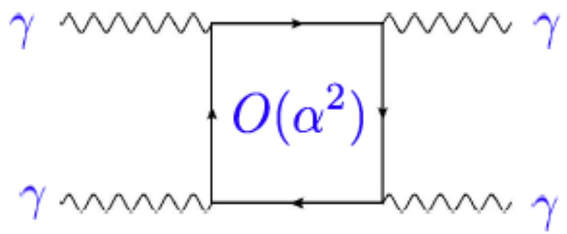
Light-by-light scattering from SLAC to the LHC and exotic searches

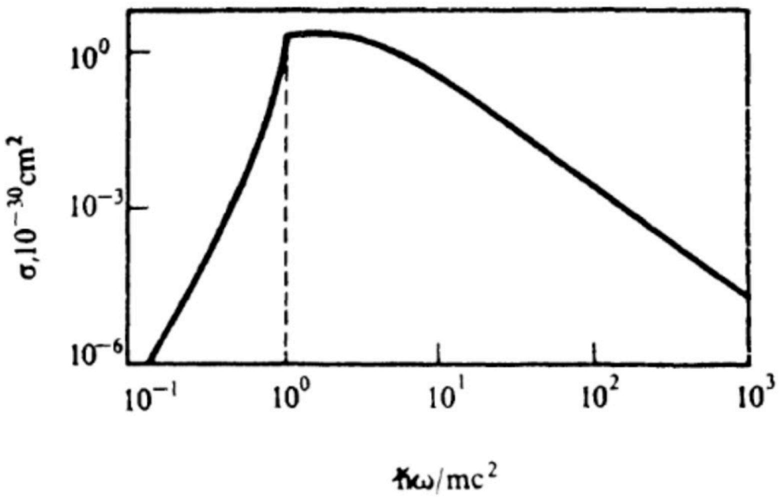
LHC Forward Physics WG 5/03/2021

Laurent Schoeffel
CEA/Saclay

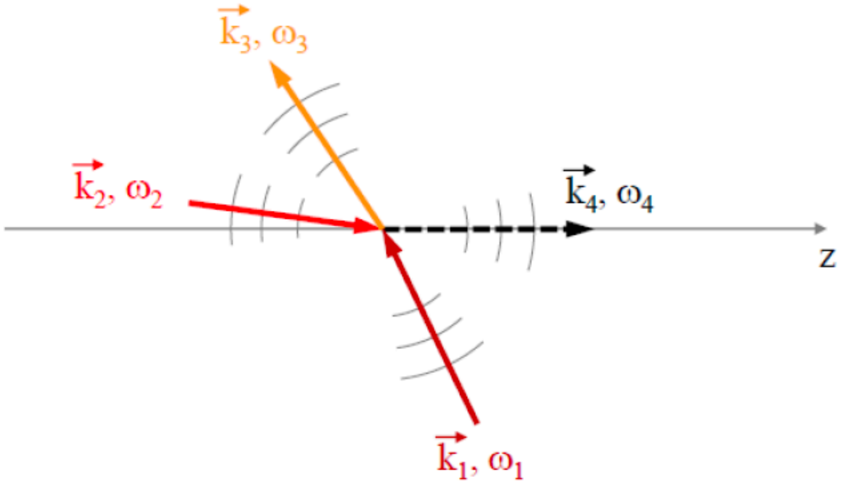
1) Light-by-light scattering (publications by the LHC) with a foreword on early SLAC experiments
   Work of many people: Krakow group, CERN, Kansas, Saclay, Mainz, Rabbat…

2) Interpretations (and perspectives) based on:
https://arxiv.org/abs/1903.04151. *with C. Baldenegro, S. Hassani, C. Royon*
https://arxiv.org/abs/2010.07855 *(review for PPNP)*





LbL scattering in its full glory



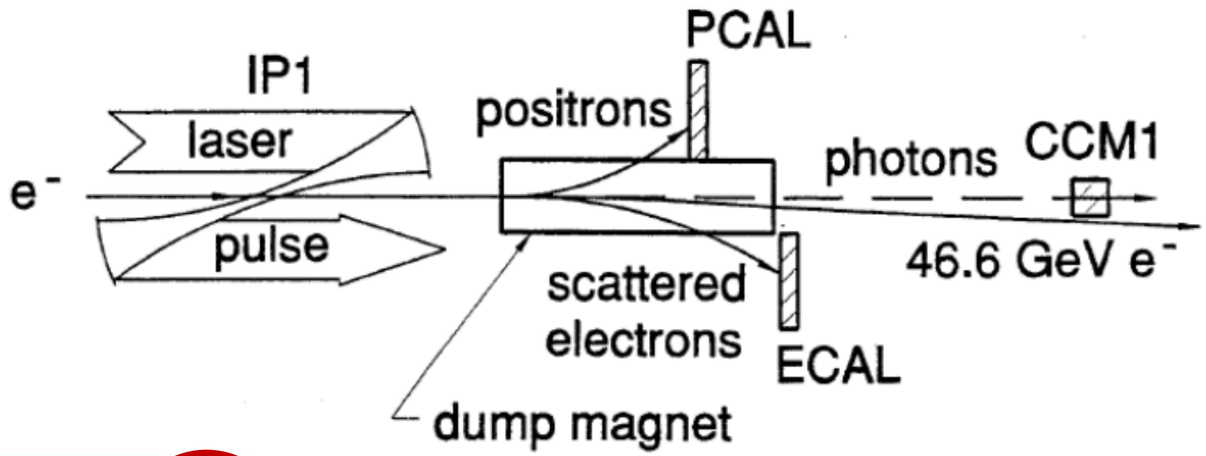
Note: to create a real pair $\gamma\gamma \to e^+e^-$, we need EM field intensity (E) of order: $eE\lambda_e(=\frac{1}{m_e}) \geq m_e$.
This gives: $E \geq E_c \sim 10^{18}$ V/m and $B \geq B_c \sim 4\ 10^9$ T (or intensity $I \sim 10^{29}$ W/cm^2).
Therefore, with laser beams $(E << E_c)$, it will be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

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

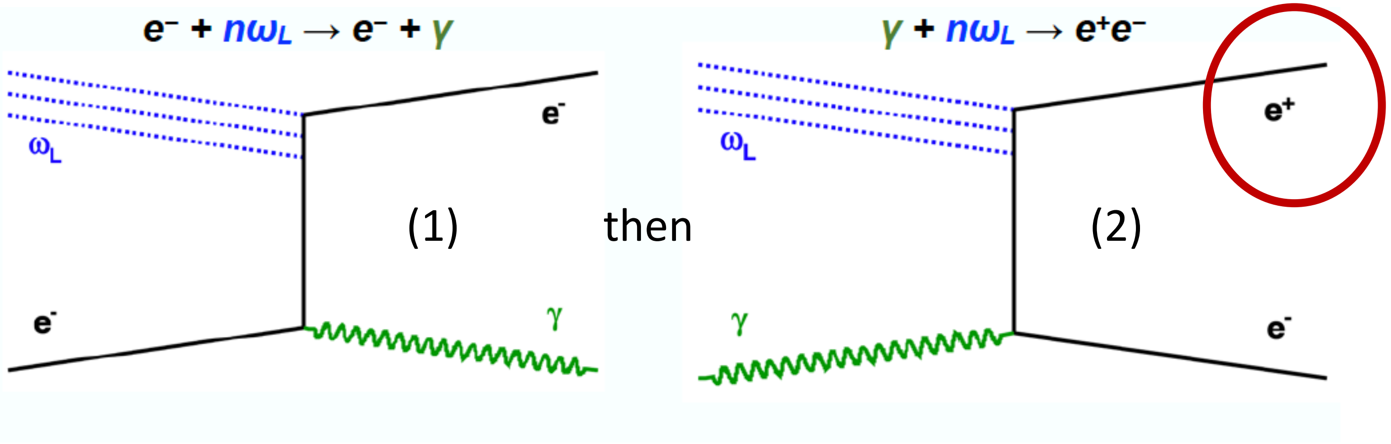
and for energies of the order of [eV-keV]. This has not yet been done… or only very indirectly.

(*) 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).

First experiments at SLAC 1990
E-144



Non-linear Compton scattering

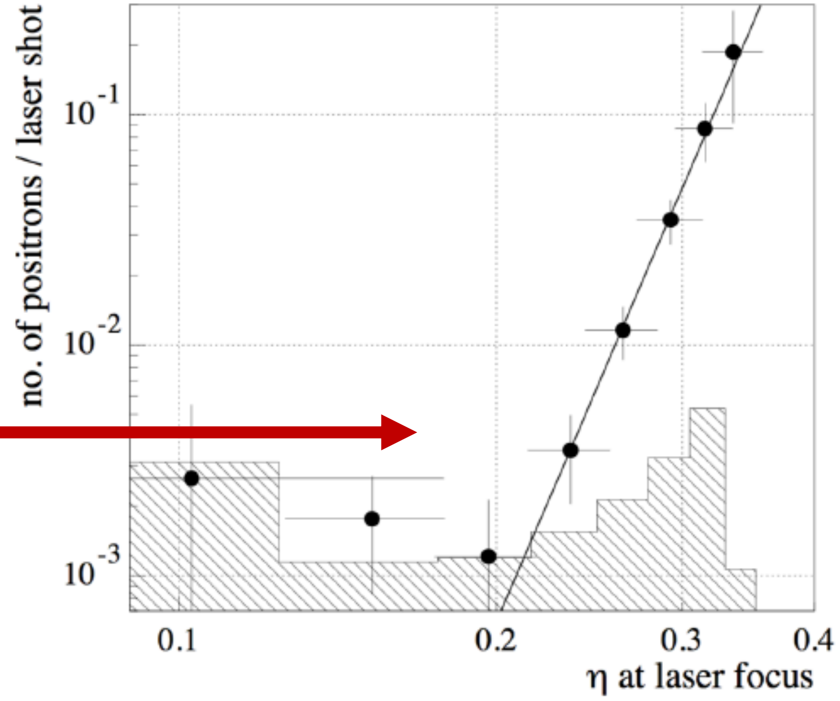


$$\eta = \frac{eE_{rms}}{\omega_0 m_e}$$

$\eta > 1$ in high intensity QED
(at SLAC, η could reach 0.3-0.4)

$R_{e+} \sim \eta^{2n}$

$\eta < 1$ but high enough to observe non-linearity effects

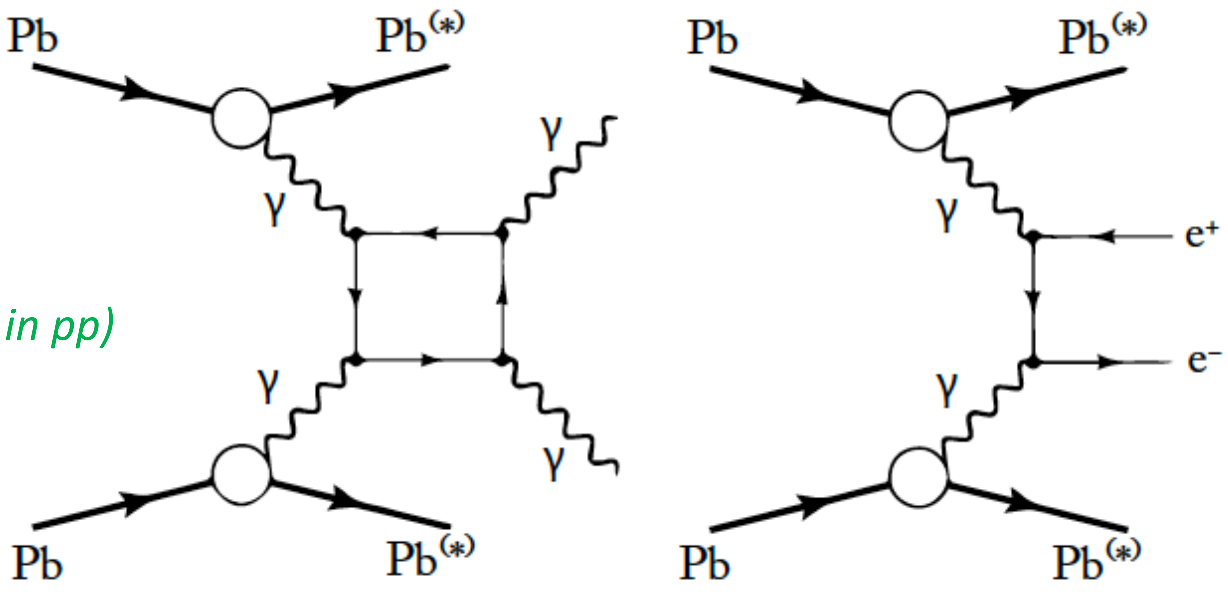


PbPb UPC scattering at the LHC

Luminosity (UPC)

$$\mathcal{L}_{\rm PbPb}(\gamma\gamma)/\mathcal{L}_{pp}(\gamma\gamma) = Z^4 \times \mathcal{L}_{\rm PbPb}/\mathcal{L}_{pp} = 4.5\cdot 10^7 \times (6\cdot 10^{27})/(2\cdot 10^{34}) \approx 10$$

All the results are obtained with
PbPb at 5.02 TeV /nucleon pair
(which corresponds to about 13 TeV in pp)

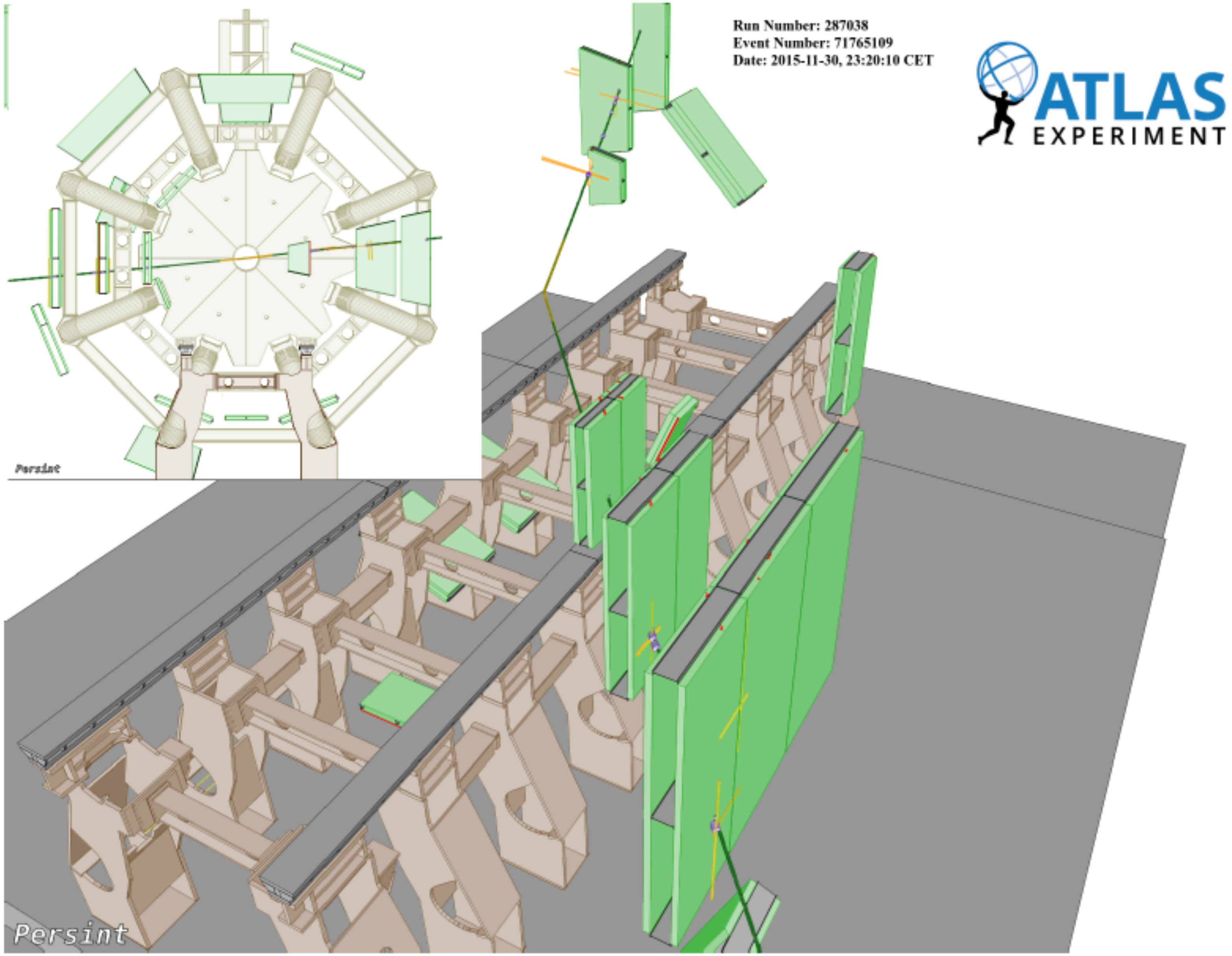


$$f_{\gamma/Pb}(\omega) = Z^2\frac{\alpha_{em}}{\omega\pi^2}\int d^2\vec{k}_{\rm T}\frac{k_{\rm T}^2}{(k_{\rm T}^2+\frac{\omega^2}{\gamma^2})^2}G_E^2(k_{\rm T}^2+\frac{\omega^2}{\gamma^2}) \simeq Z^2\frac{2\alpha_{em}}{\omega\pi}\int_0^{\frac{1}{R_{Pb}}} k_{\rm T}dk_{\rm T}\frac{k_{\rm T}^2}{(k_{\rm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

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...

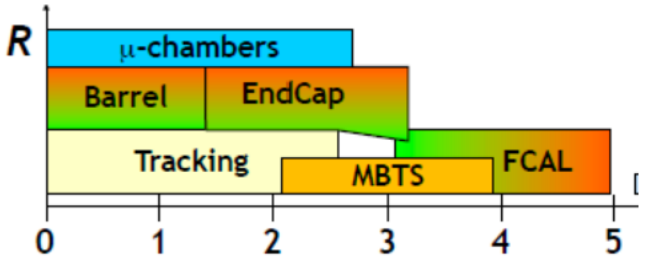
$$Pb + Pb \rightarrow PbPb(\gamma\gamma) \rightarrow Pb + Pb + \mu^+ + \mu^-$$



Trigger the events of interest at the LHC

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

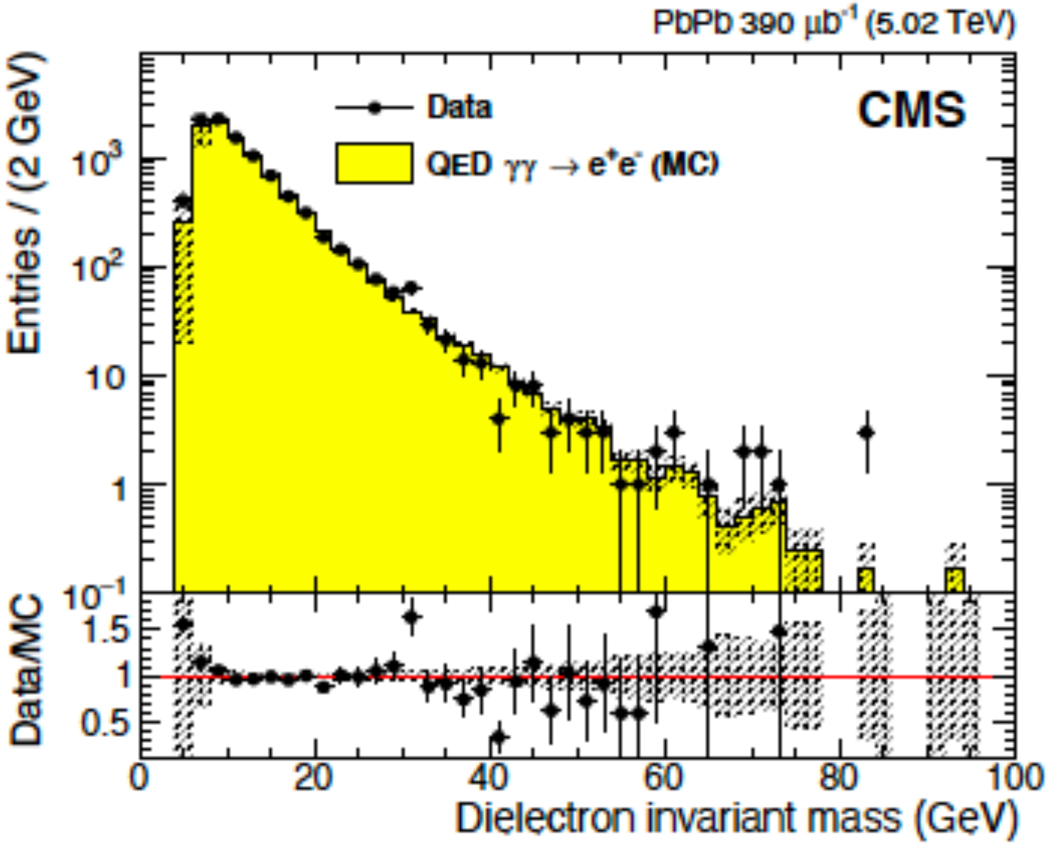


(1) UPC: low activity in the ID, defined by a maximum number of 15 hits in the Pixel Detector (imposed in hi_gg_upc), FCal veto: rejection of events with $E_{T,FCal} > 3$ GeV on any side of FCal (imposed in hi_upc_FgapAC3),
(2) event topology: L1_TAU1_TE4_VTE200: coincidence of 1 EM cluster of $E_T >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

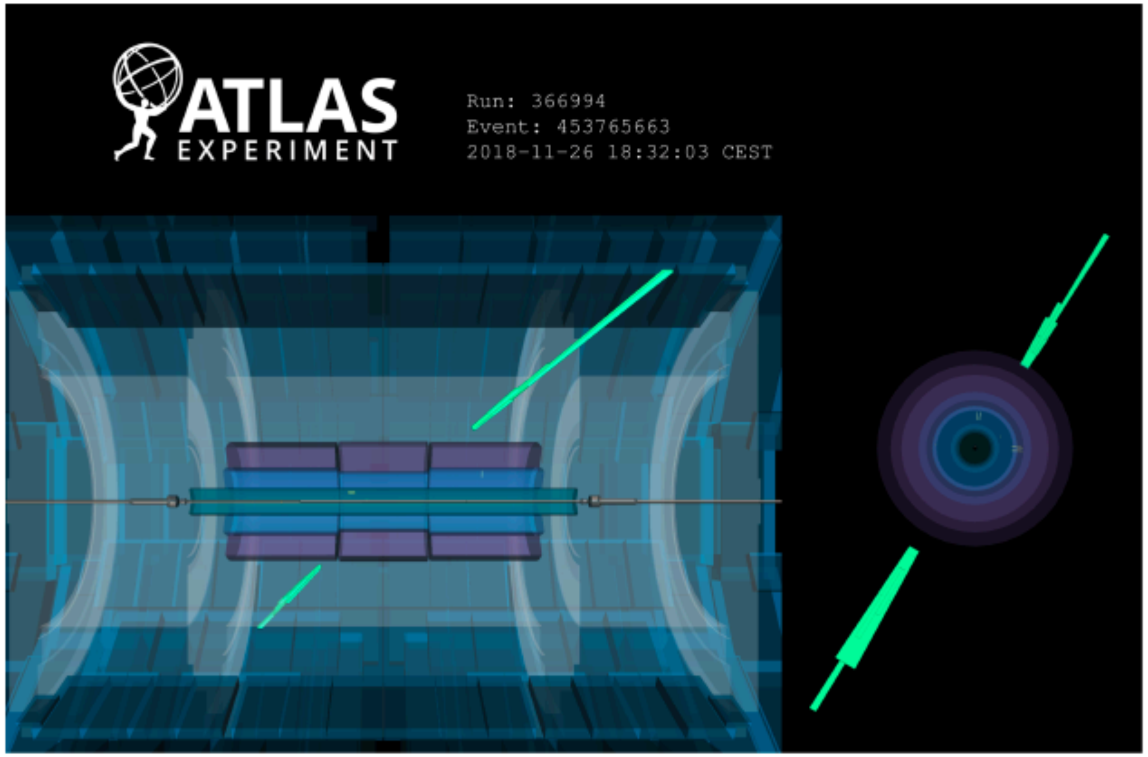
This corresponds to what we want: this gives a few Hz for triggered events (at HLT).
At this point, we know that we have selected peripheral collisions (we do not know the impact parameter) and we know that we will have events mainly with EM clusters...
Also, it happens that the trigger efficiency is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

Control sample

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.

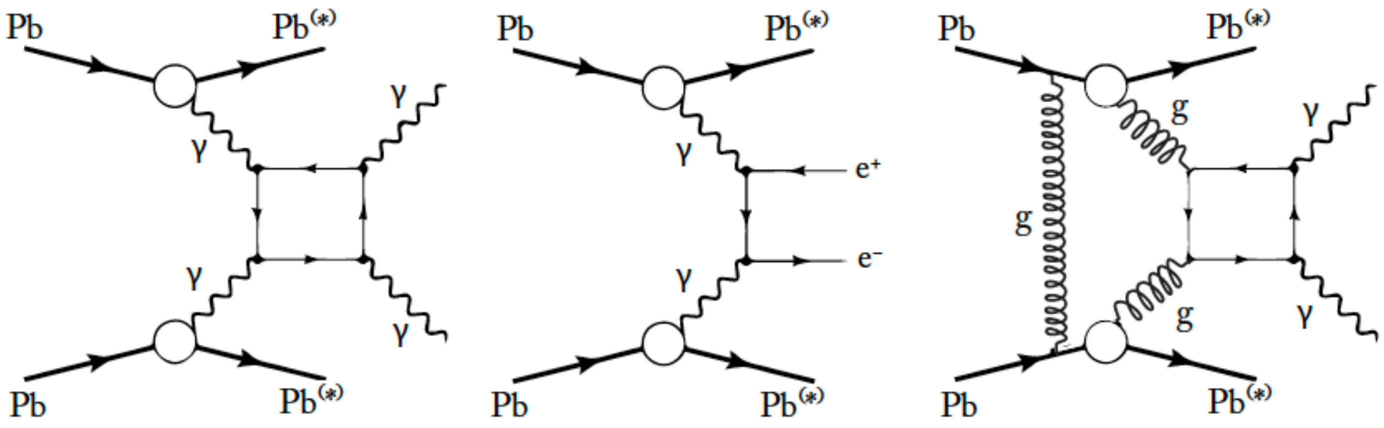


Turn electrons-selection to photons



LbL signal event as recorded in the detector

Backgrounds



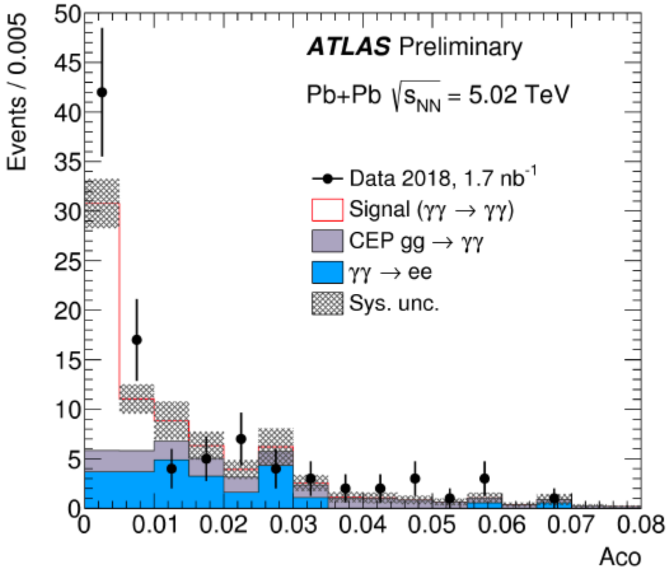
(1) In the measurement domain, the expected cross-section for $Pb + Pb \rightarrow PbPb(\gamma\gamma) \rightarrow Pb + Pb + \gamma\gamma$ is $\sigma_{LbL} \sim 45$ nb... For 1.7 nb^{-1}, we expect: 77 LbL events.

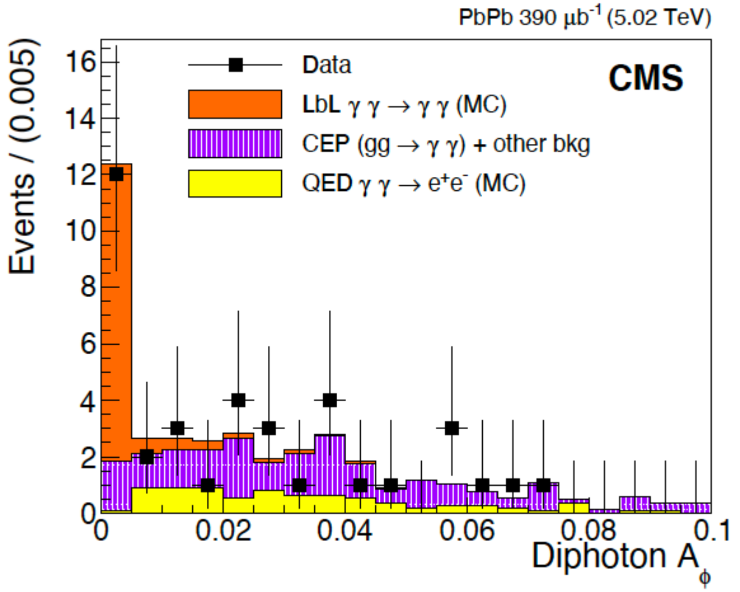
(2) One background is the mis-ID e^+e^- final state, identified as photons. From the candle $\gamma\gamma \rightarrow e^+e^-$ analysis, we get: $\sigma_{e^+e^-,obs} \sim 20\ \mu$b. Then, let us assume that we have ~ 1 % mis-ID of an electron/positron as a photon: $\sigma_{obs}.(1/100)^2 = 2$ nb. This 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*).

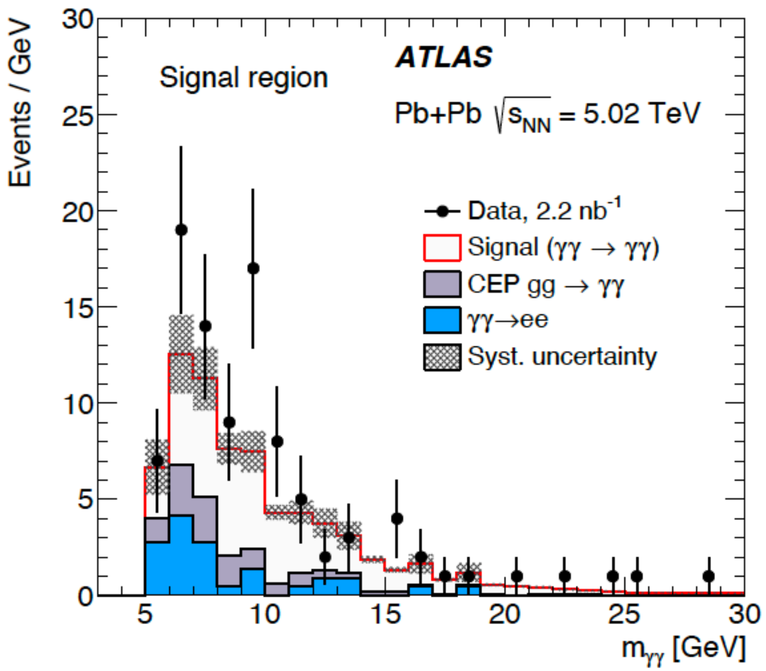
(3) The other irreductible background is from QCD (2 gluons exchange). We expect its visible σ to be < 2 nb in the measured region. *In fact, $\sigma_{QCD} \propto A^2$ while $\sigma_{LbL} \propto Z^4$... That's why the choice of PbPb is favorable to reduce the relative size of the QCD bckg.*

LbL signal events in plots

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: $Aco = |\Delta\phi_{\gamma\gamma}/\pi - 1|$)



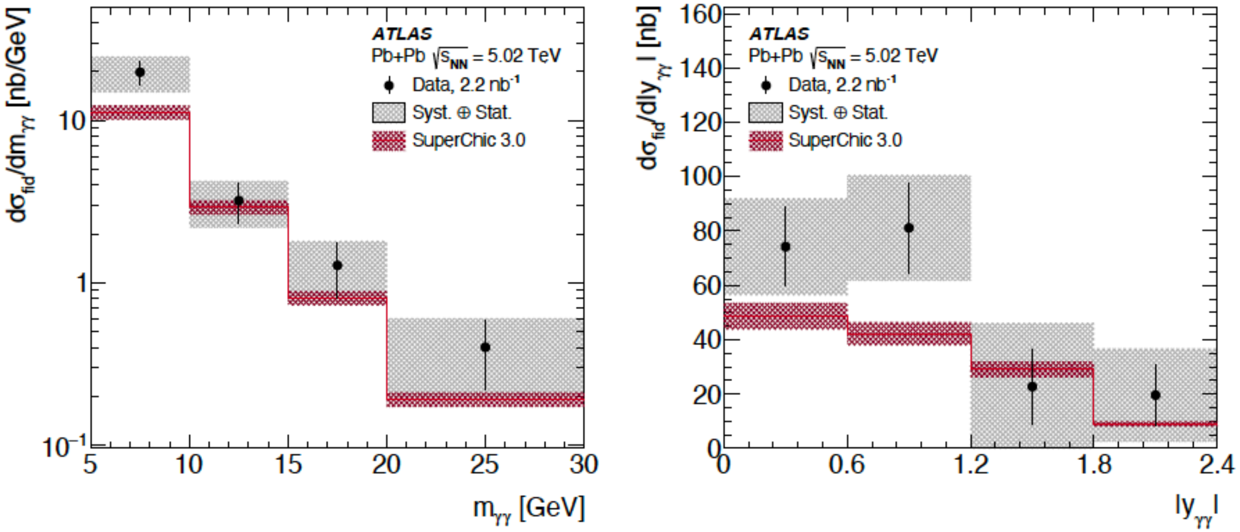




Adding the selection: $|\Delta\phi_{\gamma\gamma}/\pi - 1| < 0.01$ in order to supress most of the backgrounds, we obtain the main results. $m_{\gamma\gamma} > 6$ GeV (ATLAS) and $m_{\gamma\gamma} > 5$ GeV (ATLAS)

Results cross sections

Differential and global values



(a) Measured cross section in the fiducial domain ($m_{\gamma\gamma} > 6$ GeV and $p_T(\gamma\gamma) < 2$ GeV+...):
$\sigma(PbPb \to PbPb\gamma\gamma) = 78 \pm 13(stat) \pm 8(syst)$ 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+...):
$\sigma(PbPb \to PbPb\gamma\gamma) = 120 \pm 46(stat) \pm 28(syst) \pm 4(theo)$ nb
SM predictions: 138 ± 14 nb. σ *is increasing fast when decreasing* $m_{\gamma\gamma}$.

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

To be compared to $\gamma\gamma \to \gamma\gamma$ theoretical cross section in the visible domain:
$\sigma(\gamma\gamma \to \gamma\gamma) \sim 3\ 10^{-30}$ 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...*

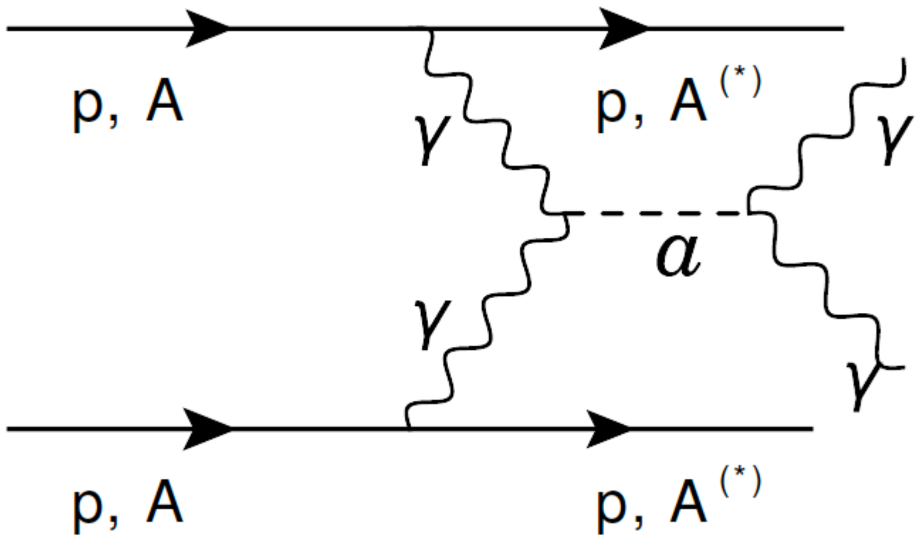
Future UPC data taking at the LHC

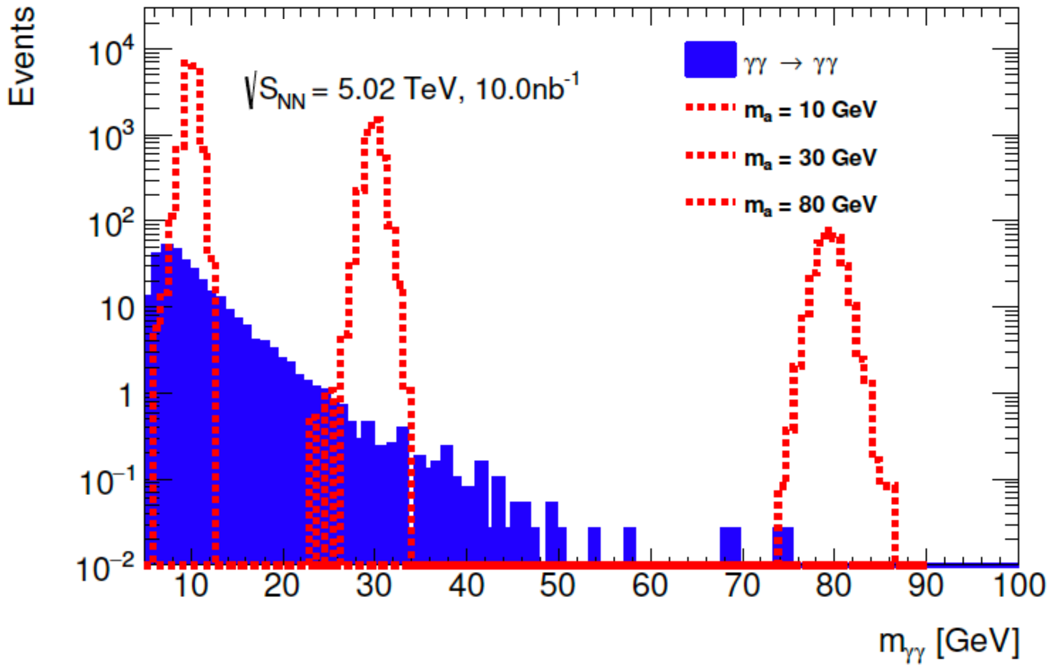
Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1} **[7-9] TeV**
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, 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	

LbL cross section for O-O is about (8/82)^4=0.9 10^{-4} the cross section for Pb-Pb
->needs a larger data-taking as foreseen for LbL
Ar-Ar (18/82)^4=2 10^{-3} would be preferable but this may happen in a long time

Use the LbL analysis for exotic searches

ALPs



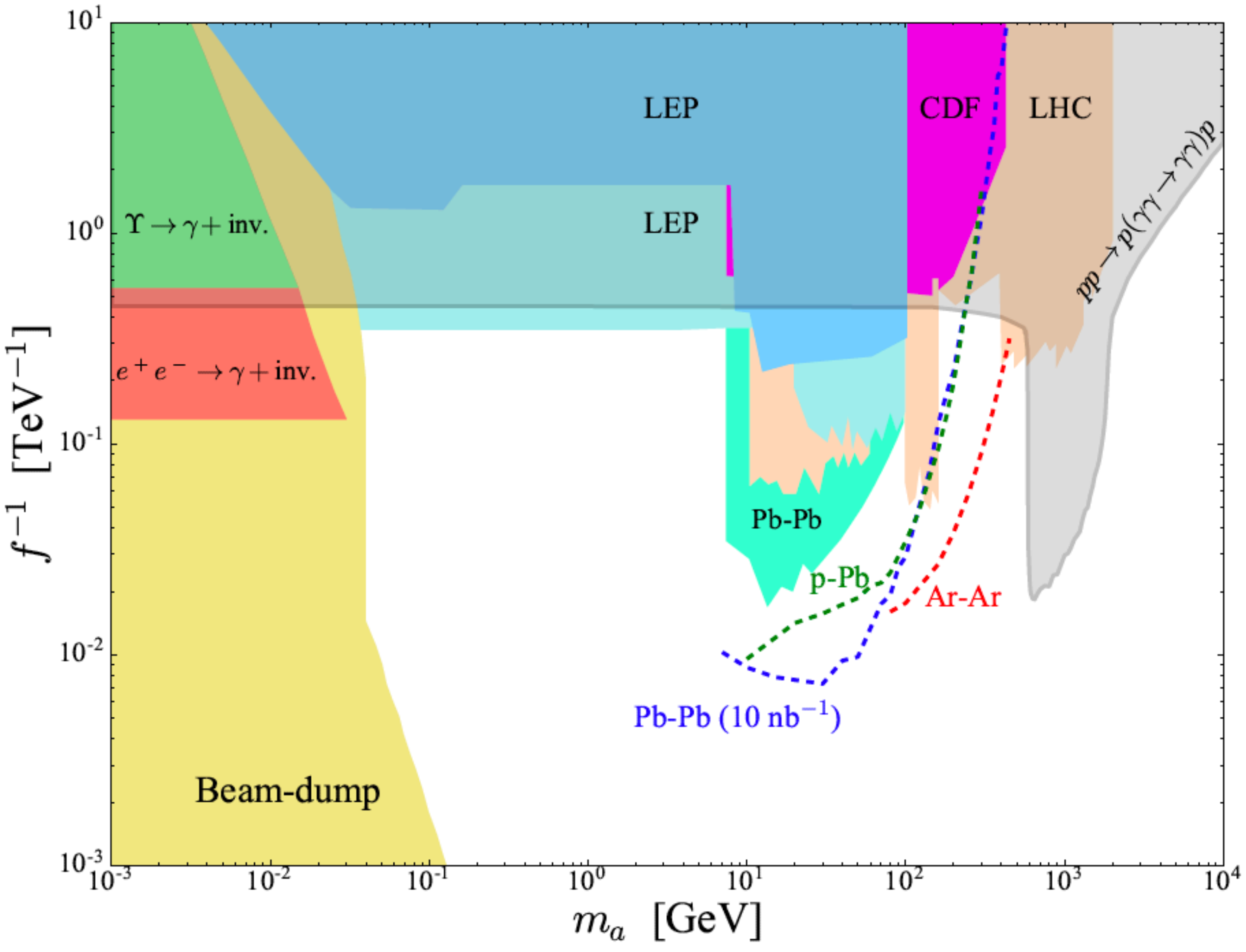


We can study deviations to the LbL cross section (or resonances) due to massive (pseudo-)scalar fields $a(.)$ (of masses $m_a > 5$ GeV) that couple to EM fields: $\mathcal{L}_{a\gamma\gamma} = \frac{1}{f} a F^{\mu\nu} \tilde{F}_{\mu\nu}$, where $1/f$ is in $1/\text{TeV} = a(.)$-photon coupling. The cross 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.

ALPs: photon-photon-ALP coupling limit (ALP mass)

Interestingly, we observe that other HI collisions would be helpful to improve these results

Also higher masses (grey area) are reachable using proton-tagging techniques... In a near future?!



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

Extra-dimensions

We assume that a coordinate system exists with a nearly Minkowski metric of the form:

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{1}{M_S^{n/2+1}} h_{\mu\nu}(x_\mu).$$

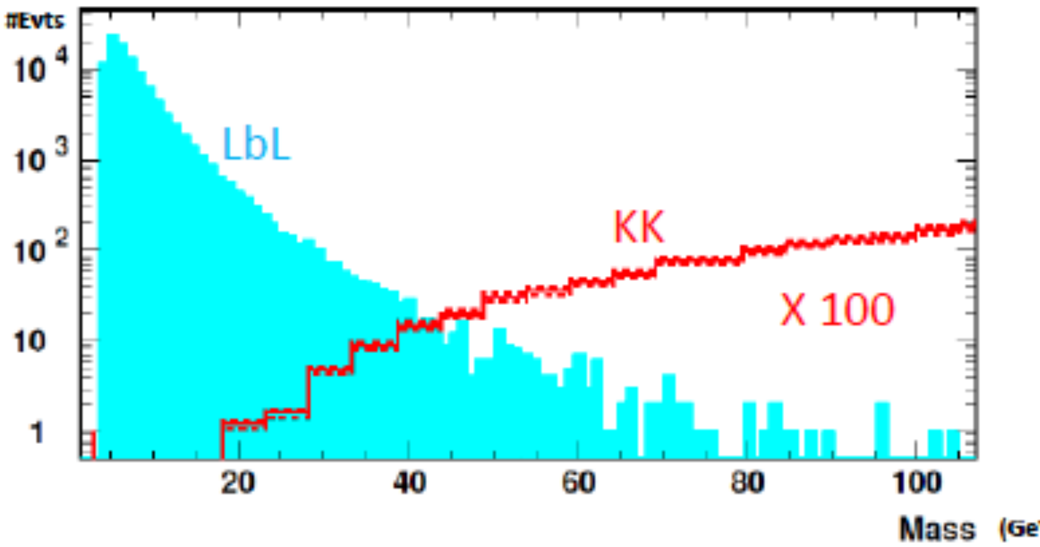
$$M_{pl}^2 \sim R^n M_S^{n+2}.$$

R is the scale of the wrapped dimensions

h(.) is the graviton field (which acts as a fluctuation of the standard metric)
From this form, it is possible to derive the photon-graviton interaction:

$$\mathcal{L}_{int} = \frac{1}{f_2} h^{\mu\nu} \left((-F_{\mu\rho} F_\nu^\rho) + \eta_{\mu\nu} F_{\rho\lambda} F^{\rho\lambda}/4 \right).$$

And then the deviation of the LbL cross section due to this new field…



Then, the observed cross section gives a limit on the mass of the (KK) graviton of smallest mass…

We found m<5.1 TeV at 95%CL

https://arxiv.org/abs/2010.07855

At low energies also, LbL and ALPs 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: $(\partial_\mu \partial^\mu + m^2)a = -\frac{4}{f}\,\mathbf{E}\cdot\mathbf{B}$, and an harmonic field $a(.)$ is of the form $\mathbf{E}\cdot\mathbf{B}$... 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 $\boxed{n_y = 1 + 28\frac{a}{E_c^2}|E_0|^2 + \frac{4(4/f)^2 m_a^2 |E_0|^2}{m_a^4 - (4\omega_0\omega)^2}}$ (keeping notations of slide 3)

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

Perspectives for LbL

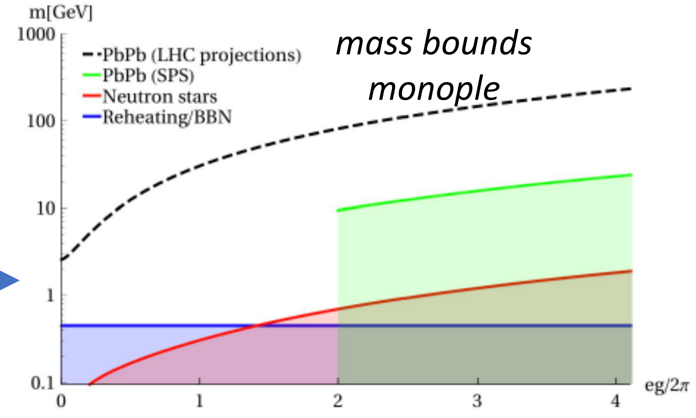
New data taking periods in PbPb and OO will happen in 2022 at the LHC
while analyses using proton-tagging techniques are still on going with existing data.

talks/results at this meeting

The interest (to my view) is to improve statistics in LbL for searches:
new particles of spin 0 or 2.
Clearly, this signal has proven its efficiency in getting some constraints on exotic searches.

Also on going, there are analyses "searching" for loops of monopoles using existing data.

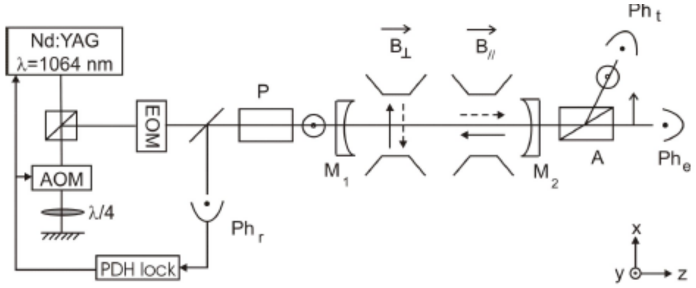
mass bounds monople



Gould, Rajantie, Phys.Rev.Lett. 119 (2017) 24, 241601

Bruce et al., J.Phys.G 47 (2020) 6, 060501

Of course, the most beautiful would be a first evidence in a way or another
in the optical domain:
Some ideas have been given in the previous slides.
There are many other possibilities…
some of them are active fields of research in different places.



@ Toulouse (Fr)