$$\gamma\gamma \to \gamma\gamma$$

in Pb-Pb collisions in ATLAS

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Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

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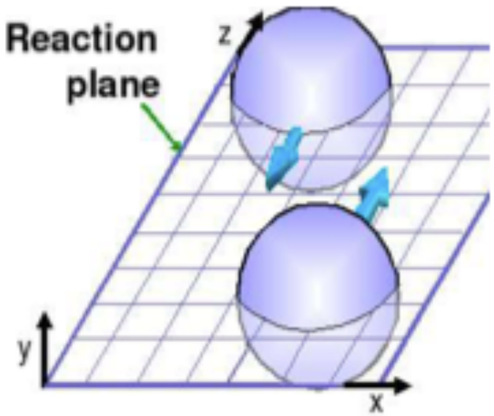
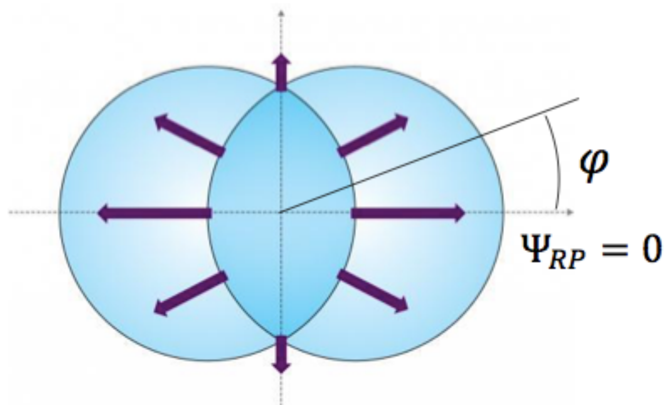
General issues on central collisions of Heavy Ions at the LHC

Let us assume that we observe a collision along the (z) axis. We call $\vec{b}$ the distance (vector) between the centers of the 2 ions. Then $(\vec{b}, \vec{e_z})$ is the reaction plane. And we obtain a collision as pictured below:

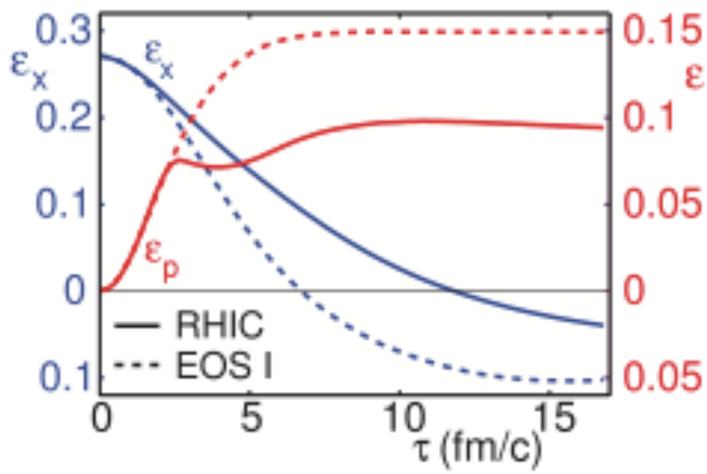




The collision volume as an ellipsoid shape with a large number of constituents in interaction.

The observation shows that the high pressure gradients (along the short axis of the ellipsoid) drives the evolution of the momentum of the constituents... This is a fluid expansion:

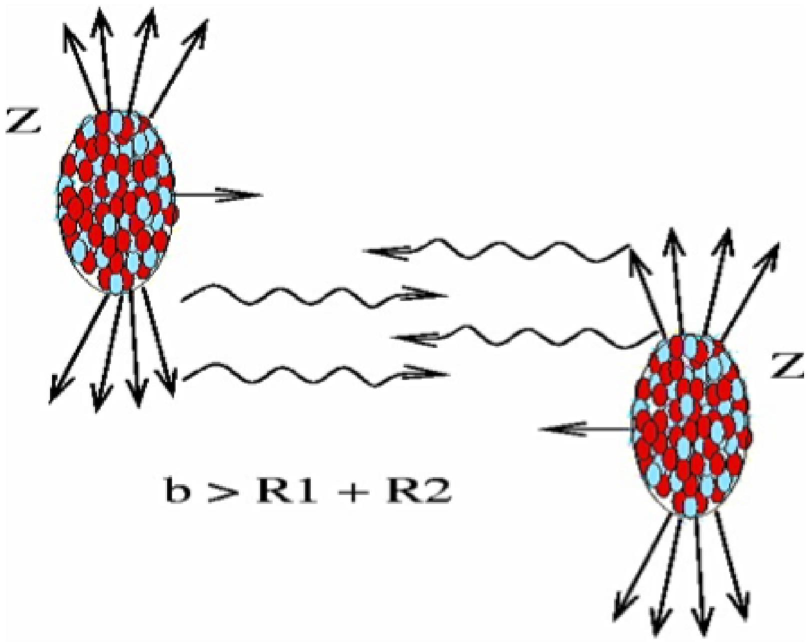
$$\frac{\partial}{\partial t}\vec{v} \simeq -\frac{1}{\epsilon + P}\left[\nabla P + \vec{v}\frac{\partial P}{\partial t}\right] + \ldots$$



The logic is as follows: (1) geometry (ϵ_2) $\rightarrow$ (2) ∇P (if the is a local thermal equilibrium) $\rightarrow$ (3) evolution of the medium following the fluid equation of motion. A lot of observables can prove this logic.

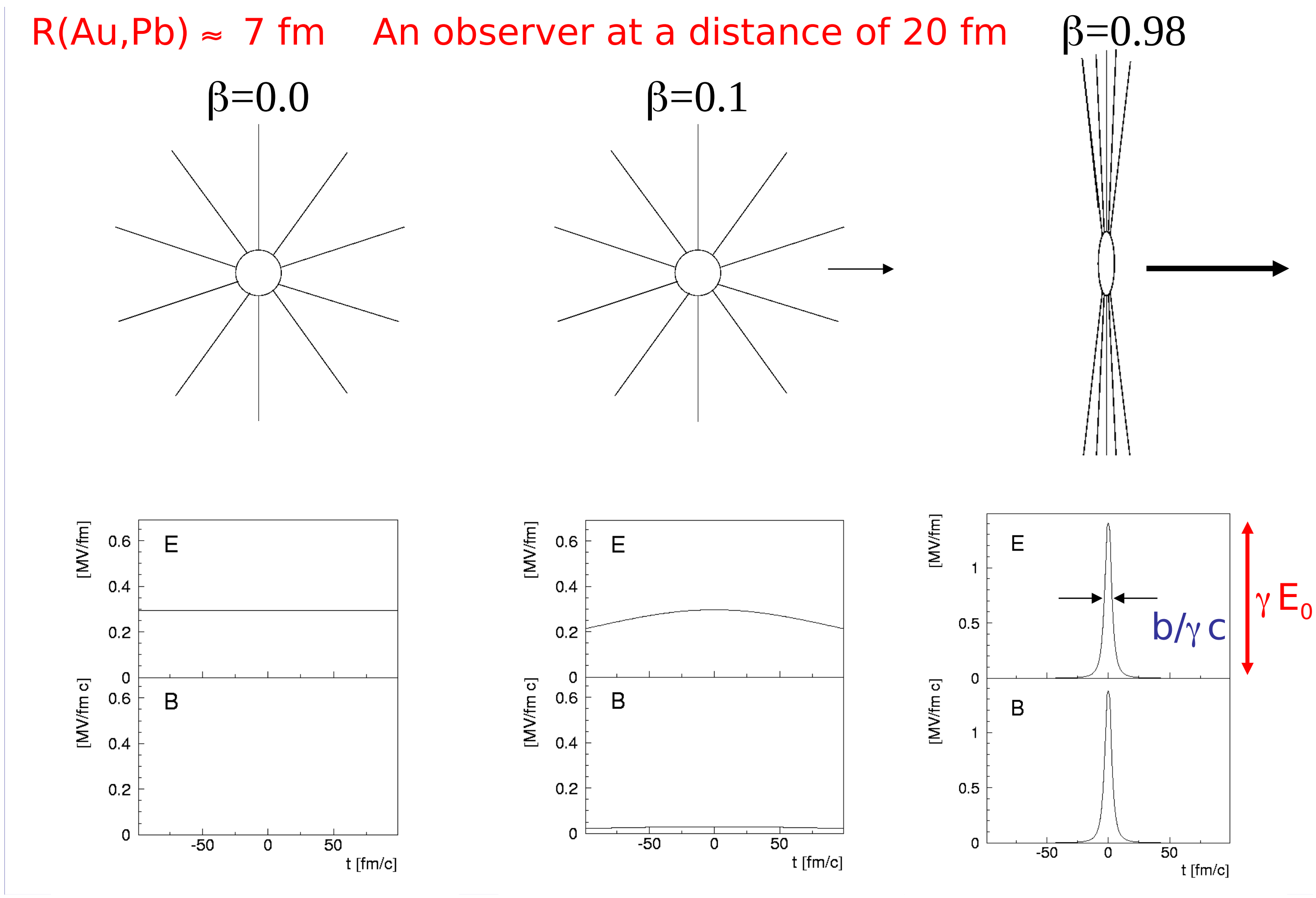
What happens if we want to avoid the central collision

Then, we can have an interaction between the EM fields of the 2 ions and thus an intercation of the form: $\gamma + \gamma \to \ldots$. The 2 ions are then left out after the EM+EM nteraction quasi-intact and along the beam axis.



A reaction like this ($b > R_1 + R_2$) is called ultra-peripheral (UPC). In the following, we discuss only this kind of reaction: EM+EM. *This justifies the triggers defined later.*

Reminder on the EM field of an ultra-relativistic HI



This is locally the field of a plane wave ($v_z \sim c$):
$\vec{E}(x,y,z=0,t) = \vec{E_{\rm T}} = \frac{q}{4\pi}\gamma\frac{\vec{b}}{[\gamma^2(vt)^2+b^2]^{\frac{3}{2}}}$ and $\vec{B} = \vec{B_{\rm T}} = \vec{v} \times \vec{E_{\rm T}}$.

What we read also on the formula for $\gamma >> 1$, is that $(\vec{E}, \vec{B})$ can only act for a brief interval of time such that: $\gamma c\ \delta t \simeq b$, or: $\delta t \simeq \frac{b}{\gamma c}$.

This means that the EM field produced by the HI (heavy ion) is not mono-chromatic, it includes all frequencies such that: $\omega < \frac{\gamma c}{b}$.

Under these conditions, we can then compute the cross section of an EM+EM like process: $A + A \rightarrow AA(\gamma\gamma) \rightarrow A + A + X$ as:

$$\sigma = \int\int f(\omega_1) f(\omega_2) \sigma_{\gamma\gamma\rightarrow X}(\omega_1,\omega_2)\frac{d\omega_1}{\omega_1}\frac{d\omega_2}{\omega_2}$$

where $f(\omega)$ is called the number of equivalent photons. This function is directly linked to the Poynting vector of the EM field: $\int dS E_{\rm T}^2(\vec{b},\omega)/(\pi) = \ \omega\ f(\omega)$.

- Another consequence of the relation: $\delta t < \frac{b}{\gamma c}$.
  - As $\omega < \frac{\gamma c}{b}$, we have: $k_{\mathrm{T}} < \frac{c}{b}$
  - Then, with the notation: $k = (\omega, \vec{k}_{\mathrm{T}}, \omega/v_z)$, we see that k^2 is the difference of 2 big quantities and is not exactly zero but almost zero: $k^2 = -k_{\mathrm{T}}^2 - \frac{\omega^2}{\gamma^2}$.

    We obtain: $Q^2 = -k^2 = k_{\mathrm{T}}^2 + \frac{\omega^2}{\gamma^2} < \frac{c^2}{b} \simeq 10^{-3}$ GeV^2. An consequently the EM+EM interaction is an interaction between quasi-real photons.
- Moreover:
  The electric field produced (for an ultra-relativistic Pb ion) is of the order 10^{25} V/m, therefore $>> m_e^2 c^3/e(\hbar) = 10^{18}$ V/m. This allows to produce pairs of virtual particles.

These few items cover the essentials of the UPC physics at the LHC.

Some interest(s) of Pb-Pb collisions

Here, we are interested only in $Pb + Pb$ collisions at $\sqrt{s} = 5.02$ TeV/A (A=208), such that: $\omega_{max} \sim 80$ GeV. Of course, this induces a limitation in the mass of the (exclusive) final state accessible.

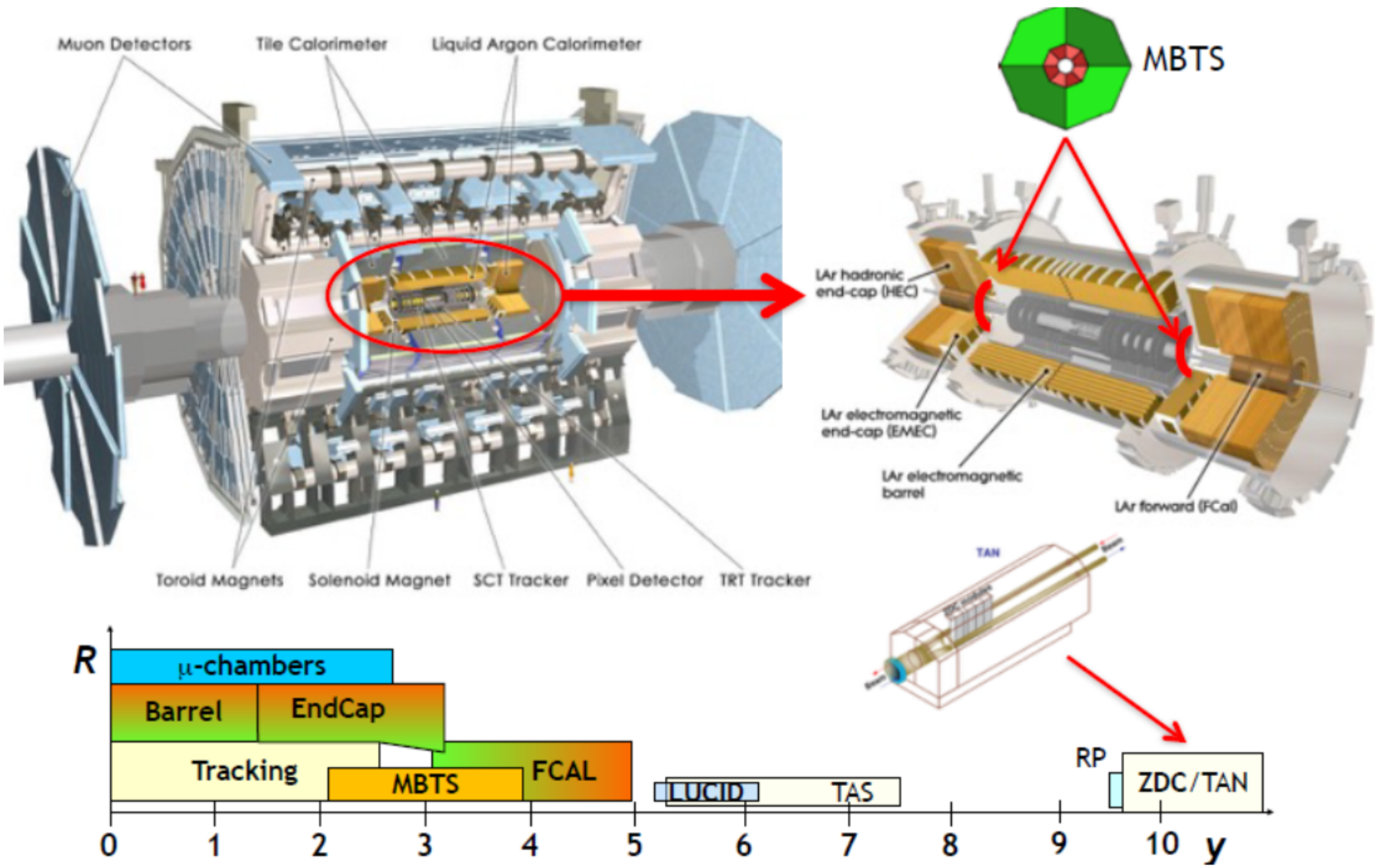
The great advantage of Pb-Pb (compared to similar EM+EM interactions after proton-proton collisions) is that the cross section is proportional to Z^4 (Z=82). This is because the equivalent photon number reads:

$$f_{\gamma/Pb}(\omega) \simeq Z^2 \frac{2\alpha_{em}}{\pi\omega} \int_0^{\frac{1}{R_{Pb}}} k_{\mathrm{T}} dk_{\mathrm{T}} \frac{k_{\mathrm{T}}^2}{(k_{\mathrm{T}}^2 + \frac{\omega^2}{\gamma^2})^2}$$

Then, $f(.)f(.)$ is proportional to $Z^4 = 82^4 \simeq 5\ 10^7$.

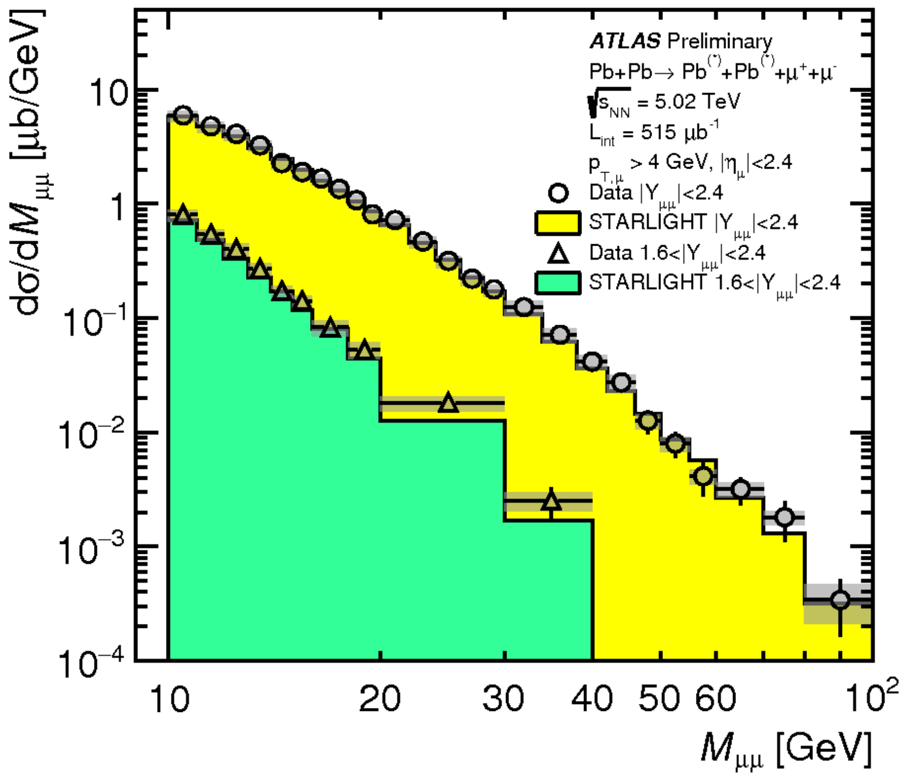
There is also another advantage which is that the QCD cross section to produce an exclusive final state is proportionnal to A^2 (w.r.t. Z^4 for the EM+EM cross section for the same final state). This means that the analysis is expected to be simpler in $Pb + Pb$ with a relative smaller QCD like background (compared to proton-proton collisions).

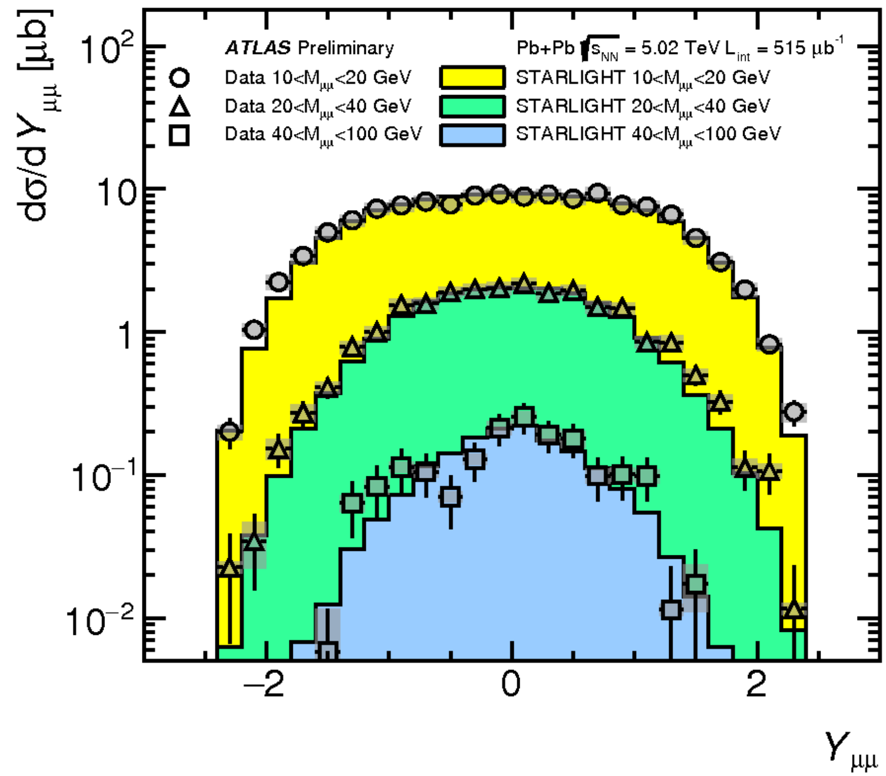
ATLAS experimental set up



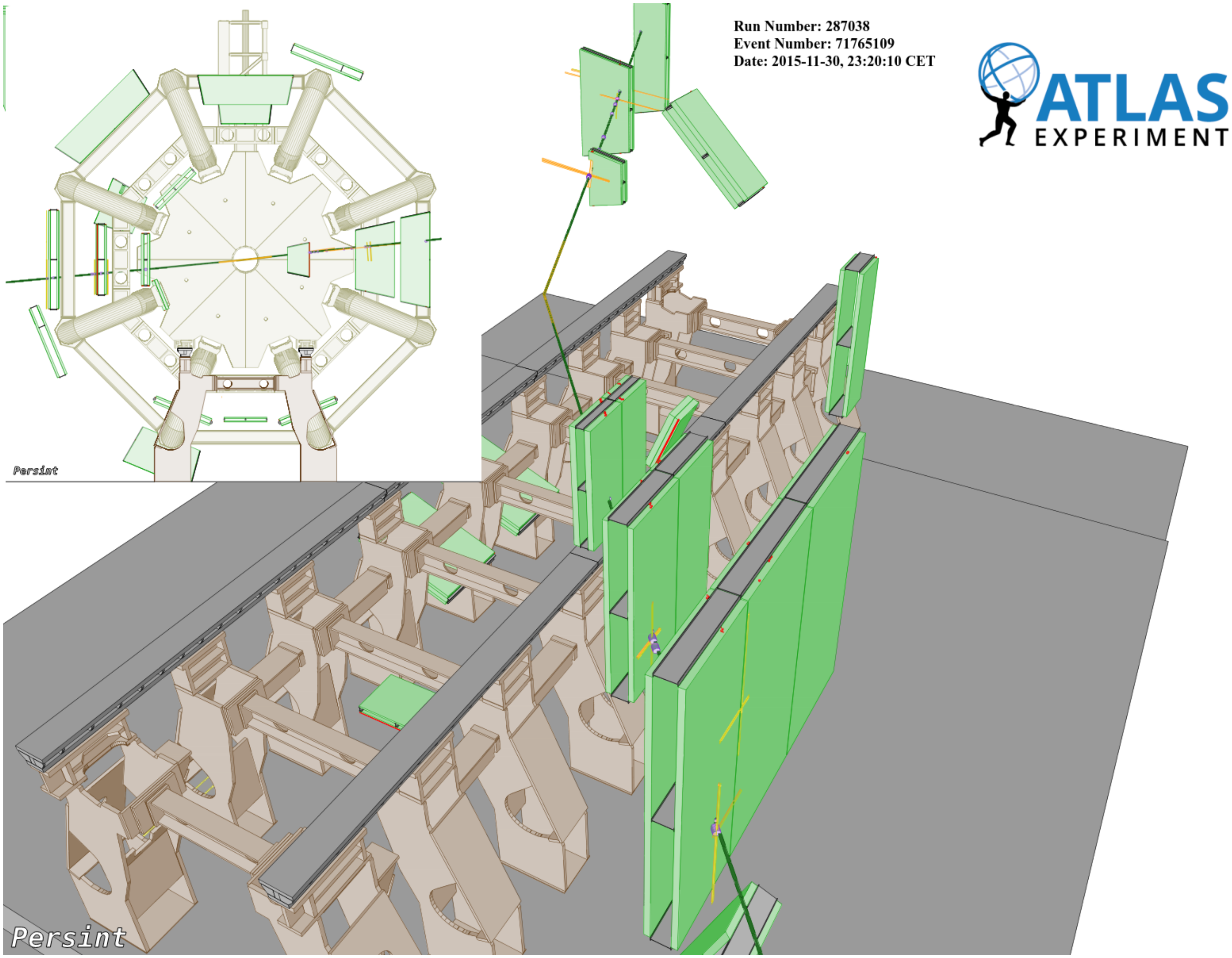
$$Pb + Pb \rightarrow PbPb(\gamma\gamma) \rightarrow Pb + Pb + \mu^+ + \mu^-$$

The exclusive production of $\mu^+\mu^-$ is well understood. This is the control (or candle) analysis.





$$Pb + Pb \rightarrow PbPb(\gamma\gamma) \rightarrow Pb + Pb + \mu^+ + \mu^-$$



The interaction with 4 photons

$$Pb + Pb \to PbPb(\gamma\gamma) \to Pb + Pb + \gamma + \gamma$$

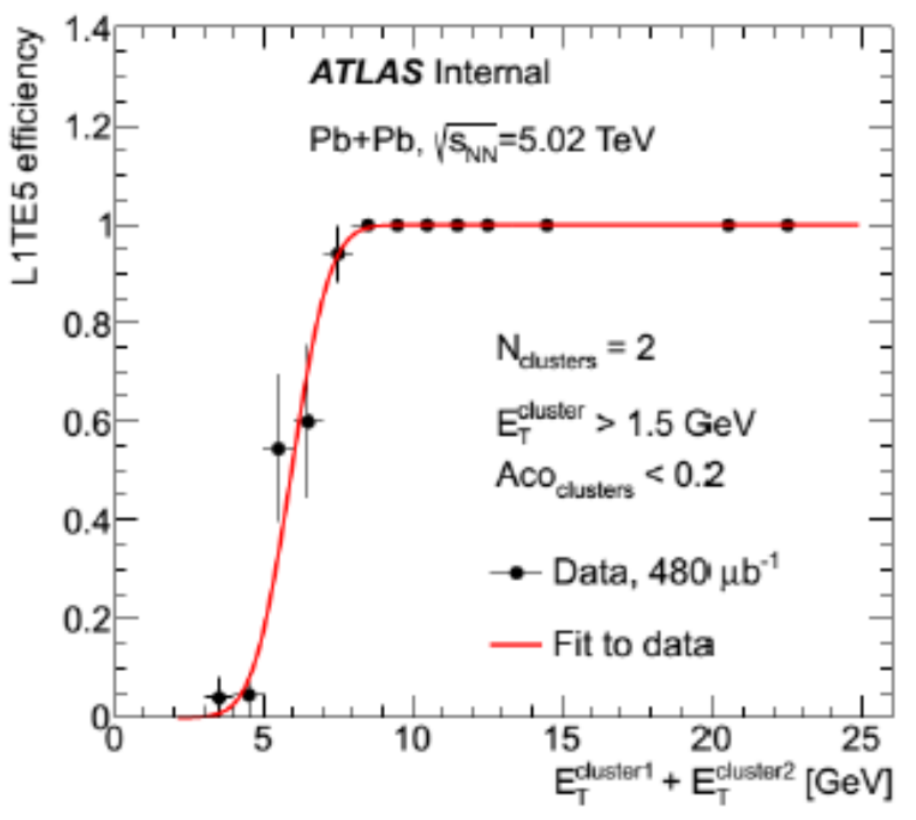
In 2014, we have defined a specific trigger with a general simple idea: small hadronic activity in central and forward detectors. Following what has been discussed on the essentials of UPC.
(1) Total transverse energy in calorimeters in the interval: 5 - 200 GeV,
(2) No signal in MBTS (≤ 1 hit) and very few hits (< 10) in Pixel (tracking) detectors.

Data taking was done during December 2015 (34 runs, 0.48 nb^{-1}).

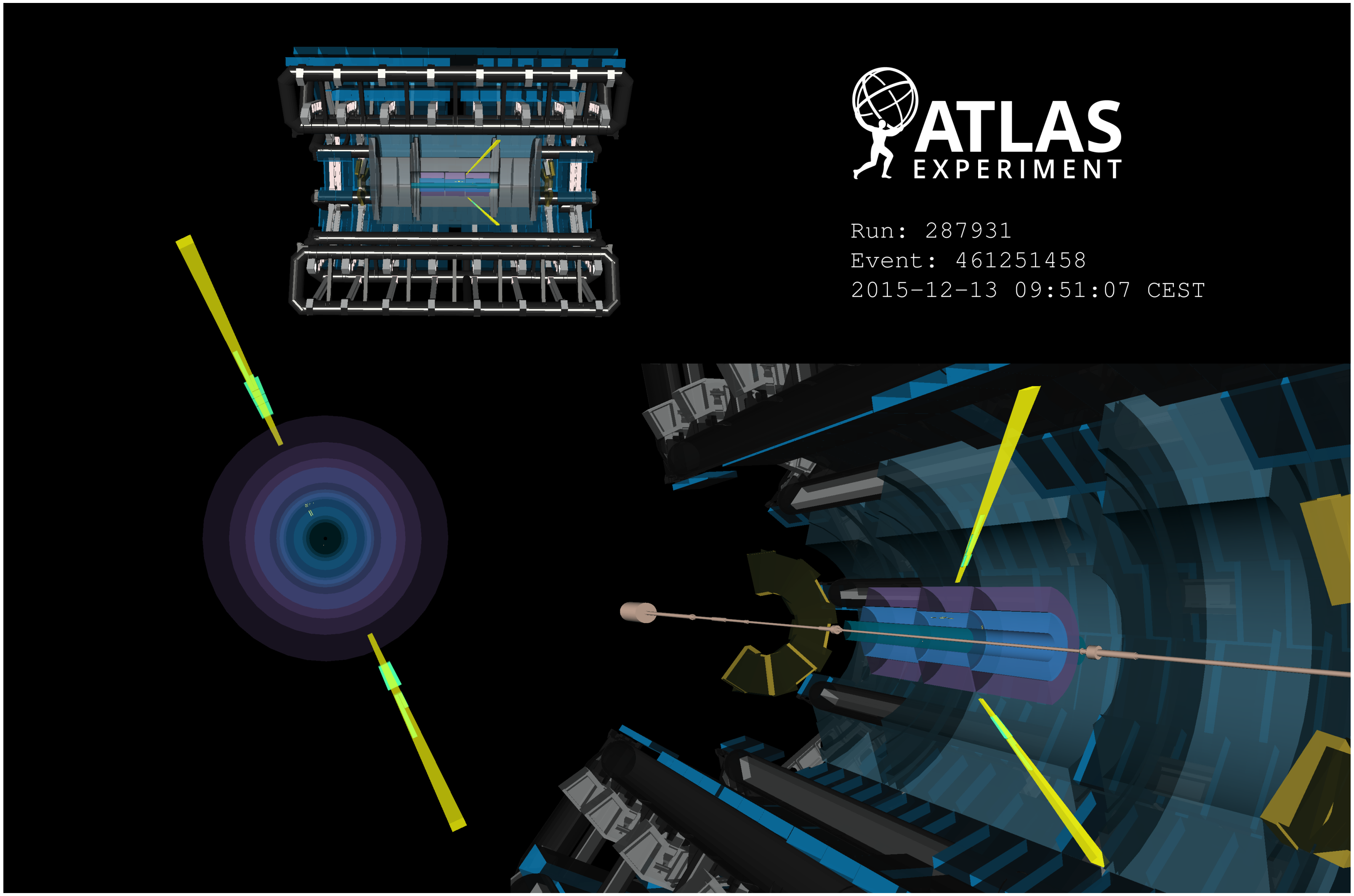
The efficiency of the trigger is 100 % in the range of the measurement (below). (This has been derived with the control process (analysis): $Pb + Pb \to PbPb(\gamma\gamma) \to Pb + Pb + e^+e^-$)

Experimental Selection:
(1) 2 photons with $E_T > 3$ GeV $|\eta| < 2.37$ and $m_{\gamma\gamma} > 6$ GeV
(2) $N_{traces} == 0$ which eliminates efficiently events of the type: $\gamma\gamma \to e^+e^-$ (for which leptons are misidentified as photons)
(3) $p_T(\gamma\gamma) < 2$ GeV and $|\Delta\phi_{\gamma\gamma} - \pi| < 0.03$ (which eliminates most of the residual QCD background, producing and exclusive final state with 2 photons).

Trigger (efficiency)



HLT-hi-gg-upc-L1TE5-VTE200 (slide above) is used to select signal event candidates. Note: The trigger selects UPC events, but not by a direct measure of impact parameter. The efficiency is determined using $\gamma\gamma \to 2l$ events.


ATLAS
EXPERIMENT
Run: 287931
Event: 461251458
2015-12-13 09:51:07 CEST

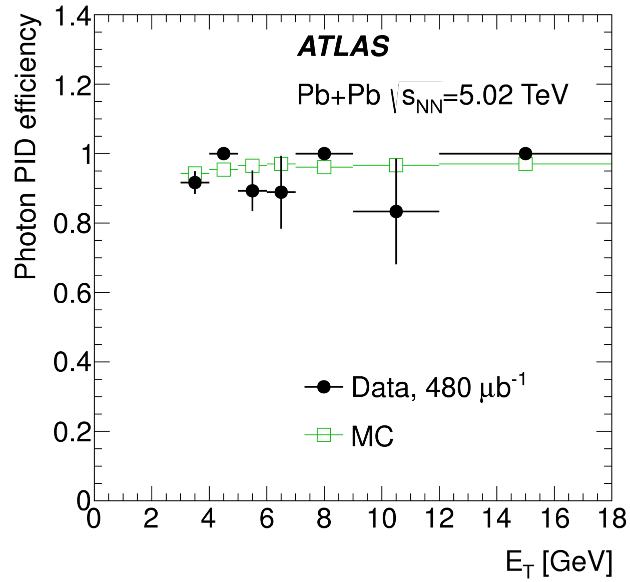
Object definition (photons)

- $\gamma\gamma$ -> $\gamma\gamma$ cross section decreases very fast with $m_{\gamma\gamma}$ and/or E_T
  - **Low-E_T photons need to be used**
- Photons
  - $E_T > 3$ GeV, $|\eta| < 2.37$ (crack region excluded), OQ requirements, photon PID based on three shower-shape variables is used:

E_{ratio}	Ratio of the energy difference associated with the largest and second largest energy deposits to the sum of these energies in the first EM calo layer
f_1	Fraction of energy reconstructed in the first layer with respect to the total energy of the cluster
W_{eta2}	Lateral width of the shower in the middle layer

The shape variables are optimized to increase the signal significance: $0.1 < f_1 < 0.8$, $w_{eta2} < 0.14$ and $E_{ratio} > 0.6$, keeping high identification and reconstruction efficiencies.

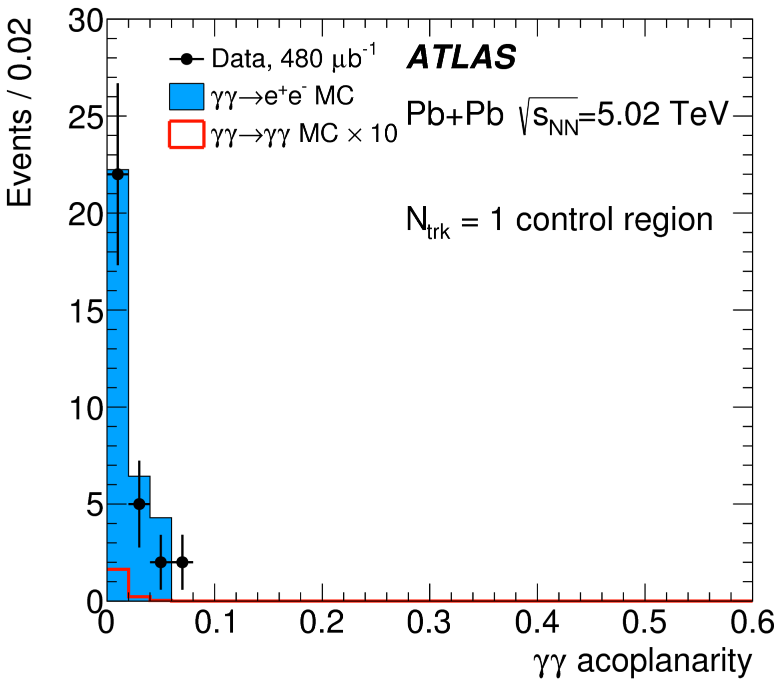
Photon identification efficiency (data driven)

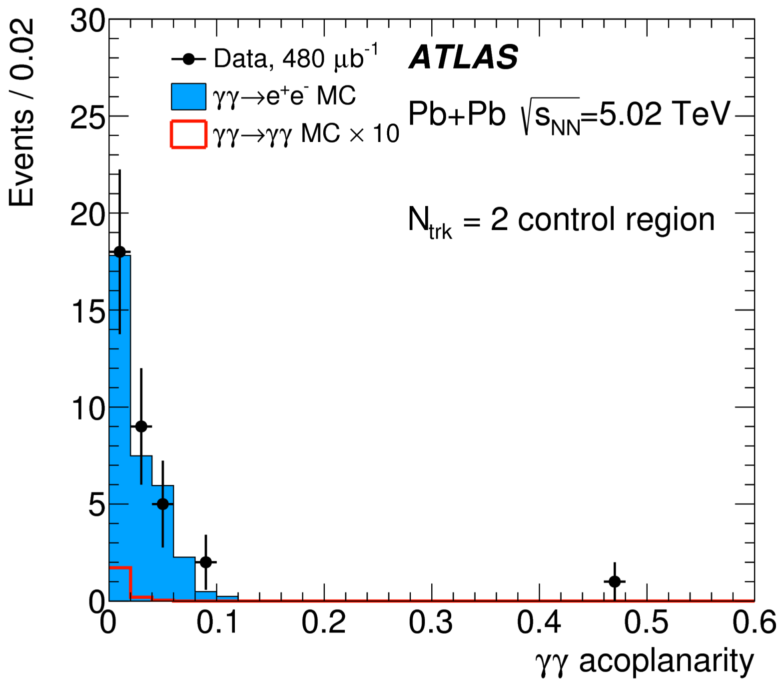


Done with: $\gamma\gamma \to e^+e^-$ with a final-state radiation (FSR) photon ($p_T^{ee\gamma} < 1$ GeV): events with a photon and two tracks corresponding to oppositely charged particles with $p_T > 1$ GeV are required to pass the same trigger as in the di-photon selection. The ΔR between a photon candidate and a track is required to be greater than 0.2. The FSR photons are then used to extract the photon PID efficiency, which is defined as the probability for a reconstructed photon to satisfy the identification criteria (previous slide).

Misidentified leptons

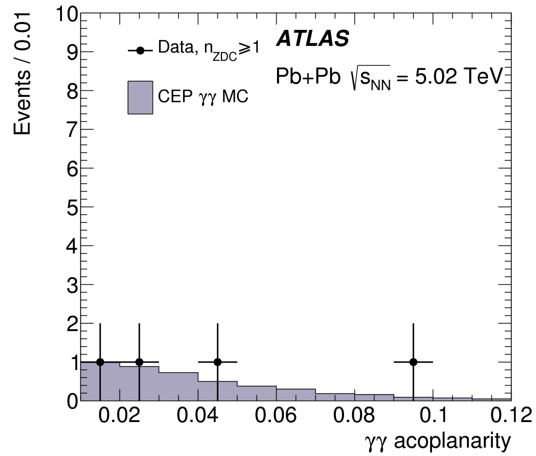
$$Pb + Pb \to PbPb(\gamma\gamma) \to Pb + Pb + \gamma/e^+ + \gamma/e^-$$





Same experimental selection as before except condition (2). Thus, we do not require: $N_{traces} == 0$. Figure: this proves that the control of the background: $\gamma + \gamma \to e^+ + e^-$ is well done, with one or two lepton(s) misidentified as photon(s). (Reminder: $Aco = |\Delta\phi_{\gamma\gamma}/\pi - 1|$).

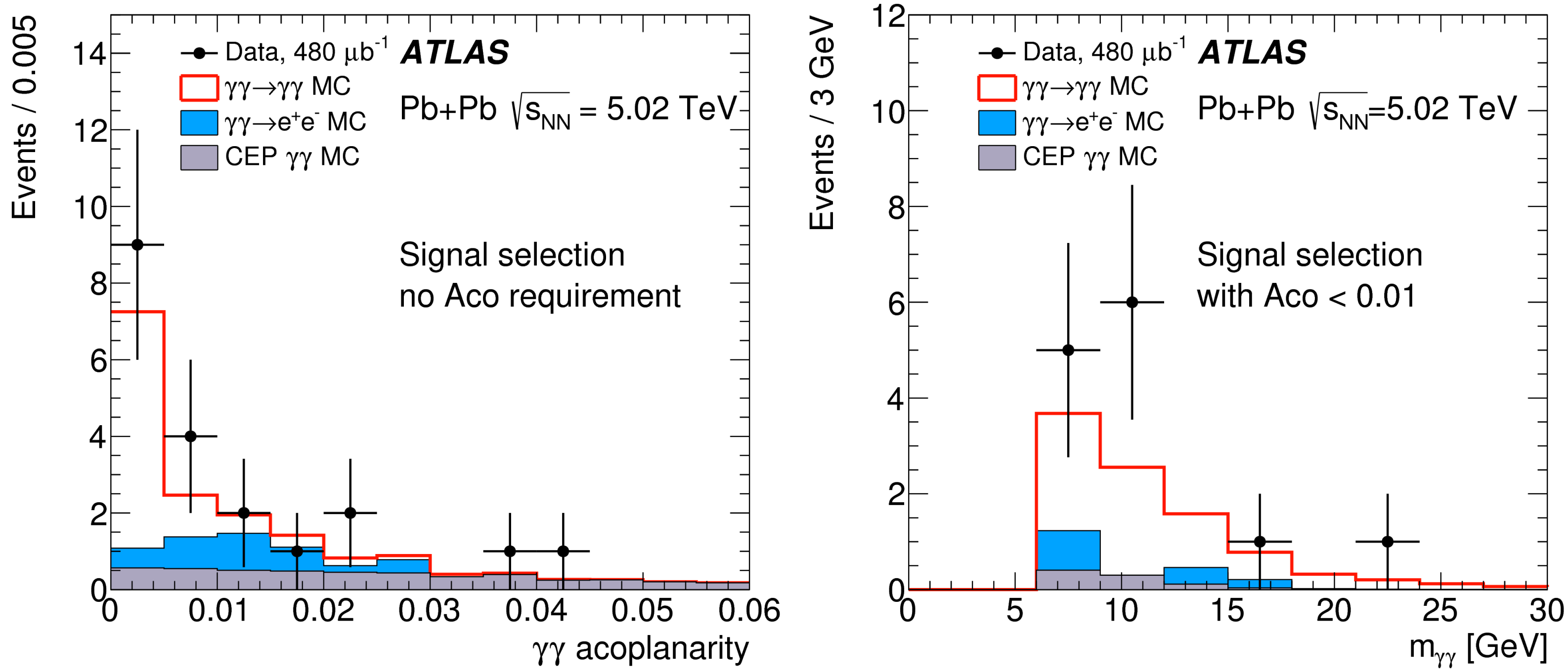
QCD background (Central Exclusive Production of 2 photons)



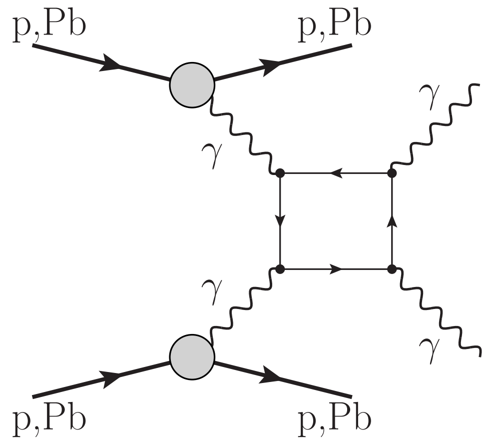
(0) Reminder: In Pb-Pb collisions, CEP is expected to be small... It is normalized for $Aco > 0.02$ (all other requirements as before) and this normalization is checked as follows:
(1) Pb-Pb CEP occurs at relatively small impact parameters ($b \sim 2R$), which implies a large probability for nuclear break-up. For example 1 forward neutron emission than can be detected in the ZDC: calorimeters located 140 m from the nominal interaction point in both directions. Therefore, the normalization of the QCD MC can be checked using an analysis requiring ZDC activity (figure) and $Aco > 0.01$ (where this process dominates).

Main result

$$Pb + Pb \to PbPb(\gamma\gamma) \to Pb + Pb + \gamma + \gamma$$



After the final requirement: $Aco = |\Delta\phi_{\gamma\gamma}/\pi - 1| < 0.01$: 13 events are observed for 2.6 ± 0.7 events predicted from the backgrounds. Observed significance: 4.4σ.



In QED, this kind of process is standard as soon as the electric fields are very large w.r.t. $m_e^2 c^3/e(\hbar) = 10^{18}$ V/m. This is the case for our experimental configuration.

In order to understand this phenomenon (very intuitively), we can modify the propagation equation of the EM field as such:

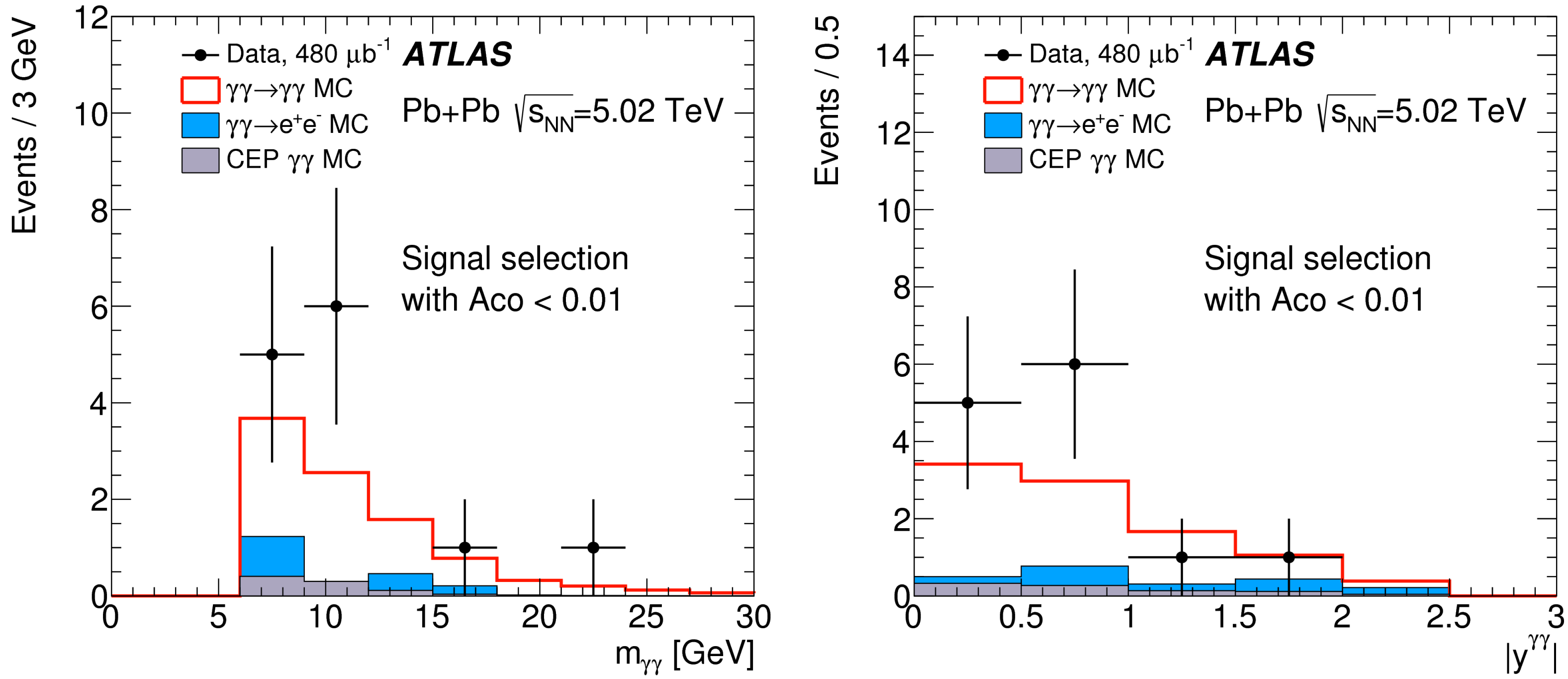
$$\frac{1}{c^2}\ddot{E} - \Delta E = -a\frac{\partial^2}{\partial t^2}(E^3) = -a\ddot{E^3}(\neq 0).$$

Which means that intense electric field can produce a polarization of the vacuum (corresponding to the term on the l.h.s.). Then the equation of propagation of the EM field is non-linear and there is a possibility for 4 waves mixing.

Simple argument: We can easily check from the above equation that if E is of the form:

$$E = \sum_{1}^{4} A_i(x) e^{i(\omega_i t - k_i x)}$$

Then, dA_4/dx is proportional to the product $A_1 A_2 A_3$.

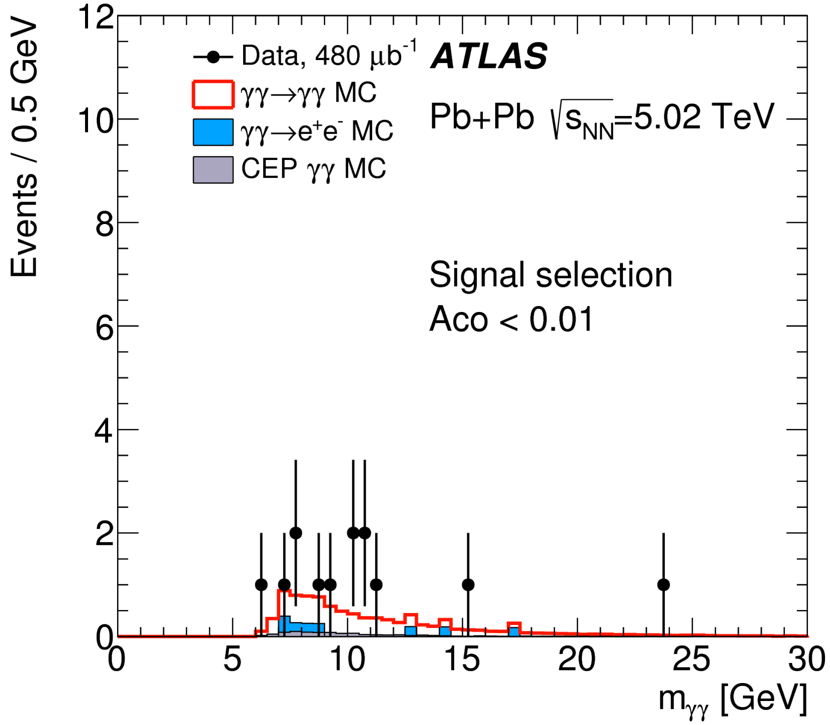


Cross section in the kinematical domain of the measurement (see selection):
70 ± 20 (stat.) ± 17 (syst.) nb. Nature Physics 13 (2017) no 9, 852-858

The predictions of QED give: 45 ± 9 nb [PRL 111 (2013) 080405], 49 ± 10 nb [PRC 93 (2016) no.4, 044907].

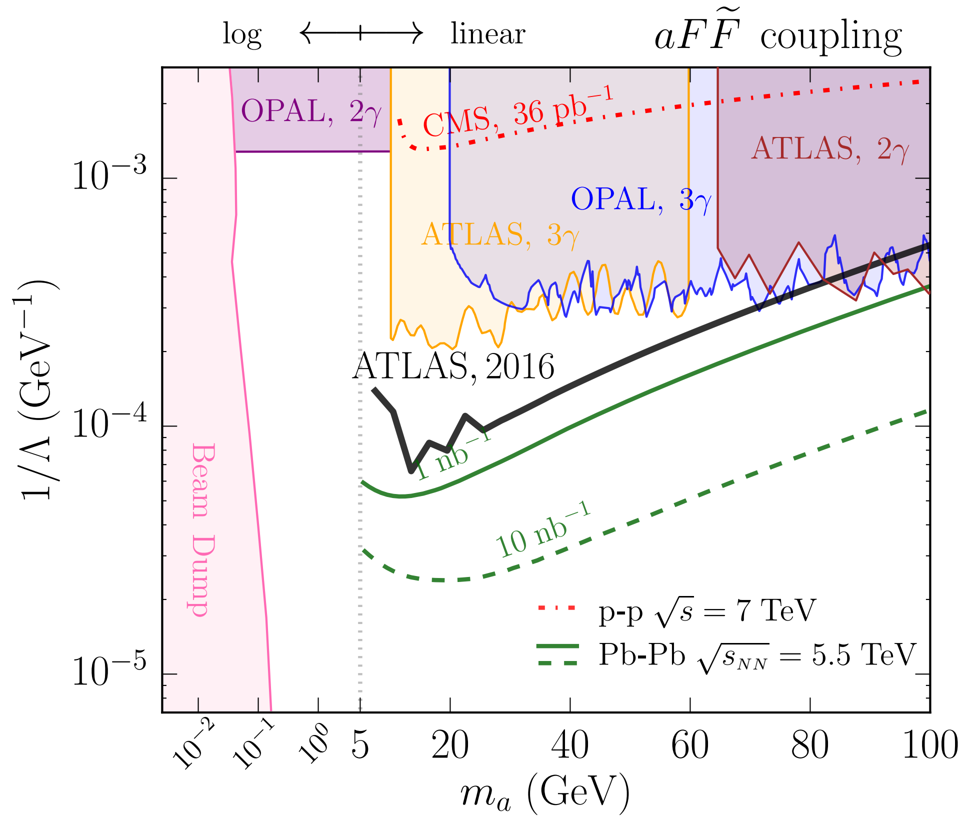
Invariant mass with a refined binning

In order to ensure that there is no resonance (for example from an intermediate state like: η_b). Alternatively, we have checked that all reactions involving production of mesons are negligible even w.r.t. the QCD CEP background...



An example of use of this measurement
Putting limits on: $\gamma\gamma \to a \to \gamma\gamma$

Let us consider the coupling of an Axion $(a,\ m_a)$ to the EM field of the form: $\frac{1}{\Lambda} a F \tilde{F}$ (arXiv:1709.07110).



Follow up and conclusions

When the 4 photons interaction is discussed in papers, it is often mentioned elements about the vacuum of QED, which is not the classical vacuum. One simple way to emphasize this point is to start from: $\frac{1}{c^2}\ddot{E} - \Delta E = -a\ddot{E}^3$. Here, a is one parameter of this QED vacuum, that we can determine from the present measurement. We obtain (not an ATLAS result): $a = (10 \pm 3)\,\frac{4\alpha^2(\hbar^3)\epsilon_0}{45m^4c^5}$.

On the experimental side, there is still a lot of work to be done in precision measurements of the control process: $Pb + Pb \rightarrow PbPb(\gamma\gamma) \rightarrow Pb + Pb + \mu^+ + \mu^-$.

At the end of 2018, there will be a new period of data taking with proper triggers to increase the statistics for: $Pb + Pb \rightarrow PbPb(\gamma\gamma) \rightarrow Pb + Pb + \gamma + \gamma$. A larger sample will let the opportunity of new items in the analysis.

In the long term (HE-LHC), in collisions PbPb at 10 TeV/A, it will be possible (in principle) to reach invariant $\gamma\gamma$ masses of 320 GeV (max) and then to study contributions of loops of W bosons to the process. Moreover, with the ATLAS upgrade, if the present measurement is extended from $|\eta| < 2.5$ to $|\eta| < 4$, the cross section will increase by about 70 %.