A historical introduction to ultra-peripheral collisions

Forward QCD: open questions and future directions

Lawrence, Kansas, 23-24 May 2022

Joakim Nystrand
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Outline

- What are ultra-peripheral collisions.

- Early (theoretical) developments in the 1930's.

- Ultra-relativistic heavy-ion collisions.

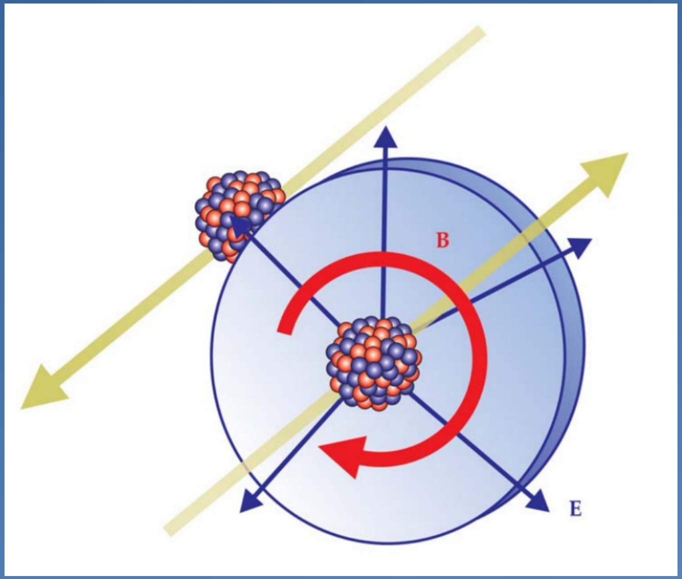
- Exclusive Vector Meson production.

- Two-photon interactions.

What are Ultra-peripheral Collisions?

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

Strong interactions suppressed. Interactions instead mediated by the electromagnetic field.

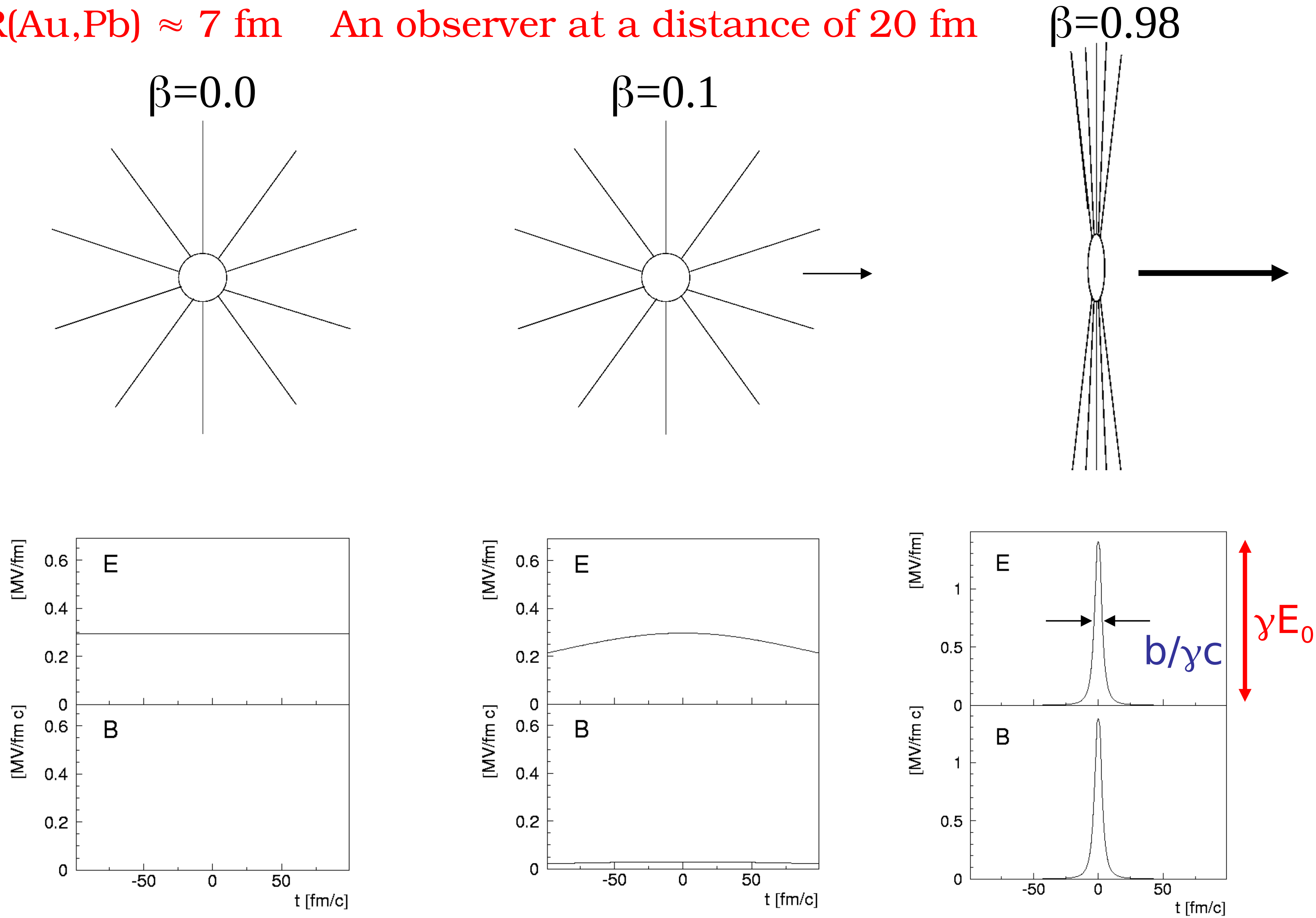


The EM fields correspond to an equivalent flux of photons (Fermi/ Weizsäcker-Williams).

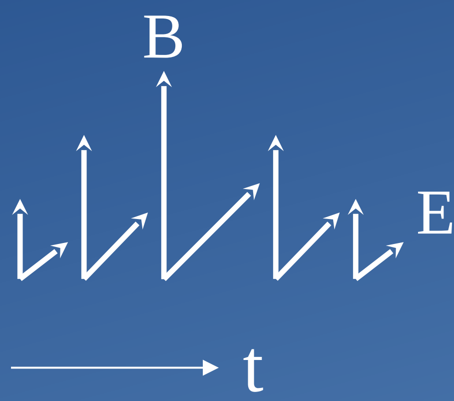
Two-photon and photonuclear/photon-proton interactions can be studied at unprecedented energies in UPC at the LHC.

Electromagnetic fields of a moving charged particle

R(Au,Pb) ≈ 7 fm   An observer at a distance of 20 fm

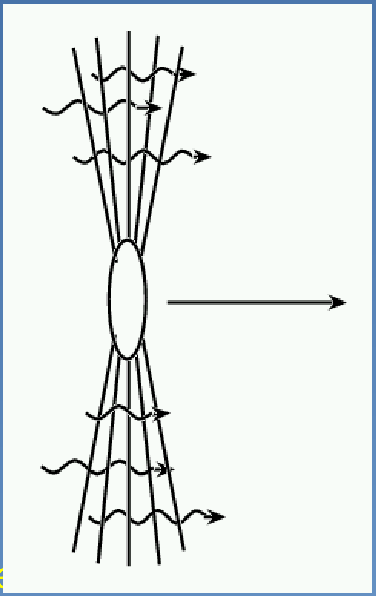


Electromagnetic fields of a moving charged particle



1) $|E| \approx |B|$ 2) $(E \perp B)$ 3) $\Delta t \sim b/\gamma c$

Fermi 1924: The effect of the field is equivalent to a flux of of photons with a continous energy spectrum. (hep-th/0205086)



Pulse width $b/\gamma c$ $\leftrightarrow$ the spectrum contains photons w/ $\omega < \gamma c/b$

Quantum Mechanical derivation 1934 by Weizsäcker,Williams. $\Rightarrow$ *Weizsäcker-Williams method*

We can calculate $n(\omega)$ through a Fourier transform.

Early developmens in the 1930's

The origins go back to the Dirac equation, the discovery of the positron, and the rudimentary quantum field theories of the 1930’s.

1928: Publication of the Dirac equation.

1932: Discovery of the positron (C.D. Anderson), “predicted” by the Dirac equation.

1934: Calculation of the cross section $\gamma\gamma \rightarrow$ e+e- (Breit-Wheeler).

1933-1937: Calculation of the cross section for two-photon production of e^+e^- pairs in nucleus-nucleus collisions (Furry, Carlson, Landau, Lifshitz, Bhabha, Racah, Nishina,Tomonaga).

Early developmens in the 1930's

From the paper by W.H. Furry, J.F. Carlson, Phys. Rev. 44 (1933) 237:

The experimental discovery of the positive electron makes possible, as has recently been observed by Oppenheirner and Plesset, a consistent development of Dirac's theory of the electron, in which the appearance of pairs (electron and anti-electron) plays an important part. *It appears that, in the experimental production of the pairs, the Coulomb fields, especially those of nuclei, are most important.*

On The Production of Positive Electrons by Electrons

The experimental discovery of the positive electron makes possible, as has recently been observed by Oppenheimer and Plesset,[1] a consistent development of Dirac's theory of the electron, in which the appearance of pairs (electron and anti-electron) plays an important part. It appears that, in the experimental production of the pairs, the Coulomb fields, especially those of nuclei, are most important. In this case the theory shows that radiation of energy greater than $2mc^2$ is required for their production. Oppenheimer and Plesset have made a preliminary study of the production of pairs by γ-rays; we have carried through the analogous work for their production by high energy electrons (and positives). For γ-rays it appears, both from OP and from the experiments of Anderson, that the production of pairs becomes increasingly important as the energy of the γ-rays is increased; we have wanted to see whether this

[1] J. R. Oppenheimer and M. S. Plesset, Phys. Rev. **44**, 53 (1933) (hereafter referred to as OP).

Early developmens in the 1930's

Also the process $\gamma\gamma\rightarrow\gamma\gamma$ was discussed during this time

First calculation: H. Euler and B. Kockel, Naturwiss. 23 (1935) 246.
Also, early calculation by Euler and Heisenberg, Z. Phys. 98 (1935) 706:

Folgerungen aus der Diracschen Theorie des Positrons.

Von **W. Heisenberg** und **H. Euler** in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 22. Dezember 1935.)

Heisenberg writes in his autobiography “Der Teil und das Ganze” (1969), recalling his conversation with Euler on this topic

“obwohl der experimentelle Nachweis hier nicht so direkt geführt werden konnte, besteht heute wohl kein Zweifel mehr daran, dass es die von Euler und Kockel behauptete Streuung wirklich gibt” (even if so far no direct experimental proof has been found, there is today no doubt that the scattering claimed by Euler and Kockel actually exists).

Early developmens in the 1930's

Also the idea to study photonuclear interactions is from these times

Charged particles are able to excite nuclei without penetrating into the nucleus by means of the action of the their electric field upon the nucleus when they pass nearby.

V.F. Weisskopf, Physical Review, 1938.

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This was the basis for several nuclear structure experiments in the 1950's and 1960's, where one bombarded a target nucleus with another nucleus with an energy below the Coulomb barrier.

But for a long time, the energy of hadronic/nuclear beams were not high enough to investigate particle production.

⇨ The energy frontier of electromagnetic (and weak) interactions used to be with lepton beams.

The first hadron collider

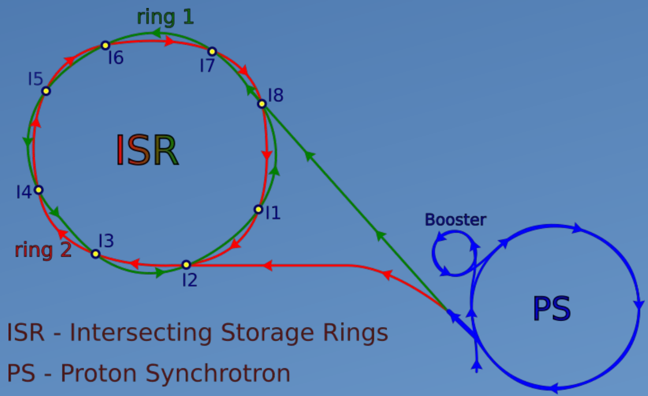
First obeservation of particle production in an ultra-peripheral collision between protons:

$p+p \rightarrow p+p+\mu^{+}\mu^{-}$

at the ISR in 1980 (by the CERN-Harvard-LAPP-MIT-Pisa Collaboration, CERN-EP/80-82, a conference proceeding, never published).

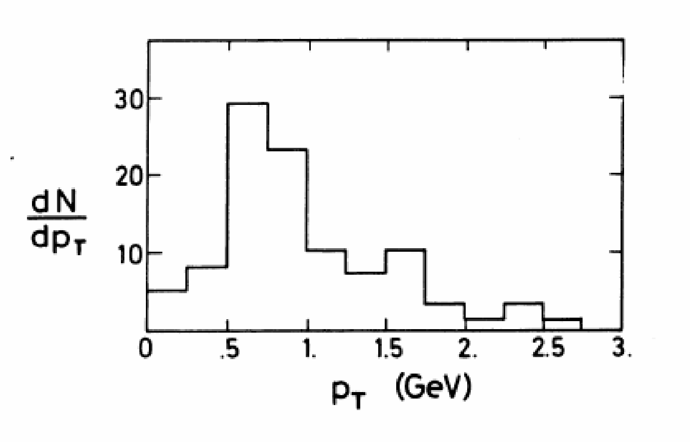
ISR: Intersecting Storage Ring – A collider at CERN for protons and α-particles, in operation 1971 – 1984, maximu energy $\sqrt{s}$ = 62 GeV.

The world's first hadron collider.

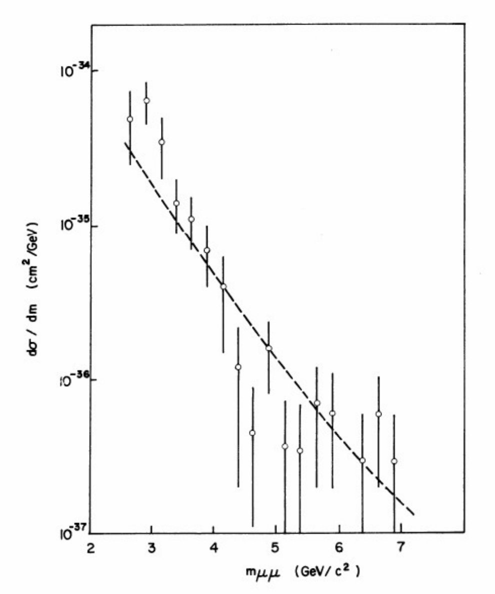


The first hadron collider

From CERN-Harvard-LAPP-MIT-Pisa Collaboration, CERN-EP/80-82:



Pair transverse momentum distribution (this is pp).



Invariant mass distribution.

CONCLUSION

We have given evidence for the production of dimuons which are created without associated hadrons in a large domain of rapidity around the central region. The topology of these events, their low transverse momentum, and the magnitude of the corresponding cross-section can be most naturally interpreted by the 2γ process. This effect which is still a small background at the ISR, compared with the dominant Drell-Yan mechanism, grows with energy and could trigger enough interest to be studied for itself, possibly at the $p\bar{p}$ collider, probably at the ISABELLE machine.

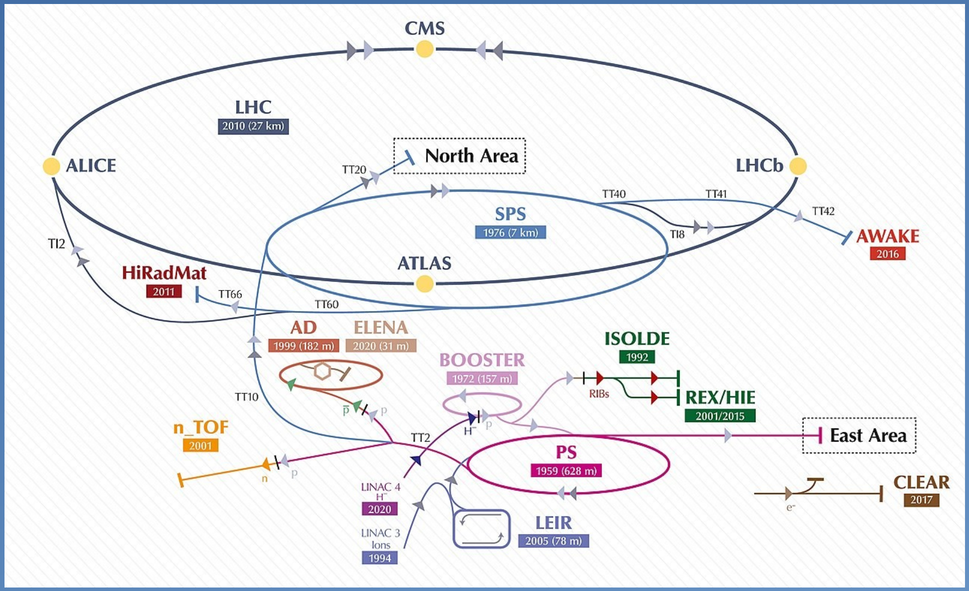
Ultra-relativistic heavy-ion collisions

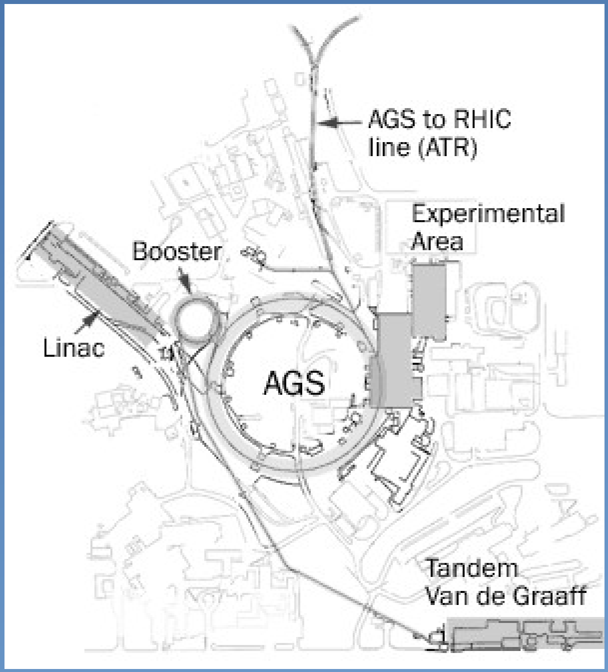
Start of the utlra-relativistic heavy-ion program in 1986:

Acceleration of oxygen ions at the AGS and SPS (followed, respectively, by Au in 1992 and Pb in 1994).

AGS – The Alternating Gradien Synchroton at Brookhaven National Laboratory, fixed target experiment, √s = 4.9 GeV.

SPS – The Super Proton Synchrotron at CERN, fixed target experiments,√s = 17.4 GeV.





Ultra-relativistic heavy-ion collisions

Energy too low for any significant particle production in UPC. But two-photon proudction of e+e- pairs could, and was, studied resulting in a few paper.

AGS: A. Belkacem, N. Claytor, T. Dinneen, B. Feinberg, and H. Gould, Phys. Rev. A 58 (1998) 1253.

SPS: C. R. Vane, S. Datz, P. F. Dittner, H. F. Krause, C. Bottcher, M. Strayer, R. Schuch, H. Gao, and R. Hutton Phys. Rev. Lett. 69 (1992) 1911 S-beams at SPS
R. Baur et al. [CERES/NA45 Collaboration], Phys. Lett. B 332 (1994) 471.

Rather hard to compare to measurements at colliders because of the analysis methods and variables used. The general conclusion is “the results are in agreement with QED calculations”.

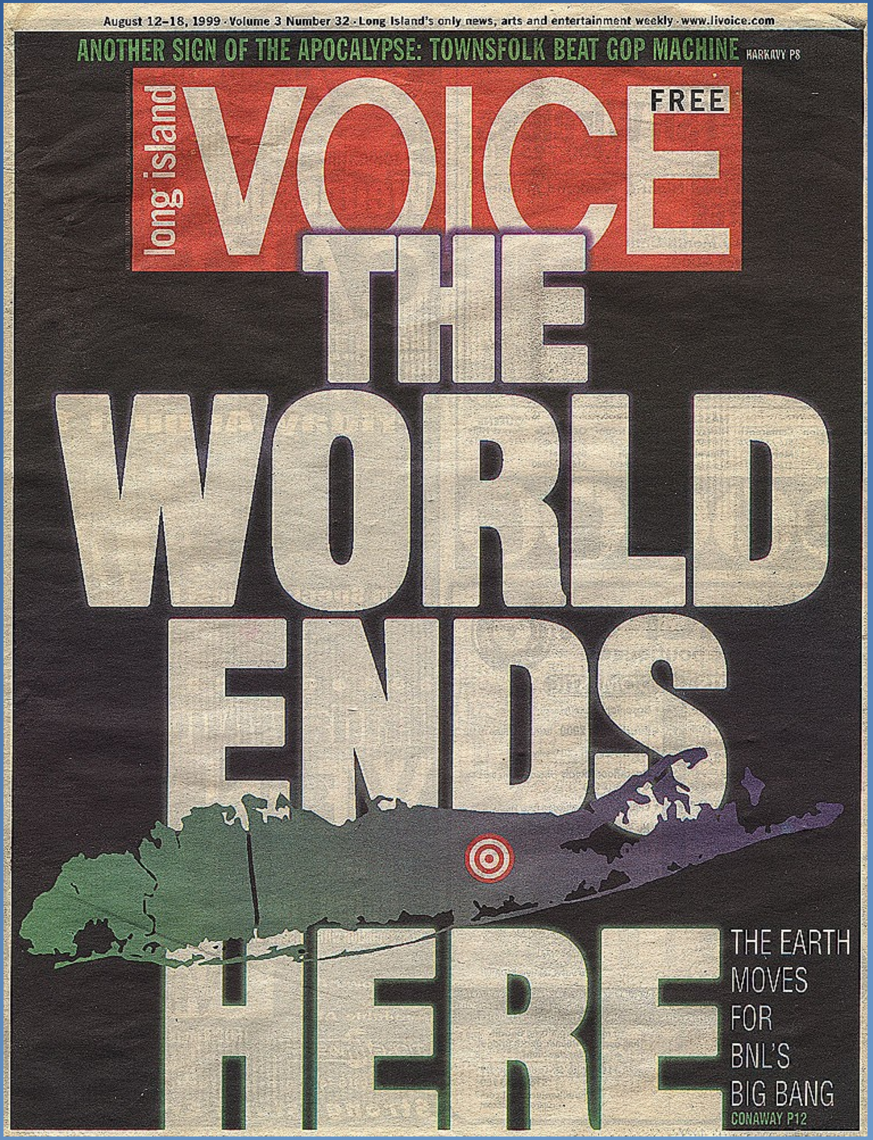
Ultra-relativistic heavy-ion collisions

Enter RHIC - The Relativistic Heavy Ion Collider at Brookhaven National Laboratory

Ultra-relativistic heavy-ion collisions

Enter RHIC - The Relativistic Heavy Ion Collider at Brookhaven National Laboratory

Initial scare that black holes would be produced and devour the earth!



Ultra-relativistic heavy-ion collisions

To maintain coherence, the maximum photon energy with a hadronic/nuclear beam will be $\sim\gamma\hbar c/R$

γ – Lorentz factor of the beam

R – Hadron/nuclear radius

At RHIC $\sqrt{s}$ = 200 GeV ==> $\gamma \approx 100$ with R = 7 fm ==> $E_{max} \approx 3$ GeV.

Final states with $m_{inv} \leq \sim 6$ GeV can be studied.

Ultra-relativistic heavy-ion collisions

So people began to do calculations. Also for heavy-ions at the LHC.

Volume 223, number 3,4 PHYSICS LETTERS B 15 June 1989

CAN ONE DETECT AN INTERMEDIATE-MASS HIGGS BOSON IN HEAVY-ION COLLISIONS?

M. DREES [a], J. ELLIS [a] and D. ZEPPENFELD [b]

[a] *CERN, CH-1211 Geneva 23, Switzerland*

[b] *Physics Department, University of Wisconsin, Madison, WI 53706, USA*

Received 1 March 1989

But how to calculate the photon spectrum?

First approaches used a form factor

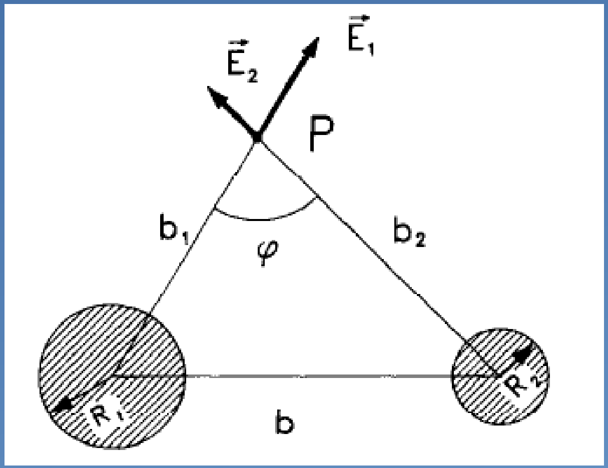
$$f_{\gamma|\mathrm{N}}(z) = \frac{\alpha}{\pi} \int_{z^2M^2}^{\infty} \mathrm{d}Q^2 \, \frac{|F(Q^2)|^2}{Q^2} \left(\frac{1}{z} - \frac{M^2}{Q^2} z \right), \qquad (4)$$

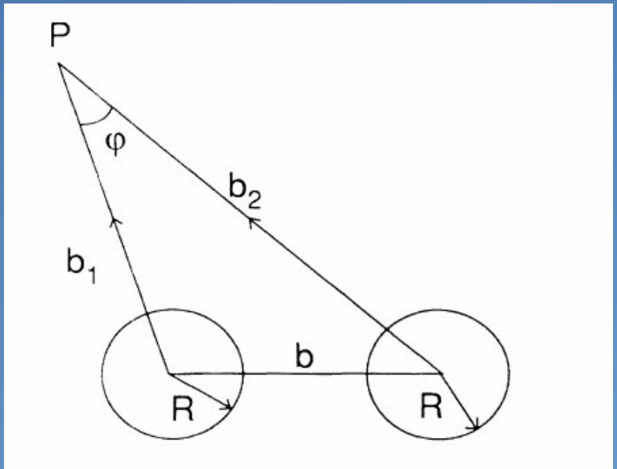
Ultra-relativistic heavy-ion collisions

But to ensure only photon-induced interactions, the nuclei can't interact hadronically. Must require impact parameter b > 2R.

==> Two papers by Cahn&Jackson (PRD 42 (1990) 3690) and Baur&Ferreira Filho (NPA 518 (1990) 786)

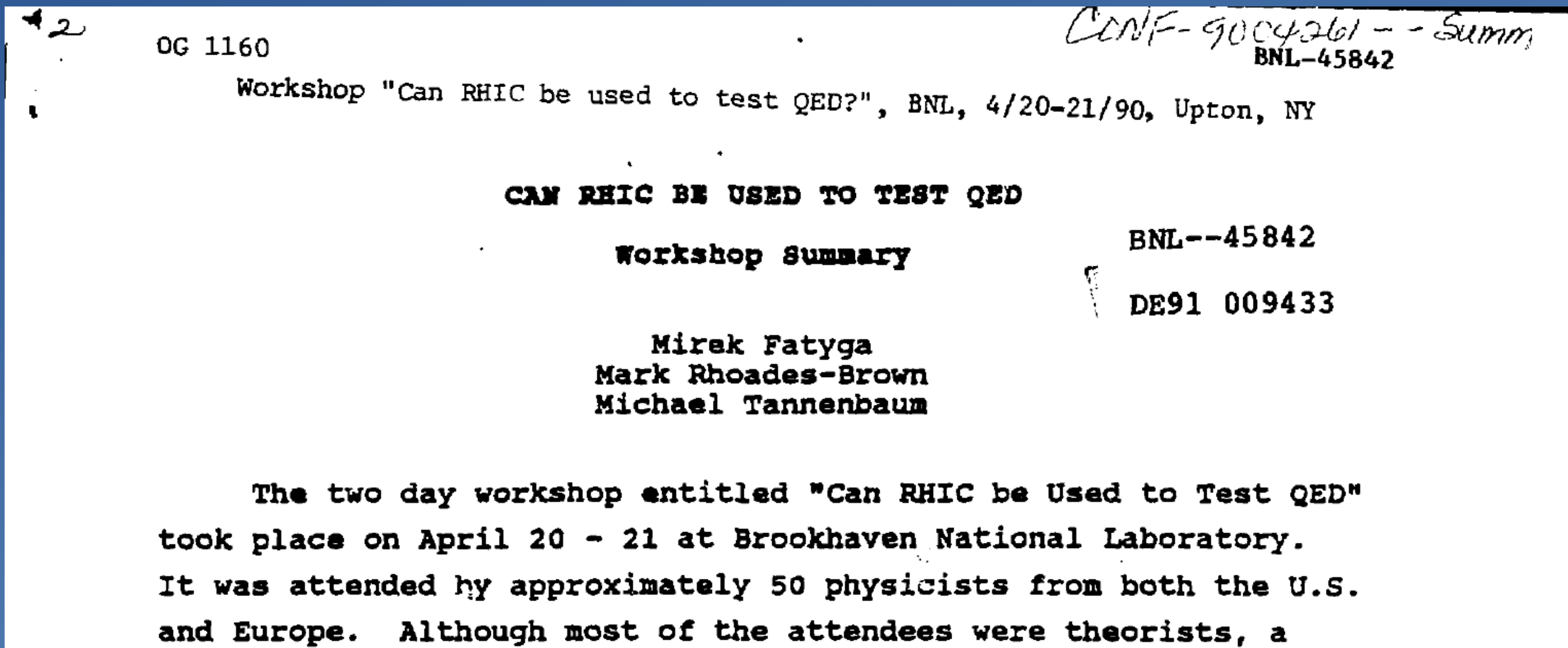
Do the calculations in impact parameter space, use the Weizsäcker-Williams photon fluxes as they can be found in the text book of Jackson!





Ultra-relativistic heavy-ion collisions

There was also a workshop at BNL the same year ”Can RHIC be Used to Test QED”



OG 1160 CONF-9004261--Summ BNL–45842

Workshop "Can RHIC be used to test QED?", BNL, 4/20-21/90, Upton, NY

CAN RHIC BE USED TO TEST QED

Workshop Summary

BNL--45842

DE91 009433

Mirek Fatyga
Mark Rhoades-Brown
Michael Tannenbaum

The two day workshop entitled "Can RHIC be Used to Test QED" took place on April 20 - 21 at Brookhaven National Laboratory. It was attended hy approximately 50 physicists from both the U.S. and Europe. Although most of the attendees were theorists, a

- $\gamma\gamma \rightarrow$ e+e- (violation of unitarity, strong field effects)

- $\gamma\gamma \rightarrow$ single (scalar, tensor) mesons.

- $\gamma\gamma \rightarrow$ Higgs (too low energy at RHIC)

Exclusive vector meson production

I came to Berkeley in April 1997 to work with Spencer (Klein) on ultra-peripheral collisions, mostly for Au+Au collisions at RHIC.

Most of the focus then was on two-photon production of mesons and meson spectroscopy.

Several papers written on $\gamma\gamma \rightarrow$ single meson (pseudoscalar and tensor mesons):

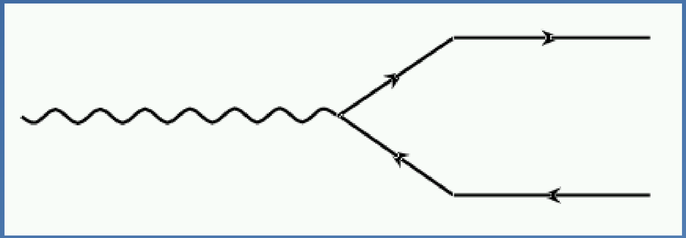
Baur, Ferreira Filho, Nucl. Phys. A 518 (1990) 786; Vidovic, Greiner, Soff, Phys. Rev. C 47 (1993) 2288; J. Phys. G 21 (1995) 545; Baur, Hencken, Trautmann, J. Phys. G 24 (1998) 1657; Chikin, Korotkih, Kryukov, Sarycheva, Pshenichnov, Bondorf, Michustin, Eur. Phys. J A 8 (2000) 537; Roldao, Natale, Phys. Rev C 61 (2000) 064907; Bertulani, Natale, Nucl. Phys. A 703 (2002) 861; Baltz, Gorbunov, Klein, Nystrand, Phys. Rev. C 80 (2009) 044902.

No measurements until now.

Exclusive vector meson production

But Spencer had the bright idea that one should also look into coherent photoproduction of vector mesons.

Vector Meson Dominance (VMD): The quantum numbers of the Photon $J^{PC} = 1^{--}$ are the same as for a Vector Meson ⇒ High probability for fluctuation to Vector Meson.



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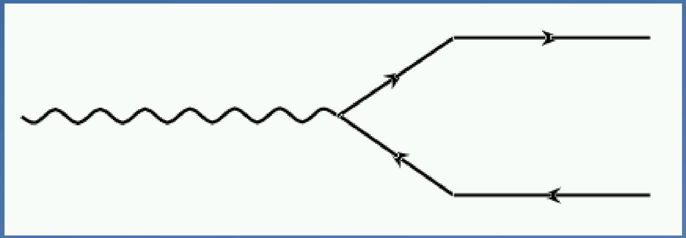

When the photon is in the vector meson state, it will interact strongly. The hadronic component can materialize if the virtual qq-pair is knocked on mass shell, e.g. through elastic nuclear scattering.

One can thus have photon-induced interactions of the type $\gamma + A \rightarrow V + A$

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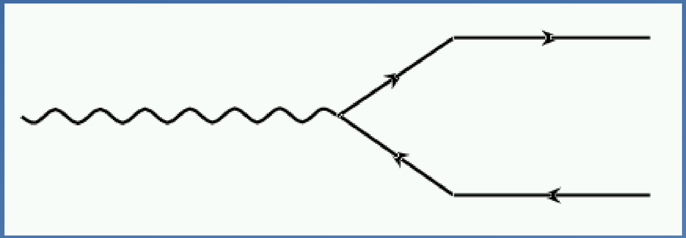

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One can thus have photon-induced interactions of the type $\gamma + A \rightarrow V + A$

There is a pretty good description of the VMD model in the book by Feynman on Photon-Hadron Interactions.

Exclusive vector meson production

The final state will be very similar to two-photon production of a single meson.

- When the vector meson couples coherently to the whole nucleus (elastic scattering), the transverse momentum of the produced state will be very low.

- The vector meson production is centered around midrapidity (many had thought that it would be produced in the far forward region).

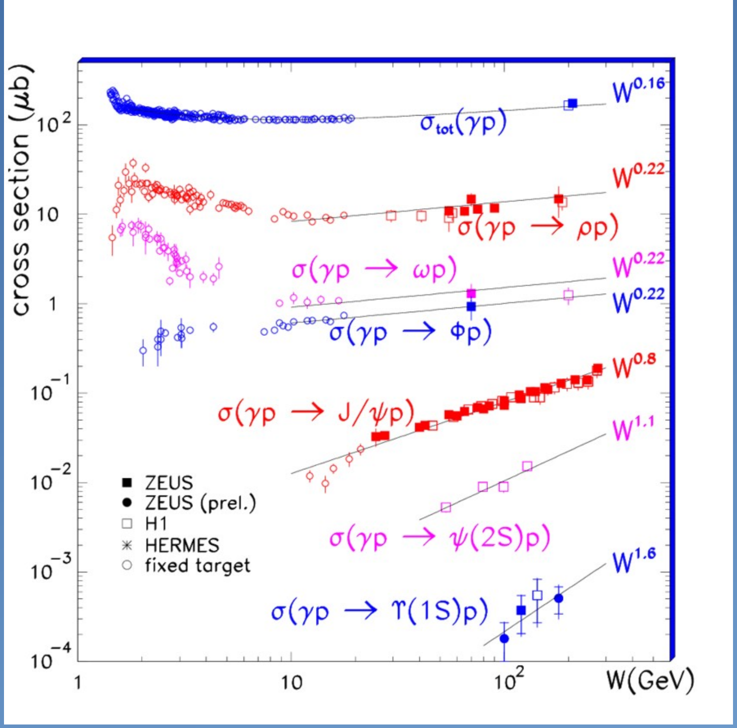
- The nuclei remain intact and there are rapidity gaps on either side of the produced state.

Exclusive vector meson production

These types of interactions had been studied in fixed target experiments with muon beams with proton targets and a few (usually light) nuclear targets.

They had also been rather extensively studied with proton targets at the electron-proton collider HERA.

Compilation of results on exclusive vector meson production on proton targets at HERA and in fixed target experiments.



Exclusive vector meson production

The idea was:

- Use these result and scale them from γ+proton to γ+nucleus using the Glauber model.

- Combine the photonuclear cross section with the appropriate photon flux at hardon colliders (a la Cahn,Jackson and Baur,Ferreira Filho).

- Thus obtain the cross sections/rates for exclusive vector meson production in Au+Au collisions at RHIC and Pb+Pb collisions at the LHC.

Exclusive vector meson production

PHYSICAL REVIEW C, VOLUME 60, 014903

Exclusive vector meson production in relativistic heavy ion collisions

Spencer R. Klein and Joakim Nystrand
Lawrence Berkeley National Laboratory, Berkeley, California 94720
(Received 8 February 1999; published 16 June 1999)

The production rates are large enough that heavy ion colliders could be used as vector meson factories. The ϕ and J/ψ production rates at LHC are comparable to those at existing or planned meson factories based on e^+e^- annihilation.

For mesons of comparable masses, the cross sections are a factor 100 higher for exclusive photonuclear production compared with two-photon production.

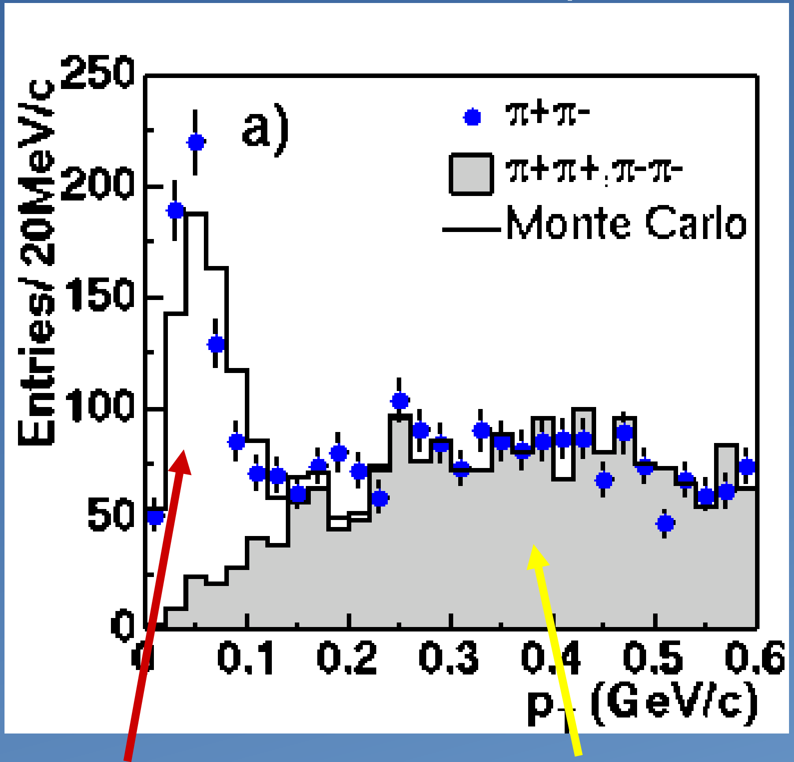
The first UPC result from RHIC

Exclusive ρ^0-production, Au+Au→Au+Au+ρ^0
(C. Adler et al. (STAR Collaboration) PRL 89(2002)272302).

Run 1 $\sqrt{s_{NN}}$ = 130 GeV –
Identification of coherent ρ^0.

"Two charged particles in an otherwise empty detector"

Clear signal for coherent production seen in p_T distribution.



Signal+background, unlike-sign pairs

background, like-sign pairs

Exclusive vector meson production

Some more results followed from RHIC, mostly from STAR:

- Two-photon production of lepton pairs.

- Interference between the production sites in exclusive vector meson production.

- Photonuclear production of J/ψ (PHENIX).

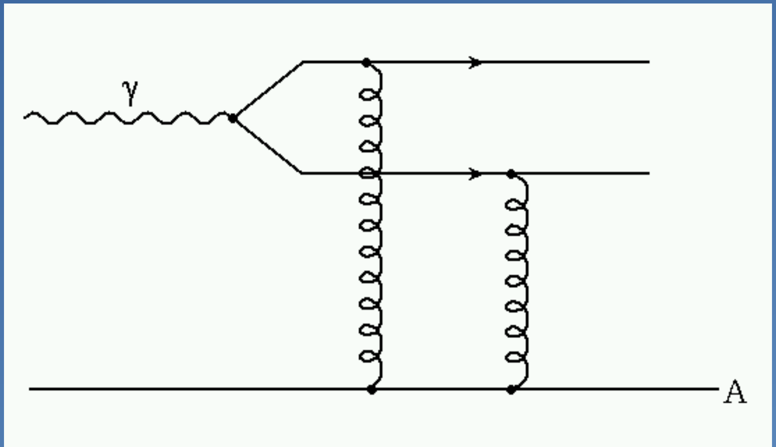
- Photoproduction associated with Coulomb breakup, exchange of multiple photons in a single event.

Exclusive vector meson production

Exclusive photoproduction of heavy vector mesons calculable from pQCD

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

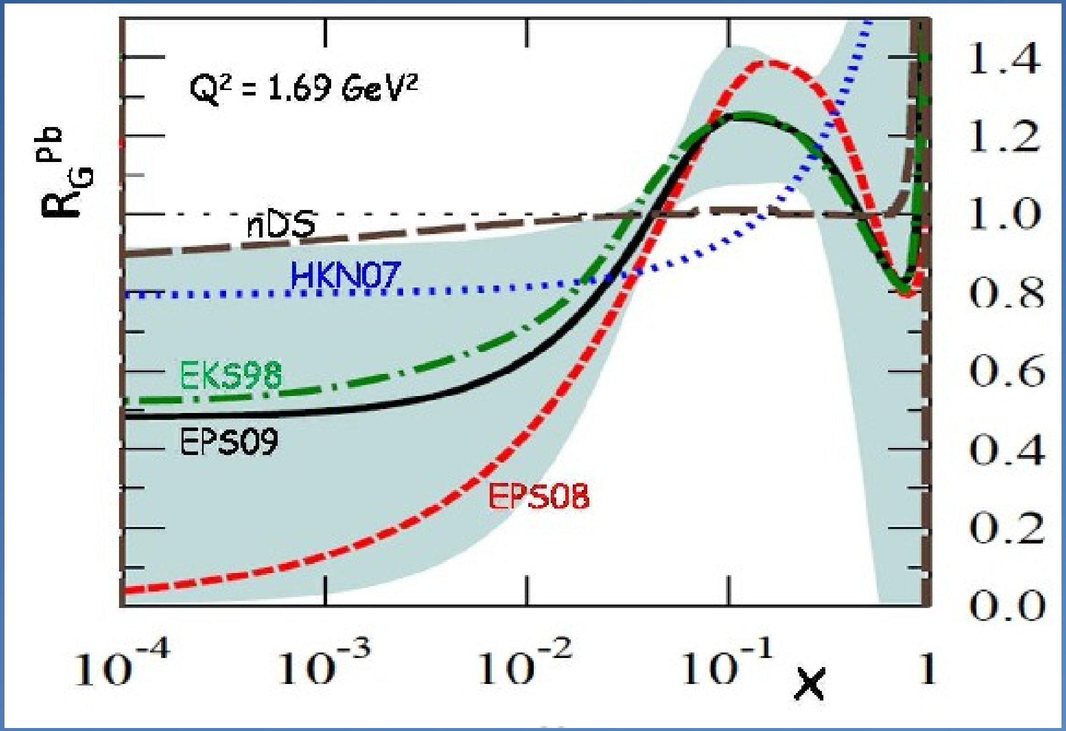
⇒ Sensitive probe of g(x), $[(g(x))^2]$



Two gluons can be exchanged without color transfer ↔ exchange of a Pomeron

Exclusive vector meson production

Big uncertainties in the nuclear gluon distribution. Different parameterizations available.



Measuring exclusive vector meson production at the LHC can Improve this for $Q^2 \sim M_V^2$ and $x \approx 10^{-2} – 10^{-4}$ (x range is rapidity dependent).

Exclusive vector meson production

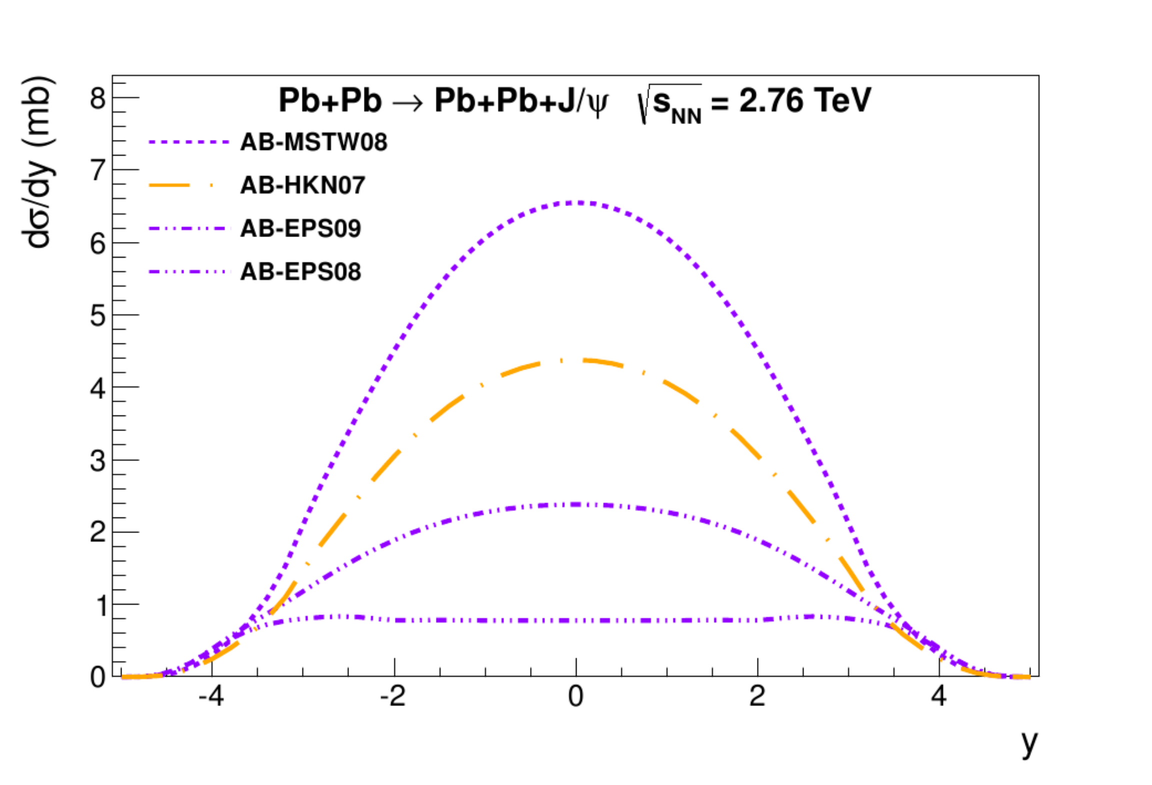
Calculation by Adeluyi and Bertulani assuming $\sigma \propto (g(x))^2$.
(Phys. Rev. C 85 (2012) 044904)

Normalizing to γp data from HERA.

MSTW08 – no nuclear effects (A^2 scaling)

HKN07, EPS09, EPS08 - different nuclear g(x).

Leads to very different cross sections for J/ψ, especially at midrapidity!



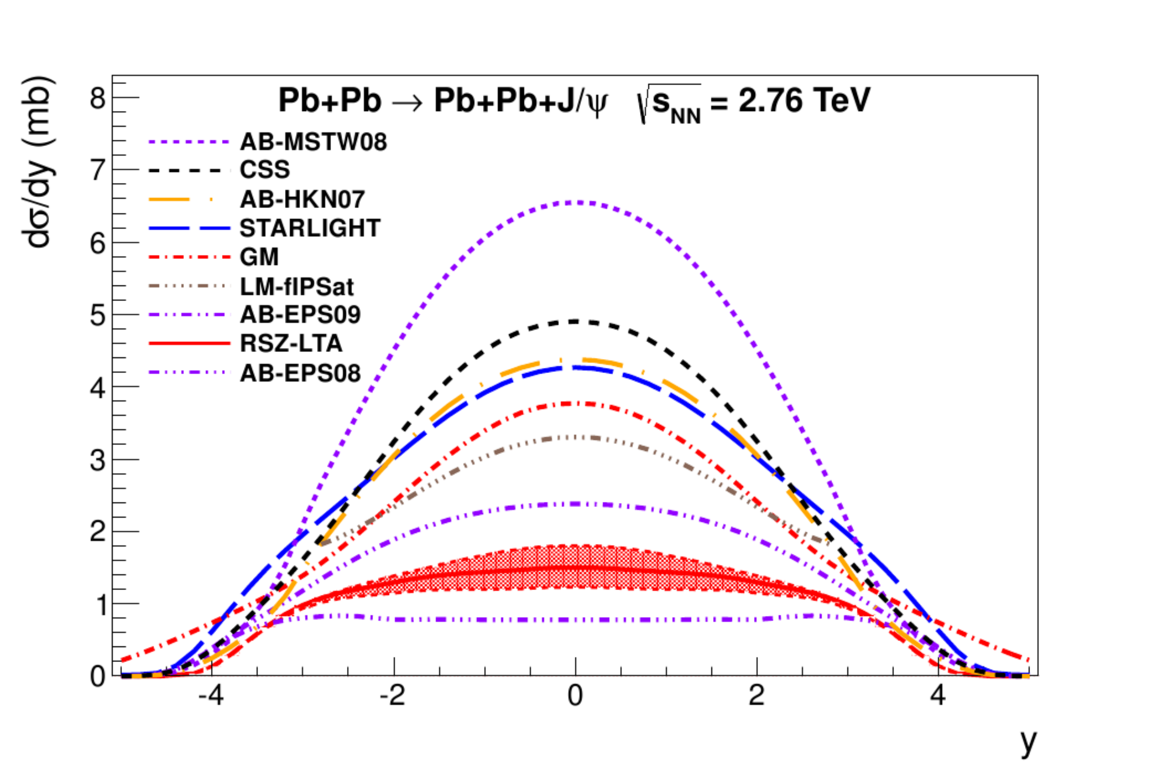
Exclusive vector meson production

Also other models on the market

Many based on the Color Dipole Model (CSS, GM, LM-fIPSat).

RSZ-LTA – calculates nuclear shadowing from Leading Twist Approximation

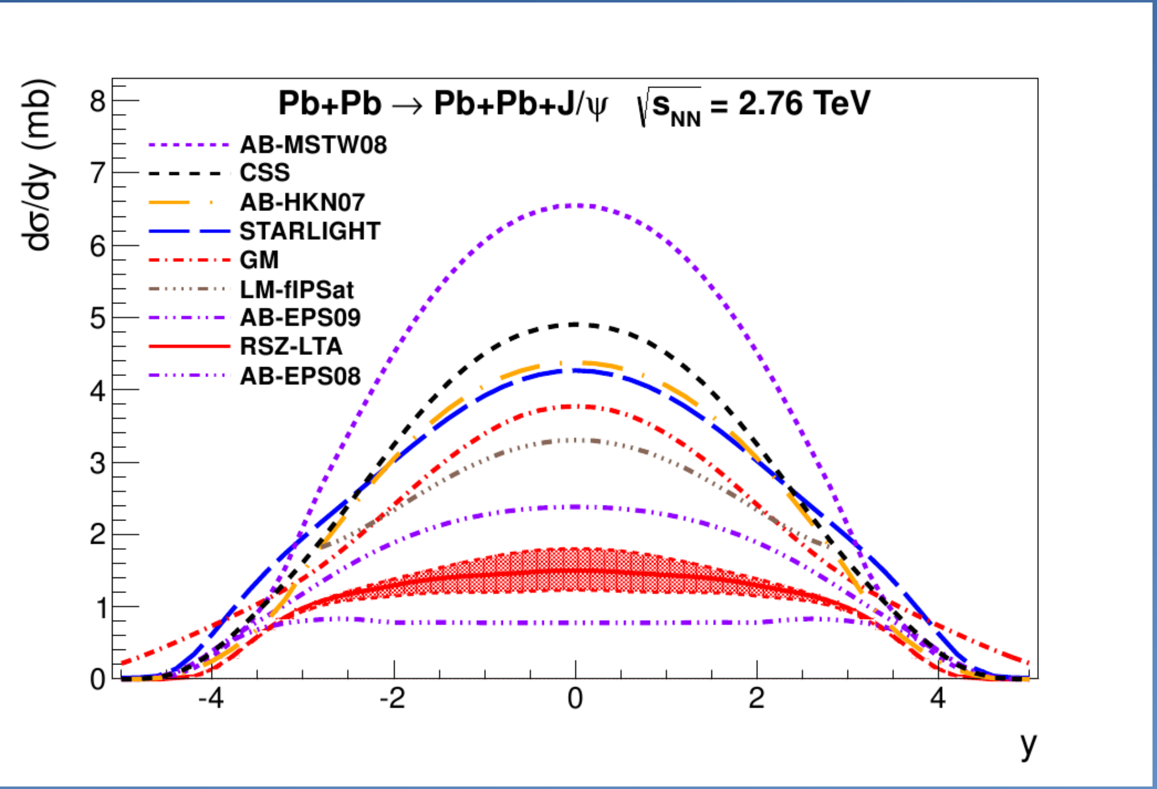
STARLIGHT – scales the measured γp cross section using a Glauber Model.



For exact references, see Eur. Phys. J 73 (2013) 2617.

Exclusive vector meson production

This was the situation before LHC.



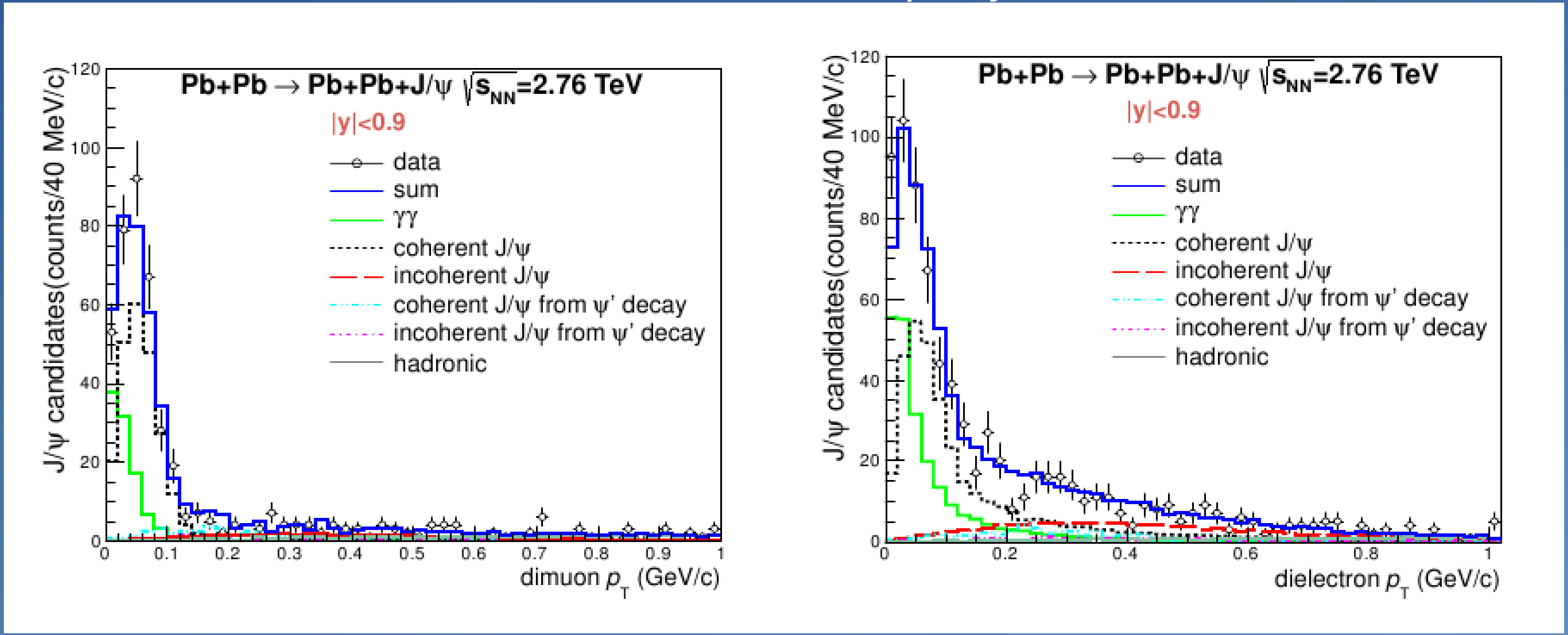
Exclusive vector meson production

Results from ALICE

Two tracks in an otherwise empty detector

$J/\psi \rightarrow ee/\mu\mu$

Transverse momentum distributions – midrapidity

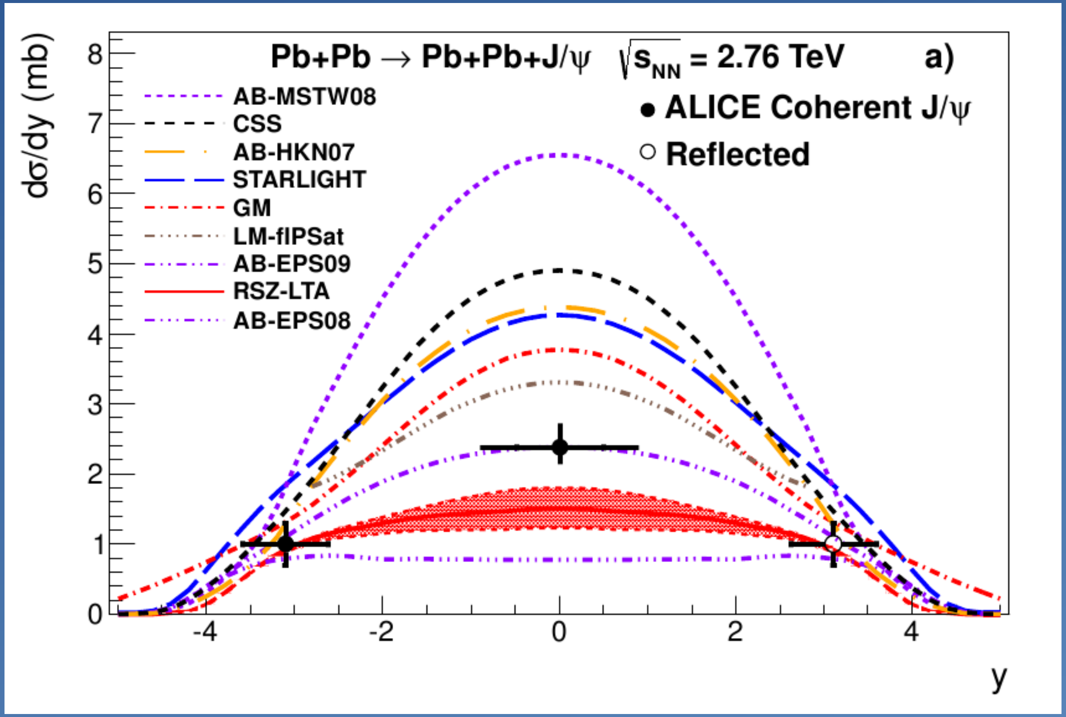


Clear coherent peak from J/ψ and continuum $\gamma\gamma \rightarrow l^+l^-$ observed at low p_T.

Full spectrum explained by, in addition, incoherent J/ψ, J/ψ from feed down from ψ', and some hadronic contribution at high p_T.

Exclusive vector meson production

First results on UPC at the LHC from ALICE



ALICE Collaboration

Phys. Lett. B 718 (2013) 1273

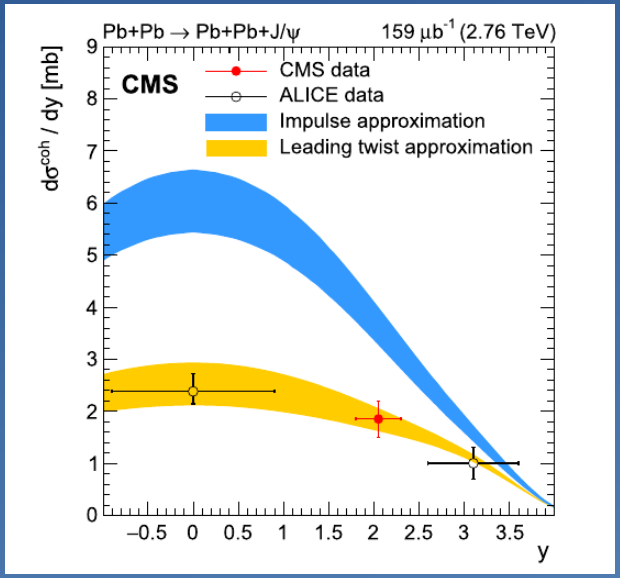
and

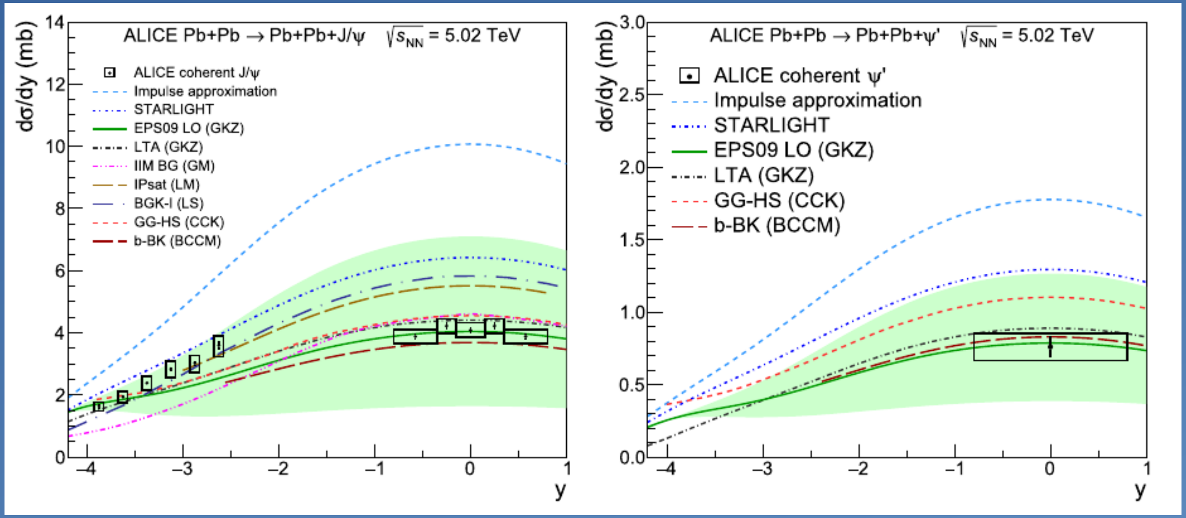
EPJ C 73 (2013) 2617.

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

Exclusive vector meson production

These results have been updated with higher statistics and also CMS has measured the same thing with similar conclusions.





CMS Collaboration Phys. Lett. B 772 (2017) 489.

ALICE Collaboration Eur. Phys. J. C 82 (2021) 712

Exclusive vector meson production

A nice picture of vector meson production!

But is it true?

Exclusive vector meson production

A nice picture of vector meson production!

But is it true?

Exclusive J/ψ photoproduction in ultraperipheral Pb+Pb collisions at the LHC to next-to-leading order perturbative QCD

K. J. Eskola,[1,2] C. A. Flett,[1,2] V. Guzey, T. Löytäinen,[1,2,*] and H. Paukkunen[1,2]
[1] *University of Jyvaskyla, Department of Physics, P.O. Box 35, FI-40014 University of Jyvaskyla, Finland*
[2] *Helsinki Institute of Physics, P.O. Box 64, FI-00014 University of Helsinki, Finland*
(Dated: March 23, 2022)

arxiv:2203.11613

There are big differences between LO and NLO calculations and uncertainties on the relevant scale.

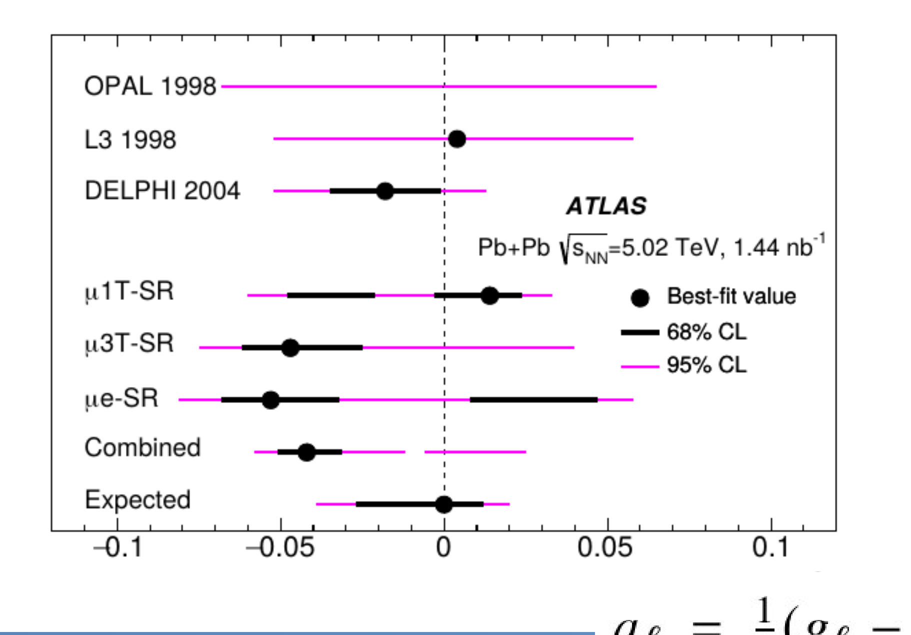
Talk on this paper by the next speaker (C.A. Flett).

Two-photon interactions

Much focus on exclusive vector meson production in ultra-peripheral collisions, but $\gamma\gamma$ has come back with a vengeance at the LHC!

Several very interesting new results:

Recent paper from Atlas on $\gamma\gamma \rightarrow \tau\tau$. (arxiv:2204.13478)



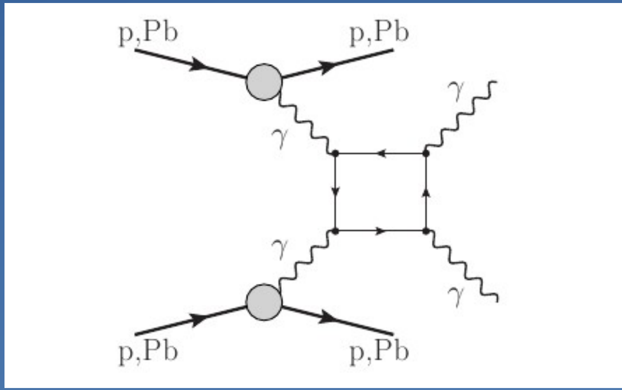
$$a_\ell = \frac{1}{2}(g_\ell - 2)$$

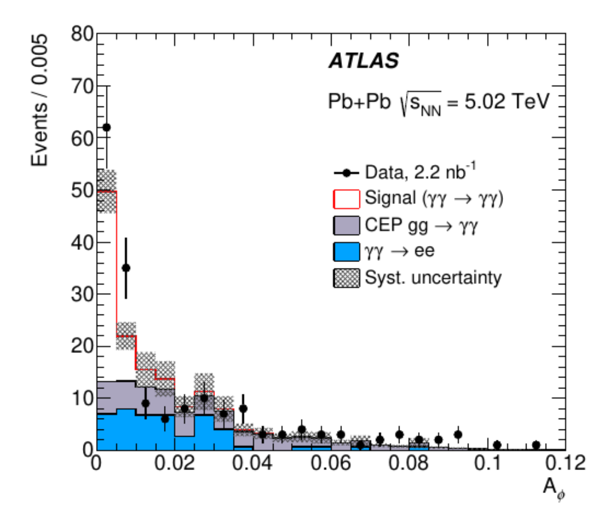
Sets limits on the anomalous magnetic moment of the τ comparable to the OPAL measurement from 1998.

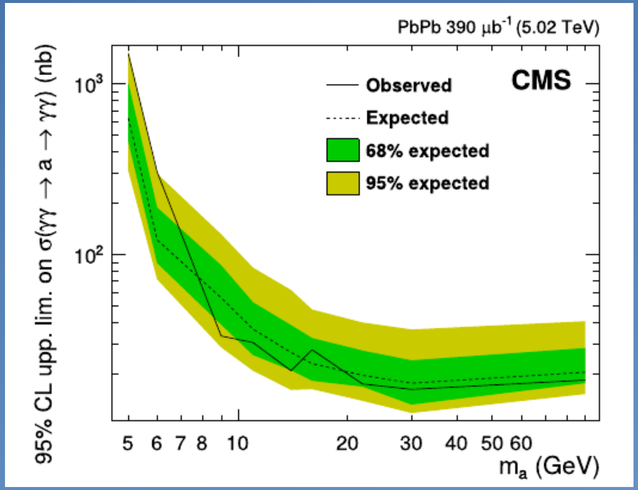
Also CMS presented results on this at Quark Matter.

Two-photon interactions

Observation by the ATLAS and CMS experiments of the process $\gamma\gamma \rightarrow \gamma\gamma$ (Atlas: Nat. Phys. 13 (2017) 852, PRL 123 (2019) 052001, JHEP 03 (2021) 243; CMS: PLB 797 (2019) 134826).





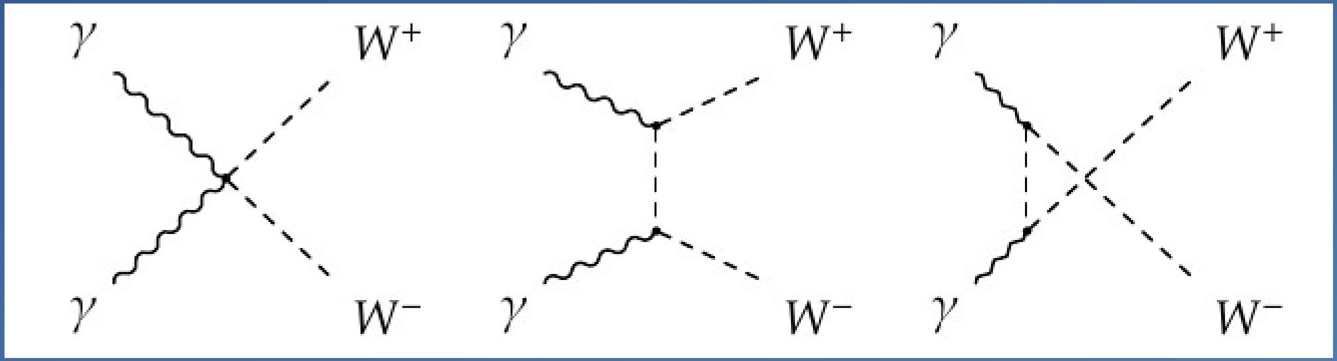


Sets new limits on axion production and the Born-Infeld extension of the Standard Model (J.Ellis, N.E. Mavromatos, T. You, PRL 118 (2017) 261802).

Two-photon interactions

Triple and quartic gauge coupling from $\gamma\gamma \rightarrow WW$ interactions.

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



This process has been observed in pp collisions by Atlas and CMS.
Atlas: Phys. Rev. D 94 (2016) 032011, Phys. Lett. B 816 (2021) 136190;
CMS: JHEP 08 (2016) 119.

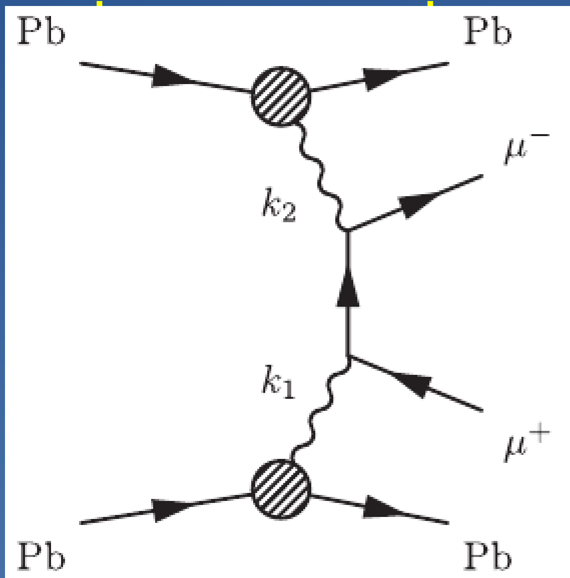
The *triple* couplings are better constrained from other measurements, but the *quartic* couplings are unique to two-photon interactions.

Yield consistent with Standard Model expectations.

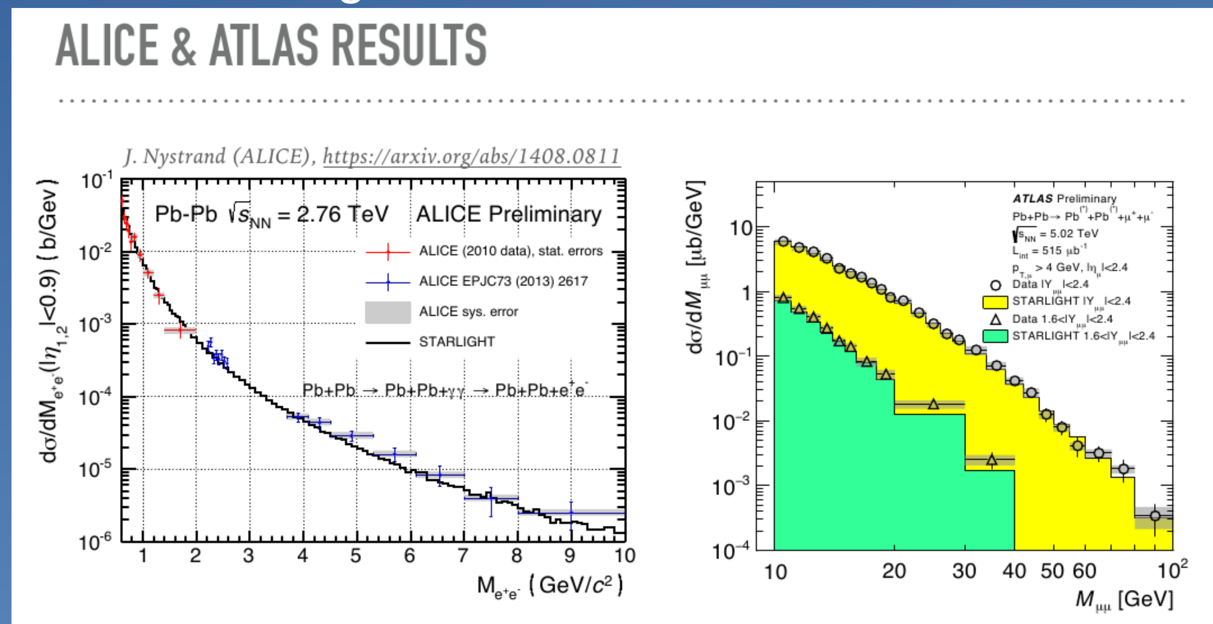
Sets the best limit so far on any anomalous quartic $\gamma\gamma WW$ coupling.

Two-photon interactions

Two photon production of lepton pairs ($e^+e^-/\mu^+\mu^-$) leading



Early results from Atlas ($\mu^+\mu^-$) and Alice (e^+e^-) showed rather good agreement with the starlight model.



ATLAS-CONF-2016-025

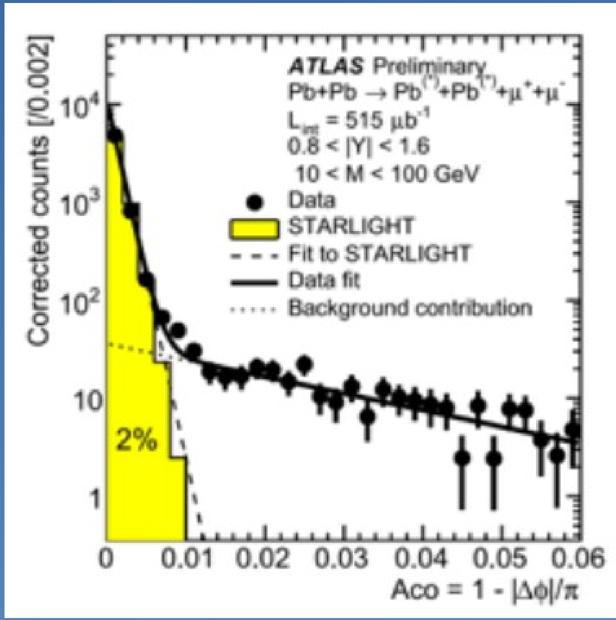
The Alice ($0.5 \leq m_{inv} \leq 10$ GeV) and Atlas ($10 \leq m_{inv} \leq 100$ GeV) measurements complement each other well.

Two-photon interactions

But discrepancies with starlight were also found.

Acoplanarity: $\alpha\ (= 1-|\Delta\phi|/\pi)$

The transverse momenta of the virutal photons are small, so the produce $\mu^+\mu^-$ and e^+e^- pairs are emitted almost back-to-back in the transverse plane.

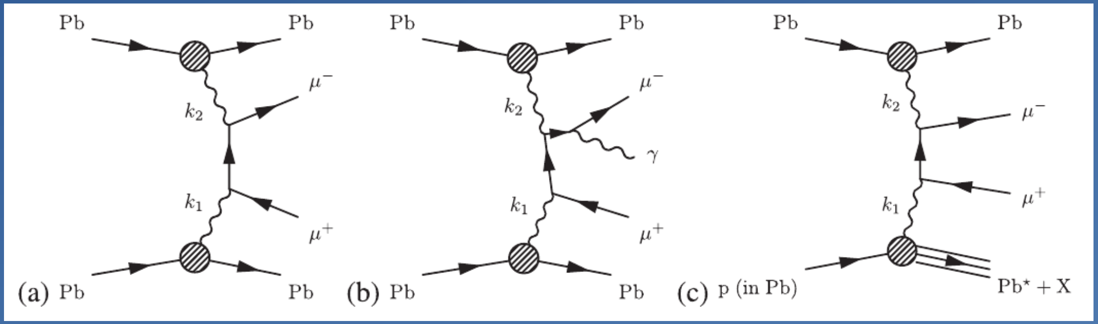


Starlight can explain the bulk of the data, but does not reproduce the high acoplanarity tail.

ATLAS-CONF-2016-025

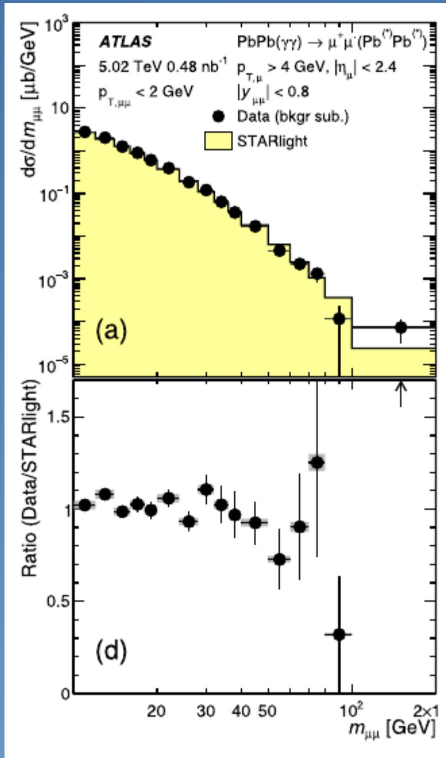
Two-photon interactions

Starlight uses LO QED, but there are higher order QED terms, and dissociative contributions.



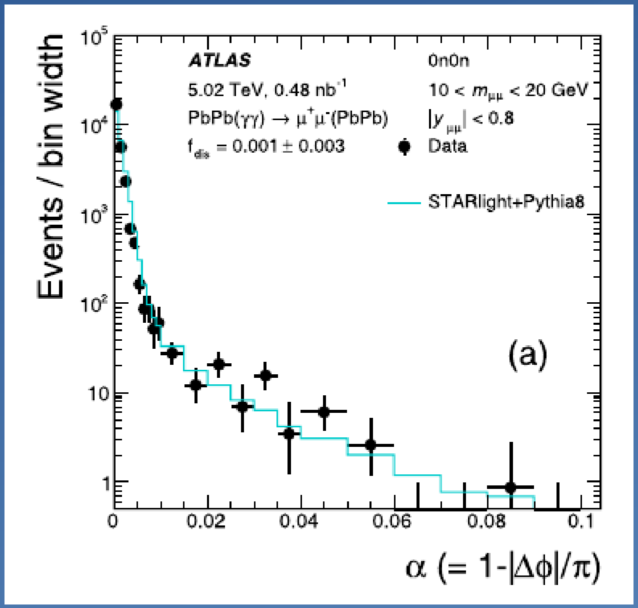
The most recent results from Atlas show that starlight does describe the bulk of the data very well, at least at mid-rapidity.

"Exclusive dimuon production in ultraperipheral Pb + Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ATLAS", Phys. Rev. C 104 (2021) 024906.

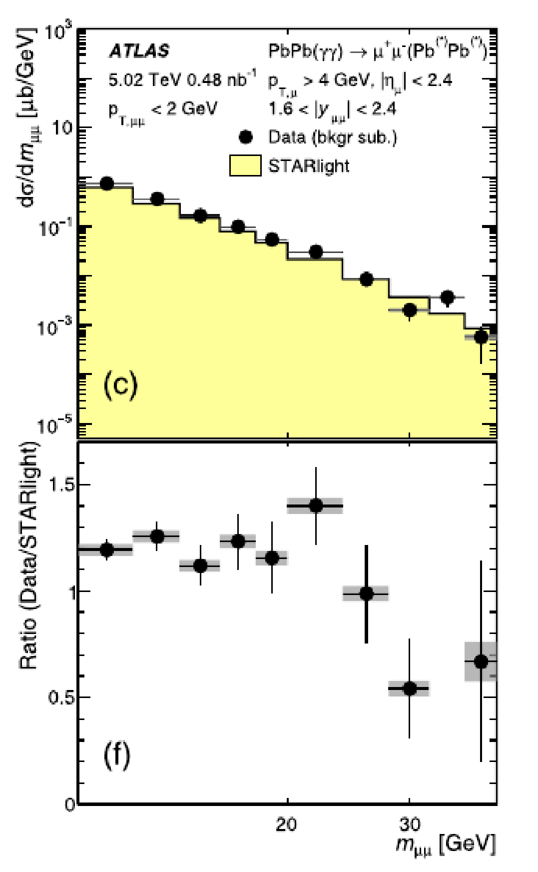


Two-photon interactions

The deviations seen earlier in the acoplanarity distribution can be explained through higher order QED processes as implemented in Pythia 8 (Final state QED showering).



At high rapidities there is an up to ≈20% deviation in the cross section.



Summary

- Ultra-peripheral collisions is the energy frontier for electromagnetic and electroweak interactions.

- A variety of interactions and final states can be studied.

- Focus initially on exclusive vector meson production, but now broadening to include other two-photon and photonuclear interactions.