Ultra-peripheral Collisions

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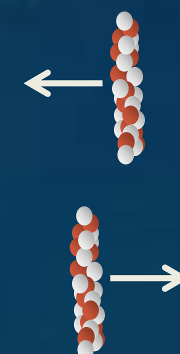
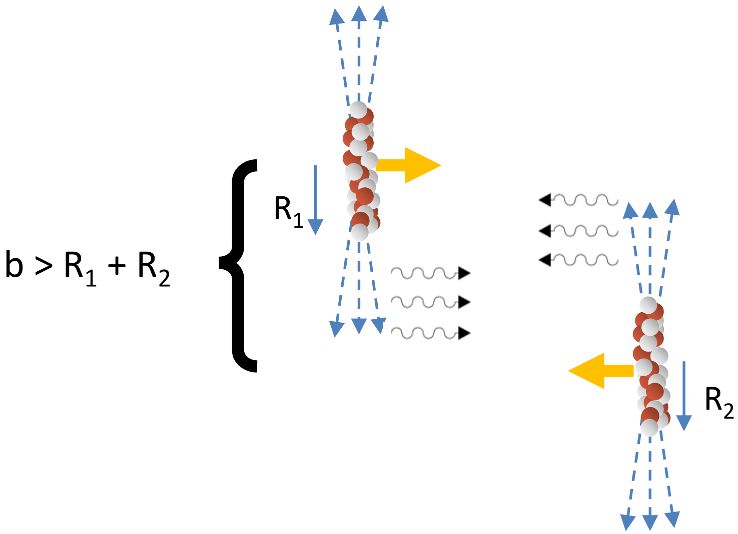


IS2019 NYC

June 24-28, 2019

Ultraperipheral Collisions



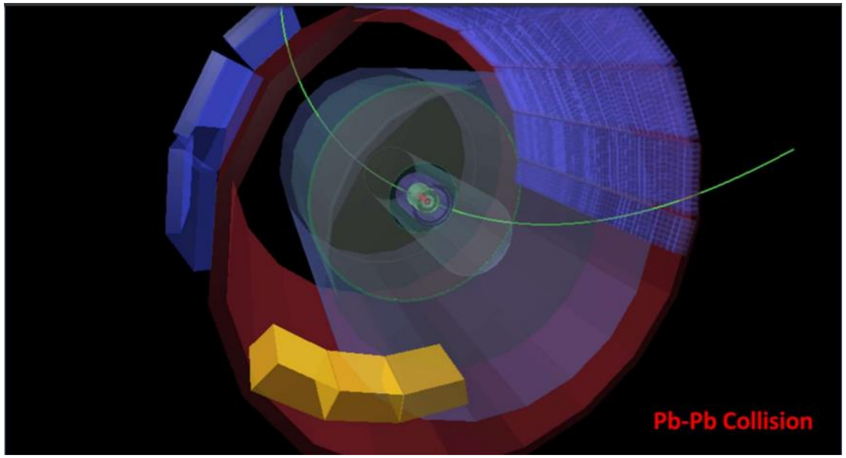
- Large impact parameter ($b > R_1 + R_2$)

  → no nuclear overlap

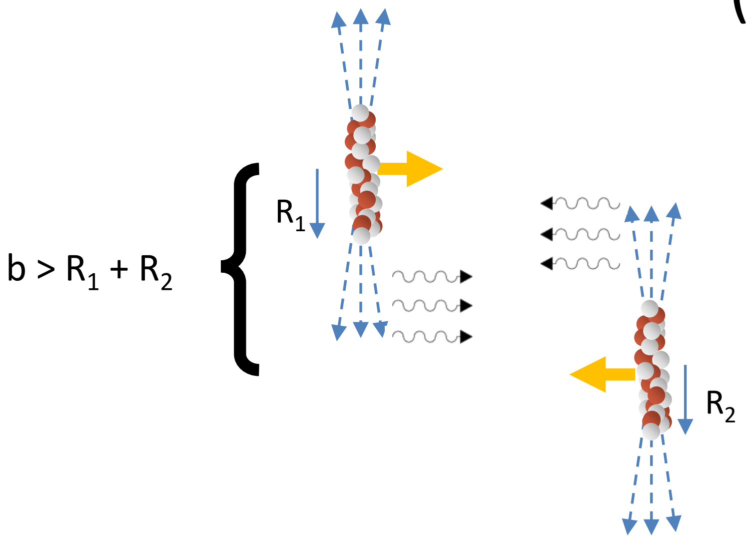
  → no "collision"

  → electromagnetic interactions dominate

- Experimentally: very low multiplicity events with small momentum transfer, rapidity gaps



RHIC and the LHC: high luminosity photon colliders



- Relativistic heavy ions are intense source of quasi-real photons (Weizsäcker-Williams)
  - Photon flux from each nucleus

$$N(k,b) = \frac{Z^2\alpha}{\pi^2}\frac{k}{(\hbar c)^2}\frac{1}{\gamma^2}\left[K_1^{\,2}\left(\tfrac{kb}{\gamma\hbar c}\right) + \tfrac{1}{\gamma^2}K_0^{\,2}\left(\tfrac{kb}{\gamma\hbar c}\right)\right]$$

  - Z^2 dependence → any incoherent emission is dramatically suppressed

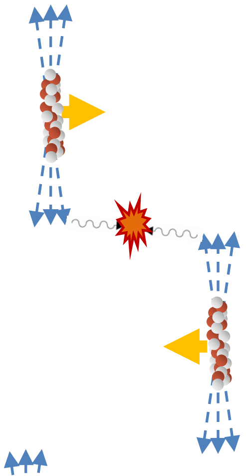
$$E_{\gamma,\max} \approx \frac{\gamma\hbar c}{R}$$

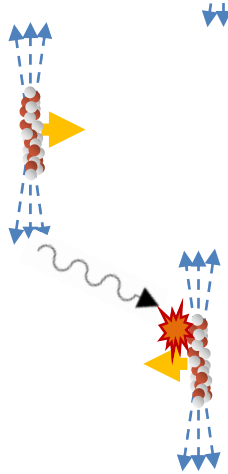
~80 GeV for Pb at LHC
~3 GeV for Au at RHIC

  - Typical p_T and virtuality constrained by size of emitting nucleus
    - Q ~ 1/R ~ 0.06 GeV (Pb) or 0.28 GeV (p)
- Photon beam is ~ parallel to ion beam, transversely polarized

Interactions in Ultraperipheral Collisions

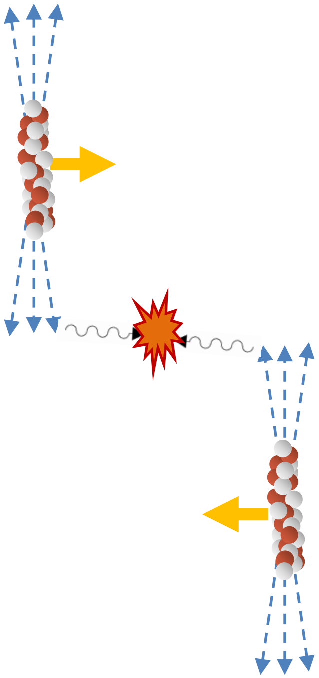
- $\gamma+\gamma$ Photons from the two nuclei can interact with each other – pure QED
- γ+N Photons from one nucleus can interact with other nucleus – involves QCD, probes the nucleus, nPDFs, shadowing, saturation
- $\gamma+N$? Some interesting results in peripheral collisions may be explained by these same photon-induced processes – probes nuclear medium effects?



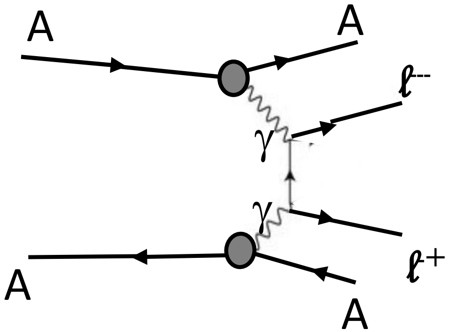


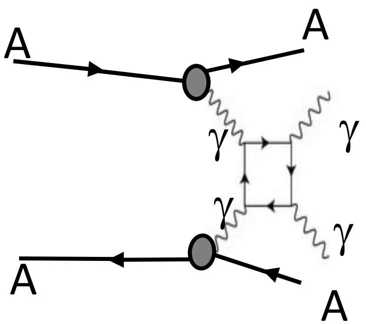
$\gamma+\gamma$

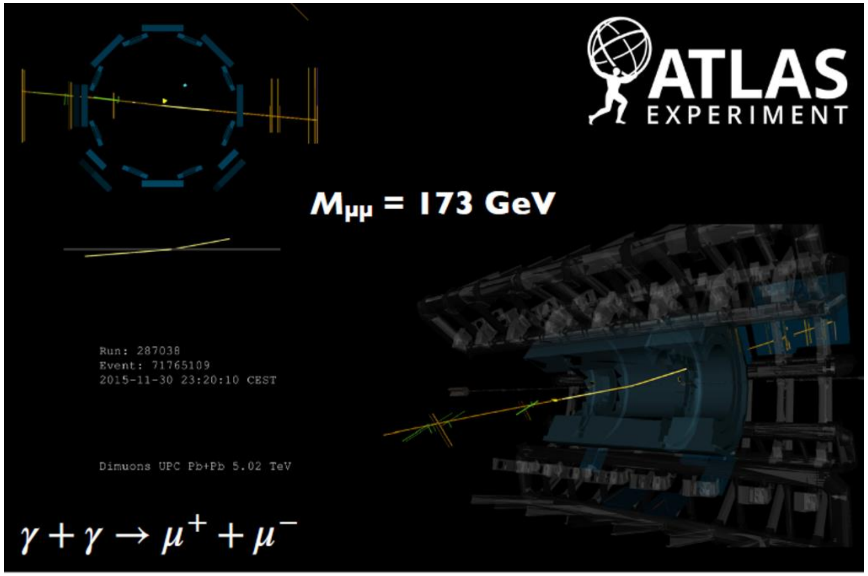
Photon-photon collisions

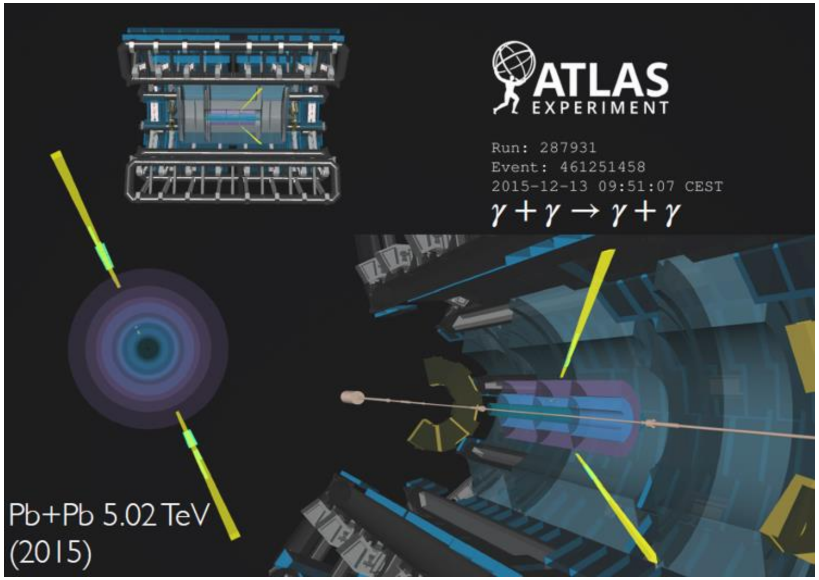


- Purely electromagnetic process

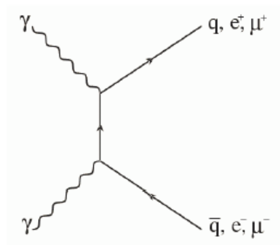




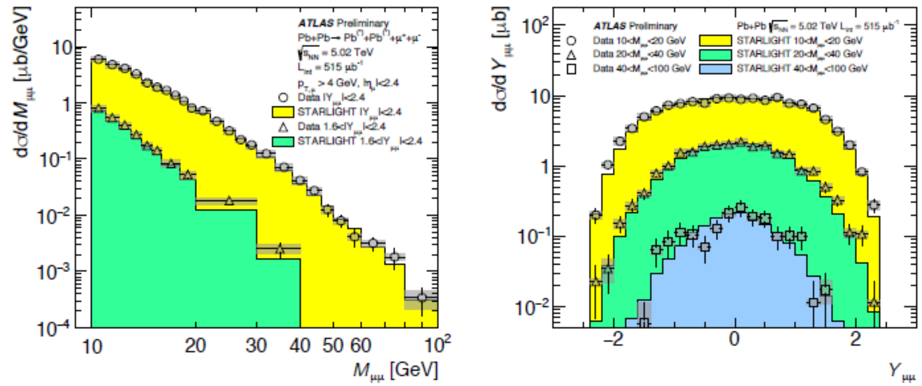




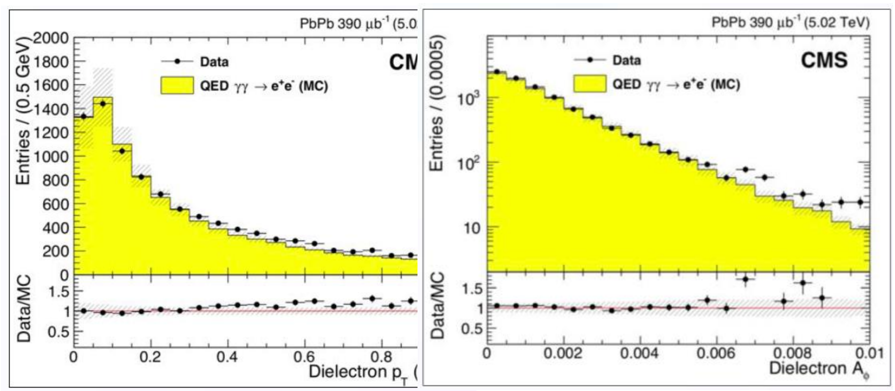
$\gamma+\gamma$ Lepton Pair Production



ATLAS $\gamma\gamma \rightarrow \mu\mu$ ATLAS-CONF-2016-025



CMS $\gamma\gamma \rightarrow ee$



1810.04602

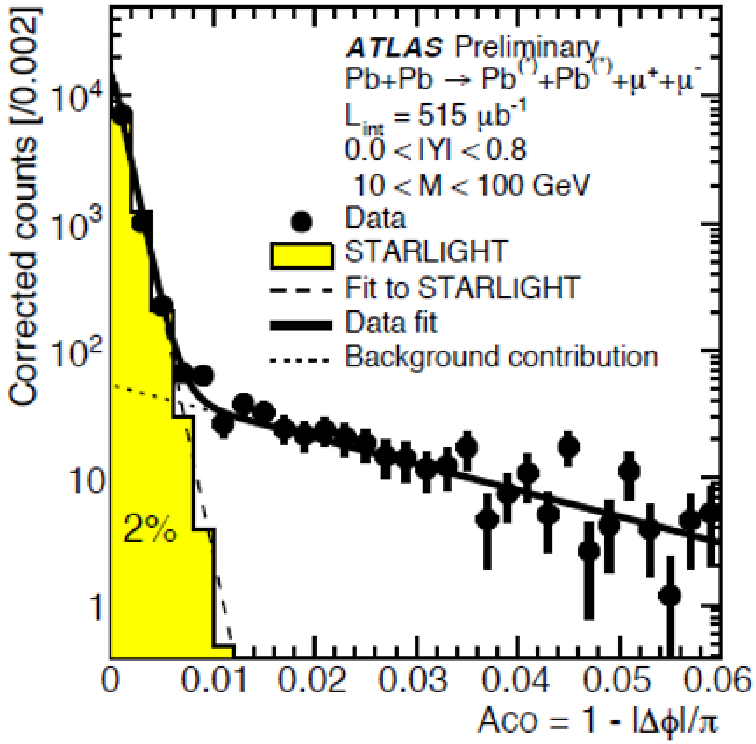
- Basic QED process
  - allows validation of EPA approach
  - Flux amplified by Z^4 over pp
  - Background for other measurements (quarkonia, light-by-light)
  - Provides baseline for more central collisions
- Kinematic distributions and overall rates generally well described by STARLIGHT generator

(S. R. Klein, J. Nystrand, S. Seger, Y. Gorbunov, J. Butterworth, Comp. Phys. Comm, 212 (2017)258.)

γ+γ

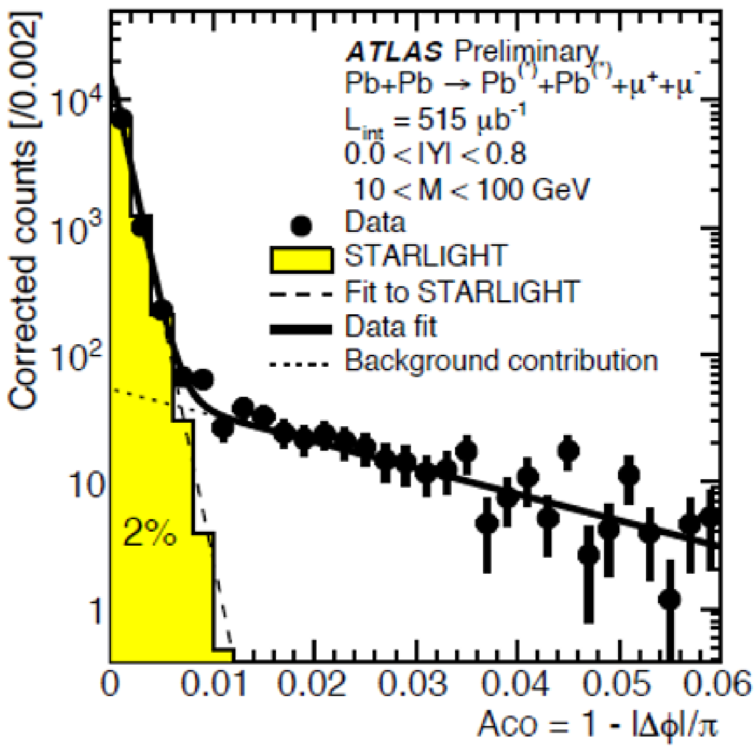
Tail at high acoplanarity

ATLAS-CONF-2016-025

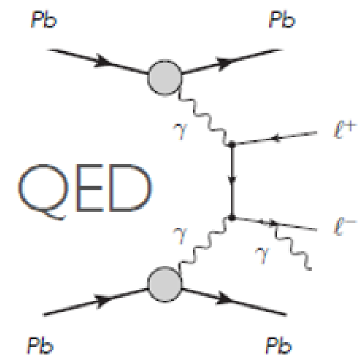


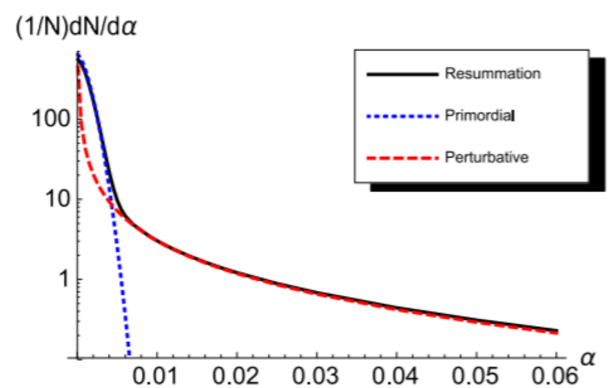
Tail at high acoplanarity

ATLAS-CONF-2016-025



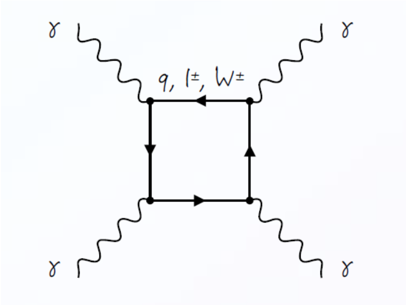
- Inclusion of soft photons via Sudakhov formula provides a long tail





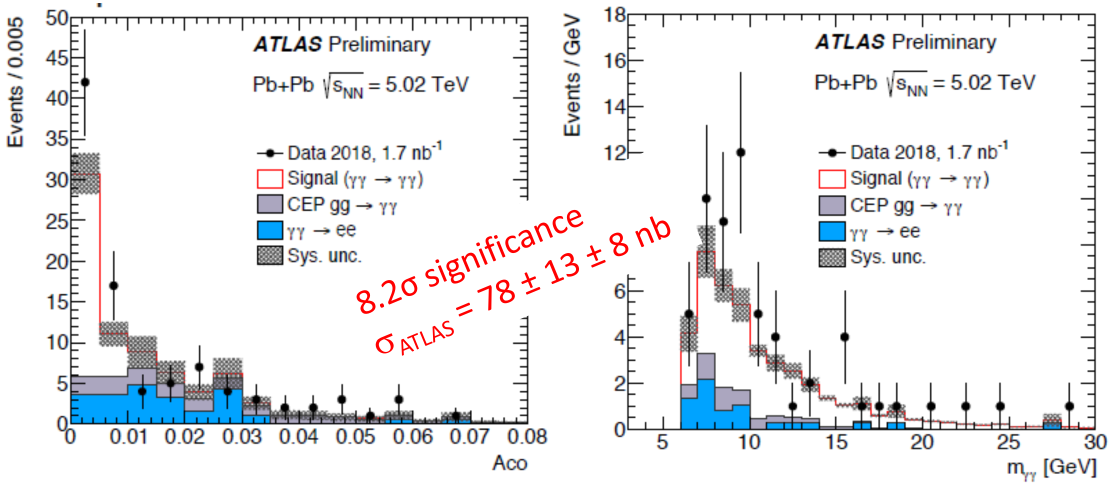
Klein, et al. Phys. PRL 122, 132301 (2019)

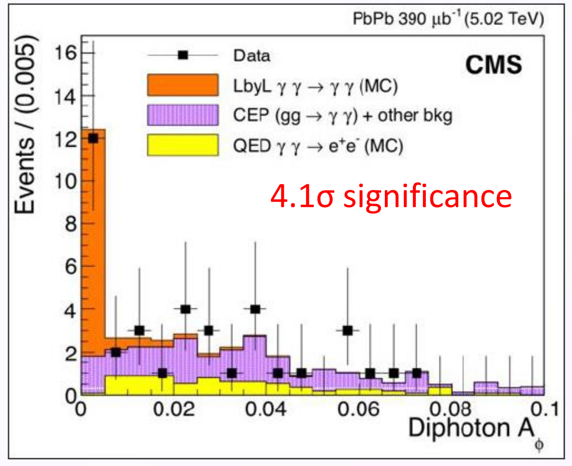
$\gamma+\gamma$ Light by Light scattering



Textbook quantum physics that had nevertheless not been directly observed

ATLAS-CONF-2019-002





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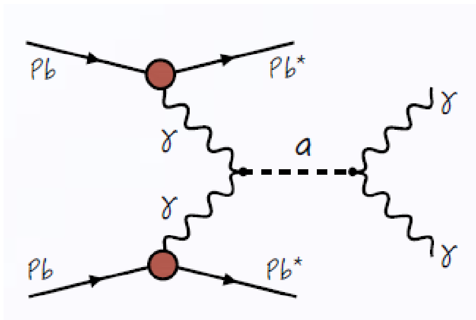
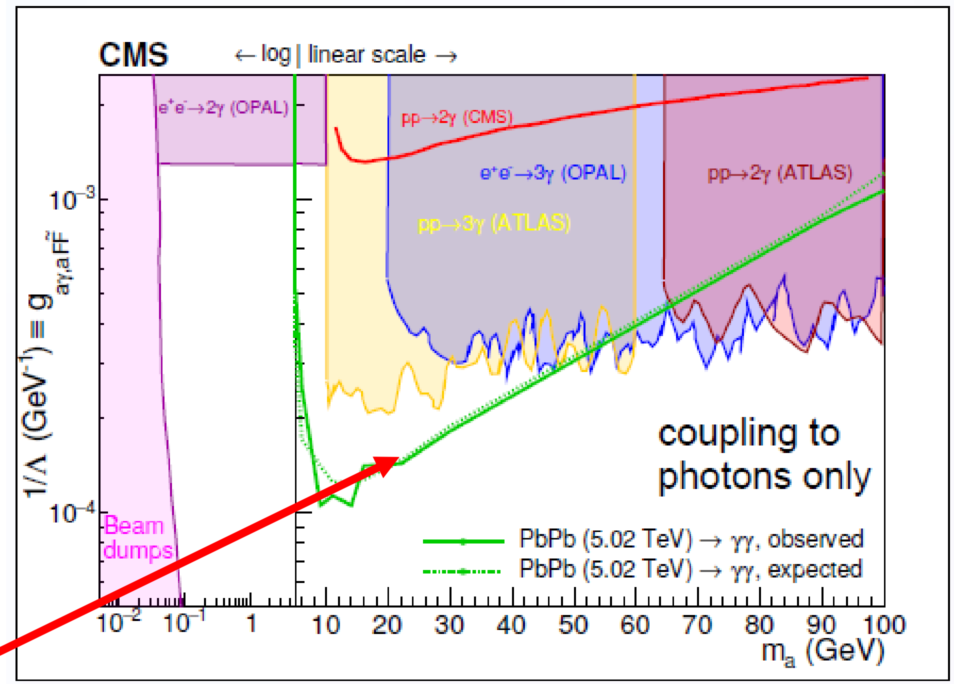
Cross sections and distributions consistent with SM expectations γ+γ

Axion-like particle search



CMS 1810.04602

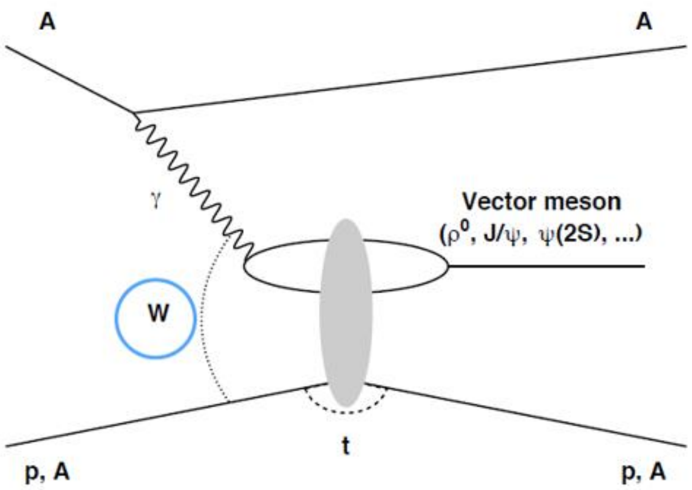


- Exclusive diphoton final-state from resonant CP-odd axion-like particles
  - LbyL, QED and CEP considered as background in this analysis,
- No evidence for this in the 2-photon signal

→ place new limits on the coupling constant

γ+N Photoproduction of vector mesons

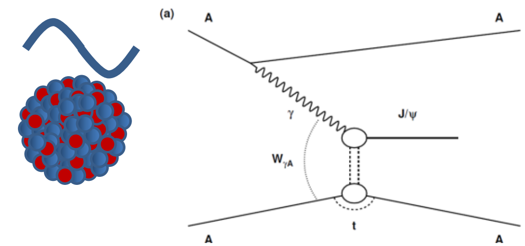
- Has been extensively studied at HERA, RHIC, LHC
- Factorize into
  - photon emission (pure QED) and
  - interactions with nuclear target (includes QCD)
- Allows probe of nucleus via QCD to learn about shadowing, saturation effects, nPDFs



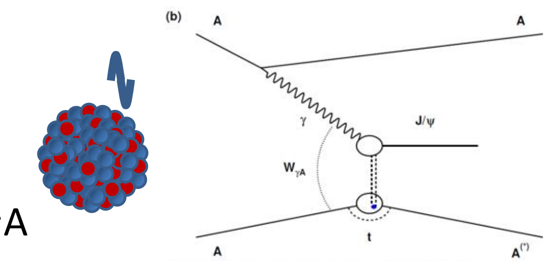
γ+N

Photoproduction of vector mesons

- Coherent interaction: Photon interacts with entire nucleus
  - Nucleus generally remains intact
  - Small momentum transfer: $p_T \sim \hbar/R_A \sim$ 15 MeV



- Incoherent interaction: Photon can interact with individual nucleons
  - Nucleus generally breaks
  - Momentum transfer is bigger: $p_T \sim \hbar/R_A$ ~ 100 MeV

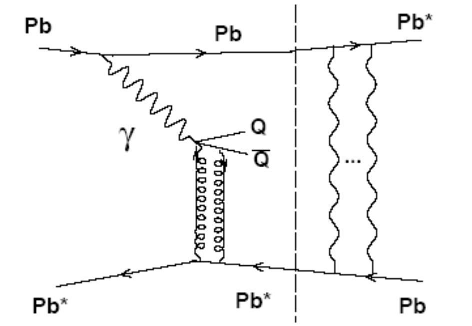


diagrams from Cepila, Jan et al. Phys.Rev. C97 (2018) no.2, 024901

γ+N

Heavy Vector Mesons: J/ψ, Υ

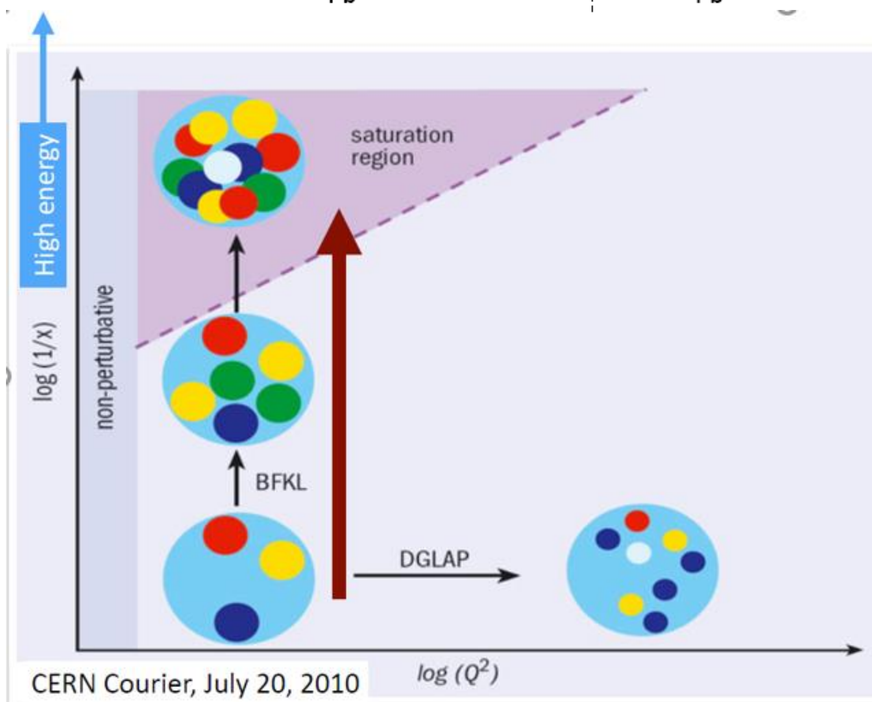
$$\frac{d\sigma^{\gamma^{*}A\rightarrow J/\psi A}}{dt} \propto \left(xG_A(x,Q^2)\right)^2$$



- 2-gluon exchange
- Sensitive probe of nuclear gluon distributions
- For vector mesons,

$$x \simeq \frac{m_{J/\psi}e^{-y}}{\sqrt{s}} \qquad Q^2 = M^2_{J/\psi}/4$$

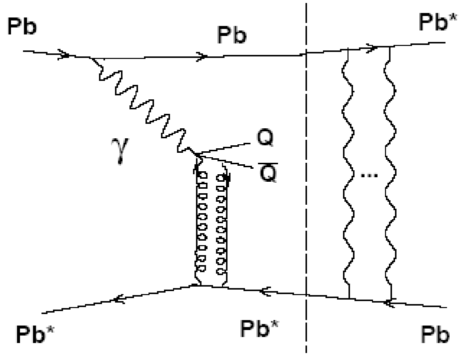
- Measurements at different rapidities sample different values of W and x
- Additional soft photons can leave nuclei in excited states
  - Decay via forward neutron emission
  - RELDIS PRC 60(4)

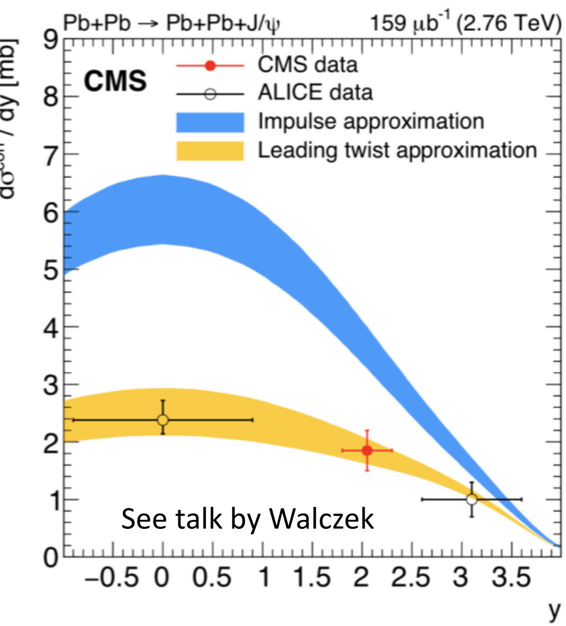


γ+N

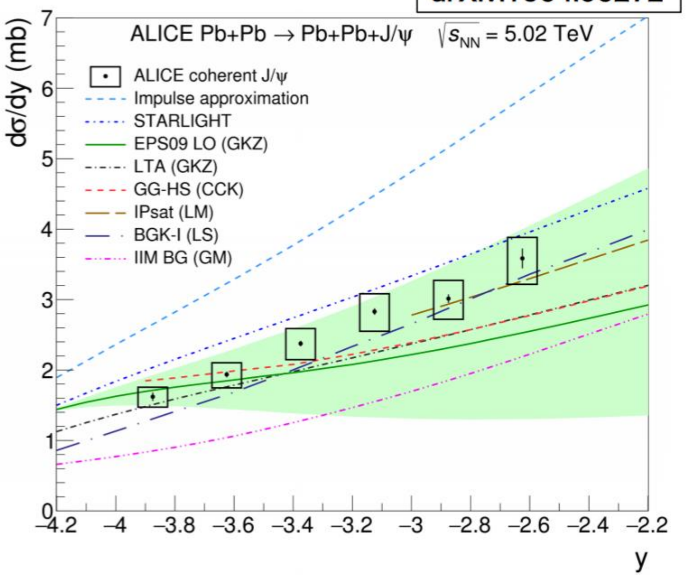
Coherent J/ψ Cross Sections

- Complementary measurements tell a consistent story
- Data shows effects of moderate shadowing
- As statistics improve, sensitive to variations in models

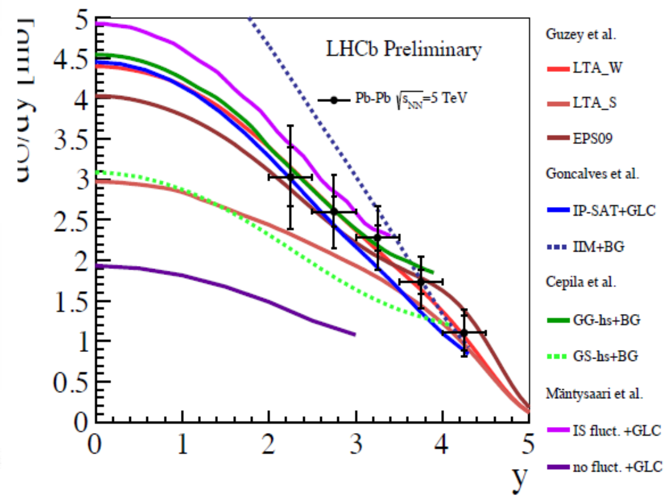




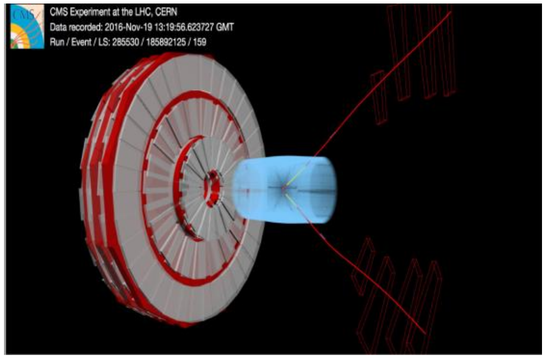
arXiv:1904.06272



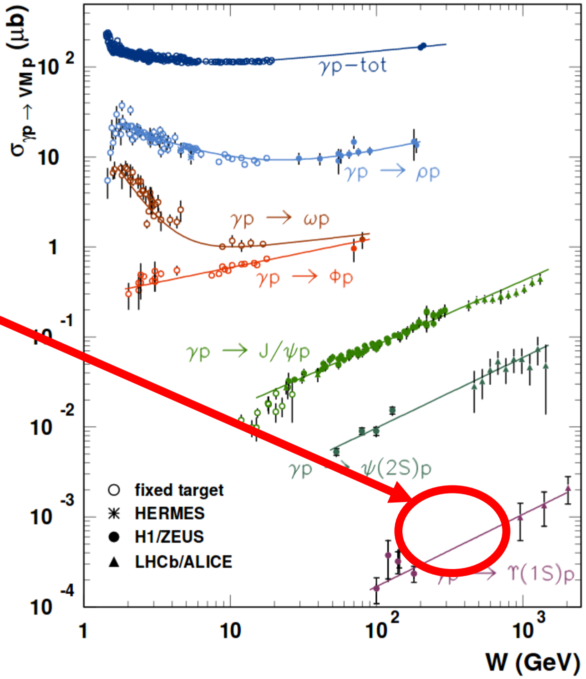
LHCb-CONF-2018-003



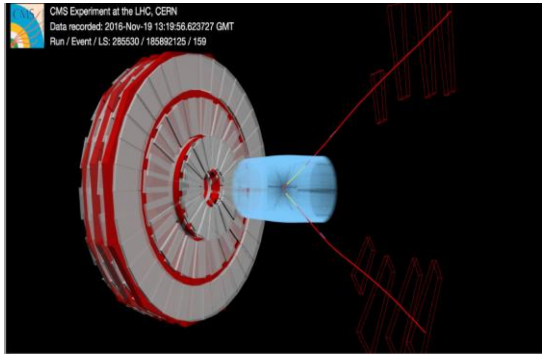
γ+N Upsilon in p+Pb at 5.02 TeV



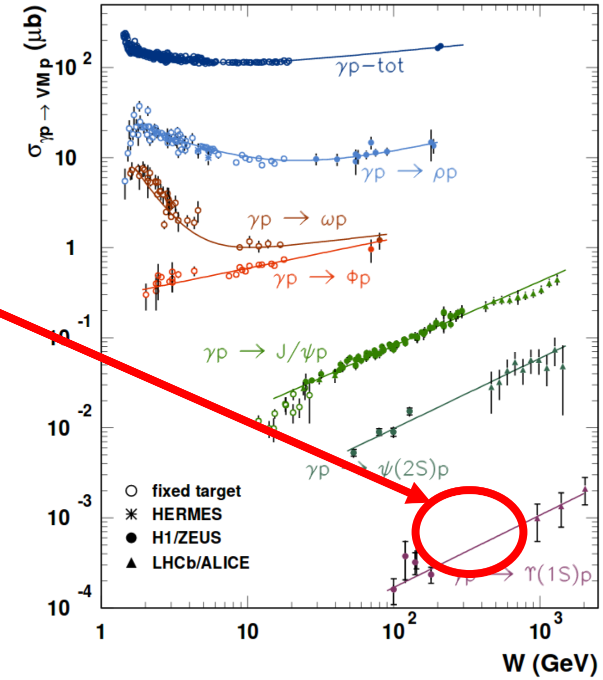
- Measure cross section in W range not covered at HERA



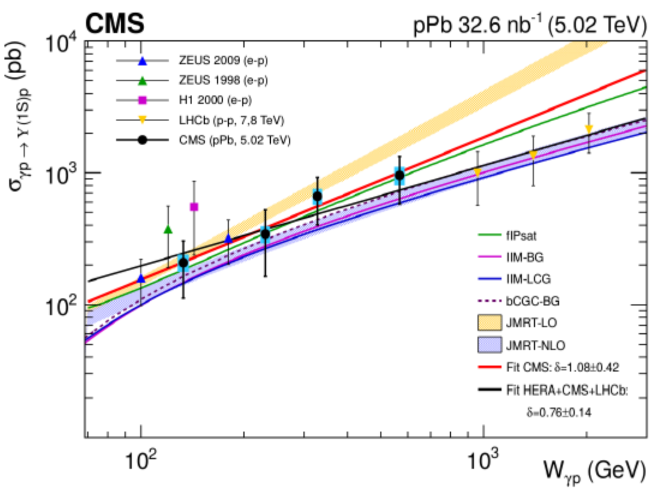
γ+N Upsilon in p+Pb at 5.02 TeV



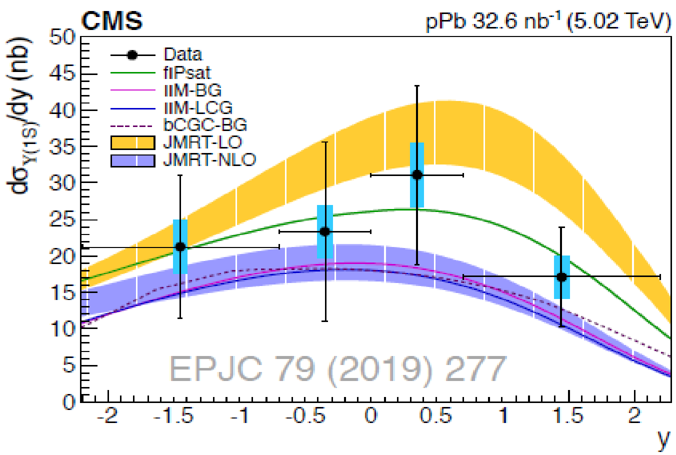
- Measure cross section in W range not covered at HERA



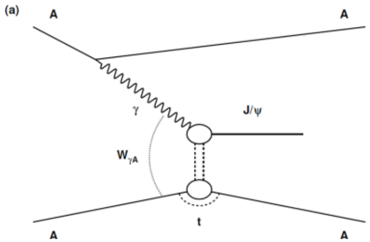
Eur. Phys. J. C 79 (2019) 277



Fit parameters of power-law dependent cross section consistent with HERA results, disfavors LO calc

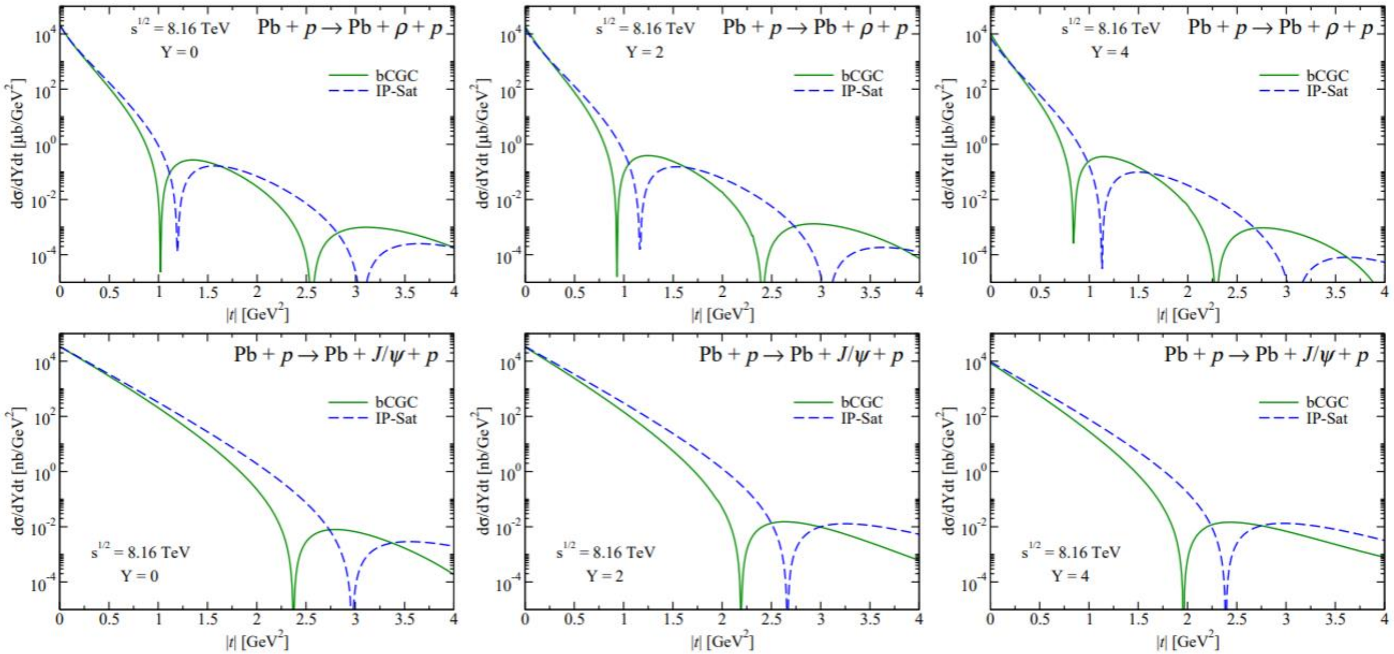


Coherent dσ/dt distribution determined by nuclear form factor



- Fourier transform gives distribution in transverse plane
- Location of diffractive dips sensitive to saturation

V. Goncalves, et al. Phys. Lett. B791 (2019) 299-304

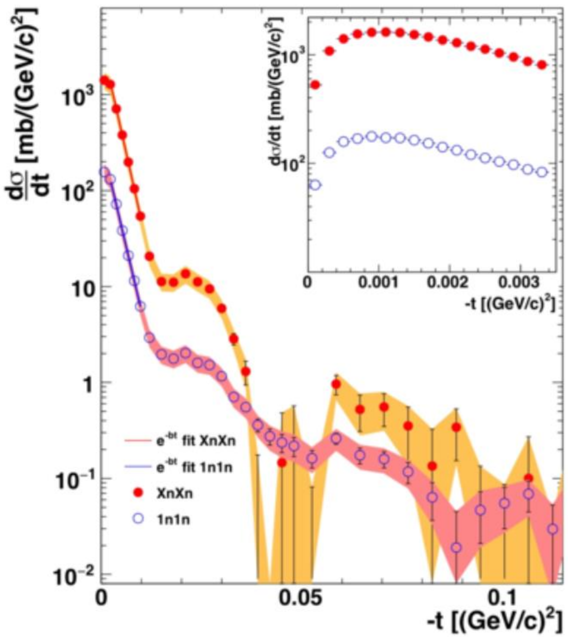


γ+N

Diffraction in coherent ρ dσ/dt

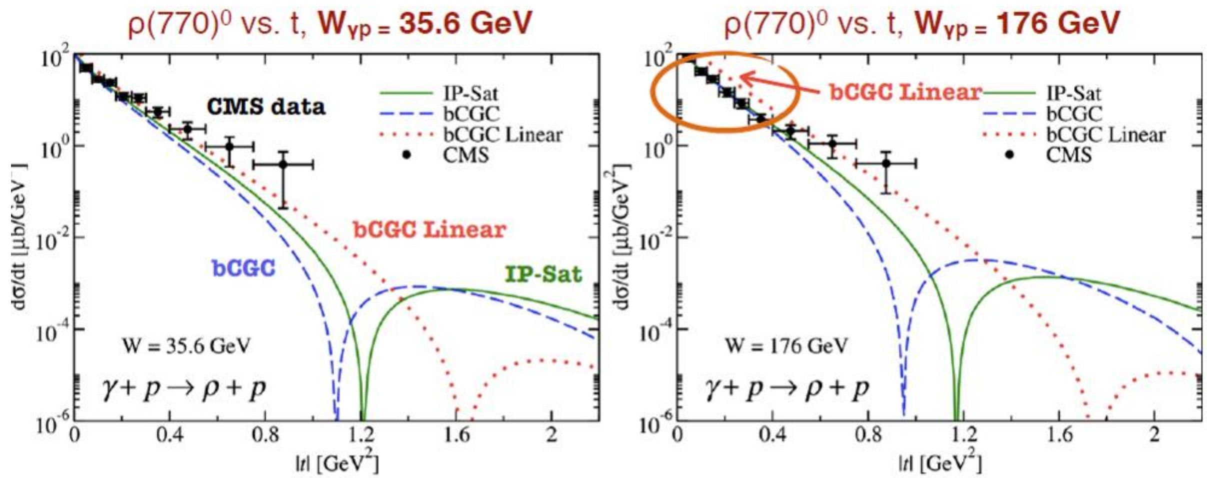
$t \approx -p_T^2$

$Au + Au \rightarrow \rho + Au + Au + XnXn,\ \sqrt{s_{NN}}$=200 GeV



STAR: Phys. Rev. C **96** (2017) 54904

arXiv:1902.01339, PLB 791(2019)299



At higher energy (→ lower x), slope at low t better matches models with saturation

γ+N

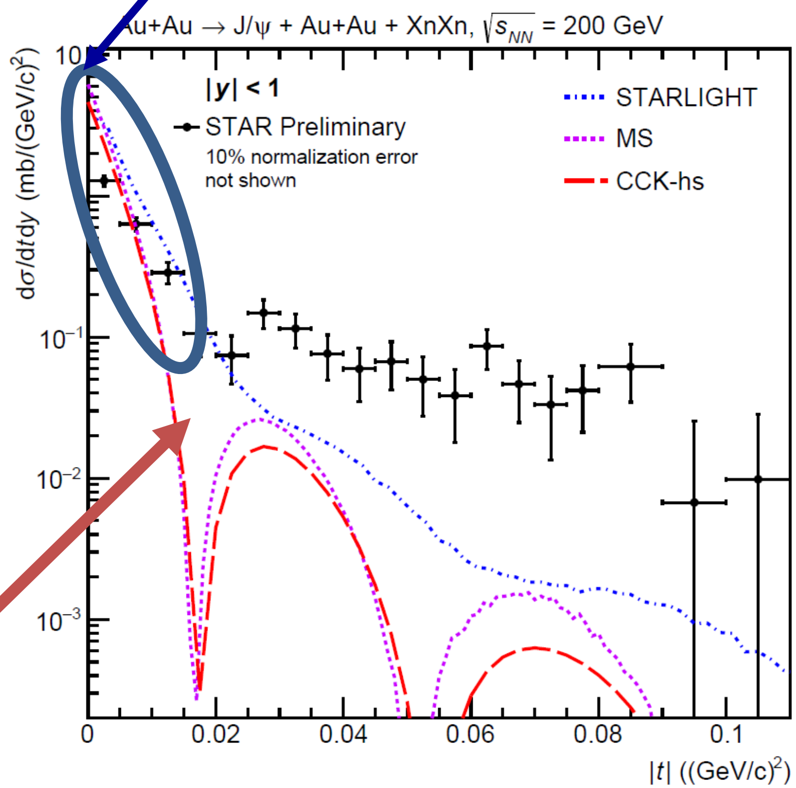
Diffraction in coherent J/ψ dσ/dt

Slope below first diffractive minimum more shallow than dipole models predict

- $t \approx -p_T^2$

Model comparisons:

- **STARLIGHT:** Klein, Nystrand, CPC 212 (2017) 258-268
  - Vector meson dominance
  - Glauber approach
  - Includes photon p_T
- **MS:** Mäntysaari, Schenke, Phys.Lett. B772 (2017) 832-838
  - Dipole approach with IPsat amplitude
  - Scaled to XnXn using STARLIGHT
- **CCK:** Cepila, Contreras, Krelina, Phys.Rev. C97 (2018) no.2, 024901
  - Hot spot model for nucleons, dipole approach
  - Scaled to XnXn using STARLIGHT



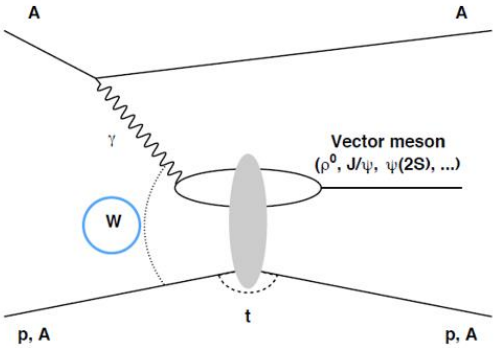
Diffractive dip around $|t| \approx 0.02$ GeV^2 is correctly predicted by the dipole MS and CCK models

γ+N

Incoherent cross section → fluctuations?

See talk by Mäntysaari

$$\sigma_{\text{incoherent}} \sim \sum_{f \neq i} |\langle f|\mathcal{A}|i\rangle|^2$$
$$= \sum_{f} \langle i|\mathcal{A}|f\rangle^\dagger \langle f|\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^\dagger \langle i|\mathcal{A}|i\rangle$$



Average over initial states:

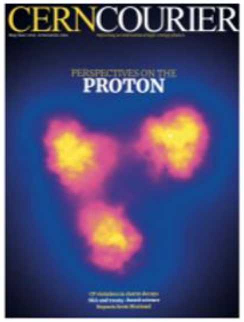
$$\sigma_{\text{incoherent}} \sim \langle |\mathcal{A}|^2 \rangle_\Omega - |\langle \mathcal{A} \rangle_\Omega|^2$$

Incoherent cross section $=$ variance of $\mathcal{A}^{\gamma^* A \to VA}$

Miettinen, Pumplin, PRD 18, 1978, Caldwell, Kowalski, Phys.Rev. C81 (2010) 025203

Models with fluctuations describe trends in $\gamma p \rightarrow J/\psi\, p$ data

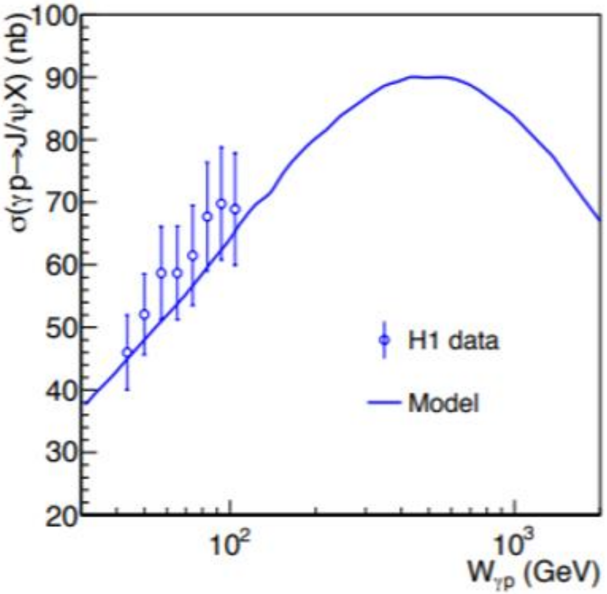
Fluctuations



See talk by Mäntysaari

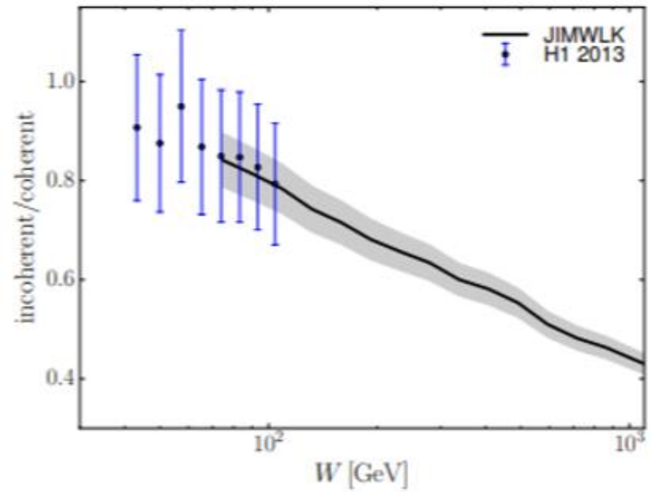
Increasing # of hot spots w energy:
Smoother proton, less fluctuations

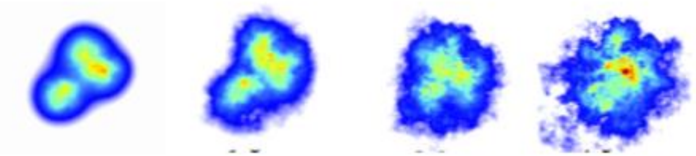
Cepila, Contreras, Tapia Takaki, 1608.07559



JIMWLK evolution event-by-event
Includes also growing RMS size

H.M., Schenke, 1806.06783



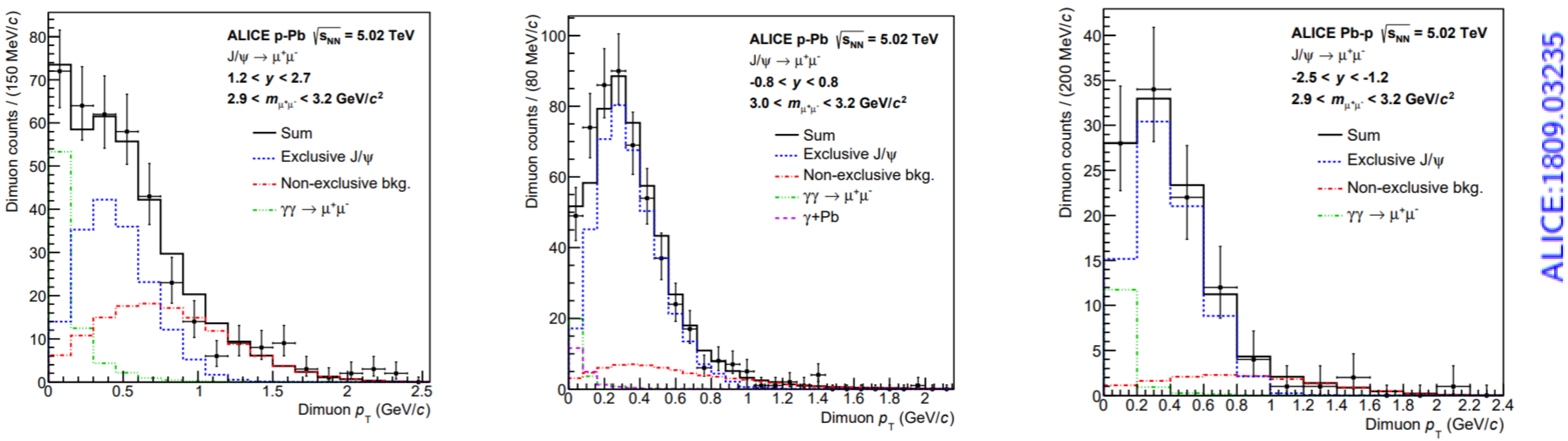


γ+N

Can we see this effect in p+Pb UPCs?

See talk by Mäntysaari

Increasing energy $$W_{\gamma A} = \sqrt{2E_{beam}M_V e^{-y}}$$

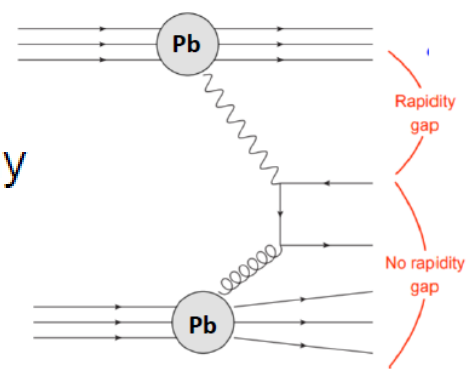


- As CM energy increases, incoherent contribution (related to fluctuations) decreases

Hard scattering in photo-nuclear events

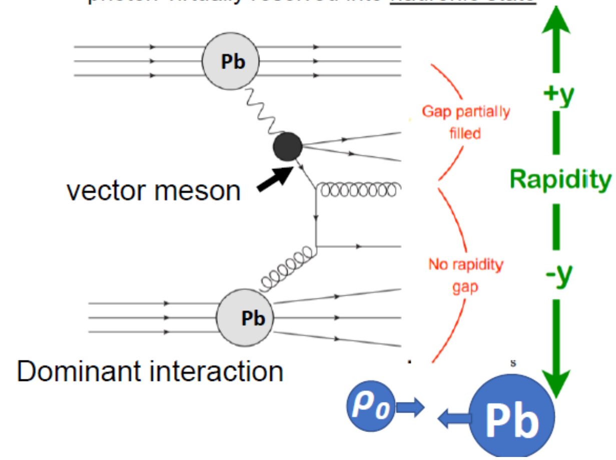
Direct γA collisions

Photon couples directly to nuclear parton



Resolved γA collisions

photon virtually resolved into hadronic state



Photon max energy
~ 80 GeV at LHC

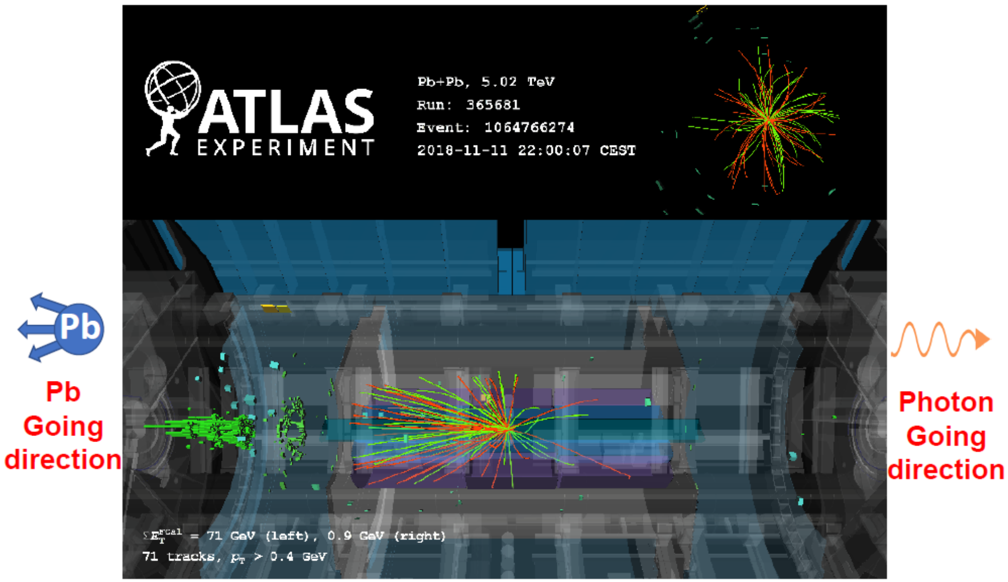
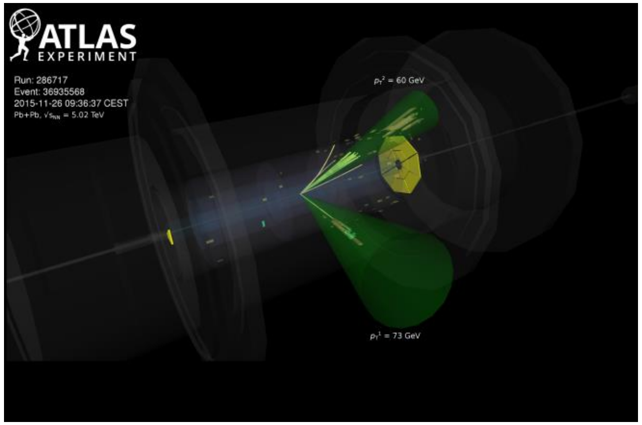


Photo-nuclear events selected via

- Large summed rapidity gap and 0 neutrons on photon-going side
- Small summed rapidity gap and >0 neutrons on Pb-going side

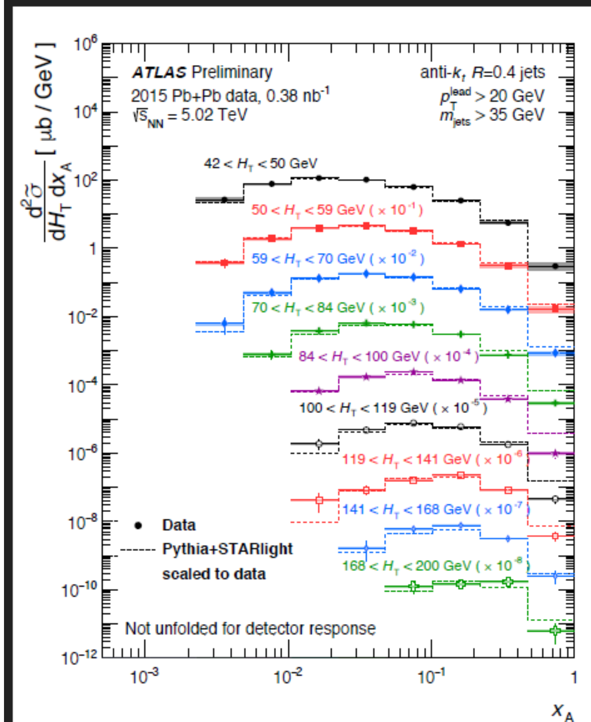
γ+N

Hard scattering: Photonuclear di-jets in 5.02 TeV Pb+Pb



- Jet selection:
  - Anti-k_T, $R = 0.4$, $|\eta| < 4.4$
  - $p_T^{\text{lead}} > 20$ GeV, $p_T^{\text{jets}} > 15$ GeV

jet variables: $H_T \equiv \sum_i p_{T\,i}\,, \quad x_A \equiv \frac{m_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}}$

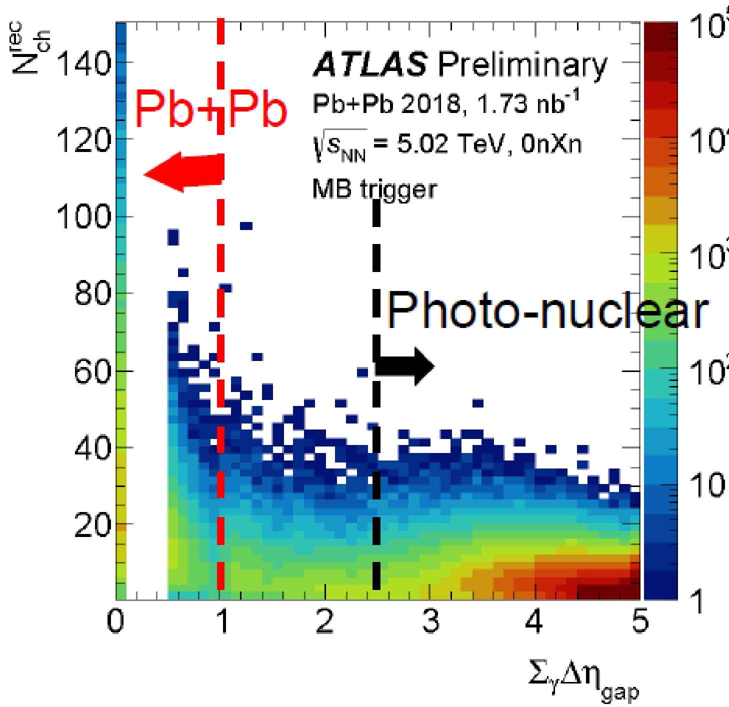


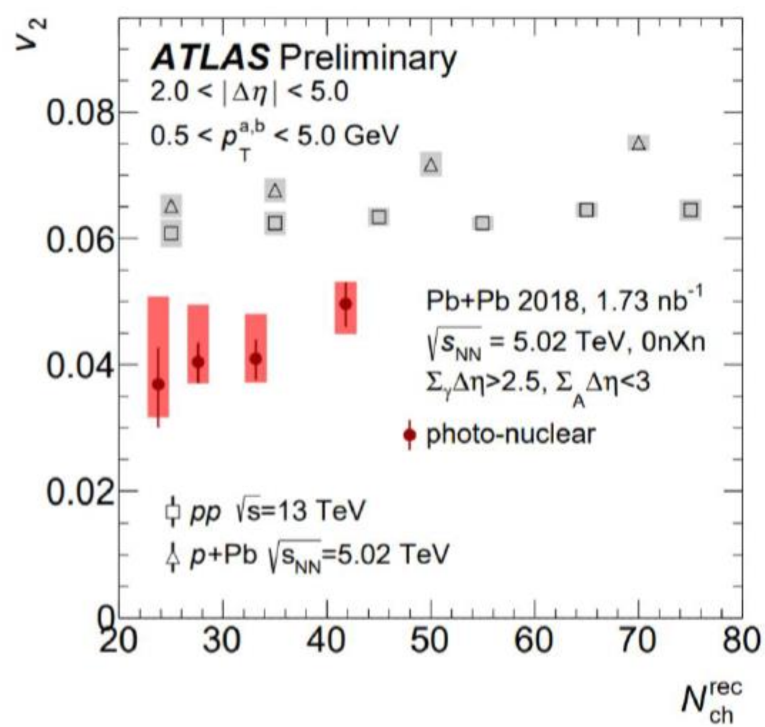
ATLAS-CONF-2017-011

- Shape qualitatively described by Pythia 6 with photon flux scaled via Starlight
- Samples PDFs directly, but will need to do the detector unfolding

γ+N Hard scattering: v_2 in photo-nuclear events

- Significant v_2 in events selected by photo-nuclear criteria
  - Less than in pp and pPb

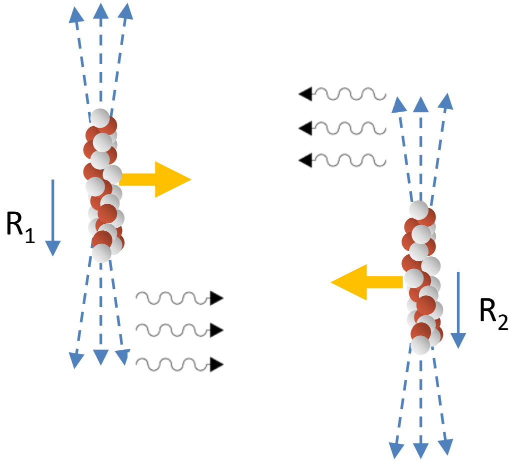




$\gamma+N$?

Can photon-induced processes probe the nuclear medium formed in hadronic collisions?

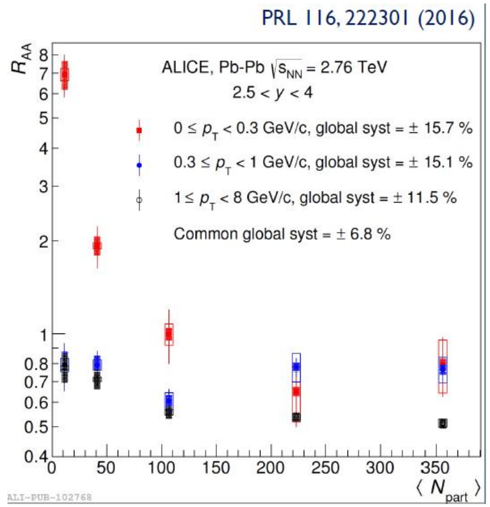
- When nuclei overlap, hadronic interactions dominate
- But…



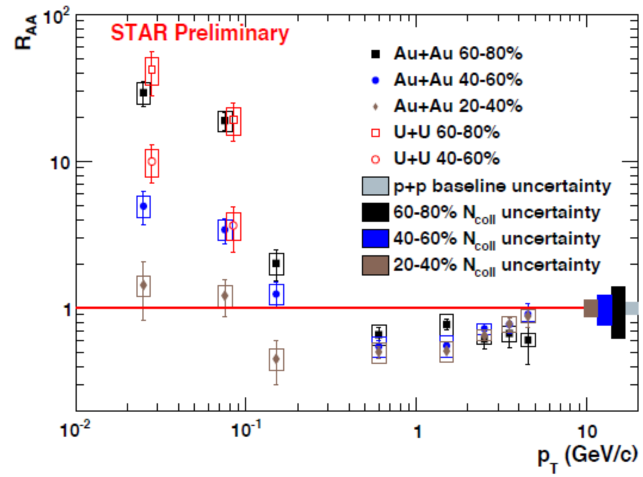
$\gamma + N$?

Anomalous low-p_T enhancement in J/ψ in peripheral AA collisions

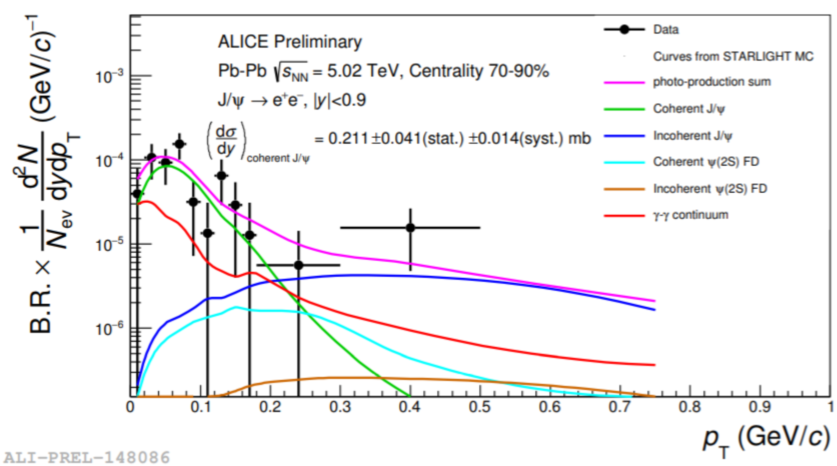
- Not explained by hadronic interactions



J/Psi in peripheral AuAu and UU collisions

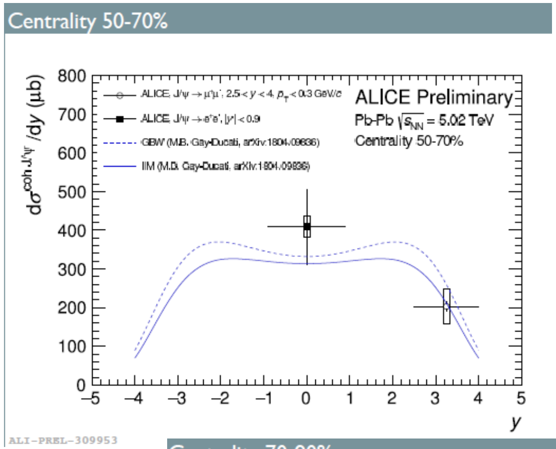


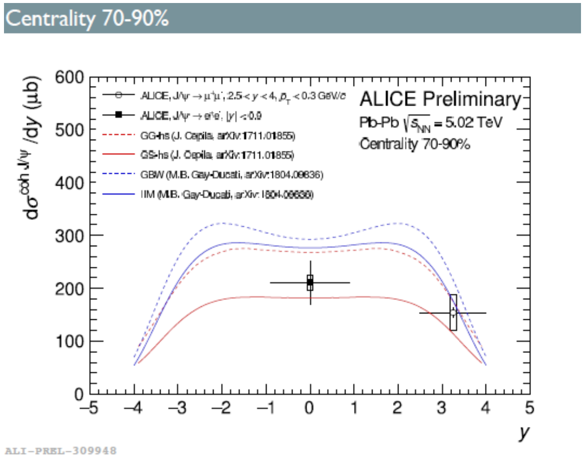
STAR, arXiv: 1904.1165



Shape of low p_T excess matches that expected from photonuclear production – can be fit with the same Starlight template as used for UPCs

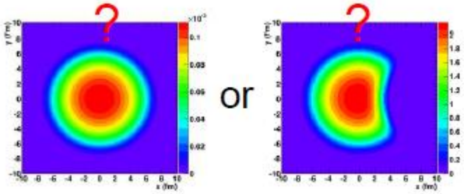
γ+N? Models used to describe UPC data and modified to account for nuclear overlap region qualitatively reproduce the J/ψ data



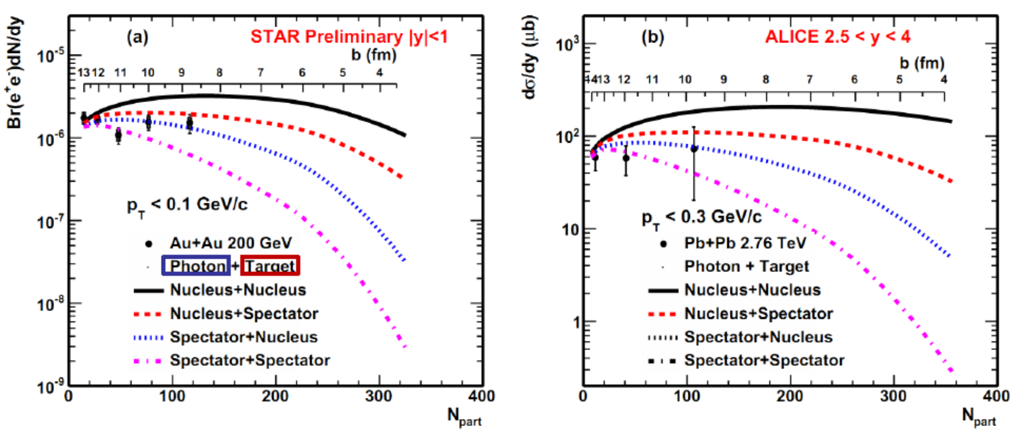


Photon emitter:

Pomeron emitter:



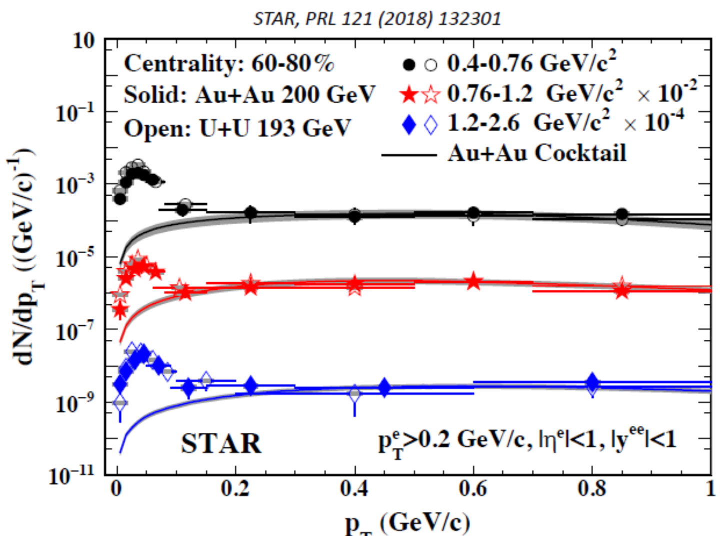
W. Zha etal., PRC **97** (2018) 044910



γ+N?

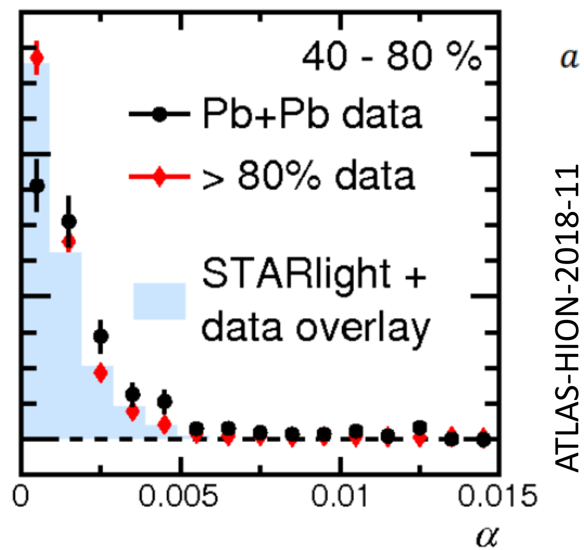
Excess also seen in di-lepton pairs

STAR: ee in peripheral AuAu and UU collisions



Excess above the hadronic cocktail at very low p_T

ATLAS: $\mu\mu$ in peripheral PbPb collisions



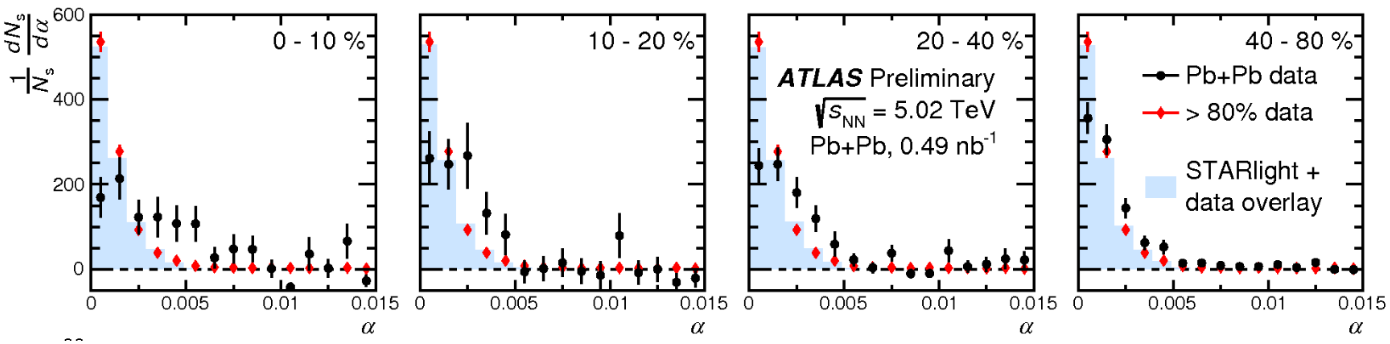
$$a = 1 - \frac{|\varphi^+ - \varphi^-|}{\pi}$$

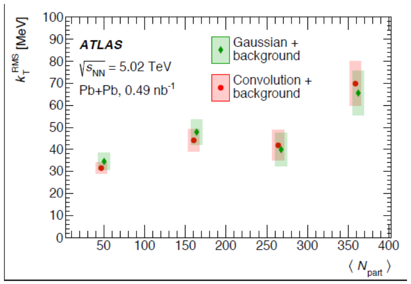
80% centrality matches UPC

Even more interesting: peak broadens with increasing centrality

γ+N?

PRL 121 (2018) 212301





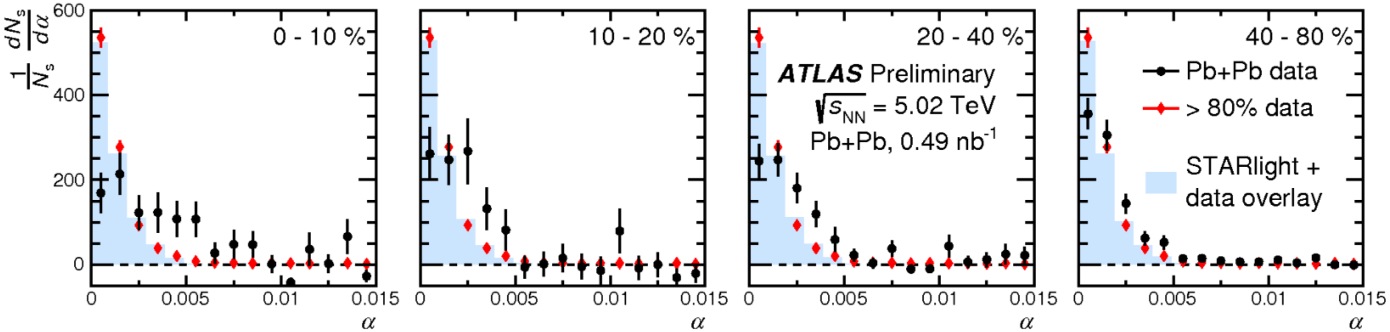
- Add additional k_T: modifications qualitatively consistent with re-scattering of the muons passing through hot matter produced in the collision

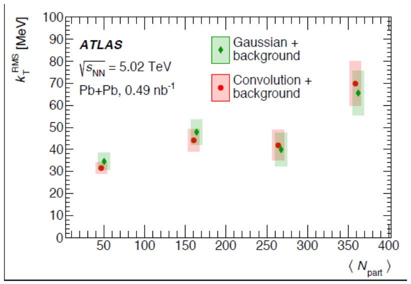
$$\langle \alpha^2 \rangle = \langle \alpha^2 \rangle_0 + \frac{1}{\pi^2}\frac{\langle \vec{k}_T^2 \rangle}{\langle p_{T\,avg}^2 \rangle},$$

γ+N?

Even more interesting: peak broadens with increasing centrality

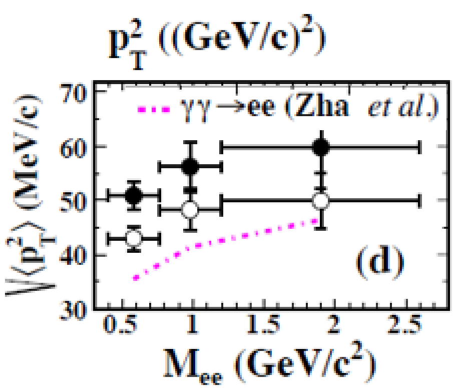
PRL 121 (2018) 212301





$$\langle \alpha^2 \rangle = \langle \alpha^2 \rangle_0 + \frac{1}{\pi^2}\frac{\langle \vec{k}_T^2 \rangle}{\langle p^2_{T\,avg} \rangle},$$

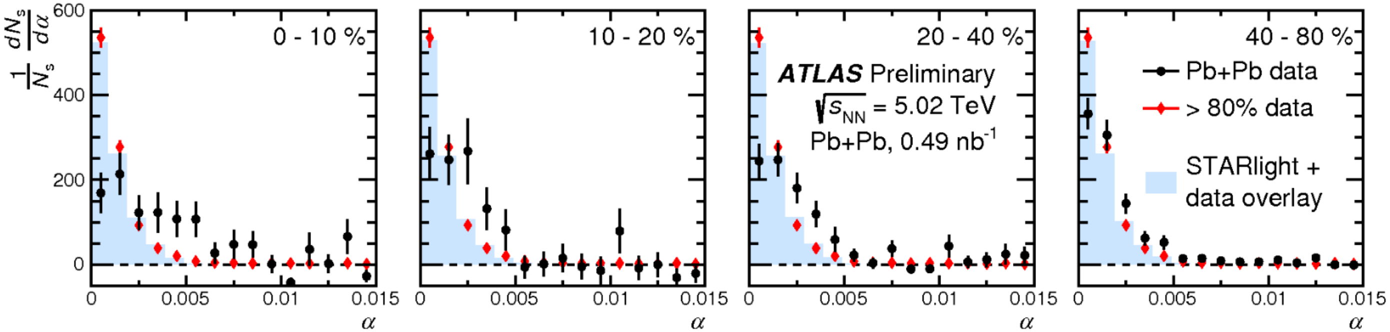
- Add additional k_T: modifications qualitatively consistent with re-scattering of the muons passing through hot matter produced in the collision

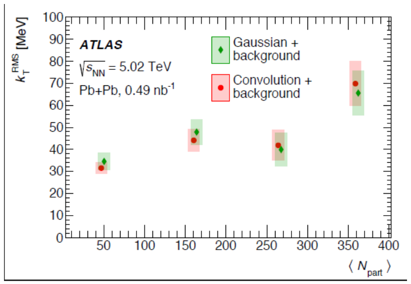


γ+N?

Even more interesting: peak broadens with increasing centrality

PRL 121 (2018) 212301





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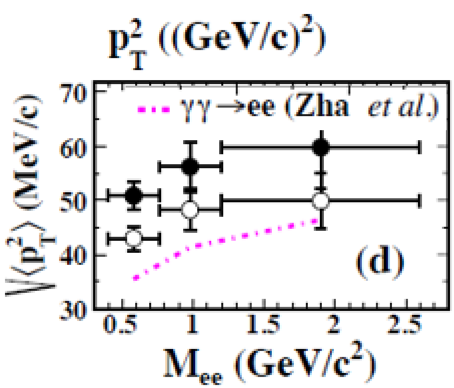
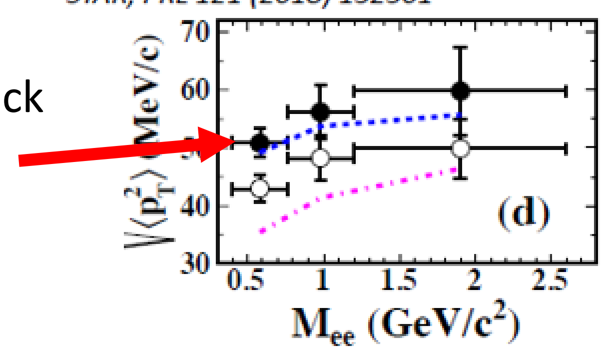
- Add additional k_T: modifications qualitatively consistent with re-scattering of the muons passing through hot matter produced in the collision



Qualitative agreement obtained by adding a kick due to pair interacting with residual magnetic field

STAR, PRL 121 (2018) 132301



$\gamma+N$?

Or, a less exotic explanation

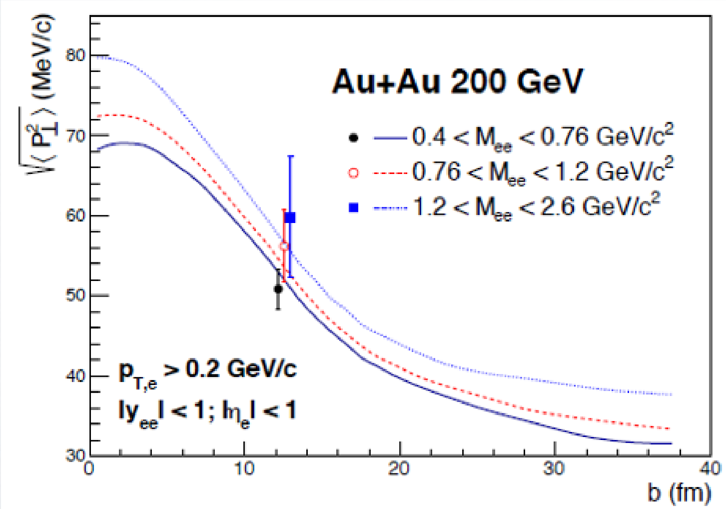
Zha et al. 1812.02820

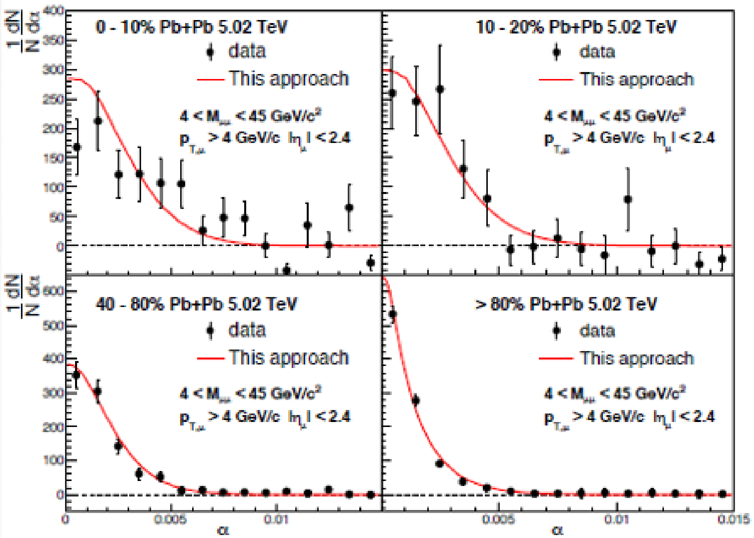
- Impact parameter and pair p_T are coupled in calculation based on classical external field approach

M. Vidović *et al.*, Phys. Rev. C **47**, 2308 (1993).

  - Creates broadening of same scale as seen in STAR & ATLAS data

    →no need for re-scattering or kick from magnetic fields
  - Can provide a baseline for whether additional effects are needed

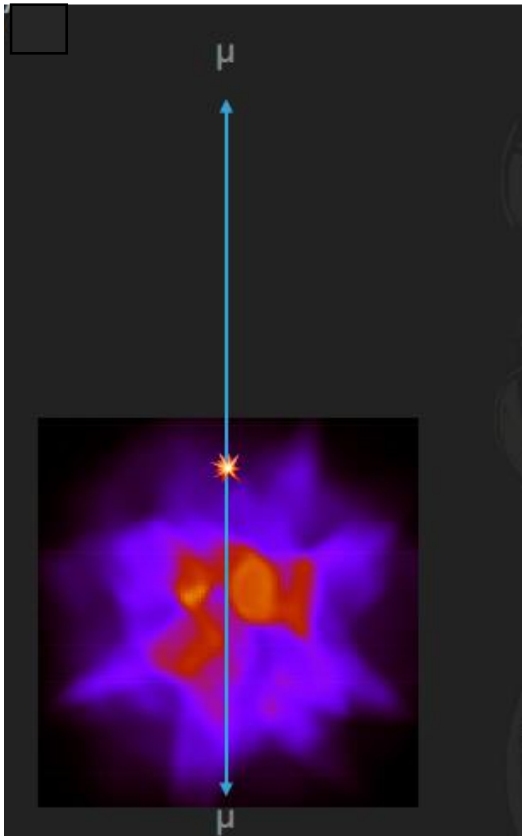




γ+N?

What does it mean?

- How can there be coherent emission in a hadronic collision?
- Is the photon source smaller than the entire nucleus (hot spots, spectators)?
- Do the leptons traverse the nuclear medium?
- Can they be a novel probe of the QGP?



Can a "non-UPC" μμ event "see" the QGP?

What is coming up?

- 10x more data from 2018 heavy ion run at LHC
  - Many of these statistics-limited analyses will be much improved
- dAu and Rb/ZR isotope data at RHIC
- Hopefully more theoretical guidance particularly regarding coherent interactions in peripheral collisions
- Better understanding of hard scattering data

Thank you for your attention