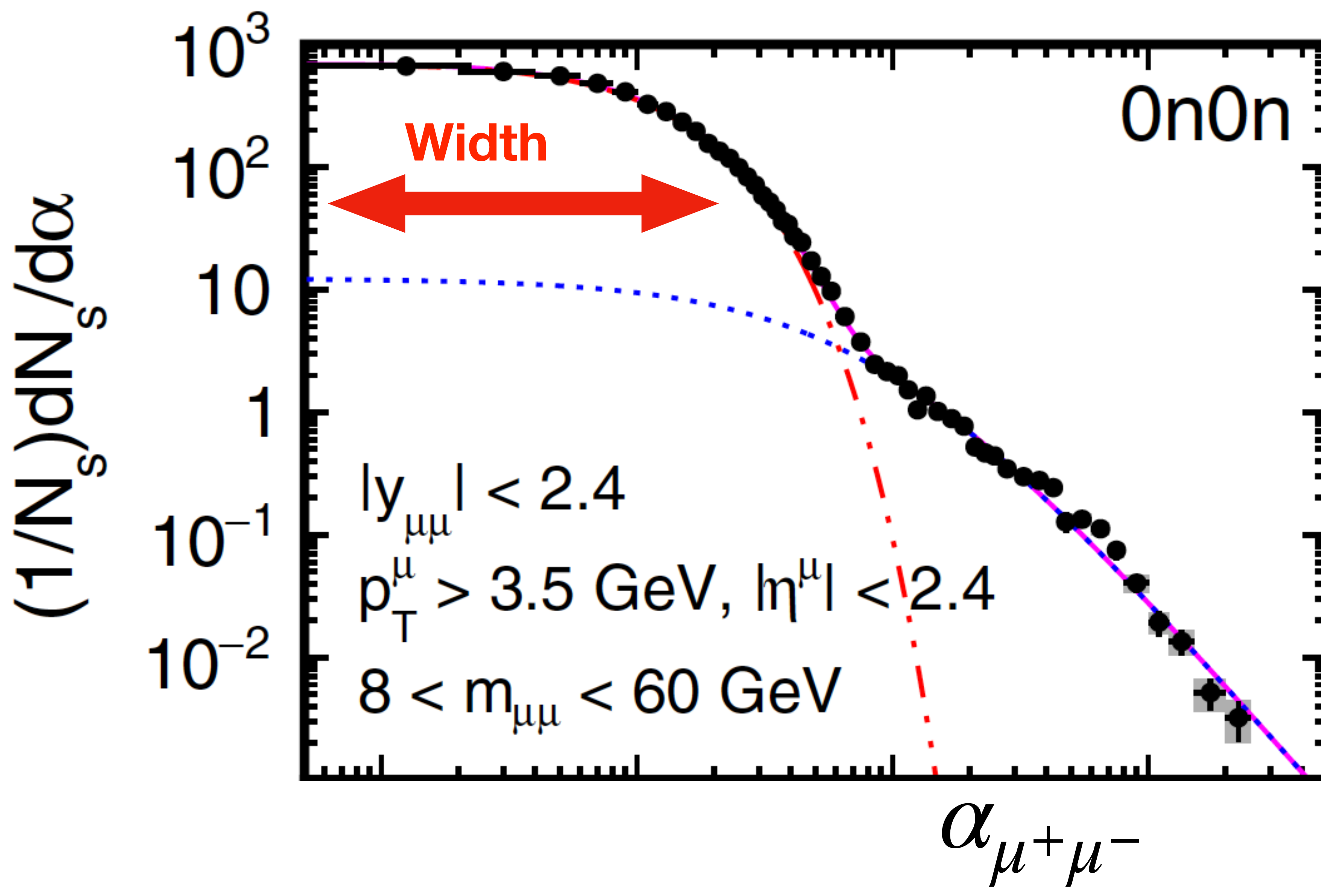
Classify UPC events according to
0n0n, Xn0n/0nXn or XnXn
→ Selection select also a impact parameter range
→ Probe impact parameter dependences

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

Varying impact parameter in UPCs

$$\alpha_{l^+l^-} = 1 - \frac{\Delta\phi_{l^+l^-}}{\pi}$$

Look at the core of the $\alpha_{l^+l^-}$ distribution dominated by LO Breit-Wheeler process



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

Varying impact parameter in UPCs

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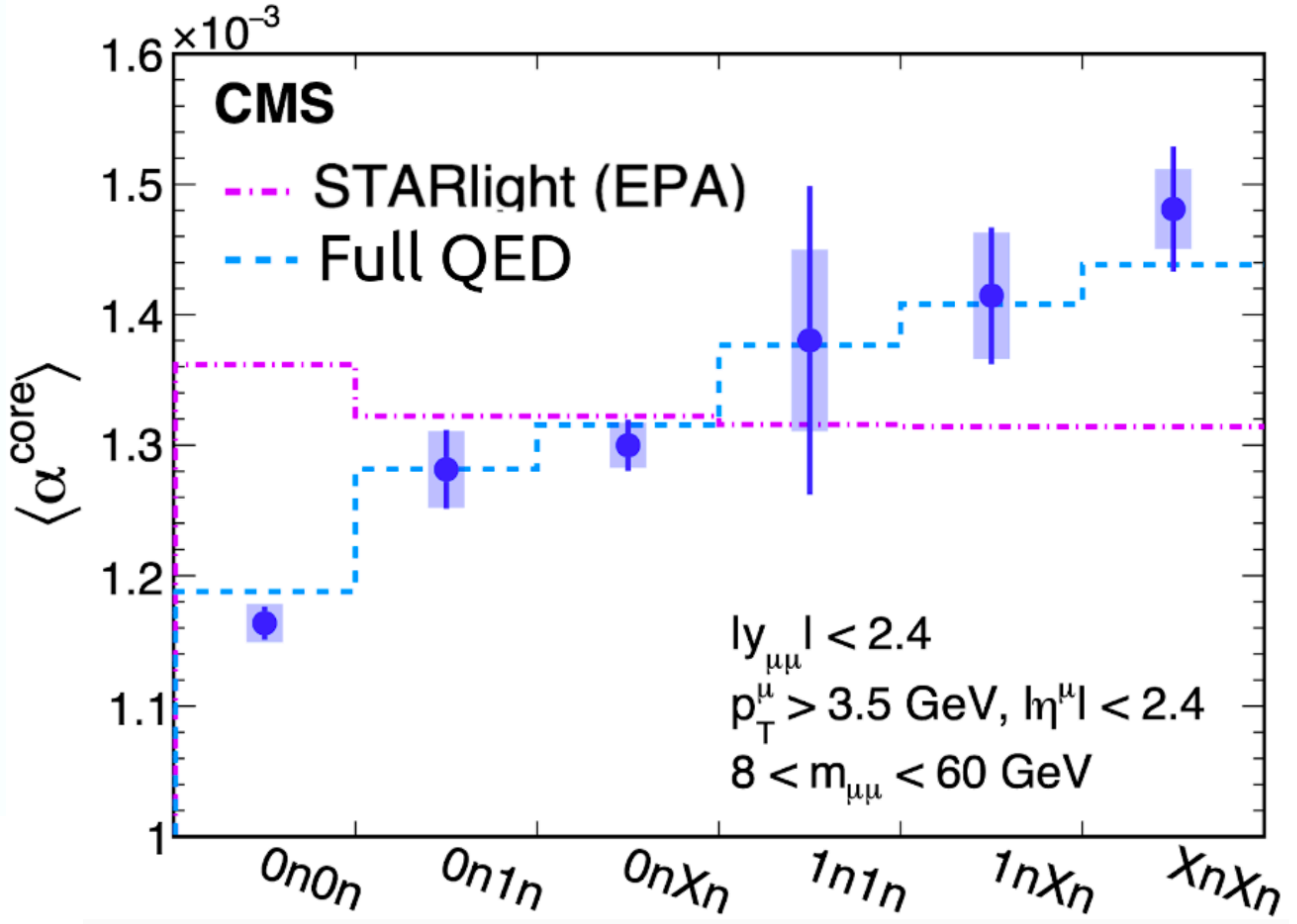
Observed broadening of $\langle\alpha_{core}\rangle$ (larger p_{T,l^+l^-}) with decreasing *b*

Full **LO-QED calculations (or Wigner approach) needed to capture *b* dependence** of the $p_{T,\gamma}$

UPCs Pb—Pb $\sqrt{s_{NN}}$ = 5.02 TeV

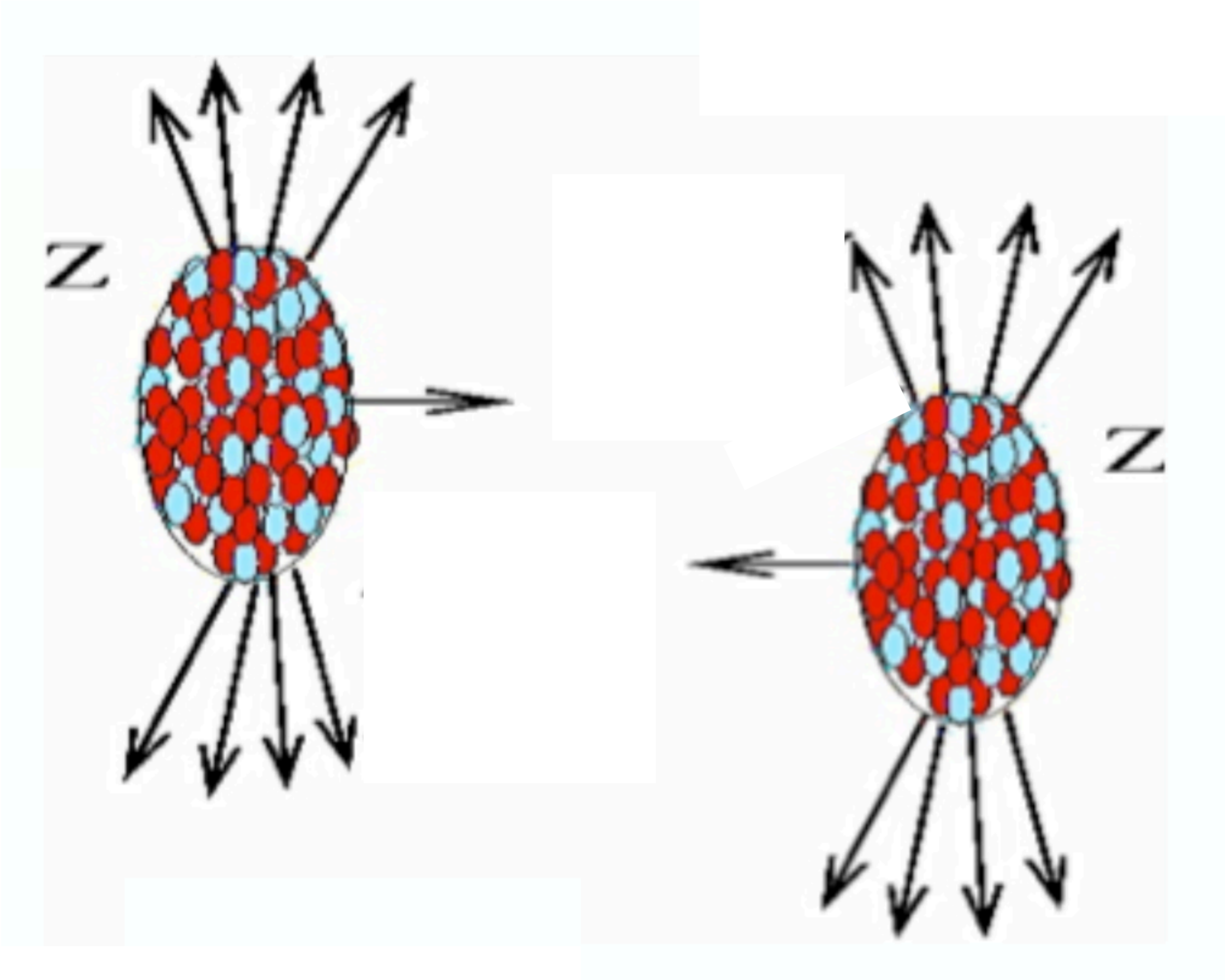
$8 < m_{\mu^+\mu^-} < 60$ GeV/c², $|\eta_\mu| < 2.4$



Larger b → Smaller b

Lower $p_{T,\gamma}$ → Larger $p_{T,\gamma}$

Collisions with hadronic interactions



Impact parameter $b < R_1 + R_2$

- **STAR in peripheral Au—Au and U—U $\sqrt{s_{NN}} \sim$ 200 GeV**
  $0.4 < m_{ee} < 2.6$ GeV/c^2 Phys. Rev. Lett. 121 (2008) 132301
- **ATLAS towards central Pb—Pb $\sqrt{s_{NN}} =$ 5.02 GeV**
  $8 < m_{\mu\mu} < 45$ GeV/c^2 Phys. Rev. Lett. 121 (2018) 212301, Phys. Rev. C107 (2023) 054907
- **ALICE in peripheral Pb—Pb $\sqrt{s_{NN}} =$ 5.02 GeV**
  $0.4 < m_{ee} < 2.7$ GeV/c^2 JHEP 06 (2023) 024

Peripheral Au—Au & U—U collisions at RHIC

First observation
Low mass e^+e^-

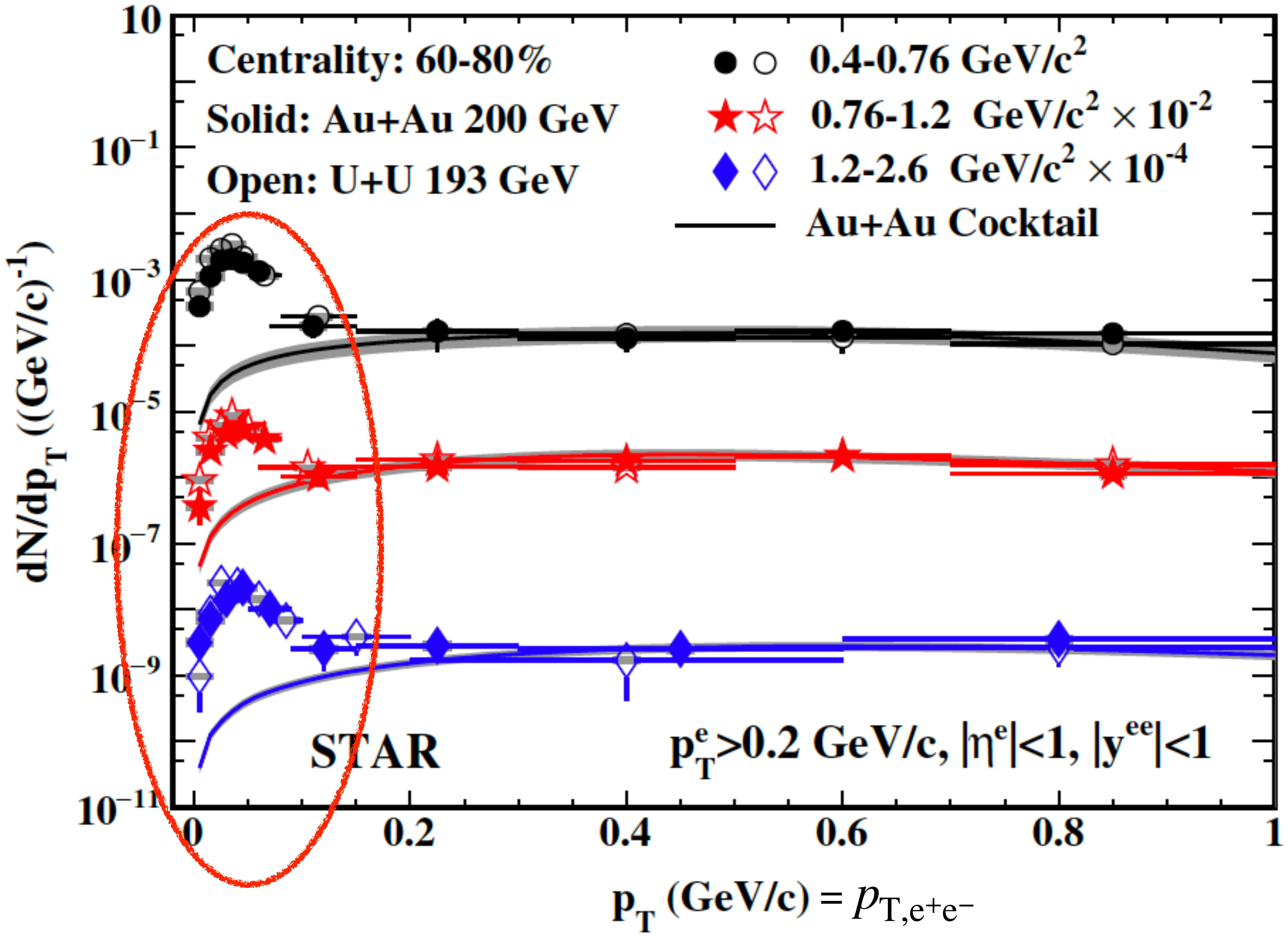
Excess observed at low p_{T,e^+e^-}

Magnitude reproduced by $\gamma\gamma \to e^+e^-$ calculations

p_{T,e^+e^-} **distribution broader compared to UPCs not reproduced by calculations at that time**
(*b* dependence of the $p_{T,\gamma}$ not included in models)

STAR, Phys. Rev. Lett. 121 (2008) 132301

Au—Au, U—U $\sqrt{s_{NN}} \sim 200$ GeV
$0.4 < m_{e^+e^-} < 2.6$ GeV/c², $|\eta_e| < 1$

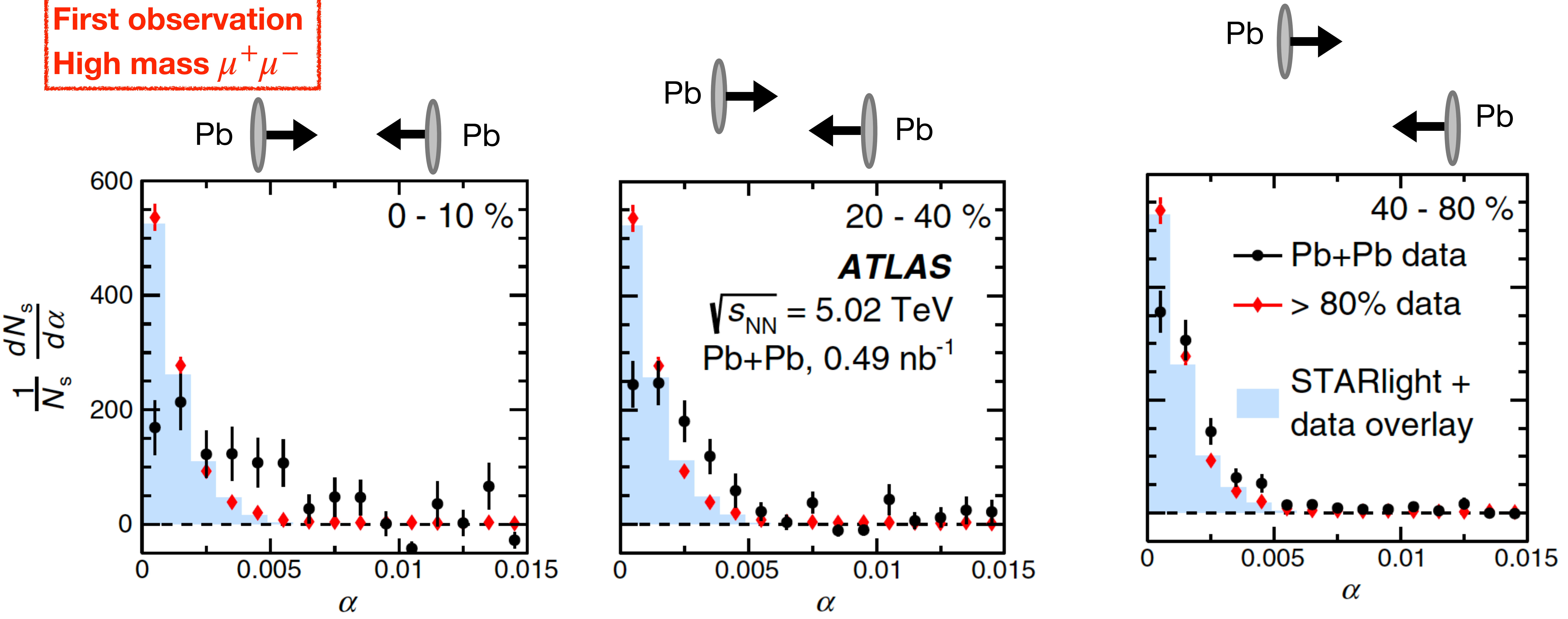


Cocktail = expected contribution from hadronic interactions

Pb—Pb collisions at the LHC

June 2018

First observation
High mass $\mu^+\mu^-$



Observe $\mu^+\mu^-$ pairs with small α (with 8 < $m_{\mu\mu}$ < 45 GeV/c², $|\eta_\mu|$ <)

Qualitative reproduced by $\gamma\gamma \to \mu^+\mu^-$ calculations but broadening of α towards central Pb—Pb

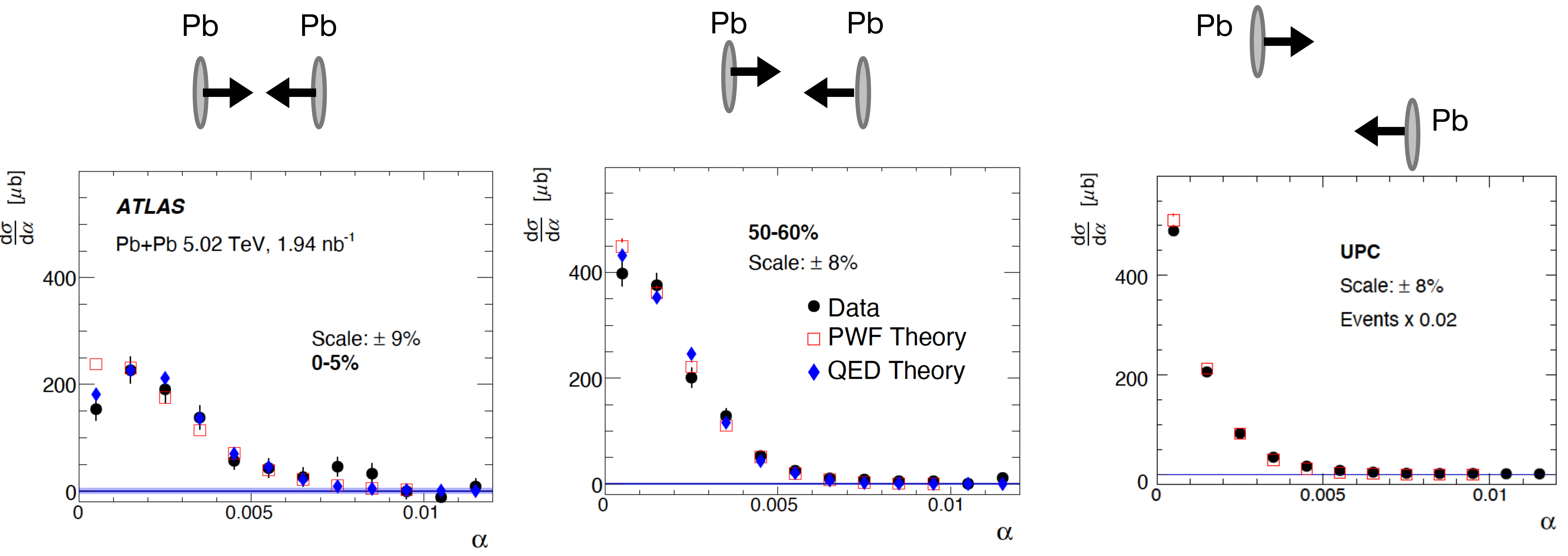
→ **Both experiments suggested hot matter effects**

(Trapped magnetic field (STAR), electromagnetic scatterings (ATLAS))

ATLAS, Phys. Rev. Lett. 121 (2018) 212301

5 years later…..

ATLAS, Phys. Rev. C107 (2023) 054907

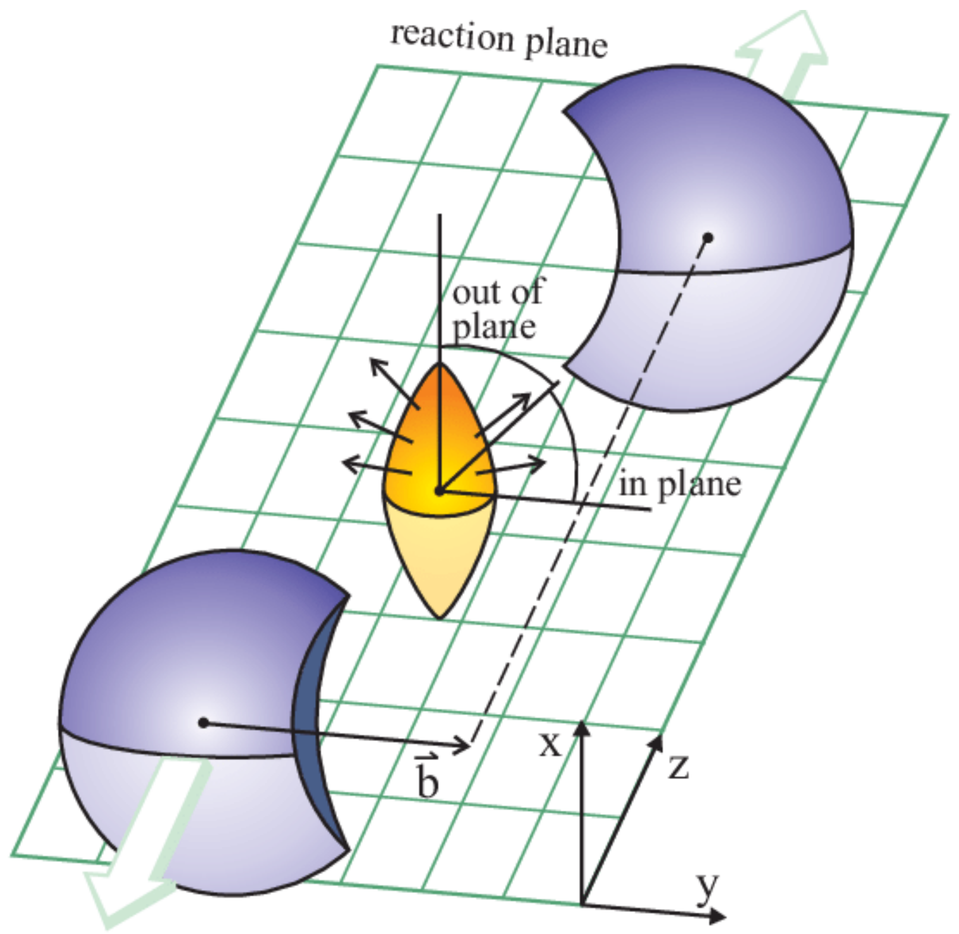


4 x more data for ATLAS + ALICE low $m_{e^+e^-}$ in peripheral collisions (see back-up)

Significant improvement of the description of the data by calculations including properly b dependence of $p_{T,\gamma}$

Hunt for medium effects

S. Klein, A. H. Mueller, B.-W.Xiao, and F.Yuan, Phys. Rev. Lett. 122 (2019) 132301
ATLAS, Phys. Rev. C107 (2023) 054907

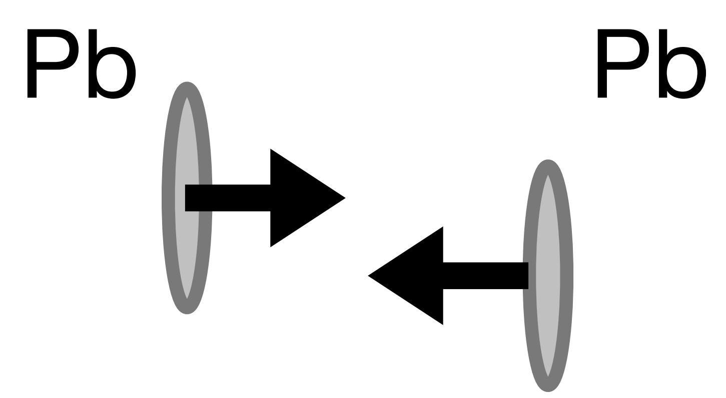


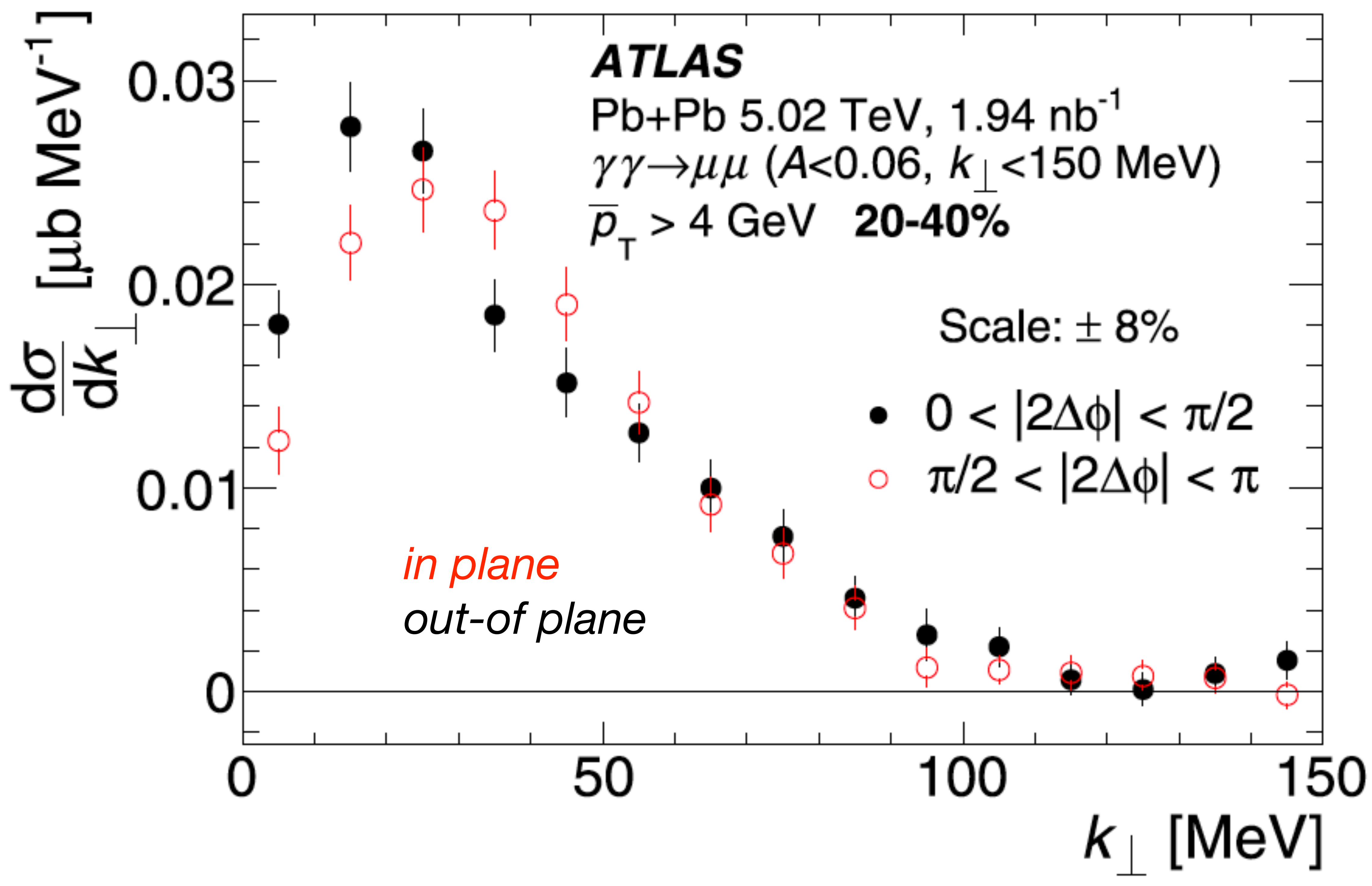
Deflection of the μ in magnetic fields generated during the Pb—Pb collision

Expect a dependence of the broadening

- For **in** and **out-of plane**, i.e. as a function of $|2(\phi_{ll} - \Psi_2)|$
  ϕ_{ll} azimuthal orientation of the dilepton
  Ψ_2 second-order event plane angle ($\sim \vec{b}$ and $\vec{B} \perp \vec{b}$)

- Increasing as a function of $|\Delta y| = |y_{\mu_1} - y_{\mu_2}|$ (as thanh(Δy))





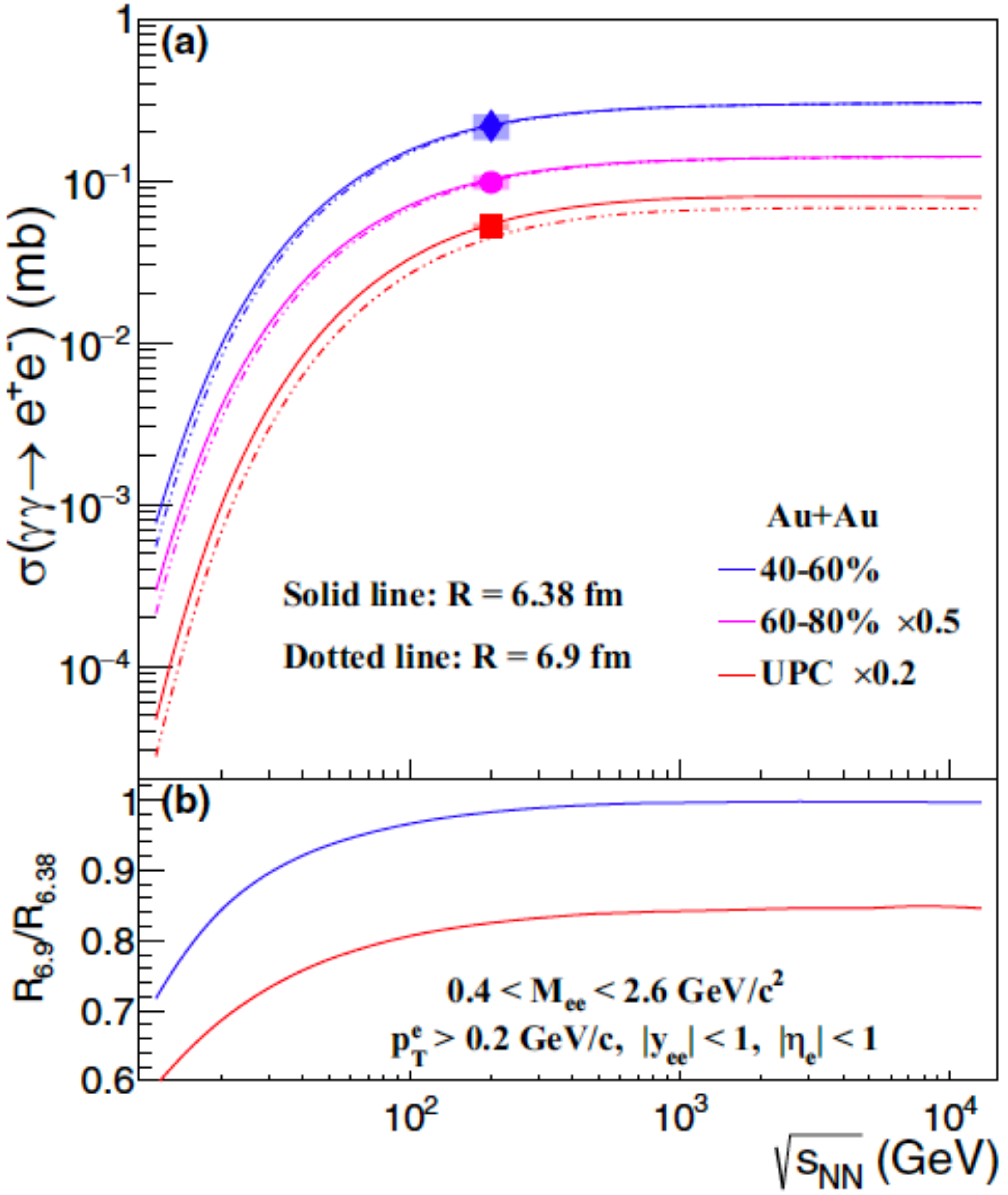
$$k_\perp \equiv \frac{1}{2}(p_{T1} + p_{T2})(\pi - |\phi_1 - \phi_2|) = \pi\alpha\bar{p}_T$$

No clear sign of such effects at the moment from ATLAS data

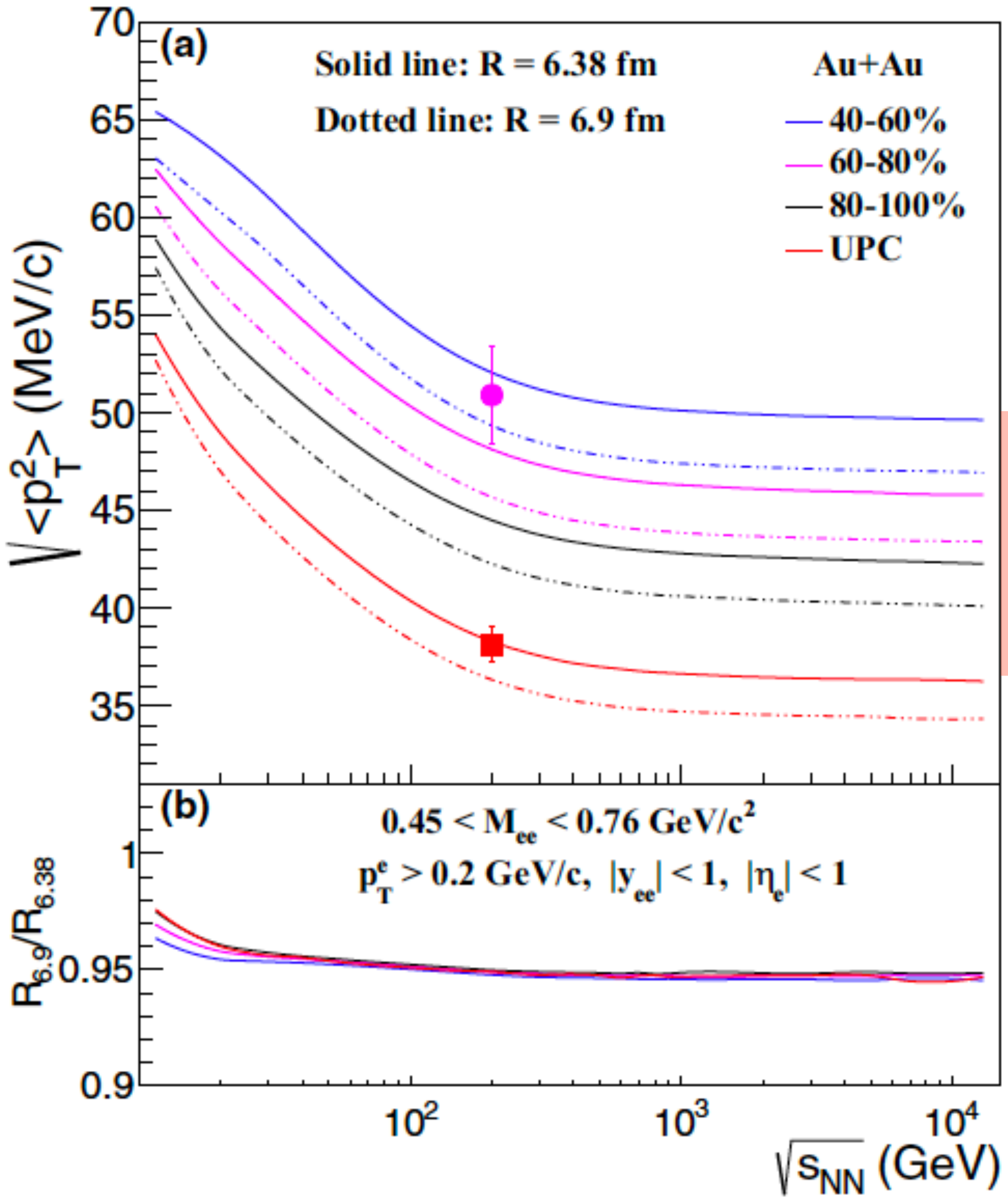
Collision-energy and centrality dependence

LO QED
Au—Au
Low mass e^+e^-

Cross section



Pair transverse momentum



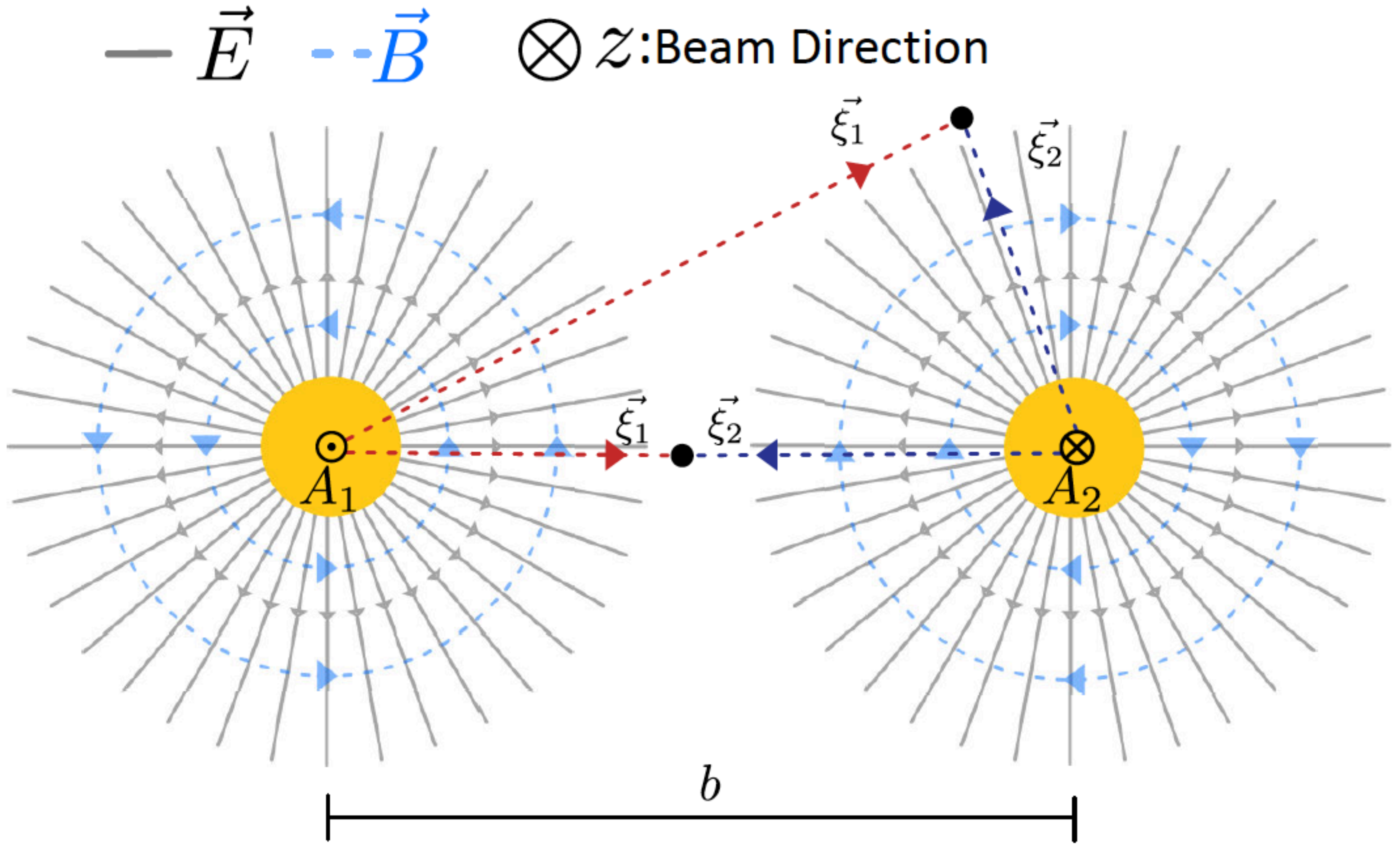
More data to come
STAR BES at RHIC
ALICE at the LHC
(See back-up for ALICE)

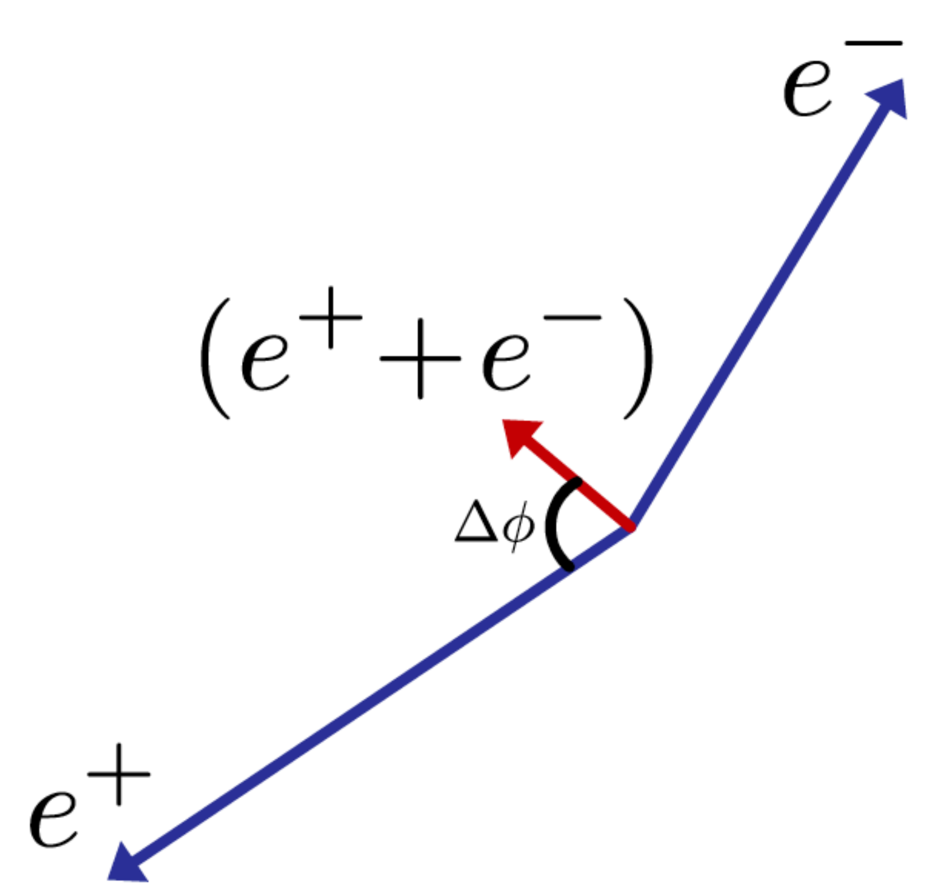
$\sigma_{\gamma\gamma\rightarrow e^+e^-}$ and $\sqrt{\langle p^2_{T,ee}\rangle}$ **sensitive to the nuclear charge distribution in the nuclei** (taken as Woods-Saxon distribution)

→ **Nuclear radius and skin depth can be extracted from simultaneous fit of the data**

X. Wang et al, Phys. Rev. C107 (2023) 044906

More: photon *polarization*





$\overrightarrow{\xi_{1,2}}$ = photon polarisation vectors

Helicity $J_z = \pm 1$ (and spin 1)

Initial transverse linearly polarised EM waves

→linearly polarised (quasi)-real photons in the traverse plane

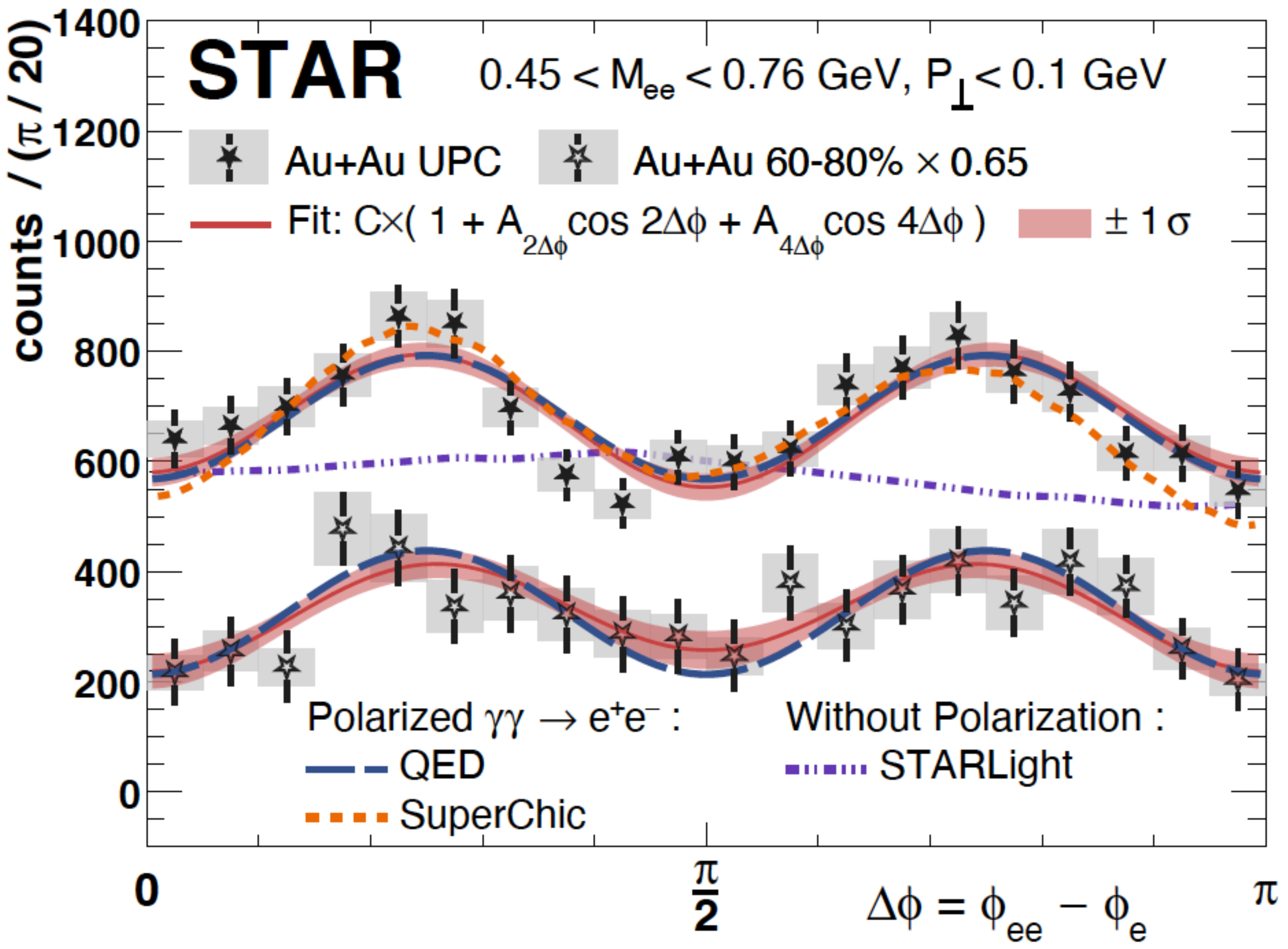
Breit-Wheeler process:

- Distinct cross sections for || & ⊥ relative $\overrightarrow{\xi_{1,2}}$
- Two-photon spin converts into orbital angular momentum

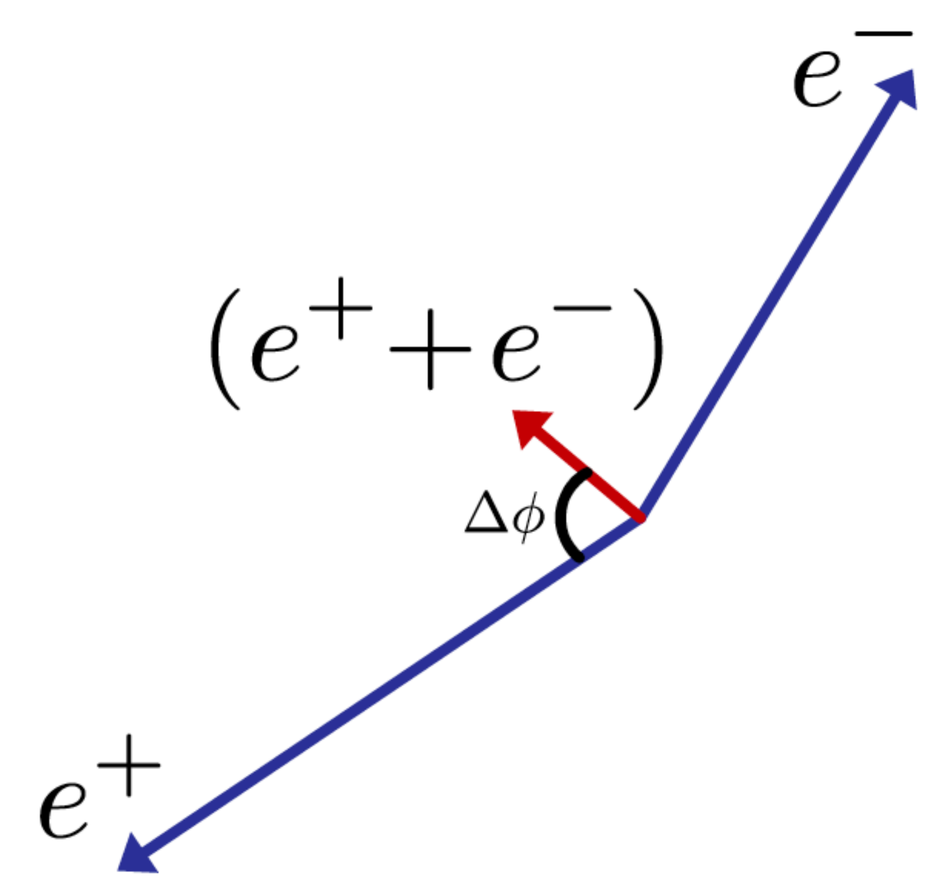
Expect cos($4\Delta\phi$) modulation for produced e^+e^-

More: photon *polarization*

STAR, Phys. Rev. Lett 127 (2021) 052302



Experimental access to photon polarisation demonstrated by STAR in Au—Au collisions at $\sqrt{s_{NN}}$ = 200 GeV



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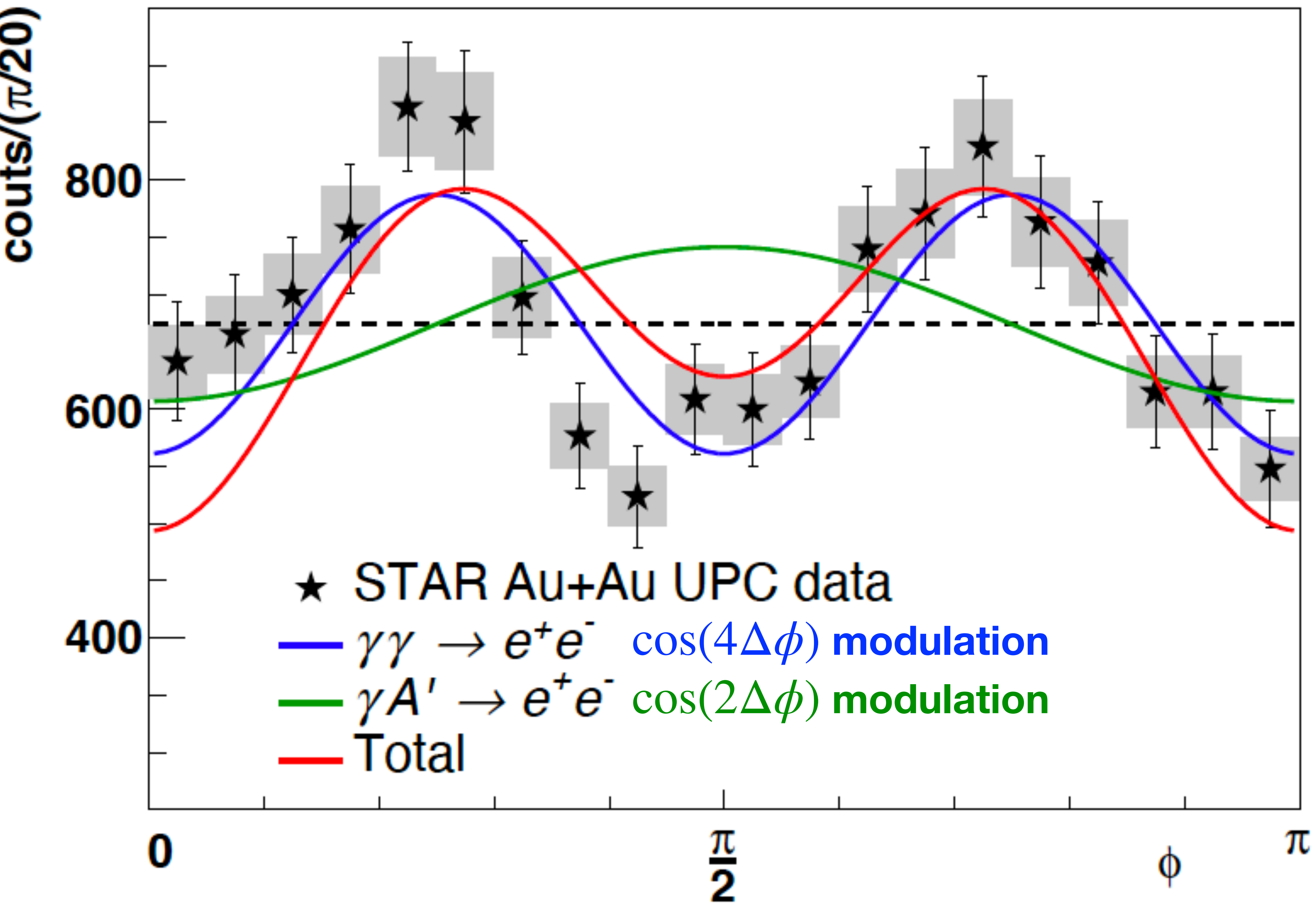
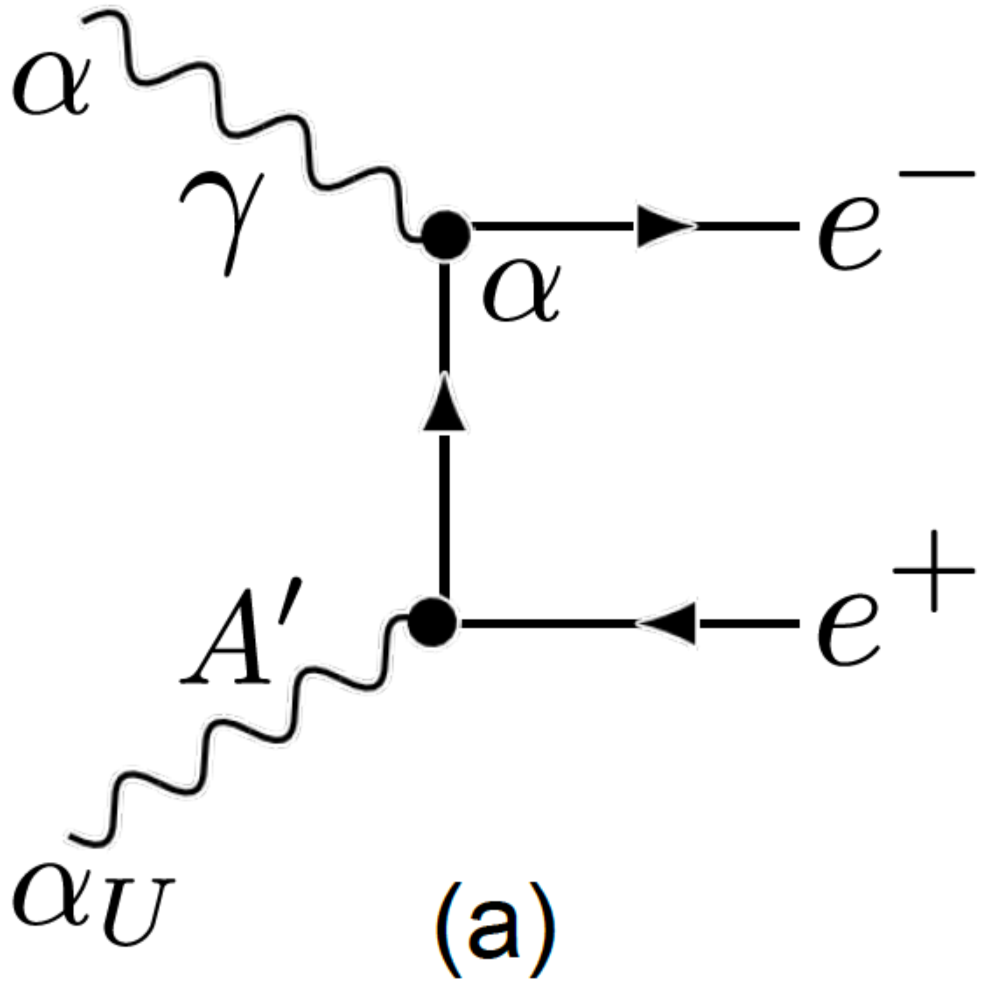
More: photon *polarization* and dark photon research

STAR, Phys. Rev. Lett 127 (2021) 052302



Absence of $\cos(2\Delta\phi)$ modulation puts limits on dark photon mass and mixing parameter to SM particles

More precise data to come



Initial transverse linearly polarised EM waves
→linearly polarised (quasi)-real photons in the traverse plane

Can be used to search for "dark photon" (A')
- Massive dark photon with helicity $J_z = 0$
- Expect cos(2$\Delta\phi$) modulation for produced e^+e^-

Conclusion and outlook

UPCs:

$\gamma\gamma \to l^+l^-$ production relatively well understood

Still some questions: higher order contributions, high-energy initial γs, nuclear dissociative contribution treated differently by different experiments.

Potential for BSM research as well with more precise measurements

Collisions with hadronic interactions:

More (precise) measurements for different centrality, energy, phase space needed:

- To search for medium effects
- To study the nuclear charge distribution in the nuclei

Other hot topic recently $\gamma\gamma \to \tau^+\tau-$ (see slides)

$\gamma\gamma \to \tau^+\tau^-$ in UPCs

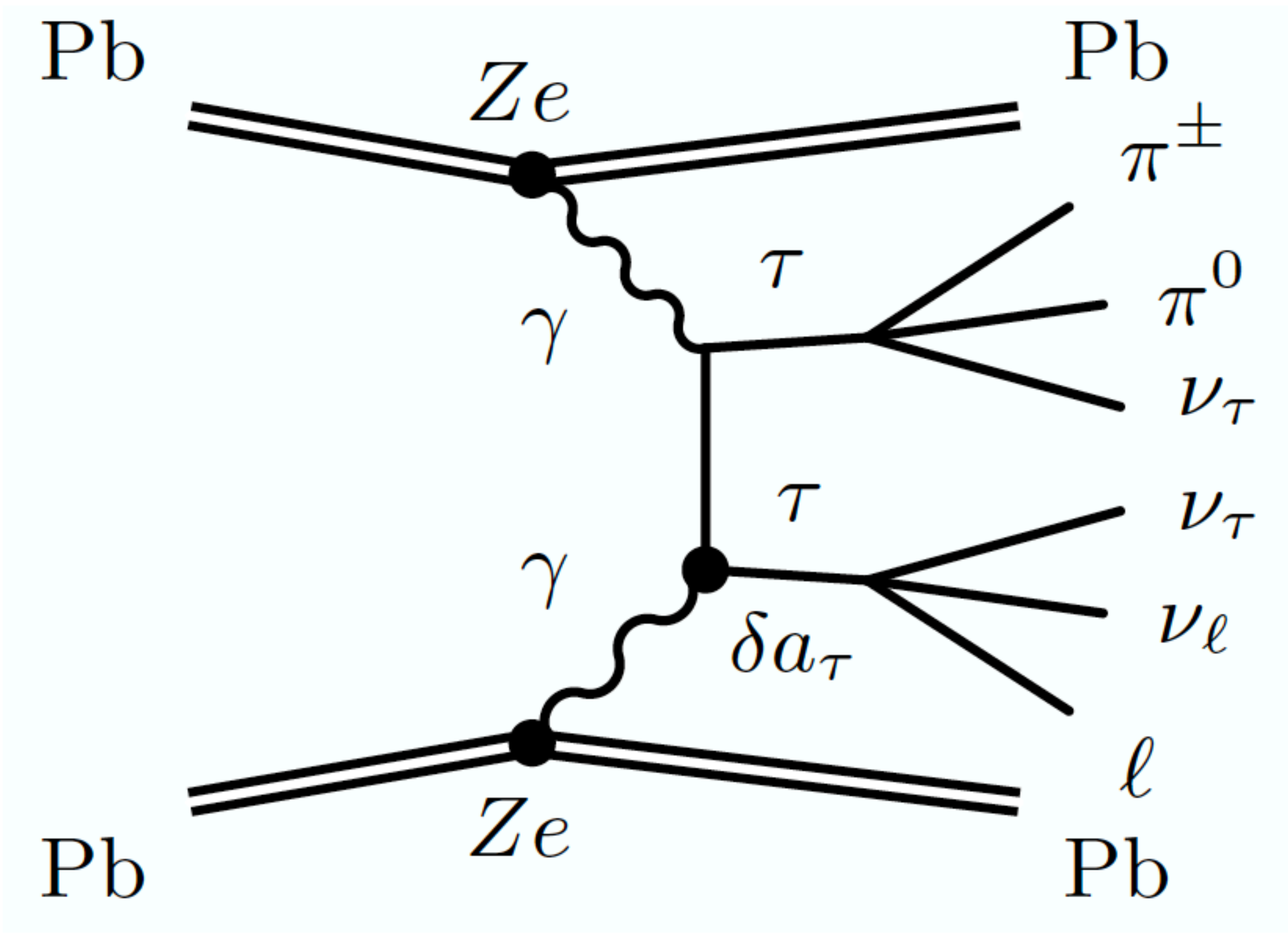
STAR, Phys. Rev. Lett. 127 (2021) 052302

- Sensitivity to the tau anomalous magnetic moment

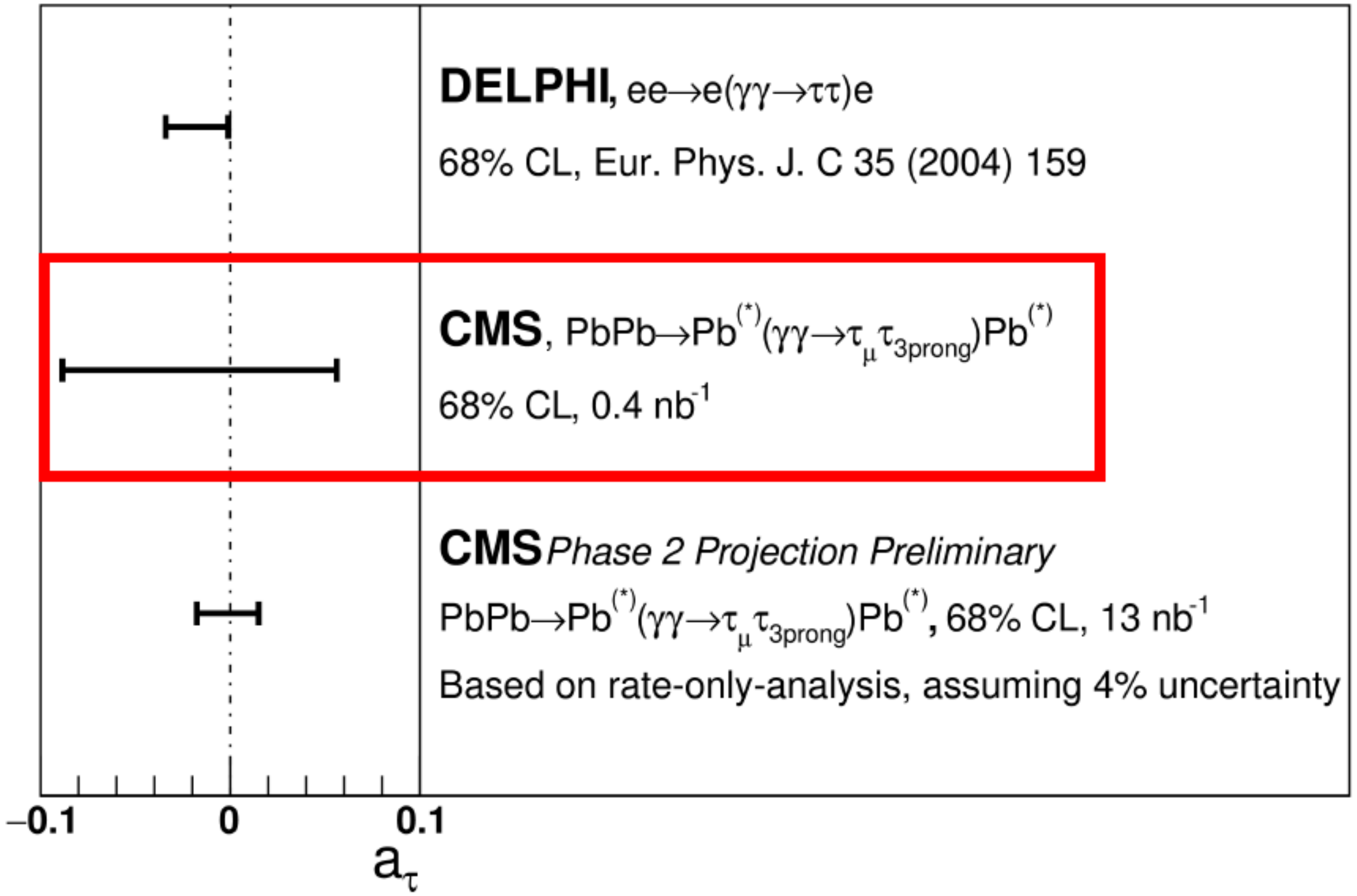
$$a_\tau = \frac{g_\tau - 2}{2}$$

- BSM sensitivity $\delta a_l \propto m_l^2 \sim 280\times$ more sensitive than μ where a $\sim 4\sigma$ tension is observed compared to SM

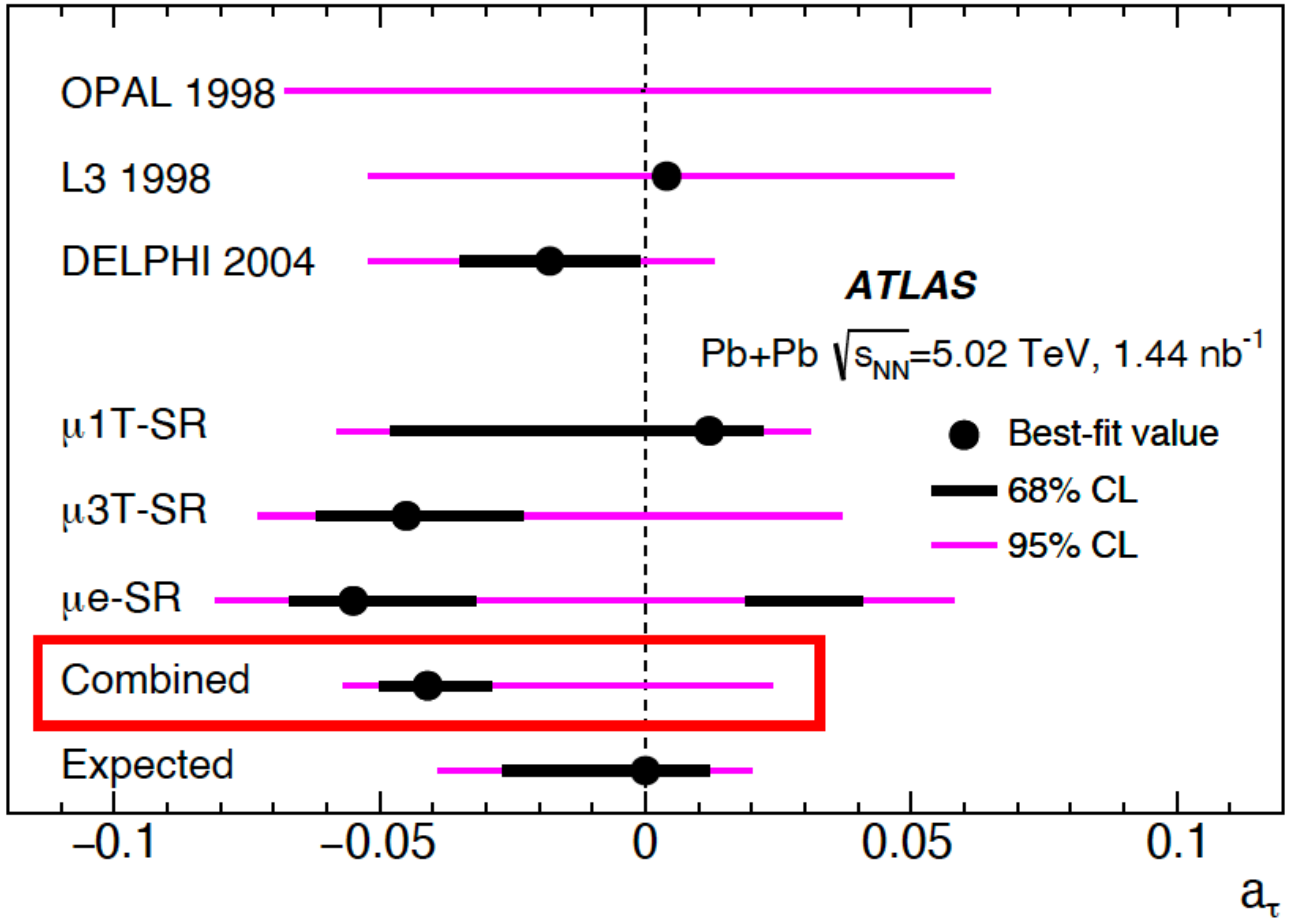
- Not easy to measure experimentally
  Due to hadronic background and ν in τ decay
  Three channels available in UPCs: eμ, μ+track, μ+3 tracks



$\gamma\gamma \to \tau^+\tau^-$ in UPCs



CMS, arXiv:2206.05192 accepted to PRL



ATLAS, arXiv:2204.13478 accepted to PRL

SM predictions $a_\tau = 0.00117721(5)$

More precise data to come

Back-up

Results in *inclusive* UPCs

As a function of:

- $m_{l^+l^-}$ = centre-of-mass energy of colliding $\gamma\gamma$
- $y_{l^+l^-} = y_{\gamma\gamma}$
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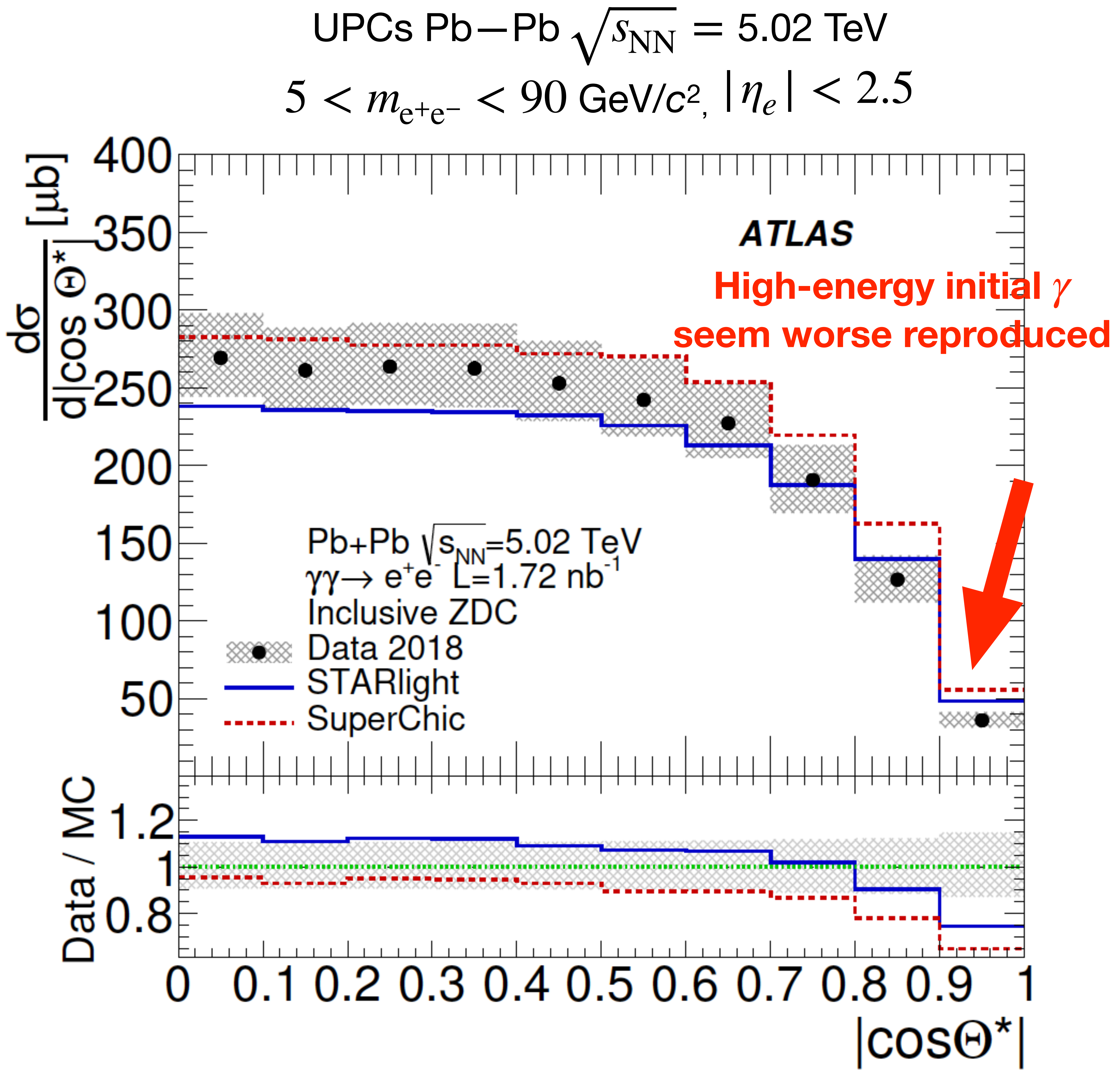
Reasonably well described by calculations



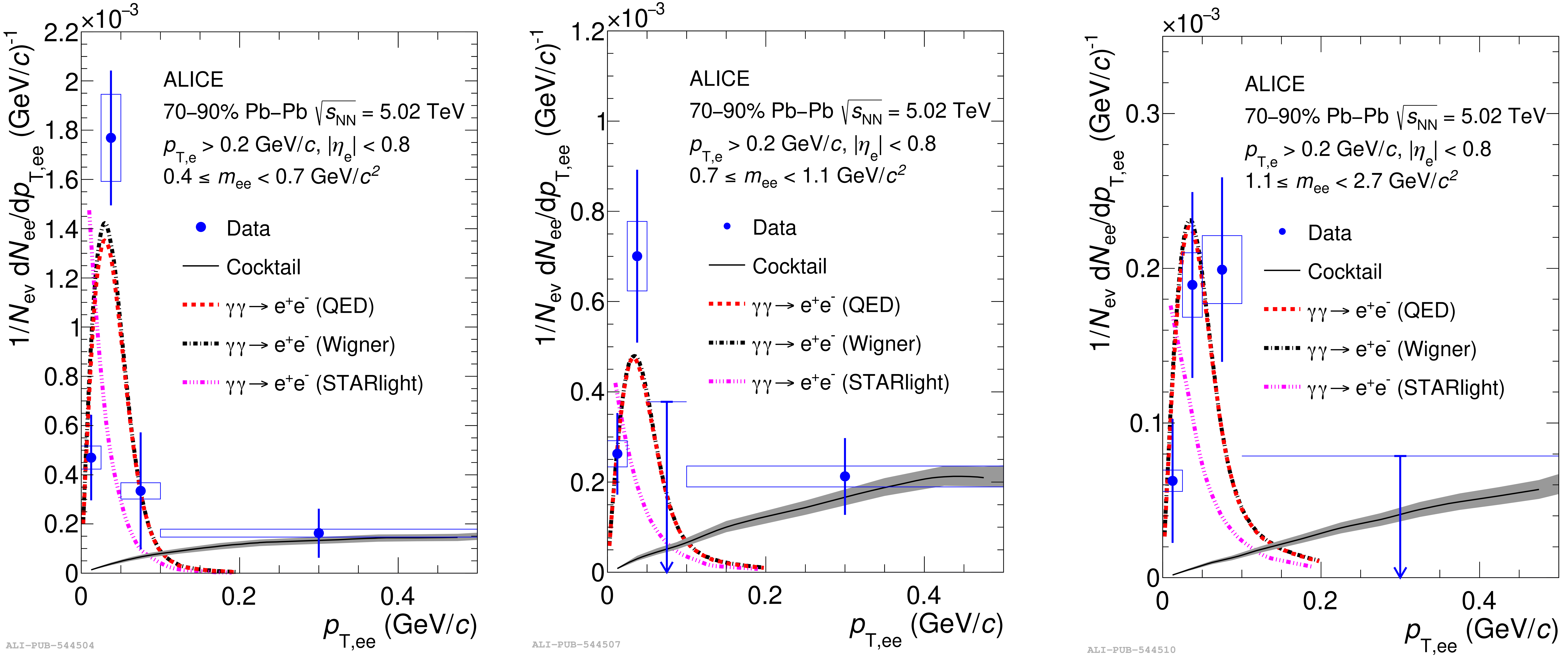
ATLAS, JHEP06 (2023) 182

ALICE, JHEP 06 (2023) 024

ALICE in peripheral Pb—Pb

70-90% Pb—Pb $\sqrt{s_{NN}}$ = 5.02 TeV

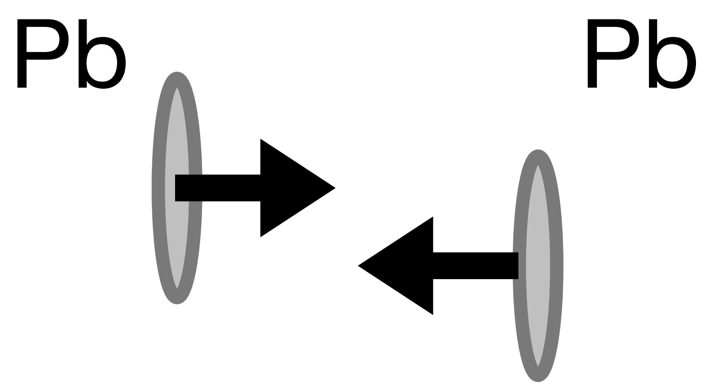
$0.4 < m_{e^+e^-} < 2.7$ GeV/c^2, $|\eta_e| < 0.8$



Hunt for medium effects

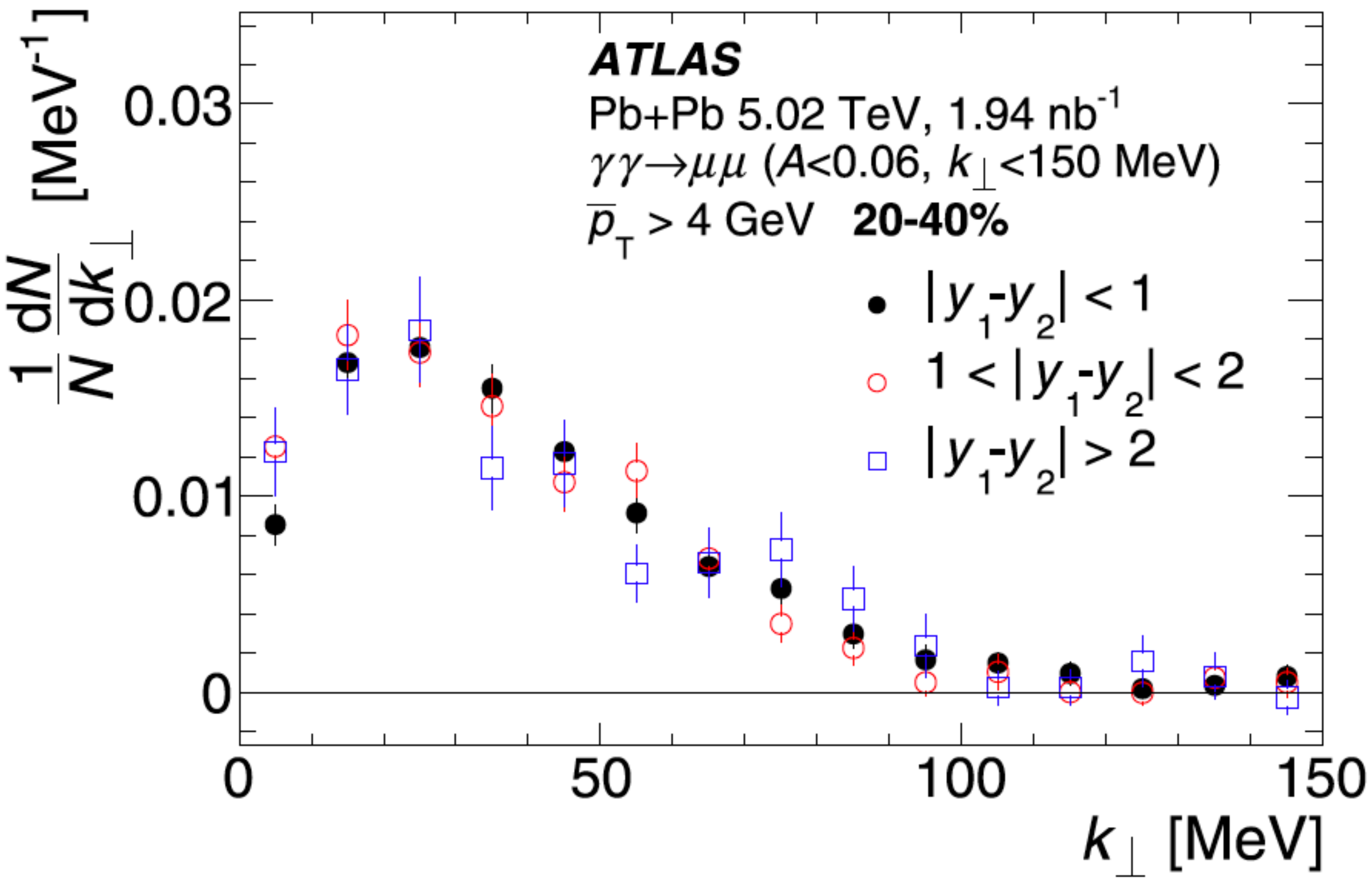
S. Klein, A. H. Mueller, B.-W.Xiao, and F.Yuan, Phys. Rev. Lett. 122 (2019) 132301
ATLAS, Phys. Rev. C107 (2023) 054907

Deflection of the μ in magnetic fields generated during the Pb—Pb collision



Expect a dependence of the broadening

- Increasing as a function of $|\Delta y| = |y_{\mu_1} - y_{\mu_2}|$ (as thanh(Δy))



$$k_\perp \equiv \frac{1}{2}\left(p_{T1} + p_{T2}\right)\left(\pi - |\phi_1 - \phi_2|\right) = \pi\alpha\bar{p}_T$$

No clear sign of such effects at the moment from ATLAS data

ALICE and STAR in peripheral heavy-ion collisions

RHIC:

$\gamma_L \sim 100$

$Z_{Au} = 79, Z_U = 92$

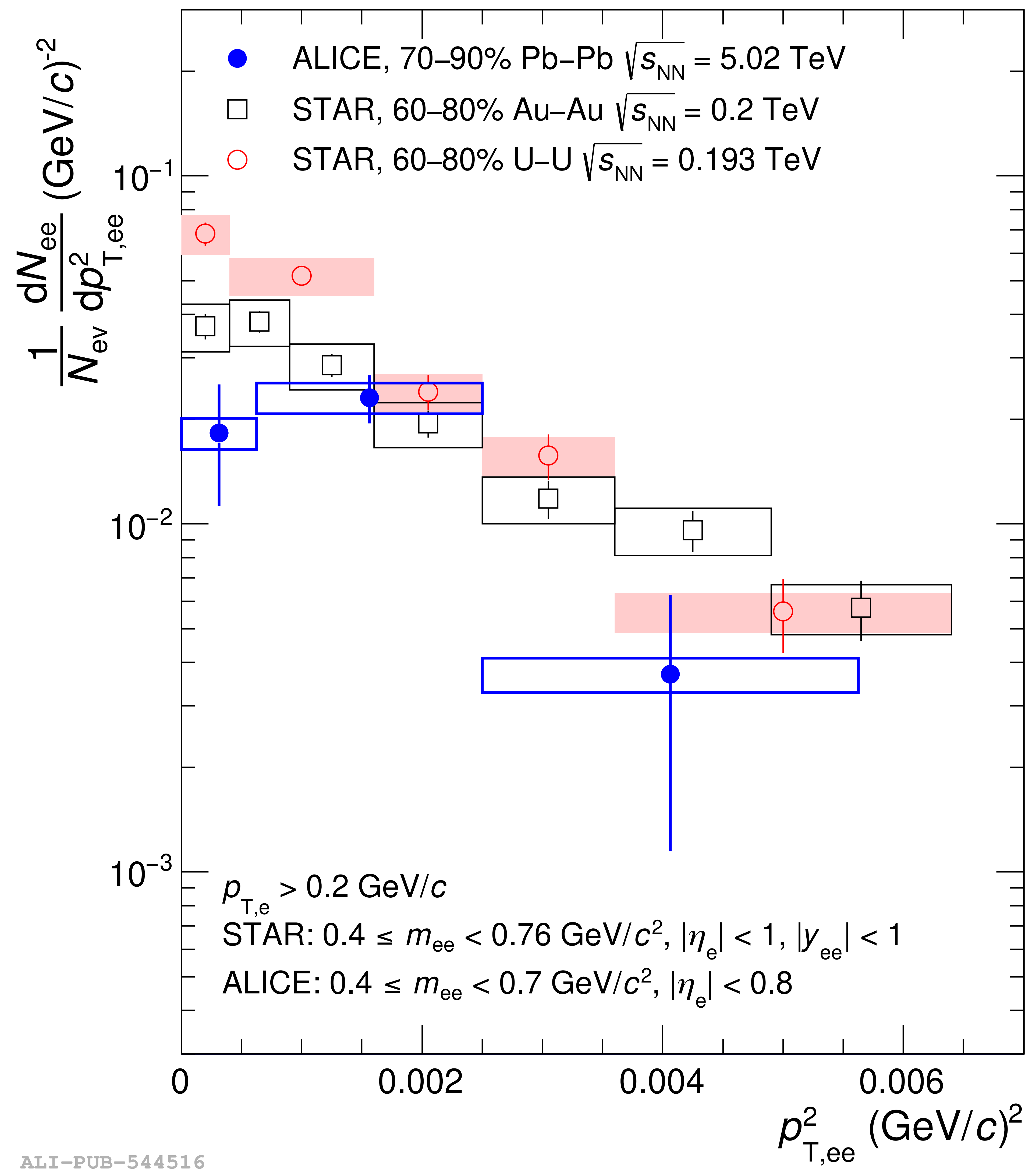
$R_{Au} = 6.38$ fm

LHC:

$\gamma_L \sim 2700$

$Z_U = 82$

$R_{Pb} = 6.62$ fm



STAR, Phys. Rev. Lett. 121 (2008) 132301
ALICE, JHEP 06 (2023) 024

Dark photons

PAMELA, Nature 458 (2009) 607
FERMI, Phys. Rev. Lett. 108 (2012) 011103
AMS, Phys. Rev. Lett. 110 (2013) 141102
Muon g-2, Phys. Rev. D73 (2006) 072003

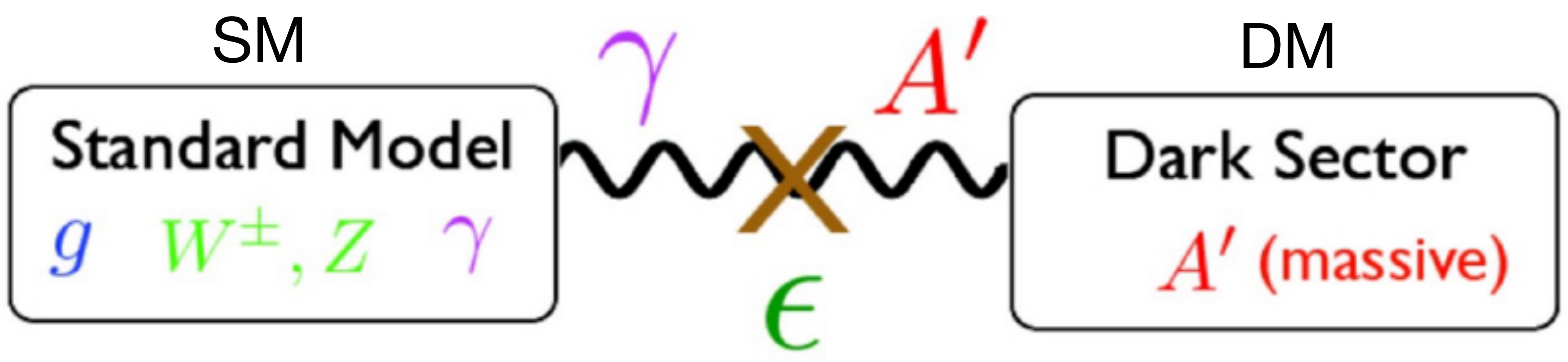
- Dark matter: $\approx$ 80% of the matter in the Universe
- Possible candidates (among others): dark photon A'
- Hypothetical extra-U(l) gauge bosons, motivated by:
    - Antiproton spectrum in the cosmic rays measured by AMS Collaboration
    - Positron excess in the cosmic rays observed by PAMELA and confirmed by FERMI & AMS
    - Muon anomalous magnetic moment

$$L = L_{SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + m^2_{A'}A'_{\mu}A'^{\mu} + \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$

Standard Model Lagrangian

Additional U(1) symmetry describing the new force carried by a massive vector boson, ***the Dark photon A'***

Kinetic mixing term with the ***standard photon γ***

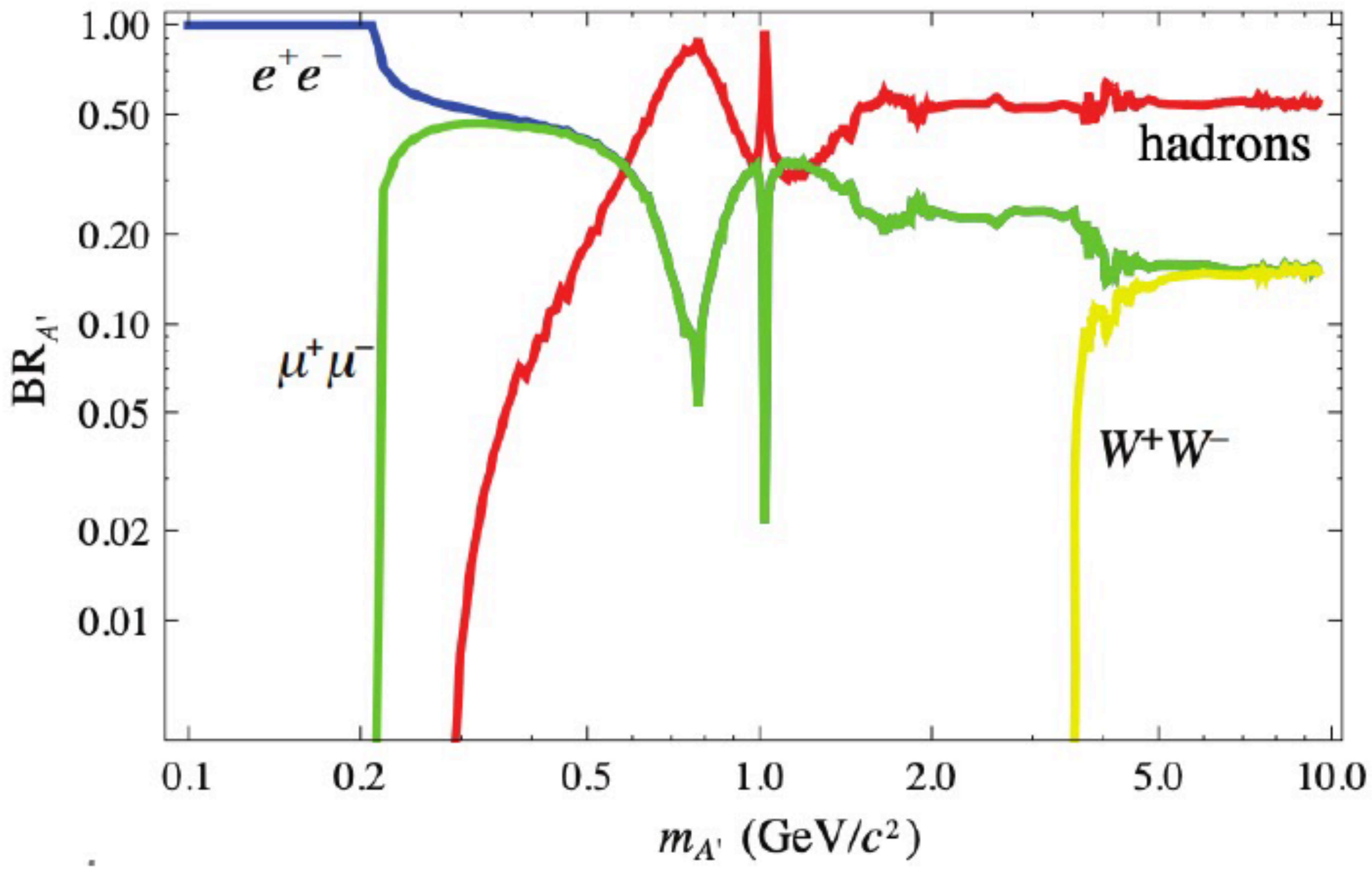


Messenger particle of a dark sector with **residual interactions** ϵ to the SM sector and **mass** $m_{A'}$

Dark photon decays

- Visible decays (No DM with $m_{\mathrm{DM}} < m_{\mathrm{A}'}/2$)
  - $A' \rightarrow$ SM particle
- Invisible decays (DM with $m_{\mathrm{DM}} < m_{\mathrm{A}'}/2$ exists)
  - $A' \rightarrow$ DM with BR≈1
    - SM decays suppressed by a factor ϵ^2

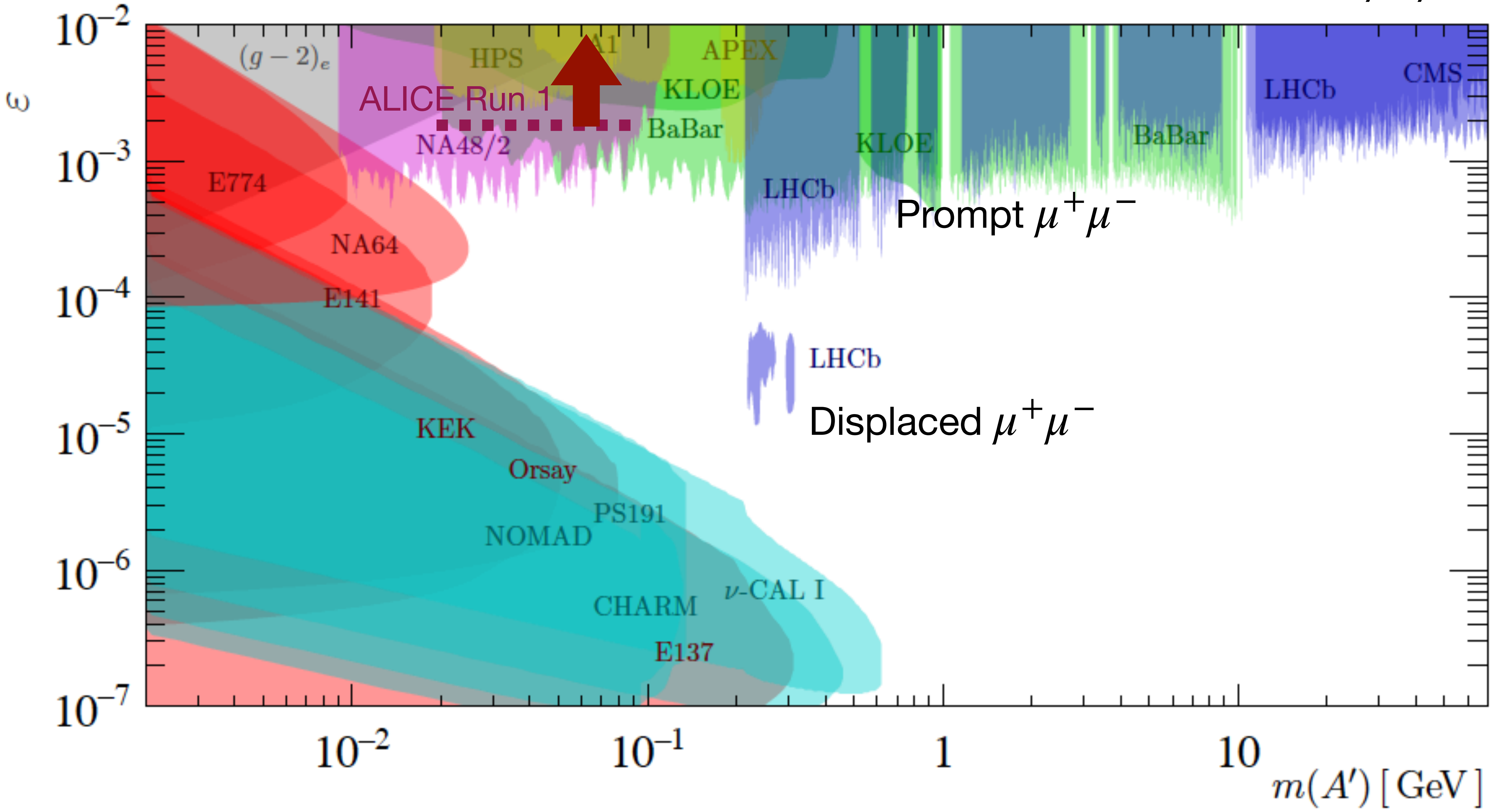
A′ visible decay Br



Gabriele Piperno, PANIC (2017)

Current limits from LHC

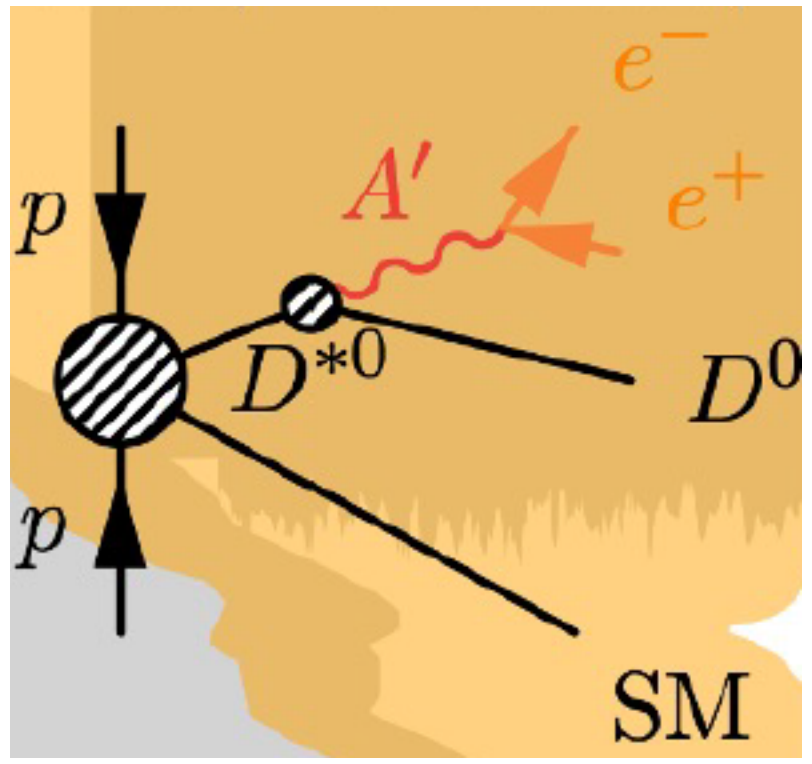
- $A' \to \mu^+\mu^-$ **in pp collisions at $\sqrt{s} = 13$ TeV**
  - Prompt searches
    - Meson decays: $m_{A'} < 1$ GeV
    - Drell-Yan: $m_{A'} > 1$ Ge
  - Displaced searches (0.1-1cm) for long lived A'
    - Background dominated by material interactions
    - Precise knowledge of location of material needed
  - Inclusive searches with $m_{A'}$ in 30-75 and 110-200 GeV ranges
- $A' \to e^+e^-$ **in pp and p—Pb collisions**
  - Inclusive searches with $0.02 < m_{A'} < 0.1$ GeV



M. Graham, C. Hearty, M. Williams, arXiv:2104.10280

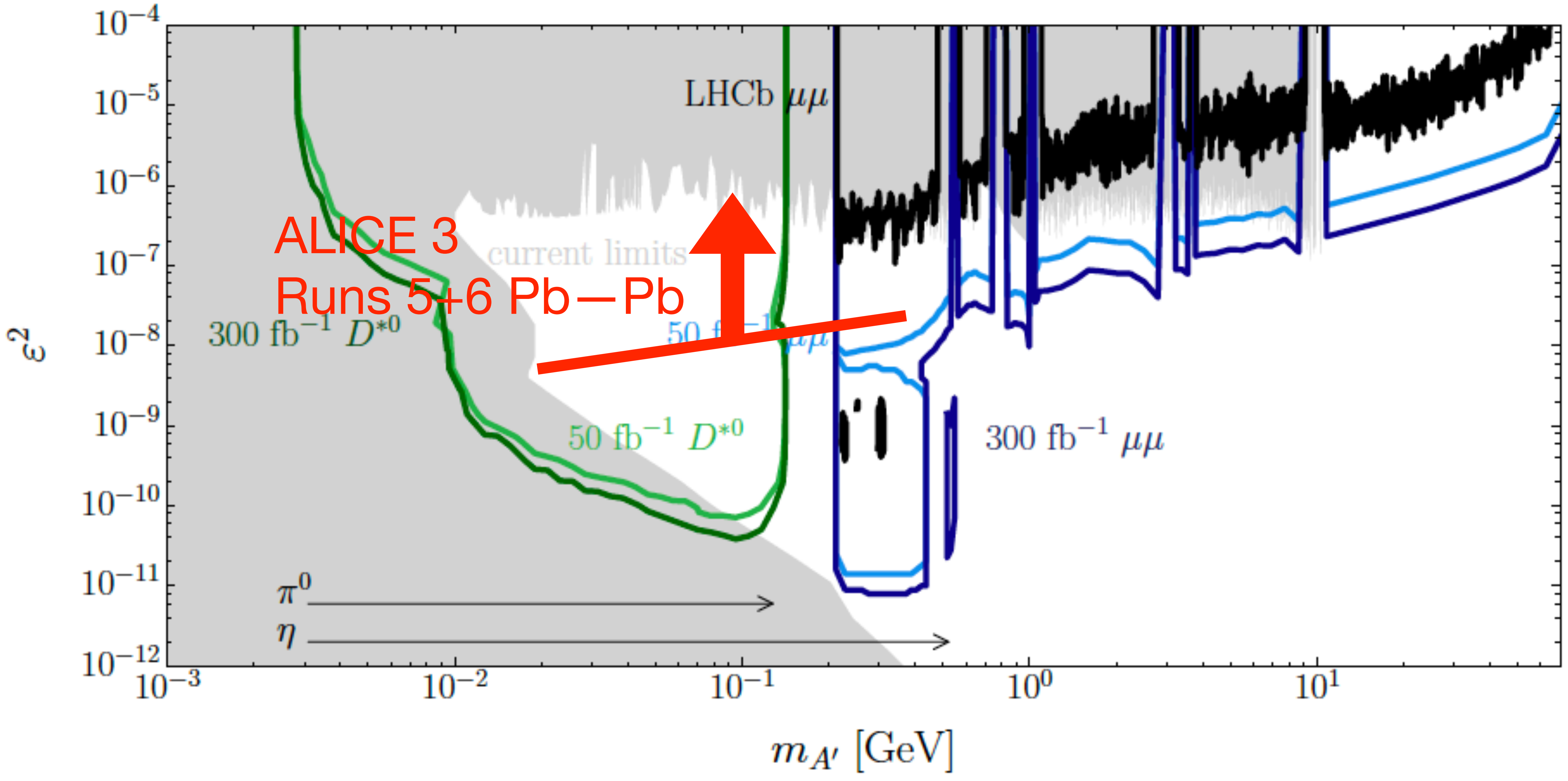
Future prospects

Search in $D^{*0} \to A'D^0, A' \to e^+e^-$



Add new constraints below $m_{A'}$ of 125 MeV

A. Dainese *et al.*, CERN-2019-007



Will profit from upgrades of the vertex detector and removing of LHCb hardware trigger (for Run > 3)

Black existing limits
Projections for pp collisions:

- Run 3 + 4: 50 fb^{-1}
- Run 5: 300 fb^{-1}