Ligh-by-light scattering at the LHC, present and future

Selection of results from the 3 publications

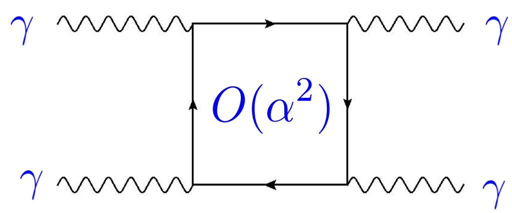
ATLAS: Nature Physics 13 (2017) no 9, 852-858 ($L = 0.48$ nb^{-1}), CERN-EP-2019-051 ($L = 1.73$ nb^{-1})
CMS: CERN-EP-2018-271 ($L = 0.39$ nb^{-1})

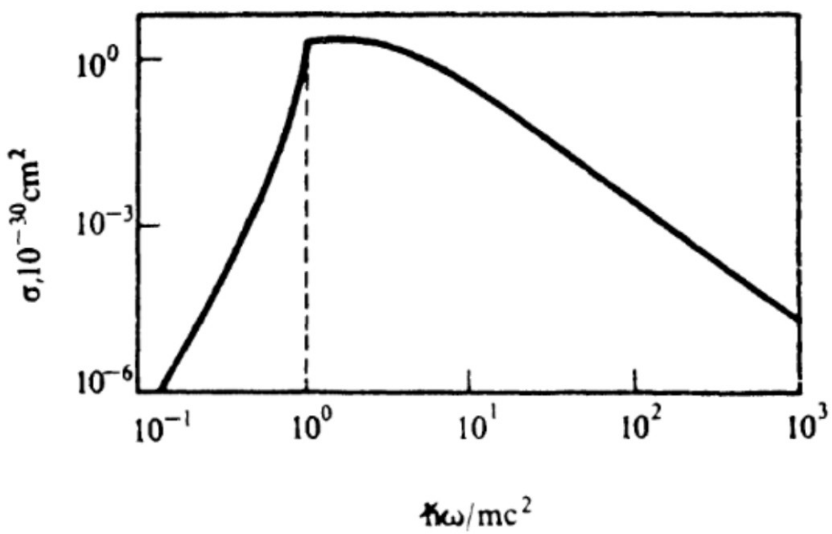
The 2 small samples have been recorded in december 2015, the large one in december 2018.

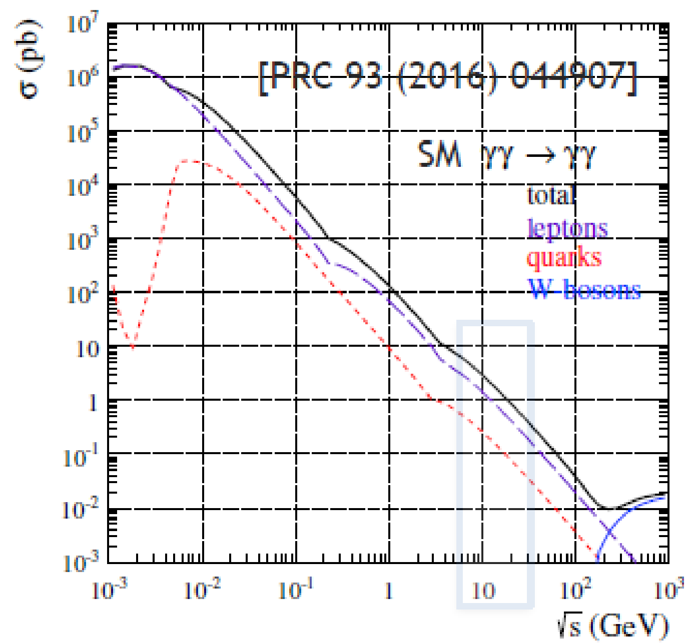
well cited: > 100 cit. (89 for the first paper)

Laurent Schoeffel

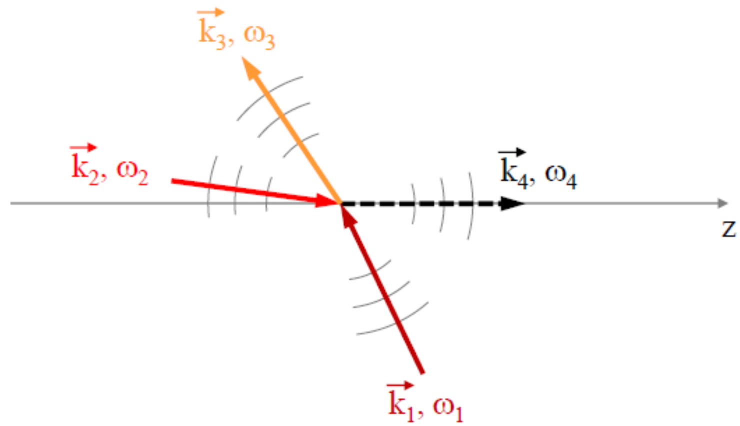
Light-by-light (LbL) process (what is known)







In its full glory



Note: to create a real pair $\gamma\gamma \to e^+e^-$, we need EM field intensity (E) of order: $eE\lambda_e (= \frac{1}{m_e}) \geq m_e$.
This gives: $E \geq E_c \sim 10^{18}$ V/m and $B \geq B_c \sim 4\ 10^9$ T (or intensity $I \sim 10^{29}$ W/cm^2).
Therefore, with laser beams ($E << E_c$), it will be possible to study only an effective theory of LbL with an expansion in the fields of the form (*):

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{a}{E_c^2} (F_{\mu\nu} F^{\mu\nu})^2 + \frac{b}{E_c^2} (\tilde{F}_{\mu\nu} F^{\mu\nu})^2.$$

and for energies of the order of [eV-keV]. This has not yet been done... or only very indirectly.

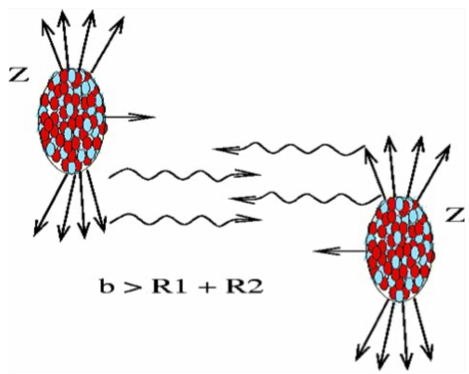
(*) This is the form that follows from QED in the limit $\omega_i << m_e$ and the QED gives in addition: $4b = 7a$ (with the notations above).

How can we get photon-photon interactions at the LHC?

The necessary condition is to have the impact parameter of the reaction b greater than the 'sizes' of the incoming particles (protons or ions): $b > R_1 + R_2$. Then, we can have an interaction between the EM fields of the 2 ions (picture): $\gamma + \gamma \rightarrow ....$

In the following, I consider only collisions of 2 ions, namely $PbPb$ collisions at 5 TeV per nucleon pair.

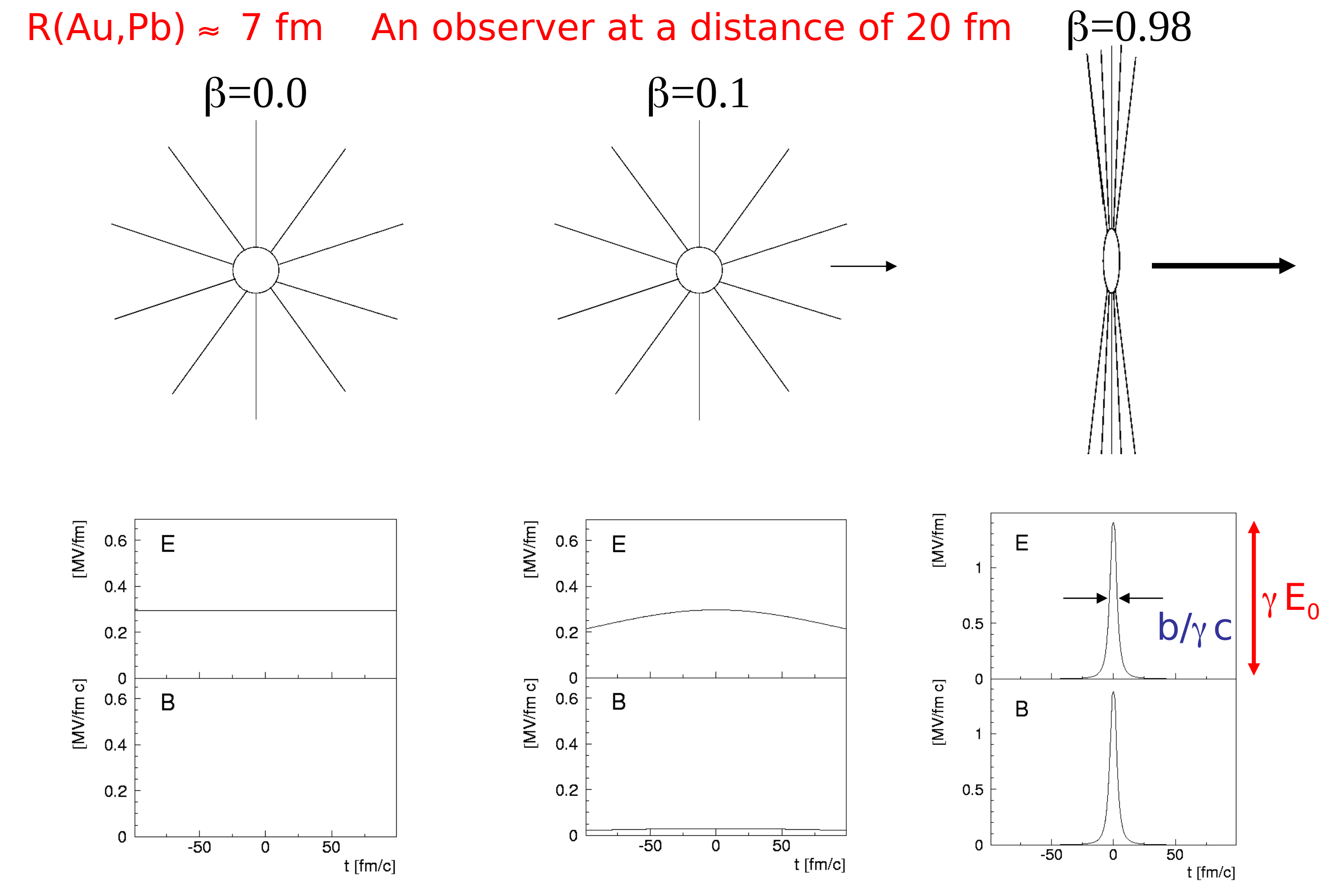
(1) An interesting consequence: the 2 incoming particles are left out quasi-intact after the EM+EM interaction flying along the beam axis.



(2) 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. *Note: in practice, we can not trigger on the condition:* $b > R_1 + R_2$.

Reminder on the EM field of an ultra-relativistic HI

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



(1) This is locally the field of a plane wave of short duration: $\delta t \simeq \frac{R}{\gamma}$.
This also means that this EM field is not mono-chromatic, it includes all frequencies such that: $\omega < \frac{\gamma}{R}$.
For $PbPb$ collisions, this gives: $\omega_{max} \sim 80$ GeV.

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

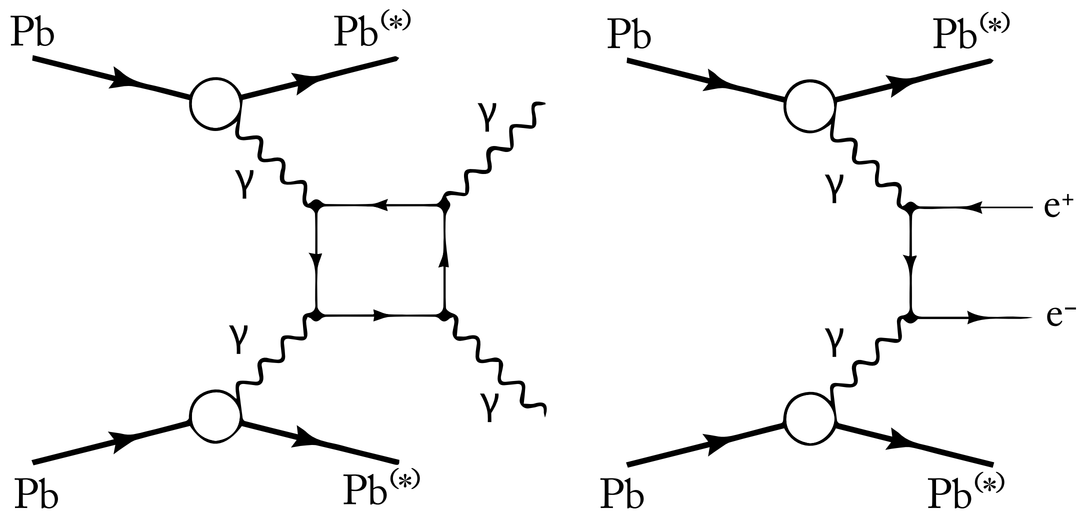
$$\sigma \sim \int\int f(\omega_1) f(\omega_2) \sigma_{\gamma\gamma\to\gamma\gamma}(\omega_1, \omega_2) d\omega_1 d\omega_2$$

$f(\omega)$ is called the number of equivalent photons (I skip technical issues with the impact parameter dependencies). This function $f(.)$ is directly linked to the Poynting vector of the EM field: $\int dSE_{\mathrm{T}}^2(\vec{b}, \omega)/(\pi) = \ \omega\ f(\omega)$.

(3) As $\omega < \frac{\gamma}{b}$, we have: $k_{\mathrm{T}} < \frac{1}{b}$, then $Q^2 = -k^2 = k_{\mathrm{T}}^2 + \frac{\omega^2}{\gamma^2} \simeq 10^{-3}$ GeV$^2 < \frac{1}{R^2}$. Consequently the EM+EM interaction is an interaction between quasi-real photons.

(4) The electric field produced (for an ultra-relativistic Pb ion) is of the order 10^{25} V/m $>> E_c = 10^{18}$ V/m. This allows to produce pairs of real/virtual particles.

Why $PbPb$ w.r.t. other ions?

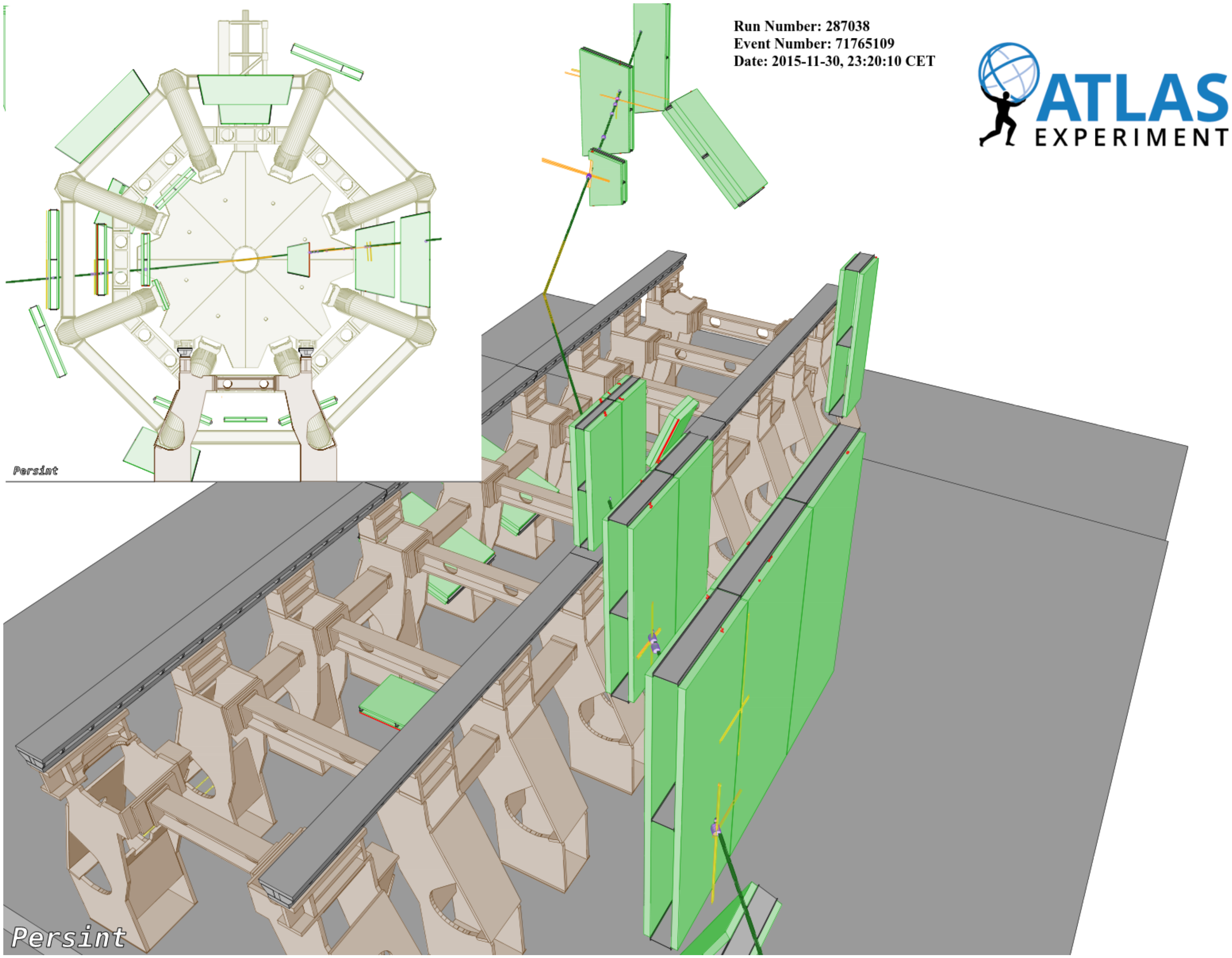


$$f_{\gamma/Pb}(\omega) = Z^2 \frac{\alpha_{em}}{\omega\pi^2} \int d^2\vec{k}_{\mathrm{T}} \frac{k_{\mathrm{T}}^2}{(k_{\mathrm{T}}^2 + \frac{\omega^2}{\gamma^2})^2} G_E^2(k_{\mathrm{T}}^2 + \frac{\omega^2}{\gamma^2}) \simeq Z^2 \frac{2\alpha_{em}}{\omega\pi} \int_0^{\frac{1}{R_{Pb}}} k_{\mathrm{T}} dk_{\mathrm{T}} \frac{k_{\mathrm{T}}^2}{(k_{\mathrm{T}}^2 + \frac{\omega^2}{\gamma^2})^2}$$

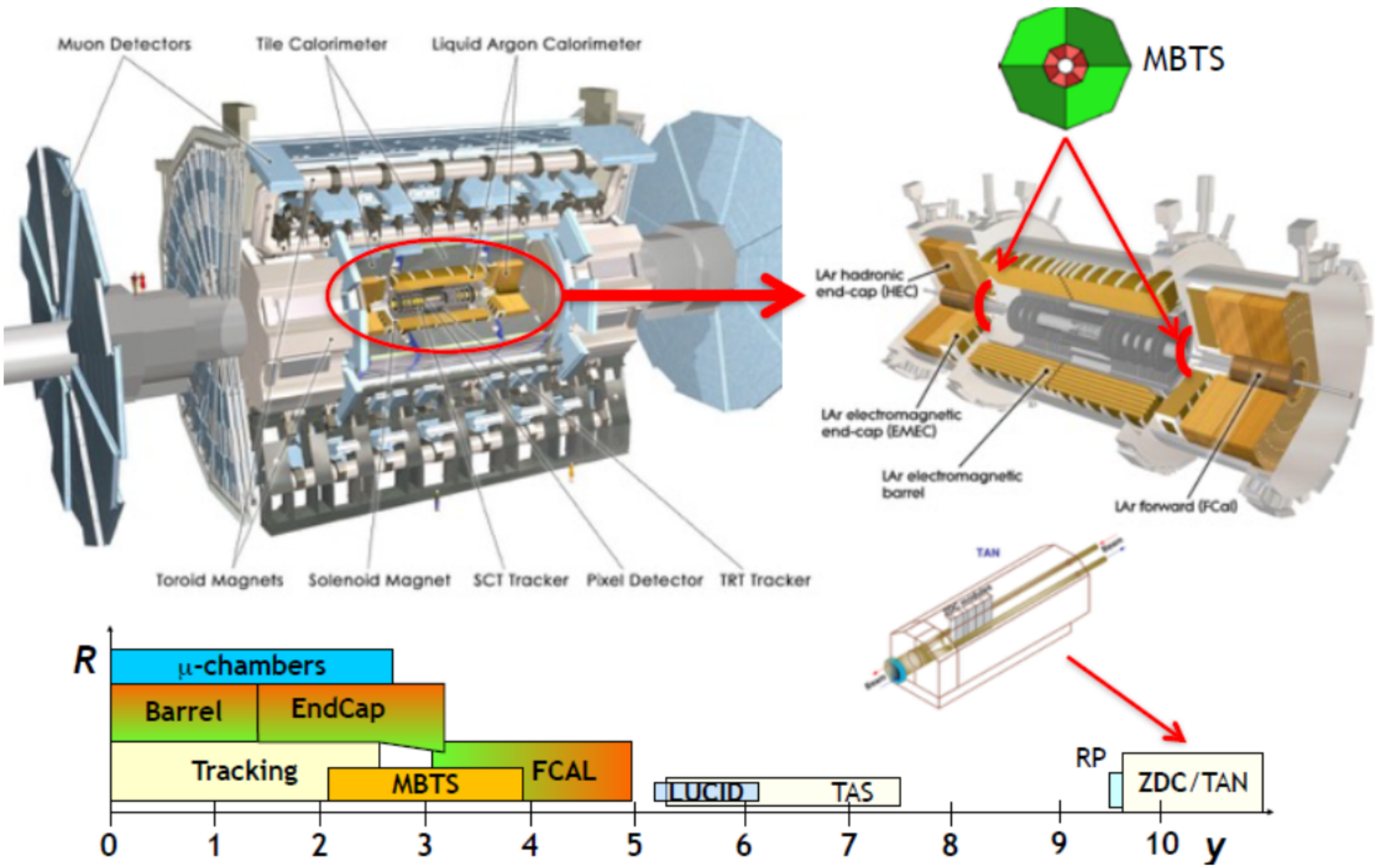
Then, $f(.)f(.)$ will be proportional to $Z^4 = 82^4 \simeq 5\ 10^7$.

OK, on the paper, it works but what happens in practice...

$$Pb + Pb \to PbPb(\gamma\gamma) \to Pb + Pb + \mu^{+} + \mu^{-}$$



Experimental set up



Trigger

The MAIN idea of the analysis is to trigger on events with almost nothing in the detectors (UPC)...
which means that Pb have passed through almost intact. Reminder: we can not require explicitely: $b > 2R$.

In practice, we have used an OR of the 2 triggers:
HLT_hi_upc_FgapAC3_hi_gg_upc_L1TAU1_TE4_VTE200
HLT_hi_upc_FgapAC3_hi_gg_upc_L12TAU1_VTE50

(1) UPC: low activity in the ID, defined by a maximum number of 15 hits in the Pixel Detector (imposed in hi_gg_upc), FCal veto: rejection of events with $E_{T,FCal} > 3$ GeV on any side of FCal (imposed in hi_upc_FgapAC3),
(2) event topology: L1_TAU1_TE4_VTE200: coincidence of 1 EM cluster of $E_T > 1$ GeV and total E_T between 4 and 200 GeV in the EM calorimeter, L1_2TAU1_VTE50: at least 2 EM clusters of $E_T > 1$ GeV and total E_T in the EM calorimeter below 50 GeV.

This corresponds to what we want: this gives a few Hz for triggered events (at HLT).
At this point, we know that we have selected peripheral collisions (we do not know the impact parameter) and we know that we will have events mainly with EM clusters...
Also, it happens that the trigger efficiency is almost 100 % in the domain of the measurement.

Candle events $\gamma\gamma \to e^+e^-$

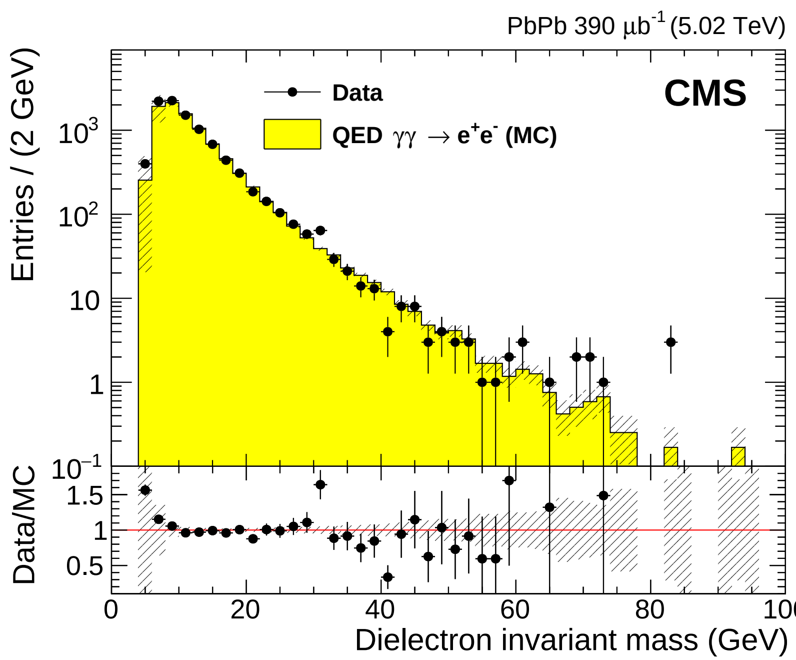
Additional analysis requirements:

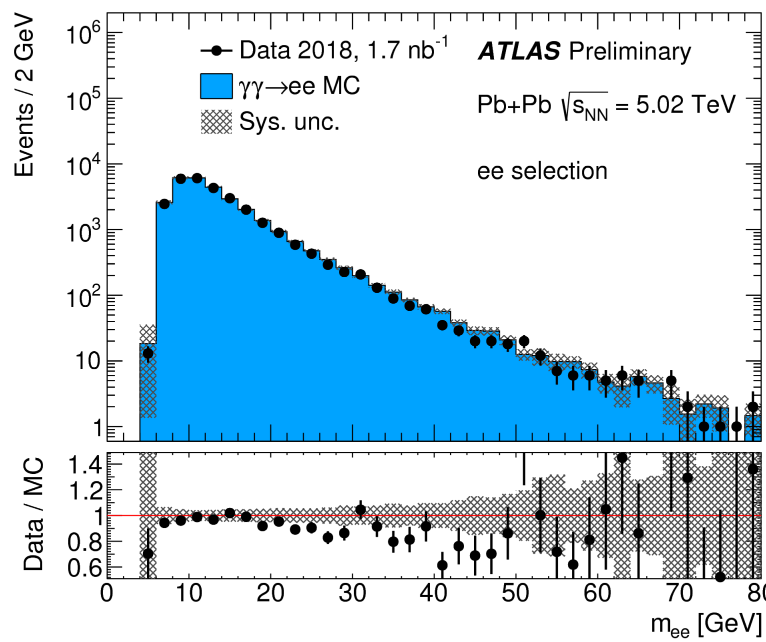
(1) 2 'electrons' with $E_T > 2.5(2)$ GeV $|\eta| < 2.4$ (cracks excluded)

(2) no other track in the event

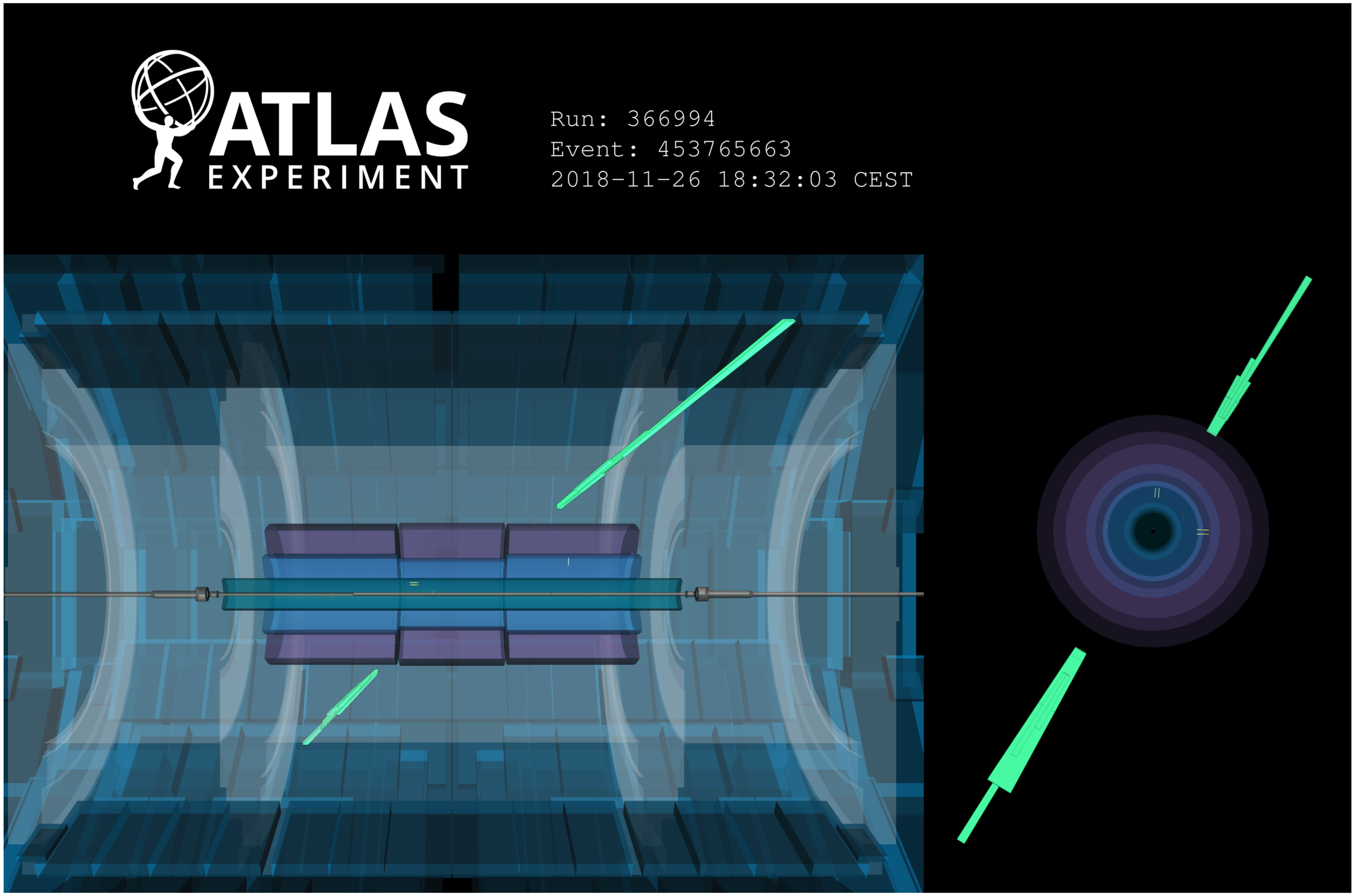
(3) $|\Delta\phi_{\gamma\gamma}/\pi - 1| < 0.01$

$\rightarrow$ the experimental procedure seems to work well.

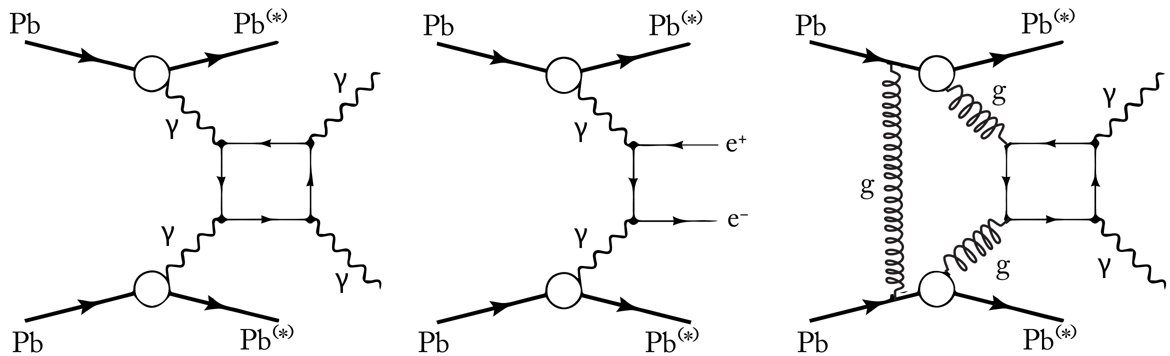




Now: if we turn 'electrons' to 'photons'... we have at least 1 event: $\gamma\gamma \to \gamma\gamma$.

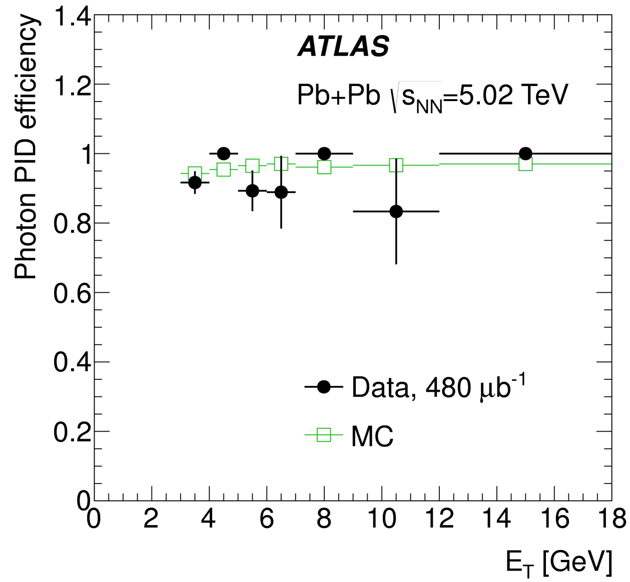


Ideas on the LbL analysis



(1) In the measurement domain, the expected cross-section for $Pb + Pb \to PbPb(\gamma\gamma) \to Pb + Pb + \gamma\gamma$ is $\sigma_{LbL} \sim 45$ nb... For 1.7 nb^{-1}, we expect: 77 LbL events.
(2) One background is the mis-ID e^+e^- final state, identified as photons. From the candle $\gamma\gamma \to e^+e^-$ analysis, we get: $\sigma_{e^+e^-,obs} \sim 20\ \mu$b. Then, let us assume that we have ~ 1 % mis-ID of an electron/positron as a photon: $\sigma_{obs}.(1/100)^2 = 2$ nb. This gives an idea of the order of magnitude of the mis-ID dilepton contribution to the LbL signal (*note:* $\sigma_{obs} \sim 20\ \mu b$ *corresponds to approximately* 82^4 *times the same cross section measured in pp collisions*).
(3) The other irreductible background is from QCD (2 gluons exchange). We expect its visible σ to be < 2 nb in the measured region. *In fact,* $\sigma_{QCD} \propto A^2$ *while* $\sigma_{LbL} \propto Z^4$*... That's why the choice of* $PbPb$ *is favorable to reduce the relative size of the QCD bckg.*

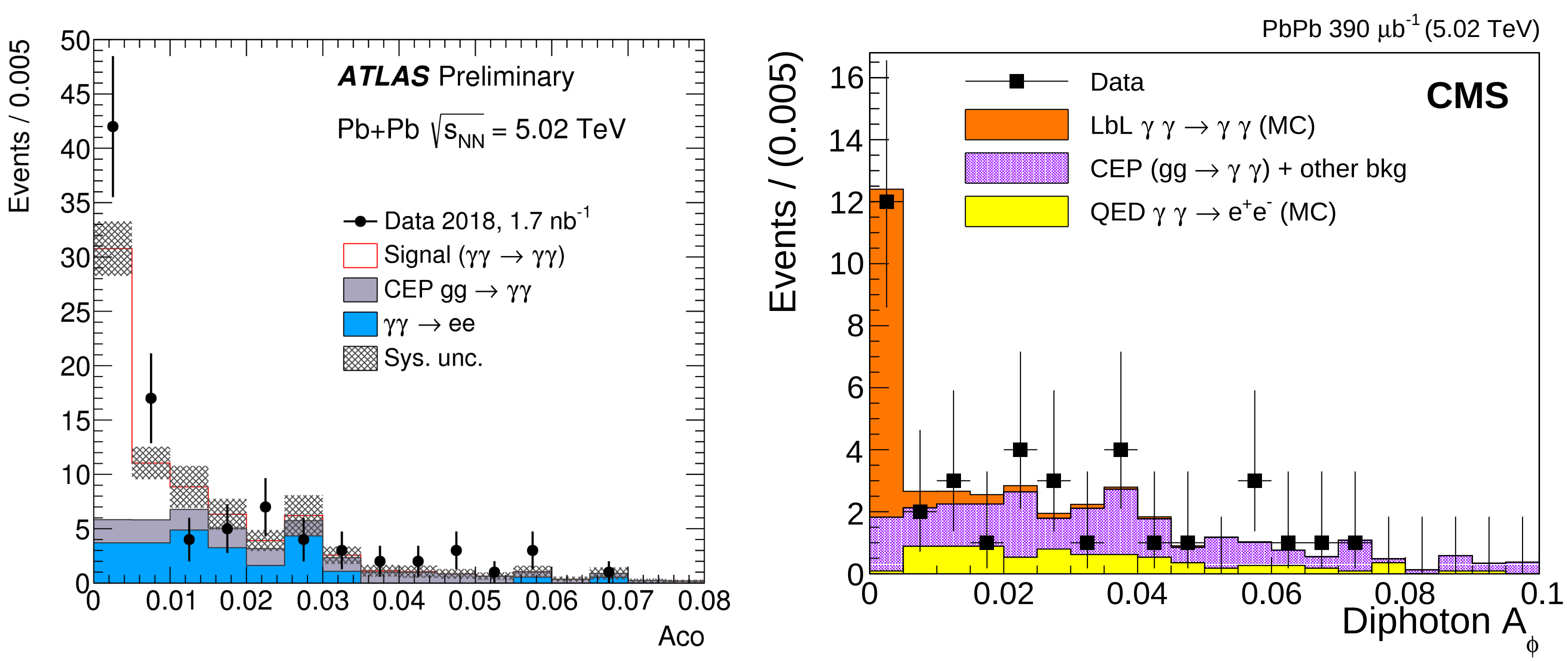
Photon identification (PID) efficiency



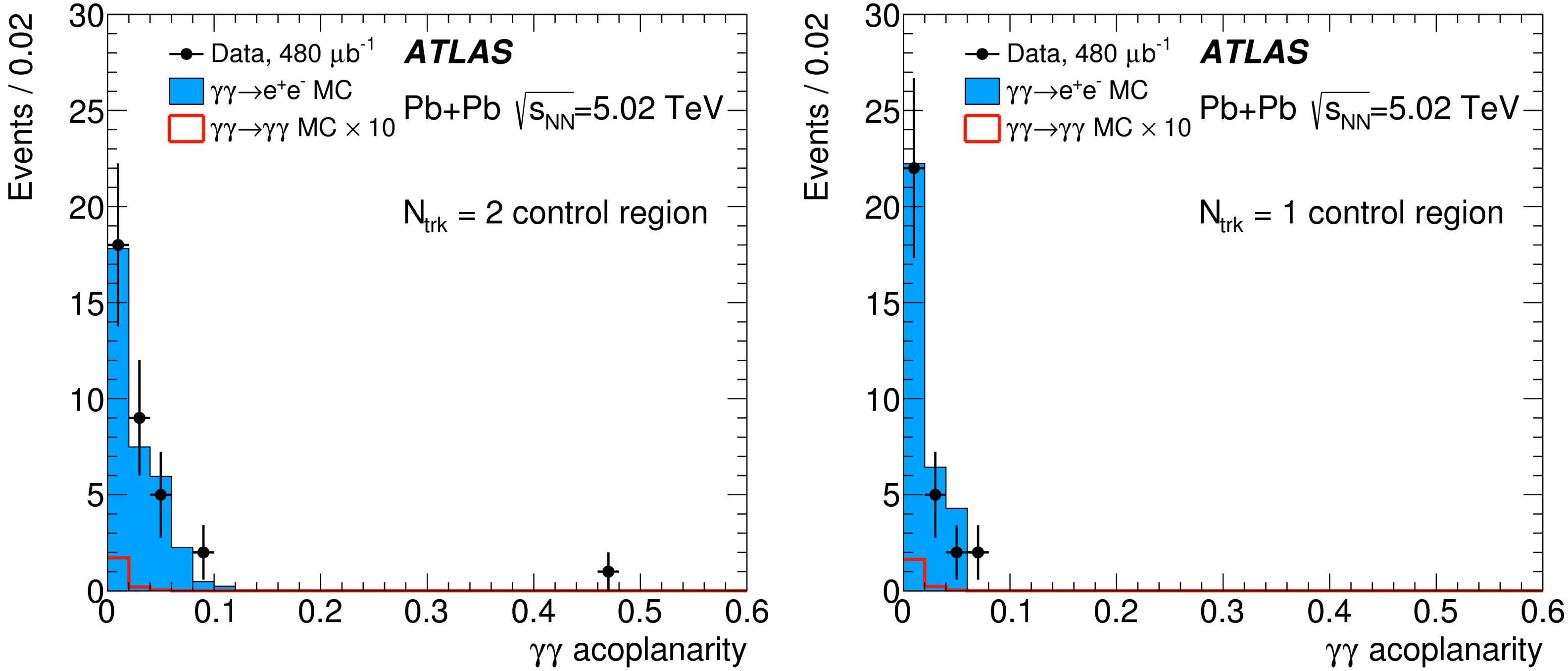
Done with: $\gamma\gamma \rightarrow e^+e^-$ with a final-state radiation (FSR) photon ($p_T^{ee\gamma} < 1$ GeV): events with a photon and two tracks corresponding to oppositely charged particles. The ΔR between a photon candidate and a track is required to be greater than 0.2. The FSR photons are then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

The LbL signal (1)

We are now at the point where we can make the selection in order to extract the LbL signal:
(1) 2 **photons identified** with $E_T > 3(2)$ GeV $|\eta| < 2.4$ (cracks excluded) and $m_{\gamma\gamma} > 6(5)$ GeV, (2) no track in the event (I skip some details here), (3) $p_T(\gamma\gamma) < 2(1)$ GeV
With the LbL signal, there see the other 2 small backgrounds (mentioned in the previous slides)...
(Reminder: $Aco = |\Delta\phi_{\gamma\gamma}/\pi - 1|$)

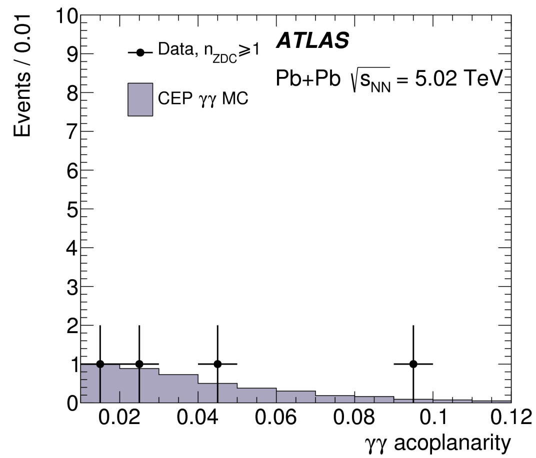


Control of the e^+e^- background



We need to open the selection: same experimental selection as before except for the 'no track' codition.
$N_{trk} = 2$ (but still 2 photons). This means the 2 tracks are not matched to the EM clusters (thus ID as photons), well described.
$N_{trk} = 1$ (but still 2 photons)...

Control of the QCD background

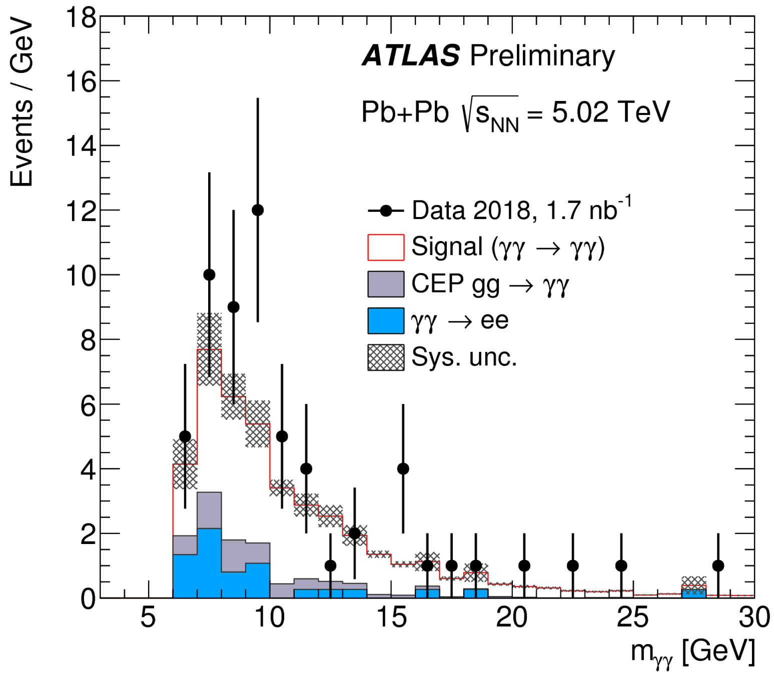


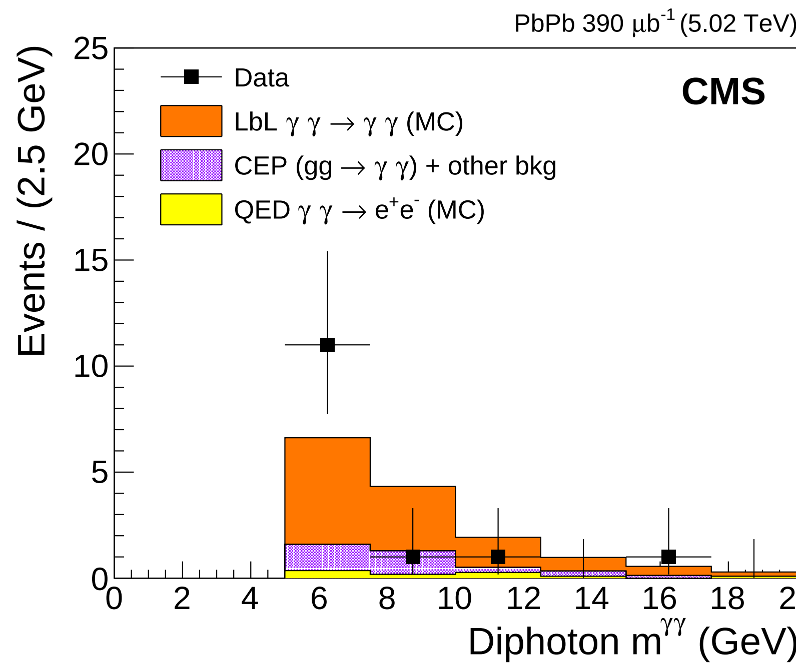
(0) Reminder: In Pb-Pb collisions, CEP is expected to be small... It is normalized for $Aco > 0.02(0.01)$ (all other requirements as before) and this normalization is checked as follows:
(1) Pb-Pb CEP occurs at relatively small impact parameters ($b \sim 2R$), which implies a large probability for nuclear 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).

This has still to be done for the large sample (from december 2018 data).

LbL signal (2)

Adding the selection: $|\Delta\phi_{\gamma\gamma}/\pi - 1| < 0.01$ in order to supress most of the backgrounds, we obtain the main results. $m_{\gamma\gamma} > 6$ GeV (ATLAS) and $m_{\gamma\gamma} > 5$ GeV (ATLAS)





Observation, cross-section

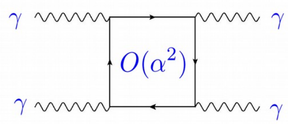
The 2 mass plots can be translated in event numbers and cross sections.
Signal region ($Aco < 0.01$ or $|\Delta\phi_{\gamma\gamma}/\pi - 1| < 0.01$): 59 events observed (12 ± 3 background events)
$Aco < 0.005$: 42 events observed (6 ± 2 background events) $\rightarrow 8.2\sigma$ (6.2σ) observed (expected).

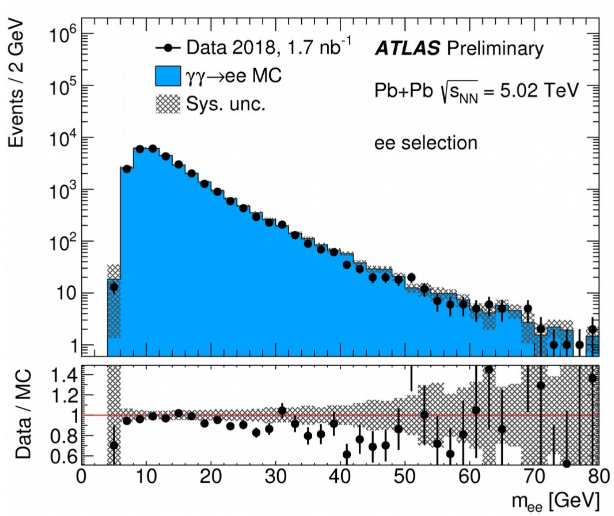
(a) Measured cross section in the fiducial domain ($m_{\gamma\gamma} > 6$ GeV and $p_T(\gamma\gamma) < 2$ GeV+...):
$\sigma(PbPb \rightarrow PbPb\gamma\gamma) = 78 \pm 13(stat) \pm 8(syst)$ nb
SM predictions: 50 ± 5 nb.
(syst)= Photon reco efficiency, PID efficiency, energy scale, energy resolution + trigger.

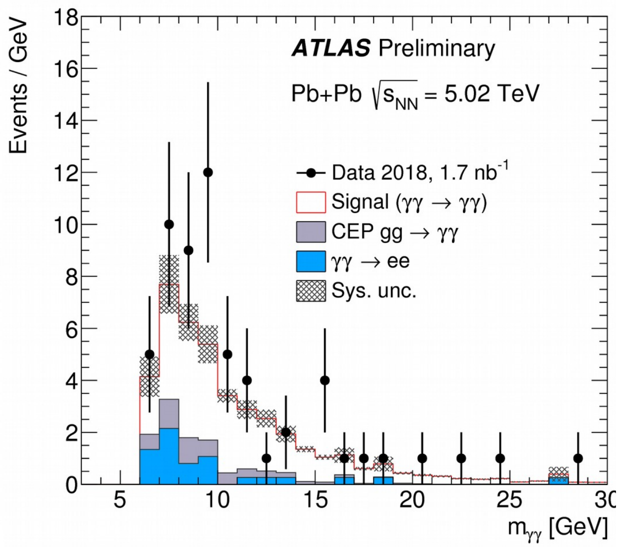
(b) Measured cross section in the fiducial domain ($m_{\gamma\gamma} > 5$ GeV and $p_T(\gamma\gamma) < 1$ GeV+...):
$\sigma(PbPb \rightarrow PbPb\gamma\gamma) = 120 \pm 46(stat) \pm 28(syst) \pm 4(theo)$ nb
SM predictions: 138 ± 14 nb. *σ is increasing fast when decreasing $m_{\gamma\gamma}$.*

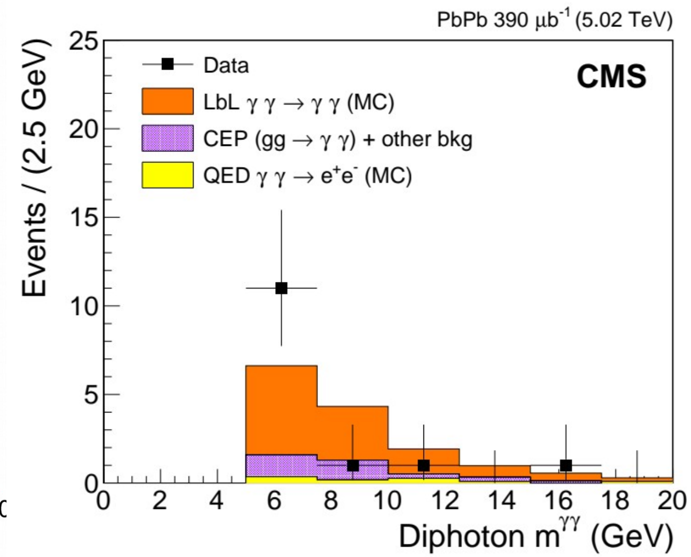
Interestingly, we can convert the PbPb cross section into $\gamma\gamma \rightarrow \gamma\gamma$ cross section: this gives:
$\sigma(\gamma\gamma \rightarrow \gamma\gamma) \sim 1$ pb for $\sqrt{s} \sim 20$ GeV.

To be compared to $\gamma\gamma \rightarrow \gamma\gamma$ theoretical cross section in the visible domain:
$\sigma(\gamma\gamma \rightarrow \gamma\gamma) \sim 3\ 10^{-30}$ pb for $\sqrt{s} \sim 1$ eV (never measured). *Remark: in laser beam experiments, the best strategy is obviously not to measure a cross section but more a deflection angle or a change in the polarisation of one laser beam...*





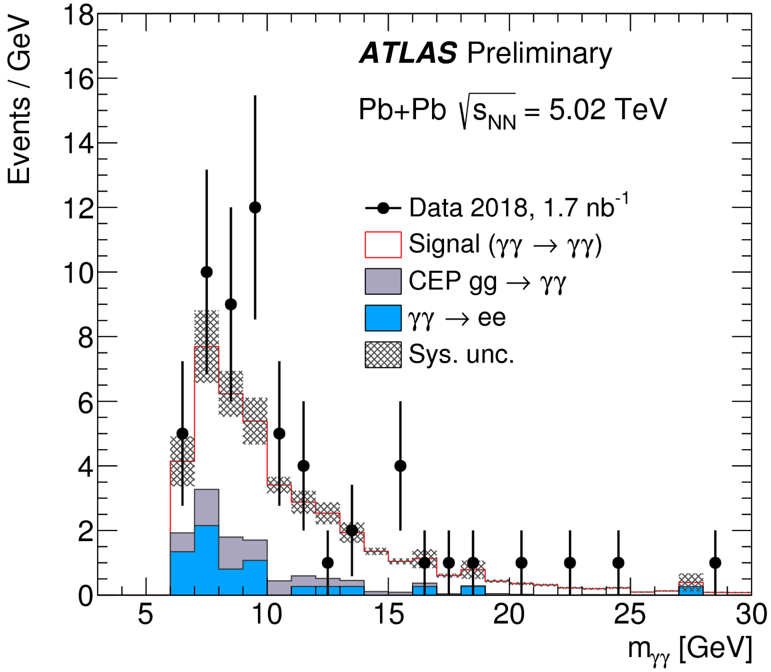


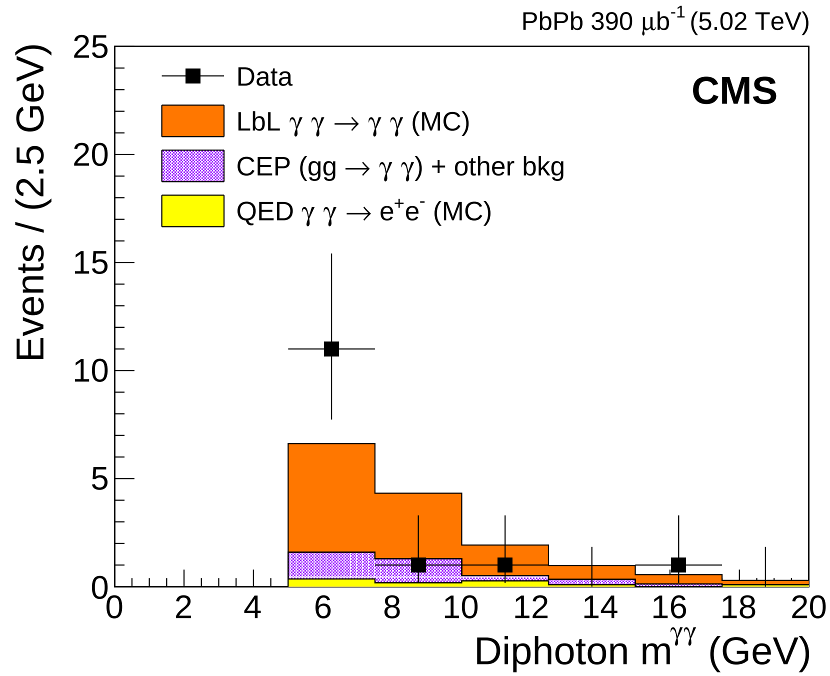


$\gamma\gamma \to e^+e^-$ in $PbPb$ at 5 TeV/A (also called inelastic photon-photon scattering) well described. This means that the photon flux $f(.)$ are correct and the simulation/calculation process is also correct.

Then, if QED is correct, there is no reason for $\gamma\gamma \to \gamma\gamma$ in $PbPb$ at 5 TeV/A (also called elastic photon-photon scattering) not to be well described.

With the measurements (data from 2015 and 2018), we observe discrepancies/fluctuations for data/theory comparisons at $\sim 2.5\ \sigma$.





Clearly, what is needed is to get the new analysis of CMS out. Also, in the future, more statistics (at least 10 nb^{-1} in $PbPb$) + other ions + larger energies.

For example, in $PbPb$ at 10 TeV/A, it will be possible to reach invariant $\gamma\gamma$ masses of 320 GeV (max) and then to study contributions of loops of W bosons to the loop.

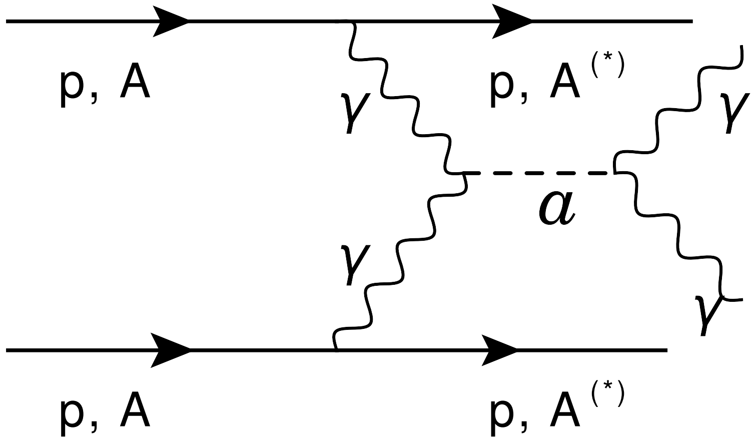
We can also consider that these discrepancies are hints of something new and test some ideas: bumps, shape...

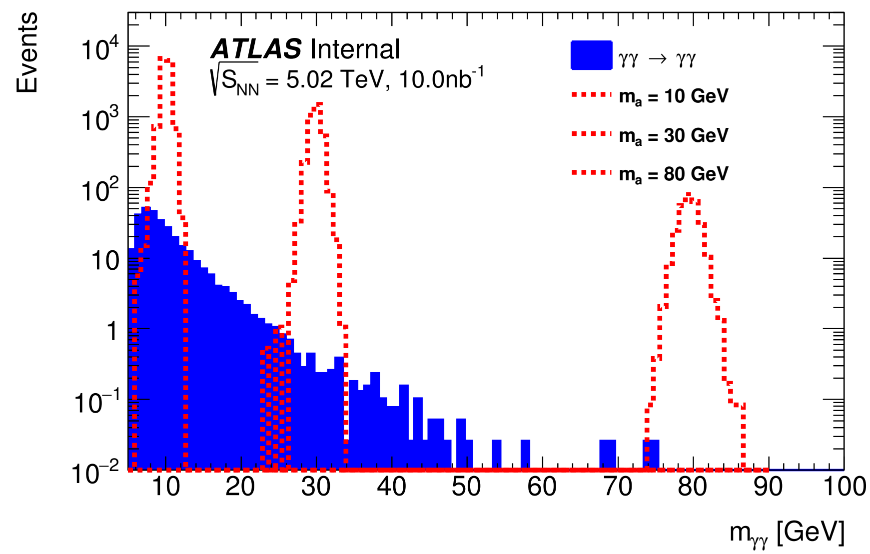
Future plans at CERN

Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1} **[7-9] TeV**
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined) **[7-9] TeV**
	pp reference	1 week	

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams: *CERN-LPCC-2018-07.*

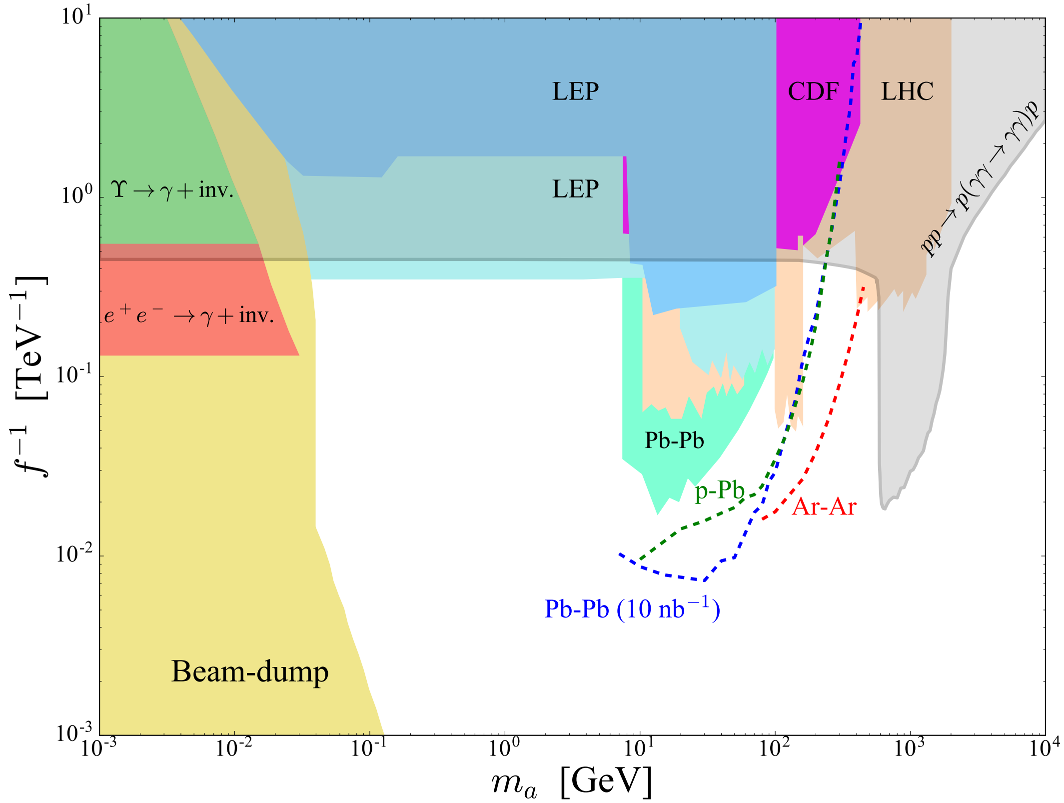
Exchange of resonant intermediate states





We can study deviations to the LbL cross section (or resonances) due to massive (pseudo-)scalar fields $a(.)$ (of masses $m_a > 5$ GeV) that couple to EM fields: $\mathcal{L}_{a\gamma\gamma} = \frac{1}{f} a F^{\mu\nu} \tilde{F}_{\mu\nu}$, where $1/f$ is in $1/$TeV $= a(.)$-photon coupling. The cross section for the production of $a(.)$ (Figure) is then:
$\sigma_a = \int f(\omega_1) f(\omega_2) \sigma_{\gamma\gamma\to a\to\gamma\gamma}(\omega_1, \omega_2) d\omega_1 d\omega_2$, that we can easily compute in the narrow resonance approximation with a decay width of $a(.)$ in 2 photons: $\Gamma(a \to \gamma\gamma) = \frac{m_a^3}{4\pi f^2}$. We call $a(.)$ Axion or ALP.
Possibly, we could have intermediate spin 2 states, but we restrict the discussion to spin 0 here.
Figure (right) from CERN-LPCC-2018-07.

Exclusion coutours



Extending the constraint for axion-like particles as resonances at the LHC and laser beam experiments: arXiv:1903.04151.

Remark: $a(.)$ that we can search (this analysis) are not the ones from QCD or astrophysics of masses from keV down to sub μeV.

At low energies also, ALP and LbL are linked

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m a^2 + \frac{1}{f} a F^{\mu\nu}\tilde{F}_{\mu\nu} + \mathcal{L}_{EM}$$

This means: $(\partial_\mu \partial^\mu + m^2)a = -\frac{4}{f}$ **E** $\cdot$ **B**, and an harmonic field $a(.)$ is of the form **E** $\cdot$ **B**... Thus the $a(.)$-photon interaction (Lagrangian density) is of the form $(F^{\mu\nu}\tilde{F}_{\mu\nu})^2$, which is also a term of the effective approach of LbL. So, depending of $1/f$ both terms (LbL vs $a(.)$) are competing.

In arXiv:1903.04151, we have studied the 'equivalent' of proton-ion or ion-ion at the LHC but with laser beams (and in thus the eV range) with the interaction of 2 counter-propagating harmonic plane waves:

$$\mathbf{E}_0 = E_0 \mathbf{e}_x e^{i\omega_0(t+z)} + c.c.$$

and

$$\mathbf{E}_1 = (E_{1,x}\mathbf{e}_x + E_{1,y}\mathbf{e}_y) e^{i\omega(t-z)} + c.c.$$

with $E_0 \gg E_{1,x}, E_{1,y}$. Then, we can show that the vacuum becomes birefringent with 2 optical indices:

$n_x = 1 + 16\frac{a}{E_c^2}|E_0|^2$ and $n_y = 1 + 28\frac{a}{E_c^2}|E_0|^2 + \frac{4(4/f)^2 m_a^2 |E_0|^2}{m_a^4 - (4\omega_0\omega)^2}$ (keeping notations of slide 3)

and here also we observe a **resonant** effect, this time for Axions of masses in the eV domain.

Perspectives

LbL at the LHC: we have clearly posed a new theme in the community. More data are needed and this is foreseen to reach 10 nb^{-1} in 2021-22 in $PbPb$ collisions at 5 TeV/A! At present, we observe some discrepancies/fluctuations of the data versus predictions. In the future, this will be closed by more data.

The most promising interpretations BSM are ALP at masses > 5 GeV but also EFT for the large energy behavior. This last part would be easier with ions of smaller R (to reach larger energies for the photons $\omega < \gamma/R$) or even to observe LbL in proton-ion collisions: at present, this is not possible, but maybe in 2023 (either in $p - Pb$ or $p - Ox$).
In this case, we would be very close to what is done in laser beam experiments but in another range of energies.

In the near future, we will commit a new paper with a single analysis for all ATLAS data 2015+2018 with interpretations. And possibly, in the intermediate future, this would be even better to make a common global paper with CMS: in this case, we could reach ~ 4.5 nb^{-1} in PbP at 5 TeV/A.

Interestingly, we can mention that LbL using laser facilities is showing a revival with groups at LAL, Japan, China... and we try to follow up all this also in terms of ideas/interpretations with already one paper and others to come.