Ultra-peripheral Pb+Pb collisions at the LHC

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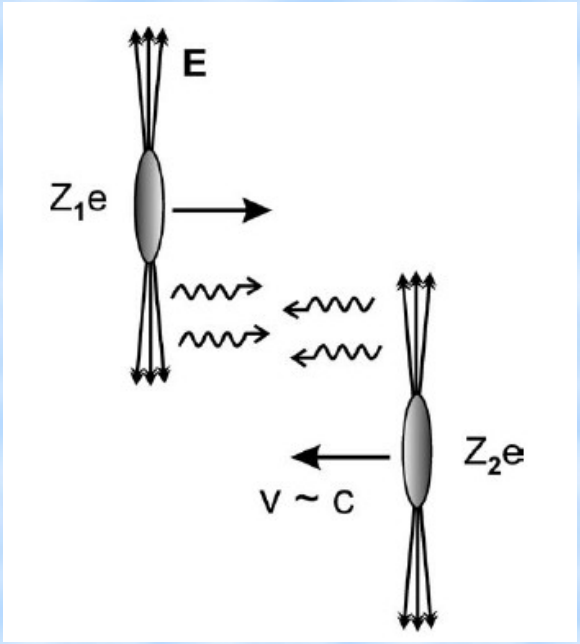
What are Ultra-peripheral Collisions?

Collisions between nuclei and protons with impact parameters larger than the sum of the radii.

Strong interactions suppressed. Proceeds via the electromagnetic field.



The EM fields correspond to an equivalent flux of photons (Fermi/ Weizsäcker-Williams).

Two-photon and photonuclear/photon-proton interactions can be studied at unprecedented energies in UPC at the LHC.

Two “recent” review articles: C.A. Bertulani, S.R. Klein, J. Nystrand, Ann. Rev. Nucl. Part. Sci. 55 (2005) 271; A.J. Baltz et al., Phys. Rept. 458 (2008) 1.

Perspectives on Ultra-peripheral Collisions

- What was expected?

- What has been done?

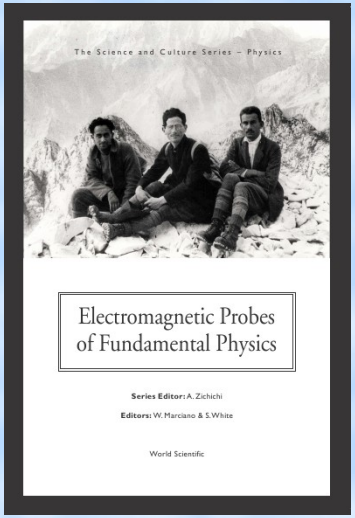
- What was not expected?

- What can be done in the future?

Outlook from a mediterranean island 12 years ago

Workshop on Electromagnetic Probes of Fundamental Physics, Erice, Sicily, 16 – 21 October 2001.

Results summarized in “Hot topics in ultra-peripheral ion collisions”, http://arxiv.org/abs/hep-ex/0201034.



Proceedings edited by S. White and W. Marciano.

Some brave souls wading out into the unknown sea of ultra-peripheral collisions...

Outlook from a mediterranean island 12 years ago

What is the most interesting physics? (from “Hot topics in ultra-peripheral ion collisions”, http://arxiv.org/abs/hep-ex/0201034):

1. Gluon shadowing in Nuclei.

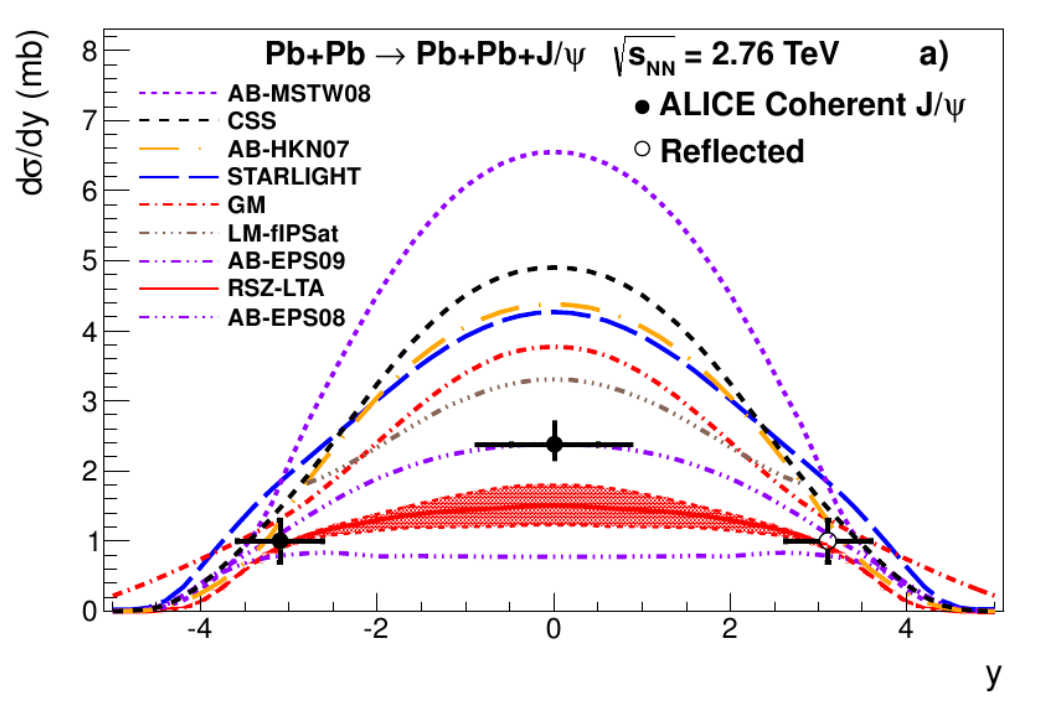
2. Pomeron Couplings to Nuclei.

3. Interferometry with Short-Lived Particles.

4. Searches for New Physics:
   - Triple gauge coupling γWW from $\gamma\gamma\rightarrow$WW interactions.
   - Two-photon production of Higgs and Z-pairs.
   - Search for glueballs and other exotic bound states.

1. Gluon shadowing in Nuclei

Measured by ALICE through exclusive production of J/ψ. (See the previous talk by Jaroslav Adam).



ALICE Collaboration

Phys. Lett. B 718 (2013) 1273

and

arxiv:1305.1467

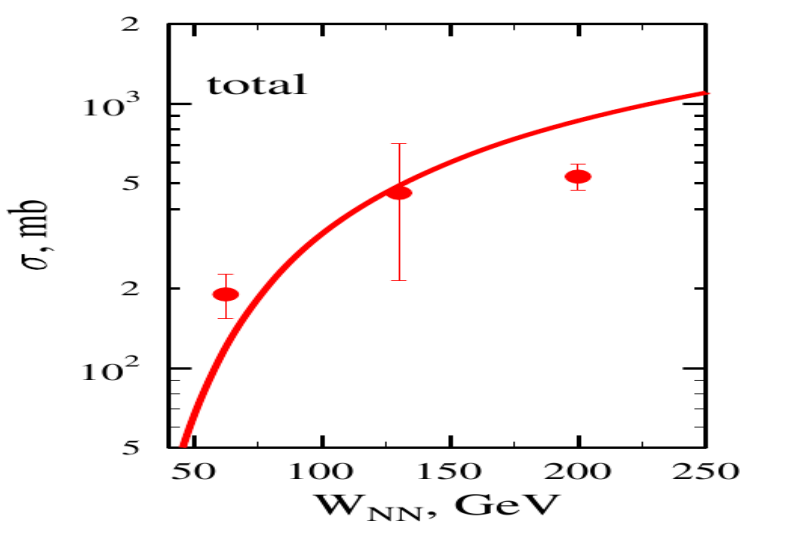
Big uncertainties in the nuclear gluon distribution until now.

This result from ALICE shows that the distribution in the $x \approx 10^{-2} - 10^{-3}$ range is consistent with the EPS09 parameterization.

2. Pomeron Couplings to Nuclei

Exclusive (light) vector meson photoproduction, γ+A $\rightarrow$ V+A.

Exclusive ρ^0 production measured by STAR at $\sqrt{s_{NN}}$ = 62.4, 130, and 200 GeV [STAR Collaboration, PRL 89(2002)272302, PRC 77(2008)034910, PRC 85(2012)014910]



A Glauber model calculation (Rebyakova, Strikman, Zhalov, PLB 710 (2012) 647) overpredicts the measured cross section at 200 GeV by nearly a factor of 2.

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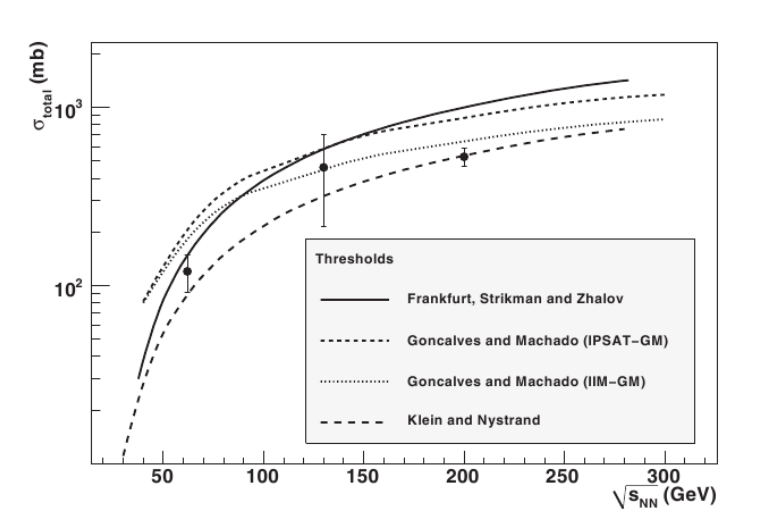
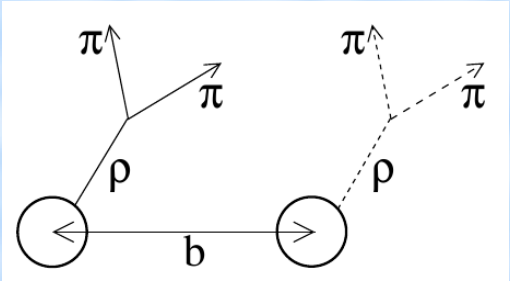


The cross section relatively well reproduced by STARLIGHT MC (based on Klein, Nystrand, PRC 60 (1999) 014903), which ignores the elastic part of the total cross section.

No measurement from the LHC yet.

3. Interferometry with Short-Lived Particles

A vector meson can be produced on either nucleus in a A+A → A+A+V reaction.



The cross section is the sum of the two possibilities

$$\frac{d\sigma}{dydp_T} = \int_{b>2R} k_1 \frac{dN}{dk_1 d^2b}\,\sigma(\gamma A_2)\, f_{1,2}(p_T) \;+\; k_2 \frac{dN}{dk_2 d^2b}\,\sigma(\gamma A_1)\, f_{2,1}(p_T)\; d^2\vec{b}\,.$$

This can be written as the sum of two amplitudes squared

$$\frac{d\sigma}{dydp_T} = \int_{b>2R} \left(|A_1|^2 + |A_2|^2\right) d^2\vec{b}\,,$$

But when p_T << 1/b, interference becomes important and one must add the amplitudes:

$$\frac{d\sigma}{dydp_T} = \int_{b>2R} |A_1 + A_2|^2\, d^2\vec{b}\,.$$

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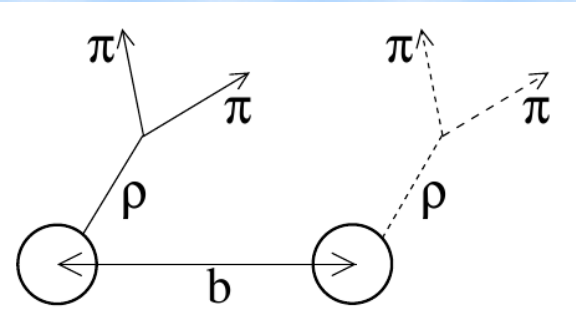
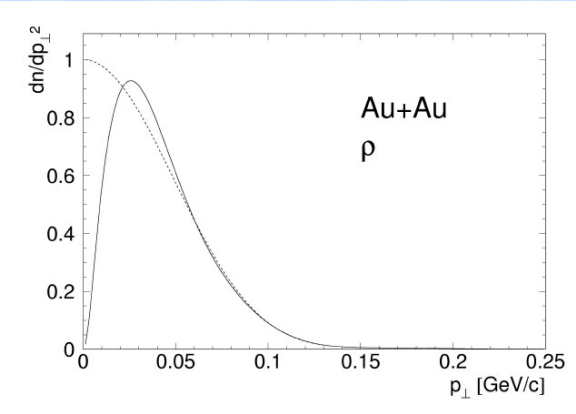




S.R. Klein, J. Nystrand, Phys. Rev. Lett. 84 (2000) 2330; K. Hencken, G. Baur, D. Trautmann, PRL 97 (2006) 012303.

Median separation between nuclei for light vector meson production typically ≈ 50 fm at RHIC.

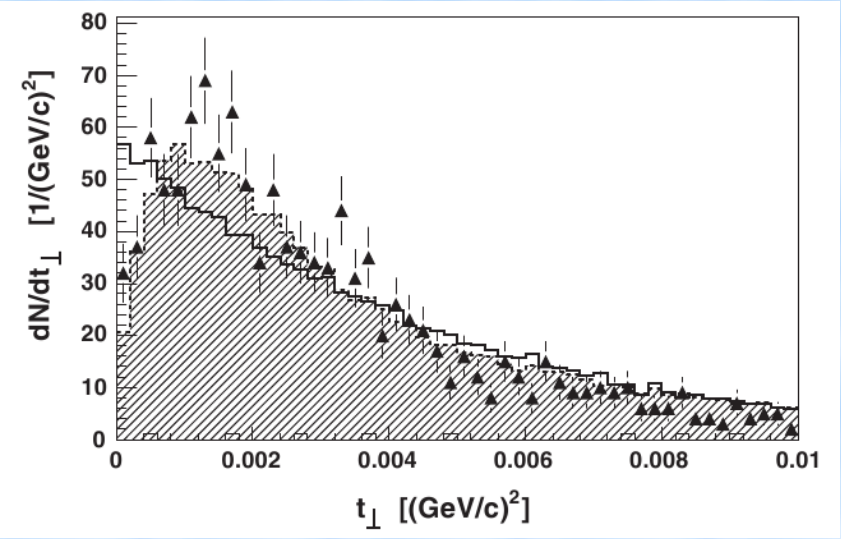
For p_T < ≈1/50 fm ≈ 5 MeV/c, the interference will suppress the yield and modify the p_T spectrum.

But the life-time of the ρ^0 is only 1 fm/c, so it will have decayed long before information is propagated from one source two the other.

One thus has “interferometry with short-lived particles”.

3. Interferometry with Short-Lived Particles

Transverse momentum spectrum of exclusive ρ^0 studied in detail by STAR at RHIC (Phys. Rev. Lett. 102 (2009) 112301)



Solid histogram – no interference

Dashed histogram – with interference

Parameterize the p_T spectrum according to

$$\frac{dN}{dt} = A\exp(-kt)[1 + c(R(t) - 1)],$$

C = 0 – no interference

C = 1 – full interference

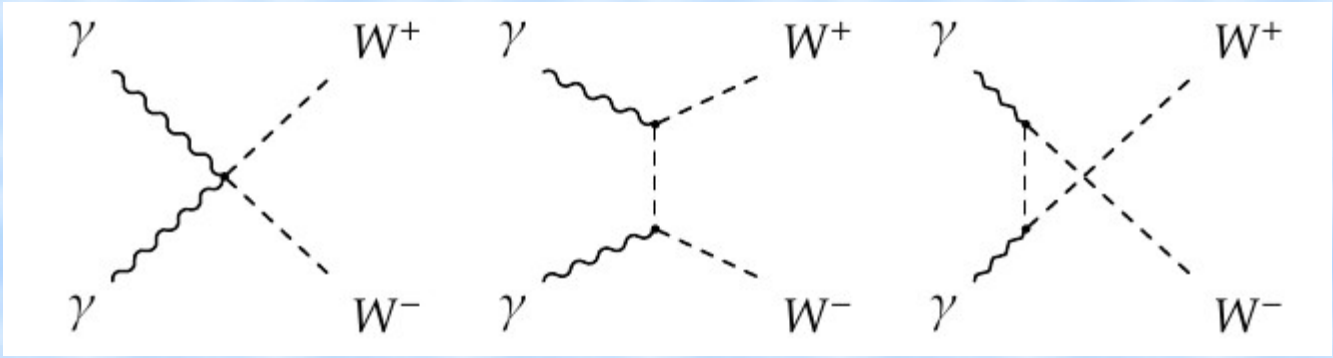
Obtain the result C = 0.87 ± 0.05(stat.) ± 0.08(syst.), consistent with full interference.

No measurement from the LHC yet.

4. Searches for New Physics

- Triple gauge coupling γWW from $\gamma\gamma\rightarrow$WW interactions.

LO diagrams for $\gamma\gamma\rightarrow$WW



Involves triple γWW and quartic $\gamma\gamma$WW couplings

The *triple* couplings are better constrained from other measurements, but the *quartic* couplings are unique to two-photon interactions.

Recent first observation of $\gamma\gamma\rightarrow$WW from CMS, arxiv:1305.5596. Finds 2 signal events to be compared with the SM prediction 2.2 $\pm$ 0.4 events. Sets best limits so far on anomalous $a^{W}_{0,C}$ couplings.

Recent constraints also from D0, Tevatron (observes no $\gamma\gamma\rightarrow$WW events!), arxiv:1305.1258.

Outlook from a mediterranean island 12 years ago

1. Gluon shadowing in Nuclei. ✓

2. Pomeron Couplings to Nuclei. ✓

3. Interferometry with Short-Lived Particles. ✓

4. Searches for New Physics:
   - Triple gauge coupling γWW from $\gamma\gamma \to$WW interactions. ✓
   - Two-photon production of Higgs and Z-pairs
   - Search for glueballs and other exotic bound states

But note that ✓ does not mean that the topic has been exhausted!

What was not expected?

(A personal and perhaps biased view)

"Ultra-peripheral collisions" can be studied also in pp collisions, for the certain final states. In addition to $\gamma\gamma \rightarrow WW$, results on

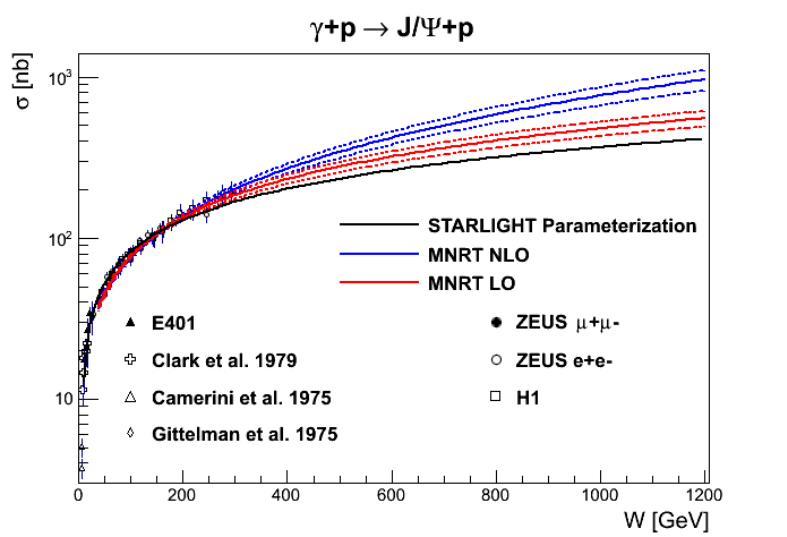
- Exclusive vector meson production, $\gamma + p \rightarrow J/\psi + p$. Predictions (S.R. Klein, J. Nystrand PRL 92 (2004) 142003) followed by data from CDF (PRL 102 (2009) 242001) and LHCb (J. Phys. G 40 (2013) 045001).

- Two-photon production of di-lepton pairs from CDF (PRL 102 (2009) 222002) and CMS (JHEP 01 (2012) 052).

Proton-Nucleus collisions provide an excellent opportunity to study certain γ+p interactions. Unlike in pp or AA collisions, the photon emitter (nucleus) and photon target (proton) can be separated.

Exclusive vector meson production in p+Pb collisions at the LHC

Exclusive J/ψ photoproduction, γ+p → J/ψ+p, measured at HERA up to center of mass energy W = 300 GeV.



MNRT – Martin, Nockles, Ryskin, Teubner, PLB 662 (2008) 252, arxiv:1307.7099.

Also calculations in b-Sat model (Graeme Watt et al.), arxiv:1206.2913, 1211.4831.

In p+Pb, W given by rapidity of the J/ψ.

Examples: y = 4.0 (ALICE muon spectrometer) ==> W = 1200 GeV
y = 5 (LHCb) ==> W = 1900 GeV

A factor 4-6 higher than at HERA.

LHCb result in pp collisions (JPG 40 (2013) 045001) covers these energy ranges, but extracting $\sigma(\gamma$+p → J/ψ+p) ambiguous because of symmetry between photon target and emitter.

What can be done in the future?

1) Exclusive vector mesons:
   Higher collision energy; new species ψ', $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$; extended acceptance ==> Better constraints on gluon distribution, wider range of x and scale Q^2 ($\sim M_V^2$) probed.

2) Electroweak final states:
   $\gamma\gamma \rightarrow WW$, $\gamma\gamma \rightarrow \gamma\gamma$, $\gamma\gamma \rightarrow ZZ$ $\gamma\gamma \rightarrow$Higgs

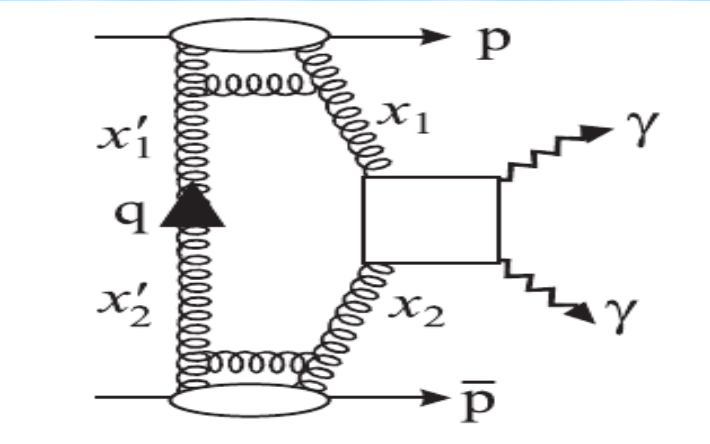
3) Inclusive photoproduction of heavy quarks and jets.
   Photoproduction of ccbar through photo-gluon fusion, $\sigma \approx 1$ b in Pb+Pb collisions at the LHC (Klein, Nystrand, Vogt, Phys. Rev. C 66 (2002) 044906).
   Photonuclear jet or dijet production, γ+parton $\rightarrow$ jet or dijet (Strikman, Vogt, White, PRL 96 (2006) 082001).

4) Meson spectroscopy (e.g. glueballs, excited vector meson states), high precision measurements of $\gamma\gamma \rightarrow$e+e- to study QED with strong fields, using Roman pots to tag the outgoing protons might improve resolution and enable new final states to be studied ...

Exclusive production in pp vs. AA

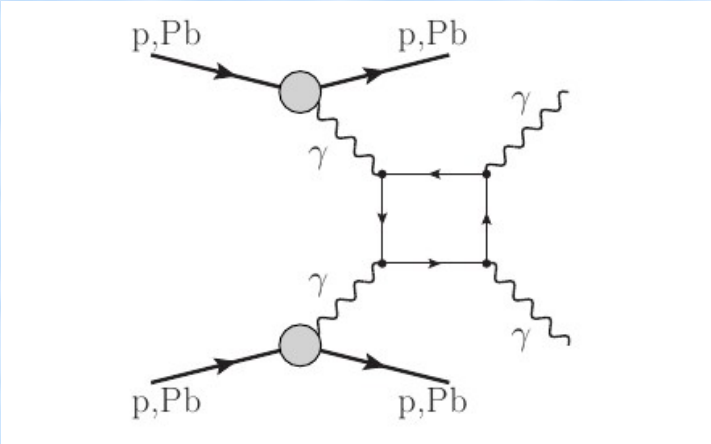
Different production mechanisms may dominate. Consider exclusive $\gamma\gamma$ (or Higgs) production:

p-p



V. A. Khoze, A.D. Martin, M.G. Ryskin, W.J. Stirling, Eur. Phys. J C 38 (2005) 475.

Pb-Pb



D. d'Enterria, G.G. Silveira, PRL 111 (2013) 080405.

In p-p collisions, 3 (or more) gluon exchange dominate, whereas for heavy-ion collisions, $\gamma\gamma \rightarrow \gamma\gamma$ dominate.

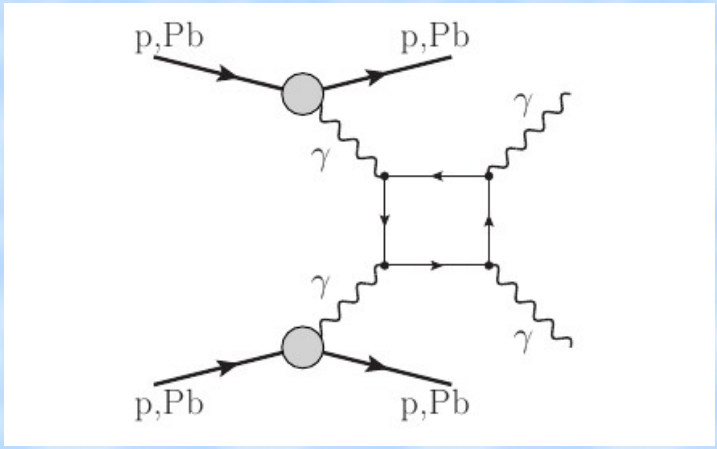
Exclusive $\gamma\gamma$ production

Light-by-light scattering, $\gamma\gamma \rightarrow \gamma\gamma$, has so far not been directly observed.

The reaction is of fundamental interest as deviations from SM prediction may be caused by anomalous gauge couplings, SUSY particle contributions in the loop etc.

According to the recent paper (d'Enterria, Silveira PRL 111 (2013) 080405), $\approx$200 signal events with $m_{inv} > 5$ GeV can be expected in the Atlas/CMS acceptance in a 10 nb^{-1} Pb-Pb run.

==> Pb-Pb collisions at the LHC might thus provide the first opportunity to study this process!



Summary

- Particles are produced in ultra-peripheral collisions at hadron colliders. The feasibility to study them with the existing detectors at RHIC, the Tevatron, and the LHC has been demonstrated.

- Many of the topics proposed as most interesting 12 years ago have actually been studied.

- Many topics remain as the LHC moves into the high energy/high luminosity phase.