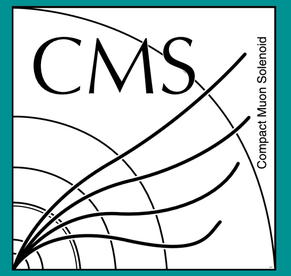
Photon induced processes results at CMS

Low-x 2021, Isola d'Elba, Italy

Beatriz Lopes
on behalf of the CMS collaboration

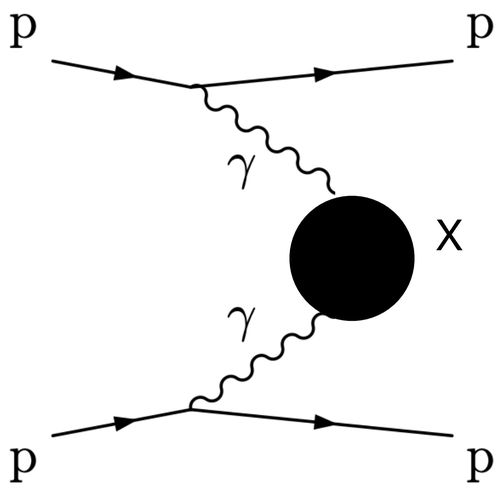
29/09/2021



HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Photon-induced processes

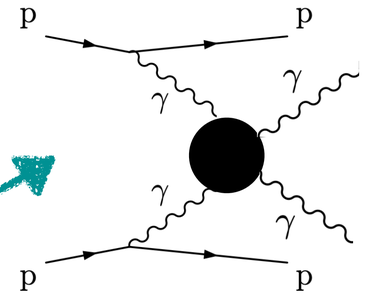
Introduction



- Photon-induced processes at the LHC can be measured as exclusive processes
- What do we call **exclusive production** of a system X?

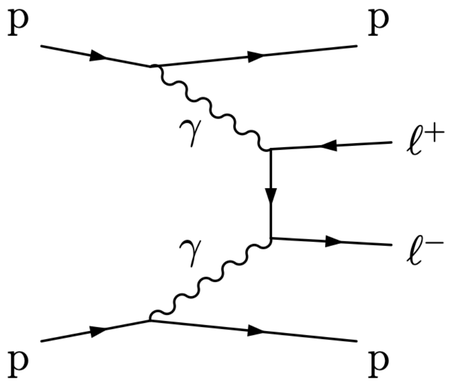
  (X can be ee, $\mu\mu$, $\gamma\gamma$, WW, ZZ, Zγ, $t\bar{t}$, etc.)

  - X is produced and protons leave collision intact (stay in the beam pipe at very small angles)
  - No proton remnants: only activity detected in central detector are decay products of X
  - Intact protons can be measured using dedicated forward detectors
  - In case X=$\gamma\gamma$, it is often called light-by-light scattering (LbyL)



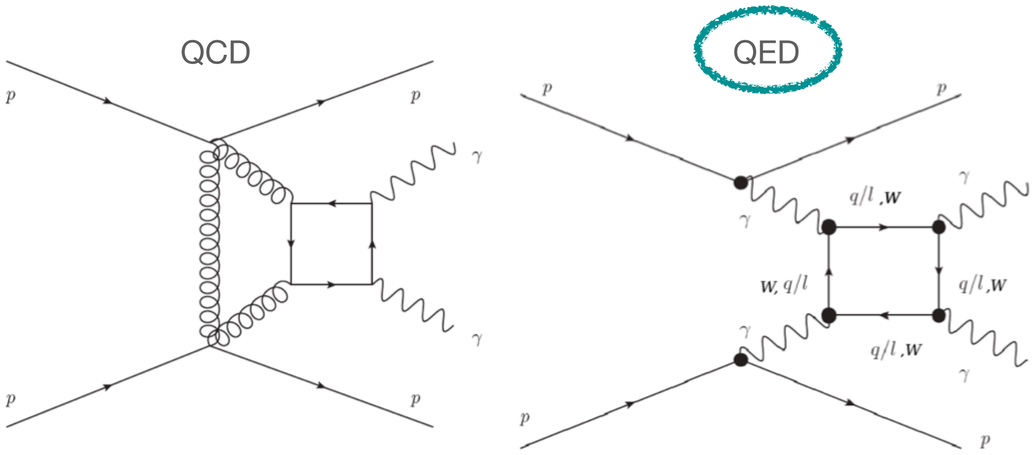
Photon-induced processes

Not all exclusive processes are photon-induced (QED)…

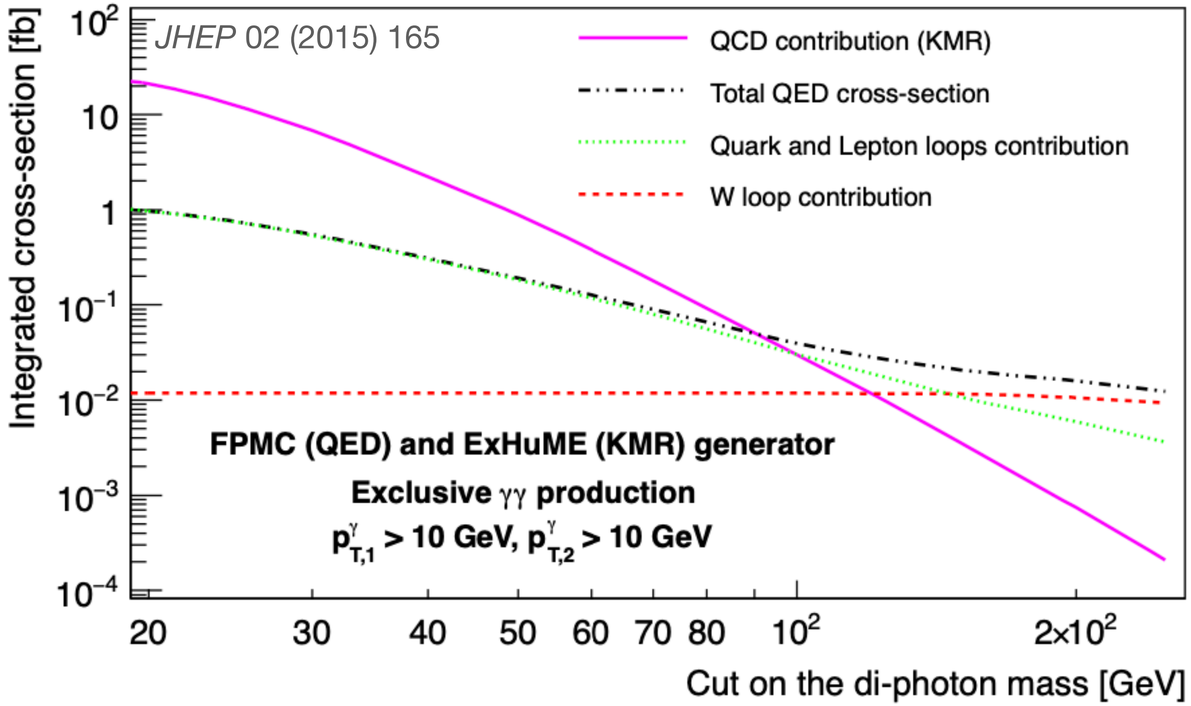


- Exclusive dilepton ($ee, \mu\mu$) production is always a QED process

- Whereas exclusive $\gamma\gamma$ is:
  - dominated by QCD at low mass
  - dominated by QED at high mass



S. Fichet, G. von Gersdorff , B. Lenzi , C. Royon , M. Saimpert



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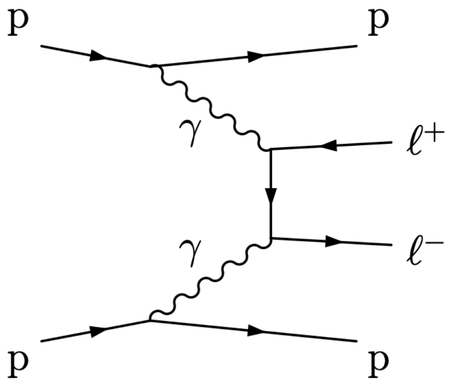

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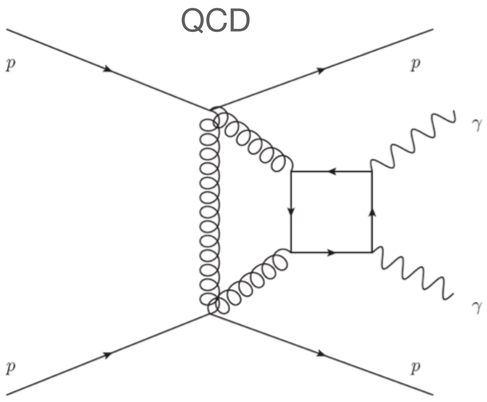
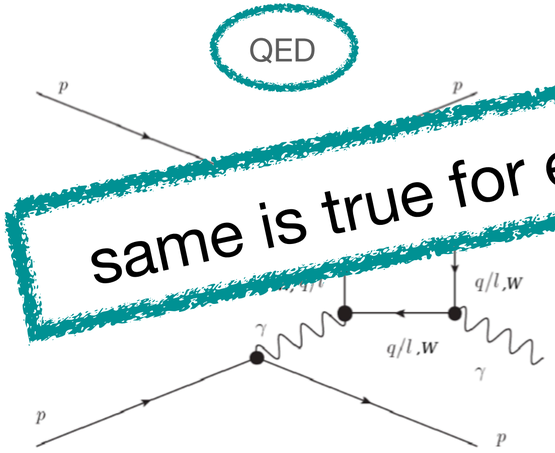
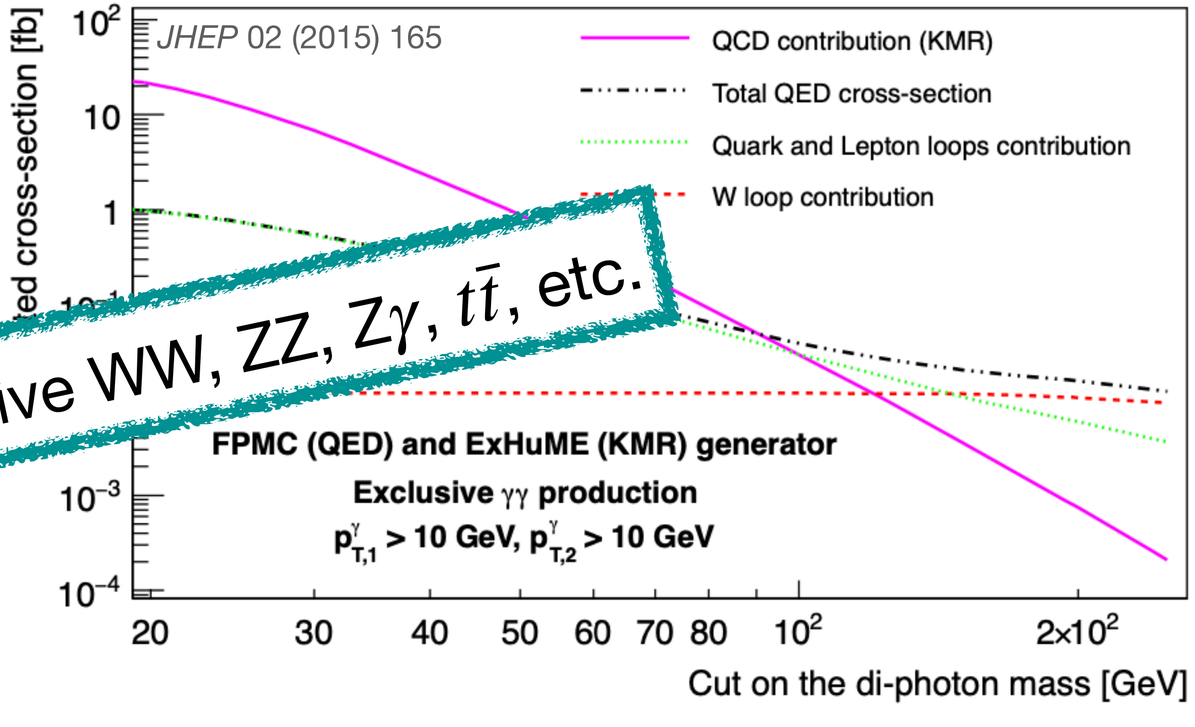




same is true for exclusive WW, ZZ, Zγ, $t\bar{t}$, etc.

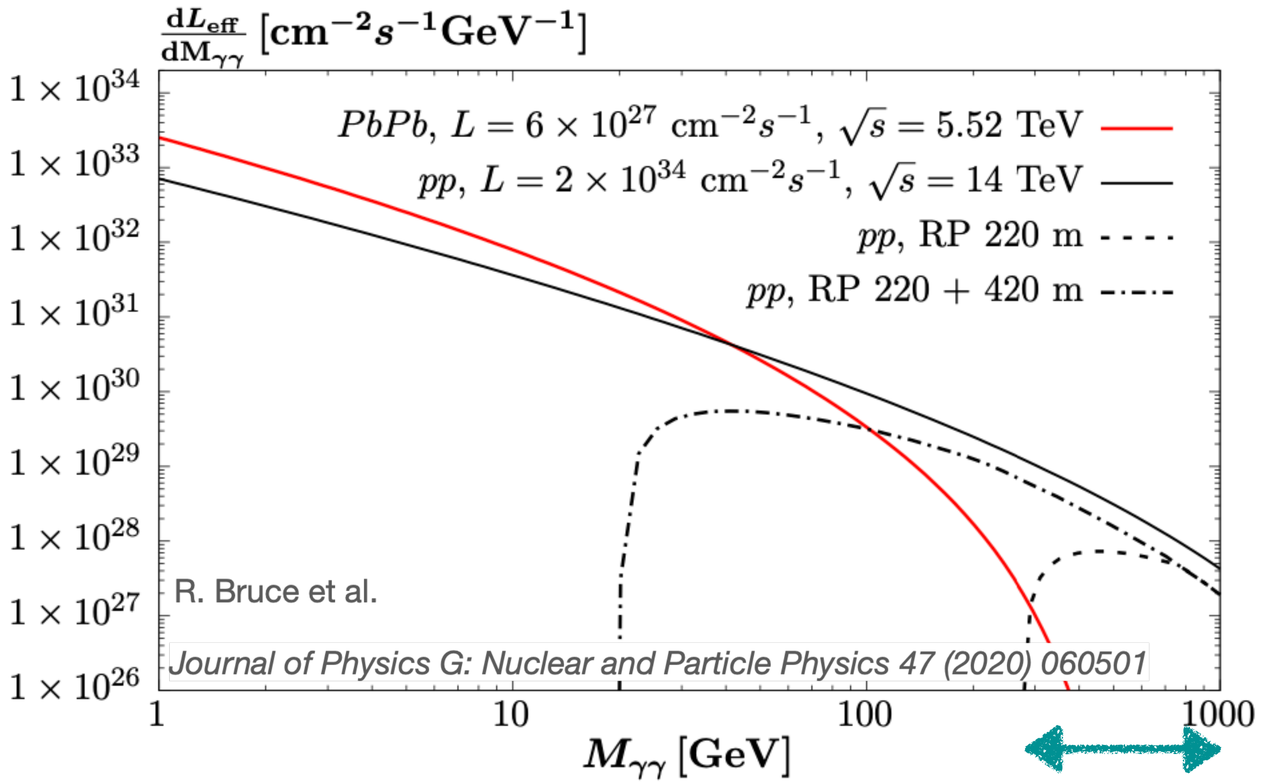
S. Fichet, G. von Gersdorff , B. Lenzi , C. Royon , M. Saimpert



Photon-induced processes

How can we measure them at the LHC?

- pp collisions only give access to high masses (where QED dominates);
- In PbPb collisions, the cross-section is enhanced (by a factor Z^4) and we gain access to the low masses



accessible with current Precision Proton Spectrometer setup

Photon-induced processes

Why do we want to measure them?

- Promising way to look for new physics
  - Sensitive to anomalous couplings of top quark, gauge bosons, …
- **Excellent mass resolution** irrespective of decay mode of central system
  - energy loss of outgoing protons directly related to invariant mass of central system
  - allows precision tests of SM couplings
- **High signal-to-background ratio:** matching protons to central system eliminates most backgrounds

“Turning” the LHC into a photon-proton and photon-photon collider offers a rich additional physics programme!

Photon-induced processes

Overview of the analysis possibilities

- Physics programme for photon-induced processes at the LHC divided in 3 categories:

LOW MASS

- PbPb collisions

  recent results:

  Exclusive dimuon production
  (Phys. Rev. Lett. 127 (2021), 122001)

  Light-by-light scattering
  (Phys. Lett. B 797 (2019))

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INTERMEDIATE MASS

- standard CMS program without tagged protons

Photon-induced processes

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INTERMEDIATE MASS

- standard CMS program without tagged protons

HIGH MASS

- CMS pp + tagged protons in PPS*

  recent results:

  (Semi)exclusive dilepton production
  (JHEP 07 (2018) 153)

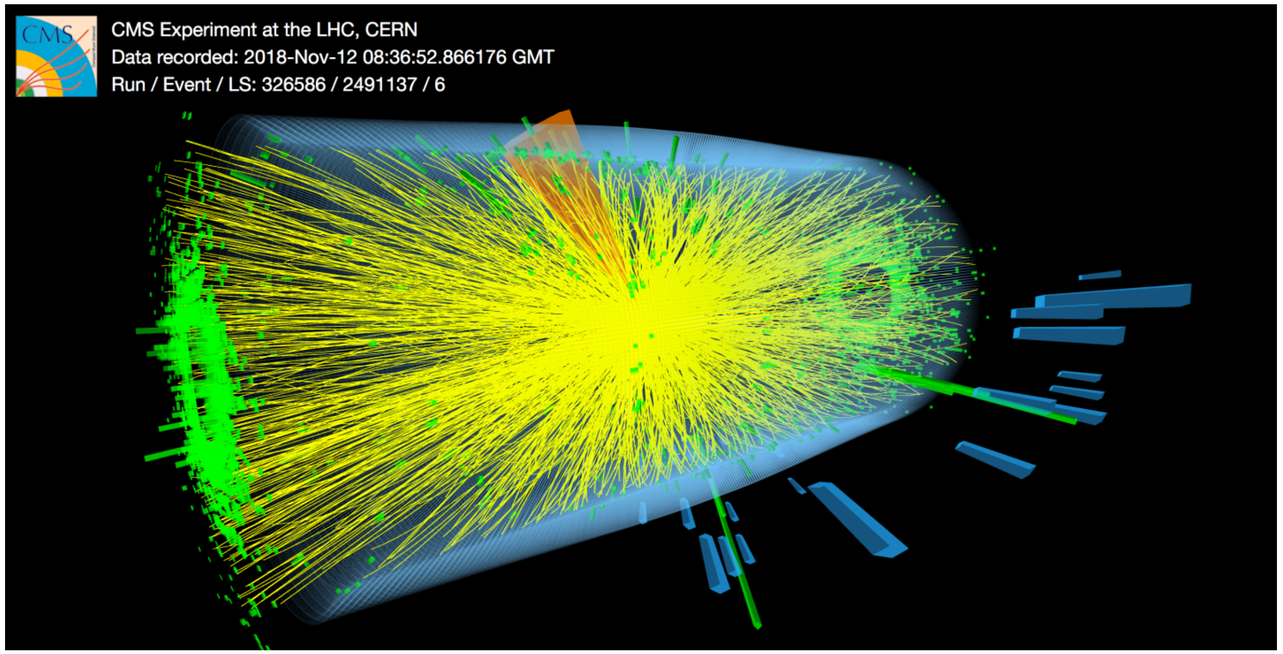
  Exclusive diphoton production
  (PAS-EXO-18-014)

*Precision Proton Spectrometer

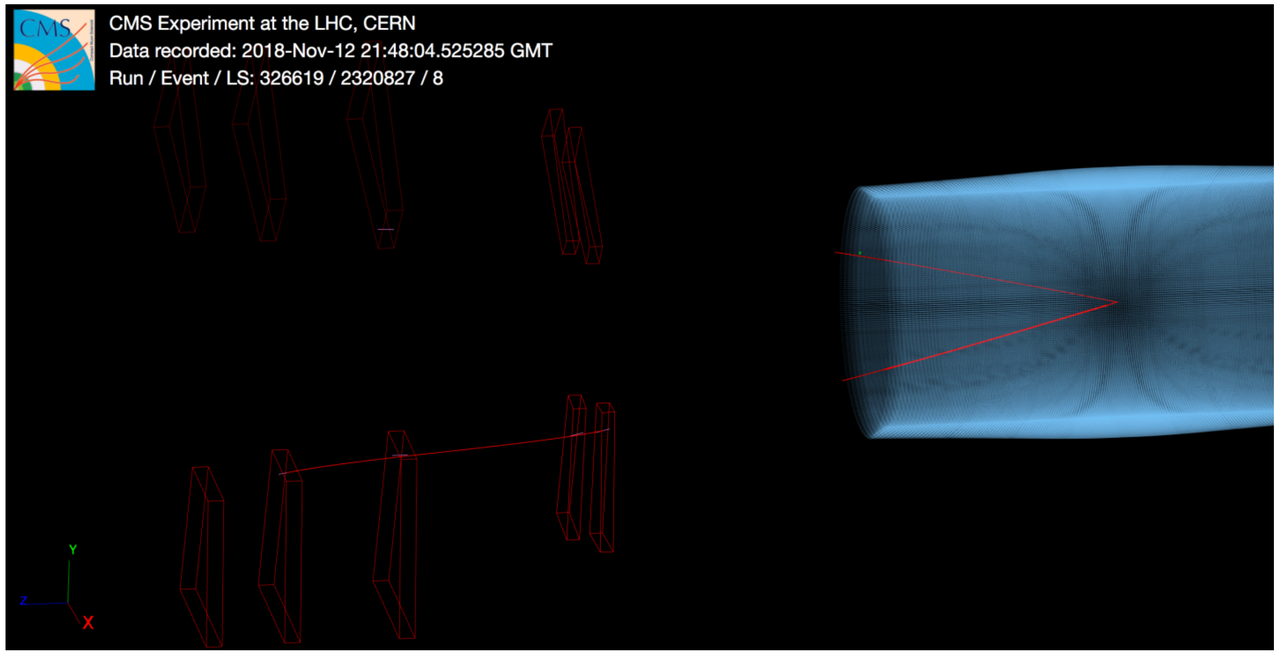
How to measure photon-induced processes?

Low mass: PbPb collisions at the LHC

- PbPb collisions: typically hundreds of particles are produced and events are very “crowded”
- Exclusive PbPb events: Pb ions stay intact and only few particles are observed in final state, creating a very distinctive signature



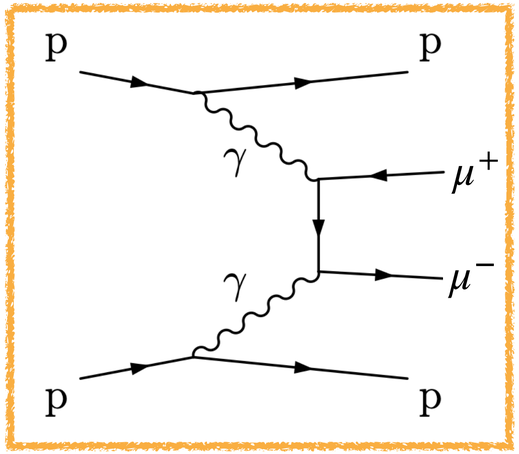
typical PbPb event



exclusive $\mu\mu$ candidate event

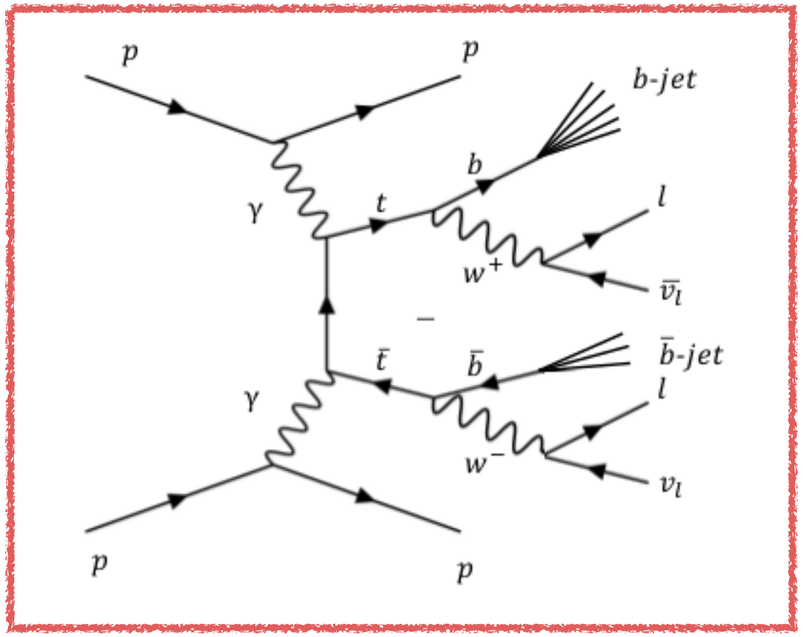
How to measure photon-induced processes?

High mass: pp collisions at the LHC



- In pp collisions, processes like $\gamma\gamma \rightarrow \mu\mu$ can be easy to tag since the muons are the only tracks in the event

- But in other processes, like $\gamma\gamma \rightarrow t\bar{t}$, it is more complicated, and a more distinctive signature is needed…

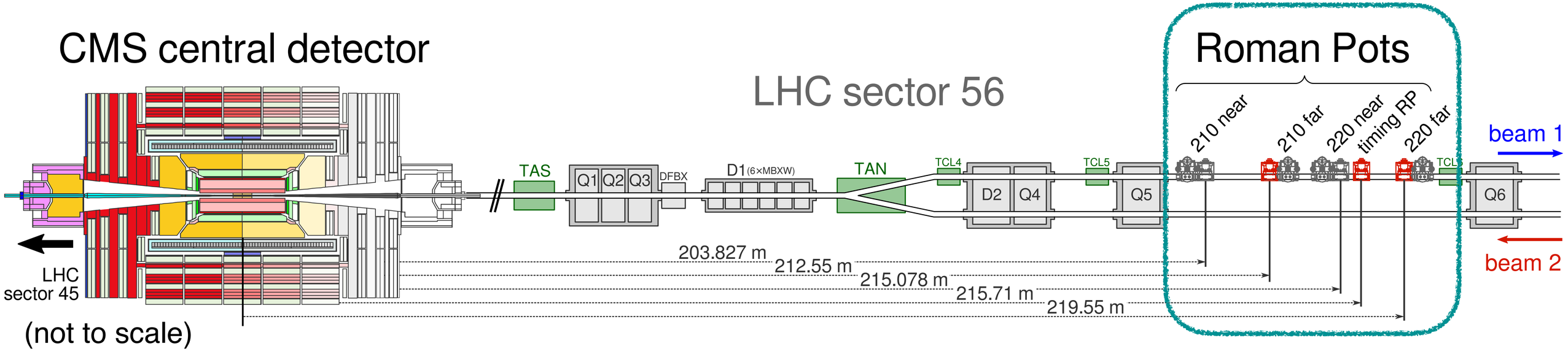


Tagging the outgoing protons!

How to measure photon-induced processes?

High mass: tagging intact protons

- Tagging protons requires development of dedicated detectors
- Measuring protons inside the beam pipe is extremely challenging
- In CMS: the CMS-TOTEM Precision Proton Spectrometer (PPS)



Tagging protons at CMS

The Precision Proton Spectrometer

- Tag protons that leave collision intact, at ~200 m from interaction point
- Can measure protons that lost ~2-20% of their momentum
  - Good acceptance at high masses (starting ~400 GeV)
- Data available for LHC Run 2 - 2016-2018 (> 100 fb^{-1})

momentum loss of each proton:

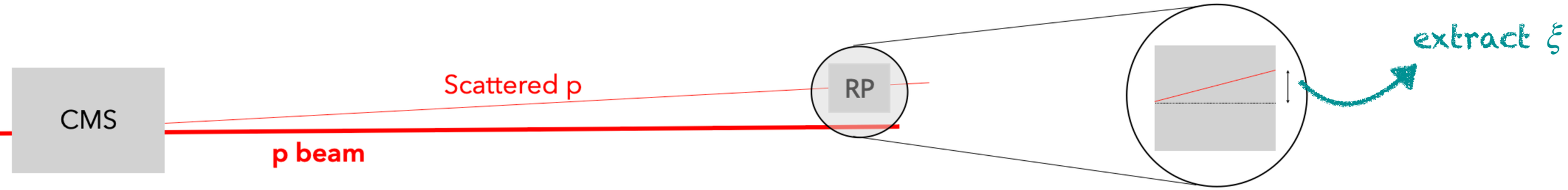
$$\xi_i = \frac{p_f - p_i}{p_i}$$

mass of the central system:

$$m_X = \sqrt{s\xi_1\xi_2}$$

rapidity of the central system:

$$y_X = \frac{1}{2}\log(\xi_1/\xi_2)$$



Overview of the results

Will focus on most recent (Run 2) results

PbPb collisions

- Exclusive dimuon production
  (Phys. Rev. Lett. 127 (2021), 122001)
- Light-by-light scattering
  (*Phys. Lett. B 797 (2019)*)

→ limits on ALPs

pp collisions with tagged protons

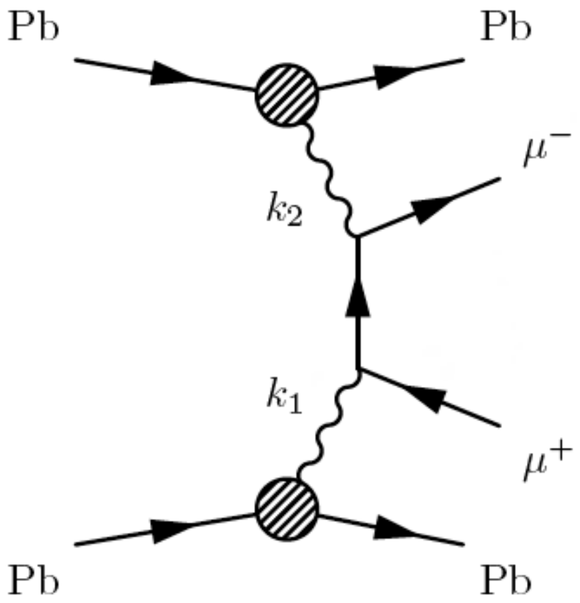
- Quasi-exclusive dilepton production
  (*JHEP 07 (2018) 153*)
- Exclusive diphoton production
  (*PAS-EXO-18-014*)

→ limits on $\gamma\gamma\gamma\gamma$ coupling

Exclusive dimuon production in PbPb

Phys. Rev. Lett. 127 (2021), 122001

- Ions accelerated with impact parameter $b > 2R_A$ can interact via photon-photon processes (ultra-peripheral collisions - UPC)



- p_T of muon pairs depends on overlap integral of the photon fluxes produced by the two nuclei → muon pair $< p_T >$ could depend on b
- QED calculation predicts larger $< p_T >$ for smaller b values → **goal is to test this!**
- Measuring $< p_T >$: larger $< p_T >$ results in larger acoplanarity $\alpha = 1 - |\Delta\phi_{\mu\mu}|/\pi$ (better experimental resolution)
- Experimental handle on b:

smaller b → more photon absorption → 1 or both ions get into higher excited states → emission of more forward neutrons detected by the ZDC*

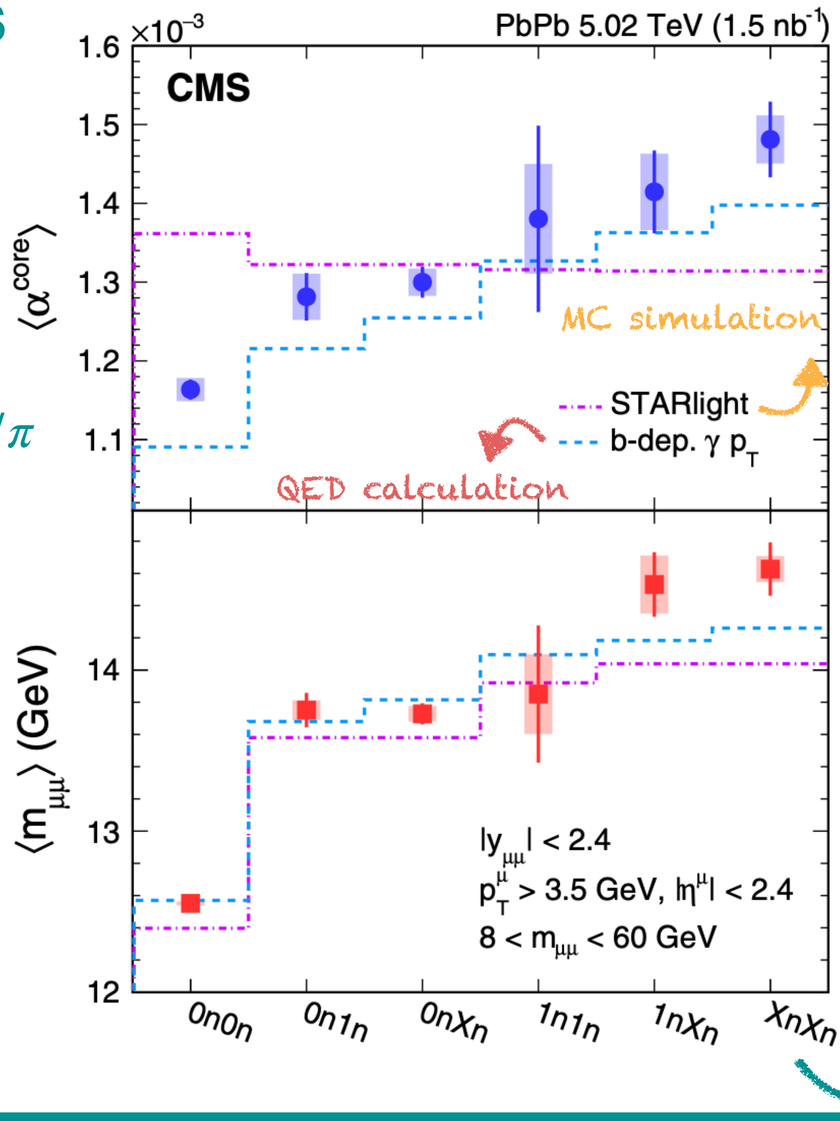
*zero-degree calorimeters, part of the CMS forward calorimeter system

Exclusive dimuon production in PbPb

Phys. Rev. Lett. 127 (2021), 122001

Results

$\alpha = 1 - |\Delta\phi_{\mu\mu}|/\pi$



number of forward neutrons emitted by each nucleus

- Initial energy and p_T of photons exchanged in ultra-peripheral collisions depend on impact parameter of interaction (b)
- Clear dependency observed, in qualitative agreement with QED calculation.

W. Zha et al.
Phys. Lett. B 800 (2020) 135089

- Dependency normally not fully taken into account when modelling photon-induced interactions

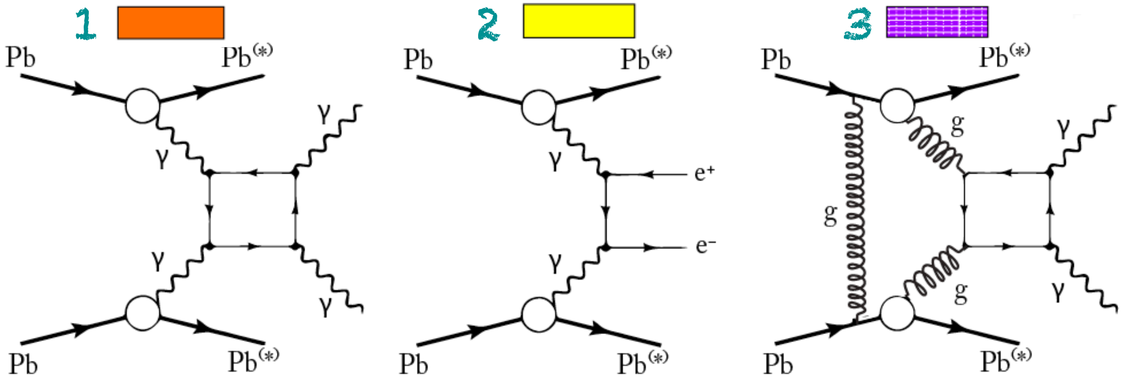
→ **theoretical effort needed in this direction**

Light-by-light scattering in PbPb

Phys. Lett. B 797 (2019)

- Signal: two back-to-back photons (1)
- Backgrounds: electrons misidentified as γ (2)

QCD $gg \to \gamma\gamma$ (3)

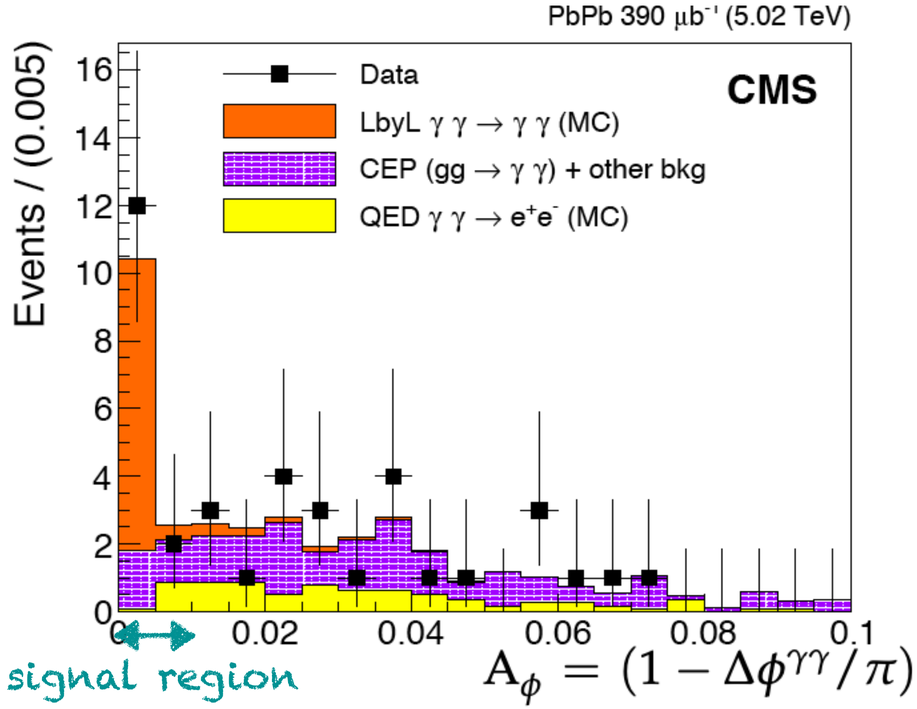


- 14 events observed
- 9.0 ± 0.9 signal expected and 4.0 ± 1.2 background (3.7σ - **evidence**)
- Measured fiducial cross-section, consistent with SM prediction

$$\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma) = 120 \pm 46\ (\text{stat}) \pm 12\ (\text{theo})\ \text{nb}$$

theory prediction: $\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma) = 116 \pm 12\,\text{nb}.$

(Phys.Rev.Lett. 111 (2013) 080405,)



Light-by-light scattering in PbPb

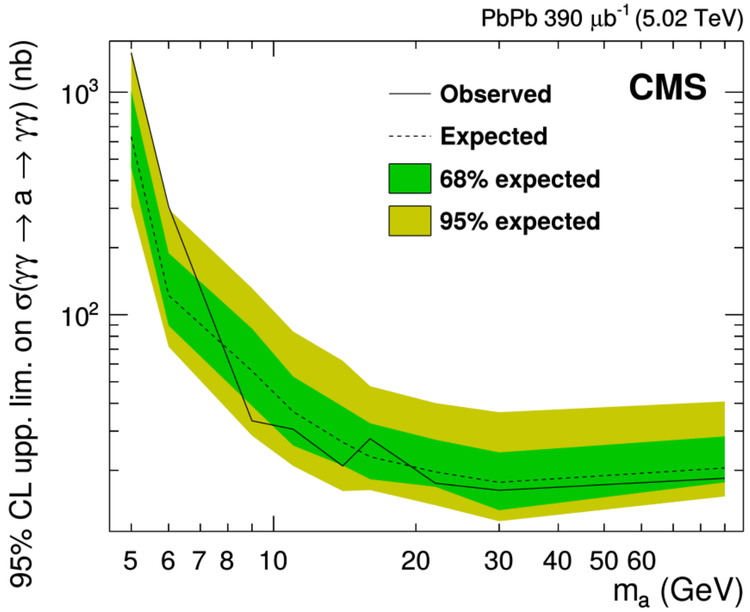
Phys. Lett. B 797 (2019)

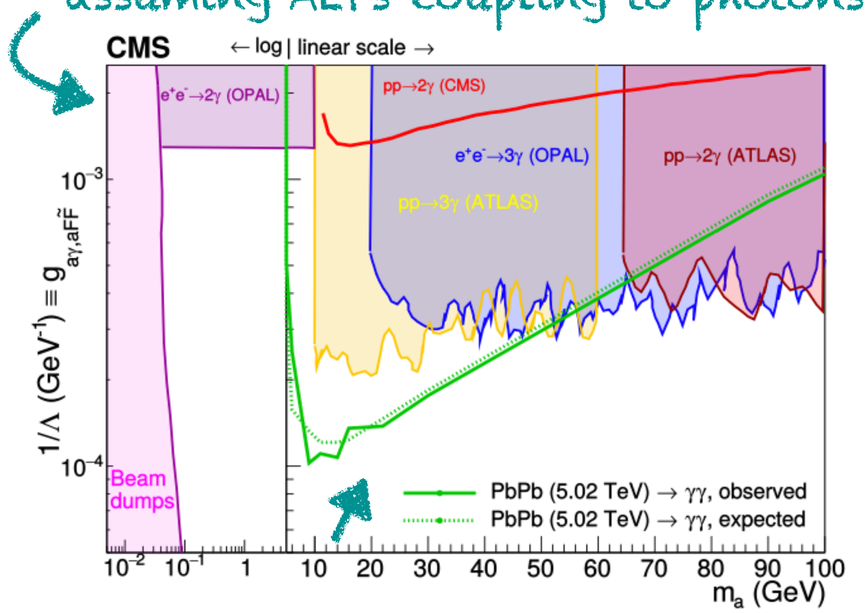
Limits on ALPs

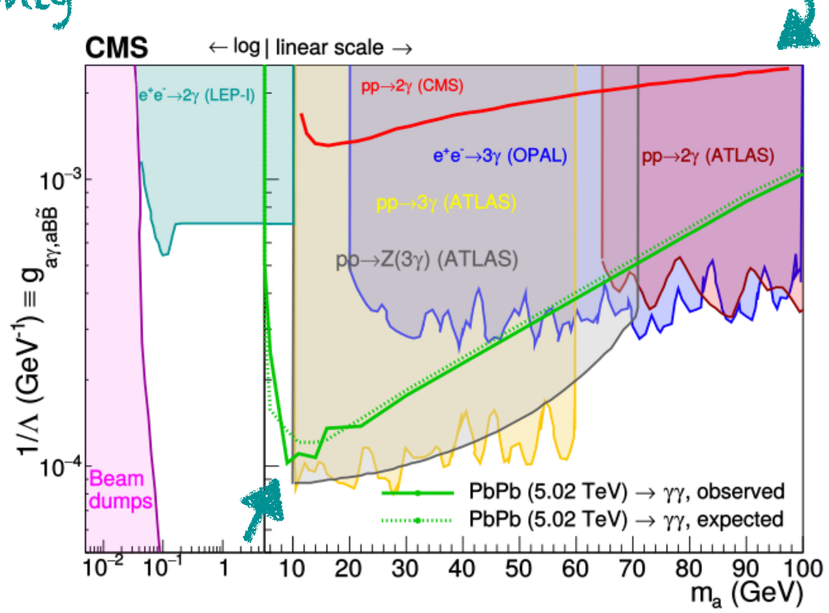
- New spin-even particles like pseudo scalar axion-like particles (ALPs) can contribute to LbyL scattering continuum or to new diphoton resonances
- This work sets limits on ALPs production in the range $m_a = 5 - 90$ GeV

assuming also the hyper charge coupling

assuming ALPs coupling to photons only







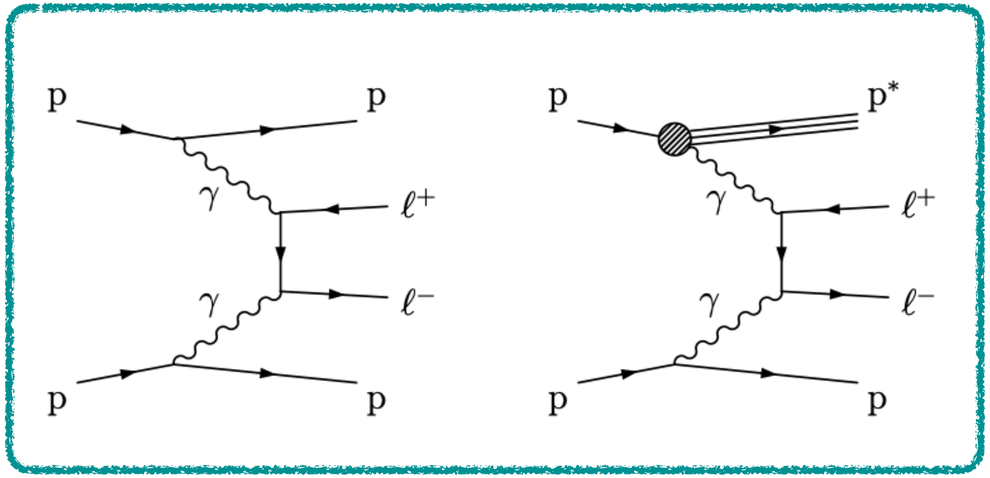
Best limits to date over the mass range $m_a = 5 - 50$ GeV ($5 - 10$ GeV) for ALPs coupling to electromagnetic (electroweak) current

JHEP 07 (2018) 153

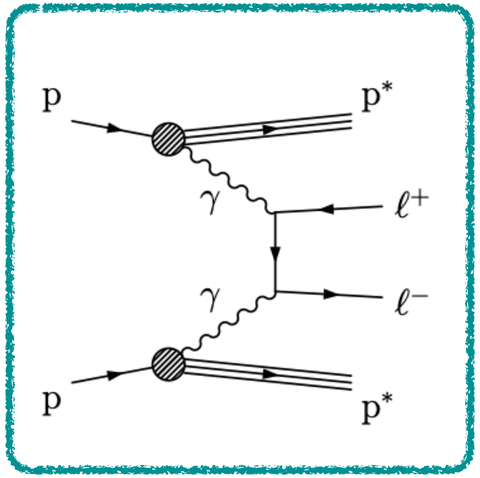
(Semi)exclusive dileptons in pp

The idea

- Exclusive and semi-exclusive production of lepton pairs, dominated by photon interaction
- Tag one (or both) protons with PPS. Double-arm acceptance of PPS starts at $m_{ll} \approx 400$ GeV →low expected number of double tagged events



Signal (1 or 2 intact protons)

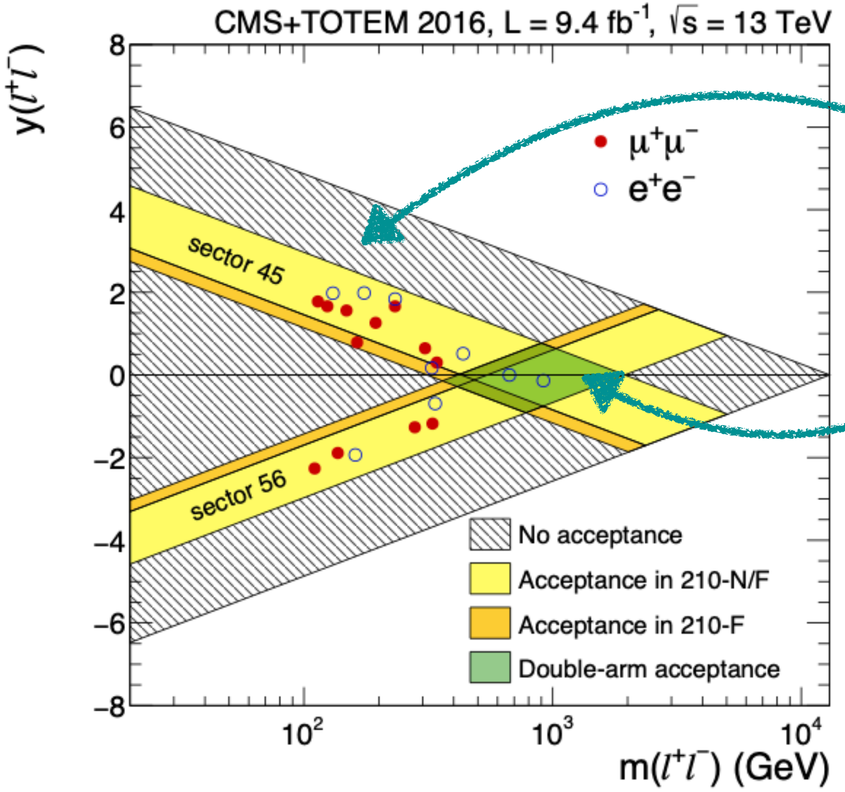


Background (both protons dissociate)

(Semi)exclusive dileptons in pp

JHEP 07 (2018) 153

The observation



Very important to validate PPS functioning (alignment, optics)

- e^+e^- / $\mu^+\mu^-$ selection in the central system combined with proton(s) in PPS (2016 data)
- Observation of semi-exclusive events with one tagged proton
- No observation for double-tagged events

$\mu^+\mu^-$: observed 12 events
exp. background of 1.49 ± 0.07 (stat) ± 0.53 (syst) → 4.3 σ

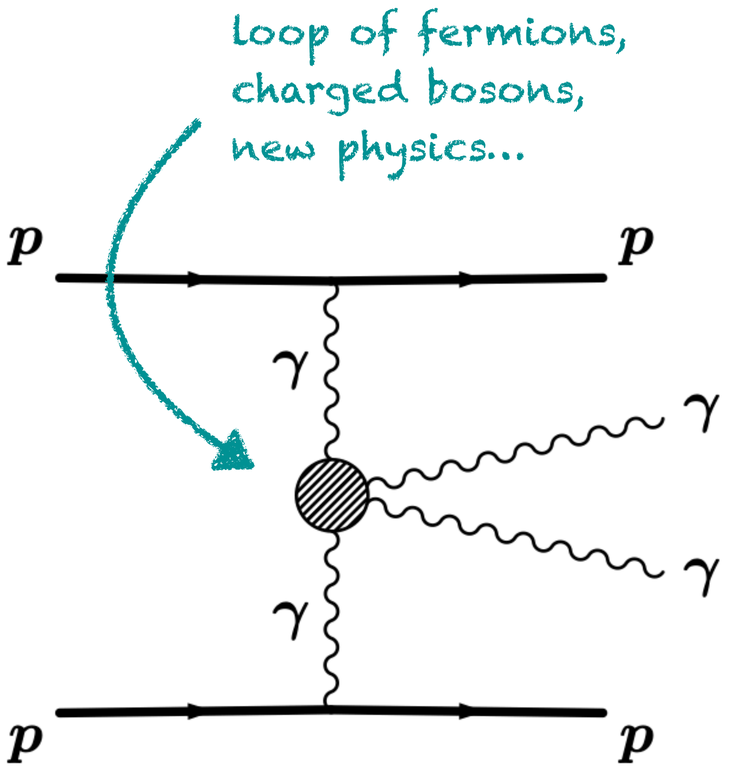
e^+e^-: observed 8 events
exp. background of 2.36 ± 0.09 (stat) ± 0.47 (syst) → 2.6 σ

Combined significance > 5 σ

PAS-EXO-18-014

Exclusive diphotons in pp

Motivation



- Light-by-light scattering (LbyL) observed by CMS and ATLAS at low mass (up to a few GeV)
- First study of LbyL at high mass ($m_{\gamma\gamma} > 350$ GeV) at a hadron collider
- Sensitive to an effective dimension-8 extension of the SM (anomalous $\gamma\gamma\gamma\gamma$ couplings)

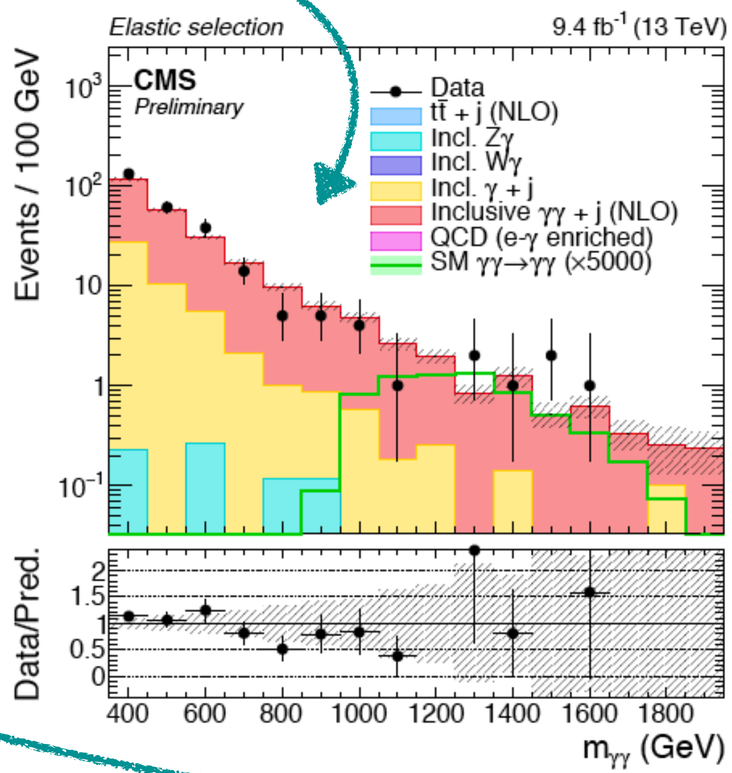
Exclusive diphotons in pp ($\gamma\gamma\gamma\gamma$ couplings)

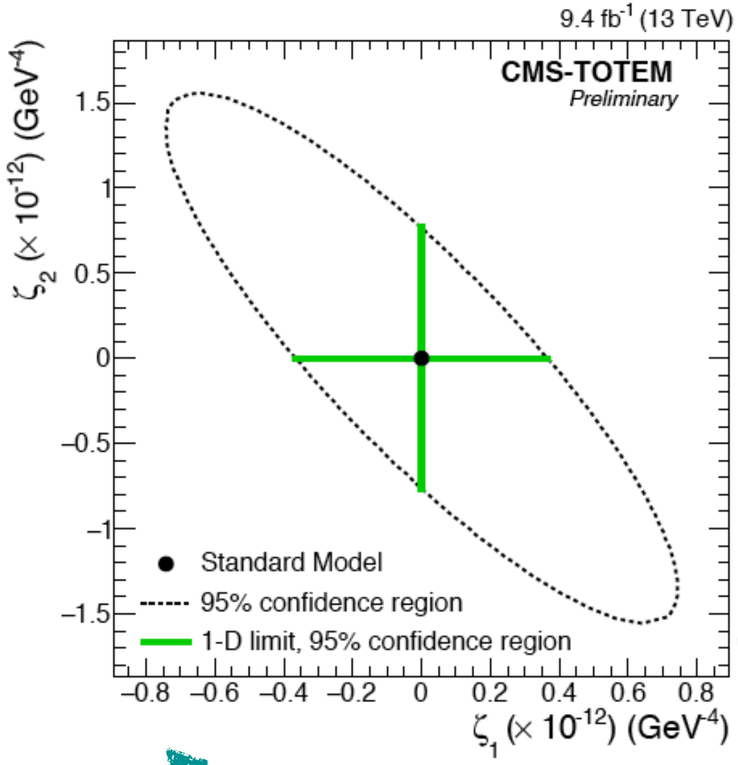
PAS-EXO-18-014

- 2016 data: detect two photons with CMS and two outgoing protons with CT-PPS
- Select events with photon $p_T > 75$ GeV, $m_{\gamma\gamma} > 350$ GeV (compatible with CT-PPS double-arm acceptance) and $1 - |\Delta\phi_{\gamma\gamma}| < 0.005$
- After proton matching: observed 0 events

Set limits on quartic gauge couplings using the coupling parameters ζ_1 and ζ_2

$$|\zeta_1| < 3.7 \times 10^{-13}\ \text{GeV}^{-4} \quad (\zeta_2 = 0),$$
$$|\zeta_2| < 7.7 \times 10^{-13}\ \text{GeV}^{-4} \quad (\zeta_1 = 0).$$





Summary

- Presented results on exclusive production of e^+e^-, $\mu^+\mu^-$, $\gamma\gamma$ in pp and PbPb collisions
- Set competitive limits on anomalous couplings and ALPs
- Current results with up to 9.4 fb^{-1}
- $>$ 100 fb^{-1} of data currently being analysed, many results to be out soon
- **Future:** more data and improved PPS setup will provide additional sensitivity

Stay tuned!

Backup slides

Photon-induced processes

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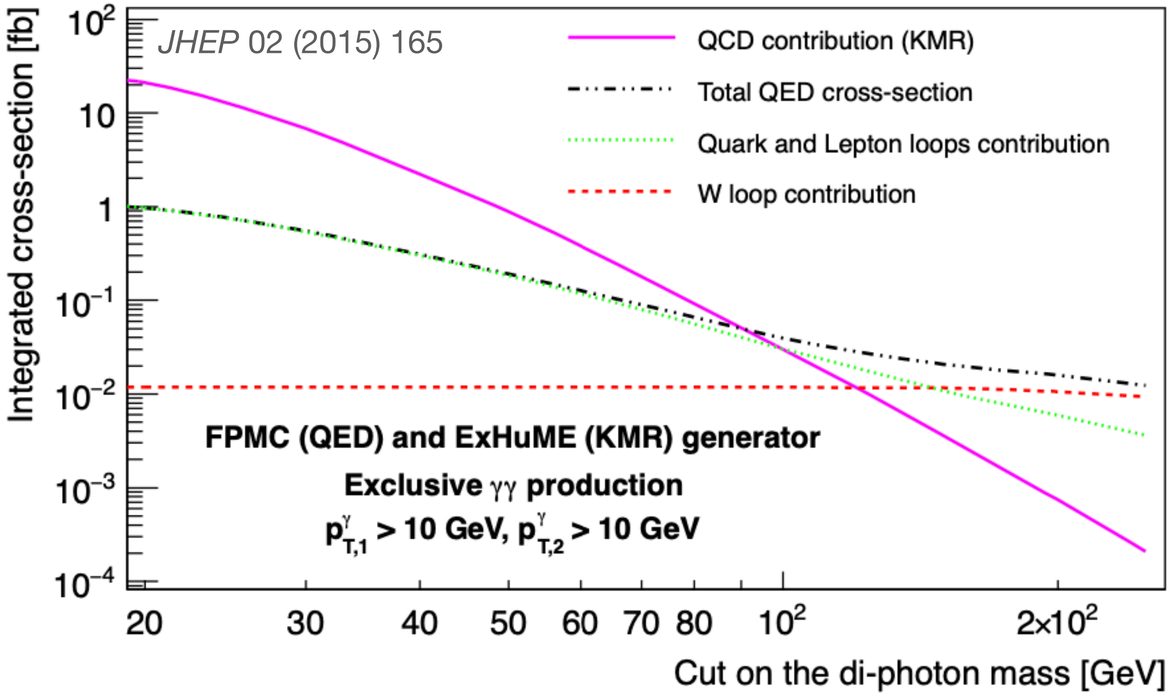

from S. Fichet, G. von Gersdorff , B. Lenzi , C. Royon , M. Saimpert

(Semi)exclusive dileptons in pp

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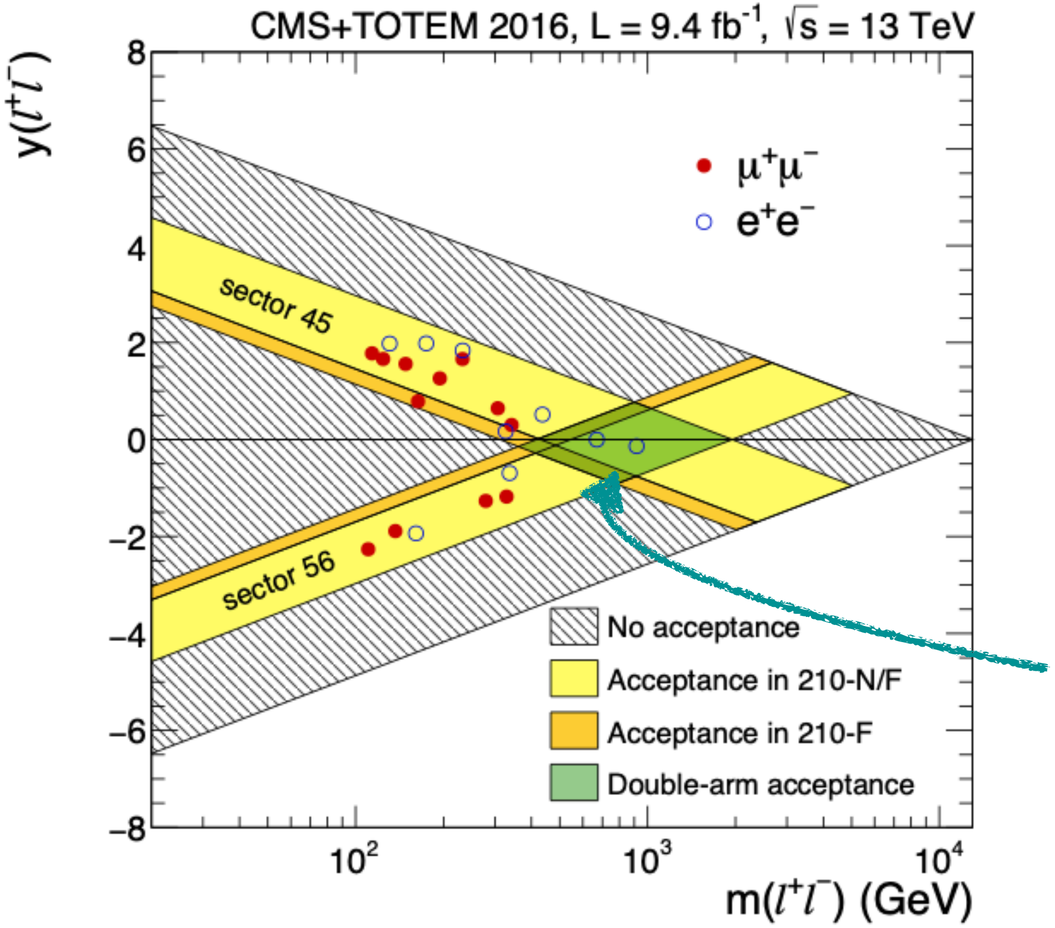
The event candidates



- e^+e^- / $\mu^+\mu^-$ selection in the central system combined with proton(s) in PPS (2016 data)
- Invariant mass and rapidity of two leptons superimposed with CT-PPS arms acceptance
- Observation of quasi-exclusive events with one tagged proton
- No observation for double-tagged events (the 2 events in the green area are consistent with expected pileup background)

(Semi)exclusive dileptons in pp

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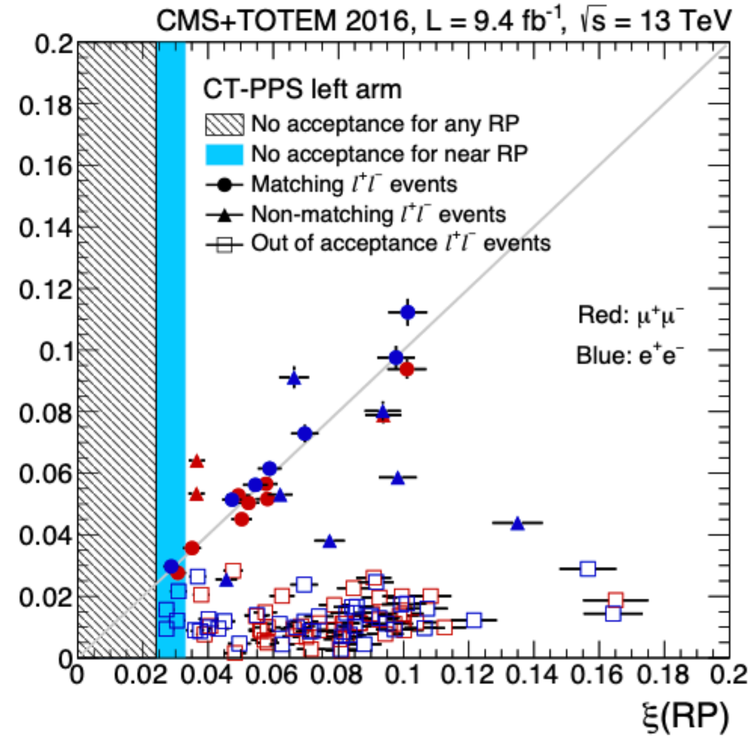
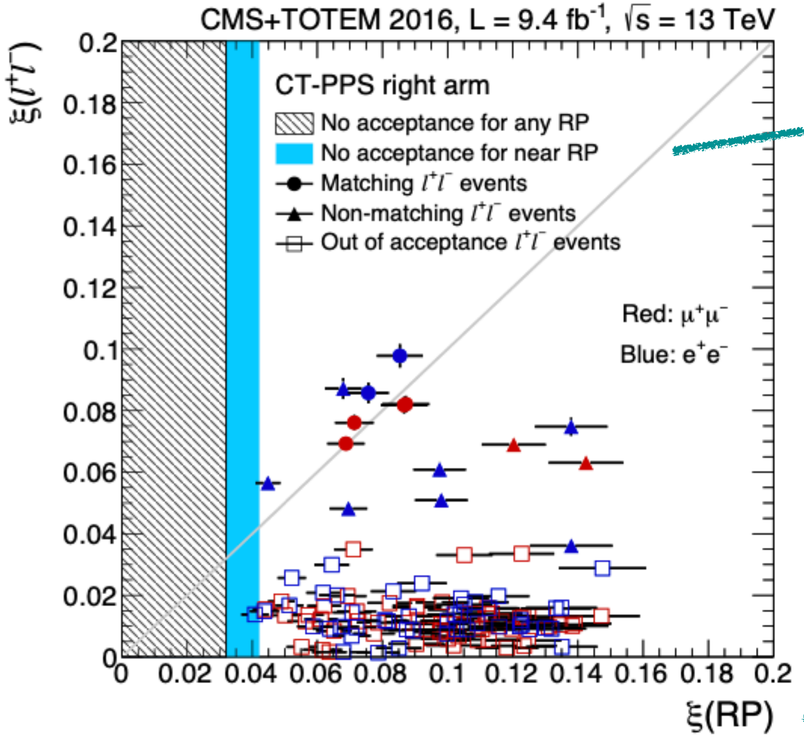
Observation

- Plots: expected proton momentum loss (ξ) from lepton kinematics vs. measured ξ in PPS

computed from lepton kinematics





events along the diagonal are the signal-like events

proton measured in PPS

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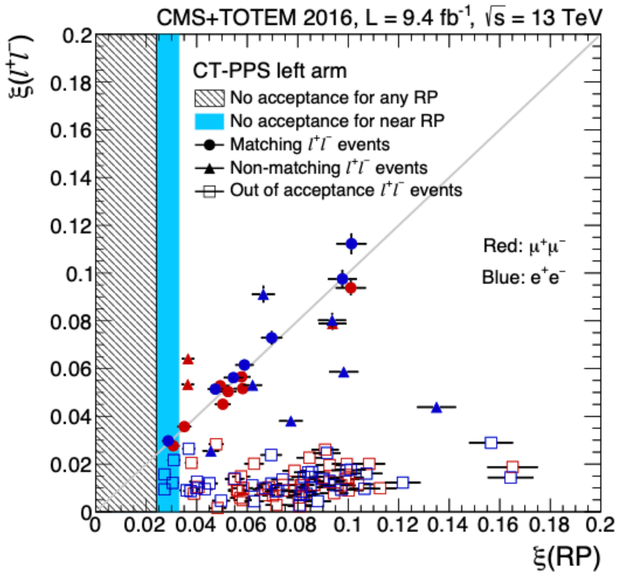
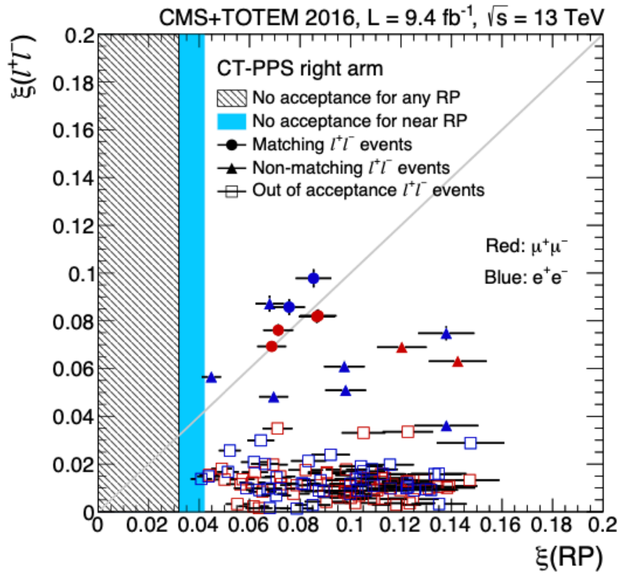
(Semi)exclusive dileptons in pp

Observation





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- ***Combined significance > 5 σ***

Very important result to validate PPS functioning (alignment, optics)

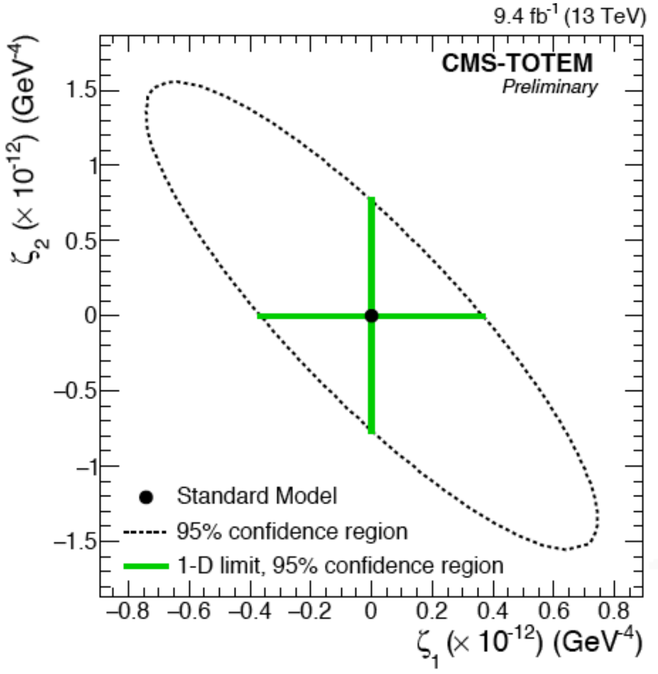
Exclusive diphotons in pp ($\gamma\gamma\gamma\gamma$ couplings)

PAS-EXO-18-014

The LbyL scattering process, which can be studied at the electroweak energy scale and higher in proton-proton collisions at the LHC, is of great interest because of its sensitivity to many SM extensions of quantum electrodynamics [9–13]. Among these, a purely effective extension of the SM Lagrangian using charge-parity conserving operators, as used, e.g., in Refs. [14–16] for the $\gamma\gamma W^+W^-$ quartic coupling, leads to a minimum dimension-eight term for the four-photon coupling. This term contains the two parameters $\zeta_{1,2} = a_{1,2}^{\gamma\gamma}/\Lambda^4$, where Λ is the scale for new physics, generally at the order of a few TeVs:

$$L_8^{\gamma\gamma\gamma\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\mu\rho}F_{\rho\sigma}F^{\sigma\nu}.$$

$$|\zeta_1| < 3.7 \times 10^{-13}\ \text{GeV}^{-4} \quad (\zeta_2 = 0),$$
$$|\zeta_2| < 7.7 \times 10^{-13}\ \text{GeV}^{-4} \quad (\zeta_1 = 0).$$



Exclusive WW + anomalous quartic gauge couplings

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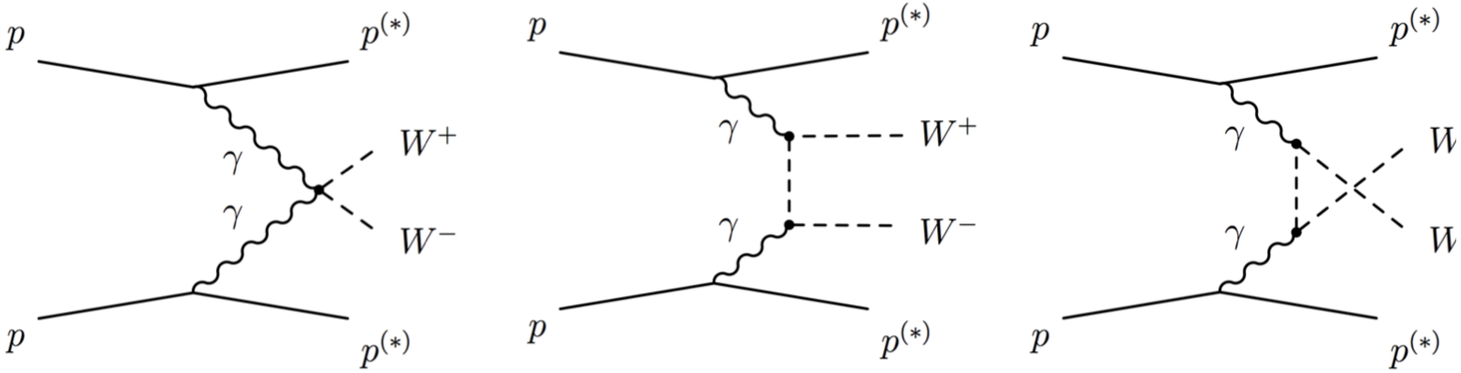
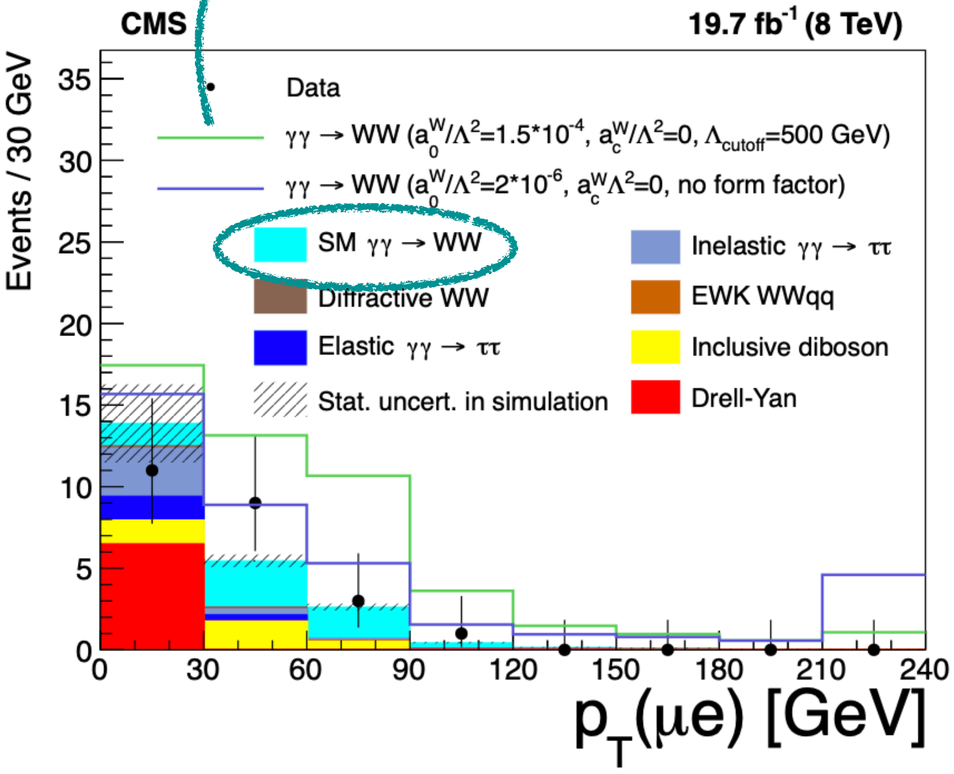
Run 1 result at 7+8 TeV (5.1+19.7 fb^{-1})

- Select events with opposite sign $e\mu$ pair and $p_T(e\mu) > 30$ GeV and no associated charged particles detected from the same vertex
- 13 (2) events are observed over an expected background of 3.9 ± 0.6 (0.84 ± 0.15) events for 8 (7) TeV → excess of 3.4σ **(evidence)**



$\gamma\gamma \rightarrow WW$ sensitive to anomalous quartic gauge couplings



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Exclusive WW + anomalous quartic gauge couplings

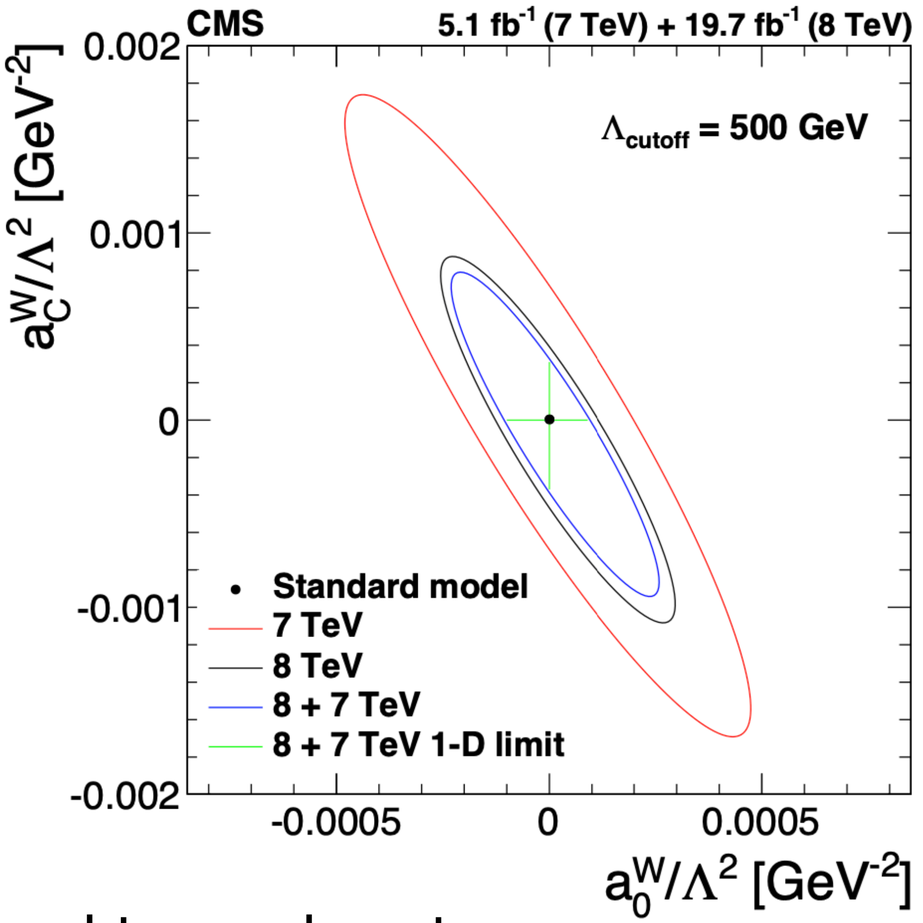
Run 1 result at 7+8 TeV (5.1+19.7 fb^{-1})

- Results compatible with SM prediction for $\gamma\gamma \to WW$

  obs.: $\sigma(\mathrm{pp} \to \mathrm{p}^{(*)}\mathrm{W}^{+}\mathrm{W}^{-}\mathrm{p}^{(*)} \to \mathrm{p}^{(*)}\mu^{\pm}\mathrm{e}^{\mp}\mathrm{p}^{(*)}) = 10.8^{+5.1}_{-4.1}\,\mathrm{fb}.$

  SM prediction: $6.2 \pm 0.5\,\mathrm{fb}$,

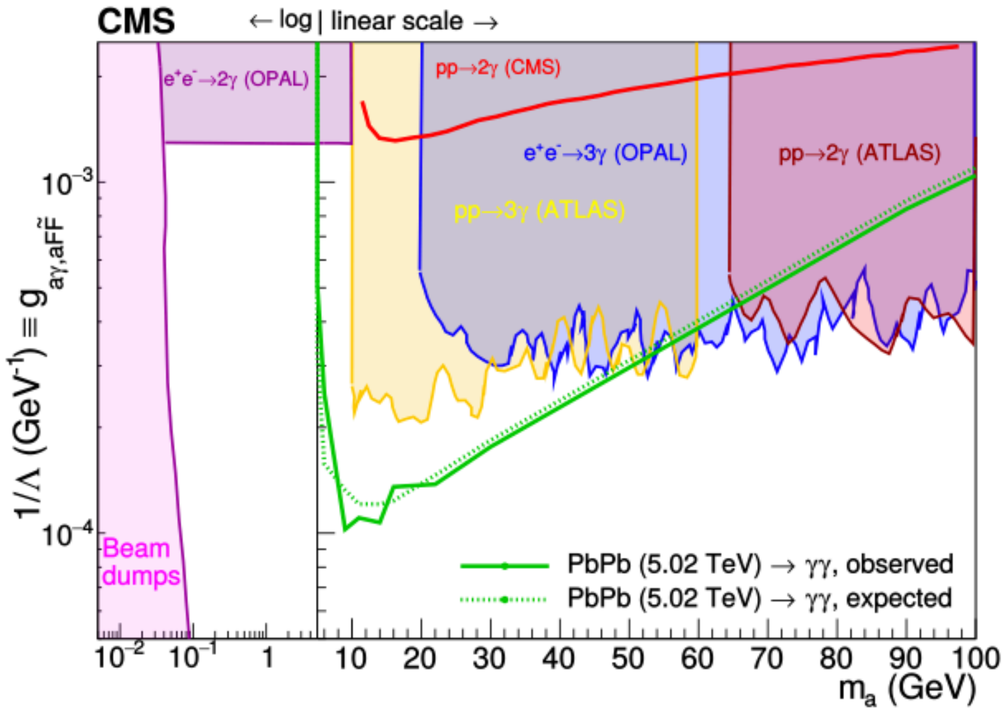
- Most stringent to date upper limits on the anomalous quartic gauge coupling operators $a^{W}_{0,C}$(dimension-6) and $f_{M0,1,2,3}$ (dimension-8) are derived



- Improved sensitivity is possible with Run 2 data and tagged protons

Light-by-light scattering in PbPb

Phys. Lett. B 797 (2019)



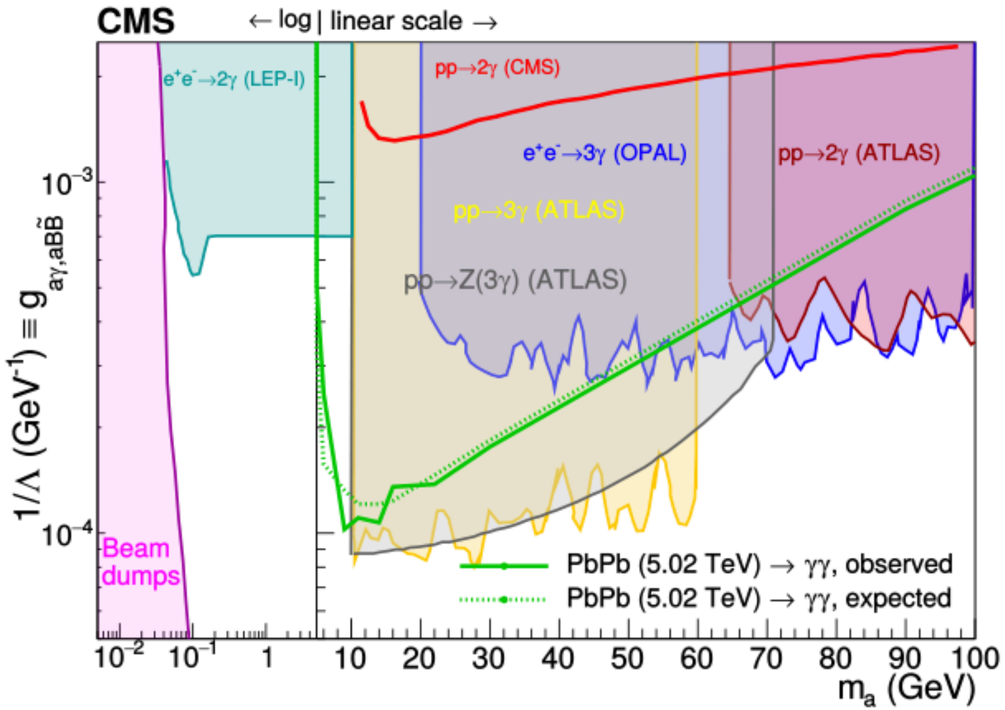
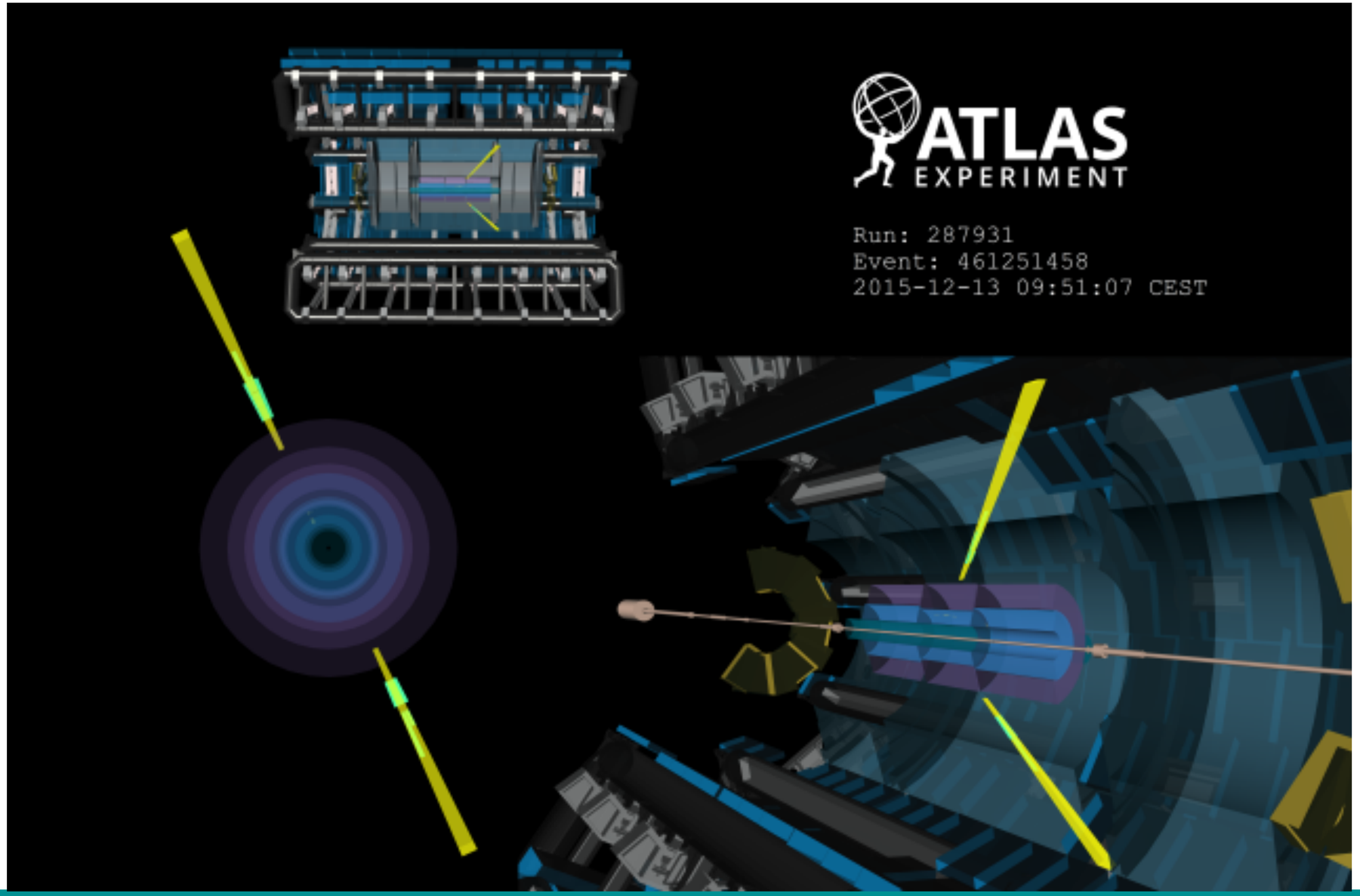


Figure 7: Exclusion limits at 95% CL in the ALP-photon coupling $g_{a\gamma}$ versus ALP mass m_a plane, for the operators $aF\widetilde{F}/4\Lambda$ (left, assuming ALP coupling to photons only) and $aB\widetilde{B}/(4\Lambda\cos^2\theta_W)$ (right, including also the hypercharge coupling, thus processes involving the Z boson) derived in Refs. [30, 56] from measurements at beam dumps [60], in $e^+ e^-$ collisions at LEP-I [56] and LEP-II [57], and in p p collisions at the LHC [13, 58, 59], and compared to the present PbPb limits.

Light-by-light scattering in PbPb at ATLAS



Typical PbPb collision event at ATLAS