Photonuclear Interactions in Heavy-Ion Collisions at the LHC

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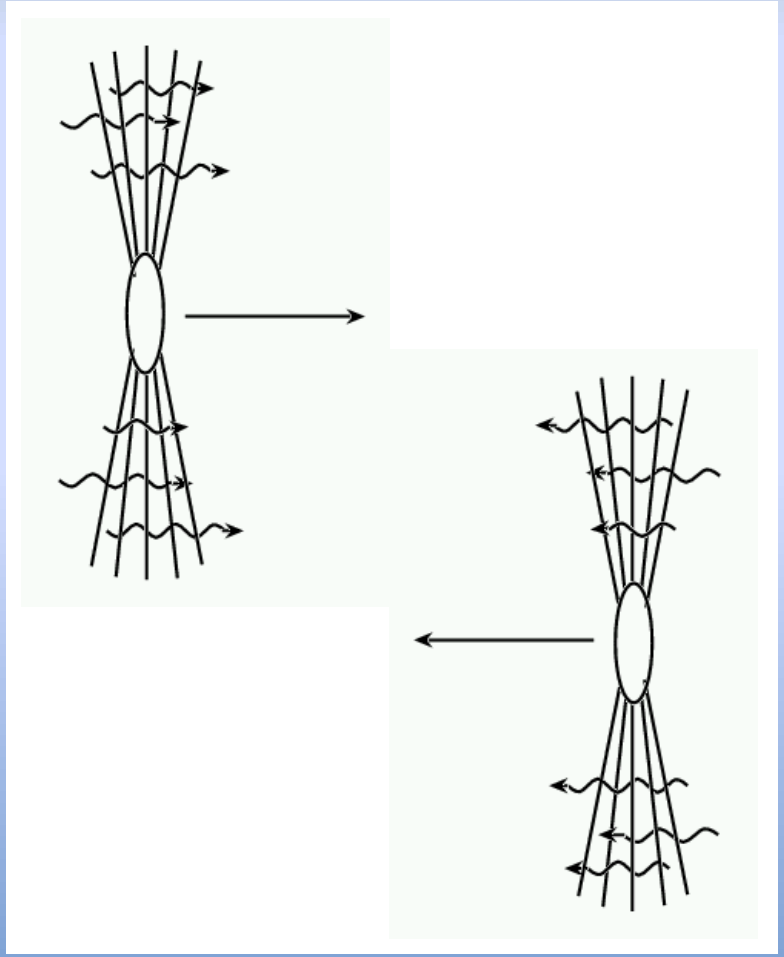
14th Workshop on Elastic and Diffractive Scattering (ESD Blois Workshop), Qui Nhon, Vietnam, 15 – 21 December 2011

Outline

- LHC as a photon collider.
- Photonuclear interactions: A signal or a background?
  - Photonuclear background to peripheral, hadronic Pb+Pb interactions.
  - Photon-proton interactions in p+Pb collisions.
  - Exclusive vector meson production as a probe of the nuclear gluon distribution.
- Conclusions.

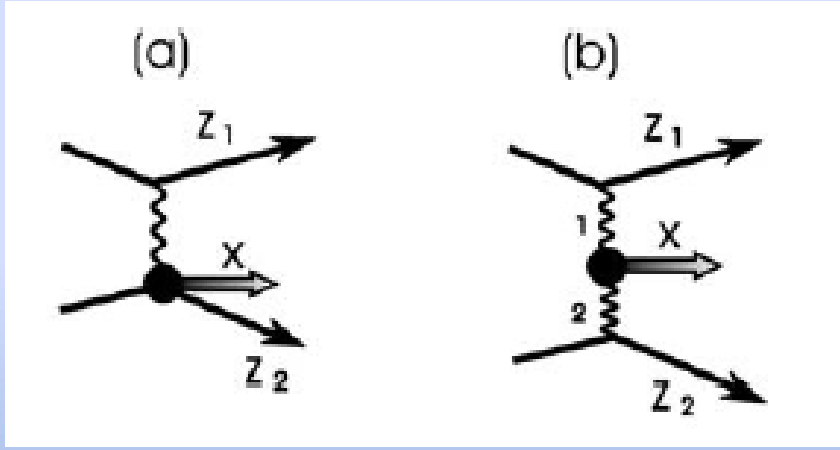
Ultra-Peripheral Collisions - Definition

- Two ions (or protons) pass by each other with impact parameters $b > 2R$.
- Only Electromagnetic interactions are possible.
- The fields can be treated as a spectrum of equivalent photons (Weizsäcker-Williams)
- Number of photons scales like Z^2 for a single source ⇒ exclusive particle production in heavy-ion collisions dominated by electromagnetic interactions.



Ultra-Peripheral Collisions – Types of processes

(a) Photonuclear processes: A photon from one nucleus interacts with the other (target) nucleus.

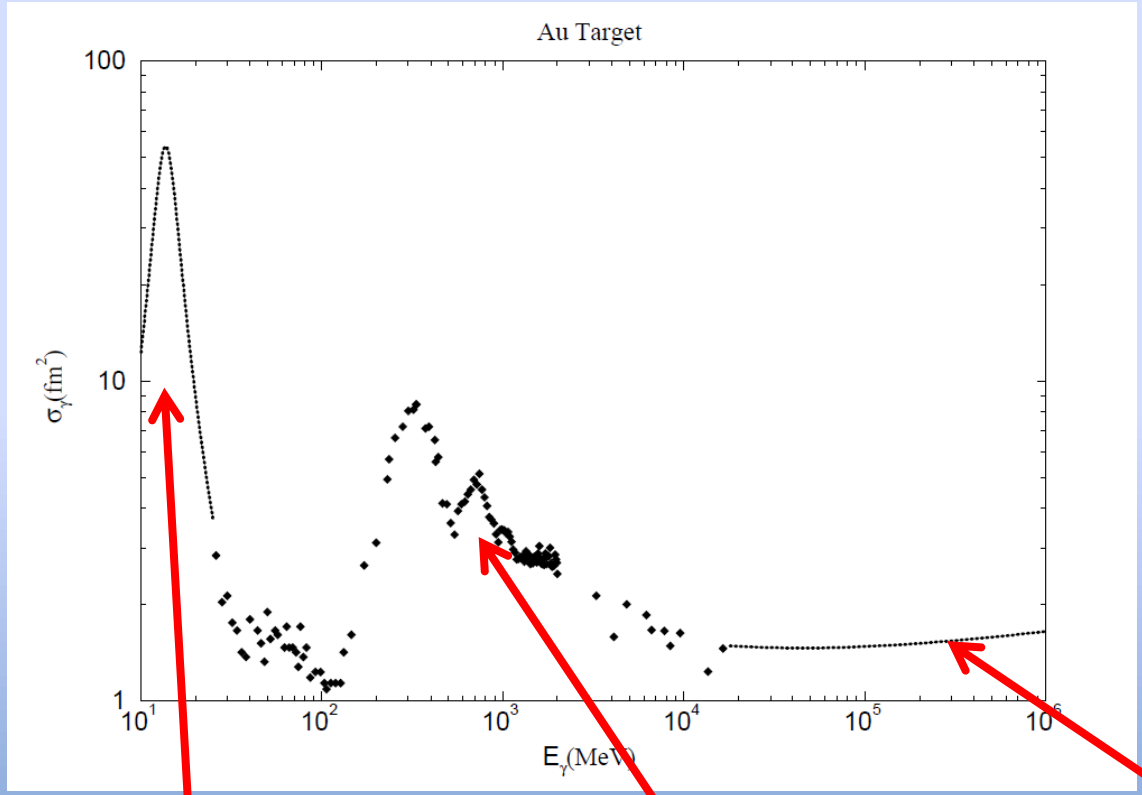


(b) Two-photon interaction: Two photons interact and produce a final state X while the nuclei remain intact.

Note: Also in coherent photonuclear processes it is possible to produce a final state, typically a vector meson, while both nuclei stay intact.

Ultra-Peripheral Collisions – Photonuclear Interactions

The photonuclear cross section for a heavy nucleus:



Compilation and parameterization by A.J. Baltz et al.

Giant Dipole Resonance, emission of neutrons.

Single nucleon excitations.

Multiparticle production.

Ultra-Peripheral Collisions – Total photonuclear cross section

- The A+A cross section is calculated by convoluting the photon spectrum with the photonuclear cross section:

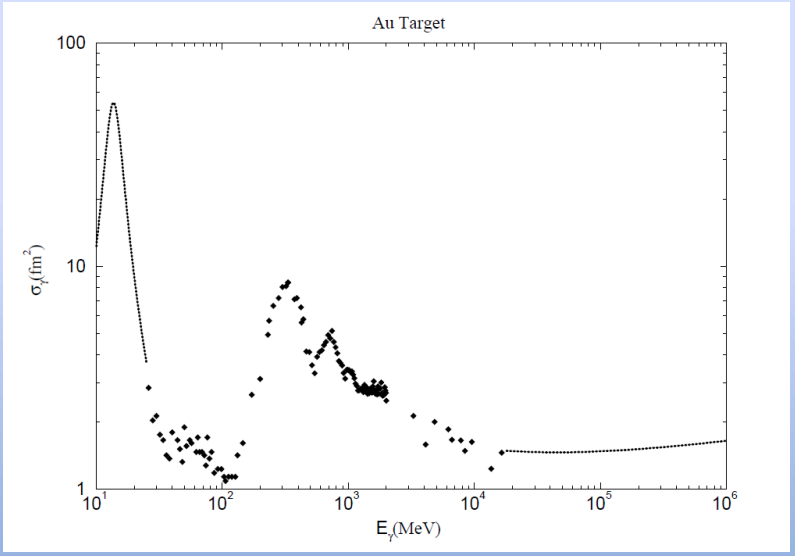
$$\sigma(A + A \rightarrow A + X) = 2\int n(\omega)\sigma_{\gamma A \rightarrow X}(\omega)d\omega$$

- The ”2” takes into account that each nucleus can act as either target or photon emitter.
- The total cross section for breaking up one nucleus is much larger than the total hadronic interaction cross section in Pb+Pb collisions at the LHC $\sqrt{s_{NN}}$ = 5.5 TeV (≈ 8 b):

220 b	A. J. Baltz, M. J. Rhoades-Brown, and J. Weneser, Phys. Rev. E 54 (1996) 4233.
214 b	F. Krauss, M. Greiner and G. Soff, Prog. Part. Nucl. Phys. 39 (1997) 503.
215 b	I. A. Pshenichnov et al., Phys. Rev. C 64 (2001) 024903.

Ultra-Peripheral Collisions – Photonuclear particle production

- The break up is dominated by excitation to a Giant Dipole Resonance, followed by emission of one or a few neutrons.
- For higher photon energies, particles can also be produced.



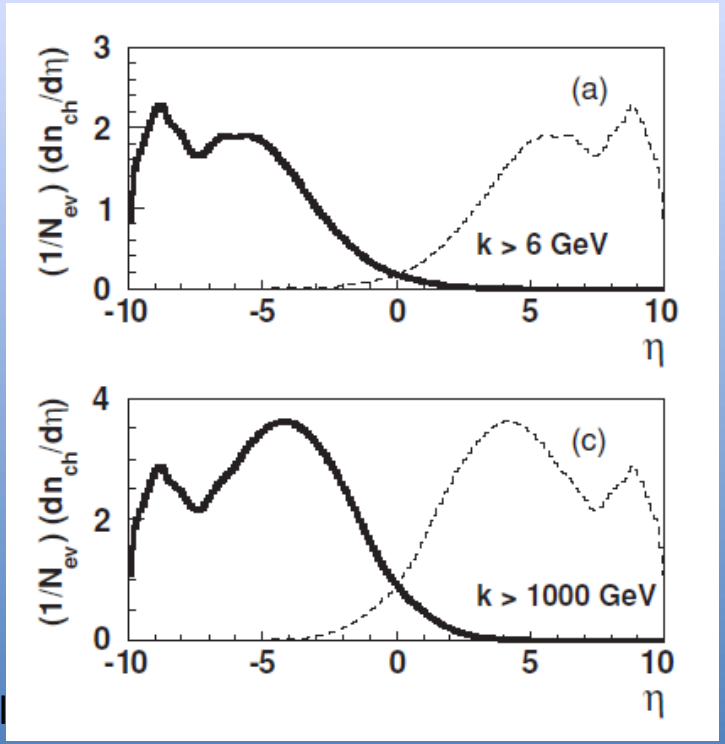
- Model the photonuclear particle production with the DPMJET Monte Carlo (AFAIK the only MC available for high energy photonuclear interactions).
- Requires $E_\gamma > 6$ GeV in rest frame of target nucleus.
- Use photon spectrum from STARLIGHT. Weizsäcker-Williams spectrum calculated in impact parameter space. Includes emission of single and mulitple photons in a single event.
- Ø. Djuvsland, J. Nystrand, Phys. Rev. C 83 (2011) 041901.

STARLIGHT Monte Carlo:
http://projects.hepforge.org/starlight

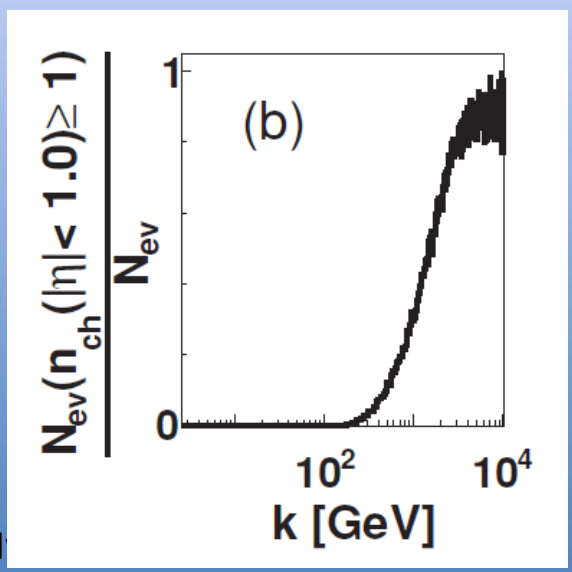
DPMJET: S. Roesler, R. Engel, J. Ranft, Phys. Rev. D 57 (1998) 2889.

Ultra-Peripheral Collisions – Photonuclear particle production

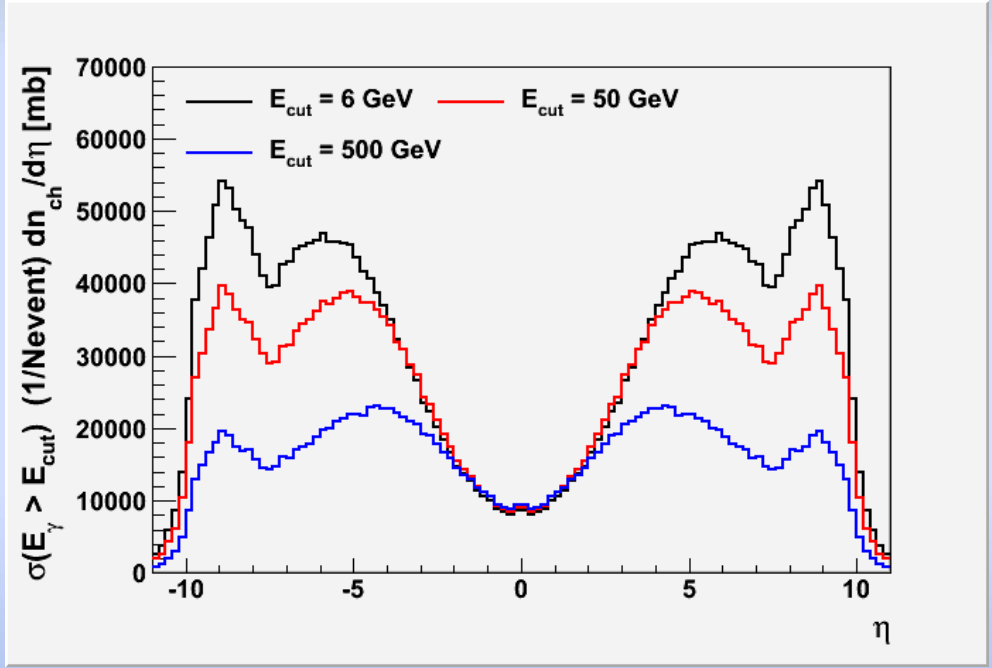
- Total cross section (Pb+Pb at $\sqrt{s_{NN}}$=2.76 TeV) for E_γ > 6 GeV: 24.2 b
- Larger than the total hadronic cross section, but a rather aribtrary number because of the selection E_γ > 6 GeV.
- However, there is a strong correlation between photon energy and the range in rapidity of the produced particles



Production around mid-rapidity dominated by photons with energies >> 6 GeV.



Ultra-Peripheral Collisions – Normalized particle yield

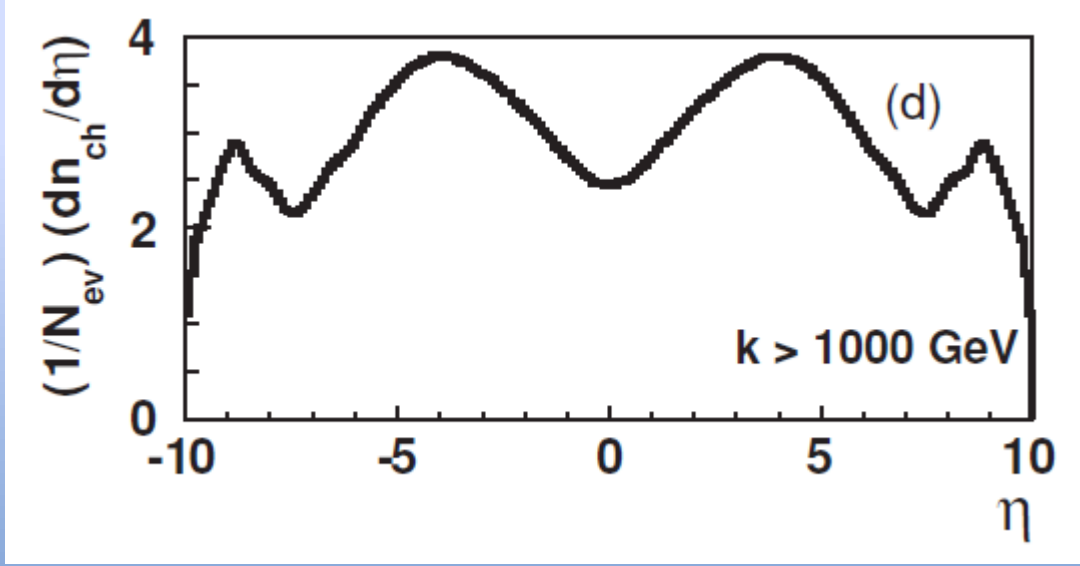


Pb+Pb at
$\sqrt{s_{NN}}$=2.76 TeV

- Changing the cut-off only affects the yield at large rapidities. The production around mid-rapidity is insensitive to the cut-off.
- Cross section for having ⩾1 charged particle within $|\eta|<1.0$: 4.2 b.
- E_γ > 6 GeV should give a complete description of particle production within $|\eta|<4.5$.

Ultra-Peripheral Collisions – Multiple photon exchange

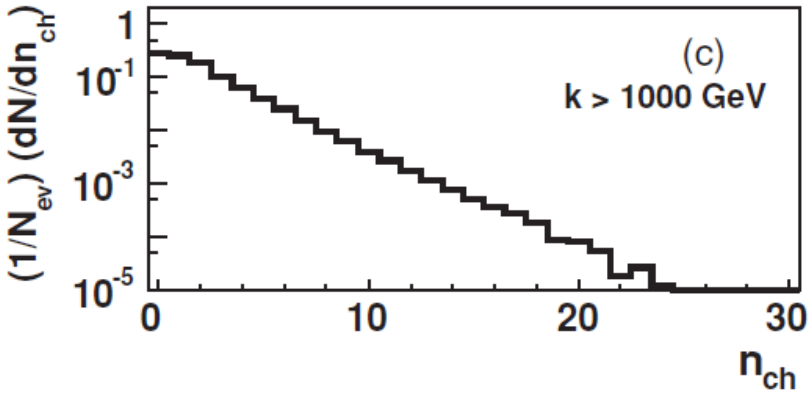
- Interaction where a single photon is exchanged are characterized by asymmetric distributions of particles in rapidity.
- However, it is possible to exchange two photons in a single event. This leads to particle production on both sides of η=0.

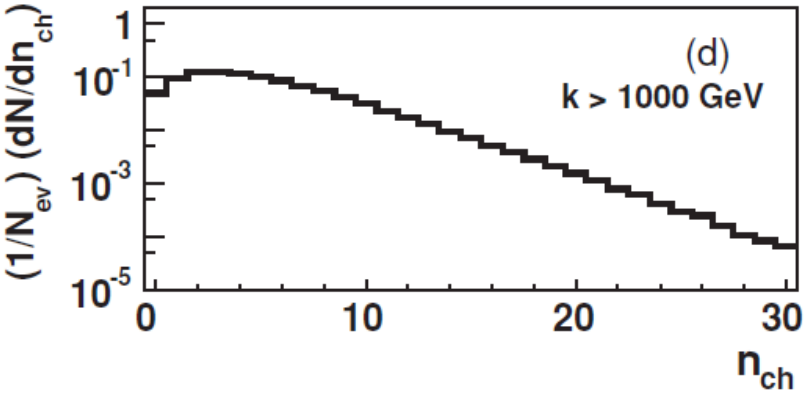


- Cross section for ⩾1 charged particle within |η|<1.0: 130 mb
- Smaller than for single excitation, but may be more important depending on trigger and event selection.

Ultra-Peripheral Collisions – Particle production

Multiplicity of charged particles with $|\eta|<1.0$





Single

Double

- Photonuclear interactions can lead to significant particle production around mid-rapidity.

Ultra-Peripheral Collisions – UPC as a Background

- Single and double photonuclear interactions a serious background to the 20% most peripheral hadronic nuclear interactions (80-100% centrality).

- See presentation by Alberica Toia (ALICE Collaboration), Quark Matter 2011, J. Phys. G 38 (2011) 124007.

- The STARLIGHT+DPMJET predictions could be tested if the central tracking detectors are read out while triggering on a signal in the Zero-Degree Calorimeters only. ALICE took some data with this configuration during the heavy-ion run this year.

Ultra-Peripheral Collisions – UPC as a signal

- The general photonuclear interactions ($\gamma + A \rightarrow X$) also contain much interesting physics.

- Example 1: Heavy quark production through photon-gluon fusion. See e.g. S.R. Klein, J. Nystrand, R. Vogt, Phys. Rev. C 66 (2002) 044906. The total cross section for photoproduing a cc-pair in a Pb+Pb collision at the full LHC energy is about 1 b!

- Example 2: Photonuclear jet production. See M. Strikman, R. Vogt, S. White, Phys. Rev. Lett. 96 (2006) 082001. Probes the nuclear PDFs at lower x than what was possible at HERA.

Ultra-Peripheral Collisions – Proton-nucleus collisions

- At the end of next year, LHC is likely to study proton-nucleus collisions, p+Pb.

- The energies will be asymmetric: E(p) = 3.5 TeV, E(Pb) = 1.38 A TeV.

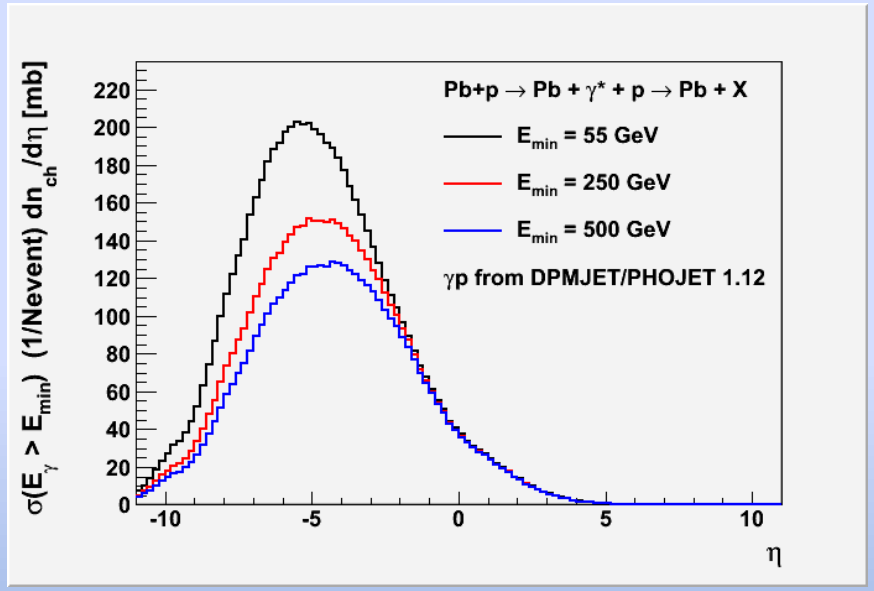
- The strong flux of photons from the lead nucleus will lead to large cross sections for several types of γ+p interactions.

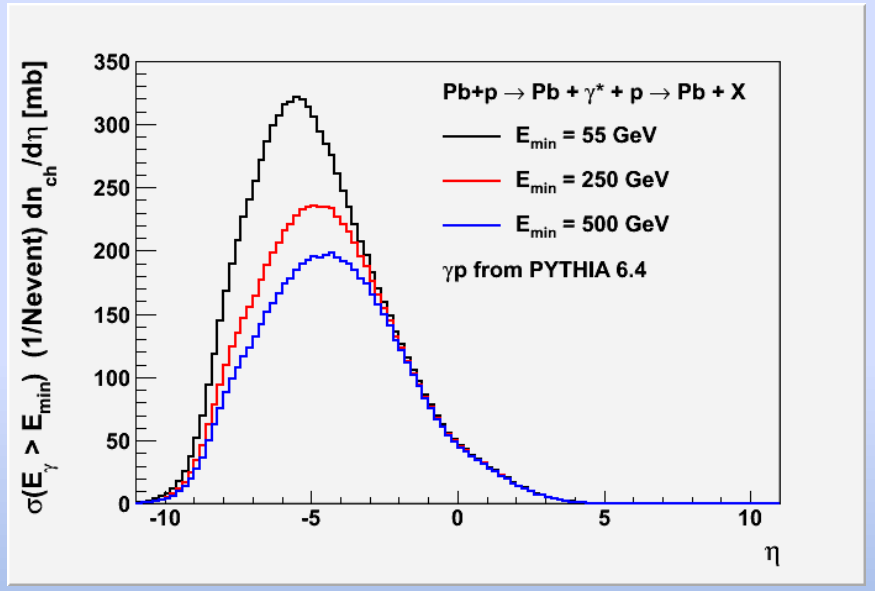
- Repeat the previous exercise for γ+p interactions. In addition to DPMJET/PHOJET*, also Pythia can be used to simulate the particle production.
- Work done together with Øystein Djuvsland.

* The γ-nucleon interactions in DPMJET are handled by PHOJET.

Ultra-Peripheral Collisions – Proton-nucleus collisions

Normalized yields from DPMJET/PHOJET and PYTHIA

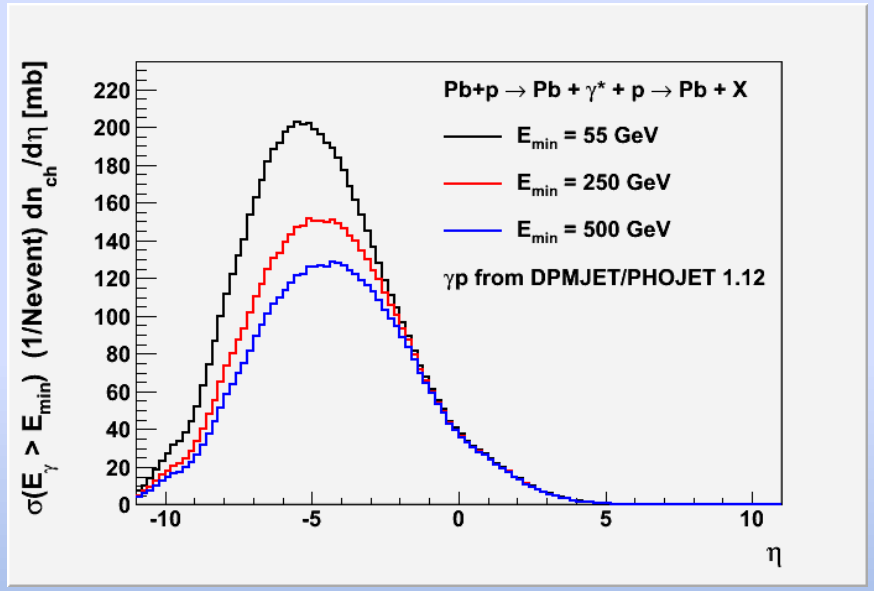


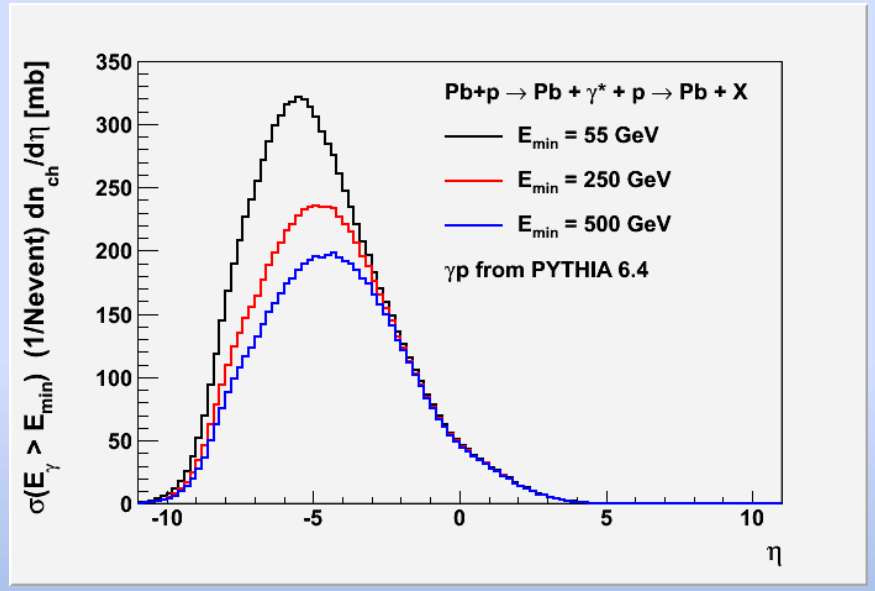


- Roughly 50% higher multiplicity in Pythia than in Phojet
- Could be checked in an early run next year.
- Cross section for having $\geqslant 1$ charged particle within $|\eta|<1.0$:
  - 32 mb (DMPJET/PHOJET)
  - 31 mb (PYTHIA)

Ultra-Peripheral Collisions – Proton-nucleus collisions

Normalized yields from DPMJET/PHOJET and PYTHIA





- Higher cut-off energy needed in Pythia (55 GeV $\leftrightarrow$ $W_{\gamma p} \geqslant 10$ GeV)
- But this only affects particle production outside $|\eta| > 3.0$.
- The proton has $p_z < 0$ and the photon has $p_z > 0$ here.

Ultra-Peripheral Collisions – Proton-nucleus collisions

- Photoproduction is dominated by photon emission from the Pb nucleus. But the opposite is also possible, i.e. that the proton emits a photon that interacts with the Pb-nucleus.
- The photon flux scale as Z^2. The size of the target scales as $A^{2/3}$.
- One thus expects the cross section for photon emission from the Pb-nucleus to be larger by a factor

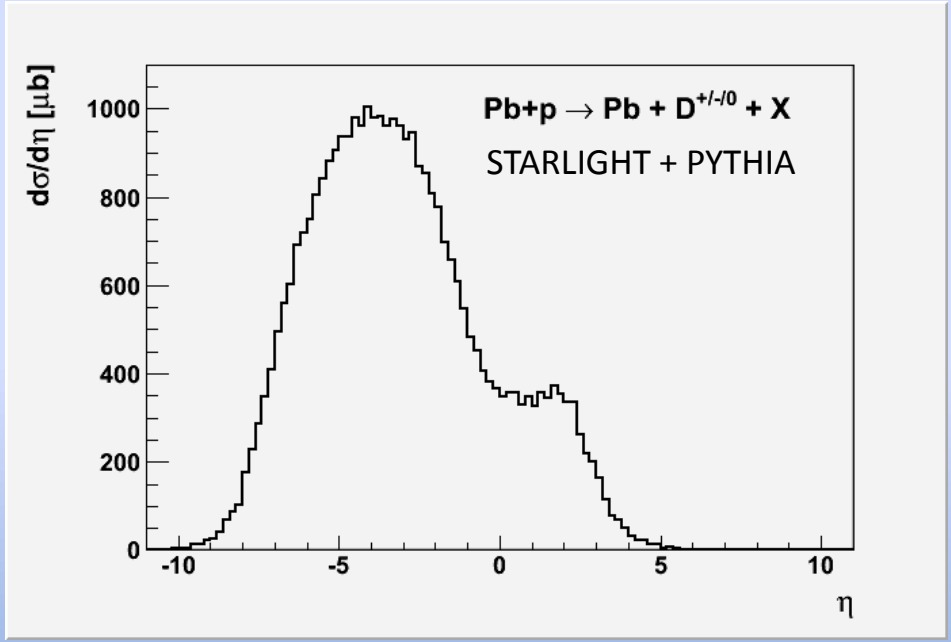
$$\frac{Z^2}{A^{2/3}} \sim 200$$

- Calculations confirm this.

- There will be a rapidity gap between the nucleus and the produced particles.

Ultra-Peripheral Collisions – Proton-nucleus collisions

Example: photoproduction of open charm in p+Pb collisions.



- Cross section for photoproducing D mesons around mid-rapidity dσ/dy ≈ 400 μb.
- Plateau in forward direction from γ fluctuating to a ccbar-pair.

Ultra-Peripheral Collisions – Exclusive Particle Production

- Originally the idea was to use ultra-peripheral heavy-ion collisions to study two-photon interactions.

- Some 10 years ago it was realized that coherent photonuclear interactions could produce events with the same topology and with cross sections >100 times higher (S.R. Klein, J. Nystrand, Phys. Rev. C 60 (1999) 014903).

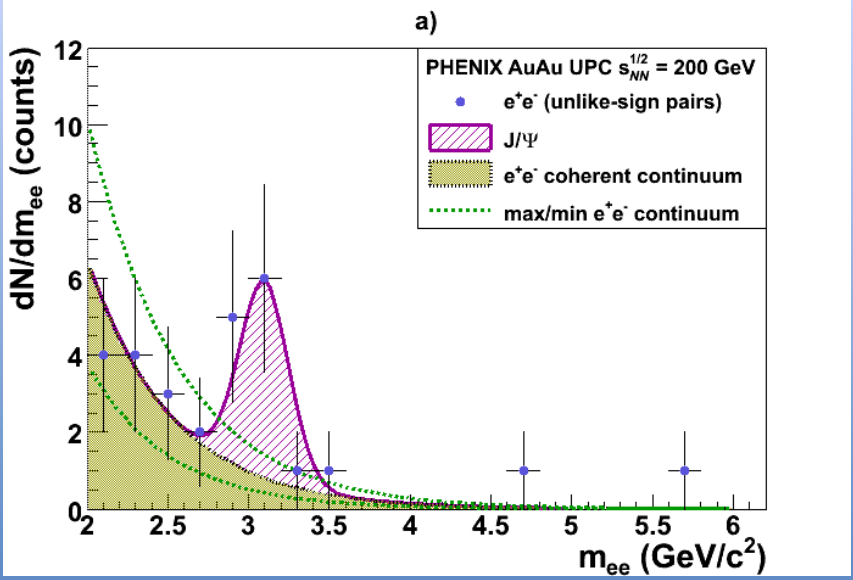
- Exclusive vector meson production in heavy-ion collisions is dominated by coherent photonuclear production of vector mesons. Example: $\sigma(Pb+Pb \rightarrow Pb+Pb+\rho^0) = 5.2$ b ($\sqrt{s_{NN}}$=5.5 TeV).

Ultra-Peripheral Collisions – Exclusive Particle Production

- Exclusive vector meson production has been studied at RHIC by the STAR and PHENIX Collaborations.

- Before RHIC, the collision energy was not sufficient.

- Example: Photoproduction of J/ by the PHENIX Collaboration (PLB 679 (2009) 321) Au+Au →Au+Au*+J/ψ. Note background from γγ→ e+e-.



Ultra-Peripheral Collisions – Exclusive Particle Production

- Heavy vector mesons caclulable from perturbative QCD.

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 [xg(x, \frac{M_V^2}{4})]^2$$ Ryskin 1993

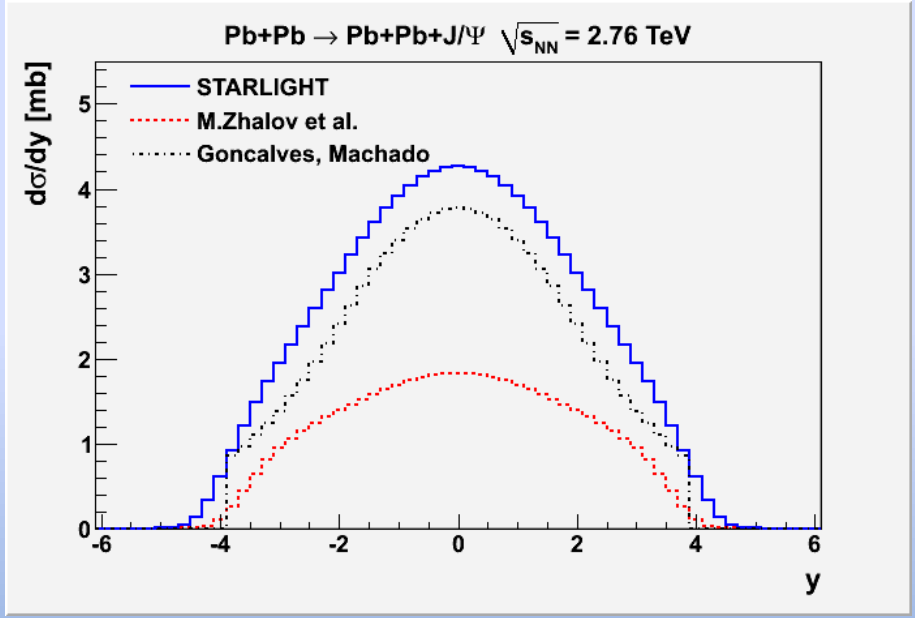
$\Rightarrow$

$$\frac{\left.\frac{d\sigma(\gamma A \to VA)}{dt}\right|_{t=0}}{\left.\frac{d\sigma(\gamma N \to VN)}{dt}\right|_{t=0}} = \left[\frac{G_A(x, M_V^2/4)}{G_N(x, M_V^2/4)}\right]^2$$

- There are good reference data on γ+N $\to$ J/ψ+N from HERA up to $W_{\gamma p}$ = 120 GeV.
- Measuring exclusive J/ψ production in Pb+Pb collisions at the LHC should put constraints on the nuclear gluon distribution.

Ultra-Peripheral Collisions – Exclusive Particle Production

- Predictions for exclusive J/ψ production in Pb+Pb collisions at $\sqrt{s}$ = 2.76 TeV.



- STARLIGHT does not include gluon shadowing.

1) STARLIGHT http://projects.hepforge.org/starlight; S.R. Klein, J. Nystrand, Phys. Rev. C 60 (1999) 014903.
2) L. Frankfurt, M. Strikman, M. Zhalov , Phys. Lett. B 626 (2005) 72; arXiv 1109:0737.
3) V.P. Goncalves, M.V.T. Machado, Phys. Rev. C 84 (2011) 011902.

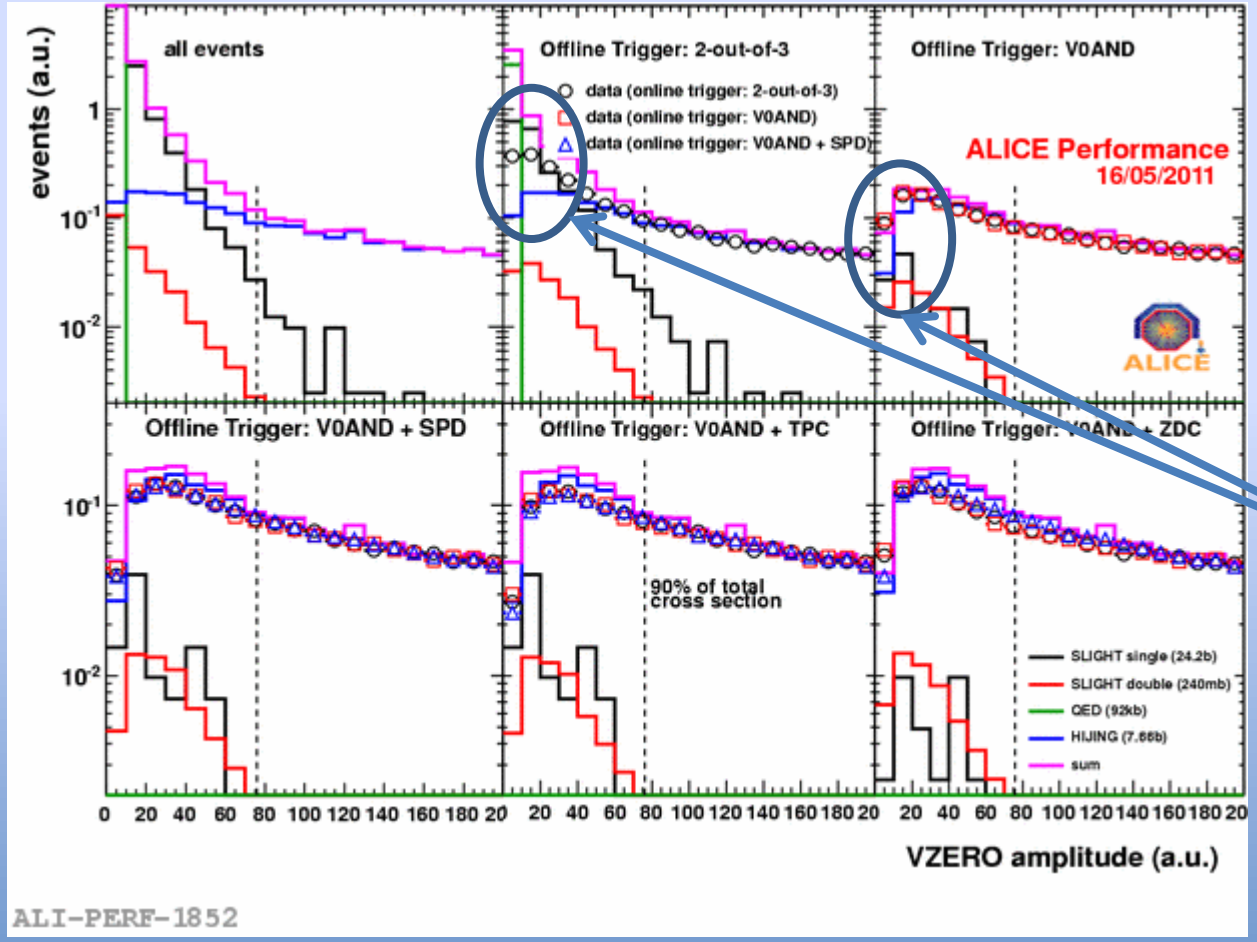
Conclusions

- Cross sections for photonuclear interactions very high in Pb+Pb collisions at the LHC – interesting signals, important background to hadronic collisions.
- Photon-proton interactions likely to be of similar importance in the foreseen p+Pb run at the LHC in 2012.
- Exclusive heavy vector meson production might help probe the nuclear gluon distribution.

Backup

Ultra-Peripheral Collisions – Photonuclear Interactions

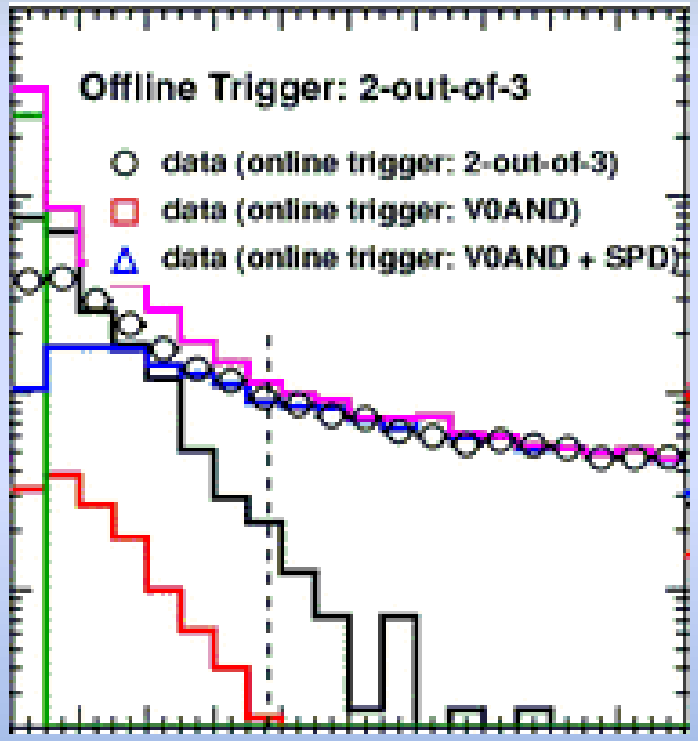
Event yield vs. V0 Signal

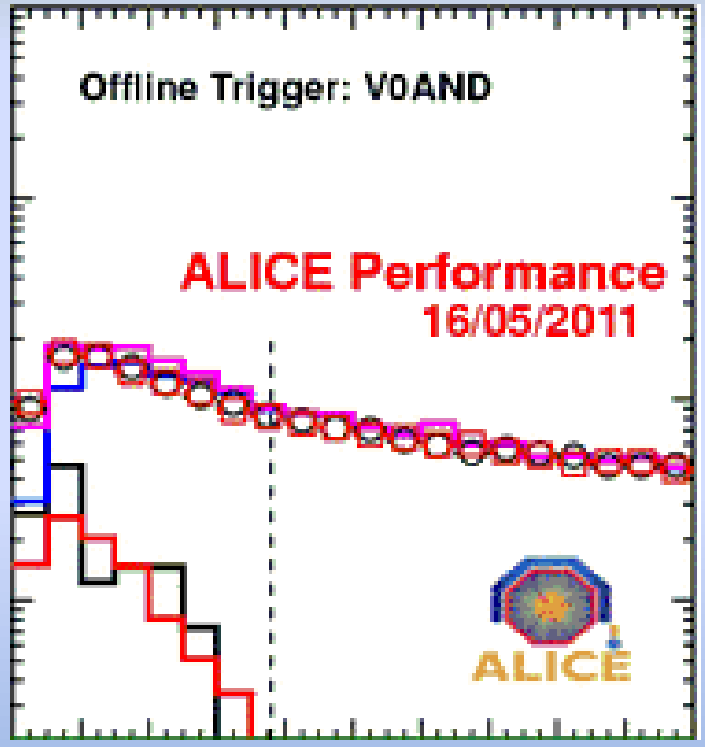


Excess over Hijing observed at low amplitudes <-> very Peripheral Collisions

Alberica Toia, ALICE Collaboration, Quark Matter 2011

Ultra-Peripheral Collisions – Photonuclear Interactions





- The model seems to reproduce the features of ALICE data, at least qualitatively.
- Black histogram – StarLight +DPMJET single; Red histogram – Starlight + DPMJET double.
- Blue histogram – Hijing; Pink histogram – total.